Electroweak Physics Results

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On behalf of
ATLAS, CMS, LHCb, CDF and D0

ICHEP 2012
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**Outline**

- **W and Z production at LHC**
  - Inclusive and differential cross sections
  - W charge asymmetry and impact on PDFs
  - Drell-Yan production
  - W and \( \tau \) polarization

- **Diboson production at the Tevatron and LHC**
  - Anomalous Triple Gauge Couplings

- **Precision measurements at the Tevatron and LHC**
  - Z Forward-Backward Asymmetry
  - Effective weak mixing angle

- **Global electroweak fit**
  - Top quark mass
  - W mass
  - Higgs mass predictions
Production rates at Hadron Colliders

**Tevatron timeline**
- W: 1988
- Z: 1988
- Top: 1994
- WW: 2005
- WZ: 2007
- ZZ: 2008

**LHC timeline**
- W: May 2010
- Z: Jun 2010
- Top: Jul 2010
- WW: Dec 2010
- WZ: Mar 2011
- ZZ: Jul 2011
- H: Last week?

**Graph Details**
- **σ** (σₜₒₜ): Total cross section
- **σₗ:** Cross section for jet with Eₗ > √s/20
- **σₑₑ:** Cross section for jet with Eₑₑ > 100 GeV
- **Mₜ:** Higgs mass = 125 GeV
- **σₜₒₜ:** Cross section for jet with Eₗ > √s/20
- **σₑₑ:** Cross section for jet with Eₑₑ > 100 GeV
- **Mₜ:** Higgs mass = 125 GeV

**Notes**
- W.J. Stirling, private communication
- Events/sec for L = 10^{33} cm⁻² s⁻¹

**Axes**
- **σ** (nb)
- **√s (TeV)**
W and Z Production

- Performance measurements
- SM tests at TeV scale
- Proton PDFs
- Backgrounds for searches

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First W/Z measurement at 7 TeV

\( \int L \, dt = 310-315 \, \text{nb}^{-1} \)

**ATLAS**

Data 2010 (\( \sqrt{s} = 7 \, \text{TeV} \))

- \( W \rightarrow \mu \nu \)
- \( W^+ \rightarrow \ell^+ \nu \)
- \( W^- \rightarrow \ell^- \nu \)

\[ \sigma_W \times \text{Br}(W \rightarrow l \nu) \, [\text{nb}] \]

**NNLO QCD**

- \( W (p\bar{p}) \)
- \( W (pp) \)
- \( W^+ (pp) \)
- \( W^- (pp) \)

- CDF \( W \rightarrow (l/e) \nu \)
- D0 \( W \rightarrow (e/\mu) \nu \)
- UA1 \( W \rightarrow l \nu \)
- UA2 \( W \rightarrow e \nu \)
- Phenix \( W^\pm \rightarrow (e^+/e^-) \nu \)
W/Z cross section measurements

- ATLAS, CMS and LHCb published precision measurements with 2010 data --> relatively recent publications
  
  JHEP 10 (2011) 132

Much larger datasets are now available

$s = 7$ TeV, 5 fb$^{-1}$

\[
\begin{align*}
W \rightarrow e/\mu \nu & : \sim 25 \text{ Million} \\
Z \rightarrow ee/\mu\mu & : \sim 3 \text{ Million}
\end{align*}
\]

$s = 8$ TeV

~6 fb$^{-1}$
**Fiducial W and Z Cross Sections**

- ATLAS, CMS and LHCb measure fiducial cross sections
- No theoretical uncertainty from extrapolation outside experimental acceptance

*Some differentiation between PDF sets already observed now*
*JR09 seems to be the most discrepant*
Lepton Universality

Result already close to best measurement ($R_W$)
- PDG: 1.9%
- This measurement: 2.4%
Benefits from experimental and theoretical systematics cancellation

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CMS

NNLO, FEWZ+MSTW08 prediction
[with MSTW08NNLO 68% CL uncertainty]

$W \rightarrow e\nu, \ Z \rightarrow ee$
$10.56 \pm 0.12_{\text{stat}} \pm 0.19_{\text{syst}}$

$W \rightarrow \mu\nu, \ Z \rightarrow \mu\mu$
$10.52 \pm 0.09_{\text{stat}} \pm 0.20_{\text{syst}}$

$W \rightarrow l\nu, \ Z \rightarrow l\ell$ (combined)
$10.54 \pm 0.07_{\text{stat}} \pm 0.18_{\text{syst}}$

$R_{W/Z} = \frac{\sigma \times B}{\sigma \times B}$

ATLAS

$\int L \, dt = 33-36 \, \text{pb}^{-1}$

Data 2010 ($\sqrt{s} = 7$ TeV)

− total uncertainty
− exp. uncertainty

△ ABKM09
▼ JR09
■ HERAPDF1.5
● MSTW08

$\sigma_{\text{W}^\pm}^\text{fid} / \sigma_{Z\gamma}^\text{fid}$

$W^\pm / Z$

| $\sigma_{\text{tot}} \times B$ | CMS | 10.54 ± 0.07 (sta) ± 0.08 (sys) ± 0.16 (theo) |
| ATLAS | 10.893 ± 0.079 (sta) ± 0.110 (sys) ± 0.116 (acc) |
Benefits from experimental and theoretical systematics cancellation

**JHEP 10 (2011) 132**

**ATLAS**

\[ \int L \, dt = 33-36 \text{ pb}^{-1} \]

**CMS**

\[ \sigma_{\text{tot}}^B \]

\[ W^+/W^- \]

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>1.454 ± 0.006 \text{ (sta)} ± 0.012 \text{ (sys)} ± 0.022 \text{ (acc)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>1.421 ± 0.006 \text{ (sta)} ± 0.014 \text{ (sys)} ± 0.029 \text{ (the)}</td>
</tr>
</tbody>
</table>

**Cross Section Ratio W^+/W^-**

**36 \text{ pb}^{-1} at \sqrt{s} = 7 \text{ TeV}**

**NNLO, FEWZ+MSTW08 prediction** [with MSTW08NNLO 68% CL uncertainty]
Z boson observation at $\sqrt{s} = 8$ TeV

$Z \rightarrow \mu\mu$

POWHEG+PYTHIA 8 MC
CT 10.0

Distributions normalized to data
W and Z production at $\sqrt{s} = 8 \text{ TeV}$

**Results**

- **W → ev, Z → ee**
  - $10.57 \pm 0.12^{\text{stat.}} \pm 0.19^{\text{syst.}}$

- **W → μν, Z → μμ**
  - $10.52 \pm 0.09^{\text{stat.}} \pm 0.20^{\text{syst.}}$

- **W → lν (combined)**
  - $10.54 \pm 0.07^{\text{stat.}} \pm 0.18^{\text{syst.}}$

- **Z → ee**
  - $1.10 \pm 0.03^{\text{stat.}} \pm 0.04^{\text{syst.}} \pm 0.05^{\text{lumi.}}$

- **Z → μμ**
  - $1.13 \pm 0.01^{\text{stat.}} \pm 0.03^{\text{syst.}} \pm 0.05^{\text{lumi.}}$

- **Z → lll (combined)**
  - $1.12 \pm 0.01^{\text{stat.}} \pm 0.02^{\text{syst.}} \pm 0.05^{\text{lumi.}}$

**Nuances**

- **Acceptances** for W and Z production
- **Statistical and systematic uncertainties**
- **Comparisons** to theoretical predictions

**Equations**

- $R_{W/Z} = \frac{\sigma \times B(W)}{\sigma \times B(Z)}$

**Adjustments**

- **Corrections** for final-state QED radiation
- **Pseudorapidity (B(W))** and (Z)

**Uncertainties**

- **Combination of theoretical uncertainties**
- **Measurement confidence interval**

**Data**

- **CMS Preliminary**
- **36 pb$^{-1}$** at $\sqrt{s} = 7 \text{ TeV}$
- **18.7 pb$^{-1}$** at $\sqrt{s} = 8 \text{ TeV}$

**Graphs**

- **Cross sections** for W and Z production
- **Error bars** for measured quantities
- **Combining** of theoretical predictions

**Interpretation**

- **Confirmation** of theoretical predictions
- **Comparison** to NNLO calculations
- **Luminosity uncertainties**

**Summary**

- **Measurements** in electron and muon channels
- **Coherent** analysis of W and Z production
W and Z Inclusive Cross Sections

Figure 9: Measured and predicted W versus Z production and W$^+$ versus W$^-$ cross sections. The ellipses illustrate the 68% coverage for total uncertainties (open black) and excluding the luminosity uncertainty (purple filled). The uncertainties of the theoretical predictions correspond to the PDF uncertainties only.

