EPS Conference on High Energy Physics

Vienna, July 23, 2015

# Z production and asymmetry at the Tevatron

- Z production kinematics
  - DØ dimuon $d\sigma/d\phi^*$ (10.4 $fb^{-1}$)
- Z decay (forward backward asymmetry → $\sin^2\theta_W$)
  - DØ dielectron (9.7 $fb^{-1}$)
  - CDF dimuon (9.2 $fb^{-1}$)
    - Indirect $M_W$ measurement
- Summary

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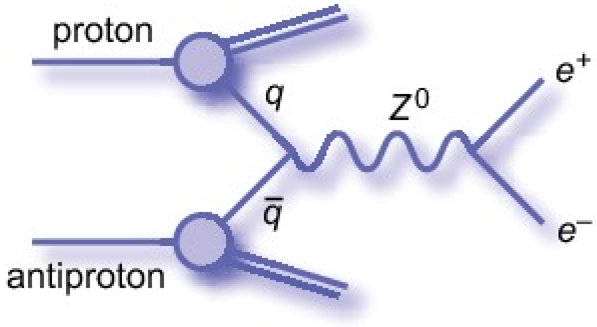
On behalf of CDF and DØ

# Motivation

- Drell/Yan production at the Tevatron: $p\bar{p} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$
- Measure production kinematics $d\sigma_Z/dp_T$
  - Sensitive to initial state radiation
  - Important background for searches



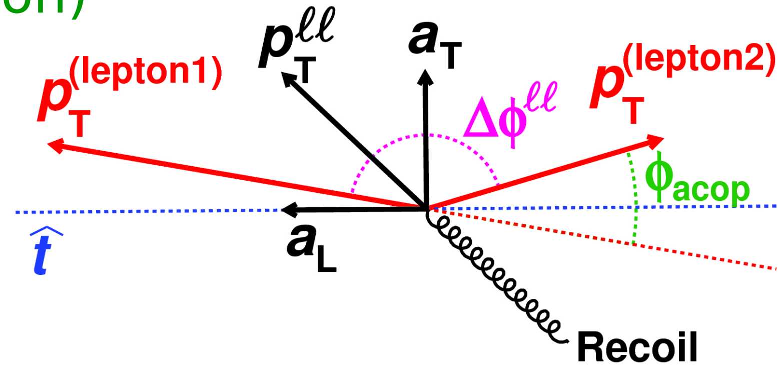

- Measure decay properties $A_{FB}$ and $\sin^2\theta_W$
  - Try to disentangle LEP/SLD tension
    - $A_{FB}^{0b}$(LEP) → 0.23221±0.00029
    - $A_\ell$(SLD) → 0.23098±0.00026 (3.2σ away)
  - Indirect measurement of W mass
- Tevatron measurement is complementary to LHC
  - Z mainly produced by valence quark annihilation
  - CP symmetric collider is ideal for asymmetry measurements

# DØ μμ kinematic distributions 10.4 $fb^{-1}$

- Measurements of $d\sigma/dp_T$ are limited by experimental resolution on $p_T(Z)$
- Introduce new variable $\phi^*$
  - Determined only from angles (good resolution)
  - Highly correlated with $a_T/M_{\ell\ell}$
  - Less correlated to lepton isolation than $p_T$
- Split analysis by rapidity and $M_{\ell\ell}$ regions:
  - $30<M_{\mu\mu}<60$ GeV: sensitive to small-x effects
    - 74k events (90% signal)
  - $70<M_{\mu\mu}<110$ GeV: peak region
    - 645k events (99.84% signal)
  - $160<M_{\mu\mu}<500$ GeV: constrain ISR unc.
    - 2k events (<70% signal)
- Correction factors in each $\phi^*$ bin to go to particle level after FSR

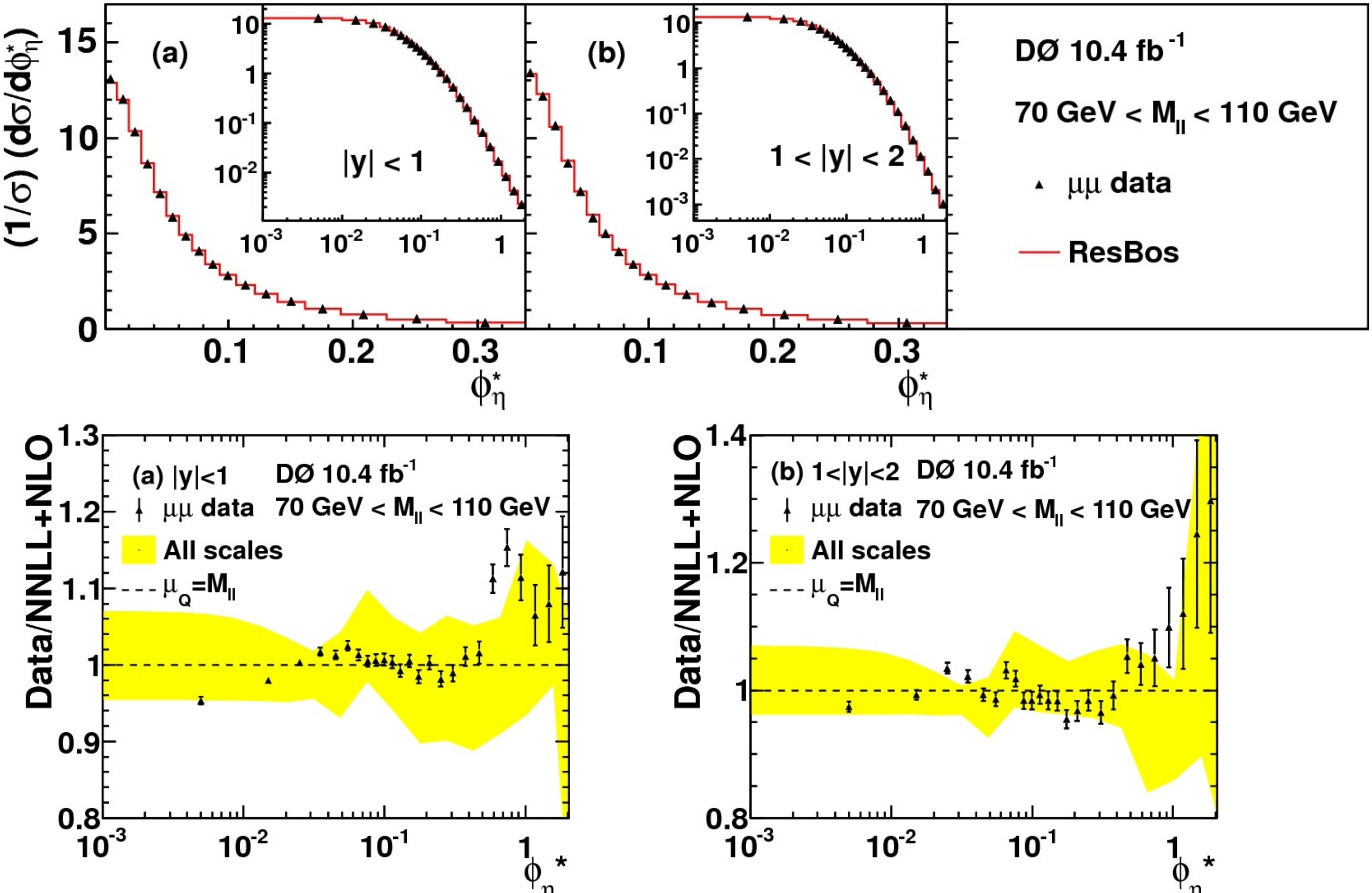
$$\phi^* = tan\left(\frac{\phi_{\rm acop}}{2}\right) sin\theta^*_\eta$$

