Measurement of the effective weak mixing angle at D0

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[1)] institution when research started
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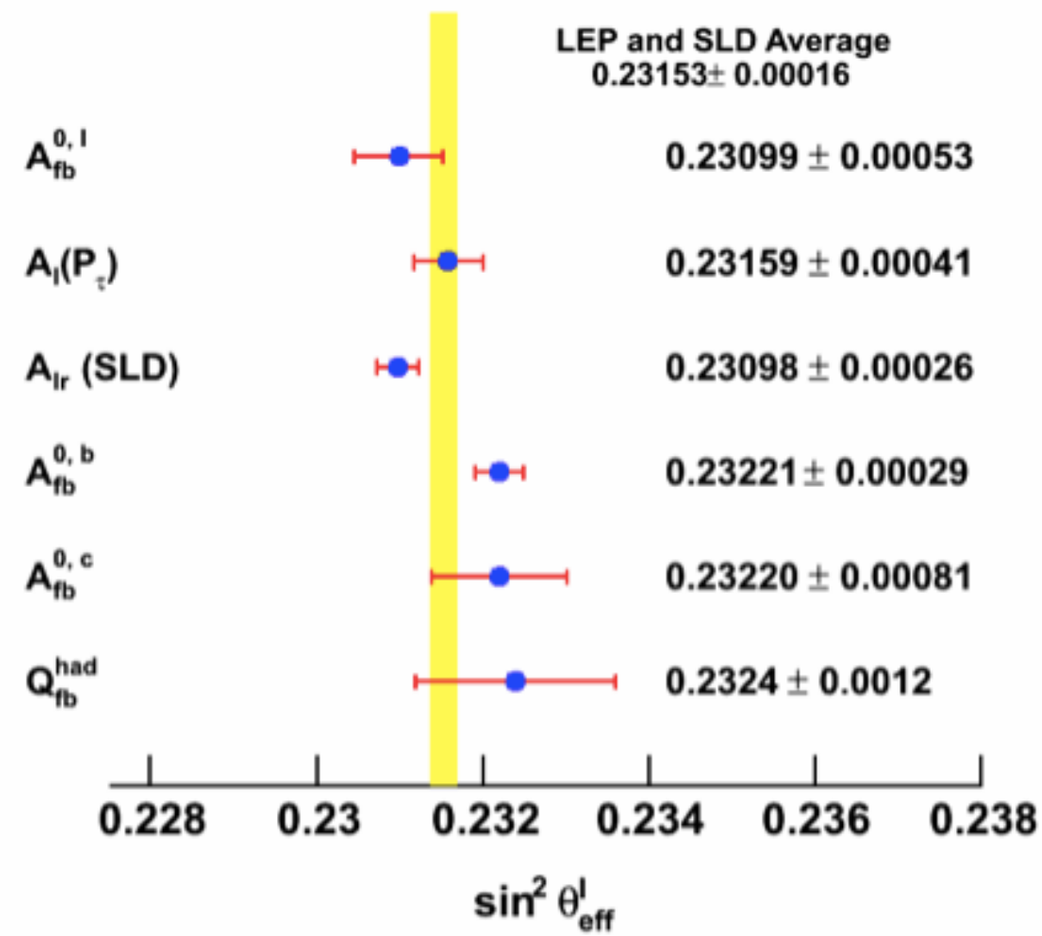
Motivation

The weak mixing angle ($\sin^2\theta_W$) measurement

- fundamental parameter of Standard Model
- most precise results from LEP/SLD
- the least precise one among all electroweak fundamental parameters
- the 2000 prediction for the Tevatron experiments single channel: ~0.00050

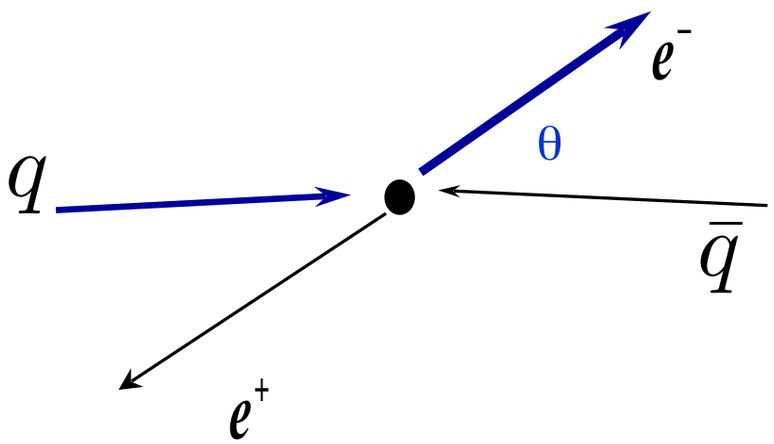
	relative uncertainty from experiments
fine structure constant α	$\sim 10^{-8}$
fermi-constant G_F	$\sim 10^{-5}$
Z boson mass M_Z	$\sim 10^{-5}$
weak mixing angle $\sin^2\theta_W$	best single measurement: 10^{-3}
	LEP/SLD combine: 6×10^{-4}

