Electroweak Heavy Flavor physics at FCC-ee (LoI #152)

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Electroweak Heavy Flavour (bottom, charm,tau) at the FCC-ee

Letter of Interest submitted to Snowmass 2021

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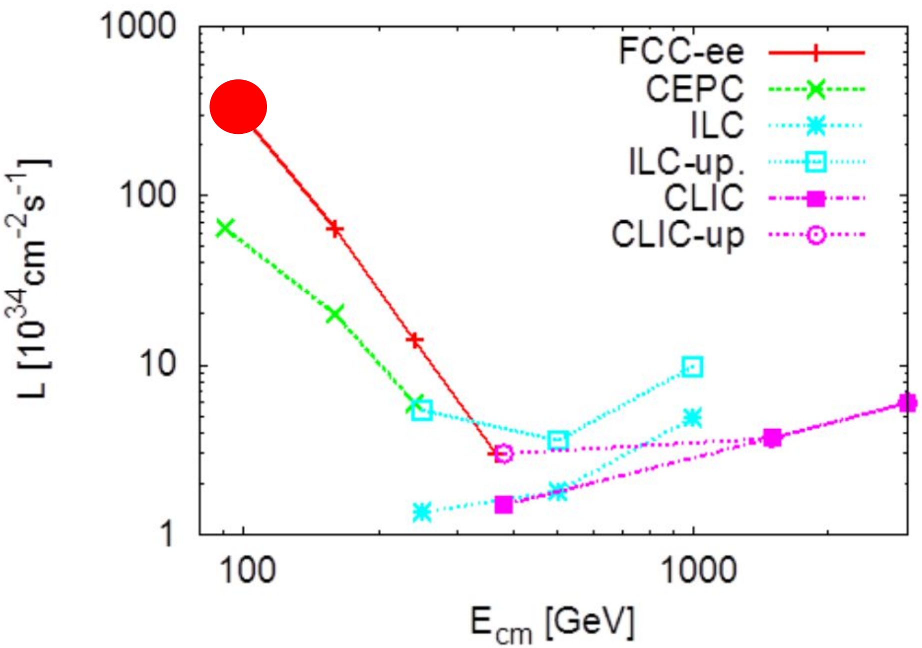
LoI #152

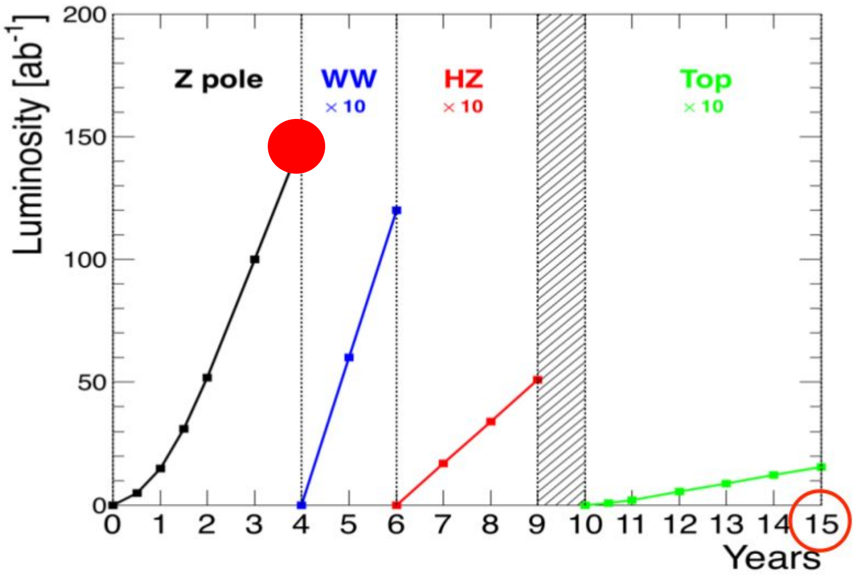
Abstract

The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100 km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100 TeV proton-proton collisions in the same infrastructure [1]. In addition to an essential and unique Higgs program, it offers powerful opportunities for discovery of direct or indirect evidence for BSM physics, via a combination of high precision measurements and searches for forbidden or rare processes, and feebly coupled particles.

A key element of the FCC-ee physics program is, thanks to the huge Z statistics, the ability to provide a complete determination of the chiral couplings of the Z to fermions via a combination of total widths, decay rates and forward-backward or polarization asymmetries, with a leap in precision of up to two orders of magnitude. In this LOI we focus on some of the heavy flavour observables (b, c, τ). The ultimate goal, that experimental and theory systematic errors match the statistical accuracy, leads to highly demanding requirements on detector design and on theoretical calculations. This letter of interest describes some of the many challenges presented by these benchmark measurements.

