Direct and Indirect Top and W mass measurements, and constraints on the Higgs from the Tevatron

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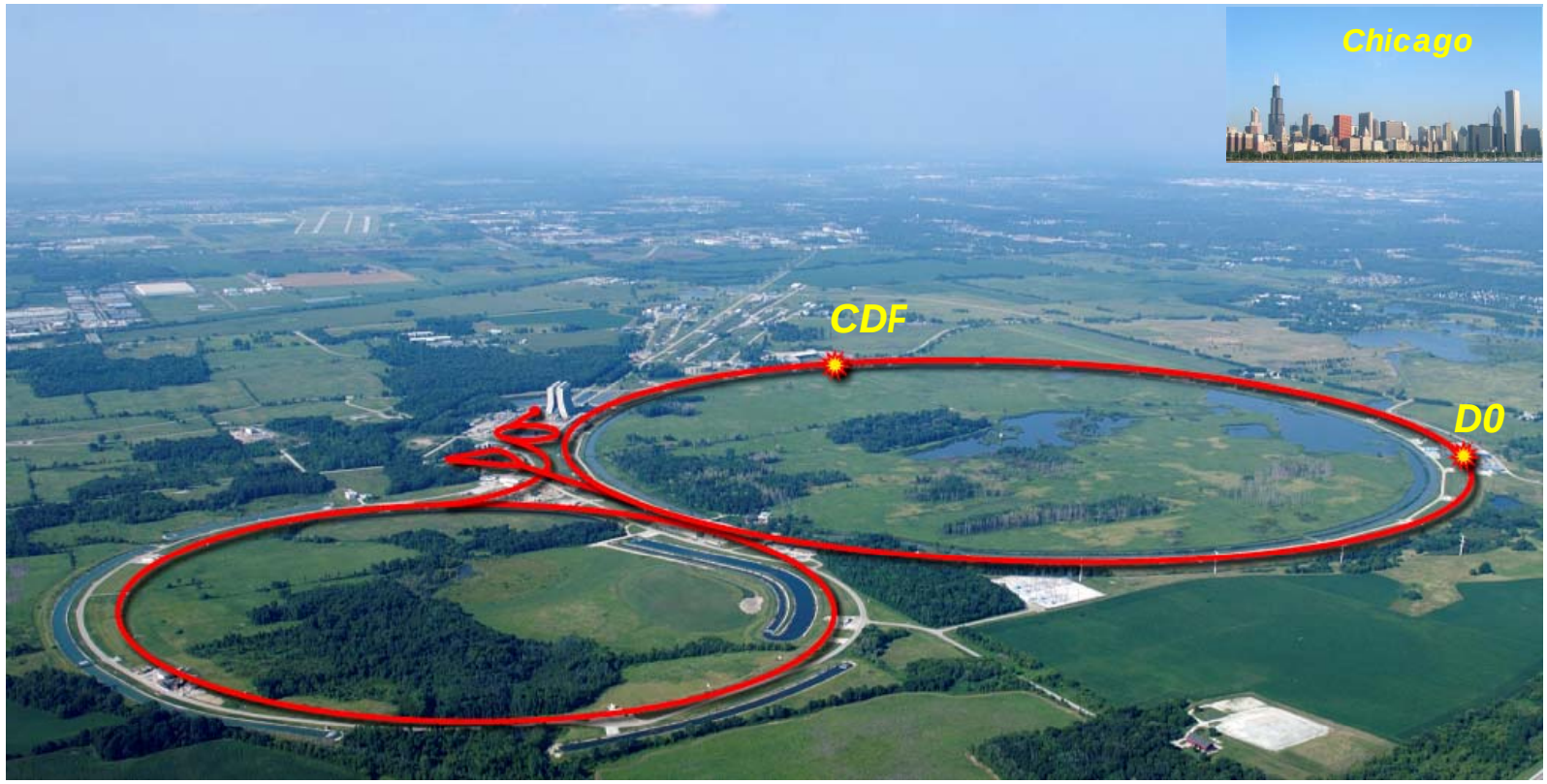
On behalf of CDF and D0

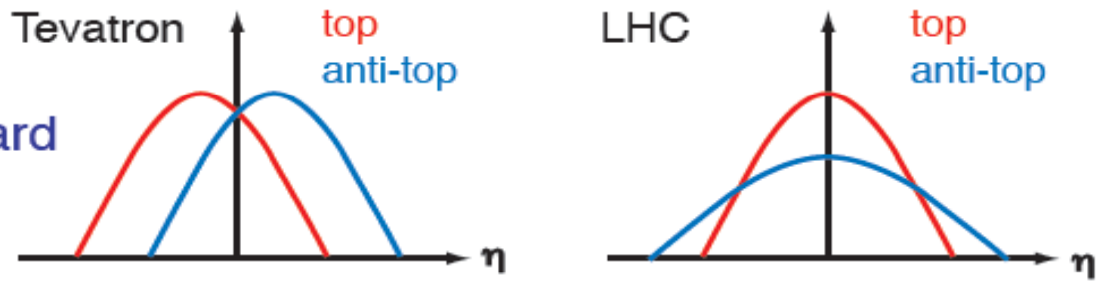
Higgs couplings 11/11/16

Thanks to all CDF & D0 colleagues



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:



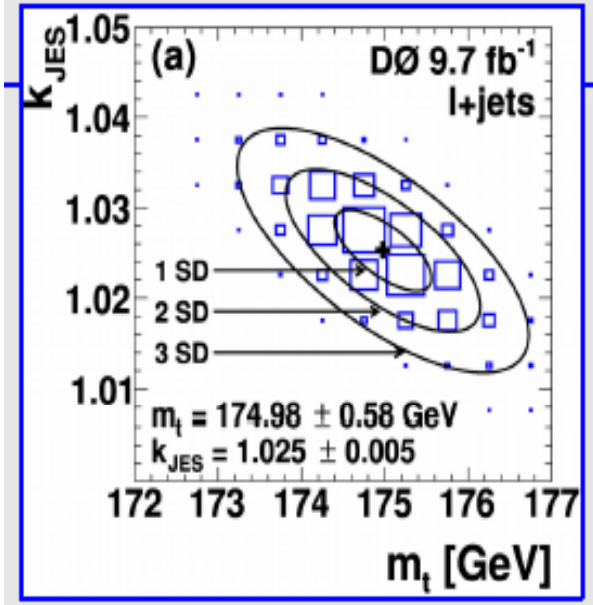
  - is an initial CP invariant state (B physics)
- Complementary! Production processes different mix of $q\bar{q}$ vs. gg collisions
  - $t\bar{t}$ spin correlations
- Well understood detector
  (plus lower level of pileup, only getting worse at LHC)
  - W boson mass
  - top quark mass

Most recent Direct top Mass measurements from Tevatron

ℓ+jets matrix element top mass

$m_t = 174.98 \pm 0.58(\text{stat} \pm 0.49(\text{syst}) \text{ GeV}$
$+\text{JES})$

$\Delta m_t / m_t = 0.43\%$

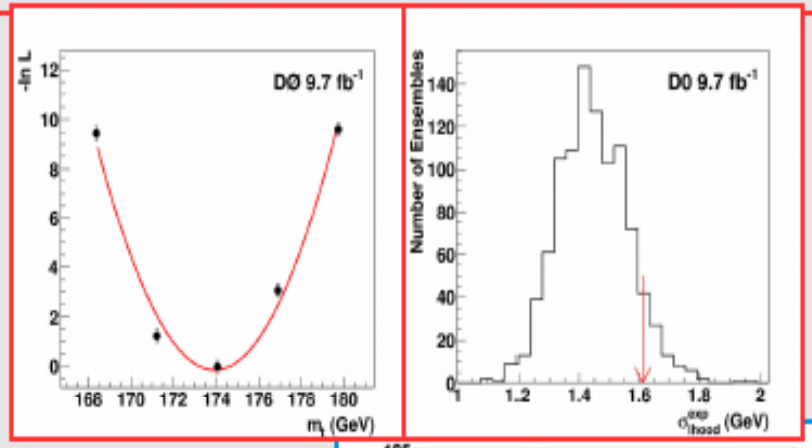


PRL 113, 032002 (2014),
PRD 91, 112003 (2015)

dilepton matrix element top mass

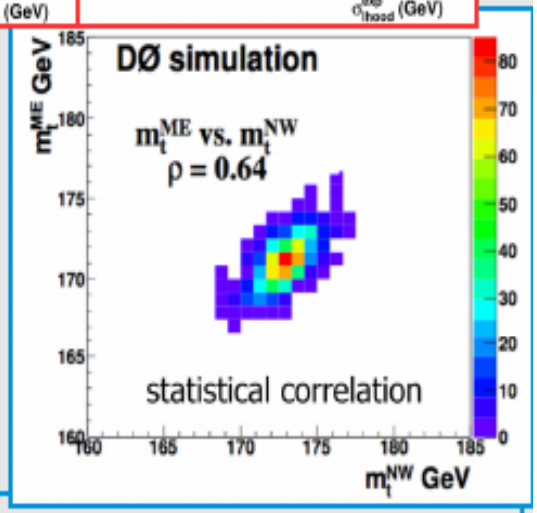
$m_t = 173.93 \pm 1.61(\text{stat}) \pm 0.88(\text{syst})\text{GeV}$

$\Delta m_t / m_t = 1.05\%$



Phys. Rev. D 94,
032004 (2016)

$$\omega = \frac{1}{N}\sum_{i=1}^{N}\prod_{j=x,y}\exp\left(-\frac{(\not{E}_{T_{j,i}}^{\text{calc}} - \not{E}_{T_j}^{\text{obs}})^2}{2\sigma^2_{\not{E}^u_{T_j}}}\right)$$



Phys. Lett. B 752 18 (2016)

dilepton neutrino weighting mass

$m_t = 173.32 \pm 1.36(\text{stat}) \pm 0.85(\text{syst})\text{GeV}$

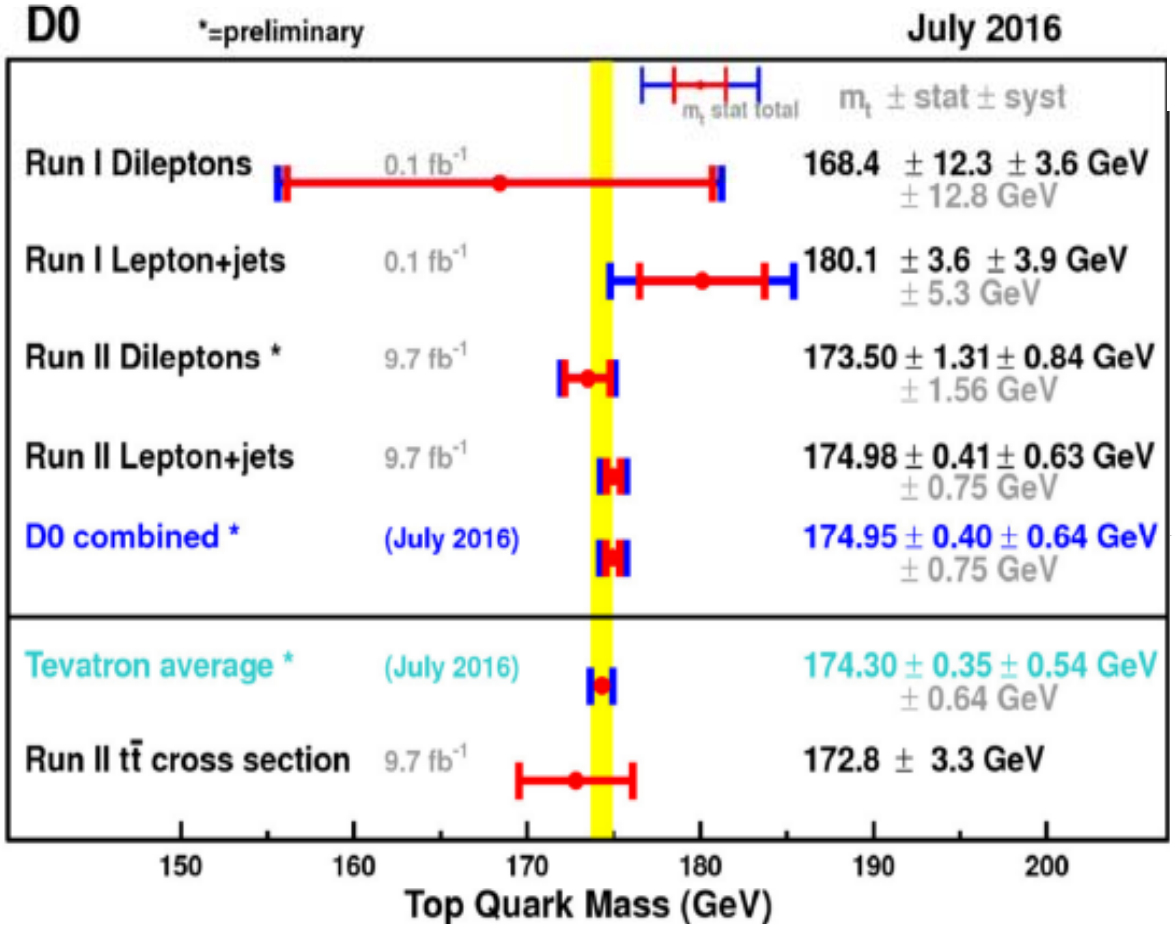
$\Delta m_t / m_t = 0.93\%$

D0 note 6484

dilepton combination (new)

