Measurement of the Effective Weak-mixing Angle $\sin^2\theta^l_{eff}$ in $p\bar{p} \to Z/\gamma^* \to l^+l^-$

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- Weak-mixing Angle $\sin^2\theta_W$
  - One of the SM fundamental parameters
    - Spontaneous symmetry breaking to produce Z and γ
    - Relationships between other electron-weak parameters

$$\sin^2\theta_W = \left(\frac{e}{g}\right)^2 = 1 - \frac{M_W^2}{M_Z^2}$$

    - Precise test of SM

- Effective Weak-mixing angle $\sin^2\theta_{eff}^l$
  - Absorb high order effect

$$\sin^2\theta_{eff}^l = Re[k_e(s,t,\sin^2\theta_W)]\sin^2\theta_W$$

➢ Effective Weak-mixing angle measurements

➢ The worst one among all electroweak fundamental parameters

Parameters	Relative uncertainty from experiment
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: $\sim 10^{-3}$
	LEP/SLD combine: $6 * 10^{-4}$

➢ Over 3σ difference between LEP and SLD

$$\sin^2\theta_{eff}^{l} = 0.23098 \pm 0.00026(SLD)$$
$$\sin^2\theta_{eff}^{l} = 0.23221 \pm 0.00029(LEP)$$

- ➢ Other independent measurement needed

➢ Overview

➢ 2008, $1.1 fb^{-1}$ RunIIa
Electron Channel
Precision:0.0019
First hadron measurement

➢ 2011, $1.1 fb^{-1}$ RunIIa
$+3.9 fb^{-1}$ RunIIb
Electron Channel
Precision:0.0010

➢ 2015, $1.1 fb^{-1}$ RunIIa
$+8.6 fb^{-1}$ RunIIb
Electron Channel
Precision:0.00047
Best single channel to date
First time close to LEP/SLD

➢ 2017, $8.6 fb^{-1}$ RunIIb
Muon Channel
Precision:0.00064
Best muon channel to date

➢ D0 combination
Precision:0.00040
Best single experiment to date
Best light-quark measurement

All D0 RunII weak-mixing angle measurements

Strategy

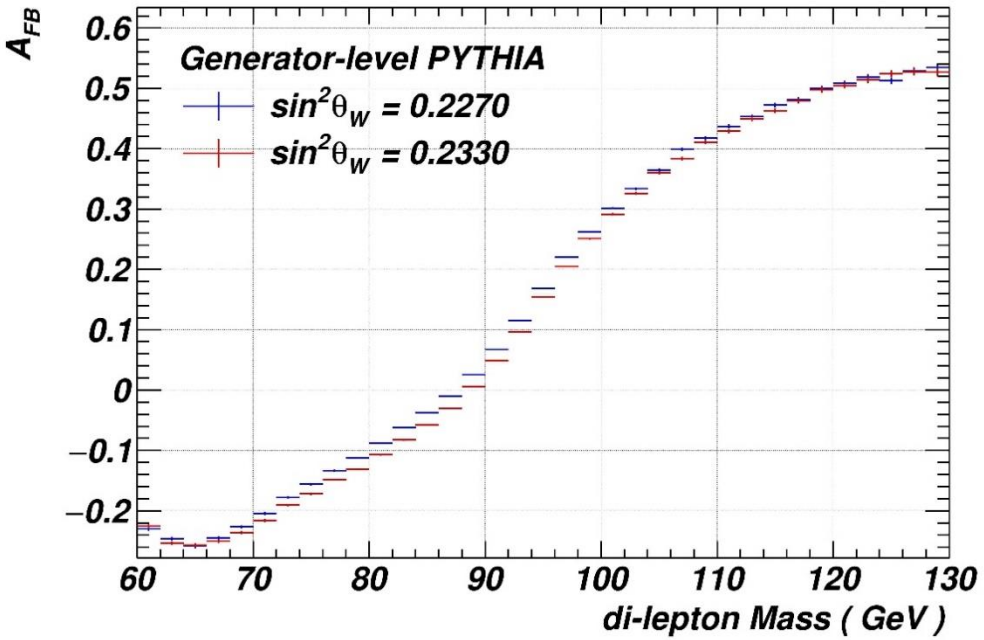
- Measured from raw $A_{FB}(M_{ll})$

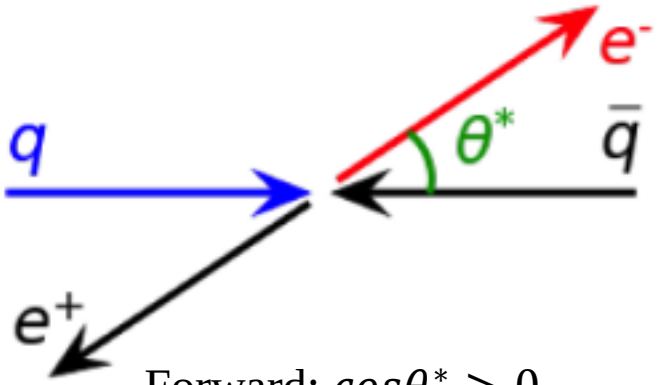
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

