QCD uncertainties in forward-backward asymmetries of b-quarks in e^+e^- at the Z pole

FCC week 2019

Brussels, 27th June 2019

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Couplings of the Z boson to fermions

- SM electroweak interaction Lagrangian in terms of weak & e.m. currents:

$$\mathcal{L} = g\vec{J}.\vec{W} + g' J^Y B = \frac{g}{\sqrt{2}}(J^- W^+ + J^+ W^-) + \frac{g}{\cos\theta_W}(J^3 - \sin^2\theta_W J^{EM})Z^0 + eJ^{EM}A^0$$

W± couplings of strength g to weak-isospin J±

Z neutral couplings: mixed weak-isospin J^3 + e.m.

γ couplings of strength e

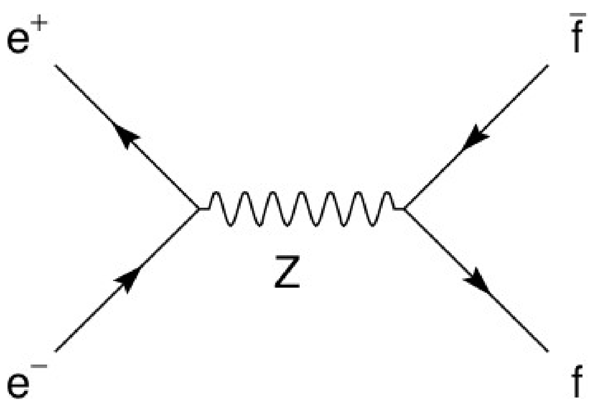
Weak-isospin (I_3), hypercharge (Y) & e.m. (Q) couplings & charges:

$$g\sin\theta_W = g'\cos\theta_W = e, \quad \sin^2\theta_W = 0.22$$

$$Q = I_3 + \frac{Y}{2} \qquad J^{EM} = J^0 + \frac{1}{2}J^Y$$

- Electron-positron annihilation into fermions: $e^+e^- \to Z \to$ ffbar

Z boson has left-handed (from J^3,J^{em}) & right-handed (from J^{em}) couplings to fermions:



$$g_L = I_3 - Q\sin^2\theta_W \qquad g_R = -Q\sin^2\theta_W$$

These are usually expressed as vector and axial-vector couplings c_V and c_A:

$$c_V = g_L + g_R = I_3 - 2Q\sin^2\theta_W \qquad c_A = g_L - g_R = I_3$$

and the vertex coupling for a neutral current interaction is written:

$$i\frac{g}{\cos\theta_W}\gamma^\mu \frac{1}{2}(c_V - c_A\gamma^5)$$

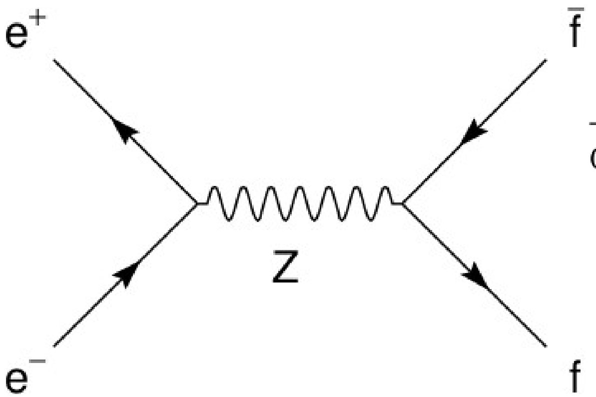
Note that c_V and c_A have different values for different types of fermion.

Lepton	$2c_V$	$2c_A$	Quark	$2c_V$	$2c_A$
ν_e, ν_μ, ν_τ	1	1	u, c, t	$1 - \frac{8}{3}\sin^2\theta_W$	1
e, μ, τ	$-1 + 4\sin^2\theta_W$	-1	d, s, b	$-1 + \frac{4}{3}\sin^2\theta_W$	-1

Z couplings depend on the fermion Q,I_3 (i.e. diff. for diff. lepton/quark type)

Forward-backward $e^+e^- \to f\bar{f}$ asymmetries

- Mixed Z vector & axial-vector couplings induce asymmetries in angular distributions of the final-state fermions (a part from e± helicity, and polarization of the produced particles) fully determined by weak mixing angle:



$$\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{3}{8}\sigma^{tot}_{f\bar{f}}\left[(1-\mathcal{P}_e\mathcal{A}_e)(1+\cos^2\theta) + 2(\mathcal{A}_e-\mathcal{P}_e)\mathcal{A}_f\cos\theta\right]$$

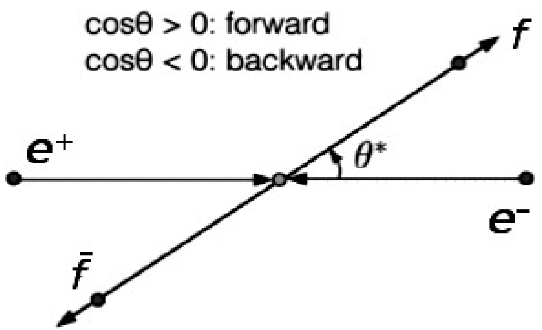
$$\mathcal{A}_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2+g_{Af}^2} = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2}\,.$$

$$\frac{g_{Vf}}{g_{Af}} = 1 - \frac{2Q_f}{T_3^f}\sin^2\theta^f_{eff} = 1 - 4|Q_f|\sin^2\theta^f_{eff}$$

- Experimentally: Take ratio of number of forward (backward) (anti)fermions in hemisphere defined by the direction of the e^- (e^+) beam: θ < (>) π/2.

