Results on Electroweak Multibosons in CMS

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On behalf of CMS Collaboration

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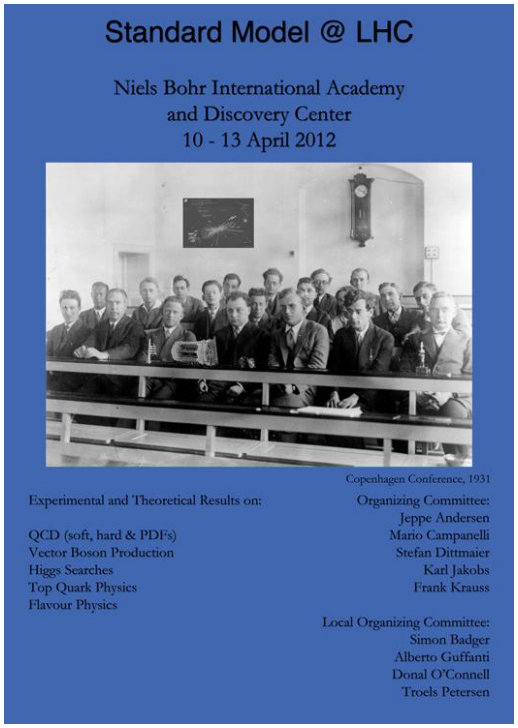


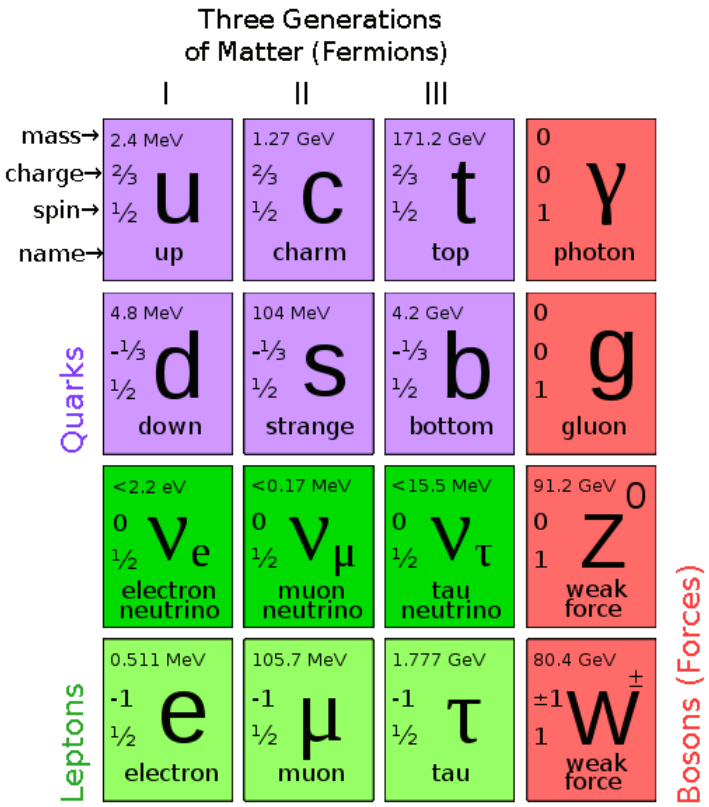
Vector bosons (V)

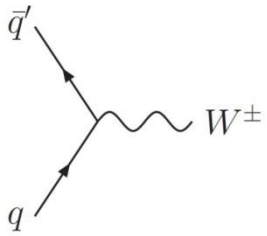
The production of multiple electroweak bosons at LHC provides an important test of the Standard Model.

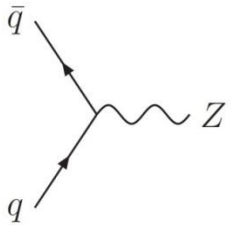
Precise measurements and predictions of electroweak gauge boson production are very important for checks of possible deviations from the SM
(anomalous Triple Gauge Couplings (TGC)).

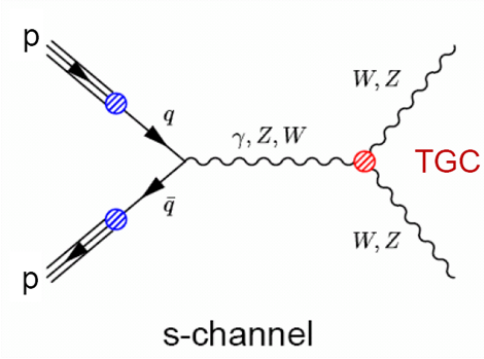
Multibosons – important background for Higgs→V V and other searches.

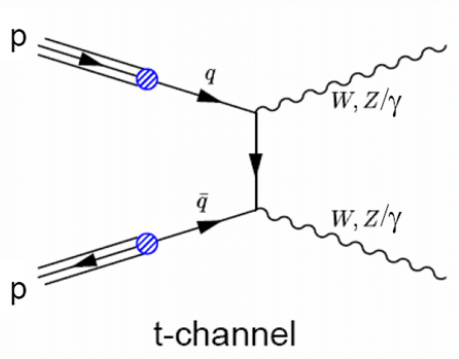
Vector bosons











TGC vertices
Allowed in SM: WWγ and WWZ.
Not allowed: Zγγ, ZZγ, ZZZ.

CMS measurements

Diboson channels measured in CMS:
1)Wγ, Zγ
2)WW, WZ, ZZ

All leptonic modes:
- clear signature
- low QCD background
- but: low branching ratio

Data 2010, 36 pb^{-1}:

WW: Phys. Lett. B699, 25-47, 2011.
W γ, Z γ: Phys. Lett. B701, 535-555, 2011.

Data 2011, 1.1 fb^{-1}:

WW,WZ, ZZ: CMS- EWK-11-010 (https://cdsweb.cern.ch/record/1370067).

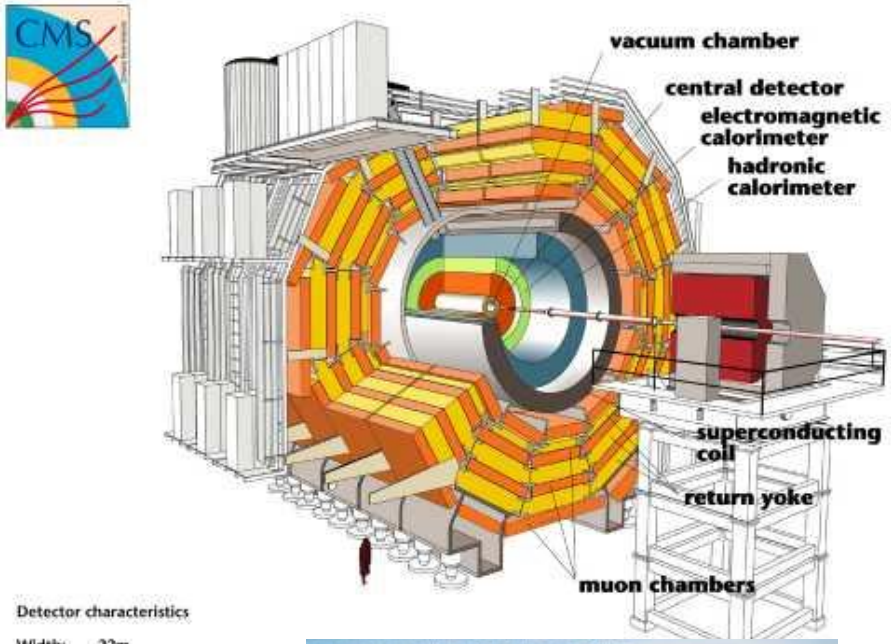
Data 2011, 4.92 fb^{-1}: New!

WW: CMS- SMP-12-005 (https://cdsweb.cern.ch/record/1440234).

