# Observation of EW vector boson scattering processes with the ATLAS detector

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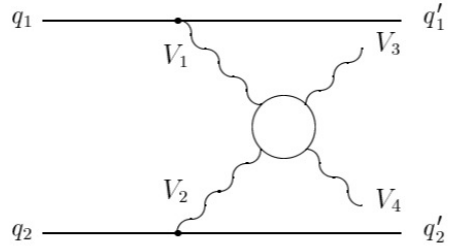
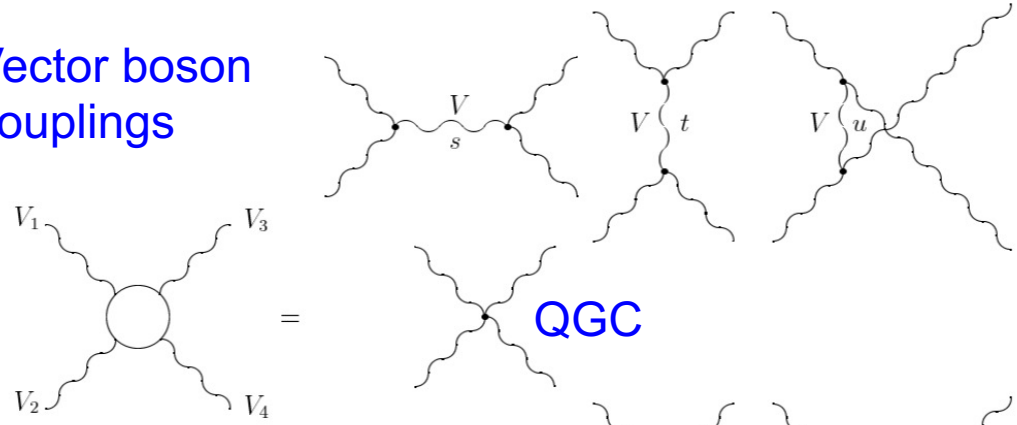
# VBS Processes at the LHC

- Vector boson scattering (VBS) directly probes EWK SM gauge structure
  - Higgs boson acts as "moderator" to unitarize high-energy longitudinal vector boson scattering
  - Stringent test of SM
- Involving Quartic Gauge Couplings (QGCs) which is sensitive to new physics
  - Only charged QGCs allowed at Standard Model (SM) tree-level (WWWW, WWZZ, WWZγ, WWγγ)
  - Constraint on anomalous QGCs (aQGCs)
  - Probe new physics through deviations from SM