$m_t = 173.50 \pm 1.31(\text{stat}) \pm 0.84(\text{syst})$ GeV

D0 Top mass Combination (July 2016)



D0 note 6484

	Run I		Run II	
	$\ell+$jets	$\ell\ell'$	$\ell+$jets	$\ell\ell'$
In situ light-jet calibration (iJES)			×	×
Response to $b/q/g$ jets (aJES)	o	o	×	×
Model for b jets (bJES)	×	×	×	×
Out-of-cone correction (cJES)	×	×	×	×
Light-jet response (dJES)	o	o	×	×
Lepton modeling (LepPt)	o	o	×	×
Signal modeling (Signal)	×	×	×	×
Jet modeling(DetMod)	×	×	×	×
b-tag modeling (b-tag)	o	o	×	×
Background from theory (BGMC)	×	o	×	o
Background based on data (BGData)				
Calibration method (Method)				
Offset (UN/MI)	×	×		
Multiple interactions model (MHI)	o	o	×	×
Statistical				

o,x: 100% correlated
o not correlated with x

D0 combination (preliminary)
m_t = 174.95 ± 0.40 (stat) ± 0.64 (syst) GeV
$\Delta m_t / m_t$ = 0.43%

χ^2 /ndof = 2.5/3, prob = 47 %

	D0 Run I		D0 Run II	
	$\ell+$jets	$\ell\ell'$	$\ell+$jets	$\ell\ell'$
Pull	0.98	−0.51	0.63	−1.06
Weight	0.00	−0.00	0.96	0.03

Tevatron Top mass Combination (July 2016)

arXiv:1608.01881

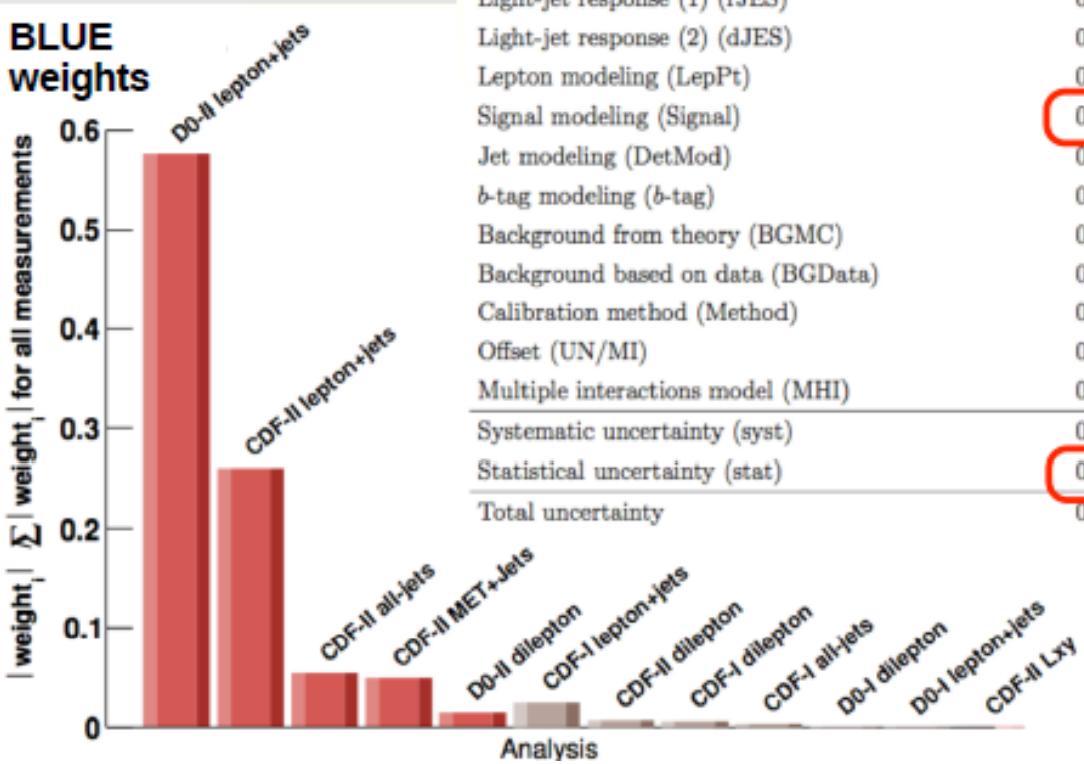
- new D0 dilepton measurement
- published CDF all-jets measurement

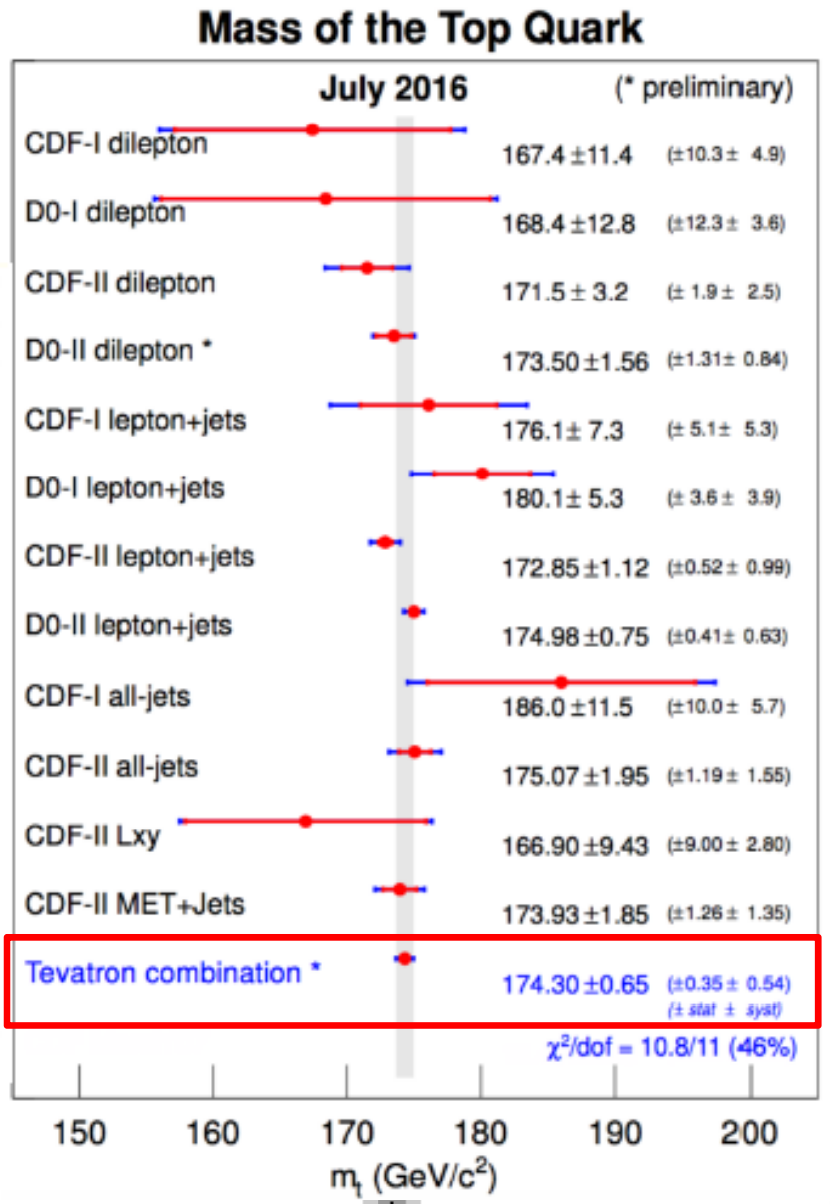
m_t = 174.30 ± 0.35 (stat) ± 0.54 (syst) GeV

$\Delta m_t / m_t$ = 0.37%

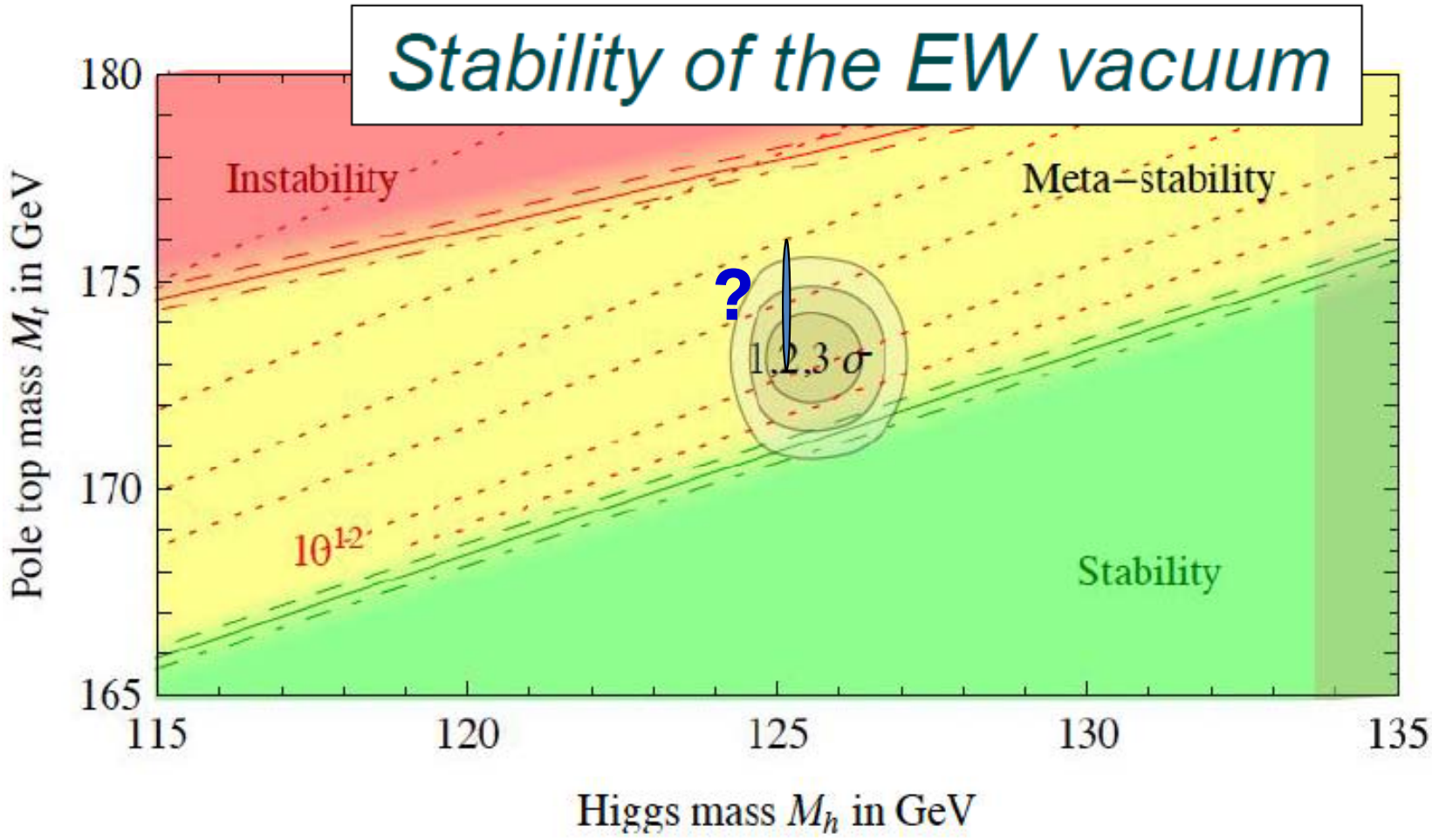
X^2/dof = 10.8/11, prob = 46%

	Tevatron combined values (GeV/c^2)
M_t	174.30
In situ light-jet calibration (iJES)	0.31
Response to $b/q/g$ jets (aJES)	0.11
Model for b-jets (bJES)	0.10
Out-of-cone correction (cJES)	0.03
Light-jet response (1) (rJES)	0.05
Light-jet response (2) (dJES)	0.14
Lepton modeling (LepPt)	0.01
Signal modeling (Signal)	0.36
Jet modeling (DetMod)	0.05
b-tag modeling (b-tag)	0.07
Background from theory (BGMC)	0.04
Background based on data (BGData)	0.07
Calibration method (Method)	0.07
Offset (UN/MI)	0.00
Multiple interactions model (MHI)	0.06
Systematic uncertainty (syst)	0.54
Statistical uncertainty (stat)	0.35
Total uncertainty	0.65





Higgs and Top pole mass

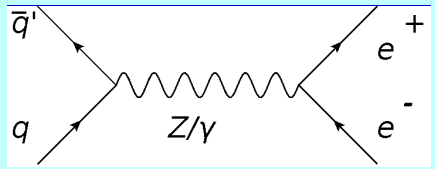


Degrassi *et al* 2013

But what is the mass difference between the directly measured mass and the top pole mass ?

Let's look now at the M_{top} , M_W , M_H constraints

Measuring $\sin^2\theta_W$ and W mass (indirectly) with 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.