$$M_{ll}^2 = 2E_1E_2(1 - cos\theta_{12})$$

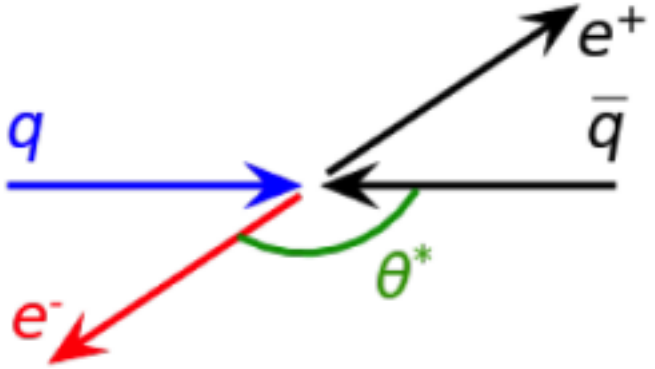
- Statistical dominated
- PDF uncertainty
- Systematic uncertainty:

Lepton energy calibration





Forward: $cos\theta^* > 0$



Backward: $cos\theta^* < 0$

➢ $1.1fb^{-1}$ electron channel measurement (2008)

➢ First hadron measurement

- ➢ Tevatron RunIIa, 35K events
- ➢ Measured by observing $A_{FB}(M_{ll})$
- ➢ PDF:CTEQ6L
- ➢ Simple higher-order correction(ZGRAD2)

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

	$1.1fb^{-1}$ results	Theoretical expectation for $10fb^{-1}$*
$\boldsymbol{\sigma_{stat}}$	0.0018	0.0005
$\boldsymbol{\sigma_{syst}}$	0.0003	0.00007
$\boldsymbol{\sigma_{PDF}}$	0.0005	0.00007
$\boldsymbol{\sigma_{Total}}$	0.0019	~0.0005

*arXiv:hep-ex/0011009

➢ $5fb^{-1}$ electron channel measurement (2011)

➢ Mid-term estimation

- ➢ Tevatron RunIIa+part of RunIIb, 160K events
- ➢ Measured by observing $A_{FB}(M_{ll})$
- ➢ PDF:CTEQ6L

$$\sin^2\theta^l_{eff} = 0.2309 \pm 0.0010$$
$$= 0.2309 \pm 0.0008(stat.) \pm 0.00029(syst.) \pm 0.00048(\text{PDF})$$

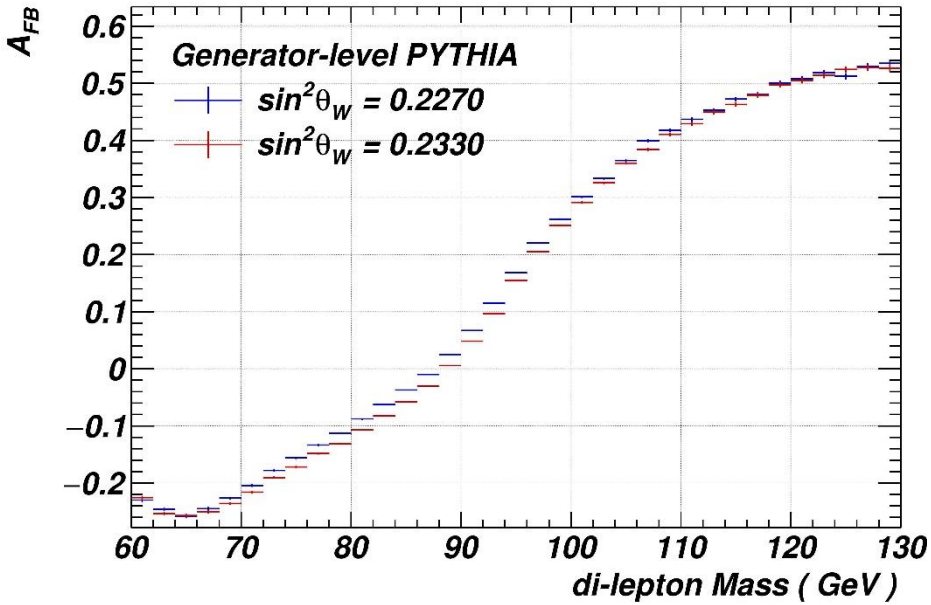
	$5fb^{-1}$ results	Theoretical expectation for $10fb^{-1}$	Expectation for $10fb^{-1}$ using $5fb^{-1}$ results
σ_{stat}	0.0008	0.0005	> 0.0006
σ_{syst}	0.00029	0.00007	0.0003
σ_{PDF}	0.00048	0.00007	~0.00048
σ_{Total}	0.0010	~0.0005	~0.00085

