W/Z Physics at CMS

Kristian Hahn  – MIT

High Energy Physics Seminar

University of Virginia
Jan 19, 2011
Introduction & Outline

- Focus of this talk: the first electron & muon-channel W/Z inclusive cross section and ratio measurements by CMS

- A simple expression for the cross sections …

\[ \sigma(pp \rightarrow \{W,Z\}) \times BR(\{\ell\nu,\ell\ell\}) = \frac{N_{\{W,Z\}}}{\alpha \varepsilon \int Ldt} \]

… but sophisticated treatments of the ingredients!

- Will address these in turn …
  - Detector
  - Selection & Efficiency
  - W & Z Signal Extraction
  - Results
Motivation

Why “rediscover” W and Z at the LHC?

- **New perspectives on familiar physics ...**
  - Cross sections ~4x larger than at Tevatron
    - $\sigma \times \text{BR}(W \rightarrow \ell \nu) \sim 10 \text{ nb per channel}$
    - $\sigma \times \text{BR}(Z \rightarrow \ell\ell) \sim 1 \text{ nb per channel}$
  - Larger sea-sea component, HERA-like low x
  - W production globally charge asymmetric
    - pp : 2x u-dbar collisions vs d-ubar due to valance quark content
    - Sea interactions dilute $W+/W-$ from 2 $\rightarrow$ ~1.4

- **CMS is a complex machine ...**
  - Develop experience with the detector, high-pT leptons & MET using W/Z
  - Verify expected performance on “familiar roads” now, avoid problems later!
History & Data Samples

- March: first pp collisions @ 7 TeV
- June: 37 nb\(^{-1}\), significant signals in all channels
- July 14: CMS approval for 78 nb\(^{-1}\) analysis. ~10% non-lumi precision
- July 20: Analysis updated to 198 nb\(^{-1}\) presented at ICHEP2010, July 22
  
  http://cdsweb.cern.ch/record/1279615

- Aug-Sept: 3 nb\(^{-1}\) collected, 10K W's, 1K Z's
- Oct-Nov: 3 nb\(^{-1}\) results complete, submitted to JHEP
  
  arXiv:1012.2466v2

- Dec: accepted for publication
- Present: 35 pb\(^{-1}\) precision measurements in-progress
CMS Detector

Pixels Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons

STEEL RETURN YOKE
~13000 tonnes

ZERO-DEGREE CALORIMETER

SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
76k scintillating PbWO₄ crystals

PRESHOWER
Silicon strips
~16m² 137k channels

CASTOR CALORIMETER
Tungsten + quartz plates

FORWARD CALORIMETER
Steel + quartz fibres

MUON CHAMBERS
Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

Pixels (100 x 150 µm²)
~1m² 66M channels
Microstrips (50-100µm)
~210m² 9.6M channels
Subsystems central to the W/Z analysis:

- **Silicon Tracker** – momentum measurements, direction, vertexing
  - ~10 M strip, 66 M pixel readout channels
- **Electromagnetic Calorimeter (ECAL)** – electron (& photon) energy
  - 76 K PbTO4 crystals
- **Muon Chambers** – muon identification
  - Drift Tubes, Cathode Strip, Resistive Plate
- **Trigger** – Level-1 (L1) and High-Level (HLT)
  - Hardware and low latency processing farm

Thorough commissioning → dividends to the analysis!

- Not easy, many obstacles overcome ...
- Ask about Tracker!
Integrated Luminosity

- Relative instantaneous luminosity from online HF occupancy
- Calibrated w/ absolute scale from Van der Meer scan for specific fills
  - Luminosity a function of beam separation (d), modeled as 2xGaussian
    \[
    \mathcal{L} = \mathcal{L}_0 \left( \frac{h_j}{\sqrt{2\pi}\sigma_{1j}} \exp \frac{-d^2}{2\sigma_{1j}^2} + \frac{(1-h_j)}{\sqrt{2\pi}\sigma_{2j}} \exp \frac{-d^2}{2\sigma_{2j}^2} \right)
    \]
  - Peak lumi (L0) depends on effective beam width
    \[
    \sigma_{\text{eff}}(j) = \left( \frac{\sigma_{1j}\sigma_{2j}}{h_j\sigma_{2j} + (1-h_j)\sigma_{1j}} \right)
    \]
  - N1, N2, ν, & Nb given, scan d and fit L vs. d to determine h, σ & L0
  - Uncertainty dominated by LHC beam currents (5% per beam, assumed correlated)

<table>
<thead>
<tr>
<th>Error</th>
<th>Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Background</td>
<td>0.1</td>
</tr>
<tr>
<td>Fit Systematics</td>
<td>1.0</td>
</tr>
<tr>
<td>Beam Shape</td>
<td>3.0</td>
</tr>
<tr>
<td>Scale Calibration</td>
<td>2.0</td>
</tr>
<tr>
<td>Zero Point Uncertainty</td>
<td>2.0</td>
</tr>
<tr>
<td>Beam Current Uncertainty</td>
<td>10.0</td>
</tr>
<tr>
<td>Total</td>
<td>11.0</td>
</tr>
</tbody>
</table>
• Large-sample Monte Carlo (MC) for Electroweak processes
  • Acceptances for signal & non-QCD backgrounds
  • $W$, $W$-background missing transverse energy (MET) & $Z$ mass shapes
  • Starting point for selection optimization
  • Initial efficiency estimates
    – Corrected with data-driven scale factors

• Baseline EWK MC generation
  • POWHEG NLO + CTEQ 6.6 (NLO)
  • PYTHIA showering
  • Tauola for $W$ & $Z$ tau-channel BGs
  • Full GEANT4 simulation

• Additional tools employed for systematics
Data handling/processing in CMS is necessarily *distributed*

- MC generated at 51 international computing sites (T2's)
- Data and MC reprocessed at 7 national computing centers (T1's), transferred to T2's/T3's for analysis
  - Prompt reconstruction direct from CERN generally not used in CMS analysis
  - Data for W/Z underwent multiple reprocessing passes with updated alignments and calibrations

DataOps a very active project in CMS!

- And *challenging*: lots of data/MC to process, many places for problems to arise
- Infrastructure, software, production tools and operators all must work seamlessly

Example, 2010 statistics
- 3.1 B MC events (2.2 PB) generated
- 10 B data events (1.6 PB) reprocessed
Offline Reconstruction : Muons & Tracks

- Tracking a challenge in a dense detector environment ...
  - Lots of Tracker material → bremsstrahlung
  - Specialized tracking algorithm addressed this
    - Baseline : Gaussian model of energy loss
    - More accurately w/ a Gaussian mixture
    - “Gaussian Sum Filter” (GSF) used for eles

- Muon reconstruction
  - Two primary categories of muons in CMS
    - Track matched to muon detector segment (“tracker-only”)
    - Hits from track and segment re-fit into a global muon track
  - Use candidates that have been reconstructed by both methods
    - But utilize kinematics from the tracker-only muons
    - Global tracking improves kinematics only at very high-pT
    - But requiring both methods reduces backgrounds
Offline Reconstruction: Electrons

- **Electron reconstruction**
  - Candidates are a combination of GSF tracks and SuperClusters
    - electrons/photons deposit most energy in clusters, 5x5 crystals
    - Bremsstrahlung → multiple clusters spread in phi
    - Combine cluster into SuperCluster, recover incident energy
  - GSF tracking driven from an ECAL SuperCluster seed
    - ECAL Seed Et > 4 GeV
    - Add pixel hits from position of energy weighted cluster sum
      - Gives incident direction before radiation
    - We use energy from ECAL, direction from track

