Z lineshape and electroweak heavy flavor physics at FCC-ee (LoIs: #167, #152)

Juan Alcaraz Maestre[1], Alain Blondel[2], Mogens Dam[3], Patrick Janot[4], and Emmanuel Perez[4]

Juan Alcaraz Maestre[1], Patrizia Azzi[2], Alain Blondel[3], Mogens Dam[4], Patrick Janot[5], Stéphane Monteil[6], and Guy Wilkinson[7]

Presented by: Juan Alcaraz (CIEMAT-Madrid)

Snowmass 2021 EF04 session
23 October 2020

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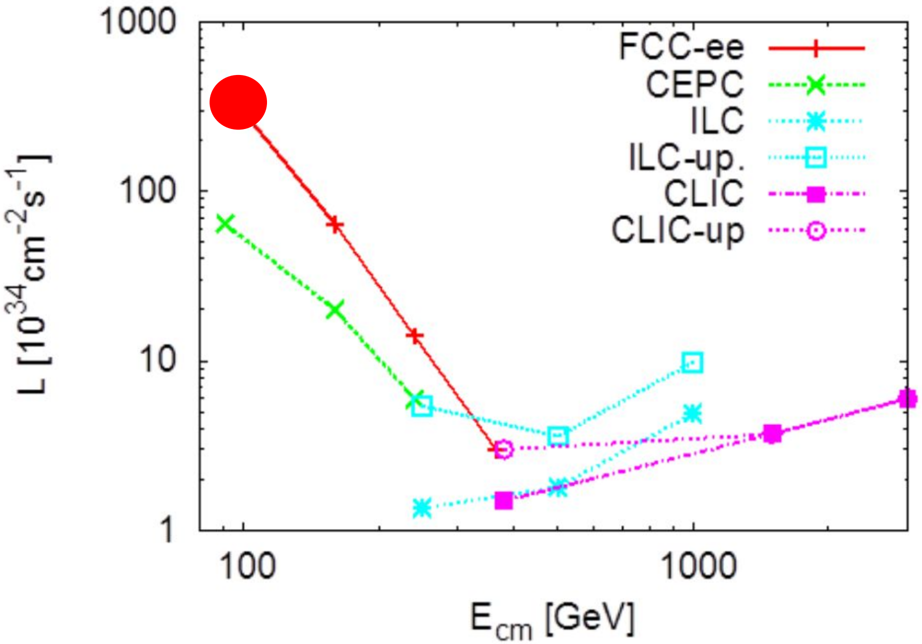
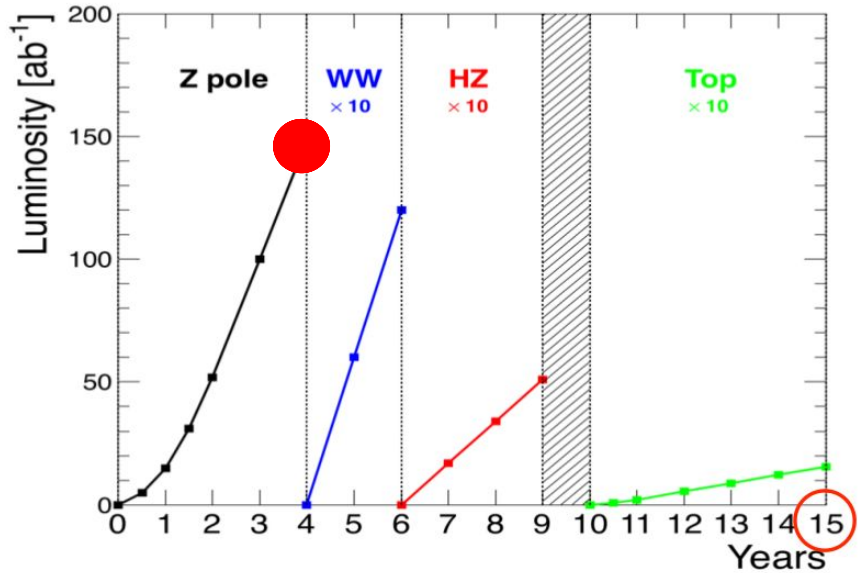
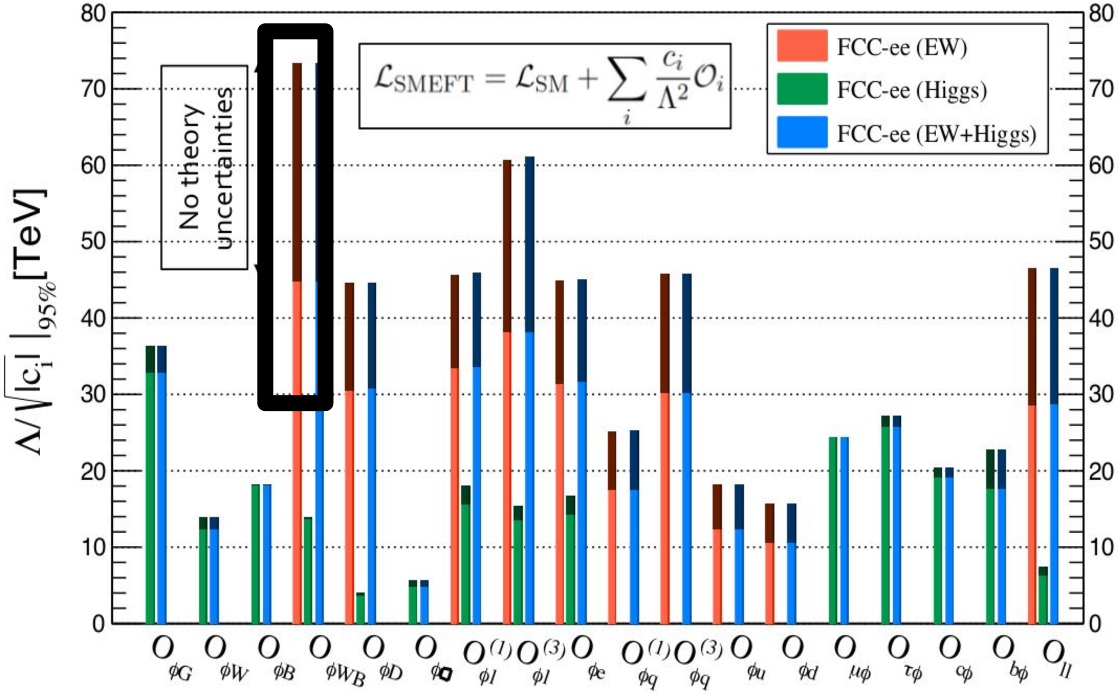
FCC-ee context

