Progress on Electroweak studies at FCC-ee

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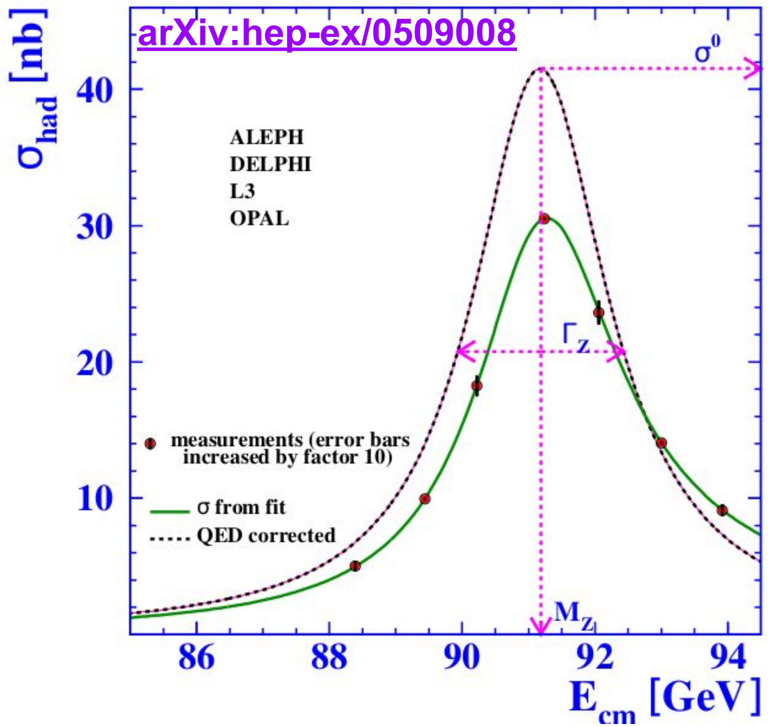
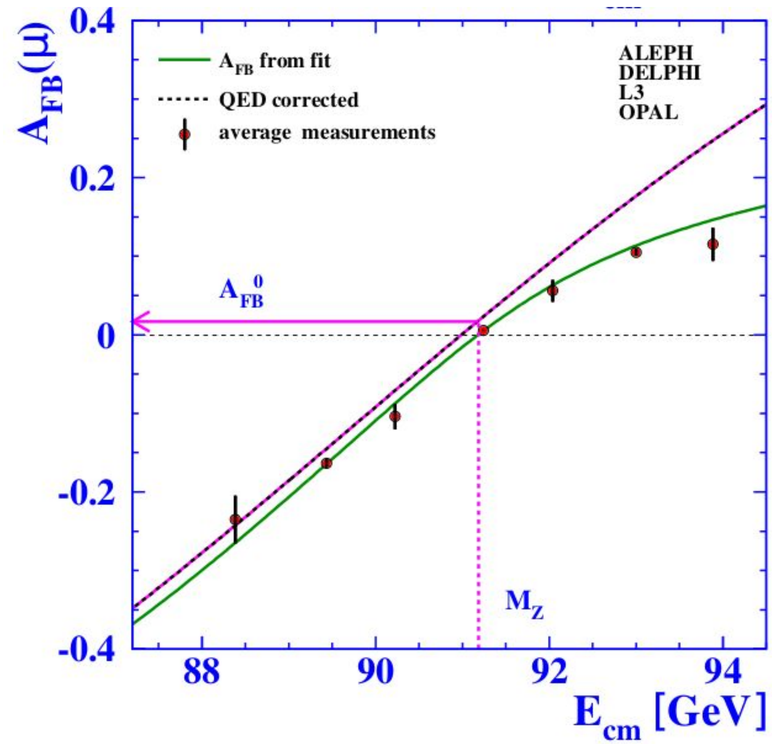
Outline

- Focus on a few recent progress/prospects:
  - $A_{FB}(b)$
  - Some prospects in the HF sector (Rb, charm sector)
  - $ee \rightarrow \gamma\gamma$ channel

- Introduction and other <per-mille physics studies already discussed by Lucia (a few slides in backup just for completeness)

Some Tera-Z key points





- 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 $\sigma(ee\to\gamma\gamma)$ 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

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

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

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

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

	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

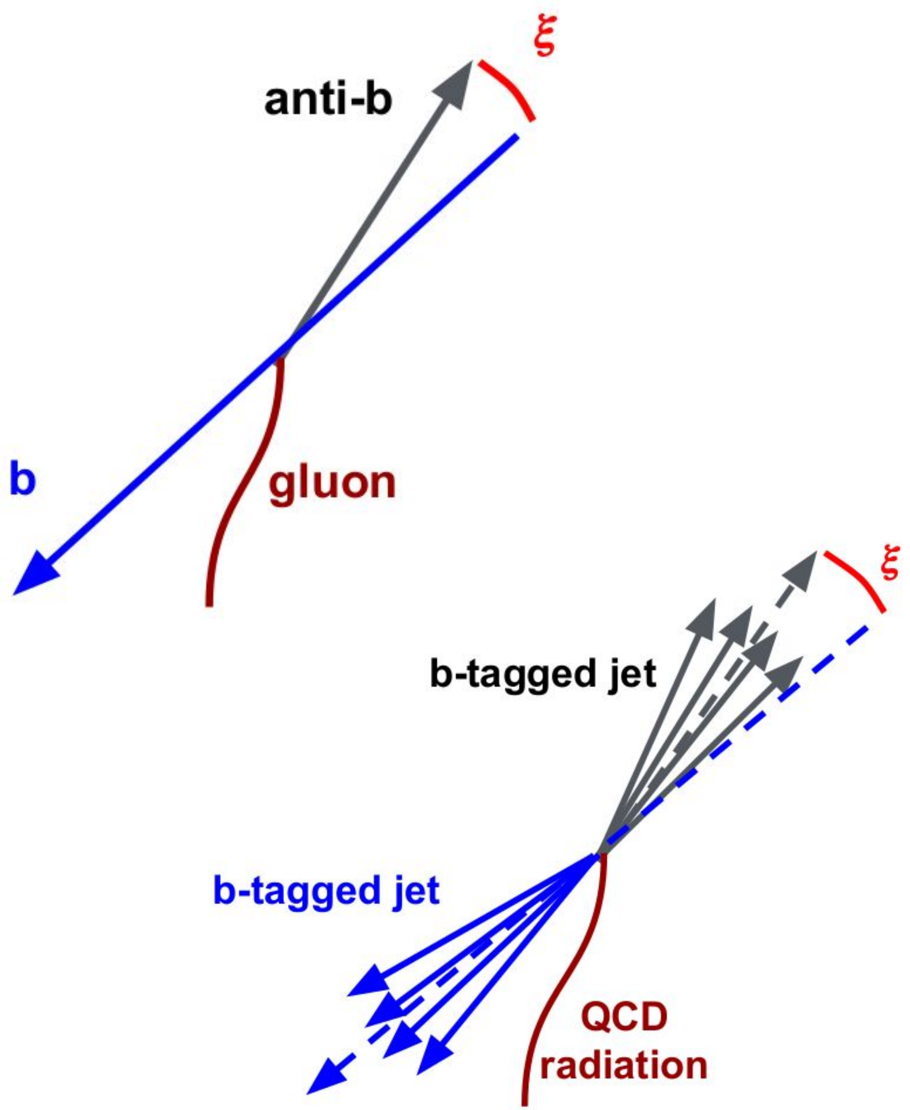
Present status of A_{FB}(Q)

