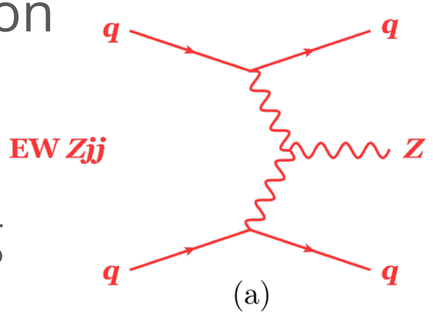
VBS/VBF measurements (without final-state photons) at ATLAS

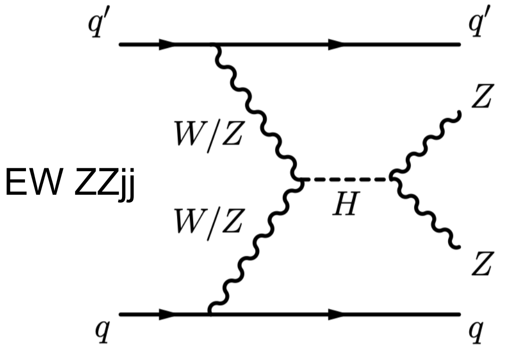
Karolos Potamianos, on behalf of the ATLAS Collaboration

9th Annual Conference on LHC Physics
June 7-12, 2021

Probing VBF and VBS :: Motivation

- Important tests of Electroweak and Strong interaction
- They directly probe EW boson self-interactions
- They are a portal to
  - Understanding Electroweak Symmetry Breaking
  - Probing BSM physics





Measurements:

- Fiducial and differential cross-sections
- Looking for anomalous couplings (EFT)
- Probing EW boson polarisation

Probing VBF and VBS :: What we measure

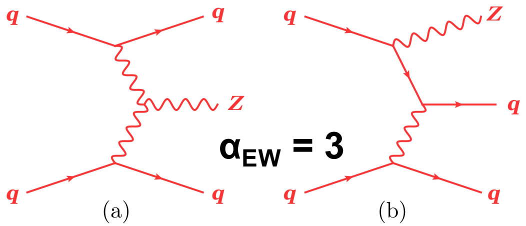
Cannot directly measure VBF/VBS

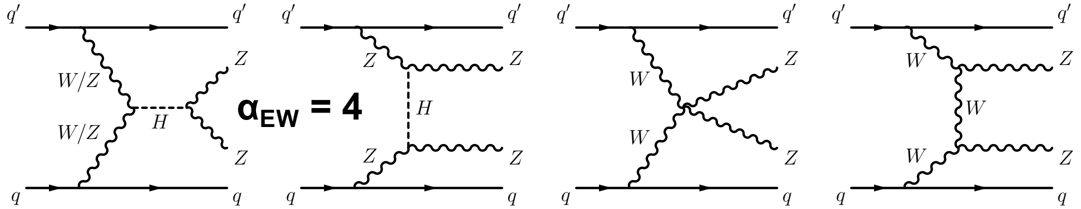
- **Significant interference with other diagrams with same order in**
- **Extracting** VBF/VBS component is **not gauge invariant**
- We can only **measure electroweak production** of VVjj (VBS) or Vjj (VBF)
- Moreover, QCD/strong production is much larger than EW (excl. $W^{\pm}W^{\pm}jj$)

Vector Boson Fusion (Vjj)

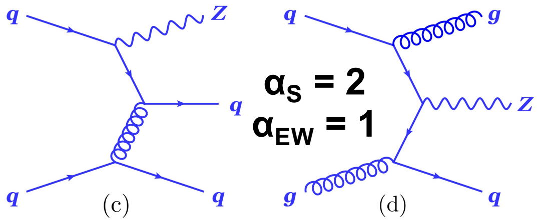
Vector Boson Scattering (VVjj)

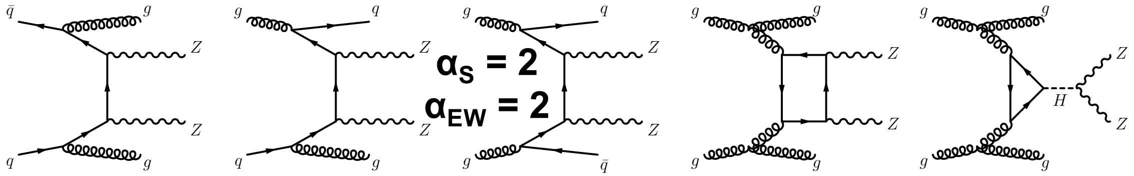
EW





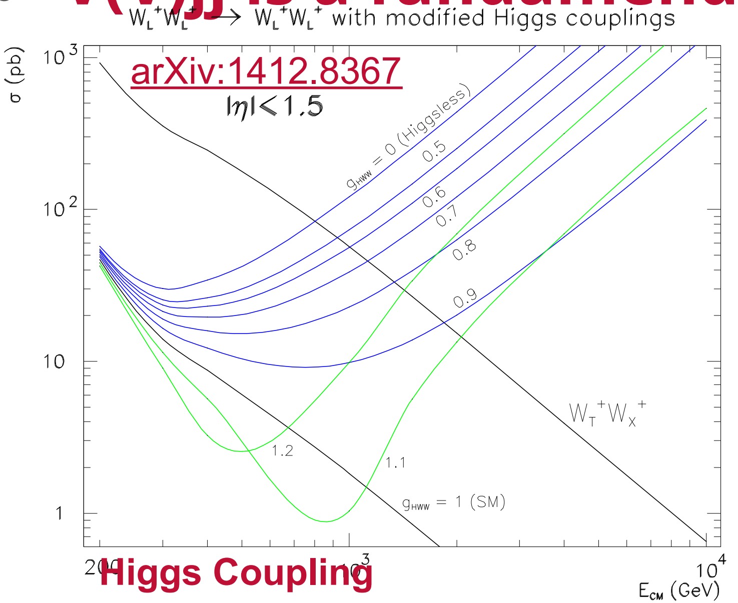
QCD



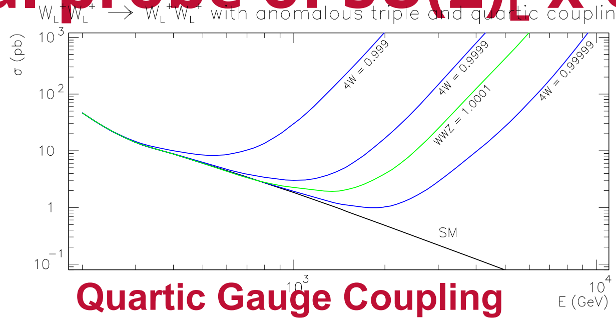


Probing Electroweak Symmetry Breaking

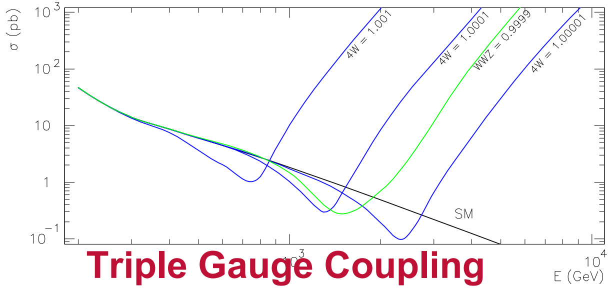
- VBS at high energy subject to **delicate cancellation between terms**
  - $\sigma(W_L W_L \rightarrow W_L W_L)$ grows with energy w/o Higgs boson
  - Very sensitive to shifts in the trilinear or quartic gauge coupling
- **V(V)jj is a fundamendal probe of $SU(2)_L \times U(1)_Y$**



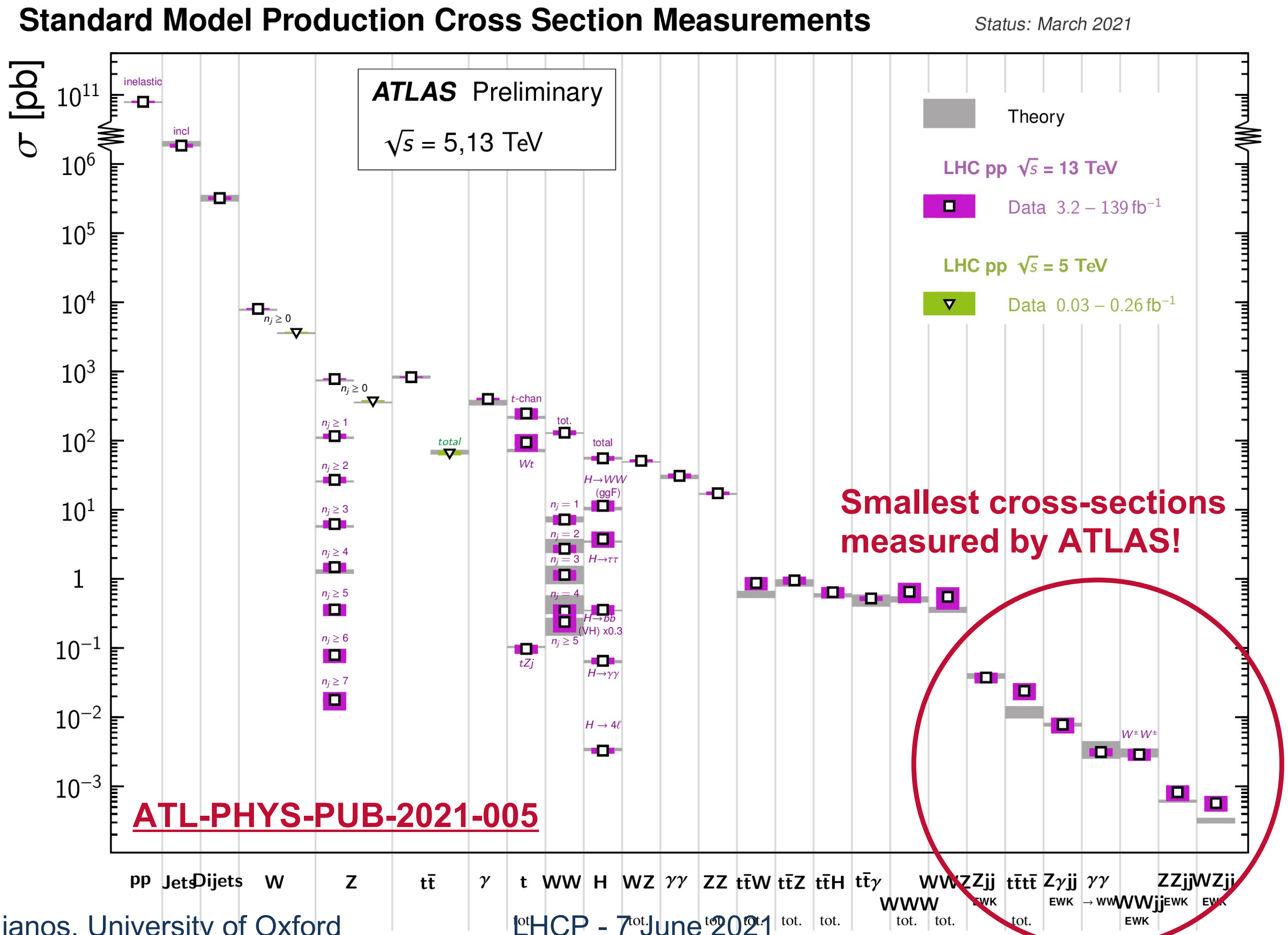
Higgs Coupling



Quartic Gauge Coupling



Triple Gauge Coupling



Smallest cross-sections measured by ATLAS!

