Z Boson Asymmetry Measurements at the Tevatron

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On behalf of the CDF and DØ Collaborations

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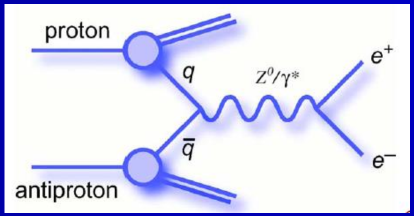
Introduction: Theory

- Drell-Yan lepton pairs are produced at the Tevatron through

$$p\bar{p} \to Z/\gamma^* \to l^+l^-$$



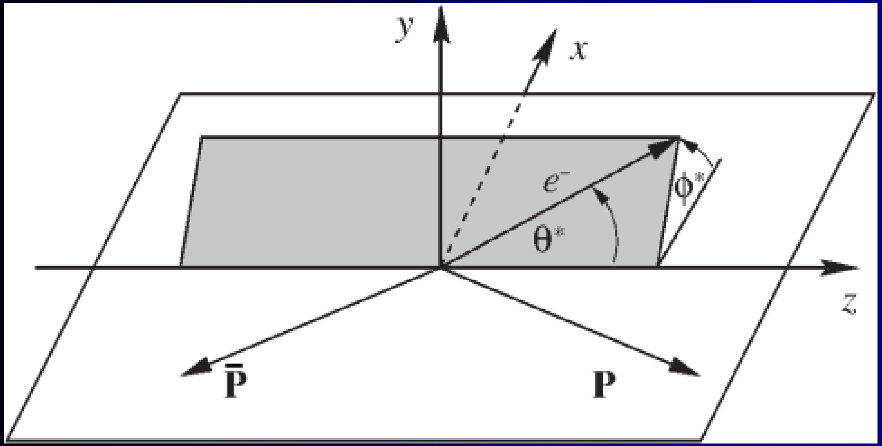
- The weak mixing angle can be measured from the forward-backward asymmetry of the polar angle distribution of these Drell-Yan pairs

$q\bar{q} \to \gamma^* \to l^+l^-$	Born level couplings	$q\bar{q} \to Z \to l^+l^-$
$g_V^f = Q_f$		$g_V^f = I_3 - 2Q_f sin^2\theta_W$
$g_A^f = 0$		$g_A^f = I_3$

$$\langle \bar{f} | (g_V + g_A\gamma^5)\gamma^\mu | f \rangle$$

- I_3, $sin^2\theta_W$ couplings altered by weak radiative corrections
  - Multiplicative factor of a few %
  - Gives effective $sin^2\theta_W$ coupling → $sin^2\theta^l_{eff}$

Introduction: Theory



- **Measure l^-l^+ angular distribution in the Collins-Soper rest frame of the boson. Polar angle, θ^*, of the l^- is defined relative to the direction of the incoming quark**
  - Forward: $cos\theta^* > 0$, Backward: $cos\theta^* < 0$

- $dN/d\Omega \propto 1 + cos^2\theta^* + A_4 cos\theta^*$
  - All coefficients† but A_4 vanish as $P_T \to 0$

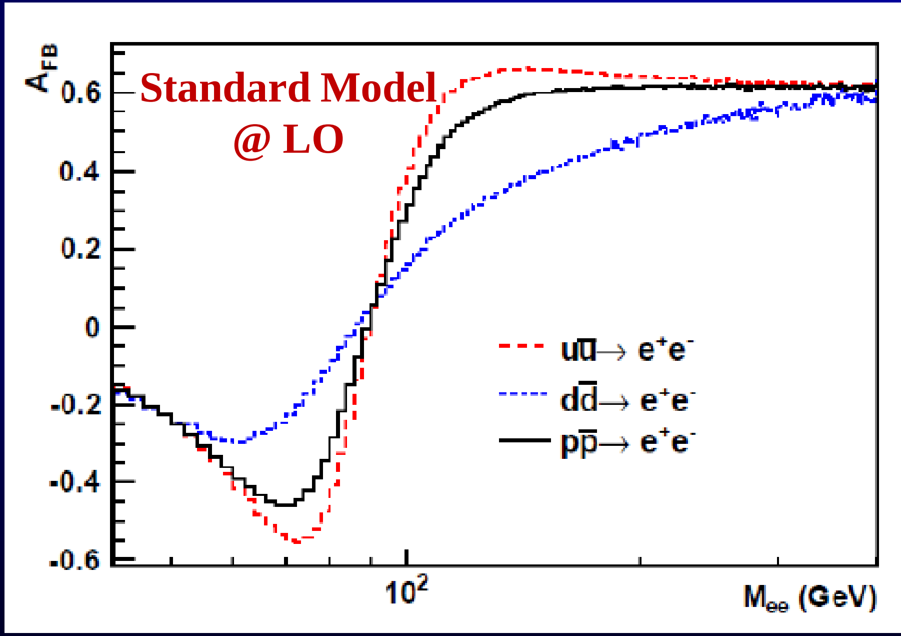
$$A_{FB} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{3}{8} A_4$$

- $A_4 cos\theta^*$**: parity violating, from interference of vector and axial vector currents**
  - Sensitive to $sin^2\theta_W$ through Z self-interference: $(1 - 4|Q_l|sin^2\theta_W)(1 - 4|Q_q|sin^2\theta_W)$

†@ NLO QCD: $dN/d\Omega = 1 + cos^2\theta^* + A_0(1 - 3cos^2\theta^*)/2 + A_1 sin2\theta^* cos\phi + A_2(sin^2\theta^* cos2\phi)/2 + A_3 sin\theta^* cos\phi + A_4 cos\theta^* + A_5 sin^2\theta^* sin2\phi + A_6 sin2\theta^* sin\phi + A_7 sin\theta^* sin\phi$

Introduction: Strategy

- **Measure A_{FB} in bins of lepton pair invariant mass**
- **Produce Monte Carlo $A_{FB}(M, sin^2\theta_W)$ templates**
- **Perform full corrections to data and simulation**
  - Background subtractions
- **Extract $sin^2\theta_W$ by a χ^2 comparison between data and MC**



