Precision Measurement of $\sin^2\theta_W$ at hadron collider experiments

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Overview

2008, D0 1 fb^{-1}
electron channel
precision: 0.0019
first hadron measurement

2011, D0 5.1 fb^{-1}
electron channel
precision: 0.0010

2013, CDF 2.1 fb^{-1}
electron channel
precision: 0.0011

2014, CDF 9.2 fb^{-1}
muon channel
precision: 0.0010
CDF muon final result

2015 ATLAS 7 TeV
precision: 0.0012

2015, D0 9.7 fb^{-1}
electron channel
precision: 0.00047
D0 electron final result
Best single channel to date
First time close to LEP/SLD

2016, CDF 9.4 fb^{-1}
electron channel
precision: 0.00053
CDF electron final result

CDF Combine precision: 0.00046

2016 LHCb 7+8 TeV
precision: 0.00105

2017 CMS 8 TeV
precision: 0.00052

2017, D0 8.6 fb^{-1}
muon channel
precision: 0.00064
D0 muon final result
Best muon channel to date

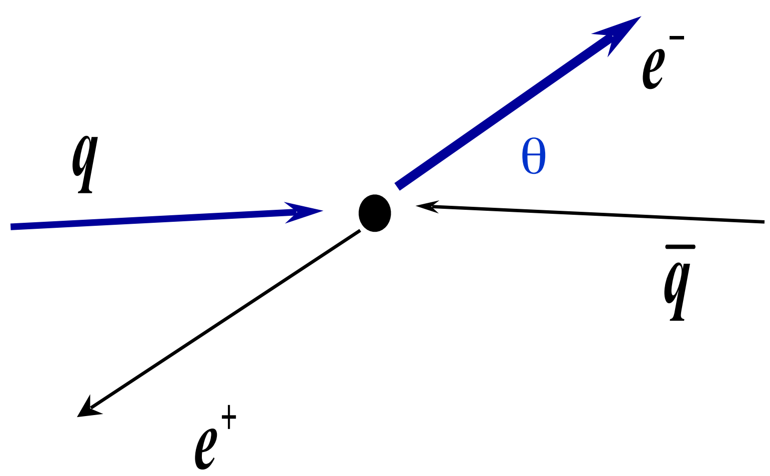
D0 Combine precision: 0.00040
Best single experiment to date
Best light-quark measurement

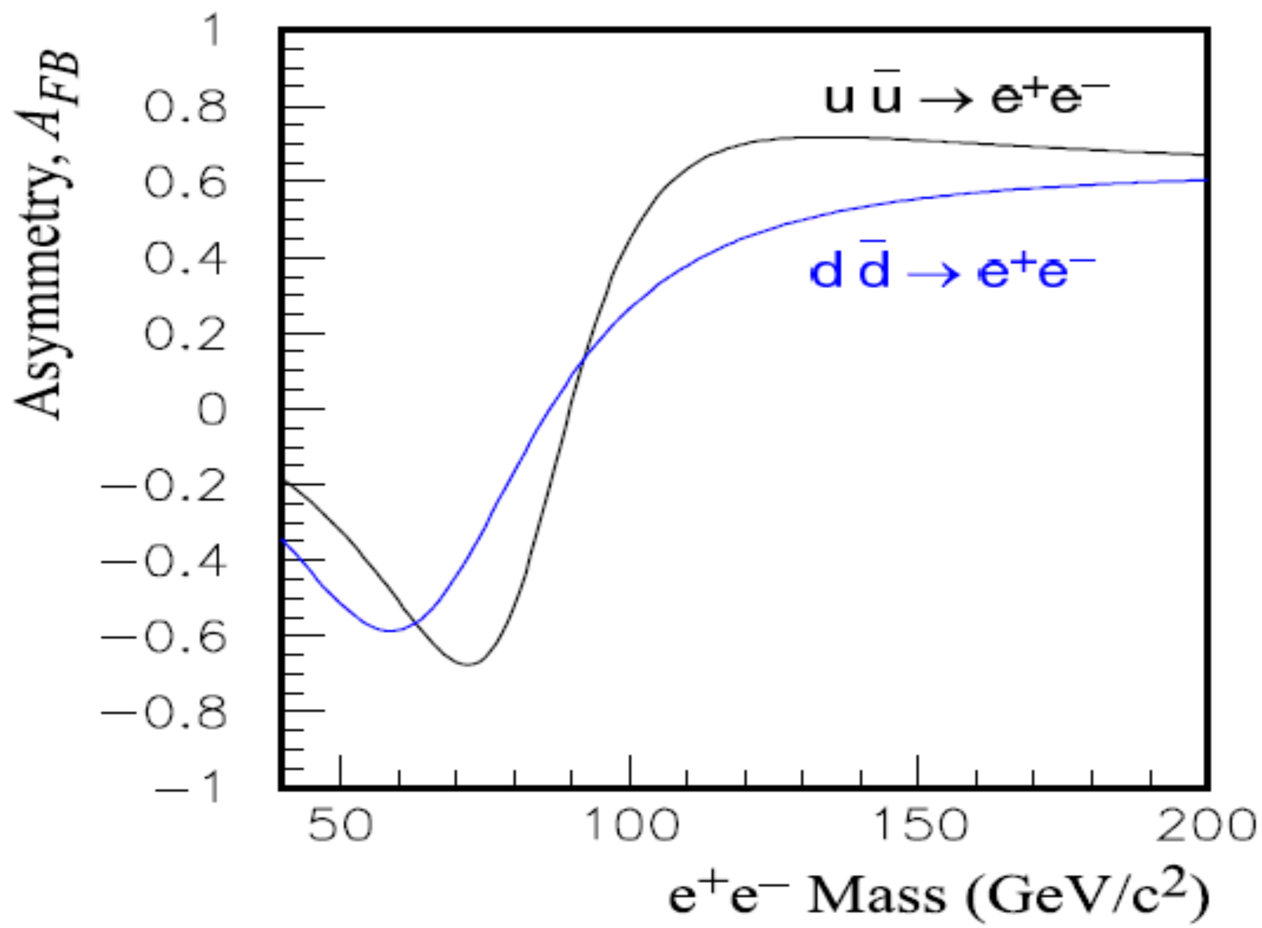
2018, Tevatron combine
precision: 0.00035