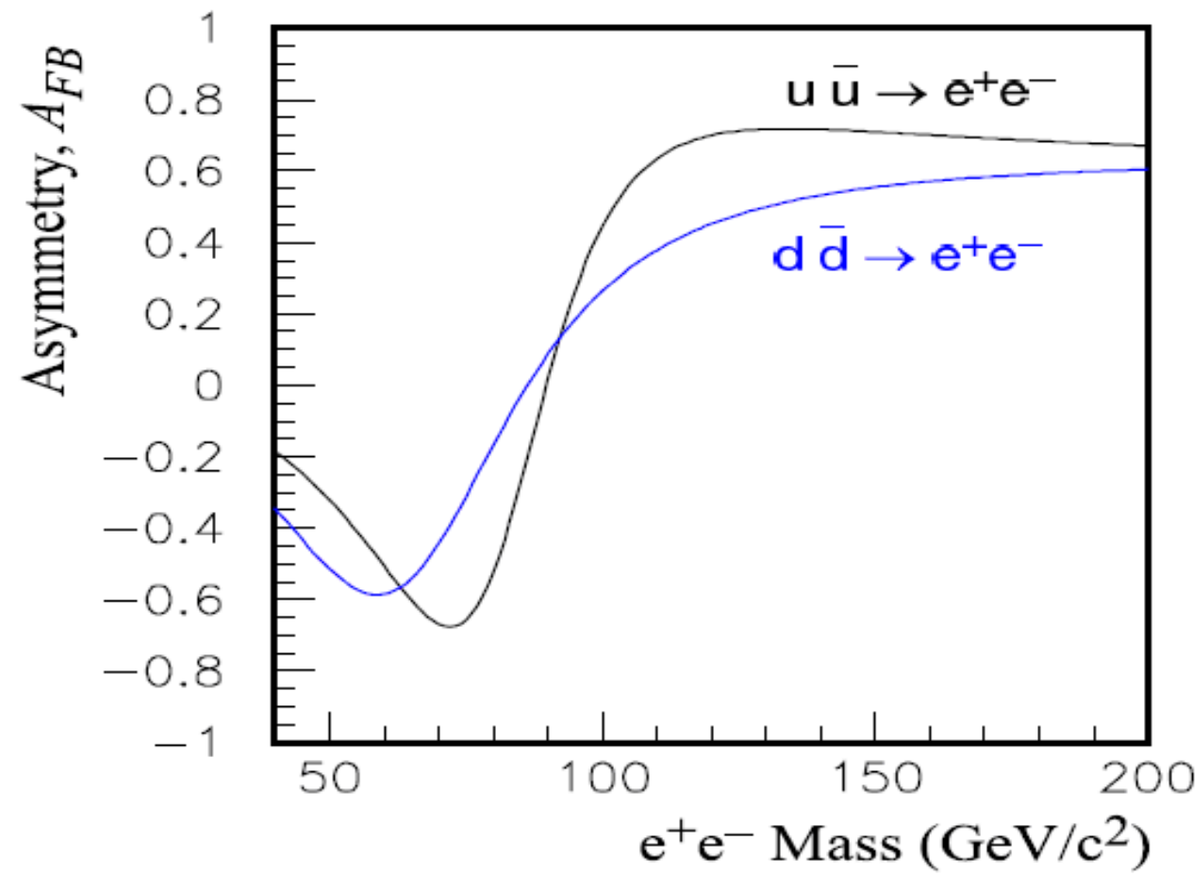


Weak mixing angle from A_{FB}

Forward-backward charge asymmetry (A_{FB})

