FCC-ee: high precision measurements

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(Table updates: J.A. + A. Blondel + P. Janot + R. Tenchini)

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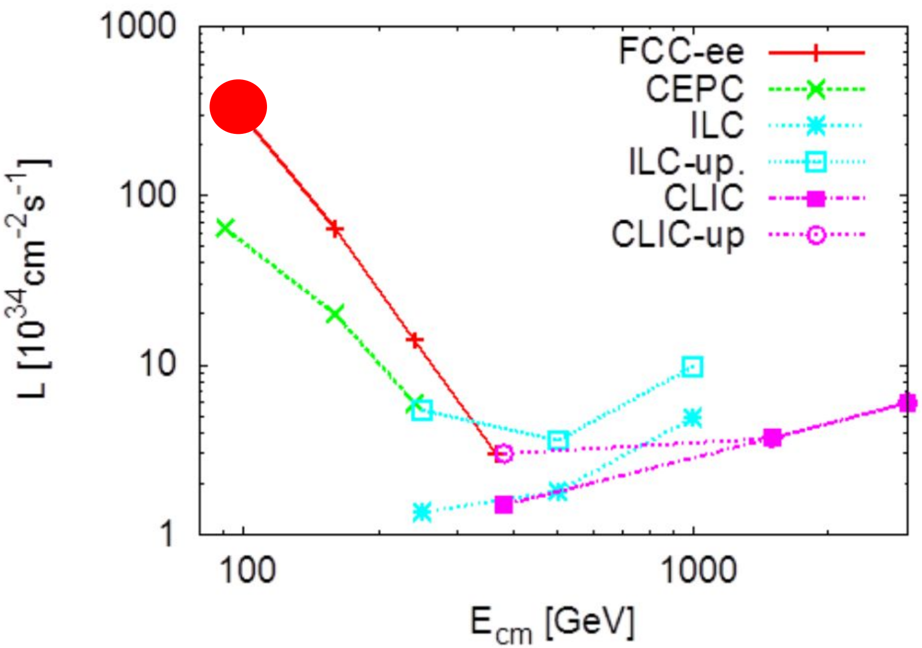
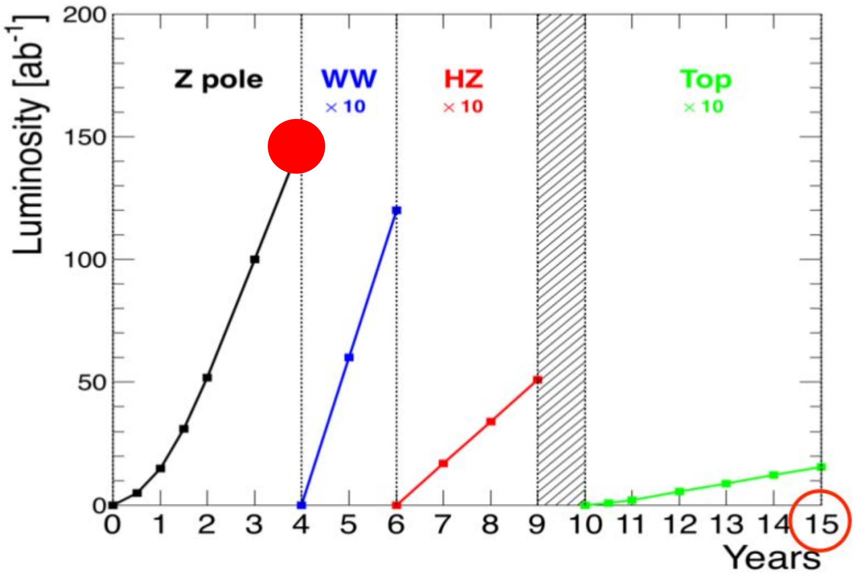
FCC-ee context

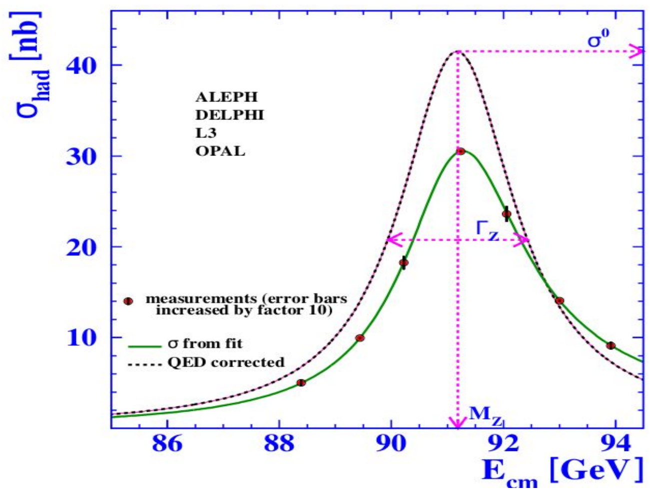


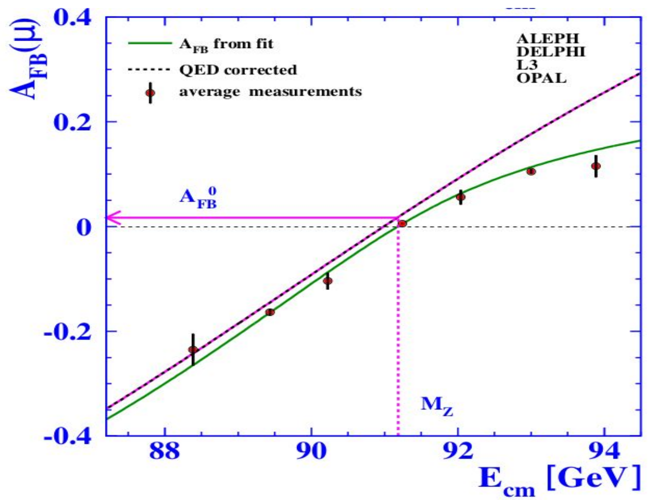


- Key point 1: huge statistics → 150 ab^{-1}, 5 x 10^{12} Z decays in ≈ 4 years of running at / around the Z pole, ≈10^3 reduction in statistical uncertainties w.r.t. LEP
- Key point 2: extraordinary √s precision → 100 keV at the Z, 300 keV at WW threshold → exquisite control of beam uncertainties (average, width, systematics)
- Aiming for up to ≈ 20 to100 times better precision than LEP/SLD on electroweak precision observables (EWPO)

Uncertainties / challenges

[LEP1: hep-ex/0509008]





- **Expected precisions in a nutshell:**
  - **≈ 10^{-6} statistical uncertainties (≈ 1/ √N) on relative measurements**
    - forward-backward charge asymmetries, cross section ratios, …
  - **≈ 10^{-4} on cross sections from luminosity unc. (Bhabhas at very low angle)**
    - Tight requirements on positioning (≈ μm level), but feasible
    - possibility to still improve by up to one order of magnitude using σ (ee→$\gamma\gamma$) at larger angles (negligible hadr. corrections, studies ongoing)
  - **Uncertainties would be dominated by systematics with today's knowledge, but there will be new level arms for improvement:**
    - on theory side: availability of higher order corrections, new developments
    - on experimental side: larger "signal" and "control" samples at "Tera-Z":
      - alternative strategies, inclusive → exclusive, huge control samples in more specific kinematic regions, …, and better detectors

Precision aspects at FCC-ee

- **1: the statistical-only asymptotic limit:**
  - It sets our maximal sensitivity.
  - In many cases it will be close to the final total uncertainty, as experience has shown in the past (systematics follows statistics)
  - It is also sets the size of the challenge: how much we need to improve theory predictions, detectors and techniques ⇒ extremely useful to catalyze activities

- **2: estimating "realistic" systematic uncertainties (hard):**
  - According to current knowledge, largely based on LEP experience
  - Also driven by expected improvements on the theory side
  - Educated guess on reduction of experimental systematics due to improved detector, techniques and the availability of control samples ≈ 10^6 larger than those used at LEP

Precision targets

- **1) fundamental masses and couplings of the SM :**
  - M_Z, M_W, M_{top}, M_H, α_s, α_{QED} , … (note: they can be exchanged with other observables to improve the precision of calculations: $G_\mu \leftrightarrow m_W$, …)
  - Their precise knowledge is essential to be able to claim deviations from the SM when measuring other observables ⇒ **"parametric" uncertainties**
- **2) other precision measurements ("predictable/derived" from fundamental parameters within the SM):**
  - Total widths (Γ_Z, Γ_W, Γ_{top}, Γ_H), invisible/rare widths (N_ν), individual chiral couplings ($(g^f_L, g^f_R) \Leftrightarrow (g^f_V, g^f_A) \Leftrightarrow (\Gamma_f, \sin^2\theta_f)$), triple/quartic couplings, …
  - Sensitive to the presence of additional particles and/or interactions, flavour non-universal effects, … ⇒ **new physics**

FCC-ee tables

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	$0.2 - 1.0$	Ratio of hadrons to leptons; acceptance for letpons
$\alpha_s(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	$0.4 - 1.6$	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{\text{QED}}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{\text{pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_s(m_W)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W

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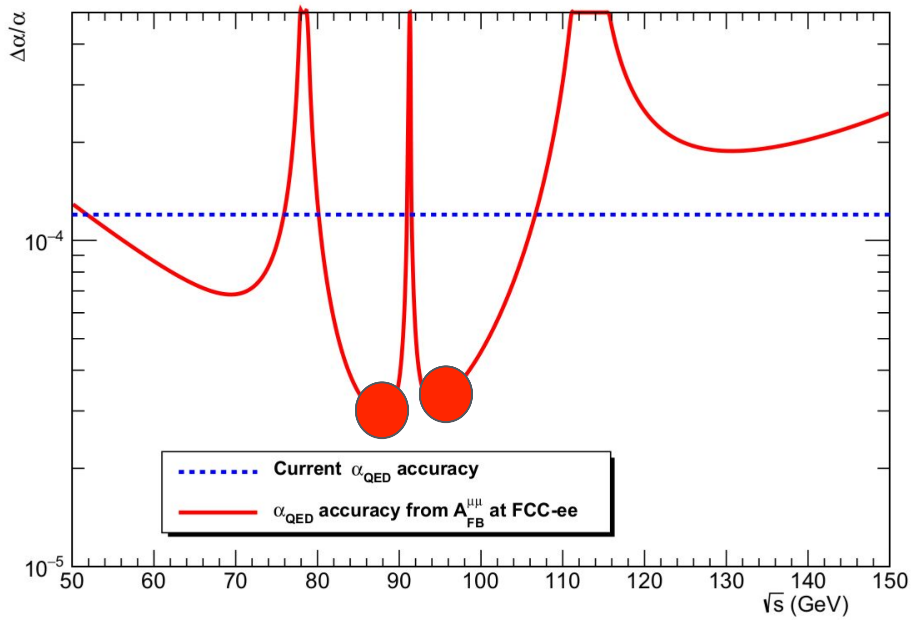
A few FCC-ee selected topics regarding precision

