Diboson production at the LHC with the CMS detector

- Introduction
- ZZ / WZ / WW production cross sections measured with 1.1 fb^{-1}
- $W\gamma$ / $Z\gamma$ production cross sections measured with 36 pb^{-1}
- Limits on anomalous triple gauge couplings

Matthieu Marionneau

On behalf of the CMS Collaboration

EPS-HEP Grenoble

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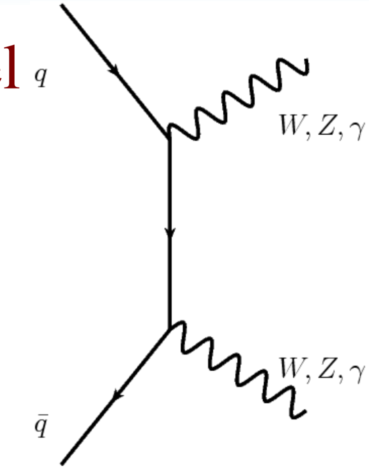
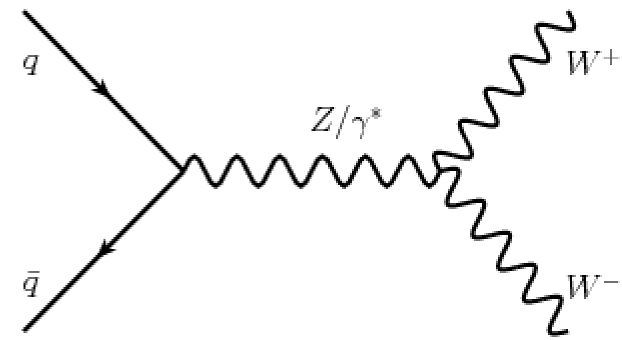
Diboson physics @ the LHC : motivation

Fundamental test of the Standard Model

→ Self interaction between electroweak boson
triple gauge couplings (TGCs)





Probe for new physics

(enhancement of diboson production cross section)

→ Resonances with diboson final states

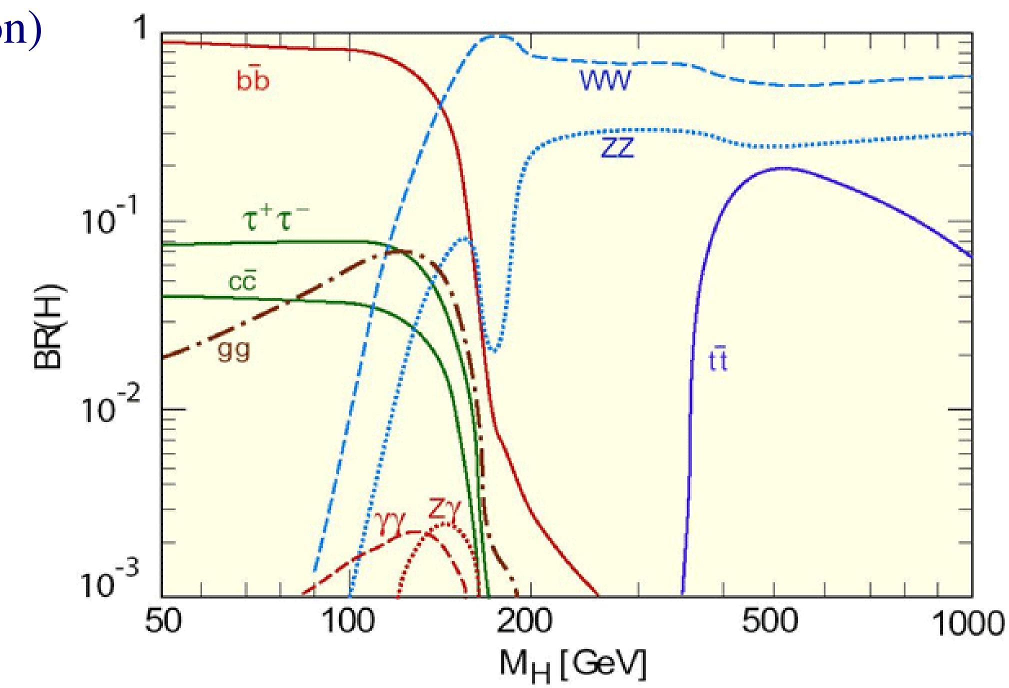
→ Anomalous TGCs

Higgs hunting

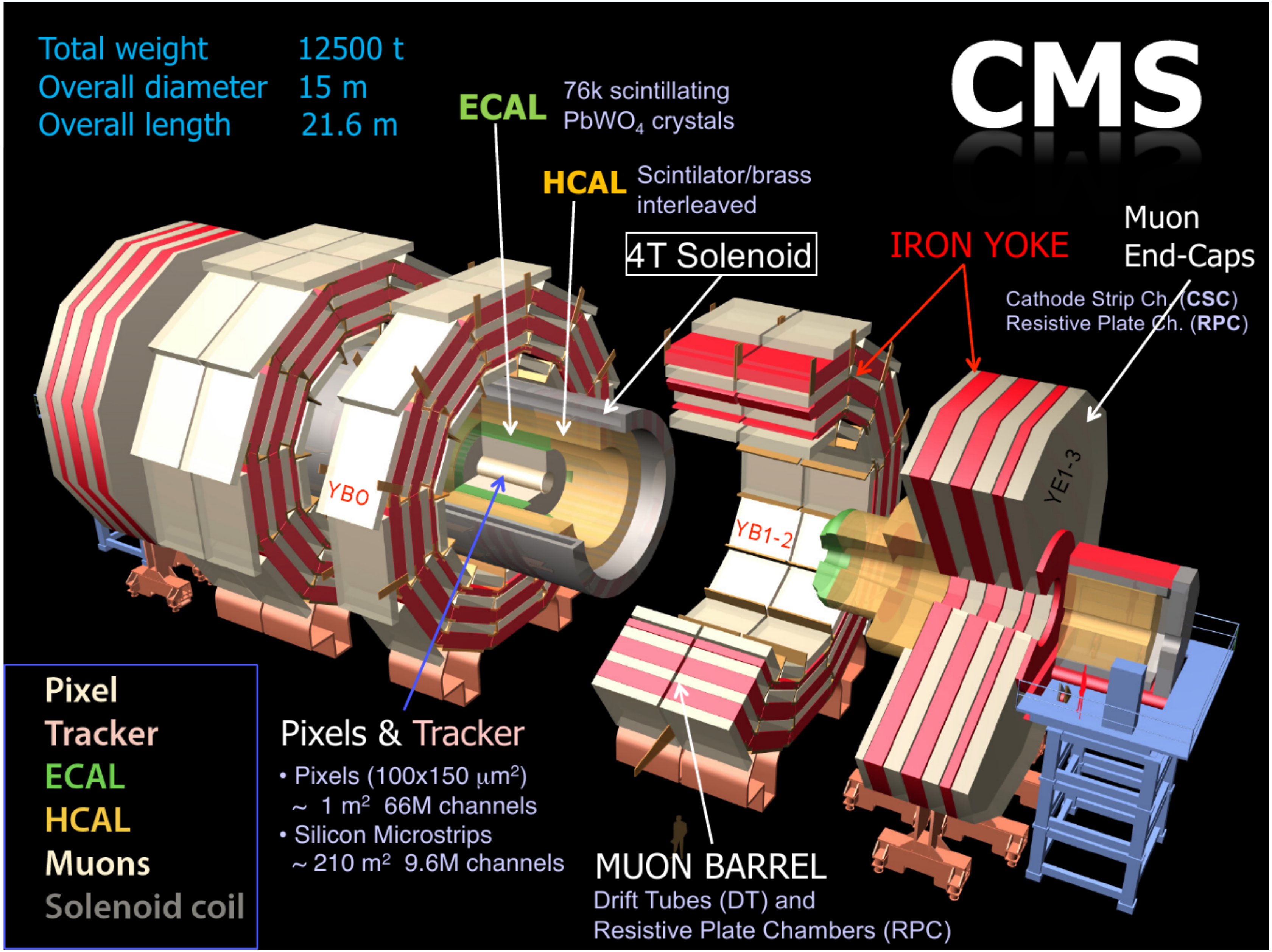
H coupled to electroweak bosons :

→ H → ZZ / H → WW

(see talks by D.Kovalsky and R.Salerno)



The CMS detector



Studied diboson final states

Only fully leptonic modes are considered ($Z^0 \rightarrow l^+ l^-$ and $W^\pm \rightarrow l^\pm \nu$)

- Electron and muon channels for all diboson processes
- Tau channel also in ZZ final state → $ZZ \rightarrow ll\tau\tau$ with $l = e, \mu$

- Advantages
  - Clear signature : isolated leptons (+ possibly missing transverse energy)
  - Low QCD background

- Challenges
  - Low branching ratio (0.09 % to 1%)

Overview of the analyses

- $ZZ \rightarrow 4l$ with 1.1 fb^{-1}
- $WZ \rightarrow 3l\nu$ with 1.1 fb^{-1}
- $WW \rightarrow ll\nu\nu$ with 1.1 fb^{-1}

} NEW results!

