Gearing up for Future Colliders — Workshop on Radiative Corrections at Future Lepton Colliders

3 Jul 2026

CERN TH CONF ROOM

Experimental Overview on Z-pole and EWPO

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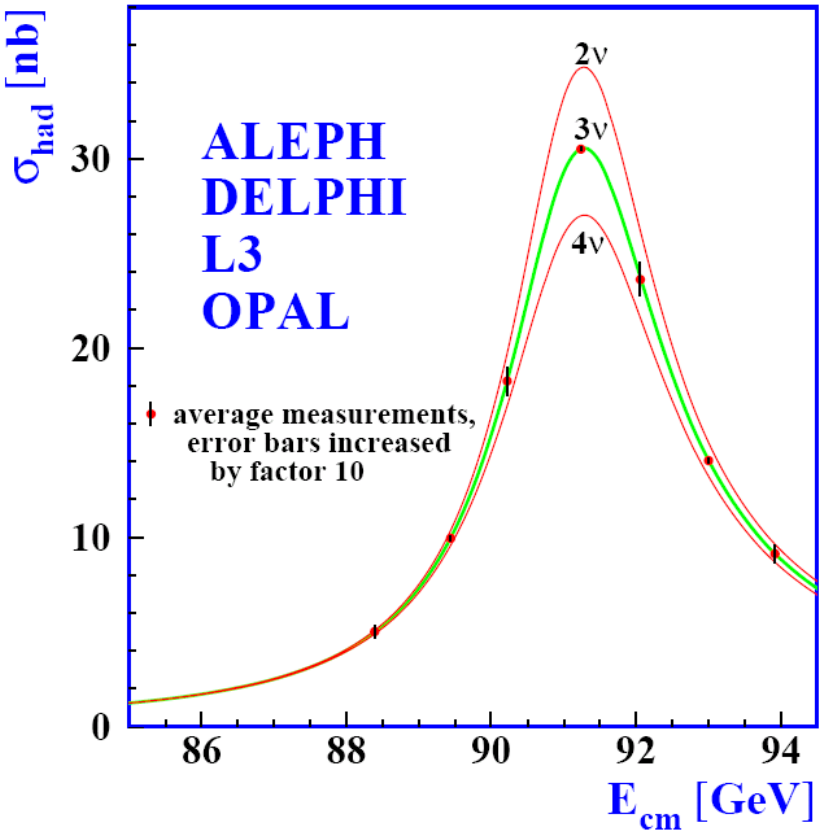


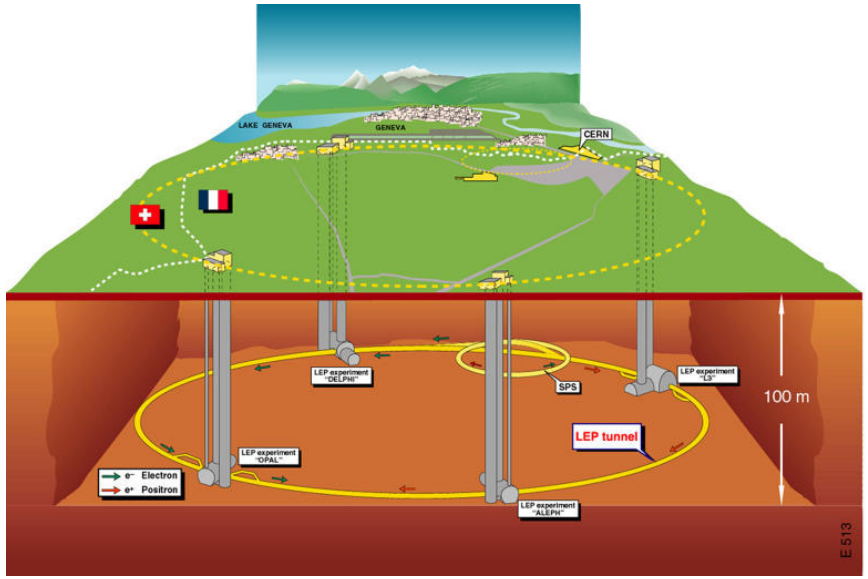
Back to the future: from Z pole to Z pole

The LEP runs at the Z took place in 1989-1995

- achieved a maximum luminosity of $2.3 \times 10^{31}\, cm^{-2}s^{-1}$,
- total integrated luminosity delivered at the Z was about **150 pb^{-1}** per experiment; the four experiments collected a total statistics of more than **15 millions hadronic Z decays** and **1.7 millions leptonic Z decays**.

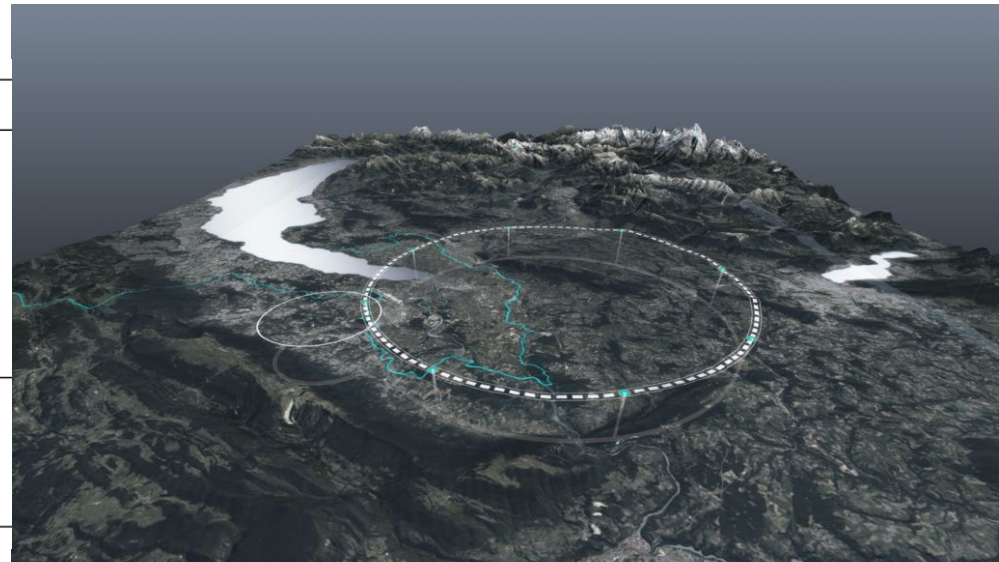
The SLC, operating from 1989 to 1998, provided longitudinal polarization of the electron beam.

- An electron-beam polarization of about 77% was achieved in 1994. At this average polarization, about 150000 Z decays were recorded by the SLD experiment.



FCC-ee : a huge leap

Working point	Z pole
$\sqrt{s}$ (GeV)	88, 91, 94
Lumi/IP (10^{34} cm^{-2}s^{-1})	140
Lumi/year (ab^{-1})	68
Run time (year)	4
Integrated lumi. (ab^{-1})	205
Number of events	6×10^{12} Z



EW Physics observables at FCC-ee

TODAY

TeraZ (6 X 10^{12} Z)

From data collected in a lineshape energy scan:

- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- R_l = hadronic/leptonic width ($\alpha_s(m^2_Z)$, lepton couplings)
- peak cross section (invisible width, N_ν)
- $A_{FB}(\mu\mu)$ ($\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$, lepton couplings)
- Tau polarization ($\sin^2\theta_{eff}$, lepton couplings)
- R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$ (quark couplings)
  (at FCC-ee R_s and $A_{FB}(ss)$ possible, too)

Standard lineshape fit

already discussed on Monday by Paolo Azzurri

OkuWW (2 X 10^8 WW)

From data collected around and above the WW threshold:

- W mass (key for jump in precision for ewk fits)
- W width (first precise direct meas)
- $R^W = \Gamma_{had}/\Gamma_{lept}$ ($\alpha_s(m^2_Z)$)
- Γ_e , Γ_μ , Γ_τ (precise universality test)
- Triple and Quartic Gauge couplings (jump in precision, especially for charged couplings)

