ELECTROWEAK PHYSICS AT CMS

Ilaria Segoni (CERN)
Seminar at INP Lyon, March 23\textsuperscript{rd} 2011
Outline

• Motivations
• Overview of the CMS experiment
• Inclusive W and Z production
• QCD-associated W and Z production
• Conclusions
Motivations

W and Z discovered in the early ‘80s, production mechanism well understood, properties known with high precision. Yet, W and Z physics plays an important role at LHC:

- Understanding the apparatus, physics analyses commissioning: isolated leptons, missing transverse energy, jets (V+Jets)

- Benchmark for theory: understanding the initial state (PDF), testing pQCD at new energy regime, tuning the Underlying Event modeling…

- Estimators of LHC Luminosity

- Enter searches for new physics as backgrounds and as direct search topologies (smoking gun may reveal in e.g. $W^+/W^-$, V+Jets, observables sensitive to couplings,…)

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

\[\sigma_{\text{F}}\]

\[\sigma_{\text{V}}\]

\[\sigma_{\text{z}}\]

\[\sigma_{\text{Higgs}}(M_H = 150 \text{ GeV})\]

\[\sigma_{\text{Higgs}}(M_H = 500 \text{ GeV})\]

\[\text{events/sec for } L = 10^{34} \text{ cm}^{-2} \text{s}^{-1}\]

\[\sqrt{s} \text{ (TeV)}\]
EWK Physics at CMS

Several measurements published by CMS in Electroweak sector:

- W and Z inclusive production cross section (e, $\mu$ decays)
- W and Z + Jets production cross section ratios (e, $\mu$ decays)
- Observation of $Z+b$
- Z differential cross sections
- Drell-Yan cross section
- W charge asymmetry
- W polarization
- Z Forward/Backward asymmetry
- $Z(\tau\tau)$ production cross section and limits on Higgs
- WW production and limits on Higgs
- $Z\gamma$ and $W\gamma$ observations

Focus of this seminar

Selected highlights
Tracking up to $|\eta|<2.5$, Resolution on impact parameter
~15\( \mu \)m, \( \sigma(P_T) \approx 1\% @ 40\text{GeV/c} \)

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO\(_4\) crystals
ECAL: \( \sigma(E) \approx 0.5\% \) above 50\( \text{GeV/c} \)

Trigger:
L1T (Hardware) +
HLT (computing farm)

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A

HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers
DATA:
Data recording efficiency exceeds 90%. Only highest quality data enters the physics analyses, i.e. 36pb$^{-1}$ for the 2010 dataset.

SIMULATION:
• Signal modeling is based on NLO simulation for the inclusive analysis (POWHEG) and matrix element + parton shower (PS) simulation for the VB+jets analysis (MADGRAPH+PYTHIA). Pure PS used for cross checks and systematic uncertainty evaluation.
• PYTHIA and MADGRAPH used for backgrounds simulation (multi-jet, top)
• Detector response modeling with GEANT4
The cross section measurement

\[ \sigma \times \text{BR} = \frac{N_{\text{SIG}} (= N_{\text{TOT}} - N_{\text{BKG}})}{\text{acceptance} \times \text{efficiency} \times \text{Lumi}} \]

- Signal purity enhanced with high Pt isolated leptons in detector acceptance, using energy deposits and/or track’s pt in a \( \Delta R = 0.3 \) cone around lepton:

  \[ I_{\text{HCAL}} = \sum E_T(\text{HCAL}) \quad I_{\text{ECAL}} = \sum E_T(\text{ECAL}) \quad I_{\text{TRK}} = \sum E_T(\text{tracks}) \]

- Signal, BKG Yields extracted with fits on distributions most sensitive to event species. Largest backgrounds from QCD, top, other W/ Z decays

- Acceptance is calculated with MC, results produced also without acceptance correction to eliminate MC dependence, direct comparison to theories

- Efficiency: evaluated directly from data or from simulation with data driven correction factors to reduce bias from poor detector modeling

- Luminosity uncertainty dominant source of uncertainty, but significantly reduced with respect to previously shown results (4%)
Electron reconstruction and selection

- **Trigger:**
  - ECAL Cluster with $E_T > 15\text{GeV} @ \text{HLT}$
- **Offline:**
  - ECAL super cluster in fiducial volume ($|\eta| < 1.44, 1.57 < |\eta| < 2.5$), $\text{ele } P_T > 25\text{GeV/c}$
  - track fit accounts for energy loss due to bremsstrahlung, $\gamma$ conversion rejected
- **Electron Identification:**
  - consistency of ECAL-Tracker $\eta$-$\phi$ coordinates, narrow shower shape in $\eta$, low energy deposit in HCAL

Veto on 2$^{nd}$ isolated electron for $W$ selection

⇒ reduces Drell-Yan and top

Multi-jet contamination rejected using relative isolations:

$I_{\text{HCAL}}/P_T(\text{ele})$, $I_{\text{ECAL}}/P_T(\text{ele})$, $I_{\text{trck}}/P_T(\text{ele})$
Muon reconstruction and selection

