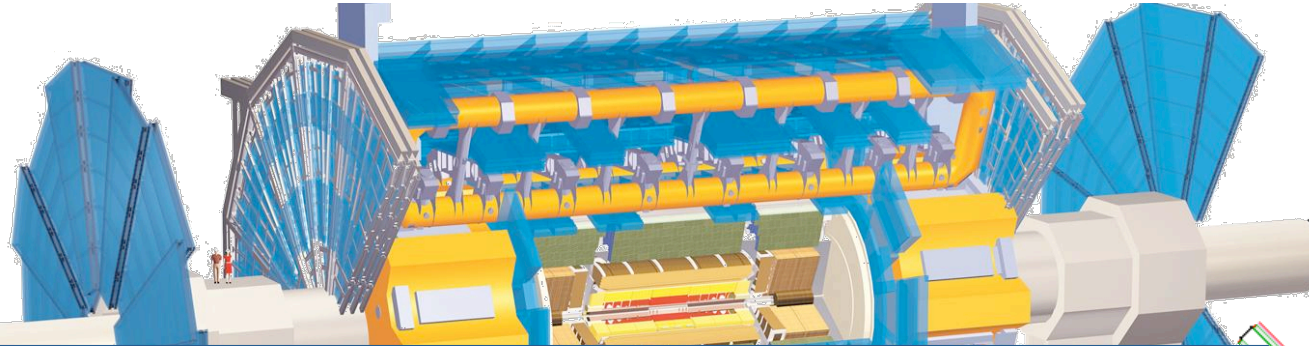
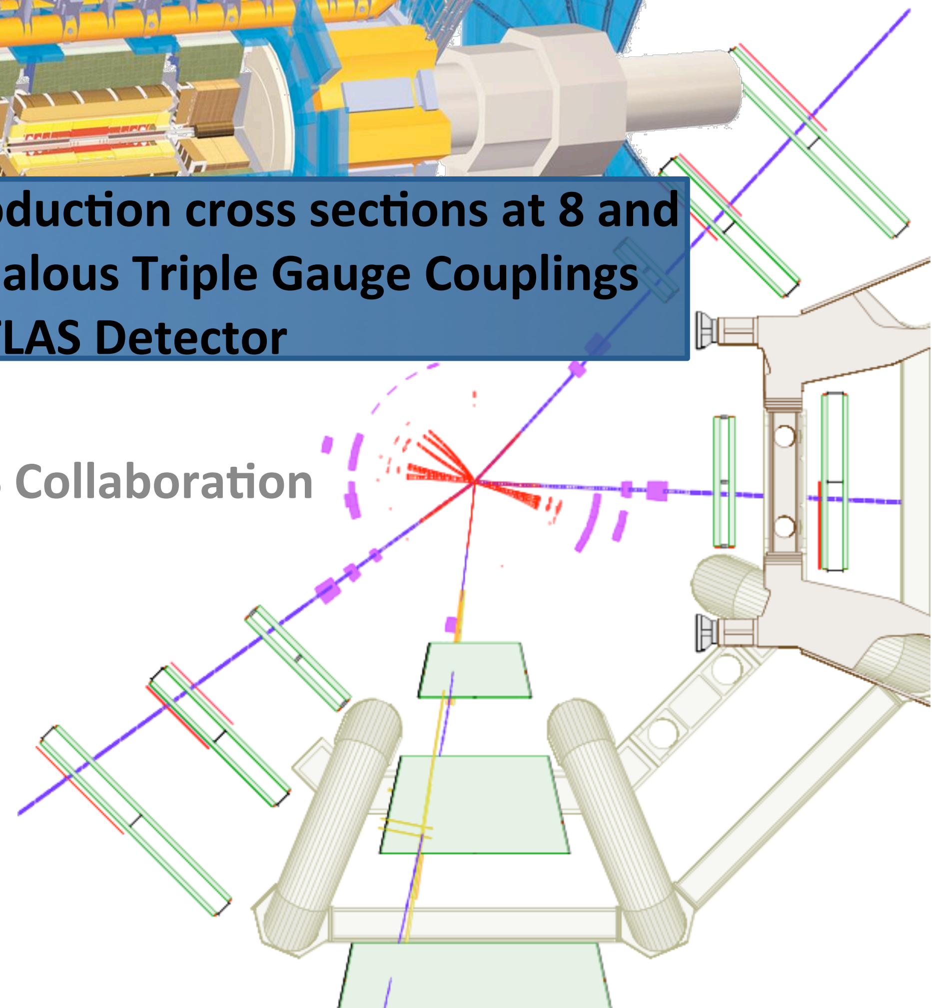


Measurement of Diboson Production cross sections at 8 and 13 TeV, and limits on Anomalous Triple Gauge Couplings with the ATLAS Detector

Will Buttinger

On Behalf of the ATLAS Collaboration



Outline

1. Diboson physics at ATLAS
   – Importance of NNLO predictions

2. Electroweak Diboson processes with fully leptonic final states
   – WW, WZ, ZZ at 13 TeV

3. Diboson processes with semileptonic final states
   – WW/WZ at 8 TeV

4. Limits on Anomalous Triple Gauge Couplings

New results
(released in 2017)

Outline

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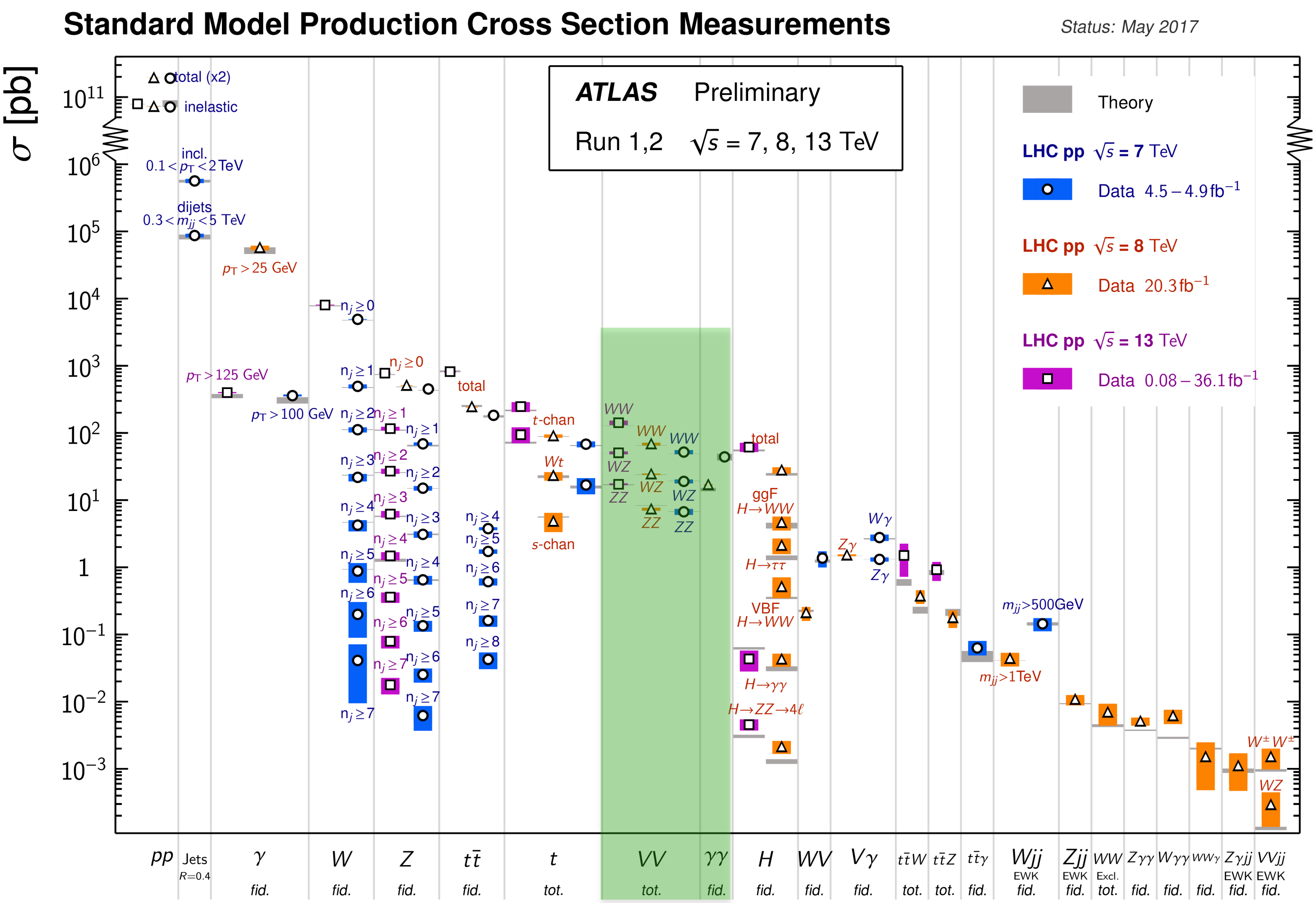
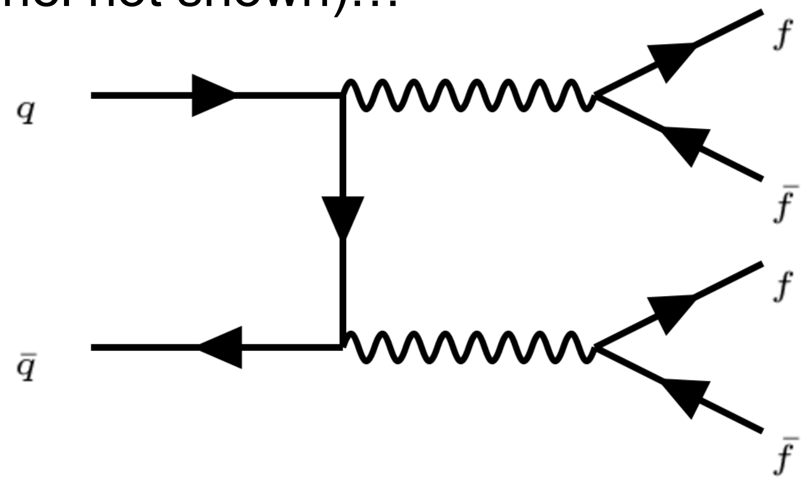
Standard Model Measurements at ATLAS

- Diboson production is a significant irreducible background to many searches
- Diboson production cross-sections are sensitive to **higher order QCD effects**

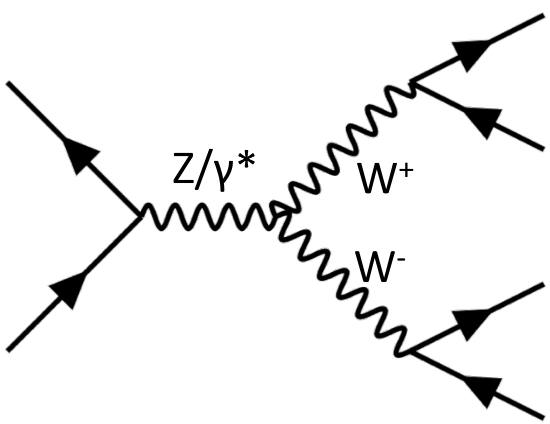


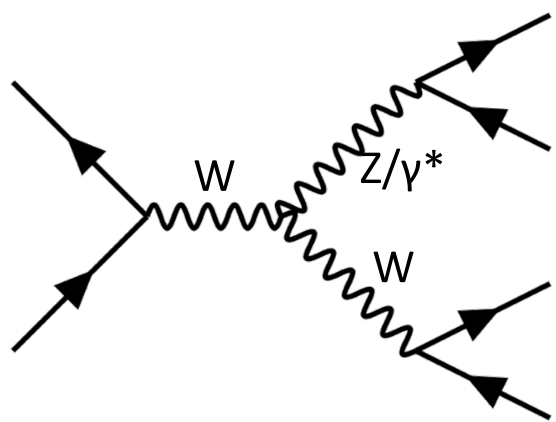
Electroweak Diboson Production @ **LO (α^4)**

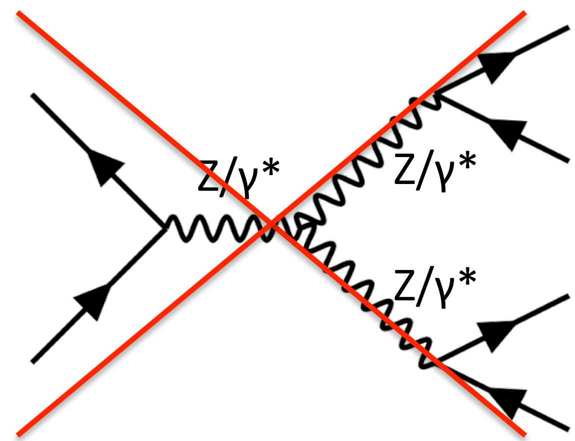
- LO process (u-channel not shown)…



- + Triple Gauge Couplings – **WW and WZ production only**!