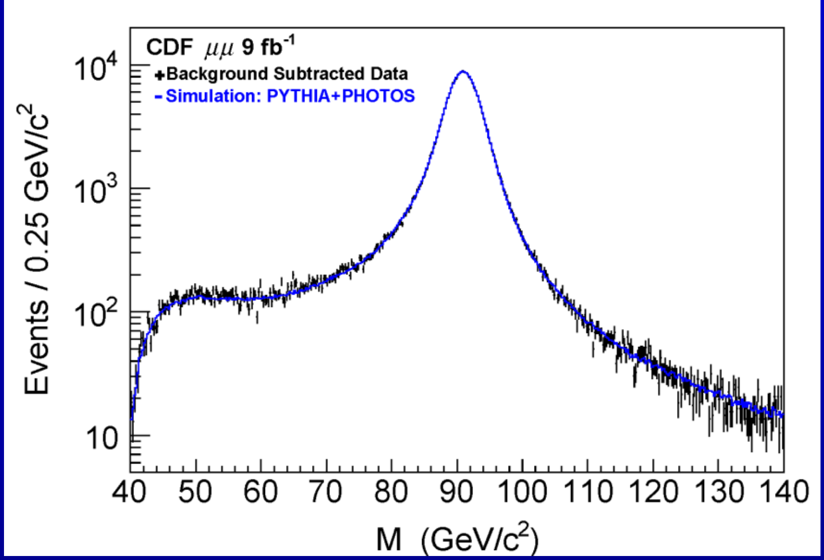
Indirect measurement of $sin^2\theta_W$ (or M_W) using $\mu^+\mu^-$ pairs from γ^*/Z bosons produced in pp collisions at a center-of-momentum energy of 1.96 TeV

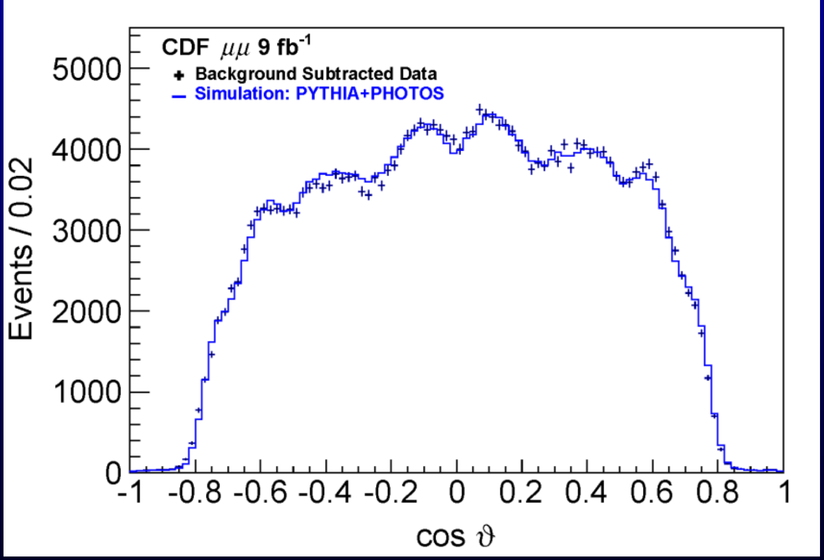
CDF Collaboration

Accepted PRD, arXiv:1402.2239

Event Selection

- **Full CDF RunII dataset: 9.2 fb^{-1}**
- **Tight muon cuts: $P_T > 20$ GeV**
- **Dimuon rapidity region: $|y| < 1$**
- **All dimuon detector topologies**
- **Mass distribution: $M > 50$ GeV**
- **Very low backgrounds**
  - EWK: 0.53% (simulation)
  - QCD: 0.10% (data)
- **276,623 events after BG subtraction**
- **Momentum Calibration**
  - Rochester Method: tune data and simulation to post-FSR generator level in 64 individually calibrated (η, ϕ) bins
- **MC: PYTHIA, CTEQ5L**





Angular Event Weighting

- **Traditional measurement with acceptance and efficiency corrections:**

$$A_{FB} = \frac{N^+/(\epsilon A)^+ - N^-/(\epsilon A)^-}{N^+/(\epsilon A)^+ + N^-/(\epsilon A)^-}$$

  - Requires measuring 22 numbers for the 11 dimuon topologies

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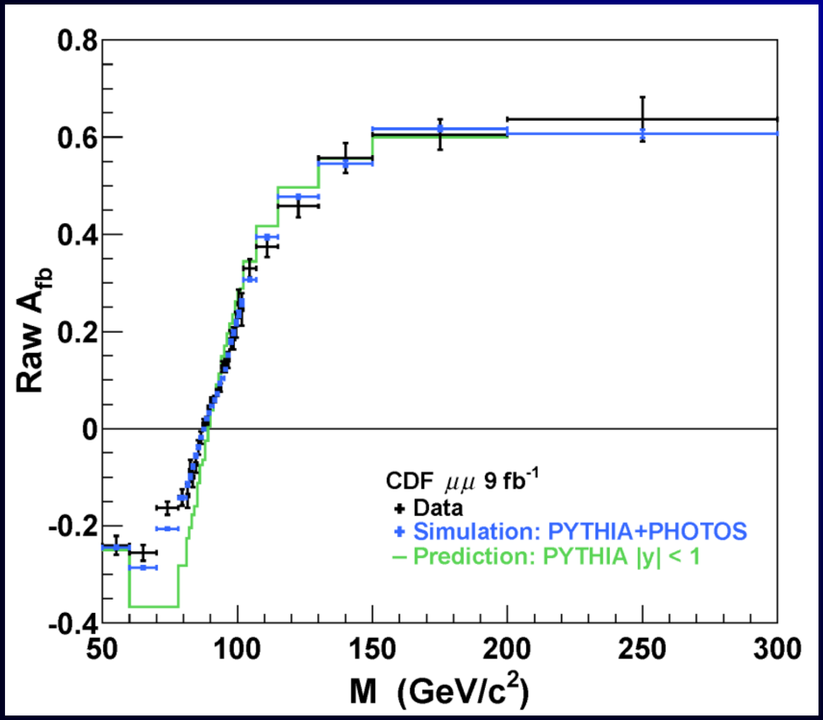
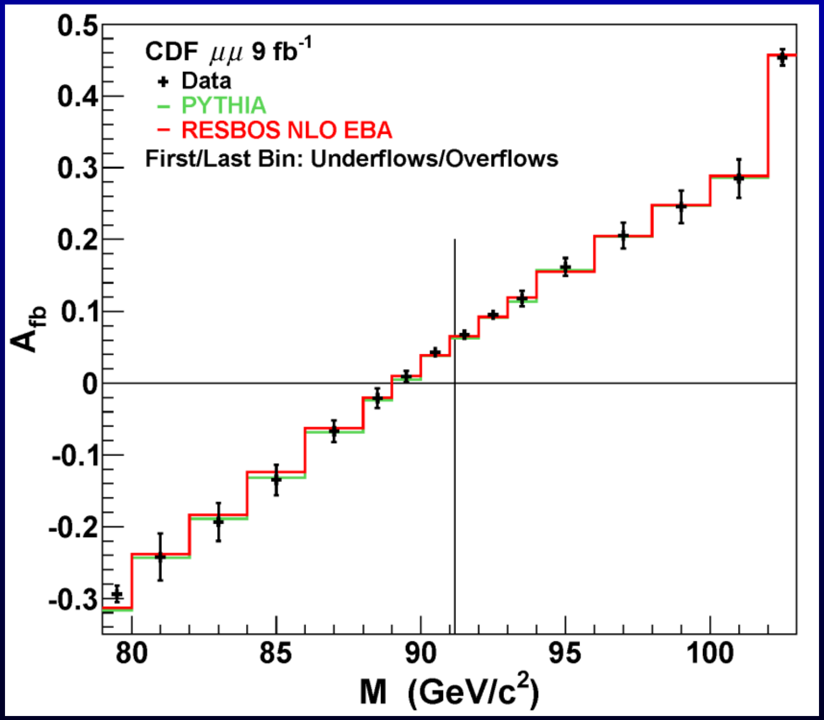
- **Use simpler event weighting method: Eur.Phys.J. C (2010) 67:321**
- **Equivalent to measuring A_{FB} in $cos\theta^*$ bins**
  - Assumes $(\epsilon A)^+ = (\epsilon A)^-$ in each bin; NLO QCD angular dist. (slide 3)
  - $A_{FB}(|cos\theta^*|) = A_{FB} \cdot |cos\theta^*|/(1 + cos^2\theta^* + \cdots)$
  - Measurements for large $cos\theta^*$ bins are more accurate
- **Recast binned measurements into unbinned weighted event sum:**
  - $A_{FB} = (N_n^+ - N_n^-)/(N_d^+ + N_d^-)$
  - Event weights for the numerator and denominator terms remove angular dependence and account for measurement accuracy at each $cos\theta^*$
  - Equivalent to maximum likelihood fit, expect 20% smaller uncertainty
- **Does not account for**
  - Smearing due to detector resolution
  - 2nd order bias due to regions of low acceptance and $(\epsilon A)^+ \neq (\epsilon A)^-$

