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LHC Results Highlights

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Abstract

The good performance of the LHC provided enough data at 7 TeV and 8 TeV to allow the experiments to perform very competitive measurements and to expand the knowledge about the fundamental interaction far beyond that from previous colliders. This report summarizes the highlights of the results obtained with these data samples by the four large experiments, covering all the topics of the physics program and focusing on those exploiting the possibilities of the LHC.

1 Introduction

The standard model (SM) [1–3] of particles and interactions is currently the most successful theory describing the Universe at the smallest distances, or equivalently, highest energies. Such task is performed with the use of three families of fermions and a number of bosons associated to the interactions as given by the $SU(3)_C \times SU(2)_L \times U(1)_Y$ symmetry group. Since in Nature the $SU(2)_L \times U(1)_Y$ is not an exact symmetry, we require an additional field, the so-called Higgs field, which sponteneously breaks the symmetry according to the BEH mechanism [4], giving rise to the weak and electromagnetic interactions as they are observed at lower energies. In addition this field is responsible to give mass to the fermions.

Although successful, the SM does not appear to be complete since several esperimental evidences are not included in the model. In this group, it should be remarked that gravitational effects are not described, neither are all the related effects, such as Dark Matter or Dark Energy. In addition the current structure of the SM does not include enough CP violation to justify the observed matter-antimatter imbalance in the Universe. Finally the neutrinos in the model are assumed to be massless, something that currently is experimentally discarded after the measurements of neutrino mixing.

In addition to the missing parts in the SM there are several points in which the model is not completely satisfactory, concretely related to theoretical aspects of it. Several issues are always mentioned in this context, but they are summarized in three main issues: the need of fine-tuning to understand the low scale of the electroweak symmetry breaking and other parameters (the hierarchy problem), the lack of understanding on why there are three families with double-nature sets (i.e. quark and leptons) and the lack of apparent relation between the different interactions (i.e. the origin of the observed values for couplings, including fermionic masses). In practice, the SM has clear limitations since it misses too many explanations about why things are as they are and it requires too many parameters to actually describe things as they are.

The proposed solution to both the experimentally-motivated limitations and the theoretical dissatisfaction is to add more interactions or particles which complete the model. In such scenario, the SM would become a low-energy approximation, or visible part, of a larger theory. By increasing the energy in our studies we gain access to the additional particles and effects, which are usually referred to as “new physics” or “physics beyond the SM” (BSM). These effects that are not explained by the SM will provide additional information about the limitations of the SM, opening the correct doors towards a more accurate description of our Universe.

With this motivation we are led to the design of a powerful hadronic collider which maximizes the reach in sensitivity to the possible BSM physics. This is achieved by maximizing the available energy, which would provide the possibility to produce more massive particles, and the number of collisions per time unit (luminosity), which increase the yield for the produced particles and effects. This is exactly

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the motivation for the Large Hadron Collider (LHC) [5] located at CERN, near Geneva (Switzerland), which is recognized as "the discovery machine" for physics beyond the SM providing a large amount of energy per collision and a large amount of collisions.

In the following sections we will describe the LHC and the related experiments and report on the main results for the different part of the program, designed to take advantage of all the possibilities given by such powerful machines.

2 The LHC and the experiments

The LHC is the most energetic and most challenging collider up to date. It is designed to collide protons or heavy ions at a maximum energy of 14 TeV of energy and very high collision rates. Technical limitations has prevented it to reach its design parameters, and the collected datasets contains collisions at 7 or 8 TeV of total center-of-mass energies. In any case this represents more than 3 times more energy than the previously most energetic collider (The Tevatron at Fermilab, USA). This allows to reach energy scales that were not accessible before, both for particle and heavy-ion physics.

But the LHC is not just about large energy: it also provides the largest collision rate ever reached, allowing to collect sizable data samples in record time. To quantify the amount of data, the previously mentioned concept of luminosity is used. The integrated luminosity relates the number of a type of events in a sample and the cross section for that type of event. Experimentally, this allows to compute the luminosity ("calibrate" the size of the sample) using a very well known process and count the number of events from it, and so $L = N/\sigma$ where L is the luminosity, N the number of events and σ the cross section of the process. Once the sample luminosity is known, the value is used to measure cross sections of processes of interest, as $\sigma = L/N$. Finally, knowing the cross section of a process, one estimates the number of expected events from that process in the sample with $N = L \cdot \sigma$. These are the basic tools to perform analysis of the data samples.

At the LHC during the first years of operations, samples of reasonable size were obtained at 7 TeV (in 2010 and 2011), accounting for 6 fb^{-1} of luminosity for proton-proton collisions and 170 $\mu\mathrm{b}^{-1}$ for lead-lead collisions. Additionally, data at 8 TeV were obtained for proton-proton collisions, accounting to 23.3 fb^{-1}, and proton-lead collisions with a luminosity of 32 nb^{-1}. The results described in this report have been obtained by using these data samples.

The collisions provided by the LHC occur at four interaction points along the 27-km ring. At those points, several experiments are located. The main four experiments are ALICE, ATLAS, CMS and LHCb and are located as shown in Fig. 1. These four experiments collect the data from the collisions and provide the results of the physics analyses, as described in the following sections.

In addition to the main experiments, other three *minor* experiments are intended for more dedicated studies: TOTEM [6], LHCf [7] and MoEDAL [8]. Neither their results nor plans will be covered here since their scientific output is very specific and beyond the aim of this report. However, this should not minimize their importance in order to understand forward production (as it is the case of the first two) or dedicated search for magnetic monoples (as it is the aim of MoEDAL).

Each of the main experiments deserved some specific description to put into context the physics output they provide.

2.1 The ATLAS experiment

ATLAS [9] is the largest experiment at the LHC. It is intended to study all possible physics topic by analysing the full final state of the LHC collisions. It is characterized by its great capabilities in tracking and calorimetry surrounded by huge muon-detection chambers in a toroidal field.

The detector has almost full solid-angle coverage with a forward-backward symmetric distribution. It is also azimuthally symmetric, as expected for the physics in the collisions. The hermetic design allows

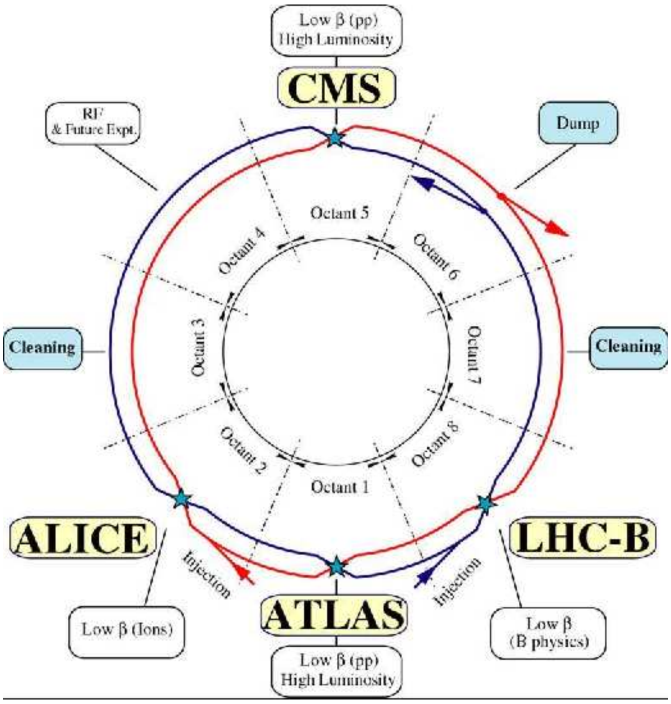

Fig. 1: Schematic layout of the LHC and the main experiments, identified at their location in the accelerator ring.

to infer the presence of undetected particles via the transverse momentum embalanace, the so-called “missing E_T” (E_T^{miss}), which can be computed as:

$$E_T^{\text{miss}} = \sqrt{\left[\sum p_x\right]^2 + \left[\sum p_y\right]^2} \quad ;$$

where the sum runs over the observed particles (regardless on the way they are detected and reconstructed).

This quantity is expected to be small due to the conservation of the momentum and therefore a significantly large value is interpreted as the presence of particle(s) that escape detection, as if the case of neutrinos and other weakly-interacting particles which do not interact with matter by mean of the nuclear or electromagnetic forces.

In order to quantify the coverage of the detector, another interesting variable is the pseudorapidity, an alternative to the polar angle θ defined as:

$$\eta = -\ln\bigl[\tan\bigl(\theta/2\bigr)\bigr] = \frac{1}{2}\ln\bigl[\frac{|p| + p_z}{|p| - p_z}\bigr]$$

which is well suited for cylindrical description of events, as it is the case of collisions involving hadrons in the initial state.

The structure of ATLAS allows to reconstruct jets up to $|\eta| \sim 4.5$, muons up to $|\eta| \sim 3$ and electrons and photons up to $|\eta| \sim 2.47$, providing a very large coverage for the main pieces to study the final states in the LHC collisions.

2.2 The CMS experiment

CMS [10] is the other multipurpose detector of the LHC. Similar to ATLAS in aim and capabilities, it present a more compact structure for a similar performance due to its stronger magnetic field. It is also hermetic and provides an impressive energy resolution for electrons and photons, for a coverage of $|\eta| < 2.5$. Muons are detected up to $|\eta| \sim 2.4$ with a more traditional approach that takes advantage of the redundancy with the inner tracking. Finally jets are reconstructed up to $|\eta| \sim 4.5$.

When comparing both detectors, the strong point of CMS is the great resolution in the inner tracking, which becomes the core of the detector, specifically when used as redundancy for reconstruction of muons and other particles. On the other hand, ATLAS has better global calorimetry and more precise and sophisticated muon detection.

However, these differences are in practice more technical than real, since the treatment of the data in the reconstruction of objects allows both collaborations to obtain very comparable results. The idea is to compensate the limitations of the detectors with the information coming from the stronger parts or redundant informations from other components.

One good example of this is provided by the concept of *particle flow* that has been extensively used in the last years, specially in the CMS analyses. The idea is that instead of reconstructing the event quantities from the detector information (calorimeter cells, tracks), an intermediate step is taken and that detector information is combined to identify "objects" that are associated to particles. From the detector information, the kinematic recontruction of each "object" is performed in an optimal way, since each class of object (lepton, photon, neutral or charge hadron and so on) is treated differently. It is then from these "objects" that the event quantities are then reconstructed.

These idea represent a big gain since each object is treated as close as possible to its expected behaviour with the detector components. Additionally, the combination of the detector parts allows to get the most of the detector information as a whole, leading to the final goal of having a global event description. The case of CMS is extremely clear since the particle-flow approach allows to use as much tracking information as possible, reducing the impact of the lower quality hadronic reconstruction in the calorimeters.

By the use of this kind of ideas and even more sophisticated techniques, the LHC experiments have been able to extract the most of the data samples, going beyond the most optimistic expectations, as we will describe in future sections.

2.3 The LHCb experiment

The LHCb detector [11] has been designed to perform studies on flavour physics, specifically of hadrons containing bottom quarks. Since their production is specially large in the forward region, the detector design is mostly oriented to maximize rate and provide very accurate reconstruction instead of maximazing the coverage. It therefore detects particles in the forward region and it reaches an impresive track and vertex reconstruction due to dedicated sophisticated components.

The main limitation of the measurements in the forward region is the high sensitivity to processes in which multiplicities are large. For this reason, the LHCb did not collect lead-lead data and required *luminosity leveling* to keep the number of collisions in the same event at reasonable levels. This leveling is the reason why the integrated luminosity of the data samples is smaller for this experiment.

On the other hand, its great coverage in the forward region allows this detector to perform measurements beyond the coverage of ATLAS and CMS, providing a nice complementarity at the LHC that is not limited to the topics for which the LHCb was intended. As we will see below, the LHCb experiment is providing nice and competetive results in areas where CMS and ATLAS were expected to be dominant.

2.4 The ALICE experiment

The ALICE detector [12] has been designed to maximize the physics output from heavy-ion collisions. The aim of the experiment is not the detection of exotic or striking signatures but to maximize the particle identification in order to retrieve as much information as possible about the properties of the medium created in the collision and how it affects the behaviour of the produced particles. Therefore, the detector components mostly focus on measurements that allows to study the dependence of statistical properties of the final states with respect of variables that correlates with the production of new matter states, i.e. the production of high energy density, high temperature and high pression states.

Due to this, the strong point of ALICE with respect to the other LHC experiments is the impressive particle identification, in order to identify relevant particles immersed in high multiplicity events. The limitations that this impose is the reduced coverage for each type of particle and the lack of symmetry in the detector: more types of different subdetectors covering different solid angle regions. This makes that the muon coverage is limited to the forward region ($2.5 < \eta < 4$) while electrons and photons are detected centrally ($\eta < 0.9$).

The specific design of the ALICE detector makes the results from ATLAS and CMS also very atractive for heavy-ion physics, due to its complementarity to ALICE, although they are not in competition when the particle identification is a key part of the study, as we will discuss later in this report.

2.5 Data adquisition and event reconstruction at the LHC experiments

The data-acquisition (DAQ) systems of the experiments have been designed to collect the information of the collisions happening at the LHC. They are very sophisticated in order to efficiently collect the information from all the detector components and store it to tape for future analysis.

On the other hand, the DAQ need to deal with the problem that having collisions every 50 ns (or 25 ns in the future) it is impossible to store all or even part of the information for every single event. For that it is needed to have an automated decision system which selects the events as soon as they are produced in order to reduce the amount of data that is physically stored to a manageable level. This system, called *trigger*, has therefore the goal of reducing the rate from tens of MHz to hundreds of Hz, providing data of 100 MB/s, which is a storable quantity.

Although the concept is simple, it should be noticed that events that are not accepted by the trigger are lost forever, implying a big responsability. Additionally, the trigger conditions at the LHC are very challenging and represent a new frontier in data acquisition due to high rates and event sizes. However, there is the need for those required rates ans event sizes since the aim of the experiments is to study rare processes with high precision, even at the cost of suffering at the DAQ level.

In addition to the DAQ challenges, other difficulty arises from the high rate: since the collision cross section is so large, it is very likely that several proton-proton pairs collide in the same event (i.e. crossing). Most of the collisions are soft uninteresting collisions that would appear at the same time as interesting ones. This situation is usually referred as *pile-up* collisions and it complicates the reconstruction of interesting events since it becomes harder to distinct them from usual background, something that is specially dramatic at the trigger level. The reason underneath being that reconstructed quantities, specially the global ones like the $E_T^{\rm miss}$, are modified and led to misleading values.

This problem with the *pile-up* is what motivated the luminosity leveling at the LHCb interaction point: to avoid the deterioration of the performance due to the overlap of collisions. Since statistics is not really the issue due to the large cross section, it is more practical to reduce the collision rate to collect higher purity events than just reject good events due to trigger limitations. It should be noticed that a similar idea may be required for the other experiments in the future when running at the highest rates.

After the data has been collected and stored in tape, it is analyzed to investigate the characterization of the physics producing it. The analysis consists on the identification and quantification of the objects contained in the event.

We have already described how to reconstruct the $E_T^{\rm miss}$ quantity that allows to associate undetected particles to the event. Additionally we also described how the reconstruction of the final state may be simplified with the use of the concept of *particle flow*.

As a specific case of the later, the presence of leptons in the final state is a fundamental tool in a hadron collider to recognize important physic events. Electrons are identified using the properties of its interaction with the calorimeters. Muons are identified using the chambers specifically designed for its detection, using the property that they are charged and highly penetrating.

Photons are also identified using the deposits in the calorimeters, where they look similar to electrons, but are distinguishable from them due to the absence of electric charge, and therefore the lack of hits in the tracking system.

The τ leptons are the hardest objects to identify in a detector, but their use is strongly motivated by their common presence in final states for BSM physics, or for Higgs searches, as we will see later. Their leptonic decays are hard to distinguish from electrons and muons, but their hadronic decays, the dominant ones, are separated from other hadron production due to their low multiplicity and the kinematical properties. The main issue is that is commonly hard to separate them from the large background of hadron production, and specially at the trigger, where the usable resources are more limited. On the other hand the experiments at LHC has used experience at previous colliders to really exploit all the possibilities of analysis with τ leptons, as it is described below.

Finally, apart from leptons and photons, it is very common the production of hadrons. They are originated from quarks and gluons that are not observed because the strong force confines them within colourless hadrons. The mechanisms transforming those coloured particles into hadrons cannot be understood in the pertubartion approach used to perform estimations from the theory, but fortunately they can be treated in such a way that their effects do not affect too much the predictions. The simpler technique to reduce this effect is by using *jets* of hadrons to reconstruct and characterize the final states.