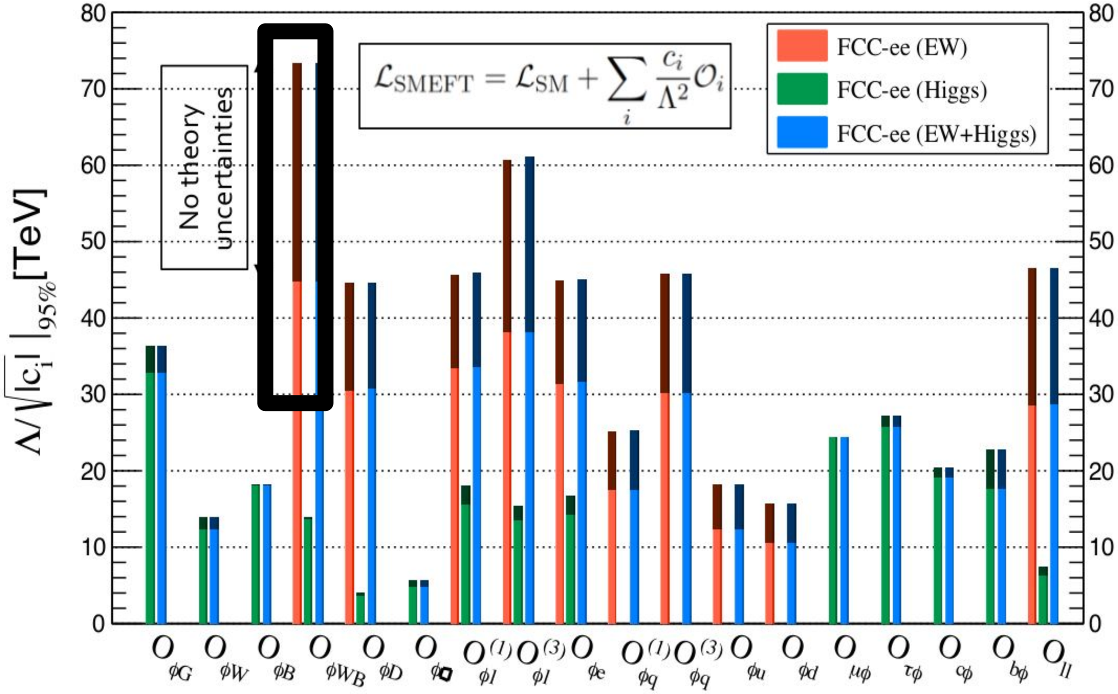
FCC-ee context

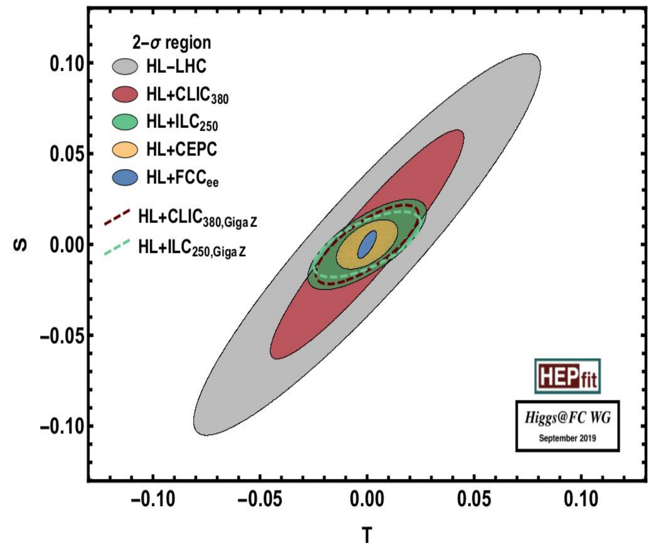


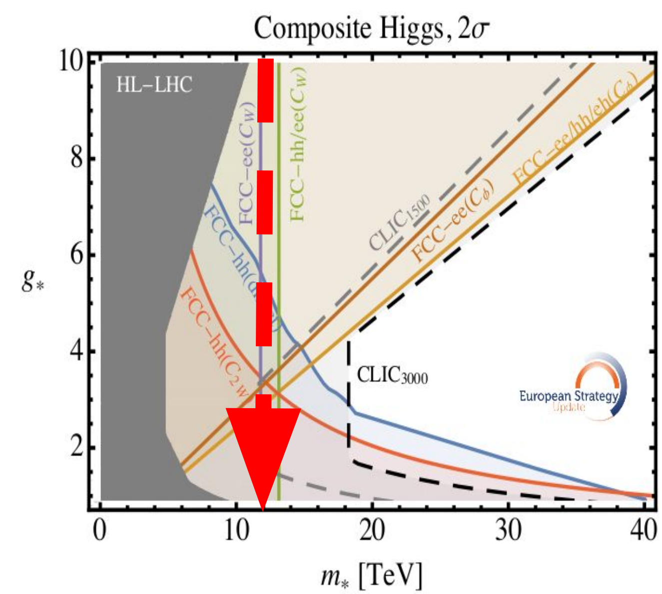


- FCC-ee: 150 ab^{-1}, 5 x 10^{12} Z decays in ≈ 4 years of running at the Z pole
- Extraordinary √s precision: 100 keV at the Z, 300 keV at WW threshold → exquisite control of beam uncertainties (average, width, systematics)
- Aiming for up to 20-100 times better precision than LEP/SLD on most electroweak precision observables (EWPO)
- **Current challenges: reduce uncertainties, establish theory / detector / machine requirements to reach the ultimate precision**

Physics potential of EWPO







- **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

This LoI: HF EW precision observables

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 bb to hadrons stat. extrapol. from SLD

- **Current projections: $\gtrsim$ 20 times better than current precision**

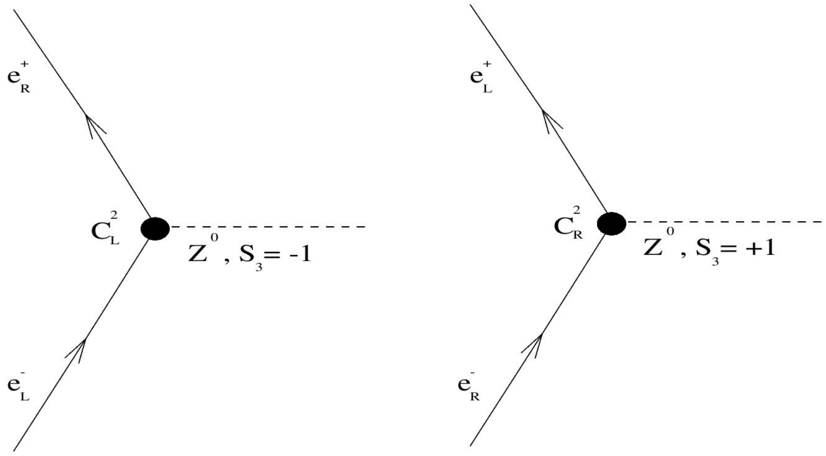
τ polarization, $\mathcal{P}_\tau$

$$\mathcal{P}_\tau \rightarrow \text{access to } \frac{v_e}{a_e}, \frac{v_\tau}{a_\tau} \;:$$