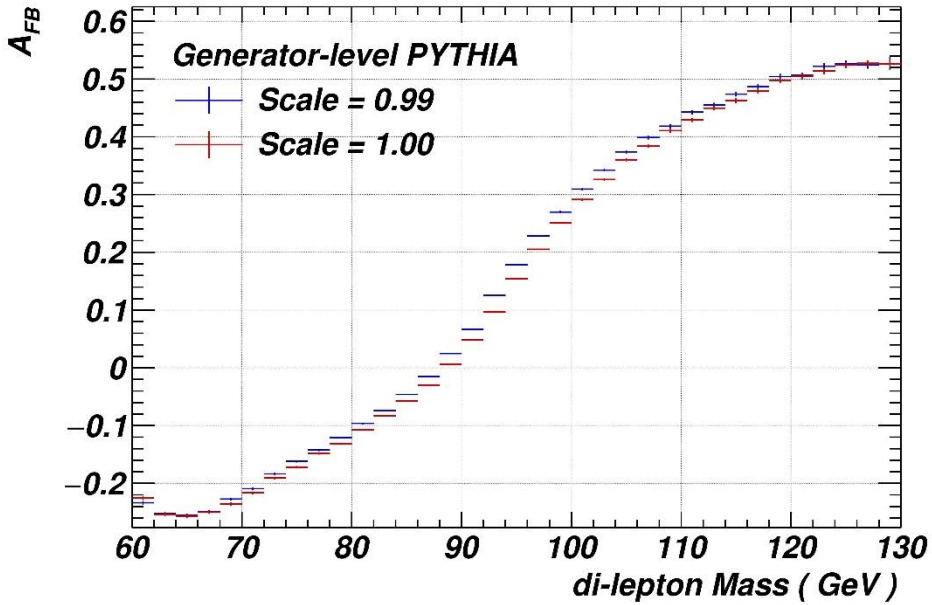
➢ Systematic uncertainty

➢ Lepton calibration

- ➢ Affects $A_{FB}(M_{ll})$ same with $\sin^2\theta_W$ does
- ➢ Very sensitive

$$\frac{\delta M}{M}\Big/\sigma_{\sin^2\theta_W} \sim 0.01\%/0.00003$$





➢ $9.7fb^{-1}$ electron channel measurement (2015)

*arXiv:1803.02252

- ➢ First high precision measurement
- ➢ Best electron channel measurement to date
  - ➢ Tevatron RunII, ~560K events
  - ➢ Measured by observing $A_{FB}(M_{ll})$
  - ➢ PDF: NNPDF2.3/3.0
- ➢ Improved by novel electron calibration method*

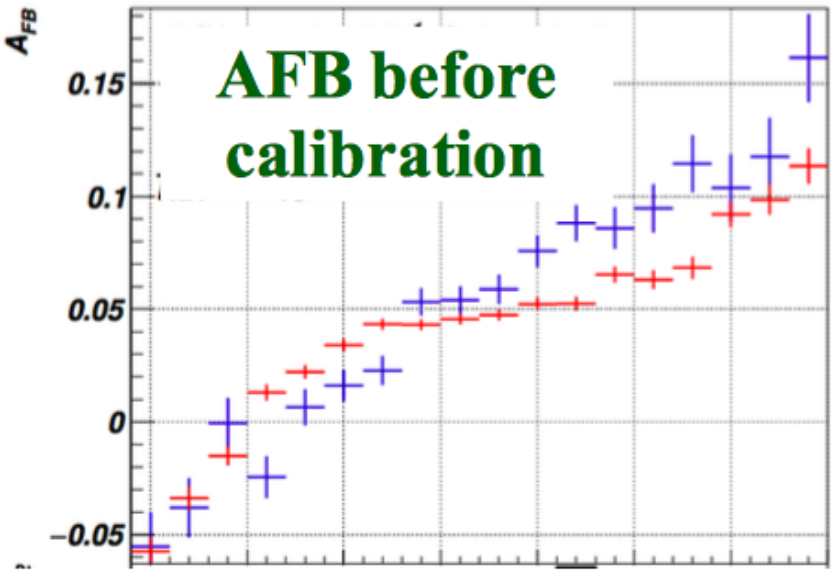
$$\sin^2\theta^l_{eff} = 0.23137 \pm 0.00047$$
$$= 0.23137 \pm 0.00043(stat.) \pm 0.00009(syst.) \pm 0.00017(\text{PDF})$$

