Electroweak Precision Measurement at Hadron Colliders

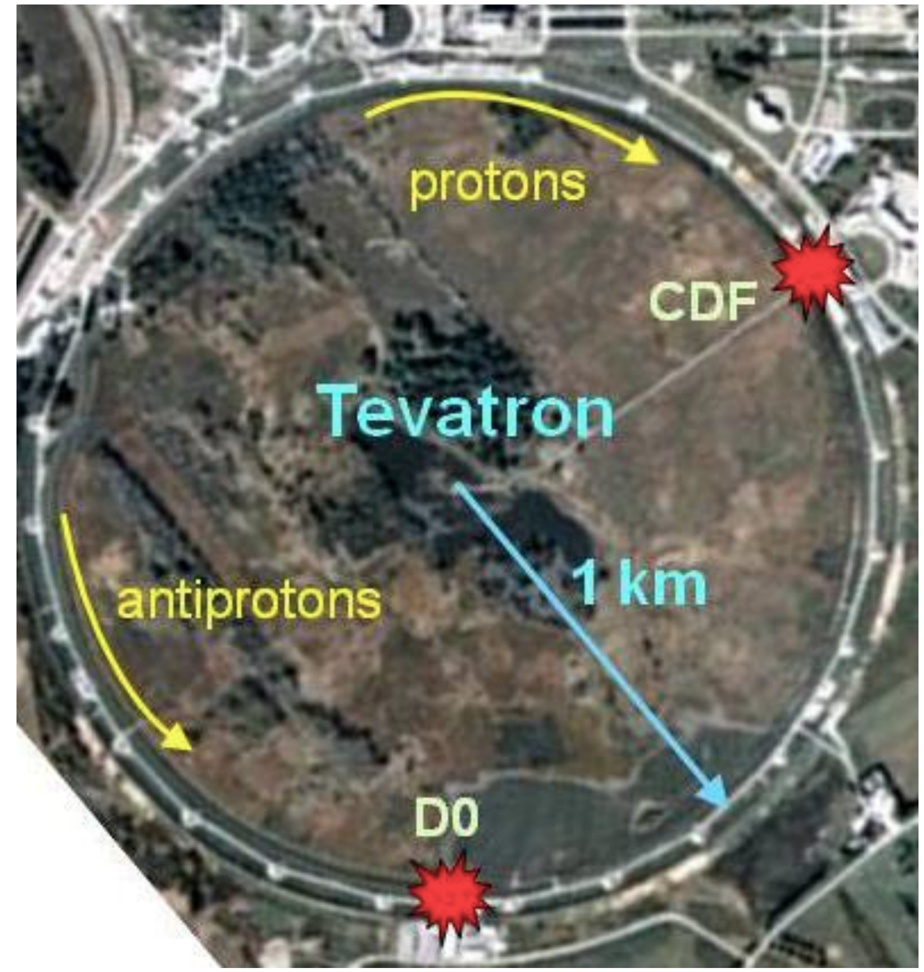
Siqi Yang
University of Iowa
University of Science and Technology of China

2019. Sept. 12th

Hadron Colliders

D0 experiments at Fermilab Tevatron

- proton-antiproton collider, 1.96 TeV



ATLAS experiments at LHC

- proton-proton collider, 13 TeV

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

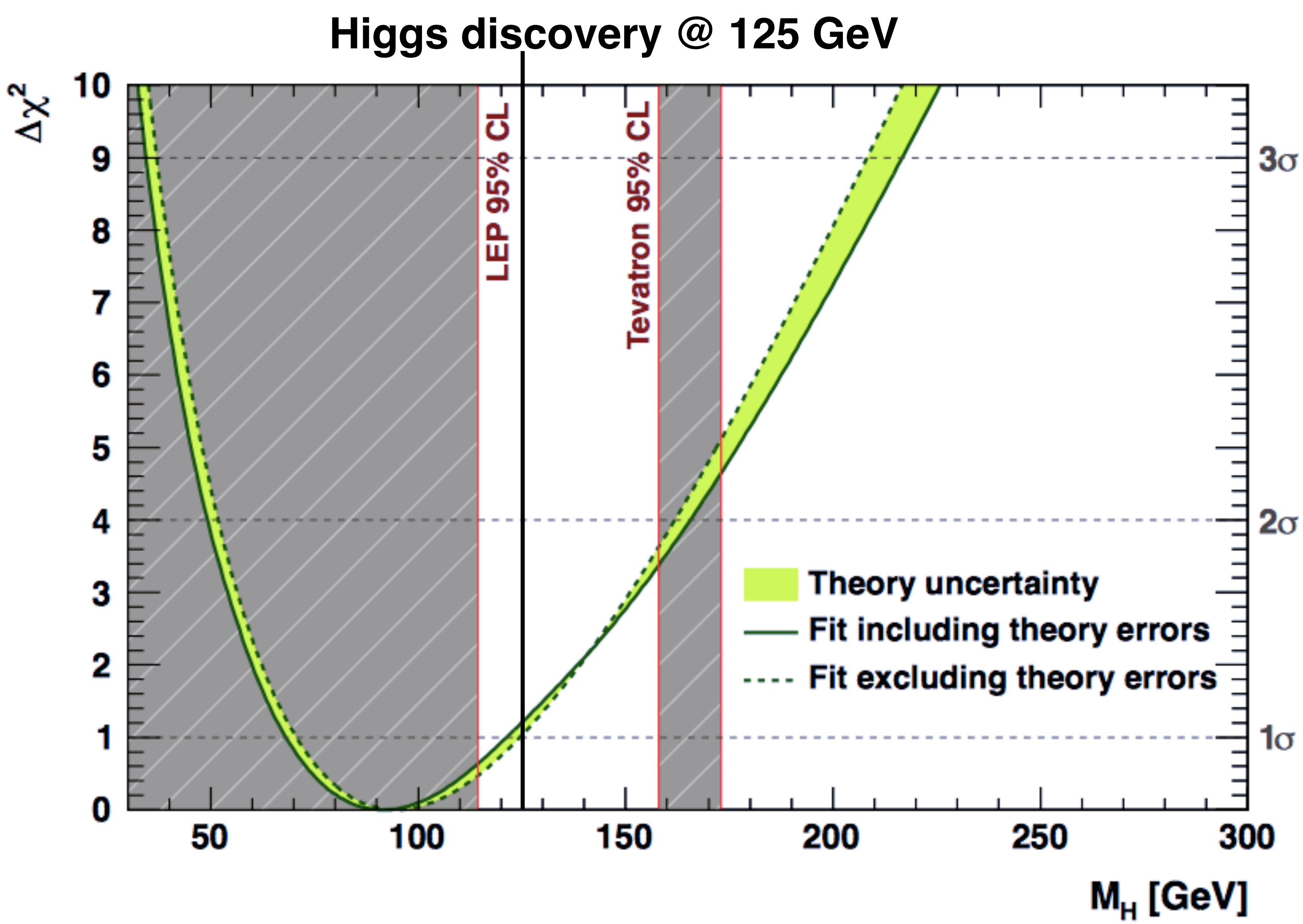
Key parameters

- M_W and $\sin^2\theta_W$ are 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

Pre-Top-Higgs Era

Aiming for top quark and Higgs boson

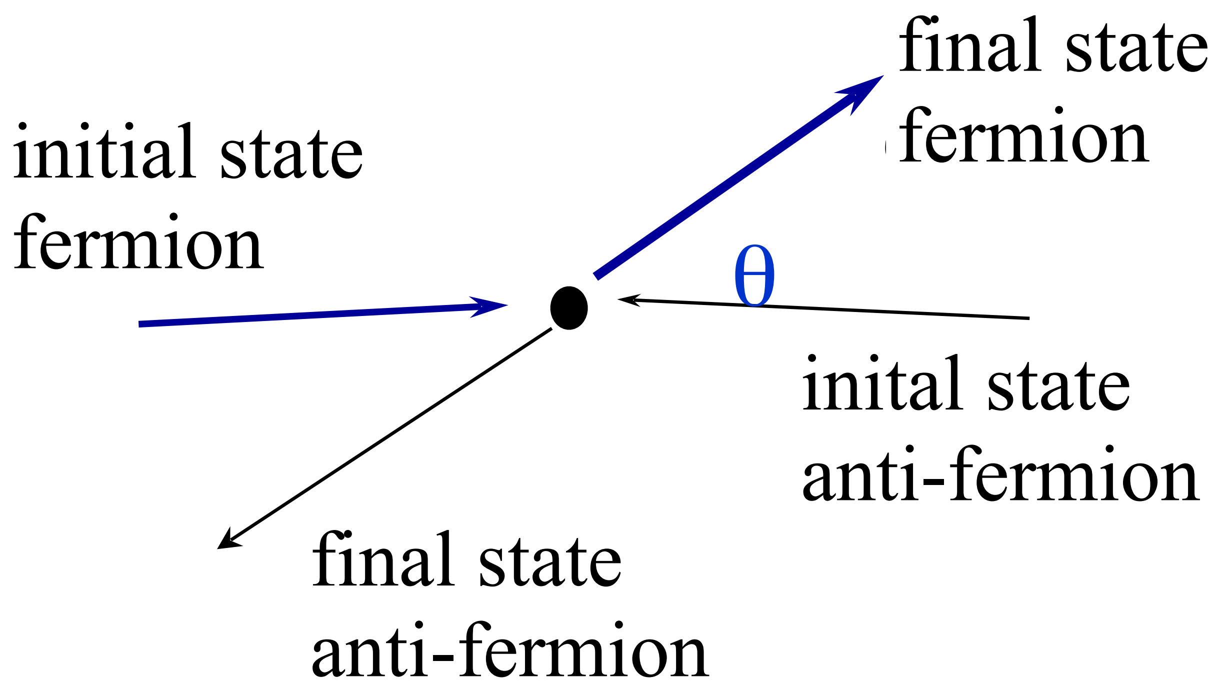
- Top quark and Higgs boson, missing freedoms
- Major task: predicting M_{top} and M_H under standard model assumptions
- Before their discoveries: M_{top} prediction within 50 GeV, M_H within 30 GeV