$$\frac{v_\ell}{a_\ell} = (1 - 4\sin^2\theta_\ell^{\text{eff}})$$

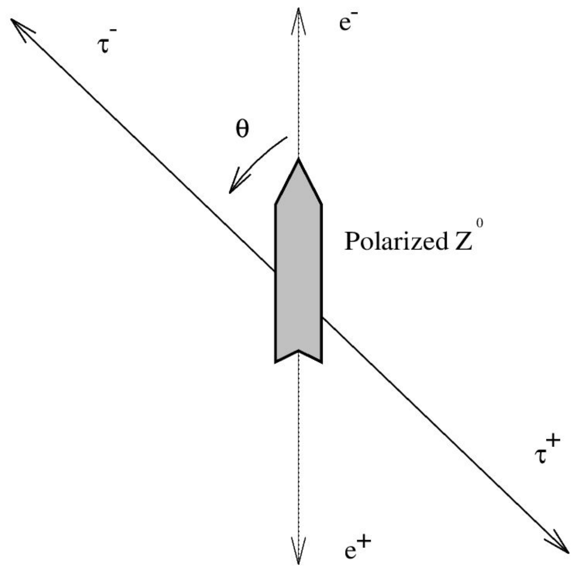
Tau polarization: A_τ , A_e

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

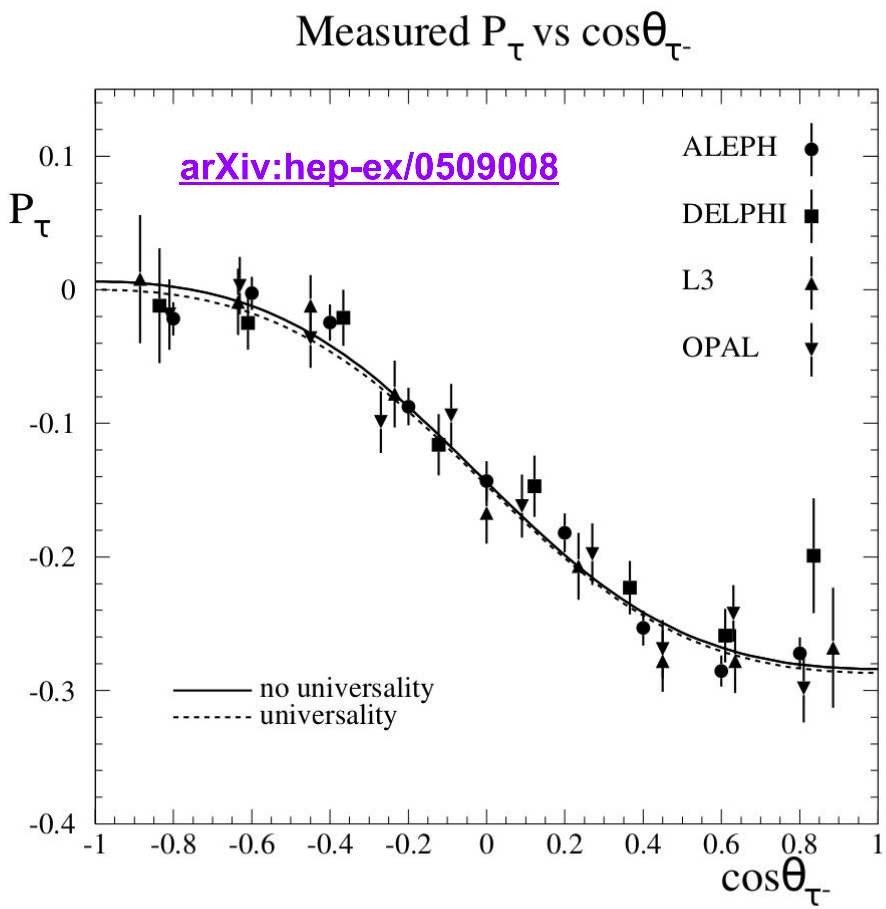


$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$

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

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

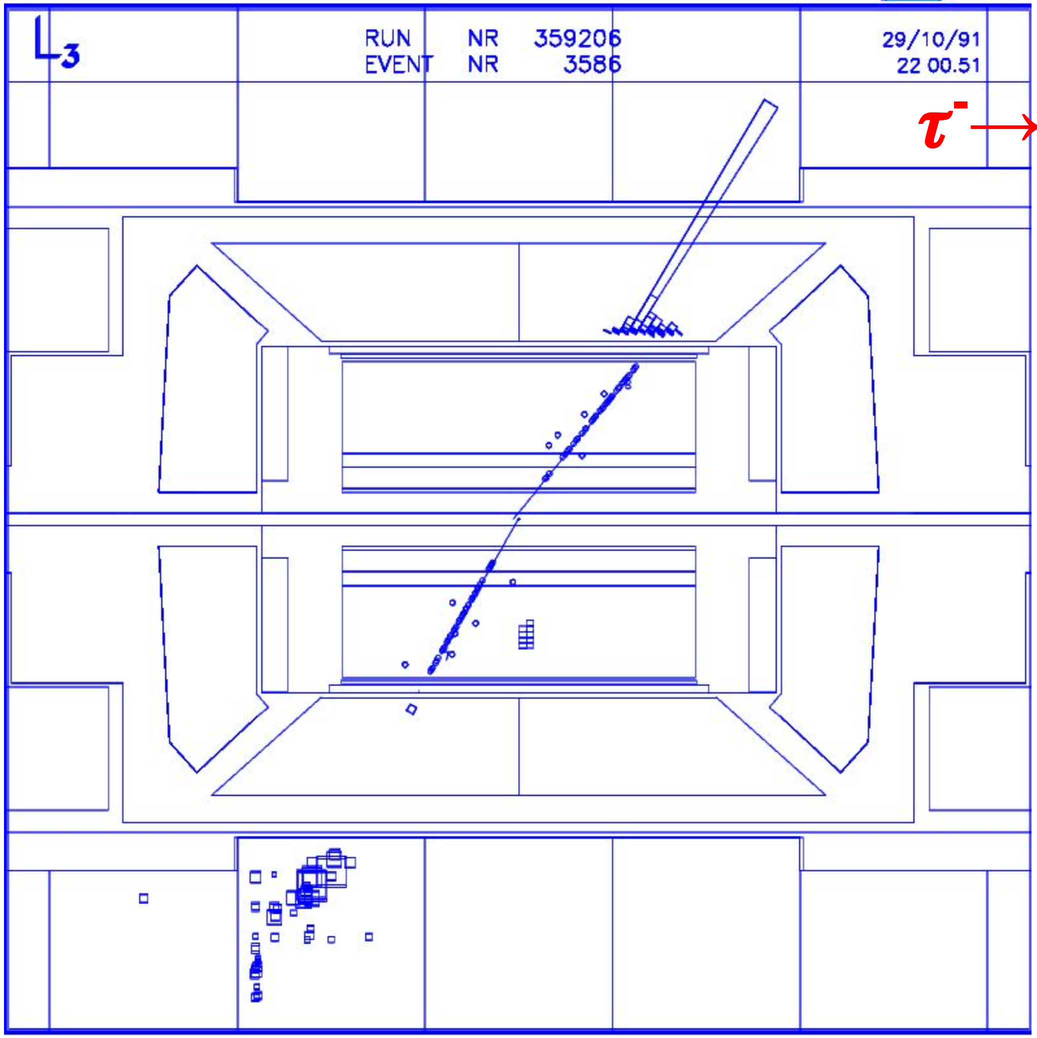
Tau polarization: A_τ , A_e



- **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 facilitate precise measurements of the L-R asymmetry parameters for all fermions: A_e,A_μ,A_τ, A_b,A_c

