Theory scenario

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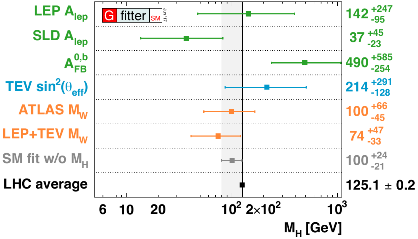
- All particles and interactions of the (minimal) SM discovered
  $\Longrightarrow$ every observable can be computed
- electroweak interactions tested at $\sim$0.1% level at LEP/SLC
- Higgs signal rates at the LHC in agreement with SM within $\sim$10%
  - in the last two years: y_τ and y_{top} direct measurements
- present and future hadron colliders provide important ew measurements
  - M_W, m_{top}
  - $\sin^2\vartheta^l_{eff}$
  - self-interactions in the gauge sector
  - self-interaction in the Higgs sector $\rightarrow$ HL LHC
- all these data can be used to check the internal SM consistency/signal hints of BSM effects

overall good agreement with EWPO

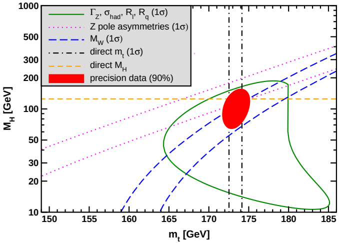
	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1180 ± 0.0010	0.1180 ± 0.0009	0.1184 ± 0.0028	-0.1
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.02750 ± 0.00033	0.02743 ± 0.00025	0.02734 ± 0.00037	0.3
M_Z [GeV]	91.1875 ± 0.0021	91.1880 ± 0.0021	91.198 ± 0.010	-1.0
m_t [GeV]	$173.1 \pm 0.6 \pm 0.5$	173.43 ± 0.74	176.1 ± 2.2	-1.3
m_H [GeV]	125.09 ± 0.24	125.09 ± 0.24	100.6 ± 23.6	1.0
M_W [GeV]	80.379 ± 0.012	80.3643 ± 0.0058	80.3597 ± 0.0067	1.4
Γ_W [GeV]	2.085 ± 0.042	2.08873 ± 0.00059	2.08873 ± 0.00059	-0.1
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.231454 ± 0.000084	0.231449 ± 0.000085	0.8
$P^{\rm pol}_\tau = A_\ell$	0.1465 ± 0.0033	0.14756 ± 0.00066	0.14761 ± 0.00067	-0.3
Γ_Z [GeV]	2.4952 ± 0.0023	2.49424 ± 0.00056	2.49412 ± 0.00059	0.5
σ^0_h [nb]	41.540 ± 0.037	41.4898 ± 0.0050	41.4904 ± 0.0053	1.3
R^0_ℓ	20.767 ± 0.025	20.7492 ± 0.0060	20.7482 ± 0.0064	0.7
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	0.01633 ± 0.00015	0.01630 ± 0.00015	0.8
A_ℓ (SLD)	0.1513 ± 0.0021	0.14756 ± 0.00066	0.14774 ± 0.00074	1.6
R^0_b	0.21629 ± 0.00066	0.215795 ± 0.000027	0.215793 ± 0.000027	0.7
R^0_c	0.1721 ± 0.0030	0.172228 ± 0.000020	0.172229 ± 0.000021	-0.05
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	0.10345 ± 0.00047	0.10358 ± 0.00052	-2.6
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	0.07394 ± 0.00036	0.07404 ± 0.00040	-0.9
A_b	0.923 ± 0.020	0.934787 ± 0.000054	0.934802 ± 0.000061	-0.6
A_c	0.670 ± 0.027	0.66813 ± 0.00029	0.66821 ± 0.00032	0.1
$\sin^2\theta^{\rm lept}_{\rm eff}$(Tev/LHC)	0.23166 ± 0.00032	0.231454 ± 0.000084	0.231438 ± 0.000087	0.7