Unfolding / Other Corrections

- **Raw A_{FB} distribution must be unfolded due to resolution smearing and QED final state radiation effects**
  - Two 16 x 16 unfolding matrices (16 mass bins, + and – regions)
  - Used to produce covariance and error matrices
- **Bin-by-bin 2nd order bias corrections**
  - Due to limited rapidity coverage ($A_{FB}(|y|)$) and detector non-uniformity



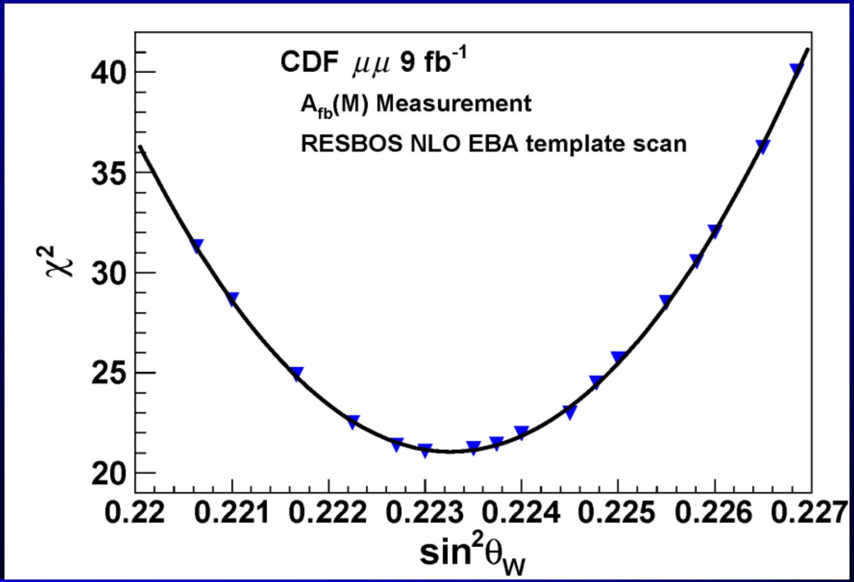


Template Fits

- The A_{FB} measurement is compared to A_{FB} templates calculated at different $sin^2\theta_W$ values
- Three sets of templates are used, with different Enhanced Born Approximation (EBA) calculations

Template	$\sin^2\theta_{\rm eff}^{\rm lept}$	$\sin^2\theta_W$	$\bar{\chi}^2$
RESBOS NLO	0.2315 ± 0.0009	0.2233 ± 0.0008	21.1
POWHEG-BOX NLO	0.2314 ± 0.0009	0.2231 ± 0.0008	21.4
Tree LO	0.2316 ± 0.0008	0.2234 ± 0.0008	24.2

- ResBos is chosen as the default A_{FB} template



Results

- **Systematic Uncertainties**

Source	$\sin^2\theta^{\rm lept}_{\rm eff}$	
Momentum scale	±0.00005	← Global scale data-MC shifts
Backgrounds	±0.00010	
QCD scales	±0.00003	← Variations of 0.5 and 2.0 of default
CT10 PDFs	±0.00037	← Quadrature sum of eigenvectors, scaled to 68% CL
EBA	±0.00012	← ResBos/Powheg-Box/Tree , and QCD rad on/off difference

$$\boxed{sin^2\theta^l_{eff} = 0.2315 \pm 0.0009 \pm 0.0004}$$

In Standard Model context, with on-shell renormalization scheme ($sin^2\theta_W = 1 - M_W^2/M_Z^2$)

$$sin^2\theta_W = 0.2233 \pm 0.0008 \pm 0.0004$$

$$M_W(indirect) = 80.365 \pm 0.043 \pm 0.019\ \text{GeV/c}^2$$

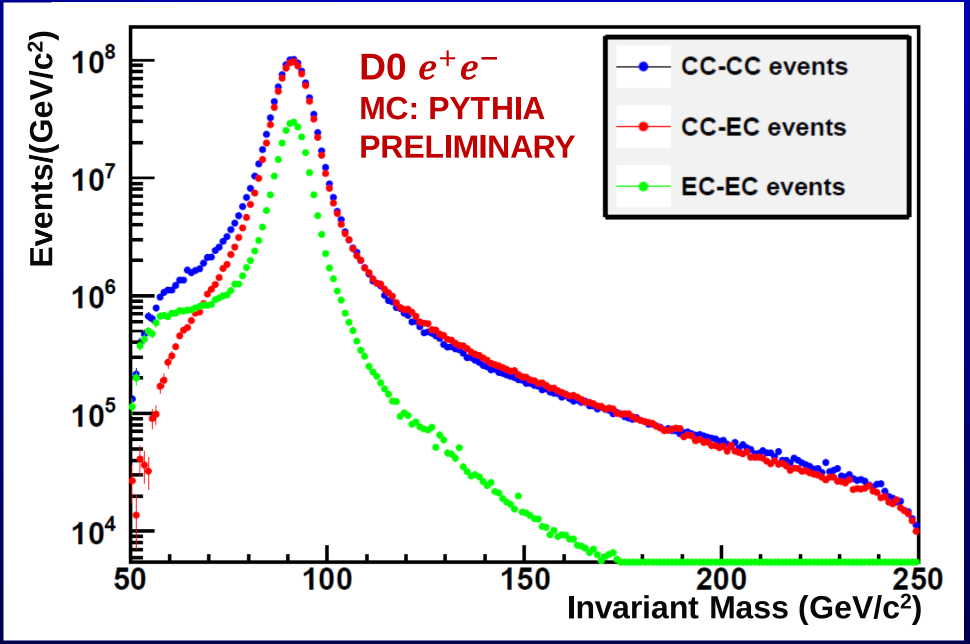
Measurement of the effective weak-mixing angle ($sin^2\theta^l_{eff}$) in $p\overline{p} \to Z/\gamma^* \to e^+e^-$ events at $\sqrt{s} = 1.96$ TeV

