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

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**Couplings of the Z boson to fermions**

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

\[
\mathcal{L} = g \bar{J} \cdot \vec{W} + g' J^Y B = \frac{g}{\sqrt{2}} (J^- W^+ + J^+ W^-) + \frac{g}{\cos \theta_W} (J^3 - \sin^2 \theta_W J^{EM}) Z^0 + e J^{EM} A^0
\]

- **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:

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

\[
Q = I_3 + \frac{Y}{2}, \quad J^{EM} = J^0 + \frac{1}{2} J^Y
\]

- **Electron-positron annihilation into fermions:** \(e^+e^- \rightarrow Z \rightarrow f\bar{f}\)

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

\[
g_L = I_3 - Q \sin^2 \theta_W \quad g_R = -Q \sin^2 \theta_W
\]

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

\[
c_V = g_L + g_R = I_3 - 2Q \sin^2 \theta_W \quad c_A = g_L - g_R = I_3
\]

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.

<table>
<thead>
<tr>
<th>Lepton</th>
<th>2(c_V)</th>
<th>2(c_A)</th>
<th>Quark</th>
<th>2(c_V)</th>
<th>2(c_A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu_e, \nu_\mu, \nu_\tau)</td>
<td>1</td>
<td>1</td>
<td>(u, c, t)</td>
<td>1 - (\frac{8}{3} \sin^2 \theta_W)</td>
<td>1</td>
</tr>
<tr>
<td>(e, \mu, \tau)</td>
<td>(-1 + 4 \sin^2 \theta_W)</td>
<td>(-1)</td>
<td>(d, s, b)</td>
<td>(-1 + \frac{4}{3} \sin^2 \theta_W)</td>
<td>(-1)</td>
</tr>
</tbody>
</table>

**Z couplings depend on the fermion Q, I_3** (i.e. diff. for diff. lepton/quark type).
Forward-backward $e^+e^- \rightarrow f \bar{f}$ asymmetries

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

$$\frac{d\sigma_{\bar{f}f}}{d\cos\theta} = \frac{3}{8} \frac{\sigma^\text{tot}_{\bar{f}f}}{(1 - \mathcal{P}_e A_e)(1 + \cos^2\theta) + 2(\mathcal{A}_e - \mathcal{P}_e) A_f \cos\theta}$$

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

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

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

$$A_{FB}^b = \frac{N_F - N_B}{N_F + N_B}$$

$$F = \int_0^1 \frac{d\sigma}{d\Omega} d\Omega$$

$$B = \int_{-1}^0 \frac{d\sigma}{d\Omega} d\Omega$$

$\cos\theta > 0$: forward

$\cos\theta < 0$: backward
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 $\sim 2.8$ pull w.r.t. theoretical prediction including QED/EWK, NNLO QCD, $b$-quark mass, jet/thrust axis corrections

$$A_{FB}^{b,0} = 0.0992 \pm 0.0016$$
$$A_{FB}^{b,th} = 0.1037 \pm 0.0008$$
Effective weak angle from b-quark asymmetry at Z pole is $2.6\sigma$ away from world-average. Largest TH-EXP discrepancy among EWPOs:
**b-quark asymmetry uncertainties at the Z pole**

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

  - **Statistical:** ±1.5%

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

  - **Systematics:** ±0.6%

    QCD-related: ±0.5%

- **QCD biases on $A_{FB}^{0,b}$ (depending strongly on exp. selection procedure):**

  - Hard gluon radiation (controlled theoretically via $\alpha_s^2$ NNLO corrections)

  - Smearing of b-jet (thrust) axis due to:

    (1) b and (b→c) c soft radiation & hadronization.

    (2) B and D hadron decay models.

**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).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$A_{FB}^{0,b}$</th>
<th>uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>stat.</td>
</tr>
<tr>
<td>ALEPH lepton (2002)</td>
<td>0.1003 ± 0.0038 ± 0.0017</td>
<td>4.1%</td>
</tr>
<tr>
<td>DELPHI lepton (2004-5)</td>
<td>0.1025 ± 0.0051 ± 0.0024</td>
<td>6.4%</td>
</tr>
<tr>
<td>L3 lepton (1999)</td>
<td>0.1001 ± 0.0060 ± 0.0035</td>
<td>6.9%</td>
</tr>
<tr>
<td>OPAL lepton (2003)</td>
<td>0.0977 ± 0.0038 ± 0.0018</td>
<td>4.3%</td>
</tr>
<tr>
<td>ALEPH jet-charge (2001)</td>
<td>0.1010 ± 0.0025 ± 0.0012</td>
<td>2.7%</td>
</tr>
<tr>
<td>DELPHI jet-charge (2005)</td>
<td>0.0978 ± 0.0030 ± 0.0015</td>
<td>3.3%</td>
</tr>
<tr>
<td>L3 jet-charge (1998)</td>
<td>0.0948 ± 0.0101 ± 0.0056</td>
<td>10.8%</td>
</tr>
<tr>
<td>OPAL jet-charge (2002)</td>
<td>0.0994 ± 0.0034 ± 0.0018</td>
<td>3.7%</td>
</tr>
</tbody>
</table>

[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($\times$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:**