- **Trigger:**
  - $P_T > 9\text{GeV}/c$ @ HLT

- **Offline:**
  - $P_T > 25\text{GeV}/c$, $|\eta|<2.1$

- **Muon Identification:**
  - Candidate reconstructed in both Tracker and Muon systems
  - Good quality of the fit and requirement on number of hits to reduce contamination from decays in flight and retain muons with good resolution on $p_T$
  - Impact parameter on transverse plane $<2\text{mm}$ to reject cosmics

\[ I_{\text{comb}}^{\text{rel}} = \sum (I_{\text{HCAL}} + I_{\text{ECAL}} + I_{\text{trk}})/P_T(\text{muon}) < 0.1 \]
Missing transverse energy (MET)

MET fundamental to disentangle processes with real/fake MET
⇒ used for signal extraction fit

Particle Flow algorithm used:
• Event particles first reconstructed,
  Unbalancing of $E_T$ to measure MET

• Extensive use of Tracking vs calorimetric information:
  • very good resolution on the MET value and direction
  • negligible effect from PU

Patricle flow algorithm also used for jet clustering, used in V+Jets analysis.
Signal extraction, $W(\nu\nu)$

- Unbinned maximum likelihood fit to the event MET, 3 fit components:
  - Signal: MC line shape with data driven (Z sample) corrections in bins of $W P_T$, yield floated
  - QCD BKG: modified Rayleigh function, yield+shape floated. Cross checks on data control sample
  - EWK BKG: shape and yields fixed to MC

$$f(x) = x \cdot \exp(-x^2 / (2(\sigma_0 + \sigma_1 x)))$$
Signal extraction, $W(\mu\nu)$

Binned maximum likelihood fit to MET, 3 fit components:

• Signal: MC line shape with data driven (Z sample) corrections in bins of $W\, P_T$, yield floated

• QCD BKG: data control sample with inverted Isolation requirement. Corrections to account for induced distortions. Yield floated

• EWK BKG: From MC, shape and yields fixed

CMS preliminary

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

number of events / 2 GeV

$\chi$
Signal extraction, $Z(\text{ee})$

Electron energy scale determined from comparison to simulation, data corrected and associated uncertainty propagated as systematic.

$Z(\text{ee})$: $N_Z$ determined with cut and count on corrected distribution.
Expected BKG = 36 $\pm$ 12 events from $Z(\tau\tau)$, diboson, top, QCD.
Signal extraction in $Z(\mu\mu)$

Muon reco and ID can be divided in 5 steps each of which has an associated efficiency

- track finding in Tracker
- track finding in Muon chambers
- isolation requirement
- trigger matching

The events are assigned to statistically independent categories based on passing or failing each requirement.

The $Z$ Yield and efficiency of each step $\nu_i$ are extracted with a simultaneous fit to the uncorrelated categories.

$$N_{\text{PAS-PAS}}^Z = N_{Z}^{\text{true}} \times \varepsilon_i^2$$

$$N_{\text{PAS-FAIL}}^Z = N_{Z}^{\text{true}} \times \varepsilon_i \times (1 - \varepsilon_i)$$
Acceptance

\[ \sigma \times \text{BR} = \frac{N_{\text{SIG}} (= N_{\text{TOT}} - N_{\text{BKG}})}{\text{acceptance} \times \text{efficiency} \times \text{Lumi}} \]

Acceptance determined with NLO MC using NNLO PDF’s. PDF variations used for systematic uncertainty determination.

<table>
<thead>
<tr>
<th></th>
<th>Acceptance ((\eta) and (P_T))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z(ee))</td>
<td>0.3876+-0.0005</td>
</tr>
<tr>
<td>(W(e\nu))</td>
<td>0.4933+-0.0003</td>
</tr>
<tr>
<td>(W^+(e^+\nu))</td>
<td>0.5017+-0.0004</td>
</tr>
<tr>
<td>(W^-(e^-\nu))</td>
<td>0.4808+-0.0004</td>
</tr>
<tr>
<td>(Z(\mu\mu))</td>
<td>0.3977+-0.0017</td>
</tr>
<tr>
<td>(W(\mu\nu))</td>
<td>0.4638+-0.0003</td>
</tr>
<tr>
<td>(W^+(\mu^+\nu))</td>
<td>0.4570+-0.0004</td>
</tr>
<tr>
<td>(W^-(\mu^-\nu))</td>
<td>0.5706+-0.0004</td>
</tr>
</tbody>
</table>
Efficiency

\[ \sigma \times \text{BR} = \frac{N_{\text{SIG}} = N_{\text{TOT}} - N_{\text{BKG}}}{\text{acceptance} \times \text{efficiency} \times \text{Lumi}} \]

Data-driven calibrations of efficiencies determined from simulation. Calibrations determined using Tag&Probe method

One lepton (tag) with tight requirements
second lepton (probe) with looser requirements.
Efficiency based on number of events where probe passes/fails the requirements from fits to the di-lepton mass at the Z-peak for the two pass/failed categories

\[ \varepsilon = \varepsilon_{\text{MC}} \times \left( \varepsilon_{\text{DATA}}^{TP} / \varepsilon_{\text{MC}}^{TP} \right) \]

Eff. determined for vs lepton charge and:
• electron: for Barrel and Endcap separately
• muon: as a function of \((p_T, \eta)\)

