# Recent ATLAS Measurements of Diboson Production in pp Collisions at 13 TeV


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ATLAS EXPERIMENT

Hellenic Society for the Study of High Energy Physics

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Recent Developments in High Energy Physics and Cosmology

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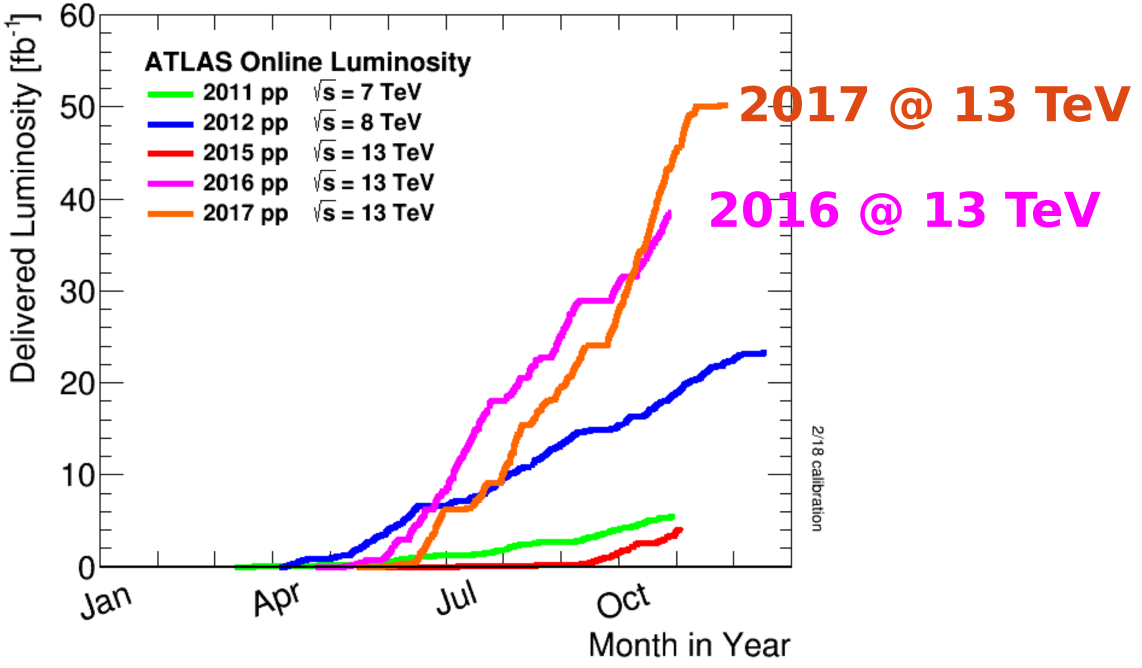
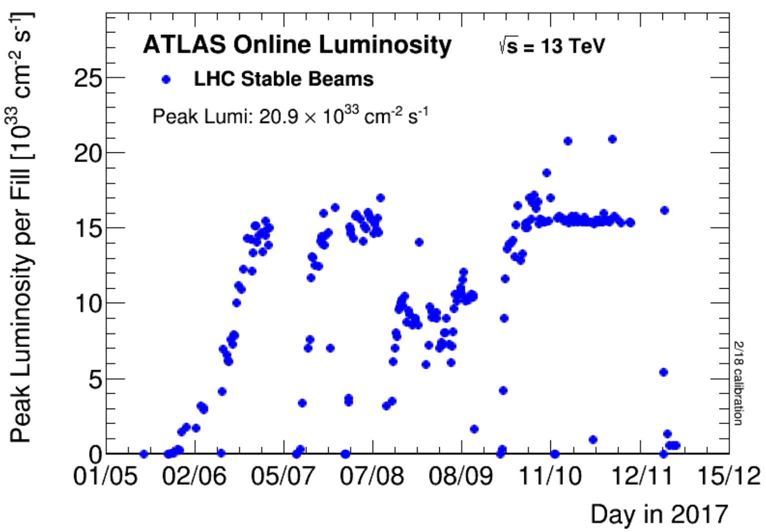
# Outline

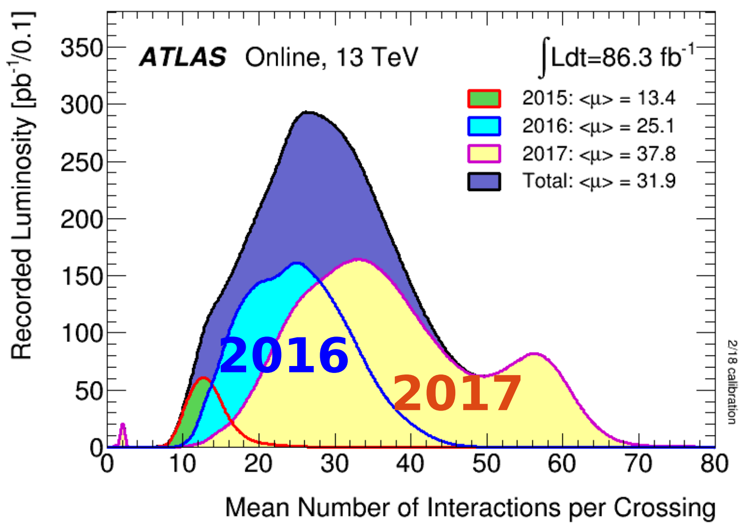
- In this talk: “diboson events” = events with two of the W and Z vector bosons, produced ~on-shell (not from Higgs decays)
  - There are interesting results on Wγ and Zγ as well, not shown
- Diboson production
- Measurements of WW, WZ and ZZ production at 13 TeV
- Limits on anomalous Triple Gauge Couplings
- Towards Vector Boson Scattering and probing of Quartic Gauge Couplings.
- All results available at:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

# ATLAS status

- pp @ 13 TeV: 13 TeV 2016 & 2016 → 86.5/fb on tape with 93-95% data-taking efficiency, lumi uncertainty ~3.2%
- Instantaneous luminosity has reached more than 2 x $10^{34}$ $cm^{-2}$ $s^{-1}$
- Kept around 1.5 x $10^{34}$ $cm^{-2}$ $s^{-1}$

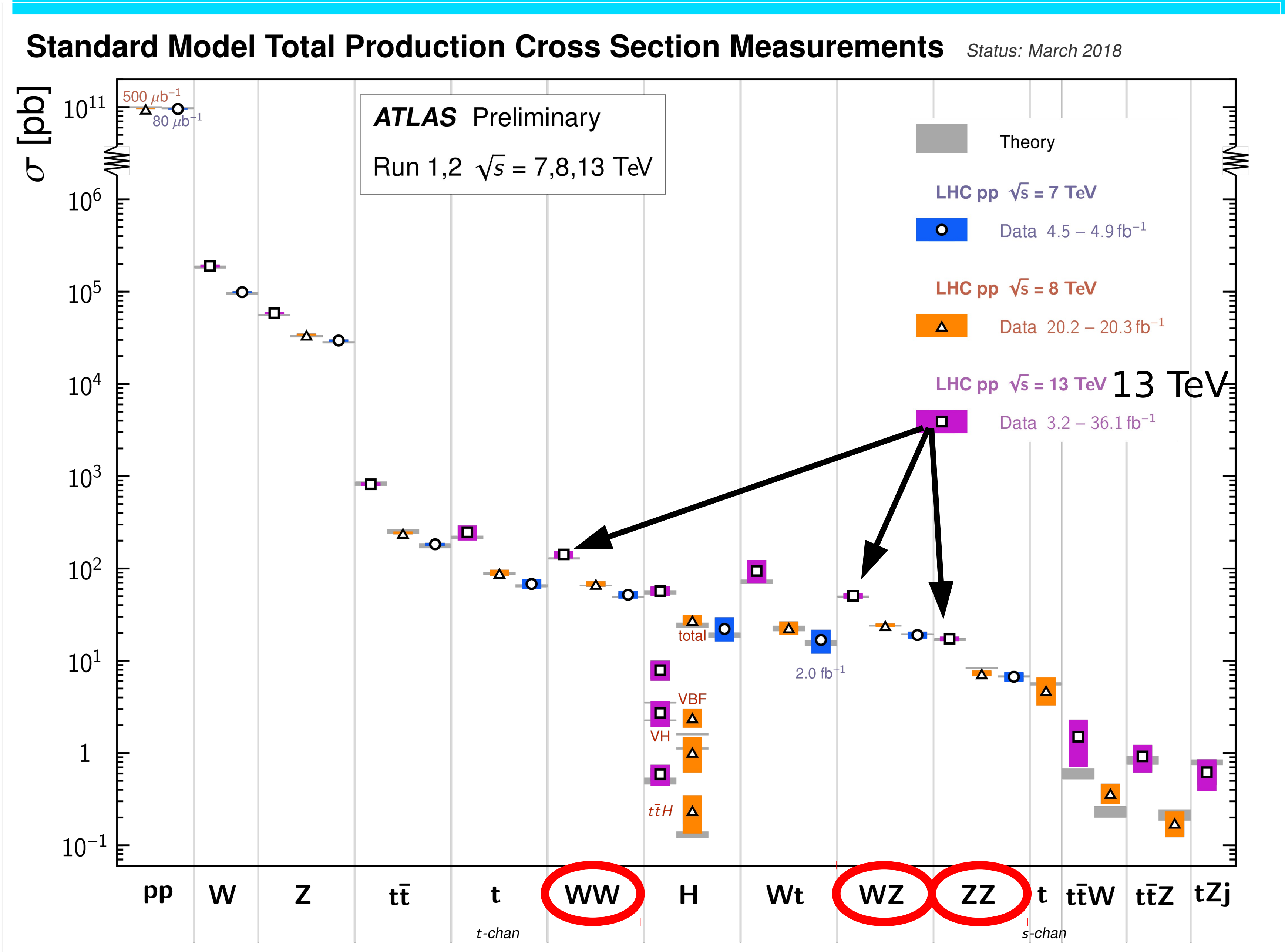


# 1) Diboson production - introduction

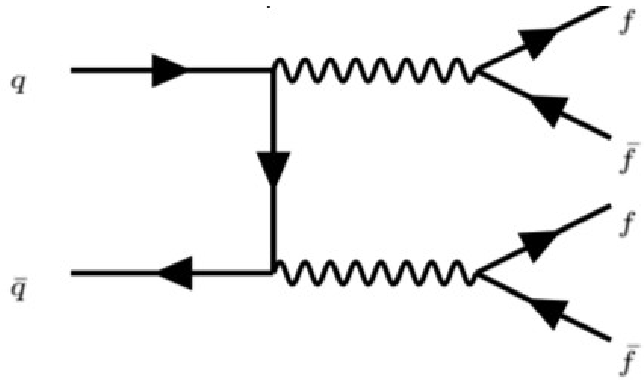
# Standard Model Measurements in ATLAS




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

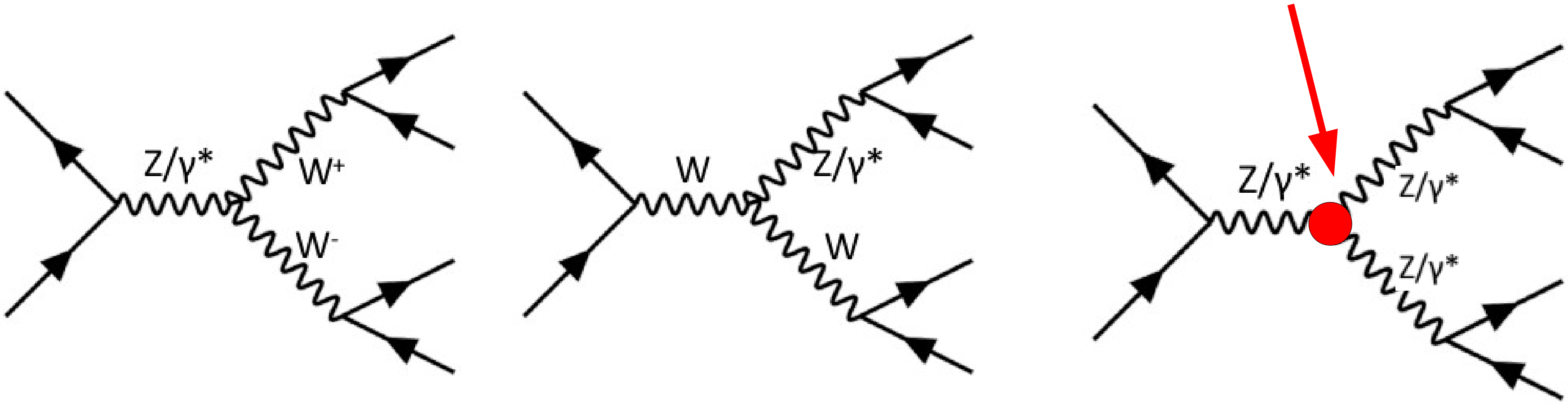
# LO EWK WW/WZ/ZZ production diagrams

- **At Leading Order with all ElectroWeak vertices**:



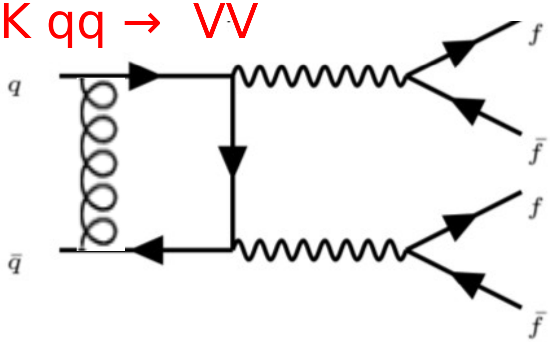

**LO EWK: 4 EWK vertices**

- Also, **Triple Gauge Couplings** (not there in SM when all three neutral):

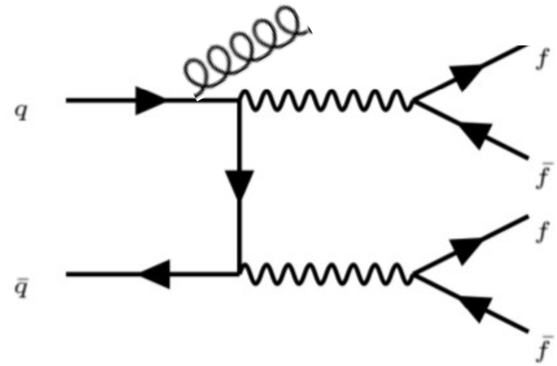


# With extra QCD vertices

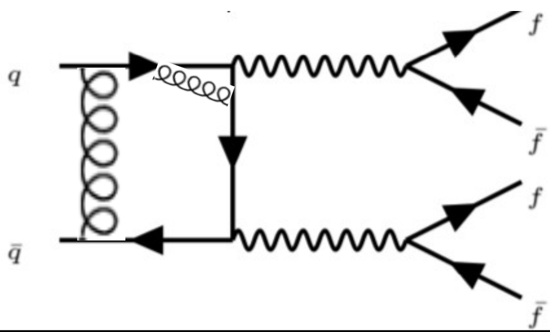
Interference with
LO EWK qq → VV

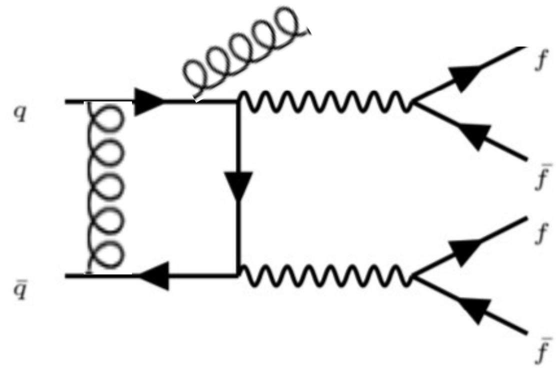



With external gluons:
VV + 1 jet



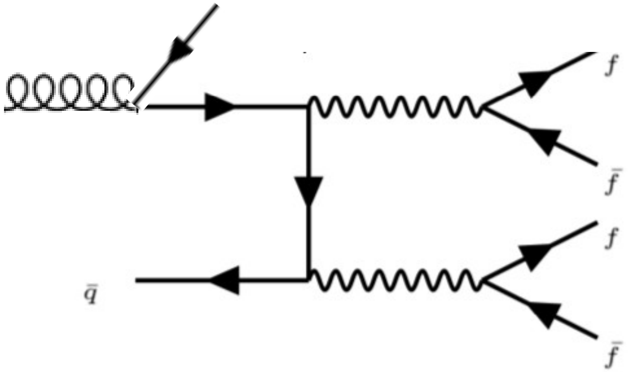

Internal gluons

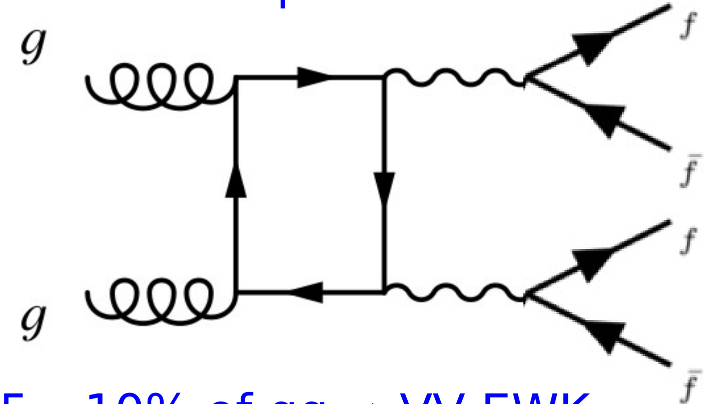



Internal + external
gluons:
VV + 1 jet

Also from gluons in the protons



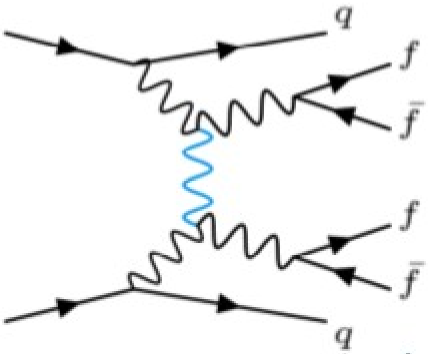




5 – 10% of qq → VV EWK

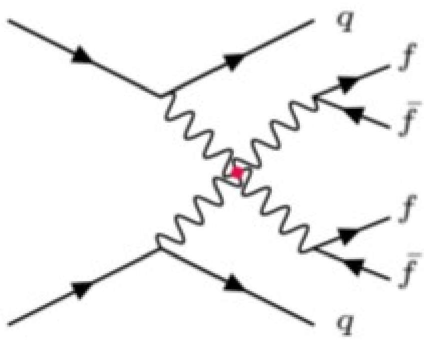
# With extra EWK vertices get 2 jets: again pure EWK and EWK + QCD

