Vector-boson scattering, diboson and triboson production at ATLAS

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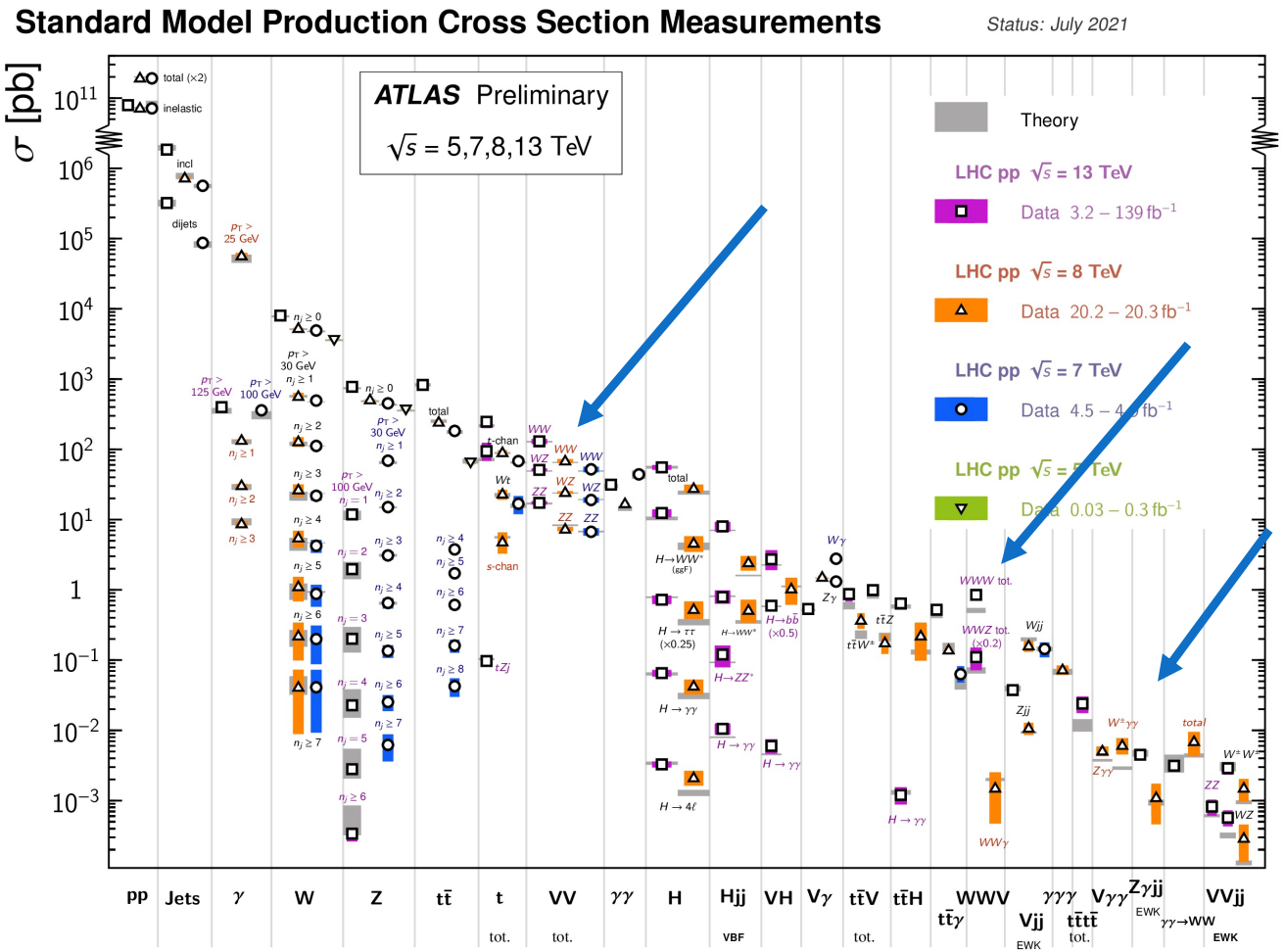
Motivation

- Electroweak-boson self-interactions are rare processes that serve as:
  - an excellent probe to the Standard Model predictions
  - a portal to Physics Beyond the standard model, through the Effective Field Theories

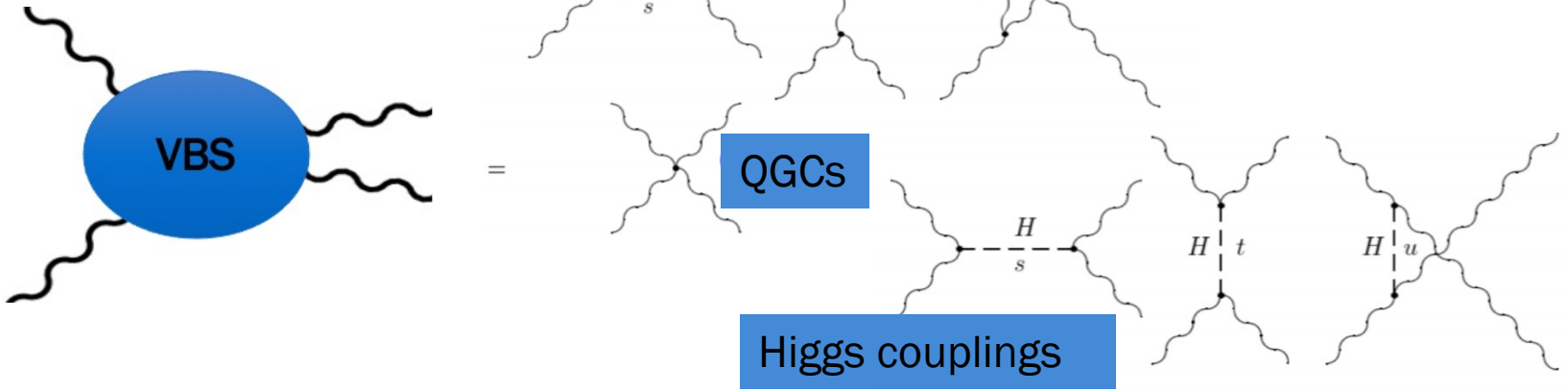
- In this talk, covering ATLAS Run-II measurements with integrated luminosity 139 fb^{-1} of:
  - EW Z(ll/vv)γjj
  - WW+>=1jet
    - Dim-6 EFT interpretations
  - Dim-6 EFT combination of various measurements
  - WWW