J. De Blas et al., arXiv:1710.05402

Looking in more detail at subsets of observables

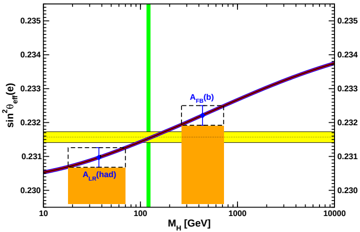


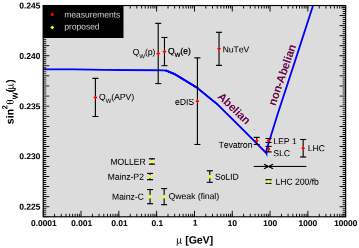
T. Pfeiffer, EPS2017



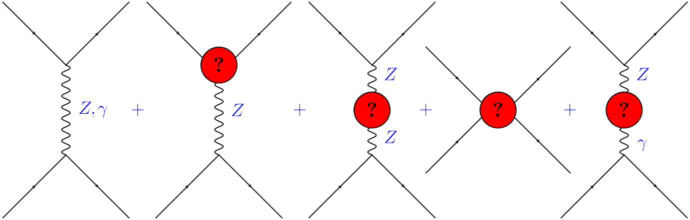
J. Erler, A. Freitas, PDG2017

- small tensions between different observables, the largest one in the asymmetry sector $\Longrightarrow \sin^2\vartheta^l_{eff}$



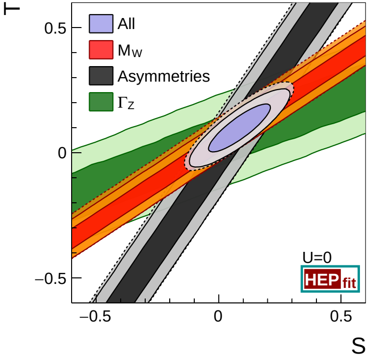


J. Erler, arXiv:1710.06503

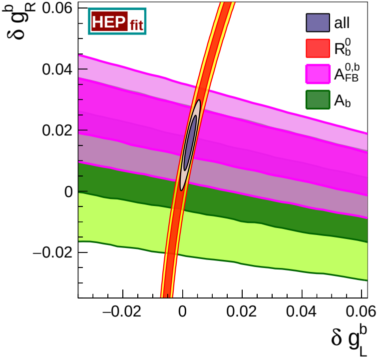


parameterizing possible New Physics

- oblique corrections with S, T U parameters
- $Zb\bar{b}$ couplings with $\delta g^b_{L/R}$



J. De Blas et al., arXiv:1710.05402

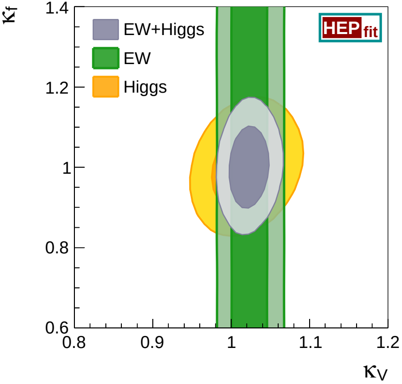


J. De Blas et al., arXiv:1611.05354

- dashed limits: excluding last Tevatron/LHC measurements of m_t, M_W and $\sin^2\vartheta^l_{eff}$

with an EFT approach for the Higgs sector

$$\mathcal{L}_{eff} = \frac{v^2}{4}\mathrm{tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2\mathcal{K}_V \frac{H}{v} + \dots\right) - m_i \bar{f}_L^i \left(1 + 2\mathcal{K}_f \frac{H}{v} + \dots\right) f_R^i + \dots$$



J. De Blas et al., arXiv:1710.05402

- on $\mathcal{K}_V$ EW precision data still dominate over LHC data

Which kind of NP?

