CMS: WW, WZ, ZZ cross sections

Clara Jordá (IFCA) on behalf of **CMS Collaboration**

Working Group on Electroweak precision measurements at the LHC

21 – 22 May 2012 at CERN

Introduction

- Inclusive cross section measurement of WW, WZ and ZZ Standard Model processes in the fully leptonic final state:
  - WW → *llνν* (*l*=e,μ) → Predicted inclusive σ_{NLO} = 47.0 ± 2.0 pb [1]
  - WZ → *lllν* (*l*=e,μ) → Predicted inclusive σ_{NLO} = 17.5 ± 0.5 pb [2]
  - ZZ → *llll* (*l*=e,μ,τ) → Predicted inclusive σ_{NLO} = 6.4 ± 0.6 pb [2]

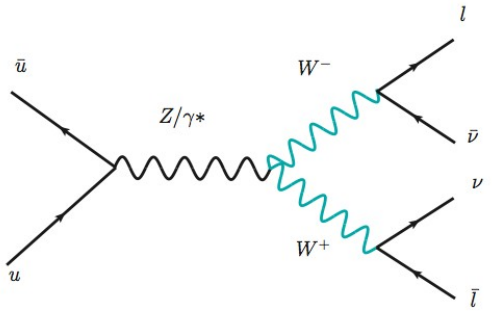
- Test of the Standard Model at 7 TeV
  - Measurement of the self-interaction boson coupling (TGC) could be a candle of new physics – Talk by Lindsey Gray
  - Main irreducible background for Higgs boson searches in H → WW and H → ZZ fully leptonic final state

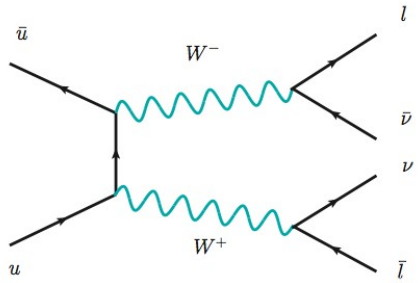
[1] J. M. Campbell, R. K. Ellis and C.Williams, "Vector boson pair production at the LHC", JHEP 1107, 018 (2011)
[2] J. M. Campbell, R. K. Ellis and C.Williams, MCFM - Monte Carlo for FeMtobarn processes

WW process

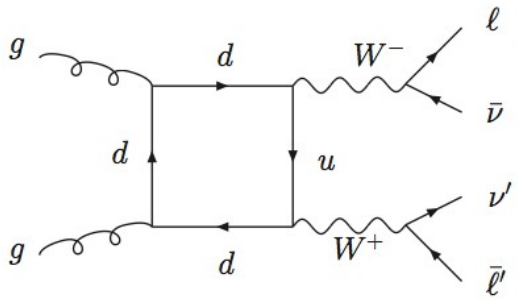
Introduction – WW process

- Production modes
  - $q\bar{q} \rightarrow WW$ (97 %)





  - $gg \rightarrow WW$ (3 %)



- Experimental Signature
  - Two high p_T leptons with opposite sign
  - Transverse missing E_T
  - Low hard jet activity
- Major background:
  - Drell-Yan, ttbar, tW, W+jets, W+γ*
  - Estimated from control regions on Data
- Others (WZ/ZZ, Wγ) from MC
- Public Results with 4.92 /fb (full 2011 data)
  - CMS SMP – 12 – 005 / CDS Link

WW Selection

Only 2 high p_T (20 GeV) isolated leptons with opposite sign	Reduce diboson WZ and ZZ and W+jets and QCD
Reject events consistent with Z boson mass for SF channels	Reduce Drell–Yan and peaking WZ / ZZ
Require high missing transverse energy, MET	Reduce Drell–Yan
Veto events with high p_T jets (30 GeV) Veto events with soft muon or low p_T jets b-tagged	Reduce top quark backgrounds: ttbar and single top, tW
Kinematical cuts i.e. on $p_T(ll)$	Reduce remaining Drell-Yan and W+jets

SF : Same flavour final state
OF: Opposite flavour final state

Signal Efficiency

- Used Monte Carlo simulation for the estimation of the signal efficiency
  - Samples: Madgraph (qq) and GG2WW (gg)
- Weigh events by trigger efficiency from data
- Correct residual discrepancies data – MC for the lepton identification and isolation with **scale factors**
  - Estimate lepton efficiencies for both with Tag & Probe method
- Studied jet veto efficiency for WW process
  - Found to be close to 1, but systematics assigned
- Studied also the effect on several objects for the experimental variations: muon momentum, electron energy scale, MET resolution, pile up, etc…