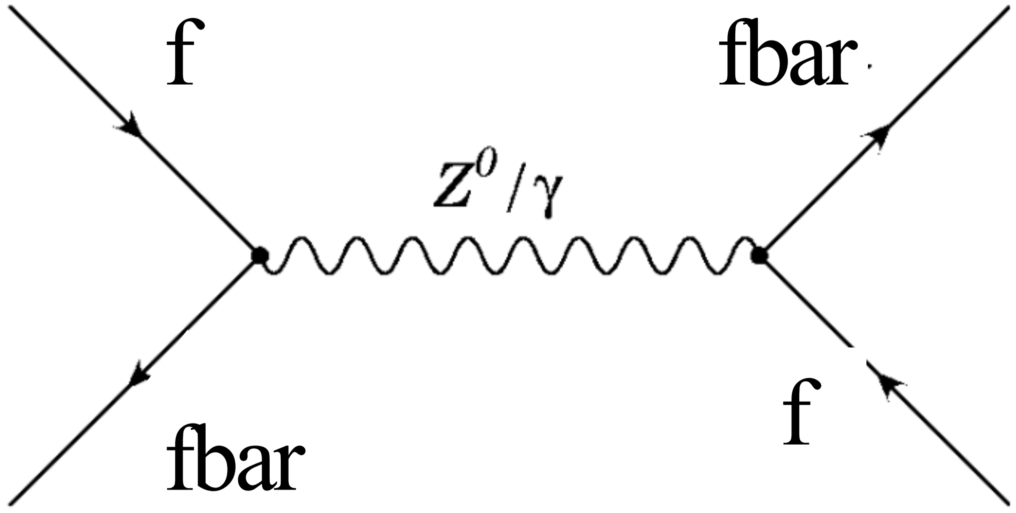


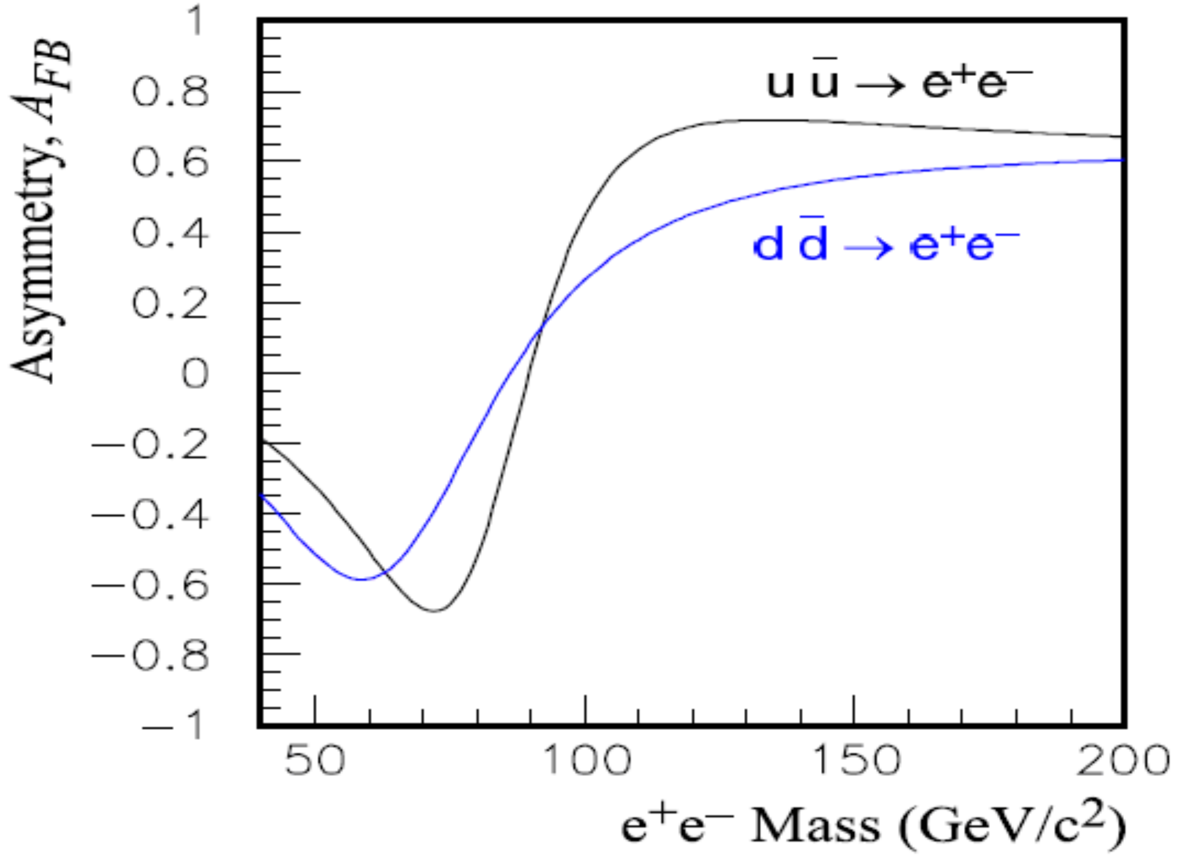
Weak mixing angle @ M_Z

Asymmetry at Z pole

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







cosθ>0, forward

cosθ<0, backward

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

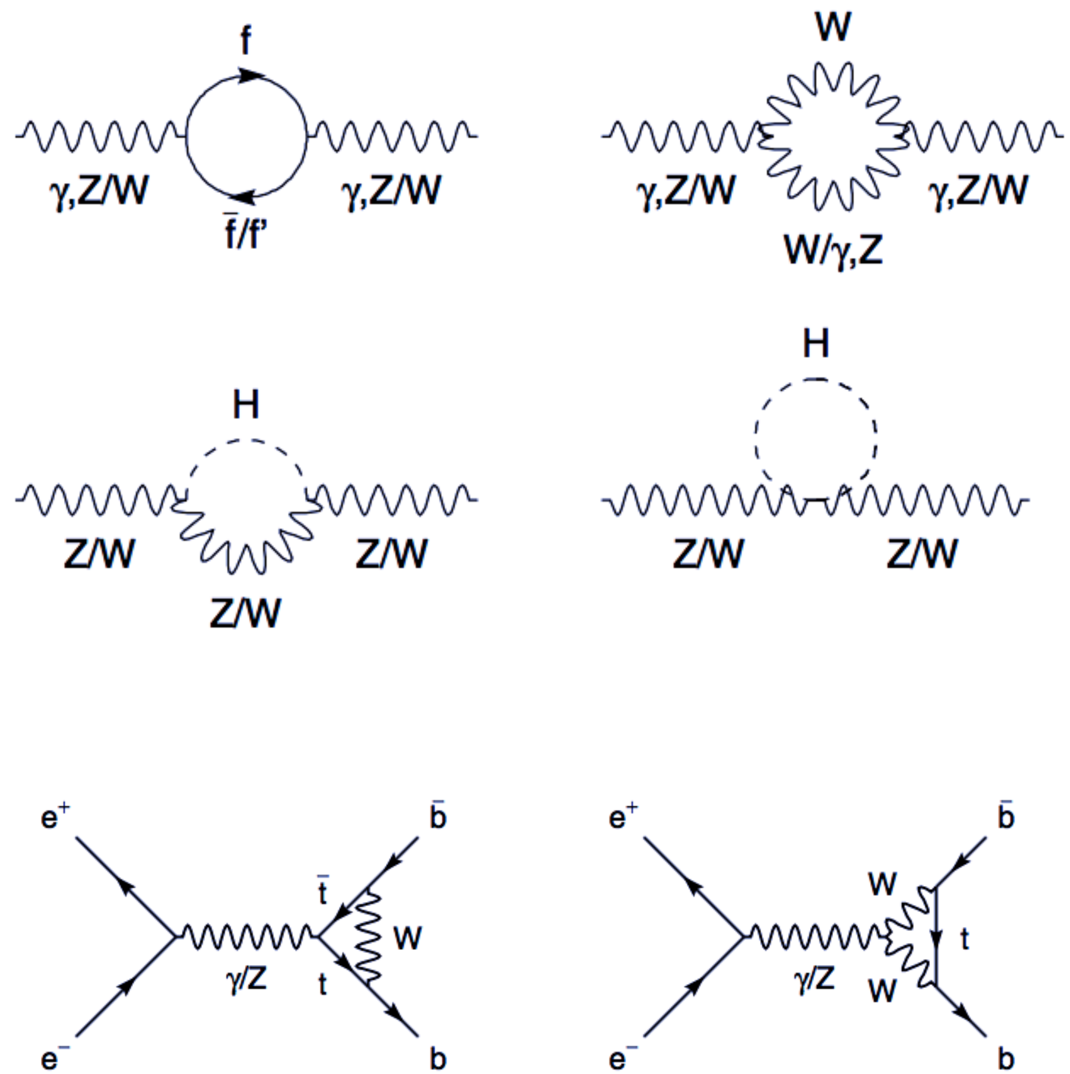
Measurement from LEP/SLC (1)

Electron Positron Collider LEP and SLC

- LEP： Spatial asymmetry AFB， SLC： Polarization asymmetry
- Final state： ee、 mumu、 tautau、 qqbar （including light quark and heavy quark）

Dominant uncertainties

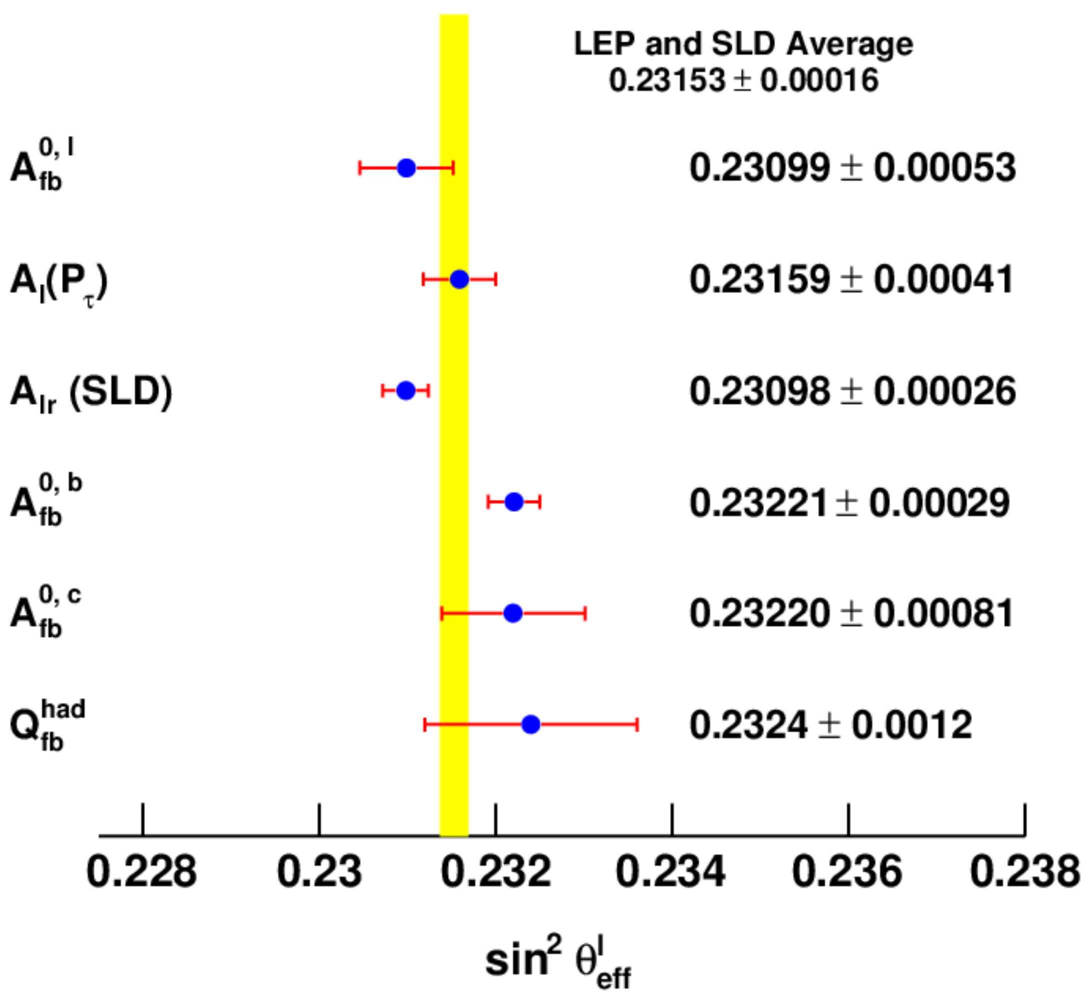
- Statistical uncertainty
- Loop correction：
  - Contribution from loops 3.7%
  - Not being systematically studied before LEP



Measurement from LEP/SLC (2)

Results (by 2006, from 1980s)

- **Most precise ones： $\Delta\sin^2\theta_W$ (LEP) = 0.00029, $\Delta\sin^2\theta_W$ (SLD) = 0.00026**
- **Statistical dominated**
- **Completely two loops + leading 3 loops： $\Delta\sin^2\theta_W$ (loop) = 0.00005**