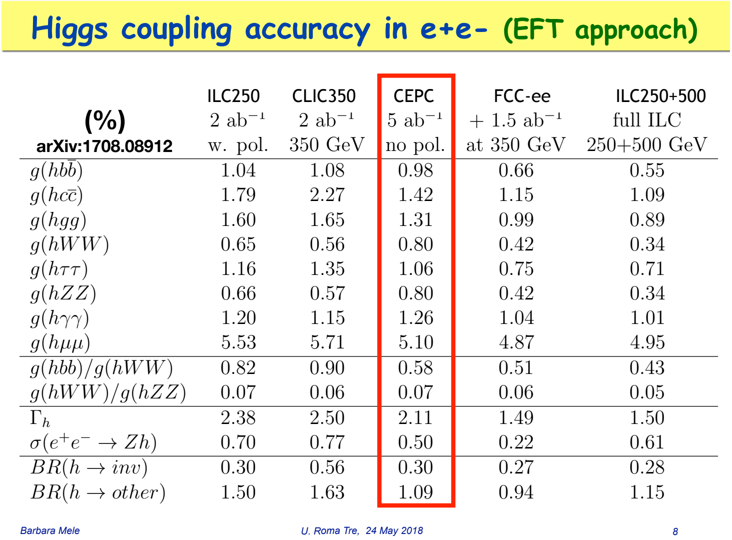
- E.g. light (even massless) dark-photon/scalars
    - experiments at the intensity frontier

see recent talk by Barbara Mele at CEPC Workshop in Rome

- If NP threshold above electroweak scale, a complete and model independent tool to study departures from the SM is given by **SMEFT**

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda^2}\sum_k c_k^{(6)} Q_k^{(6)} + \frac{1}{\Lambda^4}\sum_k c_k^{(6)} Q_k^{(8)} + \dots$$

- usually analysis performed at the leading dimension 6 order
- by fitting projected data we get constraints on the scale probed (actually $\Lambda/\sqrt{c_i}$) by the various operators
- vast literature on EFT applications to collider data; in the following one example

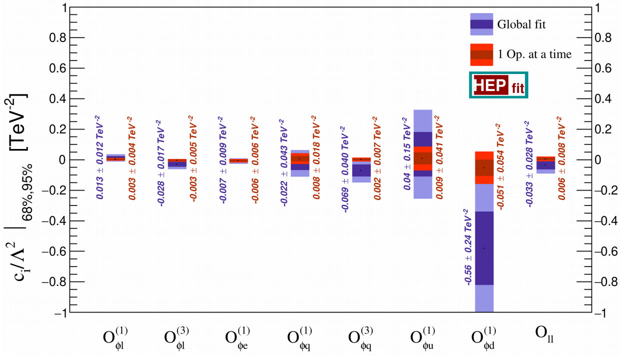


Higgs coupling accuracy in e+e- (EFT approach)

(%) **arXiv:1708.08912**	ILC250 2 ab^{-1} w. pol.	CLIC350 2 ab^{-1} 350 GeV	CEPC 5 ab^{-1} no pol.	FCC-ee + 1.5 ab^{-1} at 350 GeV	ILC250+500 full ILC 250+500 GeV
$g(hb\bar{b})$	1.04	1.08	0.98	0.66	0.55
$g(hc\bar{c})$	1.79	2.27	1.42	1.15	1.09
$g(hgg)$	1.60	1.65	1.31	0.99	0.89
$g(hWW)$	0.65	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.16	1.35	1.06	0.75	0.71
$g(hZZ)$	0.66	0.57	0.80	0.42	0.34
$g(h\gamma\gamma)$	1.20	1.15	1.26	1.04	1.01
$g(h\mu\mu)$	5.53	5.71	5.10	4.87	4.95
$g(hbb)/g(hWW)$	0.82	0.90	0.58	0.51	0.43
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.38	2.50	2.11	1.49	1.50
$\sigma(e^+e^- \to Zh)$	0.70	0.77	0.50	0.22	0.61
$BR(h \to inv)$	0.30	0.56	0.30	0.27	0.28
$BR(h \to other)$	1.50	1.63	1.09	0.94	1.15

Barbara Mele *U. Roma Tre, 24 May 2018* *8*

1 OP AT A TIME VS GLOBAL FIT



HL/HE-LHC Workshop, WG1
18/6/2018

Luca Silvestrini

PRELIMINARY

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Issues on the calculational side: Th. uncertainties could be the main systematics at future colliders

- intrinsic uncertainties (unknown higher orders)
- parametric uncertainties (input parameters: G_μ, $\alpha(M_Z)$, $\alpha_s(M_Z)$, M_Z, M_H, m_t)

