W&Z Physics at the LHC

María Cepeda, University of Wisconsin (CMS experiment)
On behalf of the CMS, ATLAS and LHCb collaborations
Why study W&Zs in the LHC?

• On the path to discovery, the LHC program encourages us to measure in detail a great number of the Standard Model known “unknowns”.

• The study of the production mechanism of W and Z in pp collisions and the precise measurement of electro-weak observables related to them to have already provided a plethora of results at 7 TeV.

• Thanks to them, we have been able to:
  • Obtain precision measurements in the TeV regime
  • Study in detail the building blocks for general analysis (leptons, met, jets, b-jets)
  • Test perturbative QCD predictions and PDFs in pp Collisions at the TeV scale
  • Cross-check our measurements of Luminosity
  • Understand in detail the backgrounds for most searches (Higgs, SuSy)
Summary: Results at 7 TeV

- **Inclusive W/Z measurements**
  - Inclusive Cross-Sections and Ratios
  - Differential Cross-Sections
  - W Charge asymmetry
  - W polarization
  - Tau polarization
  - Z $A_{FB}$ asymmetry
  - Measurement of the weak mixing angle
  - Z rapidity and transverse momentum
  - W transverse momentum
  - Study of the strange quark PDF density

- **V+jets / V+HF measurements**
  - V+Jets Cross-Sections
  - Cross-Section Ratios
  - Differential Cross-Sections
  - W asymmetry in jet bins
  - W+c study
  - W+b(b) cross-section measurement
  - Z+b / Z+bb cross-sections & kinematics

20 minutes is not enough to cover them all in the detail they deserve – just enough to focus on some of the highlights and news.

Dedicated parallel talks by the three experiments for more detailed explanations:
- **W. J. Barter** (W and Z, LHCb)
- **R. Castello** (W,Z+jets; CMS)
- **K. Nagai** (W,Z; ATLAS)
- **N. Neumeister** (Drell-Yan; CMS)
W/Z Cross-Sections

- W and Z decays are characterized by their high production rates and clean and simple experimental signatures in their leptonic decay channels:
  - **W**: High pt, isolated lepton + high Missing Transverse Energy (MET)
  - **Z**: 2 high pt isolated leptons

- CMS: JHEP **10** (2011) 132

- “Central” leptons $\rightarrow$ pseudorapidity up to 2.1 (W muon, CMS) / 2.4 (muon ATLAS, Zmumu CMS) / 2.5 (electrons)
- Excellent agreement with theoretical predictions
- Already being used to provide further input to PDF measurements.

Cross-Sections in the forward region

- New results from LHCb, complementary to the 2010 CMS/ATLAS measurements
- **Forward Muon/Electron** → 2.0<\(\eta<4.5\)
- **\(P_T\)** > 20 GeV
- For \(W \rightarrow\) isolated, Unbiased impact parameter < 40 \(\mu m\), \(E/p < 0.04\). No MET \(\rightarrow\) lepton \(p_T\) as a handle to identify \(Ws\)

- **Z**: Cut&Count (Muon and Electron)
- **W**: Fit to the \(pt\) distribution (only muon channel)

**2010**

- (37 pb\(^{-1}\))

**2011**

- (945 pb\(^{-1}\))

Muons: LHCb-PAPER-2012-008
Electron: LHCb-CONF-2011-011
Tau: LHCb-CONF-2011-041
W/Z Cross-Sections in LHCb

- d/u is not well determined from past experiments → LHC data at high $\eta$ should help settle the PDF uncertainties in this region

- The results are in general agreement with theoretical predictions, performed at next-to-next-to-leading order in QCD, using different sets of recently calculated parton distribution functions.

$LHCb-PAPER-2012-008$
Differential Cross-Sections

• In addition to the inclusive cross-sections, differential cross-sections allow precision tests of our understanding of fine details of particle production at the LHC.

• Examples: Z rapidity → sensitivity to PDFs (specially in the forward region). $q_T$ → test of the underlying collision processes at low $q_T$ and NNLO pQCD predictions at high $q_T$.

• Generally good agreement with the theoretical predictions, some discrepancies between PDF sets.