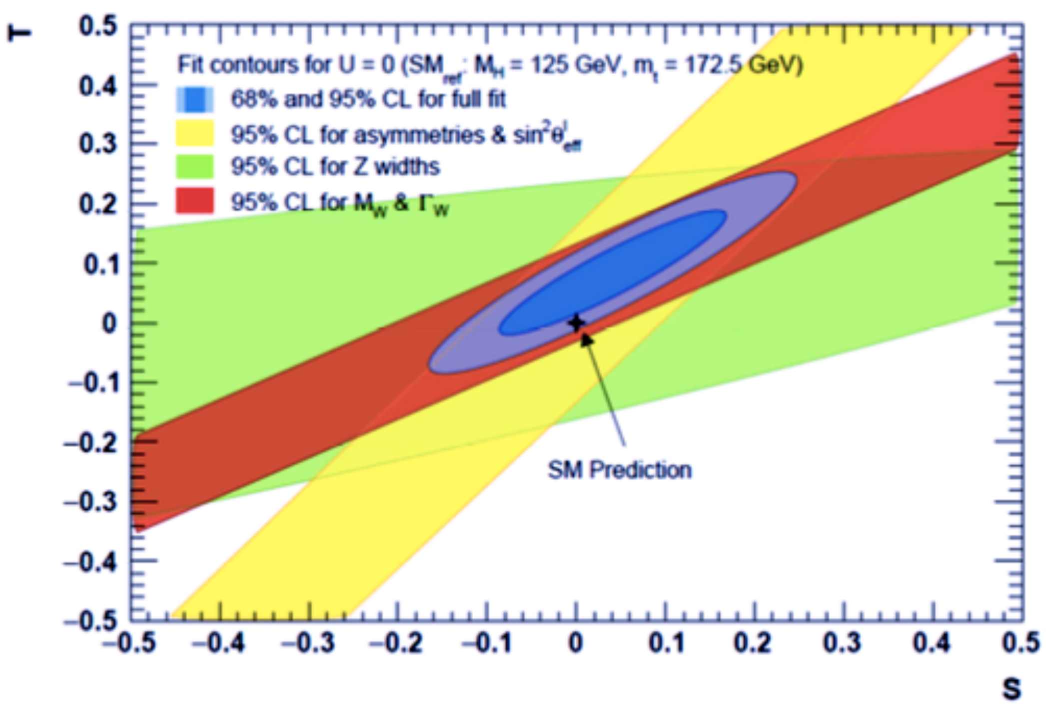


	$\Delta\sin^2\theta_{eff,lept}$	
LEP SLD	0.00029 0.00026	average 0.00016
global fit	**0.00005**	

Post-Top-Higgs Era

Aiming for SM global test, and new physics

- All freedoms have been experimentally fixed, allow for SM global test
- Predictions for potential beyond standard model new physics
- Measurement dominated by hadron colliders



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

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

New challenges at hadron colliders

- Precision need to be at O(0.01%)
- New uncertainty souces (systematics, PDF, nPQCD)
- Separate measurements for different fermions (final states)

Measurements at Hadron Colliders

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

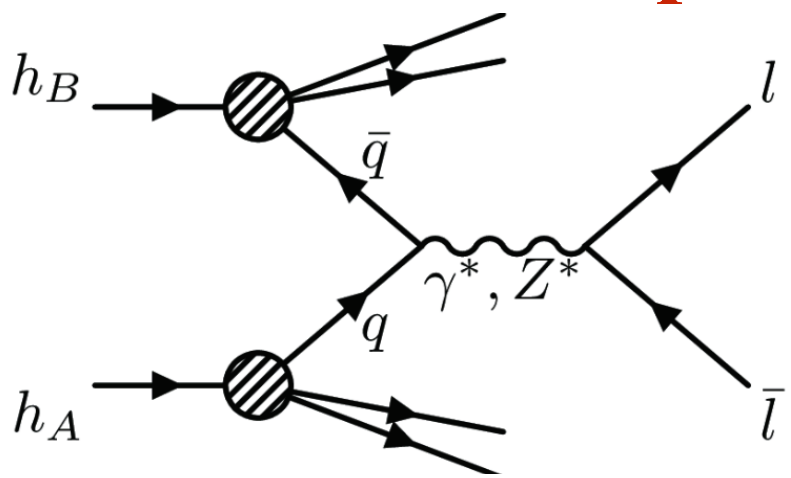
2017, D0 8.6 fb^{-1}
muon channel
precision: 0.00064
D0 muon final result

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

2018, Tevatron combined
precision: 0.00033

Measurement at hadron colliders

Dominant uncertainties and related topics

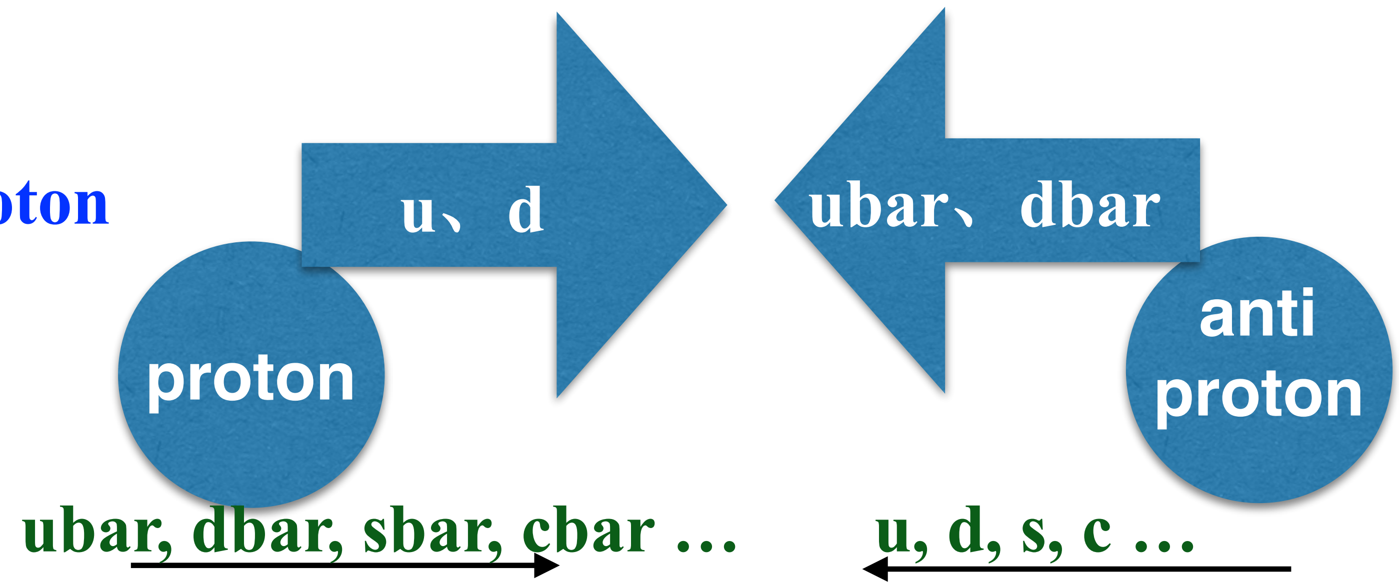


by 2011	$\Delta\sin^2\theta_{eff,lept}$	comments
EW loops	0.00005	Achieved by LEP age☑
Statistics	>0.00030 (Tevatron) <0.00010 (LHC future)	Will be reduced
PDF	0.00048	New
Initial State Radiation	>0.00010 (LHC)	New
Systmetics	0.00030	New

PDFs in the weak mixing angle measurement

Tevatron

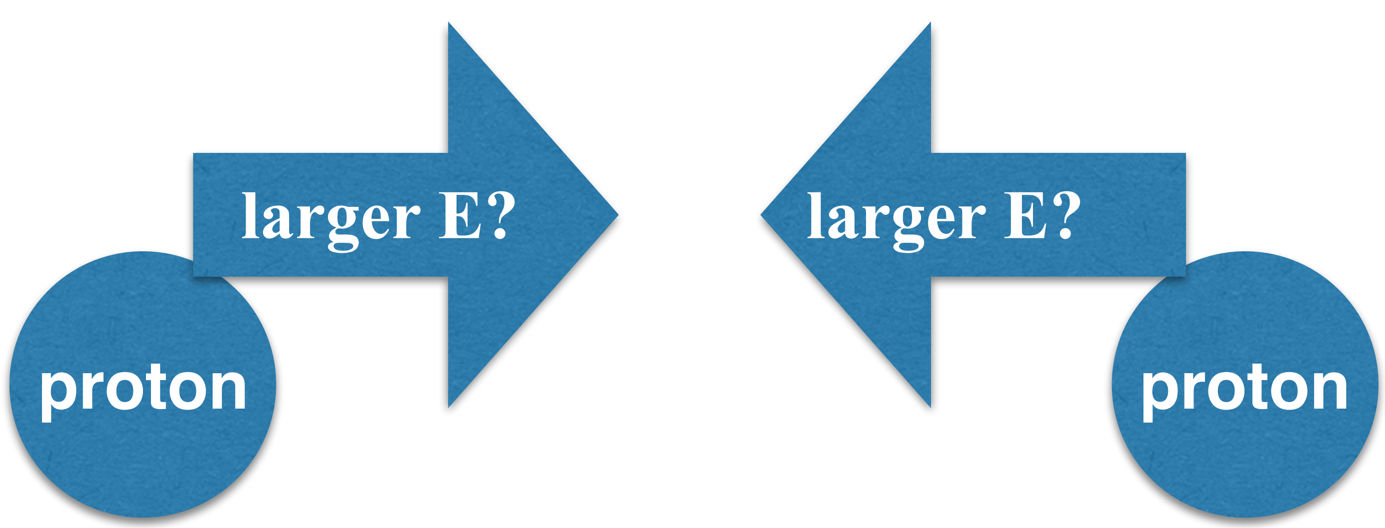
- Assume q from proton, qbar from antiproton
- ~5% opposite direction (sea quarks)
- PDF describes valence/sea quark fraction



LHC

- Assume q = Z boost direction (valence quark E > sea quark E)
- Large possibility opposite directions (dilution)
- PDF describes valence/sea quark energy spectrum

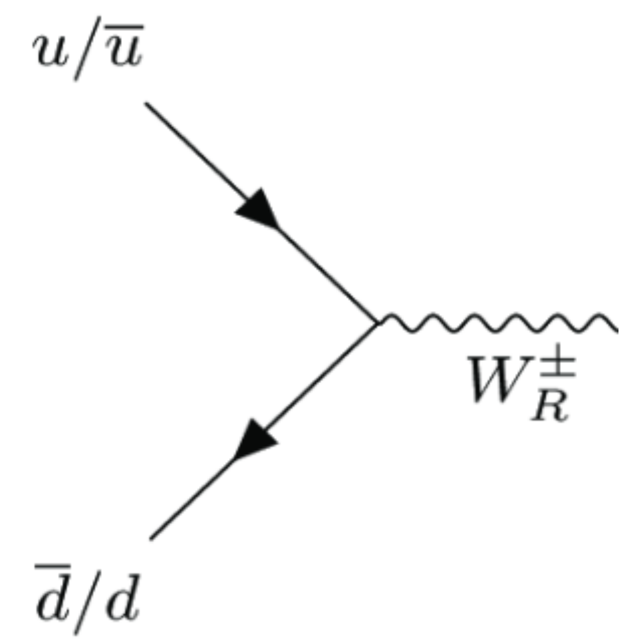
More significant PDF uncertainty at LHC



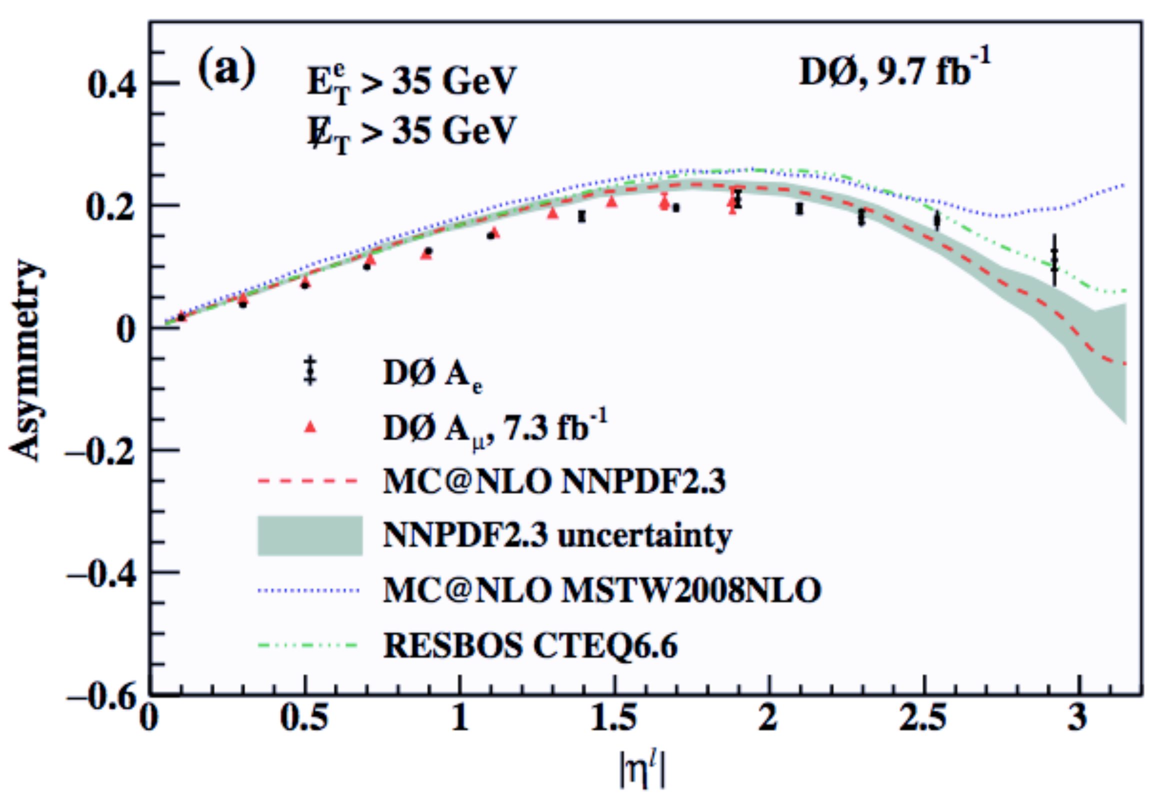
PDF and related measurements (1)