ATL-PHYS-PUB-2021-005

Overview of Run-2 ATLAS VBS/VBF Analyses

This talk

Zjj (139 fb^{-1})
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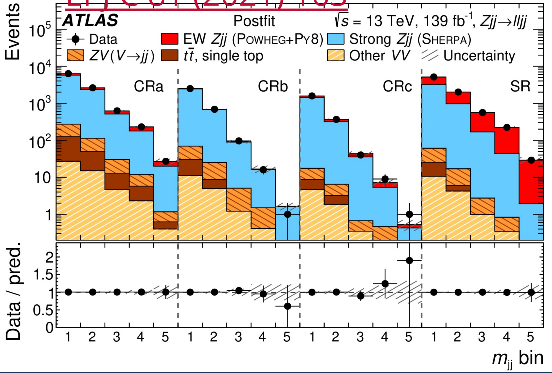
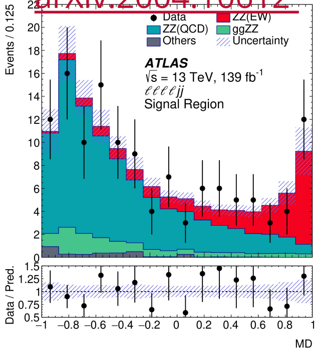
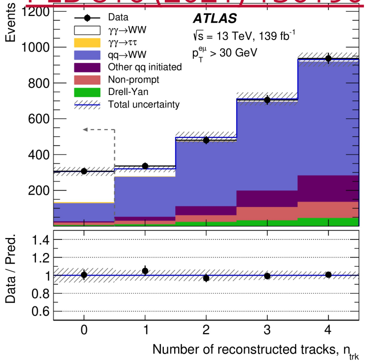


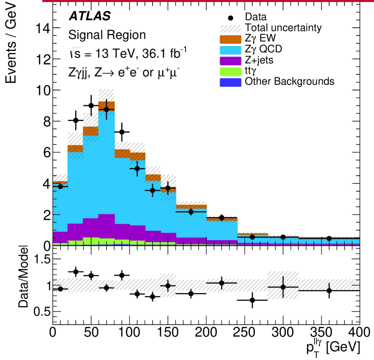
ZZjj (139 fb^{-1}): 5.5σ
arXiv:2004.10612



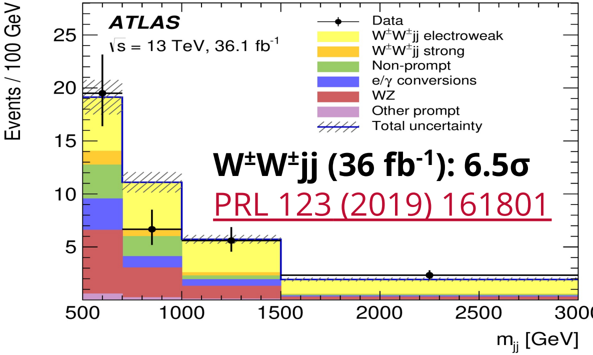
γγ → WW (139 fb^{-1}): 8.4σ
PLB 816 (2021) 136190



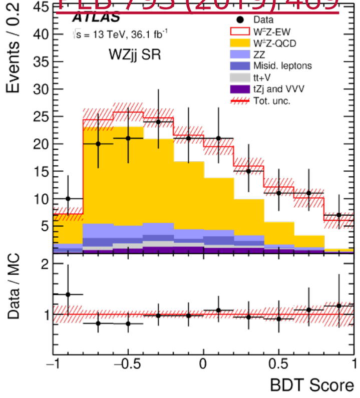
Zγjj (36 fb^{-1}): 4.1σ
PLB 803 (2020) 135341



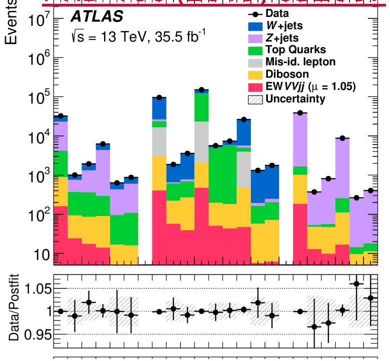
W±W±jj (36 fb^{-1}): 6.5σ
PRL 123 (2019) 161801



WZjj (36 fb^{-1}): 5.3σ
PLB 793 (2019) 469



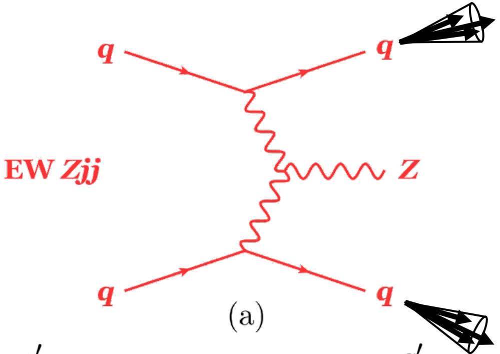
VVjj (36 fb^{-1}): 2.7σ
PRD 100 (2019) 032007

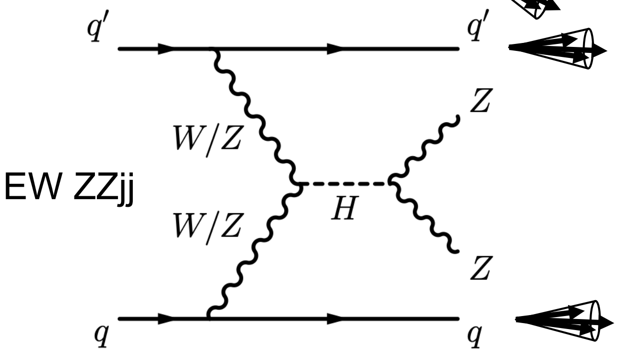


See talk by Ben Smart in this session for VBF/VBS measurements with photons

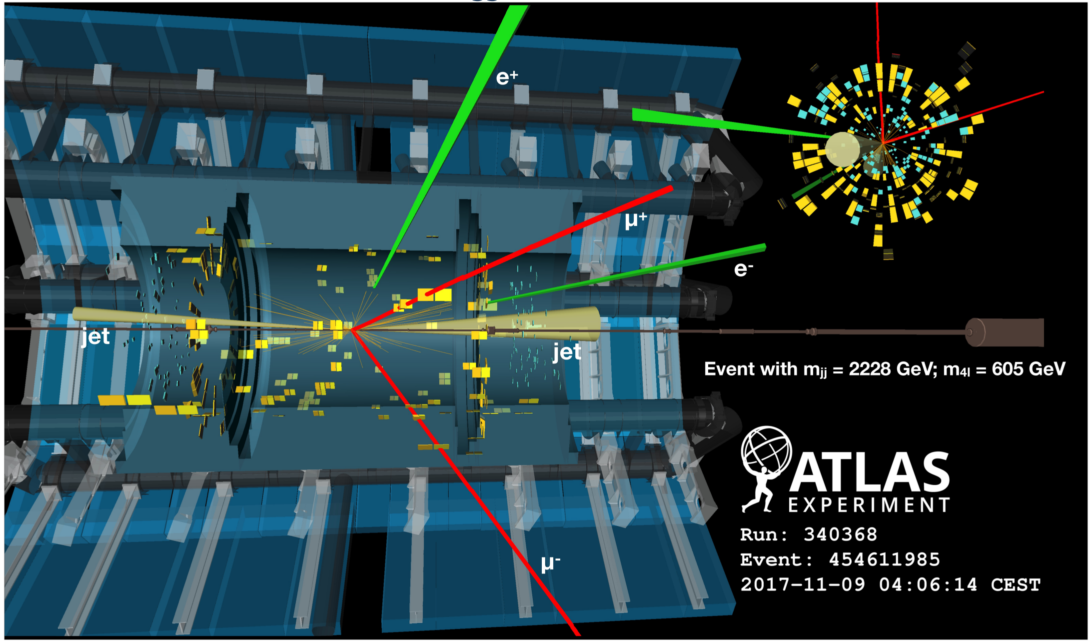
VBF/VBS Event Signature

- **Two jets with large rapidity separation and large invariant mass (m_{jj})**
- One or two **central** vector bosons (V=W or Z)