- **Post-reconstruction corrections**
  - Spike removal: Anomalous ECAL noise
    - Veto if \( \Sigma (\text{adjacent energy})/\text{energy} < 5\% \)
  - Additional Endcap alignment corrections
Offline Reconstruction : Missing Energy

- **Three types of missing Energy (MET) reconstruction**
  1) Purely calometric: negative vector sum of deposits in all towers
  2) Track-corrected: assume all tracks are pions. Corrections to energy deposits using track pT
  3) Particle-flow: MET calculated from full reconstruction of all stable particles in the event

- **Significant improvements in resolution from corrected MET**
  - TC & PF performance essentially equivalent for $W \rightarrow l\nu$
  - PFMET part of a comprehensive reconstruction routine
    - Key benefits to jet and tau reconstruction
  - We utilize PF MET in the W analyses
Lepton and Event Selection
Muon Selection: Online

- **L1 muon trigger**
  - Muon segment finding with DT & CSC, $\sigma(p_T)/p_T \sim 20\%$
  - RPC adds 1ns timing info, locates BX
  - Arbitration performed, highest $p_T$ segments passed to HLT

- **HLT: first-pass muon reconstruction**
  - Performs regional tracking using L1 inputs
  - Tracking algorithms simple, must balance precision and speed
  - Some information not available (PV)

- **A single trigger path used for W/Z**
  - L1 $p_T > 4$ GeV
  - HLT $p_T > 9$ GeV, no isolation

- **Muon “Pre-triggering”**
  - Trigger timing not exact in early 2010, sometimes trigger wrong event
  - Impacts 1% of barrel muons only, accounted for in efficiency
Muon Selection: Offline

- Kinematic and event selection
  \[ Z \rightarrow \mu\mu \]
  - 2 reconstructed \( \mu \)'s, \( p_T > 20 \text{ GeV} \)
  - \( |\eta| < 2.1 \), 2\textsuperscript{nd} \( \mu \) in \( |\eta| < 2.4 \)
  - 60 GeV < \( M_{\mu\mu} \) < 120 GeV
  - Opposite charge

- Quality Requirements
  - \( \geq 10 \) tracker hits, \( \geq 1 \) pixel hits
  - \( \geq 2 \) muon stations matched to track
  - Both Inside-out & outside-in reconstruction
  - \( \chi^2/\text{ndf} < 10 \) from global fit
  - Cosmic veto, \( d_0 < 2 \text{ mm} \)

- Combined Relative Isolation
  \[
  I_{\text{comb}}^{\text{rel}} = \left\{ \frac{\sum(p_T(\text{tracks}) + E_T(\text{em}) + E_T(\text{had}))}{p_T(\mu)} \right\} < 0.15
  \]

- \( W \rightarrow \mu\nu \)
  - 1 reconstructed \( \mu \), \( p_T > 20 \text{ GeV} \)
  - Veto if 2\textsuperscript{nd} \( \mu \), \( p_T > 10 \text{ GeV} \)
  - \( |\eta| < 2.1 \)

\[ W/Z \text{ Physics } @ \text{ CMS} \]

01/19/11
Electron Selection : Online

- **L1 Calorimeter triggers**
  - Form pairs of Calo towers, send most energetic to HLT
  - Coarse isolation also calculated

- **Electron and Photon HLT**
  - Start with ECAL seeds from L1
    - Prompt calibration of ECAL scale, sigma(ET)/ET ~
  - If matching pixel hits then follow electron path, else γ
    - Electron reconstruction algorithms similar to offline

- **Run-dependent trigger selection for W/Z**
  - Needed to reduce rate as LHC intensity improved
    - Runs 132440-137028: HLT_Photon10_L1R
    - Runs 138564-140401: HLT_Photon15_Cleaned_L1R
    - Runs 141956-144114: HLT_Ele15_SW_CaloEleId L1R
  - Tried to avoid electron HLT for as long as possible …
    - Alignment concerns could complicate measurement of $\varepsilon_{\text{trg}}$

Cuts on Calorimeter quantities only
• Kinematic & event selection
  \( Z \rightarrow ee \)
  - 2 reco ele's, \( p_T > 20 \text{ GeV} \)
  - \( |\eta| < 2.1 \), 2\textsuperscript{nd} ele in \( |\eta| < 2.4 \)
  - No opposite charge requirement
  - \( 60 \text{ GeV} < M_{ee} < 120 \text{ GeV} \)

• Identification: 2 sets of “working points” (WP), each split into Barrel and Endcap
  - \( Z \) originally WP95, later tightened to WP80

<table>
<thead>
<tr>
<th></th>
<th>WP95</th>
<th>WP80</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Barrel</td>
<td>Endcap</td>
</tr>
<tr>
<td>( I_{\text{trk}}/E_T )</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>( I_{\text{ECAL}}/E_T )</td>
<td>2.0</td>
<td>0.06</td>
</tr>
<tr>
<td>( I_{\text{HCAL}}/E_T )</td>
<td>0.12</td>
<td>0.05</td>
</tr>
<tr>
<td>Missing hits ≤</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Dcot</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Dist</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( \sigma_{i\eta_i} )</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>( \Delta \phi_{i\eta_i} )</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>( \Delta \eta_{i\eta_i} )</td>
<td>0.007</td>
<td>–</td>
</tr>
<tr>
<td>( H/E )</td>
<td>0.15</td>
<td>0.07</td>
</tr>
</tbody>
</table>

- Separate relative isolations
- Conversion rejection: inner hit requirements & partner track
- Cuts on shower shape, track/cluster matching, and energy confinement
Electron Selection: Offline (2)

- **WorkingPoint ID optimization**
  - Initially with W & QCD simulation
    - Iterative procedure, treats each variable individually, then together
  - Later, with data ...
    - BG sample: MET < 15 GeV
    - Signal: MET > 30 GeV
    - Algorithm robust against small levels of signal/background contamination

- **More sophisticated ID techniques under study**
  - Cuts categorized by E/P
  - Multivariate Methods
    - Likelihood
    - Neural Net
    - K-Nearest Neighbor (kNN)
Signal Acceptance

- What fraction of delivered signal events end up in our data sample?
  - 1\textsuperscript{st} stage of event rejection (acceptance) from limited detector geometry
  - Subsequent stages from high-quality lepton requirements (efficiency)

- **Signal acceptance (α)** from kinematic selection applied to MC
  - Primarily theoretical, compartmentalizes assoc. uncertainties
  - Dedicated studies explore effects not captured by baseline MC
    - Effects are small, taken as systematic uncertainty

\[
\sigma \times Br = \frac{N_{(W,Z)}}{\alpha \varepsilon \int L dt}
\]

<table>
<thead>
<tr>
<th>EWK &amp; FSR</th>
<th>HORACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDFs</td>
<td>CTEQ, MSTW, NNPDF</td>
</tr>
<tr>
<td>Higher-order corrections &amp; ISR</td>
<td>ResBos for missing NNLO FEWZ for beyond NNLO</td>
</tr>
<tr>
<td>$\alpha_s$ scaling</td>
<td>ResBos</td>
</tr>
</tbody>
</table>
Signal Acceptance : Electrons

- $\alpha^{\text{ECAL}}$: fraction of generated events with fiducial ECAL supercluster(s) passing kinematic selection
  - Separate into ECAL Barrel (EB : $|\eta| < 1.44$) and Endcap (EE: $1.57 < |\eta| < 2.5$)
  - SuperCluster $E_T > 20$ GeV
  - Zee : $60 \text{ GeV} < M_{ee} < 120 \text{ GeV}$