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





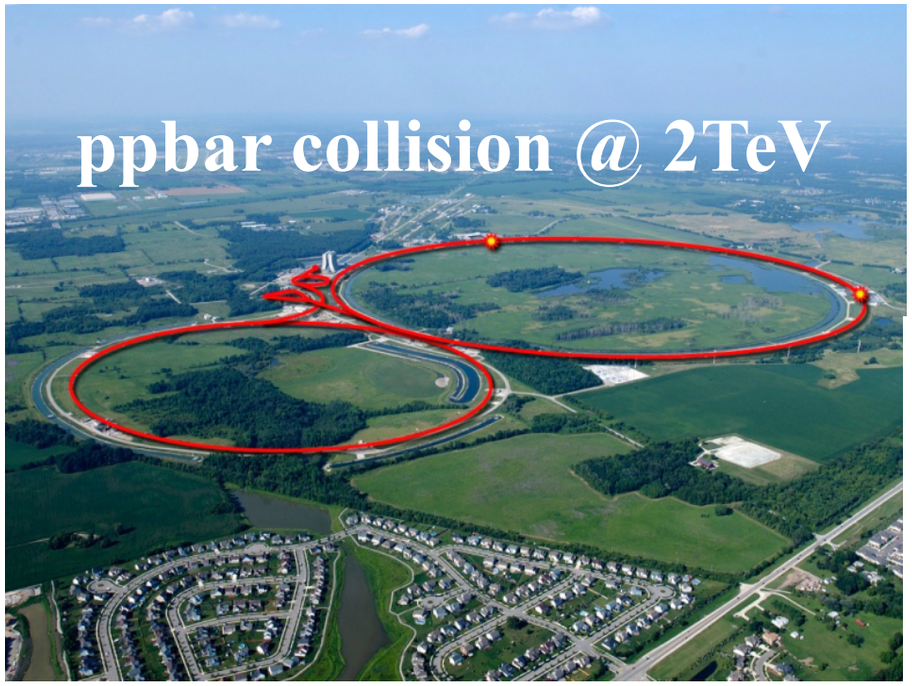
couplings of Z boson to fermions i

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

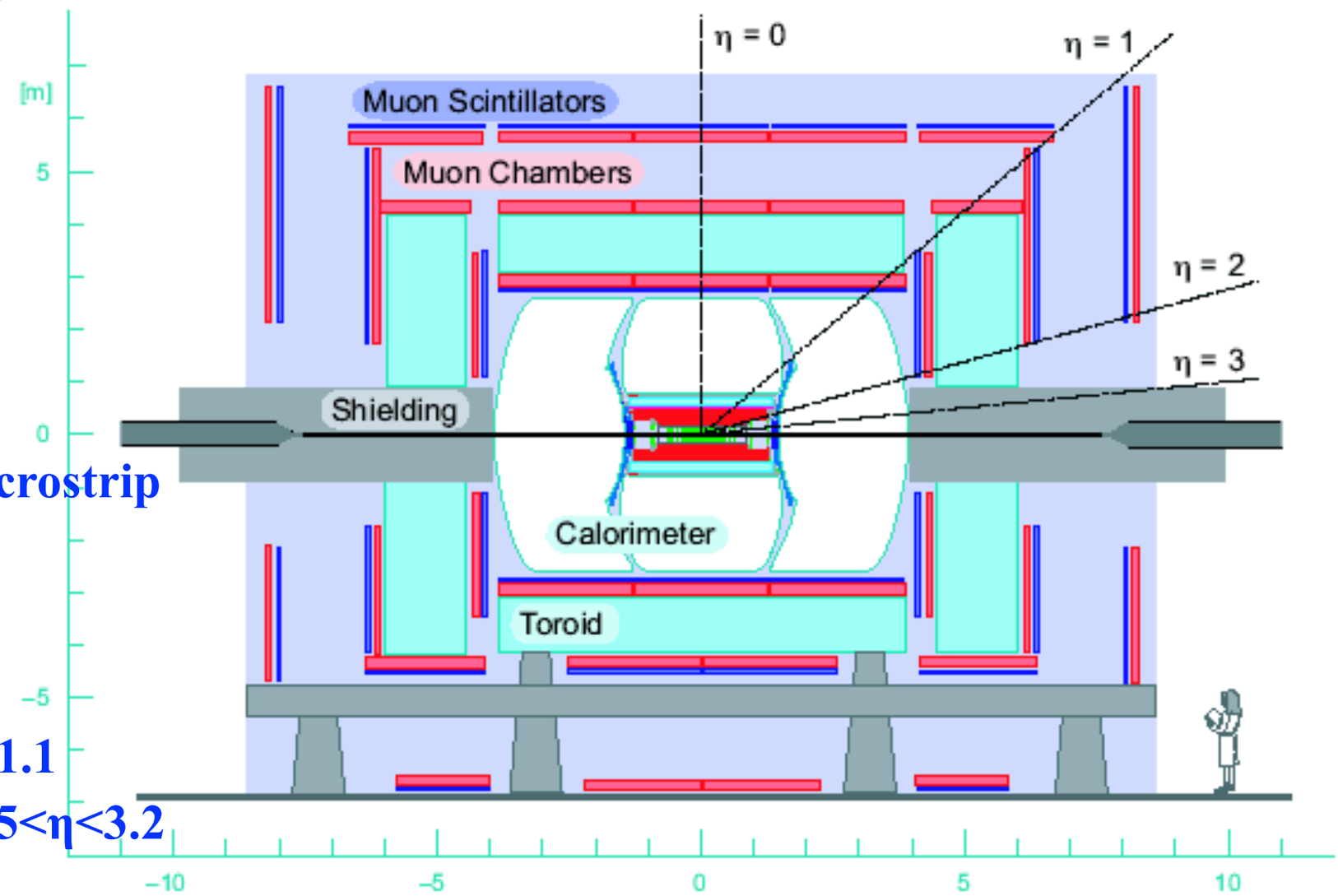
cosθ > 0: forward
cosθ < 0: backward

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

Tevatron and the D0 detector



The D0 detector



- **tracking:**
  - **scintillating fiber + silicon microstrip trackers**
  - **2T solenoid**
- **calorimeter (for electrons)**
  - **Central Calorimeter (CC) $\eta<1.1$**
