Electroweak Precision Measurement at Hadron Colliders

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2019. Oct. 24th

Electroweak precision measurement and global fitting

Basic idea

- Observation on fundamental paramaters
  - α, $G\mu$, M_Z, M_W, $\sin^2\theta_W$, M_H, M_{top}
- Input to the global fitting
- Starting from 1960s

History

- Pre-top-Higgs Era: predict M_H and m_{top} under SM assumption
  - ~50 GeV precision for m_{top} prediction before LEP/SLC
  - ~30 GeV precision for M_H prediction at LEP/SLC ages
- Post-top-Higgs Era: SM global test and new physics

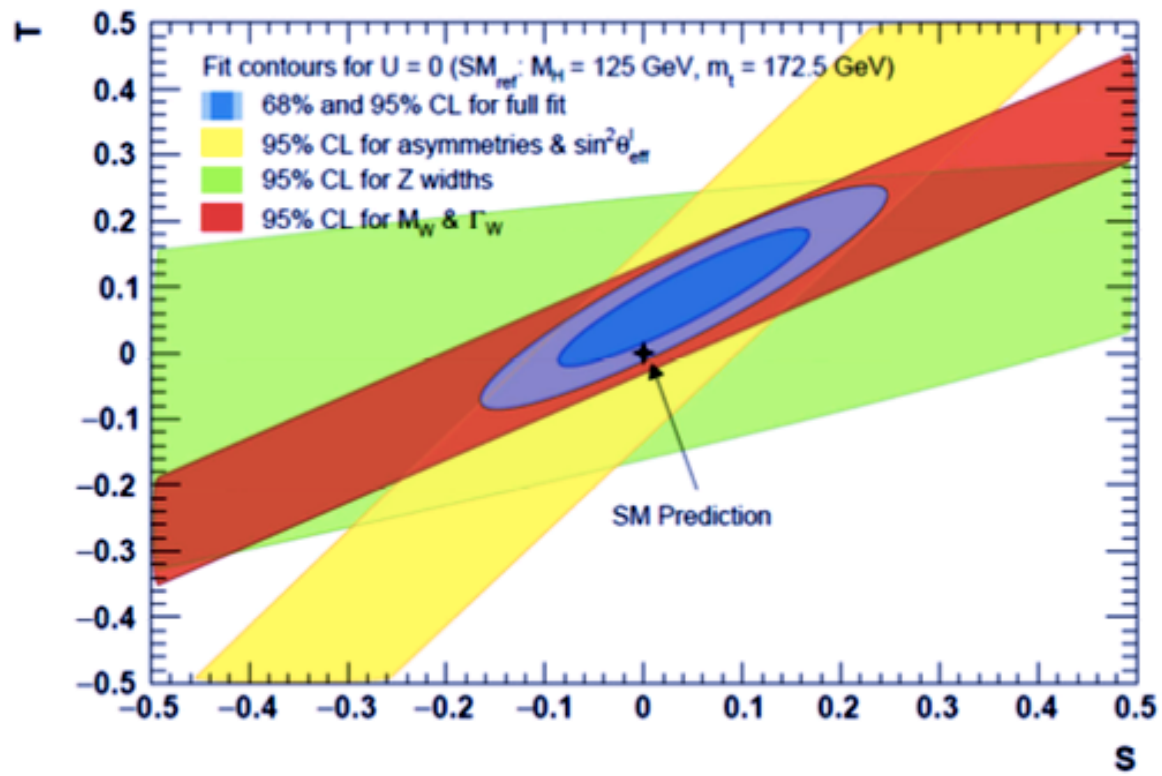
Key Parameters

M_W and $\sin^2\theta_W$

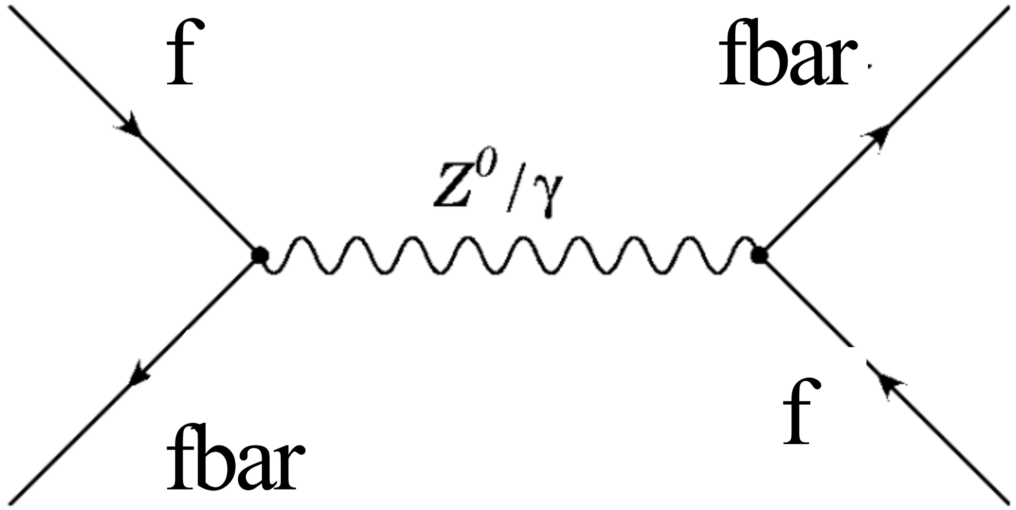
- **The most important parameters since LEP/SLC**
  - *LEP/SLC: "for the first time the experimental precision is sufficient to probe the predictions at loop level"*
- **M_W and $\sin^2\theta_W$: ~6% and 4% shift due to loop effects on their experimental observations**
- **Currently the parameters with worst precision**