- Theory uncertainties are on order 1-2%
  - Take half of max. spread after re-weighting with various PDF sets
  - Other effects studied with dedicated programs

<table>
<thead>
<tr>
<th>Source</th>
<th>$W^+ \rightarrow e\nu$</th>
<th>$W^- \rightarrow e\nu$</th>
<th>$Z \rightarrow ee$</th>
<th>$W^+/W^-$ $(e)$</th>
<th>$Z/W$ $(e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD-HO and ISR</td>
<td>-1.30%±0.09</td>
<td>-0.78%±0.10</td>
<td>±0.6%</td>
<td>0.56%±0.13</td>
<td>0.47%±0.17</td>
</tr>
<tr>
<td>QCD-$\alpha_s$ scaling</td>
<td>0.23%±0.22</td>
<td>0.37%±0.32</td>
<td>±1.1%</td>
<td>1.13%±0.63</td>
<td>0.57%±0.52</td>
</tr>
<tr>
<td>FSR</td>
<td>0.08%±0.17</td>
<td>0.07%±0.19</td>
<td>-0.11%±0.24</td>
<td>0.15%±0.27</td>
<td>-0.10%±0.30</td>
</tr>
<tr>
<td>EWK</td>
<td>0.07%±0.13</td>
<td>0.21%±0.19</td>
<td>-0.47%±0.22</td>
<td>0.00%±0.27</td>
<td>-0.70%±0.29</td>
</tr>
<tr>
<td>Total</td>
<td>1.33%</td>
<td>0.90%</td>
<td>1.34%</td>
<td>1.27%</td>
<td>1.03%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Syst. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+$ acceptance $(e)$</td>
<td>0.9</td>
</tr>
<tr>
<td>$W^-$ acceptance $(e)$</td>
<td>1.5</td>
</tr>
<tr>
<td>$W$ acceptance $(e)$</td>
<td>0.8</td>
</tr>
<tr>
<td>$Z$ acceptance $(e)$</td>
<td>1.1</td>
</tr>
<tr>
<td>$W^+/W^-$ correction $(e)$</td>
<td>1.7</td>
</tr>
<tr>
<td>$W/Z$ correction $(e)$</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Signal Acceptance : Muons

- \( \alpha^\mu \): fraction of generated events with generator-level muon(s) passing kinematic selection
  - Generator \( p_T > 20 \text{ GeV} \)
  - Calculated after FSR
  - \( W : |\eta| < 2.1 \)
  - \( Z : 60 \text{ GeV} < M_{\mu\mu} < 120 \text{ GeV}, |\eta| < 2.1, 2.5 \)

- Theory uncertainties are on order 1-2%
  - Take half of max. spread after re-weighting with various PDF sets
  - Other effects studied with dedicated programs

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Syst. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W^+ ) acceptance (( \mu ))</td>
<td>1.3</td>
</tr>
<tr>
<td>( W^- ) acceptance (( \mu ))</td>
<td>1.9</td>
</tr>
<tr>
<td>( W ) acceptance (( \mu ))</td>
<td>1.1</td>
</tr>
<tr>
<td>( Z ) acceptance (( \mu ))</td>
<td>1.2</td>
</tr>
<tr>
<td>( W^+/W^- ) correction (( \mu ))</td>
<td>2.1</td>
</tr>
<tr>
<td>( W/Z ) correction (( \mu ))</td>
<td>1.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>( W^+ \rightarrow \mu\nu )</th>
<th>( W^- \rightarrow \mu\nu )</th>
<th>( Z \rightarrow \mu^+\mu^- )</th>
<th>( W^+/W^- ) (( \mu ))</th>
<th>( Z/W ) (( \mu ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD-HO and ISR</td>
<td>-1.39%±0.09</td>
<td>-1.17%±0.14</td>
<td>±0.6%</td>
<td>0.22%±0.17</td>
<td>0.70%±0.18</td>
</tr>
<tr>
<td>QCD-( \alpha_s ) scaling</td>
<td>0.23%±0.22</td>
<td>0.37%±0.32</td>
<td>±1.1%</td>
<td>1.13%±0.63</td>
<td>0.57%±0.52</td>
</tr>
<tr>
<td>FSR</td>
<td>0.11%±0.12</td>
<td>0.01%±0.17</td>
<td>0.38%±0.24</td>
<td>-0.08%±0.19</td>
<td>0.15%±0.27</td>
</tr>
<tr>
<td>EWK</td>
<td>-0.02%±0.12</td>
<td>0.26%±0.17</td>
<td>-1.02%±0.24</td>
<td>0.28%±0.19</td>
<td>-0.98%±0.24</td>
</tr>
<tr>
<td>Total</td>
<td>1.42%</td>
<td>1.26%</td>
<td>1.58%</td>
<td>1.19%</td>
<td>1.35%</td>
</tr>
</tbody>
</table>
Efficiencies

- **Trigger, identification & isolation requirements lead to additional event loss**
  - Relevant efficiencies also determined with MC, $\varepsilon^{MC}$
  - BUT, do not expect simulation perfectly models data!
- **Correct $\varepsilon^{MC}$ with data-driven scale factors**, $\rho_i = \frac{\varepsilon_{Data}^i}{\varepsilon_{MC}^i}$
  - Eg: total single-lepton efficiency:
    - $\varepsilon^{MC\,reco} \varepsilon^{MC\,ID} \varepsilon^{MC\,trig} \rho_{reco} \rho_{ID} \rho_{trig}$
- **Determine $\rho_i$ using Z-based “tag & probe” technique**
  - Z selection: tight requirements on one leg (probe) + $60 < M_{\ell\ell} < 120$ GeV
  - Uncorrelated requirements on other leg (probe), apply selection
  - Could obtain efficiencies from counting after BG subtraction ...
  - Better, from simultaneous $M_{\ell\ell}$ fit to passing & failing samples
    - Exploits additional shape information
    - Benefits for assessing correlated uncertainties

\[
\sigma \times \text{Br} = \frac{N_{(W,Z)}}{\alpha \varepsilon \int L dt}
\]
Efficiencies : Electrons

- **Tag & Probe**
  - Tag always a WP80 electron
  - Signal shapes : MC or analytic
  - Background modeled as exp x polynomial

- \( \varepsilon_{\text{reco}} \) : SuperCluster \( \rightarrow \) GSF track
  - Background most significant for this \( \varepsilon \)
  - Probe: Supercluster with loose H/E, shower-shape and Iso\textsubscript{ECAL} cuts
  - Results cross-checked w/ MC BG template

- \( \varepsilon_{\text{ID}} \) : GSF track \( \rightarrow \) ele passing WP cuts
  - Probe : Reco electron candidate
  - Check w/ MC BG template, SS/OS method

- \( \varepsilon_{\text{ID}} \) : ID'ed ele \( \rightarrow \) trigger match
  - Probe : electron passing ID
  - No bg left at this stage, simple counting
  - Checked using ECAL activity trigger
### Efficiencies : Electrons

