Status and prospects for precision (SM) electroweak calculations

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FCC-ee physics & experiments

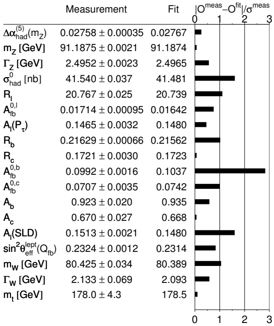
Review: Run plan and SM precision measurement

FCC Week 2017, Berlin, 29 May – 2 June 2017

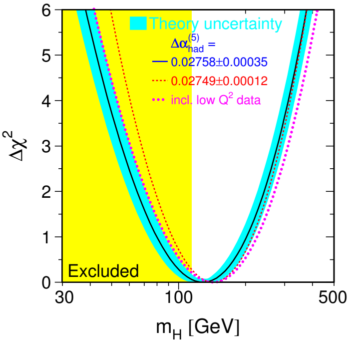
FCC-ee will

- revisit LEP physics with much larger statistics
    - at Z pole (~ 0.1% at LEP1)
    - at WW threshold (~ 1% at LEP2)
- explore for the first time at a leptonic collider
    - ZH and $t\bar{t}$ thresholds
- Given the immense available statistics, uncertainties in theoretical calculations risk to be a dangerous source of systematics
- in this talk brief overview on theoretical uncertainties in SM electroweak calculations
    - intrinsic uncertainties (unknown higher orders)
    - parametric uncertainties (input parameters: G_μ, $\alpha(M_Z)$, $\alpha_s(M_Z)$, M_Z, M_H, m_t)

LEP/SLC legacy at the Z pole



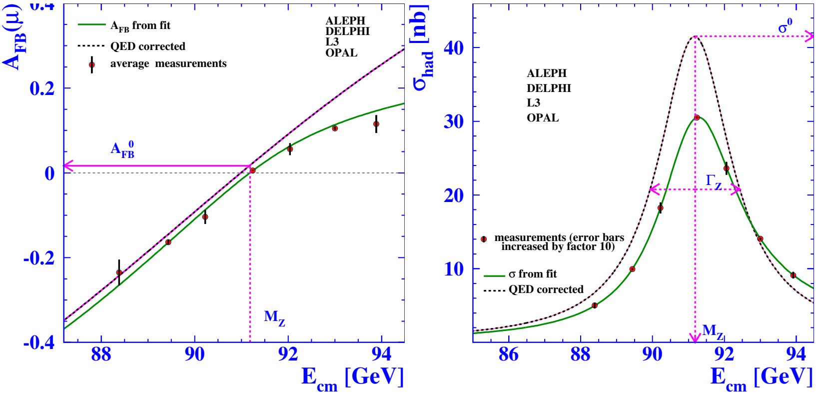
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



LEP EWWG, SLD WG, ALEPH, DELPHI, L3, OPAL, Phys. Rept. 427 (2006) 257

- electroweak fit based on *derived (pseudo-)*observables (allow easy combination among experiments and easy comparison data/theory within and beyond SM)
- primary measured observables: cross section and asymmetries

Z pole: primary observables



LEP EWWG, SLD WG, ALEPH, DELPHI, L3, OPAL, Phys. Rept. 427 (2006) 257

Deconvolution performed at LEP by means of

- TOPAZ0

  G. Montagna, O. Nicrosini, G. Passarino, F.P., R. Pittau, 1993, 1996, 1999

- ZFITTER

  D. Bardin et al., 1989, 1991, 1992, 1994, 2001

From measured observables to pseudo-observables

$$\sigma_{\rm T}(s) = \int_{z_0}^{1} dz H(z;s)\hat{\sigma}_{\rm T}(zs) \qquad A_{FB}(s) = \frac{\pi\alpha^2 Q_e^2 Q_f^2}{\sigma_{\rm tot}} \int_{z_0}^{1} dz \frac{1}{(1+z)^2} H_{\rm FB}(z;s)\,\hat{\sigma}_{\rm FB}(zs)$$

