Measurements of Gauge Bosons Self-Interactions at CMS

Vuko Brigljević
Ruđer Bošković Institute, Zagreb (Croatia)

On behalf of the CMS Collaboration

Hrvatska zaklada za znanost

LHC Seminar, CERN, 30 April 2013

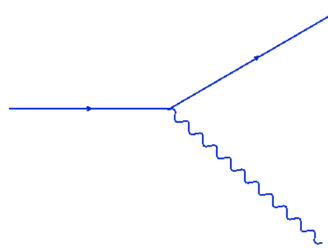
LPCC
LHC Physics Centre at CERN

Gauge Symmetries & Interactions

Invariance under
local gauge transformation
of matter fields

$$\psi(x) \rightarrow \psi'(x) = e^{-i\alpha(x)}\psi(x)$$

Gauge field
interacting with
matter fields

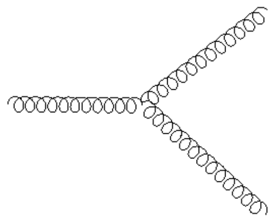


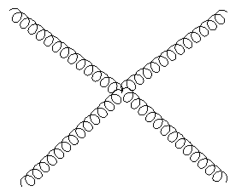
Invariance under
non-abelian
local gauge transformation, e.g. SU(n):

$$\psi(x)_i \rightarrow \psi'(x)_i = (e^{-i\theta^a(x)\tau^a})_{ij}\psi(x)_j$$

gauge-fermion int.
+
Interaction between
gauge fields
themselves

e.g.: QCD SU(3) → gluon self interactions:



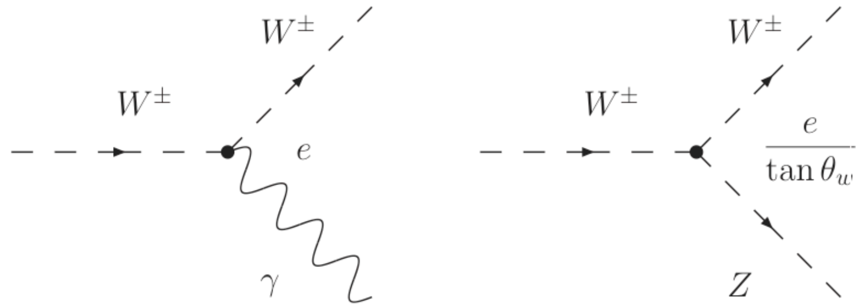


Gauge Self-Couplings in the EWK sector

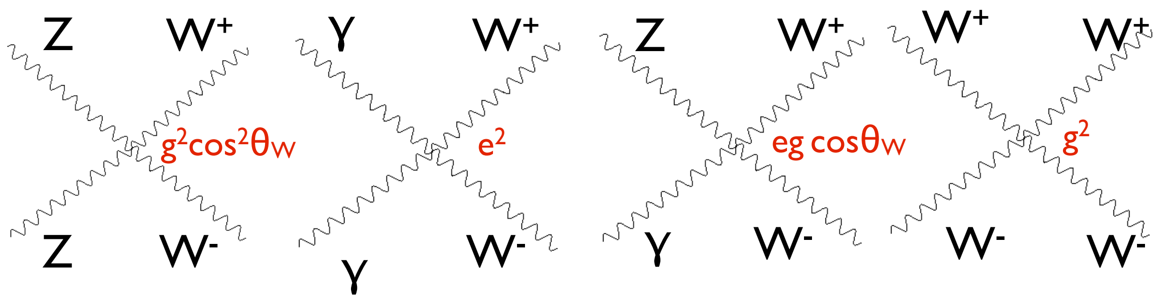
- SU(2)xU(1) symmetry leads to several gauge bosons self-interactions in the electroweak sector of the SM, following from the Gauge coupling interaction term in the EWK lagrangian:

$$\mathcal{L}_{\mathrm{GC}} = \frac{1}{2} g_2 (\partial_\mu W^i_\nu - \partial_\nu W^i_\mu)\varepsilon_{ijk} W^{j\mu} W^{k\nu} - \frac{1}{4} g_2^2 \varepsilon_{ijk}\varepsilon_{imn} W^j_\mu W^k_\nu W^{m\mu} W^{n\nu}$$

Triple Gauge Couplings (observed)



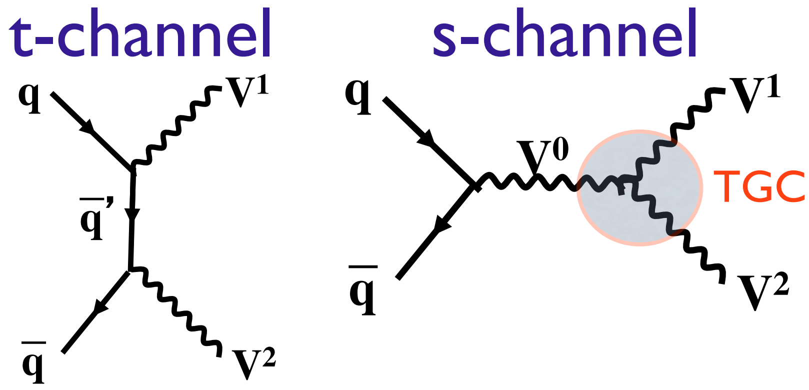
Quartic Gauge Couplings (not seen yet)



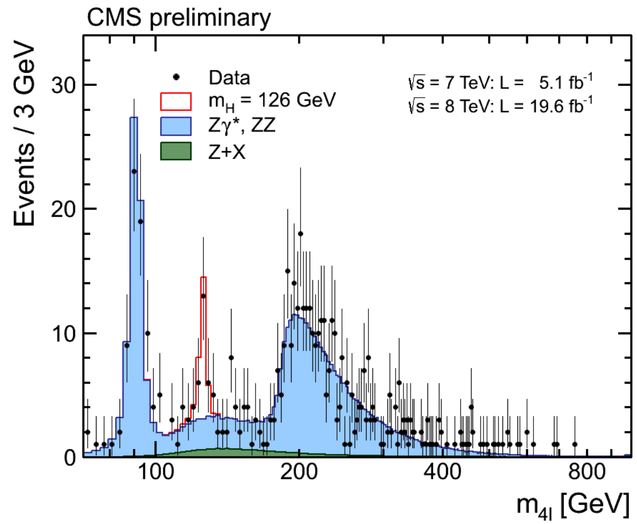
NO NEUTRAL GAUGE COUPLINGS IN THE SM!

Gauge Self-Couplings @ LHC: Dibosons

- Diboson production sensitive to TGC in s-channel
- Neutral TGCs not allowed in SM
  - Wγ, WW and WZ production get contribution from TGCs
  - Zγ and ZZ: no TGC contribution in the SM
- Diboson processes allow to probe one of the least well measured sectors of the SM
  - Also background for many searches

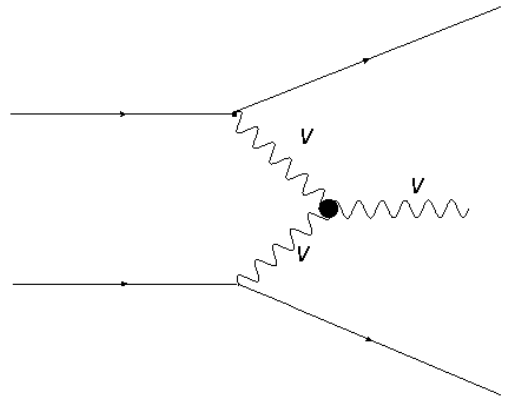


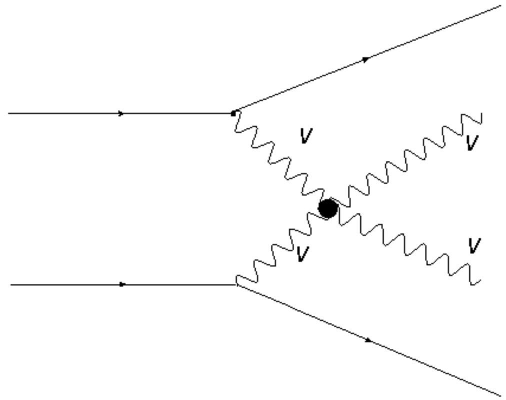
THE science news of the year 2012: a diboson resonance!



Gauge Self-Couplings @ LHC: VBF Production

- Single or multiple boson production in VBF directly sensitive to TGCs and QGCs
- Potentially the first way to see QGCs
  - QGCs not observed yet
- Very relevant for studying boson-boson scattering
  - Of key importance in the future study of the newly found boson





Measurements of diboson production with CMS

Cross section measurements

Cut & Count in most cases

Dominant contributions always data-driven

$$\sigma = \frac{N_{selected} - N_{background}}{A \cdot \epsilon \cdot \int \mathcal{L} dt}$$

- Determined from MC wrt to target measurement phase space (inclusive or reduced)
- Correction factor applied to account for data/MC efficiency differences

CMS Diboson Measurements

	Int. luminosity @ 7TeV	Int. luminosity @ 8TeV	Cross section measurement phase space	
$ZZ\to 2l2l'$ ($l = e/\mu; l' = e/\mu/\tau$)	**5.0 fb^{-1}**	**5.3 fb^{-1}**	$60<M(Z_{1,2})<120$ GeV	$pp\to ZZ+X$
$W\gamma\to l\nu\gamma$	**5.0 fb^{-1}**	-	$E_T^{\gamma}>15/60/90$ GeV & $\Delta R(l,\gamma)>0.7$	$pp\to W\gamma\to l\nu\gamma+X$
$Z\gamma\to ll\gamma$	**5.0 fb^{-1}**	-	$E_T^{\gamma}>15/60/90$GeV & $\Delta R(l,\gamma)>0.7$ & $M^{ll}>50$GeV	$pp\to Z\gamma\to ll\gamma+X$
$Z\gamma\to\nu\nu\gamma$	**5.0 fb^{-1}**	-	$E_T^{\gamma}>145$ GeV & $\lvert\eta^{\gamma}\rvert<1.4$	$pp\to Z\gamma\to\nu\nu\gamma+X$
$W^+W^-\to l\nu l\nu$	**4.9 fb^{-1}**	**3.5 fb^{-1}**	full	$pp\to W^+W^-+X$
$W^+W^-+WZ\to l\nu jj$	**5.0 fb^{-1}**	-	full	$pp\to WW+WZ+X$
$WZ\to l\nu ll$	**1.0 fb^{-1}**	-	full	$pp\to WZ+X$
Exclusive $\gamma\gamma\to W^+W^-$	**5.0 fb^{-1}**	-	full / $P_T(\mu,e)>20$GeV & $\lvert\eta(\mu,e)\rvert<2.4$ & $P_T(\mu e)>100$GeV	$pp\to p^{(*)}W^+W^-p^{(*)}\to p^{(*)}e\mu p^{(*)}$

Also presenting: EWK Z+2jets measurement

$W\gamma \rightarrow l\nu\gamma$ & $Z\gamma \rightarrow ll\gamma$ ($l=e,\mu$)

Measured cross sections:

σ ($pp \rightarrow W\gamma + X \rightarrow l\nu\gamma + X$)

σ ($pp \rightarrow Z\gamma + X \rightarrow ll\gamma + X$)

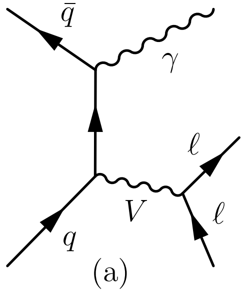
in reduced phase space:

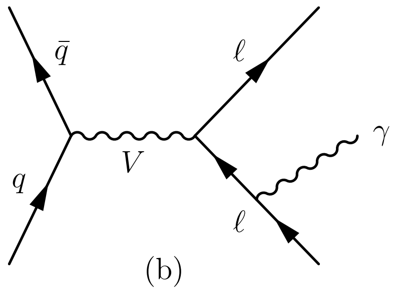
$E_T^{\gamma} > 15/40/60$ GeV;

$\Delta R(l,\gamma) > 0.7$)

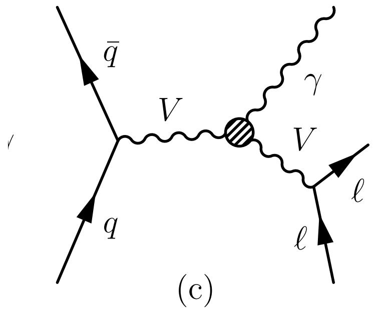
$M(ll) > 50$ GeV for $Z\gamma$

ISR





FSR



TGC

(only $W\gamma$ in SM!)

$W\gamma \rightarrow l\nu\gamma$: lepton+photon+MET

- Isolated lepton with $P_t > 35$ GeV
- Isolated Photon with $E_T > 15$ GeV
- Large transverse mass $M_T^W > 70$ GeV
- Veto events with 2nd lepton

$Z\gamma \rightarrow ll\gamma$: 2 leptons+photon

- 2 Isolated leptons with $P_t > 20$ GeV
- Isolated Photon with $E_T > 15$ GeV
- Dilepton mass > 50 GeV

Vγ: backgrounds

Vγ Backgrounds

- V+jets (fake photons), DOMINANT
- DY, Multibosons

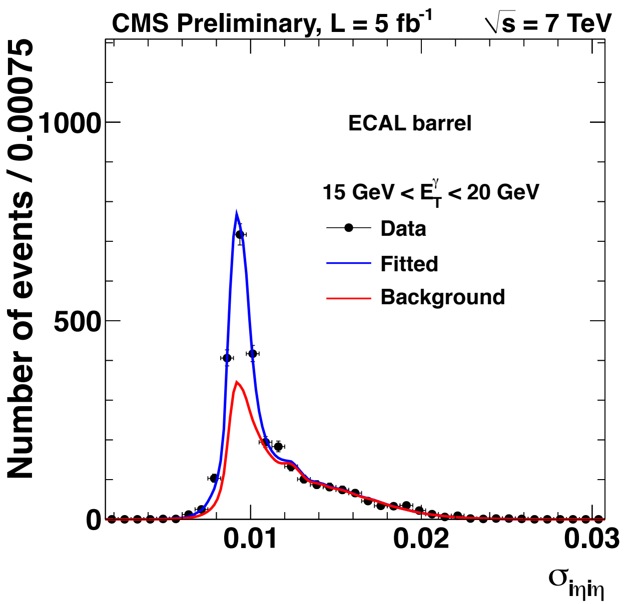
→ Data-driven estimate

- Zγ (for Wγ), γ+jets, ...

