

Diboson Production and Anomalous Triple Gauge Couplings



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On behalf of the ATLAS and CMS Collaborations



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Diboson Physics at the LHC

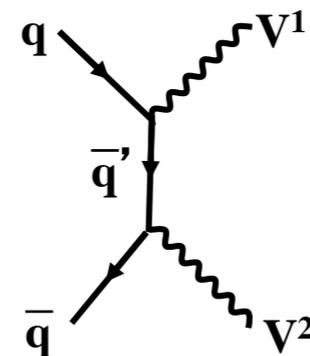
Diboson final states: $\gamma\gamma$, $W\gamma$, $Z\gamma$, WW , WZ , ZZ
 All observable at the LHC

covered in
 this talk

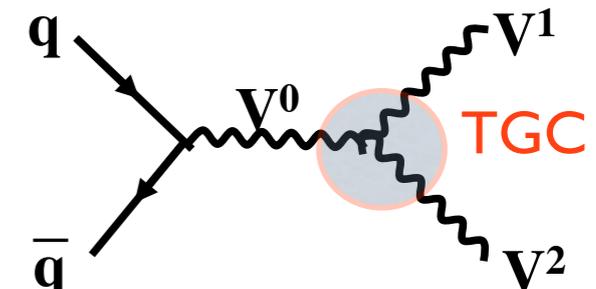
- ▶ Diboson measurements represent valuable SM test
 - Probe of perturbative QCD
 - Sensitive to triple and quartic gauge couplings
- ▶ Neutral TGCs not allowed in SM
 - Only $W\gamma$, WW and WZ production get contribution from TGCs
- ▶ Diboson processes often represent background in BSM or Higgs searches or new physics signatures are diboson final states

Production mechanisms

t-channel

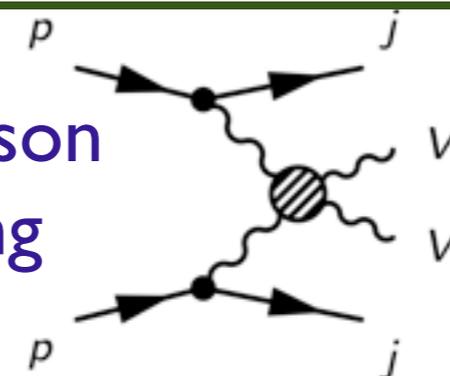


s-channel



SM: only charged TGCs
 $V^1 V^2 = W\gamma, WW, WZ$

Vector Boson Scattering



VBS ($VVjj$) and QGC
 covered by Zhijun Liang's talk



Measurement Procedure



Cut & Count
or ML

Mostly data-driven
for dominant bgd

$$\sigma = \frac{N_{meas.} - N_{bg}}{A \times C \times \int \mathcal{L} dt}$$

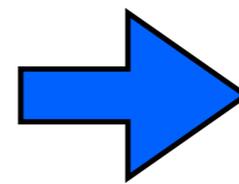
Each measurement defines

- A. Cross section region: phase space for which a cross section will be quoted (**CR**), not always full phase space
- B. Measurement fiducial region: more restricted phase space closer to analysis cuts for which a cross section will be determined (**FR**) (**Not quoted in all measurements**)

▶ **A**: fraction of events in the CR which fall in FR

$$A = \frac{N_{MC}^{gen\ FR}}{N_{MC}^{gen\ CR}}$$

affected only
by theory

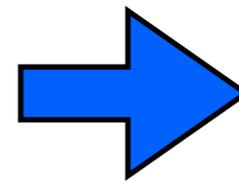


NLO Calculation
(not necessarily full MC)

▶ **C**: reconstruction and selection efficiency wrt to the FR

$$C = \frac{N_{MC}^{sel}}{N_{MC}^{gen\ FR}} \times \frac{\epsilon_{data}}{\epsilon_{MC}}$$

affected by
theory
and detector



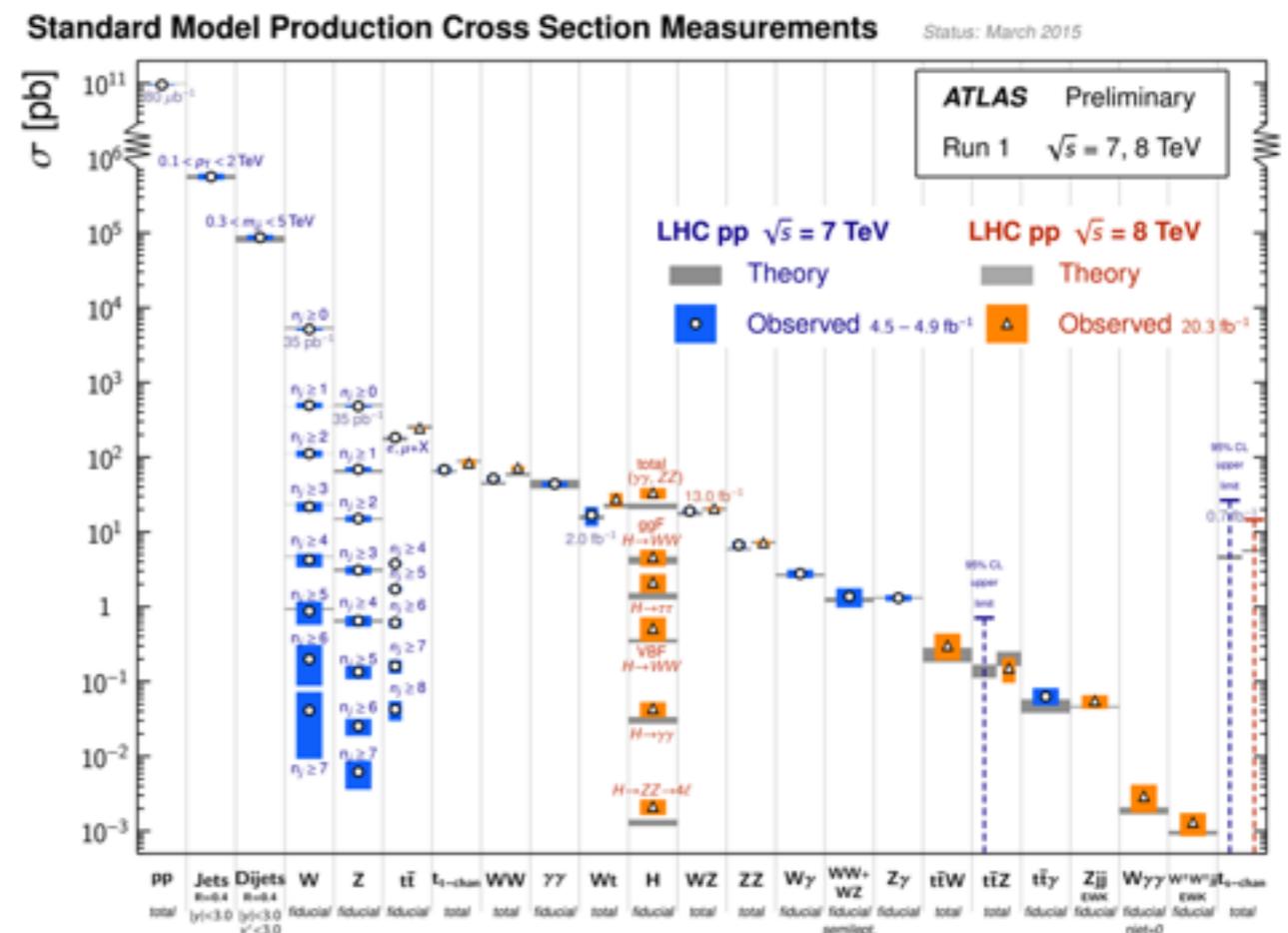
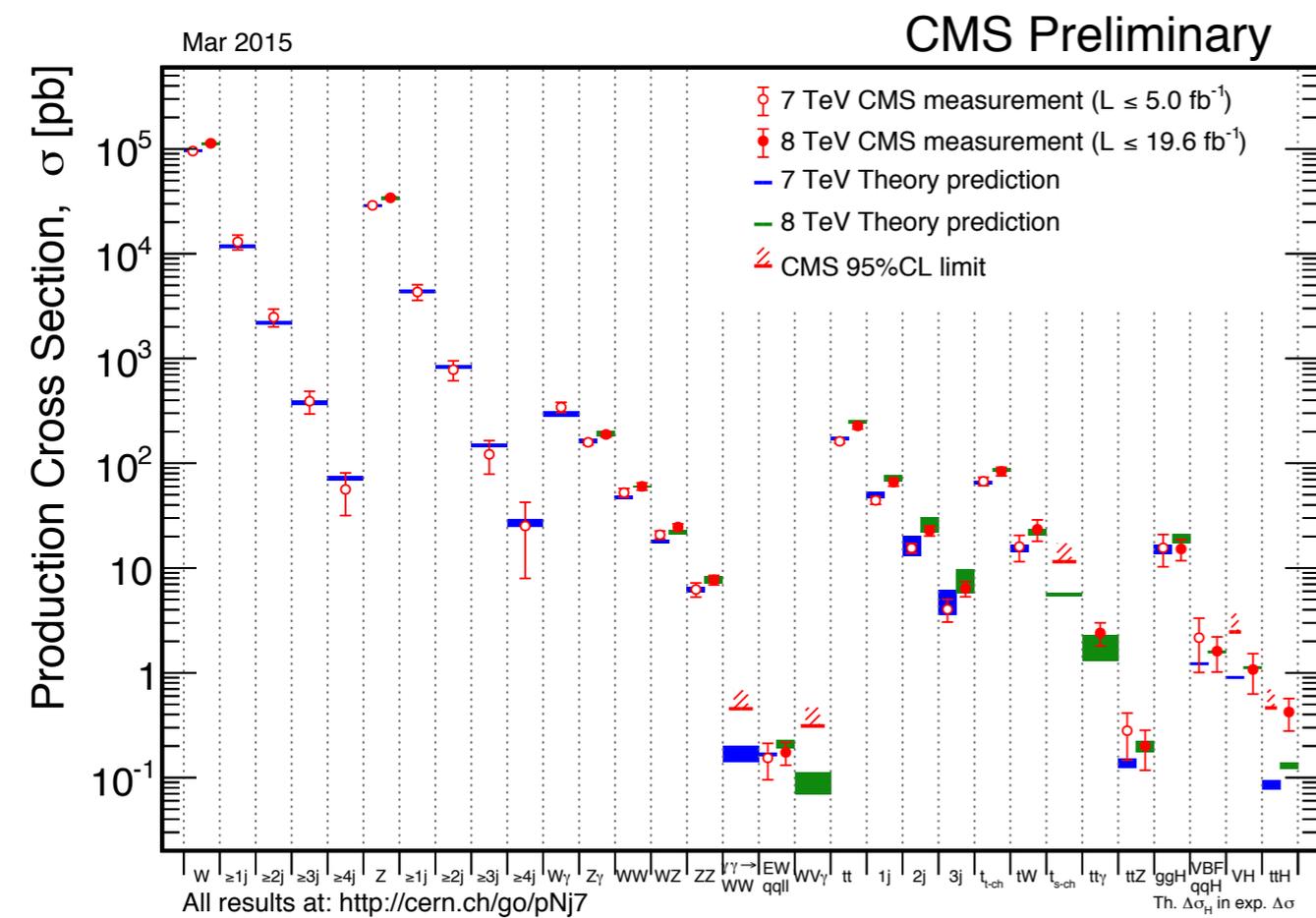
NLO or ME MC
(powheg, MC@NLO,
Madgraph, Alpgen, Sherpa)
whatever is used for signal MC



Overview of Results



- ▶ ATLAS and CMS both measured cross sections for all diboson processes
- ▶ Mostly using leptonic decay channels
- hadronic (jj) or invisible (νν) channels also used in several measurements: give complementary sensitivity
- ▶ Differential cross sections also presented for several channels





Summary of LHC Run I Results



Recent updates
(from Summer 2014)

| Channel (final state) | ATLAS | | CMS | |
|---------------------------|----------|-------|-------|----------|
| | 7 TeV | 8 TeV | 7 TeV | 8 TeV |
| $W\gamma(\ell\nu\gamma)$ | xs,dx,ac | | xs,ac | |
| $Z\gamma(\ell\ell\gamma)$ | xs,dx,ac | | xs,ac | xs,dx,ac |
| $Z\gamma(\nu\nu\gamma)$ | xs,ac | | xs,ac | |
| $WW(\ell\nu\ell\nu)$ | xs,dx,ac | xs | xs,ac | xs,dx,ac |
| $WZ(3\ell\nu)$ | xs,dx,ac | xs | xs | xs |
| $ZZ(4\ell)$ | xs,dx,ac | xs | xs,ac | xs,dx,ac |
| $ZZ(2\ell 2\nu)$ | xs,dx,ac | | xs,ac | xs,ac |
| $WV(\ell\nu jj)$ | xs,ac | | xs,ac | |