- classes of processes/observables which need high precision radiative corrections (one or two orders of magnitude w.r.t. present knowledge!), for e^+e^- colliders
  - reference process(es) for luminosity (Bhabha scattering/$\gamma\gamma$)
  - $e^+e^- \to f\bar{f}$ (σ and A_{FB})
  - $e^+e^- \to V^{(*)}V^{(*)} \to (4\,\mathrm{fermions})$
  - $e^+e^- \to Z^{(*)}H \to (4\,\mathrm{fermions})$
  - $e^+e^- \to t^{(*)}\bar{t}^{(*)} \to (6\,\mathrm{fermions})$
  - Z partial decay widths
  - H partial decay widths

- Mini workshop: Precision EW and QCD calculations for the FCC studies: methods and techniques

Blondel, Gluza, Janot organizers, CERN, 12-13 January 2018

Report to be published

- purpose of the workshop: critical discussions on
  - precision of the theoretical calculations that predict the various observables within the standard model (and beyond) required to match that of the experimental measurements to be made by the FCC-ee
  - the techniques to be applied and/or developed to reach this precision.

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

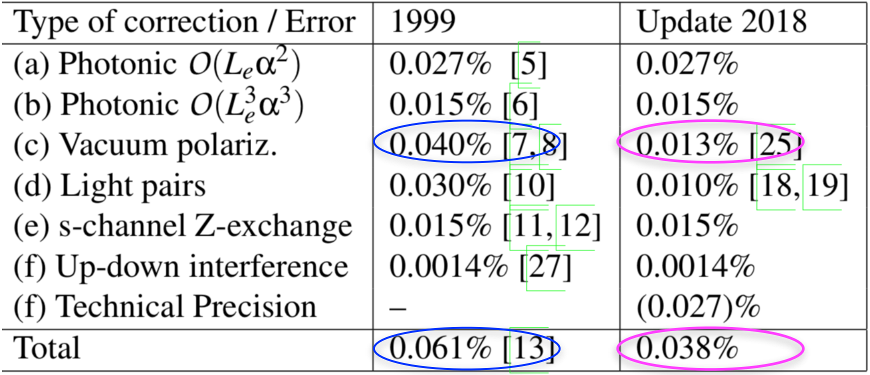
    R. Bonciani *et al.*, Nucl. Phys. **B701** (2004) 121 & Nucl. Phys. **B716** (2005) 280
    S. Actis, M. Czakon, J. Gluza and T. Riemann, Nucl. Phys. **B786** (2007) 26 R. Bonciani, A. Ferroglia and A. Penin, PRL **100** (2008) 131601
    S. Actis, M. Czakon, J. Gluza and T. Riemann, PRL **100** (2008) 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

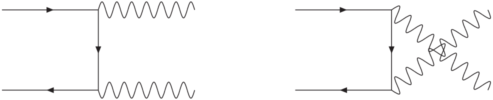
S. Jadach, talk at WG1-WG2 meeting, CERN, June 26th, 2018

LEP lumi update 2018



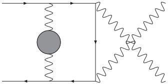
Type of correction / Error	1999	Update 2018
(a) Photonic $O(L_e\alpha^2)$	0.027% [5]	0.027%
(b) Photonic $O(L_e^3\alpha^3)$	0.015% [6]	0.015%
(c) Vacuum polariz.	0.040% [7,8]	0.013% [25]
(d) Light pairs	0.030% [10]	0.010% [18,19]
(e) s-channel Z-exchange	0.015% [11,12]	0.015%
(f) Up-down interference	0.0014% [27]	0.0014%
(f) Technical Precision	–	(0.027)%
Total	0.061% [13]	0.038%

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



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

    G. Balossini et al., Phys.Lett. B663 (2008) 209
  - ⋆ Advantages
    - ★ no Z exchange diagrams (at LO)
    - ★ no photon VP corrections (up to NNLO)



  - ⋆ Drawbacks
    - ★ lower x-section by $\sim$ three order of magnitude
    - ★ efficiency in detecting $\gamma\gamma$ events and rejection against Bhabha

