26-30 March 2012

DIS 2012
University of Bonn

Diboson measurements with the CMS detector

Santiago Folgueras for the CMS Collaboration

XX International Workshop on Deep-Inelastic Scattering and Related Subjects

UNIVERSIDAD DE OVIEDO

CMS

Outline

- Motivation
- Status of dibosons measurements
  - Wγ, Zγ - *Phys. Lett. B701 535 (2011)*
  - WW, WZ, ZZ - *CMS-PAS-EWK-11-010*
  - Z to 4 leptons - *CMS-PAS-SMP-12-009*
- Summary

Motivation

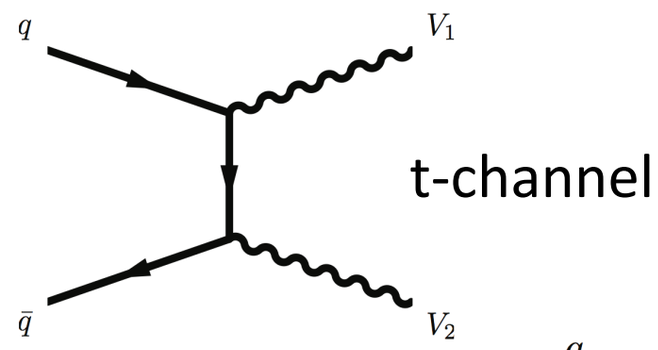
Test EWK theory

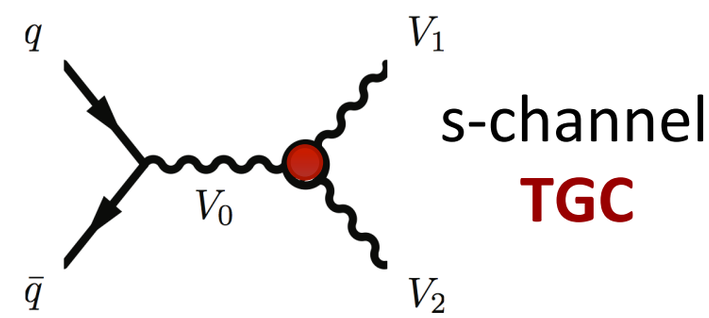
In **SM:**

WWγ, WWZ (allowed)
Zγγ, ZZγ, ZZZ (forbidden)

Constrains in TGC

Indirect probe for new physics (anomalous couplings)

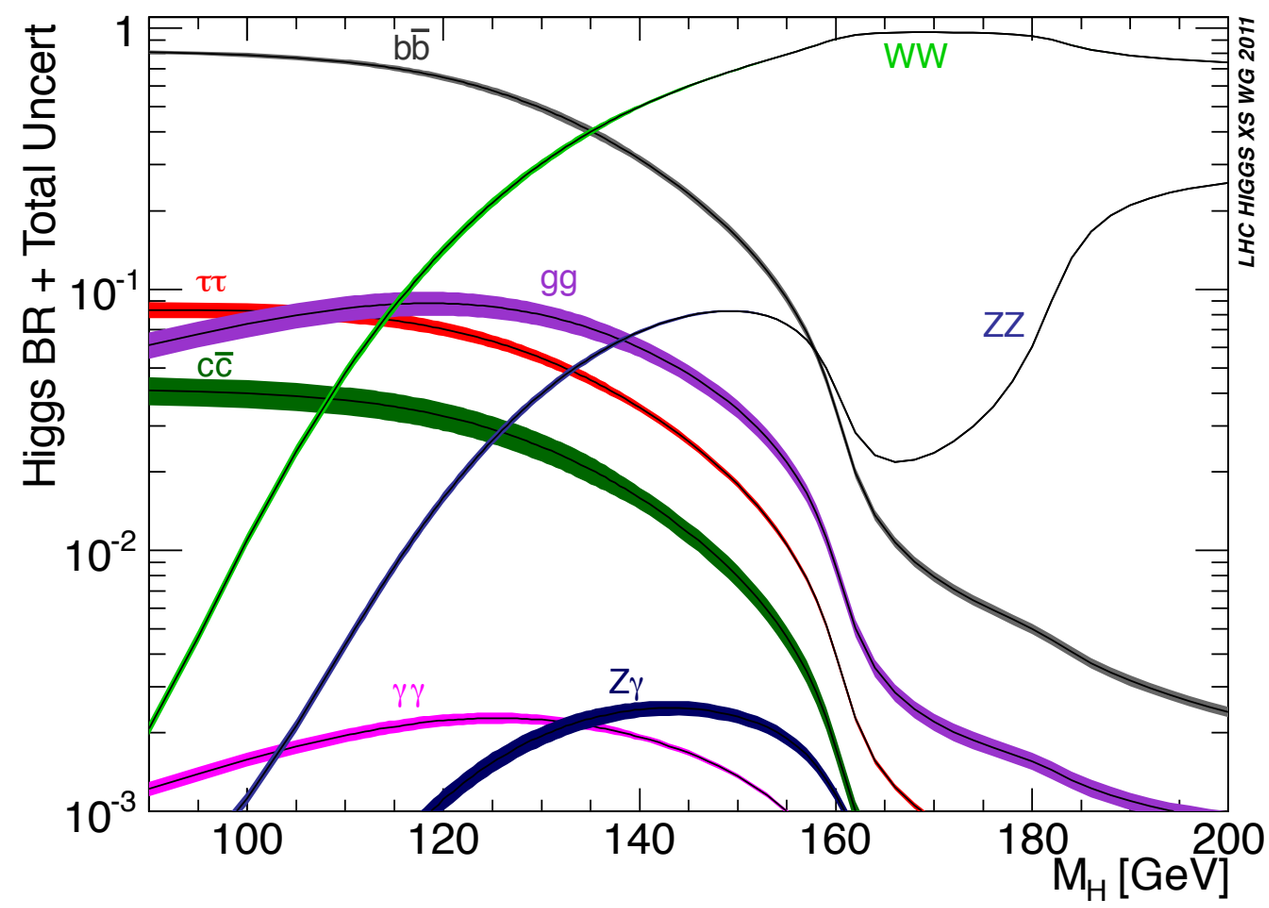




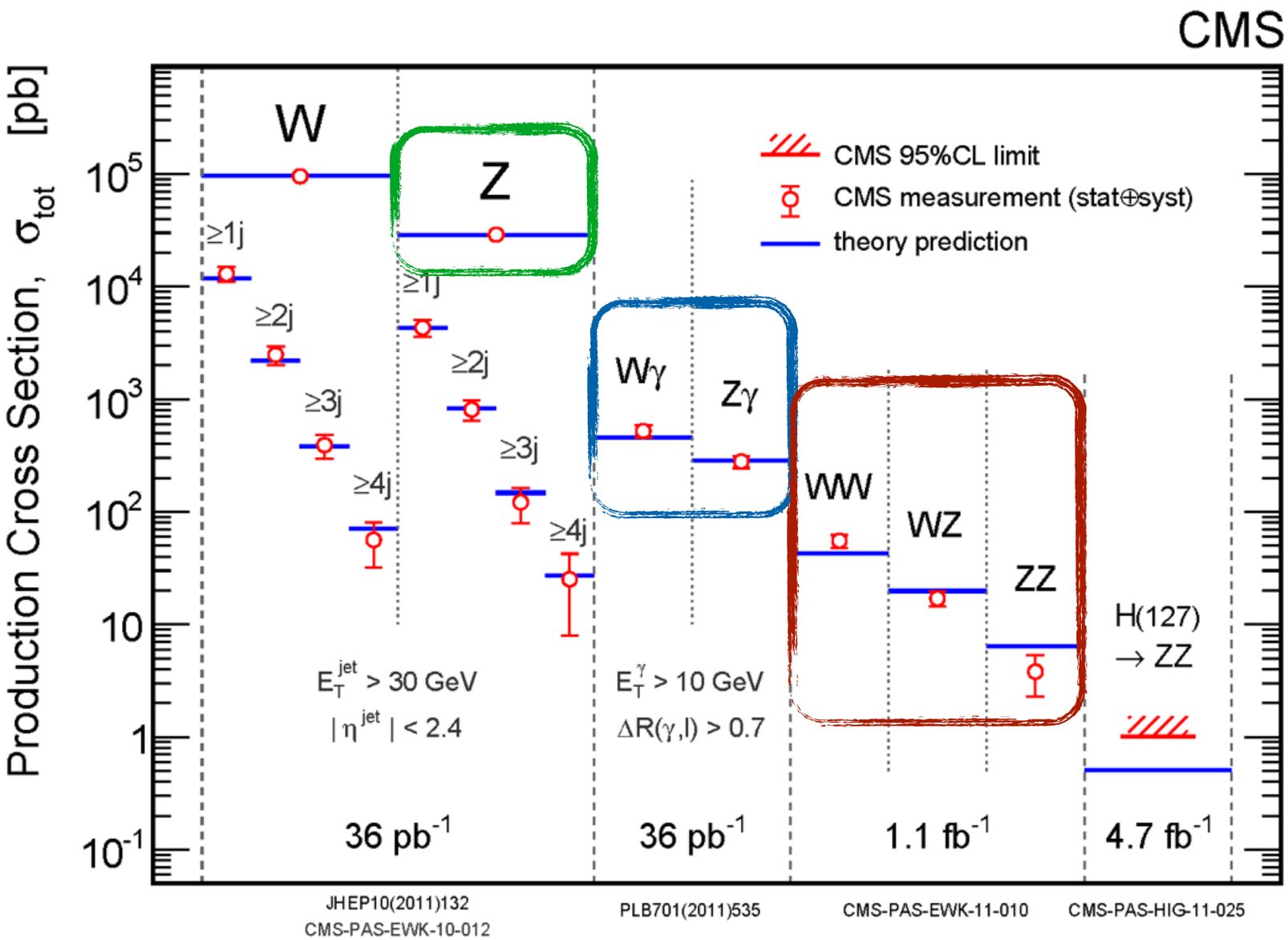
Background for many searches

Higgs searches (ZZ, WW)

BSM searches (WZ, ZZ)



Diboson measurements status



Wγ, Zγ with ~36 pb^{-1}

Cross section and TGC measurements.

WW, WZ, ZZ with ~1.1 fb^{-1}

Cross section

Z to 4l with ~4.7 fb^{-1}

First measuremnt.

Phys. Lett. B701 535 (2011)