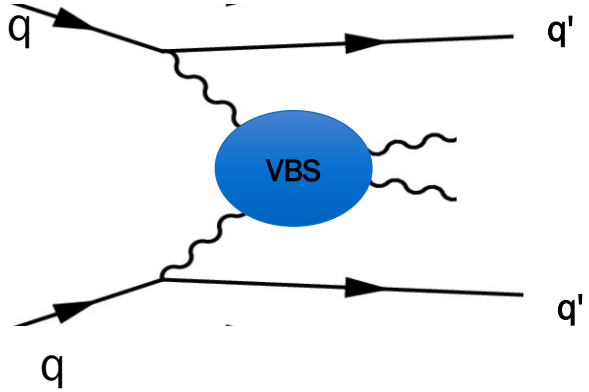


Vector Boson Scattering

Vector Boson Scattering Topology

- Unitary process in the SM, very precisely predicted

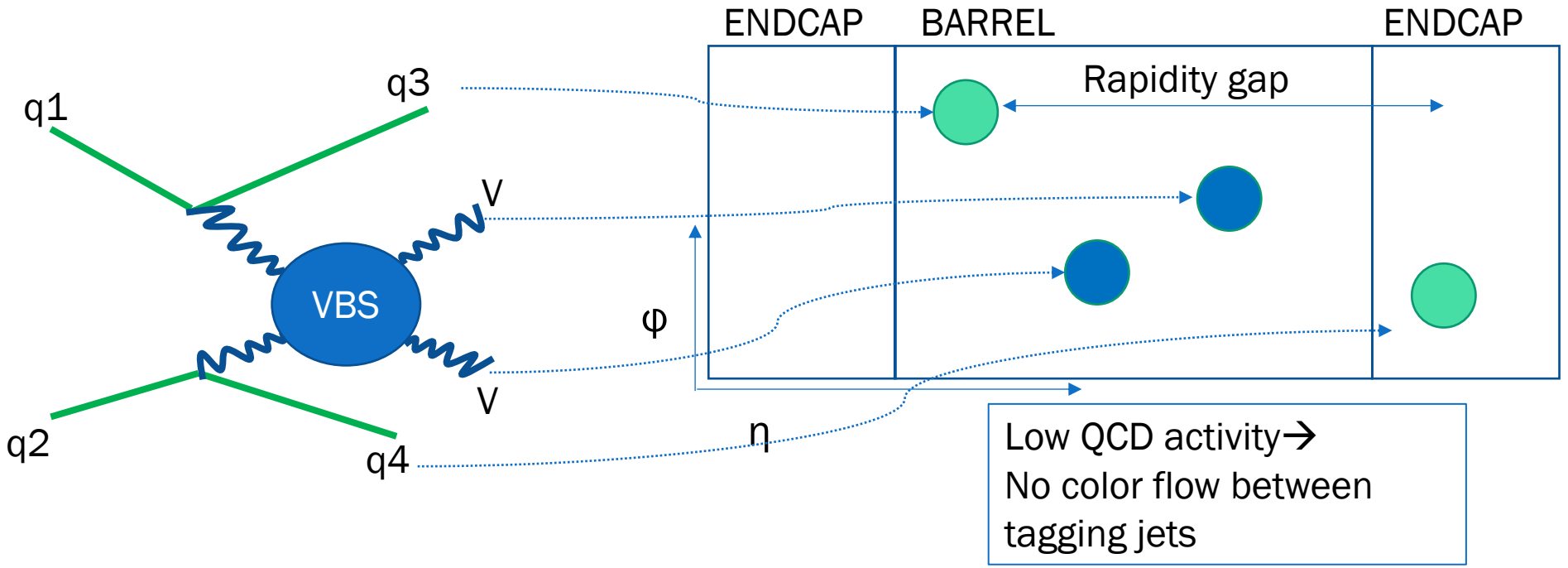




- Key process to probe the mechanism of electroweak symmetry breaking
- Provides access to quartic gauge couplings that could be modified by New Physics

VBS signature at LHC

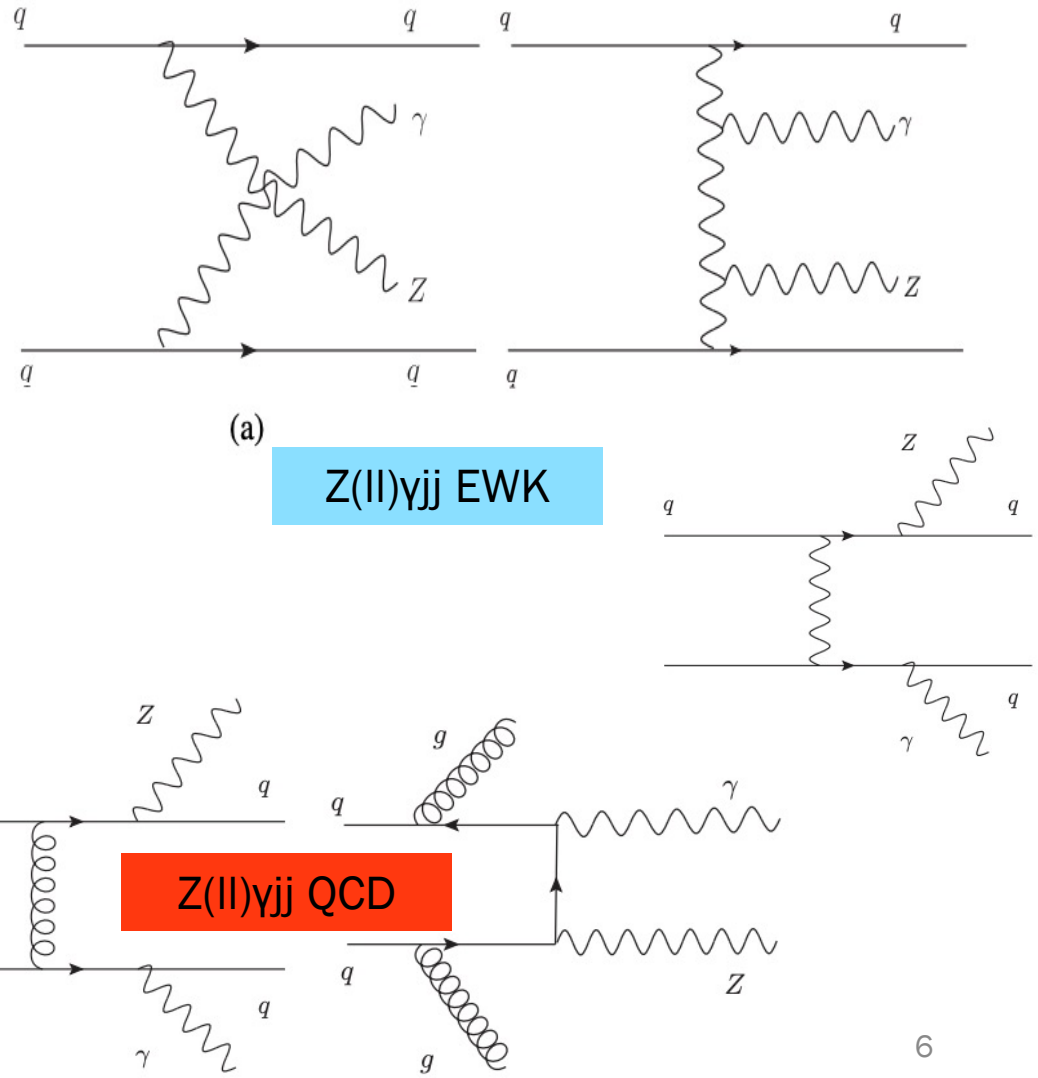
- Distinct event topology
  - Two energetic jets with large di-jet mass (m_{jj}) and high rapidity separation
  - Diboson system, centrally produced with respect to the two forward jets



Electroweak Z(→ll)γjj production

ATLAS-CONF-2021-38

- 1st Observation of EW Zγjj process in lepton channels at ATLAS
- Electroweak production of the Zγjj final state contains both VBS and non-VBS process
- Initial and final states of the Zγjj EWK and QCD production same → interference between EWK and QCD
- ZZ(→ll)γjj probes TGGs and QGCs, but with a larger expected cross-section than the ZZjj



Z(→ll)γjj: Selection and Background

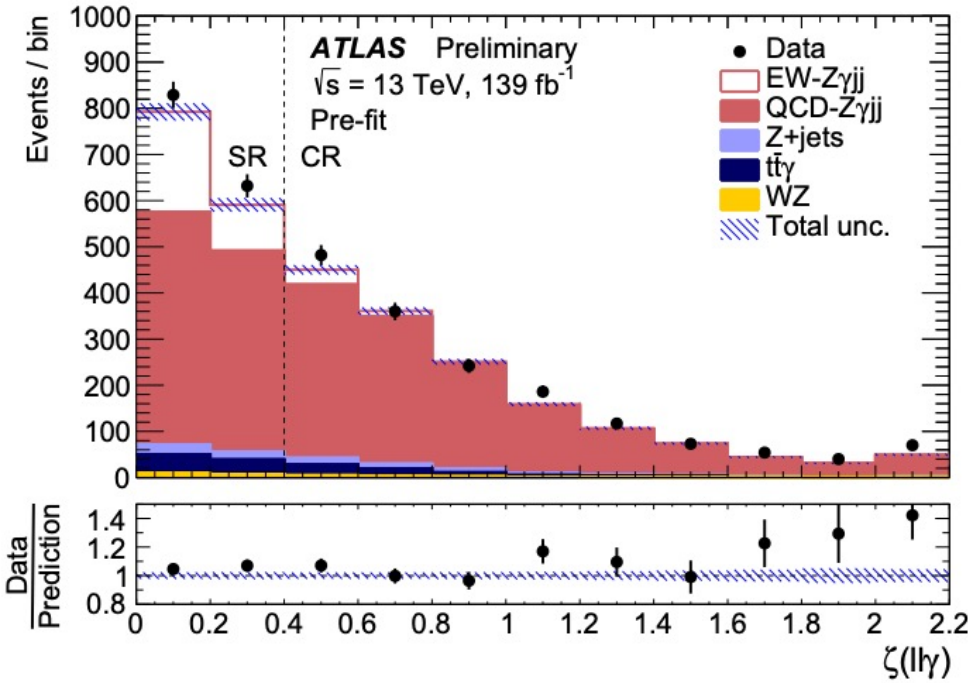
Selection

Lepton	$p_{\mathrm{T}}^{\ell} > 20, 30(\text{leading})\ \text{GeV}, \quad \lvert\eta_{\ell}\rvert < 2.47$ $N_{\ell} \geq 2$
Photon	$E_{\mathrm{T}}^{\gamma} > 25\ \text{GeV}, \quad \lvert\eta_{\gamma}\rvert < 2.37$ $E_{\mathrm{T}}^{cone20} < 0.07 E_{\mathrm{T}}^{\gamma}$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_{\mathrm{T}}^{jet} > 50\ \text{GeV}, \quad \lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150\ \text{GeV}$ remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40\ \text{GeV}$ $m_{\ell\ell} + m_{\ell\ell\gamma} > 182\ \text{GeV}$ $\zeta(\ell\ell\gamma) < 0.4$ $N_{jets}^{gap} = 0$