<table>
<thead>
<tr>
<th>Average signal efficiency within acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z(ee)</td>
</tr>
<tr>
<td>60.9+-1.1%</td>
</tr>
<tr>
<td>W(e\nu)</td>
</tr>
<tr>
<td>73.5 + - 0.9 %</td>
</tr>
<tr>
<td>W(\mu\nu)</td>
</tr>
<tr>
<td>83.0+-0.3%</td>
</tr>
</tbody>
</table>

Z(\mu\mu): no efficiency correction applied, corrected signal yield extracted from fit
### 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>1.3</td>
<td>0.9</td>
<td>1.8</td>
<td>n/a</td>
</tr>
<tr>
<td>Trigger pre-firing</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>0.5</td>
<td>0.22</td>
<td>0.12</td>
<td>0.35</td>
</tr>
<tr>
<td>$E_T$ scale &amp; resolution</td>
<td>0.3</td>
<td>0.2</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Background subtraction / modeling</td>
<td>0.35</td>
<td>0.4</td>
<td>0.14</td>
<td>0.28</td>
</tr>
<tr>
<td>Total experimental</td>
<td>1.5</td>
<td>1.1</td>
<td>1.8</td>
<td>0.7</td>
</tr>
<tr>
<td>PDF uncertainty for acceptance</td>
<td>0.6</td>
<td>0.7</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Other theoretical uncertainties</td>
<td>0.7</td>
<td>0.8</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Total theoretical</td>
<td>0.9</td>
<td>1.1</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td>Total</td>
<td>1.7</td>
<td>1.6</td>
<td>2.5</td>
<td>2.1</td>
</tr>
</tbody>
</table>

+ 4% from Luminosity determination
W and Z Cross section results

- Very good agreement with expectation, results already useful for Luminosity determination.
Cross section results by W charge

Study of valence d/u densities and sea quark densities

W charge asymmetry studied vs lepton $\eta_l$ in both electron and muon channels.
Data suggests flatter evolution with $\eta_l$ than theoretical predictions

Cross section results by W charge

Study of valence d/u densities and sea quark densities

W charge asymmetry studied vs lepton $\eta_l$ in both electron and muon channels.
Data suggests flatter evolution with $\eta_l$ than theoretical predictions
- Good consistency across different decay channels and vector boson species

- Both absolute cross section and ratios show good agreement with expectations from NNLO QCD calculations using NLO PDF sets
World measurements vs collider energy

CMS measurements in excellent agreement with predicted increase with beam energy
Drell-Yan Differential cross sections

Drell-Yan differential cross section in agreement with NNLO predictions.

Differential cross section at the Z peak (60-120 GeV) vs di-lepton $p_T$ and $\eta$ in agreement with NLO predictions.

- Bin-by-bin background subtraction and efficiency correction.
- Matrix inversion unfolding.
QCD-associated W and Z production

- With leptons, MET and jets in final state, QCD associated production of vector bosons forms a relevant background to searches
- $x$-sections are difficult to calculate especially for high jet multiplicities (NLO calculations up to 3 (4) jets available for Z (W))

Precise measurements are important as QCD tests and to constraint SM backgrounds in searches, but uncertainties rapidly grow with jet multiplicity

- Start with ratio measurements, where systematics from JES, Lumi and lepton selection (partially) cancel out
\( \sigma(V+n\text{jets}) \) versus number of jets \( n \)

- At leading order one expects 
  \( \sigma(N_{\text{jet}}) \sim \exp(c \alpha_s N_{\text{jet}}) \), scaling of the cross section known as Berends-Giele scaling

- Relation is modified by higher orders, but still approximately true, e.g. Tevatron finds good agreement with simple scaling expectations

- \( c \) hard to compute in QCD, interesting to measure it

- Higher order terms are expected to modify the scaling, e.g.: 
  \( \sigma(N_{\text{jet}}) \sim \sigma(N_{\text{jet}}-1)/(\alpha + \beta N_{\text{jet}}) \)
The measurements

- We measure different vector boson plus \( n \) jets cross section ratios:

\[
\frac{\sigma(V + n\text{jets})}{\sigma(V_{\text{tot}})} \quad \quad \frac{\sigma(V + n\text{jets})}{\sigma(V + (n-1)\text{jets})}
\]

The \( \alpha \) and \( \beta \) parameters assuming:
\[
\frac{\sigma(V + n\text{jets})}{\sigma(V + (n-1)\text{jets})} = \alpha + \beta \cdot n
\]
as a test of the Berends-Giele scaling.

For comparison with theoretical model we quote the inclusive rate of \( n \) jets, i.e. the rate of events with \( \geq n \) jets.
Analysis strategy for V+Jets

In V+jet the shape of cross sections vs number of jets is studied rather than absolute values ➔ analysis strategy differs from the inclusive VB study

➔ The acceptance in lepton and jet $p_T$ and $\eta$ is found to be strongly dependent on the jet multiplicity bin, in order to provide model-independent measurements we do not correct for acceptance.

