Diboson Production, Vector Boson Fusion and Vector Boson Scattering measurements with the ATLAS detector

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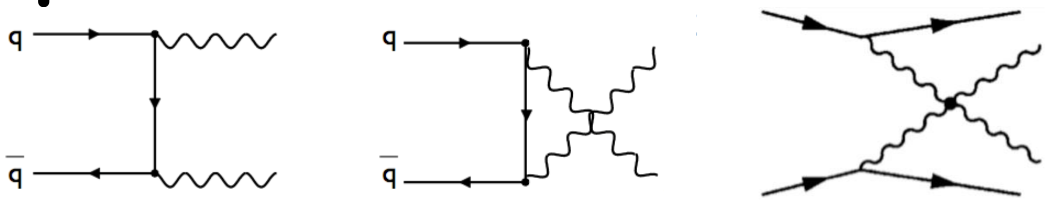
On behalf of ATLAS Collaboration

Outline

- ❑Physics motivations
- ❑Introduction to ATLAS
- ❑Productions of WW, WZ and ZZ
- ❑Productions of WWW and WVγ
- ❑VBF/VBS measurements
- ❑Summary

Physics of Di-boson production (LHC)

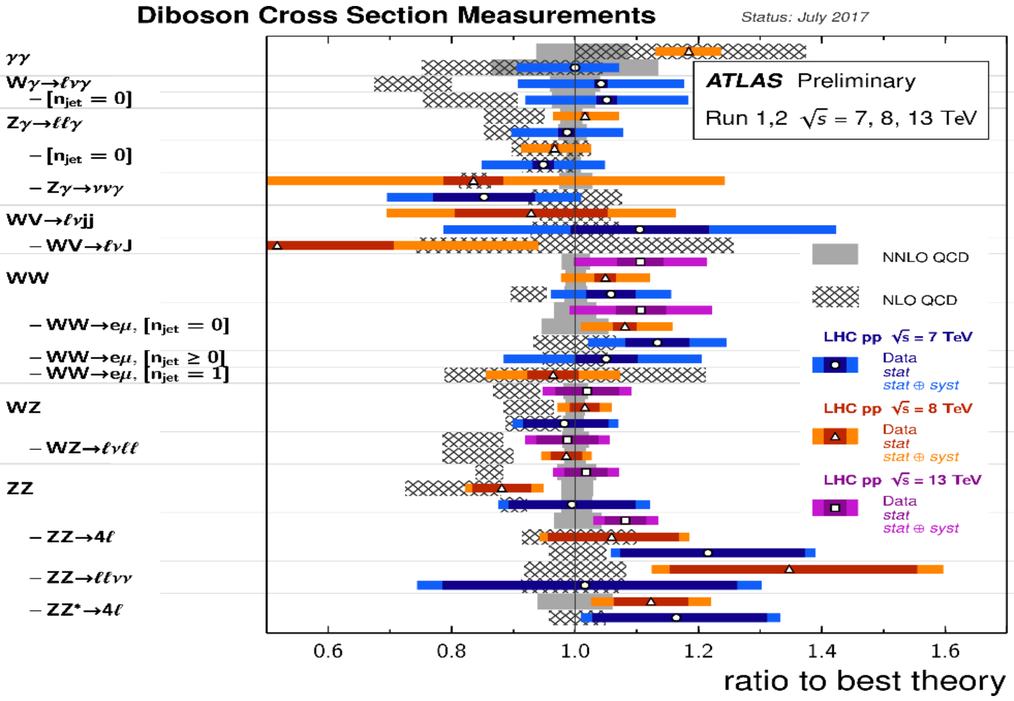
- Measurements of vector boson pair production provide excellent tests of the electroweak (EWK) sector of the Standard Model (SM).
- Precision measurement helps: 1> Higgs property measurement; 2> new physics search at TeV scale (anomalous gauge boson couplings → triple or quartic)

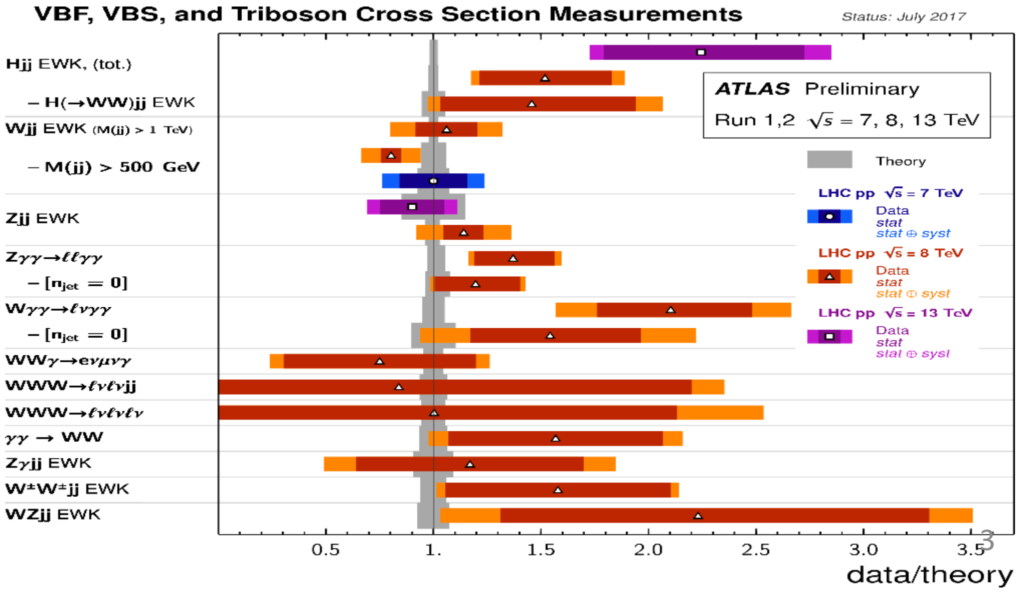


Standard Model Production

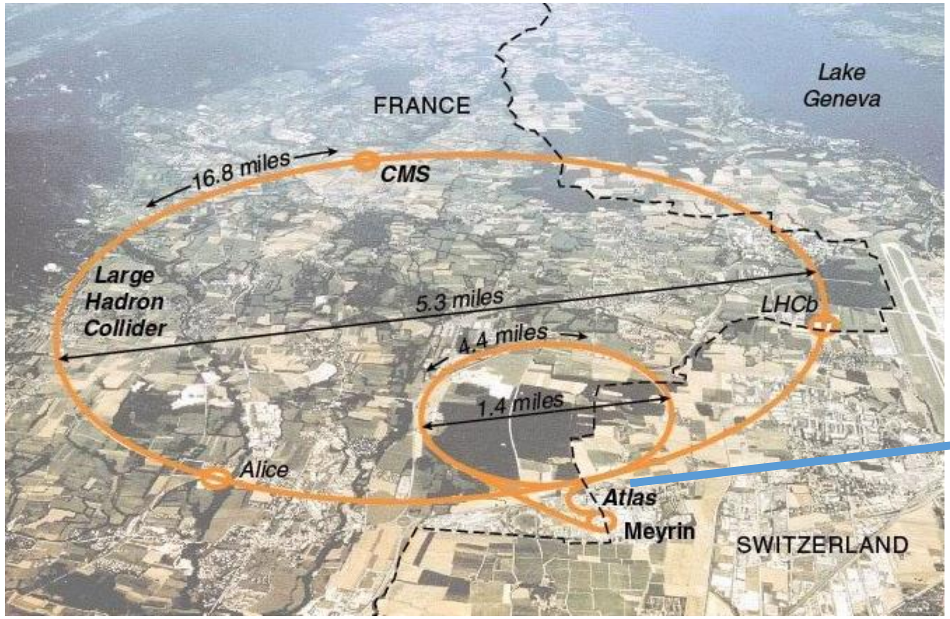
VBF/VBS

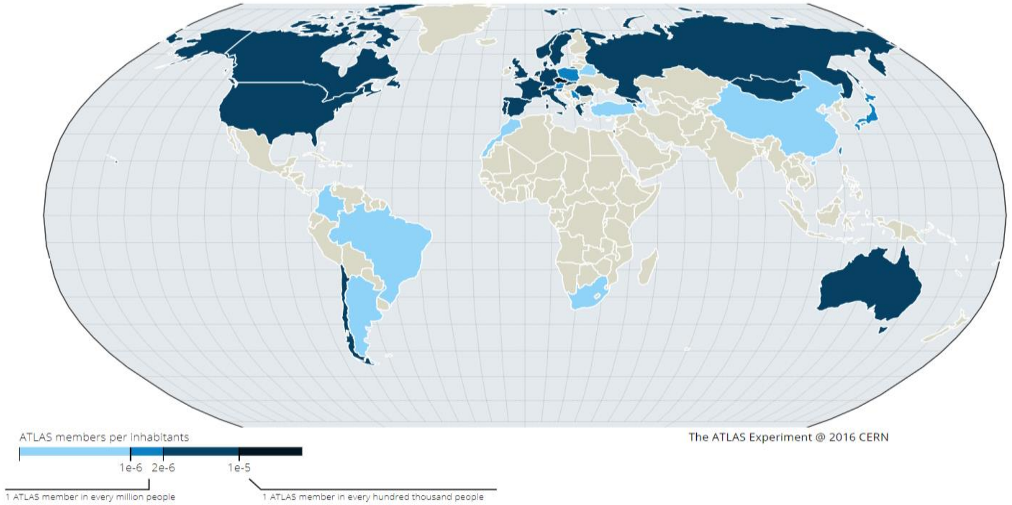
- ❑ The longitudinally polarized Vector Boson Scattering(VBS) increases as a function of the center-of-mass energy and violates unitarity at TeV scale if no SM Higgs mechanism.
- ❑ Measurements of the VBS process indirectly reflect/prove the SM Higgs mechanism and help searches for new physics in TeV scale.