- Radiator H (including exact $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha^2)$) up to $\mathcal{O}(\alpha^3 L^3)$
  1. additive form
     G. Montagna, O. Nicrosini, F.P., PLB 406, (1997) 243; D. Bardin et al., CPC 133 (2001) 229
  2. factorized form
     S. Jadach, M. Skrzypek, B.F.L. Ward, PLB257 (1991) 173, M. Skrzypek, APPB23 (1992) 135
- $H_{\rm FB}$ known up to $\mathcal{O}(\alpha) + \mathcal{O}(\alpha^2 L^2)$
- kernel cross section known with $\mathcal{O}(\alpha)$ corrections plus $\mathcal{O}(\alpha^2)$ enhanced contributions (running couplings)

Remaining intrinsic th. uncertainty estimated below the 0.01% level by comparing `TOPAZ0` and `ZFITTER`

D.Y. Bardin, M. Grünewald, G. Passarino, hep-ph/9902452

- FCC-ee will require pushing this uncertainty down by a factor of 10 on cross sections and even more on A_{FB}

prospects and issues for FCC-ee

- $\Longrightarrow$ full NNLO calculations for $e^+e^- \to f\bar{f}$ required
- $\Longrightarrow$ radiator function H up to $\mathcal{O}(\alpha^3 L^2)$
- the QED unfolding process itself should be critically reassessed

Dubovyk et al., PoS LL2016 (2016) 075

  - QED corrections to A_{FB} off Z-peak require particular consideration, in connection with the proposal of a direct measurement of $\Delta\alpha(M_Z)$@FCC-ee: the present theoretical precision of $\sim 2.5 \times 10^{-3}$ should be improved by more than a factor of 100!

P. Janot, JHEP 1602 (2016) 053; see talk by R. Tenchini yesterday

  - effects of QED initial-final state interference effects in A_{FB} slightly off peak are important

talk by S. Jadach at FCC week in Rome, 12 April 2016

    - effects at the few % level; resummation needed
    - formalism of QED resummation around a resonance developed in M. Greco, G. Pancheri and Y. Srivastava, Nucl.Phys. B101 (1975) 234; NPB171 (1980) 118
    - such resummation is implemented in the `KKMC` Monte Carlo with additional matching to NLO (and NNLO, QED ISR+FSR) corrections S. Jadach, B.F.L. Ward and Z. Was, CPC 130 (2000) 260
    - work is in progress to quantify the remaining theoretical uncertainty

Intrinsic th. uncertainties on EWPO

- from the CDR draft contribution WG 2 write-up

“Theoretical uncertainties for electroweak and Higgs-boson precision measurements at the FCC-ee”

Conveners: A. Freitas and S. Heinemeyer; Contributors: M. Beneke et al.
see talk by S. Heinemeyer

Quantity	FCC-ee	Current intrinsic error		Projected intrinsic error
M_W [MeV]	1–1.5 [‡]	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.5	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.2
R_b $[10^{-5}]$	6	15	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s)$	7
R_l $[10^{-3}]$	1	5	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s)$	1.5

[‡] The pure experimental precision on M_W is ~ 0.5 MeV [3].

- with present and conceivable loop technology, the intrinsic th. uncertainties will be at the same level of the experimental errors
- new calculation methods should be introduced

see talk by J. Gluza

see e.g. the recent review on multi-loop integrals, A. Freitas, Prog. Part. Nucl. Phys. 90 (2016) 201

Parametric uncertainties on EWPO assuming

- $\delta M_Z \sim 0.1$ MeV from FCC-ee scan around the Z-peak
- $\delta m_t \sim 50$ MeV from the $t\bar{t}$ FCC-ee scan, using recent NNNLO QCD predictions