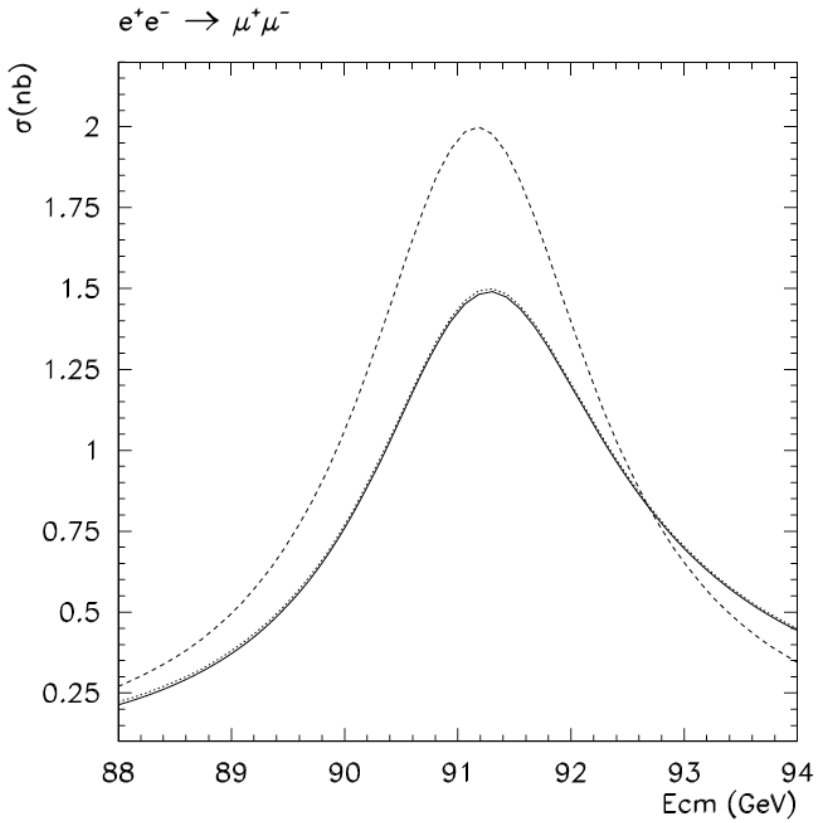
TOP AND HIGGS MASS ARE IDEALLY INCLUDED INTO THE LIST

Determination of the Z lineshape (1)

- The lineshape is highly asymmetric because of radiative effects
- At LEP the cross section was convolved with a radiator function H(s',s)

$$\sigma_{f\bar{f}}(s) = \int_{4m_f^2}^{s} ds' H(s,s') \hat{\sigma}_{f\bar{f}}(s')$$

- LEP treatment of photon radiation: corresponds to an uncertainty on Z mass and width of 100 keV , needs to be improved for FCC



LEP : O(α^2) radiative corrections+soft photon correction+exponentiation

Determination of the Z lineshape (2)

The reduced cross section, extracted after ISR de-convolution, is composed by three terms

$$\hat{\sigma}_{f\bar{f}}(s) = \sigma^{peak}_{f\bar{f}} \cdot \frac{s\Gamma_Z^2}{\left(s - m_Z^2\right)^2 + \left(\frac{s\Gamma_Z}{m_Z}\right)^2} + \text{“}(\gamma - Z)\text{”} + \text{“}|\gamma|^2\text{”}$$

the γ-Z interference component requires either model dependent assumptions (i.e. assuming the Standard Model ansatz and its parameters) or a direct measurement of the cross section off the resonance. The model independent approach follows the so-called S-matrix parametrization , interference term corresponds to a dimensionless parameter denoted J^{tot}_{had}

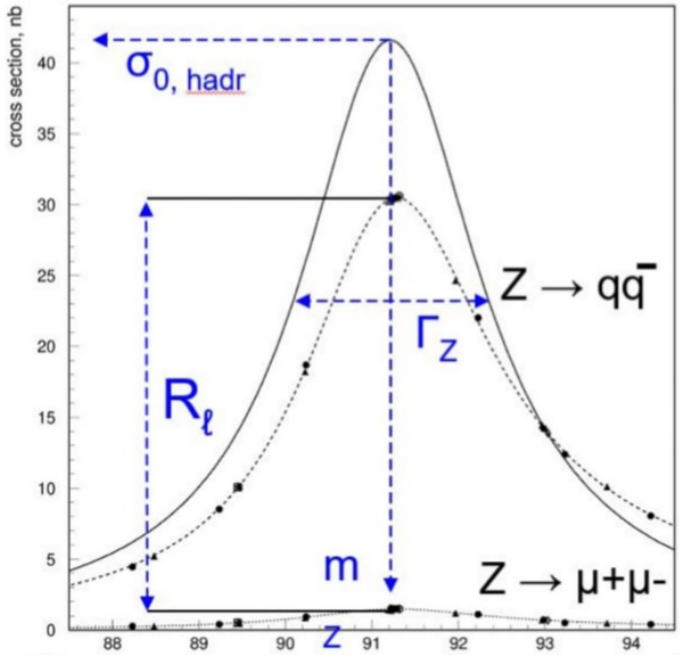
$$\frac{\partial m_Z}{\partial J^{tot}_{had}} = -1.6\,\text{MeV}/0.1$$

Nominal LEP1 results obtained assuming Standard Model for the interference term, However result cross checked using Tristan data at 60 GeV and then LEP 2 data. At FCC-ee 100 fb-1 collected at 60 GeV correspond to 100 keV on mZ, alternatively could use data above the Z (assuming a close Z’ resonance does not exists)

Determination of the Z lineshape (3)

Experimental ingredients:

- **High precision measurement of the centre-of-mass energy**
  - **(and of the energy spread)**
- **High precision measurement of the luminosity**
- **Highly efficient event selection**



With these ingredients in a typical LEP four (six) parameter fit with (without) lepton universality assumption we obtained four (six) very relevant EWPO

$$R_\ell = \Gamma_h / \Gamma_\ell$$

Parameter	Average Value
m_Z(GeV)	91.1875±0.0021
Γ_Z(GeV)	2.4952±0.0023
σ^0_{had}(nb)	41.540±0.037
R_ℓ	20.767±0.025
R_e	20.804±0.050
R_μ	20.785±0.033
R_τ	20.764±0.045

Measuring the beam energy at LEP

Initial phase:

- Flux loop : each LEP magnet was fitted with a solenoid to measure the field by integrating a current cycle. NMR were also used.
- Reference magnet with rotating coil for continuous current monitoring
- Calibration using protons (non-relativistic at the Z pole), their velocity of can be measured from the RF delay

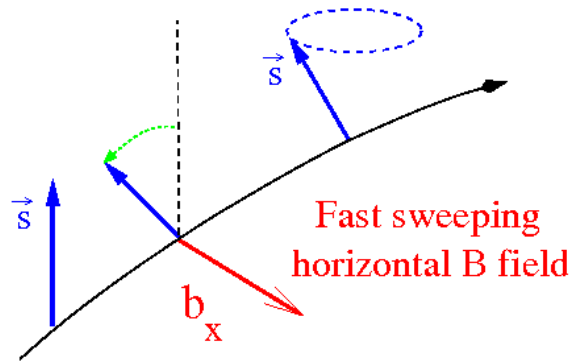
$$\langle E_{beam} \rangle = \frac{e}{2\pi} \oint B \cdot dl$$

High precision phase: beam resonant depolarization

- **Vertical polarisation built up by synchrotron radiation**
- **Thomas precession of the electron's spin**

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S}$$

$$\vec{\Omega} = -\frac{e}{\gamma m}(1 + a\gamma)\vec{B}$$



- The method works only at beam energies away from the *resonant condition* corresponding to an integer *spin tune*, i.e. an integer number of precessions per turn.
- In practice beam energies near to an half-integer tune need to be selected

