The weak mixing angle $\sin^2\theta_W$ measurement at hadron colliders

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标准模型电弱机制

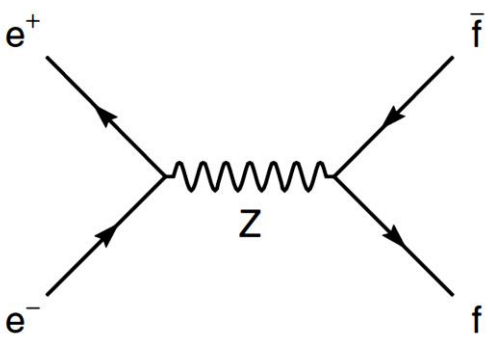
➢ 基本物理常数:

$$\alpha = e^2/4\pi; \quad G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2\sin^2\theta_W}; \quad M_Z = \frac{M_W}{\cos\theta_W}; \quad M_W = \frac{g\nu}{\sqrt{2}}; \quad m_H = 2\nu\sqrt{\lambda};$$

$$\boxed{\sin^2\theta_W = e^2/g^2 = 1 - \frac{M_W^2}{M_Z^2}}$$

(**on-shell**)

➢ 弱中性流耦合:



(Born level树图阶)

$$-i\frac{g}{2\cos\theta_W}\bar{f}\gamma^\mu(g_V^f - g_A^f\gamma_5)fZ_\mu$$

$$\begin{cases} g_V^f = I_3^f - 2Q_f\sin^2\theta_W \\ g_A^f = I_3^f \end{cases}$$

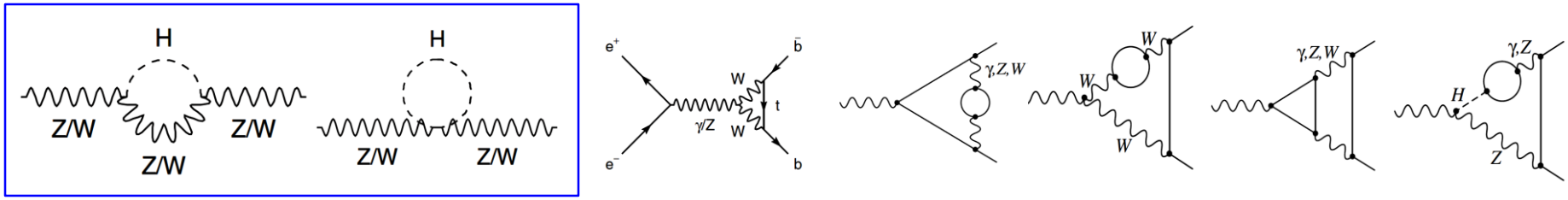
有效弱混合角

➢ 理论预言：

- High order corrections absorbed into EBA(Effective Born Approximation), i.e. flavor-related effective couplings as

$$sin^2\theta_{\mathbf{eff}}^f = \mathrm{Re}(\kappa_f)sin^2\theta_{\mathrm{W}} = \frac{1}{4|\mathrm{Q}_f|}\left(1-\frac{\mathrm{Re}[\mathrm{g}_{\mathrm{V}}^f]}{\mathrm{Re}[\mathrm{g}_{\mathrm{A}}^f]}\right)$$

- Complete EW corrections up to 2-loop orders [**JHEP0611,048**] included in ZFITTER etc.



- The effective mixing angle: converged to leptonic

$$\boxed{sin^2\theta_{\mathbf{eff}}^{\mathbf{Lept}} = \mathrm{Re}[\kappa_l(\mathrm{M_Z})]\cdot sin^2\theta_{\mathrm{W}}}$$

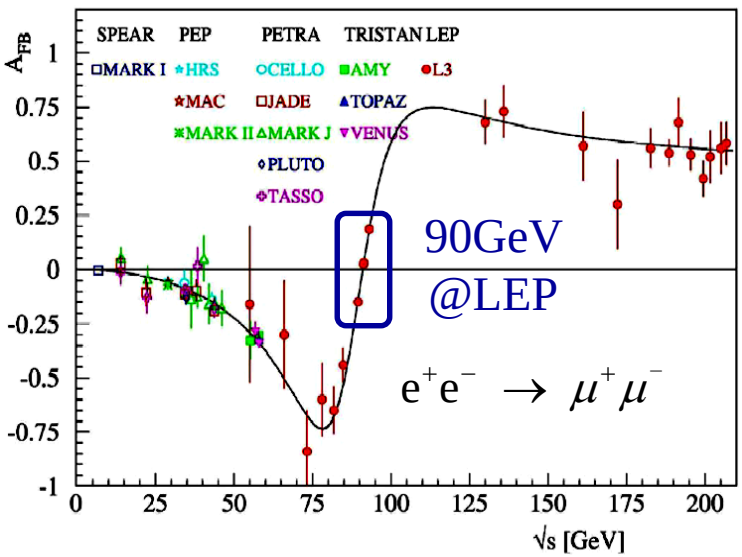
$$\begin{cases} \sin^2\theta_{\mathrm{eff}}^u \approx \sin^2\theta_{\mathrm{eff}}^l - 0.0001, \\ \sin^2\theta_{\mathrm{eff}}^d \approx \sin^2\theta_{\mathrm{eff}}^l - 0.0002. \\ \sin^2\theta_{\mathrm{eff}}^{\mathrm{b}} - \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} \approx 0.0014, \end{cases}$$

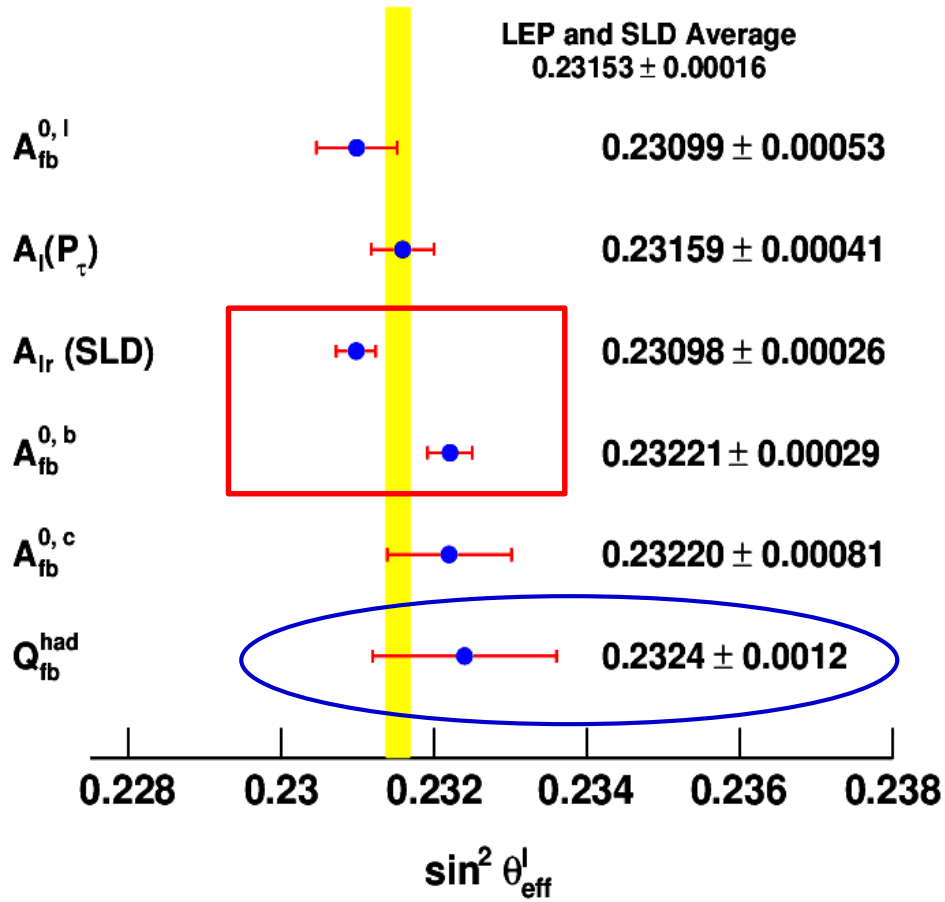
(**effective**)

