Measurements of $\sin^2\theta_{eff}^{lept}$ (M_Z), $\sin^2\theta_W$ and indirect measurement of M_W at the Tevatron (and Prospects for the LHC)

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EP Seminar Tuesday Jan 31, 2017
500-1-001 - Main Auditorium (CERN)
11:00 – 12:00
https://indico.cern.ch/event/571075/

Run II: $\sqrt{s}$ = 1.96 TeV
2001-2011: 12 fb^{-1} Delivered

Abstract

A Legacy measurement at the Tevatron

Run II: $\sqrt{s}$ = 1.96 TeV
2001-2011: 12 fb^{-1} Delivered

CDF and D0 have measured the effective leptonic weak mixing angle **$\sin^2\theta_{eff}^{lept}$ (M_Z)** , using their full Tevatron datasets.

I describe the new techniques used in CDF and D0 analyses and the Tevatron combination of these two measurements.

I also discuss the Zfitter standard model-based inference of the on-shell electroweak mixing angle sin2T_W(on-shell) , or equivalently, an indirect measurement of the W-boson mass.

The combination of CDF and D0 results yields:

$\sin^2\theta_{eff}^{lept}$ (M_Z) = 0.23179 ± 0.00035

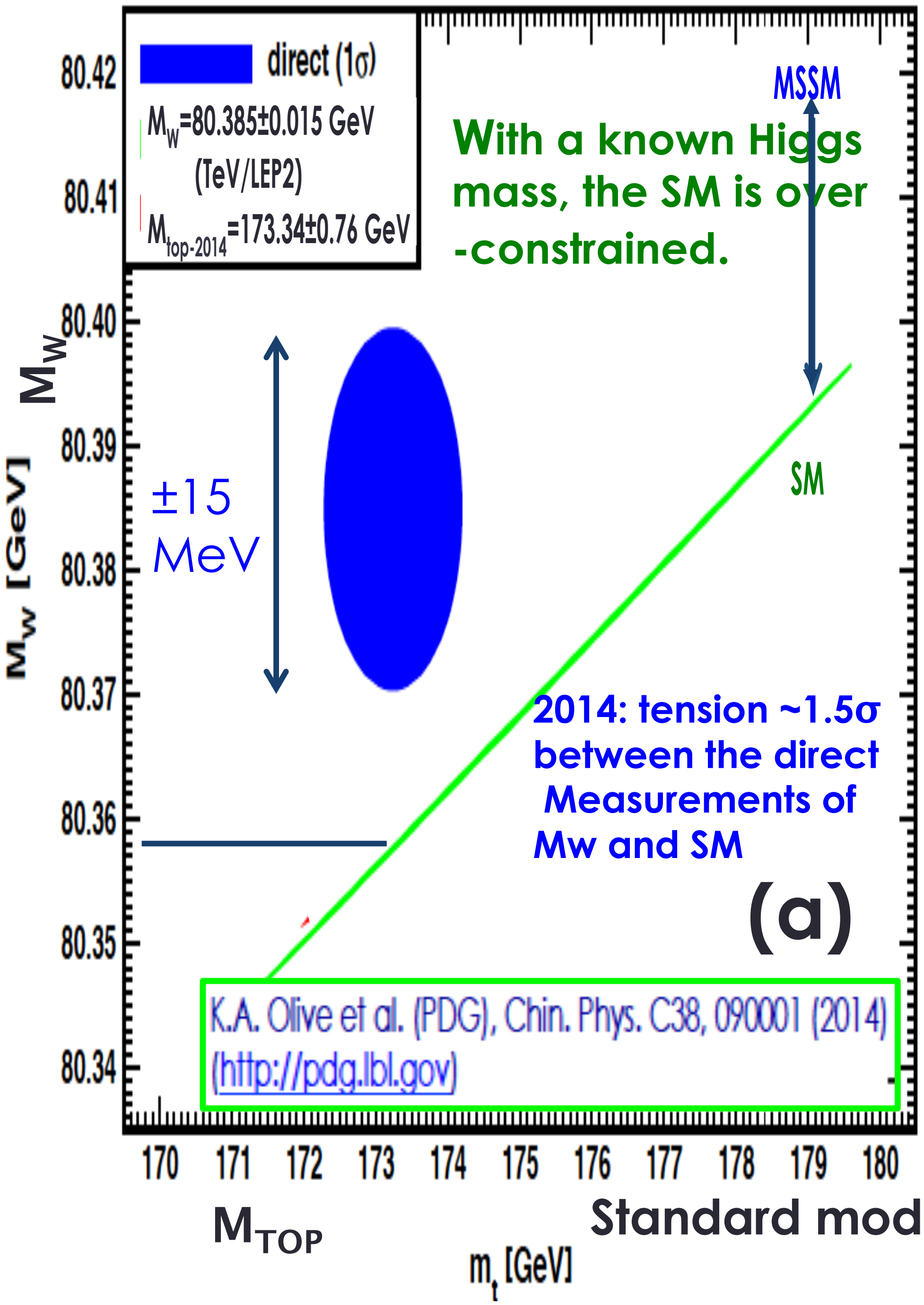
,

$\sin^2\theta_W$ (on shell) = 0.22356 ± 0.00035

M_W (indirect) = 80.351 ± 0.018 GeV/c2

I also discuss prospect for improved measurements at the LHC

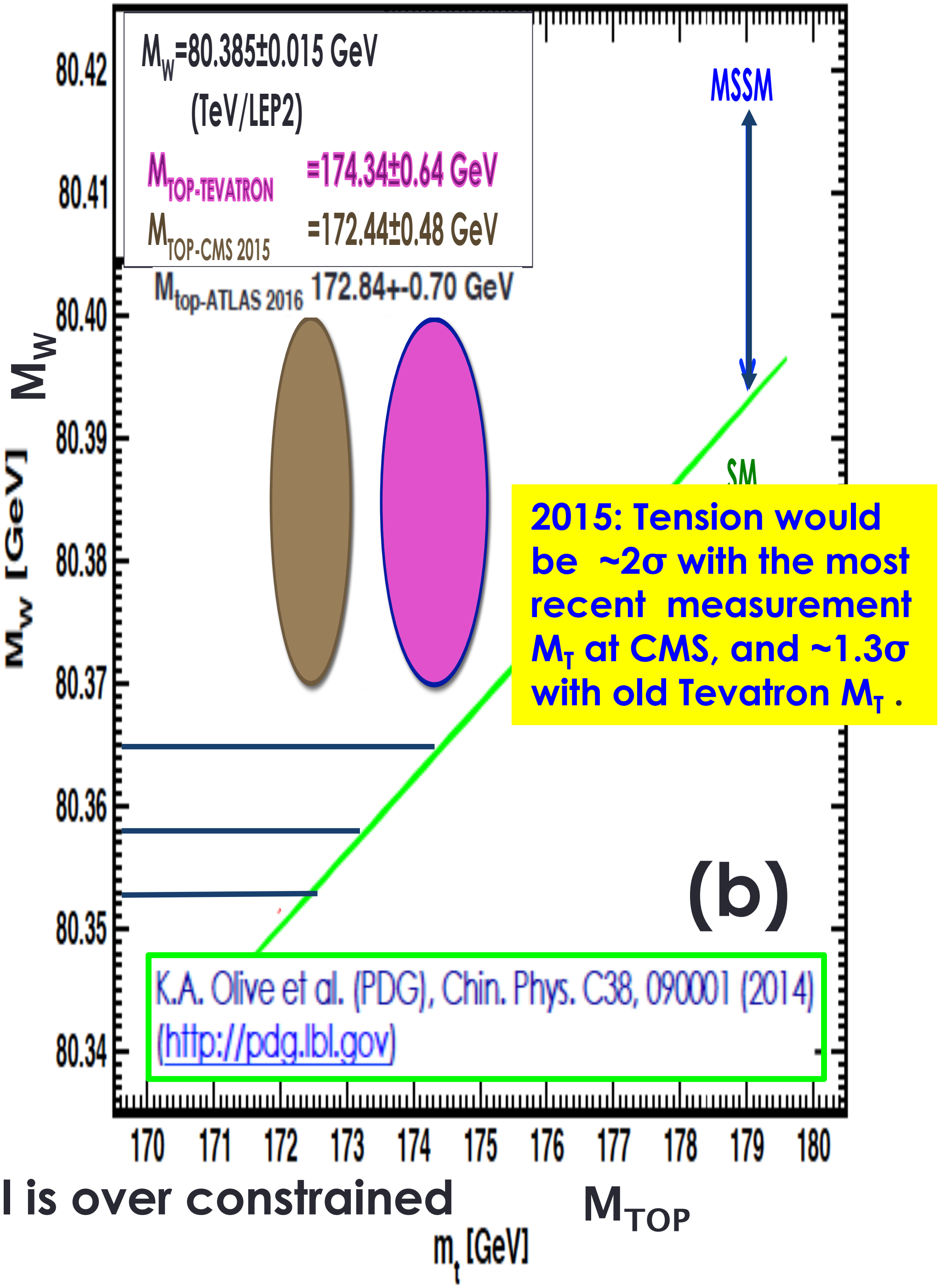
Standard Model vs Super symmetry



With a known Higgs mass, the SM is over -constrained.

2014: tension ~1.5σ between the direct Measurements of Mw and SM

K.A. Olive et al. (PDG), Chin. Phys. C38, 090001 (2014) (http://pdg.lbl.gov)



2015: Tension would be ~2σ with the most recent measurement M_T at CMS, and ~1.3σ with old Tevatron M_T .

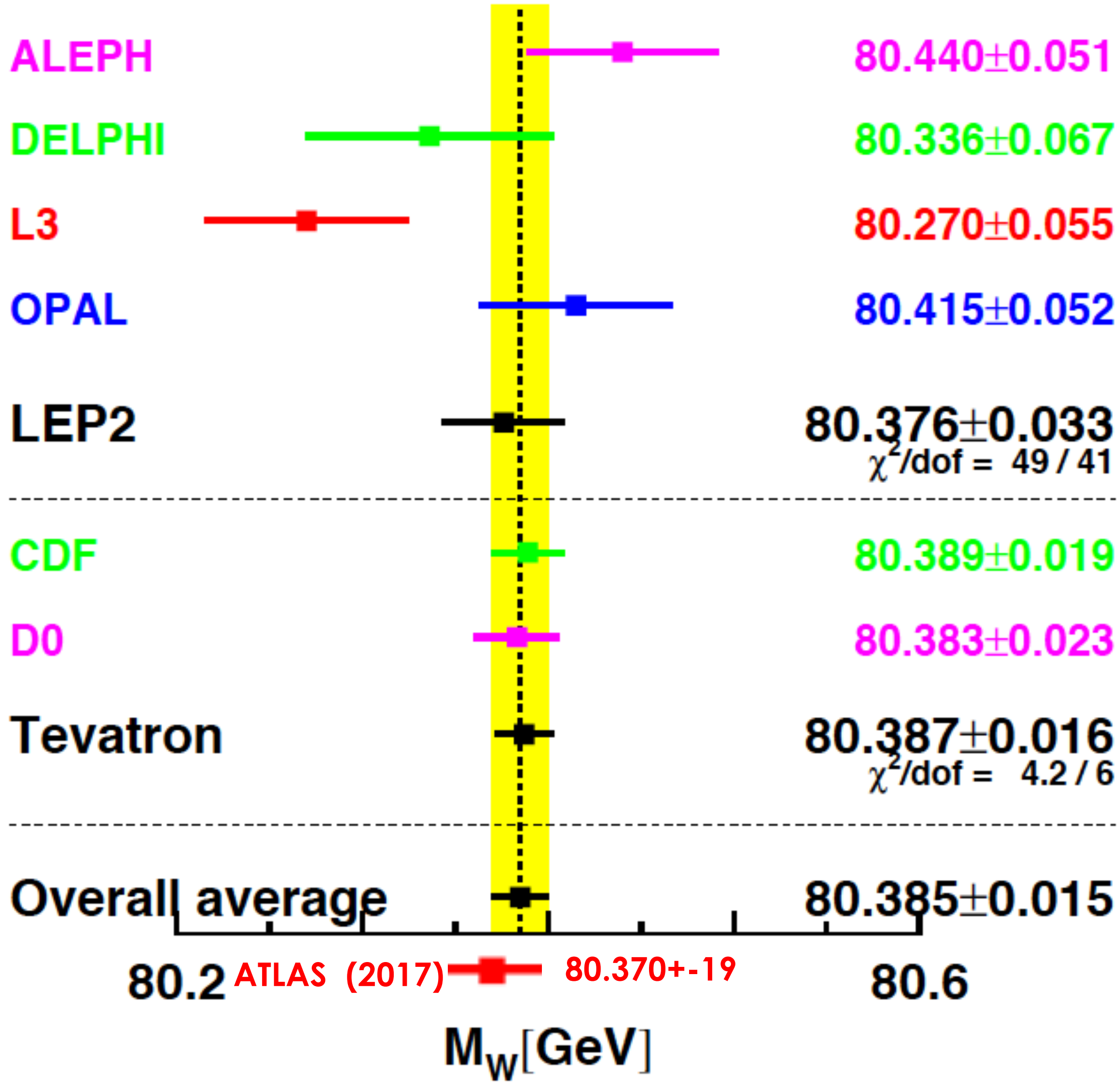
K.A. Olive et al. (PDG), Chin. Phys. C38, 090001 (2014) (http://pdg.lbl.gov)

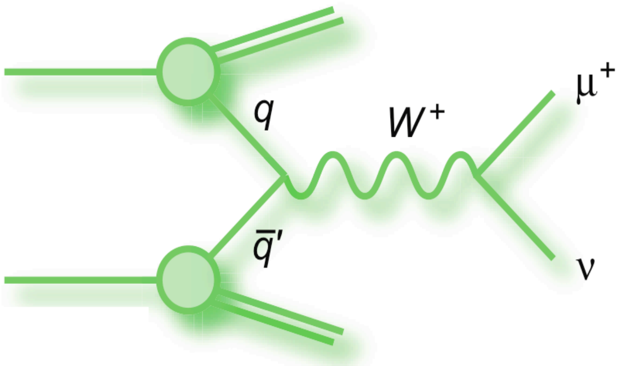
Standard model is over constrained

Direct measurement of W mass LEP & Tevatron

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-w-mass.pdf

Currently direct measurement's precision is 20 MeV



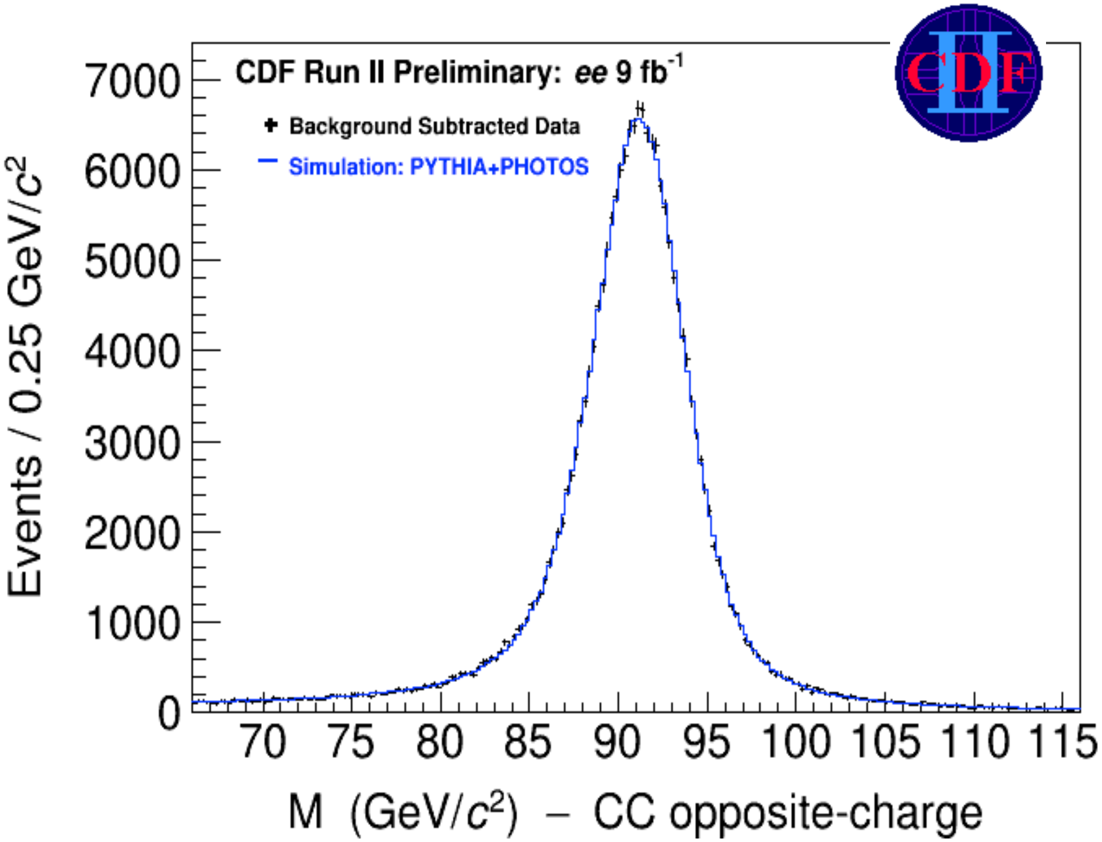


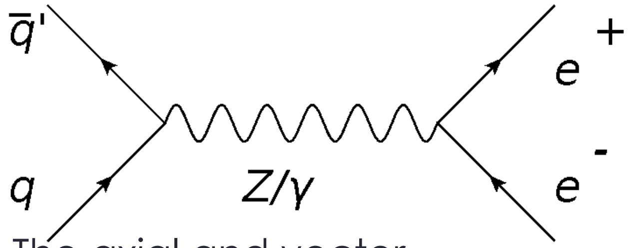
The most recent 2.2 fb^{-1} Tevatron measurements (CDF and Dzero) have errors of ~20 MeV.

Legacy sample 9.1 fb^{-1} analyses not yet completed. Aim at 10 MeV error ?

Z production Hadron colliders

Altertatively we can also make an indirect measurement of the W mass





The axial and vector
neutral currents interfere

Weak neutral current
strength related to $\sin^2\theta_{eff}$

$$\sin^2\theta_{eff}^{lept} = \mathrm{Re}[\kappa_l(M_Z^2, \sin^2\theta_W)]\sin^2\theta_W$$

↳ ≈1.037

$$\sin^2\theta_W = \sin^2\theta_W^{on\text{-}shell} = 1 - M_W^2 / M_Z^2$$

e+e- mass Z boson measured precisely in e+e- colliders)

Standard model parameters are not all independent:

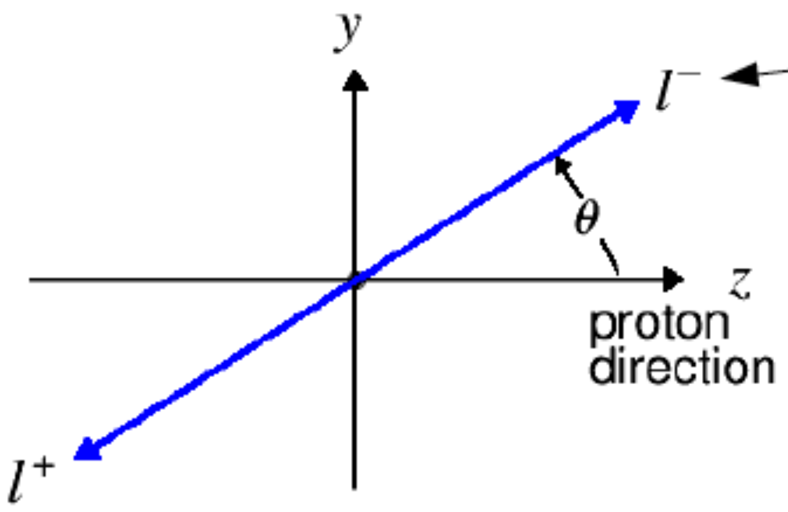
Now that we know Higgs mass, Standard model is over constrained. With EW radiative corrections, a measurement of $\sin^2\theta_{eff}$ is equivalent to a measurement of M_W

Drell – Yan Process

Forward-backwards asymmetry: A_{fb}

- Drell-Yan process at the Tevatron: $p\bar{p} \rightarrow \gamma^*/Z + X$, with $\gamma^*/Z \rightarrow l^+l^-$
  - l^+l^- polar-angle (ϑ) distribution in center-of-mass frame is asymmetric
    - Parity violation of Z decays
  - Born level angular distribution: $1 + \cos^2\vartheta + \boxed{A_4 \cos\vartheta}$

Collins-Soper Center of Mass Frame



Negatively charged lepton

- Forward (f): $\cos\vartheta \geq 0$
- Backward (b): $\cos\vartheta < 0$

$$A_{fb} = \boxed{3/8\, A_4}$$

- Forward/backward cross-section asymmetry

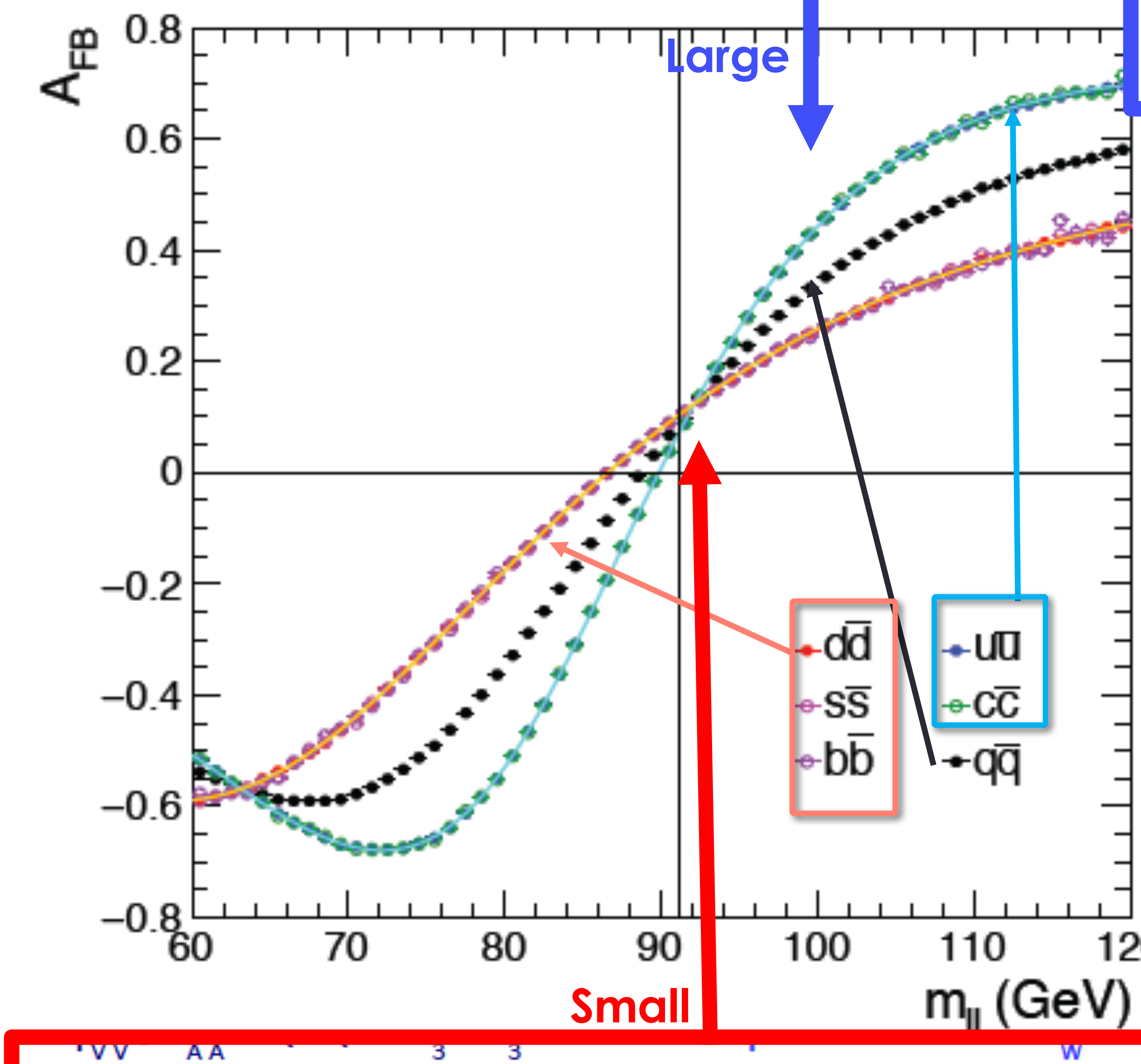
$$A_{fb} = (\sigma_f - \sigma_b)/(\sigma_f + \sigma_b) = \boxed{3/8\, A_4}$$

Is a probe to the electroweak mixing angle $\sin^2\theta_W$

Afb for u and d type quark

- $\gamma_{VV} \otimes Z_{AA}$: $Q^{(l)}Q^{(q)}$ $T_3^{(q)} T_3^{(l)}$ ← independent of $\sin^2\theta_W$

- γ-Z interference term:
  - zero at Z pole [~ $1-(M_Z/M)^2$]
  - dominates away from pole
  - sensitive to PDFs



- $Z_{VV} \otimes Z_{AA}$: $T_3^{(l)}(1-4|Q^{(l)}|\sin^2\theta_W)$ $T_3^{(q)}(1-4|Q^{(q)}|\sin^2\theta_W)$ $T_3^{(q)} T_3^{(l)}$

- Z-Z interference term:
  - sensitive to $\sin^2\theta_{eff}^{lept}$
  - best precision near M_Z
    - most events at the pole
    - minimal γ-Z interference

Precision of indirect Measurement of W mass

M_W can be determined indirectly via the relation

$$\sin^2\theta_W^{\text{on-shell}} = 1 - M_w^2 / M_z^2$$

±0.00040 error in $\sin^2\theta w$ is equiv. to ±20 MeV error in Mw (indirect)

Both $\sin^2\theta_W^{\text{on-shell}}$ and $\sin^2\theta_{\text{eff}}^{\text{leptonic}}$ (M_z) can be extracted from Drell-Yan forward-backward asymmetry (Afb).