Weak mixing angle from A_{FB}

Forward-backward charge asymmetry (A_{FB})

- **Observed as a function of dilepton mass**
- **sensitive to the weak mixing angle**





Z-light quark coupling:

$$g_V^i \equiv t_{3L}(i) - 2q_i \sin^2\theta_W \ ,$$
$$g_A^i \equiv t_{3L}(i) \ ,$$

cosθ > 0: forward
cosθ < 0: backward

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

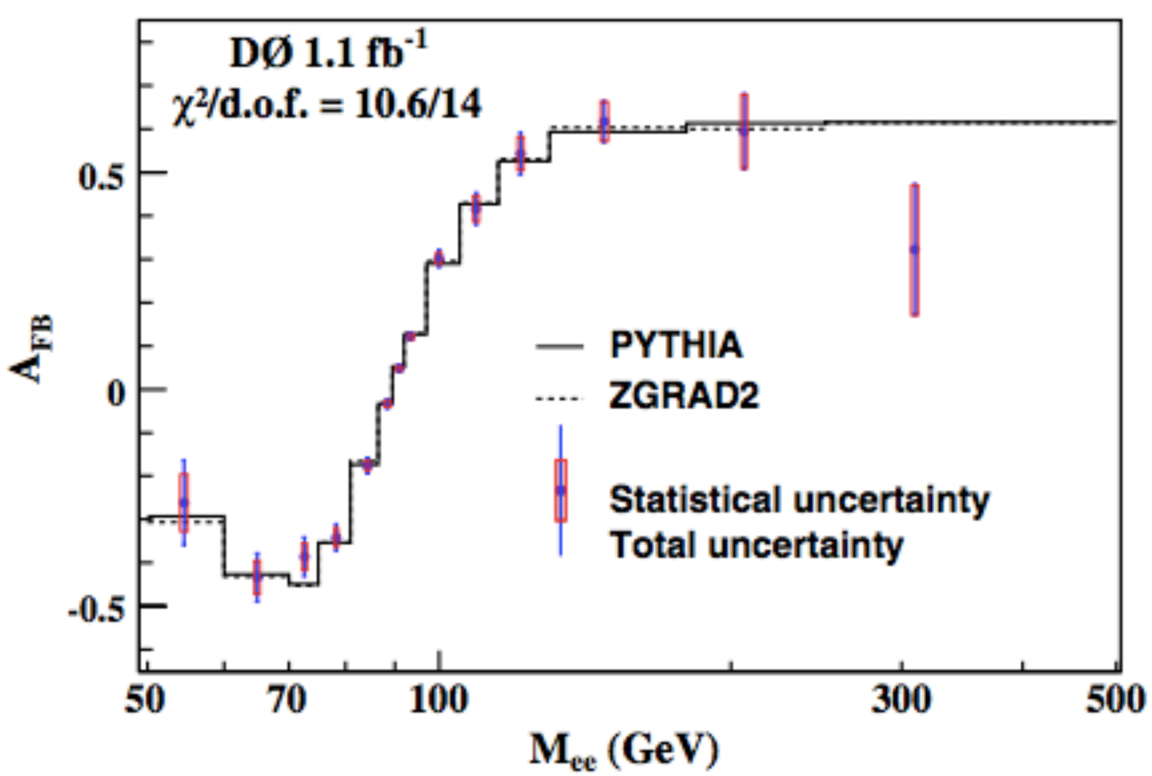
Tevatron Measurements

2008 D0 electron channel

A first trying on hadron collider experiment

- Tevatron RunII A, low instantaneous luminosity
- 1 fb^{-1}, ~35K Zee events collected
- measured via AFB vs. mass
- PDF: CTEQ6L
- A simple higher order correction: ZGRAD2 vs. pythia

$$\sin^2\theta^{\ell}_{\rm eff} = 0.2326 \pm 0.0019$$
$$= 0.2326 \pm 0.0018({\rm stat.}) \pm 0.0003({\rm syst.}) \pm 0.0005({\rm PDF})$$