• **ATLAS**: Z pt and rapidty, W pt and pseudorapidity
• **CMS**: Z pt and rapidity
• **LHCb**: W+- pseudorapidity, Z rapidity

\[ \frac{d\sigma}{dM} : \text{Differential Drell-Yan X-Section} \]

- Moving away from the Z peak we can further test pQCD predictions and probe PDFs.
- Normalizing the results to the Z peak \( \Rightarrow \) cancellation of luminosity uncertainties, reduction of overall uncertainties (eg: efficiencies)
- CMS: 40 invariant mass bins starting from 15 GeV
- Also studied in LHCb in the low mass region (See back-up, LHCb-CONF-2012-013)
- Data well described by NNLO
- Low mass range: dominated by modeling errors / High range: dominated by statistical errors

\[ \gamma^* / Z \rightarrow \mu\mu \]

\[ \gamma^* / Z \rightarrow e\bar{e} \]

\[ 4.5 \text{ fb}^{-1} \text{ at } \sqrt{s} = 7 \text{ TeV} \]

\[ \text{CMS Preliminary} \]

\[ \frac{1}{\sigma_Z} \frac{d\sigma}{dM(\mu\mu)} \text{ [GeV}^{-1}] \]

\[ \frac{1}{\sigma_Z} \frac{d\sigma}{dM(ee)} \text{ [GeV}^{-1}] \]

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

\[ \text{NNLO, FEWZ+MSTW08} \]

\[ \text{CMS-PAS-EWK-11-007} \]

\[ \text{CMS-PAS-EWK-11-020} \]
Weak Mixing Angle & $A_{FB}$

Kinematics of leptons produced in Z decays $\Rightarrow$ Forward-Backward assymmetry of DY pairs, which:

- At the Z pole $\Rightarrow$ measure $\sin^2\theta_W$ with a 1% precision. Measured through an unbinned maximum-likelihood fit to the data di-muon rapidity, invariant mass and decay angle distributions (1.1 fb$^{-1}$)

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

- Away from the Z pole $\Rightarrow$ Measure AFB as a function of rapidity and invariant mass. Observed AFB is heavily diluted wrt Born level one (results corrected) $\Rightarrow$ Precision test on SM predictions around the Z peak region / sensitive to new physics at high mass (4.7 fb$^{-1}$)
W Asymmetry

- More $u$-$\overline{d}$ than $d$-$\overline{u}$ in pp collisions $\Rightarrow$ Charge Asymmetry in W production
- Excellent probe to study parton distributions in the proton

$$A_W \approx \frac{u\overline{d} - \overline{u}d}{u\overline{d} + \overline{u}d} \approx \frac{u_{val} - d_{val}}{u_{val} + d_{val} + 2q}$$

$$A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+\overline{\nu}_\mu) - \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^-\nu_\mu)}{\frac{d\sigma}{d\eta}(W^+ \rightarrow \mu^+\overline{\nu}_\mu) + \frac{d\sigma}{d\eta}(W^- \rightarrow \mu^-\nu_\mu)}$$
W polarization

- Dominance of quark-gluon initial states, plus V-A W-fermion coupling leads to significant polarization of W bosons with large transverse momenta ($>50$ GeV) in pp collisions.
- The exact value of polarization depends on the proportion of the $qg$, $q_{barg}$, $qqbar$ contributions, reflected in the helicity angle ($\cos \theta_{3D}$)

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_{3D}} = \frac{3}{8} f_L (1 + \cos \theta_{3D})^2 + \frac{3}{8} f_R (1 + \cos \theta_{3D})^2 + \frac{3}{4} f_0 \sin^2 \theta_{3D}
\]

- Results computed in two ranges: $35<\text{Pt}(W)<50$ GeV, $\text{Pt}(W)>50$ GeV
- The measurement confirm that W bosons in pp collisions with large transverse momenta are predominantly left-handed as predicted in the Standard Model.

\[
\cos \theta_{2D} = \frac{p_T^{e^+} \cdot p_T^{W^*}}{|p_T^{e^+}||p_T^{W^*}|}
\]

Used as an approximation of $\theta_{3D}$.
V+Jets Studies

- CMS: focus on cross-sections and cross-section ratios
- ATLAS: extensive study of the kinematics (angles, differential distributions, etc)
- Comparison of different MC generators and PDF sets → the different measurements performed provide tests of $\alpha_s$, PDFs, hard parton radiation and ME to PS matching schemes
- In general good agreement with the theoretical predictions data for both CMS and ATLAS
Z+b / Z+bb

- Current cross-section predictions have large theory uncertainties, so a precise measurement by the LHC will have high impact in our understanding of V+HF production.
- Tagging efficiency and template fits dominate the systematic uncertainties.
- CMS observes a ‘larger though consistent’ cross-section in data than predicted. ATLAS is consistent within uncertainties.
- Some tension in the data/MC comparison of kinematic properties.

