Electroweak physics at future colliders

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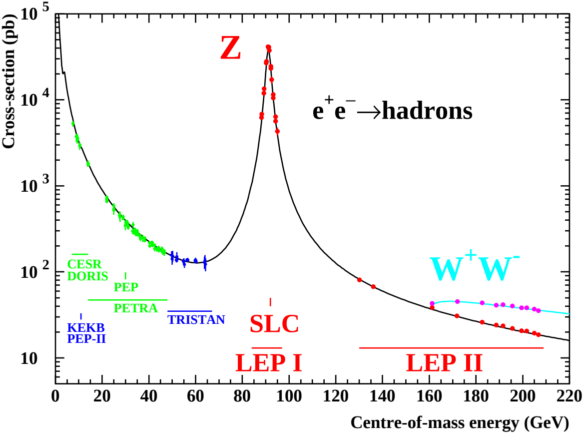
Istituto Nazionale di Fisica Nucleare

Corfu2024 Workshop on Future Accelerators

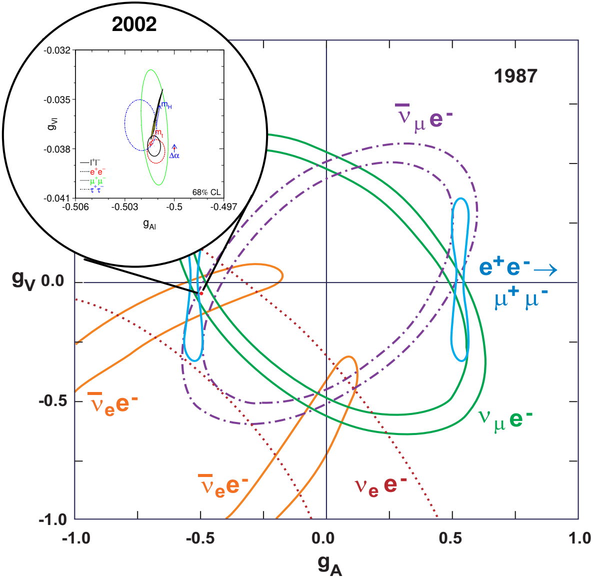
Mon Repos, Corfù, 19-26 May 2024

- The origin of precision electroweak physics in high energy dates back to the electroweak tests of the Standard Model at LEP/SLC at scales from M_Z up to $\sim$ 200 GeV



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

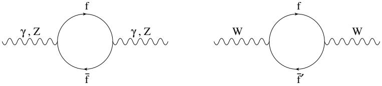
- precision $\mathcal{O}(0.1\%)$ measurements of the processes $e^+e^- \to f\bar{f}$
- $\mathcal{O}(1\%)$ for the processes $e^+e^- \to WW/ZZ \to 4$ fermions



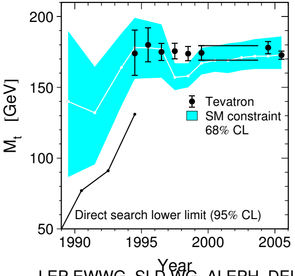
LEP EWWG, SLD WG, ALEPH, DELPHI, L3, OPAL, Phys. Rept. 427 (2006) 257

The power of precision physics

- just including one-loop corrections we gain **sensitivity to high mass d.o.f.**



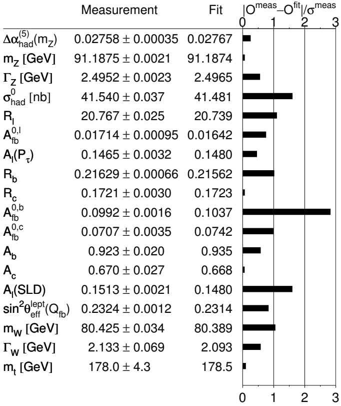
- **“indirect” evidence of top quark**, before 1995, from a best-fit to Z-peak data, assuming the validity of SM, (χ^2 depends on $G_F m_t^2$)



