Production of $W$ and $Z$ Bosons and of $W/Z+Jets$ at CMS

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On behalf of the CMS Collaboration

Standard Model Benchmarks at High-Energy Hadron Colliders
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**Electroweak Physics at the LHC**

- Understanding EWK production is essential before any discovery claims.
  - The production of W and Z bosons decaying into leptons is one of the best understood processes at the colliders.
  - Standard Candles and Backgrounds in searches for new particles
- EWK measurements are used to constrain PDFs.
- High $p_T$ leptons from W’s and Z’s are used to understand efficiency, resolution, energy scale, and in general understanding the detector.

Selected EWK Results from CMS

- W/Z Inclusive Cross Sections
- W Charge Asymmetry
- Z Differential Cross Sections
- Drell-Yan process, AFB and Weinberg Angle
- V+Jets
- Z+b jets
- W Polarization
- V+γ Production
- WW Production
Particles Reconstruction, ID and Event Selection

- Isolated high $p_T$ leptons.
- Unprescaled electron and muon triggers;
- trigger on $\tau + \text{MET}$ for $W \rightarrow \tau\nu$.
- Efficiencies determined using tag-and-probe using $Z \rightarrow ll'$.  
- Major backgrounds estimated using data-driven methods.
- Tau reconstruction using particle flow algorithm.

**Particle-Flow Algorithm** combines data from all sub-detectors to identify and reconstruct all particles from the collision; charged/neutral hadrons, photons, muons, electrons.  
Resulting list of particles are then used to construct jets, MET, taus, ..
$W \rightarrow e\nu, \mu\nu$

- W signal extracted from fits to the MET distributions.
- QCD background shape modeled from data inverting lepton ID and isolation cuts.
- Signal MET shapes from simulation for $W^+$ and $W^-$ corrected event-by-event vs $p_T^W$ determined from hadronic recoil response and resolution distributions of $Z \rightarrow l^+l^-$ from data.

$\sigma \times BR = 10.31 \pm 0.02\text{(stat)} \pm 0.13\text{(sys)} \pm 0.41\text{(lumi)} \text{ nb}$
• **Z signal**: Two isolated opposite sign high $p_T$ leptons.

• **Fit to mass spectrum**
  – $\mu\mu$: Simultaneous likelihood ratio fit of the yield and efficiencies

• $60 < M(l^+l^-) < 120$ GeV.

Small shift of the peak of MC w.r.t. data $\rightarrow$ ECAL cluster energy scale corrections (for EB and EE).

$$\sigma \times BR = 0.975 \pm 0.007 \text{(stat)} \pm 0.019 \text{(sys)} \pm 0.039 \text{(lumi)} \text{ nb}$$
Comparison with Theory

Individual cross sections, and their ratios agree well with theory predictions at NNLO.

Major Systematics:
- Luminosity normalization: 4%
- Lepton reconstruction ($\varepsilon$): 0.9-1.3%
- Backgrounds (N): 0.14-0.35%
- PDFs (A): 0.6-1.2%
Comparison with Theory

- Individual cross sections, and their ratios agree well with theory predictions at NNLO.
- The increase of the Z and W cross sections with energy is confirmed.
Important for searches of a light Higgs boson, SUSY or extra dimensions, ..

\[ W \rightarrow \tau \nu \]

\[ \tau_{\text{had}} \]: highly-collimated jet with 1 or 3 charged mesons and 0,1 or 2 neutral pions.

\[ \text{Single } \tau_{\text{had}} \text{ and MET trigger.} \]

QCD multi-jet background is controlled by dividing the phase space defined by MET and \( p_T(\tau)/\Sigma p_T(\text{PF jets}) \) into four regions.

# Signal events from simulation: 174±3
# EWK backgrounds from simulation: 46±2
# QCD events from sideband: 109±6
# Selected events in data: 372

Preliminary analysis provide a statistically significant signal on top of QCD multi-jet and electroweak backgrounds.
$Z \rightarrow \tau\tau$

*Important for searches of a light Higgs boson, SUSY or extra dimensions, ..*

Leptonic final states: $\tau_i \equiv \tau \rightarrow l \bar{v}_l \nu_l$

Hadronic final states: $\tau_{had}$

Signal yields from a maximum likelihood fit of the shapes from MC except for QCD, and $Z \rightarrow ll$ backgrounds.