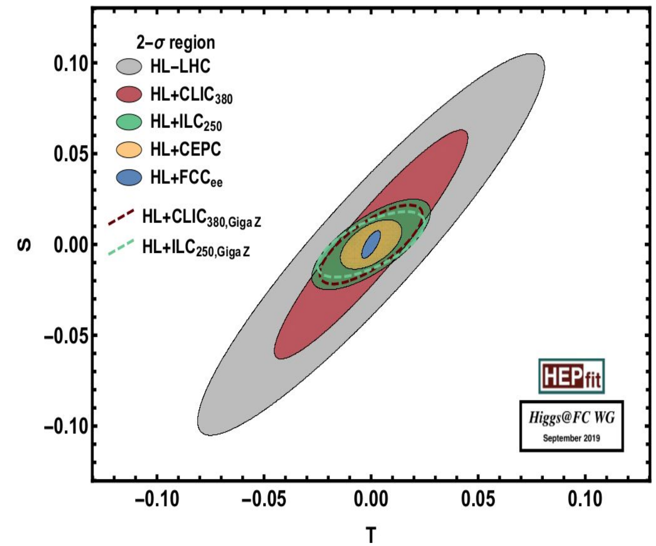


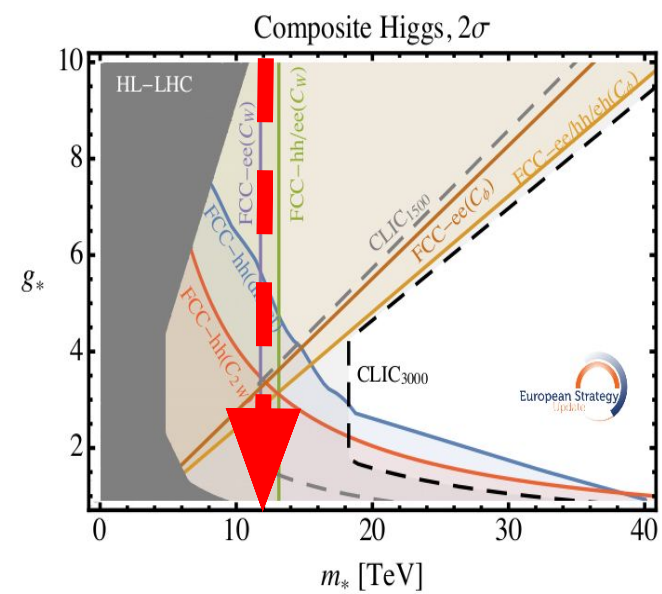


- FCC-ee: 150 ab^{-1}, 5 x 10^{12} Z decays in ≈ 4 years of running at the Z pole
- Extraordinary √s precision: 100 keV at the Z, 300 keV at WW threshold → exquisite control of beam uncertainties (average, width, systematics)
- Aiming for up to ≈ 100 times better precision than LEP/SLD on several electroweak precision observables (EWPO)
- **Current challenges: reduce uncertainties, establish theory / detector / machine requirements to reach the ultimate precision**