Phys. Rev. D **55**, 7165 – Published 1 June 1997

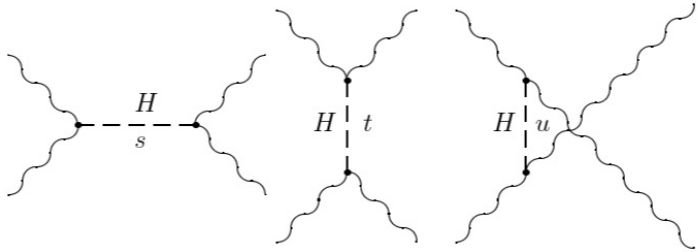



Vector boson couplings



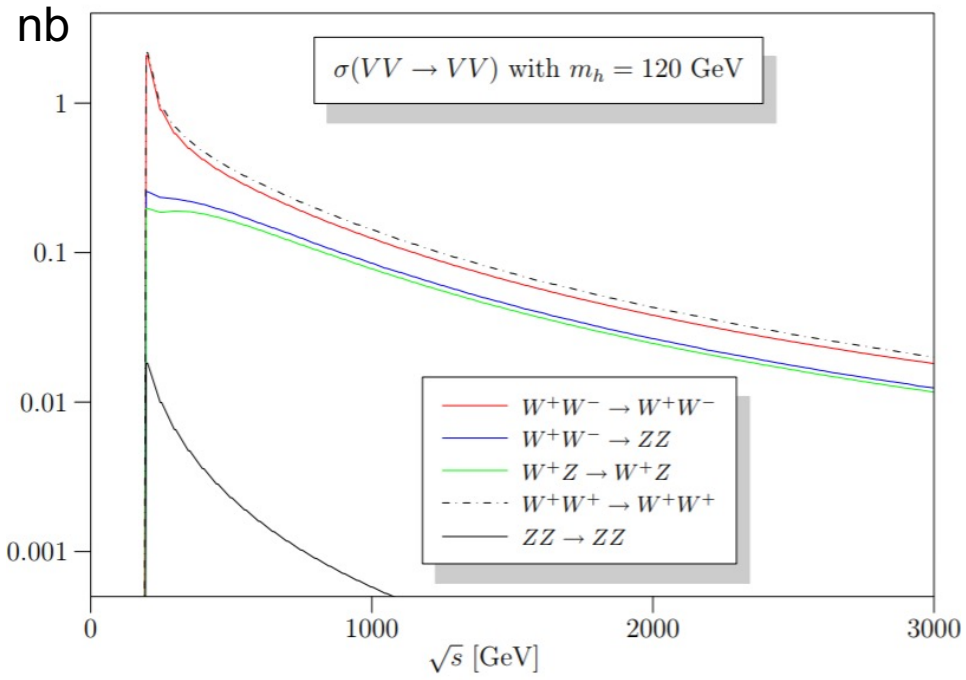

QGC

Higgs couplings

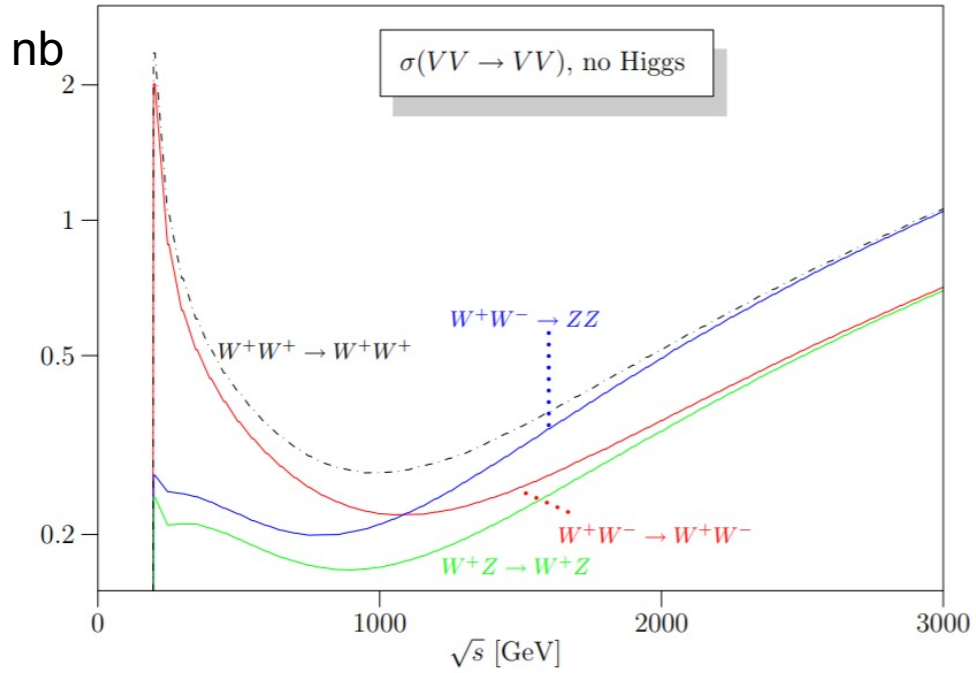


# The VBS Unitarity Violation Issue

SM VV scattering processes with low mass Higgs (120 GeV)



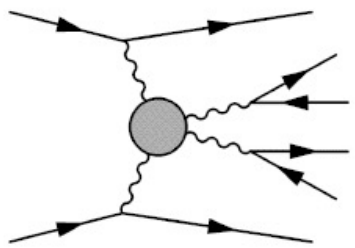

SM VV scattering processes w/o a Higgs boson



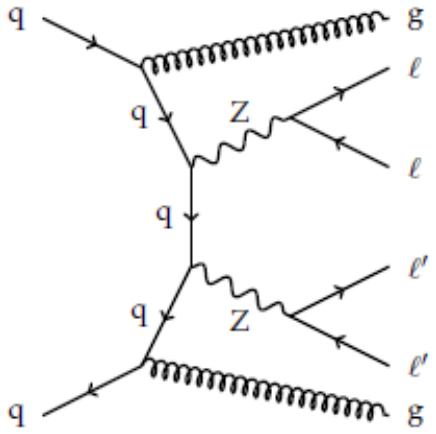

JHEP11(2008)010

- Close connection with Higgs physics
- The VBS cross sections will go diverge without Higgs or other similar underlying new unitarization mechanisms

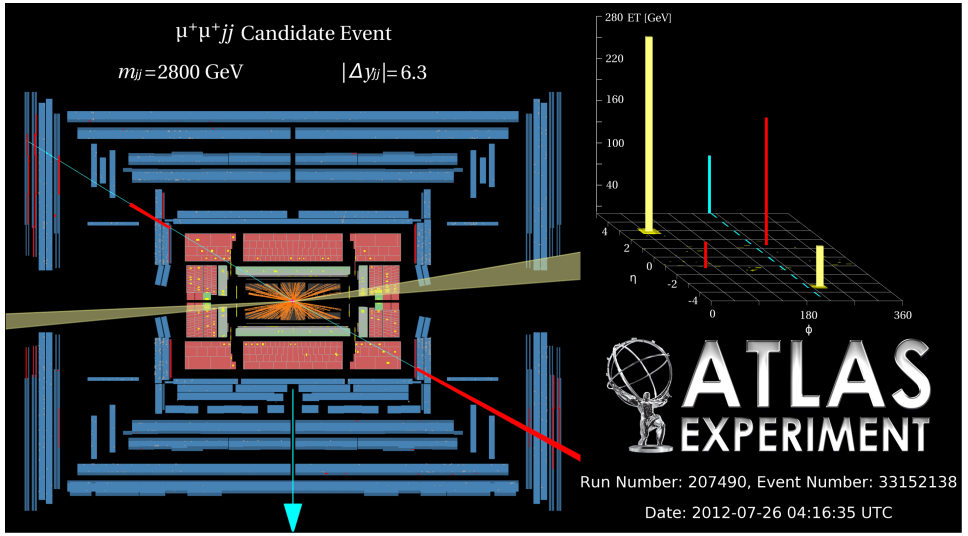
# Experimental Signatures of VBS



- Two intermediate vector bosons radiated from two incoming quarks
- Final state with two vector bosons plus two outgoing jets
- In general, two "tag" jets in forward region with large rapidity separation and large invariant mass
- Suffer from pile-up (PU) jets
- EW VBS has relatively smaller cross-sections, suffer from irreducible QCD VV + 2jets events