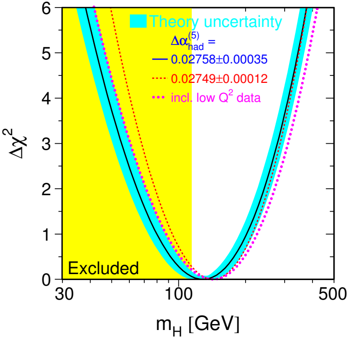
LEP EWWG, SLD WG, ALEPH, DELPHI, L3, OPAL, Phys. Rept. 427 (2006) 257

the same could be said about m_H

- however, **dependence on m_H is only logarithmic because of custodial symmetry**



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	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_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	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
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	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
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	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



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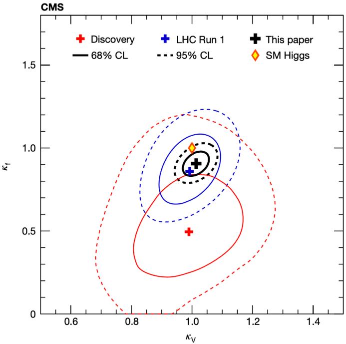
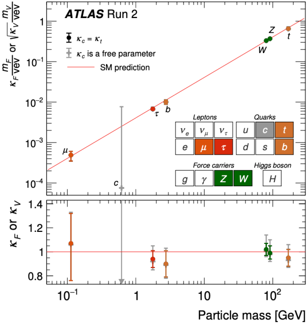
2022: Higgs @LHC



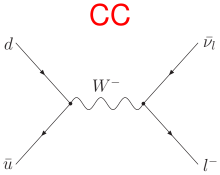
CMS Coll., Nature 607 (2022) 7917

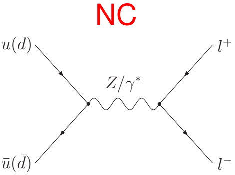


ATLAS Coll., Nature 607 (2022) 7917

Two key SM parameters for electroweak physics

- M_W
- $\sin^2 \vartheta^{\ell}_{eff}$
- opportunity of testing the SM internal consistency
  - **calculate** them with very high perturbative precision in the SM in terms of precisely known quantities: α, G_μ, M_Z, m_f, M_H, $\alpha_s(M_Z)$, $(\Delta\alpha)_h$
  - perform direct determinations of both M_W and $\sin^2 \vartheta^{\ell}_{eff}$ through **Drell-Yan** processes





$$M_W^2 = \frac{M_Z^2}{2}\left\{1+\left[1-\frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2}\left(1+\Delta r\right)\right]^{1/2}\right\}$$

$$M_W^2 = 80.358 \pm 0.009\mathrm{GeV}$$

FCC-ee CDR, Vol. 2, 2018

- one loop $\mathcal{O}(\alpha)$ calculation

A. Sirlin, PRD22 (1980) 971

- two loop $\mathcal{O}(\alpha\alpha_s)$

A. Djouadi, C. Verzegnassi, PLB195 (1987) 265

- three loop $\mathcal{O}(\alpha\alpha_s^2)$

L. Avdeev et al., PLB336 (1994) 560;

K.G. Chetyrkin, J.H. Kühn, M. Steinhauser, PLB351 (1995) 331; PRL75 (1995) 3394

- $\mathcal{O}(\alpha^2)$ for large top / Higgs mass

R. Barbieri et al., PLB288 (1992) 95; NPB409 (1993) 105

G. Degrassi, P. Gambino, A. Vicini, PLB383 (1996) 219

- exact $\mathcal{O}(\alpha^2)$

A. Freitas et al., PLB495 (2000) 338; NPB632 (2002) 189
M. Awramik, M. Czakon, PLB568 (2003) 48; PRL89 (2002) 241801
A. Onishchenko, O. Veretin, PLB551 (2003) 111; M. Awramik et al., PRD68 (2003) 053004