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Data</th>
<th>Simulation</th>
<th>Data/Simulation ($\rho_{eff}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{TNP-REC}}$</td>
<td>(98.6 ± 0.5) %</td>
<td>98.50%</td>
<td>1.001 ± 0.005</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-WF80}}$</td>
<td>(79.1 ± 1.8) %</td>
<td>85.50%</td>
<td>0.925 ± 0.021</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-WF95}}$</td>
<td>(93.9 ± 1.5) %</td>
<td>96.4%</td>
<td>0.974 ± 0.016</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-TRG80}}$</td>
<td>(98.9 ± 0.3) %</td>
<td>99.70%</td>
<td>0.992 ± 0.003</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-TRG95}}$</td>
<td>(98.7 ± 0.2) %</td>
<td>99.4%</td>
<td>0.992 ± 0.002</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-WF80-ALL}}$</td>
<td>(77.1 ± 1.8) %</td>
<td>83.9%</td>
<td>0.919 ± 0.022</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-WF95-ALL}}$</td>
<td>(91.3 ± 1.5) %</td>
<td>94.4%</td>
<td>0.967 ± 0.016</td>
</tr>
</tbody>
</table>

#### EB

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Data</th>
<th>Simulation</th>
<th>Data/Simulation ($\rho_{eff}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{TNP-REC}}$</td>
<td>(96.2 ± 0.8) %</td>
<td>96.3%</td>
<td>0.999 ± 0.009</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-WF80}}$</td>
<td>(69.2 ± 2.0) %</td>
<td>74.9%</td>
<td>0.924 ± 0.027</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-WF95}}$</td>
<td>(90.3 ± 1.9) %</td>
<td>93.9%</td>
<td>0.962 ± 0.020</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-TRG80}}$</td>
<td>(99.2 ± 0.5) %</td>
<td>98.80%</td>
<td>1.003 ± 0.005</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-TRG95}}$</td>
<td>(99.16 ± 0.02) %</td>
<td>97.7%</td>
<td>1.015 ± 0.0003</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-WF80-ALL}}$</td>
<td>(66.0 ± 2.0) %</td>
<td>71.3%</td>
<td>0.926 ± 0.028</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TNP-WF95-ALL}}$</td>
<td>(86.1 ± 1.9) %</td>
<td>88.3%</td>
<td>0.975 ± 0.022</td>
</tr>
</tbody>
</table>

- Trigger and Reco efficiency well modeled in MC
- ID efficiency less so
  - Some alignment discrepancies persist after post-hoc corrections
- Single electron $\varepsilon$ & $\rho$
- $\varepsilon$ & $\rho$ as used in the analysis, acceptance weighted
- **Background Model**
  - Consider power-law \(1/M^\alpha\) as alternative model to exponential
  - Fix \(\alpha\) to value found from fit to dijet data and generate pseudo-experiments
  - Fit each trial with exponential, measure bias

- **Energy Scale /Resolution**
  - Scale corrections discussed on next slide
  - Apply corrections \(\pm\) uncertainties to the MC, measure difference in yield

- **Signal Shape**
  - Extend Mee window to include more of the low mass tail, 50-120 GeV
  - Construct data-driven signal shapes by tightening selection on Tag+Fail
    - Fit with these templates, difference w.r.t nominal fit is the systematic

<table>
<thead>
<tr>
<th>Source</th>
<th>% (\varepsilon_{\text{reco}})</th>
<th>% (\varepsilon_{\text{reco-WP95}})</th>
<th>% (\varepsilon_{\text{reco-WP80}})</th>
<th>% (\varepsilon_{\text{WP80-HLT}})</th>
<th>% (\varepsilon_{\text{WP80-HLT}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background Model</td>
<td>0.06</td>
<td>0.25</td>
<td>0.24</td>
<td>0.01</td>
<td>&lt; 0.00</td>
</tr>
<tr>
<td>Energy Scale</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>&lt; 0.00</td>
<td>0.1</td>
</tr>
<tr>
<td>Signal Shape</td>
<td>1.2</td>
<td>1.0</td>
<td>2.0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Muon Tag & Probe

- Technique somewhat more involved than for electrons ...
- Multicategory simultaneous fit for all efficiencies and signal yield

\[
N_{\mu\mu}^{2\text{HLT}} = N_{Z\rightarrow\mu\mu} + \epsilon_{\text{HLT}}^2 \epsilon_{\text{iso}}^2 \epsilon_{\text{trk}}^2 \epsilon_{\text{sa}}^2,
\]
\[
N_{\mu\mu}^{1\text{HLT}} = 2N_{Z\rightarrow\mu\mu} - \epsilon_{\text{HLT}}^2 (1 - \epsilon_{\text{HLT}}) \epsilon_{\text{iso}}^2 \epsilon_{\text{trk}}^2 \epsilon_{\text{sa}}^2,
\]
\[
N_{\mu s} = 2N_{Z\rightarrow\mu\mu} - \epsilon_{\text{HLT}}^2 \epsilon_{\text{iso}}^2 \epsilon_{\text{trk}}^2 \epsilon_{\text{sa}}^2 (1 - \epsilon_{\text{sa}}),
\]
\[
N_{\mu t} = 2N_{Z\rightarrow\mu\mu} - \epsilon_{\text{HLT}}^2 \epsilon_{\text{iso}}^2 \epsilon_{\text{trk}}^2 \epsilon_{\text{sa}}^2 (1 - \epsilon_{\text{sa}}),
\]
\[
N_{\mu\mu}^{\text{non iso}} = N_{Z\rightarrow\mu\mu} - (1 - (1 - \epsilon_{\text{HLT}})^2) (1 - \epsilon_{\text{iso}}^2) \epsilon_{\text{trk}}^2 \epsilon_{\text{sa}}^2.
\]

- Quality criteria subsumed into \(\epsilon_{\text{trk}}\) and \(\epsilon_{\text{sa}}\) in this formulation
- Signal PDF: shape from 1 & 2 HLT categories, background free
- Background PDF: Polynomial x exponential for \(N_{\mu s}, N_{\mu s}, N_{\mu\mu}^{\text{non iso}}\)

- Correctly accounts for correlations between \(N_{Z\rightarrow\mu\mu}\) and \(\epsilon's\)
Efficiencies : Muons

- Binned Maximum Log Likelihood fit for $\varepsilon$'s and $N_{Z \to \mu\mu}$
  - Reformulate logL as (Poisson) Likelihood ratio
  - Distributed as $\chi^2$ for large $N$

\[
\chi^2 = \frac{(N_{\mu\mu}^{2\text{HLT}} - N_{Z \to \mu+\mu-} - \varepsilon_{\text{HLT}}^2 \varepsilon_{\text{iso}}^2 \varepsilon_{\text{trk}}^2 \varepsilon_{\text{sa}}^2)^2}{N_{\mu\mu}^{2\text{HLT}}} + \frac{(N_{\mu\mu}^{1\text{HLT}} - 2N_{Z \to \mu+\mu-} - \varepsilon_{\text{HLT}}(1 - \varepsilon_{\text{HLT}}) \varepsilon_{\text{iso}}^2 \varepsilon_{\text{trk}}^2 \varepsilon_{\text{sa}}^2)^2}{N_{\mu\mu}^{1\text{HLT}}} + \chi_{\text{trigger}}^2 + \chi_{\mu\mu}^2 + \chi_{\text{non iso}}^2
\]

- Extract best-fit values by minimizing a global $\chi^2$

- Systematic Uncertainties
  - Background modeling contributes 1%
  - Zero background assumption for 1 & 2 HLT : 0.2%