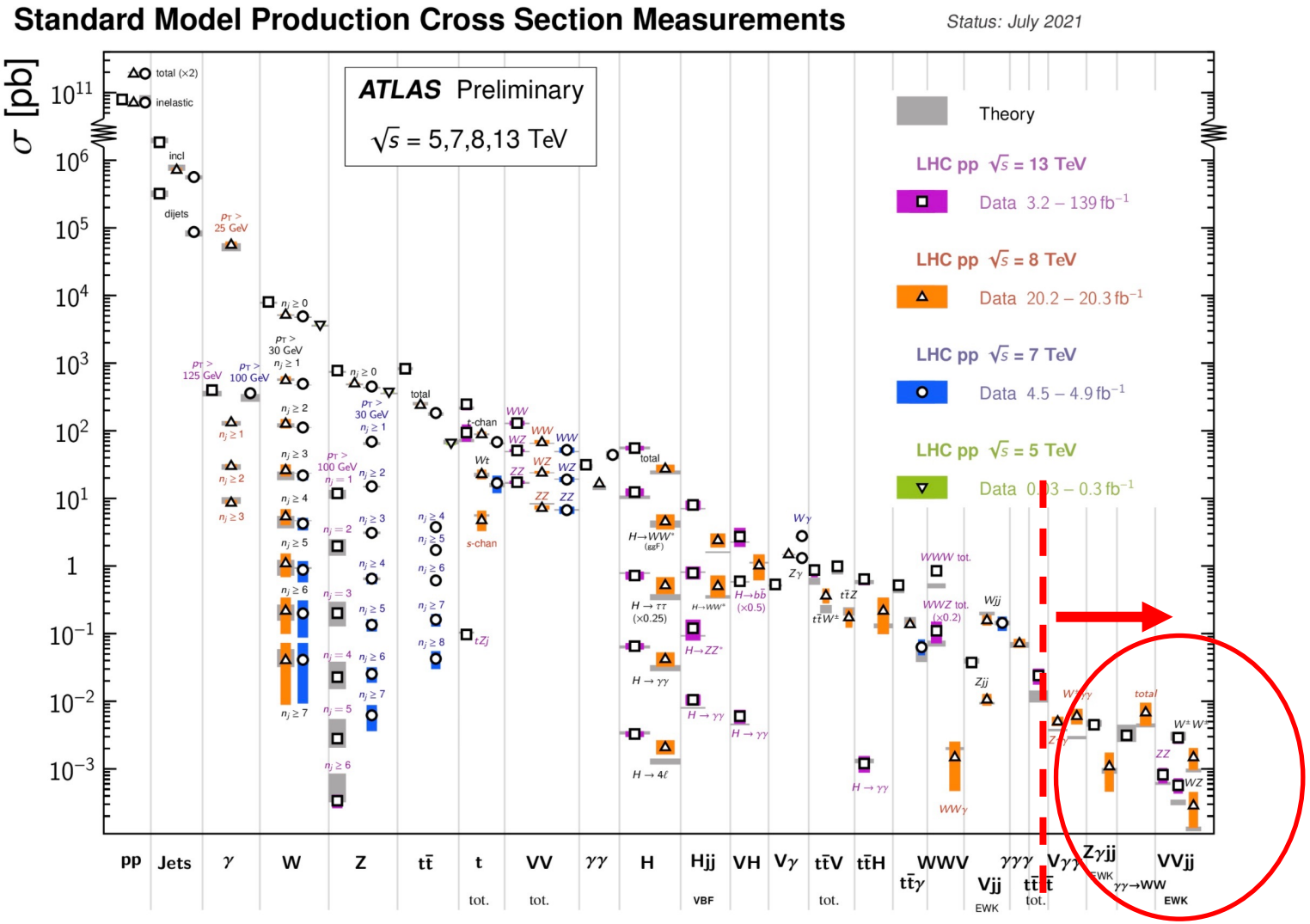


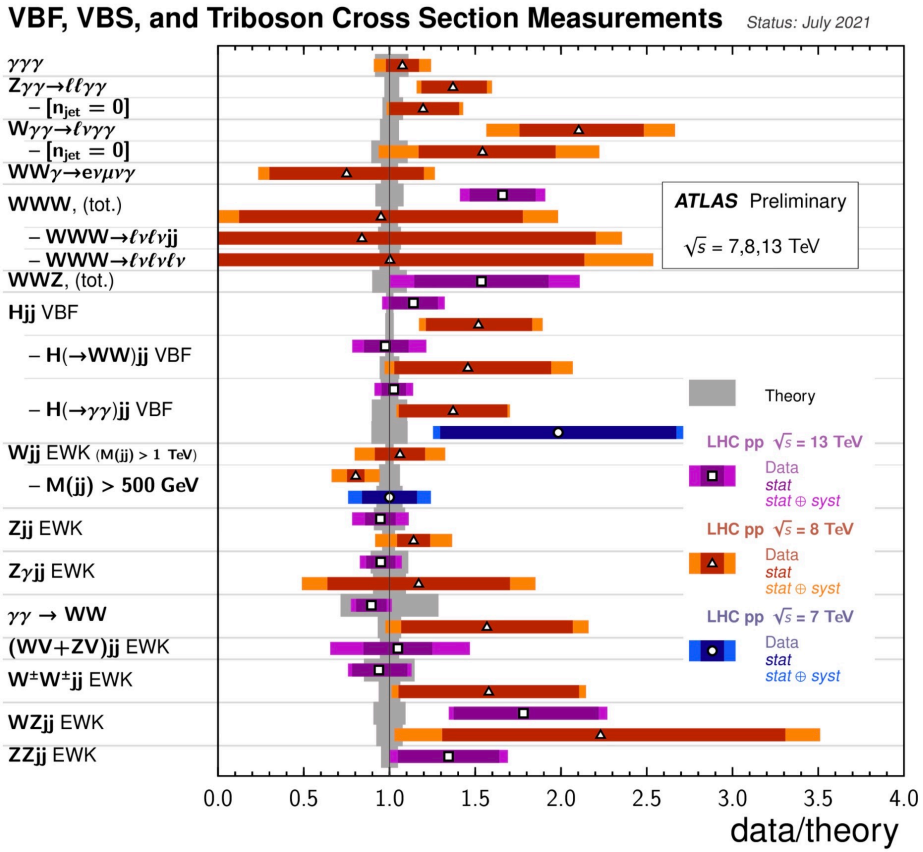

Candidate VBS event from 8 TeV ssWW
Phys. Rev. Lett. **113**, 141803



# Current Status

ATLAS Summary Plots




- ✓ We have been able to have many precision measurements of VV final states with current luminosity
- ✓ With additional two jets, cross sections go below $10^{-2}$ pb level

# Same-sign WWjj Channel

Phys. Rev. Lett. **123**, 161801

Major contributions from TDLI/SJTU, USTC. Analysis contacts as well as detailed studies

* Observation done in the same-sign dilepton channel, with 36.1 $fb^{-1}$ data
* QCD WWjj production is largely reduced by the same-sign requirement

Measured cross section

$$\sigma^{\text{fid}} = 2.89^{+0.51}_{-0.48}(\text{stat})^{+0.24}_{-0.22}(\text{exp syst}) \times {}^{+0.14}_{-0.16}(\text{mod syst})^{+0.08}_{-0.06}(\text{lumi})\ \text{fb}$$