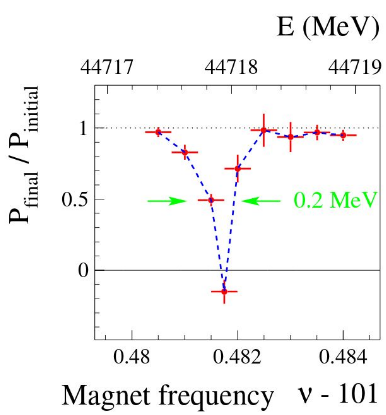
(some of them not really specific to FCC-ee)

(more observables/details in backup)

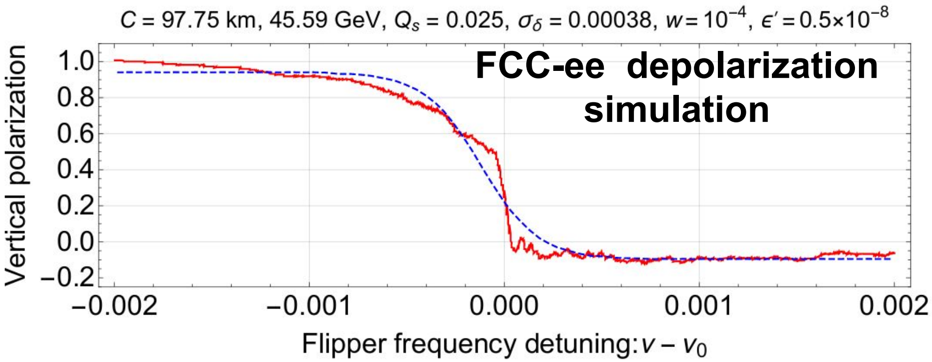
$\alpha_{QED}(m^2_Z)$: energy calibration



- $\alpha_{QED}(m^2_Z)$: off-peak/peak evolution of the asymmetry (due to interference with γ^* exchange)
- Precision determined by the ultimate statistical sensitivity: 3 x 10^{-6} (relative).
- Key experimental point: control of point-to-point energy uncertainties (≈ 1 x 10^{-6} contrib.)
- 3 energy points (≈87.7, 91.2, 93.9 GeV), corresponding to half integer spin tunes to ensure precise energy determination by resonant depolarization

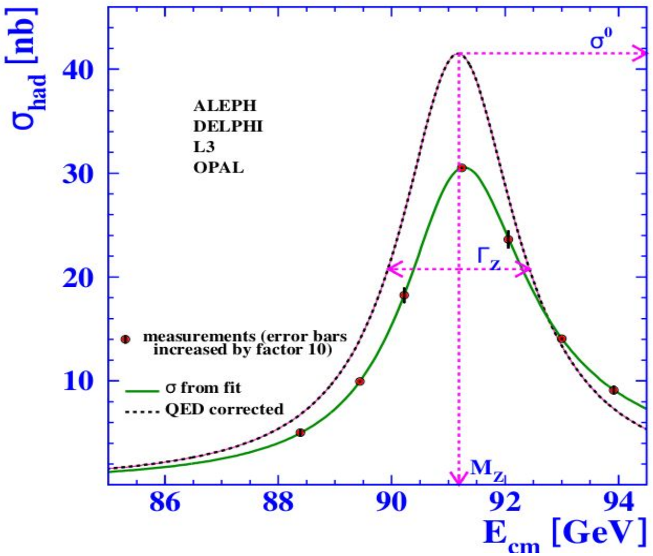


Resonant depolarization at LEP



arXiv:1909.12245

N_ν: σ^0_{had} and luminosity



- A precise measurement of N_ν / invisible width requires a measurement of cross sections at the peak ⇒ luminosity dependency ≈ 10 times improvement over LEP

$$R^0_\ell \equiv \Gamma_{had}/\Gamma_{\ell\ell}$$

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

$$R^0_{inv} = \left(\frac{12\pi R^0_\ell}{\sigma^0_{had} m^2_Z}\right)^{\frac{1}{2}} - R^0_\ell - (3 + \delta_\tau)$$

(Note: N_ν could be also measured precisely using radiative recoil ratios: $\sigma(\nu\nu\gamma)/\sigma(ll\gamma)$)

More on luminosity

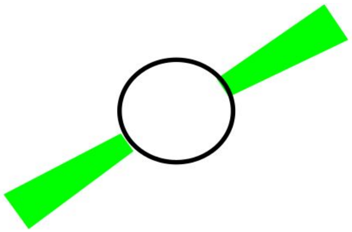
- Reference determination at ≈ 10^{-4} precision level measuring the low-angle Bhabha rate. Theoretically feasible, experimentally challenging (μm-level positioning of inner radius of luminometers)

- Alternative measurement / monitoring using large-angle ee->$\gamma\gamma$ events: potential to reach 10^{-5} at the theory level, no new physics disturbances at FCC-ee scales, enough statistics/year at Tera-Z; experimental studies in progress (CIEMAT TR 1499)

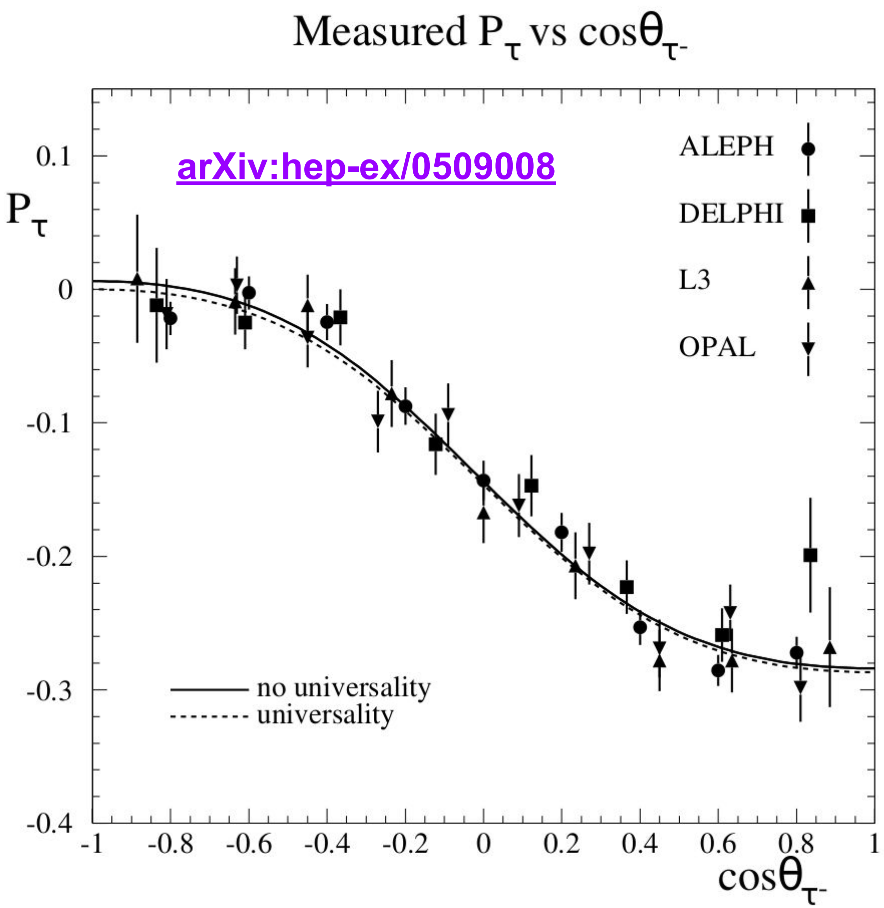
arXiv:1906.08056

$\sqrt{s}$ (GeV)	$\sigma^{\rm NNLO}_{\Delta\alpha\ \rm lep+top}/\sigma_{LO}$	$\sigma^{\rm NNLO}_{\Delta\alpha\ \rm had}/\sigma_{LO}$	$\delta\sigma_{\rm had}/\sigma_{LO}$
91	0.096%	0.085%	$3.7 \cdot 10^{-6}$
160	0.108%	0.098%	$3.8 \cdot 10^{-6}$
240	0.115%	0.108%	$3.9 \cdot 10^{-6}$
365	0.119%	0.120%	$4.0 \cdot 10^{-6}$

Table 3: Relative contribution of the NNLO leptonic(+top) and hadronic vacuum polarization correction to the cross section in setup [b] and for four FCC-ee c.m. energies. In the last column, the uncertainty due to the hadronic contribution is shown.



A FCC-ee specific feature

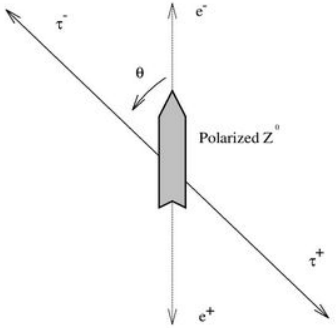


$$P(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

- **IMPORTANT: the FCC-ee baseline does not use longitudinal beam polarization:**
  - Although feasible, It would reduce too much the available luminosity
  - Not needed: tau polarization input is enough to measure A_e, thus facilitating precise measurements of the L-R asymmetry parameters for all fermions: $A_e, A_\mu, A_\tau, A_b, A_c$

$$A_{FB} = -\tfrac{3}{4}\,\mathcal{P}_Z A_f$$

- **$\mathcal{P}_Z = - A_e$ = Z polarization**

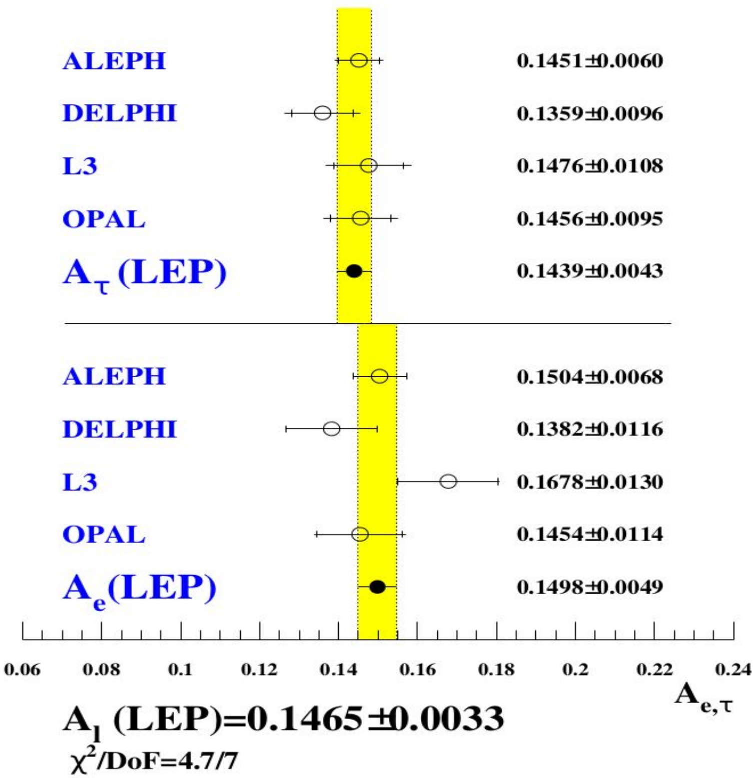


- **FB tau polarization asymmetry:**

$$\mathcal{P}_\tau^{FB} = -\tfrac{3}{4}\,\mathcal{A}_e$$

A_e is a safe measurement...