ATLAS:

\[ 3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi}) \text{ pb} \]

CMS:

\[ Z+\geq1b \quad 3.78 \pm 0.05(\text{stat.}) \pm 0.31(\text{syst.}) \pm 0.11(\text{theory}) \text{ pb} \]
\[ Z+\geq2b \quad 0.37 \pm 0.02(\text{stat.}) \pm 0.07(\text{syst.}) \pm 0.02(\text{theory}) \text{ pb} \]

Z+b/Z+j [CMS, SMP-10-015, 36 pb-1]
Z+bb [CMS, SMP-12-003; 2.1 fb-1]
Z+2SV

- Complementary approach to the standard jet-tagging procedure:
  - B-hadrons identification using secondary vertices (Inclusive Vertex Finder)
  - Not based on b-jets
  - Sensitivity at small angles → measurement of the $\Delta R(b_1,b_2)$ angle between the two displaced vertices
- Some discrepancies in shape observed between data and MC

CMS-EWK-11-015
The measurement of the cross section ratios

$$\sigma(W^+\bar{c})/\sigma(W^-\bar{c})$$ and

$$\sigma(W+c)/\sigma(W+jets)$$

provides important information on the strange and anti-strange quark parton density functions of the proton.

Measured in W+1 Jet events, through a fit to the significance of the secondary vertex decay length $D_{SSVHE}$.
Determination of Strange Quark Density

- Complementary to the CMS measurement, ATLAS has studied the impact of the inclusive W/Z differential cross-sections and their correlations on our knowledge of the strange quark distribution in the proton.
- 2 types of NNLO QCD fit of HERA DIS and ATLAS W/Z cross-section data (free sbar/fixed sbar).
- $\chi^2$/ndof improved in the free fit.
- Considerable tension with most PDF sets.

$Q^2 = 1.9 \text{ GeV}^2, x = 0.023$

$\bar{s}/d = 0.5$

$F_{\text{eprWZ free } \bar{s}} = 0.5(s + \bar{s})/\bar{d}$
W+b(b)

Measured Cross-Section is \textbf{\~1.5 sigma} larger than the theoretical prediction (both NLO(5FNS) and LO (Alpgen+Jimmy))

- Measurement performed in 3 bins: 1 btagged jet, 2 btagged jets, 1+2 btagged jets
- Significant background contributions, mostly from top (2 jets) and W+c (1 jet)
- The measurement is performed in the Electron/Muon channels, and based on a likelihood fit to the mass of the Secondary Vertex

Towards the first 8 TeV results

- The LHC SMP program will continue to yield results in 2012
  - Completing the ongoing analysis on 2011 data (7 TeV)
  - Extending and updating the results at 8 TeV

- The first results are starting to arrive: \( W^+ \), \( W^- \), MET and Z Invariant Mass distributions at 8 TeV

Note: Monte Carlo predictions fitted to the data yield (only shape comparison)
Conclusions

• ATLAS/CMS/LHCb have a healthy program of Standard Model physics studies, partially dedicated to the production of W/Z bosons at the LHC.

• At 7 TeV it has already provided:
  • Precise cross section measurements of W & Z bosons decaying into leptons, inclusively and in association with jets
  • Detailed studies of differential cross sections, in good agreement with the theoretical predictions
  • Precise measurements of other EWK observables (asymmetries, ratios, polarization), also in good agreement with NLO/NNLO predictions
  • Insight on the Parton Density Functions, both from inclusive measurements and from Vector Boson + jets production
  • First studies of the cross-sections and kinematics for V+Heavy Flavour production (which show interesting tensions with the theoretical predictions)

• Many measurements already systematics limited.
• The program will continue finishing the ongoing 2011 analysis, and moving forward to the 8 TeV era

A deep understanding of the physics behind W&Z production is mandatory in the LHC era. They are the building blocks on which TeV physics are based, without which searches could not have a solid ground.
References

• CMS Public Standard Model Results:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

• ATLAS Public Standard Model Results:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