In addition, data 2011, 4.6-4.7 fb^{-1}:

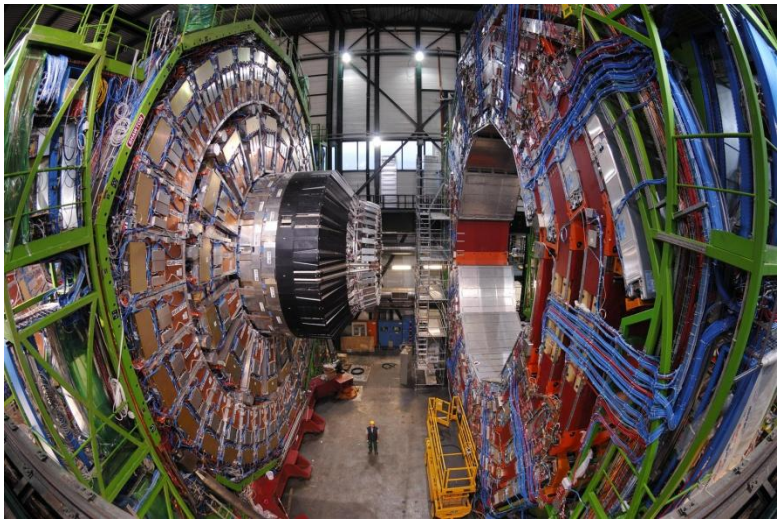
Z to 4l: CMS-SMP-12-009 (https://cdsweb.cern.ch/record/1431862).
WH->WWW: CMS-HIG-11-034 (https://cdsweb.cern.ch/record/1429927).

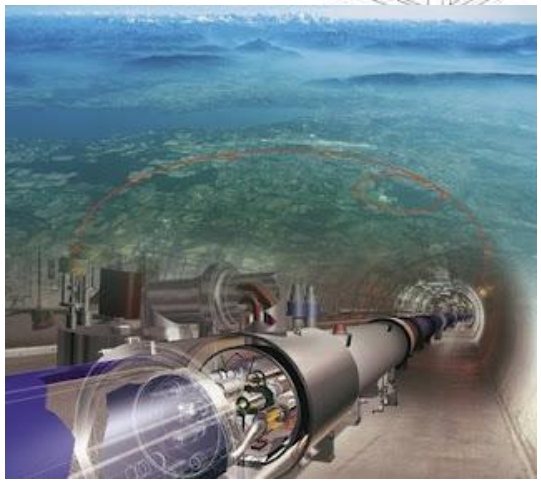
CMS detector

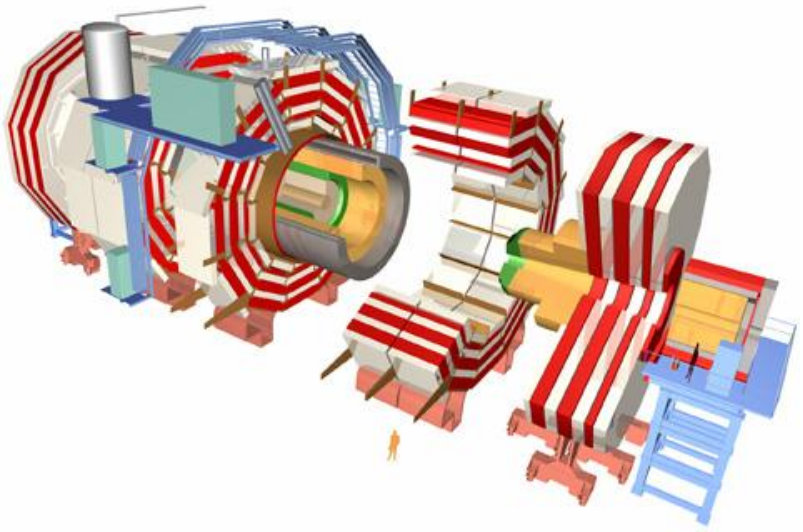


Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t



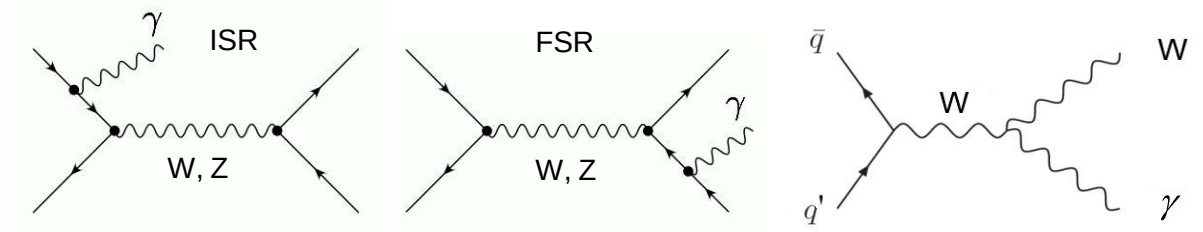




Wγ, Zγ

Data 2010, 36 pb^{-1}

Wγ state includes initial state radiation (ISR), final state radiation (FSR) and WWγ TGC. Zγ - only ISR and FSR.

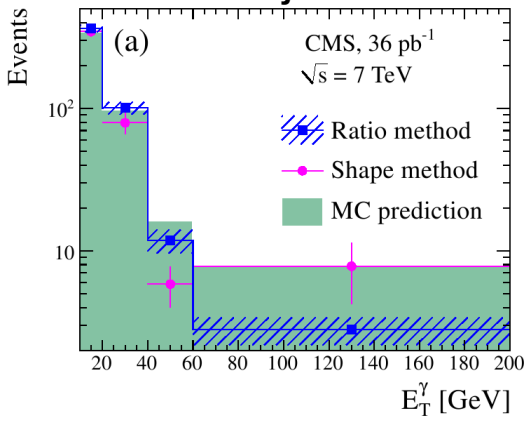


Channels:

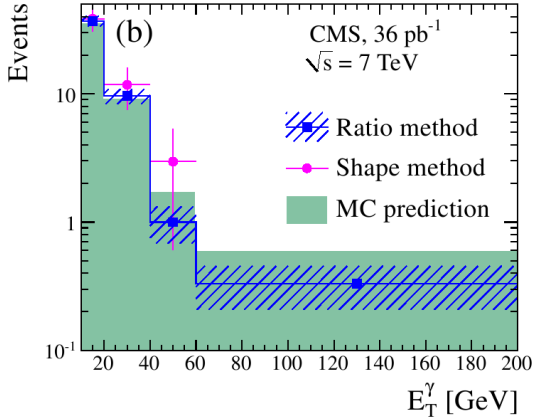
$W\gamma \to e\nu\gamma,\ \mu\nu\gamma \qquad Z\gamma \to ee\gamma,\ \mu\mu\gamma$

Main background comes from W+jets and Z+jets with misidentified jet.

W+jets:



Z+jets



Wγ

Selection:
- isolated lepton with p_T > 20 GeV
- photon with E_T > 10 GeV
- missing E_T > 25 GeV
- $\Delta R(l,\gamma)$ > 0.7
- in $e\nu\gamma$ no second loose electron
- in $\mu\nu\gamma$ no second loose muon

	$e\nu\gamma$	$\mu\nu\gamma$
W+jets bkg	$220\pm16\pm14$	$261\pm19\pm16$
Other bkg	7.7 ± 0.5	16.4 ± 1.0
All data	452	520

Other background (from $Z\gamma$, dibozons) is defined from MC.

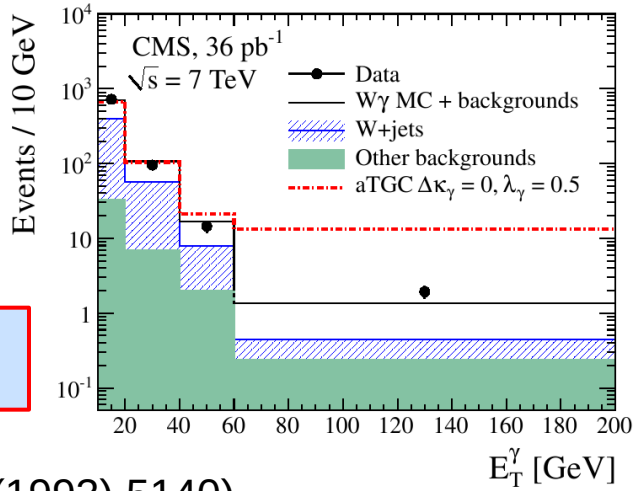
$W\gamma$ production cross section for E_T^γ > 10 GeV and $\Delta R(l,\gamma)$ > 0.7 is:

$$\sigma(pp\to W\gamma+X)\times B(W\to e\nu)=57.1\pm6.9(stat)\pm5.1(syst)\pm2.3(lumi)\,pb$$

$$\sigma(pp\to W\gamma+X)\times B(W\to \mu\nu)=55.4\pm7.2(stat)\pm5.0(syst)\pm2.2(lumi)\,pb$$

Best Linear Unbiased Estimator method:

$$\sigma(pp\to W\gamma+X)\times B(W\to l\gamma)=56.3\pm5.0(stat)\pm5.0(syst)\pm2.3(lumi)\,pb$$



NLO prediction: $49.4\pm3.8\,pb$ (U.Baur et al. Phys.Rev. D48 (1993) 5140).

