WW, WZ and ZZ production at CMS

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on behalf of CMS collaboration

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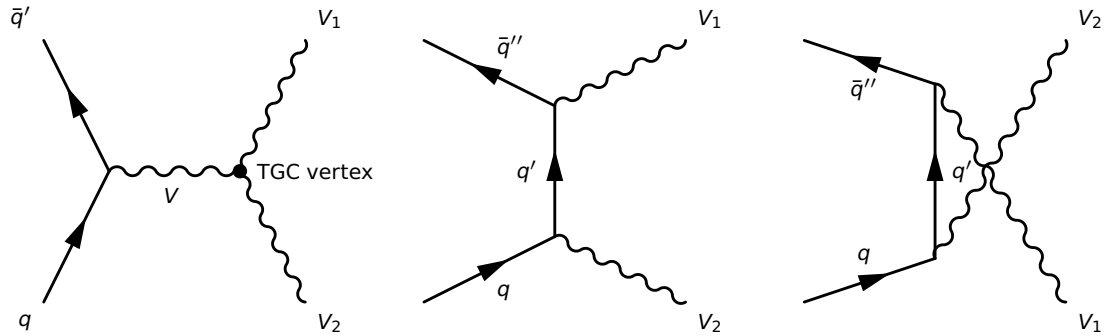
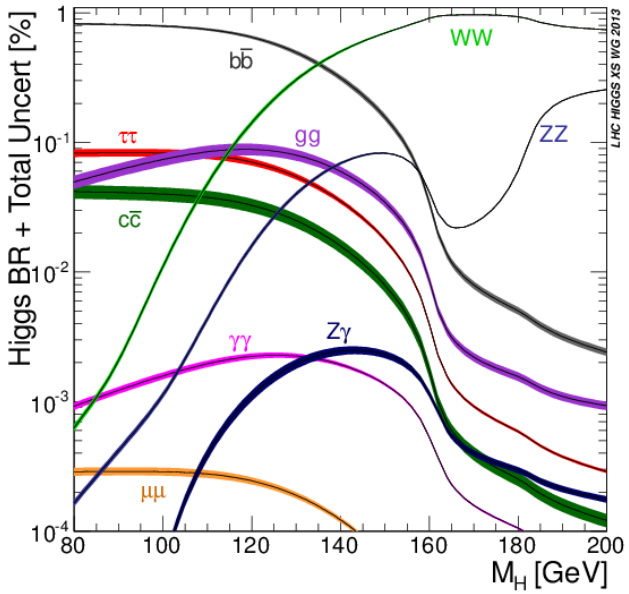
Outline

Physics Motivation

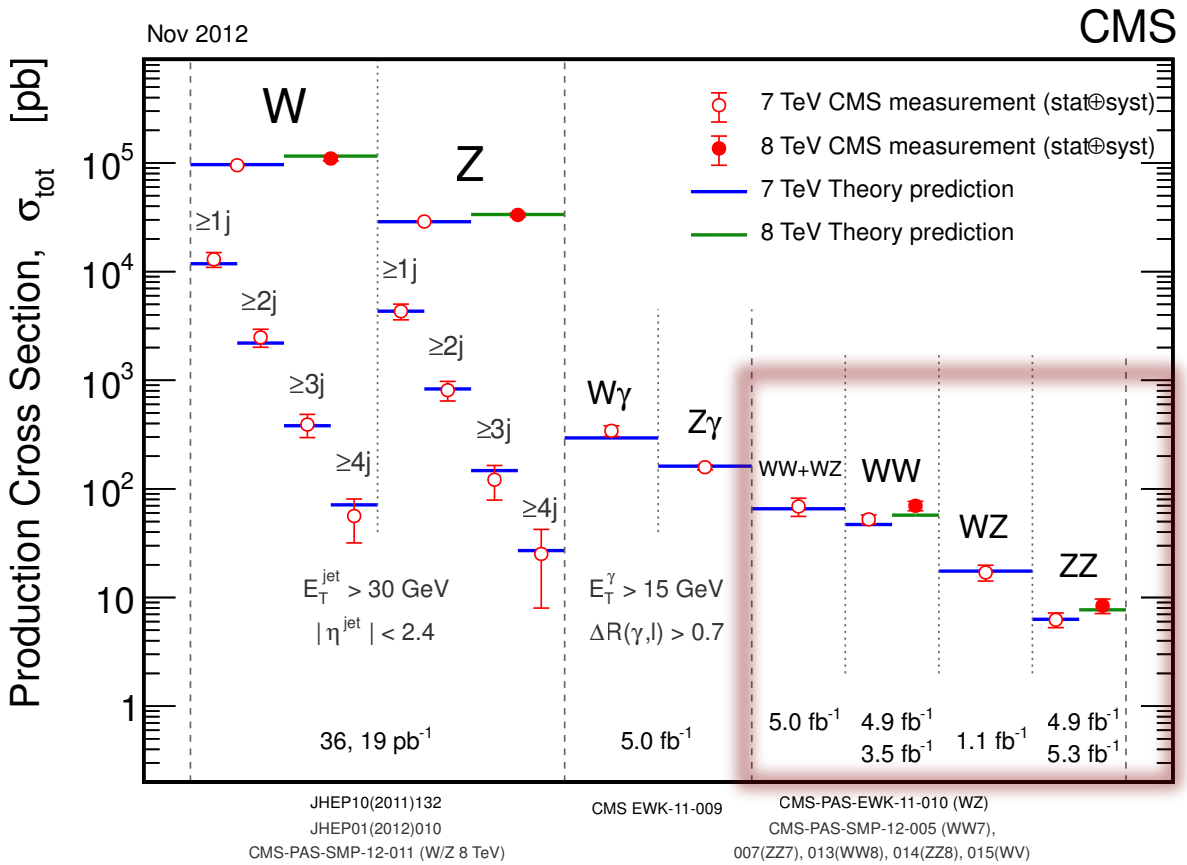
- Precision test of QCD/EW dynamics of the Standard Model
- Allow test of anomalous Triple Gauge Couplings (aTGC)