→ MC estimate

Fake photon contribution estimated from template fit to η shower width

CMS-PAS-EWK-11-009



Uncertainty on template yield dominant source of systematic

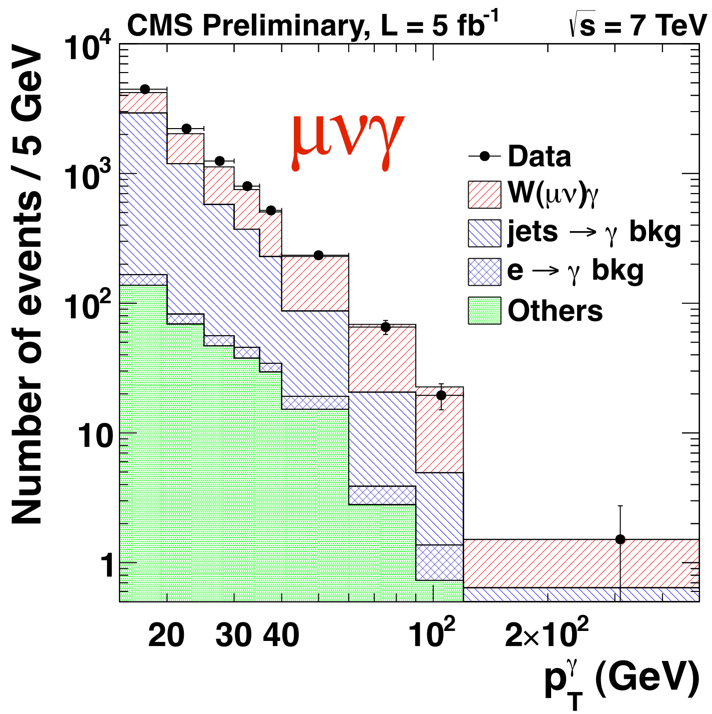
Photon E_T, GeV	Mean yield	Syst. from signal shape	Syst. from background shape	Syst. from sampling of the distribution	Syst. from $\not{E}_T$ correlation
Barrel + Endcap: $e\nu\gamma$ / $\mu\nu\gamma$					
15-20	1452.3 / 2762.9	9.3 / 20.5	83.2 / 59.4	19.2 / 35.6	129.1 / 251.7
20-25	648.4 / 1108.3	5.2 / 19.5	37.0 / 33.8	11.2 / 18.8	54.4 / 94.2
25-30	365.3 / 521.6	3.7 / 9.4	21.0 / 20.7	9.4 / 14.2	32.7 / 43.0
30-35	214.9 / 326.3	10.5 / 3.3	12.3 / 16.9	7.5 / 11.1	19.0 / 29.3
35-40	156.6 / 194.8	3.4 / 2.8	10.1 / 11.4	6.2 / 7.9	13.7 / 16.1
40-60	221.4 / 272.3	3.5 / 0.7	18.8 / 23.4	5.1 / 6.3	19.2 / 24.0
60-90	77.2 / 100.5	1.4 / 0.9	10.2 / 13.3	3.0 / 3.8	6.6 / 8.5
90-120	25.7 / 21.4	2.0 / 2.3	5.3 / 4.1	0.9 / 0.9	2.4 / 1.8
120-500	14.8 / 38.1	4.3 / 2.1	7.6 / 25.9	1.1 / 0.7	1.0 / 3.9
Total	3176.5 / 5345.9	16.9 / 30.3	97.6 / 83.3	26.7 / 45.4	277.8 / 472.1
		296.2 / 482.5			

Wγ results

	σ(Wγ→lνγ, ΔR(l,γ)>0.7) [pb]	NLO (MCFM) [pb]
E_T^γ >15 GeV	37.0±0.8(stat)±4.0(syst)±0.8(lumi)	31.81±1.80(syst)
E_T^γ >60 GeV	0.76±0.05(stat)±0.08(syst)±0.02(lumi	0.58±0.08(syst)
E_T^γ >90 GeV	0.200±0.025(stat)±0.038(syst)±0.004(lumi)	0.173±0.026(syst)

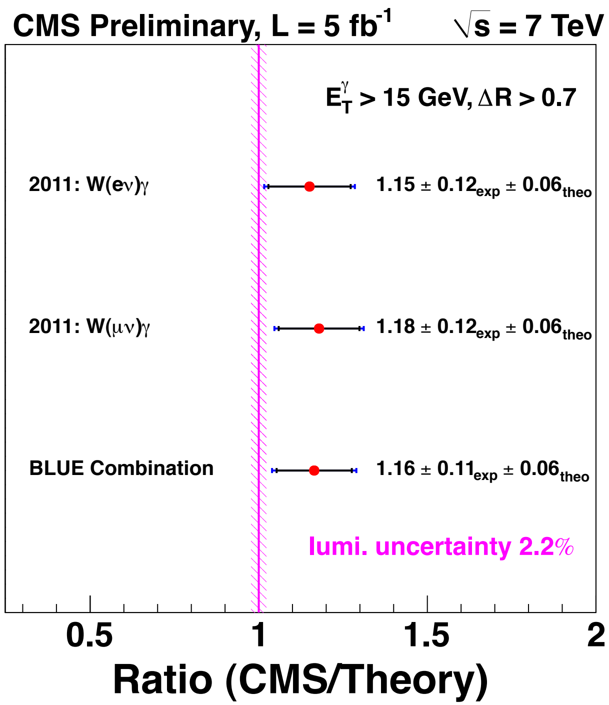
CMS-PAS-EWK-11-009

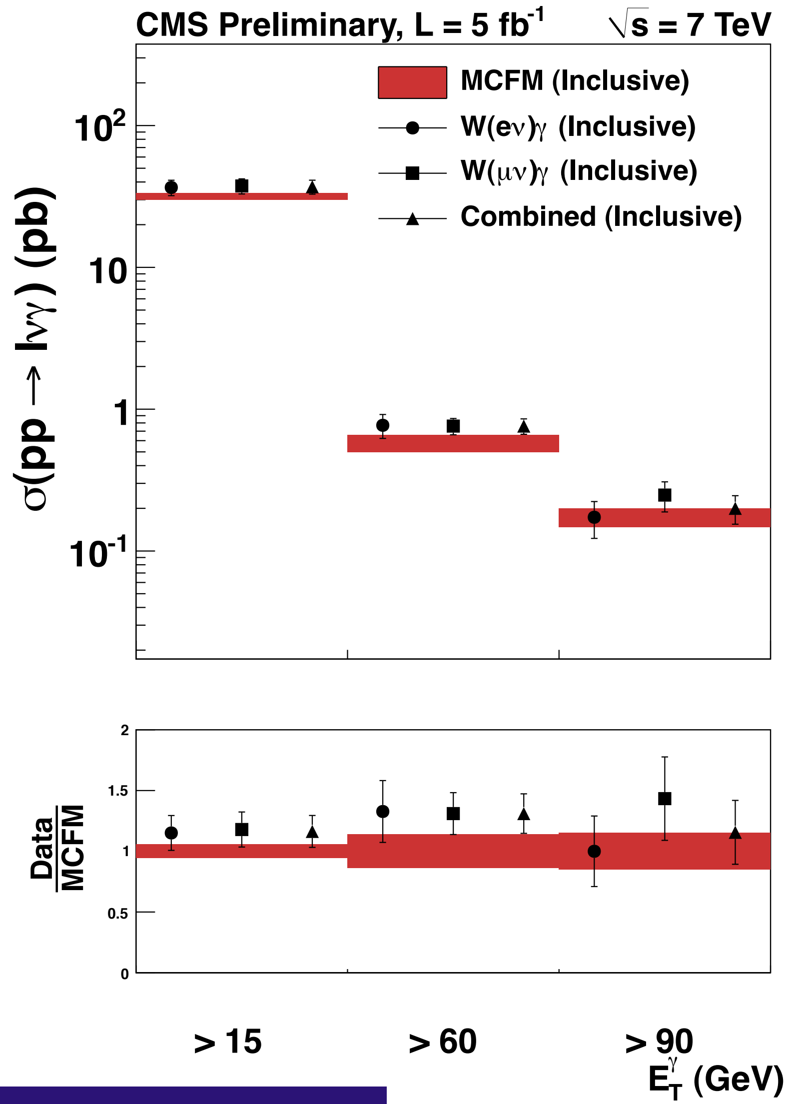
- Systematics limited
  - largest contribution from fake photons from jets
- MC signal modeled with MadGraph v5 scaled to NLO prediction from MCFM



Wγ results

- slight excess in data compared to MCFM prediction (>1 sigma)
  - Similar excess seen by ATLAS





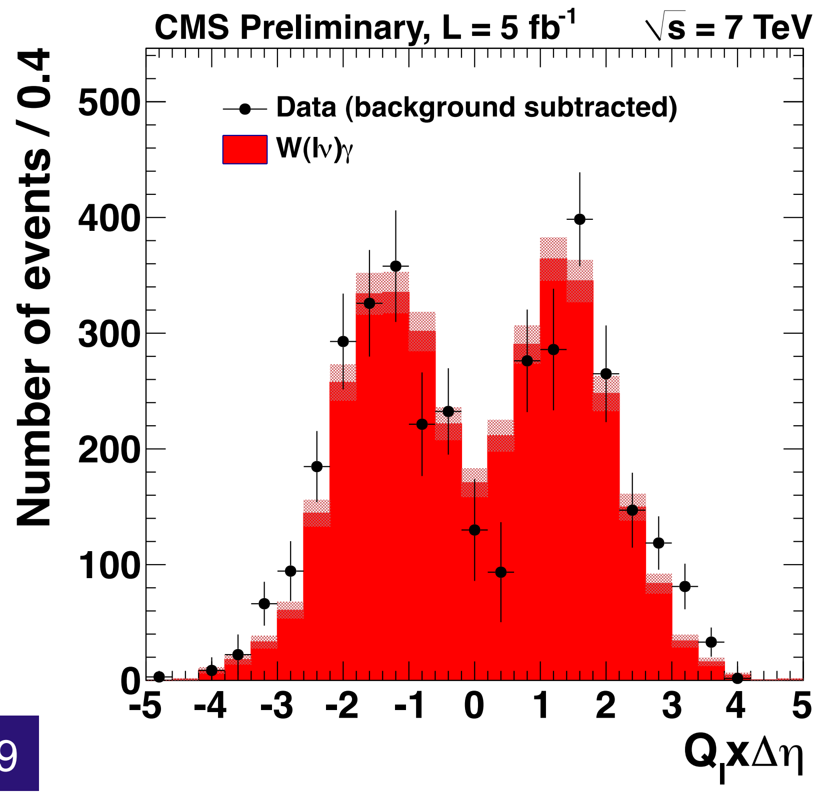
CMS-PAS-EWK-11-009

Wγ Radiation Amplitude Zero

- Interference of 3 amplitudes leads to vanishing amplitude at some defined angle in the qq'→Wγ CoM system
- At the LHC expect dip at 0 in Q_{lepton}* Δη(l,γ) distribution
- aTGCs would reduce the effect, as well as NLO contributions
- CMS data:
  - Dip clearly visible
  - In agreement with SM

CMS-PAS-EWK-11-009

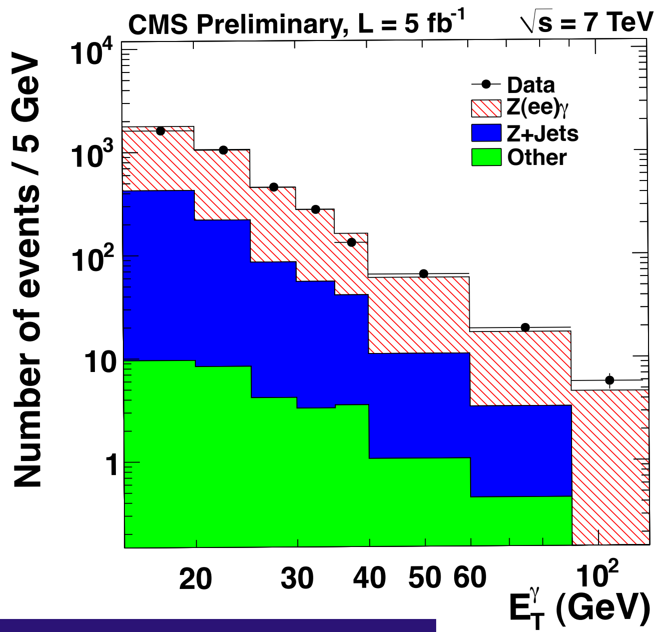
Additional selection:
Jet Veto:
no jet with E_T>30 GeV, |η|<3

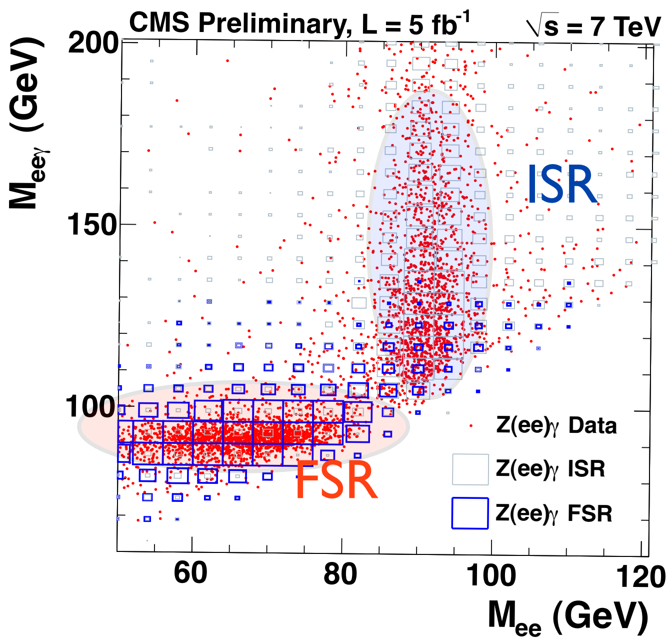


Zγ→llγ Results

	σ(Zγ→llγ, ΔR(l,γ)>0.7) [pb]	NLO (MCFM) [pb]
E_T^γ >15 GeV	5.33 ± 0.08(stat) ± 0.25(syst) ± 0.12(lumi)	5.4 ± 0.2(syst)
E_T^γ >60 GeV	0.140 ± 0.011(stat) ± 0.013(syst) ± 0.003(lumi)	0.124 ± 0.009(syst)
E_T^γ >90 GeV	0.046 ± 0.007(stat) ± 0.009(syst) ± 0.001(lumi)	0.040 ± 0.004(syst)

- Systematics limited
- MC signal modeled with MadGraph v5 scaled to MCFM NLO prediction

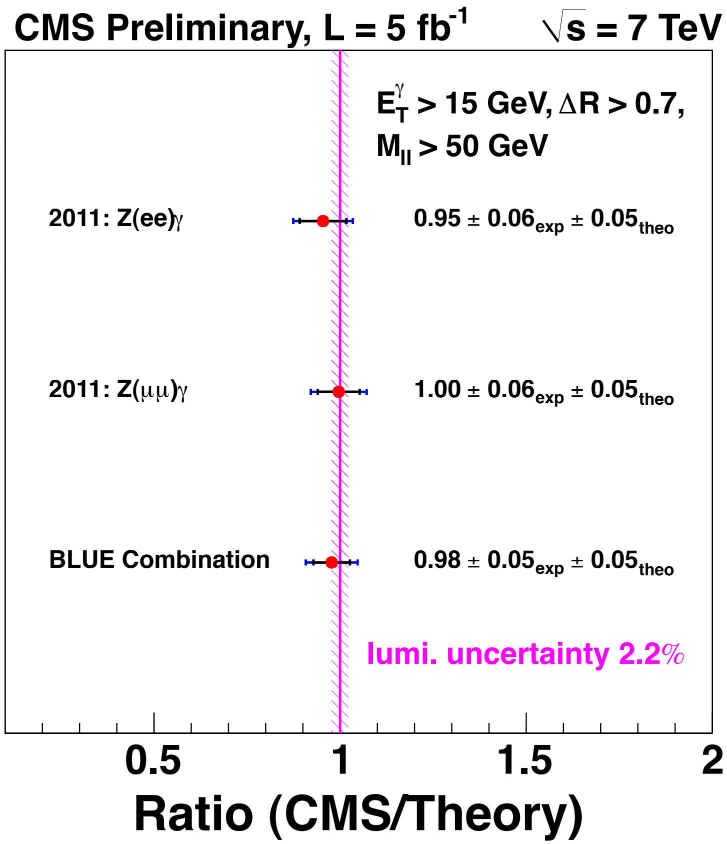


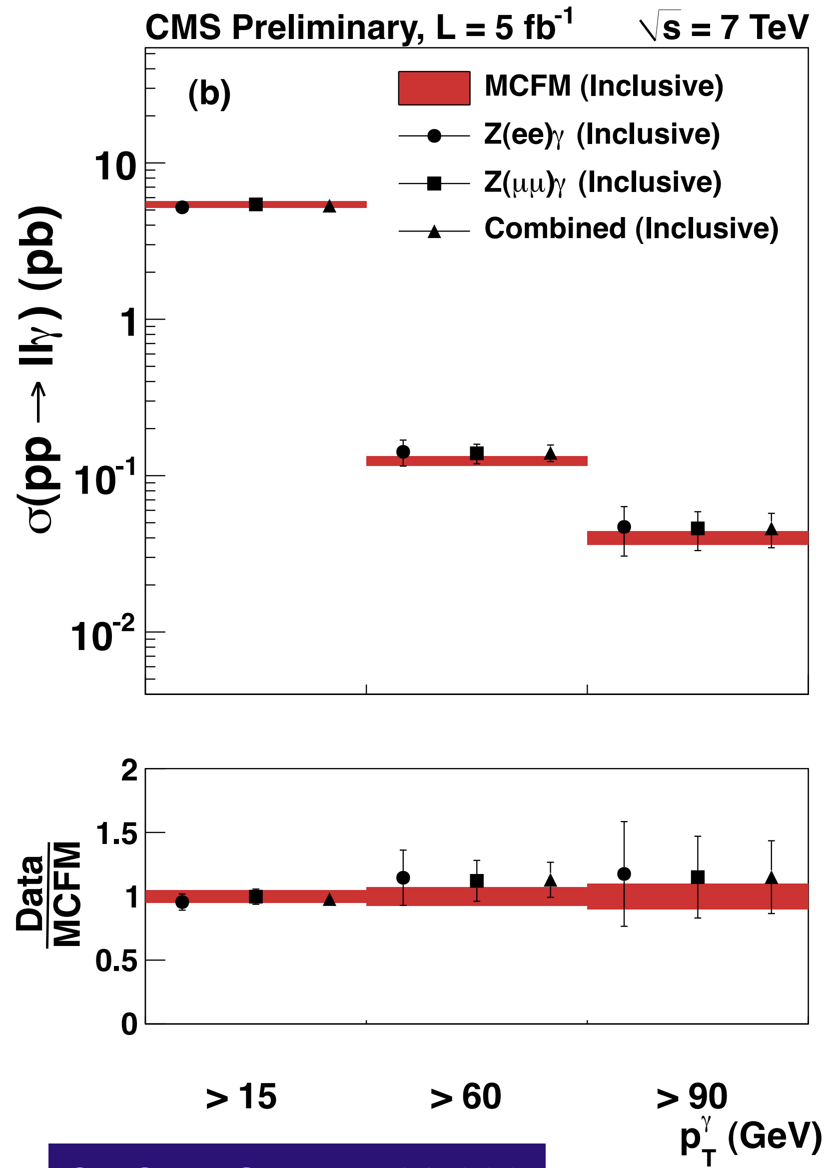


CMS-PAS-EWK-11-009

Zγ→llγ Results

- Good agreement with MCFM NLO prediction





CMS-PAS-EWK-11-009

$Z\gamma \rightarrow \nu\nu\gamma$

Measured cross sections:

σ (pp → Zγ+X → ννγ + X)

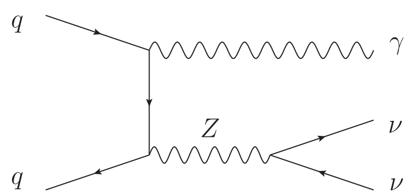
in reduced phase space:

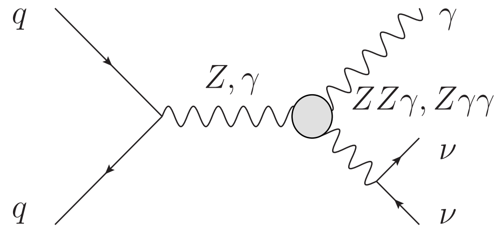
$E_T^\gamma > 145$ GeV, $|\eta^\gamma| < 1.4$

Large gain in BR
wrt charged lepton channel!

Signature:
isolated photon + large MET

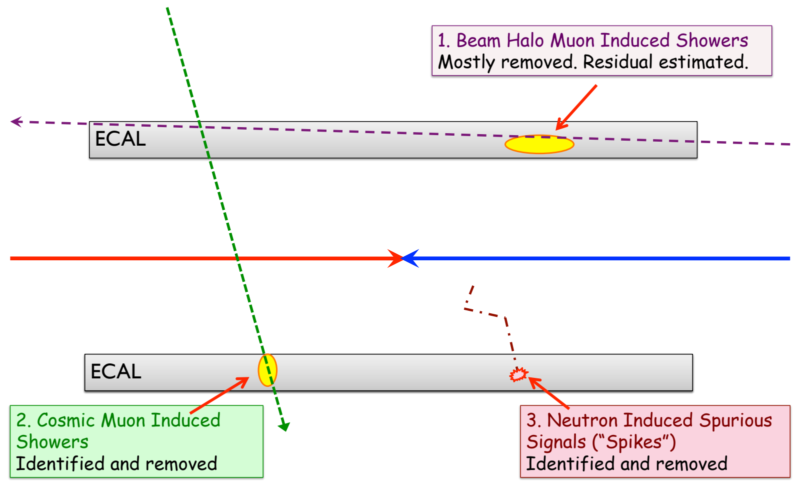
- Isolated photon with $E_T > 140$ GeV
  - Photon timing consistent with beam
- MET>130 GeV
- Jet veto
- Cosmic muon veto





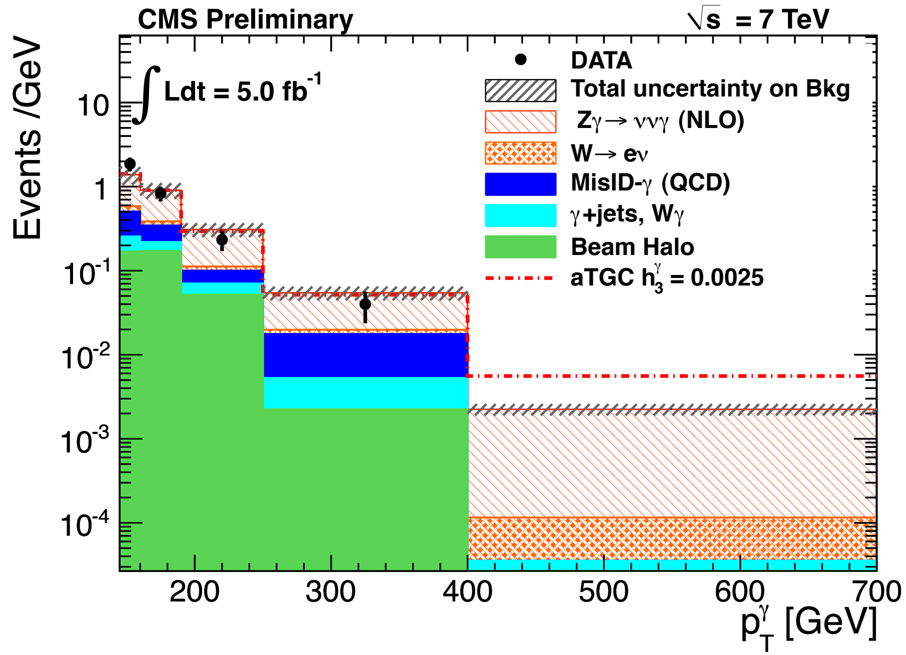
Forbidden in SM

large backgrounds:
Instrumental: jets, γ+jets, W→eν
No collision: beam halo, cosmic muons



$Z\gamma \rightarrow \nu\nu\gamma$ Results

Source	Estimate
Misidentified jets	11.2 ± 2.8
Beam-gas processes	11.1 ± 5.6
Misidentified electrons	3.5 ± 1.5
$W\gamma$	3.3 ± 1.0
$\gamma\gamma$	0.6 ± 0.3
γ+jet	0.5 ± 0.2
Total	30.2 ± 6.5
$Z\gamma \rightarrow \nu\nu\gamma$ (NLO)	45.3 ± 6.9
data	73



- Statistical uncertainty still significant
- Dominant systematics:
  - beam halo uncertainty
  - Track and Jet Veto
- Measurement in agreement with NLO prediction

σ (pp → Zγ+X → ννγ + X,

E_T^{γ} >145 GeV, $|\eta^{\gamma}|$<1.4) @ TeV:

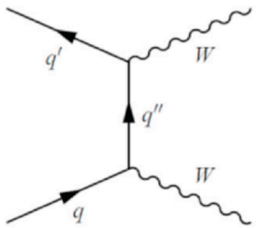
21.3 ± 4.2 (stat.) ± 4.3 (syst.) ± 0.5 (lumi.) fb

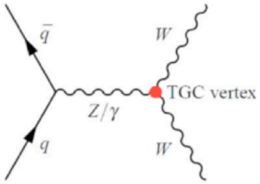
NLO prediction (Baur): 21.9±1.1 fb

CMS-PAS-SMP-12-020

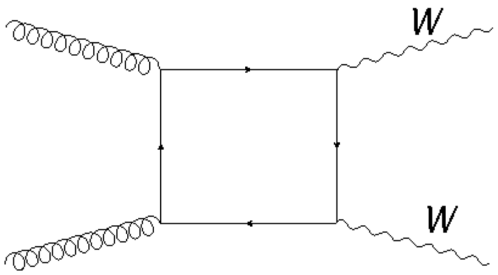
WW→lνlν

qq→WW (97%)





gg→WW (3%)



Closely tied to H→WW analysis

Signature:
2 isolated OS leptons
+
large MET

Cross section measured at 7 & 8 TeV

- 2 isolated opposite charge leptons with Pt>20 GeV
- "Projected MET" > (37 (20) + Nvtx/2) GeV for ee/μμ (eμ)
- Veto events in Z mass window for same flavour final state
- Veto events with high ET jets (ET(jet)>30 GeV)
- Veto events with top-tagged jets
- Veto events with third lepton

large backgrounds:

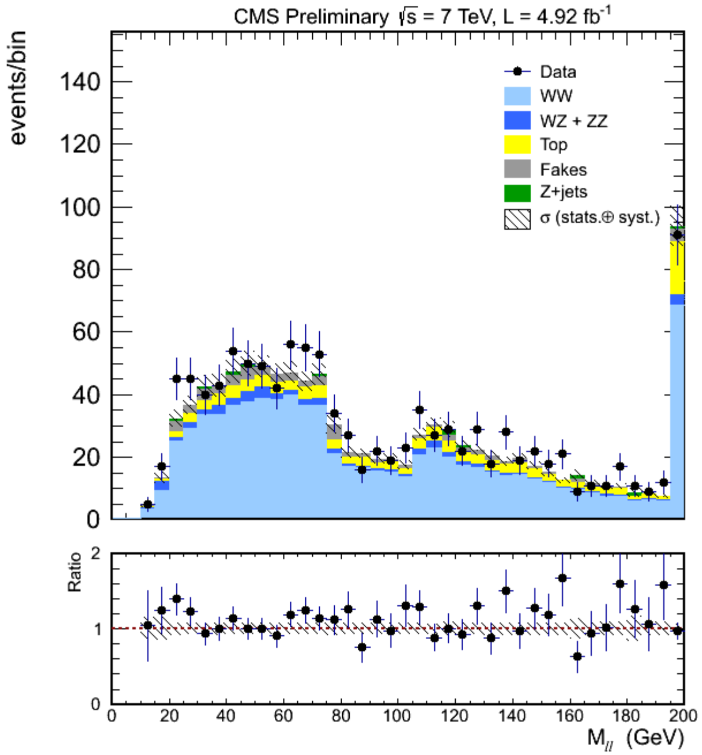
- ttbar, tW
- W+jets
- multijet
- Wγ*
- DY

} estimated from data

- Dibosons — from MC

WW→lνlν Results @ 7 TeV

Sample	Yield ± stat. ± syst.
$gg \to W^+W^-$	$46.0 \pm 0.6 \pm 14.2$
$q\bar{q} \to W^+W^-$	$750.9 \pm 4.1 \pm 53.1$
$t\bar{t}$ +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^*	$11.0 \pm 5.1 \pm 2.6$
$W+\gamma$	$18.8 \pm 2.8 \pm 4.7$
$Z/\gamma^* \to \tau\tau$	$0.0 \pm 1.0 \pm 0.1$
Total Background	$247.1 \pm 14.6 \pm 29.5$
Signal + Background	$1044.0 \pm 15.2 \pm 62.4$
Data	1134



- Largest systematics:
  - Jet Veto efficiency
  - Background estimation (top background, fake rates)
- Measured cross section above SM expectation

CMS-PAS-SMP-12-005

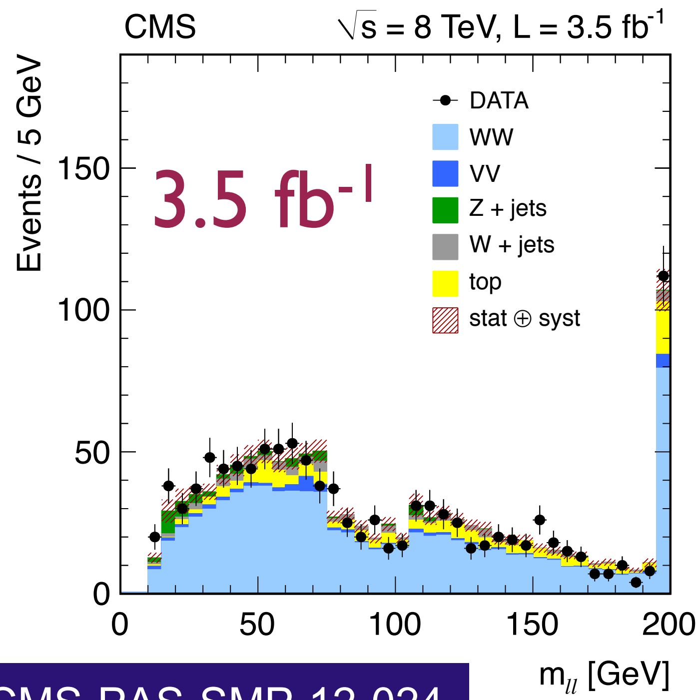
σ (pp → W^+W^- + X) @ 7 TeV:

52.4 ± 2.0 (stat.) ± 4.5 (syst.) ± 1.2 (lumi.) pb

SM NLO prediction (MCFM): 47.0±2.0 fb

WW→lvlv Results @ 8 TeV

Channel	$2\ell'2\nu$
W^+W^-	684 ± 50
$t\bar{t}$ and tW	132 ± 23
W+ jets	60 ± 22
WZ and ZZ	27 ± 3
Z/γ^*+jets	43 ± 12
$W\gamma^{(*)}$	14 ± 5
Total background	275 ± 35
Signal + background	959 ± 60
Data	1111



CMS-PAS-SMP-12-024

σ (pp →W^+W^- + X) @ 8 TeV:

69.9 ± 2.8 (stat.) ± 5.6 (syst.) ± 3.1 (lumi.) pb

SM NLO prediction (MCFM): $57.3^{+2.4}_{-1.6}$ fb

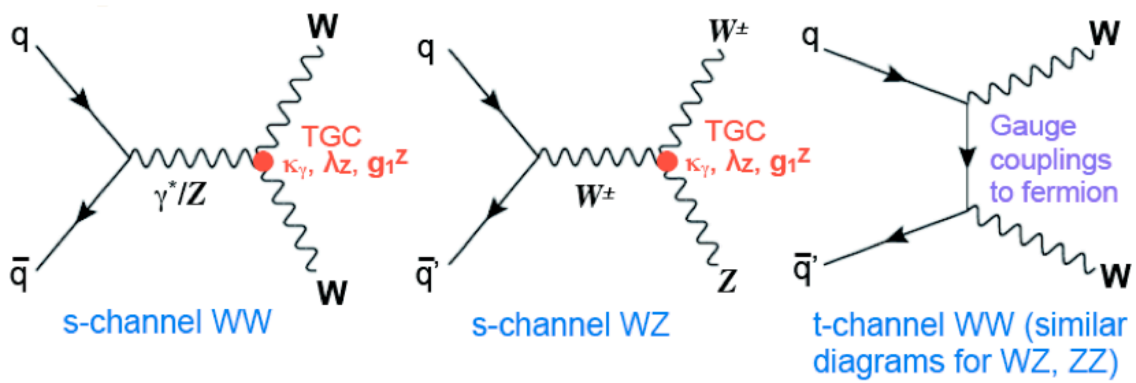
- Measured cross section again above SM expectation

<u>Not accounted for in SM prediction</u>

new (Higgs) boson: 4%
Diffractive production
Double parton interaction
QED exclusive production
} 1%