电子对撞机LEP/SLD测量标准

- The most precise results, LEP b-quark vs SLD lepton LR , differ **3.2**σ

观测量：$A_{FB} = \dfrac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$



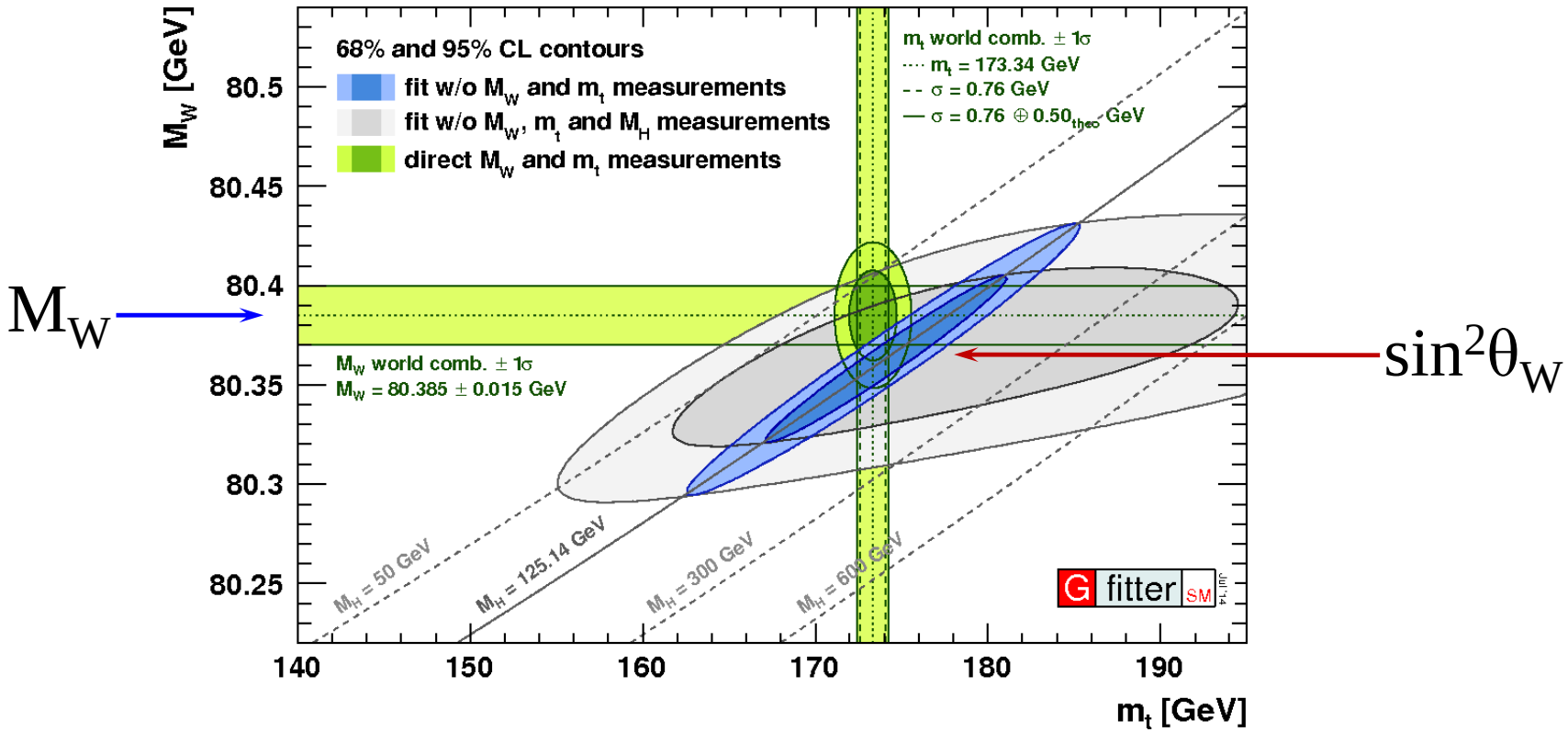


- The LEP/SLD World Average： **0.23153 ± 0.00016**

标准模型电弱机制自洽检验

- M_W determination:

80.385 ± 0.015 (LEP&Tev Direct) vs. **80.363 ± 0.020** (LEP Indirect)

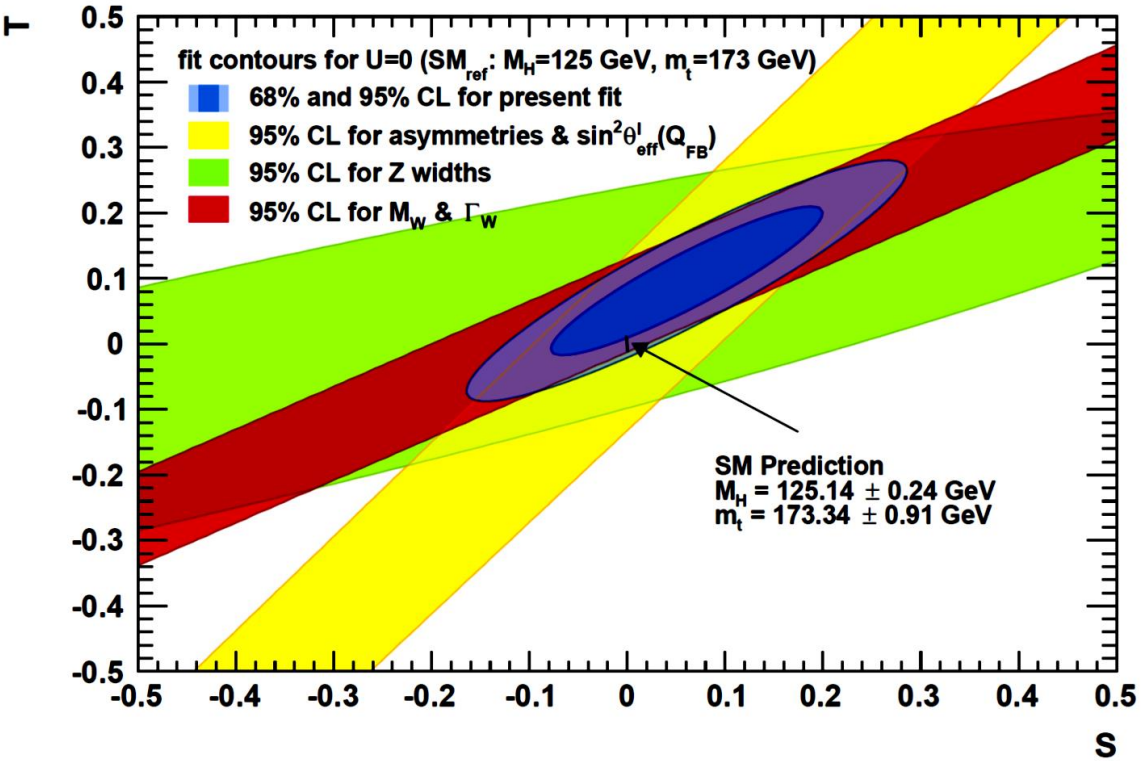


SM inconsistency?