**Vector Boson Scattering**: incoming quarks act as sources of colliding boson beams

**Signature: VV + 2 forward jets**

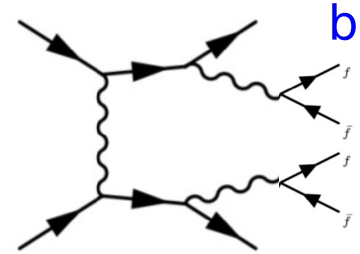


6 EWK vertices: not only vector bosons in the t-channel, but also the Higgs:
important for not letting the cross section explode at high energies (like the ZWW vertex was needed to limit the WW production cross section at e+ e- collisions at LEP)



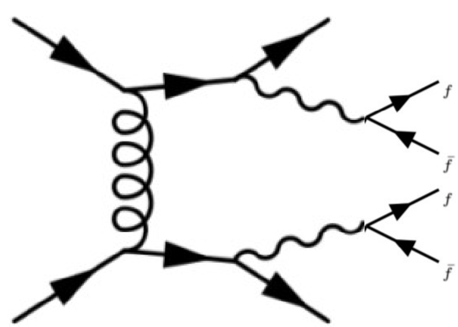
5 EWK vertices
**Quartic Gauge Couplings**:
again, SM does not allow all neutral in the quartic vertex

6 EWK vertices
but not VBS…

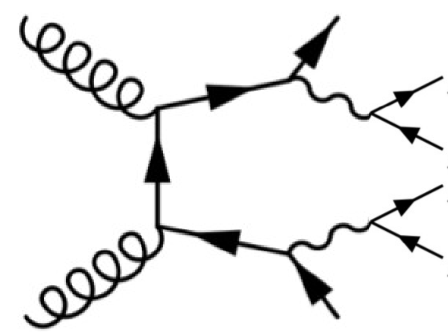


**4 EWK + 2 QCD vertices**:
same final state
→ important background

qq

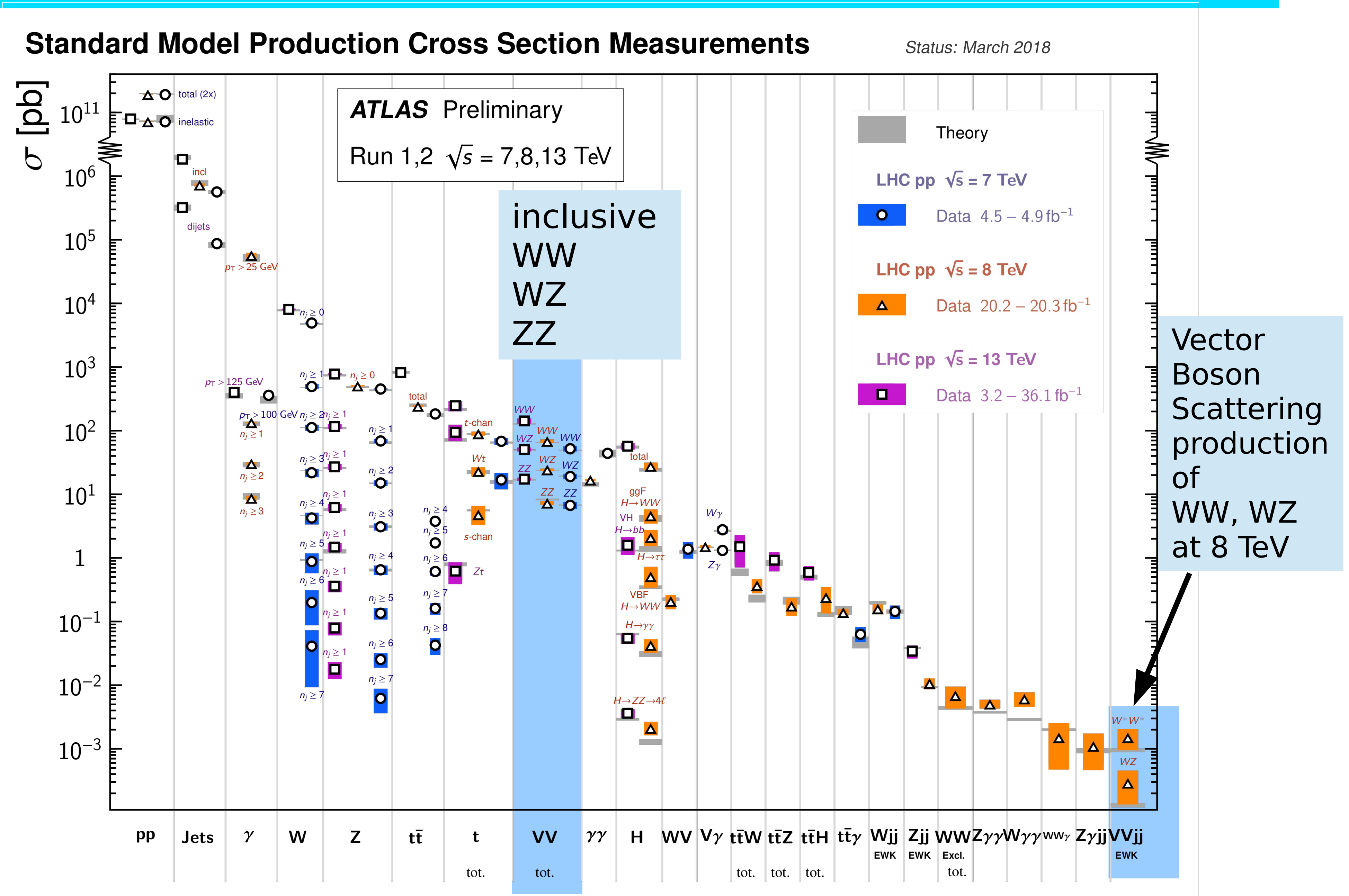


gg



+ …

# WW, WZ, and ZZ at 7, 8 and 13 TeV

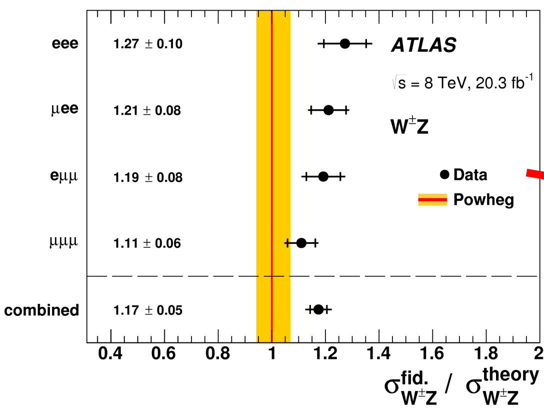



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

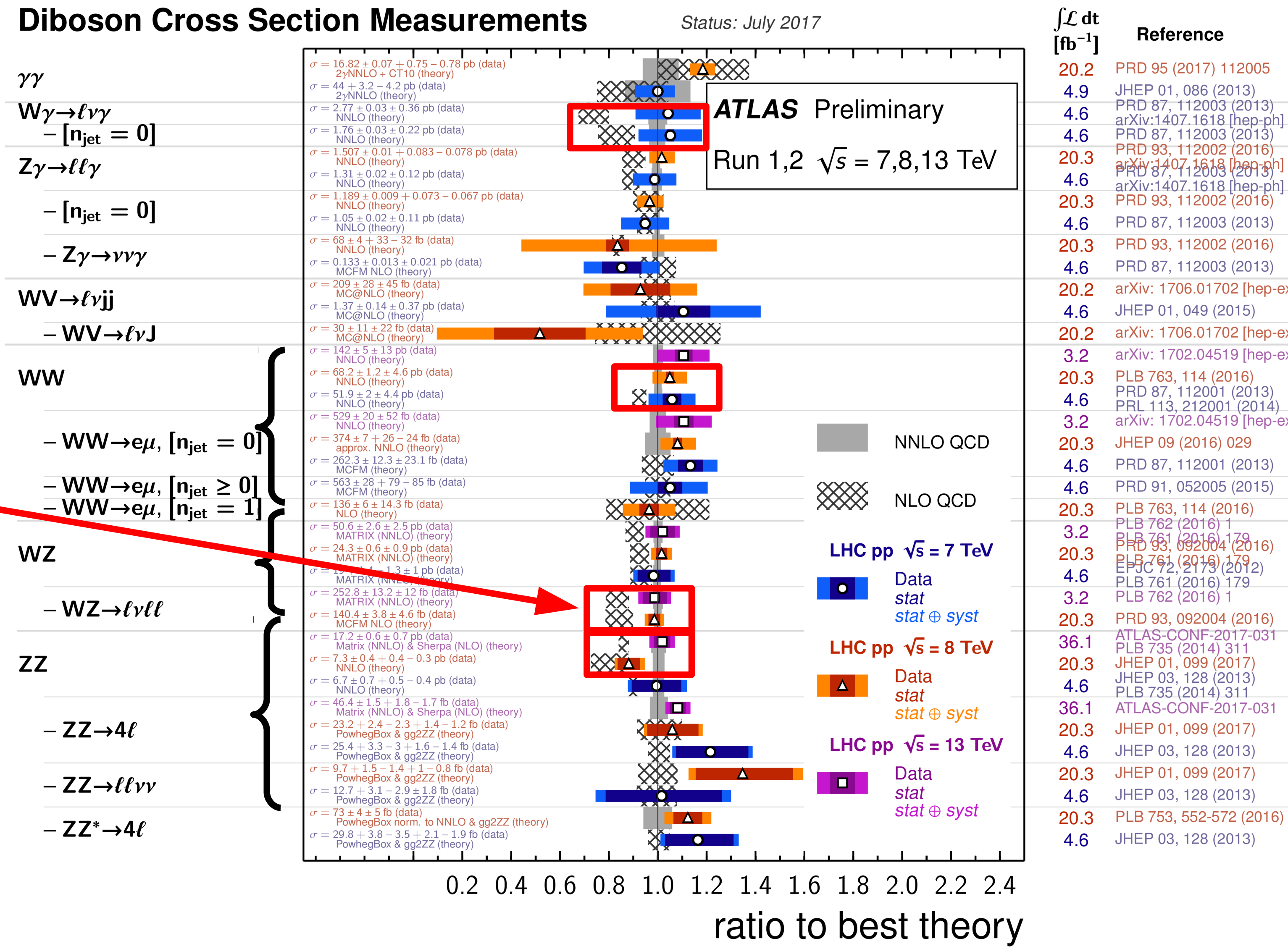
# "Best theory" now has QCD @ NNLO

NNLO calculations in QCD became available in the last couple of years [arXiv:1604.08576];
Important to **improve agreement with data**: shifts by up to 20% compared to NLO

Before that:
tension w/ NLO QCD
calulcations
e.g., WZ@8TeV

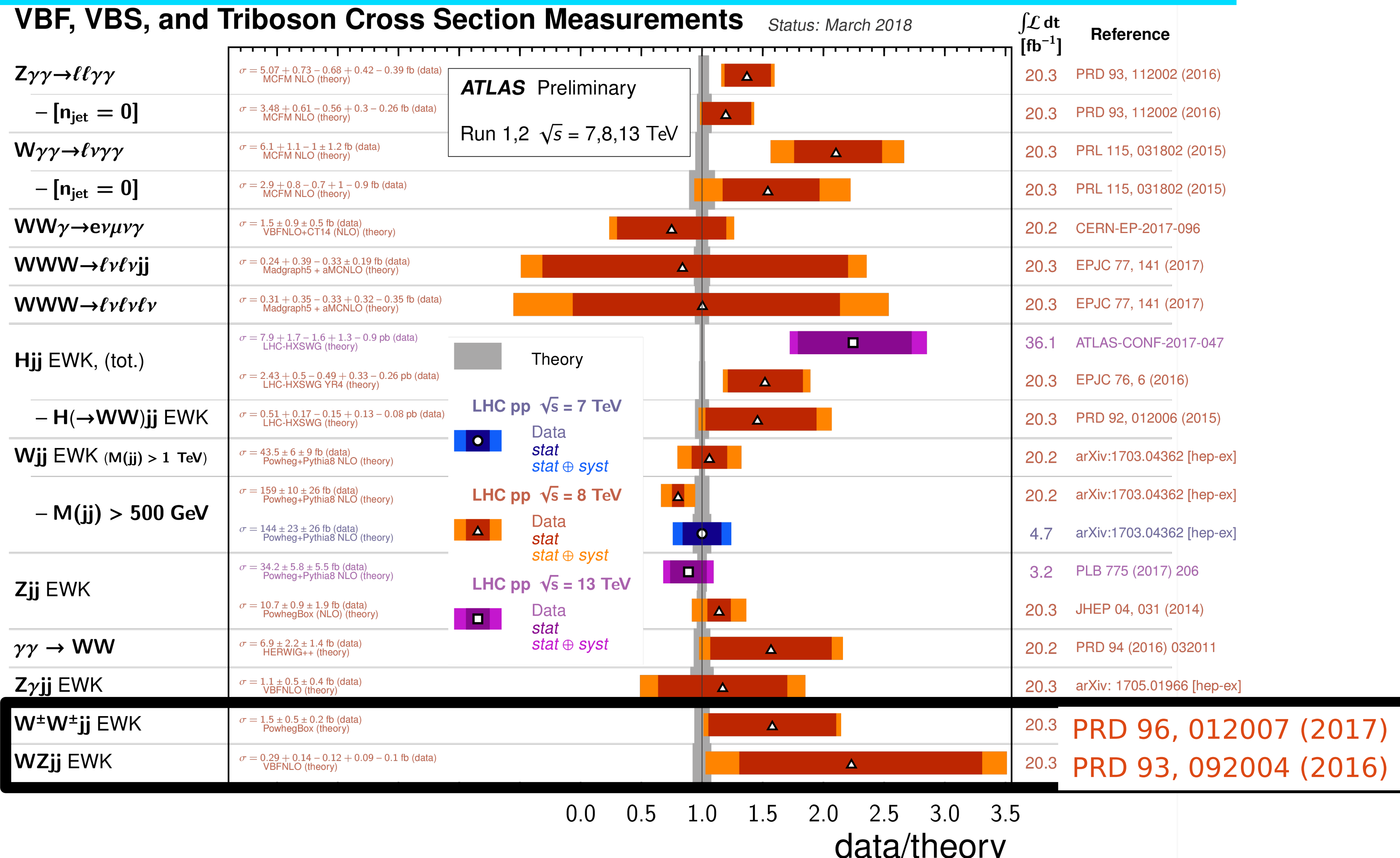



PRD93.092004(2016)




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

# Vector Boson Scattering measured in same-sign WW, and WZ at 8 TeV. WW/WZ/ZZ results at 13 TeV to come




**WW & WZ VBS**

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

# 2) ZZ, WZ and WW production @ 13 TeV

All 13 TeV measurements so far are with leptonic states:

Increasing cross section →

| | ZZ | WZ | WW |
|---|---|---|---|
| Signature: | 4 leptons | 3 leptons + MET(1$\nu$) | 3 leptons + MET(2$\nu$) |
| Backgrounds: | WZ + 1 fake lepton; WW / tt / Drell-Yan + 2 fake leptons | Drell-Yan + 1 fake lepton; ZZ (missing lepton); WW / tt +1 fake lepton | tt ; Drell-Yan |
| Signal purity: | ~98% | ~79% | ~70% |

← Increasing purity

Thessaloniki (with Hellenic Open University in ZZ) in all ZZ and WZ analyses

# 2.1) ZZ production

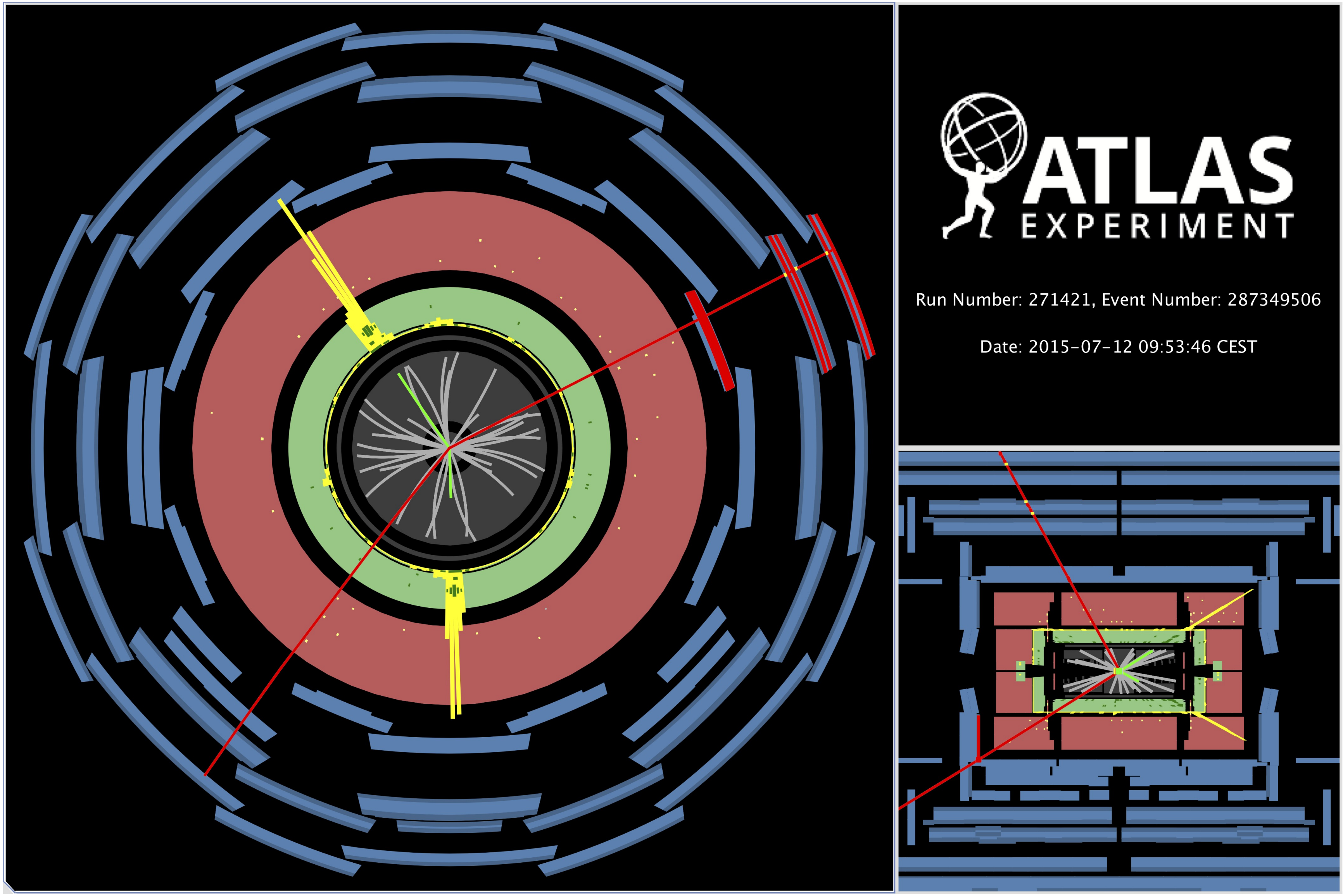
**"ZZ → 4l cross-section measurements and search for anomalous triple gauge couplings in 13 TeV pp collisions with the ATLAS detector"**

Phys. Rev. D 97 (2018) 032005

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2016-15/

# ZZ → 4l production

- ZZ → $e^+ e^- \mu^+ \mu^-$ (2e2μ)



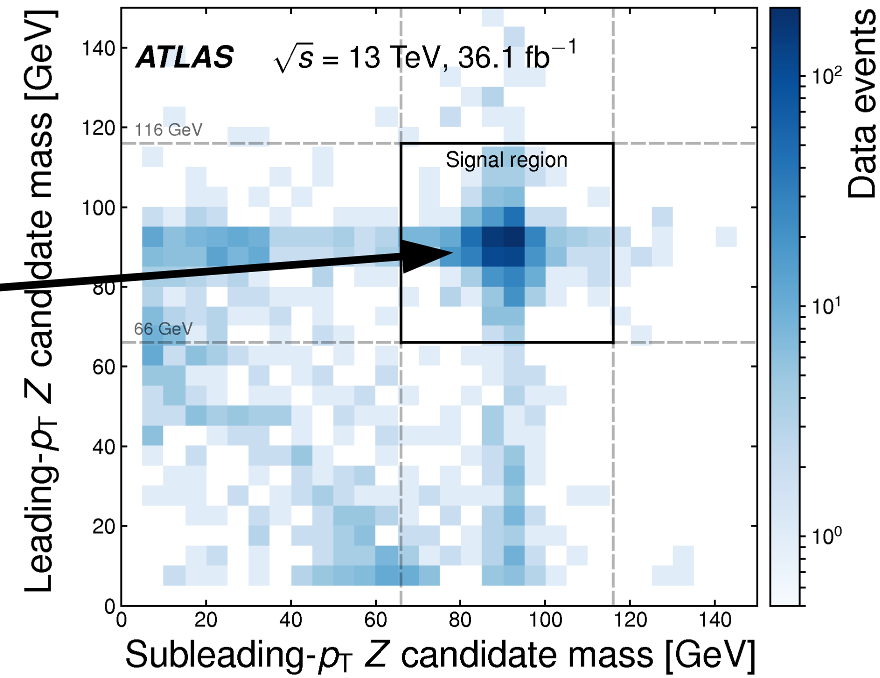
# ZZ → 4l

- 36.1 $fb^{-1}$ (2015+2016) √s = 13 TeV data
- Select events with at least 4 leptons with |η|<2.7, pT>20,>15,>10 GeV; the rest >5 GeV
- Only on-shell: $66 < m_{ll} < 116$ GeV
- Fully leptonic final state is very clean:

  21.2 bkg events (12.3 from fake leptons) out of 958 total event yield predicted

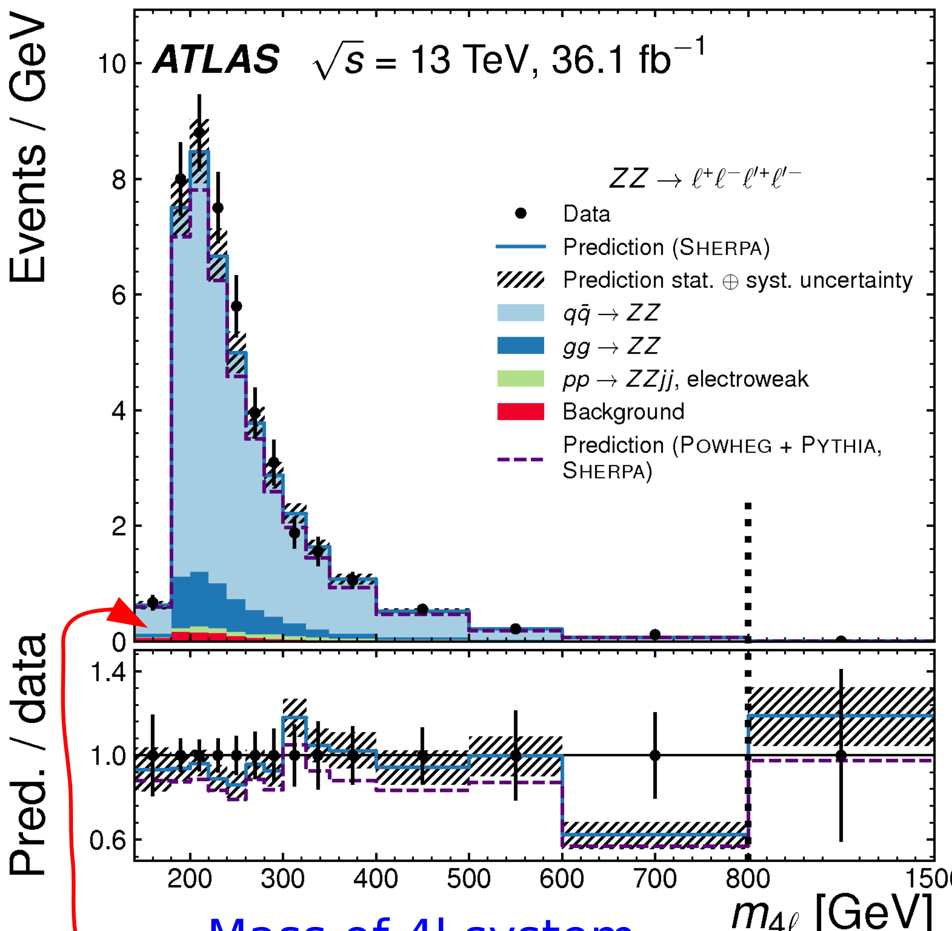
  – Main background from fake leptons (e.g. in Z + jet events)

  – SM processes with >4 leptons treated as background (e.g. ZZZ → 6l)

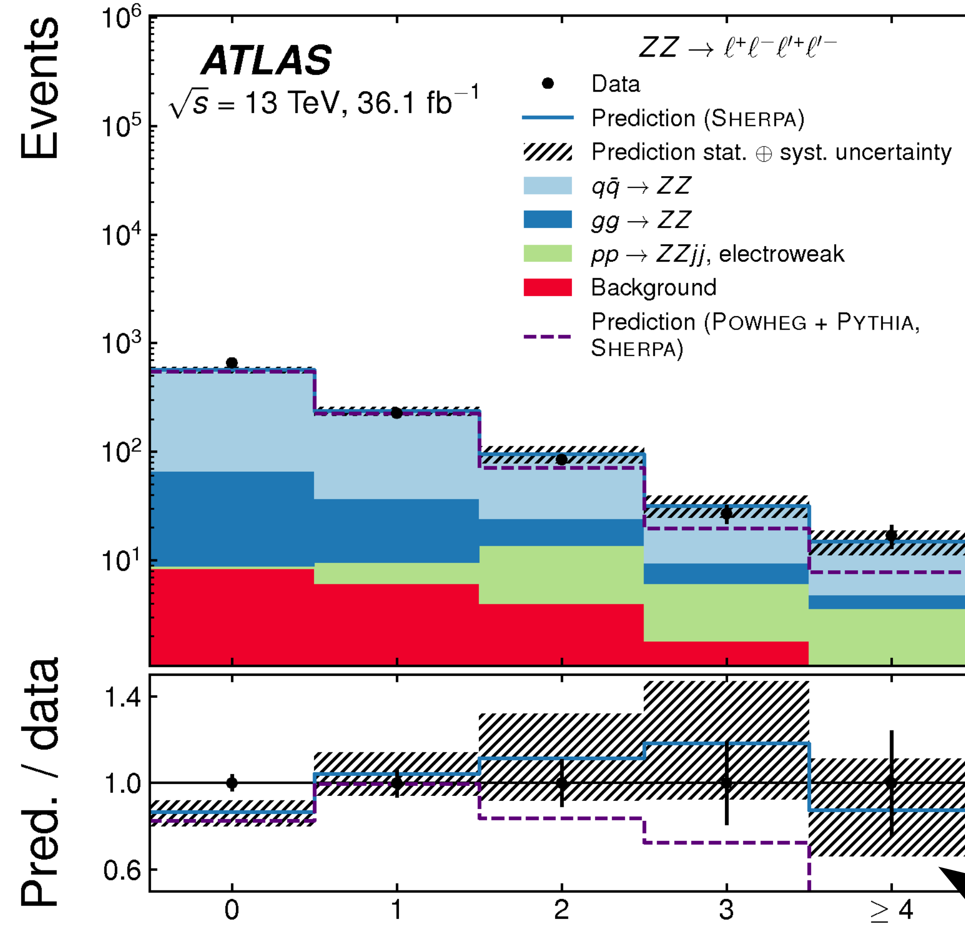



| Contribution | 4e | 2e2μ | 4μ | Combined |
|---|---|---|---|---|
| Data | 249 | 465 | 303 | 1017 |
| Total prediction (SHERPA) | $198^{+16}_{-14}$ | $469^{+35}_{-31}$ | $290^{+22}_{-21}$ | $958^{+70}_{-63}$ |
| Signal ($q\bar{q}$-initiated) | $168^{+14}_{-13}$ | $400^{+31}_{-28}$ | $246^{+19}_{-18}$ | $814^{+63}_{-57}$ |
| Signal ($gg$-initiated) | $21.3 \pm 3.5$ | $50.2 \pm 8.2$ | $29.7 \pm 4.9$ | $101 \pm 17$ |
| Signal (EW-$ZZjj$) | $4.36 \pm 0.42$ | $10.23 \pm 0.72$ | $6.43 \pm 0.55$ | $21.0 \pm 1.2$ |
| $ZZ \to \tau^+\tau^-[\ell^+\ell^-, \tau^+\tau^-]$ | $0.59 \pm 0.09$ | $0.55 \pm 0.08$ | $0.55 \pm 0.09$ | $1.69 \pm 0.16$ |
| Triboson | $0.68 \pm 0.21$ | $1.50 \pm 0.46$ | $0.96 \pm 0.30$ | $3.14 \pm 0.30$ |
| $t\bar{t}Z$ | $0.81 \pm 0.25$ | $1.86 \pm 0.56$ | $1.42 \pm 0.43$ | $4.1 \pm 1.2$ |
| Misid. lepton background | $2.1 \pm 2.1$ | $4.9 \pm 3.9$ | $5.3 \pm 5.2$ | $12.3 \pm 8.3$ |
| Total prediction (MATRIX + corrections) | $197^{+15}_{-14}$ | $470^{+34}_{-31}$ | $286^{+22}_{-21}$ | $953^{+69}_{-64}$ |
| Total prediction (POWHEG + PYTHIA with higher-order corrections, SHERPA) | $193 \pm 11$ | $456 \pm 24$ | $286 \pm 17$ | $934 \pm 50$ |

# ZZ → 4l,  kinematics etc




Mass of 4l system




Jets with $|\eta|<4.5$, $p_T>30$ GeV

Background is small and located in low mass & low pT, like most of the signal

~1000 observed events allow many distributions.

