$e^-e^+ \to b\bar{b}$ Forward Backward Asymmetry at the Z Pole: QCD Corrections Revisited

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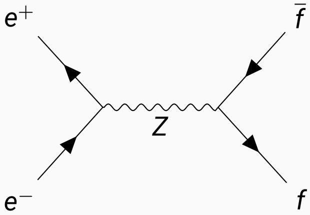
Outline

- $e^-e^+ \to b\bar{b}$ Forward-Backward Asymmetry
- LEP measurements
- Lepton-based measurements
- Jet-charge-based measurements
- Monte Carlo event generation (tunes, parton showers)
- Results
- Conclusion

$e^-e^+ \to f\bar{f}$ Forward-Backward Asymmetry



$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

- The interaction of Z boson with fermions is given by the vector and axial-vector couplings, which satisfy the following relationship with the effective electroweak mixing angle

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

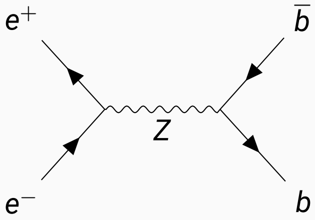
  Q_f: charge, T_3^f: the third component of weak-isospin

- The dependence of differential cross-section on the fermion couplings can be incorporated into **asymmetry parameters** $\mathcal{A}_f$

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

- Forward/backward asymmetries of the produced b and $\bar{b}$ quarks are directly related to the relevant asymmetry parameters

$e^-e^+ \to b\bar{b}$ Forward-Backward Asymmetry

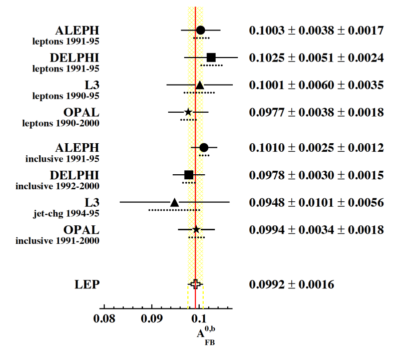


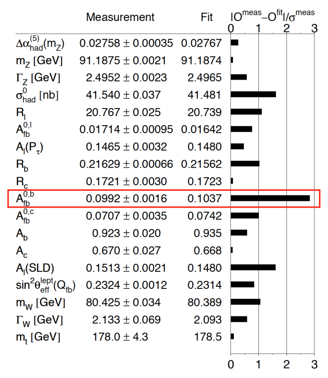
$$A_{FB}^{b} = \frac{N_F - N_B}{N_F + N_B}$$

- N_F: # of forward b-jets
- N_B: # of backward b-jets
- forward (backward): Produced in the hemisphere defined by the direction of the electron (positron) beam

LEP Measurements vs. SM Predictions

- 8 measurements of A^b_{FB} at LEP:
  4 lepton-based & 4 jet-charge-based
- A^b_{FB} shows the largest difference between SM prediction and experiment: 2.8σ





Systematic Uncertainties (LEP measurements)

Uncertainties of lepton-based extraction of A_{FB}^{b}

- ALEPH: $\pm 1.7\%$ (QCD-related: $\pm 0.6\%$)
- DELPHI: $\pm 2.4\%$ (QCD-related: $\pm 1.5\%$) | DELPHI'95: $\pm 5\%$ (QCD: $\pm 2.5\%$)
- L3: $\pm 3.4\%$ (QCD-related: $\pm 1.8\%$)
- OPAL: $\pm 1.5\%$ (QCD-related: $\pm 1.1\%$)

Uncertainties of Jet-charge-based extraction of A_{FB}^{b}

- ALEPH: $\pm 1.1\%$ (QCD-related: $\pm 0.2\%$, 0.5% including flavour prod.)
- DELPHI: $\pm 1.5\%$ (QCD-related: $\pm 0.5\%$)
- L3: $\pm 0.55\%$ (QCD-related: $\pm 0.43\%$)
- OPAL: $\pm 0.7\%$ (QCD-related: $\pm 0.6\%$)

Motivation of the study: We want to cross-check the QCD-related corrections of A_{FB}^{b} using modern MC with up-to-date models of parton shower and hadronization

