Z physics and theory requirements

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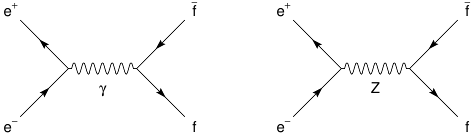
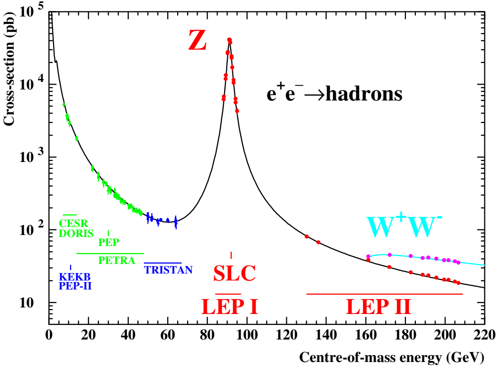
Outline

- Electroweak precision fits based on derived observables
- How to extract (at LEP) derived observables from primary measured quantities
- possible ambiguities and requirements on the procedure in view of the envisaged precision at FCCee
- requirement on the improvement on the luminosity determination

basic processes studied at the Z peak





LEP EWWG, SLD WG, ALEPH, DELPHI, L3, OPAL, hep-ph/0509008

Electroweak Fit – Experimental inputs

- **Latest experimental inputs:**
  - Z-pole observables: from LEP / SLC
    [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - M_W and Γ_W from LEP/Tevatron
    [arXiv:1204.0042, arXiv:1302.3415]
  - m_{top} latest avg from Tevatron
    [arXiv:1305.3929]
  - m_c, m_b world averages (PDG)
    [PDG, J. Phys. G33,1 (2006)]
  - $\Delta\alpha_{had}^{(5)}(M_Z^2)$ including α_S dependency
    [Davier et al., EPJC 71, 1515 (2011)]
  - M_H from LHC
    [arXiv:1207.7214, arXiv:1207.7235]
- **7 (+2) free fit parameters:**
  - M_H, M_Z, $\alpha_S(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_t, m_c, m_b
  - 2 theory nuisance parameters
    - δM_W (4 MeV), $\delta \sin^2\theta^l_{eff}$ (4.7x10^{-5})

M_H [GeV]°	125.7 ± 0.4	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	Tevatron
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ (*)	0.1499 ± 0.0018	SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	SLC
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP / SLC
R^0_b	0.21629 ± 0.00066	LEP / SLC
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.20 ± 0.87	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ (†△)	2756 ± 10	

Max Baak (CERN) The ElectroWeak fit of Standard Model 5

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

From measured observables to pseudo-observables

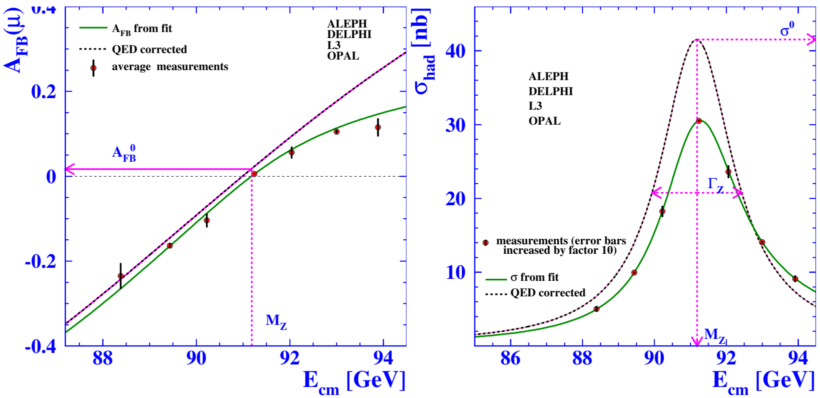
$$\sigma_{\mathrm{T}}(s) = \int_{z_0}^{1} dz H(z;s) \hat{\sigma}_{\mathrm{T}}(zs)$$

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

- Radiator function known up to $\mathcal{O}(\alpha^3)$
  1. additive form — G. Montagna, O. Nicrosini, F.P., PLB 406, (1997) 243
  2. factorized form — M. Skrzypek, Acta Phys. Pol. B23 (1992) 135
- H_{FB} known up to $\mathcal{O}(\alpha^2)$

Theoretical control on the derived observables with a certain precision requires the process of “deconvolution” of ISR and FSR with the same level of precision

Effect of QED deconvolution



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

Uncertainty on the ISR deconvolution

- obtained through the comparison of additive and factorized form of the radiator function

	LEP 1 energy in GeV				
	$M_Z - 3$	$M_Z - 1$	M_Z	$M_Z + 1$	$M_Z + 3$
	$10^4 \times$ (fact/add-1)				
σ_μ	0.44 0.88	0.63 0.63	0.61 0.68	0.72 0.72	0.49 0.49
$\sigma_{\rm had}$	0.58 0.61	0.58 0.62	0.64 0.67	0.73 0.76	0.59 0.62
	fact-add [pb]				
σ_μ	0.01 0.02	0.03 0.03	0.09 0.10	0.05 0.05	0.02 0.02
$\sigma_{\rm had}$	0.26 0.27	0.56 0.60	1.95 2.04	1.04 1.08	0.48 0.51
	$10^5 \times$ (fact-add)				
A^μ_{FB}	1.00 -4.00	1.00 -2.00	0.00 0.00	0.00 1.00	-1.00 1.00