It is worth investigating its potential for precision luminosity

$e^+e^- \to f\bar{f}$: from observables to pseudo-observables

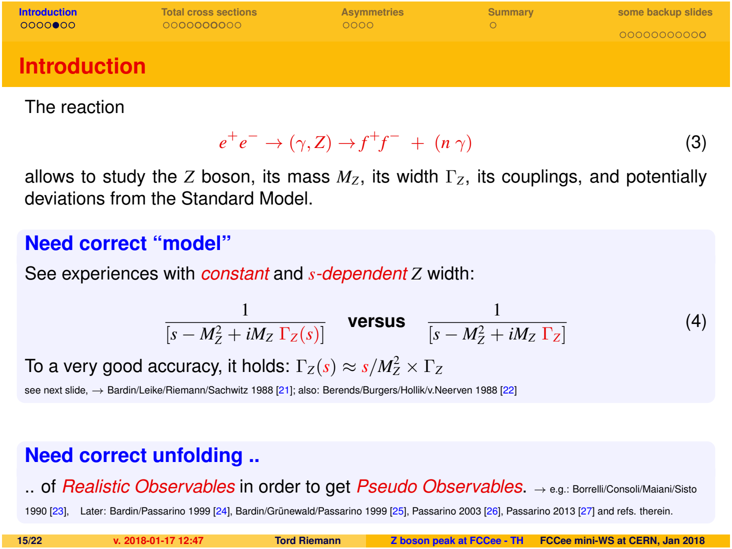
$$\sigma_{\mathrm{T}}(s) = \int_{z_0}^{1} dz H(z;s)\hat{\sigma}_{\mathrm{T}}(zs) \qquad A_{FB}(s) = \frac{\pi\alpha^2 Q_e^2 Q_f^2}{\sigma_{\mathrm{tot}}} \int_{z_0}^{1} dz \frac{1}{(1+z)^2} H_{\mathrm{FB}}(z;s)\,\hat{\sigma}_{\mathrm{FB}}(zs)$$

- 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_{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}



Introduction

The reaction

$$e^+e^- \to (\gamma, Z) \to f^+f^- \; + \; (n\,\gamma) \tag{3}$$

allows to study the Z boson, its mass M_Z, its width Γ_Z, its couplings, and potentially deviations from the Standard Model.

Need correct “model”

See experiences with *constant* and *s-dependent* Z width:

$$\frac{1}{[s - M_Z^2 + iM_Z\,\Gamma_Z(s)]} \quad \textbf{versus} \quad \frac{1}{[s - M_Z^2 + iM_Z\,\Gamma_Z]} \tag{4}$$

To a very good accuracy, it holds: $\Gamma_Z(s) \approx s/M_Z^2 \times \Gamma_Z$

see next slide, → Bardin/Leike/Riemann/Sachwitz 1988 [21]; also: Berends/Burgers/Hollik/v.Neerven 1988 [22]

Need correct unfolding ..

.. of *Realistic Observables* in order to get *Pseudo Observables*. → e.g.: Borrelli/Consoli/Maiani/Sisto 1990 [23], Later: Bardin/Passarino 1999 [24], Bardin/Grünewald/Passarino 1999 [25], Passarino 2003 [26], Passarino 2013 [27] and refs. therein.

From the theory side II

The specific problem from the theory side is:

Organize a consistent perturbation expansion at several loop orders in presence of an unstable intermediate state: the Z boson

Consistent means:

Well-defined, unitary, gauge-invariant, analytic

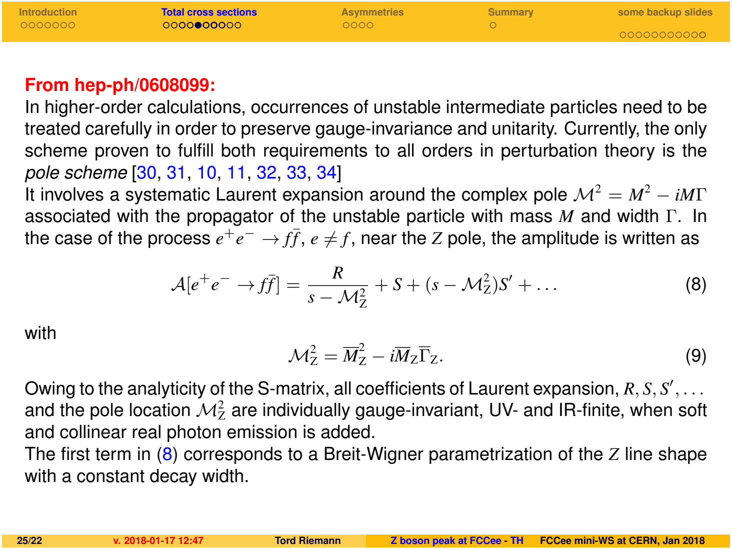
Maybe not necessarily unique in details

Since the LEP studies around 1990 we know that such a scheme may be based on an S-matrix element:

$$M_Z \sim \frac{R}{s - s_0^2} + \sum_{n=0}^{\infty} (s - s_0^2)^n M_n,$$

$$s_0^2 \equiv M_Z^2 + i M_Z \Gamma_Z$$

This is a Laurent expansion.