  M. Beneke et al., Phys. Rev. Lett. **115** (2015) 192001

  - and assuming $\delta\alpha_s \sim 10^{-4}$ for the mass translation
- $\delta\alpha_s(M_Z) \sim 2 \times 10^{-4}$ induced by the intrinsic $\delta R_l = 1.5 \times 10^{-3}$
- $\delta(\Delta\alpha) \sim 5 \times 10^{-5}$
  - from the present $\delta(\Delta\alpha) \sim 1 \times 10^{-4}$ (F. Jegerlehner, Davier et al., T. Teubner et al.)

    conceivable with dispersion relation techniques with new data from BESIII and Belle II
  - considering the possibility of direct measurement at FCC-ee using two off-peak points for $A_{FB}(\mu^+\mu^-)$

P. Janot, JHEP **1602** (2016) 053

Quantity	FCC-ee	future parametric unc.	Main source
M_W [MeV]	$1 - 1.5$	$1\ (0.6)$	$\delta(\Delta\alpha)$
$\sin^2\theta^\ell_{\text{eff}}$ $[10^{-5}]$	0.6	$2\ (1)$	$\delta(\Delta\alpha)$
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b $[10^{-5}]$	6	< 1	$\delta\alpha_s$
R_ℓ $[10^{-3}]$	1	1.3	$\delta\alpha_s$

WG 2 write-up

- Th. uncertainties dominated by $\delta\alpha_s$ and $\delta(\Delta\alpha)$
- $\delta(\Delta\alpha)$ also the main source for N_ν determination $\Longrightarrow$

N_ν from Z invisible width

$$R^0_{\mathrm{inv}} = \frac{\Gamma_{\mathrm{inv}}}{\Gamma_{ll}} = \sqrt{\frac{12\pi R^0_l}{\sigma^0_{\mathrm{had}} m_Z^2}} - R^0_l - (3+\delta_\tau)$$

- assuming lepton universality

$$\left(R^0_{\mathrm{inv}}\right)_{\mathrm{exp}} = N_\nu \left(\frac{\Gamma_{\nu\bar\nu}}{\Gamma_{ll}}\right)_{\mathrm{SM}}$$

- from LEP Z-peak measurements

$$\begin{aligned} N_\nu &= 2.9840 \pm 0.0082 \\ \delta N_\nu &\simeq 10.5\frac{\delta n_{\mathrm{had}}}{n_{\mathrm{had}}} \oplus 3.0\frac{\delta n_{\mathrm{lept}}}{n_{\mathrm{lept}}} \oplus 7.5\frac{\delta \mathcal{L}}{\mathcal{L}} \\ \frac{\delta\mathcal{L}}{\mathcal{L}} &= 0.061\% \Longrightarrow \delta N_\nu = 0.0046 \end{aligned}$$

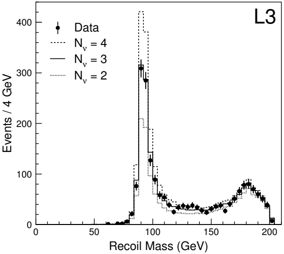
ADLO, SLD and LEPEWWG, Phys. Rept. 427 (2006) 257, hep-ex/0509008

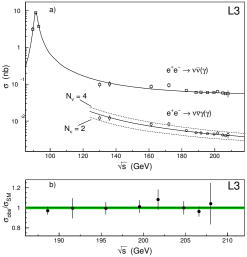
- δN_ν severely affected by luminosity uncertainty through σ_0

Independent way for ν count: $\nu\bar{\nu}\gamma$ and LEP2

- radiative return to the Z peak through emission of a hard photon
- provided large enough luminosity is available to be competitive with $\Gamma_{\rm inv}$ method (not a problem at FCC-ee!)

$$190 \text{ GeV} \leq \sqrt{s} \leq 208 \text{ GeV}, \mathcal{L} \sim 600 \text{ pb}^{-1}$$





L3 Collab., P. Achard et al., CERN-EP/2003-068 (2003)