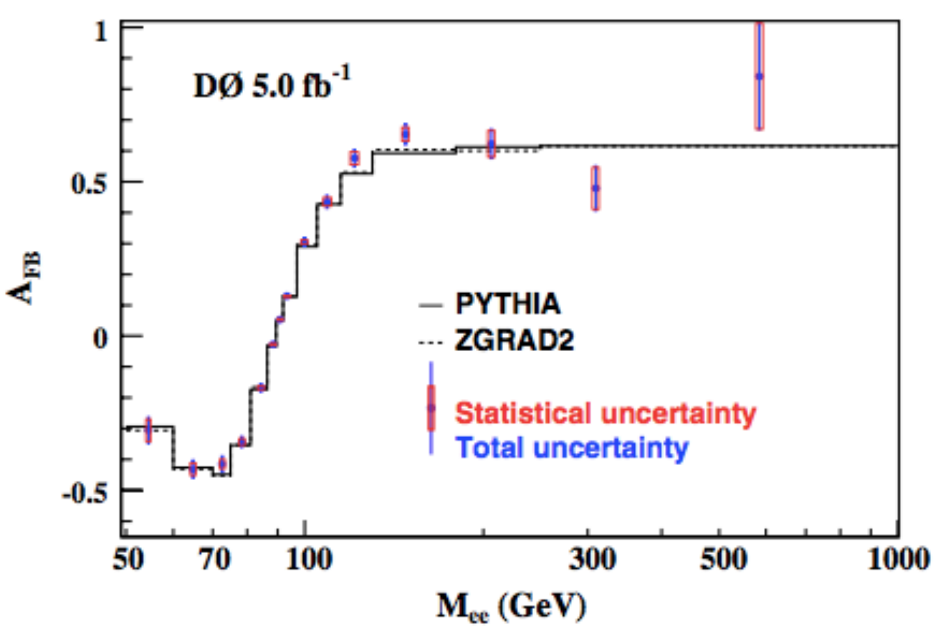
	predicted for 10 fb^{-1} using 1 fb^{-1} result
stat.	0.0005
syst.	negligible
PDF.	negligible
total	~0.0005

2011 D0 electron channel

An important mid-term estimation

- Tevatron RunII A+B
- 5 fb-1, ~160K Zee events collected
- measured via AFB vs. mass, PDF: CTEQ6L
- expectation for future not optimistic as before, syst. becomes very important!
  - syst. not reducing as data accumulates
  - syst. limits data sample (bad quality events removed)

$$\begin{aligned}\sin^2\theta^{\ell}_{\text{eff}} &= 0.2326 \pm 0.0010 \\ &= 0.2309 \pm 0.0008(\text{stat.}) \pm 0.00029(\text{syst.}) \pm 0.00048(\text{PDF})\end{aligned}$$

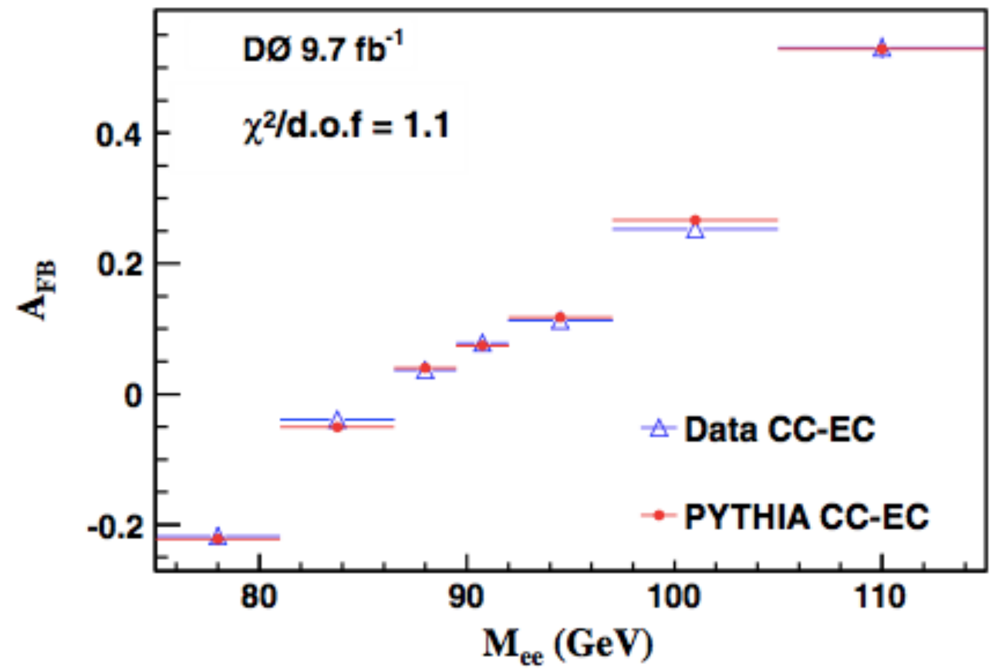


	predicted for 10 fb^{-1} using 1 fb^{-1} result	predicted for 10 fb^{-1} using 5 fb^{-1} result
stat.	0.0005	>0.0006
syst.	negligible	0.0003
PDF.	negligible	0.00048
total	~0.0005	~0.00085

2015 D0 electron channel

First time high precision!