$W\gamma \rightarrow l\nu\gamma$

36 pb^{-1}

Signature

One (and only one) isolated leptons (e, μ), $p_T > 20$ GeV, $|\eta| < 2.1$

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

$E_T^{miss} > 25$ GeV

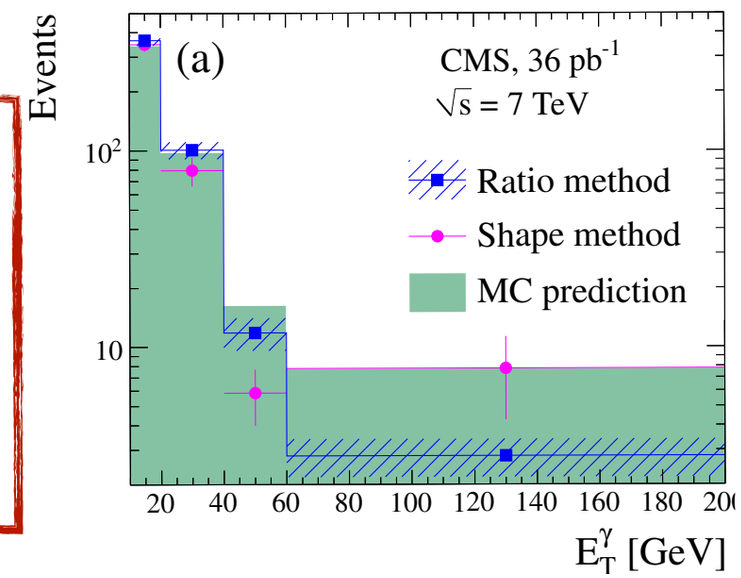
Main backgrounds

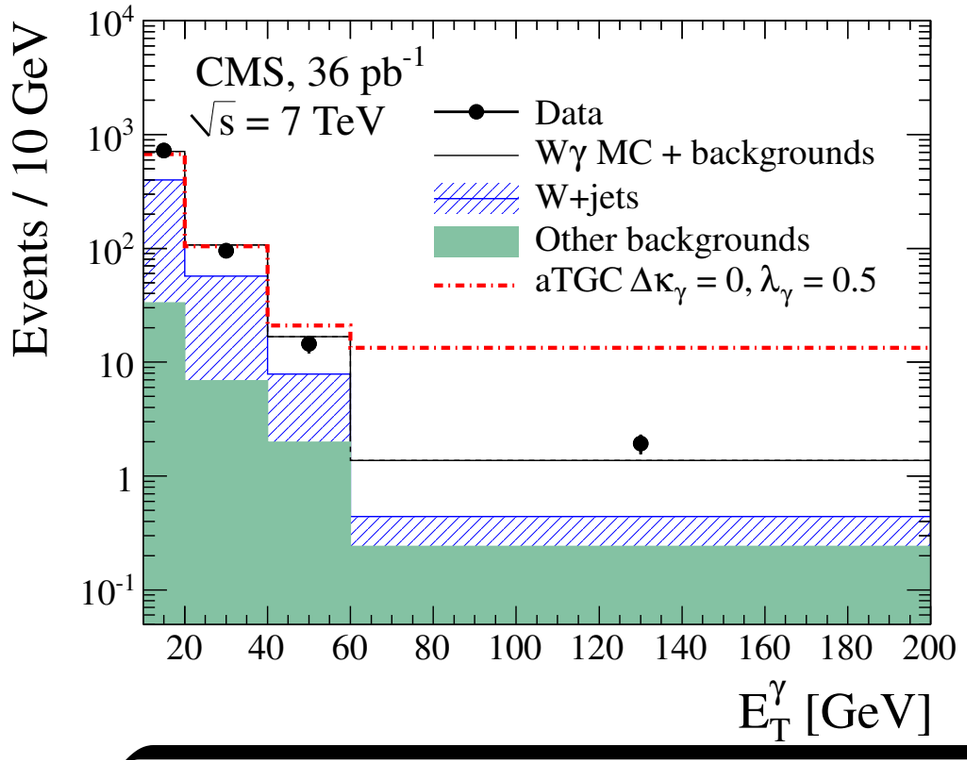
W+jets / tt + jets / Z + jets

QCD/PhotonJet

ZZ/WZ/WW

Z γ





	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

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

$$\sigma(pp \rightarrow W\gamma + X) \times B(W \rightarrow l\nu) = 56.3 \pm 5.0(stat.) \pm 5.0(syst.) \pm 2.3(lumi)$$

49.4 ± 3.8 pb @NLO (Baur)

Phys. Lett. B701 535 (2011)

$Z\gamma \rightarrow ll\gamma$

36 pb^{-1}

Signature

2 isolated leptons (ee, eμ, μμ), $p_T > 20$ GeV, $m_{ll} > 50$ GeV

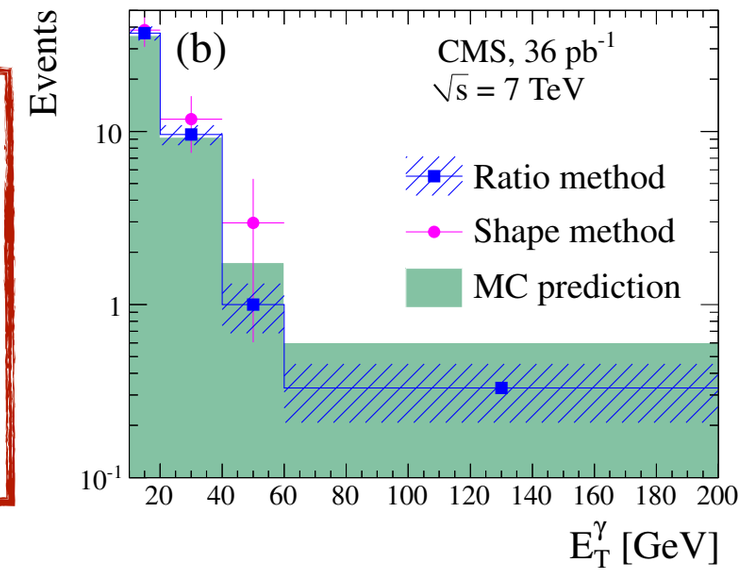
1 photon, $E_T > 10$ GeV, $\Delta R(l,\gamma) > 0.7$

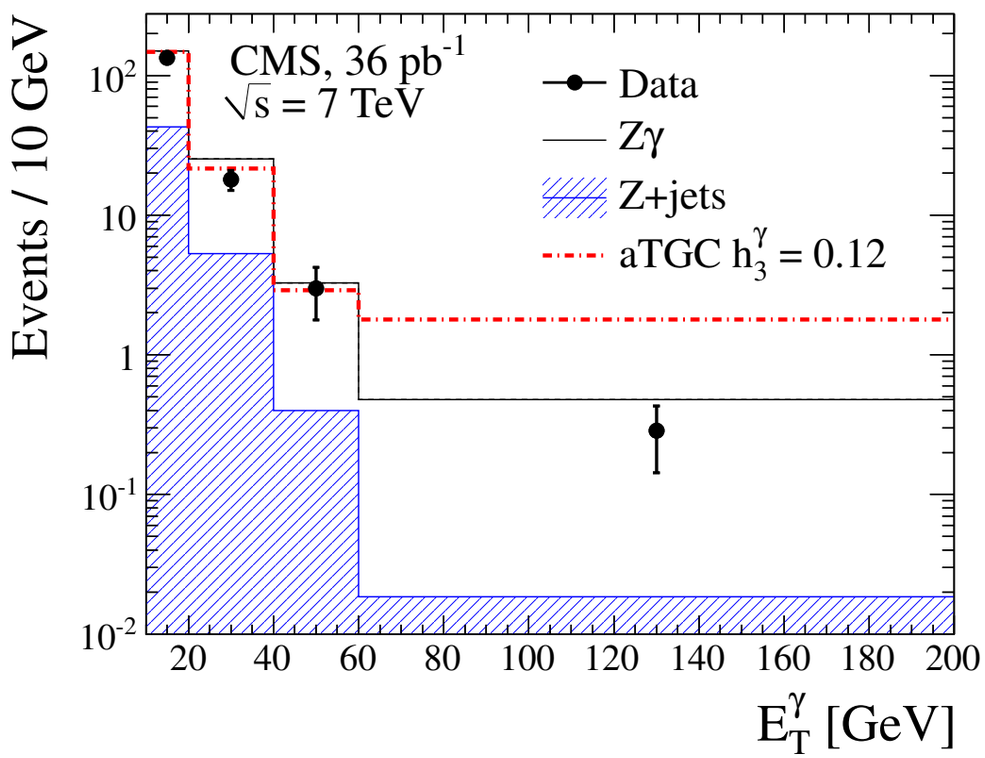
Main backgrounds

QCD / tt / Diboson

Z+Jets

Jets faking photons. Estimated using fake rate method.





	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

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

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

9.6 ± 0.4 pb @NLO (Baur)

Phys. Lett. B701 535 (2011)

WWγ - ZZγ/ Zγγ

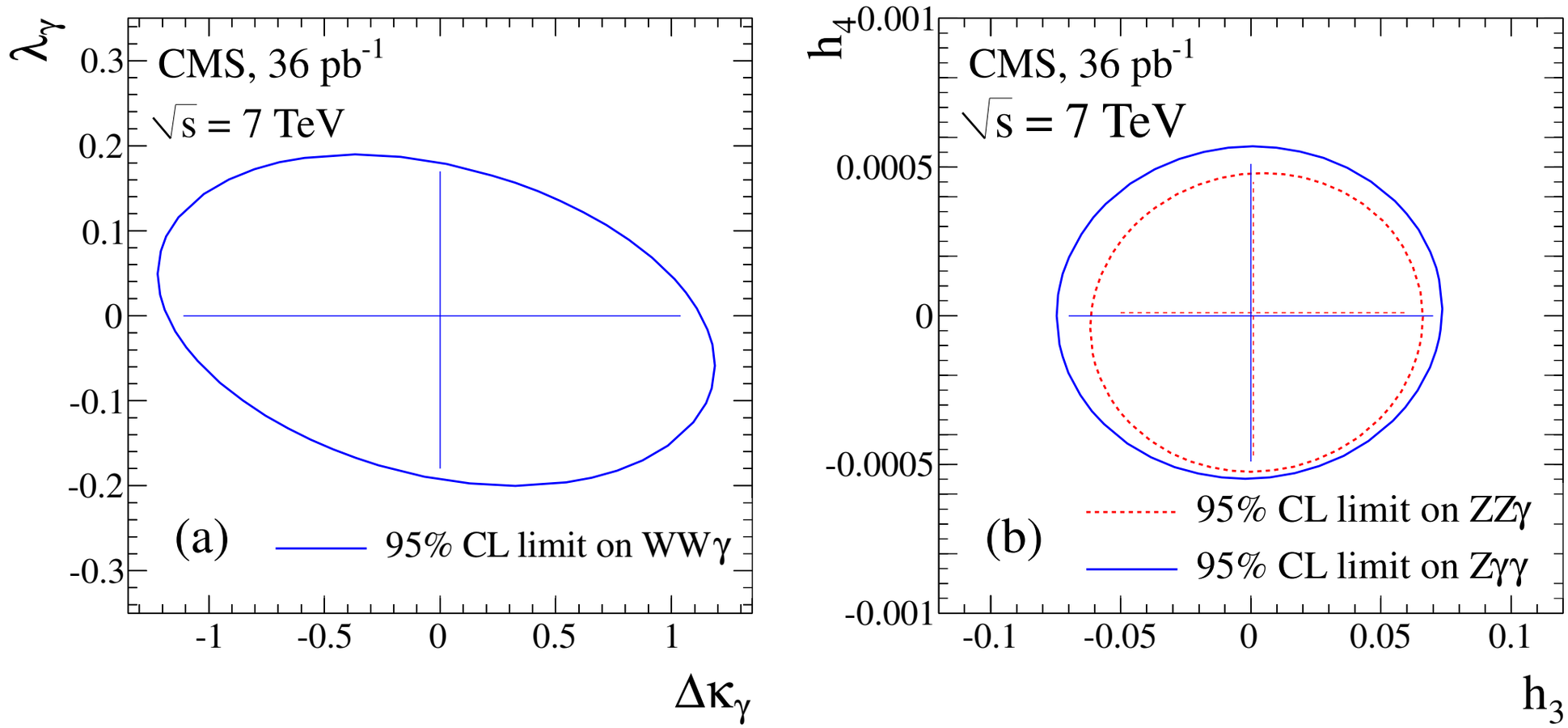
36 pb^{-1}

Anomalous couplings limits with 36 pb^{-1}

E_T photons spectrum as reference.

Profile likelihood fit

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



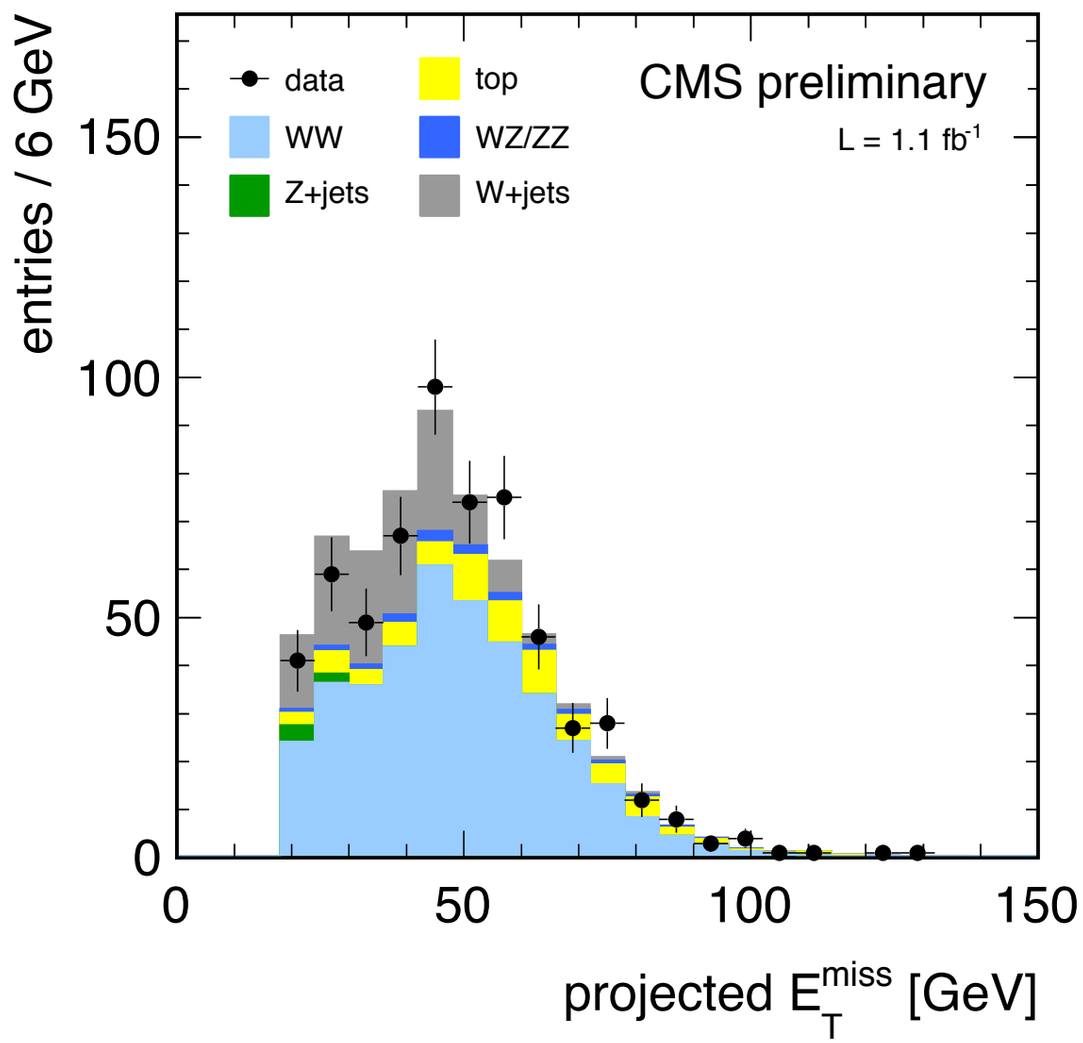
WW → llνν

1.1 fb^{-1}

Signature

2 isolated leptons (ee, eμ, μμ), opposite sign.

p_T > 20/10 GeV + E_T^{miss}



Background reduction

QCD/W+Jets background

Tight isolation lepton + id.

