11th FCC-ee Workshop

9th January 2019

Detector session

Physics requirements: Z and WW electroweak

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Operation model assumed for CDR

- 150 ab^{-1} around the Z pole,
  - 25 ab^{-1} off peak (≈ 88 and 94 GeV), 100 ab^{-1} at peak (≈ 91 GeV)
- 10 ab^{-1} around the WW threshold
  - (161 GeV with ±few GeV scan)

LEP (4 IPs)
0.6 fb^{-1}
2.4 fb^{-1}

→ precision typically driven by systematics: detector plays a role !

working point	luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	total luminosity (2 IPs)/ yr	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	**150 ab^{-1}**	**4**
Z later	200	52 ab^{-1}/year		
W	32	8.3 ab^{-1}/year	**10 ab^{-1}**	**1**
H	7.0	1.8 ab^{-1}/year	**5 ab^{-1}**	**3**
top (350 GeV)	0.8	0.2 ab^{-1}/year	**0.2 ab^{-1}**	**1**
top later (365 GeV)	1.5	0.38 ab^{-1}/year	**1.5 ab^{-1}**	**4**

These are important, too, for WW physics !

EW Physics observables at TeraZ
(5×10^{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, $\alpha_{QED}(m_Z^2)$)
- R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$ (quark couplings)

EW Physics observables at OkuWW
(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)
- direct CKM measurements (with jet-flavor tagging)
- Triple and Quartic Gauge couplings (jump in precision, especially for charged couplings)

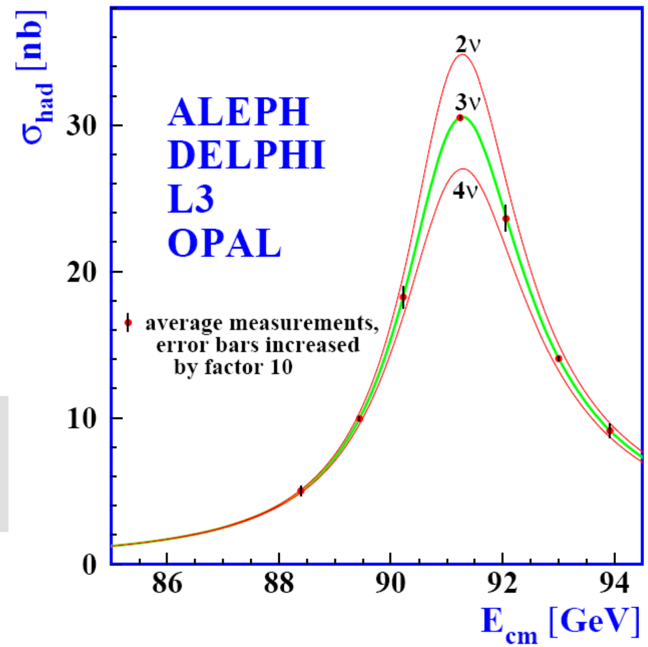
Determination of Z mass and width

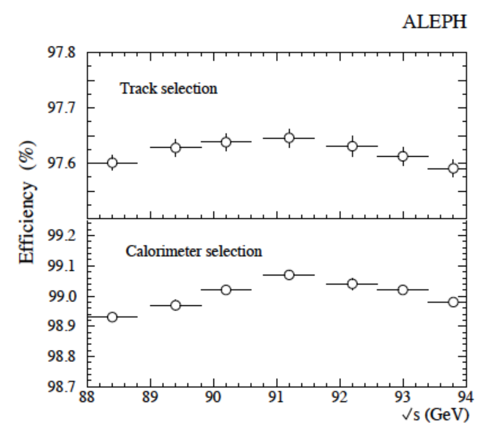
- uncertainty on m_Z (≈ 100 KeV) is dominated by the correlated uncertainty on the centre-of-mass energy at the two off peak points

at FCC-ee continuous E_{CM} calibration (resonant depolarization) gives $\Delta E_{CM} \approx$ 10 KeV (stat) + 100 KeV (syst)

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

Requirements on the detector are not crucial for these two measurements, but should not be forgotten either: excellent control of acceptance over sqrt(s) is important. For a detector and simulations a la LEP the impact was O(100 KeV).





