W/Z Boson Production and Mass

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On behalf of

ATLAS, CMS, LHCb, CDF and DO

Hadron Collider Physics Symposium 2012

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Kyoto, Japan
W/Z Production

Theoretically well established picture
Well identifiable final states
Corrections: QCD, EWK

Very Important Processes
- Performance measurements
- Proton PDFs
- Backgrounds for searches
- SM tests at TeV scale
Any cross section at the LHC is a convolution of partonic cross section and parton distribution functions (PDFs)

$$\sigma_{PP} = \hat{\sigma}_{qq}(\alpha(Q^2), Q^2) \otimes \sum_{q} \int dx_1 dx_2 f_q(x_1, Q^2) f_q(x_2, Q^2)$$

Kinematic phase space given by

$$x_{1,2} = \frac{M_{W,Z}}{\sqrt{s}} e^{\pm y}$$

0.001 < x < 0.1

$$M_{W,Z} = 80.4, 91.2 \text{ GeV}$$

Boson rapidity |y| < 2.5
ATLAS and CMS published precision measurements with 2010 data


JHEP 10 (2011) 132

Much larger dataset now available, but:
LHC luminosity is increasing \(2 \times 10^{31}\) in 2010 to \(7 \times 10^{33}\) 2012
Average number of inelastic pp interaction (pileup) increased from 2 to 20
Precise measurement of inclusive cross section requires low pileup and low \(P_T\) trigger thresholds
W/Z Production Cross Sections

CMS Preliminary

18.7 pb$^{-1}$ at $\sqrt{s} = 8$ TeV

Events / 2.0 GeV

CMS Preliminary

18.8 pb$^{-1}$ at $\sqrt{s} = 8$ TeV

Events / 2.0 GeV

CMS Preliminary

18.7 pb$^{-1}$ at $\sqrt{s} = 8$ TeV

Events / 1.0 GeV/c$^2$

CMS-PAS-12-011

8 TeV!
**Ratio of $W^+$ and $W^-$ Cross Sections**


**CMS-PAS-SMP-12-011**

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**ATLAS**

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

- Data 2010 ($\sqrt{s} = 7 \, \text{TeV}$)
- total uncertainty
- exp. uncertainty

- ABKM09
- JR09
- HERAPDF1.5
- MSTW08

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**CMS Preliminary**

18.7 pb$^{-1}$ at $\sqrt{s} = 8 \, \text{TeV}$

NNLO, FEWZ+MSTW2008 prediction [with MSTW2008 68% CL uncertainty]

- $W^+ \rightarrow e^+\nu$, $W^- \rightarrow e^-\nu$
  
  $1.44 \pm 0.01_{\text{stat}} \pm 0.05_{\text{syst}}$

- $W^+ \rightarrow \mu^+\nu$, $W^- \rightarrow \mu^-\nu$
  
  $1.38 \pm 0.01_{\text{stat}} \pm 0.03_{\text{syst}}$

- $W^+ \rightarrow \tau^+\nu$, $W^- \rightarrow \tau^-\nu$ (combined)
  
  $1.39 \pm 0.01_{\text{stat}} \pm 0.02_{\text{syst}}$

**$R_{+/−} = [σ×BR](W^+) / [σ×BR](W)^{−}$**

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**Benefits from experimental and theoretical systematics cancellation**

<table>
<thead>
<tr>
<th>Collaboration</th>
<th>Energy</th>
<th>$W^+ / W^-$</th>
<th>Statistical Error</th>
<th>Systematic Error</th>
<th>Total Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>7 TeV</td>
<td>1.454 ± 0.006</td>
<td>± 0.012</td>
<td>± 0.022</td>
<td>(acc.)</td>
</tr>
<tr>
<td>CMS</td>
<td>7 TeV</td>
<td>1.421 ± 0.006</td>
<td>± 0.014</td>
<td>± 0.029</td>
<td>(th.)</td>
</tr>
<tr>
<td>CMS</td>
<td>8 TeV</td>
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<td></td>
</tr>
</tbody>
</table>

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*Oliver Stelzer-Chilton*  
*TRIUMF*
Lepton Universality