The idea is that the processes that are not perturbately calculable occur at energy scales that are much lower than the usual hard processes taking part in the LHC collisions. Therefore they do not modify sustantially the global topology of the event and hadrons appear as collimated bunches of particles that are kinematically close to that of the hard partons produced in the event.

This qualitative description, only valid for studies of hard parton production, should be quantified with the use of a specific and well-suited algorithm that reconstruct the jets. The results are usually dependent on the algorithm, but when the same algorithm is used for comparing measurements and theory, the conclusions are independent of the algorithm, if the application is sounded.

Data analyses at the LHC experiments are performed with all these objects: leptons, photons, $E_T^{\rm miss}$, hadrons and jets, with very satisfactory results, mostly due to the high quality of the data acquisition and reconstruction.

3 Measurements to rediscover the SM

As mentioned above, the aim of the LHC is to produce unknown particles and increase sensitivity to new possible interactions by colliding protons at high energies. However, on top of the possible interesting processes there are other SM-related processes that tend to hide the most interesting ones. For a hadron collider, QCD jet production has a so large cross section that is the basic process happening in the collisions.

In fact, this makes the LHC a QCD machine aiming for discovery. Independently of what is actually done, everything depends on QCD-related effects: parton radiaton, parton distribution functions (PDFs) of the initial-state protons, hadronization processes for the final-state partons and so. Unfortunately most of these cannot be calculated due to our limited knowledge on how to deal with the QCD theory and therefore, in order to understand them requires the realization of measurements which allow to refine the existing phenomenological models used to obtain predictions on what to expect in the proton-proton collisions at the LHC.

For this reason it is impossible to simply ignore the “less interesting” events which are considered as background of the events containing effects and particles beyond the SM. In fact, at the LHC, as in any other hadron collider, the understanding of QCD is not just something needed nor a priority: it is the only possibility.

As a good example, it is needed to realize that the first measurements performed at the LHC are the total cross section and the differential cross sections for producing charged particles. They are not calculable in the pertubative approach of QCD, but they are required to perform realistic predictions (via the *tunings* of the model generators). They were performed at the beginning of the collisions by all the experiments (see e.g. [13, 14]) and from the beginning have become important tools to understand the collisions at the several energies the LHC has been operating.

In addition, even in these preliminary studies the LHC experiments proved that the LHC is crossing the lines to a new regime: an interesting effect observed looking at the correlations between charged particles: CMS observed [15] that in addition to the usual *large* $\Delta\phi$ correlations (i.e. opposite hemispheres), there are additional *near-side* (i.e. small $\Delta\phi$ and large $\Delta\eta$) correlations in events with very high multiplicities, specifically with more than 100 produced charged particles.

Figure 2 shows the mentioned observation of the so-called “rigde”. Similar effects were observed previosly in heavy-ion collisions, although it is not completely clear the source of them is the same. Currently there is not a clear explanation of the source, but the LHC data has confirmed its presence in lead-lead and proton-lead collisions, see e.g. [16].

3.1 Studies of jet production at the LHC

Apart from these soft-QCD measurements that are a fundamental piece to adjust the phenomenological models, measurements related to hard QCD are also performed at the LHC experiments in order to validate the QCD expectations on the perturbative regime, and to learn about the interactions between partons at the shortest distances and also about the partonic content of the proton.

Measurements are done for inclusive jet production, as those by ATLAS in [17], and compared to the NLO predictions, which are able to reproduce the data after soft-physics corrections (that are not large). Some kinematic regions are sometimes off, but they are correlated to problematic areas, in which proton PDFs are not well known or the effects from higher orders or soft physics are large. Similar conclusions are drawn from studies of multijet production, in which the sensitivity to QCD is enhanced using ratios, as the three-to-two jet ratio by CMS [18], in which many uncertainties cancel and the senstitivity to QCD shows up via the emission of hard partons. In fact the direct sensitivity to the strong coupling constant, $\alpha_S(Q)$, allows a measurement of this value for the first time beyond 400 GeV, confirming the expectation from the running of that coupling.

With a different aim, instead of measuring quantities that are more accurately known, there is interest in measuring in regions where uncertainties may be larger, but sensitive to unknown quantities, as it is the case of the PDFs. Measurements at the LHC experiments [19, 20] are sensitive to PDFs in regions where they are not well constrained and able to distinguish between prediction of different sets. Specially useful for the high-x gluon and sea quark PDF which is loosely constrained by the HERA data. It is worth to remark that even if the LHC aims for discovering of BSM physics, it is a very useful machine to increase the knowledge about the internal structure of the proton, via the measurements sensitive to the PDFs. In incoming sections this will be mentioned a few times.

When studying the production of jets, an important topic by its own is the measurement of production of heavy-flavour (charm and bottom) jets. Since they are not present in the proton in a sizable way, its study provides important information about QCD, specially for specific flavour production, something which is not possible for the light quarks and gluons. The fact that it is possible to perform separated studies for charm and bottom jets is due to the possibility of tagging the jets as originating/containing a heavy-flavour quark.

This has been a recent possibility due to the improvement in tracking, specifically at the closest distances to the collision. After surpassing the challenges involved in the LEP and Tevatron experiments, the detectors have reached to possibility to reconstruct vertices so precisely, that resolving secondary vertices coming from “long lived” hadrons containing a bottom and a charm quark has become a standard tool in accelerator physics.

The fact behind this *heavy-flavour tagging* is the presence of hadrons that live long enough so their decay products appear in the detector as displaced tracks and vertices within jets that are incompatible with originating at the so-called primary vertex, in which the interaction took place. These displaced tracks and vertices are resolved and conveniently used to tag jets containing these heavy-flavour hadrons and therefore likely to originate from a charm or bottom quark. The information provided by them is used either on a simple and straightforward way (that is safer and more traditional) or on multivariate techniques that allow to increase performance of the tagger. The later has become more popular as expertise with this kind of tool is well established.

Making use of the tagging tools it is possible to study the production of jets originating from a bottom quark, or b-jets. Measurements by the two collaborations has been made [21, 22] and compared to QCD precitions for heavy-flavour production computed with the MC@NLO [23] program. As shown in Fig. 3, a good agreement is observed overall although there are some small discrepancies in specific kinematic regions, similarly at what was observed in inclusive jet production. It should be noticed that the level of agreement is good due to the improvements in the theoretical calculations during the last decade. Predictions are difficult for the kind of process under study, so the level of discrepancy observed is considered a complete success of the QCD calculations. Of course further work is still needed, emphasizing the importance of the precise measurements at the LHC.

In a similar topic, one important measurement at the LHC experiments will be to try to disentangle the production of jets containing two heavy-flavour quarks. In the past the quality of the heavy-flavour tagging only allowed the separation of jets with at least a heavy-flavour quark. However, at the LHC, the improved detection techniques and the experience with tagging tools will also allow to investigate the production of multi-b jets, which are of importance in topologies with merged jets or to reject the presence of gluon jets containing a gluon-splitting process into heavy-flavour quarks.

Exploiting the subtle differences in the displacement of tracks, studies are performed on this issue [24], and good rejection power of gluon jets has been observed while keeping a big fraction of the single b jets. More dedicated studies will be needed to improve the related tools for rejecting this background, but current results has confirmed its feasibility and also that the heavy-flavour taggers at the LHC experiments are taking advantage of the improved detector capabilities.

Regarding the LHC in a new kinematic regime, it should be remarked the development during the last years of tools to investigate the production of boosted objects. Since available energies at the LHC are much larger than the masses of the SM particles, it is likely to observe their production with very large transverse momenta, giving rise to the merging of objects. This is specially worrisome in the case of jets since they are hard to separate after their constituents have been merged together. For that reason, several dedicated studies and the development of new techniques has been done at the LHC experiments [25, 26] in order to deal with the topology of boosted jets. The idea is to exploit the properties of the internal structure to recover information of the original partons whose jets have been merged, and separate them from single parton jets that are boosted in the transverse direction, i.e. produced with large transverse momentum.

Many techniques have been developed and tested in the identification of merged jet and check how the simulation reproduce the characteristics of the jets allowing the distinction of the jets containing one or more “hard” partons. Currently its performance has been proven to identify merged jets coming from boosted W bosons and top quarks, and used for searches. However its principal motivation is still the need of this kind of tools for the future running at higher energy.

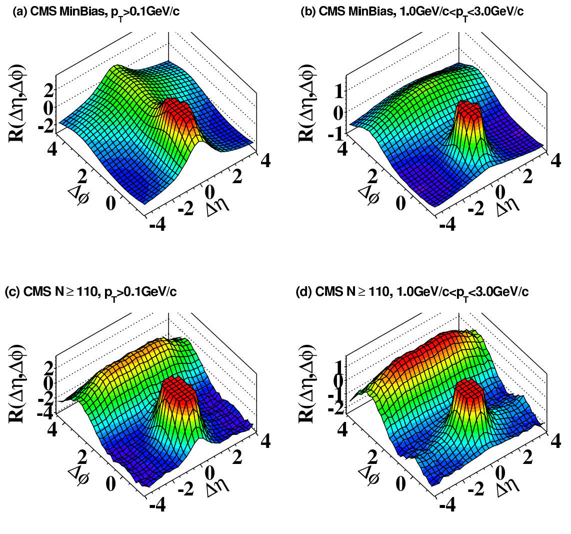

Fig. 2: Relative distribution of the charged particles in proton-proton at 7 TeV as measured by CMS in several selections in the $\Delta\eta - \Delta\phi$ plane. Apart from the expected back-to-back correlation, a near-side correlation is observed even at large $\Delta\eta$ for high-multiplicity events (plots below).

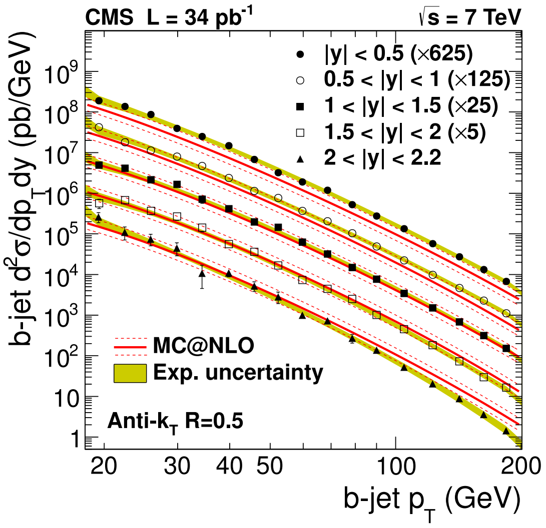

Fig. 3: Differential cross section of bottom jet production at the LHC with a center of mass energy of 7 TeV. Measurements in different rapidity regions (dots) are plotted as a function of the transverse momentum of the jet and compared to the MC@NLO predictions (lines).

3.2 Studies of soft QCD physics at the LHC

Apart from particle and jet production via QCD processes, the experiments are able to perform studies related to QCD via more complicated mechanisms. Among this, one that has become really important is the possibility of observing more than one partonic collision from the same protons. Since a proton is a bunch of partons it is not uncommon to have several partons colliding at the same time. And the LHC allows to have very hard collisions since the energy of the protons is very large.

These multiparton interactions are a complicated topic since it is not clear up to which level each collision can be considered independent of the others. In addition, the probability associated to the additional collisions to happen is not calculable and require models whose parameters require some tuning in order to improve the modeling of the underlying event. The validity test of the models is usually done in samples that are reasonably understood and trying to extract the maximum possible information to get the proper parameterization. With this aim, ATLAS has measured the contribution from double-parton interaction for W+dijet events [27] to be 0.16 ± 0.01(stat) $\pm$ 0.03(syst), in good agreement with the expectations that were tuned to previous data.

Related to QCD in strange regions, the LHC allows studies for diffractive and forward production of particles and jets at higher scales than previous hadron colliders. These are relevant in order to understand hadron interaction at softer scales, and also to adjust the models describing this kind of process.

Even the LHCb experiments has produced results for forward hadron production, which are very competitive due to the optimization of the detector for particle ID and its very forward coverage. Results of these studies [28] have been compared to the predictions obtained by traditional event generator and also those used in the simulation of cosmic-ray events, which are very sensitive to this kind of processes.

Another example of new kind of QCD measurements is the study of exclusive diboson (WW) production via the collision of photons performed by CMS [29]. This makes the LHC a photon collider at high energies, which allows dedicated studies of the electroweak interaction. The result with the dataset collected at 7 TeV allows to measure the cross section with still a low significance, implying the need of more data. However, using the sample with highest transverse momentum, it was possible to set limits on the production via anomalous quartic couplings, showing the potential of this kind of studies.

3.3 Electroweak boson and diboson production at the LHC

Although the measurements described above allow to test the predictions by QCD and even of the electroweak sector in some cases, the most sensitive studies to validate the SM predictions are coming from the events containing photons or weak bosons. The idea is that these events are usually simple to recognize and the perturbative calculations of the processes and the backgrounds are usually very accurate.

The most common process of this kind is the production of photons, whose interest have been demonstrated in the past hadron colliders, in which this was considered a “QCD study” since it provided direct information on the quarks. Hard photons radiated from quarks are good probes of the interation since they are not affected by soft processes and they are able to distinguish mong different kind of quarks. In addition the large cross section of the γ+jet allows its use as a fundamental calibration tool.

Additionally, studies of diphoton production yield to very stringent test of the SM predictions, specially for a final state that is an important background in many interesting searches of new particles, decaying in photon final states. The study by ATLAS [30] performed measurements of the photon pair production as a function of several variables and compared them to several event generators, at different orders in QCD and types of partonic showers in order to evaluate the level of performance of the available production tools.

However, when talking on boson production, the studies related to the weak bosons become a fundamental test of the SM predictions that were performed at the LHC in order to also check the performance of the detectors and tools for analyses. Even after the first analyses, the studies of events with W and Z bosons are fundamental tools for calibration and understanding of the object identification and reconstruction. Measurements at several energies, as the one at 8 TeV by CMS [31], have been performed and show very good agreeement with the expectations by the SM and also confirming the excelent predictions of the SM at several energies for measurements performed for W and Z production during the last three decades, as shown in Fig.. 4.

Although the basic goal for studying the production of weak bosons is to confirm the performance of the detectors and of the basic SM prediction, dedicated measurements related to them are also a fundamental part of the LHC program. This is the case for measurements sensitive to the internal structure of the proton and also of the SM details that could not be tested before at the level of precision reachable at the LHC. This affects both kind of processes: final states that were never available in a proton-proton collider before, like the ratio of W^+ to W^- measured by ATLAS [32], or whose yield was too small, like the measurement of $Z \to 4l$ (as in [33]) which is a calibration piece for the Higgs searches.

This explains the large effort at the LHC to measure the properties of the production of weak bosons. Some of the properties are measurements for confirmation and validation purposes, but some are really motivated by the new possibilities opened at the LHC experiments. This is seen even in experiments that are not intended for boson studies, like the results at LHCb, in which the very forward detection makes measurements of Z and W production very competitive even with lower acceptances [34], since they are measured in kinematic regions that are not available for the main detectors. Even events compatible with forward Z bosons decaying into τ leptons have been observed at the LHCb [35], indicating an important benchmark for the performance of the experiment to obtain results beyond flavour physics.

In the case of W production, Fig. 5 shows the lepton charge asymmetry as a function of η also confirms the complementarity of the several experiments at the LHC, in this case how the LHCb is able to extend the region reachable by the ATLAS and CMS, even with a reduced yield. All these measurements of forward production will have a big impact in the fits to extract the parton content of the proton, since

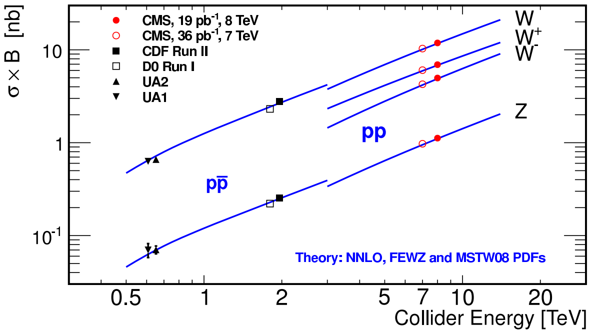

Fig. 4: Cross sections of weak boson production in hadron colliders at several center-of-mass energies. SM predictions for proton-antiproton and proton-proton collisions are compared to the measurements shown as different types of dots.