Cut to reject FSR

Background Estimation

- Main source of background is the QCD-originated Zγjj
  - Shape estimated from MC and normalization factor determined from the final fit
  - Cuts on the centrality ζ(llγ) of the llγ system defines the Signal and QCD Control Region
    - SR: ζ<0.4 QCD CR: ζ>0.4
- Z+jets: Data driven method
- ttbarγ: MC estimate applying scale factor: derived from comparing the MC prediction with the data using eμγ events



Z(→ll)γjj: Results

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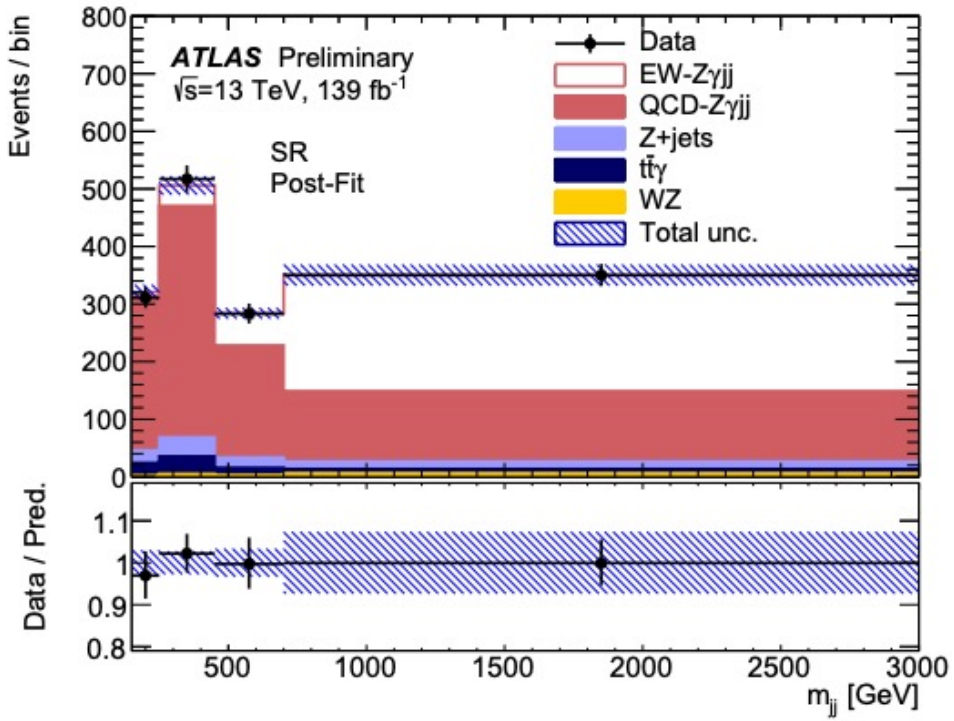
- Strategy: fit of the mjj in the Signal and QCD regions



Results

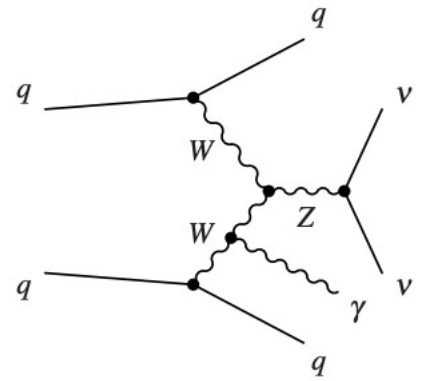
- Measured signal strength with observed significance 10σ
  - μEWK=0.95+-0.08(stat.)+-0.11(syst.)
- EWK cross section predicted from Madgraph5+PYTHIA
  - σ_{EW}(pred) = 4.73 ± 0.01 (stat.) ± 0.15(PDF)+0.23-0.22(scale) fb
- Fiducial cross-section in the signal phase space measured with 13% overall uncertainty
  - σ_{EW}(obs.) = 4.49 ± 0.40 (stat.) ± 0.42(syst.) fb

Electroweak Z(→νν)γjj production

arXiv:2109.00925

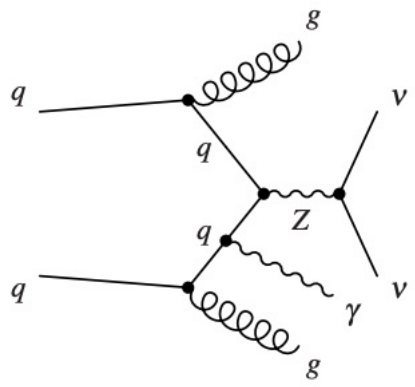
- 1st Observation of EW Zγjj process in neutrino channels at ATLAS with 5.2σ significance
- All events containing leptons are vetoed
- Analysis sets limits on the invisible Higgs decay

Z(νν)γjj EWK



- Main background: QCD $Z(\rightarrow \nu\nu)\gamma$ + jets and $W(\rightarrow \ell\nu)\gamma$ + jets events in which the lepton from the W decay is lost mostly because it falls outside of the pT or η acceptance

Z(νν)γjj QCD



Z(→νν)γjj: Results

arXiv:2109.00925

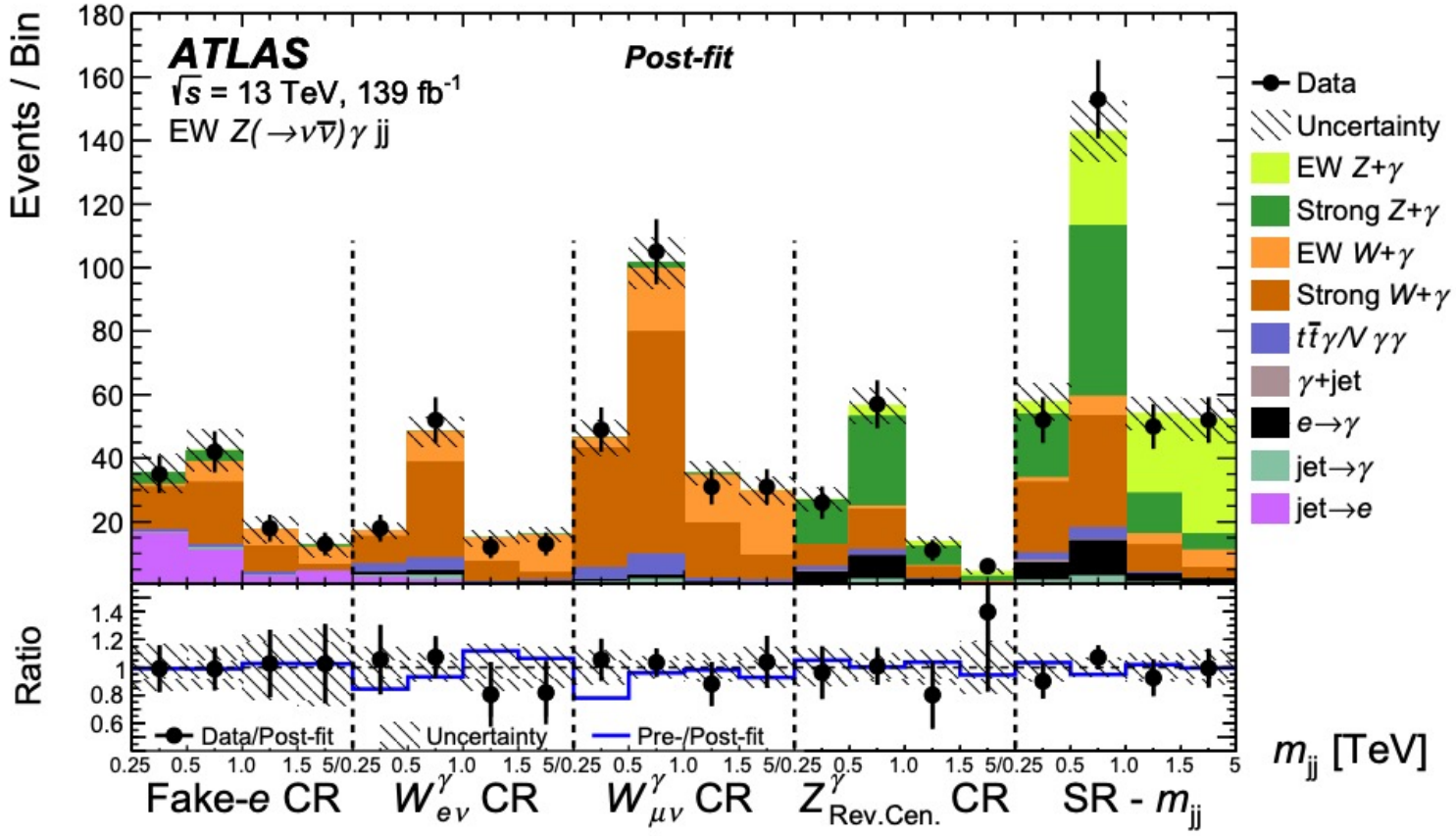
- Backgrounds are constrained in the fit in the signal region and the respective control regions
- Measured signal strength with observed significance 5.2σ