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

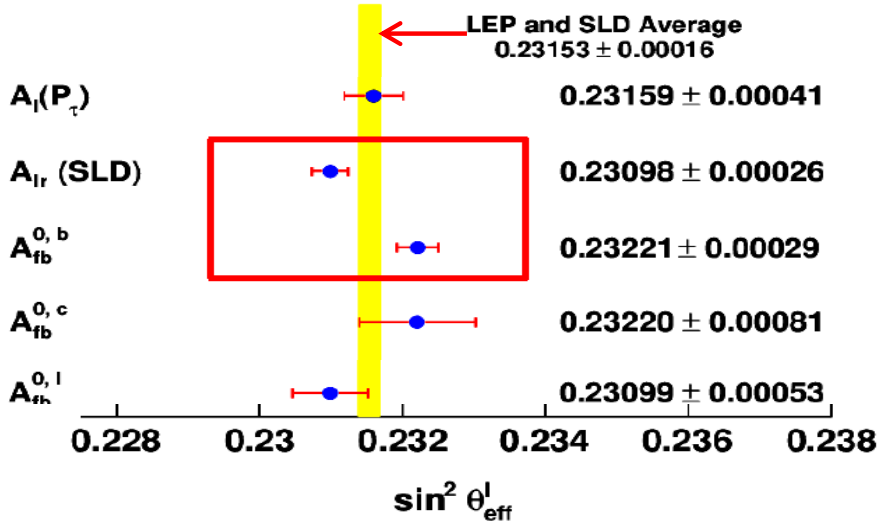
- Forward-backward asymmetry

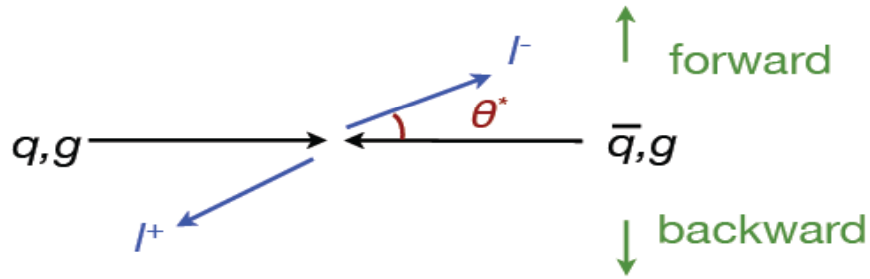
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{8} A_4$$

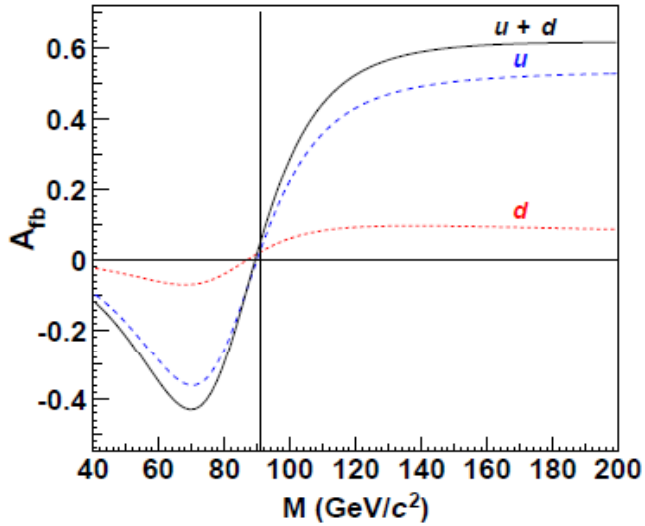
- Measurement $A_{FB} \rightarrow \sin^2\theta_{eff}^{lept}$
  (effective Z/lepton coupling)

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

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

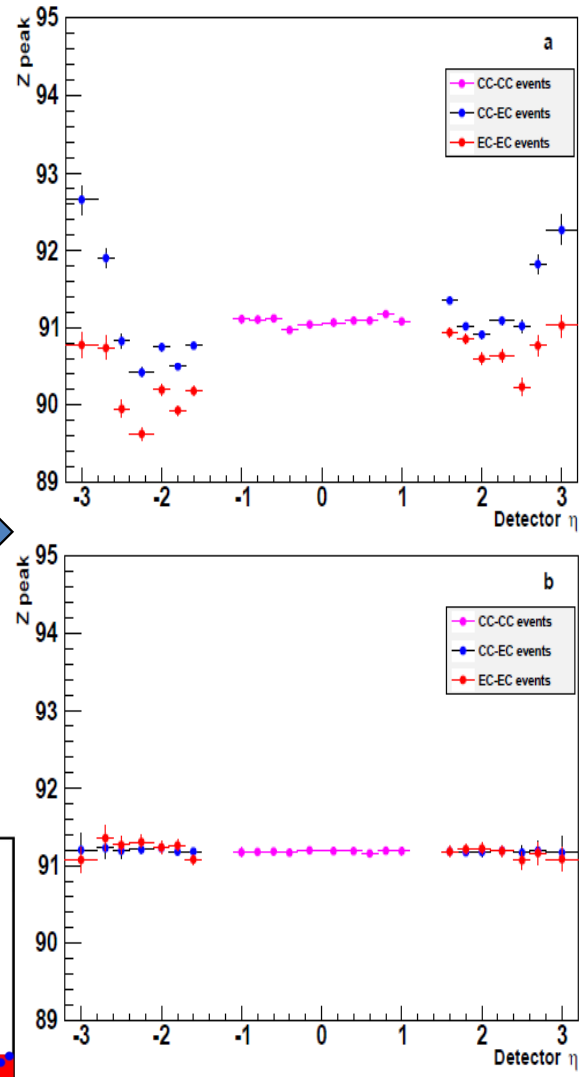


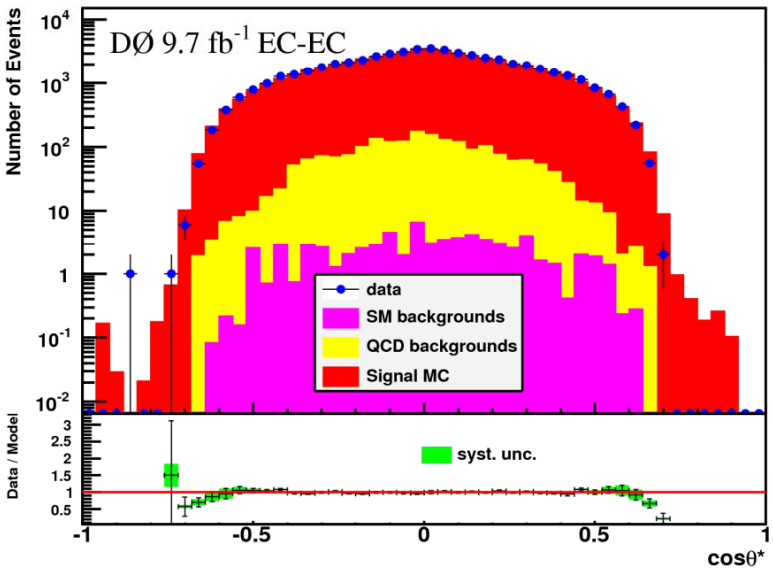


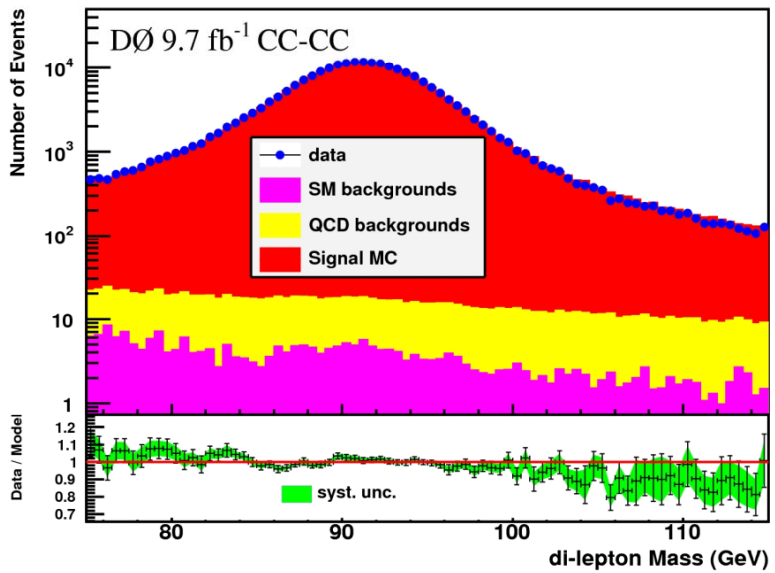


DØ e^+e^- 9.7 fb^{-1} $\sin^2\theta_{eff}^{lept}$ analysis

- two electrons with p_T > 25 GeV
- 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



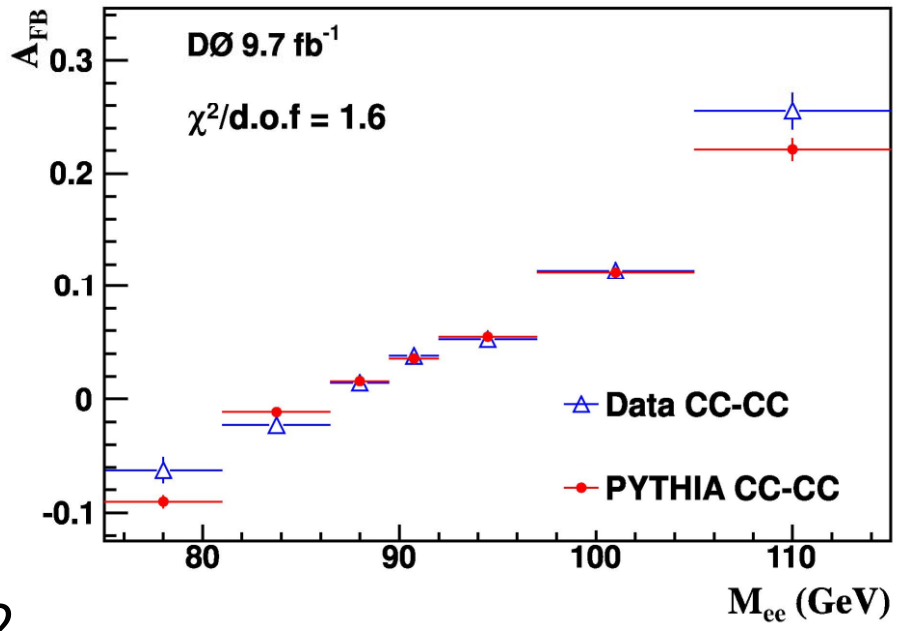




DØ e^+e^- 9.7 fb^{-1} $\sin^2\theta_{eff}^{lept}$ analysis

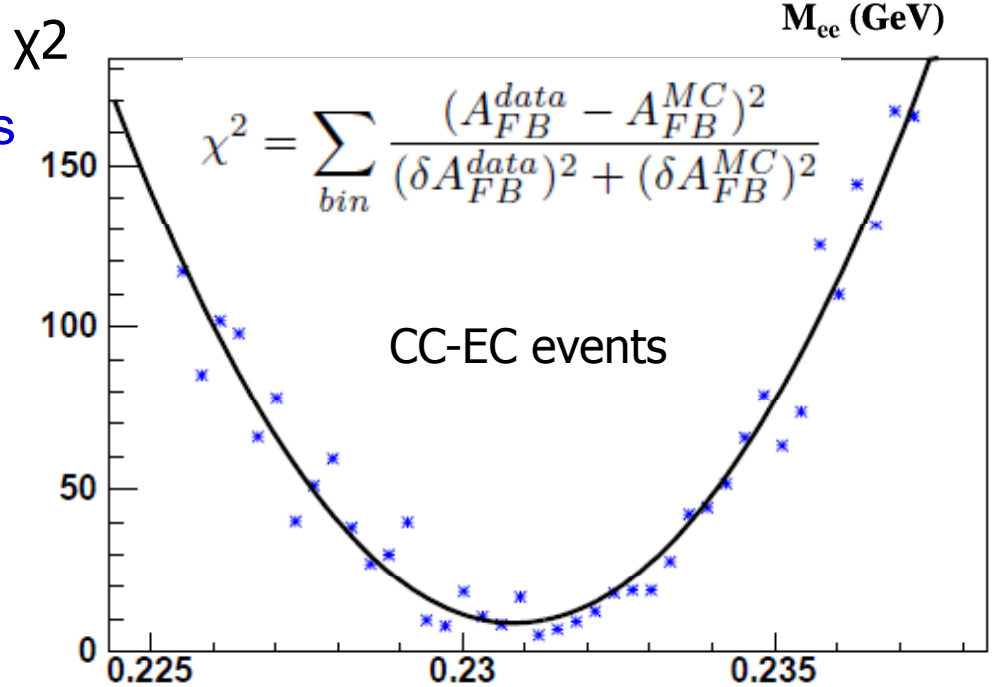
Corrections are applied to MC to account for:

- Smearing of electron energy
- Efficiency corrections in pT(e), η(e)
- L_{inst} and z_{PV} reweighting to match data
- Produce 2D templates of M_{ee} and cosθ* 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