  - **Endcap Calorimeters (EC) $1.5<\eta<3.2$**
- **muon system: $\eta<2.0$**

D0 measurements review

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

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

2018, D0 8.6 fb^{-1}
muon channel
precision: 0.00064
D0 muon final result
Best muon channel to date

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

D0 Combined precision: 0.00040
Best single hadron collider experiment to date
Best light-quark measurement

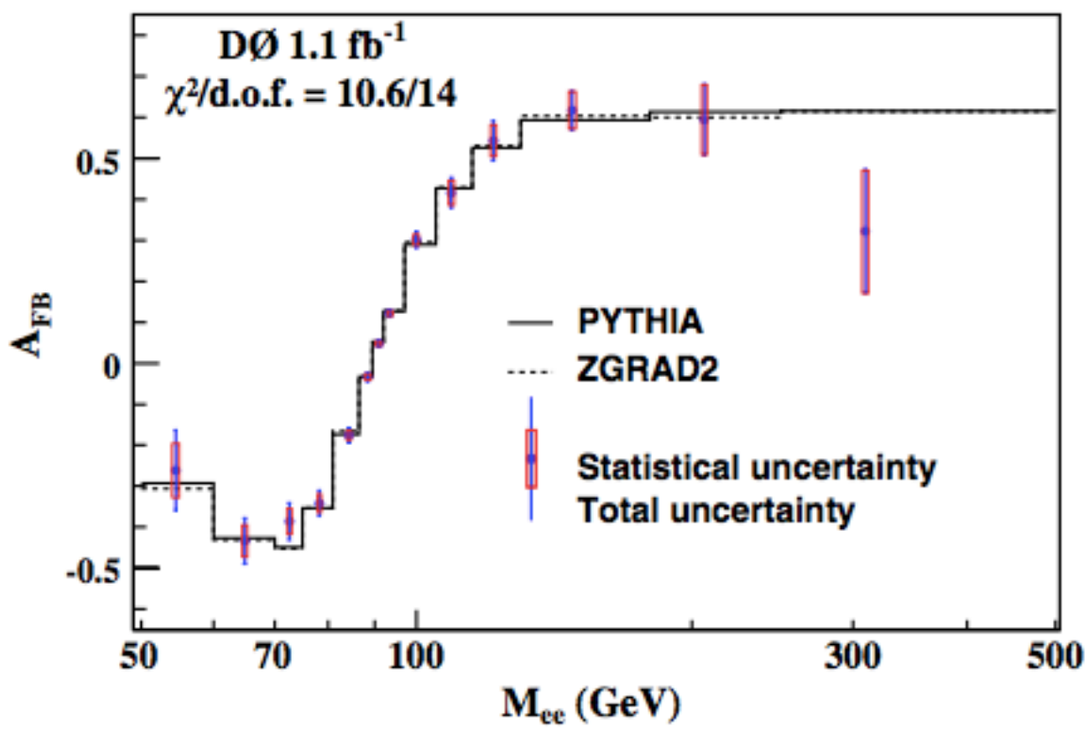
2008 D0 electron channel

Phys. Rev. Lett. 101, 191801 (2008)