- Background to several Higgs production and other new physics channels (Exotica, SUSY,...)



Overview of WW, WZ and ZZ measurements at CMS



	Integrated luminosity at 7 TeV	8 TeV	Limits on TGC
$WW \to 2\ell 2\nu$	5.0 fb^{-1}	3.5 fb^{-1}	$W\gamma W$,WZW
$WW + WZ \to \ell\nu jj$	5.0 fb^{-1}	–	$WW\gamma$,WWZ
$WZ \to 2\ell\ell'\nu$	4.9 fb^{-1}	19.6 fb^{-1}	–
$ZZ \to 4\ell$	4.9 fb^{-1}	19.6 fb^{-1}	ZZZ, $Z\gamma Z$

- Updated 7 TeV measurement for WZ
- First results at 8 TeV for WZ at CMS
- Updated results at 8 TeV for ZZ
- First measurement $\sigma_{W^+Z}/\sigma_{W-Z}$

$WW \to 2\ell 2\nu$ ($\ell = e, \mu$)

$\mathcal{L}_{int} = 4.9\ fb^{-1}$ @ 7 TeV, $\mathcal{L}_{int} = 3.5\ fb^{-1}$ @ 8 TeV

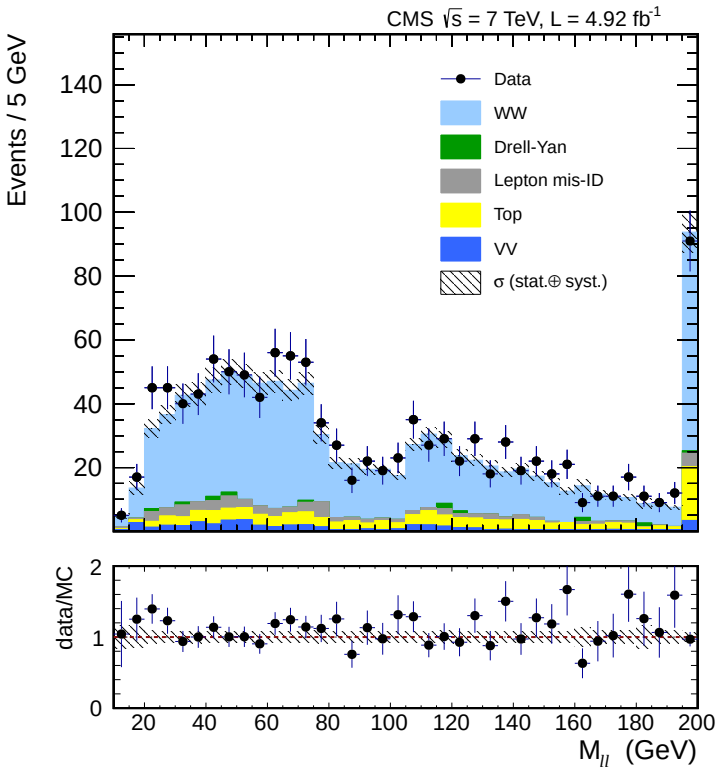
7 TeV
Phys. Lett. B 699 (2011) 25-47 ($36 fb^{-1}$)
submitted to EPJC ($4.9 fb^{-1}$)
arXiv:1306.1126
CMS-SMP-12-005, CERN-PH-EP-2013-075

8 TeV
Phys. Lett. B 721 (2013) 190-211
arXiv:1301.4698
CERN-PH-EP-2012-376

See also Jonathan Hollar's talk: $gg \to WW$ and aQCG at CMS

Signature

- 2 isolated leptons (ee, $e\mu$, $\mu\mu$) with opposite sign
- Large missing E_T



Background rejection

- QCD/W+jets: Tight isolation and ID
- top: Jet Veto (0 jets with $E_T > 30\ GeV$)
  Top Veto (b-tag + soft muon events vetoed)
- Drell-Yan: Z Veto, $|m_{\ell\ell} - m_Z| < 15\ GeV$
  $E_T^{miss} > 20/45\ GeV$ ($e\mu/\mu\mu$, ee)
  $\Delta\phi(\ell\ell, jet) > 165^0$ (jet $E_t > 15\ GeV$)
- WZ, ZZ: Veto events with third (good id,iso)lepton