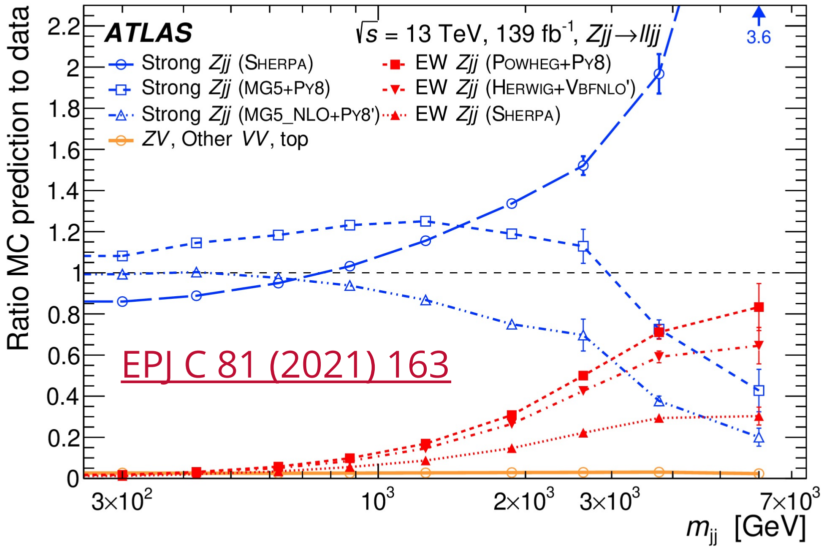


Candidate VBS ZZjj event

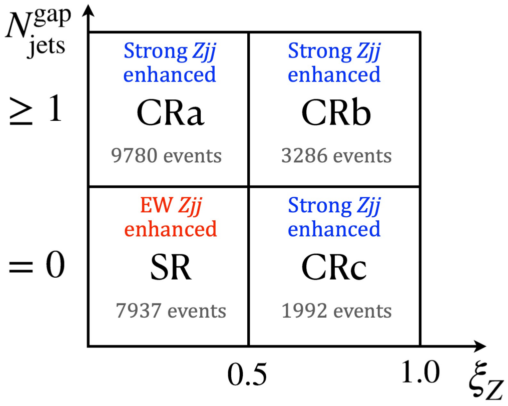


Zjj Production

Detailed event selection in backup

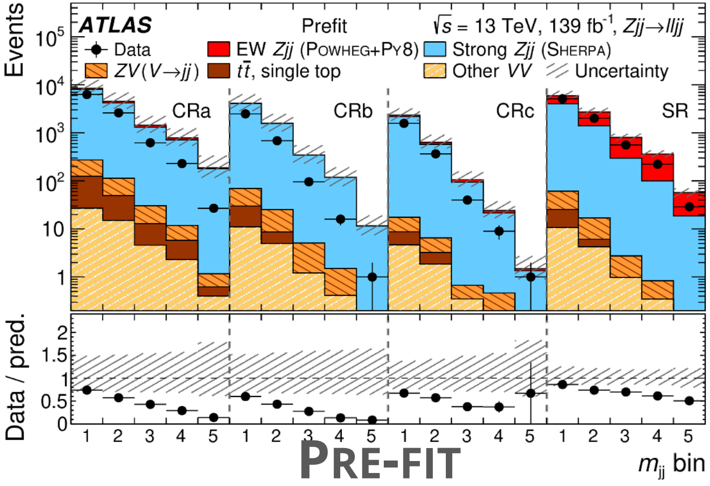


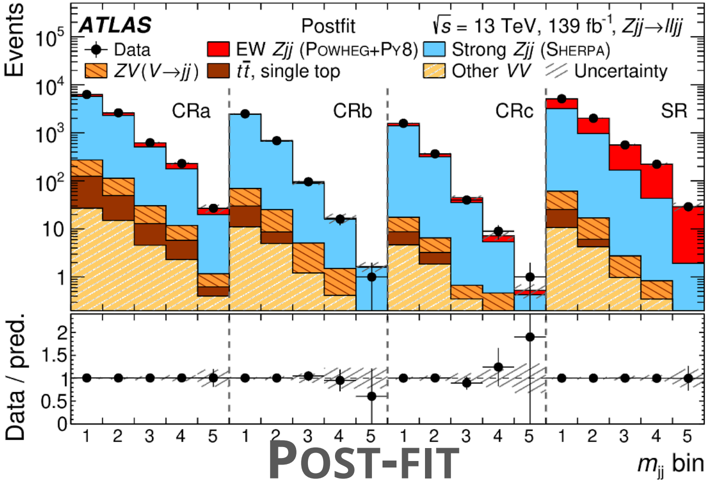
- Poor modelling of m_{jj} by MC event generators
  - Affecting both QCD/strong and EW Zjj
  - Mis-modelling of QCD Zjj especially acute in high-m_{jj} (signal region)
- Using data-driven background estimate

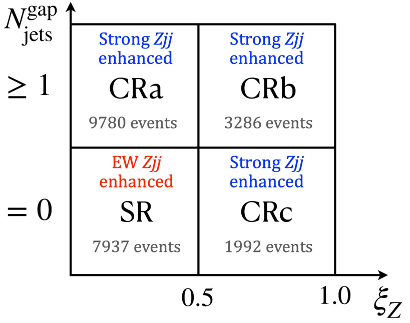


- Splitting in 4 regions according to:
  - Number of jets between the 2 leading jets (gap jets)
  - Centrality of the Z boson: $\xi_Z = |y_{ll} - ½ (y_{j1}+y_{j2})| / |\Delta y_{jj}|$
- Yields one EW-enhanced signal region and 3 strong-enhanced (control) regions

Zjj Production :: Fitting Procedure







Maximum likelihood fit performed to extract the EW Zjj signal

- ❖ Bin-by-bin weight for strong Zjj, separate between low and high centrality (linked between the two N_{jet} regions)
- ❖ Applying linear function to strong Zjj to correct for residual N_{jet} dependence
- ❖ Using same bin-by-bin weights for EW Zjj across all regions

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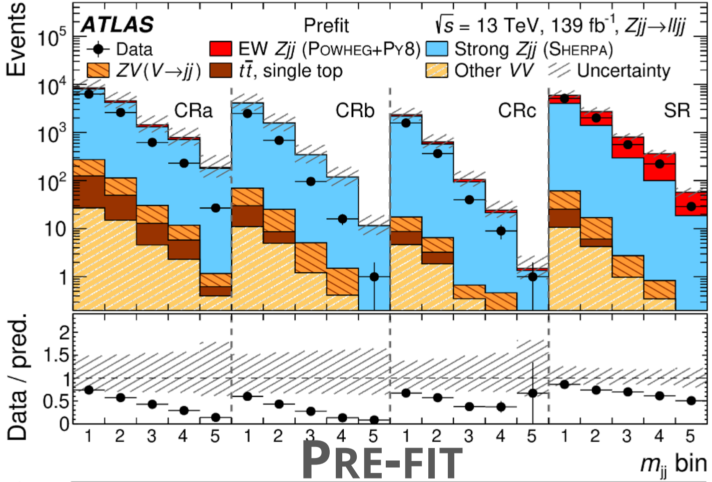
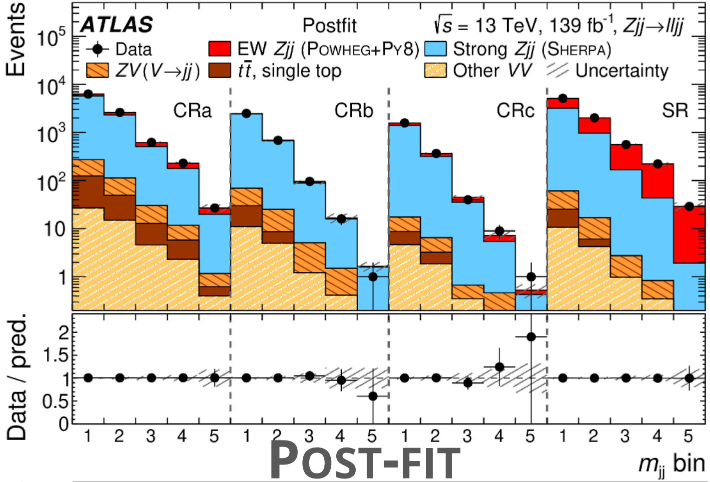
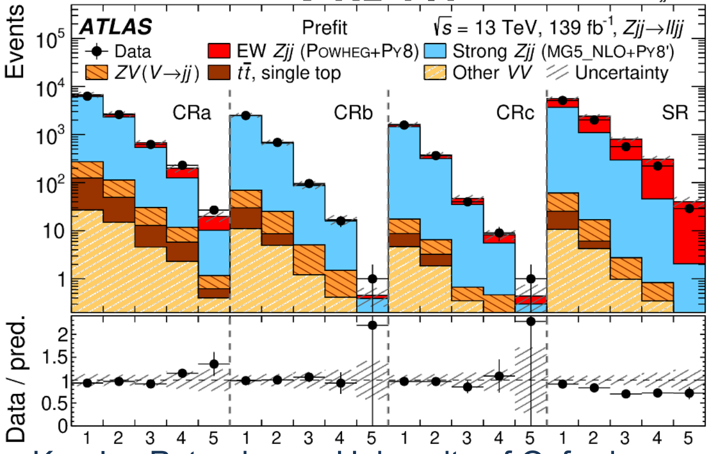
Zjj Production :: Fitting Procedure