$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

$$\sin^2\theta_{\rm eff}^f = \left(1-\frac{M_W^2}{M_Z^2}\right)(1+\Delta\kappa_f)$$

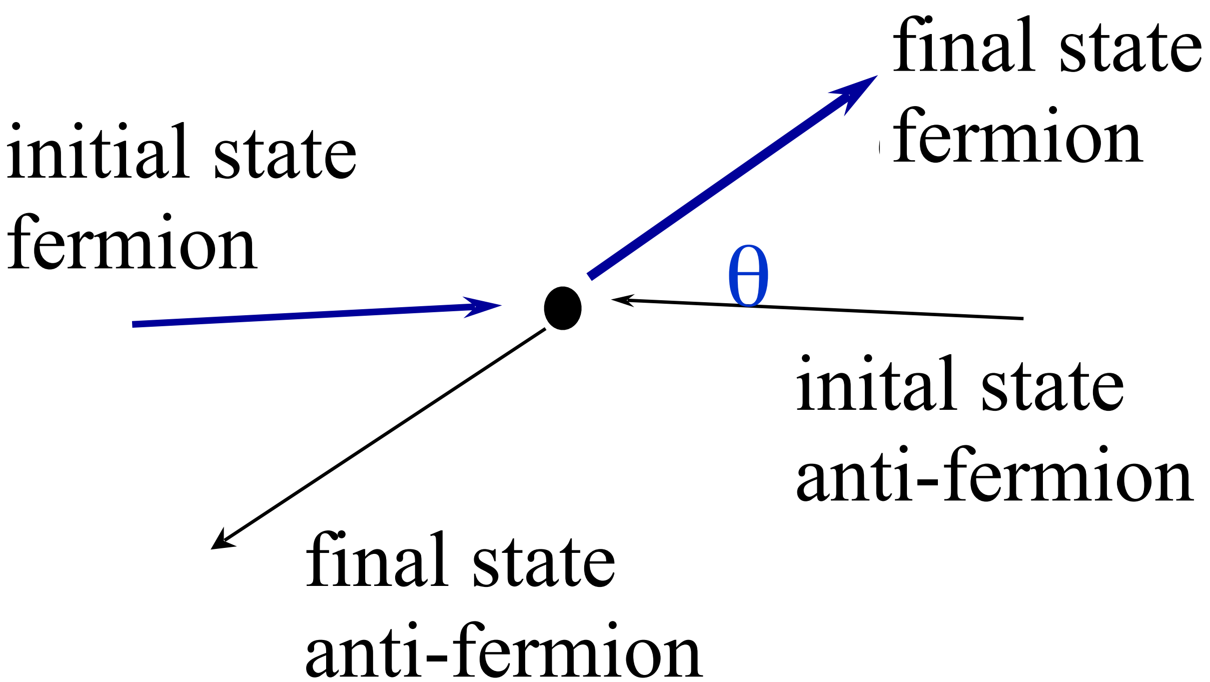


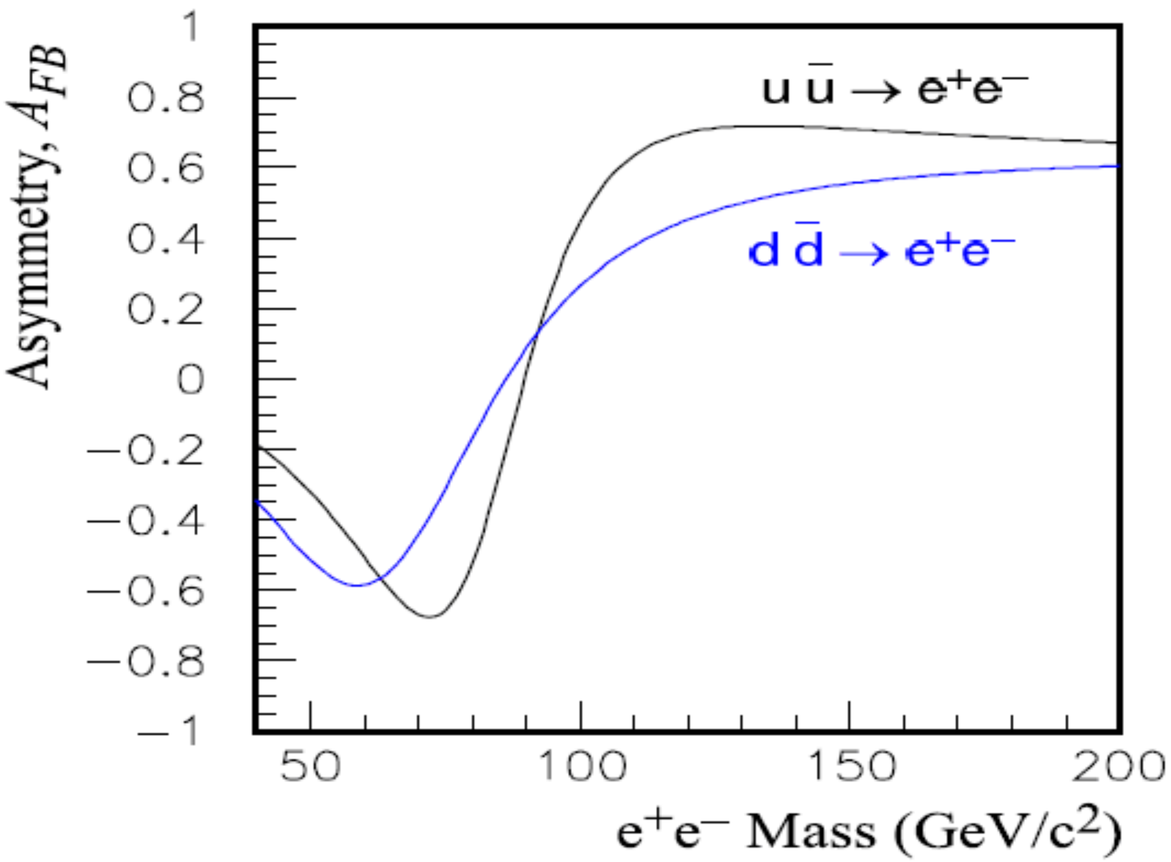
Weak mixing angle @ M_Z



Asymmetry at Z pole

- **Forward-Backward Asymmetry (A_{FB})**
- **A function of invariant mass**





cosθ>0, forward

cosθ<0, backward

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = A_{FB}(\sin^2\theta^f_{\rm eff})$$

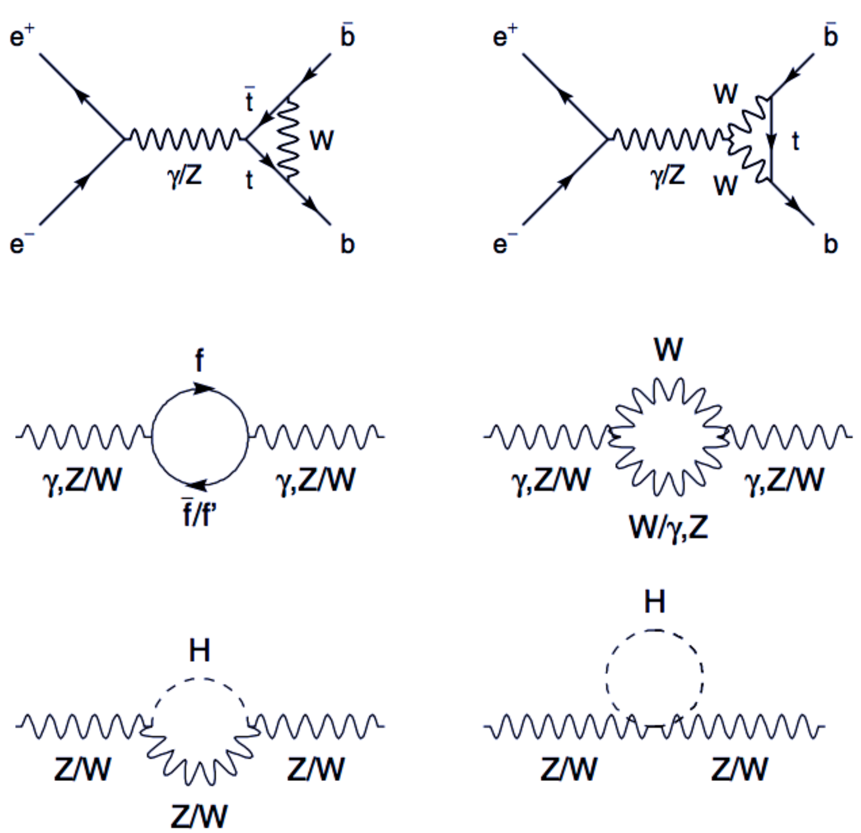
Measurement from LEP and SLC

Electron Positron Collider LEP and SLC

- Multiple-final state measured
  - ee、mumu、tautau、qqbar（including light quark and heavy quark）

1980s - 1990s: the first task in EW precision measurement

- EW Loop correction：