A first measurement at hadron collider experiment

- **Tevatron RunII, 1 fb^{-1}**
- **PDF: CTEQ6, with a simple higher order correction: ZGRAD2 vs. pythia**
- **use result to predict precision with 10 fb^{-1}**

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



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

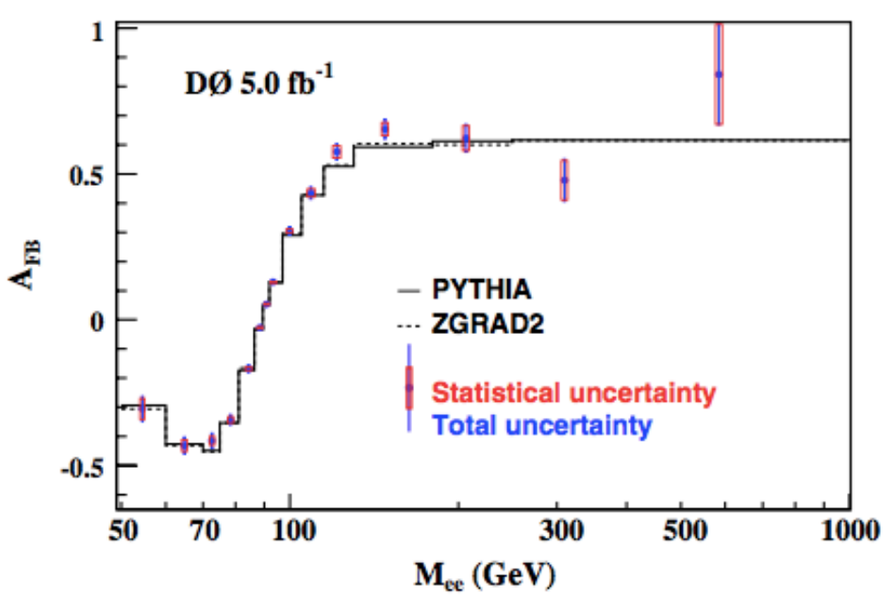
2011 D0 electron channel

Phys. Rev. D. 84, 012007 (2011)

An important next step estimation

- **Tevatron RunII, 5 fb^{-1}**
- **PDF: CTEQ6L**
- **expectation for future not optimistic as before, syst. uncertainty becomes very important!**
  - **syst. not reducing as data accumulates**
  - **syst. limits data sample (bad quality events removed)**

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



	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

Lepton calibrations

Large uncertainty

- due to noise and detector aging
- affects mass reconstruction, thus affects A_{FB} vs. mass
- the electron energy calibration was ±0.1%, but to avoid being dominated by systematics, need ±0.01%

Difficult to calibrate

- hard to simulate detector aging effects
- simple one parameter calibration Ecorr = k x Eobs is insufficient

At hadron colliders, lepton energy can be calibrated using Z mass. However, the only one constraint limits the number of parameters

$$E_{\mathrm{corr}} = k \times E_{\mathrm{obs}} \checkmark \qquad E_{\mathrm{corr}} = k \times E_{\mathrm{obs}} + b \times$$

Lepton calibrations (2)

A novel method for lepton energy calibration at hadron collider experiments, arXiv: 1803.02252

General idea

- **multip-parameters**

$$E(\eta)_{\mathrm{corr}} = k(\eta) \times E(\eta)_{\mathrm{obs}} + b(\eta)$$

- **more constraints: separating Z samples**
  - **large opening angle between leptons: lower energy**
  - **small opening angle between leptons: higher energy**