Clear signal in all channels.

A global fit of the lepton+$\tau_{jet}$ channels provides a check on the reconstruction efficiency for semi-hadronic $\tau$ decays with a precision of $\sim 7\%$.
Comparison to Theory and Previous Measurements

Statistical uncertainties smaller than the systematic uncertainties. 
σxBR measurements are compatible with each other, with NNLO predictions, Tevatron measurements, and CMS measurements with Z → e⁺e⁻, μ⁺μ⁻ events.
W Lepton Charge Asymmetry

\[ A(\eta) = \frac{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) - d\sigma/d\eta(W^- \rightarrow \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) + d\sigma/d\eta(W^- \rightarrow \ell^-\bar{\nu})} \]

Highly sensitive to PDFs due to the cancellation of systematic uncertainties.

A vs \( \eta \) can provide better understanding of u/d ratio and the sea antiquark densities at \( \sqrt{s} = 7 \text{ TeV} \).

Flatter \( \eta \)-dependence than the PDF predictions.

In each \( \eta \)-bin, precision < 1.6%. Already sufficiently small to improve global PDF fits.
**Z Differential Cross Sections**

- An accurate description of the low and high $p_T$ regions is essential for predicting the production rates and the kinematics. (Low $p_T \rightarrow$ multiple soft gluon emission. High $p_T$ (pQCD) $\rightarrow$ Sensitive to gluon PDFs.)
- **Double differential measurements will provide the most strict constraints on the PDFs.**

- **Good agreement with FEWZ(NNLO) for $p_T > 20$ GeV**
- **Disagreement for $p_T < 20$ GeV compared to POWHEG and different PYTHIA tunes.**
Drell-Yan Mass Spectrum

DY process is an irreducible background to searches for new particles such as a $Z'$. Background to $tt$ and di-boson processes. Also allows test of perturbative QCD and precise measurements will constrain PDFs.

Spectrum in good agreement with NNLO prediction. NNLO essential for describing $M < \sim 30$ GeV.

Uncertainty on modeling: difference of acceptance corrections derived from POWHEG and FEWZ.
**Z Forward-Backward Asymmetry**

Z/γ* couples to fermions both with vector and axial-vector components.

\[
\frac{d\sigma}{d\cos\theta} = A(1 + \cos^2\theta) + B\cos\theta
\]

\[
A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{N_F - N_B}{N_F + N_B} = \frac{3B}{8A}
\]

\[
A_{FB} = A_{FB}(M,Y,\sin^2\theta_W,q-flavor)
\]

Deviations from the SM prediction of AFB at high mass may indicate the existence of a new neutral gauge boson, quark-lepton compositeness, SUSY particles, ...

AFB measurement can provide a precise measurement of \(\sin^2\theta_W\).

Precise AFB measurement can also constrain PDFs.

**Collins-Soper frame**

\[\cos\theta^{\ast}_{CS} = \frac{2(P_1^+P_2^- - P_1^-P_2^+)}{\sqrt{Q^2(Q^2 + Q_i^2)}}\]

F: \(\cos(\theta^*) > 0\)

B: \(\cos(\theta^*) < 0\)

**Good agreement between data and POWHEG+CMS Simulation.**
Weinberg Angle

CMS preliminary

40 pb\(^{-1}\) at \(\sqrt{s} = 7\) TeV

Data

fit projection

background-only projection

Fit result: \(\sin^2\theta_W = 0.2287 \pm 0.0077\) (stat.) \(\pm 0.0036\) (sys.) consistent with SM predictions.

Better precision than one can obtain from raw \(A_{FB}\) measurement.
→ Provide fundamental tests of perturbative QCD.
→ Important backgrounds for
  - any new physics
  - single top and tt (W+jets)
→ Used to verify and tune ME+PS MC & NLO simulations.

**Particle flow jets with anti-$$k_T$$ algorithm (cone size=0.5) with $$E_T>30 \text{ GeV}$$ in the tracker acceptance.** Unfolding to correct for the effects of jet-resolution.