- $W\gamma \rightarrow l\nu\gamma$ with 36 pb^{-1}
- $Z\gamma \rightarrow ll\gamma$ with 36 pb^{-1}
- Anomalous triple gauge couplings WWV and $ZV\gamma$ ($V = Z,\gamma$) with 36 pb^{-1}

} Phys.Lett.B701 535-555, 2011; Phys.Lett.B699 25-47,2011

$ZZ \to 4l$: selection

2010 + 2011 data used : 1.1 fb-1

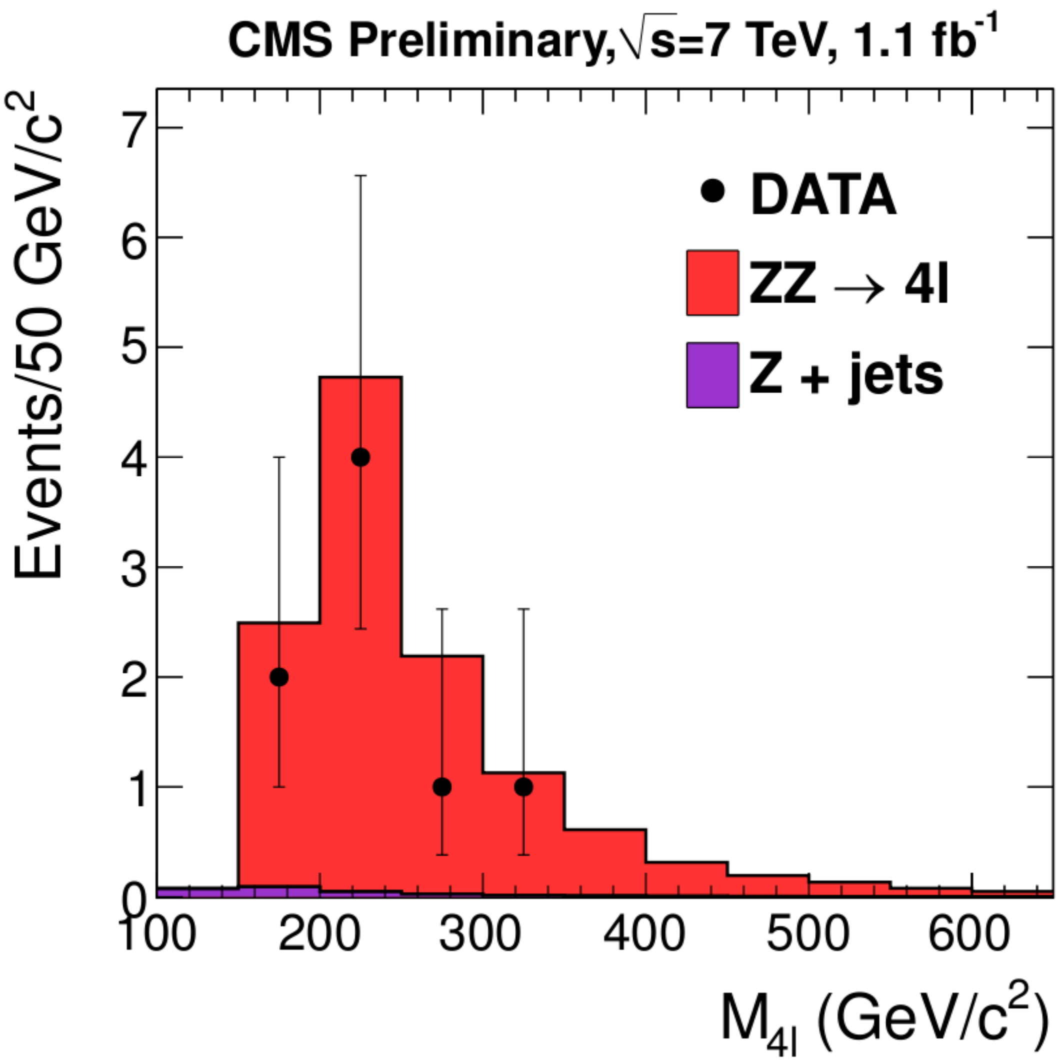
- 2010: Single lepton trigger
- 2011: Double lepton trigger

First Z

- two isolated leptons of same flavor, opposite signs, $p_T > 20 / 10$ GeV
- $60 < m_{ll} < 120$ GeV

Second Z

- $ZZ \to 4e$, 4μ and $2e2\mu$ final states
  - two isolated leptons of same flavor, opposite signs, $p_T > 7$ (5) for e (μ)
  - $60 < m_{ll} < 120$ GeV



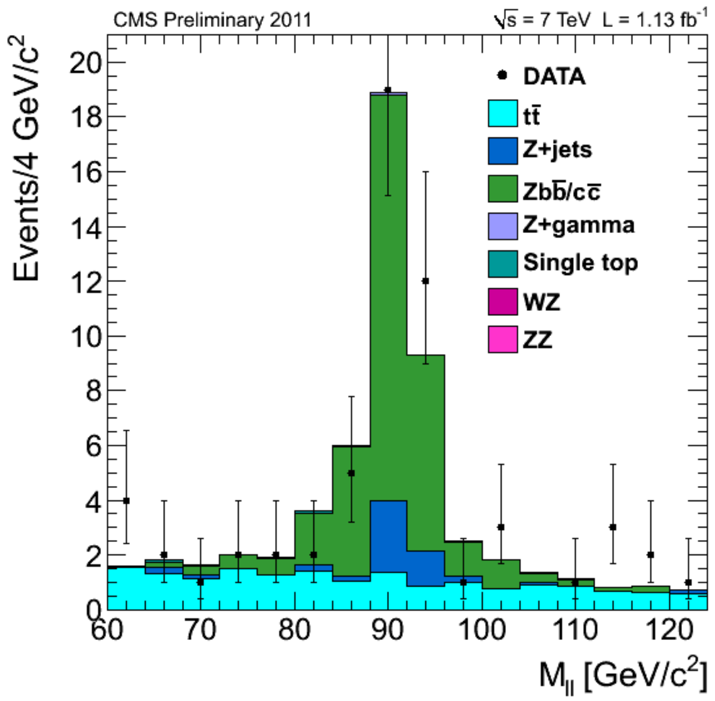
- $ZZ \to 2l2\tau$ ($l = e,\mu$) final state :
  - τ ($p_T > 15$ GeV) $\to$ lepton ($p_T > 10$ GeV) / hadron ($p_T > 20$ GeV)
  - 30 < visible mass of di-tau system < 80 GeV

$ZZ \to 4l$: remaining backgrounds

Background processes :

➞ Zbb / ttbar : reduced and estimated using lepton impact parameter value

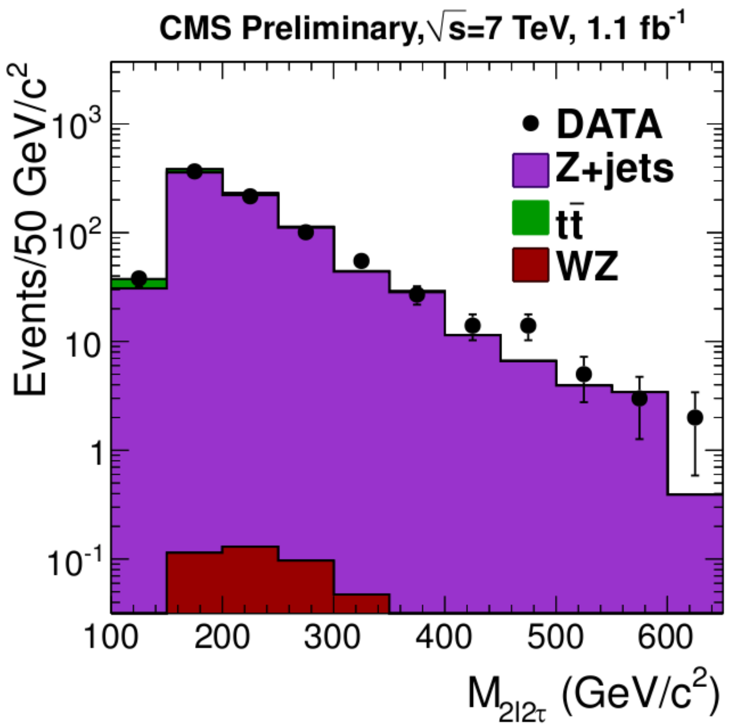
➞ Z + jet : reduced and estimated using identification and isolation variables



Mass of the best reconstructed Z in the Zbb/ttbar control sample

(relaxed cuts on isolation / impact parameter / flavour / charge)

($ZZ \to 4l$ channel ($l=e,\mu$))



Visible mass of the $2l2\tau$ system in the Z+jet control sample

(relaxed cut on isolation / flavour / charge)

($ZZ \to 2l2\tau$ channel)

ZZ cross section @ $\sqrt{s}$ = 7 TeV

Signal selection efficiency : computed with the Tag and Probe method

Number of selected events

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

Uncertainties

source	uncertainty
trigger	1.5%
lepton identification	3%
lepton isolation	2%
lepton energy scale	1%
τ reconstruction	6%
τ energy scale	3%

Cross section computed with a constrained fit using all channels :

$$\sigma(pp \rightarrow ZZ + X) = 3.8^{+1.5}_{-1.2}\,(\text{stat.}) \pm 0.2\,(\text{syst.}) \pm 0.2\,(\text{lumi.})\ \text{pb}$$

NLO Prediction (MCFM) : 6.4 ± 0.6 pb

$WZ \rightarrow 3l\nu$: selection

2011 data : 1.1 fb^{-1}

Z selection :

- Two isolated leptons with $p_T > 20$ /10 GeV (electrons) or $p_T > 15$ GeV for muons
- $60 < m_{ll} < 120$ GeV.
- Ambiguities solved by taking the Z candidate with mass closest to nominal Z mass

W selection :

- Third isolated lepton with $p_T > 20$ GeV

Which backgrounds after selection ?