Systematics

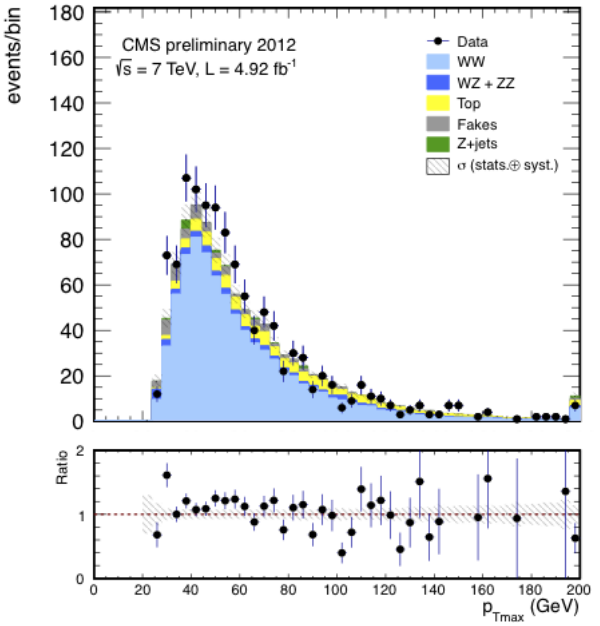
- Several sources of systematics considered
  - Experimental and theoretical
  - Major source for WW efficiency is the jet veto uncertainty

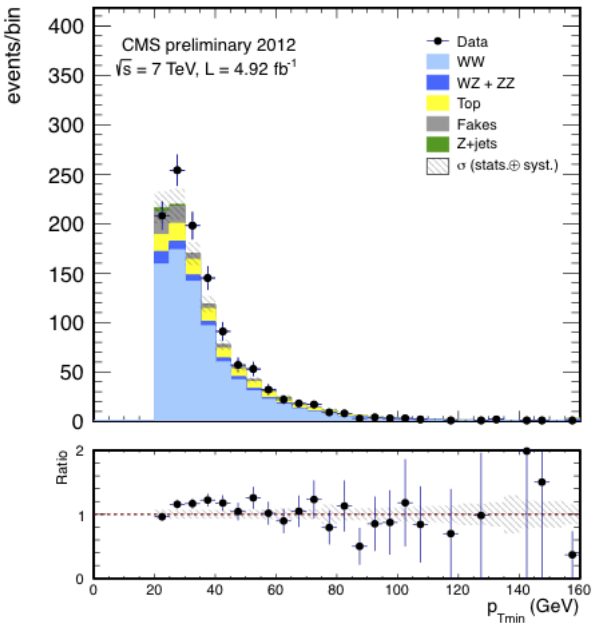
Table 2: Relative systematic uncertainties on the estimated signal and background yields, in units of percent.

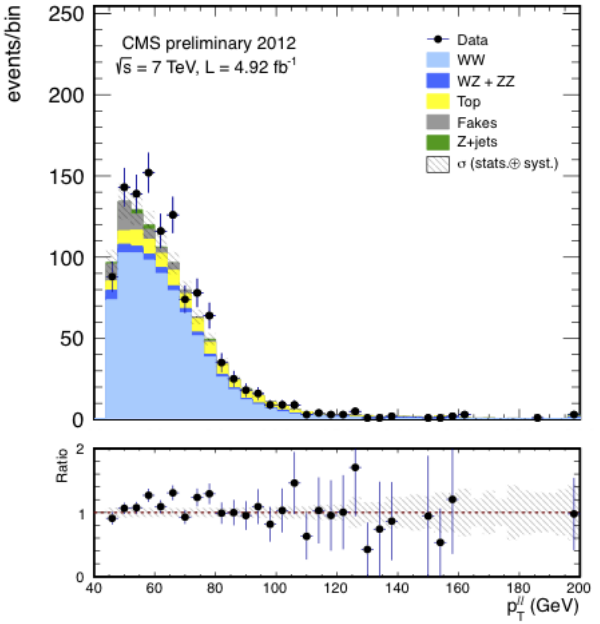
	$q\bar{q} \to W^+W^-$	$gg \to W^+W^-$	top	W + jets	WZ +ZZ	$Z/\gamma* \to \ell\ell$	$W+\gamma$	$W+\gamma^*$	$Z/\gamma* \to \tau\tau$
Luminosity	2.2	2.2	-	-	2.2	-	2.2	-	-
Trigger efficiency	1.5	1.5	-	-	1.5	-	1.5	-	-
Lepton id efficiency	2.0	2.0	-	-	2.0	-	2.0	-	-
Muon momentum scale	1.5	1.5	-	-	1.5	-	1.5	-	-
Electron energy scale	2.5	2.5	-	-	1.9	-	2.0	-	-
E_T^{miss} resolution	2.0	2.0	-	-	2.0	-	2.0	-	-
Jet veto efficiency	4.7	4.7	-	-	4.7	-	4.7	-	-
pile-up	2.3	2.3	-	-	2.3	-	2.3	-	-
top normalisation	-	-	18	-	-	-	-	-	-
W + jets normalisation	-	-	-	36.0	-	-	-	-	-
$Z/\gamma^* \to \ell^+\ell^-$ normalisation	-	-	-	-	-	50.0	-	-	-
$W+\gamma$ normalisation	-	-	-	-	-	-	30.0	-	-
$W+\gamma^*$ normalisation	-	-	-	-	-	-	-	30.0	-
$Z/\gamma^* \to \tau^+\tau^-$ normalisation	-	-	-	-	-	-	-	-	10.0
PDFs	2.3	0.8	-	-	5.9	-	-	-	-
Higher order corrections	1.5	30.0	-	-	3.3	-	-	-	-
Sample statistics	0.8	1.3	-	6.6	1.5	-	48.9	10.3	15.9