$$cos\theta^*_\eta = tanh\left(\frac{\eta^- - \eta^+}{2}\right)$$

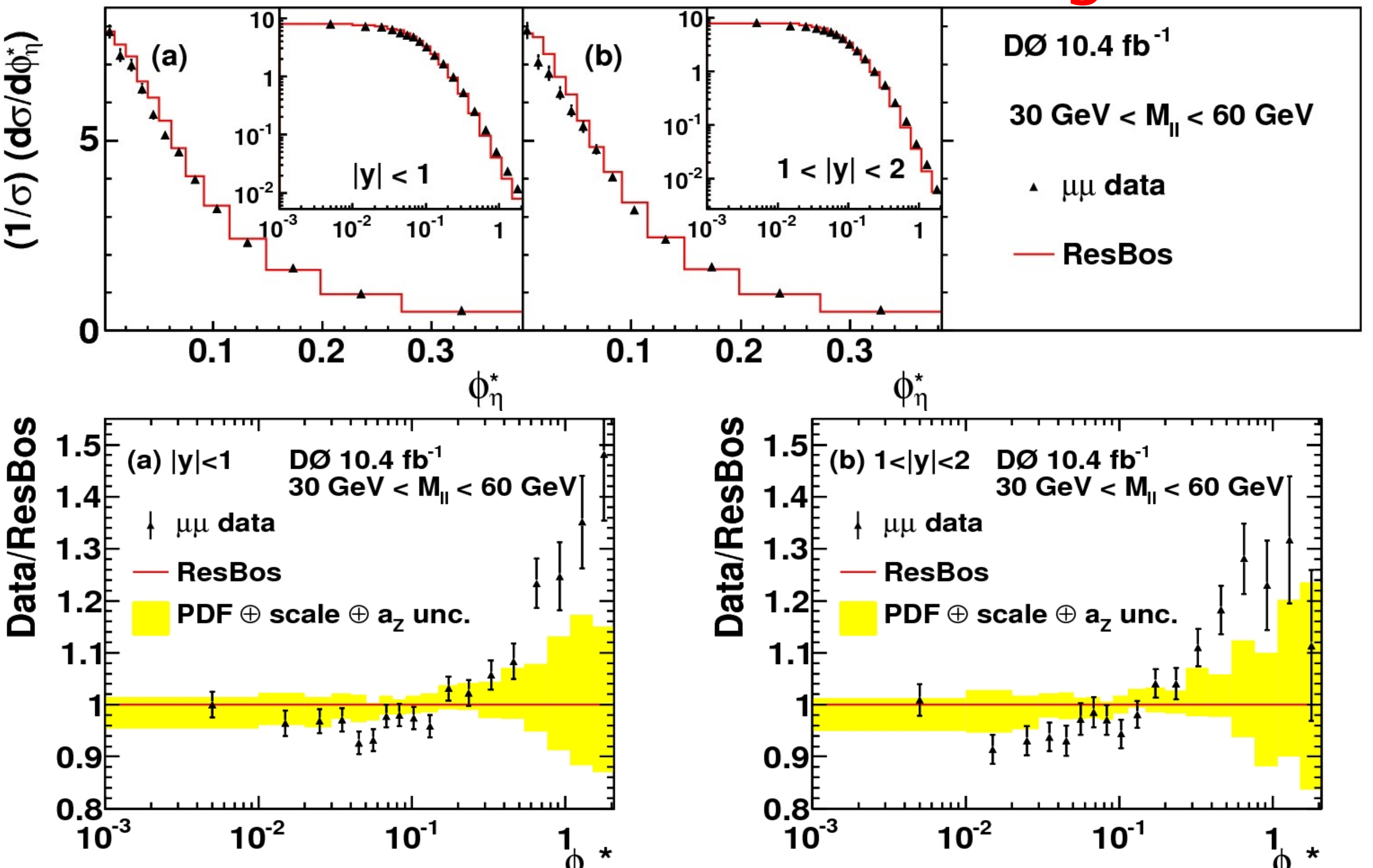



Vesterinen, Wyatt, NIM A 602, 432 (2009)
Banfi et al., EPJ C 71, 1600 (2011)

# Distributions at the Z peak

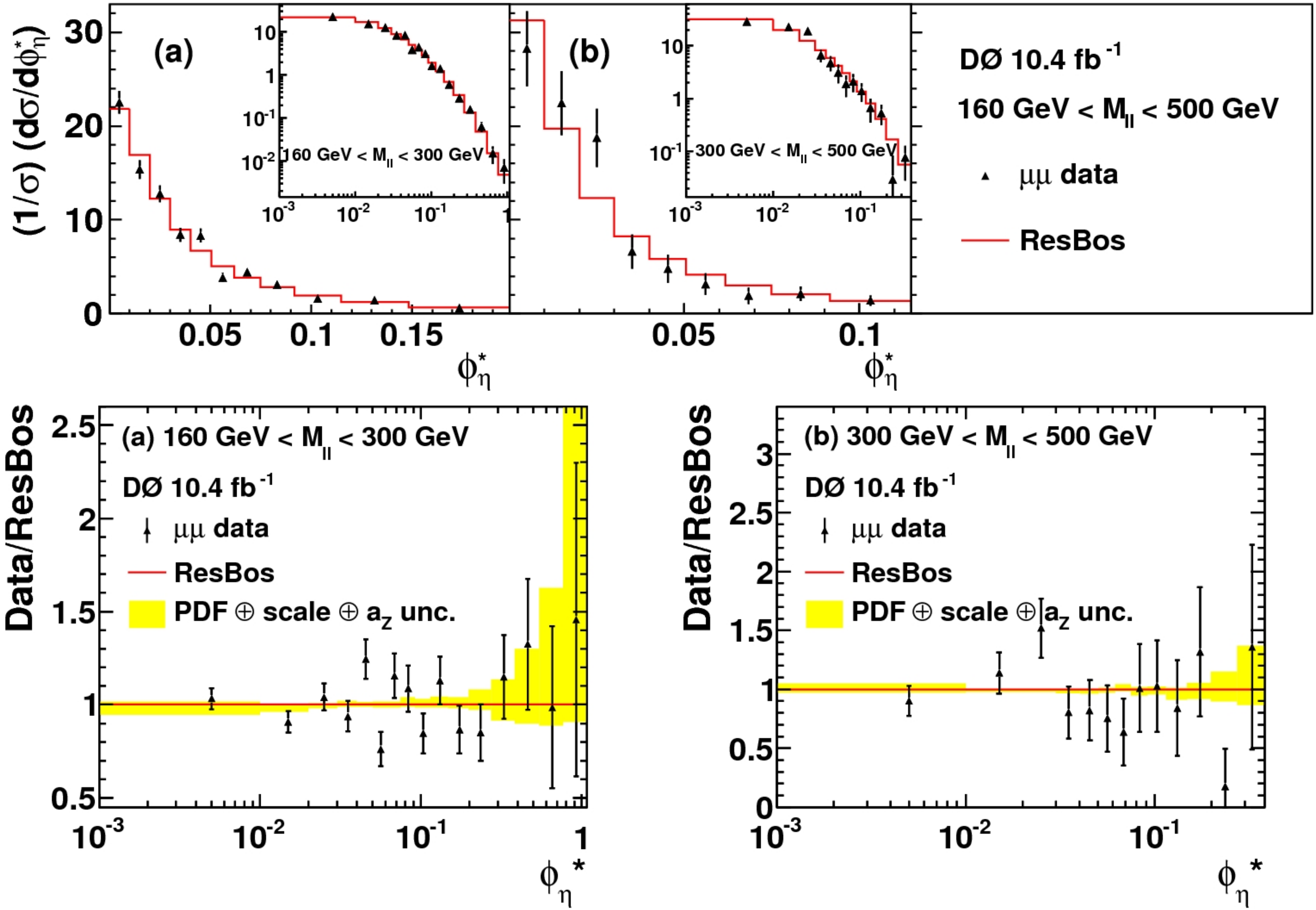


# Distributions low mass region



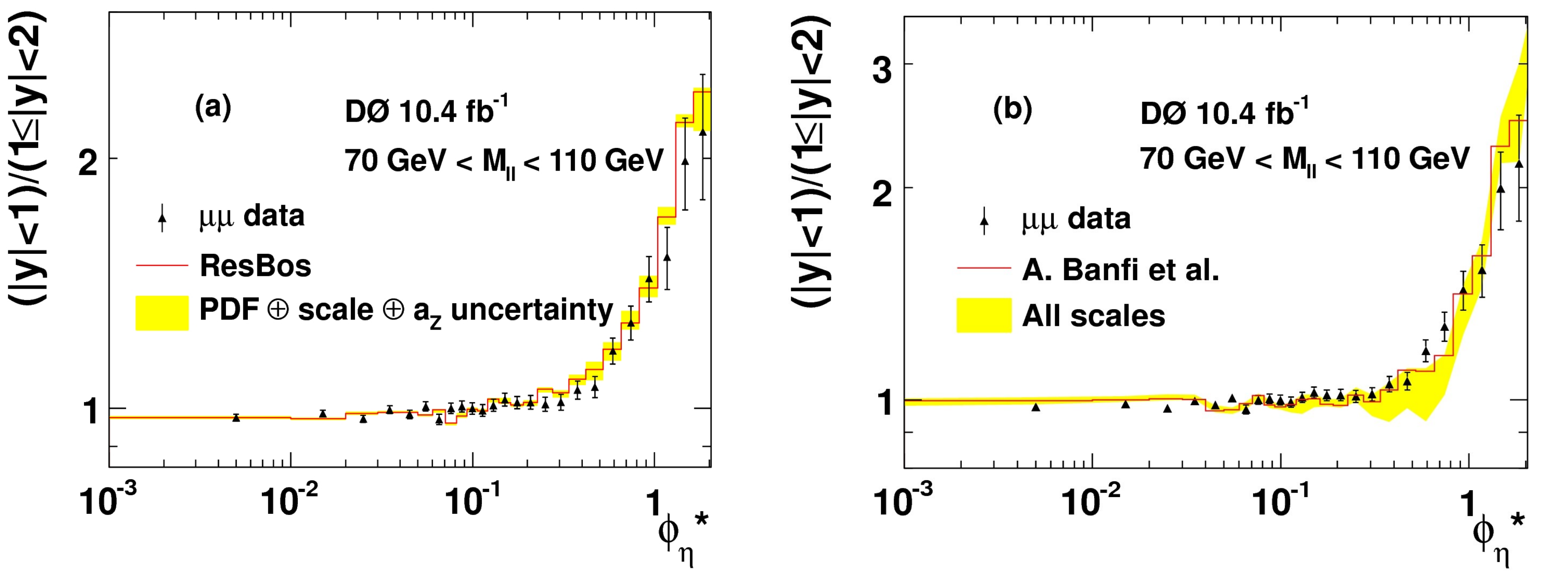

High φ* disagreement: known RESBOS absence of the NNLO correction factor for the photon exchange diagram.

