ATLAS measurements of Vector Boson Scattering

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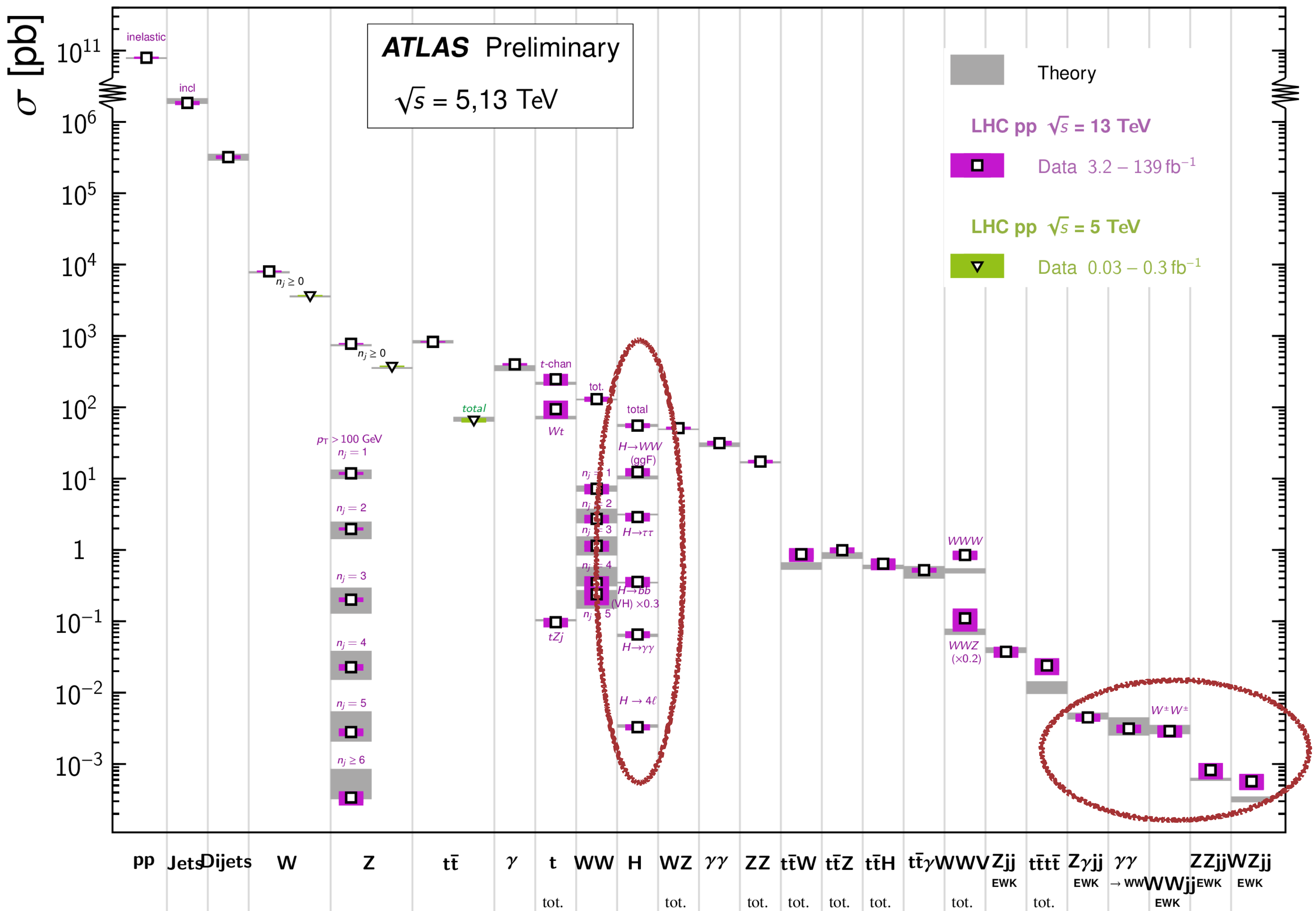
on behalf of the ATLAS collaboration

September 21st, 2021 - Higgs Hunting 2021

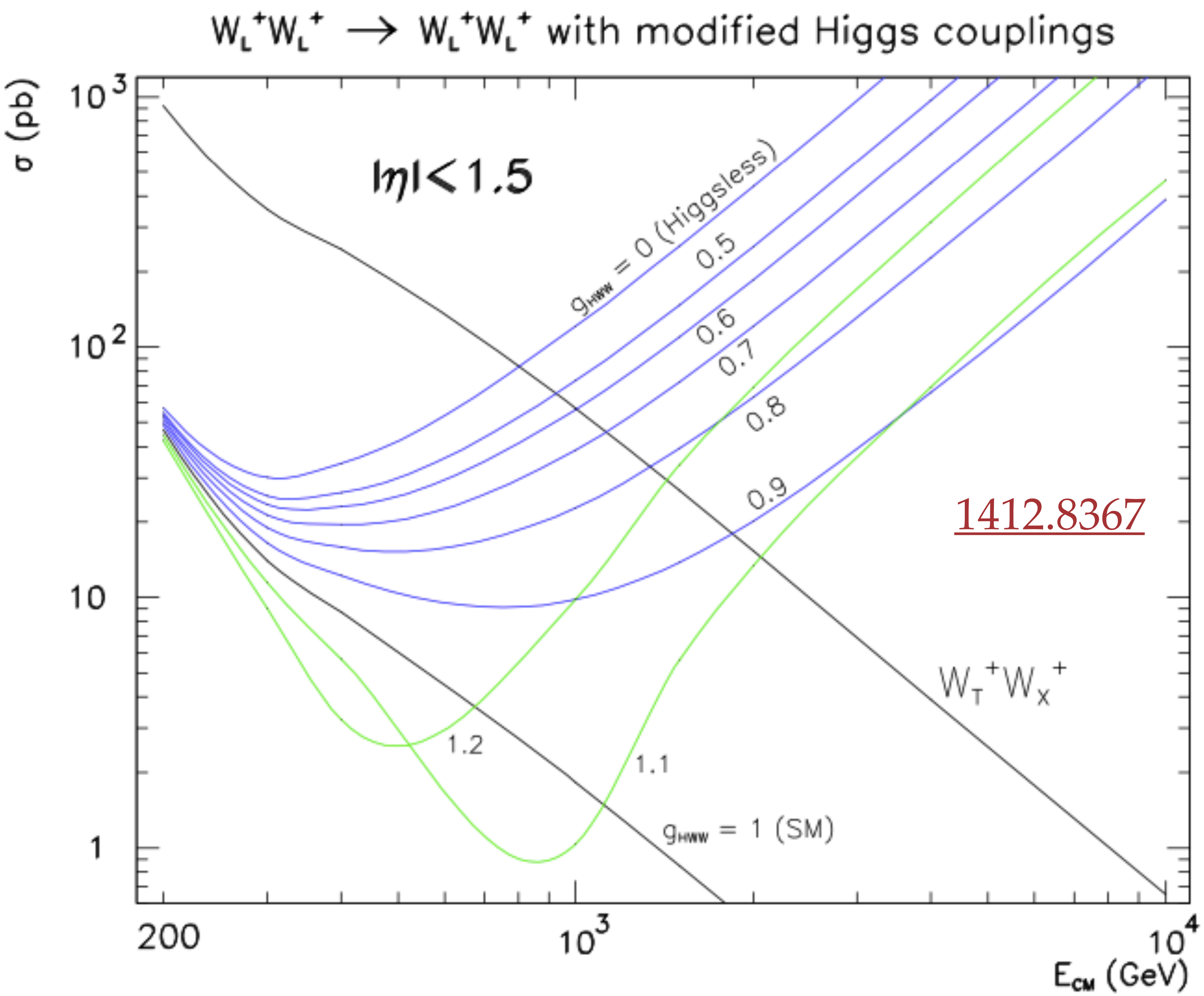
Introduction

- VBS: among the smallest cross-section processes (~1fb)
- Important and complementary test of electroweak (EW) sector and EW Symmetry Breaking



Introduction

- VBS: smallest cross-section processes to date
- Important and complementary test of electroweak (EW) sector and EW Symmetry Breaking



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VBS = tool for indirect search for new physics

ATLAS VBS studies

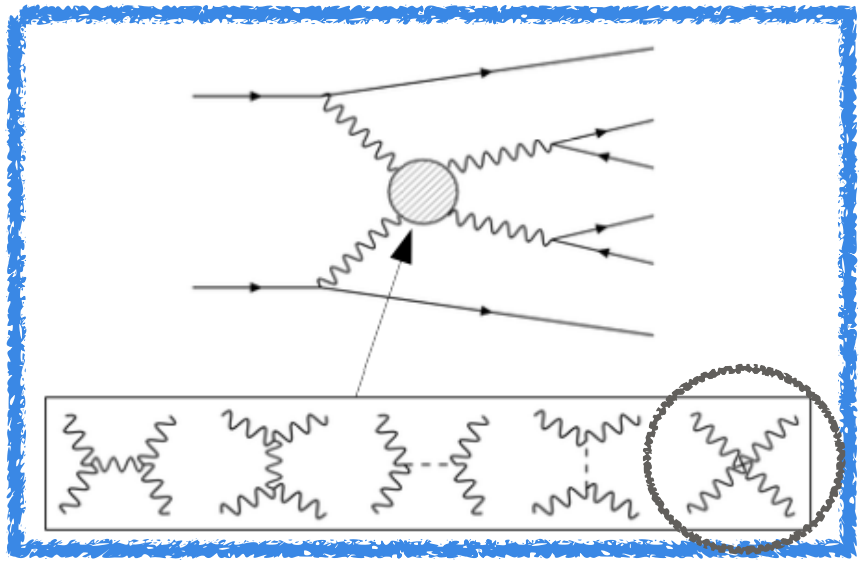
- **Datasets :** 13 TeV 2015+2016 (36.1 fb^{-1}) or 2015-2018 (139 fb^{-1})
- **Channels studied:**

Channel	Obs (Exp) Sign.	Lumi	Ref.	
$W^{\pm}Z$	5.3 (3.2) σ	36 fb^{-1}	Phys. Lett. B 793 (2019) 469	In back-up
VV semilep	2.7 (2.5) σ	35 fb^{-1}	Phys. Rev. D 100 (2019) 032007	
$W^{\pm}W^{\pm}$	6.5 (4.6) σ	36 fb^{-1}	Phys. Rev. Lett. 123 (2019) 161801	
ZZ	5.5 (4.3) σ	139 fb^{-1}	arXiv:2004.10612v1 (sub. Nature Physics)	In talk
Z(ll)γ	10 (11) σ	139 fb^{-1}	ATLAS-CONF-2021-038	
Z(νν)γ	5.2 (5.1) σ	139 fb^{-1}	arXiv:2109.00925v1 (sub. EPJC)	

- **In this talk will also present a comparison of MC for EWK and QCD VVjj**
  - ATL-PHYS-PUB-2020-026

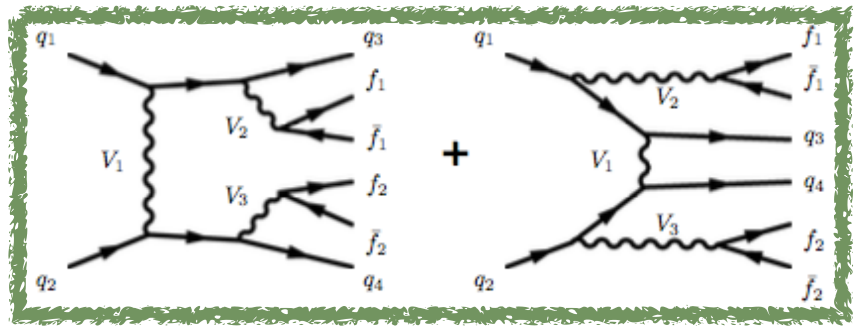
Phenomenology of VBS

- **Cannot access pure VBS and pure quartic couplings (no independently gauge invariant):**



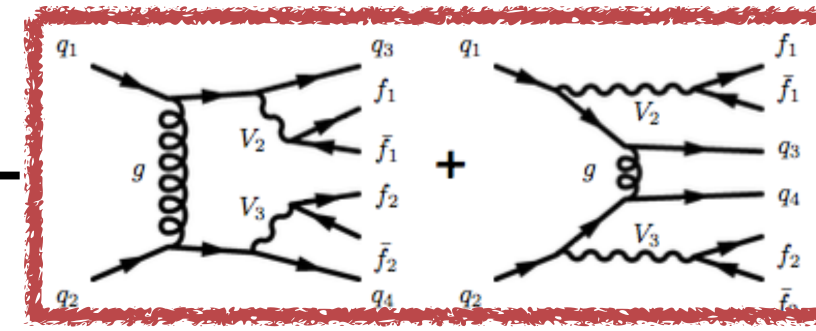
VBS with triple and quartic couplings
$O(\alpha_{EW}^4)$

\+



EW non-VBS (including tribosons)
$O(\alpha_{EW}^4)$

\+



QCD-induced
Usually much larger XS than EWK
$O(\alpha_S^2\alpha_{EW}^4)$

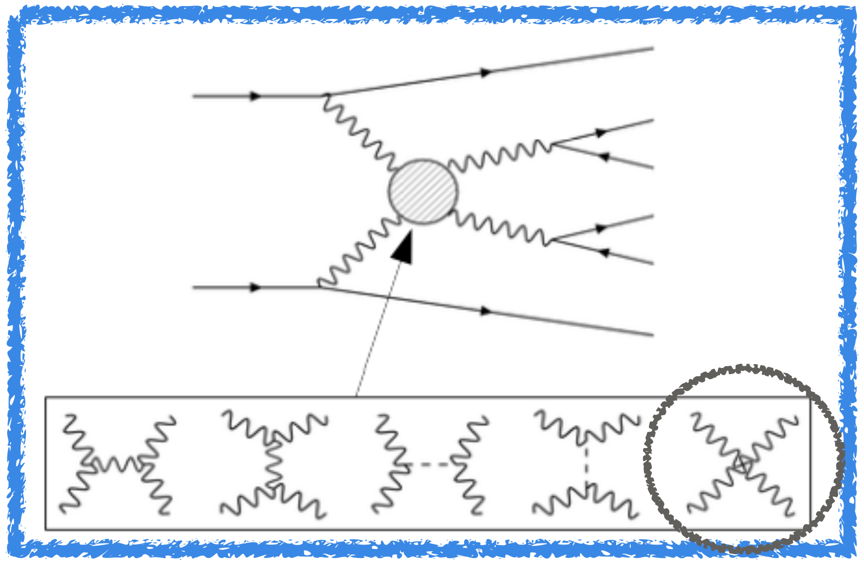
Signal

Background

Interference
$O(\alpha_S\alpha_{EW}^3)$ *(few %)*

Phenomenology of VBS

- **Cannot access pure VBS and pure quartic couplings (no independently gauge invariant):**



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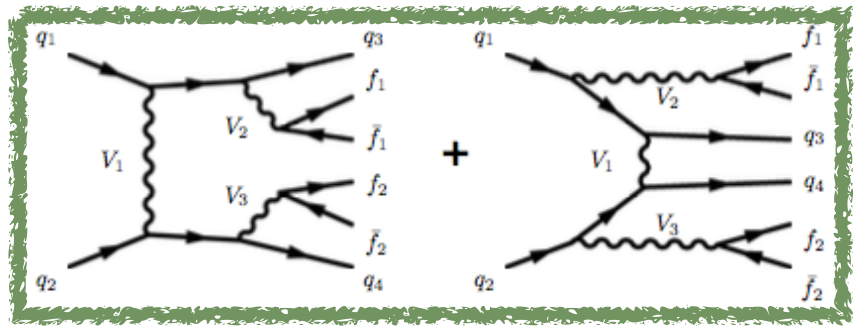

EW non-VBS (including tribosons)
$O(\alpha_{EW}^4)$

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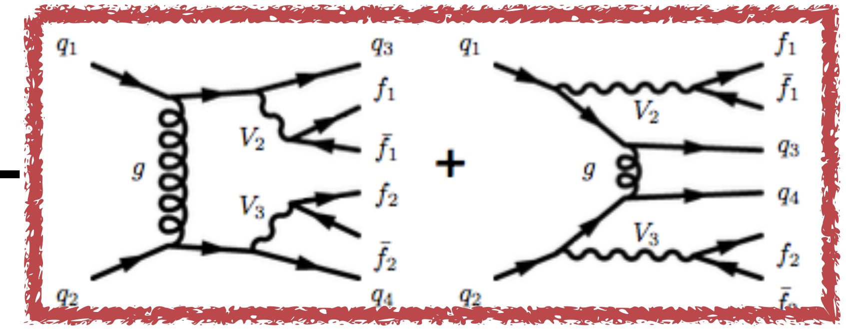
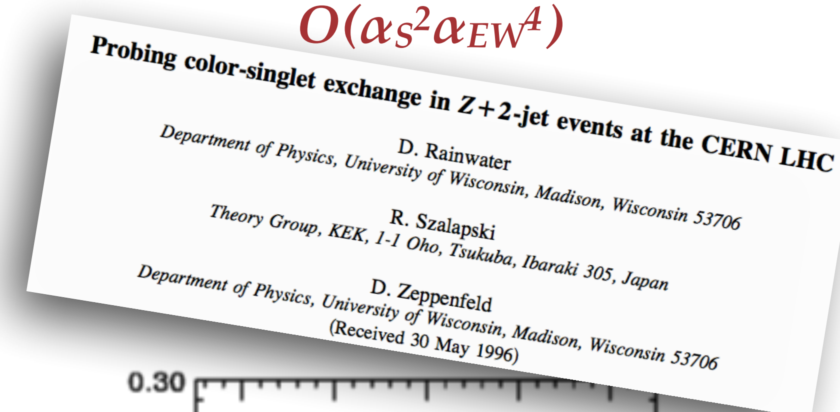
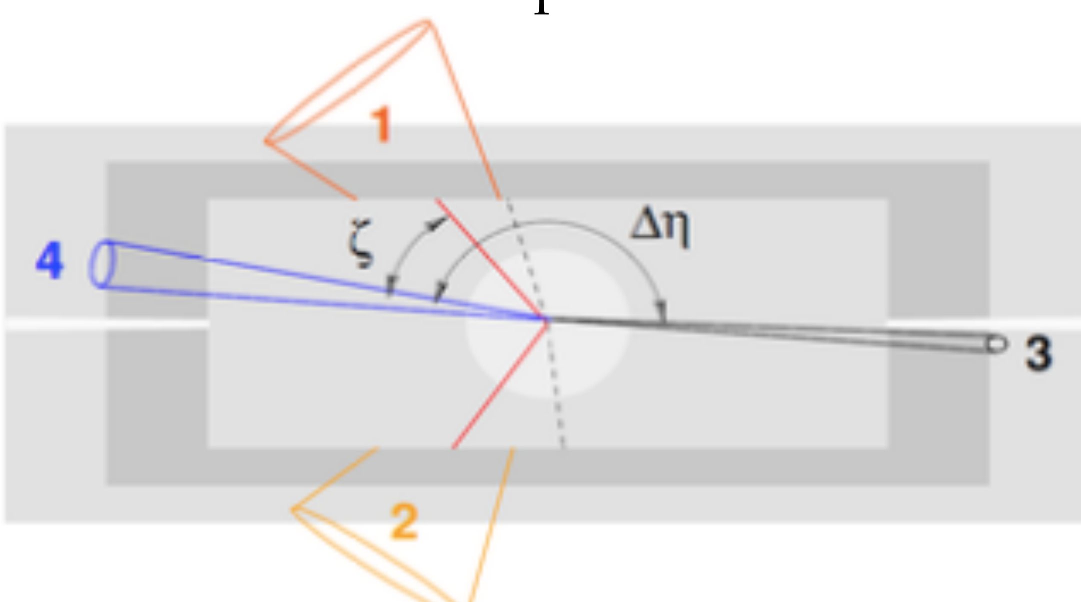


QCD-induced
Usually much larger XS than EWK
$O(\alpha_S^2\alpha_{EW}^4)$

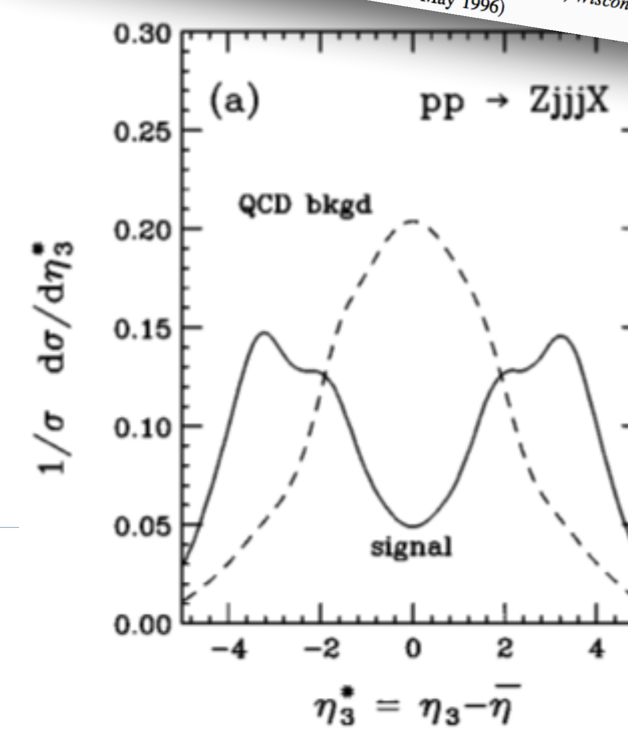

Probing color-singlet exchange in $Z+2$-jet events at the CERN LHC

D. Rainwater
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706
R. Szalapski
Theory Group, KEK, 1-1 Oho, Tsukuba, Ibaraki 305, Japan
D. Zeppenfeld
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706
(Received 30 May 1996)

- **Typical final states topology for EW VVjj**
  1. Two hadronic jets at large angles (ΔY_{jj}), high energy (m_{jj})
  2. Hadronic activity suppressed between the two jets (jet veto)
  3. Two bosons produced ~back-to-back centrally (centrality)



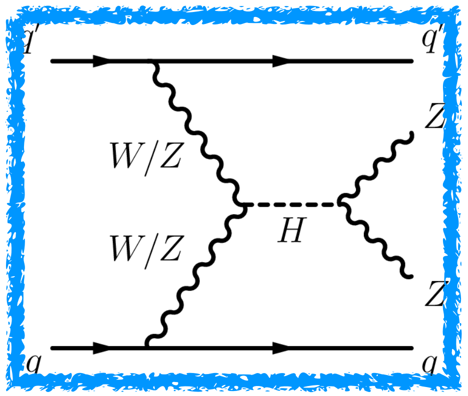
Zeppenfeld variable « centrality »