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

Most sensitive channels

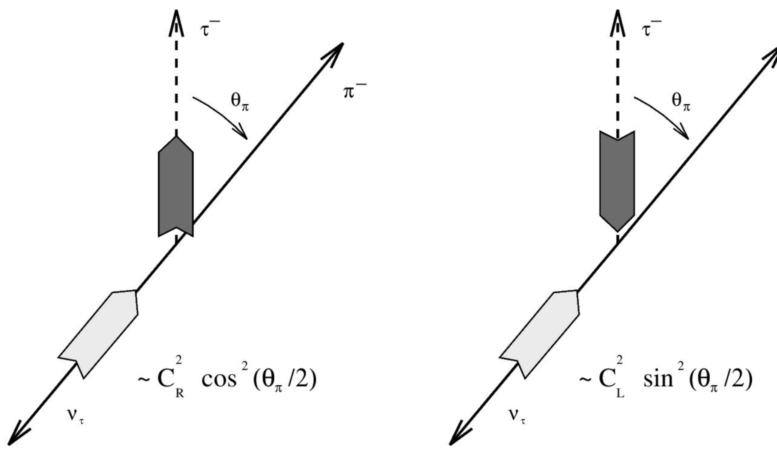


$\tau^- \to \rho^- \nu_\tau \to \pi^- \pi^0 \nu_\tau$

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

Most sensitive channels

Pseudo-scalar: $\tau^- \to \pi^- \nu_\tau$
(π,K 1-prong decays ≈13%)

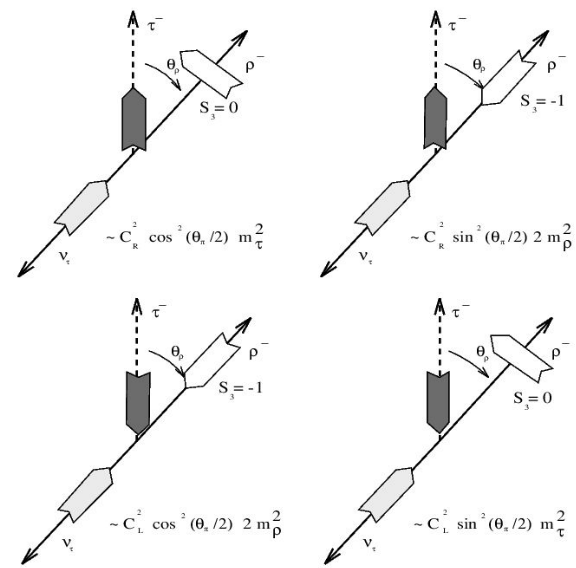


More $\cos\theta_\pi$ ⇒ more E_π^{LAB}

$$\frac{dN}{dx} \propto 1 - \xi + \mathcal{P}_\tau\,(2x - 1 - \xi)$$

($x = E_\pi^{LAB}/E_B$, $\xi = m_\pi^2/(2m_\tau)$
)