D0 Collaboration

D0 Note 6426-CONF

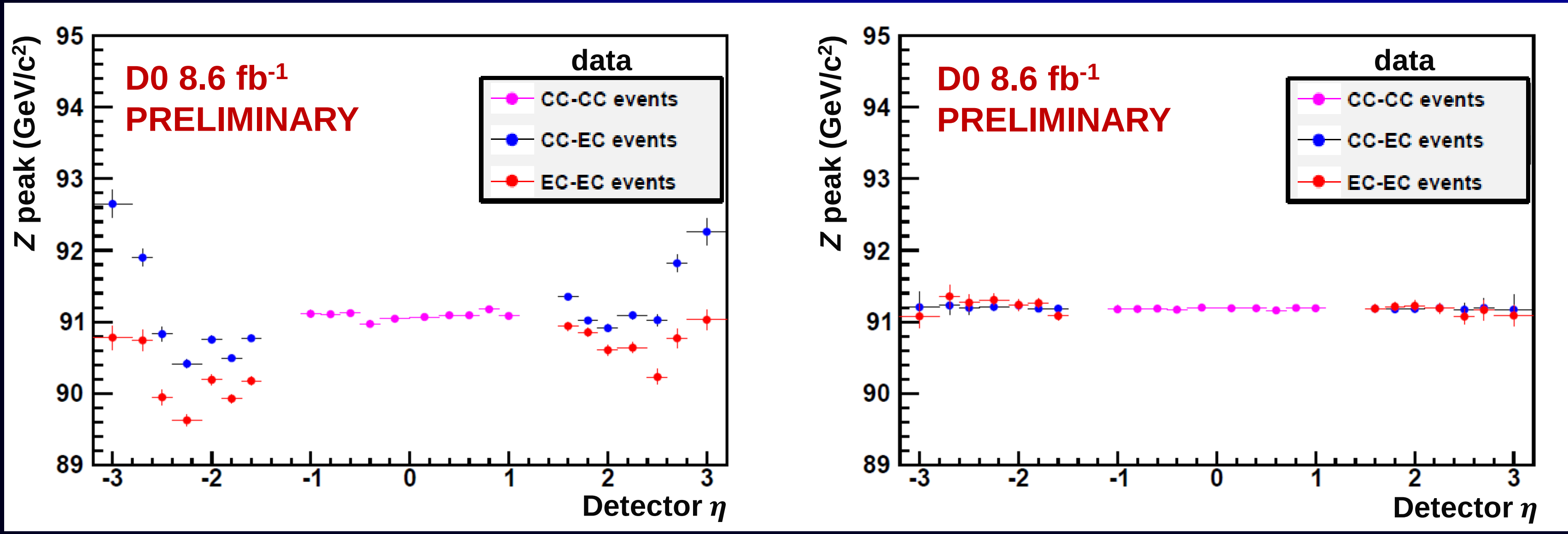
Event Selection

- **Full D0 RunII dataset: 9.7 fb^{-1}**
- **Two high-P_T electrons: $P_T > 25$ GeV**
  - Central and endcap calorimeters (CC,EC)
- **Tight track requirements**
- **Mass distribution: $M > 50$ GeV**
  - $\sin^2\theta^l_{eff}$ from $75 < M < 115$ GeV
- **85% increase in statistics**
  - Extend to $|\eta| < 1.1, 1.5 < |\eta| < 3.2$
  - Include EC-EC events
  - Include electrons near calorimeter module (phi-mod) boundaries
  - Track reconstruction improvements
- **560,267 events**
- **Low QCD backgrounds (EW negl.)**
  - CC-CC: 0.4%; CC-EC,EC-EC: < 4%
- **MC: PYTHIA, CTEQ6L1**



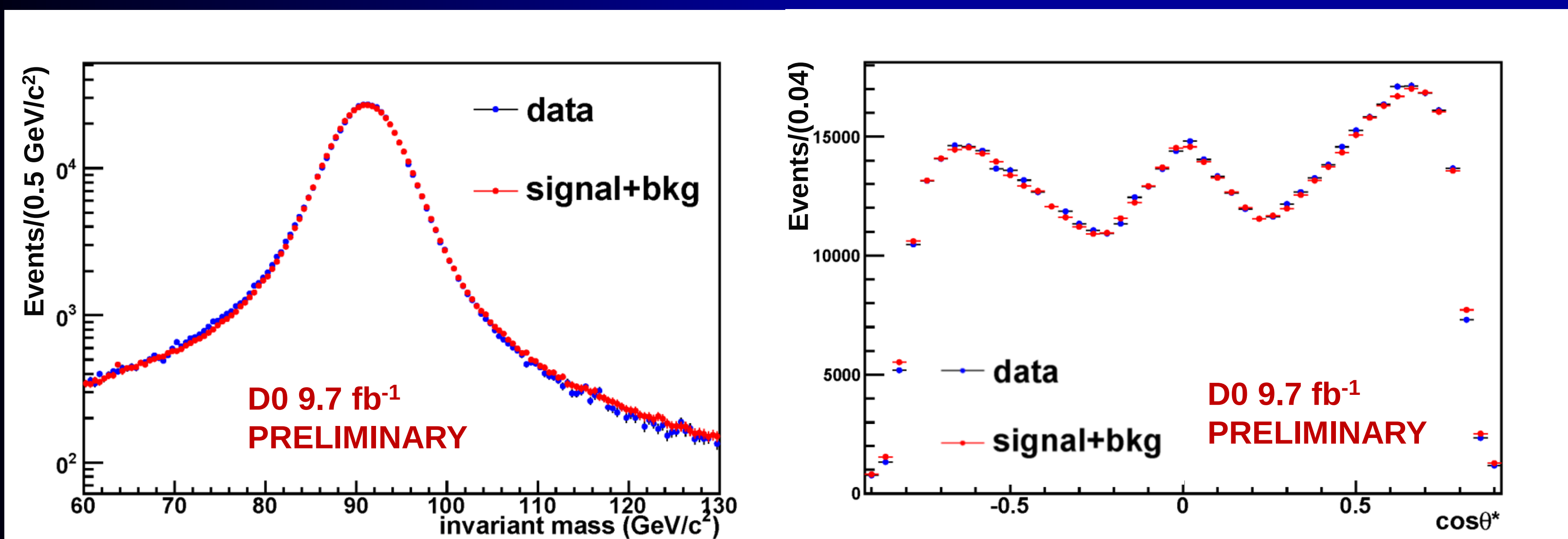
Energy Calibration

- **Global energy scale modeling in previous analysis**
  - Shape dependence inadequate for different detector responses of extended acceptance regions
- **New method corrects energy as a function of L_{inst} first, then η_{det}**
  - Z mass peak scaled to LEP value (91.1875 GeV) in each bin
  - Separate calibrations for data and MC
- **After calibration, mass peak L_{inst} dependence negligible, η_{det} dependence reduced from 2 GeV to 100 MeV (data), 10 MeV (MC)**



