Precision Measurements of Electroweak Parameters with Z Bosons at the Tevatron ($\sin^2\theta_{eff}^{lept}$, $\sin^2\theta_W^{on-shell}$, $M_W^{indirect}$)

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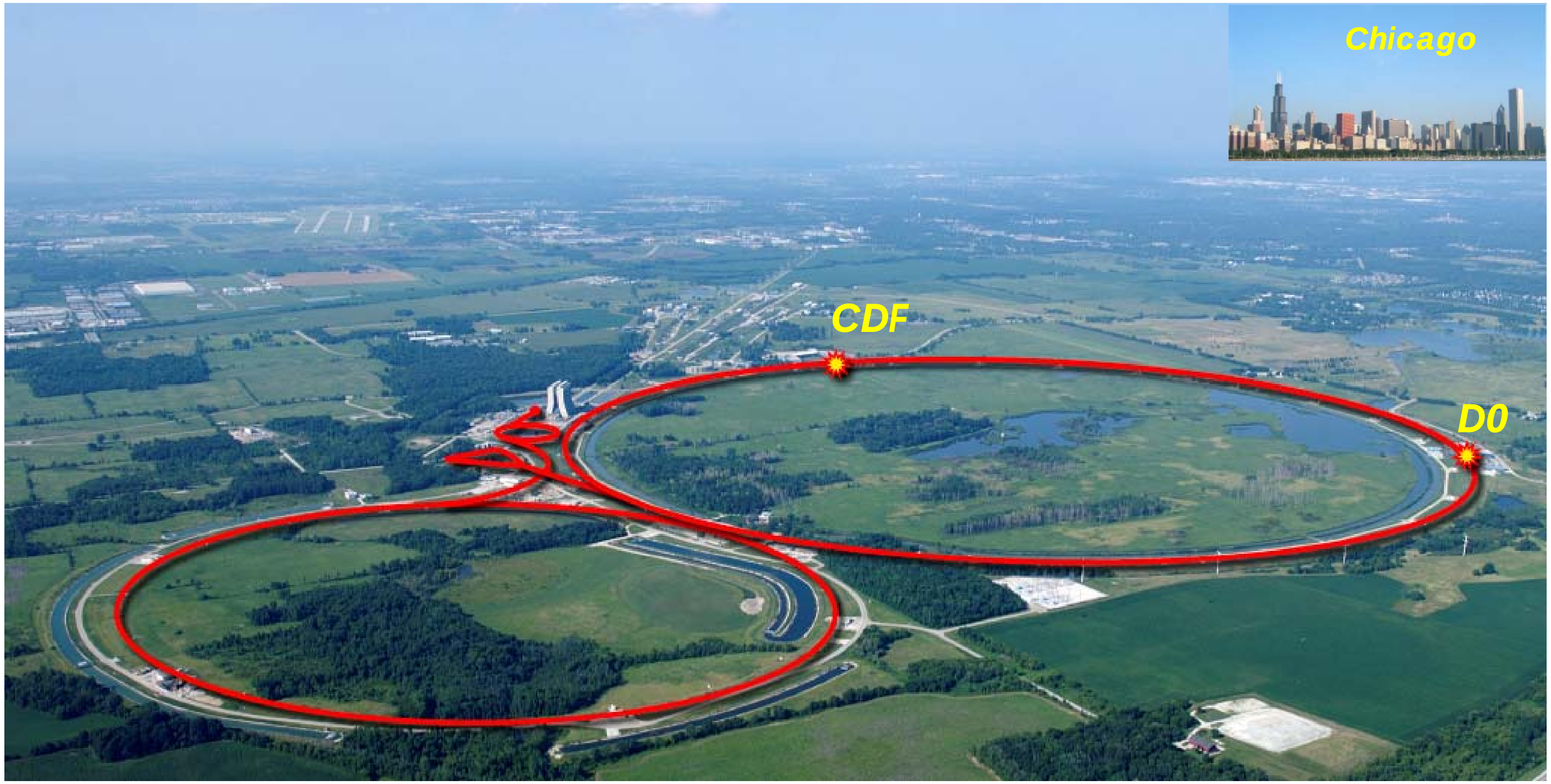
On behalf of CDF and D0

Blois 1/6/16

Thanks to all CDF & D0 colleagues



References

Dilepton forward-backward asymmetry of DY leptons $\rightarrow \sin^2\theta_{eff}^{leptonic}$

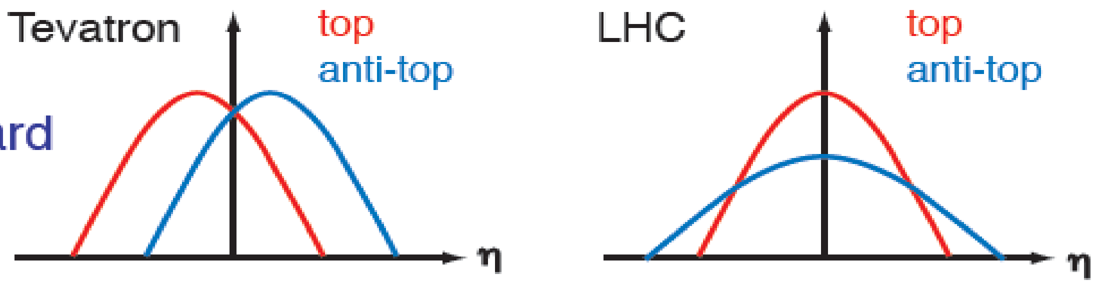
1. DØ e+e- (9.7 fb-1) Phys. Rev. Lett. 115, 041801(2015)
   ➔ $\sin^2\theta_{eff}^{leptonic}$(Mz)

2. CDF μ+μ- (9.2 fb-1) Phys. Rev. D89, 072005(2014:
   CDF e+e- + μ+μ (9.4 fb-1) submitted to Phys Rev D 2016
   ➔ $\sin^2\theta_{eff}^{leptonic}$ (Mz) & $\sin^2\theta_{eff}^{on\text{-}shell}$, M_w Indirect

See also A. Bodek et al arXiv:1507.02470
New method: PDF Constraints from Drell-Yan AFB

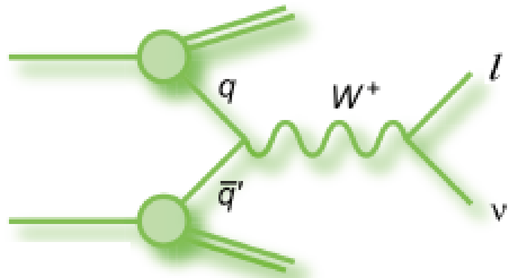
Tevatron Unique Dataset

- Different collision energy, $\sqrt{s_{\text{eff}}}$
  - Cross sections
  - Different (QCD) backgrounds
- $p\bar{p}$ collisions instead of pp
  - asymmetries; e.g., top, electroweak
  - Top quark forward-backward asymmetries:



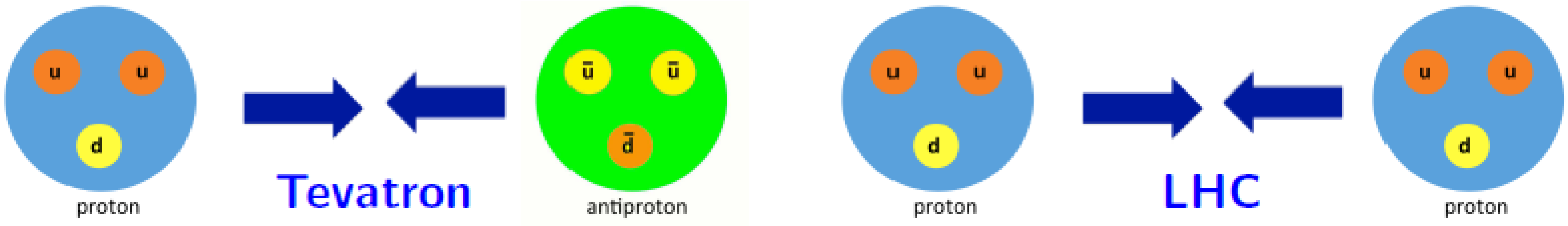
  - is an initial CP invariant state (*B* physics)
- Complementary! Production processes different mix of $q\bar{q}$ vs. gg collisions
  - $t\bar{t}$ spin correlations
- Well understood detector
  (plus lower level of pileup, only getting worse at LHC)
  - *W* boson mass
  - top quark mass

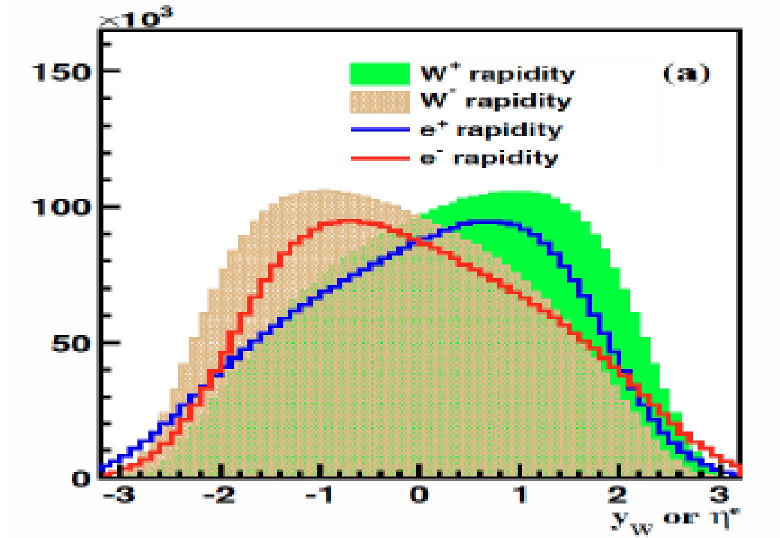
Tevatron: dominated by valence quark production