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 $\mu^+\mu^-$

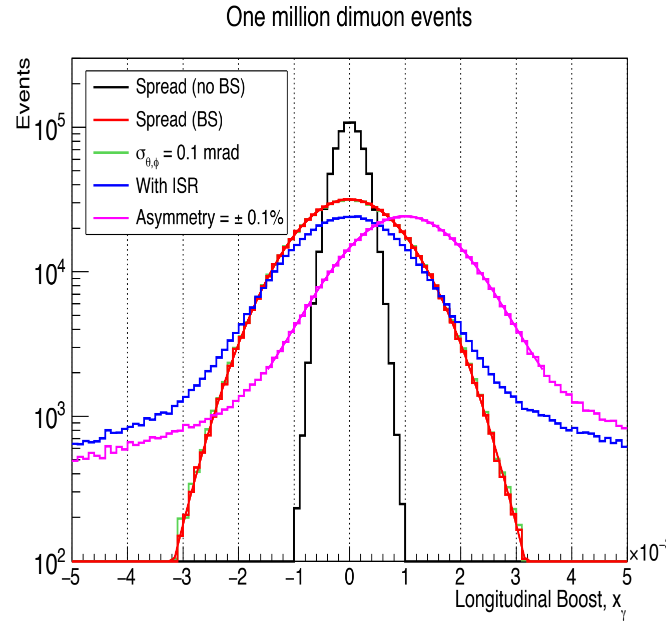
Patrick Janot

- 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

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 luminosity and σ_{had}

- Goal on theoretical uncertainty (*) from higher order for low angle Bhabha is 0.01%, corresponding to a reduction of a factor 8 in uncertainty on number of light neutrino families
- To match this goal an accuracy on detector construction and boundaries of ≈ 2 μm is required
  - clever acceptance algorithms, a la LEP, with independence on beam spot position should be extended to beam with crossing angle
- Can potentially reach an uncertainty of 0.01% also with e+e-$\rightarrow\gamma\gamma$, statistically 1.4 ab^{-1} are required.

(*) arXiv:1812.01004

Strategy for asymmetries, couplings and $\sin^2\theta_{eff}$

- Muon forward backward asymmetry at pole, $A_{FB}^{\mu\mu}$ (m_Z) gives $\sin^2\theta_{eff}$ with 5 10^{-6} precision (at least)
  - uncertainty driven by knowledge on CM energy (or rather the point to point energy errors as Alain has recently observed *)
  - 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 R_e, R_μ, R_τ)
- Quark couplings A_{FB}^{bb}, A_{FB}^{cc} provide input to quark couplings together with R_b, R_c

Asymmetries are robust measurements, independent from acceptance provided that the apparatus is forwrd-bckwrd OR charge id symmetric

(*) https://indico.cern.ch/event/779055/contributions/3241604/attachments/1769124/2873729/point-to-point-errors.pdf

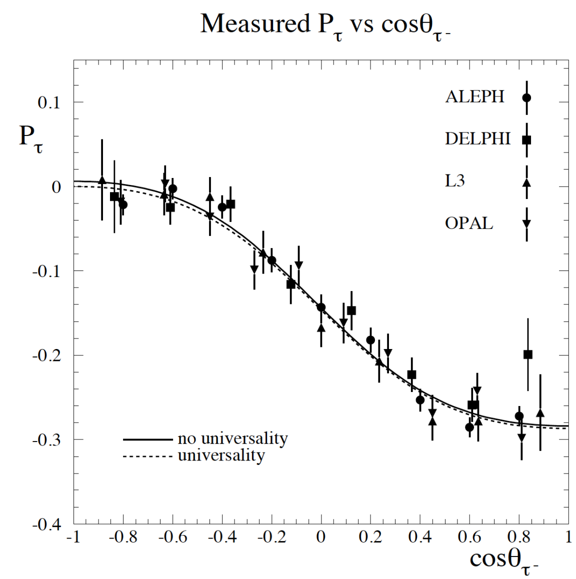
tau polarization

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

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

- Separate measurements of A_e and A_τ from

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



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 accurate reconstruction of π^0 energy and direction is very relevant**

→**measure $\sin^2\theta_{eff}$ with 6.6 10^{-6} precision**

A_{FB}^{bb} : from LEP to TLEP (FCC-ee)

LEP combination dominated by statistics, projection on FCC-ee consider conservative reduction of various uncertainty components

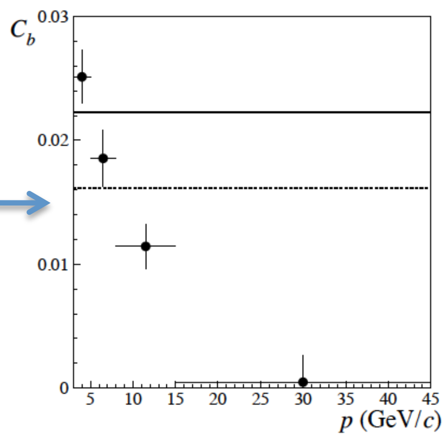
	ΔAFB(b)
STATISTICS	0.00156
UNCORRELATED SYSTEMATIC	0.00061
QCD CORRECTION	0.00030
LIGHT QUARK FRAGMENTATION	0.00013
SEMILEPTONIC DECAYS MODELLING	0.00013
CHARM FRAGMENTATION	0.00006
BOTTOM FRAGMENTATION	0.00003
TOTAL SYSTEMATIC ERROR	0.00073

0.00002

Most of this depends on stat.