• LHC Conference Notes on W/Z physics:
  W->mu, Z->mu production (37pb-1)  http://cdsweb.cern.ch/record/1439627?ln=en
  Z->ee production (945 pb-1)  http://cdsweb.cern.ch/record/1428904?ln=en
  Z->tau tau production (247 pb-1)  http://cdsweb.cern.ch/record/1368211?ln=en
  Low mass DY production (37 pb-1)  http://cdsweb.cern.ch/record/1434424?ln=en
  Z+Jets Production  LHCb-CONF-2012-016
ADDITIONAL MATERIAL
W Cross-Section at 2.76 TeV

- Measurement of W production at $\sqrt{s} = 2.76$ TeV is in agreement with Standard Model predictions (NNLO, FEWZ and MSTW08 PDF)
- Uncertainty = 5% (stat.) + 2.8% (syst.) + 6% (Lumi)

(First observation of W,Z production in HIC →arXiv:1205.6334, PRL 106 (2011) 212301)
\( \frac{d\sigma}{dM/dY} : \) Double Differential Drell-Yan X-Section

Moving to a measurement in bins of mass and rapidity we can constrain further our knowledge of PDFs (due to the different d/u composition outside the Z peak)

- 24 rapidity bins between 0 and 2.4, and 6 mass ranges
- Muon channel only

CMS-PAS-EWK-11-007
Low Mass DY in LHCb

- 2010 data: \( L = 37 \text{ pb}^{-1} \)
- DiMuon \((p_T > 3 \text{ GeV}, p > 10 \text{ GeV}, \ 2.0 < \eta(\mu) < 4.5)\)
- \(5 < M(\mu\mu) < 120 \text{ GeV}\)
- Yield extracted through a fit to the minimum muon isolation \((p_T(\mu)/p_T(\mu-Jet))\) in data to shapes expected for signal and background
- Cross-Section measured:
  - As a function of DiMuon Inv. Mass
  - As a function of rapidity in bins of Inv Mass.
**V+Jets Studies**

- Jets reconstructed using anti-kt algorithms (cone: 0.4 ATLAS, 0.5 CMS)
- Systematics dominated by jet energy scale → larger at high jet multiplicities and high jet rapidity.
- The use of ratios provides some uncertainty cancellation

---

![Graphs and plots](image-url)

**ATLAS**

- **Left Panel**: Plot showing the ratio of cross-sections for $W + (0, 1)$ jets, with data and theoretical predictions.
- **Right Panel**: Plot of $\Delta\phi$ distribution for the first and second jets, with various theoretical models compared to data.

Maria Cepeda - PLHC 6/6/2012
Integrated Total Cross-Sections

CMS, 36 pb⁻¹ at \( \sqrt{s} = 7 \) TeV

NNLO, FEWZ: MSTW08 prediction
(with MSTW08NNLO 68% CL uncertainty)

\[ W \rightarrow e\nu \]
\[ \sigma = 10.48 \pm 0.03^{\text{stat.}} \pm 0.17^{\text{syst.}} \pm 0.42^{\text{lumi.}} \text{ pb} \]

\[ W \rightarrow \mu\nu \]
\[ \sigma = 10.18 \pm 0.03^{\text{stat.}} \pm 0.16^{\text{syst.}} \pm 0.41^{\text{lumi.}} \text{ pb} \]

\[ W \rightarrow l\nu \text{ (combined)} \]
\[ \sigma = 10.31 \pm 0.02^{\text{stat.}} \pm 0.13^{\text{syst.}} \pm 0.41^{\text{lumi.}} \text{ pb} \]

\[ Z \rightarrow ee \]
\[ \sigma = 0.992 \pm 0.011^{\text{stat.}} \pm 0.024^{\text{syst.}} \pm 0.040^{\text{lumi.}} \text{ pb} \]

\[ Z \rightarrow \mu\mu \]
\[ \sigma = 0.968 \pm 0.008^{\text{stat.}} \pm 0.019^{\text{syst.}} \pm 0.039^{\text{lumi.}} \text{ pb} \]

\[ Z \rightarrow l\bar{l} \text{ (combined)} \]
\[ \sigma = 0.974 \pm 0.007^{\text{stat.}} \pm 0.019^{\text{syst.}} \pm 0.039^{\text{lumi.}} \text{ pb} \]

CMS, 36 pb⁻¹, 2010

- CMS
- CDF Run II
- D0 Run I
- UA2
- UA1

Theory: FEWZ and MSTW08 NNLO PDFs

Collider energy (TeV)

Ratio [CMS/Theory]
Fiducial Total Cross-Sections