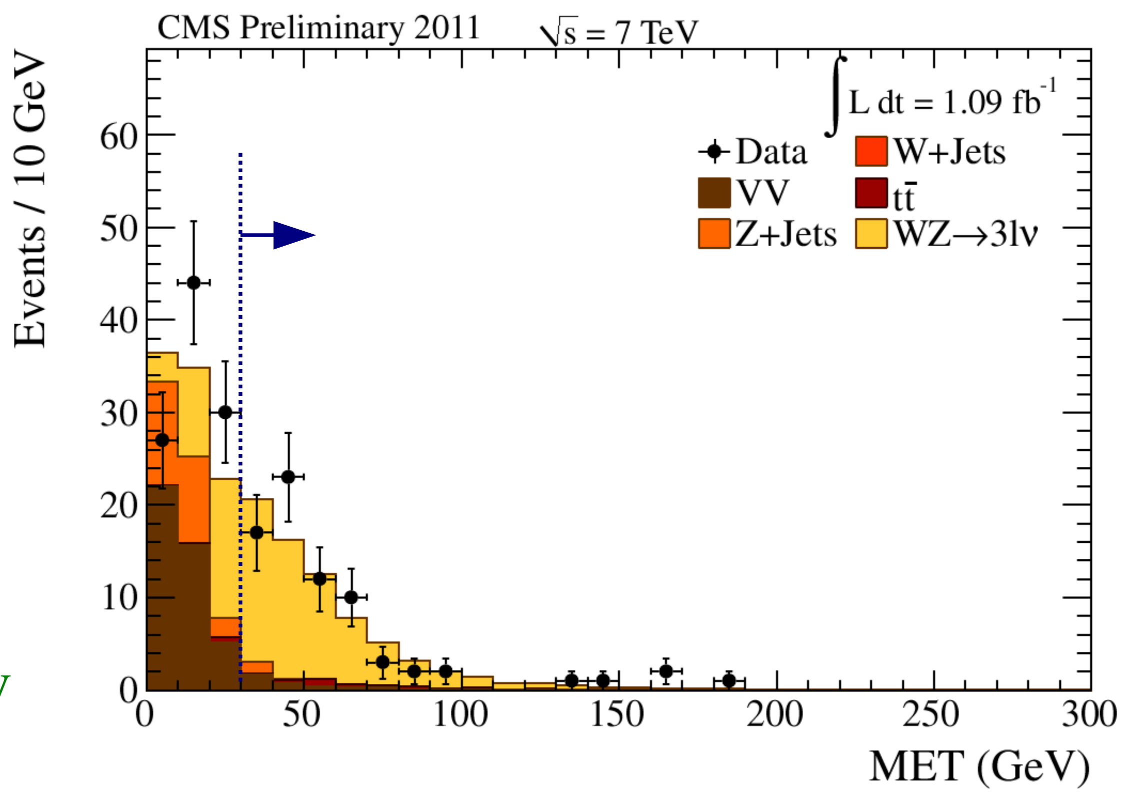
- Z+jet (jet faking a lepton)
- Top background
- Zγ (photon faking an electron)
- $ZZ \rightarrow 4l$

Rejection of ZZ :

→ Veto on a second reconstructed Z

Rejection of Z+jet and Zγ background :

→ Missing transverse energy > 30 GeV



$WZ \rightarrow 3l\nu$: remaining backgrounds and selection efficiency

Data driven estimations for
Z+jets and top backgrounds :
→ "Matrix" method $N_{sel} = \varepsilon.N_{WZ} + p_{fake}.N_{Zjet}$

MonteCarlo simulation estimations :
→ $Z\gamma$
→ $ZZ \rightarrow 4l$
Assigned systematic uncertainty : 20 %

background	N_{bkg}
Z+jet and top	8.1
other backgrounds	~ 1

Total selection efficiency $A \cdot \varepsilon \cdot \rho$

- $A \cdot \varepsilon$: selection efficiency on MonteCarlo simulation sample
- ρ : correction factor obtained on a control sample (T&P : inclusive Z, data and simulation)

Main uncertainties :

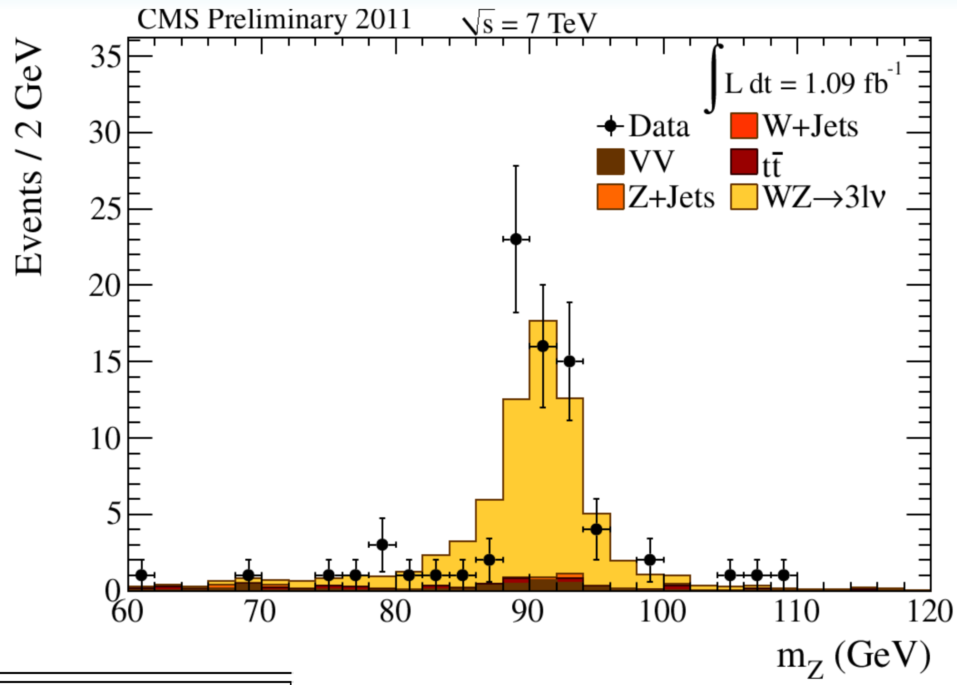
	uncertainty	main sources
$\mathcal{F} = A.\epsilon$	$2.8 - 3.2\%$	NLO Effects / PDFs / Lepton energy scale
ρ	$3.6 - 6.7\%$	reconstruction/ ID /isolation
background	$1.5 - 2.8\%/3.5 - 5.5\%$	top / Z+jet

$WZ \rightarrow 3l\nu$ cross section @ $\sqrt{s}$ = 7 TeV

What about ZW → (ll)(τν) ?

