

Contents

Abstract	v
Editors’ note	vii
Executive summary	1
A Introduction and overview	3
<i>A. Blondel, J. Gluza, S. Jadach, P. Janot, T. Riemann</i>	3
1 The FCC-ee electroweak factory	3
2 What this theory report brings: an overview	7
B Precision calculations in the Standard Model	9
1 $\alpha_{\text{QED, eff}}(s)$ for precision physics at the FCC-ee/ILC <i>F. Jegerlehner</i>	9
1.1 $\alpha(M_Z^2)$ in precision physics (precision physics limitations)	9
1.2 The ultimate motivation for high-precision SM parameters	13
1.3 <i>R</i> data evaluation of $\alpha(M_Z^2)$	14
1.4 Reducing uncertainties via the Euclidean split trick: Adler function controlled pQCD	19
1.5 Prospects for future improvements	23
1.6 The need for a space-like effective $\alpha(t)$	26
1.7 Conclusions	28
1.8 Addendum: the coupling α_2 , M_W , and $\sin^2 \Theta_f$	28
2 Precision quantum chromodynamics <i>D. d’Enterria</i>	38
2.1 Higher fixed-order pQCD corrections	39
2.2 Higher-order logarithmic resummations	40
2.3 Per-mille-precision α_s extraction	42
2.4 High-precision non-perturbative QCD	45
3 Inclusion of mixed QCD–QED resummation effects at higher orders <i>G.F.R. Sborlini</i>	51
3.1 Introduction and motivation	51
3.2 Splittings and PDF evolution	51
3.3 Fixed-order effects: application to diphoton production	52
3.4 Mixed resummation effects: Z boson production	53
3.5 Conclusions	54
4 CoLoRFulNNLO at work: a determination of α_s <i>A. Kardos, S. Kluth, G. Somogyi, Z. Trócsányi, Z. Tulipánt, A. Verbytskyi</i> . . .	57
4.1 Introduction	57

4.2	Precision through higher orders	58
4.3	Precision through small power corrections	60
4.4	Conclusions	62
5	Theoretical luminosity precision for the FCC-ee: overview of the path to 0.01% <i>B.F.L. Ward, S. Jadach, W. Płaczek, M. Skrzypek, S.A. Yost</i>	65
6	$e^+e^- \rightarrow \Upsilon\gamma$ at large angles for FCC-ee luminometry <i>C.M. Carloni, M. Chiesa, G. Montagna, O. Nicrosini, F. Piccinini</i>	71
6.1	Introduction	71
6.2	Theoretical approach and numerical results	72
6.3	Summary and outlook	73
7	Prospects for higher-order corrections to W pair production near threshold in the EFT approach <i>C. Schwinn</i>	77
7.1	Effective theory approach to W pair production	78
7.2	Estimate of NNLO ^{EFT} corrections and beyond	83
7.3	Summary and outlook	86
8	Perspectives of heavy quarkonium production at the FCC-ee <i>Z.-G. He, B.A. Kniehl</i>	89
8.1	Heavy quarkonium production through e^+e^- annihilation	90
8.2	Heavy quarkonium production in $\Upsilon\gamma$ collisions	91
8.3	Summary and outlook	94
9	Vertex functions in QCD—preparation for beyond two loops <i>J.A. Gracey</i>	97
9.1	Introduction	97
9.2	Current status	98
9.3	Three-loop strategy	101
9.4	Discussion	103
10	Effective field theory approach to QED corrections in flavour physics <i>M. Beneke, C. Bobeth, R. Szafron</i>	107
10.1	Introduction and motivation	107
10.2	QED corrections in $B_q \rightarrow \ell^+\ell^-$	108
10.3	Summary and outlook	113
11	Top pair production and mass determination <i>A. Maier</i>	117
11.1	Introduction	117
11.2	Effective theory framework	117
11.3	Higher-order corrections	117
11.4	Cross-section predictions	119
12	Higgs boson decays: theoretical status <i>M. Spira</i>	123