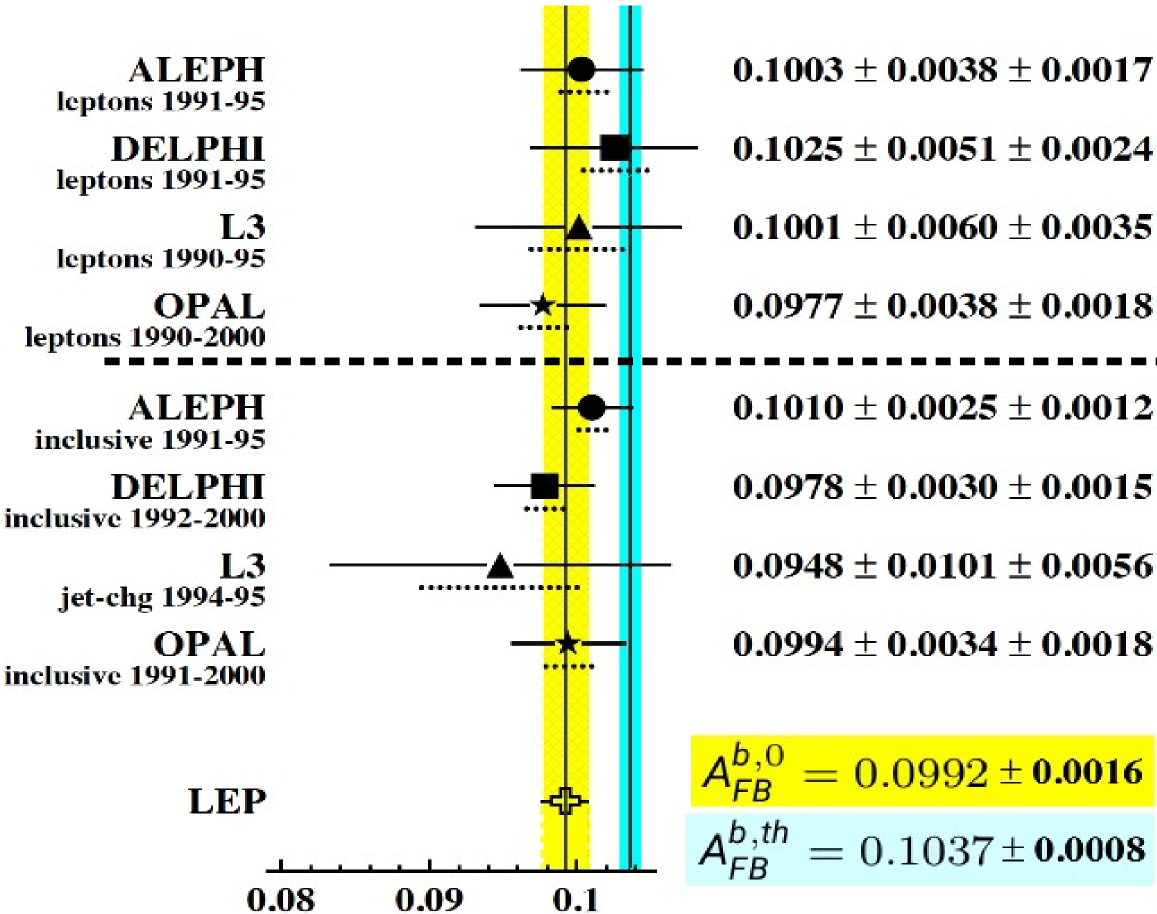
The $\cos\theta$ term gives a forward-backward asymmetry

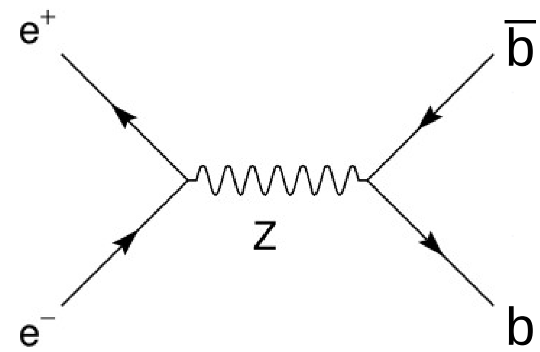
$$A^b_{FB} = \frac{N_F - N_B}{N_F + N_B} \qquad F = \int_0^1 \frac{d\sigma}{d\Omega}d\Omega \qquad B = \int_{-1}^0 \frac{d\sigma}{d\Omega}d\Omega$$

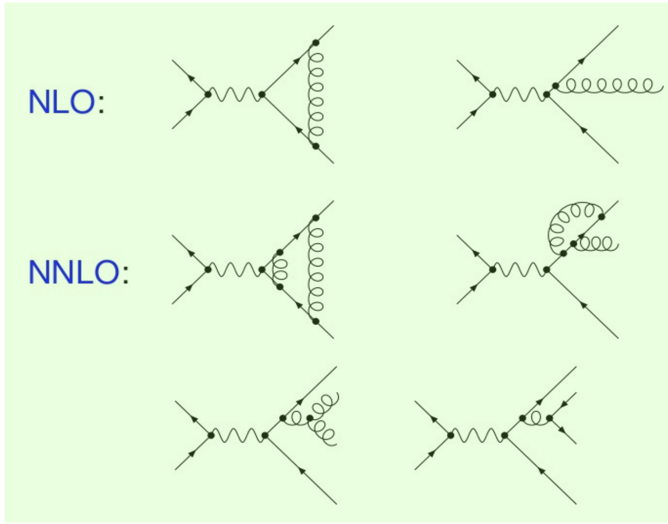


Forward-backward $b\bar{b}$ asymmetry around Z pole

- LEP exps. carried out 8 measurements (lepton- or jet-charge based) of A_{FB}^{b} (largest & most accurately measured one of all fermions):