Experiment	$\mathcal{A}_\tau$	$\mathcal{A}_e$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$	$0.1504 \pm 0.0068 \pm 0.0008$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$	$0.1382 \pm 0.0116 \pm 0.0005$
L3	$0.1476 \pm 0.0088 \pm 0.0062$	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$	$0.1454 \pm 0.0108 \pm 0.0036$
LEP	$0.1439 \pm 0.0035 \pm 0.0026$	$0.1498 \pm 0.0048 \pm 0.0009$



- The FB tau polarization asymmetry (=$\mathcal{A}_e$) is NOT affected by uncertainties on the knowledge of polarization distributions / migrations (unless they are both F-B asymmetric and charge dependent)
- Dominant systematic uncertainty should be non-tau backgrounds: assume an order of magnitude reduction w.r.t. LEP: huge control samples, reduction via cuts, ...

A_e measurement

From AFBpol(tau), roughly assuming one order of magnitude reduction w.r.t. LEP in the uncertainty from non-tau backgrounds (dominant systematic contribution, it will be estimated from huge data control samples at FCC-ee)

- **Statistical uncertainty = LEP uncertainty * 10^{-3}**
- **ΔA_e (stat.+syst.) = 2.1 x 10^{-5} (syst. dominated)**

Derived measurements: $\sin^2\theta_l$

			stat.	syst.
Δsin2Theta_lept		--	1.40E-06	1.40E-06

from AFB(mumu) alone. syst being improved. It assumes lepton universality. AFBpol(tau) provides a result with similar/competitive uncertainty

- **Here we obviously assume lepton universality:**
  - $\Delta\sin^2\theta_l \approx A_l/16\ \ \Delta A_{FB}(\mu\mu) / A_{FB}(\mu\mu)$

    $\Delta\sin^2\theta_l(\text{stat.+syst.}) \approx 2.0 \times 10^{-6}$

- **From $A_{FB,pol}(\tau\tau)$ (⇔ A_e independent measurement):**

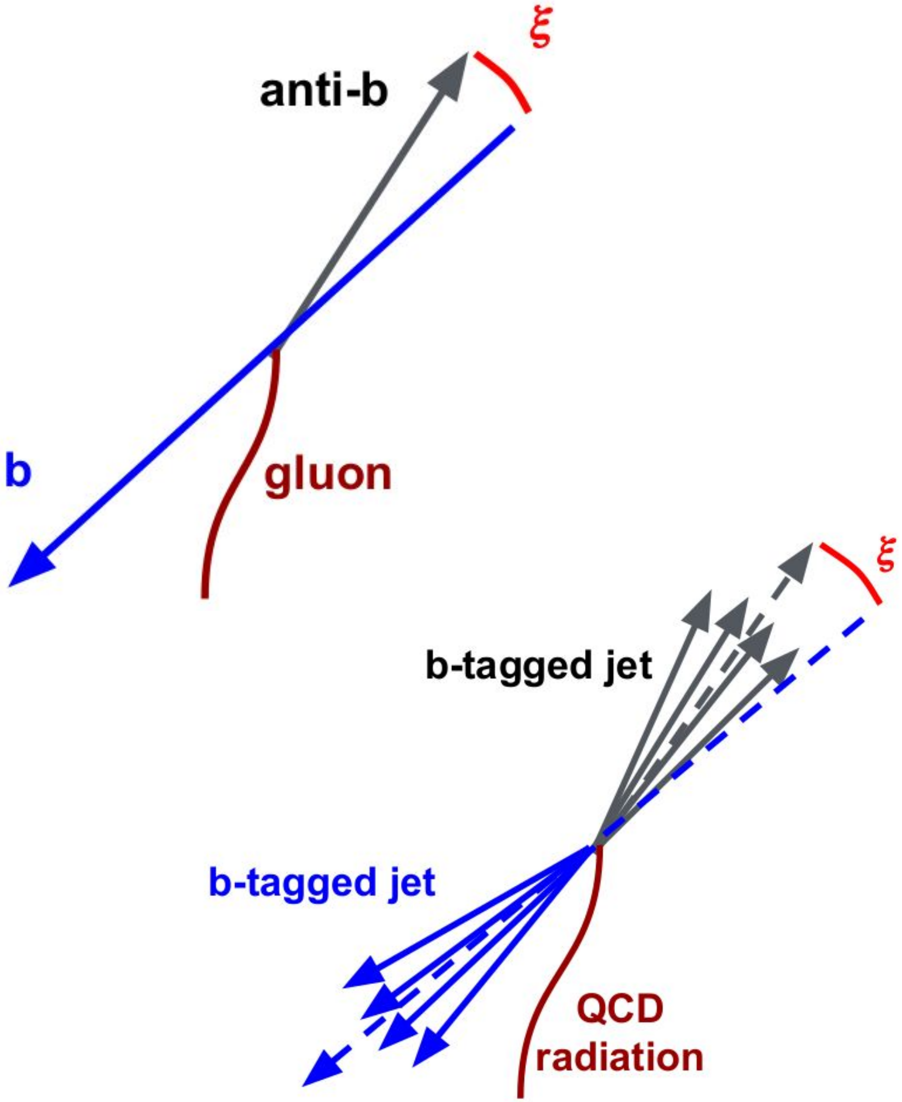
  $\Delta\sin^2\theta_l \approx 2.5 \times 10^{-6}$

Present status of A_{FB}(Q)

- QCD corrections are the dominant source of correlated systematics between measurements
- Measurement (LEPEWWG reference): 0.0992 ± 0.0015 (stat.) ± 0.0007 (syst.)
- 1/2 syst. uncertainty using today's knowledge on modelling (MC tunes) (arxXiv:2011.00530)

Source	R_b^0 $[10^{-3}]$	R_c^0 $[10^{-3}]$	$A_{FB}^{0,b}$ $[10^{-3}]$	$A_{FB}^{0,c}$ $[10^{-3}]$	$\mathcal{A}_b$ $[10^{-2}]$	$\mathcal{A}_c$ $[10^{-2}]$
statistics	0.44	2.4	1.5	3.0	1.5	2.2
internal systematics	0.28	1.2	0.6	1.4	1.2	1.5
QCD effects	0.18	0	0.4	0.1	0.3	0.2
$B(D \to \text{neut.})$	0.14	0.3	0	0	0	0
D decay multiplicity	0.13	0.6	0	0.2	0	0
B decay multiplicity	0.11	0.1	0	0.2	0	0
$B(D^+ \to K^-\pi^+\pi^+)$	0.09	0.2	0	0.1	0	0
$B(D_s \to \phi\pi^+)$	0.02	0.5	0	0.1	0	0
$B(\Lambda_c \to p K^-\pi^+)$	0.05	0.5	0	0.1	0	0
D lifetimes	0.07	0.6	0	0.2	0	0
B decays	0	0	0.1	0.4	0	0.1
decay models	0	0.1	0.1	0.5	0.1	0.1
non incl. mixing	0	0.1	0.1	0.4	0	0
gluon splitting	0.23	0.9	0.1	0.2	0.1	0.1
c fragmentation	0.11	0.3	0.1	0.1	0.1	0.1
light quarks	0.07	0.1	0	0	0	0
beam polarisation	0	0	0	0	0.5	0.3
total correlated	0.42	1.5	0.4	0.9	0.6	0.4
total error	0.66	3.0	1.6	3.5	2.0	2.7

$A_{FB}(b/c)$



arXiv:2010.08604

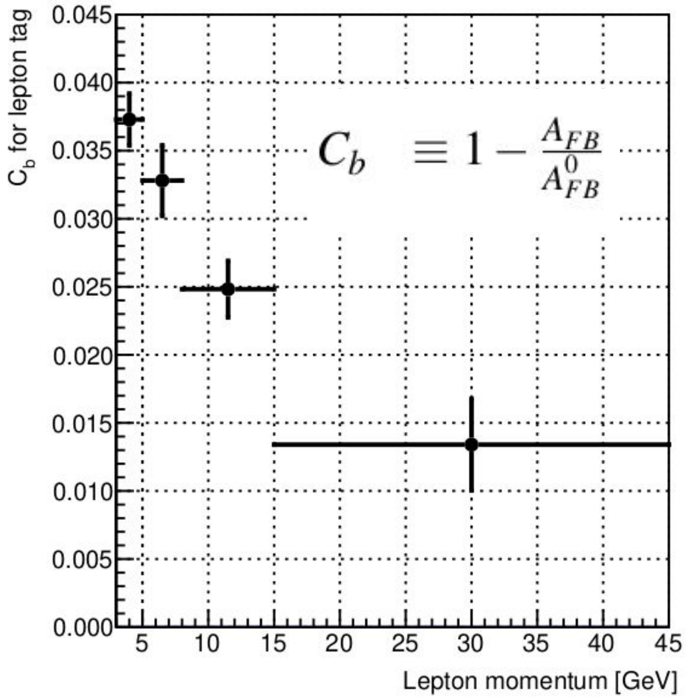
- **New developments for $A_{FB}(b/c)$: QCD corrections and uncertainties can be reduced significantly using acollinearity (ξ) cuts ⇒ important reduction in systematics, but how much ?**

- **Note that all these measurements can now be done with exclusive decays. A Tera-Z facility will provide ≈10^8 B^+ exclusive decays, for instance**

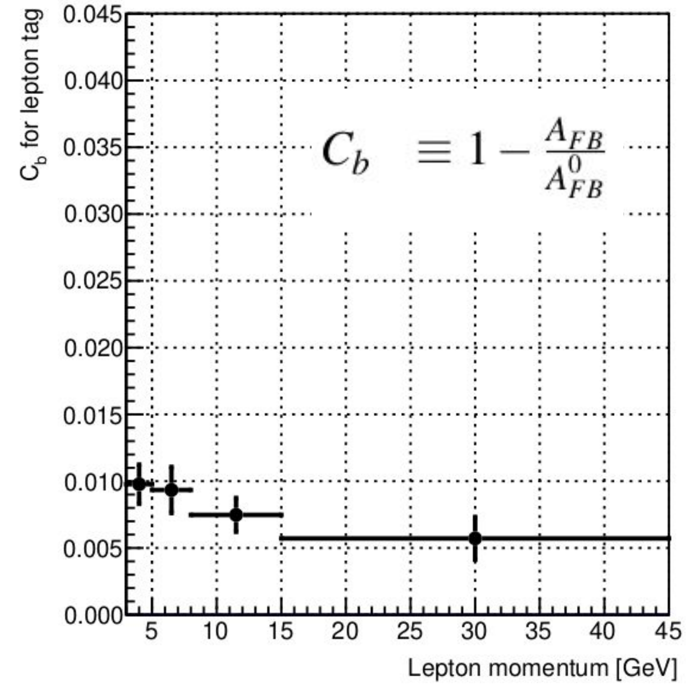
Semi-leptonic decays

- Evaluating the QCD corrections as a function of the momentum in semi-leptonic b decays, now with acollinearity cuts (generator level):