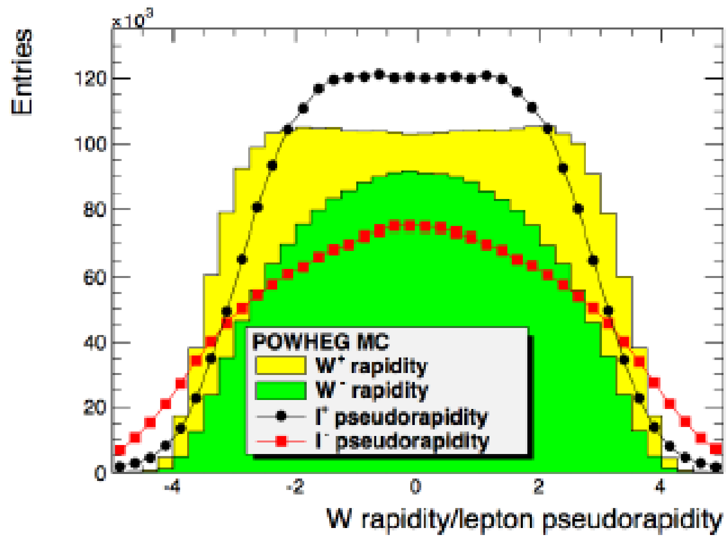


LHC: dominated by sea quark and gluon production

Measurement @Tevatron places stringent constraints on the PDFs

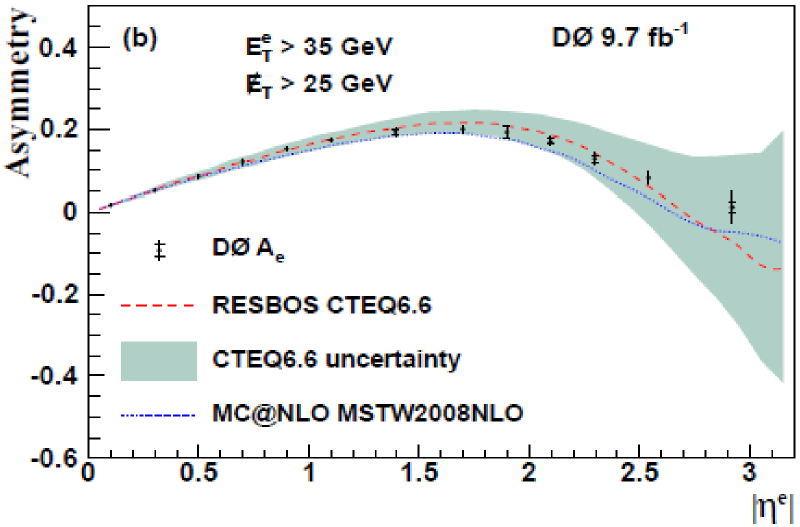






Lepton asymmetry: convolution of the W boson charge asymmetry and the V−A decay of the W boson.

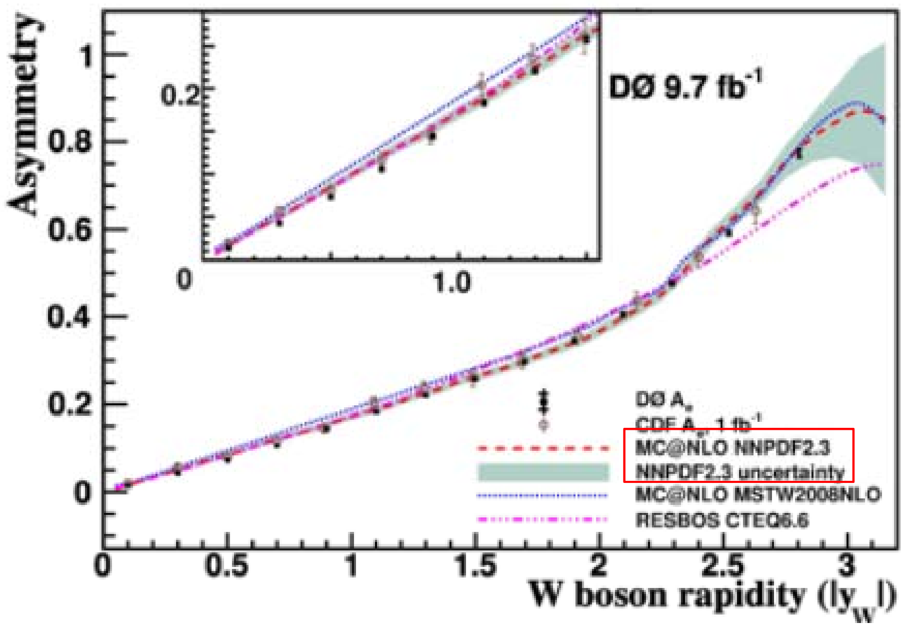
Lepton and W boson Charge Asymmetry

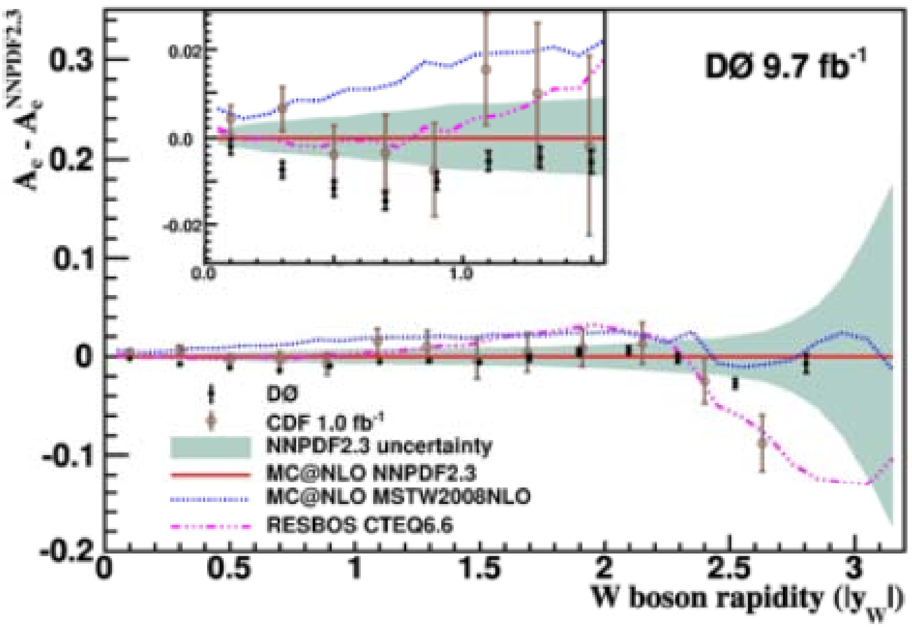


Full D0 dataset (9.7 fb^{-1}), electron channel

Lepton Charge Asymmetry:
Significant gain in precision and in η coverage
Most precise measurement of lepton charge asymmetry to date

W boson production asymmetry:
Potential improvement of PDF models in the x−Q^2 region of interest for W production at Tevatron ➔ will reduce the current PDF uncertainty in the W mass measurement by approximately 30% (down to 2-3 MeV)





Measuring $\sin^2\theta_W$ and W mass (indirectly) using Z's

- Experimentally interesting situation
- In the SM: $\sin^2\theta_W = 1 - m^2_W / m^2_Z$
  $\sin^2\theta_W$ indirectly measures m_W
- Derive $\sin^2\theta_{eff}^{lept}$ from angular distribution of leptons in Drell-Yan ($Z/\gamma^* \rightarrow l^+l^-$) events.