Vector: $\tau^- \to \rho^- \nu_\tau \to \pi^-\pi^0\, \nu_\tau$
(ρ,K* 1-prong decays ≈25%)



$$\frac{dN}{dx} \propto 1 - \xi + \alpha_R \mathcal{P}_\tau\,(2x - 1 - \xi)$$

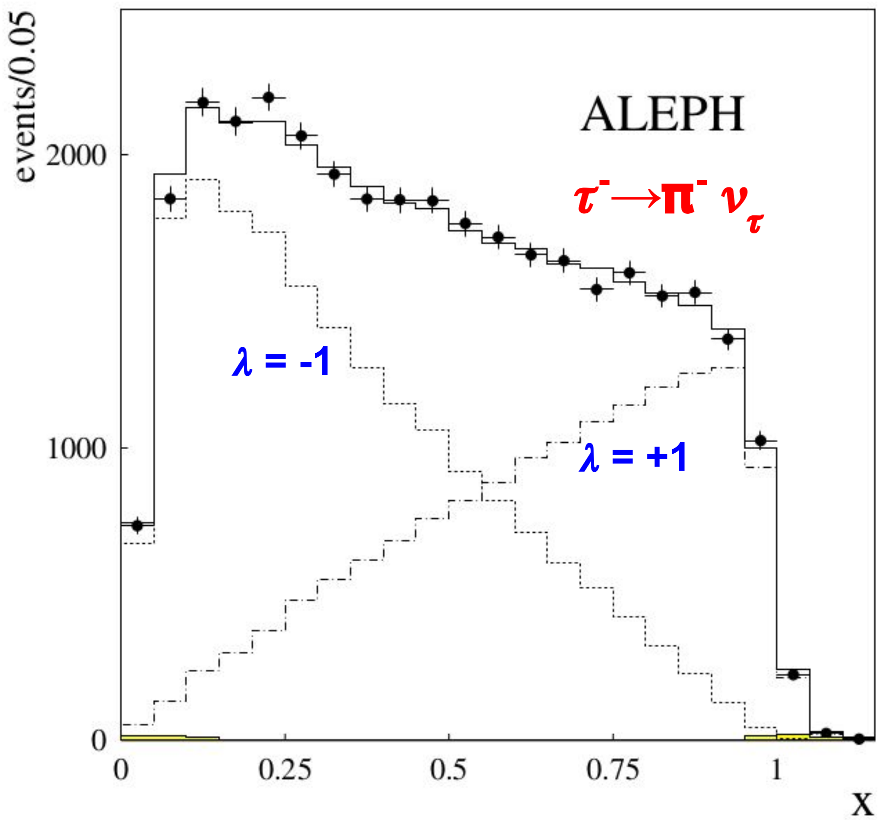
($\alpha_R = (m_\tau^2 - 2m_\rho^2)/(m_\tau^2 + 2m_\rho^2)$)

Loss of sensitivity due to dilution almost recovered using just 1 optimal variable ω:

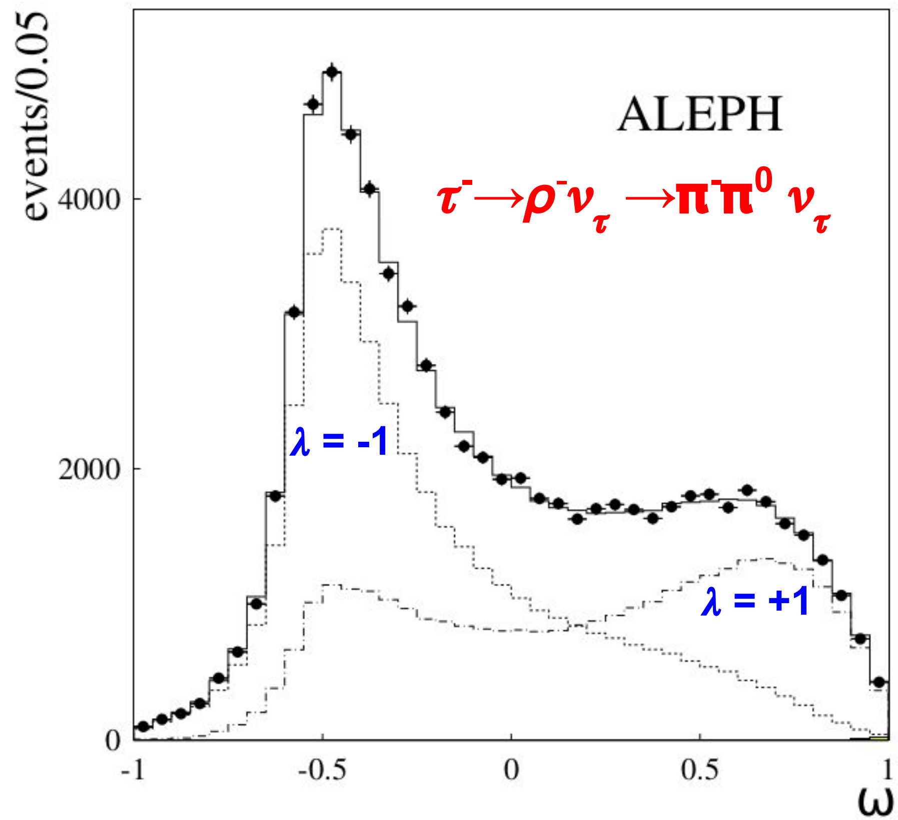
$$\hat{\xi} \equiv \text{phase space variables} \rightarrow$$

$$\frac{1}{N}\frac{dN}{d\hat{\xi}} = f(\hat{\xi})\,(1 + \mathcal{P}\,\omega)$$

Analysis at LEP



($x=E_\tau/E_{beam}$)



(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.