No acollinearity cuts



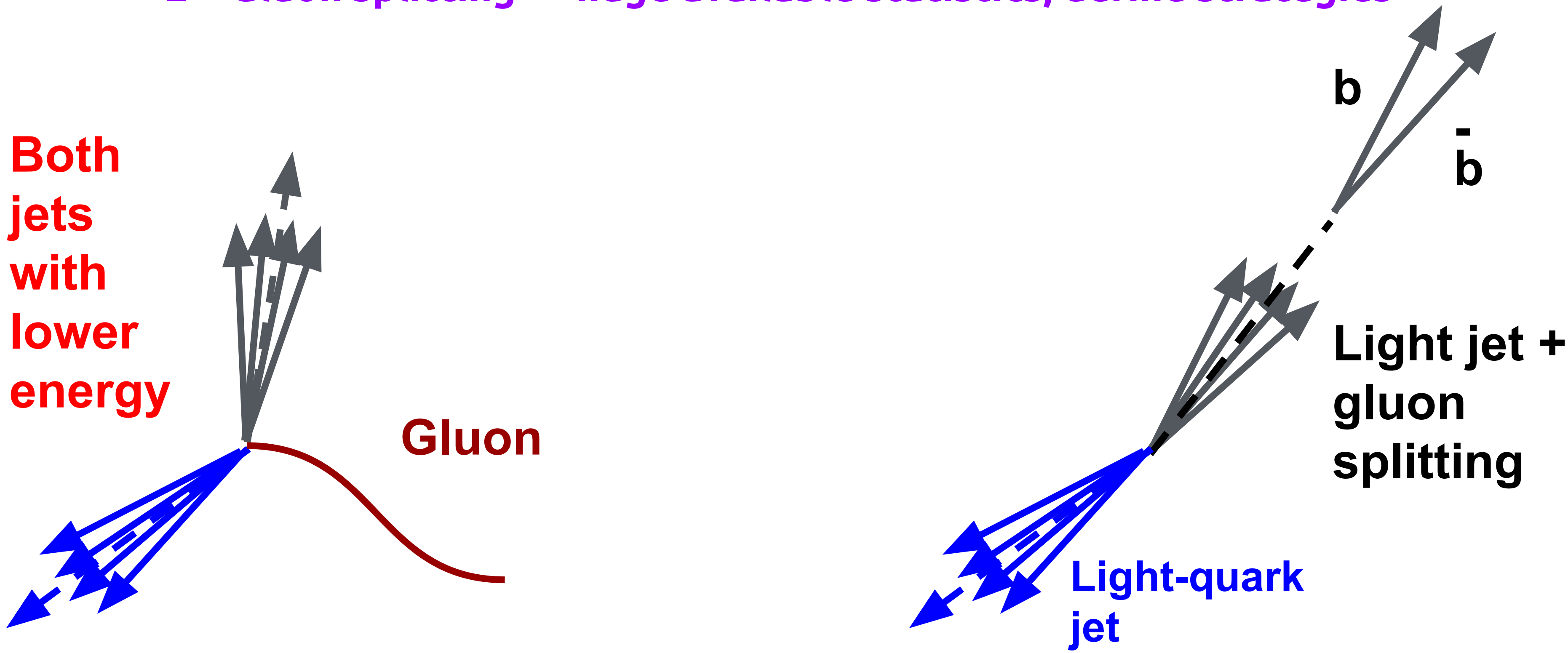
ξ<0.3



- Typical ≈5-10 reduction factor (leptonic/inclusive tagging)
- More realistic analyses still to be done

A_b, A_c, R_b, R_c: improvements w.r.t. LEP/SLC

- **Important elements of the study:**
  - **Improvement of the b (and c) purity → better detectors**
  - **Reduction of hemisphere correlations and syst. uncertainties:**
    - **Common vertex correlations (smaller in future detectors)**
    - **QCD effects (reduction with acollinearity cuts like in A_{FB}(Q) ?)**
    - **Gluon splitting → huge available statistics, define strategies**



A_b: current FCC-ee assumptions

Derived from AFB(b) and Ae=AFBpol(tau) measurements: AFB(b) =3/4*Ae*Ab; systematics assumed to be dominated by modelling/tune uncertainties (Delta(AFB(b))=1e-4); QCD correction uncertainties estimated to be reduced by at least a factor of 5 w.r.t. LEP to Delta(AFB(b))=8e-5; gluon-splitting, charm/light backgrounds assumed to lead to negligible contributions due to very high b-tagging purity and huge control samples at FCC-ee

- **ΔA_b (stat.+syst.) = 0.0013**

- **We want to stay conservative for the time being: not clear how much QCD correction uncertainties and QCD modelling can be reduced at the end of the day: $O(\alpha_s^2)$ calculations/estimates including acollinearity cuts welcome (not disturbed by large gluon-splitting effects)**

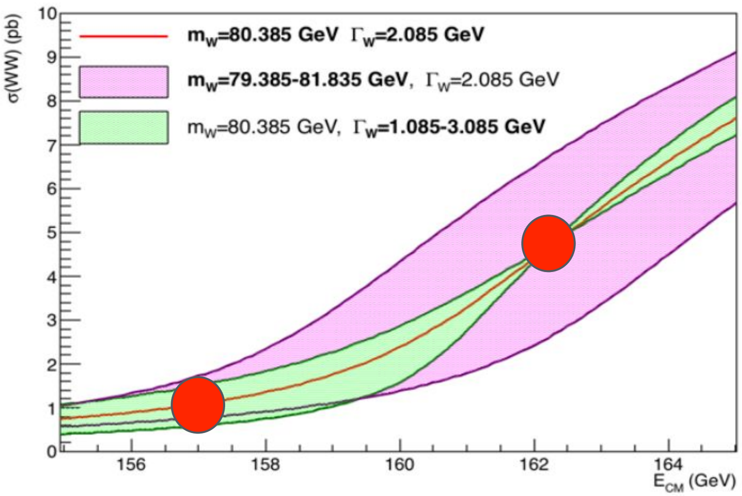
m_W, Γ_W

ΔmW (MeV)	0.4	0.25 (stat.)	0.3 (syst.)

From cross section scan at WW threshold. Precise control of beam energy uncertainties via resonant depolarization. To be revised with 4 experiments instead of 2. Theory improvements still to come.

ΔΓW (MeV)	1.2	1.2 (stat.)	0.3 (syst.)

From cross section scan at WW threshold (2 optimized points); potential improvement with direct reconstruction on the statistical side, but systematics (theo+exp) requires more studies



Outlook

- A few years of Tera-Z running should provide EWPO measurements with ≈20-100 times better than the current precision, thus giving early access to important/relevant/universal new physics effects at the deca-TeV scale

- Systematics will be the limiting factor in some of these measurements, and they are difficult to estimate ⇒ more detailed studies/work needed. Reducing associated uncertainties via:
  - theory developments
  - new analysis strategies, new control samples
  - optimized detector design

Backup

FCC-ee tables (prev., stat. ⊕ syst.)

Column with previous numbers (stat. + syst.)

		FCC errors (2 exp)		
		as of table	stat	current exp syst
Δα-1		0.00387	0.0038	0.0012
ΔmW (MeV)		0.4	0.25	0.3
ΔmZ (MeV)		0.1	0.004	0.1
ΔmH (MeV)		11	2.5	2
ΔΓW (MeV)		1.2	1.2	0.3
ΔΓZ (MeV)		0.025	0.004	0.025
ΔAe		0.000017	7.00E-06	2.00E-05
ΔAμ		0.000023	2.31E-05	2.20E-05
ΔAт		0.000045	5.00E-06	2.00E-04
ΔAт			1.00E-05	1.30E-04
Δsin2Theta_lept		--	1.40E-06	1.40E-06

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Our table (being updated)

Column with previous numbers (stat. + syst.)

ΔAb		0.0028	2.38E-05	1.29E-03
ΔAc		0.0053	2.00E-04	0.0053
Δσhad (nb)	35	3.5	0.000035	0.0049
δRe		0.0003	3.61E-06	0.00001
δRμ		0.00005	2.58E-06	0.00001
δRτ		0.0001	3.10E-06	0.00001
δRb		<0.0003	1.39E-06	<0.0003
δRc		0.0015	1.50E-04	<0.0015

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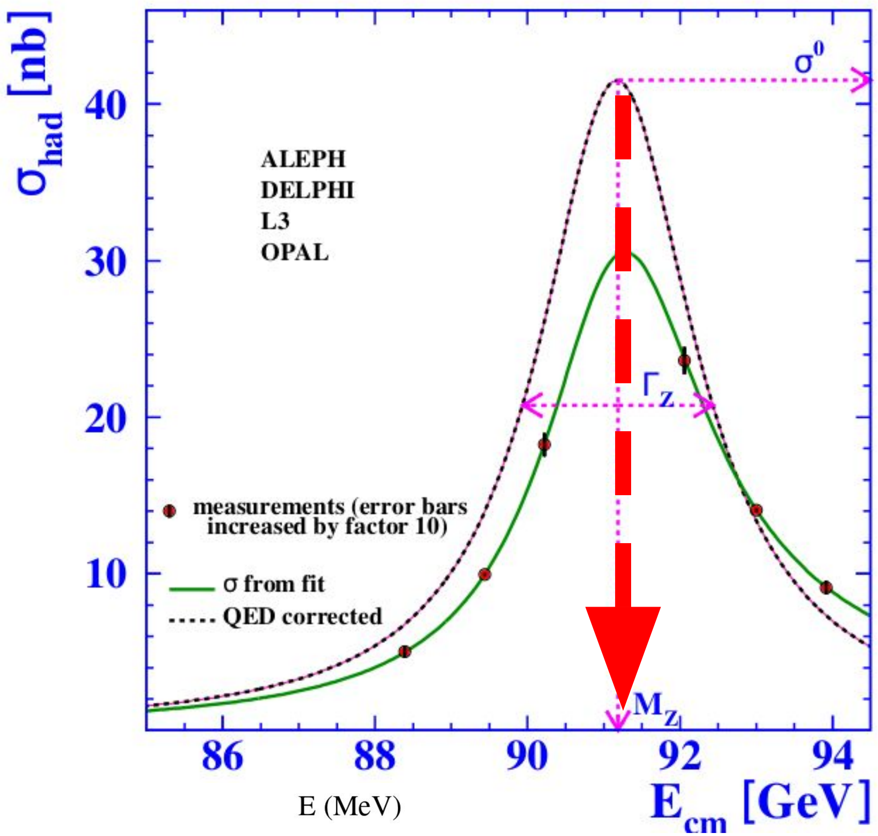
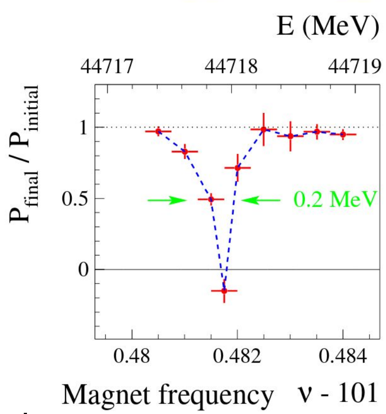
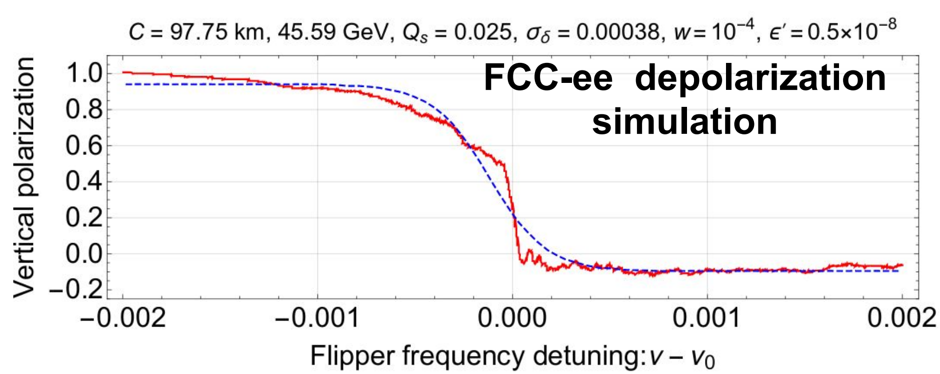
Z lineshape: mass



