Measurements of Vector-boson production via weak-boson fusion at ATLAS

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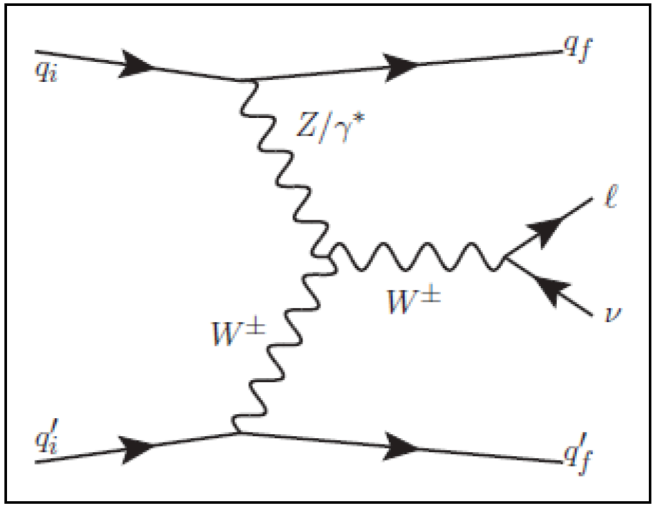
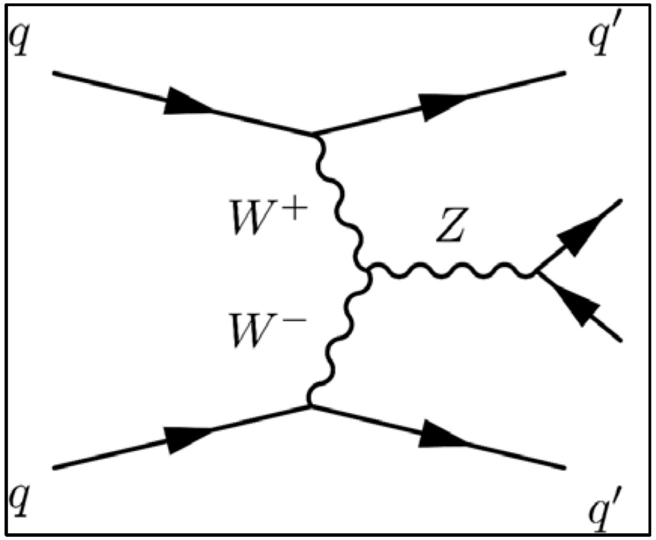
VBF

- Non-abelian nature of SM allows self-interactions of weak bosons
- Vector Boson Fusion (VBF) & Vector Boson Scattering (VBS) are key processes for studying the mechanism of EWSB
- In the latest ATLAS Zjj measurement with full Run2 data: arxiv.org/abs/2006.15458
  - Differential x-sections
  - Four variables: $p_{T,ll}$, m_{jj}, rapidity separation of two jets $|\Delta y_{jj}|$, signed azimuthal angle between two jets $\Delta\phi_{jj}$
  - Probe kinematic properties of VBF
  - Make constraints on anomalous weak-boson interactions