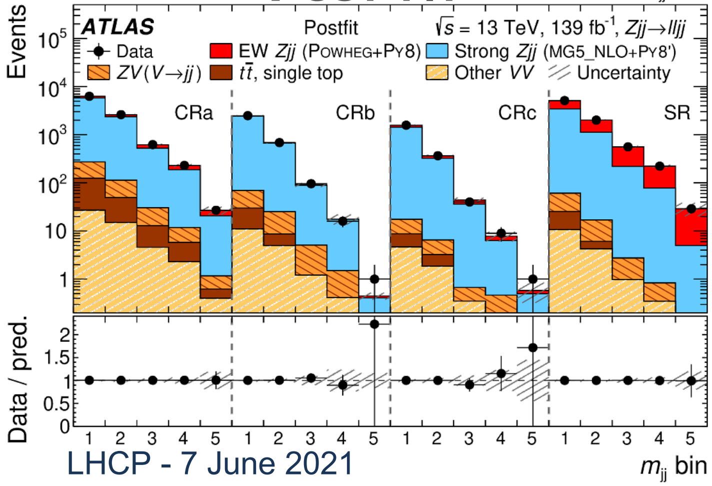


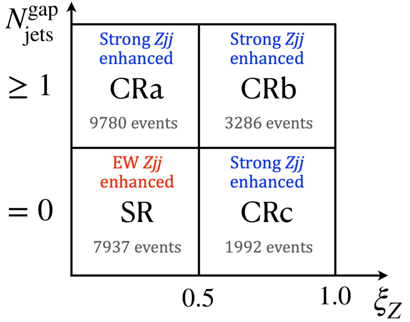


PRE-FIT

POST-FIT







Fitting for alternative generators

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Zjj Production :: Results

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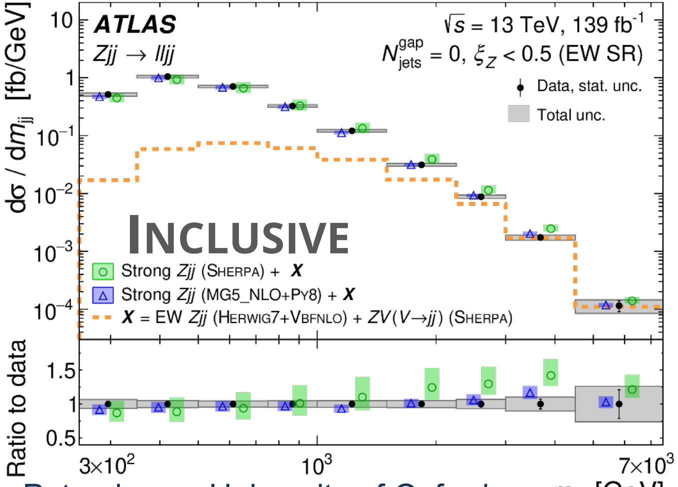
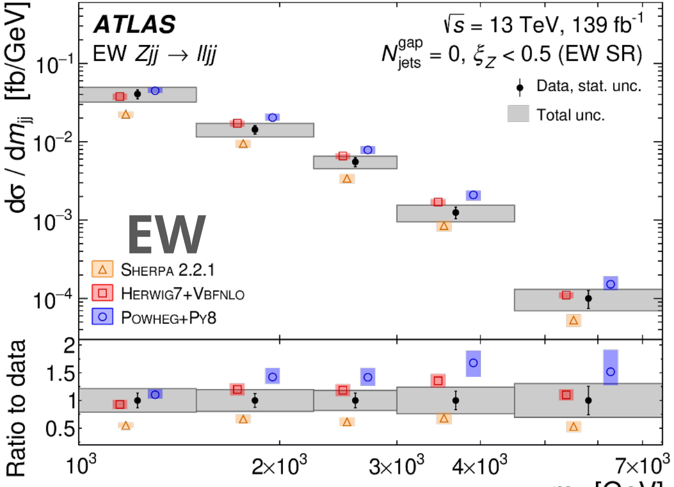
- Fiducial cross-section measurement in m_{jj}, $|\Delta y_{jj}|$, $p_{T,ll}$ and $\Delta\varphi_{jj}$ in SR
  - Inclusive cross-section also measured in CR
  - Data compared to various generators (for EW and strong)
- EW Zjj signal extracted for each of the 3 strong Zjj MC generators
  - Taking the result (midpoint) and dominant uncertainty from the envelope of 3 measurements
  - Integrated cross-section of 37.5 ± 3.5 (stat) ± 5.5 (sys) fb
  - In agreement with SM prediction of 39.5 ± 3.4 (scale) ± 1.2 (PDF) from Herwig7 + VBFNLO





Effective Field Theory Interpretation

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Constraining dim-6 operators in Warsaw basis

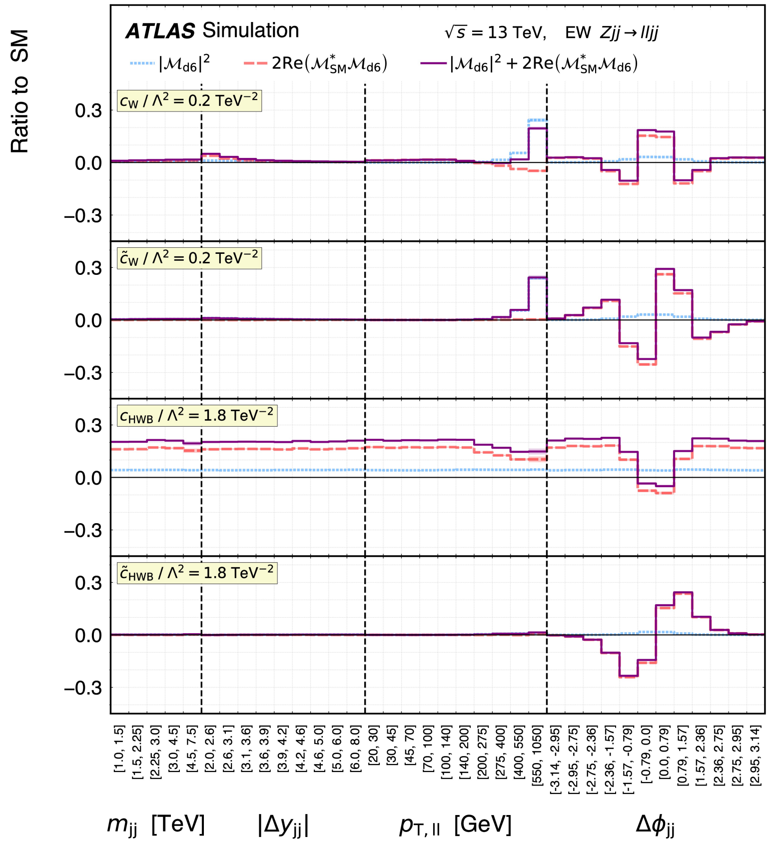
- CP-even: $\mathcal{O}_W$, $\mathcal{O}_{HWB}$; CP-odd: $\tilde{\mathcal{O}}_W$, $\tilde{\mathcal{O}}_{HWB}$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{d6}}) + |\mathcal{M}_{\text{d6}}|^2$$

Linear term is dominating: including $|Md_6|^2$ has no big effect

Wilson coefficient	Includes $\lvert\mathcal{M}_{\text{d6}}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]
	yes	[−0.31, 0.29]	[−0.19, 0.41]
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]
	yes	[−0.12, 0.12]	[−0.11, 0.14]
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]
	yes	[−3.11, 2.10]	[−6.31, 1.01]
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]
	yes	[−1.06, 1.06]	[0.23, 2.35]

Look Elsewhere Effect: there is a 6.2% probability for the SM to be outside of 95% CL when considering these for coefficients



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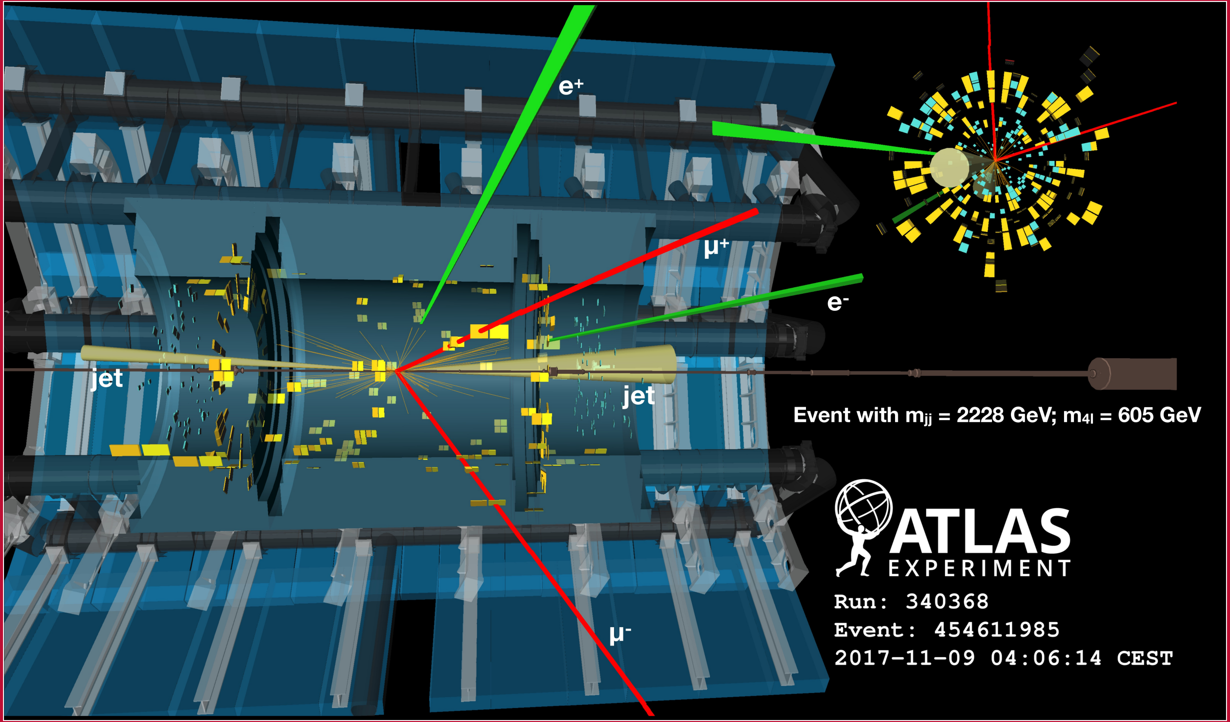


VBS ZZjj Production: Z → 4l OR Z → 2l2v

- ❖ Two jets with a large rapidity separation
- ❖ Large dijet invariant mass (m_{jj})

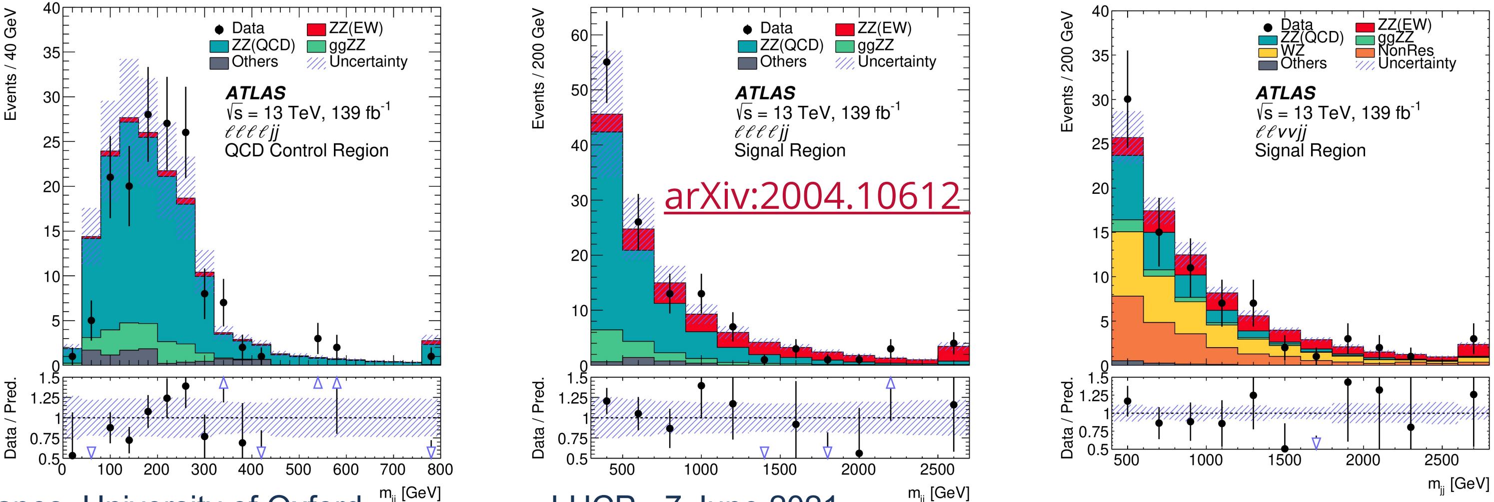
Inclusive ZZjj Production

Detailed event selection in backup

- Extracting inclusive cross-section in two SRs
- SR: EW selection + Z-mass (ll) window
  + 2 jets with $y_{j1} \cdot y_{j2} < 0$, $m_{jj} > 400/300$ GeV, $|\Delta y_{jj}| > 2$
- **Large bkg. from WZ and non-resonant ll in llννjj**