- **reduce correlation between k and b parameters**

Data/MC separately calibrated

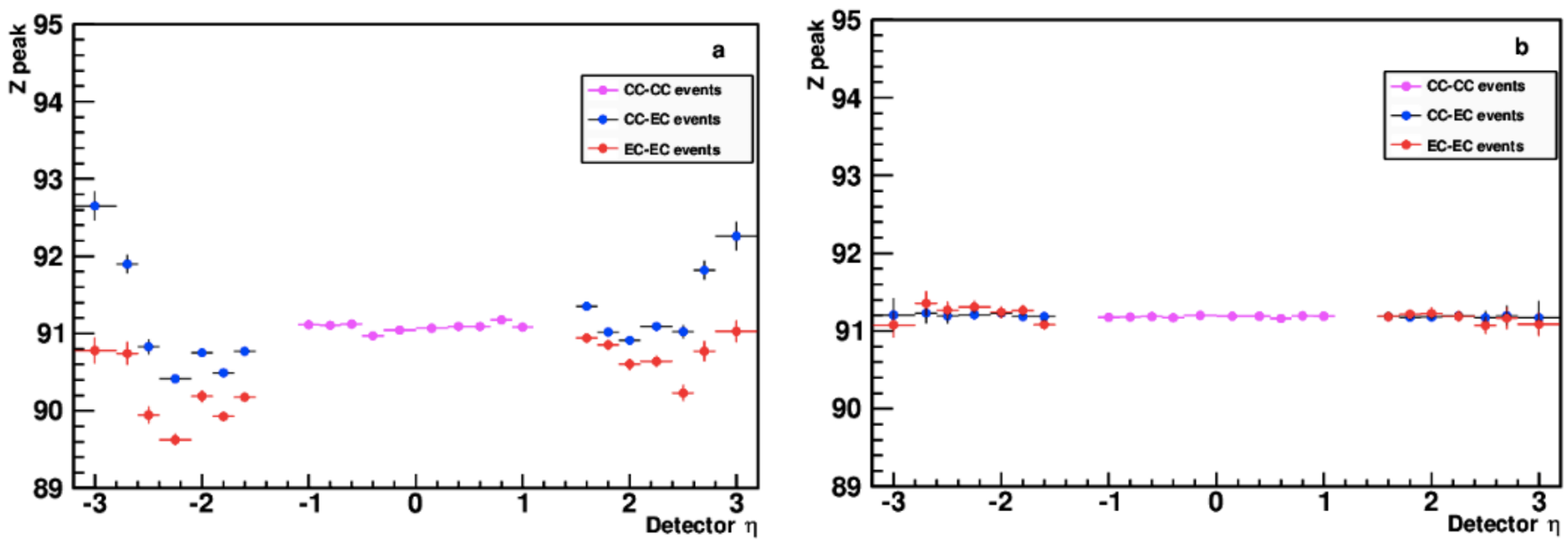
- **calibrate to generator level information**
- **not directly calibrate data to MC, because MC itself has eta-dependence**

Electron calibration

Multiple-parameter calibration

- **improve the electron energy calibration precision to ~0.01%**
- **reduce energy-eta dependence**

$$E(\eta)_{\mathrm{corr}} = k(\eta) \times E(\eta)_{\mathrm{obs}} + b(\eta)$$



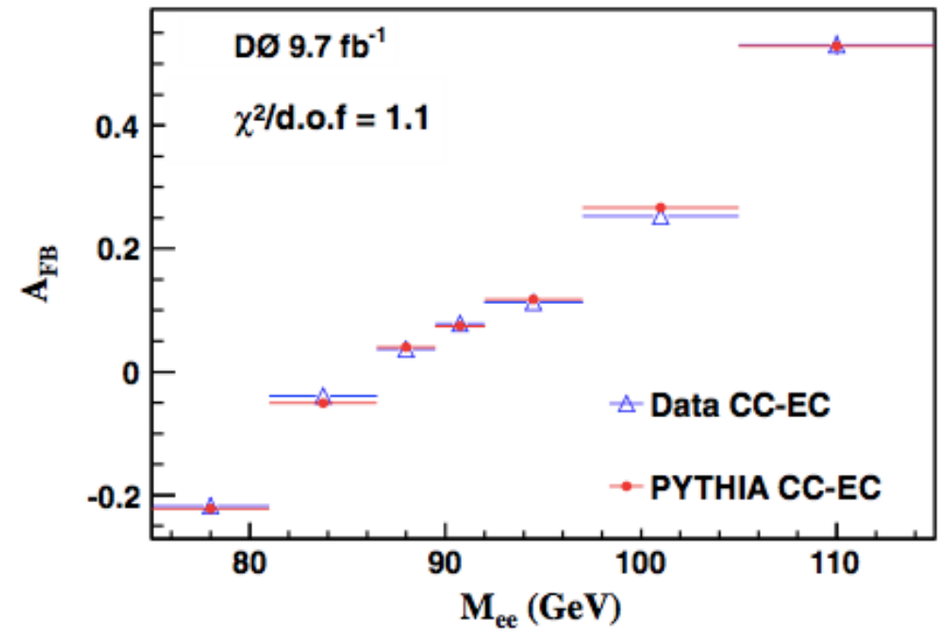
di-electron mass before (a) and after (b) our additional calibrations as a function of electron η. For events where both electrons in CC (CC-CC), both in EC (EC-EC) and one in CC and one in EC (CC-EC), the major difference is in the absolute energy of electrons. EC-EC electrons have highest energy due to Z boost, and CC-EC electrons have lowest energy.