Figure 10: Measurements of inclusive W and Z production cross sections times branching ratios as a function of center-of-mass energy for CMS and experiments at lower-energy colliders. The lines are the NNLO theory predictions.

Summary

We performed measurements of inclusive W and Z cross sections in pp collisions at $p_T = 8$ TeV using 18.7 ± 0.9 pb$^{-1}$ of data recorded with the CMS detector. The W and Z bosons are observed via their decays to electrons and muons. The measured inclusive cross sections are consistent with the expectations from theory.

Theory: NNLO, FEWZ and MSTW08 PDFs

ATLAS points same as CMS
LHCb: Measurements extended up to $|\eta_1| = 4.9$

### Important for PDF constraints

**W and Z Production at LHCb**

**ATLAS + CMS**

**LHCb**

**Z**

Both leptons inside CMS/Atlas

In LHCb

**W**

W+ W-
W and Z Production at LHCb

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LHCb, \( \sqrt{s} = 7 \text{ TeV} \)

- MSTW08
- NNNPDF21
- ABKM09
- HERA15
- JR09
- CTEQ6M (NLO)

- Data

- Data\(_{\text{stat}}\)

- Data\(_{\text{tot}}\)

- \( p_T^\mu > 20 \text{ GeV/c} \)
- \( 2.0 < \eta^\mu < 4.5 \)
- \( Z: 60 < m_{\mu\mu} < 120 \text{ GeV/c}^2 \)

\[ \sigma_{Z \rightarrow \mu\mu} [\text{pb}] \]

\[ \sigma_{W^+ \rightarrow \mu^+\nu} [\text{pb}] \]

\[ \sigma_{W^- \rightarrow \mu^-\bar{\nu}} [\text{pb}] \]

\[ \frac{\sigma_{W^+ \rightarrow \mu^+\nu}}{\sigma_{W^- \rightarrow \mu^-\bar{\nu}}} \]

\[ \frac{\sigma_{W^+ \rightarrow \mu^+\nu} + \sigma_{W^- \rightarrow \mu^-\bar{\nu}}}{\sigma_{Z \rightarrow \mu\mu}} \]

\[ \frac{\sigma_{W^+ \rightarrow \mu^+\nu}}{\sigma_{Z \rightarrow \mu\mu}} \]

\[ \frac{\sigma_{W^- \rightarrow \mu^-\bar{\nu}}}{\sigma_{Z \rightarrow \mu\mu}} \]

Hepatology JHEP 06 (2012) 058
Broadly well described by predictions

- Can impact PDF central values and uncertainties
  - Full covariance matrix available from all experiments
Broadly well described by predictions

Can impact PDF central values and uncertainties
Strangeness in the Proton

Fit ATLAS differential distributions for $W^+$, $W^-$ and $Z$ with HERA $e^\pm p$ data

NNLO pQCD analysis

Fit results:
- Light quark sea at low $x$ is flavor symmetric
- Total sea enhancement of 8%

$r_s = 1.0^{+0.25}_{-0.28}$

$r_s = 0.5(s + \overline{s})/\overline{d}$
W-Lepton Charge Asymmetry

**Definition:**
- Sensitive to valence quark
- Usable to constrain $u^v/d^v$ at low $x$

**Combined results:**
- More constrained in central region (ATLAS+CMS)
- Extended up to $|\eta| \approx 3.7$ (LHCb)

**Equation:**

\[
A(\eta_e) = \frac{d\sigma_{W^+}(\eta e) - d\sigma_{W^-}(\eta e)}{d\sigma_{W^+}(\eta e) + d\sigma_{W^-}(\eta e)}
\]

**Graph:**
- $s=7$ TeV
- $p_T^l > 20$ GeV
- ATLAS+CMS+LHCb
- Preliminary

**First LHC combined plot (LHC EWK WG)**
Figure 2: Comparison of the measured electron asymmetry to the predictions of different PDF models for electron $p_T > 35$ GeV. The error bars include both statistical and systematic uncertainties. The data points are placed in the center of the $|\eta|$ bins. The PDF uncertainty bands are estimated using the PDF reweighting technique and correspond to 68% confidence level.

Discrimination between PDF at low $|\eta|$
Drell-Yan Production at LHC

1.4 Million events
\( \gamma^*/Z \rightarrow \mu\mu \)

Needs NNLO

Data (\( \mu \), 4.5 fb\(^{-1} \) in 2011)

NNLO, FEWZ+MSTW08

CMS-PAS-EWK-11-007
**DY double-differential cross section (CMS)**

**CMS-PAS-EWK-11-007**

Significant differences between data, POWHEG NLO and FEWZ NNLO calculations at low mass
Drell-Yan production in forward region (LHCb)

Drell-Yan production in forward region (LHCb)

LHCb Preliminary, $\sqrt{s} = 7$ TeV

- Data$_{\text{stat}}$
- Data$_{\text{tot}}$
- LO PYTHIA (CTEQ5L)
- NLO FEWZ (MSTW08)
- NLO DYNNLO (MSTW08)

$2.0 < \eta^\mu < 4.5$
$p^\mu > 10$ GeV/c
$p^\mu_T > 3$ (15) GeV/c

Theory/Data ratio

Dimuon invariant mass [GeV/c$^2$]

10$^2$
10
1
0.5

Low mass DY

Figure 8: Differential cross-section for $\gamma^* \mu^+ \mu^-$ as a function of $M_{\mu\mu}$. The dark shaded (orange) bands correspond to the statistical uncertainties, the light shaded (yellow) band to the statistical and systematic uncertainties added in quadrature. Superimposed are the PYTHIA predictions and the NLO predictions from FEWZ and DYNNLO; they are displaced horizontally for presentation. The shaded vertical band corresponds to the mass region of the $\gamma^*$ which is not included in the measurement. The uncertainties of the NLO predictions contain the PDF uncertainties evaluated at the 68% confidence level and the theoretical errors added in quadrature. The two bins with $M_{\mu\mu} > 40$ GeV/c have a cut of $p^\mu_T > 15$ GeV/c for the data and the predictions. The lower plot shows the ratio of the predictions or the uncertainties to the data.
**Fully unfolded differential distributions**

**Comparison with RESBOS**


CMS $Z$ $P_T$ measurement:

RESBOS tuned to Tevatron data (but not to LHC yet)
Measurements and results:

- Get uncertainty for unfolding procedure from two generators: MC@NLO and POWHEG.
- Drastically reduced when averaged over charge.