# Distributions high-mass region



# DØ kinematic distributions

- Calculate ratio of (1/σ)(dσ/dφ*) between central and forward rapidity regions
  - Reduce uncertainties from QCD scales to percent level
  - Suggests new variable less sensitive to theoretical uncertainty

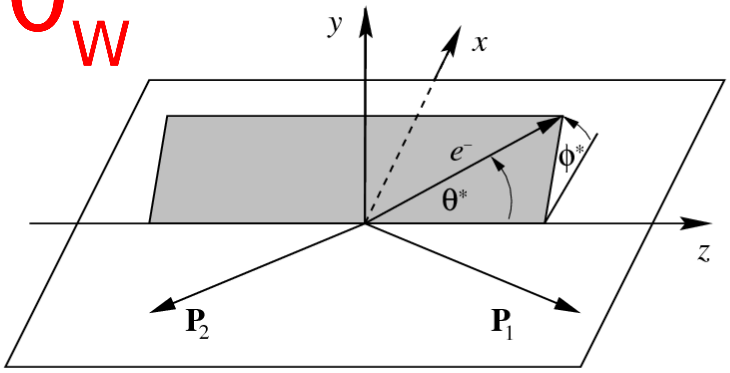



Phys. Rev. D 91, 072002 (2015)

- In summary:
  - Unprecedented precision in the peak region (645k events): tuned RESBOS in excellent agreement
  - Low-mass region (74k events) agrees reasonably well with RESBOS
  - High-mass region (2k events) seems ok, but limited statistics

# Measuring $\sin^2\theta_W$

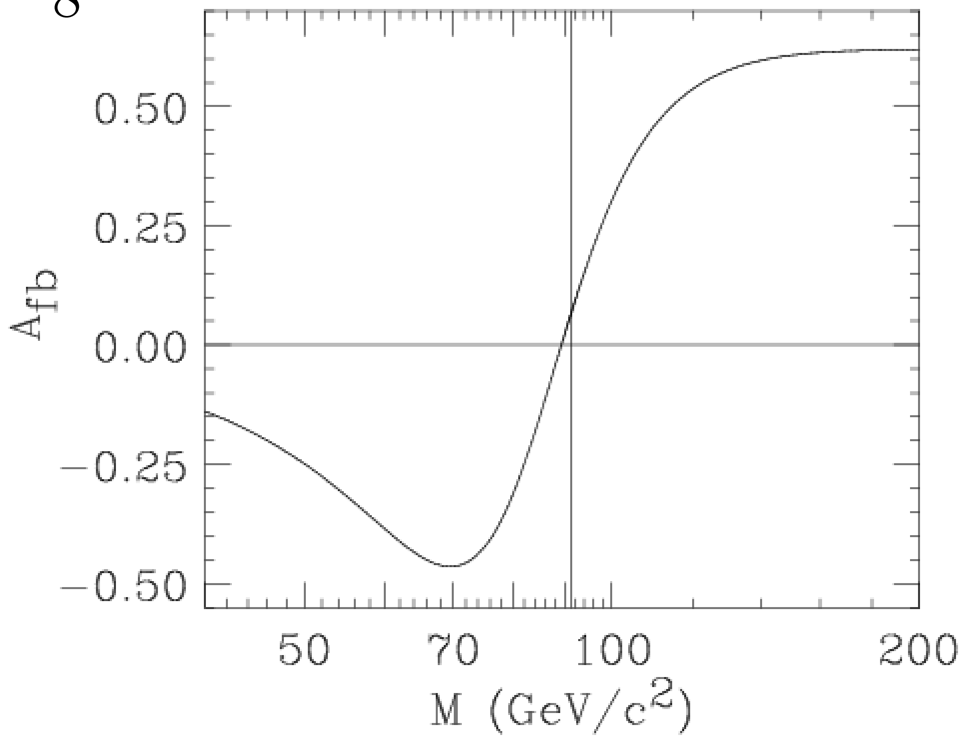
- Measure the weak mixing angle from the forward-backward asymmetry of the polar angle distribution in $Z/\gamma^*$ lepton pairs
- Dilepton frame (Collins-Soper): $\theta^*$ polar angle of the $\ell^-$ with the incoming quark
- At Born level: $$\frac{d\sigma}{dcos\theta^*} \propto 1 + cos^2\theta^* + A_4 cos\theta^*$$
  - When $p_T(Z) \to 0$ $$A_{FB} \equiv \frac{\sigma^+ - \sigma-}{\sigma^+ + \sigma^-} = \frac{3}{8} A_4$$
- $A_4$ term is parity violating from interference of vector and axial currents
- Measure $A_{FB}$ in bins of $M_{\ell\ell}$
- Produce MC templates for $A_{FB}$, $M_{\ell\ell}$, $\sin^2\theta_W$
- Extract $\sin^2\theta_W$ by a $\chi^2$ comparison between data and MC




**Forward: cosθ*>0**

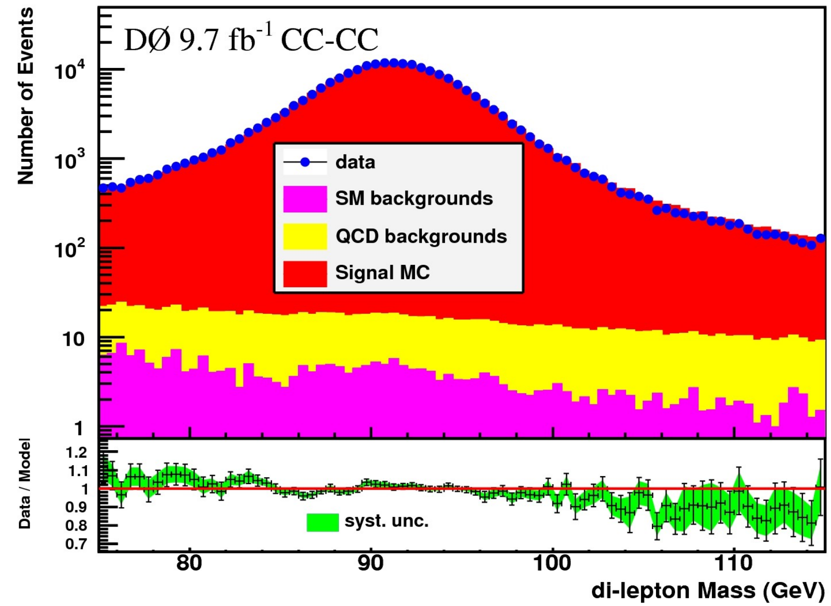
**Backward: cos θ*<0**

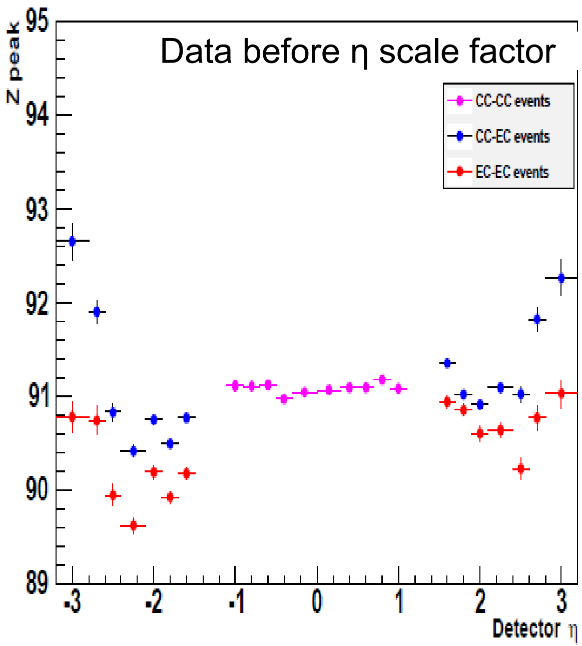
$$sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

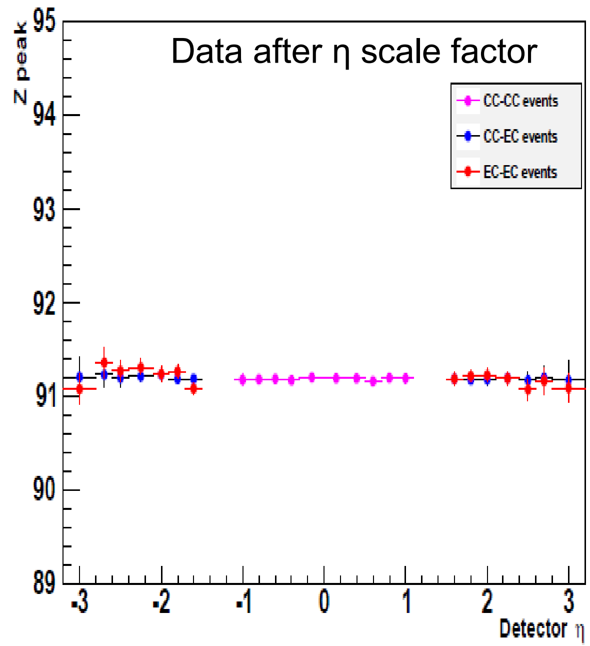


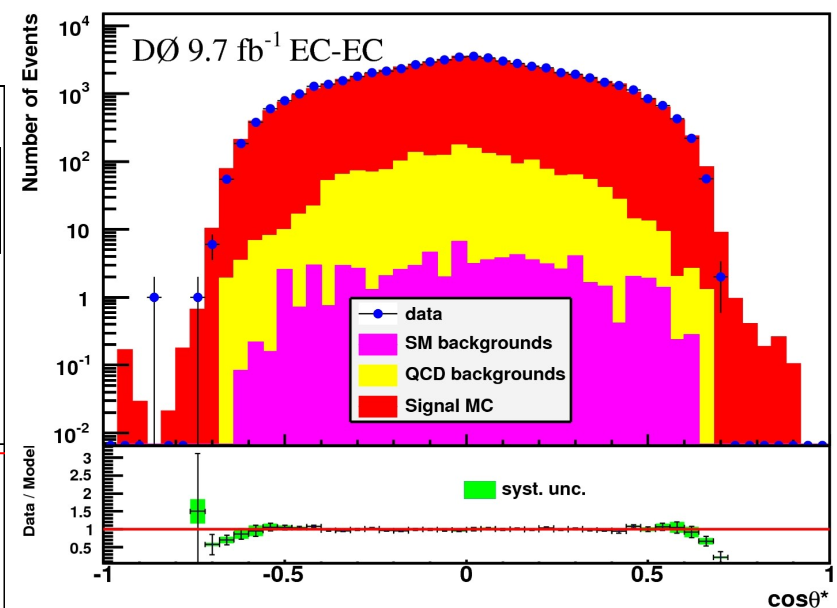
# DØ $\sin^2\theta_W$ from dielectrons in 9.7 $fb^{-1}$

- Require 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 method for energy calibration
  - Apply scale factor as a function of $L_{inst}$ first and then η
  - $M_{ee}$ peak scaled to LEP value in each bin
  - Separate calibrations for data and MC