Zγ

Selection:
- pair e^+e^- or $\mu^+\mu^-$
- each lepton with p_T > 20 GeV
- photon with E_T > 10 GeV
- missing E_T > 25 GeV
- $\Delta R(l,\gamma) > 0.7$
- m(ll) > 50 GeV

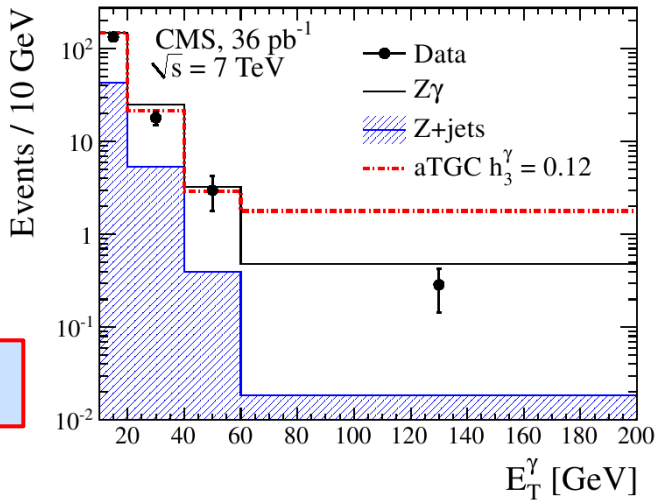
	$ee\gamma$	$\mu\mu\gamma$
Z+jets bkg	$20.5 \pm 1.7 \pm 1.9$	$27.3 \pm 2.2 \pm 2.3$
Other bkg	neglected	
All data	81	90

$Z\gamma$ production cross section for E_T^γ> 10 GeV and $\Delta R(l,\gamma)$ > 0.7 and m(ll) > 50 GeV is:

$$\sigma(pp \to Z\gamma + X) \times B(Z \to ee) = 9.5 \pm 1.4(stat) \pm 0.7(syst) \pm 0.4(lumi)\,pb$$

$$\sigma(pp \to Z\gamma + X) \times B(Z \to \mu\mu) = 9.2 \pm 1.4(stat) \pm 0.6(syst) \pm 0.4(lumi)\,pb$$

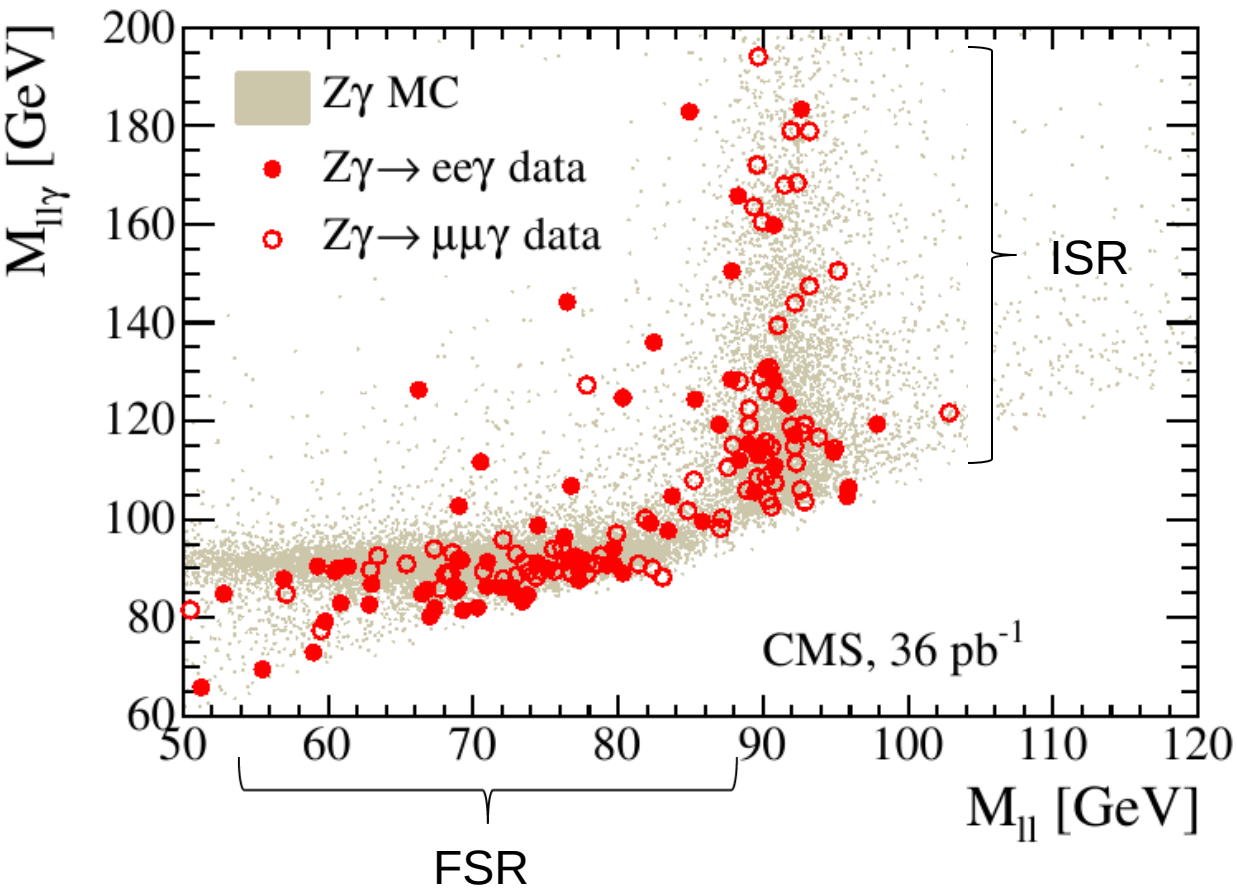
$$\sigma(pp \to Z\gamma + X) \times B(Z \to ll) = 9.4 \pm 1.0(stat) \pm 0.6(syst) \pm 0.4(lumi)\,pb$$

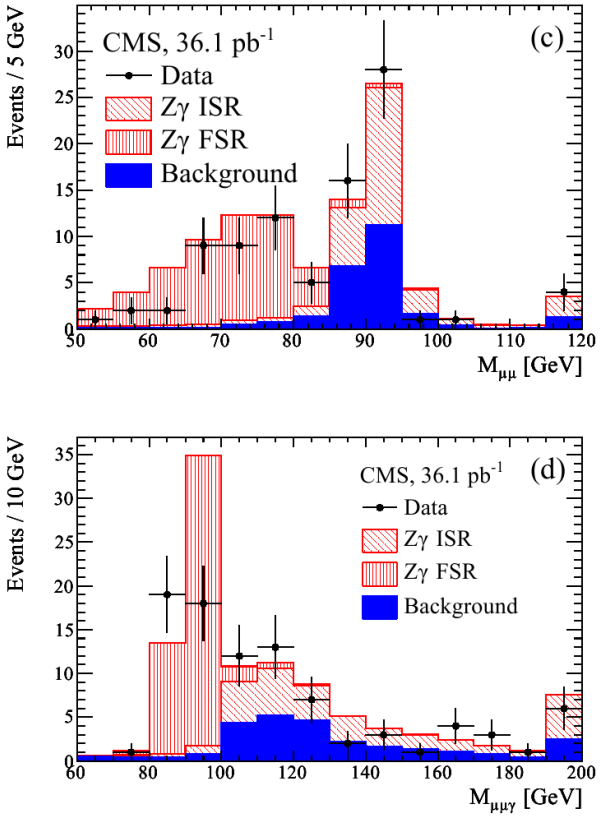


NLO prediction: $9.6 \pm 0.4\,pb$ (U.Baur and E.Berger, Phys.Rev. D47 (1993) 4889).

Zγ

Distinguishing ISR and FSR.