xs: cross section, ac: limits on aTGCs, dx: differential cross sections



Published and Preliminary Public Results

Reference numbers [x] in the next slides refer to this list



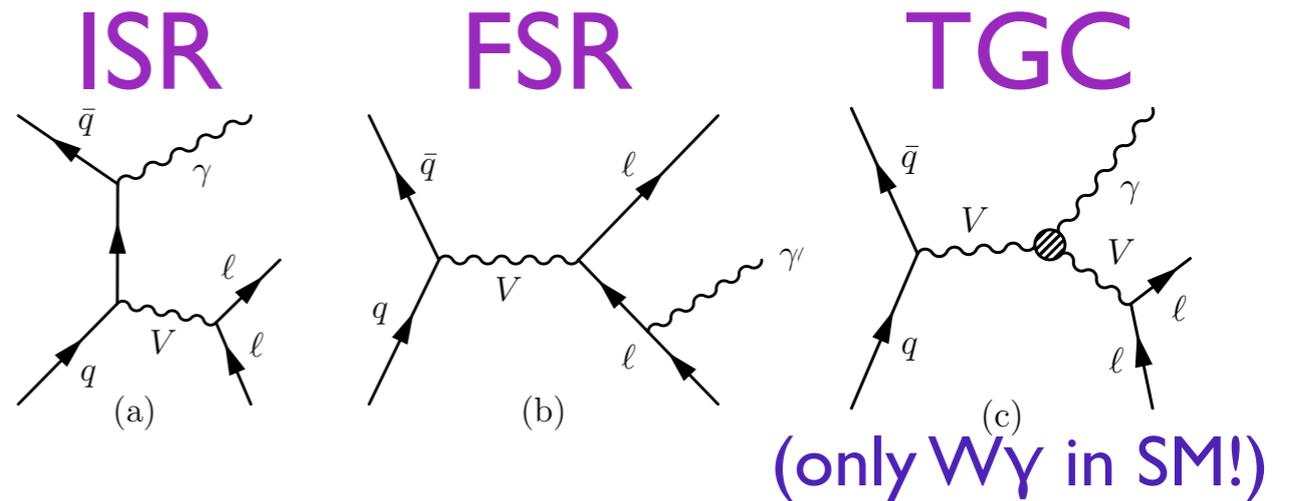
| Ref. Nr. | Title | Reference | sqrt(s) | L |
|----------|--|--|---------|---------------------------|
| 1 | ATLAS $W\gamma$ and $Z\gamma$ | Phys. Rev. D 87, 112003 (2013) | 7 TeV | 4.9 fb ⁻¹ |
| 2 | CMS $W\gamma$ and $Z\gamma$ at 7 TeV | Phys. Rev. D 89, 092005 | 7 TeV | 4.9 fb ⁻¹ |
| 3 | CMS $W\gamma$ and $Z\gamma$ at 8 TeV | | 8 TeV | 19.5 fb ⁻¹ |
| 4 | CMS WW | Eur.Phys.J. C73 (2013) 2610 | 7 TeV | 4.9 fb ⁻¹ |
| 5 | ATLAS WW | Phys. Rev. D 87, 112001 (2013) | 7 TeV | 4.6 fb ⁻¹ |
| 6 | ATLAS WW | ATLAS-CONF-2014-033 | 8 TeV | 20.3 fb ⁻¹ |
| 7 | WW cross section and anomalous gauge couplings at 8 TeV | CMS-PAS-SMP-14-016 | 8 TeV | 19.4 fb ⁻¹ |
| 8 | ATLAS $ZZ \rightarrow 4l$ @ 7 TeV | JHEP03(2013)128 | 7 TeV | 4.6 fb ⁻¹ |
| 9 | ATLAS $ZZ \rightarrow 4l$ @ 8 TeV | ATLAS-CONF-2013-020 | 8 TeV | 20.3 fb ⁻¹ |
| 10 | CMS ZZ differential cross section and aTGC in the $4l$ channel at 7 TeV | J. High Energy Phys. 01 (2013) 063 | 7 TeV | 4.9 fb ⁻¹ |
| 11 | CMS ZZ differential cross section and aTGCs in the $4l$ channel at 8 TeV | Phys. Lett. B 740 (2015) 250 | | |
| 12 | CMS ZZ cross section and aTGCs in the $2l2\nu$ channel at 7 and 8 TeV | arXiv.1503.05467 | 7+8TeV | 5.1+19.6 fb ⁻¹ |
| 13 | ATLAS WZ @ 8 TeV | ATLAS-CONF-2013-021 | 8 TeV | 13 fb ⁻¹ |
| 14 | CMS WZ @ 7 & 8 TeV | CMS-PAS-SMP-12-006 | 7+8TeV | 4.9+19.6 fb ⁻¹ |
| 15 | ATLAS $WV \rightarrow l\nu jj$ @ 7 TeV | JHEP01(2015)049 | 7 TeV | 4.6 fb ⁻¹ |
| 16 | CMS $WV \rightarrow l\nu jj$ @ 7 TeV | Eur.Phys.J. C73 (2013) 2283 | 7 TeV | 4.9 fb ⁻¹ |
| 17 | VZ cross sections in the bb channel at 8 TeV | EPJC 74 (2014) 2973 | 8 TeV | 18.9 fb ⁻¹ |
| 18 | ATLAS WZ @ 7 TeV | | 7 TeV | 4.6 fb ⁻¹ |

superseeded results are not listed

W γ & Z γ

Combine W and Z in leptonic decays with isolated photon

Dominant background: fake photons from V+jets

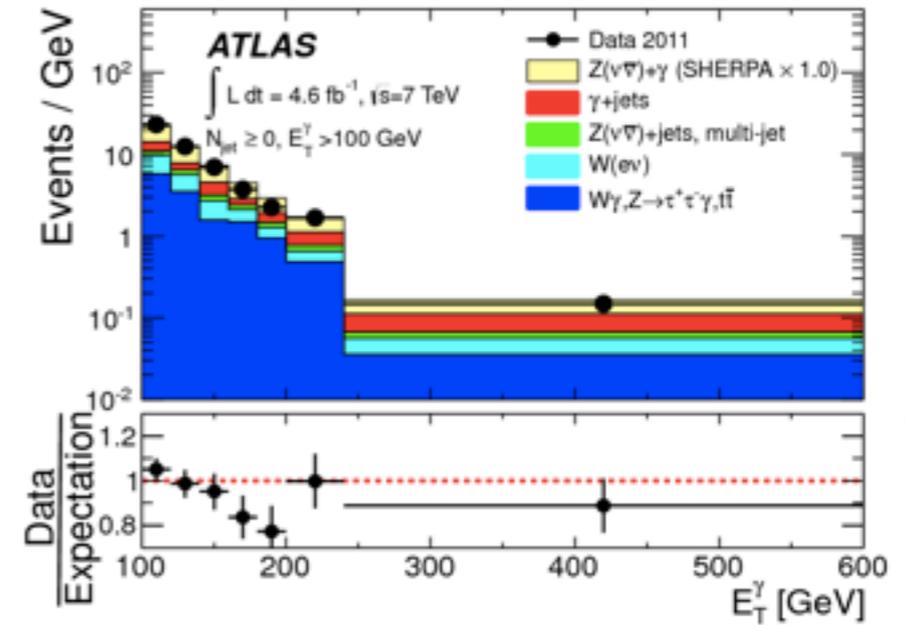
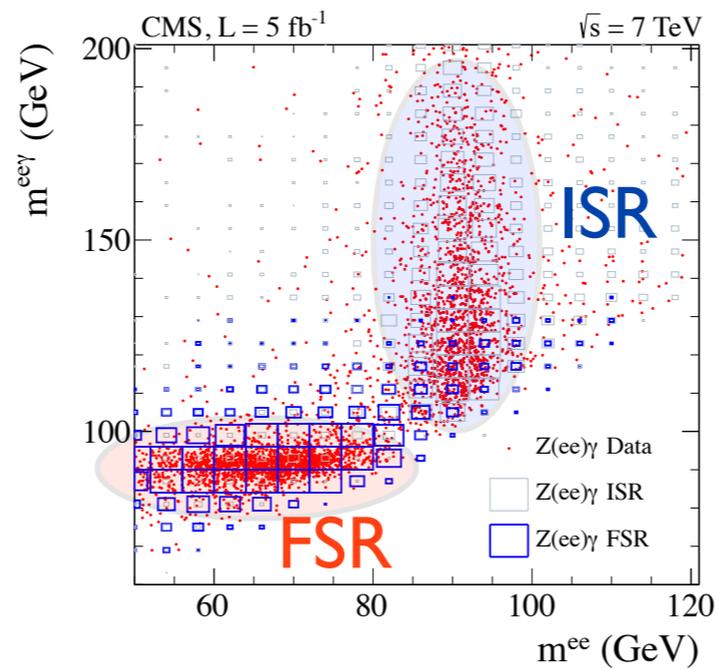
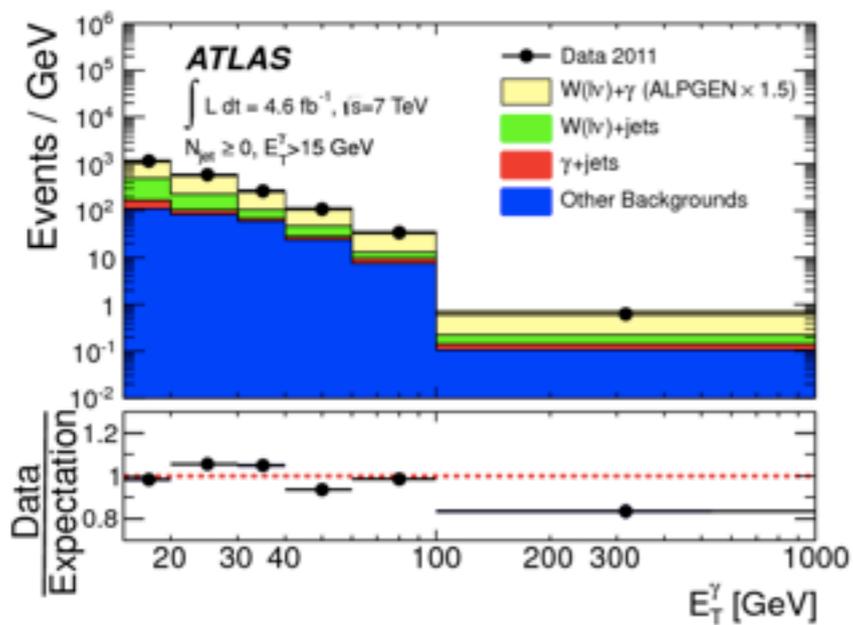


W γ \rightarrow lv γ :
lepton+photon+MET

Z γ \rightarrow ll γ :
2 leptons+photon

Z γ \rightarrow vv γ :
photon+MET

No FSR Contribution





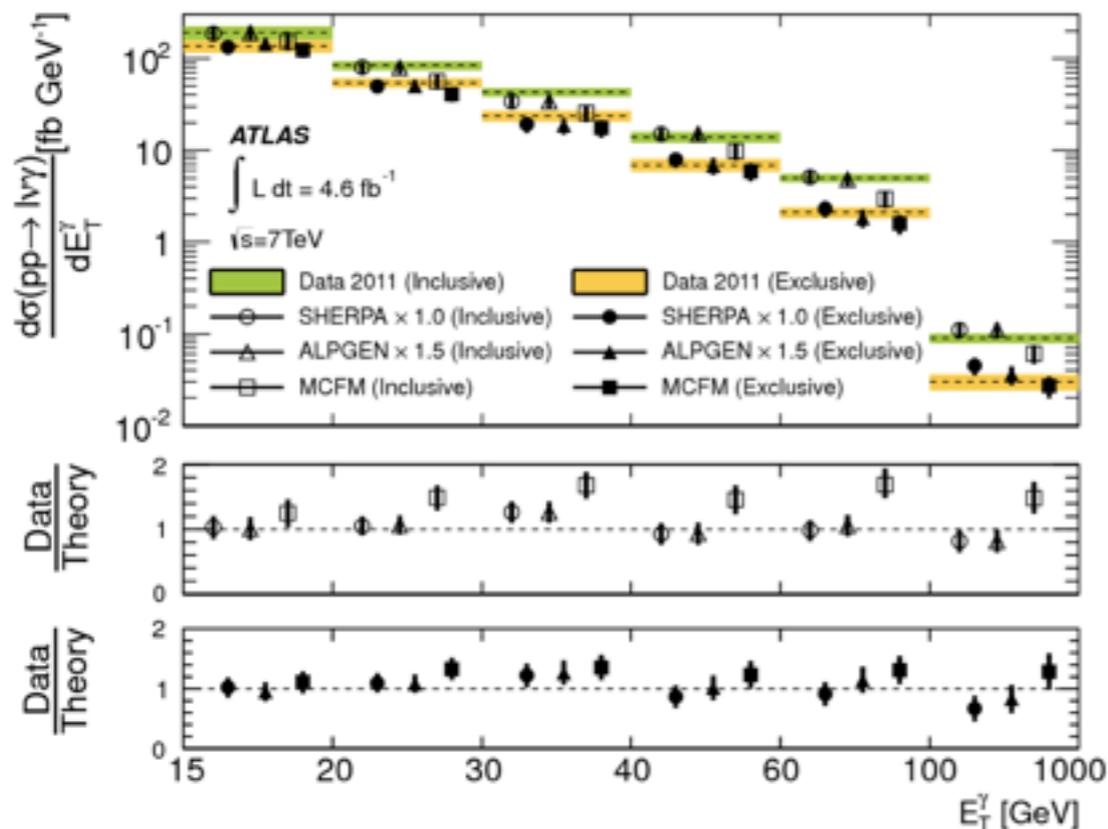
W γ and Z γ Cross Section Results



| | Channel | σ (Measurement phase space) [pb] | NLO (MCFM) [pb] |
|-----------------|---|--|---------------------------|
| CMS 7 TeV [2] | W γ \rightarrow l $\nu\gamma$ | $37.0 \pm 0.8(\text{stat}) \pm 4.0(\text{syst}) \pm 0.8(\text{lumi})$ | 31.81 ± 1.80 |
| | Z γ \rightarrow ll γ | $5.33 \pm 0.08(\text{stat}) \pm 0.25(\text{syst}) \pm 0.12(\text{lumi})$ | 5.4 ± 0.2 |
| | Z γ \rightarrow $\nu\nu\gamma$ | $21.1 \pm 4.2(\text{stat.}) \pm 4.3(\text{syst.}) \pm 0.5(\text{lum.}) \text{ fb}$ | $24.6 \pm 2.5 \text{ fb}$ |
| ATLAS 7 TeV [1] | W γ \rightarrow l $\nu\gamma$ | $2.77 \pm 0.03(\text{stat}) \pm 0.33(\text{syst}) \pm 0.14(\text{lumi})$ | 1.96 ± 0.17 |
| | Z γ \rightarrow ll γ | $1.31 \pm 0.02(\text{stat}) \pm 0.11(\text{syst}) \pm 0.05(\text{lumi})$ | 1.18 ± 0.05 |
| | Z γ \rightarrow $\nu\nu\gamma$ | $0.133 \pm 0.013(\text{stat}) \pm 0.020(\text{syst}) \pm 0.005(\text{lumi})$ | 0.156 ± 0.012 |
| CMS 8 TeV [3] | Z γ \rightarrow ll γ | $2.063 \pm 0.019(\text{stat}) \pm 0.098(\text{syst}) \pm 0.054(\text{lumi})$ | 2.100 ± 0.120 |