$$\frac{dN}{d\theta} \approx 1 + \cos^2\theta + A_4 \cos\theta$$

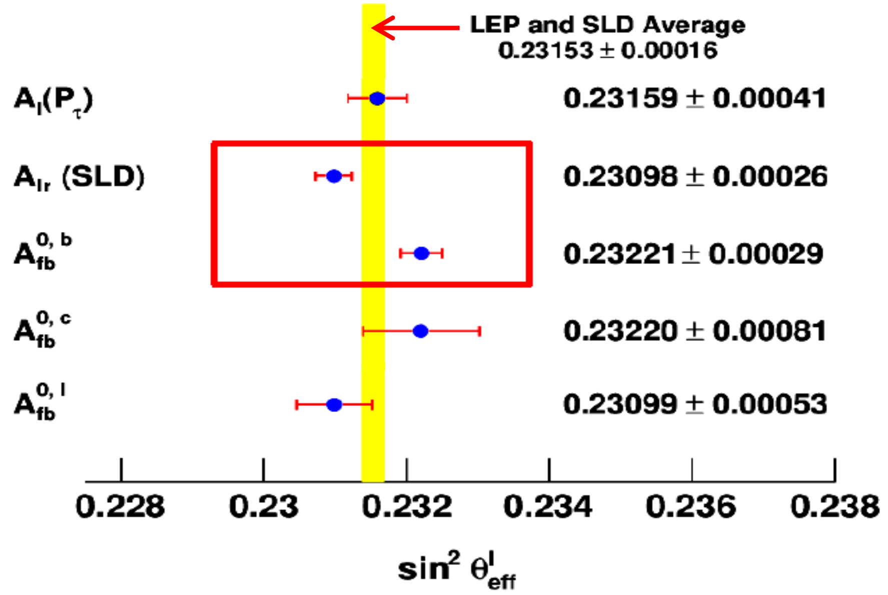
- Forward-backward asymmetry

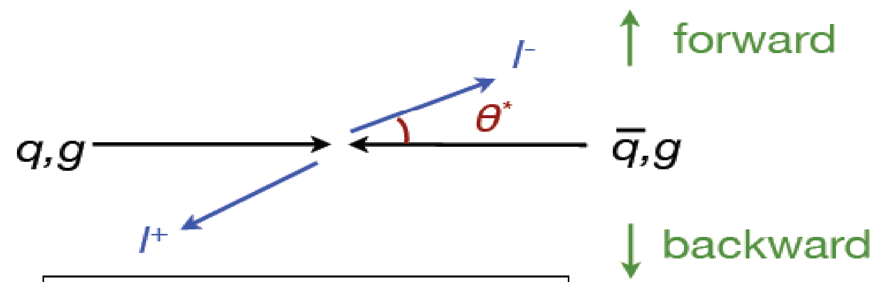
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8} A_4$$

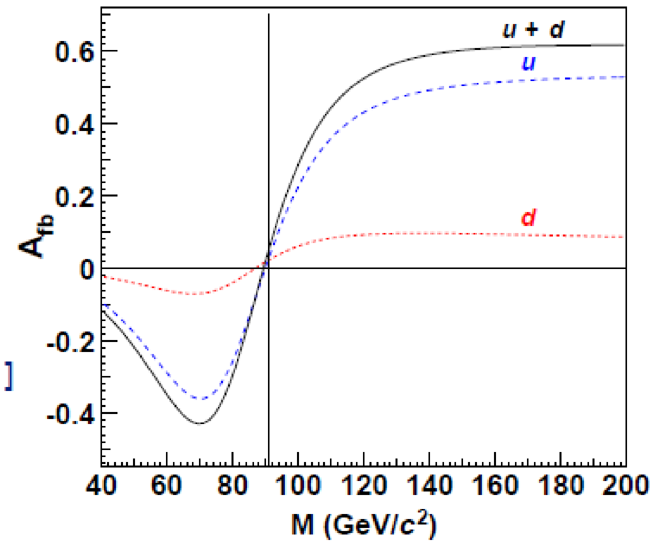
- Measurement $A_{FB} \rightarrow \sin^2\theta_{eff}^{lept}$
  (effective Z/lepton coupling)

$\sin^2\theta_{eff}^{lept} \simeq 1.037 \cdot \sin^2\theta_W$ [ZFITTER $\kappa_e(\sin^2\theta_W, M_Z)$ form factor]

$\rightarrow \sin^2\theta_W \rightarrow m_W$





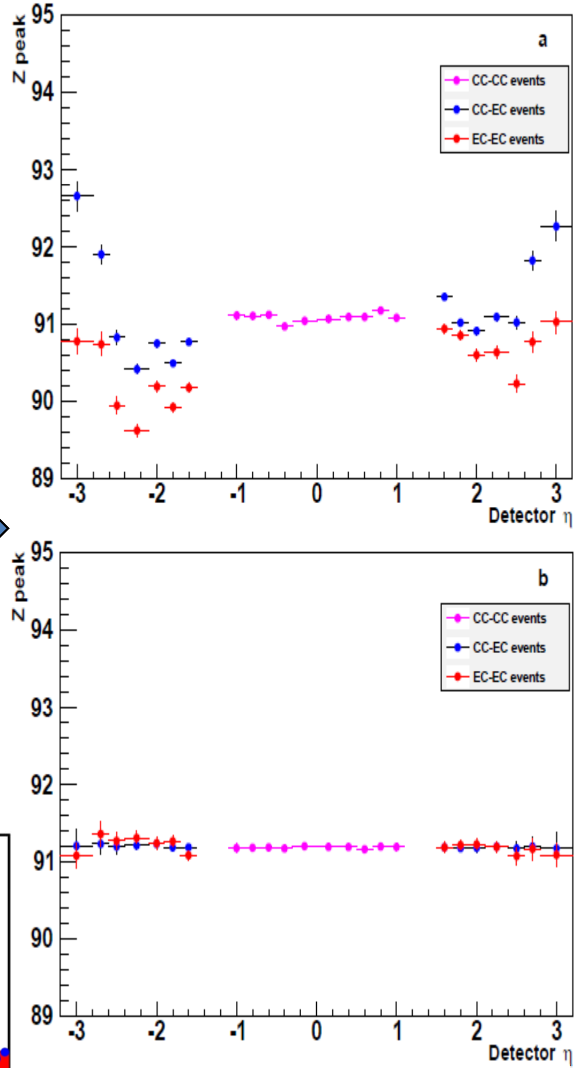


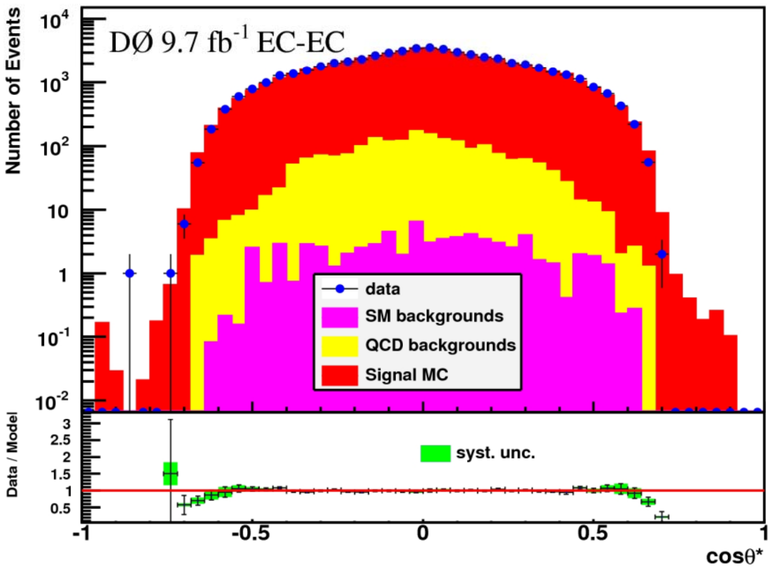
DØ e^+e^- 9.7 fb^{-1} $\sin^2\theta_{eff}^{lept}$ analysis

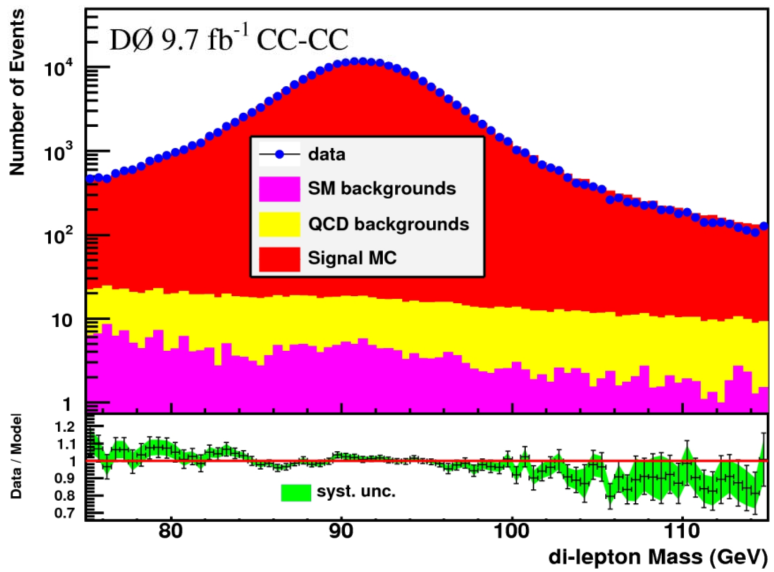
- two electrons with p_T > 25 GeV
- Tight track match requirement
- CC (|η|<1.1) and EC (1.5<|η|<3.2)
- Use 75<M_{ee}<115 GeV → 560k events
- New Lepton energy calibration

` ➔Apply scale factor as a function of L_{inst} first then as a function of η

- M_{ee} peak scaled to Z-LEP value in each bin
- Separate calibrations for data and MC