DY background

Z veto ($|m_{ll} - m_Z|$ < 15 GeV)
proj. MET > 40(20) GeV in μμ,ee (eμ)
ΔΦ(dil, jet) < 165° (jet p_T > 15 GeV) (SF)

top background

Jet veto (0 jets with E_T > 30 GeV)
Top veto (b-tag + soft muon)

WZ / ZZ

No extra leptons.

WW → llνν

1.1 fb^{-1}

Cross section measurement

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

signal

data driven

MC

Total Systematic Uncertainty

Source	uncertainty
Signal efficiency	~8%
Background estimation	~20%

Counting method

$$\sigma_{W^+W^-} = 55.3 \pm 3.3\,(\text{stat}) \pm 6.9\,(\text{syst}) \pm 3.3\,(\text{lumi})\ \text{pb}.$$

47.04 ± 2 pb @NLO [arXiv:1105.0020]

CMS-PAS-EWK-11-010

WZ → lνll

1.1 fb^{-1}

Signature

3 isolated leptons (electron, muon) + E_T^{miss}.

Z candidate: p_T > 20,10 GeV (ee), p_T > 15,15 GeV (μμ), 60 GeV < m_{ll} < 120 GeV.

W candidate: p_T > 20 GeV, E_T^{miss} > 30 GeV

Background reduction

ZZ

2nd Z veto.

mis-reconstructed objects ZZ, Zγ

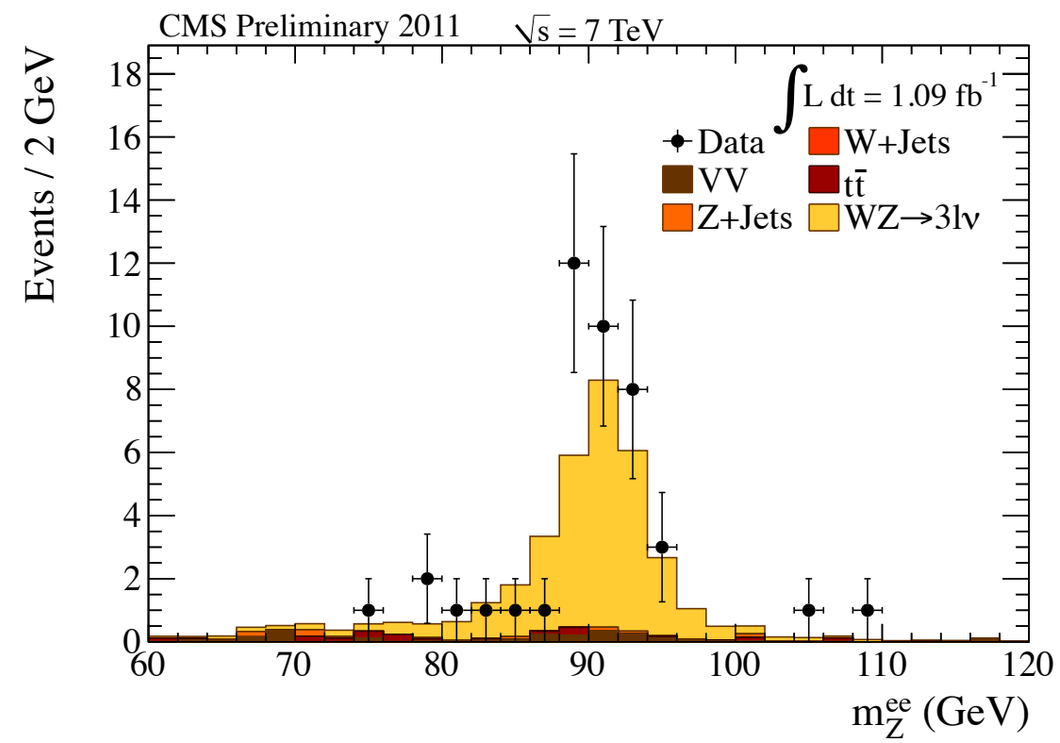
E_T^{miss}

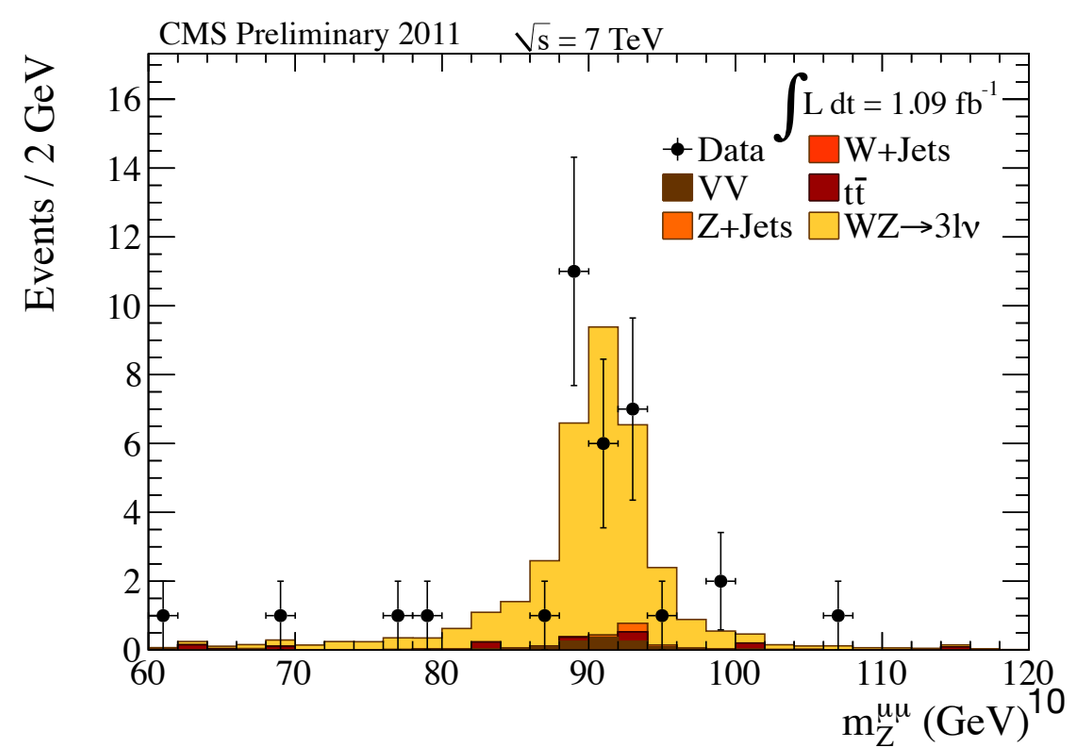
Z+jets and top background

tight lepton selection

WZ (including τ): f_τ O(6%)

from MC, subtracted when computing xsec.





CMS-PAS-EWK-11-010

WZ → lνll

1.1 fb^{-1}

Cross section measurement

Sample	$3e0\mu$	$2e1\mu$	$1e2\mu$	$0e3\mu$
$Z + Jets$	0.82	0.04	0.31	0.07
$Z \to bb + Jets$	0.04	0.06	0.00	0.10
$Z \to cc + Jets$	0.03	0.00	0.00	0.00
tt	0.83	0.95	0.56	0.59
$ZZ \to 4\ell$	0.40	0.95	0.40	0.97
$V\gamma$	0.80	0.10	0.03	0.00
$W + Jets$	0.00	0.00	0.00	0.00
$WW \to 2\ell 2\nu + Jets$	0.02	0.04	0.00	0.00
$Background$	2.95	2.14	1.31	1.72
$WZ \to 3\ell\nu$	14.47	17.49	13.95	18.56
$AllMC$	17.42	19.62	15.26	20.28
$Data$	22	20	13	20

data driven

signal

source	uncertainty
theoretical uncertainty and acceptance	2.8 - 3.2 %
lepton efficiencies	3.6 - 6.7 %
background estimation	1.5 - 2.8 % (top) 3.5 - 5.5 % (Z+jet)

$$\sigma(pp \to \mathrm{WZ} + X) = 17.0 \pm 2.4\ (\mathrm{stat.}) \pm 1.1\ (\mathrm{syst.}) \pm 1.0\ (\mathrm{lumi.})\ \mathrm{pb.}$$

19.790 ± 0.088 pb @NLO [MCFM]

CMS-PAS-EWK-11-010

ZZ → llll

1.1 fb^{-1}

Signature

First Z (→ee, μμ): two isolated leptons with p_T > 20,10 GeV (ee) with 60 GeV < m_{ll} < 120 GeV.

Second Z:

Z→ ee, μμ: p_T > 7/5 GeV, 60 GeV < mll < 120 GeV.

Z→ ττ (τ→e,μ, had): p_T (τ→e,μ) > 10 GeV, p_T (τ→had) > 20 GeV, 30 GeV < $m_{\tau\tau}^{visible}$ < 80 GeV

Main backgrounds

Heavy flavour jets: tt/Zbb

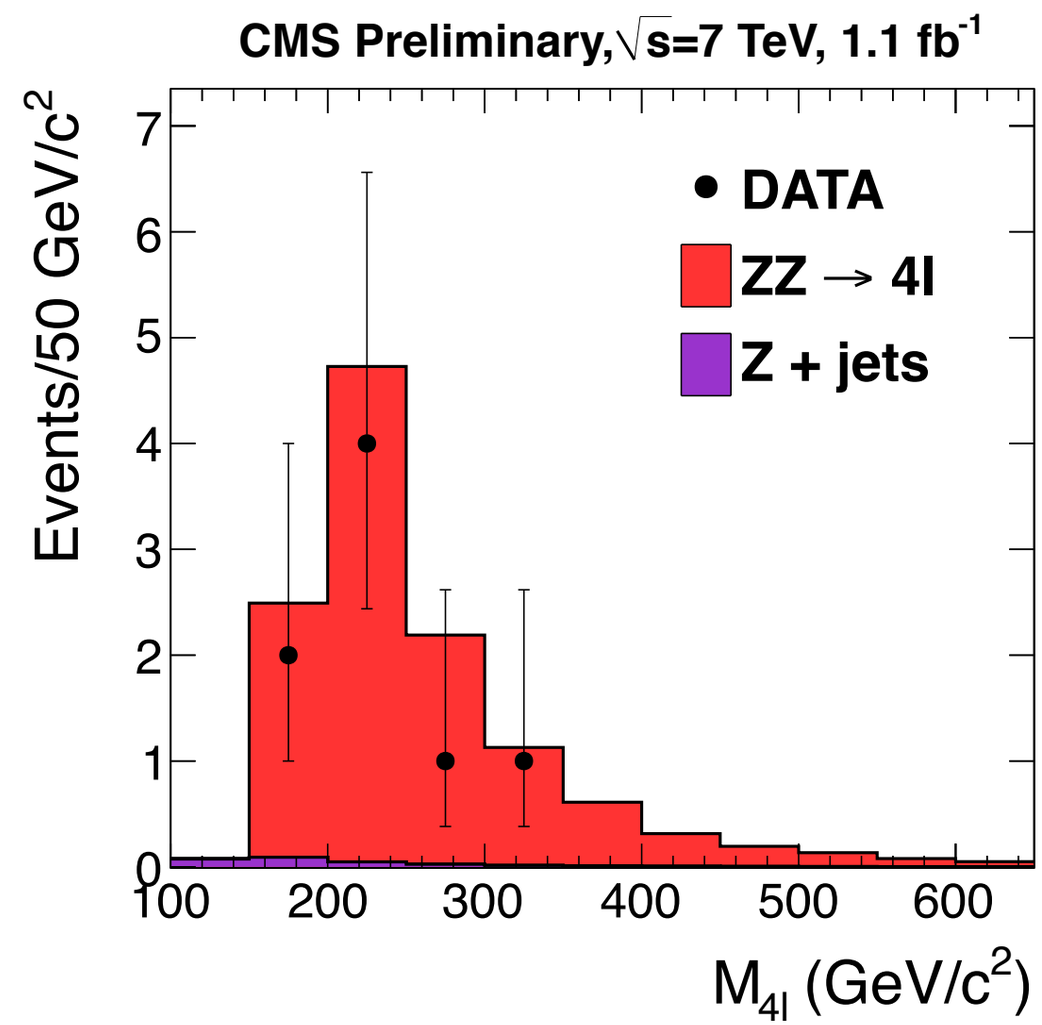
control region on SIP_{3D} reverted

Jets faking leptons Z+jets

fake ratios

Jet faking taus (Z+jets / WZ)