Result already close to world average

World average

\[ R_W = 1.017 \pm 0.019 \]
\[ R_Z = 0.9991 \pm 0.0024 \]

\[ R_W = \frac{\sigma_{W^+} \cdot BR(W^+ \to e\nu)}{\sigma_{W^+} \cdot BR(W^+ \to \mu\nu)} = 1.006 \pm 0.004 \text{ (sta)} \pm 0.006 \text{ (unc)} \pm 0.023 \text{ (cor)} = 1.006 \pm 0.024 \]

\[ R_Z = \frac{\sigma_{Z} \cdot BR(Z \to e^+e^-)}{\sigma_{Z} \cdot BR(Z \to \mu^+\mu^-)} = 1.018 \pm 0.014 \text{ (sta)} \pm 0.016 \text{ (unc)} \pm 0.028 \text{ (cor)} = 1.018 \pm 0.031 \]
W and Z from LHCb

LHCb: Measurements extended up to $|\eta| = 4.9$

Important for PDF constraints
Invariant mass distributions in good agreement with theory prediction
Forward Backward Asymmetry

\[ \frac{d\sigma}{d\cos\theta^*} \sim \frac{3}{8} (1 + \cos^2\theta^*) + A_{FB} \cos\theta^* \]

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

PRD 84, 012007 (2011)

arXiv:1207.3973, accepted by PLB

Most precise measurements of \( g^u(d)_a \) and \( g^u(d)_v \)

CMS:
Asymmetry measured as a function of mass and rapidity
Measurement in both dilepton channels and combination
$\phi_{\eta}^{*}$ depends exclusively on the angles of the two leptons which are better measured than their momenta.

**New!**

**Good description of ATLAS data by RESBOS at the ~4% level.**

**Technique used by D0**


**Similar residual shape mismatch to RESBOS prediction**

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**Z/$\gamma^{*}$ Transverse Momentum**

\[
\phi_{\eta}^{*} = \tan\left(\phi_{\text{acop}}/2\right) \sin(\theta_{\eta}^{*}) \\
\cos(\theta_{\eta}^{*}) = \tanh\left[(\eta^{-} - \eta^{+})/2\right]
\]

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**ATLAS Preliminary**

$\sqrt{s} = 7 \text{ TeV}$

$|y| < 2.4$

$p_{T} > 20 \text{ GeV}$

$66 \text{ GeV} < m_{e\mu} < 116 \text{ GeV}$

**\(\chi^{2}_{(ee+\mu\mu)} = 25/24\)**

**\(\chi^{2}_{(ee+\mu\mu)} = 27/24\)**
NEW! LHCb result using 1 fb$^{-1}$ of data

**arXiv:1210.6289v1**

Cross sections in individual channels and combined in good agreement with SM

Lepton universality

\[
\frac{\sigma_{pp \to Z \to \tau\tau}}{\sigma_{pp \to Z \to \mu\mu}} = 0.93 \pm 0.09
\]
W Charge Asymmetry

Charge Asymmetry, in pp access of $u$- over $d$- quarks

ATLAS-CONF-2011-129

Discrimination between PDF at low $|\eta|$
W Boson Mass
W Boson Mass Measurement

- Derive W mass from precisely measured electroweak quantities

\[ m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2 \theta_W (1 - \Delta r)} \]

\[ \sin \theta_W^2 = 1 - \frac{m_W^2}{m_Z^2} \]

- Radiative corrections $\Delta r$ dominated by top quark and Higgs loop

$\Rightarrow$ allows indirect constraint on Higgs mass
Successes from the (recent) Past

Predicting the top
From precision measurements from LEP and SLC on the Z boson pole

top quark loops in $Z^0$

Good agreement of the electroweak constraint with the “Higgs like” discovery

Precision measurements on Z pole constraint top mass before its discovery

Predicting the Higgs
Precision measurements from LEP, SLC and Tevatron

$\Delta \chi^2$

- SM fit
- SM fit w/o $M_t$ measurement
- ATLAS measurement [arXiv:1207.7214]
- CMS measurement [arXiv:1207.7235]
Carried out at several colliders

World average currently dominated by Tevatron (CDF precision 19 MeV)
precise charged lepton measurement is the key (achieved ~0.01%)

Recoil measurement allows inference of neutrino $E_T$ (restricted to $u<15$ GeV)

Use $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events to derive recoil model
Lepton Energy Scale

CDF

$J/\psi \rightarrow \mu\mu$
$\Upsilon \rightarrow \mu\mu$
$Z \rightarrow \mu\mu$

Muon Scale

CDF

$W \rightarrow e\nu$
$E/p$

Electron Scale

Cross Check

$Z \rightarrow ee$

D0

$Z \rightarrow ee$

Electron Scale
“Back bone” of CDF analysis is track $p_T$ measurement in drift chamber (COT). Calibrate momentum scale using samples of dimuon resonances ($J/\psi$, $Y$, $Z$). Span a large range of $p_T$.