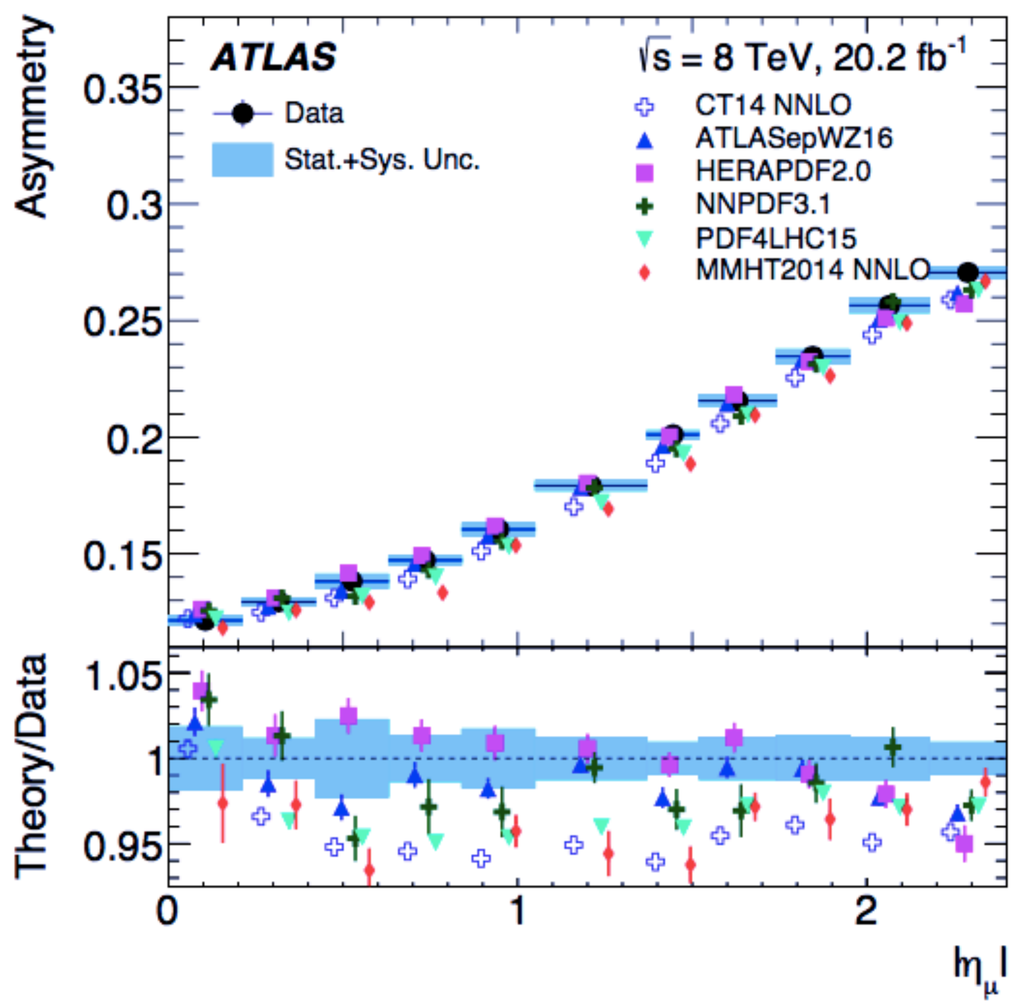
W asymmetry

- W asymmetry at Tevatron: u/d quark energy spectrum
- W asymmetry at LHC: u/d quark fraction
- Large cross section and statistics



$$A(y_W) = \frac{\frac{d\sigma_{W^+}}{dy_W} - \frac{d\sigma_{W^-}}{dy_W}}{\frac{d\sigma_{W^+}}{dy_W} + \frac{d\sigma_{W^-}}{dy_W}}$$

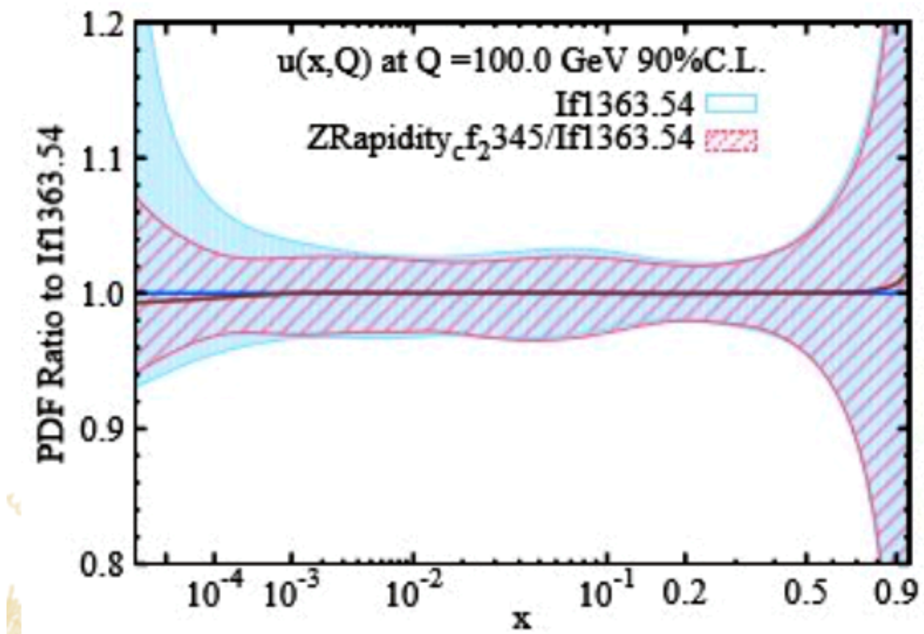




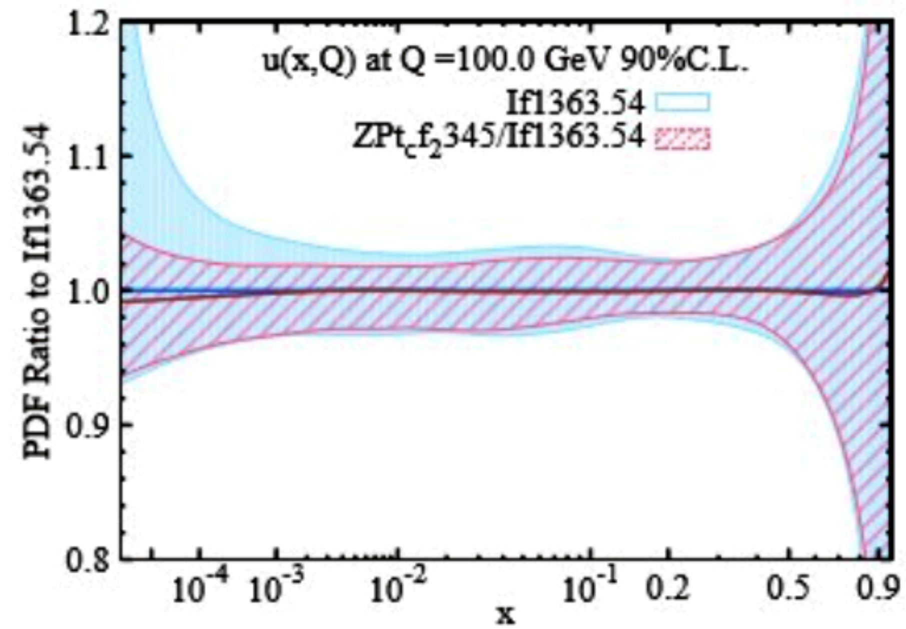
PDF and related measurements (2)

Other measurements which could contribute

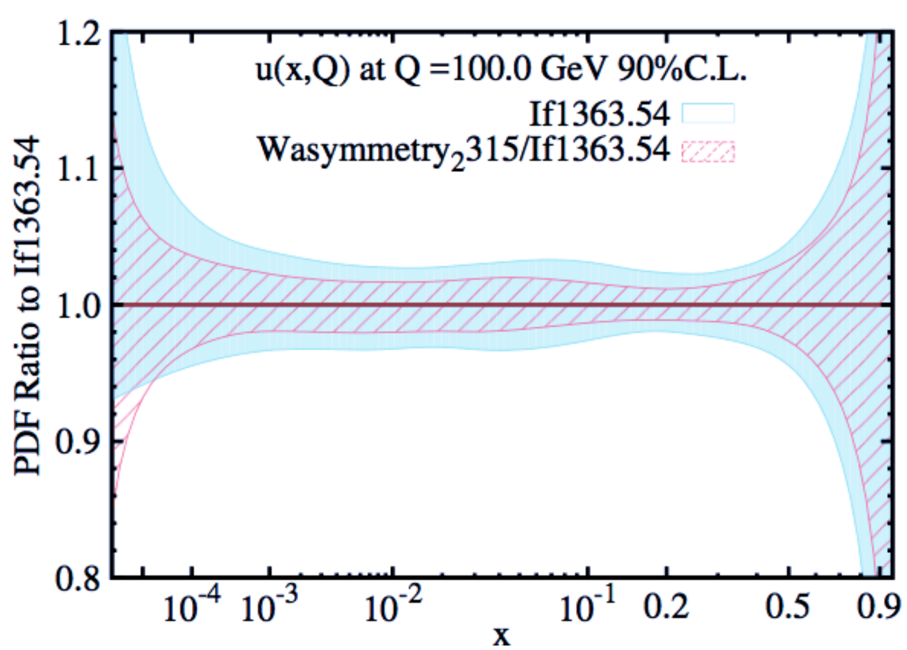
- **Z rapidity, Z pT, AFB @ high mass and low mass**