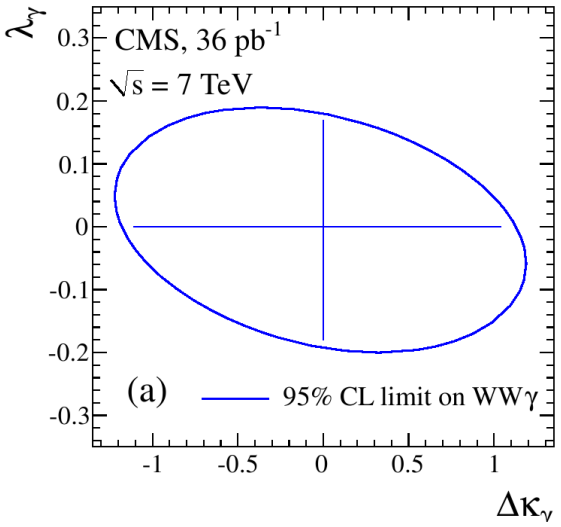
Limits on aTGC from $W\gamma, Z\gamma$

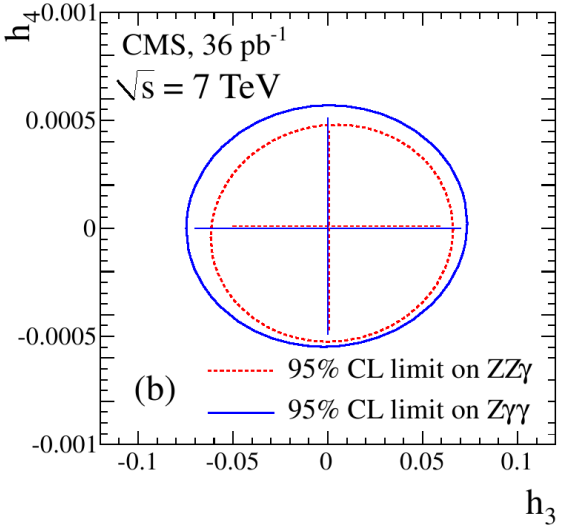
For $WW\gamma$ two parameters in Lagrangian: k_γ=1, λ_γ=0.
aTGC are deviations from SM values, so $\Delta k_\gamma \equiv k_\gamma - 1$.

For $ZZ\gamma$, $Z\gamma\gamma$ parameters h_3^Z, h_4^Z and h_3^γ, h_4^γ (=0 in SM at tree level).

Simulated samples of $W\gamma$ and $Z\gamma$ signals were produced for a greed of aTGC values.

Limits were obtained using likelihood based on E_T spectrum of the photon.





WWγ	ZZγ	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

Data 2011, 4.92 fb^{-1}. Purely leptonic modes: WW $\rightarrow ll\nu\nu$ ($ll = e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$)

Selection:

- two oppositely charged isolated leptons, each with p_T > 20 GeV;
- missing E_T > 40 (20) GeV for $ee/\mu\mu(e\mu)$ states (Z$\rightarrow\tau\tau, ll$ rejection);
- jet veto (> 30 GeV), b-tagging veto (W+jet/top rejection);
- third lepton and veto (WZ/ZZ rejection);
- veto 76 < $m(e^+e^-, \mu^+\mu^-)$< 106 GeV, Δφ(ll , jet p_T > 15 GeV) > 165^o (Z+jet rejection);
- rejected m(ll) < 20 (12) GeV for $ee/\mu\mu(e\mu)$;
- p_T^{ll} > 45 GeV.

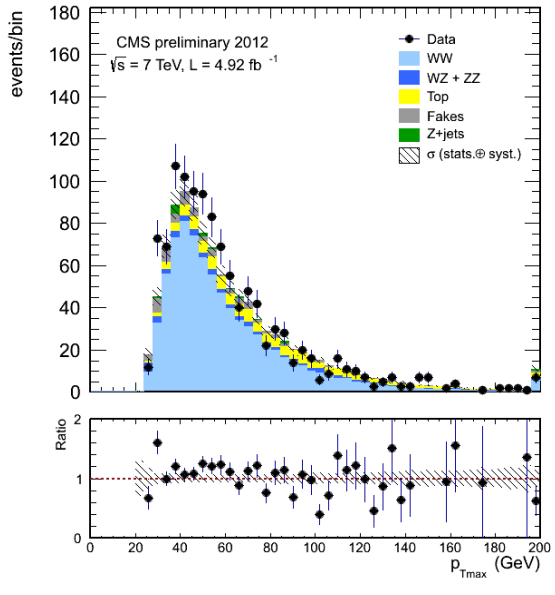
Background estimation:

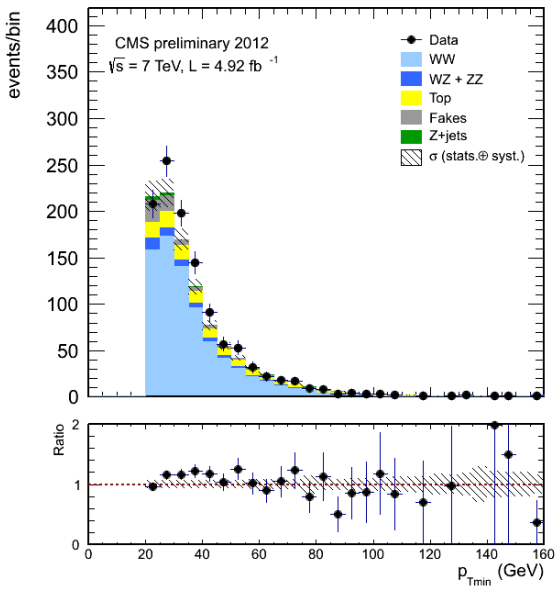
Data driven for:
- QCD/W+jet
- Top

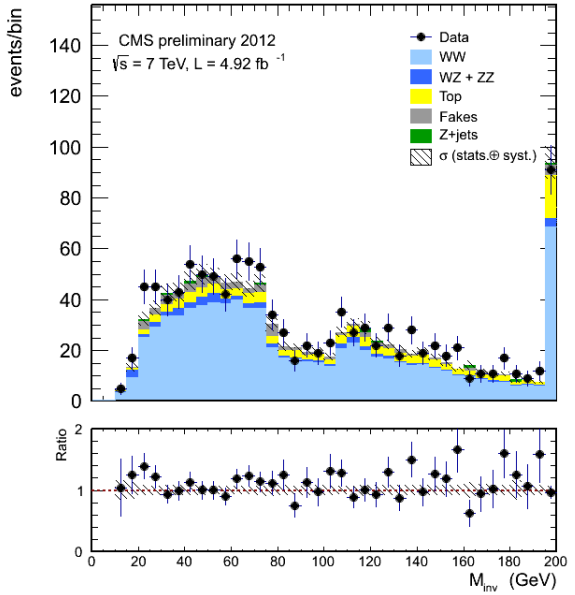
MC simulation for:
- Wγ
- Z$\rightarrow\tau\tau$
- Z/WZ/ZZ

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

WW







$$\sigma_{W^+W^-} = 52.4 \pm 2.0(stat.) \pm 4.5(syst.) \pm 1.2(lumi.)\, pb$$

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

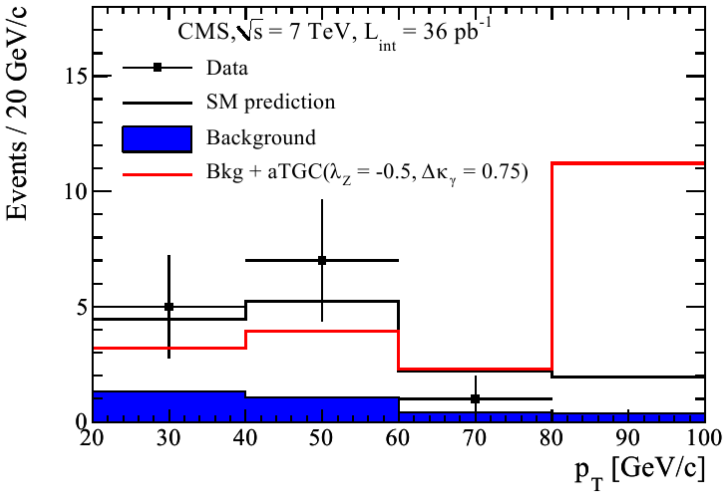
(data 2011, 1.1 fb^{-1}): $\sigma_{W^+W^-} = 55.3 \pm 3.3(stat.) \pm 6.9(syst.) \pm 3.3(lumi.)\, pb$