Can be reduced with improved calculations and proper choices of analysis methods (e.g. measure the asymmetry as a function of jet parameters, etc.

Simple method to reduce QCD corrections for lepton analysis: raise cut un lepton momentum, as statistics is no longer dominant



Improved measurements also for the charm sector: A_{FB}^{cc}

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, which can be suppressed by keeping b-tag efficiency flat in momentum)

FCC-ee projections conservatively consider reduction of uncertainty on hemisphere correlations from ≈0.1% (LEP) to ≈0.03%

W mass and width from WW cross section

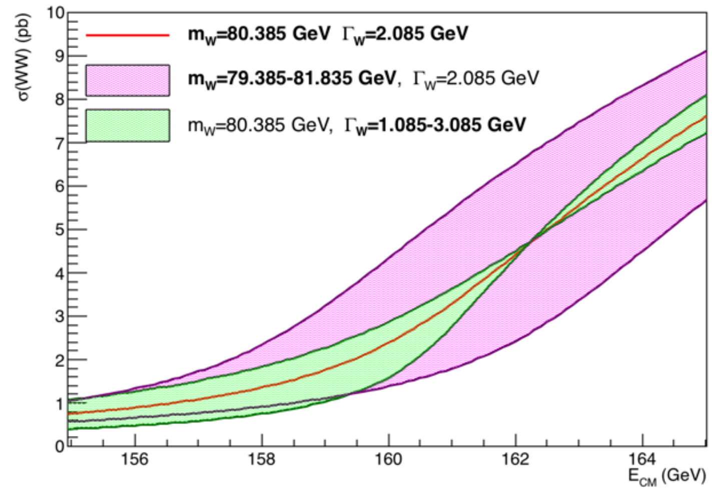
Sensitivity to mass and width is different at different E_{CM}: can optimize mass AND width by choosing carefully two energy points.

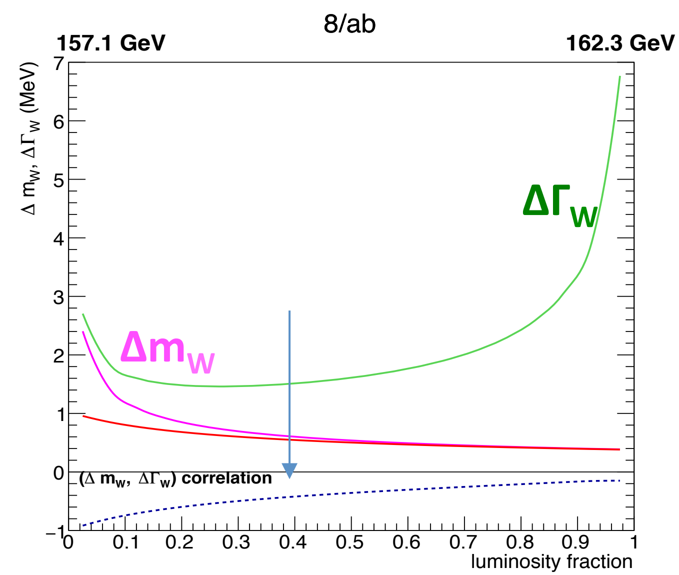
- Same concept can be used to minimize systematics (e.g. due to backgrounds)
- Centre-of-mass known by resonant depolarization (available at ≈ 160 GeV)
- Luminosity from Bhabha, requirements similar to Z pole case

need syst control on :

- **ΔE(beam)<0.35 MeV (4×10^{-6})**
- **$\Delta\varepsilon/\varepsilon$, $\Delta L/L < 2\ 10^{-4}$**
- **$\Delta\sigma_B$<0.7 fb ($2\ 10^{-3}$)**

