Double Gauge Boson Production at $\sqrt{s}$ = 7, 8, and 13TeV

- Diboson Measurements
- Electroweak VBS Productions
- Tri-boson Productions
- Summary

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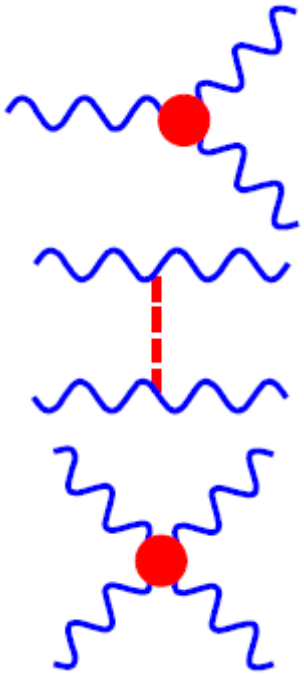
On behalf of the ATLAS and CMS Collaborations

51st Rencontres de Moriond EW 2016
La Thuile, Italy, Mar. 12-19 2016

Multi-boson Physics

Physics Processes:

- Diboson Wγ, Zγ, WW, WZ, ZZ productions, probing aTGC
- EWK Vector Boson Fusion (VBF) and Vector Boson Scattering (VBS), Wγjj, Zγjj, WWjj, WZjj – probing Higgs mech. and aQGCs
- Tri-boson productions, probing aQGCs

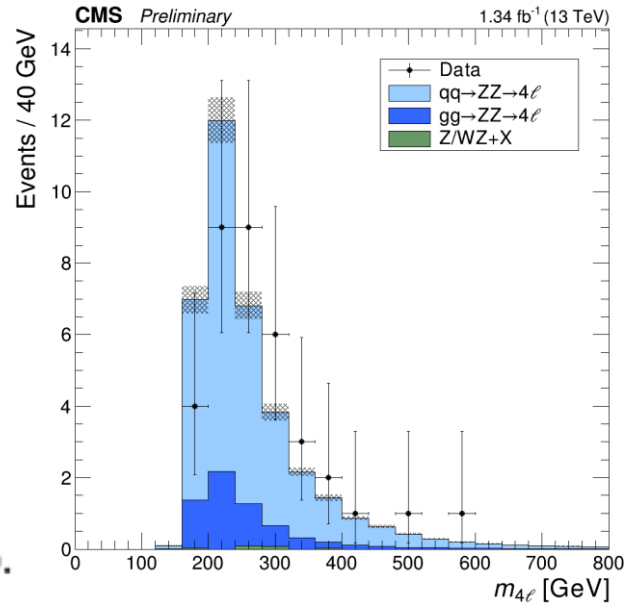


Motivations:

- EWK precision measurements with higher order corrections
- Explore new final states never observed before
- Searching for SM breakdown → new physics beyond SM

ZZ Production @13TeV

- ***ZZ→ℓℓℓ'ℓ' selection:***
  - 4 lepton (e,μ) consistent with ZZ:
  - **CMS**: $p_T^{Z\ell 1}$>20 GeV, p_T^{other}>10 GeV; 60<$M_{Z1,2}$<120 GeV.
  - **ATLAS**: $p_T^{Z\ell 1}$>20 GeV; 66<$M_{Z1,2}$<116 GeV.
- **Fake background measured from data.**



CMS : 1.34fb^{-1} CMS-PAS-SMP-15-005

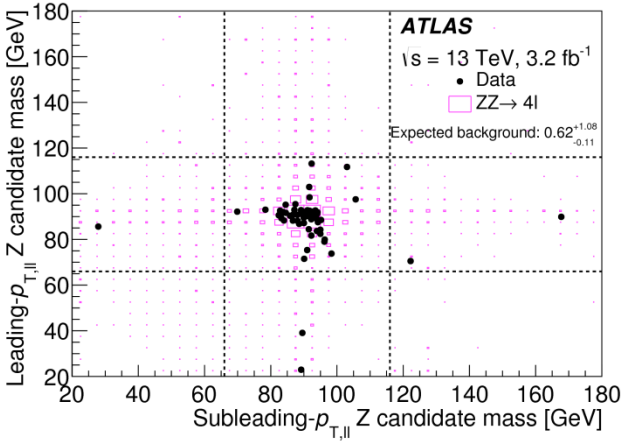
$$\sigma_{\text{fid}}(\text{pp} \to \text{ZZ} \to 4\ell) = 38.0^{+6.7}_{-6.0}\,(\text{stat})^{+1.5}_{-1.2}\,(\text{syst}) \pm 1.7\,(\text{lum})\ \text{fb}.$$

$$\sigma(\text{pp} \to \text{ZZ}) = 16.7^{+2.9}_{-2.6}\,(\text{stat})^{+0.7}_{-0.5}\,(\text{syst}) \pm 0.3\,(\text{theo}) \pm 0.8\,(\text{lum})\ \text{pb}.$$

$$\sigma^{tot}_{NNLO} = 16.5^{+0.7}_{-0.5}\ \text{pb}$$ *Phys. Lett.* **B735** (2014) 311–313

ATLAS : 3.2fb^{-1} Phys. Rev. Lett. 116, 101801 (2016)

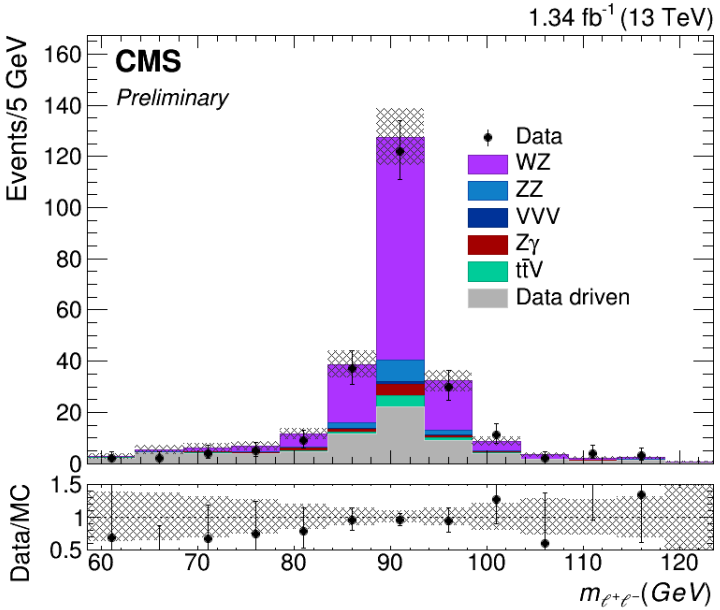
	Measurement	$O(\alpha_S^2)$ prediction
$\sigma^{\text{fid}}_{ZZ\to e^+e^-e^+e^-}$	$8.4\,^{+2.4}_{-2.0}(\text{stat.})\,^{+0.4}_{-0.2}(\text{syst.})\,^{+0.5}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to e^+e^-\mu^+\mu^-}$	$14.7\,^{+2.9}_{-2.5}(\text{stat.})\,^{+0.6}_{-0.4}(\text{syst.})\,^{+0.9}_{-0.6}(\text{lumi.})$ fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{\text{fid}}_{ZZ\to \mu^+\mu^-\mu^+\mu^-}$	$6.8\,^{+1.8}_{-1.5}(\text{stat.})\,^{+0.3}_{-0.3}(\text{syst.})\,^{+0.4}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to \ell^+\ell^-\ell'^+\ell'^-}$	$29.7\,^{+3.9}_{-3.6}(\text{stat.})\,^{+1.0}_{-0.8}(\text{syst.})\,^{+1.7}_{-1.3}(\text{lumi.})$ fb	$27.4^{+0.9}_{-0.8}$ fb
σ^{tot}_{ZZ}	$16.7\,^{+2.2}_{-2.0}(\text{stat.})\,^{+0.9}_{-0.7}(\text{syst.})\,^{+1.0}_{-0.7}(\text{lumi.})$ pb	$15.6^{+0.4}_{-0.4}$ pb



WZ Production @13TeV

CMS-PAS-SMP-15-006

- ***WZ→ℓℓℓ'ν selection:***
  - 3 lepton (e,μ) consistent with WZ
  - $p_T^{Z\ell 1}$>20 GeV, $p_T^{Z\ell 2}$>10 GeV, $p_T^{W\ell}$>20 GeV.
  - 60<M_Z<120 GeV.
- **Fake background measured from data;**
- **Consistent with NLO prediction.**



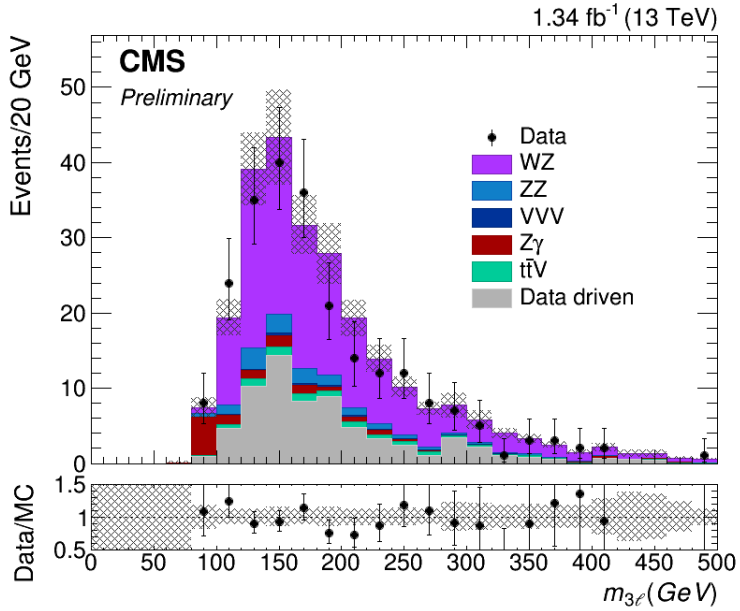
CMS results with 1.34fb^{-1}

$$\sigma_{\text{fid}}(\text{pp} \to \text{WZ} \to \ell\nu\ell'\ell') = 239 \pm 29\,(\text{stat})^{+52}_{-40}\,(\text{syst}) \pm 11\,(\text{lum})\ \text{fb}.$$

$$\sigma^{fid}_{NLO} = 274^{+13}_{-8}\ \text{fb}$$

$$\sigma(\text{pp} \to \text{WZ}) = 36.8 \pm 4.6\,(\text{stat})^{+8.1}_{-6.2}\,(\text{syst}) \pm 0.6\,(\text{theo}) \pm 1.7\,(\text{lum})\ \text{pb}.$$

$$\sigma^{tot}_{NLO} = 42.7^{+1.6}_{-0.8}\ \text{pb}$$



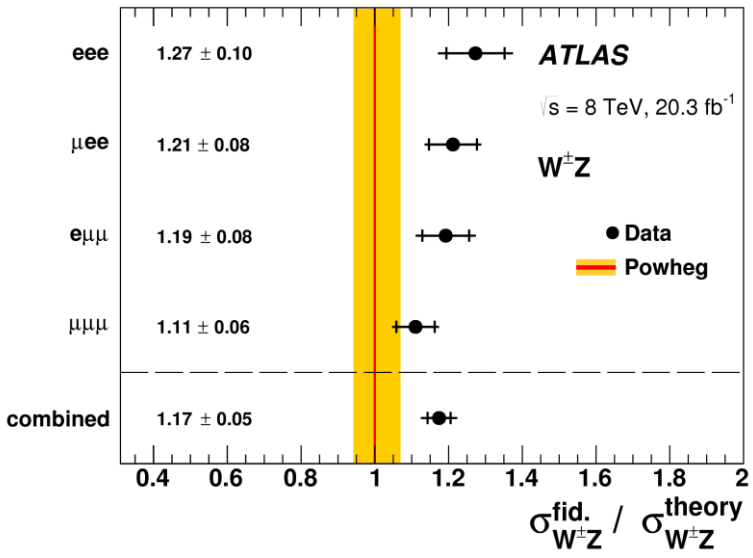
NEW

WZ Measurements @ 8TeV

arXiv:1603.02151
submitted to Phys. Rev. D.

$$\sigma^{\text{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 35.1 \pm 0.9\,(\text{stat.}) \pm 0.8\,(\text{sys.}) \pm 0.8\,(\text{lumi.})\ \text{fb}$$

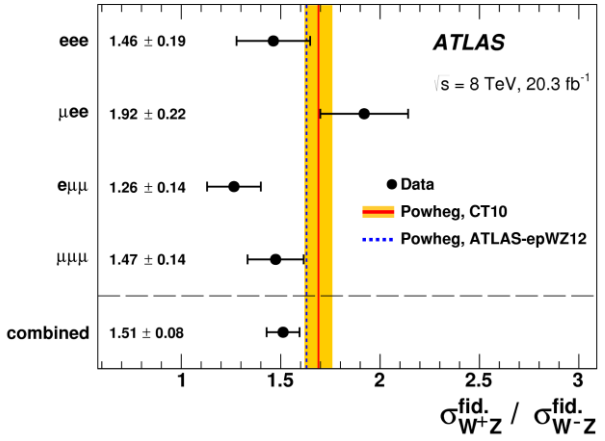
NLO MC σ = 30.0 +- 2.1fb



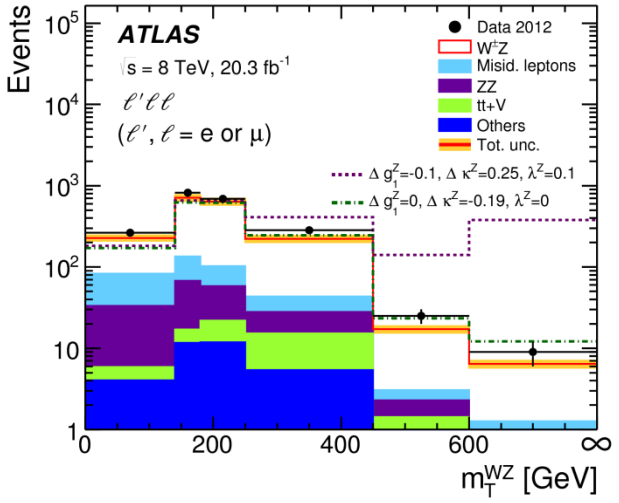
Measured σ with precision ~4%!