Physics potential



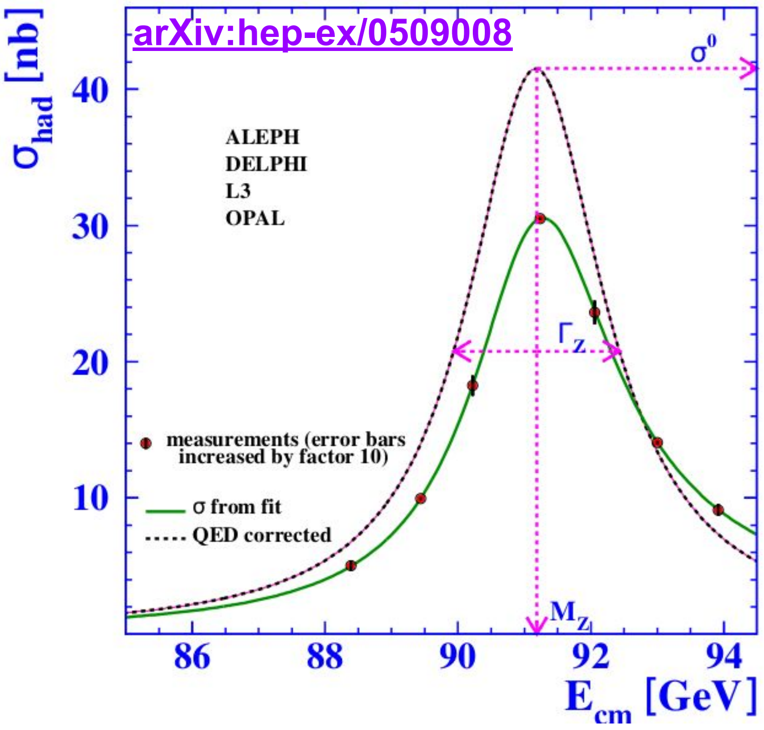


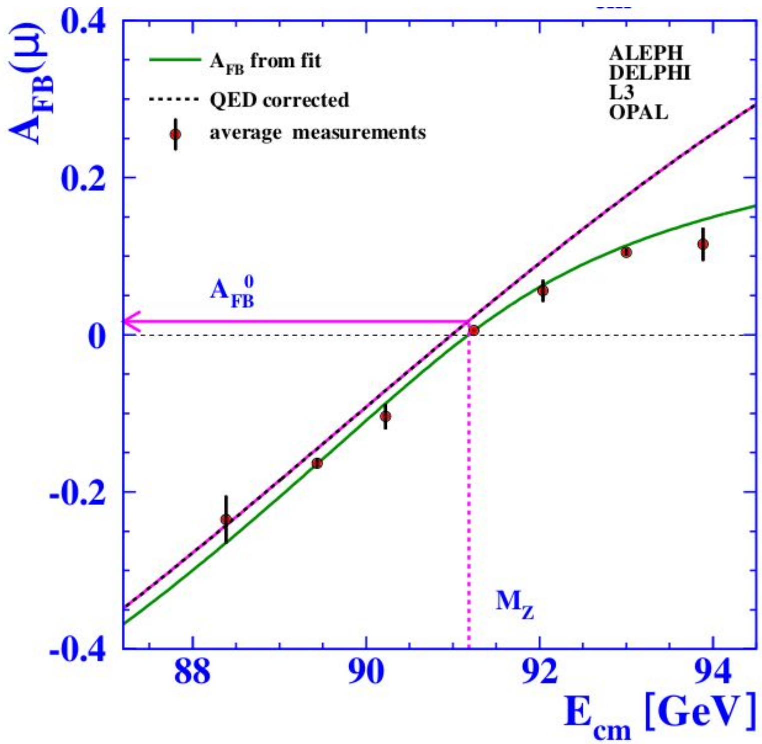


- **Probing the 10-TeV scale for universal new-physics effects with just a few years of FCC-ee EW running:**
  - Strong constraints on the S parameter ($O_{\phi WB}$, O_W+O_B in Higgs compositeness, ...)
  - and on the T parameter (violations of custodial symmetry)

[Eur. Strat.: arXiv:1910.11775]