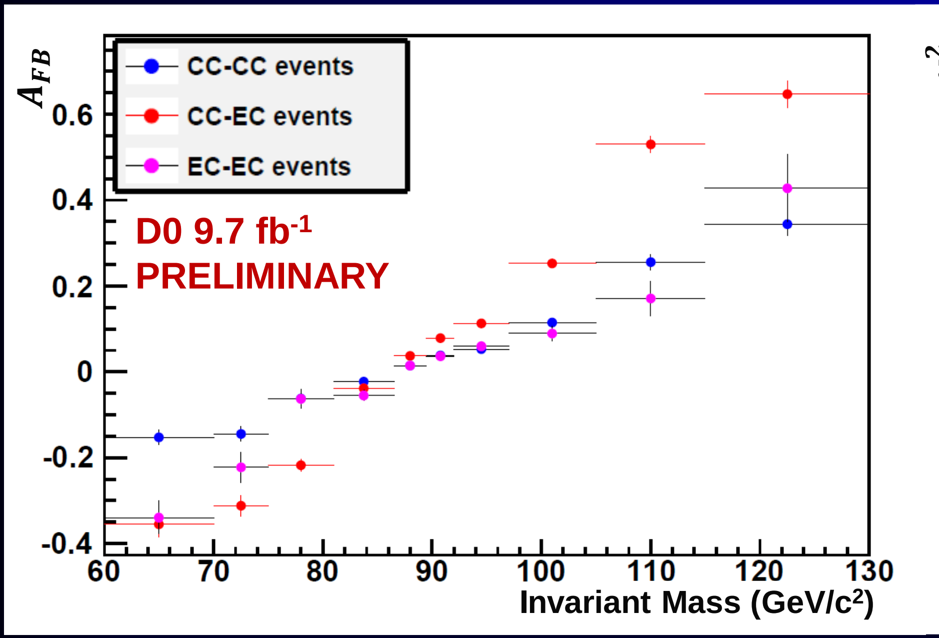
MC Corrections/Reweightings

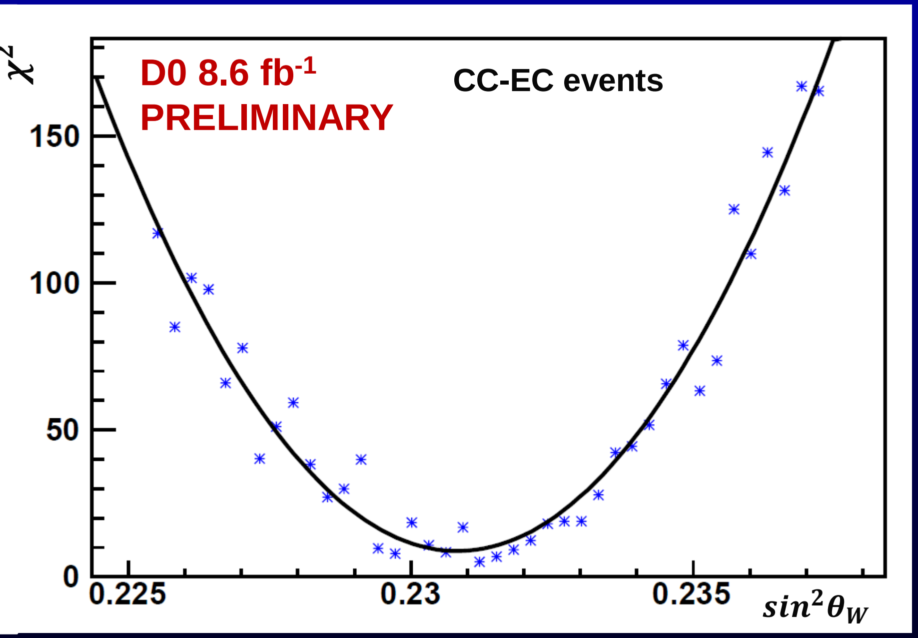
- Separate energy resolution smearing and efficiency corrections for CC phi-mod center, CC phi-mod boundary, EC electrons
- Efficiency corrections measured via tag-and-probe method, and applied as functions of P_T and η
- L_{inst} and vertex z distribution reweighting
- Higher order effects not in PYTHIA
  - 2D (P_T, η) reweighting; NNLO boson mass reweighting



$sin^2\theta_W$ Extraction

- **Raw A_{FB} measurement is compared to reweighted MC A_{FB} templates corresponding to different $sin^2\theta_W$ values**
  - Different $sin^2\theta_W$ predictions obtained by reweighting generator level 2D $(M_{Z/\gamma^*}, cos\theta^*)$ distribution of default MC ($sin^2\theta_W = 0.232$)
  - Done separately for CC-CC, CC-EC, EC-EC events, and for RunIIa (1.1 fb^{-1} low L_{inst}) and RunIIb (8.6 fb^{-1} high L_{inst}) running periods





Results

	CC-CC	CC-EC	EC-EC	Combined
$\sin^2\theta_W$	**0.23086**	**0.23108**	**0.22910**	**0.23098**
statistical unc.	0.00116	0.00047	0.00276	0.00042
systematic unc.				0.00014
Energy scale	0.000002	0.000009	0.000059	0.00012
Energy smear	0.000010	0.000022	0.000126	0.000018
Background	0.000018	0.000010	0.000025	0.000008
Charge misID	0.000020	0.000036	0.000121	0.000030
Electron ID	0.000081	0.000078	0.000053	0.000066
total unc.				0.00044
PDF unc.				0.00029

D0 9.7 fb^{-1}: PRELIMINARY

Upper bound estimate. Final value
← being finalized.
← Vary smear factor $\pm 1\sigma$