- ▶ All measurements done for specific phase space definitions
- ATLAS & CMS Measurements not directly comparable
- ▶ Overall agreement with NLO predictions
- Small excess in W γ seen by both ATLAS and CMS
- ▶ Large NNLO corrections for W γ : better agreement with NNLO prediction

Wγ Differential Distributions (7 TeV)



Unfolded E_T^γ distribution

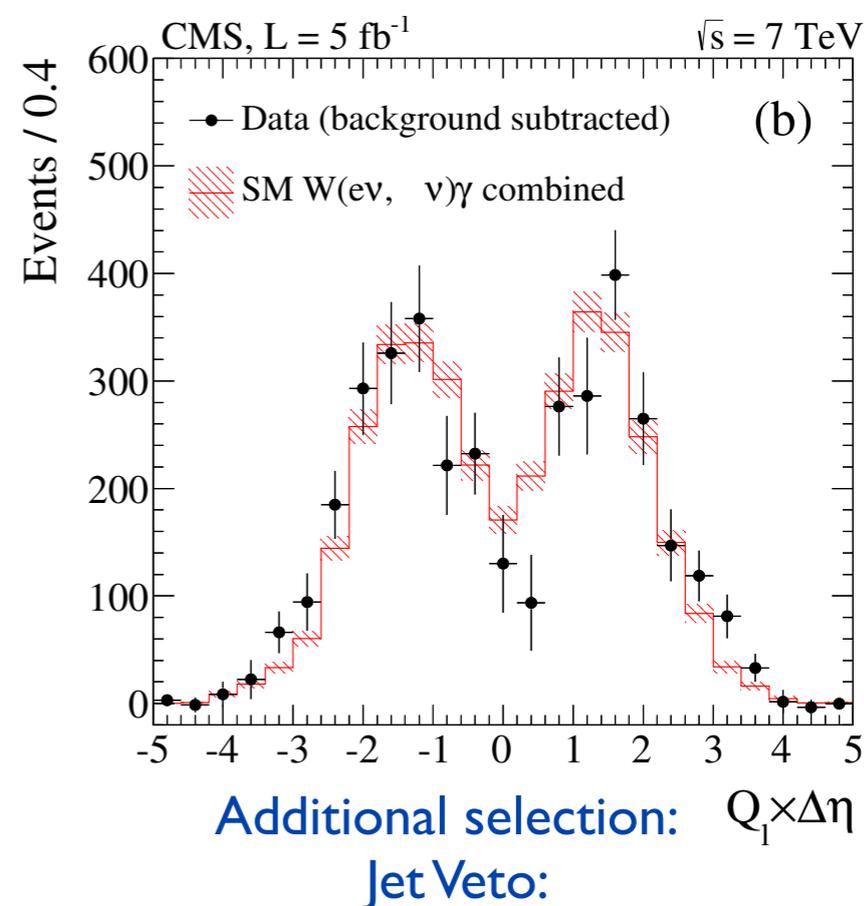
[1]

- ▶ Excess wrt MCFM (NLO) prediction
- ▶ Shape better described by Alpgen & Sherpa
- ▶ Better agreement with NNLO prediction

Radiation Amplitude Zero

[2]

- ▶ Interference of 3 amplitudes leads to vanishing amplitude at some defined angle in the $qq' \rightarrow W\gamma$ CoM system
- ▶ At the LHC expect dip at 0 in $Q_{\text{lepton}} * \Delta\eta(\ell, \gamma)$ distribution
- ▶ aTGCs would reduce the effect, as well as NLO contribution

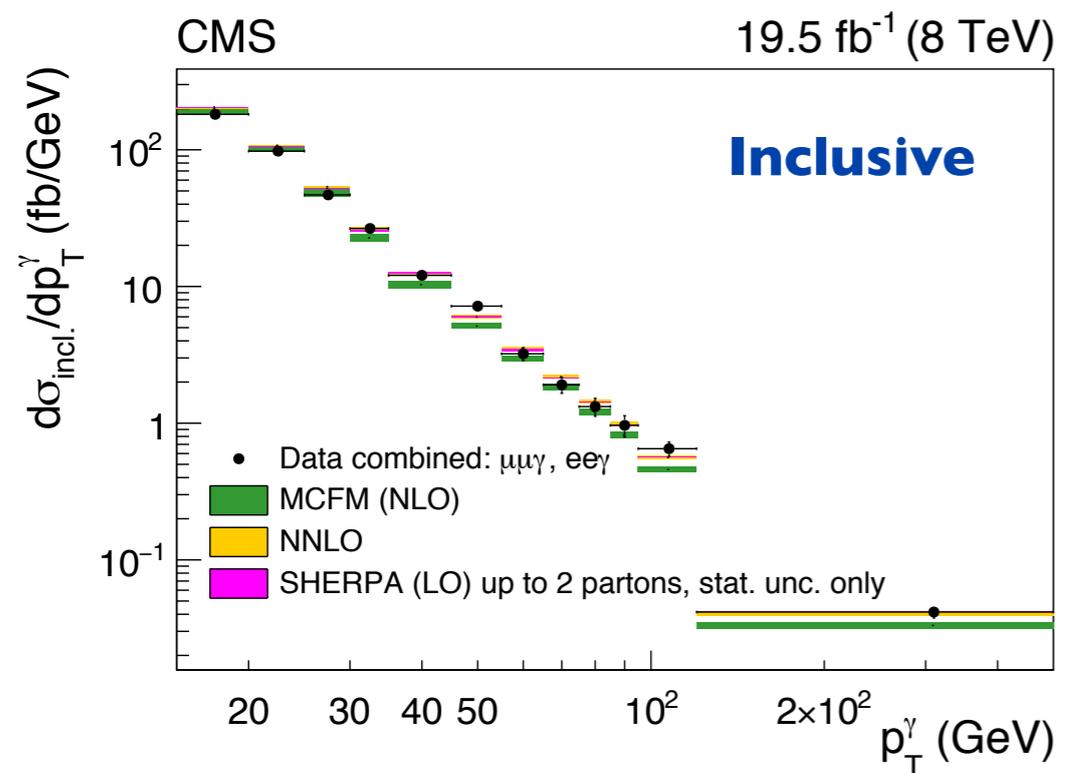




Z γ Differential Distributions (8 TeV)



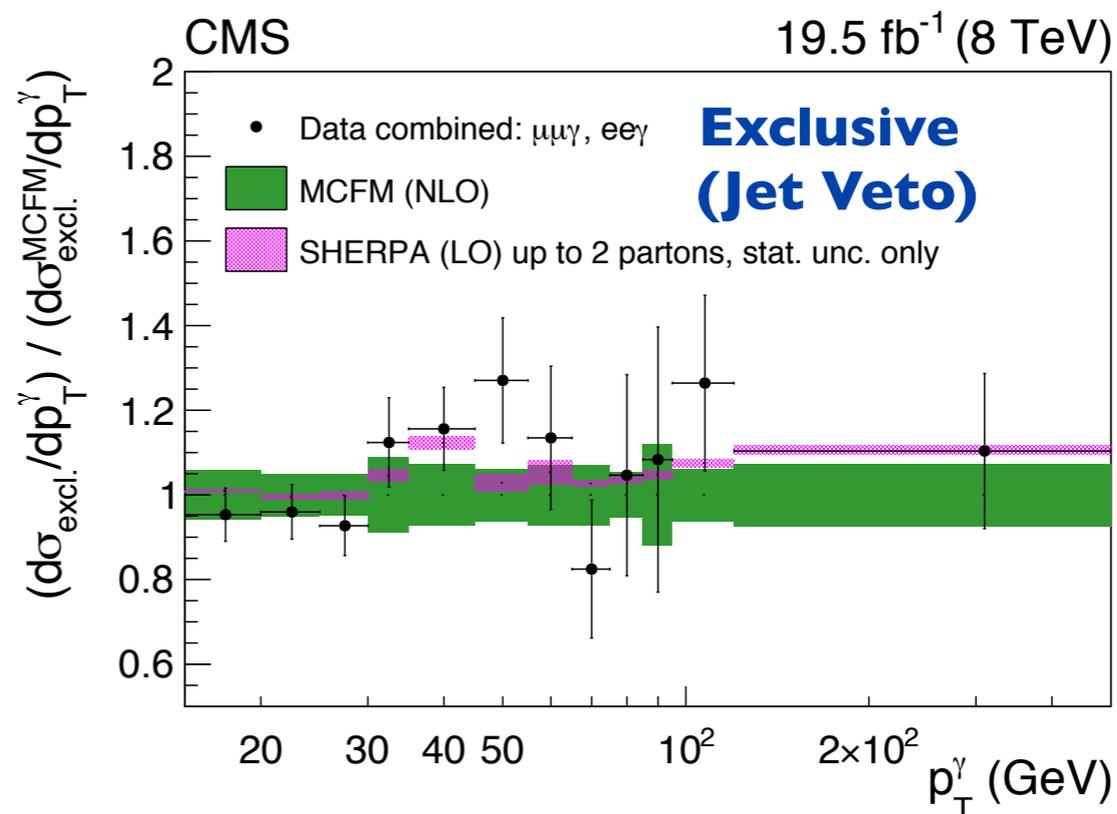
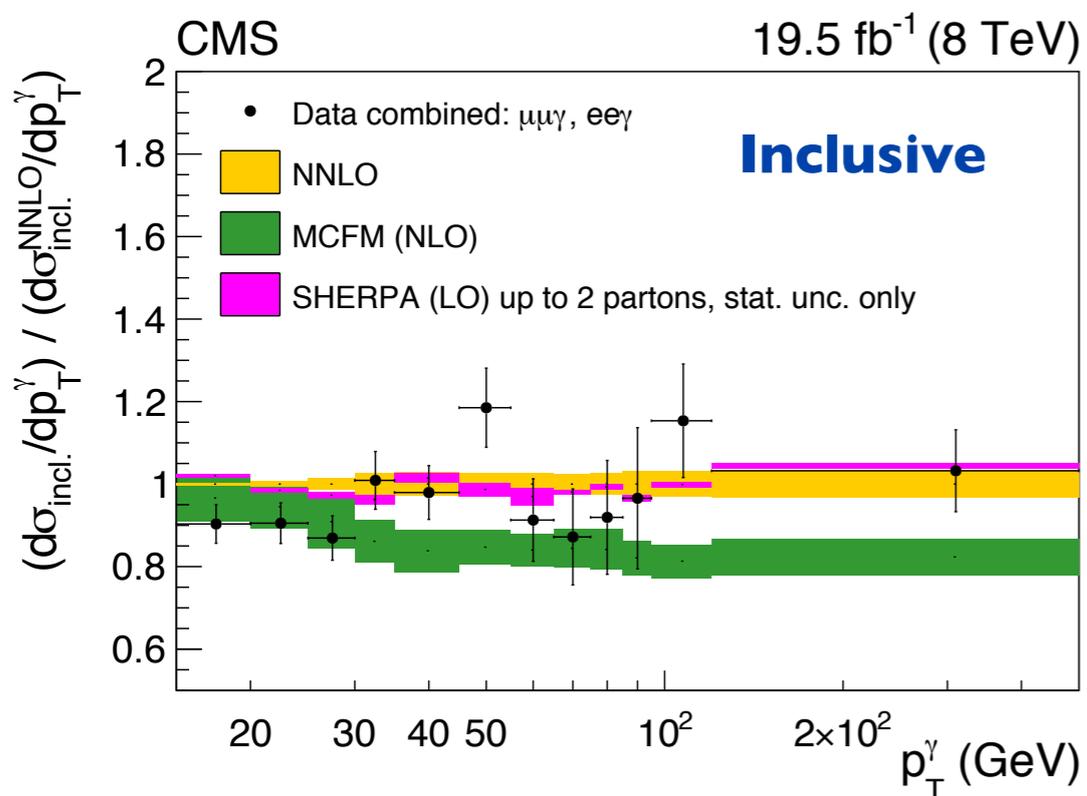
Recent



Differential cross sections vs $E_{T\gamma}$

[3]

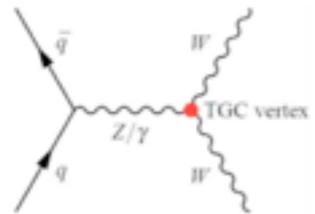
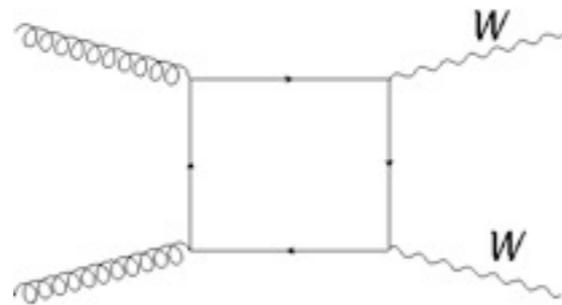
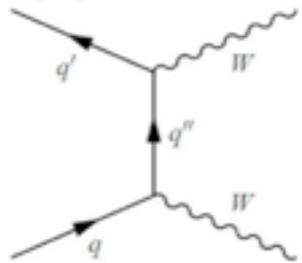
- ▶ First comparison with NNLO prediction
- [Grazzini, Rahlev et al, hep-ph:1309.7000](https://arxiv.org/abs/hep-ph/1309.7000)
- ▶ Inclusive cross section: excess over NLO but good agreement with NNLO prediction
- ▶ Exclusive cross section (0-jet): good agreement also with NLO





$W^+W^- \rightarrow e^+e^- \nu\nu$

$qq \rightarrow WW$ (97%) $gg \rightarrow WW$ (3%)