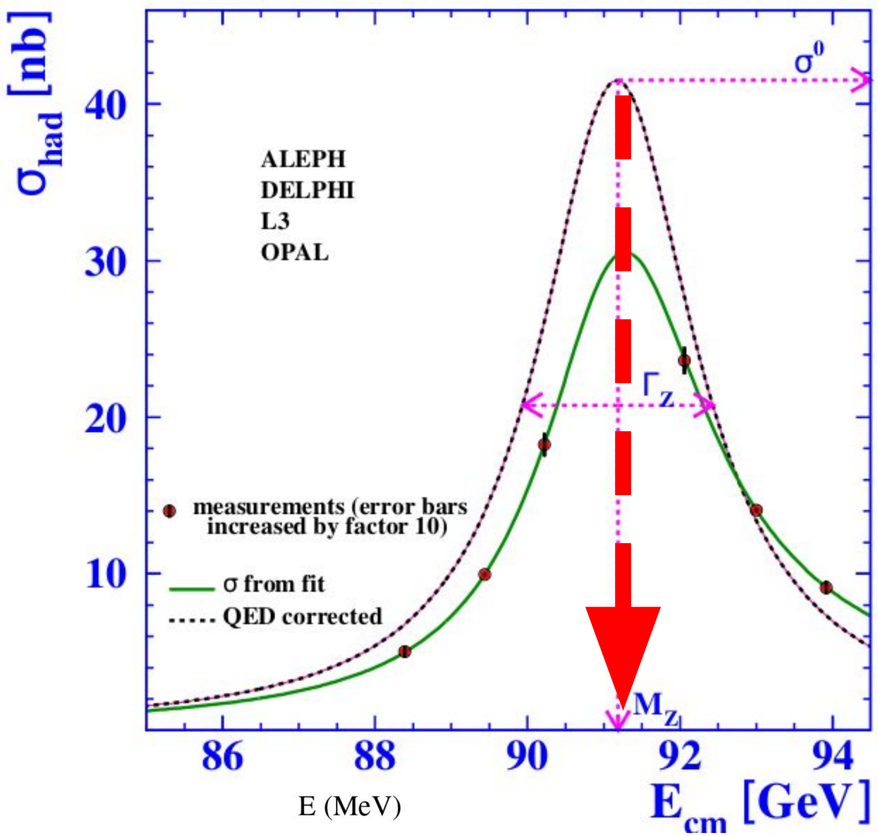
Z lineshape measurements



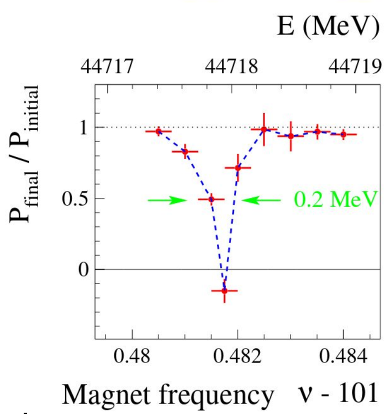


- Expected precisions in a nutshell:
  - ≈ 10^{-4} on cross sections (aimed luminosity uncertainty); possibility to reduce it by an order of magnitude using the measured $\sigma(ee\rightarrow\gamma\gamma)$ as reference
  - ≈ 10^{-6} statistical uncertainties (≈ $1/\sqrt{N}$) on relative measurements like forward-backward charge asymmetries
  - Ultimate uncertainties typically dominated by systematics; precious value of “Tera” Z samples to study / constrain many of those uncertainties

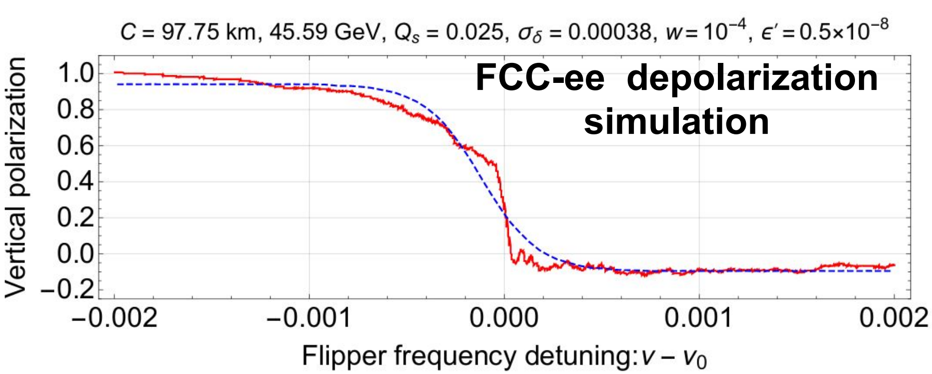
Z lineshape: mass



- m_Z: position of Z peak
- Beam energy measured with extraordinary precision ($\Delta\sqrt{s}\approx100$ 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