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>$35 &lt; p_T^W$ (GeV)</th>
<th>$p_T^W &gt; 50$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td>$23.8 \pm 2.0 \pm 3.4$</td>
<td>$25.2 \pm 1.7 \pm 3.0$</td>
</tr>
<tr>
<td><strong>MC@NLO</strong></td>
<td>$27.1 \pm 0.7$</td>
<td>$26.2 \pm 0.5$</td>
</tr>
<tr>
<td><strong>POWHEG</strong></td>
<td>$19.9 \pm 1.0$</td>
<td>$21.2 \pm 0.8$</td>
</tr>
</tbody>
</table>
\[ P_{\tau} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \]

\[ \tau \rightarrow \rho^{-} \nu_{\tau} \rightarrow \pi^{-} \pi^{0} \nu_{\tau} \]

BR = 25.94 ± 0.09%

\[ \gamma = \frac{2p_{T}^{\tau}}{p_{T}^{\gamma}} - 1 \approx \frac{E_{T}^{\pi^{-}} - E_{T}^{\pi^{0}}}{p_{T}} \]

\[ P_{\tau} = -1.06 \pm 0.04 \text{ (stat)}^{+0.05}_{-0.07} \text{ (syst)} \]
Diboson Production

- Fundamental test of Standard Model
  - Triple gauge couplings (TGC)
  - Probe for new physics
- Resonances with diboson final states
- Higgs hunting
- Background to Higgs
Electroweak measurements at the Tevatron

- **1983 CERN**
  - $W$
  - $Z$

- **1995 Fermilab**
  - $W\gamma$
  - $Z\gamma$

- **Run I**
  - $WW$
  - $WZ$

- **Run II**
  - $ZZ$

- **Observed Theory**
ATLAS: arXiv:1205.2531
CMS: PLB 701 (2011)

**Zγ**: Agreement with NLO MCFM calculation is poor
Exclusive calculation (N_{jet} = 0) looks good

**Wγ**: Agreement with NLO MCFM calculation is poor
Exclusive calculation (N_{jet} = 0) looks good
**Dibosons: $W\gamma/Z\gamma$**

**ATLAS: arXiv:1205.2531**  
**CMS: PLB 701 (2011)**

**$W\gamma$**

- $W(\ell\nu)+\gamma$
- $W(\ell\nu)+\text{jets}$
- $\gamma+\text{jets}$
- $Z(\ell\ell)$
- $t\bar{t}$
- $W(\tau\nu)+WW+\text{single top}$

**$Z\gamma$**

- $Z(\ell\ell)+\gamma$
- $Z(\ell\ell)+\text{jets}$
- $\gamma+\text{jets}$
- $t\bar{t}$
- $EW+t\bar{t}$

**W+jets and Z+jets simulated with ALPGEN + 5 partons and SHERPA + 3 partons**

**ATLAS**

- $\int L \, dt = 1.02 \, \text{fb}^{-1}$
- $\mathcal{L}=7 \, \text{TeV}$
- $N_{\text{jet}}=0$

**Events / 20 GeV**

**Data**

- $W(\ell\nu)+\gamma$
- $W(\ell\nu)+\text{jets}$
- $\gamma+\text{jets}$
- $Z(\ell\ell)$
- $t\bar{t}$
- $W(\tau\nu)+WW+\text{single top}$

**Events / 10 GeV**

**Data**

- $Z(\ell\ell)+\gamma$
- $Z(\ell\ell)+\text{jets}$
- $\gamma+\text{jets}$
- $t\bar{t}$
- $EW+t\bar{t}$

**Number of jets**

- $E_T(\gamma)>60 \, \text{GeV}$
- $E_T(\gamma)$

**$E_T^\gamma$ [GeV]**

- $E_T^\gamma$ [GeV]
- $E_T^\gamma$ [GeV]
- $E_T^\gamma$ [GeV]
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- $E_T^\gamma$ [GeV]
- $E_T^\gamma$ [GeV]
Challenge: missing energy

Both experiments have shown good ability to control missing energy in the 2011 dataset
ATLAS-CONF-2012-025

\[ \sqrt{s} = 7 \text{ TeV} \]

**ATLAS:**
\[ \sigma = 53.4 \pm 2.1 \pm 4.5 \pm 2.1 \text{ pb} \]

**CMS:**
\[ \sigma = 52.4 \pm 2.0 \pm 4.5 \pm 1.2 \text{ pb} \]

**Theory:**
\[ \sigma = 45.1 \pm 2.8 \text{ pb} \]

CMS PAS SMP-12-013

\[ \sqrt{s} = 8 \text{ TeV} \]

**CMS:**
\[ \sigma = 69.9 \pm 2.8 \pm 5.6 \pm 3.1 \text{ pb} \]

**Theory:**
\[ \sigma = 57.3^{+2.4}_{-1.6} \text{ pb} \]
Dibosons: WZ @ 7 TeV

### ATLAS Preliminary

Data 2011 ($\sqrt{s} = 7$ TeV)

- **Integral:** $\int L d\tau = 4.6 \text{ fb}^{-1}$

#### $P_T^Z$

- **Unfolded differential distribution**

#### $M_{WZ}$

- **Unfolded differential distribution**

### Table: WZ Results

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{observed}}$</th>
<th>$N_{\text{bkg}}$</th>
<th>$\sigma_{\text{measured}}$ (pb)</th>
<th>$\sigma_{\text{NLO}}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong></td>
<td>317</td>
<td>$68 \pm 8$</td>
<td>$19.0^{+1.4}_{-1.3} \pm 0.8 \pm 0.4$</td>
<td>$17.6^{+1.1}_{-1.0}$</td>
</tr>
<tr>
<td><strong>CMS</strong></td>
<td>75 (1.1 fb$^{-1}$)</td>
<td>$\sim 9.1$</td>
<td>$17.0 \pm 2.4 \pm 1.1 \pm 1.0$</td>
<td>$17.5 \pm 0.6$</td>
</tr>
</tbody>
</table>

**Notes:**
- New results indicated.
- ATLAS and CMS data compared.
- Uncertainties include systematic and statistical contributions.
CDF, 7.1 fb$^{-1}$: $\sigma_{WZ} = 3.93^{+0.60}_{-0.53} +0.59 -0.46$ pb

arXiv:1202.6629
ZZ → 4 leptons (eeee, μμμμ, eμμμ)

$\sqrt{s} = 7$ TeV

$66 < M_{Z1} < 116$ GeV
$66 < M_{Z2} < 116$ GeV

New CMS PAPER SMP-12-007

ATLAS-CONF-2012-027
**Dibosons: ZZ @ 7 TeV**

**ZZ → 4 leptons (eeee, μμμμ, eeμμ)**

### ATLAS Preliminary

![ATLAS ZZ 4l Distribution](image)

- **Events / 20 GeV**: 
  - Data
  - ZZ Simulation
  - Total Uncertainty

- **Estimated Background**: 
  - $0.7 \pm 0.7$ (stat) $^{+1.3}_{-0.7}$ (syst)

- **ZZ → 4l**

### CMS

- **$\sqrt{s} = 7$ TeV, $L = 5.0$ fb$^{-1}$**

- **Events / 20 GeV**
  - DATA
  - ZZ
  - WZ/Z + jets

- **$M_{4l}$ (GeV)**
  - ZZ → 4l

- **(*) includes ZZ → 2l2τ**

### ZZ Results

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{obs}(4l)}$</th>
<th>$N_{\text{signal}(4l)}$</th>
<th>$N_{\text{bkg}(4l)}$</th>
<th>$\sigma_{\text{measured}}$ (pb)</th>
<th>$\sigma_{\text{NLO}}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong></td>
<td>62</td>
<td>$53.2 \pm 2.2$</td>
<td>$0.7 \pm 2.1$</td>
<td>$7.2^{+1.1}<em>{-0.9}^{+0.4}</em>{-0.3}$ ± 0.3</td>
<td>$6.5^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td><strong>CMS</strong></td>
<td>54</td>
<td>$54.4 \pm 4.8$</td>
<td>$1.4 \pm 0.5$</td>
<td>($^*$) $6.24^{+0.86}<em>{-0.80}^{+0.41}</em>{-0.32}$ ± 0.14</td>
<td>$6.3 \pm 0.4$</td>
</tr>
</tbody>
</table>
Dibosons: \( ZZ \to 7 \text{ TeV} \)

\[ ZZ \to 4 \text{ leptons (eeee, } \mu\mu\mu\mu, \text{ ee} \mu\mu) + ZZ \to 2l2\tau \]

*New*

**ZZ**

<table>
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<tr>
<th>ATLAS</th>
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</tr>
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<tbody>
<tr>
<td>( N_{\text{obs}(4l)} )</td>
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</tr>
<tr>
<td>62</td>
<td>54</td>
</tr>
<tr>
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</tr>
<tr>
<td>53.2 ± 2.2</td>
<td>54.4 ± 4.8</td>
</tr>
<tr>
<td>( N_{\text{bkg}(4l)} )</td>
<td>( N_{\text{bkg}(4l)} )</td>
</tr>
<tr>
<td>0.7 ± 2.1</td>
<td>1.4 ± 0.5</td>
</tr>
</tbody>
</table>