Paolo Azzurri





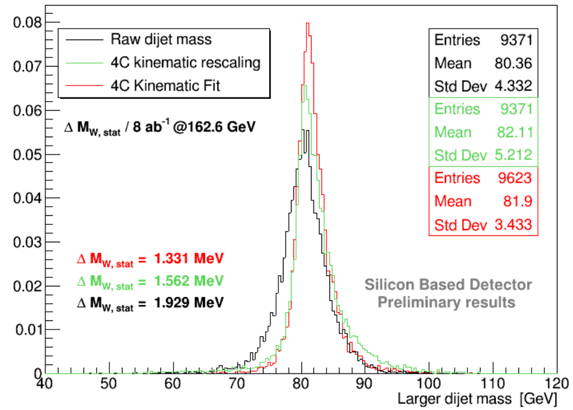
with E_1=157.1 GeV E_2=162.3
Δm_W=0.62 $\Delta\Gamma_W$=1.5 (MeV)

W mass from di-jet invariant mass

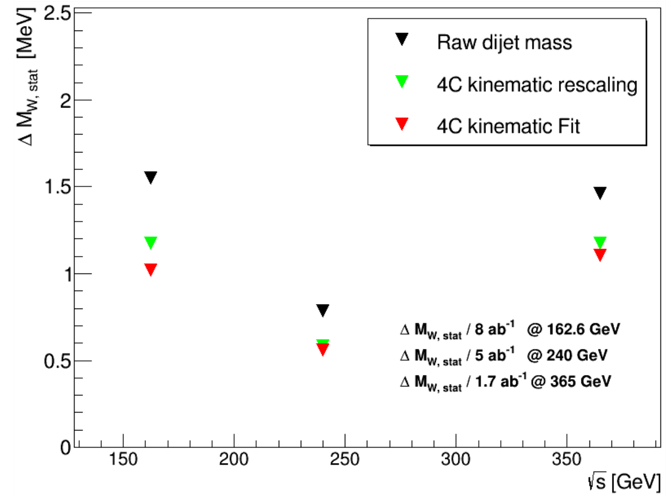
Marina Béguin, P. Azzurri, E. Locci

- Expected Statistical uncertainty at the ≈ 1 MeV level
- Statistics will help in reducing LEP systematics (e.g. fragmentation, jet mass)
- Interplay between E_{beam} and m_W with the kin fit.
- Need to make use similar of Zγ & ZZ events to control E_{beam} at E_{CM}>200 GeV (no resonant dep)
- Ultimate aim to fit simultaneously WW, ZZ and Zγ to extract a m_W/m_Z ratio with potential large cancellations of systematic uncertainties.

Larger dijet mass



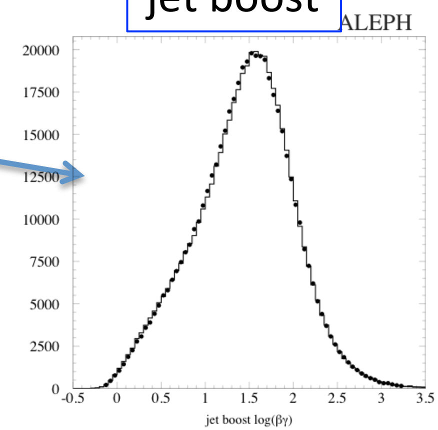
Best result likely to be be provided by the lvqq channel, 4q channel will provide information on mass and color reconnection



Statistical uncertainties with various kinematic fit option, as a function of the centre-of-mass

jet reconstruction and W physics

jet boost



Performant jet reconstruction (particle flow) required to control boost and direction bias

Jet reconstruction important not only for W mass, but also for measurement of TGC's