$WV \rightarrow l\nu jj$

Signature:
isolated lepton
+ MET
+ 2 jets



Backgrounds: W+jets, dibosons, tt, t, DY+jets, multijets

- ➡ Jet resolution does not allow to separate W and Z: get admixture of the two
- ➡ 6*larger BR than in leptonic channel: gives access to higher boson P_t
- ➡ S/B worse than in leptonic channel:
  - tighter cuts
  - Main challenge: background modeling for signal extraction and control of systematics

Selection

- Only one isolated high Pt lepton: $P_t^{\mu\,(e)}$>25 (30) GeV
- Exactly 2 high Pt jets (PT>35 GeV)
- MET>25 (30) GeV for μ(e)
- MTW>30(50) GeV for μ(e)
- Veto events containing b-tagged jet
- Additional cuts on dijet system: $\Delta\eta_{jj}$, $P_T(jj)$

WV→lvjj Results

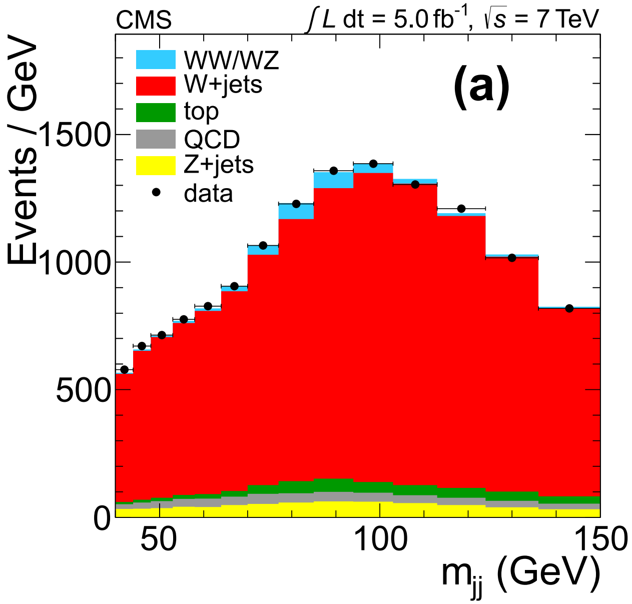
- Signal and background yields obtained from UML fit to M_{jj} distribution

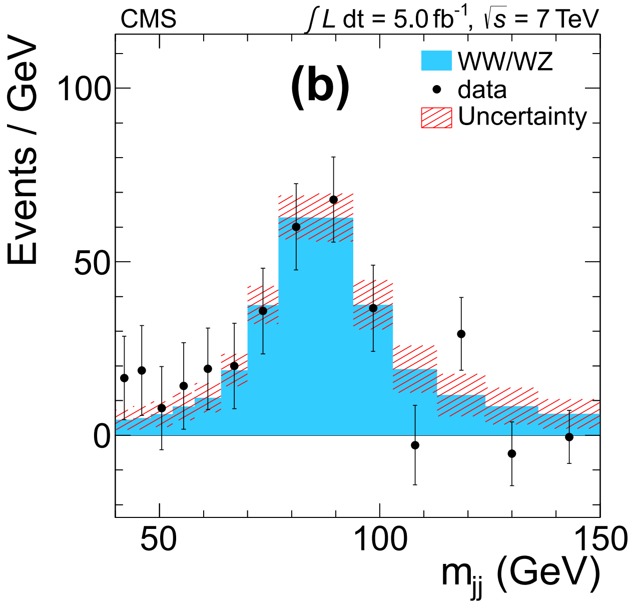
Process	Muon channel	Electron channel
Diboson (WW+WZ)	1899 ± 373	783 ± 306
W+jets	67384 ± 586	31644 ± 850
$t\bar{t}$	1662 ± 117	946 ± 67
Single top	650 ± 33	308 ± 17
Drell–Yan+jets	3609 ± 155	1408 ± 64
Multijet (QCD)	296 ± 317	4195 ± 867
Fit χ^2/dof (probability)	9.73/12 (0.64)	5.30/12 (0.95)
Total from fit	75420	39371
Data	75419	39365
Acceptance × efficiency ($\mathcal{A}\varepsilon$)	5.153×10^{-3}	2.633×10^{-3}
Expected WW+WZ yield from simulation	1697 ± 57	867 ± 29

σ (pp → W^+W^- +WZ) @ 7 TeV:

68.9±8.7(stat.)±9.7(syst.)±1.5(lumi.) pb

SM NLO prediction (MCFM): 65.6±2.2 pb





Significance of observation: 4.3σ

EPJC 73 (2013) 2283

$ZZ \rightarrow 2l2l'$ ($l=e,\mu$; $l'=e,\mu,\tau$)

Measured cross section:

σ (pp → ZZ + X; 60 GeV < M_{Z1}, M_{Z2} < 120 GeV)

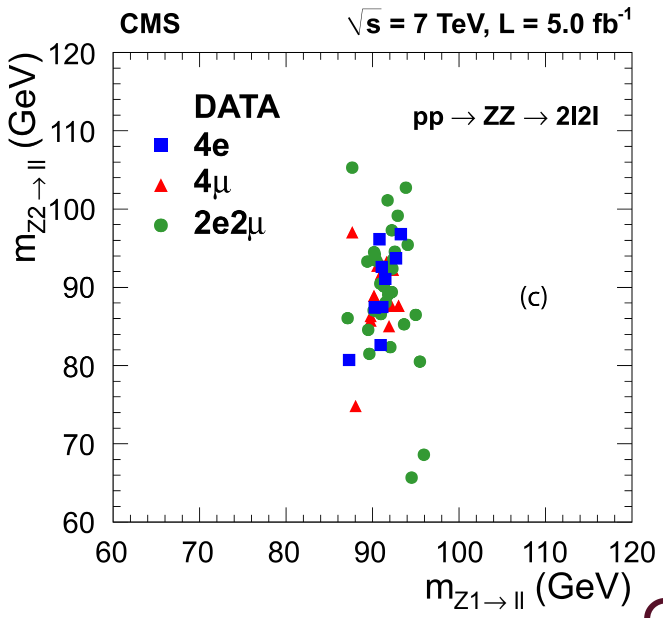
Signature: 4 isolated leptons

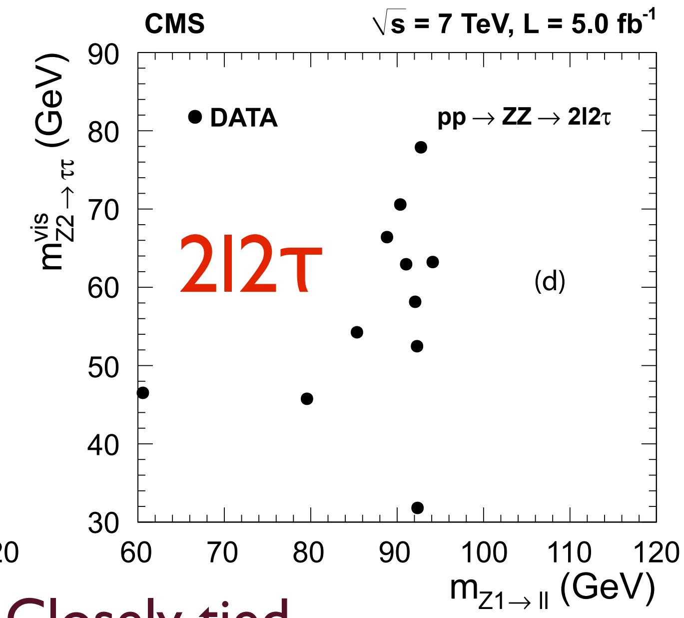
- ➡ Very low backgrounds
- ➡ Selection tuned to maximize efficiency, especially at low lepton P_t

Backgrounds:
Zbb, tt, Z+jets, WZ+jets
(estimated from data)

Selection

- 4 isolated leptons: P_t^l> 20/10/7/5 GeV
- 2 same flavour opposite charge lepton pairs
- 60 GeV < $M_{Z1,2}$ < 120 GeV





Closely tied to H→ZZ analysis

ZZ→4l Results @ 7 TeV

- Cross section obtained from simultaneous fit to event yields in all studied decay channels
- Result still statistics limited
- In agreement with SM prediction

Final state channels	4e	4μ	$2e2\mu$	4ℓ
Irreducible background ($pp \to Z\gamma^* \to 4\ell$)	0.07	0.25	0.14	0.46 ± 0.05
Other (reducible) backgrounds	0.01	0.01	0.05	0.07 ± 0.1
Expected signal ($pp \to Z \to 4\ell$)	3.8	13.6	12.0	29.4 ± 2.6
Total expected (simulation)	3.9	13.9	12.2	30.0 ± 2.6
Observed events	2	14	12	28
Yield from fit to the observed mass distribution	—	13.6 ± 3.8	11.5 ± 3.1	27.3 ± 5.4

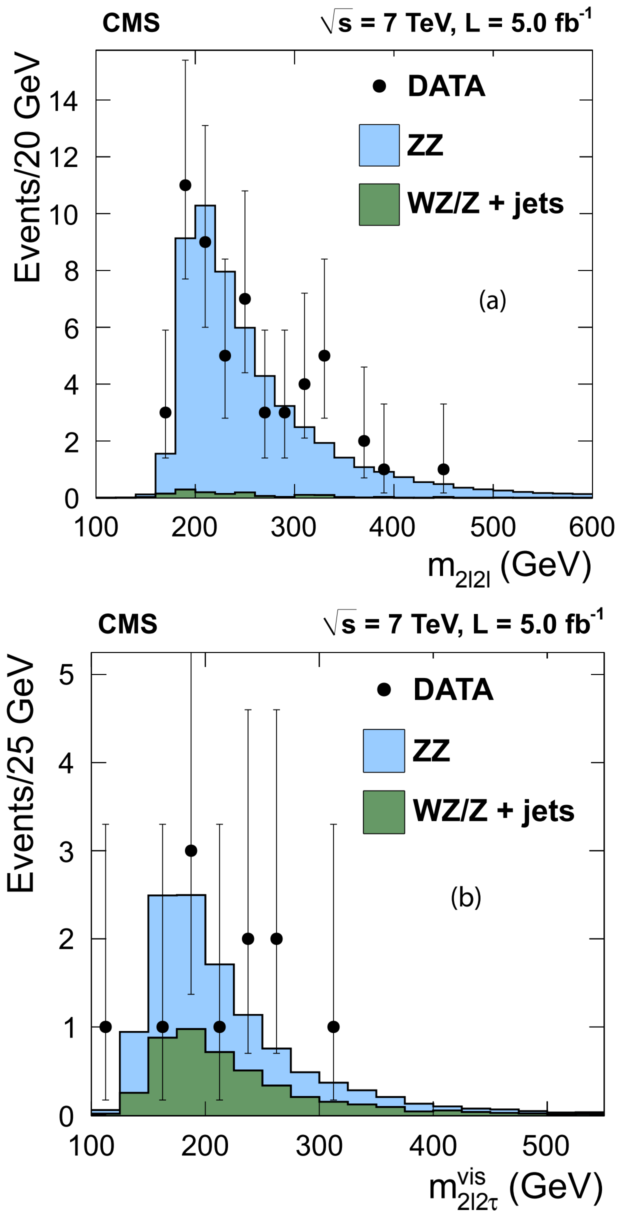
CMS-PAS-SMP-12-007

σ (pp → ZZ + X;

60 GeV < $M_{Z1,Z2}$ < 120 GeV) @ 7 TeV:

$6.24^{+0.86}_{-0.8}$(stat.)$^{+0.41}_{-0.32}$(syst.)±0.14(lumi.) pb

SM NLO prediction (MCFM): 6.3±0.4 pb



ZZ→4l Results @ 8 TeV

- Same strategy as for 7 TeV
- Measurement agrees with SM

Channel	4e	4μ	2e2μ	2ℓ2τ
ZZ	11.6 ± 1.4	20.3 ± 2.2	32.4 ± 3.5	6.5 ± 0.8
Background	0.4 ± 0.2	0.4 ± 0.3	0.5 ± 0.4	5.6 ± 1.4
Signal + background	12.0 ± 1.4	20.7 ± 2.2	32.9 ± 3.5	12.1 ± 1.6
Data	14	19	38	13

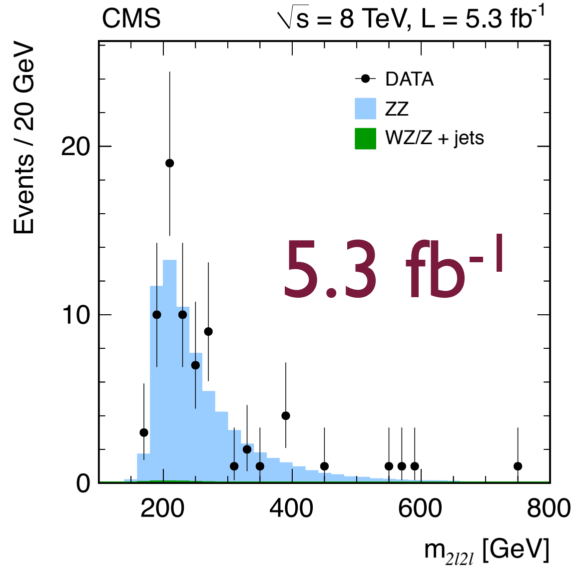
CMS-PAS-SMP-12-024

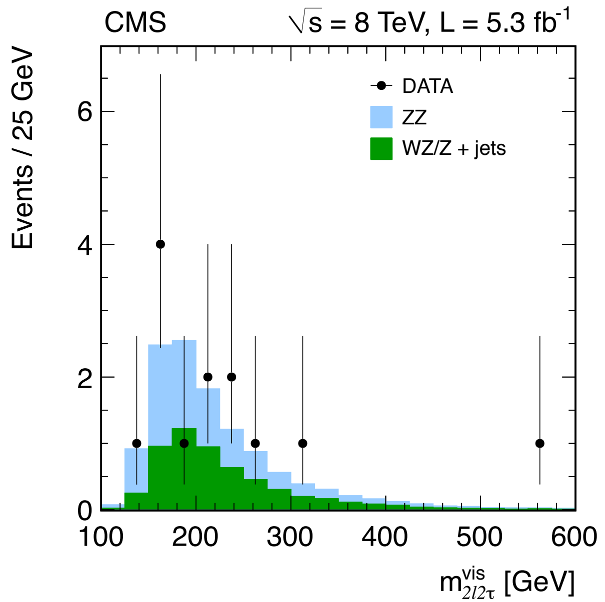
σ (pp → ZZ + X;