- The level of agreement between TOPAZ0 and ZFITTER around the Z peak is below the 0.01% level $\longrightarrow$ analysis at the 0.1% level on the derived observables are robust
- passing from 0.1% to 0.01% (or even more) precision requires an improvement of the deconvolution process

model-independent parameterization

$$A_{\rm SM} = A_\gamma + A_Z + \text{non-factorizable}$$

- aim: write the Z-line shape in a model independent way

Borrelli, Consoli, Maiani, Sisto, NPB333 (1990) 357

$$\sigma^Z_{f\bar f} = \sigma^{\rm peak}_{f\bar f} \frac{s\Gamma_Z^2}{(s-M_Z)^2 + s^2\Gamma_Z^2/M_Z^2}$$

$$\sigma^{\rm peak}_{f\bar f} = \frac{\sigma^0_{f\bar f}}{R_{\rm QED}}; \qquad \sigma^0_{f\bar f} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar f}}{\Gamma_Z^2}$$

- what is not factorizable on the Z-exchange tree-level has to be taken for fixed SM parameters
- $\longrightarrow$ model independence is lost. At LEP the remainders taken from the SM show dependence on the SM Lagrangian parameters below the 0.1% level

example: interference $\gamma - Z$

	Centre-of-mass energy in GeV				
	$M_Z - 3$	$M_Z - 1.8$	M_Z	$M_Z + 1.8$	$M_Z + 3$
$\delta^{\rm int}\sigma_\mu$	$-0.209\,\%$	$-0.136\,\%$	$-0.028\,\%$	$+0.072\,\%$	$+0.132\,\%$
$\delta^{\rm int}\sigma_{\rm had}$	$-0.492\,\%$	$-0.301\,\%$	$-0.029\,\%$	$+0.226\,\%$	$+0.384\,\%$
$\Delta^{\rm int}\mu$	-0.27703	-0.16611	0.00145	0.15923	0.25441

$$\delta^{\rm int}\sigma = \frac{\sigma_{\rm T}^{\rm DD}}{\sigma_{Z+\gamma}^{\rm DD}} - 1 \qquad \text{in percent}$$

$$\Delta^{\rm int} A_{FB}^{\mu} = A_{FB}^{\mu,{\rm DD}} - \left(A_{FB}^{\mu,{\rm DD}}\right)_{Z+\gamma} .$$

m_H [GeV]	Centre-of-mass energy in GeV $M_Z - 3$	$M_Z - 1.8$	M_Z	$M_Z + 1.8$	$M_Z + 3$
$\delta^{\rm int}\sigma_\mu$					
10	$-0.229\,\%$	$-0.150\,\%$	$-0.030\,\%$	$+0.082\,\%$	$+0.149\,\%$
100	$-0.209\,\%$	$-0.136\,\%$	$-0.028\,\%$	$+0.072\,\%$	$+0.132\,\%$
1000	$-0.181\,\%$	$-0.119\,\%$	$-0.026\,\%$	$+0.060\,\%$	$+0.111\,\%$
$\delta^{\rm int}\sigma_{\rm had}$					
10	$-0.518\,\%$	$-0.317\,\%$	$-0.029\,\%$	$+0.240\,\%$	$+0.407\,\%$
100	$-0.492\,\%$	$-0.301\,\%$	$-0.029\,\%$	$+0.226\,\%$	$+0.384\,\%$
1000	$-0.457\,\%$	$-0.281\,\%$	$-0.028\,\%$	$+0.207\,\%$	$+0.353\,\%$

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

another possible approach: S-Matrix formalism

A. Leike, T. Riemann, J. Rose, PLB273 (1991) 513

- general parameterization of σ and A_{FB} in terms of exchange of a massless and a massive vector boson

$$\sigma^{0,f}_{\rm tot}(s) = \frac{4}{3}\pi\alpha^2 + \left[\frac{g_f^{\rm tot}}{s} + \frac{j_f^{\rm tot}(s-\overline{m}_{\rm Z}^2) + r_f^{\rm tot} s}{(s-\overline{m}_{\rm Z}^2)^2 + \overline{m}_{\rm Z}^2\overline{\Gamma}_{\rm Z}^2}\right]$$

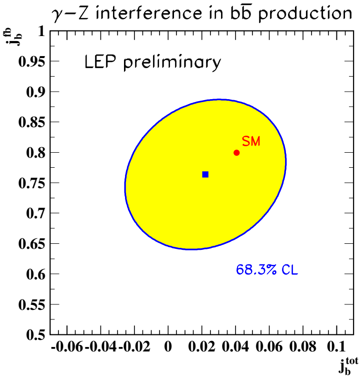
$$\sigma^{0,f}_{\rm fb}(s) = \frac{4}{3}\pi\alpha^2 + \left[\frac{g_f^{\rm fb}}{s} + \frac{j_f^{\rm fb}(s-\overline{m}_{\rm Z}^2) + r_f^{\rm fb} s}{(s-\overline{m}_{\rm Z}^2)^2 + \overline{m}_{\rm Z}^2\overline{\Gamma}_{\rm Z}^2}\right]$$