NLO prediction: $47.0^{+2.0}_{-1.5}\, pb$ (J.M.Campbell et al, JHEP **1107 (2011) 018**)

Limits on $WW\gamma$ and WWZ couplings

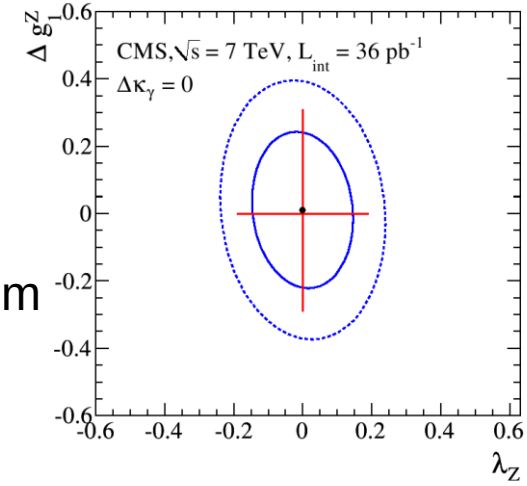
From WW analysis, data 2010, 36 pb^{-1}

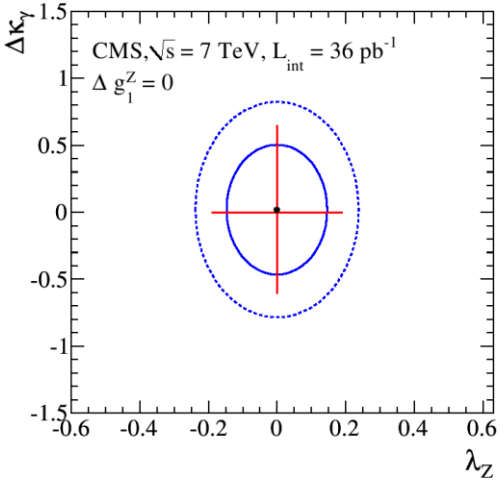
Leading lepton transverse momentum:



Three parameters:
λ_Z, g_1^Z, k_γ
in SM = 0, 1, 1).

Δg_1^Z , Δk_γ - deviations from SM values.





	λ_Z	Δg_1^Z	Δk_γ
Unbinned fit	[-0.19,0.19]	[-0.29,0.31]	[-0.61,0.65]
Binned fit	[-0.23,0.23]	[-0.33,0.40]	[-0.75,0.72]

WZ

Data 2011, 1.09 fb^{-1}. Leptonic modes: WZ$\rightarrow l^{\pm}\nu l'^{+}l'^{-}(l,l'=e,\mu)$

Z selection:
- two isolated electrons with p_T > 20 / 10 GeV or
- two isolated muons with p_T > 15 GeV
- 60 < m(l^+l^-) < 120 GeV
- Z candidate is taken with mass more close to nominal Z mass

W selection:
- third isolated lepton with p_T > 20 GeV

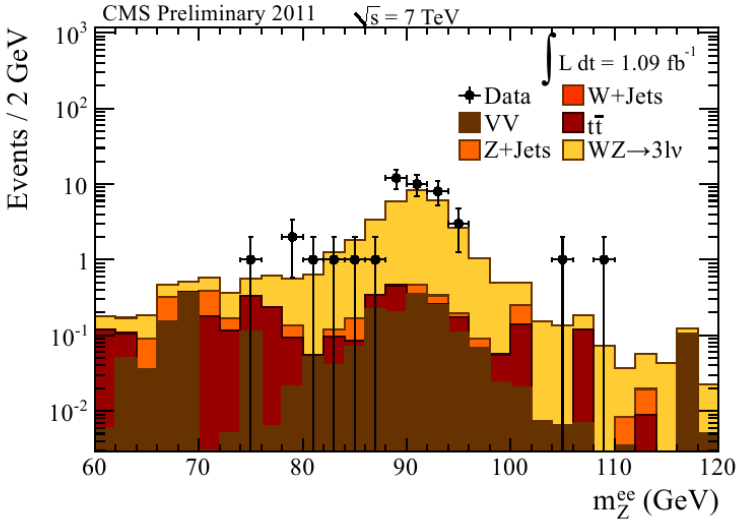
Veto on:
- second reconstructed Z (ZZ rejection)
- E_T > 30 GeV (ZZγ and ZZ$\rightarrow 4l$ rejection)

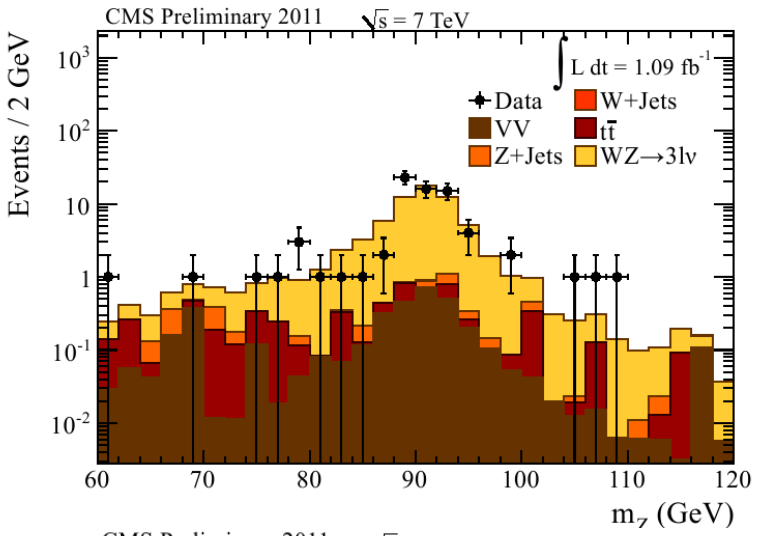
Background estimation:

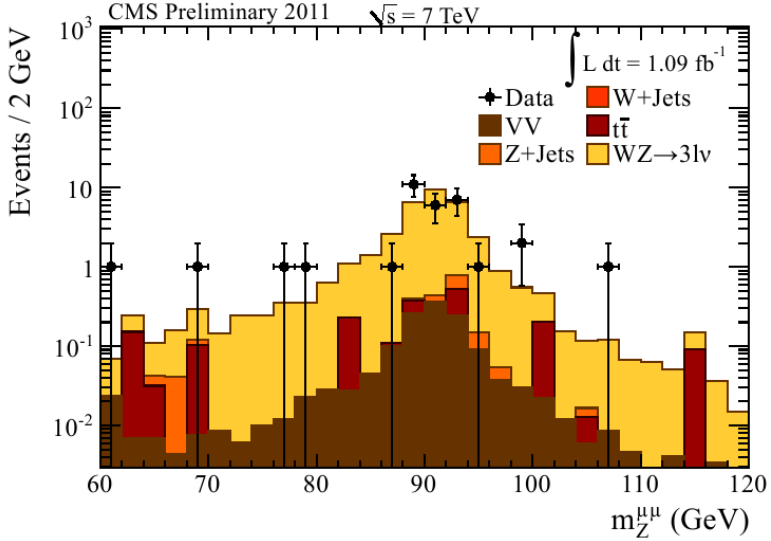
Data driven for:
- Z+jets
- Top

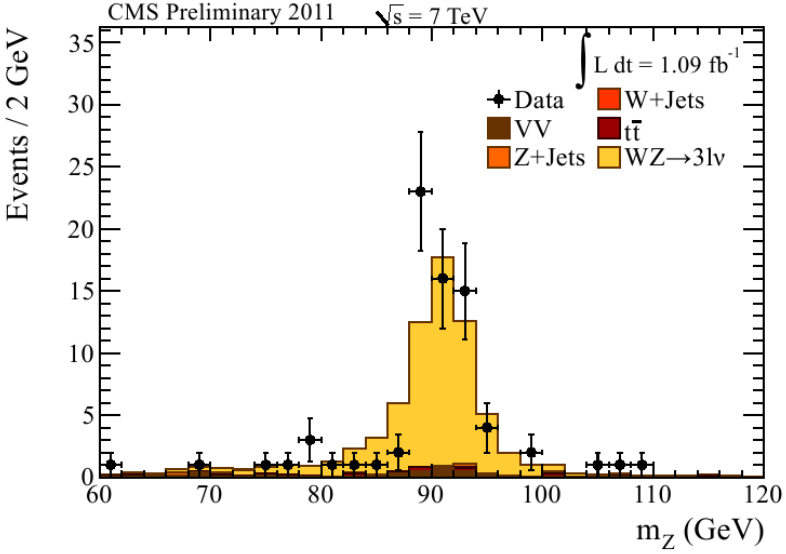
MC simulation for:
- Zγ
- ZZ$\rightarrow 4l$