  - Contribution from loops 3.7%. Not systematically studied before LEP
  - By 2006: complete two-loop + partial 3-loop corrections !



	$\Delta\sin^2\theta_{eff,lept}$
Total unc.	0.00029 (LEP) 0.00026 (SLC) ~0.1%
Loop-corrections (theory)	0.00005 ~0.02%

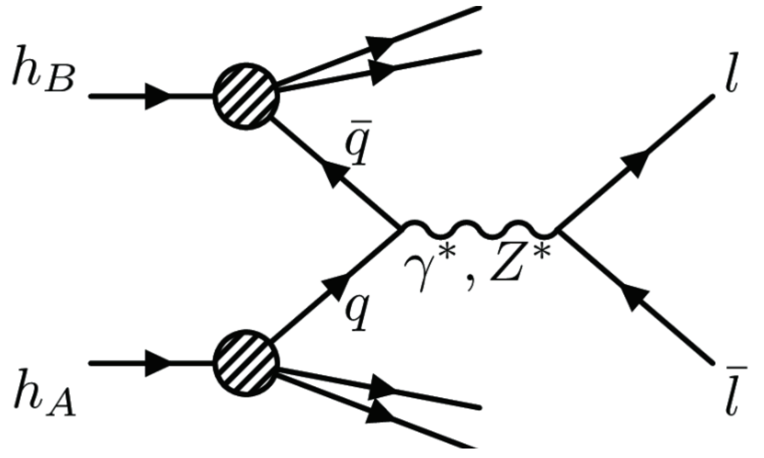
Measurement from Tevatron

New goals in the post-top-Higgs era

- SM global test and new physics predictions
- Aiming for ~0.01% experimental precision, to compare with the theories
- Separately high precision measurements in different channels instead of average combination under standard model

Since 2000s: the second challenge

- Systematics at hadron colliders



	relative unc.	needed precision
electron energy	0.1% - 1%	0.01%
muon momentum	>1%	0.01%
efficiency	1% ~ 10%	<1%

Systematics: why significant @ hadron colliders ?