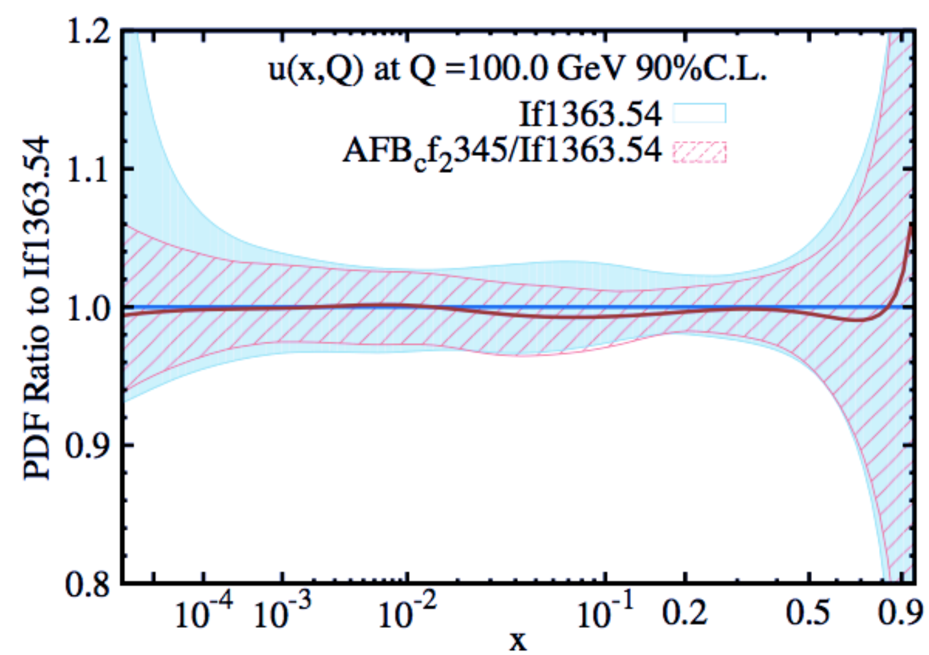
PDF update using Z rapidity



PDF update using Z pT



PDF update using W asymmetry

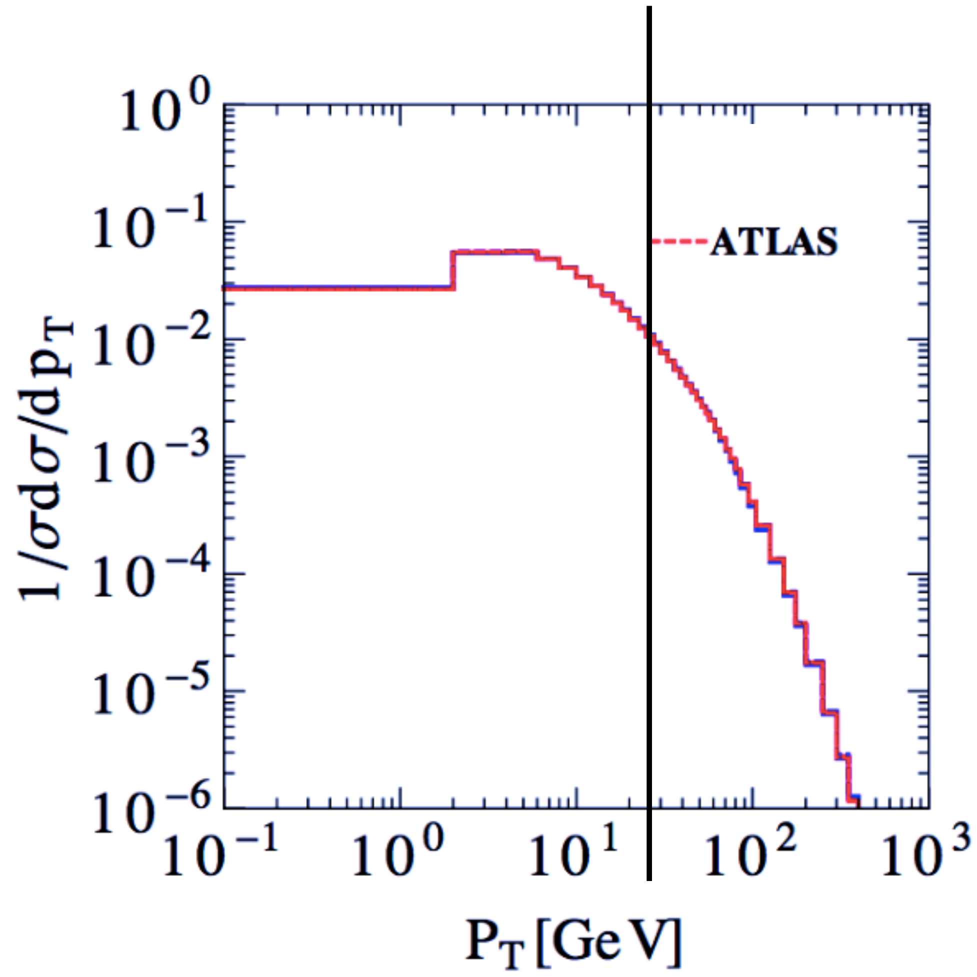


PDF update using AFB

Initial state radiation and QCD

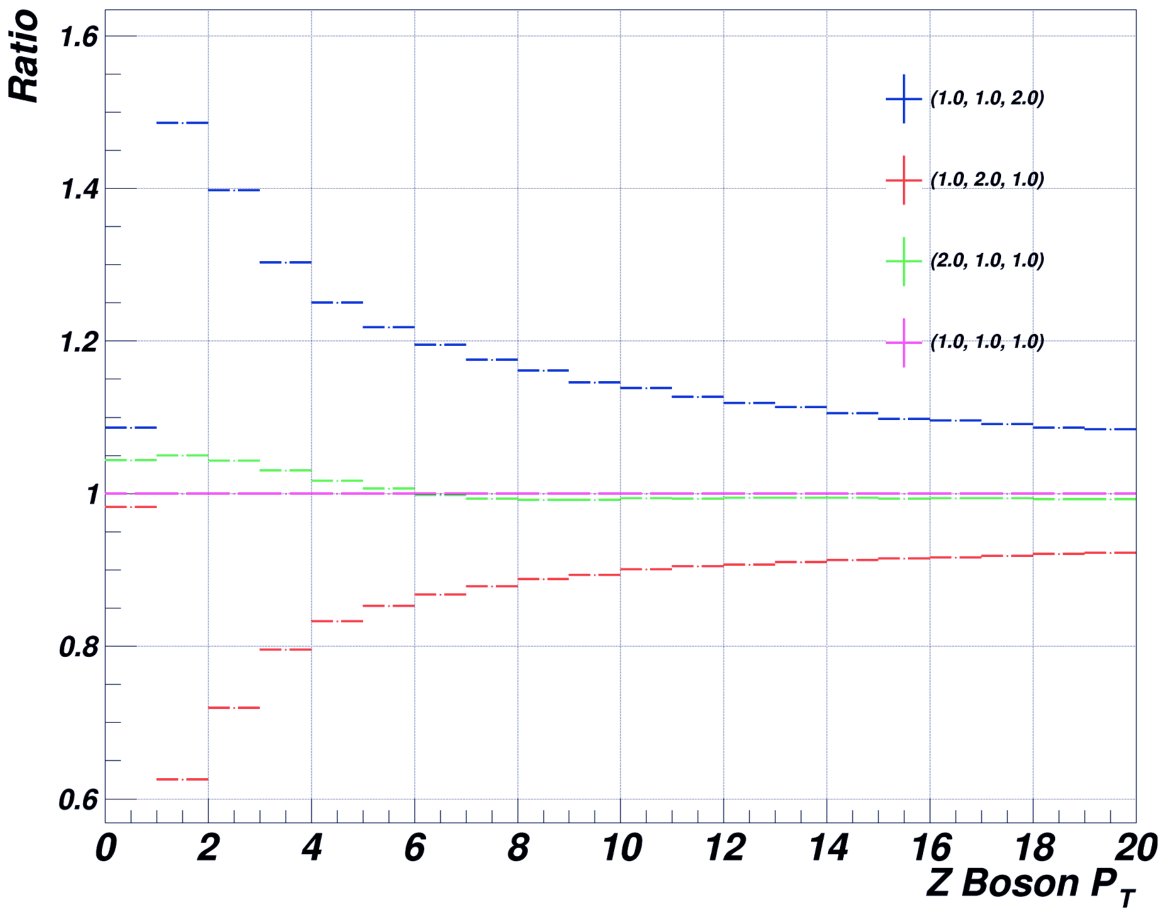
Significant at LHC

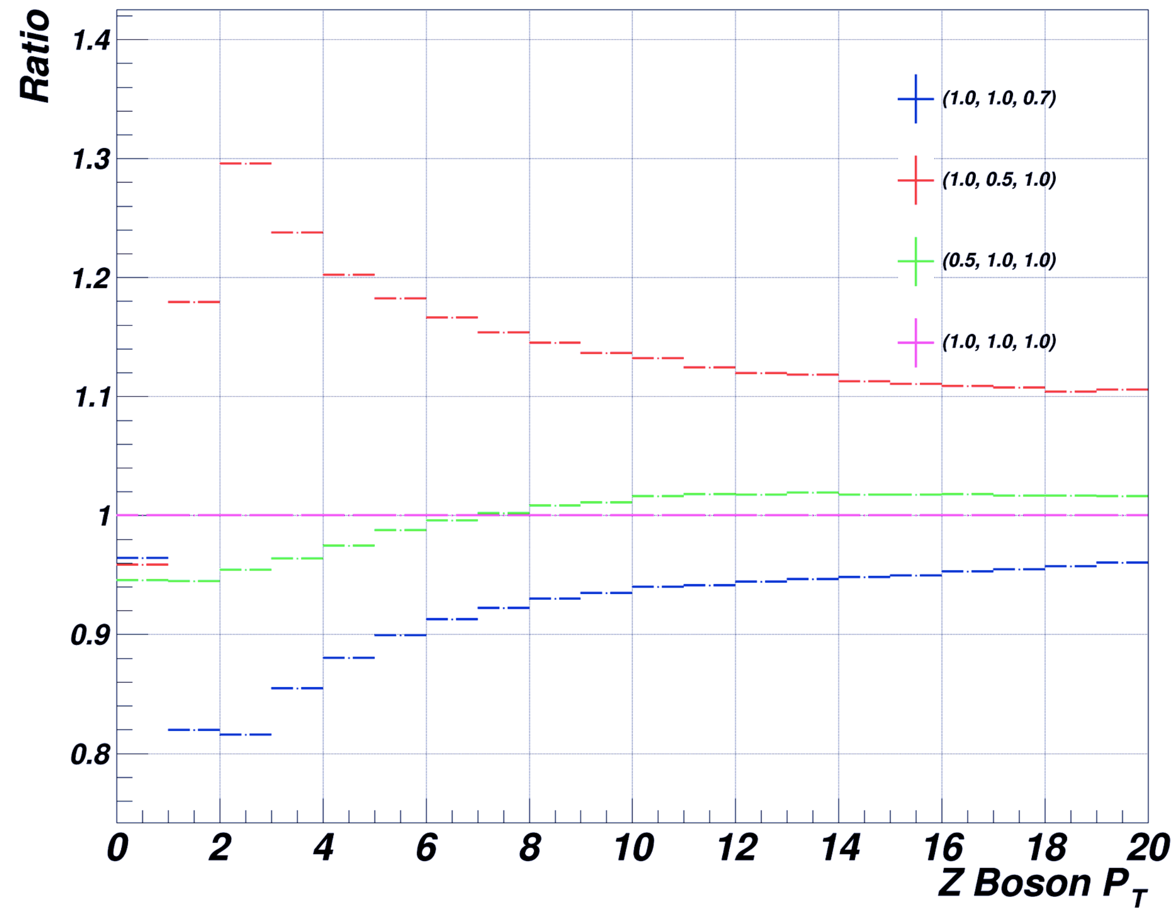
- Significantly affects boson pT
- QCD resummation: low transverse momentum of Z (Z pT), non-perturbative QCD
- Rely on the Z pT and W pT measurement



Z pT distribution at LHC pp collision. Majority of the events have low Z pT (<20 GeV)

Initial state radiation and QCD





Z pT spectrum with QCD scale changes

Compared to nominal Z pT, changing scales gives unreasonable large shifts. It means a better experimental constraint is needed.

Overall planning for EW measurement

A collection of physics topics

- Drell-Yan and AFB@Z pole: weak mixing angle
- W asymmetry, Z rapidity, AFB@high mass/low mass : PDF
- W pT, Z pT: QCD resummation
- PDF/QCD/Weak mixing angle extraction

However

- Difficult, long time schedule, less paper publication
- physics, experimental techique, theory
- Systematic control

Systematics: lepton performance (1)

Above topics limited by lepton performance

- **lepton energy/momentum: AFB, weak mixing angle, Z pT, W pT**
- **direction/selection efficiency: W asymmetry, Z rapidity**

by 2011	relative uncertainty	needed precision
electron energy	0.1% - 1%	0.01%
muon momentum	>1%	0.01%
efficiency	1% ~ 10%	<1%

lepton performance limits the related W/Z measurements

Systematics: lepton performance (2)

Hadron collider and e+e- collider

- e+e- colliders:
  - mass (c.m.s. energy) determined from beam
  - efficiency almost 100%
- hadron colliders:
  - mass reconstructed from final state particles
  - efficiency ~50%, depends on particle directions
- Especially forward regions!