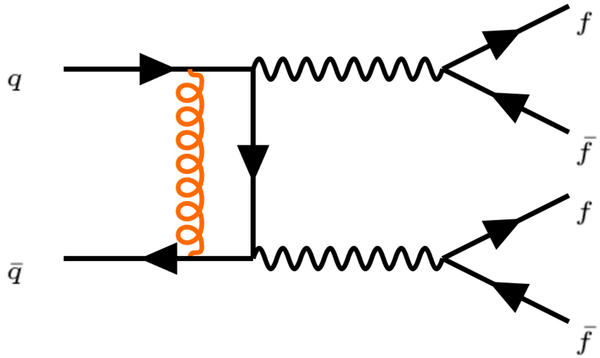


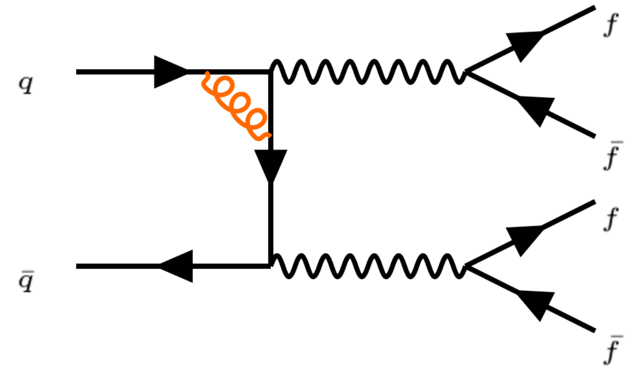


There are no Neutral Triple Gauge vertices (ZZZ, ZZγ,…) in SM

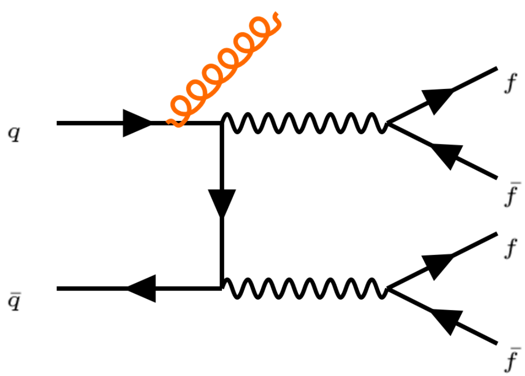
Electroweak Diboson Production @ NLO QCD ($\alpha^4\alpha_s$)

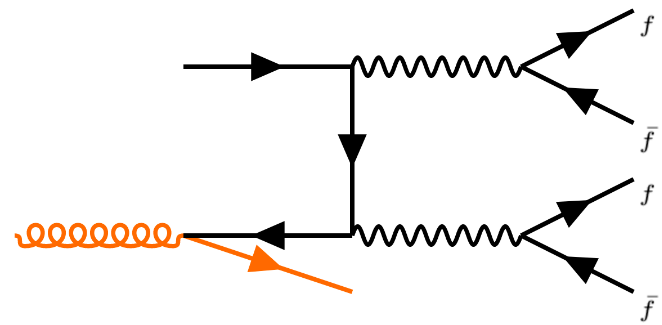
- Interference with LO process …





- + new processes .. e.g. …



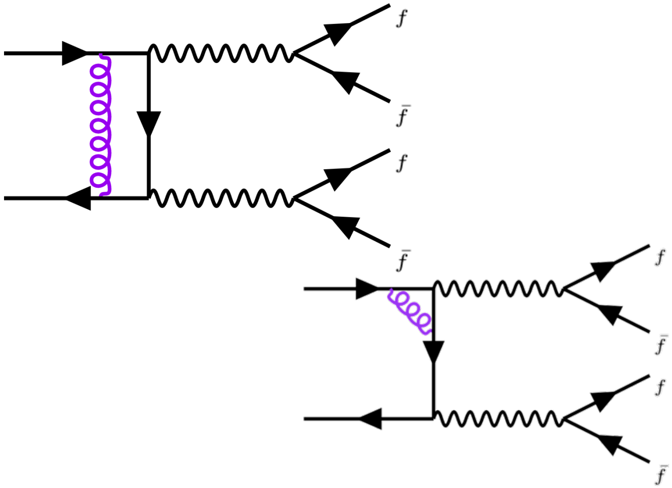


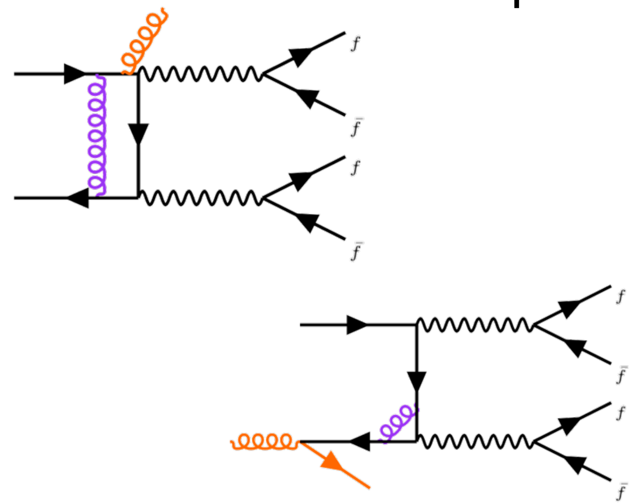
Important if we exclusively require 1 jet

Important contribution due to gluon component of PDF

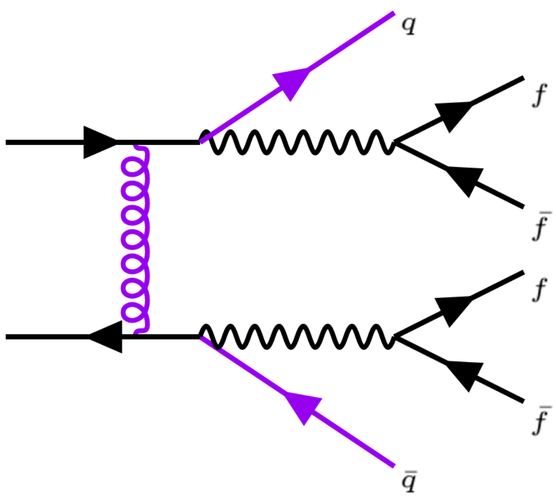
Electroweak Diboson Production @ NNLO QCD ($\alpha^4\alpha_s^2$)

- NNLO versions of LO process ……. And interferences to NLO process…

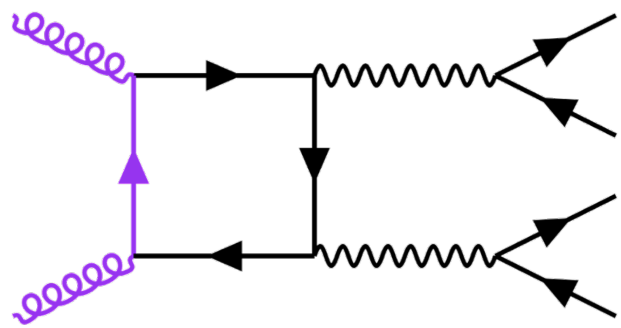




- + new processes .. e.g. …



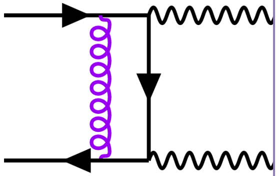
Important if we exclusively require 2 jets



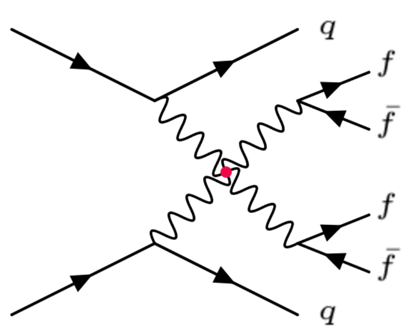
Important contribution due to gluon component of PDF (5-10 % of total cross-section)

Electroweak Diboson Production @ NNLO QCD ($\alpha^4\alpha_s^2$)

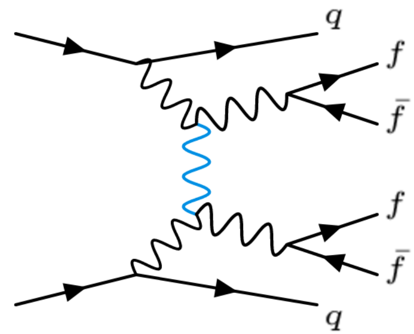
- NNLO versio… And interferences to NLO process…



NNLO QCD is major background when we want to probe rare EW processes

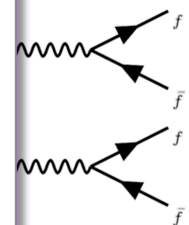


Quartic Coupling

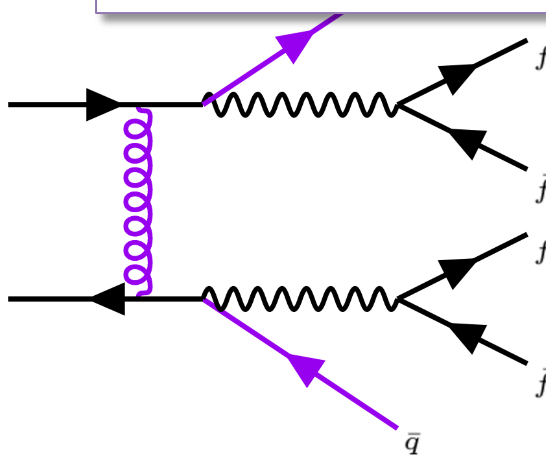


Vector Boson Scattering (α^6)

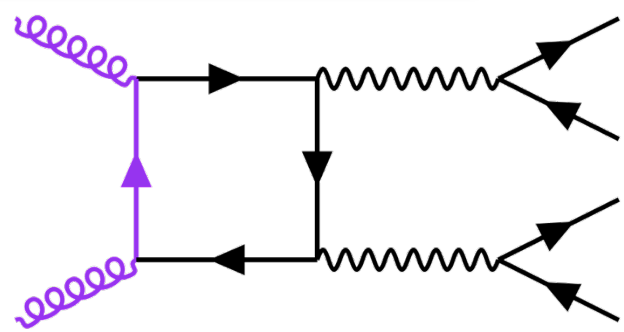
See the next talk, by Bing Li



- + new proces…



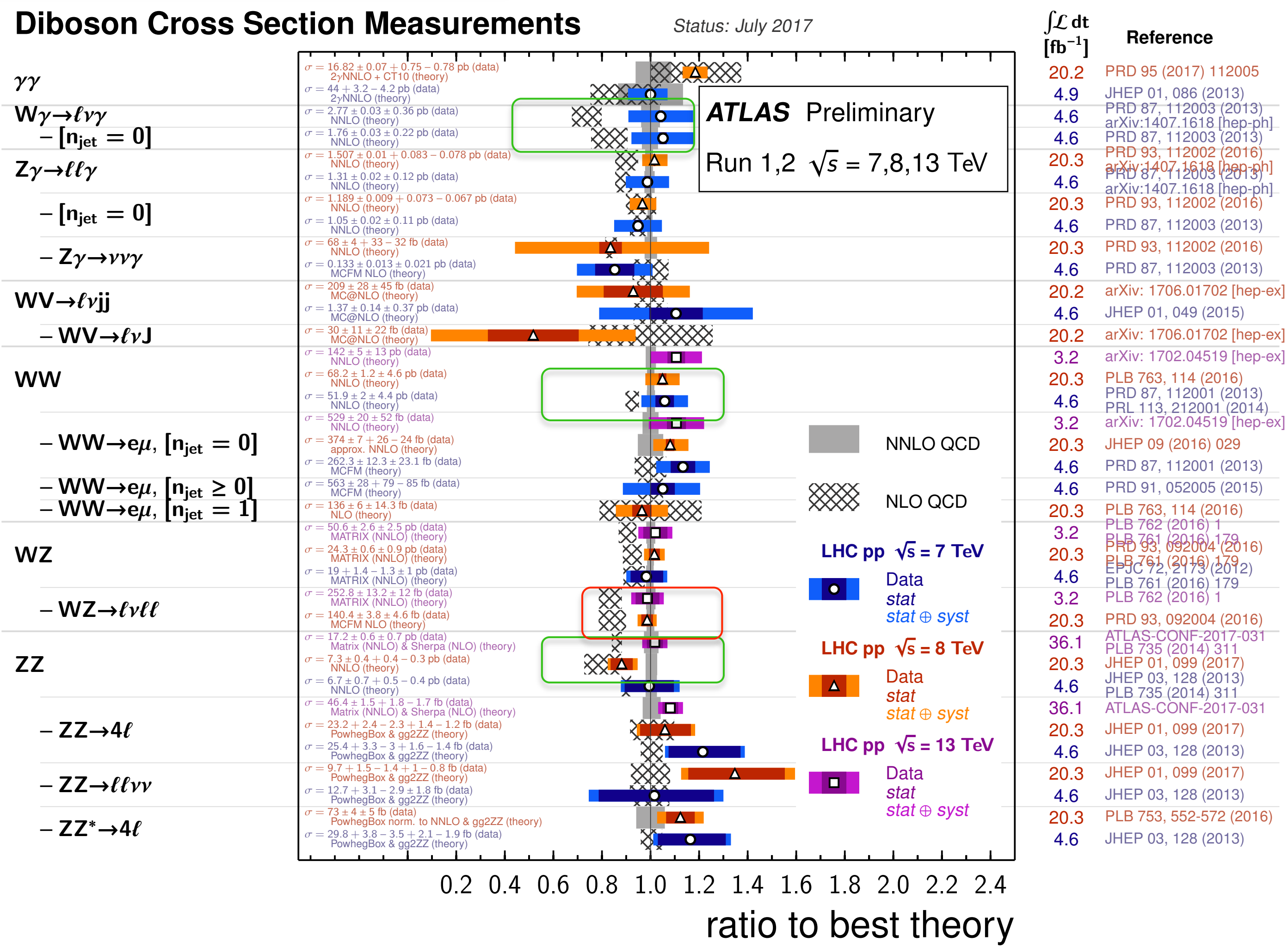
Important if we exclusively require 2 jets



