Electroweak Measurements from Run II at the Tevatron

Presented on behalf of CDF and DØ by:

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Overview

• Introduction
• Measurements of:
  – $\sigma_Z \cdot \text{Br}(Z \to l^+l^-)$
  – $\sigma_W \cdot \text{Br}(W \to l\nu)$
• CDF + DØ combinations:
  – $\sigma_Z \cdot \text{Br}(Z \to l^+l^-)$, $\sigma_W \cdot \text{Br}(W \to l\nu)$
  – $R = \frac{\sigma_W \cdot \text{Br}(W \to l\nu)}{\sigma_Z \cdot \text{Br}(Z \to l^+l^-)}$
• Other measurements with W and Z
• Di-boson production
• Summary and Outlook
Delivered and Collected Luminosity

Tevatron Run II: proton-antiproton collisions at 1.96 TeV
W and Z Production

- Need accurate knowledge of PDFs:
  - modify longitudinal boost $\rightarrow$ experimental acceptance
- “Correct” for photon: $N_Z = N_{\text{cand}} \cdot \left[ \frac{\sigma_Z}{\sigma_{Z\gamma}} \right]_{\text{MC}}$
Experimental Signature: $Z \rightarrow l^+l^-$

- pair of charged leptons:
  - high $p_T$
  - isolated
  - opposite-charge

- redundancy in trigger and offline selection
- low backgrounds
- control of systematics
Experimental Signature: $W \rightarrow l\nu$

- single charged lepton:
  - high $p_T$
  - isolated
- $E_T^{\text{miss}}$ (from neutrino)
- less redundancy in trigger and offline selection
- more difficult to control backgrounds and systematics
- need to understand hadronic recoil
- but more ‘interesting’ than Z! (post-LEP)
- $\sigma \cdot \text{Br}$ 10 times larger than Z
DØ $Z \rightarrow \mu^+\mu^-$

(updated for this conference)

Event selection:
- Two central tracks:
  - ‘loose’ μ-id
  - $p_T > 15$ GeV
  - opposite charge
  - $|\eta| < 1.8$
- $M_{\mu\mu} > 30$ GeV
- Cosmic veto
- $\geq 1$ isolated μ

- Dominant systematics:
  - luminosity: 10%
  - efficiency measurements from $Z \rightarrow \mu^+\mu^-$ data: 3.3%
  (statistics limited)

- $N_{\text{cand}} = 6126$
- $\int \mathcal{L} = 117$ pb$^{-1}$
- Backgrounds:
  - QCD: $(0.6 \pm 0.3)\%$
  - $Z \rightarrow \tau^+\tau^-$: $(0.5 \pm 0.1)\%$
- $\varepsilon_{\text{total}} = 19\%$

![DØ Run II Preliminary](image)

6126 events
$\int \mathcal{L} = 117$ pb$^{-1}$
$|\eta| < 1.8$
Measuring Efficiencies using the $Z \rightarrow \mu^+\mu^-$ data

- There are two $\mu$'s
- The backgrounds are low
- Can select pure $Z$ sample with even looser cuts on one $\mu$

\[ \sigma_Z \cdot Br(Z \rightarrow \mu^+\mu^-) = 261.8 \pm 5.0 \pm 8.9 \pm 26.2 \text{ pb} \]

stat. syst. lumi.
CDF: $Z \rightarrow \mu^+\mu^-$

Event selection:
- Two central tracks:
  - $p_T > 20$ GeV
  - opposite charge
  - minimum ionizing in CAL
  - at least one $|\eta| < 0.6$
  - both $|\eta| < 1.0$
- $66 < M_{\mu\mu} < 116$ GeV
- Cosmic veto
  - cosmic background $(0.9 \pm 0.9)$ %

$N_{\text{cand}} = 1631$
$\int L = 72$ pb$^{-1}$
$\epsilon_{\text{total}} = 9\%$

$\sigma_Z \cdot \text{Br}(Z \rightarrow \mu^+\mu^-) = 246 \pm 6 \pm 12 \pm 15$ pb
stat.  syst.  lumi.
CDF and DØ $Z \rightarrow e^+e^-$