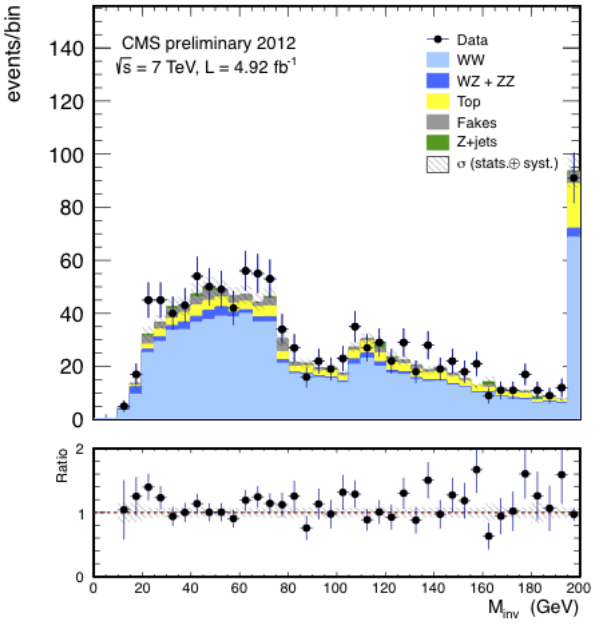
Results

- Distributions after signal selection for 4.92 /fb
- Backgrounds scaled by control regions on data estimations









Results

- Yields for L_{int} = 4.92 /fb (2011)
- Cross section estimated as:

$$\sigma_{WW} = \frac{N_{Data} - N_{bkg}}{L_{int} \cdot \epsilon}$$

  - Efficiency corrected by the corresponding Branching Ratio: BR($W \rightarrow l\nu$) = 0.108

Sample	Yield ± stat. ± syst.
$gg \rightarrow W^+W^-$	$46.0 \pm 0.6 \pm 14.2$
$q\bar{q} \rightarrow W^+W^-$	$750.9 \pm 4.1 \pm 53.1$
$t\bar{t}$ +tW	$128.5 \pm 12.8 \pm 19.6$
W+jets	$59.5 \pm 3.9 \pm 21.4$
WZ+ZZ	$29.4 \pm 0.4 \pm 2.0$
Z/γ^*	$11.0 \pm 5.1 \pm 2.6$
W+γ	$18.8 \pm 2.8 \pm 4.7$
$Z/\gamma^* \rightarrow \tau\tau$	$0.0 \pm 1.0 \pm 0.1$
Total Background	$247.1 \pm 14.6 \pm 29.5$
Signal + Background	$1044.0 \pm 15.2 \pm 62.4$
Data	1134

- Measured cross section for WW

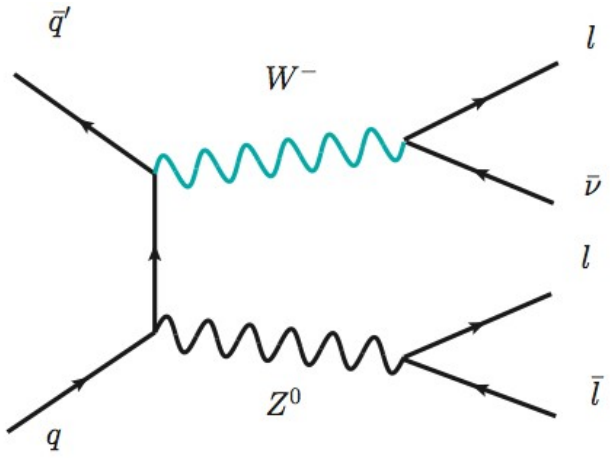
$$\sigma_{WW} = 52.4 \pm 2.0 \text{ (stat.)} \pm 4.5 \text{ (syst.)} \pm 1.2 \text{ (lumi.) pb}$$

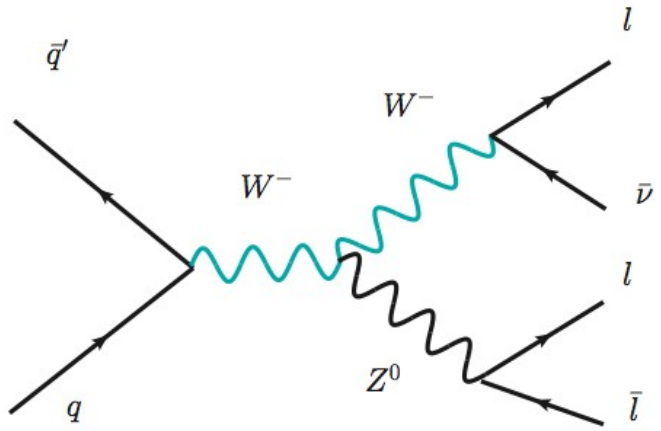
Theoretical prediction: $\sigma_{NLO} = 47.0 \pm 2.0$ pb