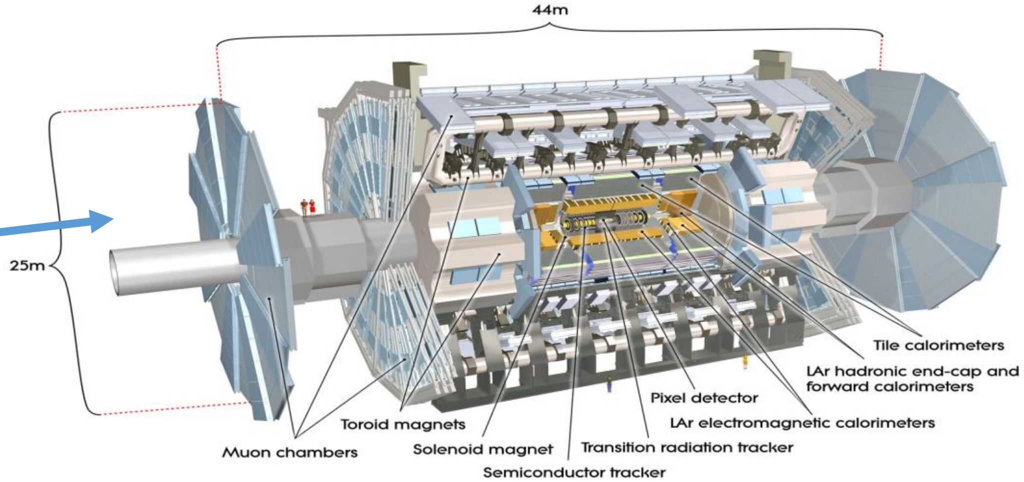




ATLAS Collaboration

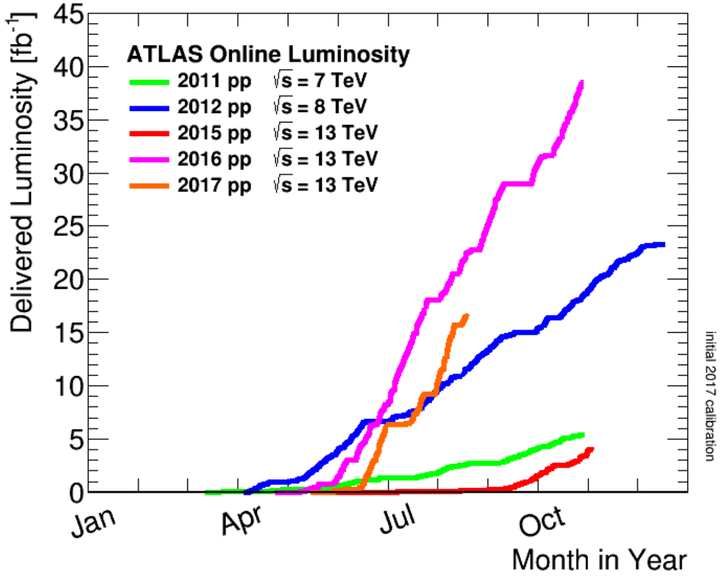




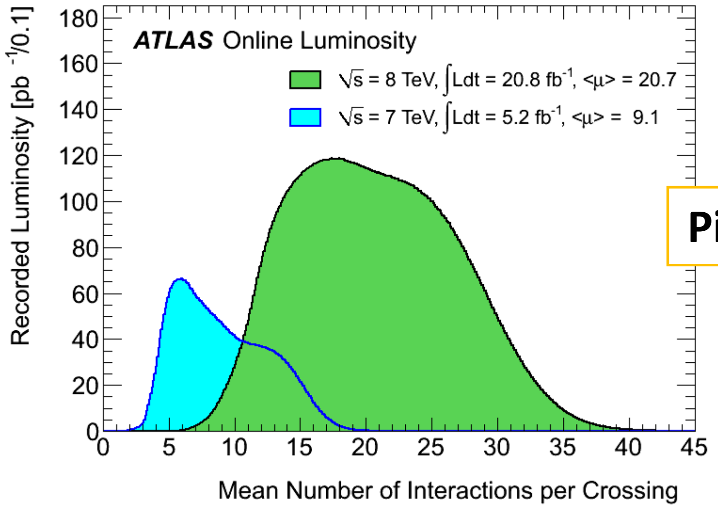


- CERN: Hadron Collider, crossing border between France and Switzerland
- ATLAS: >3000 scientific authors from about 182 institutions in 38 countries.
- Almost 1200 doctoral students are involved in detector development, data collection and analysis.

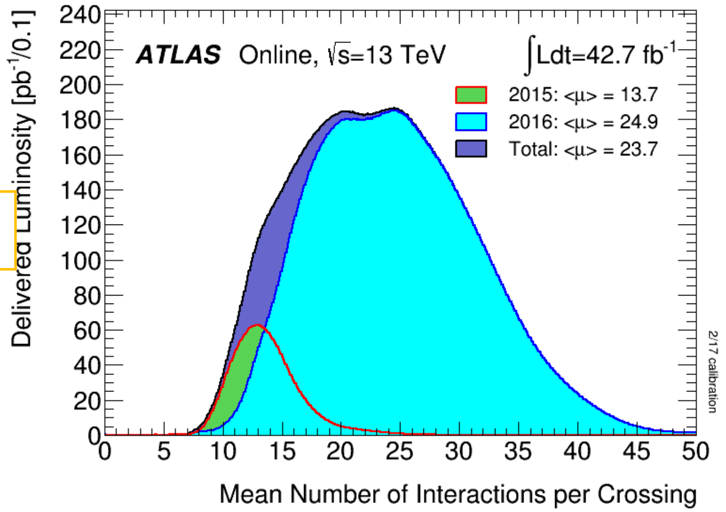
ATLAS data taking (proton-proton)



	2010-2011	2012	2015	2016
E.C.M	7 TeV	8 TeV	13 TeV	13 TeV
Peak Lumi.	$3.7*10^{33}$	$7.7*10^{33}$	$5.0*10^{33}$	$13.8*10^{33}$
Good Run Lumi.	4.57 fb^{-1}	20.3 fb^{-1}	3.2 fb^{-1}	32.9 fb^{-1}



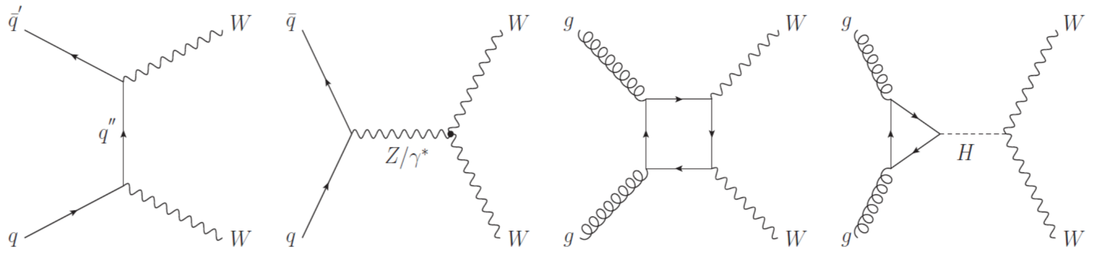
Pile-up



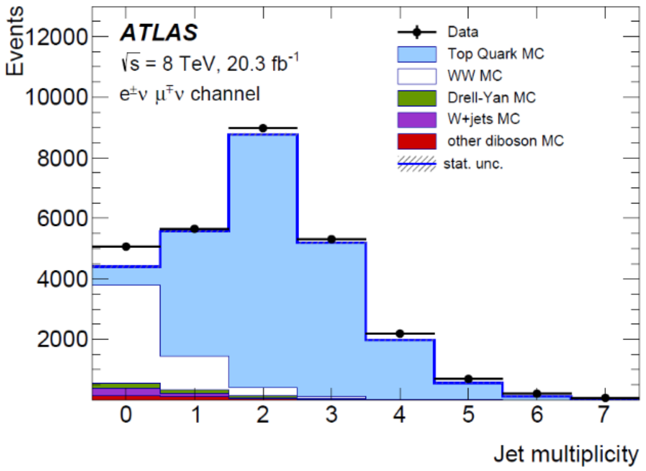
Cross section measurements:
WW, WZ and ZZ

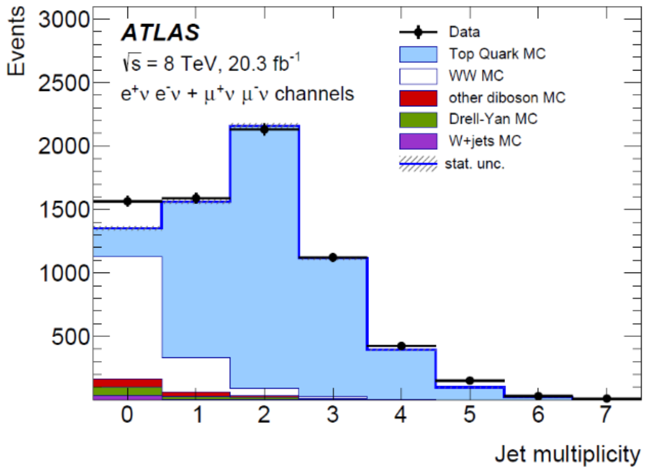
WW at 8TeV

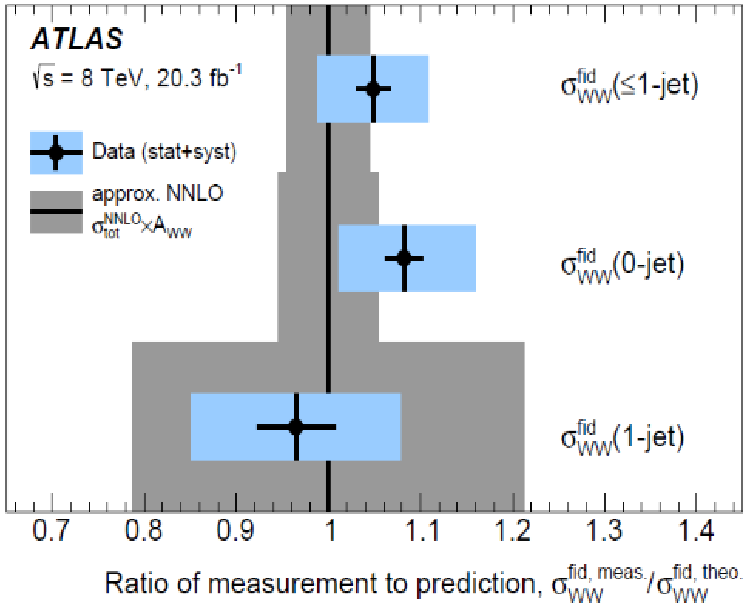
- Methodology: select **leptonic decay** of W ➔ eμ, ee, μμ
- Major background: Top, drell-Yan, W+jets, WZ, ZZ



(a) *t*- channel (b) *s*- channel (TGC vertex) (c) gluon fusion (d) Higgs boson production







8TeV [JHEP 09(2016)029, PLB 763(2016)114]

- WW+0jet : eμ, ee, μμ
- WW+1jet: only eμ

In **good agreement** with predictions:

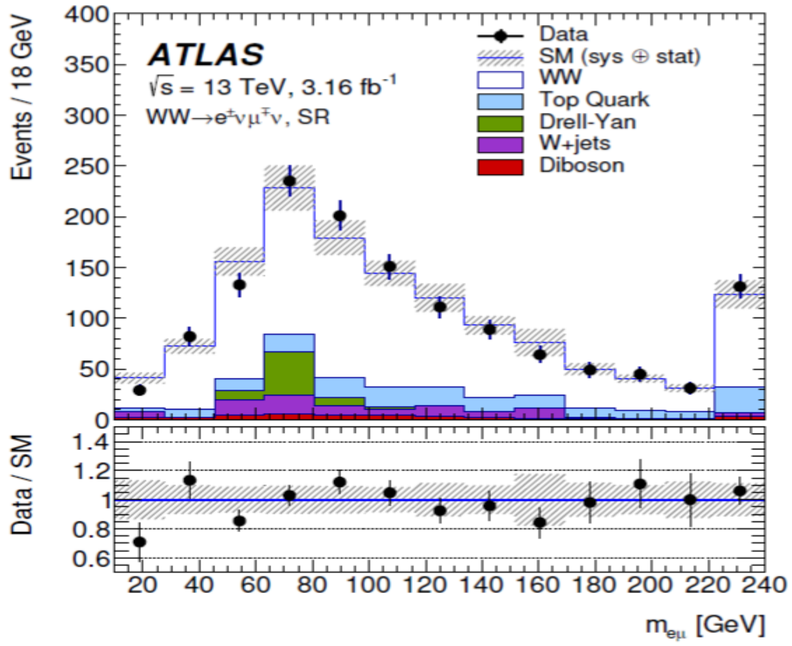
- qq→WW: at $O(\alpha_s^2)$
- gg→WW: at $O(\alpha_s^3)$
- gg→H→WW: at $O(\alpha_s^4)$