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)

Powheg+Pythia does not follow at high jet multiplicities, due to lack of jets in ME

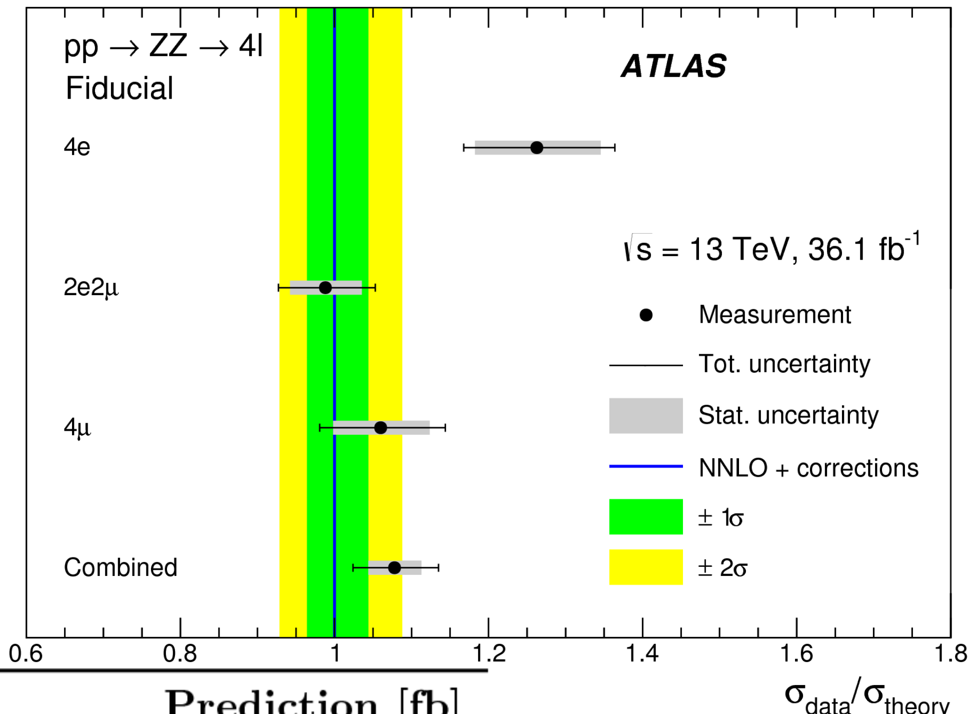
# ZZ fiducial cross section

- "Fiducial cross sections" reported: a fraction A of the total, corresponding to the reduced phase-space and the decay channels of the actual measurements (so it includes the Branching Ratios, BR)

$$\sigma^{fid}(pp \to VV + X, V \to leptons) = \frac{N-B}{L*C}$$

N-B: Observed events – bkg estimate
C: detector efficiency , L: integrated luminosity

- "NNLO + corrections":
  - NNLO calculation from Matrix
  - gg-initiated contribution (Sherpa) multiplied by a global NLO correction factor of 1.67.
  - global NLO EW correction factor of 0.95, except to the gg-initiated loop-induced contribution, and the contribution of around 2.5% from EW-ZZjj generated with Sherpa is added.




| Channel | Measurement [fb] | Prediction [fb] |
|---|---|---|
| $4e$ | $13.7^{+1.1}_{-1.0}$ [$\pm 0.9$ (stat.) $\pm 0.4$ (syst.) $^{+0.5}_{-0.4}$ (lumi.)] | $10.9^{+0.5}_{-0.4}$ |
| $2e2\mu$ | $20.9^{+1.4}_{-1.3}$ [$\pm 1.0$ (stat.) $\pm 0.6$ (syst.) $^{+0.7}_{-0.6}$ (lumi.)] | $21.2^{+0.9}_{-0.8}$ |
| $4\mu$ | $11.5^{+0.9}_{-0.9}$ [$\pm 0.7$ (stat.) $\pm 0.4$ (syst.) $\pm 0.4$ (lumi.)] | $10.9^{+0.5}_{-0.4}$ |
| Combined | $46.2^{+2.5}_{-2.3}$ [$\pm 1.5$ (stat.) $^{+1.2}_{-1.1}$ (syst.) $^{+1.6}_{-1.4}$ (lumi.)] | $42.9^{+1.9}_{-1.5}$ |

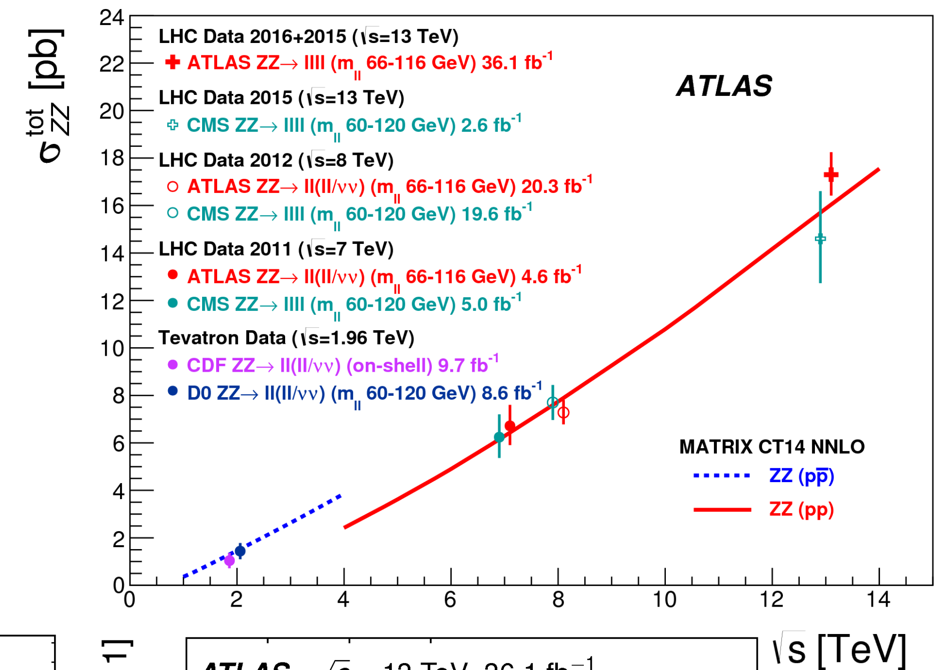
- Statistics limited, dominant systematics lepton identification/reconstruction efficiencies (tension in 4e channel)

# ZZ total cross section & differential fiducial

- Fiducial measurement extrapolated to "total cross sections" by correcting for the BRs and the Acceptance, A.

- Total pp → ZZ production:

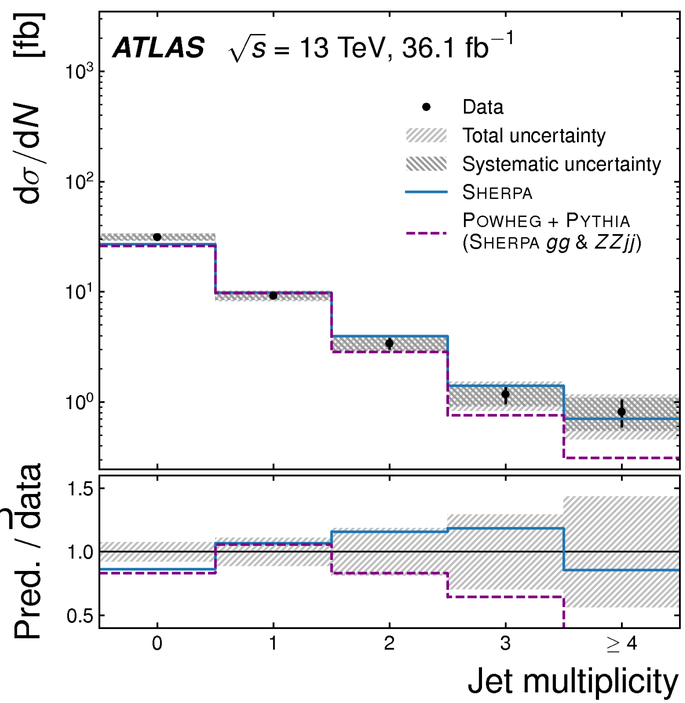
$$17.3 \pm 0.9\ [\pm 0.6\ \text{(stat.)}\ \pm 0.5\ \text{(syst.)}\ \pm 0.6\ \text{(lumi.)}]\ \text{pb}$$

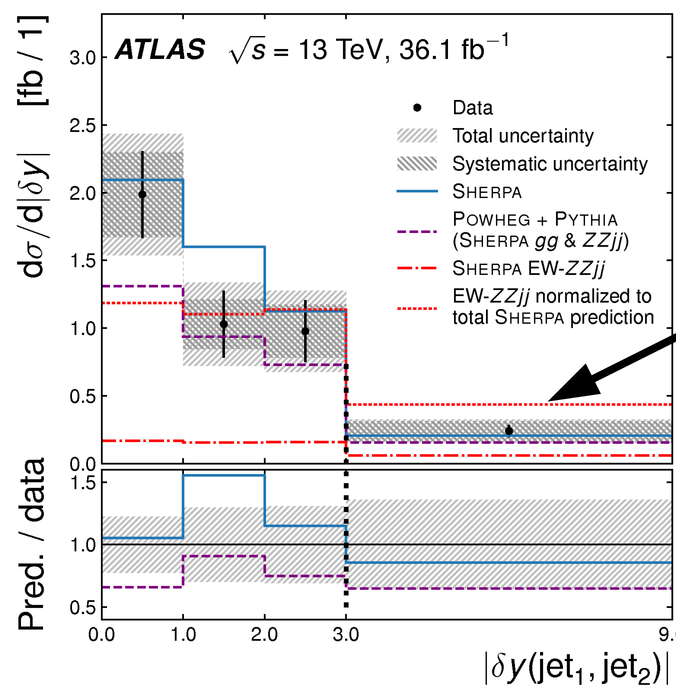



- (Fiducial) differential cross-sections provided in 20 variables, a lot of them for first time:

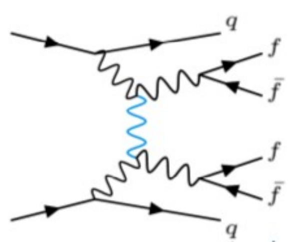
nnNLO Sherpa vs. NLO POWHEG

(Powheg does not follow at high jet muliplicities: parton emission at Matrix-Element level necessary




Large distance in rapidity between jets: important for VBS topology



# 2.2) WZ production

**“Measurement of $W^{\pm}Z$ boson pair-production in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS Detector and confidence intervals for anomalous triple gauge boson couplings”**

ATLAS-CONF-2016-043

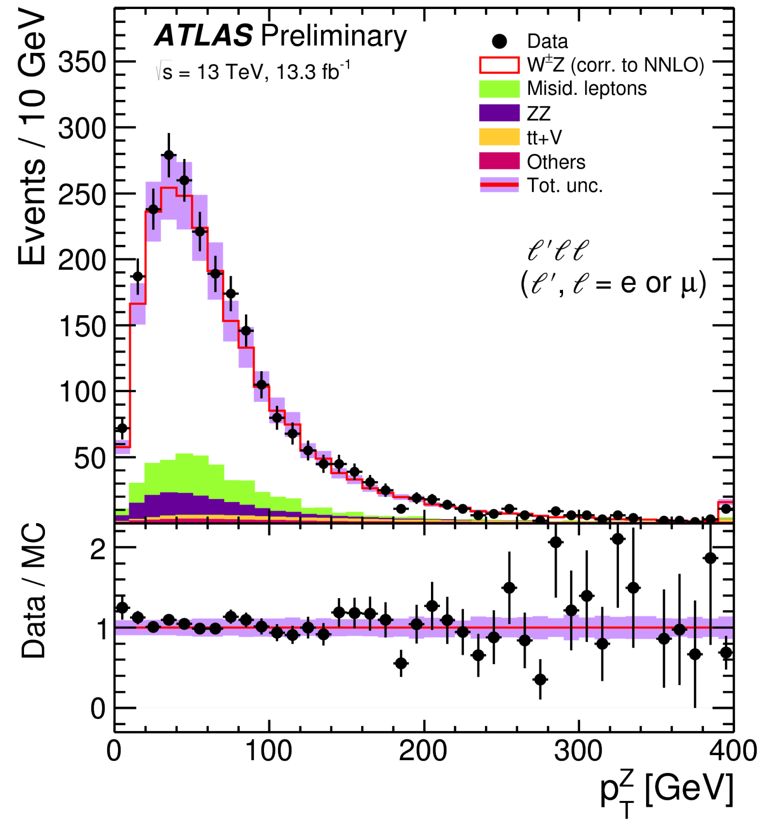
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-043/

[ update on first measurement with 3.2 $fb^{-1}$ ; Phys. Lett. B 762 (2016) 1
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-19/ ]

# WZ → 3l ν

- 13.3 $fb^{-1}$ (2015+2016) √s = 13 TeV data
- Includes 3e, 3μ, μ2e, and e2μ final states
- Biggest uncertainty from fake-lepton estimate (3% , from a total of ~7% )

| Channel | $eee$ | $\mu ee$ | $e\mu\mu$ | $\mu\mu\mu$ | All |
|---|---|---|---|---|---|
| Data | 516 | 537 | 612 | 752 | 2417 |
| Total Expected | 504 ± 7 | 588 ± 5 | 552 ± 6 | 671 ± 4 | 2315 ± 11 |
| $W^{\pm}Z$ | 354.0± 2.5 | 442.7± 2.9 | 453.2± 2.9 | 581.1± 3.4 | 1831 ± 6 |
| $ZZ$ | 27.7 ± 0.4 | 36.0 ± 0.5 | 32.9 ± 0.4 | 46.5 ± 0.5 | 143.2± 0.9 |
| Misid. leptons | 103 ± 7 | 87 ± 4 | 45 ± 6 | 17.9 ± 2.5 | 253 ± 10 |
| $t\bar{t}$+V | 12.8 ± 0.1 | 14.49± 0.13 | 13.50± 0.12 | 15.59±0.13 | 56.41±0.25 |
| $tZ$ | 5.506±0.029 | 6.674±0.033 | 6.653±0.032 | 8.22 ±0.04 | 27.05±0.07 |
| $VVV$ | 0.974±0.029 | 1.219±0.034 | 1.166±0.031 | 1.44 ±0.04 | 4.80 ±0.07 |

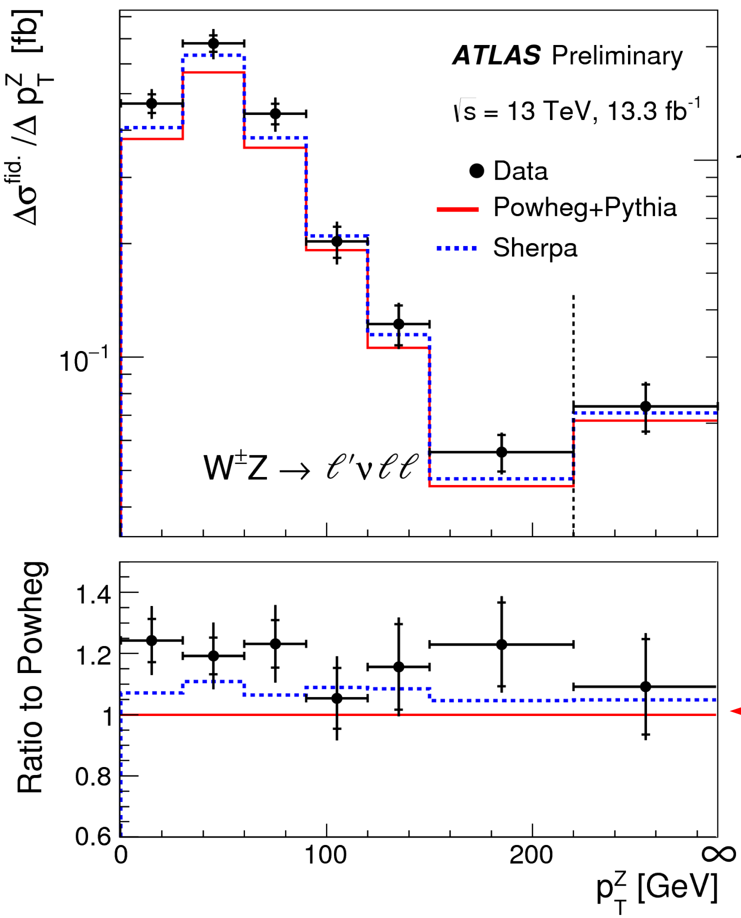



- From event count to fiducial cross section:

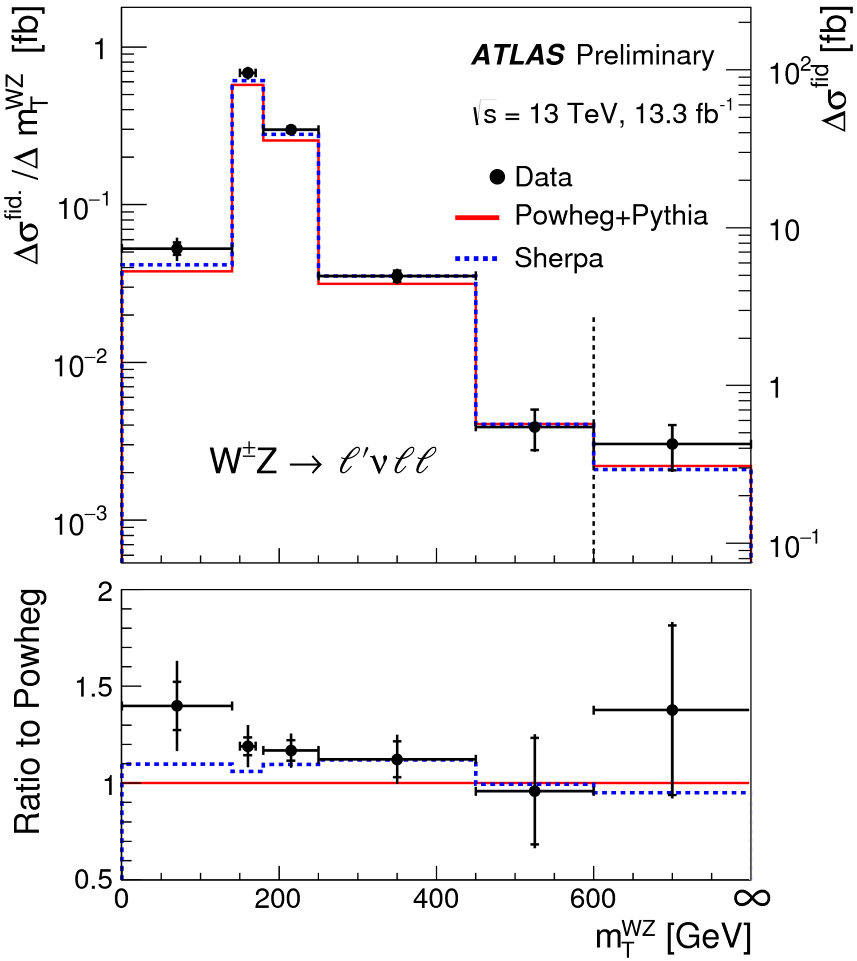
$$\sigma^{\text{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 66.2 \pm 1.8\,(\text{stat.}) \pm 3.6\,(\text{sys.}) \pm 2.1\,(\text{lumi.})\ \text{fb}$$