$$\mu_{EW} = 1.03 \pm 0.25$$

- Theoretical fid. cross section: σ_{EW}(pred) = 1.27 ± 0.01 (stat.) ± 0.17(QCD MadGraph scale) ±0.03(PDF) fb

- Measured fiducial cross-section: σ_{EW}= 1.31 ± 0.2 (stat) ± 0.2 (syst) fb

$\mu_{Z\gamma_{EW}}$	$\beta_{Z\gamma_{strong}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20

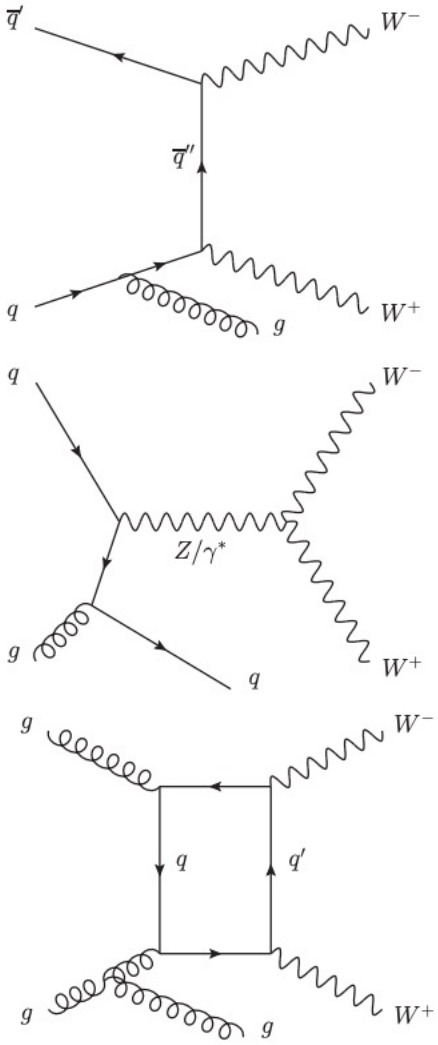


Diboson

JHEP06(2021)003

W+W- + ≥ 1 Jets Inclusive Measurement

- Measurement of WW pair production with a jet inclusive phase space
  - First time at LHC, differential measurements performed in jet-inclusive phase space
- The measurement serves as a test of theoretical predictions:
  - Perturbative QCD
  - Higher order EWK corrections
- Sensitive to TGCs



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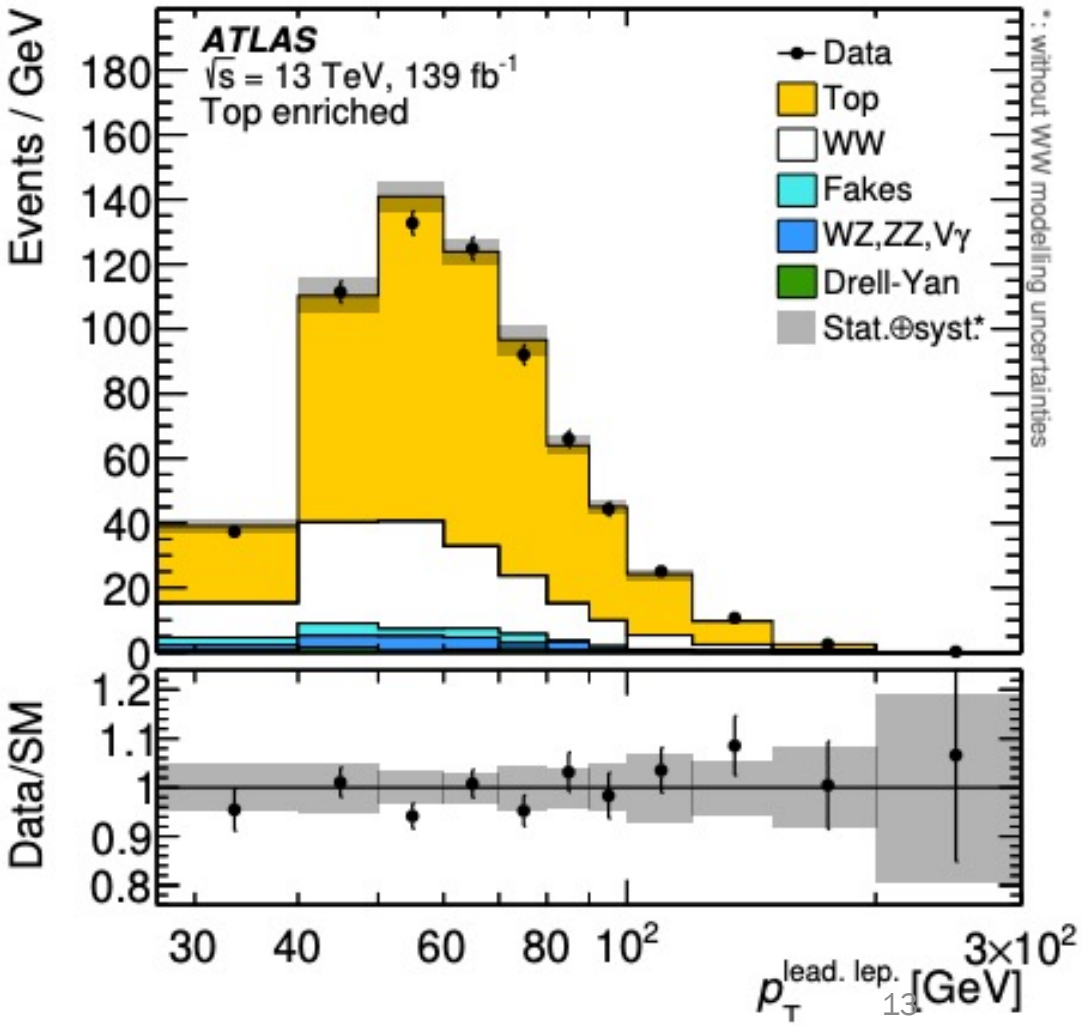
W+W- + ≥ 1 Jets: Selection and Background

Selection

- eμ channel only
- b-jet veto to reduced large top background
- $m_{e\mu} > 85$ MeV to suppress Drell-Yan background as well as H⟶WW resonance

Background Estimation

- Main source of background is the top contribution
  - ttbar is estimated with data-driven method, considering two control regions with exactly 1 b-tag and exactly 2 b-tags
- Drell-Yan contribution is estimated using the MC
- Fake leptons: data-driven method
- Single top and diboson background estimated using MC