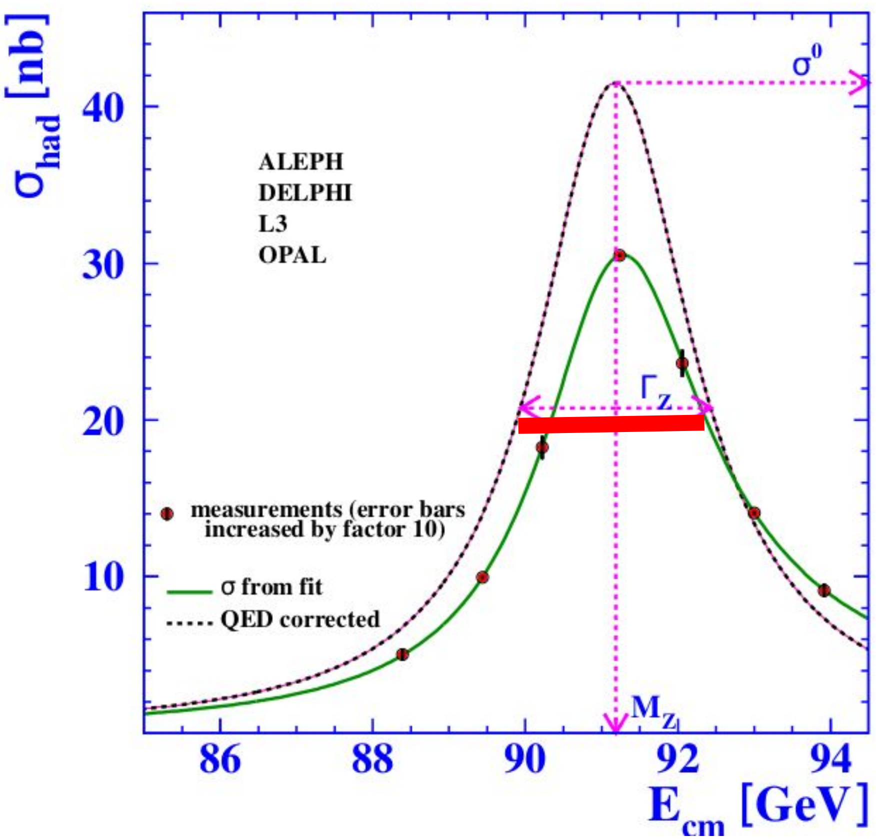


Resonant depolarization at LEP



arXiv:1909.12245

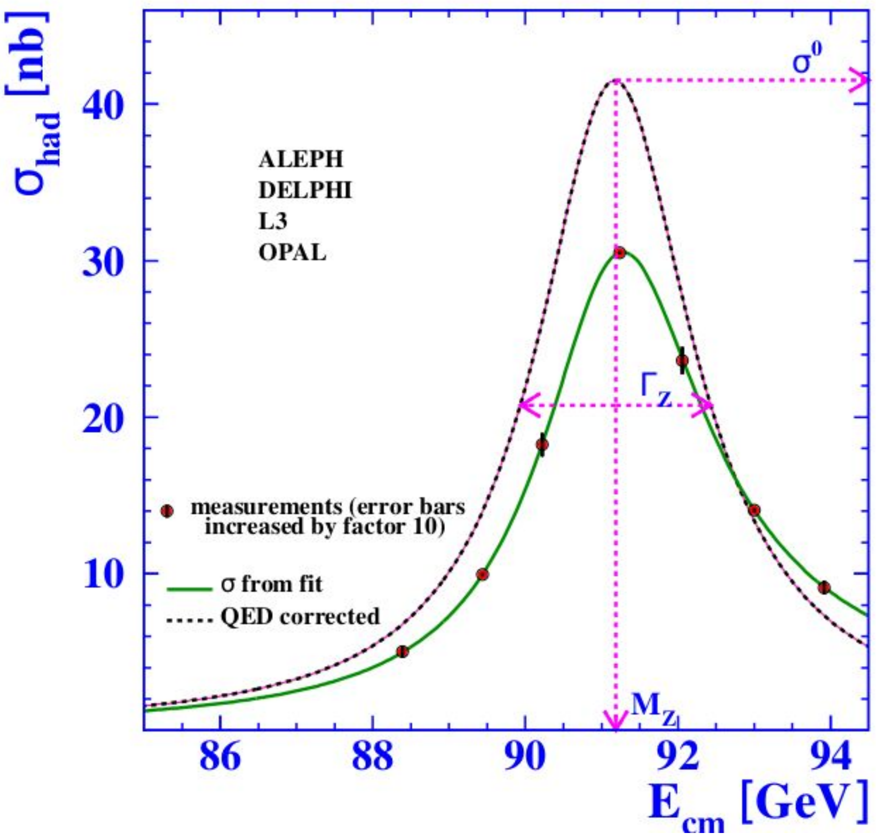
Γ_Z, N_ν



- **Total Z width → basically coming from the visible width of the lineshape**
- Statistical precision of 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**