G. Degrassi, P. Gambino, P.P. Giardino, JHEP 1505 (2015) 154

$$\sin^2\vartheta^l_{eff} = \frac{1}{4}\left(1 - \mathrm{Re}\frac{g_v}{g_a}\right), \qquad \mathrm{Zl\bar{l}\,vertex} \sim \bar{l}\gamma^\mu(g_v - g_a\gamma_5)lZ_\mu$$

- measured at Z peak: 0.23153 ± 0.00016
- uncertainty in the SM calculations: ~ 0.00007
  - at one loop $\mathcal{O}(\alpha)$

    A. Sirlin, PRD22, (1980) 971, W.J. Marciano, A. Sirlin, PRD22 (1980) 2695

    G. Degrassi, A. Sirlin, NPB352 (1991) 352, P. Gambino and A. Sirlin, PRD49 (1994) 1160
  - at higher orders:
    - $\mathcal{O}(\alpha\alpha_s)$

      A. Djouadi, C. Verzegnassi, PLB195 (1987) 265
      B. Kiehl, NPB353 (1991) 567; B. Kniehl, A. Sirlin, NPB371 (1992) 141, PRD47 (1993) 883

      A. Djouadi, P. Gambino, PRD49 (1994) 3499
    - $\mathcal{O}(\alpha\alpha_s^2)$

      L. Avdeev et al., PLB336 (1994) 560;

      Chetyrkin, Kühn, Steinhauser, PLB351 (1995) 331; PRL75 (1995) 3394; NPB482 (1996) 213
    - $\mathcal{O}(\alpha\alpha_s^3)$

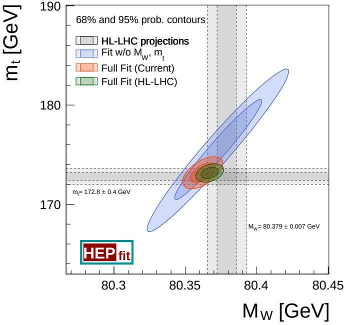
      Y. Schröder, M. Steinhauser, PLB622 (2005) 124;

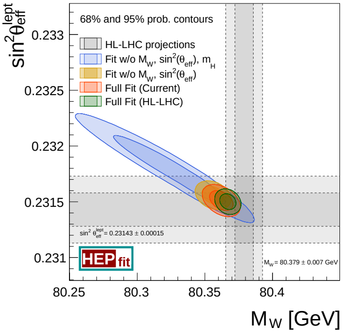
      K.G. Chetyrkin et al., hep=ph/0605201; R. Boughezal, M. Czakon, hep-ph/0606232
    - $\mathcal{O}(\alpha^2)$ for large Higgs / top mass

      G. Degrassi, P. Gambino, A. Sirlin, PLB394 (1997) 188
    - exact $\mathcal{O}(\alpha^2)$ M. Awramik, M. Czakon, A. Freitas, JHEP0611 (2006) 048

      W. Hollik, U. Meier, S. Uccirati, NPB731 (2005) 213; I. Dubovik et al., arXiv:1906.08815

Prospects for HL-LHC: SM EW fit





J. de Blas et al., (Azzi, Farry, Nason, Tricoli, Zeppenfeld Eds.)

CERN-LPCC-2018-03, arXiv:1902.04070

not including the latest CDF M_W measurement

- **a direct (independent) determination is of great importance**

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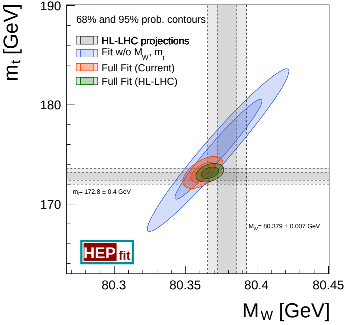