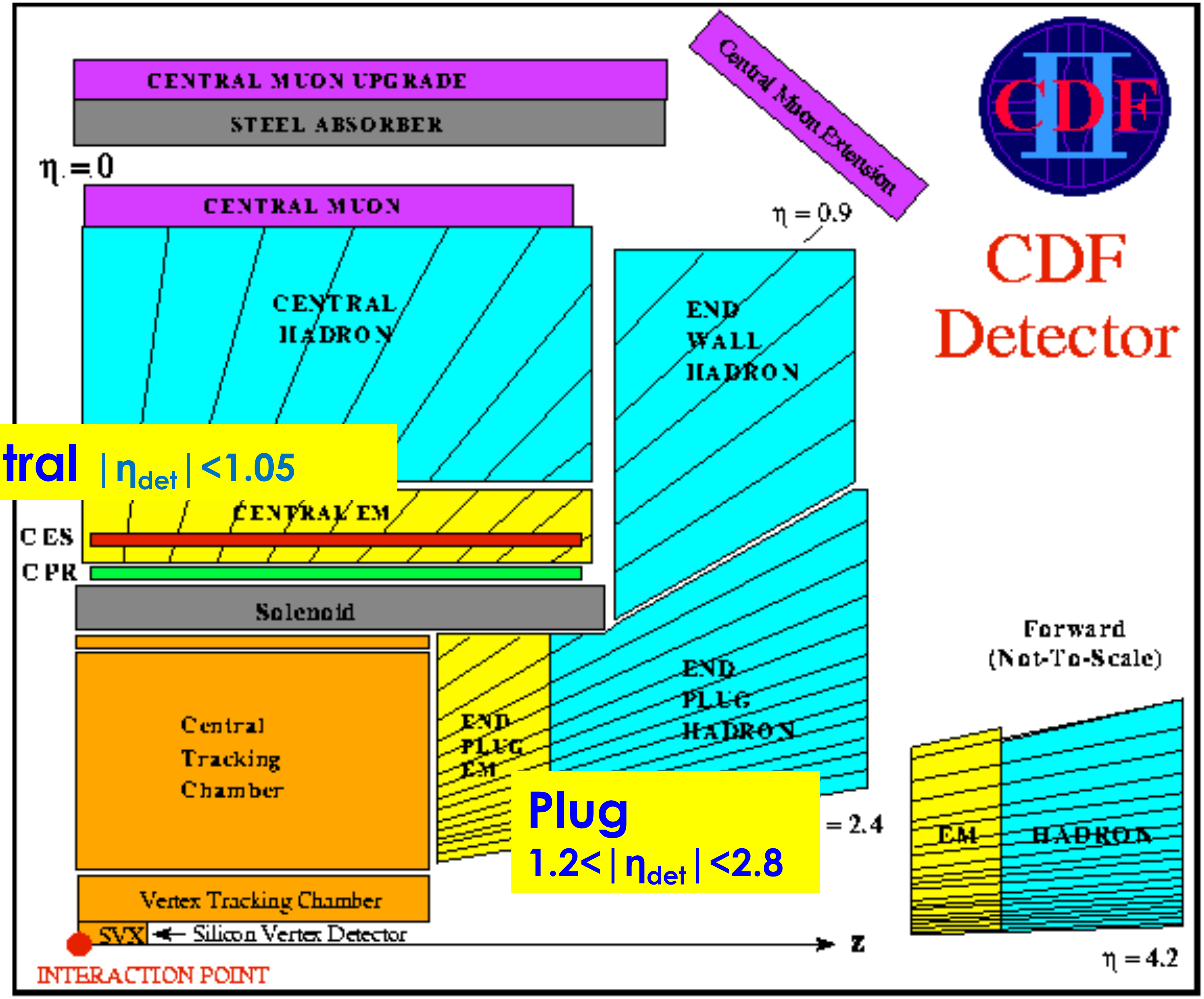
if we include EW radiative corrections. M_w^{indirect} can be extracted from $\sin^2\theta_W^{\text{on-shell}}$

- If the SM is correct, then both direct and indirect measurements of M_W should agree. Deviations may imply the possibility of new physics.

- Similarly different measurements of $\sin^2\theta_{\text{eff}}^{\text{lleptonic}}$ (M_z) should also agree and deviations may imply new physics.

As shown in this talk, for the full Run II 9. fb^{-1} Tevatron data, the uncertainties in direct and indirect measurements of M_w are now comparable.

Start with CDF detector



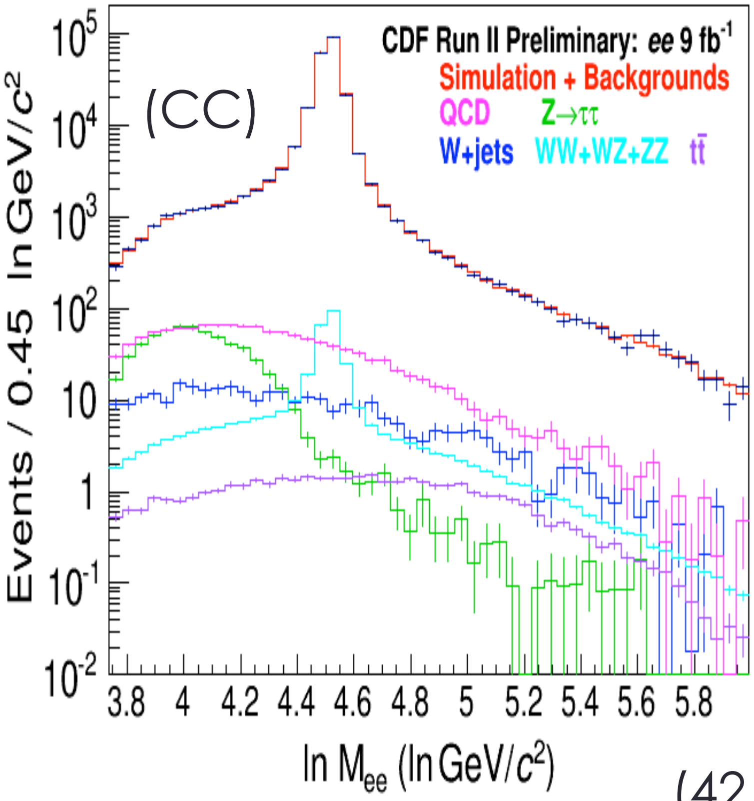
central $|\eta_{det}|<1.05$

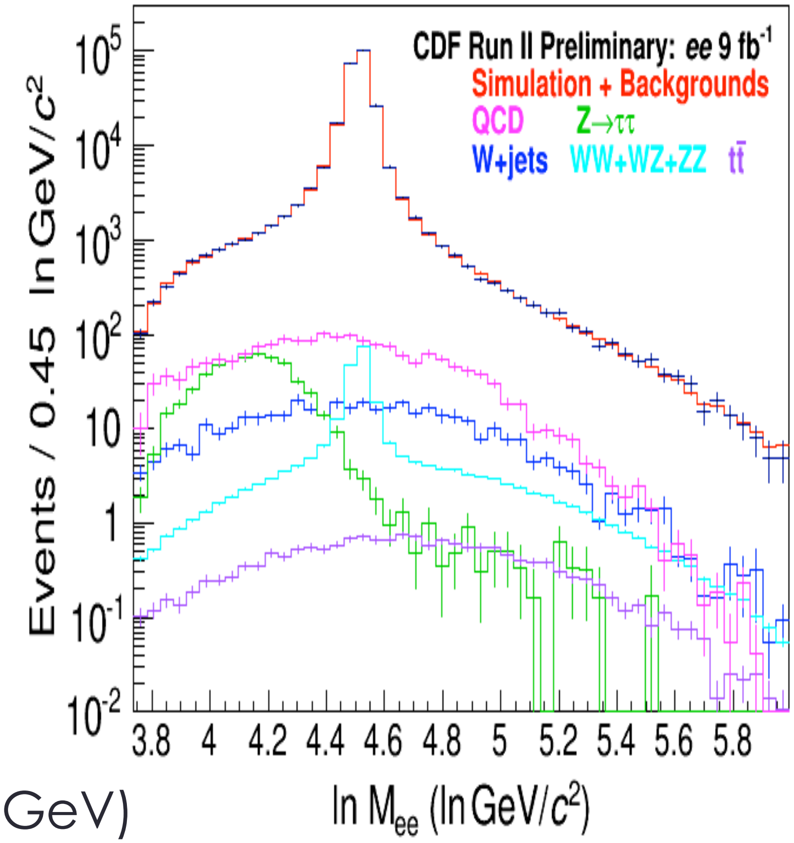
Plug $1.2<|\eta_{det}|<2.8$

CDF e^+e^- mass spectrum (CC and CP)

CDF e^+e^- Central-Central (CC)
227K events. background ~1.1%

CDF e^+e^- Central-Plug (CP)
258K events bkgd ~ 1.2 %





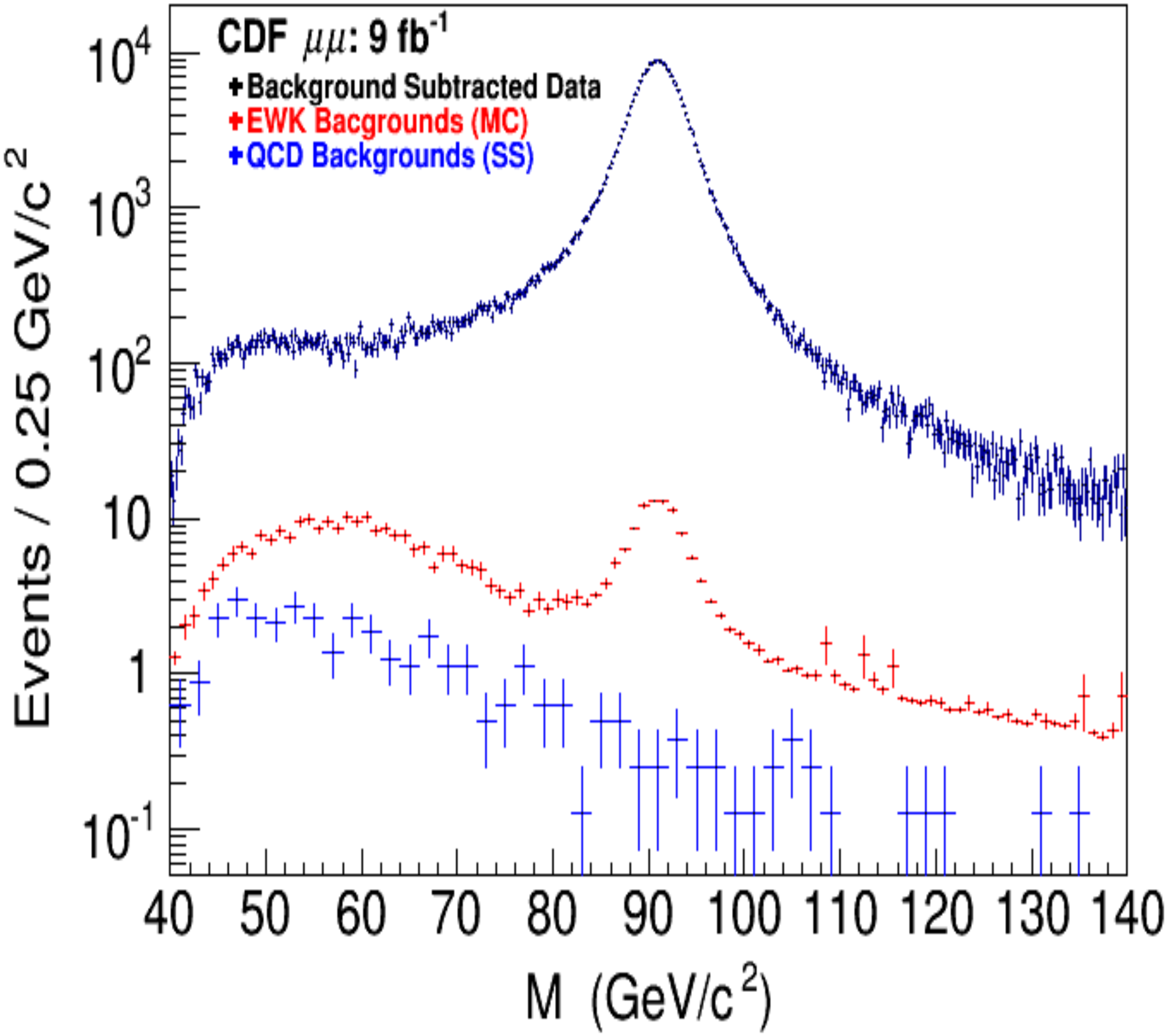
(42 to 400 GeV)

CDF ee PHY REV D 93, 112016 (2016

The data are the crosses and the red histogram the sum of the simulation and all backgrounds.
The backgrounds are: QCD (magenta), Z → ττ (green), W+jets (blue), WW+WZ+ZZ (cyan), and tt (purple).
The χ2 between the data and sum of the simulation and backgrounds is 56 for 50 bins.

$\mu^+\mu^-$ mass spectrum (CC)

CDF $\mu^+\mu^-$ (CC) 227K events Bkgd: EWK 0.5%
QCD 0.1% (same sign

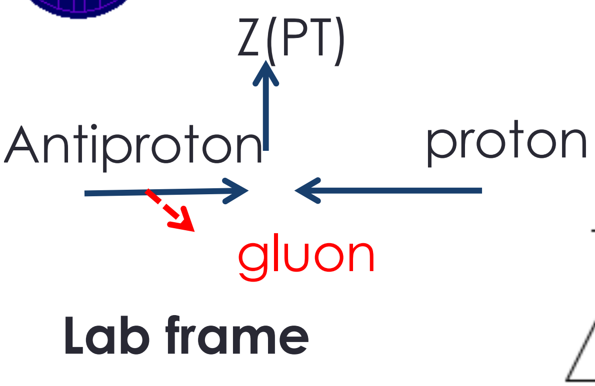


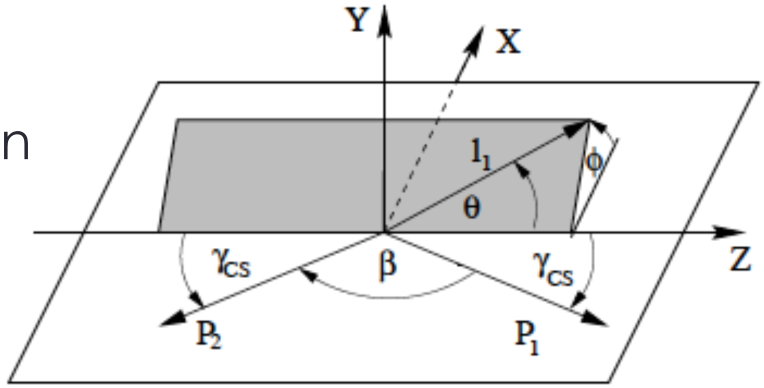
Central-central (CC)
$\mu^+\mu^-$

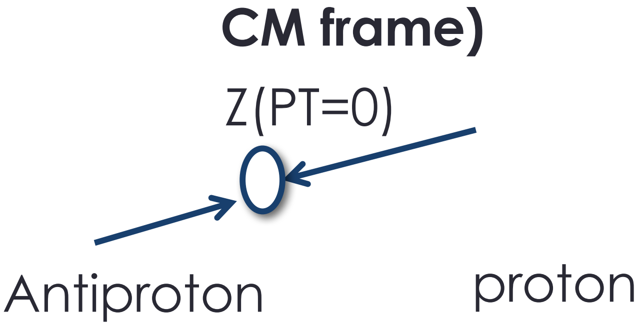
CDF $\mu^+\mu^-$: :Phys. Rev. D89, 072005 (2014)

Collins Soper frame angles

Cosθ in the Collins-Soper (CM frame of the dilepton pair)







$$\cos\vartheta = \frac{l_+^- l_-^+ - l_-^- l_+^+}{M\sqrt{M^2+P_T^2}}\,, \qquad \tan\varphi = \frac{\sqrt{M^2+P_T^2}}{M}\,\frac{\vec{\Delta}\cdot\widehat{R}_T}{\vec{\Delta}\cdot\widehat{P}_T}\,,$$

C-S Frame angles Can be expressed in terms of lab variables

where $l_\pm = (E \pm P_z)$ and the + (−) superscript specifies that $l_\pm$ is for the positively (negatively) charged lepton. Similarly, the Collins-Soper expression for φ in terms of laboratory-frame quantities is

where $\vec{\Delta}$ is the difference between the ℓ^- and ℓ^+ momentum vectors; $\widehat{R}_T$ is the transverse unit vector along $\vec{P}_p \times \vec{P}$, with $\vec{P}_p$ being the proton momentum vector and $\vec{P}$ the lepton-pair momentum vector; and $\widehat{P}_T$ is the unit vector along the transverse component of the lepton-pair momentum vector. At $P_T = 0$, the angular distribution is azimuthally symmetric.

CDF $\mu^+\mu^-$ & e^+e^- 9.7 fb^{-1} $\sin^2\theta_W$ analyses

Several new techniques are used:

1: Electroweak radiative corrections:

$\sin^2\theta_W$ is constant while $\sin^2\theta_{eff}^{lept}$ (M_{ee} ,flavor) is not. Implement Full ZFITTER EW radiative corrections, Enhanced Born Approximation (EBA), include full complex form factors implemented in private versions of RESBOS, POWHEG, and LO.

Ref Phys. Rev. D 88, 072002 (2013) Appendix A'. Implemented in CDF in 2013 by Willis Sakumoto (Rochester).

Phys. Rev. D89, 072005 (2014)

2: Precise lepton momentum/energy scale for muons and electrons using a new method (is also relevant for W mass) (used in CDF, CMS, D0)

(will also reduce scale error for M_W measurement) Ref: A. Bodek et al. Euro. Phys. J. C72, 2194 (2012)

3: Event weighting method for A_{FB} analyses:

(systematic errors in acceptance, and efficiencies cancel)- Ref. A. Bodek. Euro. Phys. J. C67, 321 (2010)

in addition, less sensitive to momentum calibration (used in CDF → CMS)

4:: New PDF constraints using the same Drell Yan Data. (is also relevant for W mass)

Use Drell-Yan forward-backward asymmetry to constrain parton distribution functions - (will also reduce PDF errors for M_W measurement) Ref A. Bodek et al Euro. Phy. J. C76:115 (2016) (used in CDF-→ CMS)

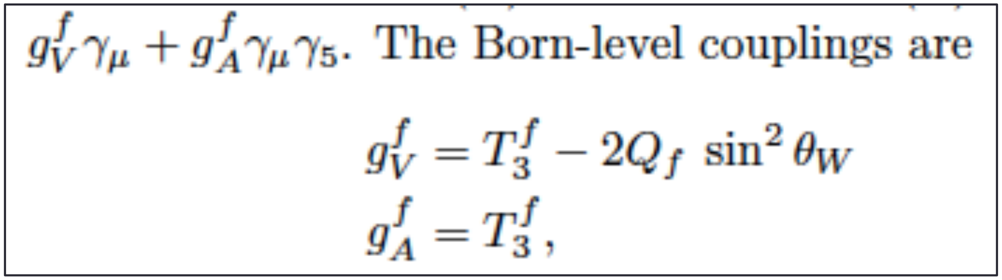
Next I describe each one of the four new techniques in more detail

(and also how these techniques can be used at the LHC)

1. Implement ZFITTER EBA EW radiative corrections

$\sin^2\theta_W$ (on-shell) is a constant while $\sin^2\theta_{eff}^{\,lept}$ (M_{ee}, flavor) is not.

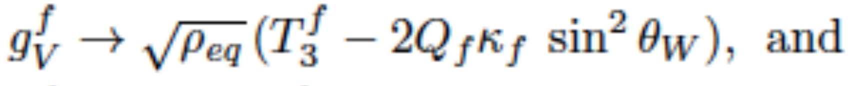
Full ZFITTER EW radiative corrections, Enhanced Born Approximation (EBA), include full complex form factors implemented private versions of RESBOS, POWHEG, and LO) Phys. Rev. D 88, 072002 (2013) Appendix A' (W. Sakumoto, University of Rochester)



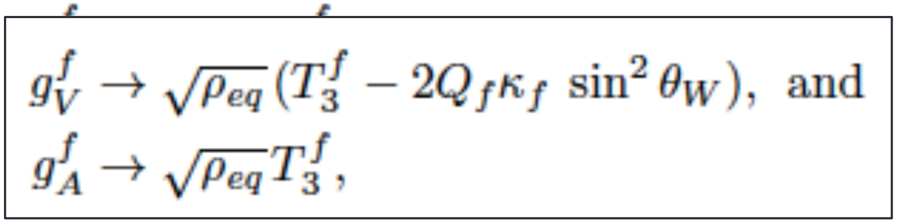
$g_V^f \gamma_\mu + g_A^f \gamma_\mu \gamma_5$. The Born-level couplings are

$$g_V^f = T_3^f - 2Q_f \sin^2\theta_W$$
$$g_A^f = T_3^f\,,$$

They are modified by ZFITTER 6.43 form factors (which are complex)



$$g_V^f \to \sqrt{\rho_{eq}}\,(T_3^f - 2Q_f\kappa_f \sin^2\theta_W),\ \text{and}$$



$$g_V^f \to \sqrt{\rho_{eq}}\,(T_3^f - 2Q_f\kappa_f \sin^2\theta_W),\ \text{and}$$
$$g_A^f \to \sqrt{\rho_{eq}}\,T_3^f\,,$$

- T_3 and $\sin^2\theta_W$ → effective T_3 and $\sin^2\theta_W$: 1-4% multiplicative form factors
- On-mass shell scheme: $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$ to all orders

We account for $\sin^2\theta_{eff}$ dependence on quark flavor (weak isospin) and dilepton mass → get $\sin^2\theta_{eff}^{\,leptonic}(M_Z)$

CDF $\sin^2\theta_{eff}^{leptonic}$ (M_z) and $\sin^2\theta_W^{on\text{-}shell}$

Afb(M) depends on $\sin^2\theta_{eff}^{electron}$ (M), $\sin^2\theta_{eff}^{u\text{-}quark}$ (M), $\sin^2\theta_{eff}^{d\text{-}quark}$ (M).

$\sin^2\theta_{eff}$ has a small flavor and dilepton mass dependent. The convention is to extract $\sin^2\theta_{eff}^{leptonic}$ (M_z)

Start with theory $\sin^2\theta_W^{on\text{-}shell}$

→ add SM form factors and EW rad corrections

Predict → $\sin^2\theta_{eff}^{electron}$ (M), $\sin^2\theta_{eff}^{u\text{-}quark}$ (M), $\sin^2\theta_{eff}^{d\text{-}quark}$ (M)

Add QCD +PDFs→ Predict Afb (M)& A_4 (M)

Compare predicted Afb (M) to data.

Extract both $\sin^2\theta_W^{on\text{-}shell}$ and $\sin^2\theta_{eff}^{leptonic}$ (M_z).

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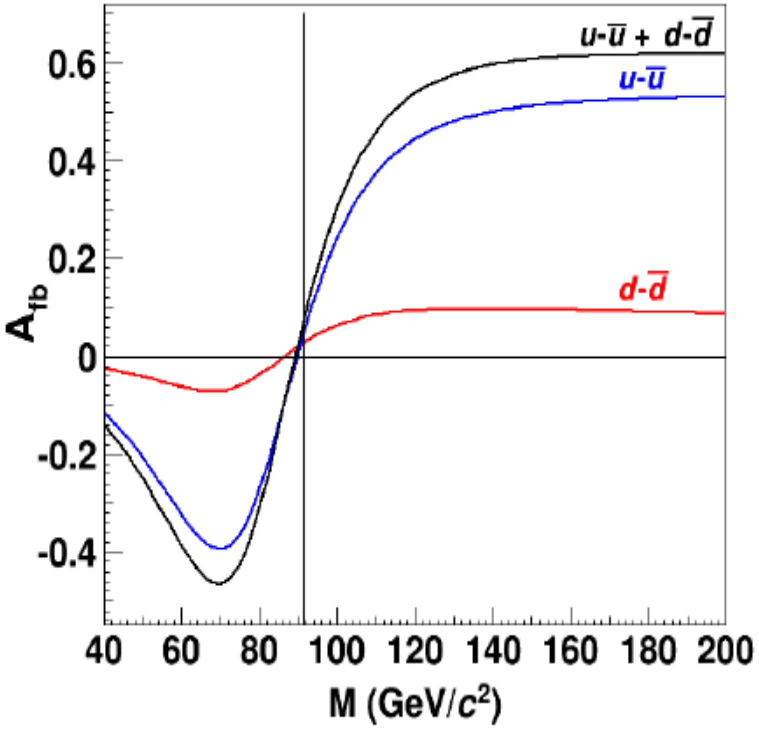
previous analyses neglect mass and flavor dependence of $\sin^2\theta_{eff}$ and extracted an average value only.



$$A_{FB}^{d-type} \approx \frac{(dd)_F - (dd)_B}{(dd)_F + (dd)_B + (uu)_F + (uu)_B}$$

$$A_{FB}^{u-type} \approx \frac{(uu)_F - (uu)_B}{(dd)_F + (dd)_B + (uu)_F + (uu)_B}$$

$A_{FB} = (3/8)\ A_4$

$$\mathrm{SM}(\sin^2\theta_W) \overset{\mathrm{EWK}}{\longmapsto} \sin^2\theta_{\mathrm{eff}}(s) \overset{\mathrm{QCD}}{\longleftrightarrow} A_4(s),$$

2. Precise Energy/Momentum Scale corrections

New technique used for both $\mu^+\mu^-$ and e^+e^- for both data and MC. (Ref A. Bodek et al. **Euro. Phys. J. C72, 2194 (2012)**) We use it in CDF and CMS for muons and electrons. A similar method is used in D0 for electrons.

In some cases, MC is more misaligned than data.

Step I : Remove the correlations between the scale for the two leptons by getting an initial calibration using Z events and requiring that the **mean $<1/P_T>$** of each lepton in bins of η, Φ and charge be correct.

Step II: The Z mass used as a reference scale. The Z mass as a function of η, Φ, (and charge for $\mu^+\mu^-$) of each lepton be correct (done in bins of η, Φ).

- **Reference scale for muons:** The expected Z mass (post FSR) smeared by resolution (with acceptance cuts). (in CMS J/Ψ and ϒ are also used for tuning dE/dx). ---**yield true momentum**
- **Reference scale for electrons (used at D0):** PDG Z mass †

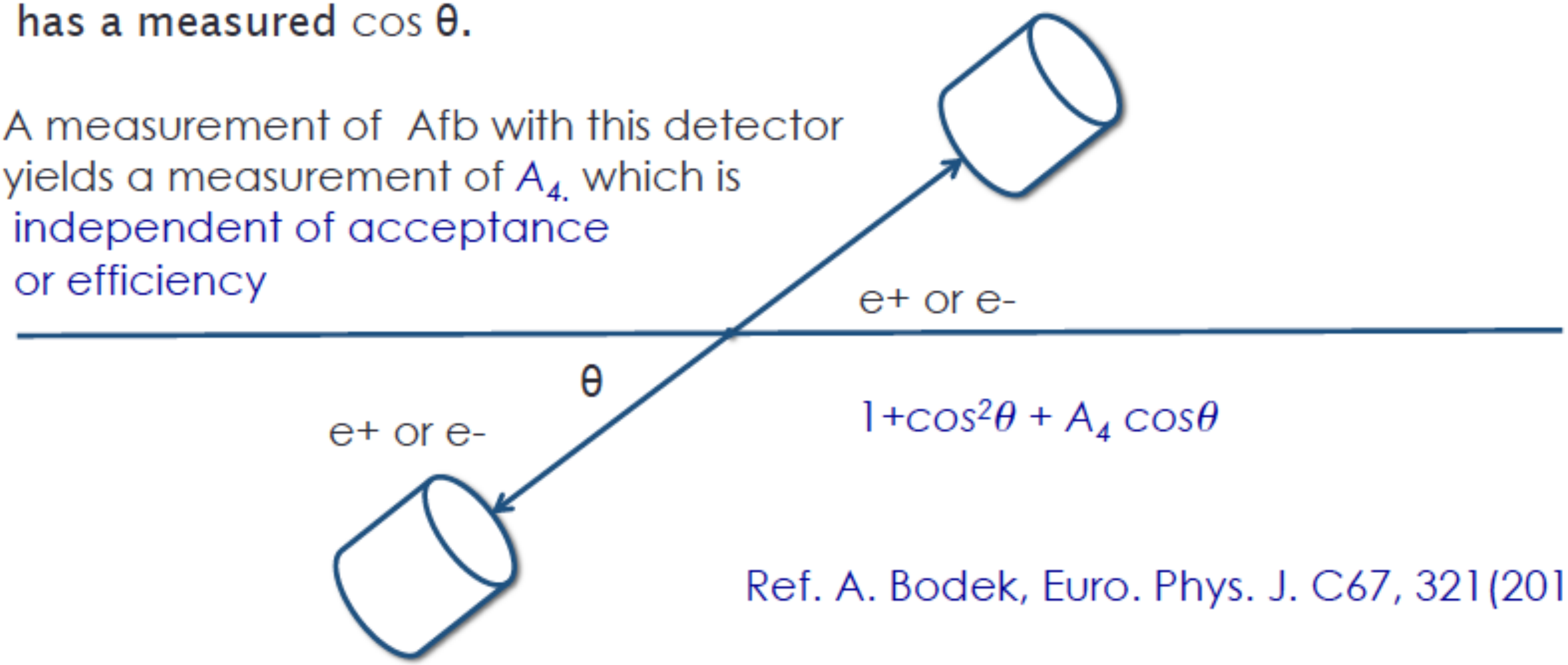
Usually, both data and MC are misaligned (or mis-calibrated for electrons) Corrections must be apply to both data and MC to agree with the Z reference scale.