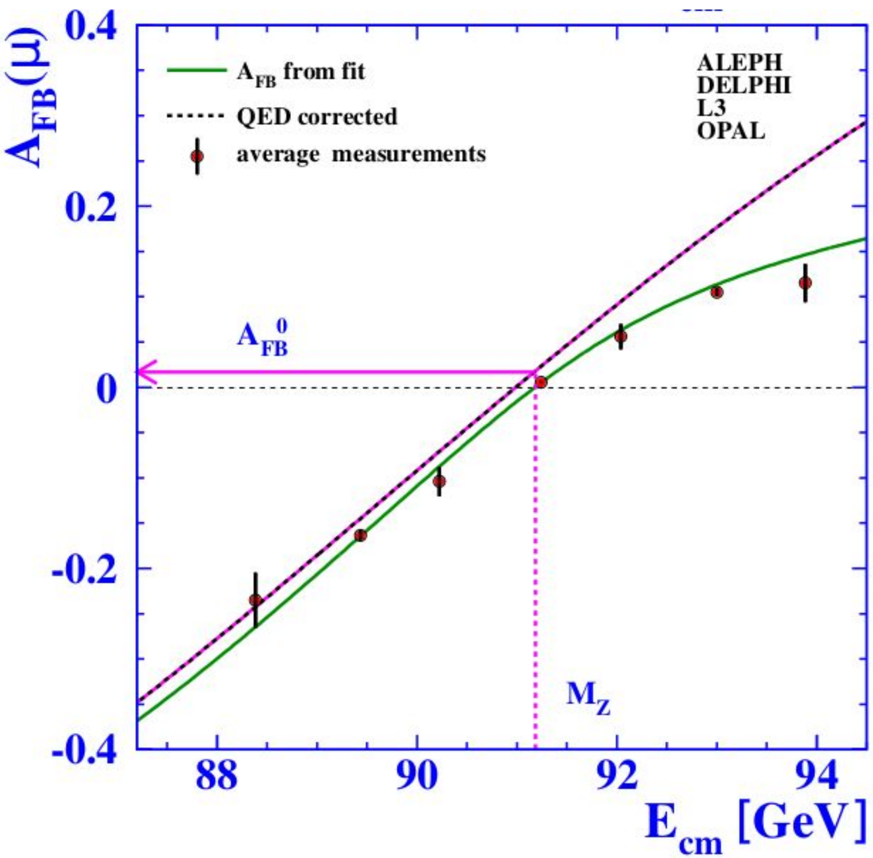
- **A precise measurement of N_ν / invisible width requires a measurement of cross sections at the peak, not just Γ_Z → luminosity dependency → ≈ 10 times improvement over LEP (it will be measured with better precision using radiative recoil ratios: $\sigma(\nu\nu\gamma)/\sigma(ll\gamma)$)**

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



- 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)**

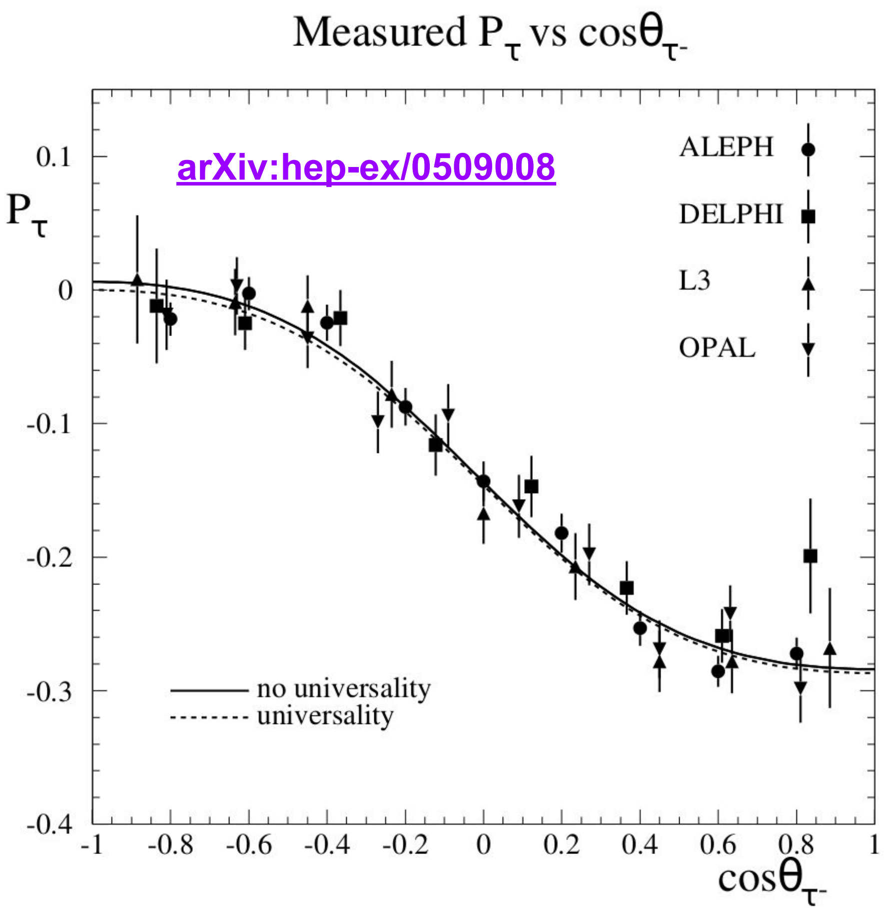
$\sin^2\theta_W^{eff}$ and $\alpha_{QED}(m^2_Z)$