Measurement at hadron colliders

Dominant uncertainties and related topics

by 2012	$\Delta\sin^2\theta_{eff,lept}$	Comment
EW loops	0.00005	Achieved by LEP age ☑
Statistics	>0.00030 (Tevatron) <0.00010 (LHC future)	Will be reduced
PDF	0.00048	Tevatron+LHC W asymmetry, Z rapidity
Initial state radiation	>0.00010 (LHC)	Tevaron+LHC Z pT, W pT
Systemics	0.00030	Key Point

Systematic at hadron colliders

Traditional method

- **based on detector simulation and hardware calibration**
  - **material, electronics …**
- **systematic controlled to 0.1% - 1%**

Difficulties

- **aiming for 0.01%, effects which are not simulable become significant**

	Detector response	Problem
electron energy	pileup noise, calo-algorithm, energy loss	dependence with energy, direction, luminosity
muon momentum	magnetic, misalignment, photon radiation, multiple interaction	dependence with pT, direction, charge

How to control systematics

Parameterization

- **Factorize all potential effects into parameters, e.g.:**

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

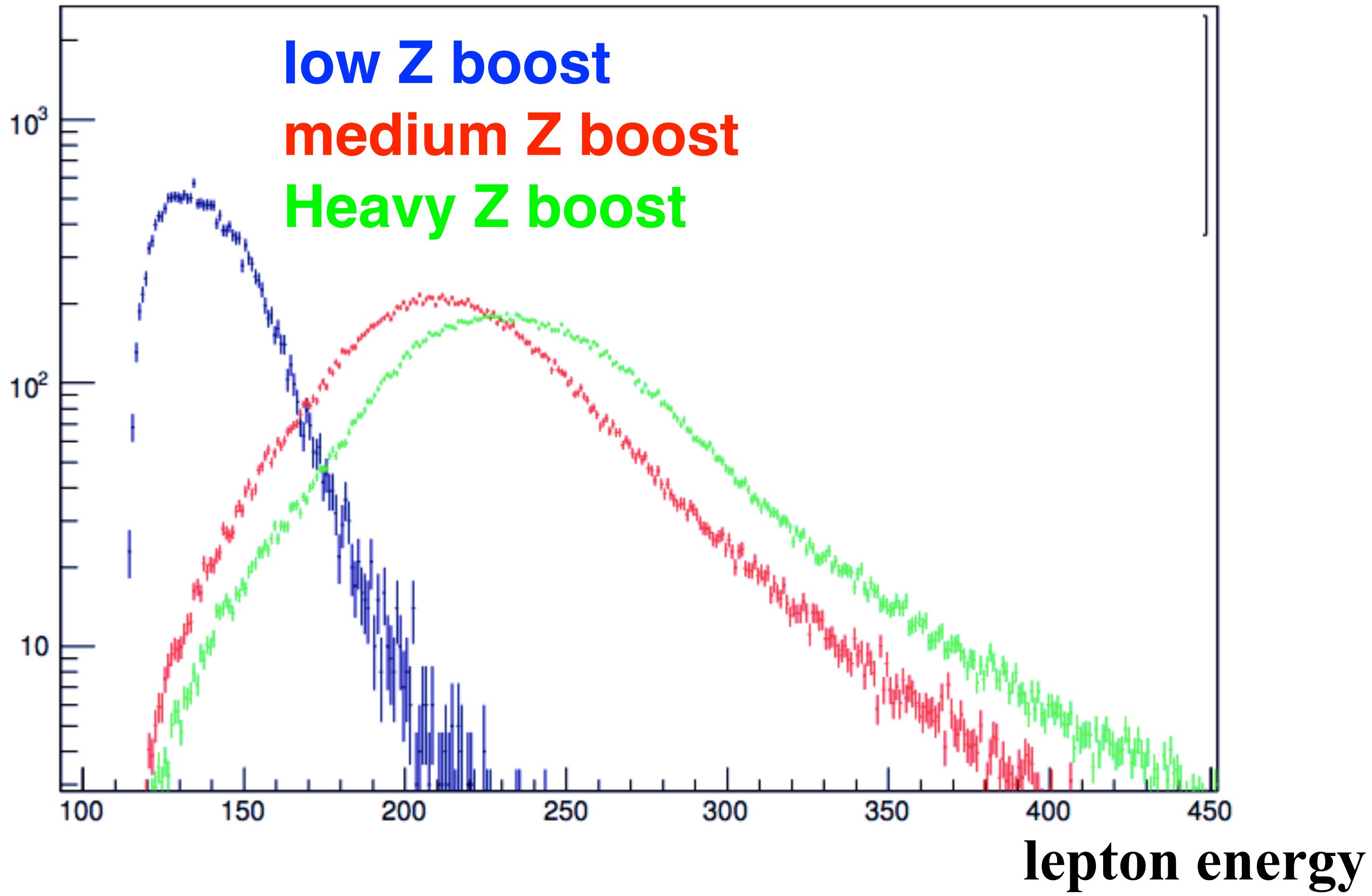
- **Use physics constraints to determine their values**
- **Precision determined by how many parameters considered**
- **difficulties: number of parameters limited by the only physics constraint we have: M_Z**

Lepton calibrations

More physics constraints

- **At hadron colliders, Z boson boost varies from initial quark energy difference**
- **Final state leptons are dominated by the Z boost rather than Z decay**
- **Difference Z boost provide difference lepton kinematics**

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



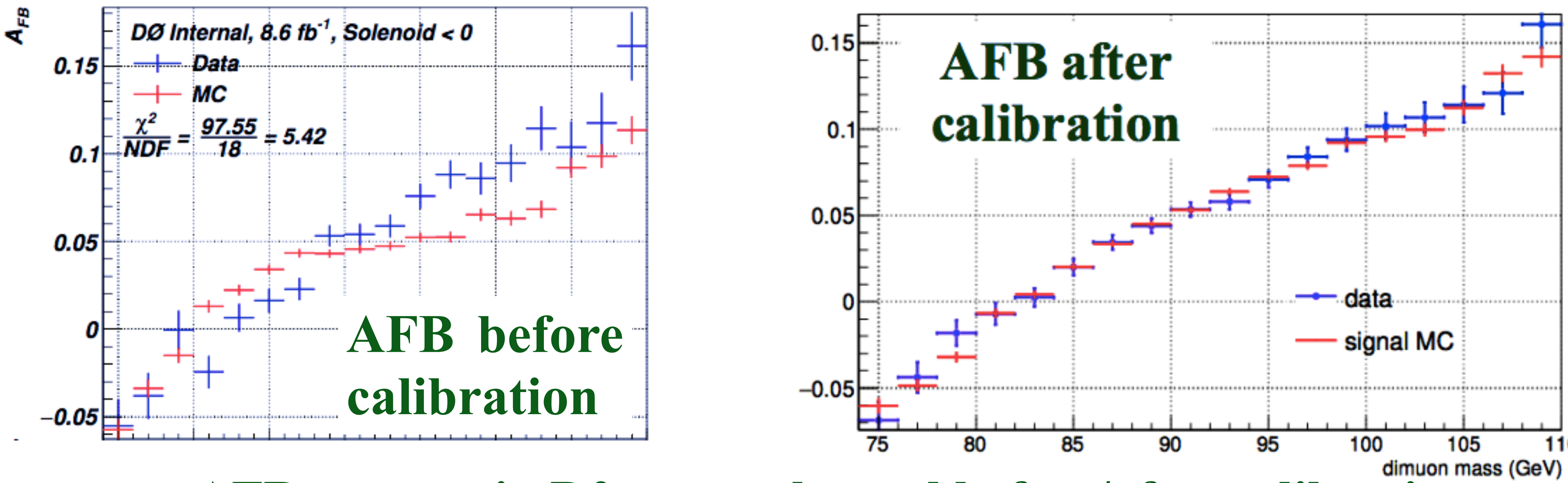
Calibration on particles

Improvement both on D0 and ATLAS performance

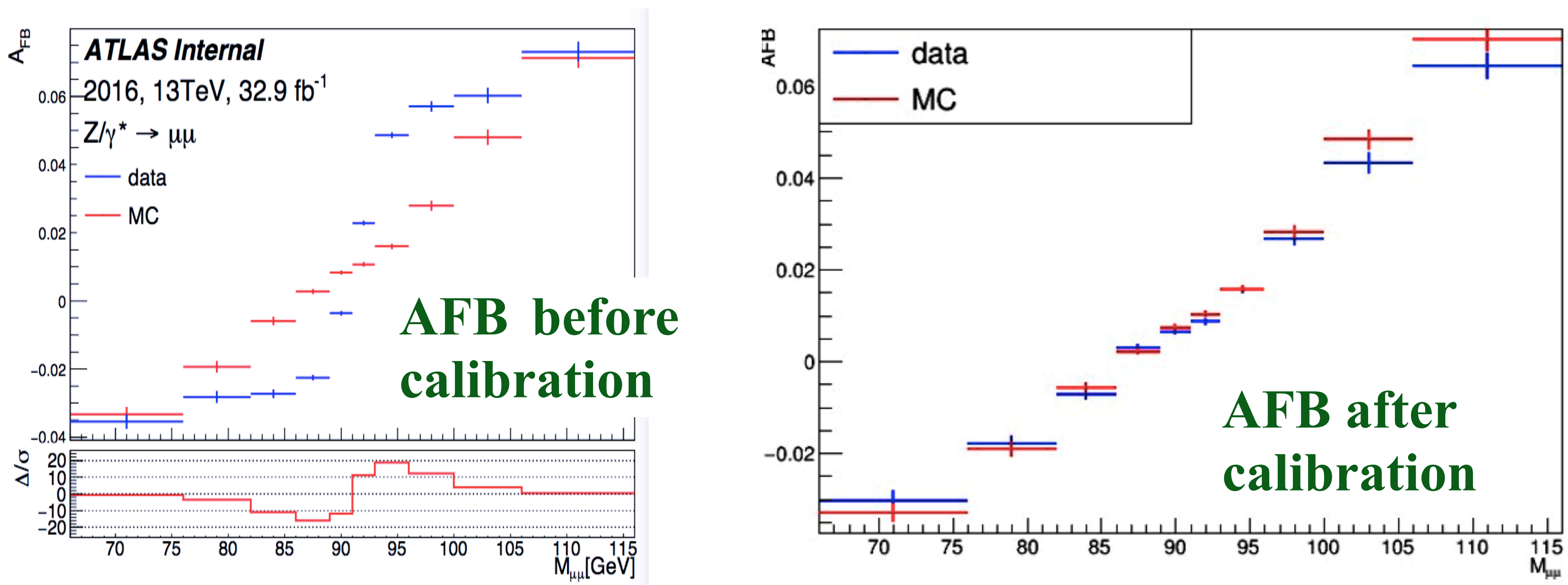
- **2018: accepted as standard calibration procedure (electron energy calibration + efficiency corrections) by ATLAS collaboration**

	relative uncertainty before my calibration	improvement
electron energy	0.1% - 1%	0.01%
muon momentum	>1%	0.01% - 0.1%
efficiency	1% ~ 10%	~1%