† For some applications, reference choice does not matter as much as long as both data and MC use the same reference.

3. Angular event weighting method

Imagine a detector with acceptance for only one value of cos θ. **Each event has a measured** cos θ.

A measurement of Afb with this detector yields a measurement of A_4, which is independent of acceptance or efficiency



Ref. A. Bodek, Euro. Phys. J. C67, 321(2010)

cos θ=1 **yields best** measurement of A_4. cos θ=0 **yields no measurement of** A_4

We can combine measurements of A_4 with different detectors at different values of θ by weighting events. Events with cos θ=0 **have zero weight.** Events with cos θ=1 **have maximum weight. → obtain smaller statistical error.**

Afb (all cos θ) **= (3/8)** A_4 **→ No acceptance corrections needed.**

3. Angular event weighting method: Summary

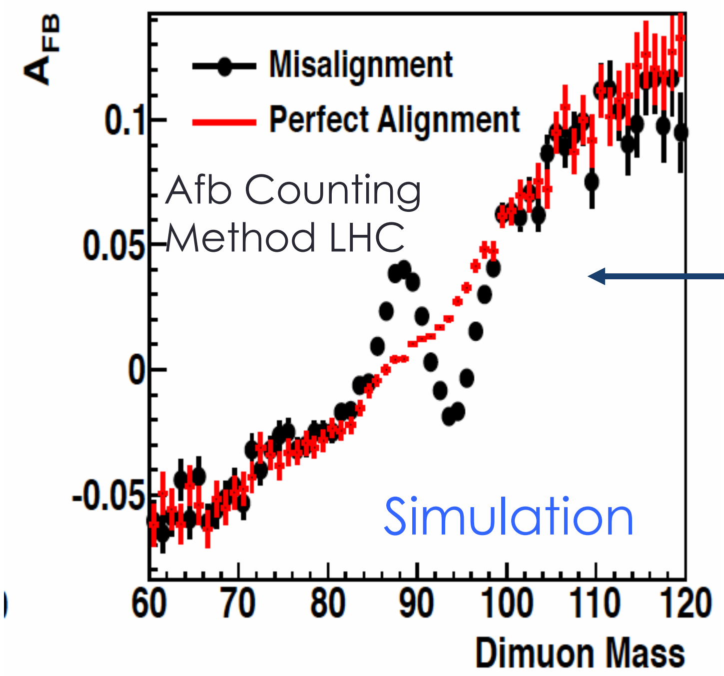
Angular event weighting method for A_{FB} analyses

Ref. A. Bodek, Euro. Phys. J. C67, 321(2010)

$$dN/d\cos\theta = 1+\cos^2\theta + A_0(M,P_T)\,(1-3\cos^2\theta)/2 + A_4(M, P_T)\cos\theta$$

- Angular event weighting is equivalent to extraction of $A_4(M)$ in bins of cos θ, and averaging the results.
- Events at large cosθ provide better determination of A4, so they are weighted more than events at small cosθ.
- For each cosθ acceptance and efficiencies cancel to first order. The resulting statistical errors are 20% smaller. A_{fb} (all cosθ)=(3/8) $A_4(M)$. A_{fb} (all cosθ) is effectively the fully acceptance corrected asymmetry.
- Since cosθ=0 events do not contribute, method is no sensitive to miscalibrations

Muon scale corrections and Event weighting



- For standard Afb analysis. Misalignments flip Afb for events near cosθ=0 and shift their mass, causing wiggles in Afb vs mass.

  Scale corrections
  Bodek et al. Euro. Phys. J. C72, 2194 (2012))

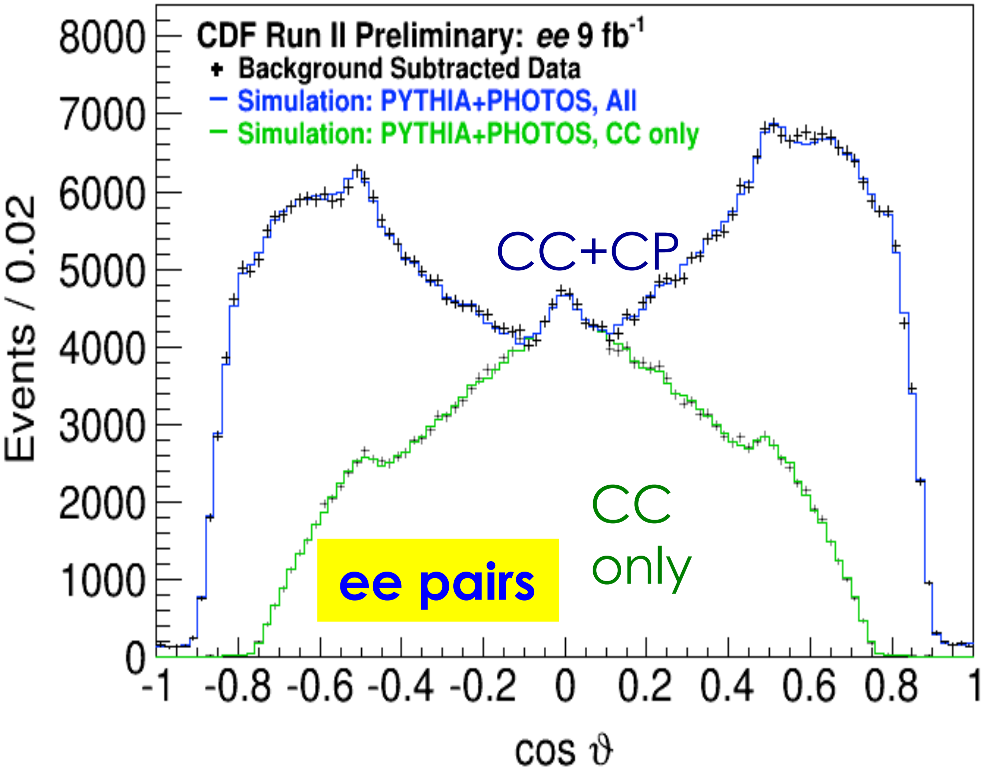
- Since events near cosθ=0 do no contribute to event weighting, the event weighting method is not as sensitive to misalignments.

  Event weighting method for A_{FB} analyses
  A. Bodek, Euro. Phys. J. C67, 321(2010)

- *Angular event weighting does not correct for resolution smearing and final state radiation, which are included later in the unfolding.*

- *Angular event weighting does not correct for the dependence of A_{fb} on rapidity. Rapidity dependence can be taken care of by using rapidity weighting, or binning in rapidity, or by using a MC bias correction. In CDF it is small so we use MC bias correction.*
  (At the LHC, we need to use bins in rapidity).

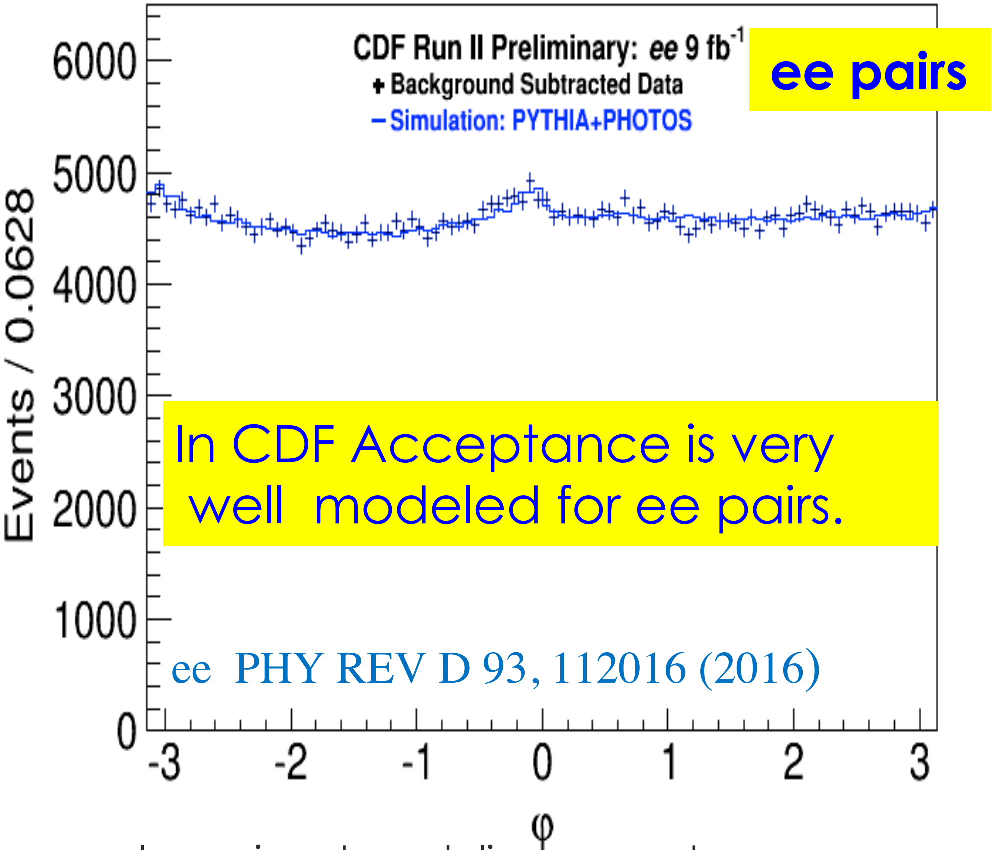
CDF electron θ and φ distributions in Collins-Soper frame



CC+CP

CC only

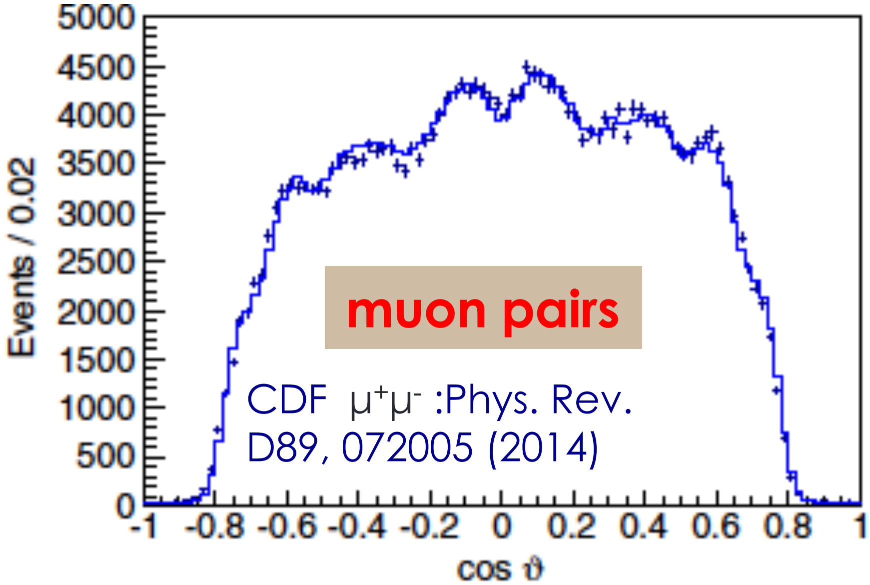
ee pairs



ee pairs

In CDF Acceptance is very well modeled for ee pairs.

ee PHY REV D 93, 112016 (2016)



muon pairs

CDF $\mu^+\mu^-$:Phys. Rev. D89, 072005 (2014)

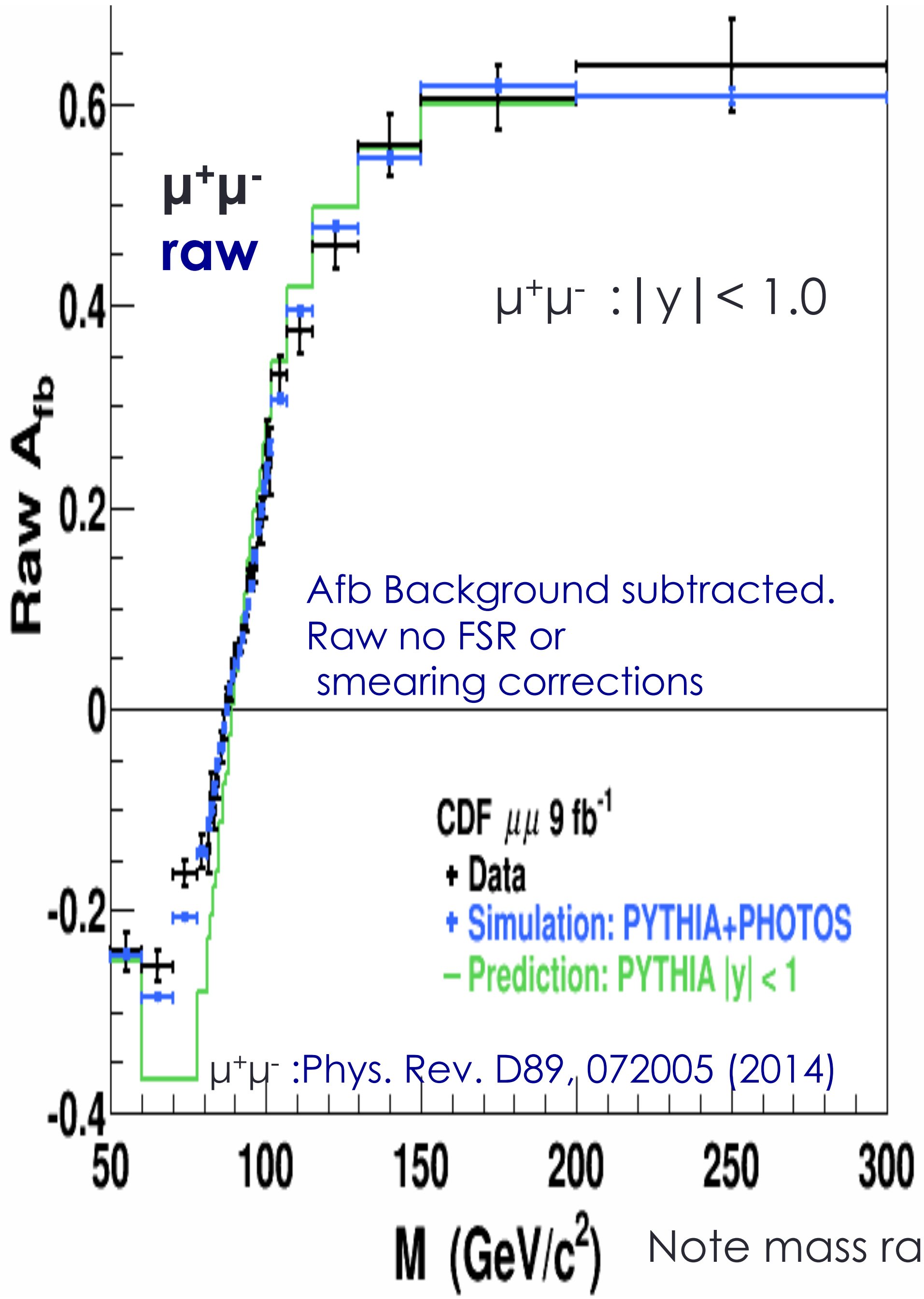
In general we aim at modeling acceptance +eff very well AND use event weighting

In CDF muon detectors have many components, so it is more difficult to model Acceptance for **muon pairs.**

Here we Must use event weighting.

CDF Raw Afb CDF $\mu^+\mu^-$ and e^+e^-

http://www-cdf.fnal.gov/physics/ewk/2015/zAfb9ee/



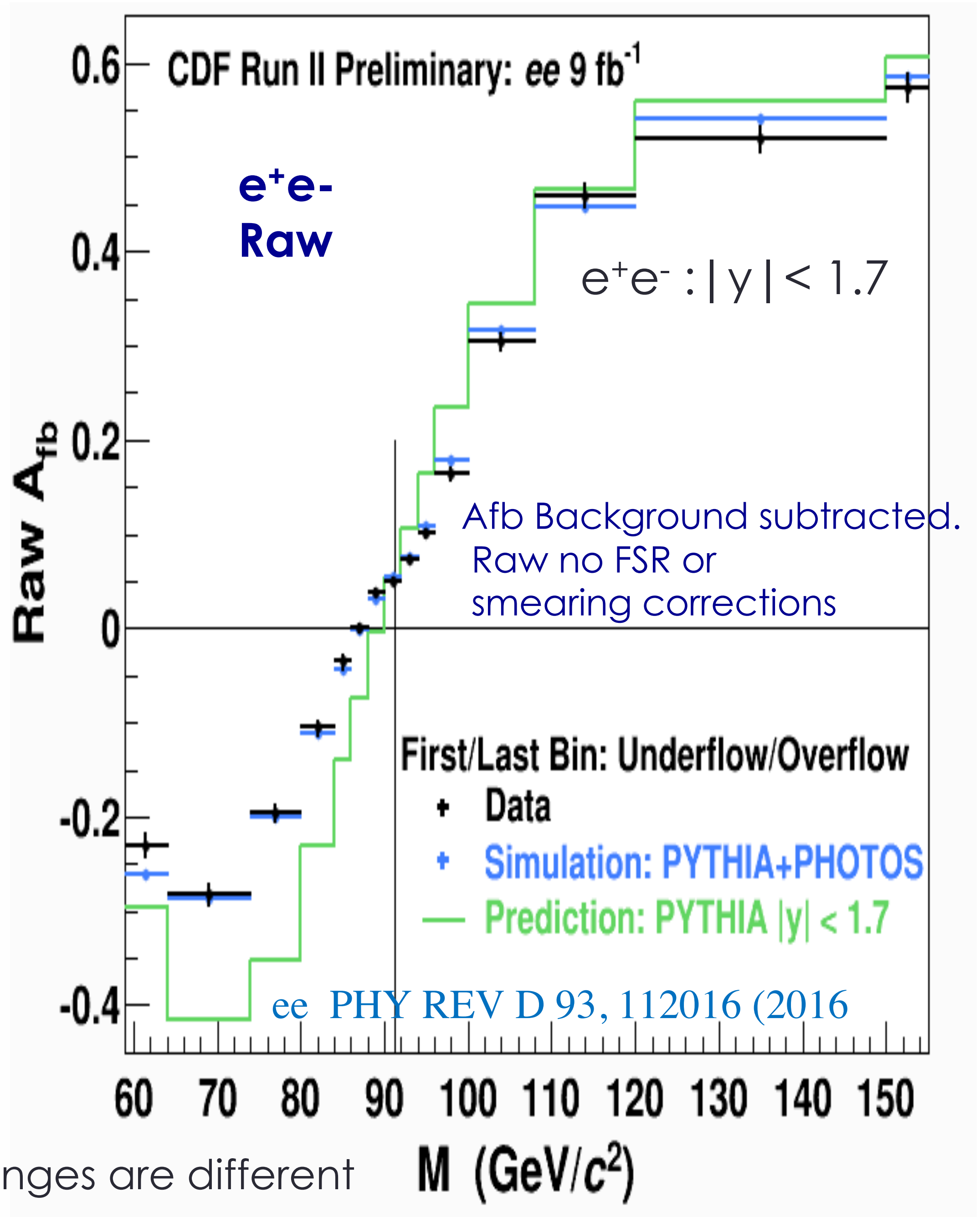
$\mu^+\mu^-$ raw

$\mu^+\mu^-$: |y| < 1.0

Afb Background subtracted.
Raw no FSR or
smearing corrections

$\mu^+\mu^-$:Phys. Rev. D89, 072005 (2014)

Note mass ranges are different



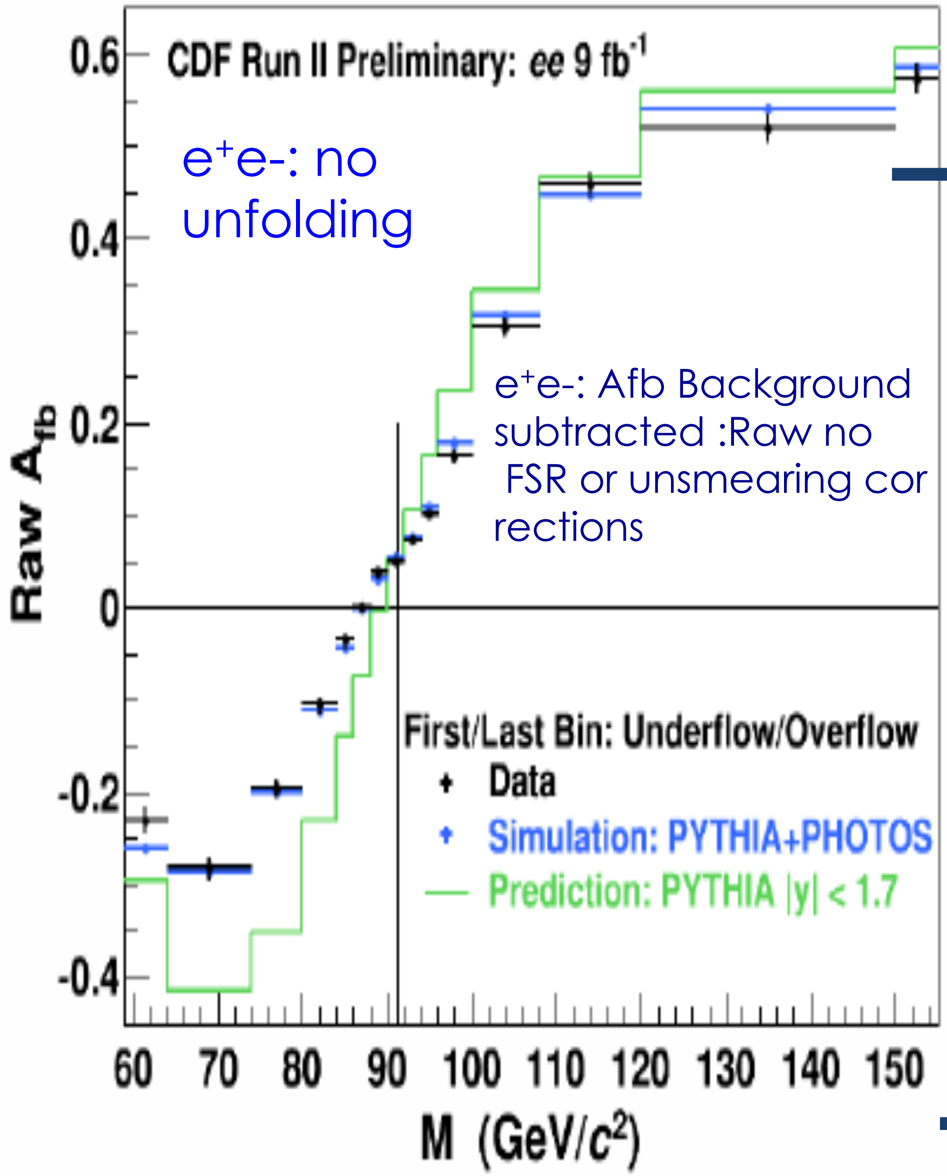
e^+e^- Raw

e^+e^- : |y| < 1.7

Afb Background subtracted.
Raw no FSR or
smearing corrections

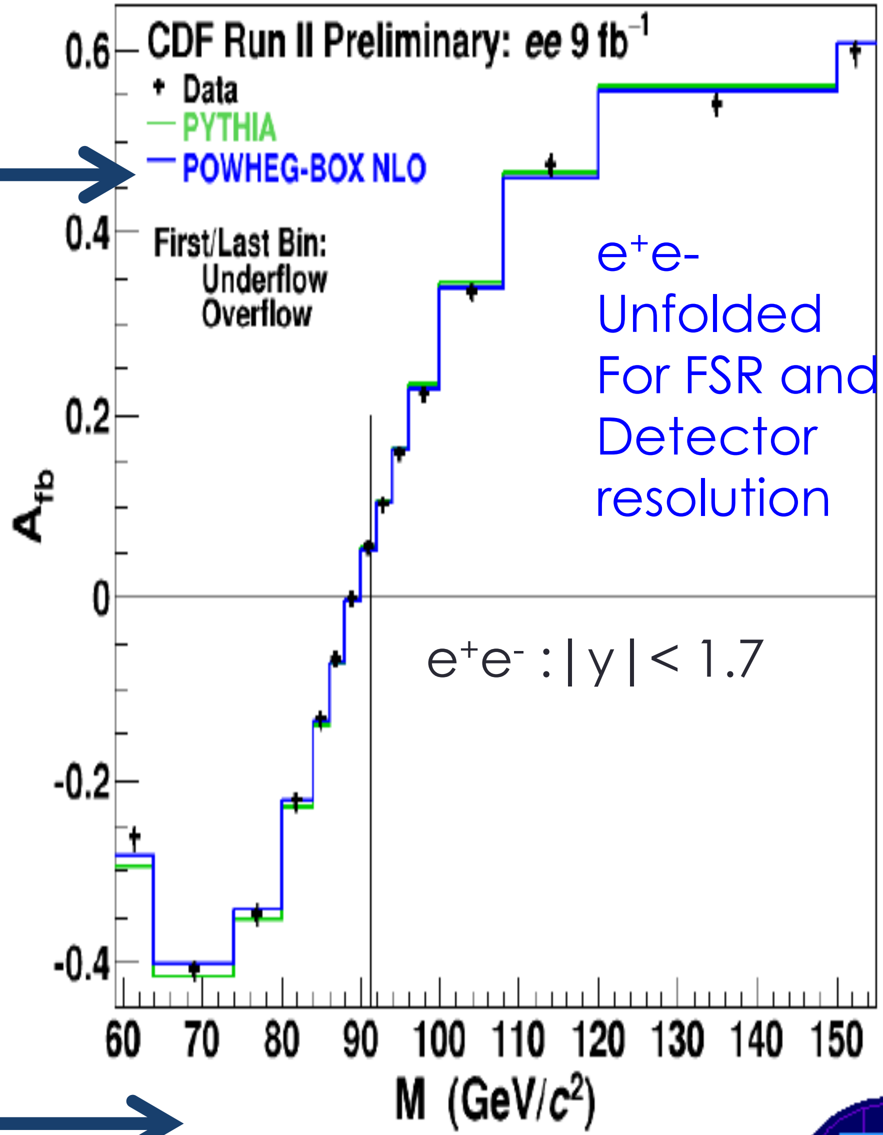
ee PHY REV D 93, 112016 (2016

CDF e^+e-: unfolding for Resolution and FSR



e^+e-: no unfolding

e^+e-: Afb Background subtracted :Raw no FSR or unsmearing corrections



e^+e- Unfolded For FSR and Detector resolution

e^+e^- : |y| < 1.7

In principle, unfolding is not needed in this analysis. However it is needed if in the future, a theorist wants to do a NNLO analysis.