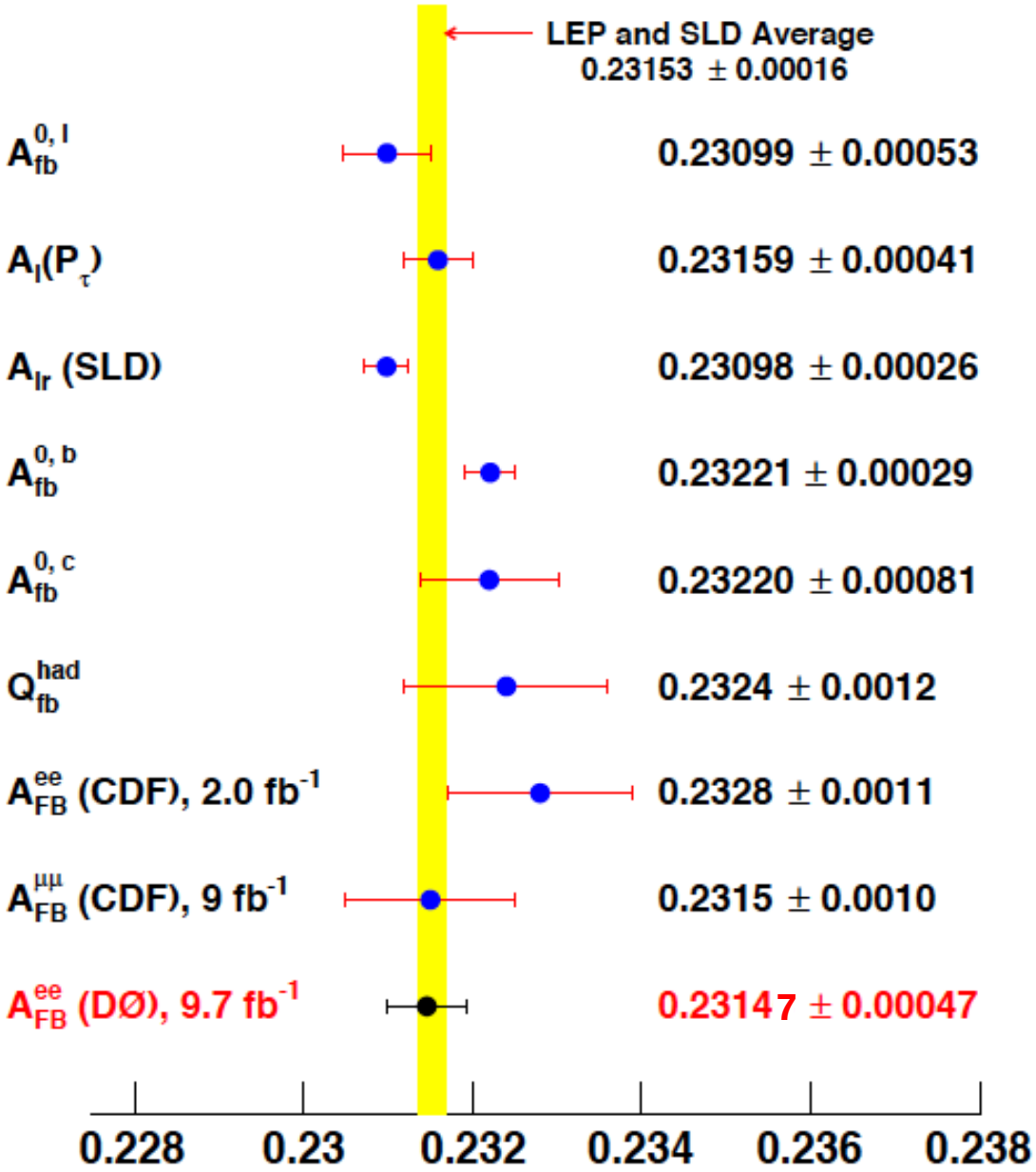


$\sin^2\theta_{eff}$ = 0.23138 ± 0.00043(stat) ± 0.00008(syst) ± 0.00017(NNPDF2.3 PDFs)

(no EW radiative corrections)

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

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



Situation in 2015

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

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

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

Change is +0.00008

Final results :DØ ee

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

= 0.23147 ± 0.00043 (statistical)
± 0.00008 (systematics)
± 0.00017 (PDFs NNPDF2.3 NLO)

= 0.23147 ± 0.00047 (total)

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

Main improvements are in the following areas:
(some details in the next slides and in the backup)

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). Extract A_{FB} , then, unfold and correct.

Since $\sin^2\theta_W$ is constant while $\sin^2\theta_{eff}^{lept}$ (M_{ee} ,flavor) is not
➔ Implement full ZFITTER ElectroWeak radiative corrections,

Use Drell-Yan forward-backward asymmetry to constrain parton distribution functions - (will also reduce PDF errors for Mw measurement)

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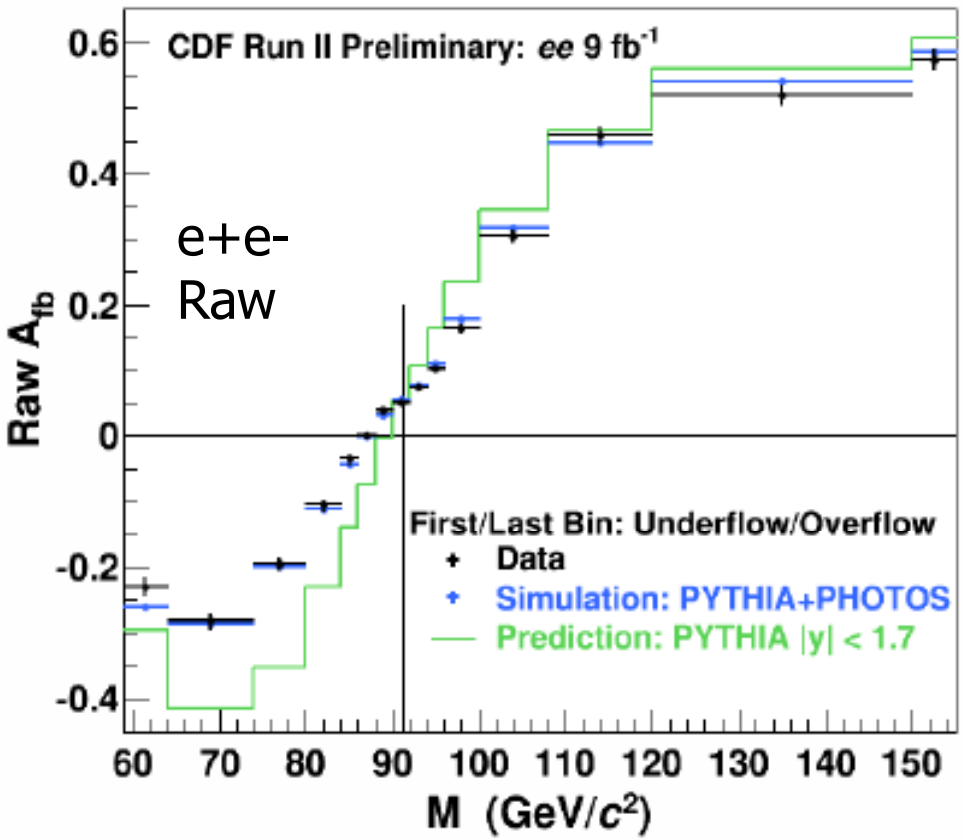
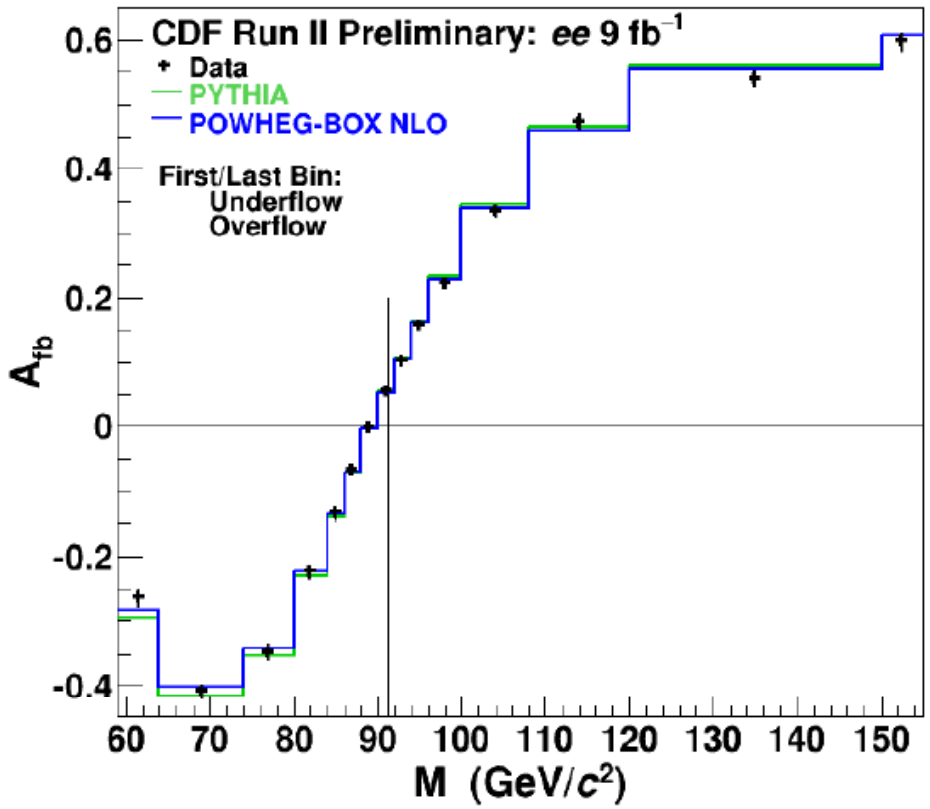
Unfolding/corrections in CDF e+e- analysis



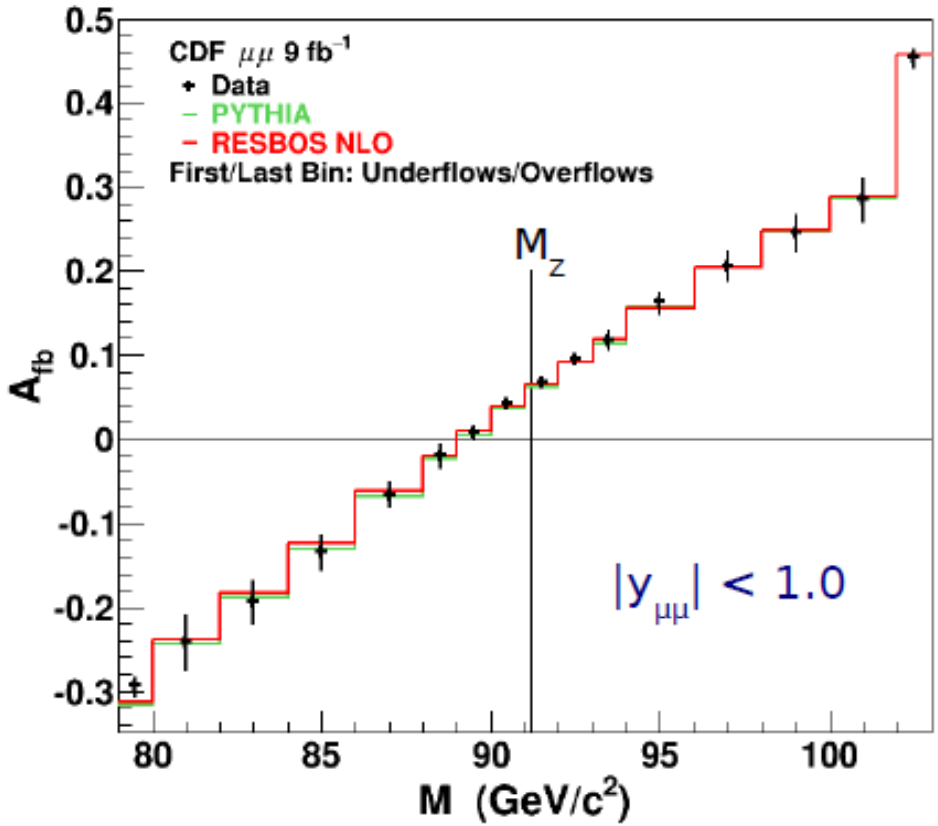


e+e-: A_{FB} Background subtracted
Raw no corrections

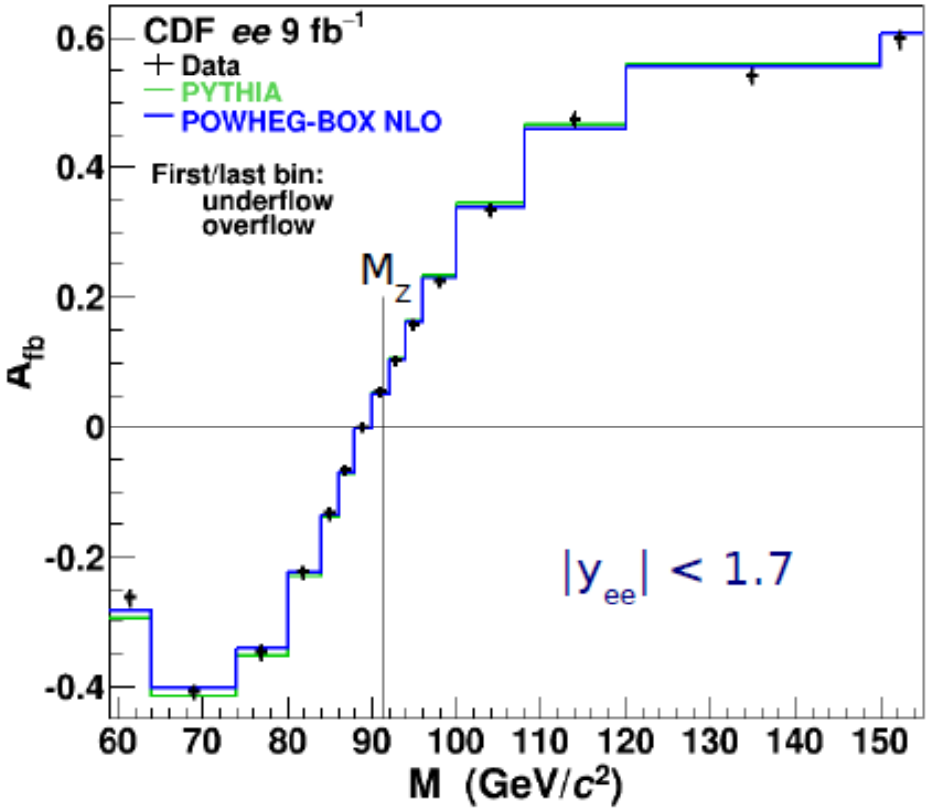
e+e- : A_{FB} unfolded, fully corrected

CDF $\mu^+\mu^-$ & e^+e^- 9.7 fb^{-1} A_{FB} measurements

PRD 89, 072005 (2014)