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>Data</th>
<th>Simulation</th>
<th>Data/Simulation ($\rho_{\text{eff}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_{\text{SA}}$</td>
<td>(96.4 ± 0.5) %</td>
<td>97.2%</td>
<td>0.992 ± 0.005</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TRK}}$</td>
<td>(99.1 ± 0.4) %</td>
<td>99.3%</td>
<td>0.998 ± 0.003</td>
</tr>
<tr>
<td>$\varepsilon_{\text{SEL}}$</td>
<td>(99.7 ± 0.3) %</td>
<td>99.7%</td>
<td>1.000 ± 0.003</td>
</tr>
<tr>
<td>$\varepsilon_{\text{ISO}}$</td>
<td>(98.5 ± 0.4) %</td>
<td>99.1%</td>
<td>0.994 ± 0.004</td>
</tr>
<tr>
<td>$\varepsilon_{\text{TRG}}$</td>
<td>(88.3 ± 0.8) %</td>
<td>93.2%</td>
<td>0.947 ± 0.009</td>
</tr>
<tr>
<td>Net ($W$)</td>
<td>(82.8 ± 1.0) %</td>
<td>88.7%</td>
<td>0.933 ± 0.012</td>
</tr>
</tbody>
</table>

- Largest data/MC scale factor for trigger
  - Known L1 inefficiencies
  - Imperfect modeling of HLT seeding
Z & W Signal Extraction
Electrons $p_T = 34.0, 31.9$ GeV/c
Inv. mass = 91.2 GeV/c$^2$

Muon $p_T = 67.3, 50.6$ GeV/c
Inv. mass = 93.2 GeV/c$^2$
Z→μμ Signal Extraction: Results

- Yield from simultaneous fit, as discussed
- Event selection for the “golden” category
  - 2 opposite-Q muons passing ID
  - At least one passing trigger
  - 60 GeV < M_{μμ} < 120 GeV
- Yield in the “golden” category
  - Yield : 913
  - Expected Signal: 950

\[ \sigma \times Br = \frac{N_{\{W, Z\}}}{\alpha \varepsilon \int L dt} \]

<table>
<thead>
<tr>
<th>source</th>
<th>fraction</th>
<th>( N_{\text{est}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD multi-jet</td>
<td>negl.</td>
<td>0.048 ± 0.002</td>
</tr>
<tr>
<td>W → μν</td>
<td>negl.</td>
<td>0.03 ± 0.03</td>
</tr>
<tr>
<td>t¯t</td>
<td>(0.12 ± 0.01)%</td>
<td>1.19 ± 0.10</td>
</tr>
<tr>
<td>Z → τ⁺τ⁻</td>
<td>(0.05 ± 0.01)%</td>
<td>0.52 ± 0.07</td>
</tr>
<tr>
<td>WZ</td>
<td>(0.08 ± 0.01)%</td>
<td>0.82 ± 0.09</td>
</tr>
<tr>
<td>WW</td>
<td>(0.03 ± 0.01)%</td>
<td>0.31 ± 0.05</td>
</tr>
<tr>
<td>ZZ</td>
<td>(0.06 ± 0.01)%</td>
<td>0.55 ± 0.12</td>
</tr>
<tr>
<td>total</td>
<td>(0.37 ± 0.02)%</td>
<td>3.48 ± 0.18</td>
</tr>
</tbody>
</table>

EWK backgrounds normalized to Z signal template

CMS 2010

2.9 pb⁻¹ @ \( \sqrt{s} = 7 \) TeV
Z→ee Signal Extraction

- **Electroweak backgrounds estimated from MC**
  - Normalized to signal via NLO cross sections, \( N_{EWK} = 2.4 \)

- **Several estimates for contributions from W+j, p+j, QCD multijets**
  - **“Fake Rate”**
    - Find rates for jets in dijet samples to pass full selection
    - Apply to electron + jet events in signal sample
    - \( N_{QCD} = 0.4 \pm 0.4 \text{ (sys + stat)} \)
  - **Same-Sign/Opposite-Sign**
    - Infer QCD background from same-sign events and charge misID
    - Charge misID measured from Z using tighter ID cuts
    - \( N_{QCD} = 0.0 \pm 7.5 \text{ (stat) } \pm 1.3 \text{ (sys)} \)
  - **Isolation template fit**
    - Shapes from \( M_{ee} \) side and Z peak with tighter ID
    - \( N_{QCD} = 2.1 \pm 4.6 \text{ (stat) } \pm 0.1 \text{ (sys)} \)

- **Use 0.4 ± 0.4 for the final estimate (expect 0.0 from MC)**
Z→ee Signal Extraction: Results

- Event selection
  - 2 WP80 e's
  - ≥ 1 passing trigger
  - 60 GeV < M_{ee} < 120 GeV
  - No opposite charge requirement

- Yields
  - Observed: 677
  - Signal: 674 ± 26

<table>
<thead>
<tr>
<th>source</th>
<th>fraction</th>
<th>N_{est}</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD multi-jet</td>
<td>0.06%</td>
<td>0.4 ± 0.4</td>
</tr>
<tr>
<td>Z → τ^+τ^- (MC)</td>
<td>0.11%</td>
<td>0.77</td>
</tr>
<tr>
<td>di-boson production (MC)</td>
<td>0.12%</td>
<td>0.76</td>
</tr>
<tr>
<td>t\bar{t} (MC)</td>
<td>0.11%</td>
<td>0.83</td>
</tr>
<tr>
<td>EWK (MC)</td>
<td>0.35%</td>
<td>2.36</td>
</tr>
<tr>
<td>total</td>
<td>0.41%</td>
<td>2.8 ± 0.4</td>
</tr>
</tbody>
</table>
Electron $p_T = 35.6$ GeV/c
$M_{E_T} = 36.9$ GeV
$M_T = 71.1$ GeV/c$^2$

Muon $p_T = 38.7$ GeV/c
$M_{E_T} = 37.9$ GeV
$M_T = 75.3$ GeV/c$^2$
MET a basis for signal extraction for both e & μ

- Though some differences in approach ...

Muons : extraction utilizes transverse mass (MT)

$$M_T = \sqrt{2p_T(\mu)E_T(1 - \cos(\Delta\phi_{\mu,E_T}))}$$

- Binned maximum likelihood template fit
  - Signal MT shapes from data-corrected MC
  - Background shape from cut inverted sample (w/ corrections)

- Fit simultaneously for W+, W- and inclusive yields

Electrons : employs MET distribution directly

- Unbinned maximum likelihood “hybrid” fit
  - Signal MET shape from corrected MC
  - Background shape : Analytic function

- Perform fit for inclusive yield and simultaneous fit for W+, W-
W Shape Corrections : Recoil

- Poor agreement for $W \to l\nu$ out of the box …
  - MC MET /MT shapes must be corrected for:
    - Lepton energy/momentum scale
    - Calorimeter response/resolution
    - Pileup and underlying event
- All addressed via the “recoil method”
  - Produces an improved, “best-fit” $W \to e/\nu$ signal template

- Recoil vector ($u$) defined as MET after subtracting off the electron(s)
  - With PFMET, subtract using SC energy
  - Recoil components $u_1, u_2$ parallel/perpendicular to boson $q_T$ axis
  - Calculate $u_1, u_2$ for Z MC, Z data and W MC

![Graph showing CMS preliminary 2010 results with data, W, EWK, QCD distributions]
- Model components with Gaussians in qT
  - Fit response (mean) and resolution (width) in qT with 2\(^{nd}\) order polynomials
  - Determine Z data/MC scale factors to correct W MC response/resolution
- Recalculate MET for each W MC event
  - Again, subtract off the electron electron
  - Sample u1/u2 distributions, parameters from scaled W MC curves
  - Add the lepton energy/momentum back to obtain corrected MET
W Shape Corrections : Energy Scale