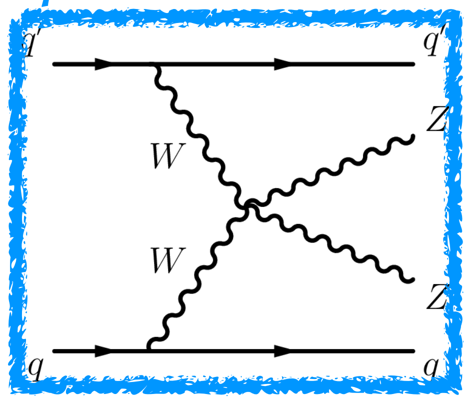


Observation of EW production of ZZjj

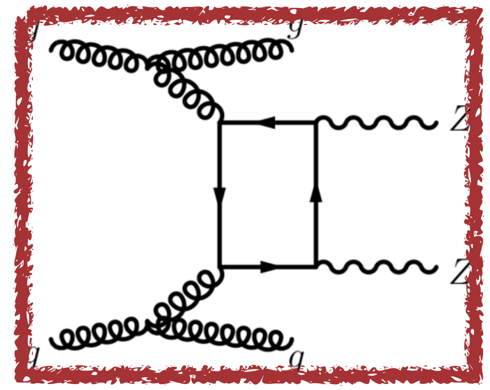
- Both 4l and 2l2v channels considered

MadGraph5

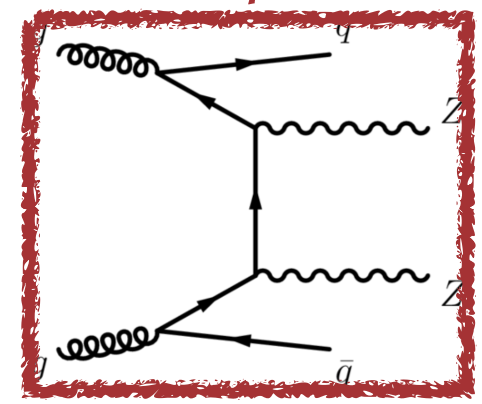




Sherpa 222 (4l) or GG2VV (2l2v)



Sherpa 222



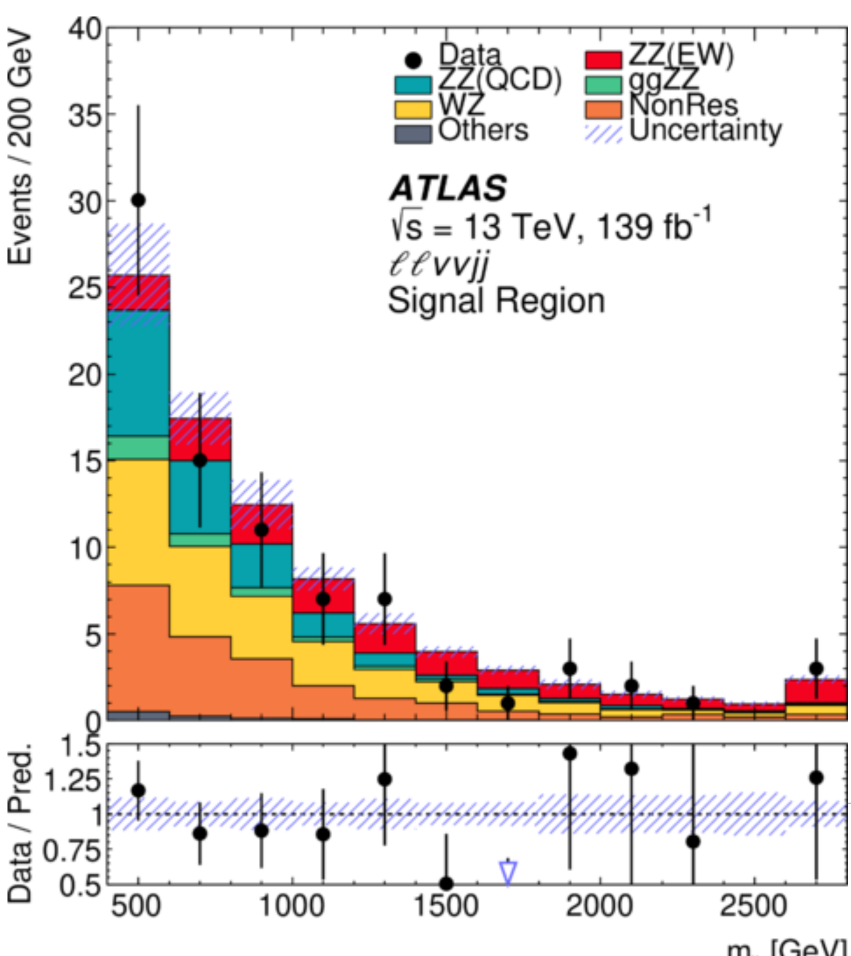
	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$ $\lvert d_0/\sigma_{d_0}\rvert < 5$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm (both channels)	
Muons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.7$	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
	$\lvert d_0/\sigma_{d_0}\rvert < 3$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm (both channels)	
Jets	$p_{\mathrm{T}} > 30$ (40) GeV for $\lvert\eta\rvert < 2.4$ ($2.4 < \lvert\eta\rvert < 4.5$)	$p_{\mathrm{T}} > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_{\mathrm{T}} > 20, 20, 10$ GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\lvert m_{\ell^+\ell^-} - m_Z\rvert + \lvert m_{\ell'^+\ell'^-} - m_Z\rvert$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_{\mathrm{T}} > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV No b-tagged jets $E_{\mathrm{T}}^{\mathrm{miss}}$-significance > 12
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ (both channels)	
	$m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

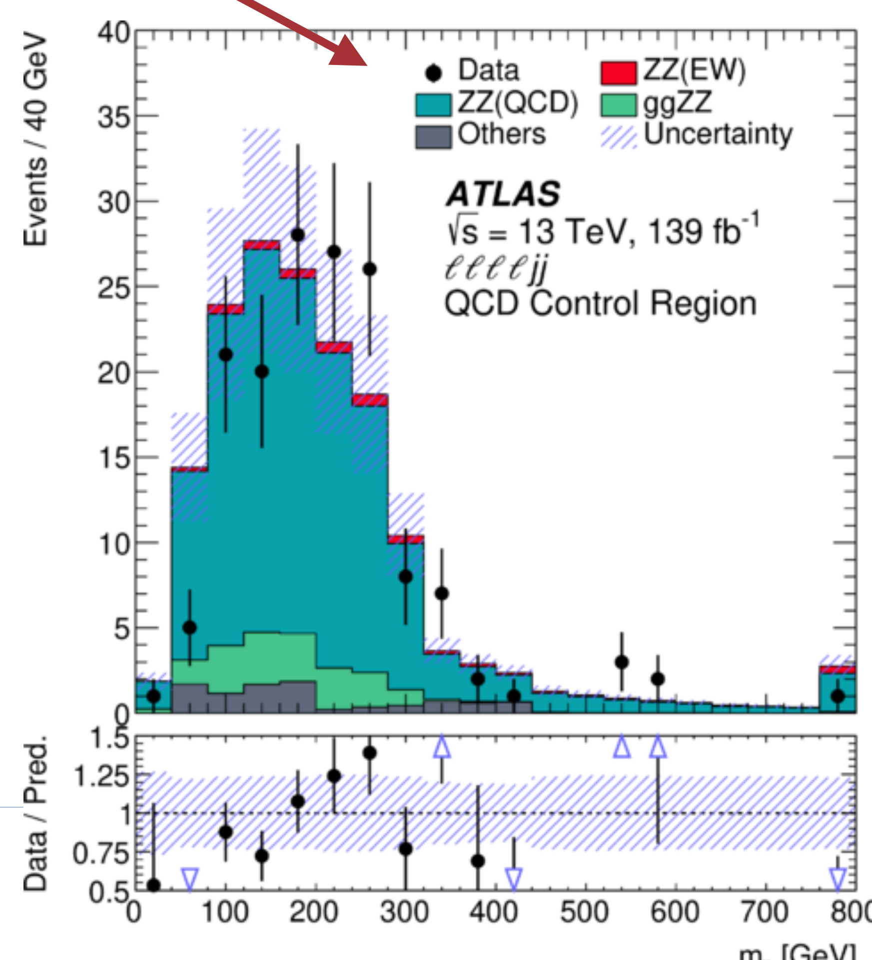
Typical VBS cuts

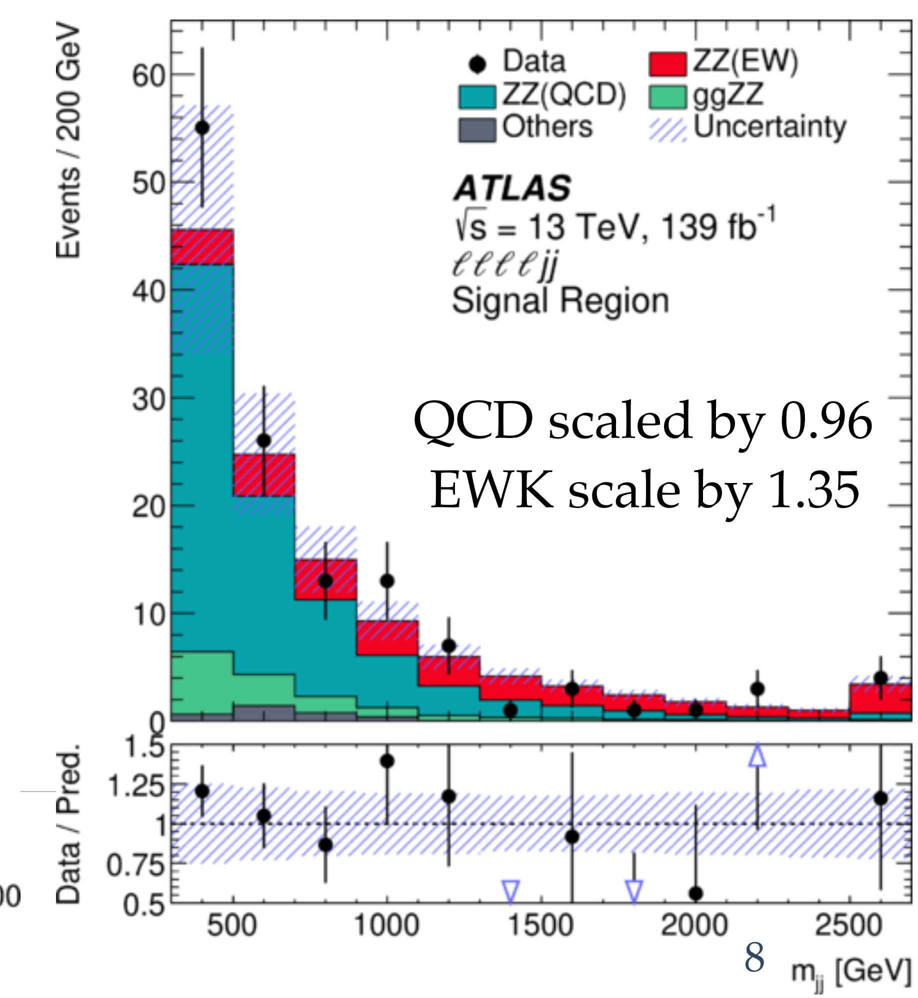
Yields

- 4l region dominated by QCD ZZjj events (~80%)
- 2l2v dominated by WW and WZ backgrounds
- 4l QCD-CR build by reversing either m_{jj} or ΔY requirement

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







Backgrounds and uncertainties

- **QCD ZZjj**
  - normalisation extracted from QCD-CR, shape validated in region with centrality>0.5

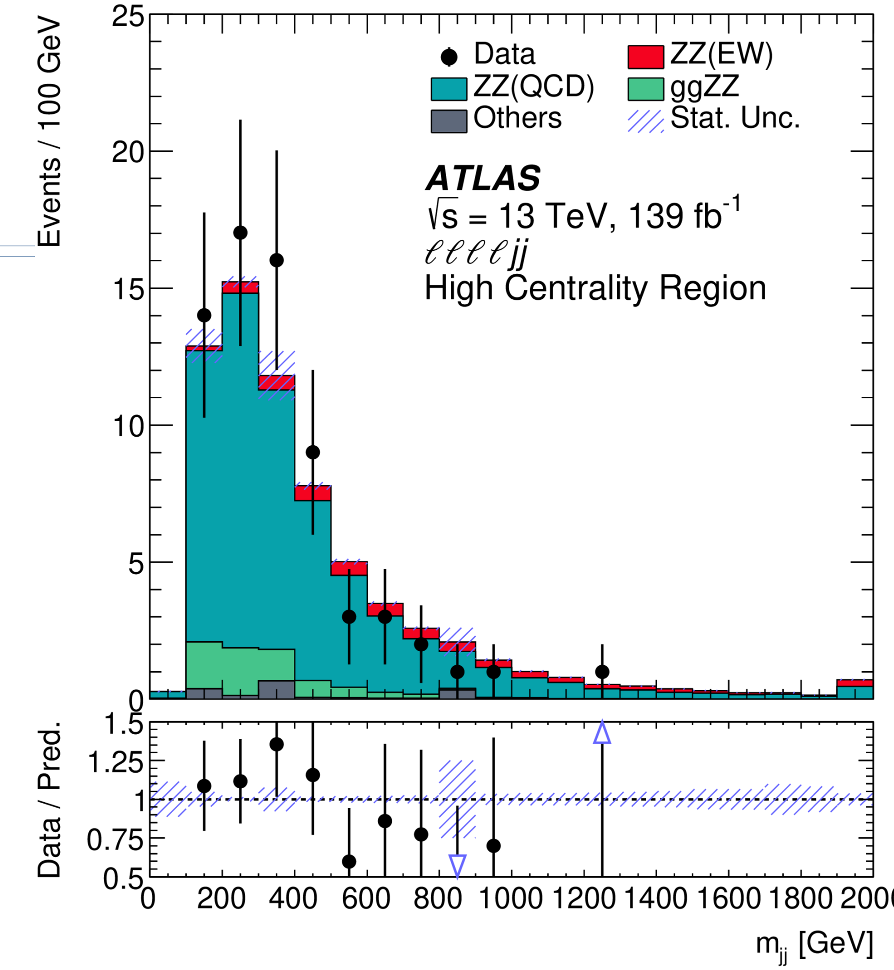
- **WZjj**
  - CR with 3leptons: simulation over-estimate by 15% data yield.

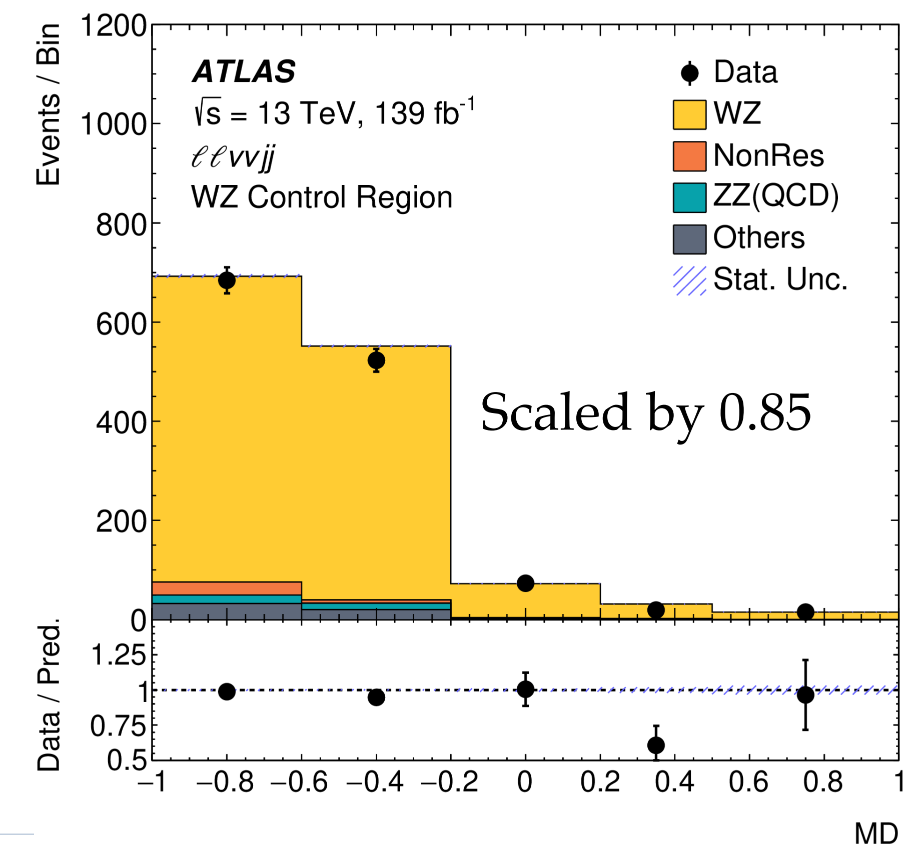
- **WWjj, ttbar (non-resonnant ll) (2l2ν):** estimated using a eμ CR

- **Others**: very small (~1%), typically from simulation

- Uncertainties:

Unc.	4l	2l2ν
Exp.	10 %	5 %
Bkg CR stat	15 %	15 %
EW theo	10 %	10 %
QCD theo	30 %	30 %





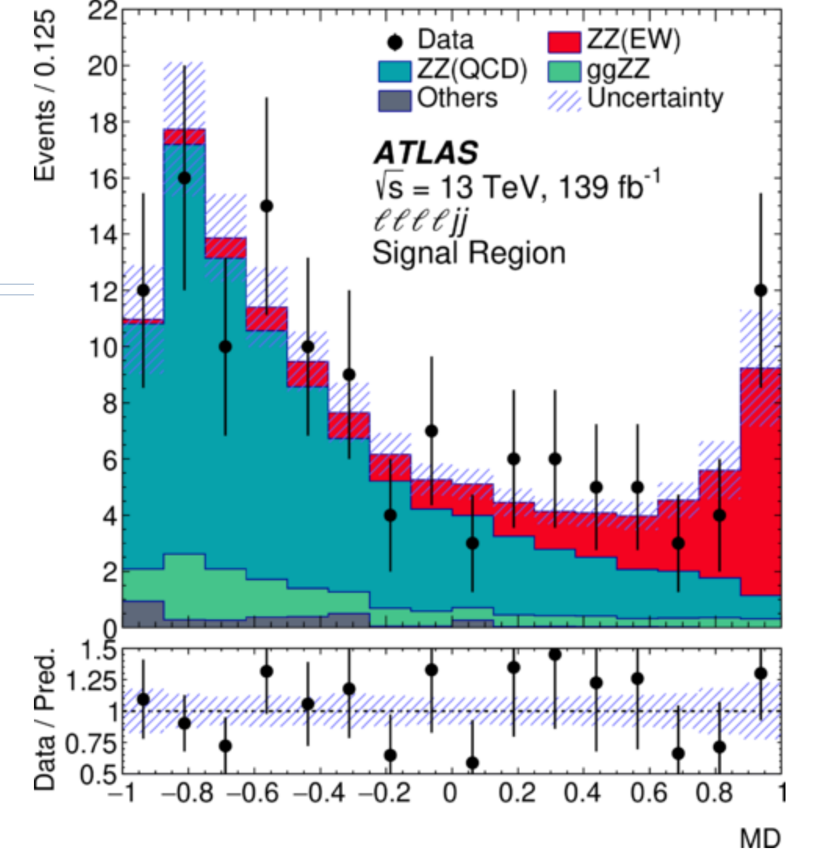
Signal extraction

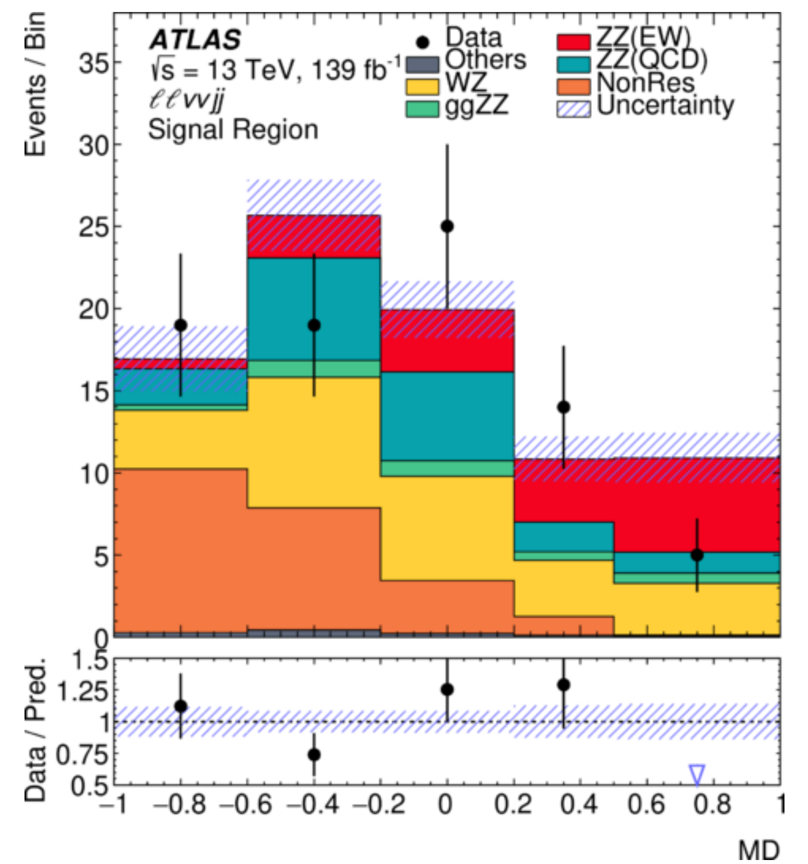
- Using a multivariate discriminant (MD) with 12 (13) jet-based and lepton based variables for 4l (2l2ν)

- Normalisation of QCD ZZjj varied simultaneously in CR and SR

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

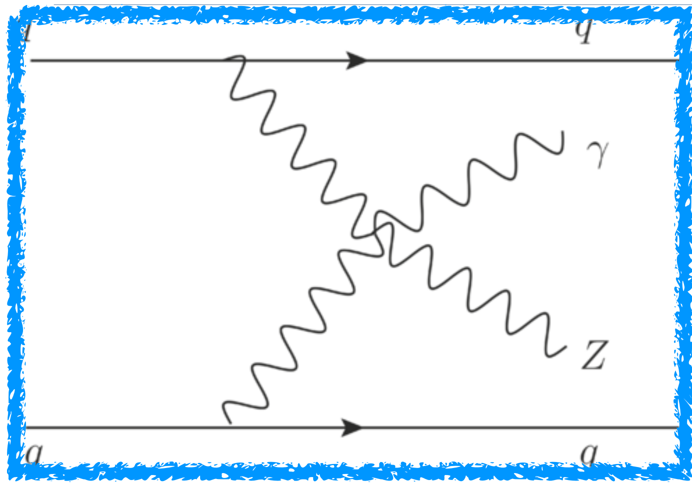
- Fiducial XS also extracted
  - exp. dominated by jet unc. for 4l and by bkg unc. for llνν