← Vary correction factor $\pm 1\sigma$
← Vary correction factor $\pm 1\sigma$

← Quadrature sum of eigenvectors, scaled to 68% CL

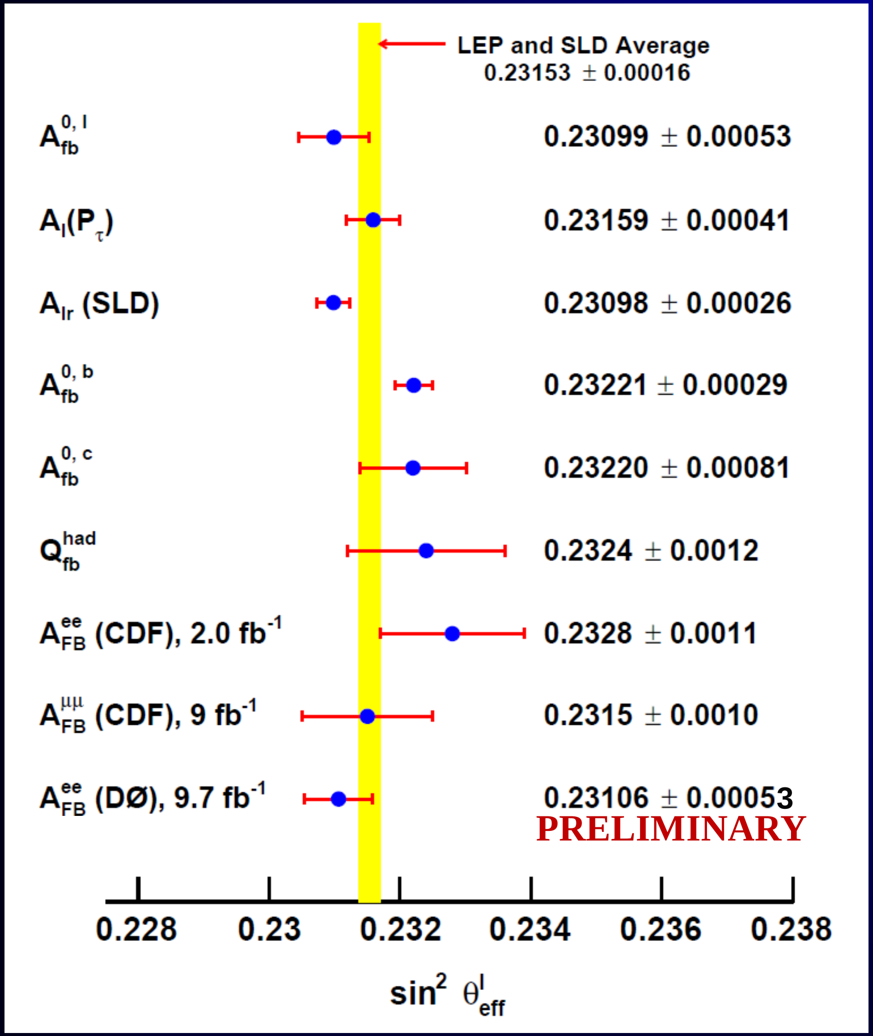
$$\sin^2\theta_W = 0.23098 \pm \underset{(stat)}{0.00042} \pm \underset{(syst)}{0.00014} \pm \underset{(PDF)}{0.00029}$$

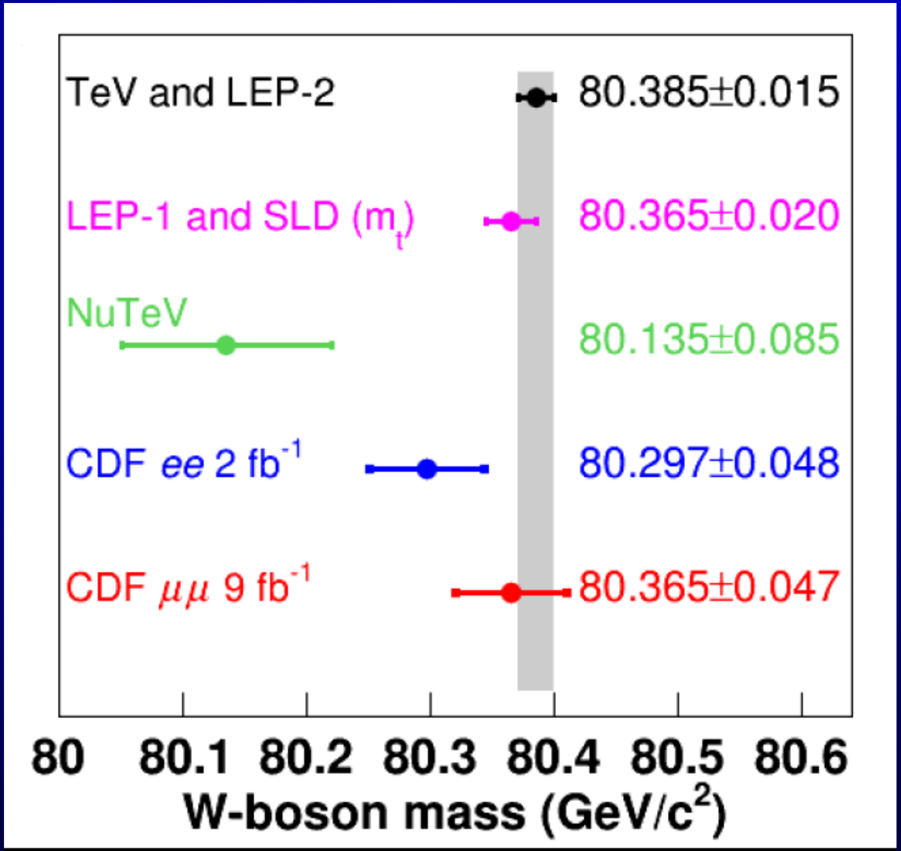
In Standard Model context, with on-shell renormalization scheme, ResBos EBA correction