12.1	Introduction	123
12.2	SM Higgs boson decays	123
12.3	Uncertainties	126
C	Methods and tools	135
1	Heritage projects, preservation, and re-usability concerns <i>S. Banerjee, M. Chrzaszcz, Z. Was, J. Zaremba</i>	135
1.1	Common tools for all FCC design studies	136
2	Scalar one-loop Feynman integrals in arbitrary space–time dimension d – an update <i>T. Riemann, J. Usovitsch</i>	139
2.1	Introduction	139
2.2	Interests in the d -dependence of one-loop Feynman integrals	140
2.3	Mellin–Barnes representations for one-loop Feynman integrals	143
2.4	The basic scalar one-loop functions	149
2.5	The cases of vanishing Cayley determinant $\lambda_n = 0$ and of vanishing Gram determinant $G_n = 0$	154
2.6	A massive four-point function with vanishing Gram determinant	154
2.7	Calculation of Gauss hypergeometric function ${}_2F_1$, Appell function F_1 , and Saran function F_S at arbitrary kinematics	155
3	NNLO corrections in four dimensions <i>R. Pittau</i>	163
3.1	Introduction	163
3.2	FDR integration and loop integrals	163
3.3	Keeping unitarity in the virtual component	165
3.4	Keeping unitarity in the real component	167
3.5	Results and conclusions	167
4	Unsubtractions at NNLO <i>J.J. Aguilera-Verdugo, F. Driencourt-Mangin, J. Plenter, S. Ramírez-Urbe, G. Rodrigo, G.F.R. Sborlini, W.J. Torres Bobadilla, S. Tracz</i>	169
4.1	Introduction	169
4.2	Loop-tree duality	170
4.3	Four-dimensional unsubtraction	171
4.4	Unitarity thresholds and anomalous thresholds	172
4.5	Conclusions	173
5	Numerics for elliptic Feynman integrals <i>C. Bogner, I. Hönemann, K. Tempest, A. Schweitzer, S. Weinzierl</i>	177
6	Numerical multiloop calculations: sector decomposition and QMC integration in pySECDEC, <i>S. Borowka, G. Heinrich, S. Jahn, S.P. Jones, M. Kerner, J. Schlenk</i>	185
6.1	Feynman integrals and sector decomposition	185
6.2	Quasi-Monte Carlo integration	187

6.3	Summary and outlook	188
7	Analytics from numerics: five-point QCD amplitudes at two loops <i>S. Abreu, J. Dormans, F. Febres Cordero, H. Ita, B. Page</i>	193
7.1	Introduction	193
7.2	Amplitudes	194
7.3	Simplifications for functional reconstruction	195
7.4	Implementation and results	197
7.5	Conclusion	198
8	Recent developments in Kira <i>P. Maierhöfer, J. Usovitsch</i>	201
8.1	Introduction	201
8.2	Improved symmetrization	201
8.3	Parallel simplification algorithms for coefficients	201
8.4	Basis choice	203
8.5	Conclusions	203
9	Precision Monte Carlo simulations with WHIZARD <i>S. Braß, W. Kilian, T. Ohl, J. Reuter, V. Rothe, P. Stienemeier</i>	205
10	FCC tau polarisation <i>S. Banerjee, Z. Was</i>	211
11	Electron–positron annihilation processes in MCSANCee <i>A. Arbuzov, S. Bondarenko, Y. Dydyshka, L. Kalinovskaya, L. Rumyantsev, R. Sadykov, V. Yermolchuk</i>	213
11.1	Introduction	213
11.2	Cross-section structure	213
11.3	Numerical results and comparison	214
11.4	Conclusion	214
12	Global electroweak fit in the FCC-ee era <i>J. Erler, M. Schott</i>	217
D	SMEFT	221
1	CoDEx: BSM physics being realised as SMEFT <i>S.D. Bakshi, J. Chakrabortty, S.K. Patra</i>	221
1.1	Introduction	221
1.2	The package in detail	222
E	Beyond the Standard Model (BSM)	231
1	(Triple) Higgs coupling imprints at future lepton colliders <i>J. Baglio, C. Weiland</i>	231
1.1	Triple Higgs coupling studies in an EFT framework	231
1.2	Probing heavy neutral leptons via Higgs couplings	232
1.3	Conclusions	236

2	Exotic Higgs decays (and long-lived particles) at future colliders	
	<i>J.F. Zurita</i>	241
2.1	Exotic Higgs decays: motivations and signatures	241
2.2	Long-lived particles (LLPs)	241
2.3	Exotic Higgs decays vis-à-vis current LHC data	242
2.4	Future experiments: HL-LHC, FCC, CEPC, LHeC	243
2.5	Conclusions	244
3	Precision predictions for Higgs decays in the (N)MSSM	
	<i>F. Domingo, S. Heinemeyer, S. Paßehr, G. Weiglein</i>	247
3.1	Introduction	247
3.2	Higgs decays to SM particles in the $\mathcal{CP}$ -violating NMSSM	248
3.3	Discussion concerning the remaining theoretical uncertainties	258
	Acknowledgements	267