Need new experimental inputs!

间接探测新物理效应

➢ Oblique parameter S, T and U: [**EPJC74 (2014) 3046**]



- Effects via vacuum polarization corrections to the EW gauge bosons W/Z.
- Non-zero S, T, U are unambiguous indication of new physics (NP)
- S and T, NP to the neutral/charged weak currents.
- U, NP to the mass and width of the W boson

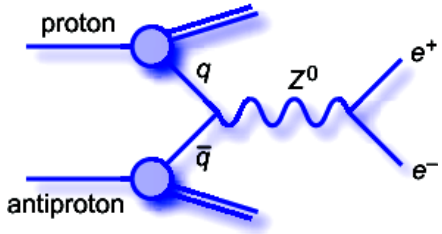
Hits of New Physics?

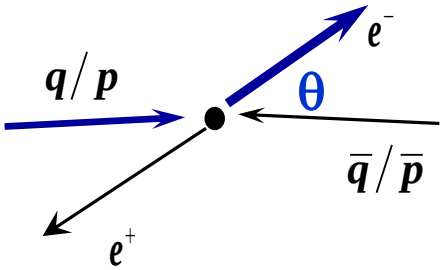
Need new experimental inputs!

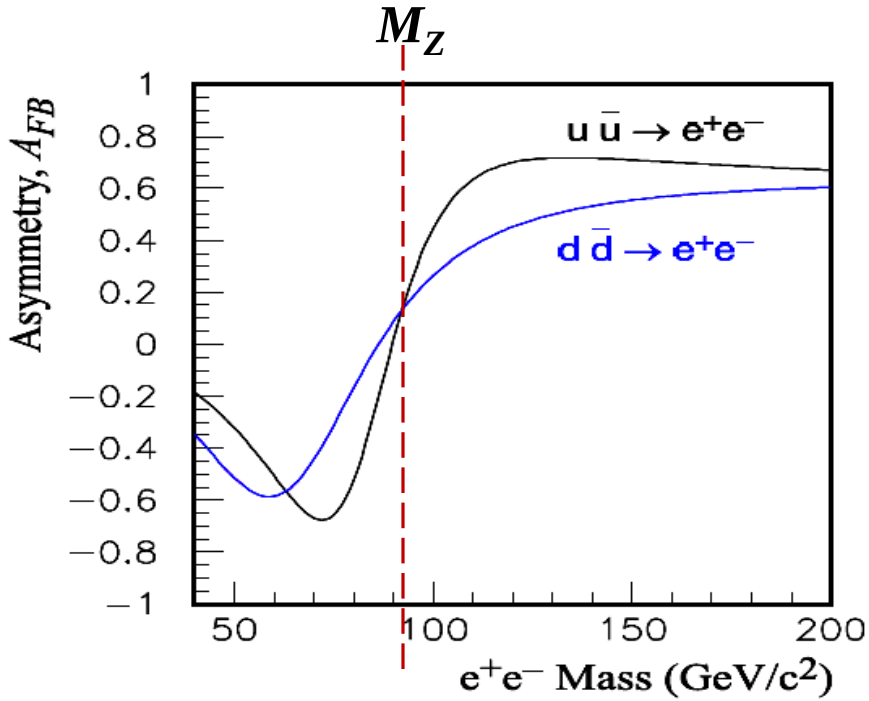
强子对撞机Tevatron测量

➢ DØ实验正负电子前后不对称测量

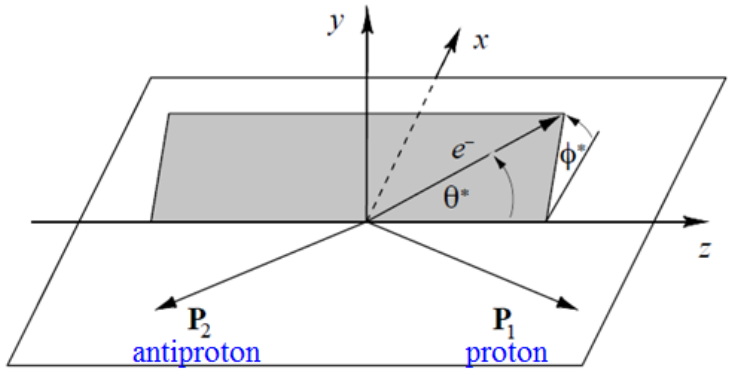
$$p\bar{p} \to q\bar{q} \to Z \to e^- e^+$$







Collins-Soper frame



$$\cos\theta^* = \frac{2(p_l^+ p_{\bar{l}}^- - p_l^- p_{\bar{l}}^+)}{m(l\bar{l})\sqrt{m^2(l\bar{l}) + p_T^2(l\bar{l})}}$$

DØ实验$\sin^2\theta_W$测量

① Run2a 1fb^{-1}：**验证可行性**

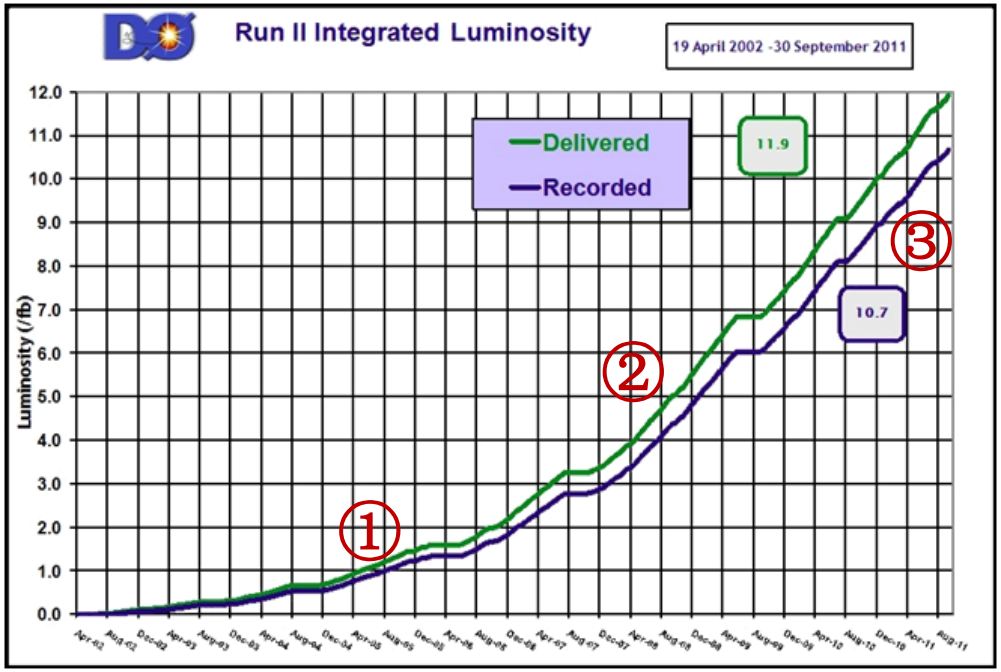
0.2326±0.0018(stat.)±0.0006 (syst.)

PRL101 (2008)191801

② Run2b 5fb^{-1}：**系统误差控制**

0.2309±0.0008(stat.)±0.0006 (syst.)