- m_Z: position of Z peak
- Beam energy measured with extraordinary precision (**Δ√s≈100 keV**) using resonant depolarization of transversely polarized beams (method already used at LEP, much better prepared now, calibrations in situ with pilot bunches, no energy extrapolations, …)
- Beam width/asymmetries studied analyzing the longitudinal boost distribution of the $\mu\mu$ system

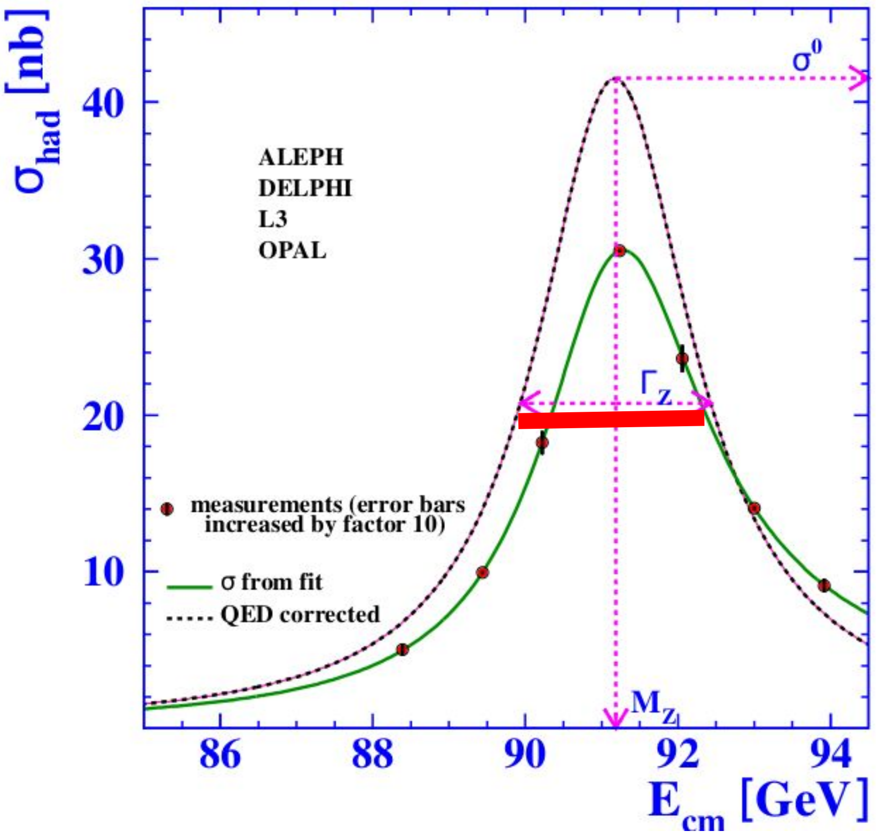


Resonant depolarization at LEP



arXiv:1909.12245

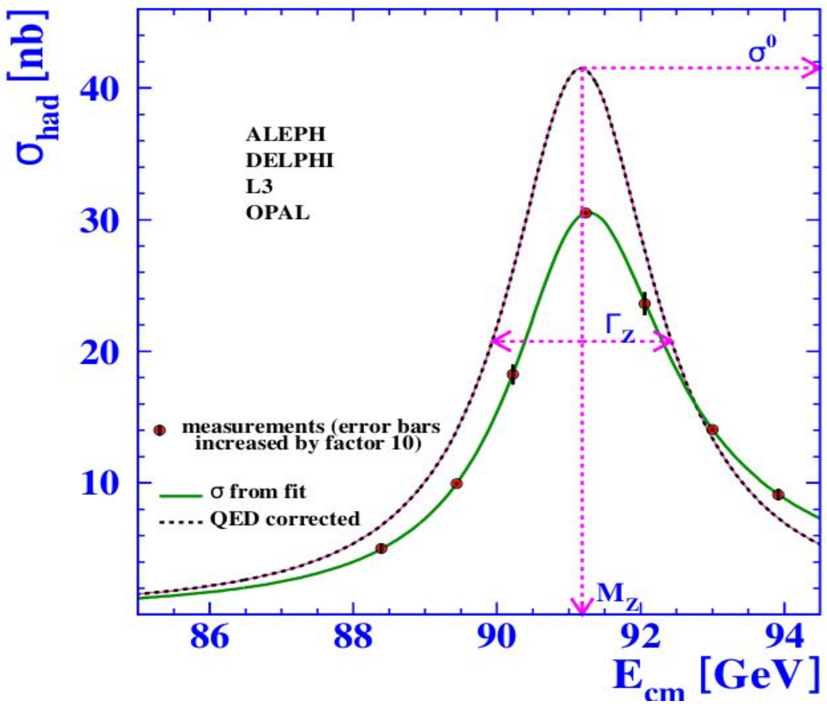
Γ_Z, N_ν and luminosity



- **Total Z width → basically coming from the visible width of the lineshape**
- **Statistical precision of $\Delta\Gamma_Z \approx$ 4 keV** using hadronic lineshape
- Dominant systematics is the "point-to-point" beam uncertainty
- Study the point-to-point changes (3-5 points) using the invariant mass of dimuon events at each energy and realistic conditions at the beam interaction region: **current estimate is $\Delta\Gamma_Z \approx$ 25 keV**

- **A precise measurement of N_ν / invisible width requires a measurement of cross sections at the peak, not just Γ_Z → luminosity dependency → ≈ 10 times improvement over LEP (it will be measured with better precision using radiative recoil ratios: $\sigma(\nu\nu\gamma)/\sigma(ll\gamma)$)**

$R_l = \Gamma_{had} / \Gamma_l$

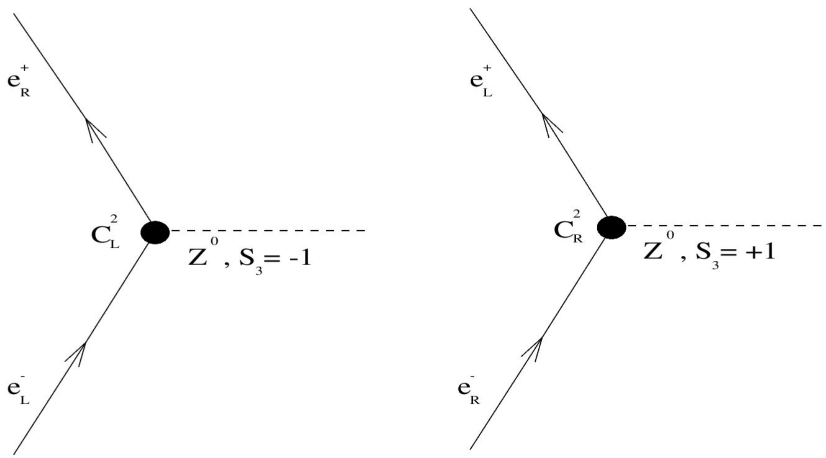


- Relative measurement, independent of luminosity: aiming for a 10^{-5} precision
- Extremely sensitive to new physics deviations (ϱ,T parameters: deviations of custodial symmetry)
- $\alpha_s(m^2_Z)$ modifies the hadronic partial width → R_l provides an ultra-precise measurement
- **Studies to define detector requirements to ensure negligible systematic uncertainties on acceptance (a priori more critical on leptons)**

δRe		0.0003	3.61E-06	0.00001
δRμ		0.00005	2.58E-06	0.00001
δRτ		0.0001	3.10E-06	0.00001

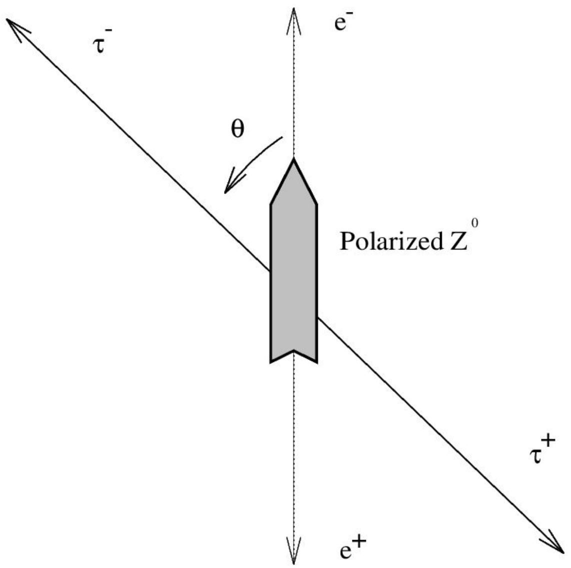
Tau polarization: A_τ , A_e

Z: naturally polarized



$$\mathcal{P}_{Z^0} = \frac{C_R^2 - C_L^2}{C_R^2 + C_L^2} = -\frac{2v_e a_e}{v_e^2 + a_e^2} \equiv -\mathcal{A}_e$$