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

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

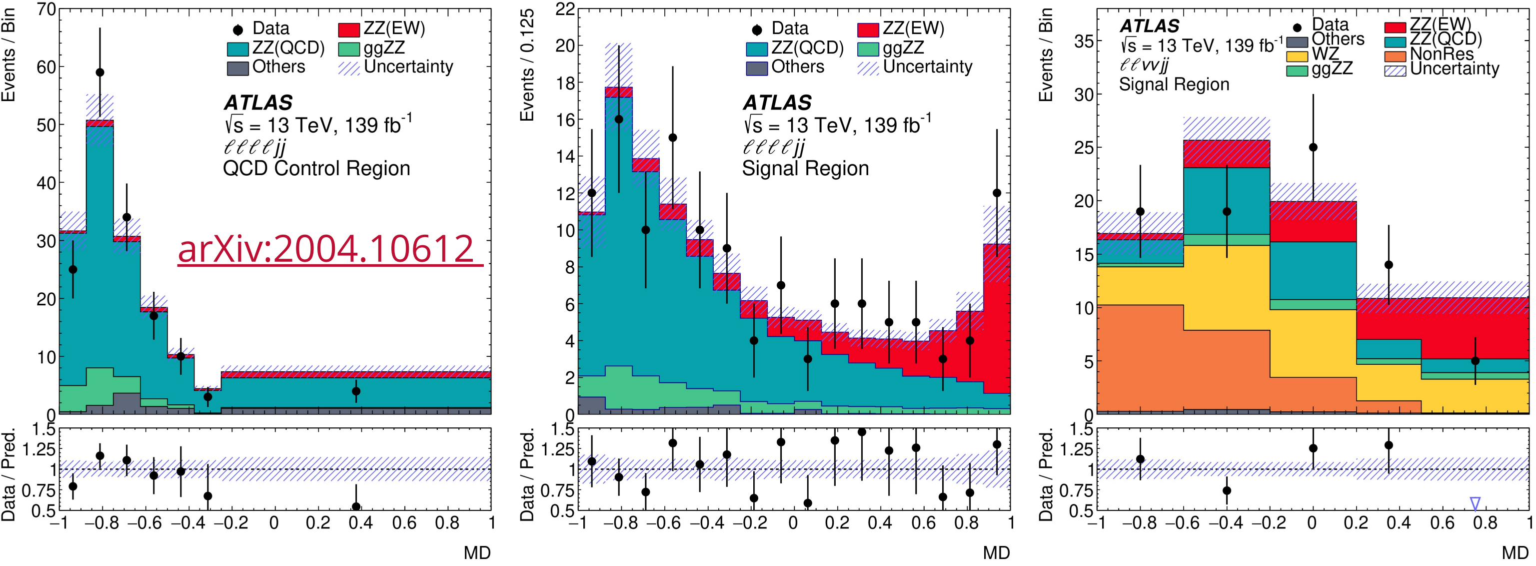


Electroweak ZZjj Production

- **Using BDT to separate EW and QCD ZZjj**
- Also fitting QCD CR to constrain background
- **EW ZZjj cross-section : 0.82 ± 0.21 fb**
  (one of the smallest measured by ATLAS)

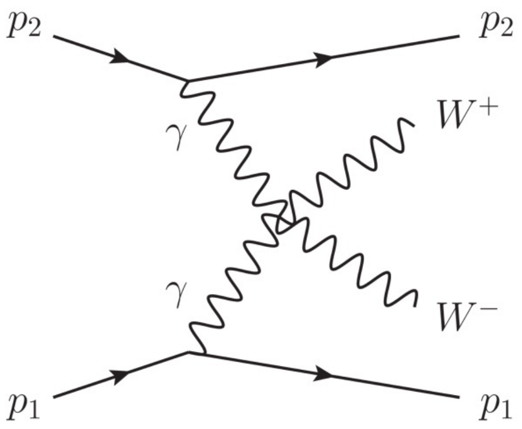
Observation of EW ZZjj (LO MG5+Pythia8)

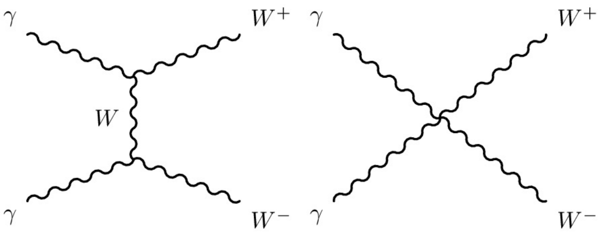
	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	$5.5\ (3.9)\ \sigma$
$\ell\ell\nu\nu jj$	$1.2\ (1.8)\ \sigma$
Combined	$5.5\ (4.3)\ \sigma$

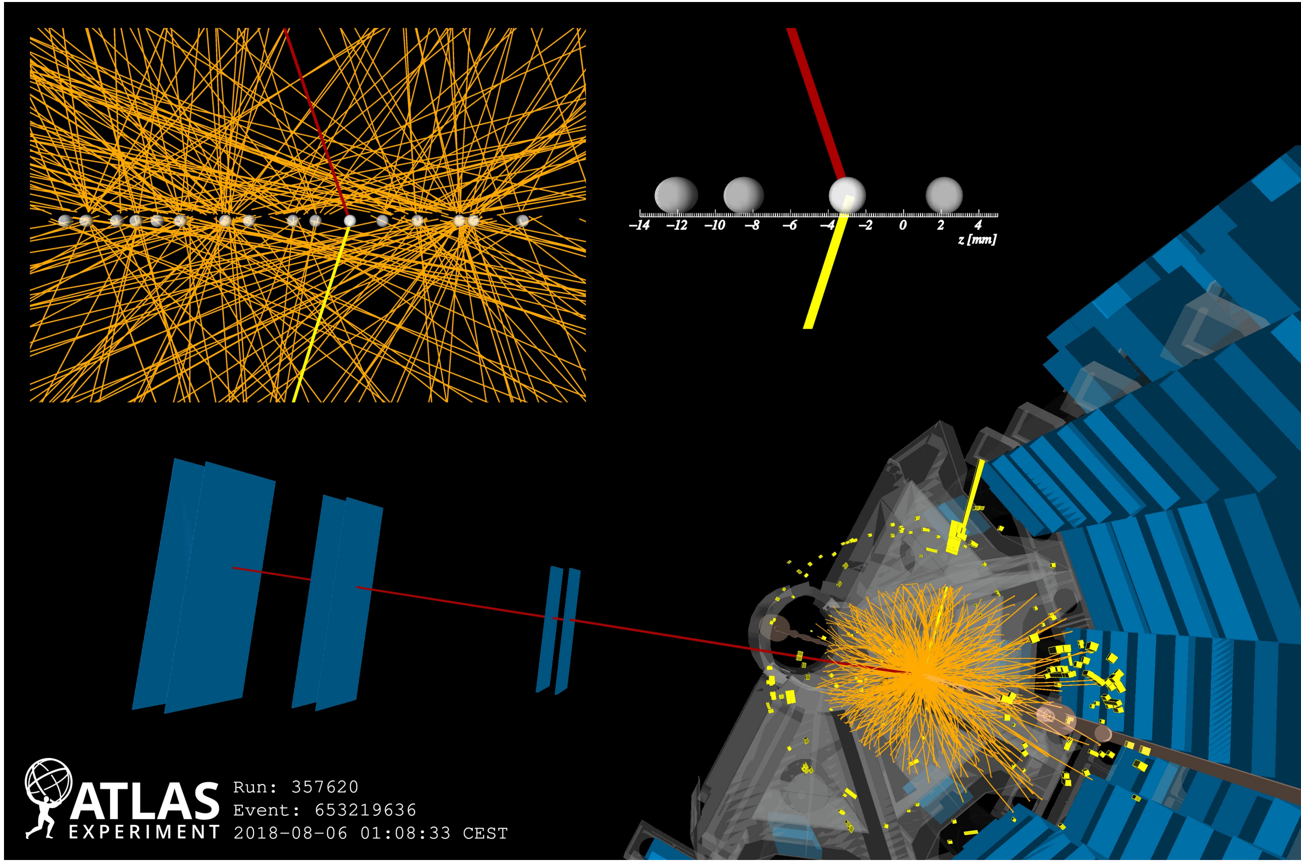


arXiv:2004.10612

Photon-induced WW :: γγ → WW

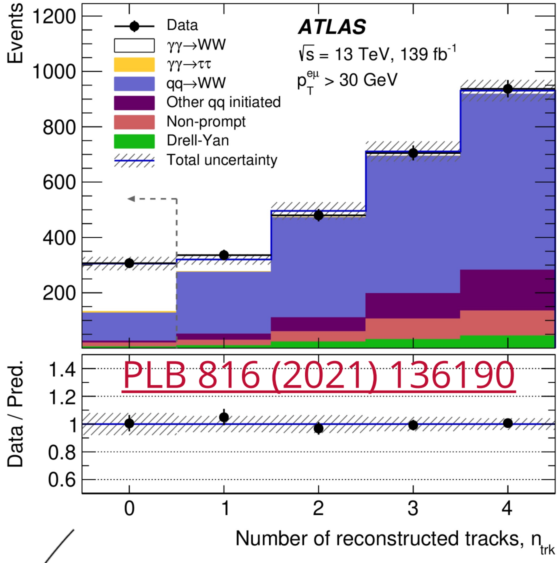






Photon-induced WW :: γγ → WW

σ(γγ→WW) = 3.13 ± 0.31(stat) ± 0.28(sys) fb
Observation: 8.4 σ



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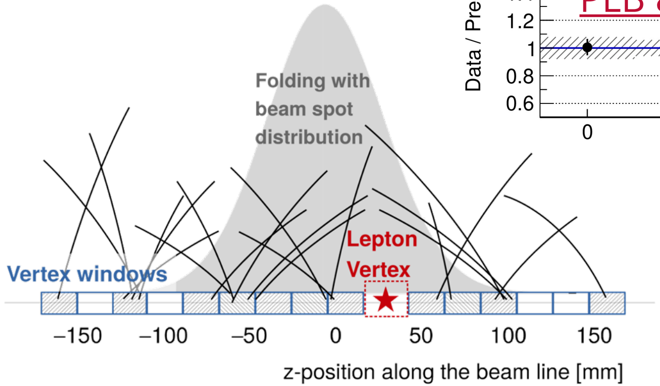