PRD84 (2011)012007



Tevatron ceased operations on 2011/09/30 with 9.7fb^{-1} data recorded at DØ

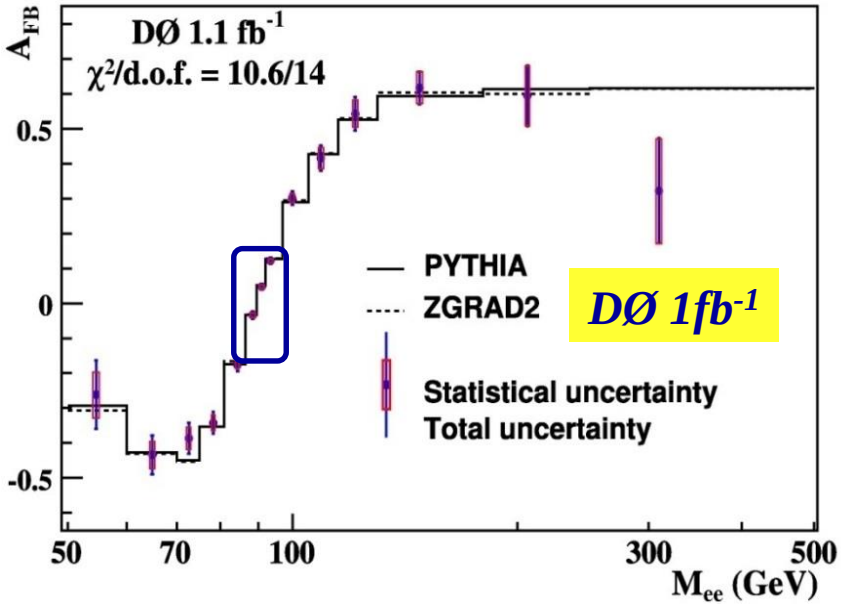
③ Run2 9.7fb^{-1}：**电子刻度新方法**

0.23147 ± 0.00043(stat.) ± 0.00008 (syst.) ± 0.00017 (theory)

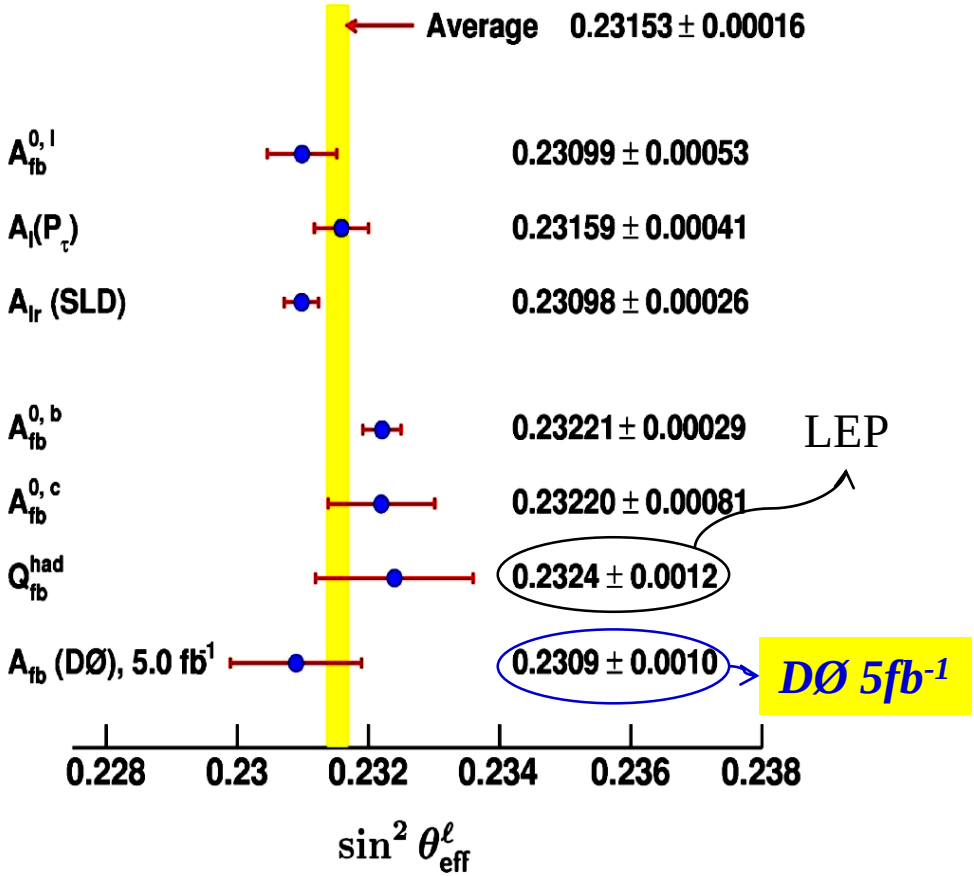
PRL115 (2015)041801

➢ DØ实验早期测量结果

PRL 101,191801 (2008)