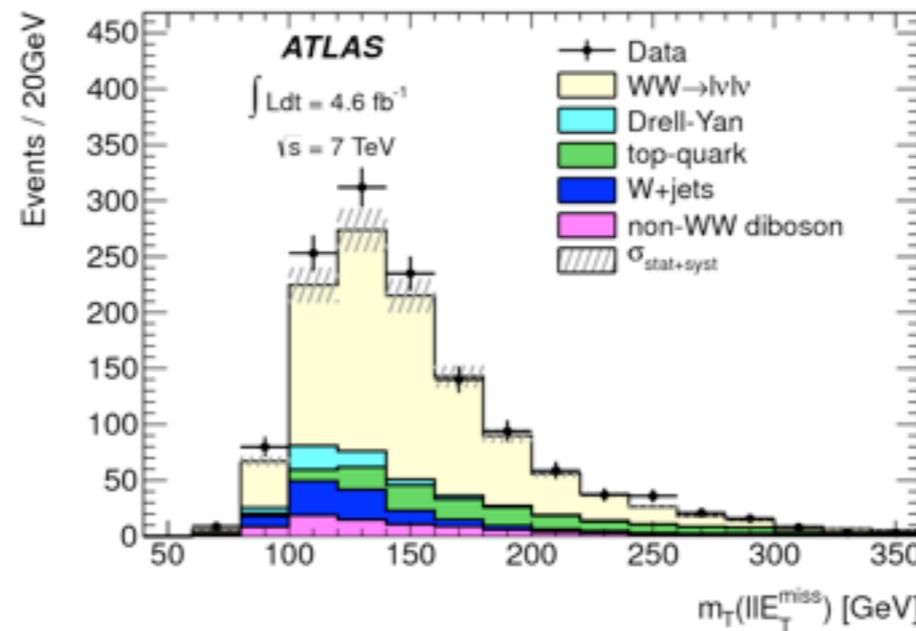
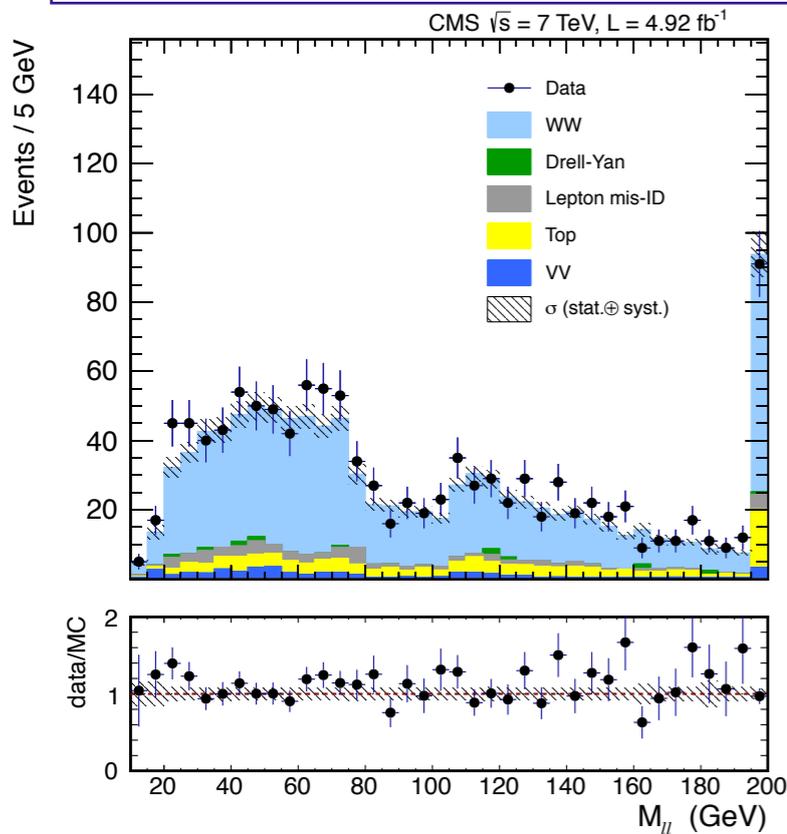


Closely tied
to $H \rightarrow WW$ analysis

Signature:
2 isolated OS leptons + large MET

- ▶ 2 isolated opposite charge leptons: $ee, e\mu, \mu\mu$
- ▶ Veto Z mass window for $ee/\mu\mu$ events
- ▶ Require large amount of MET
- ▶ Jet Veto (suppress top background)

large backgrounds:
 $t\bar{t}$, tW , W +jets, $W\gamma^*$, DY, Dibosons



Both ATLAS & CMS
observe more events
than expected

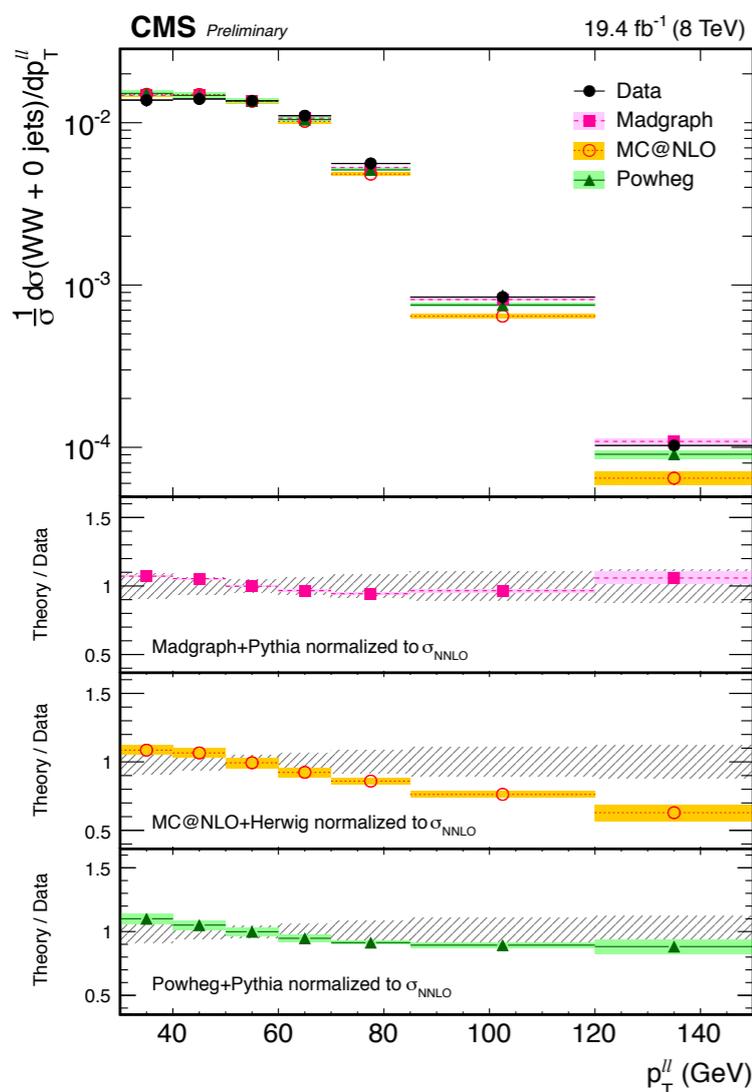
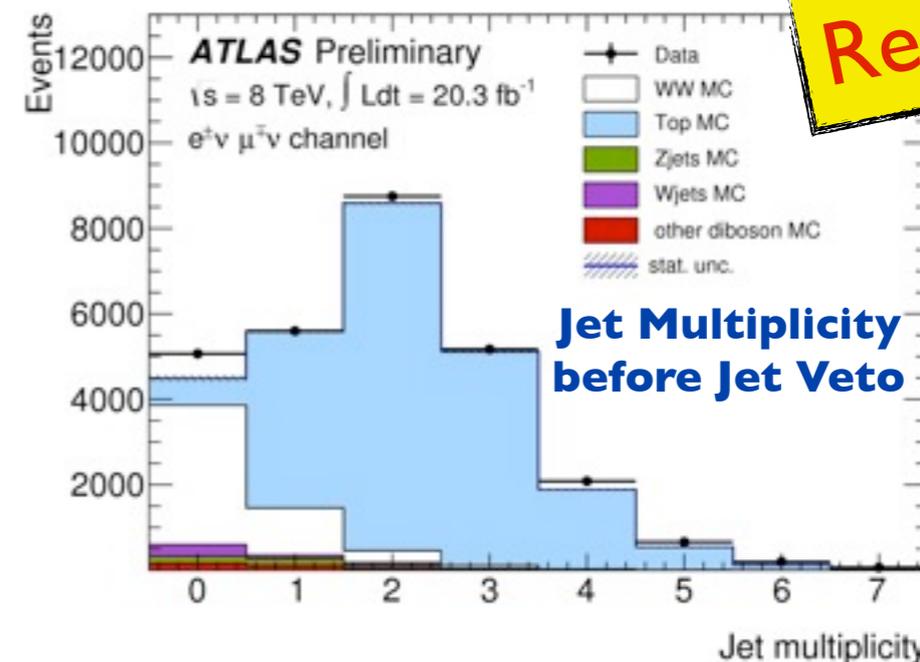


$W^+W^- \rightarrow e^+e^- \nu\nu$: new 8 TeV results

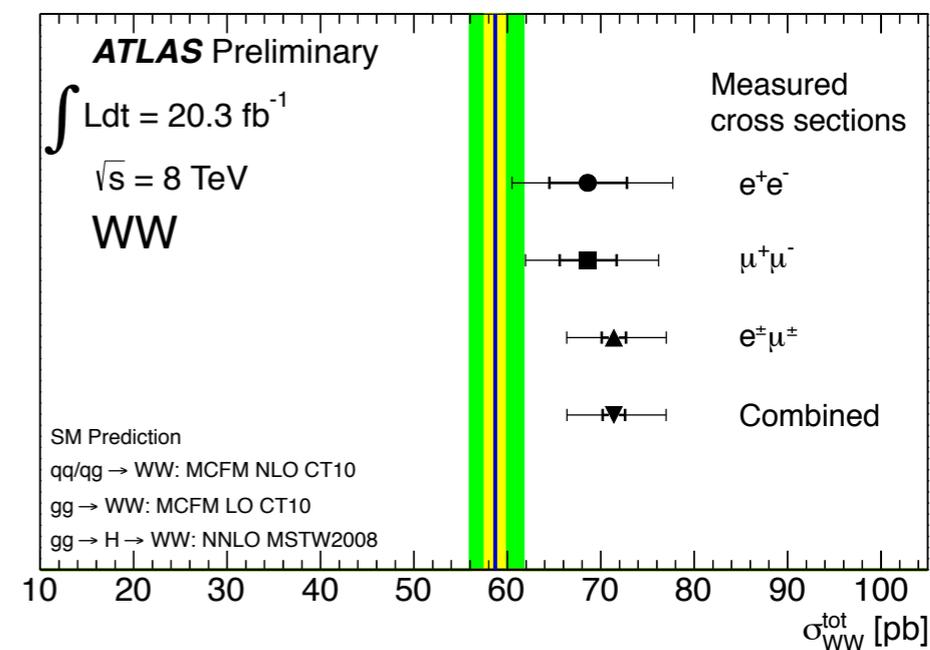


Recent

- ▶ Updated 8 TeV results from both CMS and ATLAS presented in the last year
- ▶ Both using powheg NLO MC for signal modeling
- ▶ Also differential cross sections presented for several variables (CMS)



See A. Calderon's talk for more details on CMS Result





$W^+W^- \rightarrow \ell^+\ell^- \nu\nu$ Cross Section Results



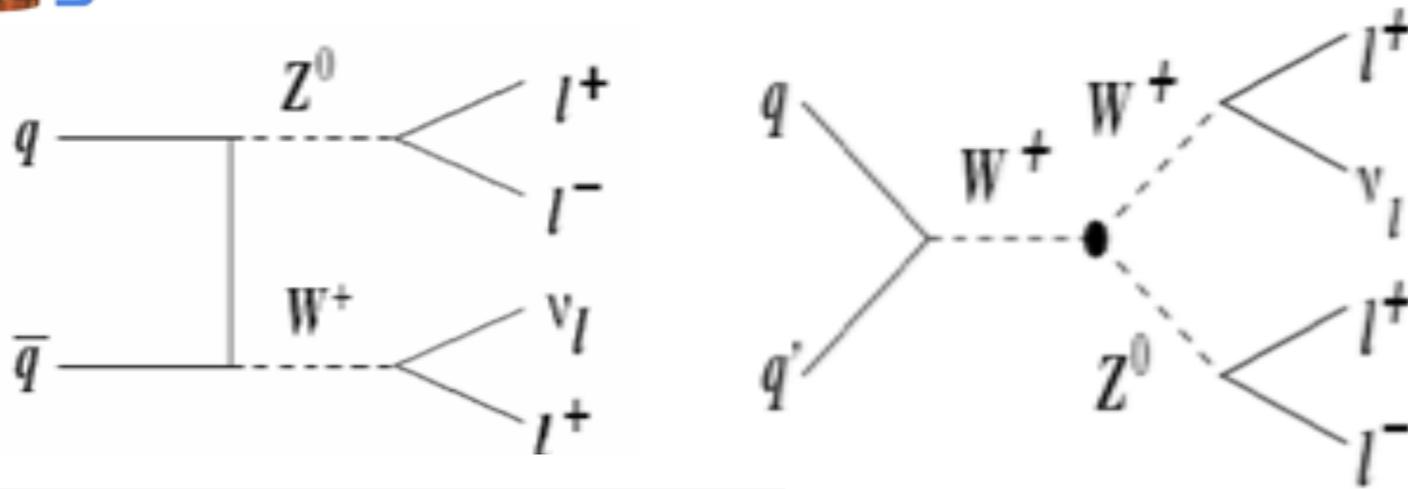
| | | Measured cross section (pb) | Theory (pb) | |
|-------|-------|---|----------------------|-----|
| 7 TeV | ATLAS | 51.9 ± 2.0 (stat) ± 3.9 (syst) ± 2.0 (lumi) | $44.7^{+2.1}_{-1.9}$ | [5] |
| | CMS | 52.4 ± 2.0 (stat.) ± 4.5 (syst.) ± 1.2 (lumi.) | 47.0 ± 2.0 | [4] |
| 8 TeV | ATLAS | $71.4^{+1.2}_{-1.2}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.2}_{-2.1}$ (lumi) | $58.7^{+3.0}_{-2.7}$ | [6] |
| | CMS | 60.1 ± 0.9 (stat.) ± 3.2 (exp.) ± 3.1 (th.) ± 1.6 (lum.) | $59.8^{+1.3}_{-1.1}$ | [7] |