- 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 (arxXiv:2011.00530)
- **Aiming for a ≈±0.0001 precision measurement at FCC-ee: one order of magnitude improvement !!**

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 ⇒ 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 heavy quark flight direction
- **Performing a realistic measurement with more sophisticated b/c tagging techniques → define detector requirements**
- Note that all these measurements can be done with exclusive decays. Certainly for the charm case. For instance, a Tera-Z facility will provide ≈10^8 B^+ exclusive decays

Reduction of QCD uncertainties

- Detailed table of central values and uncertainties:

stat. unc. for 7x10^7 Z→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

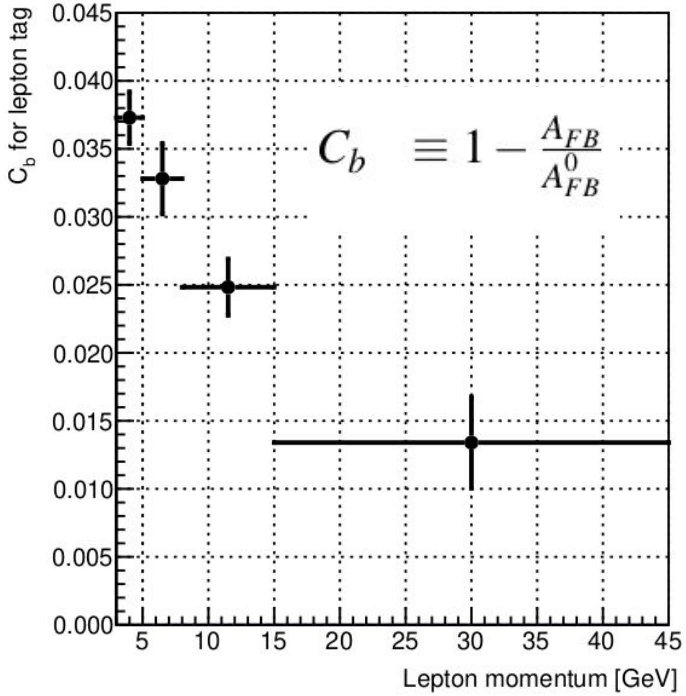
Table 9: Central values and components of the uncertainty in the measurement of the A_{FB} asymmetry with 7×10^7 $e^+e^- \to b\bar{b}(g)$ events at the Z pole, for different $\xi < \xi_0$ cuts at the reconstructed level.

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

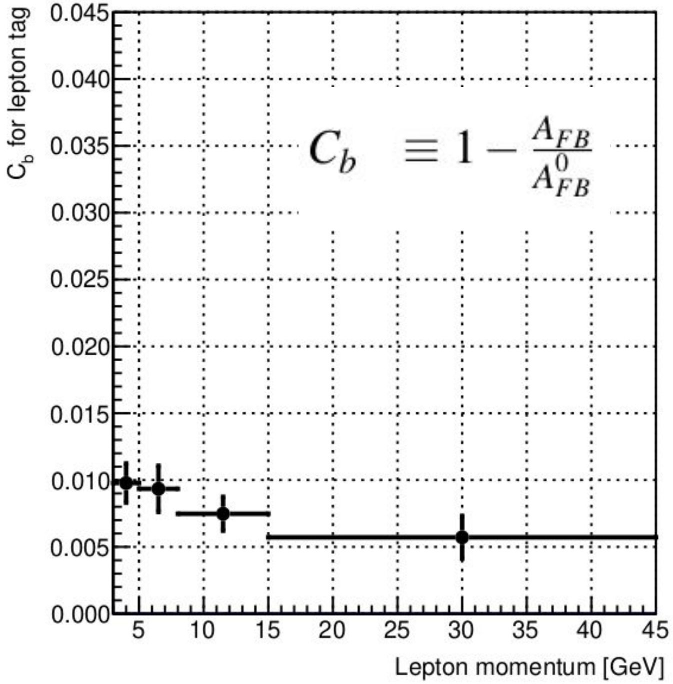
... also in semi-leptonic decays

- 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



- Significant reduction (note: p_l>3 GeV cut in preselection)
- Full realistic analysis still to be done

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:

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

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: $R_b = 0.21629 \pm 0.00066$
- **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 $[10^{-3}]$	$A_{FB}^{0,b}$ $[10^{-3}]$	$A_{FB}^{0,c}$ $[10^{-3}]$	$\mathcal{A}_b$ $[10^{-2}]$	$\mathcal{A}_c$ $[10^{-2}]$
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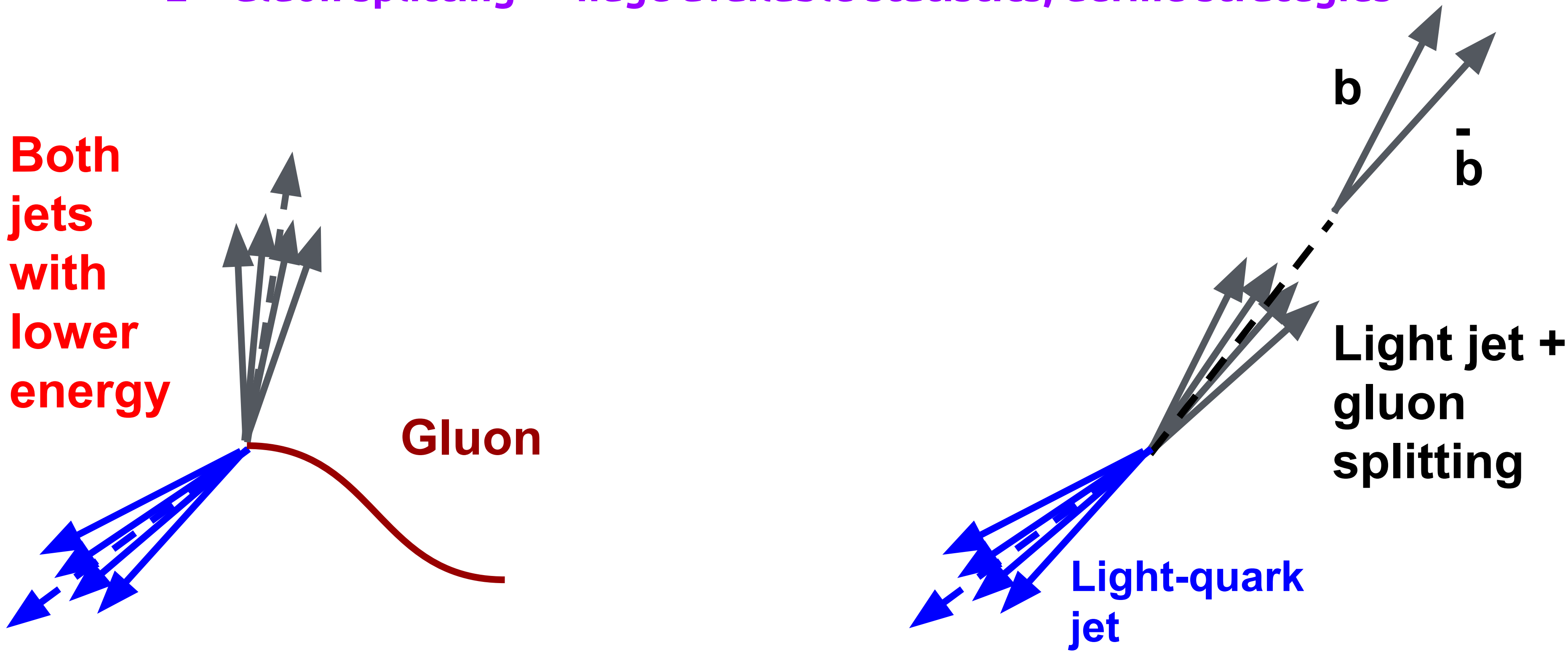
R_b, R_c

- **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**



Interest of the $e^+e^- \to \gamma\gamma$ at FCC-ee

- Process minimally affected by theoretical uncertainties:
  - Hadronic corrections only appear at the 10^{-5} level (arXiv:1906.08056)
- Measurable at "relatively" high polar angles with respect to the beam:
  - **$1/\sqrt{N}$=1.3e-5 for $|\cos\theta|<0.95$,**
  - **$1/\sqrt{N}$=2.0e-5 for $|\cos\theta|<0.7$**

(√s=91.2 GeV, assuming LO cross section and 100% acceptance)

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.

- Hopefully not much sensitive to new physics.
  - **Can we quantify a bit more the potential of this channel ?**

New physics deviations in $e^+e^- \to \gamma\gamma$

- If we stop at the s^2/Λ^4 order (justified with large statistics and well below the true scale of physics, which is guaranteed in e^+e^- collisions):

$$\left(\frac{d\sigma}{d\cos\theta}\right)_{SM+new} = \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} \left[1 + \frac{c_8\ s^2}{8\pi\alpha\Lambda^4}\ \sin^2\theta\right]$$

- **This is the only possible "leading" behavior of new physics deviations in $e^+e^- \to \gamma\gamma$. It largely simplifies the task of measuring/excluding new physics effects if we want to use this process as luminosity reference**

- Physical examples (actually all, according to the previous statement, but just in case…):
    - Excited electrons (exchanged in t-channel), large extra-dimension effects (graviton exchange in s-channel)

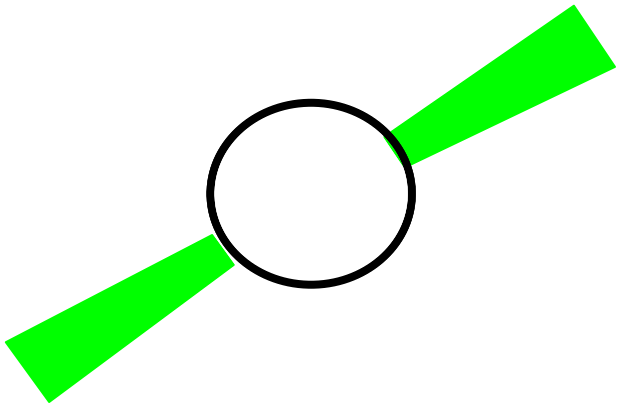
Likelihood shape fit with $|\cos\theta|<0.95$