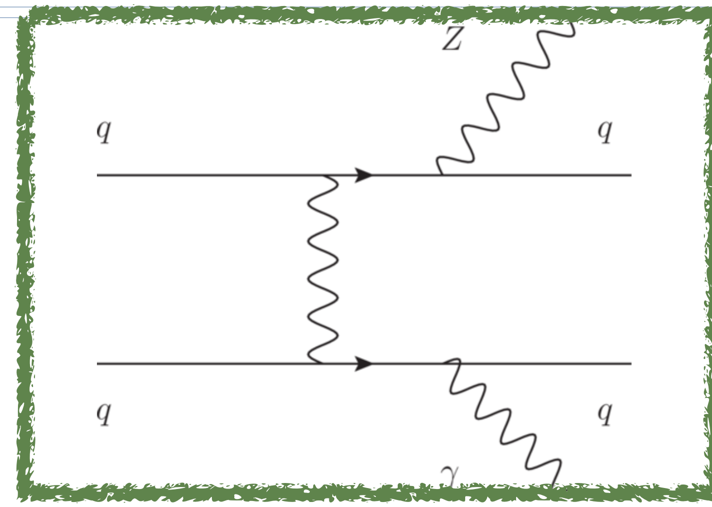




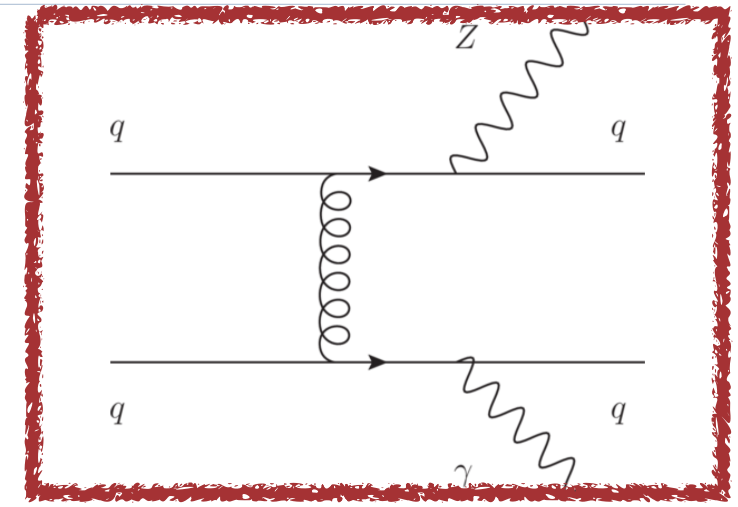
	Measured fiducial σ [fb]	Predicted fiducial σ [fb]
$\ell\ell\ell\ell jj$	$1.27 \pm 0.12(\text{stat}) \pm 0.02(\text{theo}) \pm 0.07(\text{exp}) \pm 0.01(\text{bkg}) \pm 0.03(\text{lumi})$	$1.14 \pm 0.04(\text{stat}) \pm 0.20(\text{theo})$
$\ell\ell\nu\nu jj$	$1.22 \pm 0.30(\text{stat}) \pm 0.04(\text{theo})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

Observation of EWK Z(ll)γjj



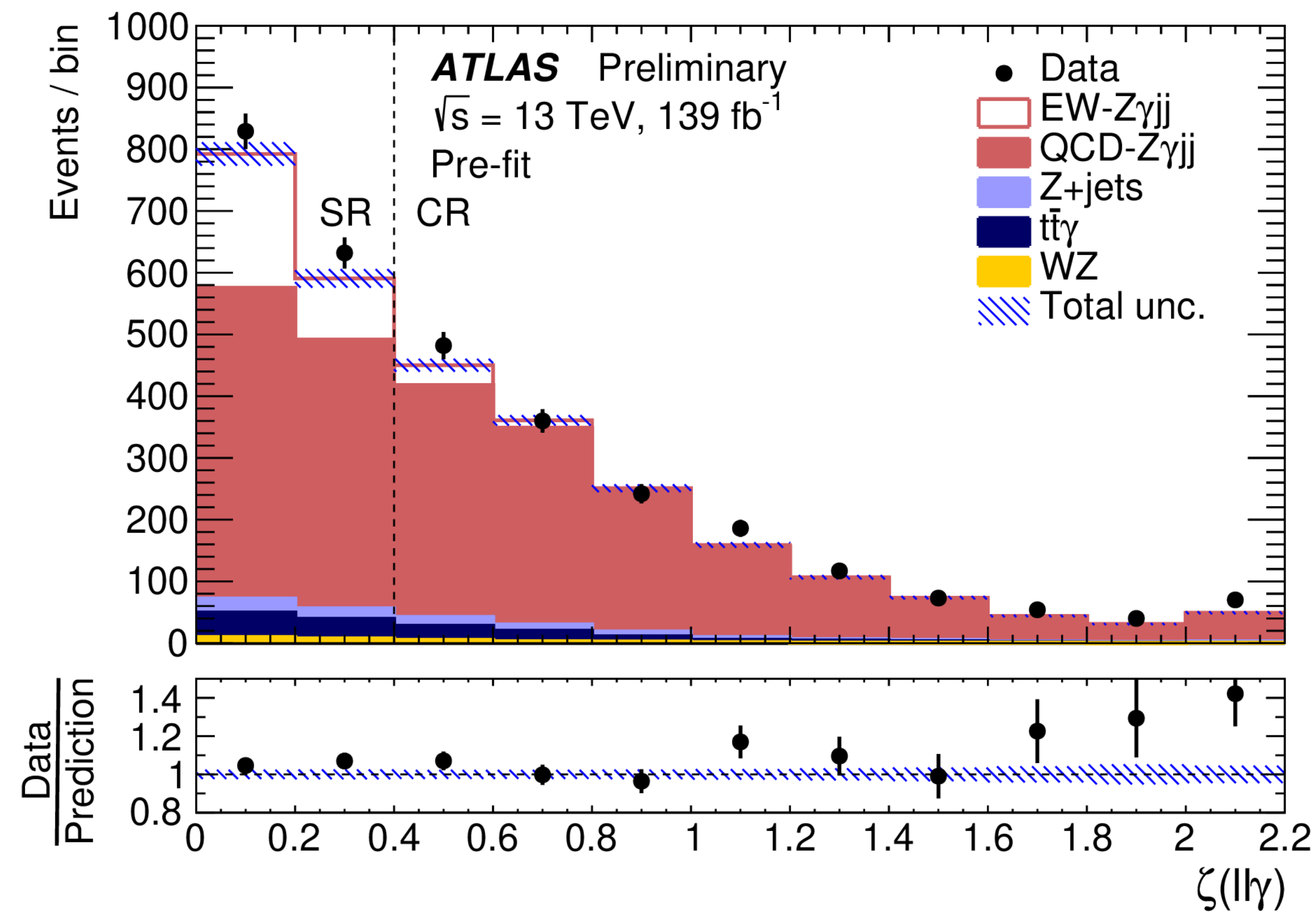


MadGraph5 EWK



MadGraph5 QCD

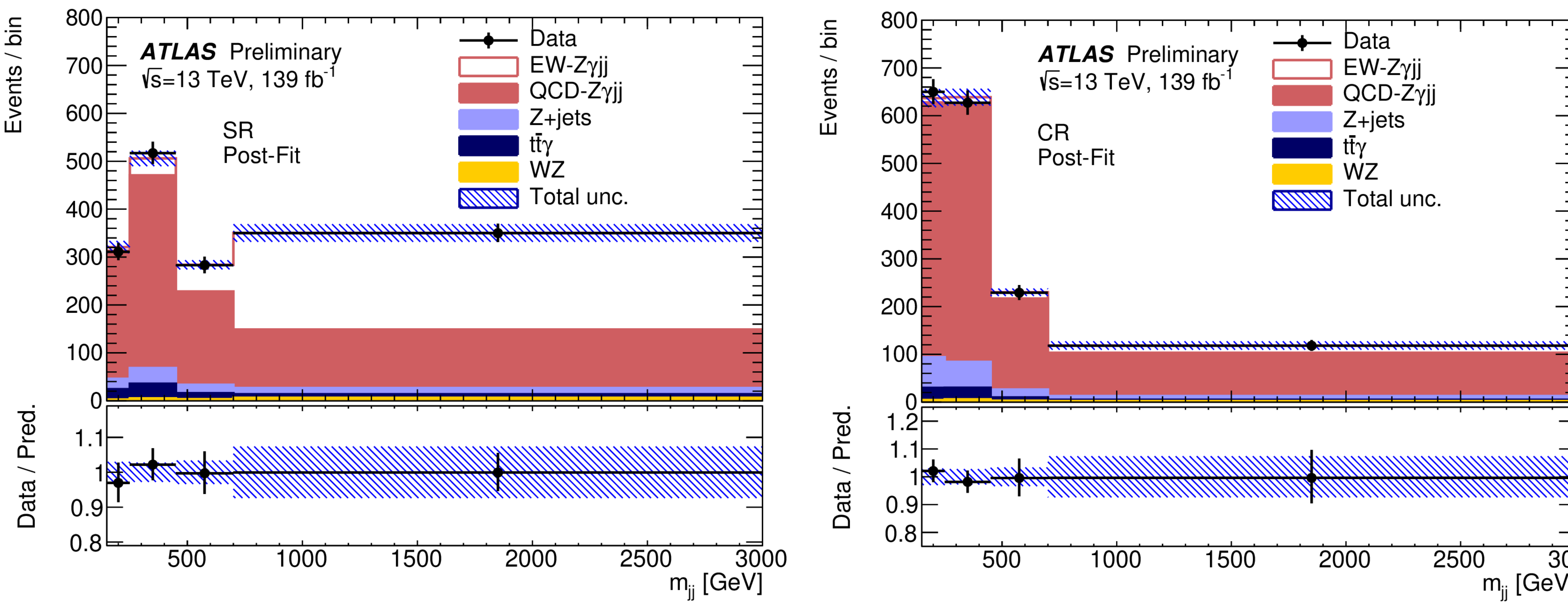
Lepton	$p_T^\ell > 20, 30\text{(leading) GeV}, \quad \lvert\eta_\ell\rvert < 2.47$ $N_\ell \geq 2$
Photon	$E_T^\gamma > 25\ \text{GeV}, \quad \lvert\eta_\gamma\rvert < 2.37$ $E_T^{cone20} < 0.07 E_T^\gamma$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_T^{jet} > 50\ \text{GeV}, \quad \lvert y_{jet}\rvert < 4.4$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



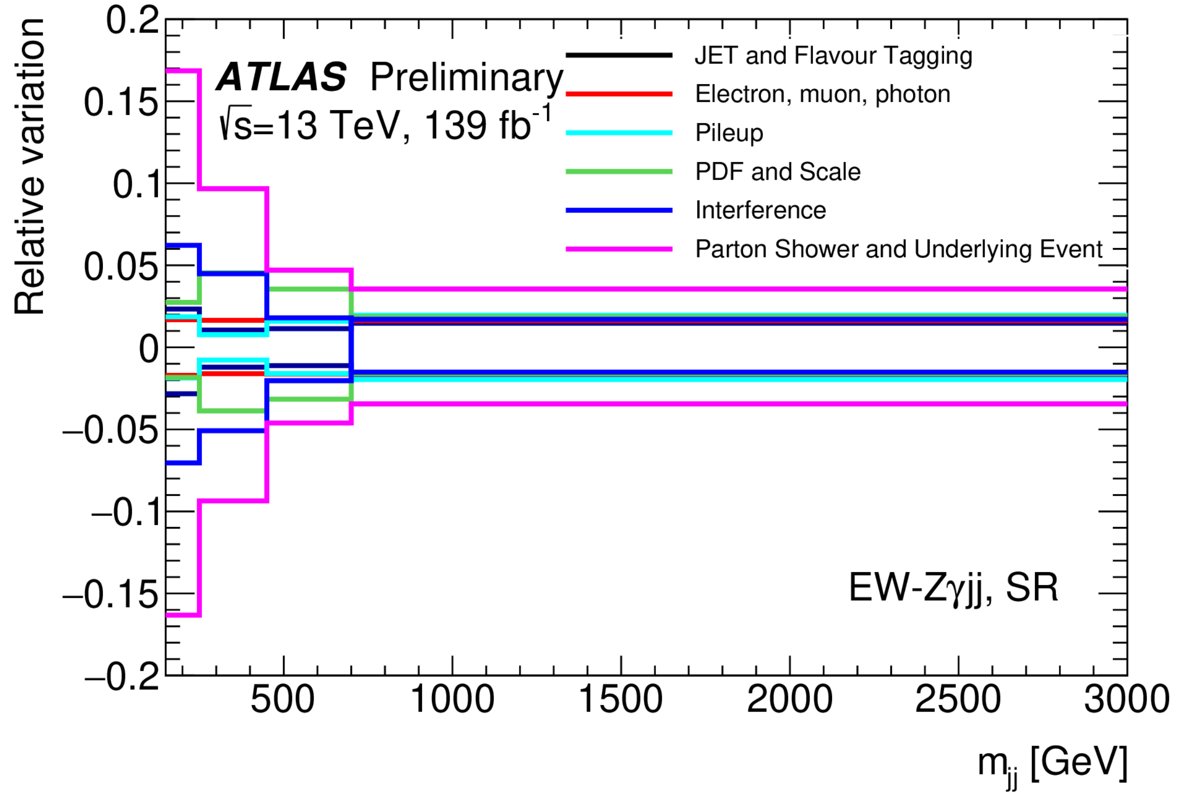
Yields

Sample	SR	CR
$N_{EW-Z\gamma jj}$	300 ± 36	55 ± 7
$N_{QCD-Z\gamma jj}$	987 ± 55	1352 ± 60
$N_{t\bar{t}\gamma}$	72 ± 11	59 ± 9
N_{WZ}	17 ± 3	14 ± 3
N_{Z+jets}	85 ± 30	143 ± 43
Total	1461 ± 38	1624 ± 40

- CR used to validate **QCD Zγjj** mjj shape, normalisation from fit
- **Z+jet** from DD method (ID, Iso)
- **ttbarγ** validated in eμγ CR -> k-factor of 1.44 adopted
- **WZ** from simulation (Sherpa 2.2.4 / MadGraph5)



Results



- **Observation of signal with 10σ (11σ expected)**

$$\mu_{EW} = 0.95^{+0.14}_{-0.13}$$
$$= 0.95 \pm 0.08\ (\text{stat}) \pm 0.11\ (\text{syst}).$$

- **EW Zgjj cross-section:**

$$\sigma_{EW} = 4.49 \pm 0.40\ (\text{stat.}) \pm 0.42\ (\text{syst.})\ \text{fb}$$
$$\sigma^{pred}_{EW} = 4.73 \pm 0.01\ (\text{stat.}) \pm 0.15\ (\text{PDF})^{+0.23}_{-0.22}\ (\text{scale})\ \text{fb}.$$

- **EW+QCD Zgjj cross-section:**

$$\sigma_{EW+QCD} = 20.6 \pm 0.6\ (\text{stat.})^{+1.2}_{-1.0}\ (\text{syst.})\ \text{fb},$$
$$\sigma^{pred}_{EW+QCD} = 20.4 \pm 0.1\ (\text{stat.}) \pm 0.2\ (\text{PDF})^{+2.6}_{-2.0}\ (\text{scale})\ \text{fb}.$$

Most precise measurement with 13% precision

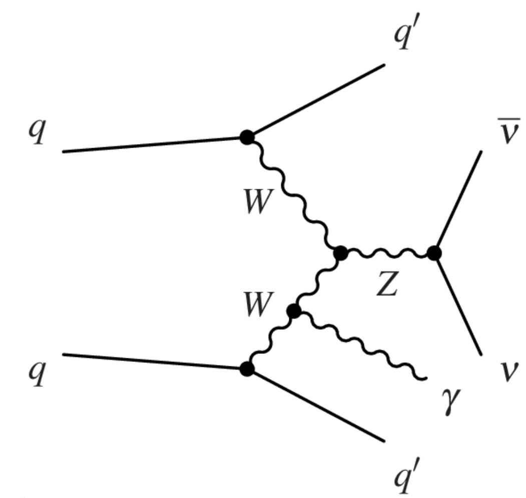
- **Theory unc. dominate, followed by jet unc.**

	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	± 9	± 1	± 1	± 5	$^{+6}_{-5}$	$^{+5}_{-4}$	± 13

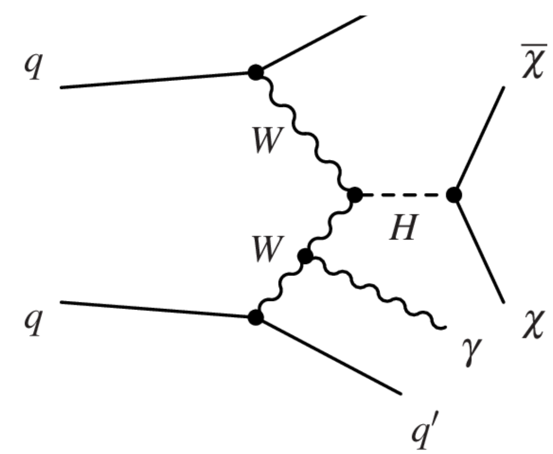
arXiv:2109.00925v1

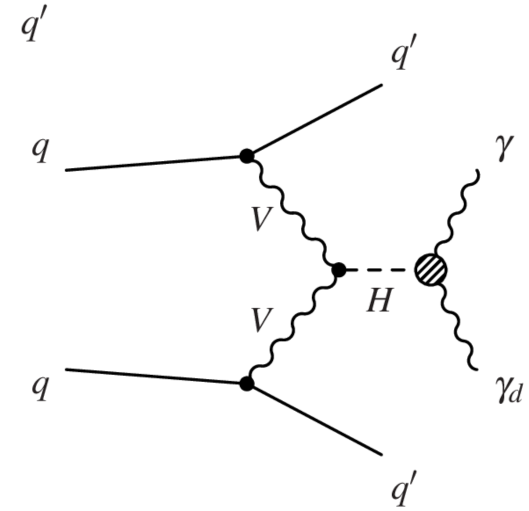
Observation of EWK Z(νν)γ jj

- **Studied as main background of BSM search for MET+photon+2 jets**
  - Targeting invisible Higgs decay and Higgs decay to a pair dark photon + photon
- **Fiducial volume of EWK Z(νν)γ jj measurement:**



Observable	Requirements
N_{jet} with $p_{\text{T}} > 25$ GeV	≥ 2
$\lvert\eta(j_{1,2})\rvert$	< 4.5
$p_{\text{T}}(j_1)$ [GeV]	> 60
$p_{\text{T}}(j_2)$ [GeV]	> 50
$\Delta R(j,\ell)$	> 0.4
$\lvert\Delta\eta_{\text{jj}}\rvert$	> 3.0
C_3	< 0.7
m_{jj} [TeV]	> 0.5
truth-$E_{\text{T}}^{\text{miss}}$ [GeV]	> 150
$\Delta\phi(\text{truth-}\vec{E}_{\text{T}}^{\text{miss}}, j_i)$	> 1.0
$p_{\text{T}}(\gamma)$ [GeV]	$> 15, < 110$
$\lvert\eta(\gamma)\rvert$	< 2.37
$E_{\text{T}}^{\text{cone20}}/E_{\text{T}}^{\gamma}$	< 0.07
$\Delta R(\gamma, \text{jet-or-}\ell)$	> 0.4
C_γ	> 0.4
$\Delta\phi(\text{truth-}\vec{E}_{\text{T}}^{\text{miss}}, \gamma)$	> 1.8
N_ℓ with $p_{\text{T}} > 4$ GeV and $\lvert\eta\rvert < 2.47$	0





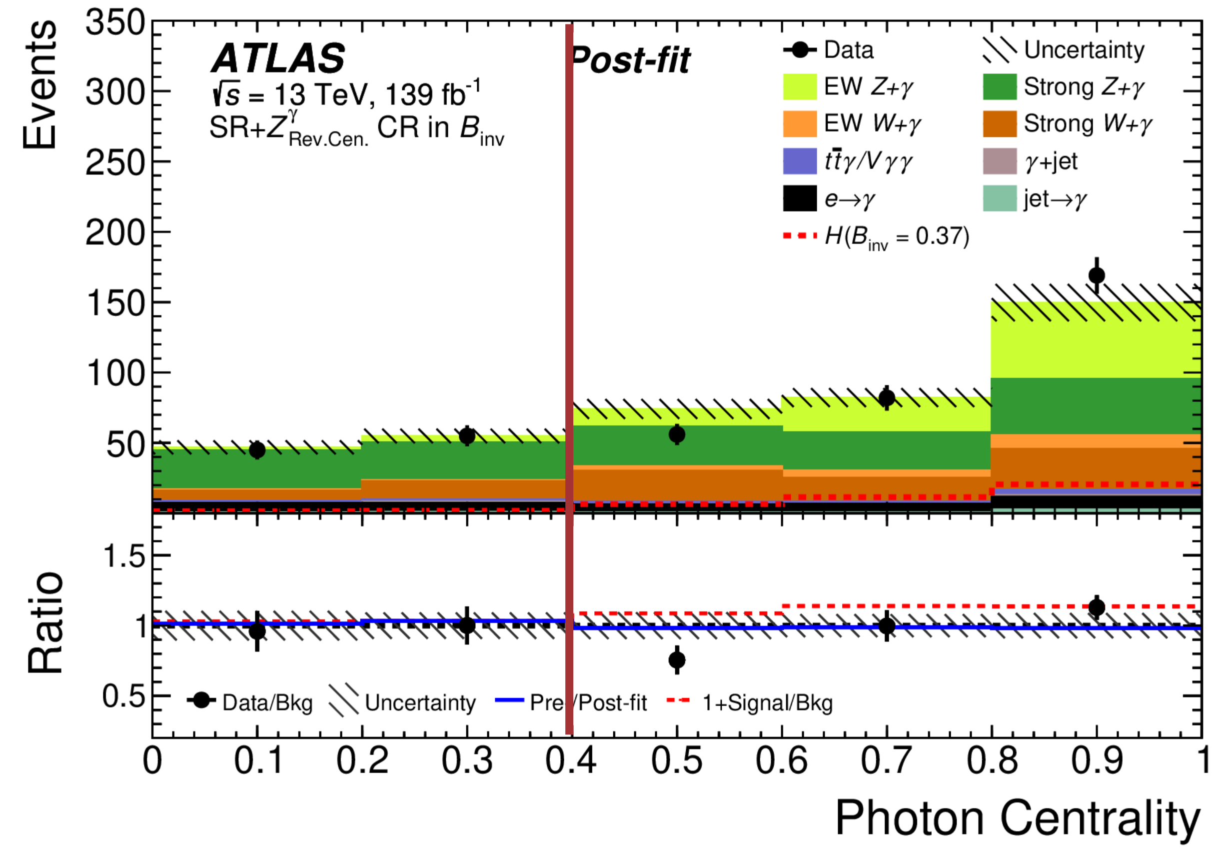
$$C_\gamma = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_\gamma - \frac{\eta_1+\eta_2}{2}\right)^2\right]$$