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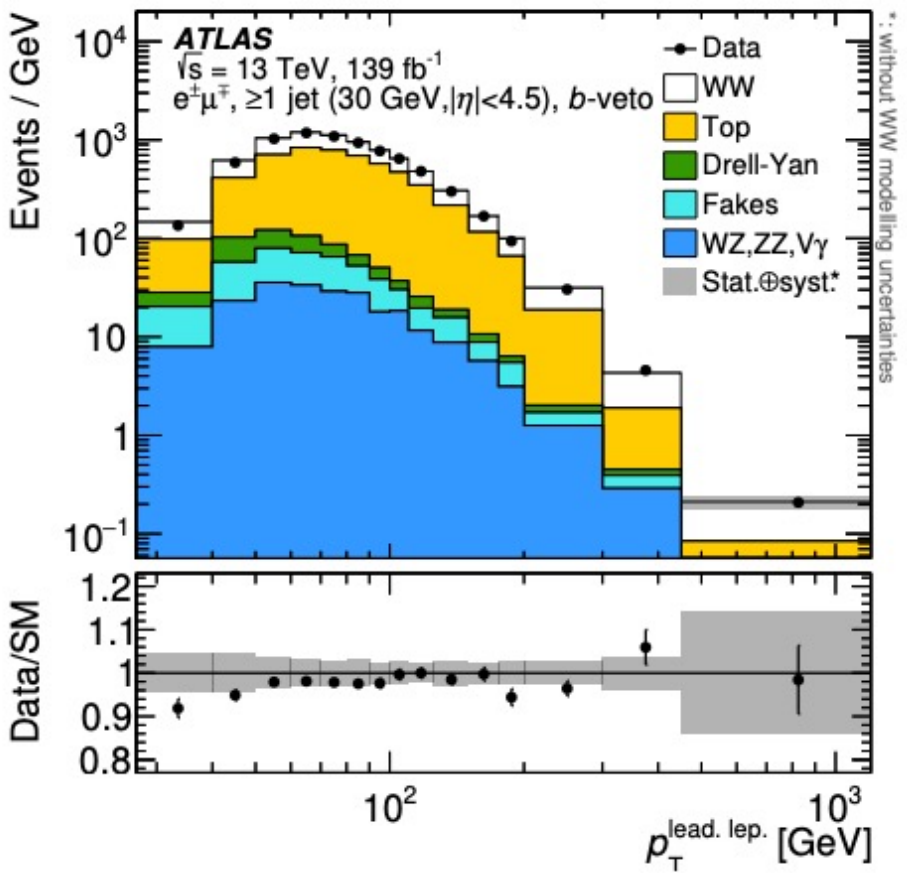
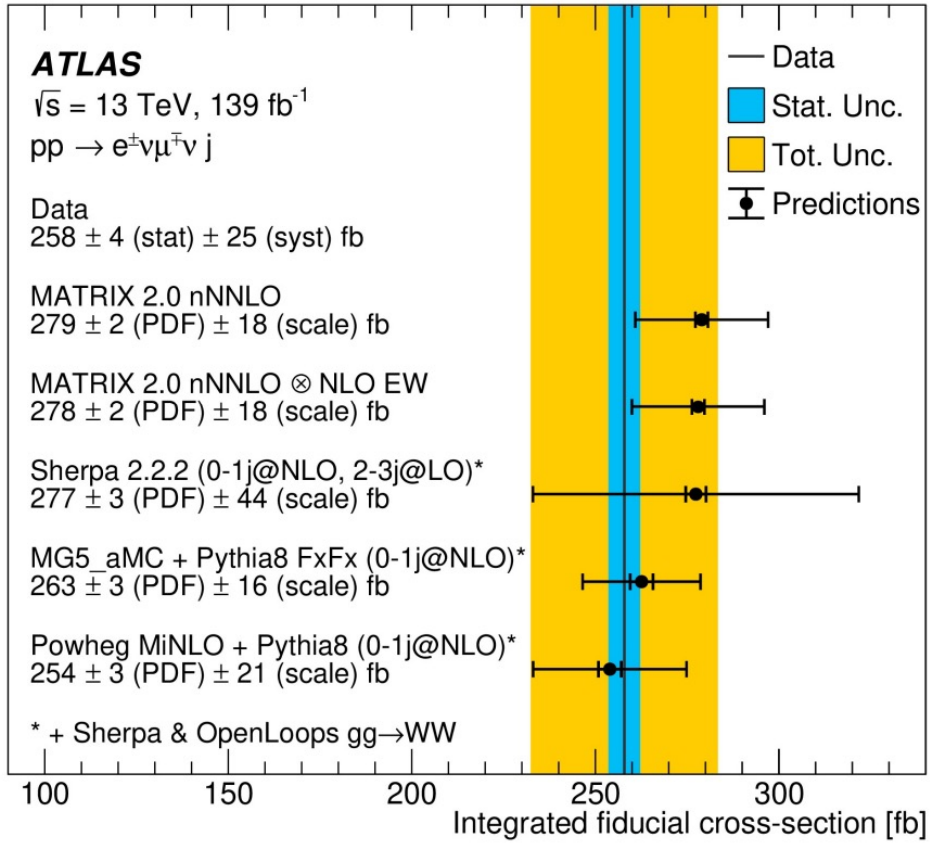
W+W- + ≥ 1 Jets: Fiducial Cross section

- σ_{fid}=258 ± 4 (stat.) ± 25 (syst.) fb with overall uncertainty 10%
- NLO predictions with Sherpa, Madgraph and Powheg generators are consistent with theory prediction





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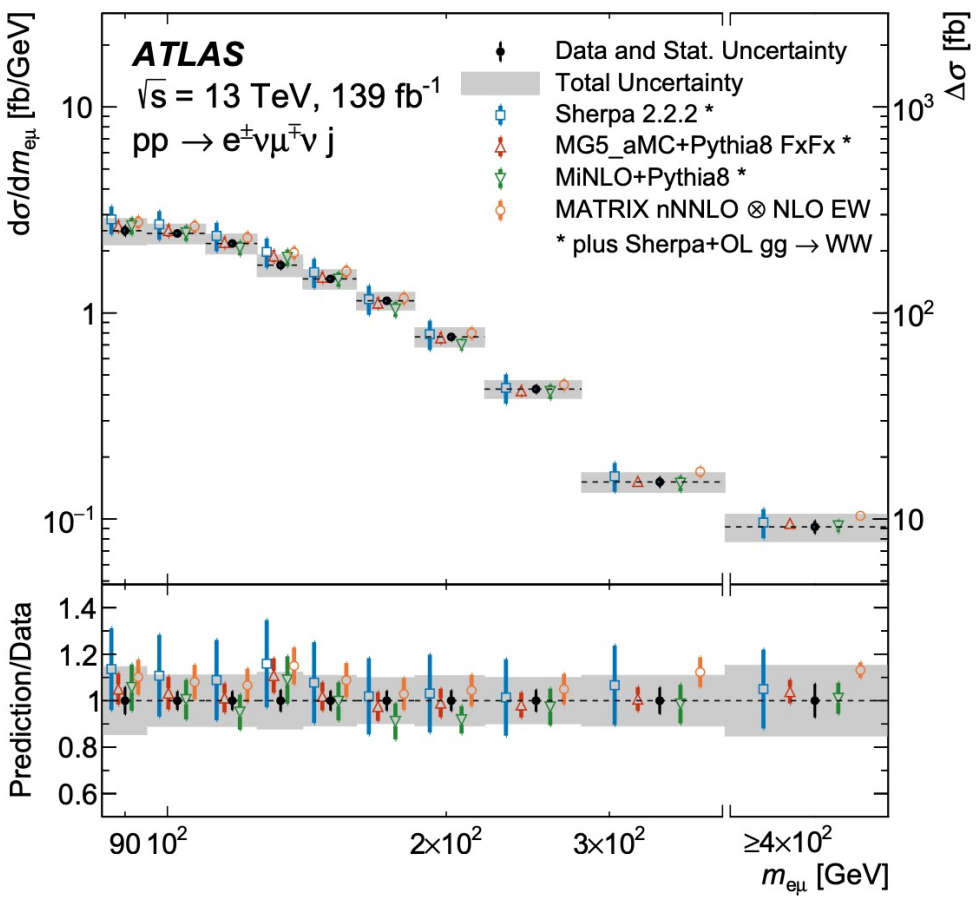
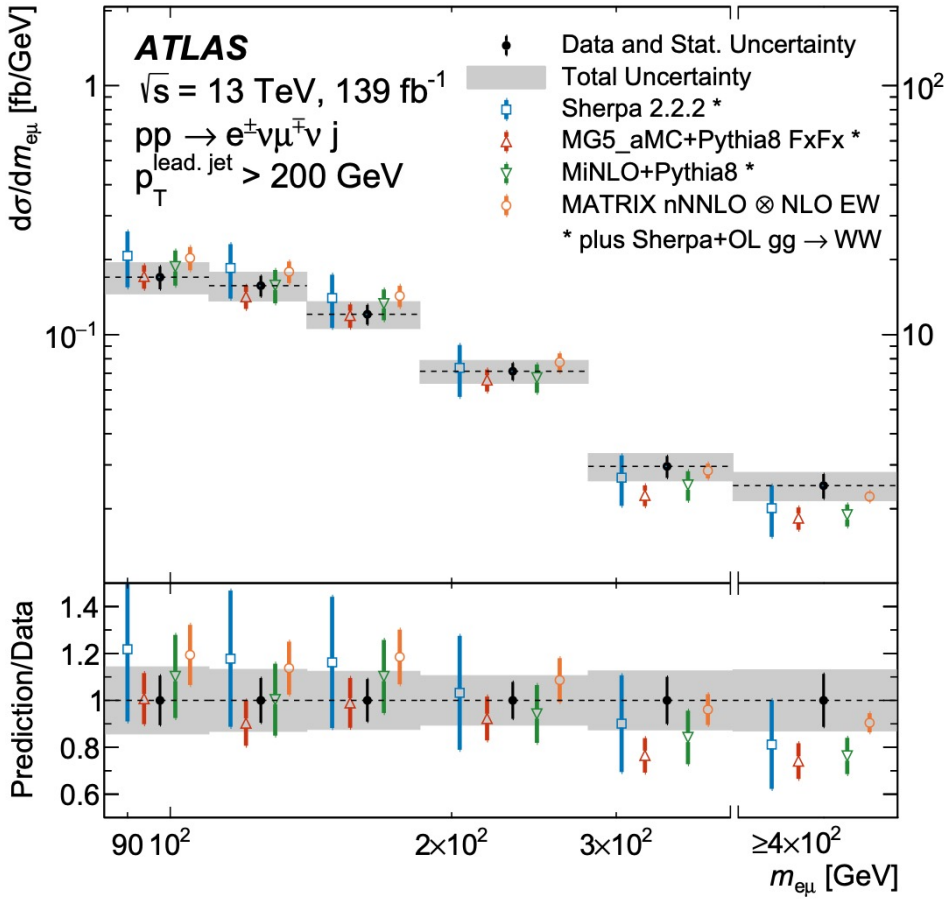
W+W- + ≥ 1 Jets: Differential Cross-section