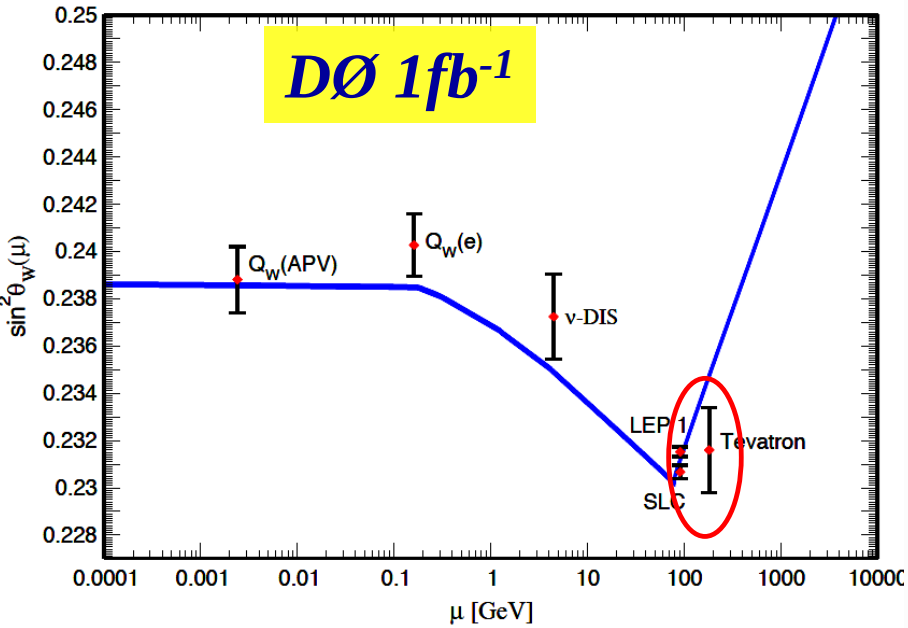


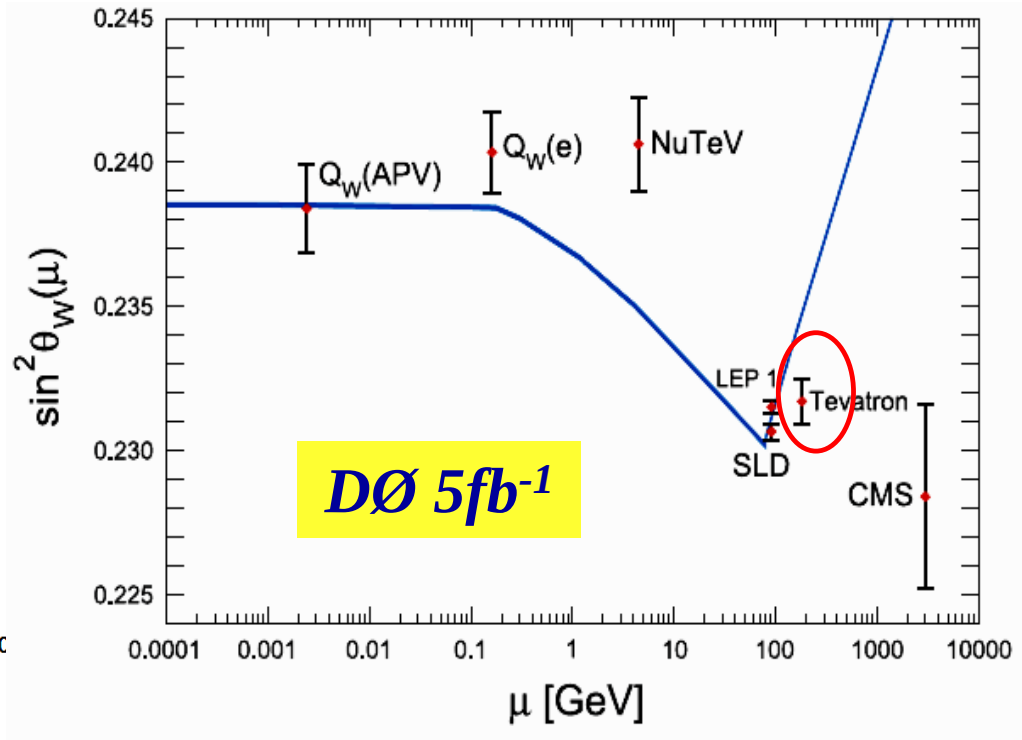
PRD 84,012007 (2011)



$\sin^2\theta_W$ = **0.2309 ± 0.0010** measured @ D0 5fb^{-1}

➢ PDG引用 “Electroweak model and constraints on new physics”





- PDG 2010：
  DØ 首次测量
  PRL 101(2008)191801

- PDG 2012 ：
  最精确轻夸克相关测量
  PRD 84(2011)012007

➢ DØ实验5fb^{-1}误差分析

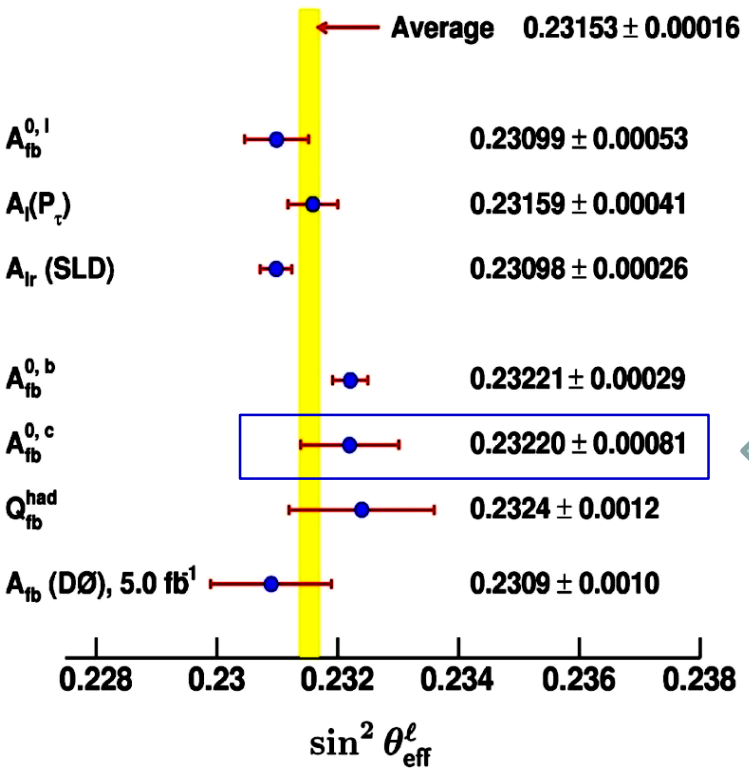
$$0.2310 \pm 0.0008 \pm 0.0006$$

Uncertainty source	$\Delta \sin^2 \theta^{\ell}_{\mathrm{eff}}$
Statistical	0.00080
Systematics	0.00061
PDF/Acceptance	0.00048
EM scale/resolution	0.00029
MC Statistics	0.00020
Electron identification	0.00008
Bkg. modeling	0.00008
Charge misidentification	0.00004
Higher order	0.00008
Total uncertainty	0.00102

- Statists
- CTEQ6 PDF
- Electron energy measurement

➢ DØ实验9.7fb^{-1}估计

	$\sin^2\theta_W$ ± stat. ± syst.
DØ 5fb^{-1} measured	0.2310 ± **0.0008** ± **0.0006**
DØ 9.7fb^{-1} expected	? ± **0.0006** ± **0.0006** -- systematic would be comparable/dominant