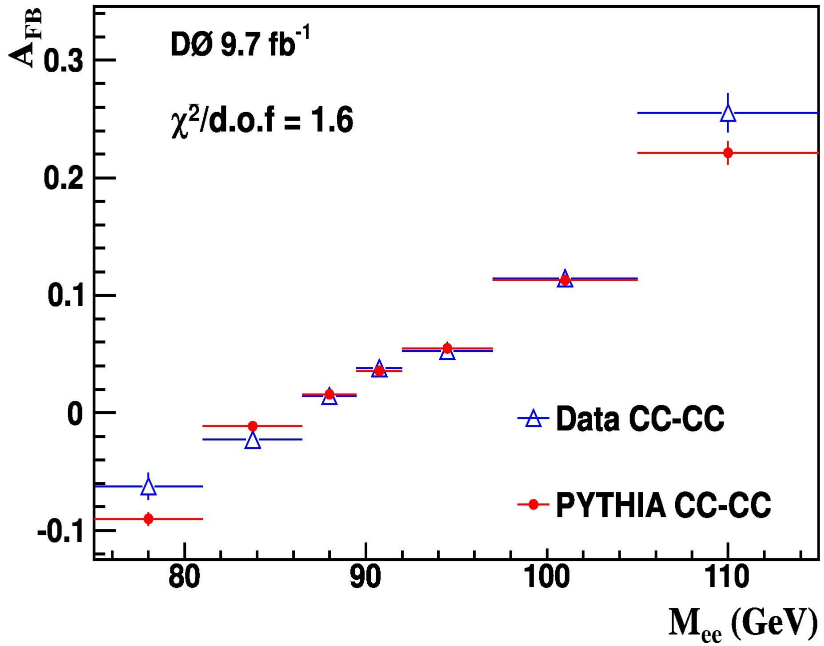



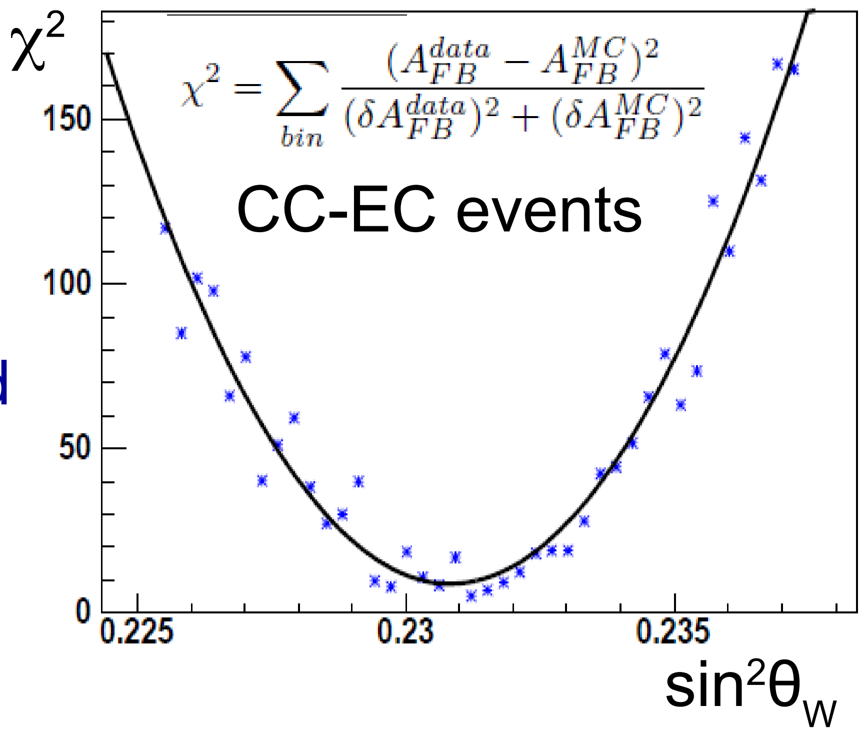



# DØ $\sin^2\theta_W$ dielectron analysis

- Corrections are applied to MC to account for:
  - Smearing of electron energy
  - Efficiency corrections in $p_T(e)$, $\eta(e)$
  - $L_{inst}$ and $z_{PV}$ reweighting to match data
  - Higher order effects: NNLO Z $p_T$ and y to match RESBOS
- Produce 2D templates of $M_{ee}$ and $\cos\theta^*$ by reweighing default MC ($\sin^2\theta_W=0.232$) as a function of $\sin^2\theta_W$
- Extract $\sin^2\theta_W$ by fitting raw $A_{FB}$ to templates with different $\sin^2\theta_W$ values
- No unfolding: MC is carefully corrected to describe the data



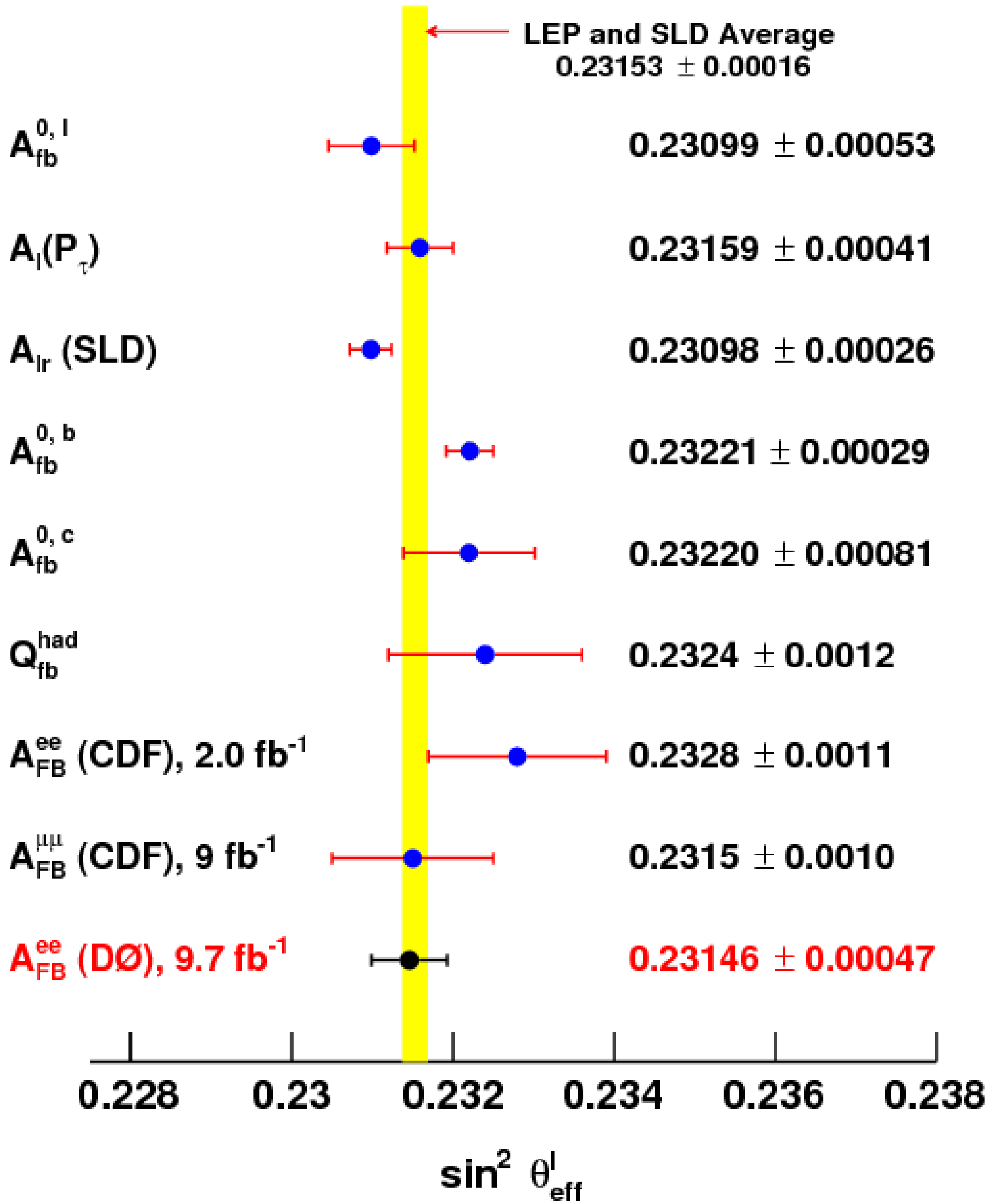



# DØ $\sin^2\theta_W$ dielectron results 9.7 fb$^{-1}$

$\sin^2\theta_W = 0.23139 \pm 0.00043(\text{stat}) \pm 0.00008(\text{syst}) \pm 0.00017(\text{PDF})$

- Transform to $\sin^2\theta^{\ell}_{eff}$ by comparing Pythia and RESBOS (with enhanced Born approximation corrections):

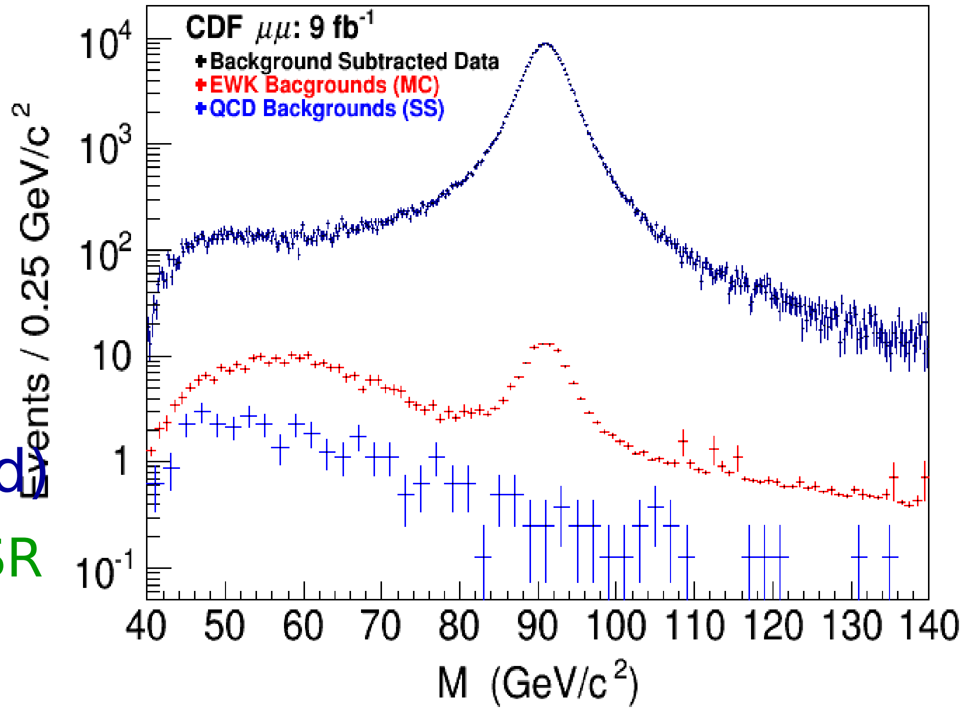
$\sin^2\theta^{\ell}_{eff} = 0.23146 \pm 0.00047$