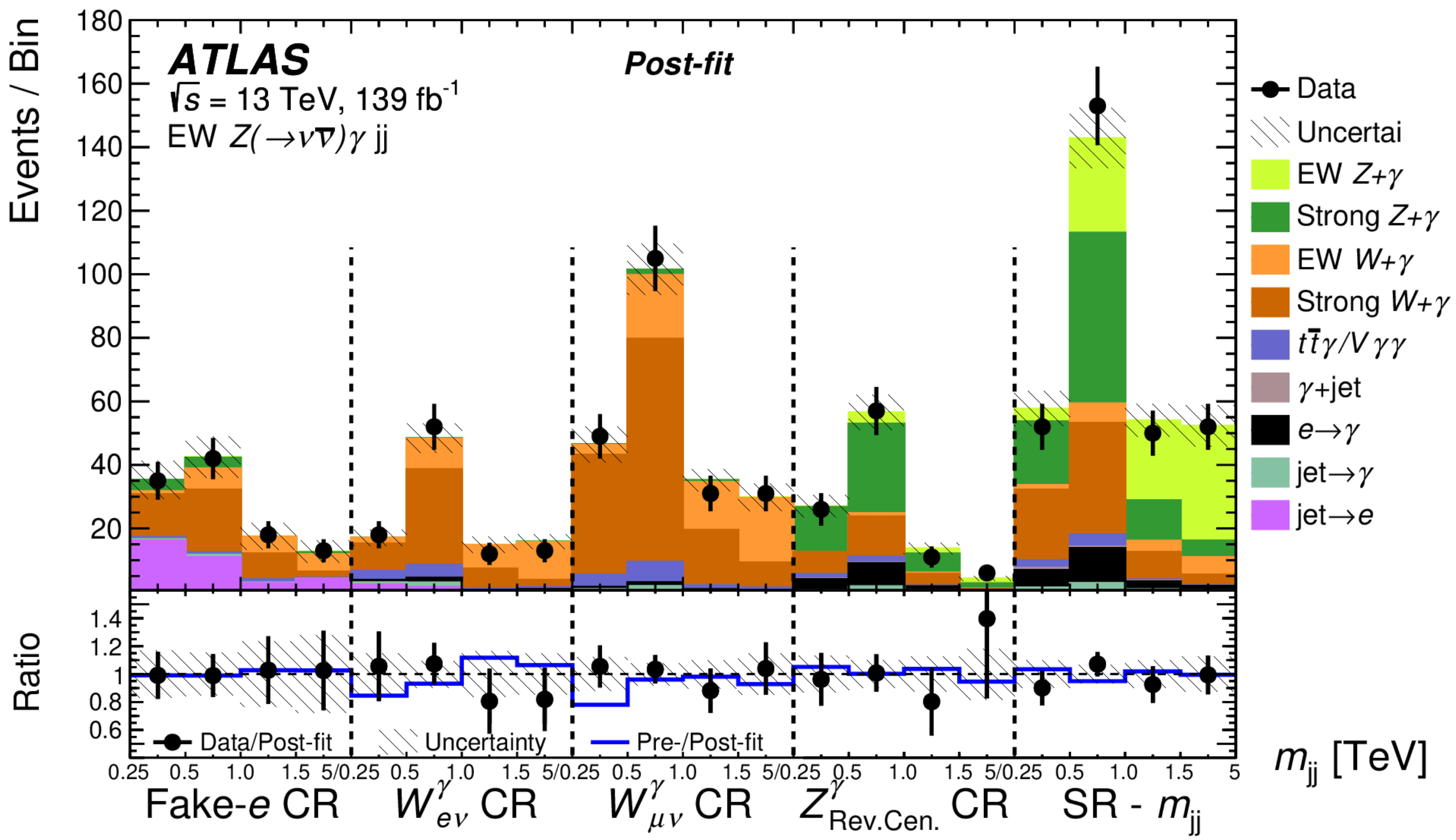
=1 for central photon

=0 for more forward photon than jets

Fit and Results

- Use mjj to discriminate EWK Z(νν)γ jj from QCD background
- CRs defined to control main backgrounds: Wγjj (by changing zero-lepton requirement) and QCD Z(νν)γ (reversing centrality cut)





- Signal observed with 5.2 σ (5.1 σ expected)
- Cross sections:

$$\sigma^{\text{fid.}}_{Z(\to\nu\nu)\gamma\text{EW}} = 1.31 \pm 0.20(\text{stat}) \pm 0.20(\text{syst})\ \text{fb},$$

$$\sigma^{\text{fid.}\,\text{MadGraph}}_{Z(\to\nu\nu)\gamma\text{EW}} = 1.27 \pm 0.17\ \text{fb}.$$

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

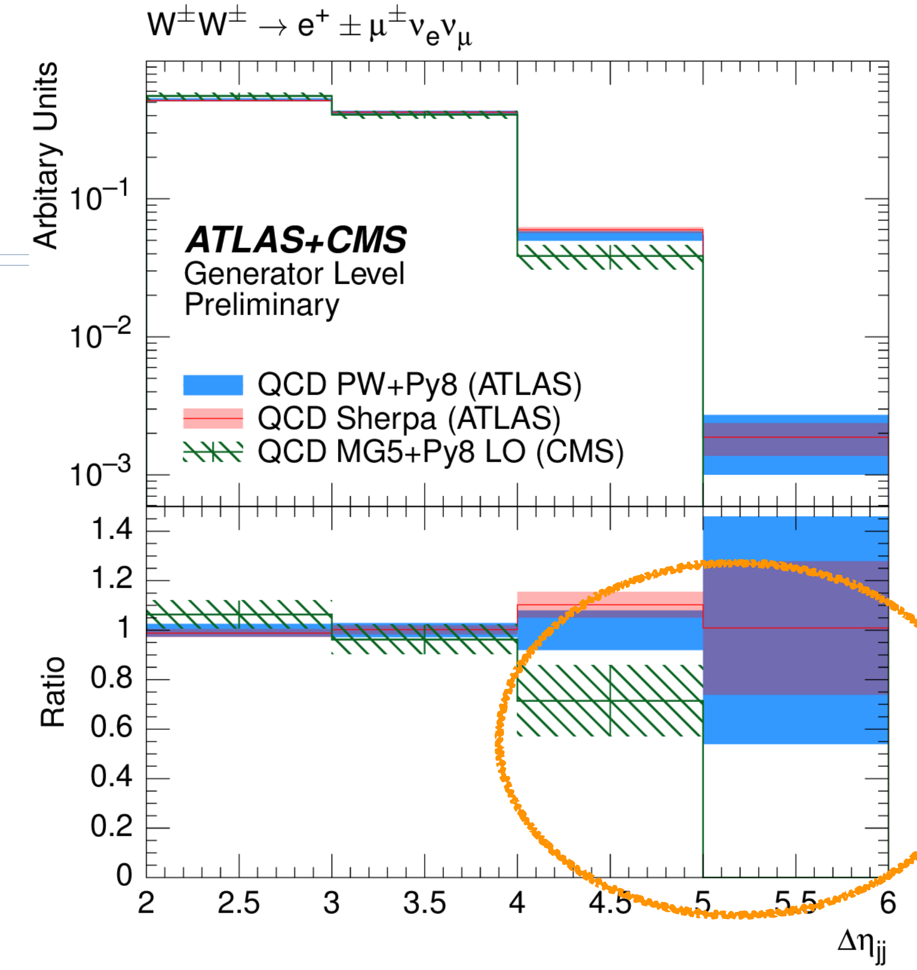
Comparison of ATLAS and CMS VBS MCs

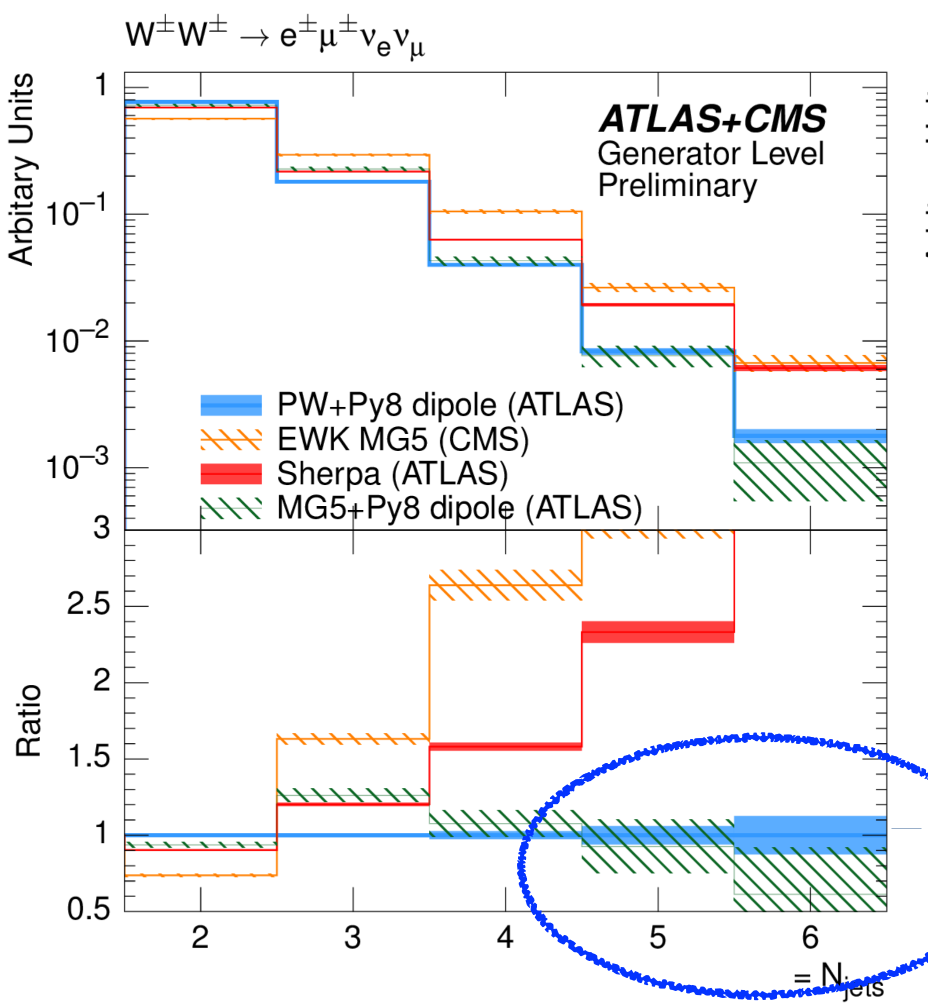
- Ability to use VBS to constrain BSM models depends on reliable theoretical predictions with well understood systematic uncertainties
- Comparison of several MCs from ATLAS, CMS and VBScan COST (particle level)

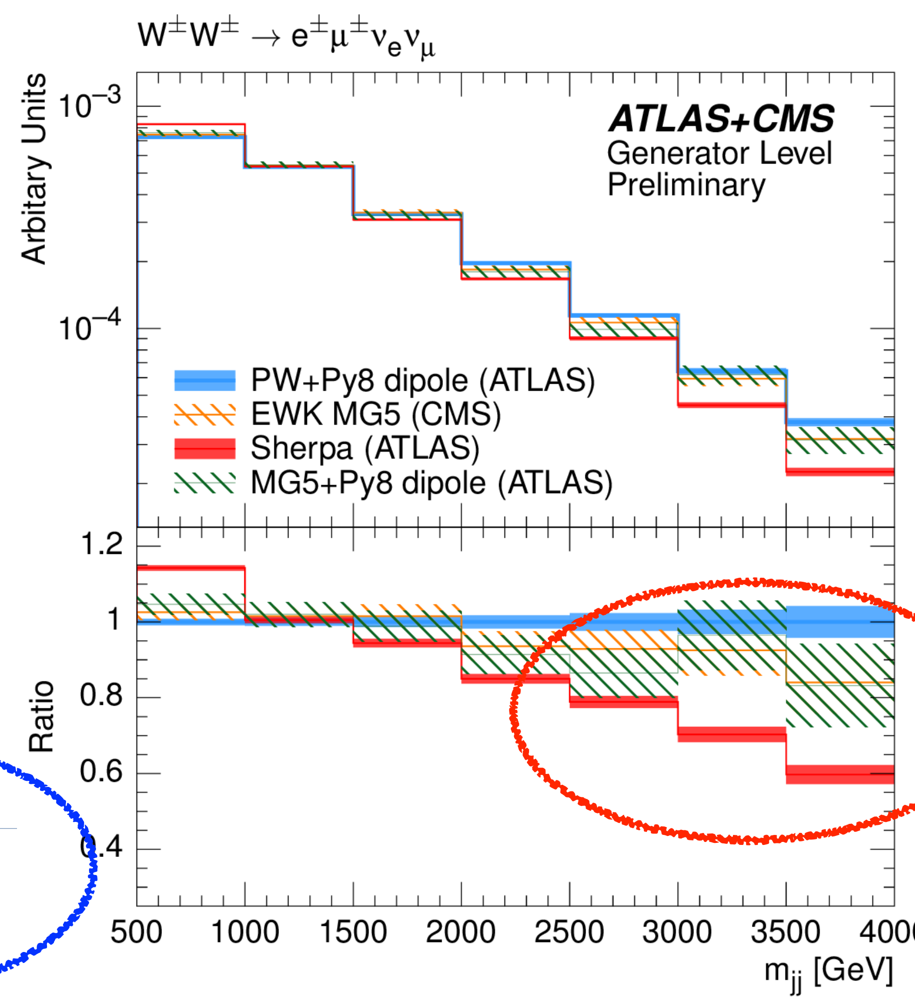
Sample name	Generator	μ-scale	Shower	Tune	PDF	further settings
Sherpa (ATLAS)	SHERPA v2.2.2 *Bug in colour flow*	dynamic scale, m_{WW}	internal	internal	NNPDF3.0-NNLO	multileg-LO, exactly six EW vertices with one additional parton at LO accuracy in QCD
PW+Py8 (ATLAS)	POWHEG v2, VBS approx.	fixed scale, m_W	PYTHIA 8.212	AZNLO	NNPDF3.0-NLO	NLO
PW+Py8 dipole-recoil (ATLAS)	POWHEG v2	fixed scale, m_W	PYTHIA 8.235	AZNLO	NNPDF3.0-NLO	Dipole Recoil [6]
MG5+Py8 dipole-recoil (ATLAS)	MG5_AMCNLO v2.6.2	dynamic scale, $\sqrt{p_T^{\text{jet1}} p_T^{\text{jet1}}}$	PYTHIA 8.235	A14	NNPDF3.0-NLO	LO, Dipole Recoil [6]
MG5+Py8 (CMS)	MG5_AMCNLO v2.3.3	dynamic scale, using a 2→2 topology from the clustered external state	PYTHIA 8.212	CUETP8M1 [7]	NNPDF3.0-LO	LO, exactly six EW vertices
PW+Py8 (VBScan)	POWHEG v2	dynamic scale, $\sqrt{p_T^{\text{jet1}} p_T^{\text{jet2}}}$	PYTHIA 8.230	Monash	NNPDF3.0-NLO	NLO

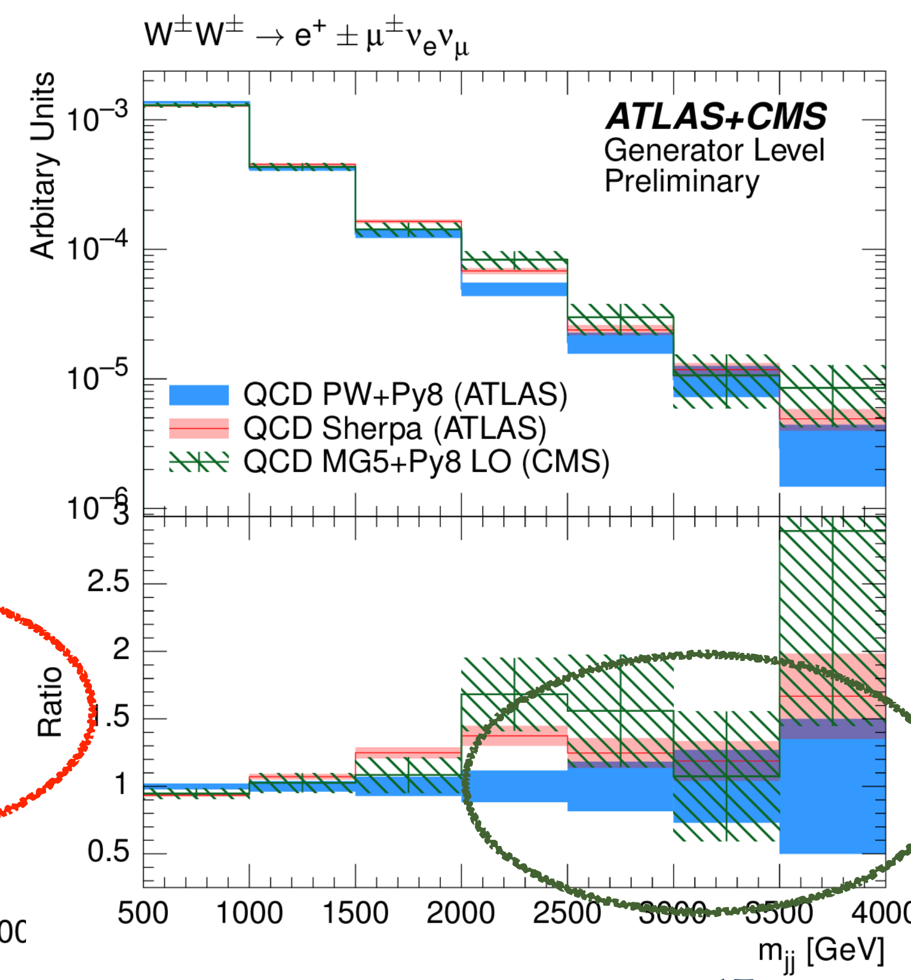
Comparisons

- **EWK samples**
  - Samples with new dipole-recoil scheme have **significantly smaller jet multiplicity**
  - The ***mjj* and $\Delta\eta jj$ distribution are softer for Sherpa** (ATLAS) sample
- **QCD samples:**
  - **mjj much softer for the QCD PW+Py8** (ATLAS) samples
  - **$\Delta\eta_{jj}$ much more central for the QCD MG5+Py8** (CMS) sample





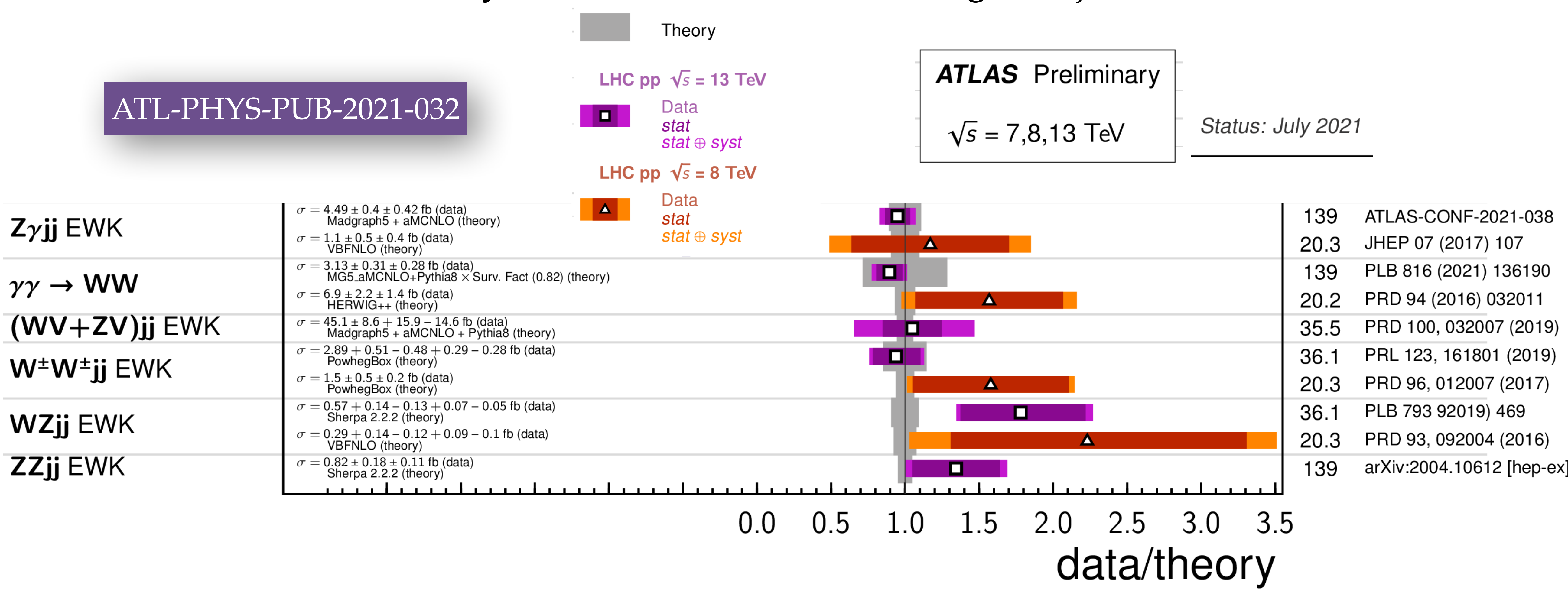




Summary

- Most of the VBS channels now observed by ATLAS using 13 TeV data
- Precision greatly improved using these data compared to 8 TeV data
- Results in agreement with SM prediction
- Some of the channels start to be sensitive to uncertainties other than statistical ones
  - Main limitations : **theory uncertainties (MC modelling)** and jet uncertainties