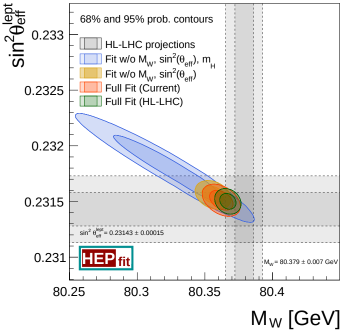

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relevant observables

- M_W
  - M_T^W mainly sensitive to QED FSR
  - $p_\perp^\ell$ sensitive to both QCD ISR and QED FSR

- $\sin^2\vartheta^\ell_{eff}$
  - integrating over the azimuthal angle the general parameterization of production and decay of a spin-one vector in terms of angular coefficients,

$$\frac{d\sigma}{dq_T^2\; dy\;\; d\cos\vartheta} = \frac{3}{8}\,\frac{d\sigma^{\text{unpol.}}}{dq_T^2\;\; dy\;\; d\cos\vartheta}\Big\{1+\cos^2\vartheta + \frac{1}{2}A_0(1-3\cos^2\vartheta) + A_4\cos\vartheta\Big\}$$

$$\Downarrow$$

$$A_{FB}(M,y) = \frac{\sigma^+(M,y)-\sigma^-(M,y)}{\sigma^+(M,y)+\sigma^-(M,y)} = \frac{3}{8}A_4(M,y)$$

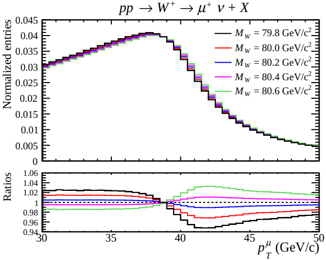
- **crucial common ingredients**
  - $p_\perp^Z$, $p_\perp^W$ (and their ratio), mainly sensitive to ISR QCD and different parton luminositites
  - reliable PDF's determinations

lepton pair $p_\perp$: two regimes

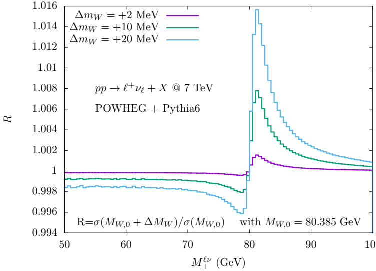
- large $p_\perp$ ($\gtrsim 20$ GeV), where pert. th. is reliable

- small $p_\perp$ ($\lesssim 20$ GeV): $\sim$90% of the cross section
  - resummation of $\log\left(\frac{M_V}{q_\perp}\right)$ is needed
  - sensitivity to the non-perturbative model of the MC Evt Gen

The challenges at the LHC



Farry, Lupton, Pili, Vesterinen, arXiv:1902.04323



by A. Vicini

- control of shapes below 1% scale for $\Delta M_W \sim 10 - 20$ MeV

Strong challenges to theoretical data description

- combined resummation of QCD and QED contributions
- perturbative contributions at least at NNLO QCD and mixed QCD-EW, on top of NLO EW

$$\begin{aligned} d\sigma &= d\sigma_0 \\ &+ d\sigma_{\alpha_s} + d\sigma_{\alpha} \\ &+ d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} \\ &+ d\sigma_{\alpha_s^3} + d\sigma_{\alpha^2} + \ldots \end{aligned}$$

a history of $>$ 40 years of calculations

from the first NLO QCD calculation (1979)

Altarelli, Ells, Martinelli, 1979

to N3LO QCD

Duhr, Mistlberger, 2022

to the complete mixed NNLO $\mathcal{O}(\alpha\alpha_s)$

Bonciani et al., 2021,2022; Armadillo et al., 2024, Buccioni et al., 2022

- accurate MC generation tools matched to the matrix elements
- **control of uncertainties from PDF's**