Good agreement with ME calculation (MadGraph) and discrepancies with Pythia (as expected) for $$n > 1$$. 

**Good agreement with ME calculation (MadGraph) and discrepancies with Pythia (as expected) for $$n > 1$$.**
$V$+Jets: Berends-Giele “Scaling”

CMS-PAS-EWK-10-012

$C_n = \frac{\sigma(V + \geq n\text{jets})}{\sigma(V + \geq (n+1)\text{jets})}$, $n>0$

Leading-order prediction $C_n = \text{constant } \alpha \alpha_s^{-1}$.

NLO + phase space effects (for high $n$) $\rightarrow C_n = \alpha + \beta n$.

Fit to the data with $c(n)=\alpha + \beta n$:

Good agreement between $W$+jets and $Z$+jets and fair agreement with the simulations.
**Z+b jets**

Benchmark for associated production of Higgs boson with b-quarks and as a background to Higgs and new physics searches.

Precise measurement of Z+b can choose between fixed- and variable-flavour calculations.

**fixed flavor** (no b-quark at the parton level)

qq, gg → ZQQ

**variable flavor** (b-quark at the parton level)

gQ → ZQ

*b-quark in the hard scattering by integrating the gluon splitting process into the PDF.*

b-tag discriminant chosen such that mis-tagging rate is

High purity (ε~20%): <0.1%.

High efficiency (ε~40%): <1%.

Yields from Z(→ ll)+b-jet are in good agreement with MadGraph+Pythia predictions. Ratio $\sigma(Z+b)/\sigma(Z+j)$ is found to be in good agreement with NLO expectations. Both calculation schemes describe the data well – more events are needed to distinguish between them.
**W Polarization**

- At high $p_T$ the dominant production mechanism at the LHC is the quark-gluon initial state (only sea anti-quarks & more gluons than anti-quarks for $x>0.1$).
- V-A coupling $\rightarrow$ left handed polarizations to quarks (relativistic limit).
  - $W$ bosons are expected to be produced predominantly in a left-handed state at the LHC.
  - significant asymmetry in $p_T^{\nu}$ and charged lepton from $W$ decays.

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

Helicity frame: polarization axis is defined to be along the $W$ boson flight direction.
$\theta^*$ = The angle between the polarization axis and the charged lepton decay direction in the $W$ boson rest frame.

$$A_0 \propto f_0 \quad A_4 \propto \pm(f_L - f_R) \quad f = f(p_T^W, \eta^W)$$

Parameters $f_L, f_R, f_0$ determine the fractions of left, right, and longitudinal helicity states.
$W$ Polarization

Not possible to precisely determine the $W$ rest frame, but
→ “lepton projection variable” correlated to $\cos \theta^*$ can be used.

$\rightarrow$ Reject QCD: $M_T^{e\text{-chan}}>50$ GeV, $M_T^{\mu\text{-chan}}>30$ GeV
$\rightarrow$ Reject $tt$: ≤3 jets with $p_T>30$ GeV
$\rightarrow$ Increase polarization: $p_T(W)>50$ GeV

$L_p = \frac{\vec{p}_T(l) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$

$(f_L - f_R)^W = 0.240 \pm 0.036(\text{stat}) \pm 0.031(\text{syst})$
$f_0^W = 0.138 \pm 0.087(\text{stat}) \pm 0.123(\text{syst})$
$(f_L - f_R)^{W^*} = 0.310 \pm 0.036(\text{stat}) \pm 0.017(\text{syst})$
$f_0^{W^*} = 0.171 \pm 0.085(\text{stat}) \pm 0.099(\text{syst})$

Main systematic uncertainties from recoil energy scale and resolution.