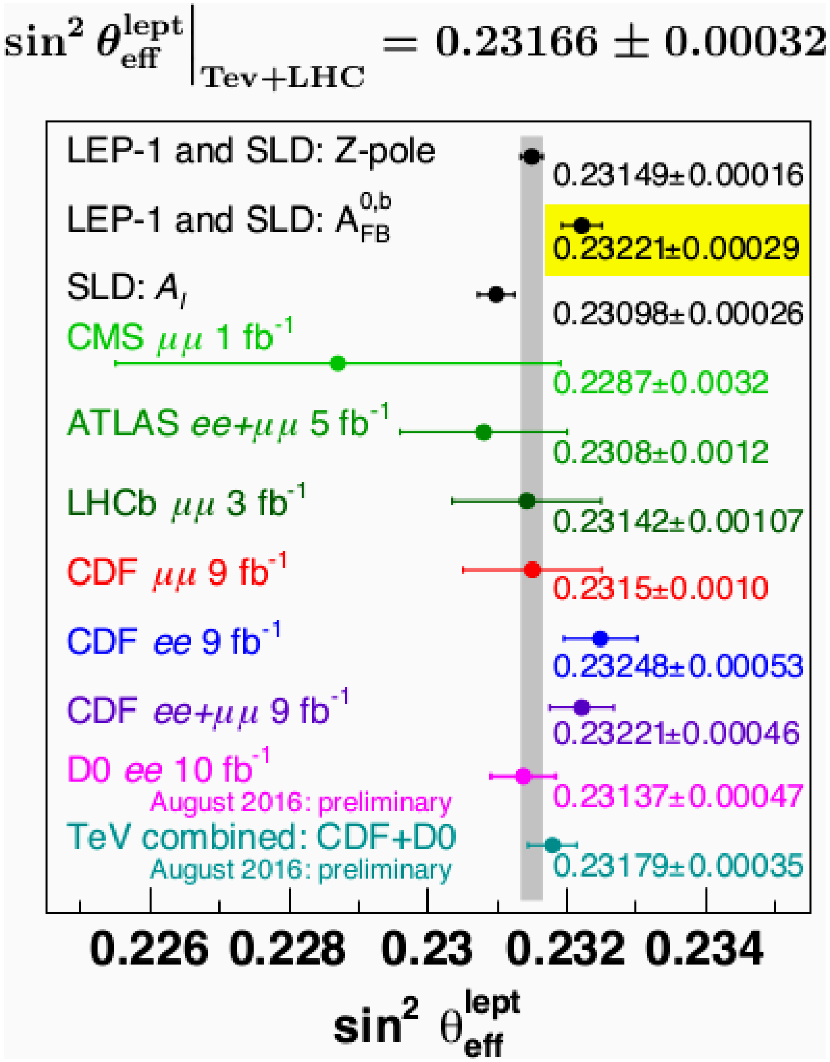


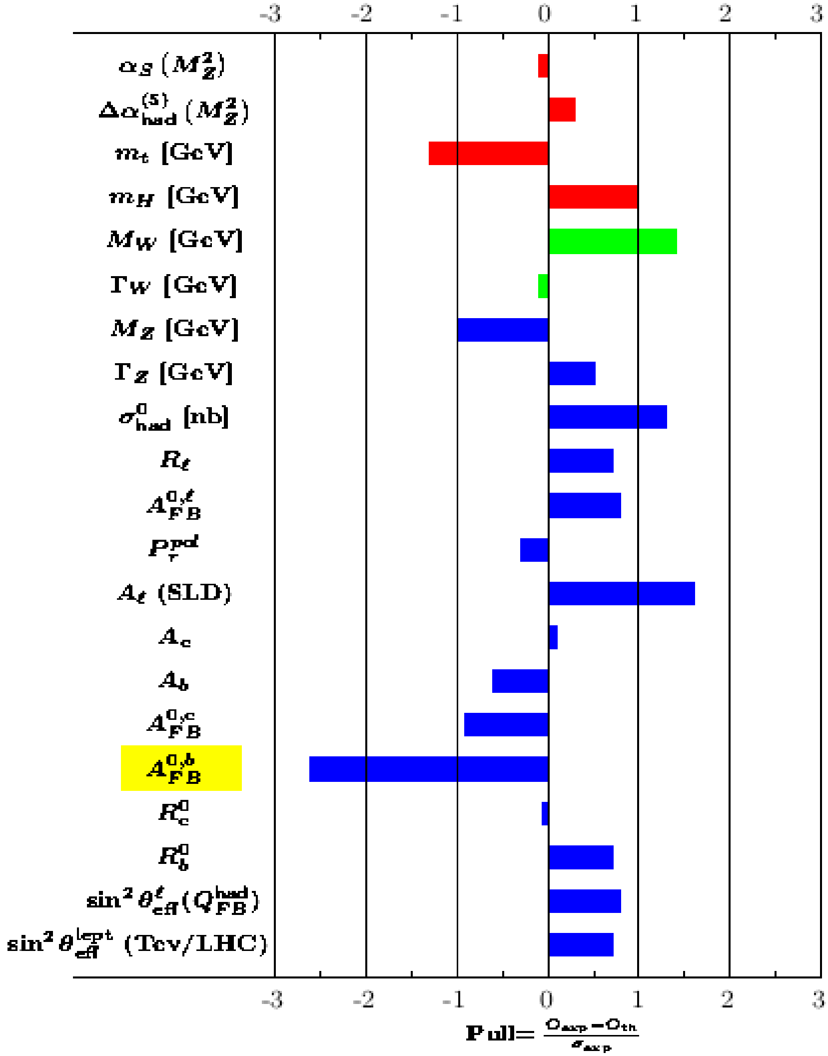


- Experimental b-quark asymmetry has a ~2.8 pull w.r.t. theoretical prediction including QED/EWK, NNLO QCD, b-quark mass, jet/thrust axis corrections

$\sin^2\theta_{eff}$ from b-$\bar{b}$ fwd-bckwd asymmetry in e^+e^-

- Effective weak angle from b-quark asymmetry at Z pole is 2.6σ away from world-average. Largest TH-EXP discrepancy among EWPOs:





b-quark asymetry uncertainties at the Z pole

- Experimental uncertainties on $A_{FB}^{0,b}$ extraction:

  – Statistical: ±1.5%

  At planned FCC-ee, with ×10^5 more $e^+e^-\rightarrow Z$'s than LEP, stat. uncert. will be negligible: ~0.05%

  – Systematics: ±0.6%

  QCD-related: ±0.5%

Table 1: LEP measurements of $A_{FB}^{0,b}$ and associated statistical, total systematic, and QCD-systematic uncertainties (with the newly-computed QCD systematics quoted in parentheses).

Measurement	$A_{FB}^{0,b}$	uncertainties stat.	total syst.	QCD syst. (new)
ALEPH lepton (2002) [4]	$0.1003 \pm 0.0038 \pm 0.0017$	4.1%	1.7%	0.6% (0.8%)
DELPHI lepton (2004-5) [5]	$0.1025 \pm 0.0051 \pm 0.0024$	6.4%	2.4%	1.5% (1.3%)
L3 lepton (1999) [6]	$0.1001 \pm 0.0060 \pm 0.0035$	6.9%	3.4%	1.8% (0.8%)
OPAL lepton (2003) [7]	$0.0977 \pm 0.0038 \pm 0.0018$	4.3%	1.5%	1.1% (1.4%)
ALEPH jet-charge (2001) [8]	$0.1010 \pm 0.0025 \pm 0.0012$	2.7%	1.1%	0.5% (0.5%)
DELPHI jet-charge (2005) [9]	$0.0978 \pm 0.0030 \pm 0.0015$	3.3%	1.5%	0.5% (0.4%)
L3 jet-charge (1998) [10]	$0.0948 \pm 0.0101 \pm 0.0056$	10.8%	5.9%	4.1% (0.4%)
OPAL jet-charge (2002) [11]	$0.0994 \pm 0.0034 \pm 0.0018$	3.7%	1.8%	1.5% (0.3%)

- QCD biases on $A_{FB}^{0,b}$ (depending strongly on exp. selection procedure):
  – Hard gluon radiation (controlled theoretically via α_s^2 NNLO corrections)
  – Smearing of b-jet (thrust) axis due to:
    (1) b and (b→) c soft radiation & hadronization.
    (2) B and D hadron decay models.

[Estimated via parton-shower simulations by Abbaneo et al., EPJC 4 (1998)]

QCD Monte Carlo setup (I)

- LEP QCD uncertainties based on JETSET (1998). Lots of progress in parton-shower & hadronization in the last 20 years. Impact on A_{FB}?
- We run 10^7 $e^+e^- \rightarrow Z \rightarrow bb$ events in 8(×8) MC setups mimicking the 8 (4 lepton-based, 4 jet-charge-based) LEP measurements.
- PYTHIA 8.226 with 7 different parton-shower & hadronization tunes:

tune 1	the original PYTHIA8 parameter set, based on some very old flavor studies (with JETSET around 1990) and a simple tune of alpha_strong to three-jet shapes to the new pT-ordered shower.
tune 2	a tune by Marc Montull to the LEP 1 particle composition, as published in the RPP (August 2007).
tune 3	a tune to a wide selection of LEP1 data by Hendrik Hoeth within the Rivet + Professor framework, both to hadronization and timelike-shower parameters (June 2009).
tune 4	a tune to LEP data by Peter Skands, by hand, both to hadronization and timelike-shower parameters (September 2013). use CMW convention for the shower alpha_s scale.
tune 5	first tune to LEP data by Nadine Fischer (September 2013), based on the default flavor-composition parameters. Input is event shapes (ALEPH and DELPHI), identified particle spectra (ALEPH), multiplicities (PDG), and B hadron fragmentation functions (ALEPH).
tune 6	second tune to LEP data by Nadine Fischer (September 2013).
tune 7	the Monash 2013 tune by Peter Skands at al. to both $e^+ + e^-$ and $pp/p\bar{p}$ data.