WZ process

Introduction – WZ process

- Production mode
  - $q\bar{q}' \rightarrow WZ$





- Experimental Signature
  - Pair of same flavour leptons with opposite sign – Z boson
  - One high p_T lepton and transverse missing E_T – W boson
  - Low hard jet activity
- Major backgrounds
  - Z+jets, ttbar
  - Estimated from control region on data
- Others: ZZ, WZ (tau decays), Zγ
- Public Results with 1.09 /fb (2011 data)
  - CMS EWK – 10 – 010 / CDS Link

WZ Selection

Pair of SF high pT isolated leptons opposite sign **consistent with Z boson**

If more than 1 pair, select the closest to nominal Z mass

+

One high p_T (20 GeV) isolated lepton from **W boson**

Require high missing transverse energy MET > 30 GeV

Reduce Z+jets, ZZ (ttbar, W+jets)

Reduce Z+jets and Zγ

SF : Same flavour final state
OF: Opposite flavour final state

Signal Efficiency

- Used Monte Carlo simulation for the estimation of the signal efficiency
- Correct residual discrepancies data – MC for the lepton, trigger, identification and isolation with **scale factors**
  - Estimate lepton efficiencies for both with Tag & Probe method
- Detailed study of the effect of PDFs and higher order effects for the signal acceptance
- Studied also the effect on several objects for the experimental variations:

  muon momentum, electron energy scale, MET resolution, pile up, etc…

Systematics

Systematics in the signal **efficiency** (experimental) and **acceptance** (theoretical)

Systematics in the signal **efficiency** (experimental)

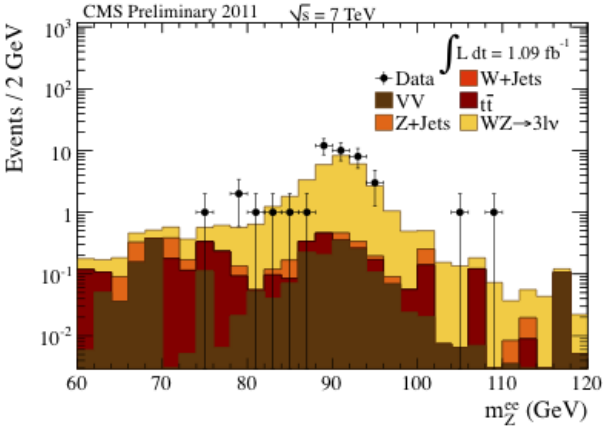
Systematics from the **background estimation**

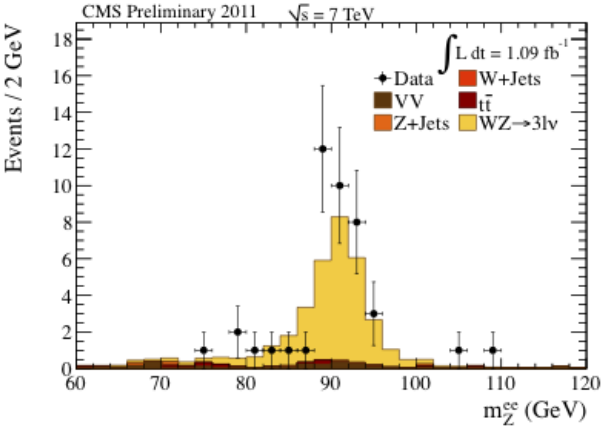
Table 9: Summary of systematic uncertainties for the WZ $\to 3\ell$ cross section measurement.

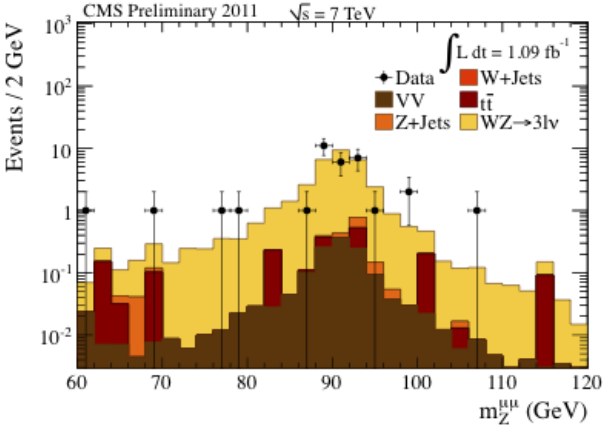
		eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
Source	Systematic uncertainty	Effect on $\mathcal{F} = A \cdot \epsilon_{MC}$			
Electron energy scale	2%	1.7%	0.25%	0.9%	n/a
Muon p_T scale	1%	n/a	0.5%	0.2%	0.9%
MET Resolution		0.5%	0.5%	0.5%	0.5%
MET Scale		0.3%	0.2%	0.1%	0.1%
Pileup		3.1%	0.8%	1.6%	1.6%
PDF	1.0%	1.0%	1.0%	1.0%	1.0%
NLO effect	2.5%	2.5%	2.5%	2.5%	2.5%
Total uncertainty on $\mathcal{F} = A \cdot \epsilon_{MC}$		4.5%	2.9%	3.3%	3.3%
Source	Systematic uncertainty	Effect on ρ_{eff}			
Electron trigger	1.5%	1.5%	1.5%	n/a	n/a
Electron reconstruction	0.9%	2.7%	1.8%	0.9%	n/a
Electron ID and isolation	2.5% (loose), 3.2% (tight)	5.9%	5.0%	3.2%	n/a
Muon trigger	0.54%	n/a	n/a	1.08%	1.08%
Muon reconstruction	0.74%	n/a	0.74%	1.48%	2.22%
Muon ID and isolation	0.74%	n/a	0.74%	1.48%	1.94%
Total uncertainty on ρ_{eff}		6.7%	5.6%	4.2%	3.6%
Source	Systematic uncertainty	Effect on WZ yield			
Background estimation					
ZZ	7.5%	0.2%	0.4%	0.3%	0.4%
$Z\gamma$	13%	0.5%	0.08%	0.04%	0.08%
$t\bar{t}$		1.3%	1.3%	0.9%	0.5%
P_{fake}		3.3%	4.9%	5.2%	4.2%
Source	Systematic uncertainty	Effect on luminosity			
Luminosity	6.0%	6.0%	6.0%	6.0%	6.0%