➔ Efficiencies are measured in bins of jet multiplicity using Z+jet data samples. Bin-by-bin efficiency ratios enter in the measurement and absolute scale effects cancel out. In muon channel efficiencies are available in $(n\ jet, \eta^{\mu}, p_T^{\mu})$ bins

➔ In order to increase statistics and minimize bin-by-bin efficiency dependence, we use softer $p_T$ requirements on leptons matched to trigger object ($p_T>$20 GeV). Softer requirements on the second lepton for Z sample: $p_T>$10GeV, looser selection cuts.
Jet Counting

After event selection+assignment to the uncorrelated W or Z samples, event is further assigned to jet multiplicity bin \( n \) based on number \( n \) of Particle Flow jets in the event with \( E_T > 30 \text{ GeV} \) (after energy scale corrections and pile up subtraction, AntiK_\text{T}5 algorithm). Exclusive counting for \( n=0,1,2,3 \) to perform analysis on uncorrelated samples, results then combined to quote cross section ratios vs inclusive jet multiplicity.
Very good agreement with predictions from matrix element + parton shower predictions (MADGRAPH+PYTHIA) normalized to NNLO cross sections (MCFM).

For the $W$ channels a cut on $M_T > 50\text{GeV}$ is applied to enhance signal purity.

$$M_T = \sqrt{2MET \cdot p_T^{\text{lepton}} (1 - \cos \theta_{\text{MET-lepton}})}$$
Raw jet rates, W

Requirement on $W$ $M_T > 20\text{GeV}$, also with larger backgrounds

good agreement with simulations.
Raw jet rates, Z

CMS preliminary

36 pb⁻¹ at √s = 7 TeV

E_{T}^{jet} > 30 GeV

number of events

CMS preliminary

36 pb⁻¹ at √s = 7 TeV

E_{T}^{jet} > 30 GeV

number of events

exclusive jet multiplicity

exclusive jet multiplicity

data

Z \rightarrow \mu\mu \text{ (MadGraph)}

all backgrounds

data/MC

data

Z \rightarrow ee \text{ (MadGraph)}

all backgrounds

data/MC
Signal extraction in Z(\(\ell\ell\))+jet Channels

- Extended Unbinned Maximum Likelihood fits to the di-lepton invariant mass with two components:

- Signal PDF:
  - Crujiff function \(\rightarrow\)
  - Left-hand tail (\(\alpha_L\)) determined on high purity data sample and fixed in the fits, all other parameters floated, but constrained to be the same for the N\(\geq\)1 samples (which are fit simultaneously).

- Background:
  - Exponential, floated independently on each jet bin

- For muons, where the efficiency is available in bins of (njets, \(\eta(\mu)\), \(p_T(\mu)\)), the fit is weighted and returns lepton-efficiency-corrected number of events.
Z(II) Fit results in n=1 jet multiplicity bin

![Graphs showing the distribution of M(\mu\mu) and M(ee) for Z \rightarrow \mu\mu + \geq 1-jet and Z \rightarrow ee + \geq 1-jet with data, Z \rightarrow \mu\mu, and backgrounds.](image-url)
Signal extraction in W(lν) channels

• Dominant sources of background: multi-jet events and top
  • top contamination is a challenge for signal extraction. Level of contamination becomes important as jet multiplicity increases, with real W decay(s) in the final state the MET and \( M_T \) distributions are not powerful disentangling observables.

\[ \Rightarrow \] 2Dimensional fit to W \( M_T \) and number of jets tagged as b in the event

\[ \Rightarrow \text{allows for floating both multi jet background and top in the fit} \]

Jet b-tagging based on the “Track counting high efficiency” algorithm, based on number of tracks in the jet with significance of impact parameter above given threshold S. Medium working point for S chosen such that:
• efficiency \( \varepsilon_b = (63\pm6.3)\% \) (from MC+top control sample cross checks)
• mistag rate \( \varepsilon_{nob} = (2.42\pm0.003)\% \) (from MC+data driven correction factors)
**W(\nu) + jet Fit Results**

Fit results for W(e\nu)+3jets shown, more results in backup slides.

We select events with $M_T > 20 \text{GeV}$ and correct for efficiency. Efficiency is determined in each n jet bin with pure $W(l\nu)$ +jets simulation events, with data-driven cross check of shape using $Z(\mu\mu)$+jets data.

**2D extended maximum likelihood fit using:**
- $M_T$ modeled with Cruijff or sum of two Cruijff for signal and top. Multi jet with Exponential or left-hand side of a Cruijff.
- $n_{\text{jet}}^{b\text{tag}}$: analytical PDF's for each species built from:
  - n jets
  - number of real b jets in acceptance
  - $\varepsilon_b$
  - $\varepsilon_{nob}$

**Graphs:**
- $36 \text{ pb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$
- $W \rightarrow e\nu + \geq 3$-jets
Fit results for $W(\mu\nu)+3$-jets shown, more results in backup slides

- Extensive cross checks with toy MC, PDF’s uncertainties propagated as a systematic uncertainty.
- Fit results validated with comparison with parallel analysis using template fit on same variables.
Systematic uncertainties

Jet energy determination affects the jet counting. Different sources of systematic uncertainties related to jet counting were considered:

- Jet Energy Scale (including flavor dependence)
- MET Resolution
- Jet Energy Resolution
- Pile up

Other sources of systematics derive from the efficiency determination due to limited statistics in the Z samples used for efficiency measurement and in the choice of PDF’s used for the fits in the Tag and Probe.