Lepton-based Measurements

- Reconstruct b-jets with Jade algorithm. Determine the thrust axis of the event (as a proxy of the $b\overline{b}$ direction)
- 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 χ_B 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 has been produced as an $\overline{b}$-quark)

Jet-charge-based Measurements

- 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 component 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 $1 + C = 1.0034 \pm 0.0019$ (the full QCD correction in an unbiased sample of $b\bar{b}$ events, C uncertainty is slightly smaller and experimental-dependent)

ALEPH Collaboration, A. Heister et al., Eur. Phys. J. C22 (2001) 201-215.

Monte Carlo Event Generation

- PYTHIA8 with 7 different hadronization & parton-shower tunes

`mode` **Tune:ee** (`default = 7`; `minimum = -1`; `maximum = 7`)
Choice of tune to *e^+e^-* data, mainly for the hadronization and timelike-showering aspects of PYTHIA. You should study the `Settings::initTuneEE(...)` method to find exactly which are the settings for the respective tune.
`option` **-1** : reset all values that are affected by any of the *e^+e^-* tunes to the default values. This option can be used on its own, but is also automatically used as a first step for either of the positive tune values below, to undo the effect of previous tune settings.
`option` **0** : no values are overwritten during the initial setup, step 2 above. Note that changing to `0` in the user code has no effect; if you want to restore the individual settings you should instead use `-1`.
`option` **1** : the original PYTHIA 8 parameter set, based on some very old flavour studies (with JETSET around 1990) and a simple tune *of alpha_strong* to three-jet shapes to the new *pT*-ordered shower. These were the default values before version 8.125.
`option` **2** : a tune by Marc Montull to the LEP 1 particle composition, as published in the RPP (August 2007). No related (re)tune to event shapes has been performed, however.
`option` **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). These were the default values starting from version 8.125.
`option` **4** : a tune to LEP data by Peter Skands, by hand, both to hadronization and timelike-shower parameters (September 2013). Note the use of the CMW convention for the shower *alpha_s* scale.
`option` **5** : first tune to LEP data by Nadine Fischer (September 2013), based on the default flavour-composition parameters. Input is event shapes (ALEPH and DELPHI), identified particle spectra (ALEPH), multiplicities (PDG), and B hadron fragmentation functions (ALEPH).
`option` **6** : second tune to LEP data by Nadine Fischer (September 2013). Similar to the first one, but event shapes are weighted up significantly, and multiplicites not included.
`option` **7** : the Monash 2013 tune by Peter Skands at al. [Ska14], to both *e^+e^-* and *pp/pbarp* data.

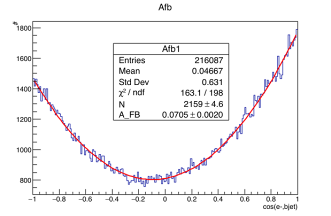
- Pythia8 + Vincia (alternative parton shower)
- Pythia8 + Dire (alternative, SHERPA-based, parton shower. In progress)

Monte Carlo Event Generation

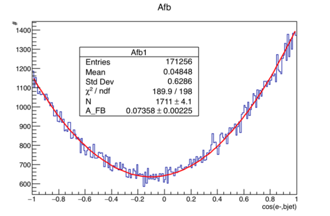
- Generate 4M $e^+e^- \to b\bar{b}$ events at $\sqrt{s} = 91.2$ GeV
- Analyze them implementing exactly all the lepton-based and jet-charge based analysis of the experimental papers
  - jet reconstruction
  - thrust-axis determination
  - lepton selection
  - fitting of the kinematical distributions
  - extraction of A_{FB}

Lepton-based Results

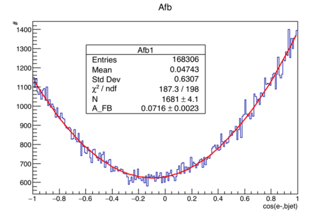
Examples of fitting graphs (tune$= 7$)