WZ production rate is higher than MC NLO calculation

W⁺Z/W⁻Z production ratio consistent with NLO prediction

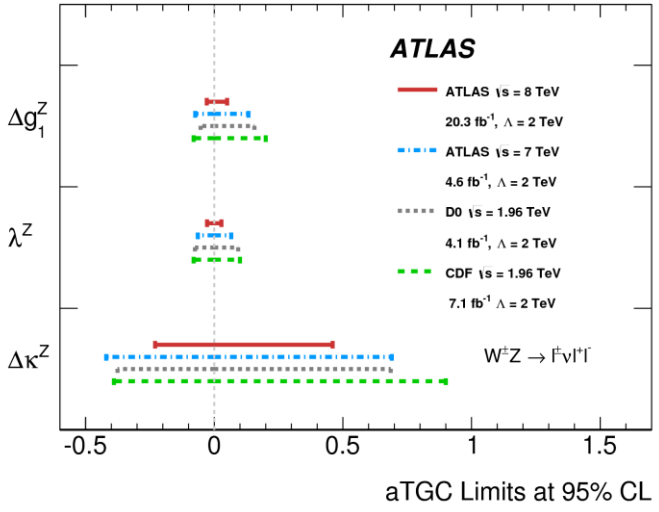


Fit



➔

aTGC Limits



W^+W^- Cross-section @ 8TeV

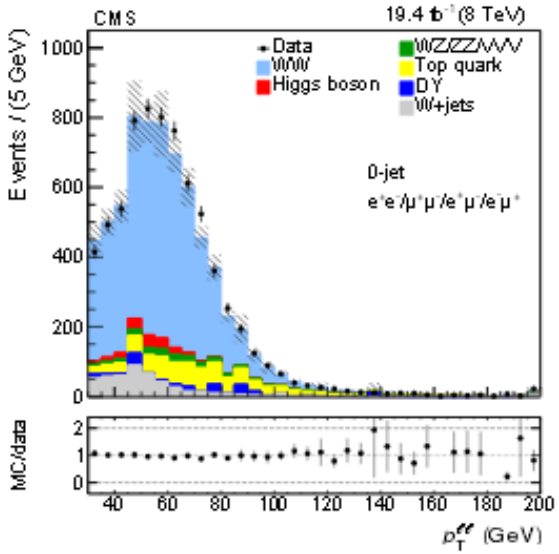
Theoretical calculation advancements:

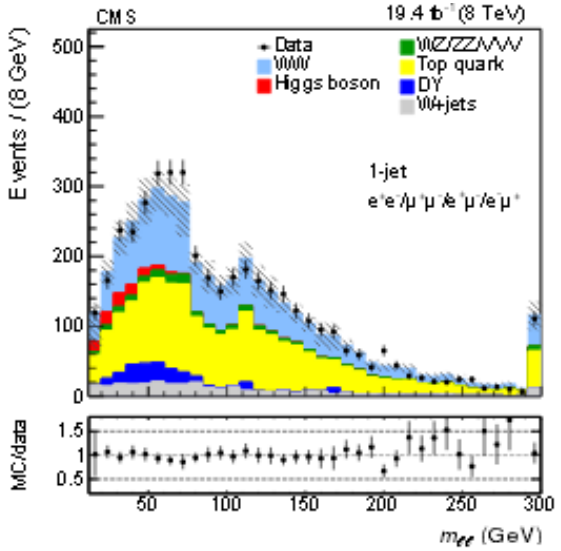
- NNLL transverse momentum resummation, 3-7% (arXiv:1407.4537 [hep-ph], YITP-SB-14-22)
- NNLO qq + LO gg + NNLO ggH~63.2±2.0pb vs NLO qq + LO gg + NNLO ggH~58.7±3.0pb from MCFM, ~8% effect (Phys. Rev. Lett. 113, 212001 (2014))

CMS new measurements:

CMS WW→ℓνℓν: ArXiv 1507.03268 submitted to EPJC

- Better background estimation from DY, top and Higgs;
- Improved MC modeling : NNLO calculation, WW P_T resummation reweighting, LO MADGRAPH ➔ NLO POWHEG;





- Good agreement with NNLO (no Higgs→WW):

$$\sigma_{tot} = 60.1 \pm 4.8 \text{ pb}$$
$$\sigma_{NNLO} = 59.8^{+1.3}_{-1.1} \text{ pb}$$

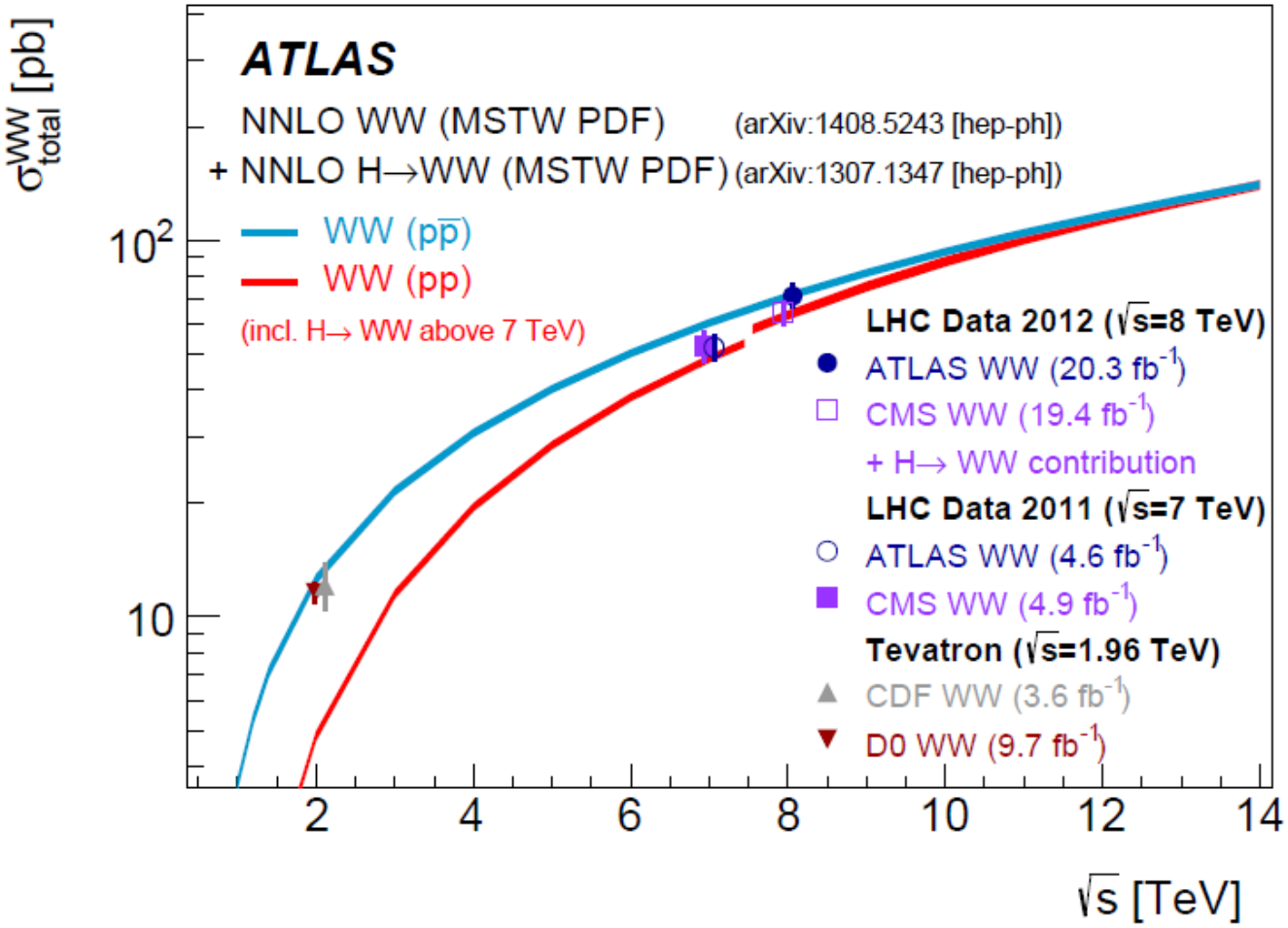
8TeV $W^+W^- \rightarrow l\nu l\nu$ Measurements

NEW

ATLAS: arXiv:1603.01702 submitted to JHEP

- **Events selected with two leptons (ee,eμ, μμ) with missing energy and with jet veto**
- **8TeV data 20.3 fb^{-1}, incl. Higgs → WW as signal**

	σ(total) (pb)
Data	$71.1^{+1.1}_{-1.1}(\text{stat})\ ^{+5.7}_{-5.0}(\text{syst})\ ^{+1.4}_{-1.4}(\text{lumi})$
NNLO	$63.2^{+1.6}_{-1.4}(\text{scale}) \pm 1.2(\text{PDF})$



Zγ production @8TeV

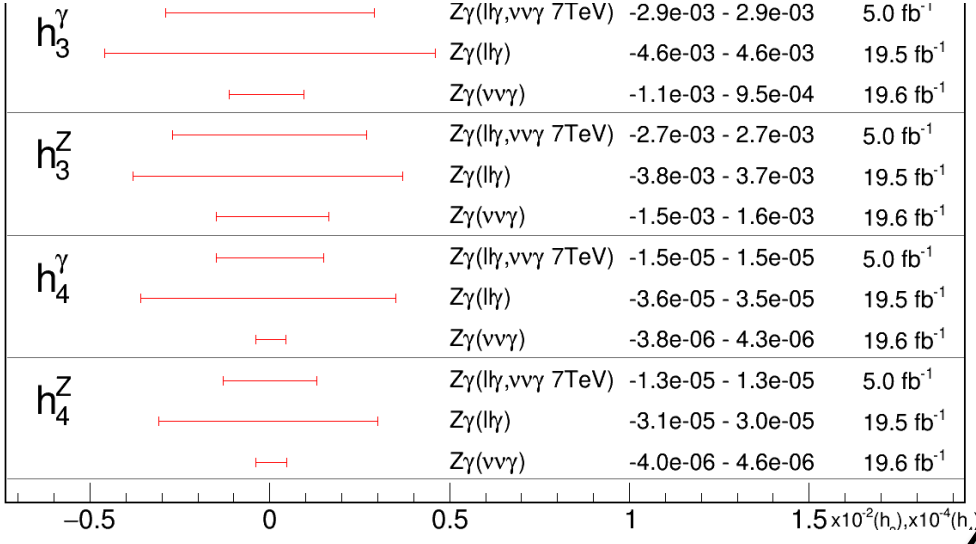
CMS: arXiv:1602.07152

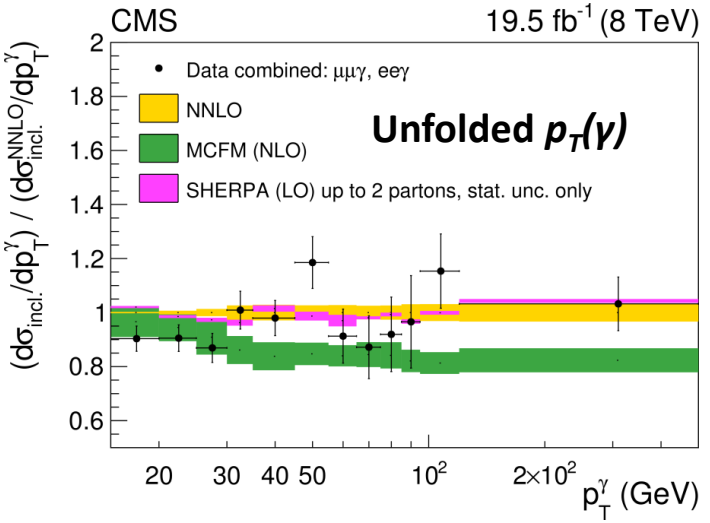
J. High Energy Phys. 04 (2015) 164 (ℓℓγ)

- Zγ→νννγSelection:
  - 1central ($|\eta|<1.44$) high p_T(>145 GeV) photon
  - $E_T^{Miss}>140$ GeV
- Large W(**ℓνγ**) BKG from MC but checked in CR.
- Measurements found in good agreement with NNLO predictions:

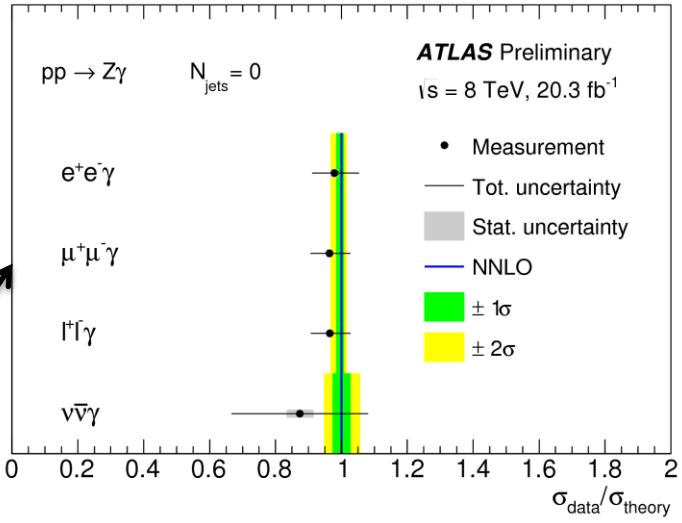
$$\sigma_{fid} = 52.7 \pm 2.1(stat) \pm 6.6(sys) \text{ fb}$$
$$\sigma_{theo}^{NNLO} = 50. \pm 2.4 \text{ fb}$$

- Best 95% CL aTGC (**CMS**) limits.