τ decay: excellent polarimeter

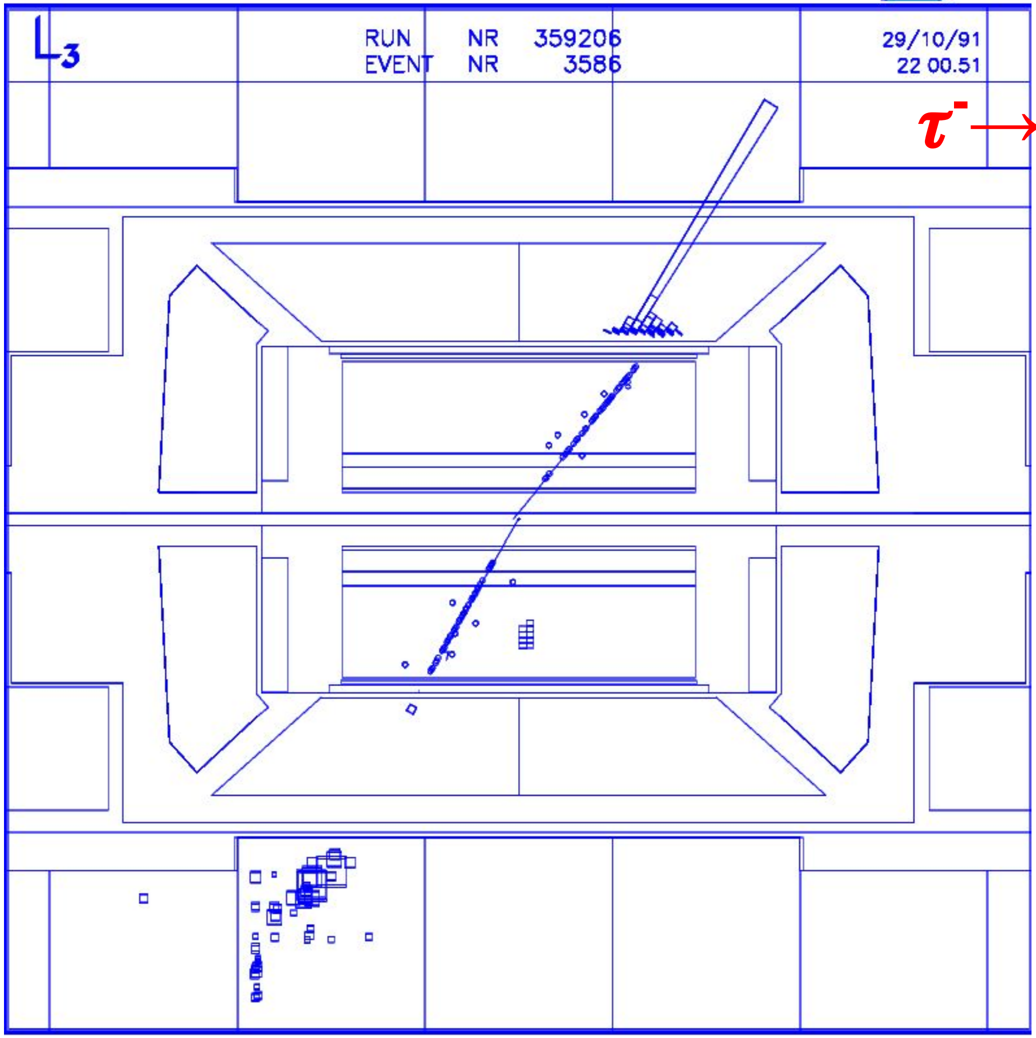


$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

$$<\mathcal{P}_\tau> = -\mathcal{A}_\tau$$

$$\mathcal{P}_\tau^{FB} = -\tfrac{3}{4}\mathcal{A}_e$$

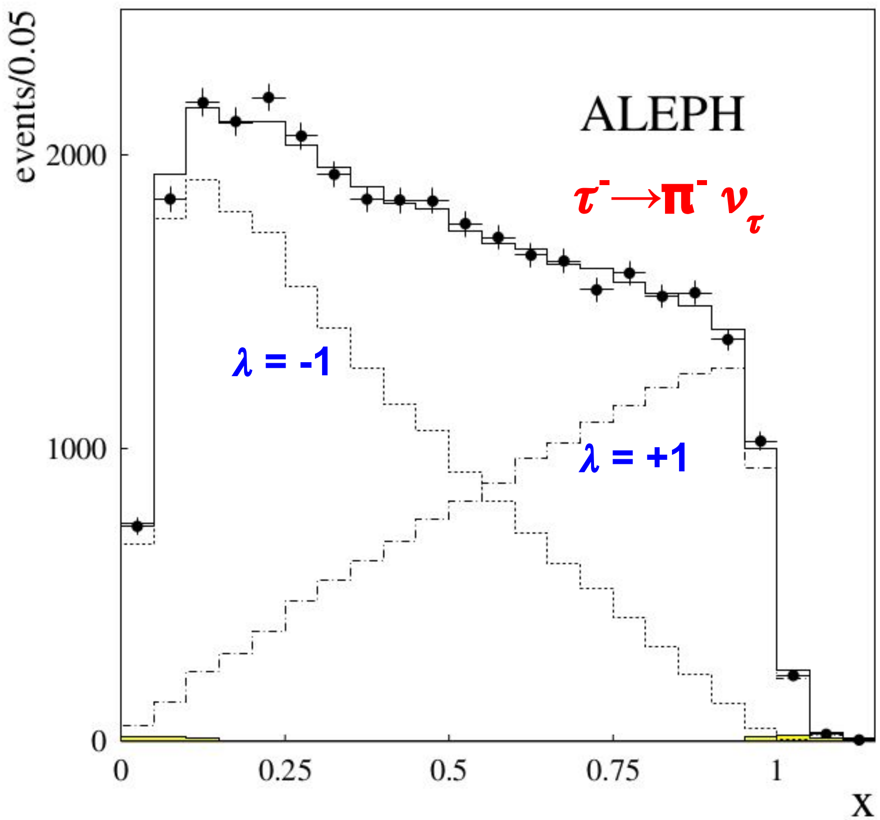
Most sensitive channels



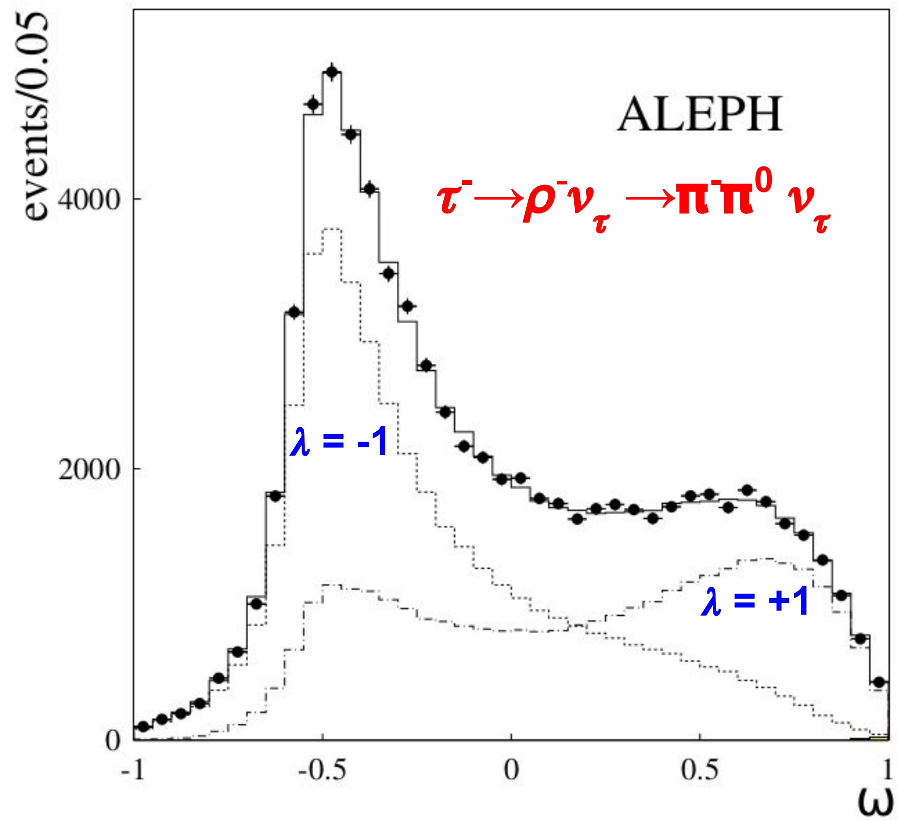
$\tau^- \to \rho^- \nu_\tau \to \pi^- \pi^0 \nu_\tau$

$\tau^- \to \pi^- \nu_\tau$

Analysis at LEP



(x=E_τ/E_{beam})



(Optimal variable)

- **Cross-talk between τ decay channels and the precise understanding of the helicity shape are main items to study to reduce systematics:**
  - **≈ 11% τ background from other decay channels in these plots**
  - **the tiny yellow shaded area is the non-τ background**

A_τ to do: optimize channel separation

Table 2: Summary of the systematic uncertainties (%) on A_τ and A_e in the single-τ analysis.

ALEPH

	A_τ						
Source	h	ρ	$3\,h$	$h\,2\pi^0$	e	μ	Incl. h
selection	-	0.01	-	-	0.14	0.02	0.08
tracking	0.06	-	0.22	-	-	0.10	-
ECAL scale	0.15	0.11	0.21	1.10	0.47	-	-
PID	0.15	0.06	0.04	0.01	0.07	0.07	0.18
misid.	0.05	-	-	-	0.08	0.03	0.05
photon	0.22	0.24	0.37	0.22	-	-	-
non-τ back.	0.19	0.08	0.05	0.18	0.54	0.67	0.15
τ BR	0.09	0.04	0.10	0.26	0.03	0.03	0.78
modelling	-	-	0.70	0.70	-	-	0.09
MC stat	0.30	0.26	0.49	0.63	0.61	0.63	0.26
TOTAL	0.49	0.38	1.00	1.52	0.96	0.93	0.87

- **ALEPH was the best detector for this: large tracking volume for separation, large magnetic field for bending, high granularity for π0 → $\gamma\gamma$ identification**
- **Photon separation / π^0 identification was still the dominant systematics**

A_τ

ΔAτ		0.000045	5.00E-06	2.00E-04
ΔAτ			1.00E-05	1.30E-04

- **From polarization analysis:**
  - **Stat. uncertainty: 10^3 reduction w.r.t. ALEPH analysis (160 pb^{-1})**
  - **Systematics: reduction of systematics by an order of magnitude w.r.t. LEP**

- **From $A_{FB}(\tau\tau)$ and A_e (≈ independent measurement):**
  - **Stat. uncertainty: 10^3 reduction w.r.t. LEP**
  - **Systematics: reduction of systematics by an order of magnitude w.r.t. LEP (dominated by knowledge of Bhabha background)**

$$A_{FB} = \frac{3}{4} A_e A_f$$

A_μ (without lepton universality)

ΔAμ		0.000023	2.31E-05	2.20E-05

- Revised estimate from $A_{FB}(\mu\mu)$ and A_e

$$A_{FB} = \frac{3}{4} A_e A_f$$

- Statistical uncertainty assumes $N=1.5 \times 10^{11}$ selected events: $\Delta A_{FB}(\mu\mu) \approx 1/\sqrt{N}$
- Systematics assumed to be dominated by point-to-point uncertainties: $\Delta A_{FB}(\mu\mu) \approx 2.5 \times 10^{-6}$
- ΔA_μ (stat.+syst.) = 0.000032

Present status of $A_{FB}(Q)$

- Electroweak measurement presenting the largest deviations in the global SM fit ([final LEPEWWG paper](2005))