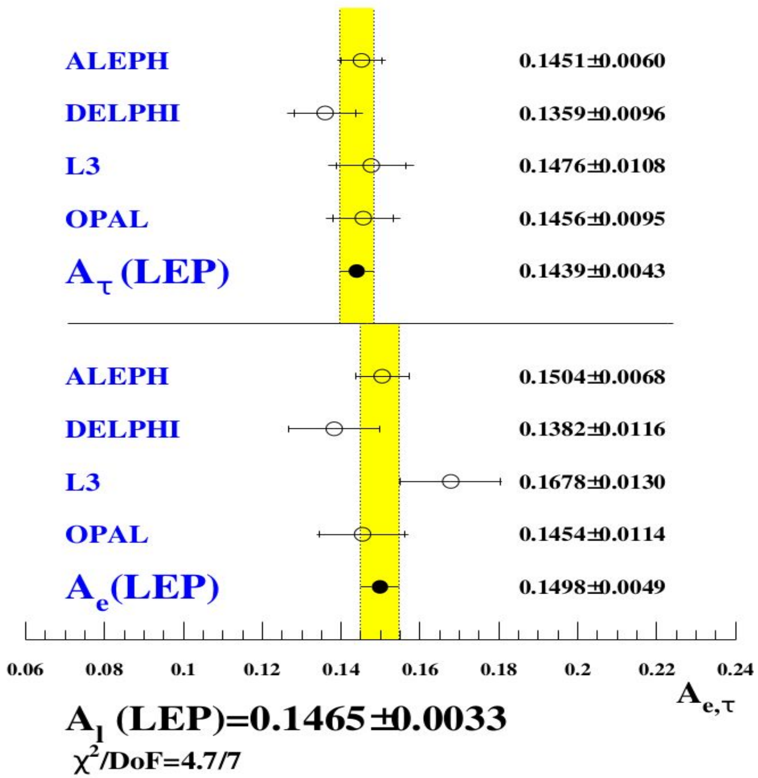
ALEPH

	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

$A_{FB}(Q)$, Q=b,c

Assuming $\frac{v_e}{a_e}$ precisely known :

$$\mathcal{A}_{FB}(b) \rightarrow \frac{v_b}{a_b} = (1 - \frac{4}{3}\sin^2\theta_b^{\text{eff}})$$

$$\mathcal{A}_{FB}(c) \rightarrow \frac{v_c}{a_c} = (1 - \frac{8}{3}\sin^2\theta_c^{\text{eff}})$$