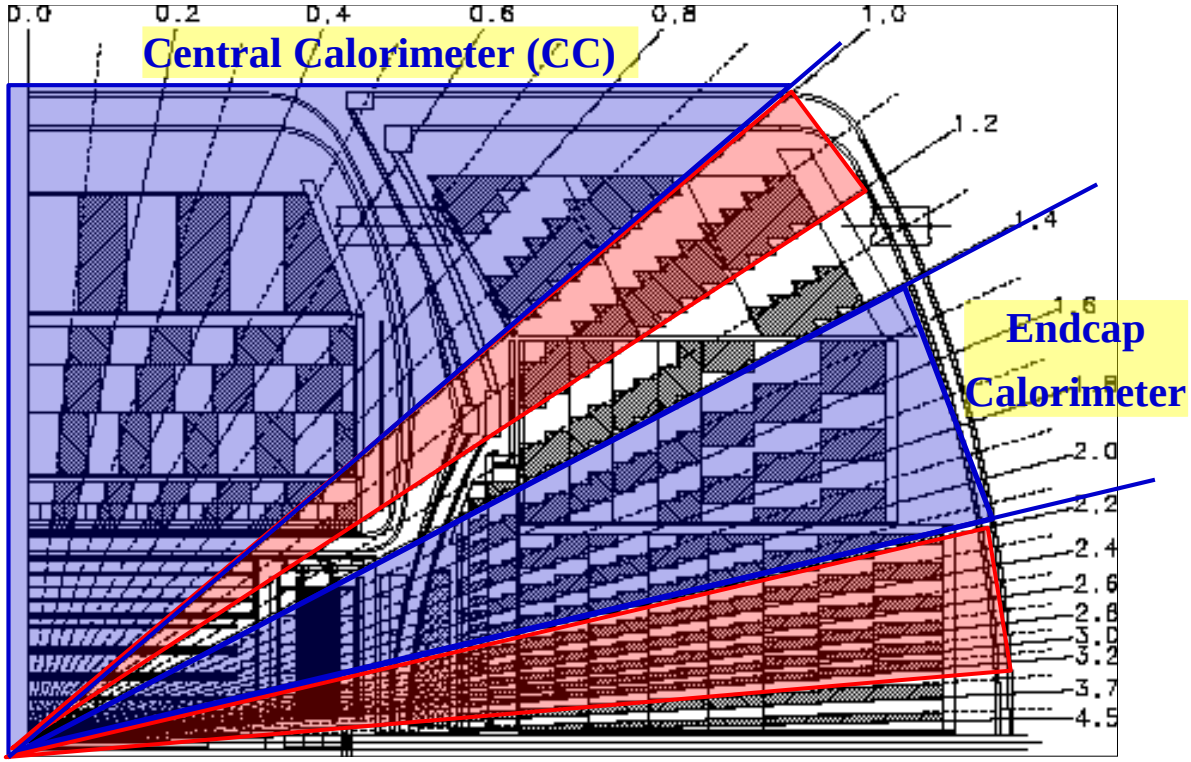


⟺ ± 0.00085 exp. @ D0 9.7fb^{-1}

~ 3% of LEP/SLD Average precision

➢ DØ实验9.7fb^{-1}测量改进：

Novel electron calibration + Extension of detector coverage

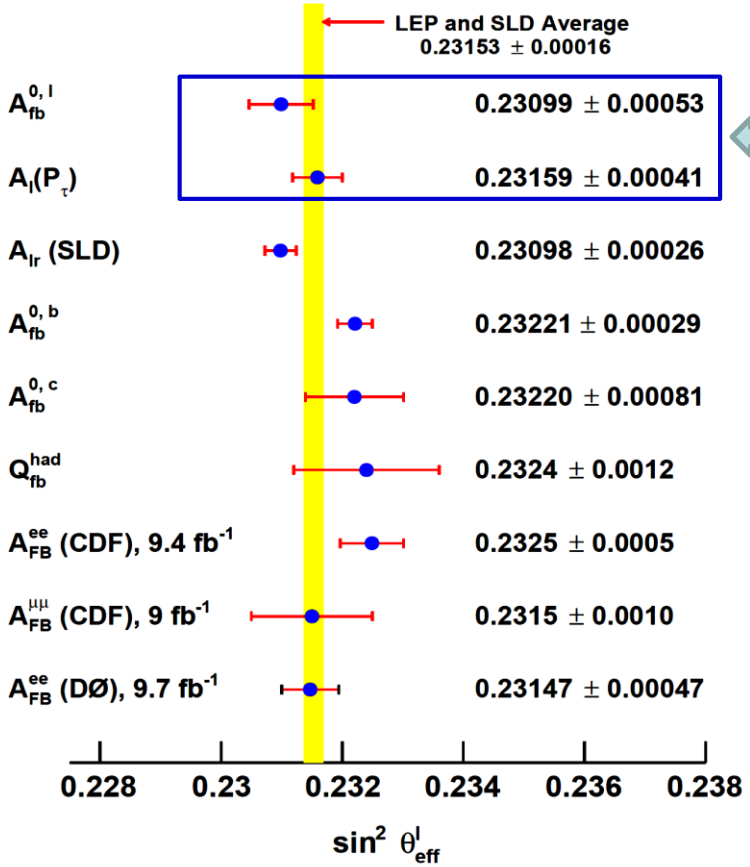


- gain **80**% extra data
- Uncertainties of EM scale/resolution → **ignorable**

(杨思奇“晨光杯”报告)

➢ DØ实验9.7fb^{-1}测量结果

	$\sin^2\theta_W$ ± stat. ± syst. ± theory
DØ 9.7fb^{-1} expected	? ± **0.00058** ± **0.00035** ± 0.00048 (CTEQ6)
DØ 9.7fb^{-1} measured	0.23147 ± **0.00043** ± **0.00008** ± 0.00017(NNPDF)



$\sin^2\theta_W$ = **0.23147 ±0.00047**

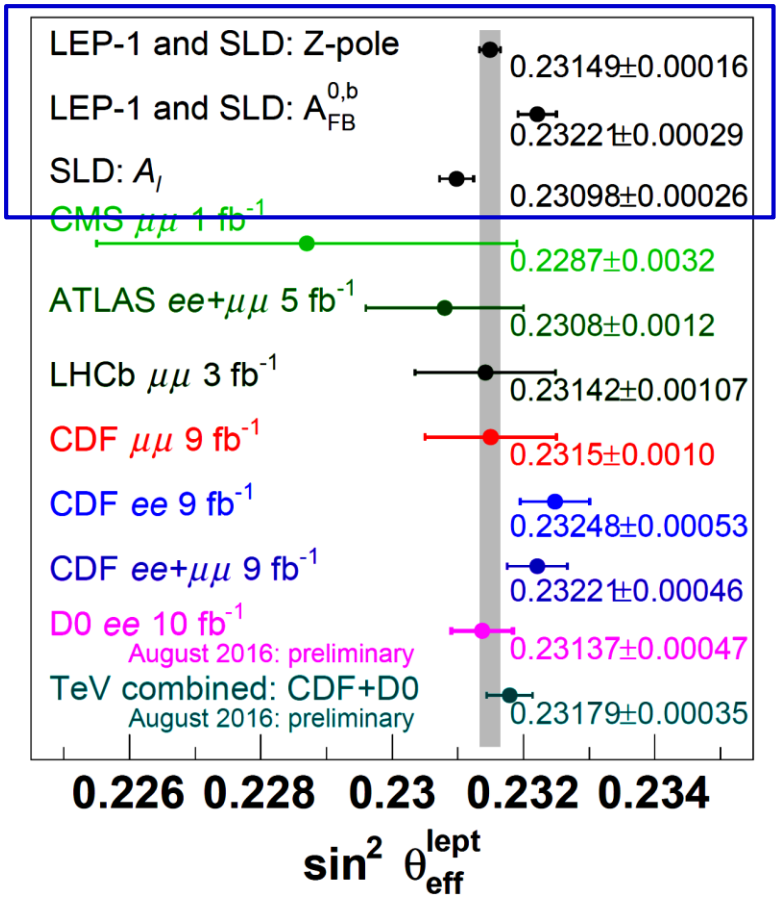
measured @ D0 9.7fb^{-1}

~ 11% of LEP/SLD Average precision

PRL 115, 041801 (2015)

Preliminary Tevatron Combination*

	$\sin^2\theta_W \pm$ stat. $\pm$ syst. $\pm$ PDF	
CDF 9fb^{-1} Zμμ	0.2315 ± 0.0009 ± 0.0002 ± 0.0004	PRD 89,072005 (2014)
DØ 9.7fb^{-1} Zee	0.23147 ± 0.00043 ± 0.00008 ± 0.00017	PRL115,041801(2015)
CDF 9fb^{-1} Zee	0.23248 ± 0.00049 ± 0.00004 ± 0.00019	PRD 93,112016 (2016)



$\Leftrightarrow$ $\sin^2\theta_W$ = **0.23179 ± 0.00035**

~ 21% of LEP/SLD Average precision

- M_W determination:

  80.385 ± 0.015 (Direct)

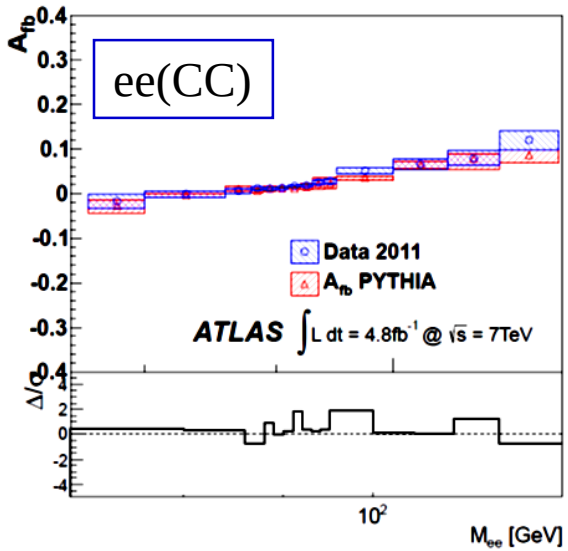
  80.351 ± 0.018 (Latest Tevatron Indirect)