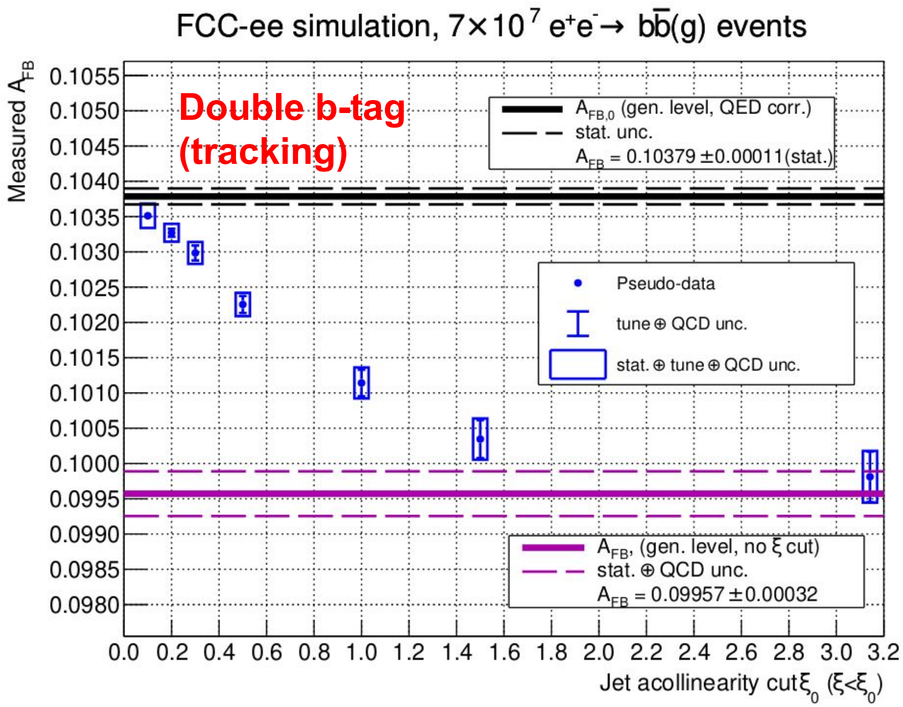
$$A_{FB}(Q) = \frac{\sigma_F^Q - \sigma_B^Q}{\sigma_F^Q + \sigma_B^Q}$$

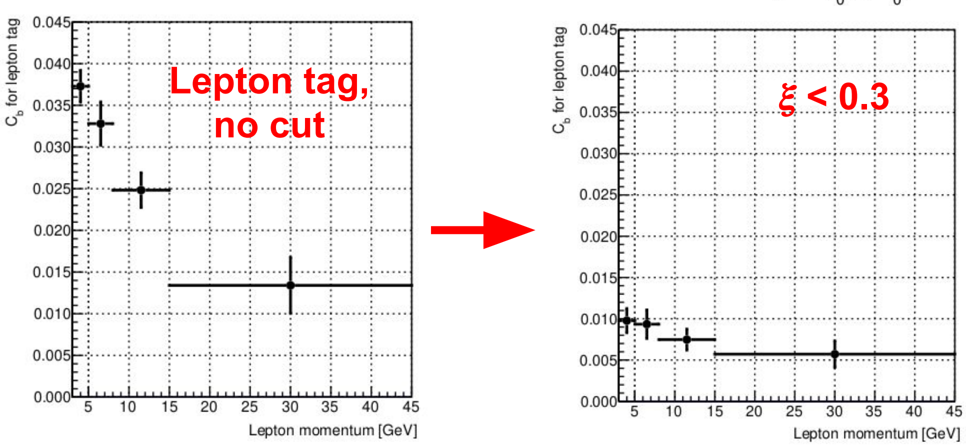
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ±0.00035	0.02767
m_Z [GeV]	91.1875 ±0.0021	91.1874
Γ_Z [GeV]	2.4952 ±0.0023	2.4965
σ_{had}^0 [nb]	41.540 ±0.037	41.481
R_l	20.767 ±0.025	20.739
$A_{fb}^{0,l}$	0.01714 ±0.00095	0.01642
$A_l(P_\tau)$	0.1465 ±0.0032	0.1480
R_b	0.21629 ±0.00066	0.21562
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

- New physics explanations require a substantial modification of Zbb right-hand couplings (arxiv:0610173)

A_{FB}(b/c), $R_{b/c} = \Gamma_{b/c}/\Gamma_{had}$

J.A., arXiv:2010.08604





- New developments for A_{FB}(b/c): QCD corrections and uncertainties can be reduced significantly using acollinearity (ξ) cuts ⇒ not a limiting factor anymore to reach the $\lesssim$ 0.1% precision level
- Further improvements expected from better heavy flavor tagging capabilities and a more accurate measurement of the b flight direction
- **Performing a realistic measurement with more sophisticated b-tagging techniques → detector requirements**
- Studies to be extended to R_b, R_c double-tag measurements: increasing tag purity, better understanding of gluon-splitting and hemisphere correlations, ...

Reduction of QCD uncertainties

- Detailed table of central values and uncertainties:

stat. unc. for 7×10^7 $Z \to b\bar{b}$ events

ξ_0 cut	Measured A_{FB}	ΔA_{FB}(stat)	ΔA_{FB}(tune)	ΔA_{FB}(theo. QCD corr)
No cut	0.0998 ± 0.0004	0.00008	0.00014	0.00033
1.50	0.1003 ± 0.0003	0.00011	0.00014	0.00023
1.00	0.1011 ± 0.0002	0.00011	0.00010	0.00016
0.50	0.1023 ± 0.0002	0.00011	0.00010	0.00007
0.30	0.1030 ± 0.0002	0.00011	0.00010	0.00003
0.20	0.1033 ± 0.0001	0.00011	0.00005	0.00002
0.10	0.1035 ± 0.0002	0.00016	0.00005	0.00001

Table 9: Central values and components of the uncertainty in the measurement of the A_{FB} asymmetry with 7×10^7 $e^+e^- \to b\bar{b}(g)$ events at the Z pole, for different $\xi < \xi_0$ cuts at the reconstructed level.

$\lesssim$ 0.1% relative systematic uncertainties for $\xi \lesssim 0.3$

A_c: no changes for the time being

ΔAc		0.0053	2.00E-04	0.0053

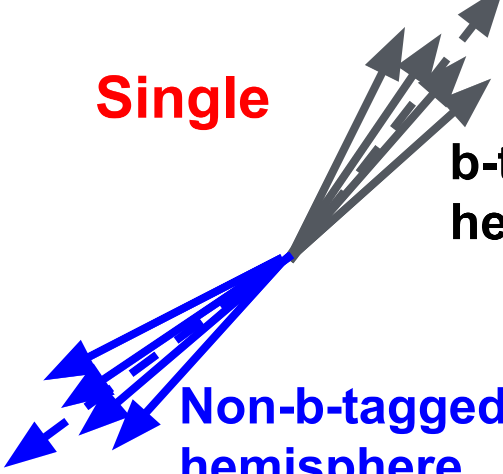
Conservative extrapolation from LEP analyses assuming a factor of 3 reduction in charm modelling systematics and a factor of 5 reduction in QCD correction uncertainties

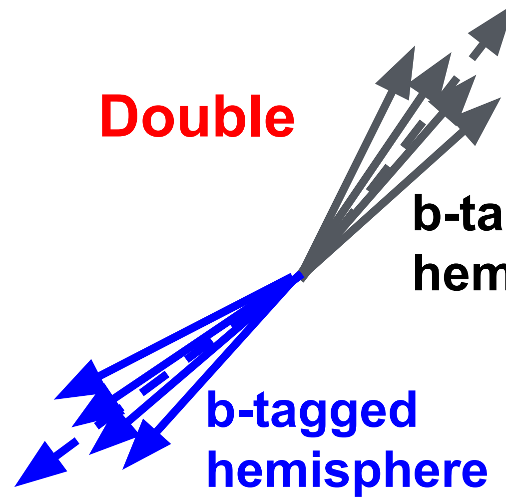
- **ΔA_b (stat.+syst.) = 0.0053**
- **Large improvements expected (better use of exclusive channels with such a large statistics, new strategies), but too early to assess uncertainties: dedicated studies necessary**

R_b, R_c

$$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}}, \quad R_c = \frac{\Gamma_{c\bar{c}}}{\Gamma_{had}}$$

- Measured at LEP/SLC very precisely using single and double-tag event fractions for the b case:





$$\text{No Bckgd, no hemisphere correlations} \Rightarrow \mathbf{R_b} = \frac{\mathbf{f^2_{single}}}{\mathbf{f_{double}}}$$

Real life:

$$f_{single} = R_b\epsilon_b + R_c\epsilon_c + (1 - R_b - R_c)\epsilon_{uds}$$

$$f_{double} = c_b\ R_b\epsilon_b^2 + c_c\ R_c\epsilon_c^2 + c_{uds}\ (1 - R_b - R_c)\epsilon_{uds}^2$$

$$c_b = c_c = c_{uds} = 1 \ \text{ if no hemisphere correlations}$$

Present status of Rb, Rc

- **Hemisphere correlation effects (QCD) and gluon splitting are large sources of correlated uncertainty among experiments**
  - LEPEWWG result: R_b=0.21629 ± 0.00066
- **Aiming for a ≲ 3x10^{-4} precision measurement on R_b at FCC-ee: one order of magnitude improvement**
- **R_c to be re-studied for a Tera-Z factory via exclusive / inclusive single+double-tag methods (SLD way, not LEP main way)**

Source	R_b^0 $[10^{-3}]$	R_c^0 $[10^{-3}]$	$A_{FB}^{0,b}$ $[10^{-3}]$	$A_{FB}^{0,c}$ $[10^{-3}]$	$\mathcal{A}_b$ $[10^{-2}]$	$\mathcal{A}_c$ $[10^{-2}]$
statistics	0.44	2.4	1.5	3.0	1.5	2.2
internal systematics	0.28	1.2	0.6	1.4	1.2	1.5
QCD effects	0.18	0	0.4	0.1	0.3	0.2
$B(D \to \text{neut.})$	0.14	0.3	0	0	0	0
D decay multiplicity	0.13	0.6	0	0.2	0	0
B decay multiplicity	0.11	0.1	0	0.2	0	0
$B(D^+ \to K^-\pi^+\pi^+)$	0.09	0.2	0	0.1	0	0
$B(D_s \to \phi\pi^+)$	0.02	0.5	0	0.1	0	0
$B(\Lambda_c \to p K^-\pi^+)$	0.05	0.5	0	0.1	0	0
D lifetimes	0.07	0.6	0	0.2	0	0
B decays	0	0	0.1	0.4	0	0.1
decay models	0	0.1	0.1	0.5	0.1	0.1
non incl. mixing	0	0.1	0.1	0.4	0	0
gluon splitting	0.23	0.9	0.1	0.2	0.1	0.1
c fragmentation	0.11	0.3	0.1	0.1	0.1	0.1
light quarks	0.07	0.1	0	0	0	0
beam polarisation	0	0	0	0	0.5	0.3
total correlated	0.42	1.5	0.4	0.9	0.6	0.4
total error	0.66	3.0	1.6	3.5	2.0	2.7