ATL-PHYS-PUB-2021-032



Additional infos

VBS WZ

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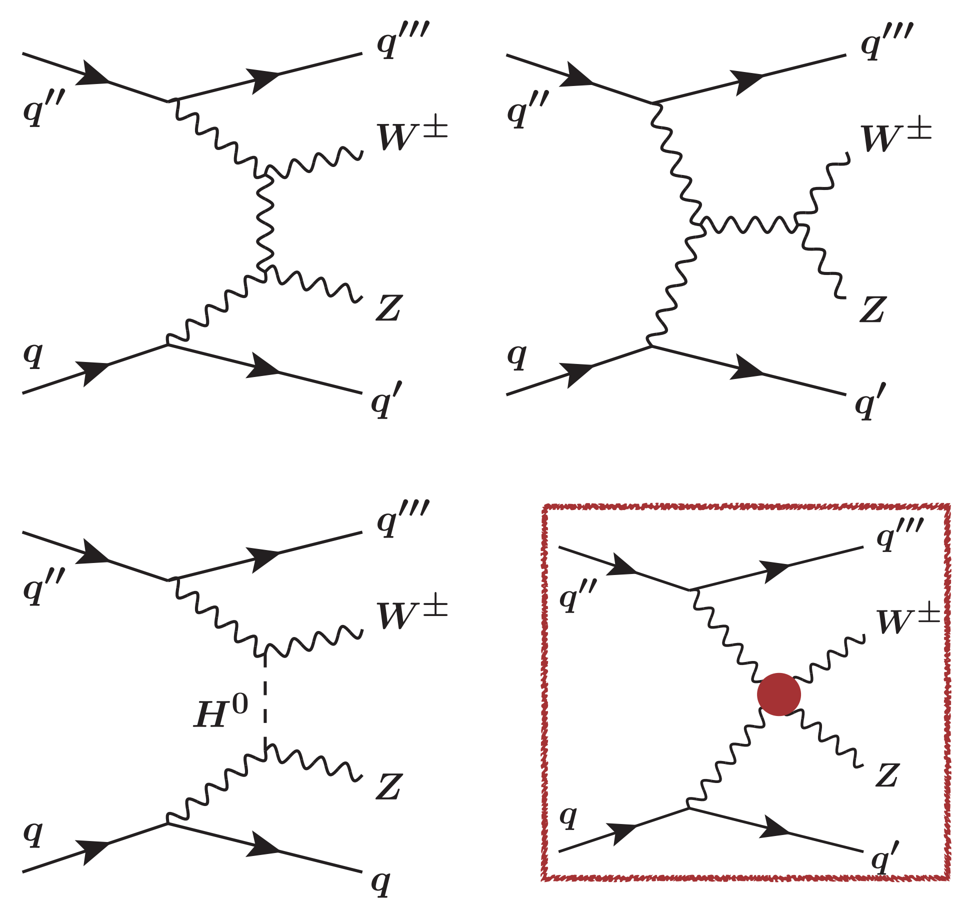
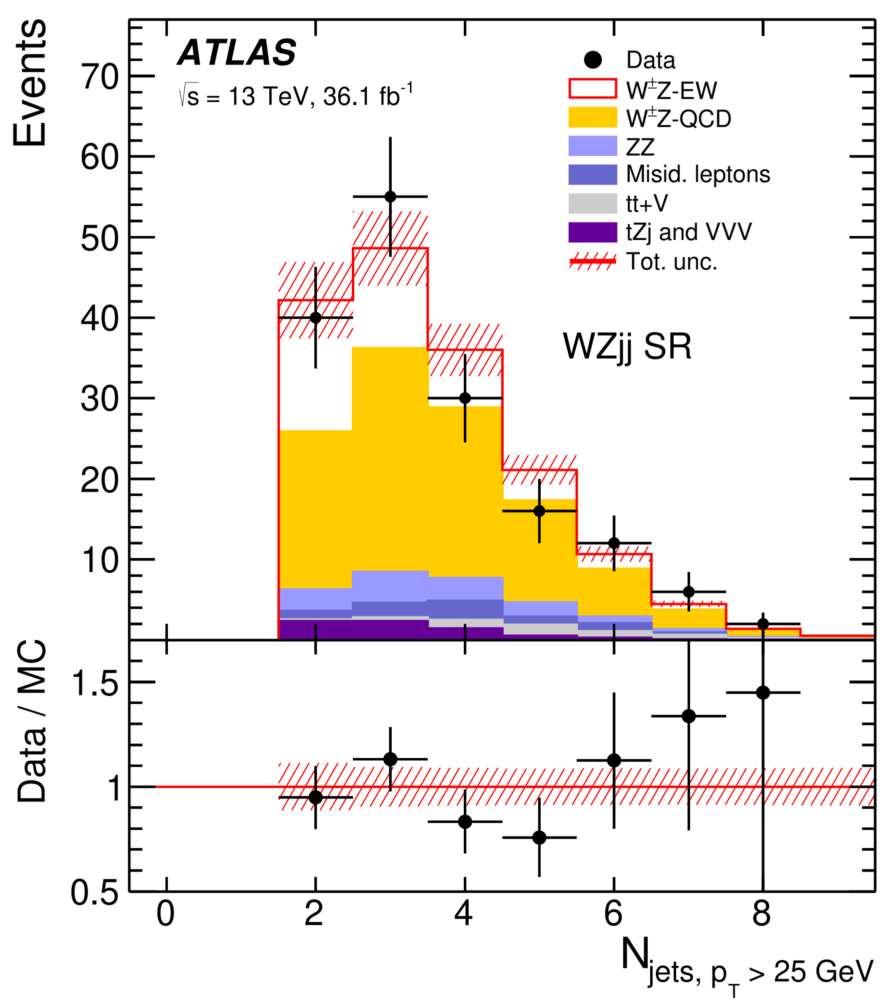
Observation of EW WZ(lllν) + 2 j

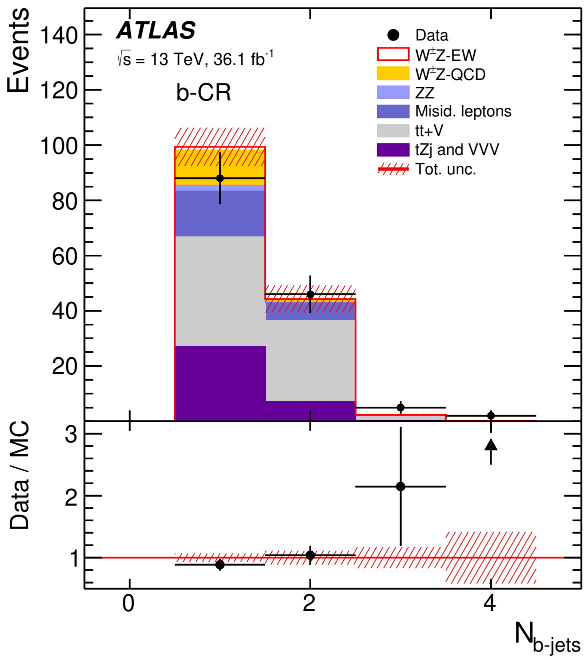
- **Selection:**
  - **3 leptons (e/μ) with $p_T > 15$ GeV and $|\eta| < 2.5$**
    - at least one with 25(27) p_T threshold in 2015(2016) data
  - **Z selection**: $|M_{ll} - M_Z^{PDG}| < 10$GeV
  - **W selection**: $p_T > 20$GeV + tighter quality cuts, $m_T(W) > 30$ GeV
  - **Jets:** 2 jets with $p_T > 40$ GeV, $|\eta| < 4.5$, η of opposite sign, $m_{jj} > 150$ GeV





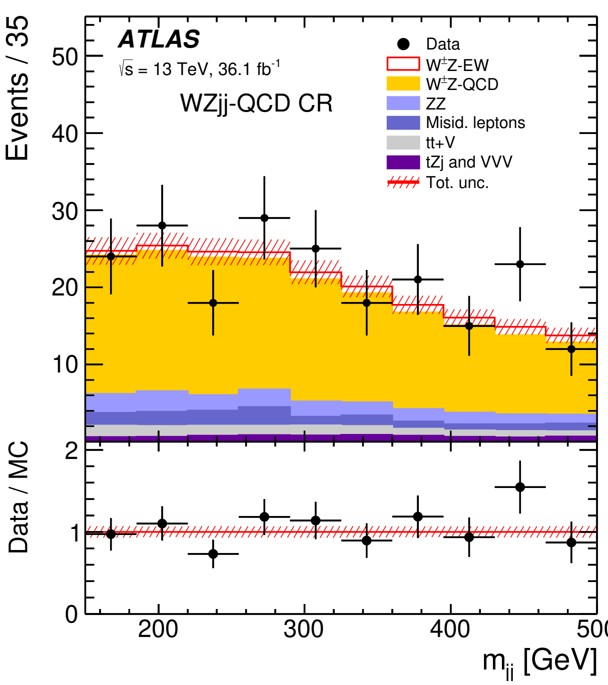
- **Signal and backgrounds:**
  - **EW WZjj** (Sherpa 2.2.2)
  - **QCD WZjj**: **main background**, MC (Sherpa 222) normalised in CR
  - **Misidentified leptons (Z+jets, Zγ, (tt)‾, Wt,WW):** data-driven
  - **ZZ QCD+EW**: MC (Sherpa 222), normalised in CR
  - ttV: MC (MadGraph5), normalised in CR
  - **tZ, VVV**: MC (MadGraph5, Sherpa 2.1)

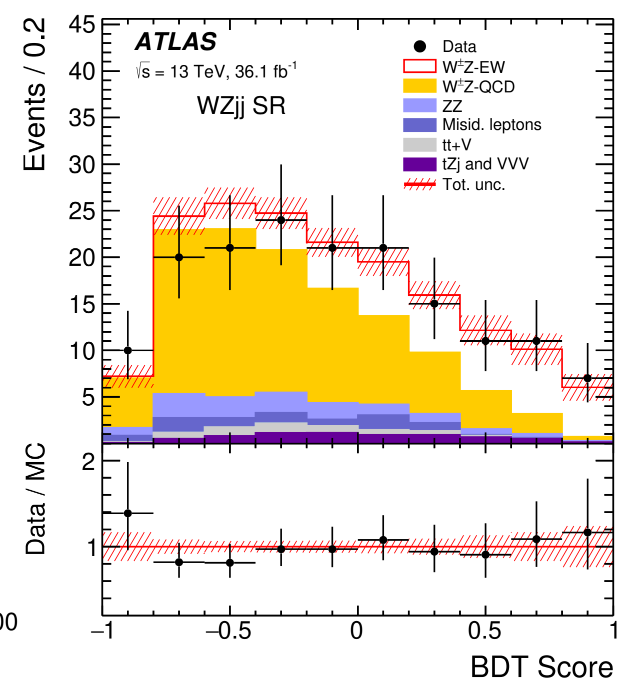
Analysis strategy

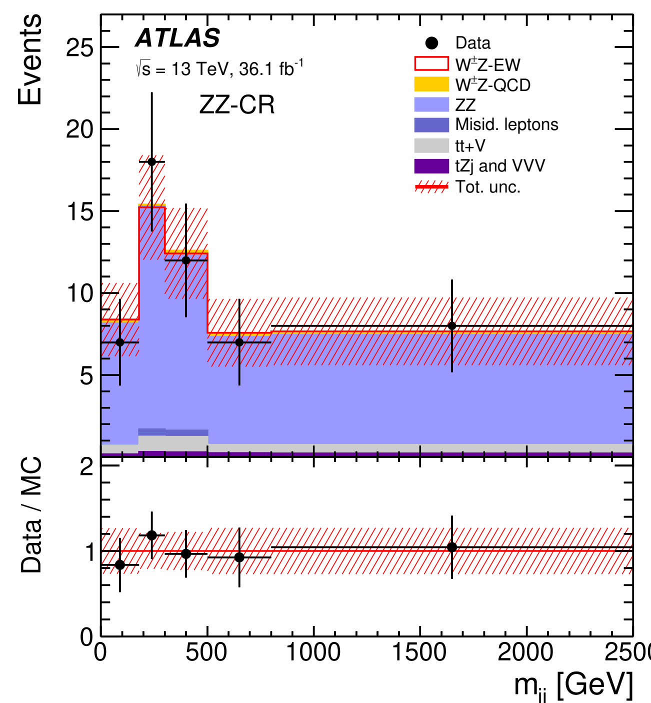


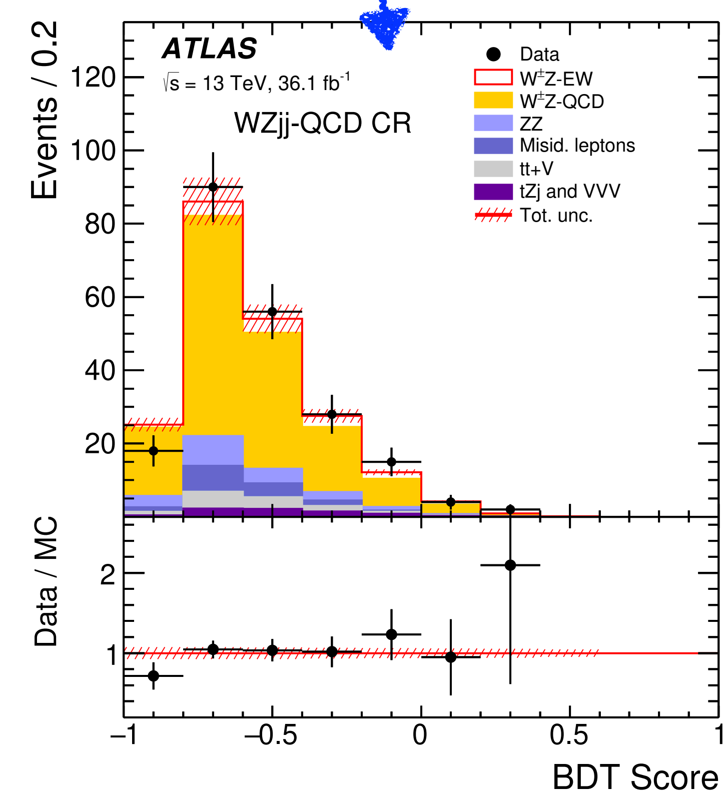
b-control region:
N_{bjet}**>0**
To normalise ttbarV

- **3 orthogonal regions + 1 ZZ CR**
- **BDT discriminant used in signal region to extract XS (15 variables)**
  - Description of BDT score controlled in QCD-CR
- **Combined fit on the SR + 3CRs** to extract simultaneously the background and signal normalisations









QCD control region:
$\mathbf{m_{jj}}$**<500 GeV,** $\mathbf{N_{bjet}}$**=0**

Search region:
$\mathbf{m_{jj}}$**>500 GeV,** $\mathbf{N_{bjet}}$**=0**
For cross section measurement WZjj EW

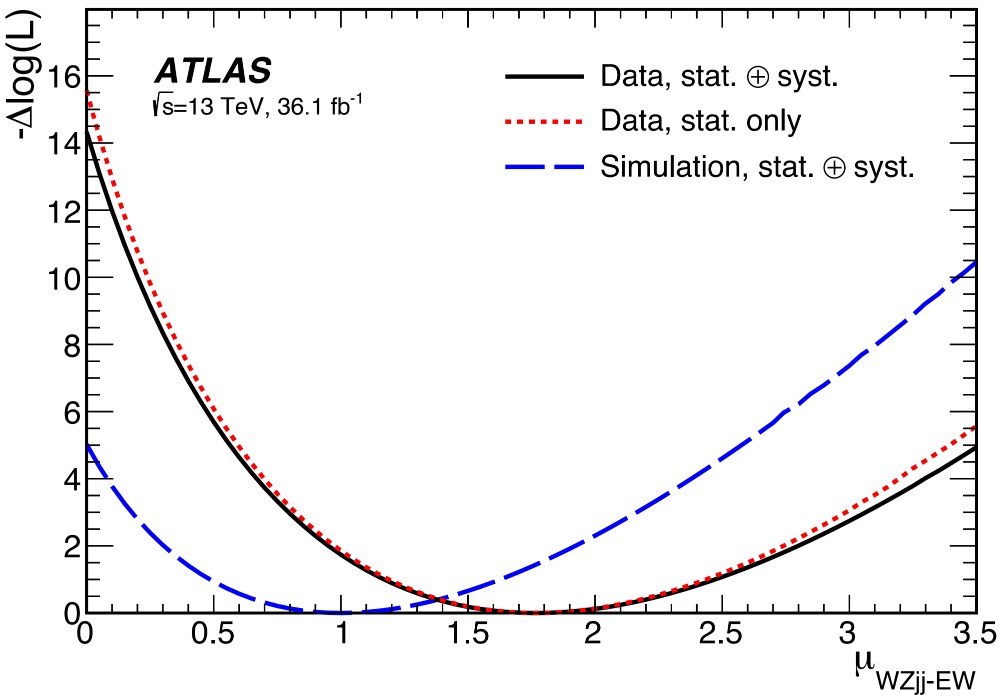
ZZ-CR
4 loose leptons
(reverting ZZ veto)

Post-fit distribution

EWjj cross-section results

- **Result on mu:**

$$\mu_{WZjj\text{-EW}} = 1.77\ ^{+0.44}_{-0.40}\ \text{(stat.)}\ ^{+0.15}_{-0.12}\ \text{(exp. syst.)}\ ^{+0.15}_{-0.12}\ \text{(mod. syst.)}\ ^{+0.04}_{-0.02}\ \text{(lumi.)} = 1.77\ ^{+0.49}_{-0.43}$$



5.3σ observed
(3.2σ expected)

Main systematics from:
jet (6.6%),
QCD theory modelling (5.2%)
EW theory modelling (4.8%),

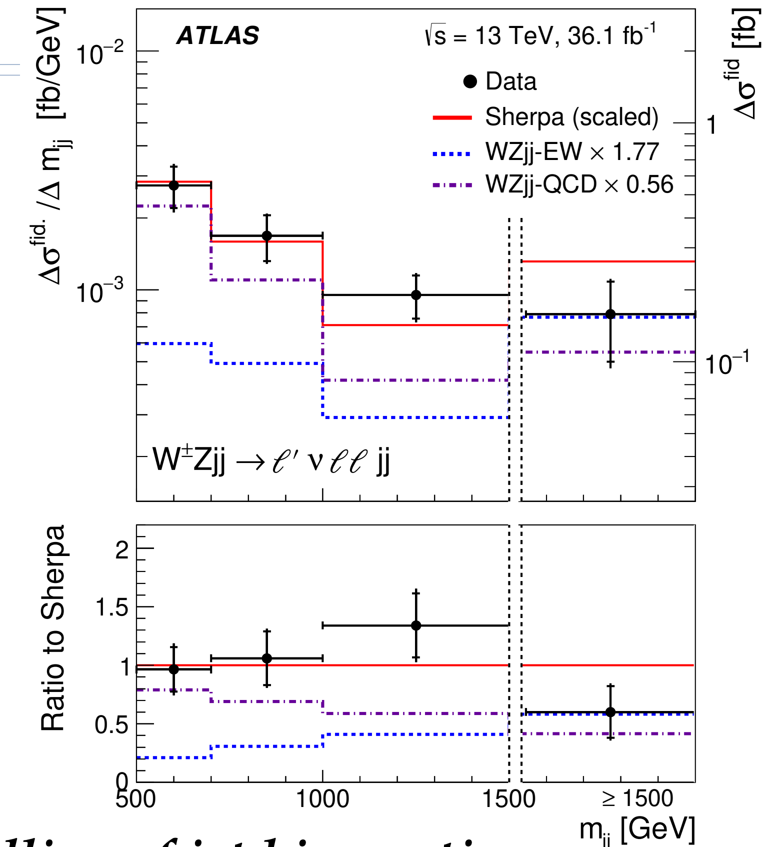
Process	Fitted normalisation
$WZjj$-QCD	0.56 ± 0.16
$t\bar{t}+V$	1.07 ± 0.23
ZZ-QCD	1.34 ± 0.24

- **Observed WZjj-EW cross-section and comparison with SM LO prediction from Sherpa and MadGraph**

	Cross section in fb
$\sigma^{fid}_{WZjj-EW}$	$0.57\ ^{+0.14}_{-0.13}$ (stat) $^{+0.05}_{-0.04}$ (exp.syst.) $^{+0.05}_{-0.04}$ (mod.syst.) $^{+0.01}_{-0.01}$ (lumi)
$\sigma^{fid,Sherpa}_{WZjj-EW}$	0.321 ± 0.002 (stat) ± 0.005 (PDF) $^{+0.027}_{-0.023}$ (scale)
$\sigma^{fid,MadGraph}_{WZjj-EW}$	0.366 ± 0.004 (stat)

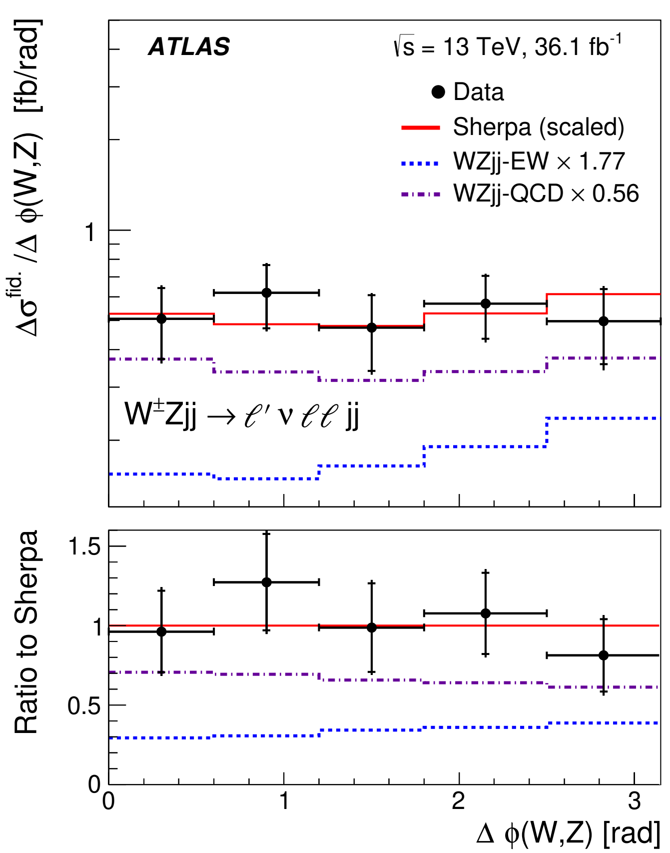
Differential cross-sections

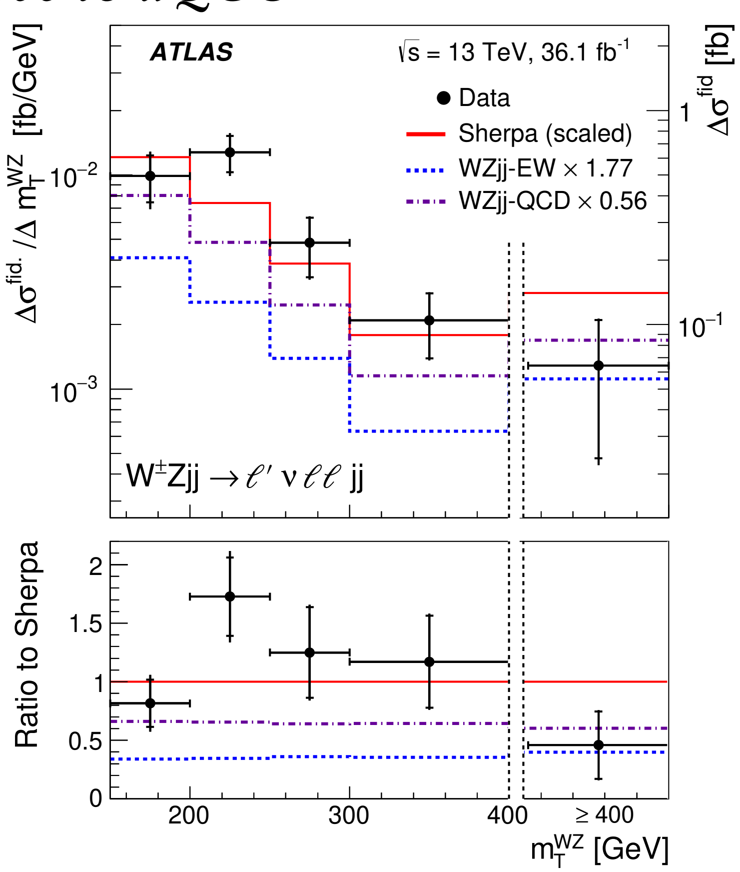
- **Differential cross section computed in the SR (dominated by QCD)**
  - iterative Bayesian unfolding method
  - Sherpa QCD and EW prediction normalised by their corresponding μ