Predicted cross section

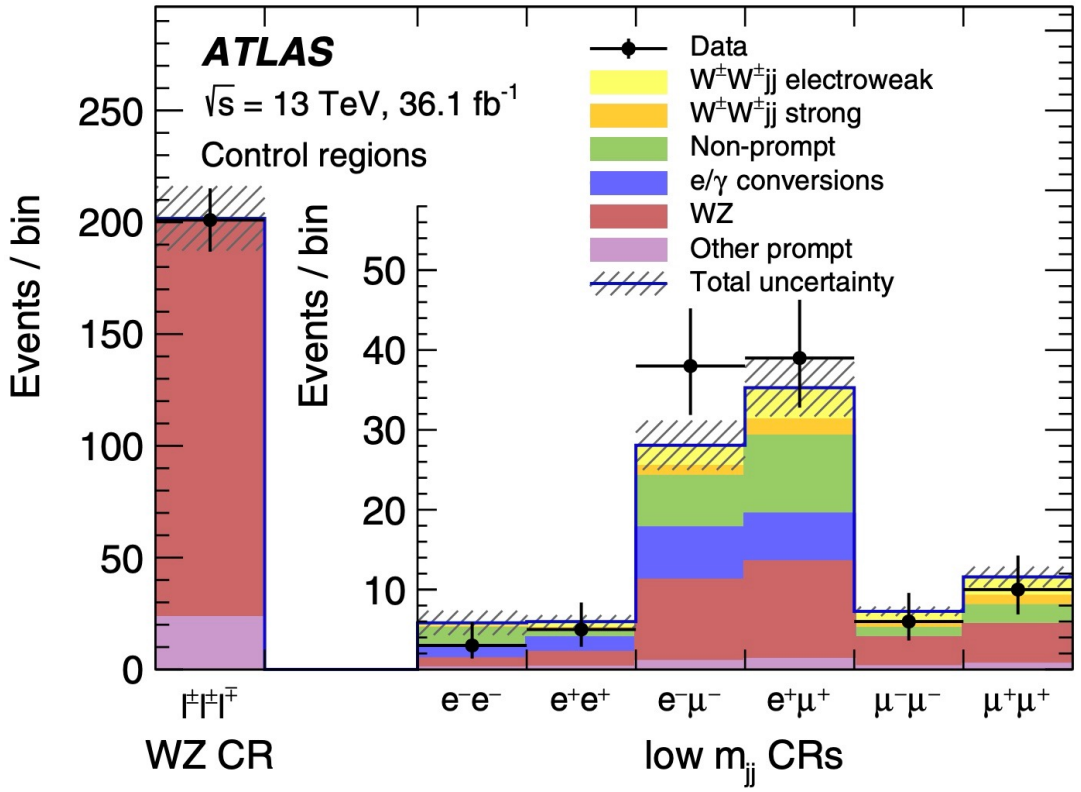
Sherpa: 2.01 +0.33 -0.23 fb

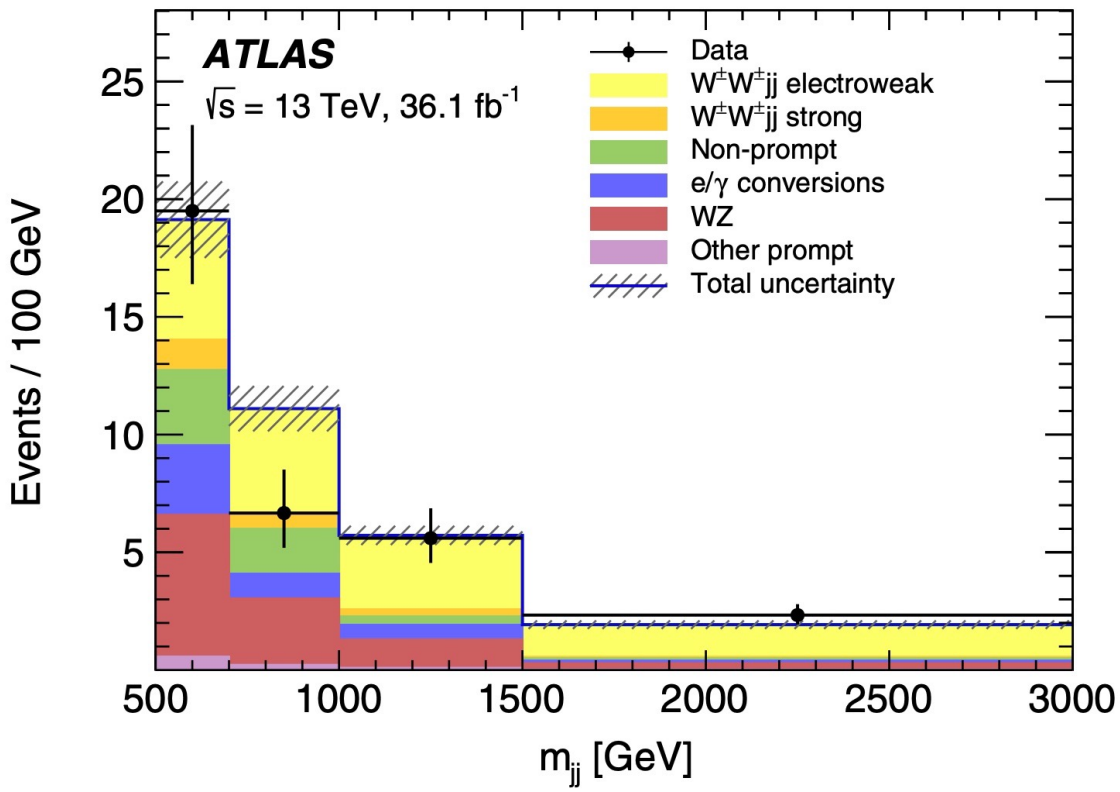
Powheg+Pythia8: 3.08 +0.45 -0.46 fb

Eveng yields in each channel

| | $e^+e^+$ | $e^-e^-$ | $e^+\mu^+$ | $e^-\mu^-$ | $\mu^+\mu^+$ | $\mu^-\mu^-$ | Combined |
|---|---|---|---|---|---|---|---|
| $WZ$ | 1.48 ± 0.32 | 1.09 ± 0.27 | 11.6 ± 1.9 | 7.9 ± 1.4 | 5.0 ± 0.7 | 3.4 ± 0.6 | 30 ± 4 |
| Non-prompt | 2.2 ± 1.1 | 1.2 ± 0.6 | 5.9 ± 2.5 | 4.7 ± 1.6 | 0.56 ± 0.05 | 0.68 ± 0.13 | 15 ± 5 |
| $e/\gamma$ conversions | 1.6 ± 0.4 | 1.6 ± 0.4 | 6.3 ± 1.6 | 4.3 ± 1.1 | — | — | 13.9 ± 2.9 |
| Other prompt | 0.16 ± 0.04 | 0.14 ± 0.04 | 0.90 ± 0.20 | 0.63 ± 0.14 | 0.39 ± 0.09 | 0.22 ± 0.05 | 2.4 ± 0.5 |
| $W^\pm W^\pm jj$ strong | 0.35 ± 0.13 | 0.15 ± 0.05 | 2.9 ± 1.0 | 1.2 ± 0.4 | 1.8 ± 0.6 | 0.76 ± 0.25 | 7.2 ± 2.3 |
| Expected background | 5.8 ± 1.4 | 4.1 ± 1.1 | 28 ± 4 | 18.8 ± 2.6 | 7.7 ± 0.9 | 5.1 ± 0.6 | 69 ± 7 |
| $W^\pm W^\pm jj$ electroweak | 5.6 ± 1.0 | 2.2 ± 0.4 | 24 ± 5 | 9.4 ± 1.8 | 13.4 ± 2.5 | 5.1 ± 1.0 | 60 ± 11 |
| Data | 10 | 4 | 44 | 28 | 25 | 11 | 122 |