fake ratios



ZZ → llll

1.1 fb^{-1}

Cross section measurement

Final state	N_{obs}	$N^{\text{backg.}}_{\text{estimated}}$	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

data driven signal

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

Simultaneous constrained fit in all channels

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

6.4 ± 0.6 pb @NLO [MCFM]

CMS-PAS-SMP-12-009

Z → llll

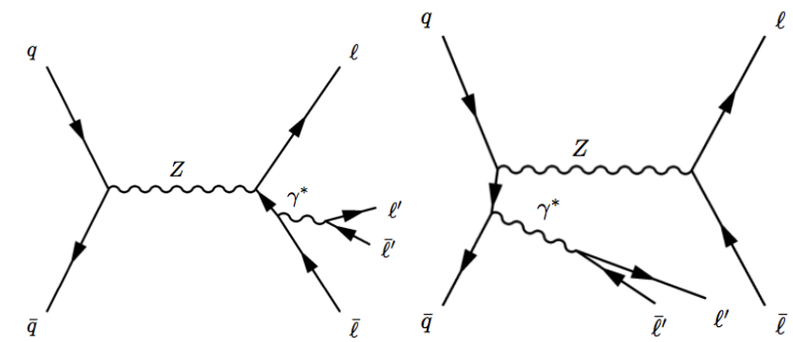
4.7 fb^{-1}

Signature

4 isolated leptons with p_T > 20,10 GeV for the hardest leptons, and p_T > 7/5 GeV for other e/μ.

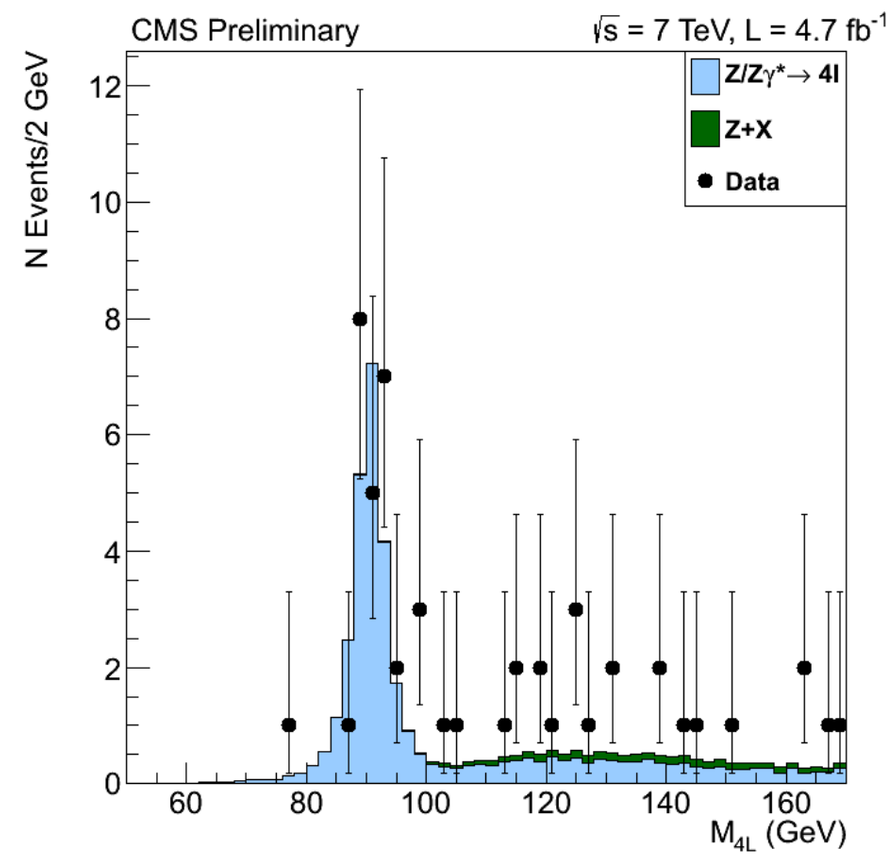
Opposite charge pairs

80 GeV < m_{4l} < 100 GeV.



Background free sample.

Final state channels	$4e$	4μ	$2e2\mu$	4ℓ
Irreducible background ($pp \to Z\gamma^* \to 4\ell$)	0.04	0.16	0.08	0.3 ± 0.03
Other reducible backgrounds	0.01	0.01	0.05	0.1 ± 0.13
Expected signal ($pp \to Z \to 4\ell$)	3.1	12.3	9.2	24.6 ± 2.2
Total expected (MC)	3.2	12.5	9.3	25.0 ± 2.2
Observed events	2	14	10	26
Rate from the fit of the observed mass distribution		13.6	9.7	25.4



Systematics

Interference: 0.2 %

Efficiencies: 1 to 6 %

Acceptance and theoretical: ~5 %

Efficiencies

MC efficiencies corrected by Data/MC from Z→2l

CMS-PAS-SMP-12-009

Z → llll

4.7 fb^{-1}

Cross section times BR measurement

Minimization of a likelihood including:

Number of signal events in each final state.

$$s_i = L \cdot \sigma(pp \to Z) \cdot BR(Z \to 4\ell) \cdot f_i \cdot \epsilon_i^{acc} \cdot \epsilon_i^{exp} \cdot c_i,$$

Number of background events

Nuisance parameters to handle systematics

Same method for **BR extraction** using a Zμμ control region to get rid of the xsec.

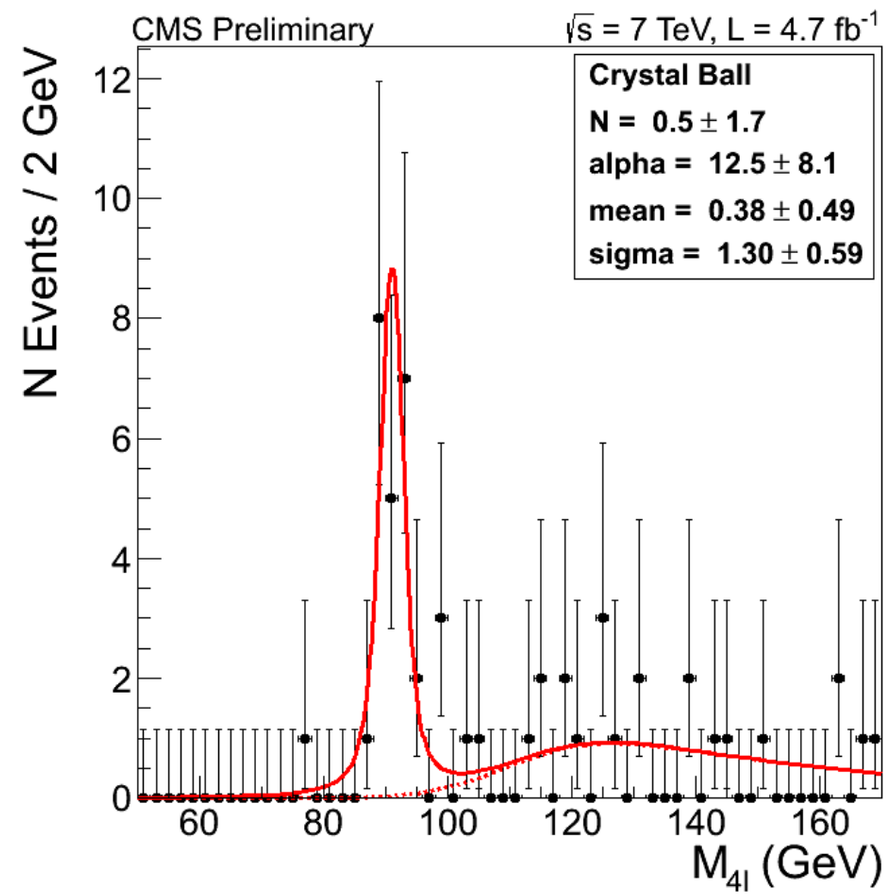
$$\sigma \times BR(Z \to 4\ell) = 125^{+26}_{-23}(\text{stat})^{+9}_{-6}(\text{syst})^{+7}_{-5}(\text{lumi})\ \text{fb},$$

120 ± 4.92 pb

$$BR(Z \to 4\ell) = 4.4^{+1.0}_{-0.8}(\text{stat}) \pm 0.2(\text{syst}) \times 10^{-6}.$$