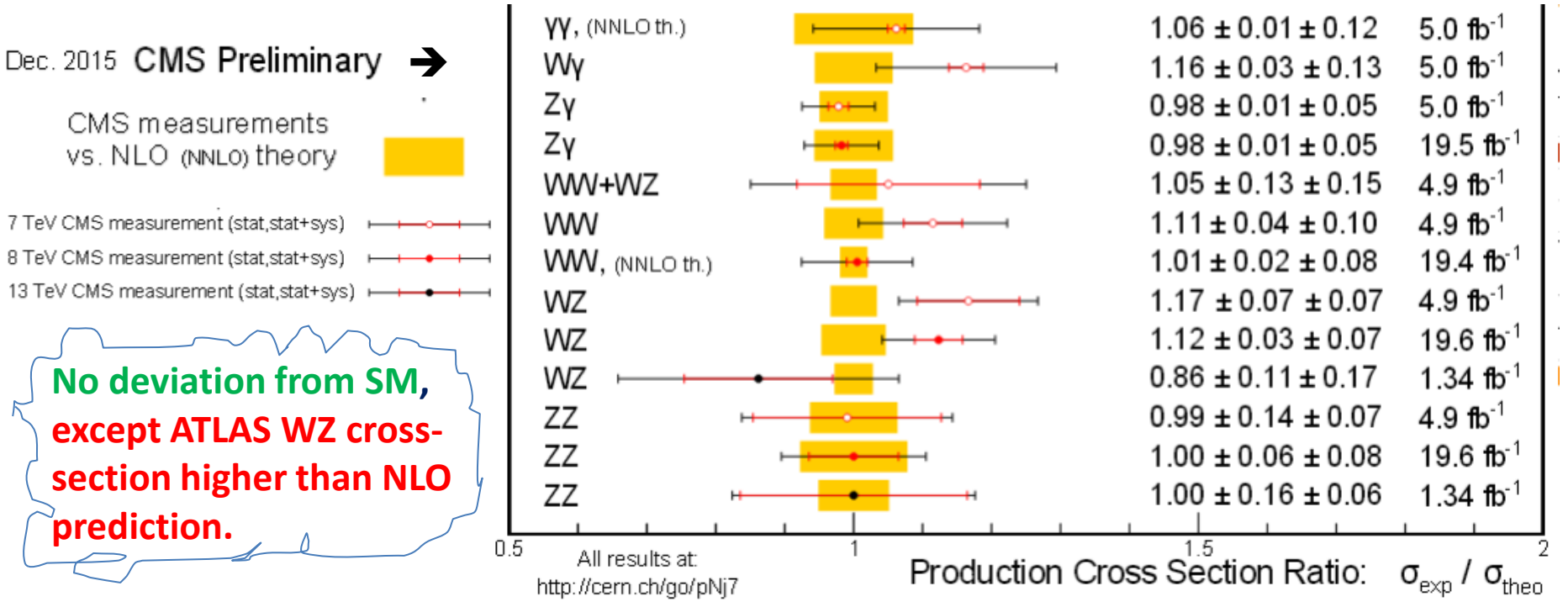


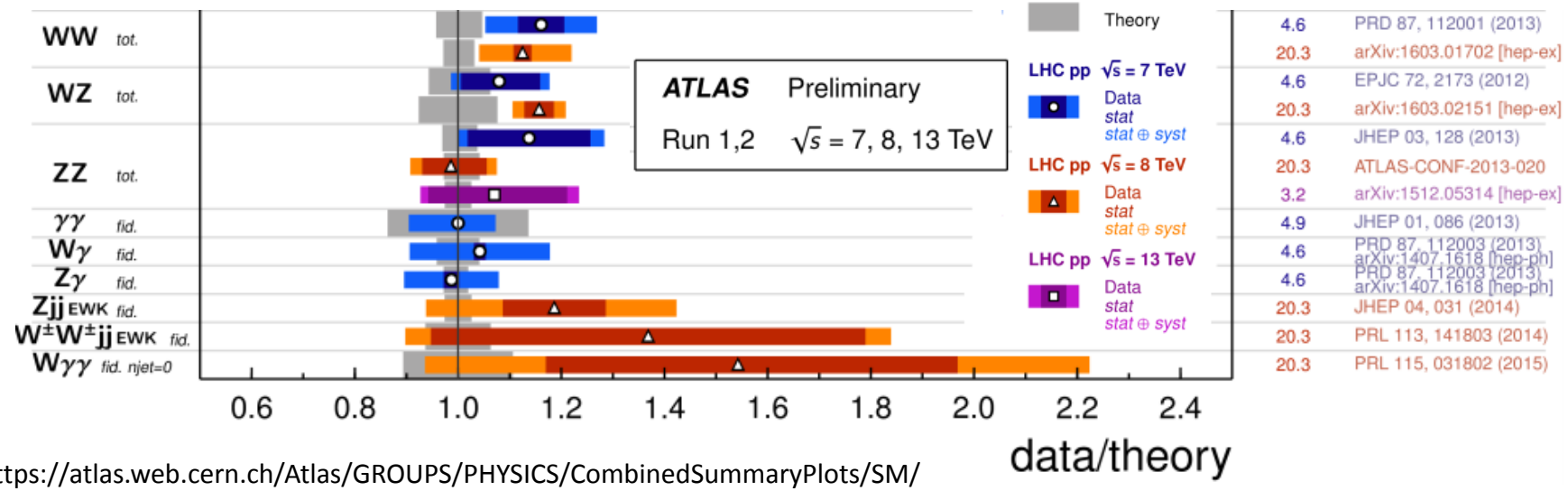
- Zγ→ℓ (=e,μ) ℓγ
- Good agreement meas. to NNLO pred.



NEW **ATLAS Zγ results see Evgeny Soldatov's talk in Young Scientist Forum**

7, 8, and 13TeV Diboson Cross-section Results



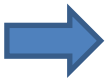


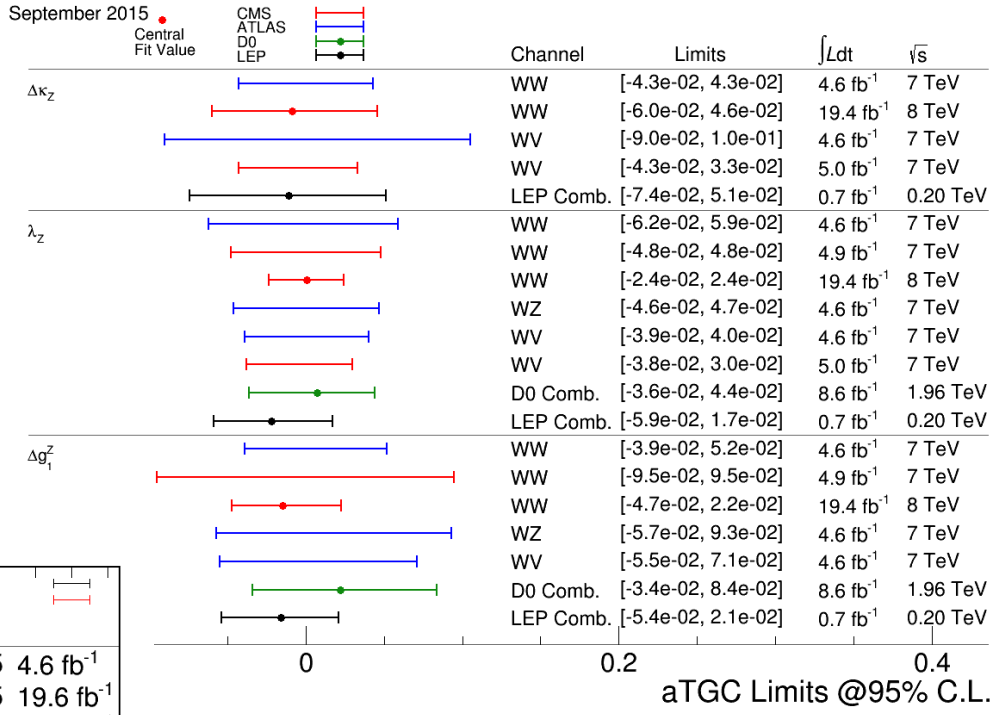
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

Summary of aTGC Limits

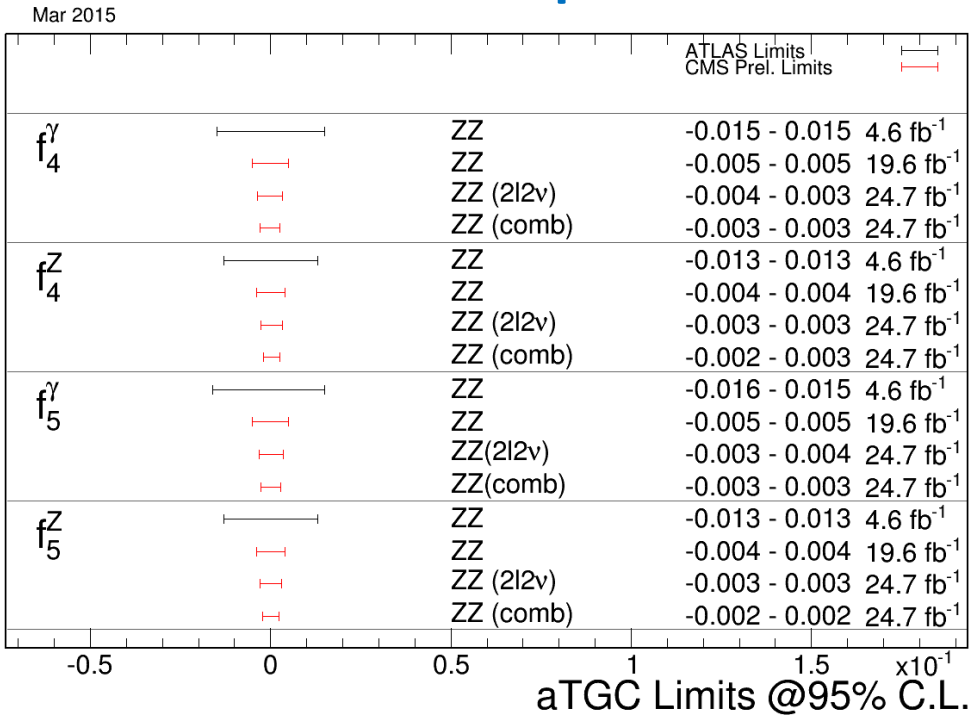
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Charged aTGC for WWZ vertex