**\( \sigma_{\text{measured}} \) (pb)**

- **ATLAS**
  - 7.2 ± 0.3
  - \( +1.1 \) \( -0.9 \)
  - \( +0.4 \) \( -0.3 \)

- **CMS**
  - 6.5 ± 0.3
  - \( +0.3 \) \( -0.2 \)

**\( \sigma_{\text{NLO}} \) (pb)**

- **ATLAS**
  - 6.24 ± 0.14
  - \( +0.86 \) \( -0.80 \)
  - \( +0.41 \) \( -0.32 \)

- **CMS**
  - 6.3 ± 0.4

(*) includes \( ZZ \to 2l2\tau \)
**Dibosons: $ZZ \ @ \ 8 \ TeV$**

**$ZZ \rightarrow 4 \ leptons \ (eeee, \ \mu\mu\mu\mu, \ ee\mu\mu) \ + \ ZZ \rightarrow 2\ell 2\tau$**

*New*

**Figure 1: (Top) Distribution of the four-lepton reconstructed mass for the sum of the 4 $e$ and $2 \mu$, and sum of the $\ell^{+}\ell^{-}$ channels. The points represent the data, and the shaded histograms represent the expected $ZZ$ signal and background. The histogram shapes are taken from MC simulation and are normalized to the corresponding estimated values from Table 1. The bottom plots show the correlation between the reconstructed masses of $Z_1$ and $Z_2$.**

<table>
<thead>
<tr>
<th>$ZZ$</th>
<th>$\mathbf{N}_{\text{obs}}(4\ell)$</th>
<th>$\mathbf{N}_{\text{signal}}(4\ell)$</th>
<th>$\mathbf{N}_{\text{bkg}}(4\ell)$</th>
<th>$\sigma_{\text{measured}} \ (pb)$</th>
<th>$\sigma_{\text{NLO}} \ (pb)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong></td>
<td>85</td>
<td><strong>70.5 \pm 1.7</strong></td>
<td>1.5 \pm 1.3</td>
<td>$9.3 \ ^{+1.1}<em>{-1.0} \ ^{+0.4}</em>{-0.3} \pm 0.3$</td>
<td>7.4 \pm 0.4</td>
</tr>
<tr>
<td><strong>CMS</strong></td>
<td>71</td>
<td><strong>64.3 \pm 4.4</strong></td>
<td>1.3 \pm 0.5</td>
<td>($^*\ 8.4 \pm 1.0 \pm 0.7 \pm 0.4$)</td>
<td>7.7 \pm 0.4</td>
</tr>
</tbody>
</table>

(*) includes $ZZ \rightarrow 2\ell 2\tau$
Dibosons: $ZZ \@$ Tevatron

$\sqrt{s} = 1.96$ TeV

MCFM MSTW2008

CDF, 1.9 fb$^{-1}$

$\ell\ell \ell\ell$ and $\ell\ell\ell\ell$

1.30 $\pm$ 0.10

CDF, 6.0 fb$^{-1}$

$\ell\ell\ell\ell$ and $\ell\ell\ell\ell$

1.64 $^{+0.44}_{-0.38}$

D0, 2.7 fb$^{-1}$

$\ell\ell\ell\ell$

2.01 $\pm$ 0.97

D0, 6.4 fb$^{-1}$

$\ell\ell\ell\ell$

1.30 $^{+0.52}_{-0.38}$

D0, 8.6 fb$^{-1}$

$ee\ell\ell$

0.98 $^{+0.53}_{-0.54}$

$\mu\mu\ell\ell$

2.52 $^{+0.79}_{-0.79}$

$\ell\ell\ell\ell$

1.64 $^{+0.46}_{-0.47}$

PRL 108, 101801 (2012)

Dibosons: ZZ Overview

**ATLAS Preliminary**

NLO QCD (MCFM, CT10.0)
- **ZZ** (p\(\bar{p}\))
- **ZZ** (pp)

CMS

**ATLAS Data 2012 (√s=8 TeV)**
- **ZZ** \(\rightarrow\) **III (66<m_\|<116 GeV) L=5.8 fb^{-1}\)

**ATLAS Data 2011 (√s=7 TeV)**
- **ZZ** \(\rightarrow\) **III (on-shell) L=4.7 fb^{-1}\)
- **ZZ** \(\rightarrow\) **ll\nu\nu (on-shell) L=4.7 fb^{-1}\)

**Tevatron (√s=1.96 TeV)**
- **CDF ZZ** \(\rightarrow\) **ll(ll/\nu\nu) (on-shell) L=6.0 fb^{-1}\)
- **D0 ZZ** \(\rightarrow\) **ll(ll/\nu\nu) (60<m_\|<120 GeV) L=8.6 fb^{-1}\)
Production cross sections in ATLAS

**ATLAS Preliminary**

LHC pp $\sqrt{s} = 7$ TeV
- Theory
- Data 2010 (L = 35 pb$^{-1}$)
- Data 2011 (L = 1.0 - 4.7 fb$^{-1}$)

LHC pp $\sqrt{s} = 8$ TeV
- Theory
- Data 2012 (L = 5.8 fb$^{-1}$)

---

Production cross sections in ATLAS

<table>
<thead>
<tr>
<th>Process</th>
<th>LHC pp $\sqrt{s} = 7$ TeV</th>
<th>LHC pp $\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>Theory</td>
<td>Theory</td>
</tr>
<tr>
<td>Z</td>
<td>Data 2010 (L = 35 pb$^{-1}$)</td>
<td>Data 2012 (L = 5.8 fb$^{-1}$)</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>Data 2011 (L = 1.0 - 4.7 fb$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WZ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- $\sigma_{total}$ values are given in pb
- LHC data points are shown for different luminosities
- Theory predictions are compared with data
Production cross sections in CMS

Electroweak Results -- ICHEP 2012 -- Joao Guimaraes

Production cross sections in CMS

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥1j</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥2j</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥3j</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥4j</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Production Cross Section, $\sigma_{\text{tot}}$

- $W^{\gamma}$
  - $E_T > 10$ GeV
  - $|\eta^{\gamma}| < 2.4$
  - $\Delta R(\gamma, l) > 0.7$

- $WZ$
  - $36$ pb$^{-1}$
  - $4.9$ fb$^{-1}$

- $ZZ$
  - $36$ pb$^{-1}$
  - $3.5$ fb$^{-1}$

- $WW$
  - $1.1$ fb$^{-1}$
  - $5.3$ fb$^{-1}$

- $Z^{\gamma}$
  - $≥3j$
  - $≥4j$

- $7$ TeV CMS measurement (stat ± syst)
- $8$ TeV CMS measurement (stat ± syst)

7 TeV Theory prediction

8 TeV Theory prediction

New

JHEP10(2011)132
JHEP01(2012)010
PLB701(2011)535
CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005,
007, 013, 014 (WW ZZ)
Possible vertices using an effective Lagrangian

\[ \mathcal{L}_{\text{VZZ}} = -\frac{e}{M_Z^2} \left[ f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\alpha V^{\alpha\mu}) \tilde{Z}^{\mu\beta} \tilde{Z}_\beta \right] \]

**ZZZ, ZZγ**

\((f_4^Z, f_4^γ, f_5^Z, f_5^γ) = (0,0,0,0)_{\text{SM}}\)

*Scale dependent form-factors*

\[ \alpha(\hat{s}) = \frac{\alpha(0)}{(1 + \hat{s}/\Lambda^2)^2} \]

with cutoff scale \(\Lambda\)

---

**CMS Preliminary** \(\sqrt{s} = 7\ TeV, \ L = 5.0\ fb^{-1}\)

- **Observed**
- **Expected ± 1σ**
- **Expected ± 2σ**

95% CL

- **pp → ZZ → llll**
- **ATLAS limits consistent and competitive**
- **Use of differential distributions**: will increase sensitivity