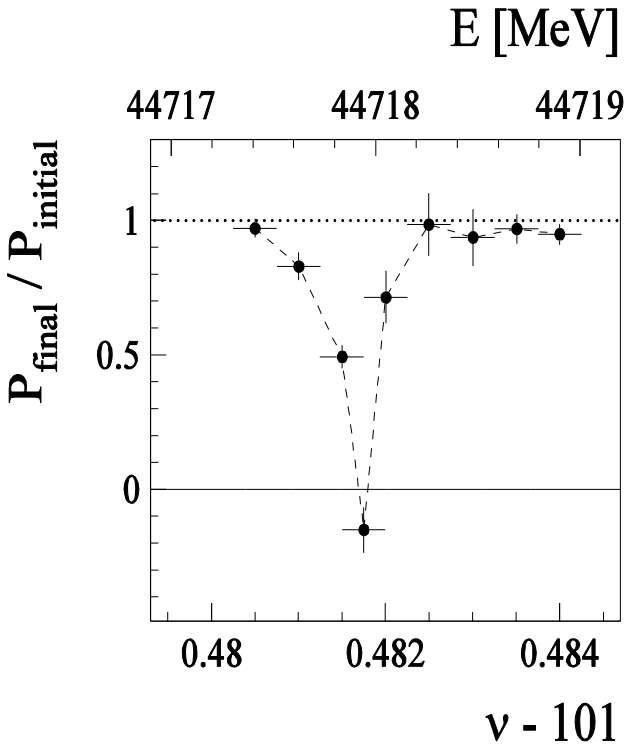
An oscillating and resonant radial B_x field has a depolarization effect if it oscillates at a frequency corresponding to the beam energy (spin tune ν_0)

$$\nu_0 = a_e\gamma = \frac{a_e E}{m_e c^2} = \frac{E_{beam}}{440.6486(1)[MeV]}$$

Beam energy measurement accuracy

LEP

- Intrinsic precision of resonant depolarisation ≈ 100 keV (!!)
- Systematic effects on the depol. measurement ≈ 1.1 MeV
- Transport from Ebeam in dedicated experiment to actual Ecm :
  - instability effects in the dipole field (es.: temperature)
  - effects due to variations in the quadrupole field as seen from orbit (es.: tides)
  - effects that alter the energy at the point of interaction (es.: RF corrections)
- Final precision on the Z mass 2 X 10^{-5}



FCC-ee

- Measurement of E beam done continuosly on ≈ 160 non colliding bunches, no need of transport from dedicated experiment
- Depolarizing effects reduced with larger ring, because of lower energy spread $\sigma_E \propto E^2/\sqrt{\rho}$
- At FCC-ee 30 mrad crossing angle to be calculated at high precision with dimuon events
- Aim at ≈ 100 keV uncertainty on E beam

LEP Energy, alternative methods gave important cross checks

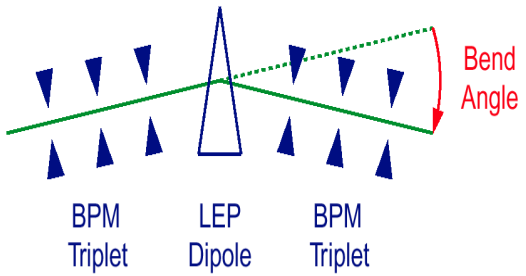
Energy loss

Based on the frequency of the field provided to beam to compensate from syncroton radiation.

$$Q_s^2 = \left(\frac{\alpha_c h}{2\pi E}\right)\sqrt{e^2 V_{RF}^2 - U_0^2}$$

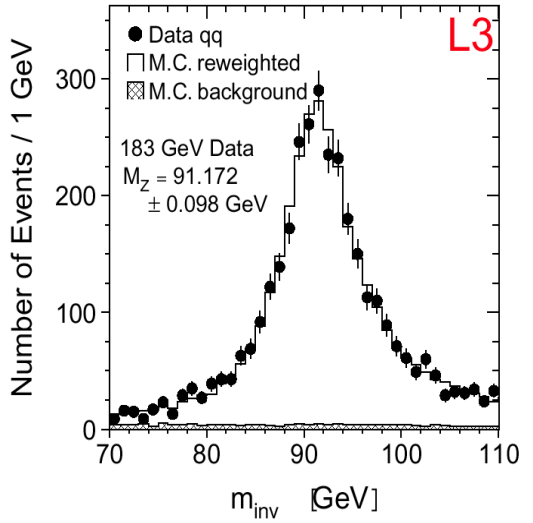
E loss by sync.

Spectrometer



Based on measurement of lepton bending angle

Radiative return



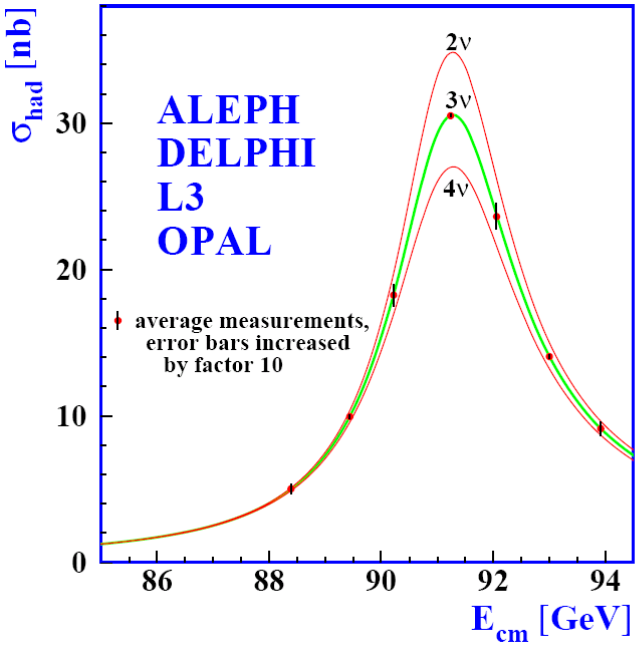
Compare radiative return peak with Z mass

Determination of Z mass and width

- uncertainty on m_Z (≈ 100 KeV) is dominated by the correlated uncertainty on the centre-of-mass energy at the two off peak points

  at FCC-ee continuous E_{CM} calibration (resonant depolarization) gives ΔE_{CM} ≈ 10 KeV (stat) + 100 KeV (syst)

- the off peak point-to-point anti-correlated uncertainty has a similar impact (≈ 100 KeV) on Γ_Z

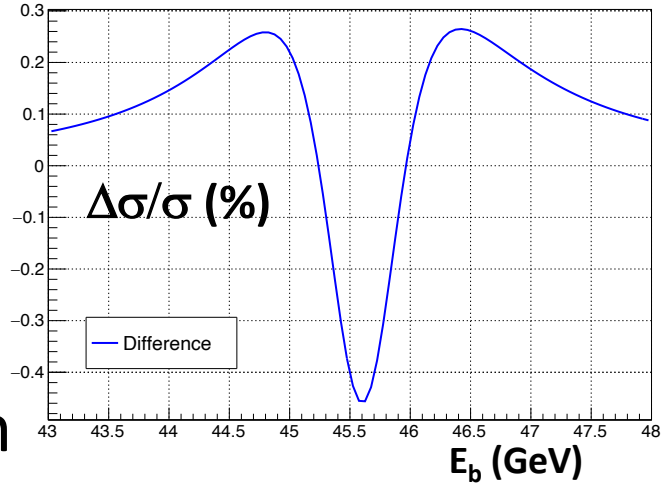


The exact choice of the off peak energies for m_Z , Γ_Z is not very crucial at FCC-ee (differently from LEP) because of the high statistics.
Instead the exact choice is crucial for $\alpha_{QED}(m_Z^2)$ which is driving the choice of $\sqrt{s}_-$ ≈ **88 GeV** and $\sqrt{s}_+$ ≈ **94 GeV**