EW physics @ Z pole

- As a function of energy in center of mass frame (invariant mass)
- As a function of final state lepton directions (differential xsection)

e+e- colliders

- mass: determined by beam energy (unc. <MeV)
- efficiency: >99%

Hadron colliders

- mass: reconstructed from measured lepton energy/momentum
- efficiency: ~50% for single Z events, large dependence with lepton direction

Dealing with systematics

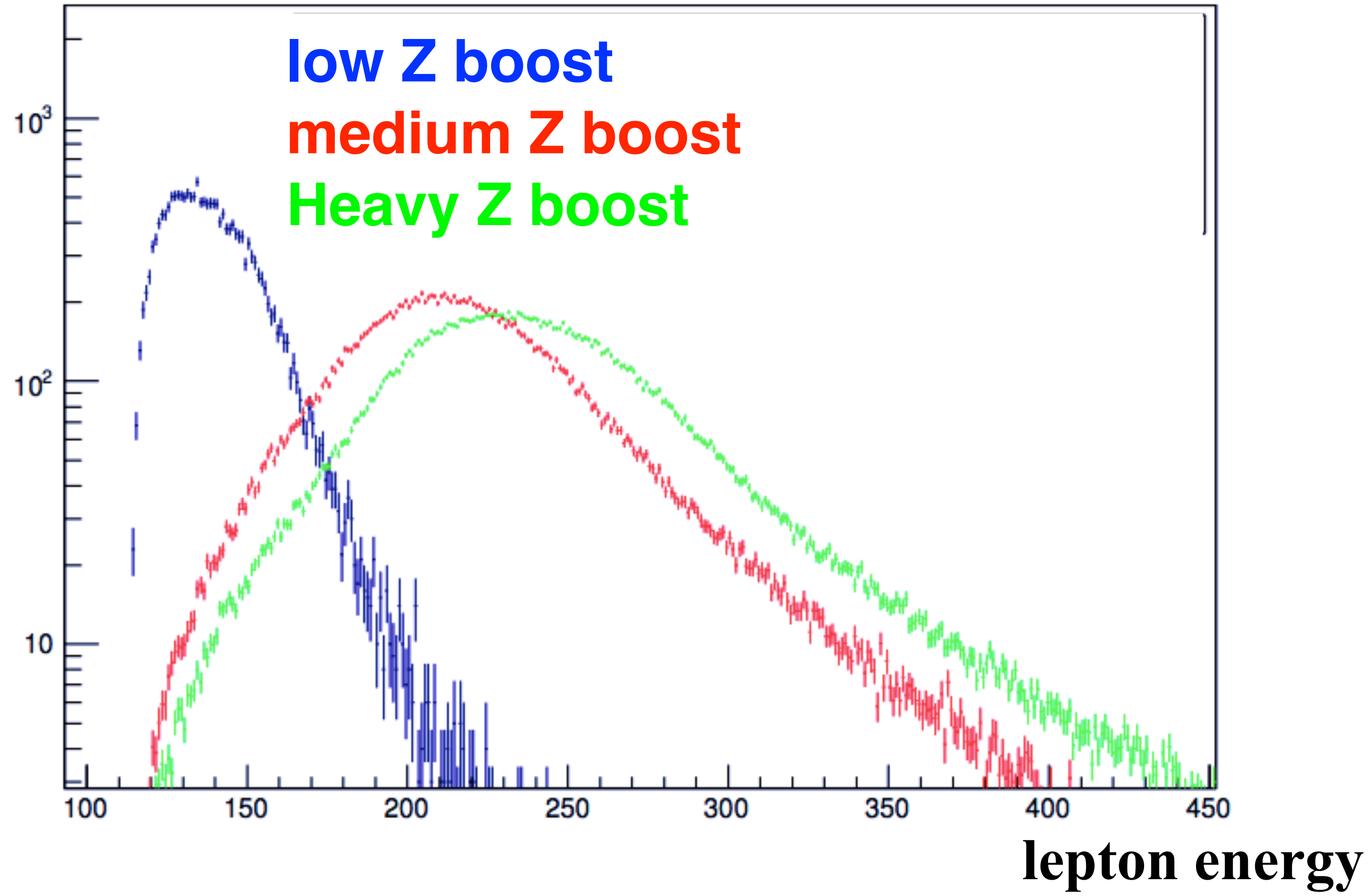
Where comes the improvement?

- **Traditional calibration: using Z->l+l- invariant mass**
  - **single physics constrain, thus single parameter in factorization**