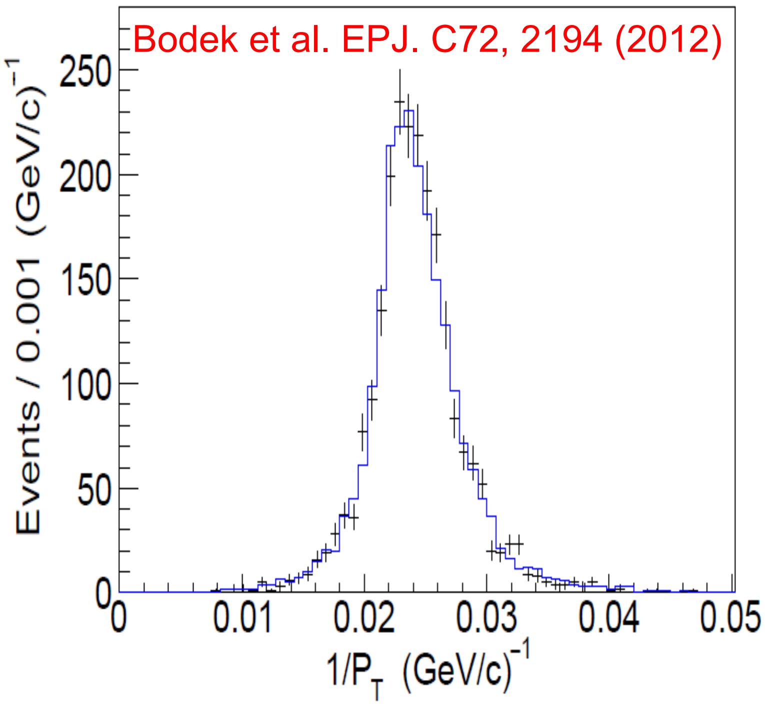


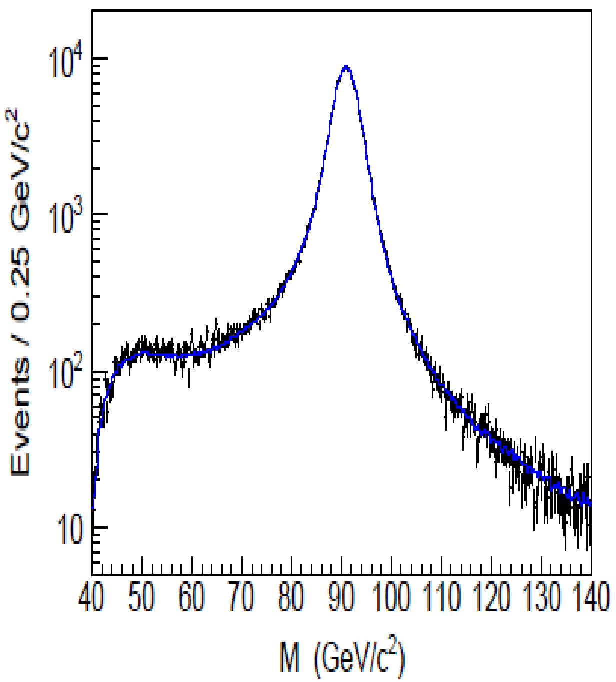

arXiv:1408.5016 Accepted by PRL

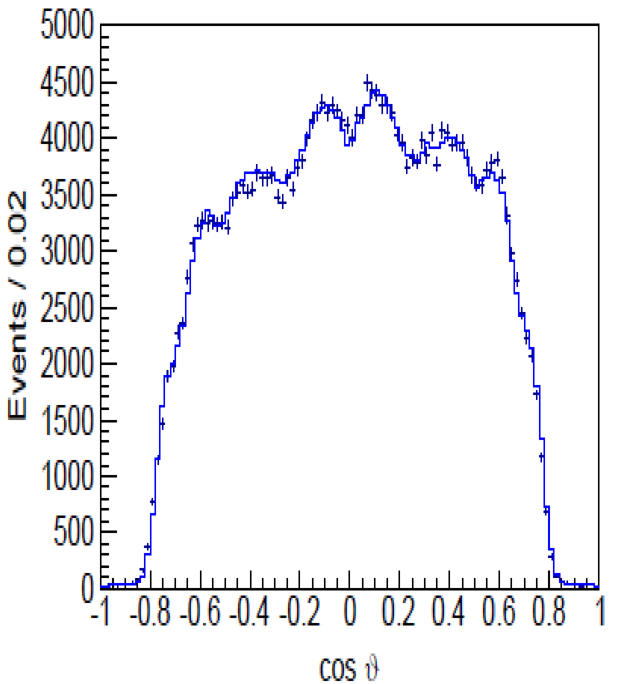
# CDF $\sin^2\theta_W$ from dimuons in 9.2 fb$^{-1}$

- Tight muon cuts: $p_T$>20 GeV
- Dimuon pairs ($|\eta_1|<1$, $|\eta_2|<1.5$)
  - All dimuon detector topologies
  - $|y| < 1$ ; $M_{\mu\mu} > 40$ GeV
- 276k events
- $p_T(\mu)$ calibration (Rochester method)
  - Tune data and simulation to post-FSR generator level in 64 individually calibrated $\eta$, $\varphi$ bins



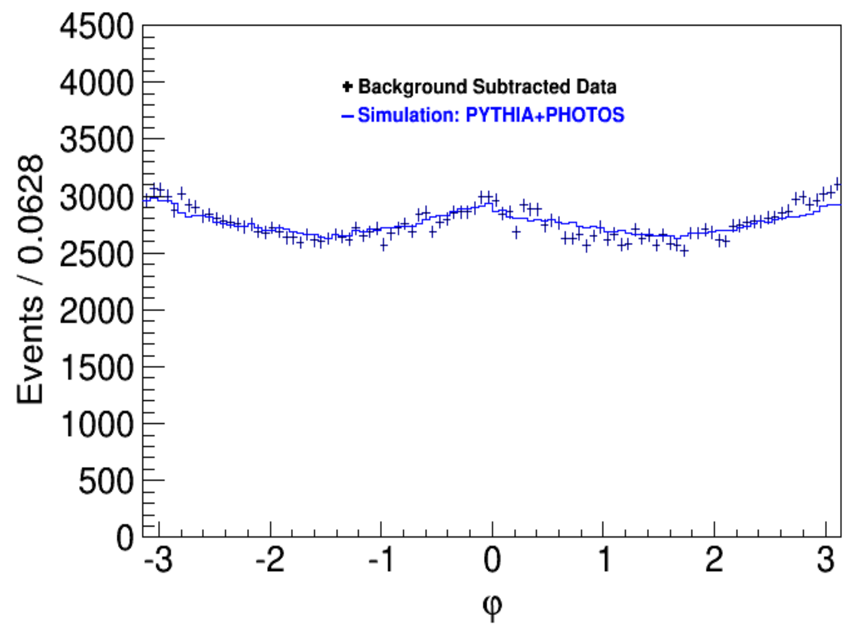



# CDF angular event weighting

- Extract $A_4(M_Z)$ in bins of cosθ* and average the results
  - Assume $(\varepsilon A)^- = (\varepsilon A)^+$ in each bin
  - $A_{FB}(|\cos\theta^*|) = A_{FB} \cdot |\cos\theta^*| / (1+\cos^2\theta^* + \ldots)$
- Recast binned measurement into unbinned weighted event sum
  - Weights depend on $M_{\ell\ell}$, $p_T(\ell\ell)$, cosθ*, φ*
- All acc. and effs. cancel to first order
- Equivalent to ML fit, improves the statistical precision up to 20%
- Does not take into account:
  - Smearing due to detector resolution
  - 2nd order bias due to low acceptance regions and non-uniformity: $(\varepsilon A)^- \neq (\varepsilon A)^+$

$$\frac{d\sigma}{dcos\theta^*} \propto 1 + cos^2\theta^* + \frac{A_0}{2}(1 - 3cos^2\theta^*) + A_4 cos\theta^*$$