# WZ → 3l ν

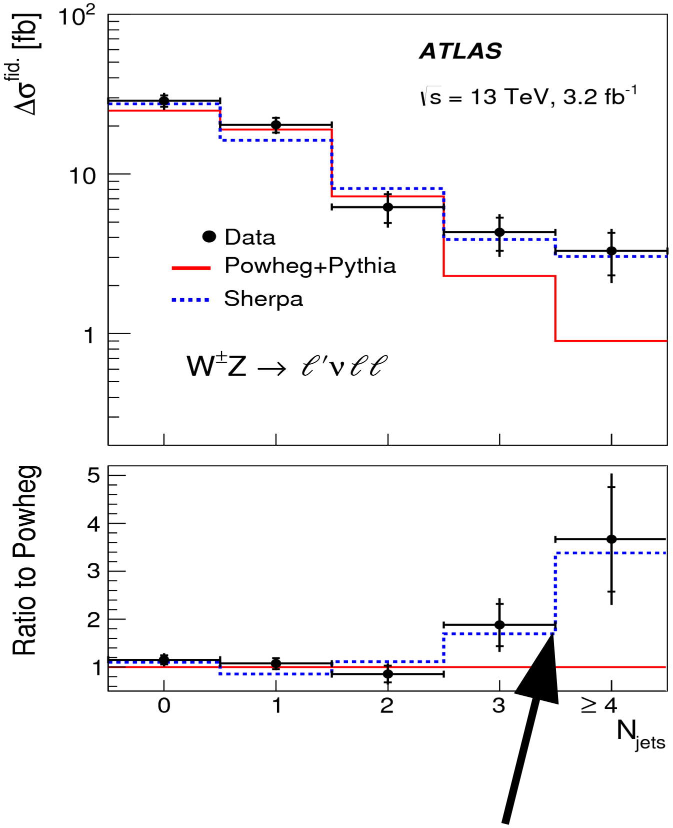
- 13.3 $fb^{-1}$ (2015+2016) $\sqrt{s}$ = 13 TeV data
- Includes 3e, 3μ, μ2e, and e2μ final states
- Differential fiducial cross section: in $p_T^Z$ , $m_T^{WZ}$ , $N_{jets}$

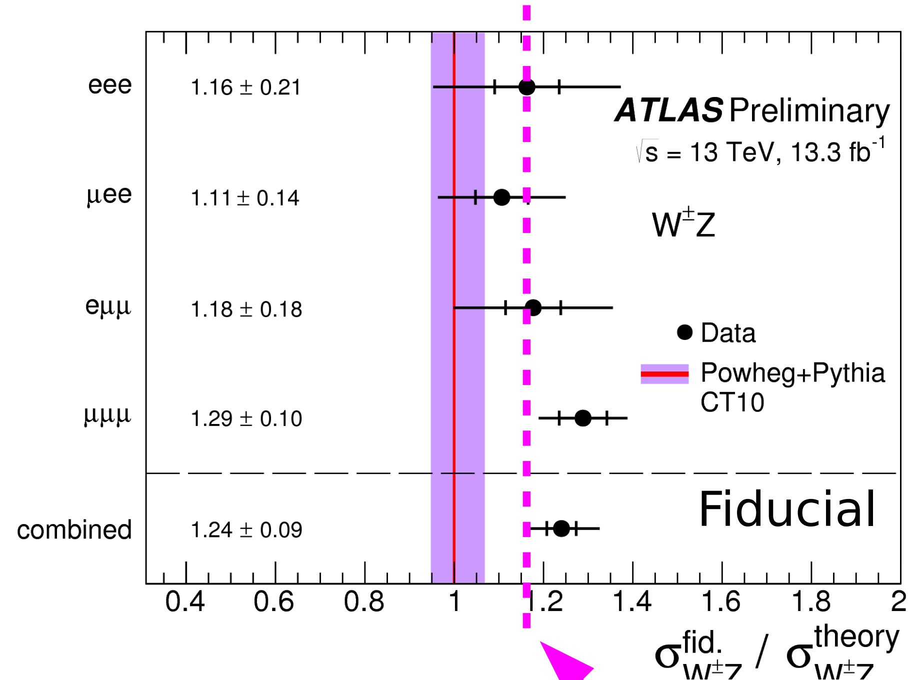


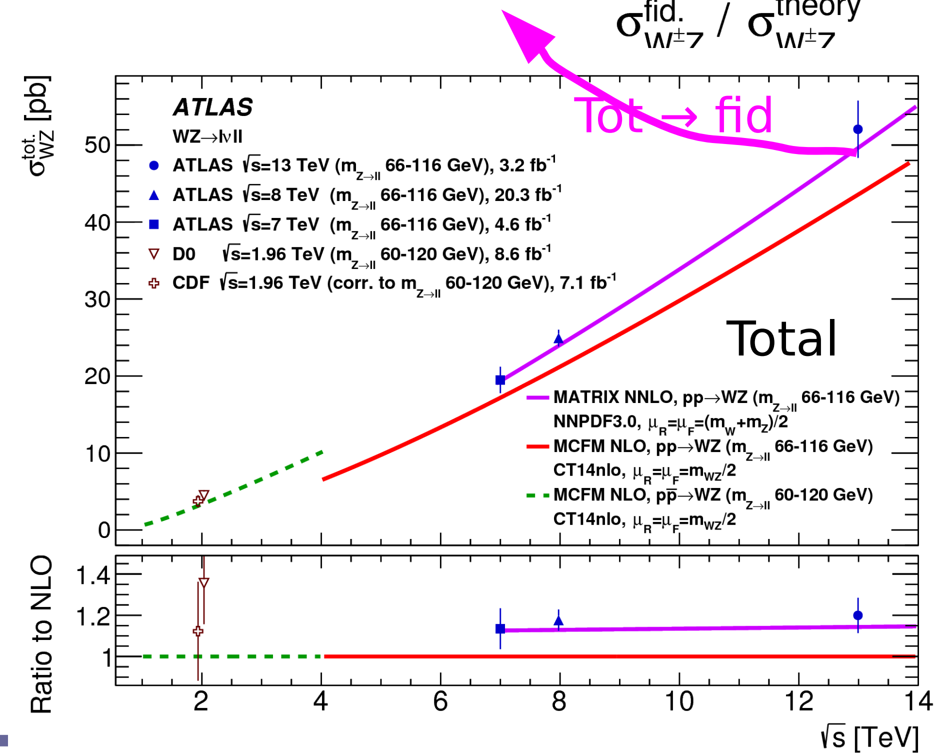

Evident that we need to enhance the Powheg+Pythia Prediction to match the data



# WZ → 3l ν : need NNLO for agreement




Definitely need extra jets in Matrix Element
(Powheg+Pythia does not follow data,
While Sherpa does, as we also saw in ZZ)

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

NNLO calculation from Matrix: 48.2 ± 1.1 pb

# 2.3) WW production

**“Measurement of the $W^+W^-$ production cross section in pp collisions at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV with the ATLAS experiment”**

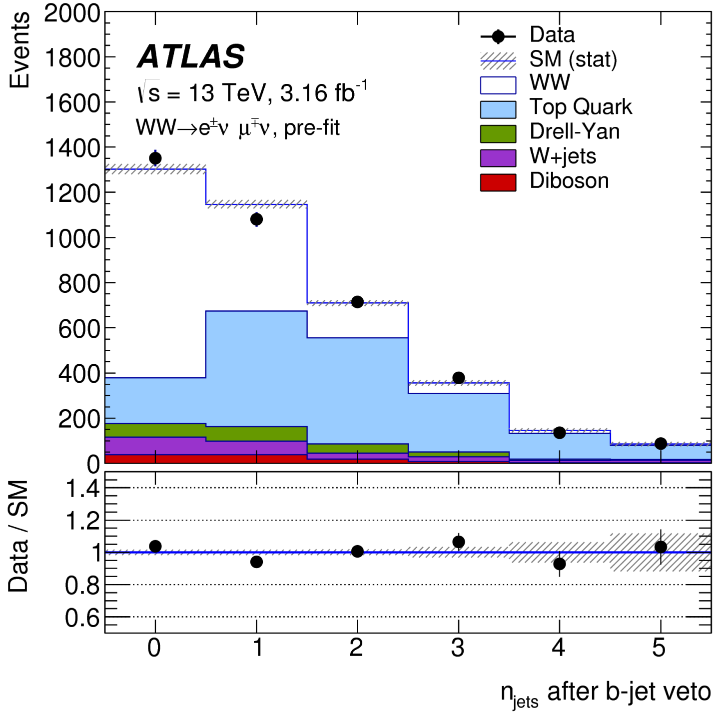
Phys. Lett. B 773 (2017) 354

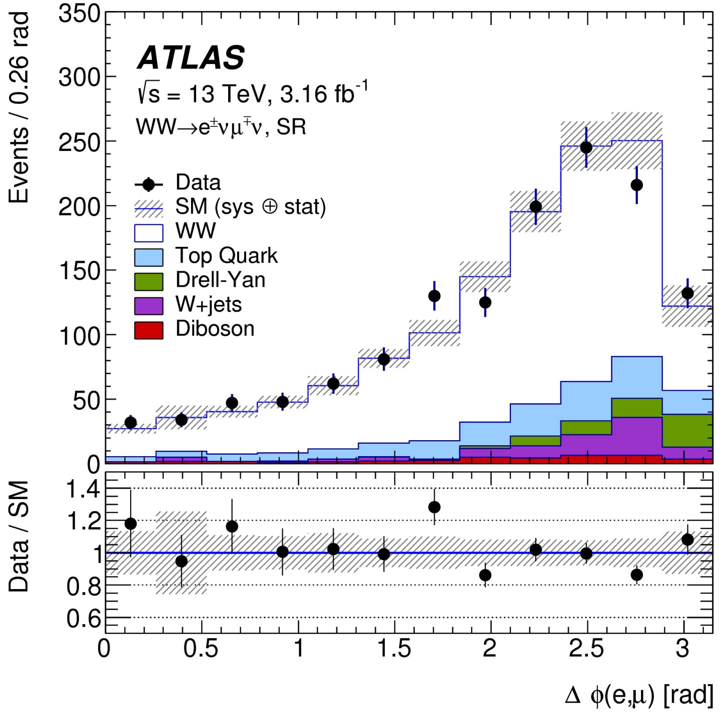
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-20/

# WW → 2l 2ν

- 3.16 $fb^{-1}$ (2015) √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

| Process | Signal region | Top-quark control region | Drell–Yan control region |
|---|---|---|---|
| $WW$ signal | $997 \pm 69$ | $49 \pm 12$ | $75.3 \pm 5.4$ |
| Drell–Yan | $62 \pm 23$ | $49 \pm 29$ | $1568 \pm 45$ |
| $t\bar{t}$+single top | $177 \pm 33$ | $2057 \pm 81$ | $3.5 \pm 1.6$ |
| $W$+jets/multi-jet | $78 \pm 41$ | $70 \pm 55$ | $0 \pm 17$ |
| Other dibosons | $38 \pm 12$ | $6.3 \pm 3.5$ | $19.2 \pm 6.1$ |
| Total | $1351 \pm 37$ | $2232 \pm 47$ | $1666 \pm 41$ |
| Data | 1351 | 2232 | 1666 |

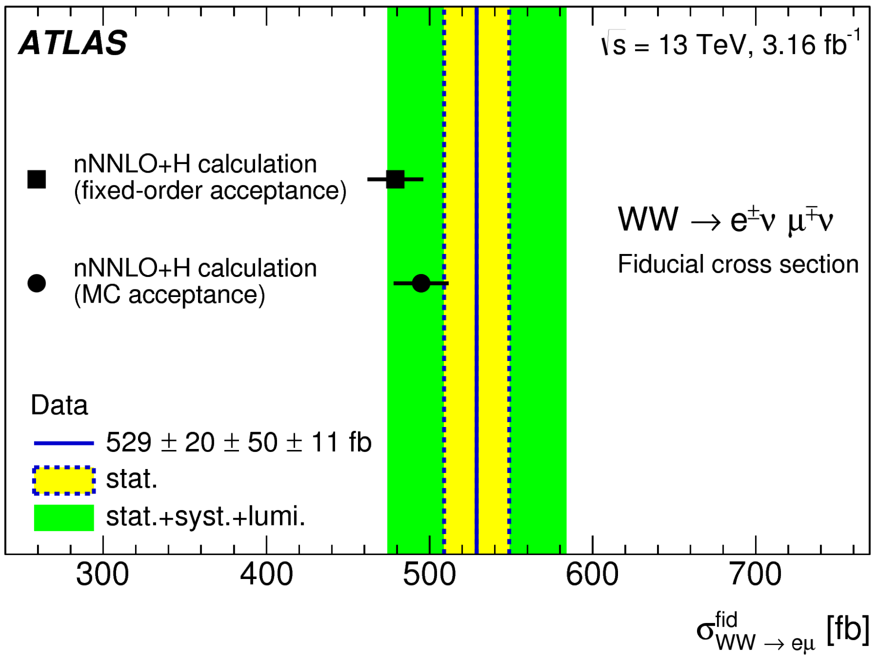


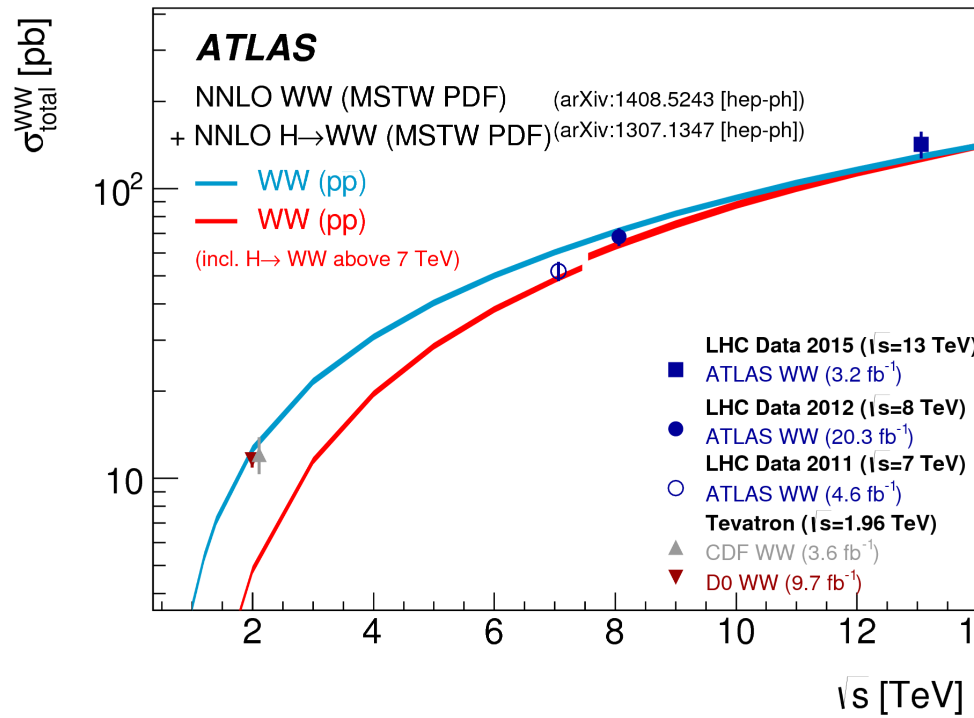
# WW → 2l 2ν

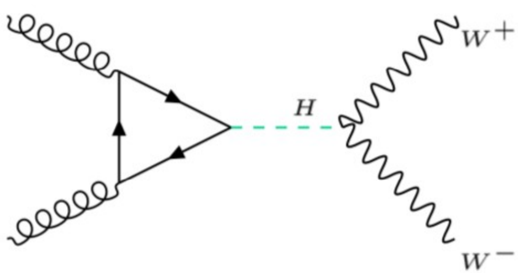
- 3.16 $fb^{-1}$ (2015) $\sqrt{s}$ = 13 TeV data
- Only **e μ** channel, to suppress Drell-Yan
- From event count to fiducial cross section:

$$\sigma^{\mathrm{fid}}_{WW\to e\mu} = 529 \pm 20\ (\mathrm{stat.}) \pm 50\ (\mathrm{syst.}) \pm 11\ (\mathrm{lumi.})\ \mathrm{fb}$$