60 GeV < $M_{Z1,Z2}$ < 120 GeV) @ 8 TeV:

8.4±1.0(stat.)±0.7(syst.)±0.4(lumi.) pb

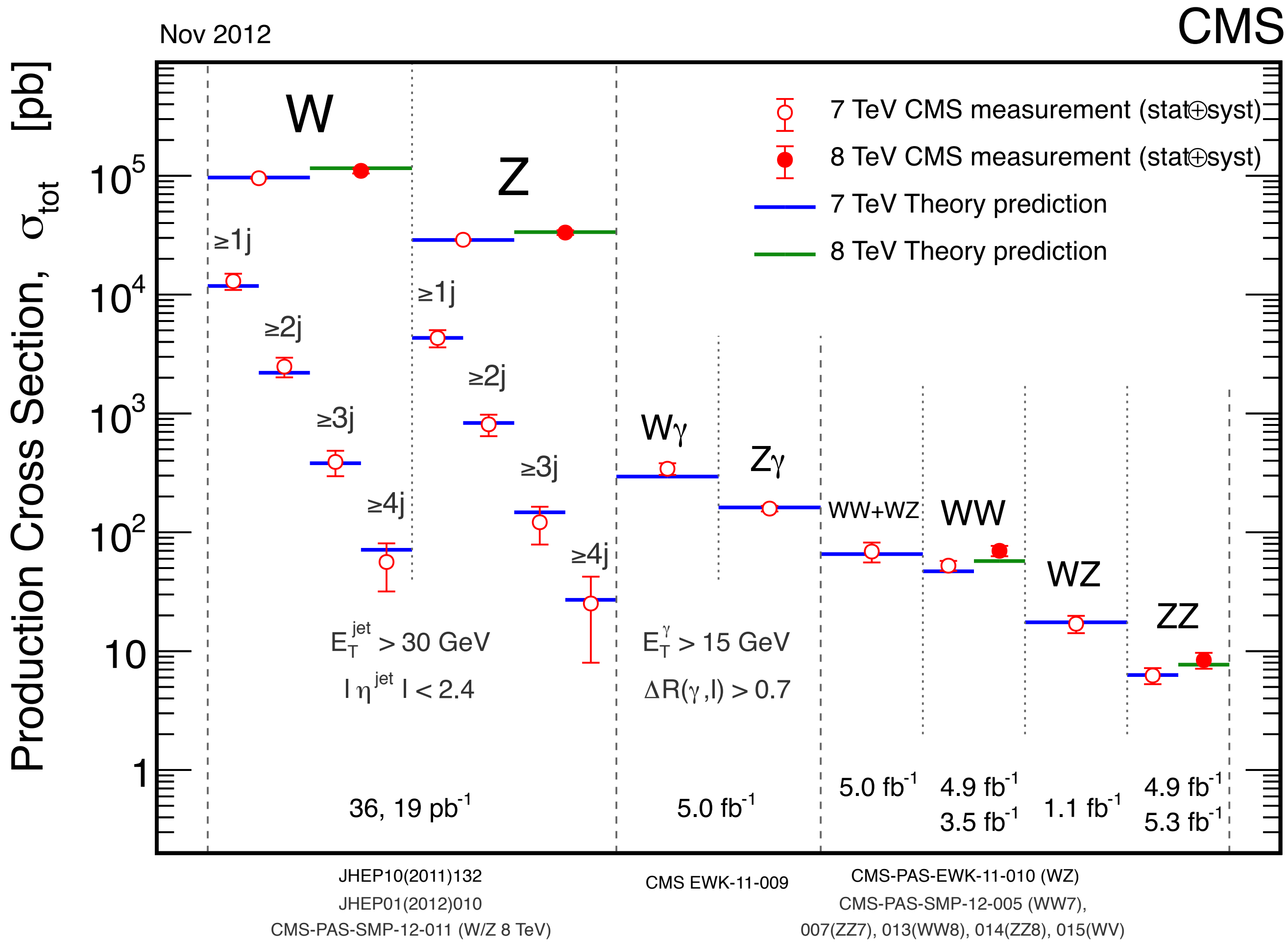
SM NLO prediction (MCFM): 7.7±0.4 pb





CMS EWK Cross Sections Summary

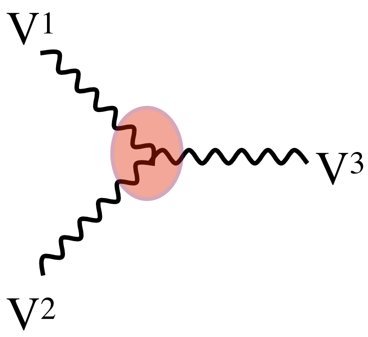
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP



- SM seems overall to be in excellent shape at the TeV scale, good or bad news?
- Some tensions in WW and Wγ: fluctuations or smoking gun?

Searches for anomalous couplings

Anomalous couplings



Is New Physics hiding in this vertex?

- Parameterization of most general new VVV interactions→anomalous triple gauge couplings
- Reduce number of aTGCs by requiring some symmetries

$$
\begin{aligned}
L_{WWV}/g_{WWV} = & \; i g_1^V (W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\
& + i \frac{\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
& + g_5^V \epsilon^{\mu\nu\lambda\rho} (W^\dagger_\mu \partial_\lambda W_\nu - \partial_\lambda W^\dagger_\mu W_\nu) V_\rho \\
& + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + i \frac{\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu \tilde{V}^{\nu\lambda}
\end{aligned}
$$

aTGC parameterizations

- Charged couplings: WWV (V=Z,γ)

$$L/g_{WWV} = ig_1^V(W^*_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{*\mu}V^\nu) + i\kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2}W^*_{\rho\mu}W^\mu_\nu V^{\nu\rho}$$

  - 5 parameters: $\Delta g_1^Z(=g_1^Z-1)$, $\Delta\kappa_Z(=\kappa_Z-1)$, $\Delta\kappa_\gamma(=\kappa_\gamma-1$, λ_Z,λ_γ
  - Additional constraints may be imposed:

used in CMS measurements

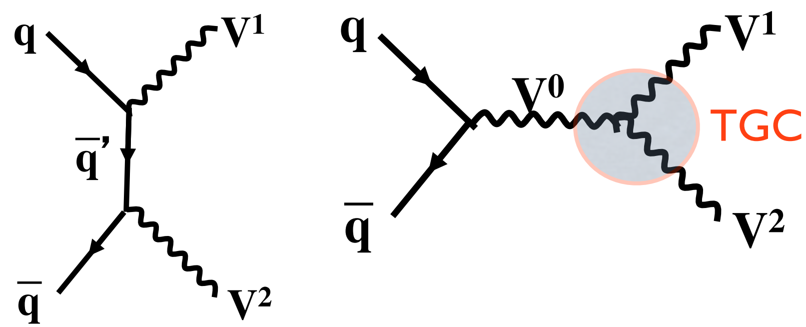
LEP scenario	$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot tan^2\theta_w$ and $\lambda_Z = \lambda_\gamma = \lambda$	3 free parameters
HISZ scenario	$\Delta\kappa_z = \Delta g_1^z(\cos^2\theta_w - \sin^2\theta_w)$, $\Delta\kappa_\gamma = 2\Delta g_1^Z \cos^2\theta_w$ and $\lambda_Z = \lambda_\gamma$	2 free parameters
Equal coupling scenario	$\Delta g_1^Z = \Delta g_1^\gamma = 0$ $\Delta\kappa_Z = \Delta\kappa_\gamma$ and $\lambda_Z = \lambda_\gamma = \lambda$	2 free parameters

- Neutral couplings: ZZV (V=Z,γ)

$$L = -\frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

  - 4 parameters: f_4^Z, f_4^γ, f_5^Z, f_5^γ

aTGCs & Diboson production



- Diboson production sensitive to TGC in s-channel
  - Neutral TGCs not allowed in SM
- aTGCs would modify both total rate and kinematics
  - Charged and Neutral couplings probed by different channels

Coupling	Parameters	Channel
$WW\gamma$	$\lambda\gamma$, $\Delta\kappa\gamma$	WW, $W\gamma$
WWZ	λZ, $\Delta\kappa_Z$, Δg_1^Z	WW, WZ
$ZZ\gamma$	h_3^Z, h_4^Z	$Z\gamma$
$Z\gamma\gamma$	h_3^γ, h_4^γ	$Z\gamma$
ZZZ	f_4^Z, f_5^Z	ZZ
$Z\gamma Z$	f_4^γ, f_5^γ	ZZ

Production	$\Delta\kappa_Z$, $\Delta\kappa_\gamma$ term	Δg_1^Z term	λ_Z, λ_γ term
WW	**grow as $\hat{s}$**	**grow as $\hat{s}^{1/2}$**	**grow as $\hat{s}$**
WZ	grow as $\hat{s}^{1/2}$	grow as $\hat{s}$	grow as $\hat{s}$
$W\gamma$	grow as $\hat{s}^{1/2}$	---	grow as $\hat{s}$

aTGC Searches in CMS

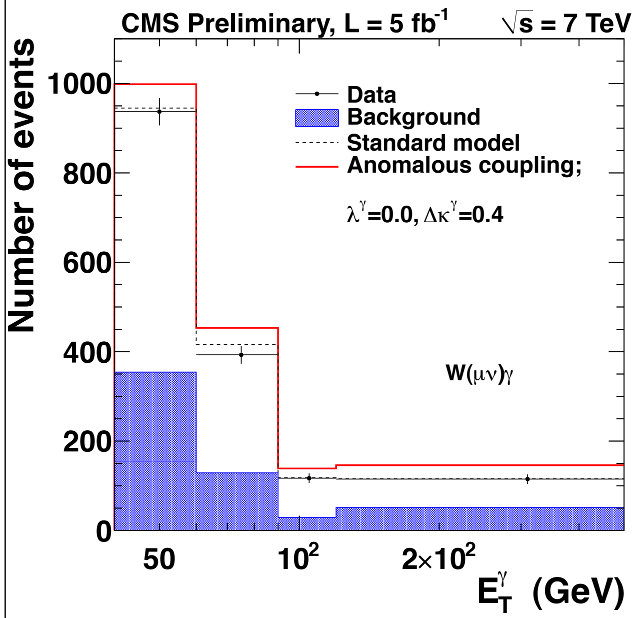
- ➡All analyses use differential shape
- ➡No form factors used (effective theory approach)
- ➡All analyses based on 7 TeV data

	Int. luminosity @ 7 TeV	*Vertex*	*Measured parameters*	*Variable for limit setting*
ZZ→2l2l' (l = e/μ;l' = e/μ/τ)	**5.0 fb^{-1}**	ZZZ, ZZγ	$f^Z_4, f^Z_5, f^\gamma_4, f^\gamma_5$	M(2l2l)
Wγ→lνγ	**5.0 fb^{-1}**	WWγ	λ^γ, $\Delta\kappa^\gamma$	E_T^γ
Zγ→llγ	**5.0 fb^{-1}**	ZZγ, Zγγ	$h^Z_3, h^Z_4, h^\gamma_3, h^\gamma_4$	E_T^γ
Zγ→ννγ	**5.0 fb^{-1}**	ZZγ, Zγγ	$h^Z_3, h^Z_4, h^\gamma_3, h^\gamma_4$	E_T^γ
W^+W^-→lνlν	**4.9 fb^{-1}**	WWγ, WWZ	λ^Z, $\Delta\kappa^\gamma$, Δg_1^Z	P_T(l)
W^+W^-+WZ→lνjj	**5.0 fb^{-1}**	WWγ, WWZ	λ^Z, $\Delta\kappa^\gamma$	P_T(jj)
Exclusive γγ→W^+W^-	**5.0 fb^{-1}**	WWγγ	a^W_0/Λ^2, a^W_C/Λ^2	P_T(eμ)