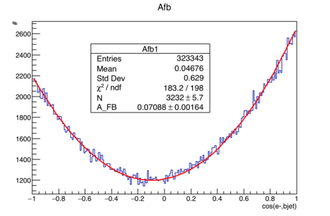
ALEPH



DELPHI



L3



OPAL

Lepton-based Results

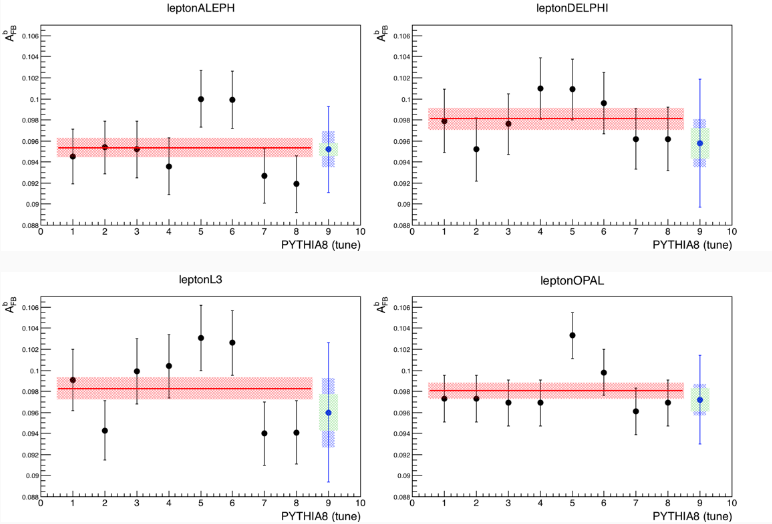
lepton	A_{FB}^b (experiment)	χ_B	A_{FB}^{obs} (pythia8)	A_{FB}^b (pythia8)
ALEPH	$0.0952 \pm 0.0041 \pm 0.0017$	0.1196	0.0705 ± 0.0020	0.0927 ± 0.0026
DELPHI	$0.0958 \pm 0.0061 \pm 0.0023$	0.1177	0.0736 ± 0.0023	0.0963 ± 0.0030
L3	$0.0960 \pm 0.0066 \pm 0.0033$	0.1192	0.0716 ± 0.0023	0.0940 ± 0.0030
OPAL	$0.0972 \pm 0.0042 \pm 0.0015$	0.1312	0.0709 ± 0.0016	0.0961 ± 0.0022

lepton	ALEPH	DELPHI	L3	OPAL
1	0.0945 ± 0.0026	0.0979 ± 0.0030	0.0991 ± 0.0029	0.0973 ± 0.0022
2	0.0954 ± 0.0025	0.0952 ± 0.0030	0.0943 ± 0.0028	0.0973 ± 0.0022
3	0.0952 ± 0.0027	0.0976 ± 0.0029	0.0999 ± 0.0031	0.0969 ± 0.0022
4	0.0936 ± 0.0027	0.1010 ± 0.0029	0.1004 ± 0.0030	0.0969 ± 0.0022
5	0.1000 ± 0.0027	0.1009 ± 0.0029	0.1031 ± 0.0031	0.1033 ± 0.0022
6	0.0999 ± 0.0027	0.0996 ± 0.0029	0.1026 ± 0.0031	0.0998 ± 0.0022
7	0.0927 ± 0.0026	0.0962 ± 0.0029	0.0940 ± 0.0030	0.0961 ± 0.0022
average	0.0959 ± 0.0029	0.0984 ± 0.0022	0.0991 ± 0.0037	0.0982 ± 0.0025

the std. deviation of the tunes goes from 2.2% to 3.7% of the central value

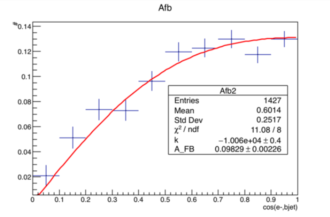
Lepton-based Results

Compilation of measurements and results

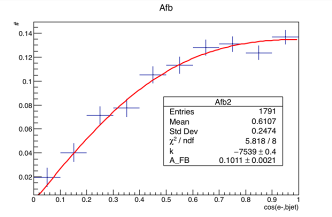


Jet-charge-based Results

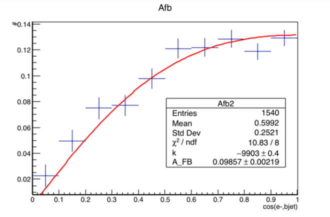
Examples of fitting graphs (tune$=7$)