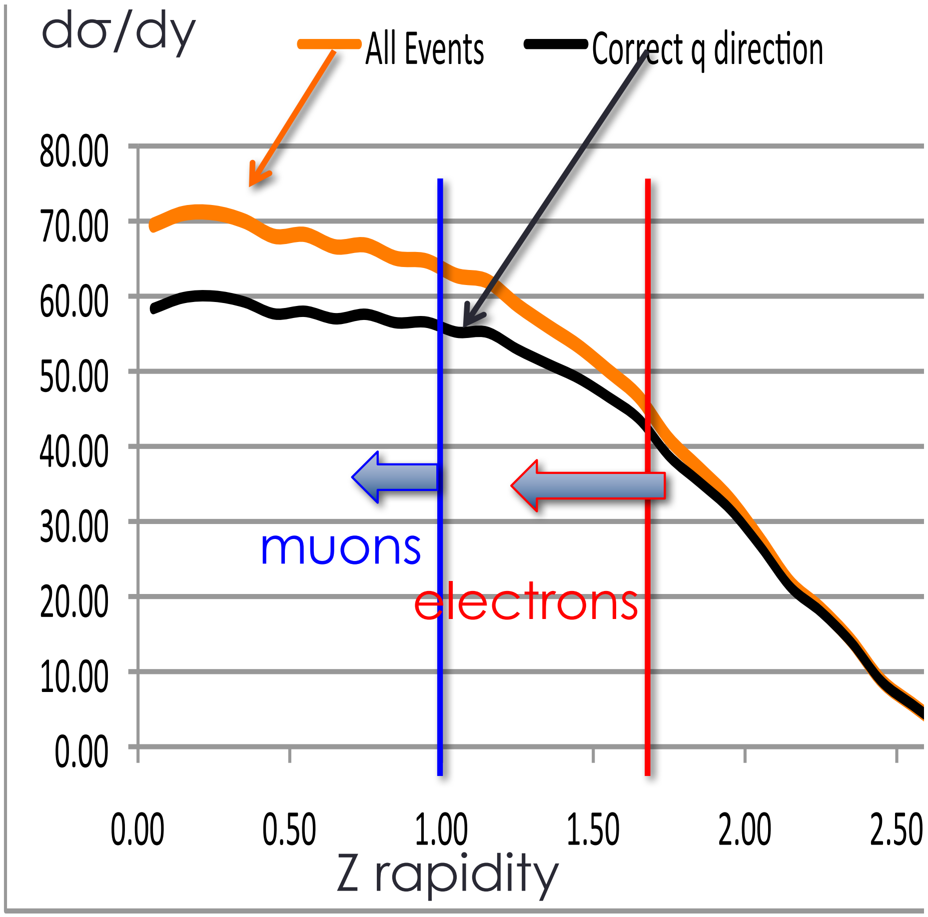
e^+e- Afb: Afb unfolded fully corrected for FSR and Detector resolution

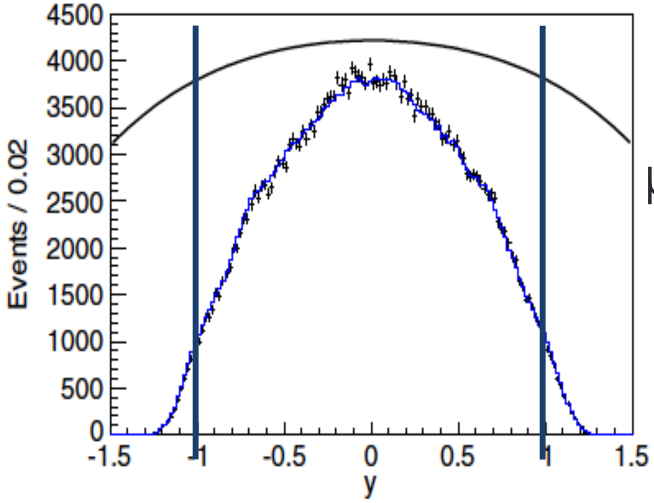
CDF ee PHY REV D 93, 112016 (2016

Rapidity dependence of antiquark dilution

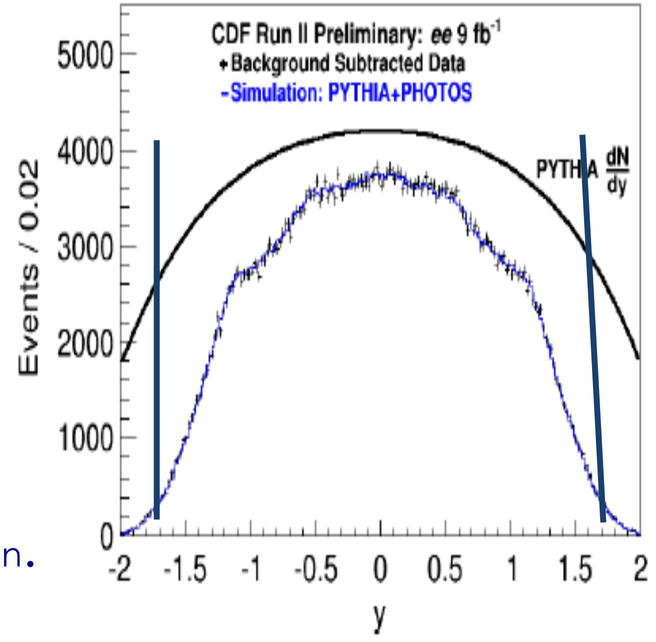
The measured Afb depend on the coverage in rapidity. This comes from the fraction of events where antiquarks in the proton interact with quarks in the antiproton.

A small dilution effect depends on the antiquark distributions and the rapidity range of the data





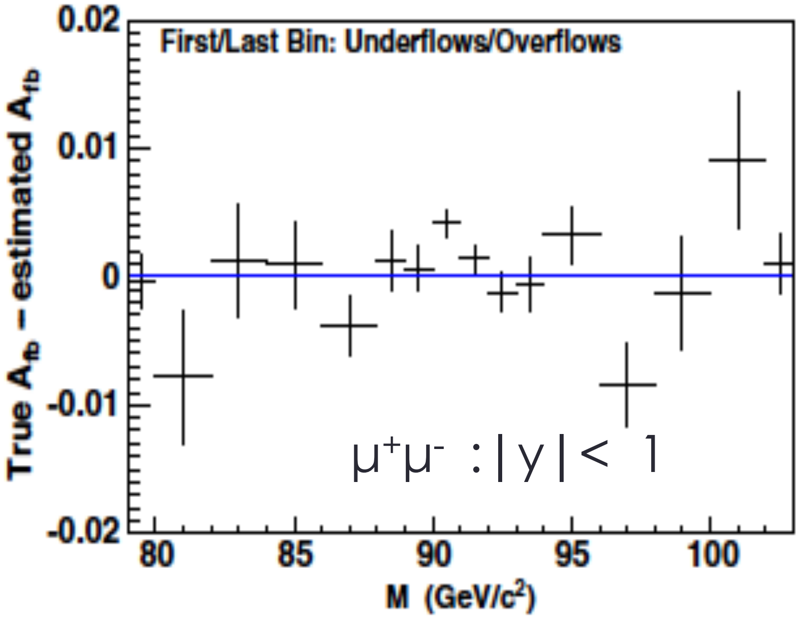
$\mu^+\mu^-$: require |y|< 1

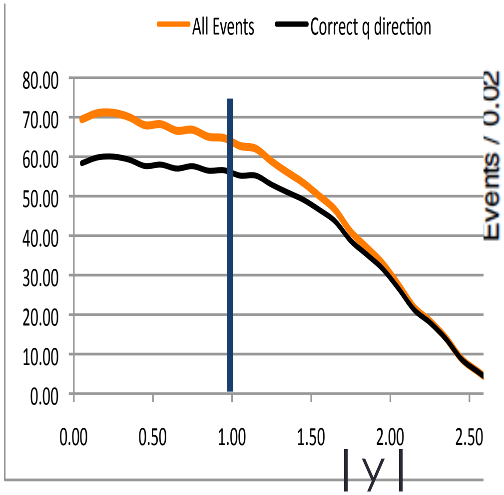


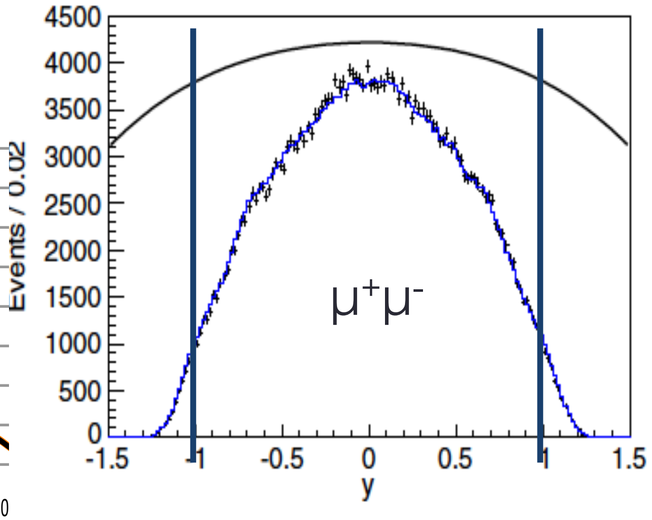
e^+e^- : require |y|< 1.7

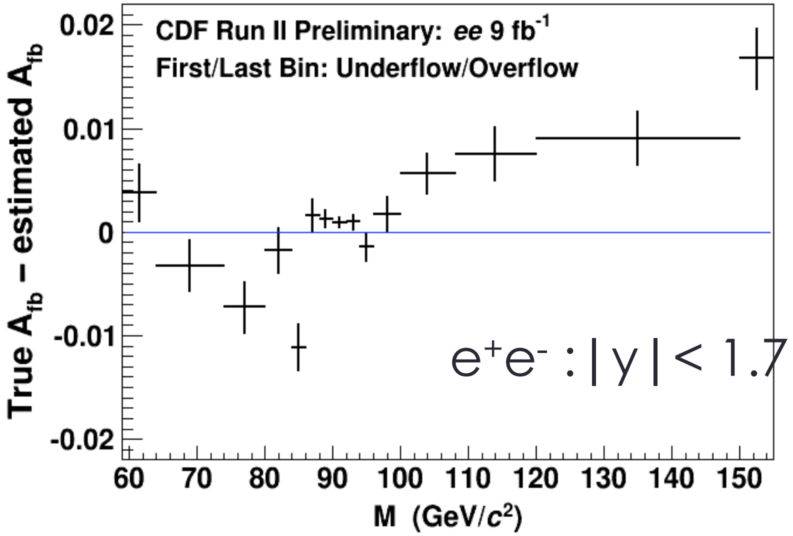
For y<1 very little y dependence of dilution. Small Bias correction.

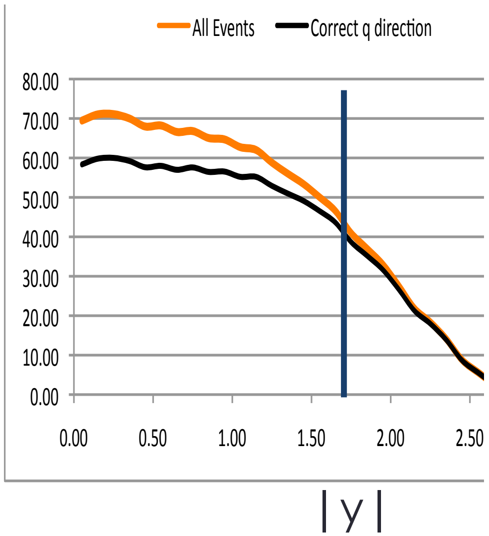
CDF Bias correction (mostly for dilution)

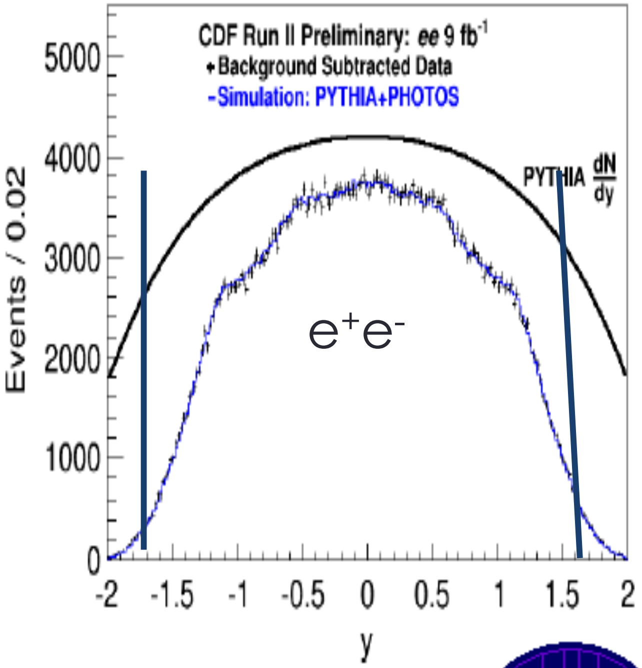












Compare MC input Afb(M) to fully reconstructed and unfolded MC.

This bias correction – corrects for all 2nd order effects mostly rapidity coverage.

At LHC rapidity depencence is large and we must use rapidity bins instead.

CDF $\sin^2\theta_W$ extraction using templates

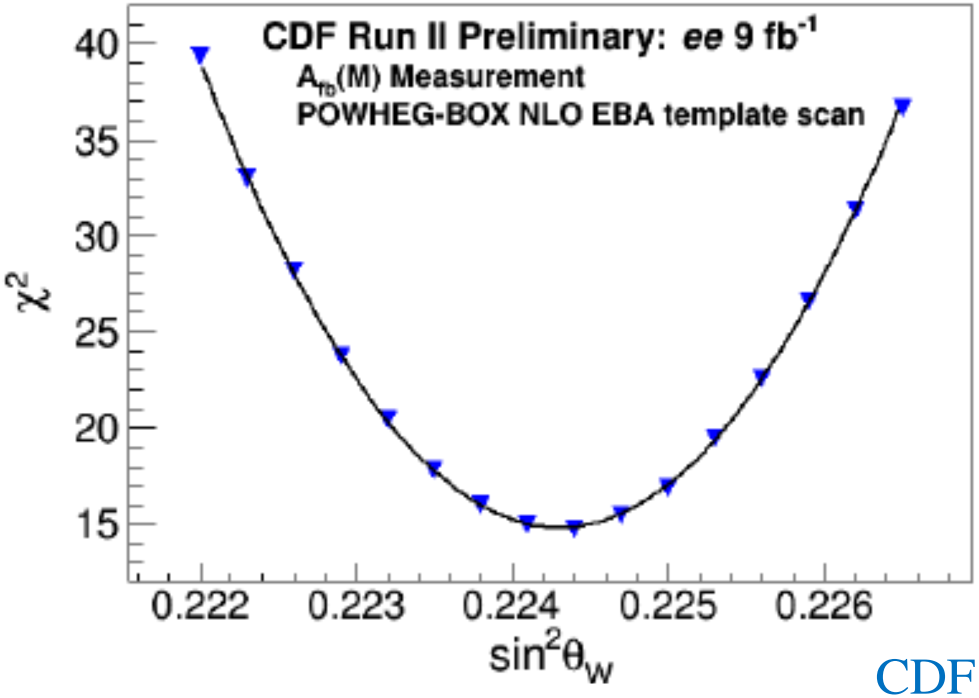
Comparisons of A_{fb} Measurement to Calculations

- Comparison χ^2: $\Sigma_M \, \Delta A_{fb}(M)^{\sim} \bullet E \bullet \Delta A_{fb}(M)$
  - Measurement: Fully corrected $A_{fb}(M)$
  - Calculated templates: $A_{fb}(M, \sin^2\theta_W)$ for 16 values of $\sin^2\theta_W$
  - E: Measurement error matrix

Example $\sin^2\theta_W$ template scan using data

– Afb template: Powheg-Box NLO + default PDF of NNPDF 3.0 (261000)

– Fit of scan points to a parabola: $\chi^2_{min} + (\sin^2\theta_W - \sin^2\theta_{W\,min})^2/\sigma_{min}^2$



This analysis is repeated with1. POWEG 2. RESBPOS
3. Tree-Level LO

For the POWHEG analysis, the extraction is repeated 100 times for all 100 NNPDF3.0 replicas to get PDF error
.

CDF ee PHY REV D 93, 112016 (2016)

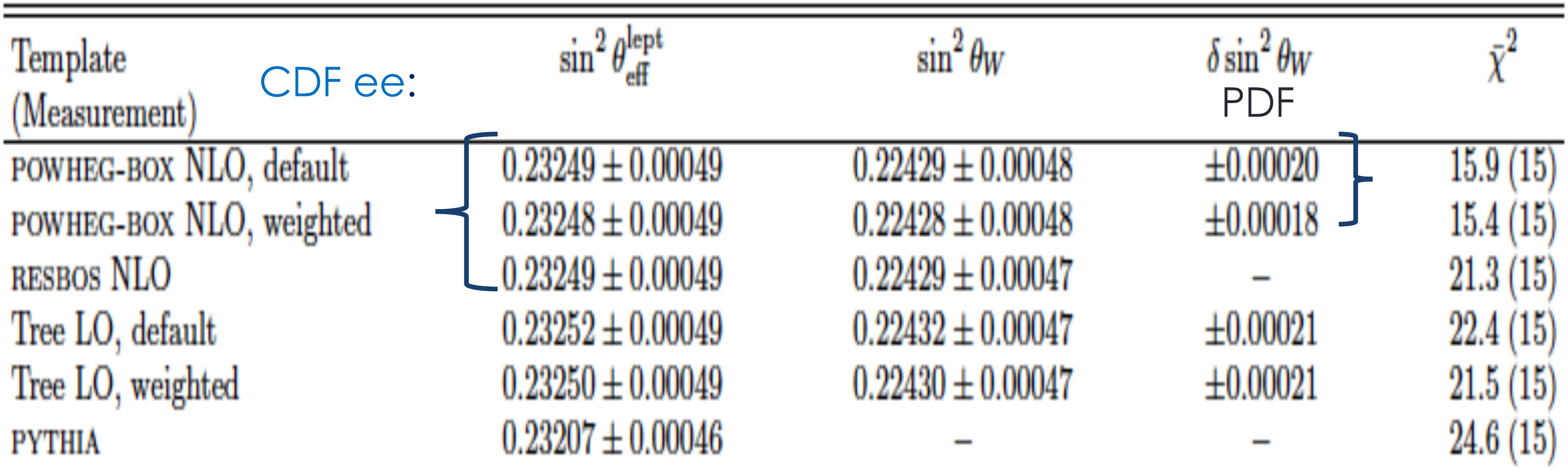
CDF e^+e $\sin^2\theta_{\rm eff}$ and $\sin^2\theta_W$ results

e+e- data only

Phys. Rev. D93, 112016 (2016)

PDF Weighted= *reduced pdf error discussed later in talk*

CDF ee:



Template (Measurement)	$\sin^2\theta_{\rm eff}^{\rm lept}$	$\sin^2\theta_W$	$\delta\sin^2\theta_W$ PDF	$\bar{\chi}^2$
POWHEG-BOX NLO, default	0.23249 ± 0.00049	0.22429 ± 0.00048	± 0.00020	15.9 (15)
POWHEG-BOX NLO, weighted	0.23248 ± 0.00049	0.22428 ± 0.00048	± 0.00018	15.4 (15)
RESBOS NLO	0.23249 ± 0.00049	0.22429 ± 0.00047	–	21.3 (15)
Tree LO, default	0.23252 ± 0.00049	0.22432 ± 0.00047	± 0.00021	22.4 (15)
Tree LO, weighted	0.23250 ± 0.00049	0.22430 ± 0.00047	± 0.00021	21.5 (15)
PYTHIA	0.23207 ± 0.00046	–	–	24.6 (15)

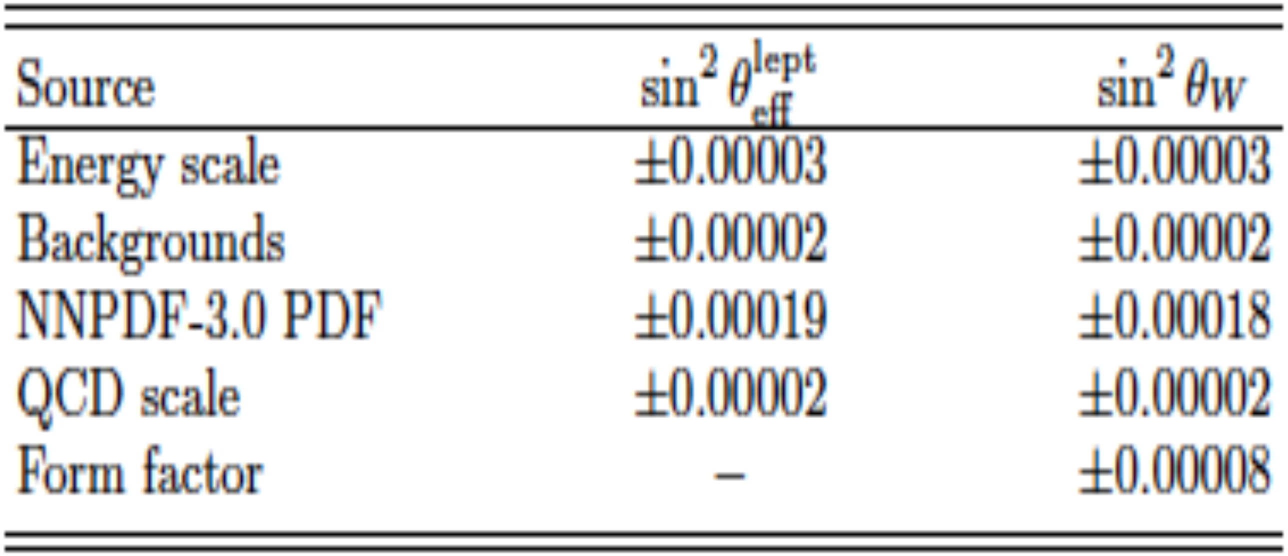
The statistical error of 0.00049 (e+e- data only) dominates

QCD order diference: **(NLO - LO)** =+- 0.00002

QCD scale error **(vary running scales x2, and 0.5)** = +-0.00003
(renormalization/factorization scale)

CDF e^+e only $\sin^2\theta_{eff}$ and $\sin^2\theta_W$ errors

e+e- data only : Systematic errors-



Source	$\sin^2\theta^{\text{lept}}_{\text{eff}}$	$\sin^2\theta_W$
Energy scale	±0.00003	±0.00003
Backgrounds	±0.00002	±0.00002
NNPDF-3.0 PDF	±0.00019	±0.00018
QCD scale	±0.00002	±0.00002
Form factor	–	±0.00008

"PDFs constrained"

Phys. Rev. D93, 112016 (2016)

CDF ee:

$$\sin^2\theta^{\text{lept}}_{\text{eff}} = 0.23248 \pm 0.00049 \pm 0.00019$$

$$\sin^2\theta_W = 0.22428 \pm 0.00048 \pm 0.00020$$

$$M_W \text{ (indirect)} = 80.313 \pm 0.025 \pm 0.010 \text{ GeV}/c^2$$

The " PDF constrained" errors Include constraints from Afb data (described later in this talk).

The statistical error of 0.00048 dominates

The experimental systematic error of 0.00005 is negligible

Next: Combine with muon data

CDF combination: electron and muon errors

The Afb measurements using ee-pairs and μμ-pairs which are over different kinematic ranges: $|y_{ee}| < 1.7$ and $|y_{\mu\mu}| < 1$.

For the combined result on $\sin^2\theta_W$ Afb templates are calculated separately, and the joint χ2 of the individual comparisons used to extract $\sin^2\theta_W$

The combination values for $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ and $\sin^2\theta_W$ (M_W) are

CDF ee+ μμ: $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} = 0.23221 \pm 0.00043 \pm 0.00018$ 0.2322±0.00046

$$\sin^2\theta_W = 0.22400 \pm 0.00041 \pm 0.00019$$

$$M_W\ (\mathrm{indirect}) = 80.328 \pm 0.021 \pm 0.010\ \mathrm{GeV}/c^2,$$ 80.328±0.024

PHY REV D 93, 112016 (2016)

The systematic error is dominated by 0.00016 PDF uncertainties (reduced from 0.00020)
The PDF errors include constraints from Afb data (described in later in the slides that follow).