Important contribution due to gluon component of PDF (5-10 % of total cross-section)

Diboson cross-section measurements at ATLAS

- NNLO predictions only really became available over past couple of years
- NNLO predictions have been essential to improve agreement with data
  - New NNLO calculation for WZ (arxiv:1604.08576)



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

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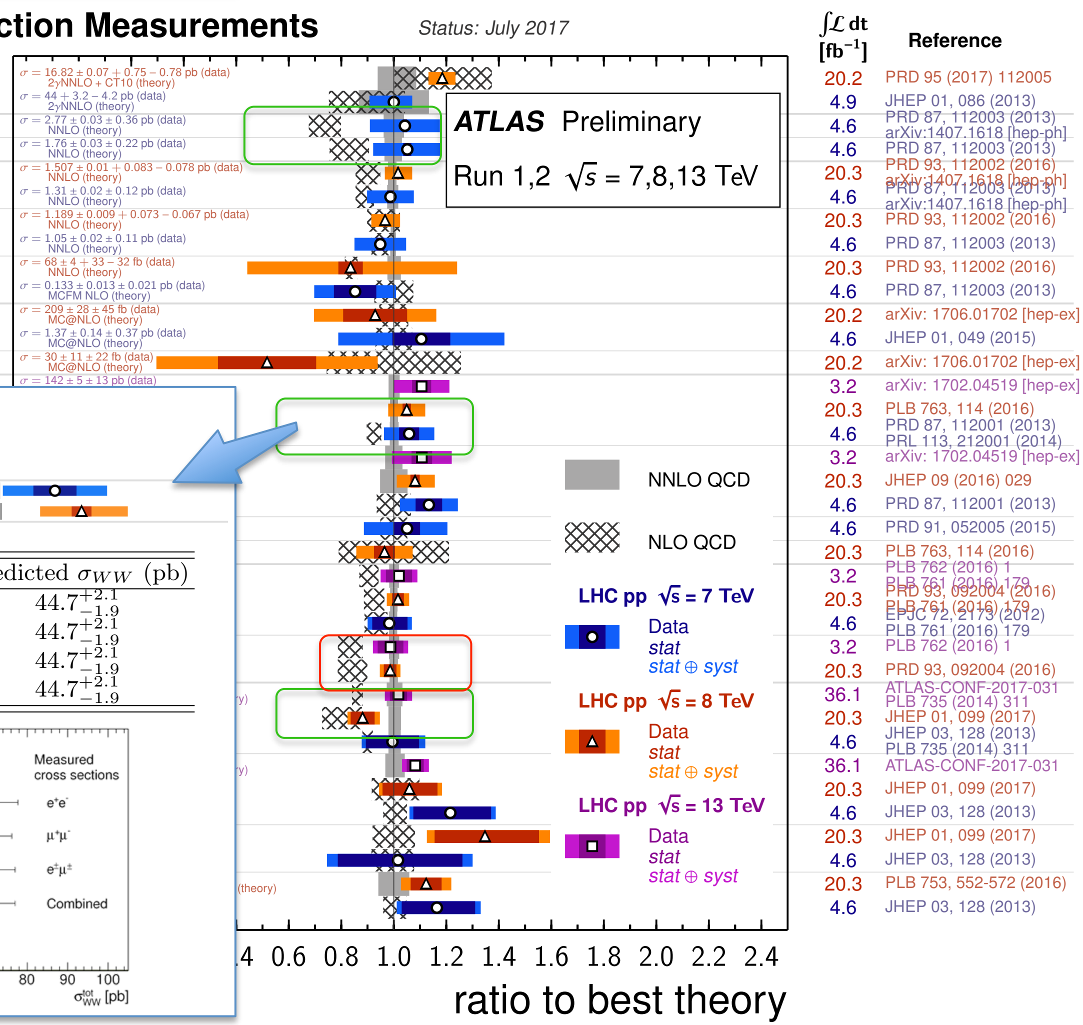


2015 Flashback

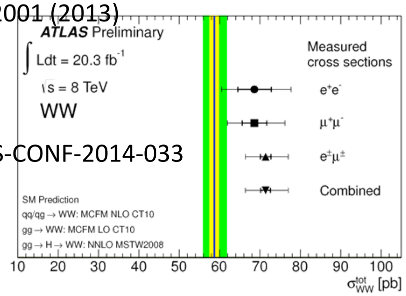
7 TeV

	Measured σ_{WW} (pb)	Predicted σ_{WW} (pb)
ee	$46.9 \pm 5.7 \pm 8.2 \pm 1.8$	$44.7^{+2.1}_{-1.9}$
$\mu\mu$	$56.7 \pm 4.5 \pm 5.5 \pm 2.2$	$44.7^{+2.1}_{-1.9}$
$e\mu$	$51.1 \pm 2.4 \pm 4.2 \pm 2.0$	$44.7^{+2.1}_{-1.9}$
Combined	$51.9 \pm 2.0 \pm 3.9 \pm 2.0$	$44.7^{+2.1}_{-1.9}$

Phys. Rev. D 87, 112001 (2013)

8 TeV

ATLAS-CONF-2014-033



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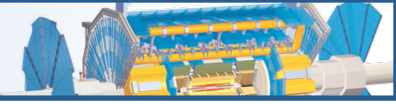
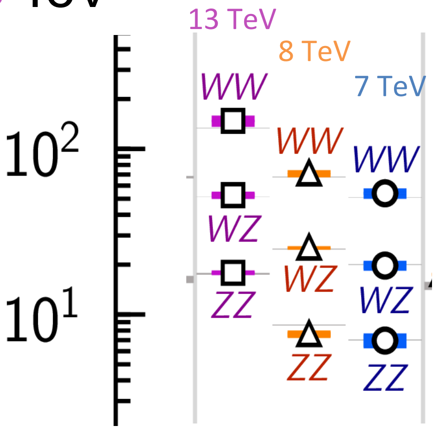
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

Diboson leptonic final states [lepton = e,μ]



- ATLAS has measurements of WW, WZ, and ZZ cross-sections at 7, 8, and 13 TeV



Statistics (Higher cross-sections)

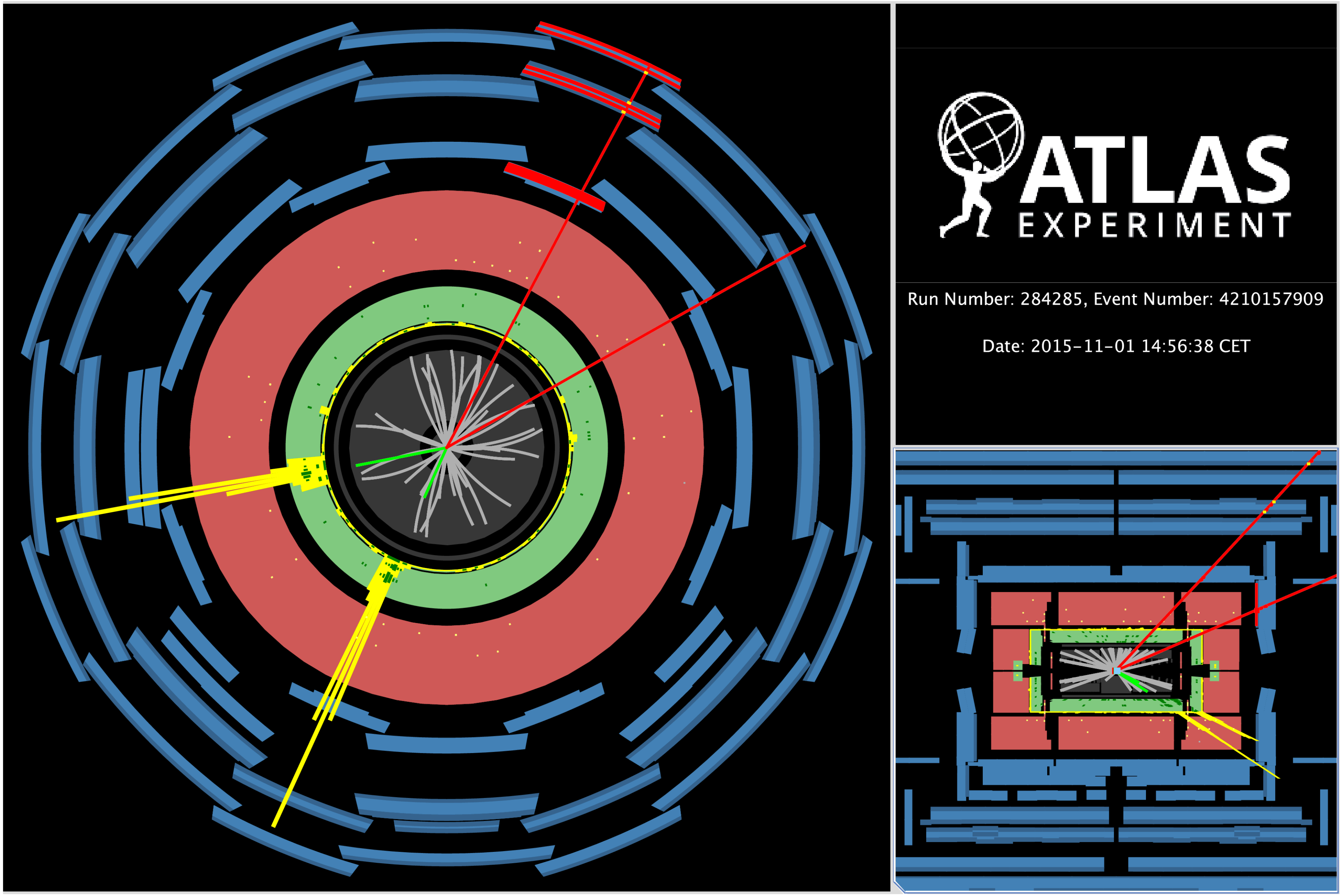
	WW	WZ	ZZ
Final State / Signature:	2 leptons (+2ν)	3 leptons (+1ν)	4 leptons
Main Backgrounds:	(leptonic) tt, Drell-Yan	Drell-Yan + 1 fake lepton ZZ (1 missed lepton) WW, tt + 1 fake lepton	WZ + 1 fake WW, tt, Drell-Yan + 2 fake
Signal region purity:	~70%	~75%	~98%

Cleanliness (background rejection)

ZZ Production at ATLAS @ 13 TeV

[ATLAS-CONF-2017-031]