- Main source of systematic uncertainty from background estimation (20 %)
- Measured cross sections slighty above the NLO prediction
- Expected contribution from SM $H \to WW$ about $\simeq 4$ % (not included in the theoretical prediction)

WW inclusive cross section

	$\sigma^{meas.}_{CMS}$ [pb]	$\sigma^{theo.}_{NLO}$ [pb] (MCFM)
7 TeV	$52.5 \pm 2.0(stat.) \pm 4.5(syst.) \pm 1.2(lumi.)$	47.0 ± 2.0
8 TeV	$69.9 \pm 2.8(stat.) \pm 5.6(syst.) \pm 3.1(lumi.)$	$57.3^{+2.4}_{-1.6}$

$WW + WZ \to \ell\nu jj$ ($\ell = e, \mu$)

$\mathcal{L}_{int} = 5.0\ fb^{-1}$ @ 7 TeV

Eur.Phys.J. C73 (2013) 2283
arXiv:1210.7544 [hep-ex]
CMS-SMP-12-015, CERN-PH-EP-2012-311

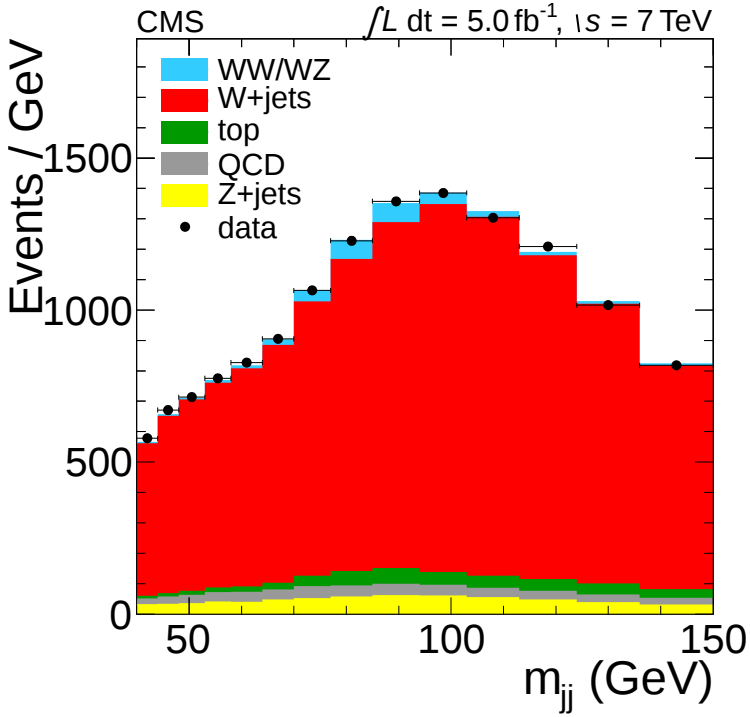
- Large branching ratio w.r.t the fully leptonic decay (6 times higher)
- Jet resolution does not allow to separate W and Z mass
- Large background
  - Signal and background yields determined with unbinned likelihood fit to the dijet mass spectrum
- Sample used for $WV\gamma$ triple gauge boson search. See Chia Ming, Kuo's talk "Vector boson plush photon production at CMS"

Signature and signal selection

- Exactly 1 isolated lepton: $p_t > 20/30\ GeV$ (μ/e) + trigger
- Exactly 2 jets: $p_t > 35\ GeV$
- Large missing E_t: $\not{E}_T > 25/30\ GeV$ (μ/e)
- W transverse mass: $M_T(\ell, \not{E}_T) > 30/35\ GeV$ (μ/e)

Main backgrounds

- W+jets
- top ($t\bar{t}$,tW)
- DY+jets
- Multijets (QCD)



CMS cross section measurement

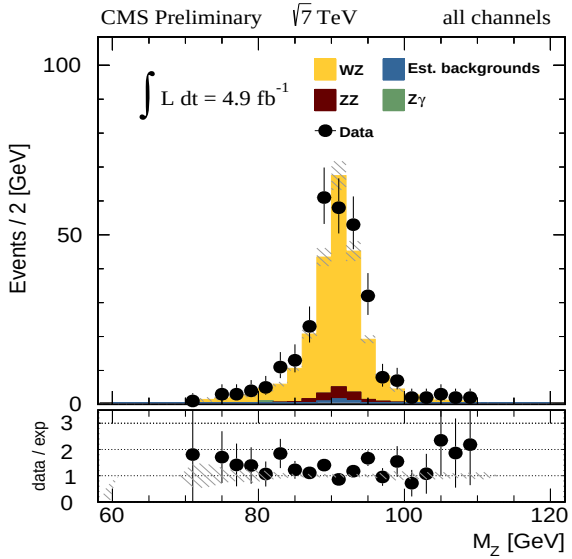
$$\sigma(pp \to WW + WZ) = 68.89 \pm 8.71(\text{stat.}) \pm 9.70(\text{syst.}) \pm 1.52(\text{lumi.})\ pb$$
$$\sigma^{NLO}_{theo.} = 65.6 \pm 2.2\ pb\ (\text{MCFM})$$