- 10 fb-1, ~560K Zee events collected
- measured via AFB vs. mass, PDF: NNPDF2.3/3.0
- improved by novel electron calibration method
    - 75% more statistics
    - negligible uncertainty



	predicted for 10 fb^{-1} using 1 fb^{-1} result	predicted for 10 fb^{-1} using 5 fb^{-1} result	10 fb^{-1} results
stat.	0.0005	>0.0006	0.00043
syst.	negligible	0.0003	0.00008
PDF.	negligible	0.00048	0.00017
total	~0.0005	~0.00085	0.00047

2018 Tevatron combination

D0 combination:

$$\sin^2\theta^\ell_{\rm eff} = 0.23095 \pm 0.00040$$
$$= 0.23095 \pm 0.00035({\rm stat.}) \pm 0.00007({\rm syst.}) \pm 0.00019({\rm PDF.})$$

Tevatron combination(preliminary):

$$\sin^2\theta^\ell_{\rm eff} = 0.23179 \pm 0.00035$$
$$= 0.23179 \pm 0.00030({\rm stat.}) \pm 0.00006({\rm syst.}) \pm 0.00017({\rm PDF.})$$

CDF combination:

$$\sin^2\theta^\ell_{\rm eff} = 0.23223 \pm 0.00046$$
$$= 0.23223 \pm 0.00043({\rm stat.}) \pm 0.00007({\rm syst.}) \pm 0.00016({\rm PDF.})$$

Basics

- ~10 fb^{-1}, electron+muon
- measured via AFB vs. mass
- PDF: NNPDF3.0
- pythia-MC with corrections

	corrections
different u/d-quark stw values (u: -0.0001 d: -0.0002)	+0.00008
mass-scale dependence and complex calculation	+0.00014
total	+0.00022

What do we learn from 10 years Tevatron measurements?

Higher order corrections (1)

What does an experimental measurement originally provide?

- **the most important is: the central value and uncertainties before any higher order corrections (we call it: non-correct level)**

Experimentally, the central value is acquired by searching for the best agreement between the MC and data AFB vs. mass distributions

It means, using the same MC generator + central value as stw input + same PDF + same mass window, we can get an AFB vs. mass distribution at generator level, which represents the AFB in our data

Uncertainties can be converted by changing the input stw with experimental uncertainties

Higher order corrections (2)

Advantages

- higher order corrections becomes easy and straight forward
  - just compare the non-correct level AFB to the AFB from a trustable generator

- anyone can make an own higher order corrections using the non-correct level results, if does not like the higher order corrections made by the experimental paper

Some conclusions

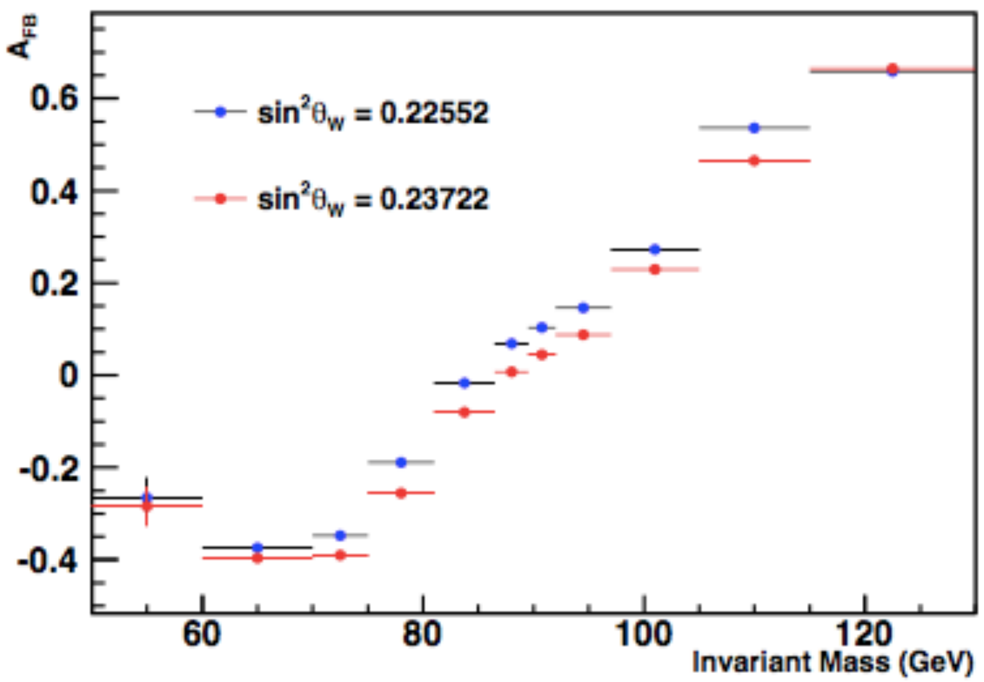
- for stw measurement, AFB is better than angular coefficient A4
  - A4 is not an input parameter in event generator
  - difficult for higher order correction procedure in the measurement
  - even difficult if we want to redo the correction