And from fiducial to total (fiducial is ~60% of total, times BR) :




Measurement agrees with most up-to-date SM predictions which include high-order QCD effects

← Include also ~8% contribution from Higgs

# 2.4) WV = W + W/Z → lν + jets production

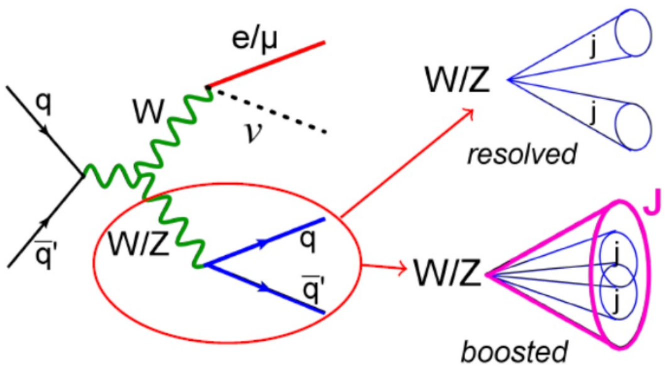
**"Measurement of WW/WZ production with the hadronically decaying boson reconstructed as one or two jets in pp collisions at 8 TeV with ATLAS, and constraints on anomalous gauge couplings"**

Eur. Phys. J. C 77 (2017) 563

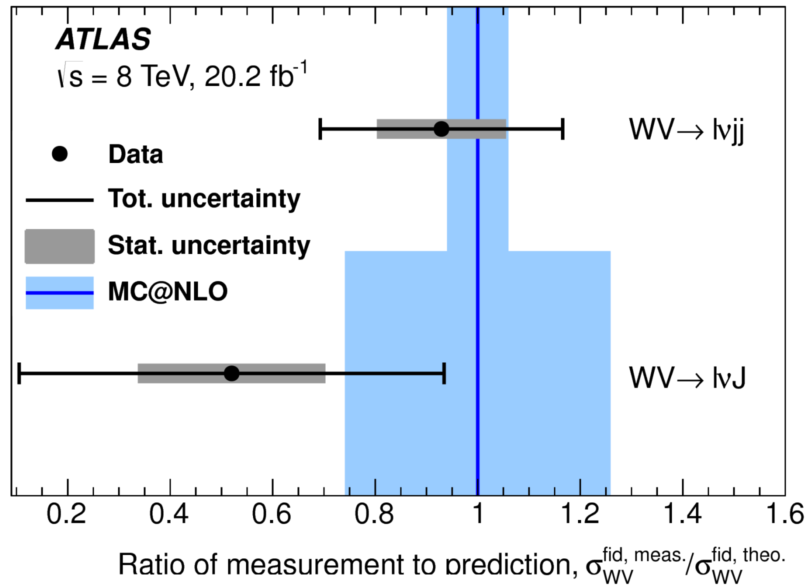
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-23/

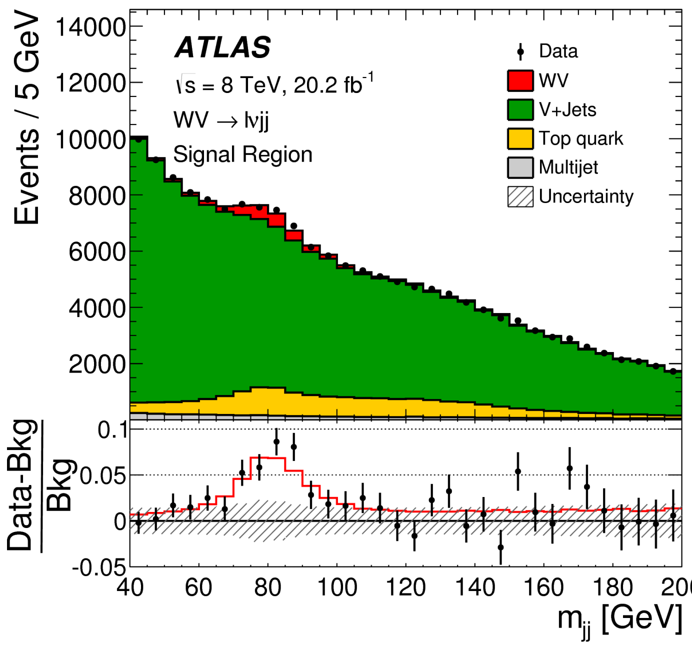
# W V : W (→ lν) + V (→ jj) @ 8 TeV

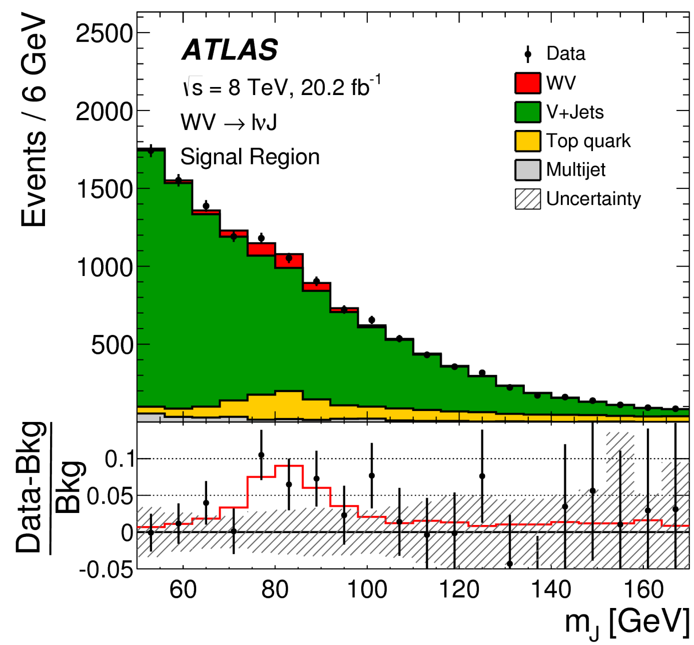
- 20.2 fb$^{-1}$ of 8 TeV data




•Branching Ratio ~ 6x fully leptonic;
•→ Great sensitivity to anomalous TGC



# A lesson from comparing the measurements to theory perdictions

- Overall good agreement with the Standard Model
  - NNLO QCD improves agreement substantially
  - NNLO reduces uncertainty to 10~20% from NLO at 60% (arXiv: 1604.08576)
- Almost all recent measurements are limited by systematic uncertainties (only ZZ is almost equal to statistics)

- These and many more results in:

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

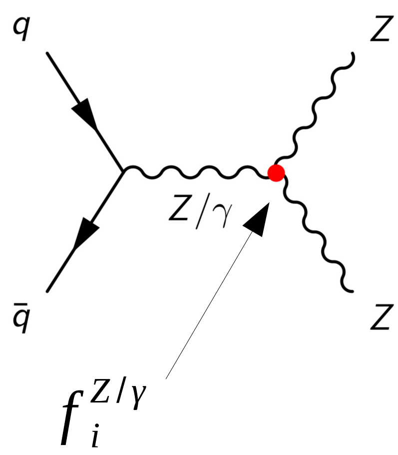
# 3. Anomalous Triple Gauge Couplings (aTGCs)

In all analyses reported before

# anomalous Triple Gauge Couplings (aTGCs), 1

- "Traditional", effective Lagrangian, approach: add terms to the SM Lagrangian to describe the Triple Gauge vertices; the deviation of the triple vector boson couplings from the SM predicted values are introduced as dimensionless anomalous couplings:
  - For the WW+Z/γ vertices, 5 parameters: $\Delta g_1^Z$ , $\Delta\kappa_Z$ , $\lambda_Z$ , $\Delta\kappa_\gamma$ , $\lambda_\gamma$

    * Just 3 in LEP scenario: $\lambda_\gamma = \lambda_Z$, $\Delta g_1^Z = \Delta\kappa_Z + \tan^2\theta_W \Delta\kappa_\gamma$
  - For the ZZ+Z/γ vertices: $f_4^\gamma$, $f_4^Z$, $f_5^\gamma$, $f_5^Z$




- The contribution of anomalous couplings to the diboson production cross section grows with the partonic centre-of-mass energy s-hat , and quadratically with the TGC value.

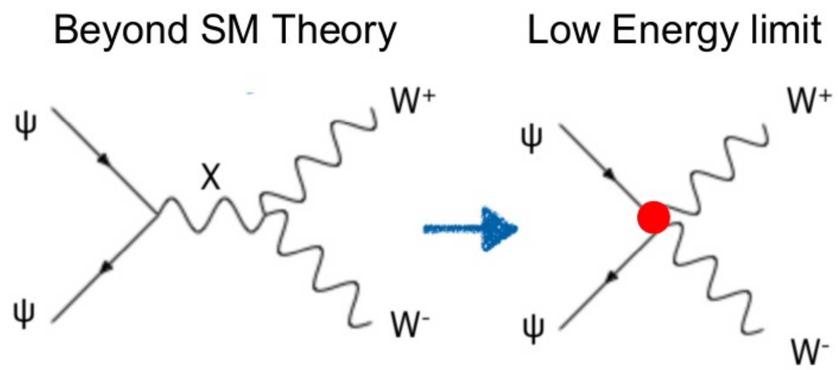
- Anomalous TGCs will lead to excesses in high-end tails of sensitive observables, related to the s-hat of the partonic system

With one aTGC active:

$$d\sigma_{SM+TGC} = F_0 + fF_1 + f^2 F_2$$

# anomalous Triple Gauge Couplings (aTGCs), 2

- Effective Field Theory (EFT) approach: Standard Model is the low energy limit of a more fundamental theory at scale $\Lambda \gg \sqrt{s}$




At low energies (E << Λ) interactions between SM fields only look like Fermi's contact interaction (which was indeed valid when much below W mass scale)

Add to the SM Lagrangian a linear combination of operators of mass dimension higher than four. Independent operators can lead to anomalous triple vector boson couplings.

$$L_{EFT} = L_{SM} + \sum_{d \geqslant 5} L^d_{EFT} \text{ with } L^d_{EFT} = \sum_i \frac{C^d_i}{\Lambda^{d-4}} O^d_i$$

The dimensionless coefficients $C_i$ represent the strength of the new couplings.

Charged TGC: first contributing operators have dimension 6 ⇒ coupling parameters c/ $\Lambda^2$

Neutral TGC: first contributing operators have dimension 8 ⇒ coupling parameters c/ $\Lambda^4$

There is a one-to-one mapping between EFT coupling parameters and traditional aTGCs

e.g:

Traditional ⇔ EFT

$$g_1^Z = 1 + c_W \frac{m_Z^2}{2\Lambda^2}$$

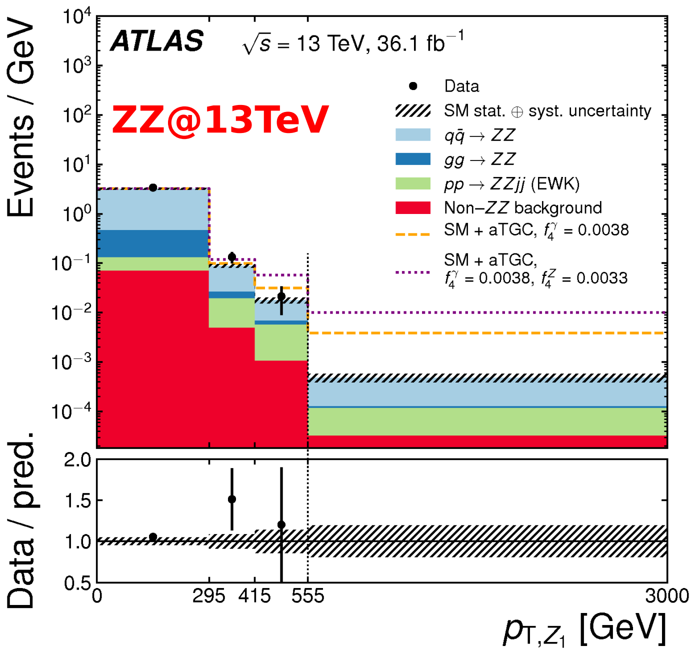
$$\kappa_\gamma = 1 + (c_W + c_B)\frac{m_W^2}{2\Lambda^2}$$

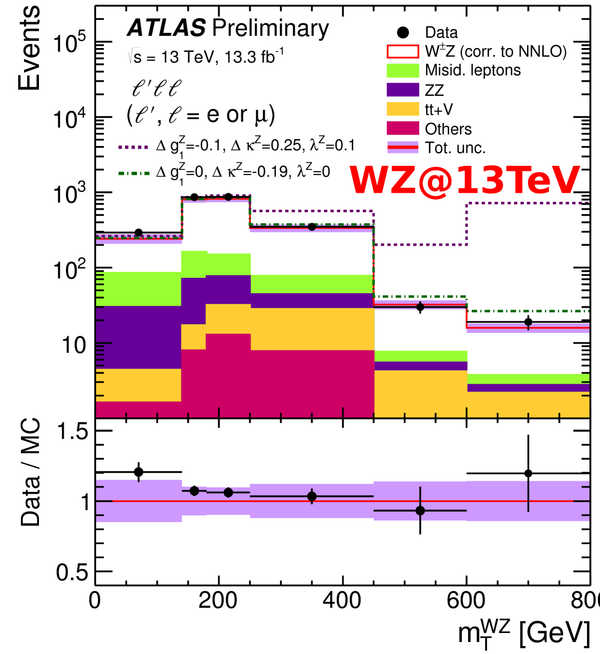
$$\kappa_Z = 1 + (c_W - c_B \tan^2\theta_W)\frac{m_W^2}{2\Lambda^2}$$

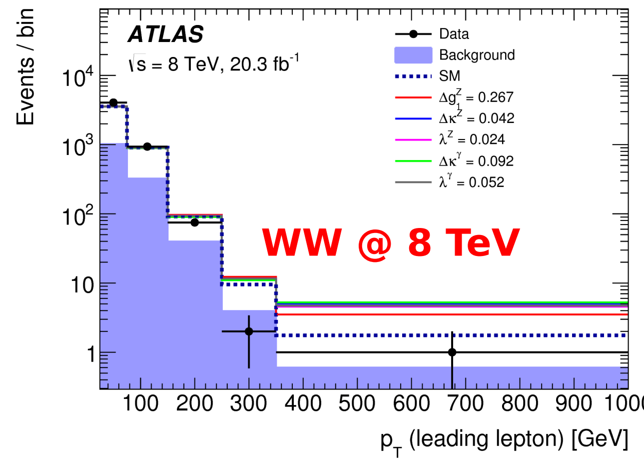
$$\lambda_\gamma = \lambda_Z = c_{WWW}\frac{3g^2 m_W^2}{2\Lambda^2}$$

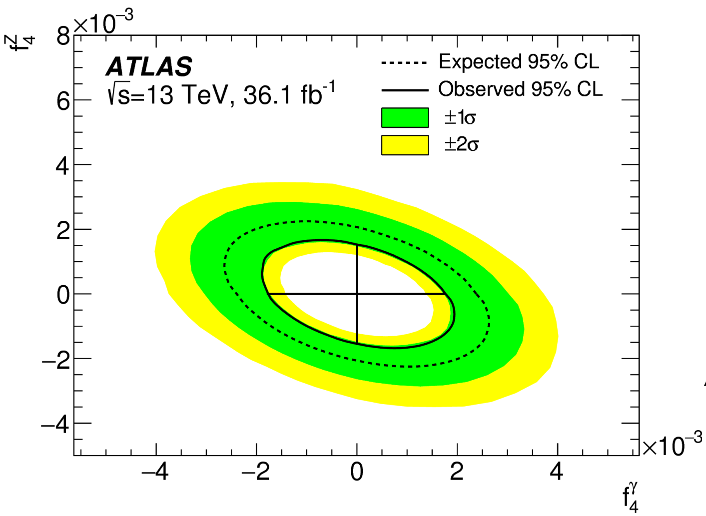
# aTGCs from ZZ, WZ and WW

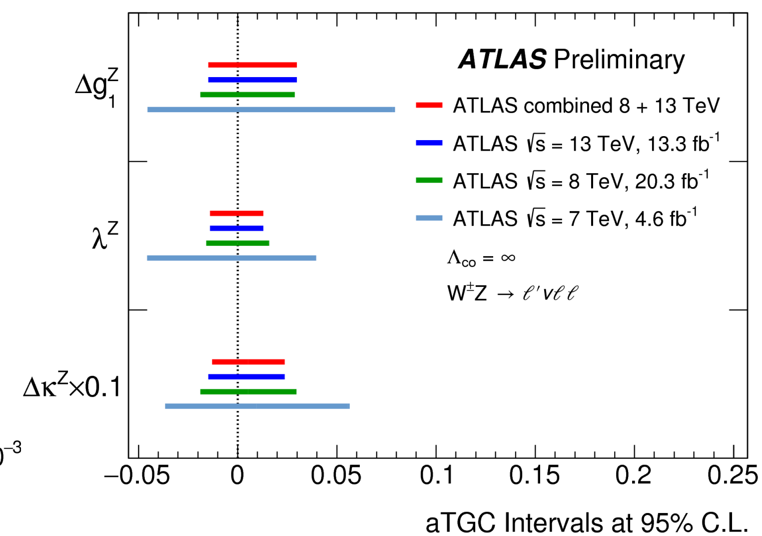
- Anomalous TGCs will lead to enhanced event yields in high-end tails of sensitive observables, related to the s-hat of the partonic system system.