For W we also find a non negligible contribution to the systematic uncertainty related to the signal extraction method.
Uncertainties from efficiency measurement and from jet counting comparable
Uncertainties shown are on absolute rates, partial cancellation effects in ratios for jet counting and efficiency
Unfolding to particle level rates

- Bin to bin event migrations due to jet energy resolution, smear the observed n-jet distribution with respect to the particle level distributions

We unfold the smearing effects with the SVD method. Simulation is used to build the matrix that relates the number $n_{\text{true}}$ of jets produced at particle level to the number $n_{\text{obs}}$ of observed jets.

- We use a regularization parameter value equal to the number of bins (5) $\Rightarrow$ full matrix inversion.

- Proper propagation of statistical and systematic uncertainties
- Uncertainty from unfolding procedure estimated by varying the method (Bayesian) and the simulation of the unfolding matrix (different generator, different tuning of the underlying event)
**Results: W+Jets cross section ratios**

Data are compared to expectations from ME+PS simulation using different tunes for the underlying event and to pure PS expectations (NNLO normalization in all cases). Very good agreement with ME+PS, pure PS fails in predicting cross sections for n jets >1.
Larger statistical uncertainties for $Z$+jet, good agreement with both ME+PS and pure PS predictions.
Berends-Giele parameters fit

- Previous results show that $d\sigma(V+n\text{jets})/d(n\text{ jets})$ is in agreement with theoretical calculations in each jet multiplicity bin, which predict a roughly constant scaling factor for each additional jet.
- We further characterize the scaling by performing a second fit where we assume a functional dependence of the rates, which holds for both inclusive and exclusive counting, given by:

$$\sigma(V + n\text{jets}) / \sigma(V + (n-1)\text{jets}) = \alpha + \beta \cdot n$$

Separate background pdf for each jet bin

Common signal shape across jet bins

The scaling is applied to the jet bins with $n = 1$, where it is expected to apply ($n=0$ proofs the full phase space up to $p_T(V) \to 0$)

We fit for the yield in the 1 jet bin, $\alpha$, $\beta$ in all $W$ and $Z$ channels
Berends-Giele parameters results, W

\[ \frac{\sigma(W + \geq n\text{-jets})}{\sigma(W + \geq (n+1)\text{-jets})} = \alpha + \beta \times n \]

Contours statistical error only, arrows indicate center of ellipses shift when considering different sources of systematic uncertainty.

Good agreement with ME+PS expectations considering uncertainties
Berends-Giele parameters results, $Z$

\[ \frac{\sigma(Z + \geq n\text{-jets})}{\sigma(Z + \geq (n+1)\text{-jets})} = \alpha + \beta \times n \]

uncertainties:
- electron efficiency

$Z \rightarrow ee$
- data
- MadGraph
- stat. only 68% C.L. contours

$Z \rightarrow \mu\mu$
- data
- MadGraph
- stat. only 68% C.L. contours

Very good agreement for Z with ME+PS prediction.
**Z+b observation**

Benchmark study for the MSSM Higgs searches, by providing insight into fixed flavor (FF) schema vs variable flavor (VF) schema calculations.

**FF: b only from gluon splitting**

**VF: b allowed in initial state**

**Z selection + one b-tagged jet**, based on displaced secondary vertex. High purity (mistag>0.01%) and high efficiency (mistag<0.1) points used. High purity shown.

**VF schema predicts softer spectrum of b quark. With current statistics good agreement with simulation using both schemas.**
Z+b cross section measurement

With a limited sample the measurement is affected by large statistical uncertainties. We find consistency with the other CMS results.

For electron and muon channels we measure the section ratios $\sigma(Z+b)/\sigma(Z+\text{jets})$ and find good agreement with theoretical expectations:

<table>
<thead>
<tr>
<th>Channel</th>
<th>CMS</th>
<th>NLO expectations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow ee$</td>
<td>0.054+0.016</td>
<td>0.043+0.005</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>0.046+0.014</td>
<td>0.047+0.005</td>
</tr>
</tbody>
</table>
Conclusions & References

CMS is pursuing a rich programme in the electroweak sector. Results the with full 2010 datasets were shown, with emphasis on the cross section measurements of W and Z inclusive and in association with jets.

• The precision measurement era is well ongoing, with results becoming useful input for Luminosity calculation and theory constraints (PDF’s, pQCD calculations).

CMS PAS’es on EWK measurements using full 2010 dataset:

• Study of W and Z Boson Production at 7 TeV CMS-PAS-EWK-10-005
• Measurement of the W boson charge asymmetry CMS-PAS-EWK-10-006
• Measurement of the Drell-Yan cross section (dσ/dM) CMS-PAS-EWK-10-007
• Observation of W-gamma and Z-gamma final states CMS-PAS-EWK-10-008
• Observation of WW final state CMS-PAS-EWK-10-009
• Differential Cross Section of Z boson CMS-PAS-EWK-10-010
• Forward-Backward Asymmetry of di-lepton pairs CMS-PAS-EWK-10-011
• Rates of Jets Produced in Association with W and Z Bosons CMS-PAS-EWK-10-012
• Observation of Z+b CMS-PAS-EWK-10-015
Back UP Slides
Electron Selection & ID

**HLT Efficiency for offline electrons**

![Efficiency of Electron Step of HLT](image)

- **CMS Preliminary, 7 TeV**
- $|\eta|<1.442$
- $1.56<|\eta|<2.00$
- $\int L \, dt = 23 \, nb^{-1}$

**Electron fake rate**

![Electron fake rate](image)
The table shows the cut values for two electron selections corresponding to an efficiency of ~80% and ~95% with respect to the electron reconstructed in the Tracker+ ECAL acceptance volume.