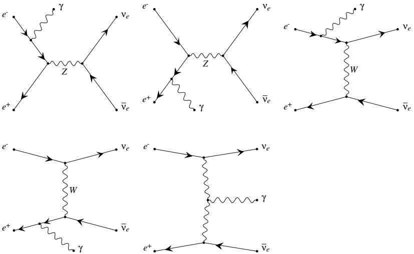
- agreement of data with SM predictions at % level
- $N_\nu = 2.98 \pm 0.05 \pm 0.04$ (L3) (important but not competitive with the $\Gamma_{\rm inv}$ method)
- similar results for ALEPH, DELPHI and OPAL

$\nu\bar{\nu}\gamma$@FCC-ee: ratio measurements

- a factor $10^3/10^4$ of improvement in luminosity w.r.t. LEP allows to exploit the ratios

$$\frac{d\sigma(e^+e^- \to \nu\bar{\nu}\gamma)}{d\sigma(e^+e^- \to \mu^+\mu^-\gamma)}$$

in order to cancel common systematics (such as luminosity)



- $\mu^+\mu^-$ only $s-$channel but ISR and FSR
- ν_μ and ν_τ f.s.: only $s-$channel ISR
- ν_e f.s.: ISR with $t-$channel
- ν_e f.s.: also W radiation

- preliminary investigations show that QED effects are very small

talk by S. Jadach at FCC-ee physics Workshop, Paris, 27-29 October 2014

- the technology for full $2 \to 3$ EW one-loop calculations is available

Luminosity: theoretical systematics on σ normalization

- theoretical error in small angle Bhabha process at LEP1

Type of correction/error	(%)	(%)	updated (%)
missing photonic $O(\alpha^2 L)$	0.100	0.027	0.027
missing photonic $O(\alpha^3 L^3)$	0.015	0.015	0.015
vacuum polarization	0.040	0.040	0.040
light pairs	0.030	0.030	0.010
Z-exchange	0.015	0.015	0.015
total	0.110	0.061	0.054

I column: Jadach, Nicrosini et al. Physics at LEP2 YR 96-01, Vol. 2; Arbuzov et al., Phys. Lett. B389 (1996) 129
II column: Ward, Jadach, Melles, Yost, hep-ph/9811245; III column: Montagna et al., Nucl. Phys. B547 (1999) 39

- after LEP, progress in complete NNLO contributions to QED Bhabha scattering:
  - NNLO photonic corrections A. Penin, PRL **95** (2005) 010408 & NPB**734** (2006) 185
  - fermionic loop corrections

    R. Bonciani *et al.*, Nucl. Phys. **B701** (2004) 121 & Nucl. Phys. **B716** (2005) 280
    S. Actis, M. Czakon, J. Gluza and T. Riemann, Nucl. Phys. **B786** (2007) 26 R. Bonciani, A. Ferroglia and A. Penin, PRL **100** (2008) 131601
    S. Actis, M. Czakon, J. Gluza and T. Riemann, PRL **100** (2008) 131602
    J.H. Kühn and S. Uccirati, Nucl. Phys. **B806** (2009) 300
  - one-loop soft+virtual corrections to single hard bremsstrahlung

    S. Actis, P. Mastrolia and G. Ossola, Phys. Lett. **B682** (2010) 419
- VP present at NLO, recent estimate: $0.040\% \rightarrow 0.021\%$

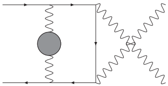
C.M. Carloni Calame, 9th FCC-ee Workshop, Pisa, February 2015

possible alternative to Bhabha scattering: $\mathrm{e^+e^-} \to \gamma\gamma$

- $e^+e^- \to \gamma\gamma$ could be used to cross-check independently $\mathcal{L}$
  - ⋆ present theoretical accuracy: QEDPS NLO ~ 0.1%

G. Balossini et al., Phys.Lett. B663 (2008) 209

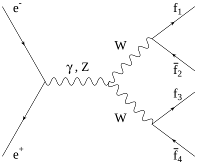
  - ⋆ Advantages
    - no Z exchange diagrams (at LO)
    - no photon VP corrections (up to NNLO)