Calibration on physics



AFB vs mass in D0 muon channel before/after calibration



AFB vs mass in ATLAS muon channel before/after calibration

D0 electron final state measurement

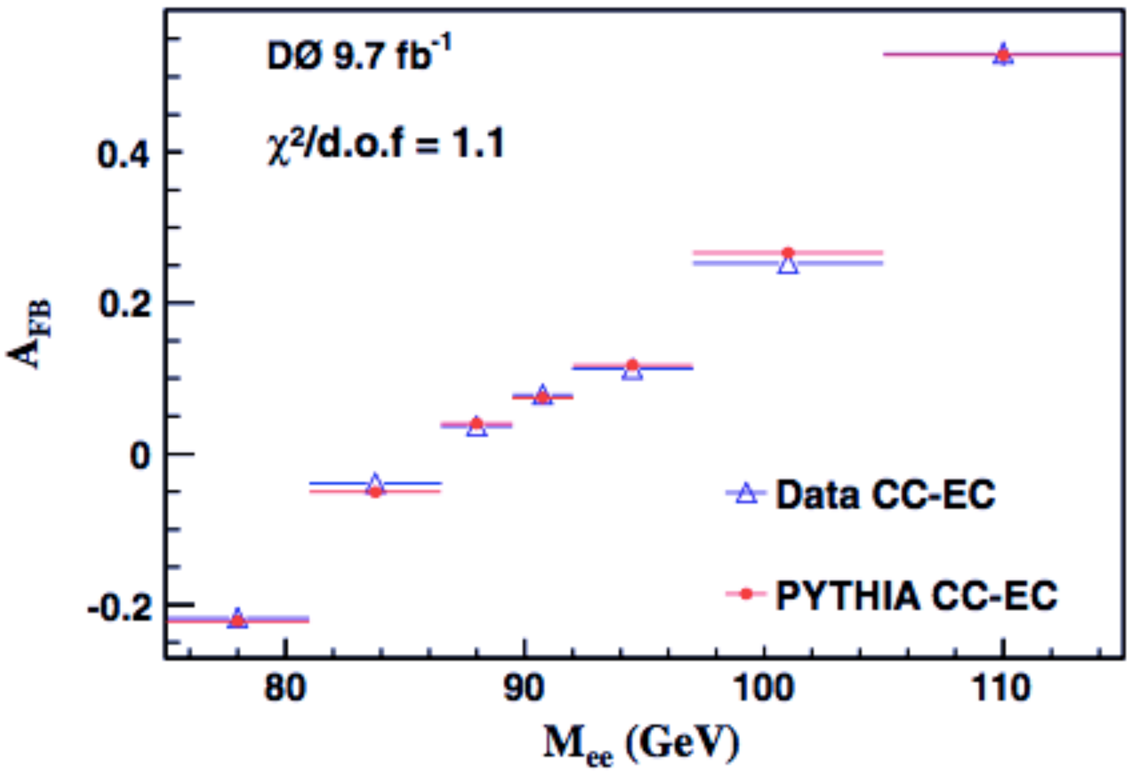
A collection of records

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

- The first time that
  - weak mixing angle measurement at hadron collider has a precision close to the best LEP/SLD
- The most precise measurement of:
  - electron-final state determination @ hadron colliders
  - light quark involved determination (including LEP/SLD)
  - single channel determination @ hadron colliders

$$\sin^2 \theta_{\rm eff}^{ee} = 0.23137 \pm 0.00047$$

The original expected unc. is >0.00085!



D0 muon final state measurement

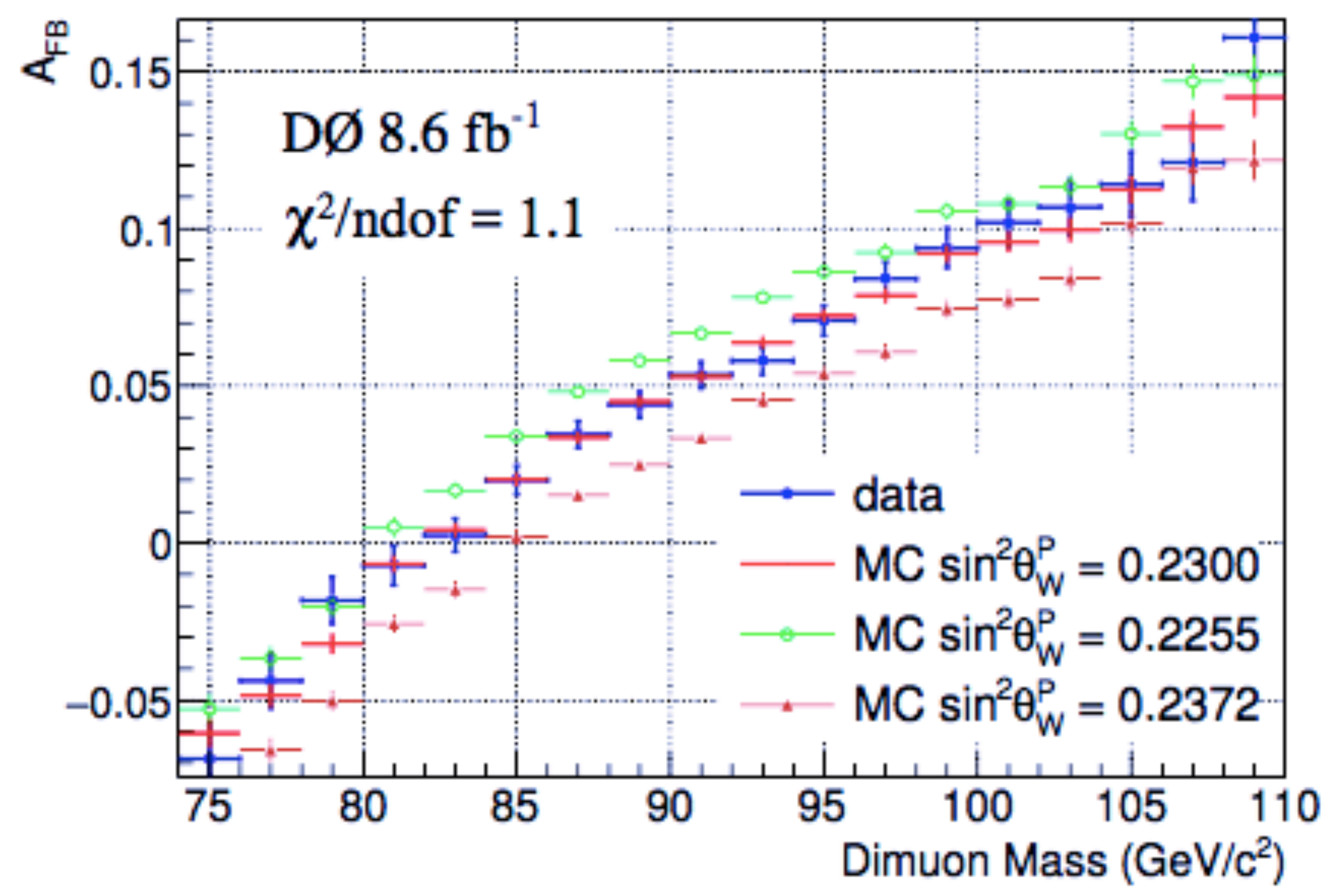
A collection of records

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

- The first time that
  - muon final state used at D0 in precision measurement
- One of the most precise measurements of:
  - muon final state determination (including LEP/SLD)
- Combined with D0 electron:
  - the most precise single experimental determination

$$\sin^2\theta^{\mu\mu}_{\rm eff} = 0.23016 \pm 0.00064$$

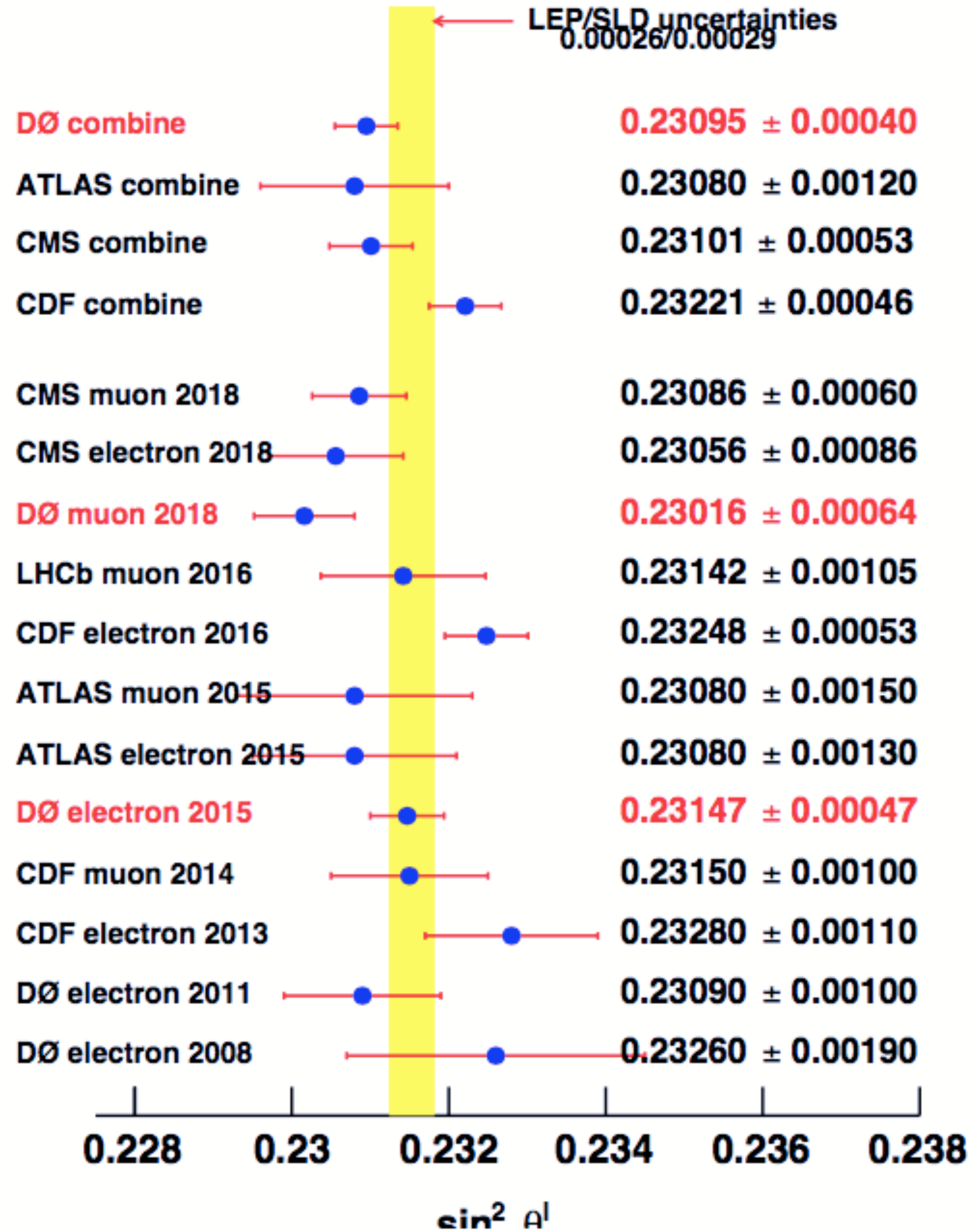
Muon channel was not planned
in D0 precision measurement !



Tevatron combination

Phys. Rev. D 97, 112007 (2018)

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



Academic Influences

Invited talks at international conferences

- **14 talks at top conferences**
- **2014 Moriond, 2014 ICHEP**
- **2015 LHCP**
- **2016 Blois, 2016 ICHEP**
- **2017 Mriond, 2017 MITP, 2017 EPS (2 talks), 2017 PANIC**
- **2018 ICHEP (2 talks)**
- **2019 Moriond, 2019 EPS**

On going work

ATLAS
$\Delta \sin^2\theta_W < 0.00010$

electron calibration

muon calibration

efficiency

W asymmetry
13 TeV/5 TeV ATLAS

Z boson rapidity
at D0

W/Z boson pT
at D0

W/Z decay
angular coefficients

High mass DY

QCD and PDF
(ePump ResBos
Project (ERP)
collaboration)