Neutral aTGC ZZγ and ZZZ



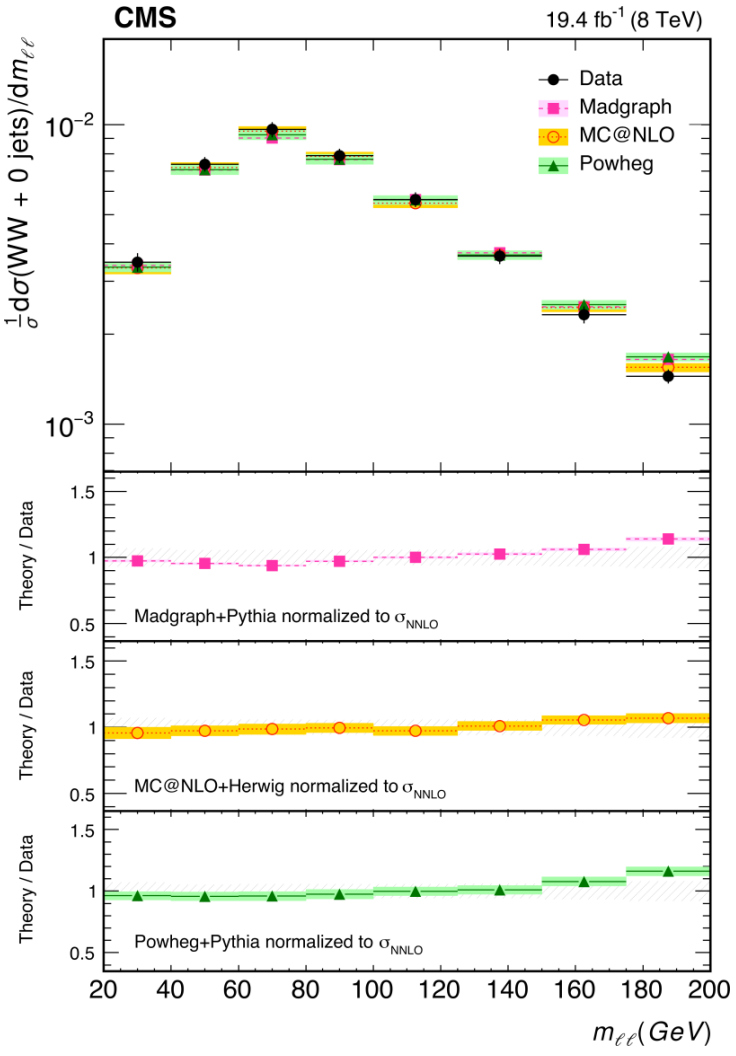
- **Stringent 95% CL Limits, and agree with SM prediction**
- **Limits similar or (way) better than previous experiments at Tevatron (D0) and at LEP.**

Diboson Differential Measurements

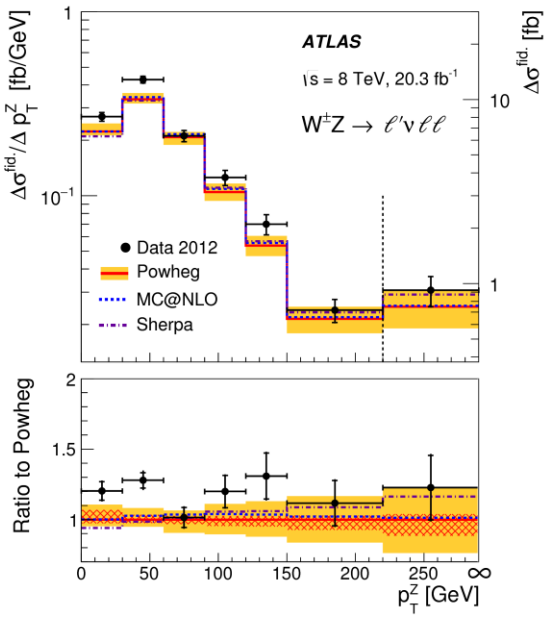
- **Probe new physics**
- **Provide kinematic distributions for better MC modeling**

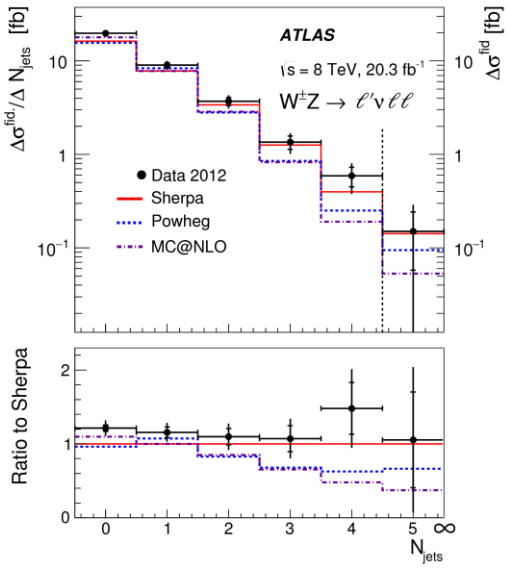
NEW Differential Measurements: $W^+W^- \rightarrow l\nu l\nu$, $WZ \rightarrow lvll$

CMS WW→ℓνℓν: ArXiv 1507.03268 submitted to EPJC

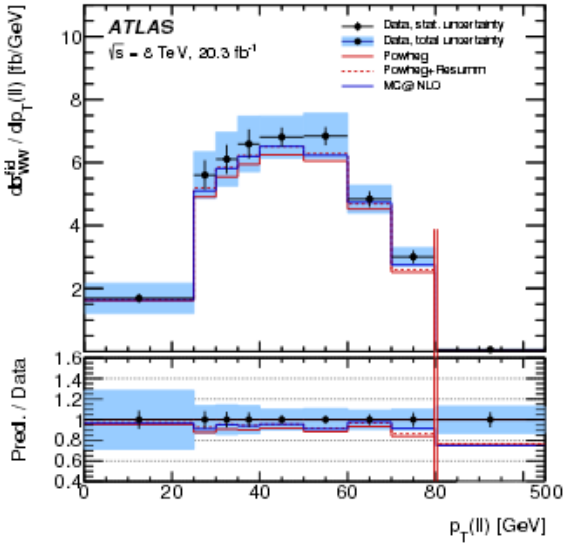


arXiv:1603.02151 submitted to Phys. Rev. D.





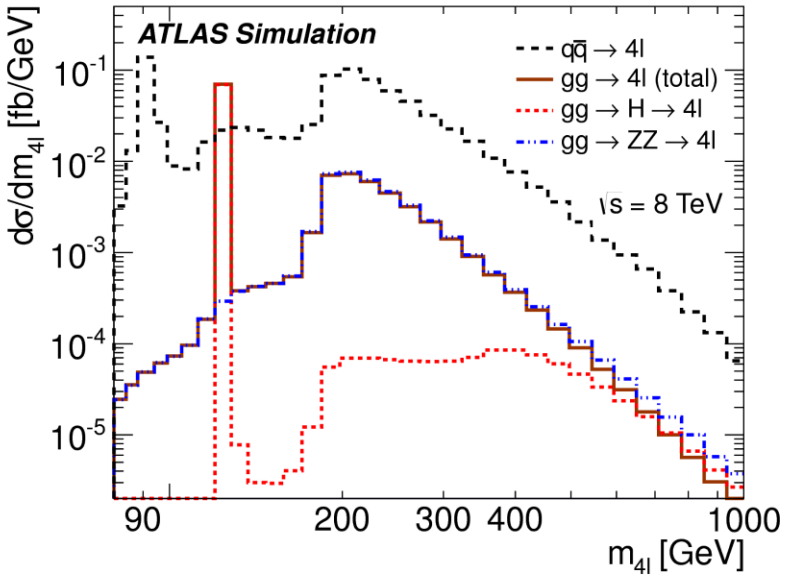
ATLAS arXiv:1603.01702, submitted to JHEP



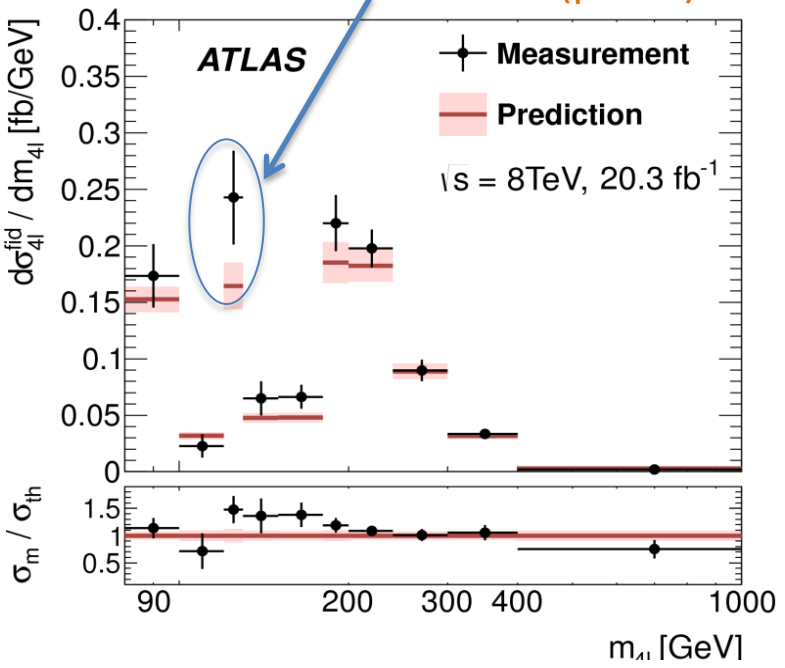
- ✓ **WW: agree with NNLO expectation**
- ❖ **WZ: is higher than NLO prediction**

Lineshape: ZZ→4l @ 8TeV

Physics Letter B753 (2016) 552-527



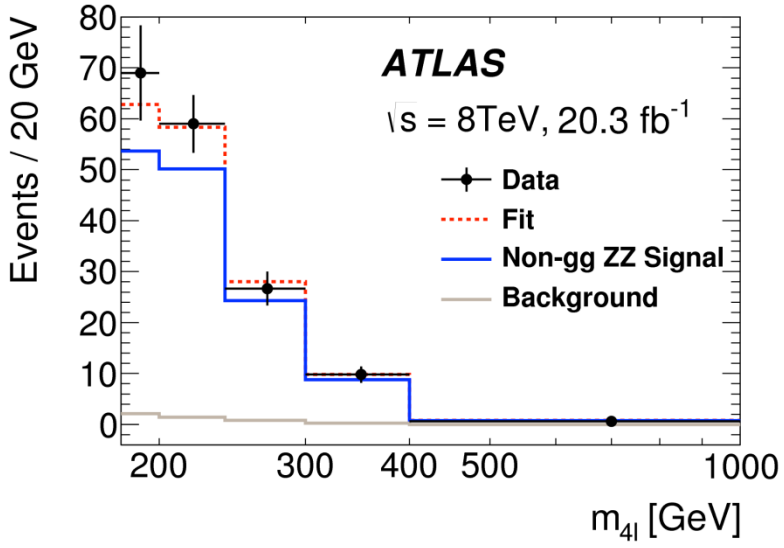
Consistent with H→4ℓ (μ~1.4)



- **$m_{4\ell}$unfolded measurement:**
  - LO: non resonant gg→4ℓ.
  - NLO QCD: qq→4ℓ.
  - NNLO QCD+NLO EW:H→4ℓ and on-shell qq→4ℓ.
- **Extract gg component σ(LO) in $m_{4\ell}$>180 GeV region.**

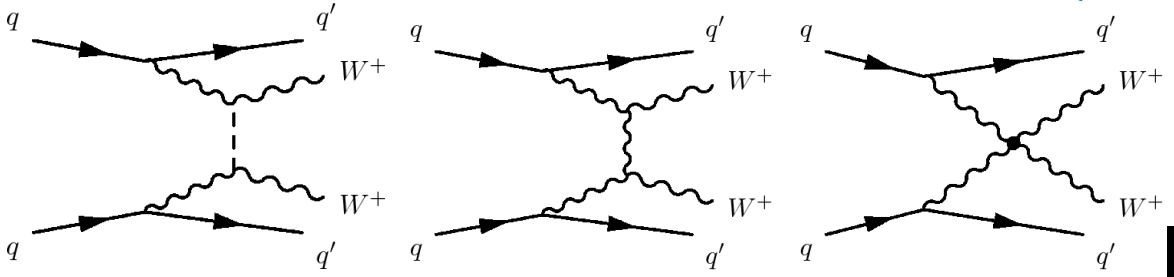
$$\mu_{gg} = 2.4 \pm 1.0(stat) \pm 0.5(sys) \pm 0.8(theory)$$

$$\sigma_{\mathrm{LO}}^{gg\to ZZ} = 0.97^{+0.3}_{-0.2}\ \mathrm{fb}, \quad \sigma_{\mathrm{NLO}}^{gg\to ZZ} = 1.8^{+0.2}_{-0.2}\ \mathrm{fb}$$



arXiv:1509.06734

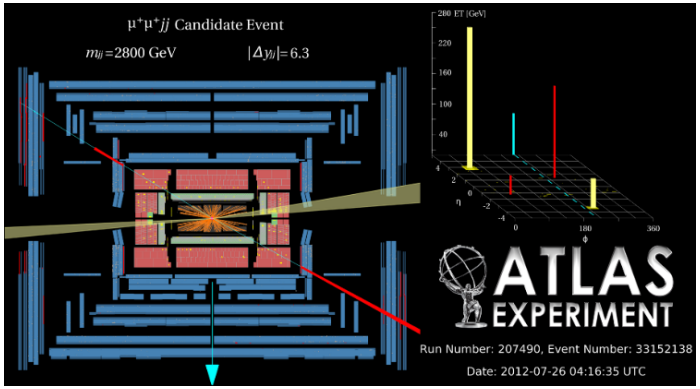
Vector-Boson Scattering Diboson Production