- ▶ All but the CMS 8 TeV measurements show an excess wrt prediction
- ▶ Some tension between CMS and ATLAS 8 TeV results
 - but beware of differences, which account for at least part of the difference

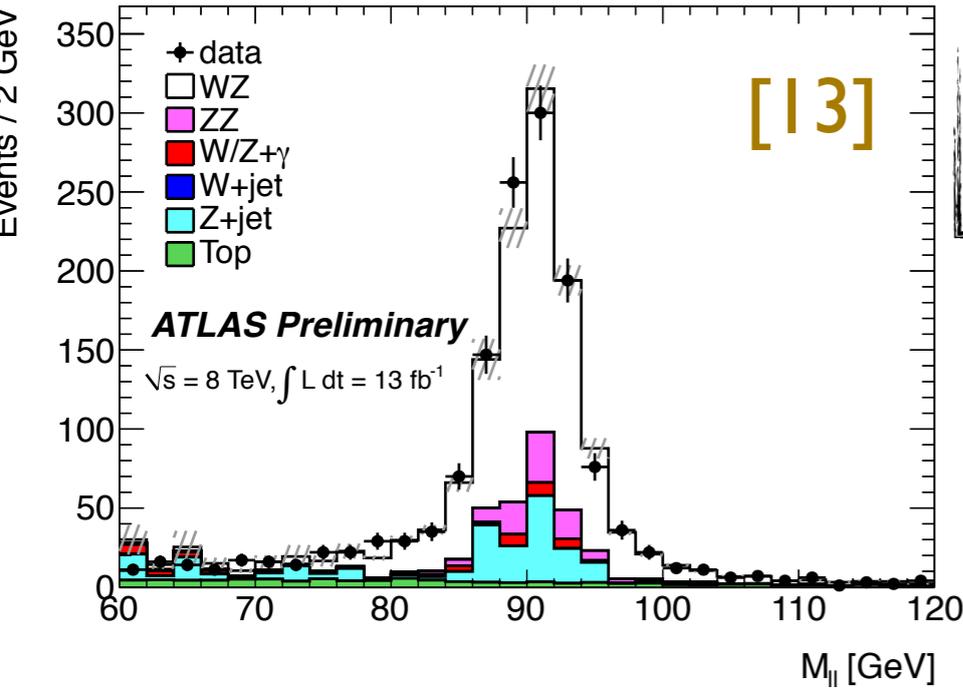
| | Higgs treatment | Theory | Resummation correction |
|-------|-----------------------------|---|--|
| CMS | subtracted from measurement | inclusive $pp \rightarrow WW$ (NNLO) | Applied in signal acceptance determination |
| ATLAS | included in measurement | $qq \rightarrow WW$ (NLO MCFM) + $gg \rightarrow WW$ (LO MCFM) + $gg \rightarrow H \rightarrow WW$ (NNLO) | Not applied |



WZ → 3ℓν

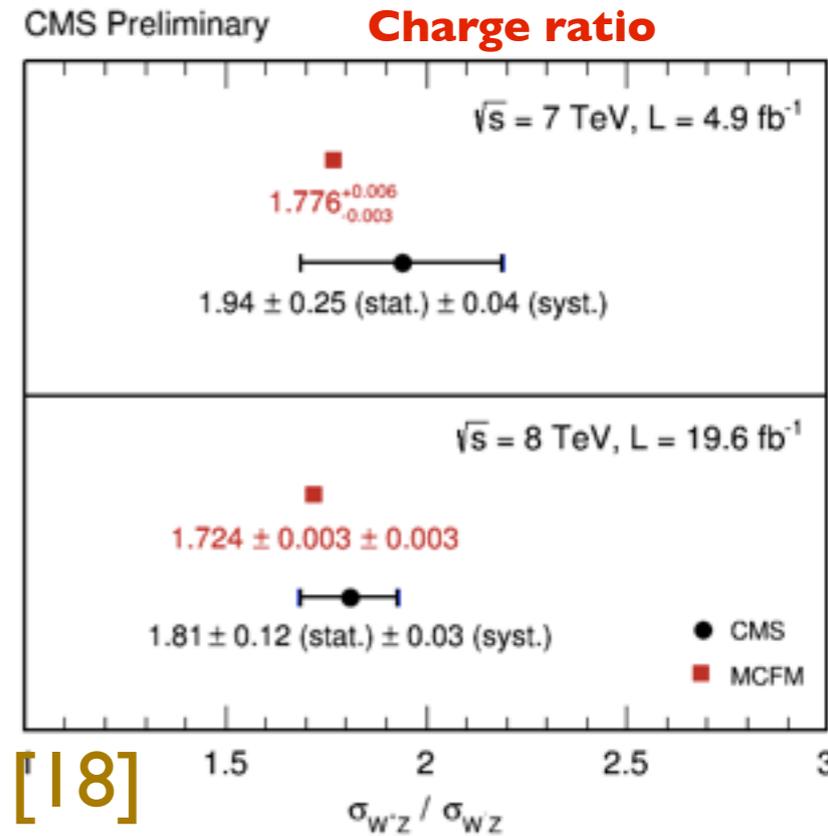


- ▶ 4 channels
- eee, eeμ, μμε, μμμ
- ▶ Measurement phase space defined by Z window
- $M_Z \pm 25$ (20) GeV for ATLAS (CMS)



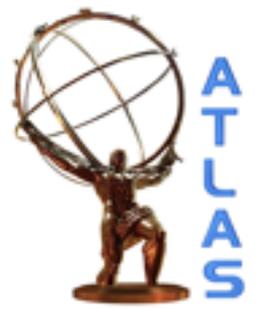
Signature:
3 isolated leptons + MET

Excess
 in 3 out of 4
 measurements
 ($\sim 1-2 \sigma$)

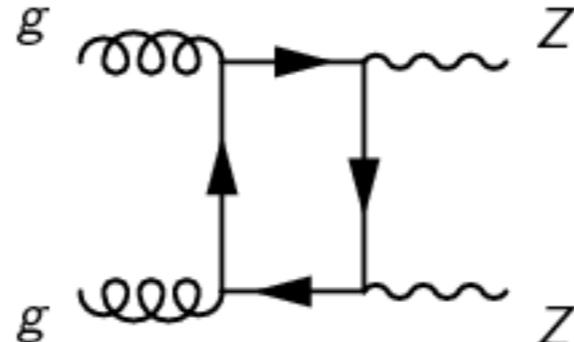
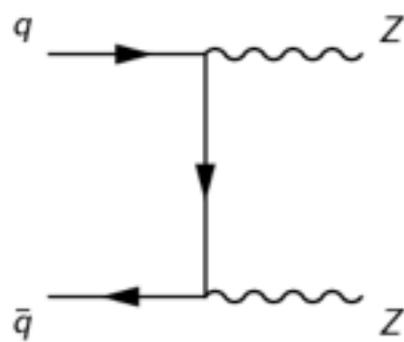


| Experiment | \sqrt{s} | Measured cross section | Theory |
|------------|------------|---|------------------------------------|
| ATLAS | 7 TeV | $19.0^{+1.4}_{-1.3}(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.4(\text{lumi.}) \text{ pb}$ | $17.6^{+1.1}_{-1.0} \text{ pb}$ |
| CMS | 7 TeV | $20.76 \pm 1.32(\text{stat.}) \pm 1.13(\text{syst.}) \pm 0.46(\text{lumi.}) \text{ pb}$ | $17.8^{+0.7}_{-0.5} \text{ pb}$ |
| ATLAS | 8 TeV | $20.3^{+0.8}_{-0.7}(\text{stat.})^{+1.2}_{-1.1}(\text{syst.})^{+0.7}_{-0.6}(\text{lumi.}) \text{ pb}$ | $20.3 \pm 0.8 \text{ pb}$ |
| CMS | 8 TeV | $24.61 \pm 0.76(\text{stat.}) \pm 1.13(\text{syst.}) \pm 1.08(\text{lumi.}) \text{ pb}$ | $21.91^{+1.17}_{-0.88} \text{ pb}$ |

[18]
 [14]
 [13]
 [14]



$ZZ \rightarrow 2\ell 2\ell'$ ($\ell = e, \mu; \ell' = e, \mu, \tau, \nu$)



Closely tied to $H \rightarrow ZZ$ analysis

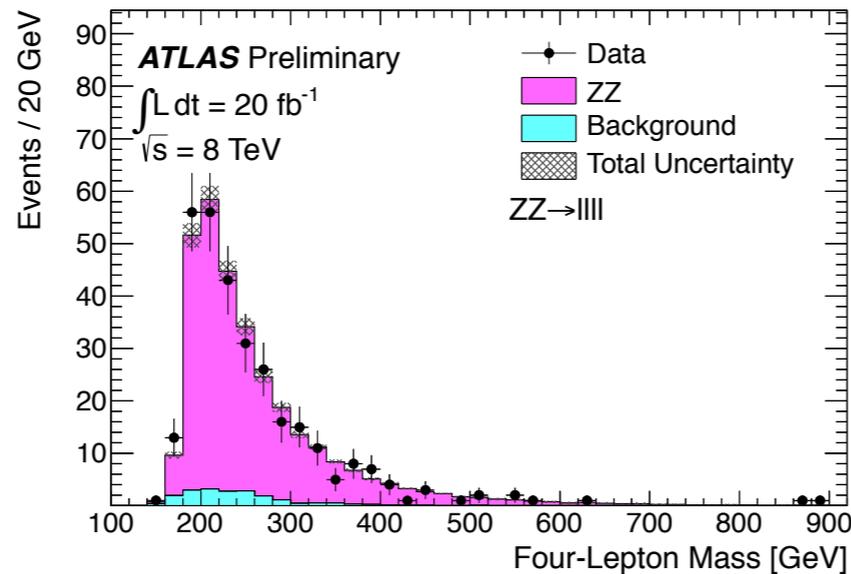
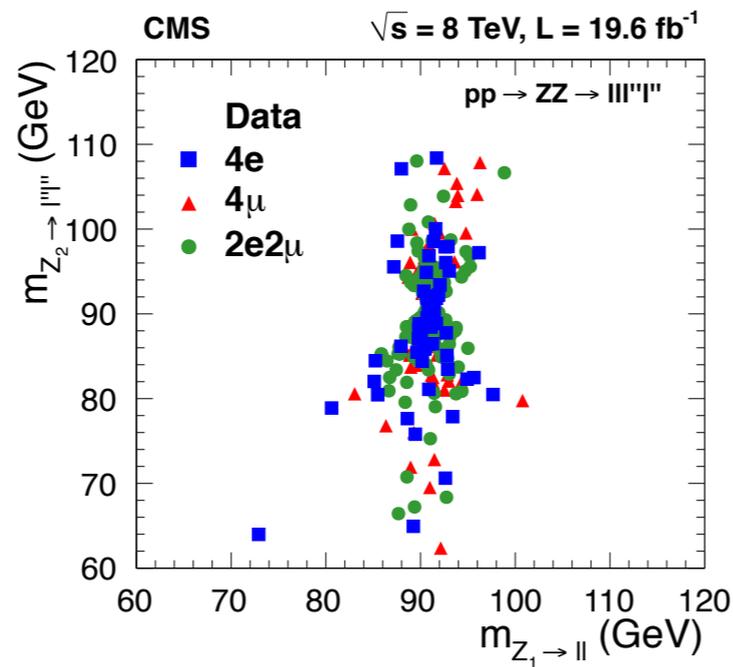
Low rate
low backgrounds

Challenge:
optimize efficiency

$ZZ \rightarrow llll$:
4 isolated leptons

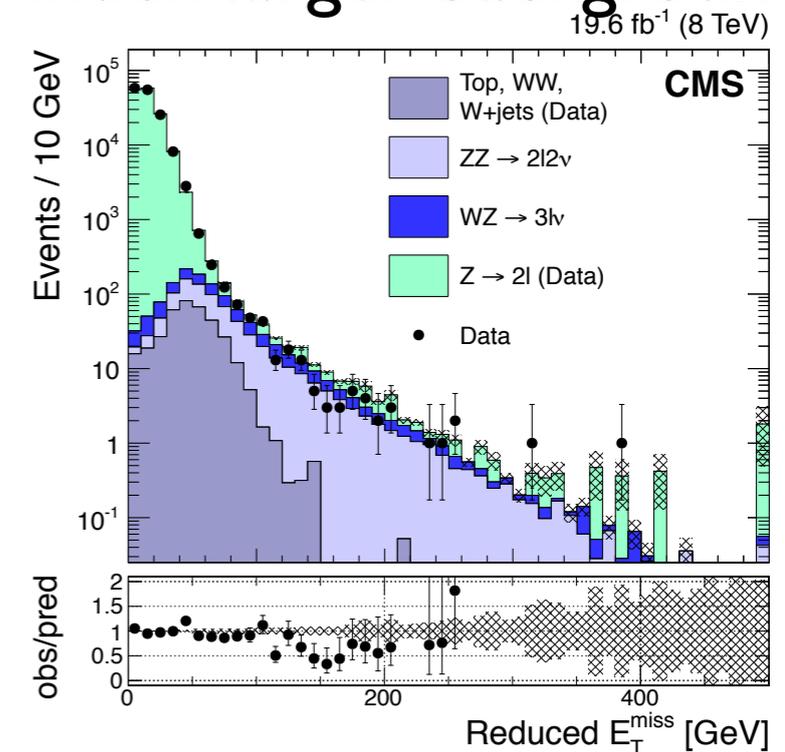
Channels:
 $eeee, ee\mu\mu, \mu\mu\mu\mu$
CMS: + $ee\tau\tau + \mu\mu\tau\tau$