	Signal region	Control regions		
n_{trk}	$n_{\mathrm{trk}} = 0$		$1 \leq n_{\mathrm{trk}} \leq 4$	
$p_{\mathrm{T}}^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \to WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \to \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell–Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \to WW$ (incl. gg and VBS)	101 ± 17	55 ± 10	1700 ± 270	970 ± 150
Non-prompt	14 ± 14	36 ± 35	220 ± 220	500 ± 400
Other backgrounds	7.1 ± 1.7	1.9 ± 0.4	311 ± 76	81 ± 15
Total	305 ± 18	459 ± 19	2460 ± 60	6320 ± 130
Data	307	449	2458	6332

Source of uncertainty	Impact [% of the fitted cross section]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons, systematic	1.5
Misidentified leptons, statistical	5.9
Other background, statistical	3.2
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other background modelling	1.7
Luminosity	1.7
Total	8.9

Talk by Christophe Royon June 8 @ 15:27 CEST

The Start of a Long Journey

These sets of results using Run-2 data are ony the beginning…

As we learned to understand the backgrounds and signal, we can proceed with further probes:

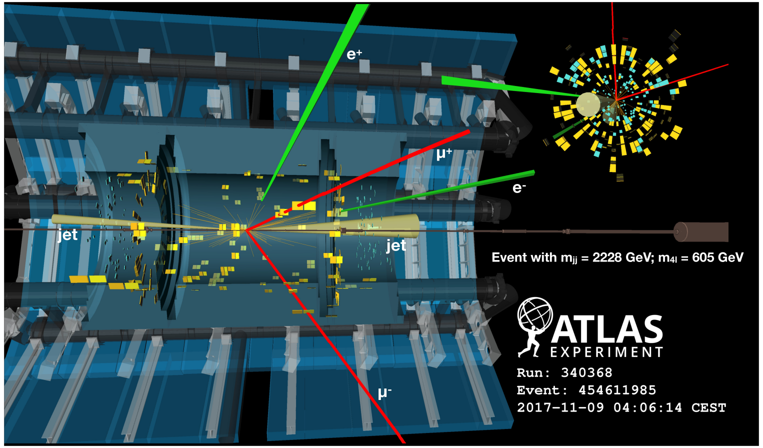
- ❖ **Differential distributions**
- ❖ **Probing polarisation**
- ❖ **Preparing for HL-LHC**

Stay tuned on this exciting field!

Summary

ZOOM room after session: https://cern.zoom.us/j/68001154922
(Same password as this session)

- The Vjj and VVjj final states are an **essential probe of EWSB**
  - Delicate cancellation of terms to achieve unitarity
  - **But very challenging to measure precisely**
- Comprehensive program within ATLAS to measure Vjj and VVjj
  - Background modelling is key to precisely measure these processes
- **More ATLAS results in the pipeline: Stay Tuned!**



Zjj (139 fb^{-1})

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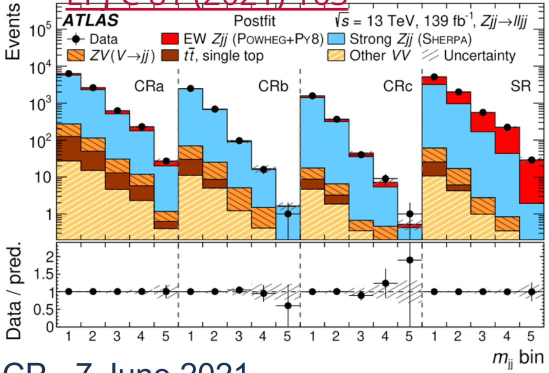
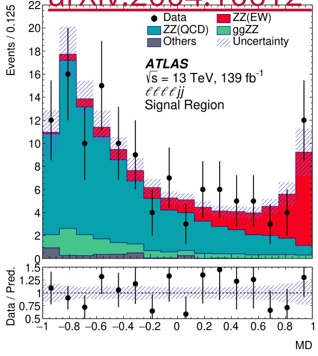