CDF combining electron and muon results

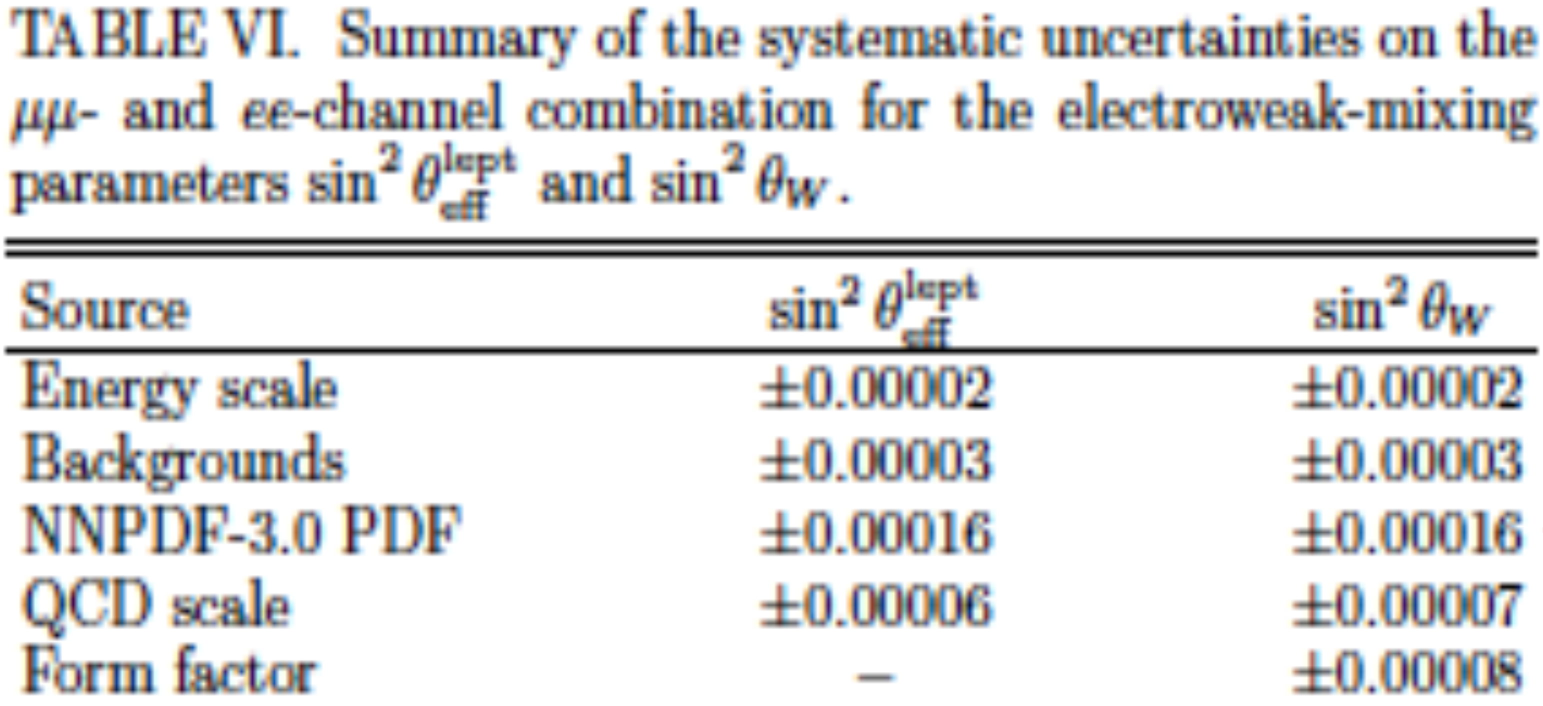


TABLE VI. Summary of the systematic uncertainties on the $\mu\mu$- and ee-channel combination for the electroweak-mixing parameters $\sin^2\theta^{\rm lept}_{\rm eff}$ and $\sin^2\theta_W$.

Source	$\sin^2\theta^{\rm lept}_{\rm eff}$	$\sin^2\theta_W$
Energy scale	±0.00002	±0.00002
Backgrounds	±0.00003	±0.00003
NNPDF-3.0 PDF	±0.00016	±0.00016
QCD scale	±0.00006	±0.00007
Form factor	–	±0.00008

“PDF constrained

CDF ee+ μμ:

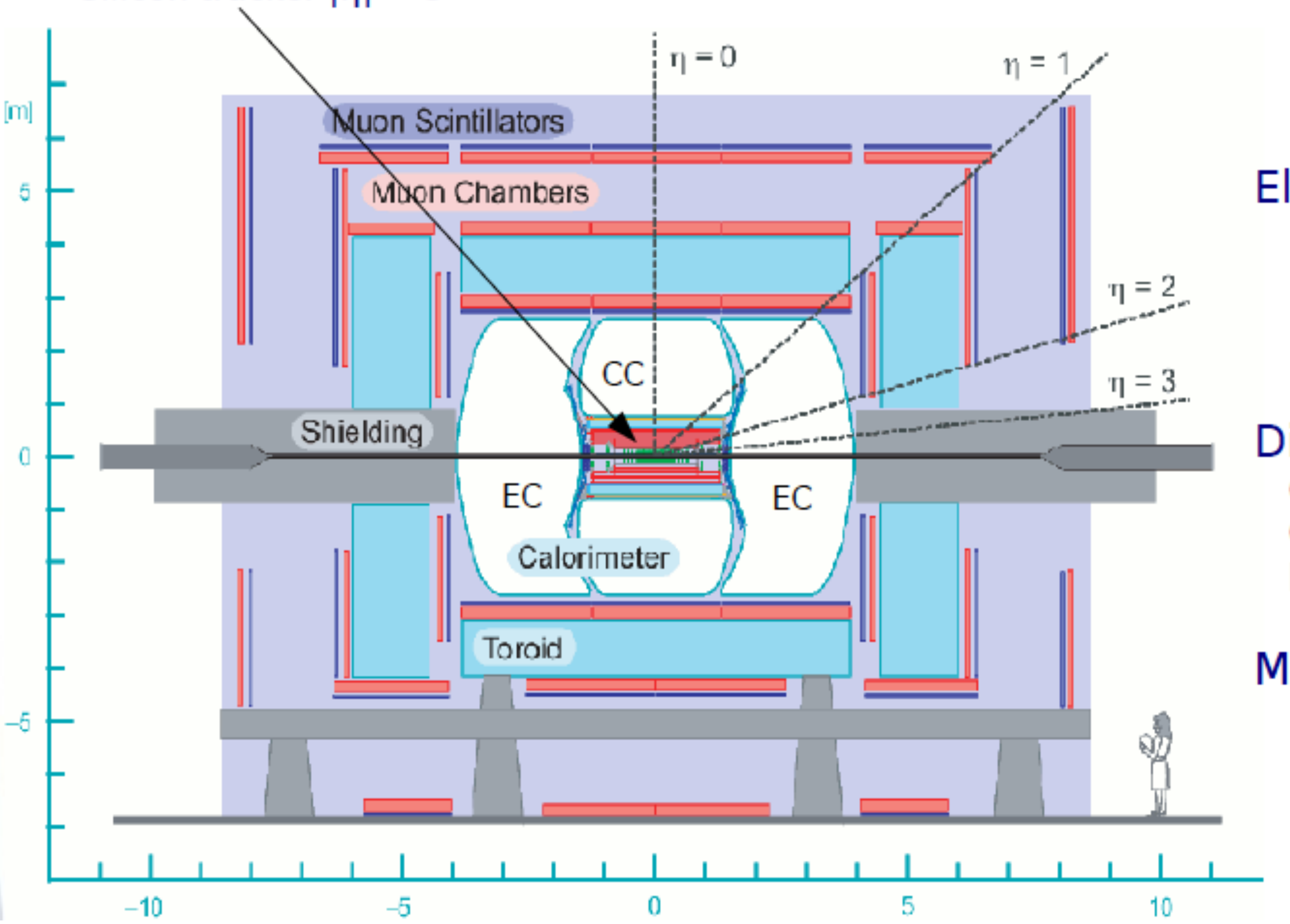
The combined statistical error of 0.00043 dominates
The experimental systematic error of 0.00005 is negligible

The largest systematic is the
“constrained” 0.00016 PDF error (reduced from 0.00020)

The “PDF constrained” errors include constraints from Afb data (described later in this talk).

D0 A_{fb} dataset selection

Precision tracking
Solenoid field 1.9 T
Fiber tracker $|\eta| < 2$
Silicon tracker $|\eta| < 3$



D0: ee

Electrons: CC + EC
$P_T > 25$ GeV/c
CC: $|\eta| < 1.1$
EC: $1.5 < |\eta| < 3.2$

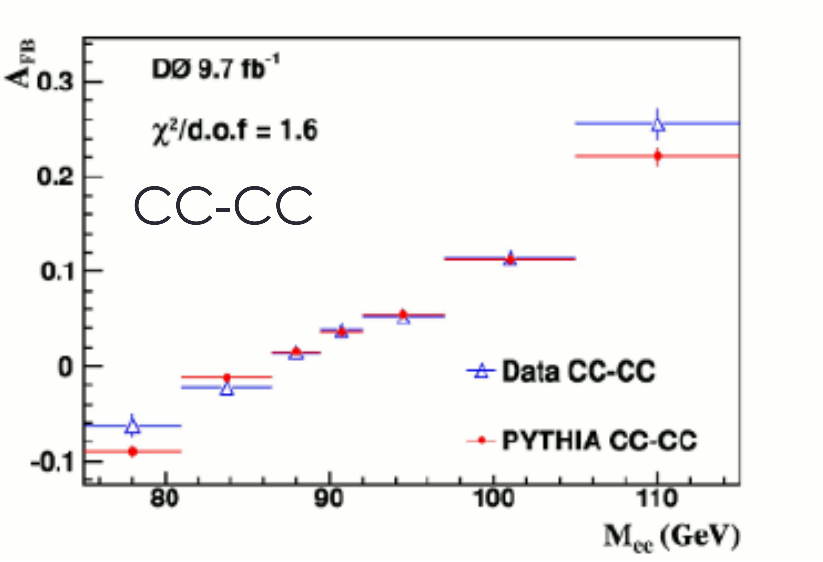
Dielectrons
CC-CC: 248K events
CC-EC: 241K events
EC-EC: 71K events

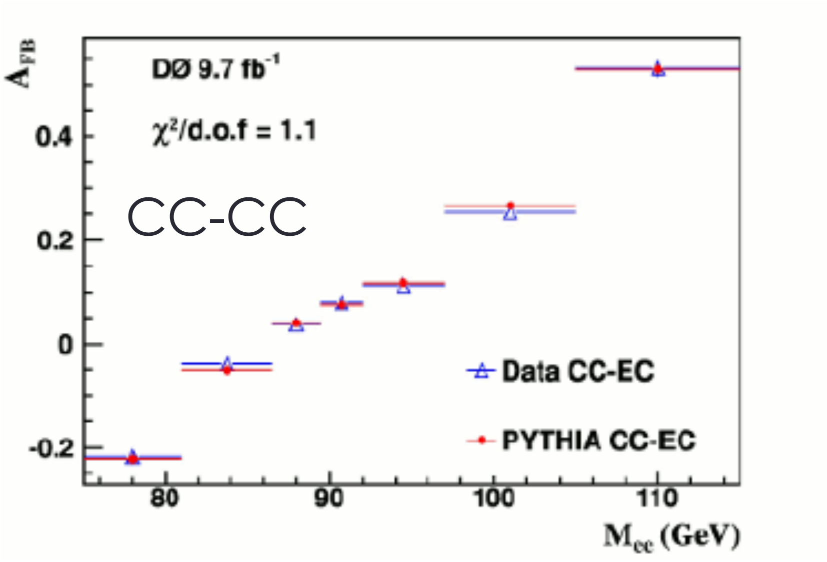
Muon analysis:
in progress

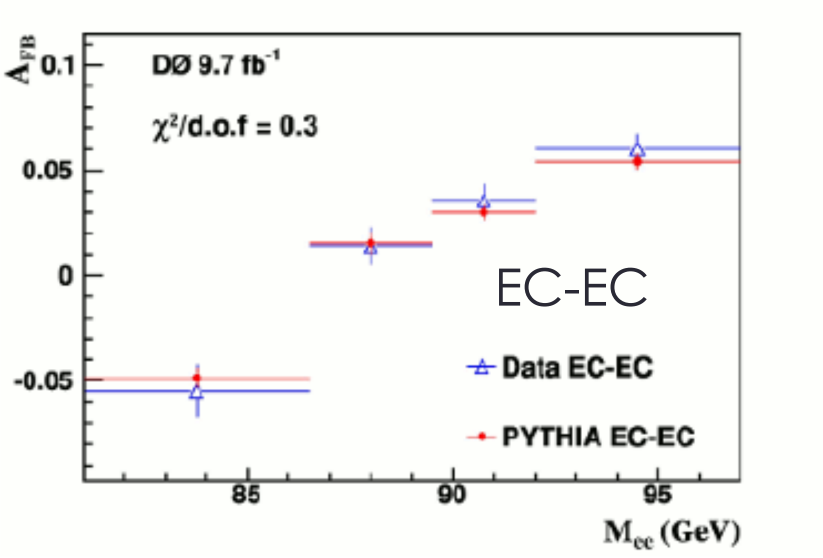
D0 ee analysis

D0: ee A_{fb} measurements

PRL 115, 041801 (2015), PRD 84, 012007 (2011)





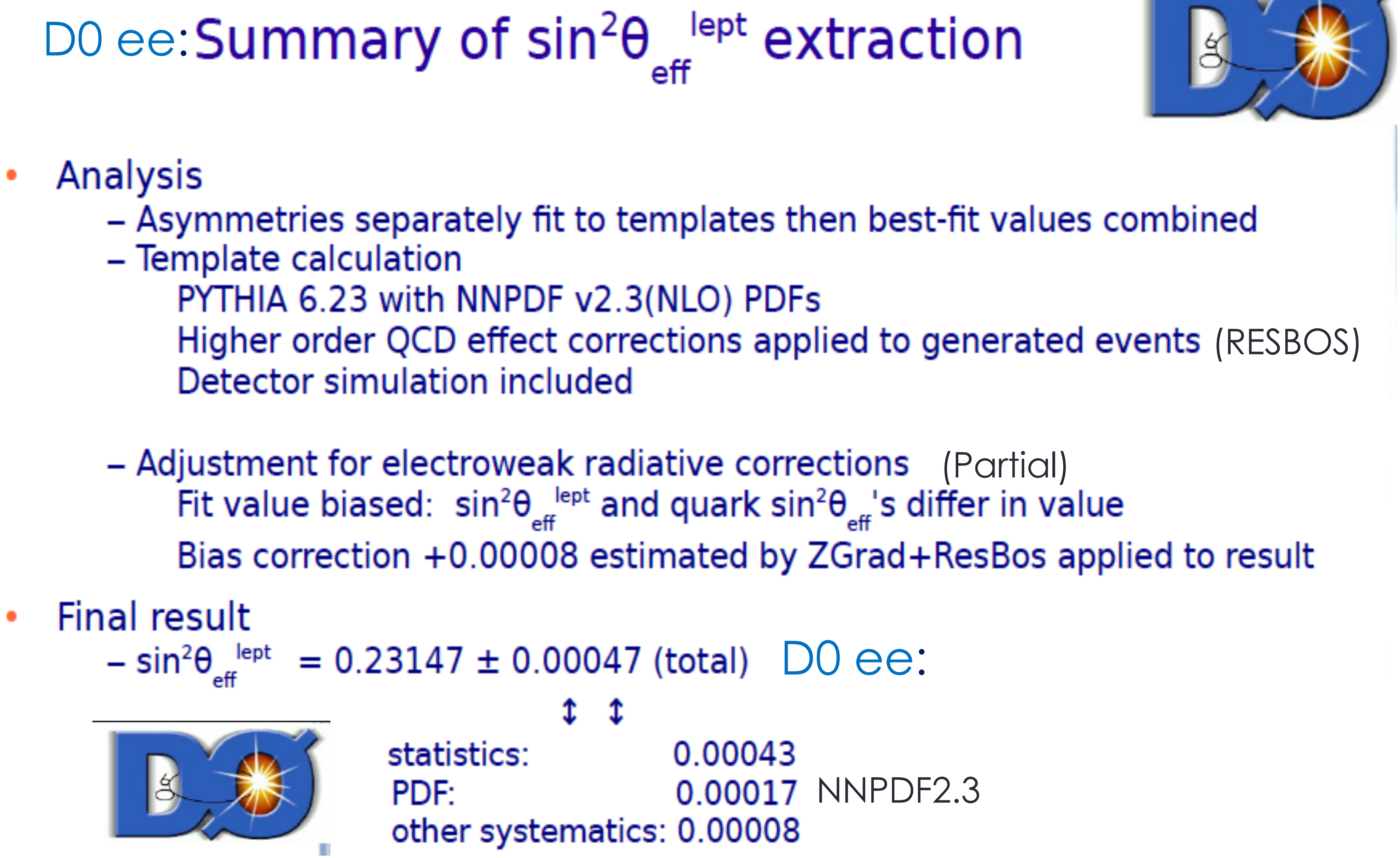


Inputs:

- A_{fb} measurement
- templates (PYTHIA)
  include detector simulation,
  varying values of $\sin^2\theta_{eff}^{lept}$

Fit A_{fb} to templates for best-fit $\sin^2\theta_{eff}^{lept}$

D0 ee analysis



D0 ee: Summary of $\sin^2\theta_{\text{eff}}^{\text{lept}}$ extraction

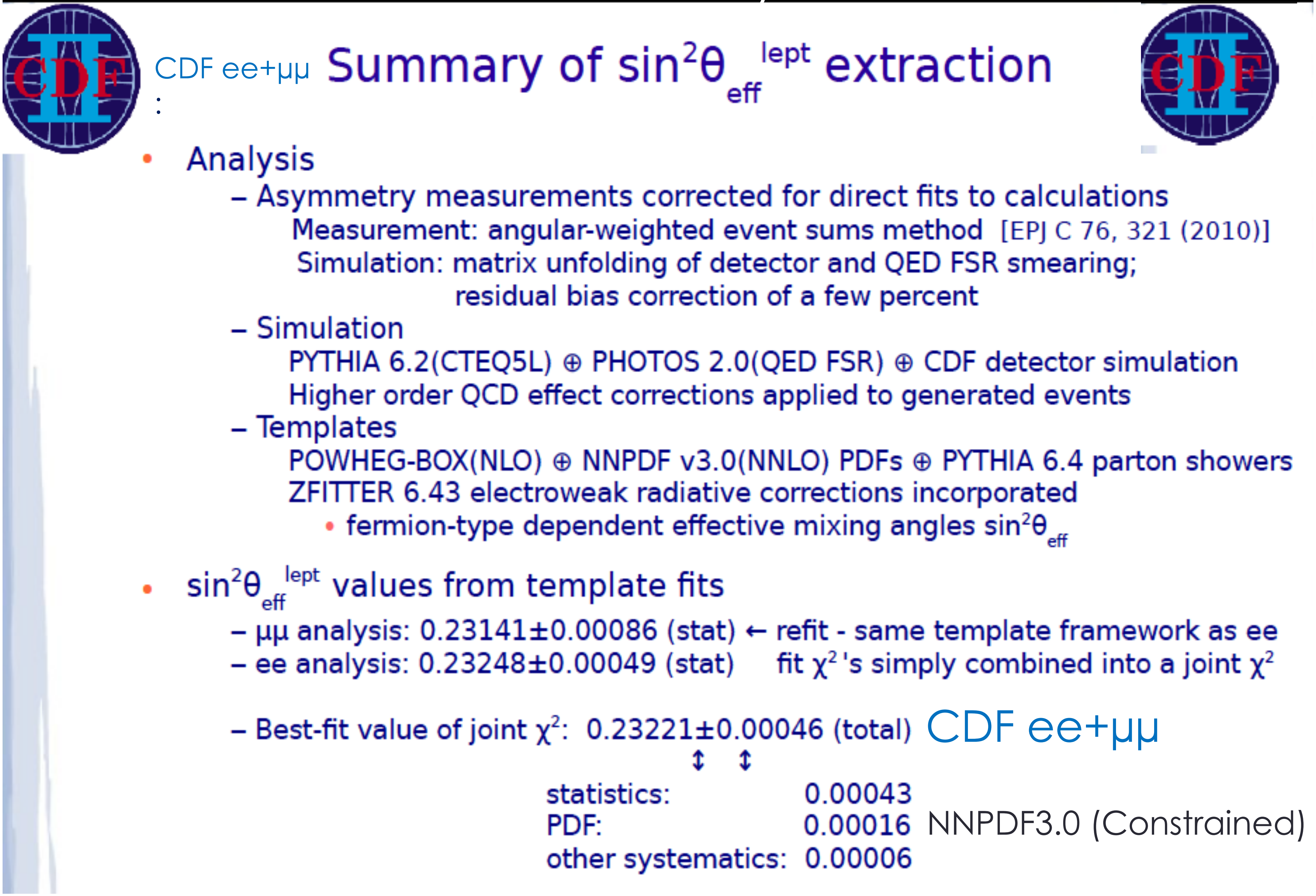
- Analysis
  - Asymmetries separately fit to templates then best-fit values combined
  - Template calculation
    PYTHIA 6.23 with NNPDF v2.3(NLO) PDFs
    Higher order QCD effect corrections applied to generated events (RESBOS)
    Detector simulation included
  - Adjustment for electroweak radiative corrections (Partial)
    Fit value biased: $\sin^2\theta_{\text{eff}}^{\text{lept}}$ and quark $\sin^2\theta_{\text{eff}}$'s differ in value
    Bias correction +0.00008 estimated by ZGrad+ResBos applied to result
- Final result
  - $\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23147 \pm 0.00047$ (total) D0 ee:

↕ ↕

statistics:	0.00043	
PDF:	0.00017	NNPDF2.3
other systematics:	0.00008	

CDF analysis - 1

CDF ee+μμ :



Summary of $\sin^2\theta_{eff}^{lept}$ extraction

- Analysis
  - Asymmetry measurements corrected for direct fits to calculations
    Measurement: angular-weighted event sums method [EPJ C 76, 321 (2010)]
    Simulation: matrix unfolding of detector and QED FSR smearing;
    residual bias correction of a few percent
  - Simulation
    PYTHIA 6.2(CTEQ5L) ⊕ PHOTOS 2.0(QED FSR) ⊕ CDF detector simulation
    Higher order QCD effect corrections applied to generated events
  - Templates
    POWHEG-BOX(NLO) ⊕ NNPDF v3.0(NNLO) PDFs ⊕ PYTHIA 6.4 parton showers
    ZFITTER 6.43 electroweak radiative corrections incorporated
    - fermion-type dependent effective mixing angles $\sin^2\theta_{eff}$
- $\sin^2\theta_{eff}^{lept}$ values from template fits
  - μμ analysis: 0.23141±0.00086 (stat) ← refit - same template framework as ee
  - ee analysis: 0.23248±0.00049 (stat) fit χ^2's simply combined into a joint χ^2
  - Best-fit value of joint χ^2: 0.23221±0.00046 (total) CDF ee+μμ

↕ ↕

statistics:	0.00043
PDF:	0.00016
other systematics:	0.00006

NNPDF3.0 (Constrained)

Comparison D0 and CDF rad corr

Radiative correction treatments

- D0 mixing angle results: improved (Partial Zgrad)
  - PYTHIA template: single mixing angle and running α_{em}

D0 ee:
  - ZGrad+ResBos adjustment: improves accounting for differences of fermion-dependent effective mixing angles @ M_Z

(Partial) Changes by $\sin^2\theta_W$ by +0.00008

- CDF ZFITTER based results: improved even more (Full EBA)
  - Complex-valued form-factors ρ and κ for Born Z-couplings

CDF ee+μμ

$$g_V^f(\text{Born}) \rightarrow \sqrt{\rho_f}\, T_3^f(1 - 4|Q_f|\kappa_f \sin^2\theta_W)$$

$$g_A^f(\text{Born}) \rightarrow \sqrt{\rho_f}\, T_3^f$$

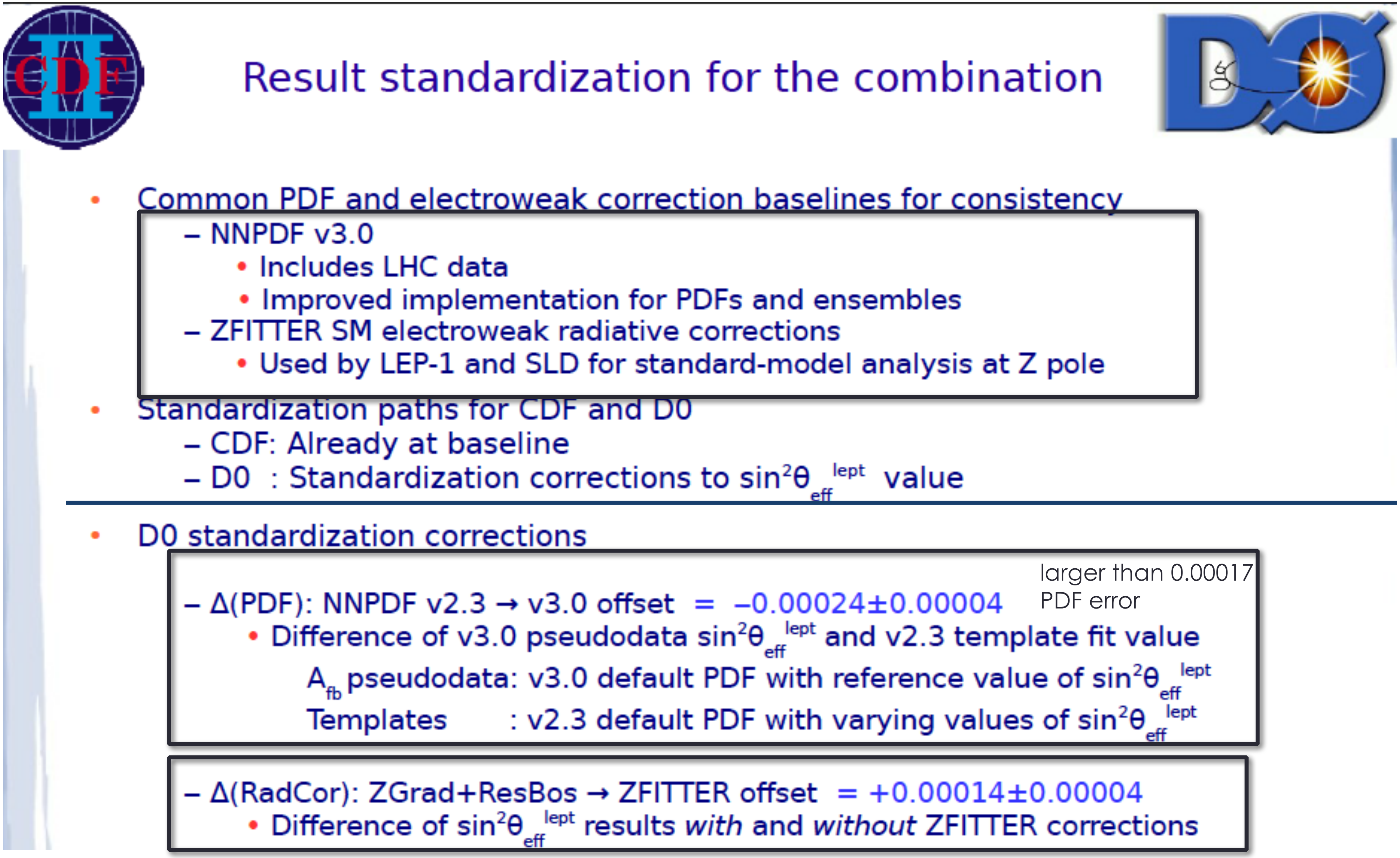
ρ_f / κ_f: functions of fermion type, M_{ll}^2, $\sin^2\theta_W$

1-4% corrections

  - Photon-propagator form factor (real part aka running α_{em})

(Full) Changes by $\sin^2\theta_W$ by + 0.00022

Combining CDF and D0



Result standardization for the combination

- Common PDF and electroweak correction baselines for consistency
  - NNPDF v3.0
    - Includes LHC data
    - Improved implementation for PDFs and ensembles
  - ZFITTER SM electroweak radiative corrections
    - Used by LEP-1 and SLD for standard-model analysis at Z pole
- Standardization paths for CDF and D0
  - CDF: Already at baseline
  - D0 : Standardization corrections to $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ value