★ **New!**

Statistical treatment: CLs or profile likelihood

Searches for charged aTGCs: differential distributions

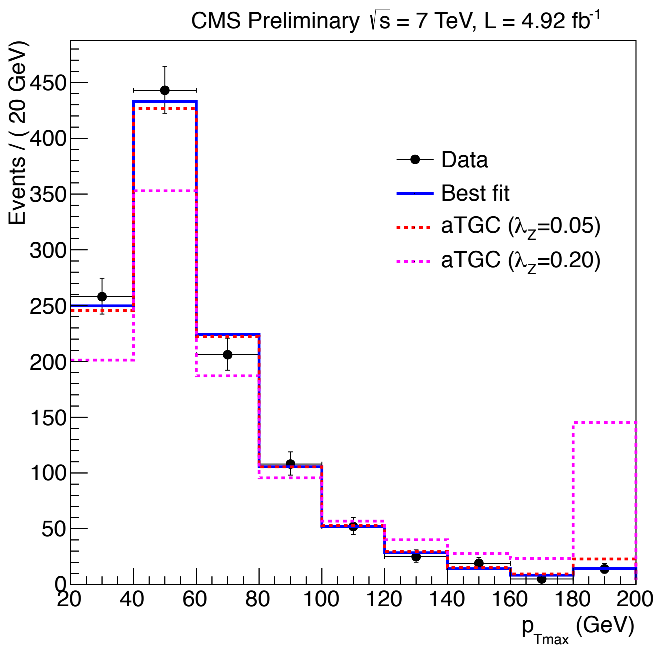


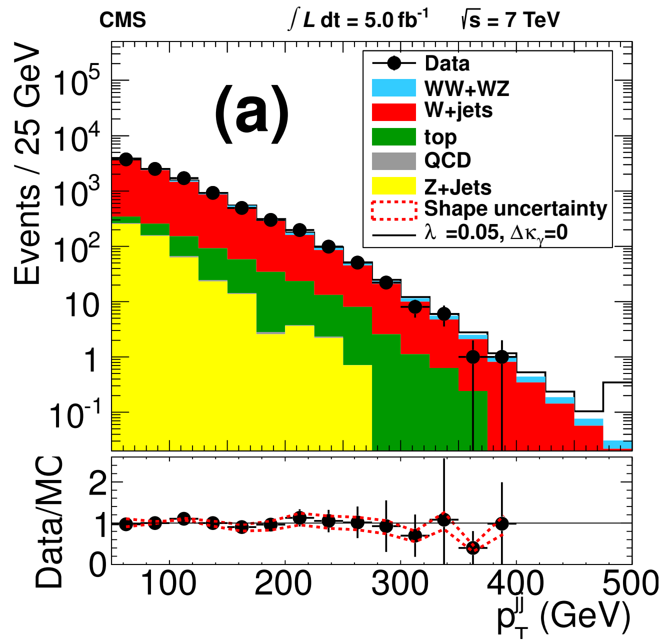
Wγ

Photon E_T

WW→lνlν

Leading lepton P_T

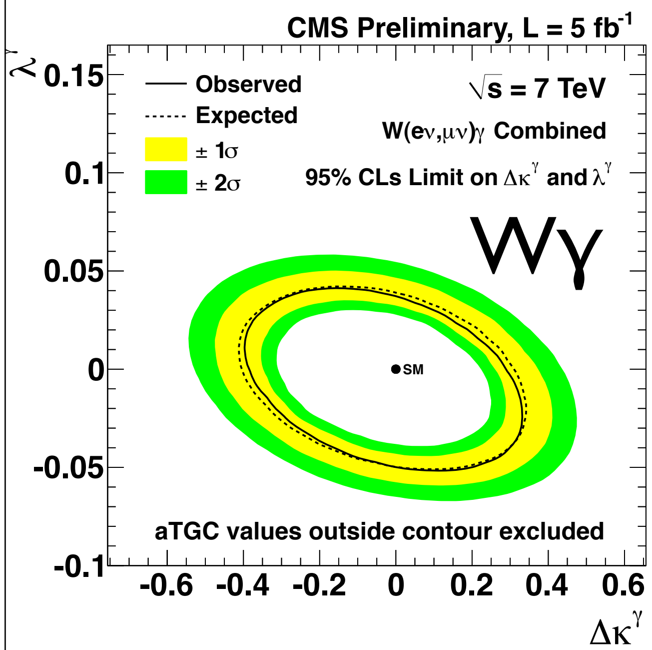


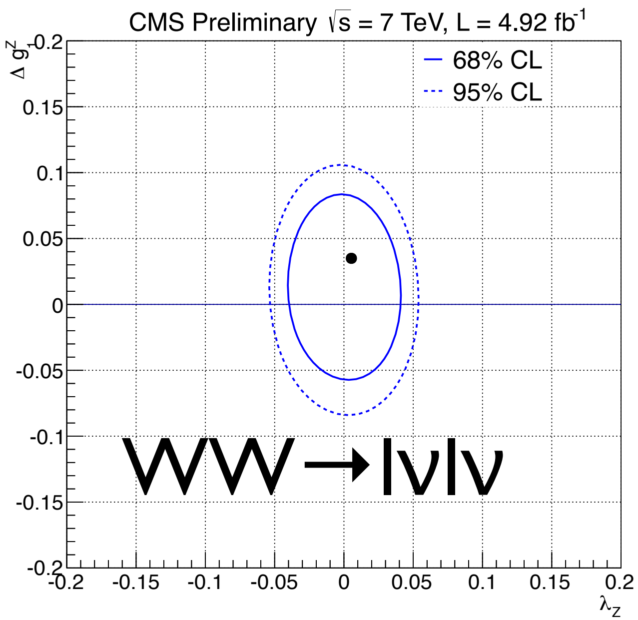


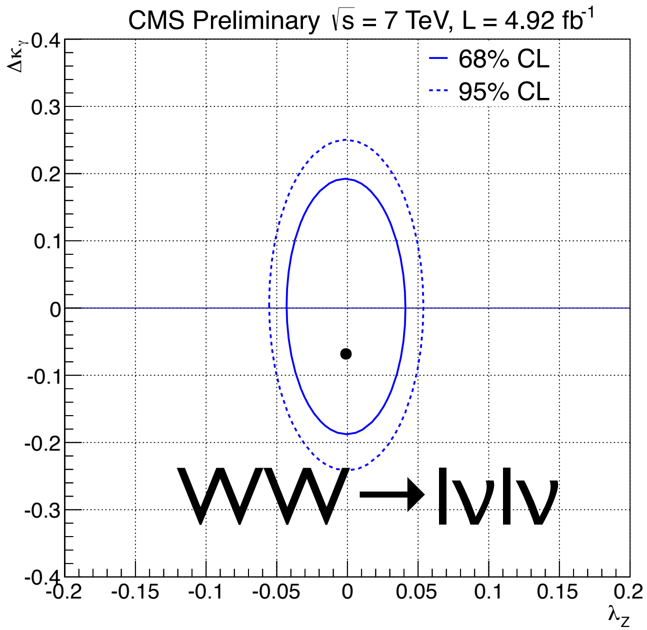
WV→lνjj

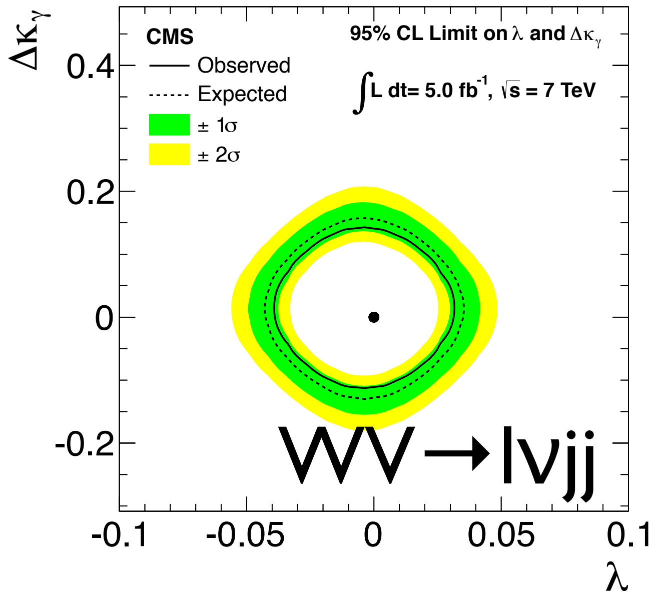
Dijet P_T

Charged aTGC searches: Results





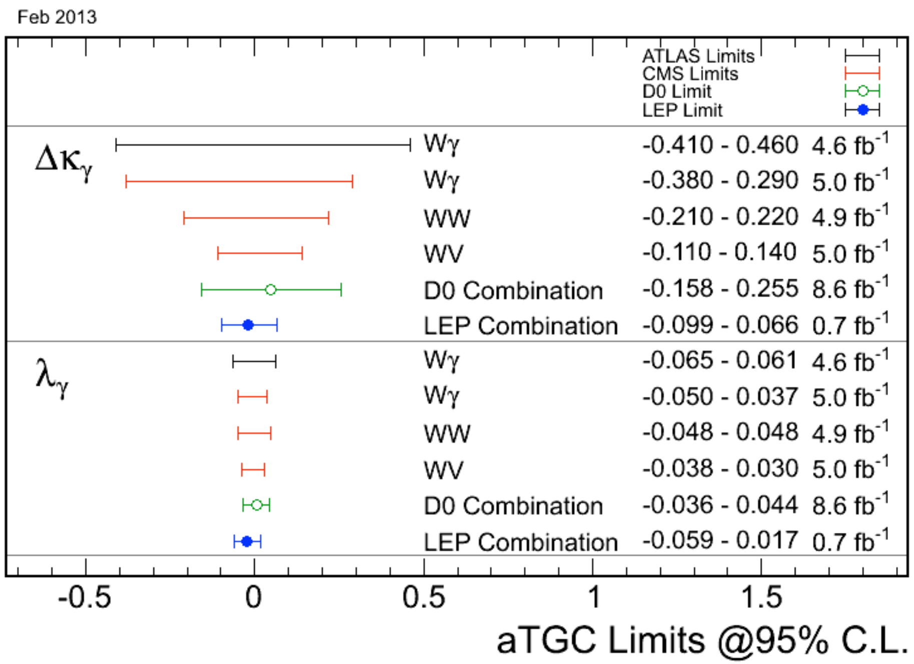


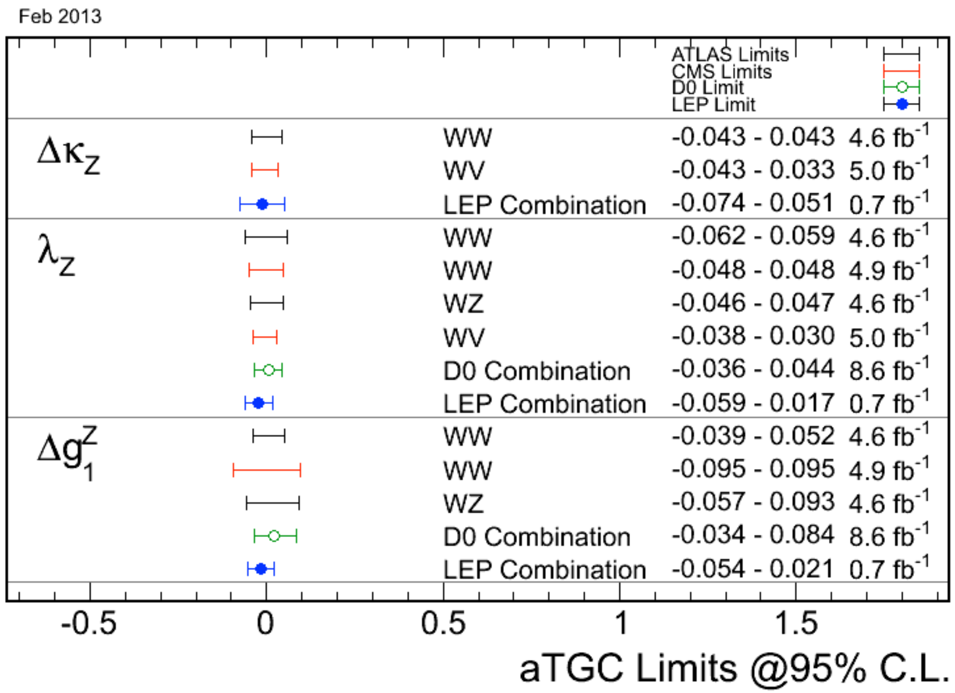


95% C.L.	$\Delta\kappa^{\gamma}$	λ	Δg_1^{Z}
Wγ→lνγ	[-0.38, 0.29]	[-0.05, 0.037]	-
$W^{+}W^{-}$→lνlν	[-0.21, 0.22]	[-0.048, 0.048]	[-0.095, 0.095]
$W^{+}W^{-}$+WZ→lνjj	[-0.111, 0.142]	[-0.038, 0.030]	-

Results agree with SM:
no sign of aTGCs

Charged TGCs: comparison with other results

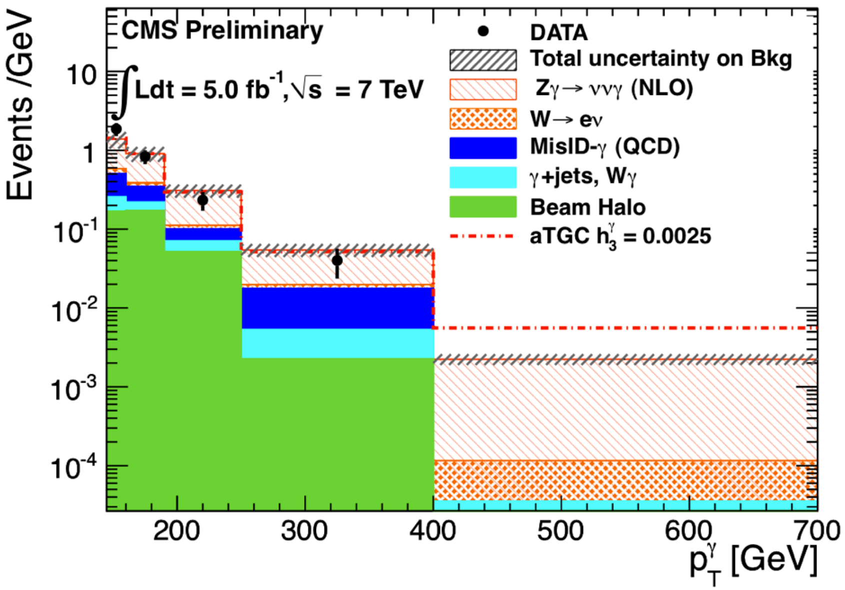




LHC measurements approaching LEP sensitivities

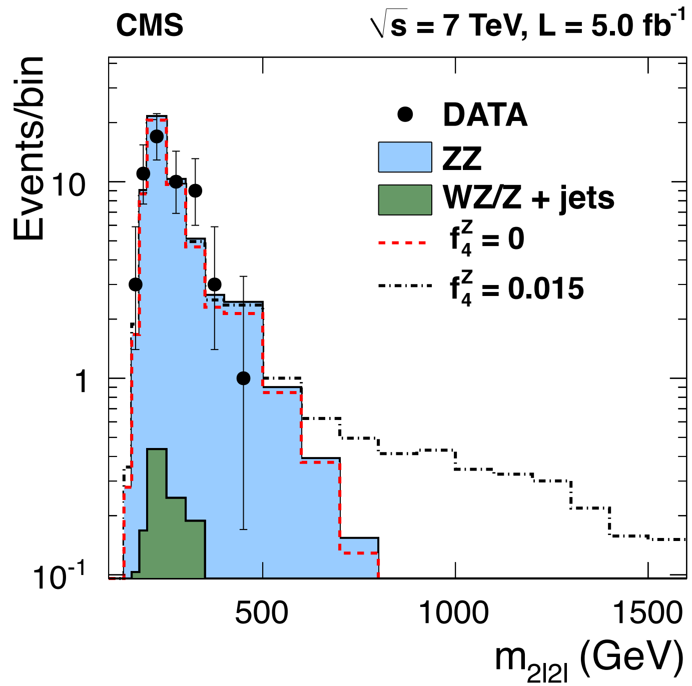
Neutral aTGC searches: Differential distributions

Zγ
Photon E_T

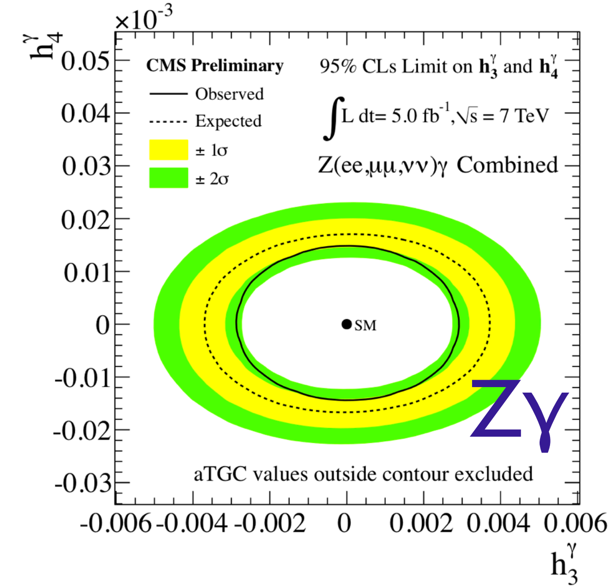


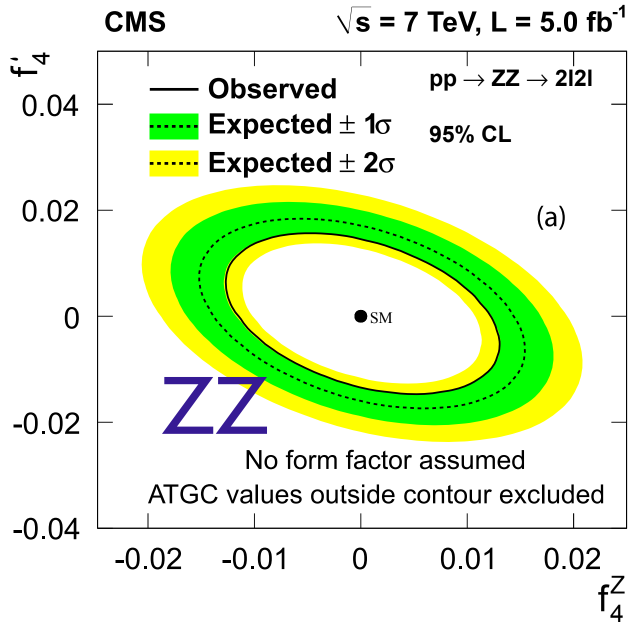
- ννγ final state has 6 times larger BR and no FSR: much more sensitive to aTGC