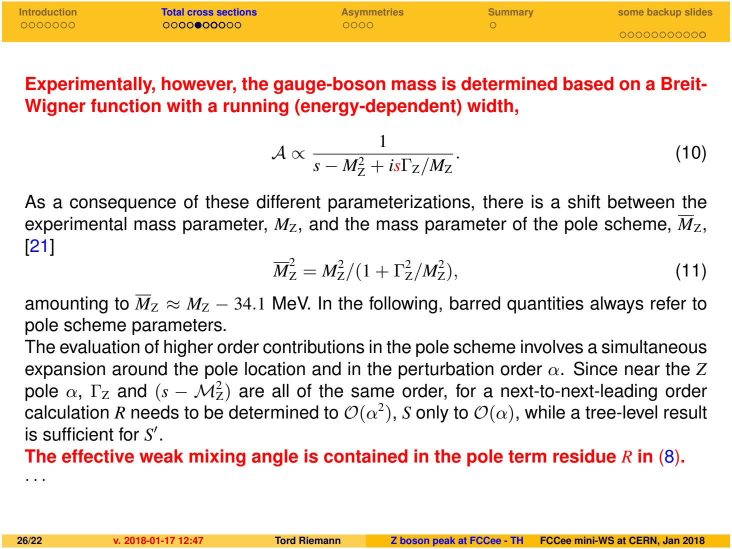
From hep-ph/0608099:
In higher-order calculations, occurrences of unstable intermediate particles need to be treated carefully in order to preserve gauge-invariance and unitarity. Currently, the only scheme proven to fulfill both requirements to all orders in perturbation theory is the *pole scheme* [30, 31, 10, 11, 32, 33, 34]
It involves a systematic Laurent expansion around the complex pole $\mathcal{M}^2 = M^2 - iM\Gamma$ associated with the propagator of the unstable particle with mass M and width Γ. In the case of the process $e^+e^- \to f\bar{f}$, $e \neq f$, near the Z pole, the amplitude is written as

$$\mathcal{A}[e^+e^- \to f\bar{f}] = \frac{R}{s - \mathcal{M}_Z^2} + S + (s - \mathcal{M}_Z^2)S' + \dots \qquad (8)$$

with

$$\mathcal{M}_Z^2 = \overline{M}_Z^2 - i\overline{M}_Z\overline{\Gamma}_Z. \qquad (9)$$

Owing to the analyticity of the S-matrix, all coefficients of Laurent expansion, $R, S, S', \dots$ and the pole location $\mathcal{M}_Z^2$ are individually gauge-invariant, UV- and IR-finite, when soft and collinear real photon emission is added.
The first term in (8) corresponds to a Breit-Wigner parametrization of the Z line shape with a constant decay width.



Experimentally, however, the gauge-boson mass is determined based on a Breit-Wigner function with a running (energy-dependent) width,

$$\mathcal{A} \propto \frac{1}{s - M_{\mathrm{Z}}^2 + i s \Gamma_{\mathrm{Z}}/M_{\mathrm{Z}}}. \tag{10}$$

As a consequence of these different parameterizations, there is a shift between the experimental mass parameter, M_{Z}, and the mass parameter of the pole scheme, $\overline{M}_{\mathrm{Z}}$, [21]

$$\overline{M}_{\mathrm{Z}}^2 = M_{\mathrm{Z}}^2/(1 + \Gamma_{\mathrm{Z}}^2/M_{\mathrm{Z}}^2), \tag{11}$$

amounting to $\overline{M}_{\mathrm{Z}} \approx M_{\mathrm{Z}} - 34.1$ MeV. In the following, barred quantities always refer to pole scheme parameters.