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- D0 standardization corrections
  - Δ(PDF): NNPDF v2.3 → v3.0 offset = –0.00024±0.00004
    - Difference of v3.0 pseudodata $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ and v2.3 template fit value

      A_{fb} pseudodata: v3.0 default PDF with reference value of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$

      Templates : v2.3 default PDF with varying values of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$

larger than 0.00017
PDF error

  - Δ(RadCor): ZGrad+ResBos → ZFITTER offset = +0.00014±0.00004
    - Difference of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ results *with* and *without* ZFITTER corrections

Note full EBA rad correction changes by $\sin^2\theta_{\mathrm{eff}}$ =0.00022

Combining CDF and D0

BLUE combination of $\sin^2\theta_{eff}^{lept}$ results

- Input observable values
  - Standardized D0 value : 0.23137±0.00043 (stat) ± 0.00019 (syst) D0 ee
  - CDF ee⊕μμ value : 0.23221±0.00043 (stat) ± 0.00018 (syst) CDF ee+μμ
- Input uncertainty categories
  - Statistics: CDF: 0.00043, D0: 0.00043
  - PDF: CDF: 0.00016, D0: 0.00017 (100% correlated)
  - Other systematics: CDF: 0.00007, D0: 0.00008 (uncorrelated)
  - Standardization: D0 0.00005 (only applies to D0)
- Results of BLUE method

Combined CDF&D0

- $\sin^2\theta_{eff}^{lept}$ = 0.23179 ± 0.00030 (stat) ± 0.00017 (syst)

0.00035 (total)

- χ^2 of combination: 1.8 (18% probability)
- Uncertainties

Statistics:	0.00030
PDF:	0.00017
Other systematics:	0.00005
Standardization:	0.00003

ICHEP Aug 2016 FERMILAB-CONF-16-295-E
http://tevewwg.fnal.gov/wz/sw2eff/

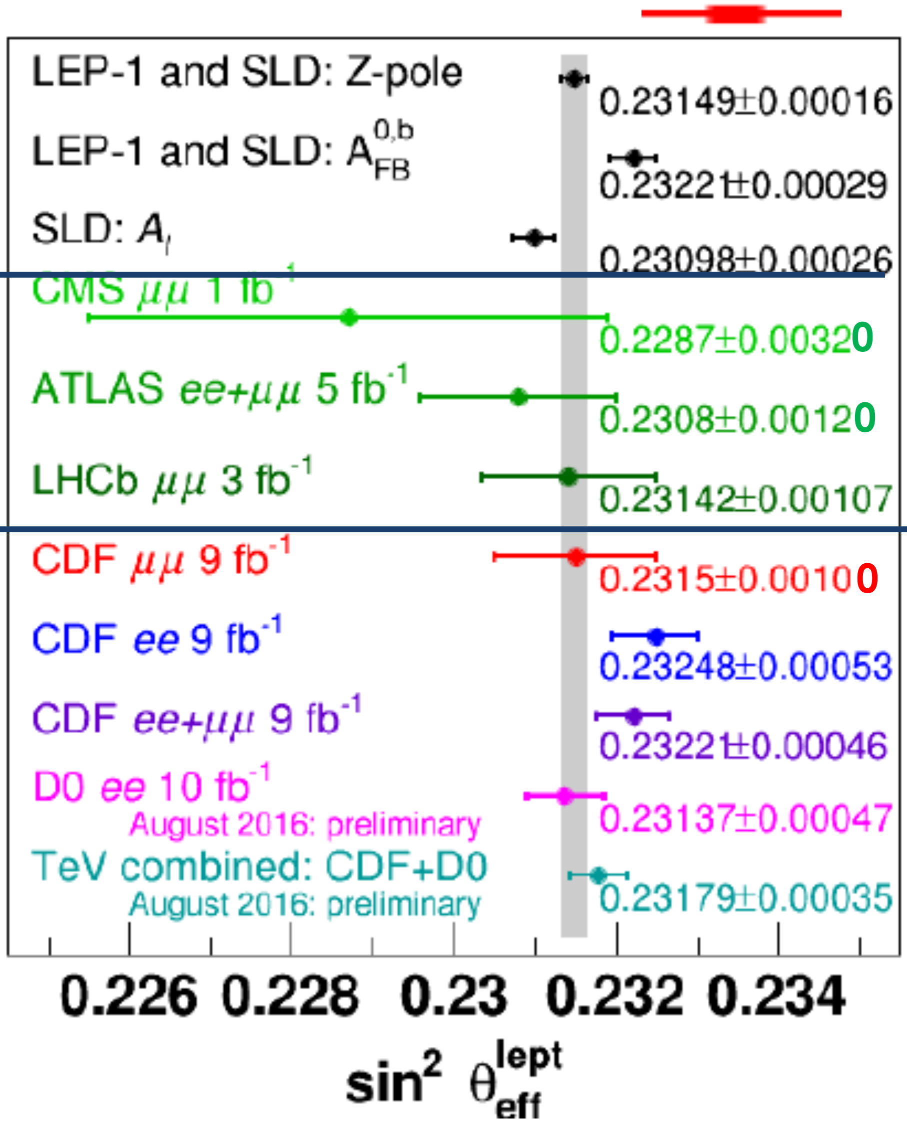
tevewwg.fnal.gov/wz/sw2eff/drafts/Fermilab_Conf_16_295_E.pdf

Combining CDF and D0

http://tevewwg.fnal.gov/wz/sw2eff/

HERA (2016) **0.23350 +-0.00110 +-0.00060**

arXiv:1603.09628



Phys. Rep. 427, 257 (2006)
Phys. Rep. 532, 119 (2013)

No EW Rad corr*

Phys. Rev. D84, 11202 (2011)

J. High Energy Phys. 09 (2015) 049

J. High Energy Phys. 11 (2015) 190

EBA EW Rad corr

Phys. Rev. D89, 072005 (2014)

Phys. Rev. D93, 112016 (2016)

ICHEP preliminary:

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23179 \pm 0.00030 \text{ (stat)} \pm 0.00017 \text{ (syst)}$$

Combined CDF&D0

***full EBA EW Rad corr increases $\sin^2\theta_{\text{eff}}^{\text{lept}}$ by +0.00022**

Inference of W-boson mass

$\sin^2\theta_W$ and M_W equivalent in SM on-shell renormalization scheme (ZFITTER)

- $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$ all orders definition
- M_Z well measured by LEP-1 and SLD: 91.1875±0.0021 GeV/c^2

Standard model help from ZFITTER is needed

- $\sin^2\theta_{eff}^{lept} = \mathrm{Re}[\kappa_l(M_Z^2, \sin^2\theta_W)]\sin^2\theta_W$

  ↳ ≈1.037

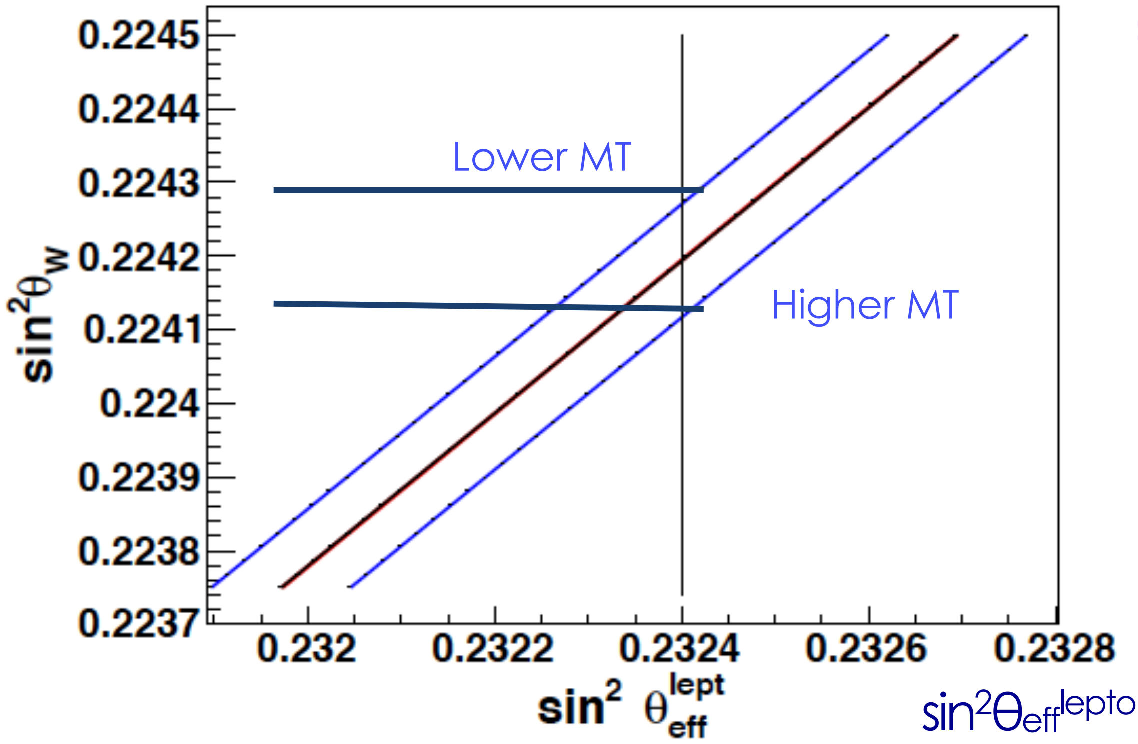
- Form factors depend on standard-model input parameters
  - Most sentitive to top-quark mass 173.2±0.9 GeV/c^2
  - Form factor uncertainty to $\sin^2\theta_W$: 0.00008
  - Higgs mass value: 125 GeV/c^2

Inferences

	$\sin^2\theta_W$	M_W	Total
– CDF only:	0.22400±0.00041±0.00019	80.328±0.021±0.010 GeV/c^2	0.024 GeV
– D0 only:	0.22313±0.00041±0.00020	80.373±0.021±0.010 GeV/c^2	0.024 GeV
– Combination:	0.22356±0.00029±0.00019	80.351±0.015±0.010 GeV/c^2	0.018 GeV
	(stat) (syst)	(stat) (syst)	

$\sin^2\theta_W^{\text{on-shell}}$ vs $\sin^2\theta_{\text{eff}}^{\text{leptonic}}(M_Z)$

- Form factors depend on standard-model input parameters
  - Most sentitive to top-quark mass 173.2±0.9 GeV/c^2
  - Form factor uncertainty to $\sin^2\theta_W$: 0.00008 (4 MeV in Mw indirect)
  - Higgs mass value: 125 GeV/c^2



$\sin^2\theta_{\text{eff}}^{\text{leptonic}}(M_Z)$

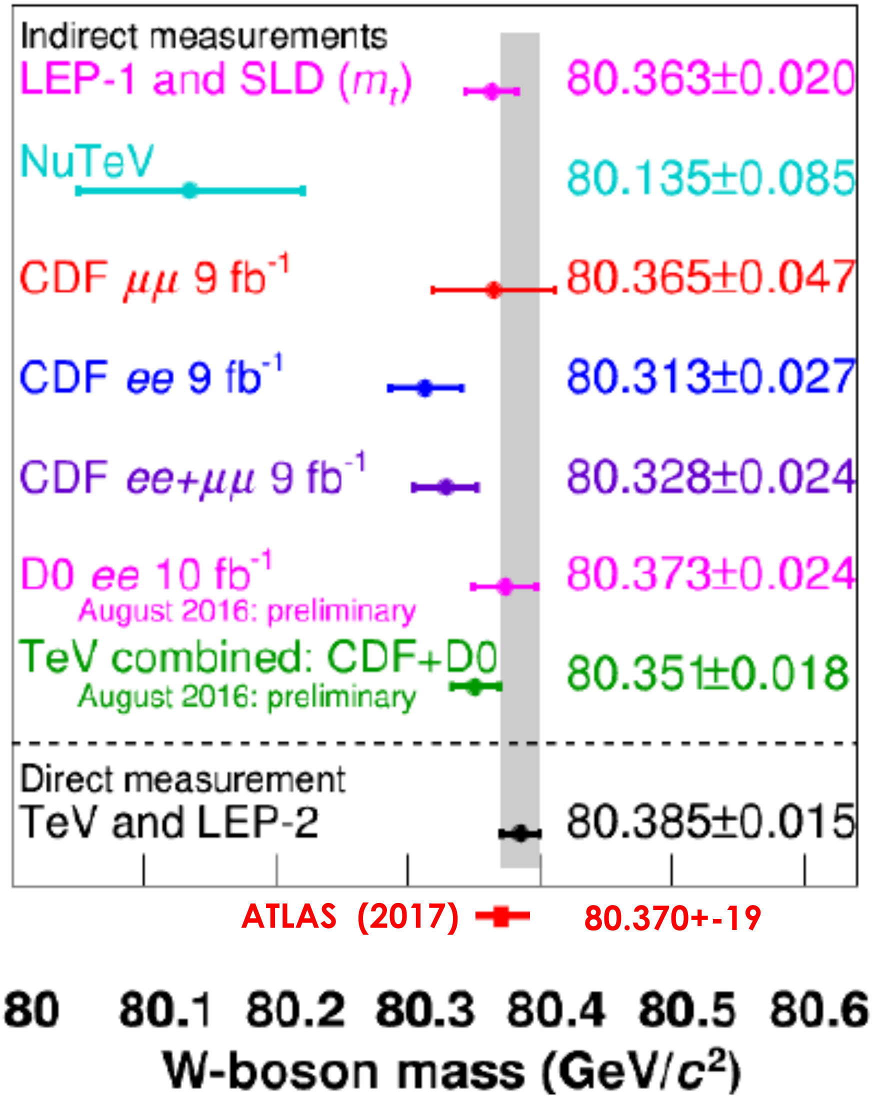
$$\sin^2\theta_{\text{eff}}^{\text{lept}} = \mathrm{Re}[\kappa_l(M_Z^{\,2},\sin^2\theta_W)]\sin^2\theta_W$$

↳ ≈1.037

[ZFITTER $\kappa_e(\sin^2\theta_W, M_Z)$ form factor]

Indirect W mass - Combining CDF and D0

ICHEP Aug 2016 FERMILAB-CONF-16-295-E
http://tevewwg.fnal.gov/wz/sw2eff/
evewwg.fnal.gov/wz/sw2eff/drafts/Fermilab_Conf_16_295_E.pdf



Phys. Rep. 427, 257 (2006)
Phys. Rep. 532, 119 (2013)*

Phys. Rev. Lett. 88, 091802 (2002)

Phys. Rev. D89, 072005 (2014)*

Phys. Rev. D93, 112016 (2016)*

* m_t = 173.2±0.9 GeV/c^2

ICHEP preliminary:

80.351±0.015±0.010 GeV/c^2
(stat) (syst)

Phys. Rev. D88, 05218 (2013)

Tevatron Summary

CDF and D0 have

- extracted $\sin^2\theta_{eff}^{lept}$ from Drell-Yan lepton-pair asymmetries

  CDF: electron and muon pairs

  D0 : electron pairs
- combined the resulting values of $\sin^2\theta_{eff}^{lept}$

- Using ZFITTER SM calculations, inferred $\sin^2\theta_W$ or equivalently M_W
- D0 muon-pair asymmetry analysis is in progress — stay tuned!

Tevatron combination

– $\sin^2\theta_{eff}^{lept} = 0.23179 \pm 0.00030$ (stat) ± 0.00017 (syst)

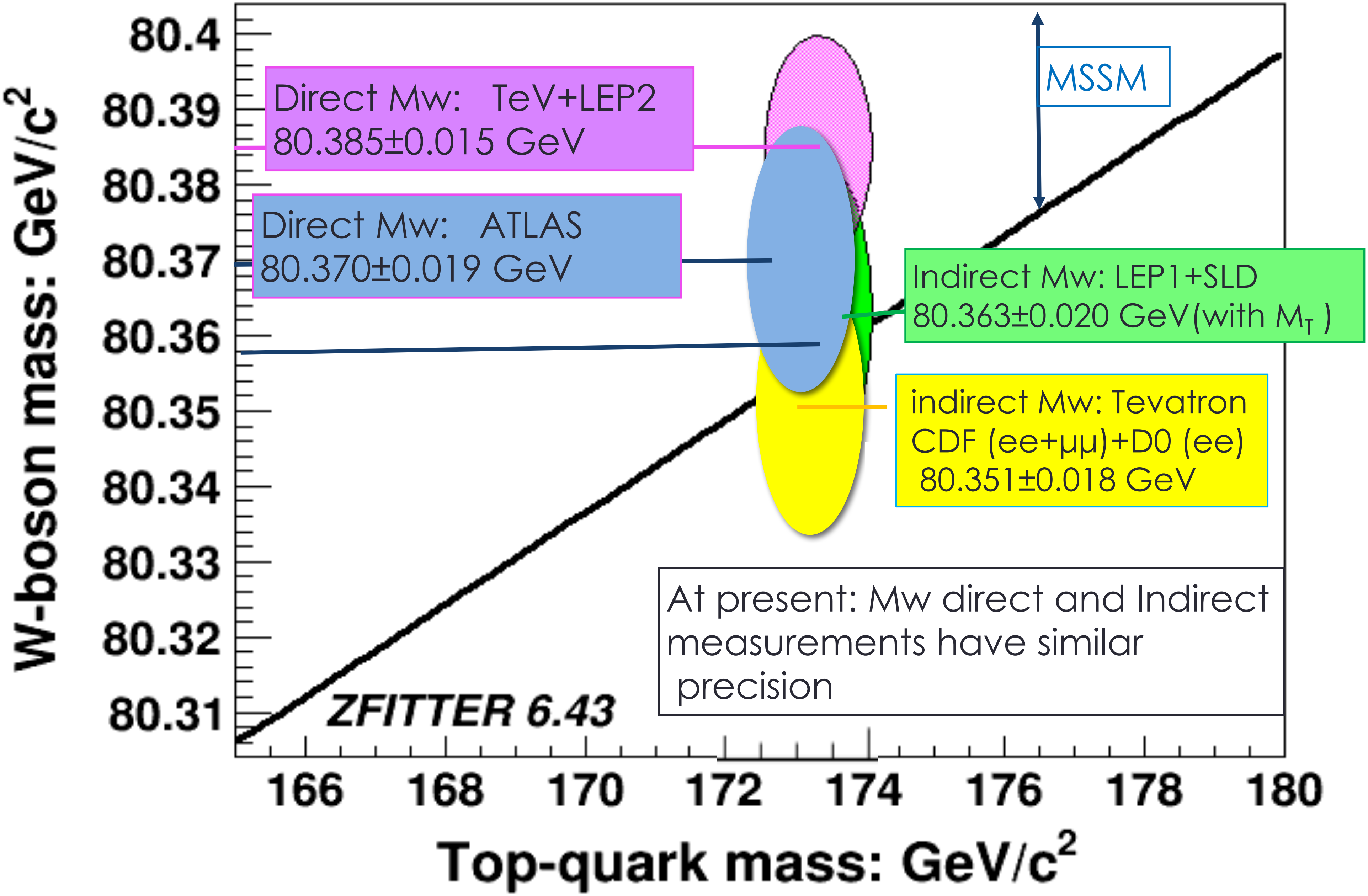
0.00035 (total)

Inferences

	$\sin^2\theta_W$	M_W	Total
– CDF only:	0.22400±0.00041±0.00019	80.328±0.021±0.010 GeV/c^2	+- 0.024 GeV
– D0 only:	0.22313±0.00041±0.00020	80.373±0.021±0.010 GeV/c^2	+-0.024 GeV
– Combination:	0.22356±0.00029±0.00019	80.351±0.015±0.010 GeV/c^2	+-0.018 GeV
	(stat) (syst)	(stat) (syst)	

Standard Model vs Super symmetry

M_T=173.34+-0.76 GeV (Mar 2014 world average), Higgs mass 125.3 GeV.



Direct Mw: TeV+LEP2
80.385±0.015 GeV

Direct Mw: ATLAS
80.370±0.019 GeV

Indirect Mw: LEP1+SLD
80.363±0.020 GeV(with M_T)

indirect Mw: Tevatron
CDF (ee+μμ)+D0 (ee)
80.351±0.018 GeV

At present: Mw direct and Indirect measurements have similar precision

Theoretical Errors $\sin^2\theta_{eff}^{lept}(M_Z)$,

A. QCD Scale/QCD higher order Error: 0.00003

B. PDF Error 0.00020 reduced to 0.00016 with PDF reweighting

C. EW radiative corrections (increase extracted value by 0.00022)

(1/3 from form factors, 1/3 from u-d dependence, 1/3 from M dependence)

QCD order diference (CDF ee y<1.7): (NLO - LO) = 0.00002
QCD scale error ee (vary running scales x2, and 0.5) = 0.00003
(renormalization/factorization scale)
The statistical error of 0.00049 (e+e- data only) dominates

QCD order diference (CDF μμ y<1.0): (NLO - LO) = 0.00002
QCD scale error ee (vary running scales x2, and 0.5) = 0.00006
(renormalization/factorization scale)
The statistical error of 0.00090 (μμ data only) dominate

For comparison for LHC 8 TeV μμ CMS-like detector
QCD scale error LHC (vary running scales x2, and 0.5) = 0.00010
(renormalization/factorization scale)

Conclude: QCD scale error can be neglected at Tevatron and also at LHC.
PDF error is largest systematic error, so focus on it

CDF: Reducing PDF errors

We use combined e+e $\mu^+\mu$ Afb data to constrain PDFs using a new method

Ref : A. Bodek. J. Han, A. Khukhunaishvili, W. Sakumoto:" Using Drell-Yan forward-backward asymmetry to constrain parton distribution functions" EPJC, 76(3), 1-12 (2016) arXiv:1507.02470.

Reduces NNPDF 3.0 PDF (NNLO) error in $\sin^2\theta_{eff}$ from ± 0.00020 to ± 0.00016

All PDF groups provide a default (central) PDF set. There are two methods that are used for the determination of PDF uncertainties in the analysis.

1. Hessian Matrix: Use a set of eigenvector error PDFs.

The PDF uncertainties in a measurement are determined by repeating the analysis for all of the error PDF sets, and adding in quadrature the difference in the result obtained with the error PDFs and the result obtained with the default PDF.

2. Monte Carlo Replicas: Use a set of N (e.g. 100 or 1000) replica PDFs.

Each of the PDF replicas has equal probability of being correct. The central value of any observable is the average of the values of $\sin^2\theta_{efff}$ extracted with each one of the N PDF replicas. The PDF error is the RMS of the values extracted using all N replicas.

The calculated PDF uncertainty is the same for both methods. The two Methods are equivalent. From Hessian PDFs one can construct a set of Monte Carlo replicas.

CDF analysis PDF errors: Monte Carlo Replica Method

MC Replica Method:

$$\langle s \rangle = \frac{1}{N} \sum_{i=1}^{N} s_i \qquad (12)$$

$s=\sin^2\theta$

$$\sigma_{pdf} = \sqrt{\frac{\sum_{i=1}^{N} (s_i - \langle s \rangle)^2}{N-1}} \qquad (13)$$

and the uncertainty in the PDF error is $\Delta\sigma_{pdf} = \frac{\sigma_{pdf}}{\sqrt{2(N-1)}}$

For any given a set of Hessian eigenvector PDFs there is a prescription to generate an arbitrary number of PDF replicas.

We use 100 NNPDF3.0 NNLO PDFs (NNPDF3.0 Includes LHC data)

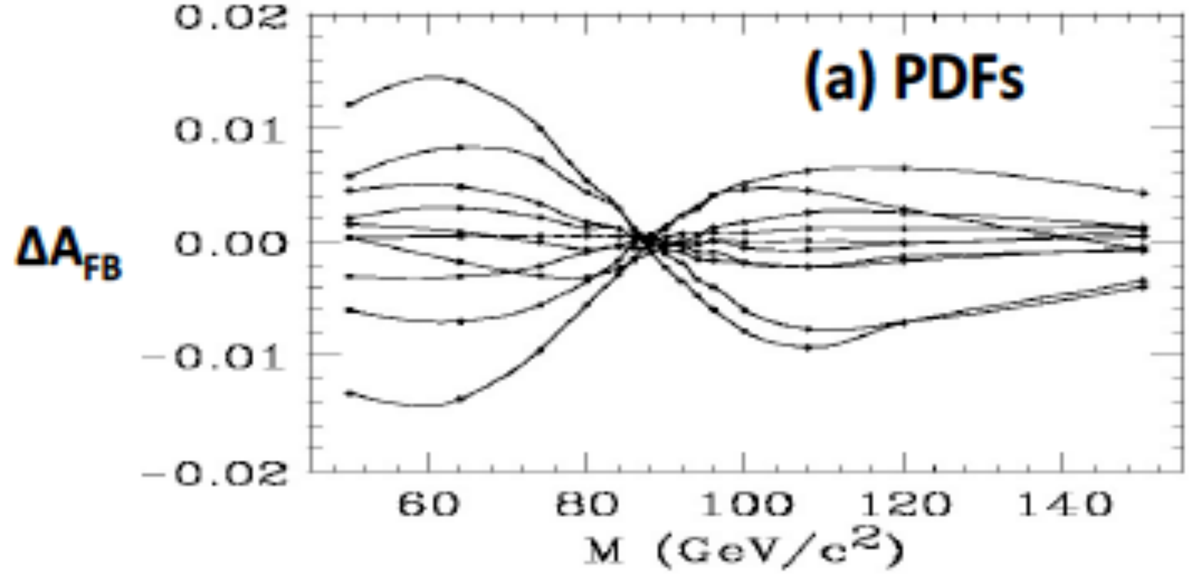
For these100 replicas RMS is the PDF error(Tevatron): ± 0.00020 (PDF)

Although equivalent, the replica method is more useful for two reasons:

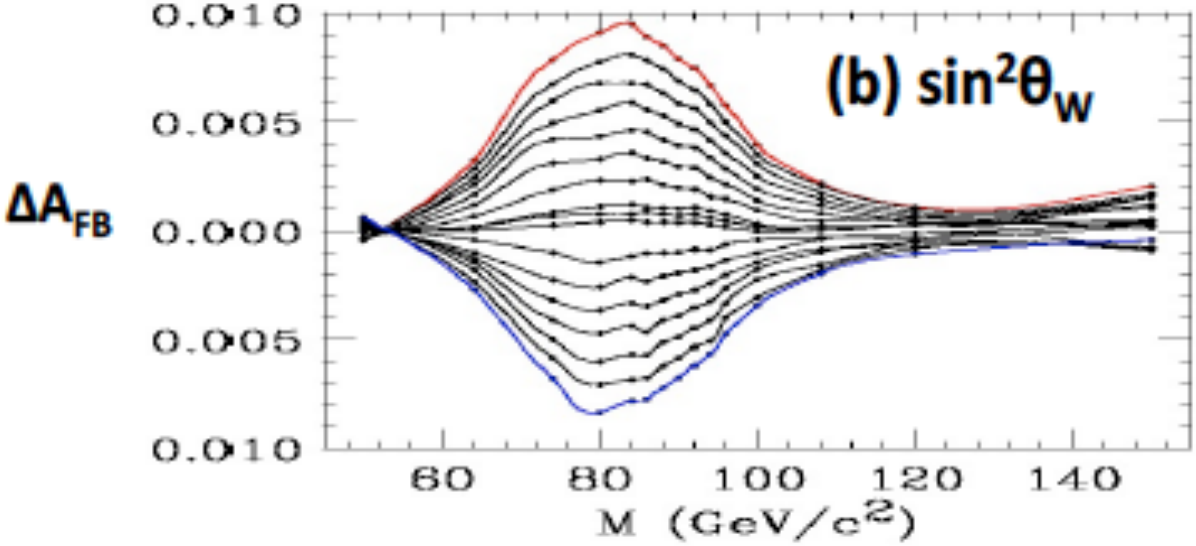
1. We can easily add constraints from new data (can also be done with Hessian PDFs).
2. We can easily find if the new data is consistent or inconsistent with the PDFs

Sensitivity of $A_{FB}(M)$ to $\sin^2\theta_W$ and PDFs.