WW at 13TeV

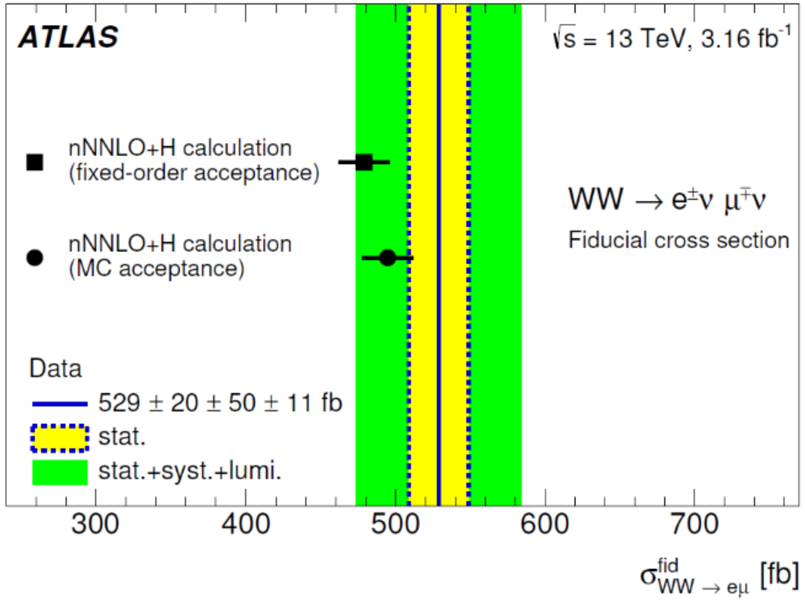
arXiv:1702.04519

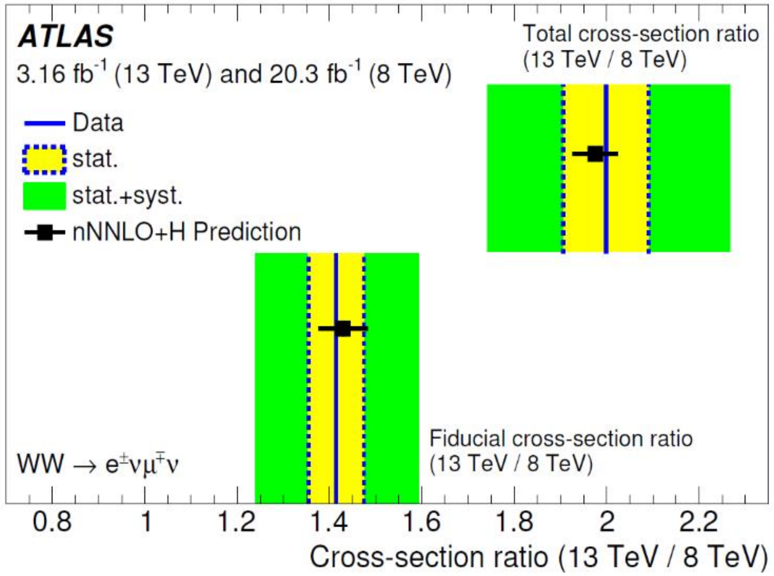
Methodology: select **leptonic decay** of W ➔ eμ + 0jet

In **good agreement** with predictions of 'approximate NNLO' + Higgs



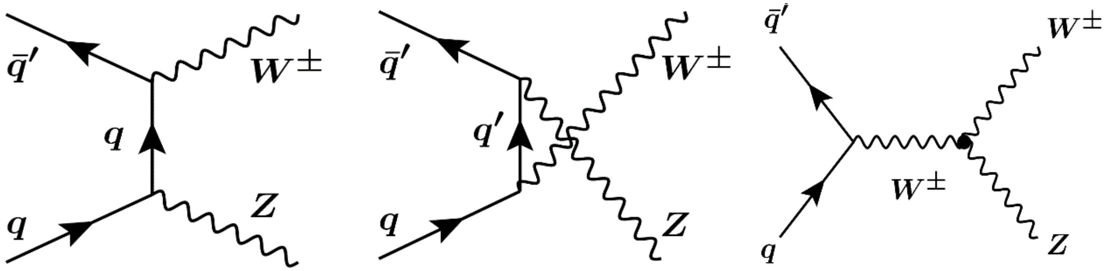
$pp \to WW$ sub-process	Order of α_s	σ^{tot}_{WW} [pb]	A [%]	$\sigma^{fid}_{WW\to e\mu}$ [fb]
$q\bar{q}$	$O(\alpha_s^2)$	111.1 ± 2.8	16.20 ± 0.13	$422\ ^{+12}_{-11}$
gg (non-resonant)	$O(\alpha_s^3)$	$6.82\ ^{+0.42}_{-0.55}$	$28.1\ ^{+2.7}_{-2.3}$	44.9 ± 7.2
$gg \to H \to WW$	$O(\alpha_s^5)$ tot. / $O(\alpha_s^3)$ fid.	$10.45\ ^{+0.61}_{-0.79}$	4.5 ± 0.6	11.0 ± 2.1
$q\bar{q} + gg$ (non-resonant) + $gg \to H \to WW$	nNNLO+H	$128.4\ ^{+3.5}_{-3.8}$	$15.87^{+0.17}_{-0.14}$	478 ± 17



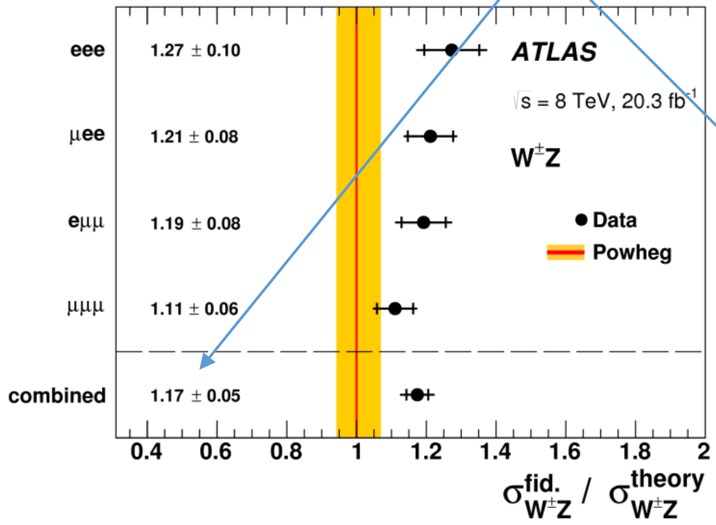


WZ at 8TeV and 13TeV

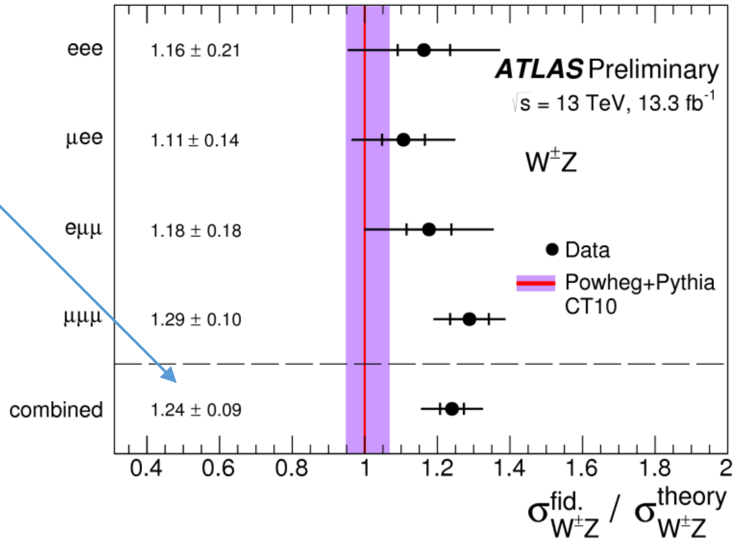
- Methodology: select **leptonic decays** of W/Z ➔ three lepton final states (eee, eeμ, μμe, μμμ) + E_T^{miss}
- Major background: Z+jets, Top, WW (Jets fake lepton); ZZ, ttV, VVV (irreducible)

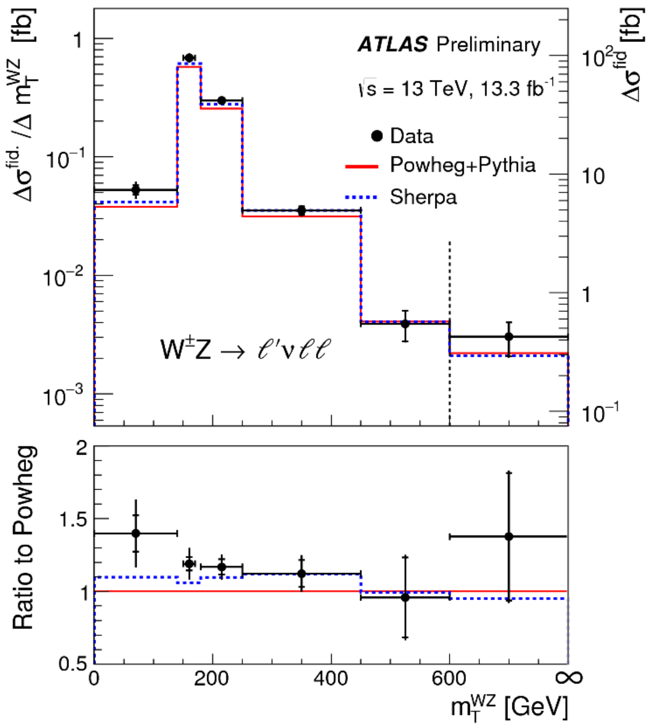


➢ Comparison with NLO prediction evidently show the NNLO QCD effect is needed to improve the agreement between data and prediction:>15% level for both 8TeV and 13TeV.