# Same-sign WWjj Channel



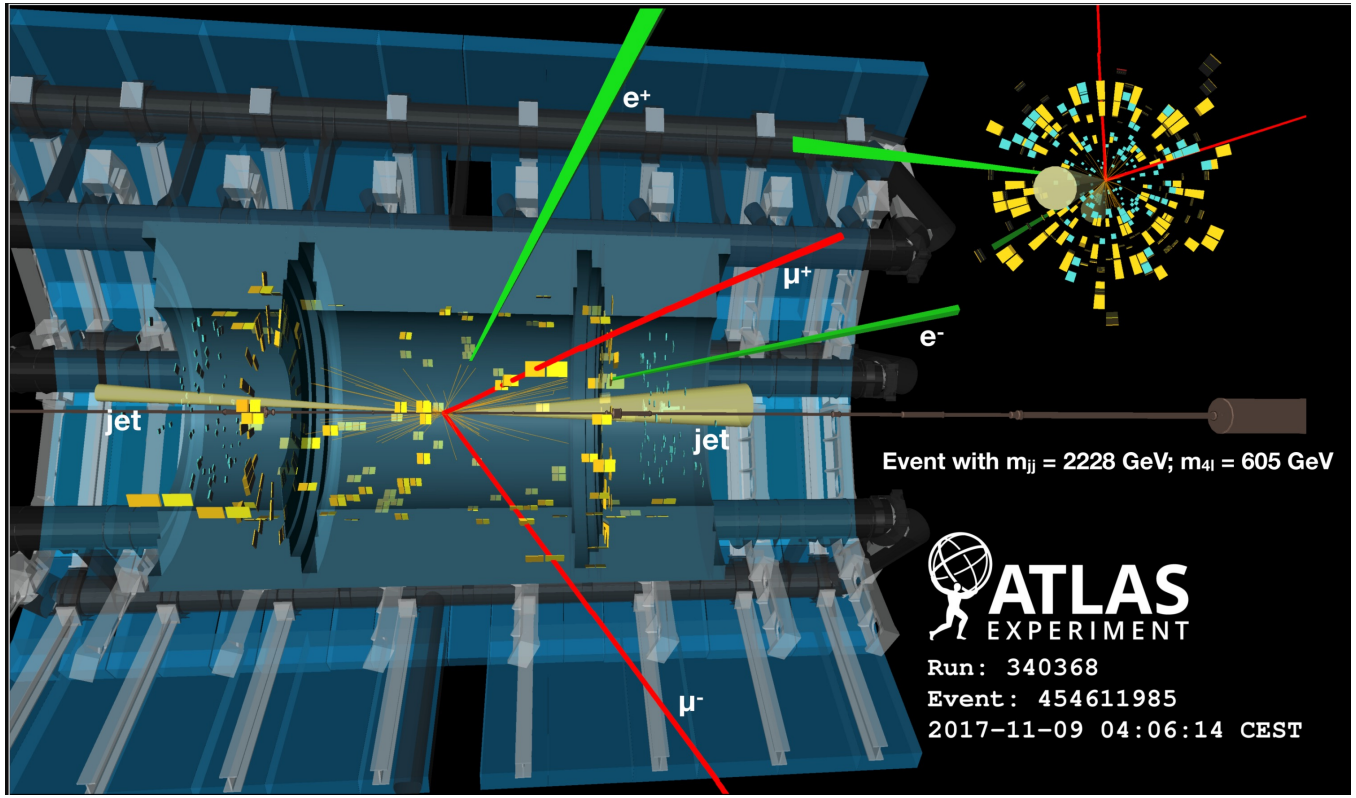




Observed significance of EW ssWWjj process: 6.5σ

# ZZjj Channel

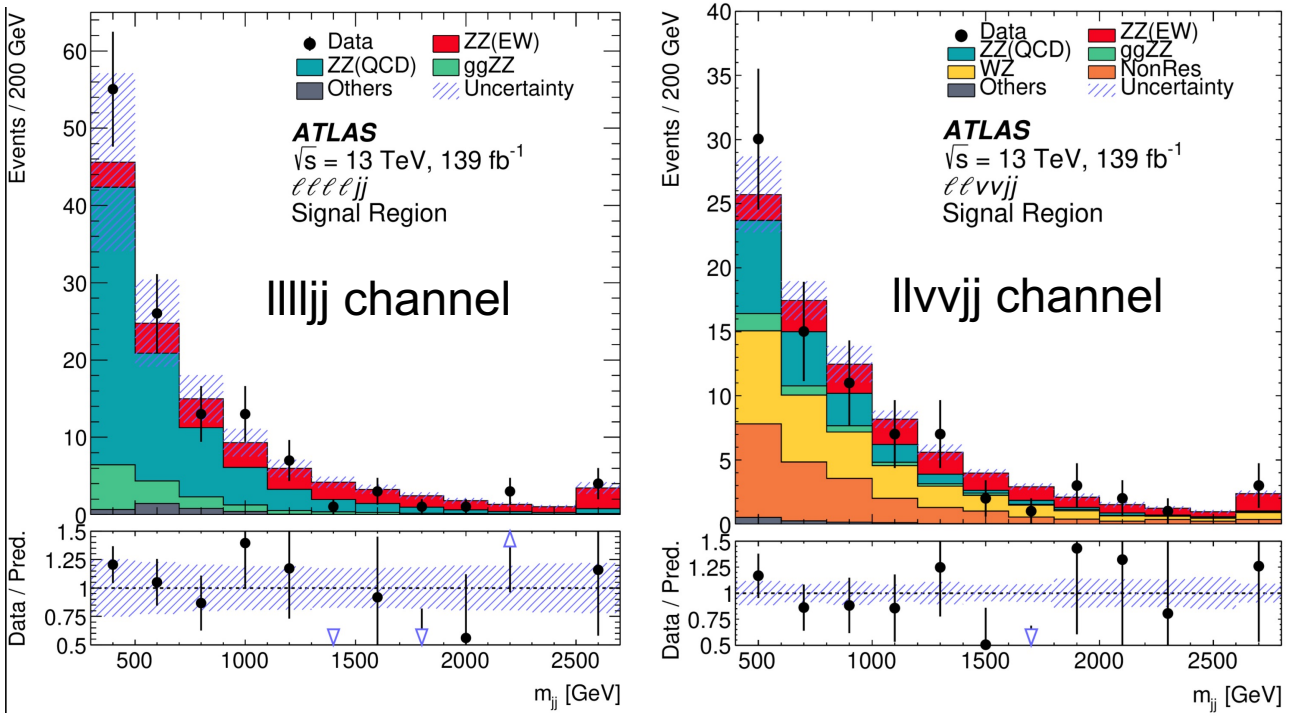
arXiv:2004.10612
Major contributions from Shandong, TDLI/SJTU, USTC. Analysis contacts as well as detailed studies

- Full Run 2 datasets with 139 $fb^{-1}$
- Two Z bosons decaying leptonically
  - ZZ → llll (4e, 4μ, 2e2μ)
  - ZZ → llvv (2e2v, 2μ2v)
- Two jets in the back and forward regions
- Clear experimental signatures
- Large modeling uncertainties of the dijets



# Kinematics and Cross-section Measurements

| Process | $\ell\ell\ell\ell jj$ | $\ell\ell\nu\nu jj$ |
|---|---|---|
| EW $ZZjj$ | $20.6 \pm 2.5$ | $12.3 \pm 0.7$ |
| QCD $ZZjj$ | $77 \pm 25$ | $17.2 \pm 3.5$ |