4.45 x 10^{-6}

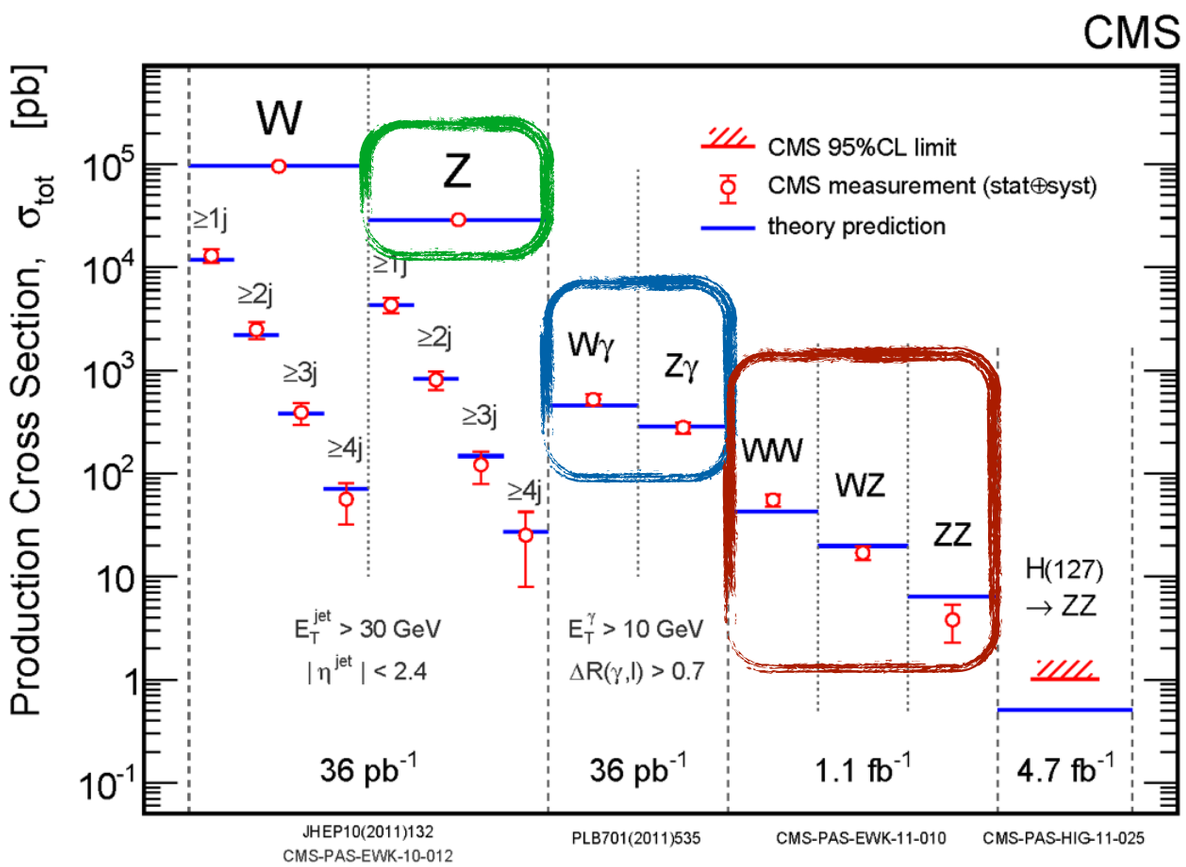
Standard candle for H search

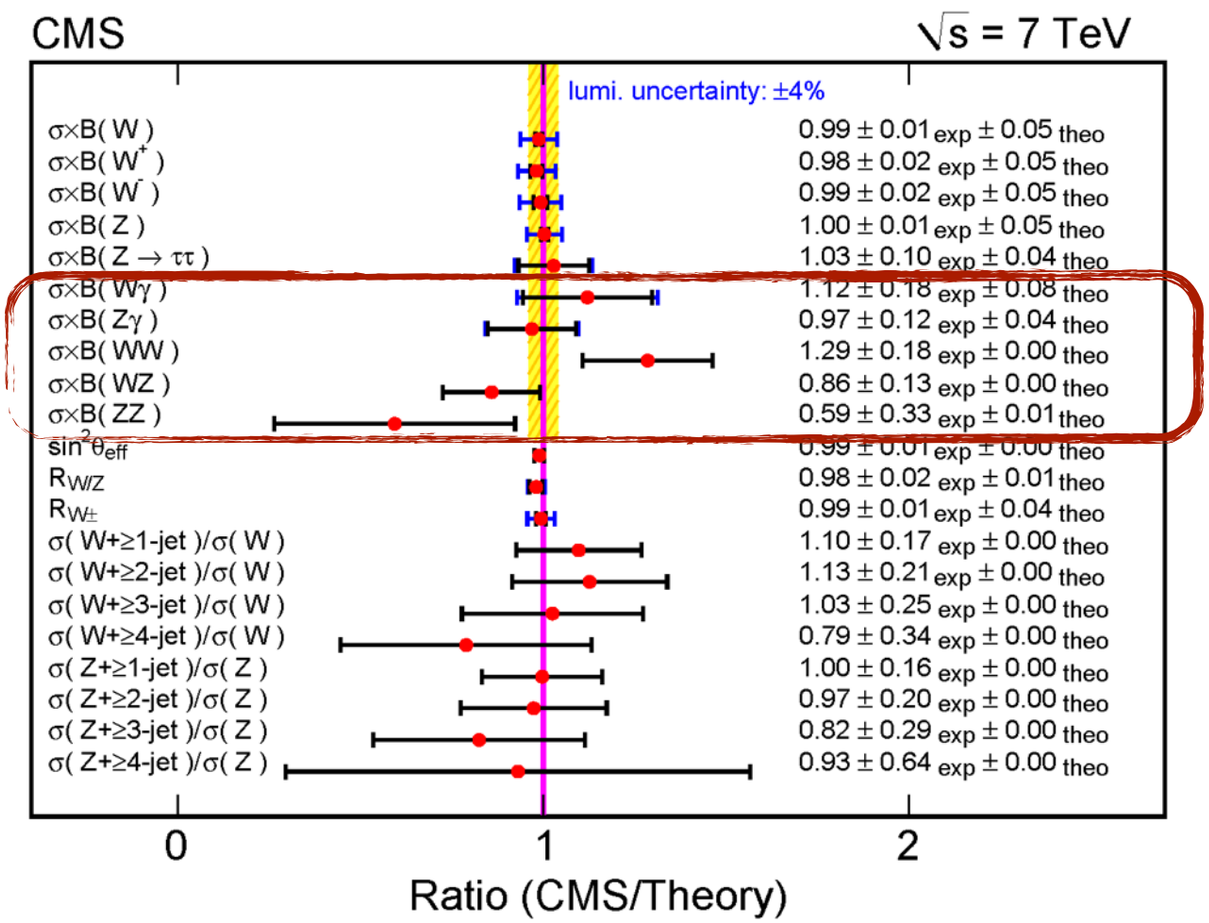


m_{4l} scale known to 0.4 %
(offset 0.4 ± 0.5 GeV)

m_{4l} mass resolution to 46%
(width 1.3 ± 0.6 GeV)

Summary





- Measured cross sections are on agreement with SM expectations
- New results with 5 fb^{-1} coming soon. Stay tuned.
- All these measurements will be repeated this year's data @ 8 TeV.

Back up slides

Wγ / Zγ fake estimation background.

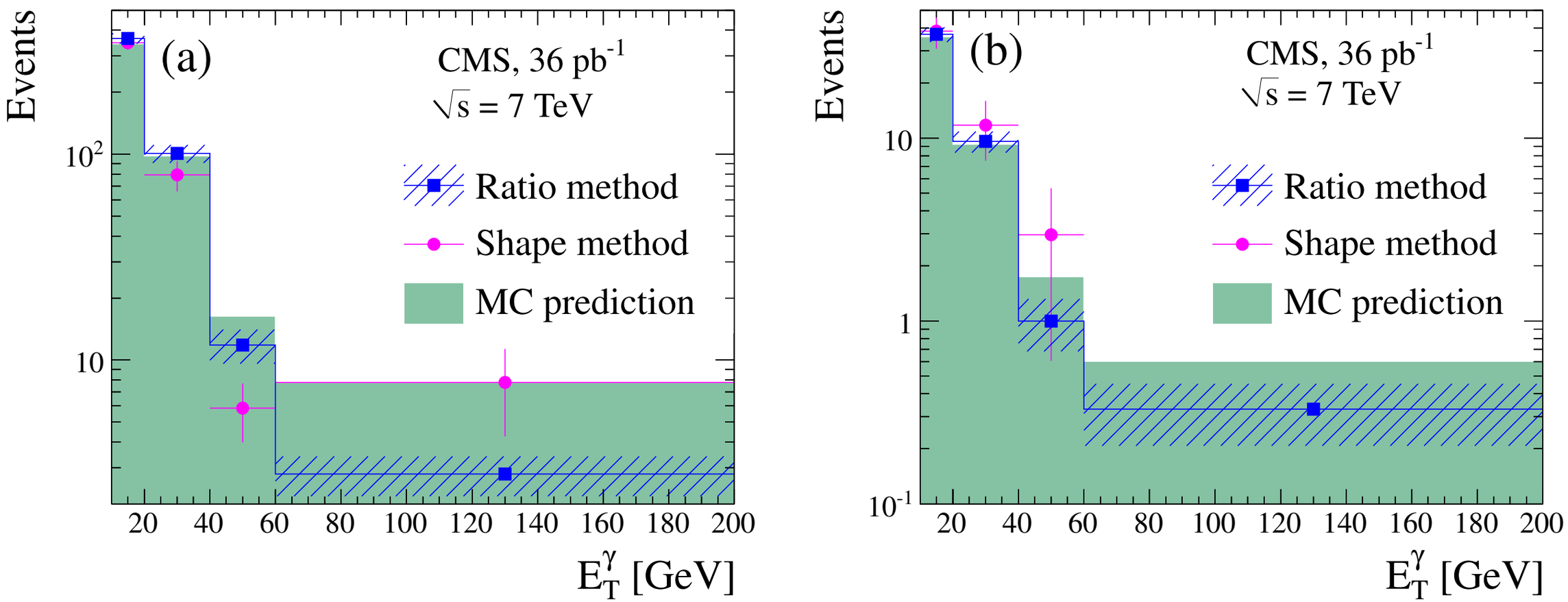
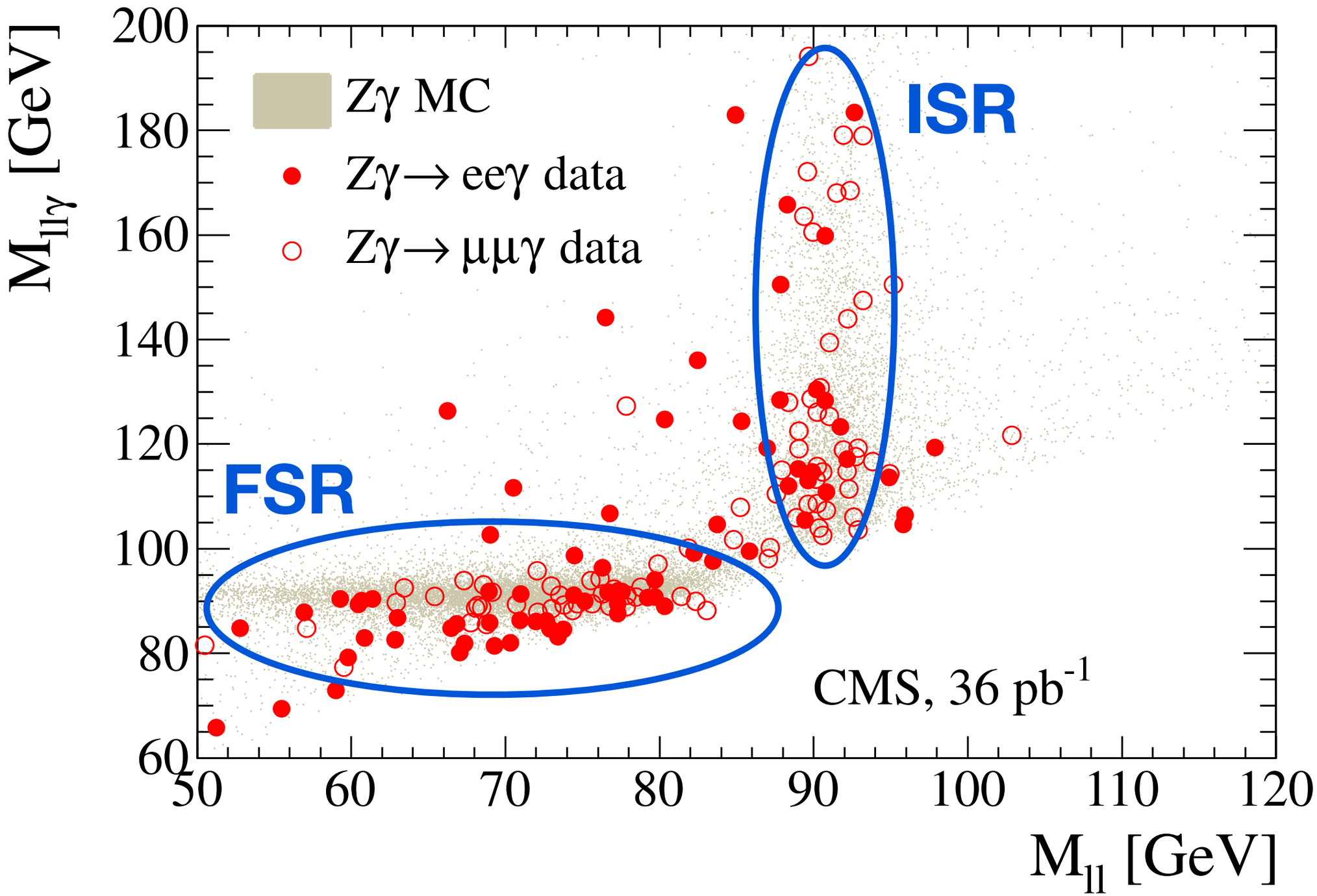


Figure 1: Background from misidentified jets as a function of the photon candidate E_T, estimated from the ratio method, is shown with blue squares together with an alternative method that uses energy deposition shape templates (magenta circles), and MC simulation (green filled histogram) for (a) Wγ and (b) Zγ channels. Uncertainties include both statistical and systematic sources.

$ll\gamma = f(m_{ll})$



Systematic uncertainties for Wγ / Zγ

Table 1: Summary of systematic uncertainties.