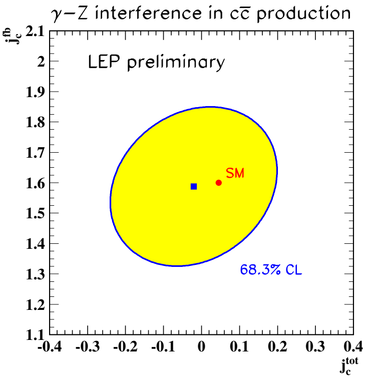
$$A^{0,f}_{\rm fb}(s) = \frac{3}{4}\frac{\sigma^{0,f}_{\rm fb}(s)}{\sigma^{0,f}_{\rm tot}(s)}$$

$$\overline{m}_{\rm Z} \sim m_{\rm Z}/\sqrt{1+\Gamma_{\rm Z}^2/m_{\rm Z}^2} \qquad \overline{\Gamma}_{\rm Z} \sim \Gamma_{\rm Z}\sqrt{1+\Gamma_{\rm Z}^2/m_{\rm Z}^2}$$

- however, with very high precision, it should be carefully checked how MC extrapolation of data before fitting brings in SM dependence

results for heavy flavours at LEP





LEP Coll., LEPEWWG, SLD HF and EWWG, hep-ph/0103048

Higher order calculations

- within or Beyond the SM, the high precision of FCCee will require higher order perturbative calculations
- during the last decay great technological advances for the calculation of higher order (beyond one-loop) radiative corrections
- however, a bottleneck will be represented by the hadronic contributions to the vacuum polarization
  - Will be enough the precision of Belle II on the hadronic cross section for the FCCee requirements?

Vacuum polarization: historical perspective

- two kinds of contributions
  - contribution to NLO corrections (and higher orders)
  - irreducible contribution to NNLO corrections
    Bonciani, Ferroglia, Mastrolia, Remiddi, van der Bij, 2004, 2005
    Actis, Czakon, Gluza and Riemann, 2007; Kühn, Uccirati, 2009; Carloni Calame et al., 2011
- reliably calculated for leptons and heavy particles
- calculation not reliable for light hadrons in the loop $\Longrightarrow$ dispersion relations using data for $e^+e^- \to$hadrons
- recent progress in hadronic contributions, thanks to precise data at low energies e^+e^- meson factories   Actis et al., EPJC66 (2010) 585

- $\Delta\alpha(M_Z^2) = 0.0280 \pm 0.0007 \Longrightarrow \alpha^{-1}(M_Z^2) = 128.89 \pm 0.09$
  H. Burkhardt and B. Pietrzyk, Phys. Lett. B356 (1995) 398
- $\Delta\alpha(M_Z^2) = 0.02750 \pm 0.00033$ H. Burkhardt and B. Pietrzyk, Phys. Rev. D84 (2011) 037502
- $\Delta\alpha(M_Z^2) = 0.027498 \pm 0.000135[0.027510 \pm 0.000218]$
  F. Jegerlehner, arXiv:1107.4683
- $\Delta\alpha(M_Z^2) = 0.02757 \pm 0.0001$ Davier, Hoecker, Malaescu, Zhang, arXiv:1010.4180
- $\Delta\alpha(M_Z^2) = 0.027626 \pm 0.000138$ T. Teubner et al., Nucl. Phys. Proc. Suppl. 225 (2012) 282

luminosity: theoretical systematics on σ

- theoretical error in SABH 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: S. Jadach, O. Nicrosini et al. Physics at LEP2 YR 96-01, Vol. 2
A. Arbuzov et al., Phys. Lett. B389 (1996) 129
II column: B.F.L. Ward, S. Jadach, M. Melles, S.A. Yost, hep-ph/9811245
III column: G. Montagna et al., Nucl. Phys. B547 (1999) 39

- recent progress in complete two-loop pure photonic contributions to QED Bhabha scattering

Bern, Dixon, Ghinculov Phys. Rev. D63 (2001) 053007
A. Penin Phys. Rev. Lett., 95 (2005) 010408
Becher, Melnikov, JHEP 0706 (2007) 084

  - $\Longrightarrow$ building blocks available for MC programs with th. precision below 0.1% on the perturbative side

- what would be the impact of vacuum polarization uncertainties on SABH?

Summary

- very high statistics at the Z peak poses some challenges for a model-independent extraction of the derived parameters
- a data/theory comparison at the level of measured cross sections could be more safe, even if
  - it requires more involved complete theoretical calculations for the processes $e^+e^- \to f\bar{f}$ within and in models beyond SM
  - it renders more involved the average over different experiments
- high precision predictions for Bhabha scattering will be required
- hadronic contributions to vacuum polarization will require input from high intensity low energy machines