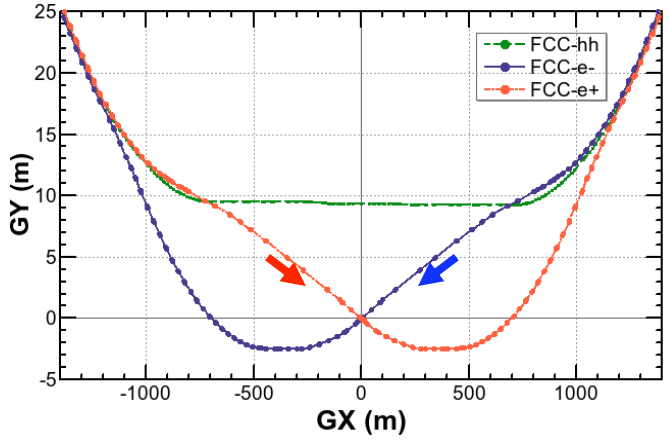
Γ_Z and beam energy spread

- The beam energy spread affects the lineshape changing the cross section by

$$\delta\sigma \simeq 0.5 \frac{d^2\sigma}{dE^2} \epsilon^2_{CMS}$$



- The size of the energy spread (≈ 60 MeV) and its impact on Γ_Z (≈4 MeV) is similar to LEP, but the approach to tackle the corresponding systematic uncertainty different because of FCC-ee beam crossing angle
- At LEP it was controlled at 1% level by measuring the longitudinal size of the beam spot, at FCC-ee can be measured with similar precision from the scattering angles of $\mu^+\mu^-$ events



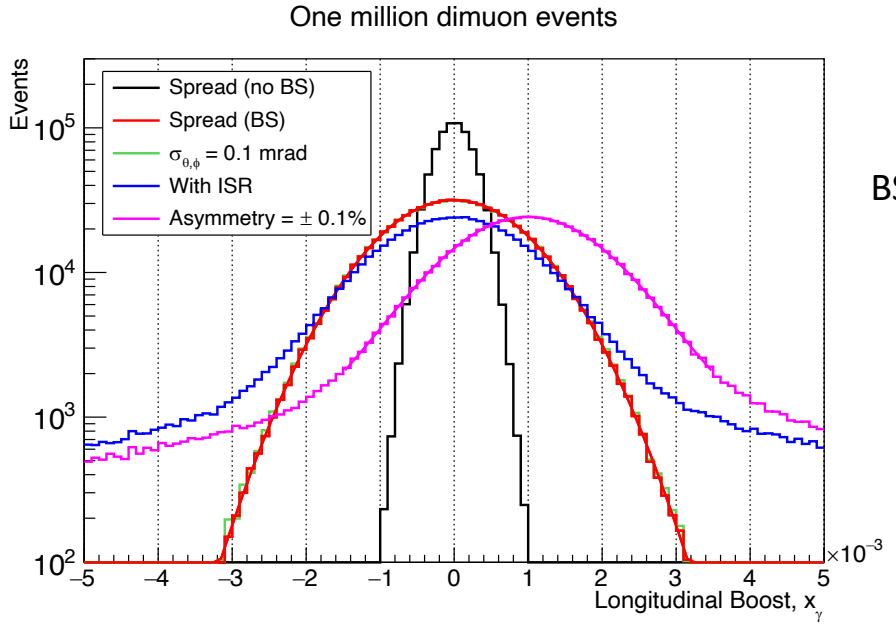
Control of energy spread with $\mu^+\mu^-$

- FCC-ee: Asymmetric optics with beam crossing angle α of 30 mrad
- α is measured in e+e-→$\mu^+\mu^-(\gamma)$

$$\alpha = 2\arcsin\left[\frac{\sin(\varphi^- - \varphi^+)\sin\theta^+\sin\theta^-}{\sin\varphi^-\sin\theta^- - \sin\varphi^+\sin\theta^+}\right]$$

together with γ (ISR) energy, both distributions sensitive to energy spread.

- Energy spread measured at 0.1% with 10^6 muons (4 min at FCC-ee)
- Current calculations of ISR emission spectrum sufficient
- Detector requirement on muon angular resolution 0.1 mrad



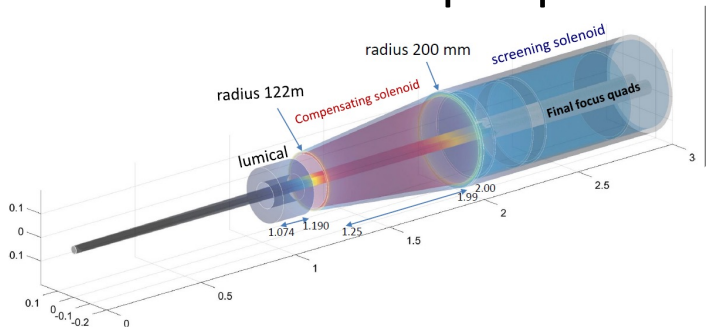
BS=beamstrahlung

$$x_\gamma = -\frac{x_+\cos\theta^+ + x_-\cos\theta^-}{\cos(\alpha/2) + |x_+\cos\theta^+ + x_-\cos\theta^-|}$$

Can keep related systematic uncertainty on Γ_Z at less than 30 keV

Measurement of luminosity, σ_{had} and neutrino families

- FCC-ee goal on theoretical uncertainty from higher order for low angle Bhabha is 0.01%, corresponding to a **reduction of a factor 10 in uncertainty on number of light neutrino families** (LEP final uncertainty = 0.11%)
  - Another goal is a point to point relative normalization of 5 10^{-5} for Γ_Z
- To match this goal an accuracy on detector construction and boundaries of ≈ 2 μm is required (LEP accuracy ≈ 10 microns)
  - clever acceptance algorithms, a la LEP, with independence on beam spot position should be extended to beam with crossing angle
  - luminometer fixed to central beam pipe



- Can potentially reach much lower uncertainty (up to of 0.001%) with e+e-→γγ , statistically ≈ 100 ab^{-1} are required (theory uncertainty progressing to this level, requires control of large angle Bhabha)

(Potential to improve the measurement of neutrino families also with e^+e^-→Zγ)

About Highly efficient event selection at the Z (1)

The **trigger rate at LEP was typically 5 Hz**,

- luminosity triggers accounted for 2-3 Hz,
- Z events 0.5 Hz
- and $\gamma\gamma$ 0.5 Hz (example from Aleph)

Trigger Efficiency for hadronic Z decays 99.999 % with an **uncertainty of 0.001%** determined by comparing independent triggers

Inefficiency for leptonic channels (e,μ,τ) in fiducial region **< 3 x 10^{-5}**

Studies done for the CEPC TDR show that the trigger rate for ≈ 100% efficiency of EW events is totally manageable

Table 12.2: Expected Standard Model processes event rate at the Z mode for 12.1 MW.

Z mode processes	Cross section (fb)	Event rate (Hz)
Physical events (top priority)		
$q\bar{q}$	3.1×10^7	7970
$\mu^+\mu^-$	1.5×10^6	400
$\tau^+\tau^-$	1.5×10^6	396
Bhabha	6.6×10^6	1714
Diphoton process (low priority)		
$\gamma\gamma \to b\bar{b}$	2.7×10^5	71
$\gamma\gamma \to c\bar{c}$	5.1×10^5	132
$\gamma\gamma \to q\bar{q}$	3.5×10^7	9014
$\gamma\gamma \to \mu^+\mu^-$	1.3×10^8	33696
$\gamma\gamma \to \tau^+\tau^-$	6.3×10^5	163

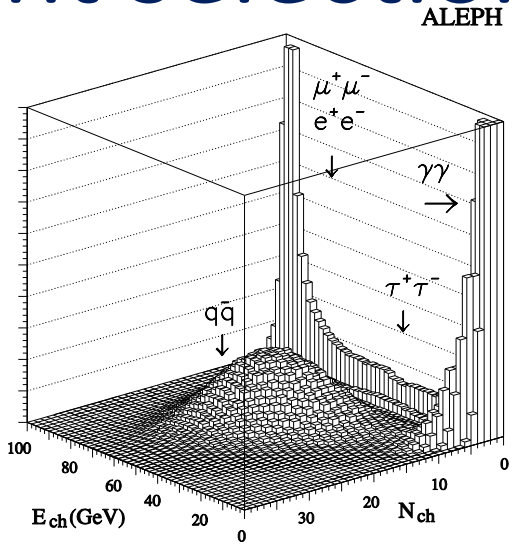
About Highly efficient event selection at the Z (2)

LEP hadronic selection:

- A minimum number of tracks (~5) or clusters in the calorimeters
- Visible energy >10–20% of the centre-of-mass energy
- Efficiencies 97–99.5%
- Background below 1% (tau and two-photon processes)