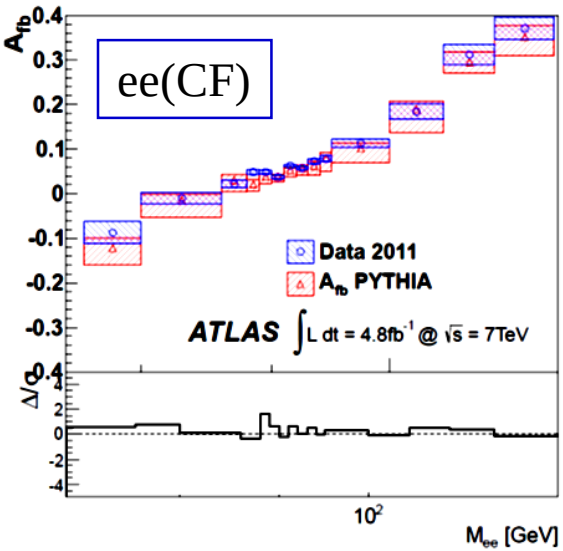
* Presented at ICHEP2016
http://indico.cern.ch/event/432527/contributions/2212775/

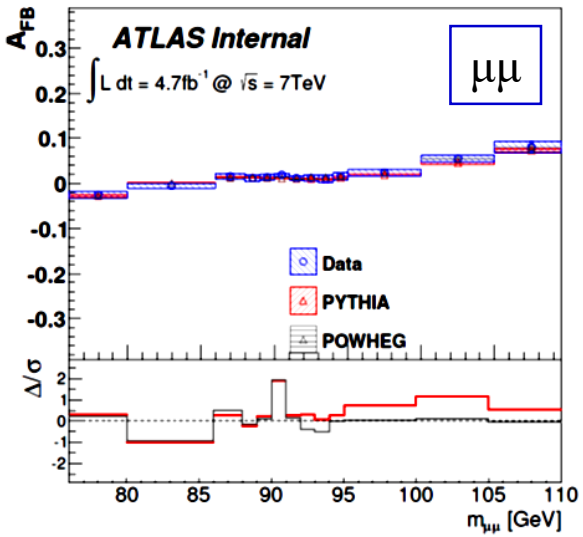
强子对撞机LHC测量

➢ Dilution of pp collision：

$$\cos\theta^* = \boxed{\frac{p_z(l\bar{l})}{|p_z(l\bar{l})|}} \frac{2(p_l^+ p_{\bar{l}}^- - p_l^- p_{\bar{l}}^+)}{m(l\bar{l})\sqrt{m^2(l\bar{l}) + p_T^2(l\bar{l})}}$$







$\sin^2\theta_W$ = **0.2308** ± **0.0005**(stat.) ± **0.0012**(syst.)

measured @ ATLAS 7TeV 4.8fb^{-1} ee(CC/CF)+μμ

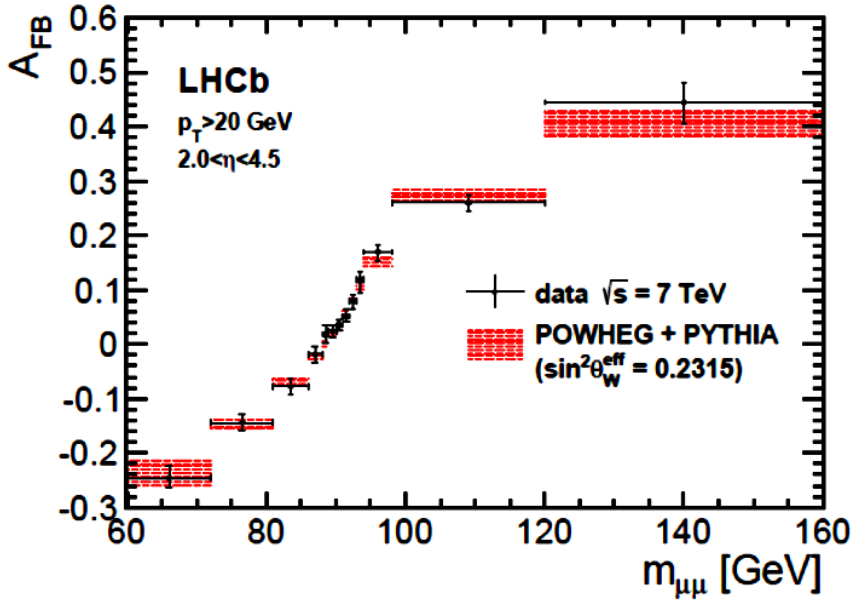
➢ ATLAS实验7TeV 4.8fb^{-1}误差分析

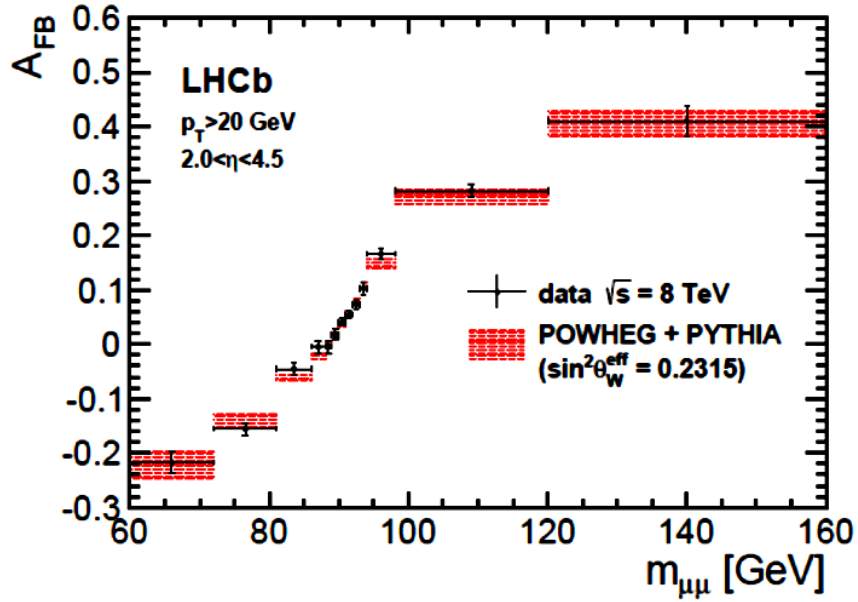
$$0.2308 \pm 0.0005 \pm 0.0012$$

Systematic uncertainty	Deviation [10^{-5}]
PDF (CT10/ATLAS-epWZ12)	46/97
Energy Scale	57
Energy Smearing	45
Electron ID	4
Pile-up	5
Background	8
MC statistics	23
EWK NLO corrections	6
QCD NLO corrections	10
Total (CT10/ATLAS-epWZ12)	90/ 124

