Z production and asymmetry at the Tevatron

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

Summary
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
    - $A_{FB}^{0b}(\text{LEP}) \rightarrow 0.23221\pm0.00029$
    - $A_{FB}(\text{SLD}) \rightarrow 0.23098\pm0.00026$ (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
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
Distributions at the Z peak

(a) $|y| < 1$

(b) $1 < |y| < 2$

DØ 10.4 fb$^{-1}$

70 GeV < $M_\parallel$ < 110 GeV

- $\mu\mu$ data
- ResBos

Data/NNLO

(a) $|y|<1$ DØ 10.4 fb$^{-1}$
- $\mu\mu$ data 70 GeV < $M_\parallel$ < 110 GeV
- All scales
- $\mu_Q = M_\parallel$

(b) 1<|y|<2 DØ 10.4 fb$^{-1}$
- $\mu\mu$ data 70 GeV < $M_\parallel$ < 110 GeV
- All scales
- $\mu_Q = M_\parallel$
Distributions low mass region

High $\phi^*$ disagreement: known RESBOS absence of the NNLO correction factor for the photon exchange diagram.
Distributions high-mass region

(a) $160 \text{ GeV} < M_{ll} < 300 \text{ GeV}$
DØ $10.4 \text{ fb}^{-1}$

- $\mu\mu$ data
- $\text{ResBos}$
- $\text{PDF} \oplus \text{scale} \oplus a_z \text{ unc.}$

(b) $300 \text{ GeV} < M_{ll} < 500 \text{ GeV}$
DØ $10.4 \text{ fb}^{-1}$

- $\mu\mu$ data
- $\text{ResBos}$
- $\text{PDF} \oplus \text{scale} \oplus a_z \text{ unc.}$
DØ kinematic distributions

- Calculate ratio of \((1/\sigma)(d\sigma/d\phi^*)\) between central and forward rapidity regions
  - Reduce uncertainties from QCD scales to percent level
  - Suggests new variable less sensitive to theoretical uncertainty

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: \[ \frac{d\sigma}{d\cos \theta^*} \propto 1 + \cos^2 \theta^* + A_4 \cos \theta^* \]

- When $p_T(Z) \to 0$ \[ A_{FB} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{3}{8} A_4 \]

- $A_4$ 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.
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 ($|\eta| < 1.1$) and EC ($1.5 < |\eta| < 3.2$)
- Use $75 < M_{ee} < 115$ GeV $\rightarrow$ 560k events
- New method for energy calibration
  - Apply scale factor as a function of $L_{\text{inst}}$ first and then $\eta$
  - $M_{ee}$ peak scaled to LEP value in each bin
  - Separate calibrations for data and MC

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Z production and decay at the Tevatron
DØ $\sin^2 \theta_W$ dielectron analysis

- Corrections are applied to MC to account for:
  - Smearing of electron energy
  - Efficiency corrections in $p_T(e), \eta(e)$
  - $L_{\text{inst}}$ 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
\textbf{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 $\sin^2\theta^\ell_{\text{eff}}$ by comparing Pythia and RESBOS (with enhanced Born approximation corrections):

$$\sin^2\theta^\ell_{\text{eff}} = 0.23146 \pm 0.00047$$

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Z production and decay at the Tevatron
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 $\eta, \phi$ bins

Bodek et al. EPJ. C72, 2194 (2012)
CDF angular event weighting

- Extract $A_4(M_Z)$ in bins of $\cos\theta^*$ and average the results
  - Assume $(\varepsilon A)^- = (\varepsilon A)^+$ in each bin
  - $A_{FB}(|\cos\theta^*|) = A_{FB} \cdot |\cos\theta^*|/(1 + \cos^2\theta^* + ...)$

- Recast binned measurement into unbinned weighted event sum
  - Weights depend on $M_{\ell\ell}$, $p_T(\ell\ell)$, $\cos\theta^*$, $\phi^*$

- 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
  - 2$^{nd}$ order bias due to low acceptance regions and non-uniformity: $(\varepsilon A)^- \neq (\varepsilon A)^+$

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

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

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)

$\sin^2\theta_{\text{eff}} = 0.23150 \pm 0.00090\text{(stat)} \pm 0.00011\text{(sys)} \pm 0.00036\text{(PDF)}$

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

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

![Graph showing $\chi^2$ vs $\sin^2\theta_W$]

CDF indirect $M_W$ measurement

- $M_W$ measured at the Tevatron directly: $M_W = 80.385 \pm 0.015$ GeV
- By measuring the on-shell $\sin^2 \theta_W$ we obtain an indirect measurement of $M_W$: $M_W(\text{indirect}) = 80.365 \pm 0.047$ GeV
- Using $M_Z = 91.1876 \pm 0.0021$ 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

\[ M_W(\text{indirect}) = 80.365 \pm 0.047 \text{ GeV} \]

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Z production and decay at the Tevatron
Conclusions

- **DØ** (μμ, 10.4 fb⁻¹): \( \frac{d\sigma}{d\phi^*} \) is well described by the data
- **DØ** (ee, 9.7 fb⁻¹): \( \sin^2\theta^\ell_{\text{eff}} = 0.23146 \pm 0.00047 \)
- **CDF** (μμ, 9.2 fb⁻¹): \( \sin^2\theta^\ell_{\text{eff}} = 0.2315 \pm 0.00100 \)
  - \( M_W \) (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
The systematic error is smaller than the statistical error in all bins of $\phi^*$ in the peak region.
Additionally:
Δhigher orders = “small”
ΔPDF = 0.00017
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)
  - $\sin 2\theta_W$ 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 $\sin 2\theta_W$ is reduced from 0.00027 to 0.00020.
1st innovation: $\sin^2 \theta_W$ is constant $\rightarrow \sin^2 \theta_{\text{eff, lept}}(M_Z, \text{flavor})$

Full FITTER EW radiative corrections Enhanced Born Approximation (EBA)


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

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

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

$g_A^f \rightarrow \sqrt{\rho_{eq}}T_3^f$,

- $T_3$ 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

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