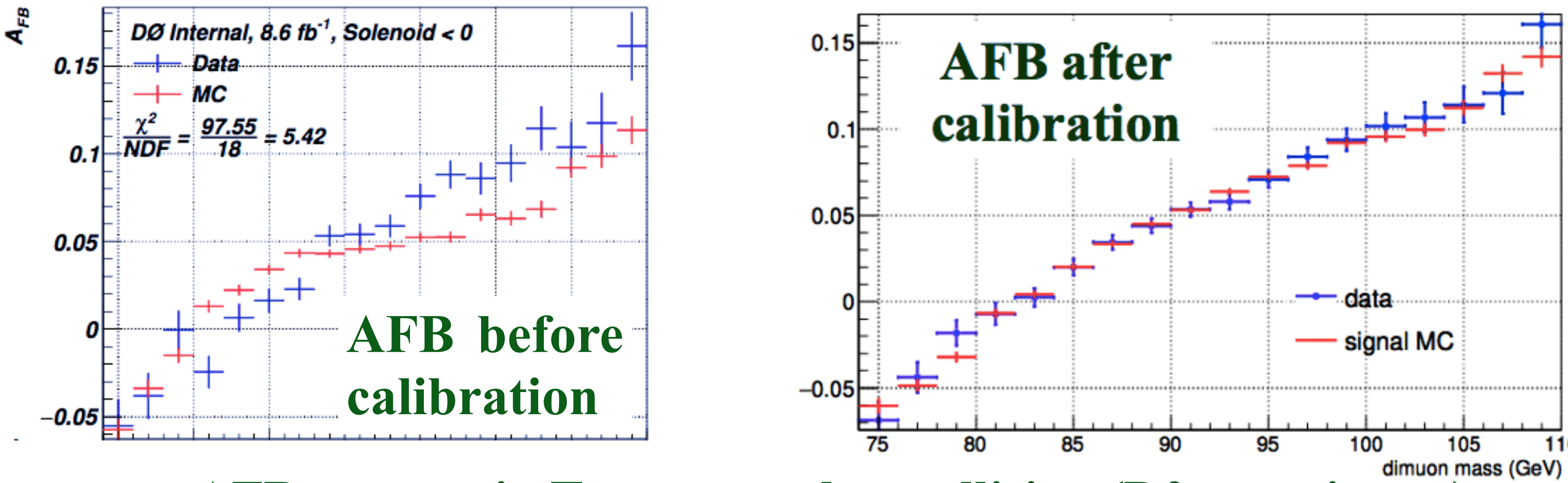
$$E_{\text{obs}} = k \times E_{\text{truth}}$$

- **New calibration technique: multip-Z mass constrain**
  - **for the first time, we can perform multi-parameter factorization**

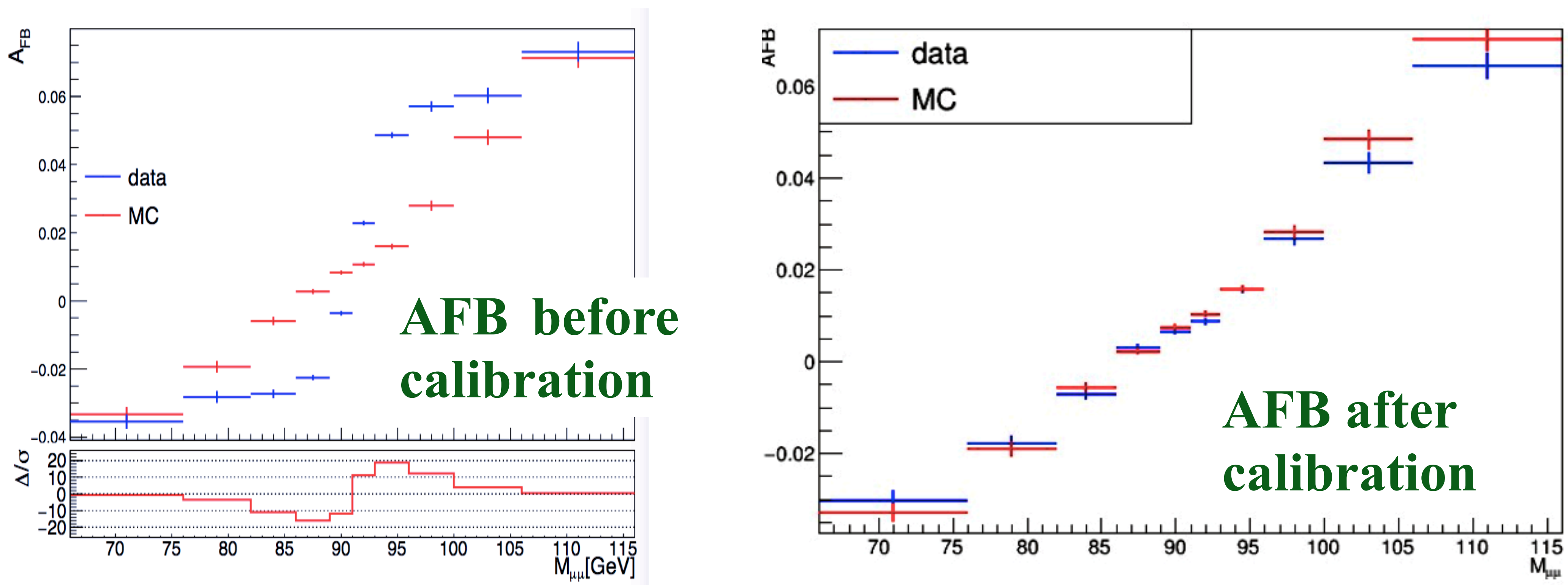
$$E_{\text{obs}} = k \times E_{\text{truth}} + b + \gamma \times E_{\text{truth}}^2 + \cdots$$



So what's the benifit?