LEP leptonic selection:

- Selection efficiencies: ~95% for e/mu, ~85% for tau
- Background relevant only for the tau (~2% from two-photon processes)
- <u>The only significant background is cross-contamination between channels</u>



Real issue for R_l and cross section measurements: **knowledge of acceptance**

- At LEP acceptance effects were at **10^{-4}** level, sufficient for cross sections measured at the **10^{-3}** level. At FCC-ee we have to exploit a statistical uncertainty at **10^{-5}** level… !
- <u>The main effects were due to track losses, angle mis-measurements and knowledge of boundaries.</u>
- This requires a detector acceptance knowledge of ≈ 10-20 μm for lower boundaries at 2.5 m from the interaction point

Partial widths ratio (R_l)

- $R_l = \Gamma_l/\Gamma_{had}=\sigma_l/\sigma_{had}$ is a robust measurement, necessary input for a precise measurement of lepton couplings (and $\alpha_s(m^2_Z)$)
- Exploiting FCC-ee potential requires an accurate control of acceptance, particularly for the leptons
  - acceptance uncertainties were sub-dominant at LEP, but need to be reduced by a factor ≈ 5 to match precision goal on R_l of 5 10^{-5}
  - knowledge of boundaries, mechanical precisions: need to exploit 40 years of improvements in technology, need to use clever selections (at LEP was necessary only for luminosity)
  - fiducial acceptance is asymmetric in azimuth at FCC-ee because of 30 mrad cross angle→ boost in trasverse direction $\beta_x = tg(\alpha/2) \approx 0.015$, however can measure ϕ^* and $\cos(\theta^*)$ event by event for dileptons !

Measurement of R_b : double tagging

Divide event in two hemispheres according to thrust direction

- F_1 fraction of single tag
- F_2 fraction of double tag

$$F_1 = R_b(\varepsilon_b - \varepsilon_{uds}) + R_c(\varepsilon_c - \varepsilon_{uds}) + \varepsilon_{uds}$$

$$F_2 = R_b(C_b\varepsilon_b^2 - \varepsilon_{uds}^2) + R_c(\varepsilon_c{}^2 - \varepsilon_{uds}{}^2) + \varepsilon_{uds}{}^2$$

$$R_b \approx \frac{C_b F_1^2}{F_2}$$

$$\varepsilon_b \approx \frac{F_2}{C_b F_1}$$

LHC detectors and current taggers can reach three times b tagging efficiency at same suppression of charm and uds, in a more harsh environment → sizeable improvement possible at FCC-ee

- statistical uncertainty coming from double tag sample
- **systematic uncertainty from hemisphere correlations becomes dominating**

Efficient and pure secondary vertex finding will be important to study gluon splitting and nasty sources of correlations (e.g. momentum correlations) → **keep b-tag efficiency flat in momentum**

hemisphere correlations at LEP ≈0.1% (LEP), FCC-ee studies using exclusive channel expects 3 orders of magnitude reduction !

Improved measurements also for the charm and strange sectors R_c, R_s

Asymmetries (neutral couplings and $\sin^2\theta_{eff}$)

Forward-backward and polarization asymmetries at the Z pole are a powerful experimental tool to investigate quarks and leptons electroweak quantum numbers, e.g. axial and vector neutral couplings and the Weinberg electroweak mixing angle $\sin^2\theta_{eff}$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_f$$ Can measure for e,μ,τ,c,b

$$A_{pol} = \frac{\sigma_{F,R} + \sigma_{B,R} - \sigma_{F,L} - \sigma_{B,L}}{\sigma_{tot}} = -A_f$$ Can measure with τ's

$$A_{pol}^{FB} = \frac{\sigma_{F,R} - \sigma_{B,R} - \sigma_{F,L} + \sigma_{B,L}}{\sigma_{tot}} = -\frac{3}{4} A_e$$

$$A_f = \frac{2 g_{Vf} g_{Af}}{(g_{Vf})^2 + (g_{Af})^2}$$

$$\sin^2 \theta_{eff}^{\ l} \equiv \frac{1}{4}\left(1 - \frac{g_{Vl}}{g_{Al}}\right)$$

Only with polarized beam

$$A_{LR} = \frac{\sigma_l - \sigma_r}{\sigma_{tot}} = A_e$$

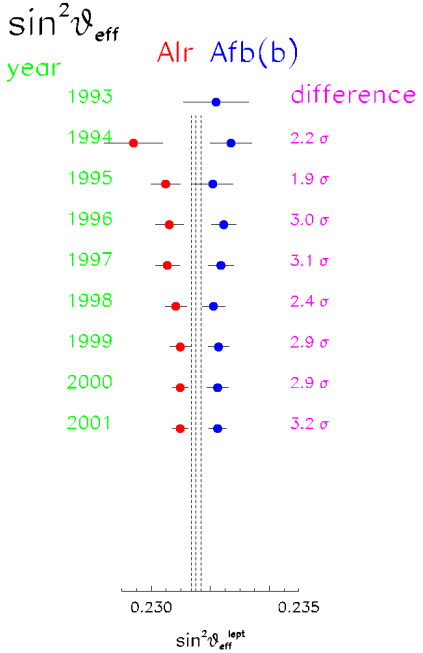
$$A_{FB}^{pol} = \frac{\sigma_{F,l} - \sigma_{B,l} - \sigma_{F,r} + \sigma_{B,r}}{\sigma_{tot}} = \frac{3}{4} A_f$$

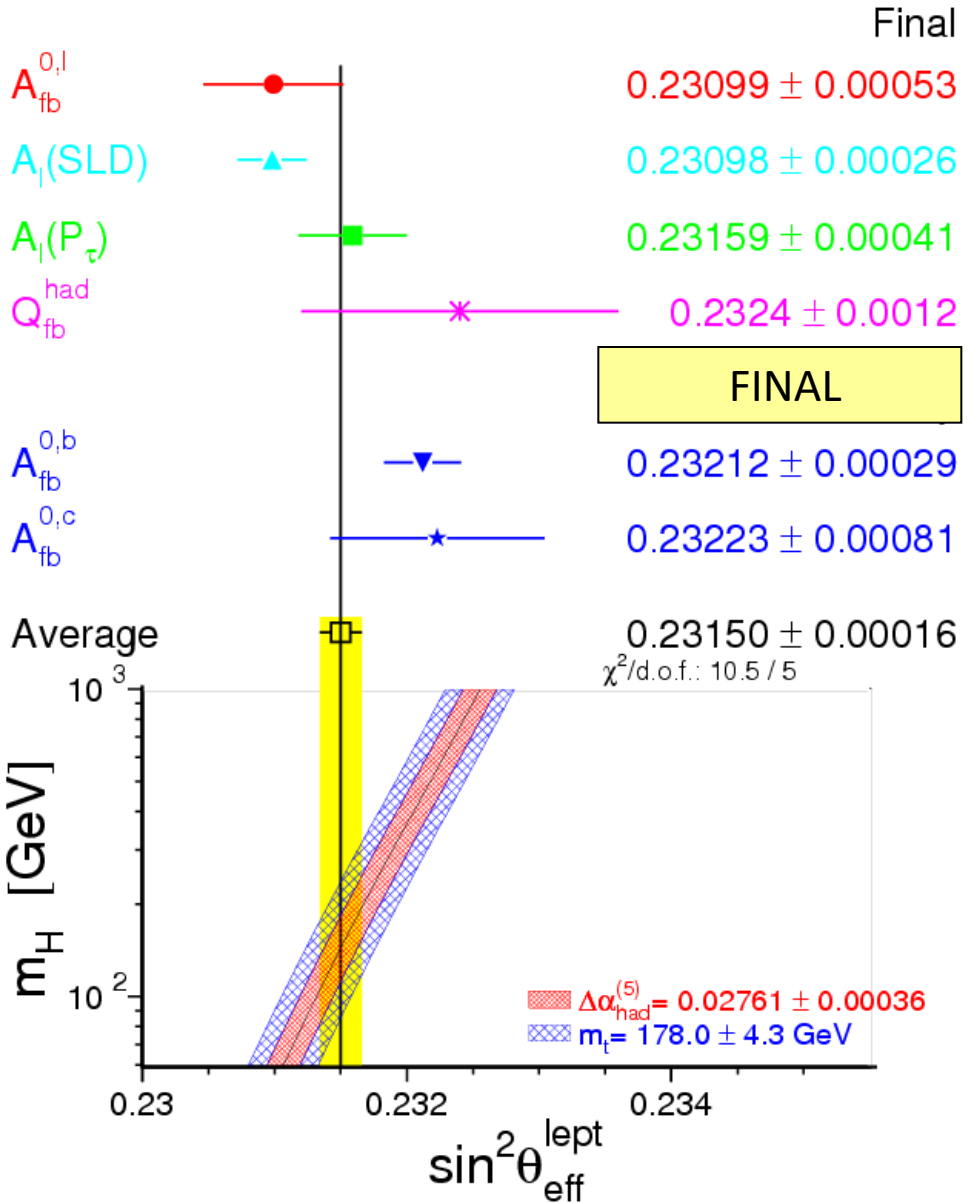
Very robust measurements, e.g. can show that they are independent of acceptance if the selection is either charge- or forward-backward symmetric