- Lepton energy/momentum also summed in the MET calculation
  - This must also be calibrated against data ...
- Electrons - energy scale & resolution correction factors from Z's
  - Scale and smear MC electron energy with Gaussian probability function
    \[ E_{\text{new}} = \text{Gaus}(\alpha E_{\text{old}}, \beta) \]
  - Scan ranges of \( \alpha \) and \( \beta \), apply to reco MC
  - Calculate a new Mee in MC, fit to data, store -log(L) at each step
    - Results in a grid of -log(L) values vs \( \alpha \) and \( \beta \)
  - Likelihood from fit approx. Gaussian in vicinity of maximum
    - Fit a 2D parabola to the minimum of -log(L)
    - This determines most probable scale factors
    - Stat. uncertainties from \[ [-\frac{\partial^2 \ell}{\partial \alpha^2}]^{-1/2} \]

\[ \text{MET} \]
• Overall corrected MC shape: use scaled/smeared MC electrons when adding to corrected recoil
  • 1% shift in EB, 3% in EE
  • Smearing by 1-2 GeV
• Similar procedure for muons ...
  • Muon pT scale/resolution found to be adequate in MC
  • Use only for systematic bound: 0.4%
W→eν Background Model

- Unbinned EML fit w/ static signal & parametrized background shape
  - Signal + EWK backgrounds : POWHEG
  - QCD background : Functional form from first principles ...
    - Rayleigh distribution: magnitude of vector w/ independent Gaussian components
      \[ f(x) = C x \exp \left( -\frac{x^2}{2(\sigma_0 + x\sigma_1)^2} \right) \]
    - Tail parameter \( \sigma_1 \) for \( \Sigma E_T \) dependence
    - And for real MET from b/c decays

- Validate background model with cut-inverted data samples
  - \( \text{Iso}_{\text{Trk}} \) & \( \Delta\phi \) least correlated w/ MET
  - Also used to assess modeling uncertainty
W→ev Extraction : Results

- Selected Events : 28601
- Extracted Yield : 11895 ± 115
- KS Probability : 0.49

This fit performed with an inclusive W template

<table>
<thead>
<tr>
<th>source</th>
<th>$N_{bkg}/N_W$</th>
<th>how estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD multi-jet + $\gamma$-jet</td>
<td>$\sim 1.3$</td>
<td>from UML fit</td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^- + Z \rightarrow \tau^+\tau^-$</td>
<td>8.3%</td>
<td>MC</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>4.5%</td>
<td>MC</td>
</tr>
<tr>
<td>di-boson production</td>
<td>0.13%</td>
<td>MC</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.4%</td>
<td>MC</td>
</tr>
<tr>
<td>EWK</td>
<td>13.3%</td>
<td>MC</td>
</tr>
</tbody>
</table>
$W \rightarrow e \nu$ Extraction: Results (2)

- $e^+$ events obs.: 15859
- $7193 \pm 89$
- KS Prob.: 0.39

- $e^-$ events obs.: 12742
- $4728 \pm 73$
- KS Prob.: 0.53

This simultaneous fit performed with $W^+$ & $W^-$ templates.
W→eν Extraction Systematics

- **Signal shape**: propagate recoil model & energy scale uncertainties to MET & MT
  - This gives fluctuated shapes w.r.t. that determined from best-fit parameters
  - Perform pseudo-experiments, generate with fluctuated shapes, fit with nominal
  - \( \sigma(\text{recoil}) : 1.8\% \), \( \sigma(\text{scale}) : 2.0\% \)

- **Background model**
  - Add an additional power to the model tail, \( \sigma_x^2 \)
  - Constrain parameter to largest value found among anti-selected data, anti-selected MC, selected MC
  - Use this shape for generation of pseudo-experiments, fit w/ nominal
  - \( \sigma(\text{background}) : 1.3\% \)
W→μν Background Model

- Expect MC to describe QCD only qualitatively
- Better description from sample with isolation requirement inverted
  - Signal contamination negligible here
- But MT and Isolation are correlated …
  - Hadronic activity decreases isolation, increases SumET, influences MET

- Determine needed MET correction from behavior in iso-inverted sample
  - MET → MET/(1+axIso), a ~ 0.2
  - Largest spread among 3 predictions as systematic
**W→μν Extraction : Results**

- $\mu^+$ events obs. : 10682
- W Yield : $7445 \pm 87$

- $\mu^-$ events obs. : 7889
- W Yield : $4812 \pm 68$

- $\mu$ events Obs. : 18571
- W Yield : $12257 \pm 111$

- **W+ & W- yields extracted from a simultaneous fit**
  - Total W yield and ratio follow as a result
Measurements of Inclusive W and Z Cross Sections  
in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

Abstract

Measurements of inclusive W and Z boson production cross sections in pp collisions at $\sqrt{s} = 7$ TeV are presented, based on 2.9 pb$^{-1}$ of data recorded by the CMS detector at the LHC. The measurements, performed in the electron and muon decay channels, are combined to give $\sigma(pp \rightarrow WX) \times \mathcal{B}(W \rightarrow \ell\nu) = 9.95 \pm 0.07^{\text{stat}} \pm 0.26^{\text{syst}} \pm 1.09^{\text{lumi}}$ nb and $\sigma(pp \rightarrow ZX) \times \mathcal{B}(Z \rightarrow \ell^+\ell^-) = 0.93 \pm 0.026^{\text{stat}} \pm 0.023^{\text{syst}} \pm 0.015^{\text{lumi}}$ nb, where $\ell$ stands for either e or $\mu$. Theoretical predictions, calculated at the next-to-next-to-leading order in QCD using recent parton distribution functions, are in agreement with the measured cross sections. Ratios of cross sections, which incur an experimental systematic uncertainty of less than 4%, are also reported.

Submitted to the Journal of High Energy Physics
<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma \times B$ (nb)</th>
<th>NNLO (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$ e$\nu$</td>
<td>10.04 ± 0.10 (stat.) ± 0.52 (syst.) ± 1.10 (lumi.)</td>
<td>10.44 ± 0.52</td>
</tr>
<tr>
<td>$W$ $\mu$</td>
<td>9.92 ± 0.09 (stat.) ± 0.31 (syst.) ± 1.09 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>$W$ $\ell$</td>
<td>9.95 ± 0.07 (stat.) ± 0.28 (syst.) ± 1.09 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>$W^+$ e$^+\nu$</td>
<td>5.93 ± 0.07 (stat.) ± 0.36 (syst.) ± 0.65 (lumi.)</td>
<td>6.15 ± 0.29</td>
</tr>
<tr>
<td>$W^+$ $\mu^+\nu$</td>
<td>5.84 ± 0.07 (stat.) ± 0.18 (syst.) ± 0.64 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>$W^+$ $\ell^+\nu$</td>
<td>5.86 ± 0.06 (stat.) ± 0.17 (syst.) ± 0.64 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>$W^-$ e$^-\bar{\nu}$</td>
<td>4.14 ± 0.06 (stat.) ± 0.25 (syst.) ± 0.45 (lumi.)</td>
<td>4.29 ± 0.23</td>
</tr>
<tr>
<td>$W^-$ $\mu^-\bar{\nu}$</td>
<td>4.08 ± 0.06 (stat.) ± 0.15 (syst.) ± 0.45 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>$W^-$ $\ell^-\bar{\nu}$</td>
<td>4.09 ± 0.05 (stat.) ± 0.14 (syst.) ± 0.45 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>$Z$ e$^+e^-$</td>
<td>0.960 ± 0.037 (stat.) ± 0.059 (syst.) ± 0.106 (lumi.)</td>
<td>0.972 ± 0.042</td>
</tr>
<tr>
<td>$Z$ $\mu^+\mu^-$</td>
<td>0.924 ± 0.031 (stat.) ± 0.022 (syst.) ± 0.102 (lumi.)</td>
<td></td>
</tr>
<tr>
<td>$Z$ $\ell^+\ell^-$</td>
<td>0.931 ± 0.026 (stat.) ± 0.023 (syst.) ± 0.102 (lumi.)</td>
<td></td>
</tr>
</tbody>
</table>