Sensitive to QGCs

Phys. Rev. Lett. 113, 141803

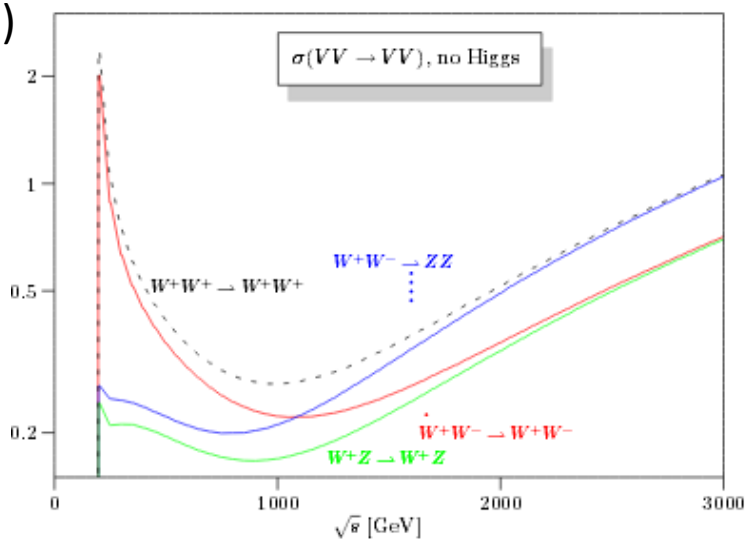
VBS pp → $W^{\pm}W^{\pm}jj$ (1st evidence of VBS diboson production)



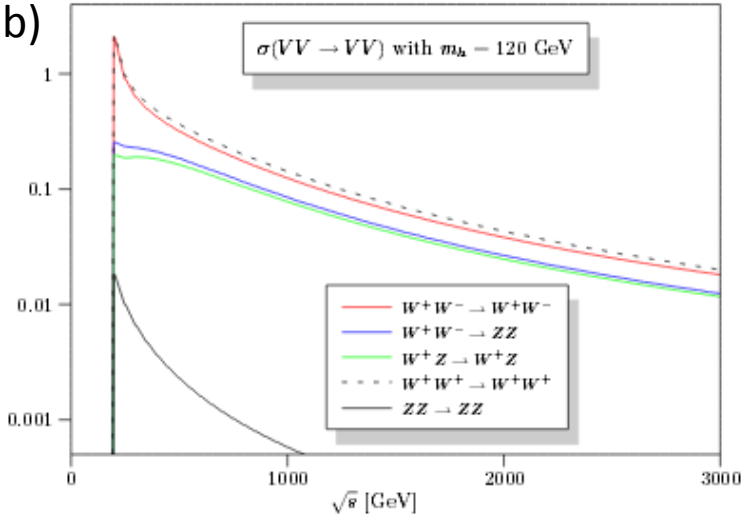
VBS topology : 2 bosons with two high momentum, forward jets →

Violate unitarity without a SM Higgs arXiv:0806.4145

σ(nb)

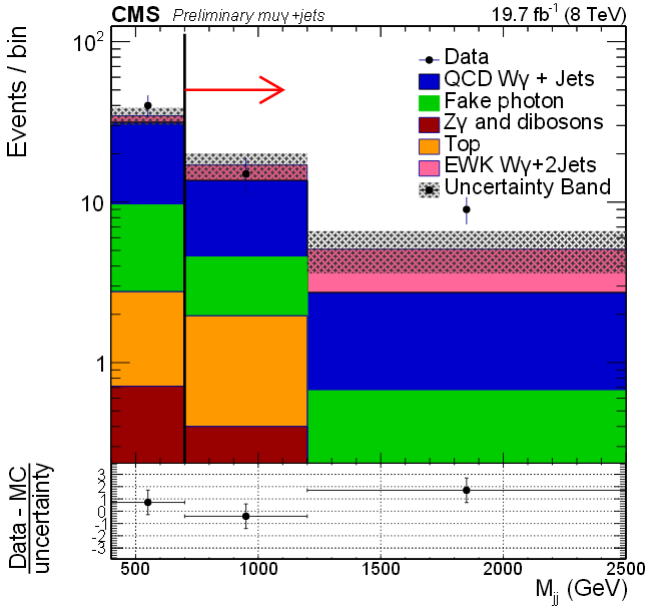


σ(nb)



VBS: Wγjj→lνγjj

8TeV 19.7fb^{-1}, CMS-PAS-SMP-14-011

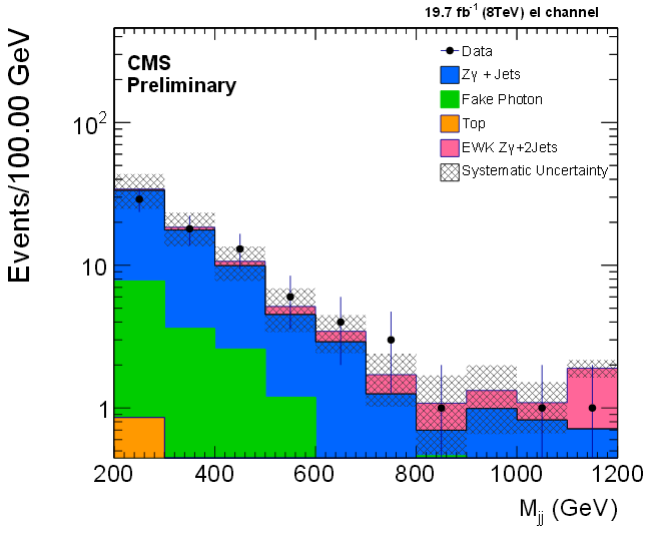


Items	EWK measurement
$\hat{\mu}$	$1.78^{+0.99}_{-0.76}$
EWK fraction (search region)	100%
EWK fraction (fiducial region)	100%
Observed (Expected) significance	2.67(1.52) σ
Theory cross section (fb)	6.1 ± 1.2 (scale) ± 0.2 (PDF)
Measured cross section (fb)	10.8 ± 4.1 (stat.) ± 3.4 (syst.) ± 0.3 (lumi.)

Items	EWK+QCD measurement
$\hat{\mu}$	$0.99^{+0.21}_{-0.19}$
EWK fraction (search region)	27.1%
EWK fraction (fiducial region)	25.8%
Observed (Expected) significance	7.69(7.49) σ
Theory cross section (fb)	23.5 ± 6.6 (scale) ± 0.8 (PDF)
Measured cross section (fb)	23.2 ± 4.3 (stat.) ± 1.7 (syst.) ± 0.6 (lumi.)

VBS: Zγjj→l$^+$l$^-$γjj

8TeV 19.7fb^{-1}, CMS-PAS-SMP-14-018



- **Large Zγ QCD BK measured in CR;**
- **Significance over BKG only hypothesis : 3.0σExp: 2.1σ);**
- **Measured cross-section consistent with MC prediction:**

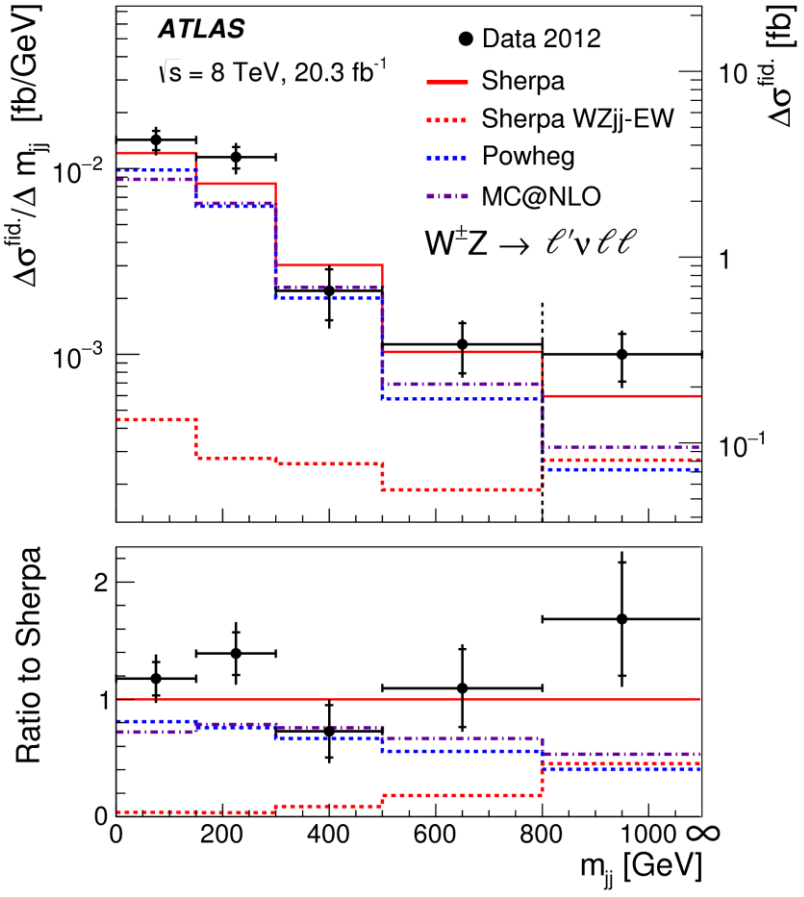
$$\sigma^{Z\gamma}_{fid} = 1.86^{+0.89}_{-0.75}(stat)^{+0.42}_{-0.27}(sys)fb$$

$$\sigma^{Z\gamma}_{theo} = 1.26 \pm 0.12fb$$

NEW

VBS: WZjj @ 8 TeV

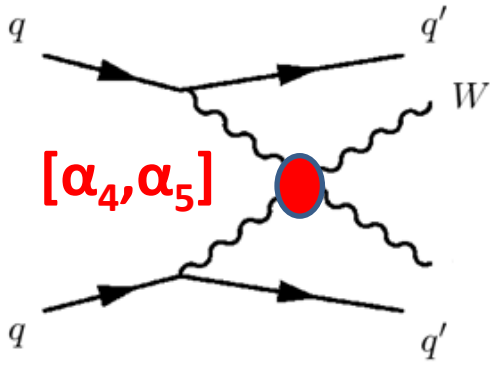
arXiv:1603.02151
submitted to Phys. Rev. D.



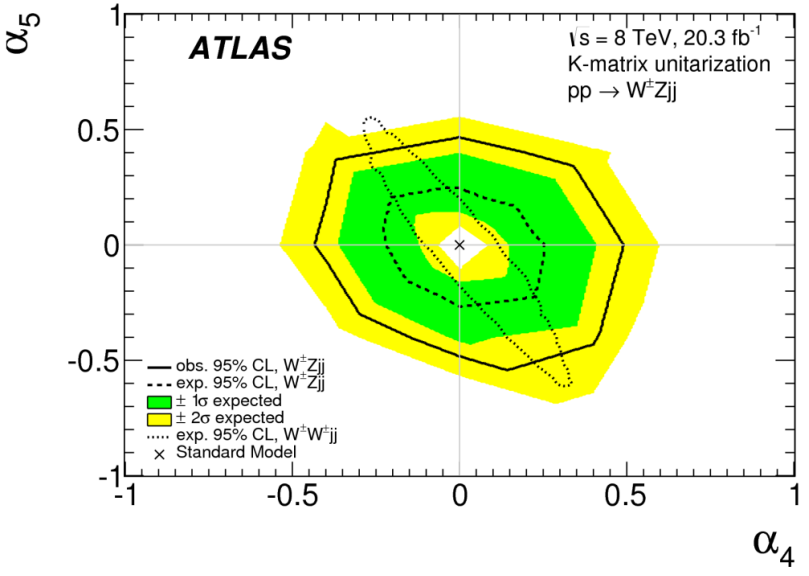
The SHERPA MC for the SM WZjj-QCD and WZjj-EW predictions

$$\sigma^{\text{fid.}}_{W^{\pm}Zjj\text{-EW}\to\ell'\nu\ell\ell} \quad 0.29\,^{+0.14}_{-0.12}\,(\text{stat.})\,^{+0.09}_{-0.1}\,(\text{sys.})\ \text{fb}$$