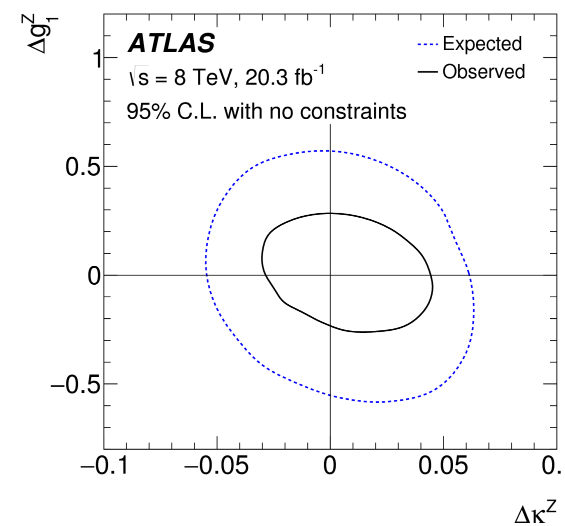


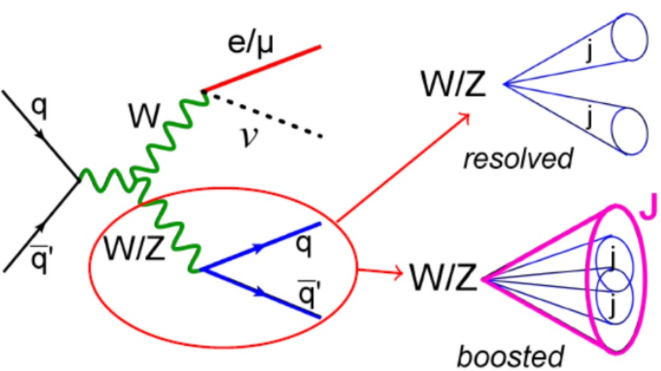



# W V : W (→ lν) + V (→ jj) @ 8 TeV

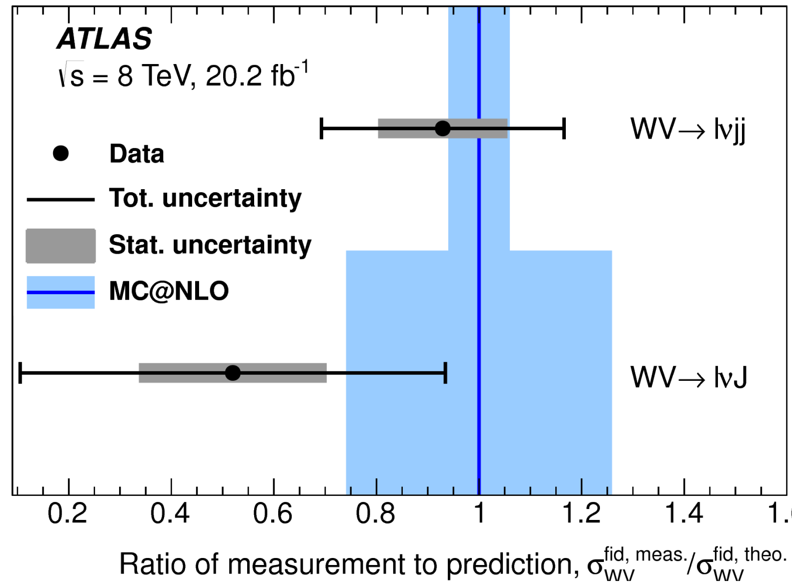
Eur. Phys. J. C 77 (2017) 563

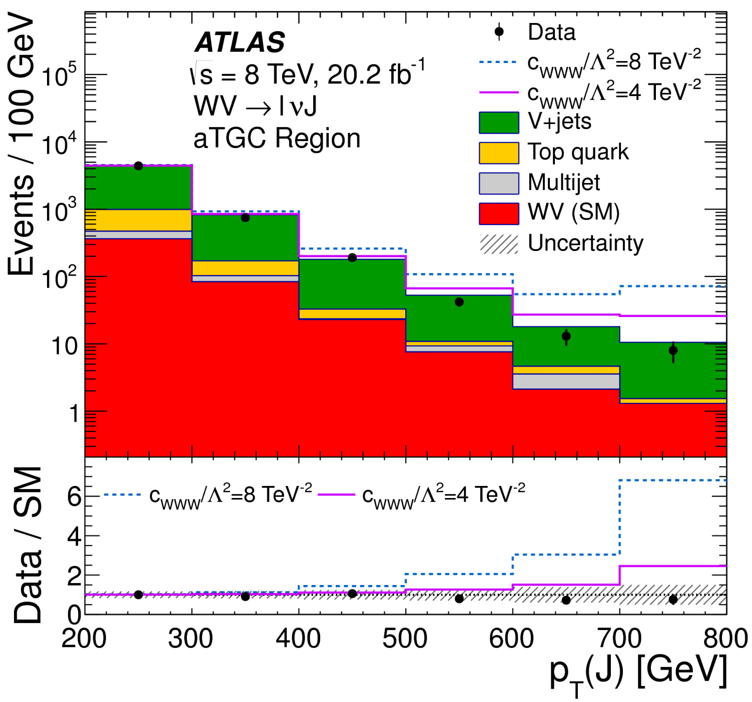
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2015-23/

- 20.2 $fb^{-1}$ of 8 TeV data

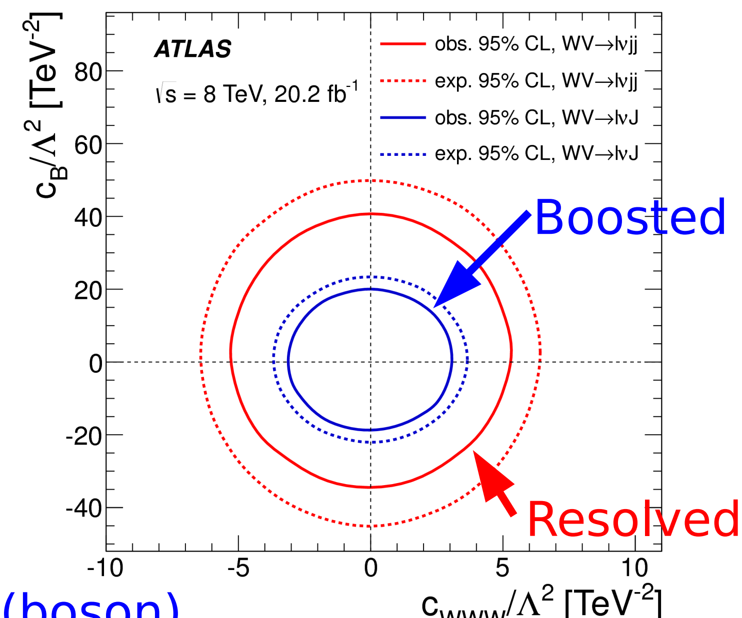



- Branching Ratio ~ 6x fully leptonic;
- → Great sensitivity to anomalous TGC



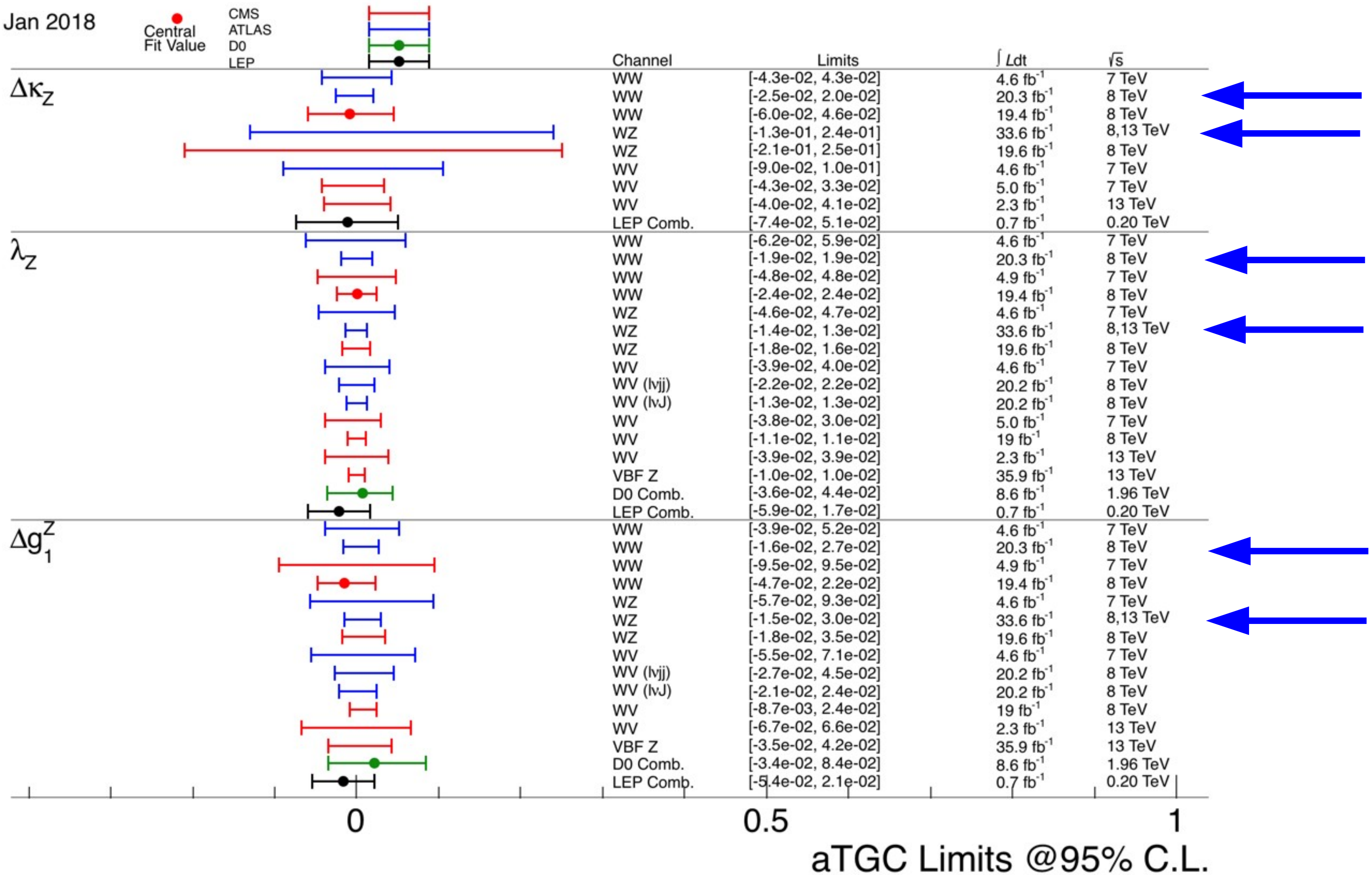

Resolved topology has similar power for aTGCs to fully leptonic; Boosted has about double the sensitivity, due to higher pT(boson)



# Charged aTGCs status

Limits comparable between ATLAS and CMS, for similar datasets

- These aTGC limits are better than LEP results by now



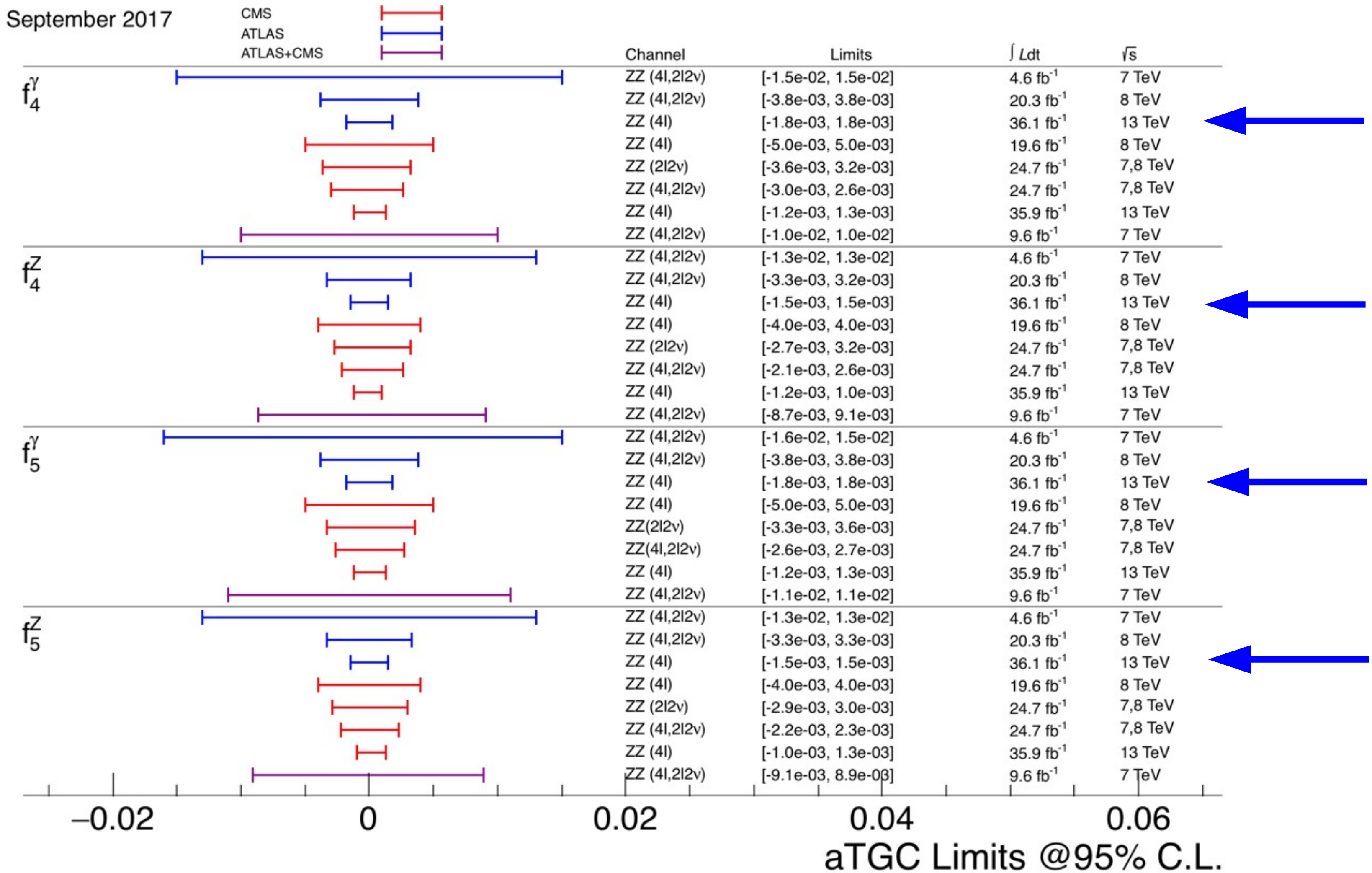

Compilation of ATLAS and CMS results on Triple and Quartic Gauge Couplings at:

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

# Neutral aTGCs status

Limits comparable between ATLAS and CMS, for similar datasets

- These aTGC limits constrain a variety of BSM models at higher energies

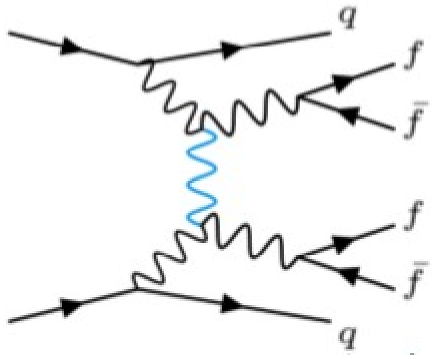



Compilation of ATLAS and CMS results on Triple and Quartic Gauge Couplings at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