2015 D0 electron channel

Phys. Rev. Lett. 115, 041801 (2015)

First time high precision!

- **10 fb^{-1}, full RunII data**
- **improved by novel electron calibration method**
  - **75% more statistics than simple sample size scaling (increased acceptance and improved track reconstruction)**
  - **negligible syst. uncertainty**



$$\sin^2\theta^{\ell}_{\rm eff} = 0.23147 \pm 0.00047$$

NNPDF2.3+simple higher order correction

$$\sin^2\theta^{\ell}_{\rm eff} = 0.23137 \pm 0.00047$$

NNPDF3.0+zfitter higher order correction

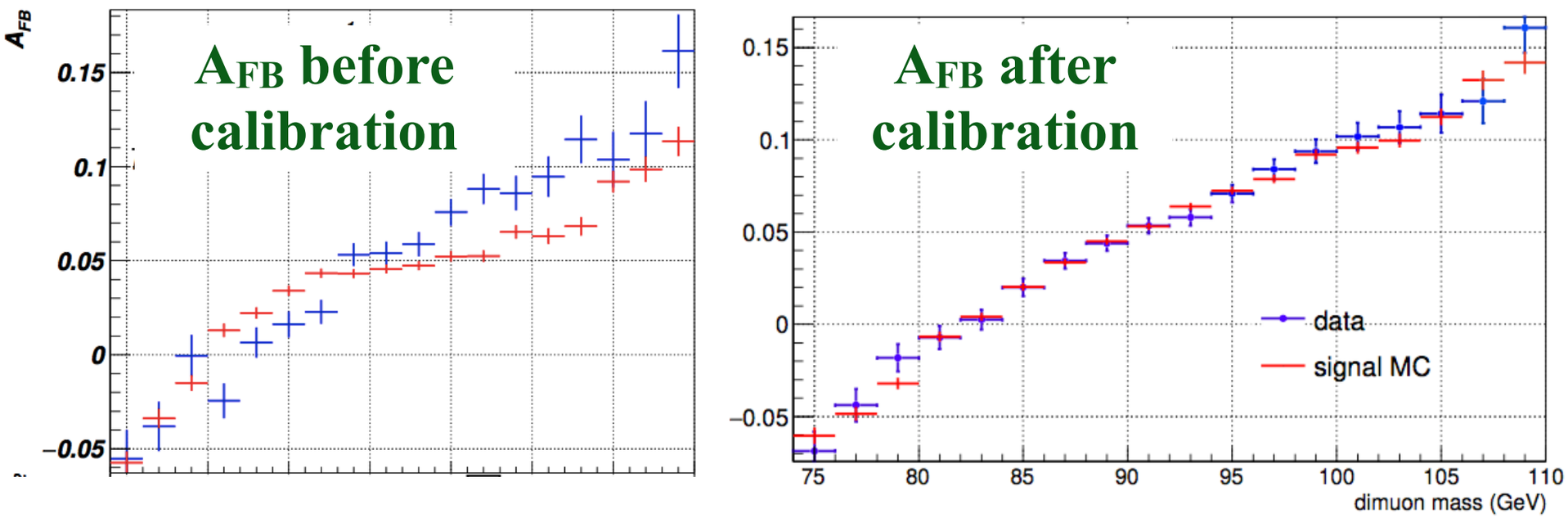
	predicted for 10 fb^{-1} using 1 fb^{-1} result	predicted for 10 fb^{-1} using 5 fb^{-1} result	10 fb^{-1} results
stat.	0.0005	0.0006	0.00043
syst.	negligible	0.0003	0.00008
PDF.	negligible	0.00048	0.00017
total	~0.0005	~0.00085	0.00047

2018 D0 muon channel channel

Phys. Rev. Lett. 120, 241802 (2018)

Last channel at Tevatron

- **8.6 fb^{-1} RunII data**
- **PDF: NNPDF3.0**
- **Not previously included in D0 high precision plan**
  - **charge-eta dependence in muon momentum reconstruction**
  - **solved by special calibration similar to the electron channel**