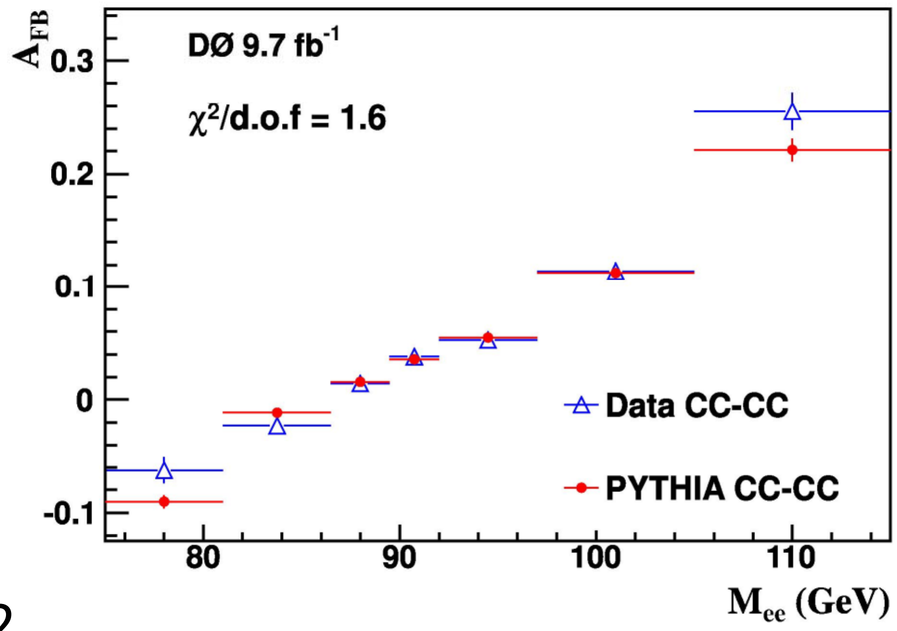




DØ e^+e^- 9.7 fb^{-1} $\sin^2\theta_{eff}^W$ analysis

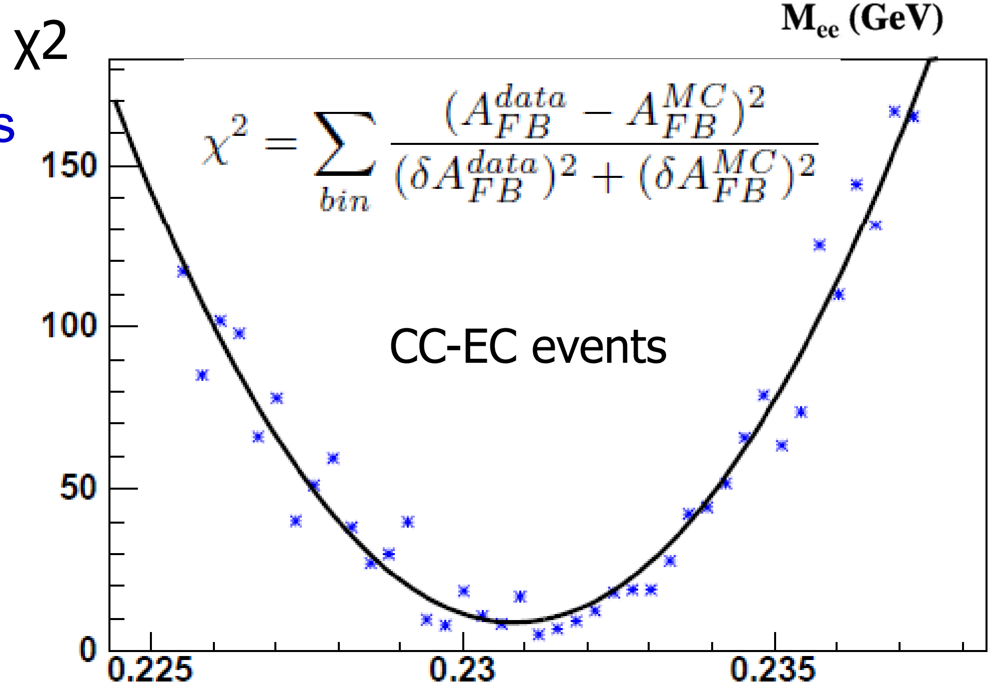
Corrections are applied to MC to account for:

- Smearing of electron energy
- Efficiency corrections in pT(e), η(e)
- L_{inst} and z_{PV} reweighting to match data
- Higher order effects: NNLO Z pT and y to match RESBOS
- Produce 2D templates of M_{ee} and $\cos\theta^*$ by reweighing default MC ($\sin^2\theta_{eff}$=0.232) as a function of $\sin^2\theta_{eff}$



Extract $\sin^2\theta_{eff}$ by fitting raw AFB to templates with different $\sin^2\theta_{eff}$ values

- No unfolding: MC is carefully corrected to describe the data

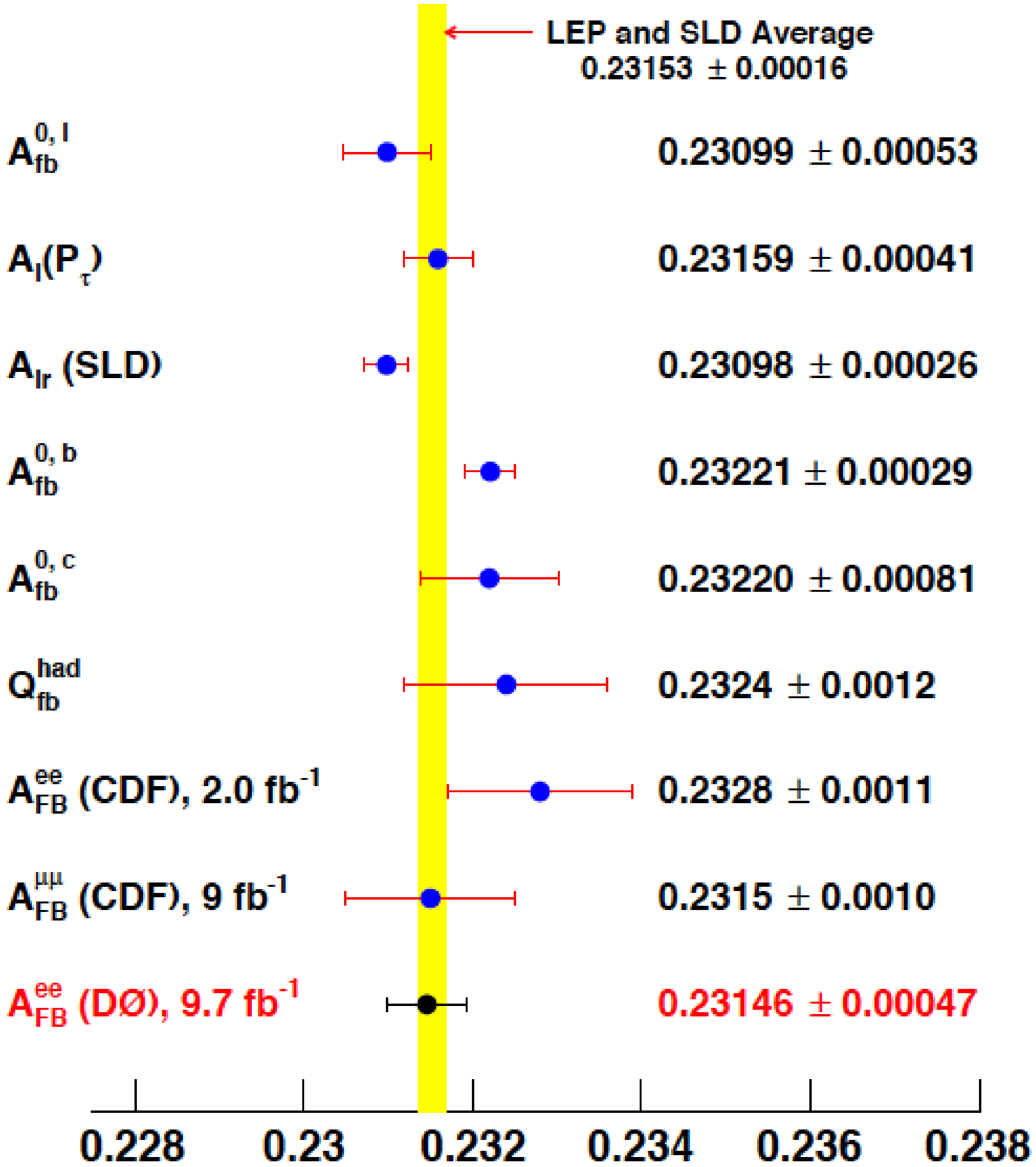


$\sin^2\theta_{eff}$ = 0.23138 ± 0.00043(stat) ± 0.00008(syst) ± 0.00017(NNPDF2.3 PDFs)

(no EW radiative corrections)

D0: Phys. Rev. Lett. 115, 041801 (2015)

DØ e^+e^- 9.7 fb^{-1} $\sin^2\theta_{eff}^W$ analysis



Situation in 2015

An approximate way to correct for the flavor dependence of $\sin^2\theta_{\text{eff}}$ from EW radiative corrections is used by the D0 collaboration. This is done by making the following corrections (proposed by Baur and collaborators [8]):

$$\sin^2\theta_{\text{eff}}^{\text{u-quark}} = \sin^2\theta_{\text{eff}}^{\text{lept}} - 0.0001$$

$$\sin^2\theta_{\text{eff}}^{\text{d-quark}} = \sin^2\theta_{\text{eff}}^{\text{lept}} - 0.0002$$

Change is +0.00008

Final results :DØ ee

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

$= 0.23146 \pm 0.00043$ (statistical)
± 0.00008 (systematics)
± 0.00017 (PDFs NNPDF2.3 NLO)

$= 0.23146 \pm 0.00047$ (total)

CDF $\mu^+\mu^-$ & e^+e^- 9.7 fb^{-1} $\sin^2\theta_{eff}^W$ analysis / indirect M_W

Main improvements are in 4 areas:

Since $\sin^2\theta_W$ 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'.