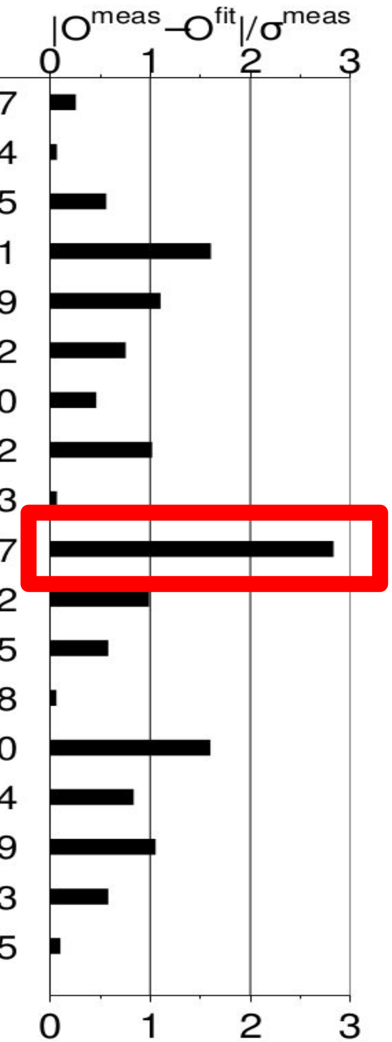
Present status of $A_{FB}(Q)$

- 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



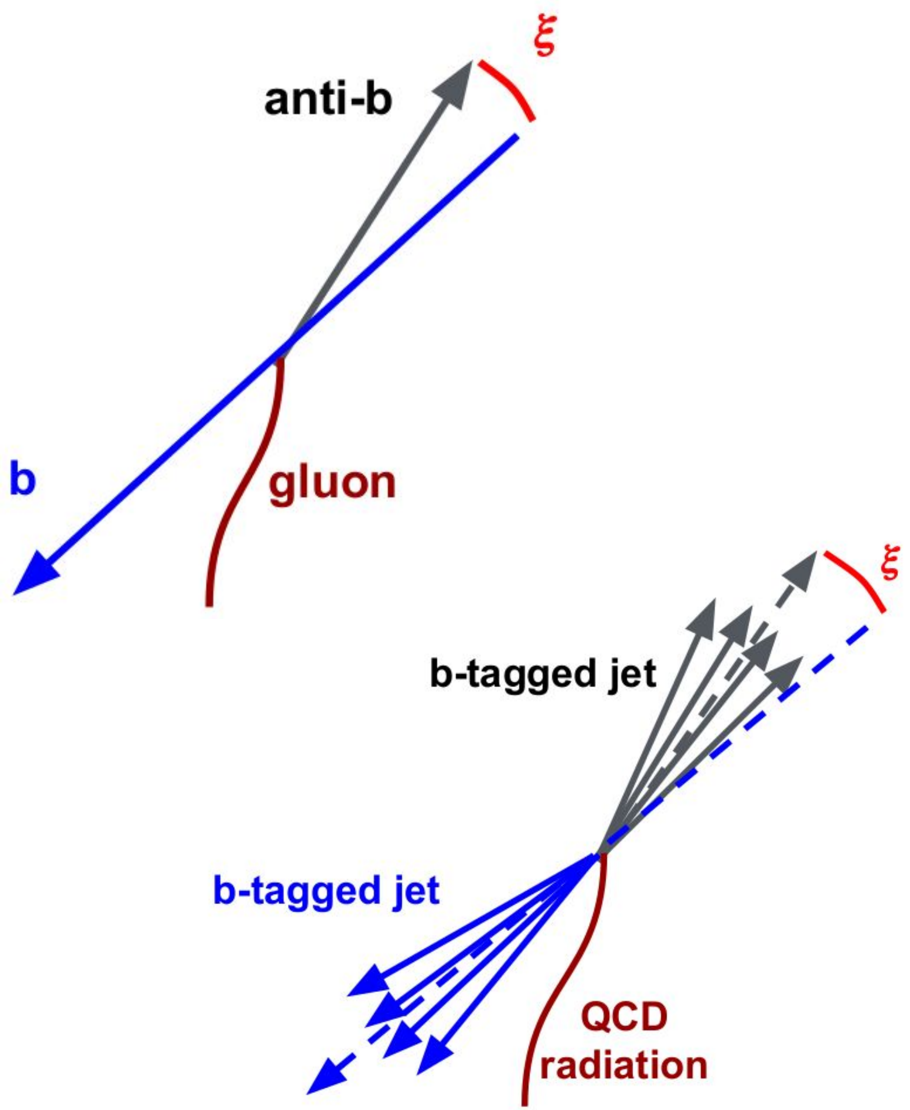
Present status of $A_{FB}(Q)$

- 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 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

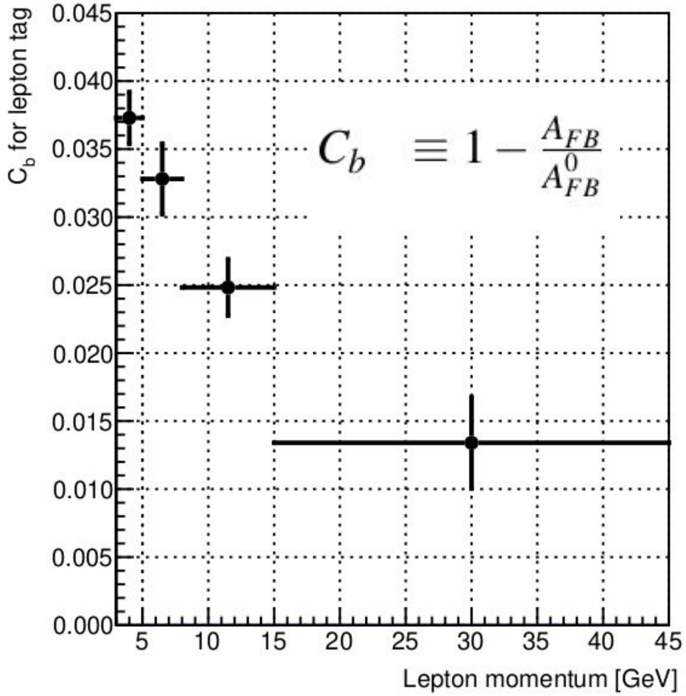
Table 9: Central values and components of the uncertainty in the measurement of the A_{FB} asymmetry with 7×10^7 $e^+e^- \to b\bar{b}(g)$ events at the Z pole, for different $\xi < \xi_0$ cuts at the reconstructed level.