- $\sin^2\theta_W$ effective: g_V/g_A coupling ratio → forward-backward charge asymmetries (most precise in $\mu\mu$ in final state)
- $\alpha_{QED}(m^2_Z)$: off-peak/peak evolution of the asymmetry (due to interference with γ^* exchange)
- Measurement approaching the ultimate statistical sensitivity: 3×10^{-6}
- 3 energy points (≈88, 91.2, 94 GeV)

- **Studies to establish the experimental/theoretical needs (energy resolutions, exact angular description at this level of precision, …)**

Tau polarization: A_τ , A_e



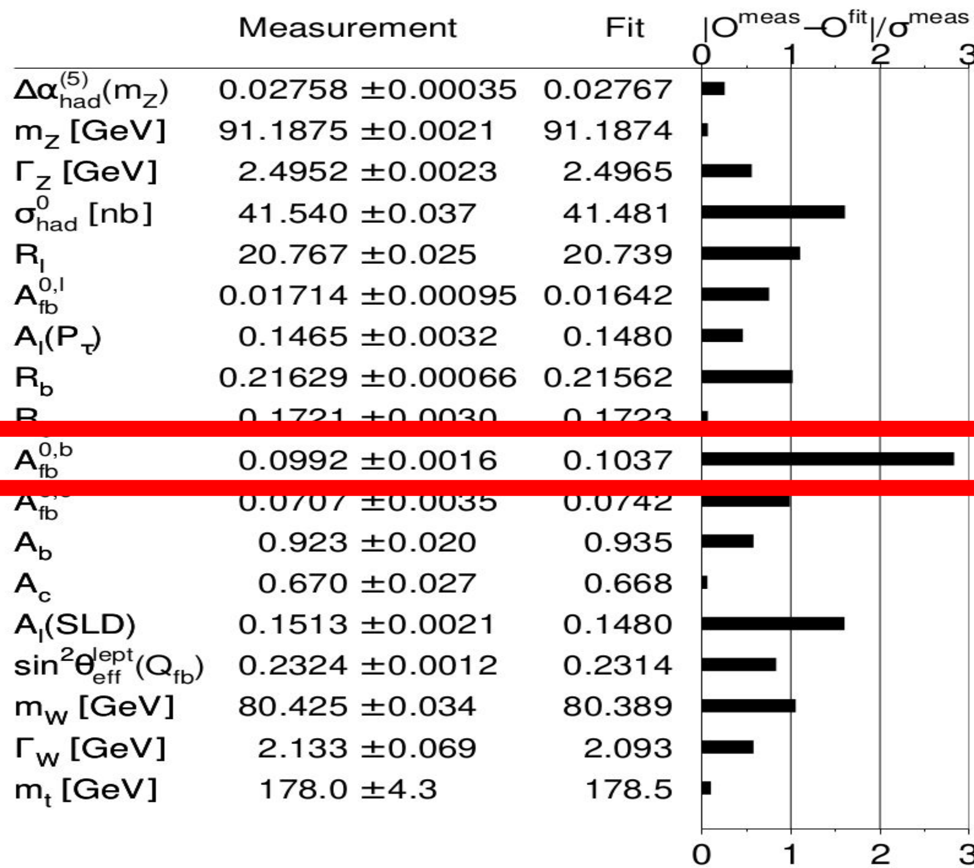
- **FCC-ee does not use longitudinal beam polarization:**
  - It would reduce too much the statistics
  - Not needed: tau polarization asymmetry enough to precisely measure all L-R asymmetry parameters A_f:

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

- Current uncertainties for FCC-ee can be substantially reduced
- **Proposal to study in detail the detector requirements (granularity, resolution, ...) to get optimal tau decay identification/separation and minimal systematic uncertainties in this measurement**

A_{FB}(b): present status

- Electroweak observable presenting the largest deviations in the global SM fit (final LEP EW Working Group paper: **arXiv:hep-ex/0509008**)