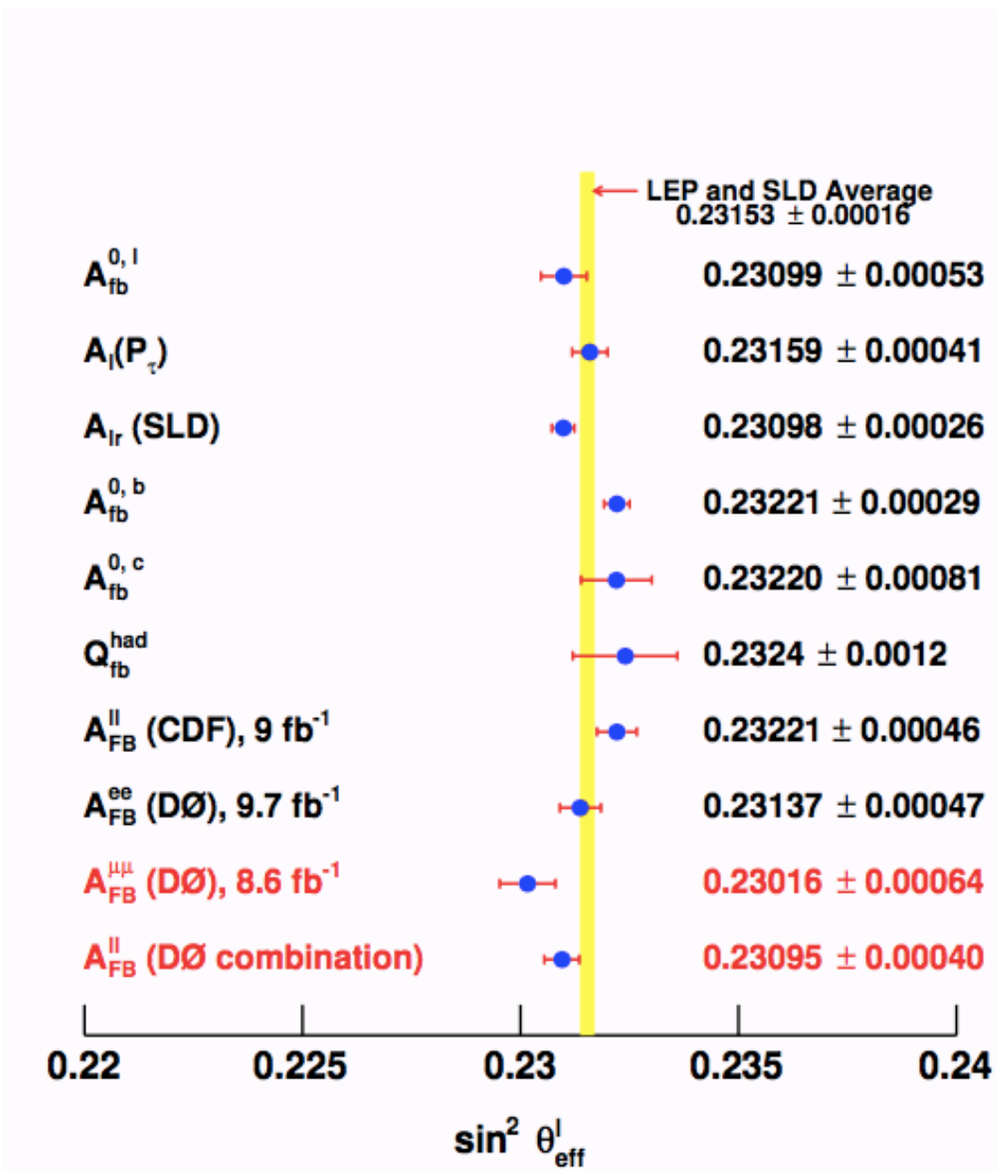
$$\begin{aligned}\sin^2\theta^{\ell}_{\text{eff}} &= 0.23016 \\ &= \pm 0.00059(\text{stat}) \pm 0.00006(\text{syst}) \pm 0.00024(\text{PDF}) \\ &= 0.23016 \pm 0.00064\end{aligned}$$

2018 D0 combination

Phys. Rev. Lett. 120, 241802 (2018)

Best result from single hadron experiment

- full RunII data
- PDF: NNPDF3.0
- higher order correction based on zfitter calculation and ResBos event generator
- good agreement compared with world average



$$\begin{aligned}\sin^2\theta_{\rm eff}^{\ell} &= 0.23095 \pm 0.00040 \\ &= 0.23095 \pm 0.00035({\rm stat}) \\ &\quad \pm 0.00007({\rm syst}) \pm 0.00019({\rm PDF})\end{aligned}$$