- Differential cross sections obtained using iterative Bayesian unfolding approach
- Various differential distributions
- Good agreement among the MC predictions and data





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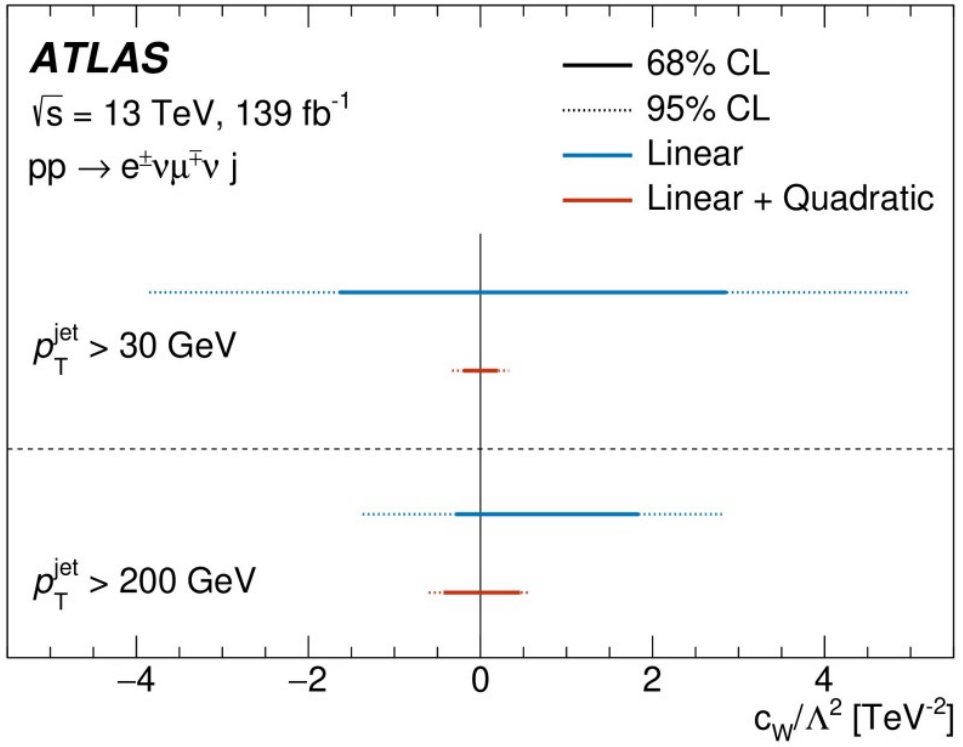
EFT Dim-6 operator in W+W- + ≥ 1 Jets

- EFT:SM expansion to higher order terms

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \sum_j \frac{c_j}{\Lambda^4} O_j + O_k$$

- Experimental Approach to EFTs→ associate the operators to couplings between bosons and fermions
  - Triple gauge couplings can be parametrized in terms of Dim-6 operators
- Final state sensitive to Dim-6 operator Qw→ constraint on Cw
- m_{eu} used as a discriminant in an enhanced phase space with $p_T^{lead.jet} > 200$ GeV



Jet p_T	Linear only	68% CI obs.	95% CI obs.	68% CI exp.	95% CI exp.
> 30 GeV	yes	[−1.64, 2.86]	[−3.85, 4.97]	[−2.30, 2.27]	[−4.53, 4.41]
> 30 GeV	no	[−0.20, 0.20]	[−0.33, 0.33]	[−0.28, 0.27]	[−0.39, 0.38]
> 200 GeV	yes	[−0.29, 1.84]	[−1.37, 2.81]	[−1.12, 1.09]	[−2.24, 2.10]
> 200 GeV	no	[−0.43, 0.46]	[−0.60, 0.58]	[−0.38, 0.33]	[−0.53, 0.48]

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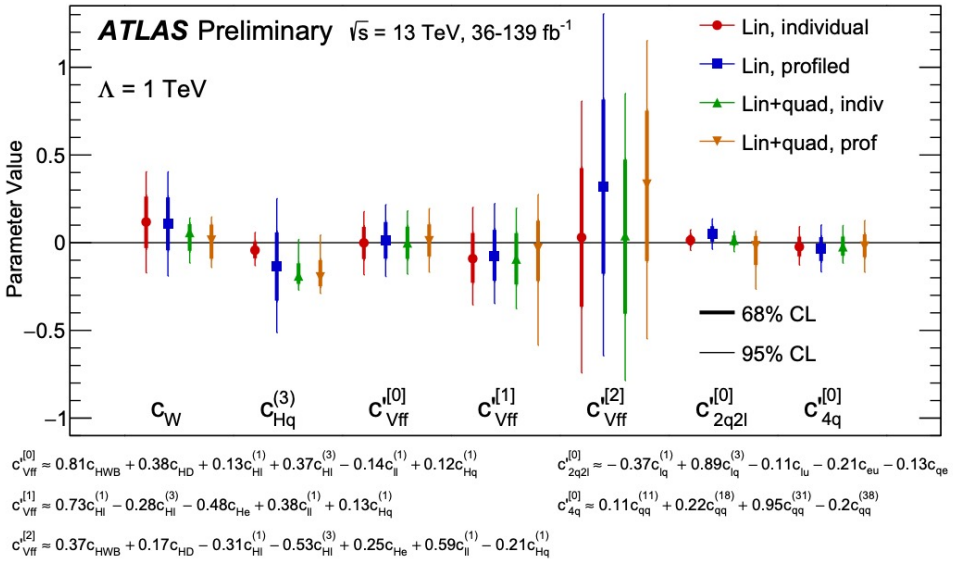
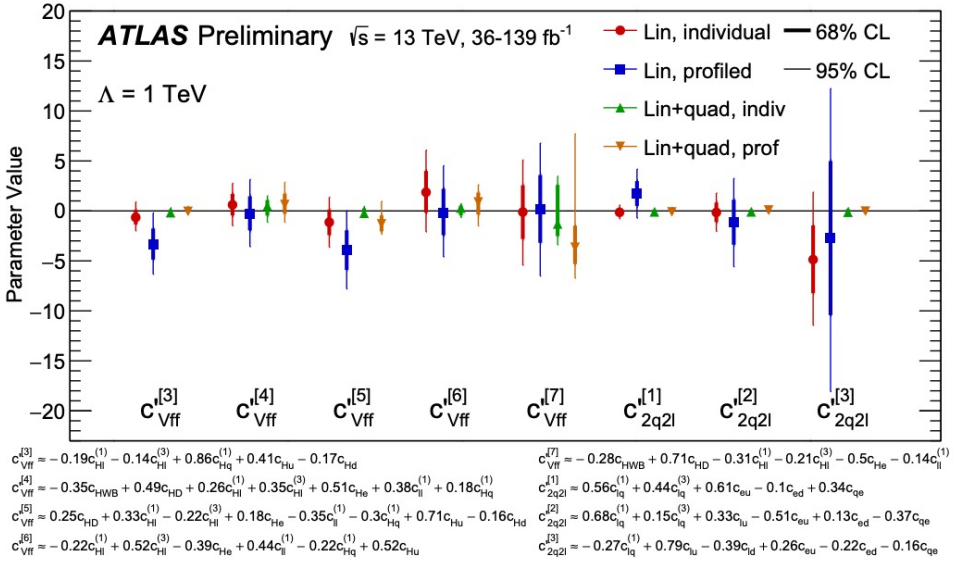
EFT Dim-6 combination: WW, WZ, 4l, and Zjj