VBFNLO MC Prediction: 0.13 ± 0.01 fb



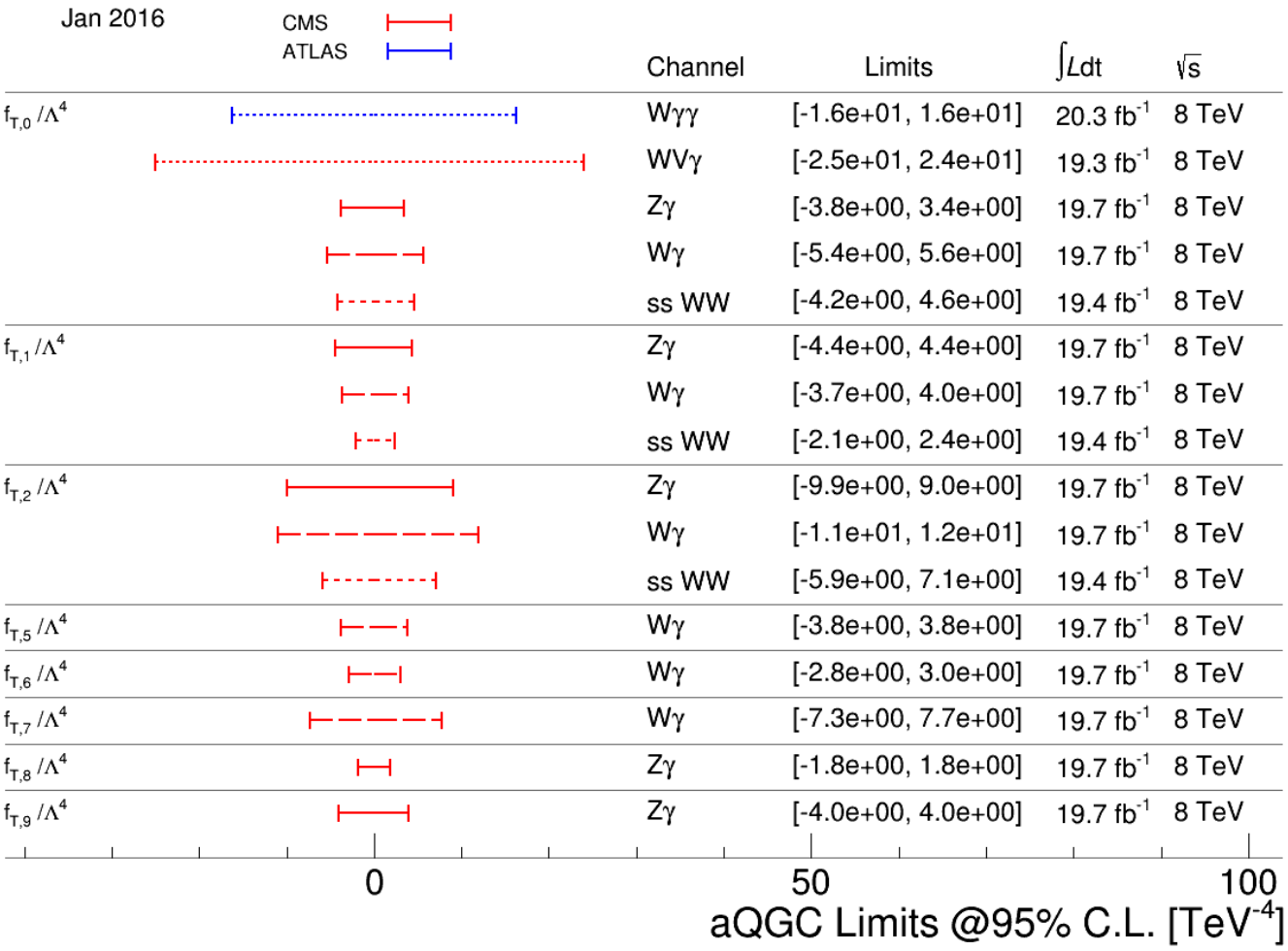
WIZARD MC for aQTGC cross-section contribution used in the fit



Summary of aQGCs at LHC

CMS Phys. Rev. Lett. 114, 051801 (2015) , Phys. Rev. D 90, 032008 (2014) , JHEP 1307 (2013) 116 , CMS-PAS-FSQ-13-008 , CMS-PAS-SMP-14-018, CMS-PAS-SMP-14-011, **ATLAS** Phys.Rev.Lett. 115 (2015) 3, 031802 https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Limits on 8-D Transverse Parameters



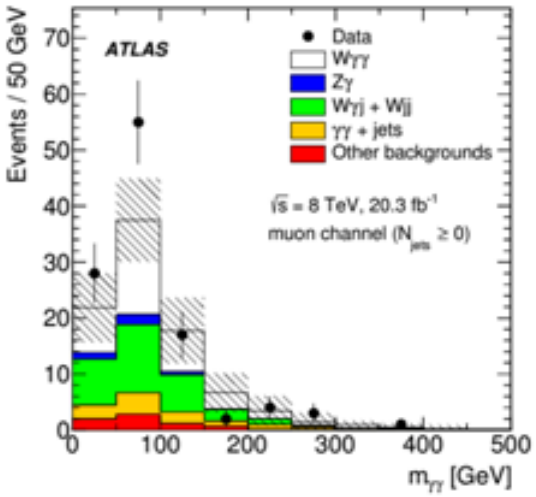
- **No deviation from SM so far;**
- **Probing the area never done before ➔……**

Tri-boson Production

Evidence of Wγγ Production

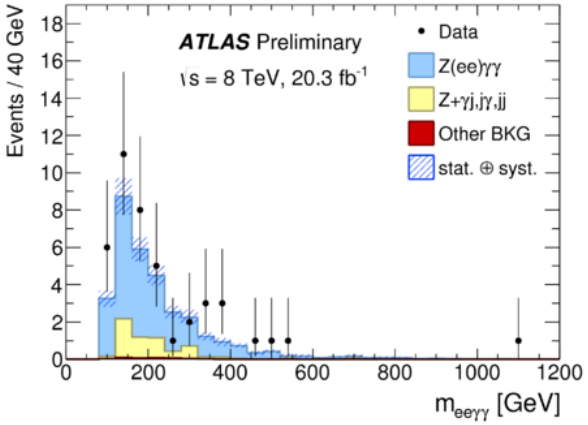
Final state: lepton + Etmiss + two photons

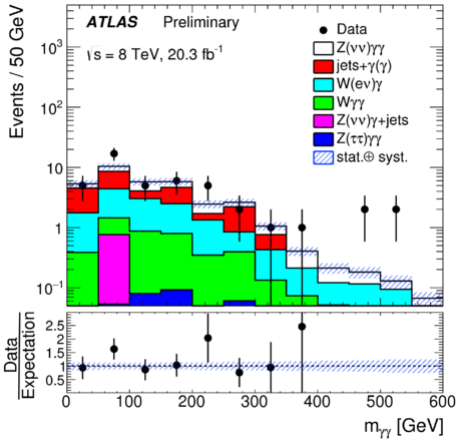
ATLAS: Phys. Rev. Lett. 115, 031802 (2015)

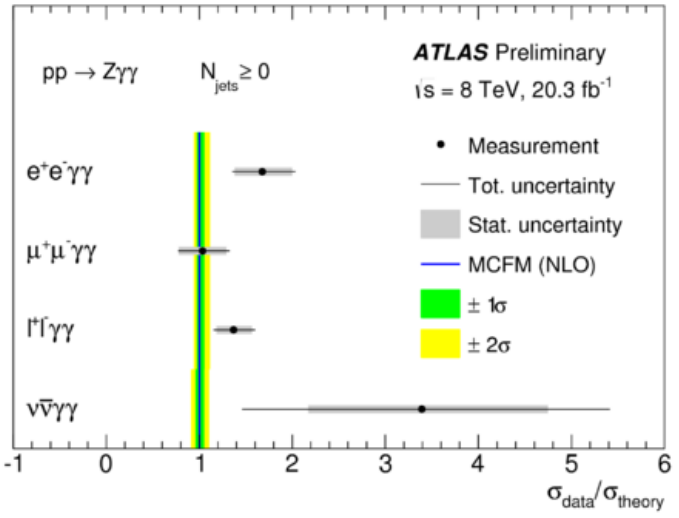


	σ^{fid} [fb]	σ^{MCFM} [fb]
Inclusive ($N_{\text{jet}} \geq 0$)		
$\mu\nu\gamma\gamma$	$7.1\ ^{+1.3}_{-1.2}$ (stat.) ± 1.5 (syst.) ± 0.2 (lumi.)	2.90 ± 0.16
$e\nu\gamma\gamma$	$4.3\ ^{+1.8}_{-1.6}$ (stat.) $^{+1.9}_{-1.8}$ (syst.) ± 0.2 (lumi.)	
$\ell\nu\gamma\gamma$	$6.1\ ^{+1.1}_{-1.0}$ (stat.) ± 1.2 (syst.) ± 0.2 (lumi.)	
Exclusive ($N_{\text{jet}} = 0$)		
$\mu\nu\gamma\gamma$	3.5 ± 0.9 (stat.) $^{+1.1}_{-1.0}$ (syst.) ± 0.1 (lumi.)	1.88 ± 0.20
$e\nu\gamma\gamma$	$1.9\ ^{+1.4}_{-1.1}$ (stat.) $^{+1.1}_{-1.2}$ (syst.) ± 0.1 (lumi.)	
$\ell\nu\gamma\gamma$	$2.9\ ^{+0.8}_{-0.7}$ (stat.) $^{+1.0}_{-0.9}$ (syst.) ± 0.1 (lumi.)	

❖ **First 3σ evidence of Wγγ production**







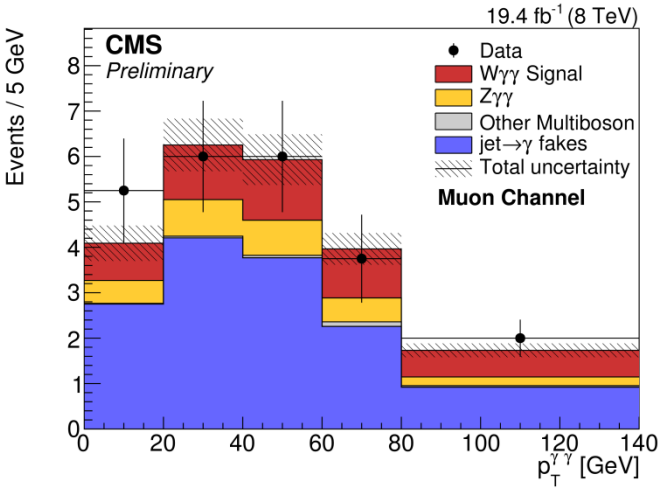
NEW

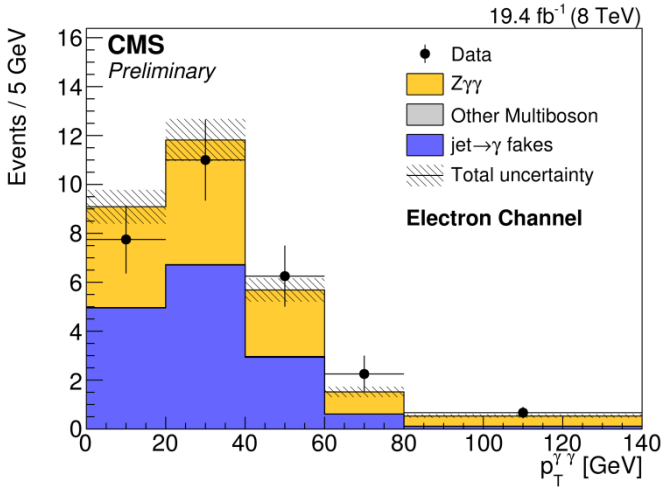
ATLAS Zγγ see Evgeny Soldatov's talk in Young Scientist Forum

Wγγ & Zγγ Production Observation

CMS-PAS-SMP-15-008

- Done in fiducial regions
- Wγγ μ only, Zγγ both μμ & ee
- Jet BKG from data





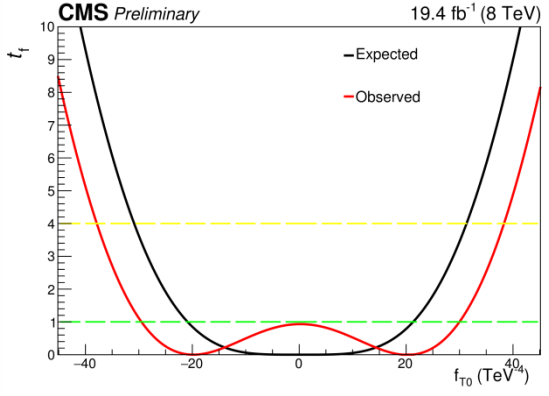
$$\sigma^{\text{fid}}_{W^{\pm}\gamma\gamma} \cdot \text{BR}(W \to \ell\nu) = 6.0 \pm 1.8\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 0.2\,(\text{lumi})\ \text{fb}$$

aMC@NLO :4.76 ±0.53 fb, 2.4σ significance

$$\sigma^{\text{fid}}_{Z\gamma\gamma} \cdot \text{BR}(Z \to \ell\ell) = 12.7 \pm 1.4\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 0.3\,(\text{lumi})\ \text{fb}$$