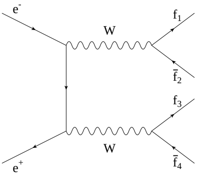


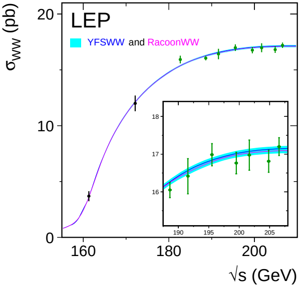
  - ⋆ Disadvantages
    - lower x-section by $\sim$ three order of magnitude
    - efficiency in detecting $\gamma\gamma$ events

It is worth investigating its potential for precision luminosity

WW threshold: $e^+e^- \to 4$ fermions







- first NLO exact calculation completed in 2005 for $WW \to 4$f
  - th. accuracy $\lesssim 1\%$ A. Denner et al., PLB612 (2005) 223; NPB 724 (2005) 247
- the same accuracy can be extended to other $e^+e^- \to 4f$ f.s., with recent automated tools for LHC (e.g. GoSam, MadLoop, OpenLoops, RECOLA, etc.)
- NNLO enhanced contributions because of Coulomb photon effects calculated by means of EFT methods

M. Beneke et al., NPB 792 (2008) 89; S. Actis et al., NPB807 (2009) 1

  - th. accuracy $\sim 0.5\%$ $\Delta M_W \sim 3$ MeV

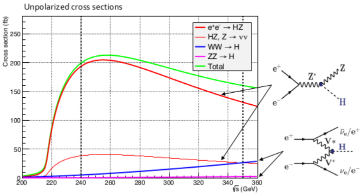
WW threshold: future prospects

see talk by Paolo Azzurri for experimental issues

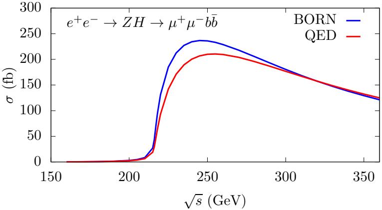
- Having in mind a target precision $\Delta M_W \sim 1$ MeV we would need
  - an improved treatment of EFT, which requires
    - NNLO corrections to $e^+e^- \to WW$ in NWA
    - NNLO accuracy in the W decay
  - improved treatment of subleading effects in ISR

  - full NNLO $e^+e^- \to 4$ fermions out of reach with present methods
    - new ideas necessary

Higgs production at ZH threshold



Bicer et al., 2014



M. Greco et al., in progress

- ISR QED corr. large, $\sim 35\%$ at threshold; $\sim 15\%$@240 GeV
- NLO corrections available for $e^+e^- \to ZH$ and to $e^+e^- \to \nu\bar{\nu}H$

  J. Fleischer and F. Jegerlehner, NPB216 (1983) 469; B.A. Kniehl, Z. Phys. C55 (1992) 605;
  A. Denner et al., Z. Phys. C56 (1992) 261; G. Belanger et al., Nucl. Phys. Proc. Suppl. 116 (2003) 353
  - weak corrections at the $\sim 5\%$ level
- recently calculated dominant contributions to NNLO corrections
  - $\mathcal{O}(\alpha_s\alpha) \gtrsim 1\%$

  Y. Gong et al., Phys Rev. D95 (2017) 093003;
  Q.F. Sung et al., arXiv:1609.03995
- for the future, to match the 0.4% experimental accuracy
  - full NNLO to $e^+e^- \to ZH$ and maybe $\mathcal{O}(\alpha\alpha_s^2)$ needed
  - complete calculation of $e^+e^- \to ZH \to f\bar{f}H$