**ZZZ, ZZγ**

*Most powerful limit to date*

---

**ATLAS**

- **ATLAS, ∫Ldt = 1.02 fb⁻¹**
- **ATLAS, ∫L dt = 700 pb⁻¹**
- **LEP, ∫L dt = 130-209 GeV**
- **D0, ∫L dt = 1 fb⁻¹**

**ZZ**

- **95% C.I.**

*Using ZZ total cross section*

---

---

**Possible vertices using an effective Lagrangian**

\[
\mathcal{L}_{WWV}^{\text{eff}} = \frac{1}{g_{WWV}} \left[ g_1^V (W^+_{\mu\nu} W^{\mu\nu} - W^+_{\mu\nu} W^{\mu\nu} V^{\nu}) + \kappa^V W^+_{\mu\nu} W^{\mu\nu} V^{\nu} + \frac{\lambda^V}{m_W^2} W^+_{\rho\mu} W^{\mu\nu} V^{\nu} \right]
\]

**WWZ**

\((g_1^Z, \kappa^Z, \lambda) = (1, 1, 0)_{\text{SM}}\)

---

**ATLAS** Preliminary

<table>
<thead>
<tr>
<th>Variable</th>
<th>ATLAS, (\sqrt{s} = 7) TeV</th>
<th>ATLAS, (\sqrt{s} = 7) TeV</th>
<th>CDF, (\sqrt{s} = 1.96) TeV</th>
<th>D0, (\sqrt{s} = 1.96) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta g_1^Z)</td>
<td>4.6 fb(^{-1}), (\Lambda = \infty)</td>
<td>4.6 fb(^{-1}), (\Lambda = 2) TeV</td>
<td>7.1 fb(^{-1}), (\Lambda = 2) TeV</td>
<td>4.1 fb(^{-1}), (\Lambda = 2) TeV</td>
</tr>
</tbody>
</table>

**95% CL intervals**

- **ATLAS** (1.02 fb\(^{-1}\), \(\Lambda = 2\) TeV)
- ATLAS (1.02 fb\(^{-1}\), \(\Lambda = \infty\))
- D0 (4.2 fb\(^{-1}\), \(\Lambda = 2\) TeV)
- CMS (36 pb\(^{-1}\), \(\Lambda = \infty\))

**Parameters**

- \(\lambda^Z\)
- \(\Delta \kappa^Z\)

**Scale dependent form-factors**

\[
\alpha(\hat{s}) = \frac{\alpha(0)}{(1 + \hat{s}/\Lambda^2)^2}
\]

with cutoff scale \(\Lambda\)
Anomalous Triple Gauge Couplings

\[ Z_{\gamma\gamma}, \Lambda = 1.5 \text{ TeV} \]

\[ Z_{\gamma\gamma} \left| h_{03}^\gamma \right| < 0.027 \]
\[ \left| h_{04}^\gamma \right| < 0.0014 \]

PRD 85, 052001 (2012)
Z forward-backward asymmetry at Hadron Colliders

The SM leading order (LO) prediction [4] for the forward-backward charge asymmetry is defined as

\[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \]

where \( \sigma_F \) and \( \sigma_B \) are the cross sections for forward and backward processes, respectively.

Precise determinations of \( \sin^2\theta_{ee} \) due to lepton universality have been made in previous measurements, we take into account the difference in the measurement can be used to investigate possible new physics (new neutral bosons, LED)

Events with electron cosine \( \cos \theta \) are measured in the lab frame, and the momenta in Fig. 2 for \( \theta^* \).

Almost constant (\( \sim 0.4 \)), and those with electron cosine \( \cos \theta \) are the energy and the longitudinal components, respectively.

The forward-backward charge asymmetry is proportional to both the vector and axial-vector couplings of the atomic parity violation (APV) and is numerically close to 0. At large invariant mass, the asymmetry is almost constant (\( \sim 0.4 \)).

For the fermion species, \( \theta_{ff} \) is sensitive to the gauge bosons or large extra dimensions [6–14].

In the SM, asymmetries measured at the \( \text{Z} \) pole, \( \text{Z} \rightarrow \ell^+\ell^- \), and the negative of the anti- \( \text{Z} \) pole, \( \text{Z} \rightarrow \ell^+\ell^- \), are the four momentum

\[ q(g) \quad X \quad \theta^* \quad \ell^- \quad \ell^+ \quad \bar{q}(g) \]

depend only on the value of \( \sin^2\theta_{ee} \).

Precise determinations of \( \sin^2\theta_{ee} \) have been made in previous measurements, we take into account the difference in the measurement can be used to investigate possible new physics (new neutral bosons, LED).
Unfolded AFB agrees well with theoretical predictions

No evidence for new physics at high-mass
Effective Weak Mixing Angle

**Most precise measurement from Z to light-quark coupling**

**Statistical uncertainty still dominant**

**Dominant systematic uncertainty**

**PDF uncertainty** (0.00048)

**DO**

Average $0.23153 \pm 0.00016$

- $A^0_{fb}$
  - $0.23099 \pm 0.00053$

- $A_{l}(P_{z})$
  - $0.23159 \pm 0.00041$

- $A_{lr} (SLD)$
  - $0.23098 \pm 0.00026$

- $A^{0,b}_{fb}$
  - $0.23221 \pm 0.00029$

- $A^{0,c}_{fb}$
  - $0.23220 \pm 0.00081$

- $Q^{had}_{fb}$
  - $0.2324 \pm 0.0012$

- $A_{fb} (DØ), 5.0 fb^{-1}$
  - $0.2309 \pm 0.0010$

$0.2309 \pm 0.0008$ (stat) $\pm 0.0006$ (syst)
Effective Weak Mixing Angle

**CMS: First measurement at the LHC**

Extracted from $Z/\gamma^* \rightarrow \mu\mu$ data using unbinned maximum likelihood fit:

di-lepton rapidity, invariant mass and $\cos \theta^*_{CS}$

\[
\sin^2 \theta_{\text{eff}} = 0.2287 \pm 0.0020 \text{ (stat)} \pm 0.0025 \text{ (syst)}
\]

**Major systematics:** PDF, FSR and detector alignment

---

*Phys. Rev. D 84 (2011) 112002*
**Effective Weak Mixing Angle**

**CMS: First measurement at the LHC**

\[
sin^2 \theta_{\text{eff}} = 0.2287 \pm 0.0020 \text{ (stat)} \pm 0.0025 \text{ (syst)}
\]

**Results**

- \( A^{0, l}_{\text{fb}} \) 0.23099 ± 0.00053
- \( A_l(P_{\tau}) \) 0.23159 ± 0.00041
- \( A_{l_r} \text{(SLD)} \) 0.23098 ± 0.00026
- \( A^{0, b}_{\text{fb}} \) 0.23221 ± 0.00029
- \( A^{0, c}_{\text{fb}} \) 0.23220 ± 0.00081
- \( Q^{\text{had}}_{\text{fb}} \) 0.2324 ± 0.0012
- \( A_{\text{fb}} \text{(DØ), 5.0 fb}^1 \) 0.2309 ± 0.0010

**Average** 0.23153 ± 0.00016
Weak mixing angle: scale dependence

Scale dependence due to radiative effects

Jens Erler, private communication, July 2012

Future experiments

Electroweak Results -- ICHEP 2012 -- Joao Guimaraes
Electroweak Fit

- Precise measurement of electroweak parameters constrains
- New physics
- The Higgs mass
- Updated results from EPS’11
Electroweak Theory and Top Mass

![Graph showing top mass measurements over years]

- **DO experiment**
- **CDF experiment**
- **Tevatron Combination**
- **Electroweak fit**