$$\boxed{\sin^2\theta^l_{eff} = 0.23106 \pm 0.00053}$$

World's Best From Hadron Collider & from Light Quark Interactions

Measurement Comparisons





Conclusions

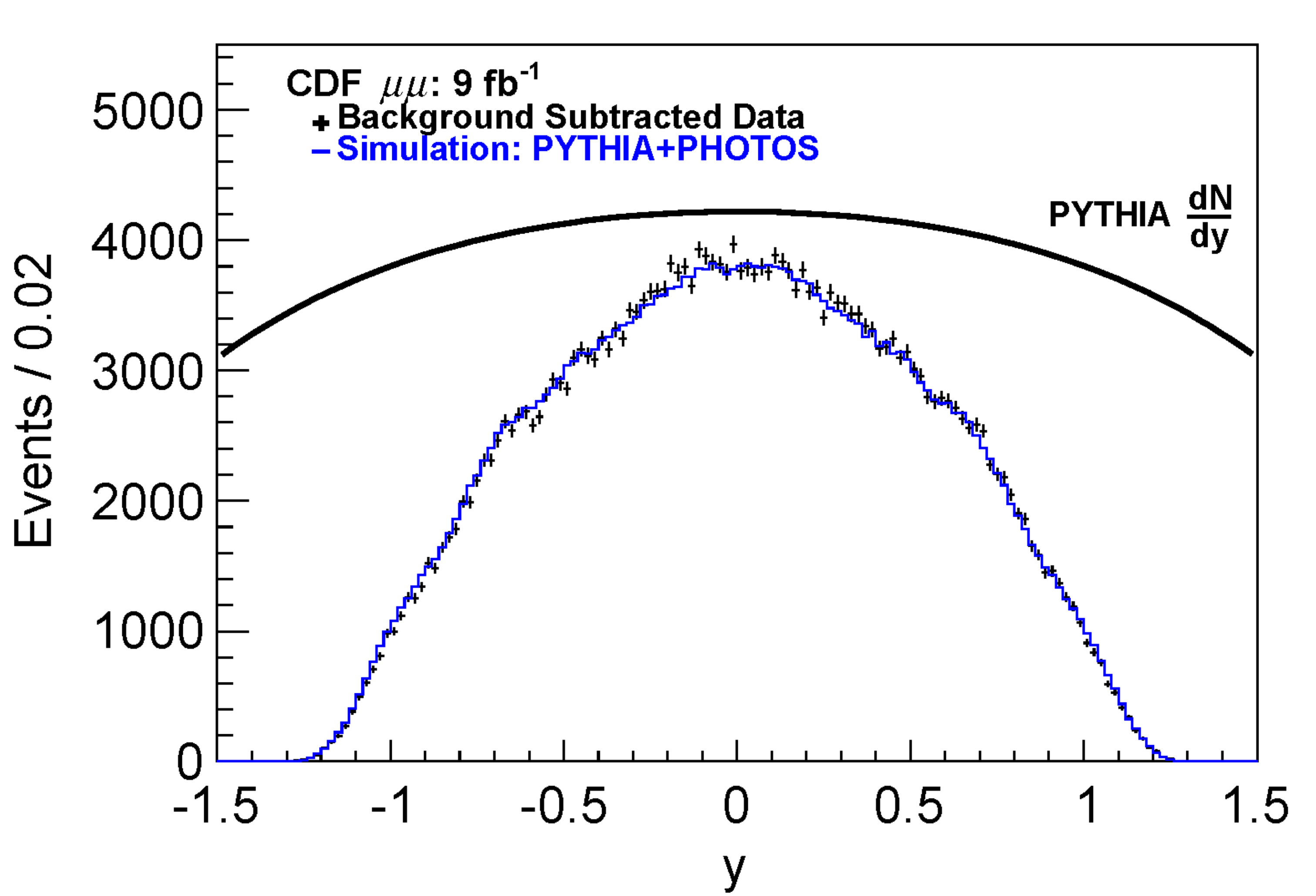
- **CDF 9.2 fb^{-1} Dimuon: $sin^2\theta^l_{eff} = 0.2315 \pm 0.0010$**
- **D0 9.7 fb^{-1} Dielectron: $sin^2\theta^l_{eff} = 0.23106 \pm 0.00053$** **PRELIMINARY**
  - **Most precise from hadron colliders and with light quark couplings**

<u>Still To Come: strong PDF constraints</u> (full dataset unless indicated)

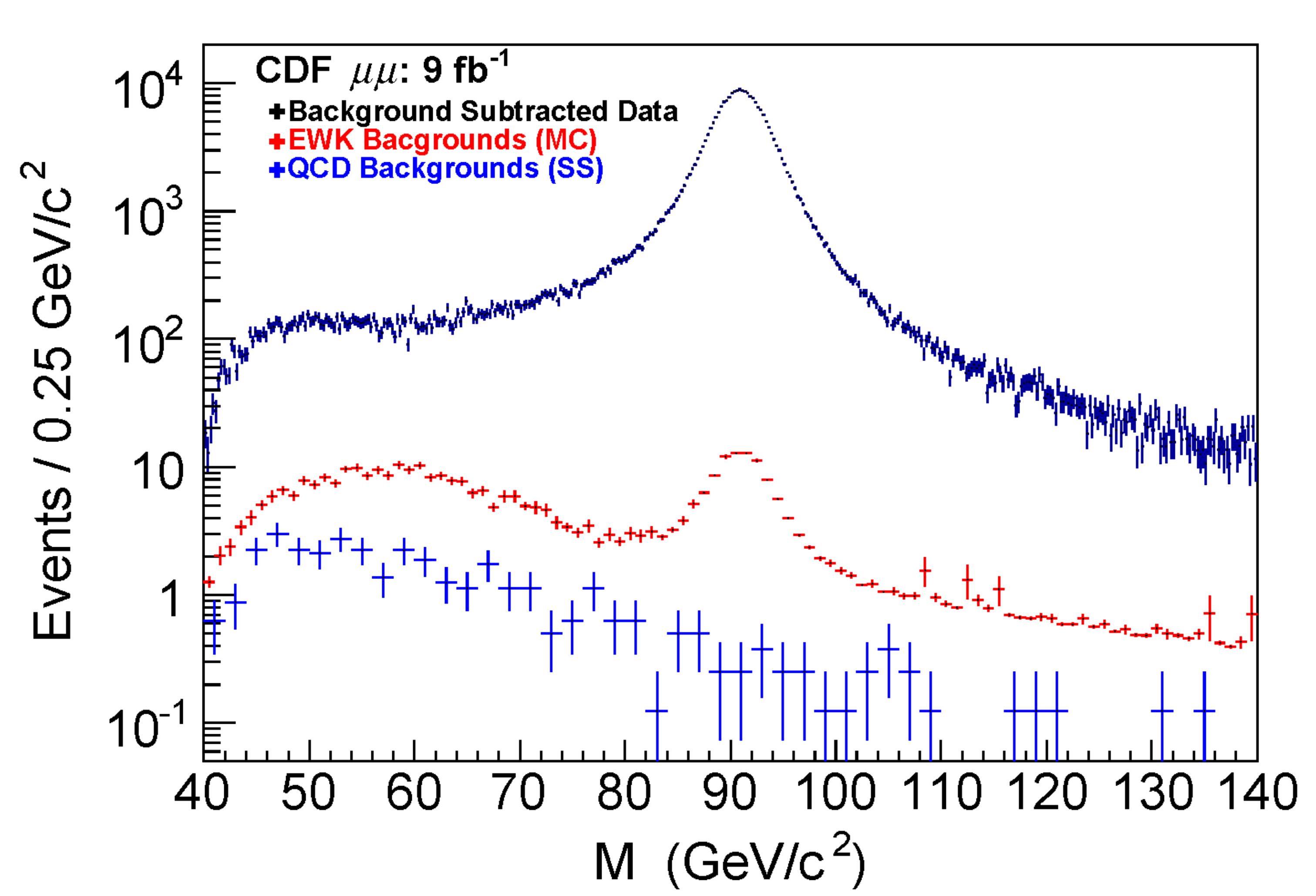
- **CDF:**
  - Dielectron A_{FB} - 4 times stats, PDF limiting systematic
  - Dielectron angular coefficients $sin^2\theta^l_{eff}$(2.1 fb^{-1}): PRD88, 072002 (2013) arXiv:1307.0770
- **D0:**
  - Dielectron A_{FB}: $sin^2\theta^l_{eff}$ PRL soon, PRD with A_{FB}, coupling details later
  - Dimuon A_{FB} - Z peak, low mass, high mass analyses
  - Charge asymmetries:
    - W muon (7.3 fb^{-1}): PRD 88, 091102(R) (2013), arXiv:1309.2591
    - W boson (electron channel): Submitted 12/10/13: PRL, arXiv:1312.2895
    - W electron: PRD in preparation
  - Z ϕ^*, Z rapidity, angular coefficients