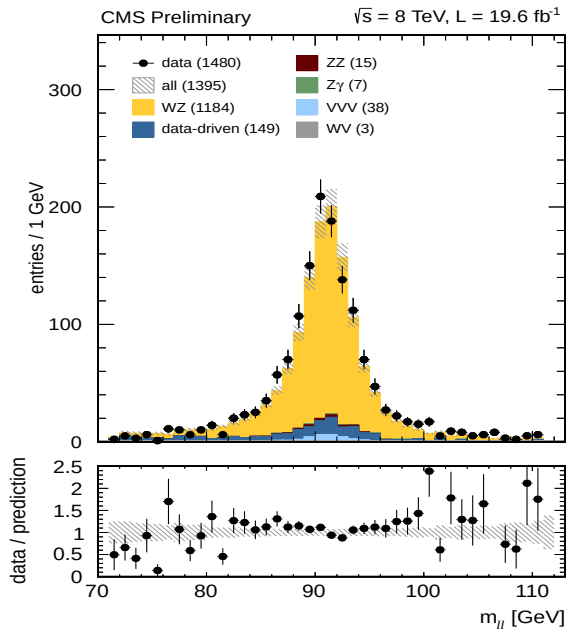
$WZ \to 2\ell\ell'\nu$ ($\ell = e, \mu$)

$\mathcal{L}_{int} = 4.9\ fb^{-1}$ @ 7 TeV, $\mathcal{L}_{int} = 19.6\ fb^{-1}$ @ 8 TeV

CMS-PAS-EWK-11-003 ($\mathcal{L} = 1.1\ fb^{-1}$@7TeV)
CMS-SMP-12-006

7 TeV UPDATED, 8 TeV NEW!





Signature

- 3 isolated leptons ($3e$, $2e1\mu$, $2\mu1e$, 3μ)
  - Z candidate: 2 same flavor, opposite charge; $p_t > 20, 10\ GeV$ and $|m_{\ell\ell} - m_Z| < 20\ GeV$
  - W candidate: $p_t > 20\ GeV + E_T^{\text{miss}} > 30\ GeV$
- Large missing E_T

Background rejection

- ZZ (irreducible background)
  - vetoed events with > 3 good id. and iso. leptons
  - $E_T^{\text{miss}} > 30\ GeV$
- Fakes leptons Instrumental background due to mis-identified particles or leptons not decaying from W/Z: Z+jets, top ($t\bar{t}$, tW ,$\bar{t}W$), WW, W+jets, QCD, ...
  - Tight isolation, Z mass, Large E_T^{miss}, ...

- Analysis signal dominated
- Main background coming from instrumental background: Z+jets, $t\bar{t}$

$WZ \to 2\ell\ell'\nu$ ($\ell = e, \mu$)

$\mathcal{L}_{int} = 4.9\ fb^{-1}$ @ 7 TeV, $\mathcal{L}_{int} = 19.6\ fb^{-1}$ @ 8 TeV

CMS-PAS-EWK-11-003 ($\mathcal{L} = 1.1\ fb^{-1}$@7TeV)
CMS-SMP-12-006

7 TeV UPDATED, 8 TeV NEW!

Cross section measurements

	$\sigma^{meas.}_{CMS}$ [pb]	$\sigma^{theo.}_{NLO}$ [pb] (MCFM, MSTW08 pdf sets)
7 TeV	$20.8 \pm 1.3(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.5(\text{lumi.})$	$17.8^{+0.7}_{-0.5}$
8 TeV	$24.7 \pm 0.8(\text{stat.}) \pm 1.1(\text{syst.}) \pm 1.1(\text{lumi.})$	$22.0^{+1.2}_{-0.8}$

- Statistical errors dominates 7 TeV measurement
- Main systematic uncertainty source coming from background estimation ($\simeq 6\,\%$)
- Cross section measured slighlty above the NLO predictions

$\sigma_{W^+Z}/\sigma_{W^-Z}$ ratio measurements NEW!!

	$\sigma^{meas.}_{CMS}$ [pb]	$\sigma^{theo.}_{NLO}$ [pb] (MCFM, MSTW08 pdf sets)
7 TeV	$1.94 \pm 0.25(\text{stat.}) \pm 0.04(\text{syst.})$	$1.776^{+0.006}_{-0.003}$
8 TeV	$1.81 \pm 0.12(\text{stat.}) \pm 0.03(\text{syst.})$	1.724 ± 0.003

- Luminosity systematic uncertainty cancels
- Background systematic uncertainties highly reduced
- Added systematic uncertainty in efficiency ratio $\varepsilon^-/\varepsilon^-$ and charge misidentification rate. Main systematic source: efficiency ratio ($\simeq 3\,\%$)
- Good agreement with NLO predictions

$$\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}} = \frac{N_S^+}{N_S^-} \cdot \frac{(\mathcal{A}\cdot\varepsilon)^-_{\text{resc.}}}{(\mathcal{A}\cdot\varepsilon)^+_{\text{resc.}}}$$