ZZjj (139 fb^{-1}): 5.5σ

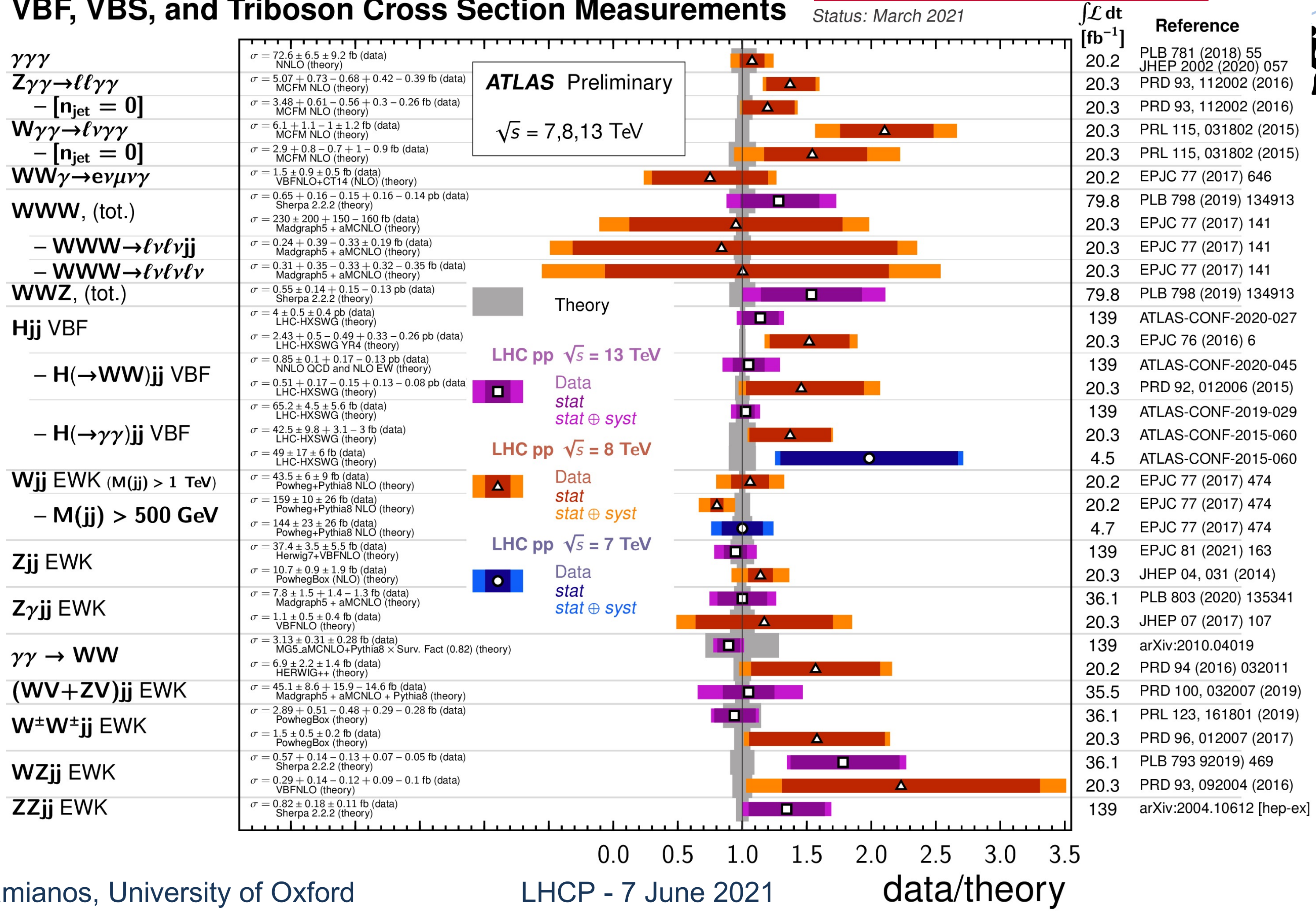
arXiv:2004.10612



VBF, VBS, and Triboson Cross Section Measurements

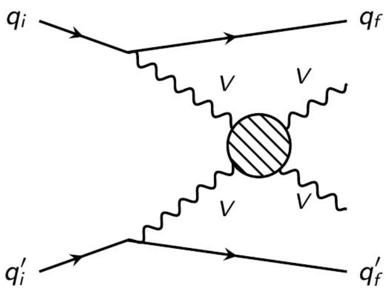
ATL-PHYS-PUB-2021-005

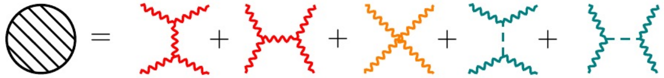
Status: March 2021



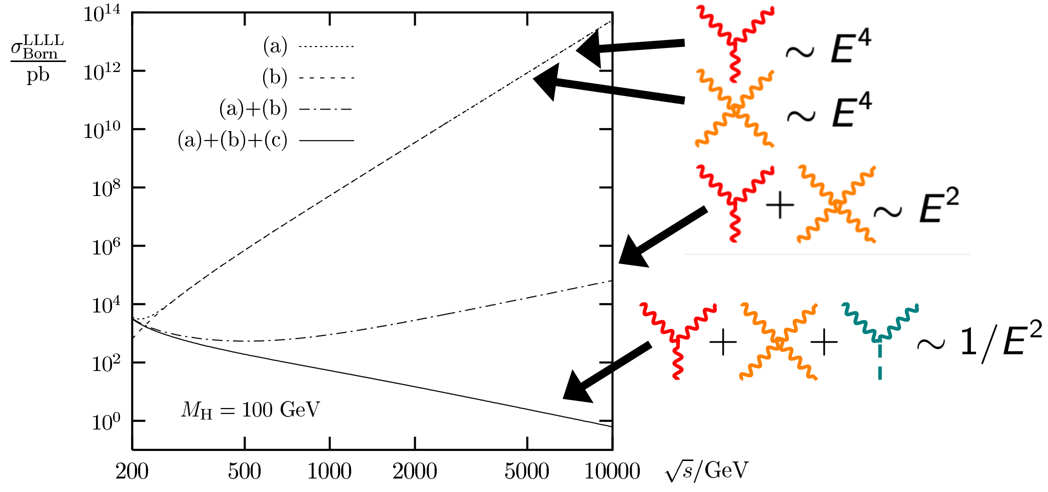
ADDITIONAL MATERIAL

Unraveling Electroweak Symmetry Breaking





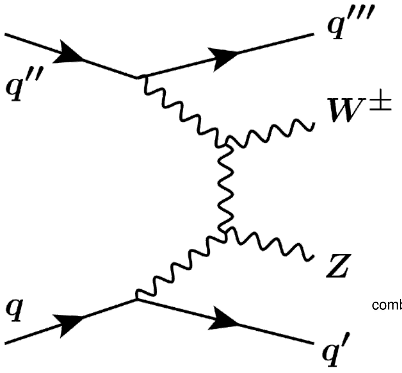
Denner, Hahn, Nucl.Phys.B525:27-50,1998

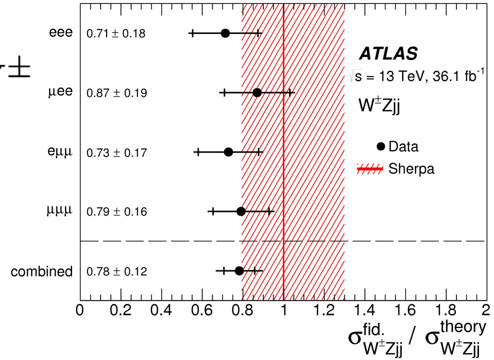


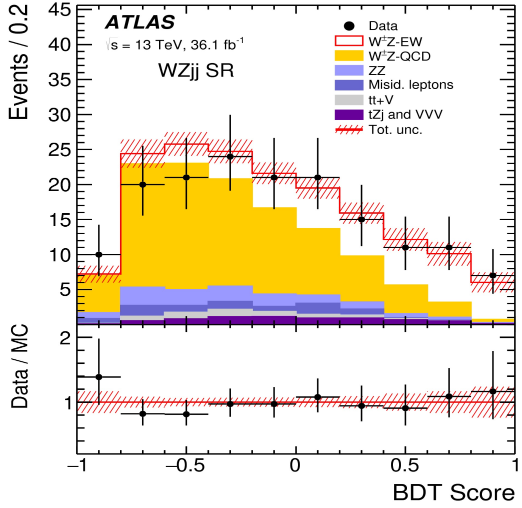
EW WZjj Production

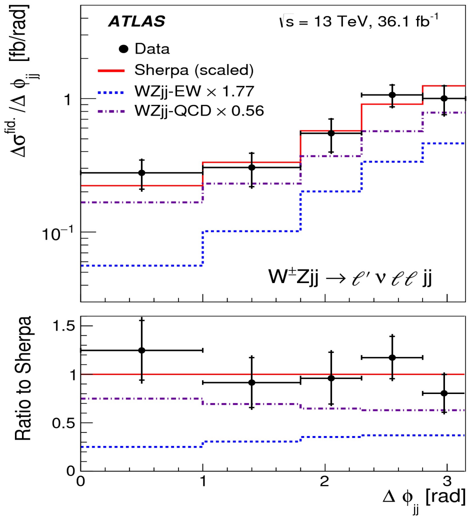
WZjj (36 fb^{-1}): 5.3σ

PLB 793 (2019) 469







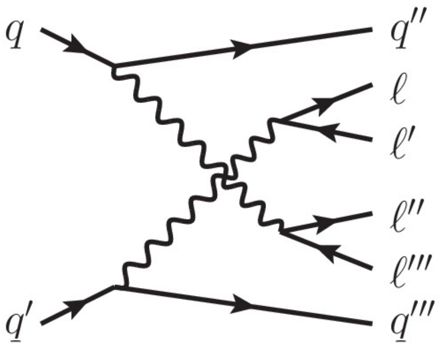


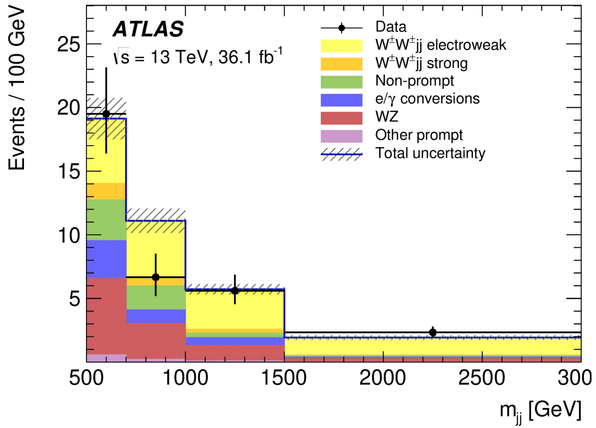
Source	Uncertainty [%]
$WZjj$−EW theory modelling	4.8
$WZjj$−QCD theory modelling	5.2
$WZjj$−EW and $WZjj$−QCD interference	1.9
Jets	6.6
Pile-up	2.2
Electrons	1.4
Muons	0.4
b-tagging	0.1
MC statistics	1.9
Misid. lepton background	0.9
Other backgrounds	0.8
Luminosity	2.1
Total Systematics	10.7

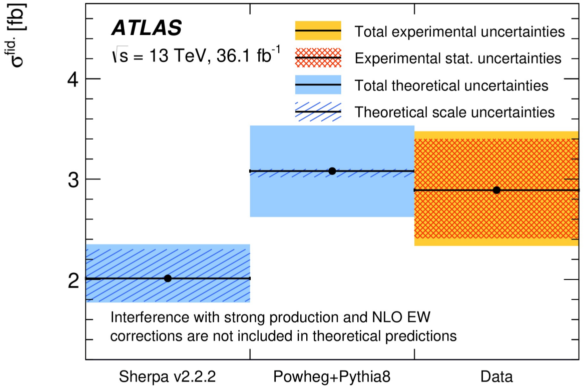
	SR	$WZjj$−QCD CR	b-CR	ZZ-CR
Data	161	213	141	52
Total predicted	167 ± 11	204 ± 12	146 ± 11	51.3 ± 7.0
$WZjj$−EW (signal)	44 ± 11	8.52 ± 0.41	1.38 ± 0.10	0.211 ± 0.004
$WZjj$−QCD	91 ± 10	144 ± 14	13.9 ± 3.8	0.94 ± 0.14
Misid. leptons	7.8 ± 3.2	14.0 ± 5.7	23.5 ± 9.6	0.41 ± 0.18
$ZZjj$−QCD	11.1 ± 2.8	18.3 ± 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

EW W±W±jj Production

W±W±jj (36 fb^{-1}): 6.5σ
PRL 123 (2019) 161801







Source	Impact [%]
Experimental	
Electrons	0.6
Muons	1.3
Jets and E_T^{miss}	3.2
b-tagging	2.1
Pileup	1.6
Background, statistical	3.2
Background, misid. leptons	3.3
Background, charge misrec.	0.3
Background, other	1.8
Theory modeling	
$W^\pm W^\pm jj$ electroweak-strong interference	1.0
$W^\pm W^\pm jj$ electroweak, EW corrections	1.4
$W^\pm W^\pm jj$ electroweak, shower, scale, PDF & α_s	2.8
$W^\pm W^\pm jj$ strong	2.9
WZ	3.3
Luminosity	2.4

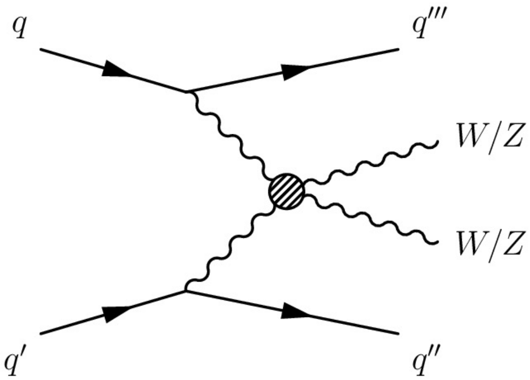
Observation using 36 fb^{-1}

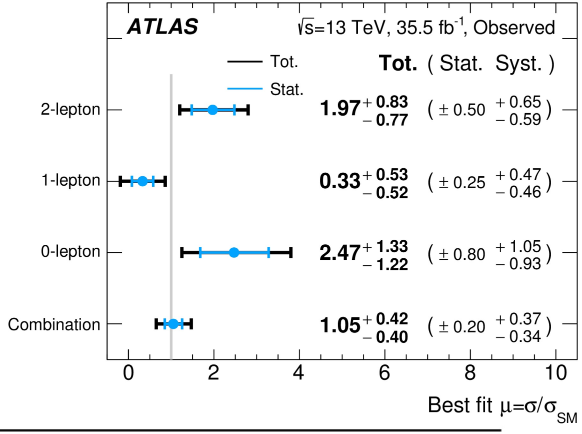
	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	Combined
WZ	1.48 ± 0.32	1.09 ± 0.27	11.6 ± 1.9	7.9 ± 1.4	5.0 ± 0.7	3.4 ± 0.6	30 ± 4
Non-prompt	2.2 ± 1.1	1.2 ± 0.6	5.9 ± 2.5	4.7 ± 1.6	0.56 ± 0.05	0.68 ± 0.13	15 ± 5
e/γ conversions	1.6 ± 0.4	1.6 ± 0.4	6.3 ± 1.6	4.3 ± 1.1	—	—	13.9 ± 2.9
Other 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

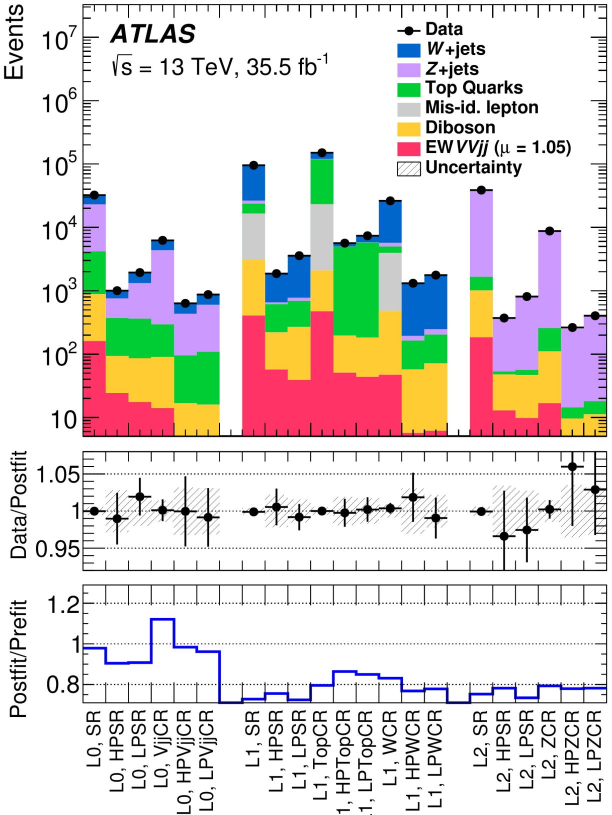
$$\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48}\,(\text{stat.})\,^{+0.24}_{-0.22}\,(\text{exp. syst.})\,^{+0.14}_{-0.16}\,(\text{mod. syst.})\,^{+0.08}_{-0.06}\,(\text{lumi.})\text{ fb}$$