WZ


CMS Preliminary 2011
√s = 7 TeV
∫ L dt = 1.09 fb⁻¹
Data
W+Jets
VV
tt̄
Z+Jets
WZ→3lν
Events / 2 GeV
m_Z^ee (GeV)


CMS Preliminary 2011
√s = 7 TeV
∫ L dt = 1.09 fb⁻¹
Data
W+Jets
VV
tt̄
Z+Jets
WZ→3lν
Events / 2 GeV
m_Z (GeV)


CMS Preliminary 2011
√s = 7 TeV
∫ L dt = 1.09 fb⁻¹
Data
W+Jets
VV
tt̄
Z+Jets
WZ→3lν
Events / 2 GeV
m_Z^μμ (GeV)


CMS Preliminary 2011
√s = 7 TeV
∫ L dt = 1.09 fb⁻¹
Data
W+Jets
VV
tt̄
Z+Jets
WZ→3lν
Events / 2 GeV
m_Z (GeV)

WZ

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
$t\bar{t}$	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

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	$0.060 \pm 0.016(stat) \pm 0.004(syst) \pm 0.004(lumi)$

$$\sigma(pp \to \mathrm{WZ} + X) \times \mathcal{B}(\mathrm{Z} \to \ell\ell)\mathcal{B}(\mathrm{W} \to \ell\nu_\ell) = 0.062 \pm 0.009\ (\mathrm{stat.}) \pm 0.004\ (\mathrm{syst.}) \pm 0.004\ (\mathrm{lumi.})\ \mathrm{pb}$$

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

NLO prediction: $19.79 \pm 0.09\,pb$ (MCFM calculation)

ZZ

Data 2010+2011, 1.13 fb^{-1}. Leptonic modes: ZZ$\rightarrow l^{\pm}l^{\mp}l'^{\pm}l'^{\mp}$ ($l, l' = e, \mu$ or τ)

First Z selection:

- two isolated leptons of the same flavor with p_T > 20 / 10 GeV
- 60 < m(l^+l^-) < 120 GeV

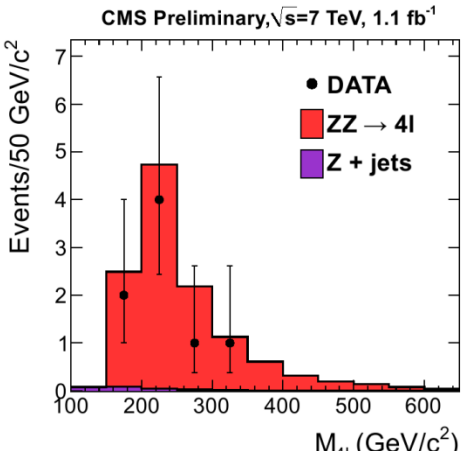
Second Z selection:

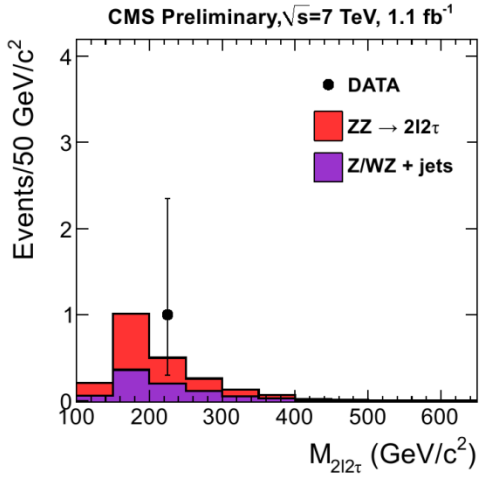
1) ZZ$\rightarrow 4e, 4\mu, 2e2\mu$

- two isolated leptons of the same flavor
- p_T > 7 GeV for e , p_T > 5 GeV for μ
- 60 < m(l^+l^-) < 120 GeV

2) ZZ$\rightarrow 2l2\tau$

- $\tau \rightarrow$ lepton, p_T > 10 GeV
- $\tau \rightarrow$ hadron, p_T > 20 GeV
- 30 < visible mass $\tau\tau$ < 80 GeV

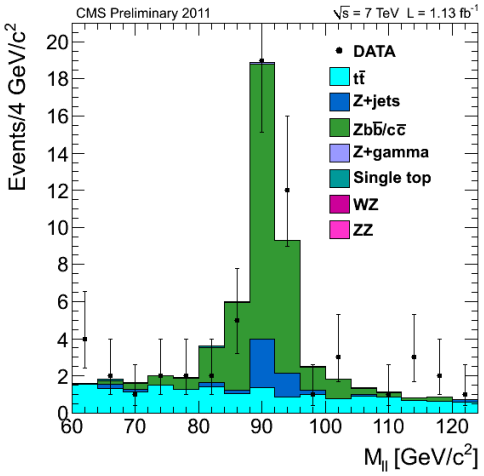




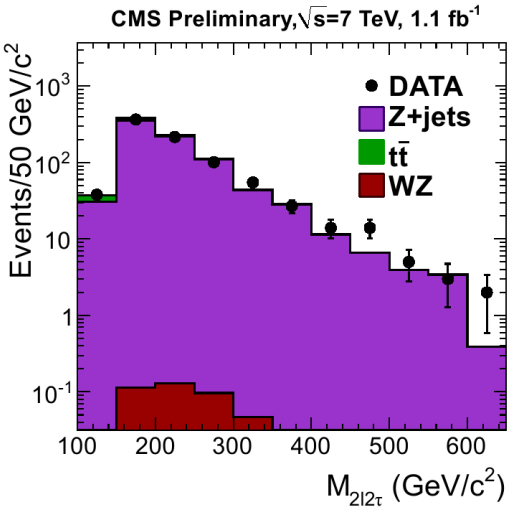
ZZ

Background estimation:

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



Visible mass of $2l2\tau$ in Z+jets control sample:

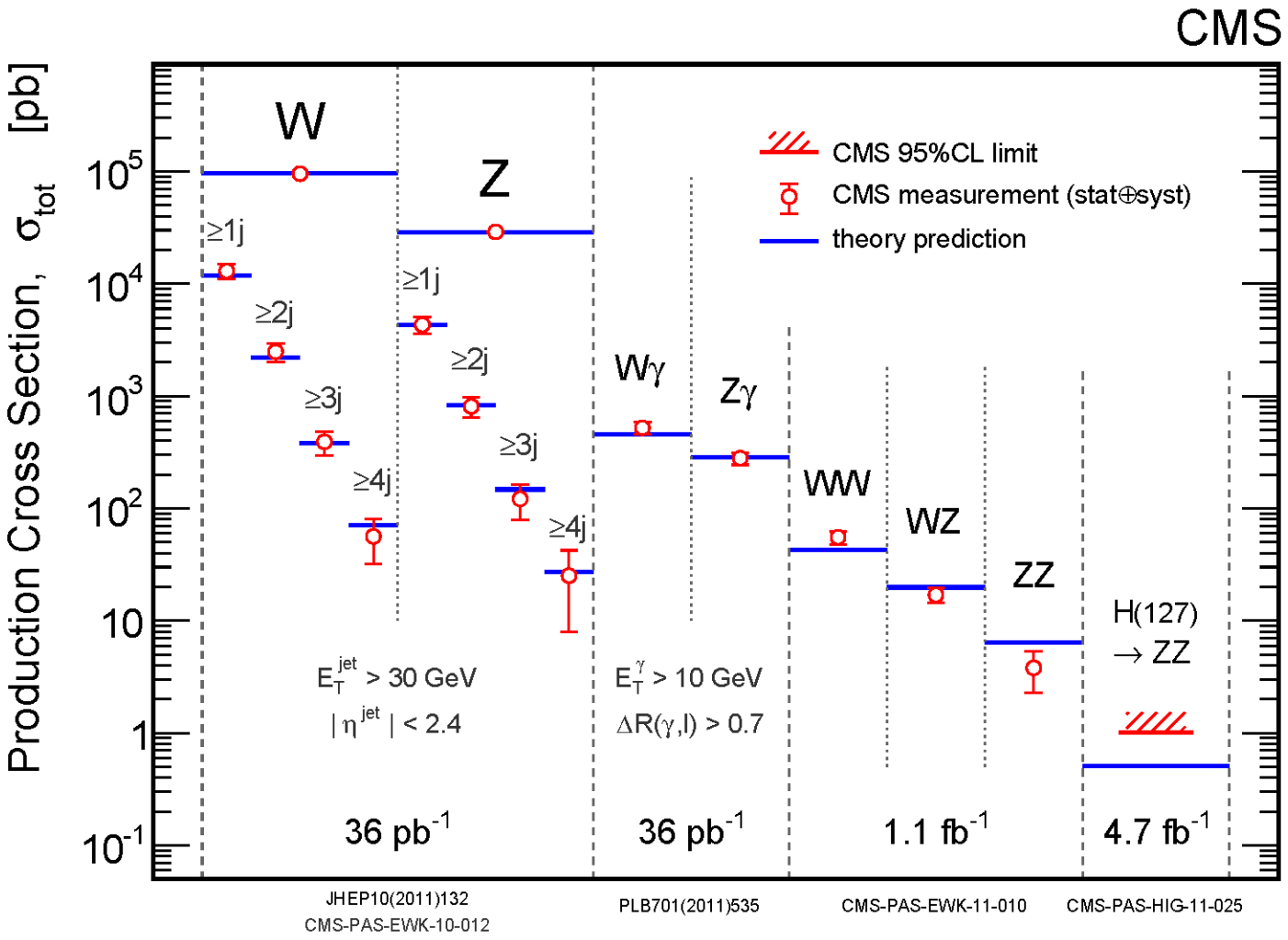


Final state	N_{obs}	$N^{backg.}_{estimated}$	$N^{ZZ}_{expected}$
4μ	2	0.004 ± 0.004	3.7 ± 0.4
$4e$	0	0.14 ± 0.06	2.5 ± 0.2
$2e2\mu$	6	0.15 ± 0.06	6.3 ± 0.6
$2l2\tau$	1	0.8 ± 0.1	1.4 ± 0.1

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

NLO prediction: $6.4 \pm 0.6\, pb$ (MCFM calculation)

Dibosons


CMS
Production Cross Section, σ_{tot} [pb]
10^5
10^4
10^3
10^2
10
1
10^{-1}
W
Z
≥1j
≥2j
≥3j
≥4j
≥1j
≥2j
≥3j
≥4j
Wγ
Zγ
WW
WZ
ZZ
H(127)
→ ZZ
CMS 95%CL limit
CMS measurement (stat⊕syst)
theory prediction
E_T^{jet} > 30 GeV
$|\eta^{jet}|$ < 2.4
E_T^{γ} > 10 GeV
ΔR(γ,l) > 0.7
36 pb^{-1}
36 pb^{-1}
1.1 fb^{-1}
4.7 fb^{-1}
JHEP10(2011)132
CMS-PAS-EWK-10-012
PLB701(2011)535
CMS-PAS-EWK-11-010
CMS-PAS-HIG-11-025

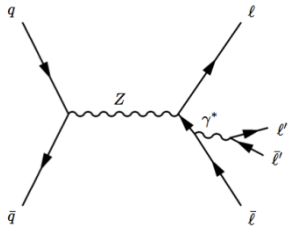
$Z \rightarrow 4l$

Data 2011, 4.7 fb^{-1}.

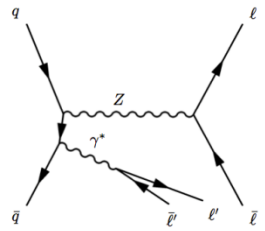
First observation and measurement of this decay on hadron collider.

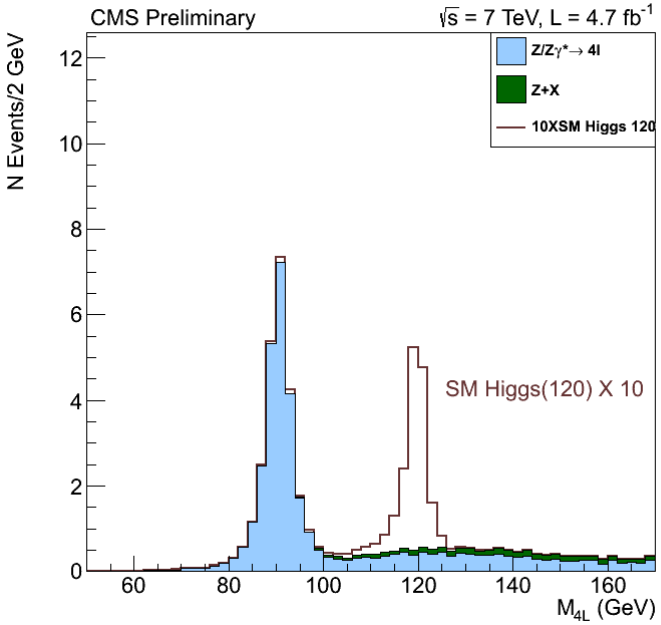
Background for Higgs searches; calibration of m_{4l} and resolution.

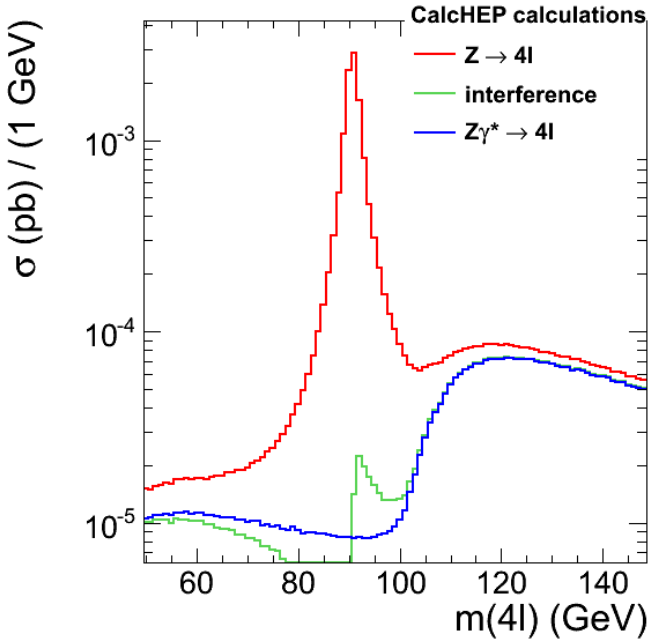
Signal (FSR):



Background (ISR):







Signal events: $e^+e^-e^+e^-\,(4e)$, $\mu^+\mu^-\mu^+\mu^-\,(4\mu)$, $e^+e^-\mu^+\mu^-\,(2e2\mu)$

Signal definition: 80 < m($4l$) < 100 GeV, m(ll) > 4 GeV for all pairings.

$Z \rightarrow 4l$

Selection: 1) four leptons $(4e, 4\mu, 2e2\mu)$;
2) two leading leptons with p_T at least 20 and 10 GeV;
3) two another with p_T > 7 GeV for electrons and p_T > 5 GeV for muons;
4) relative isolation < 0.275 (ΔR< 0.3).