Importance of
high lepton efficiency
up to low P_t



$ZZ \rightarrow ll\nu\nu$:
2 isolated leptons + MET

Larger BR
much larger background



ZZ Results

| Experiment | \sqrt{s} | Channel | Measured cross section | Theory |
|------------|------------|--------------------------|---|----------------------------------|
| ATLAS | 7 TeV | 4ℓ and $2\ell 2\nu$ | $6.7 \pm 0.7(stat.)_{-0.3}^{+0.4}(syst.) \pm 0.3 (lumi.)$ pb | $5.89_{-0.18}^{+0.22}$ pb [8] |
| CMS | 7 TeV | 4ℓ | $6.24_{-0.80}^{+0.86}(stat.)_{-0.32}^{+0.41}(syst.) \pm 0.14(lumi.)$ pb | 6.3 ± 0.4 [10] |
| CMS | 7 TeV | $2\ell 2\nu$ | $5.2_{-1.4}^{+1.5}(stat.)_{-1.1}^{+1.4}(syst.) \pm 0.2(lumi.)$ pb | $6.46_{-3.3\%}^{+4.7\%}$ pb [12] |
| ATLAS | 8 TeV | 4ℓ and $2\ell 2\nu$ | $7.1_{-0.4}^{+0.5}(stat.) \pm 0.3(syst.) \pm 0.2(lumi.)$ pb | $7.2_{-0.2}^{+0.3}$ pb [9] |
| CMS | 8 TeV | 4ℓ | $7.7 \pm 0.5(stat.)_{-0.4}^{+0.5}(syst.) \pm 0.4(theory) \pm 0.2(lumi.)$ pb | 7.7 ± 0.6 pb [11] |
| CMS | 8 TeV | $2\ell 2\nu$ | $6.9_{-0.8}^{+0.8}(stat.)_{-1.4}^{+1.8}(syst.) \pm 0.3 (lumi.)$ pb | $7.92_{-3.0\%}^{+4.7\%}$ pb [12] |

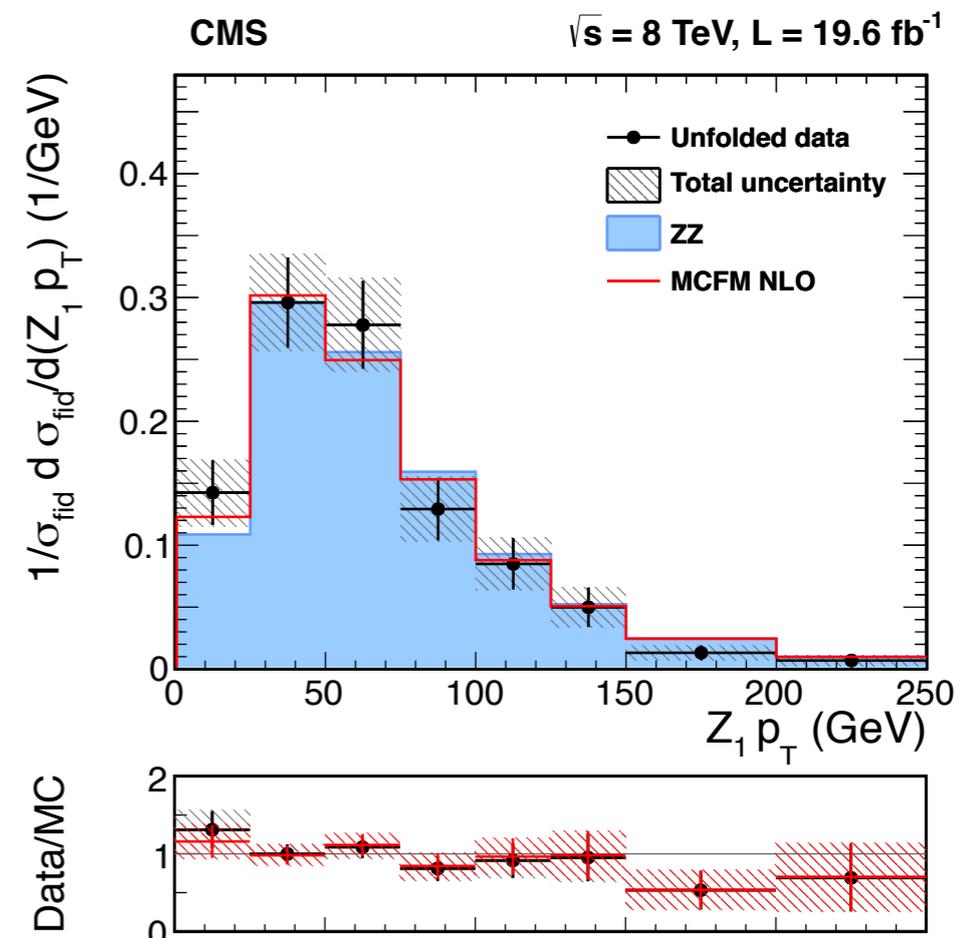
Cross section phase space defined

only by Z mass window:

ATLAS: $66 \text{ GeV} < M_Z < 116 \text{ GeV}$

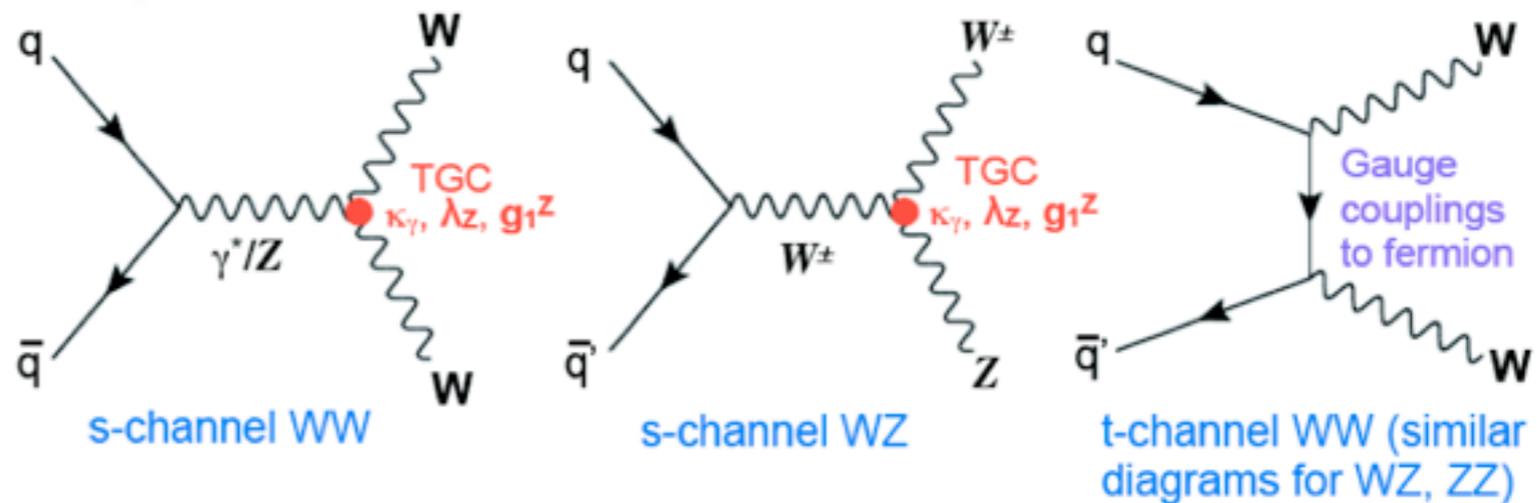
CMS: $60 \text{ GeV} < M_Z < 120 \text{ GeV}$

- ▶ All results are in good agreement with NLO predictions
- ▶ Differential cross sections also available at 8 TeV



Semileptonic decays: $VV \rightarrow l\nu jj$

Signature:
isolated lepton
+ MET
+ 2 jets



Backgrounds: W +jets, dibosons, $t\bar{t}$, 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

Considered final states

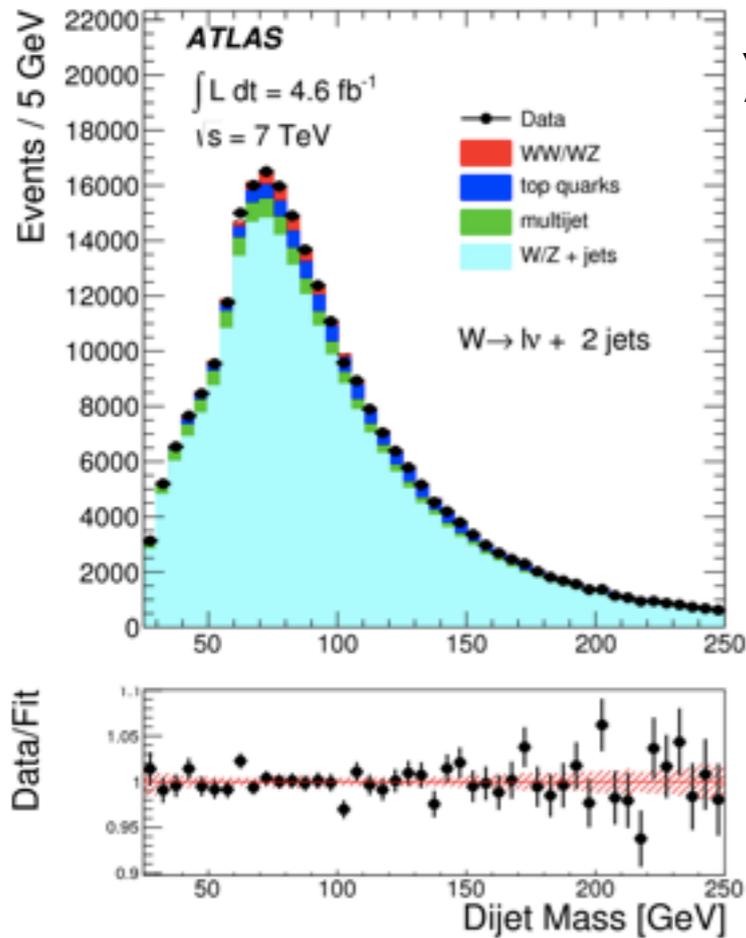
- ▶ **$WW+WZ \rightarrow l\nu jj$**
 - Isolated lepton + large MET
 - 2 high P_t jets (b-veto)
- ▶ **$WZ+ZZ \rightarrow l\nu bb+l\bar{\nu}bb+\nu\nu bb$ (CMS)**
 - Identify leptonic W/Z decay
 - 2 b-tagged jets
 - Use BDT discriminant to discriminate signal from background



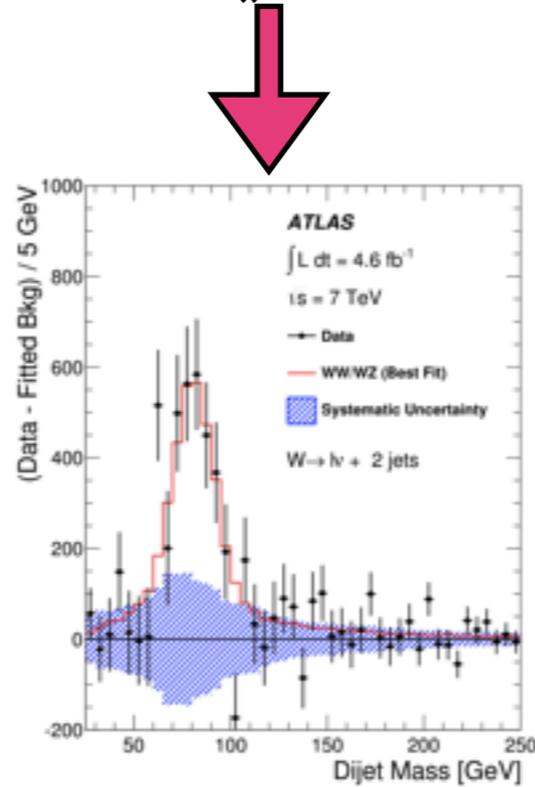
WW → ll'jj Results



WW → ll'jj:

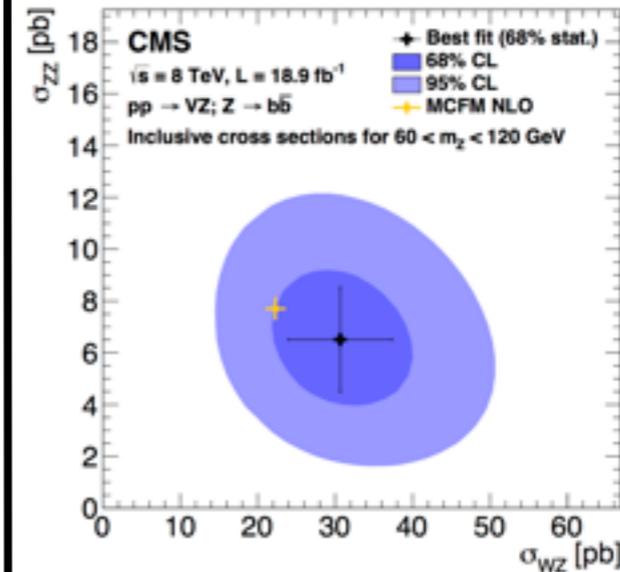
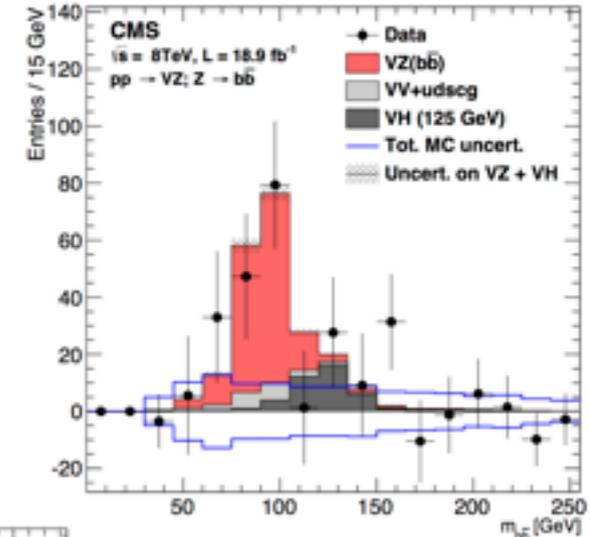


Signal and background yields obtained from UML fit to M_{jj} distribution



VZ → ll'bb:

Evidence for Z peak in M_{bb} distribution



WW and WZ cross sections extracted simultaneously

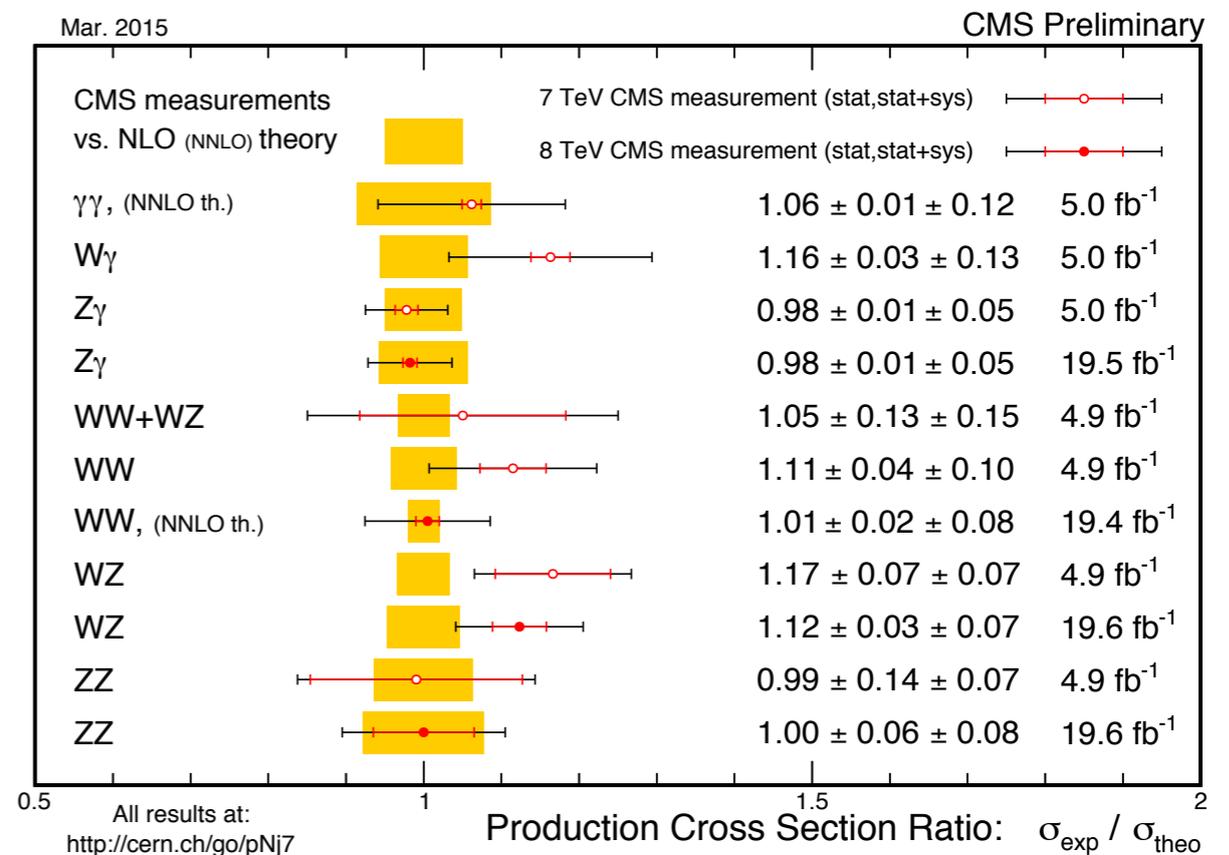
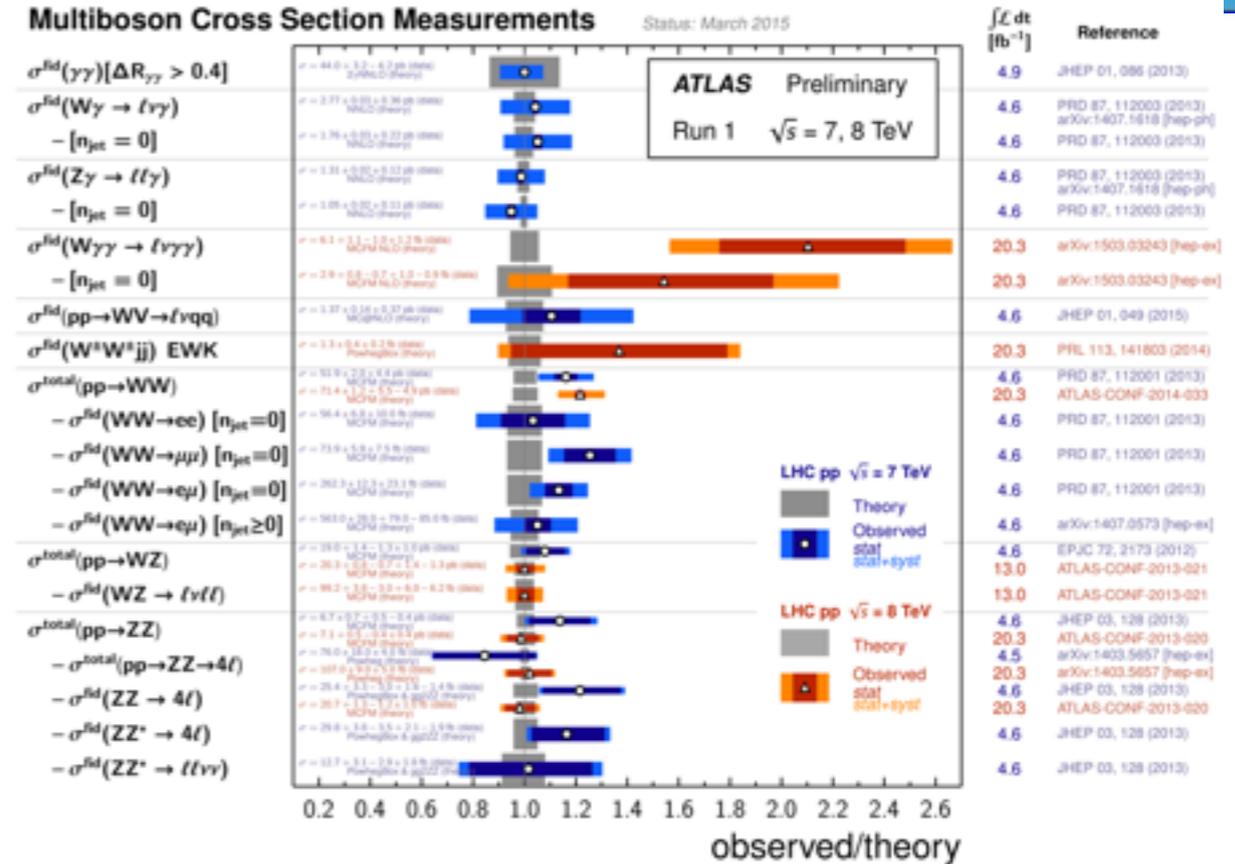
| Experiment | \sqrt{s} | Channel | Measured cross section | Theory |
|------------|------------|-----------------|---|--------------------------------|
| ATLAS | 7 TeV | WW+WZ → ll'jj | $72 \pm 9(stat.) \pm 15(syst.) \pm 13(MC \text{ stat}) \text{ pb}$ | $63.4 \pm 2.6 \text{ pb}$ [15] |
| CMS | 7 TeV | WW+WZ → ll'jj | $68.9 \pm 8.7(stat.) \pm 9.7(syst.) \pm 1.5(lum.) \text{ pb}$ | $65.6 \pm 2.2 \text{ pb}$ [16] |
| CMS | 8 TeV | WZ → ll'bb | $30.7 \pm 9.3(stat.) \pm 7.1(syst.) \pm 4.1(th.) + 1.0(lum.) \text{ pb}$ | 30.7 ± 9.3 [17] |
| CMS | 8 TeV | ZZ ll'bb + ννbb | $6.5 \pm 1.7(stat.) \pm 1.0(syst.) \pm 0.9(th.) \pm 0.2(lum.) \text{ pb}$ | $7.7 \pm 0.4 \text{ pb}$ [17] |



Summary on Cross Section Measurements

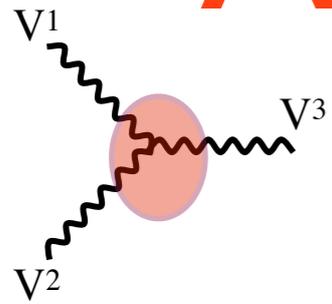


- ▶ All diboson final states seen and measured by both ATLAS & CMS
- Still waiting for $W\gamma$ @ 8 TeV
- ▶ Differential cross sections also available for several channels, allow for more detailed data/theory comparisons
- ▶ Agreement with SM expectations seen in all channels
- ▶ Some excess seen in charged channels: $W\gamma$, WW and WZ
- Nothing dramatic, up to 2σ , but worth following up
- Excess of events in the bulk, not at high P_t : does not point to aTGCs
- ▶ NNLO contribution accounts for at least part of the excesses
- $W\gamma$: NNLO agrees with data

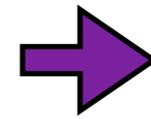




Anomalous couplings



Is New Physics hiding in this vertex?



Parameterization of most general new VVV interactions

Anomalous Couplings (Vertex approach)

▶ Charged couplings: WWV (V=Z,γ)

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

○ 5 parameters:

○ $\Delta g_1^Z (=g_1^Z - 1), \Delta\kappa_Z (= \kappa_Z - 1), \Delta\kappa_{\gamma} (= \kappa_{\gamma} - 1), \lambda_Z, \lambda_{\gamma}$

○ Additional constraints may be imposed to further reduce the number of parameters

▶ Neutral couplings: ZZV (V=Z,γ)

○ ZZV vertices: 4 parameters: $f_4^Z, f_4^{\gamma}, f_5^Z, f_5^{\gamma}$

○ ZγV vertices: 4 parameters: $h_3^Z, h_3^{\gamma}, h_4^Z, h_4^{\gamma}$

LEP scenario: 3 free parameters

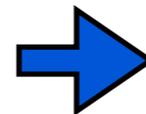
$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_{\gamma} \cdot \tan^2 \theta_w \text{ and } \lambda_Z = \lambda_{\gamma} = \lambda$$

HISZ scenario: 2 free parameters

$$\Delta\kappa_Z = \Delta g_1^Z (\cos^2 \theta_w - \sin^2 \theta_w), \\ \Delta\kappa_{\gamma} = 2\Delta g_1^Z \cos^2 \theta_w \text{ and } \lambda_Z = \lambda_{\gamma}$$

Equal coupling scenario: 2 free pars.

$$\Delta g_1^Z = \Delta g_1^{\gamma} = 0 \\ \Delta\kappa_Z = \Delta\kappa_{\gamma} \text{ and } \lambda_Z = \lambda_{\gamma} = \lambda$$



Approach used in most analyses so far

Effective Field Theory approach

Λ : new physics scale

Add higher order operators to \mathcal{L}_{SM}

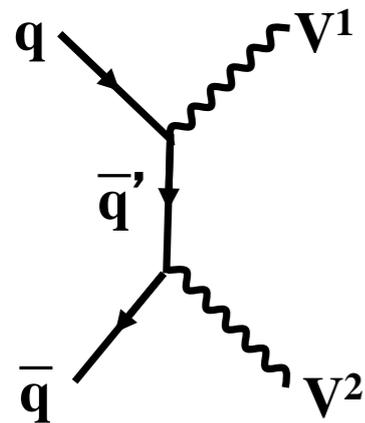
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Dominant contribution from dim. 6 operators

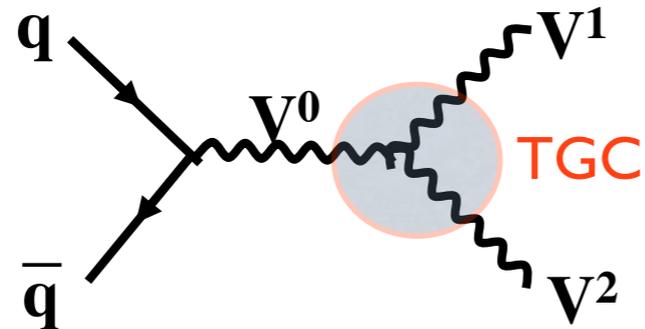


aTGCs & Diboson production

t-channel



s-channel



► 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 | $\lambda_Z, \Delta\kappa_Z, \Delta g_1^Z$ | 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 | $\lambda_Z, \lambda_\gamma$ 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} |