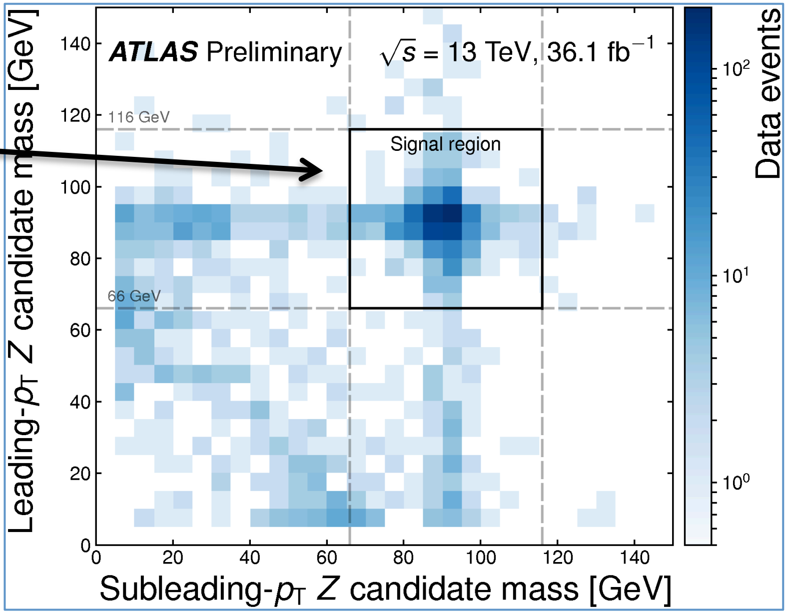
- An eeμμ candidate ZZ event

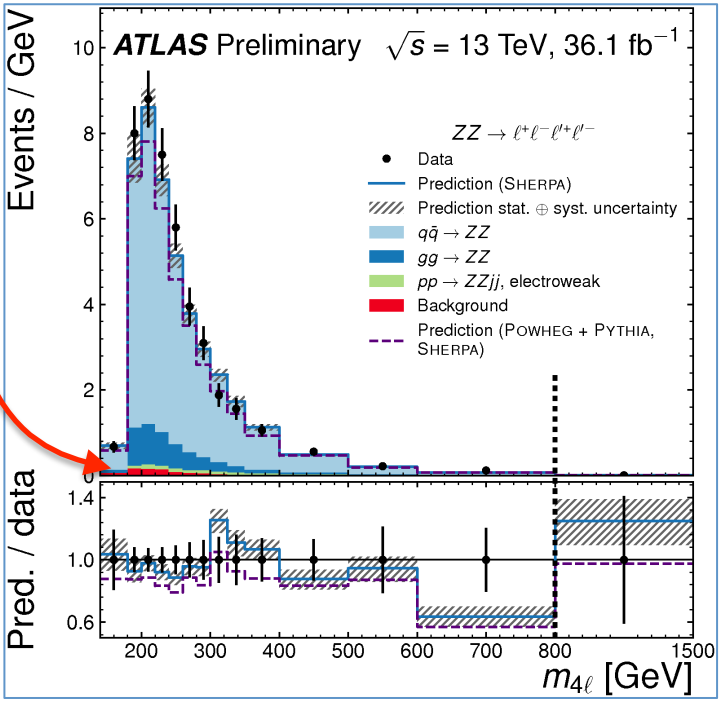


ZZ Production at ATLAS @ 13 TeV

[ATLAS-CONF-2017-031]

- 36.1 fb^{-1} (2015+2016) $\sqrt{s}$ = 13 TeV data
- Select events with *at least* 4 leptons
- Only on-shell: **66 < m_{ll} < 116 GeV**
- **Fully leptonic final state** is very clean signature
  - Main backgrounds from fake leptons (e.g. in Z + jet events)
  - SM processes w/ > 4 leptons treated as background (e.g. ZZZ -> 6l)





Contribution	$4e$	$2e2\mu$	4μ	Combined
Data	249	465	303	1017
Total prediction (SHERPA)	207 ± 10	470 ± 23	298 ± 17	975 ± 46
Signal ($q\bar{q}$-initiated)	177.6 ± 8.3	400 ± 19	253.7 ± 13.4	832 ± 36
Signal (gg-initiated)	21.3 ± 3.5	50 ± 8	30 ± 5	101 ± 16
Signal (EWK-jj)	4.4 ± 0.6	10.3 ± 1.3	6.5 ± 1.0	$21.3^{+1.7}_{-2.6}$
$ZZ \to \tau^+\tau^-[\ell^+\ell^-, \tau^+\tau^-]$	0.6 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	1.7 ± 0.2
Triboson	0.7 ± 0.2	1.5 ± 0.5	1.0 ± 0.3	3.1 ± 0.9
$t\bar{t}Z$	0.8 ± 0.2	1.9 ± 0.6	1.4 ± 0.4	4.1 ± 1.2
Misid. lepton background	2.0 ± 1.1	4.9 ± 2.8	5.2 ± 5.0	12.1 ± 8.3
Total prediction (POWHEG + PYTHIA with higher-order corrections, SHERPA)	193 ± 9	456 ± 23	286 ± 16	934 ± 47

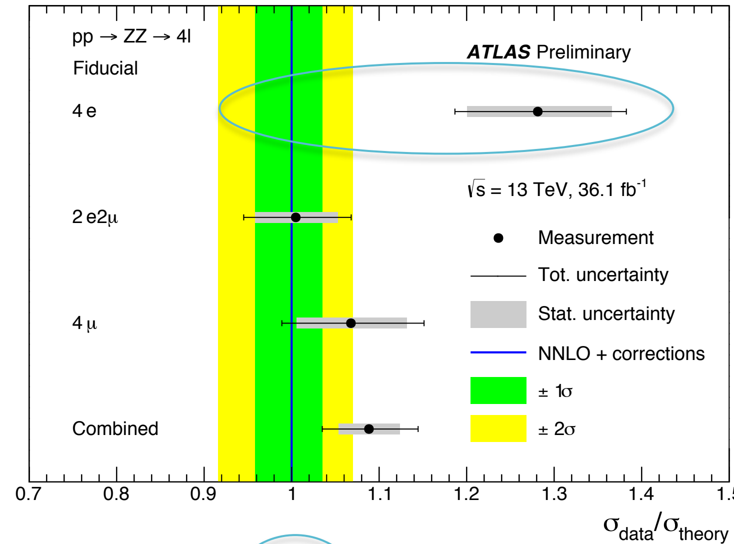
Sherpa prediction is nnNLO (missing e.g. NNLO versions of LO process) … up to 3 jets in ME (0/1 are NLO, 2/3 are LO)

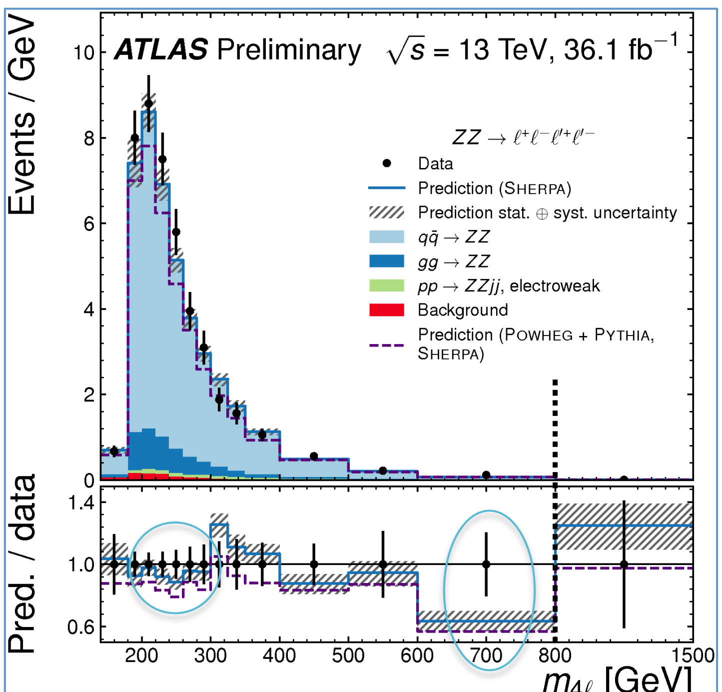
- Measure cross-section per channel in a fiducial volume (mirrors analysis selections):
  - Statistics-limited
  - Dominant systematic is lepton reconstruction/ identification efficiencies
- Total cross-section for pp->ZZ measured by extrapolation:

17.2 ± 0.9 [±0.6 (stat.) ±0.4 (syst.) ±0.6 (lumi.)] pb

Predicted: 16.9 ± 0.2 pb

NNLO prediction from MATRIX, with nLO EWK corrections, NLO correction to gg-initiated diagrams, and α^6 4l2j from sherpa





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Sherpa prediction is nnNLO (missing e.g. NNLO versions of LO process) … up to 3 jets in ME

See L. Carminati talk (yesterday, Higgs stream)

ZZ Production at ATLAS @ 13 TeV

[ATLAS-CONF-2017-031]

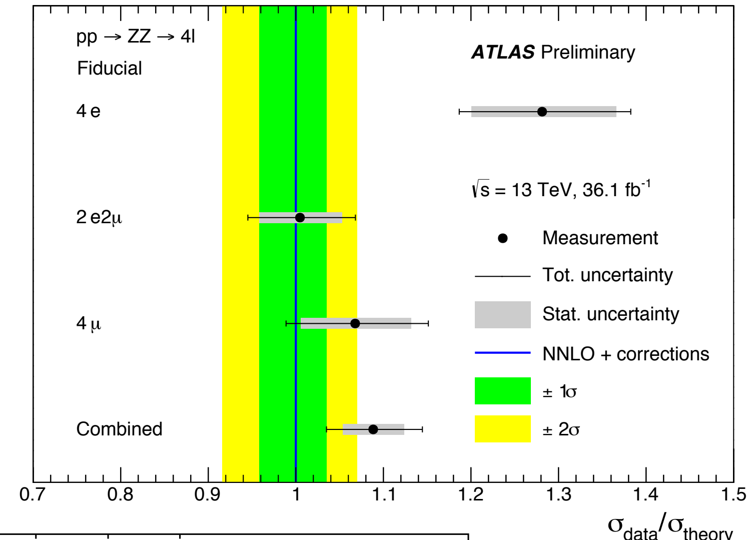
- Measure cross-section per channel in a fiducial volume (mirrors analysis selections):
  - Statistics-limited. Dominant systematic is lepton reconstruction/identification efficiencies
  - Tension in the 4e channel (excess at m_{4l} ~ 250 GeV)
- Total cross-section for pp->ZZ measured by extrapolation:

17.2 ± 0.9 [±0.6 (stat.) ±0.4 (syst.) ±0.6 (lumi.)] pb

Predicted: 16.9 ± 0.2 pb

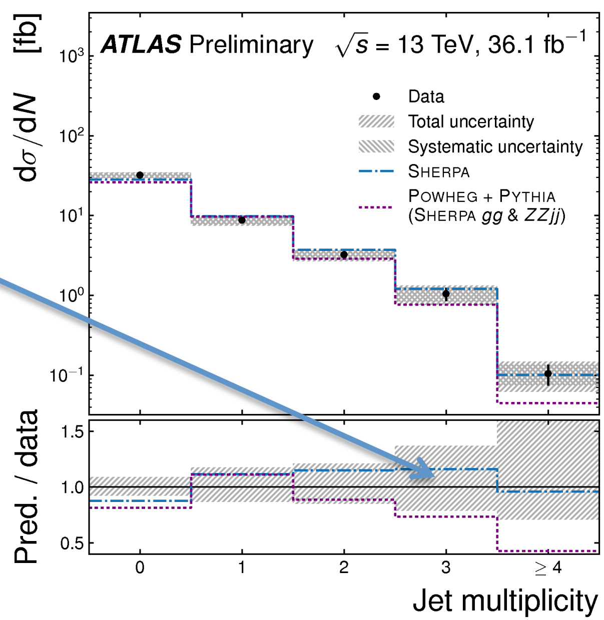
- Differential cross-sections provided in 20 variables: *many for the first time*

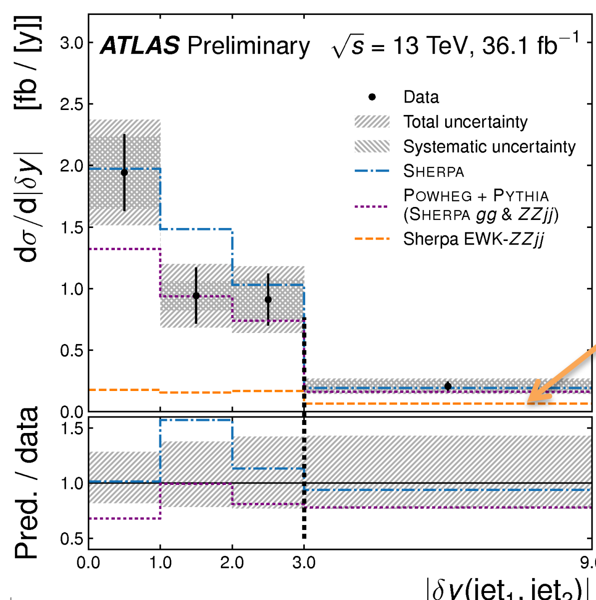
NNLO prediction from MATRIX, with nLO EWK corrections, NLO correction to gg-initiated diagrams, and α^6 4l2j from sherpa

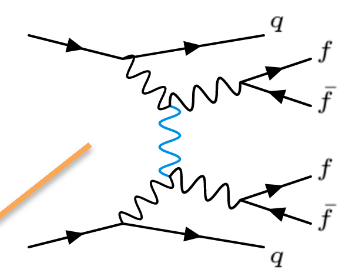


nnNLO Sherpa vs. NLO POWHEG

(Parton emission at Matrix-Element level is necessary to correctly model jet multiplicity)