Limit from electroweak fit

Chris Quigg, private communication
### Mass of the Top Quark

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass (GeV/c²) ± (stat ± syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I dilepton</td>
<td>167.4 ± 11.4 (±10.3 ± 4.9)</td>
</tr>
<tr>
<td>DØ-I dilepton</td>
<td>168.4 ± 12.8 (±12.3 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II dilepton</td>
<td>170.6 ± 3.8 (± 2.2 ± 3.1)</td>
</tr>
<tr>
<td>DØ-II dilepton</td>
<td>174.0 ± 3.1 (± 1.8 ± 2.5)</td>
</tr>
<tr>
<td>CDF-I lepton+jets</td>
<td>176.1 ± 7.4 (± 5.1 ± 5.3)</td>
</tr>
<tr>
<td>DØ-I lepton+jets</td>
<td>180.1 ± 5.3 (± 3.9 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II lepton+jets</td>
<td>173.0 ± 1.2 (± 0.6 ± 1.1)</td>
</tr>
<tr>
<td>DØ-II lepton+jets</td>
<td>174.9 ± 1.5 (± 0.8 ± 1.2)</td>
</tr>
<tr>
<td>CDF-I alljets</td>
<td>186.0 ± 11.5 (±10.0 ± 5.7)</td>
</tr>
<tr>
<td>CDF-II alljets *</td>
<td>172.5 ± 2.1 (± 1.4 ± 1.5)</td>
</tr>
<tr>
<td>CDF-II track               *</td>
<td>166.9 ± 9.5 (± 9.0 ± 2.9)</td>
</tr>
<tr>
<td>CDF-II MET+Jets *</td>
<td>172.3 ± 2.6 (± 1.8 ± 1.8)</td>
</tr>
<tr>
<td>Tevatron combination *</td>
<td>173.2 ± 0.9 (± 0.6 ± 0.8)</td>
</tr>
</tbody>
</table>

\[ \chi^2/\text{dof} = 8.3/11 (68.5\%) \]

**Tevatron:**
\[ M_t = 173.2 \pm 0.9 \text{ GeV} \]

**LHC:**
\[ M_t = 173.3 \pm 0.5 \pm 1.3 \text{ GeV} \]
- Updated with EPS’11 results
- Excludes direct Higgs searches from ATLAS and CMS

**Standard Fit**

$m_h = 94.5$ GeV  
Range $m_h = [71, 124]$  
$m_h (@ 95%) < 166.5$ GeV

**Complete Fit**

(including direct limits on Higgs from LEP and Tevatron)

$m_h = 125.2$ GeV  
Range $m_h = [116, 133]$  
$m_h (@ 95%) < 153.9$ GeV
New W Boson Mass at the Tevatron

**Constraints Higgs mass:**
\[ \Delta m_t = 0.9 \text{ GeV} \iff \Delta m_W \approx 5 \text{ MeV} \]

Need excellent understanding of detector and MC simulation

- For the same constraining power on Higgs mass:
  - World-average of W mass (Feb. 2012)
  - Progress on \( m_t \) has the biggest impact on Higgs constraint!

**Motivation for Precision Measurements**

\[ m_t = 0.9 \text{ GeV} \]
\[ m_W = 80.399 \pm 23 \text{ MeV} \]

Constraints Higgs mass:

- Monte Carlo (MC) Simulation
- Electron Model
- Recoil Model

**Diagram:**
- Energy under the electron cone
- In-cone FSR
- Underlying event
- Soft Recoil
- OoC FSR
- Min Bias
- Zero Bias
- \( O(10 \text{ GeV}) \)
New W Boson Mass at the Tevatron

**Fits transverse mass, lepton $p_T$ and neutrino $p_T$**

**Uses both $e$ and $\mu$**

- 2.2 fb$^{-1}$
- 1.1 M W events
- $\Delta m_W$ (sys) = 18 MeV ($e$)
- $\Delta m_W$ (sys) = 16 MeV ($\mu$)

**Uses only $e$**

- 4 + 1 fb$^{-1}$
- 1.7 M W events
- $\Delta m_W$ (sys) = 22 MeV ($e$)

---

**PRL 108, 151803 (2012)**

CDF II

$\int L dt = 2.2$ fb$^{-1}$

- Data
- Simulation

$M_W = (80379 \pm 16_{\text{stat}})$ MeV

$\chi^2$/dof = 58/48


(b) D0, 4.3 fb$^{-1}$

- Data
- FAST MC
- Background

$\chi^2$/dof = 26.7/31
Combined electron channel and muon channel fits:
- Most precise measurement of W boson mass to date
- Exceed the precision of all previous measurements combined
- Reduces uncertainty of world average by ~30%

Combined with D0 W mass result:
- New SM Higgs constraint: $m_H < 152 \text{ GeV} / c^2$ at 95% C.L.

**Conclusion**
- CDF has achieved the most precise measurement of the W boson mass
- Significantly more precise than all previous measurements

$|m_{W_{\text{CDF}}} = 80387 \pm 19 \text{ MeV} / c^2$

Expect CDF with full CDF dataset already recorded
- The W mass will continue to play an important role as a stress test of SM.

**Dominant uncertainties:**
- Parton distribution functions: 10-14 MeV
- Lepton calibration: 16 MeV (D0) / 5 MeV (CDF)

**Improvements still to come**

More than double statistics with full run II dataset
Precision Electroweak Constraints

- Disentangle if “observed” Higgs boson is SM or SUSY-like
Precision Electroweak Constraints

- Disentangle if “observed” Higgs boson is SM or SUSY-like

Challenges for LHC to reach $\Delta M_W = 5$ MeV

- Theoretical understanding of $P_T(W)$
- Improved PDFs (strangeness)
- Large pileup affecting measurement of soft recoil

experimental errors 68% CL:
- LEP2/Tevatron: today
- LHC: future ($\delta M_W = 5$ MeV)

$M_h = 123 \ldots 127$ GeV

$M_h = 123$ GeV

SM $M_h = 127$ GeV

MSSM, $M_h = 123\ldots127$ GeV

Heinemeyer, Hollik, Stockinger, Weiglein, Zeune ’12
Conclusions

- Large Hadron Collider program well underway towards precision physics with W and Z bosons
  - Stable ground for new physics searches
  - SM physics offers spin-offs into discoveries

- Tevatron still putting out high quality results
  - It will have the better hand on the W and top mass for a long time

- Agreement with theory across orders of magnitude is impressive

- EW precision measurements in a fair agreement with a Higgs boson with mass of 125 GeV
  - Future precision measurements should help disentangle possible new physics
CMS: W and Z cross sections at $\sqrt{s} = 8$ TeV

- CMS requested special LHC conditions during luminosity ramp up period to achieve low pile-up events (~5) for good MET resolution at W:
  - LHC separate beams in transverse plane to reduce effective overlap
  - Separation was periodically adjust to keep instantaneous $\mathcal{L}_{\text{inst}} \sim 3 \text{E32} - 6 \text{E32 cm}^2\text{s}^{-1}$
  - Integrated $\mathcal{L} = 18.8 \text{ pb}^{-1}$
  - Special HLT menu with low thresholds:
    - 22 GeV for e and 15 GeV for $\mu$
  - Minimal ID/Iso requirement to suppress background

Event Selection:

- e-channel:
  - $E_T > 25$ GeV and $|\eta| < 2.5$, exclude $1.4442 < |\eta| < 1.566$ (barrel/forward transition)
  - $W \rightarrow e\nu$: Reject events with 2nd $e$ with $E_T > 20$ GeV

- $\mu$-channel:
  - $p_T > 25$ GeV and $|\eta| < 2.1$
  - $W \rightarrow \mu\nu$: Reject events with 2nd $\mu$ with $p_T > 10$ GeV

- $Z \rightarrow ll$: $60$ GeV < $M_{ll}$ < 120 GeV

The dominant source of systematic uncertainty:

- Experimental:
  - Luminosity (4.4%) for absolute cross sections
  - Lepton efficiency (1-3%)
  - Theoretical uncertainty in acceptance (2-3%)

- Theoretical:
  - PDFs
  - Higher order QCD corrections
  - Higher order electroweak corrections
Event selection in tau polarization analysis