QCD Monte Carlo setup (II)

- We run 10^7 $e^+e^- \to Z \to bb$ events in 8(×8) MC setups mimicking the 8 (4 lepton-based, 4 jet-charge-based) LEP measurements.
- PYTHIA 8.226+VINCIA 2.2 (alternative dipole antenna parton shower): Different PS impacts b-jet thrust & (refitted) $b \to B$ fragmentation:

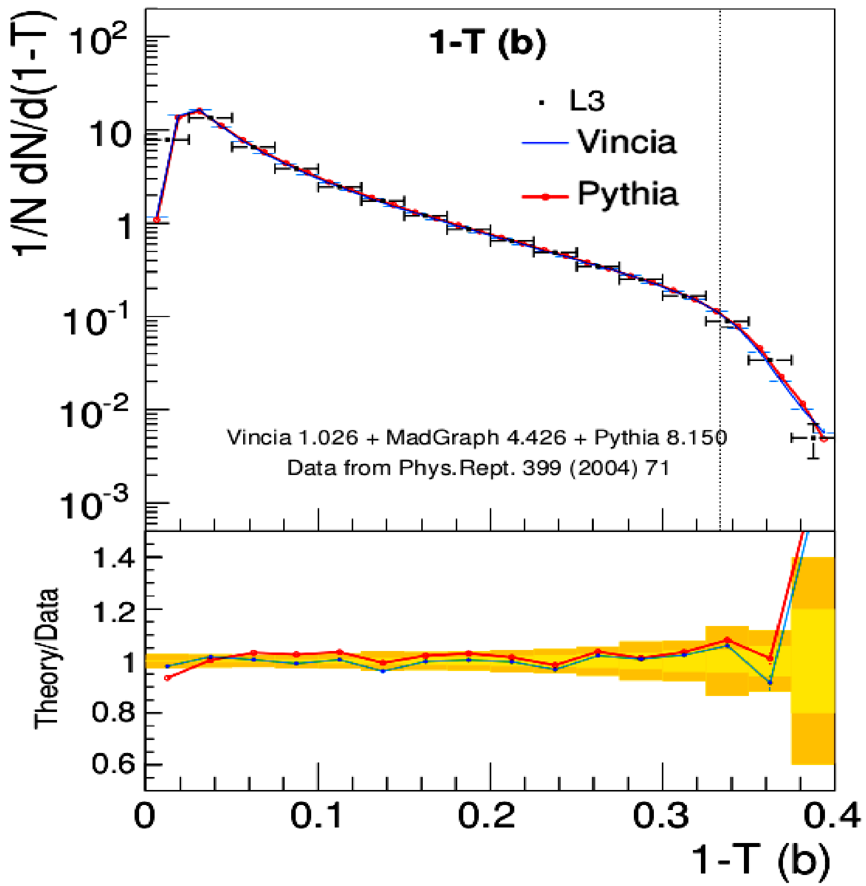
Central VINCIA tune with uncertainty given by 10 parameter variations:

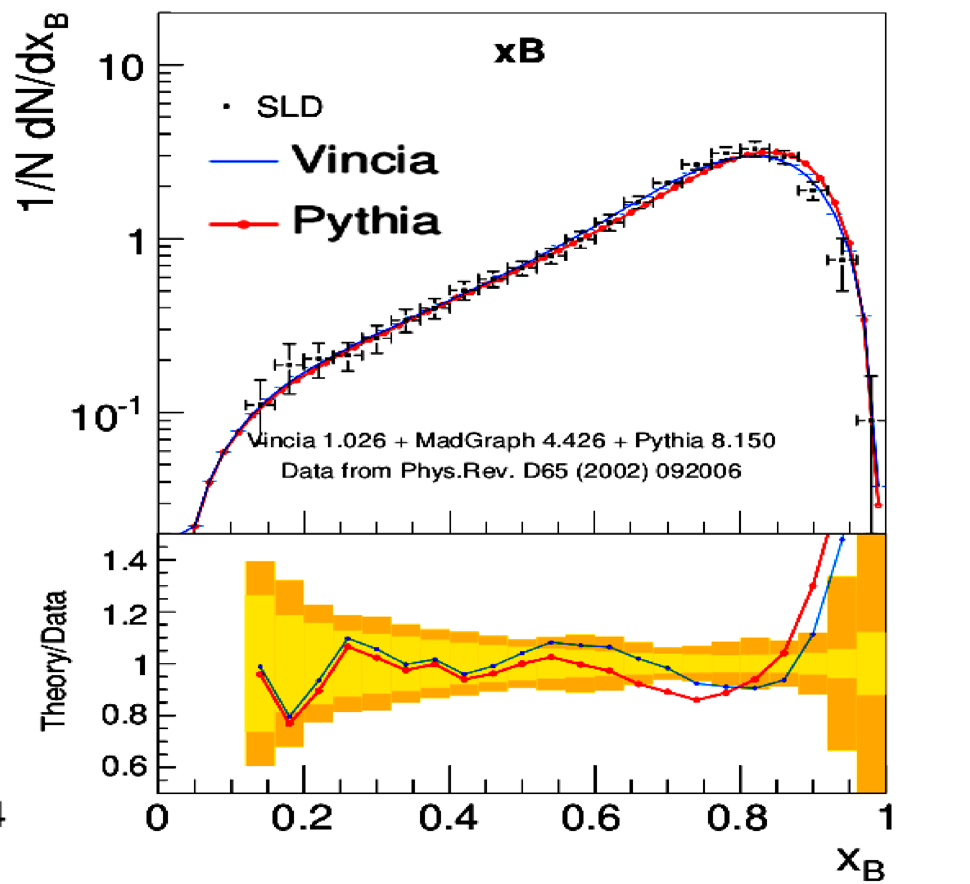
variation 0	Current (user) settings.
variation 1	Default settings(default antenna functions, default α_s settings).
variation 2	User settings with $\alpha_s(Q/k_\mu^{ub})$, where $Q = k_\mu \mu_R$ is the user scale choice and k_μ^{ub} is an additional scaling factor.
variation 3	User settings with $\alpha_s(k_\mu^{ub} Q)$.
variation 4	MAX antenna set (large finite terms) with user α_s settings.
variation 5	MIN antenna set (large finite terms) with user α_s settings.
variation 6	NLO-Hi: user settings with branching probabilities multiplied by $(1 + \alpha_s(Q))$ to represent unknown (but finite) NLO corrections.
variation 7	NLO-Lo: as above, but with division instead of multiplication.
variation 8	User settings with all color factors for gluon emission =3.
variation 9	User settings with all color factors for gluon emission =8/3.
variation 10	User settings with a modified Pimp factor, scales enter with 4th power instead of 2nd power,only if smooth ordering on.

QCD Monte Carlo setup (II)

- We run 10^7 $e^+e^- \to Z \to b\bar{b}$ events in 8(×8) MC setups mimicking the 8 (4 lepton-based, 4 jet-charge-based) LEP measurements.