Precise lepton momentum/energy scale for muons and electrons using a new method- (will also reduce scale error for Mw measurement)
Ref: A. Bodek et al. Euro. Phys. J. C72, 2194 (2012)

Use event weighting method for AFB analyses (systematic errors in acceptance and efficiencies cancel)

Use Drell-Yan forward-backward asymmetry to constrain parton distribution functions - (will also reduce PDF errors for Mw measurement)
Ref A. Bodek et al arXiv:1507.02470v2 (2015)

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 in private versions of RESBOS, POWHEG, and LO) → Phys. Rev. D 88, 072002 (2013) Appendix A'

$g_V^f \gamma_\mu + g_A^f \gamma_\mu \gamma_5$. 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)

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

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

AFB = (3/8) A4

- 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

Accounts for $\sin^2\theta_{eff}$ dependence on quark flavor and dilepton mass
→ get $\sin^2\theta_{eff}^{\,leptonic}$(Mz) using A_{FB} over a range of dilepton mass

Precise Energy/Momentum Scale corrections

New technique used for both μ+μ- and e+e- for both data and hit level MC

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

2: Use the Z mass for calibration. The Z mass as a function of η,Φ, (and charge for μ+μ-) of each lepton must be correct

• Reference for electrons: expected Z mass (post FSR + clustered FSR photons), smeared by resolution (with acceptance cuts).

• Reference for muons: expected Z mass (post FSR) smeared by resolution (with acceptance cuts).

Gregorio Bernardi / LPNHE-Paris

Use event weighting Method

Event weighting method for A_{FB} analyses

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

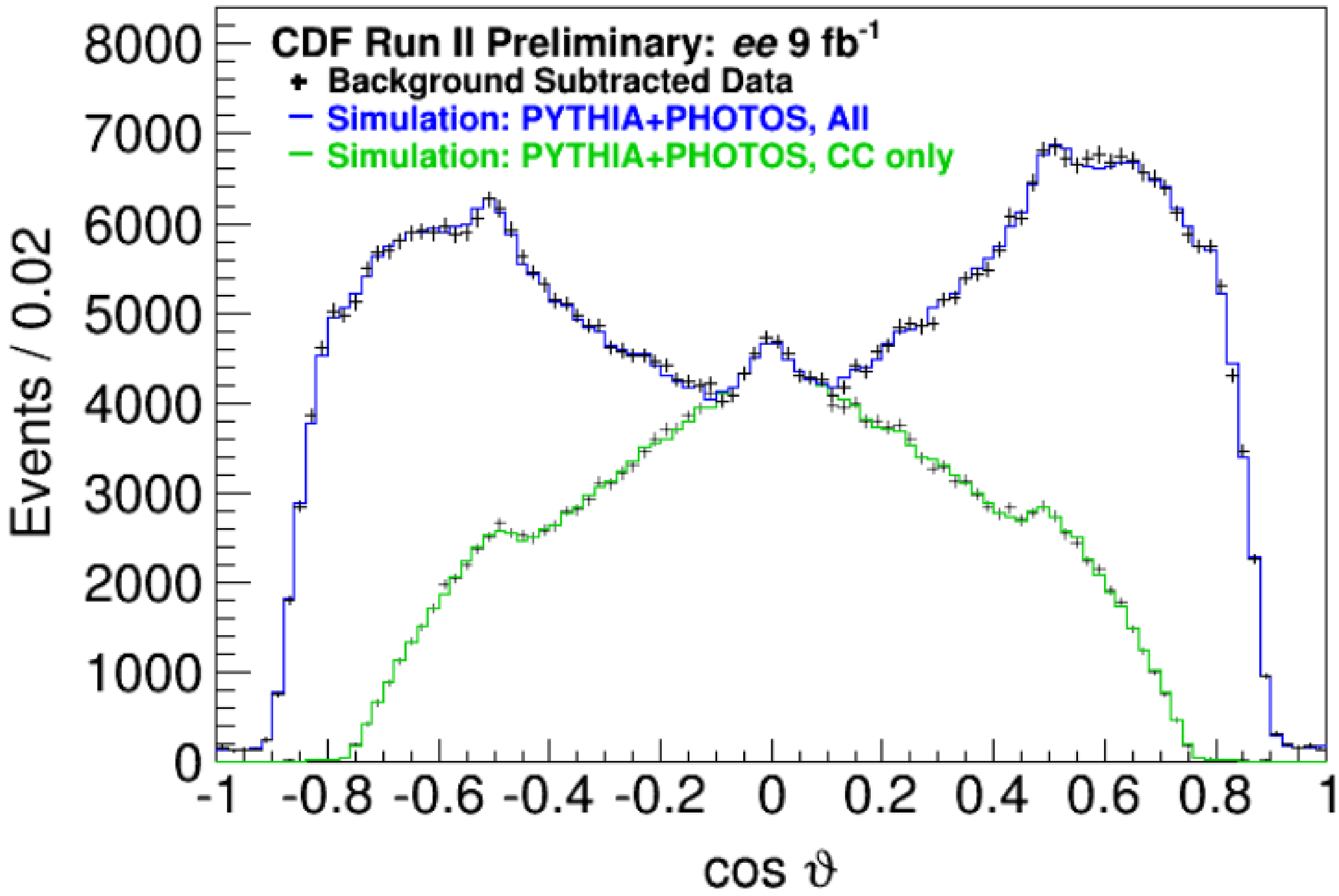
Angular event weighting is equivalent to extraction of $A_4(M)$ in bins of cos θ, and averaging the results.

Events at large cosθ provide better determination of A_4, so they are weighted more than events at small cosθ.

For each cosθ acceptance and efficiencies cancel to first order and the statistical errors are 20% smaller. Then extract $A_{FB} = (3/8)A_4$

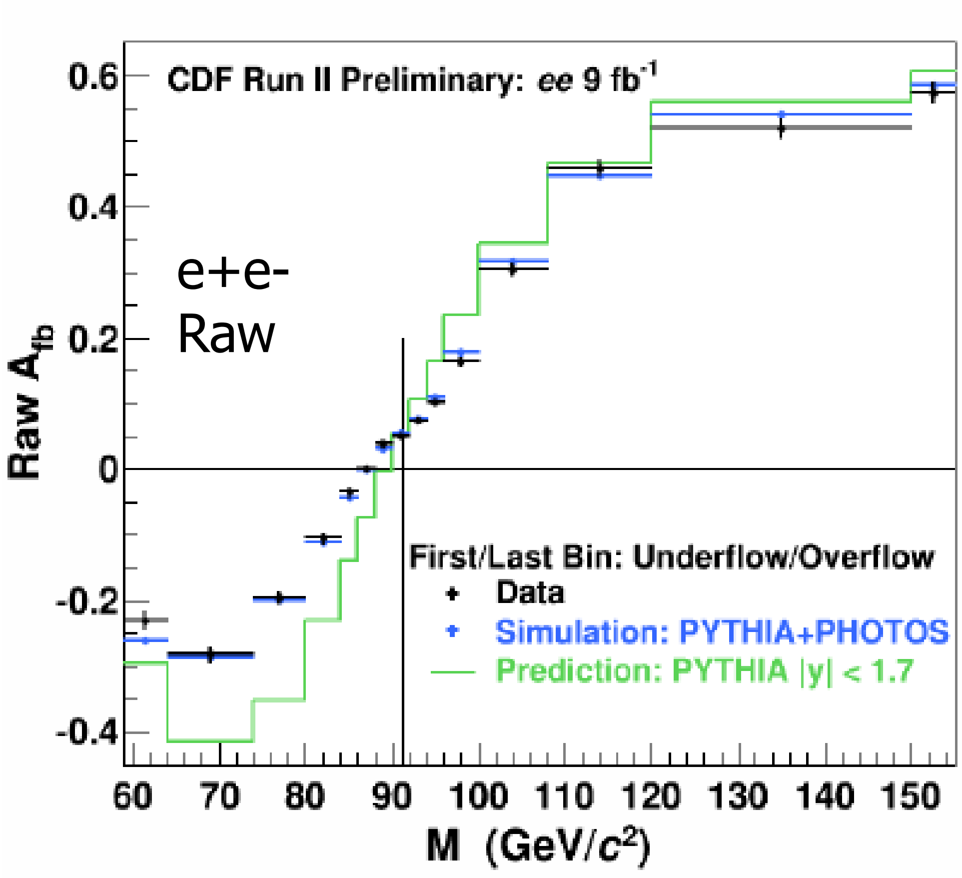
Event weighting does not correct for resolution smearing and final state radiation, which are included later in the unfolding.