- 24 pb-1 from 2010 data with tau (16 GeV) + Missing $E_T$ (22 GeV) trigger
- Offline: single-track tau with $p_T > 20$ GeV and Missing ET greater than 30 GeV
- Reject events with jet activity in region between the central and endcap detectors
- Reject events with electron or muon greater than 15 GeV $E_T$
- Reject events with jet activity along direction of event Missing $E_T$
- Require Missing ET significance > 6

$$S_{E^\text{miss}_T} = \frac{E^\text{miss}_T}{\sigma(E^\text{miss}_T)}$$

*Based on ATLAS W-$\rightarrow\tau\nu$ cross section measurement: Phys. Lett. B 706, 276 (2012)*
**W Polarization**

**Motivation:**
- W in three states: $f_L$, $f_0$, and $f_R$
- LO: predominantly left-handed
- NLO: all states possible

**Measurement principle:**
- No neutrino $p_z$: use transverse quantity
- Two bins in $W p_T$:
  - $35 < p_T(W) < 50$ GeV
  - $p_T(W) > 50$ GeV

**Model:**

$$\cos \theta_{2D} = \frac{p_T \ell^* \cdot p_T W}{|p_T \ell^*||p_T W|}$$

**Data ($\sqrt{s} = 7$ TeV)$^{\text{ATLAS}}$**

$W^+ \rightarrow e^+ \nu$

$W^+ p_T > 50$ GeV

$\int L dt = 37 \text{ pb}^{-1}$

$W^-$

$W^-$

$\int L dt = 37 \text{ pb}^{-1}$

$\nu p_T > 50$ GeV

**template fits give access to $f_0$ and $f_L - f_R$**

Excellent tau identification at LHC

- **Z→ττ cross section**
  - CMS: Published
  - ATLAS: New

- **W→τν cross section**
  - ATLAS: New

**Good prospects for new physics searches with taus**

### Data

- **Z→ττ cross section**
  - CMS: Published
  - ATLAS: New

- **W→τν cross section**
  - ATLAS: New

**Good prospects for new physics searches with taus**
Excellent tau identification at LHC

Z→ττ cross section
  - CMS: Published
  - ATLAS: New

W→τν cross section
  - ATLAS: New

Good prospects for new physics searches with taus
### Electroweak Top Production at Hadron Colliders

#### $\sigma$ (NNLO)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Tevatron @ 1.96 TeV</th>
<th>LHC @ 7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td>$1.04 \pm 0.4$</td>
<td>$4.6 \pm 0.2$</td>
</tr>
<tr>
<td>t-channel</td>
<td>$2.26 \pm 0.12$</td>
<td>$64.6 \pm 2.7$</td>
</tr>
<tr>
<td>Wt-channel</td>
<td>$0.28 \pm 0.06$</td>
<td>$15.7 \pm 1.1$</td>
</tr>
</tbody>
</table>

- **σ** (NNLO) (pb) ($m_{\text{top}} = 172.5$ GeV)
- **Tevatron @ 1.96 TeV**:
  - s-channel: $1.04 \pm 0.4$
  - t-channel: $2.26 \pm 0.12$
  - Wt-channel: $0.28 \pm 0.06$
- **LHC @ 7 TeV**:
  - s-channel: $4.6 \pm 0.2$
  - t-channel: $64.6 \pm 2.7$
  - Wt-channel: $15.7 \pm 1.1$

**Notes**:
- Very difficult at LHC
- Not possible at Tevatron
> Predictions describe the data well in the full range
CMS: $W_c$

ATLAS: $W_b$

Important background for Higgs and top

Agreement with theoretical expectations at 1.5 $\sigma$ level

CMS preliminary

36 pb$^{-1}$ at $\sqrt{s} = 7$ TeV

$\sigma(W + \text{charm}) = 0.142 \pm 0.015\text{(stat.)} \pm 0.024\text{(syst.)}$

ATLAS Preliminary

Data 2010, $\sqrt{s} = 7$ TeV

$\int Ldt = 35$ pb$^{-1}$

$\sigma(W \rightarrow \ell v + \geq 1\text{~b-jet})$ [pb]

Electroweak Results -- ICHEP 2012 -- Joao Guimaraes
**New Tevatron Combination**
- Uncertainty below 1 GeV for the first time
- Systematic uncertainties will decrease further with larger datasets
  - Dominated by JES
- To improve:
  - b-jet modelling
  - uncertainties in signal and background simulations

**LHC Experiments still far away**
- CMS result in lepton+jets
  \[ m_t = 173.1 \pm 2.1 \text{(stat)}^{+2.8}_{-2.5} \text{(syst)} \text{ GeV} \]
  - Dominant systematic: JES

### Mass of the Top Quark

\[ \text{July 2011} \quad (*) \text{preliminary} \]

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I dilepton</td>
<td>167.4 ± 11.4 (± 10.3 ± 4.9)</td>
</tr>
<tr>
<td>DØ-I dilepton</td>
<td>168.4 ± 12.8 (± 12.3 ± 3.6)</td>
</tr>
<tr>
<td>CDF-II dilepton</td>
<td>170.6 ± 3.8  (± 2.2 ± 3.1)</td>
</tr>
<tr>
<td>DØ-II dilepton</td>
<td>174.0 ± 3.1  (± 1.8 ± 2.5)</td>
</tr>
<tr>
<td>CDF-I lepton+jets</td>
<td>176.1 ± 7.4  (± 5.1 ± 5.3)</td>
</tr>
<tr>
<td>DØ-I lepton+jets</td>
<td>180.1 ± 5.3  (± 3.9 ± 3.6)</td>
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<tr>
<td>CDF-II lepton+jets</td>
<td>173.0 ± 1.2  (± 0.6 ± 1.1)</td>
</tr>
<tr>
<td>DØ-II lepton+jets</td>
<td>174.9 ± 1.5  (± 0.8 ± 1.2)</td>
</tr>
<tr>
<td>CDF-I alljets</td>
<td>186.0 ± 11.5 (± 10.0 ± 5.7)</td>
</tr>
<tr>
<td>CDF-II alljets *</td>
<td>172.5 ± 2.1  (± 1.4 ± 1.5)</td>
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<tr>
<td>CDF-II track</td>
<td>166.9 ± 9.5  (± 9.0 ± 2.9)</td>
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<tr>
<td>CDF-II MET+Jets *</td>
<td>172.3 ± 2.6  (± 1.8 ± 1.8)</td>
</tr>
<tr>
<td>Tevatron combination *</td>
<td>173.2 ± 0.9  (± 0.6 ± 0.8)</td>
</tr>
</tbody>
</table>

\[ \chi^2/\text{dof} = 8.3/11 \text{ (68.5\%)} \]

**M_{top} = 173.2 ± 0.9 GeV**
Gfitter/GSM sub-package used in the global EW fit of the SM

Indirect determination of $m_t$ and $m_W$

Results prior to EPS’11

$M_W = 80.359^{+0.017}_{-0.010}$ GeV

1.6σ below measured value

$m_t = [173.5, 181.1] \text{ GeV}$ and $[184.3, 190.3] \text{ GeV}$
Free fit parameters

- $M_Z$, $M_H$, $m_t$, $D_{\text{had}}^{(S)}(M_Z^2)$, $a_s(M_Z^2)$, $m_c$, $m_b$

- Scale parameters for theoretical uncertainties on $M_W$, $sin^2 \theta'_\text{eff}$ (and the EW form factors $r_Z^f$, $k_Z^f$)

Latest experimental input

- Z-pole observables: LEP / SLC results
  [ADLO+SLD, Phys. Rept. 427, 257 (2006)]

- $M_W$ and $G_W$ latest from LEP/Tevatron (03/2010)
  [ADLO,CDF+D0: arXiv:0908.1374v1]

- $m_{\text{top}}$: latest Tevatron average (07/2010)
  [CDF&D0: new combination ICHEP’10]

- $m_c$, $m_b$ world averages [PDG, J. Phys. G33,1 (2006)]

- $\Delta a_{\text{had}}^{(S)}(M_Z^2)$ including $a_s$ dependency (10/2010)
  [Davier et al., arXiv:1010.4180]