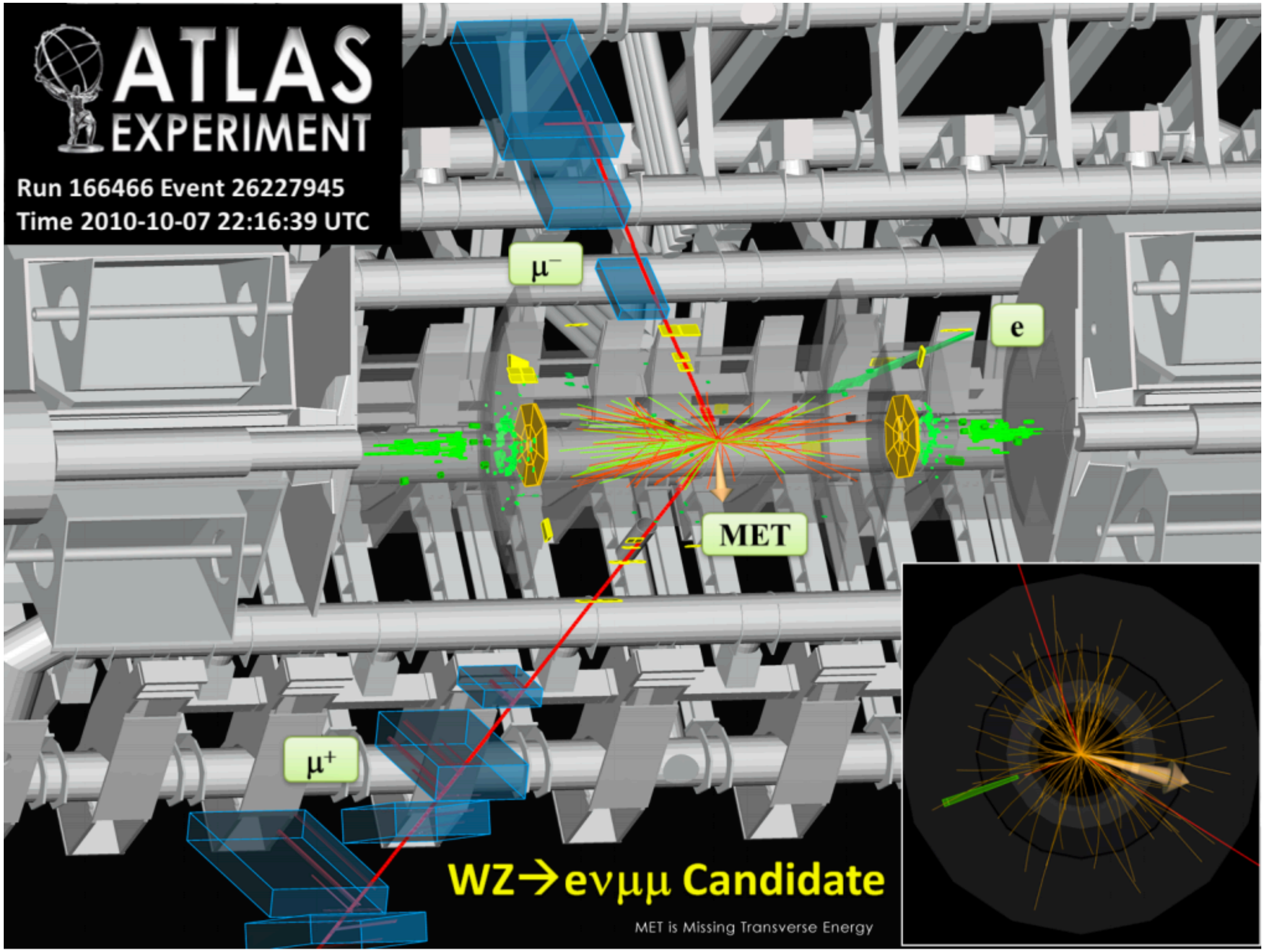






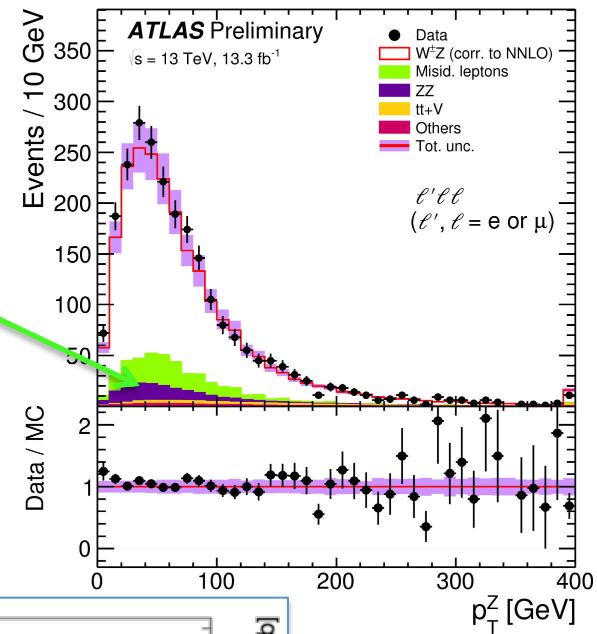
Important at large δy

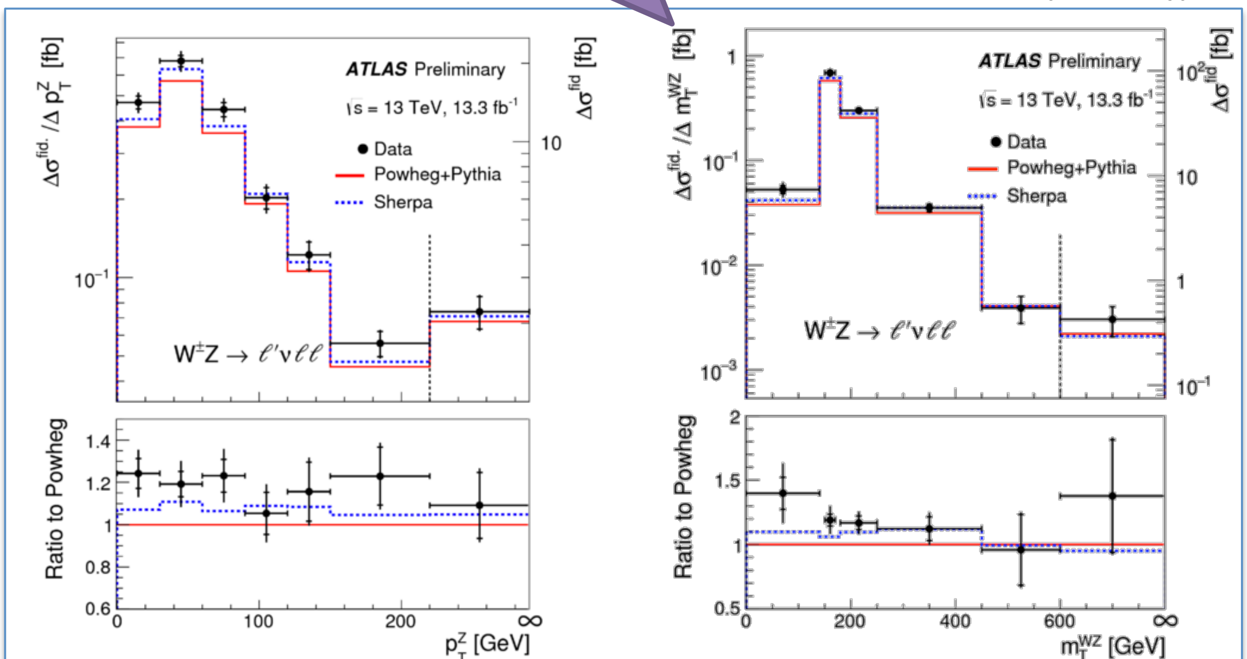
- An eνμμ candidate WZ event



WZ Production at ATLAS @ 13 TeV

- 13.3 fb^{-1} at $\sqrt{s}$ = 13 TeV data
  - An update on first measurement with 3.2 fb^{-1} [Phys. Lett. B 762 (2016) 1]
- Includes 3e, 3μ, μ2e, and e2μ final states
- Dominant uncertainties from fake lepton backgrounds (~3%) and lepton identification (~1%)
- Differential distributions in p_T^Z, m_T^{WZ}, N_{jets}



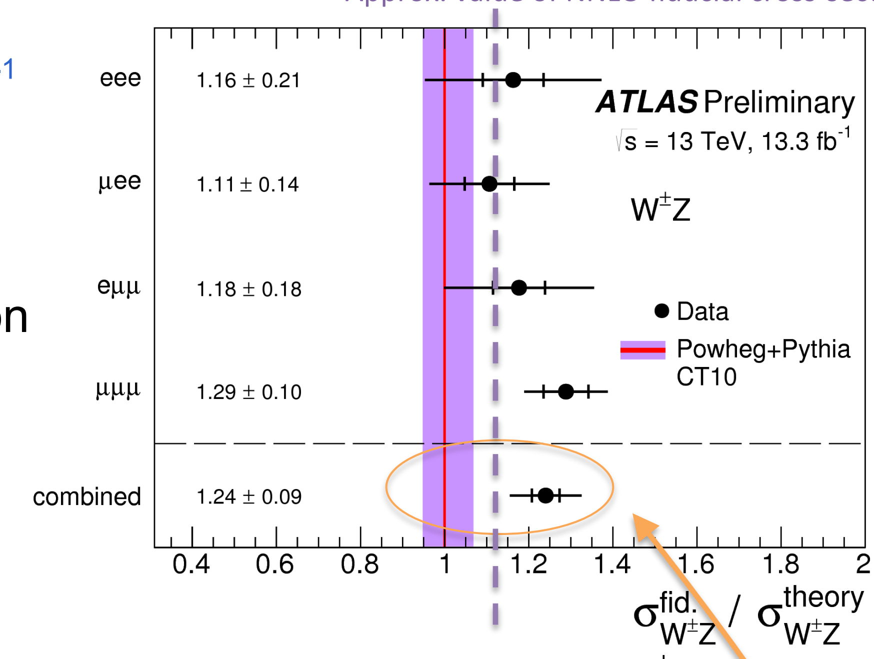


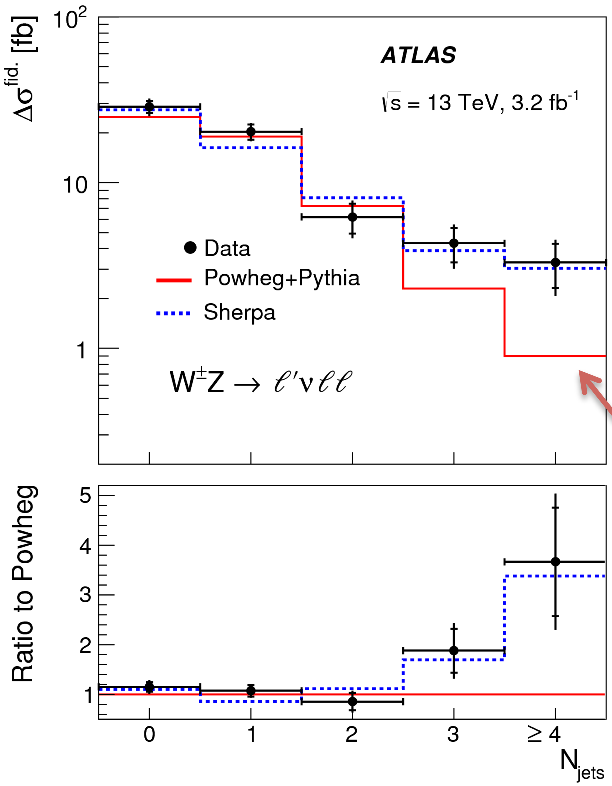
WZ Production at ATLAS @ 13 TeV

[ATLAS-CONF-2016-043]

- 13.3 fb^{-1} at $\sqrt{s}$ = 13 TeV data
  - An update on first measurement with 3.2 fb^{-1} [Phys. Lett. B 762 (2016) 1]
- Includes 3e, 3μ, μ2e, and e2μ final states
- Dominant uncertainties from fake lepton backgrounds (~3%) and lepton identification (~1%)
- Differential distributions in p_T^Z, m_T^{WZ}, N_{jets}