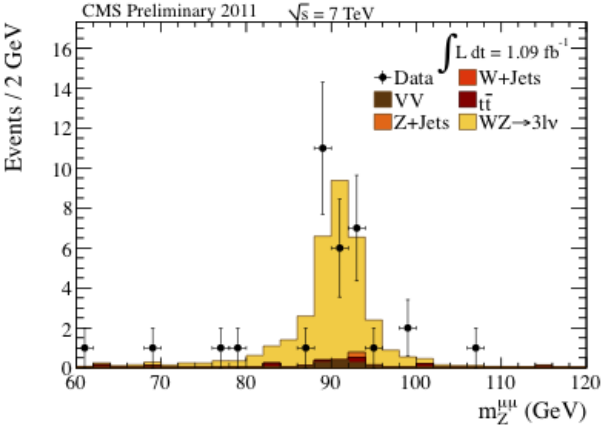
Results

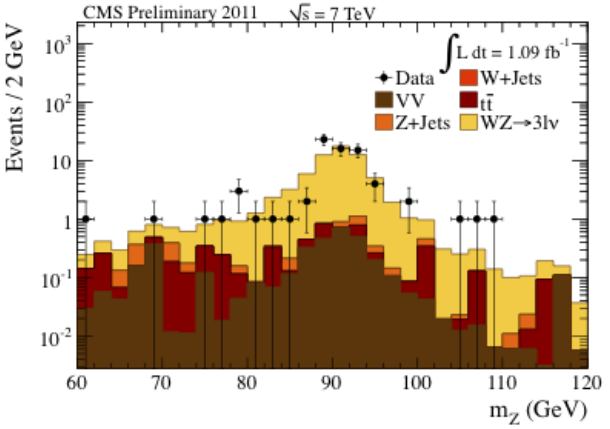
- Distributions after signal selection for 1.09 /fb
- Backgrounds scaled by control regions on data estimations

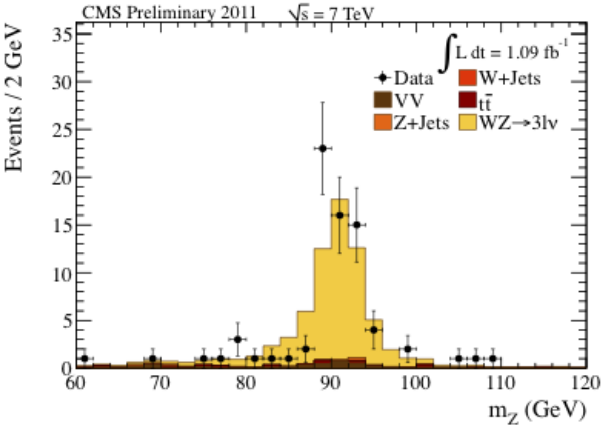












Results

- Results for L_{int} = 1.09 /fb (2011)
- Cross section estimated as:

$$\sigma = \frac{N_{sig}}{A \cdot \epsilon \cdot \mathcal{L}} \longrightarrow \sigma = (1 - f_\tau)\frac{N_{obs} - N_{backg}}{\mathcal{F} \cdot \rho \cdot \mathcal{L}}$$

- f_τ: corrects for the tau decay
- $F\rho$: acceptance x efficiencies, including data-MC corrections

Table 11: Observed WZ candidate events and cross sections for $\int \mathcal{L}\, dt = 1.09$ fb^{-1} per channel

channel	$N_{observed}$	cross section (pb)
$\sigma_{WZ\to eee\nu}$	22	$0.086 \pm 0.022(stat) \pm 0.007(syst) \pm 0.005(lumi)$
$\sigma_{WZ\to ee\mu\nu}$	20	$0.060 \pm 0.017(stat) \pm 0.005(syst) \pm 0.004(lumi)$
$\sigma_{WZ\to \mu\mu e\nu}$	13	$0.053 \pm 0.018(stat) \pm 0.004(syst) \pm 0.003(lumi)$
$\sigma_{WZ\to \mu\mu\mu\nu}$	20	$0.060 \pm 0.016(stat) \pm 0.004(syst) \pm 0.004(lumi)$