### Source Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$W^+ (e)$</th>
<th>$W^- (e)$</th>
<th>$W^+ / W^- (e)$</th>
<th>$W / Z (e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton reconstruction &amp; identification</td>
<td>5.1</td>
<td>5.1</td>
<td>5.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Momentum scale &amp; resolution</td>
<td>2.2</td>
<td>1.8</td>
<td>0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>$E_T$ scale &amp; resolution</td>
<td>1.6</td>
<td>1.9</td>
<td>0.4</td>
<td>1.8</td>
</tr>
<tr>
<td>Background subtraction / modeling</td>
<td>1.1</td>
<td>1.5</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>PDF uncertainty for acceptance</td>
<td>0.9</td>
<td>1.5</td>
<td>1.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Other theoretical uncertainties</td>
<td>1.3</td>
<td>0.9</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>6.1</td>
<td>6.2</td>
<td>5.7</td>
<td>4.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$W^+ (\mu)$</th>
<th>$W^- (\mu)$</th>
<th>$W^+ / W^- (\mu)$</th>
<th>$W / Z (\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton reconstruction &amp; identification</td>
<td>1.5</td>
<td>1.5</td>
<td>2.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Momentum scale &amp; resolution</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>$E_T$ scale &amp; resolution</td>
<td>0.4</td>
<td>0.4</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>Background subtraction / modeling</td>
<td>1.7</td>
<td>2.3</td>
<td>0.7</td>
<td>2.2</td>
</tr>
<tr>
<td>PDF uncertainty for acceptance</td>
<td>1.3</td>
<td>1.9</td>
<td>2.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Other theoretical uncertainties</td>
<td>1.4</td>
<td>1.3</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>3.0</td>
<td>3.6</td>
<td>3.8</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Cross Sections

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma \times B$ (nb)</th>
<th>NNLO (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$</td>
<td>$e^\nu$</td>
<td>10.04 ± 0.10 (stat.) ± 0.52 (syst.) ± 1.10 (lumi.)</td>
</tr>
<tr>
<td></td>
<td>$\mu^\nu$</td>
<td>9.92 ± 0.09 (stat.) ± 0.31 (syst.) ± 1.09 (lumi.)</td>
</tr>
<tr>
<td></td>
<td>$\ell^\nu$</td>
<td>9.95 ± 0.07 (stat.) ± 0.28 (syst.) ± 1.09 (lumi.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.44 ± 0.52</td>
</tr>
<tr>
<td>$W^+$</td>
<td>$e^+\nu$</td>
<td>5.93 ± 0.07 (stat.) ± 0.36 (syst.) ± 0.65 (lumi.)</td>
</tr>
<tr>
<td></td>
<td>$\mu^+\nu$</td>
<td>5.84 ± 0.07 (stat.) ± 0.18 (syst.) ± 0.64 (lumi.)</td>
</tr>
<tr>
<td></td>
<td>$\ell^+\nu$</td>
<td>5.86 ± 0.06 (stat.) ± 0.17 (syst.) ± 0.64 (lumi.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.15 ± 0.29</td>
</tr>
<tr>
<td>$W^-$</td>
<td>$e^-\bar{\nu}$</td>
<td>4.14 ± 0.06 (stat.) ± 0.25 (syst.) ± 0.45 (lumi.)</td>
</tr>
<tr>
<td></td>
<td>$\mu^-\bar{\nu}$</td>
<td>4.08 ± 0.06 (stat.) ± 0.15 (syst.) ± 0.45 (lumi.)</td>
</tr>
<tr>
<td></td>
<td>$\ell^-\bar{\nu}$</td>
<td>4.09 ± 0.05 (stat.) ± 0.14 (syst.) ± 0.45 (lumi.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.29 ± 0.23</td>
</tr>
<tr>
<td>$Z$</td>
<td>$e^+e^-$</td>
<td>0.960 ± 0.037 (stat.) ± 0.059 (syst.) ± 0.106 (lumi.)</td>
</tr>
<tr>
<td></td>
<td>$\mu^+\mu^-$</td>
<td>0.924 ± 0.031 (stat.) ± 0.022 (syst.) ± 0.102 (lumi.)</td>
</tr>
<tr>
<td></td>
<td>$\ell^+\ell^-$</td>
<td>0.931 ± 0.026 (stat.) ± 0.023 (syst.) ± 0.102 (lumi.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.972 ± 0.042</td>
</tr>
</tbody>
</table>

- Good agreement across channels
- Combine $e$ & $\mu$ by maximizing a joint likelihood
  - Including statistical and correlated systematic errors
- Additionally quote cross-sections restricted to acceptance region
  - Transfer theoretical uncertainties from measurements → predictions
- POWHEG acceptance after QED, basic cuts

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma \times B$ in acceptance $A$ (nb)</th>
<th>$A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow e\nu_e$</td>
<td>6.04 ± 0.06 (stat.) ± 0.31 (syst.) ± 0.66 (lumi.)</td>
<td>0.601 ± 0.005</td>
</tr>
<tr>
<td>$W^+ \rightarrow e^+\nu_e$</td>
<td>3.69 ± 0.05 (stat.) ± 0.22 (syst.) ± 0.41 (lumi.)</td>
<td>0.622 ± 0.006</td>
</tr>
<tr>
<td>$W^- \rightarrow e^-\bar{\nu}_e$</td>
<td>2.36 ± 0.04 (stat.) ± 0.14 (syst.) ± 0.26 (lumi.)</td>
<td>0.571 ± 0.009</td>
</tr>
<tr>
<td>$Z \rightarrow e^+e^-$</td>
<td>0.460 ± 0.018 (stat.) ± 0.028 (syst.) ± 0.051 (lumi.)</td>
<td>0.479 ± 0.005</td>
</tr>
<tr>
<td>$p_T &gt; 20$ GeV $</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu_{\mu}$</td>
<td>5.21 ± 0.05 (stat.) ± 0.15 (syst.) ± 0.57 (lumi.)</td>
<td>0.525 ± 0.006</td>
</tr>
<tr>
<td>$W^+ \rightarrow \mu^+\nu_{\mu}$</td>
<td>3.16 ± 0.04 (stat.) ± 0.10 (syst.) ± 0.35 (lumi.)</td>
<td>0.541 ± 0.006</td>
</tr>
<tr>
<td>$W^- \rightarrow \mu^-\bar{\nu}_{\mu}$</td>
<td>2.05 ± 0.03 (stat.) ± 0.06 (syst.) ± 0.22 (lumi.)</td>
<td>0.502 ± 0.006</td>
</tr>
<tr>
<td>$Z \rightarrow \mu^+\mu^-$</td>
<td>0.368 ± 0.012 (stat.) ± 0.007 (syst.) ± 0.040 (lumi.)</td>
<td>0.398 ± 0.005</td>
</tr>
<tr>
<td>$p_T &gt; 20$ GeV $</td>
<td>\eta</td>
<td>&lt; 2.1$</td>
</tr>
</tbody>
</table>
Cross Section Ratios