PRD 93, 092004 (2016)



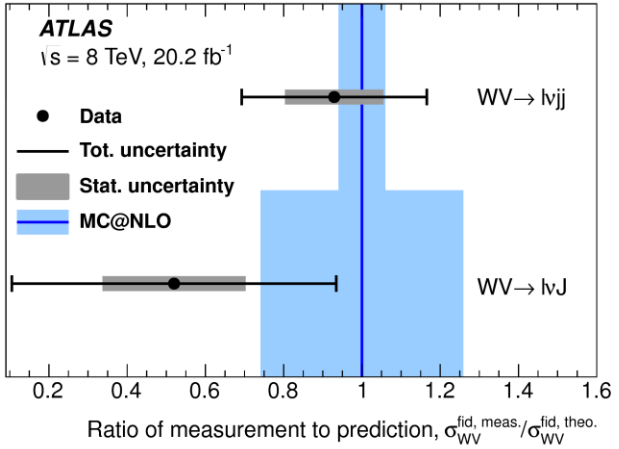


ATLAS-CONF-2016-043

Semileptonic WV (V=W,Z) production at 8TeV

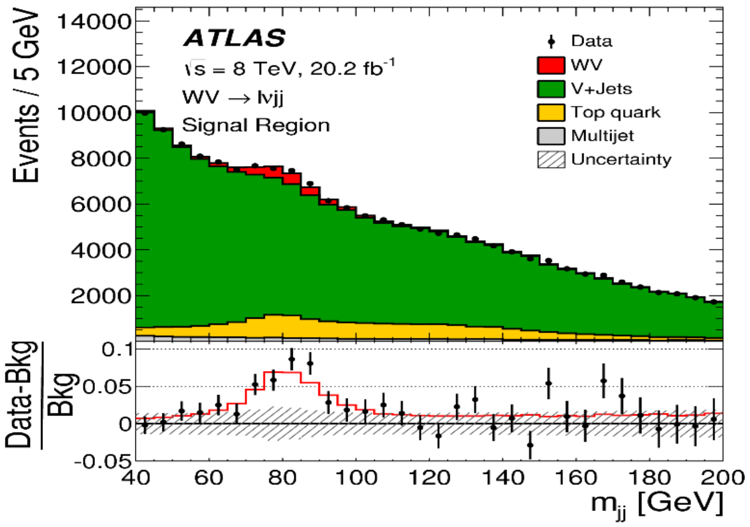
arXiv:1706.01702

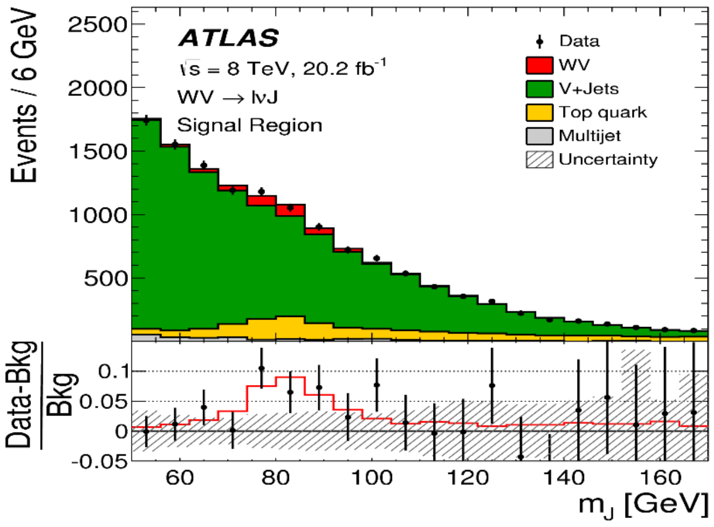
- Semileptonic WV: W→eν/μν, V(W,Z)→qq' (two jets) → higher statistics than leptonic channel.
- At reconstruction level, there will be cases with two separated jets or a merged jet for the qq' ➔ two categories: **lvjj** and **lvJ** (J means a large R jet) in the reco analysis.
- Major background: W+jets (dominant), Z+jets, Top and ZZ



Significance	Observed	Expected
WV→lvjj	4.5σ	5.2σ
WV→lvJ	1.3σ	2.5σ

Jet algorithm → anti-k_t algorithm
Small-R jet: radius parameter R=0.4
Large-R jet: R=1.0, jet trimming to reduce the pile-up effect.

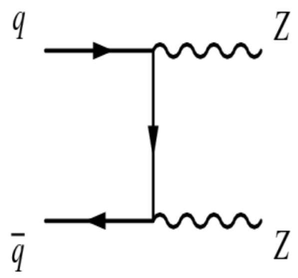


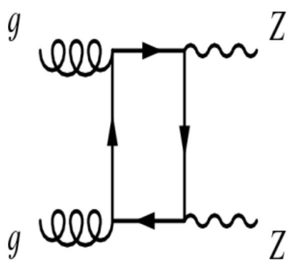


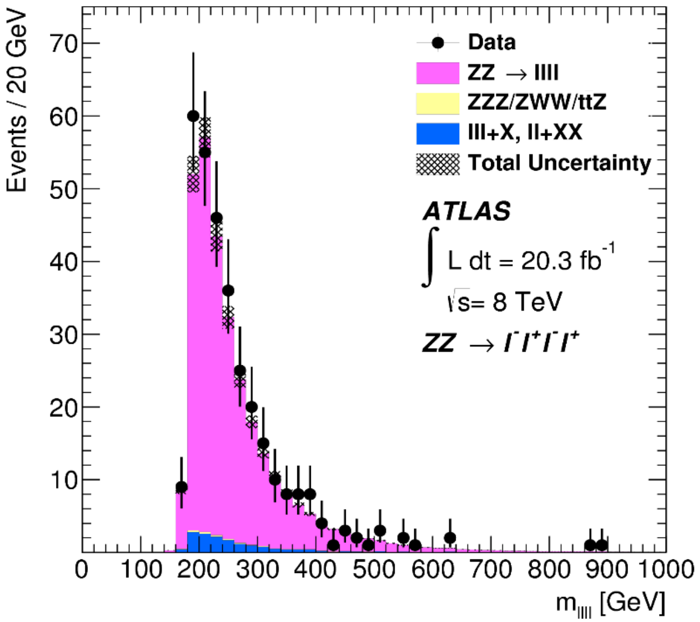
ZZ at 8TeV

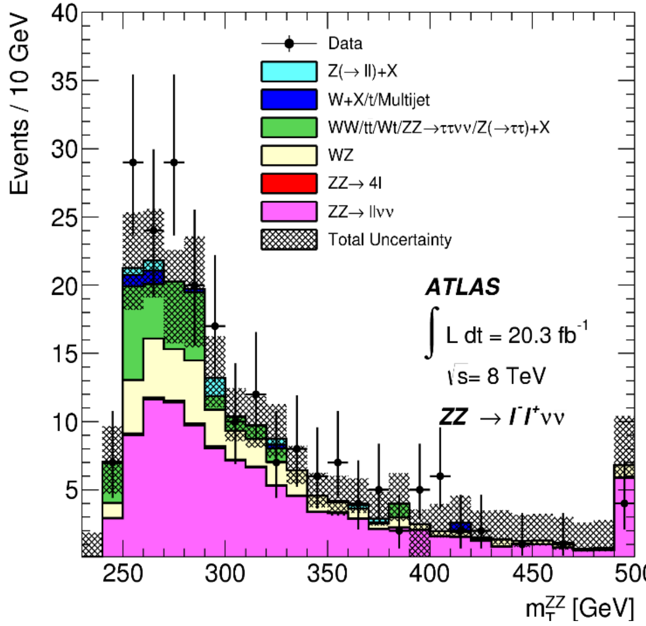
JHEP 01(2017)99

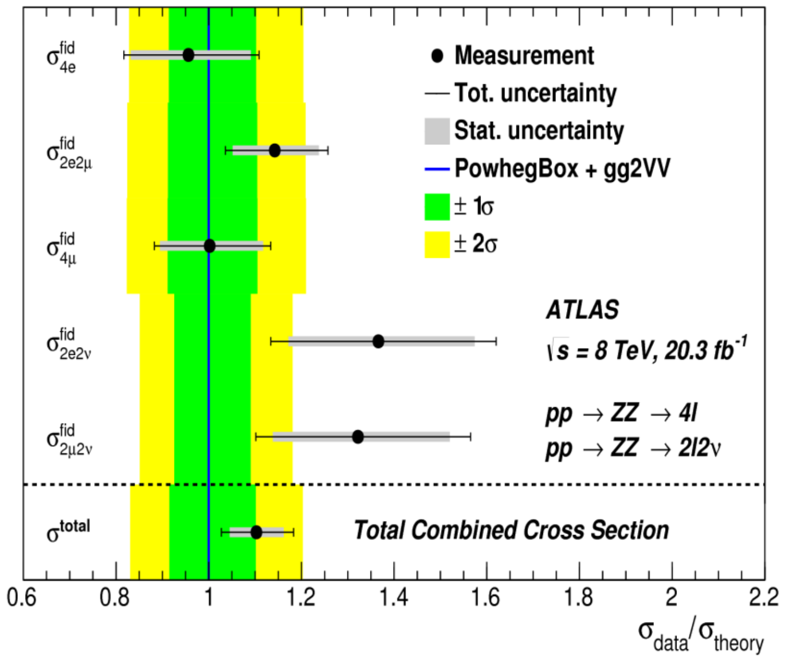
- Methodology: select **leptonic decays** of ZZ ➔ four leptons (4l) or two-lepton+two-neutrinos (2l+E_T^{miss})
- Major background: Z+jets, Top (jets fake bkg) for four-lepton channel; WZ, Top, Z+jets for 2l2v
- **Good Agreement** with SM predictions.











Both Z's are on-shell, 66GeV< M(ll) < 116 GeV

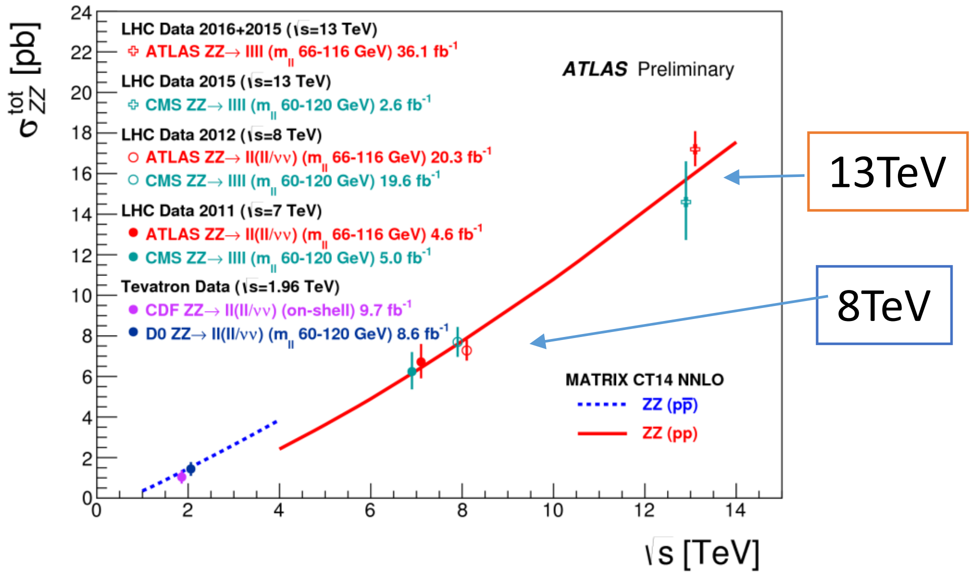
$$(m_{\mathrm{T}}^{ZZ})^2 \equiv \left(\sqrt{m_Z^2 + \left|p_{\mathrm{T}}^{\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|\vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}\right)^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2$$