The cross-section results are extracted using the working point eff~80% (WP80). WP95 is sued as a cross check for systematic studies.
Muon Selection and ID

• Match between muon candidate in tracker and muon candidate in Tracker+Muon chambers

• At least one good muon chamber hit

• Tracker muon must have at least two muon stations with hits (eliminate punch through)

• Matching hits in Tracker Strips (>10) and Pixels (>1)

• $\chi^2/\text{ndf} < 10$

• $D_{xy} < 2\text{mm}$
CMS Detector
Systematic uncertainties

Largest uncertainty from Luminosity: 4%

Statistical Uncertainty on correction factors for lepton triggering and selection efficiency propagated as systematics. For muons correction for trigger timing effects applied to the yields, related systematic ~0.5%

Momentum and MET scale and resolution determined with fit shapes variations, corrections applied to leptons

Background subtraction uncertainty determined with variation on QCD templates in W, alternative estimate methods for Z

Theoretical uncertainties from reweighting of the generated events using different PDFs (acceptance) and modeling of ISR, QED FSR, on factorization/renormalization scale)
Parameterization

- We build the probability of tagging $n_{jets}^{b\text{tagged}}$:

$$P(n_{j}^{\text{tagged}}|n_j, n_{bj}, \epsilon_{nob}, \epsilon_b) =$$

$$\begin{cases} 
(1 - \epsilon_{nob})^{n_j-n_{bj}} \cdot (1 - \epsilon_b)^{n_{bj}} & n_{j}^{\text{tagged}} = 0 \\
(1 - \epsilon_{nob})^{n_j-n_{bj}-1} \cdot \epsilon_{nob} \cdot (n_j - n_{bj}) \cdot (1 - \epsilon_b)^{n_{bj}} + (1 - \epsilon_{nob})^{n_j-n_{bj}} \cdot (1 - \epsilon_b)^{n_{bj}-1} \cdot \epsilon_b \cdot n_{bj} & n_{j}^{\text{tagged}} = 1 \\
1 - P(0) - P(1) & n_{j}^{\text{tagged}} \geq 2 
\end{cases}$$

- $n_j$: number of reconstructed jets
- $n_{bj}$: number of real b-jets within acceptance
- $\epsilon_{nob}$: mis-tagging rate $\left(2.42 \pm 0.03(\text{stat}) \pm 0.5(\text{syst})\right)$% from W and top MC using b-POG Scaling Factors (negative tags)
- $\epsilon_b$: tagging efficiency: $\left(63 \pm 6.3\right)$% value from MC uncertainty from top control sample ($e\mu$)
The likelihood is build as:

\[ \mathcal{L} = \frac{e^{N_{\text{evts}}}}{N_{\text{evts}}!} \prod_i N^\text{evts}_i \left[ \sum_s N_s^\text{evts} P_s(n^\text{tagged}_j | n_j, \epsilon\text{nob}, \epsilon_b) P_s(m_T) \right] \]

where \( s \) runs over five species:
- W with no real b-jets
- top with no bjets in acceptance
- top with one bjet in acceptance
- top with two bjets in acceptance
- multijet

Multijet BKG is constrained with the fit to MT, therefore the PDF for the njet tagged variable can be left unspecified in the fit (binned PDF with only normalization constraint)
W(eν) fit results

- **Graph 1:**
  - **Data Points:** ○
  - **Plots:**
    - Yellow: $W \rightarrow e\nu$
    - Purple: non-top
    - Orange: top
  - **Legend:**
    - Data
    - $W \rightarrow e\nu$
    - non-top
    - top
  - **CMS preliminary**
  - **36 pb$^{-1}$ at \( \sqrt{s} = 7 \text{ TeV} \)
  - **Legend:**
    - Data
    - $W \rightarrow e\nu$
    - non-top
    - top

- **Graph 2:**
  - **Data Points:** ○
  - **Legend:**
    - Data
    - $W \rightarrow e\nu$
    - non-top
    - top
  - **CMS preliminary**
  - **36 pb$^{-1}$ at \( \sqrt{s} = 7 \text{ TeV} \)
  - **Legend:**
    - Data
    - $W \rightarrow e\nu$
    - non-top
    - top

- **Wednesday, March 22, 2011**

- **Events / 2.5 GeV:**
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60
  - 70
  - 80

- **$M_T$ [GeV]:**
  - 0
  - 50
  - 100
  - 150

- **$n_{\text{jet}^{b\text{-tagged}}}$:**
  - 0
  - 1
  - 2

- **Events / bin:**
  - 0
  - 10
  - 20
  - 30
  - 40

- **$e\nu$ non-top**

- **$e\nu$ top**
$W(\mu\nu)$ fit results

![Graph showing $W \rightarrow \mu\nu + \geq 1$-jet distribution with bins for $M_T$ and $n_{jet \, b\text{-tagged}}$.]