Approx. value of NNLO fiducial cross-section





- NNLO prediction from MATRIX agrees with total cross-section measurement

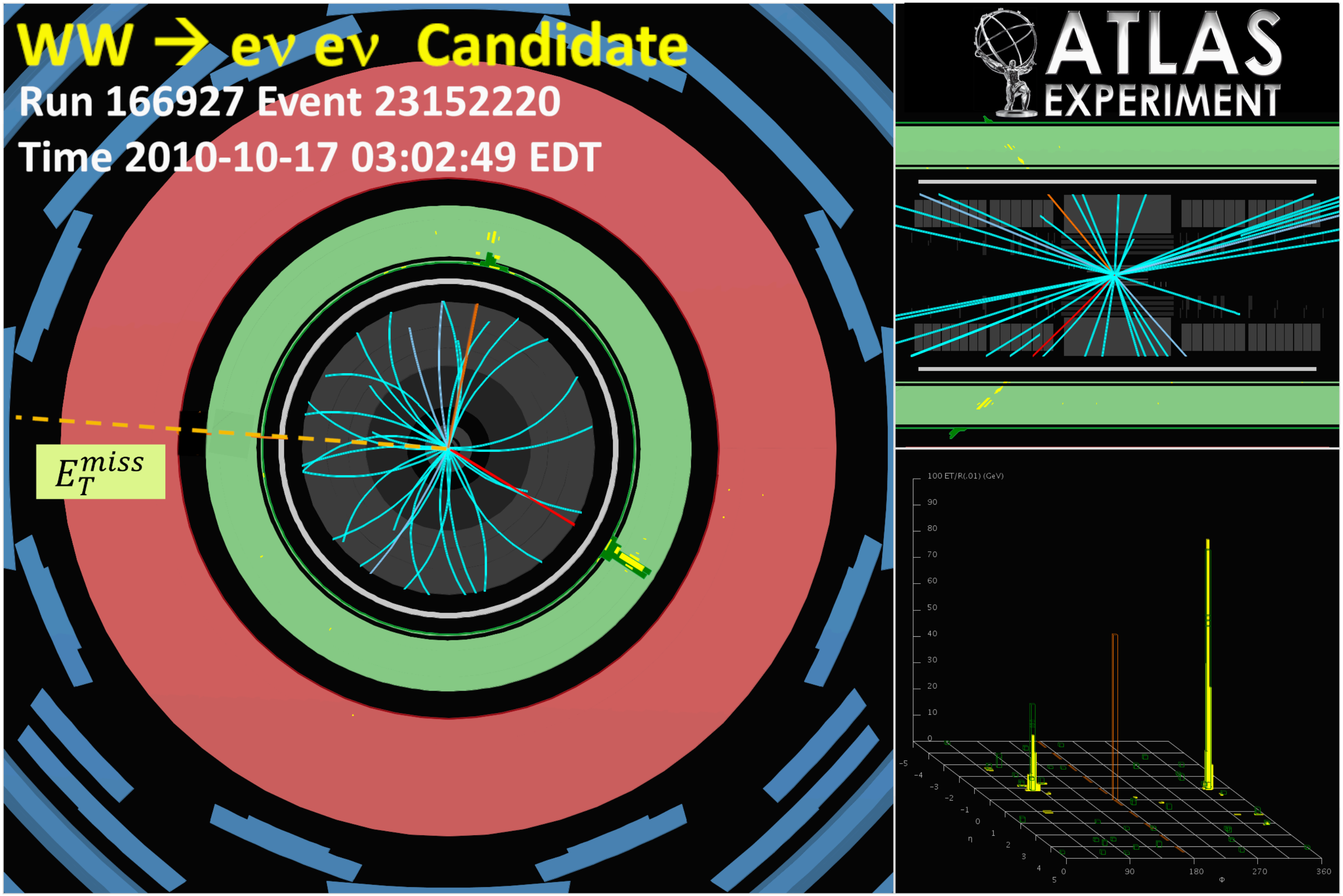
$$\sigma^{tot.}_{W^\pm Z} = 50.6 \pm 2.6\,(\text{stat.}) \pm 2.0\,(\text{sys.}) \pm 0.9\,(\text{th.}) \pm 1.2\,(\text{lumi.})\,\text{pb}$$

Predicted: 48.2 ± 1.1 pb

- Powheg's NLO prediction shows difference to data in fiducial volume, particularly at high jet multiplicities
  - nnNLO sherpa shows better agreement

WW Production at ATLAS @ 13 TeV [STDM-2015-20 – submitted to PLB]

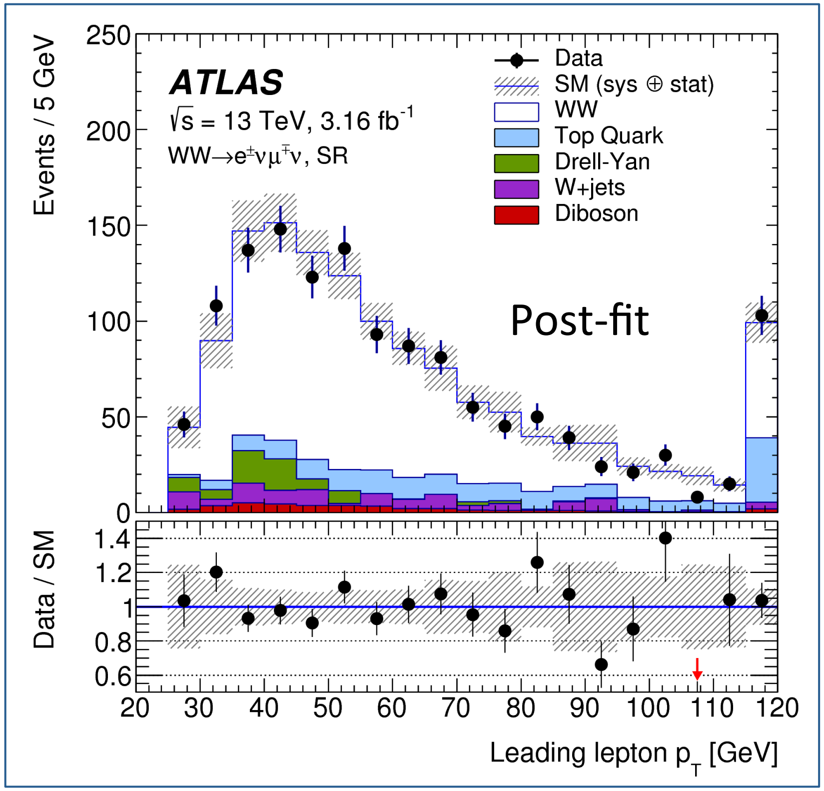
- An example WW event from run 1



WW Production at ATLAS @ 13 TeV

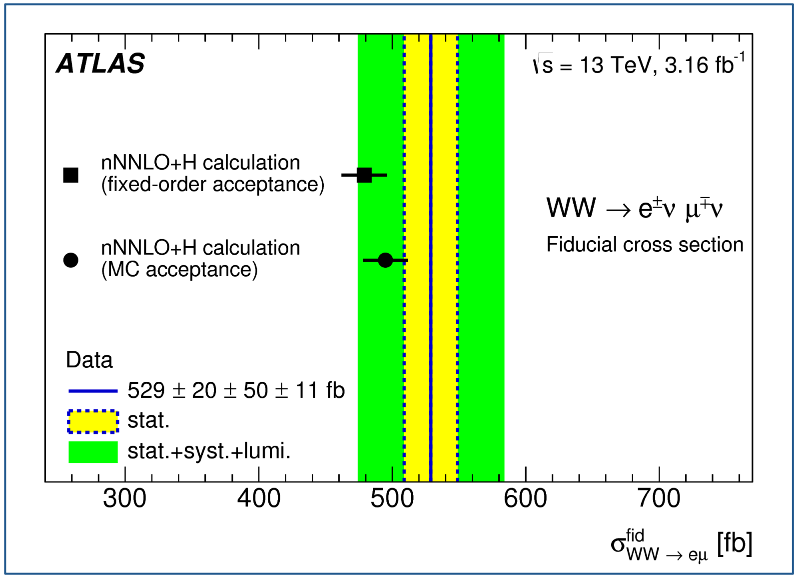
arXiv:1702.04519
[STDM-2015-20 – submitted to PLB]

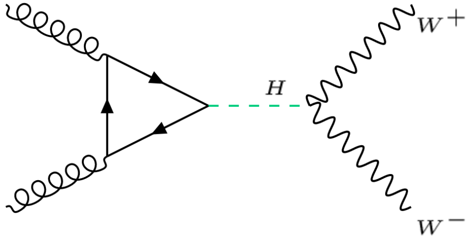
- 3.16 fb^{-1} $\sqrt{s}$ = 13 TeV data
- Only e μ channel, to suppress Drell-Yan
- Apply a **jet veto** to suppress Top background. Require MET > 20 GeV to further suppress Drell-Yan
  - Jet calibration is dominant uncertainty
- Top and Drell-Yan background shapes from MC, normalization from simultaneous fit in control regions:
  - Post-fit scale factors are 0.875 ± 0.035 for Top and 1.03 ± 0.03 for DY



$$\sigma^{tot}_{WW} = 142 \pm 5\,(\text{stat.}) \pm 13\,(\text{syst.}) \pm 3\,(\text{lumi.})\ \text{pb}$$

Predicted: $128.4^{+3.5}_{-3.8}$ pb





Prediction includes ~ 8% contribution from Higgs

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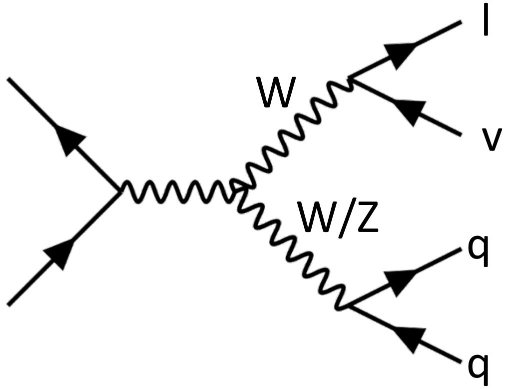
4. Limits on Anomalous Triple Gauge Couplings

WW/WZ Semi-leptonic final states

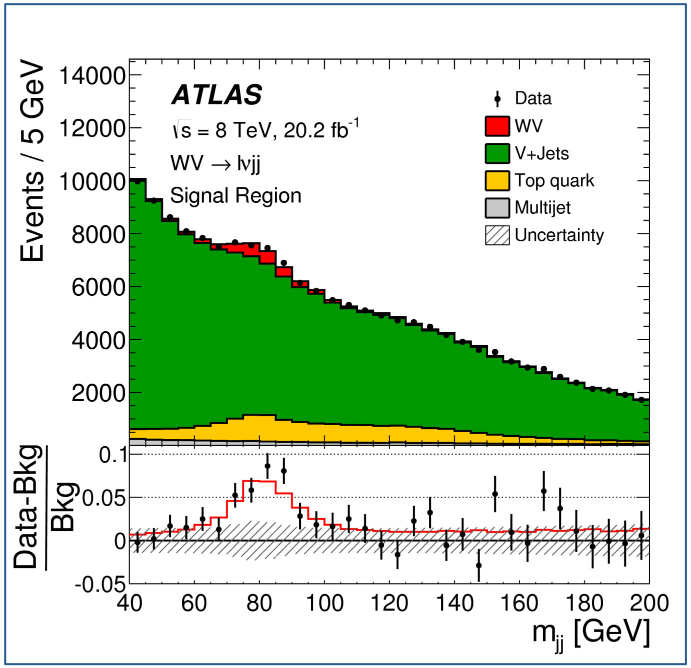
- 20.2 fb-1 of 8 TeV data
- ~ Six times higher branching ratio than fully leptonic
  - Greater sensitivity to anomalous TGCs
- Select events with (among other cuts):
  - exactly 1 lepton (p_T >15 GeV),
  - MET > 40 GeV,
  - and either:

Selects the leptonically decaying W boson

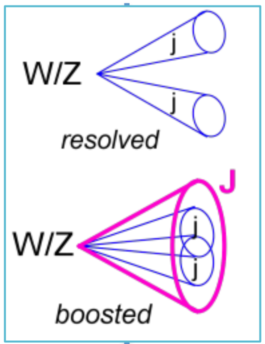


Two AntiKt R=0.4 jets (resolved)

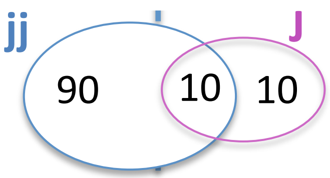
Higher stats and smaller systs



Dominant backgrounds (V+Jet) MC reweighted with CR distributions, and then normalization floats in fit