PRD 93, 112016 (2016)



Measurements corrected, templates are pure calculations and for the specified kinematic range

RESBOS and POWHEG-BOX best-fit templates include EWK radiative corrections

CDF $\mu^+\mu^-$ & e^+e^- 9.7 fb^{-1} $\sin^2\theta_{eff}^{lept}$ extraction

- 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

- $\mu\mu$ 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)

statistics:	0.00043
PDF:	0.00016
other systematics:	0.00006

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Standardization of the results 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 $\sin^2\theta_{eff}^{lept}$ value

D0 standardization corrections

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

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

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

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

    ↳ analog of PYTHIA templates

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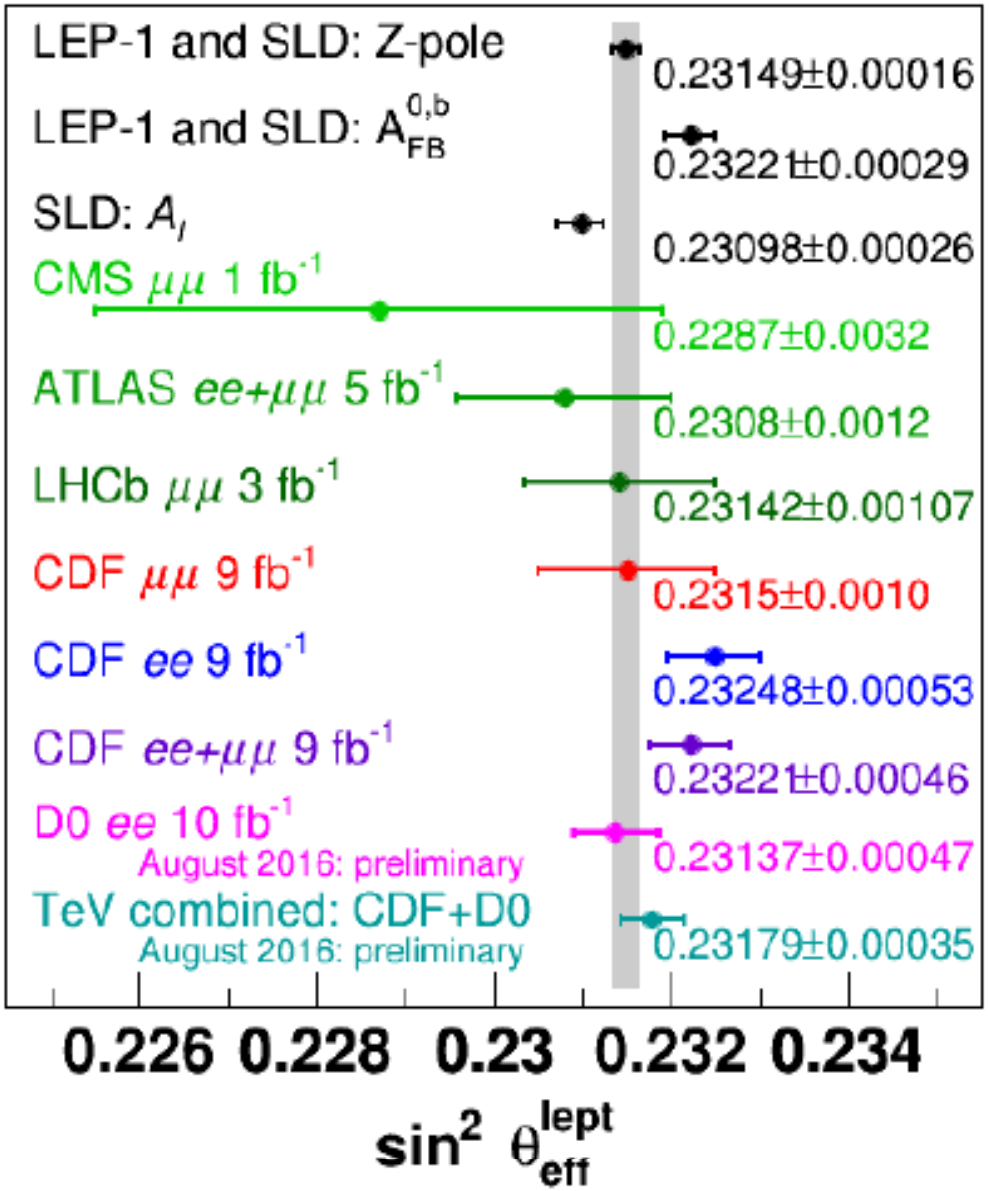
Combination of $\sin^2\theta_{eff}^{lept}$ results



Input observable values
- Standardized D0 value:
0.23137±0.00043 (stat) ± 0.00019 (syst)
- CDF ee⊕μμ value:
0.23221±0.00043 (stat) ± 0.00018 (syst)

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

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

$\chi 2$ of combination: 1.8 (18% probability)

Uncertainties

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

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)

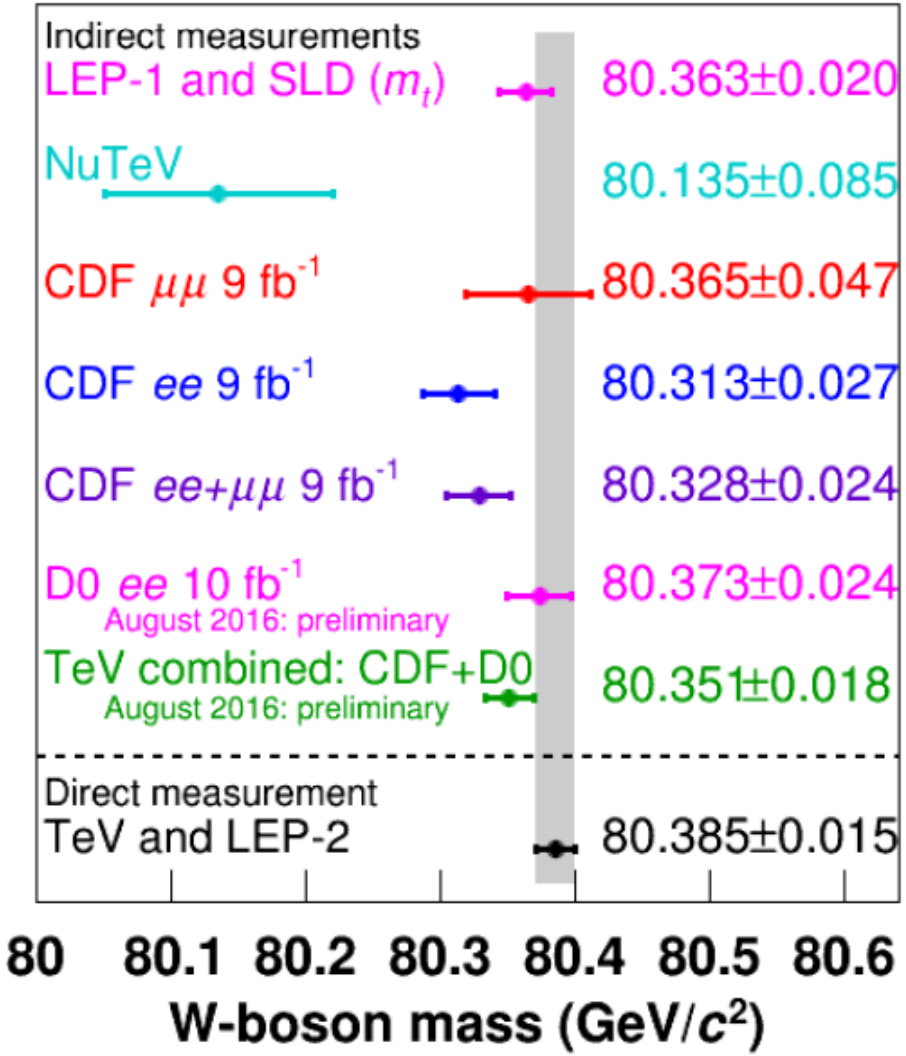
Both $\sin^2\theta_W^{\text{on-shell}}$ and $\sin^2\theta_{eff}^{\text{leptonic}}$ (Mz) can be extracted from Drell-Yan forward-backward asymmetry (Afb) if we include EW radiative corrections.

➔ 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.

Indirect W mass results



$\sin^2\theta_W$ 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 : 91.1875±0.0021 GeV

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
  - Form factor uncertainty to $\sin^2\theta_W$: 0.00008
  - Higgs mass value: 125 GeV

	$\sin^2\theta_W$	M_W
CDF only:	0.22400±0.00041±0.00019	80328±21±10 MeV
D0 only:	0.22313±0.00041±0.00020	80373±21±10 MeV

Combination:

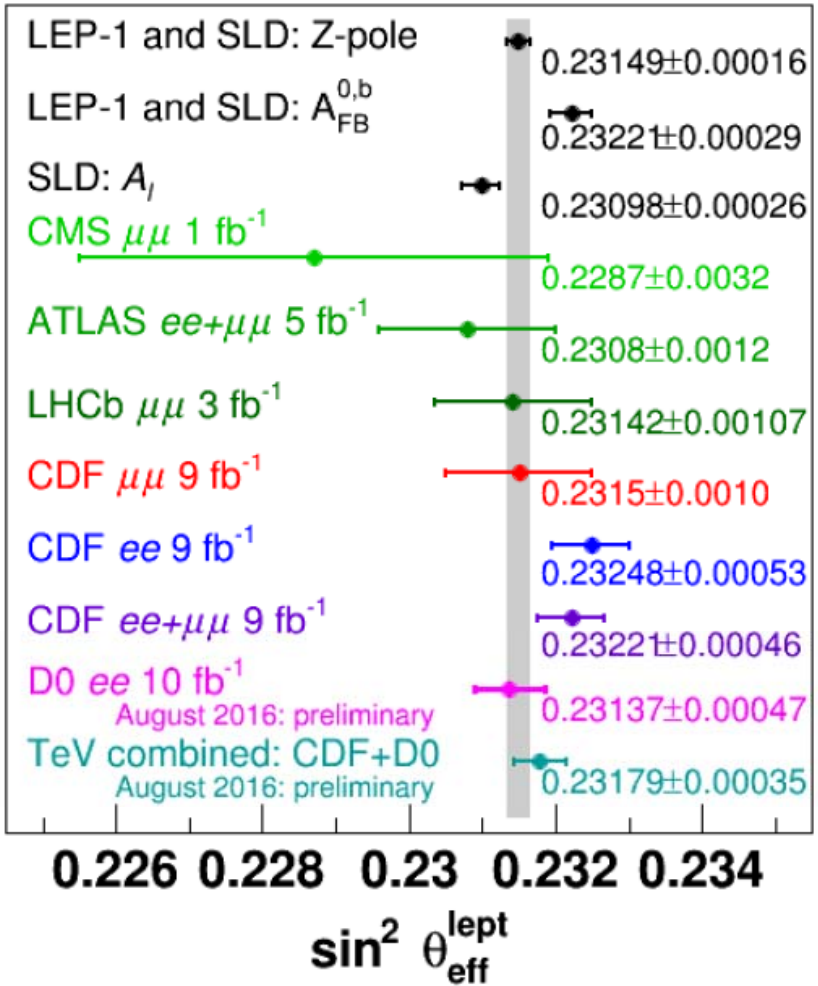
0.22356±0.00029±0.00019			**80351±15±10 MeV**	
(stat)	(syst)		(stat)	(syst)