- Data points and bins for $W \rightarrow \mu\nu$ and non-top processes.
- Events / 2.5 GeV.
- 36 pb$^{-1}$ at $\sqrt{s} = 7$ TeV.
Error propagation in the unfolding

- Unfolding is performed on the uncorrelated, n jet -bins (n=0, n=1, n=2, n=3, n>=4). The unfolded exclusive jet rates are used to compute the inclusive rates.

- Uncertainties are divided in three categories:
  - Statistical (from the fit)
  - Systematics uncorrelated across bins, i.e. from lepton efficiency, fit
  - Systematics correlated across bins, i.e. from jet counting

- The unfolding procedure is run multiple times to determine final values with proper uncertainty estimate:
  - Using the statistical errors only
  - Using the statistical + uncorrelated systematics summed
  - Using central values shifted by correlated systematics
  - Using unfolding alternatives in algorithm, response matrix, w/o PU
Table 5: $\sigma(W+\geq N\text{ jets})/\sigma(W)$, the jet multiplicities normalized to the inclusive cross section.

<table>
<thead>
<tr>
<th>num jets</th>
<th>$\sigma$ ratio</th>
<th>stat</th>
<th>stat + fit and efficiency</th>
<th>JES</th>
<th>unfolding</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1/\geq 0$ jets</td>
<td>0.126</td>
<td>0.001</td>
<td>0.004</td>
<td>+0.018</td>
<td>+0.000</td>
</tr>
<tr>
<td>$\geq 2/\geq 0$ jets</td>
<td>0.026</td>
<td>0.000</td>
<td>0.002</td>
<td>-0.016</td>
<td>-0.002</td>
</tr>
<tr>
<td>$\geq 3/\geq 0$ jets</td>
<td>0.0043</td>
<td>0.0002</td>
<td>0.0005</td>
<td>-0.004</td>
<td>0.0000</td>
</tr>
<tr>
<td>$\geq 4/\geq 0$ jets</td>
<td>0.0007</td>
<td>0.0000</td>
<td>0.0002</td>
<td>-0.000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

**electron channel**

<table>
<thead>
<tr>
<th>num jets</th>
<th>$\sigma$ ratio</th>
<th>stat</th>
<th>stat + fit and efficiency</th>
<th>JES</th>
<th>unfolding</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1/\geq 0$ jets</td>
<td>0.137</td>
<td>0.001</td>
<td>0.007</td>
<td>+0.019</td>
<td>+0.000</td>
</tr>
<tr>
<td>$\geq 2/\geq 0$ jets</td>
<td>0.026</td>
<td>0.000</td>
<td>0.001</td>
<td>-0.017</td>
<td>-0.002</td>
</tr>
<tr>
<td>$\geq 3/\geq 0$ jets</td>
<td>0.0044</td>
<td>0.0001</td>
<td>0.0005</td>
<td>-0.004</td>
<td>0.0000</td>
</tr>
<tr>
<td>$\geq 4/\geq 0$ jets</td>
<td>0.0007</td>
<td>0.0000</td>
<td>0.0002</td>
<td>-0.000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

**muon channel**

Table 6: $\sigma(Z+\geq N\text{ jets})/\sigma(Z)$, the jet multiplicities normalized to the inclusive cross section.

<table>
<thead>
<tr>
<th>num jets</th>
<th>$\sigma$ ratio</th>
<th>stat</th>
<th>stat + fit and efficiency</th>
<th>JES</th>
<th>unfolding</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1/\geq 0$ jets</td>
<td>0.148</td>
<td>0.003</td>
<td>0.007</td>
<td>+0.020</td>
<td>+0.000</td>
</tr>
<tr>
<td>$\geq 2/\geq 0$ jets</td>
<td>0.028</td>
<td>0.001</td>
<td>0.003</td>
<td>-0.019</td>
<td>-0.002</td>
</tr>
<tr>
<td>$\geq 3/\geq 0$ jets</td>
<td>0.0035</td>
<td>0.0005</td>
<td>0.0010</td>
<td>-0.004</td>
<td>0.0000</td>
</tr>
<tr>
<td>$\geq 4/\geq 0$ jets</td>
<td>0.0008</td>
<td>0.0000</td>
<td>0.0005</td>
<td>-0.000</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

**electron channel**

<table>
<thead>
<tr>
<th>num jets</th>
<th>$\sigma$ ratio</th>
<th>stat</th>
<th>stat + fit and efficiency</th>
<th>JES</th>
<th>unfolding</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1/\geq 0$ jets</td>
<td>0.136</td>
<td>0.003</td>
<td>0.009</td>
<td>+0.022</td>
<td>+0.003</td>
</tr>
<tr>
<td>$\geq 2/\geq 0$ jets</td>
<td>0.026</td>
<td>0.001</td>
<td>0.003</td>
<td>-0.020</td>
<td>-0.018</td>
</tr>
<tr>
<td>$\geq 3/\geq 0$ jets</td>
<td>0.0040</td>
<td>0.0005</td>
<td>0.0010</td>
<td>+0.004</td>
<td>0.002</td>
</tr>
<tr>
<td>$\geq 4/\geq 0$ jets</td>
<td>0.0009</td>
<td>0.0000</td>
<td>0.0005</td>
<td>+0.000</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

**muon channel**

Table 7: $\sigma(W^+ \geq N \text{ jets}) / \sigma(W^+ \geq (N-1) \text{ jets})$, the ratio of jet multiplicities.