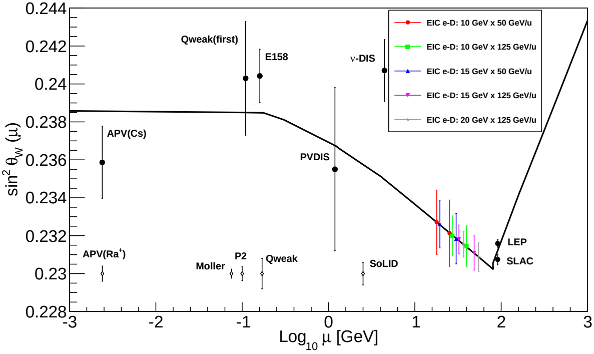
ongoing work within the “precision subgroup” of the LHC EWWG

two main activities

- $p_\perp^W$, $p_\perp^Z$
  - collecting recent progress with different resummation techniques
  - benchmarking numbers by independent groups
- QED/EW issues and their uncertainties, bearing in mind that $\Delta A_{FB} \sim 10^{-4} \Longrightarrow \Delta \sin^2 \vartheta^\ell_{eff} \sim 2 \cdot 10^{-4}$ (for inclusive event selection)
  - effect of $\gamma-$induced processes
  - quantitative assessment of QED initial-final intereference effects, with benchmarking by different groups
  - input parameter schemes, critical comparisons between different options
  - numerical benchmarking on all the above items among several groups and codes

Another mixing angle: $\sin^2\theta_W$ $\overline{\mathrm{MS}}$ running

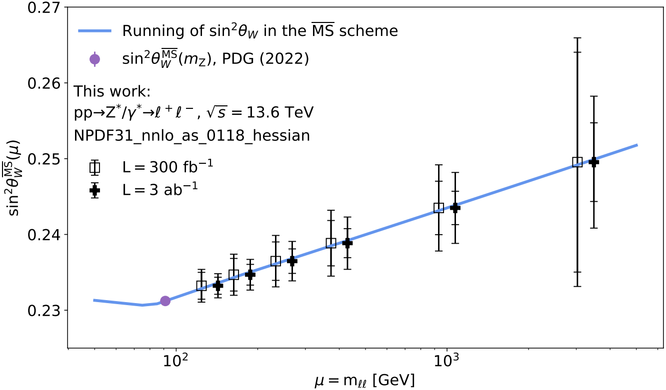
$$\sin^2\theta_W^{\overline{\mathrm{MS}}}(\mu) \equiv 4\pi \frac{\alpha_{\mathrm{EM}}^{\overline{\mathrm{MS}}}(\mu)}{g_2^{2\,\overline{\mathrm{MS}}}(\mu)}$$



Erler, Ramsey Musolf, PRD72 (2005) 073003

Zhao, Deshpande, Huang, Kumar, Riordan, arXiv:1612.06927

sensitivity at HL-LHC



Amoroso, Chiesa, Del Pio, Lipka, FP, arXiv:2302.10782

- interesting possibility to study the running up to the TeV energy scale at HL-HC
    - in this regime electroweak Sudakov corrections enter the game and their effects should be studied in detail, in order to avoid reabsorbing them in the running

Looking at future H/T/EW factories

- revisit LEP physics with unprecedented statistics
  - at Z pole (∼ 0.1% at LEP1)
  - at WW threshold (∼ 1% at LEP2)
- explore for the first time at a leptonic collider
  - ZH threshold
  - $t\bar{t}$ threshold

Uncertainties on EWPO

- **Intrinsic uncertainties**

Quantity	FCC-ee	Current intrinsic error		Projected intrinsic error
M_W [MeV]	0.5–1‡	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^{\ell}_{\text{eff}}$ $[10^{-5}]$	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.4	$(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.15
R_b $[10^{-5}]$	6	11	$(\alpha^3, \alpha^2\alpha_s)$	5
R_l $[10^{-3}]$	1	6	$(\alpha^3, \alpha^2\alpha_s)$	1.5

A. Freitas, S. Heinemeyer et al., arXiv:1906.05379

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

see e.g. talk by J. Usovitsch at FCC-ee 2024 Physics Workshop, Annecy

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.)