Final scale error of $9 \times 10^{-5}$
Transfer momentum calibration to calorimeter using E/p distribution of electrons from W decay by fitting peak of E/p

Excellent description of E/p tail
Constraints overall material

E/p also used to constrain calorimeter non-linearity
$E_{\text{measured}} = \alpha \times E_{\text{TRUE}} + \beta$

Measured in luminosity and energy bins

Consistent with PDG by construction

D0 is measuring $M_W / M_Z$

$M_Z = 91.193 \pm 0.017(\text{stat})$ GeV
- Perform blinded measurement of $Z$ mass using derived scales from independent samples
- Comparison to PDG value is a powerful cross-check of the calibration
- After unblinding, $M_Z$ added as further calibration to both p- and E-scales

CDF II
\[ \int L \, dt = 2.2 \, \text{fb}^{-1} \]

$M_Z = (91180 \pm 12_{\text{stat}}) \, \text{MeV}$
\[ \chi^2/\text{dof} = 30/30 \]

Z masses in good agreement with PDG ($91188 \pm 2 \, \text{MeV}$)

Include $Z \rightarrow \ell\ell$ masses for final momentum scale and energy scale
Recoil definition:
→ Energy vector sum over all calorimeter towers, excluding:
  - lepton towers

• Measured recoil:
  - hard recoil from initial state QCD in W/Z event
  - underlying event/spectator interaction energy

• Calibrate detector response and resolution using Z and minimum-bias data

• Validate using measured recoil in W events
Similar calibration samples and procedures between D0 and CDF

Typically only detect 50-70% of "true" QCD radiation

Validate model in W events

\[ m_T \sim 2p_T + U_{||} \] 
Component of hadronic recoil along charged lepton direction
Generator-level input for W&Z simulation provided by RESBOS
[Balazs et.al. PRD56, 5558 (1997)]

Custom fast simulation makes smooth, high statistics templates

Extract the W mass from fit to:
\[ m_T, p_T \text{ and } E_{T\text{miss}} \]
distributions in muon and electron decay channel
Transverse mass fits

90% of $M_W$ information is in transverse mass
Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>D0</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton energy scale/resn/modelling</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>Hadronic recoil energy scale and resolution</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Parton distributions</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>QED radiation</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>$p_T(W)$ model</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>22</td>
<td>15</td>
</tr>
<tr>
<td>$W$-boson statistics</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>26 MeV</td>
<td>19 MeV</td>
</tr>
</tbody>
</table>

- Largely stat. in origin: 10 MeV
- Largely theory in origin: 12 MeV

90% of $M_W$ information is in transverse mass
World Average

Mass of the W Boson

<table>
<thead>
<tr>
<th>Measurement</th>
<th>(M_W) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-0/I</td>
<td>80432 (\pm) 79</td>
</tr>
<tr>
<td>DØ-I</td>
<td>80478 (\pm) 83</td>
</tr>
<tr>
<td>DØ-II (1.0, fb^{-1})</td>
<td>80402 (\pm) 43</td>
</tr>
<tr>
<td>CDF-II (2.2, fb^{-1})</td>
<td>80387 (\pm) 19</td>
</tr>
<tr>
<td>DØ-II (4.3, fb^{-1})</td>
<td>80369 (\pm) 26</td>
</tr>
<tr>
<td>Tevatron Run-0/I/II</td>
<td>80387 (\pm) 16</td>
</tr>
<tr>
<td>LEP-2</td>
<td>80376 (\pm) 33</td>
</tr>
<tr>
<td>World Average</td>
<td>80385 (\pm) 15</td>
</tr>
</tbody>
</table>

Tevatron Run-II has halved the \(M_W\) uncertainty

March 2012
90% of $M_W$ information is in transverse mass
Limited lepton acceptance produces dependence on PDFs
Will likely be the limiting factor in reducing uncertainty
Evaluated with CTEQ and MSTW eigenvectors

Tevatron and LHC measurements that can further constrain PDFs:
• Z boson rapidity distribution
• $W \to l \nu$ lepton rapidity distribution
• W boson charge asymmetry
At LHC (unlike TeV) significant contribution from “cs” production.