$ZZ \to 2\ell 2\ell' \ (\ell = e, \mu, \ell' = e, \mu, \tau)$

$\mathcal{L}_{int} = 5.0\ fb^{-1}$ @ 7 TeV, $\mathcal{L}_{int} = 19.6\ fb^{-1}$ @ 8 TeV

7 TeV
J. High Energy Phys. 01 (2013) 063
arXiv:1211.4890
CERN-PH-EP-2012-336

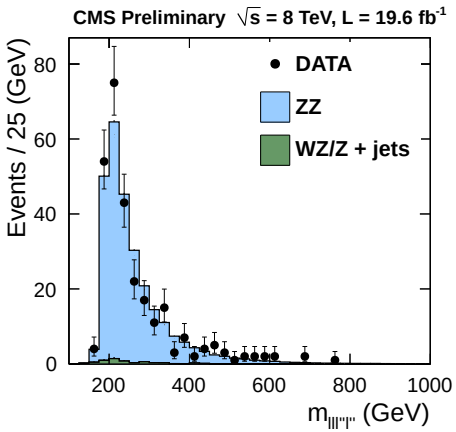
8 TeV
Phys. Lett. B 721 (2013) 190-211 ($\mathcal{L} = 5.3 fb^{-1}$)
arXiv:1301.4698 ($\mathcal{L} = 5.3 fb^{-1}$)
CERN-PH-EP-2012-376 ($\mathcal{L} = 5.3 fb^{-1}$)
CMS-SMP-13-005

8 TeV UPDATED!

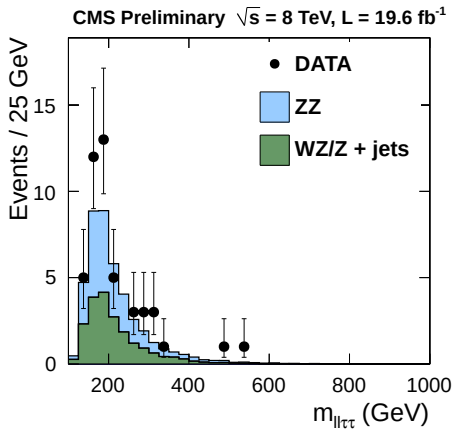
Signature

- First Z($\to ee, \mu\mu$): 2 isolated leptons, $p_t > 20, 10\ GeV$, same flavor with opposite charge and $60 < m_{\ell\ell} < 120\ GeV$
- Second Z:
  - $Z_2 \to ee, \mu\mu$: 2 isolated leptons, $p_t > 7, 5$, same flavor with opp. charge and $60 < m_{\ell\ell} < 120\ GeV$
  - $Z_2 \to \tau\tau(\tau \to e, \mu, had)$: $p_t(\tau \to e, \mu > 10$, $p_t(\tau \to had) > 20$, and $30 < m_{\tau\tau}^{visible} < 90\ GeV$

$4e, 2\mu 2e, 4\mu$



$2\ell 2\tau$



- Very clean signature
- Results dominated by statistical uncertainties at 7 TeV
- Main systematic uncertainty source: tau reconstruction
- Measured cross sections in good agreement with the NLO prediction

Main Backgrounds

- Jets faking ℓ or τ (WZ+jets,Z+jets)
- Heavy flavour jets ($t\bar{t}$, Zbb)

ZZ inclusive cross section

	$\sigma_{CMS}^{meas.}$ [pb]	$\sigma_{NLO}^{theo.}$ [pb] (MCFM)
7 TeV	$6.2^{+0.9}_{-0.8}(stat.)^{+0.4}_{-0.3}(sys.) \pm 0.1(lumi.)$	6.3 ± 0.4
8 TeV	$7.7 \pm 0.5(stat.) \pm 0.6(syst.) \pm \pm 0.3(lumi.)$	7.7 ± 0.4

Differential cross-sections are also measured. See CMS-SMP-13-005

Triple Gauge Couplings

See same references as cross-section meas.

- The SM predicts exact values for vector boson couplings
- the effective Lagrangian used to describe the effect of non-SM processes on TGCs depends on several parameters

Coupling	Parameters	Channels
$WW\gamma$	λ_γ,$\Delta\kappa_\gamma$	WW
WWZ	λ_Z, $\Delta\kappa_Z$, Δg_1^Z	WW,WZ
$Z\gamma Z$	f_4^Z, f_5^Z	ZZ
ZZZ	f_4^γ, f_5^γ	ZZ