aMC@NLO :12.95 ±1.47 fb, 5.9σ significance

Obtained aQGC 95% CL limits



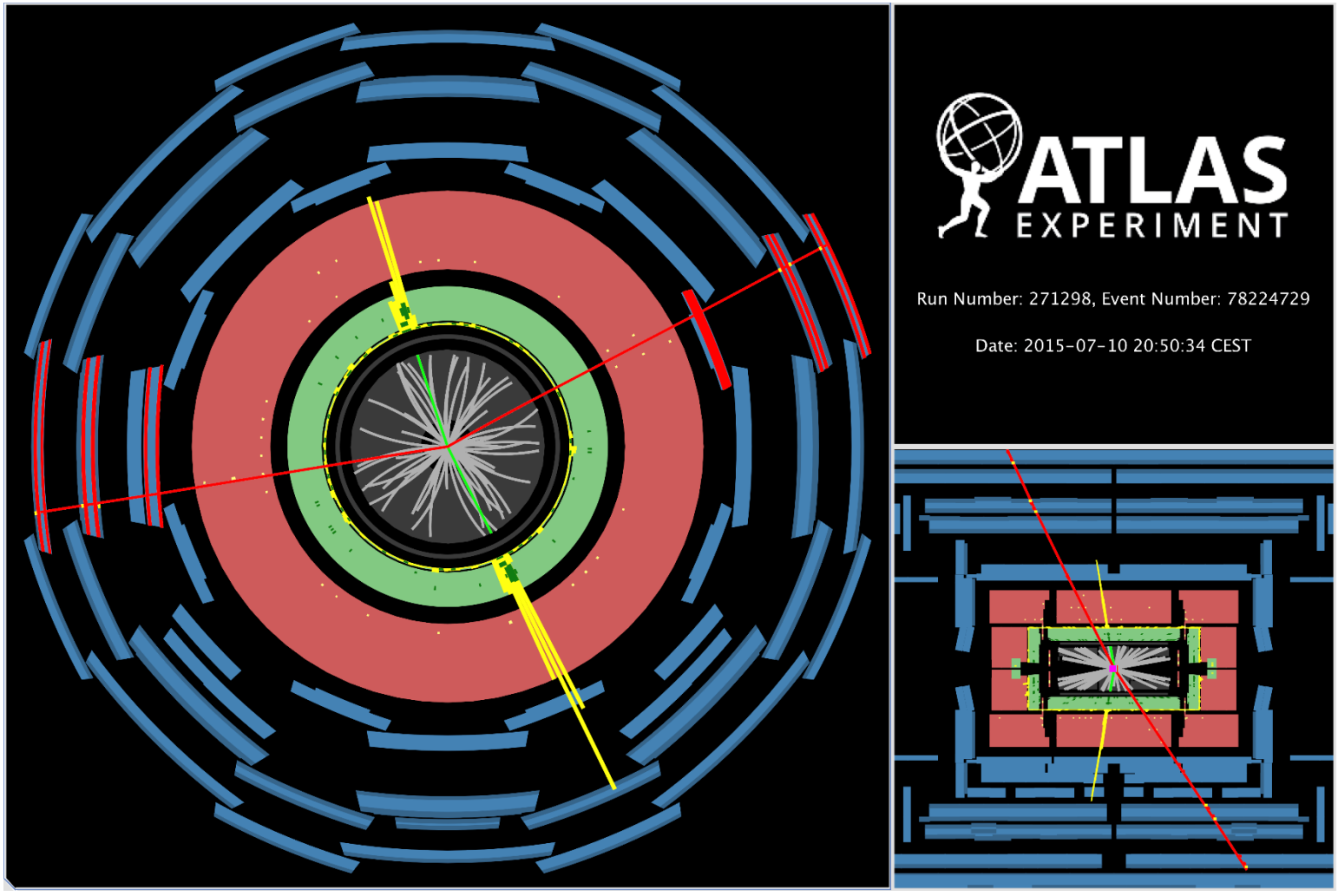
Expected Limits (TeV^{-4})	Observed Limits (TeV^{-4})
$-30.5 < \frac{f_{T0}}{\Lambda^4} < 31.1$	$-37.5 < \frac{f_{T0}}{\Lambda^4} < 38.1$
$-36.9 < \frac{f_{T1}}{\Lambda^4} < 37.5$	$-46.1 < \frac{f_{T1}}{\Lambda^4} < 46.9$
$-83.2 < \frac{f_{T2}}{\Lambda^4} < 83.2$	$-103 < \frac{f_{T2}}{\Lambda^4} < 103$
$-623 < \frac{f_{M2}}{\Lambda^4} < 603$	$-751 < \frac{f_{M2}}{\Lambda^4} < 729$
$-1080 < \frac{f_{M3}}{\Lambda^4} < 1110$	$-1290 < \frac{f_{M3}}{\Lambda^4} < 1340$

Summary

- **Diboson**
  - ✓ **Most measured cross-sections agree with SM predictions (compared to calculations with NNLO QCD corrections)**
  - ✓ **Differential measurements consistent with SM prediction**
  - ✓ **Explored aTGC with good sensitivities**
- **NNLO QCD calculations (MC) are needed**
- **Electroweak Vector Boson Scattering**
  - ✓ **Evidence of VBS observed on ($W\gamma$, $Z\gamma$, $W^{\pm}W^{\pm}$, WZ)jj**
  - ✓ **Cross-sections measured, consistent with SM**
  - ✓ **Starting to probe aQGC**
- **Starting probe triple boson physics including aQGC**
- **Looking forward on LHC Run 2**

Backup

ATLAS 13 TeV ZZ candidate



Inv. Masses of two Z candidates: 94 GeV, 86 GeV

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayRun2Collisions

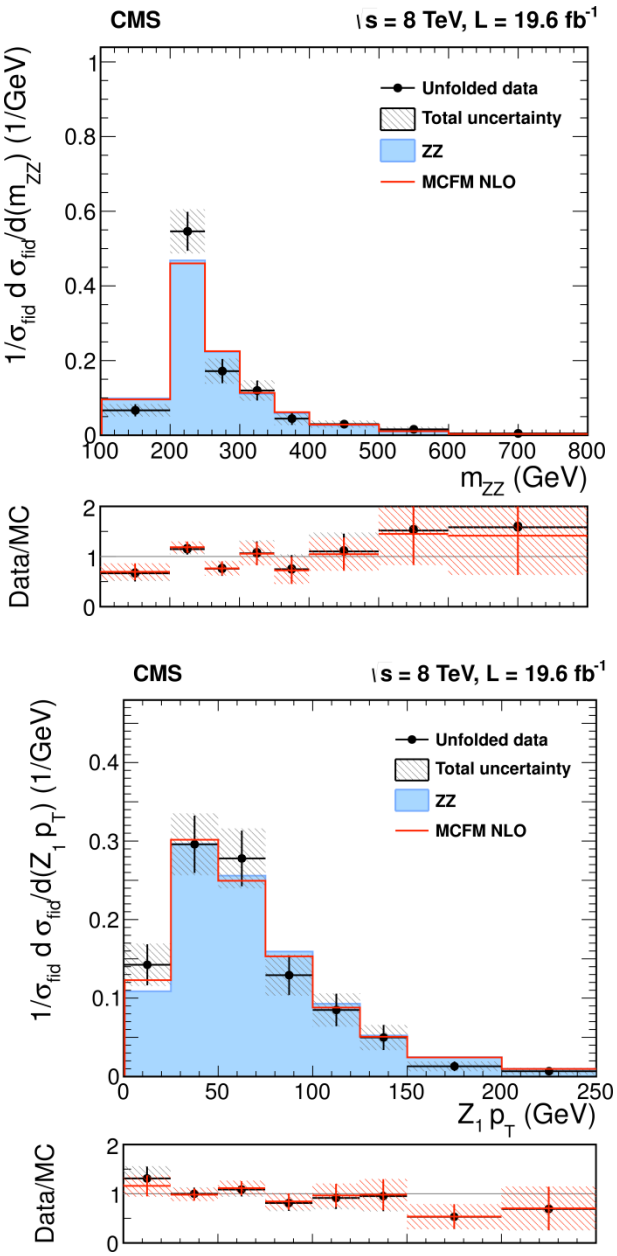
CMS ZZ→4l @8TeV

CMS ZZ-4l: PLB 740 (2015) 250

- ZZ→ℓℓℓ'ℓ' Selection:
  - 4 ℓ(e,μ, ℓ from τ) consistent with ZZ: (ie 2 pair SFOS).
  - $p_T^{Z\ell 1}$>20 GeV, p_T^{other}>10 GeV.
  - 60 < $M_{Z1,2}$< 120 GeV.
- Almost background free
- Measurements found in good agreement with SM NLO qq and LO gg:

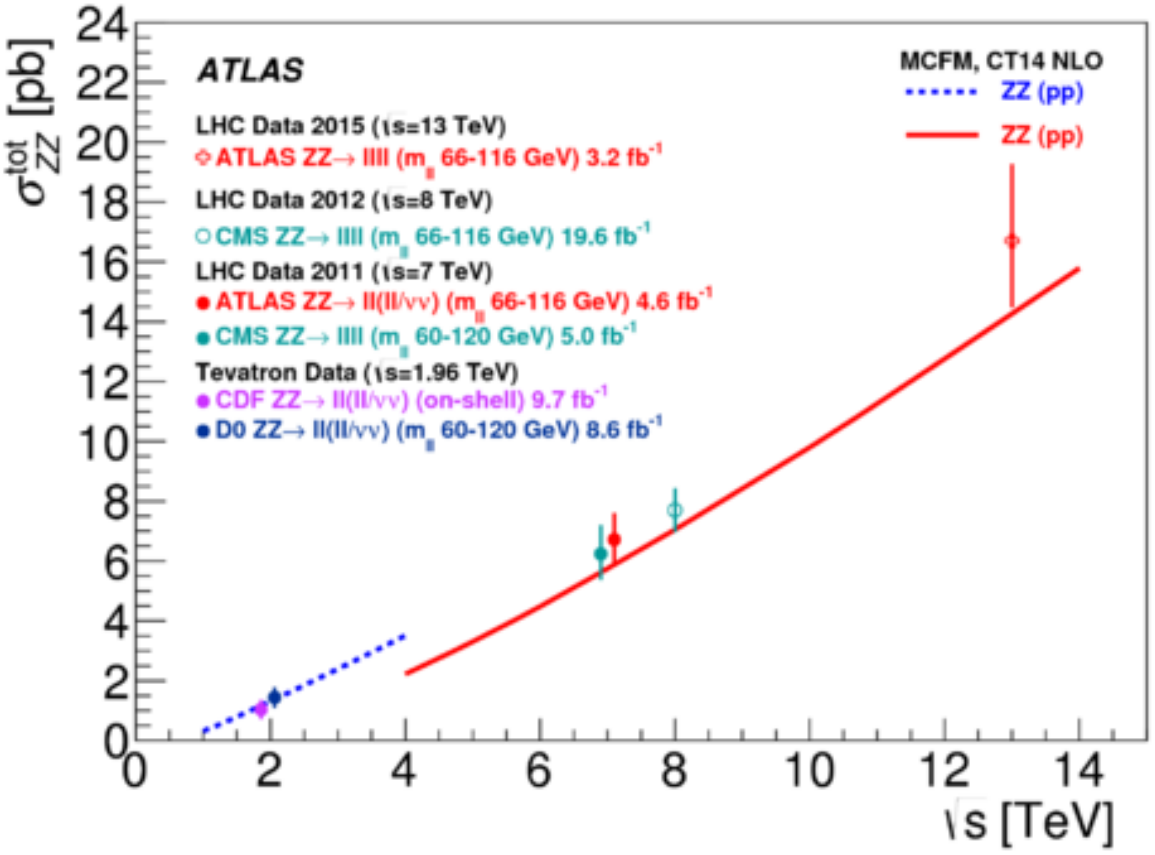
$$\sigma^{tot} = 7.7 \pm 0.5(stat) \pm 0.7(sys) \text{ pb}$$
$$\sigma^{theo}_{NLO} = 7.7 \pm 0.6 \text{ pb}$$

- Provide many differential measurements: $m_{4\ell}$,$p_T^{4\ell}$, $p_T^{\ell 1}$, p_T^{Z1},ΔΦ(ZZ), and ΔR(ZZ)



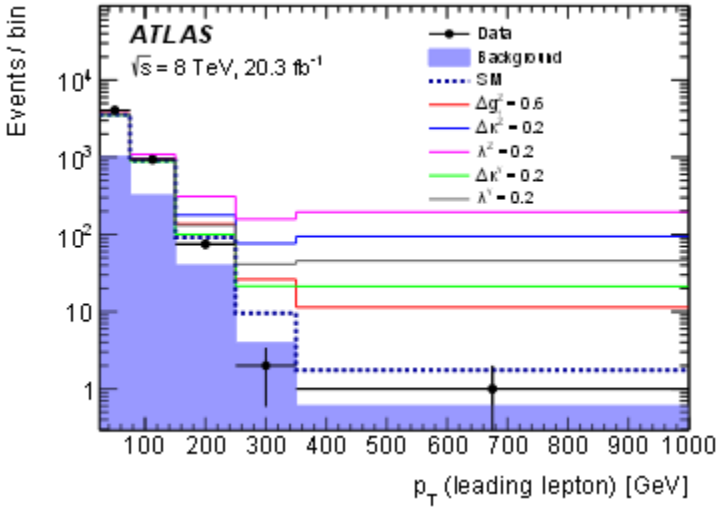
ZZ Cross-section Comparison at different Energy

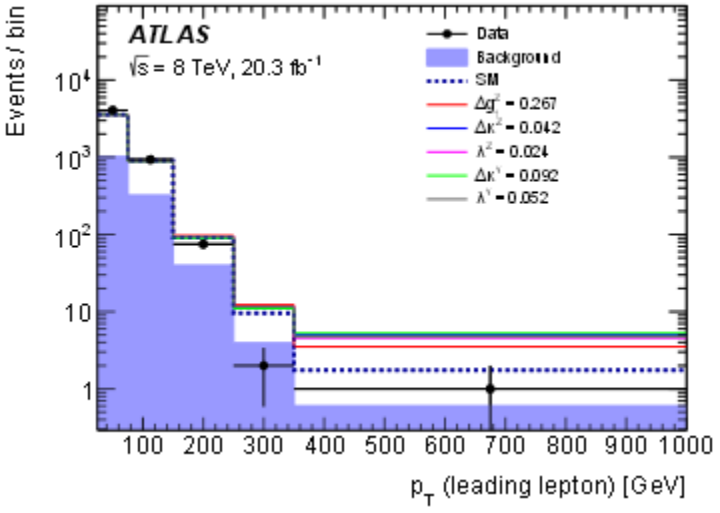
Total cross section compared to measurements at lower center-of-mass energies by ATLAS, CMS, CDF, and D0, and to a prediction from MCFM at $O(\alpha_s^1)$ accuracy for the qq-initiated process and at $O(\alpha_s^2)$ accuracy for the loop-induced gg-initiated process.