Because the dependence of Afb(M) on PDFs
is different from the dependence of Afb(M) on $\sin^2\theta_W$



Dependence of Afb(M) on PDFs



Dependence of Afb(M) on $\sin^2\theta_W$

Difference of Afb(M) from a default PDF with default $\sin^2\theta_W$

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Baysian Reweighting (incorporating new data)

- New measurements can be incorporated into the ensemble without refits
  - Ensemble PDFs are reweighted

$$w_k = \frac{\exp(-\chi^2_k/2)}{\sum_{l=1}^{N} \exp(-\chi^2_l/2)}$$

χ^2_k: between new measurement and prediction with ensemble PDF k

The new central value
= weighted mean.
The new weighted RMS
is the reduced PDF uncertainty

It is clear how to do this for new data that has not been used in previous PDF fits.
(e.g. new LHC W asymmetry data)

A_{FB} (M) data has never been used In PDF fits before
.

How can we get both $\sin^2\theta_w$ AND constrain PDFs from the same A_{FB} (M) data ?????

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A. Bodek. J. Han A. Khukhunaishvili, W. Sakumoto:
EPJC, 76(3), 1-12 (2016) arXiv:1507.02470

CDF $\sin^2\theta_W$: Reduce PDF errors with Baysian Reweighting

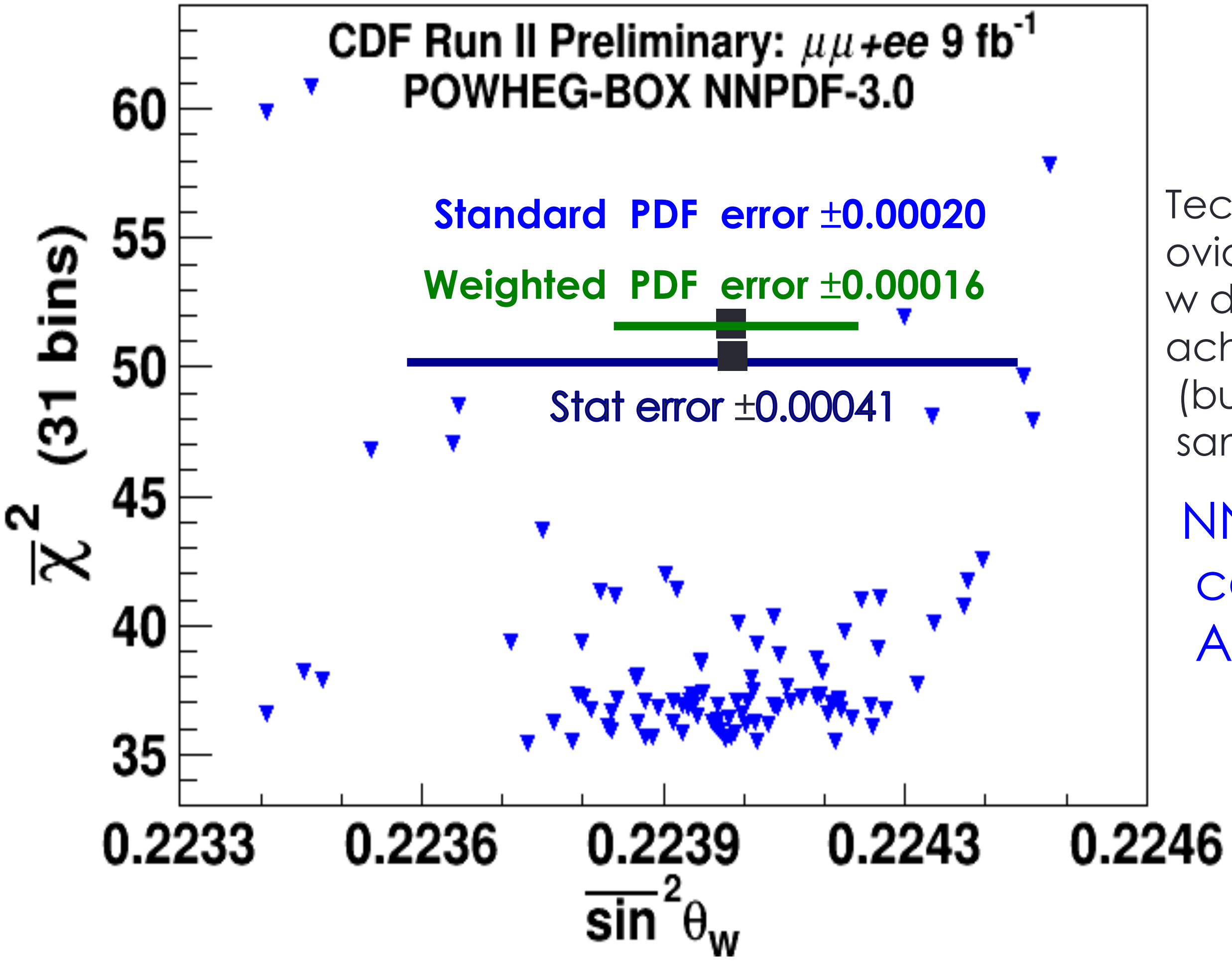
χ^2_{min} versus $\sin^2\theta_W$ for each ensemble PDF:

Weighted Mean → $\sin^2\theta_W$ = 0.22400± 0.00041 (stat)

Weighted RMS = reduced PDF error= ± 0.00016

Ensemble PDFs are constrained by reweighting

$$w_k = \frac{\exp(-\chi^2_k/2)}{\sum_{l=1}^{N} \exp(-\chi^2_l/2)}$$



100 NNPDF 3.0 (NNLO) replicas

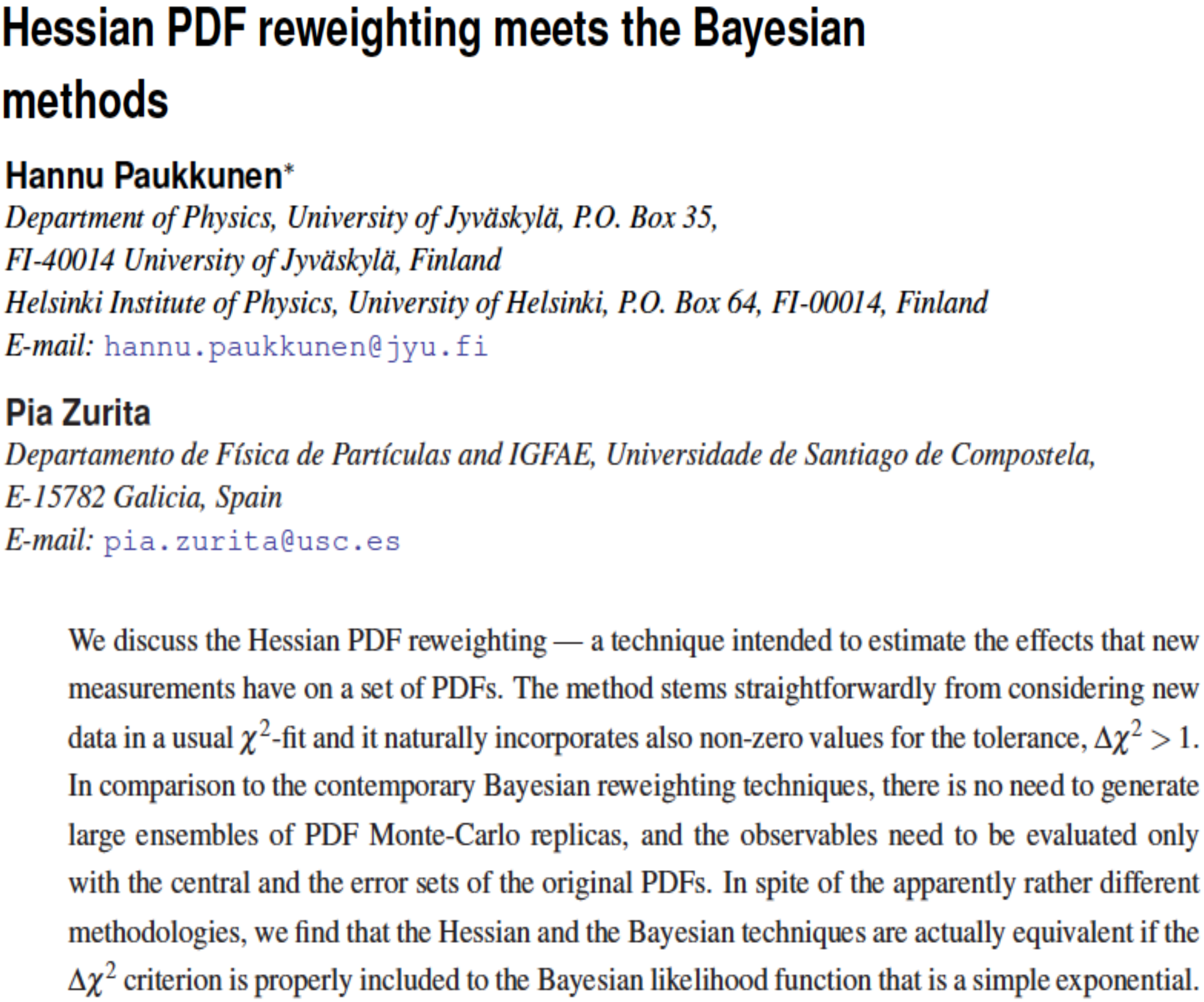
Technique can be used with any PDF set provided the PDF set is consistent with the new data. If the PDF sets are consistent with each other the result (but not the PDF error) will be the same.

NNPDF3.0 NNLO PDFs are consistent with the CDF A_{FB} (M) data

These constrained PDFs can be used for other analyses (e.g. direct measurement of the W mass)

MC Replica vs Hessian Method

https://]https://arxiv.org/pdf/1408.4572v1.pdf



Hessian PDF reweighting meets the Bayesian methods

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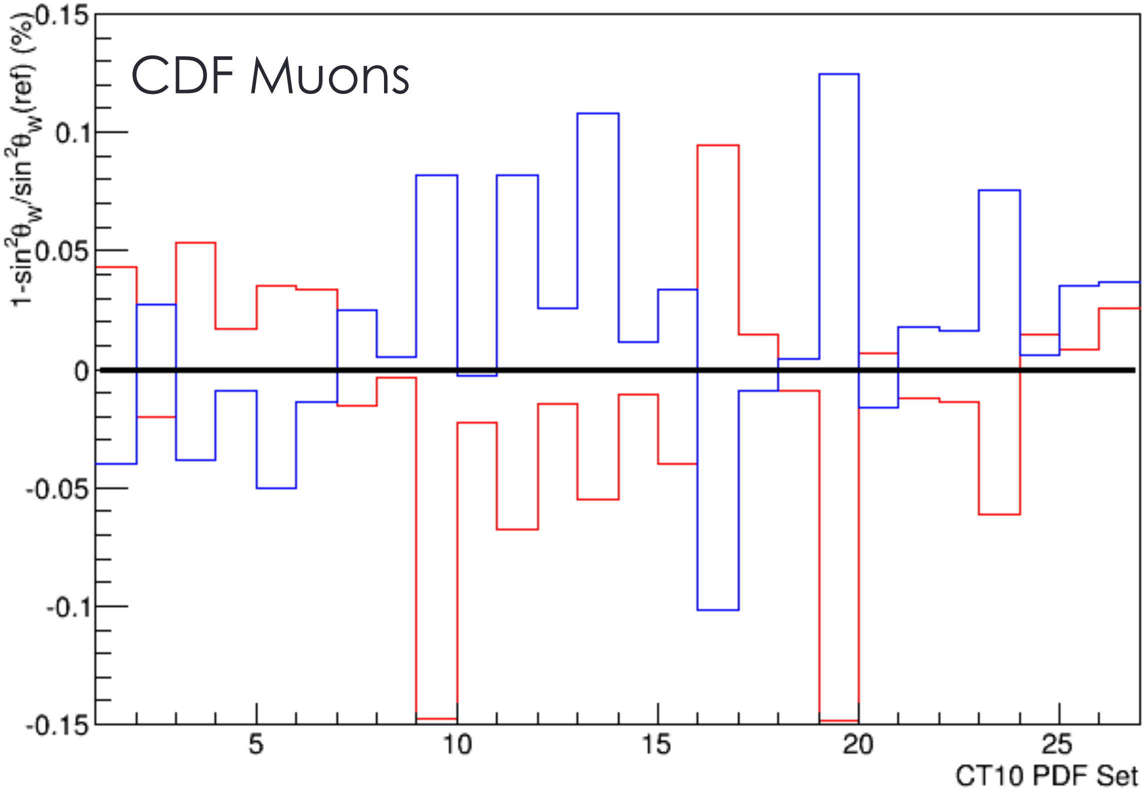
We discuss the Hessian PDF reweighting — a technique intended to estimate the effects that new measurements have on a set of PDFs. The method stems straightforwardly from considering new data in a usual χ^2-fit and it naturally incorporates also non-zero values for the tolerance, $\Delta\chi^2 > 1$. In comparison to the contemporary Bayesian reweighting techniques, there is no need to generate large ensembles of PDF Monte-Carlo replicas, and the observables need to be evaluated only with the central and the error sets of the original PDFs. In spite of the apparently rather different methodologies, we find that the Hessian and the Bayesian techniques are actually equivalent if the $\Delta\chi^2$ criterion is properly included to the Bayesian likelihood function that is a simple exponential.

Hessian Method

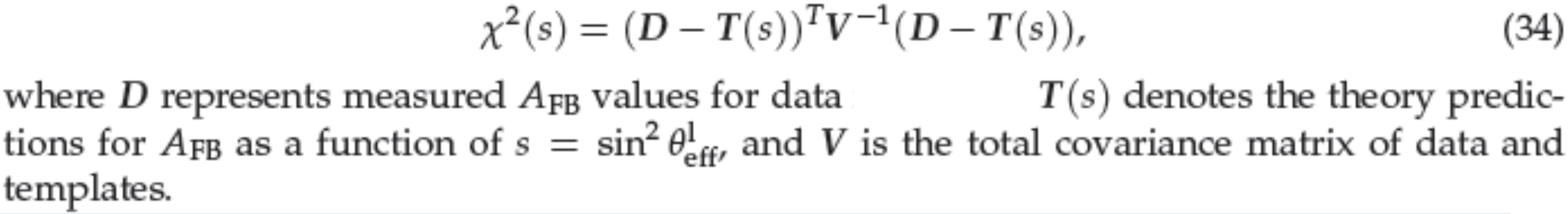


Reminder: With Hessian PDFs we use a set of eigenvector error PDFs.

The PDF uncertainties in a measurement are determined by repeating the analysis for all of the error PDF sets, and adding in quadrature the difference in the result obtained with the error PDFs and the result obtained with the default PDF.

Baysian vs Hessian Reweighting

MC Replica Method: No constraint = RMS of the results all 100 PDFs
With constraint = Weight PDFs using $\chi^2(s)$

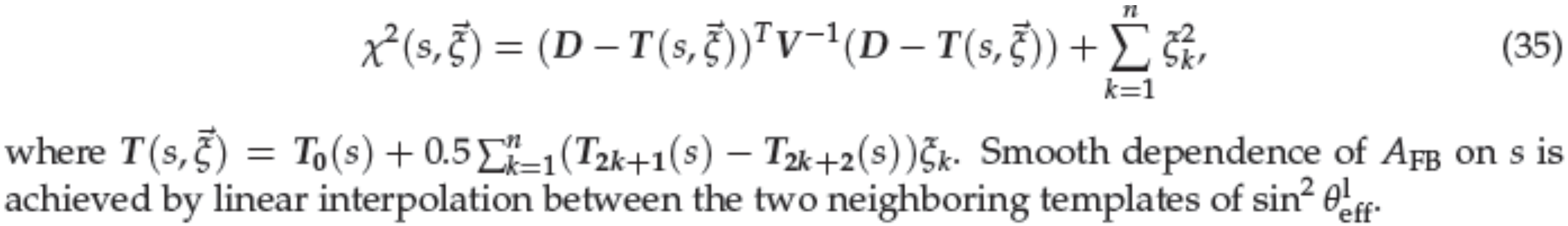


$$\chi^2(s) = (D - T(s))^T V^{-1} (D - T(s)), \quad (34)$$

where D represents measured A_{FB} values for data $T(s)$ denotes the theory predictions for A_{FB} as a function of $s = \sin^2\theta^{\mathrm{l}}_{\mathrm{eff}}$, and V is the total covariance matrix of data and templates.

Hessian Matrix: No constraint = quadratic sum of the difference in sw2 from the nominal PDF for all **n** eigenvector error PDFs

With constraint = minimize $\chi^2(s,\vec{\xi})$



$$\chi^2(s,\vec{\xi}) = (D - T(s,\vec{\xi}))^T V^{-1} (D - T(s,\vec{\xi})) + \sum_{k=1}^{n} \xi_k^2, \quad (35)$$

where $T(s,\vec{\xi}) = T_0(s) + 0.5\sum_{k=1}^{n}(T_{2k+1}(s) - T_{2k+2}(s))\xi_k$. Smooth dependence of A_{FB} on s is achieved by linear interpolation between the two neighboring templates of $\sin^2\theta^{\mathrm{l}}_{\mathrm{eff}}$.

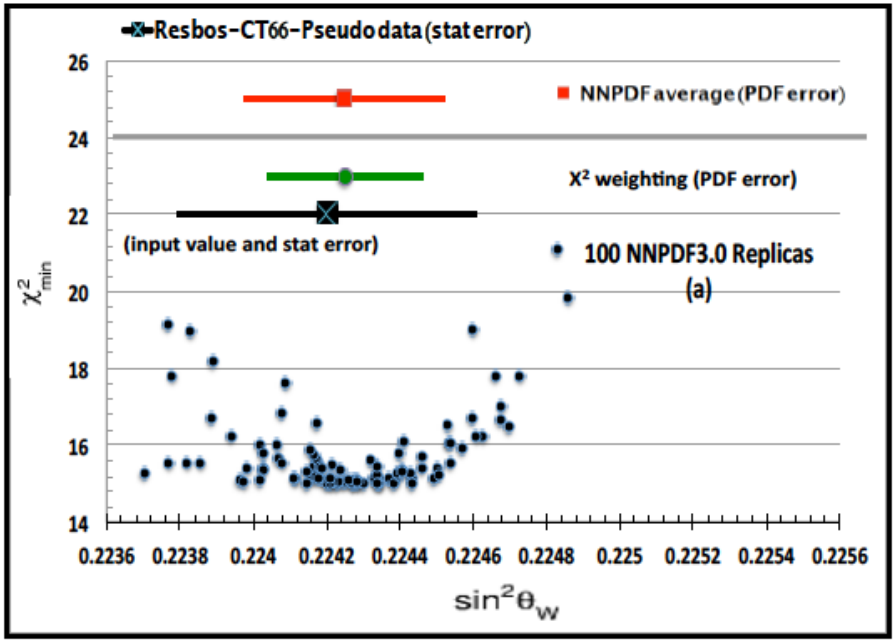
Both methods give the same result for the best value of $\sin^2\theta_W$
And also the same value for the combined statistical and PDF errors for both the unconstrained and constrained cases.

Although both give the same results, the replica method also provides information about the consistency of the PDF set with the Afb data.

Checking consistency of new data with PDFs

Bodek et al. EPJC, 76(3), 1-12 (2016): MC study: **Fake data: CTEQ6.6 , $\sin^2\theta_w$=0.2242**

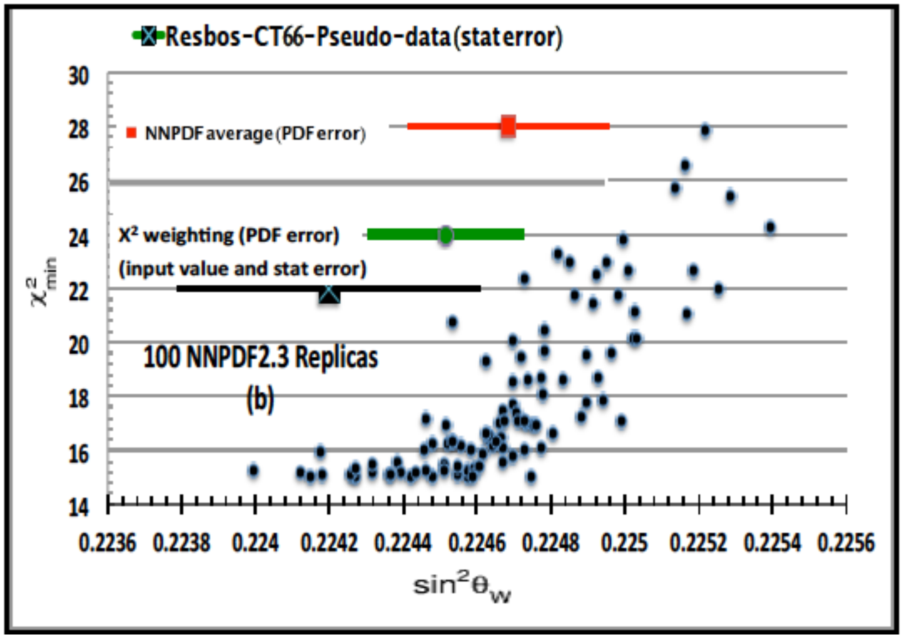
Statistics similar to CDF sample. CDF like detector



Analysis done using NNPDF3.0 NLO replicas.

The average $\sin^2\theta_w$ from the fake data is equal to the input value of $\sin^2\theta_w$. The weighted $\sin^2\theta_w$ is also equal to the input value of $\sin^2\theta_w$

Find that the CTEQ6.6 NLO Fake data is consistent with the NNPDF3.0 NNLO set. (Note NNPDF3.0 fits includes LHC data).



Analysis is done with NNPDF2.3 NLO replicas.

The average $\sin^2\theta_w$ from the fake data is NOT equal to the input value of $\sin^2\theta_w$. However, weighted $\sin^2\theta_w$ analysis is closer to the input value.

We find that CTEQ6.6 Fake data is not consistent with NNPDF2.3 NNLO set. Note NNPDF2.3 fits do not include LHC data, it

Note: this analysis can also be done with Hessian PDFs.

Prospects at the LHC

Reducing PDF errors using constraints from new data

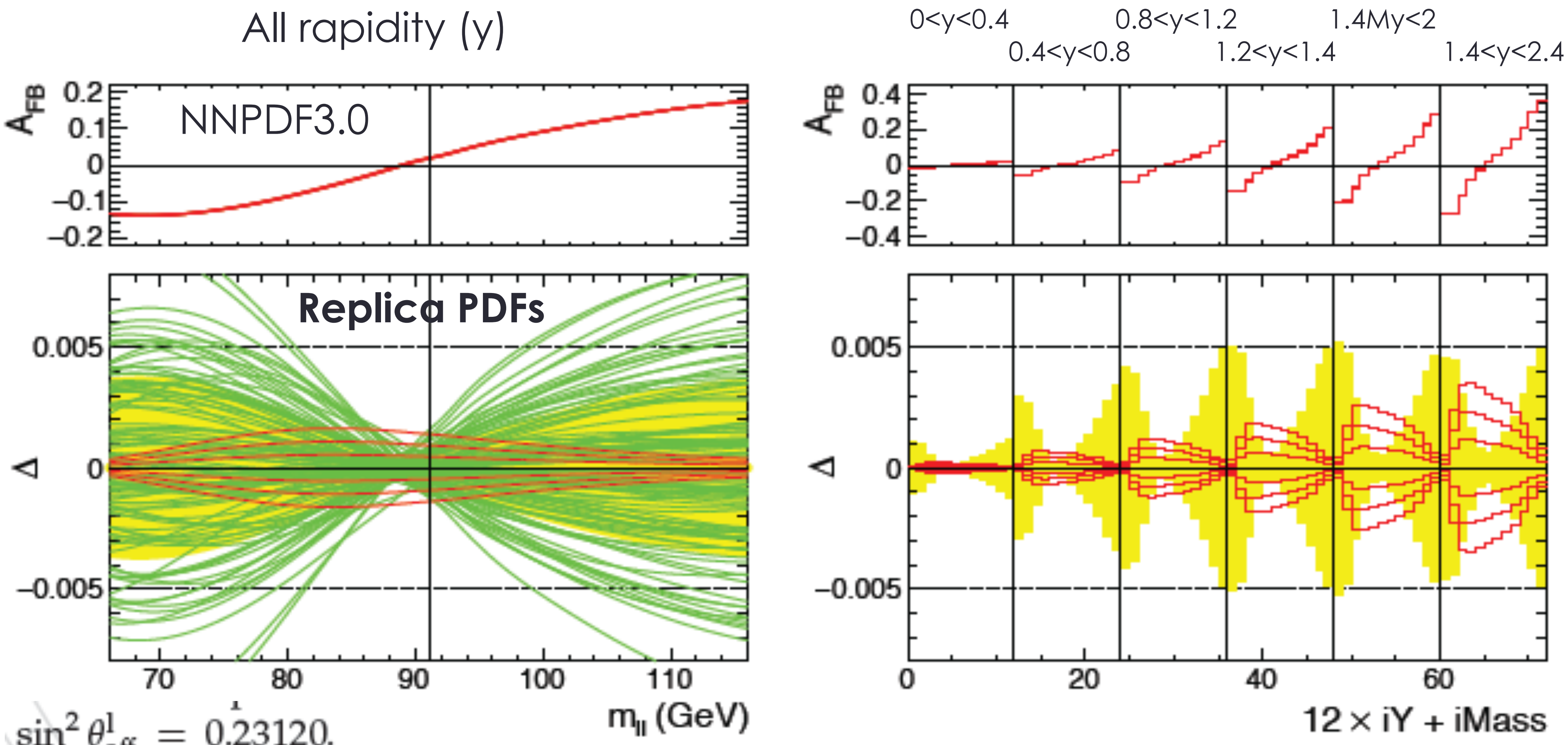
At Tevatron CDF detector:
From 0.00020 to 0.00016

LHC 8 TeV CMS Like detector 10M Z events:
From 0.00050 to 0.00028

LHC 16 TeV CMS like detector: 120M Z events
From 0.00050 to 0.00014

Much more important at LHC

Toy Study: Sensitivity to $\sin^2\theta_{eff}^{leptonic}$ and PDFs at 8 TeV



$\sin^2\theta_{\rm eff}^{\rm l} = 0.23120.$

Horizontal axis shows index of dimuon mass and rapidity bins. In the bottom panel the yellow band shows the PDF uncertainty calculated with NNPDF3.0 set. The red lines correspond to six variations of $\sin^2\theta_{\rm eff}^{\rm l}$ around the central value: ±0.00040, ±0.00080 and ±0.00120.