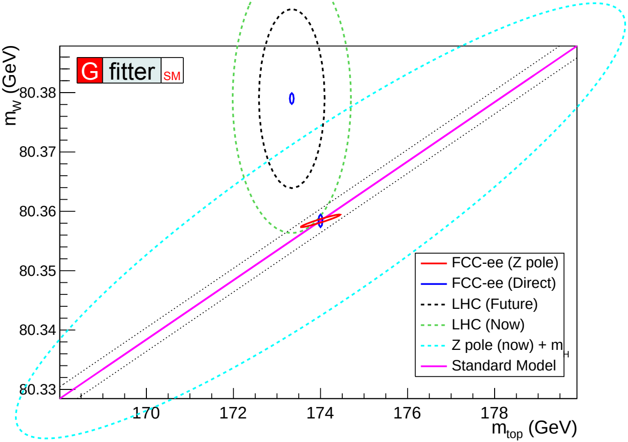
    conceivable with dispersion relation techniques with new data from BESIII and Belle II
  - considering the possibility of direct measurement at FCC-ee using two off-peak points for $A_{FB}(\mu^+\mu^-)$

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

Quantity	FCC-ee	future parametric unc.	Main source
M_W [MeV]	$1 - 1.5$	1 (0.6)	$\delta(\Delta\alpha)$
$\sin^2\theta^\ell_{\rm eff}$ [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	$\delta\alpha_s$

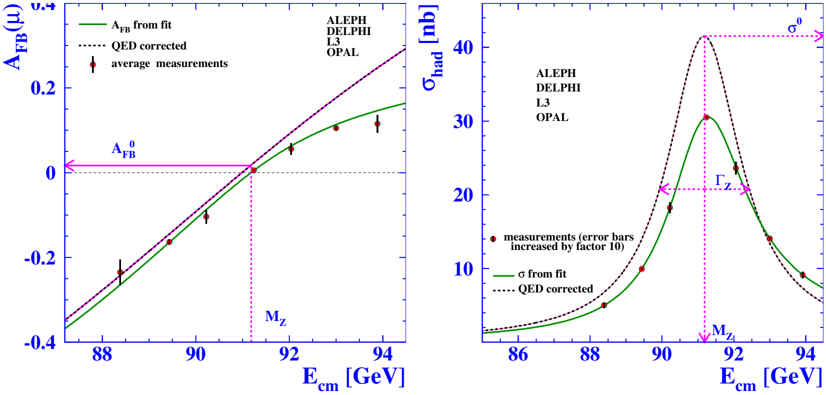
- Th. uncertainties dominated by $\delta\alpha_s$ and $\delta(\Delta\alpha)$

The projection of the $m_t - m_W$ dependence



FCC-ee CDR vol 2

What about primary observables at Z pole?



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

th. uncertainty should be pushed down by at least a factor of 10 on cross sections and even more on A_{FB} w.r.t LEP

- **Need for th. at $\sqrt{s}$ around the Z pole**
  - improved description of ISR QED radiation and IF interference (non-factorizable effects larger than the required precision, contrary to LEP precision)
    - recent progress in electron PDF's at NLL

      Bertone, Cacciari, Frixione, Stagnitto, 2021-2022
  - sensible procedure for extracting EWPO in presence of higher order corrections (beyond one loop)

Blondel, Gluza, Jadach, Janot, Riemann (Eds), CERN-2019-003

  - at least complete NNLO accuracy in $e^+e^- \to f\bar{f}$
  - expansion of the amplitude for $e^+e^- \to f\bar{f}$ around the complex pole $s_0 = M_Z^2 - i\Gamma_Z M_Z$

$$\begin{aligned} \mathcal{M} &= \frac{R}{s-s_0} + S + S'(s-s_0) \\ R &\to \text{known@NNLO + leading higher orders} \\ S &\to \text{known@NLO} \\ S' &\to \text{known@(N)LO} \end{aligned}$$

  - EWPO extraction: $\to Zf\bar{f}$ vertex at N3LO and leading N4LO
  - new simulation tools implementing consistently the perturbative matrix elements and resummation methods

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The recent case of luminosity at LEP

Several key measurements at an e^+e^- machine depend on L, e.g.