| QCD $ggZZjj$ | $13.1 \pm 4.4$ | $3.5 \pm 1.1$ |
| Non-resonant-$\ell\ell$ | – | $21.4 \pm 4.8$ |
| $WZ$ | – | $22.8 \pm 1.1$ |
| Others | $3.2 \pm 2.1$ | $1.2 \pm 0.9$ |
| Total | $114 \pm 26$ | $78.4 \pm 6.2$ |
| Data | 127 | 82 |



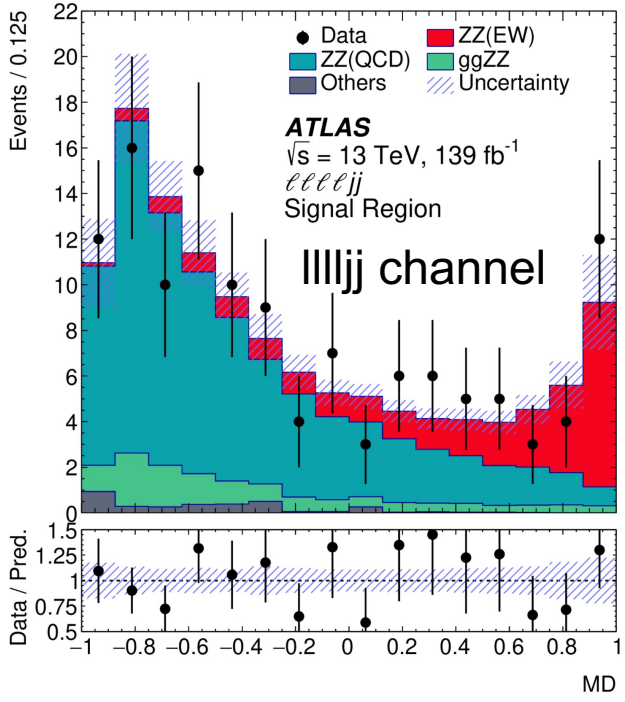

Inclusive (EW+QCD) cross-section of ZZjj

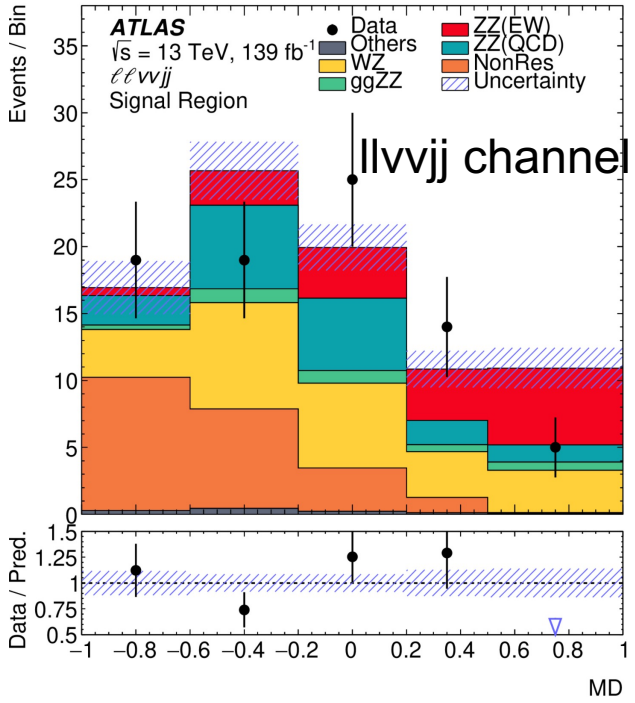
| | Measured fiducial $\sigma$ [fb] | Predicted fiducial $\sigma$ [fb] |
|---|---|---|
| $\ell\ell\ell\ell jj$ | $1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$ | $1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$ |
| $\ell\ell\nu\nu jj$ | $1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo}) \pm 0.06(\text{exp}) \pm 0.16(\text{bkg}) \pm 0.03(\text{lumi})$ | $1.07 \pm 0.01(\text{stat}) \pm 0.12(\text{theo})$ |