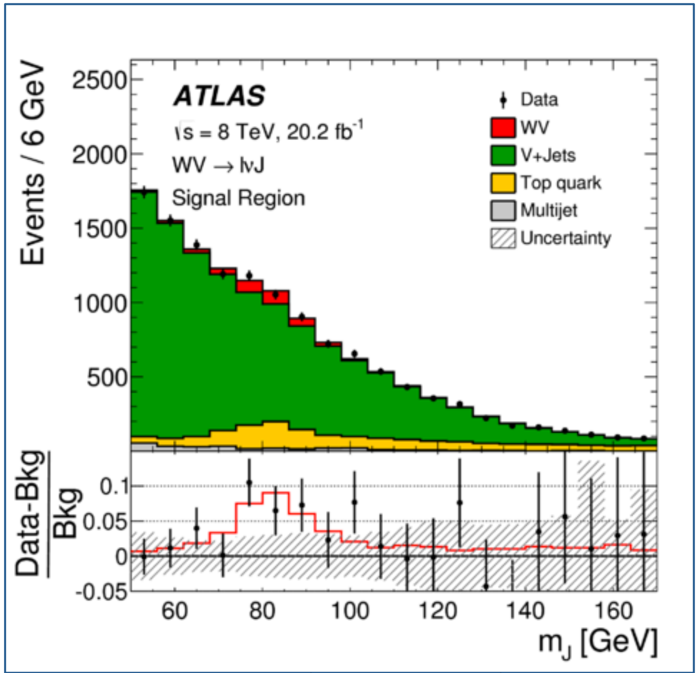


Signal overlap
(number of events)



One AntiKt R=1.0 jet (boosted)

More sensitive to BSM physics



Dominant backgrounds (V+Jet and Top) normalized in Control Regions

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arXiv:1706.01702
[STDM-2015-23 submitted to EPJC]

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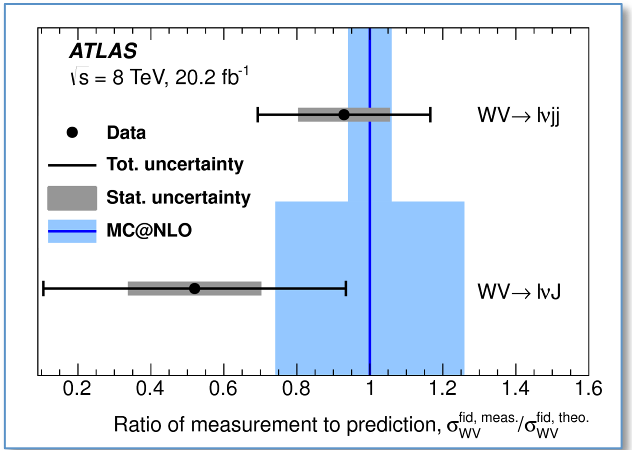

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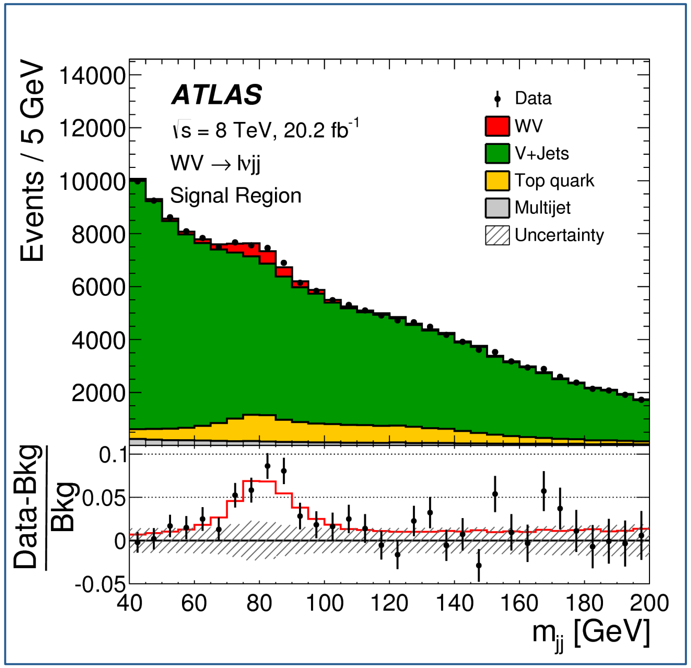

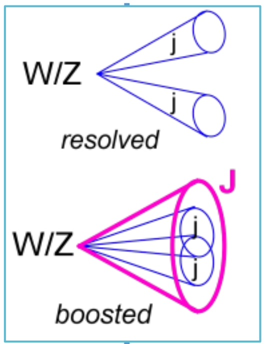

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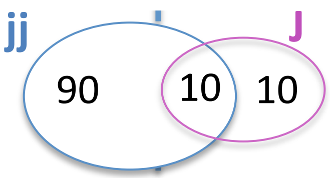

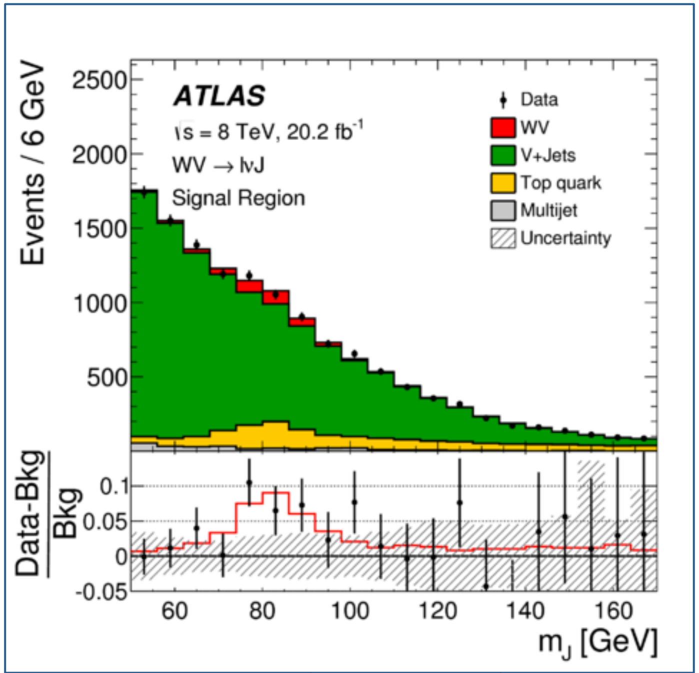

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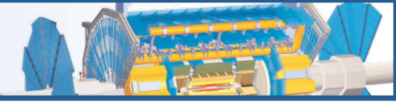
Outline



1. Diboson physics at ATLAS
   – Importance of NNLO predictions

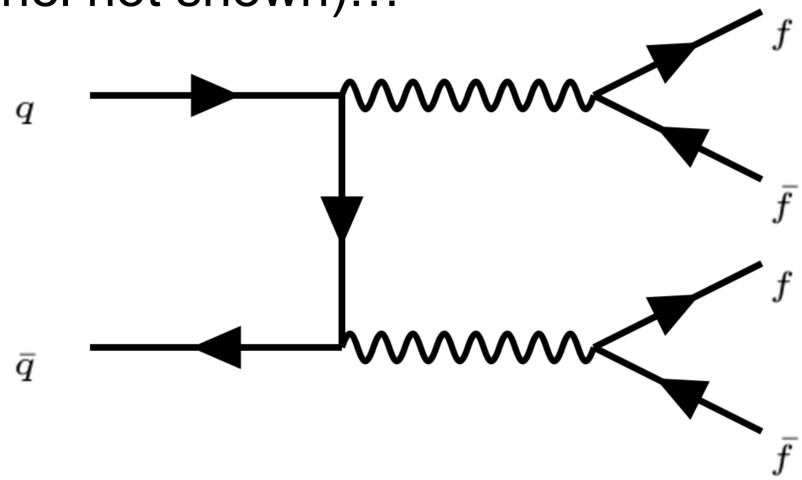
2. Electroweak Diboson processes with fully leptonic final states
   – WW, WZ, ZZ at 13 TeV

3. Diboson processes with semileptonic final states
   – WW/WZ at 8 TeV

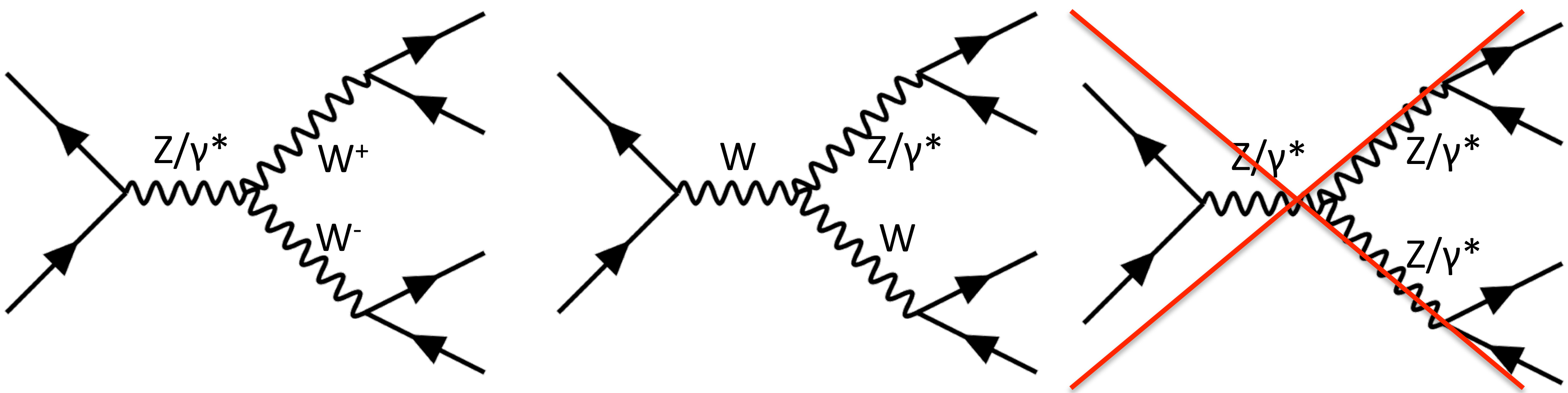
4. Limits on Anomalous Triple Gauge Couplings

Anomalous Triple Gauge Couplings

- LO process (u-channel not shown)…



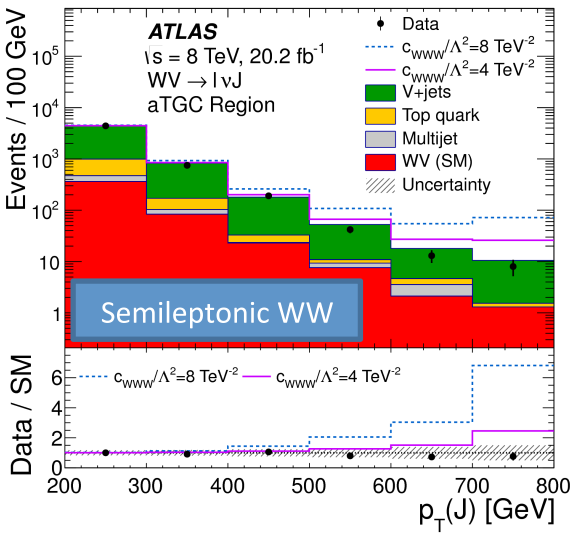
- + Triple Gauge Couplings – **WW and WZ production only**!