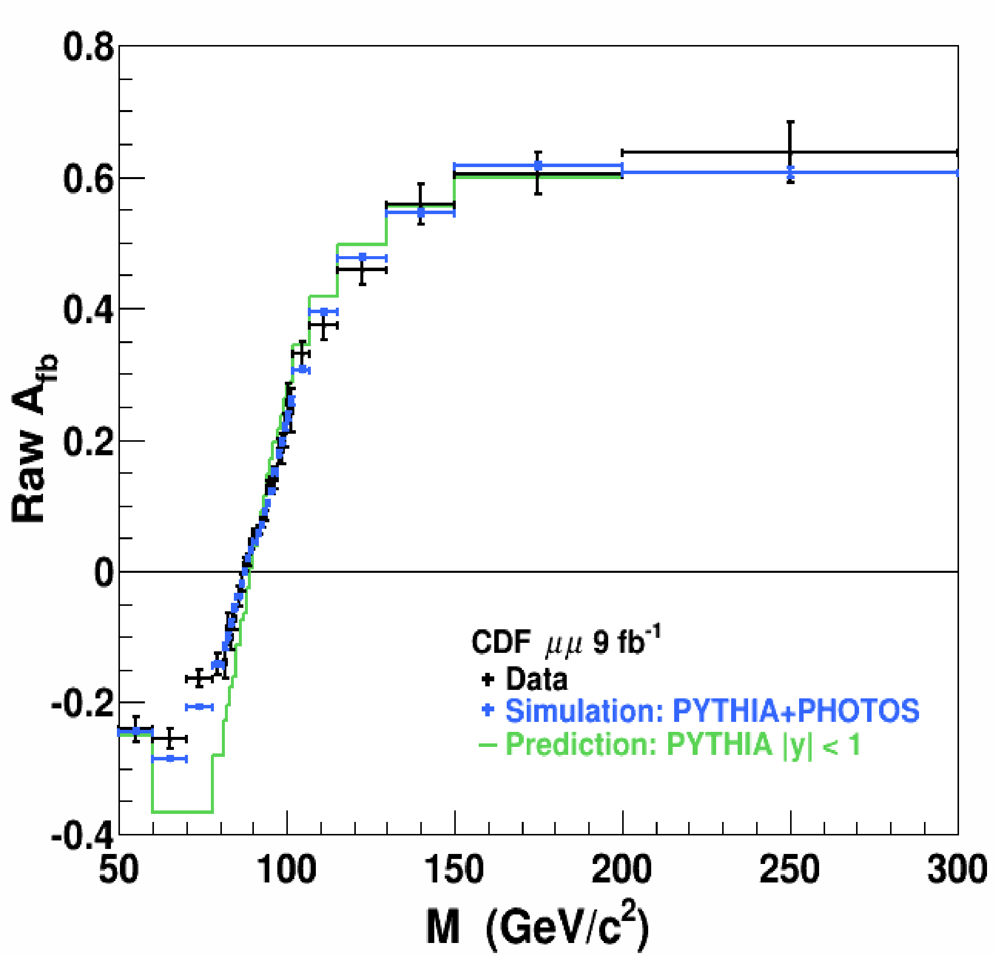
$A_0$ = 0 for $p_T(Z) \rightarrow 0$

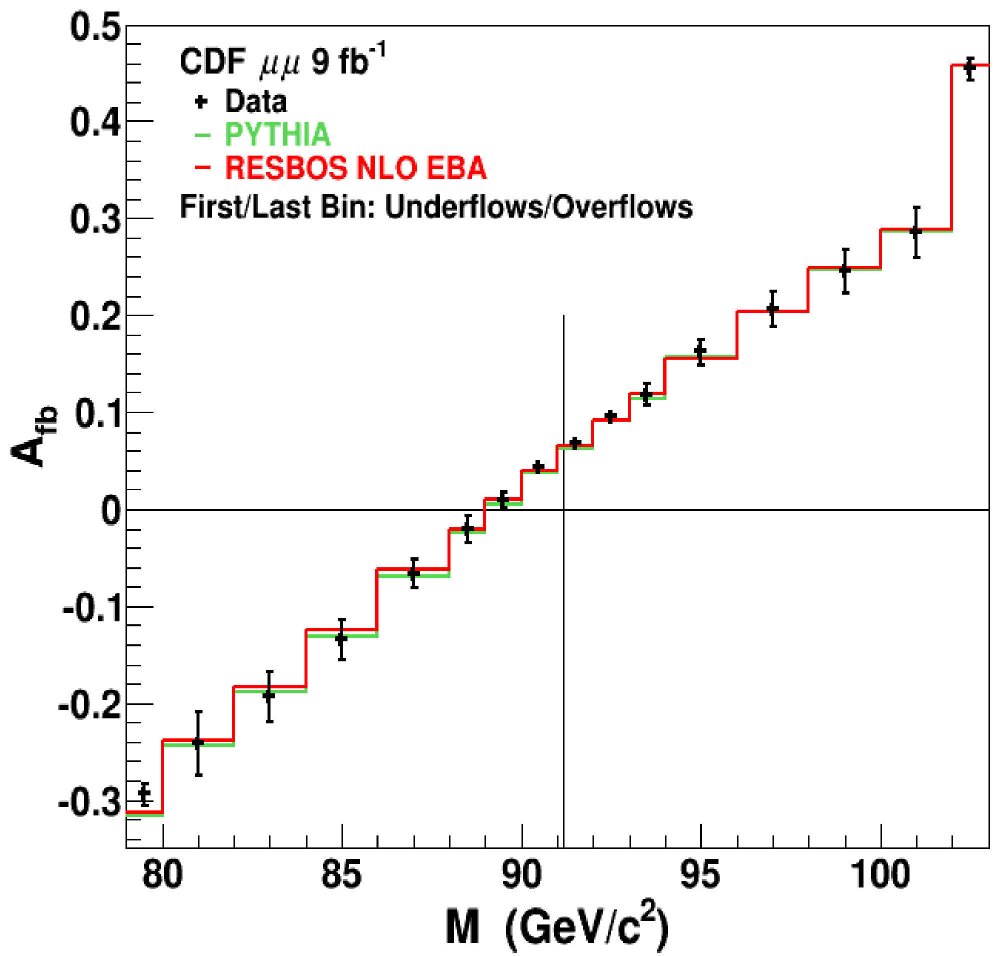



A. Bodek, EPJ. C67, 321 (2010)

# CDF unfolding

- Angular event weighting provides first order acceptance correction
- Use unfolding to correct for resolution and QED FSR:
  - Two 16x16 unfolding matrices (16 mass bins, +, - regions)
- Bin-by-bin second order bias correction:
  - Additive factor (True-Estimated) to unfolded $A_{FB}$ in M bins



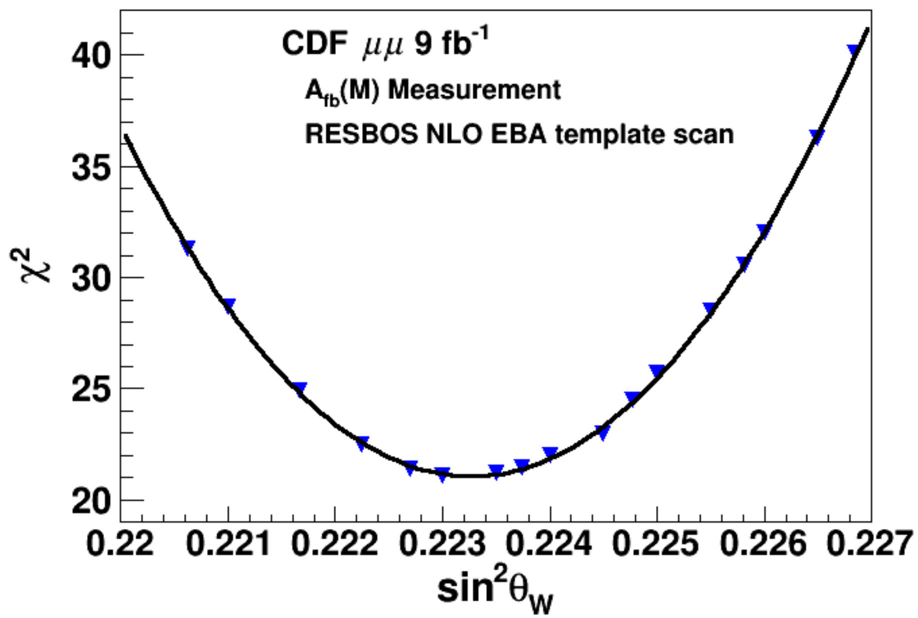
# CDF dimuon $\sin^2\theta_W$ results

- Perform $\chi^2$ fit based on RESBOS templates with different $\sin^2\theta_W$
  - Full ZFITTER EW radiative corrections, Enhanced Born Approximation
  - Include full complex form factors (also compared to POWHEG, LO)

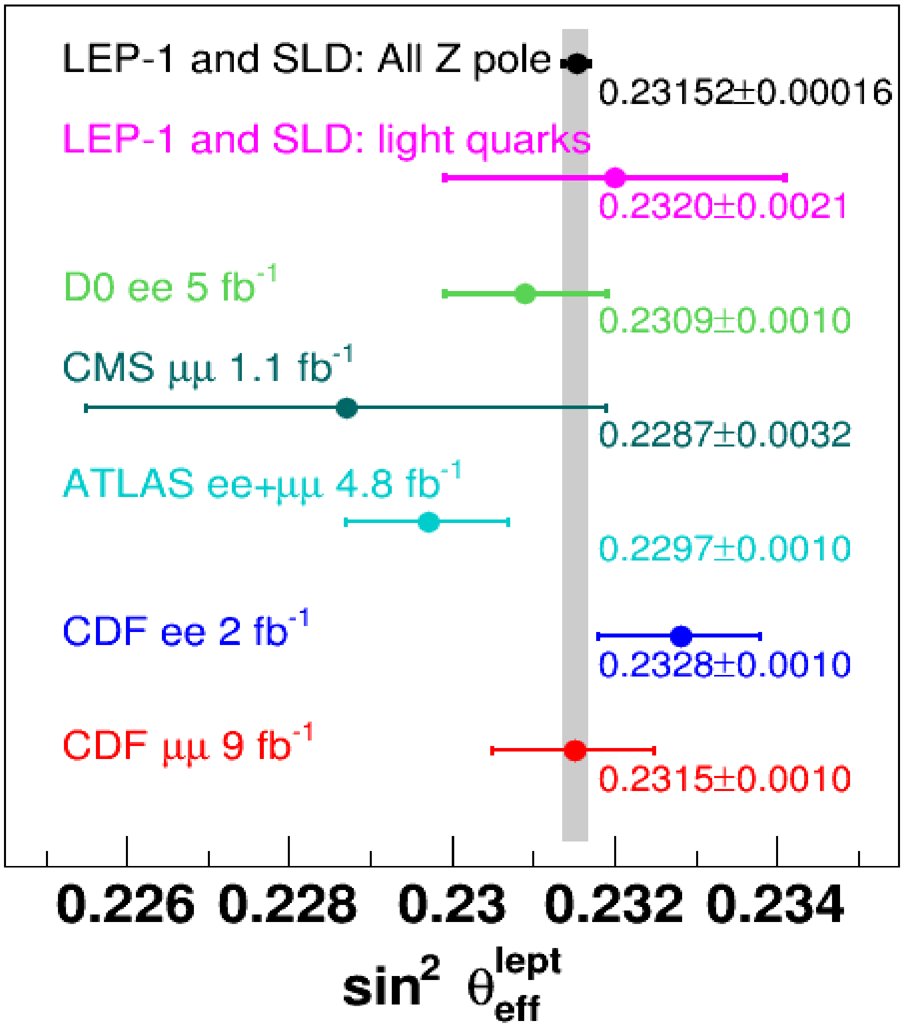
$\sin^2\theta^{\ell}_{eff} = 0.23150 \pm 0.00090(stat) \pm 0.00011(sys) \pm 0.00036(PDF)$