Benefits from event weighting Method

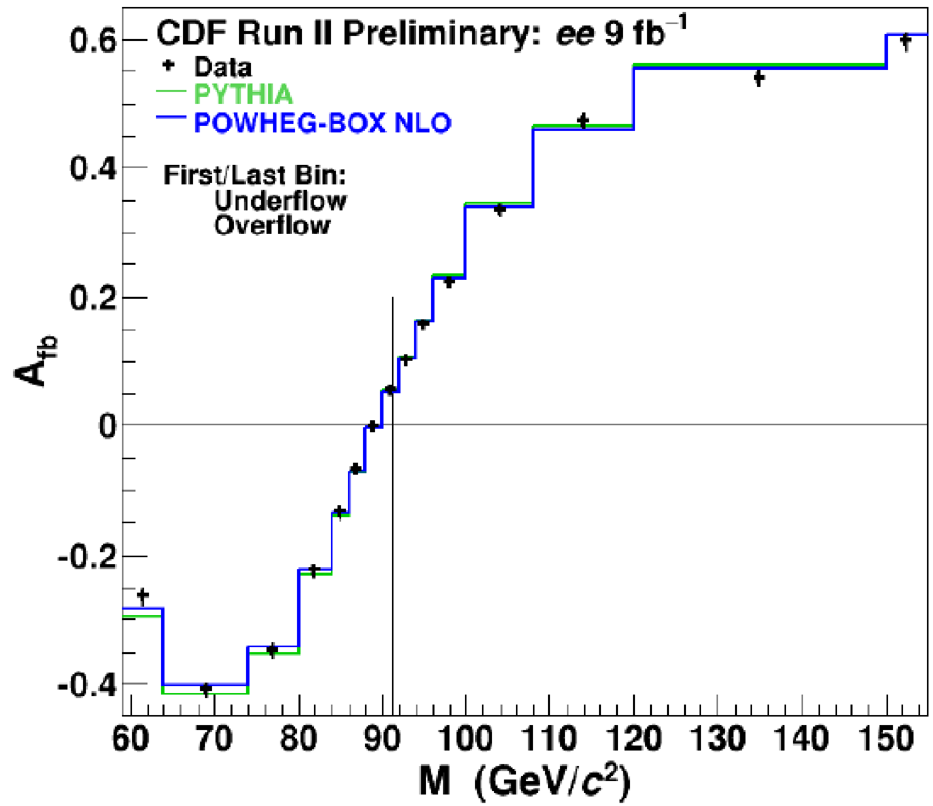


The error in A_{FB} is reduced if we have more acceptance at large cosθ,
Standard A_{FB} method requires precise knowledge of acceptance and efficiencies.
Measure A_4 → $\mathbf{A_{FB}}$

Unfolding/corrections in CDF e+e- analysis



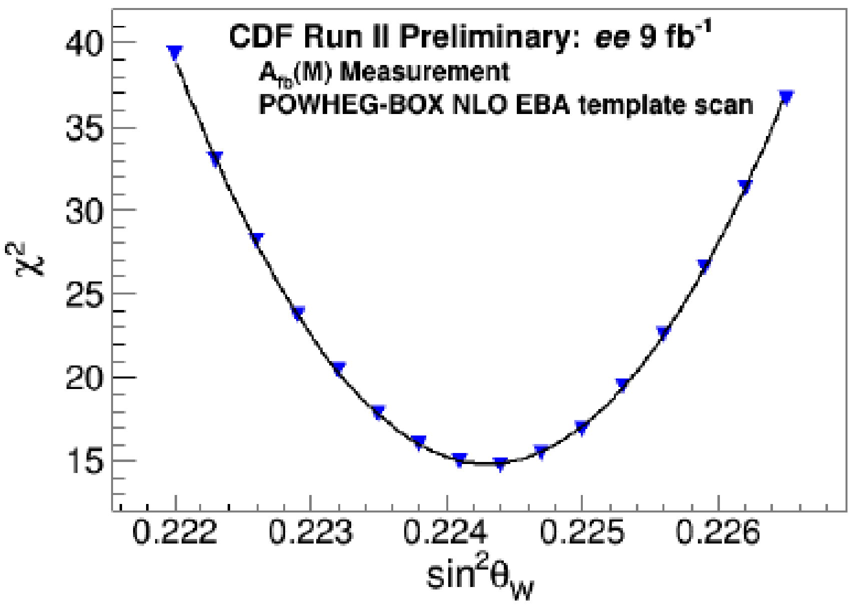
e+e-: A_{FB} Background subtracted
Raw no corrections



e+e- : A_{FB} unfolded, fully corrected

CDF e^+e^- : $\sin^2\theta_W$ extraction using templates

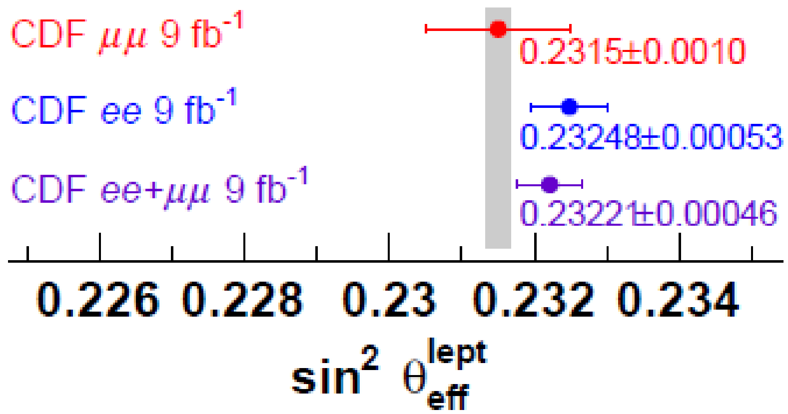
- Comparison χ^2: $\Sigma_M \Delta A_{fb}(M)^{\sim} \cdot E \cdot \Delta A_{fb}(M)$
  - Measurement: Fully corrected $A_{fb}(M)$
  - Calculated templates: $A_{fb}(M,\sin^2\theta_W)$ for 16 values of $\sin^2\theta_W$
  - E: Measurement error matrix
- Extraction of $\sin^2\theta_W$ from the scan points
  - Fit $\chi^2(\sin^2\theta_W)$ scan points to a parabola: $\chi^2_{min}+(\sin^2\theta_W-\sin^2\theta_{W\,min})^2/\sigma_{min}^2$
    - Assign each scan point $\chi^2(\sin^2\theta_W)$ an error of 0.1 in the parabolic fit
    - $(\sin^2\theta_{W\,min}, \sigma_{min})$ are the fit values of $\sin^2\theta_W$ and its uncertainty
    - χ^2_{min} = minimum $\chi^2(\sin^2\theta_W)$ at $\sin^2\theta_{W\,min}$ for 15 mass bins



This analysis is repeated with

1. POWEG ,2. RESBOS 3. Tree-Level LO

For the POWHEG analysis, the extraction is repeated for all 100 NNPDF3.0 Replicas to get PDF uncertainty



Indirect measurement of W mass

M_W also 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 equivalent to ±20 MeV error in M_w (indirect)

Both $\sin^2\theta_W^{\text{on-shell}}$ and $\sin^2\theta_{eff}^{\text{leptonic}}$ (Mz) 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 $\sin^2\theta_{eff}^{\text{leptonic}}$ (Mz) should also agree and deviations may imply new physics.