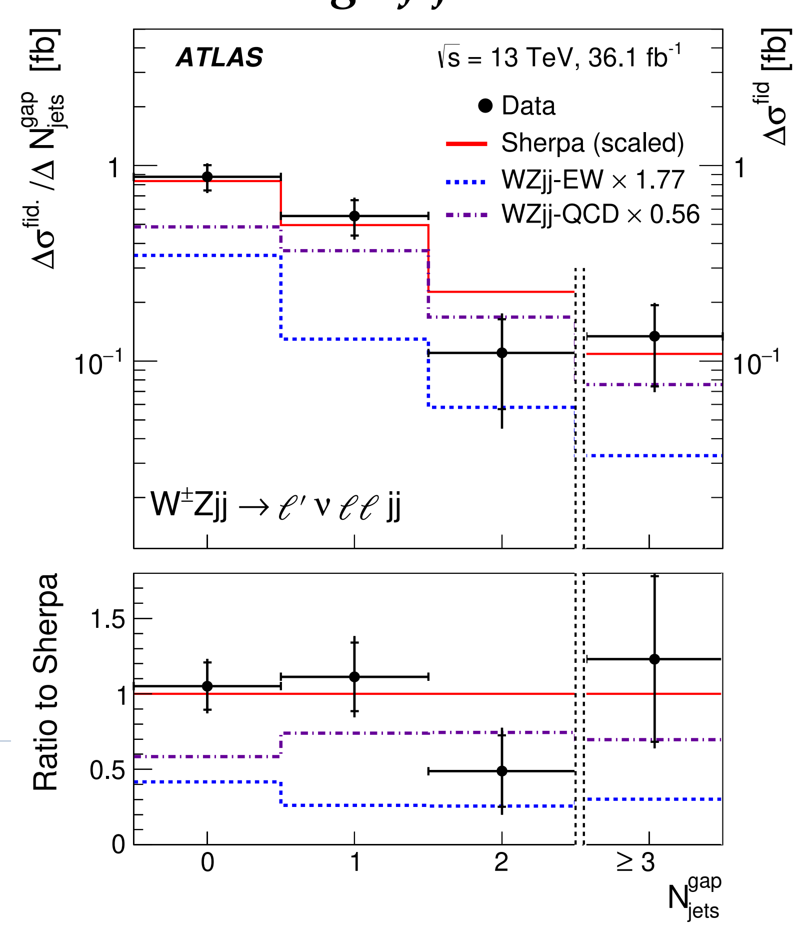
- **Two categories of variables:**
  - **Sensible to aQGCs**: $m_T(WZ)$, $\sum p_T^l$, $\Delta\phi(W,Z)$
  - **Constraining jets kinematic in MC :** N_{jets}, m_{jj}, $\Delta\phi(j_1,j_2)$, $\Delta y(j_1,j_2)$, N_{jets}^{gap} (p_T>25 GeV)

Variables sensitive to aQGC





MC modelling of jet kinematics

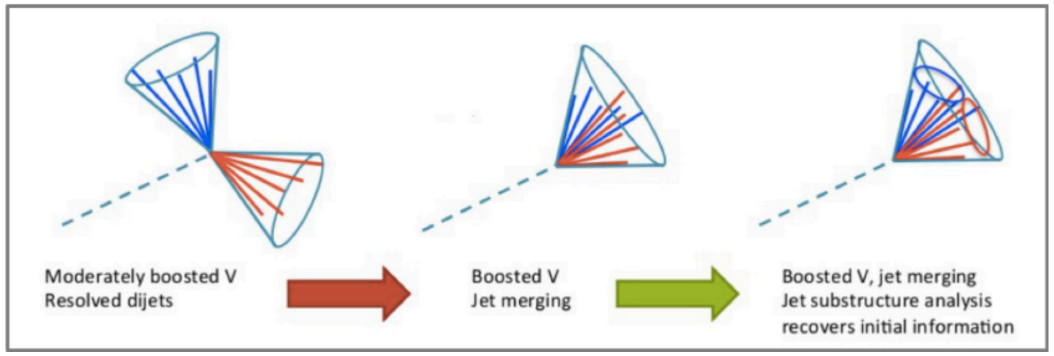


VV semileptonic

Phys. Rev. D 100 (2019) 032007

VV (WW, ZZ, WZ) semileptonic

- **3 channels** : ZV->vvqq (**0-lept**), WV->lvqq (**1-lept**), ZV ->llqq (**2 lept**)
- **2 techniques for V->qq:**
  - **resolved**: identify 2 small-radius jets (j)
  - **merged**: jet substructure large radius jet (J).



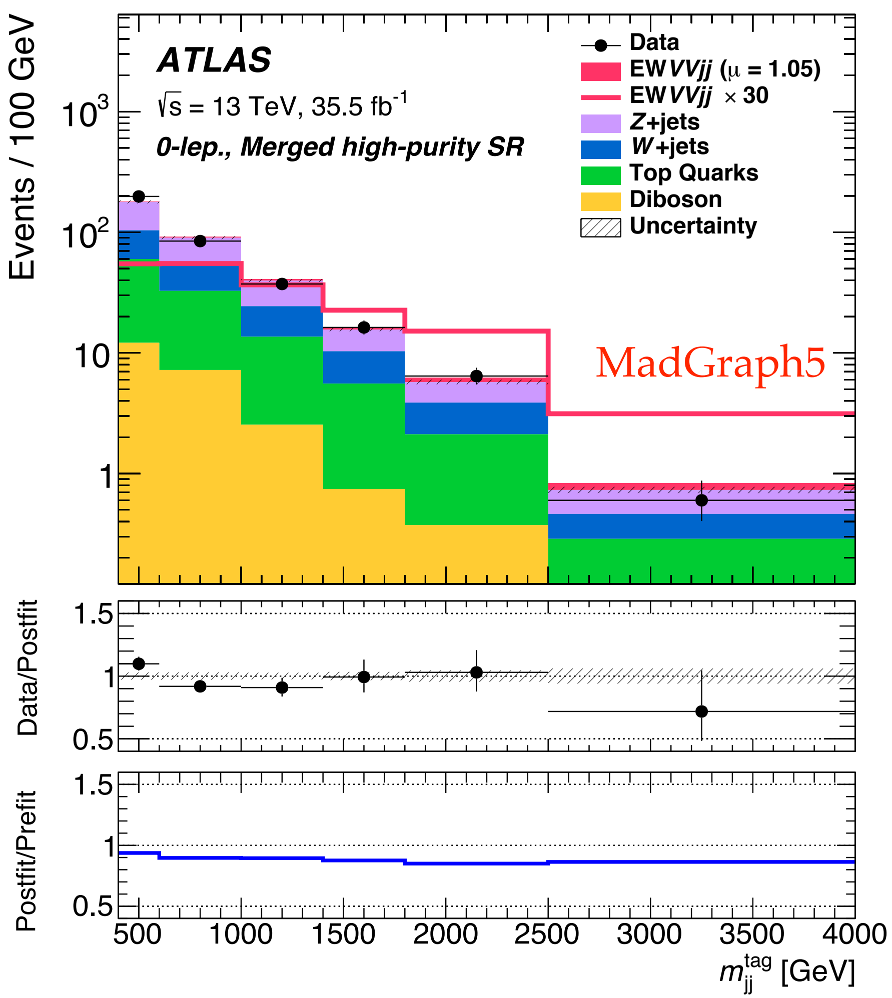
- **Channel interesting because strong production is small for all channels.**
- **Selection**: Vlept+Vhad+ 2 tagging jets (small-R)

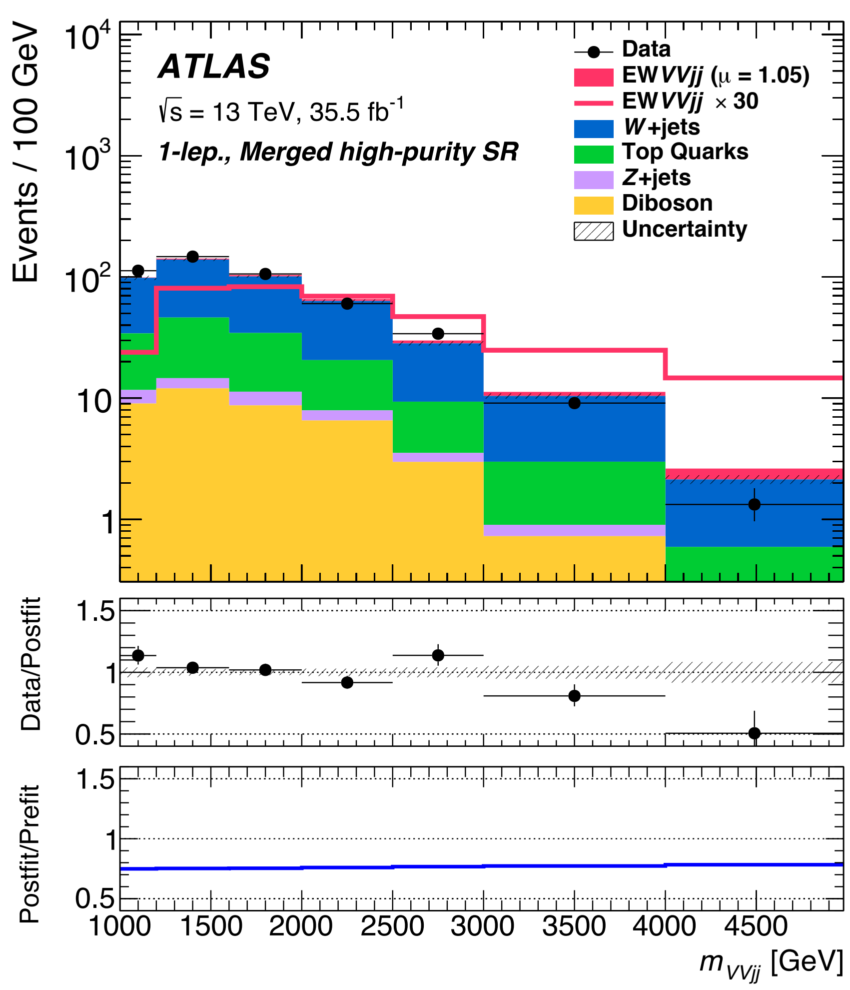
Selection	0-lepton	1-lepton	2-lepton
Leptons	0 'loose' leptons with $p_{\mathrm{T}} > 7$ GeV	1 'tight' lepton with $p_{\mathrm{T}} > 27$ GeV 0 'loose' leptons with $p_{\mathrm{T}} > 7$ GeV	2 'loose' leptons with $p_{\mathrm{T}} > 20$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 28$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV	> 80 GeV	–
$m_{\ell\ell}$	–	–	$83 < m_{ee} < 99$ GeV $-0.0117 \times p_{\mathrm{T}}^{\mu\mu} + 85.63 < m_{\mu\mu} < 0.0185 \times p_{\mathrm{T}}^{\mu\mu} + 94$ GeV
Small-R jets	$p_{\mathrm{T}} > 20$ GeV if $\lvert\eta\rvert < 2.5$, and $p_{\mathrm{T}} > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$		
Large-R jets	$p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2$		
$V_{\mathrm{had}} \to J$ $V_{\mathrm{had}} \to jj$	V boson tagging, $\min(\lvert m_J - m_W\rvert, \lvert m_J - m_Z\rvert)$ $64 < m_{jj} < 106$ GeV, jj pair with $\min(\lvert m_{jj} - m_W\rvert, \lvert m_{jj} - m_Z\rvert)$, leading jet with $p_{\mathrm{T}} > 40$ GeV		
Tagging-jets	$j \notin V_{\mathrm{had}}$, not b-tagged, $\Delta R(J, j) > 1.4$ $\eta_{\mathrm{tag},j_1} \cdot \eta_{\mathrm{tag},j_2} < 0$, $m_{jj}^{\mathrm{tag}} > 400$ GeV, $p_{\mathrm{T}} > 30$ GeV		
Num. of b-jets	–	0	–

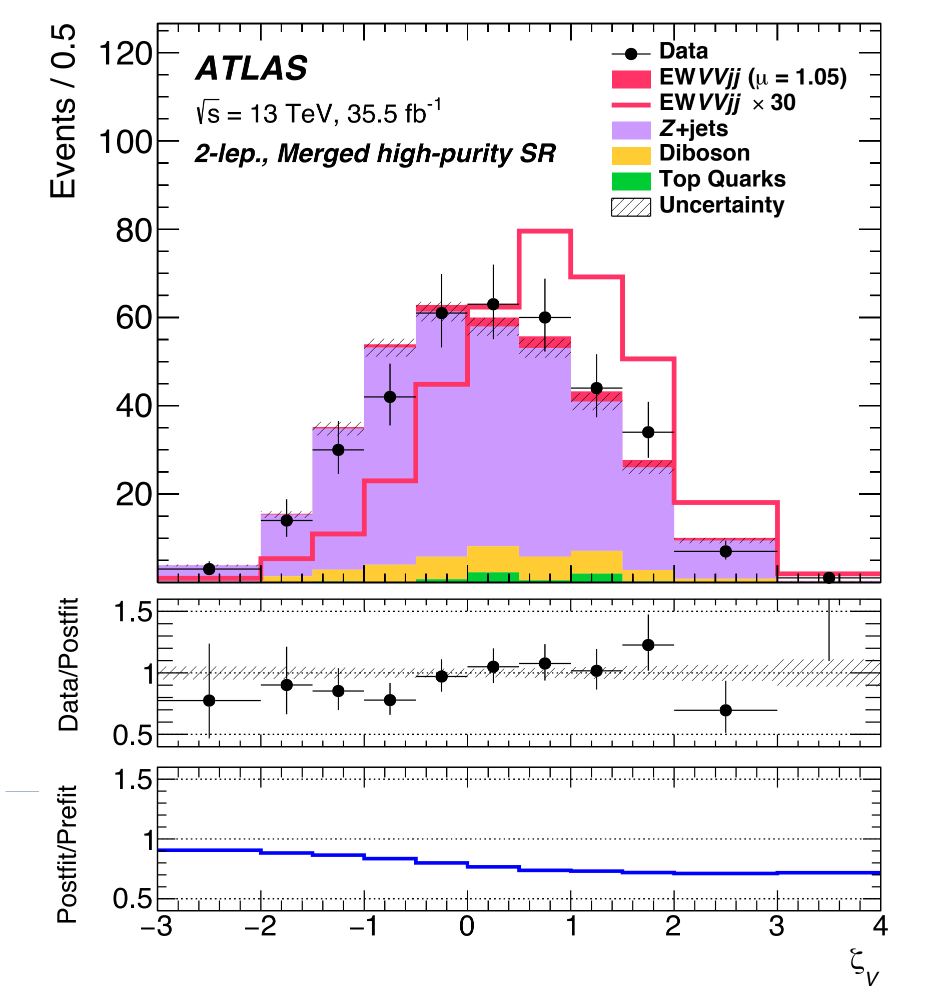
+ $p_{\mathrm{T}}^{\mathrm{miss}}$ selection and angular selection (0-lepton) to suppress Multijet background

Main Backgrounds, control regions

- Shape of kinematic variables taken from MC in almost all cases
- **0-lepton category:**
  - all backgrounds important -> **VjjCR** from mass window of Vhad
- **1-lepton category:**
  - **W+jet** (Sherpa 2.1)-> **WCR** by reverting invariant mass requirement of Vhad
  - **ttbar** (PowhegBox v2)-> **TopCR** by reverting b-jet requirement
- **2-lepton category:**
  - **Z+jet** dominant (Sherpa 2.2.1)-> **ZCR** by reversing m_J or m_{jj} requirement





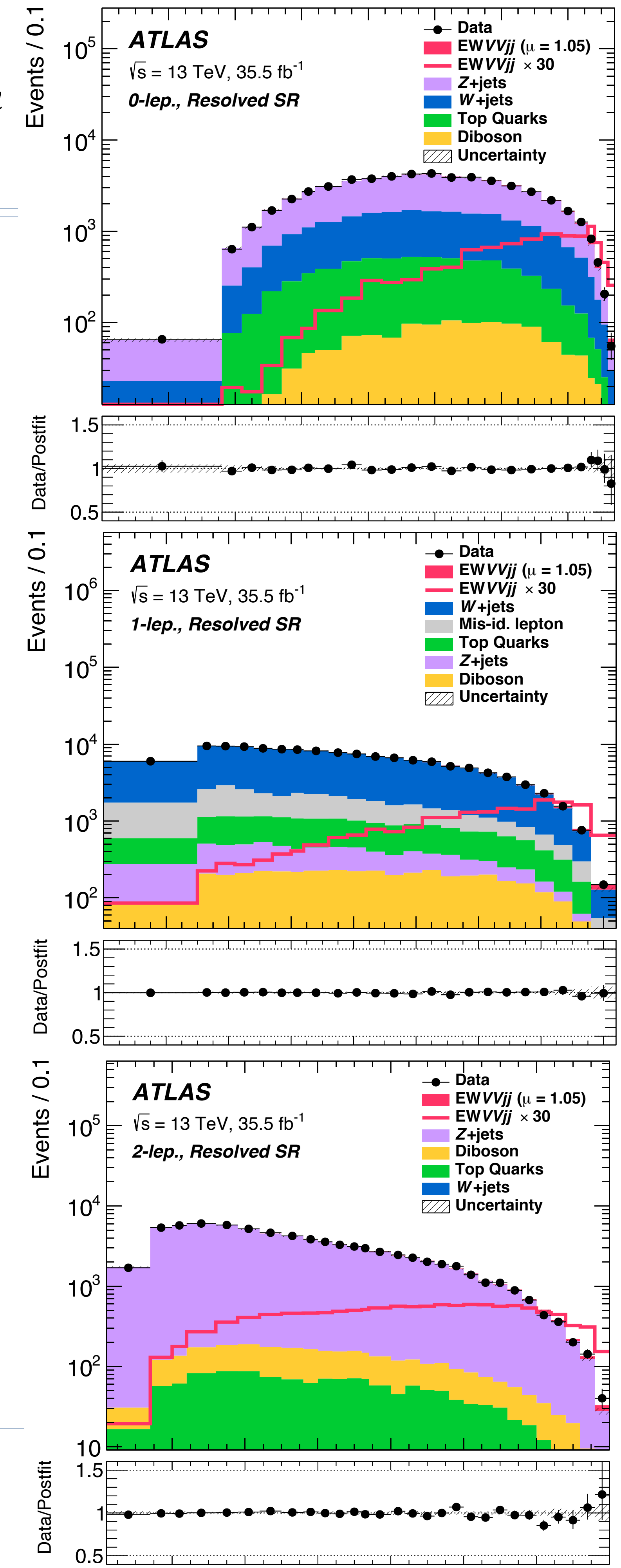


Analysis strategy

BDT distribution in the 3 channels Resolved jets

- **21 regions fitted simultaneously**
  - **9 signal region**: 0,1,2 lept x (resolved, low purity merged, high purity merged)
    - high purity (HP): pass 50% boson tagger working point (WP)
    - low purity (LP): pass 80% boson tagger WP requirement but fail 50%
  - **12 control regions**: ZCR, WCR, TopCR, VjjCR for the 3 lepton channels
- **Distribution used in the global likelihood:**
  - BDT in signal regions
  - m_{jj} or unique bin histograms for CRs
- **BDT trained in each channel and region separately**
- **Main systematics:**

Category	Systematic	Size
Jets	small-R jet pT	6-2% (low-high pT)
	small-R jet resolution	10-20% (low-high pT)
	large-R jet pT	2-5% (low-high pT)
	large-R jet resolution	20-15% (low-high pT)
Backgrounds norm	VVjj QCD	30%
	single-top	20%
	Z+jets	22(42)% in merged (resolved)
	W+jets	8(14)% in merged (resolved)
EW VVjj modelling	PDF, PS, QCD scale	3-5%, 1-5%, 1-3%
	Interference shape and norm	5-10%
Discriminant modelling		5-30%