AFB vs mass in Tevatron ppbar collision (D0 experiment)



AFB vs mass in LHC pp collision (ATLAS experiment)

Tevatron results

A great achievement from Chinese Scientists

Tevatron combination: D0+CDF

Comparable with LEP/SLC

Phys. Rev. D 97, 112007 (2018)

$$\sin^2 \theta_{\mathrm{eff}}^{\mathrm{lept}} = 0.23148 \pm 0.00033$$

D0 ee-channel state:

Best single channel, best electron channel, best light-quark process measurement, first time high precision @ hadron colliders

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

D0 mumu-channel:

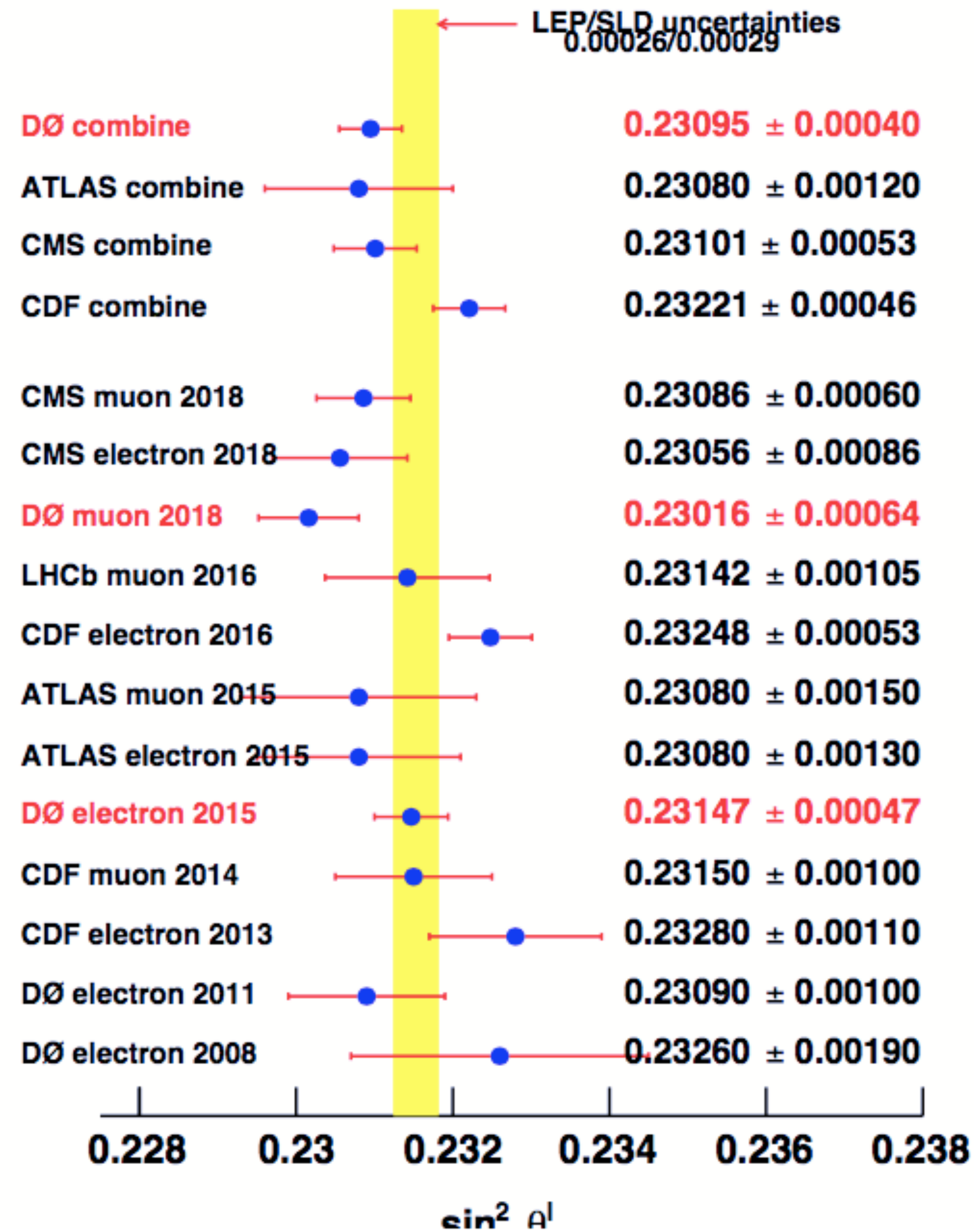
One of best muon channel results

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

D0 combination: ee+mumu

Best single experiment determination

Phys. Rev. D 97, 112008 (2018)



Measurement @ LHC: ongoing and the future

Lepton performance

- Studies just went to the last stage, providing similar precisions to Tevatron
- Calibrations become standard recommendation in ATLAS

The third challenge

- Parton Distribution Functions (PDFs)
  - Describing quark momentum from hadrons
  - Current unc.: $\Delta \sin^2\theta_W$ (PDF) ~ 0.00025 (ATLAS and LHCb)

- non-perturbative QCD resummation (nPQCD)
  - Affecting Z boson momentum
  - Current unc.: $\Delta \sin^2\theta_W$ (QCD) > 0.00010

Particle physics cares only if LHC could provide ~0.01% precision on weak mixing angle !