- On-shell renormalization scheme, $\sin^2\theta_W \equiv 1-(M_W^2/M_Z^2)$ to all orders

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



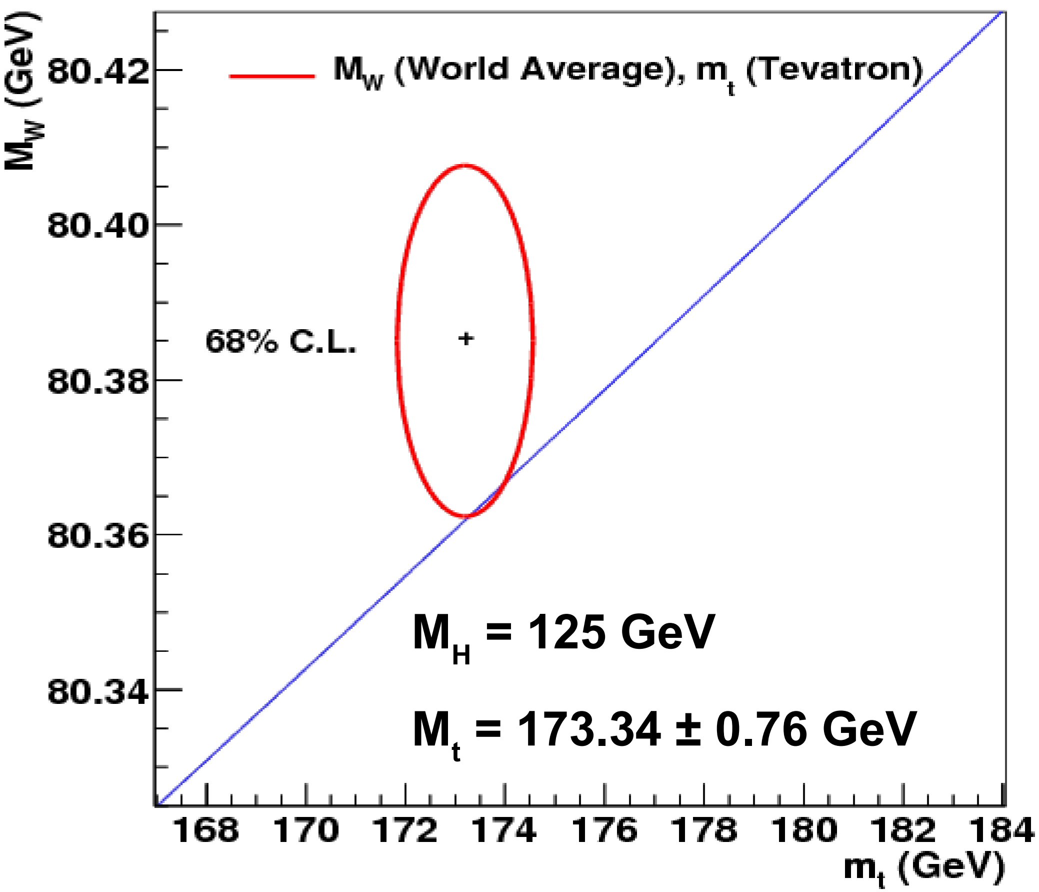

Phys. Rev. D 89, 072005 (2014)

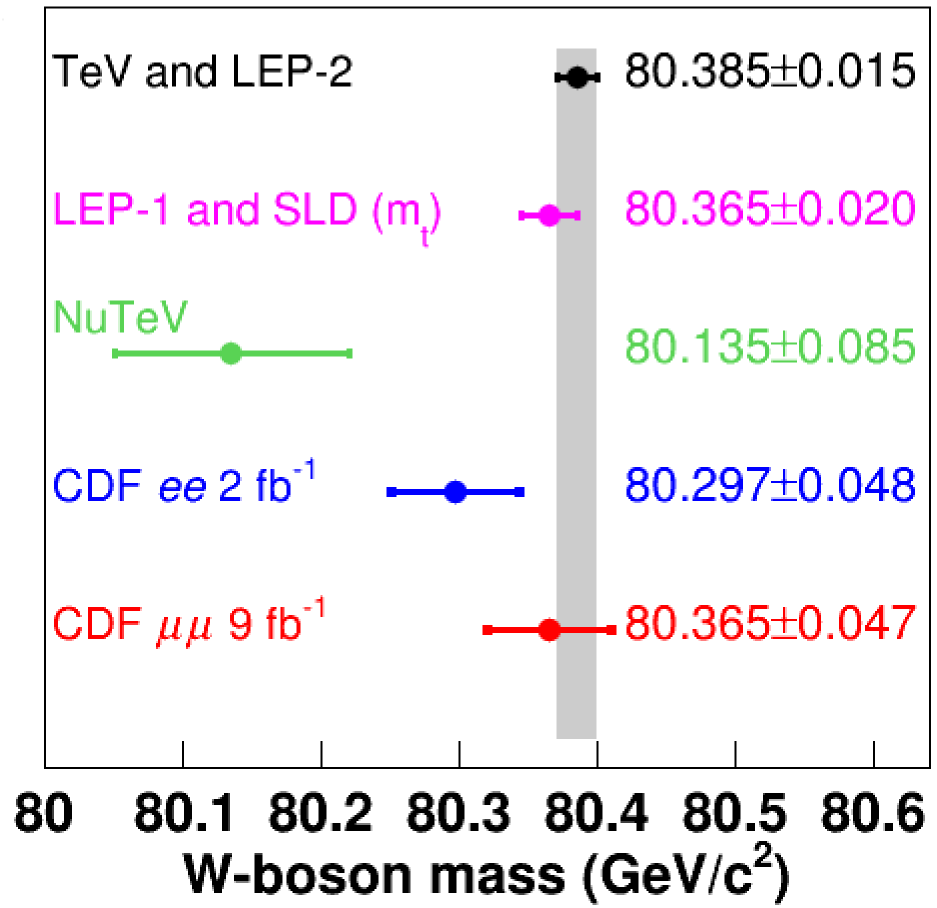


# CDF indirect $M_W$ measurement

- $M_W$ measured at the Tevatron directly: $M_W$=80.385±0.015 GeV
- By measuring the on-shell $\sin^2\theta_W$ we obtain an indirect measurement of $M_W$: $M_W$(indirect) = 80.365 ± 0.047 GeV
  - Using $M_Z$ = 91.1876 ± 0.0021 GeV $$sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$
- $\Delta\sin^2\theta_W$=0.00030 yields to $\Delta M_W$=15 MeV

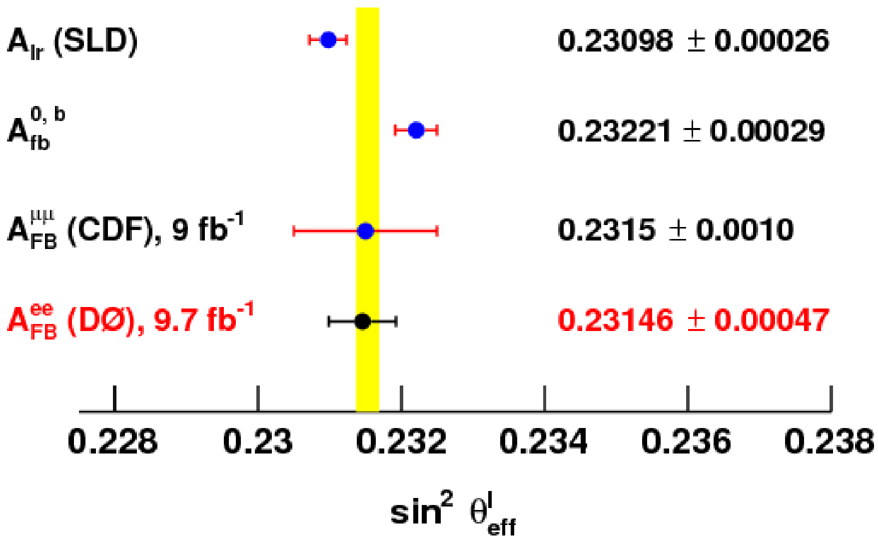
Phys. Rev. D 89, 072005 (2014)