(Historical slide, Vietnam 2004)

Asymmetries at the Z and $\sin^2\theta_{eff}^{\ l}$

- Consistency is at 6.2%
- Long standing difference between Alr and $A_{FB}(b)$ [3 σ]

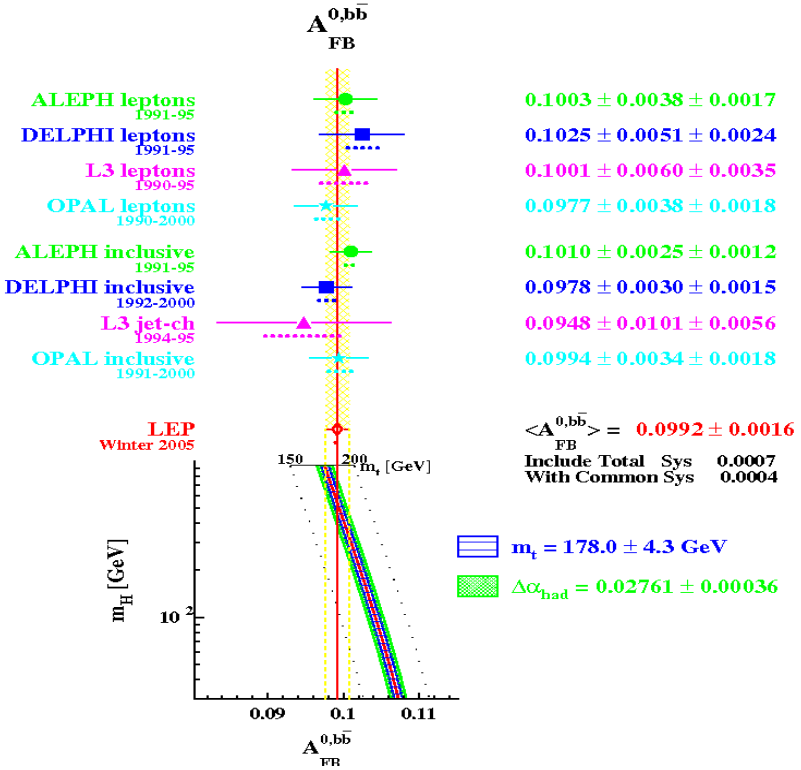




At FCC-ee can sizably improve b asymmetry

- Two techniques
  - use semileptonic b decays
  - use weighted charge of particles in the hemisphere
- Very different systematic effects
- **LEP final combination statistically dominated**

	ΔAFB(b)	
STATISTICS	0.00156	
UNCORRELATED SYSTEMATIC	0.00061	
QCD CORRECTION	0.00030	
LIGHT QUARK FRAGMENTATION	0.00013	
SEMILEPTONIC DECAYS MODELLING	0.00013	
CHARM FRAGMENTATION	0.00006	
BOTTOM FRAGMENTATION	0.00003	
TOTAL SYSTEMATIC ERROR	0.00073	



(TODO) Can be reduced with improved calculations and proper choices of analysis methods

tau polarization plays a central role at FCC-ee

- Separate measurements of A_e and A_τ from

$$P_\tau(\cos\theta) = \frac{A_{pol}(1+\cos^2\theta) + \frac{8}{3}A_{pol}^{FB}\cos\theta}{(1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta}$$

$$A_{pol} = \frac{\sigma_{F,R} + \sigma_{B,R} - \sigma_{F,L} - \sigma_{B,L}}{\sigma_{tot}} = -A_f$$

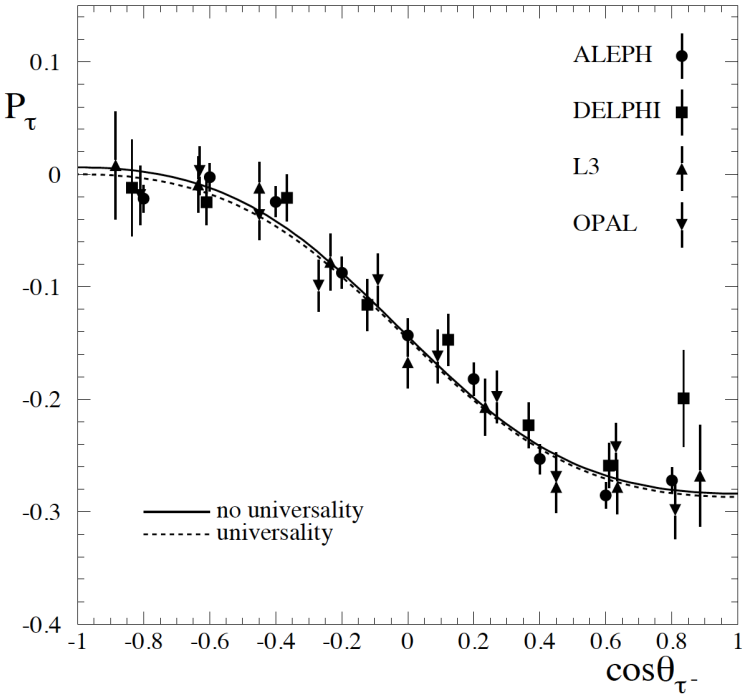
$$A_{pol}^{FB} = \frac{\sigma_{F,R} - \sigma_{B,R} - \sigma_{F,L} + \sigma_{B,L}}{\sigma_{tot}} = -\frac{3}{4}A_e$$

At FCC-ee

- very high statistics: improved knowledge of tau parameters (e.g. branching fraction, tau decay modeling) with FCC-ee data
- use best decay channels (e.g. $\tau \rightarrow \rho\nu_\tau$ decay very clean), note that detector performance for photons / π^0 very relevant

→**measure $\sin^2\theta_{eff}$ with 2 10^{-6} precision**

Measured P_τ vs $\cos\theta_{\tau^-}$



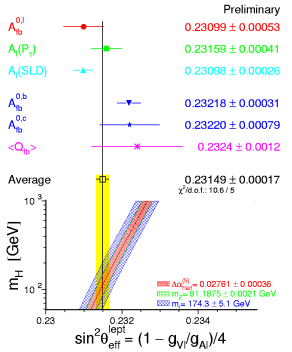
FCC-ee strategy for neutral couplings and $\sin^2\theta_{eff}$

$$\mathcal{A}_e = \frac{2g_{Ve}g_{Ae}}{(g_{Ve})^2 + (g_{Ae})^2} = \frac{2g_{Ve}/g_{Ae}}{1 + (g_{Ve}/g_{Ae})^2}$$

- Muon forward backward asymmetry at pole, $A_{FB}^{\mu\mu}(m_Z)$ gives $\sin^2\theta_{eff}$ with 2 10^{-6} precision
  - **uncertainty driven by knowledge on CM energy**
  - **assumes muon-electron universality**
- **Tau polarization can reach similar precision without universality assumption**
  - tau pol measures A_e and A_τ, can input to **$A_{FB}^{\mu\mu} = 3/4\ A_e\ A_\mu$** to measure separately electron, muon and tau couplings, (together with Γ_e, Γ_μ, Γ_τ)
- Asymmetries A_{FB}^{bb}, A_{FB}^{cc} provide input to quark couplings together with Γ_b, Γ_c