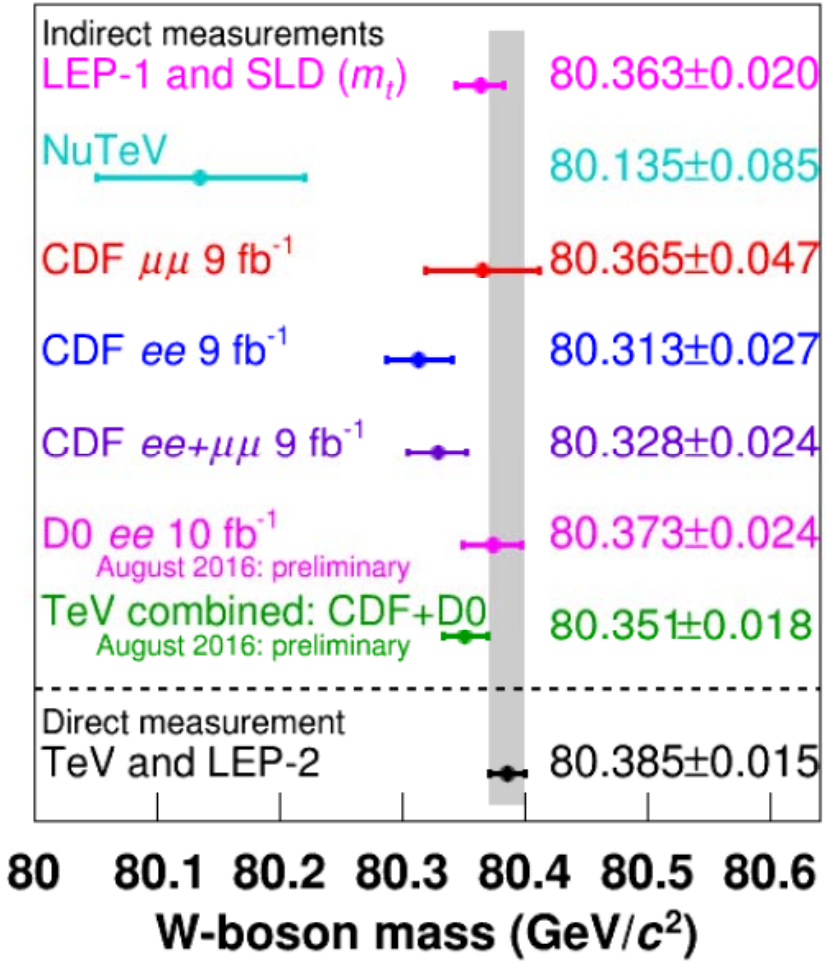
Summary of CDF & DØ $\sin^2\theta_{eff}^{lept}$ analysis / indirect M_W results

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!





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

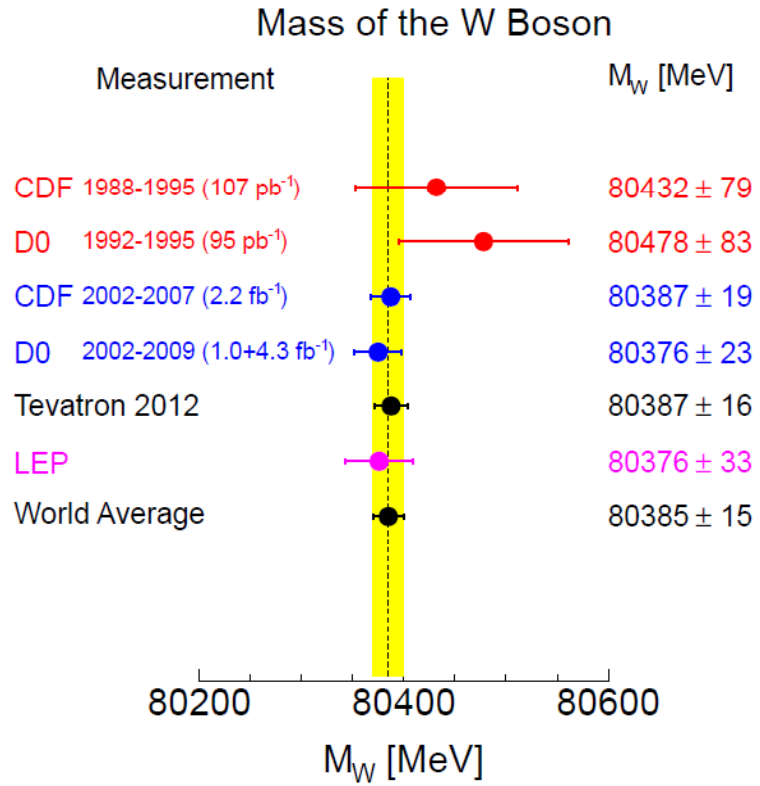
  ➔ 0.02% precision!

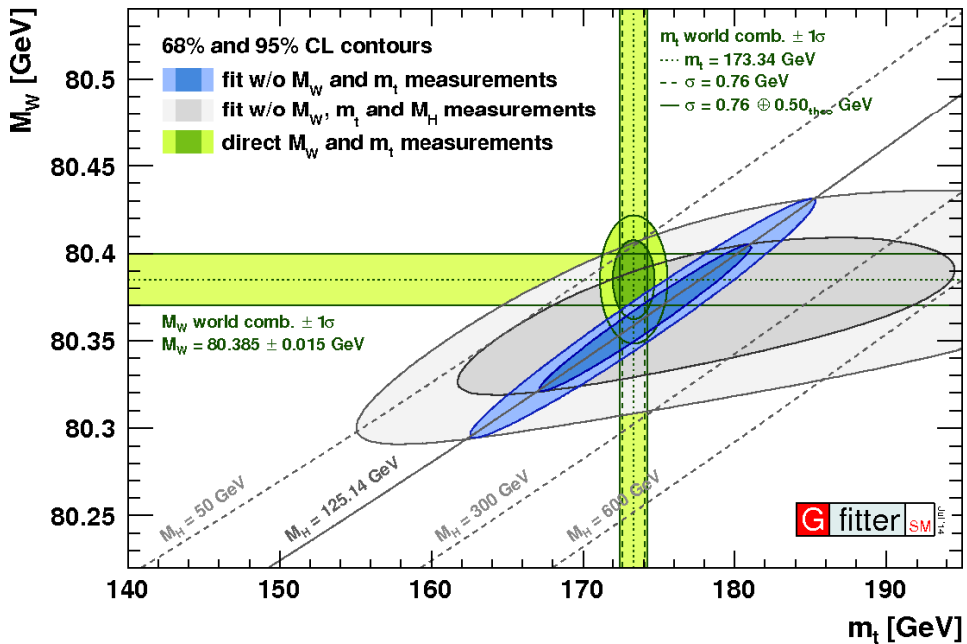
  dominates the World combination (15 MeV)

- 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

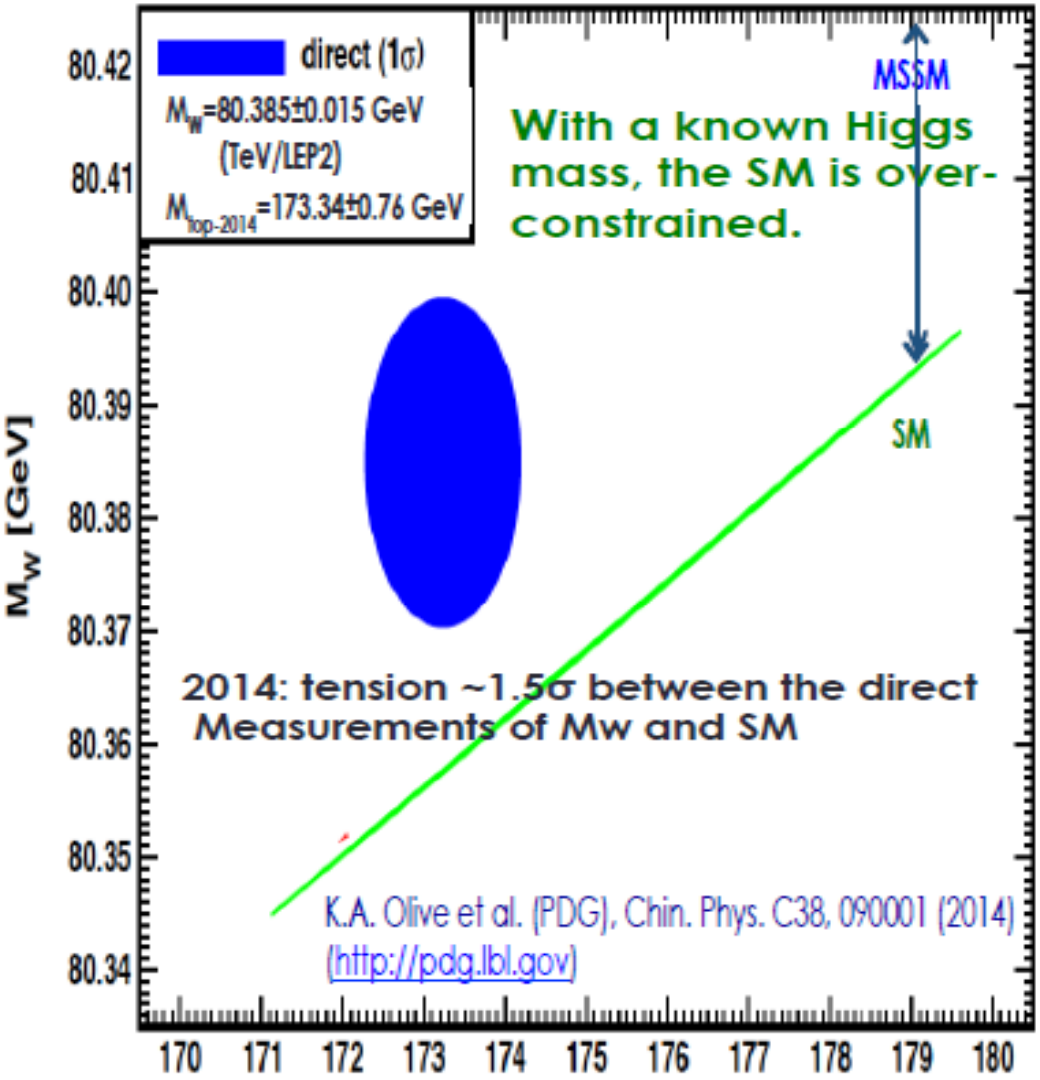
- Target 10 MeV world average with new CDF and D0 measurements using full statistics.

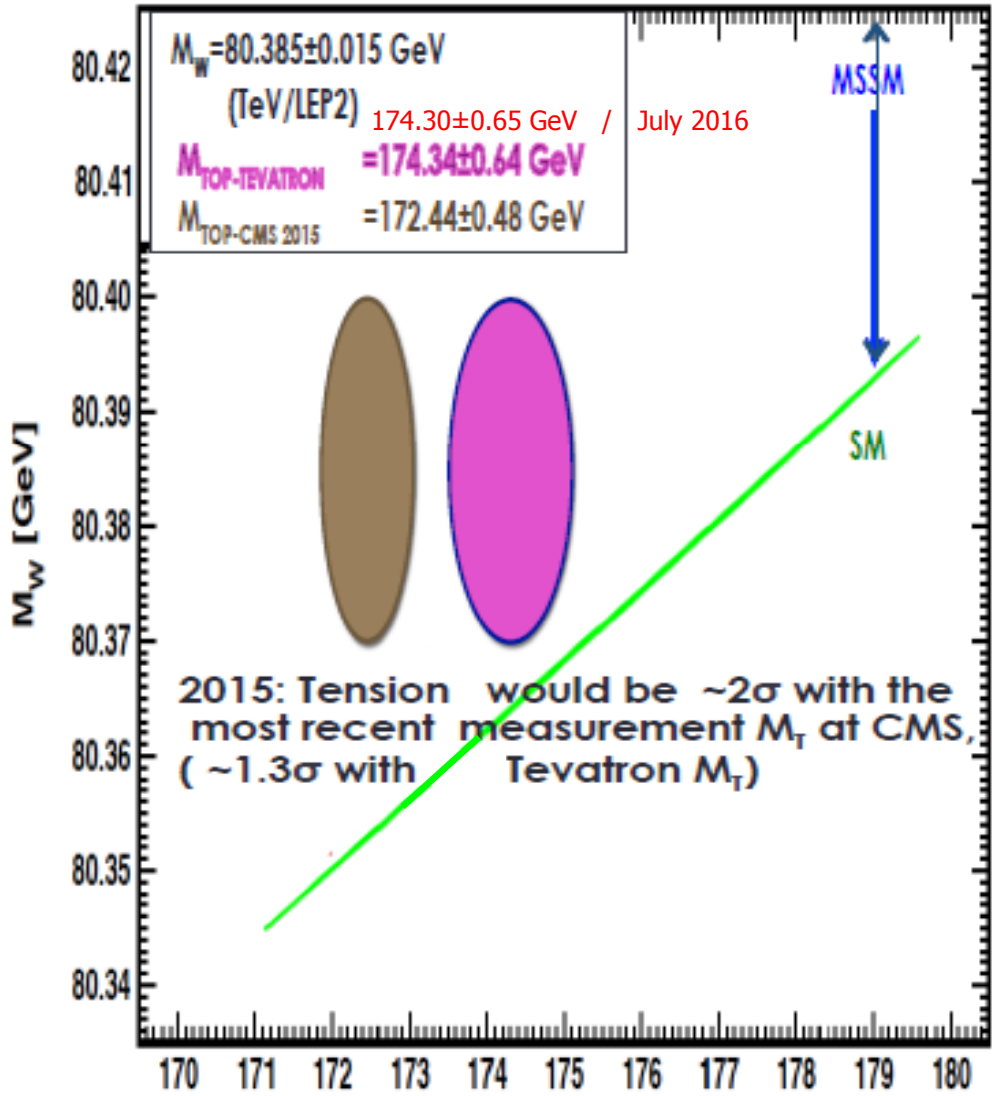
- Consistency check of the SM (top-W-Higgs)