- Dilution: 7TeV→13TeV
- Lepton E/pT scale uncertainties

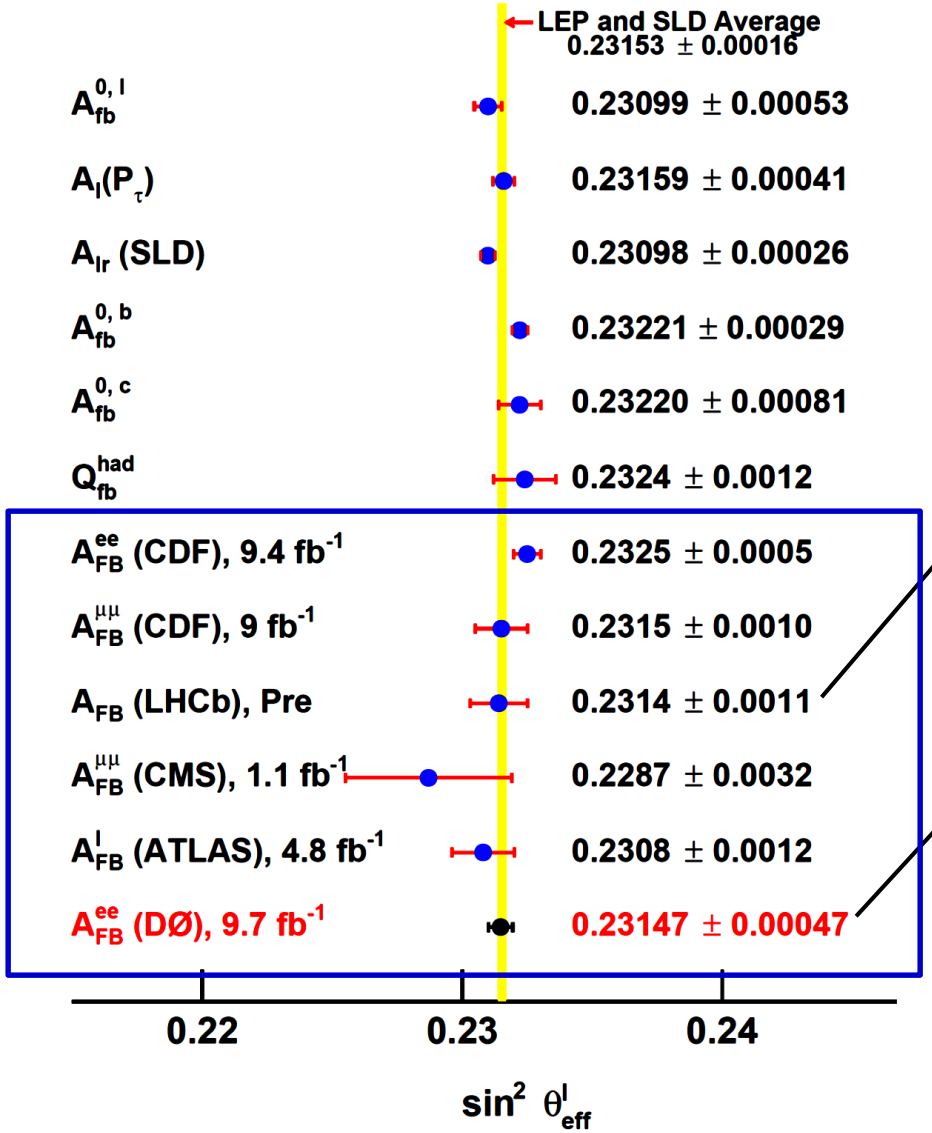
➢ LHCb实验7/8TeV 1/2fb^{-1}测量





$$\sin^2\theta_W = \mathbf{0.23142} \pm \mathbf{0.00073}(\text{stat.}) \pm \mathbf{0.00052}(\text{syst.}) \pm \mathbf{0.00056}(\text{theory})$$

State of the art of $\sin^2\theta_W$



LHCb:

- most precise measurement among LHC experiments

DØ:

- most precise measurement at hadron colliders
- comparable to the best LEP and SLD's results

研究计划与展望

- Tevatron:

  Fulfill DØ measurement in Z→μμ to achieve the Tevatron Legacy

- LHC:

  Estimation of 13/14TeV 2017-2018 Run1 data, single experiment and single channel[1,2,3]

$$\Delta\sin^2\theta_W = 0.00011\ (\text{stat.}) \pm 0.00014\ (\text{PDF}) \pm X\ (\text{syst.})$$

$$\Delta M_W(\text{Indirect}) \sim \pm 9\ \text{MeV}$$

reduce lepton uncertainties ~ $10^{-3} \rightarrow 10^{-5}$

[1] A. Bodek et al, Eur. Phys. J. C (2016) 76,
[2] M.H. Liu et al, 23 May 2016, ATLAS SM W/Z meeting, "Precise $\sin^2\theta_W$ with 13TeV data"
[3] S.Q. Yang et al, 18 July 2016, ATLAS SM W/Z meeting, "$\sin^2\theta_W$ @ method of the analysis"

Backup slides

$$L = g_{hff}\bar{f}Hf + \frac{g_{hhh}}{6}H^3 + \frac{g_{hhhh}}{24}H^4 + \eta_v V_\mu V^\mu (g_{hvv}H + \frac{g_{hhvv}}{2}H^2)$$

$$g_{hff} = \frac{m_f}{v}, \quad g_{hvv} = \frac{m_v^2}{v}, \quad g_{hhvv} = \frac{2m_V^2}{v^2}, \quad g_{hhh} = \frac{3m_H^2}{v}, \quad g_{hhhh} = \frac{3m_H^2}{v^2}$$

CEPC：250GeV ZH → g_{ZZh}

ILC： 350GeV ZHH → g_{ZZhh}, g_{hhh}

375GeV HHH → g_{ZZh}

500GeV ZHHH → g_{ZZhh}, g_{hhh}, g_{hhhh}

有效弱混合角

➢ 理论预言：

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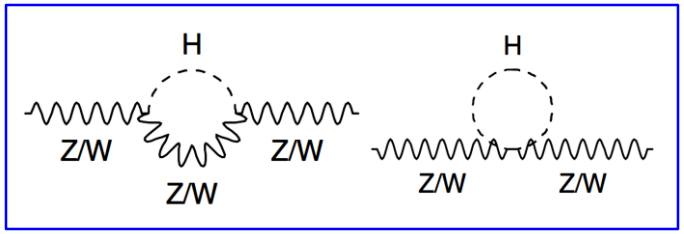
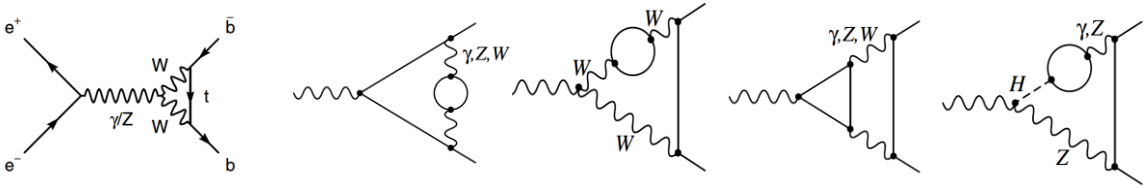
$$\sin^2\theta_{\mathrm{eff}}^{f} = \mathrm{Re}(\kappa_f)\sin^2\theta_{\mathrm{W}} = \frac{1}{4|Q_f|}\left(1-\frac{\mathrm{Re}[g_{\mathrm{V}}^{f}]}{\mathrm{Re}[g_{\mathrm{A}}^{f}]}\right)$$

- Complete EW corrections up to 2-loop orders [**JHEP0611,048**] included in ZFITTER etc.





Indirect constraints on g_{Zhh} and g_{ZZhh} and new physics

CEPC: 90GeV Z → A_{FB}(b/Bc, τ-pol), $A_{L/R}$

160GeV WW → direct M_W

180GeV ZZ → calibration

250GeV ZH → g_{ZZh}