- σ^0_Z, the Z peak cross section
- light neutrino species from radiative return $(e^+e^- \to \nu\bar{\nu}\gamma)$
- Γ_Z from the line-shape of $e^+e^- \to f\bar{f}$
- M_W and Γ_W from line-shape of $e^+e^- \to W^+W^-$ close to threshold
- total cross section for $e^+e^- \to HZ \Longrightarrow HZZ$ coupling and total Γ_H

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The recent case of N_ν from Γ_Z^{inv} at LEP Z peak (LEP)

- assuming lepton universality

$$N_\nu \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{ll}}\right)_{\mathrm{SM}} = \sqrt{\frac{12\pi R_l^0}{\sigma^0_{\mathrm{had}} m_Z^2}} - R_l^0 - (3+\delta_\tau)$$

$$\mathbf{N}_\nu = \mathbf{2.9840 \pm 0.0082}$$

$$\delta N_\nu \simeq 10.5\frac{\delta n_{\mathrm{had}}}{n_{\mathrm{had}}} \oplus 3.0\frac{\delta n_{\mathrm{lept}}}{n_{\mathrm{lept}}} \oplus 7.5\frac{\delta\mathcal{L}}{\mathcal{L}}$$

$$\frac{\delta\mathcal{L}}{\mathcal{L}} = 0.061\% \Longrightarrow \delta N_\nu = 0.0046$$

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

2σ away from SM: hint for BSM? Right handed neutrinos?

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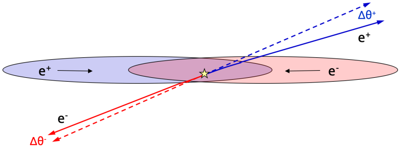
Beam-beam effects studied in detail recently

G. Voutsinas, E. Perez, M. Dam, P. Janot, arXiv:1908.01704

- systematics bias on the acceptance due to e.m. beam-beam interactions $\Longrightarrow$ underestimate of luminosity by $\sim 0.1\%$

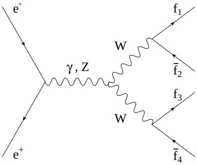


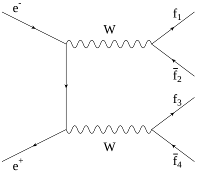
- together with an update on Bhabha cross sections $\Longrightarrow$ Luminosity

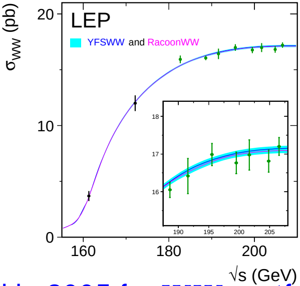
P. Janot, S. Jadach, arXiv:1912.02067

$$\mathbf{N_\nu = 2.9963 \pm 0.0074}$$

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







- first NLO exact calculation completed in 2005 for $WW \to 4f$
  - th. accuracy $\lesssim 1\%$ A. Denner et al., PLB612 (2005) 223; NPB 724 (2005) 247
- at present $e^+e^- \to 4f$ cross sections @NLO accuracy can be calculated with automated tools
- 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

Summary and outlook

- Electroweak physics, together with its interplay with flavour and Higgs will be a central theme at future accelerators
- at the (HL-)LHC, electroweak physics will play an important role as precision physics at the electroweak scale as well as in the asymptotic regime of high scales, where Sudakov logarithms become dominant
- In addition to M_W and $\sin^2\theta^{\ell}_{eff}$, also the running of the weak mixing angle could be tested for the first time at $\mathcal{O}$(TeV) scales

- the run at $\sqrt{s}\sim M_Z$ of future e^+e^- colliders will require a true jump in precision in the theoretical predictions, with new calculation methods
- At the same time, the luminosity at the Z-peak should reach the target precision of at least 10^{-4} or better