Collider option	$\sqrt{s}$ [TeV]	L [ab^{-1}]	$\Delta\lambda$ [TeV^{-4}]	$\Delta\sigma_{NP}/\sigma_{SM}$	$\Lambda_\pm$ limit [TeV]	Λ limit [TeV]
FCC-ee	0.09	150.0	1.2	1.9×10^{-5}	0.8	1.4
FCC-ee	0.16	10.0	8.9×10^{-1}	1.3×10^{-4}	0.9	1.6
FCC-ee	0.24	5.0	3.7×10^{-1}	2.8×10^{-4}	1.1	2.0
FCC-ee	0.35	1.5	2.2×10^{-1}	7.5×10^{-4}	1.2	2.2
ILC	0.25	2.0	5.2×10^{-1}	4.6×10^{-4}	1.0	1.8
ILC	0.50	4.0	4.6×10^{-2}	6.5×10^{-4}	1.8	3.3
CLIC	0.38	1.0	2.1×10^{-1}	9.9×10^{-4}	1.2	2.3
CLIC	1.50	1.5	2.8×10^{-3}	3.3×10^{-3}	3.7	6.7
CLIC	3.00	5.0	1.9×10^{-4}	3.5×10^{-3}	7.2	13.0

- Reaching the ultimate FCC-ee limit at the Z requires $<10^{-4}$ precision in acceptance, but one can decouple SM rate and new physics effects
  - a simultaneous fit to both the measured SM rate and λ can be envisaged

Some thoughts on systematics control

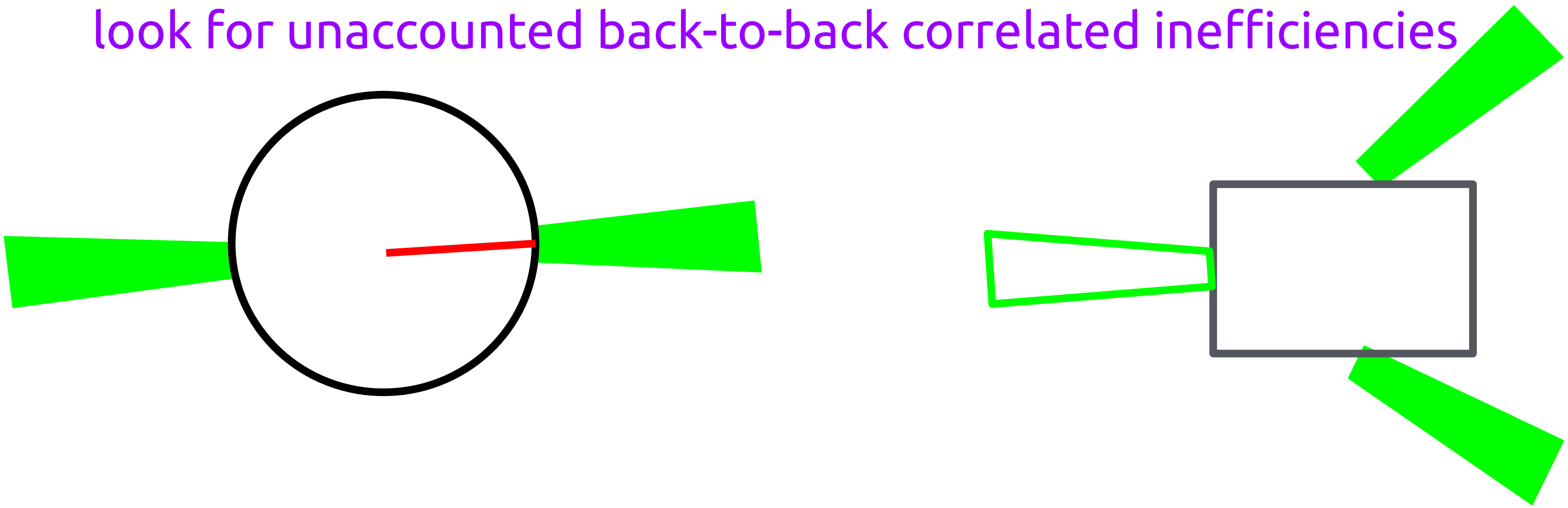
- Mostly based on past LEP2 experience:
  - Use relatively soft em-shape criteria to keep selection systematics under control
  - Use (loose) acollinearity cuts to reduce the size of radiative corrections (LEP2 studies). This also rejects additional high-energy (ISR) photons in the beam pipe



  - Compact detector is a must. Minimize barrel-endcap gaps or just eliminate that region in analysis in a limit case
  - Edge effects and precise measurement of the fiducial region also important (like in the $\mu\mu$ case, I guess)

Some thoughts on systematics control

- Accounting for percent effects:
  - Control sample: events with 1 good photon with zero track activity and another "loosely tagged" photon: stronger acollinearity cuts and electromagnetic energy
    - Measure/correct photon conversion probability and fermion-pair FSR on loosely tagged photons
    - Measure/correct electron identification acceptance on loosely tagged photons with zero track activity
    - Maybe a good idea to measure everything in a kind of global fit
  - Use acolinear $\gamma\gamma$ (or ee) events (hard photon in the beam pipe) to look for unaccounted back-to-back correlated inefficiencies