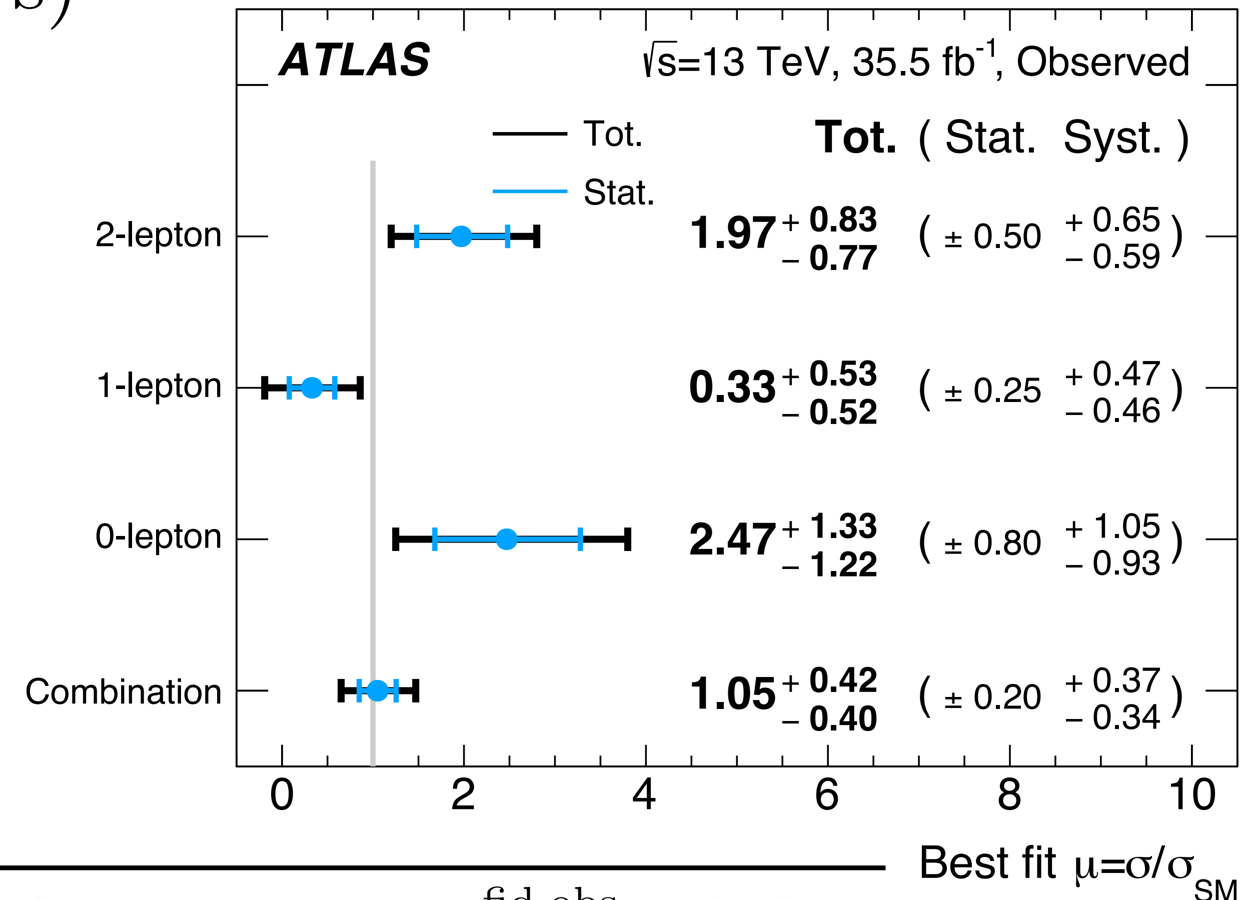


Results

$$\mu_{EW} = 1.05 \pm 0.20(\text{stat})^{+0.37}_{-0.34}(\text{sys})$$

2.7σ observed
(2.5σ expected)

Good compatibility between different channels (prob. that there are compatible = 36%)



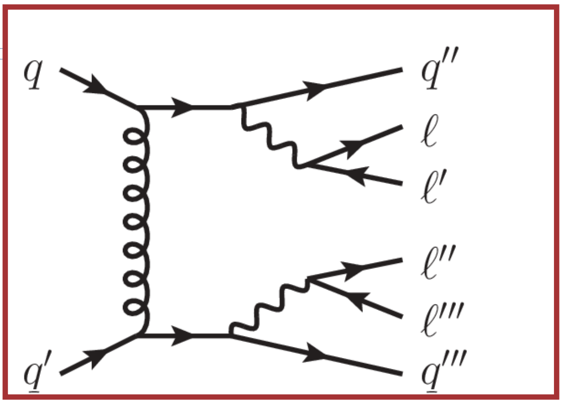
- Cross section prediction from MadGraph5_aMC@NLO 2.4.3 at LO
- Cross-section measurements:

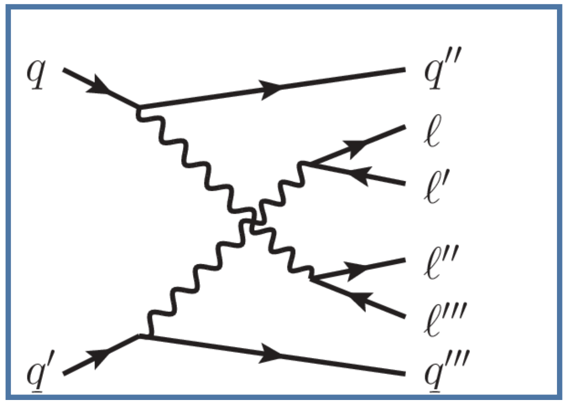
Fiducial phase space	Predicted $\sigma^{\text{fid,SM}}_{\text{EW}\,VVjj}$ [fb]	Measured $\sigma^{\text{fid,obs}}_{\text{EW}\,VVjj}$ [fb]
Merged	$11.4 \pm 0.7\,(\text{theo.})$	$12.7 \pm 3.8\,(\text{stat.})\,^{+4.8}_{-4.2}\,(\text{syst.})$
Resolved	$31.6 \pm 1.8\,(\text{theo.})$	$26.5 \pm 8.2\,(\text{stat.})\,^{+17.4}_{-17.1}\,(\text{syst.})$
Inclusive	$43.0 \pm 2.4\,(\text{theo.})$	$45.1 \pm 8.6\,(\text{stat.})\,^{+15.9}_{-14.6}\,(\text{syst.})$

ssWW

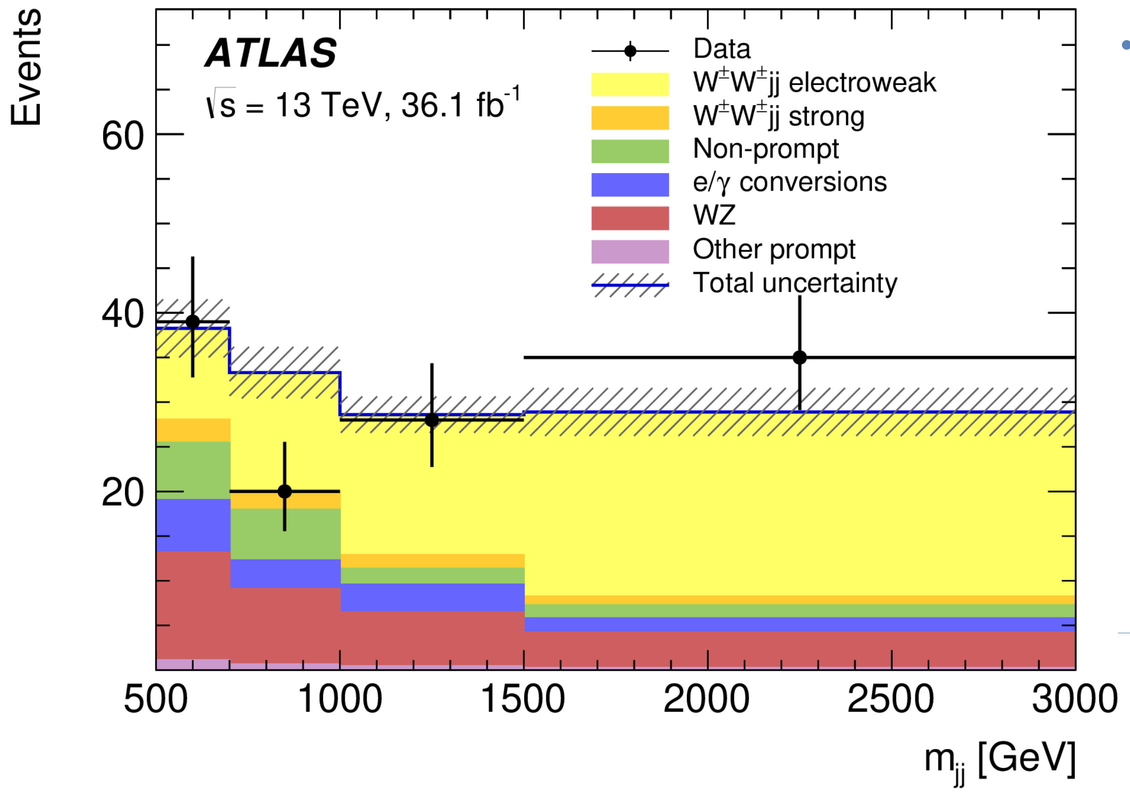
Phys. Rev. Lett. 123 (2019) 161801

Observation of EW W±W±jj





- **Strong production** doest not dominate the **EW** one + same sign leptons in final state reducing other backgrounds —> **golden channel**
- **Selection:**
  - **2 leptons with pT>27 GeV**, E_T^{miss}> 30 GeV, m_{ll}> 40 GeV
    - Events with |m_{ee}-91.2|<15 GeV removed for |η|<1.37 (reduce electron charge misID)
  - **Jets** with p_T >65, 35 GeV , m_{jj}> 200 GeV, |ΔY|>2
    - Events with >=1 b-tagged jet rejected (reduce ttbar background)
  - **Signal region:** m_{jj}> 500 GeV (4 bins)
    - Region 200<m_{jj}<500 GeV used as CR (1 bin)

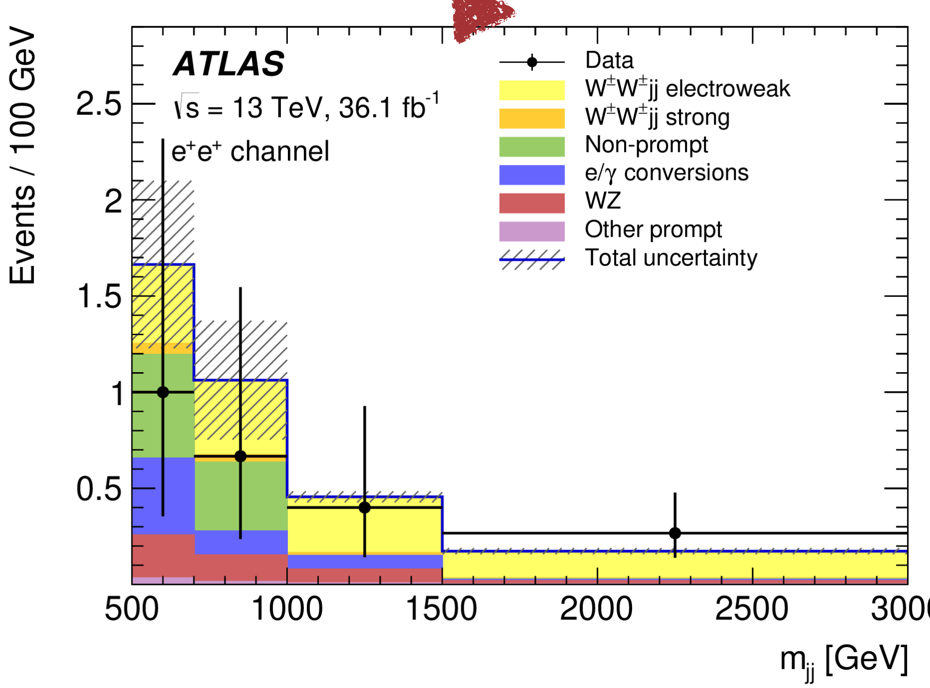


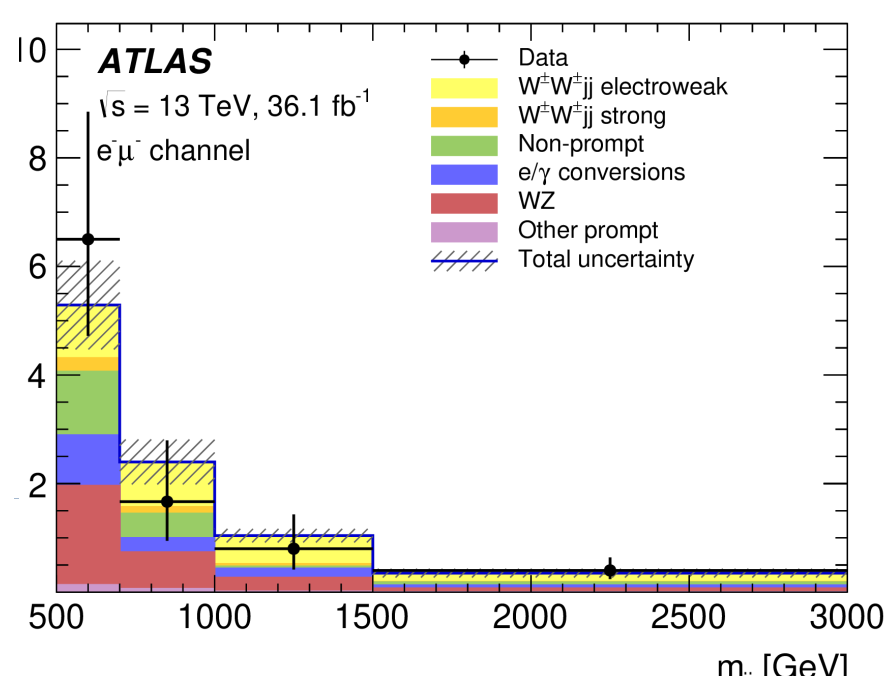
- **Backgrounds:**
  - **WWjj QCD** : MC (Sherpa 222)
  - **Non-prompt** (ttbar, W+jets): data-driven
  - **e/γ conversion** :
    - Charge misID: data-driven estimate
    - Wγ, Zγ: MC (Sherpa 2.1), pre-normalised in CR
  - **WZ:** MC (Sherpa 222), normalised from CR
  - **Other prompt**: MC (Sherpa 222 for VVV and ZZ, MadGraph5 for ttV)

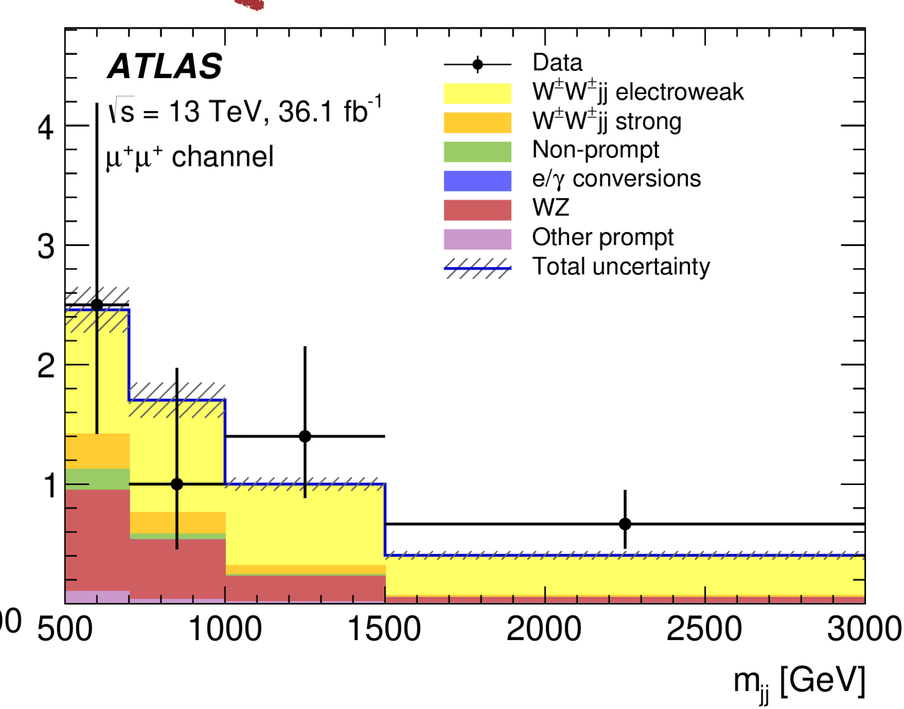
Event yield in channels

- **Events categorised in 6 channels (lepton flavour and charge)**
- **30 bins combined in likelihood fit to extract EW ssWW cross-section** (5 bins of m_{jj} x 6 channels)
  - + WZ control region (1 bin) with 1 WZ free norm. parameter

	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	combined
WZ	1.9 ± 0.6	1.3 ± 0.4	14 ± 4	8.9 ± 2.5	5.5 ± 1.6	3.6 ± 1.1	35 ± 10
Non-prompt	4.0 ± 2.3	2.3 ± 1.7	9 ± 5	6 ± 4	0.55 ± 0.15	0.67 ± 0.25	23 ± 10
e/γ conversions	1.74 ± 0.29	1.8 ± 0.4	6.1 ± 1.6	3.7 ± 0.8	—	—	13.4 ± 2.5
Other prompt	0.17 ± 0.05	0.14 ± 0.04	0.90 ± 0.19	0.60 ± 0.14	0.36 ± 0.10	0.19 ± 0.05	2.4 ± 0.5
$W^\pm W^\pm jj$ strong	0.38 ± 0.13	0.16 ± 0.05	3.0 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.25	7.3 ± 2.4
Expected background	8.2 ± 2.4	5.7 ± 1.8	33 ± 7	21 ± 5	8.2 ± 1.7	5.3 ± 1.1	81 ± 14
$W^\pm W^\pm jj$ electroweak	3.8 ± 0.6	1.49 ± 0.22	16.5 ± 2.4	6.5 ± 1.0	9.1 ± 1.4	3.5 ± 0.5	41 ± 6
Data	10	4	44	28	25	11	122





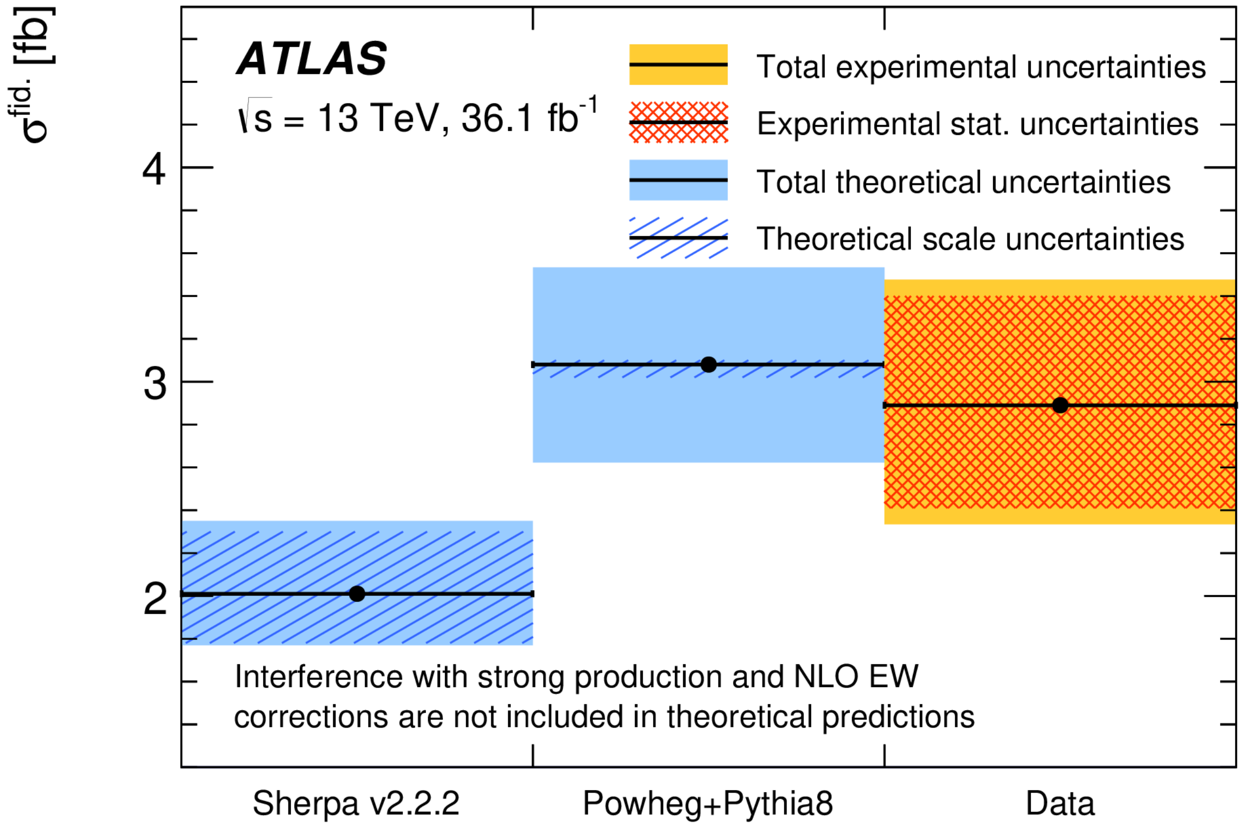


Results

$$\mu_{EW} = 1.44^{+0.26}_{-0.24}\ (\text{stat.})\ ^{+0.28}_{-0.22}\ (\text{syst.})$$

6.5σ observed
4.4σ (6.5 σ) expected Sherpa (PowhegBox)

WZ norm. parameter: 0.86



- **Dominant systematic uncertainties:**
  - **Backgrounds:**
    - Non-prompt lepton: 50% μμ, 40-90% ee, eμ
    - Electron charge misID: 10-20%
    - Theoretical modelling for ZZ, Vγ, triboson, ttV = 20-30%
  - **Object syst:**
    - JES (2% for signal and 10% for WZ)

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

Sherpa: $2.01^{+0.33}_{-0.23}$ fb MadGraph: $3.08^{+0.45}_{-0.46}$ fb,

aQGC

Anomalous quartic gauge couplings

- New physics could modify couplings between bosons, and allow neutral couplings ZZZγ, ZZγγ, Zγγγ (forbidden in SM) -> aQGCs

- Presence of aQGC enhance EW XS at high-energy tails
  - **use variable that carry the energy of the system: transverse momentum or mass**

- ATLAS and CMS interpretation strategy: **as much model-independent as possible**

- **Common choice:** effective field theory (EFT) with higher order dimensions operators
  - Dim8 is lowest-**dimension** operators inducing only QGC without TGC vertices
  - VBS not competitive with dibosons/VBF for dim6 constraints.

- **Two approaches**
  - C,P conserving dim8 EFT operators that maintains Su(2)_L x U(1)_Y gauge symmetry of the type fi/lamda4 (**ATLAS** Zg, CMS Zg, Wg, ssWW, ZZ)
  - α_4 α_5: coefficients of the two linearly independent dim4 operators contributing to aQGCs (ATLAS WZ, ssWW, WV semilept.)