- Measured cross sections for the 4 channels are combined, taken into account correlation in systematic uncertainties. Inclusive cross section value:

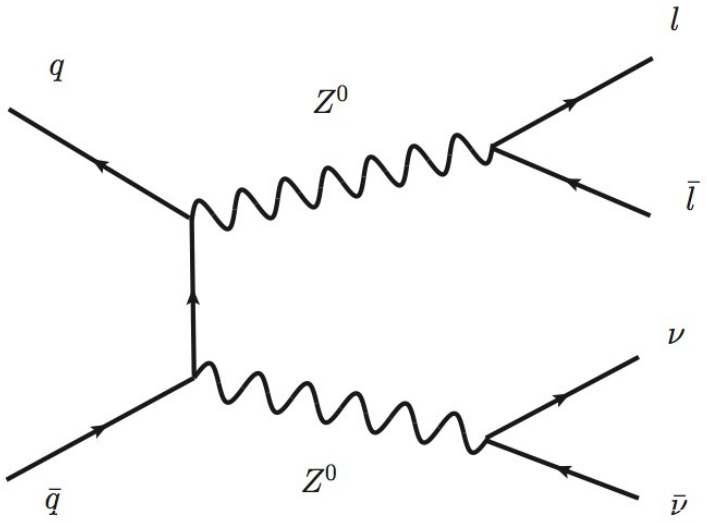
$$\sigma_{WZ} = 17.0 \pm 2.4\ (stat.) \pm 1.1\ (syst.) \pm 1.0\ (lumi.)\ pb$$

Theoretical prediction: $\sigma_{NLO} = 17.5 \pm 0.5$ pb

ZZ process

Introduction – ZZ process

- Production mode
  - $q\bar{q} \rightarrow ZZ$



  - $gg \rightarrow ZZ$

- Experimental Signature
  - Two Pairs of same flavour leptons with opposite sign – 2 Z bosons
  - 4 lepton final states considered: 4e, 4μ, 2e2μ, 2*l*2τ (*l*=e,μ)
  - Tau channels include hadronic decays for the leptons
- Major backgrounds:
  - Zbb/cc, Z+jets, WZ
  - Estimated from control regions on data
- Nearly background free at final selection

- Public Results with 1.09 /fb (2011 data)
  - CMS EWK – 10 – 010 / CDS Link

ZZ Selection

First Z: Pair of SF high pT leptons with opposite sign with m2l > 60 GeV

If more than 1 pair, select the closest to nominal Z mass

At least 1 more high pT lepton of any flavour or sign
+
A fourth high pT lepton with same flavour as previous & opposite sign

Control WZ

Reduce QCD, Z + jets ...

Choice of the best 4l ZZ candidate, such as Z2 with Z1 selected gives m4l > 100 GeV

ID requirements for leptons

Reduce Zbbar/ccbar, ttbar and WZ+jets ...

4e, 2e2μ, 4μ: 60 < mZ1, mZ2 < 120 GeV
2l2τ: 30 < visible mass (ττ) < 80 GeV

Signal efficiency & Systematics

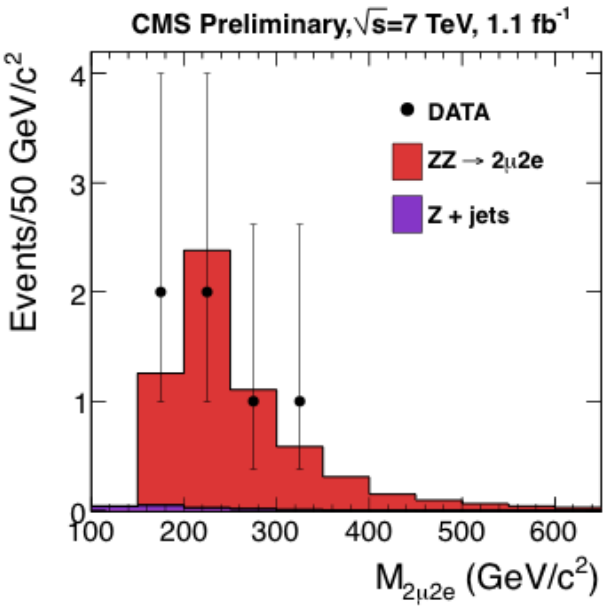
- Several sources of systematics considered
- **Experimental**
  - $4l$ final states: evaluated from data: trigger (1.5%), identification (3%) and isolation (2%) lepton efficiencies, lepton momentum scale (1%)
  - τ channels: additional 6% for τ reconstruction and 3% for energy scale
- **Theoretical**: PDF + α_s and QCD scale