LHC pp collision: dilution

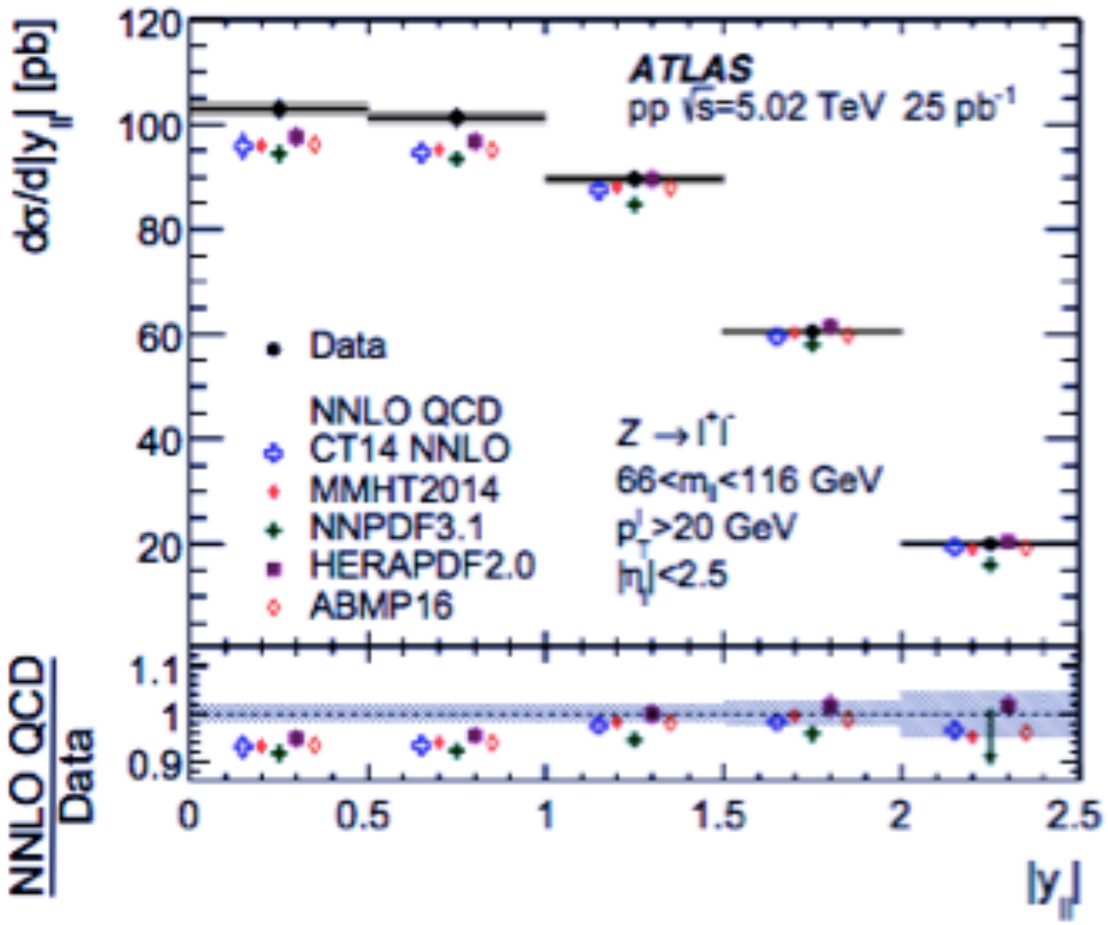
EW asymmetry @ Z pole

- Need knowlege on the direction of initial state fermions and anti-fermions
- e+e- collider: exactly determined from beam, no dilution
- ppbar collider: assume quark from proton and anti-quark from anti-proton, very small dilution factor ~5%
- pp collider: assume Z boson boost along the quark direction (valence quark energy larger than sea quark energy), very large dilution factor
  - average dilution: ~22%
  - central acceptance dilution: ~38%

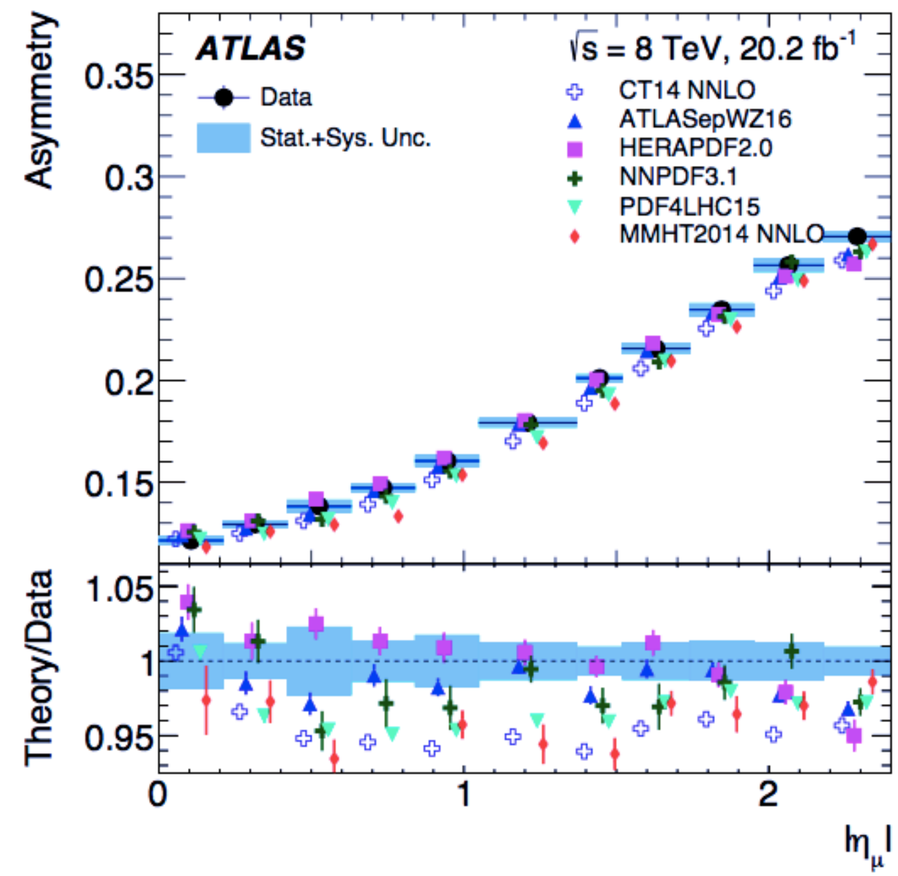
PDFs and nPQCD

Theory compared to single W/Z measurement

- Difference exist, NOT covered by uncertainties !