All parameters are 0 in SM

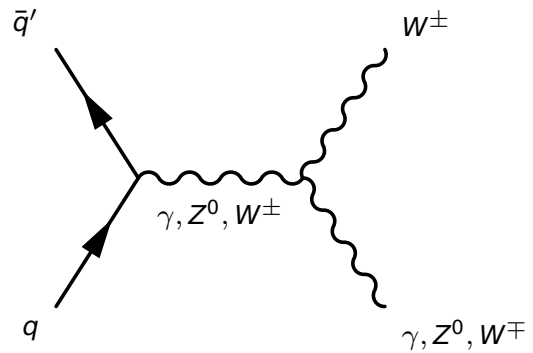
This parametrization is $SU(2) \times U(1)$ gauge symmetry respecting

- aTGCs modify total production rates as well as event kinematics
  - New physics is expected at high boson transverse momentum or high diboson invariant mass
- the expected number of signal events can be written as function of the SM cross section plus some aTGC parameters
- In absence of deviations from the SM expectations, upper limits on aTGC parameters can be set using the profile-likelihood formalism and CLs method

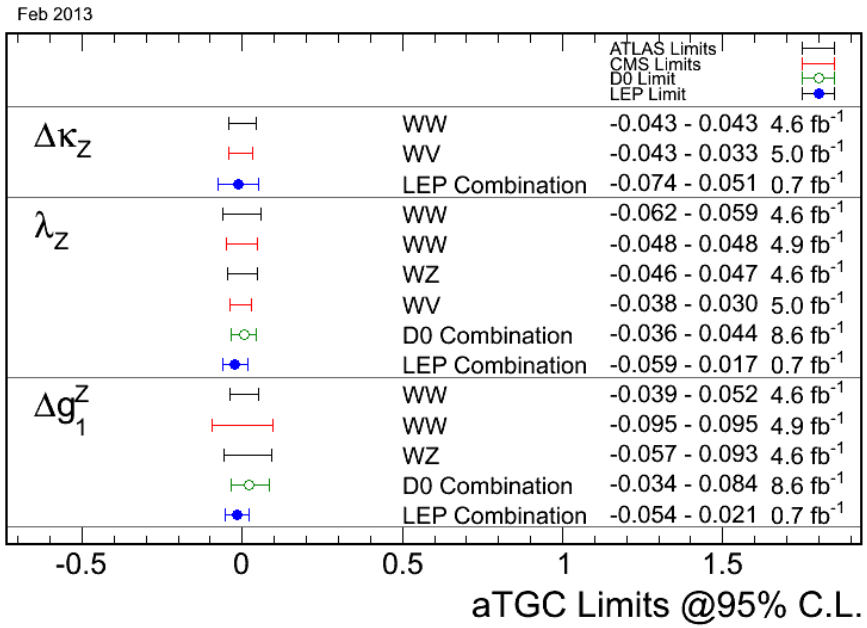
Triple Gauge Couplings

Charged aTGCs

- WV (V=W,Z) production used to probe vertex WWV (V=Z,γ)
- Set limits on parameters (applying gauge constrains: 3 independent parameters),
  1. $\mathbf{\Delta g_1^Z}$
  2. $\boldsymbol{\lambda} = \lambda_\gamma = \lambda_Z$
  3. $\mathbf{\Delta \kappa_Z} = \Delta g_1^Z - \Delta\kappa_\gamma tan^2(\theta_W)$
- 95 % CL limits sets using leading lepton p_t (WW) or p_t^{jj} (WW+WZ)

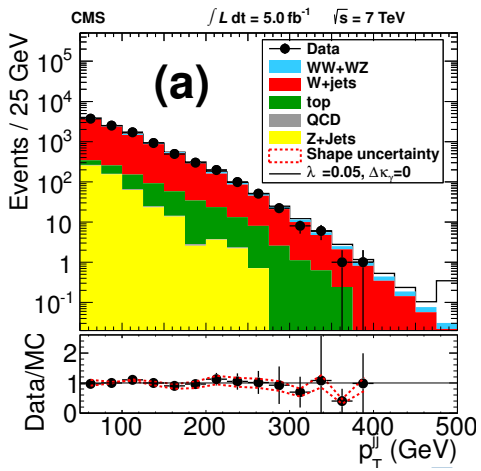


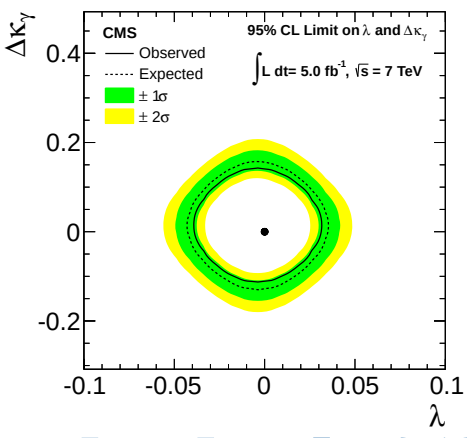
No deviations from SM observed

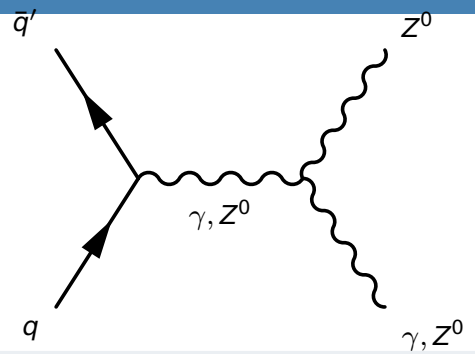


Equal or World Leading Sensitivity

From WV (V=Z, $W \rightarrow jj$)