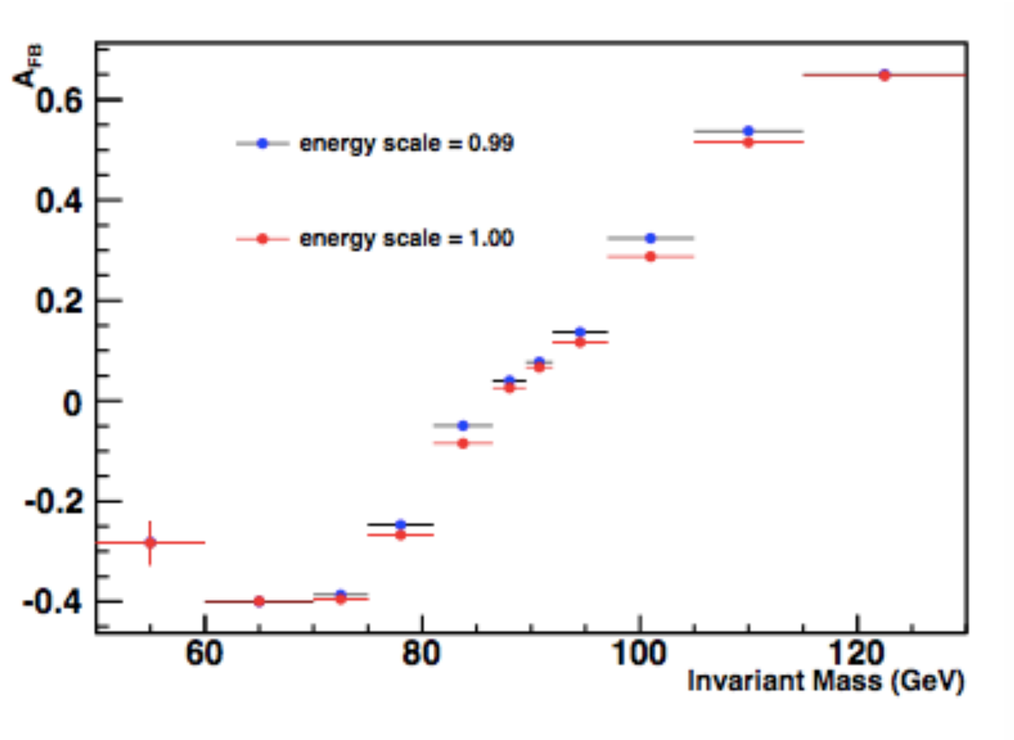
- keep the non-correct level AFB around Z-pole!
  - the non-correct level AFB does not equivalent to an unfolded AFB in wide mass range

Systematics

lepton energy scale

- the most important systematic: affects AFB same as stw does   **Δstw=0.00003 / 0.01%**