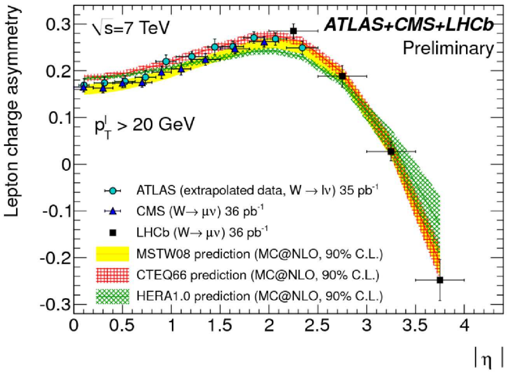

Fig. 5: Lepton charge asymmetry of W production as a function of η at the LHC with the 7-TeV data from the ATLAS, CMS and LHCb experiment. The inclusion of the later experiment allows to extend the measurement to very forward regions never reached before.

most of the current uncertainty is reduced by forward production of particles, more sensitive to the less constrained partonic content, as gluons and sea quarks at high-x.

But not only the proton structure benefits from the large yields at the LHC for producing weak bosons since the presence of a massive object allows studies of QCD processes in an environment where perturbative calculations are accurate enough to bring very stringent tests of the expectations.

The typical example is the use of bosons as “probes” of the underlying hard process involving the partons, whose rules are naturally dictacted by strong interactions. This is the case of the measurment of jet production in association to a Z or W, as in [36, 37], which are sensitive to the partons interacting and also major backgrounds to most of the new models for BSM physics. The measurements are able to constrain the room for the new physics, and, in other kienmatic regions, to check the validity of the tools used to estimate these final states. It should be noted that not only the yields are interesting, but also the kinematic distributions of the final state objects, specially those sensitive to unexpected underlying physics, as in [38, 39], in which specific distributions of bosons and jets are studied in order to perform accurate tests of the SM predictions, taking advantage of the large yields.

Similarly, another topic that directly benefits from the high cross section and luminosity at the LHC is the production of heavy flavour quarks in association with a weak boson. Being very sensitive to the SM structure, some of the processes have not being accurately tested due to the limited statistics at previous colliders. In fact, results at the Tevatron have been controversial regarding the way the event generators reproduce the measurements. The larger statistics at the LHC allows the improvement in the precision of the measurement. This is the case for the W+b-jet measurement by ATLAS [40], which clearly shows that description by event generators could be improved, which is not a trivial case, since it is a background for many studies for BSM physics. Understanding this discrepancy should be a clear priority of the physics at LHC, from the theoretical and experimental point of view.

Another final state that has benefit a lot by the new frontier set at the LHC is the production of charm in association with a W boson. Its interest is given by the fact that since W is able to change the flavour of a quark, the production of single charm is dominated by interactions involving down and strange quarks in the proton. Therefore directly sensitive to the strange content of the proton. In addition, the charge of the produced W is completely correlated to the charge of the charm and down/strange quark. As mentioned above, the W is used as a direct probe of the structure of the underlaying parton collision. In this case the result of the measurement by CMS [41] is presented as the fraction of charm jets in W+jet events and also of the ratio of W$^+$ to W^- in events with a charm produced in association with the W.

Both quantities are sensitive to the PDF of the strange quark and antiquark. The measurements are in good agreement with the expectations and they will allow to improve the accuracy of the proton PDFs.

In the case of the Z boson, the low cross sections prevented detailed studies of the production associated with heavy flavour quarks to be performed at the Tevatron. Again the LHC has brought the possibility to study this in detail. The analyses studying the production of Z+b-jet, as in [42], show that the event generators, in this case MADGRAPH [43], are able to describe the distributions. However, with the explicit requirement of two b-jets the agreement get clearly worse [44], implying that some theoretical work may be required: although the processes (and calculation diagrams) are the same, the relative weight is different due to the kinematic requirements on the second jet.

Finally, the last topic entering the scene when talking about weak bosons and jets is the study for electroweakly produced bosons, the so-called *Vector-boson fusion* (VBF) production. In this case the boson is produced in association of two jets that tends to be forward, due to the kinematics. Those forward jets are used to "VBF-tag" the event and separate them from the main processes, weak radiation from partons or parton annihilation. Measurement by CMS [45] allowed to measure a cross section in agreement with NLO calculations. In addition, this kind of analysis also contributes to understand the production of jets in the forward region, which is less understood due to the challenges in experimental studies and also in theoretical calculations.

It should be remarked that the interest of all the results involving jet production in association with weak bosons will be kept in the future, as the measurements get more precise, implying larger challenges for the modeling of very important processes at the LHC, either for their own interest or just as background estimations for searches of all kind.

3.4 Diboson production at the LHC

As it is well known, the production of more than one boson is one of the most sensitive test of the non-abelian structure of the electroweak sector of the SM, so it is very sensitive to deviation produced by new couplings involving the SM bosons.

The main limitation is that precisely the presence of several weak couplings makes the cross section small, and the observation of these final states has been very difficult. However, the LHC has open a new era for this kind of studies since large samples are available to perform detailed studies, allowing precise studies of diboson production for the first time. In fact, the LHC will allow in the future the observation of multiboson production, which has never been observed. In addition, the large samples available has allowed that diboson production has become a standard reference for calibration in advanceed analyses.

The basic processes testing the SM structure and with large cross section is the production of a weak boson and a photon (Wγ and Zγ) which are directly sensitive to the unification of the electromagnetic and weak interactions. The results of the analysis, like [46], shown that data are in good agreement with expectations, even at higher transverse momenta, which may be sensitive to new physics affecting the unification of interactions.

In the case of two massive boson, the process with the highest cross section is the production of two W bosons, in which the samples are large enough to allow detailed comparisons with the predictions by the event generators, even via differential distributions [47]. The conclusion of the studies is that the SM predictions reproduce very well the shapes of the observed distributions in data, but they underestimate the total cross section.

This discrepancy has been observed by the two collaborations and at the two energies of the LHC. Investigation of the origin of it is under study. Similarly, studies of the production of two Z bosons shows a slight excess in the data with respect to the expectations [47, 48]. In this case, the yields are small and the excess is not as significant, but the clean final state, requiring four isolated leptons, leads to very straightforward conclusions. This channel, which leads to a pure sample of ZZ events and with fully

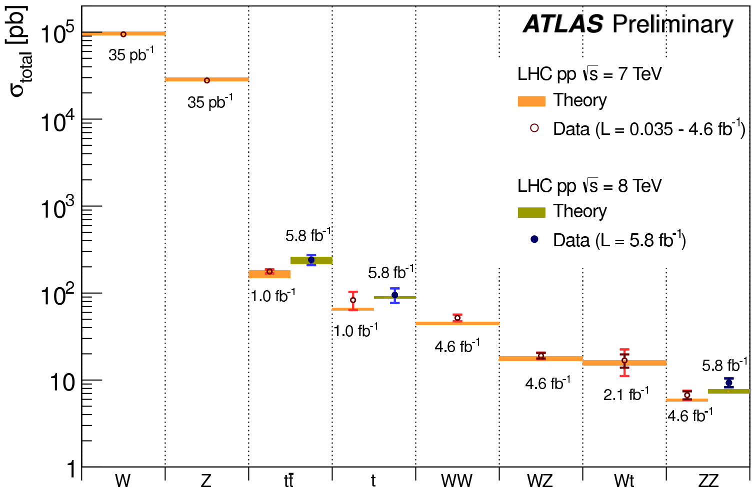

Fig. 6: Summary of the measurements by ATLAS for massive particles (weak bosons and top quarks) in single and double mode at the LHC with a center-of-mass energy of 7 TeV.

reconstructed kinematics, provides the best test bed for diboson studies, specially with the amount of events expected at the LHC.

In addition to the pure leptonic channels, that are much cleaner in a hadron collider, the semileptonic channels are also exploited at the LHC, since it is the most precise way to study the hadronic decays of Z and W bosons, not available in the inclusive production due to the large dijet backgrounds. The performed measurements in the W+dijet sample [39, 49] yield the observation of the diboson signal. Separation of the Z and W in the hadronic channel is not possible due to resolution, and therefore this final state is able to measure the mixture of WW and WZ events. The result is in agreement with the observation, and the analysis has also tested the W+dijet background, whose interest was mentioned above. Finally it should be remarked that WZ has been also measured in the fully leptonic channel [50] which provides the topology of three charged leptons and E_T^{miss} which has a large relevance in searches for new physics, in particular supersymmetry, and therefore the understanding of the kinematics in this diboson process is a fundamental part of the program.

In conclusion, it should be remarked that even if the LHC is intended to discover the physics beyond the SM, measurements of the know processes has produced many interesting results, some to confirm the observations at previous colliders, but also new results that were not previously accessible. In this sense, and as summarized in Fig. 6, the impressive agreement of the measurements provides a solid base on which the experiments are building the tools and confidence for the observation of unexpected results, when higher precision or new final states are reachable in the data.

4 Measurements on bottom and charm hadrons

The spectroscopy of hadrons has been a fundamental source of information in particle physics, since it has allowed to detect effects beyond the reachable energy scale and since it provides the only direct way to understand quarks and QCD at low energies.

The case of heavy flavour hadrons, which include at least a bottom or charm quark, is of a broader interest due to the higher masses involved that allows to perform more accurate theoretical calculations related to the properties of the hadrons. With the measurements in hadron spectroscopy, it is possible to perform several classes of studies, as the properties of bound states, production of new states, measure branching ratios and interference effects. All of them provide information about possible BSM physics or improve the knowledge about partons in confinement states.

It should be remarked that in order to perform studies with hadrons, it is needed to reconstruct them. This sets a very different approach to the ones described above in which the hadrons are just merged together in jets that are related to the original partons. The goal in the physics with hadrons is to explicitly identify the interesting objects. This is achieved in several steps: The first consists in the identification of the detected particles, as pions, kaons and more commonly muons and electrons. Some of these objects are (pseudo)stable and are identified as tracks or similar. Sometimes the nature of the particle is also inferred by using specifically designed detectors, but in other cases the nature is just assumed as part of the reconstruction process.

After the detected particles are identified, they are combined to reconstruct "mother" particles that may have decayed into them. The usual method is to reconstruct the invariant mass of several identified objects and find events in which they are coming from another particle (over a possible continuous background) as a resonant excess. Those events associated to a decaying particle may be used to extract information about the particle, apart from the direct identification of the particle itself in the mass distribution. Furthermore, the particles identified this way via its decay products may be further used to reconstruct other partental particles in a recursive reconstruction that allows the full identification of the decay chain of the original particle.

With these tools and the goal of measuring the hadron properties in mind, the LHC experiments have been able to identify hadrons, some of them completely unknown. One example is the observation by ATLAS of the new exited state, χ_b(3P), belonging to the bottomonium family decaying into Υ(1S/2S) by the emission of a photon [51]. The mass distribution showing the resonances produced by the new state is shown in Fig. 7 centered at a mass of 10.530 ± 0.005(stat) $\pm\ 0.009$(syst) GeV. Also the CMS experiments was able to find the $\Xi_b^* \to \Xi_b^{\mp}\pi^{\pm}$ state, which has been the first baryon and fermion found at the LHC, and with a mass of 5945.0 ± 0.7(stat) $\pm\ 0.3$(syst)] $\pm\ 2.7$(PDG) MeV [52].

However, and as expected, it is the main experiment focusing in heavy-flavour physics, LHCb with its larger samples with higher purity who is able to measure the properties of bottom hadrons with higher precision. Specially about the recently discovered baryons, for which this experiment has already relatively large samples with high purity selection. The measurements for Λ_b, Ω_b^- and Ξ_b^- documented in [53] required very detailed understanding of the detector momentum scales, in order to get the most precise mass measurements in the World.

Additionally the LHCb is also leading the effort in searching for rare decays of known hadrons. These decays are of interest for its possible sensitivity to new interactions involving quarks because they include loop diagrams or interesting vertices that could be affected by unknown effects. Among the rare decays, one of the most attractive ones is $B_s/B^0 \to \mu\mu$ since it is associated to a well-controlled and easily identifiable final state. Additionally, the branching ratio is very small but expected to be enhanced in several of the possible BSM extensions. This explains the intensive search for this signal in the last decade at the Tevatron, where exclusion limit approached the SM expectation. However, the large sample collected by the LHCb experiment allowed to get evidence of the decay, with a significance of 3.5σ, for B_s that is in good agreement with the SM value [54]. The decay for B^0, searched in the same analysis, is also in agreement with the SM, but significance of the excess is smaller. The absence of discrepancy has set strong limits on possible new physics affecting the decay, confirming the negative results from direct searches at the other LHC experiments, as described in sections 8 and 9.

Another interesting decay under study is $B^0 \to K^*\mu\mu$, whose branching fraction in the SM is not that small but whose kinematics is sensitive to the presence of new physics. One is the forward-backward asymmetry as a function of the invariant mass of the muons, measured by LHCb [55] and observed to be in agreement with the SM calculations.

All these measurements confirm the good performance of the detectors for heavy hadron physics, although the measurements are not bringing information about the possible BSM physics, but setting stringent constraints on the way the new physics may modify the interaction between quarks.

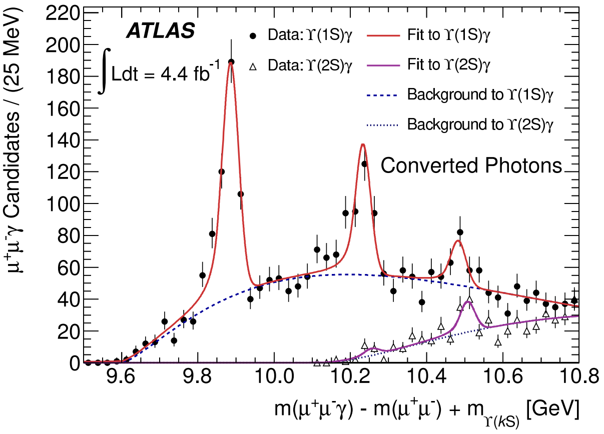

Fig. 7: Invariant mass distribution of $\mu^+\mu^-\gamma$ to observe the resonances decaying into Υ(1S/2S) and a photon. A clear state at 10.5 GeV is observed in both decays, compatible with being the χ_b(3P) state of the bottomonium family.

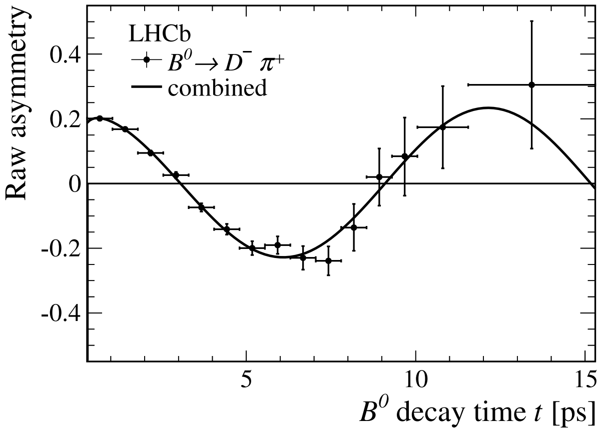

Fig. 8: Raw mixing asymmetry for $B^0 \to D^-\pi^+$ as a function of the decay time. The solid black line is the projection of the mixing asymmetry of the combined probability function for the sample.

4.1 Mixing and oscillations

Within the properties of hadrons, one that has become of large relevance is that of the mixing of neutral mesons, in which the flavour eigenstates differ from the mass eigenstates, leading to a change in its nature according to the quantum mechanics rules. These oscillations are well steblished for the K^0, B^0 and B^0_s and are starting to become accessible for the D^0.

In the case of the B^0, the LHCb samples are reaching unprecedent precision and even providing new channels of observation. Figure 8 shows the result of the oscillations for the very pure sample of $B^0 \to D^-\pi^+$ as a function of the decay time [56]. As it can be observed, the measurements are well reproduced by the expectation obtained taking into account the composition of the sample used to compute the raw asymmetry.

In the case of the D^0, the oscillations are now becoming accessible thanks to the large samples, specially at the LHCb. Its study is strongly motivated since charm is the only up-type quark in which mixing and CP violation are accessible. It can also provide surprises since it is a previously unexplored region. The study of the mixing and oscillations for the D^0 is done by exploiting the interference between the mixing and the double-Cabibbo-suppressed decays. The same channel provide a right sign and a wrong sign set of candidates that are used to perform the measurement. The first set is not sensitive to the mixing and therefore provides a perfect reference sample.

In order to reduce uncertainties in the production, the initial D^0 state is tagged by using the decay product of the $D^* \to D^0\pi_s$. Using all these events, it is possible to measure the mixing and the LHCb has provided the first observation from a single measurement, with a significance of 9.1σ [57]. The result is in good agreement with previous measurements, but the increased significance is another proof of the reach available at the LHC even for studies of low-mass objects.