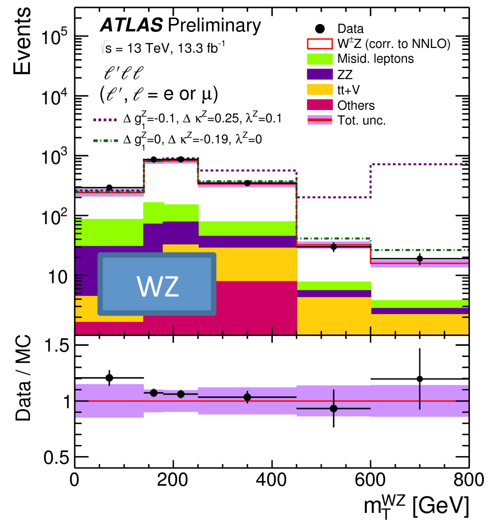


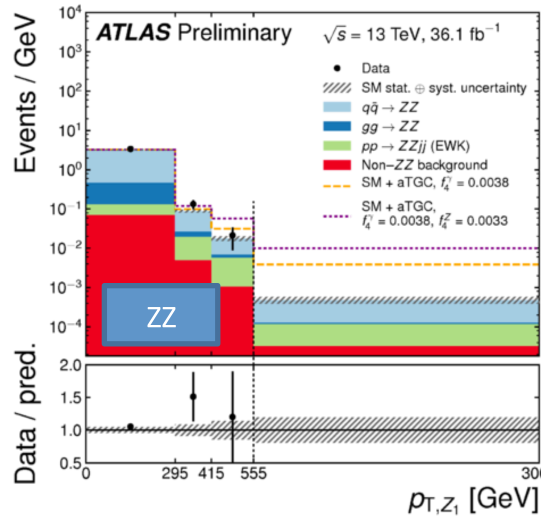
There are no Neutral Triple Gauge Couplings (ZZZ, ZZγ,…) in the SM

Anomalous Triple Gauge Couplings

- Anomalous TGCs will lead to excesses in tails of sensitive observables







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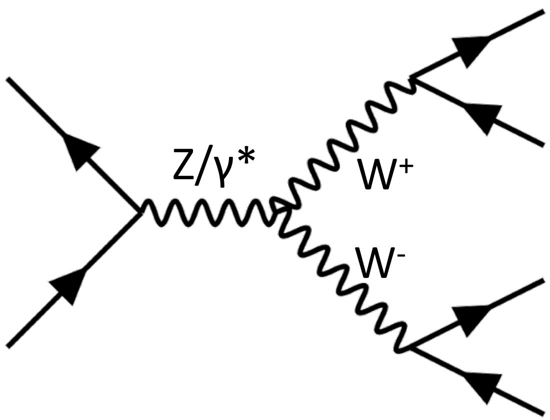

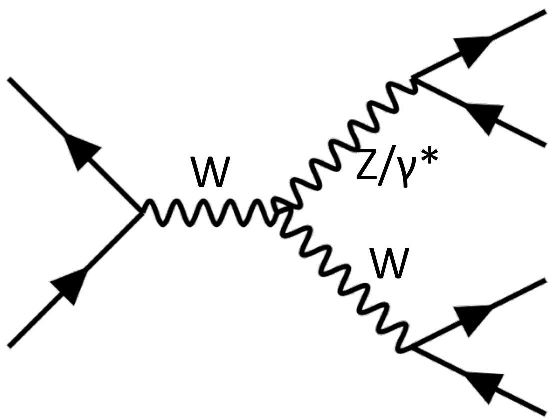

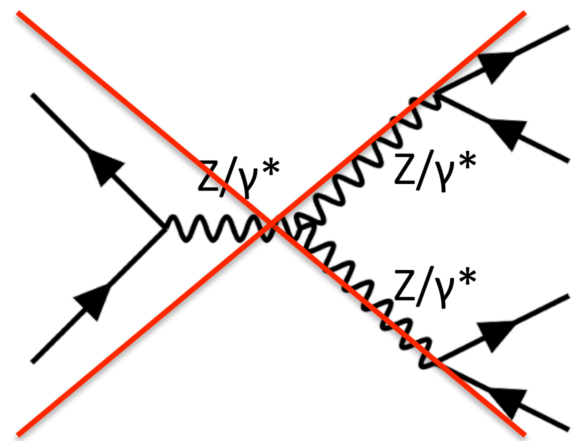

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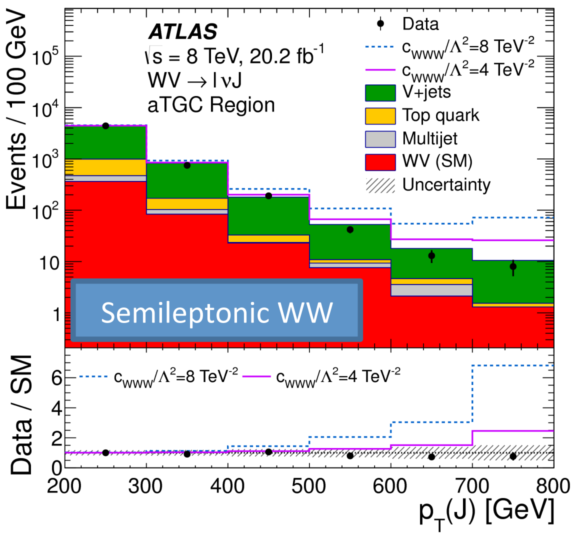
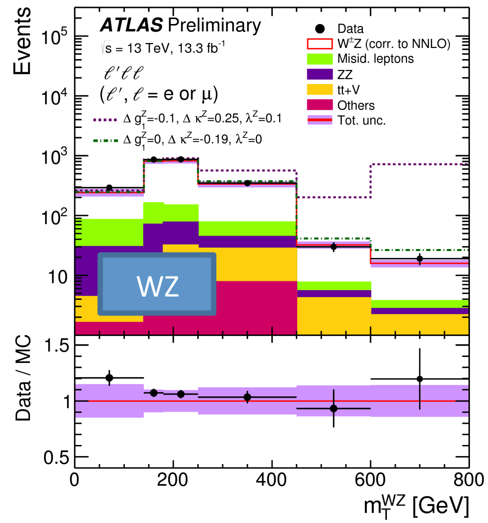
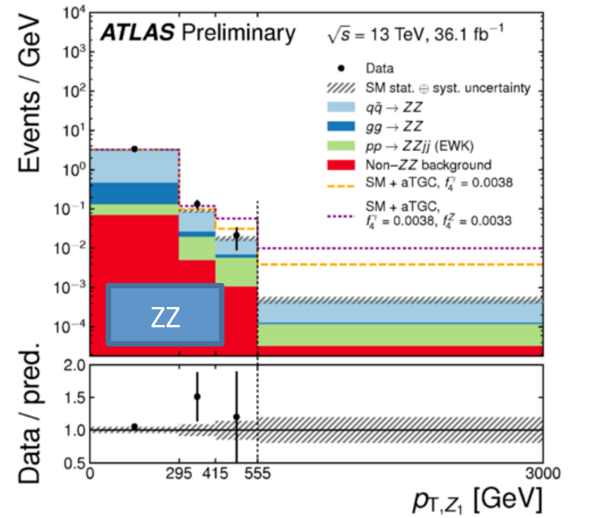






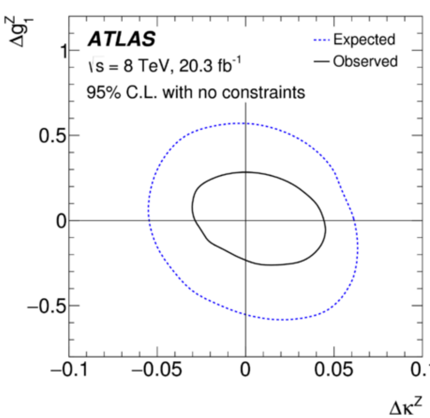
Define $\Delta x = x - 1$

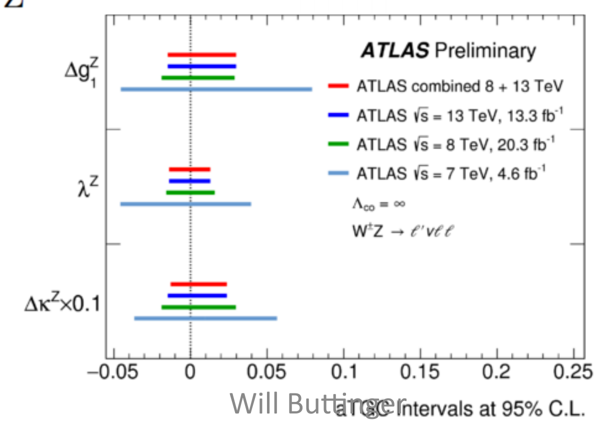
$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1^V \left(W^+_{\mu\nu} W^{\mu} V^{\nu} - W^+_{\mu} V_{\nu} W^{\mu\nu} \right) + i\kappa_V W^+_{\mu} W_{\nu} V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W^+_{\lambda\mu} W^{\mu}_{\nu} V^{\nu\lambda}$$

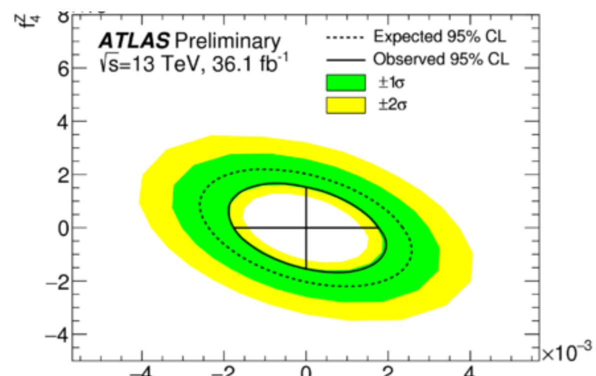
($g_1^V = 1$, $\kappa_V = 1$, $\lambda_V = 0$)

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

($f_4^V = 0$, $f_5^V = 0$)

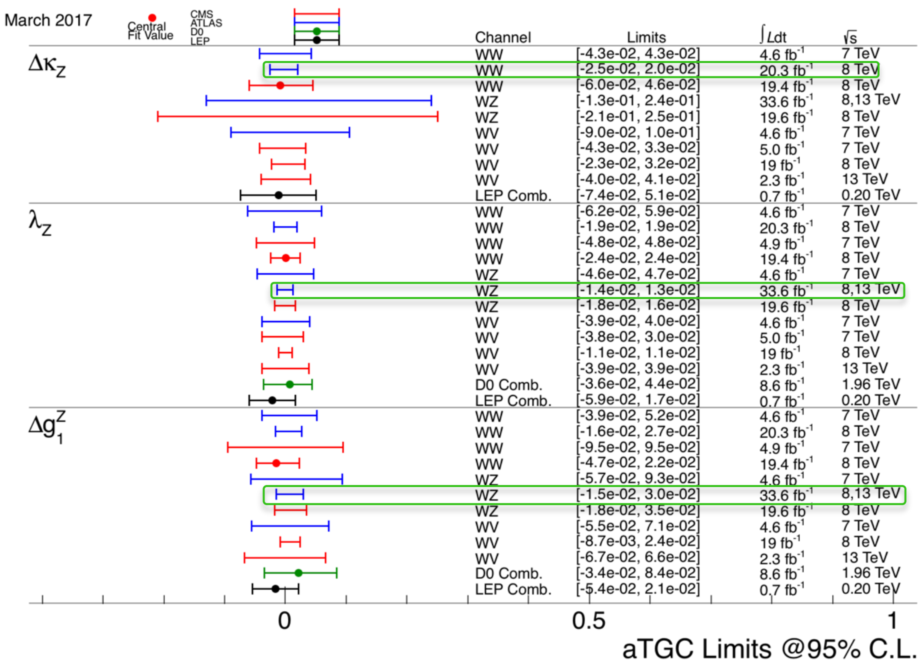


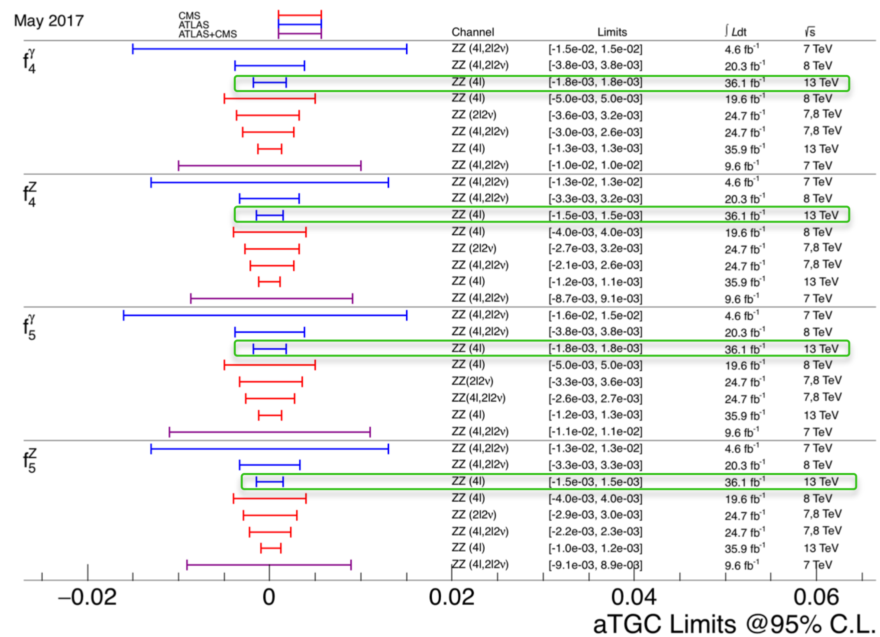




Anomalous Triple Gauge Couplings

- Anomalous TGCs will lead to excesses in tails of sensitive observables
- Limits are now tighter than at **LEP**
  - Limits also comparable between ATLAS and CMS, for similar datasets
- These aTGC limits constrain a variety of BSM models at higher energies





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

Summary

- ATLAS has a full programme of diboson cross-section measurements
  - SM diboson production is often a background to BSM physics searches
- Today I showcased electroweak diboson production (WW,WZ,ZZ)
  - Fully-leptonic final states are the first measurements we do of these processes
  - Also now gaining sensitivity to these processes in the semi-leptonic final states
- These measurements have challenged theorists to compute predictions to NNLO and beyond
  - So far, theorists (and the Standard Model) have risen to that challenge!
- No evidence yet of enhancement of these processes from BSM physics
  - Targeting high momentum transfer phase space we have continued to set limits on anomalous Triple Gauge boson Couplings