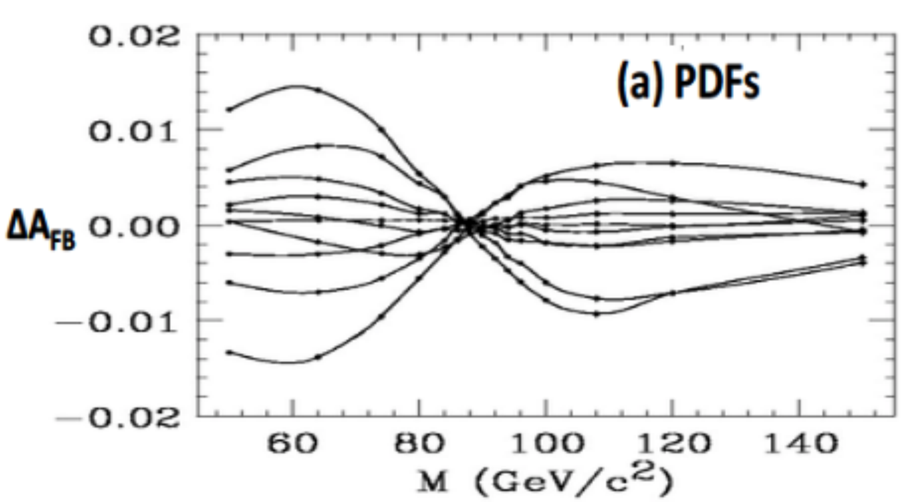


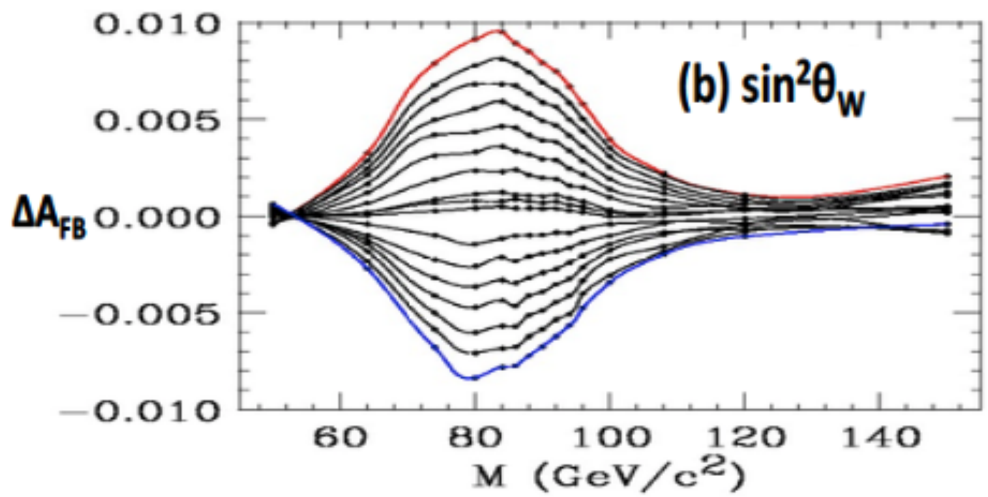
A novel method in calibration: arXiv 1803.02252

PDF

Reducing PDF by AFB self-constrain

- modern PDF allows fast re-fit by introducing a new data results
- AFB can be used for such self-constrain





Studied for future LHC

- improvement negligible at Tevatron
- expected to be significant at LHC

constrain PDF using AFB: Eur. Phys. J. C76 (2016), no.3, 115

LHC Measurements

From Tevatron to LHC

Expected Achievement

- Tevatron: precision as high as possible, contribute to world average
- LHC: aiming for total unc. <0.00010 (close to theoretical 0.00006/9 from two-loop)

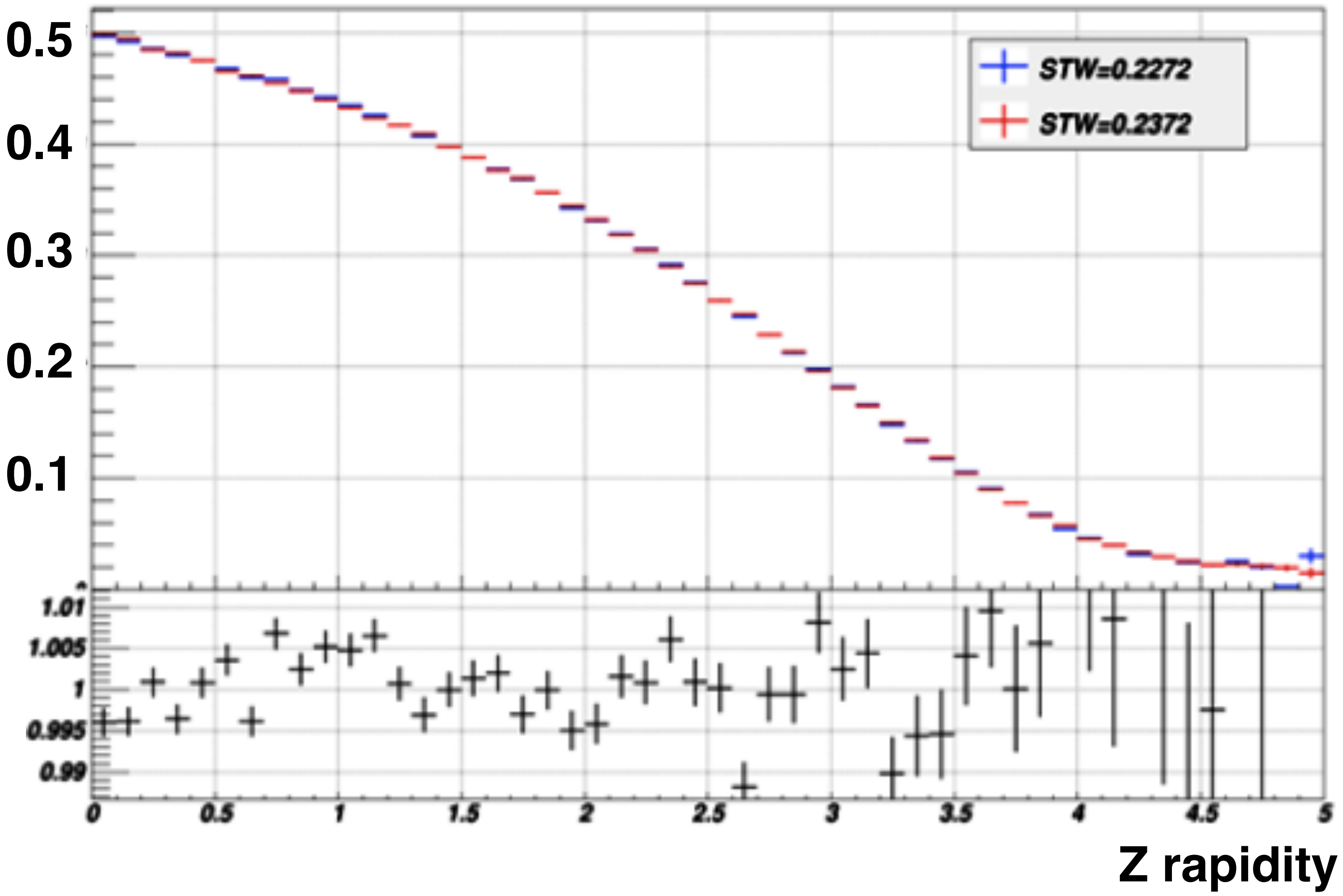
What's different?