- Fraction f_τ of WZ selected events containing a τ is estimated from simulation : $f_\tau \sim 6\%$
- This fraction is subtracted in the cross section calculation :

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



Results for each channel :

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

Combined : $\sigma(pp \rightarrow \mathrm{WZ} + X) = 17.0 \pm 2.4\ (\mathrm{stat.}) \pm 1.0\ (\mathrm{syst.}) \pm 1.0\ (\mathrm{lumi.})\ \mathrm{pb}$

NLO prediction : 19.8 ± 0.1 pb

$WW \rightarrow 2l2\nu$: 2011 selection

Signal signature :

- Two isolated high p_T leptons and significant missing transverse energy from neutrinos
- Leading lepton $p_T > 20$ GeV, trailing lepton $p_T > 10$ GeV

W+jet / top background rejection :

→ Jet-veto (30 GeV) and b-tagging veto

WZ / ZZ rejection :

→ Third lepton veto

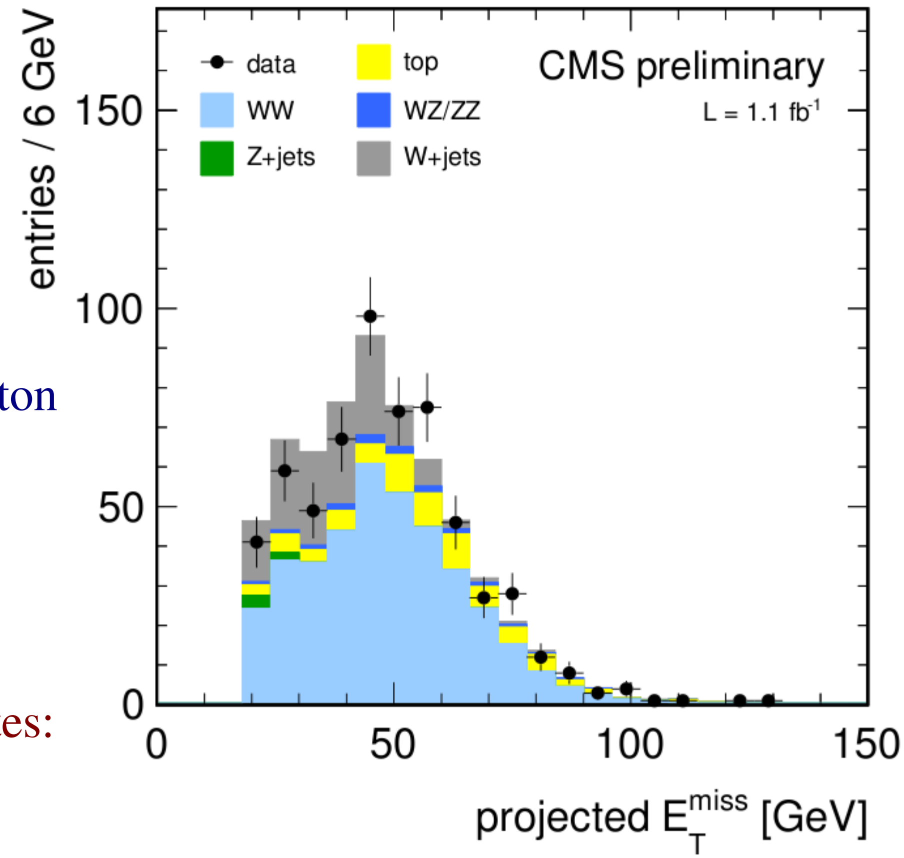
$Z \rightarrow \tau\tau$, missing E_T along the lepton axes

→ Projection along the transverse axis of the nearest lepton

Fake missing E_T in Z+jet events :

→ Missing E_T treatment against pile-up

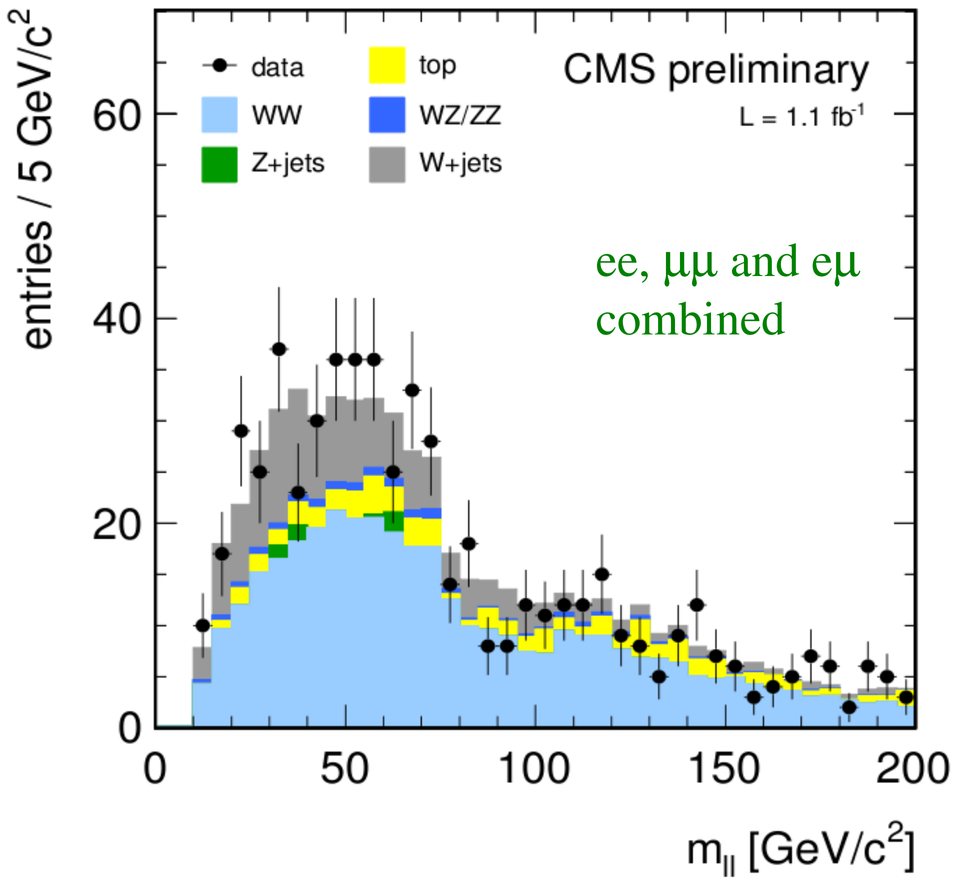
→ Missing ET > 40 (20) GeV for ee/μμ (eμ) final state



Drell-Yan background reduction for same flavour final states:

- m_{ll} >12 GeV
- Veto window $76 < m_{ll} < 106$ GeV
- $\Delta\phi$(di-lepton, remaining jet $p_T > 15$ GeV) < 165°

$WW \to 2l2\nu$: background estimation, selection efficiencies



Background estimation :

- Data-driven methods for dominant backgrounds
  - → QCD / W+jet
  - → Top
  - → Z / WZ / ZZ
- MonteCarlo simulation for smaller backgrounds
  - → Wγ
  - → $Z \to \tau\tau$
  - → non resonnant WZ/ ZZ

Efficiencies :

- Tag and Probe method for lepton related efficiencies
- Jet veto : simulation plus correction with a Z+jet control sample
- Missing E_T selection : simulation

Total selection efficiency : $\varepsilon = 6.7 \pm 0.5$ %

$WW \rightarrow 2l2\nu$ cross section @ $\sqrt{s}$ = 7 TeV

Number of events

Sample	Yield
$qq \rightarrow W^+W^-$	349.7 ± 30.3
$gg \rightarrow W^+W^-$	17.2 ± 1.6
W + jets	106.9 ± 38.9
$t\bar{t} + tW$	63.8 ± 15.9
$Z/\gamma^* \rightarrow \ell\ell + WZ + ZZ$	12.2 ± 5.3
$Z/\gamma^* \rightarrow \tau\tau$	1.6 ± 0.4
WZ/ZZ not in $Z/\gamma^* \rightarrow \ell\ell$	8.5 ± 0.9
$W + \gamma$	8.7 ± 1.7
signal + background	568.6 ± 52.2
Data	626

Main uncertainties

source	uncertainty
background estimation	$\sim 20\%$
W + jet	36%
top	25%
signal efficiency	$\sim 8\%$
lepton efficiencies	$1.5 - 2.5\%$
E_T^{miss} resolution	2.0%
jet counting	5.5%

In 2011 with 1.1 fb^{-1} : $\sigma_{W^+W^-} = 55.3 \pm 3.3\,(\text{stat}) \pm 6.9\,(\text{syst}) \pm 3.3\,(\text{lumi})$ pb

In 2010 with 36 pb^{-1} : $\sigma_{W^+W^-} = 41.1 \pm 15.3\,(\text{stat}) \pm 5.8\,(\text{syst}) \pm 4.5\,(\text{lumi})$ pb.