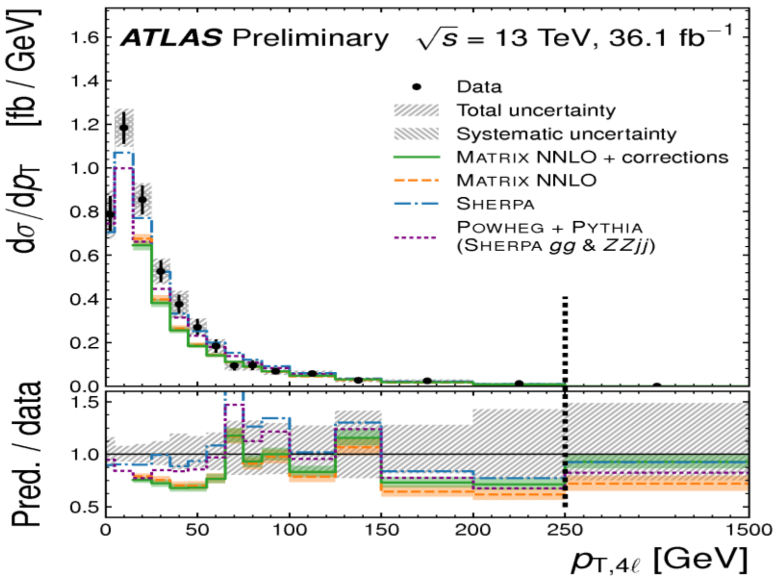
ZZ at 13TeV

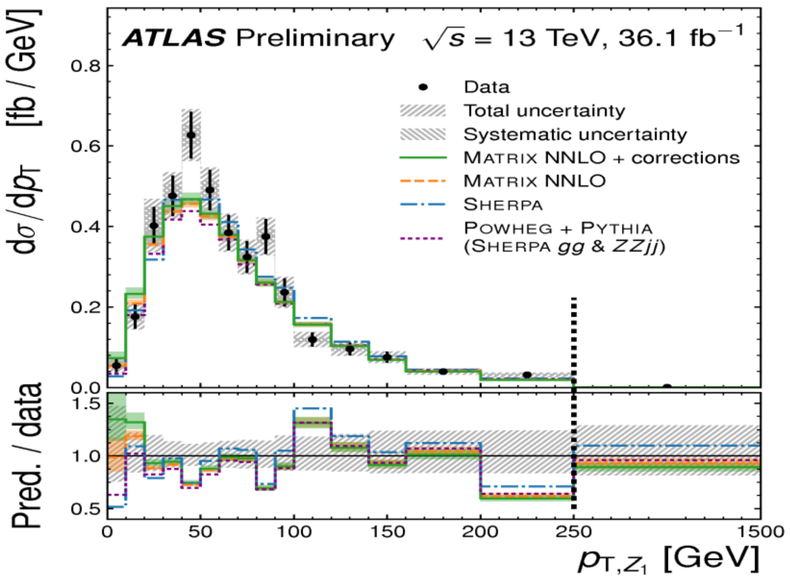
ATLAS-CONF-2017-031; PRL 116,101801(2016)

- Methodology: select **leptonic decays** of ZZ ➔ four leptons
- Major background: Z+jets, Top (jets fake lepton)

➢ Good Agreement with "***MATRIX NNLO+correction***":
  - ✓ qq→ZZ: at $O(\alpha_s^2)$; gg→ZZ: at $O(\alpha_s^3)$





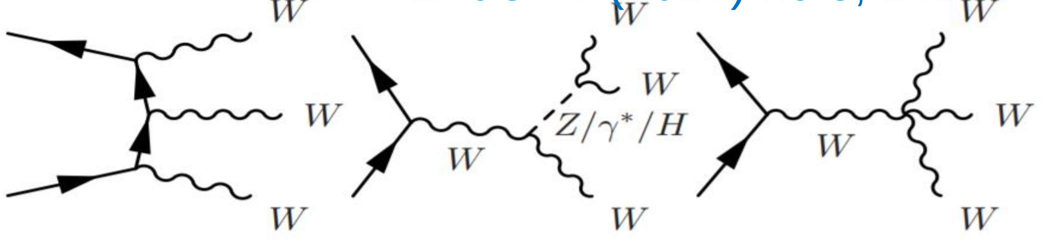


Measurements of
WWW and WVγ

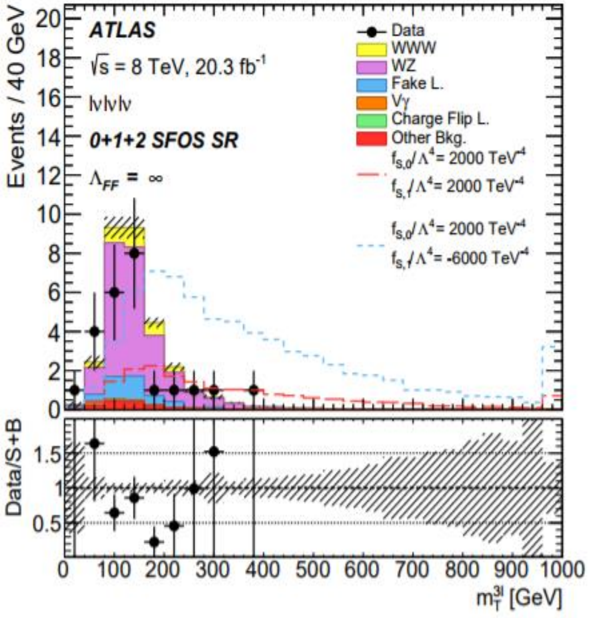
Tri-boson WWW production at 8TeV

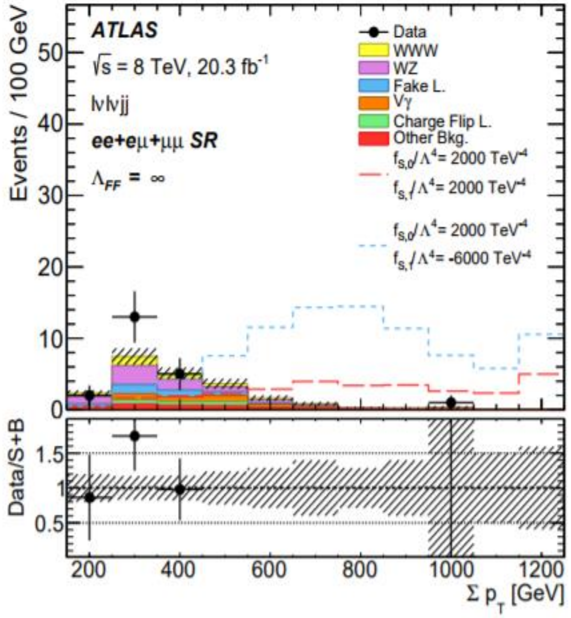
EPJC 77 (2017) no.3, 141

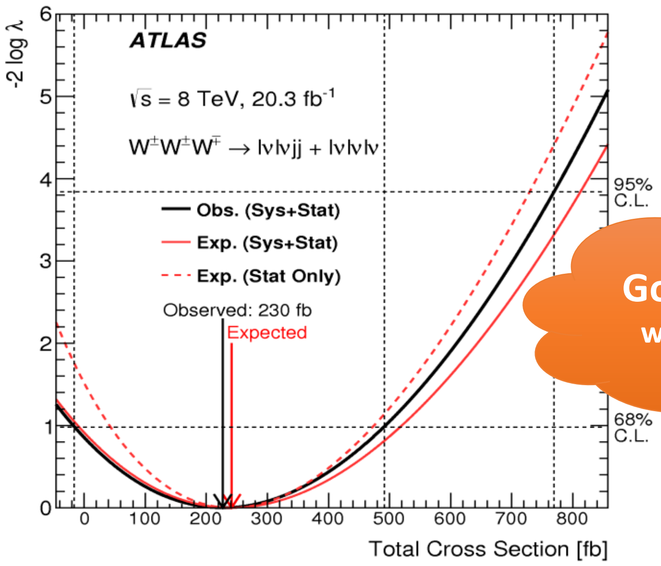
- Help to test the triple and quatic gaugle boson self-interactions, and search for any deviation in high energy.
- Methodology: select WWW→lvlvlv and same-charge lepton pair WWW→lvlvjj
- Major background: WZ+jets, Wγ+jets (photon→lepton), charge-flipped, fake bkg (jets→lepton)



Significance	Observed	Expected
lvlvlv + lvlvjj	0.96σ	1.05σ





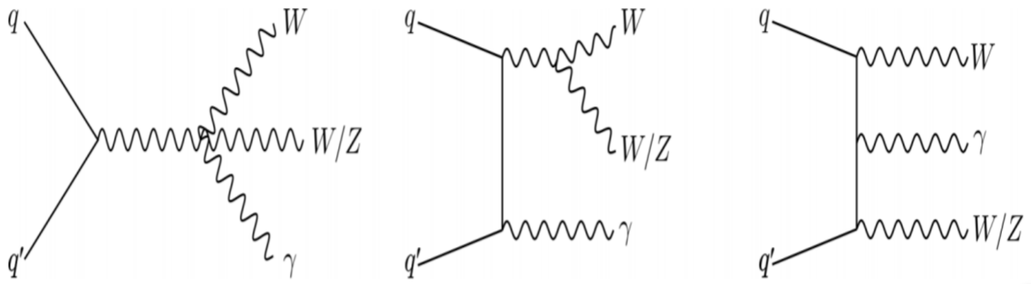


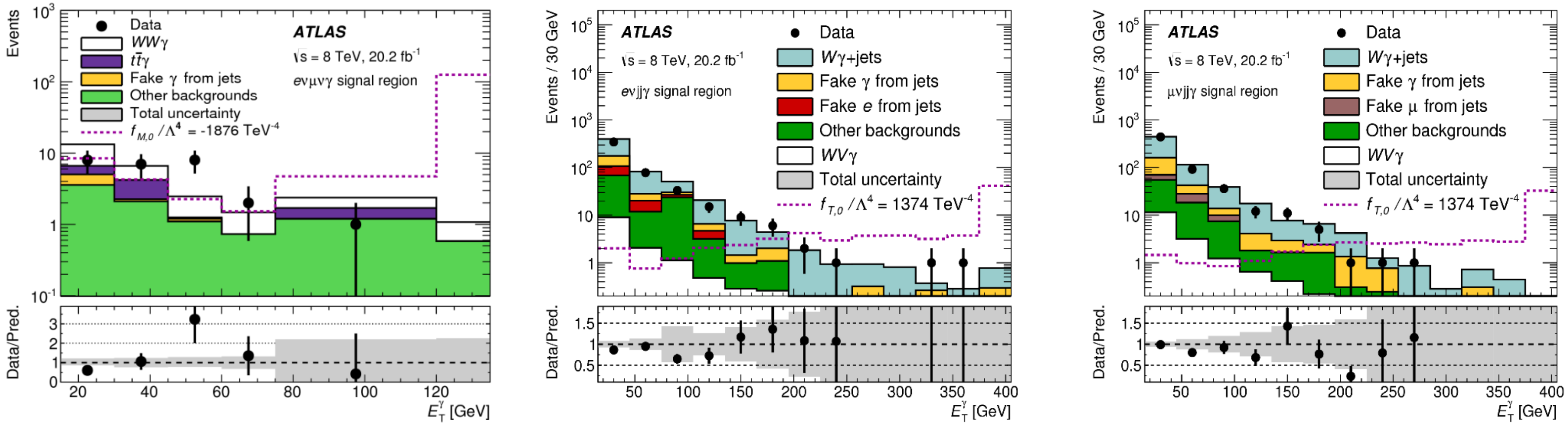
Good Agreement
with SM prediction!