<table>
<thead>
<tr>
<th>num jets</th>
<th>$\sigma$ ratio</th>
<th>stat</th>
<th>stat + fit and efficiency</th>
<th>JES</th>
<th>unfolding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electron channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq 1 / \geq 0$ jets</td>
<td>0.126</td>
<td>0.002</td>
<td>0.004</td>
<td>+0.018</td>
<td>+0.002</td>
</tr>
<tr>
<td>$\geq 2 / \geq 1$ jets</td>
<td>0.208</td>
<td>0.009</td>
<td>0.012</td>
<td>-0.016</td>
<td>-0.000</td>
</tr>
<tr>
<td>$\geq 3 / \geq 2$ jets</td>
<td>0.165</td>
<td>0.015</td>
<td>0.018</td>
<td>+0.003</td>
<td>+0.000</td>
</tr>
<tr>
<td>$\geq 4 / \geq 3$ jets</td>
<td>0.167</td>
<td>0.035</td>
<td>0.039</td>
<td>+0.004</td>
<td>+0.002</td>
</tr>
<tr>
<td>muon channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq 1 / \geq 0$ jets</td>
<td>0.137</td>
<td>0.001</td>
<td>0.007</td>
<td>+0.019</td>
<td>+0.002</td>
</tr>
<tr>
<td>$\geq 2 / \geq 1$ jets</td>
<td>0.190</td>
<td>0.005</td>
<td>0.013</td>
<td>-0.017</td>
<td>-0.000</td>
</tr>
<tr>
<td>$\geq 3 / \geq 2$ jets</td>
<td>0.170</td>
<td>0.011</td>
<td>0.018</td>
<td>+0.004</td>
<td>+0.006</td>
</tr>
<tr>
<td>$\geq 4 / \geq 3$ jets</td>
<td>0.151</td>
<td>0.025</td>
<td>0.037</td>
<td>+0.003</td>
<td>+0.023</td>
</tr>
</tbody>
</table>

Table 8: $\sigma(Z^+ \geq N \text{ jets}) / \sigma(Z^+ \geq (N-1) \text{ jets})$, the ratio of jet multiplicities.

<table>
<thead>
<tr>
<th>num jets</th>
<th>$\sigma$ ratio</th>
<th>stat</th>
<th>stat + fit and efficiency</th>
<th>JES</th>
<th>unfolding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electron channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq 1 / \geq 0$ jets</td>
<td>0.148</td>
<td>0.006</td>
<td>0.007</td>
<td>+0.020</td>
<td>+0.002</td>
</tr>
<tr>
<td>$\geq 2 / \geq 1$ jets</td>
<td>0.190</td>
<td>0.020</td>
<td>0.020</td>
<td>-0.019</td>
<td>+0.002</td>
</tr>
<tr>
<td>$\geq 3 / \geq 2$ jets</td>
<td>0.125</td>
<td>0.034</td>
<td>0.034</td>
<td>-0.001</td>
<td>-0.010</td>
</tr>
<tr>
<td>$\geq 4 / \geq 3$ jets</td>
<td>0.214</td>
<td>0.117</td>
<td>0.117</td>
<td>+0.003</td>
<td>+0.022</td>
</tr>
<tr>
<td>muon channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\geq 1 / \geq 0$ jets</td>
<td>0.136</td>
<td>0.005</td>
<td>0.009</td>
<td>+0.022</td>
<td>+0.018</td>
</tr>
<tr>
<td>$\geq 2 / \geq 1$ jets</td>
<td>0.189</td>
<td>0.017</td>
<td>0.025</td>
<td>+0.020</td>
<td>-0.003</td>
</tr>
<tr>
<td>$\geq 3 / \geq 2$ jets</td>
<td>0.157</td>
<td>0.038</td>
<td>0.041</td>
<td>+0.001</td>
<td>-0.009</td>
</tr>
<tr>
<td>$\geq 4 / \geq 3$ jets</td>
<td>0.218</td>
<td>0.109</td>
<td>0.110</td>
<td>-0.004</td>
<td>-0.043</td>
</tr>
</tbody>
</table>
ATLAS and CMS cross section measurements

ATLAS with 35 pb\(^{-1}\)

\[
\sigma(W) = 10.391 \pm 0.022 \pm 0.238 \pm 0.353 \pm 0.312 \\
\sigma(Z) = 0.945 \pm 0.006 \pm 0.011 \pm 0.032 \pm 0.038 \\
\sigma(W)/\sigma(Z) = 10.906 \pm 0.079 \pm 0.215 \pm 0.164
\]

CMS with 36pb\(^{-1}\)

\[
\sigma(W) = 10.48 \pm 0.03 \pm 0.15 \pm 0.42 \pm 0.09 \\
\sigma(Z) = 0.992 \pm 0.011 \pm 0.018 \pm 0.040 \pm 0.018 \\
\sigma(W)/\sigma(Z) = 10.54 \pm 0.07 \pm 0.08 \pm 0.16
\]

(Errors: stat – syst –lumi – theo)