Yellow band illustrates the standard deviation over the NNPDF replicas.

Green lines correspond to $A_{\rm FB}$ predictions for 100 NNPDF replicas.

Hessian PDFs: Sensitivity to $\sin^2\theta_{eff}^{leptonic}$ and PDFs at 8 TeV

$$\sin^2\theta^l_{\rm eff} = 0.23120.$$

MMHT Hessian PDFs

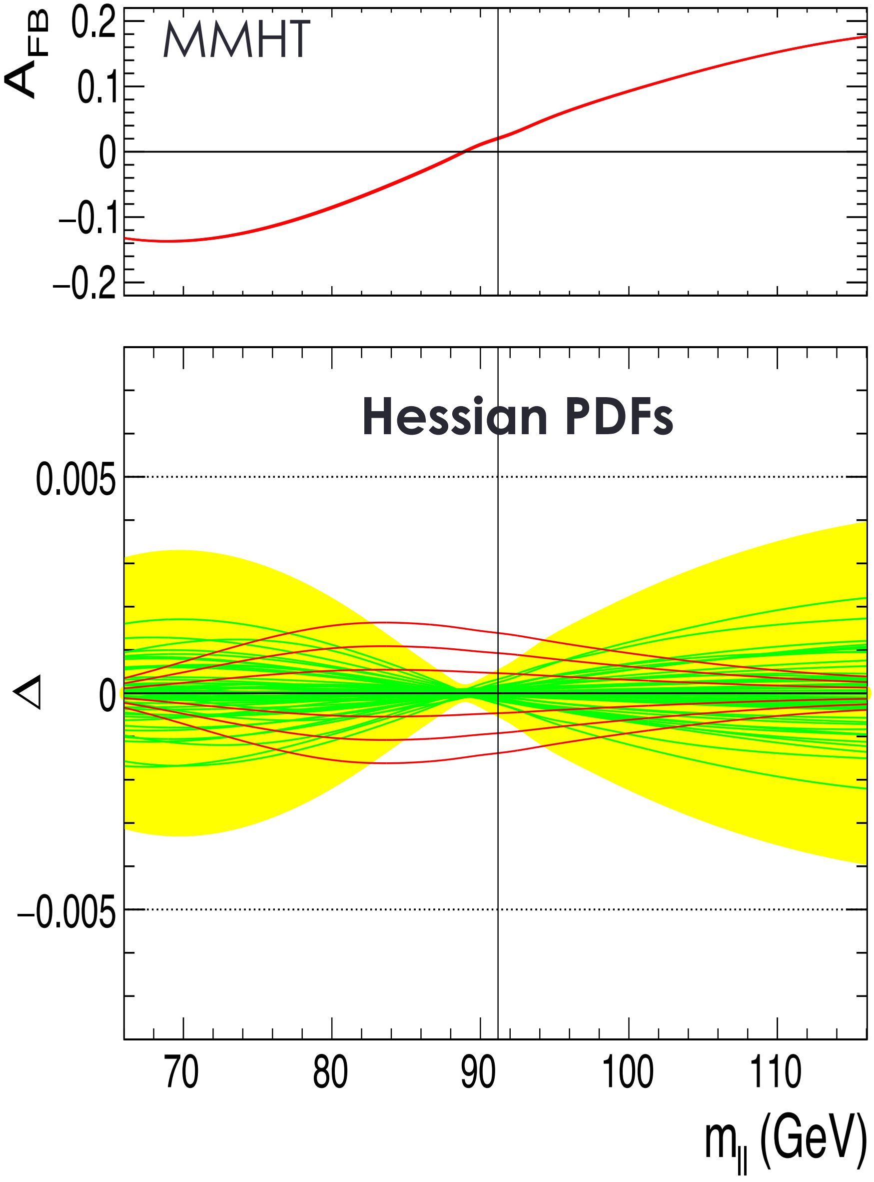
Horizontal axis dimuon mass. The red lines show six variations of sin2eff around the central value:

+-0.00040, +-0.00080, +-0.00120

The green bands are the 25 O- and 25 O+ Hessian eigenvoctor error PDFs.

The yellow band corresponds to the sum in quadrature of the deviations of all the 25 error PDFs.

All rapidity (y)

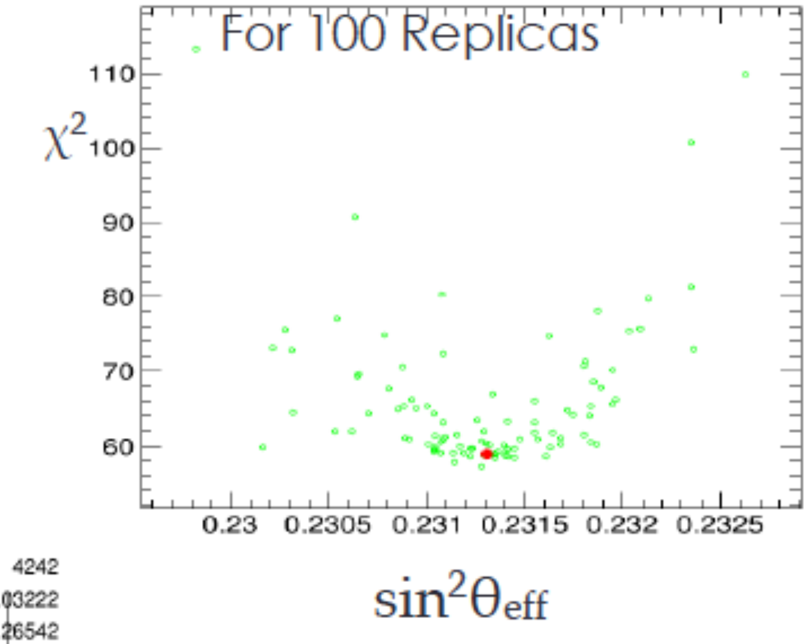


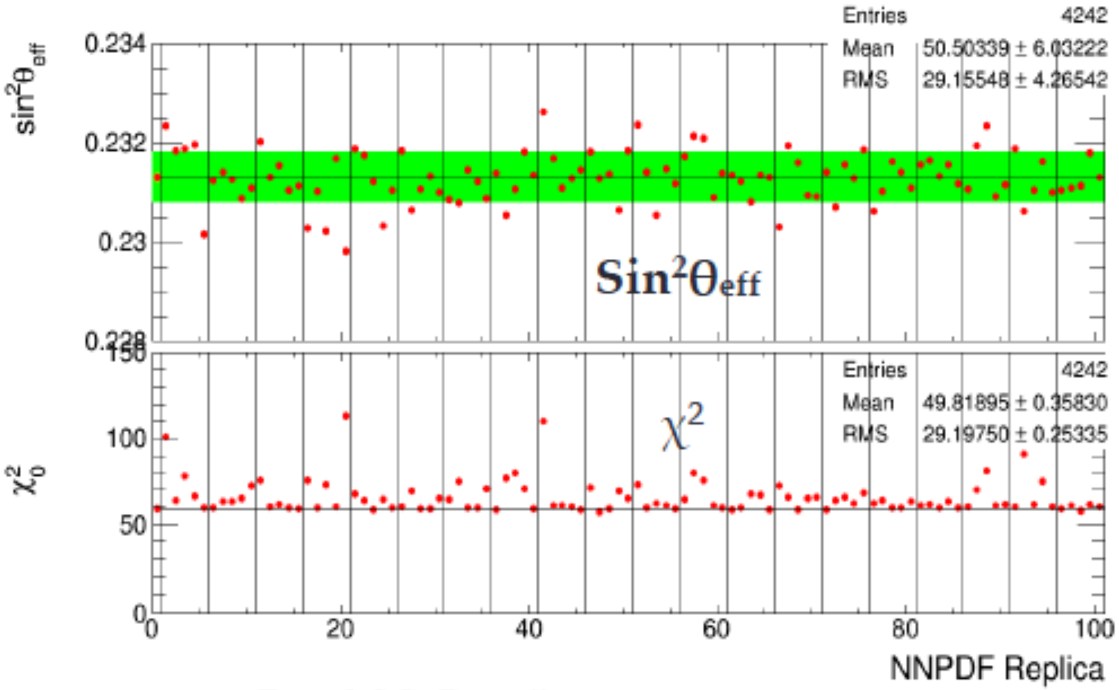
Toy Study: Sensitivity to $\sin^2\theta_{eff}^{leptonic}$ and PDFs at 8 TeV

Extract $\mathbf{Sin^2\theta_{eff}}$ for each PDF replica. Plots shown for one pseudo experiment

- We now assign NNPDF replicas weights, based on how well they describe Afb data. weight ~ $\exp(-\chi^2/2)$

- PDFs with bad χ^2 will have small weights





For 100 Replicas

Example of one of the 64 pseudo experiments

χ^2

Method and PDF error

NNPDF3.0 Unconstrained

100 replicas σ_{PDF}= +- 0.00051

NNPDF3.0 8 TeV $\mu\mu$ AFB

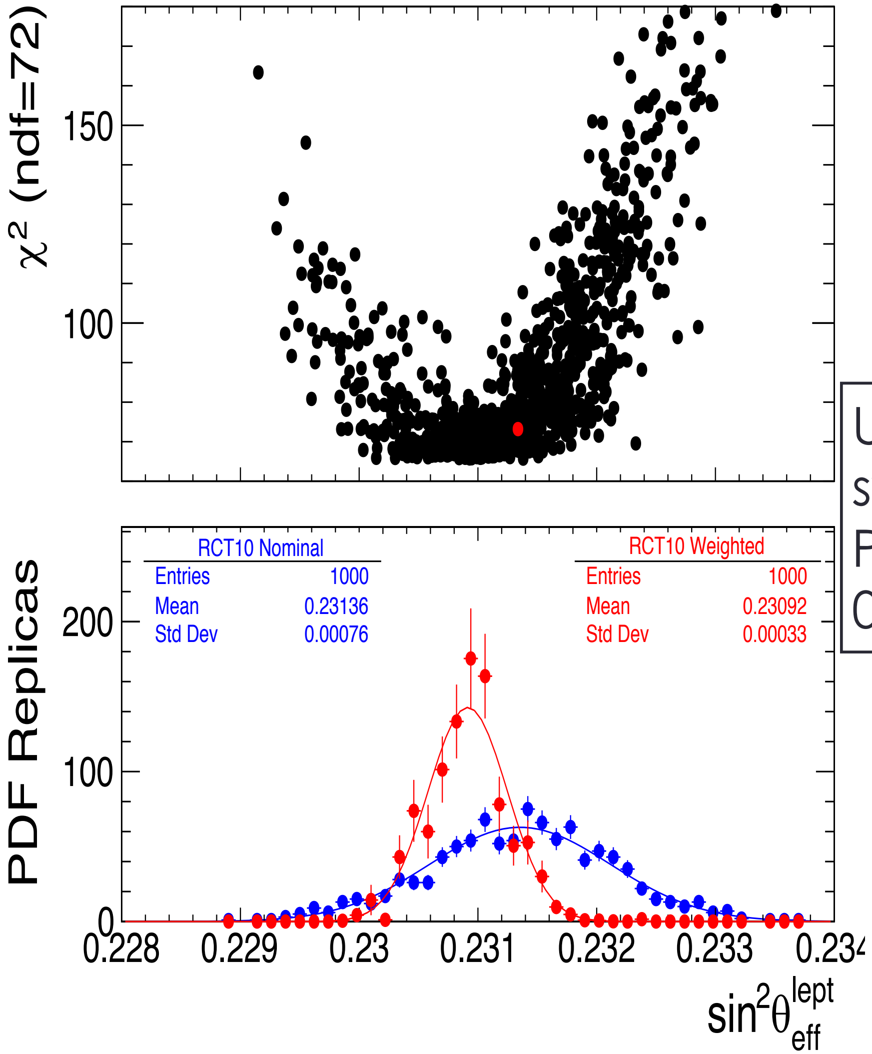
constrained weight ~ $\exp(-\chi^2/2)$

σ_{PDF}= +- 0.00029

CMS like 8 TeV LHC toy Study -1

Pseudo data: NNPDF 3.0 (nlo) smeared default sw2eff (powheg)=0.23120
Analyze pseudo-data with **CT10** using Replica and Hessian approaches

CT10 is an old PDF with a large PDF error (0.00076)



Statistics, 8 TeV CMS-like detector

Using PDF reweighting, with NNPDF3.0
sw2eff =0.23132 bias = +0.00012
PDF error reduced from
0.00051 to 0.00029

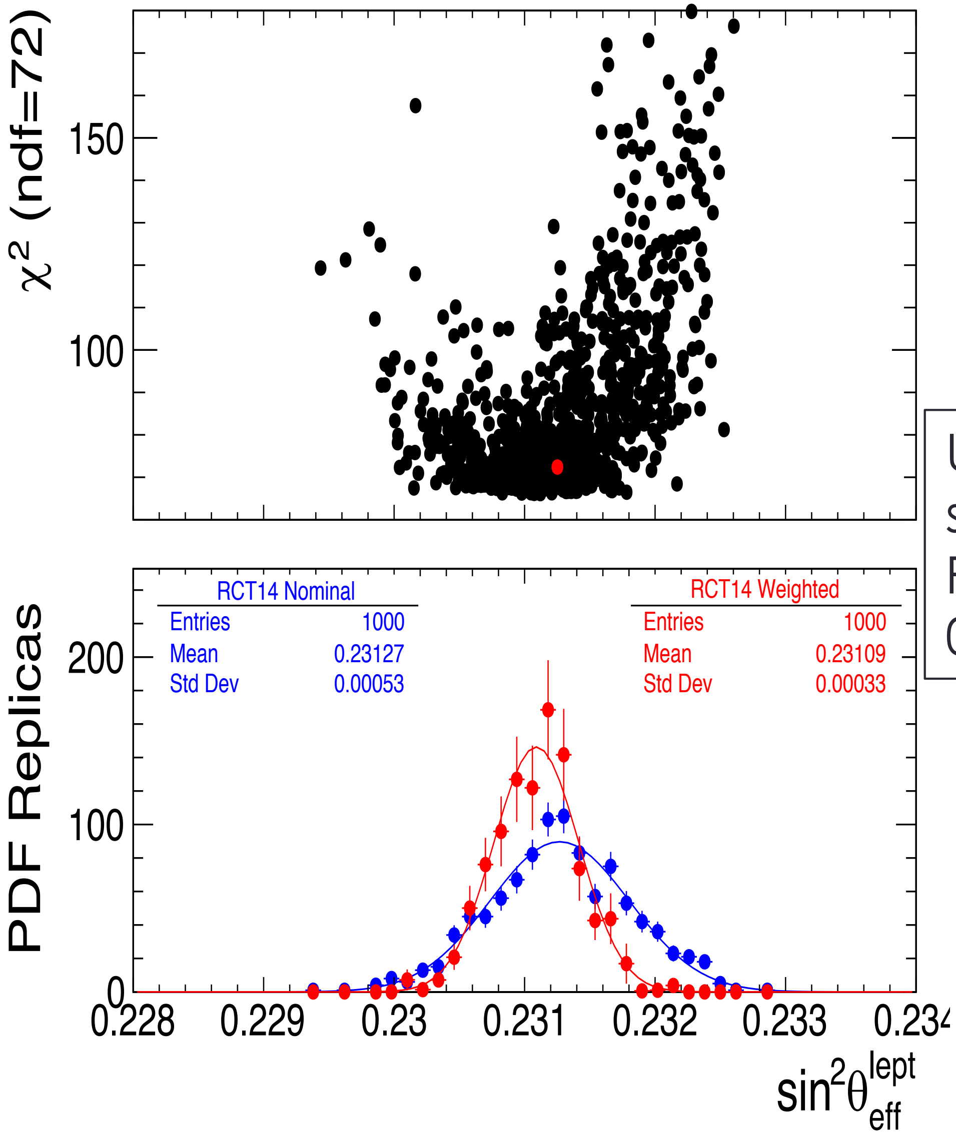
Using PDF reweighting, with CT10
sw2eff =0.23092 bias =-0.00018
PDF error reduced from
0.00076 to 0.00033

CMS like 8 TeV LHC toy Study -3

Pseudo data: NNPDF 3.0 (nlo) smeared default sw2eff (poheg)=0.23120

Analyze pseudo-data with **CT14** using Replica and Hessian approaches

CT10 PDF include LHC data has a smaller PDF error (0.00053)



Statistics, 8 TeV CMS-like detector

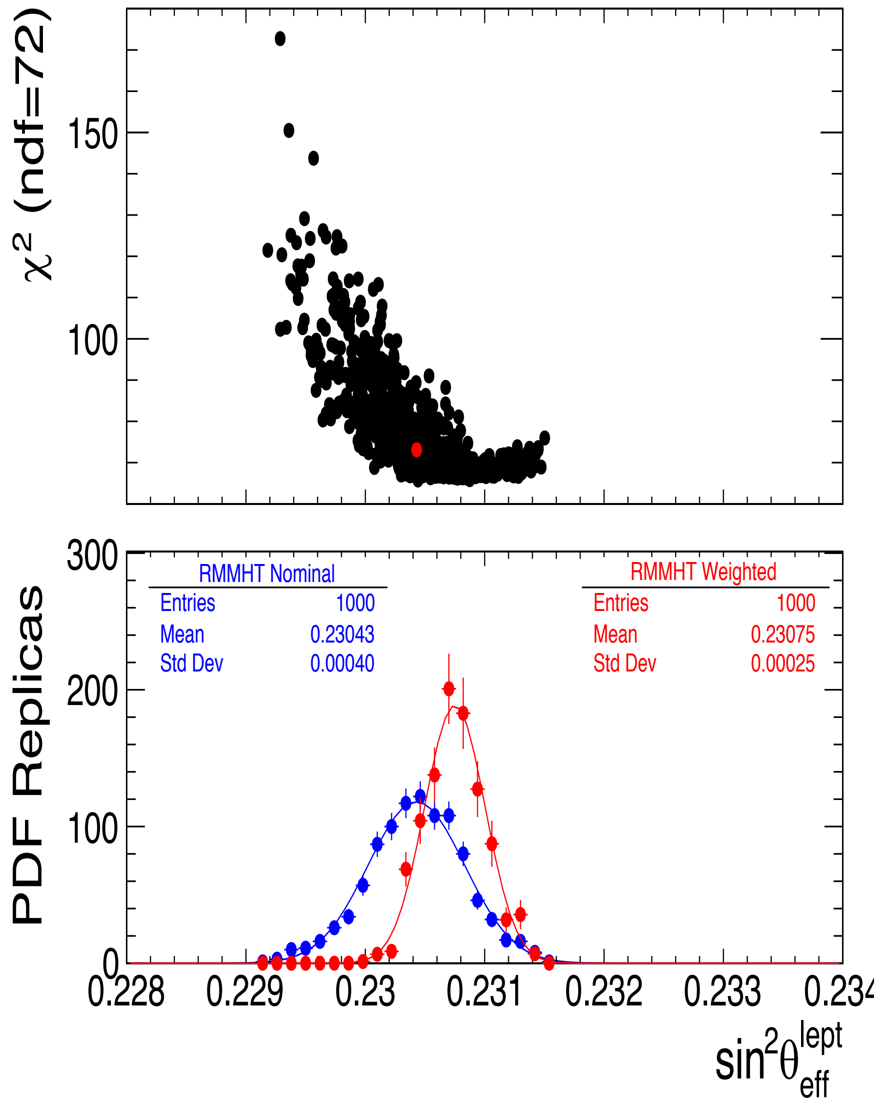
Using PDF reweighting, with NNPDF3.0
sw2eff =0.23132 bias = +0.00012
PDF error reduced from
0.00051 to 0.00029

Using PDF reweighting, with CT14
sw2eff =0.23109 bias=-0.00011
PDF error reduced from
0.00053 to 0.00033

Analysis with CT14 provides a good check on NNPDF3.0

CMS like 8 TeV LHC toy Study -2

Pseudo data: NNPDF 3.0 (nlo) smeared default sw2eff (poheg)=0.23120
Analyze pseudo-data with **MMHT** using Replica and Hessian approaches



Statistics, 8 TeV CMS-like detector

Using PDF reweighting, with NNPDF3.0
sw2eff =0.23132 bias = +0.00012
PDF error reduced from
0.00051 to 0.00029

Using PDF reweighting, with MMHT
sw2eff =0.23075 bias= -0. 00035
PDF error reduced from
0.00040 to 0.00025

MMHT PDFs appear to be not consistent with NNPDF3.0 pseudo-data. Therefore, should not be used

Nonetheless: With PDF reweighting, central value Bias is reduced.
Sw2eff changes from
-0.00077 to -0.00035

Reducing PDF errors in W mass measurements

arXiv:1501.05587

PDF uncertainties on the W boson mass measurement from the lepton transverse momentum distribution

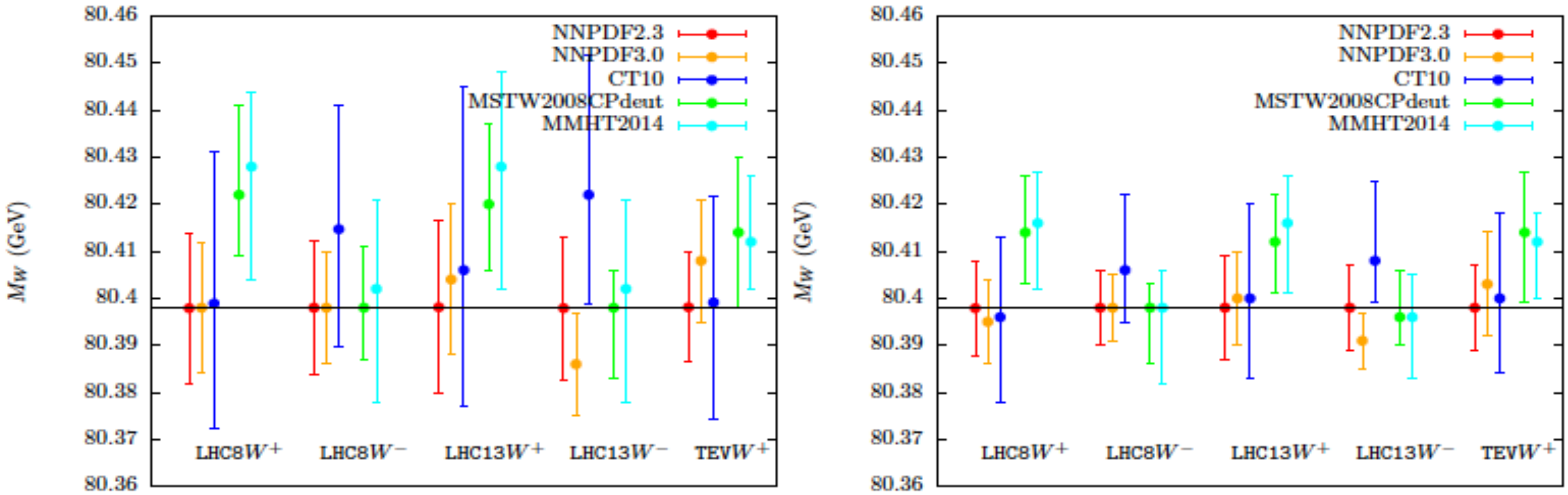
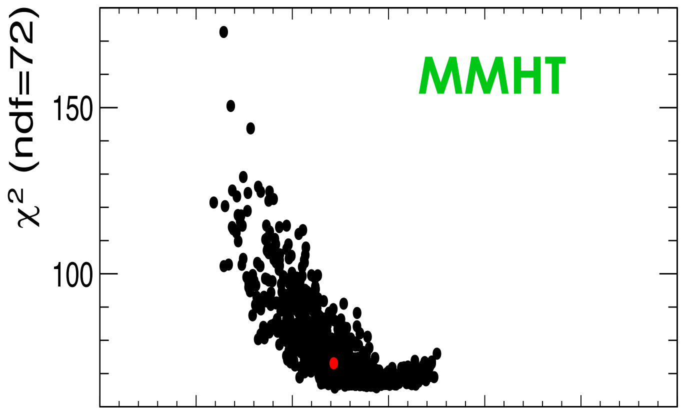
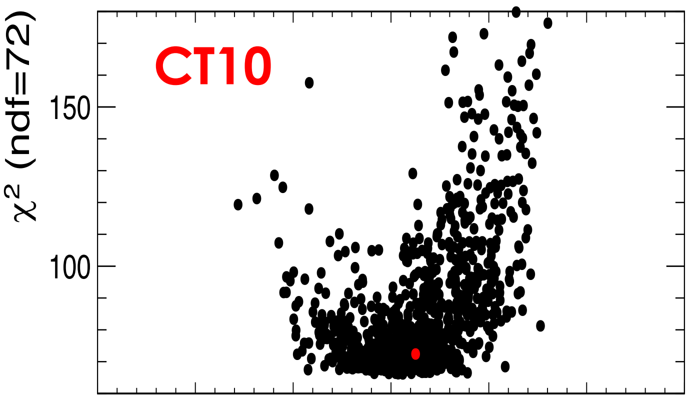


Figure 4: Summary of the PDF uncertainty on m_W computed with different PDF sets, colliders and final states. The basic acceptance criteria have been used in the left plot, while in the right plot an additional cut $p_\perp^W < 15$ GeV has been applied.





Direct Mw Measurement with CT10 and MMHT differ by 15 MeV.

AFB data would favor one set over another (also W asym data)

Outlook for the future

Tevatron combination

– $\sin^2\theta_{eff}^{lept} = 0.23179 \pm 0.00030$ (stat) ± 0.00017 (syst)

0.00035 GeV (total)

Inferences

	$\sin^2\theta_W$	M_W	Total
– CDF only:	$0.22400 \pm 0.00041 \pm 0.00019$	$80.328 \pm 0.021 \pm 0.010$ GeV/c^2	0.024 GeV
– D0 only:	$0.22313 \pm 0.00041 \pm 0.00020$	$80.373 \pm 0.021 \pm 0.010$ GeV/c^2	0.024 GeV
– Combination:	$0.22356 \pm 0.00029 \pm 0.00019$	$80.351 \pm 0.015 \pm 0.010$ GeV/c^2	0.018 GeV
	(stat) (syst)	(stat) (syst)	

MC studies: LHC with the new techniques:

Bodek et al. EPJC, 76(3), 1-12 (2016)

With current 8 TeV sample (12M dilepton events):
A CMS like detector at the LHC can match D0 or CDF errors at the Tevatron

In constraining PDFs, the more data the better. Therefore, with more integrated luminosity, both statistical errors and PDF errors are reduced (though not as much as statistical errors). Therefore, with increasing integrated luminosity, or by combining data from several experiments, it is possible to reduce both statistical and PDF errors.

With a 13 TeV sample (120M dilepton events):
A CMS like detector at the LHC can reduce the errors by a factor of 2.

With the same statistical samples: Direct and indirect measurements of W mass have similar errors.