WVγ (V=W or Z) production at 8TeV

arXiv:1707.05597

- Methodology: select WWγ → evμvγ and WVγ (V=W,Z)→ evjjγ or μvjjγ
- Major background: WZ, ZZ, Zγ, Top, W+jets and Z+jets





		Observed limit [fb]	Expected limit [fb]	σ_{theo} [fb]
Fully leptonic	$e\nu\mu\nu\gamma$	3.7	$2.1^{+0.9}_{-0.6}$	2.0
Semileptonic	$e\nu jj\gamma$	10	16^{+6}_{-4}	2.4
	$\mu\nu jj\gamma$	8	10^{+4}_{-3}	2.2
	$\ell\nu jj\gamma$	6	$8.4^{+3.4}_{-2.4}$	2.3

Obs Significance of full leptonic channel: 1.4σ (1.6σ exp)

→ **No deviation from SM**

VBF/VBS measurements

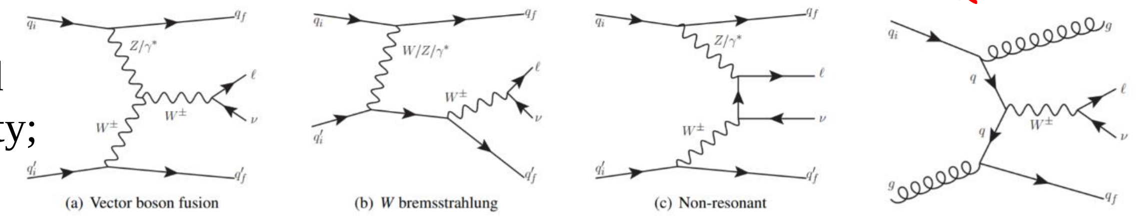
EWK W+2jets at 7TeV and 8TeV

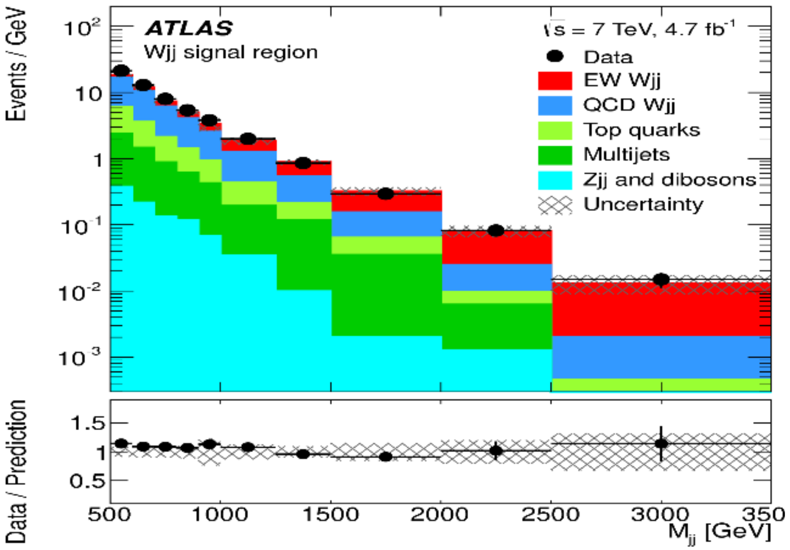
arXiv:1703.04362

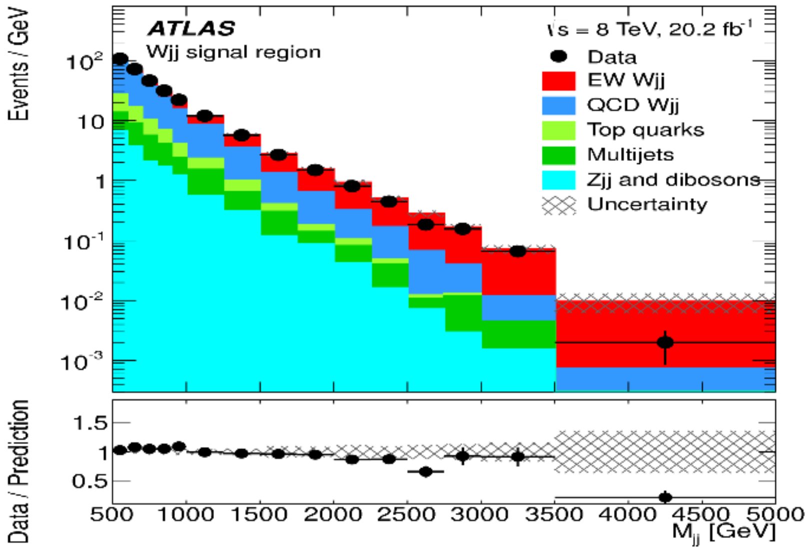
- Methodology: select leptonic W decay + 2jets (EWK)
  - ❑ Signal region (EWK): >=2 large pT jets; only the lepton and no additional jets are in the interval of two leading-jet rapidity; m(jj)>500GeV, etc
  - ❑ Control region (forward-lepton): neither the lepton from W nor any additional jets in the interval of two leading-jet rapidity ➔ to control the contribution of **QCD W+2jets (dominant background)**.

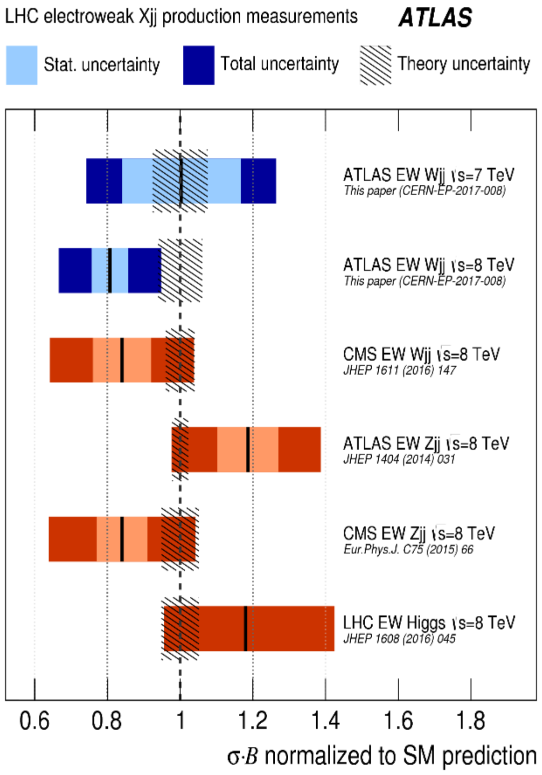
EWK

QCD





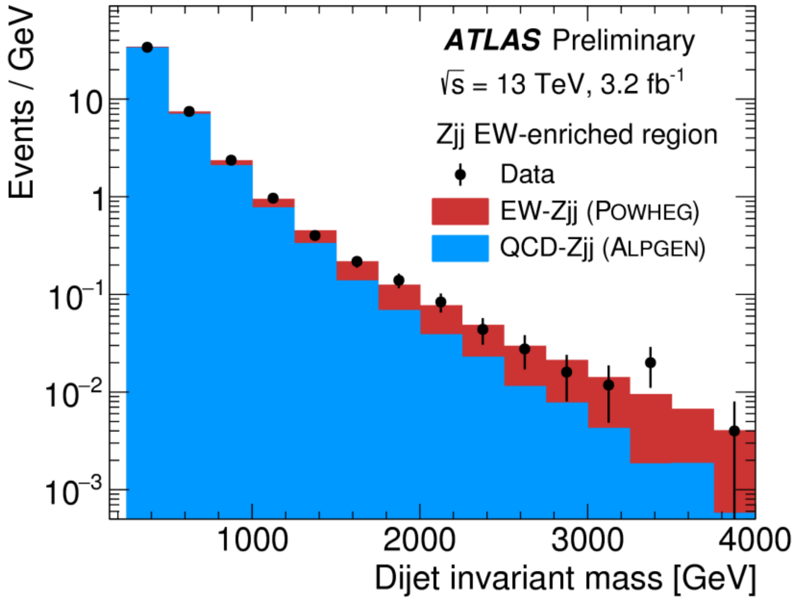




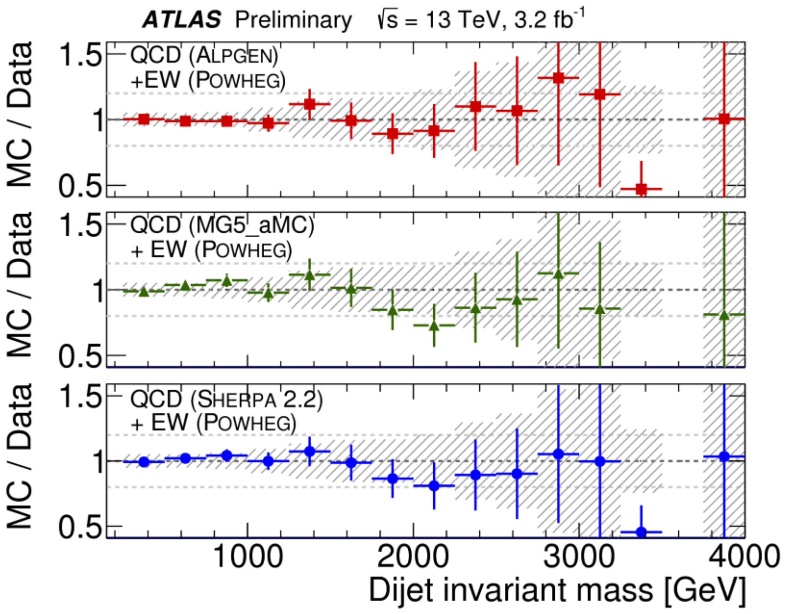
EWK Z+2jets at 13TeV

(a) EW-enriched region: comparison of the sum of EW-Zjj and m_{jj}-reweighted QCD-Zjj templates to the data (minus the non-Zjj backgrounds).