4.2 Measurements of the CKM matrix and CP violation

As remarked several times, the main goal of the studies in flavour physics is to investigate the details of the fermion families, specially the relationship among them. In the case of the quarks, the relation between the flavour eigenstates (from the point of view of the weak interaction) and the mass eigenstates. is given by the so-called CKM matrix [58] which is expected to be unitary (when all families are included) and that can be parameterized with three mixing angles and one complex phase. The unitary condition allows the representation of combinations of elements in rows and columns of the matrix as a triangle whose area is related to the CP violation in the family mixing.

The goal is therefore to identify the processes that are sensitive to combinations of elements in the matrix and extract the associated information about the matrix and the triangle. The measurement of single elements in the matrix is associated to processes that are not observable in hadron physics. However, that is not a complete limitation, as proben by the large set of results in the last decade related to the CKM and CP violation parameters. Still, certain measurements are newly coming from the LHC. As an example, the LHCb experiment has measured the angle γ using the tree processes $B^{\pm} \to D^0 K^{\pm}$ [59] which has the advantage of being very clean: as we mentioned before, processes with loops are sensitive to new physics, so the values measured at tree level are dominated by SM-only physics. The measured value, $\gamma = (71.1^{+16.6}_{-15.7})^{\circ}$ is in agreement with the World average, with comparable uncertainty.

Other interesting result from the LHCb is the study of CP violation in charmless three-body decays of B mesons [60], that are sensitive to transitions between the first and third generation. The observed asymmetry is interesting because it is opposite in $\pi^{\pm}\pi^{+}\pi^{-}$ (enhacement for B^{-}) with respect to $K^{+}K^{-}\pi^{\pm}$ (enhacement for B^{+}) and it seems to be enhanced locally for some kinematics regions.

In the case of the mixing, one of the most important channel is $B_s \to J/\psi\phi$ since it is sensitive to new physics affecting the CP violation. Measurements [61] agree with the SM expectations, and they were also used to obtain the first measurement of the width difference of the mass eigenstates which is not compatible with zero ($\Delta\Gamma_s = 0.116 \pm 0.018$(stat) $\pm\, 0.006$(syst) ps^{-1}).

Finally, the last open topic for CP violation is its study in charm decays, which has been measured by the LHCb collaboration [62] to be significantly different from zero, an unexpected result since most of the SM-based predictions suggest almost no violation. Although calculations are difficult and the usual estimations may underestimate the value, the measured value, confirmed at other experiments, seems a bit large, which may be pointing to some BSM effects.

As with most of the discrepancies observed, more data is needed to increase our knowledge, but theoretical development is an additional requirement to quantify the level of disagreeement observed and before its origin is further investigated.

5 Results on the top quark

In the hadron physics described in the previous section, one quark is not investigated: the top. Being the most massive of the quarks (and of any observed fundamental particle) it is hard to produce and also it does not hadronize but directly decays into a W and a bottom quark. Additionally, its exceptionally high value of the mass makes him the best candidate to be related to new physics, so its study is mandatory and one of the big goals of the LHC program: the top quark may lead the path to BSM physics, in the same way as neutrinos are leading the path in non-collider results.

At the LHC the dominant process to produce a top quark is QCD pair-production that has a large cross section. In fact the LHC is the first machine that is able to produce top quarks at high rate, allowing detailed studies to be performed. This also applies to other production mechanisms, as that of single-top and tW production, the latter being available at the LHC for the first time. In fact the production cross sections of processes involving top are so large that it is also a very common background in many types of searches, which is an additional motivation for studying its properties.

The study of the top quark at the LHC follows a similar strategy developed at Tevatron: channels are identified with the number and type of leptons in the final state. Depending on that, events are analyzed to extract all available information in a sample as clean as possible. Additionally all channels are considered, in order to investigate all possible events and the presence of discrepancies with respect to the SM expectations.

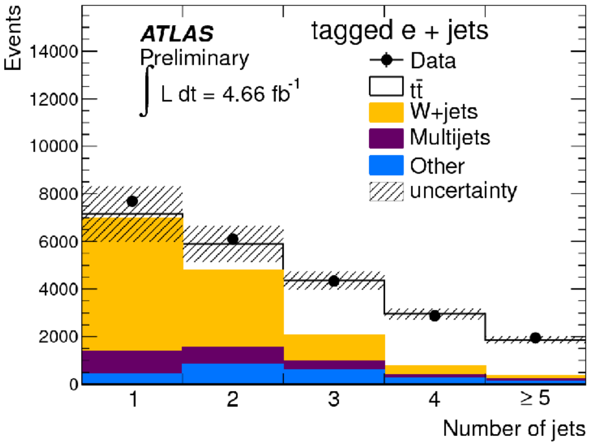

Fig. 9: Distribution of the number of jets in events with an electron or positron, a b-jet and significant E_T^{miss} as measured by ATLAS at 7 TeV. Sample composition is split into the main components.

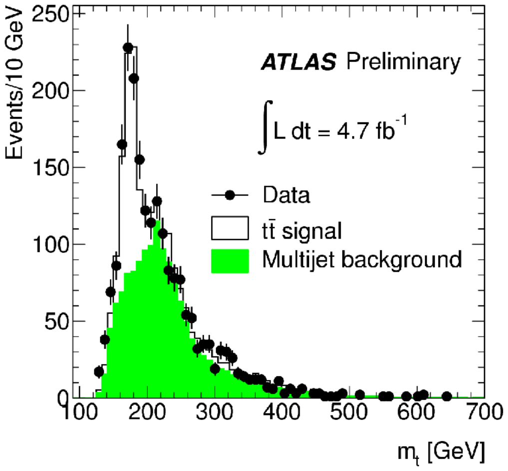

Fig. 10: Invariant mass distribution for three jets forming a top candidate in fully-hadronic of top-pair production events. Measurement by ATLAS at 7 TeV. Expectations for the top-pair signal and the multijet background (histograms) are shown and compared to the data (dots).

5.1 Measurements of the top-pair production cross section

The first property to be measured for the top quark is the production cross section in the main mechanism (pair production) and the simpler channel: the semileptonic events in which there is a good identified lepton and at least one jet tagged as coming from a bottom quark. Results were obtained for the sample collected at 7 TeV by ATLAS, giving a cross section of 165 ± 2(stat) $\pm$ 17(syst) $\pm$ 3(lumi) pb [63]. Distribution of the number of jets is presented for events with an electron in Fig.9, showing the clear signal yield for high jet multiplicities.

It should be noted that the semileptonic events apply only to electrons and muons, not to the τ lepton that is considered aside. That channel has also being studied since it is very important for the possible new physics related to the third generation and the measurements (like the one in [64]) are found to be in good agreement with the expectations. Additionally the all-hadronic channel has also being investigated [65] in order to confirm the expectations. These two channels used the invariant mass distribution of the top quark candidates, as shown in Fig. 10, in order to separate the large backgrounds. It should be remarked that the lack of precision for these channels is basically driven by the systematic uncertainties affecting the background or the acceptances.

On the other extreme, channels containing two leptons (electrons and muons) provide the cleanest signature. At the Tevatron this channel was not precise because of the lower yield, but the LHC has proven this is no longer an issue with the single most precise measurement of the cross section from the dilepton channel at CMS [66], 161.9 ± 2.5(stat)$^{+5.1}_{-5.0}$(syst) $\pm$ 3.6(lumi) pb, again at 7 TeV.

All these channels provide experimentally independent measurements of the production cross section that have been combined [67] to give a value of 173.3 ± 2.3(stat) $\pm$ 9.8(syst) pb. The combination has also proven the good consistency among the different channels and the two experiments. In addition to these results at 7 TeV, the two collaborations are working on getting a similar picture with the data collected at 8 TeV and measure the top-pair production cross section, whose interest is to test the model at higher energies but also to open the possibility of performing ratios of energies (and even double ratios with the addition of the Z-boson production cross section) which will enhance the sensitivity to BSM physics. The first measurements of the cross section at 8 TeV are reported in [68] and [69].

However it should be remarked that the large samples of top events are also allowing new sets of studies that were not available at Tevatron: measuring SM quantities using events containing top quarks. Those provide good tests of the SM, but also a useful frame to perform precise measurements. One example is the extraction of α_S from the top-pair production cross section [70], which leads to a competitive value because it is determined in an energy regime that has only been accessible to a reduced amount of measurements.

Besides of the total production cross section, the experiments are measuring differential cross sections [71, 72]. These studies provide very stringent test of the SM predictions and of the modeling in simulation. In addition the sensitivity to possible discrepancies is enhanced, since such discrepancies could appear in tails of distributions, as expected from possible new physics, and not affect the bulk of them in any visible way.

The results of the measurements does not present any significant discrepancy and good agreement is observed, which increases the confidence on the predictive power of the theoretical tools. These are going to be fundamental when larger samples are investigated, as those collected in 2012 at 8 TeV, since precision will be much larger and the challenges and sensitivity to new physics increases to previously unknown levels.

5.2 Measurement of the properties of the top quark

Until more data is available for detailed studies of the production mechanism, the current data samples allow the measurement of the properties of the top quark to an unprecendent precision. The first one is the determination of the mass, since it ia a parameter that determines many other properties, and its high value is already a motivation by itself.

The LHC experiments are exploiting the experience at the Tevatron and are already measuring the mass of the top quark with very advanced techniques: template fits, jet calibration in-situ and similar. In addition the measurements are performed in several samples that are later combined, even to get a combined LHC result, as summarized in Fig. 11 and documented by the collaborations [73]. It should be remarked that the achieved precision will be very hard to improve, but still the mass of the top quark is a relevant quantity of study at the LHC. Specfically larger samples will allow differential measurements of the mass, $\mathrm{d}M_t/\mathrm{d}X$, which provides additional information and constraints.

In addition to the direct measurement of the mass, the LHC experiments are also measuring the mass indirectly from the measured cross section and the comparison to the theoretical expectations. The value extracted from this [74, 75] is not as precise as the direct measurements, but the comparison provides a new handle to find inconsistencies in the theory predictions (and therefore opening the way to possible BSM physics). The results are in good agreement, confirming the impressive performance of the SM predictions for top production and properties.

Additionally to the mass there are other several quantities that have been measured for the top at the LHC by CMS and ATLAS. As an incomplete summary, here are brief references to them:

– Electric charge

Within the SM there is a fixed expectation for the electric charge of the top quark (+2/3 of that of the positron). However, some models would allow a charge of -4/3 (same units) which is still fully compatible with the observed decays since the inclusive measurements do not relate the charge of the lepton from the W boson and that of the bottom quark, specially due to the difficulties to measure the latter.

However performing studies of the charge asasociated to the bottom quark (and the jet) and the pairing of jet and W boson to identify the ones coming from the same top, it is possible to obtain sensitivity to the charge of the top quark. Even with limited luminosities, analyses by the two collaborations [76, 77] by testing the two models again sensitive distributions are excluding the alternative value beyond any reasonable doubt.

– Mass difference for top and antitop

CMS has measured the mass difference between the quark and the antiquark version of the top [78], which provides a stringent test of the CPT invariance in Nature and of the possible compositeness of the top quark state. The result is in agreement with the SM expectation in which there is no difference.

– Polarization and spin correlations

Due to the short lifetime of the top quark, its decay happens before a change of the spin. This allows to perform studies related to the spin that are not available to any other quark.

In pair production the polarization of the top quark is investigated by using the angle between the quark and the lepton. Measurements by CMS in the dilepton channel [79] and by ATLAS in the lepton+jet sample [80] has confirmed that the polarization is in agreement with the SM expectation: top quarks are produced unpolarized.

However, the SM predicts that even if the quarks are not polarized, the spins of que quark and antiquark are correlated. The degree of correlation as measured by ATLAS in helicity basis is $0.40^{+0.09}_{-0.08}$ [81], in perfect agreement with NLO SM predictions, which sets additional constraints to possible anomalous production, i.e. BSM physics.

– Helicity of W from top decays

Due to the characteristics of the coupling of the W boson to fermions, we expect that helicity of the W decaying from top quarks to be fully determined. This property is parameterized in different components that are accessible by studying the angular ditributions between the lepton from the W boson and the top quark in the W rest frame.

Measurements performed by the two collaborations [82, 83] are in agreement with the SM expectations and the results are used to set limits on anomalous couplings between the W boson and the top quark, basically testing the V-A structure of the weak coupling of the only quark in which it is directly accessible.

– Forward-Backward asymmetry in top-pair production

In top-quark pair production a stricking assymetry was observed at the Tevatron regarding the foward-backward production of the quarks, which a clear preference of the top quark to be produced in the direction of the proton (and the antiquark in that of the antiproton).

Although this is somewhat expected, the observed value is much larger than the NLO predictions. Some uncertainties involved in the calculations may be large but the effect may be also produced by some unknown effect, specially because the effect increases with the mass of the produced pair.

At the LHC the available energy and production yield motivates a more precise study of the effect. However, the symmetric initial state prevents the realization of exactly the same measurement. On the other hand, the matter-dominated initial state introduces differences in the rapidity distributions of the quark and antiquark that is related to the distribution studied at the Tevatron experiments.

The measurements of the asymmetry for the quantity $\Delta|y| = |y_t| - |y_{\bar{t}}|$ performed by the two experiments [85, 86] show good agreement with the SM expectations. It should be remarked this does not exclude the Tevatron result, since there are no final model explaining the asymmetry. However, the LHC results exclude some proposed models and adds some additional information that is very useful for this subject, that is a good candidate to be one of the hot topics for the incoming years, specifically regarding top physics.

– Study of $t\bar{t} + X$ production

Since the pair production cross section of top quarks is so large, it has become possible to start studying the properties of the top quark with the associated production of additional objects, usually radiated from the top. Sizes of the current datasamples do not allow detailed studies of the most interesting processes, as the production of a pair of tops and electroweak bosons, but current studies are showing the possibilities for the future running.

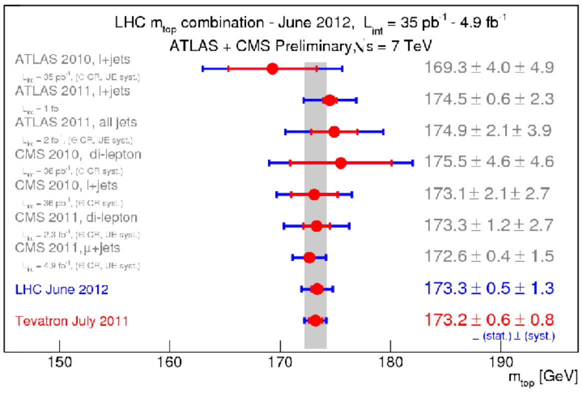

Fig. 11: Summary of the more relevant measurements of the top-quark mass at the LHC, including the combined from the two experiments and the comparison with the best Tevatron combination.

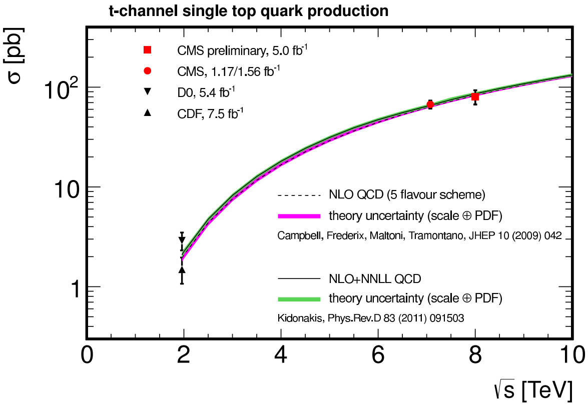

Fig. 12: Measurements of the single-top production cross section in the t-channel by CMS at 7 TeV and 8 TeV. For comparison, measurements at the Tevatron experiments are also shown.

On the other hand, other processes that have not been studied in detail are already reachable for accurate comparison with the SM predictions. Two examples are given by the production of jets in association with a top pair [87] or even the production of bottom jets [88]. These measurements are in good agreement with expectations and are setting strong constraints on the model predictions in regions that were not investigated before.

In summary, the LHC has been proven as a *top factory* allowing a high rate of produced top quarks to perform very detailed measurements of its properties. It is expected that the precision of these will increase with the future samples, providing information and constraints for models related to the less known of the quarks in the standard model. Therefore it is not an exaggeration to claim that particle physics has already entered in the era of precision in top-quark physics.

5.3 Single-top production

A very important topic regarding top production is that of *single top* that is dominated by electroweak production of top quarks. The process, observed at the Tevatron, has not being studied in detail until the arrival of the LHC, in which the available yields allow accurate comparison to the theory.