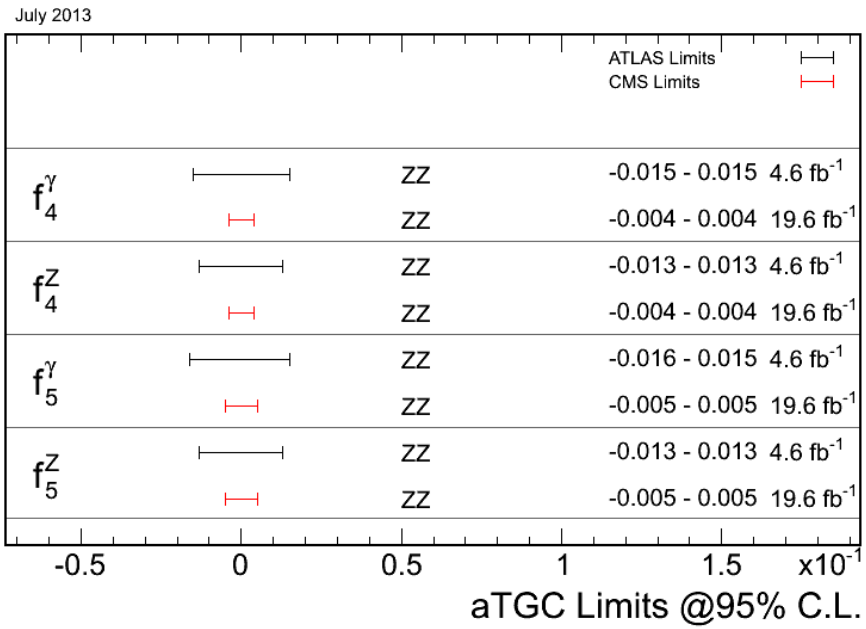


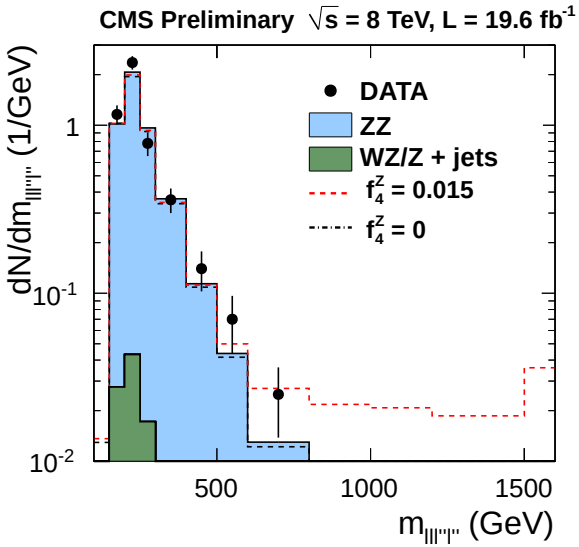


- ZZ production used to probe vertex ZVZ (V=Z,γ)
- Set limits on parameters f_4^V, f_5^V (V=Z,γ)
- 95 % CL limits sets using 4ℓ invariant mass

No deviations from SM observed

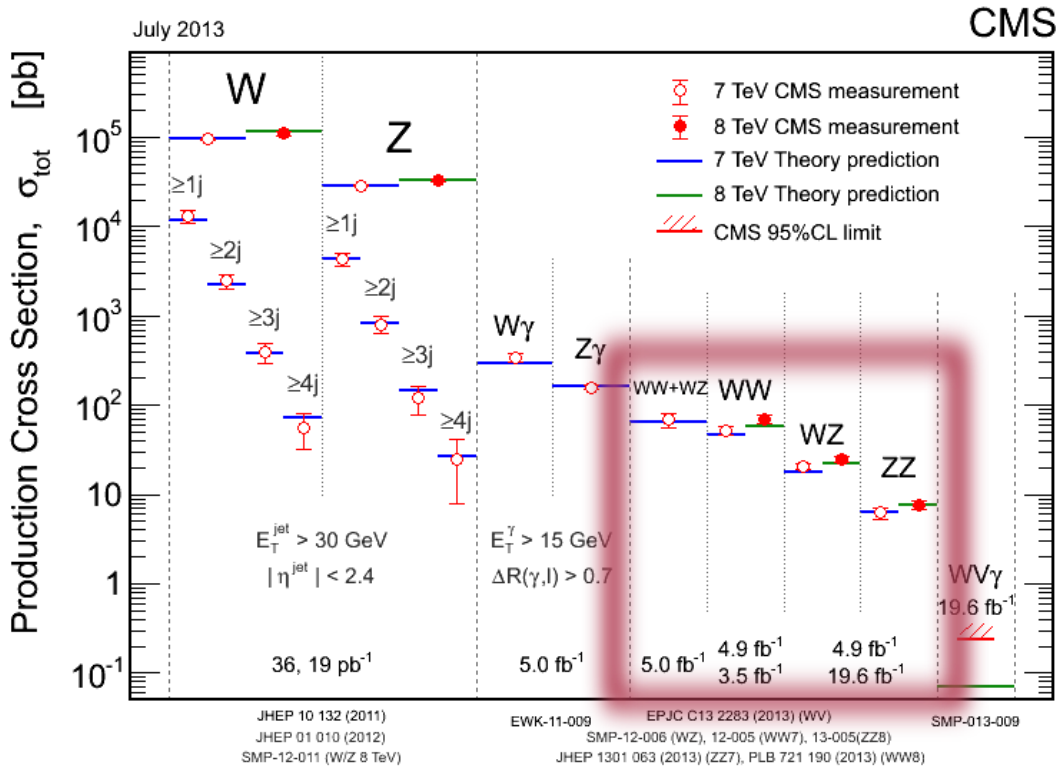
NEW IMPROVED LIMITS
World Leading Sensitivity