Backup

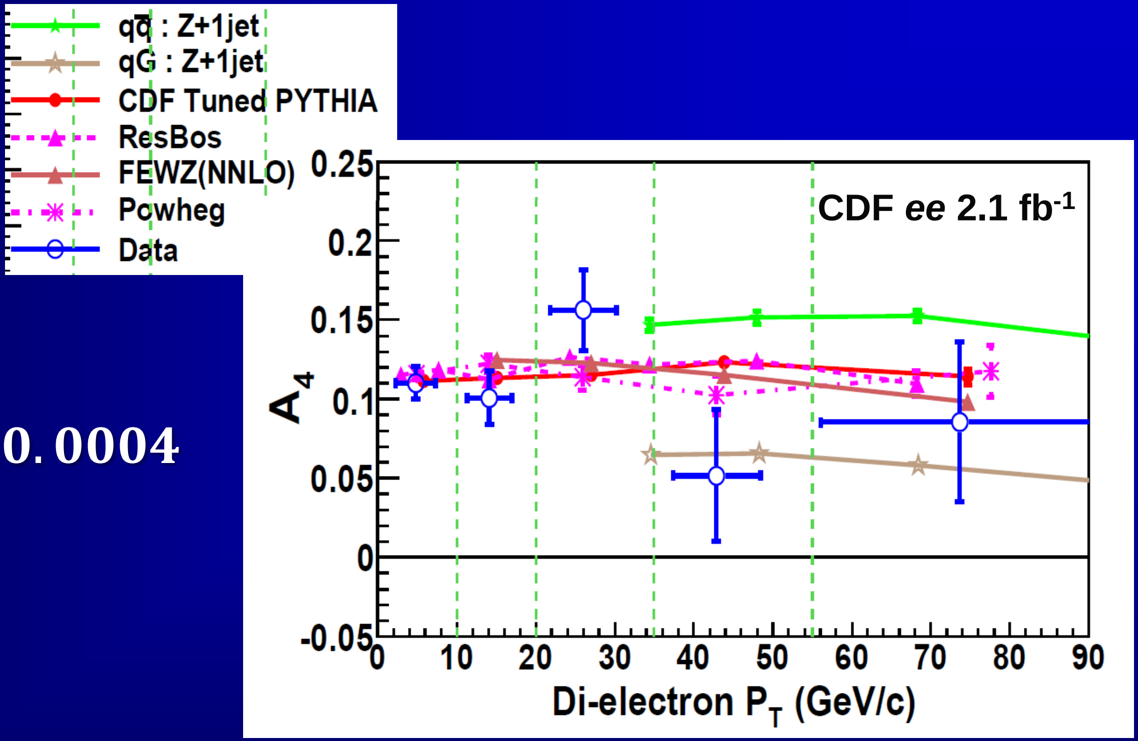
Rapidity Distribution



Background Distribution



$sin^2\theta_W$ from Angular Coefficients



$$A_4 = 0.1100 \pm 0.0079 \pm 0.0004$$

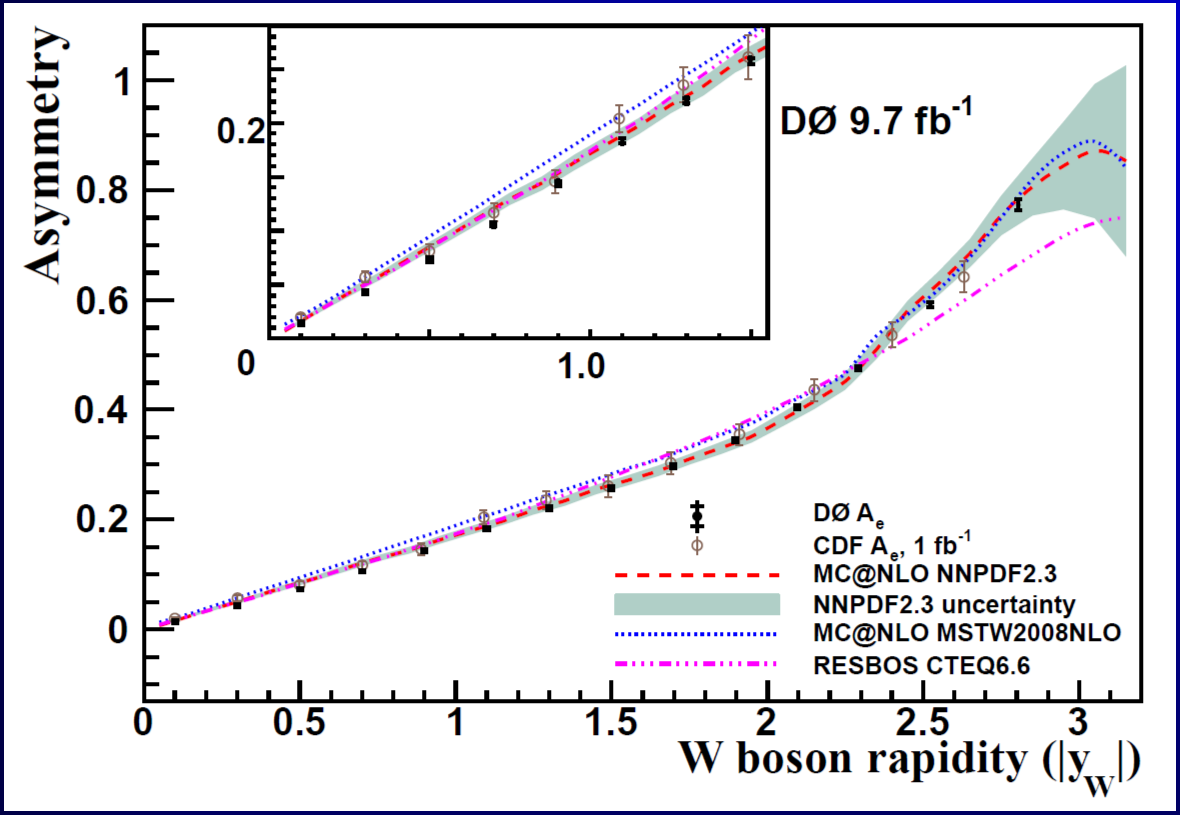
$$sin^2\theta^l_{eff} = 0.2328 \pm 0.0010$$

$$sin^2\theta_W = 0.2246 \pm 0.0009$$

$$M_W(indirect) = 80.297 \pm 0.0048$$

PRD88, 072002 (2013) arXiv:1307.0770

W Charge Asymmetry



- Most precise direct measurement to date
- Coverage to $|\eta| < 3.2$, can be used to improve PDF sets, particularly at high x

Submitted 12/10/13: PRL, arXiv:1312.289