8TeV $W^+W^- \rightarrow l\nu l\nu$ aTGCs

arXiv:1603.01702, submitted to JHEP





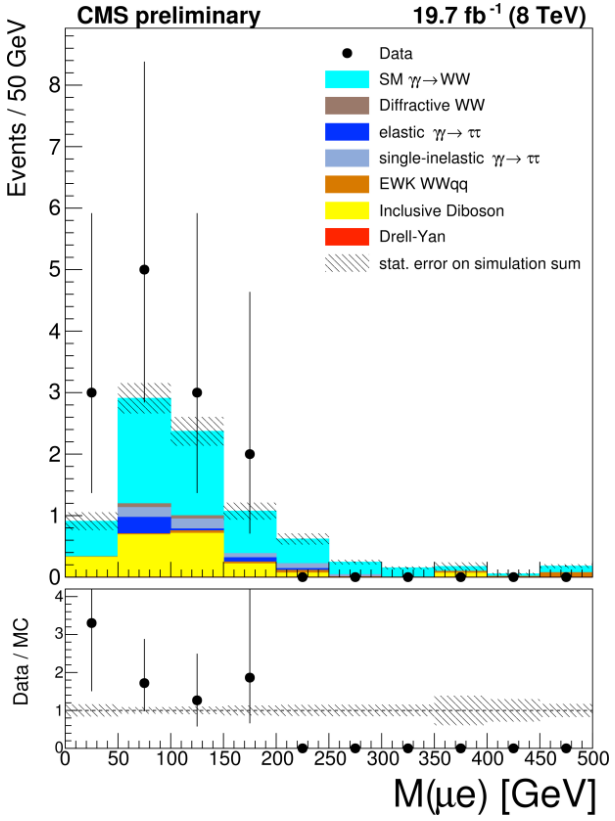
Scenario	Parameter	Expected	Observed	Expected	Observed
		$\Lambda = \infty$		$\Lambda = 7$ TeV	
No constraints scenario	Δg_1^Z	$[-0.498, 0.524]$	$[-0.215, 0.267]$	$[-0.519, 0.563]$	$[-0.226, 0.279]$
	Δk^Z	$[-0.053, 0.059]$	$[-0.027, 0.042]$	$[-0.057, 0.064]$	$[-0.028, 0.045]$
	λ^Z	$[-0.039, 0.038]$	$[-0.024, 0.024]$	$[-0.043, 0.042]$	$[-0.026, 0.025]$
	Δk^γ	$[-0.109, 0.124]$	$[-0.054, 0.092]$	$[-0.118, 0.136]$	$[-0.057, 0.099]$
	λ^γ	$[-0.081, 0.082]$	$[-0.051, 0.052]$	$[-0.088, 0.089]$	$[-0.055, 0.055]$
LEP	Δg_1^Z	$[-0.033, 0.037]$	$[-0.016, 0.027]$	$[-0.035, 0.041]$	$[-0.017, 0.029]$
	Δk^Z	$[-0.037, 0.035]$	$[-0.025, 0.020]$	$[-0.041, 0.038]$	$[-0.027, 0.021]$
	λ^Z	$[-0.031, 0.031]$	$[-0.019, 0.019]$	$[-0.033, 0.033]$	$[-0.020, 0.020]$
HISZ	Δk^Z	$[-0.026, 0.030]$	$[-0.012, 0.022]$	$[-0.028, 0.033]$	$[-0.013, 0.024]$
	λ^Z	$[-0.031, 0.031]$	$[-0.019, 0.019]$	$[-0.033, 0.034]$	$[-0.020, 0.020]$
Equal Couplings	Δk^Z	$[-0.041, 0.048]$	$[-0.020, 0.035]$	$[-0.045, 0.052]$	$[-0.021, 0.037]$
	λ^Z	$[-0.030, 0.030]$	$[-0.019, 0.019]$	$[-0.034, 0.033]$	$[-0.020, 0.020]$

CMS 8TeV: Observation of γγ → W^+W^-

CMS-PAS-FSQ-13-008

- **Large P_T OS eμ from same vertex;**
- **Very challenging from pile-ups: Use** γγ → ll as control sample at pT (ll) ~ 0 to study charged track veto and characterize to correct for non-elastic contributions
- **Significance over BKG only hypothesis 3.6σ(Exp:2.4σ), Good agreement with LO predictions**

$$\sigma_{tot} = 12.3^{+5.5}_{-4.4} \text{ fb}$$
$$\sigma_{LO} = 6.9 \pm 0.6 \text{ fb}$$



LHC VBS $W^{\pm}W^{\pm}jj$

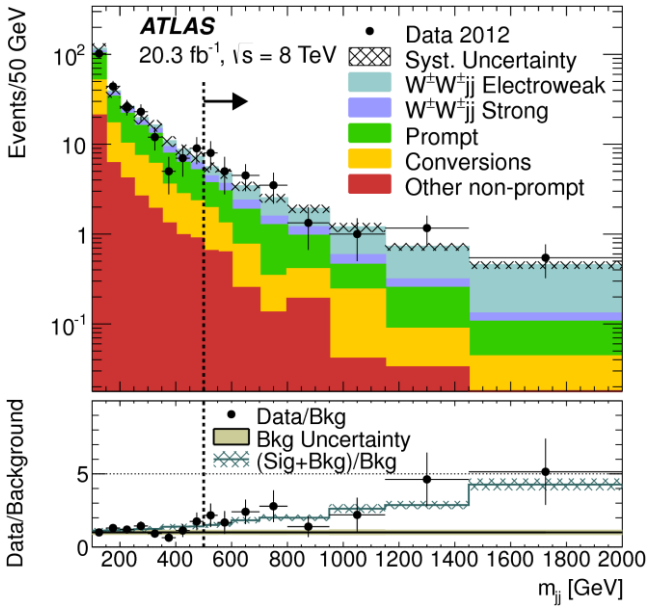
8TeV, [ATLAS: PRL. 113, (2014) 141803](#) [CMS: PRL. 114 (2015) 051801](#)

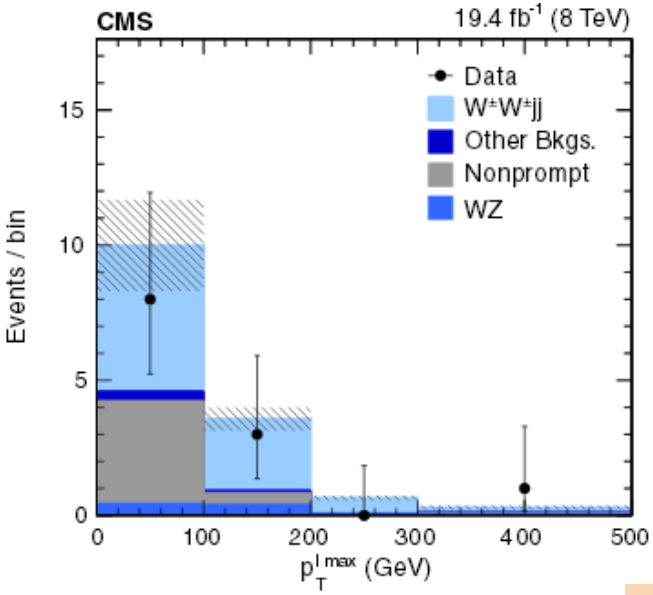
- Very interesting channel since QCD (gg) production is suppressed, and benefits from small background. Very good signal (EWK $W^{\pm}W^{\pm}$) over background ratio.
- Essential to probe EWSB mechanism (would violate unitarity without a SM Higgs).
- Events selected by requiring a pair SS leptons & two well separated jets with large jet invariant mass
- Important BKG from fake and charge flip (e) estimated from data.
- **Both analyses have sensitivity to first evidence: ATLAS 3.6σ (2.8σ), CMS 2.0σ (3.1σ)**
- **Measurements consistent with prediction:**

$$\sigma_{fid}^{CMS} = 4.0 \pm 2.4(stat) \pm 1.1(sys) fb$$
$$\sigma_{theo}^{CMS} = 5.8 \pm 1.2 fb$$

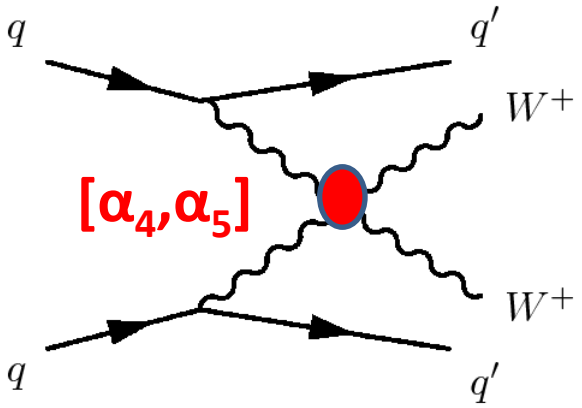
ATLAS:

$$\sigma_{fid}^{all} = 2.1 \pm 0.5(stat) \pm 0.3(sys) fb$$
$$\sigma_{theo}^{all} = 1.52 \pm 0.11 fb$$
$$\sigma_{fid}^{EWK} = 1.3 \pm 0.4(stat) \pm 0.2(sys) fb$$
$$\sigma_{theo}^{EWK} = 0.95 \pm 0.06 fb$$





LHC VBS $W^{\pm}W^{\pm}jj$: aQGC Limits



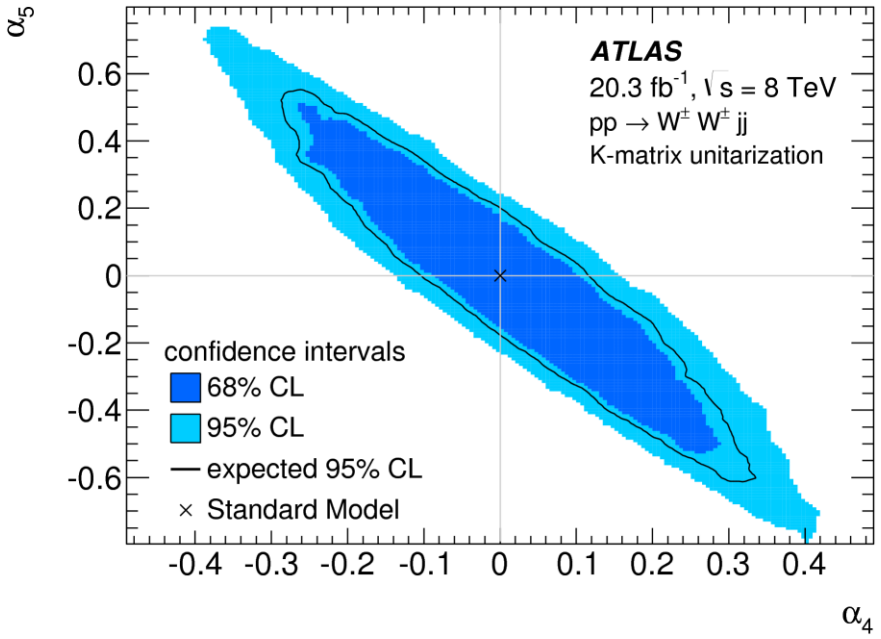
$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_d \sum_i \frac{\alpha_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Use measured "VBS" cross section to limit aQGCs:
F_{S0} and F_{S1} non unitarized for CMS and unitarized with Kmatrix formalism for ATLAS

CMS observed/expected QGC limits (TeV^{-4})

Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08

ATLAS aQGC limits



CSM Wγγ & Zγγ Fiducial Definitions

CMS-PAS-SMP-15-008

Definition of $W^{\pm}\gamma\gamma$ Fiducial Region
$p_T^{\gamma} > 25\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_T^{\ell} > 25\,\text{GeV}$, $\lvert\eta^{\ell}\rvert < 2.5$
Exactly one candidate muon and two candidate photons
$m_T(\ell, \nu_{(s)}) > 40\,\text{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$ and $\Delta R(\gamma,\ell) > 0.4$

Definition of $Z\gamma\gamma$ Fiducial Region
$p_T^{\gamma} > 15\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 2.5$
$p_T^{\ell} > 10\,\text{GeV}$, $\lvert\eta^{\ell}\rvert < 2.5$
Exactly two candidate leptons and two candidate photons
lead $p_T^{\ell} > 20\,\text{GeV}$
$M_{\ell\ell} > 40\,\text{GeV}$
$\Delta R(\gamma,\gamma) > 0.4$, $\Delta R(\gamma,\ell) > 0.4$, and $\Delta R(\ell,\ell) > 0.4$