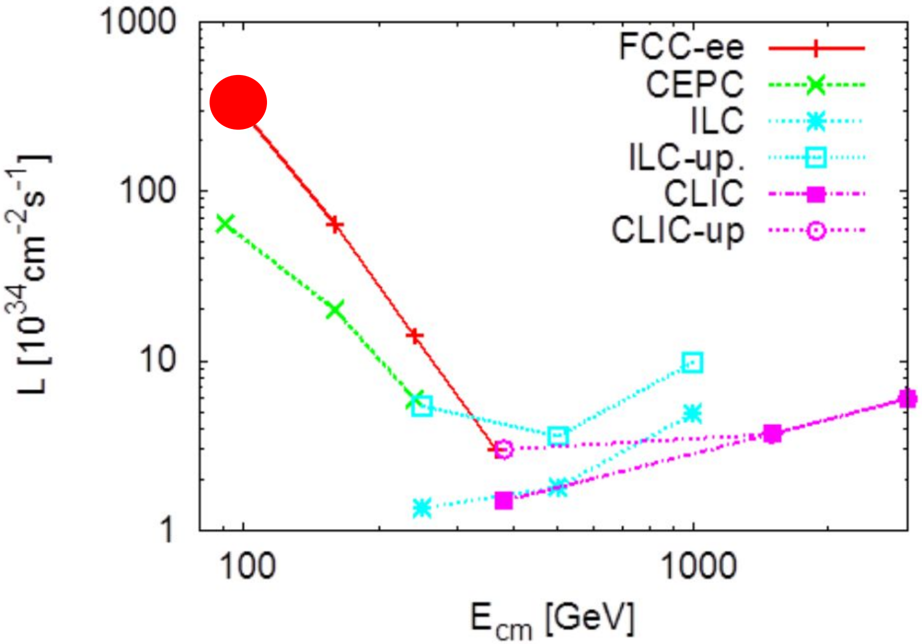
Summary/outlook

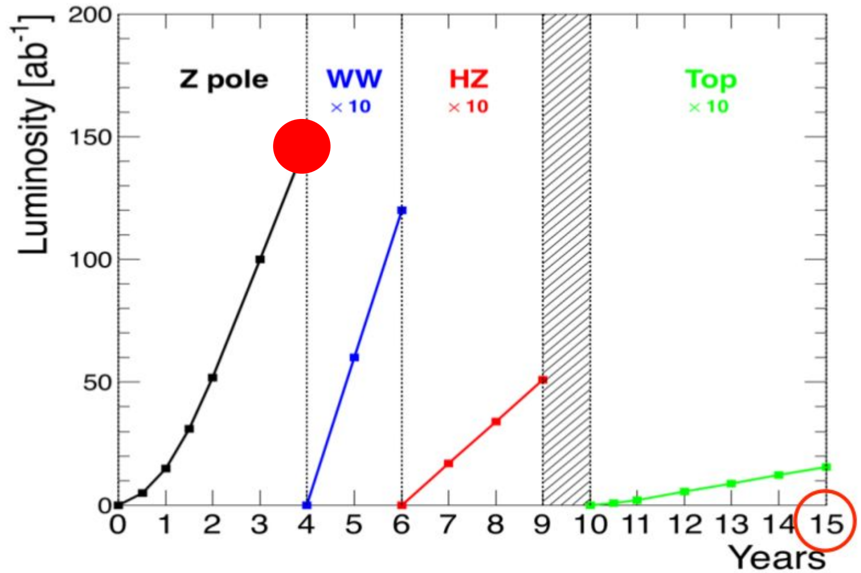
- **Advancing in the EW front:**
  - ppm precision measurements: fine-tuning simulations and experimental techniques to keep systematics under control
  - b/c/τ front: significant step beyond LEP status/precision, refining experimental strategies to reduce systematics to a minimum
  - ee$\rightarrow\gamma\gamma$: $\approx 10^{-5}$ precision measurement in acceptance/efficiency/backgrounds possible, independently of new physics deviations $\Rightarrow$ luminosity measurement beyond 10^{-4} precision feasible