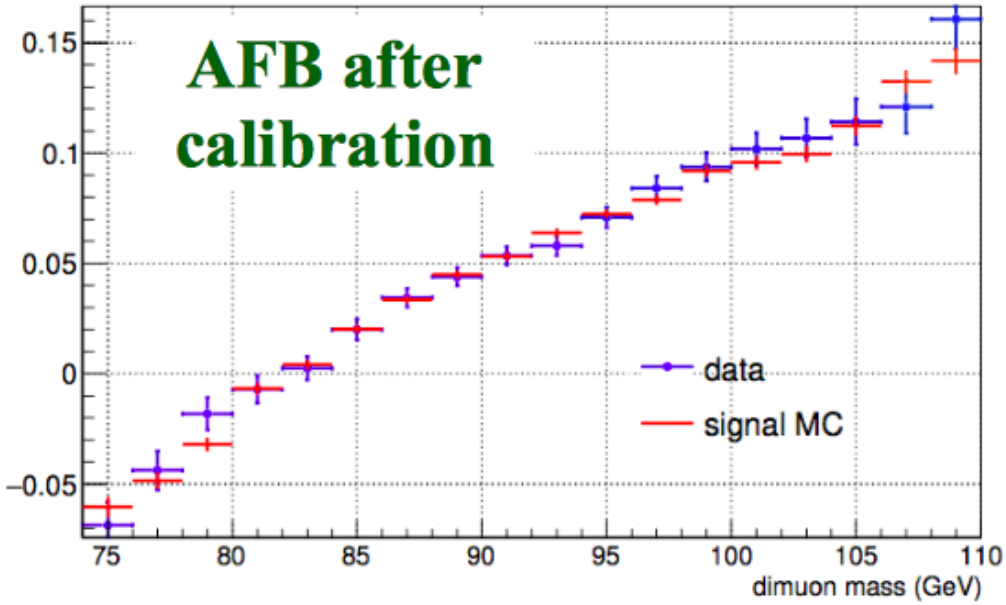
	$9.7fb^{-1}$ results	Theoretical expectation for $10fb^{-1}$	Expectation for $10fb^{-1}$ using $5fb^{-1}$ results
$\boldsymbol{\sigma_{stat}}$	0.00043	0.0005	> 0.0006
$\boldsymbol{\sigma_{syst}}$	0.00009	0.00007	0.0003
$\boldsymbol{\sigma_{PDF}}$	0.00017	0.00007	~0.0002
$\boldsymbol{\sigma_{Total}}$	0.00047	~0.0005	~0.00085

- $8.6fb^{-1}$ muon channel measurement (2017)
  - Best muon channel measurement to date
    - Tevatron RunIIb, ~480K events
    - Measured by observing $A_{FB}(M_{ll})$
    - PDF: NNPDF3.0

$$\sin^2\theta^l_{eff} = 0.23016 \pm 0.00064$$
$$= 0.23016 \pm 0.00059(stat.) \pm 0.00006(syst.) \pm 0.00024(\text{PDF})$$

  - Originally not in the plan
    - Charge-dependent muon momentum scale





- DZero combination (2017)

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

- Higher order correction
  - Straight forward high order corrections
    - ZFITTER-based form factor calculation
    - ResBos vs. PYTHIA comparision

	$\Delta sin^2\theta^l_{eff}$
Different effective coupling for u and d quarks	+0.00008
Mass-scale dependence and complex calculation	+0.00014
Total	+0.00022

$$\Delta \sin^2\theta_W = +0.00022 \pm 0.00004(\text{Dominated by } m_t)$$

Summary

$$\sin^2\theta_{eff}^{l} = 0.23095 \pm 0.00040$$
$$= 0.23095 \pm 0.00035(stat.) \pm 0.00007(syst.) \pm 0.00019(\mathrm{PDF})$$

- Best single experiment to date
- Best light-quark measurement

- High precision calibration
  - Both statistical uncertainty and systematic uncertainty

- Higher order correction
  - Straight forward higher order corrections
  - Uncertainty dominated by m_t