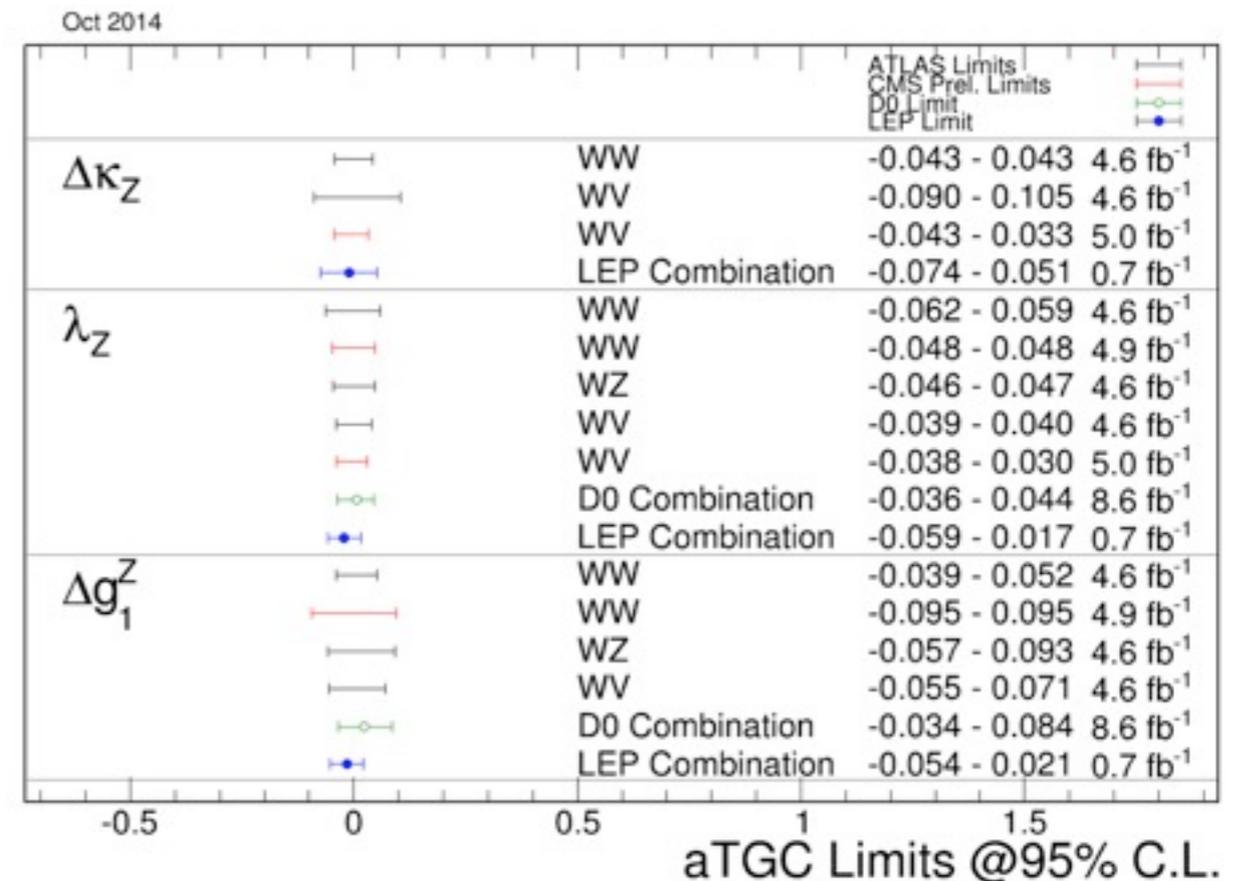
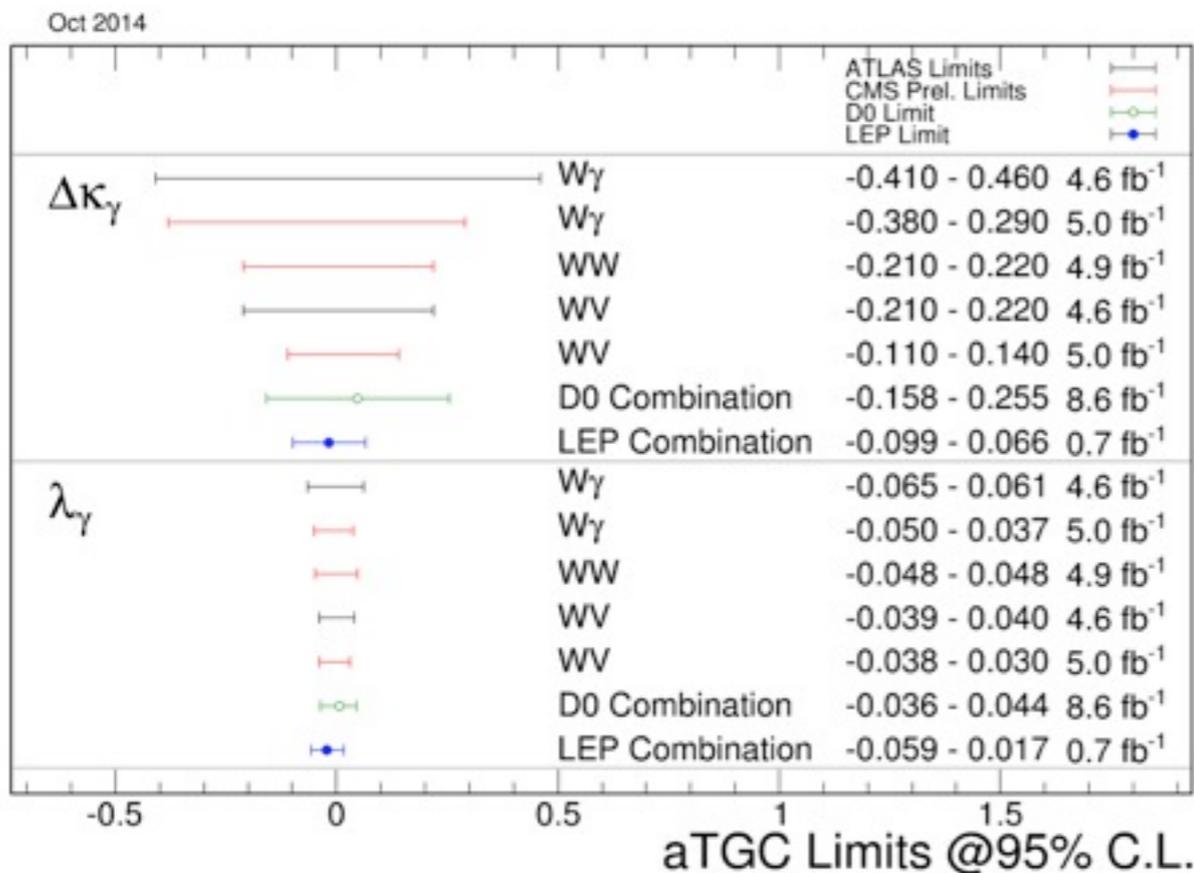
Results on charged aTGCs: WWZ and WW γ couplings



- ▶ Limits obtained from:
 - $W\gamma$: Photon Et spectrum
 - WZ: total cross section (ATLAS)
 - WW: leading lepton Pt (CMS@7 TeV)
- ▶ Reaching LEP sensitivity
- ▶ Tables below do not include limits from CMS 8 TeV WW measurements: formulated in EFT approach

Limits on EFT parameters from WW @ 8 TeV

| Coupling constant | This result (TeV ⁻²) | This result 95% interval (TeV ⁻²) |
|---------------------|-------------------------------------|--|
| c_{WWW}/Λ^2 | $0.1^{+3.2}_{-3.2}$ | [-5.7, 5.9] |
| c_W/Λ^2 | $-3.6^{+5.0}_{-4.5}$ | [-11.4, 5.4] |
| c_B/Λ^2 | $-3.2^{+15.0}_{-14.5}$ | [-29.2, 23.9] |

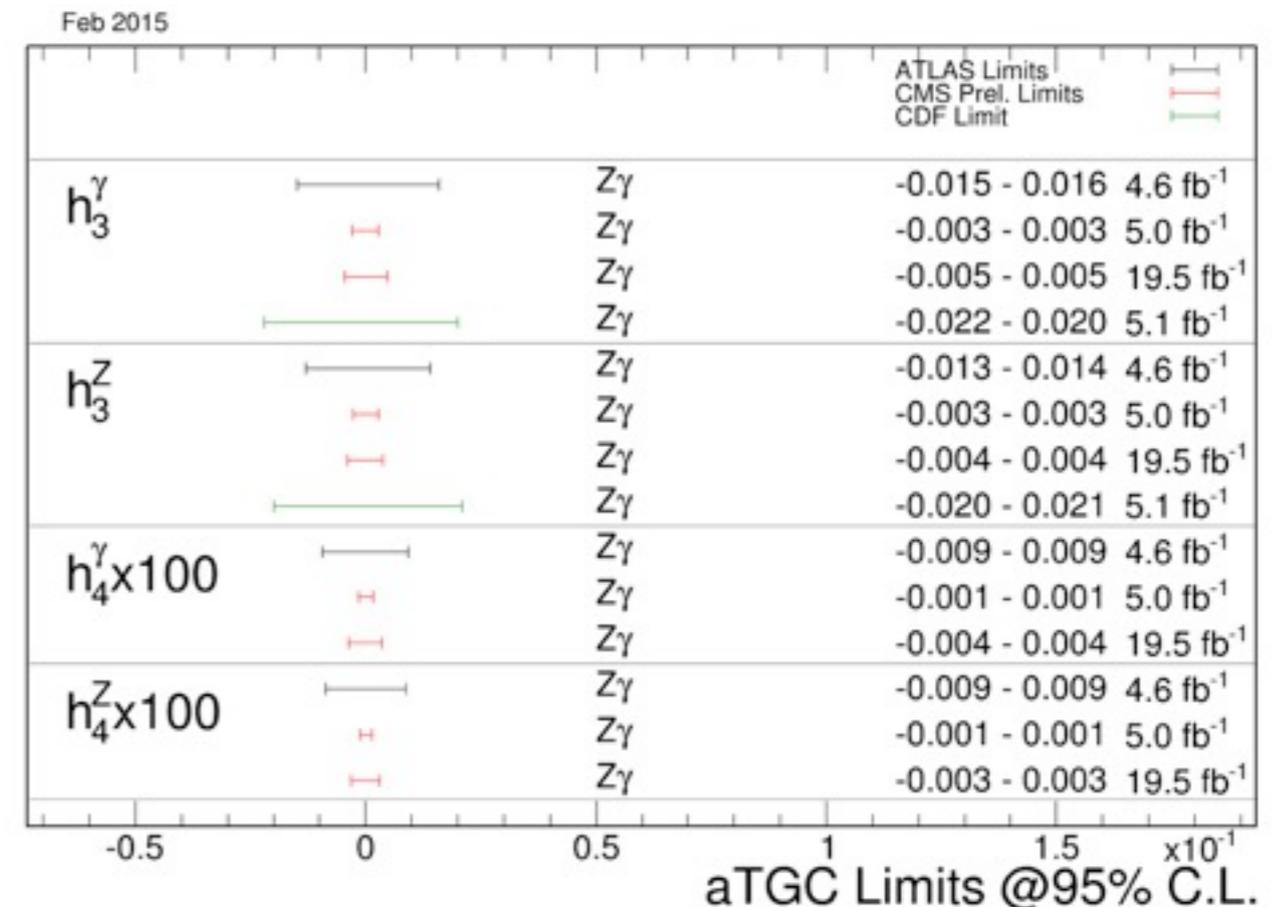
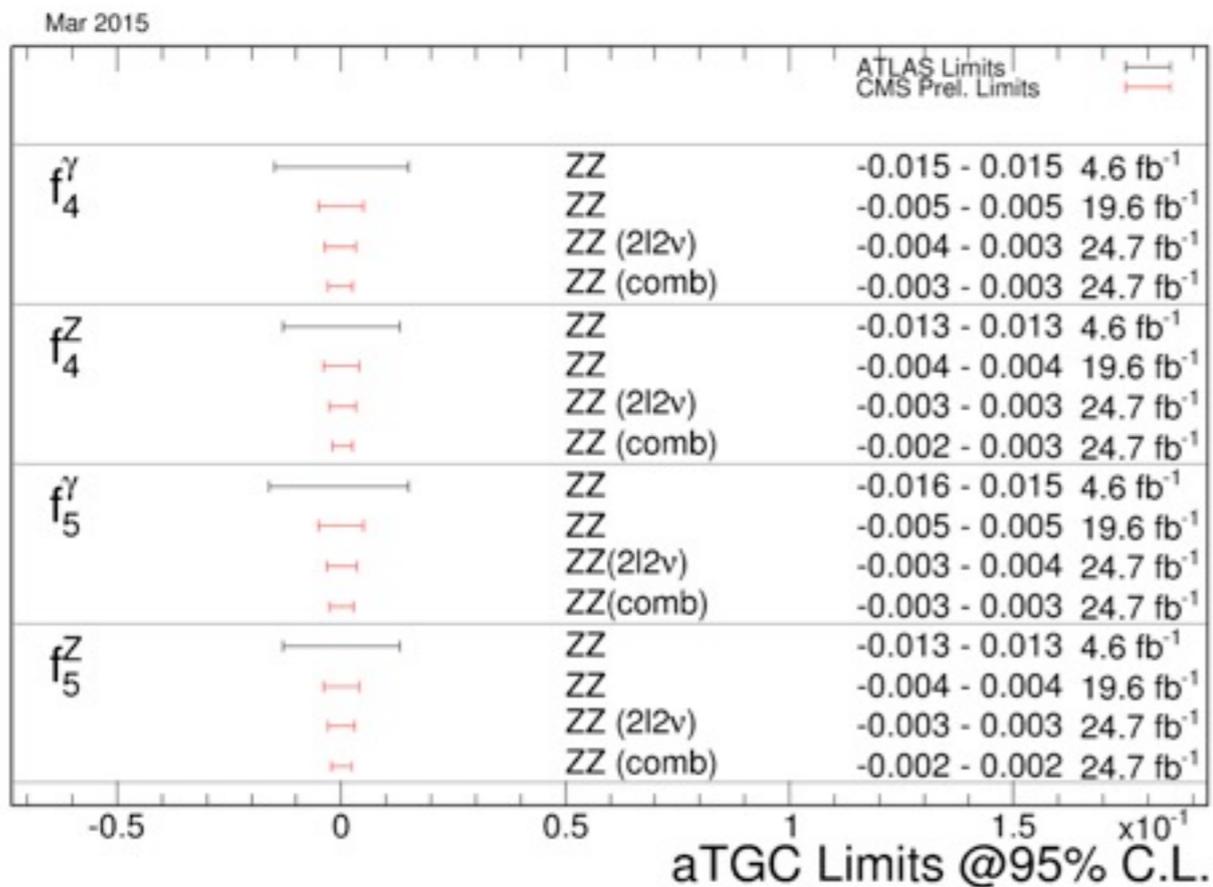




Results on neutrals aTGCs: ZZZ, ZZ γ and Z $\gamma\gamma$ couplings



- ▶ In each case, 4 parameters, 2 CP conserving and 2 CP violating
- ▶ Limits obtained fitting CP conserving parameters
- ▶ Observable used for the measurement:
 - Z γ : Photon Et
 - ZZ: 4 lepton invariant mass (4l final state) or dilepton Pt (2l2v)
- ▶ LHC now setting most stringent constraints





Summary on Diboson Physics from LHC Run I



- ▶ Both ATLAS and CMS have presented measurements of all diboson final states
 - Mostly using leptonic W and Z channels, but also several measurements with hadronic channels or invisible ($\nu\nu$) Z decays
 - Several measurements still coming, notably @ 8 TeV
- ▶ All measurements are in agreement with SM expectations
 - Some excess seen in charged channels
 - Differential cross sections allow for better comparison with QCD prediction: NNLO predictions become testable
- ▶ Searches for anomalous couplings show no sign of new physics
 - LHC measurements now provide the tightest constraints in several couplings
- ▶ Many measurements now dominated by systematic uncertainties: important to reduce theoretical uncertainties

Thanks to ATLAS & CMS for producing these many results
and to the LHC for making it possible!