- **Significant amount of work ahead, but prospects are exciting !!**

Backup

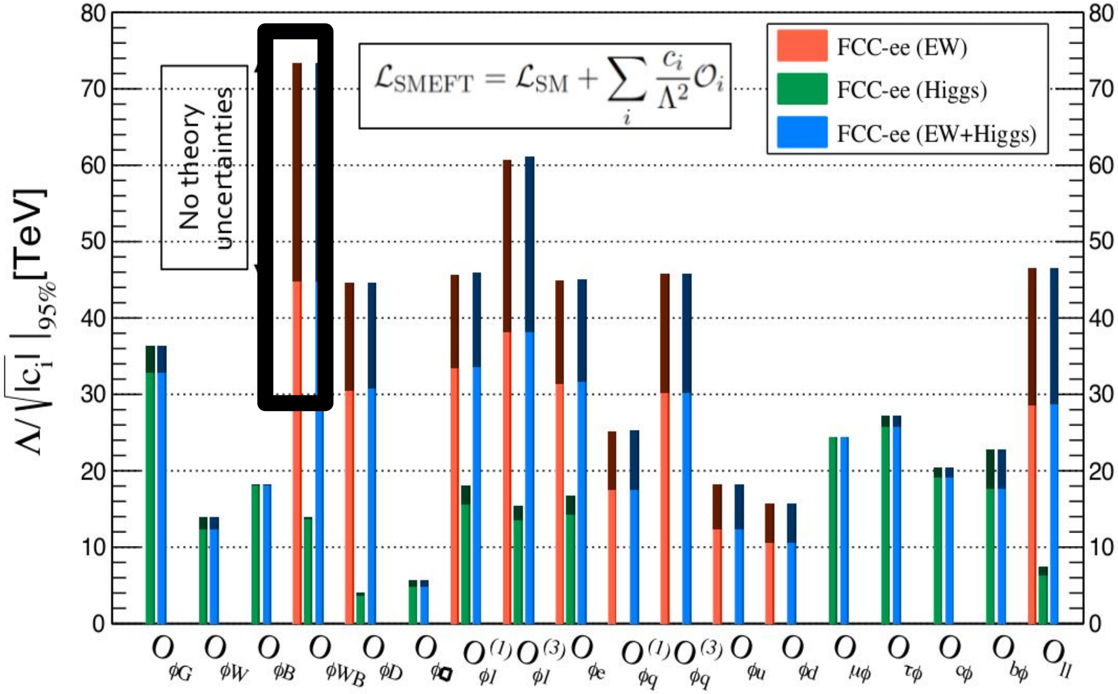
FCC-ee context

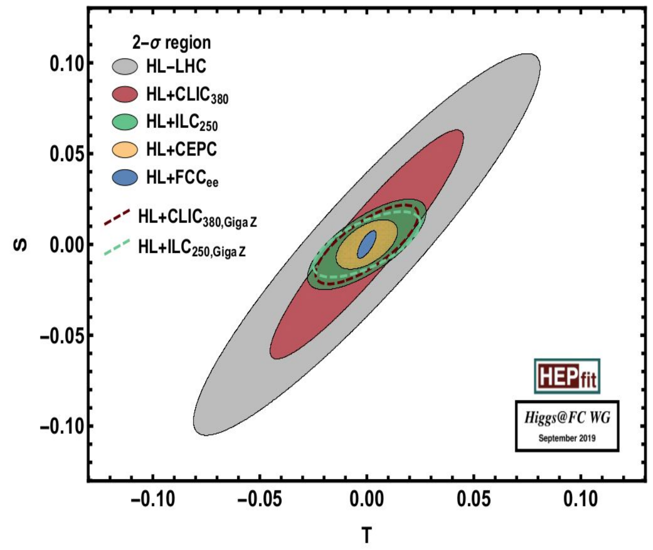


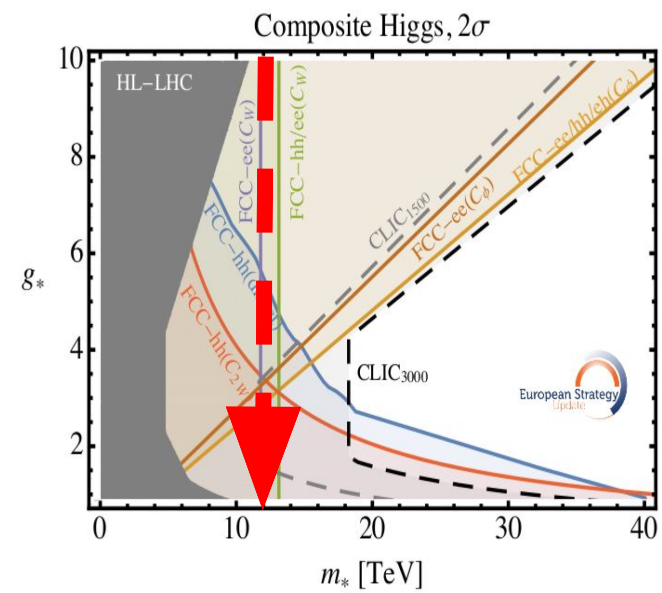


- FCC-ee: 150 ab^{-1}, 5 x 10^{12} Z decays in ≈ 4 years of running at the Z pole
- Extraordinary √s precision: 100 keV at the Z, 300 keV at WW threshold → exquisite control of beam uncertainties (average, width, systematics)
- Aiming for up to ≈ 100 times better precision than LEP/SLD on several electroweak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

Physics potential of Tera-Z







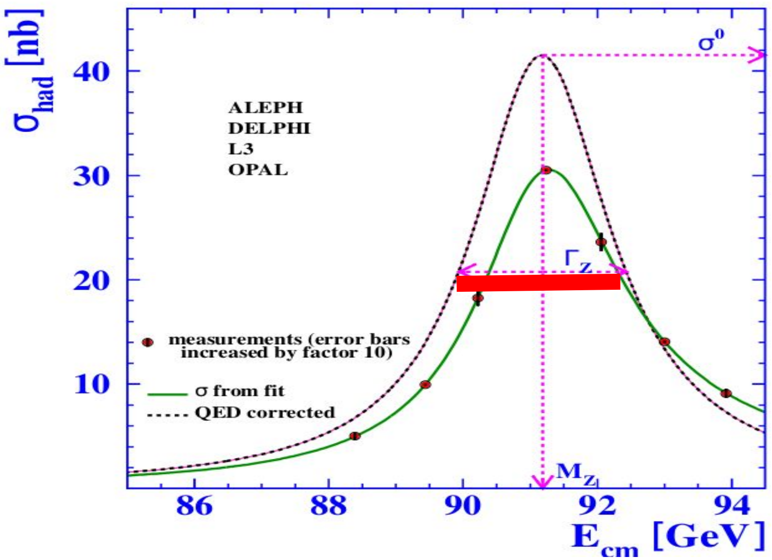
- **Efficiently probing the 10-TeV scale for universal new-physics effects (Higgs compositeness, ...) with just a few years of EW running at the FCC-ee:**
  - Strong constraints on the S parameter ($O_{\phi WB}$, O_W+O_B in SILH, ...)
  - Also on the T parameter (violations of custodial symmetry)

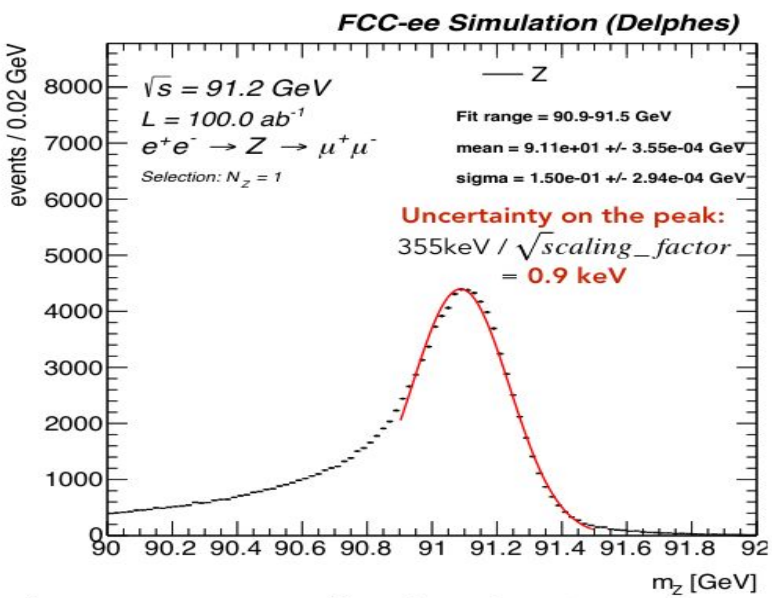
Summary table

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 bb to hadrons stat. extrapol. from SLD
σ^0_{had} ($\times 10^3$) (nb) $N_\nu(\times 10^3)$	41541 ± 37 2996 ± 7	**0.1** **0.005**	4 1	peak hadronic cross section luminosity measurement 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, $\sin^2\theta_W^{eff}$