- Direct Higgs searches from LEP/Tevatron/LHC
  [ATLAS+CMS: Moriond 2011]

- Not considered: $sin^2 \theta'_\text{eff}$ results from NuTeV. APV and polarized Möller scattering

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
<th>Free in fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>yes</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>–</td>
</tr>
<tr>
<td>$a_s^{0}_{\text{had}}$ [GeV]</td>
<td>41.540 ± 0.037</td>
<td>–</td>
</tr>
<tr>
<td>$R_F$</td>
<td>20.707 ± 0.025</td>
<td>–</td>
</tr>
<tr>
<td>$A^{0}_{FB}$</td>
<td>0.0171 ± 0.0010</td>
<td>–</td>
</tr>
<tr>
<td>$A^{0}_{\ell}$</td>
<td>0.1499 ± 0.0018</td>
<td>–</td>
</tr>
<tr>
<td>$A_e$</td>
<td>0.670 ± 0.027</td>
<td>–</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.923 ± 0.020</td>
<td>–</td>
</tr>
<tr>
<td>$A^{0,0}_{FB}$</td>
<td>0.0707 ± 0.0035</td>
<td>–</td>
</tr>
<tr>
<td>$A^{0,1}_{FB}$</td>
<td>0.0992 ± 0.0016</td>
<td>–</td>
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<tr>
<td>$R^0_F$</td>
<td>0.1721 ± 0.0030</td>
<td>–</td>
</tr>
<tr>
<td>$R^0_b$</td>
<td>0.21629 ± 0.00066</td>
<td>–</td>
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<tr>
<td>$sin^2 \theta'<em>\text{eff}(Q</em>{FB})$</td>
<td>0.2324 ± 0.0012</td>
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</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Likelihood ratios</th>
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<tr>
<td>$M_W$ [GeV]</td>
<td>80.399 ± 0.023</td>
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</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.085 ± 0.042</td>
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</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
<th>Free in fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{m}_c$ [GeV]</td>
<td>1.27 ±0.14</td>
<td>–</td>
</tr>
<tr>
<td>$\bar{m}_b$ [GeV]</td>
<td>4.20 ±0.17</td>
<td>–</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>173.3 ± 1.1</td>
<td>–</td>
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<tr>
<td>$\Delta a_{\text{had}}^{(S)}(M_Z^2)$</td>
<td>2749 ± 10</td>
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<td>$a_s(M_Z^2)$</td>
<td>–</td>
<td>–</td>
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
<th>Free in fit</th>
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<tr>
<td>$\delta_{\chi} M_W$ [MeV]</td>
<td>$[-4.4]_{\text{theo}}$</td>
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<tr>
<td>$\delta_{\chi} sin^2 \theta'_\text{eff}$</td>
<td>$[-4.7]_{\text{theo}}$</td>
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<td>$\delta_{\chi} r^f_Z$</td>
<td>$[-2.2]_{\text{theo}}$</td>
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<tr>
<td>$\delta_{\chi} k^f_Z$</td>
<td>$[-2.2]_{\text{theo}}$</td>
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### Detailed systematic uncertainties

#### Luminosity: 3.4%

<table>
<thead>
<tr>
<th>Electron channels (%)</th>
<th>$W^+$</th>
<th>$W^-$</th>
<th>$W^\pm$</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Identification</td>
<td>0.9</td>
<td>0.8</td>
<td>1.1</td>
<td>1.8</td>
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<tr>
<td>Isolation</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>—</td>
</tr>
<tr>
<td>Energy scale and resolution</td>
<td>0.5</td>
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<td>0.2</td>
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<tr>
<td>Defective LAr channels</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
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<tr>
<td>Charge misidentification</td>
<td>&lt;0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>0.8</td>
<td>0.7</td>
<td>1.0</td>
<td>—</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Vertex position</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>QCD Background</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.7</td>
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<tr>
<td>EWK+$t\bar{t}$ Background</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>&lt;0.1</td>
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<tr>
<td>$C_{W/Z}$ Theor. uncertainty</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.3</td>
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<tr>
<td>Total Exp. uncertainty</td>
<td>1.8</td>
<td>1.8</td>
<td>2.0</td>
<td>2.7</td>
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<tr>
<td>$A_{W/Z}$ Theor. uncertainty</td>
<td>1.4</td>
<td>1.6</td>
<td>1.9</td>
<td>1.9</td>
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<tr>
<td>Total including Luminosity</td>
<td>2.3</td>
<td>2.4</td>
<td>2.8</td>
<td>3.3</td>
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</table>

<table>
<thead>
<tr>
<th>Muon channels (%)</th>
<th>$W^+$</th>
<th>$W^-$</th>
<th>$W^\pm$</th>
<th>$Z$</th>
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<tbody>
<tr>
<td>Trigger</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Isolation</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>$p_T^\text{miss}$ Resolution</td>
<td>0.04</td>
<td>0.03</td>
<td>0.05</td>
<td>0.02</td>
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<td>$p_T^\text{Scale}$</td>
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<tr>
<td>$E_T^{\text{miss}}$</td>
<td>0.5</td>
<td>0.4</td>
<td>0.6</td>
<td>—</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Vertex position</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>QCD Background</td>
<td>0.6</td>
<td>0.5</td>
<td>0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>EWK+$t\bar{t}$ Background</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
<td>0.02</td>
</tr>
<tr>
<td>$C_{W/Z}$ Theor. uncertainty</td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
<td>0.3</td>
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<tr>
<td>Total Exp. uncertainty</td>
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<td>1.7</td>
<td>1.7</td>
<td>0.9</td>
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<tr>
<td>$A_{W/Z}$ Theor. uncertainty</td>
<td>1.4</td>
<td>1.6</td>
<td>2.0</td>
<td>2.0</td>
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<tr>
<td>Total including Luminosity</td>
<td>2.1</td>
<td>2.3</td>
<td>2.6</td>
<td>2.2</td>
</tr>
</tbody>
</table>
**Detailed systematic uncertainties**

- **Luminosity: 4%**

<table>
<thead>
<tr>
<th>Source</th>
<th>$W \to e\nu$</th>
<th>$W \to \mu\nu$</th>
<th>$Z \to e^+e^-$</th>
<th>$Z \to \mu^+\mu^-$</th>
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</thead>
<tbody>
<tr>
<td>Lepton reconstruction &amp; identification</td>
<td>1.4</td>
<td>0.9</td>
<td>1.8</td>
<td>n/a</td>
</tr>
<tr>
<td>Trigger prefiring</td>
<td>n/a</td>
<td>0.5</td>
<td>n/a</td>
<td>0.5</td>
</tr>
<tr>
<td>Energy/momentum scale &amp; resolution</td>
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<td>0.22</td>
<td>0.12</td>
<td>0.35</td>
</tr>
<tr>
<td>$E_T$ scale &amp; resolution</td>
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<td>0.2</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Background subtraction / modeling</td>
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<td>0.4</td>
<td>0.14</td>
<td>0.28</td>
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<tr>
<td>Trigger changes throughout 2010</td>
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<td>n/a</td>
<td>n/a</td>
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</tr>
<tr>
<td>Total experimental</td>
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<td>1.1</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td>PDF uncertainty for acceptance</td>
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<td>0.8</td>
<td>0.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Other theoretical uncertainties</td>
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<td>0.8</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Total theoretical</td>
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<td>1.1</td>
<td>1.6</td>
<td>1.9</td>
</tr>
<tr>
<td>Total (excluding luminosity)</td>
<td>1.8</td>
<td>1.6</td>
<td>2.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>
The yellow band around the vertical yellow line at one represents the luminosity uncertainty. Measurements in the electron and muon channels, and combined, are compared to the theoretical predictions computed at the NNLO in QCD with recent PDF sets. Statistical uncertainties cancel in the ratios. The systematic uncertainties, including the combining of theoretical uncertainties on the predictions and measured quantities, are represented as black error bars while the red error bars also include experimental uncertainties.