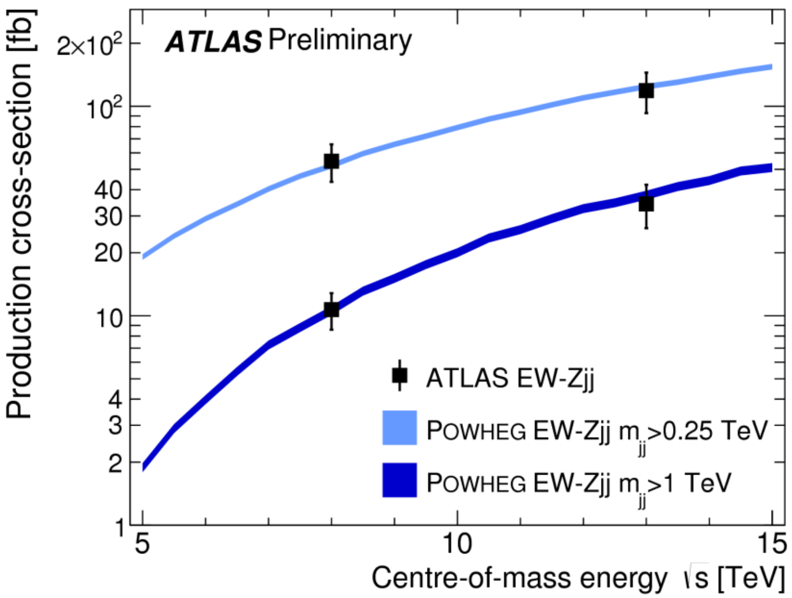
(b) The ratio of predictions of the EW-Zjj + estimatied QCD-Zjj to the background-subtracted data in the EW-enriched region (for three different QCD-Zjj MC predictions).



(a)



(b)



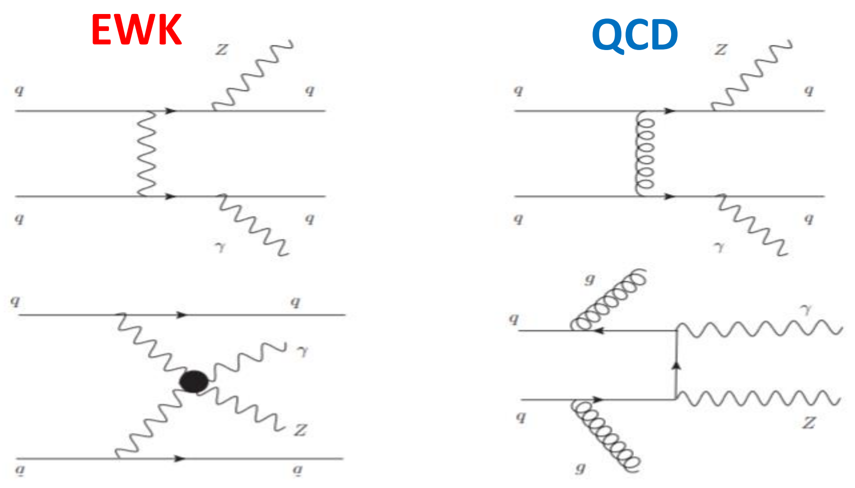
EWK Zγ production at 8TeV

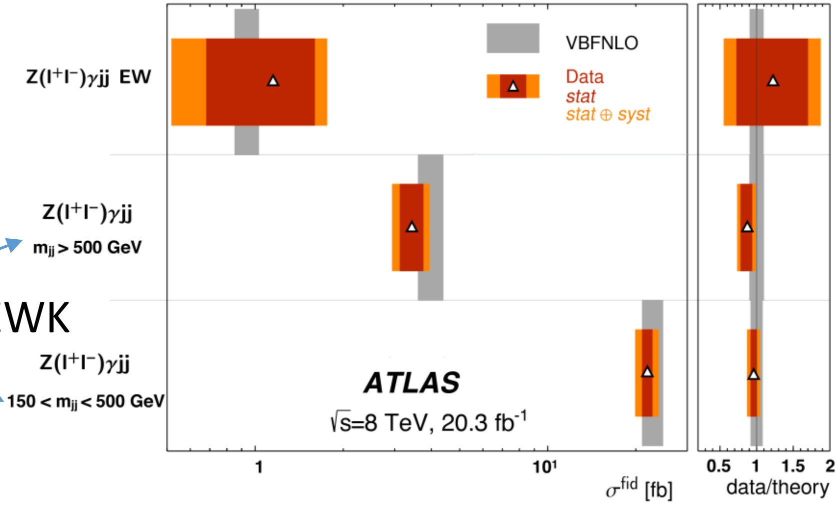
JHEP 07(2017)107

- Methodology: select Z→ ee/μμ + a photon + >=2jets (EWK)
- Major background: Z+jets, WZ+jets, ttγ

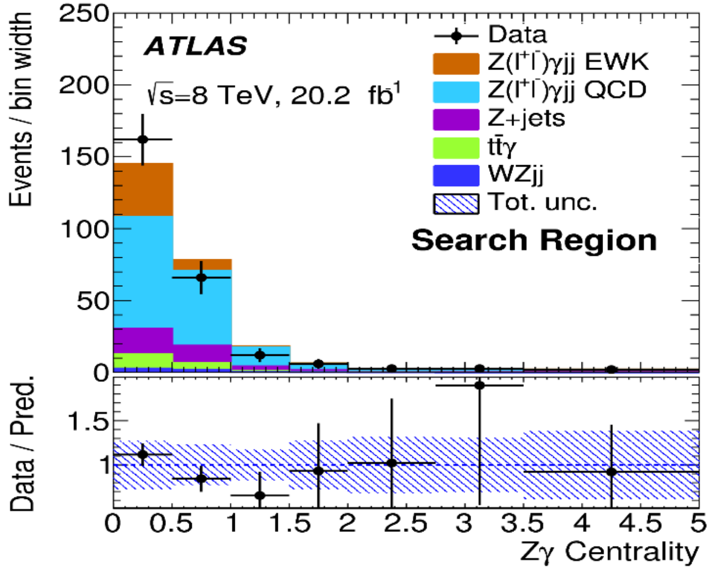
➢ The significance of the observed EWK production signal is 2.0σ (1.8σ expected)

	Inclusive region $Z(\ell^+\ell^-)\gamma + \geq 2$ jets		Control region $150 < m_{jj} < 500$ GeV		Search region $m_{jj} > 500$ GeV	
	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$	$e^+e^-\gamma jj$	$\mu^+\mu^-\gamma jj$
Data	781	949	362	421	58	72
Z+jets bkg.	134 ± 36	154 ± 42	57 ± 16	67 ± 18	8.5 ± 2.5	9.4 ± 2.7
Other bkg. ($t\bar{t}\gamma$, WZ)	88 ± 17	91 ± 18	47 ± 9	46 ± 9	5.8 ± 1.1	5.0 ± 1.0
$N_{\text{data}} - N_{\text{bkg}}$	559 ± 46	704 ± 53	258 ± 24	308 ± 27	44 ± 7	58 ± 8
$N_{Z\gamma\ \text{QCD}}$ (SHERPA MC)	583 ± 41	671 ± 47	249 ± 24	290 ± 26	37 ± 5	41 ± 5
$N_{Z\gamma\ \text{EWK}}$ (SHERPA MC)	25.4 ± 1.5	27.3 ± 1.7	8.6 ± 0.6	9.3 ± 0.6	11.2 ± 0.8	11.6 ± 0.7
$N_{Z\gamma}$ (SHERPA MC)	608 ± 42	698 ± 49	258 ± 25	299 ± 27	48 ± 6	53 ± 6





Combine QCD and EWK



Summary

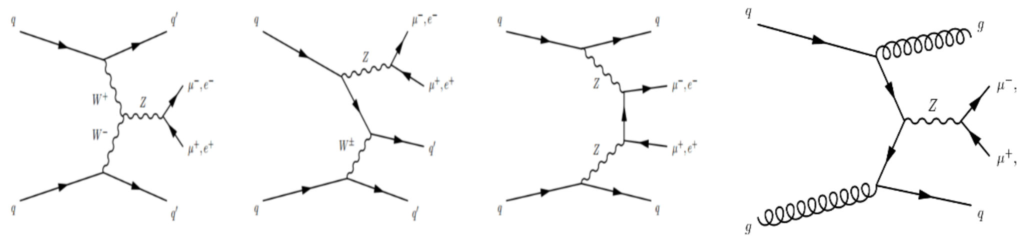
- Di-boson processes, WW, WZ and ZZ, have been measured with proton-proton collision data at 8TeV and 13TeV collected with ATLAS detector. Good agreements with SM predictions are observed from the full-leptonic and semi-leptonic decays channels.
- After the $W\gamma\gamma$ evidence and $Z\gamma\gamma$ observation, the tri-boson processes, WWW and $WV\gamma$, have been searched for with 8TeV data sets, which gives consistent upper limits @95% CL with SM predictions.
- VBF/VBS processes have been measured for single and di-boson:
  - VBF single boson, Z and W, have been observed with >5σ (for W) and resulted in a consistent cross section as SM predictions.
  - VBS di-boson process $Z\gamma$ has been searched for after the VBS ssWW evidence, which agrees with SM prediction.
  - The measurement of other VBS diboson processes will come soon with ATLAS 13TeV data.

EWK Z+2jets productions at 8TeV

- Methodology: select Z → ee/μμ + 2jets (EWK)
  - Signal region (EWK): >=2 large pT jets; no additional jets in the interval of two leading jets; m(jj)>250 GeV, etc
  - Control region: >=1 additional jets in the interval of two leading jets → to control the contribution of **QCD Z+2jets (dominant background)**.