Examples: Γ_Z, $\sin^2\theta_W^{eff}$





- Total Z width → basically coming from the visible width of the lineshape
- $\sin^2\theta_W$ effective: g_V/g_A coupling ratio → forward-backward charge asymmetries (most precise in $\mu\mu$ in final state)
- **3 energy points (≈88, 91.2, 94 GeV)**

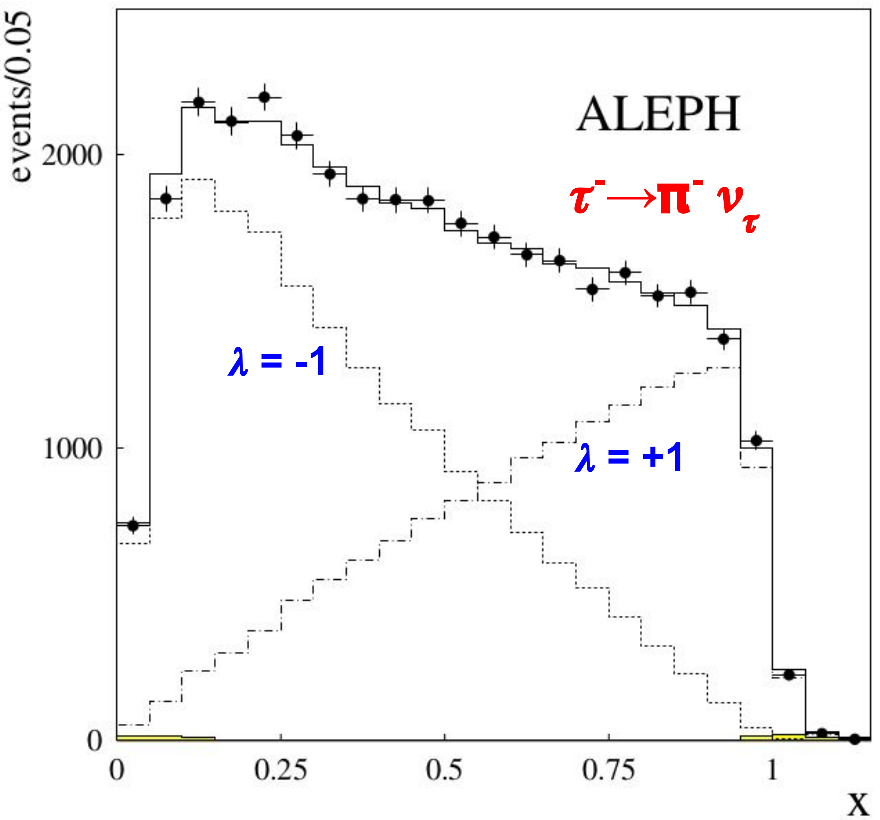
- **Development of utilities/generators to study in mch more detail point-to-point energy uncertainties, momentum-scale effects, … , taking into account beam-energy spread, ISR, eventually initial-final state interference effects (E. Leogrande, E. Perez, P. Janot, …)**

HF-EW summary table

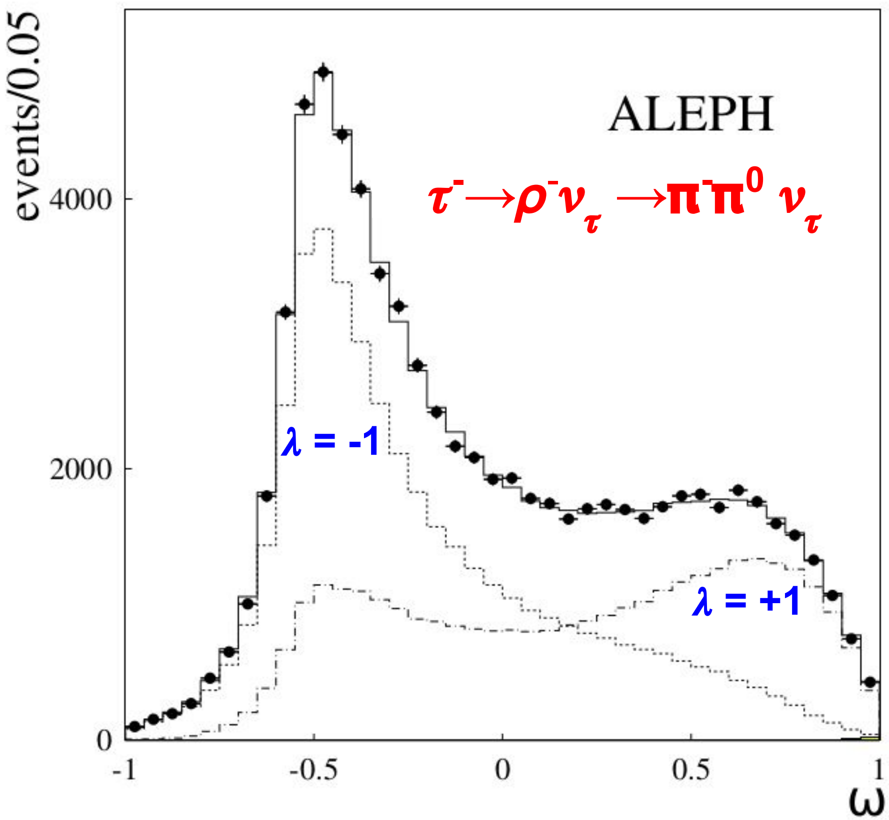
Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
$A_{FB}^{b}, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
R_b $(\times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

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

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.