NLO prediction : 43.0 ± 2.1 pb (qq → WW) + 1.46 pb (gg → WW)

$W\gamma \rightarrow l\nu\gamma$: selection

2010 data : 36 pb^{-1}

Final state of interest includes initial and final state radiation (ISR / FSR) as well as WWγ TGC

W selection : Isolated lepton p_T > 20 GeV
Missing E_T > 25 GeV

Photon selection : E_T > 10 GeV
$\Delta R(l,\gamma) > 0.7$ (avoid soft γ divergence)

No additional lepton

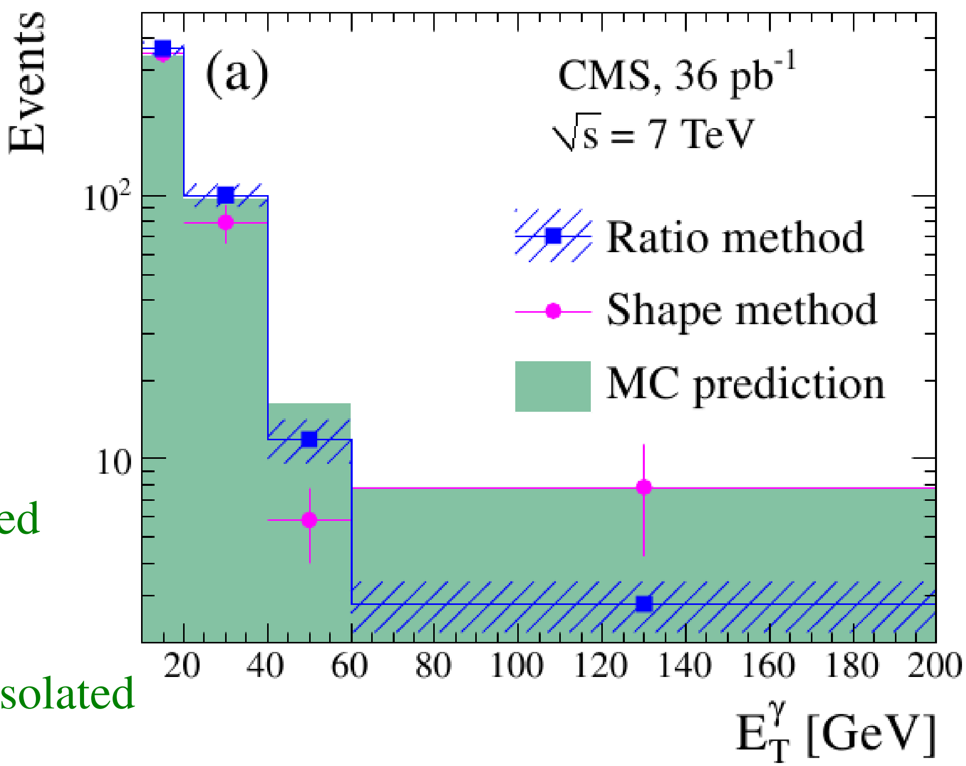
Dominant background : W + jet

- Rejected with tight isolation on photon
- Estimated with two data-driven method

→ Shower shape variable distribution fit with templated PDFs + signal component extraction

→ Use of the ratio between number of isolated / non-isolated photon, estimated on a QCD control sample

W+jet background estimation



Other backgrounds are estimated with MonteCarlo simulation

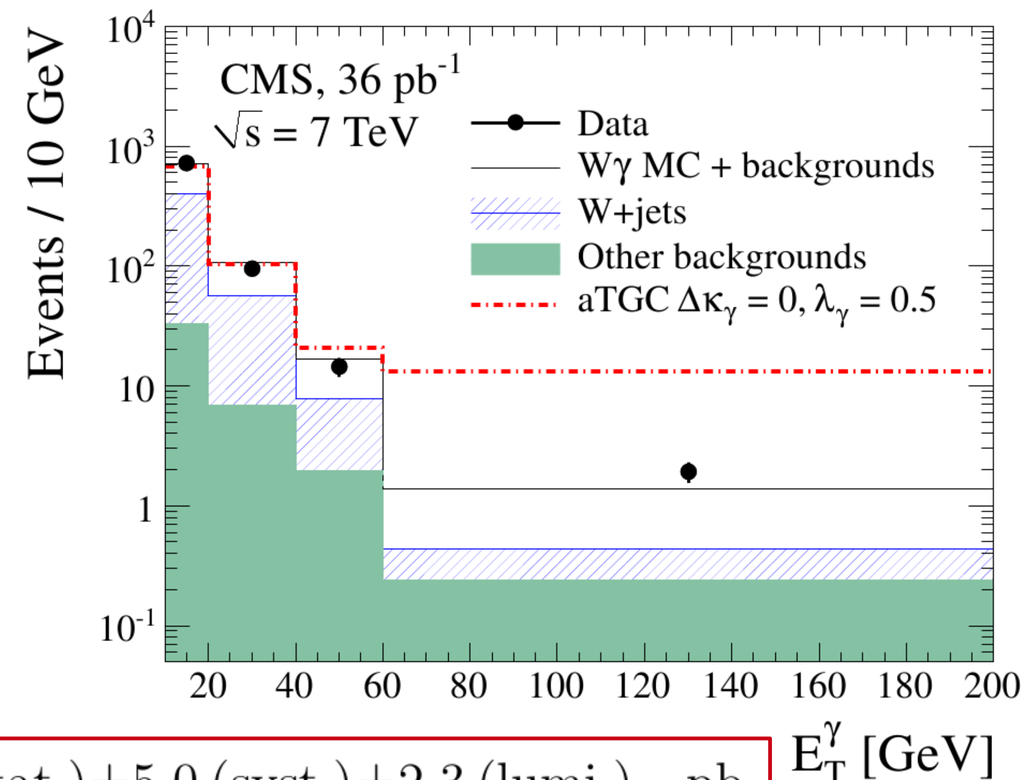
$W\gamma \rightarrow l\nu\gamma$ cross section @ $\sqrt{s}$ = 7 TeV

Main systematic uncertainties

	uncertainty	main sources
$A.\epsilon$	5.2 – 6.1%	PDFs / energy scales
ρ	1.6 – 1.9%	γ ID-Isolation / E_T^{miss} selection
backgrounds	6.3%	W + jet

Number of selected events

process	$N_{bkg}^{e\nu}$	$N_{bkg}^{\mu\nu}$
W+jet	$220 \pm 16 \pm 14$	$261 \pm 19 \pm 16$
other backgrounds	7.7 ± 0.5	16.4 ± 1.0
all data	452	520



Measured cross section with 36 pb^{-1} :

(E_T > 10 GeV , $\Delta R(l,\gamma) > 0.7$)

$$\sigma(pp \rightarrow W\gamma + X) \times \mathcal{B}(W \rightarrow \ell\nu) = 56.3 \pm 5.0\ (\text{stat.}) \pm 5.0\ (\text{syst.}) \pm 2.3\ (\text{lumi.})\quad \text{pb}$$

NLO prediction : 49.4 ± 3.8 pb

$Z\gamma \rightarrow ll\gamma$: selection

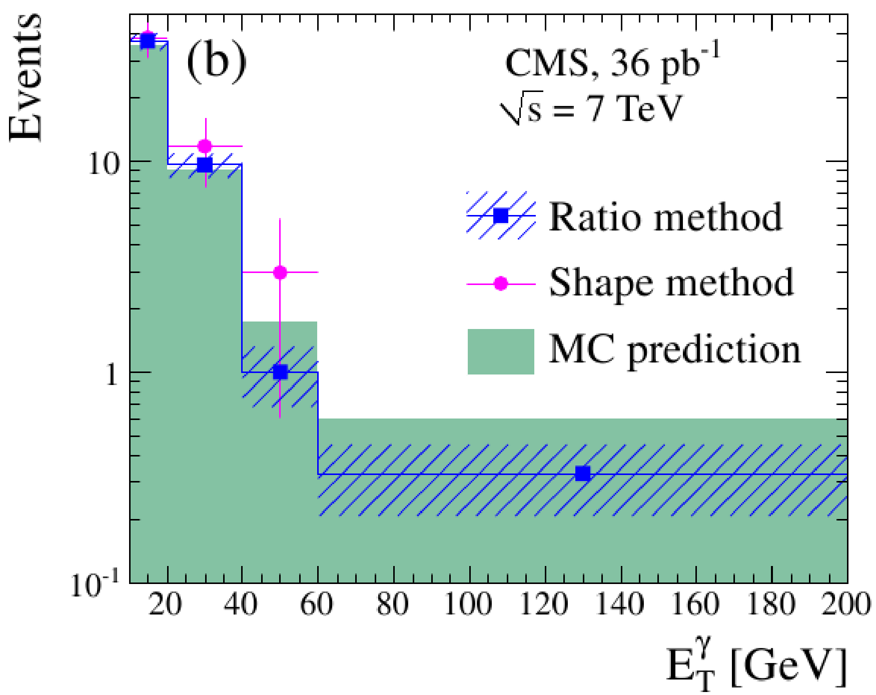
ZZγ and Zγγ not allowed by SM : only ISR and FSR contribution