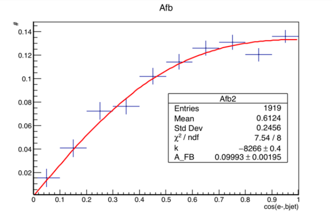
ALEPH



DELPHI



L3



OPAL

Jet-charge-based Results

jetq	A_{FB}^{b} (experiment)	$1+C$	A_{FB}^{obs}	A_{FB}^{obs} (pythia8)
ALEPH	$0.1000 \pm 0.0027 \pm 0.0011$	$\div 1.0034 \pm 0.0019$	0.0997	0.09829 ± 0.00226
DELPHI	$0.0958 \pm 0.0032 \pm 0.0014$			0.1011 ± 0.0021
L3	$0.0931 \pm 0.0101 \pm 0.0055$			0.09857 ± 0.00219
OPAL	$0.0977 \pm 0.0036 \pm 0.0015$	$0.9923 \pm 0.0063 \pm 0.0038$	0.09846	0.09993 ± 0.00195

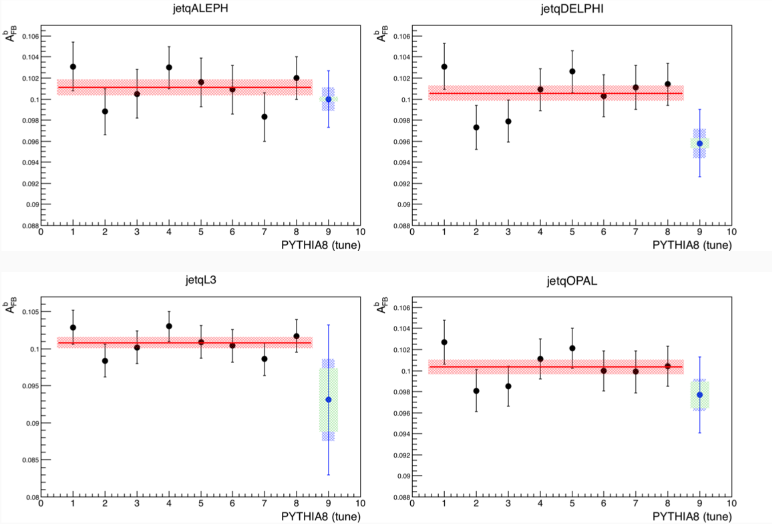
L3 uses a max likelihood fit and DELPHI has a correlation factor.

jetq	ALEPH	DELPHI	L3	OPAL
1	0.1031 ± 0.0023	0.1031 ± 0.0022	0.1029 ± 0.0023	0.1027 ± 0.0021
2	0.0988 ± 0.0022	0.0973 ± 0.0021	0.0984 ± 0.0022	0.0981 ± 0.0020
3	0.1005 ± 0.0023	0.0979 ± 0.0020	0.1002 ± 0.0022	0.0985 ± 0.0019
4	0.1030 ± 0.0020	0.1009 ± 0.0020	0.1030 ± 0.0020	0.1011 ± 0.0019
5	0.1016 ± 0.0023	0.1026 ± 0.0020	0.1009 ± 0.0022	0.1021 ± 0.0019
6	0.1009 ± 0.0023	0.1003 ± 0.0020	0.1004 ± 0.0022	0.1000 ± 0.0019
7	0.0983 ± 0.0023	0.1011 ± 0.0021	0.0986 ± 0.0022	0.0999 ± 0.0020
average	0.1009 ± 0.0017	0.1005 ± 0.0020	0.1006 ± 0.0017	0.1004 ± 0.0016

the std. deviation of the tunes goes from 1.6% to 2% of the central value

Jet-charge-based Results

Compilation of measurements and results



Acknowledgements

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QUESTIONS

References

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