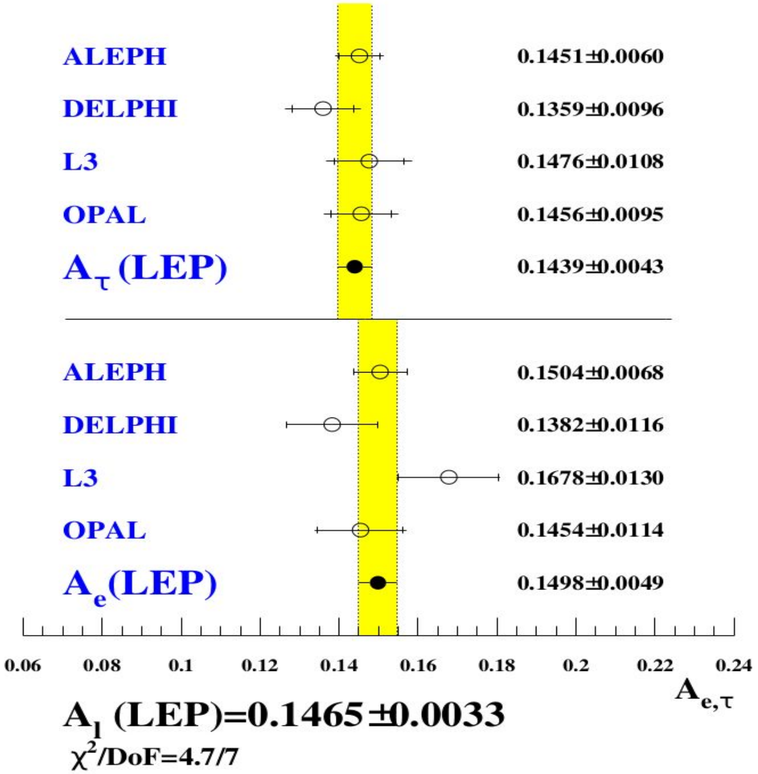
ALEPH

	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 $\pi 0 \rightarrow \gamma\gamma$ identification**
- **Photon separation / π^0 identification was still the dominant systematics**

A_e is slightly different...

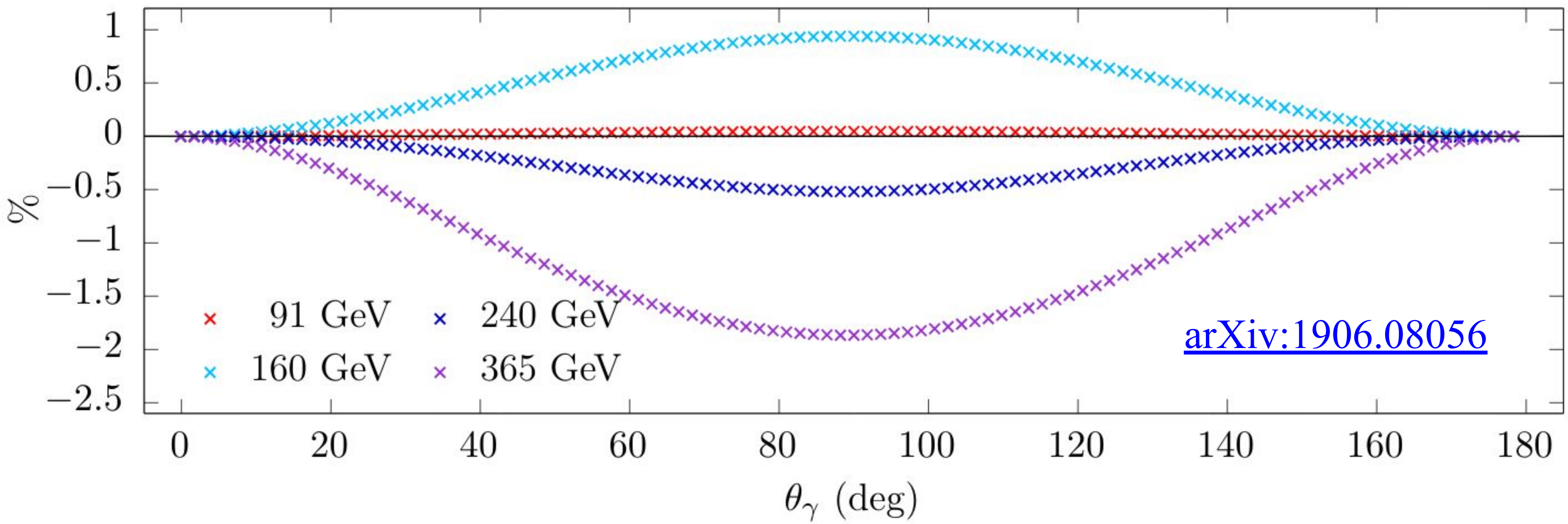
Experiment	$\mathcal{A}_\tau$	$\mathcal{A}_e$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$	$0.1504 \pm 0.0068 \pm 0.0008$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$	$0.1382 \pm 0.0116 \pm 0.0005$
L3	$0.1476 \pm 0.0088 \pm 0.0062$	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$	$0.1454 \pm 0.0108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



- Note that $\mathcal{A}_e$ ($\equiv$ $-P_\tau^{FB}$) is much less affected by systematic uncertainties, because forward-backward asymmetry measurements are largely independent of (charge symmetric) acceptance uncertainties

By-products

- **Do QED radiative corrections include anyway terms equivalent to SM deviations of this $\sin^2\theta$ type ?**



Relative contribution of the weak NLO corrections to the ee→$\gamma\gamma$ cross section (which approximately follows a $\sin^2\theta_\gamma$ dependence)

Some thoughts on systematics control

- These ideas could be tested on realistic simulations, of course, but several of them could be just tested at the generator level (to be done)
  - Generator level:
    - gamma*->fermion-pair contributions
    - Rates of collinear vs acollinear photons
  - Simulation level:
    - Rate of conversion effects (much smaller for pixel+TPC ?)
    - Homogeneity of calorimeter, back-to-back effects, holes, ...

- We will be hardly able to conclude on an optimal polar angle cut before time is due. Typically, problems related with acceptance, electromagnetic identification or the presence of additional tracks / photons are more disturbing at the large $|\cos\theta|$ edges, while the sensitivity loss by going more central is not so big.

- Not clear whether detailed simulations will offer much more than approximate simulations to conclude whether 10^{-5} precisions (or $\approx 10^{-4}$ precision in a local $\cos(\theta)$ region) are reachable/realistic...