Z selection : two isolated lepton with $p_T > 20$ GeV

$m_{ll} > 50$ GeV

Photon selection : $E_T > 10$ GeV and $\Delta R(l,\gamma) > 0.7$

Z+jet background estimation



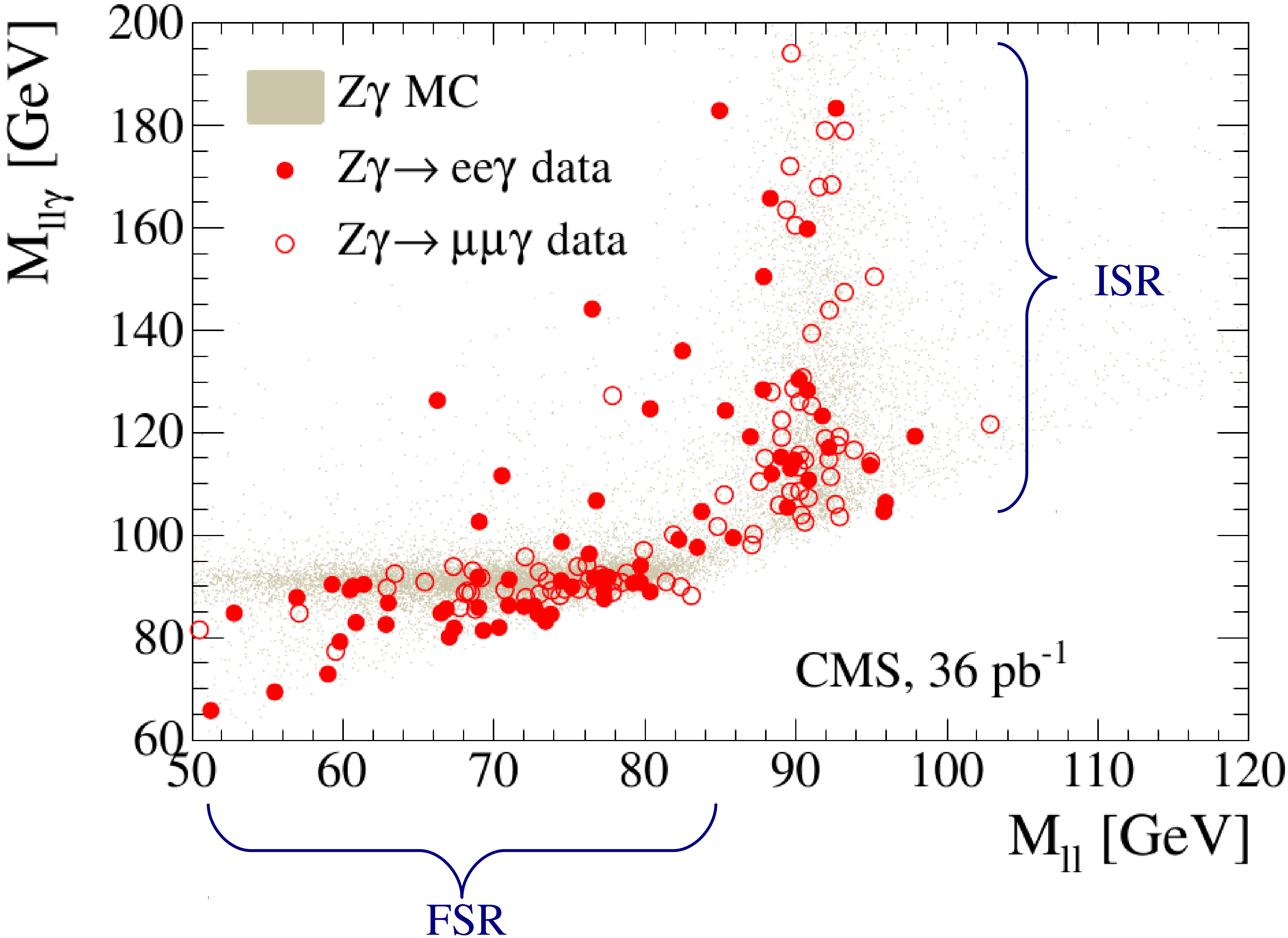
Large background contribution from Z + jet process :

- Same data driven estimation as for Wγ
- Other backgrounds estimated with simulation

Main systematic uncertainties :

	uncertainty	main sources
$A.\epsilon$	4.3 – 5.8%	PDFs / energy scales
ρ	1.5%	γ / lepton ID-Isolation
backgrounds	9.3 – 11.4%	Z + jet

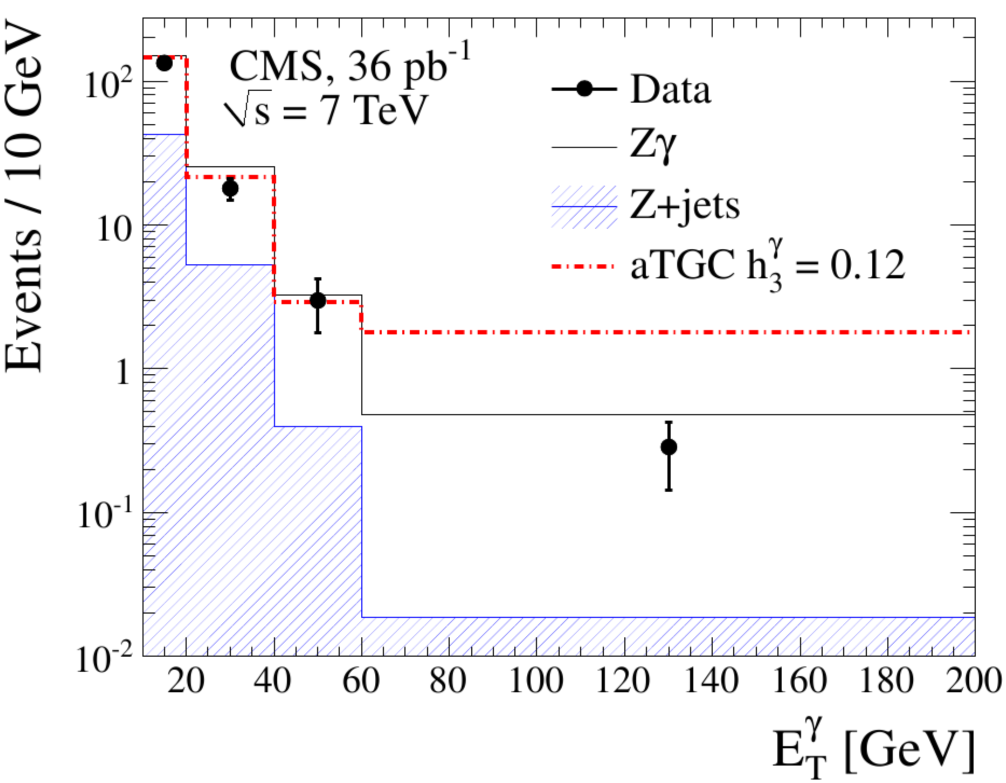
$Z\gamma \rightarrow ll\gamma$: separation between ISR and FSR



$Z\gamma \rightarrow ll\gamma$ cross section @ $\sqrt{s}$ = 7 TeV

Number of selected events

process	N^{ee}_{bkg}	$N^{\mu\mu}_{bkg}$
Z+jet	$20.5 \pm 1.7 \pm 1.9$	$27.3 \pm 2.2 \pm 2.3$
other backgrounds	neglected	
all data	81	90



Measured cross section with 36 pb^{-1} :

(E_T > 10 GeV , $\Delta R(l,\gamma)$ > 0.7, m_{ll}> 50 GeV)

$$\sigma(pp \rightarrow Z\gamma + X) \times \mathcal{B}(Z \rightarrow \ell\ell) = 9.4 \text{ pb} \pm 1.0 \text{ (stat.)} \pm 0.6 \text{ (syst.)} \pm 0.4 \text{ (lumi.)}$$

NLO prediction : 9.6 ± 0.4 pb

Limits on aTGCs : $WW\gamma$/ $ZZ\gamma$/ $Z\gamma\gamma$

Deviation to SM modelled by an effective Lagrangian

- No form-factor
- SU(2)xU(1) gauge invariance
- No C/P-violating parameters

Two parameters for WWγ : $\Delta\kappa_\gamma = 1-\kappa_\gamma$ (SM $\Delta\kappa_\gamma$=0), $\lambda_\gamma=\lambda_Z$ (SM =0)

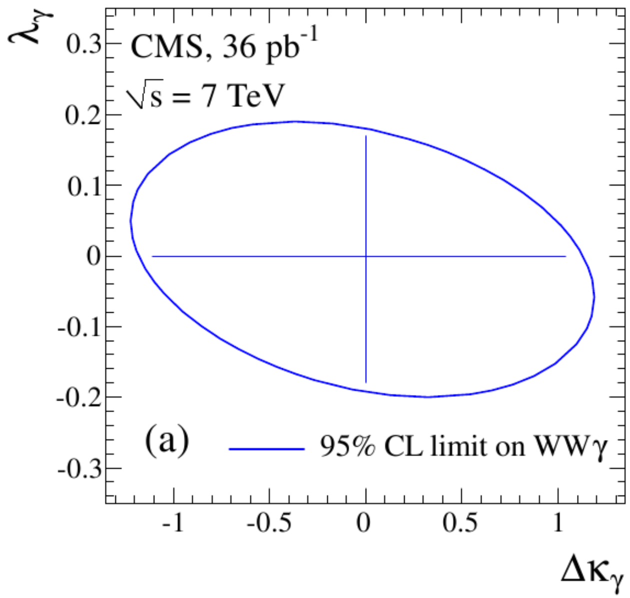
ZVγ (V=Z,γ) : h_3^γ, h_4^γ and h_3^Z, h_4^Z (=0 at tree level in SM)