Difference between left- and right-handed polarization parameters 7.8$\sigma$ for $W^+$ and 5.1$\sigma$ for $W^-$. First observation that $W$ bosons produced in pp collisions with large $p_T$ are predominantly left-handed (for both charges) as expected in the SM.
**V+γ Production**

- $Z\gamma, W\gamma$ production important test of SM because of its sensitivity to the self-interaction between gauge bosons via TGC.
- Main backgrounds: $V+\text{jets}$, $t\bar{t}$, QCD multijet

\[
\sigma(W\gamma+X)\times B(W\rightarrow l\nu) = 56.3\pm 5.0 \text{(stat.)} \pm 5.0 \text{(syst.)} \pm 2.3 \text{(lumi.)} \text{ pb}
\]

\[
\sigma(Z\gamma+X)\times B(Z\rightarrow ll) = 9.4\pm 1.0 \text{(stat.)} \pm 0.6 \text{(syst.)} \pm 0.4 \text{(lumi.)} \text{ pb}
\]

$E_T^{\gamma} > 10$ GeV and $\Delta R(l,\gamma) > 0.7$

$M_{ll} > 50$ GeV ($Z\gamma$)

Fake isolated photons estimated from $V+\text{jets}$.

Main systematic sources: photon and lepton energy scales, pile-up, PDFs, photon $Id/iso$, backgrounds.

$W\gamma$ and $Z\gamma$ cross sections are in good agreement with NLO predictions.

No evidence for anomalous $WW\gamma$, $ZZ\gamma$, and $Z\gamma\gamma$ trilinear gauge couplings.
Benchmark for Higgs boson search in H→WW and limits on WWγ and WWZ anomalous couplings.

- **DY→ee,μμ veto**: require MET and reject events within 15 GeV around Z mass peak.
- **DY→ττ veto**: projected MET transverse to the closest lepton > 35 GeV.
- **Top quark veto**: reject events with jets of $p_T$>25 GeV, $|\eta|<$5. + veto based on soft-muon and b-jet tagging.
- **Suppress WZ, ZZ**, by rejecting events with >2 leptons.

13 signal events in data with estimated background of 3.3±1.2 evts.

$$\sigma(WW)=41.1\pm15.3\text{(stat)}\pm5.8\text{(syst)}\pm4.5\text{(lumi)}$$ consistent with the SM prediction.
WW Production: Higgs Boson Search

- $\Delta \phi_{ll}$ provides the best discriminating power.
- Cut based and Boosted Decision Tree (BDT) technique
- Additional backgrounds: WH, WZ, tt, VBF $\rightarrow$ by 0-jet and <=2 lepton requirements.
- Systematic uncertainty
  - signal yield $\sim$14% $\rightarrow$ due to jet veto efficiency and luminosity uncertainty.
  - Background (in signal region) $\sim$ 40% dominated by statistical uncertainties in the control regions.

No access above the SM expectations.
No Higgs boson in a 4-generation SM scenario in the range 144-207 GeV with 95% C.L.
Summary

CMS preliminary

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

- $\sigma \times B( W )$
- $\sigma \times B( W^+ )$
- $\sigma \times B( W^- )$
- $\sigma \times B( Z )$
- $\sigma \times B( Z \rightarrow \tau \tau )$
- $\sigma \times B( W\gamma )$
- $\sigma \times B( Z\gamma )$
- $\sigma \times B( WW )$
- $R_{WWZ}$
- $R_{WW}$
- $W_{\text{jet}} \rightarrow e\nu \alpha$
- $W_{\text{jet}} \rightarrow \mu\nu \alpha$
- $Z_{\text{jet}} \rightarrow ee \alpha$
- $Z_{\text{jet}} \rightarrow \mu\mu \alpha$
- $Z_{b-\text{jet}/Z_{\text{jet}}}(\rightarrow ee)$
- $Z_{b-\text{jet}/Z_{\text{jet}}}(\rightarrow \mu\mu)$
- $\sin^2 \theta_W$

lumi. uncertainty: $\pm 4\%$

Values:

- $0.988 \pm 0.009^{\text{exp}} \pm 0.050^{\text{theo}}$
- $0.982 \pm 0.017^{\text{exp}} \pm 0.049^{\text{theo}}$
- $0.993 \pm 0.019^{\text{exp}} \pm 0.054^{\text{theo}}$
- $1.003 \pm 0.010^{\text{exp}} \pm 0.047^{\text{theo}}$
- $1.029 \pm 0.097^{\text{exp}} \pm 0.043^{\text{theo}}$
- $1.121 \pm 0.177^{\text{exp}} \pm 0.077^{\text{theo}}$
- $0.969 \pm 0.121^{\text{exp}} \pm 0.042^{\text{theo}}$
- $0.956 \pm 0.381^{\text{exp}} \pm 0.007^{\text{theo}}$
- $0.981 \pm 0.018^{\text{exp}} \pm 0.015^{\text{theo}}$
- $0.994 \pm 0.013^{\text{exp}} \pm 0.035^{\text{theo}}$
- $0.894 \pm 0.097^{\text{exp}} \pm 0.017^{\text{theo}}$
- $0.833 \pm 0.088^{\text{exp}} \pm 0.017^{\text{theo}}$
- $0.992 \pm 0.199^{\text{exp}} \pm 0.020^{\text{theo}}$
- $1.208 \pm 0.280^{\text{exp}} \pm 0.021^{\text{theo}}$
- $1.059 \pm 0.281^{\text{exp}} \pm 0.167^{\text{theo}}$
- $1.000 \pm 0.272^{\text{exp}} \pm 0.185^{\text{theo}}$
- $0.989 \pm 0.037^{\text{exp}} \pm 0.001^{\text{theo}}$
Conclusions

• With 36 pb\(^{-1}\) of data at 7 TeV, CMS has made fundamental measurements of the benchmark SM processes of W and Z production
  – Differential cross sections, Drell-Yan production
  – Asymmetries: W charge asymmetry and polarization, Z forward/backward asymmetry and Weinberg angle measurement.
  – V+jets including Z+b-jet measurement.
  – WW, W\(_\gamma\), Z\(_\gamma\) and measurements of anomalous triple gauge boson couplings.
• All results are in good agreement with SM predictions.

Standard Model benchmarks established.
Many new measurements to come from the already collected > 700 pb\(^{-1}\).
Back-up
**Compact Muon Solenoid (CMS)**

- **ECAL**: PbWO$_4$, High resolution, ~70 k crystals
- **HCAL**: Brass and scintillator
- **Tracker**: 66 M Si pixels and 10 M Si strips
- **Superconducting Solenoid magnet**: 6 m x 13 m, $B=3.8$ T, $E = 1.6$ GJ
- **Muon System**: Drift tubes (DT), Cathode Strip Chambers (CSC), Resistive plate chambers (RPC).

+ **Forward Calorimeter**: steel absorber, fibers

**Within the solenoid field volume**

**Embedded within the iron yoke**

- **Total weight**: 12,500 t
- **Overall diameter**: 15 m
- **Overall length**: 21.6 m
- **Magnetic field**: 4 Tesla
## W/Z Systematic Uncertainties in Electron and Muon Final States

<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>
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<td>Lepton reconstruction &amp; identification</td>
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<td>1.6</td>
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Electron Identification in HF

- HF is located about 11 m from the interaction point, covers $3 < |\eta| < 5$ with depth of $10 \lambda_{\text{int}}$

  **No tracker in front of HF.**

- Consists of iron absorber embedded with quartz fibers parallel to the beam direction in a 5x5 mm matrix

**Electrons in HF can be identified using longitudinal and transverse shower shape variables:**

**Isolation:** $E(L+S)_{3x3}/E(L+S)_{5x5} > XX$,

**Compactness:** $E(L_{\text{core}})/E(L_{3x3}) - cE_s/E_L = (\text{shower shape}) - c(\text{shower depth}) > XX$
**WW Production: Limits on WWγ and WWZ Anomalous Couplings**

- Effective Lagrangian with HISZ parametrization without form factors.
  - \( \lambda_Z, \kappa_\gamma, \) and \( g_1^Z \) describe all the operators.
  - In SM, \( \lambda_Z = 0, \kappa_\gamma = g_1^Z = 1 \). \( \Rightarrow \) \( \Delta \kappa_\gamma \) and \( \Delta g_1^Z \): deviation from SM.

Two different measurements both using the leading \( p_T^{\text{lep}} \) distribution.

Results are in agreement with SM predictions and are consistent with the LEP precision measurements and comparable with Tevatron results.
$W\gamma$

CMS 2010, 36 pb$^{-1}$
$\sqrt{s} = 7$ TeV

Events / (bin width/10 GeV)

$E_T^{\gamma}$ [GeV]