Two isolated electrons, $E_T > 25$ GeV, $|\eta| < 1.1$

CDF: $\sigma_Z \cdot Br(Z \rightarrow e^+e^-) = 267.0 \pm 6.3 \pm 15.2 \pm 16.0$ pb

DØ: $\sigma_Z \cdot Br(Z \rightarrow e^+e^-) = 275 \pm 9 \pm 9 \pm 28$ pb

$N_{\text{cand}} = 1631$

$\int \mathcal{L} = 42$ pb$^{-1}$

stat.  syst.  lumi.
CDF: $W \rightarrow e \nu$

- $p_T(e) > 25$ GeV
- $E_T^{\text{miss}} > 25$ GeV
- $N_{\text{cand}} = 38628$
- QCD background estimate
  - $(3.5 \pm 1.7)\%$

$\sigma_W \cdot \text{Br}(W \rightarrow e \nu) = 2.64 \pm 0.01 \pm 0.09 \pm 0.16$ nb stat. syst. lumi.
CDF: $W \rightarrow \mu \nu$

- $p_T(\mu) > 20$ GeV
- $E_T^{\text{miss}} > 20$ GeV
- $N_{\text{cand}} = 21599$
- Backgrounds: $(10.8\pm1.1)\%$

- Systematics:
  - PDFs 2.6%
  - hadronic recoil 1.6%

$\sigma_W \cdot \text{Br}(W \rightarrow \mu \nu) = 2.64 \pm 0.02 \pm 0.12 \pm 0.16$ nb
  
  stat. syst. lumi.
DØ: \( W \rightarrow e \nu \) and \( W \rightarrow \mu \nu \)

- \( p_T(e) > 25 \text{ GeV} \)
- \( E_T^{\text{miss}} > 25 \text{ GeV} \)
- \( N_{\text{cand}} = 27370 \)
- \( \int L = 42 \text{ pb}^{-1} \)
- \( p_T(\mu) > 20 \text{ GeV} \)
- \( E_T^{\text{miss}} > 20 \text{ GeV} \)
- \( N_{\text{cand}} = 8302 \)
- \( \int L = 17 \text{ pb}^{-1} \)

\[ \sigma_W \cdot \text{Br}(W \rightarrow e \nu) = 2.884 \pm 0.021 \pm 0.128 \pm 0.284 \text{ nb} \]
\[ \sigma_W \cdot \text{Br}(W \rightarrow \mu \nu) = 3.226 \pm 0.128 \pm 0.100 \pm 0.322 \text{ nb} \]
CDF: $W \rightarrow \tau \nu$

- Look for jet within narrow 10 degree cone
- Isolated within wider 30 degree cone
- $p_T(\tau) > 25$ GeV
- $E_T^{\text{miss}} > 25$ GeV
- $N_{\text{cand}} = 2345$

$\sigma_W \cdot \text{Br}(W \rightarrow \tau\nu) = 2.62 \pm 0.07 \pm 0.21 \pm 0.16$ nb

stat.  syst.  lumi.
Comparing and Combining $\sigma \cdot Br\ (W,Z)$ Measurements from CDF and DØ

- **Luminosity determination:**
  - measure total rate of inelastic pp collisions

- $\sigma_{inelastic}$
  - measurements by CDF and E811 @ 1.8 TeV disagree at ~3$\sigma$ level
  - different methods of averaging CDF and E811 give values in the range:
    - $59.1 < \sigma_{inelastic} < 60.7$ mb (extrapolated to 1.96 TeV)
    (2.7% difference)

- **For $\sigma \cdot Br\ (W,Z)$ results quoted above:**
  - CDF uses $\sigma_{inelastic} = 60.7$ mb
  - DØ uses $\sigma_{inelastic} = 57.6$ mb (5.3% difference)
Comparing and Combining $\sigma \cdot Br (W,Z)$ Measurements from CDF and DØ

For “my combinations”§ presented below I have chosen to:

– Scale reported $\sigma \cdot Br (W,Z)$ values to correspond to consistent value of $\sigma_{\text{inelastic}}$
  • Arbitrarily chose: $\sigma_{\text{inelastic}} = 60.7 \text{ mb}$
  • Multiply $\sigma \cdot Br (DØ)$ by factor 1.053

– Quote additional 2.7% syst. error to cover ambiguity in choice of $\sigma_{\text{inelastic}}$
  • total error of $(4 + 2.7 = 4.8)\%$ assumed for $\sigma_{\text{inelastic}}$
  • 100% correlated between CDF and DØ

– PDFs next most significant error (1—3)%

N.B.

§ These issues have been discussed within Tevatron EWWG, but ….

§ No official policy yet agreed by CDF and DØ

§ “my combinations” should be taken as the responsibility of a review speaker: not official CDF / DØ results
Standard Model:
\[ \sigma_Z \cdot Br(Z \rightarrow l^+l^-) = 252 \pm 9 \text{ pb} \]
- NNLO calculation
- NNLO MRST2002 PDFs
- 3.5% uncertainty assessed using CTEQ error PDFs
  [But also see talk by Robert Thorne at this conference]
- LEP \( Br(Z \rightarrow l^+l^-) = 0.03366 \pm 0.00002 \)

Tevatron Average
\[ \sigma_Z \cdot Br(Z \rightarrow l^+l^-) = 258 \pm 10 \pm 16 \text{ pb} \]
expt. lumi.

expt. error from counting Z's
→ statistics limited
Standard Model:
\[ \sigma_w \cdot \text{Br}(W\rightarrow l\nu) = 2.72 \pm 0.10 \text{ nb} \]
- NNLO calculation
- NNLO MRST2002 PDFs
- 3.5% uncertainty assessed using CTEQ error PDFs
- SM \text{Br}(W\rightarrow l\nu) = .1082 \pm .0002

Tevatron Average
\[ \sigma_w \cdot \text{Br}(W\rightarrow l\nu) = 2.69 \pm 0.09 \pm 0.17 \text{ nb} \]

N.B. expt. error will always be smaller than lumi.
In the future we can use \( \sigma \cdot \text{Br}(W, Z) \) to determine the luminosity
\[ R = \frac{\sigma_W \cdot \text{Br}(W \rightarrow l\nu)}{\sigma_Z \cdot \text{Br}(Z \rightarrow l^+l^-)} \]

- Luminosity error cancels
- Other important systematics partially cancel:
  - PDFs
  - Experimental: high $p_T$, isolated leptons
- Tevatron EWWG:
  - Evaluated correlated systematics
  - Performed ‘official’ average of CDF($e, \mu$) and DØ($e$) — shown at EPS-Aachen
- Update including DØ($\mu$) here
Tevatron measurements of

\[ R = \sigma \times \text{Br}(W \rightarrow l\nu)/\sigma \times \text{Br}(Z \rightarrow ll) \]

10.59 ± 0.20  Run (I + II)

10.61 ± 0.30  Run II

\[ ^\S \text{Standard Model} \]

\[ ^\S \text{Tevatron combined} \]

\[ ^\S \text{Run I + II combined} \]

\[ ^\S \text{DØ (e)} \]

\[ ^\S \text{DØ (µ)} \]

\[ ^\S \text{CDF (e)} \]

\[ ^\S \text{CDF (µ)} \]

\[ ^\S \text{Tevatron combined} \]

\[ ^\S \text{Run I} \]

\[ ^\S \text{DØ (e)} \]

\[ ^\S \text{CDF (e)} \]

\[ ^\S \text{my combination} \]
Indirect measurement of $\text{Br}(W \rightarrow l\nu)$

$$R = \frac{\sigma_W}{\sigma_Z} \frac{\text{Br}(W \rightarrow l\nu)}{\text{Br}(Z \rightarrow l^+l^-)}$$

$\sigma_W, \sigma_Z$ NNLO LEP calculation

$\text{Br}(W \rightarrow l\nu)$ (\%)