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Ratio (CMS/Theory)</th>
<th>Lumi. Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma \times B$</td>
<td></td>
<td>±0.11</td>
</tr>
<tr>
<td>$W$</td>
<td>0.953 ± 0.028 (exp.) ± 0.048 (theo.)</td>
<td></td>
</tr>
<tr>
<td>$W^+$</td>
<td>0.953 ± 0.029 (exp.) ± 0.045 (theo.)</td>
<td></td>
</tr>
<tr>
<td>$W^-$</td>
<td>0.954 ± 0.034 (exp.) ± 0.051 (theo.)</td>
<td></td>
</tr>
<tr>
<td>$Z$</td>
<td>0.960 ± 0.036 (exp.) ± 0.040 (theo.)</td>
<td></td>
</tr>
<tr>
<td>$R_{W/Z}$</td>
<td>0.990 ± 0.038 (exp.) ± 0.004 (theo.)</td>
<td>nil</td>
</tr>
<tr>
<td>$R_{+/−}$</td>
<td>1.002 ± 0.038 (exp.) ± 0.028 (theo.)</td>
<td></td>
</tr>
</tbody>
</table>

- Luminosity drops out in the ratio
- good agreement w/ NNLO

- Relative to theory ...
  - Systematic shift in cross sections observed, not in ratio
  - Presumably luminosity bias
    - Well covered by present uncertainties
Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$W \rightarrow e\nu$</th>
<th>$W \rightarrow \mu\nu$</th>
<th>$Z \rightarrow e^+e^-$</th>
<th>$Z \rightarrow \mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton reconstruction &amp; identification</td>
<td>3.9</td>
<td>1.4</td>
<td>5.9</td>
<td>n/a</td>
</tr>
<tr>
<td>Pre-triggering</td>
<td>n/a</td>
<td>0.5</td>
<td>n/a</td>
<td>0.5</td>
</tr>
<tr>
<td>Momentum scale &amp; resolution</td>
<td>2.0</td>
<td>0.3</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>$p_T$ scale &amp; resolution</td>
<td>1.8</td>
<td>0.4</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Background subtraction / modeling</td>
<td>1.3</td>
<td>2.0</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>PDF uncertainty for acceptance</td>
<td>0.8</td>
<td>1.1</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Other theoretical uncertainties</td>
<td>1.3</td>
<td>1.4</td>
<td>1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Total</td>
<td>5.1</td>
<td>3.1</td>
<td>6.2</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Statistical (%)  
1.0 0.9 3.9 3.4

- W cross-section limited by signal/background modeling and lepton efficiency measurements
- Z cross-section limited by statistics and systematics from lepton efficiency
Systematics Uncertainties (2)

<table>
<thead>
<tr>
<th>Source</th>
<th>$W^+ (e)$</th>
<th>$W^- (e)$</th>
<th>$W^+/W^- (e)$</th>
<th>$W/Z (e)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton reconstruction &amp; identification</td>
<td>5.1</td>
<td>5.1</td>
<td>5.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Momentum scale &amp; resolution</td>
<td>2.2</td>
<td>1.8</td>
<td>0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>$E_T$ scale &amp; resolution</td>
<td>1.6</td>
<td>1.9</td>
<td>0.4</td>
<td>1.8</td>
</tr>
<tr>
<td>Background subtraction / modeling</td>
<td>1.1</td>
<td>1.5</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
<td>PDF uncertainty for acceptance</td>
<td>0.9</td>
<td>1.5</td>
<td>1.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Other theoretical uncertainties</td>
<td>1.3</td>
<td>0.9</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>6.1</td>
<td>6.2</td>
<td>5.7</td>
<td>4.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$W^+ (\mu)$</th>
<th>$W^- (\mu)$</th>
<th>$W^+/W^- (\mu)$</th>
<th>$W/Z (\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton reconstruction &amp; identification</td>
<td>1.5</td>
<td>1.5</td>
<td>2.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Momentum scale &amp; resolution</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>$E_T$ scale &amp; resolution</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Background subtraction / modeling</td>
<td>1.7</td>
<td>2.3</td>
<td>0.7</td>
<td>2.2</td>
</tr>
<tr>
<td>PDF uncertainty for acceptance</td>
<td>1.3</td>
<td>1.9</td>
<td>2.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Other theoretical uncertainties</td>
<td>1.4</td>
<td>1.3</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>3.0</td>
<td>3.6</td>
<td>3.8</td>
<td>3.0</td>
</tr>
</tbody>
</table>

- $W^+ W^-$ ratio limited by ratio of lepton efficiencies
  - Determined from statistically limited sample of Z
- $W/Z$ ratio limited by BG model and lepton efficiencies
W cross section non-lumi error 2.9%
Z cross section non-lumi error 3.9%
W/Z ratio total error 3.8%

Internally consistent across channels
Everywhere close to systematics limited
W+ and W- consistent with PDF expectations

Close to challenging global PDF precision!

Limited primarily by +/- efficiency ratio (Z statistics)
Results vs Theory

CMS 2010

2.9 pb^{-1} @ √s = 7 TeV

σ × B (W)  
0.953 ± 0.028_{\text{exp.}} ± 0.048_{\text{theo.}}

σ × B (W^{+})  
0.953 ± 0.029_{\text{exp.}} ± 0.045_{\text{theo.}}

σ × B (W^{-})  
0.954 ± 0.034_{\text{exp.}} ± 0.051_{\text{theo.}}

σ × B (Z)  
0.960 ± 0.036_{\text{exp.}} ± 0.040_{\text{theo.}}

R_{W/Z}  
0.990 ± 0.038_{\text{exp.}} ± 0.004_{\text{theo.}}

R_{+/-}  
1.002 ± 0.038_{\text{exp.}} ± 0.028_{\text{theo.}}
Cross Section vs Collision Energy

Theory: FEWZ and MSTW08 NNLO PDFs
Preview: $Z \rightarrow ll$ with 35 pb$^{-1}$

- Observed candidates agree with expectations (within old systematics)
- Dimuon candidates exhibit excellent first pass scale and resolution
- Dielectron candidates require ECAL crystal transparency correction
  - In progress EB,EE-averaged rescaling shown here
First pass fit: 161k Ws
W+ yield: 98156
W- yield: 62714

First pass fit: 144k Ws
W+ yield: 87884
W- yield: 56912

- Observed candidates agree with expectations (within old systematics)
- Updated recoil corrections to W signal, electron energy scale
- Method continues to give an excellent description of data
The Road Ahead

- **Target experimental precision of 2% (non-lumi)**
  - Then theory error from acceptance dominates
  - 2% is a x2 improvement in uncertainties

- **Key systematics to reduce**
  - Lepton efficiency
    - Signal and background shapes for passing and failing samples
    - Some improvement expected from better statistics
  - Background modeling for $W \rightarrow l\nu$

- **Other improvements will be required …**
  - Efficiencies and corrections in finer binning
  - Simultaneous fit for efficiencies extended to electrons
Conclusions

• Just eight months into its first 7 TeV collision run, CMS has achieved 4% precision tests of electroweak physics.

• Electrons, muons, and missing energy are well-calibrated detector objects ready for precision analysis.

• Extraordinary performance by detector operations, computing, detector simulation, and physics objects groups made this possible.

• W and Z production rates are already superior estimators of integrated luminosity and real time detector performance.