	$W\gamma \to e\nu\gamma$	$W\gamma \to \mu\nu\gamma$	$Z\gamma \to ee\gamma$	$Z\gamma \to \mu\mu\gamma$
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%			

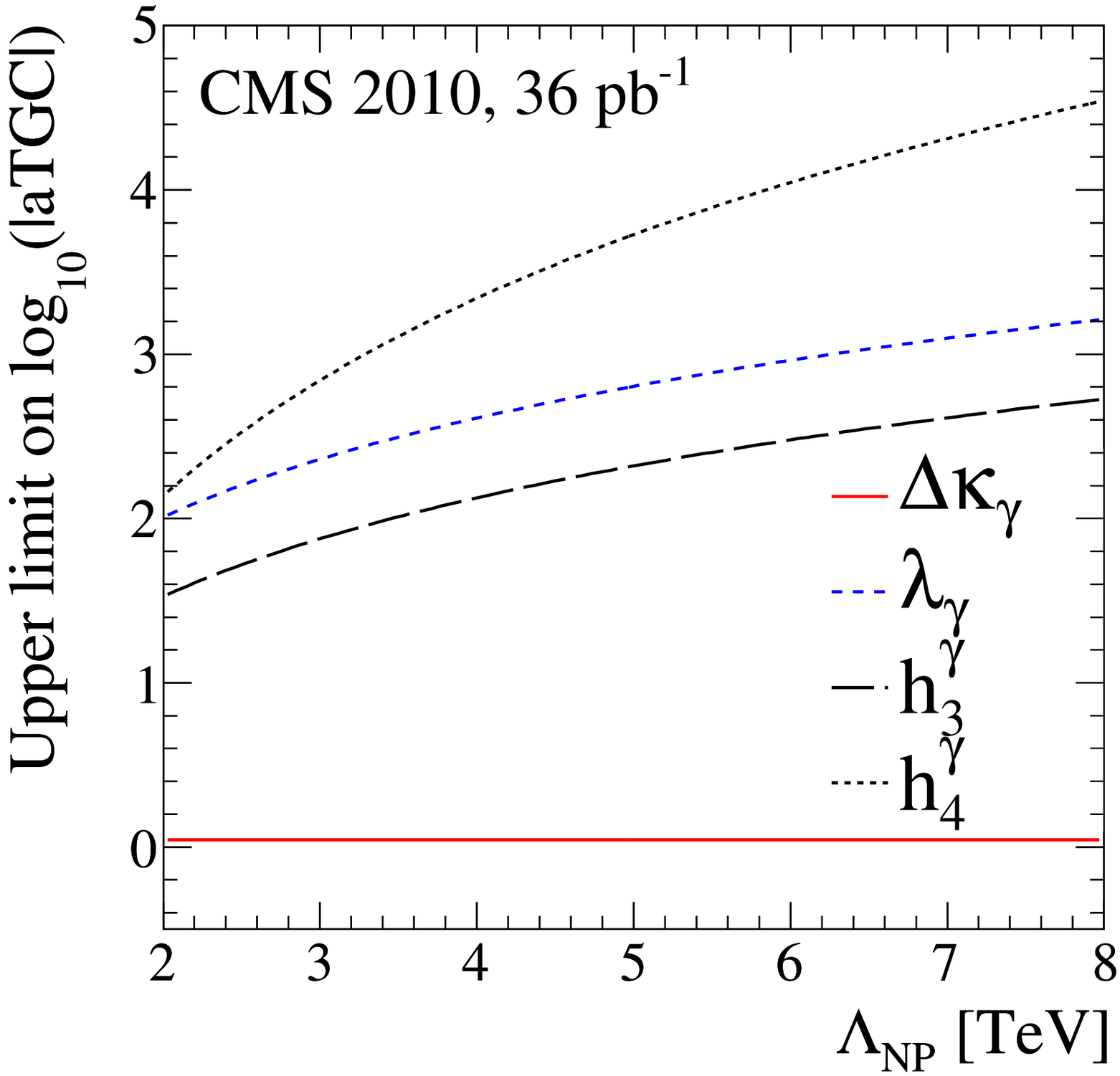
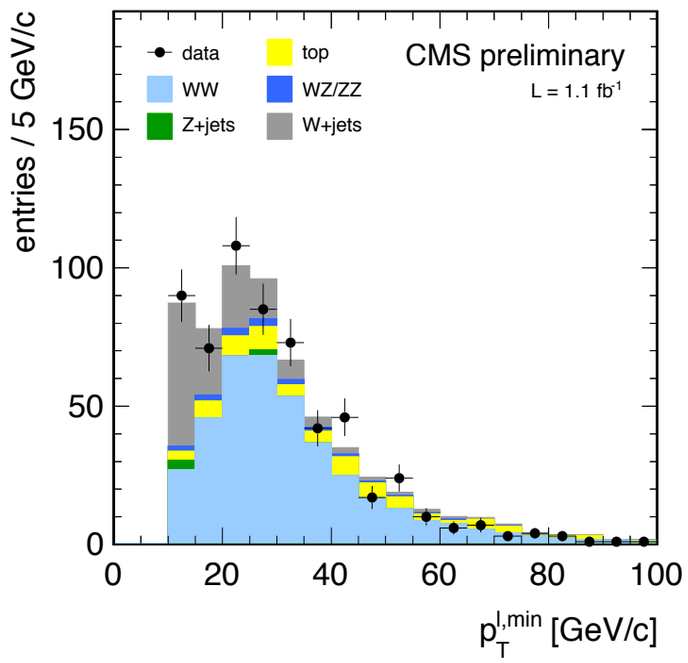
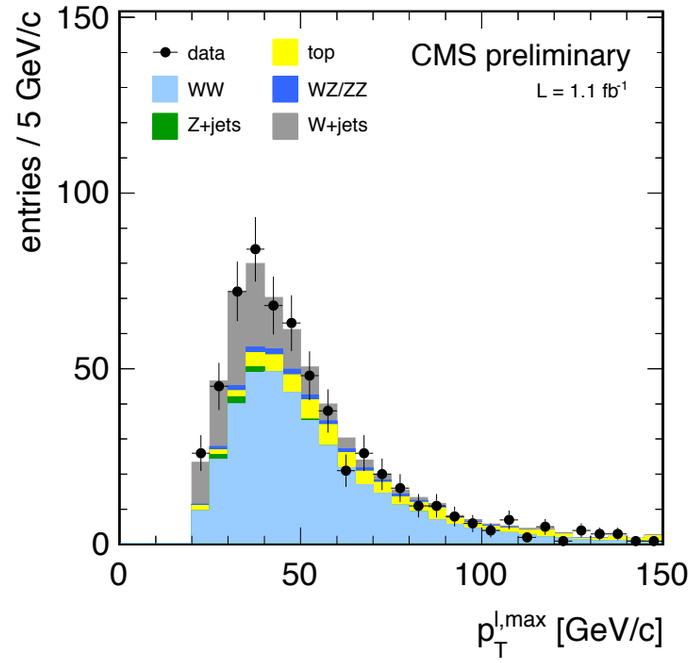


Figure 7: Upper 95% CL limits on $\log_{10}(|\text{aTGC}|)$ as a function of Λ_{NP} for $\Delta\kappa_\gamma$, λ_γ, h_3^γ, and h_4^γ. Limits on the latter two couplings are similar to those for h_3^Z and h_4^Z. These limits refer to the formulation in which the new physics Lagrangian terms are scaled with $\alpha/\Lambda_{\text{NP}}^n$, where Λ_{NP} is the characteristic energy scale of new physics and α is the aTGC.

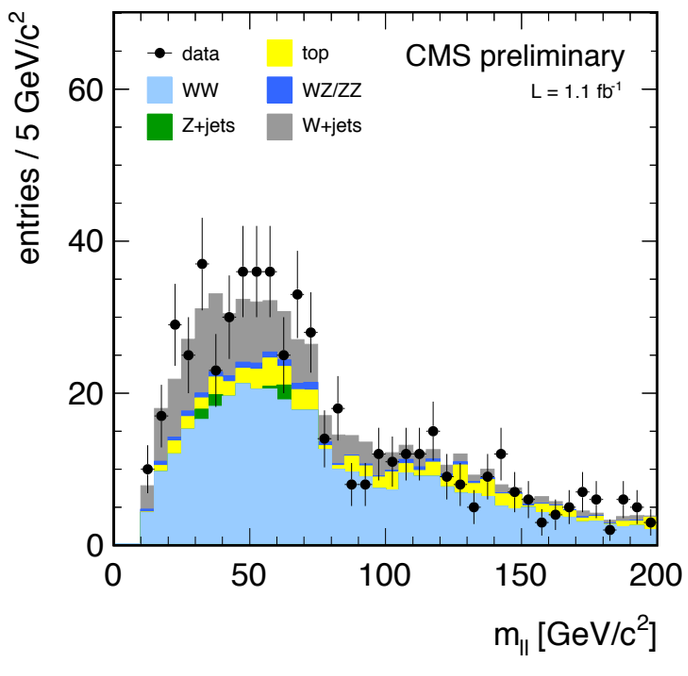
Kinematic distributions after WW selection

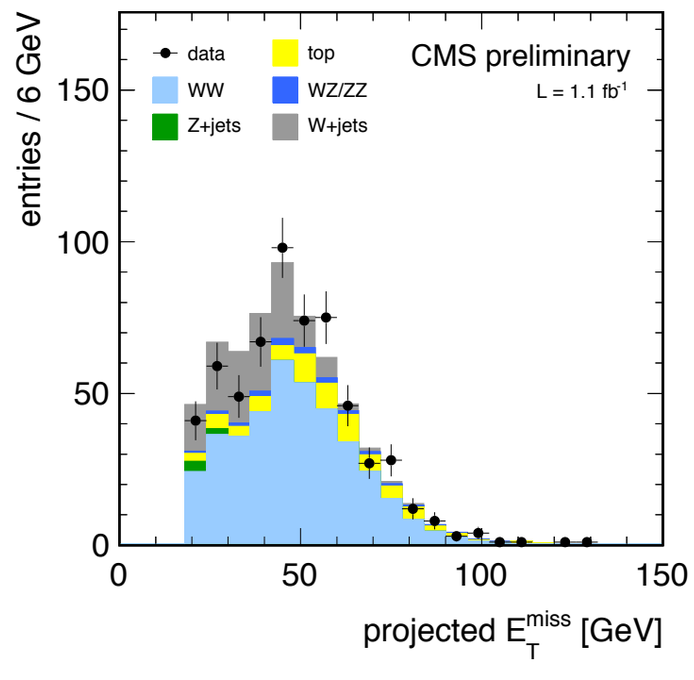


(a)



(b)