NOTE that LEP approach was different: all asymmetries were limited by statistics and primarily used to measure $\sin^2\theta_{eff}$

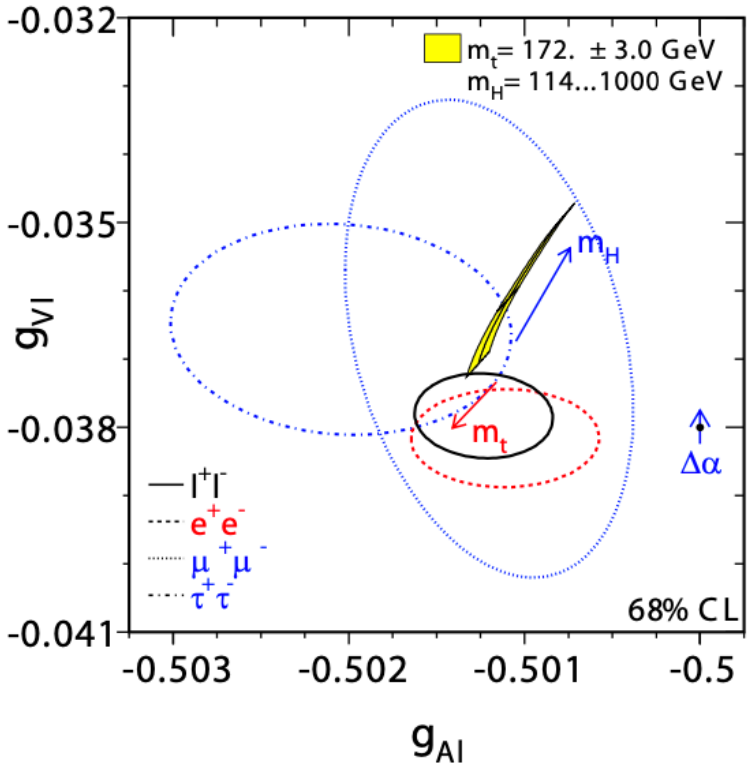
Improvements 1 – 2 orders of magnitudes with respect to LEP, depending on the fermion (even more for the s quark coupling !)



Extraction of the neutral couplings (1)

The couplings of the neutral current to fermions can be determined using three ingredients:

- the Z partial widths,
- the A_f fermion chiral parameters as determined by the forward-backward asymmetries and tau polarization,
- the energy dependence of the forward-backward asymmetries.

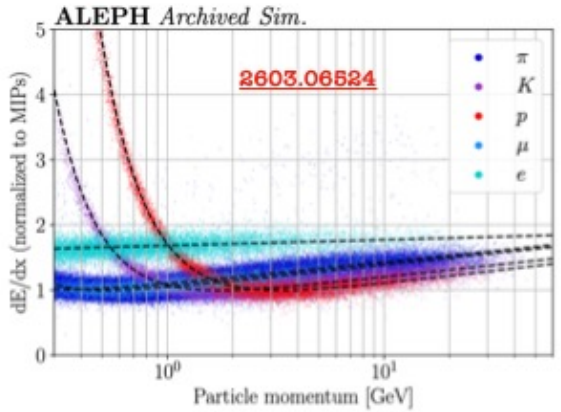


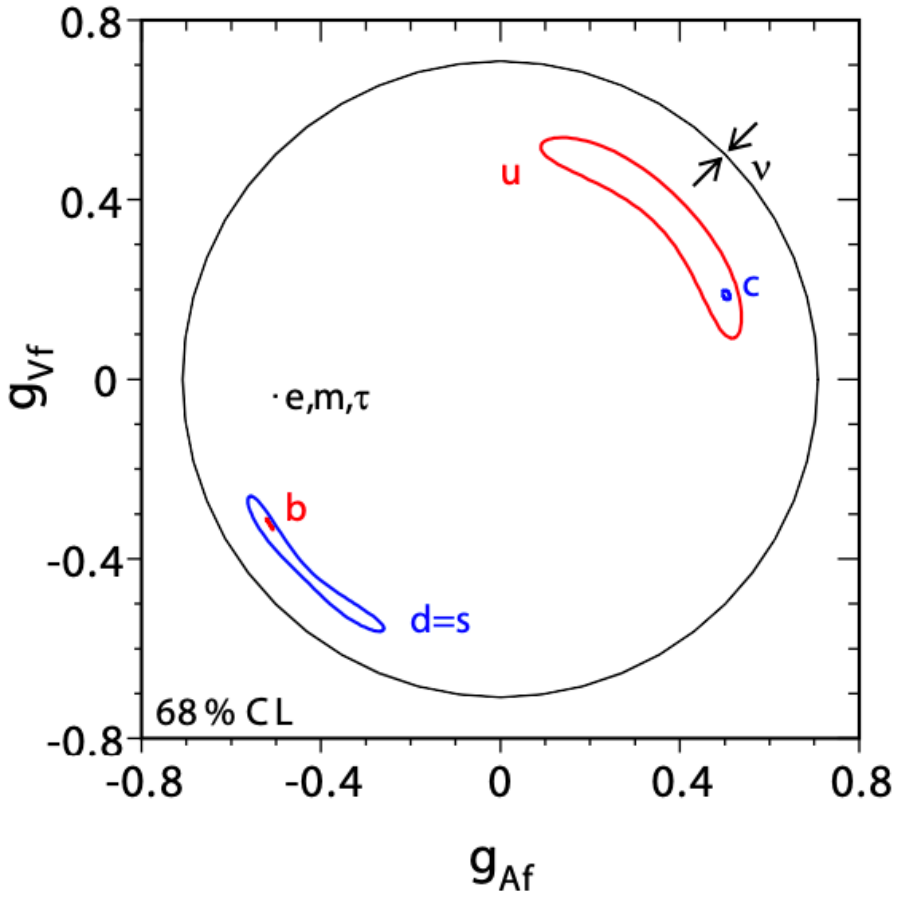
Extraction of the neutral couplings (2)

The precision of couplings in the quark sector obtained at LEP is considerably lower than in the lepton sector, here FCC-ee can make a big difference

Z->qq at LEP and FCC-ee

- **Archived ALEPH data** converted to edm4hep
- **Modern jet flavour tagging techniques** significantly improve heavy flavour jet identification
- First dedicated s-flavour tagger!

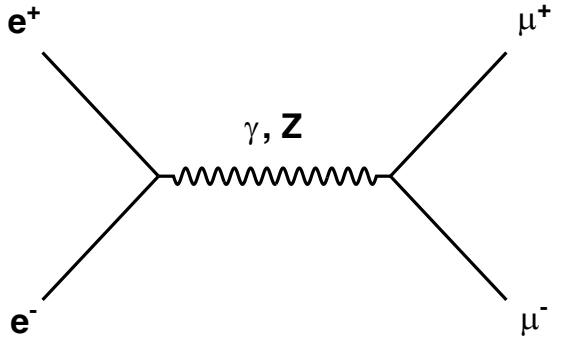




e.m. coupling: direct measurement of $\alpha_{QED}(m_Z^2)$

At LEP hadronic contributions to the vacuum polarization as external input (dispersion relations+ lower energy experiments) $\Delta_{rel} \approx 10^{-4}$

FCC-ee: direct measurement with better precision



Patrick Janot: JHEP 02 (2016) 53

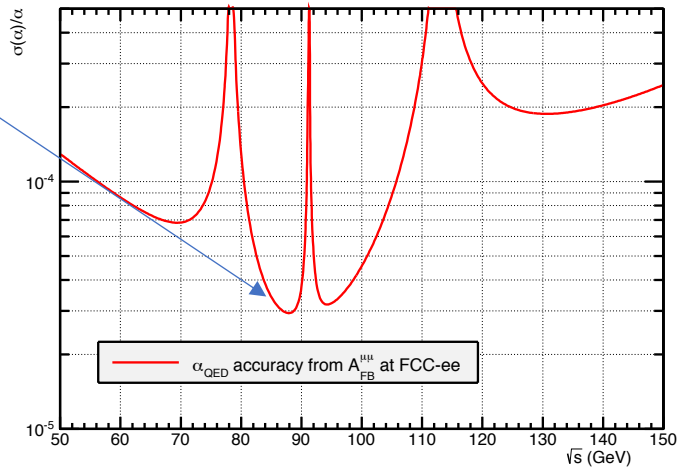
also complementary method comparing differential distributions of electron, muons and positrons in forward region, M. Riembau arXiv:2501.05508