ATLAS 5 TeV Z boson measurement



ATLAS 8 TeV W boson asymmetry

What do we need?

More precice measurement on W/Z differential xsections

- Z rapidity, W/Z pT, W asymmetry, Z asymmetry @ high mass and low mass …
- Especially low pT region and high rapidity region (forward), which means more difficult in systematic control, even rely on lepton performance.

PDF and nPQCD theory studies

- weak mixing angle extraction / PDF global fitting / nPQCD test: correlated !
  - Update PDF and extract weak mixing angle simultaneously is NOT unbiased
  - Fixed order QCD calculation is not precise enough at low pT region

In general

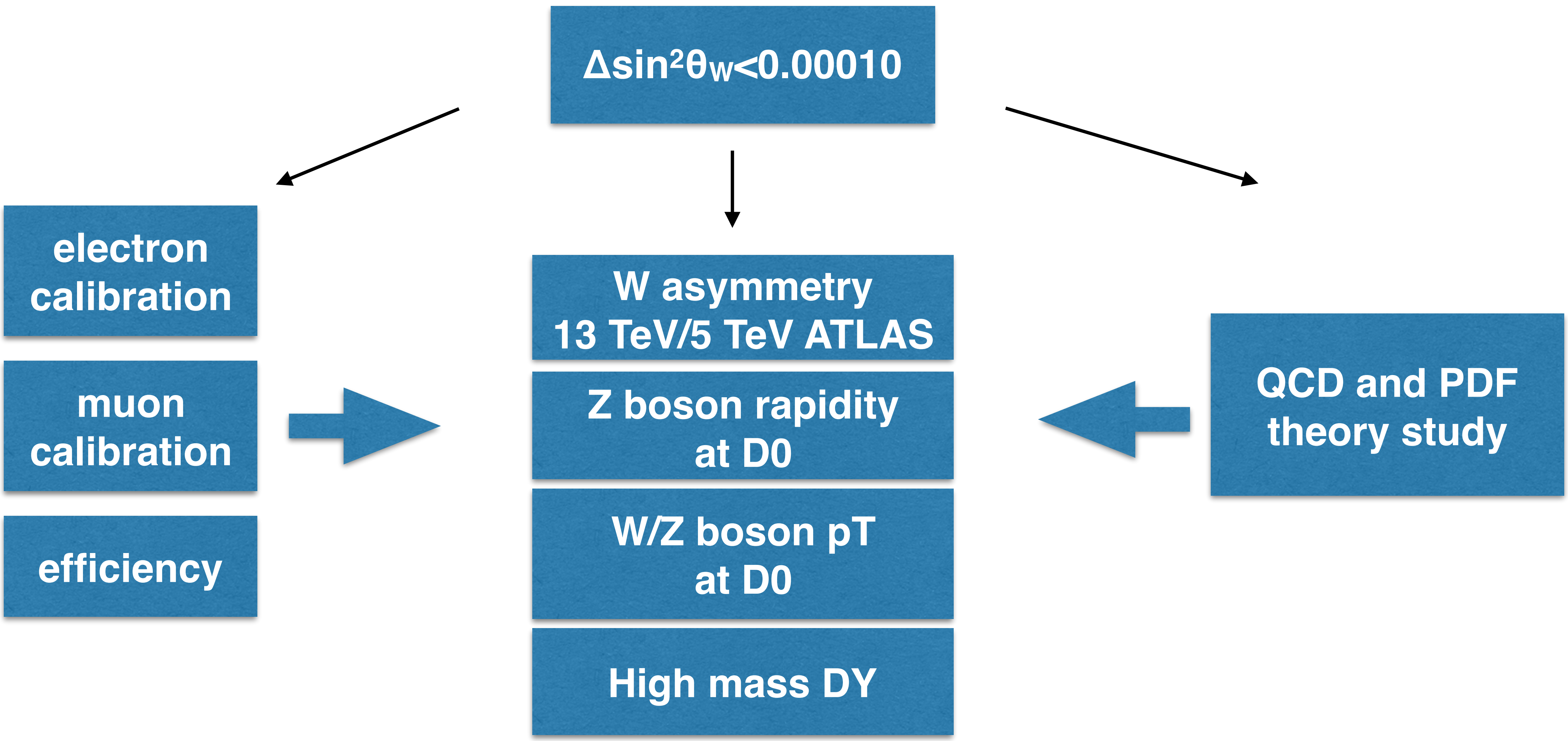
- ~1% precision in related PDF and nPQCD determination
- Current uncertainty is a few % to ~10%

More details @ Tiejiun Hou's talk in Saturday

A collection of physics topics ongoing

EW precision measurements @ hadron colliders means

- Determination of key parameters in SM global test and new physics prediction
- Highest required precision in lepton performance, PDF and nPQCD, which leads the corresponding studies
- Corresponding theory study in PDF global fitting and nPQCD calculation



Chinese scientists

Best experience and techniques

- Significantly improve lepton performance
- Dominate Z-related EW precision measurement at Tevatron
- Holds a series of precision record

Already started strategic researches

- Ongoing Tevatron W/Z measurement
- ATLAS lepton performance aiming for extreme high precision
- EW precision measurement at D0, ATLAS and LHCb

Strong backup

- Widely spread researchers at LHC experiments

It would be great if CMS
experts can join~

Thanks

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

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

2018, Tevatron combined
precision: 0.00033

To the future…