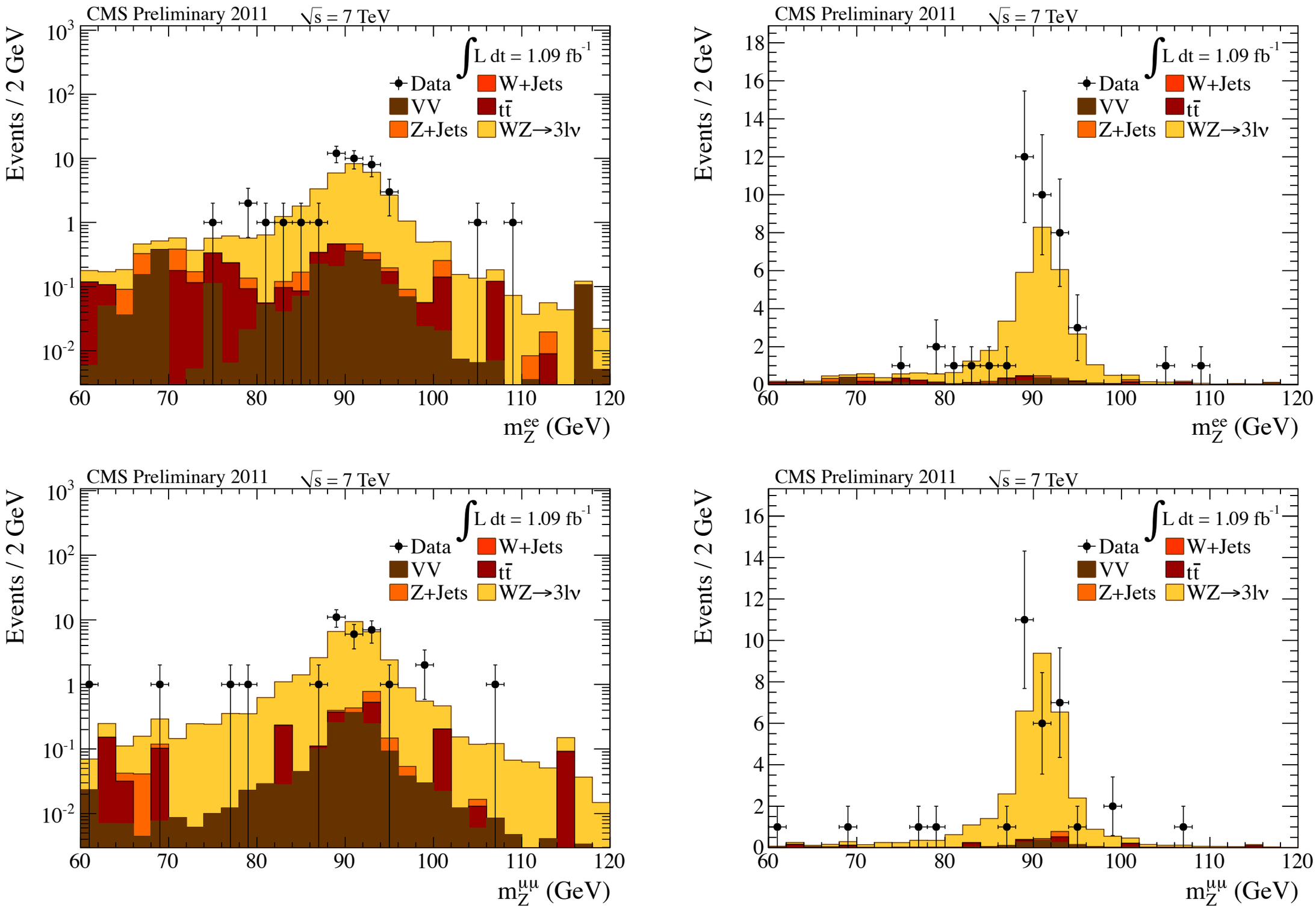




Summary of systematic uncertainties for WW

Source	$qq \to$ W^+W^-	$gg \to$ 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
$gg \to WW$ QCD scale	—	50	—	—	—	—	—
W + jets norm.	—	—	—	—	—	36	—
top norm.	—	—	—	25	—	—	—
$Z/\gamma^* \to \ell\ell$ norm.	—	—	—	—	60	—	—
Monte Carlo statistics	1	1	4	6	20	20	10

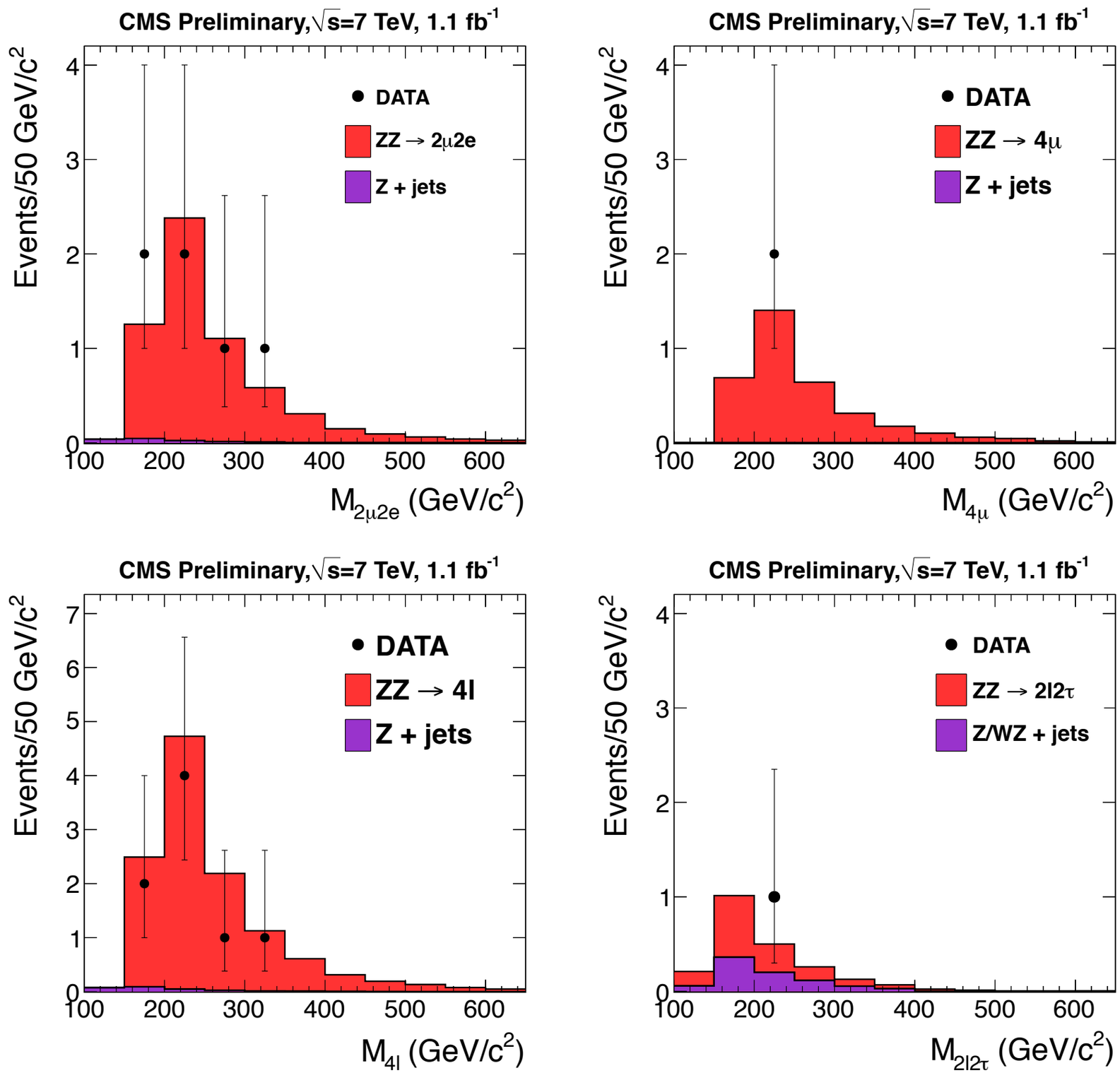
Kinematic distributions after WZ selection



Summary of systematic uncertainties for WZ

		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%

Kinematic distributions after ZZ selection



Kinematic distributions after ZZ selection

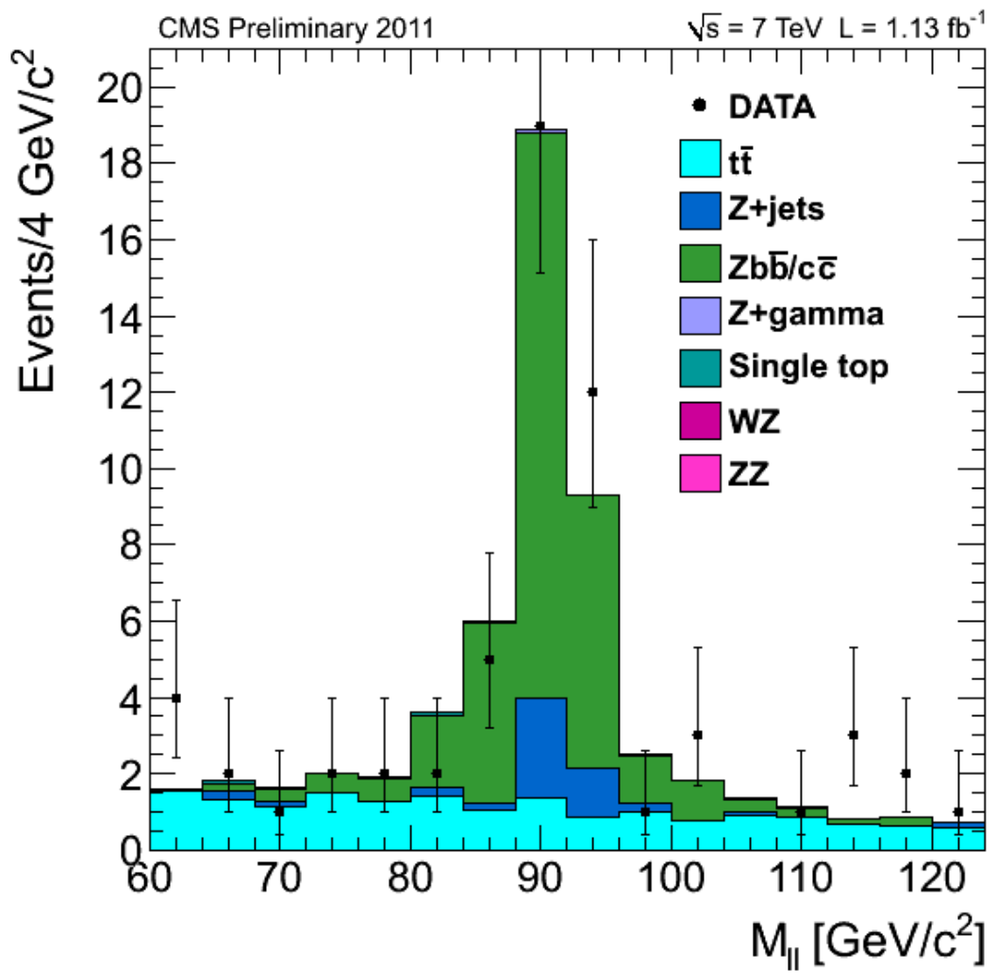


Figure 4: Distribution of the best reconstructed Z candidate invariant mass for the events in the four-lepton background control region defined by a pair of identified leptons with opposite charge and matching flavour and another pair of leptons with isolation cut relaxed, flavour and charge requirements removed and high impact parameter. Solid points with errors represent the data, solid histograms represent the MC expectations, the signal and the ZZ background are fully absent. The samples correspond to an integrated luminosity of $\mathcal{L} = 1.1\,\mathrm{fb}^{-1}$.

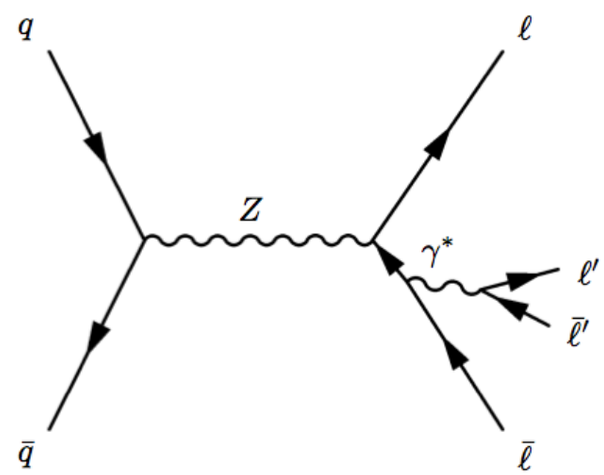
Summary of systematic uncertainties for ZZ

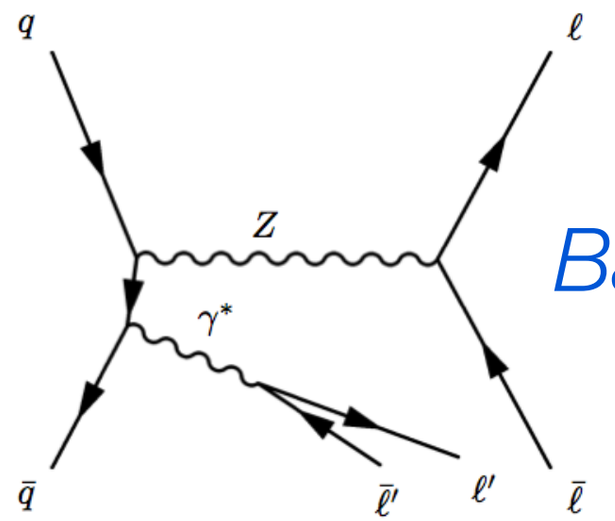
Table 12: Summary of statistical and systematic uncertainties.