Coming soon …

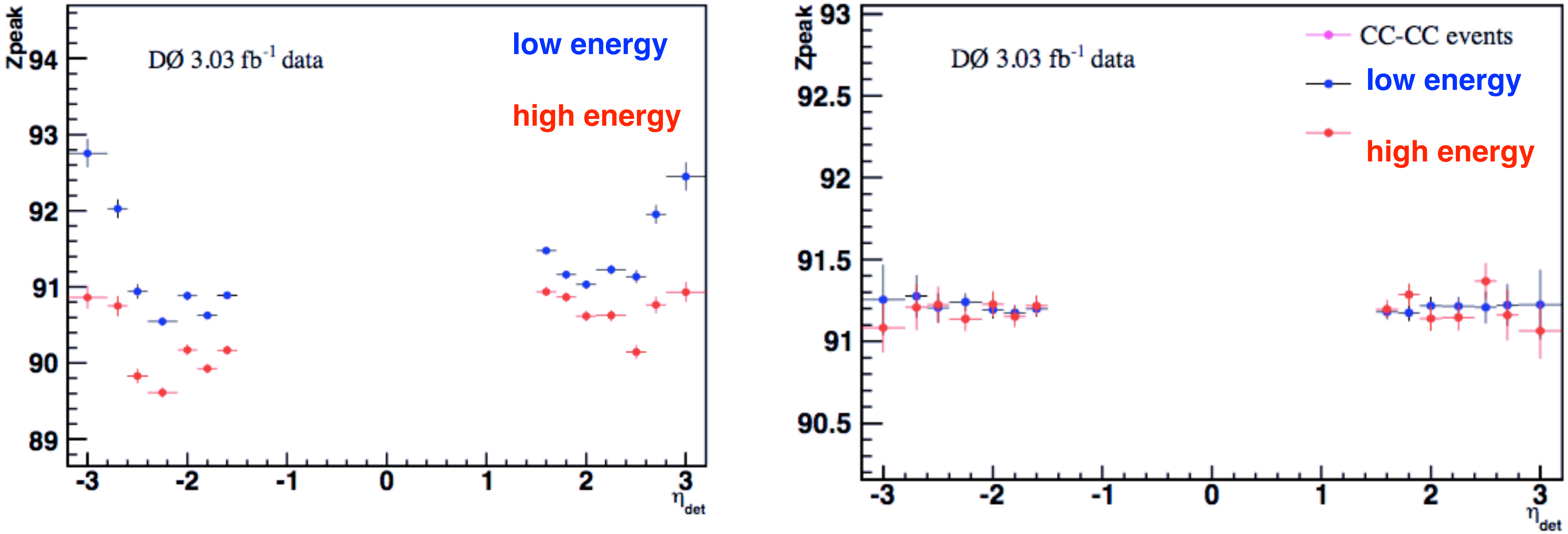
Next few years

- Weak mixing angle determination using ATLAS 2015+2016 data, $\Delta\sin^2\theta_W \sim 0.00045$
  - followed by measurement using full Run 2 data, $\Delta\sin^2\theta_W < 0.00025$
- W pT measurement using D0 data
- Z rapidity measurement using D0 data
- W asymmetry measurement using ATLAS Run 2 data (ongoing)
- PDF study in CT18 vs precision EW measurement
- QCD resummation vs precision EW measurement at LHC

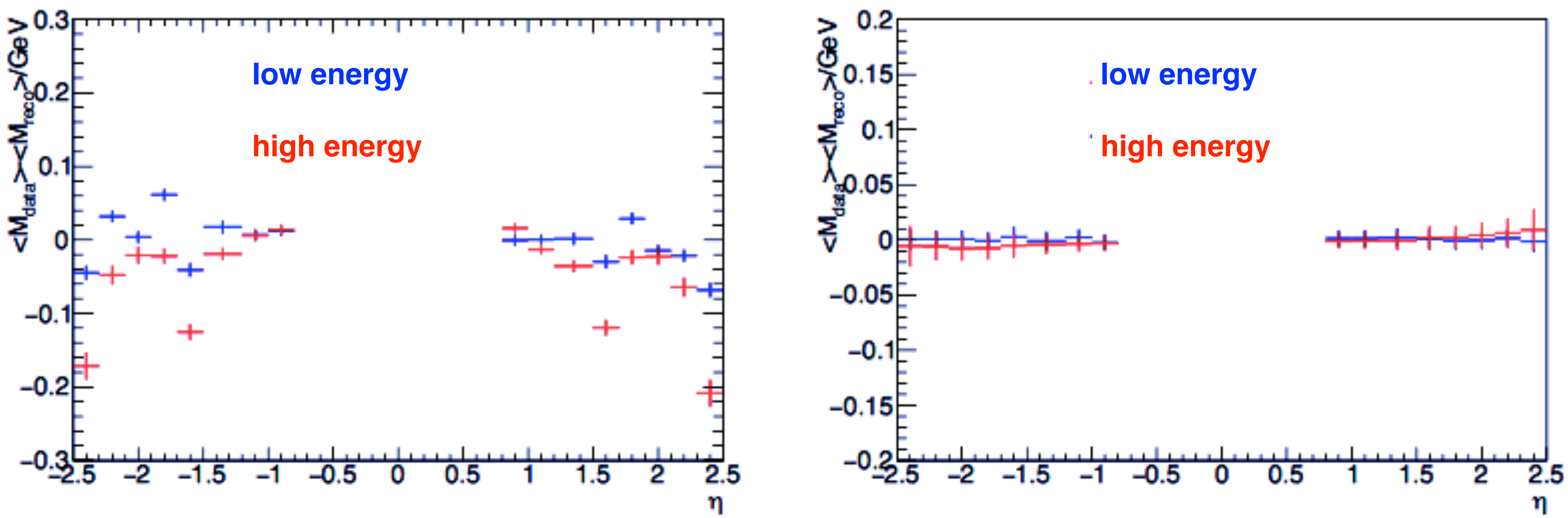
Thanks

Backup

electron calibration

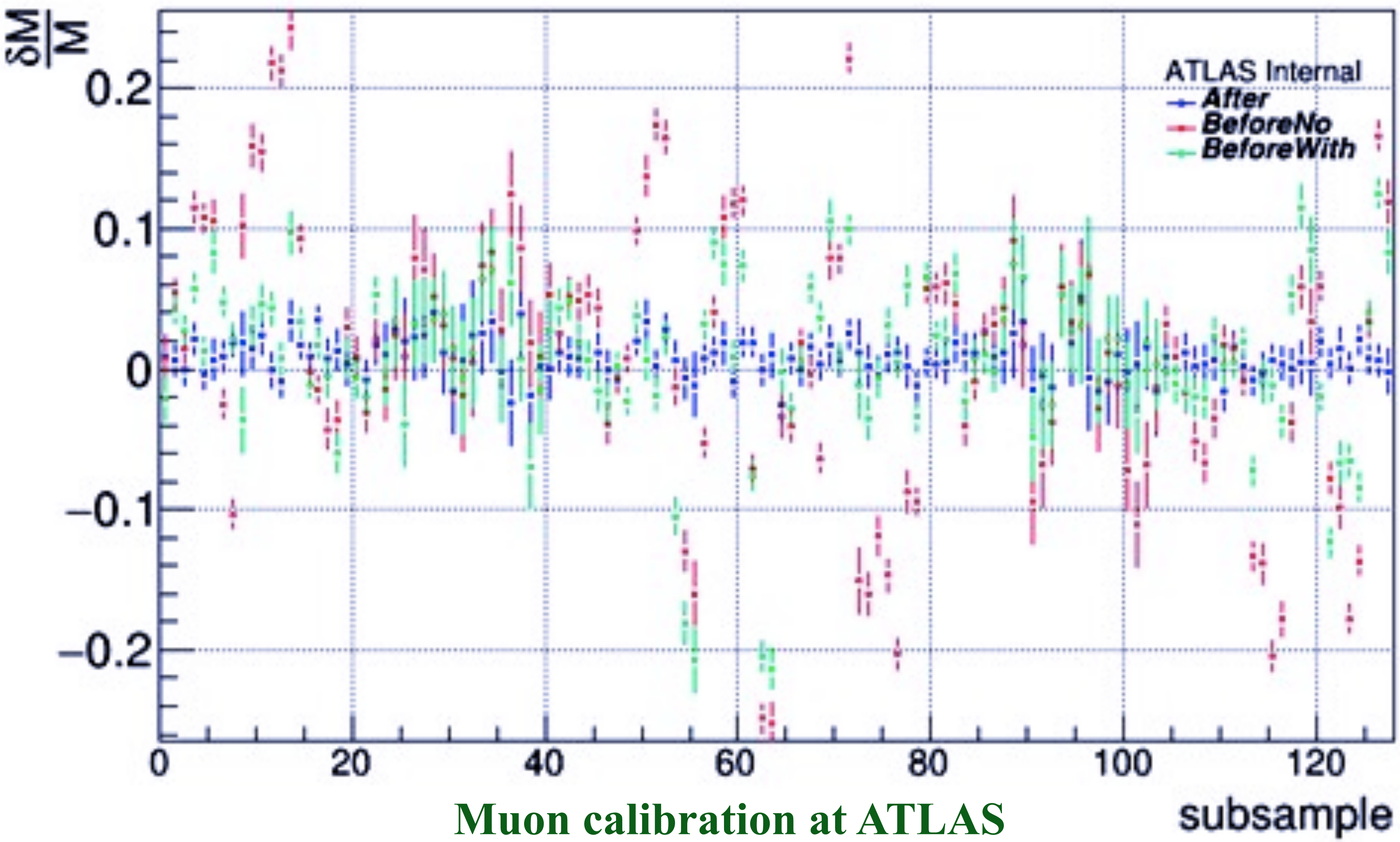


Electron calibration at D0



Electron calibration at ATLAS

Muon calibration @ ATLAS



Muon calibration at ATLAS

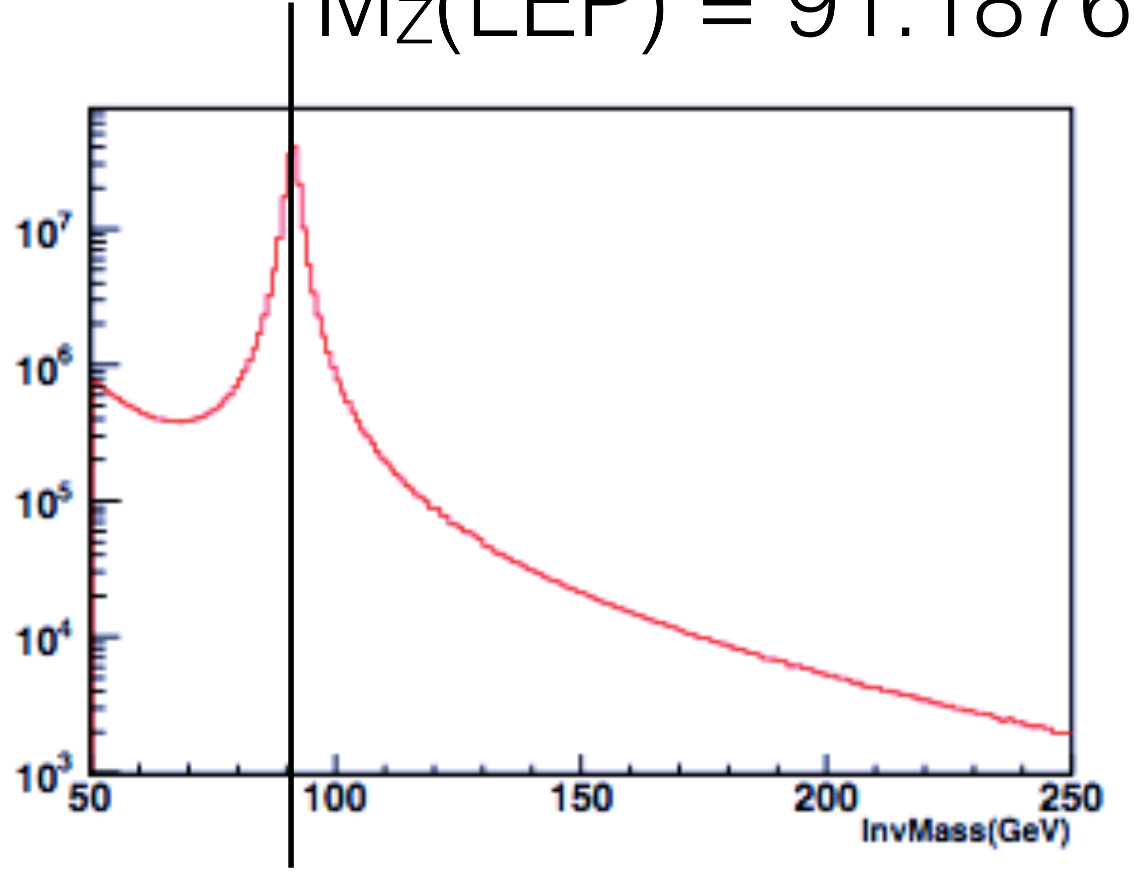
Red: before calibration
Green: calibrate using traditional method
Blue: calibrate using new method

Systematics: lepton performance (3)

Lepton calibration

- **Limited precision using hardware-level corrections and simulation**
- **Physics calibration: M_Z**

M_Z(LEP) = 91.1876 +/- 0.0021 GeV



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

ATLAS performance