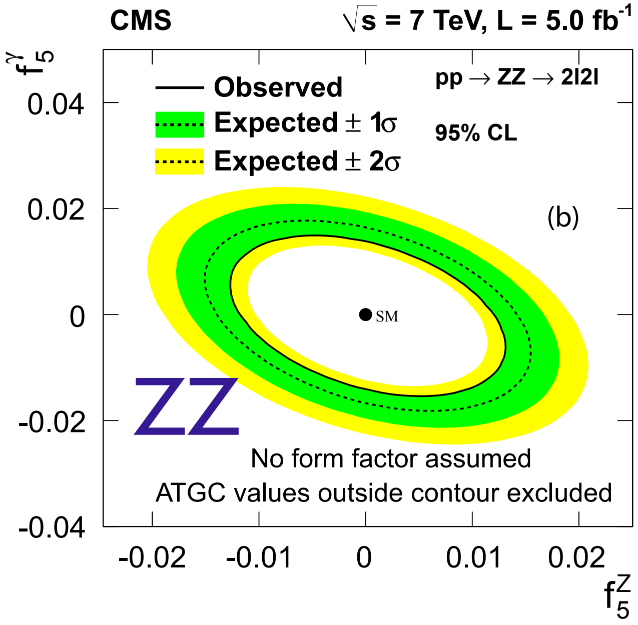
ZZ
4 lepton mass

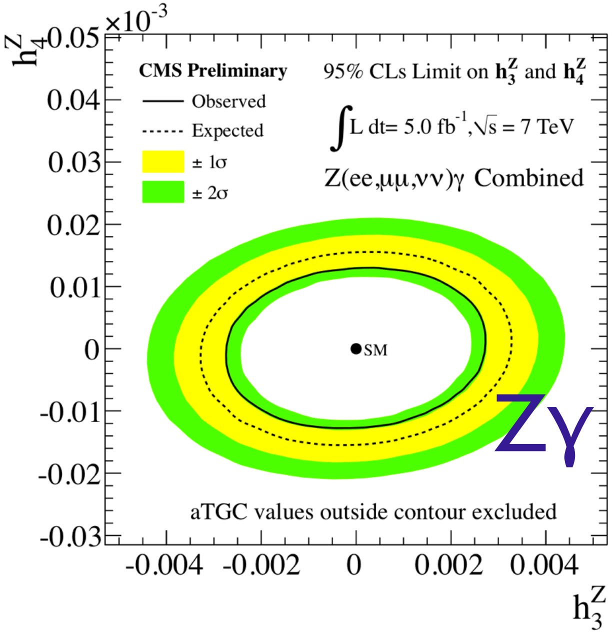


Neutral aTGCs searches: Results





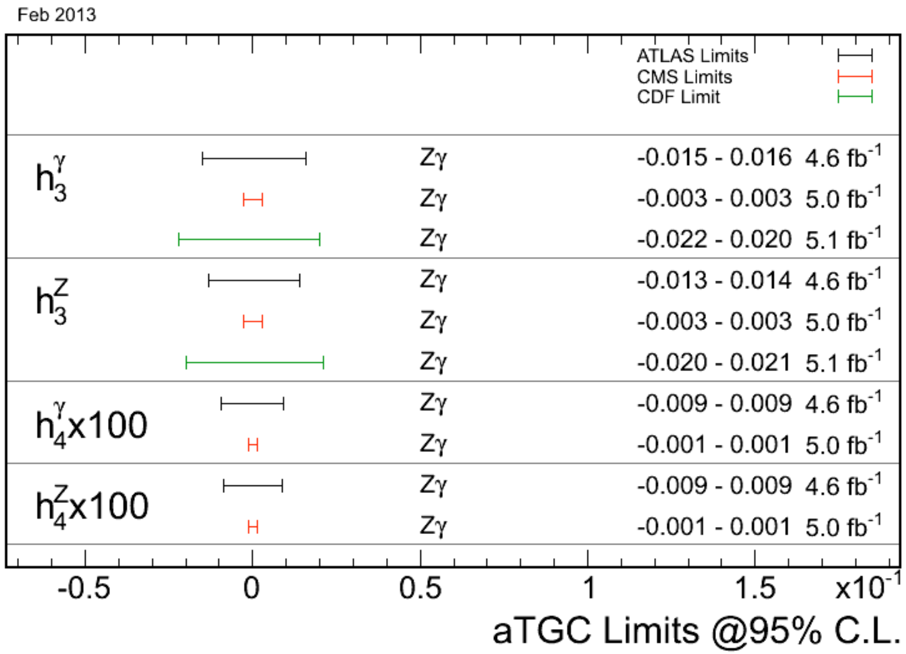


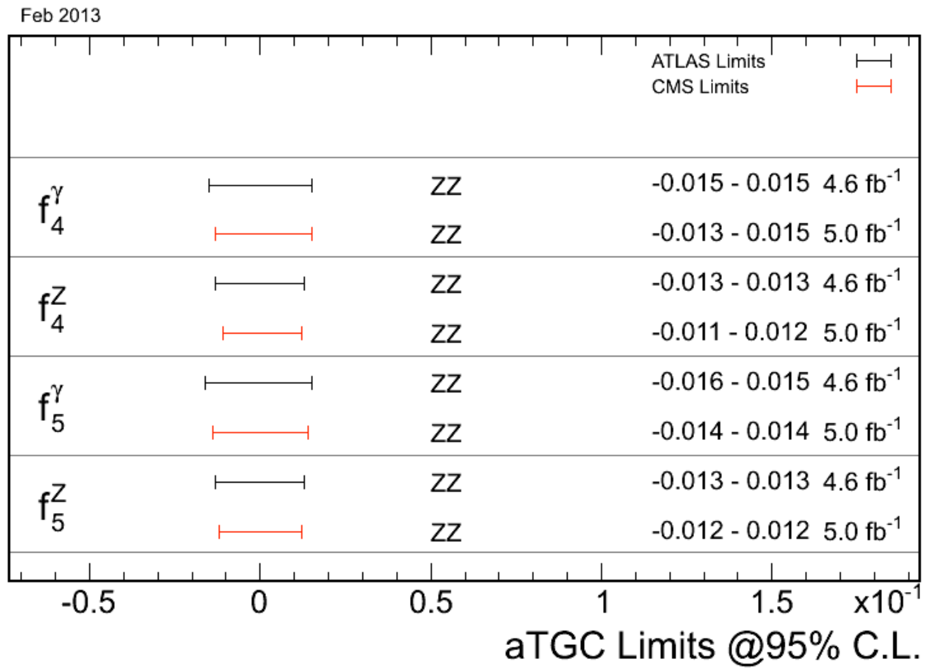


$x10^{-3}$	h^Z_3	h^Z_4	h^γ_3	h^γ_4
Zγ→llγ	[-8.6, 8.4]	[-0.080, 0.079]	[-10, 10]	[-0.088, 0.088]
Zγ→ννγ	[-3.1, 3.1]	[-0.014, 0.014]	[-3.2, 3.2]	[-0.016, 0.016]
Zγ→ννγ,llγ	[-2.7, 2.7]	[-0.013, 0.013]	[-2.9, 2.9]	[-0.014, 0.015]

- All measurements consistent with SM: no sign of neutral aTGCs

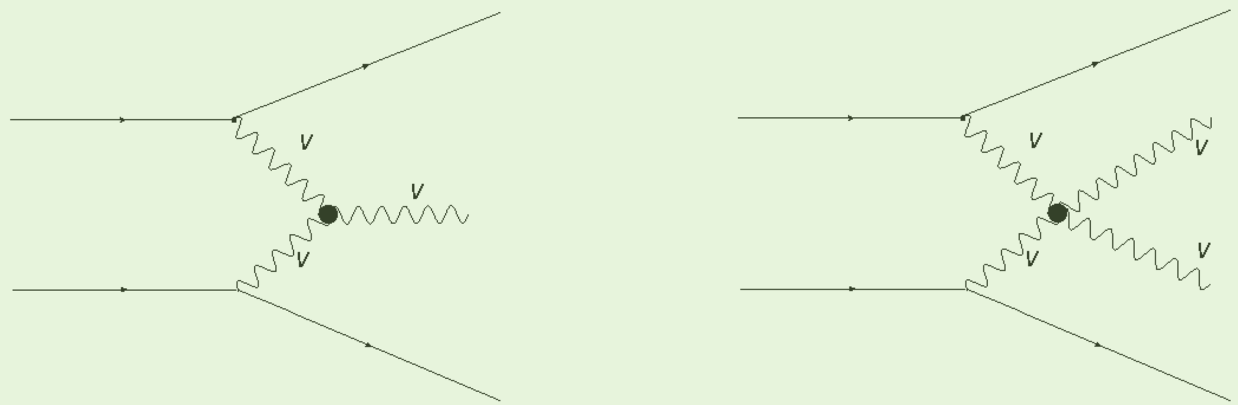
Neutral TGCs: comparison with other results





LHC measurements already exceeded LEP sensitivities

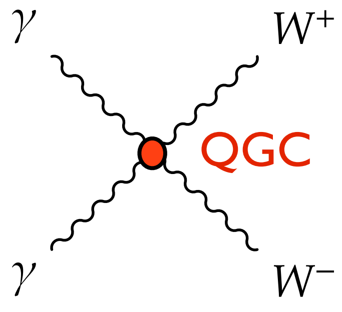
Gauge Self-Interactions in VBF processes

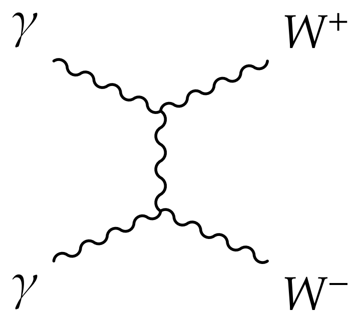


Exclusive $\gamma\gamma \to W^+W^-$ Production

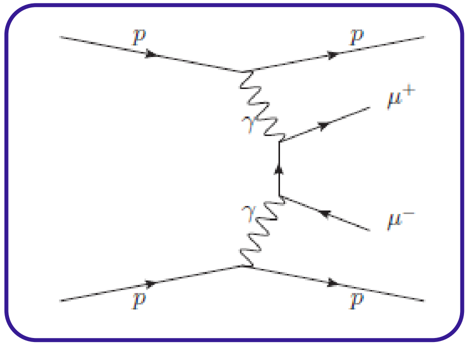
Process $\gamma\gamma \to W^+W^-$

- ➡ Never observed before
- ➡ Sensitive to anomalous QGC

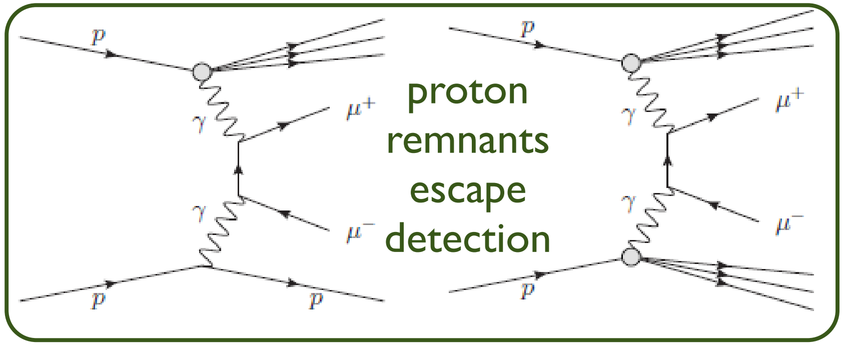




"Exclusive"



"Quasi-Exclusive"



"Untagged analysis":
Signal: exclusive + quasi-exclusive
$pp \to p^{(*)}W^+W^-p^{(*)}$

Signature:
2 isolated leptons (e+μ) and no other visible track from their vertex

$pp \rightarrow p^{(*)}W^{+}W^{-}p^{(*)} \rightarrow p^{(*)}l\nu l'\nu p^{(*)}$ Selection

Measurement strategy

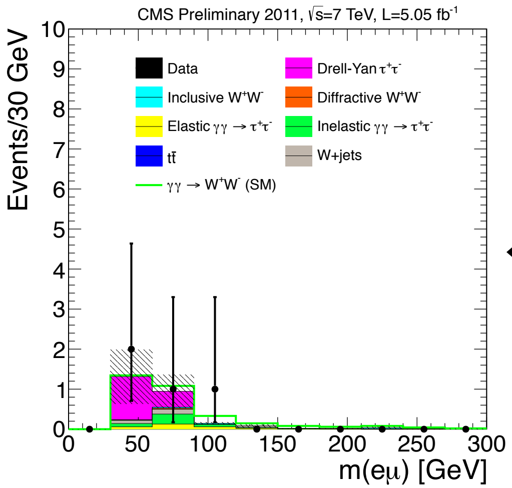
- Use only eμ channel
  - Much larger background for ee/μμ
- Purely track-based analysis
  - reduced PU sensitivity
- 2 discriminating variables used:
  - # tracks associated to eμ vertex
  - P_T(eμ)
- Estimate backgrounds from sidebands of these variables
- Use γγ→μμ to estimate quasi-exclusive fraction

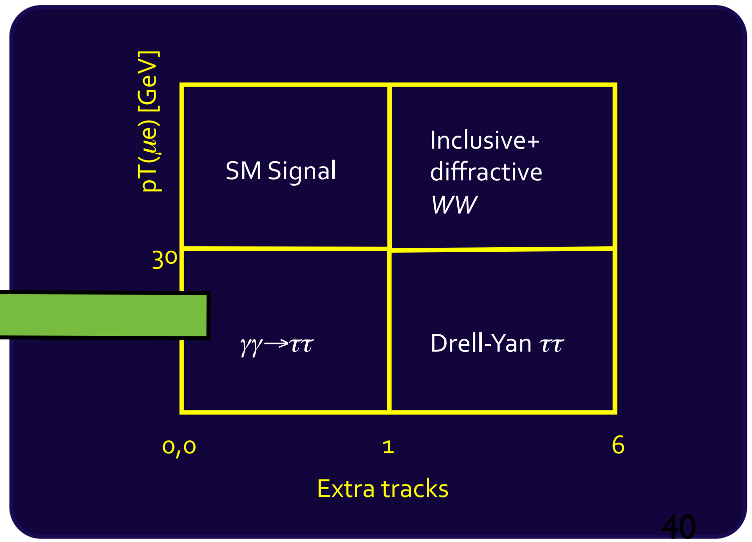
Define 2 regions depending on measurement aim:

	nr tracks	Pt(eμ)
"SM region"	<1	>30 GeV
"aQGC region"	<1	>100 GeV

Backgrounds:
W+jets, γγ→ττ, DY ττ,

CMS-PAS-FSQ-12-010

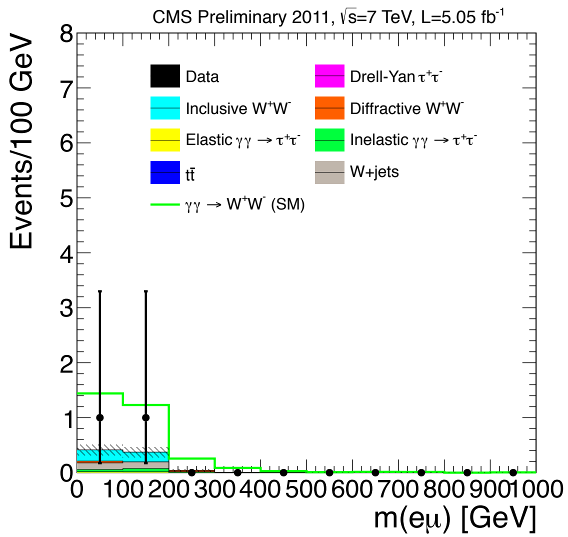


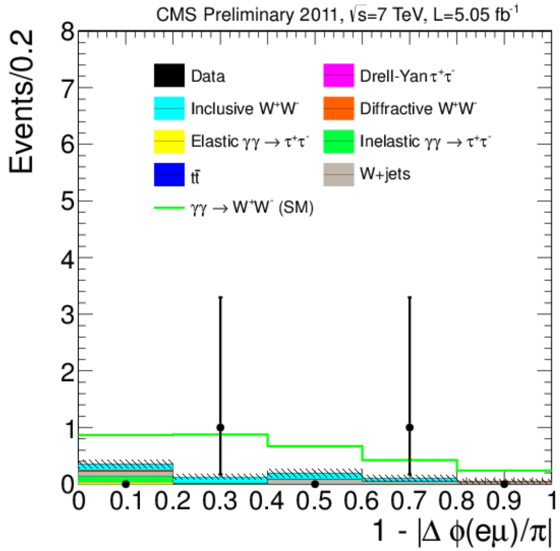


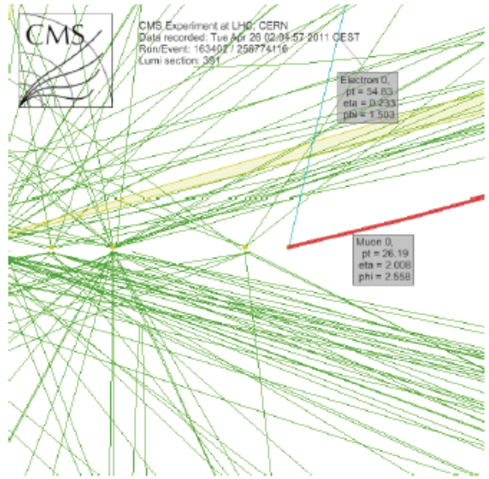
$pp \rightarrow p^{(*)}W^{+}W^{-}p^{(*)} \rightarrow p^{(*)}l\nu l'\nu p^{(*)}$ Cross Section

CMS-PAS-FSQ-12-010

- 2 events observed in SM signal region
- Expected: 2.2±0.5 (signal) + 0.84±13 (background)







- Upper limit extrapolated to full phase space, assuming SM: <8.4 fb @ 95% C.L.
- Expressed as cross section (~ 1 sigma):

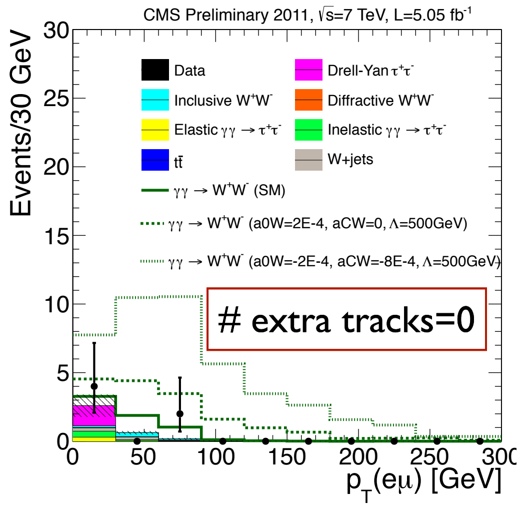
$$\sigma(pp \rightarrow p^{(*)}W^{+}W^{-}p^{(*)} \rightarrow p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}) = 2.1^{+3.1}_{-1.9}\ \text{fb},$$