Summary and Conclusions

- Presented cross sections measurements for WW, WZ and ZZ production at CMS at 7 TeV and 8 TeV
  - Updated WZ cross section measurement at 7 TeV
  - First CMS measurement of WZ at 8 TeV
  - First measurement of $\sigma_{W^+Z}/\sigma_{W^-Z}$ at 7 TeV and 8 TeV
  - Updated ZZ cross section measurement at 8 TeV
- Cross sections measured compatible with NLO SM predictions
  - WZ and WW slightly above SM prediction
- aTGC searches using the WW, WZ and ZZ channels showed no deviation from SM
  - Improved limits from f_4^V, f_5^V parameters (a factor $\simeq$ 3-4 since last measurement)



BACKUP SLIDES

Summary of cross section measurements

	$\sigma^{CMS}_{meas.}$ [pb]	Channel	$\sqrt{s}$ [TeV]	$\mathcal{L}_{int}$ [fb^{-1}]	
$\sigma(pp \to WW + WZ)$	$68.5 \pm 8.7(\text{stat.}) \pm 9.7(\text{syst.}) \pm 1.5(\text{lumi.})$	$\ell\nu jj$, $(\ell = e, \mu)$	7	5.0	
$\sigma(pp \to WW)$	$52.5 \pm 2.0(\text{stat.}) \pm 4.5(\text{syst.}) \pm 1.2(\text{lumi.})$	2ℓ, $(\ell = e, \mu)$	7	4.9	
$\sigma(pp \to WW)$	$69.9 \pm 2.8(\text{stat.}) \pm 5.6(\text{syst.}) \pm 3.1(\text{lumi.})$	2ℓ, $(\ell = e, \mu)$	8	3.5	
$\sigma(pp \to WZ)$	$20.8 \pm 1.3(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.5(\text{lumi.})$	$2\ell\ell'\nu$, $(\ell\ell' = e, \mu)$	7	4.9	NEW
$\sigma(pp \to WZ)$	$24.7 \pm 0.8(\text{stat.}) \pm 1.1(\text{syst.}) \pm 1.1(\text{lumi.})$	$2\ell\ell'\nu$, $(\ell\ell' = e, \mu)$	8	19.6	NEW
$\sigma(pp \to ZZ)$	$6.2 \pm 0.9(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.1(\text{lumi.})$	$2\ell 2\ell'$, $(\ell = e, \mu, \ell' = e, \mu, \tau)$	7	4.9	NEW
$\sigma(pp \to ZZ)$	$7.7 \pm 0.5(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.3(\text{lumi.})$	$2\ell 2\ell'$, $(\ell = e, \mu, \ell' = e, \mu, \tau)$	8	19.6	NEW
$\sigma(pp \to W^+Z)/\sigma(pp \to W^-Z)$	$1.94 \pm 0.25(\text{stat.}) \pm 0.04(\text{syst.})$ [no units]	$2\ell\ell'\nu$, $(\ell\ell' = e, \mu)$	7	4.9	NEW
$\sigma(pp \to W^+Z)/\sigma(pp \to W^-Z)$	$1.81 \pm 0.12(\text{stat.}) \pm 0.03(\text{syst.})$ [no units]	$2\ell\ell'\nu$, $(\ell\ell' = e, \mu)$	8	19.6	NEW

Cross section measurement methodology

- Selection cuts and count analysis yields observed events
- Background estimation with data-driven and MC methods
- Measured the cross section within the fiducial region:
  - Fiducial region is defined by the limited coverage of the detector and selection cuts

$$\sigma_{fiducial} = \frac{N_{obs} - N_{bkg}}{\varepsilon \cdot \mathcal{L}_{int}}$$

- Correct the fiducial cross section by the acceptance and branching ratio of measured channel to measure the total cross section

$$\sigma_{total} = \frac{\sigma_{fiducial}}{\mathcal{A} \cdot BR} = \frac{N_{obs} - N_{bkg}}{\mathcal{A} \cdot \varepsilon \cdot BR \cdot \mathcal{L}_{int}}$$