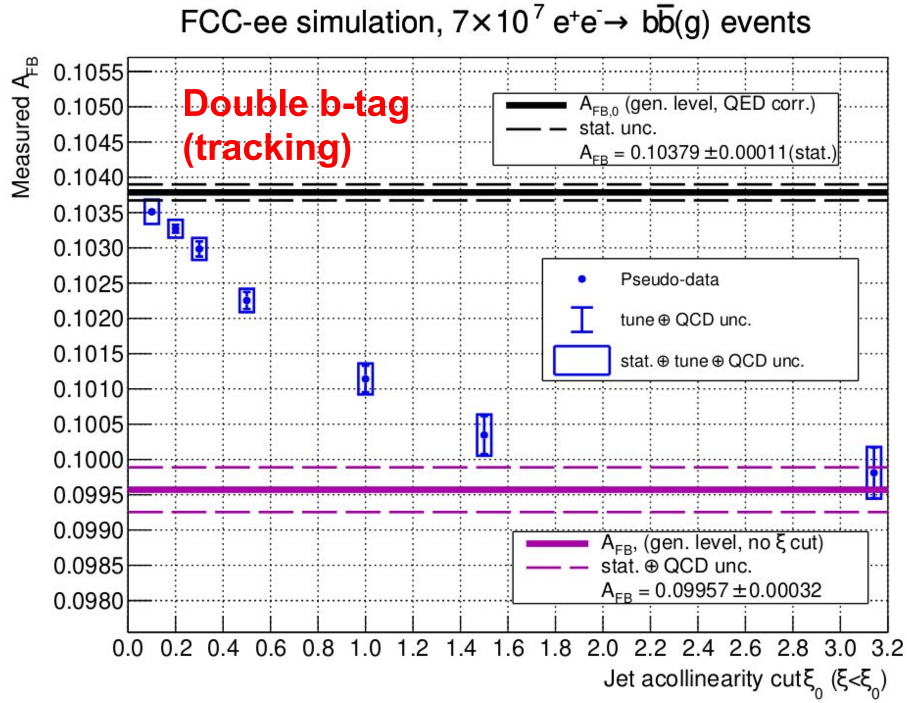


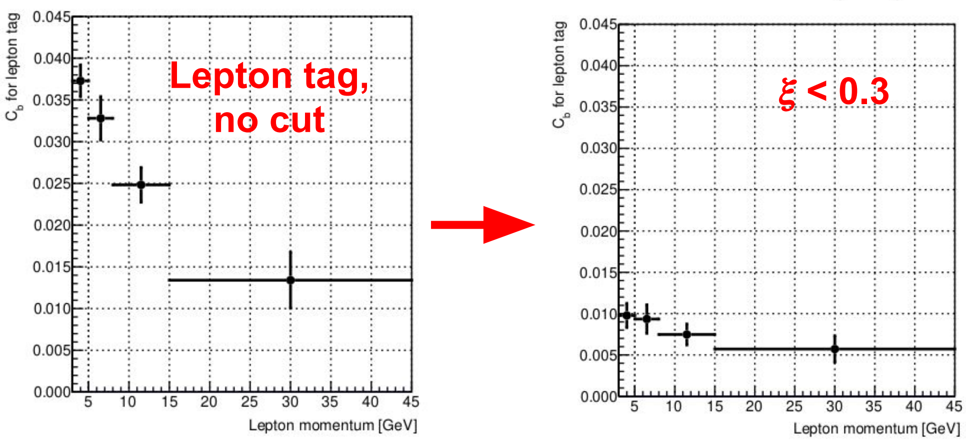
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ±0.00035	0.02767
m_Z [GeV]	91.1875 ±0.0021	91.1874
Γ_Z [GeV]	2.4952 ±0.0023	2.4965
σ_{had}^0 [nb]	41.540 ±0.037	41.481
R_l	20.767 ±0.025	20.739
$A_{fb}^{0,l}$	0.01714 ±0.00095	0.01642
$A_l(P_\tau)$	0.1465 ±0.0032	0.1480
R_b	0.21629 ±0.00066	0.21562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

- **Aiming for a ≲ 0.1% relative precision measurement at FCC-ee ⇒ factor of ≳20 improvement w.r.t. LEP/SLC results**

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, ...

Summary table

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
R_b ($\times 10^6$)	216290 ± 660	**0.3**	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu (\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff} (\times 10^6)$	231480 ± 160	**3**	1	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate

- ≈ two orders of magnitude improvement expected for Γ_Z , R_l , α_s , $\sin^2\theta_W^{eff}$

HF-EW summary table

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
$A_{FB}^{b}, 0$ ($\times 10^4$)	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
R_b ($\times 10^6$)	216290 ± 660	**0.3**	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD

- **Objective: ≳ 20 times better than current precision**

Outlook

- A few years of FCC-ee running at the Z pole should provide EWPO measurements with 20-100 times the current precision, thus giving early access to universal (and also flavor-dependent) new physics effects at the 10 TeV scale:
  - M_Z, $\alpha_{QED}(M^2_Z)$, $\alpha_s(M^2_Z)$, N_ν, $\sin^2\theta_W^{eff}$, P_τ, $A_{FB}(b/c)$, $R_{b/c}$
- Systematics will be the limiting factor in many measurements ⇒ very detailed studies needed (theory+experiment) to reduce it. These studies will set the requirements for the future detectors
- We invite you to join these studies, intended to better understand those limitations and find new ways to reduce the associated uncertainties, via new theory developments / analysis methods / detector modifications

Backup

Present status of A_{FB}(b)

- QCD corrections are the dominant source of correlated systematics between measurements

- Measurement (arXiv:hep-ex/0509008): 0.0992 ± 0.0015 (stat.) ± 0.0007 (syst.)

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 → 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