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

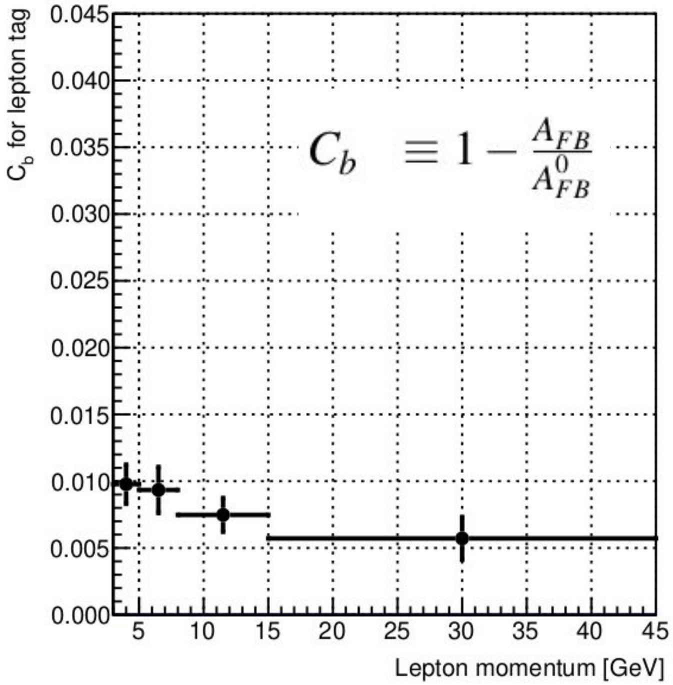
... also in semi-leptonic decays

- 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

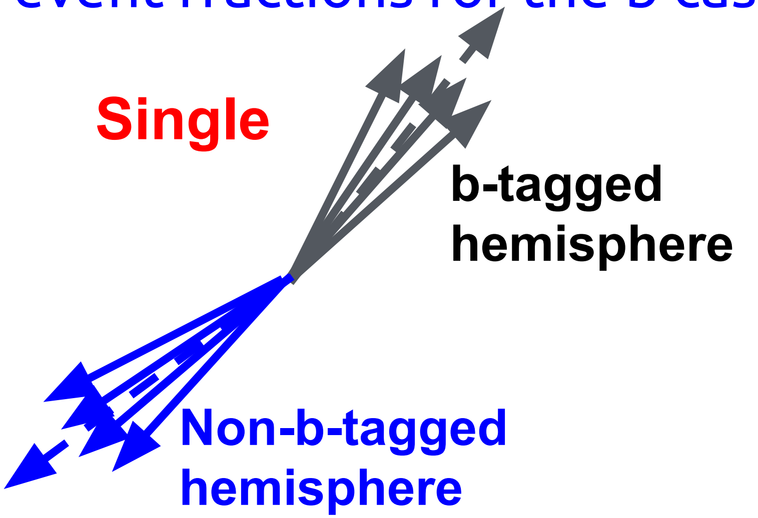
R_b, R_c

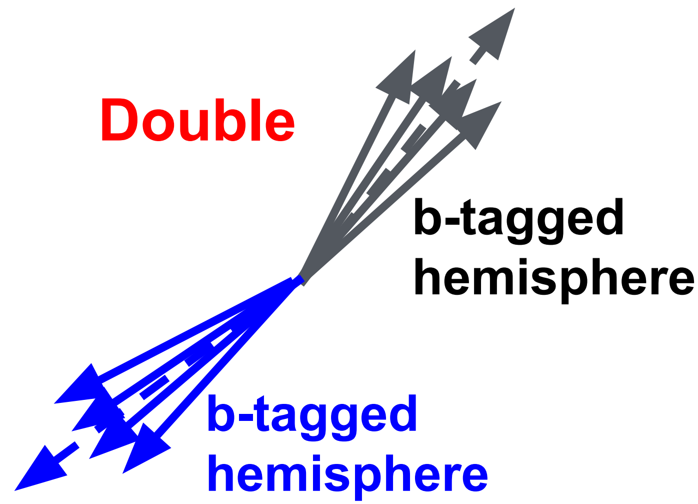
$$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{had}}, \quad R_c = \frac{\Gamma_{c\bar{c}}}{\Gamma_{had}}$$

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 ± 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^0_b $[10^{-3}]$	R^0_c $[10^{-3}]$	$A^{0,b}_{FB}$ $[10^{-3}]$	$A^{0,c}_{FB}$ $[10^{-3}]$	$\mathcal{A}_b$ $[10^{-2}]$	$\mathcal{A}_c$ $[10^{-2}]$
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
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$B(D^+ \to K^-\pi^+\pi^+)$	0.09	0.2	0	0.1	0	0
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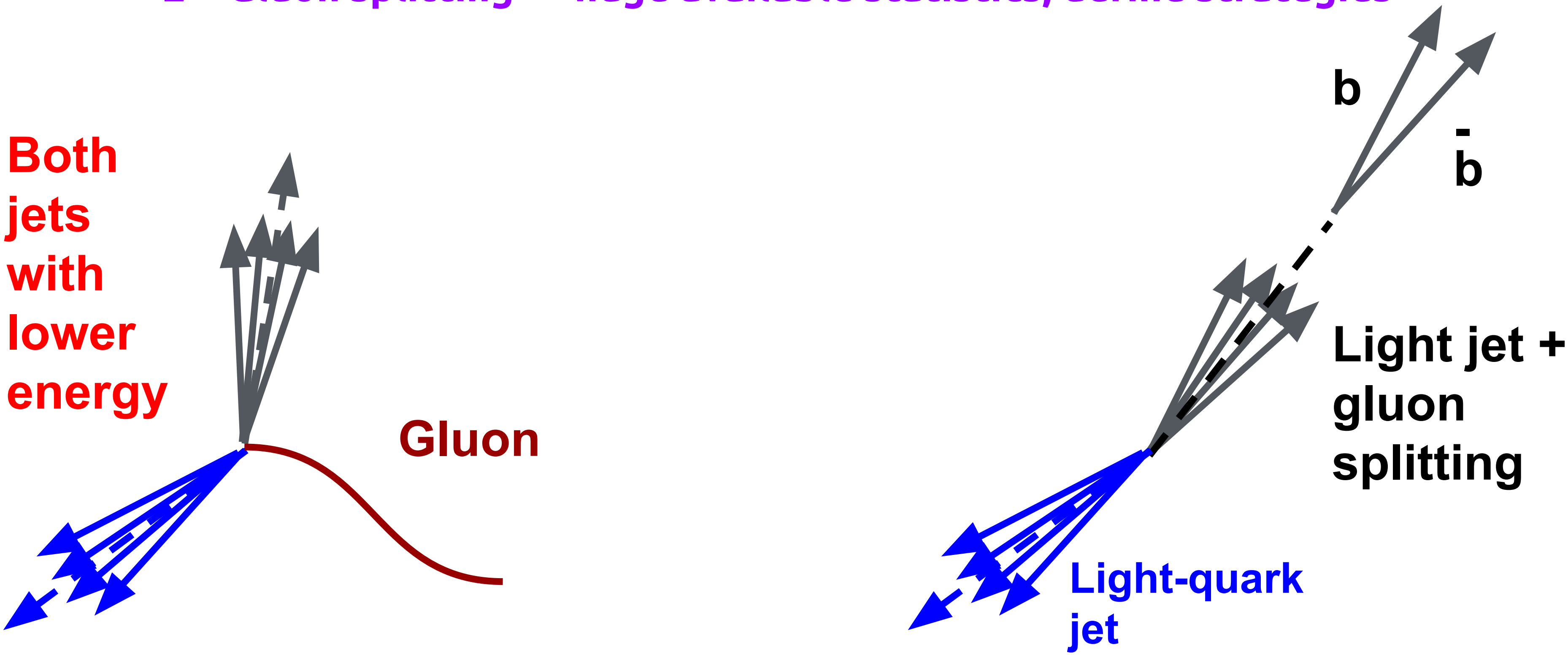
total error	0.66	3.0	1.6	3.5	2.0	2.7

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**



Summary/Outlook

- A few years of Tera-Z running should provide EWPO measurements in the heavy flavor sector with ≳20 times the current precision, thus giving early access to 3rd generation univeral and flavor-dependent new physics effects at the ≈10 TeV scale:
  - P_τ, A_{FB}(b/c), R_b, R_c

- Systematics will be the limiting factor in all these measurements ⇒ more detailed studies needed to estimate the ultimate precision. Reducing associated uncertainties via:
  - theory developments
  - new analysis strategies
  - optimized detector design

- Significant amount of work still to be done...