EW VVjj Production

VVjj (36 fb^{-1}): 2.7σ
PRD 100 (2019) 032007







Fiducial phase space		Predicted $\sigma^{\text{fid,SM}}_{\text{EW}\,VVjj}$ [fb]	Measured $\sigma^{\text{fid,obs}}_{\text{EW}\,VVjj}$ [fb]
Merged	0-lepton	4.1 ± 0.3 (theo.)	10.1 ± 3.3 (stat.) $^{+4.2}_{-3.8}$ (syst.)
	1-lepton	6.1 ± 0.5 (theo.)	2.0 ± 1.5 (stat.) $^{+2.9}_{-2.8}$ (syst.)
	2-lepton	1.2 ± 0.1 (theo.)	2.4 ± 0.6 (stat.) $^{+0.8}_{-0.7}$ (syst.)
Resolved	0-lepton	9.2 ± 0.6 (theo.)	22.8 ± 7.4 (stat.) $^{+9.4}_{-8.5}$ (syst.)
	1-lepton	16.4 ± 1.0 (theo.)	5.5 ± 4.1 (stat.) $^{+7.7}_{-7.5}$ (syst.)
	2-lepton	6.0 ± 0.4 (theo.)	11.8 ± 3.0 (stat.) $^{+3.8}_{-3.5}$ (syst.)
Inclusive	0-lepton	13.3 ± 0.8 (theo.)	32.9 ± 10.7 (stat.) $^{+13.5}_{-12.3}$ (syst.)
	1-lepton	22.5 ± 1.5 (theo.)	7.5 ± 5.6 (stat.) $^{+10.5}_{-10.2}$ (syst.)
	2-lepton	7.2 ± 0.4 (theo.)	14.2 ± 3.6 (stat.) $^{+4.6}_{-4.2}$ (syst.)

Zjj Production :: Event Selection

Dressed muons	$p_T > 25$ GeV and $\|\eta\| < 2.4$
Dressed electrons	$p_T > 25$ GeV and $\|\eta\| < 2.37$ (excluding $1.37 < \|\eta\| < 1.52$)
Jets	$p_T > 25$ GeV and $\|y\| < 4.4$
VBF topology	$N_\ell = 2$ (same flavour, opposite charge), $m_{\ell\ell} \in (81, 101)$ GeV
	$\Delta R_{\min}(\ell_1, j) > 0.4,\ \Delta R_{\min}(\ell_2, j) > 0.4$
	$N_{\text{jets}} \geq 2,\ p_T^{j1} > 85$ GeV, $p_T^{j2} > 80$ GeV
	$p_{T,\ell\ell} > 20$ GeV, $p_T^{\text{bal}} < 0.15$
	$m_{jj} > 1000$ GeV, $\|\Delta y_{jj}\| > 2,\ \xi_Z < 1$
CRa	VBF topology $\oplus\ N_{\text{jets}}^{\text{gap}} \geq 1$ and $\xi_Z < 0.5$
CRb	VBF topology $\oplus\ N_{\text{jets}}^{\text{gap}} \geq 1$ and $\xi_Z > 0.5$
CRc	VBF topology $\oplus\ N_{\text{jets}}^{\text{gap}} = 0$ and $\xi_Z > 0.5$
SR	VBF topology $\oplus\ N_{\text{jets}}^{\text{gap}} = 0$ and $\xi_Z < 0.5$

Zjj Production :: MC Generators

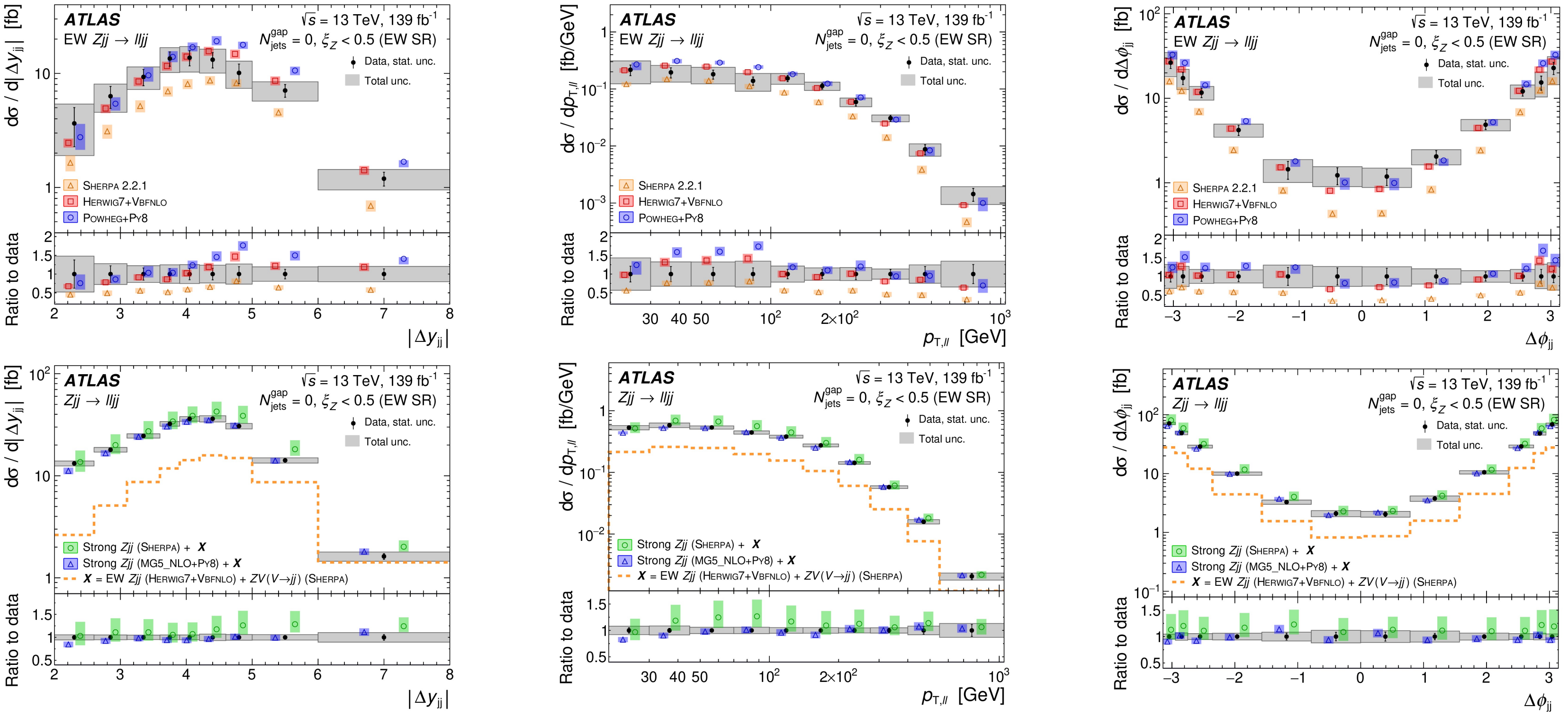
Process	Generator	ME accuracy	PDF	Shower and hadronisation	Parameter set
EW Zjj	Powheg-Box v1	NLO	CT10nlo	Pythia8 + EvtGen	AZNLO
	Herwig7 + Vbfnlo	NLO	MMHT2014lo	Herwig7 + EvtGen	default
	Sherpa 2.2.1	LO (2–4j)	NNPDF3.0nnlo	Sherpa	default
Strong Zjj	Sherpa 2.2.1	NLO (0–2j), LO (3–4j)	NNPDF3.0nnlo	Sherpa	default
	MadGraph5_aMC@NLO	NLO (0–2j), LO (3–4j)	NNPDF2.3nlo	Pythia8 + EvtGen	A14
	MadGraph5	LO (0–4j)	NNPDF3.0lo	Pythia8 + EvtGen	A14
VV	Sherpa	NLO (0–1j), LO (2–3j)	NNPDF3.0nnlo	Sherpa	default
$t\bar{t}$	Powheg-Box v2 hvq	NLO	NNPDF3.0nnlo	Pythia8 + EvtGen	A14
VVV	Sherpa	LO (0–1j)	NNPDF3.0nnlo	Sherpa	default
W+jets	Sherpa	NLO (0–2j), LO (3–4j)	NNPDF3.0nnlo	Sherpa	default

Zjj Production :: (Pre-Fit) Event Yields

Sample	$Z \to ee$	$Z \to \mu\mu$
Data	10 870	12 125
EW Zjj (Powheg+Py8)	2670 ± 120 ± 280	2740 ± 120 ± 290
EW Zjj (Sherpa)	1280 ± 60 ± 140	1350 ± 60 ± 150
EW Zjj (Herwig7+Vbfnlo′)	2290 ± 100 ± 210	2350 ± 100 ± 220
Strong Zjj (Sherpa)	13 500 ± 600 ± 4500	15 100 ± 600 ± 5000
Strong Zjj (MG5+Py8)	13 140 ± 480 ± N/A	14 810 ± 540 ± N/A
Strong Zjj (MG5_NLO+Py8′)	8800 ± 300 ± 1000	10 000 ± 400 ± 1200
ZV ($V \to jj$)	179 ± 8 ± 6	178 ± 8 ± 6
Other VV	45 ± 2 ± 2	45 ± 2 ± 2
$t\bar{t}$, single top	92 ± 8 ± 6	98 ± 8 ± 6
$W(\to \ell\nu)$+jets, $Z(\to \tau\tau)$+jets	negligible	negligible

Zjj Production :: Results

- Also performing measurement using of observables: $|\Delta y_{jj}|$, $p_{T,ll}$ and $\Delta\phi_{jj}$



ZZjj Production :: Event Selection

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_{\mathrm{T}} > 7$ GeV, $\|\eta\| < 2.47$	$p_{\mathrm{T}} > 7$ GeV, $\|\eta\| < 2.5$
Muons	$p_{\mathrm{T}} > 7$ GeV, $\|\eta\| < 2.7$	$p_{\mathrm{T}} > 7$ GeV, $\|\eta\| < 2.5$
Jets	$p_{\mathrm{T}} > 30$ (40) GeV for $\|\eta\| < 2.4$ ($2.4 < \|\eta\| < 4.5$)	$p_{\mathrm{T}} > 60$ (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 $\|m_{\ell^+\ell^-} - m_Z\| + \|m_{\ell'^+\ell'^-} - m_Z\|$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $60 < m_{\ell^+\ell^-} < 120$ 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 $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 400$ GeV and $\Delta y(jj) > 2$