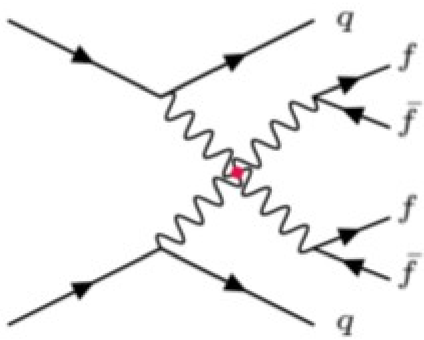
# VBS and anomalous Quartic Couplings

**Vector Boson Scattering**: incoming quarks act as sources of colliding boson beams

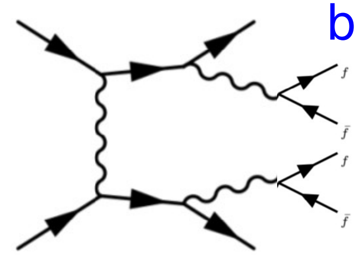
**Signature: VV + 2 forward jets**



6 EWK vertices: not only vector bosons in the t-channel, but also the Higgs: important for not letting the cross section explode at high energies (like the ZWW vertex was needed to limit the WW production cross section at e+ e- collisions at LEP)

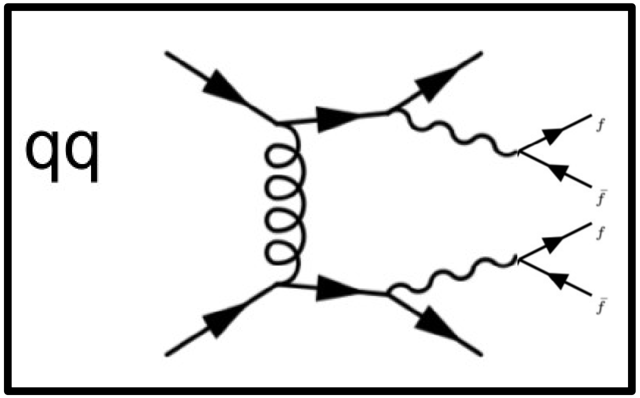


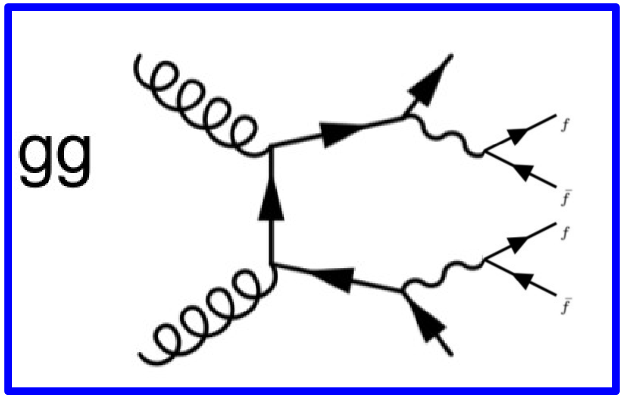
5 EWK vertices
**Quartic Gauge Couplings**: again, SM does not allow all neutral in the quartic vertex



6 EWK vertices but not VBS...

**4 EWK + 2 QCD vertices**: same final state → important background




+ ...

# VBS and anomalous Quartic Couplings

- Searches of anomalous QGC always assume aTGC=0
- The first operators leading to aQGC but no aTGC have dimension 8

⇒ coupling parameters $c/\Lambda^4$

No time here to show results;
You'll see dedicated discussion on VBS physics by Iro Koletsou on Saturday.

<u>Very Brief summary:</u>
* ATLAS has ~seen EWK production of **same sign WW** @ 8TeV and put limits on aQGCs
PRD96 012007 (2017), https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-05/
* ATLAS put upper limit on **WZ** EWK production and put limits on aQGCs
PRD93 092004 (2016) , https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2014-02/

* CMS has established same sign WW production with 5.7σ observation @13 TeV and set limits on aQGCs
* CMS has ~seen EWK production of ZZ → 4l (~2.7σ, expected 1.6σ) and set limits on aQGC parameters

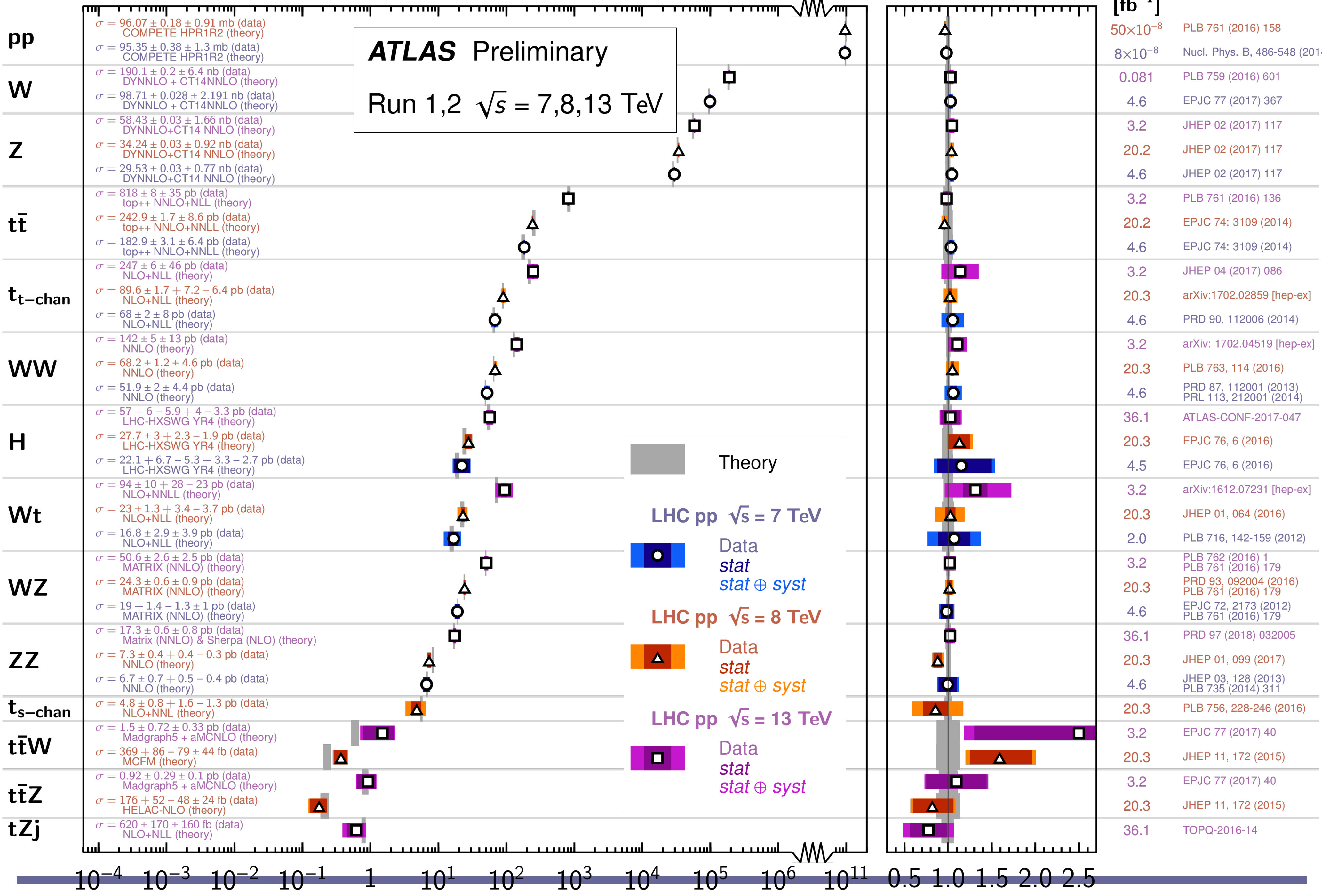
* ATLAS working on all channels (ZZ, WZ, and WW) for VBS
For work in progress in ZZ see related VBS talk on Friday (Alexandros Marantis)

# Summary & Conclusions

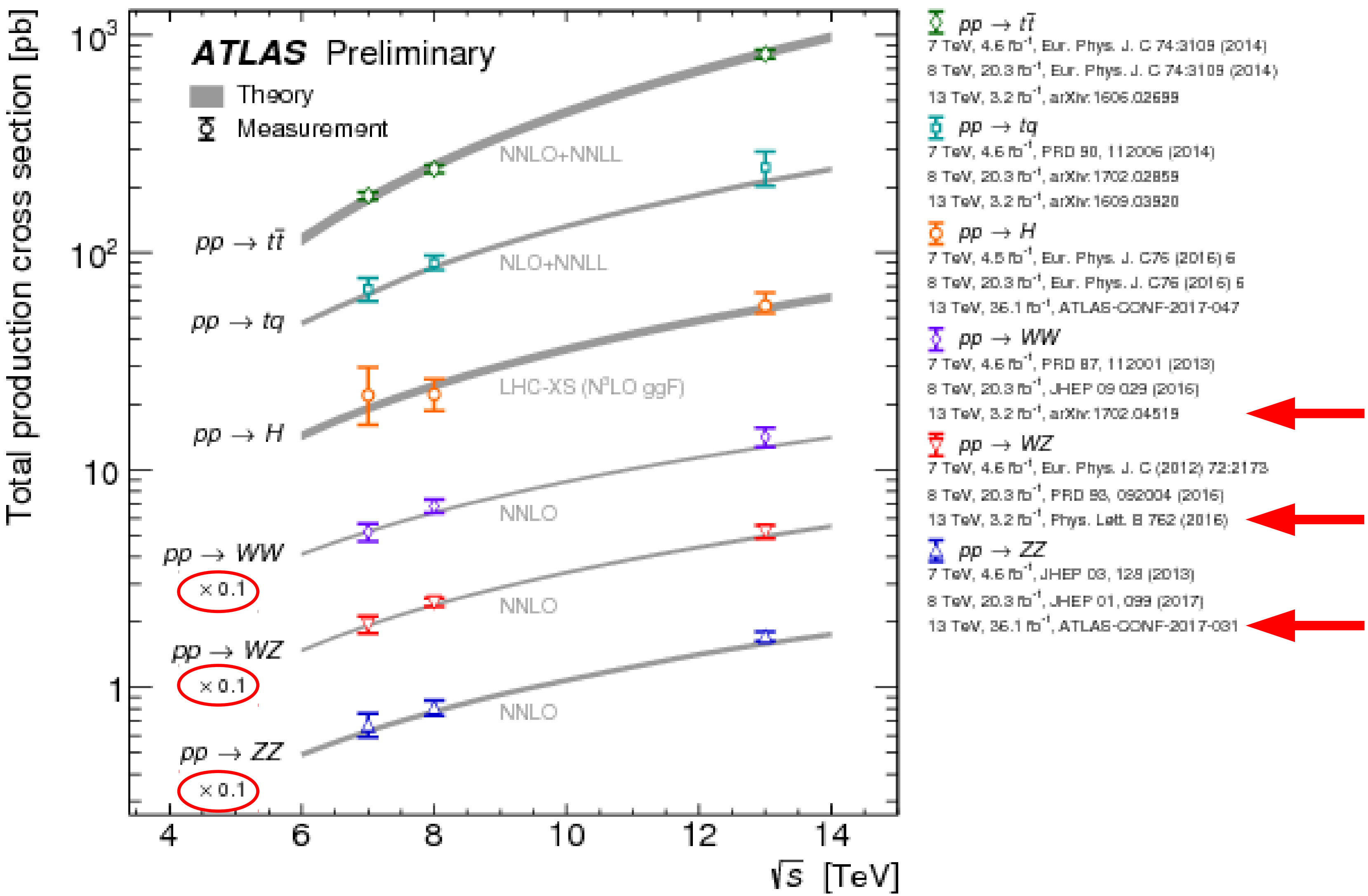
- Full programme of diboson measurements in ATLAS
  - SM diboson production is often a background to BSM physics searches
- Shown here: electroweak diboson production (WW,WZ,ZZ)
  - Fully-leptonic final states are the first measurements we do of these processes
- These measurements have challenged theorists 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 s-hat regions we have continued to set limits on anomalous Triple Gauge boson Coupling

# Thank you

# Standard Model Total Production Cross Section Measurements



# WW, WZ, and ZZ increase with sqrt(s), OK with theory




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

# ZZ production cross section

$$N_{sigal}(pp \to ZZ \to 4l) = L \cdot \sigma^{tot}(pp \to ZZ) \cdot BR(ZZ \to 4l) \cdot A \cdot C$$

Measured in a reduced phase-space (geometrical & kinematic requirements on the decay products)
4l = {4e  or 4μ  or 2e2μ}

Total cross section for ZZ production

$$A = \frac{Fiducial\ events}{Total\ events}$$

Acceptance correction for the geometrical & kinematic criteria

$$C = \frac{Reconstructed\ events}{Generated\ fiducial\ events}$$

Efficiency correction for detector ability to reconstruct these objects

1. We measure a "fiducial cross section", which corresponds to the reduced phase-space of the actual measurement,
* This is a fraction of the total:

$$\sigma^{fiducial}(pp \to ZZ \to 4l) = \frac{N_{obs} - N_{bkg}}{L \cdot C}$$

$$\sigma^{fiducial}(pp \to ZZ \to 4l) = \sigma^{tot}(pp \to ZZ) \cdot BR(ZZ \to 4l) \cdot A$$

2. We then extrapolate to the "total cross section" for ZZ production by extrapolating the leptons to the full phase-space,
and correcting for the BR(ZZ → 4l) ~ 4 * (3.4% * 3.4%) for 4e, 4μ and 2e2μ together

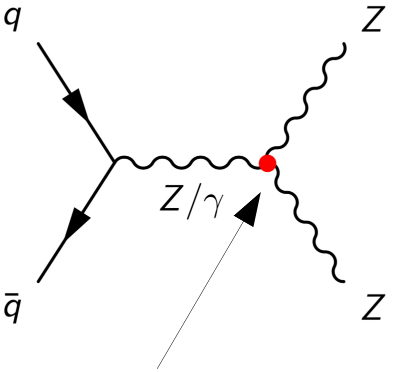
$$\sigma^{tot}(pp \to ZZ \to 4l) = \frac{N_{obs} - N_{bkg}}{L \cdot BR(ZZ \to 4l) \cdot A \cdot C}$$

# Contribution of neutral aTGCs to the cross section

- Traditionally, effective Lagrangian used to include effect of aTGCs: e.g., G.L.Gounaris et al: PRD61 073013; Bauer, Reiwater: PRD 62, 113011

Effective Lagrangian

$$L = \frac{e}{m_Z^2}\left[ f_4^V \left(\partial_\mu V^{\mu\beta}\right) Z_\alpha \left(\partial^\alpha Z_\beta\right) + f_5^V \left(\partial^\sigma V_{\sigma\mu} \tilde{Z}^{\mu\beta} Z_\beta\right) \right], V = Z, \gamma$$




SM values:

$$f_4^\gamma = f_4^Z = f_5^\gamma = f_5^Z = 0$$

- ZZ cross section enhanced by aTGCs with ~quadratic dependence on them

With one aTGC active:

$$d\sigma_{SM+TGC} = F_0 + fF_1 + f^2 F_2$$

$$d\sigma_{SM+TGC} = \overbrace{F_{00}}^{\text{SM contribution}} + f_4^\gamma F_{01} + f_4^Z F_{02} + f_5^\gamma F_{03} + f_5^Z F_{04}$$
$$+ \left(f_4^\gamma\right)^2 F_{11} + f_4^\gamma f_4^Z F_{12} + f_4^\gamma f_5^\gamma F_{13} + f_4^\gamma f_5^Z F_{14}$$
$$+ \left(f_4^Z\right)^2 F_{22} + f_4^Z f_5^\gamma F_{23} + f_4^Z f_5^Z F_{24}$$
$$+ \left(f_5^\gamma\right)^2 F_{33} + f_5^\gamma f_5^Z F_{34}$$
$$+ \left(f_5^Z\right)^2 F_{44}$$

# A note on dibosons from heavy resonances

- Di-boson resonance searches in ATLAS

  - High mass state motivated by multiple BSM models

    - Direct way to explore the TeV scale
    - Experimentally challenging: Boosted object tagging with large-R jet

- Searches:

  - $WW/WZ \rightarrow l\nu\ qq$ https://arxiv.org/abs/1710.07235
  - $ZZ/ZW \rightarrow llqq\ ,\ \nu\nu\ qq$ https://arxiv.org/abs/1708.09638
  - $VV \rightarrow qqqq$ https://arxiv.org/abs/1708.04445
  - $WW \rightarrow e\nu\mu\nu$ https://arxiv.org/abs/1710.01123
  - $ZZ \rightarrow 4l\ ,\ 2l2\nu$ https://cds.cern.ch/record/2273874

- No statistically significant excess observed in ATLAS

  - Much more data coming in Run2 : Stay tuned