- Dilution: unkown quark direction in pp collision
- Heavy Z-boost
- Great pileup, underlying events and noise effect

Dilution

Z-boost direction

- quark direction assumed to be Z-boost direction
- very large dilution possibility, as a function of Z-rapidity



$$A_{FB}^{pp} \approx (1 - 2f) A_{FB}^{q\bar{q}}$$

Issues from Dilution: sensitivity

Detector acceptance

- central: lepton |eta|<2.5
  - much more precise, low systematic
  - in physics: low cosθ* events, lower sensitivity
  - huge dilution: average ~40%, sensitivity on AFB futhur reduced by ~80%
- high eta lepton |eta|>2.5
  - very bad quality, huge systematic
  - in physics: high cosθ* events, higher sensitivity
  - small dilution: average <10%, sensitivty on AFB reduced by ~20%

As a result

- high eta event / central event: overall sensitivity ~30 times higher
- 70% sensitivity comes from forward events
- challenging in systematic control: we have to rely on bad quality events

Issues from Dilution: boson kinematic

Z rapidity has to be introduced

- in principle, boson kinematic means differential xsection, independent with stw
  - we are not measuring stw vs. boson kinematic

- but LHC AFB observation needs Z rapidity
  - pp-AFB comes from qqbar-AFB reduced by dilution
  - dilution has strong dependence with Z rapidity

$$A_{FB}^{pp} \approx \int [1 - 2f(Y_Z)]\, A_{FB}^{q\bar{q}}(Y_Z) \times \frac{d\sigma}{dY_Z} dY_Z$$

As a result

- the stw determination is technically related to boson kinematic
  - aiming for precision better than 0.00010, that matters

- PDF has more significant impact
  - there's always sea-quark in pp->Z->ll process

Issues from Dilution: PDF vs. systematic

Correlation between PDF and energy scale

- at Tevatron, PDF and systematic considered to be independent

- but at LHC, they are correlated
  - Z boson pz reconstructed from lepton pz
  - thus PDF and energy scale, together, affect dilution!

e.g.: one lepton pz = +200 GeV, the other pz = -198 GeV, Z pz is along + direction

If energy scale uncertainty is 1%, it is very likely to have wrong Z pz direction, thus forward/backward mis-judged —— even though the absolute value of cosθ* not changed too much, the sign changed!

As a result

- energy scale becomes more important!
- non-correct level result becomes more necessary!