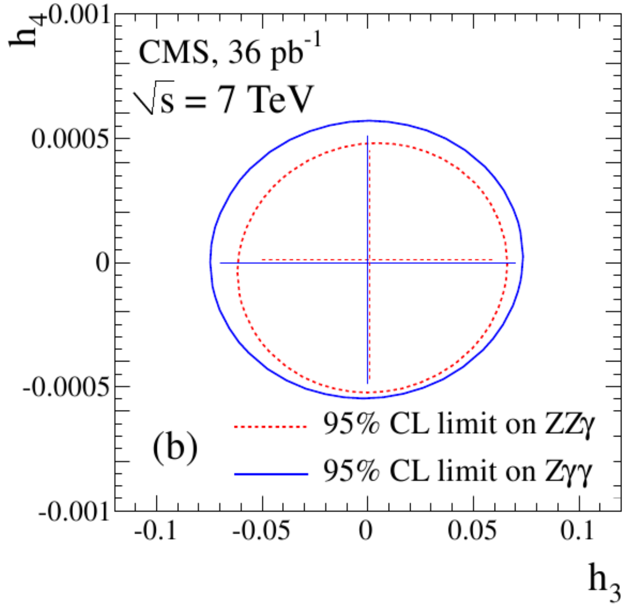
Limits obtained by using a profiled likelihood based on the E_T spectrum of the photon

Baur and Sherpa MC tools used for generation with aTGCs

$WW\gamma$	$ZZ\gamma$	$Z\gamma\gamma$
$-1.11 < \Delta\kappa_\gamma < 1.04$	$-0.05 < h_3 < 0.06$	$-0.07 < h_3 < 0.07$
$-0.18 < \lambda_\gamma < 0.17$	$-0.0005 < h_4 < 0.0005$	$-0.0005 < h_4 < 0.0006$

Sensitivity similar to that of the Tevatron
Stringent limit on h_4





Anomalous TGC from WW analysis : WWV

2010 data : 36 pb^{-1}

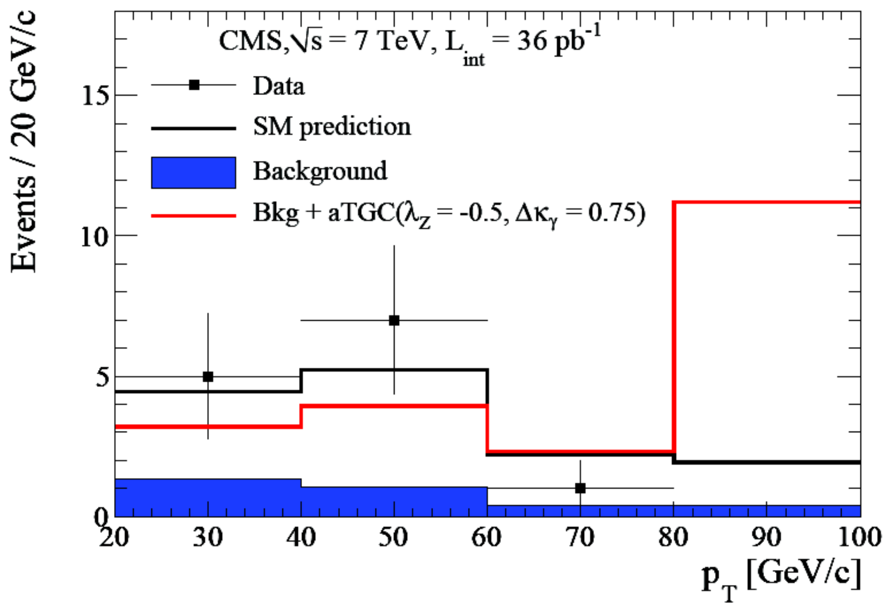
Same assumptions as for WWγ from Vγ analysis

Three parameters : λ_Z (=0 in SM)

κ_λ and g_1^Z (=1 in SM) → $\Delta\kappa_\lambda$ / Δg_1^Z

Limits set using the leading lepton transverse momentum spectrum (unbinned fit)

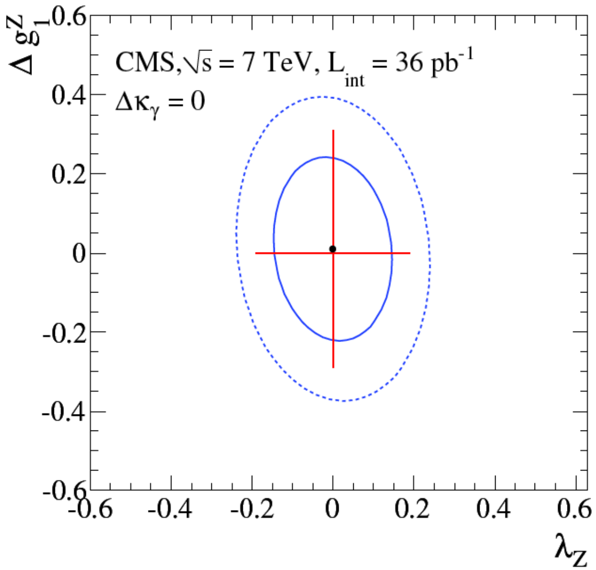
	λ_Z	Δg_1^Z	$\Delta\kappa_\gamma$
Unbinned fit	$[-0.19, 0.19]$	$[-0.29, 0.31]$	$[-0.61, 0.65]$

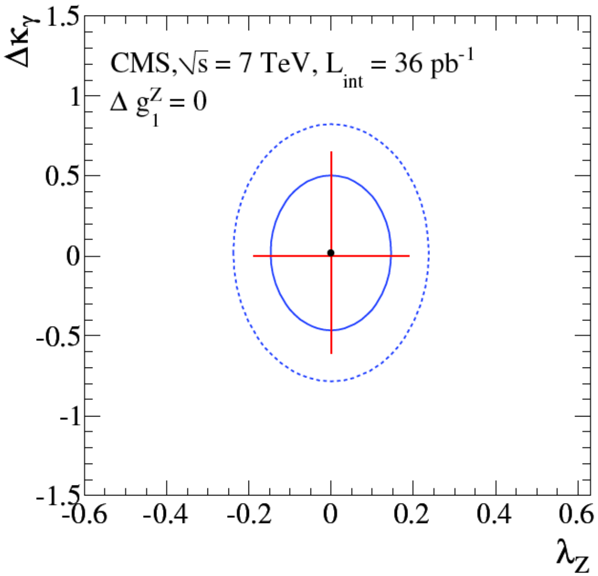


Modelisation of aTGCs with Sherpa and MCFM

Similar sensitivity to Tevatron results presented in :