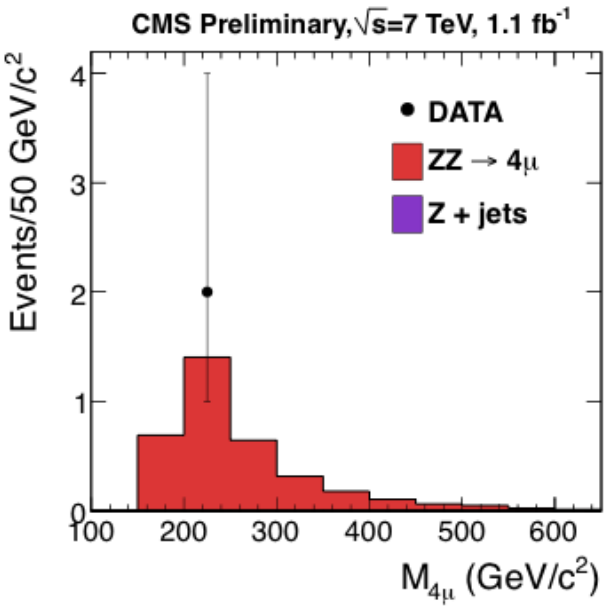
Table 12: Summary of statistical and systematic uncertainties.

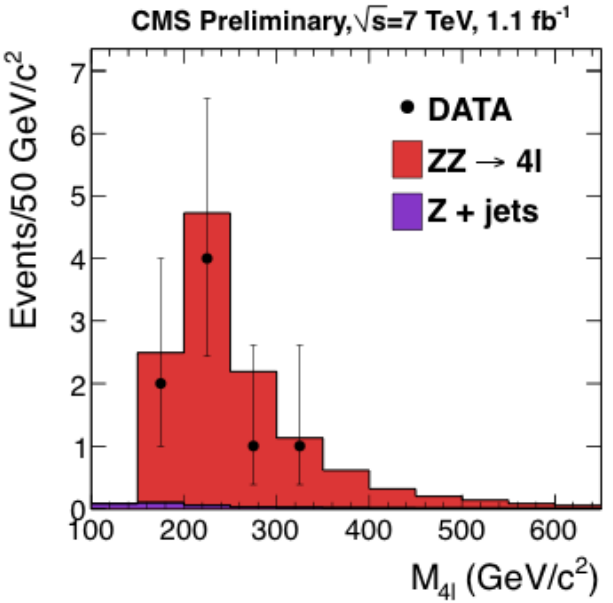
	4μ	4e	$2e2\mu$
source	Effects on acceptance A		
PDF+QCD scale	2.2 %	2.2 %	1.8 %
source	Effects on efficiency ϵ (from [6])		
total uncertainty on ϵ	1.7 %	3.7 %	3.0 %
Background (Z+jets)	100 %	43 %	40 %
Luminosity	6 %		

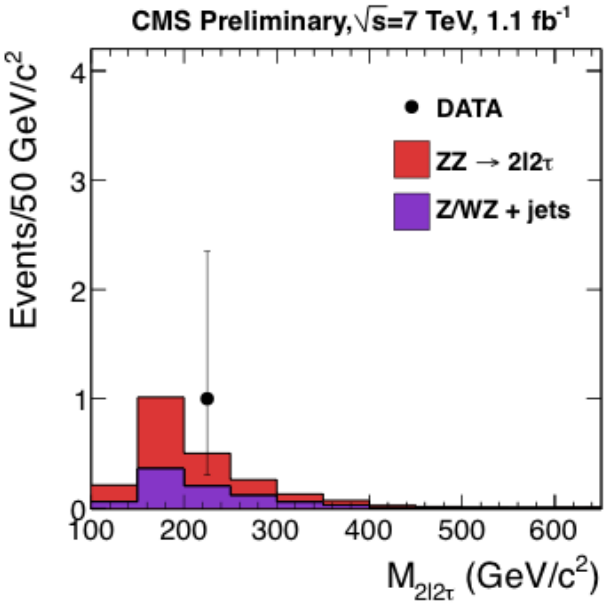
Results

- Distributions after signal selection for 1.10 /fb









Results

- Results for L_{int} = 1.10 /fb (2011)
- Cross section estimated as a simultaneous constrained fit on the number of observed events in all decay channels, using a Likelihood function

Final state	N_{obs}	$N^{backg.}_{estimated}$	$N^{ZZ}_{expected}$
4μ	2	0.004 ± 0.004	3.7 ± 0.4
$4e$	0	0.14 ± 0.06	2.5 ± 0.2
$2e2\mu$	6	0.15 ± 0.06	6.3 ± 0.6
$2l2\tau$	1	0.8 ± 0.1	1.4 ± 0.1

$$\mathcal{L}(r) = \prod_i \mathcal{L}_i(N_i^{obs}, r, S_i, B_i, \nu_S, \nu_B),$$

- N^{obs}: observed events
- r: signal strength
- S: number of expected signal events
- B: number of expected background events
- ν_S, ν_B: statistical and systematics uncert. in form of scaling nuisance parameters

- The resulting cross section was found to be:

$$\sigma_{ZZ} = 3.8^{+1.5}_{-1.2} \text{ (stat.)} \pm 0.2 \text{ (syst.)} \pm 0.2 \text{ (lumi.) pb}$$