<table>
<thead>
<tr>
<th>Tune 1</th>
<th>the original PYTHIA8 parameter set, based on some very old flavor studies (with JETSET around 1990) and a simple tune of $\alpha_{\text{strong}}$ to three-jet shapes to the new pT-ordered shower.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tune 2</td>
<td>a tune by Marc Montull to the LEP 1 particle composition, as published in the RPP (August 2007).</td>
</tr>
<tr>
<td>Tune 3</td>
<td>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).</td>
</tr>
<tr>
<td>Tune 4</td>
<td>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 $\alpha_{\text{sh}}$ scale.</td>
</tr>
<tr>
<td>Tune 5</td>
<td>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).</td>
</tr>
<tr>
<td>Tune 6</td>
<td>second tune to LEP data by Nadine Fischer (September 2013).</td>
</tr>
<tr>
<td>Tune 7</td>
<td>the Monash 2013 tune by Peter Skands at al. to both $e^+ + e^-$ and $pp/\bar{p}$ data.</td>
</tr>
</tbody>
</table>
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 $\alpha_s$ settings). |
| variation 2 | User settings with $\alpha_s(Q/k_{\mu}^{ub})$, where $Q = k_{\mu}k_{\mu}$ is the user scale choice and $k_{\mu}^{ub}$ 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 $\alpha_s$ settings. |
| variation 5 | MIN antenna set (large finite terms) with user $\alpha_s$ 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 $10^7 \, e^+e^- \rightarrow Z \rightarrow bb$ events in 8($\times$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) $b \rightarrow B$ fragmentation:
### e^+e^- → b̅b at \( \sqrt{s} \approx 91.2 \) GeV: MC simulation analyses

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

<table>
<thead>
<tr>
<th>Lepton measurement</th>
<th>Lepton cuts applied</th>
<th>Jet-based measurement</th>
<th>Jet-charge cuts applied</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ALEPH-2002</strong></td>
<td>( y_{\text{cut}} \geq 0.02 ).&lt;br&gt;( M_{\text{jet}} \geq 6 ) GeV/c².&lt;br&gt;For e, ( p \geq 2 ) GeV/c.&lt;br&gt;For ( \mu ), ( p \geq 2.5 ) GeV/c.</td>
<td>ALEPH-2001</td>
<td>( y_{\text{cut}} \geq 0.02 ).&lt;br&gt;( M_{\text{jet}} \geq 6 ) GeV/c².&lt;br&gt;( \kappa = 0.5 )</td>
</tr>
<tr>
<td><strong>DELPHI-2004</strong></td>
<td>( y_{\text{cut}} \geq 0.01 ).&lt;br&gt;For e, ( p \geq 2 ) GeV/c.&lt;br&gt;For ( \mu ), ( p \geq 2.5 ) GeV/c.&lt;br&gt;For both e and ( \mu ), ( p_\perp \geq 1.6 ) GeV/c.</td>
<td>DELPHI-2005</td>
<td>( y_{\text{cut}} \geq 0.01 ).&lt;br&gt;( \kappa = 0.6 )</td>
</tr>
<tr>
<td><strong>L3-1999</strong></td>
<td>( y_{\text{cut}} \geq 0.02 ).&lt;br&gt;( M_{\text{jet}} \geq 6 ) GeV/c².&lt;br&gt;For e, ( p \geq 3 ) GeV/c.&lt;br&gt;For ( \mu ), ( p \geq 4 ) GeV/c.&lt;br&gt;For both e and ( \mu ), ( p_\perp \geq 1 ) GeV/c</td>
<td>L3-1998</td>
<td>( y_{\text{cut}} \geq 0.02 ).&lt;br&gt;( M_{\text{jet}} \geq 6 ) GeV/c².&lt;br&gt;( \kappa = 0.4 )</td>
</tr>
<tr>
<td><strong>OPAL-2003</strong></td>
<td>( y_{\text{cut}} \geq 0.02 ).&lt;br&gt;For both e and ( \mu ), ( p \geq 2 ) GeV/c.</td>
<td>OPAL-2002</td>
<td>( y_{\text{cut}} \geq 0.02 ).&lt;br&gt;( \kappa = 0.5 )</td>
</tr>
</tbody>
</table>
Lepton-based $A_{FB}^b$ measurements

- Original LEP analyses reimplemented in 8x8 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 $\theta$ 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 $A_{FB}^b$

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

$\chi_B$: the $B^0\bar{B}^0$ effective mixing parameter (the probability that a semileptonically decaying $b$-quark is reconstructed as a $\bar{b}$-quark)
Lepton-based $A_{FB}^b$ extraction

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

ALEPH-2002

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

DELPHI-2004

L3-1999

OPAL-2003
Jet-charge-based $A_{FB}^{b}$ measurements

- Original LEP analyses reimplemented in $8 \times 8$ 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 $Q_J = \sum p_L^k Q / \sum p_L^k$, 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

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

- $Q_F$ 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 $A_{FB}^b$ 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 $A_{FB}^b$: QCD uncertainties

Consistent old & new QCD uncertainties:

New QCD uncertainties smaller than old ones

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.

New QCD uncertainties larger than old ones

ALEPH (2001)

New QCD uncertainties (much) smaller than old ones

L3 (1998)

Consistent old & new QCD uncertainties:

ALEPH [jet-charge]

DELPHI [jet-charge]

Consistent old & new QCD uncertainties:

ALEPH (2001)

DELPHI (2005)

New QCD uncertainties larger than old ones

L3 [jet-charge]

OPAL [jet-charge]

New QCD uncertainties smaller than old ones

OPAL (2002)
Summary

- Forward-backward asymmetry of b-quarks in $e^+e^- \rightarrow Z(bb)$ shows largest TH-EXP discrepancy today among EWPO: $A_{FB} = 0.0992\pm0.0016$ (2.8$\sigma$ from th.: $0.1037\pm0.0008$)

- 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+VINCIJA):
  - New QCD uncertainties consistent (slightly smaller) with old ones. Jet-based more precise than lepton-based extraction. Updated $A_{FB} = 0.0996\pm0.0015$

- Ongoing sim. with $\times100$ times more stats. to “approach” FCC-ee conditions. FCC-ee QCD b-jet fragmentation studies needed to further reduce uncertainty.
Backup slides