- PYTHIA 8.226+VINCIA 2.2 (alternative dipole antenna parton shower) Different PS impacts b-jet thrust & (refitted) b→B fragmentation:





$e^+e^- \to b\bar{b}$ at $\sqrt{s}\approx 91.2$ GeV: MC simulation analyses

- Original LEP analyses reimplemented in 8×8 PY8(+VINCIA) simulations:

lepton measurem	lepton cuts applied
ALEPH-2002	$y_{cut} \geq 0.02$. $M_{jet} \geq 6\text{GeV/c}^2$. For e, $p \geq 2\text{GeV/c}$. For μ, $p \geq 2.5\text{GeV/c}$.
DELPHI-2004	$y_{cut} \geq 0.01$. For e, $p \geq 2$ GeV/c. For μ, $p \geq 2.5$ GeV/c. For both e and μ, $p_\perp \geq 1.6$ GeV/c.
L3-1999	$y_{cut} \geq 0.02$. $M_{jet} \geq 6\text{GeV/c}^2$. For e, $p \geq 3$ GeV/c. For μ, $p \geq 4$ GeV/c. For both e and μ, $p_\perp \geq 1\text{GeV/c}$
OPAL-2003	$y_{cut} \geq 0.02$. For both e and μ, $p \geq 2$ GeV/c.

jet-based measurem	jet-charge cuts applied
ALEPH-2001	$y_{cut} \geq 0.02$. $M_{jet} \geq 6\text{GeV/c}^2$. $\kappa = 0.5$
DELPHI-2005	$y_{cut} \geq 0.01$. $\kappa = 0.6$
L3-1998	$y_{cut} \geq 0.02$. $M_{jet} \geq 6\text{GeV/c}^2$. $\kappa = 0.4$
OPAL-2002	$y_{cut} \geq 0.02$. $\kappa = 0.5$

Lepton-based A^b_{FB} measurements

- Original LEP analyses reimplemented in 8×8 PY8(+VINCIA) simulations:
  - Reconstruct b-jets with Jade algorithm.
  - Determine the thrust axis of event (as a proxy of the $b\bar{b}$ direction)
  - Determine b-quark charge from hardest lepton charge.
  - Measure θ between e$^-$ and thrust axis
  - Fit differential cross section and extract A_{FB}^{obs}

$$\frac{d\sigma}{d\cos\theta} = \sigma\frac{3}{8}\left(1+\cos^2\theta+\frac{8}{3}A_{FB}^{obs}\cos\theta\right)$$

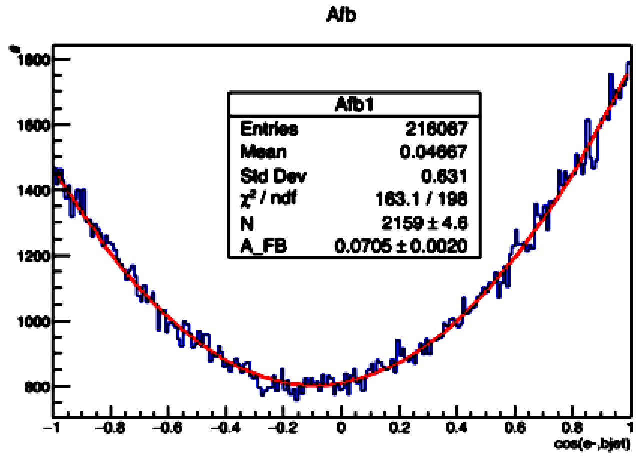
  - Correct for $\chi_B \sim 0.12$ to transform A_{FB}^{obs} to A_{FB}^{b}

$$A_{FB}^{obs} = A_{FB}^{b}(1-2\chi_B)$$

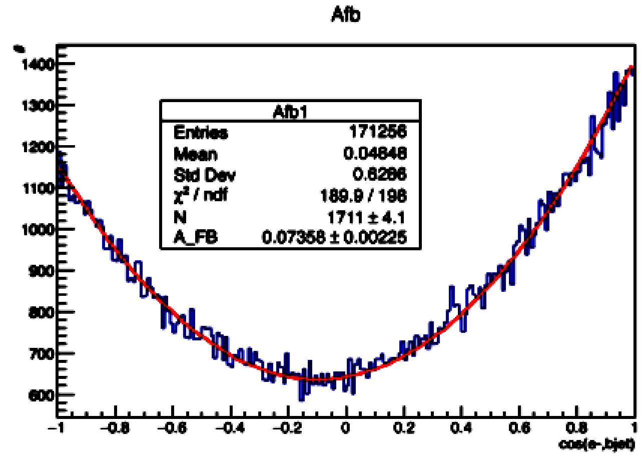
χ_B: the $B^0\overline{B^0}$ effective mixing parameter (the probability that a semileptonically decaying b-quark is reconstructed as a $\bar{b}$-quark)

Lepton-based A^b_{FB} extraction

Examples of fits of reconstructed polar angle $\frac{d\sigma}{d\cos\theta}$ distributions (tune= 7)

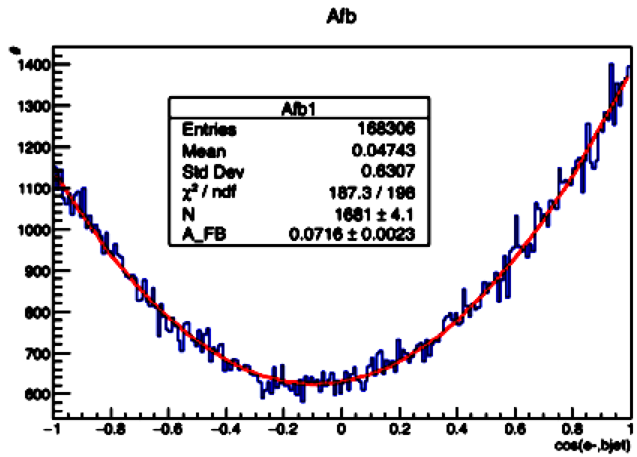


ALEPH-2002

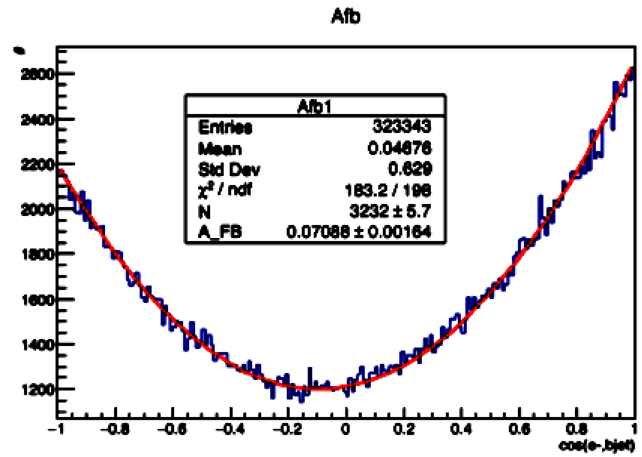


DELPHI-2004

$$\frac{d\sigma}{d\cos\theta} = \sigma\frac{3}{8}\left(1+\cos^2\theta+\frac{8}{3}A_{FB}^{obs}\cos\theta\right)$$