Final state channels	$4e$	4μ	$2e2\mu$	4ℓ
Irreducible background ($pp \rightarrow Z\gamma^* \rightarrow 4\ell$)	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 ($pp \rightarrow Z \rightarrow 4\ell$)	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

Minimization of likelihood, including:

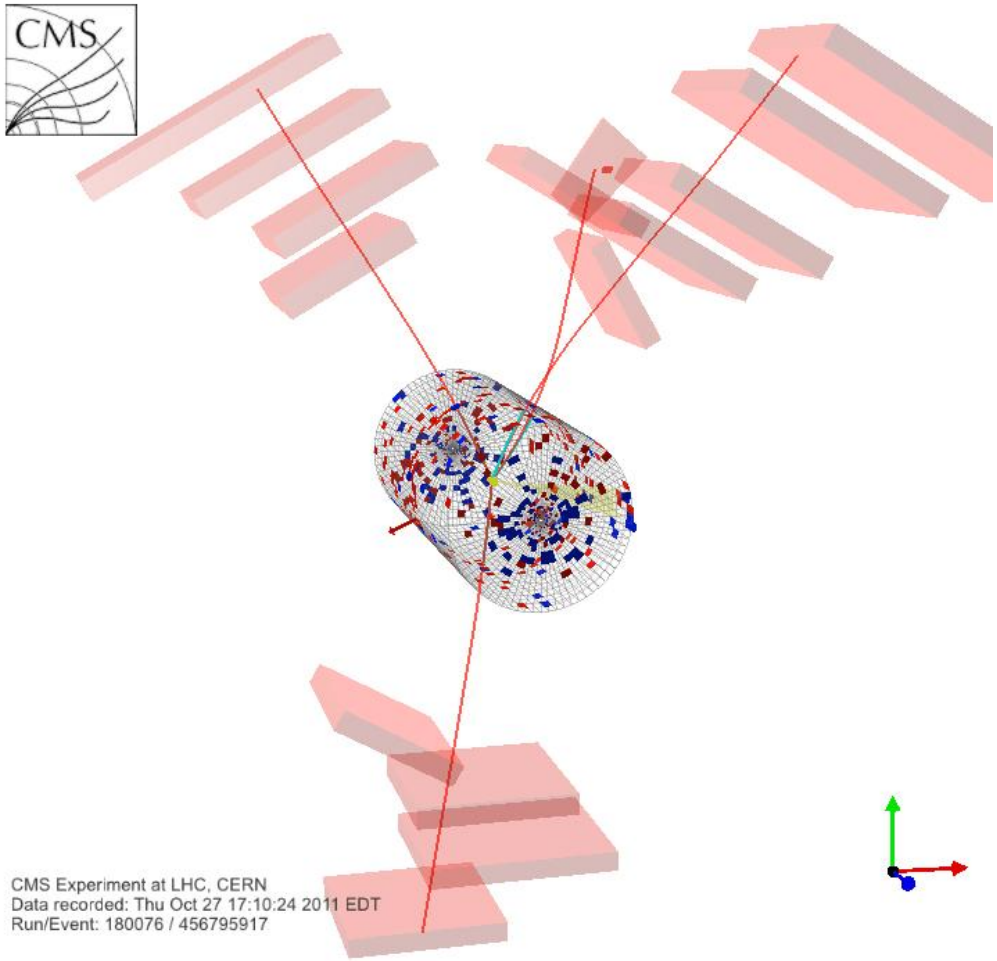
- Number of events in each final state i:

$$s_i = L \cdot \sigma(pp \rightarrow Z) \cdot BR(Z \rightarrow 4l) \cdot f_i \cdot \varepsilon_i^{acc} \cdot \varepsilon_i^{\exp} \cdot c_i$$

- Number of background events
- Nuissance parameters for systematics

$Z \rightarrow 4l$

Typical event display:



$Z \rightarrow 4l$

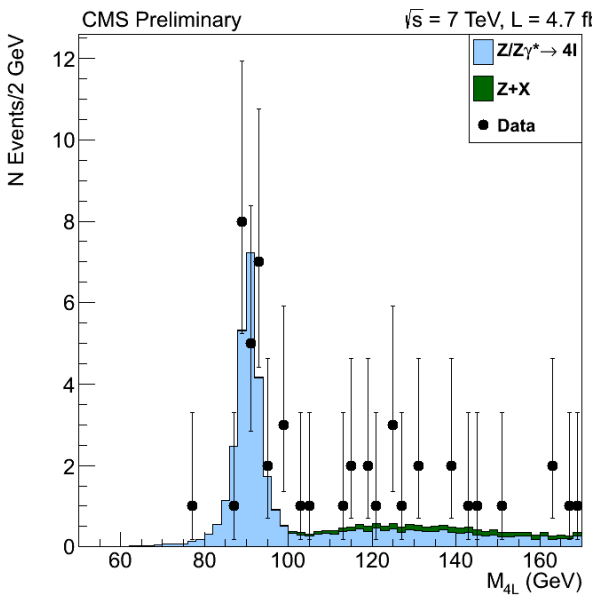
$$\sigma \times BR(Z \rightarrow 4l) = 125^{+25}_{-23}(stat)^{+9}_{-6}(syst)^{+7}_{-5}(lumi)\ fb$$

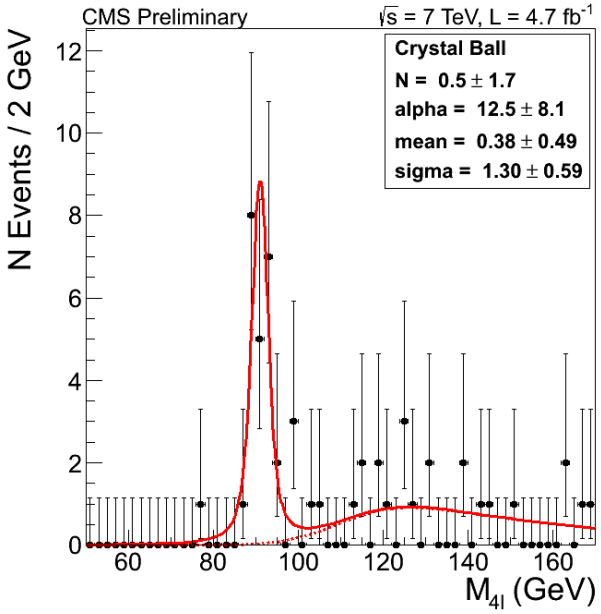
SM prediction: $120 \pm 5\ fb$

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

SM prediction: 4.45×10^{-6}

The four-lepton mass peak arising from $Z \rightarrow 4l$ decay provides a natural standard candle for the Higgs boson search in the $H \rightarrow ZZ \rightarrow 4l$ decay mode.





m_{4l} scale known to 0.5%.

m_{4l} width known to 45%.

Significance 8.9 σ .

WH→WWW

Data 2011, 4.6 fb^{-1} .

Search for $WH \to WWW \to l\nu l\nu l\nu \, (l = e, \mu)$.

WH (120) $H \to \tau\tau$	WH (120) $H \to WW$	data	all bkg.	WZ $\to 3\ell\nu$	ZZ $\to 4\ell$	top+Z/γ^*
0.1 ± 0.0	0.5 ± 0.1	7	8.4 ± 0.9	5.7 ± 0.2	0.3 ± 0.1	2.6 ± 0.9

95% CL upper limit is 10.4 times larger than SM Higgs expectation for $m_H = 120\,GeV$.

See talk Alessandro Thea, "Higgs decays to gauge bosons in CMS, H -> gamma, WW, ZZ“ later today.

Summary of results

	CMS	SM prediction	[1]
$W\gamma$	$56.3 \pm 5.0 \pm 5.0 \pm 2.3\, pb$	$49.4 \pm 3.8\, pb$	$51.2^{+2.3}_{-3.5}\, pb$
$Z\gamma$	$9.4 \pm 1.0 \pm 0.6 \pm 0.4\, pb$	$9.6 \pm 0.4\, pb$	$9.83^{+0.35}_{-0.46}\, pb$
WW	$52.4 \pm 2.0 \pm 4.5 \pm 1.2\, pb$	$47.0^{+2.0}_{-1.5}\, pb$	$47.0^{+2.0}_{-1.5}\, pb$
WZ	$17.0 \pm 2.4 \pm 1.1 \pm 1.0\, pb$	$19.79 \pm 0.09\, pb$	$18.6^{+1.0}_{-0.8}\, pb$
ZZ	$3.8^{+1.5}_{-1.2} \pm 0.2 \pm 0.2\, pb$	$6.4 \pm 0.6\, pb$	$6.5^{+0.3}_{-0.2}\, pb$
$Z \rightarrow 4l$	$125^{+25}_{-23}(stat)^{+9}_{-6}(syst)^{+7}_{-5}(lumi)\ fb$	$120 \pm 5\, fb$	
$BR(Z \rightarrow 4l)$	$4.4^{+1.0}_{-0.8} \pm 0.2 \times 10^{-6}$	4.45×10^{-6}	

[1] John M. Campbell, R. Keith Ellis and Ciaran Williams, Vector boson pair production at the LHC. arxiv:1105.0020v1 (29 April 2011). JHEP 1107:018,2011.