- Combined EFT interpretation of differential measurements of the following leptonic final states:

Final state	Dataset	Diff. input distributions
WW	36 fb-1	pTlead. lepton
WZ	36 fb-1	mTWZ
4leptons	139 fb-1	mZ2
Zjj	139 fb-1	Δφjj

- Linear combinations of the Dim-6 EFT coefficients are constrained
  - Including only linear terms
  - Including both linear and quadratic terms

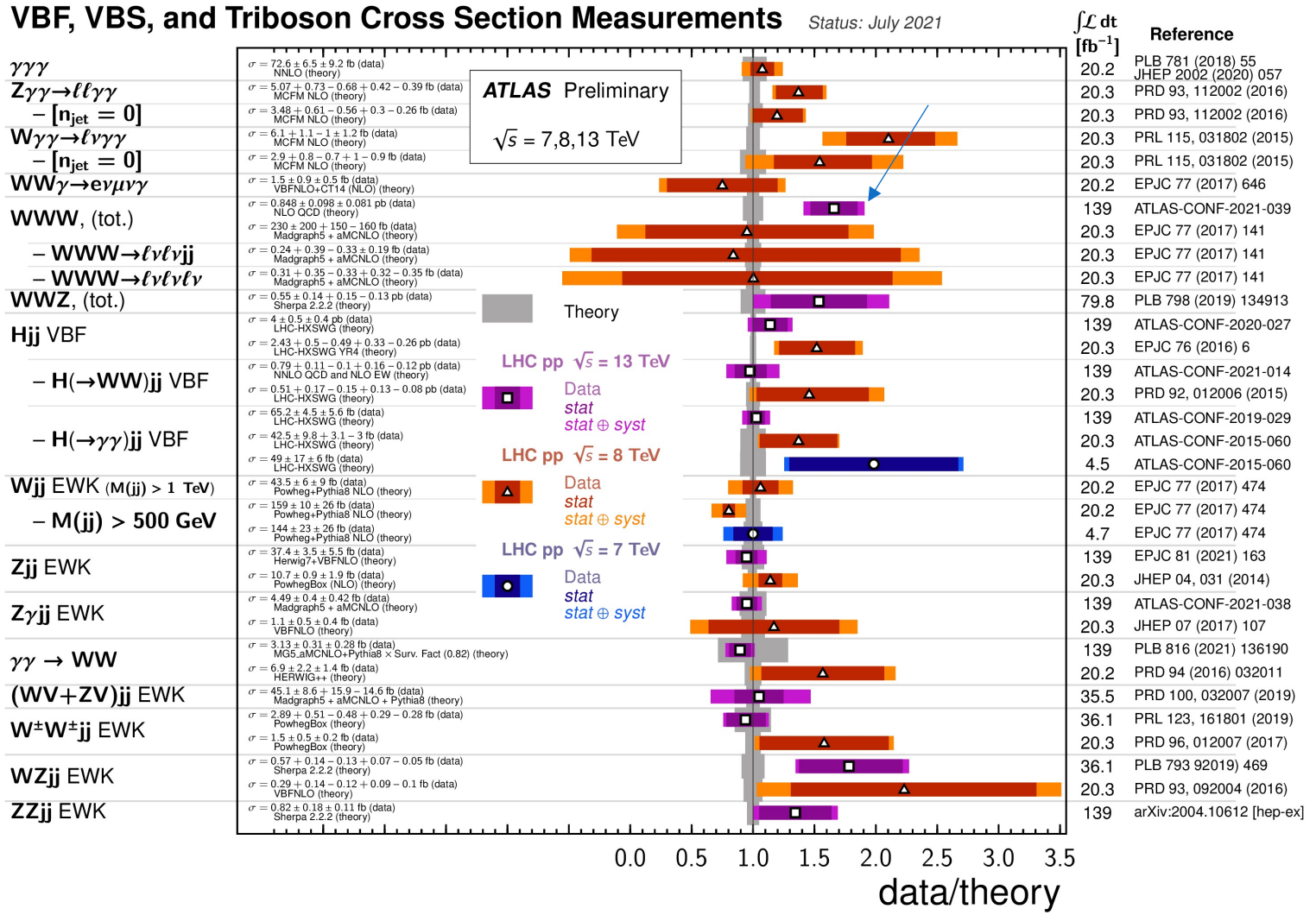




Triboson

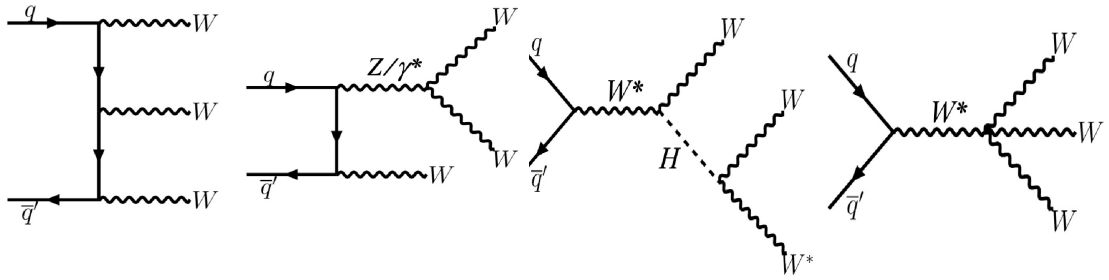
Triboson Production

- First evidence for WWW and WWZ at ATLAS in 2019
  - Partial Run 2 dataset 80 fb-1
  - Observed: WVV 4.1 σ, WWW 3.2σ
  - Physics Letter B. 2019
- First observation of VVV at CMS in 2020
  - Full Run 2 dataset 137 fb-1
  - Observed: VVV 5.7σ, WWW 3.3σ
  - Physics Review Letters 2020
- ATLAS achieved observation results with 8.2σ in stand alone WWW channel with full Run II 139 fb-1 data experiment!
  - ATLAS-CONF-2021-39