L3-1999



OPAL-2003

Jet-charge-based A_{FB}^{b} measurements

- Original LEP analyses reimplemented in 8×8 PY8(+VINCIA) simulations:
  - Reconstruct b-jets with Jade algorithm.
  - Determine the thrust axis of the event (as a proxy of the $b\bar{b}$ direction)
  - Identify b-quark and $\bar{b}$-quark using jet charge $Q_J = \frac{\sum p_L^\kappa Q}{\sum p_L^\kappa}$ where p_L is the longitudinal momentum of the final-state particles with respect to the thrust axis
  - Extract A_{FB}^{obs} by fitting $\cos\theta$ distribution

$$\frac{\langle Q_F - Q_B \rangle}{\langle Q_b - Q_{\bar{b}} \rangle} = A_{FB}^{obs} \frac{8}{3} \frac{\cos\theta}{1+\cos^2\theta}$$

    Q_F jet charge in the forward hemisphere

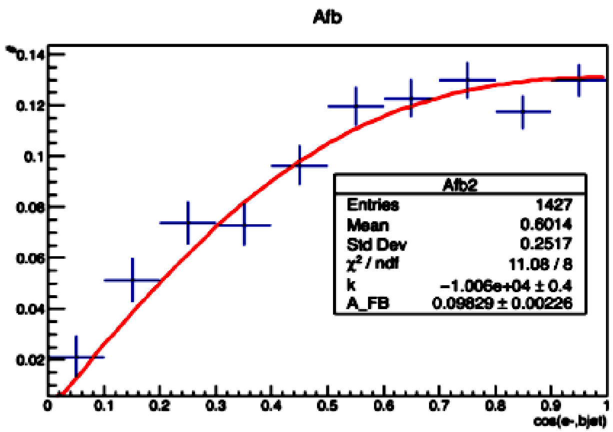
    Q_B jet charge in the backward hemisphere

  - Correct for missing higher-order QCD terms and for difference between thrust axis and b-direction $1 + C = 1.00319 \pm 0.00033$

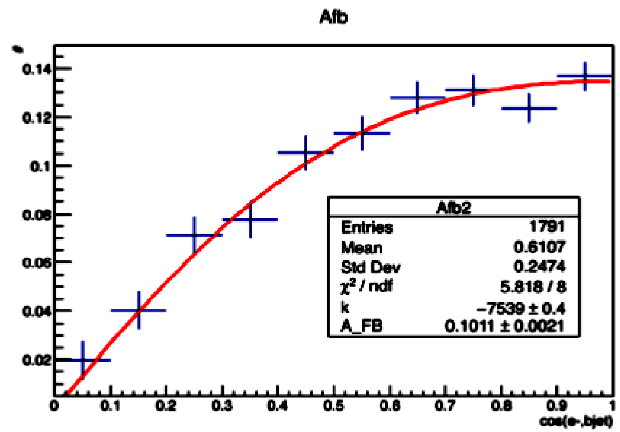
    (full QCD correction in an unbiased sample of $b\bar{b}$ events: C value is slightly different for parton- and hadron-level corrections, and is experiment-dependent)

Jet-charge-based A^b_{FB} extraction

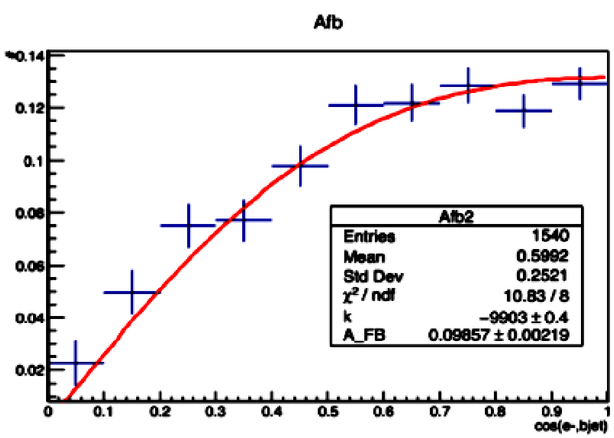
Examples of fits of reconstructed polar angle Q_F, Q_B distributions (tune= 7)