- $W \rightarrow l\nu$
  - LEP: $10.74 \pm 0.09$
  - TeV: $10.60 \pm 0.26$

- $W \rightarrow \tau\nu$
  - LEP: $11.20 \pm 0.22$

- $W \rightarrow \mu\nu$
  - LEP: $10.55 \pm 0.16$
  - TeV: $11.11 \pm 0.41$

- $W \rightarrow e\nu$
  - LEP: $10.59 \pm 0.17$
  - TeV: $10.48 \pm 0.27$

Standard Model

§ 'my combination'
Indirect measurement of $\Gamma_W$:

- $\text{Br}(W \rightarrow l\nu) = \frac{\Gamma(W \rightarrow l\nu)}{\Gamma_W}$

Tevatron combined result:\n$\Gamma_W = 2.135 \pm 0.053$ GeV

cf LEP+Tevatron direct measurements:\n$\Gamma_W = 2.139 \pm 0.069$ GeV

Promising future for such measurements with $\sim 2$ fb$^{-1}$:
- $O(10^6)$ $W \rightarrow l\nu$ events per channel per experiment
- $O(10^5)$ $Z \rightarrow l^+l^-$ events per channel per experiment for calibration
- LEP2: $O(10^3)$ $W \rightarrow l\nu$ decays per channel per experiment

§ “my combination”
Other measurements with W, Z events

- High mass tail of Z

- Forward-backward asymmetry
Other Measurements with W, Z Events

- Data/MC comparisons for $p_T(Z)$

$Z \rightarrow \mu^+\mu^-$ → probe QCD phenomenology

Many more such measurements to come:
- e.g., W/Z rapidity → probe PDFs
Looking for $Z \rightarrow \tau^+\tau^-$

- Look for isolated, high $p_T$ $e$ or $\mu$ opposite narrow hadronic jet

CDF

DØ

- small numbers of candidates
- rates consistent with expectations
CDF $W_\gamma, Z_\gamma$ Events

- Require central $\gamma$
- $E_T(\gamma) > 7$ GeV
- $\Delta R(l-\gamma) = \sqrt{(\Delta \eta^2 + \Delta \Phi^2)} > 0.7$

∫$L = 128$ pb$^{-1}$

σ • Br quoted for these cuts

47 seen
43 expected

133 seen
141 expected.

$σ \cdot Br = 5.8 \pm 1.0$ (stat.) $\pm 0.4$ (syst.) $\pm 0.4$ (lumi.) pb

$σ \cdot Br = 17.2 \pm 2.2$ (stat.) $\pm 2.0$ (syst.) $\pm 1.1$ (lumi.) pb
CDF $W W$ Search

- isolated lepton pair
- opposite-charge, high $p_T$
- $E_T^{\text{miss}}$
- $Z$ veto
- veto events with jets
- $\int \mathcal{L} = 126 \text{ pb}^{-1}$
- 5 events seen
- 9.2 events expected
  
  (2.3 background, 6.9 ± 1.5 $W W \rightarrow l\nu l\nu$)

\[
\sigma_{\text{meas}}^{p\bar{p} \rightarrow WW} = 5.1^{+5.4}_{-3.6} \text{ (stat)} \pm 1.3 \text{ (syst)} \pm 0.3 \text{ (lumi)} \text{ pb} .
\]

\[
\sigma_{\text{theo: NLO}}^{p\bar{p} \rightarrow WW} = 13.25 \pm 0.25 \text{ pb} \quad \text{J.M.Campbell, R.K.Ellis} \quad \text{hep--ph/9905386}
\]
Summary, Outlook

• EW analyses with Run II $\int L > 100$ pb$^{-1}$ becoming available
• Detectors/triggers/simulations becoming better understood → entire physics programme benefits
• Looking forward to a flood of new EW results this autumn:
  – $\sigma$ • Br (W,Z) and ratios
  – QCD of W,Z production
• Tevatron EWWG becoming very active
  – Need more streamlined procedure for CDF/DØ to approve combinations of updated measurements
    • once combination methods are well-established