difference in jet direction from different jet components

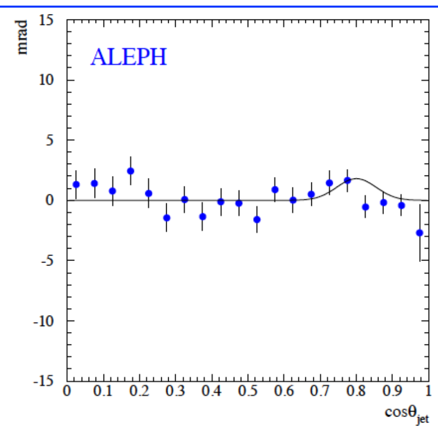
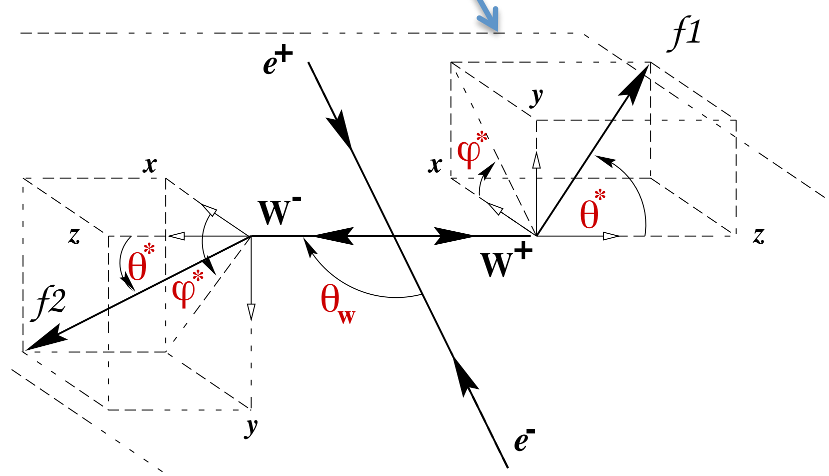
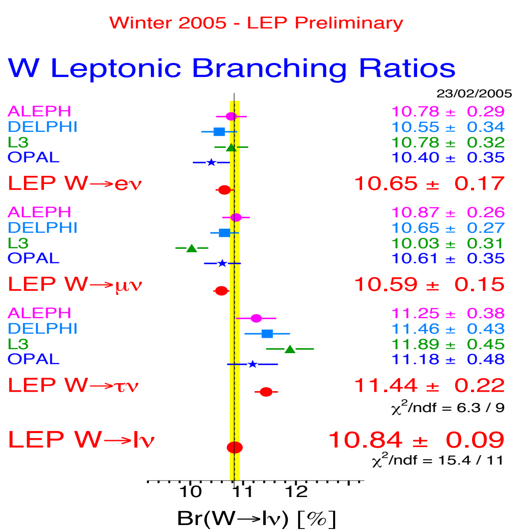
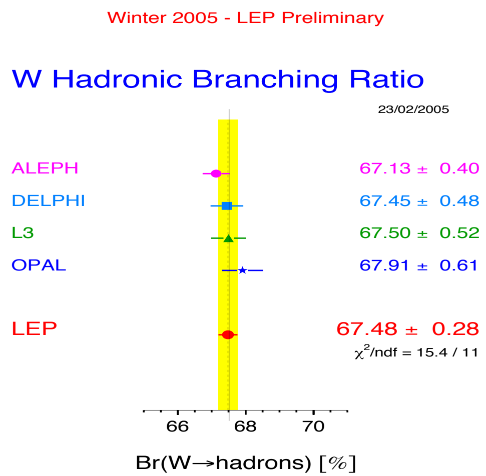


Figure 4: The mean difference, Data – MC, of $\theta_{\mathrm{hadrons}} - \theta_{\mathrm{photons}}$ as a function of $\cos\theta_{\mathrm{jet}}$ for 45 GeV jets collected in calibration runs at the Z. The continuous curve is not a fit to the plotted values, but represents a function which fits well the higher statistics Z data from 1994. $\theta_{\mathrm{hadrons}}$ and $\theta_{\mathrm{photons}}$ are the polar directions of the hadronic and photonic components of a jet.



W decay Branching Fractions





8/ab@160GeV + 5/ab@240GeV
➔ 30M+ 80M W-pairs

➔ ΔBR(qq) (stat) =[1] 10^{-4} (rel)
➔ $\Delta\alpha_S \approx (9\,\pi/2)\Delta BR \approx 2\ 10^{-4}$

➔ ΔBR(e/μ/τν)(stat)=[4]10^{-4} (rel)

lepton universality test at 2% level
tau BR 2.7 σ larger than e/μ
➔ **FCCee @ 4 10^{-4} level**

quark/lepton universality at 0.6%
➔ **FCCee @ 10^{-4} level**

Flavor tagging →W coupling to c & b-quarks (V_{cs}, V_{cb} CKM elements)

requires excellent control of lepton id
i.e. cross contaminations in signal channels
(e.g., τ→e,μ versus e,μ channels)

Paolo Azzurri

Conclusions (1)

- Specific points deserving particular attention in the design of the detector (EWK physics):
  - acceptance effects, e.g. related to the knowledge of large-detector boundaries and of tracking efficiency should be given special attention: the required level of accuracy is typically one order of magnitude better than for LEP detectors; in addition acceptance of low momentum/ energy objects must be kept as high as possible
  - the tracker, with $\Delta p_T/p_T^2 \approx 10^{-4}(\text{GeV}^{-1})$, and angular resolution ≈ 0.1 rad for muons, must be as light as possible.

Conclusions (2)

– efficient detection of photons and excellent measurement of their energy (e.g. tau polarization), important detection of low energy photons (e.g. $\mu\mu\gamma$)

– the hadron calorimeter should allow an efficient use of particle flow reconstruction

– identification of secondary verteces (measurement of quark couplings). A performance (identification efficiency vs background rejection) similar and better than modern LHC detectors should be the target (a factor 3 better than LEP detectors).