Top, and W Direct Mass Measurements





15 MeV error in W mass

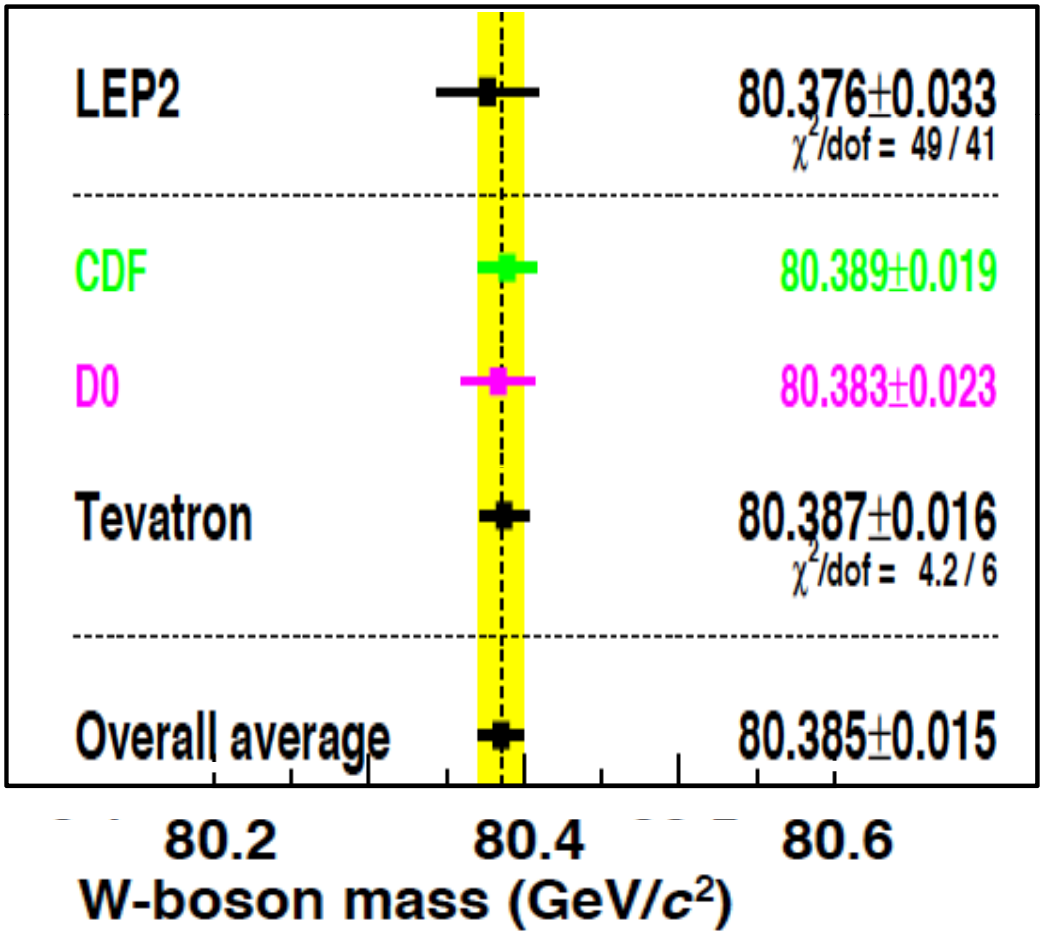
Direct and Indirect W mass measurements

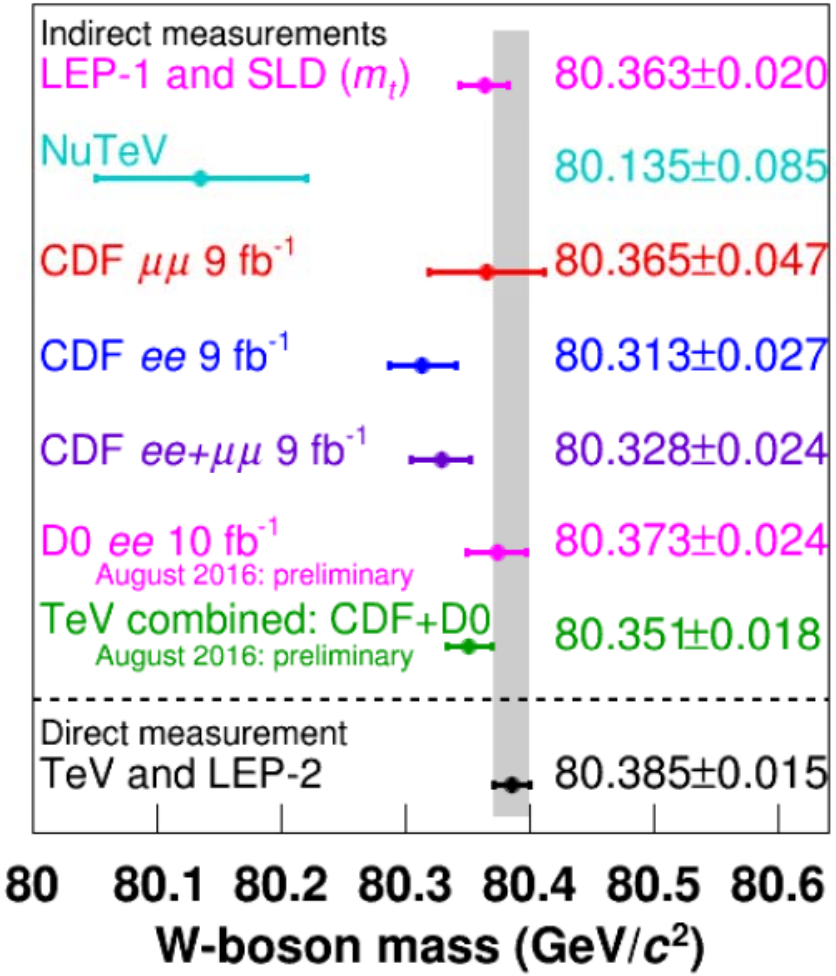
Direct measurements:

Waiting for update from CDF and D0 on full 10 fb^{-1} dataset (currently 2 and 5 fb^{-1})

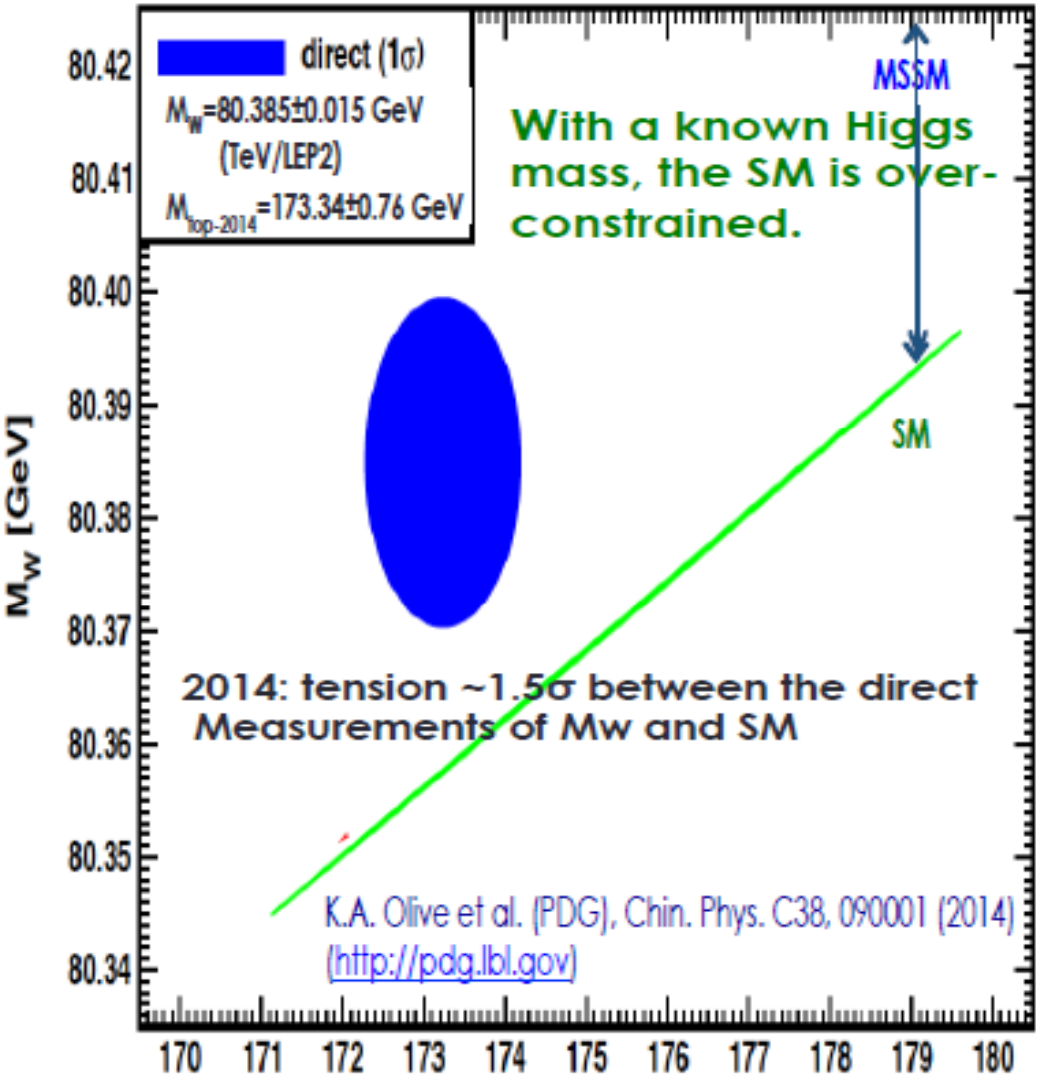
Indirect measurements:

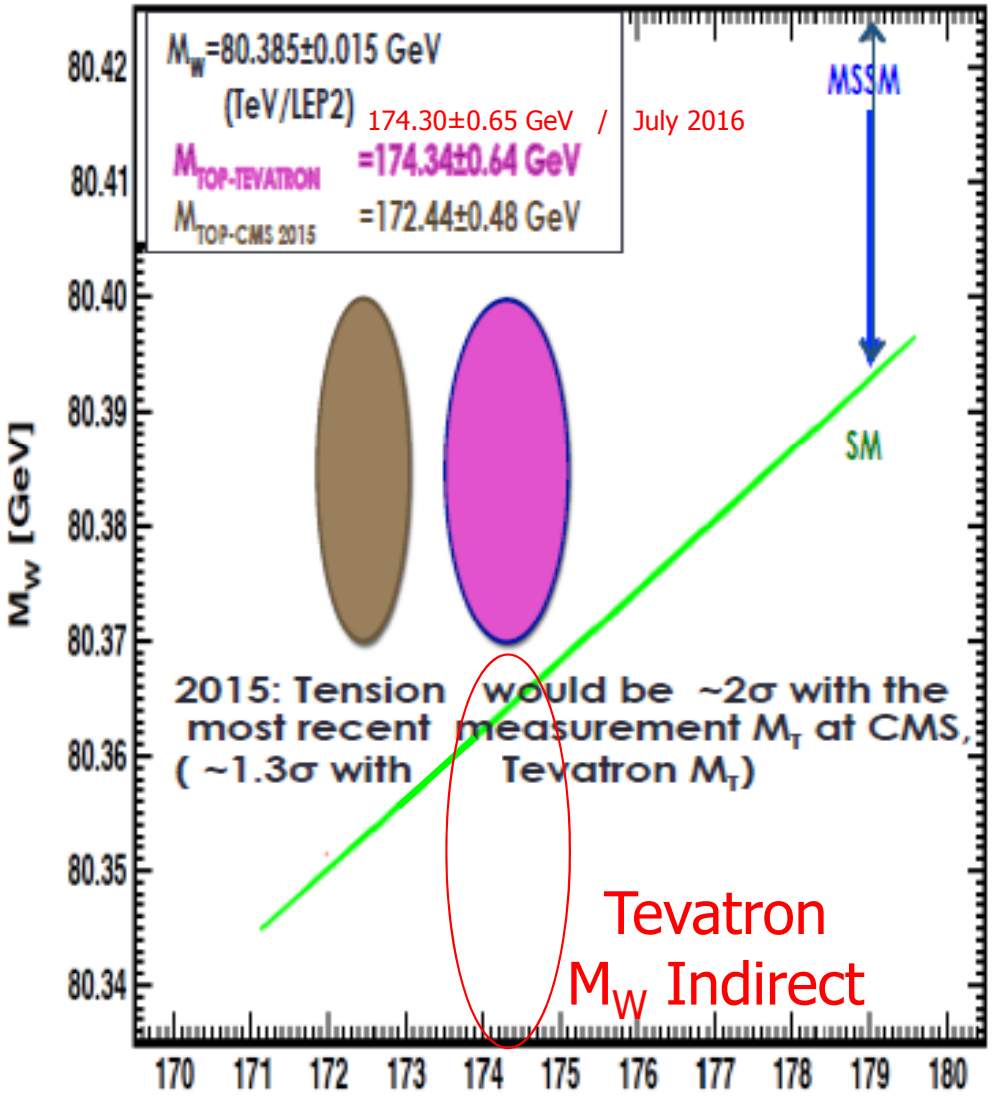
Tevatron:
18 MeV indirect Mw uncertainty is similar to 15 MeV direct Mw uncertainty





Top, and W Direct Mass Measurements





15 MeV error in W mass

Conclusions / Tevatron Legacy

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

- The Top mass measurements are essentially complete, the combination gives:

  174.30 ± 0.65 GeV (172.8 ± 3.3 GeV top pole mass from D0 ttbar cross sections)

- Currently the Tevatron direct (L= 2.2 fb-1) and indirect (L=9.4 fb-1) measurements of M_W have similar errors (15 vs.18 MeV)

- 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.