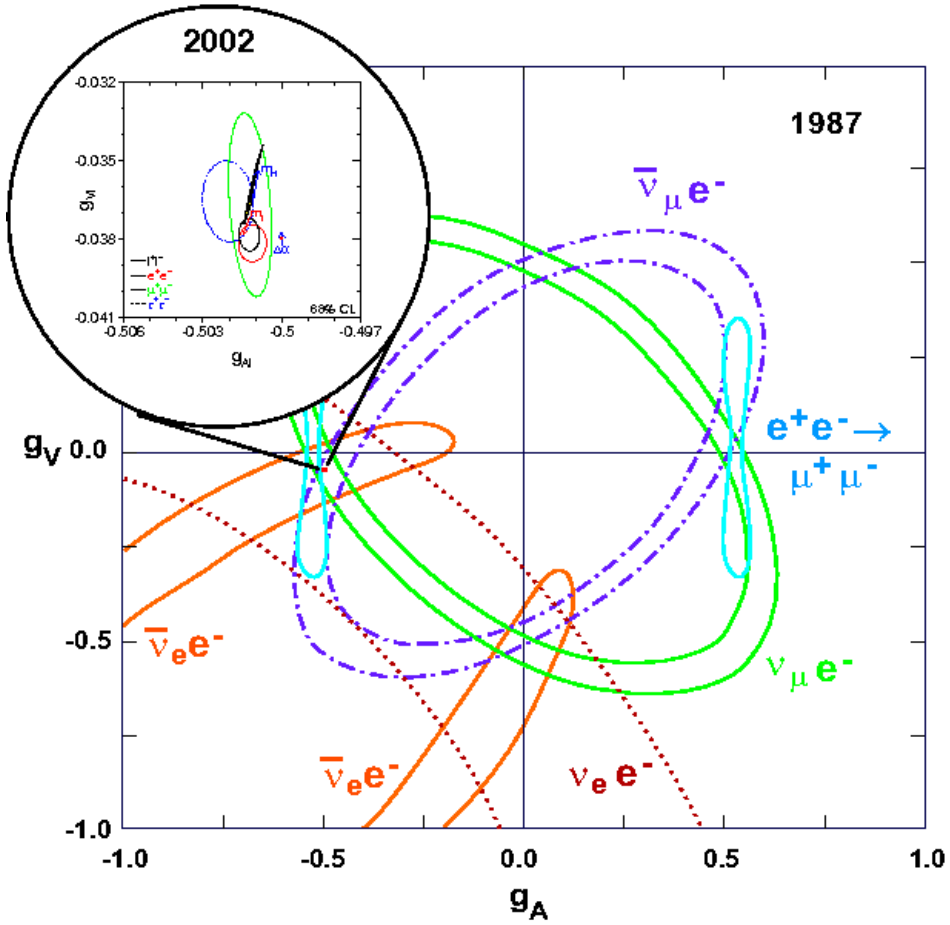
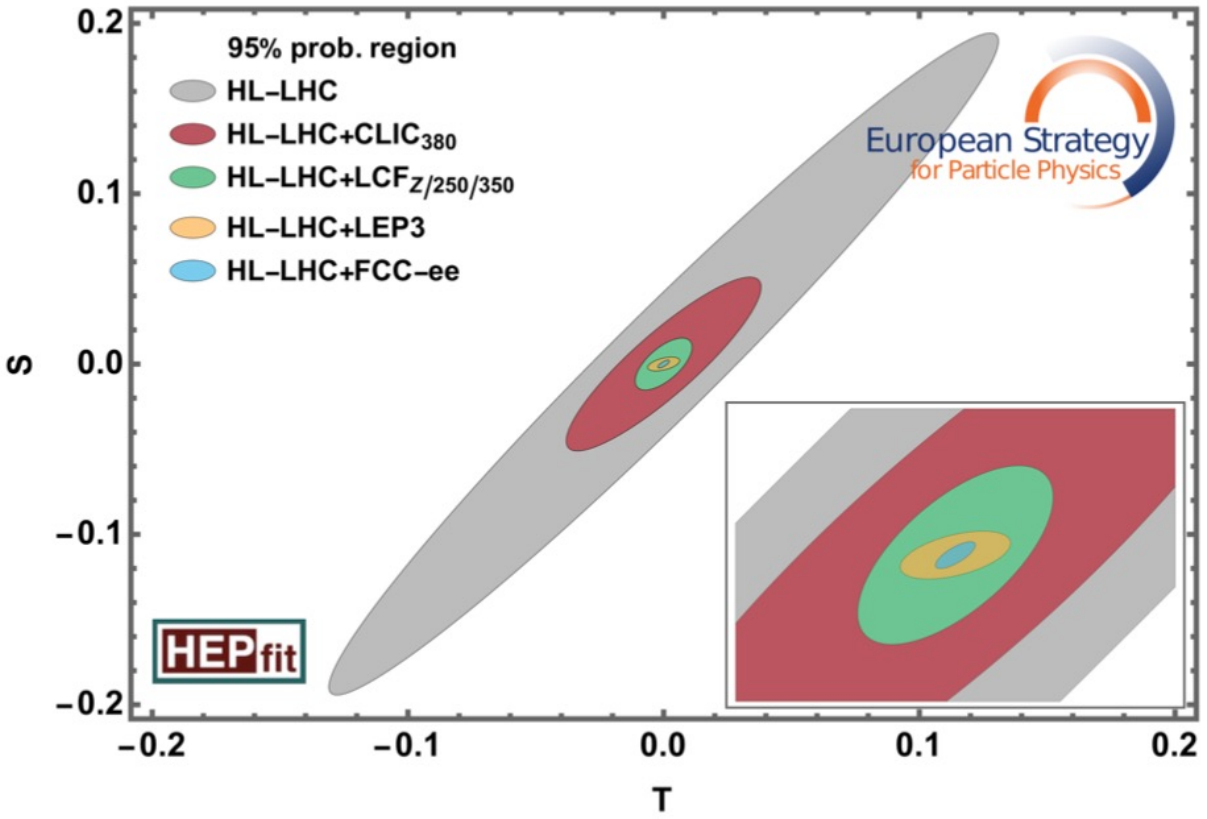
$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu+} - N_B^{\mu+}}{N_F^{\mu+} + N_B^{\mu+}} \approx f(\sin^2\vartheta_W^{eff}) + \alpha_{QED}(s)\frac{s - m_Z^2}{2s} g(\sin^2\vartheta_W^{eff})$$

Optimal centre-of-mass energies for a 3×10^{-5} uncertainty on α_{QED} : $\sqrt{s}_- =$ **87.9 GeV** and $\sqrt{s}_+ =$ **94.3 GeV**

Type	Source	Uncertainty
Experimental	E_{beam} calibration	1×10^{-5}
	E_{beam} spread	$< 10^{-7}$
	Acceptance and efficiency	negl.
	Charge inversion	negl.
	Backgrounds	negl.
Parametric	m_Z and Γ_Z	1×10^{-6}
	$\sin^2\theta_W$	5×10^{-6}
	G_F	5×10^{-7}
Theoretical	QED (ISR, FSR)	$< 10^{-6}$
	Missing EW higher orders, QED(IFI)	few 10^{-4}
	New physics in the running	0.0
Total (except missing EW higher orders)	Systematics	1.2×10^{-5}
	Statistics	3×10^{-5}

Work on EWK theoretical corrections required to reach ≈ 3 10^{-5}



σ(α)/α plot, for a year of running at any √s

Final propitiatory page for next leap in EWPO precision