	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 %		

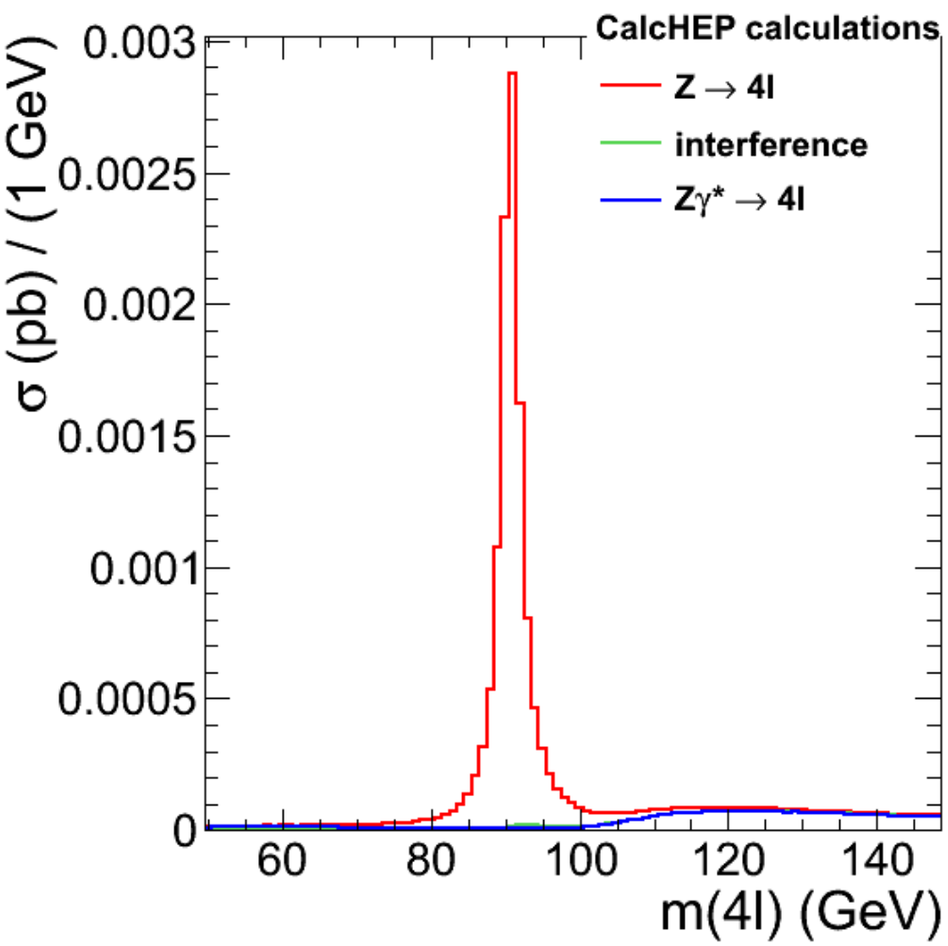
ISR and FSR diagrams interference

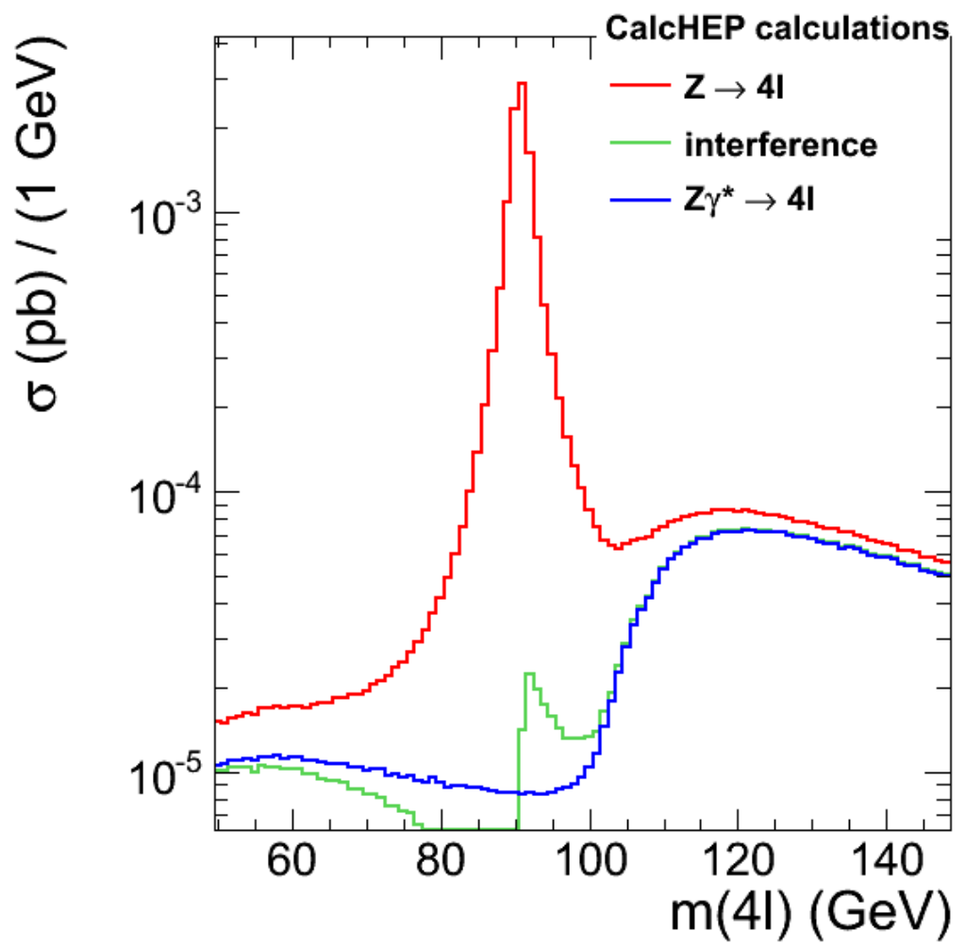
Signal



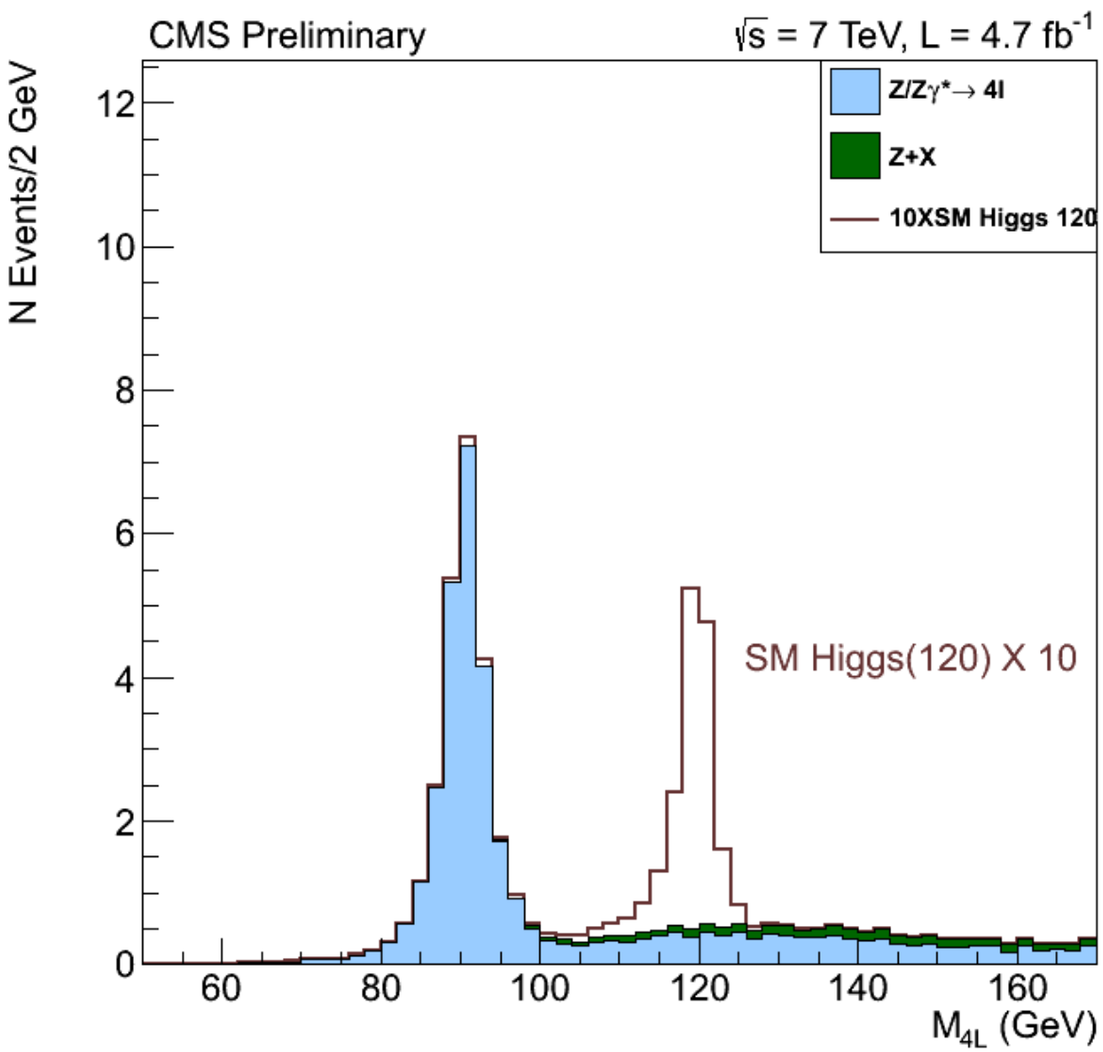


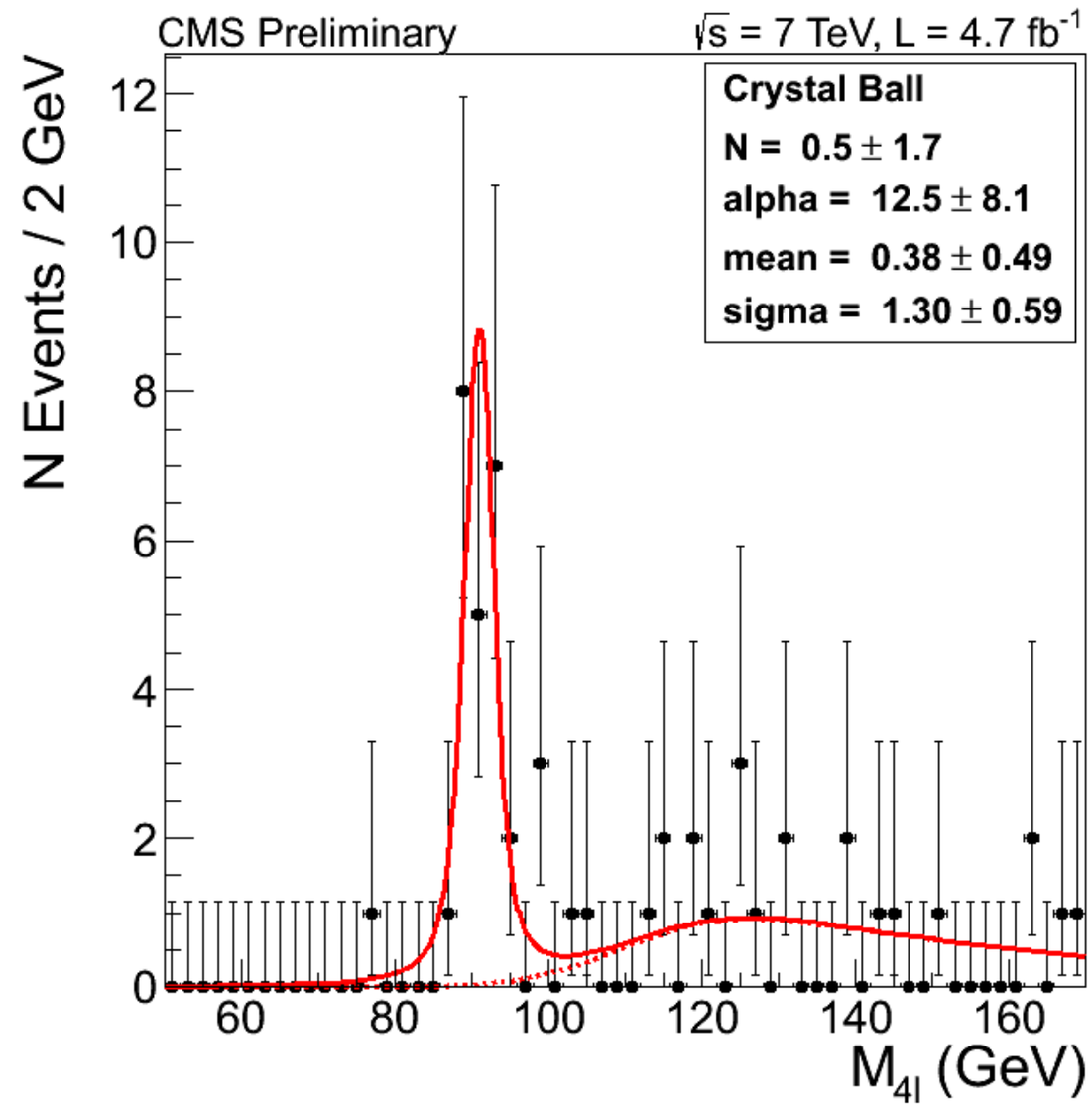
Background





Standard candle for H search





Kinematic distributions of Z → 4l events