In the production of single top there are traditionally three channels under consideration: the t-channel (via a W exchange) which is the one with the highest cross section and sensitive to the bottom-quark content of the proton, the s-channel (via virtual W production) and Wt production, which was not observed at the Tevatron. From them, the t-channel is relatively easy to be studied at the LHC and current results have reached a good precision and even allowed separate sudies of the quark and antiquark production. Figure 12 show the measurements at CMS at 7 TeV and 8 TeV [89] and comparison with Tevatron measurements. Similar studies has been produced by ATLAS, with similar reach and conclusions [90]. Additionally, results on the s-channel were able to set limits on the process that are around 5 times the SM predictions [91]. However, the current analysis does not include the full data available. With more data the results will become much more relevant. It should be noted that the s-channel is more sensitive to possible anomalous production of particles.

Regarding the third channel, the associated production of a W boson and a top quark, both experiments reached the level of evidence using the 7 TeV sample [92, 93]. The observed distributions are in agreement with the SM expectations, but more data is needed to perform accurate comparisons. The 8 TeV data should allow the observation and first precise measurements of this process, although the analysis is a bit challenging due to the harder conditions.

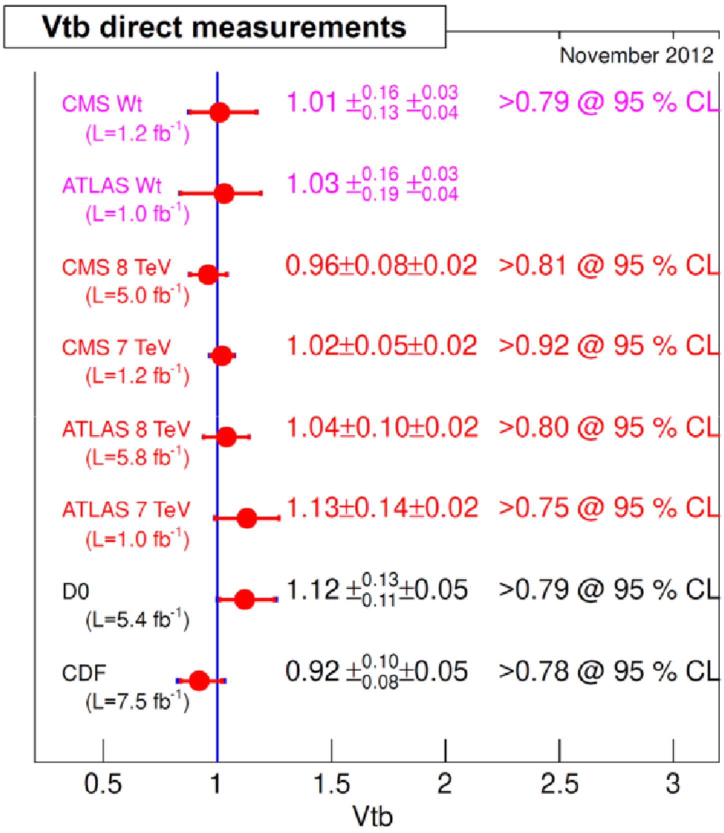

Fig. 13: Summary of all the direct determinations of the CKM element V_{tb} at the Tevatron and LHC experiments from single-top production.

Once the production of single-top events has been established, the study of them allows to provide information about the electroweak couplings of the top quark, specifically due to the sensitivity of the production mechanism to the CKM element V_{tb} ruling the coupling between the top quark, the bottom quark and the W boson. Several determinations of this quantity have been performed at Tevatron and LHC, as summarized in Fig. 13.

In conclusion, studies of the single-top production are starting to reach a precision that will put the SM under test in the unexplored sector of electroweak physics with top quarks. Without doubt, this will also contribute in the next years to complete the picture we have of this quark as a key piece of the SM and its link to its possible extensions.

6 Results on heavy-ion collisions

Although the main goal of the LHC is to understand the interactions at the highest energies (or shortest distances), this collider also allows to produce extreme conditions in terms of energy density, pressure affecting baryonic matter. This is achieved by colliding heavy-ion nuclei, as it is the case of lead. The main goal is to try to study the strong interaction at lower levels, i.e. investigate concepts as confinement, thermal phenomena, chiral symmetry and so on, more closely related to the conditions affecting quarks and gluons in the early universe than the clean parton-parton collisions usually studied at the LHC when colliding protons.

Also in the case of the LHC the increase in energy represents a big step forward in studies of heavy-ion collisions: the experiments at RHIC were intended to discover the production of strongly-interacting perfect fluid. The LHC experiments shall characterize the details of this new class of matter with the increased precision. For that, one of the most useful quantities is the *elliptic flow*, defined as the second momentum of the azimuthal distribution of produced particles. It contains very important physics information because larger values of the quantity indicates the presence of viscosity in the medium at the early times after the collision. Such values were observed at RHIC and by ALICE [94], confirming the expectations from hydrodynamic models. Adiditionally, ALICE has measured the elliptic flow and production yields (and ratios) for specific particles, as e.g. in [95] identified via its sophisticated detector subsystems. Some of the results are a bit unexpected, as the reduced production of baryons with respect to pions, which may be pointing to some presence of hadronic rescattering, an effect never observed. Other interesting measurements have already been performed by the collaborations with the aim of quantifying the characteristics of the collisions, as studies of higher-order harmonics (as in [96]), or particle correlations, and the studies related to the measurements sensitive to the Chiral Margnetic Effect [97] which is a fundamental study in the heavy-ion program at the LHC after the first hints at RHIC.

However, most of the current studies in heavy-ion collisions are more pointing to the confirmation of the results found at RHIC in order to tests new tools and fix a solid base to go beyond in terms of energy and sizes of data samples. In fact, it is in terms of hard probes of the created medium where the LHC experiments have clearly go beyond previous experiments.

ATLAS was the first one presented a result on jet quenching [98], in which one expect dijet events produced from hard parton interactions in lead-lead collisions are observed as assymetric production of jets: opposite to a produced jet with large transverse momentum it is not straightforward to find a second jet, as in the usual proton-proton collisions. In fact a factor 2 of suppresion in central collision is observed, very independent of the jet momentum. This is explained by the presence of a strongly interacting medium which affects more one hard parton than its companion, and therefore giving the impression of disappearence of jets.

In addition to jets, it has been very common the use of hard photons as probes of the medium. Photons are transparent to the medium, so they are perfect to quantify effects on jet quenching in the production of γ+jet, as in [99]. However, photons may also be coming from the hadrons in the medium, or in the final state, so they represent as small limitation that the LHC experiments may avoid with the use of more massive probes that were not available at RHIC: the weak bosons. Currently the experiments have been focusing on detecting the presence of those bosons, since available data samples does not allow its use as actual probes, e.g. in Z+jet production. However, the detection of leptonic Z bosons by CMS [100] and ATLAS [101] have already allowed the first differential measurements to characterize the production of these ideal probes, completely insensitive to initial state or hadronization and for which the medium is transparent. Studies of the W bosons have also been performed [102] and have already provided interesting confirmation regarding proton-neutron differences: isospin effect yields a reduced asymmetry in charge with respect to proton-proton collisions at the same energy per nucleon. Again larger samples are needed for more detailed studies, but the LHC is probing all its potential in heavy-ion collisions.

Another area in which the LHC allows to reach much further than RHIC is the sudy of heavy-flavour production. As in the case of proton-proton collisions, the possibility of identifying secondary vertices allows specific studies to be performed. In fact ALICE has shown its great capabilities with the reconstruction of open-charm mesons, D mesons [103] which are not only nicely observed but also used to perform measurements, like the one shown in Fig. 14, which probes the confirmation of suppression for open charm in central collisions, in good agreement with more inclusive studies. The aim of using open-charm mesons (and perhaps B mesons) is that they bring the possibility of quantifying differences in the energy loss in the medium between heavy or light quarks and even gluons.

But the identification of heavy-flavour states is much more powerful in the dilepton resonances, specifically for the quarkonia states. They have a long history of being studied in heavy-ion collisions due to their clean signature and the big theoretical/phenomenological knowledge on them. Regardless

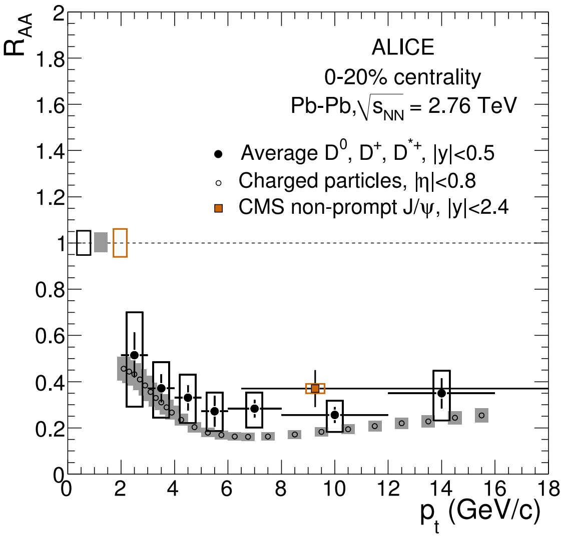

Fig. 14: The nuclear modification factor with respect to proton-proton measured in lead-lead collisions for D mesons in the most central events as measured by ALICE. Data (black dots) are compared to the nuclear modification factors of charged particles (open circles) and non-prompt J/ψ from CMS (squares).

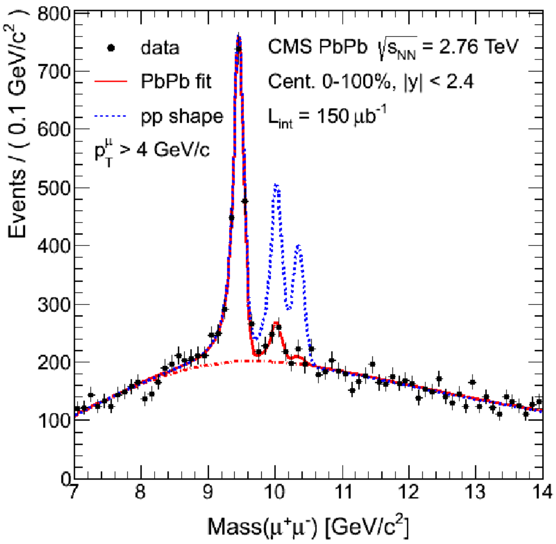

Fig. 15: Invariant mass of dimuon pairs measured by CMS in the region of the Υ family as produced in heavy-ion collisions (dots and red-line fit). Comparison to the data from proton-proton collisions normalized to the Υ(1S) peak (blue dashed line) shows the sequential suppression of the family in heavy-ion collisions.

of being colourless they are sensitive to the medium since they rely on the strong force to keep the two quarks bounded. In fact these states are affected by screening effect and they become an actual thermometer of the medium: the larger the radius of the system (larger for e.g. 2S states than 1S) the larger the screening. Therefore we expect to observe a *sequential suppresion* or *melting* within the quarkonia families: less bound states are more suppressed than those that are more bound. This has been clearly observed in measurements by CMS [104] for the Υ family, as shown in Fig. 15. Clearly the excited states are affected more in relative terms than the ground state when comparing reasults from lead-lead collisions with those of proton-proton at the same energy per nucleon. This is an additional confirmation that a strongly interacting medium is created in the relativistic heavy-ion collisions at the LHC.

It should be noted however that even if the qualitative picture seems clean, the quantitative details do not completely fit, so further measurements and theoretical developments will be needed in order to fully understand the generated medium. Such kind of studies are already in place, as the measurements of J/ψ suppresion by CMS [105] (in central rapidities) and ALICE [106] (in forward rapidities), probing the nice complementarity between experiments. However the agreement in the suppression does not apply to the observation by CMS that ψ(2S) is less suppressed than the J/ψ for transverse momenta larger than 3 GeV, something not confirmed by the ALICE measurements.

In conclusion the heavy-ion program of the LHC experiments is already providing interesting results bringing the field to unexplored areas with a new energy regime and new possibilities, like the use of new available tools and probes. The propects for the future, with further analyses of the data, including the 30 nb^{-1} collected for proton-lead collisions (as the previews in [107, 108]), will help towards the ultimate goal of the program: detailed characterization of QCD thermal matter by means of precise measurements from heavy-ion collisions at LHC.

7 Searches for the SM Higgs boson

The SM structure and its implications in the description of the Universe is based on the presence of a field, known as *Higgs field* that is responsible for the symmetry breaking giving rise to the electromagnetic and weak interaction and also to give masses to the weak bosons. In this process, a single degree of freedom is translated into a scalar particle, *the Higgs boson*, that should be observed and whose coupling to the fermions are introduced in such a way that these last ones acquire the masses that are forbidden by the symmetry before it gets broken.

This particle is therefore the missing keystone of the SM and it was extensively searched for in previous colliders without success. The good performance of the SM strongly motivated the existence of the particle, and the measurements and fits from pre-LHC colliders pointed to a mass of around 100 GeV [109].

Under this situation, the LHC started collecting the data that should provide light to the existence of this boson and eventually find it. This was the most important search for the first years of the LHC experiments and for this reason it deserves a full section describing the analyses and the strategy to follow in order to observe the presence of the boson and also the related measurements wich are aiming to confirm whether the observed resonance actually matches the properties expected for the SM Higgs boson.

7.1 Strategy to search for the boson at the LHC

Before the LHC had collected enough data for being competitive in searches of the Higgs boson, the results from LEP and the Tevatron were the richest source of information. In fact, LEP had excluded at 95% C.L. the SM Higgs boson below 114 GeV and its measurements had constrained the mass of the Higgs to be around 100 GeV.

In the case of Tevatron, the direct searches were excluding a Higgs aroung 165 GeV, leaving the available regions to be clearly separated into two: The low-mass region, for masses between 115 and 160 GeV, that was very strongly motivated. The second region, with relatively high masses beyond 170 GeV, was less motivated, but still not discarded, specially considering that the motivation was assuming negligible effects from possible BSM physics (or more complex Higgs models).

The first step therefore for the LHC was to look into these two regions and during 2011 all channels were considered to investigate all the mass ranges. For low masses, although the decay is dominated by that to bottom quarks, the involved channels were those having the Higgs decaying into ZZ (in 4 leptons) or $\gamma\gamma$, with some information from the WW, $\tau^+\tau^-$ and $b\bar{b}$ decays in all accessible production modes. For high masses the most useful channels were those involving decays into WW and ZZ in all posible signatures. With this approach the two experiments presented results on December 13th 2011 with the data collected at 7 TeV. The results presented at that time led to a complete exclusion of the Higgs boson in the high-mass region (up to more than 400-500 GeV) and most of the low-mass one, leaving alone a small window around 125 GeV.

In that window the exclusion was not possible because both experiments saw an excess, not completely significant but enough to prevent exclusion of the presence of a SM Higgs boson. the excess was appearing in several of the channels Naturally, the presence of a resonance in the most motivated channels to detect the SM Higgs boson was a clear suggestion that such boson was the responsible for the excess, so all the focus from that moment was to intensively search for a possible boson with a mass around 125 GeV whose properties were close to those expected for the SM Higgs boson.

This effort was designed to be applied to the 8 TeV data collected right after the Winter in 2012 and the idea was to maximize sensitivity in the two most sensitive channels at that mass (4-lepton ZZ and $\gamma\gamma$) and also look at the complementary channels (WW, $\tau^+\tau^-$ and $b\bar{b}$) that could provide some further sensitivity and also some additional information regarding the nature of the boson: more couplings involved.

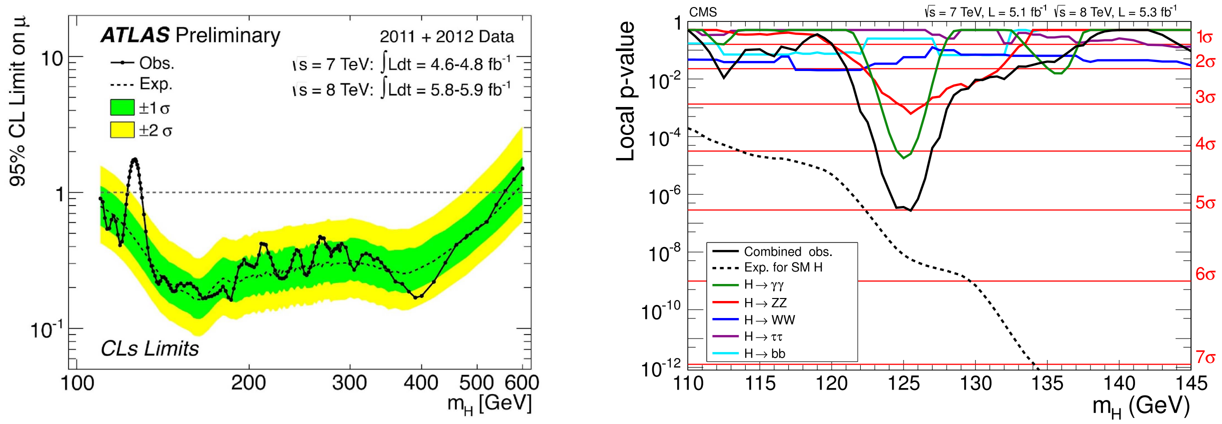

Fig. 16: On the left, 95% C.L. limit on the ratio of the cross section over the SM expectation for the production of a Higgs boson as a function of its mass as obtained by ATLAS at the time of ICHEP-2012. Observed limit is compared with the expected limit (in absence of such a particle) and the uncertainty intervals. On the right, the local p-values for a similar study in several analyses by CMS. In both cases a very significant excess is observed around 125 GeV that is interpreted as observation of a new particle, likely the SM Higgs boson.