Affects:
- acceptance via rapidity and kinematic cuts
- contribution to $p_T(W)$ ($m_C$ mass)

Constraints from W and Z data will reduce this

But assumptions of s vs s-bar
Naive expectation: $s = u = d$
But: strange mass is larger

Reduction to: $<10$ MeV ?
Large Hadron Collider program well underway towards precision physics with W and Z bosons

Constraints on PDF’s and large backgrounds for new physics

Tevatron leading precision measurements of W boson mass

EW precision measurements in a good agreement with a “Higgs like” boson with mass of ~125 GeV

Little room for new physics

Need better measurements of $m_W$, $m_{top}$, $\alpha_{EM}$, $\alpha_S$, HO corrections
Extras
**Ratio of W and Z Cross Sections**

**ATLAS**

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

- Data 2010 ($\sqrt{s} = 7 \text{ TeV})$
- total uncertainty
- exp. uncertainty

- ABKM09
- JR09
- HERAPDF1.5
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**CMS Preliminary**

18.7 pb$^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$

**NNLO, FEWZ+MSTW2008 prediction**

- with MSTW2008 68% CL uncertainty

**W→ev, Z→ee**

\[ 10.99 \pm 0.16_{\text{stat}} \pm 0.39_{\text{syst}} \]

**W→μν, Z→μμ**

\[ 10.44 \pm 0.14_{\text{stat}} \pm 0.29_{\text{syst}} \]

**W→νv, Z→ll (combined)**

\[ 10.65 \pm 0.11_{\text{stat}} \pm 0.23_{\text{syst}} \]

**R_{W/Z} = [\sigma \times \text{BR}](W) / [\sigma \times \text{BR}](Z)**

**Benefits from experimental and theoretical systematics cancellation**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Energy (TeV)</th>
<th>Ratio (W/Z)</th>
<th>(stat.)</th>
<th>(syst.)</th>
<th>(acc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>7</td>
<td>10.893 +/- 0.079</td>
<td>+/- 0.110</td>
<td>+/- 0.116</td>
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<td>CMS</td>
<td>7</td>
<td>10.54 +/- 0.07</td>
<td>+/- 0.08</td>
<td>+/- 0.16</td>
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<tr>
<td>CMS</td>
<td>8</td>
<td>10.65 +/- 0.11</td>
<td>+/- 0.23</td>
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</tr>
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</table>
NNLO predictions generally describe the data
Differences due to PDFs are observed
W Polarization

The left-handed, right-handed and longitudinal polarization fractions are measured using both muon and electron decays.

\[
\cos \theta_{2D} = \frac{\overrightarrow{p_T^{\ell^*}} \cdot \overrightarrow{p_T^W}}{|\overrightarrow{p_T^{\ell^*}}| \cdot |\overrightarrow{p_T^W}|}
\]
**W Polarization**

\[ W^+ : \sigma(\theta^*) \propto f_L \frac{(1 - \cos \theta^*)^2}{4} + f_o \frac{\sin^2 \theta^*}{2} + f_R \frac{(1 + \cos \theta^*)^2}{4} \]


CMS, \( \sqrt{s} = 7 \) TeV, \( L_{\text{int}} = 36 \) pb\(^{-1} \)

**Stat. Total**

\( W^- \)

7.8\( \sigma \)

\( f_0^+ \)

\( f_0^- \)

**ATLAS**

\( p_T^W > 50 \) GeV

\( \eta < 2.4, p_T^W > 20 \) GeV,

50 < \( m_W^* \) < 110 GeV,

W at high-\( P \) in pp are left-handed, as expected by SM
Enhanced Strange Contribution

\[ Q^2 = M_Z^2, \ x = 0.013 \]

- ABKM09
- NNPDF2.1
- MSTW08
- CT10 (NLO)

**ATLAS**

- total uncertainty
- experimental uncertainty
Limitations and NP Contributions to $M_W$

SM prediction of $M_W$ is good to only 10 MeV