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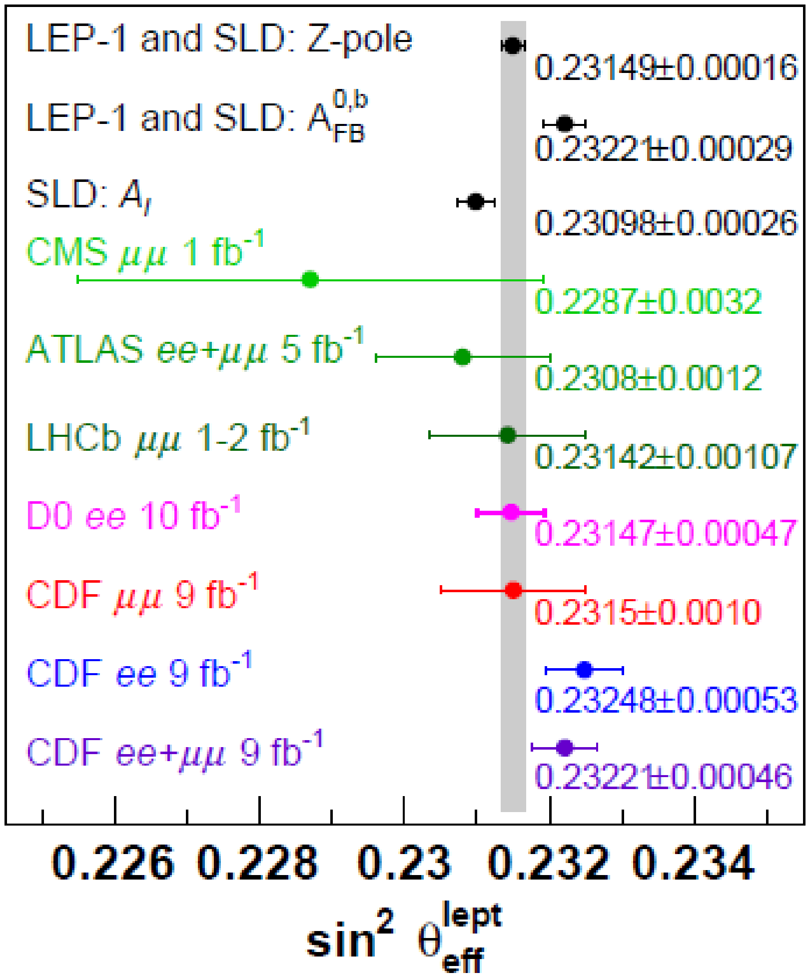
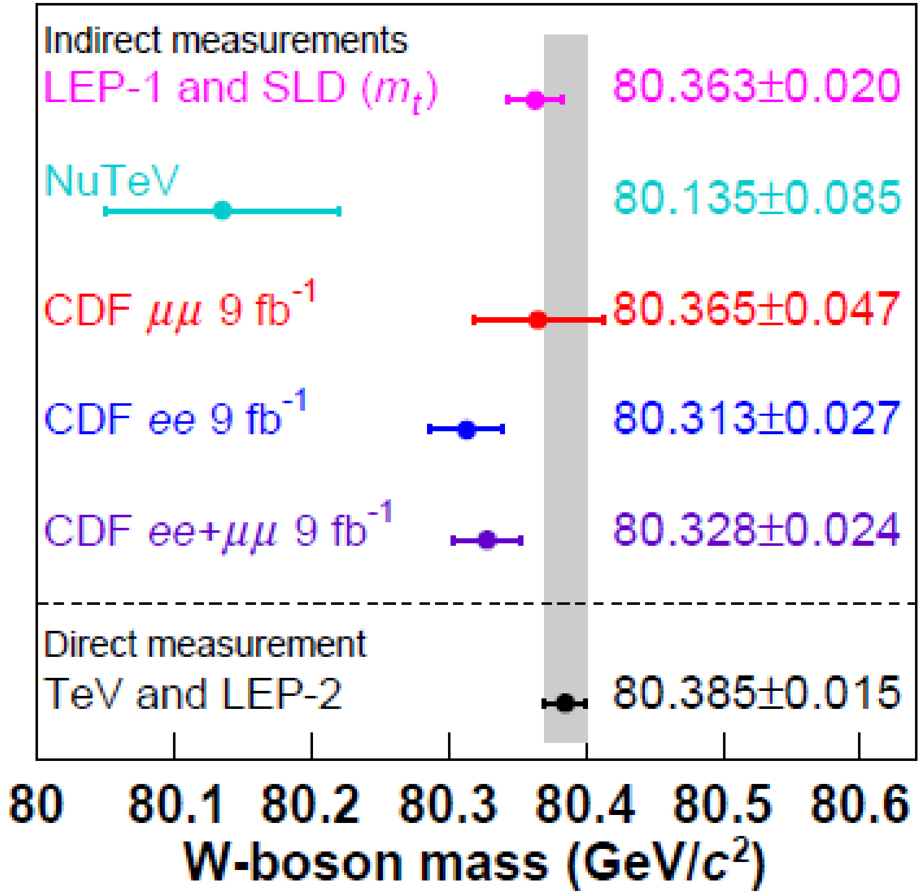
CDF and DØ results

Differences between D0 and CDF Analyses
1. CDF uses NNPDF 3.0 PDFs (NNLO) which include LHC data and supersede the NNPDF2.3 (NLO) used by D0
2. CDF uses full EBA EW rad correction. D0 uses partial Zgrad EW rad corr. Need to resolve these issues before the two results can be combined.





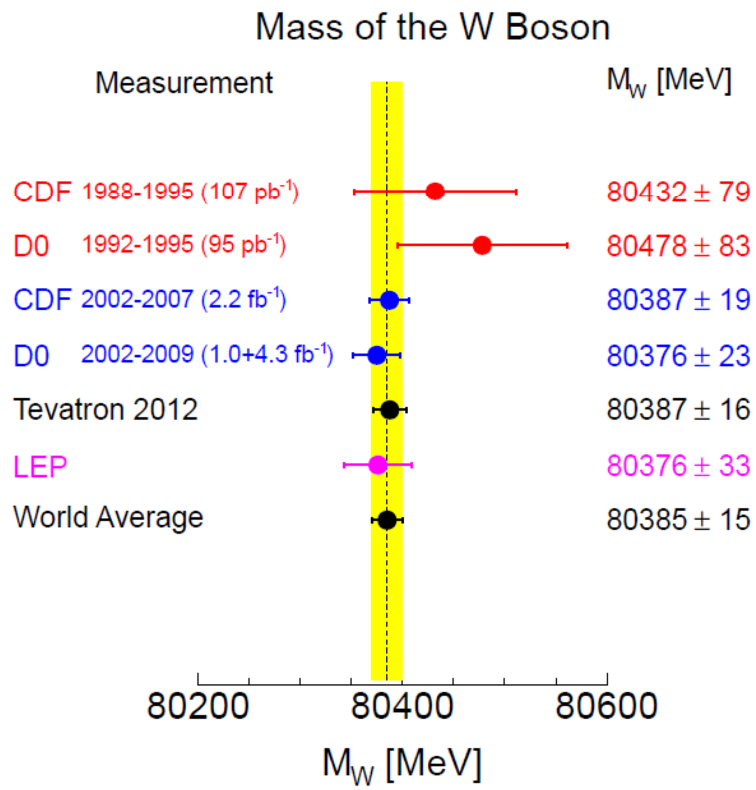
W Mass direct Measurement

- Tevatron Combination based on CDF (2.2 fb^{-1}) and D0 (5.1 fb^{-1}) results:

  M_w = (80387 ± 16) MeV

  ➔ 0.02% precision!

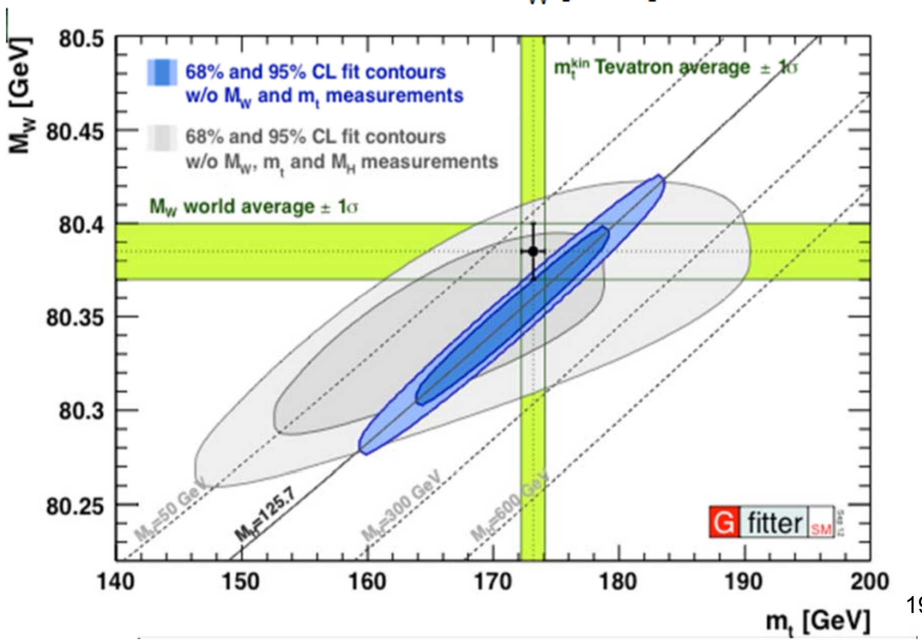
  dominates the World combination (15 MeV)