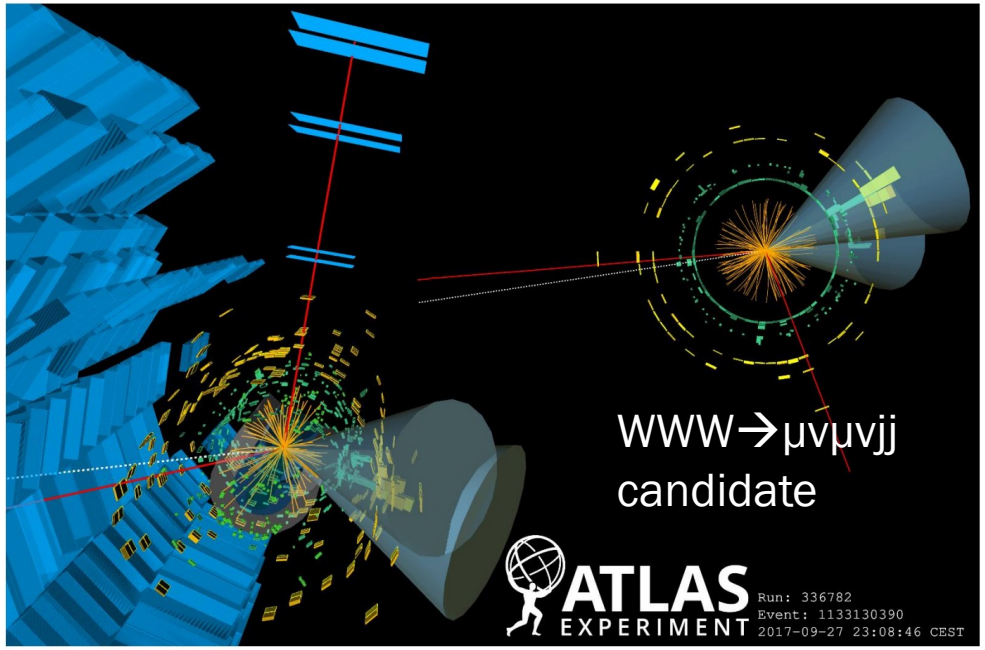


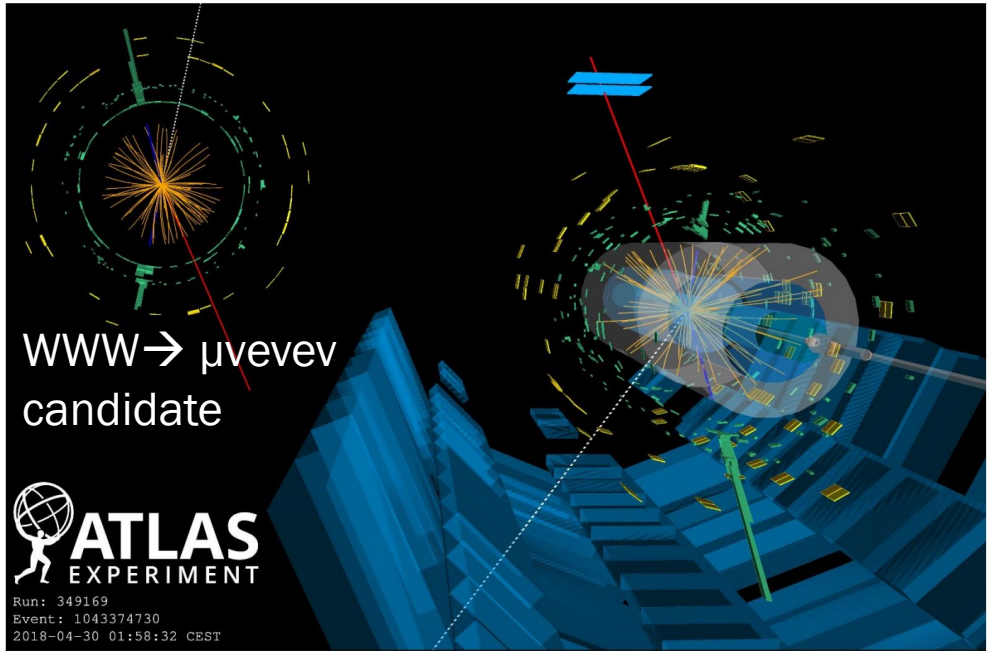
WWW: Final states

- 2 final states:
  - W±W±W∓ →2l2v2j :
    - Signature: e± e± jj + ETmiss e± μ± jj + ETmiss μ± μ± jj + ETmiss
  - W±W±W∓ → 3l3v :
    - Signature: e± e± μ∓ jj + ETmiss μ± μ± e∓jj + ETmiss



- Principle: avoiding opposite sign, same flavor pairs of leptons (OSSF) and SM processes that produce oppositely charged leptons pairs





WWW: Selections and background estimation

Selections

2l2v2j
No SFOS pairs,
3rd lepton veto
Leading lepton pT > 27 GeV
40 < mll < 400 GeV
mee < 80GeV OR 100 GeV < mee (ee only)
≥ 2 jets, mjj < 160 GeV, $\lvert\Delta\eta jj\rvert$ < 1.5
$ET\ miss$ significance > 3 (ee only)
no b-quark jet

Non-prompt leptons

Charge flip

3l3v
No OSSF pairs
4th lepton veto
Leading lepton pT > 27 GeV
Sum of lepton charge = 1
b-jet veto

Non-prompt leptons from b-decays

Background Estimation

- Main background source is WZ → constrained using data from dedicated control regions(WZ+0,1,>2jets) to normalize the MC

- Non-prompt leptons
- Vγ events where the photon is misidentified as an electron
- Prompt electron mis-identification (charge-flip)

Data-driven estimates

WWW: Results

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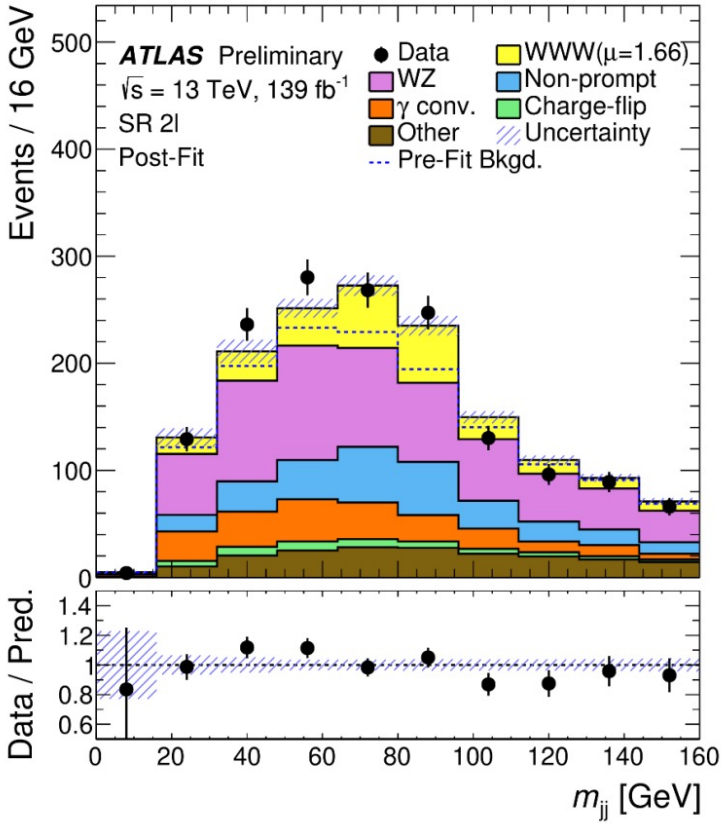
- Fit strategy: simultaneous binned log-likelihood fit of BDT distributions in all signal regions and mlll distribution in WZ control regions

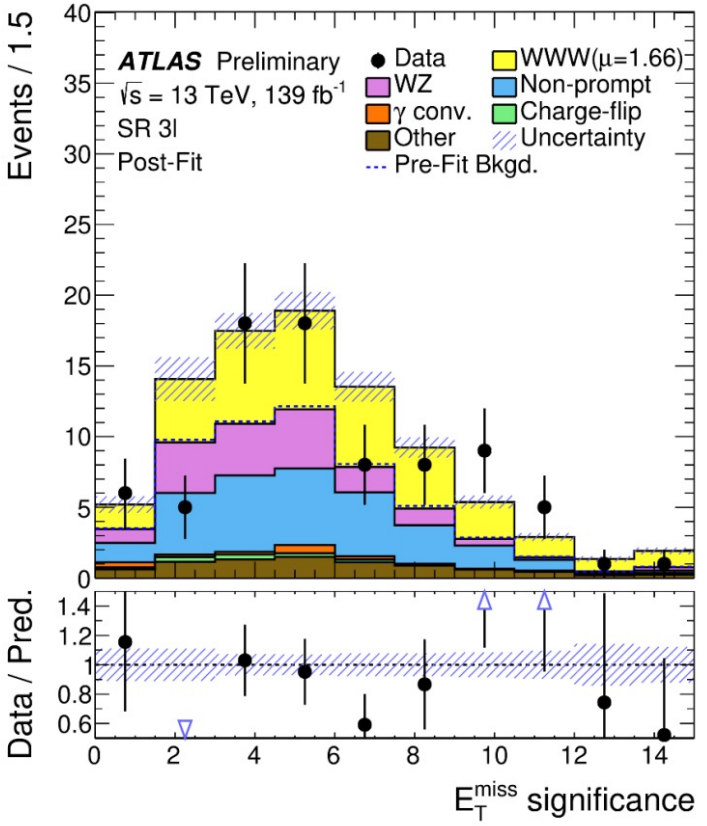
- Observed signal strength with 8.2σ observed significance :

  μ = 1.66 ± 0.28

- Observed cross-section:

  850 ± 100 (stat.) ± 80 (syst.) fb





Summary

- LHC Run2 provides a large amount of pp collision data at a higher center-of-mass energy, giving rise to the observation sensitivity of the gauge boson self-couplings
- New ATLAS measurements of VBS and diboson and triboson using the Full Run2 data set with integrated luminosity 139 fb-1 are presented:
  - Z(ll)γ VBS, Z(νν)γ VBS observations with 10σ and 5.2σ respectively
  - WW+>=1jet differential cross sections and EFT interpretations
  - WWW observed for the first time with 8.2 σ