- ✓ Statistical dominant
- ✓ Precision in lllljj channel measurement better than theory prediction

# Extract the EW Component

- BDT used to separate EW from other processes
- Large systematic uncertainties due to the modeling of QCD ZZjj




Physics Briefing

ATLAS Physics Briefing
CERN Press Release

New milestone reached in the study of electroweak symmetry breaking

With a statistical fit over the BDT output distributions

| | $\mu_{\mathrm{EW}}$ | $\mu_{\mathrm{QCD}}^{\ell\ell\ell\ell jj}$ | Significance Obs. (Exp.) |
|---|---|---|---|
| $\ell\ell\ell\ell jj$ | $1.5 \pm 0.4$ | $0.95 \pm 0.22$ | 5.5 (3.9) $\sigma$ |
| $\ell\ell\nu\nu jj$ | $0.7 \pm 0.7$ | – | 1.2 (1.8) $\sigma$ |
| Combined | $1.35 \pm 0.34$ | $0.96 \pm 0.22$ | 5.5 (4.3) $\sigma$ |

Leads to the first observation of the EW ZZjj production at the LHC

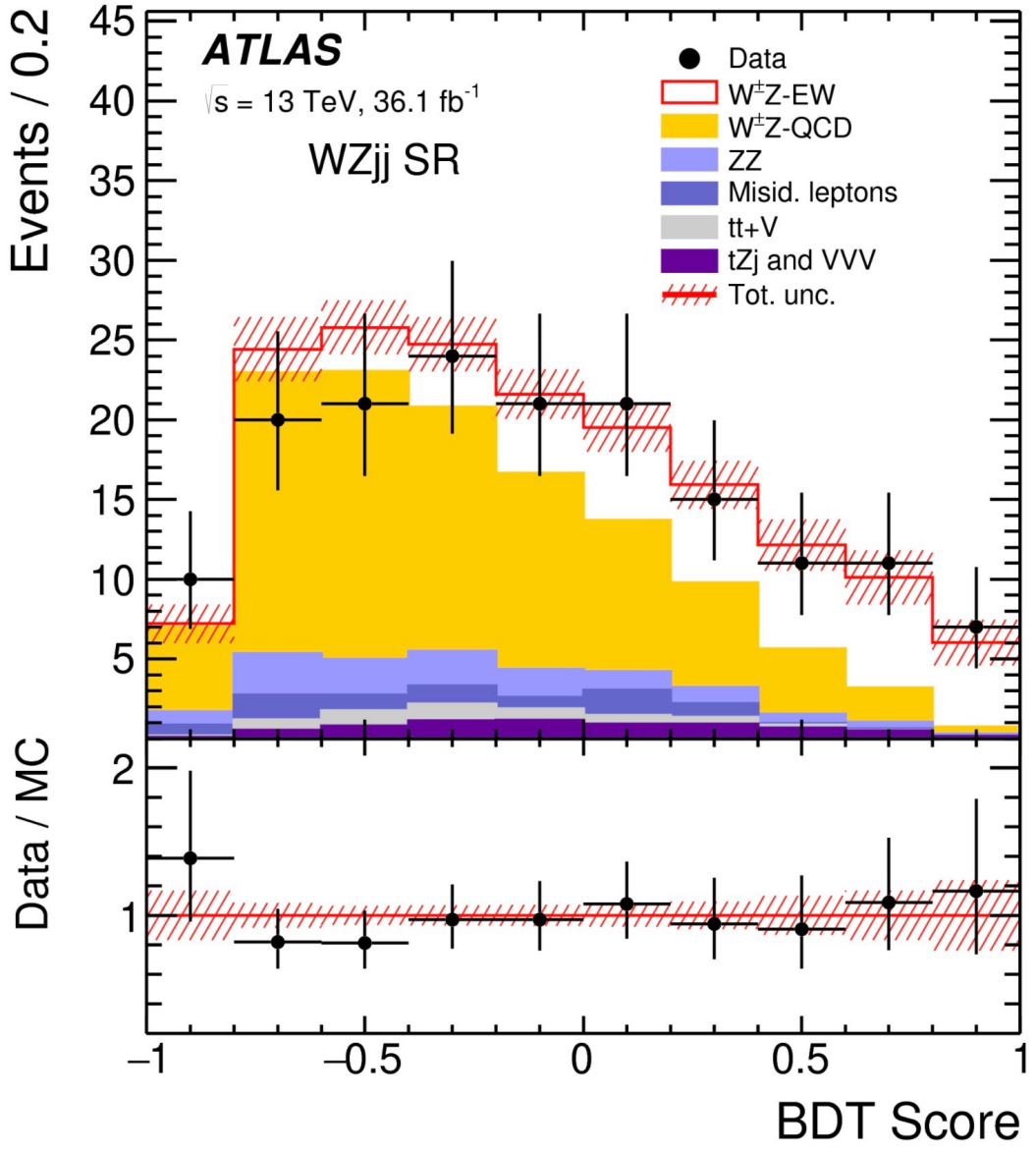
Measured cross-section of the EW ZZjj: 0.82 +/- 0.21 fb

# WZjj Channel

*Phys. Lett. B 793 (2019) 469*
Major contributions from TDLI/SJTU.