R_b, R_c

δRb		<0.0003	1.39E-06	<0.0003
δRc		0.0015	1.50E-04	<0.0015

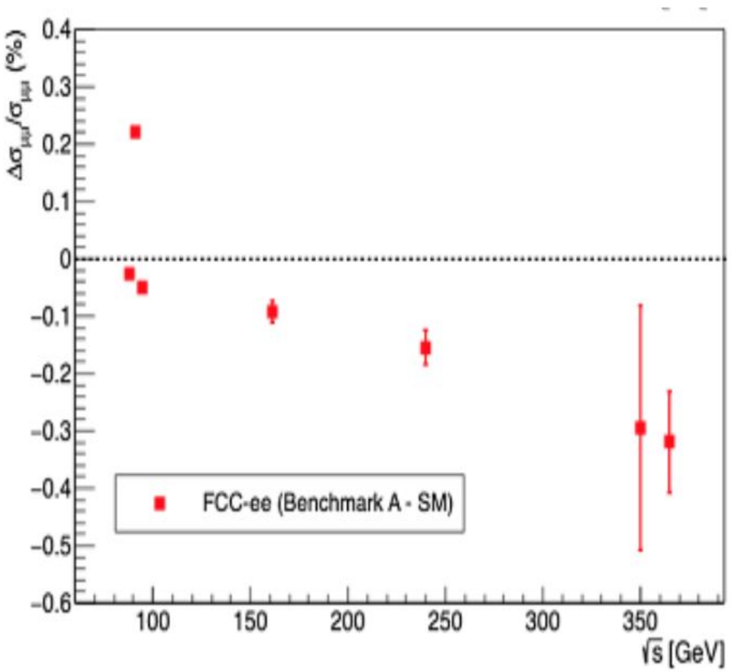
extrapolation from SLD <=> reduction by a factor of 3 in correlation systematics w.r.t. LEP. Expect big reductions of systematics

σ and A_{FB} away from Z peak

√s (GeV)	Relative error on XS	Absolute error on AFB
87.9	0.00010	1.8 E-5
91.2	0.00010	2.5 E-6
94.3	0.00010	1.6 E-5
161	0.00019	1.0 E-4
240	0.00030	2.0 E-4
350	0.00153	1.0 E-3
365	0.00088	6.2 E-4

- **$\mu\mu$ analysis (4D Higgs compositeness study); sensitivity to ‰ deviations in cross sections**

- **Uncertainties on account for:**
  - Statistical uncertainties + 10^{-4} (rel.) **uncertainty from luminosity** (only for σ)
  - No theory error assigned → needs progress on calculations
- **Why it is important:**
  - **Small signals with not so small widths at the LHC below 6-7 TeV (and not just "quarkfobic")**



m_H

ΔmH (MeV)		11	2.5	2

might improve with four experiments and all channels. Systematic uncertainty included here is the in situ energy calibration with Zgamma events.

At $\sqrt{s} = 240\,\text{GeV}$, the same method still enjoys 70 million $Z\gamma$ events (with a twice smaller luminosity, a twice smaller cross section, and a twice smaller acceptance due to the larger longitudinal boost than at the WW threshold), which suffice for a determination of the average centre-of-mass energy with a precision of 1.7 MeV.

- **Uncertainty < 4 MeV necessary to define a potential running at √s = 125 GeV to test Yukawa coupling to electrons**
- **Also external input in many high precision calculations**

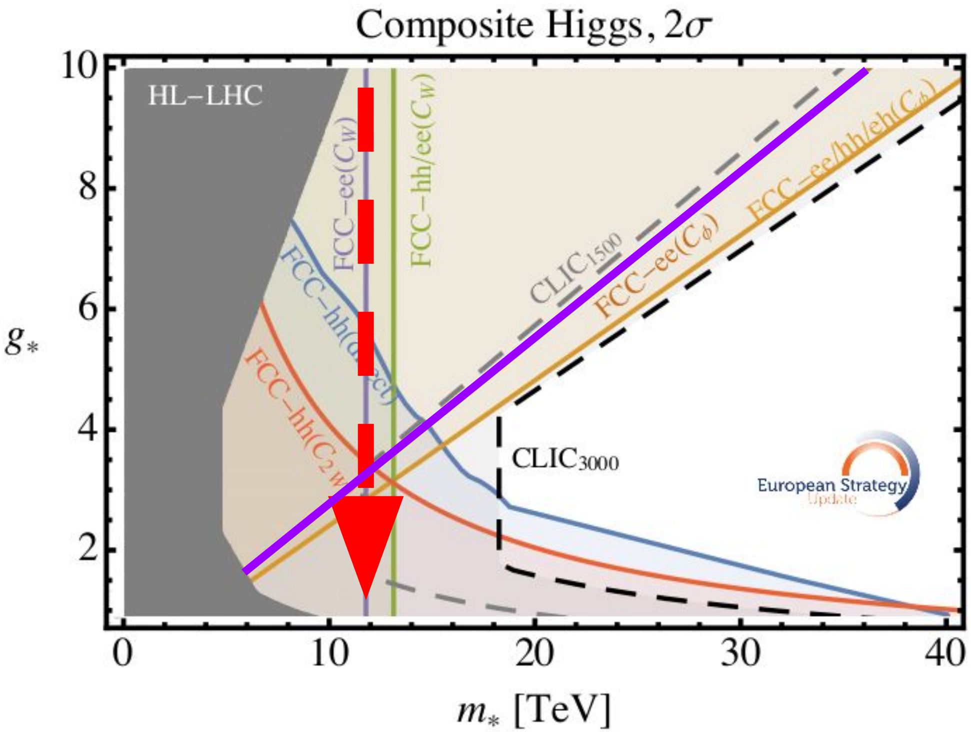
Access to the deca-TeV scale: Higgs compositeness

European Strategy, J.A., A. Wulzer
in BSM discussion, arXiv:1910.11775

Simple back-of-the-envelope calculation:

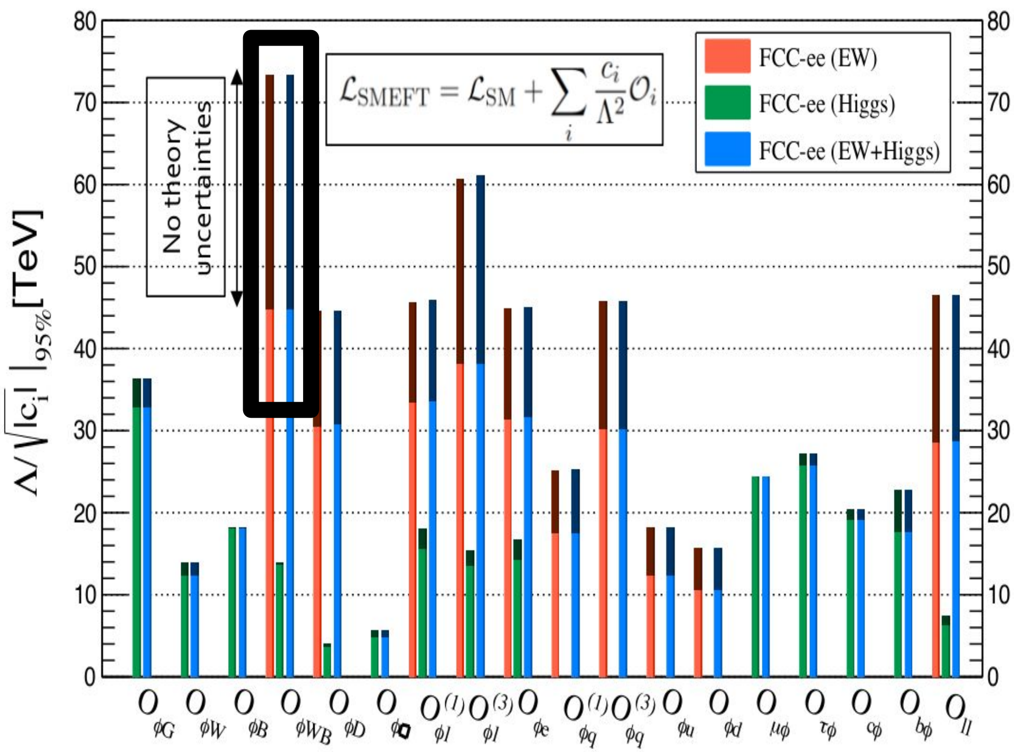
S parameter precision from LEP (PDG 18) ⇒
m* > 2.5 TeV

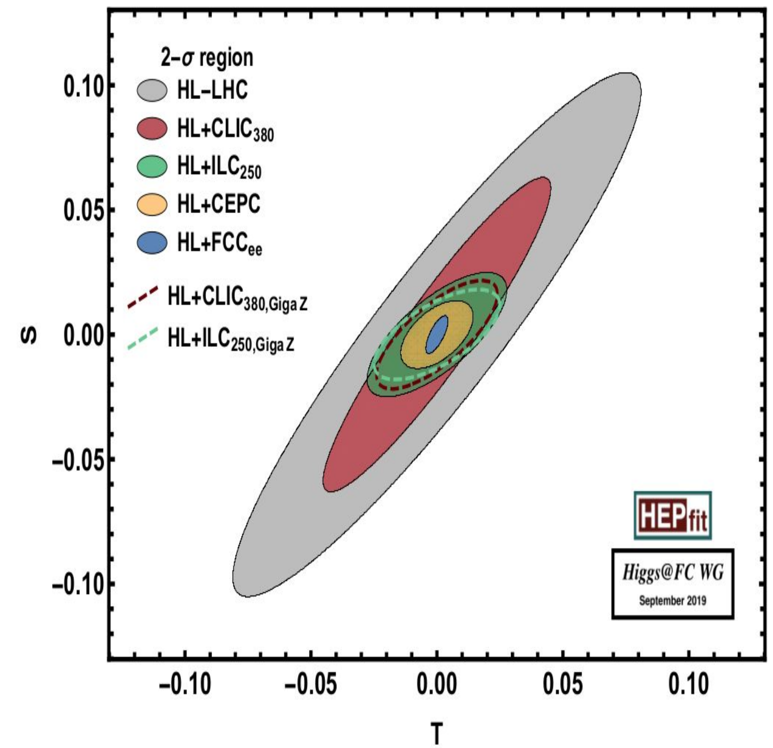
Factor of 20-100 increase in precision ⇒
m* > 11-25 TeV



- **Higgs compositeness ⇒ S parameter modified effects (= O_W+O_B operator in SILH scenario, related to 2f-2boson contact interactions):**
  - **Sensitive to compositeness scales > 10 TeV, independently of the strength of the g* coupling**
  - Complementary to measurements in the Higgs sector (cross section scaling ∝ g^{*2})

Physics potential: deca-TeV scale





- **Probing (really) the deca-TeV scale for universal new-physics effects with just a few years of FCC-ee EW running:**
  - Strong constraints on the S parameter ($O_{\phi WB}$ operator)
  - and on the T parameter (violations of custodial symmetry)

Eur. Strat.: arXiv:1910.11775