Top quark mass from tt cross-section

- compare the experimental tt cross section measurement with the theory computation (depend differently on the top quark mass)
- cross section vs m_t parametrized with (third order polynomial)/m_t^4
  - theoretical cross section computed at NNLO with top++
  - experimental $\ell\ell$ & ℓ+jets with 9.7 fb^{-1}

$$\sigma_{t\bar{t}} = 7.26 \pm 0.13(\text{stat})^{+0.57}_{-0.50}(\text{syst})\ \text{pb}$$

Advantage/Drawback

- extract the top quark mass in a well defined renormalization scheme (pole mass in theory computation)
- less precise than direct measurements

$$L(m_t) = \int f_{\text{exp}}(\sigma|m_t)\ [f_{\text{scale}}(\sigma|m_t) \otimes f_{\text{PDF}}(\sigma|m_t)]\ d\sigma.$$

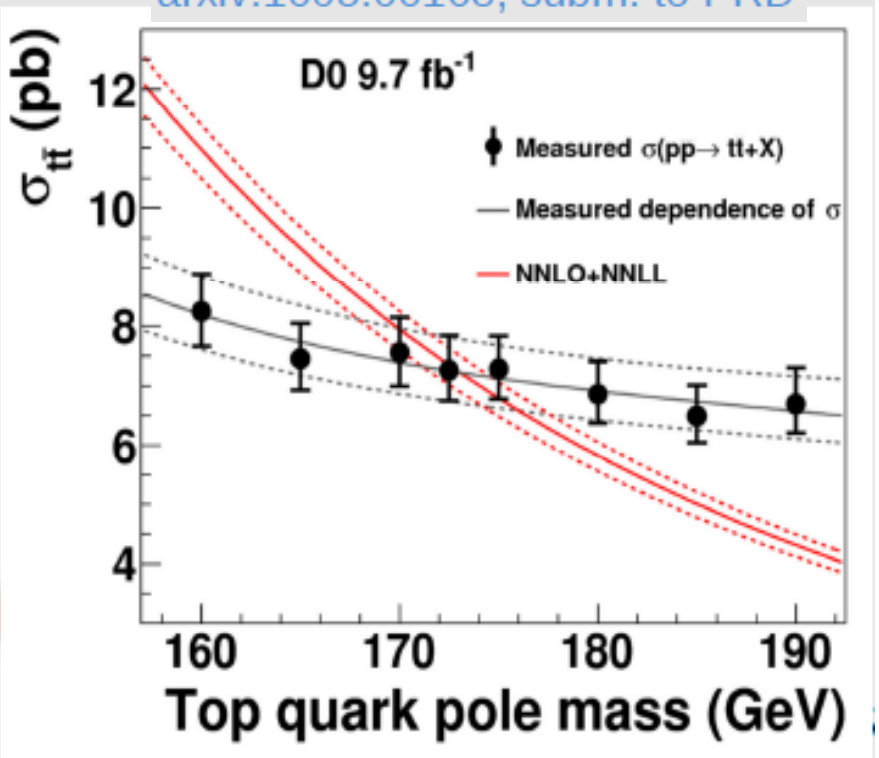
gaussian flat gaussian

$$m_t = 172.8 \pm 1.1\,(\text{theo.})\,^{+3.3}_{-3.1}\,(\text{exp.})\ \text{GeV}$$

$$m_t = 172.8^{+3.4}_{-3.2}\,(\text{tot.})\ \text{GeV}$$

$\Delta m_t/m_t$ = 1.9%

arxiv:1605.06168, subm. to PRD



CDF: 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

CDF: Use event weighting Method

Event weighting method for A_{FB} analyses

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

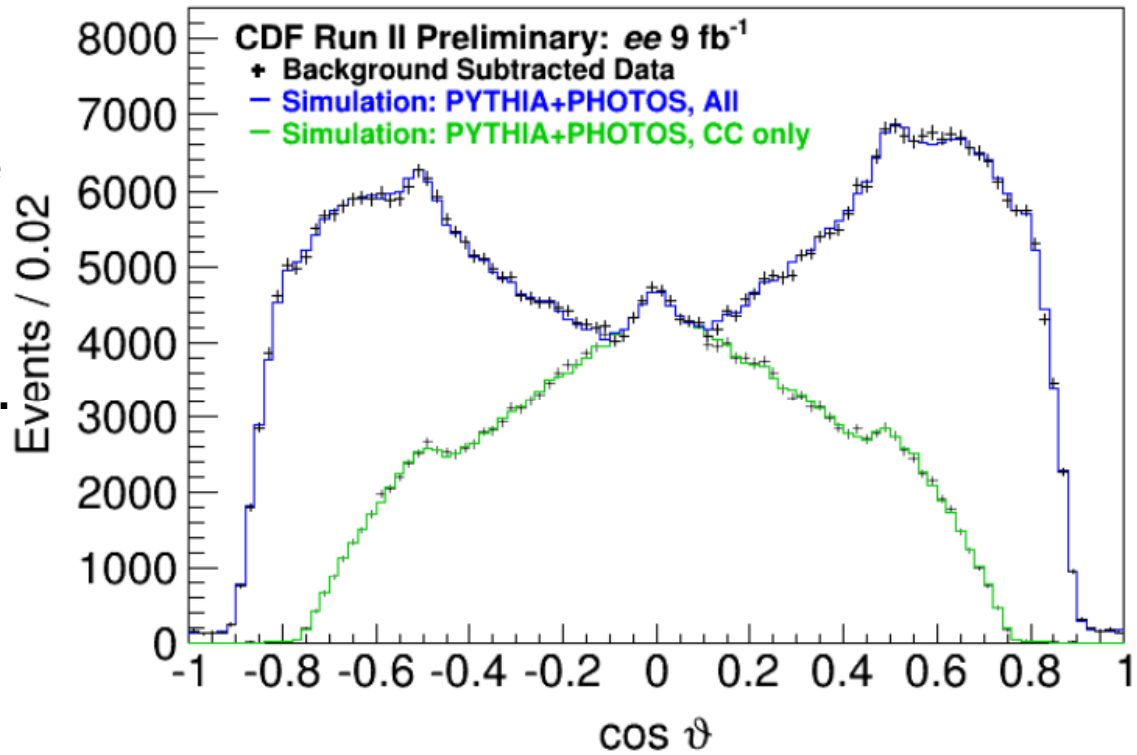
Angular event weighting is equivalent to extraction of $A_4(M)$ in bins of $\cos\theta$, and averaging the results. Events at large $\cos\theta$ provide better determination of A_4, so they are weighted more than events at small $\cos\theta$.

For each $\cos\theta$, acceptance and efficiencies cancel to first order and the statistical errors are 20% smaller.

Uncertainty in A_{FB} is reduced if we have more acceptance at large $\cos\theta$

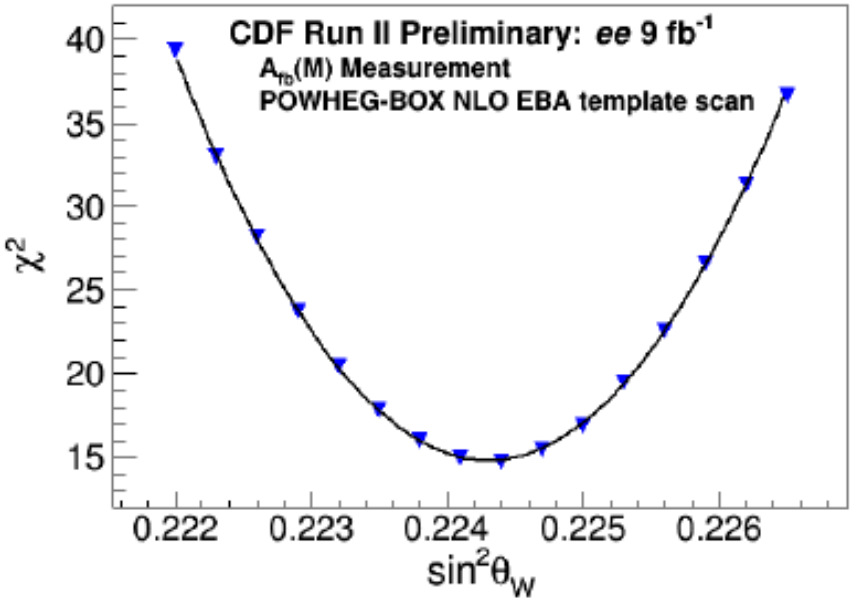
Standard A_{FB} method requires precise knowledge of acceptance & efficiencies.

Measure A_4 → $\mathbf{A_{FB}}$



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

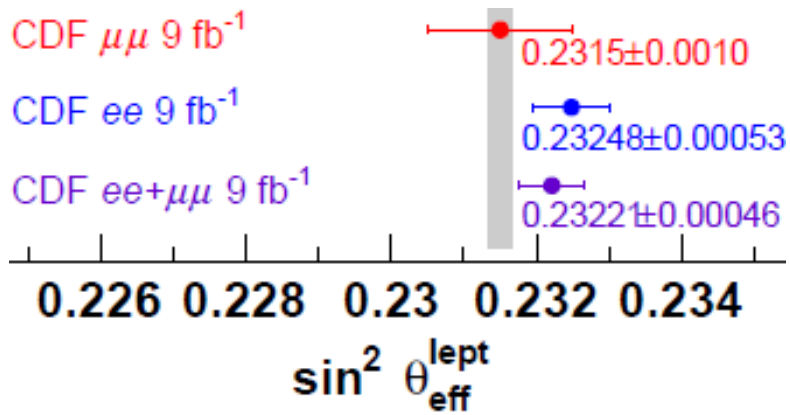
- Comparison χ^2: $\Sigma_M \Delta A_{fb}(M)^{\sim} \bullet E \bullet \Delta A_{fb}(M)$
  - Measurement: Fully corrected $A_{fb}(M)$
  - Calculated templates: $A_{fb}(M,\sin^2\theta_W)$ for 16 values of $\sin^2\theta_W$
  - E: Measurement error matrix
- Extraction of $\sin^2\theta_W$ from the scan points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



CDF: 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)

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

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

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

Systematics on M_W

Source	Uncertainty 2.2 fb^{-1} (MeV)
Lepton energy scale	7
Lepton energy resolution	2
Recoil energy scale	4
Recoil energy resolution	4
Lepton removal	2
Backgrounds	3
p_T (W) model	5
PDFs	10
QED radiation	4
Total systematics	*15*
W statistics	12
Total	***19***

Systematic uncertainties in CDF measurement

Many of the systematic uncertainties scale with the size of the calibration samples (Z decays)

With full data sample (10 fb^{-1}) measurement becomes dominated by PDF and theoretical uncertainties

Reaching 10 MeV precision possible with

- **Improved determination of PDF at Tevatron (W charge asymmetry)**
- **Extension of measurements to endcap region (reduced sensitivity to production modeling)**

From effective to on-shell $\sin^2\theta_W$

- Drell-Yan lepton angular distributions are used to infer $\sin^2\theta_W$
  - Lepton (e,μ^-) angular distributions (ϑ,φ) measured in γ^*/Z CM frame: separates boson production and decay kinematics
  - Born level polar angle distribution: $1 + \cos^2\vartheta + A_4\cos\vartheta$
  - $\cos\vartheta$ forward-backward asymmetry: sensitive to $\sin^2\theta_W$
- Vector with axial-vector interference: contributes to A_4 coefficient
  - A_4 term due to Z-boson self-interference $\propto (1-4|Q^e|\sin^2\theta_W)(1-4|Q^q|\sin^2\theta_W)$
  - Fermion (f) couplings to γ^*/Z bosons: $(g_V+g_A\gamma^5)\gamma^\mu$

    $q\bar{q} \rightarrow \gamma^* \rightarrow e^+e^-$: $g_V^f = Q^f$ $\quad g_A^f = 0$ (Q: fermion charge)

    $q\bar{q} \rightarrow Z \rightarrow e^+e^-$: $g_V^f = T_3^f(1-4|Q^f|\sin^2\theta_W)$ $\quad g_A^f = T_3^f$ (T_3: weak isospin)

    $\sin^2\theta_W = 1-M_W^2/M_Z^2$ ($\sin^2\theta_W$ equiv. to M_W)
- Weak radiative corrections complicate this simple Born interpretation
  - Implementation: ZFITTER 6.43 enhanced Born approximation (EBA)
  - T_3 and $\sin^2\theta_W \rightarrow$ 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