Theoretical prediction: σ_{NLO} = 6.4 ± 0.6 pb

Conclusions

- Inclusive cross section measurement for WW, WZ and ZZ Standard Model processes at 7 TeV done with 2011 Data
- The cross section for WW with an integrated luminosity of 4.92 /fb
  - $\sigma_{WW} = 52.4 \pm 2.1\ (stat.) \pm 4.4\ (syst.) \pm 2.5\ (lumi.)$ pb
  - Theoretical expectation 47.0 ± 2.0 pb
- The cross section for WZ with an integrated luminosity of 1.09 /fb
  - $\sigma_{WZ} = 17.0 \pm 2.4\ (stat.) \pm 1.1\ (syst.) \pm 1.0\ (lumi.)$ pb
  - Theoretical expectation 17.5 ± 0.5 pb
- The cross section for ZZ with an integrated luminosity of 1.10 /fb
  - $\sigma_{ZZ} = 3.8\ ^{+1.5}_{-1.2}\ (stat.) \pm 0.2\ (syst.) \pm 0.2\ (lumi.)$ pb
  - Theoretical expectation 6.4 ± 0.6 pb

Conclusions

- Experimental results compatible with the Standard Model predictions
- Measurements for the WZ and ZZ at 7 TeV cross section to be made public soon with the full 2011 Data – 4.92 /fb
- WW, WZ and ZZ cross section measurements at 8 TeV planned with 2012 Data
- Limits on the anomalous TGC also being performed

Back Up Slides

Signal Monte Carlo Production

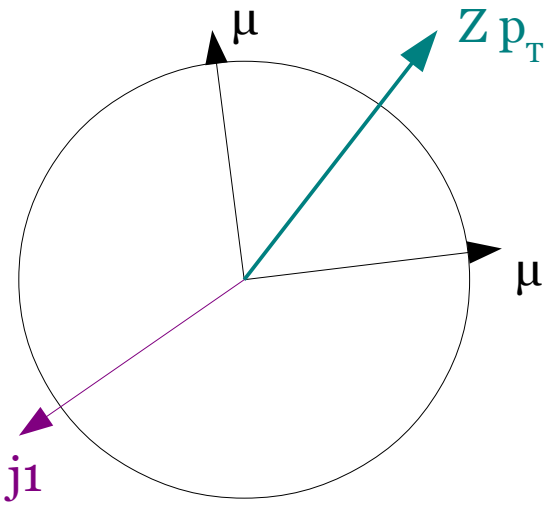
- WW: Madgraph (qq) and GG2WW (gg)
- WZ: PYTHIA
- ZZ: PYTHIA. NLO evaluated with MCFM

WW: Other selections

- Veto events with a third lepton to reduce diboson backgrounds WZ and ZZ

- Same flavour final states: ee and μμ
  - Drell Yan events: Z can recoil against jets in the event
  - Take advantage of the azimuthal angle Φ between the leading low p_T jet and the Z boson direction
  - Reject events with $\Delta\Phi(ll, j) > 165^{\circ}$
    - *j*: leading jet with $15 < p_T < 30$ GeV
    - *ll*: dilepton system → Z boson direction

- Kinematical cut $p_T(ll) > 45$ GeV
  - Further removes DY/Z backgrounds and fakes



WW Backgrounds estimation

- Main backgrounds estimated from control regions on Data
- **Drell-Yan**
  - Control region on data defined by Z mass window. Extrapolate to signal region by ratio out – in
- **Top processes: ttbar and tW**
  - Estimate on data the low pT jet tagging efficiency. Extrapolate from a pure top control region on data with top-tagged events to signal region
- **W+jets and QCD**
  - Fake rate method – probability for a jet to fake a lepton. Weight a data sample with relaxed lepton cuts with this fake rate
- **W + γ***
  - Estimate k-factor to correct the cross section from a pure control sample on data
- **WZ, ZZ, Drell-Yan → ττ, W+γ:** Predicted from MC

WZ Backgrounds estimation

- Main backgrounds estimated from control regions on Data
- **Z+jets and ttbar**
  - [One SF pair within Z mass] & [Jet that can fake a lepton]
  - Estimated from Matrix Method
  - Two data control regions defined by W boson candidates with tight and loose requirements on lepton isolation
  - Measure efficiency for tight isolation on leptons (true) and jets (fake)
  - From measurable number of Tight and Loose events, extrapolate the number of fake W candidates → Z+jets + ttbar events
- **ttbar** remaining from MC
- **WZ → 3*lν* (*l*=τ)** Subtracted from the final as a fraction determined by MC
- **ZZ and Zγ** Small contribution, estimated from MC

ZZ Backgrounds estimation

- Main backgrounds estimated from control regions on Data
  - This channel is very clean and background free
- **Zbbar/ccbar and ttbar**
  - Select the first Z boson (Z1)
  - Remove isolation, flavour and charge requirements for the lepton pair for Z2 & Reverse the impact parameter cut
  - Extrapolate from this region to signal region using the impact parameter distribution. Final contribution < 10^{-3}
- **Z+jets**
  - Select the first Z boson (Z1)
  - Same sign for the second pair of leptons, with inverted isolation and relaxed identification cuts
  - Number of Z+jets events estimated from this control region with the fake rate probability