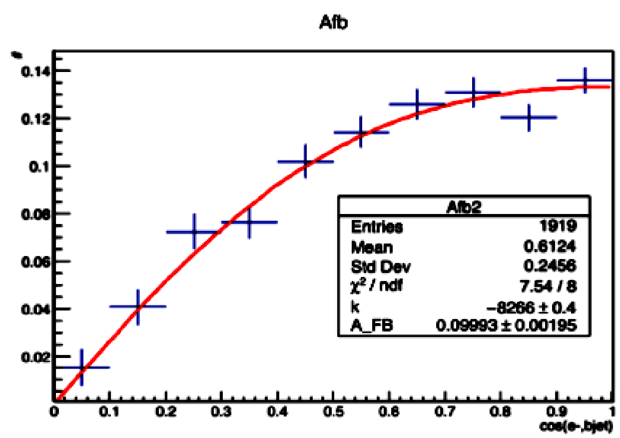
ALEPH-2001



DELPHI-2005

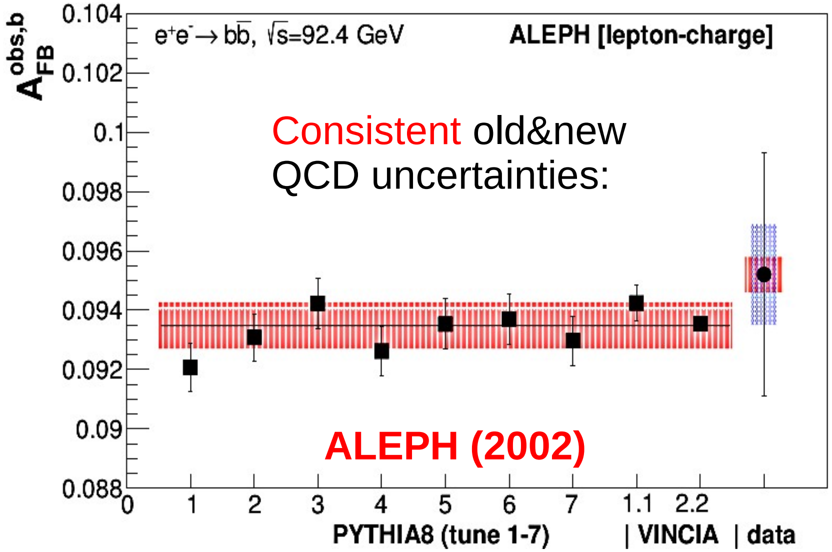


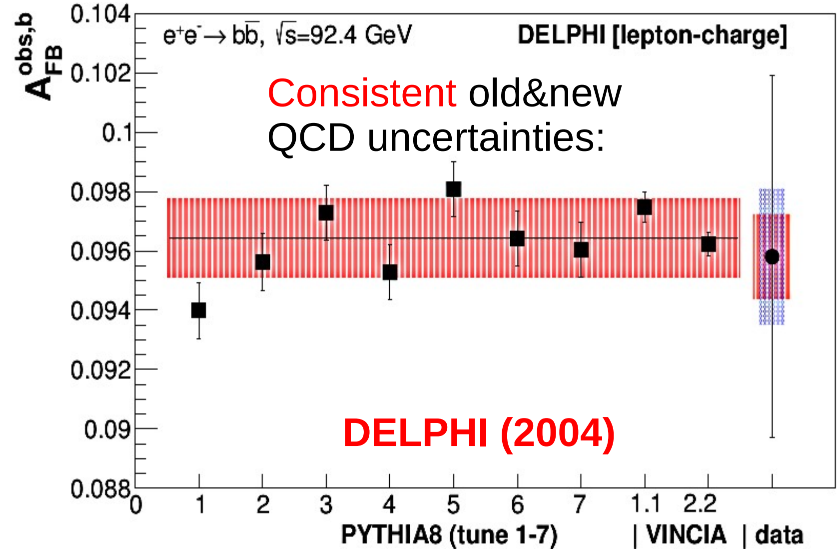
L3-1998

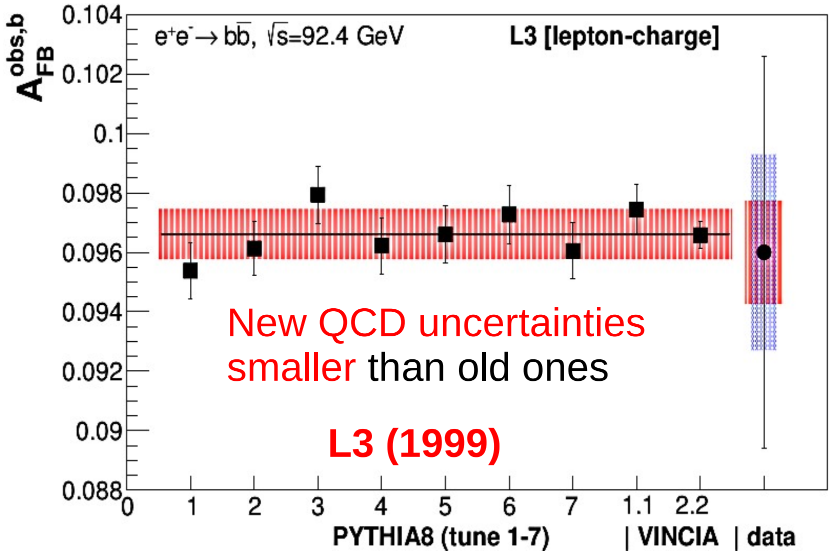


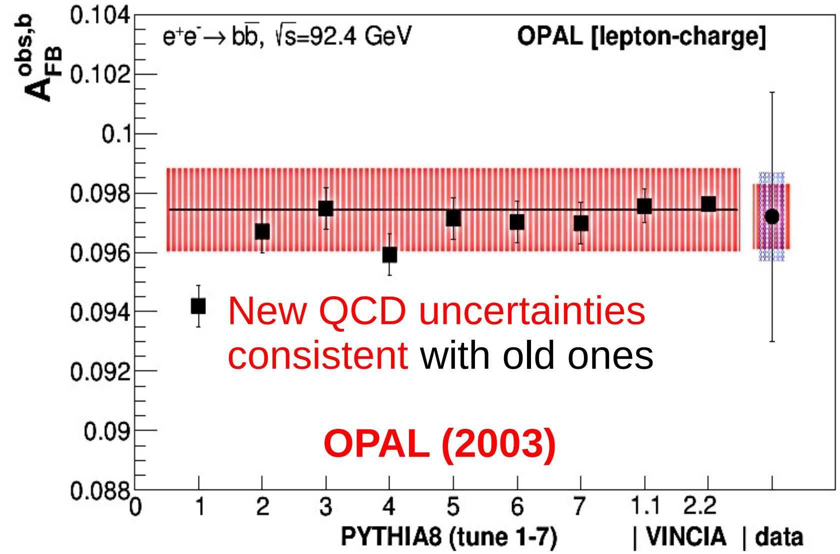
OPAL-2002

Lepton-based A^b_{FB}: QCD uncertainties



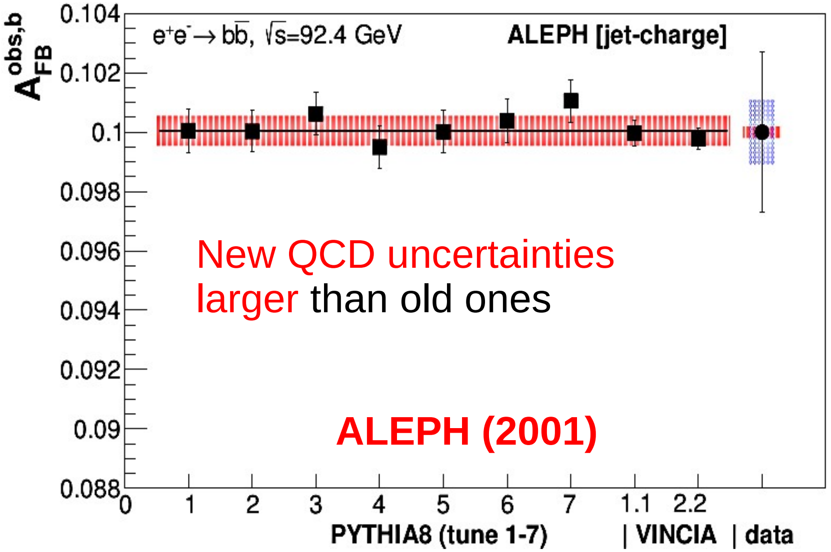


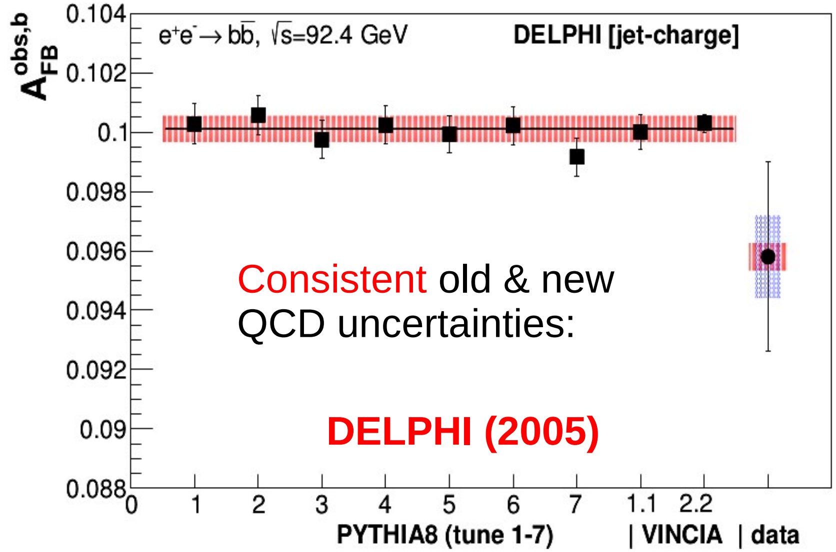


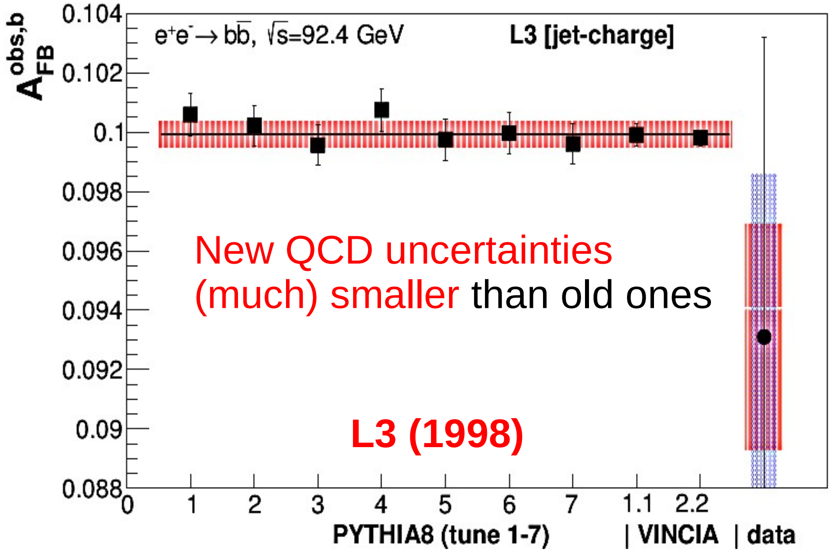


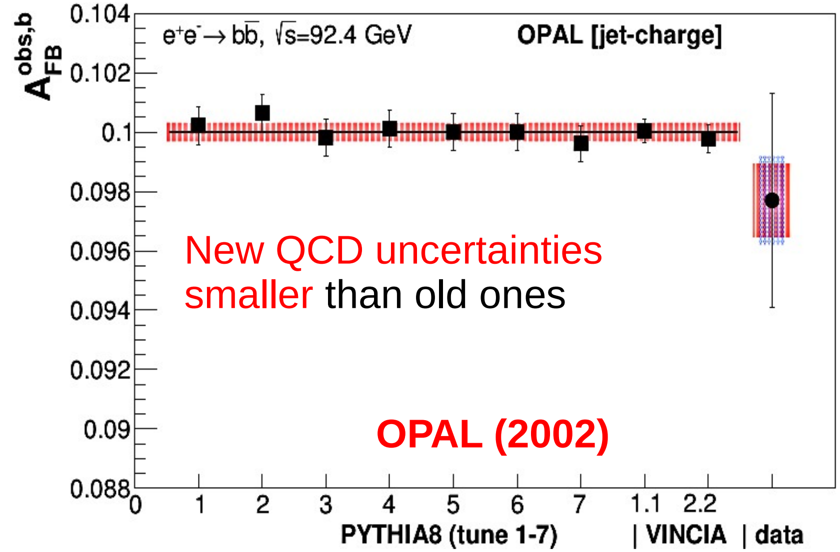
- New average QCD uncertainties ~consistent with original ones

Jet-charge-based A_{FB}^{b}: QCD uncertainties





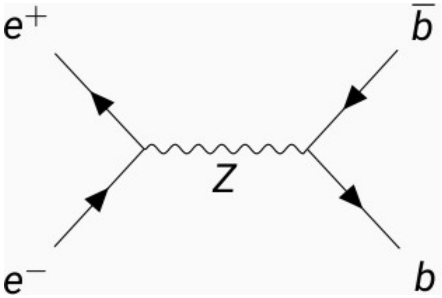


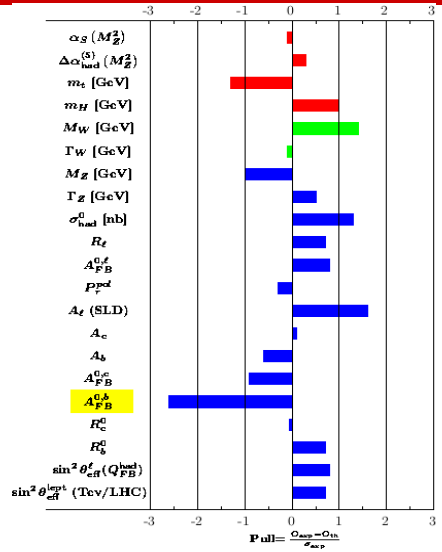


- Smaller average uncertainties than lepton-based analysis.
  New QCD uncertainties consistent or smaller than original ones