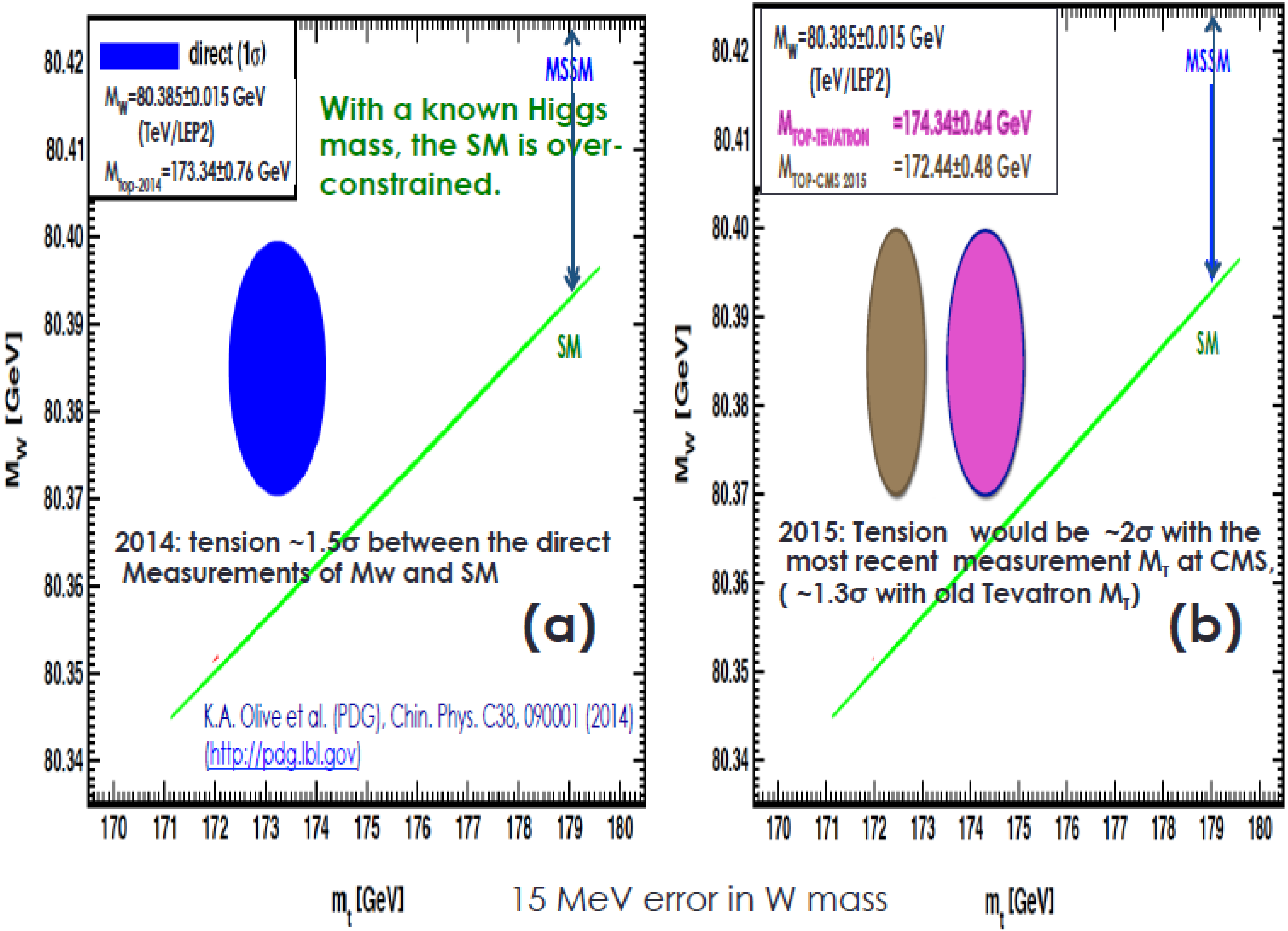
- Full-data results from both CDF and D0 in progress ➔ further reduction of uncertainties
  - Statistics gain ➔ energy scale uncertainty
  - Extension to forward leptons and PDF improvements will allow significant gain

- Target 10 MeV world average with new CDF and D0 measurements using full statistics.

- Consistency check of the SM (top-W-Higgs)



Top, and W Direct Mass Measurements



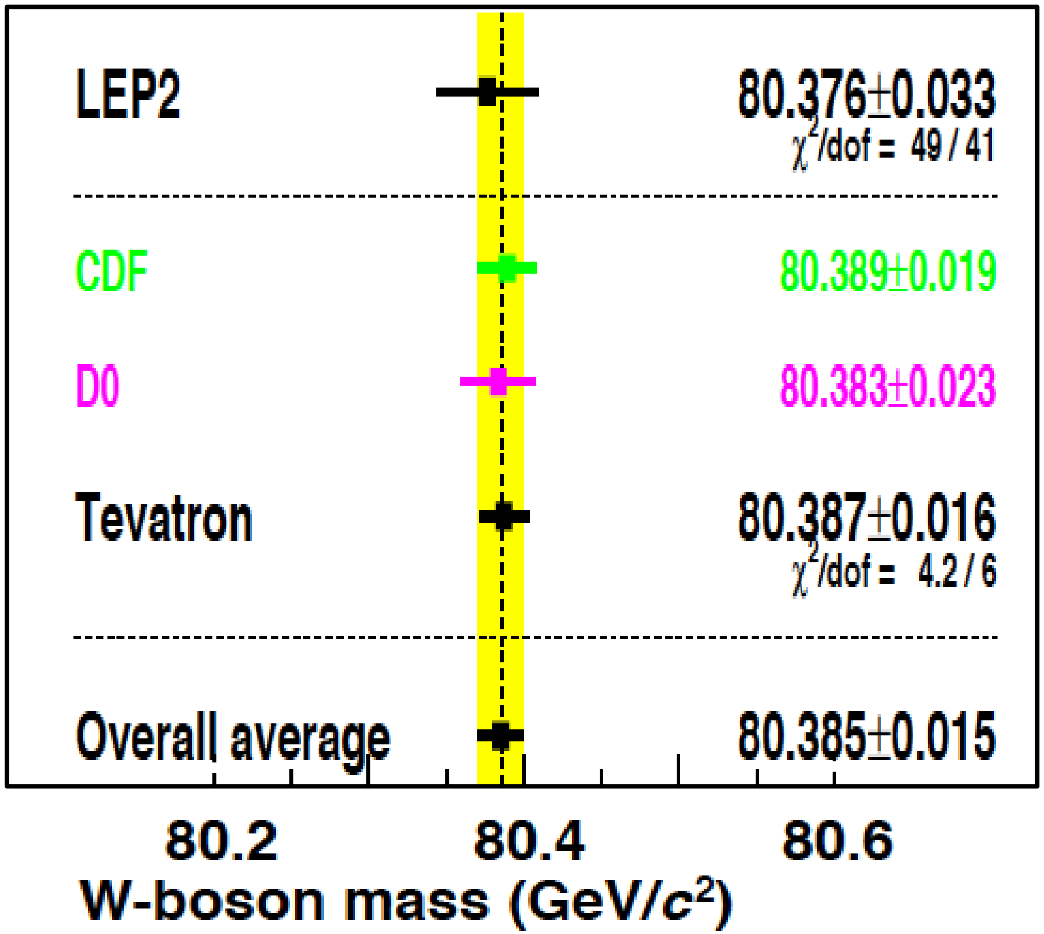
15 MeV error in W mass

Direct and Indirect W mass measurements

Direct measurements:

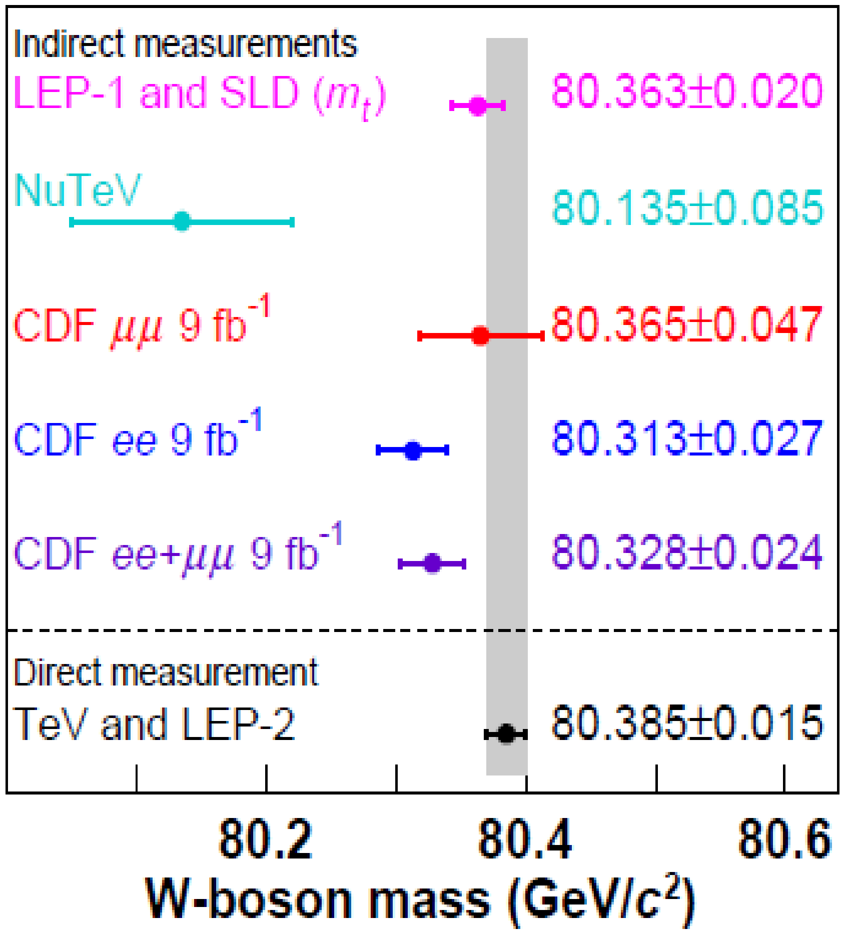
Waiting for update from CDF and D0 on

full dataset (currently 2 and 5 fb^{-1})



Indirect measurements:

CDF Mw 24 MeV indirect Mw uncertainty is similar to
CDF M_W 19 MeV direct Mw uncertainty



Conclusions / Tevatron Legacy

- The CDF and DZero collaborations are still producing competitive physics results in particular in the electroweak sector

- Currently the Tevatron direct (L= 2.2 fb-1) and indirect (L=9.4 fb-1) measurements of Mw have similar errors. (~ 20 MeV per experiment)

- Tevatron Run II Legacy measurements of $\sin^2\theta_w$ and Mw indirect are in agreement with SM predictions from M_H and M_{top}, and with direct measurement of M_W

- $A_{FB}(M)$ data can also be used to put additional constraints on PDFs. These constraints will help reduce PDF errors in the ongoing Tevatron Run II Legacy (L=9.4 fb-1) direct measurement of Mw.