Anomalous quartic gauge couplings

- Dim8 operators: 3 types:
  - pure Higgs field (fS) pure longitudinal(cannot induce couplings with photons)
  - pure Field-strength tensor (fT) pure transverse
  - Mixed Higgs-field-strength (fM), mixed longitudinal-transverse

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

Not all independent !

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,3} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\hat{W}^{\nu\alpha}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,4} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\alpha\mu}\hat{W}^{\beta\nu}\right] \times B_{\beta\nu}$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

Only neutral couplings

Exemple of conversion to α_4,α_5 framework:

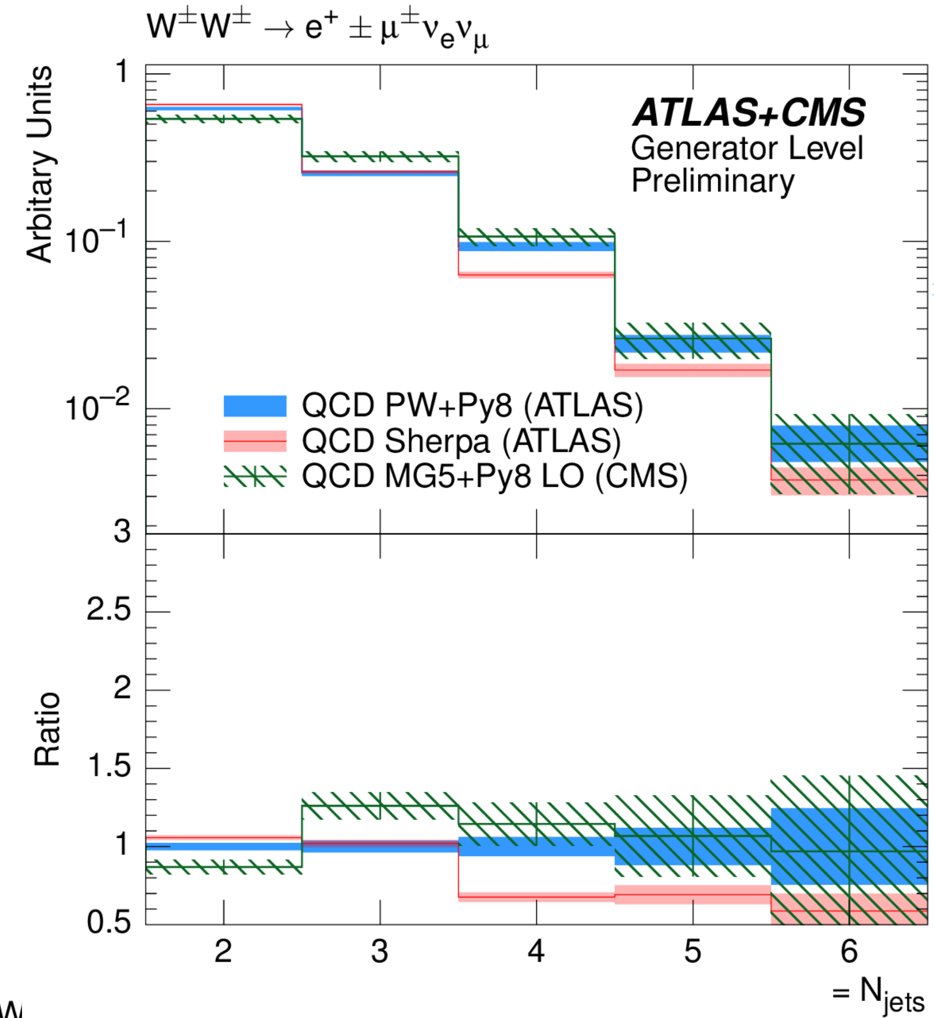
$$\frac{f_{S,0(1)}}{\Lambda^4} = \alpha_{4(5)} \times \frac{16}{v^4},$$

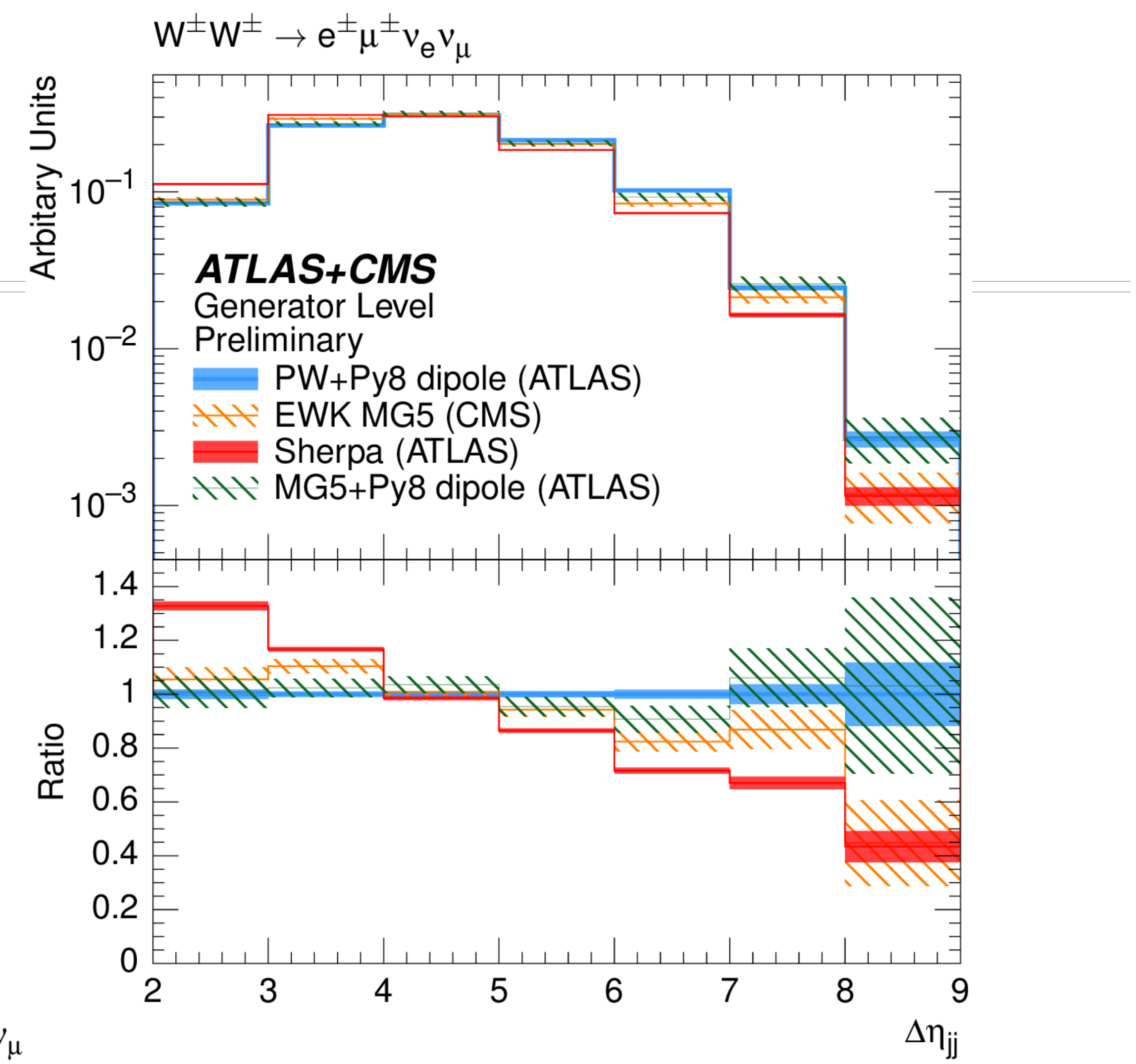
for the WWZZ vertex

ATLAS/CMS MC comparison details

Selection requirement	Selection value
dressed leptons with dressing cone of $\Delta R = 0.1$ and minimum p_{T}^{ℓ}	> 20 GeV
η_{ℓ}	$\lvert\eta_{\ell}\rvert \leq 2.5$
Charge of leading electron and muon	$c_e \times c_{\mu} > 0$
minimum ΔR between any of the leptons	$\Delta R \geq 0.3$
Jets, anti-k_t with $R = 0.4$, excluding leptons and neutrinos	$p_{\mathrm{T}} > 30$ GeV, $\lvert\eta\rvert < 4.5$
Minimum jet distance to lepton, otherwise jet is removed	$\Delta R \geq 0.3$
Minimum number of jets with above criteria	2
distance in pseudo-rapidity of the jets	$\Delta\eta_{jj} \geq 2.5$
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 40 GeV
Signal region: invariant mass of jet system	$m_{jj} \geq 500$ GeV
Control region: invariant mass of jet system	200 GeV $< m_{jj} <$ 500 GeV

Sample name	Fiducial cross section [fb] $\mathrm{W}^{+}\mathrm{W}^{+} \rightarrow e^{+}\mu^{+}\nu_e\nu_{\mu}$	Fiducial cross section [fb] $\mathrm{W}^{\pm}\mathrm{W}^{\pm} \rightarrow e^{\pm}\mu^{\pm}\nu_e\nu_{\mu}$
Sherpa (ATLAS)	0.968 ± 0.005	1.136 ± 0.005
PW+Py8 (ATLAS)	1.320 ± 0.009	1.768 ± 0.009
PW+Py8 dipole-recoil (ATLAS)	1.322 ± 0.009	1.769 ± 0.009
MG5+Py8 dipole-recoil (ATLAS)	1.313 ± 0.028	1.734 ± 0.028
MG5+Py8 (CMS)	1.281 ± 0.018	1.707 ± 0.021
PW+Py8 (VBScan)	1.364 ± 0.0004	n/a


$W^{\pm}W^{\pm} \rightarrow e^{+} \pm \mu^{\pm}\nu_e\nu_\mu$
ATLAS+CMS
Generator Level
Preliminary
QCD PW+Py8 (ATLAS)
QCD Sherpa (ATLAS)
QCD MG5+Py8 LO (CMS)
Arbitary Units
Ratio
= N_jets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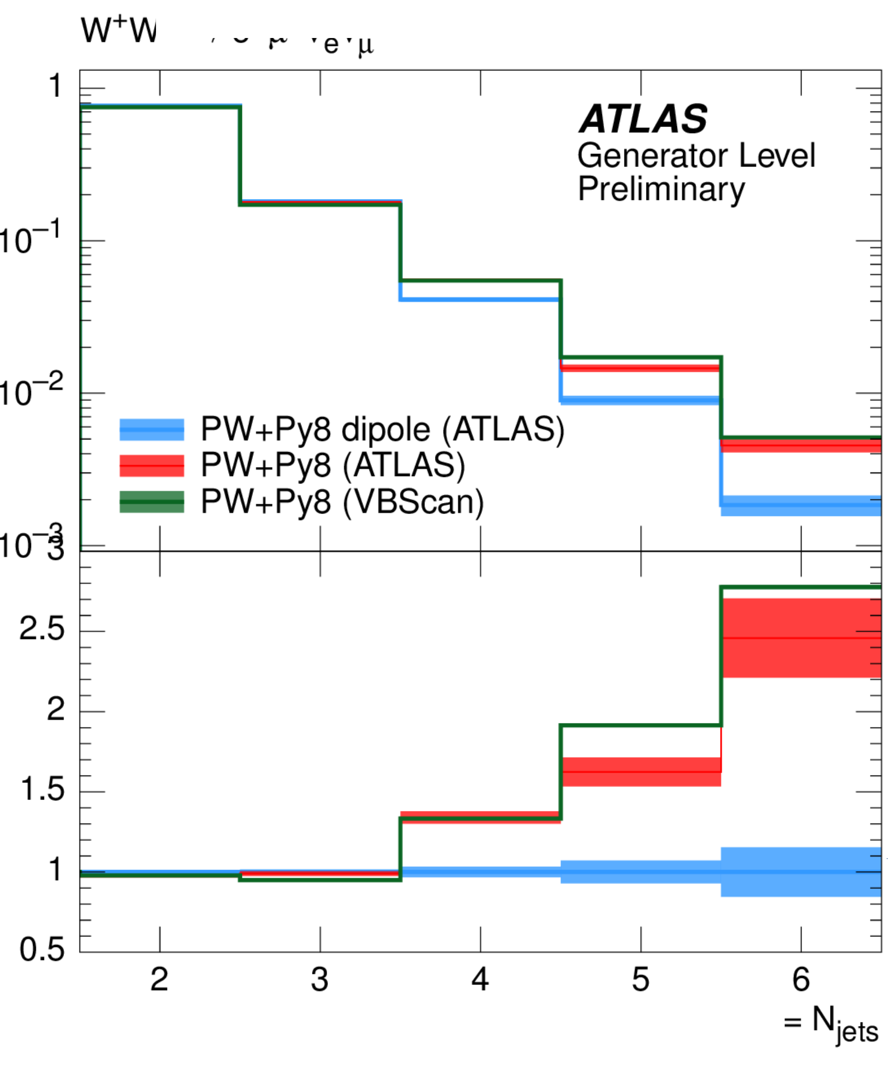
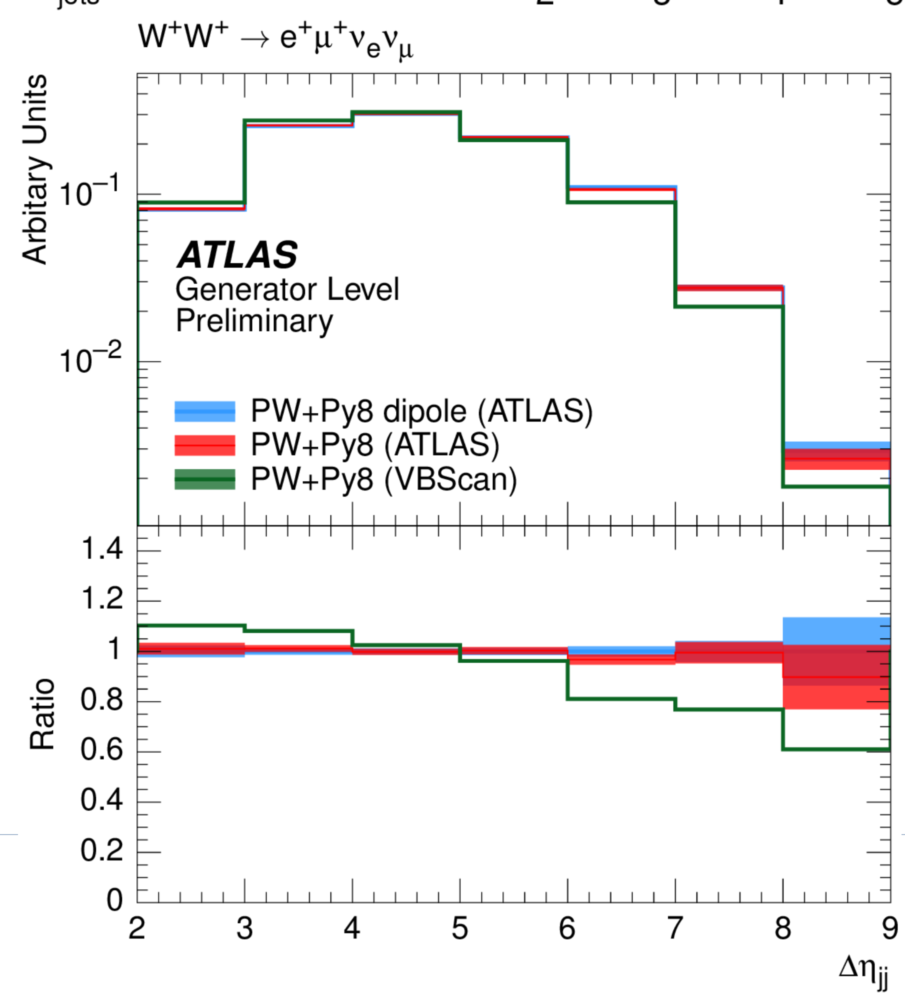
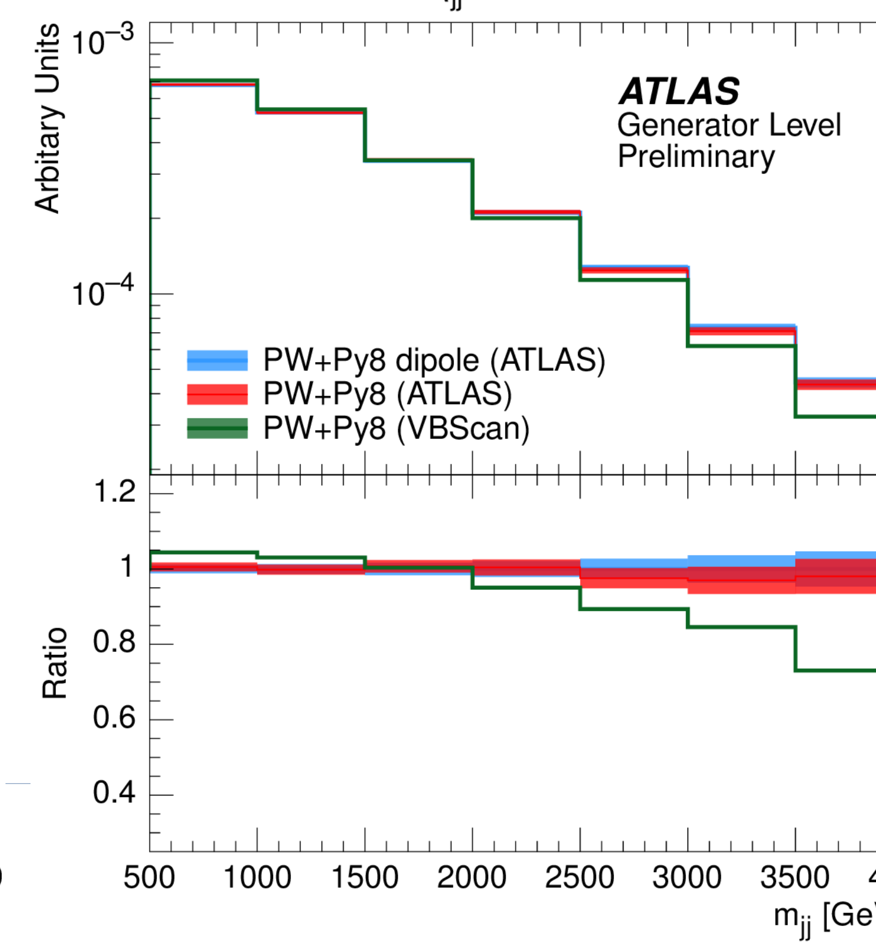
ATLAS+CMS
Generator Level
Preliminary
PW+Py8 dipole (ATLAS)
EWK MG5 (CMS)
Sherpa (ATLAS)
MG5+Py8 dipole (ATLAS)
Arbitary Units
Ratio
$\Delta\eta_{jj}$


ATLAS
Generator Level
Preliminary
PW+Py8 dipole (ATLAS)
PW+Py8 (ATLAS)
PW+Py8 (VBScan)
= N_jets


$W^{+}W^{+} \rightarrow e^{+}\mu^{+}\nu_e\nu_\mu$
ATLAS
Generator Level
Preliminary
PW+Py8 dipole (ATLAS)
PW+Py8 (ATLAS)
PW+Py8 (VBScan)
Arbitary Units
Ratio
$\Delta\eta_{jj}$


ATLAS
Generator Level
Preliminary
PW+Py8 dipole (ATLAS)
PW+Py8 (ATLAS)
PW+Py8 (VBScan)
Arbitary Units
Ratio

$Z(\nu\nu)\gamma$ VBS

Process	Fake-e CR	$W^{\gamma}_{e\nu}$ CR	$W^{\gamma}_{\mu\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	SR - m_{jj} [TeV] 0.25-0.5	0.5-1.0	1.0-1.5	≥ 1.5
Strong $Z\gamma$ + jets	8 ± 8	0 ± 1	3 ± 2	50 ± 12	20 ± 6	54 ± 12	13 ± 5	5 ± 2
EW $Z\gamma$ + jets	0.6 ± 0.2	0.3 ± 0.2	0.4 ± 0.2	7 ± 2	4 ± 1	30 ± 7	25 ± 5	36 ± 7
Strong $W\gamma$ + jets	43 ± 9	47 ± 9	133 ± 21	24 ± 6	22 ± 6	35 ± 10	9 ± 3	3 ± 1
EW $W\gamma$ + jets	19 ± 6	31 ± 7	59 ± 13	1.4 ± 0.5	2 ± 1	6 ± 1	4 ± 1	5 ± 1
jet$\rightarrow \gamma$	1 ± 1	2 ± 2	3 ± 2	2 ± 2	1 ± 1	2 ± 2	1 ± 1	0.4 ± 0.3
jet$\rightarrow e$	34 ± 17	5 ± 3	–	–	–	–	–	–
$e \rightarrow \gamma$	–	2.7 ± 0.4	2.9 ± 0.4	13 ± 1	6 ± 1	11 ± 1	2.6 ± 0.4	1.4 ± 0.3
γ + jet	–	–	–	0.7 ± 0.5	0.7 ± 0.5	0.4 ± 0.3	0.1 ± 0.1	0.1 ± 0.1
$t\bar{t}\gamma/V\gamma\gamma$	3 ± 1	9 ± 2	13 ± 2	3 ± 1	2 ± 1	4 ± 1	0.4 ± 0.2	0.1 ± 0.1
Fitted Yields	108 ± 10	96 ± 8	213 ± 14	102 ± 9	58 ± 6	143 ± 12	54 ± 5	52 ± 6
Data	108	95	216	100	52	153	50	52
Data/Fit	1.00 ± 0.14	0.99 ± 0.12	1.01 ± 0.09	0.98 ± 0.13	0.90 ± 0.15	1.07 ± 0.11	0.93 ± 0.16	0.99 ± 0.18

Source	1σ Uncertainty on $\mu_{Z\gamma_{\text{EW}}}$	1σ Uncertainty on $\mathcal{B}_{\text{inv}}$	1σ Uncertainty on $\mathcal{B}(H \rightarrow \gamma\gamma_{\text{d}})$
Jet scale and resolution	0.076	0.045	0.0011
$V\gamma$ + jets theory	0.067	0.044	0.0018
pile-up	0.040	0.021	0.0004
Photon	0.035	0.031	0.0011
$e \rightarrow \gamma$, jet$\rightarrow e, \gamma$ Bkg.	0.035	0.034	0.0028
Lepton	0.027	0.003	0.0008
$E_{\text{T}}^{\text{miss}}$	0.023	0.018	0.0003
Signal theory shape	0.020	–	–
Signal theory acceptance	0.12	–	–
Data stats.	0.16	0.11	0.0056
$W\gamma$ + jets/$Z\gamma$ + jets Norm.	0.073	0.013	0.0004
MC stats.	0.063	0.046	0.0026
Total	0.25	0.15	0.0073