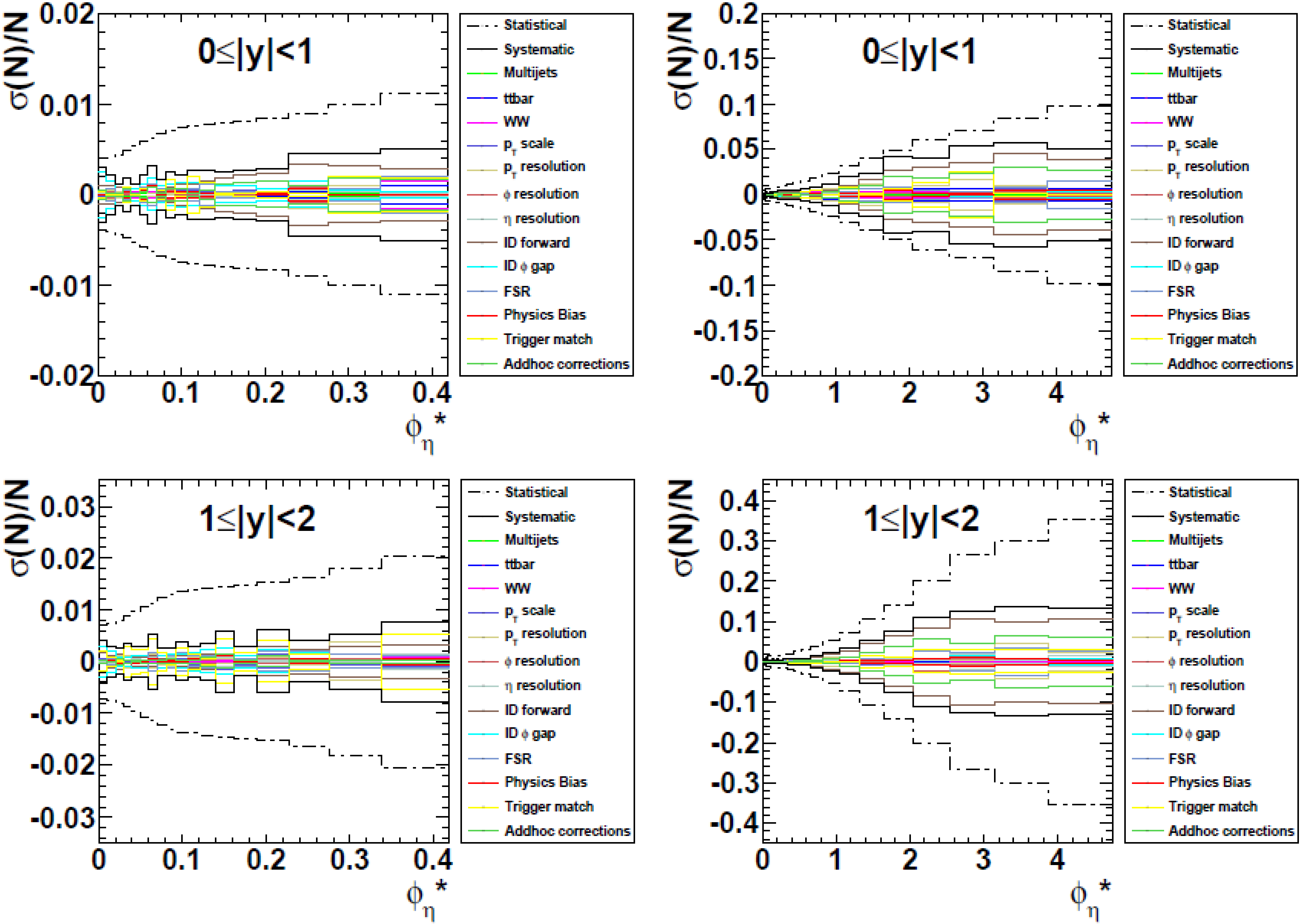
# Conclusions

- DØ (μμ, 10.4 $fb^{-1}$): dσ/d$\phi^*$ is well described by the data
- DØ (ee, 9.7 $fb^{-1}$): $\sin^2\theta^{\ell}_{eff} = 0.23146 \pm 0.00047$
- CDF (μμ, 9.2 $fb^{-1}$): $\sin^2\theta^{\ell}_{eff} = 0.2315 \pm 0.00100$
  - $M_W$(indirect) = 80.365 ± 0.047 GeV
- Still to come from DØ:
  - $\sin^2\theta_W$ μμ channel
  - Z decay angular coefficients (ee)
- Still to come from CDF:
  - $\sin^2\theta_W$ ee channel
- Combining all channels for CDF and DØ, expect $\Delta\sin^2\theta_W \sim 0.00030$
  - Similar to LEP and SLD
- Indirect and direct measurements of $M_W$ will have similar uncertainties



# Extras

The systematic error is smaller than the statistical error in all bins of φ∗ in the peak region.



- DØ

| | CC-CC | CC-EC | EC-EC | Combined |
|---|---|---|---|---|
| $\sin^2\theta_W$ | 0.23140 | 0.23142 | 0.22986 | 0.23138 |
| Statistical | 0.00116 | 0.00047 | 0.00276 | 0.00043 |
| Systematic | 0.00009 | 0.00009 | 0.00019 | 0.00008 |
| Energy Calibration | 0.00003 | 0.00001 | 0.00004 | 0.00001 |
| Energy Smearing | 0.00001 | 0.00002 | 0.00013 | 0.00002 |
| Background | 0.00002 | 0.00001 | 0.00002 | 0.00001 |
| Charge Misidentification | 0.00002 | 0.00004 | 0.00012 | 0.00003 |
| Electron Identification | 0.00008 | 0.00008 | 0.00005 | 0.00007 |
| Total | 0.00116 | 0.00048 | 0.00277 | 0.00044 |

Additionally:
Δhigher orders = "small"
ΔPDF = 0.00017

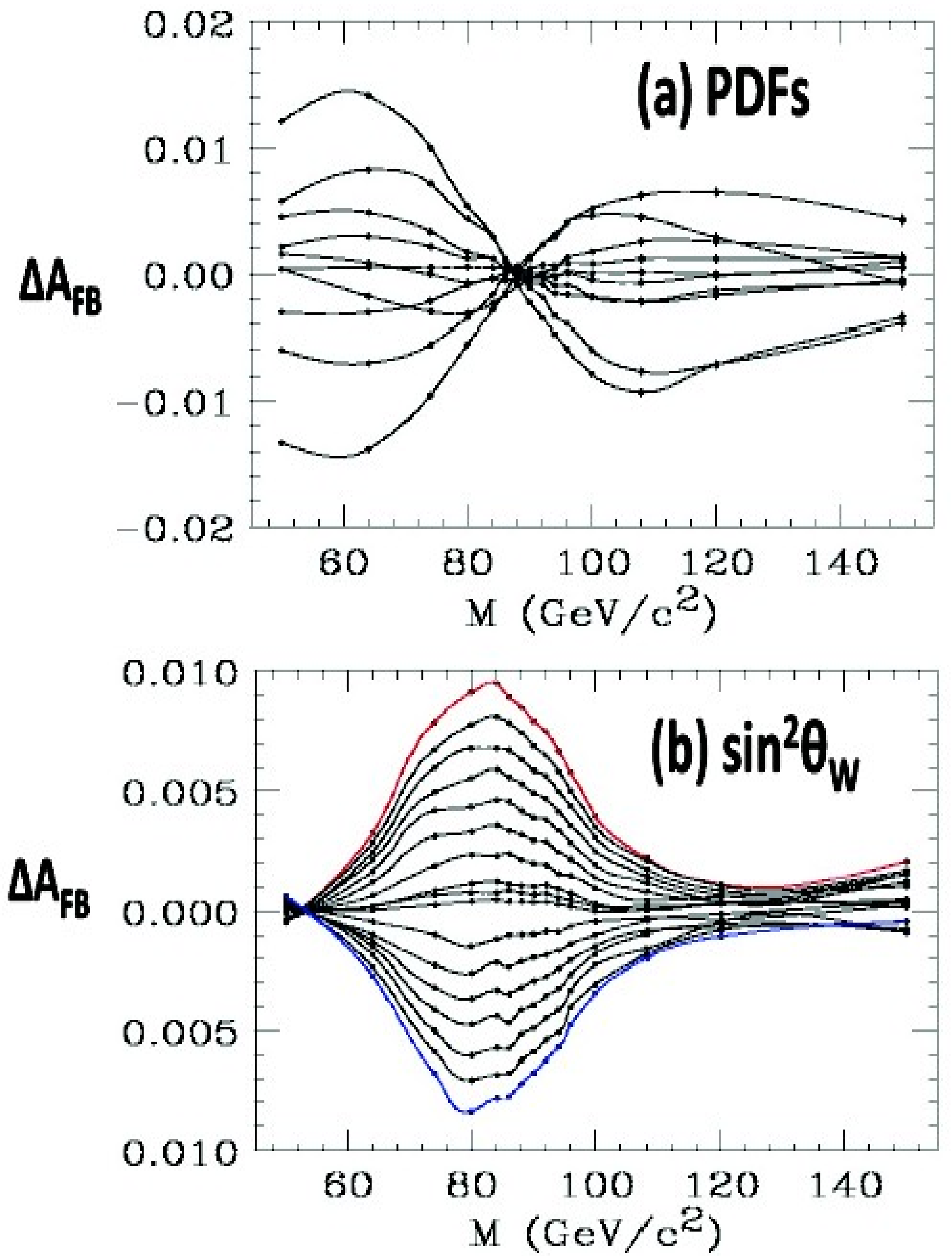
- CDF

TABLE IV. Summary of the systematic uncertainties on the extraction of the weak mixing parameters $\sin^2\theta_{\text{eff}}^{\text{lept}}$ and $\sin^2\theta_W$.

| Source | $\sin^2\theta_{\text{eff}}^{\text{lept}}$ | $\sin^2\theta_W$ |
|---|---|---|
| Momentum scale | ±0.00005 | ±0.00005 |
| Backgrounds | ±0.00010 | ±0.00010 |
| QCD scales | ±0.00003 | ±0.00003 |
| CT10 PDFs | ±0.00037 | ±0.00036 |
| EBA | ±0.00012 | ±0.00012 |

# New method to constrain PDFs

- Bodek et al., arXiv: 1507.02470
- Sensitivity plot of $A_{FB}(M)$
  - 10 replicas of NNPDF3.0 and the default (261000)
  - sin2θW is fixed at a value of 0.2244
  - The difference originates from the differences in d/u(x) and the antiquark fractions for the different PDF replicas
  - With the $\chi^2$ AFB weighting method the PDF error in the extracted value of sin2θW is reduced from 0.00027 to 0.00020.



**1st innovation:** $\sin^2\theta_W$ **is constant --> $\sin^2\theta_{eff}^{lept}$ ($M_Z$, flavor)**

**Full FITTER EW radiative corrections Enhanced Born Approximation (EBA)**

Implemented by the Rochester CDF group (**Willis Sakumoto**, A. Bodek, J.-Y. Han), see Phys. Rev. D88, 072002 (2013) Appendix A arXiv:1307.0770v3 [hep-ex]

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

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

If RESBOS is used then the EBA EW correction to $\sin^2\theta_{eff}$ = 0.00031 +-0.00012
Vs. stat error 0.00080 ($\mu^+\mu^-$) 9 $fb^{-1}$
Vs. stat error 0.00040 ($e^+e^-$) 9 $fb^{-1}$

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

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

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

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

- $T_3$ 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

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