- Phys. Rev. Lett. 104 (2010) 201801
- Phys. Rev. Lett. 103 (2009) 191801





Summary

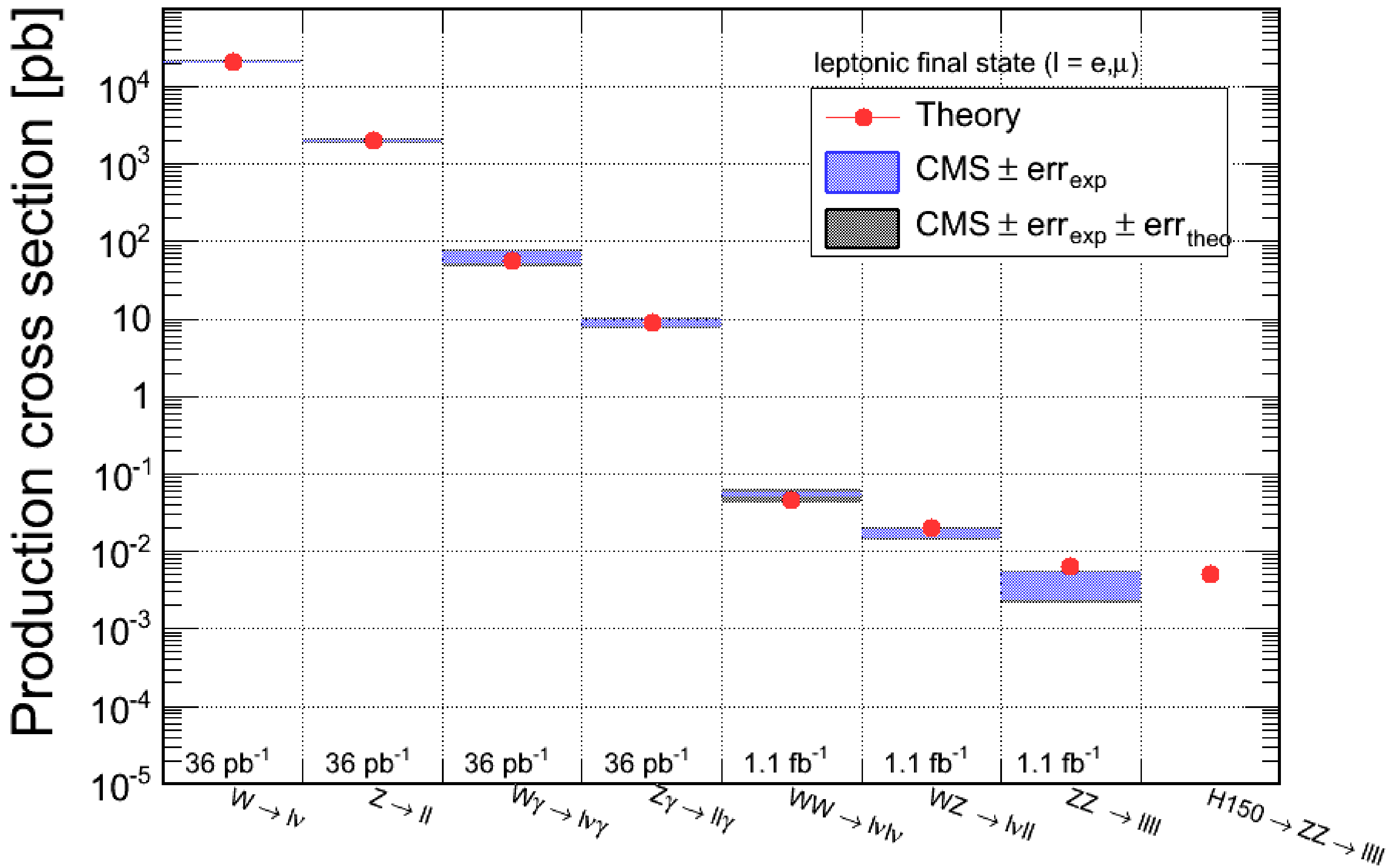
Diboson processes WW, WZ, ZZ, Wγ and Zγ measured in CMS
using 36 pb^{-1} (2010) or 1fb^{-1} (2011)

Measured cross sections in agreement with Standard Model expectations

Limits on WWγ, ZZγ and Zγγ anomalous triple gauge coupling values with sensitivity similar to that of the Tevatron, using 2010 data

More exiting results with the increasing of luminosity

Where are we now ?



Backup

ZZ 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 %		

WZ systematic uncertainties

		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%
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 $\mathcal{F} = A \cdot \epsilon_{MC}$		3.2%	2.8%	2.9%	2.9%
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%(WP95), 3.2%(WP80)	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	20%	0.4%	1.1%	0.7%	1.1%
$Z\gamma$	20%	0.08%	0.01%	0.005%	0.01%
$t\bar{t}$		1.5%	1.8%	2.8%	1.7%
P_{fake}		3.5%	5.2%	5.5%	4.0%
Source	Systematic uncertainty	Effect on luminosity			
Luminosity	6.0%	6.0%	6.0%	6.0%	6.0%

WW systematic uncertainties

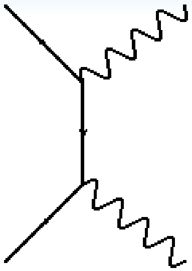
Source	$qq \rightarrow$ W^+W^-	$gg \rightarrow$ W^+W^-	non-Z resonant WZ/ZZ	top	DY	W + jets	$V(W/Z)$ $+\gamma$
Luminosity	—	—	6	—	—	—	6
Trigger efficiencies	1.5	1.5	1.5	—	—	—	1.5
Muon efficiency	1.5	1.5	1.5	—	—	—	1.5
Electron id efficiency	2.5	2.5	2.5	—	—	—	2.5
Momentum scale	1.5	1.5	1.5	—	—	—	1.5
E_T^{miss} resolution	2.0	2.0	2.0	—	—	—	1.0
pile-up	1.0	1.0	1.9	—	—	—	1.0
Jet counting	5.5	5.5	5.5	—	—	—	5.5
PDF uncertainties	3.0	3.0	4.0	—	—	—	4.0
$gg \rightarrow WW$ QCD scale	—	50	—	—	—	—	—
W + jets norm.	—	—	—	—	—	36	—
top norm.	—	—	—	25	—	—	—
$Z/\gamma^* \rightarrow \ell\ell$ norm.	—	—	—	—	60	—	—
Monte Carlo statistics	1	1	4	6	20	20	10

$V\gamma(V = W,Z)$ systematic uncertainties

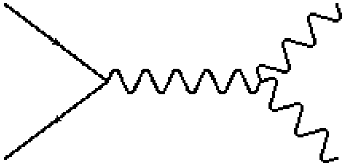
	$W\gamma \rightarrow e\nu\gamma$	$W\gamma \rightarrow \mu\nu\gamma$	$Z\gamma \rightarrow ee\gamma$	$Z\gamma \rightarrow \mu\mu\gamma$
Source	Effect on $A \cdot \epsilon_{MC}$			
Lepton energy scale	2.3%	1.0%	2.8%	1.5%
Lepton energy resolution	0.3%	0.2%	0.5%	0.4%
Photon energy scale	4.5%	4.2 %	3.7%	3.0%
Photon energy resolution	0.4%	0.7%	1.7%	1.4%
Pile-up	2.7%	2.3%	2.3%	1.8%
PDFs	2.0%	2.0%	2.0%	2.0%
Total uncertainty on $A \cdot \epsilon_{MC}$	6.1%	5.2%	5.8%	4.3%
	Effect on $\epsilon_{data} / \epsilon_{MC}$			
Trigger	0.1%	0.5%	$< 0.1\%$	$< 0.1\%$
Lepton identification and isolation	0.8%	0.3%	1.1%	1.0%
E_T^{miss} selection	0.7%	1.0%	N/A	N/A
Photon identification and isolation	1.2%	1.5%	1.0%	1.0%
Total uncertainty on $\epsilon_{data} / \epsilon_{MC}$	1.6%	1.9%	1.6%	1.5%
Background	6.3%	6.4%	9.3%	11.4%
Luminosity	4%			

$W\gamma \rightarrow l\nu\gamma$: radiation-amplitude zero

Destructive interferences between following diagrams



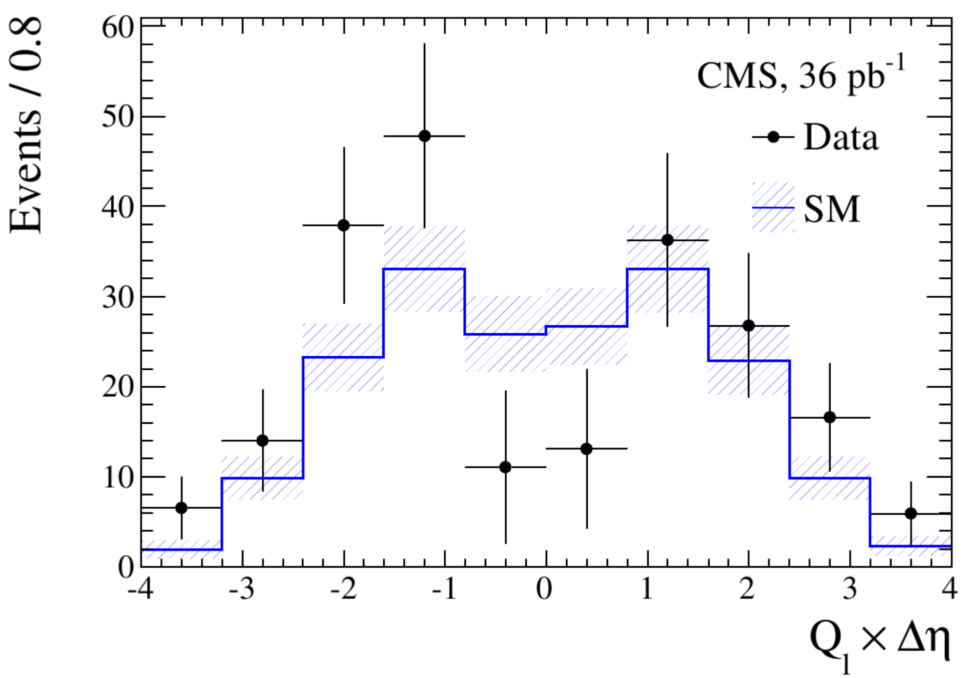
and



Already observed by D0 using the "charge-signed rapidity" : $Q_l.\Delta\eta(l,\gamma)$

For pp collision : minimum located at $Q_l.\Delta\eta(l,\gamma) = 0$

FSR $W\gamma$ radiation amplitude reduced by requiring $M_T(l, \gamma, MET) > 90$ GeV.



Background is subtracted

Kolmogorov-Smirnov probability of 57 %