In parallel more analyses were still considered in order to complete the pictures, even those that were looking (and excluding) the presence of a SM Higgs boson at higher and higher masses.

All these analyses are described in the following sections.

7.2 Analyses for the discovery (ICHEP-2012 results and afterwards)

At the time of ICHEP-2012 the size of the available data at 8 TeV was comparable to that collected at 7 TeV, allowing already enough sensitivity to perform statements on the boson. Both collaborations presented results in the main channels on July th 2012, and they confirmed the presence of a new boson at the discovery (5σ) level. The presented results are summarized by the plots in Fig. 16, where the results from the statistical analyses of the studies are shown.

The measurements performed at 8 TeV also increased the precision on the knowledge of the boson and in general tend to confirm its nature as that of the SM Higgs boson. Later improvements to the analyses and the addition of the data that was provided by the LHC during 2012 have brought additional support for this hypothesis. However, some questions are still to be investigated and further data would allow more precise measurements in the future. Here we will discuss some of the more relevant results bringing to the current knowledge about the boson dicovered at a mass of 125 GeV.

In the case of CMS, the $H \to \gamma\gamma$ search [110] is performed by using several categories of diphoton (for inclusive production mode) and two categories for tagging Vector-Boson Fusion (VBF) processes. It should be noted that VBF is very important because it is sizable (mostly because the leading Higgs production occurs via loops) and it involves different couplings than the dominant mechanism, e.g. it is very important for fermiophobic models.

With all those categories, the analysis is able to achieve a significant excess of 4.1σ with a yield a bit higher than expectation.

In addition to that, the 4-lepton search was dealt in this collaboration with the use of a kinematic discriminant that accounts for the fact that the Higgs boson is a scalar. This kind of tools have made that this analysis [111] is the central reference for measuring the properties of the boson, as described below. As shown in Fig. 17 the channel has very little background and the signal is clearly observed in spite of the low yield. The significance of the excess at a mass of 126 GeV is very high, although in this case the yield comes a bit lower than the SM expectation, but still in agreement.

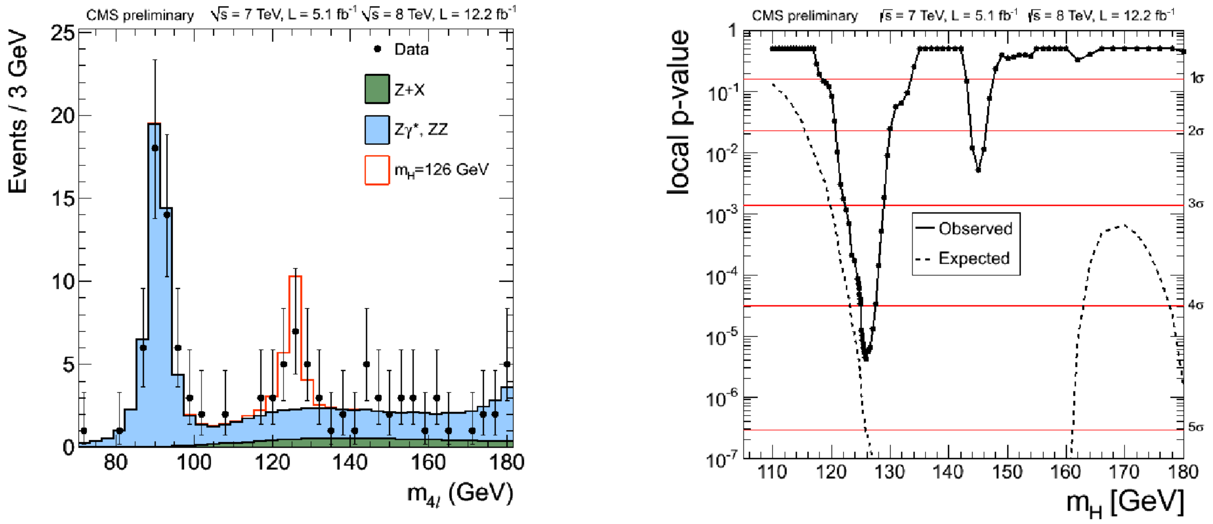

Fig. 17: On the left, the mass distribution of 4 leptons in events selected for the Higgs search at CMS. Data (dots) are compared to the background expectation (solid histograms) and a Higgs signal with $m(H)$=126 GeV (red line). On the right, local p-values associated to the same analysis, with a clear excess for a Higgs mass around 125 GeV.

In addition with the most sensitive channels, CMS has put a lot of effort on the secondary channels which are giving additional constraints about the boson, with a small sensitivity. Specifically, the WW decay also suggests the existence of a boson, but with a yield on the lower side [112]. The $\tau^+\tau^-$ shows clear limitations on the size of the data sample and although the result is compatible with a SM Higgs, it is also in agreement with the background-only hypothesis [113]. A similar conclusion is extracted from the decay into bottom quarks [114], in which the Higgs need to be observed in the production associated with a weak boson, in order to keep the dijet background under reasonable limits. The studies of diboson production described in section 3.4, specifically in the semileptonic channels, provide a solid support to the search of the boson in this decay channel. In any case, more data will provide stronger constraints on the fermionic decay channels, currently compatible with the existence of the SM Higgs boson but with small significance.

From the ATLAS side, also several updates came after ICHEP-2012, bringing further confirmation to the signal and, as in the CMS case, higher precision in the results. The diphoton search [115], performed with several categories, has lead to a very strong signal, which approaches the level of being very high when compared to the SM expectation with a signal strength value approaching a factor of 2 (being 1 the SM prediction). Dedicated studies of this value in a per-channel basis does not indicate anything striking, but uncertainties in those cases are large since it is the combination of them which is bringing the high significance of the signal. Plot on the left of Fig. 18 shows the invariant mass distribution of diphotons in which the resonance at a mass around 125 GeV is clearly observed.

As in the diphoton search, the 4-lepton channel in ATLAS gives a signal strength higher than the expectation, although in this case in agreement with the SM value (and with the CMS result). The study of this final state [116] is performed by exploiting the kinematical properties of the decay products from a spin-0 particle. As shown in the plot on the right of Fig. 18, the signal is clearly observed with a reasonable amount of background, which leads to this channel as the main reference to measure the properties of the boson, as in the case of CMS.

Regarding the complementary channels, ATLAS also puts a big effort on those with similar conclusions to those obtained by CMS. In the case of the decay into bottom quarks [117], sensitivity has not yet reached the level to allow quantitative statements about the boson to be made. The other two channels [118, 119] give higher yields than expected, but still with large uncertainties. In the case of $\tau^+\tau^-$,

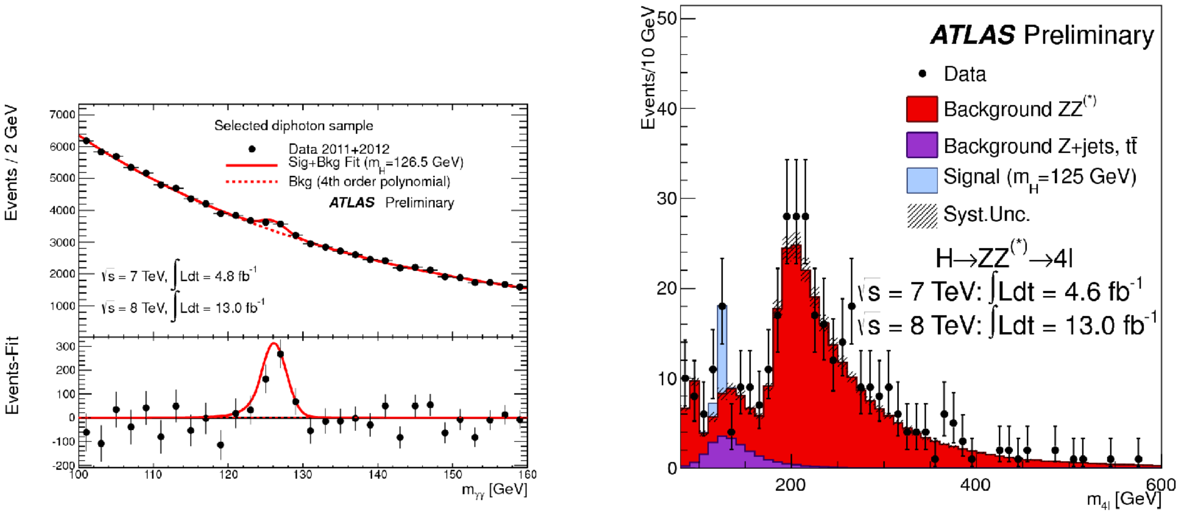

Fig. 18: On the left, invariant mass of two photons in the search for the Higgs decaying into diphotons performed by ATLAS. The fitted background is subtracted in the plot below in order to enhance a resonant excess close to 125 GeV. On the right, invariant mass distribution of 4 leptons in events selected for the Higgs search at ATLAS.Data are compared to the background and a signal hypothesis with $m(H)$=125 GeV.

the value seems to be high in the case of the main production channel, but in VBF and in associated production with a weak boson (VH) the signal strength is clearly on the low side [119]. It is too early to be considered a problem since the uncertainty is still large enough to cover the SM value within 1σ.

7.3 Post-discovery goals: measuring the properties

As described in the previous section, a new boson has been observed and its properties are compatible to those expected from the Higgs boson of the SM. With the additional analysis the picture is getting more complete, but precision needs to be improved to extract further conclusions.

One of the goals in the incoming *post-discovery* years is the measurements of all the properties. This has been already started, and some answers are already provided, as we will discuss here.

The first set of results is the comparison of the signal strength for the several channels that have been investigated. The results are summarized in the plots of Fig. 19. As mentioned in the previous section, values are not completely matching the expectations from the SM, but they are not significantly discrepant. More data will be needed to reduce the uncertainty and investigate possible anomalies in the production and decay mechanisms. Explicit disentangling of the couplings show they are fully compatible with the SM expectations, as in [120].

After the production mechanism has been checked, the first obvious property to measure is the mass of the found resonance. Dedicated studies has been performed at the two collaborations using the most sensitive channels. In the case of CMS, the last study has been based on the 4-lepton sample and provides a mass value of $m(H) = 126.2 \pm 0.6$(stat) $\pm\, 0.2$(syst) GeV [121]. In the same analysis, studies of the spin and the parity leads to the conclusion that the data clearly favours a pure scalar versus a pseudoscalar. Additionally, data is not precise enough to distinguish between spin-0 and spin-2 particles in this channel.

In the case of ATLAS, the results presented in [122] show some tension between the masses extracted from the 4-lepton and the diphoton channels. In the first case a value of $m(H) = 123.5 \pm 0.9$(stat) $\pm$ 0.3(syst) GeV is obtained. For the second, the value is $m(H) = 126.6 \pm 0.3$(stat) $\pm$

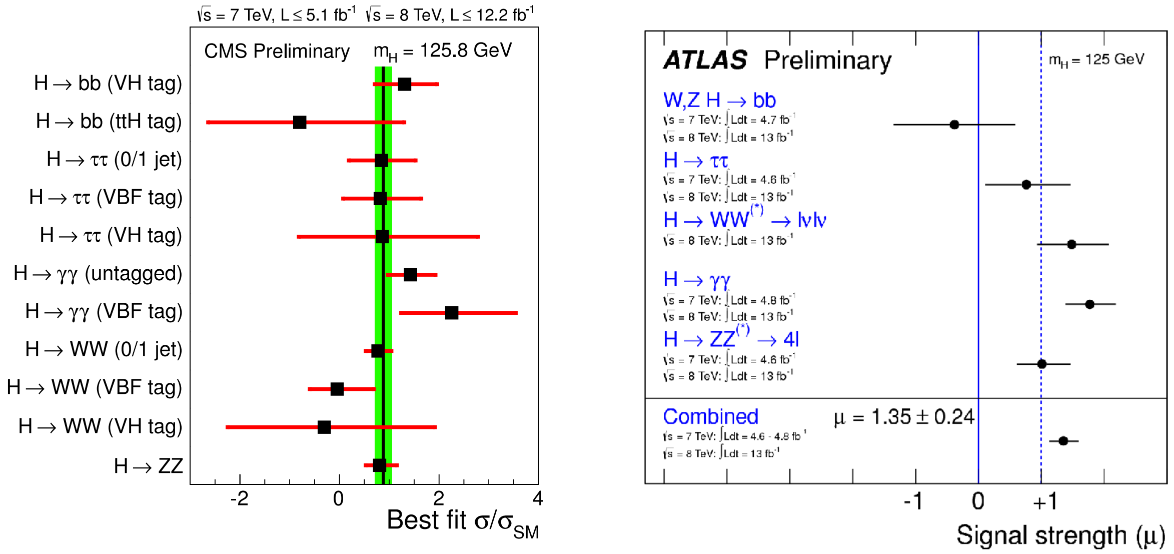

Fig. 19: Signal strength in the several channels sensitive to a Higgs boson with a mass close to 125 GeV in CMS (on the left) and ATLAS (on the right). SM prediction should be centered at 1, which is compatible with the measured values and with the combined average.

0.7(syst) GeV, in better agreement with the measured value at CMS using the 4-lepton channel. This discrepancy will require some further investigation and perhaps data to be understood. It should be added to the issue that the signal strength values as measured by ATLAS tend to be higher than the SM expectations.

In addition to the mass measurement, studies of the spin and parity has also been performed by ATLAS [123]. They are similar to those by CMS, but more complete since information is also extracted from the $H \to \gamma\gamma$ analysis. This has allow to add more sensitivity to the distinction between sipn-0 and spin-2 particles.

7.4 Other searches for SM-like Higgs and within models of new physics

Even though a boson that is a good candidate to be the Higgs as predicted by the SM has been found, other analyses looking for SM-like Higgs bosons are still of interest. The main motivation is that they may be sensitive to scalar resonances with a mass larger than that of the boson, or smaller but with lower production cross sections.

Most of these searches are following very closely the searches for the SM Higgs at the correspondent masses, since they inherit from analyses performed before the boson was observed. They are naturally diverging from the optimal search for the SM Higgs, in order to look for similar particles, but not with exactly those properties of the SM Higgs. Many searches has been performed by ATLAS [124] and CMS [125] and have computed limits for possible presence of particles that are SM-Higgs alike, since no hint for a resonant scalar has been seen.

Furthermore, several BSM theories include the modification of the Higgs-sector, which implies that other Higgs particles may be present in Nature, even with the presence of the SM one. The suggested discrepancies in the Higgs properties add further motivations for this kind of models. Note we discussed them here even if searches for BSM physics are included in sections 8 and 9.

As usual in searches for new physics, supersymmetric models are the most attractive to be considered. In the case of Higgses, Supersymmetry (SUSY) requires the presence of at least five Higgses, one basically like that predicted in the SM and others that are relevant due to their properties: charged Higgses and Higgses with enhanced couplings to bottom quarks and τ leptons. This later case motivated the search for a Higgs decaying into $\tau^+\tau^-$ interpreted in SUSY models. Lack of any observed signal bring the experiments to use the results [126, 127] to set constraints in the SUSY parameter space.

In addition, searches for charged Higgs have been performed in order to look for their presence in decays of the top quark. CMS has focused on the τ channel [128], looking for an anomalous presence of τ-based decays with respect to other leptonic channels. Limits were set for several models due to the good agreement of the data with the W-only-decay hypothesis. In the case of ATLAS, one of the investigated channel was $H^\pm \to cs$ [129], in which the presence of a dijet resonance not peaking at the mass of the W boson will be identified as a signal. In addition, we expect a lower yield due to the competing channel that is purely hadronic (assuming that the charged Higgs decay preferably into that channel). Data does not confirm these expected anomalies, so additional limits are set for this kind of model.