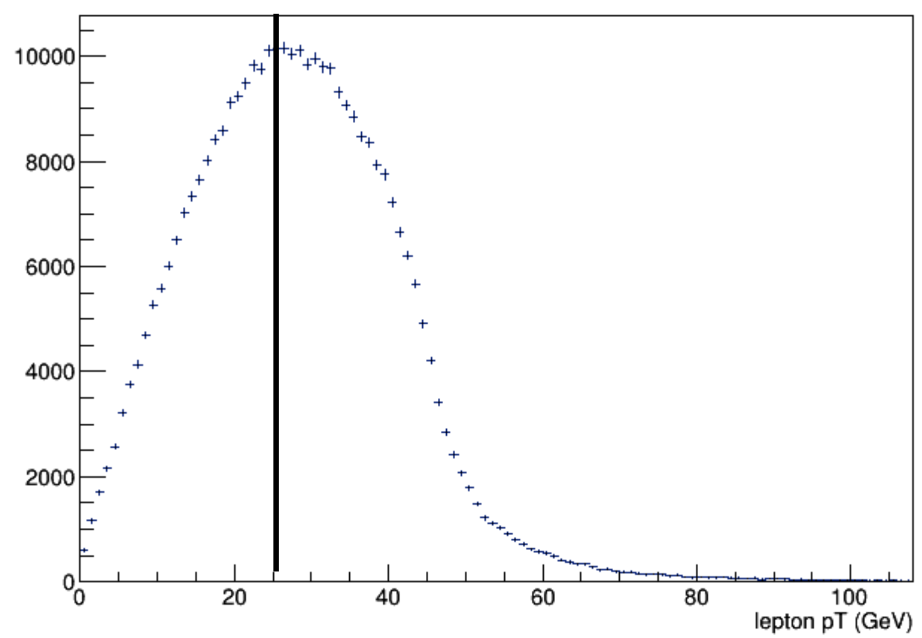
Heavy Z boost

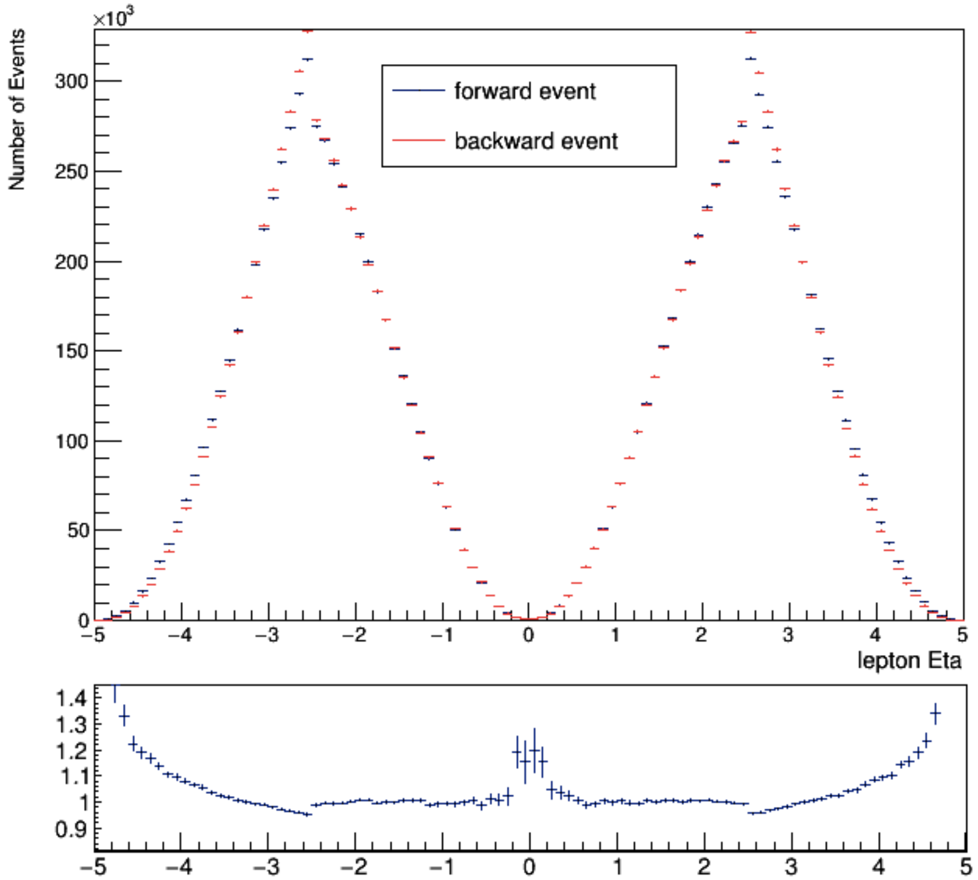
Z boson boost

- With higher energy at LHC, Z boson boost becomes heavier
  - high-eta-lepton pT becomes lower!
  - forward/backward events kinematics different

As a result

- detector efficiency modelling becomes important!
  - forward/backward events have different lepton eta distributions
  - efficiency vs. eta can’t be cancelled in AFB definition





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LHC expectation and current status (1)

Expectation with ATLAS

- **8 TeV results / 13 TeV RunII (2015 - 2018 data)**
  - **a preicision comparable to LEP/SLC**

- **in the future (with >1000 fb^{-1} data)**
  - **statistical uncertainty ~0.00005**
  - **PDF: ~0.00005?**
  - **systematic: negligible?**

Important:

- **statistics will be reduced anyway**
- **PDF will be reduced too, even if official PDF may be delayed**
  - **self-constrain will be used**
  - **make sure the non-correct level results are provided!**
- **systematic is the most important one!**
  - **current systematic control not good enough!**
  - **efficiency: <1%**
  - **energy scale <0.01%**

LHC expectation and current status (2)

Possible contribution

- ATLAS+CMS+LHCb
  - LHCb could be the one with best syst. control, but suffer from statistical unc.
  - ATLAS currently giving best hope for its forward detector
  - CMS: depends on their forward detector plan

- without forward detector, we need ~5 times larger data sample to achieve a total precision of ~0.00010

More discussion on systematic

- we will rely on single-experiment
  - systematic will be a dominant uncertainty source
  - which means, combination of different experiment results will not improve the precision