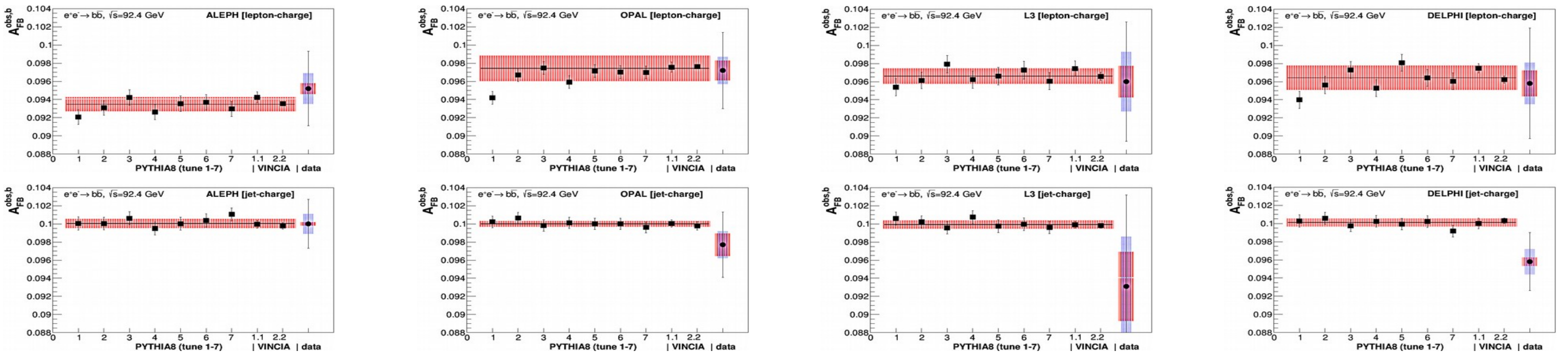
Summary

- Forward-backward asymetry of b-quarks in $e^+e^- \to Z(bb)$ shows largest TH-EXP discrepancy today among EWPO: A_{FB} = 0.0992±0.0016 (2.8σ from th.: 0.1037±0.0008)





- Dominant systematic uncertainties due to QCD effects (parton shower, hadronization) have not been cross-checked in 20 years.
- Reanalysis of QCD uncertainties with modern PS (PY8, PY8+VINCIA):



- New QCD uncertainties consistent (slightly smaller) with old ones. Jet-based more precise than lepton-based extraction. Updated A_{FB} = 0.0996±0.0015
- Ongoing sim. with ×100 times more stats. to “approach” FCC-ee conditions. FCC-ee QCD b-jet fragmentation studies needed to further reduce uncertainty.

Backup slides