Electroweak (EWK) Z+2jets

QCD Z+2jets

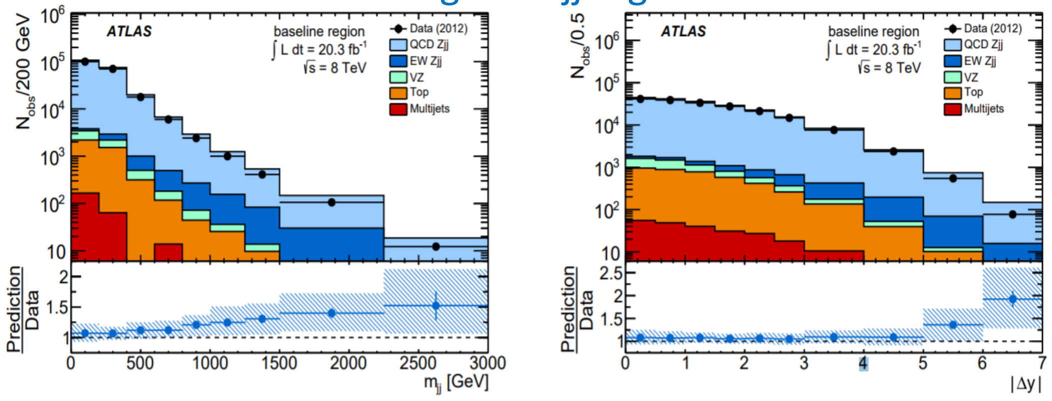


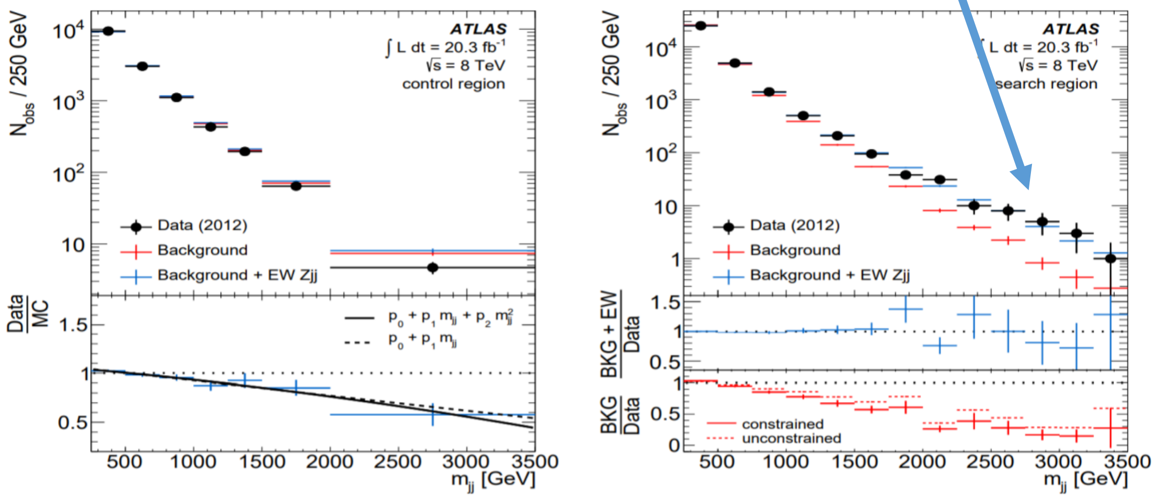
(a) vector boson fusion (b) Z-boson bremsstrahlung (c) non-resonant $\ell^+\ell^- jj$

- The significance of EWK Z+2jets: >5σ

Obs (fb)	**54.7±4.6 (stat)$^{+9.8}_{-10.4}$ (syst)±1.5 (lumi)**
Exp (fb)	46.1±0.2 (stat)$^{+0.3}_{-0.2}$ (scale)±0.8 (PDF)±0.5 (model)

Loose-selection distributions: EWK increases in higher mjj regions



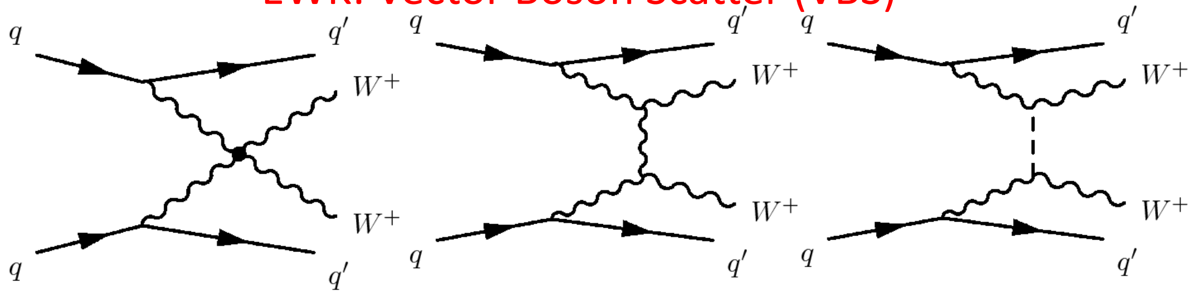


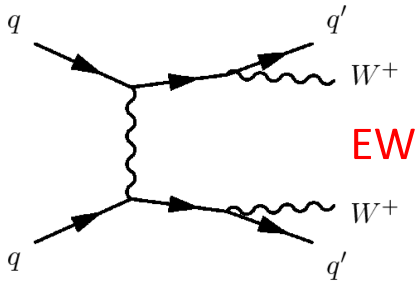
EWK ssWW evidence at 8TeV (I)

- ❑ The longitudinally polarized VBS amplitude increases as a function of the center-of-mass energy and violates unitarity at energies around 1 TeV, if no SM Higgs mechanism.
- ❑ Many physics scenarios predict enhancements in VBS either from additional resonances or if the observed SM-like Higgs boson only partially unitarizes this amplitude.
- ❑ Observation of the VBS process is indirectly to prove the SM Higgs mechanism and helpful for new physics in higher energy.

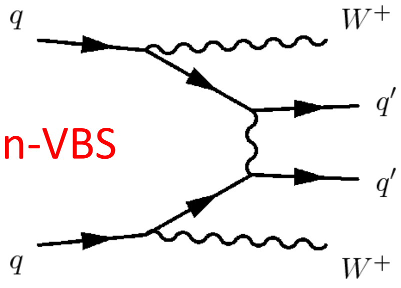
- ➢ Same-sign(ss) WW is a clean channel for VBS searches ➔ the QCD ssWW production are highly "suppressed" (gg process does not contribute)
- ➢ Methodology: select only leptonic decays of W ➔ (eμ, ee, μμ) + (>=2 jets) + E_t^{miss}
- ➢ Major background: Z+jets (charge-flip for electron), Top (fake background), WZ etc.

EWK: Vector Boson Scatter (VBS)

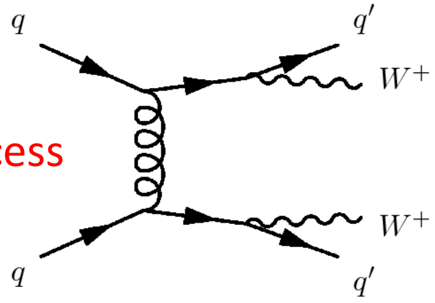




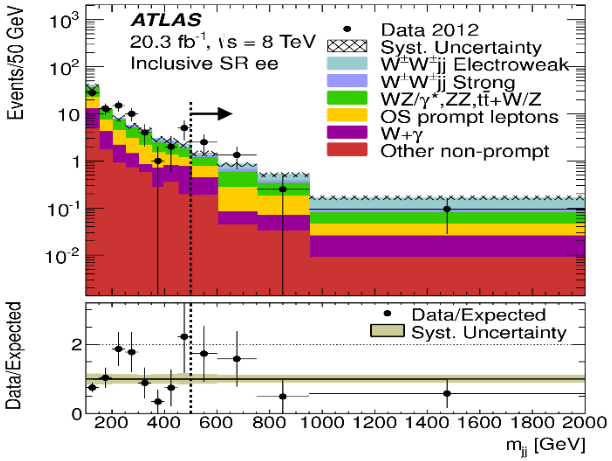
EWK: non-VBS

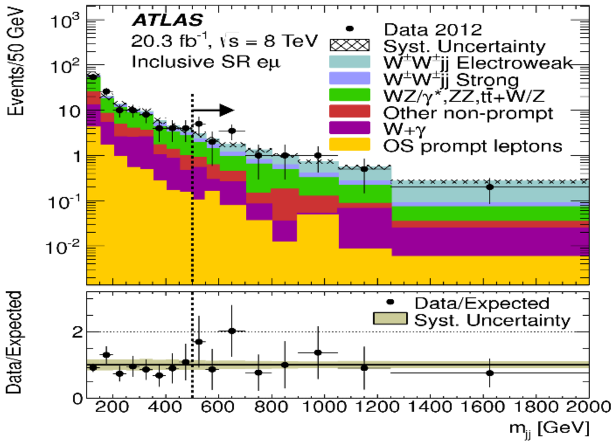


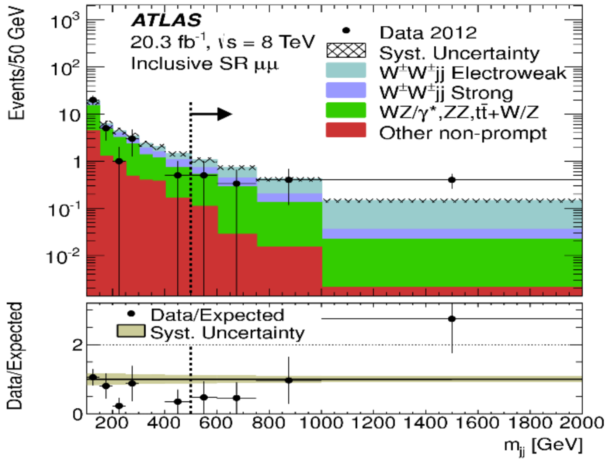
QCD process



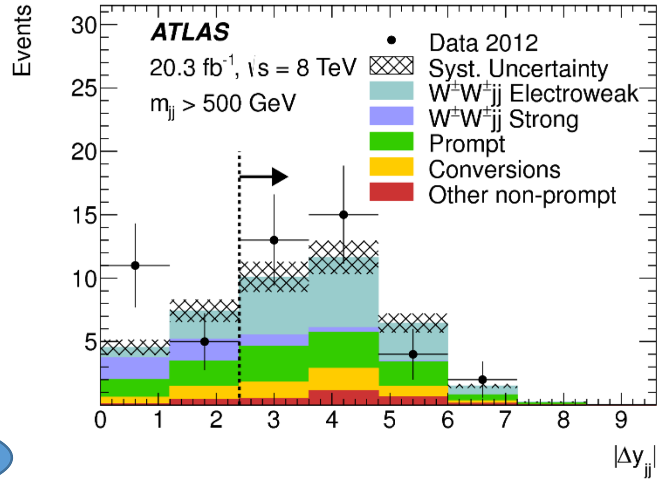
EWK ssWW evidence at 8TeV (II)







	Inclusive Region			VBS Region		
	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
Prompt	3.0 ± 0.7	6.1 ± 1.3	2.6 ± 0.6	2.2 ± 0.5	4.2 ± 1.0	1.9 ± 0.5
Conversions	3.2 ± 0.7	2.4 ± 0.8	–	2.1 ± 0.5	1.9 ± 0.7	–
Other non-prompt	0.61 ± 0.30	1.9 ± 0.8	0.41 ± 0.22	0.50 ± 0.26	1.5 ± 0.6	0.34 ± 0.19
$W^{\pm}W^{\pm}jj$ Strong	0.89 ± 0.15	2.5 ± 0.4	1.42 ± 0.23	0.25 ± 0.06	0.71 ± 0.14	0.38 ± 0.08
$W^{\pm}W^{\pm}jj$ Electroweak	3.07 ± 0.30	9.0 ± 0.8	4.9 ± 0.5	2.55 ± 0.25	7.3 ± 0.6	4.0 ± 0.4
Total background	6.8 ± 1.2	10.3 ± 2.0	3.0 ± 0.6	5.0 ± 0.9	8.3 ± 1.6	2.6 ± 0.5
Total predicted	10.7 ± 1.4	21.7 ± 2.6	9.3 ± 1.0	7.6 ± 1.0	15.6 ± 2.0	6.6 ± 0.8
Data	12	26	12	6	18	10



ssWW evidence: obs 4.5σ (exp 3.4σ) in inclusive Region and 3.6σ (exp 2.8σ) in VBS region