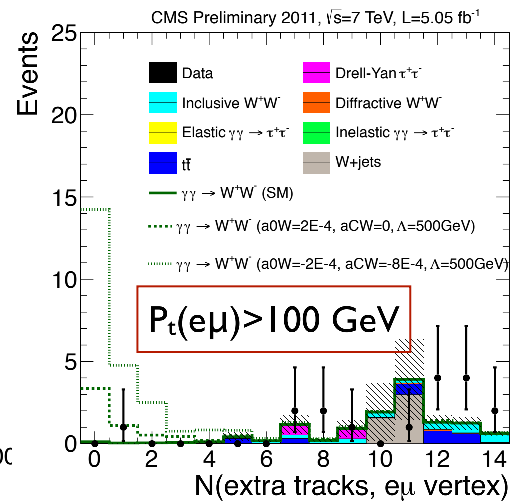
Theory: $\sigma(pp \rightarrow p^{(*)}W^{+}W^{-}p^{(*)} \rightarrow p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}) = 3.8 \pm 0.9\ \text{fb}.$

$pp \to p^{(*)}W^{+}W^{-}p^{(*)} \to p^{(*)}e\nu\mu\nu p^{(*)}$: search for aQGC

No events observed in aQGC search region

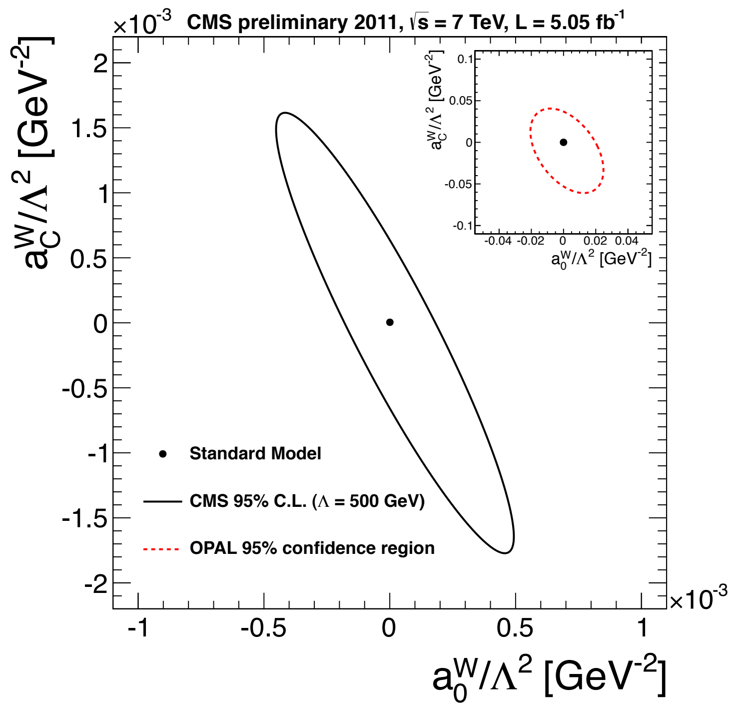
CMS-PAS-FSQ-12-010





Limit on partial x-section*BF:

$$\sigma(pp \to p^{(*)}W^{+}W^{-}p^{(*)} \to p^{(*)}\mu^{\pm}e^{\mp}p^{(*)}) < 1.9 \text{ fb.}$$



Can be interpreted as limit on aQGC with "LEP-like" (Belanger & Boudjema) aQGC:

with form factor Λ=500 GeV

without form factor

$$-0.00017 < a_0^W/\Lambda^2 < 0.00017 \text{ GeV}^{-2} \ (a_C^W/\Lambda^2 = 0, \Lambda = 500 \text{ GeV}),$$
$$-0.0006 < a_C^W/\Lambda^2 < 0.0006 \text{ GeV}^{-2} \ (a_0^W/\Lambda^2 = 0, \Lambda = 500 \text{ GeV}),$$

$$-2.80 \times 10^{-6} < a_0^W/\Lambda^2 < 2.80 \times 10^{-6} \text{ GeV}^{-2} \ (a_C^W/\Lambda^2 = 0, \text{no form factor}),$$
$$-1.02 \times 10^{-5} < a_C^W/\Lambda^2 < 1.02 \times 10^{-5} \text{ GeV}^{-2} \ (a_0^W/\Lambda^2 = 0, \text{no form factor}),$$

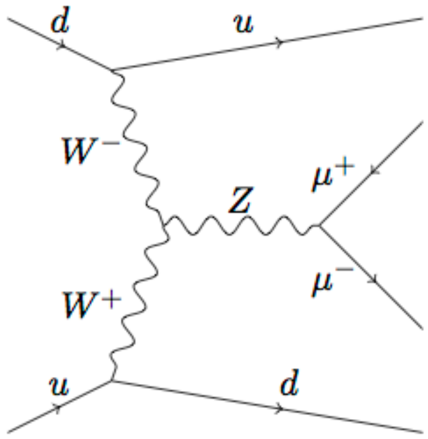
Sensitivity by far exceeds LEP!

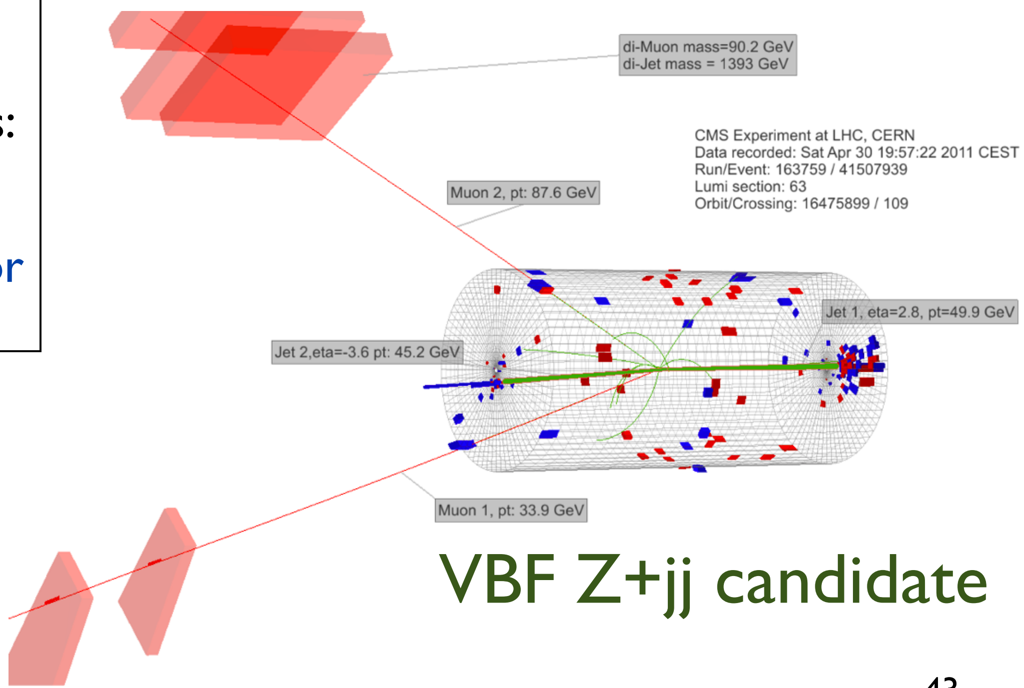
EWK Production of Z+2jets

Vector boson fusion: WW→Z

- Central Z decay with energetic forward-backward jets
- Large η separation between jets
- Large invariant dijet mass
- Pure EWK process: no color exchange between tagging jets:
  - → low hadronic activity in central part of the detector

Signature:
2 isolated leptons
+ 2 tagging jets





VBF Z+jj candidate

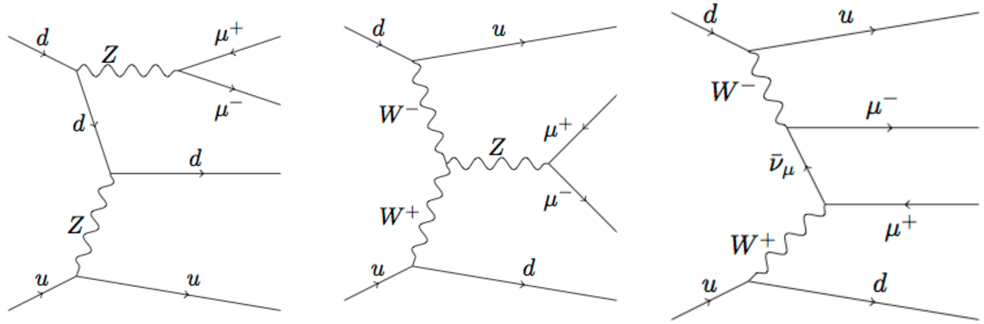
EWK Z+2jets: Measurement strategy

Measurement goals

- Establish pure EWK Z+jets production
- Set benchmark for other VBF processes (Higgs!)
- Study central activity in rapidity gap

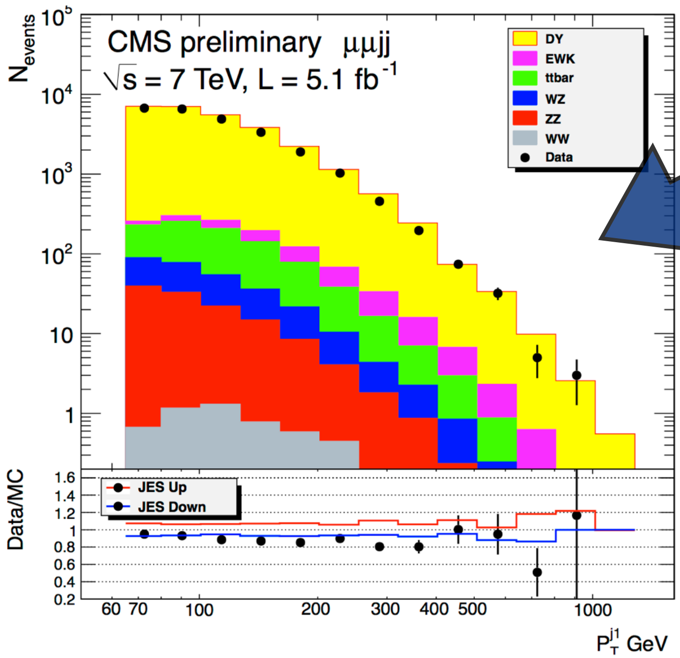
"EWK Z+2jets signal"

Several pure EWK processes lead to Zjj final state



Very large backgrounds: dominated by DY+jets

CMS-PAS-FSQ-12-019



Specific optimized Selection

(1) $P_t^{jet1(2)} > 65\ (40)$ GeV

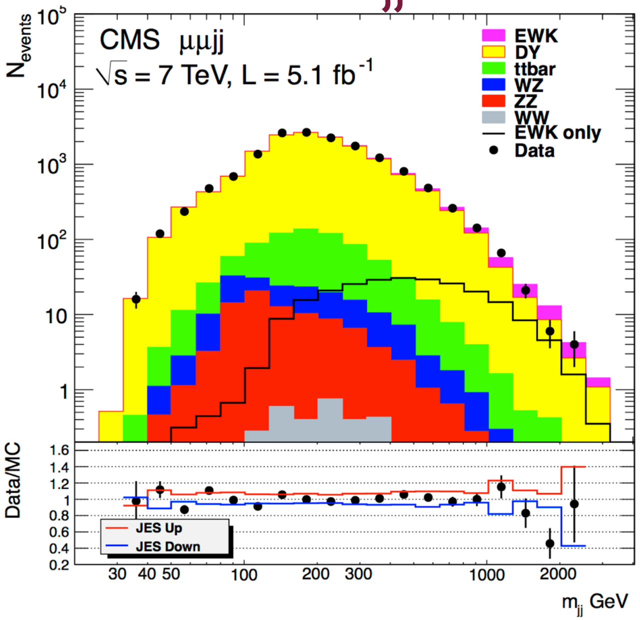
(2) $|y^*| = |y_Z - 0.5(y_{j1}+y_{j2})| < 1.2$

(3) $M(j_1,j_2) > 600$ GeV

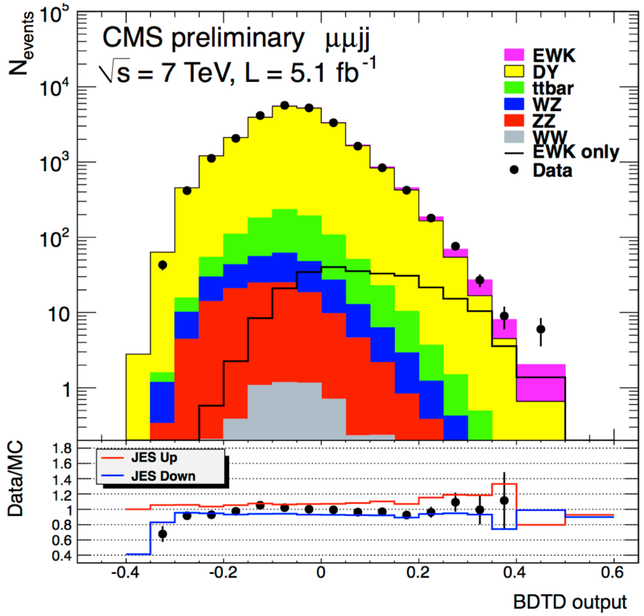
EWK Z+2jets: signal extraction

- EWK Signal extracted in 2 ways:
  - Fit to M_{jj} distribution
  - MVA Analysis: fit to BDT output trained to give high output value for signal-like events
- Present BDT result as it provides smaller uncertainty:

M_{jj}



BDT



$$\sigma^{EW}_{\ell\ell,\ell = \mathrm{e\ or\ }\mu} = 154 \pm 24\,(\mathrm{stat.}) \pm 46\,(\mathrm{exp.\ syst.}) \pm 27\,(\mathrm{th.\ syst.}) \pm 3\,(\mathrm{lum.})\ \mathrm{fb}.$$

in agreement with NLO (VBFNLO) prediction: 166 fb

Measurement limited by large systematic uncertainties: signal and background modeling, Jet energy scale and resolution, MC statistics

CMS-PAS-FSQ-12-019

Conclusions and Outlook

- CMS has measured all diboson processes @ 7 TeV and done first measurements at 8 TeV
  - All measurements consistent with SM expectations
  - Some tensions present however in some channels: WW, Wγ; Fluctuations or disagreement?
- Anomalous coupling limits set in many channels:
  - Measured couplings agree with SM so far
  - Charged couplings approaching LEP sensitivity
  - Neutral coupling sensitivity already exceeded LEP
- Much more to come
  - More final states being worked on
  - Full results on 8 TeV data; Larger luminosity opens the possibility of more detailed studies, e.g. differential cross sections
  - Working on increasing sensitivity through combinations between channels and with ATLAS
- The study of Quartic Gauge Couplings has started!

Gateway to collection of all CMS Results:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Backup

CMS Diboson Results

$WW\to l\nu l\nu$	PLB	$36\ pb^{-1}$ @ 7 TeV
$W\gamma\to l\nu\gamma$ & $Z\gamma\to ll\gamma$	PLB	$36\ pb^{-1}$ @ 7 TeV
$WZ\to l\nu ll$	CMS-PAS-EWK-11-010	$1.1\ fb^{-1}$ @ 7 TeV
$ZZ\to 4l$	JHEP 1301 (2013) 063	$5.0\ fb^{-1}$ @ 7 TeV
$WW\to l\nu l\nu$	CMS-PAS-SMP-12-005	5.0 fb-1 @ 7 TeV
$WW+WZ\to l\nu jj$	EPJC 73 (2013) 2283	5.0 fb-1 @ 7 TeV
$W\gamma\to l\nu\gamma$ & $Z\gamma\to ll\gamma$	CMS-PAS-EWK-11-009	5.0 fb-1 @ 7 TeV
$Z\gamma\to\nu\nu\gamma$	CMS-PAS-SMP-12-020	5.0 fb-1 @ 7 TeV
$WW\to l\nu l\nu$ & $ZZ\to 4l$	arXiv:1301.4698	3.5 fb-1 (WW) & 5.3 fb-1 @ 8 TeV
$\gamma\gamma\to W+W-$	CMS-PAS-FSQ-12-010	5.0 fb-1 @ 7 TeV
Z with 2 forward jets	CMS-PAS-FSQ-12-019	5.0 fb-1 @ 7 TeV

Exclusive γγ→W⁺W⁻ Production