The evaluation of higher order contributions in the pole scheme involves a simultaneous expansion around the pole location and in the perturbation order α. Since near the Z pole α, Γ_{Z} and $(s - \mathcal{M}_{\mathrm{Z}}^2)$ are all of the same order, for a next-to-next-leading order calculation R needs to be determined to $\mathcal{O}(\alpha^2)$, S only to $\mathcal{O}(\alpha)$, while a tree-level result is sufficient for S'.

The effective weak mixing angle is contained in the pole term residue R in (8).

. . .

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 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)	$\delta(\Delta\alpha)$
$\sin^2\theta^{\ell}_{\rm eff}$ $[10^{-5}]$	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	$\delta\alpha_s$

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 $\Longrightarrow$

$\mathbf{N}_\nu$ from $\mathbf{Z}$ invisible width

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

- assuming lepton universality

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

- from LEP Z-peak measurements

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

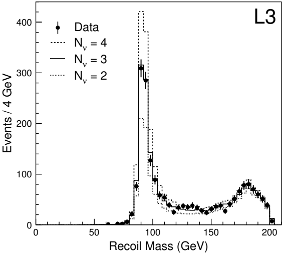
ADLO, SLD and LEPEWWG, Phys. Rept. 427 (2006) 257, hep-ex/0509008

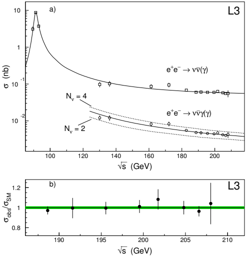
- δN_ν severely affected by luminosity uncertainty through σ_0

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)

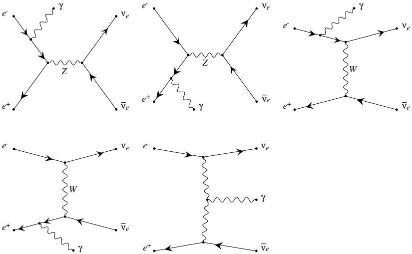
- agreement of data with SM predictions at % level
- $N_\nu = 2.98 \pm 0.05 \pm 0.04$ (L3) (important but not competitive with the $\Gamma_{\rm inv}$ method)
- similar results for ALEPH, DELPHI and OPAL

$\nu\bar{\nu}\gamma$@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)



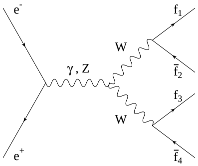
- $\mu^+\mu^-$ only $s-$channel but ISR and FSR
- ν_μ and ν_τ f.s.: only $s-$channel ISR
- ν_e f.s.: ISR with $t-$channel
- ν_e f.s.: also W radiation

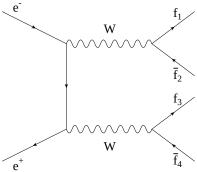
- preliminary investigations show that QED effects are very small

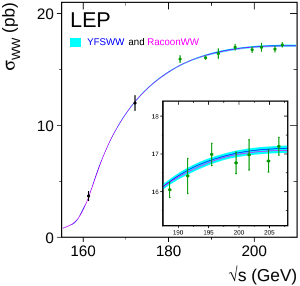
talk by S. Jadach at FCC-ee physics Workshop, Paris, 27-29 October 2014

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

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







- first NLO exact calculation completed in 2005 for $WW \to 4\mathrm{f}$
  - 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

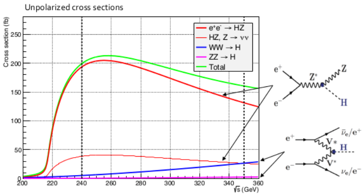
  - th. accuracy $\sim 0.5\%$ $\Delta M_W \sim 3$ MeV

WW threshold: future prospects

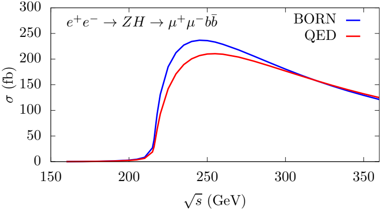
see talk by Paolo Azzurri for experimental issues

- 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 $\mathbf{ZH}$ threshold



Bicer et al., 2014



M. Greco et al., arXiv:1711.00826

- 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