Aside for the basic SUSY models, other extensions of the SM incorporate modifications of the Higgs sector and therefore they have been searched for. There are many possibilities here, and several classes of Higgses show up. However, we should emphasize that some of them yield topologies that may have been missed due to kinematic selection, as it is the case of Higgses with low masses (as the dimuon resonance search in [130]) which may be produced just as boosted objects due to their own couplings. Other possible exotic particle in the Higgs sector is the presence of doubly-charged particles whose searches, as the one in [131], have not reported any visible discrepancy with respect to the expected SM backgrounds.

In conclusion, no significant hint of alternative or extended Higgs sectors has been found to complement the boson observed at a mass around 125 GeV. However, this does not imply that the physics beyond the SM is out of reach, since the Higgs sector is well known for providing very elusive particles. For this reason, searches of new particles have been performed independently of the discovery of the possible Higgs, as discussed in the following sections.

8 Searches for new physics

As it has been discussed before, the LHC is intended as a machine to bring information about new physics beyond the SM. The possibility that the Higgs boson has been found does not only confirm the validity of the SM, but also its limitations that should be investigated to find even more correct answers about the structure of the Universe at the smallest distances.

Finding these answers at the LHC requires a huge effort in order to cover the many possibilities, and therefore corners of the parameter space. This makes the search topic a very broad field of investigation. In this report we just summarize the most interesting searches of all those developed at the LHC.

Within the searches for BSM physics, the models involving SUSY are strongly motivated due to their good theoretical performance to solve the SM limitations. Specifically the doubling of the particle spectrum, in order to have a supersymmetric partner to each SM particle, allows a very reach phenomenology that translates into many analyses investigating several types of final state topologies. Those are discussed in section 9.

On the other hand, there are well-defined alternatives to supersymmetric models that also provide possible explanations to the issues of the SM as the full description of the Universe. In the following subsections we focus on summarizing the searches for these alternative models.

8.1 Searches for unknown high-mass resonances

When looking for new physics, the more direct approach is to look for particles that are not included in the SM spectrum. For that, the search for resonances decaying into detectable and well-known particles is the simplest approach. Some of these resonances are naturally predicted in extensions of the SM, specially with the addition of new interactions. Figure 20 show the invariant mass of dileptons as measured by

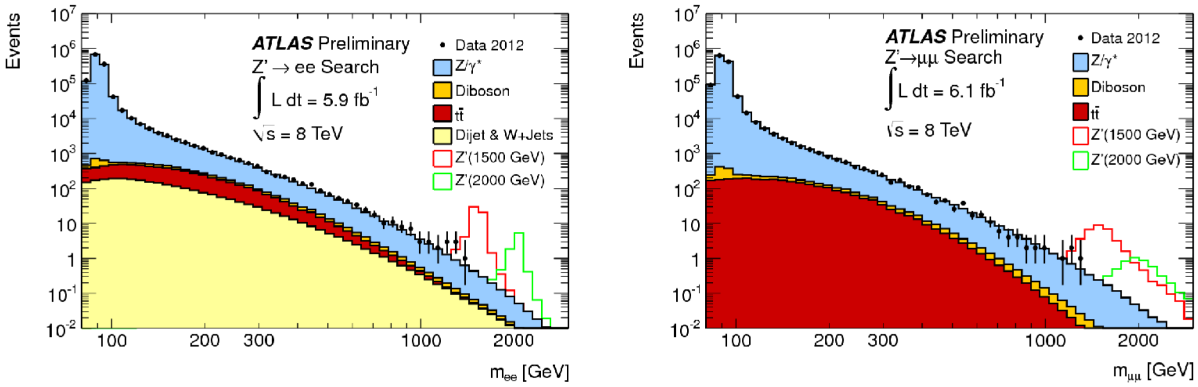

Fig. 20: Invariant mass distributions of electron-positron (left) and dimuon (right) in dilepton events collected by ATLAS. Data (dots) are compared with the SM predictions (solid histograms) and some expectations for BSM resonances (lines).

ATLAS when looking for a massive resonance that would appear as a peak in those distributions. The comparison of the data with the SM expectation show very good agreement and results [132] (and [133] for CMS) are used to set limits on the production cross section for resonances, and lower mass limits on possible Z-like particles in the order of 2.5-3 TeV.

Similar to the lepton search, the production of dijet resonances has also been considered, as in the CMS result documented in [134], in which special treatment has been performed in order to separate between resonances decaying into gluons or into quarks (or a mix). Also in this case, a good agreement has been observed, but the main issue is how to handle the huge background at the lower invariant mass, that forces to reject events even at the trigger level.

This has been the testing analysis of a new technique, called *data scouting*, which allows to collect interesting events passing around the trigger limits. The idea is to collect events at a higher rate but storing only the final reconstructed objects, which allows the reduction of the data content per event. This permitted CMS to trigger and perform studies for lower invariant masses with competitive results [135] even with a reduced datasample of 0.13 fb^{-1}.

When looking for resonances, the presence of neutrinos is not a limitation, and the search is also extended to the use of the *transverse mass* of a lepton and the $E_T^{\rm miss}$, defined as

$$M_T = \sqrt{2 \cdot p_{T,\ell} \cdot E_T^{\rm miss} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

to investigate the presence of new resonances decaying into a charged lepton and a neutrino. In the case of a resonance, this variable shows a Jacobian peak that is on top of a smooth background. The current results, as those in [136], do not show any hint of such type of structure, and limits on production of W-like particles has been set.

However, when we talk about limits on very massive W-like particle, a possible decay channel is into a top and a bottom quark, which is not allowed for the W. This was investigated by ATLAS [137] and found no sign of a resonance decaying into those quarks, and independently of the number of the identified b-jets. It should be noted that the searches of this kind of resonance have become very powerful at the LHC due to the available energy for producing high-mass resonances decaying to the most massive particles in the SM spectrum. This is also confirmed in the study of resonances decaying to weak bosons, which are predicted to appear in several BSM theories. A result by ATLAS has taken advantage of the trilepton final state to look for resonances decaying into WZ [138], providing a very competitive result, although usually this kind of search is performed with semileptonic or fully hadronic channels to make use of the larger branching ratio.

In fact, the energy at the LHC is so large and the possibility for producing resonance so large, that very massive object could appear and the decay products will be boosted, which may lead to dijet (e.g. from W) merged into one reconstructed jet. This has been turned into a benefit to enhance signal, by using merged jets to tag the presence of hadronically decayed bosons. The result of the analysis by CMS [139] shows the good performance of the boosted-jet tools. Unfortunately no sign of new physics was found.

A similar analysis by ATLAS looking for a resonance decaying into ZZ in the semileptonic channel [140] also exploits the merged jet topology to increase acceptance to very massive resonances and set a much constraining limit than that accessible by the obvious dijet topology.

Among the searches for resonances indicating BSM physics, one common topic is the studies of possible excited states of fundamental particles, which could be related to new physics (e.g. contact interactions or internal substructure). This is the case for the search of excited muon states decaying into a muon and a photon as the one by ATLAS [141] looking for the Drell-Yan production of a muon and an excited muon. The results are in good agreement with SM predictions for the most discriminant variable: the invariant mass of the two muons and the photon, which allows to set stringent limits in the possible scale for such a excited state to exist.

In addition to the searches for resonant states in the two-body decays, the high masses accesibles at the LHC allows the searches for more complicated topologies, with more objects in the final state. One example is the search for boosted resonances decaying into three jets. The search performed by CMS [142] assumes pair-production of these objects, and therefore the idea is to study three-jet ensambles whose transverse momentum is large but the corresponding mass may show a peak structure related to a decaying resonance. The requirement of large transverse momentum allows the reduction of the combinatorial background, for which the mass and the transverse momentum will show a correlation. Although the result of the analysis does not show hints of any possible resonance, the used technique can be used in other searches in the future. In the current case, limits are set on the existence of resonances.

Another alternative that is open at the LHC is the cascade decay with initial massive objects sequentally decaying into states. A very syummetric case considered at CMS consists on the pair production of objects (e.g. technicolour particles) decaying into pairs of particles (e.g. other lighter state in the technicolour spectrum) which decay into dijet. This process will lead to an 8-jet topology in which there are resonant peaks in four dijet masses, two 4-jet masses and perhaps in the 8-jet mass in case the original pair-production occurs from the decay of a single-produced particle. All this information is combined into an artificial Neural-Network to enhance signal-like topologies. The results [143] show that there is no peak structure on top of the combinatorial background coming from usually-produced 8-jet events and limits has been set for models motivating this kind of signature.

8.2 Searches for leptoquarks

One special case of pair-produced resonances that are motivated by unification models is *leptoquarks*, particles having both lepton and baryon numbers. They are detected via their decay into a lepton and a quark, which gives a resonant peak in the invariant mass (in the case of charged leptons) or significant excess in E_T^{miss}-related variables (in the case of neutrinos).

Since these particles carry colour, they are pair-produced with a large cross-section, giving rise to clean signatures due to the leptons in the decay. Furthermore, they also have a rich phenomenology, since these particles could be of different classes (scalar, vector) and also appear in different generations, although they are usually not mixing fermions of different families.

The basic analyses, mostly oriented to the first two generations are easily identified by the kind of lepton, which determines the generation we are focusing. Searches by ATLAS [144] show good agreement with the SM expectations for the $eejj$ and $\mu\mu jj$ final states. These results are used to set limits that are going beyond previous searches of these particles.

Since the first generations are not providing hints of leptoquarks, even in the channels with neutrinos, searches have also been focused on the third generation, where τ leptons and bottom quarks are expected. Specifically the search by CMS [145] with the use of b-jets exploits the sensitivity given by the scalar sum of the transverse momenta of the decay products. The results are in good agreement with the SM expectations, and they are used to set limits on the leptoquark production, but also on the production of scalar tops within R-parity (R_P)-Violating SUSY models (see details in section 9.3), giving an explicit proof that searches of new physics are usually sensitive to several classes of models bringing similar final states, an in similar areas of the phase space.

8.3 Extradimensions and graviton searches

The extensions of the SM do not only consider the extension of the particle spectrum or the interaction sector. Several models introduce the modification of the structure of the Universe by incorporating additional dimensions, that would be microscopic and whose existence may explain the large scale difference between the electroweak interaction and gravitation. The idea is that the new dimensions will be forbiden to the SM particles and effects, while gravity expands in all the available dimensions. The signatures will be striking with the production of gravitons (producing large E_T^{miss} since they escape detection) and SM particles, leading to single-photon (monophoton) or single-jet (monojet) topologies,

These have been looked for by the collaborations. As an example, ATLAS has looked for events with a photon with large transverse momentum that is accompanied with large E_T^{miss}, which is the most significant variable to identify the presence of new physics [146]. Good agreement is observed with respect to the SM expectations for this signature, dominated by undetected weak bosons (neutrino decays) in association with a photon. Also some background contribution is present due to detector effects generating artificial kinematics looking like the signal.

Furthermore, ATLAS and CMS have also looked for the monojet topology [147, 148]. Although the main motivation for this signature is the production of gravitons produced in association with quarks, there has been an increase use of this kind of search for studying the production of invisible particles (as generic Dark Matter candidates) in a model-independent way, being the jet balancing the E_T^{miss} produced by initial-state radiation. This keeps a small fraction of the total signal, but allows to look for hard-to-detect particles that may be copiously produced at the LHC collisions. It should be remarked that this makes a strong case when compared to the more clean monophoton signature: results are more sensitive to other classes of models.

The results of the monojet searches has also found good agreeement with the SM predictions. Figure 21 shows the E_T^{miss} distribution of the ATLAS analysis [147], that has also been used to set limits in the production of gravitino from the decays of squarks and gluinos.

Another possiblity related to extra-dimensions and accessible production of graviton is that particles may appear as Kaluza-Klein towers which sequentally decay into less massive objects. Specifically, gravitons may appear as diphoton resonances, which is an easy-to-identify signature, but it suffers from large backgrounds. Anyway, they have been investigated by the LHC experiments, as the analysis in [149], and no hint of such a resonance has been found on top of the diphoton high-mass spectrum, as shown in Fig. 22, which also includes the expectation from a resonance as those predicted by Randall-Sundrum models and the expected effect due to a more generic model including additional dimensions.

8.4 New physics in the top sector and new generations

As discussed before, the top quark is usually suggested as the primary candidate to open the path towards new physics. Its large mass and coupling to the Higgs, which are the basic quantities related to the loose ends of the SM, make this quark a very attractive place to search for discrepancies with respect to the SM expectations, Since the first step to fix the hierarchy problem is to have a partner canceling the top-induced corrections to the Higgs mass, such a partner should be at reach of the LHC independently of its

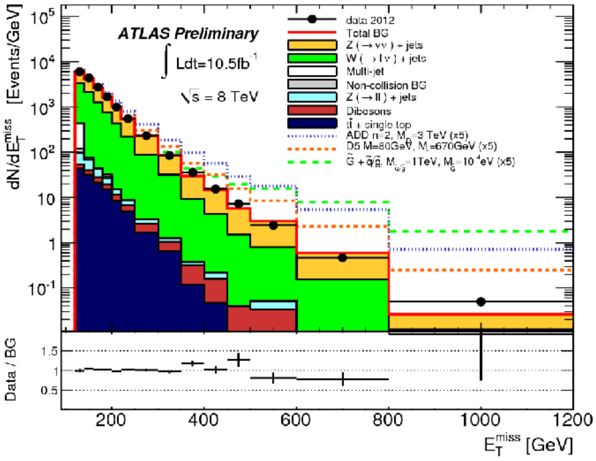

Fig. 21: Distribution of the E_T^{miss} variable in events with a single jet with large transverse momentum. Data (dots) are compared to the background expectations (filled histograms) and possible signals for BSM physics (coloured lines).

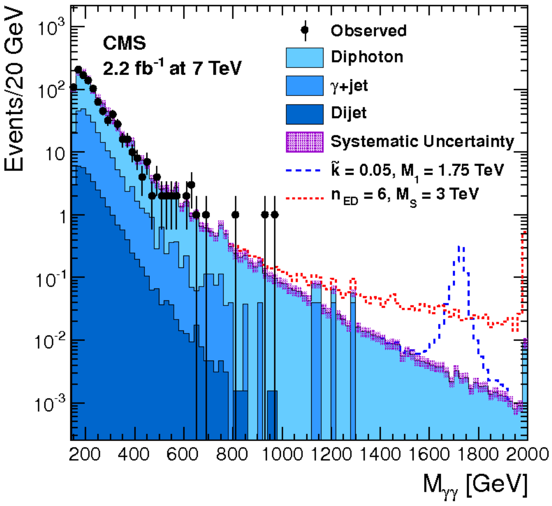

Fig. 22: Distribution of the diphoton invariant mass in events with two photons with large transverse momentum. Data (dots) are compared to the background expectations (filled histograms) and possible signals for BSM physics (coloured lines) containing a Randall-Sundrum resonance or a generic extradimention model.

nature. Although the most obvious choice is a SUSY partner (see section 9.2), alternative options have been made, including the possibility of the existence of a very massive 4th generation.

One option considered by ATLAS [150] is the search for the pair-production of a top partner having an electric charge of 5/3 (of that of the positron). Appearing in several models, the decay into a top quark and a W boson allows to have good acceptance with same-sign dileptons and also to use the hardness of the event (scalar sum of transverse momenta of final objects) as discriminating variable. No significant discrepancy has been observed with respect to the low expected SM background.

As a general rule, the existence of additional generations (containing canonical or exotic particles) that would contain coloured particles more masive than the SM ones leads to very busy final states in terms of multiplicity and of energy. This is used in the optimization looking for this kind of topologies, being very common the requirement of hard events or with rare combination of objects (same-sign leptons, leptons and b-jets in high multiplicities and similar requirements). The performed analyses searching for a 4th generation, as those in [151,152]. All searches have brought the conclusion that there are no hints for the existence of a 4th generation (in the reachable masses) nor of any new physics that may look like massive particles regarding busy final-state topologies.

8.5 Searches for very exotic signatures

The lack of success to find hint of straightforward BSM physics has open the possibility that Nature is not as predictable as we might think and the new physics may appear in some even more exotic signatures than those considered for the theoretically-motivated BSM final states. This has led to the study of final states that could have escaped the more traditional selection or based on models less related to the confirmed SM predictions, which bring to new classes of final states.

One option that has been considered is the production of microscopic black holes at the LHC collisions. Some generic properties of them from quantum gravity provide general rules of final-state expectations: high multiplicities and democratic treatment of objects. The search for this kind of events [153] was performed by exploting that the scalar sum of transverse energies for the SM background presents a shape that is independent of the multiplicity. Therefore the lower multiplicity events are used to get the shape that is compared to the data with high multiplicities. Good agreement has been observed and limits in a model-independent approach are set.