Higgs decays (thanks to recent progress for LHC)

intrinsic uncertainties

Partial width	QCD	electroweak	total
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$
$H \to \tau^+\tau^-/\mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	$<1\%$
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW/ZZ \to 4\mathrm{f}$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$

decay	para. m_q	para. α_s	para. M_H
$H \to b\bar{b}$	1.4%	0.4%	–
$H \to c\bar{c}$	4.0%	0.4%	–
$H \to \tau^+\tau^-$	–	–	–
$H \to \mu^+\mu^-$	–	–	–
$H \to gg$	$< 0.2\%$	3.7%	–
$H \to \gamma\gamma$	$< 0.2\%$	–	–
$H \to Z\gamma$	–	–	2.1%
$H \to WW$	–	–	2.6%
$H \to ZZ$	–	–	3.0%

- projected param. uncertainties
  - $\delta\alpha_s = 0.0002$
  - $\delta m_t = 50$ MeV, $\delta m_H = 10$ MeV, $\delta m_b = 13$ MeV, $\delta m_c = 7$ MeV

decay	intrinsic	para. m_q	para. α_s	para. M_H	FCC-ee prec. on g^2_{HXX}
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–	$\sim 0.8\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–	$\sim 1.4\%$
$H \to \tau^+\tau^-$	$< 0.1\%$	–	–	–	$\sim 1.1\%$
$H \to \mu^+\mu^-$	$< 0.1\%$	–	–	–	$\sim 12\%$
$H \to gg$	$\sim 1\%$		0.5%	–	$\sim 1.6\%$
$H \to \gamma\gamma$	$< 1\%$	–	–	–	$\sim 3.0\%$
$H \to Z\gamma$	$\sim 1\%$	–	–	$\sim 0.1\%$	
$H \to WW$	$\lesssim 0.4\%$	–	–	$\sim 0.1\%$	$\sim 0.4\%$
$H \to ZZ$	$\lesssim 0.3\%^\dagger$	–	–	$\sim 0.1\%$	$\sim 0.3\%$
Γ_{tot}	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$	$\sim 1\%$

[†] From $e^+e^- \to HZ$ production

WG 2 write-up

Summary

- with present status, theoretical uncertainties would dominate systematics at FCC-ee in SM measurements
- recent advances in calculation methods will allow to increase the level of precision of th. predictions (intrinsic uncertainties)
  - new calculation methods will be necessary to reduce the intrinsic uncertainties for several observables
- a more accurate treatment of ISR will be necessary at all energies
- important role played by the parametric uncertainties, which should be kept under control by future precise measurements
- among the sources of parametric uncertainties, a big challenge will be posed by $\alpha(M_Z)$
  - complementary strategies should be pursued
    - e.g., direct measurement of $\alpha(M_Z)$@FCC-ee $\Longrightarrow$ improvement required of two orders of magnitude in the calculation of A_{FB} off Z-peak $\Longrightarrow$ QED i.f.s. interference uncertainty key ingredient
    - for normalization, perform studies on $e^+e^- \to \gamma\gamma$, which is less exposed to $\alpha(M_Z)$ uncertainties by one perturbative order w.r.t Bhabha scattering
- incredible amount of work ahead for theorists!

Acknowledgements for comments/discussions

A. Blondel, C.M. Carloni Calame, P. Janot, A. Freitas, J. Gluza, M. Greco, S. Jadach, S. Heinemeyer, G. Montagna, O. Nicrosini, T. Riemann, R. Tenchini

CDR outline

Experimental studies: WG1 and WG2

with R. Tenchini

- WG1: Electroweak physics at the Z pole
  - The Z line-shape
  - Experimental categorisation of Z decays
  - Luminosity measurement
  - Measurement of the number of neutrino species
  - Measurements of R_b and R_c
  - Measurement of forward-backward asymmetries
- WG2: Dibosons
  - Measurement of the W mass
  - Measurement of W decay branching fractions
  - Measurement of gauge couplings
  - Measurement of ZZ and $Z\gamma$ cross sections
  - Measurement of neutral gauge self-couplings
  - Z radiative return events