* WZ decays leptonically. 36.1 $fb^{-1}$ data used

| | SR | $WZjj$−QCD CR | $b$-CR | $ZZ$-CR |
|---|---|---|---|---|
| Data | 161 | 213 | 141 | 52 |
| Total predicted | 167 ± 11 | 204 ± 12 | 146 ± 11 | 51.3 ± 7.0 |
| $WZjj$−EW (signal) | 44 ± 11 | 8.52 ± 0.41 | 1.38 ± 0.10 | 0.211 ± 0.00 |
| $WZjj$−QCD | 91 ± 10 | 144 ± 14 | 13.9 ± 3.8 | 0.94 ± 0.14 |
| Misid. leptons | 7.8 ± 3.2 | 14.0 ± 5.7 | 23.5 ± 9.6 | 0.41 ± 0.18 |
| $ZZjj$−QCD | 11.1 ± 2.8 | 18.3 ± 1.1 | 2.35 ± 0.06 | 40.8 ± 7.2 |
| $tZj$ | 6.2 ± 1.1 | 6.3 ± 1.1 | 34.0 ± 5.3 | 0.17 ± 0.04 |
| $t\bar{t}+V$ | 4.7 ± 1.0 | 11.14 ± 0.37 | 71 ± 15 | 3.47 ± 0.54 |
| $ZZjj$−EW | 1.80 ± 0.45 | 0.44 ± 0.10 | 0.10 ± 0.03 | 4.2 ± 1.2 |
| $VVV$ | 0.59 ± 0.15 | 0.93 ± 0.23 | 0.13 ± 0.03 | 1.06 ± 0.30 |




Measured cross section

$$\sigma_{WZjj\text{−EW}} = 0.57\ ^{+0.14}_{-0.13}\ (\text{stat.})\ ^{+0.07}_{-0.06}\ (\text{syst.})\ \text{fb}$$

Observed significance of EW WZjj process: 5.3σ

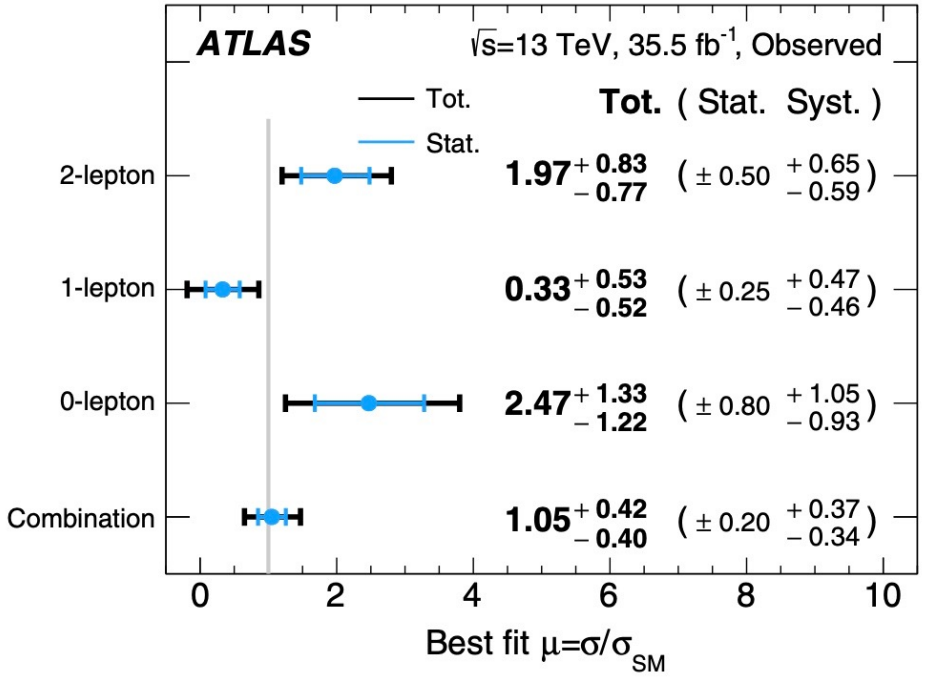
# Other Channels

Major contributions from TDLI/SJTU, USTC. Analysis contacts as well as detailed studies

Major contributions from TDLI/SJTU

***Phys. Rev. D 100 (2019) 032007***

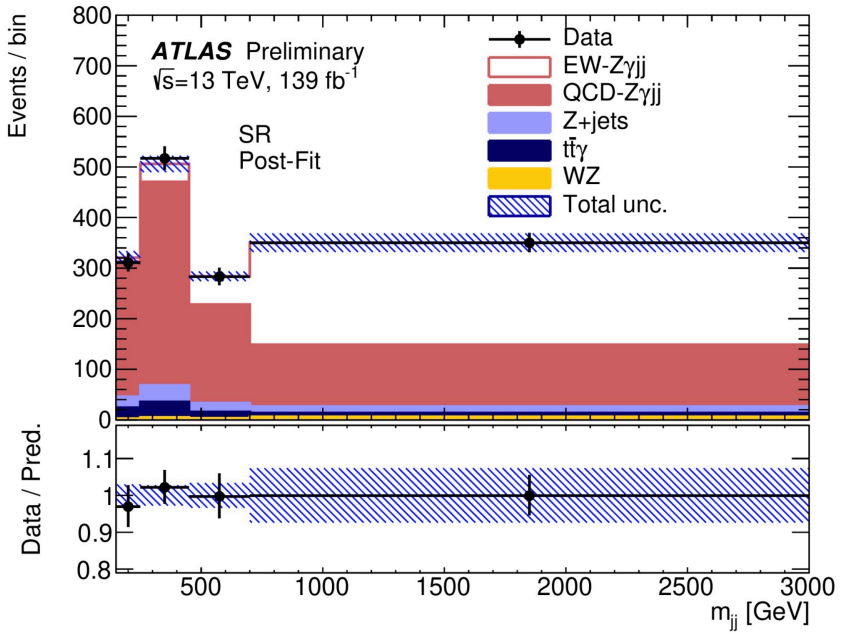
- WW/WZ/ZZ semileptonic decay
- 35.3 $fb^{-1}$ data used
- Events split into different categories based on number of leptons
- Observed significance: 2.7σ




***ATLAS-CONF-2021-038***

- Zγjj channel, with Z decays leptonically
- 139 $fb^{-1}$ data used
- Measured cross section
- Observed significance: 10σ

$$\sigma_{EW} = 4.49 \pm 0.40\ (\text{stat.}) \pm 0.42\ (\text{syst.})\ \text{fb}$$



# Summary

- The VBS processes have been observed in all the massive boson channels (WW, WZ, ZZ)
- This completes observation stage of weak boson scattering

The observation of this process marks another milestone in the study of EWSB. Further scrutiny of EWSB will continue in other channels as well as with future datasets at the LHC.

- More data is coming, allowing more precise measurement of such processes
  - Looking into longitudinal part
  - Further studies of the EWSB
  - Looking for new physics

# backup