Other rare topology that is not commonly considered is the presence of long-lived particles that may escape even the trigger selection. Some of these particles appear in several models as quasi-stable particles. In this context, searches for charged massive particles (CHAMPs) by CMS [154] or more dedicated searches like the stable chargino using track-disappearance by ATLAS [155] are good examples of the possibilities beyond the usual approaches and how the detectors <re used with non-standard event reconstructions to look for unexpected classes of particles. In this, we should also mention the search for magnetic monopoles (as that by ATLAS in [156]), whose existence is very strongly motivated due to the electric charge quantization and as part of the electromegnetic unification. The need for specific reconstruction of the events (since these particles are not electric charges, and behave very differently inside magnetic fields) add some complication to the analysis, but still the results are very competitive when compared to direct searches because of the possibility to produce them with high cross section at the LHC. In any case no hint for production of monopoles has been observed and further data will help to increase the sensitivity, specially with the addition of the dedicated experiment for this (MoEDAL [8]).

In conclusion, after the first datasamples provided by the LHC collisions have been analyzed, no discrepancy with the SM prediction has been found that could be considered as a significant hint of new physics or particles beyond the SM spectrum. The future running of the LHC at a higher energy and higher luminosities, discussed in section 10, should provide more information on the possible BSM physics.

9 Searches for supersymmetry

In SUSY models the particle spectrum is at least doubled [157], bringing a lot of possible processes that could distort the measured values with respect to the SM expectations. Depending on the considered process, the final state to be investigated is different, providing a rich phenomenology.

However, since at the LHC the initial state is based on partons, the dominant production mechanism is usually the production of coloured superpartners. In usual models they are produced in pairs since R-parity (R_P, a quantity being 1 for particles and -1 for superpartners) is conserved. In addition, the conservation of R_P implies that the lightest SUSY particle (LSP) is stable and a Dark Matter candidate.

These basic properties allow to make general analysis in searches for SUSY which focus on specific parts of the spectrum. In addition, this also brought a new way of interpreting the results which are based on “simplified models” which provide well-determined processes for the given final states. This has simplified the interpretation of the results in terms of the possible theoretical models. On the other hand, the more traditional, “full model”, approach are still advantageous to interpret results from different analysis and experiments within a common framework.

Independently of the model the most basic search for SUSY is to look for jets and E_T^{miss}. The latter being a hint of the stable LSP, and the jets appearing as the decay products of coloured superpartners, which are the ones associated with larger production cross sections: squarks and gluinos. These analyses are just dependent on the reconstruction of the E_T^{miss} and they try to quantify its presence with variables that are less sensitive to misreconstruction. In addition several categories are investigated in order to be sensitive to different kind of SUSY processes. The categories are usually identified by the hardness of the event (with E_T^{miss} or momenta of jets), the multiplicity of jets, or the multiplicity of b-jets.

The analyses by the collaborations, as those in [158, 159], do not show any significant discrepancy with respect to the expected backgrounds. Results are used to set limits in several types of models, and are typically excluding the presence of squarks (of the first generations) and gluinos below 1-1.5 TeV.

In the case of massive squarks, it is feasible to produce gauginos that are lighter but still hard to produce directly from the proton collisions. These gauginos may decay in leptons with large transverse momenta which simplify the identification of the events at the trigger and reconstruction levels. Both collaborations have searched for SUSY events in final states with leptons, jets and significant E_T^{miss} [160, 161] and the results shows good agreement with the SM expectation. Results have been used to set limits on the production of SUSY particles that produce leptons in the final state. It should be noted that the studies with leptons include the τ lepton (as in [162]) since they provide increased sensitivity to the case of Higgsino-like gauginos.

When one consider leptons in the final state, the presence of multileptons may be a good hint of SUSY due to the reduced SM backgrounds. Specially when there are at least three leptons and significant E_T^{miss}, which is the golden final state detecting the production of a pair of chargino and neutralinos decaying leptonically or even production of scalar leptons. The background of these kind of studies [163, 164] is dominated by diboson (or multiboson) production in which leptons are the decay products of the massive weak bosons.

Again, the presence of τ leptons is fundamental is some areas of the parameter space since the gauginos may not be as “flavour symmetric” as the corresponding SM bosons. In any case, no significant excess has been observed and the results are used to set limits on the production of gauginos. It should be noted that this kind of final state is sensitive to a different area of the SUSY parameter space, so they are complementary to the search of events in which coloured superpartners are producted and sequentially decay into SM particles.

9.1 Gauge-mediated Supersymmetry breaking

After the simplest topologies have been investigated and report negative results regarding the existence of SUSY, other models providing significant differences in the final states need to be considered. A qualitative change is set by models in which SUSY is broken in a hidden sector and communicated via gauge interaction [165], since the LSP is the gravitino and the phenomenology depends on the next-to-lightest SUSY particles (NLSP) because most of the decays go preferably via that particle.

In the cases where such particle is a scalar lepton, usually the scalar τ, the final state contains leptons that are easy to identify. Searches by both collaborations [166, 167] show good agreement with expectations in several types of final states.

Other case that is very relevant is when the NLSP is a neutralino, decaying into a gauge boson (usually a photon) and the gravitino. This is also a relatively simple final state, since the presence of photons helps to make the event selection much cleaner. The analysis searching for diphoton and E_T^{miss} by CMS [168] observed a good agreement between the observed data and the expected SM backgrounds, as displayed in Fig. 23, where the E_T^{miss} distribution in events with two photons is shown, including some possible signals to explicitly shown the sensitivity to a signal in this variable.

Even if the considered final state in models with gauge-mediated SUSY breaking was able to avoid limits set for MSSM-inspired searches, the results are not showing any significant discrepancy that could be attributed to the production of SUSY particles.

9.2 Natural SUSY and third generation squarks

After the studies of the more obvious SUSY final states, the obtained limits are moving the SUSY scale to high values so it starts to approach the decoupling with respect to the electroweak scale. Since the motivation for SUSY is to fix problems at this latter scale, new concepts are required to keep the connections between the two scales and, at the same time, avoid the current limits from more inclusive final states.

In this sense the two obvious things is first to keep the neutralino (or equivalent) as the LSP in order to have a Dark Matter candidate that is stable and weakly coupled. Secondly, we need the lightest scalar top to be light enough to keep the divergences in the Higgs mass as smaller as possible. This means $m(\tilde{t}) \lesssim 400$ GeV. This expression also requires a gluino not far from 2 TeV to avoid a strong correction on the scalar top mass. With these requirements, all other SUSY particles may have any value, since their influence is much smaller. Therefore current limits on general searches are avoided.

However, this "natural" SUSY becomes only completely natural when other superpartners are associated to the needed ones. For this reason it is not uncommon to have also light scalar bottom quarks or scalar τ (as mentioned above). Additionally, the LSP could be a family of degenerated gauginos of several classes. It should be noted that in spite of the reduced number of superparticles involved, the possible final states are very complex due to the involvement of the third generation of fermions.

For example, with the described spectrum, it is feasible to have gluino-pair production as the process with higher cross section. These gluinos decay into quarks and E_T^{miss}. In the case the scalar bottom is available, the gluinos may give rise to final states containing E_T^{miss} and four bottom quarks, that may be identified as b-jets. This topology is very clean due to the reduced backgrounds and therefore sensitivity may be enhanced by the b-jet requirements, allowing some additional room with respect to the more inclusive limits, where the limitation was the huge backgrounds. The study done by ATLAS [169] shows no hint for anomalous production of multi-b-jets and significant E_T^{miss}, a selection sensitive to this final state. Limits in SUSY and other models are set. Regarding the interpretation, it should be noted that this analysis is also sensitive to the decay into top quarks, since also four bottom-quarks appear in the final state.

On the other hand, the case of top and scalar top quarks produced via gluino production is much richer than just the presence of b-jets, due to the large multiplicity of W bosons. It is possible then to identify the events containing four top quarks and significant E_T^{miss} in several approaches and with very challenging final states for the SM expectations: analyses in this topic [170, 171] are testing the SM predictions in very specific corners of the phase space, and specifically in regions that were not tested before. Even there the SM predictions provide a very good description of the measurements, which translates into further contraints to SUSY production.

Even if the use of gluino-mediated production allows the use of striking signatures, it is more attractive the direct production of squarks of the third generation which are those strongly motivated to be relatively light, according to "naturalness". Therefore experiments performed searches of scalar bottom quarks as that in [172] in which the identification of b-jets is fundamental to reduce the SM background. In addition, searches for direct production of scalar top quarks [173–176] still provide enough complexity in the final state to allow several classes of searches. This is seen in summary plots as that displayed in Fig. 24, containing the exclusion areas from several searches of direct production of scalar top.quarks.

As the summary plot shows, the several assumptions on the decay and kinematics of the final states allows to exclude large areas of the parameter space. But in summary, the lack of observation of hints for scalar top quarks just bring the scale for SUSY (in this case given by the mass of the scalar top) to higher values, similarly of the results in more inclusive searches. Threfore, it seems that SUSY may not show up in the most obvious way to fix the issues of the SM and particle physics.

9.3 Searches for R_P-Violating SUSY

Although usually it is assumed that R_P is conserved because it directly provides a Dark Matter candidate, it is obvious that there is no reason a priori why that quantity needs to be conserved. By relaxing the conservation condition it is possible to avoid many of the most stringent limits, since they are usually obtained with the requirement on E_T^{miss}, which is inspired by the assumption of conserving R_P. In addition, the phenomenology becomes much richer due to the possibilities in the spectrum and in the possible interactions. For example with the presence of unusual resonances in the final state (like $\tilde{\nu}_\tau \to e\mu$).

One general characteristic of the R_P-Violating signatures is that since all the superpartners decay into SM particles, the final state usually is related with high multiplicity of objects, and involving many

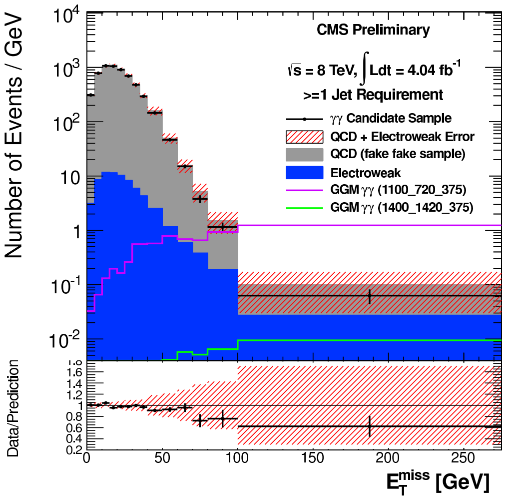

Fig. 23: Distribution of the $E_T^{\rm miss}$ in diphoton events as measured by the CMS collaboration. Data (dots) are compared to the SM predictions (solid histograms) and to possible models of new physics (lines).

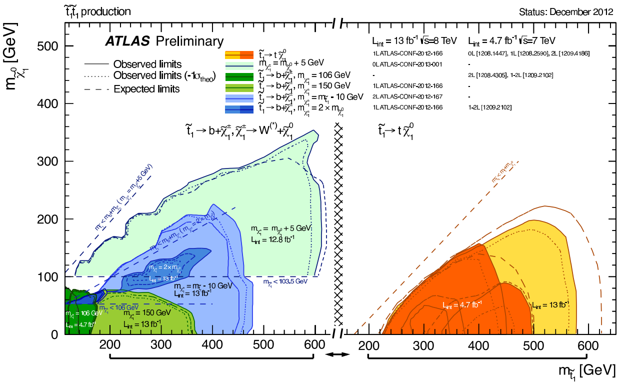

Fig. 24: Summary of the limits for scalar tops from the available analyses by ATLAS, drawn in the neutralino (LSP)-stop plane according to the assumptions of all the channels.

different types of them. This also brings the fact that basically every final state is available in R_P-Violating SUSY due to the rich phenomenology.

As reference analyses, we should mention the multilepton searches, as that by ATLAS [177] looking for anomalous production of events containing 4 or more leptons having either large $E_T^{\rm miss}$ or large energy activity (quantified via the concept of effective mass). Reasonable agreement with the small SM expectations has been observed.

Other typical search in the context of R_P-Violating models is the search for resonances decaying into two leptons of different type, as the one performed by ATLAS in [178], wich considers the case of $e\mu$, $e\tau$ and $\mu\tau$ resonances. No hint of such states was found and limits were set in the relevant models. It should be noted that the open possibilities in this set of models have the clear disadvantage that the application of the limits is very reduced in comparison with the parameter space.

A last analysis that needs to be discussed is the search for events containing multileptons and identified b-jets, that has been investigated by CMS [179]. The interest of this search is not only about possible presence of new physics, but also since it is sensitive to very rare SM processes, whose observation is as interesting as the search for BSM physics. This includes some of the associated production of top quark and weak bosons mentioned in section 5.2. Although no hint of new physics has beeen observed, the analysis already probes the sensitivity to the rare SM processes that should be investigated in future datasamples collected at the LHC.

10 Future of the LHC experiments and physics

After the running ended in March 2013, the LHC accelerator is currently in a shutdown period which is needed for maintenance and repair work which will allow the running at the highest energy and luminosity conditions. This shutdown will last until 2015 and it is also used by the experiments for additional improvements and work.

The plan after the shutdown is to run for a few years at nominal energy (probably 13 TeV) and collect a sample of 100 fb^{-1} . Afterwards a new shutdown is expected to bring the luminosity to the design value and run for a few more years (2019-2022) to collect additional 350 fb^{-1} at a center of mass energy of 14 TeV.

Afterwards a third shutdown will bring the machine to a Phase-2 upgrade that may allow to collect additional 3000 fb^{-1} along the next decade. All these data will allow accurate studies for particles and interactions observed during the first runs of the collider. An alternative will be to upgrade the LHC so it may be able to reach higher energies and set a new frontier on the investigated energy scales.

In addition to the improvements by the accelerator, the experiments are getting ready to upgrade their components in order to exploit the possibilities the several stages of the LHC will provide. ATLAS and CMS will need to face new challenges in terms of collection rate, luminosity and radiation and are therefore working on improvements for the DAQ and trigger selection, upgrades of the internal parts of the detectors and replacements of the parts that may be limiting factors in the incoming phases.

In the case of ALICE, the main goal is to have the best possible detector for the run after the second shutdown, in order to get all the reachable information about the heavy ion program of the LHC, hopefully understanding the Quark-Gluon Plasma with unprecendent accuracy and being able to provide enough information for the theoretical characterization of its properties. It is not completely clear yet whether ALICE will be present in the LHC running beyond 2022,

The case of the LHCb is special due to the reduced need for luminosity. The plan is to collect 5 fb^{-1} after the current shutdown and then collect 50 fb^{-1} during the main part of the main run of the current LHC. As in the case of ALICE, it is not clear whether LHCb will be present in future improvements of the LHC projects, either in terms of luminosity or of new energy regimes.

To summarize, the LHC is planning the future runnings with improved performance in order to provide large amount of data that will yield to important measurements during the several stages of the accelerator. The expected program and the results from the experiments are awaited from the particle-physics community to confirm and improve the results already obtained at the LHC and described in previous sections.

However, it should be remarked that even the current datasample are still providing important and relevant results, as reported on the web pages of the experiments [180].

11 Overview and conclusions

The LHC experiments have finished a very sucessful *Run I* with very important milestones and discoveries in all the topics planned for the program. Confirmations of the SM expectations, measurements of heavy-flavour and top quark physics and results related to heavy-ion collisions have clearly overrule most of the previous achievements due to the new energy frontier, the good performance of the accelerator and the detectors and also to the high quality of the studies.

In the part dedicated to searches for new particles, which is the main goal of the LHC, the current results already made the first big discovery by finding of a new boson having a mass of 125 GeV. For other possible particles expected in extensions of the SM, new limits have been set, highly increasing the constraints for BSM physics.

The properties of the new boson has been measured in the current datasample and they seem to confirm that this boson may be the long-awaited Higgs boson expected in the standard model, the last missing piece of this theory. Further studies are on-going, and others waiting for further running of the LHC, in order to increase the precision of the measurements and confirm this extrem.

Expectations for the future running in 2015 at 13 TeV are getting higher with the increase in reach for possible new particles and also the improved precision of the measurements with the larger data samples expected. Specifically, precision measurements of the properties of the new boson and of other observations that have been accessible at the LHC keep the focus on the LHC results as the more-likely door to the new discoveries in the second half of this decade.

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