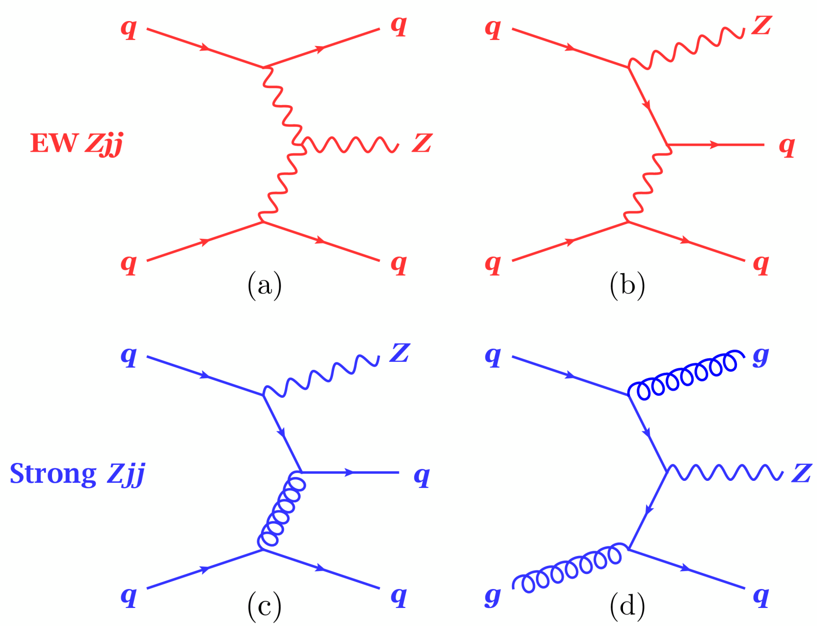




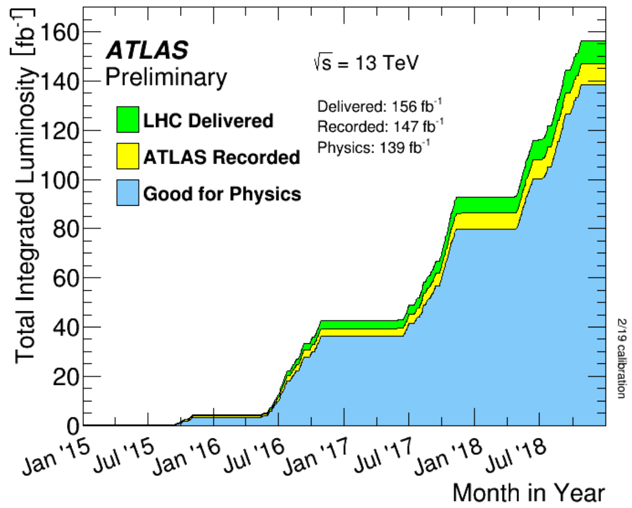
Measurement of Zjj

arxiv.org/abs/2006.15458

- Zjj: t-channel exchange of weak boson, extremely sensitive to VBF
  - Z-> e^+e^- or $\mu^+\mu^-$, 139 fb^{-1} Run2 @13 TeV, 2015 to 2018
- Model-independent measurement, to compare generator performance
- Simulation:
  - Signal: EW Zjj (Powheg, Herwig, Sherpa)
  - Dominant bkgd: Strong Zjj (Sherpa, NLO MG5_aMC, LO MG5)
  - Others: VV, tt, VVV, W+jets



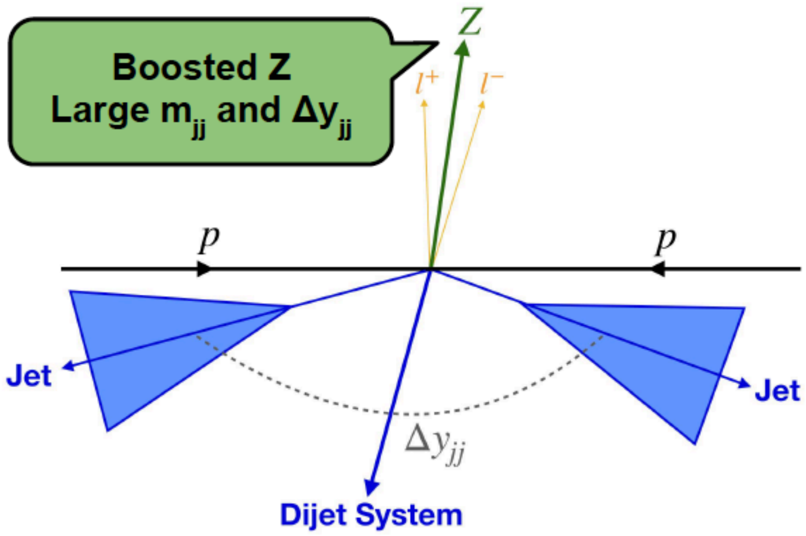
Process	Generator	ME accuracy	PDF	Shower and hadronisation	Parameter set
EW Zjj	Powheg-Box v1	NLO	CT10nlo	Pythia8 + EvtGen	AZNLO
	Herwig7 + Vbfnlo	NLO	MMHT2014lo	Herwig7 + EvtGen	default
	Sherpa 2.2.1	LO (2–4j)	NNPDF3.0nnlo	Sherpa	default
Strong Zjj	Sherpa 2.2.1	NLO (0–2j), LO (3–4j)	NNPDF3.0nnlo	Sherpa	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



Event Selection

arxiv.org/abs/2006.15458

- Select events consistent with EW Zjj topology
  - Opposite charge, same flavor lepton pair
  - Dijet system: m_{jj}>1 TeV, $|\Delta y_{jj}|$>2.0
  - Z boson centrally produced relative to dijet
  - Z boson & dijet required to be approximately balanced in transverse momentum



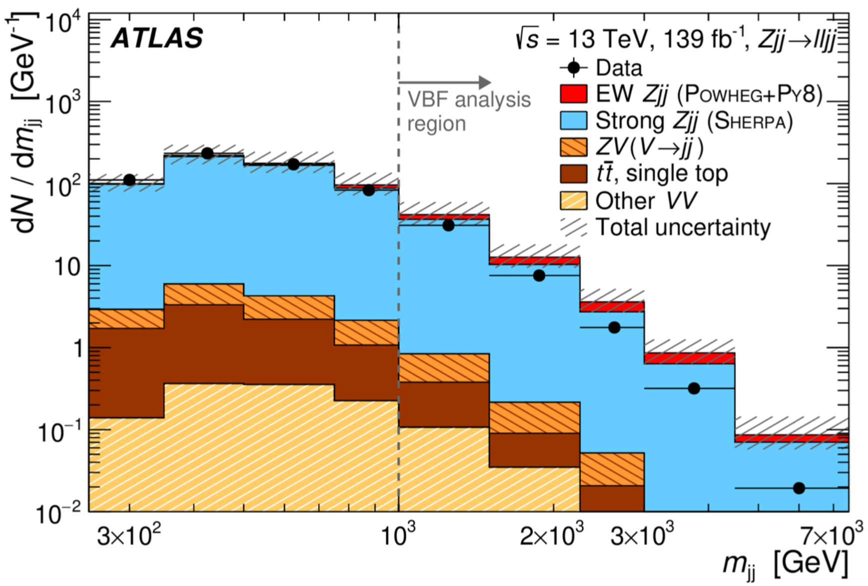
Sample	$Z \to ee$	$Z \to \mu\mu$
Data	10 870	12 125
EW Zjj (Powheg+Py8)	2670 ± 120 ± 280	2740 ± 120 ± 290
EW Zjj (Sherpa)	1280 ± 60 ± 140	1350 ± 60 ± 150
EW Zjj (Herwig7+VbfNLO′)	2290 ± 100 ± 210	2350 ± 100 ± 220
Strong Zjj (Sherpa)	13 500 ± 600 ± 4500	15 100 ± 600 ± 5000
Strong Zjj (MG5+Py8)	13 140 ± 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

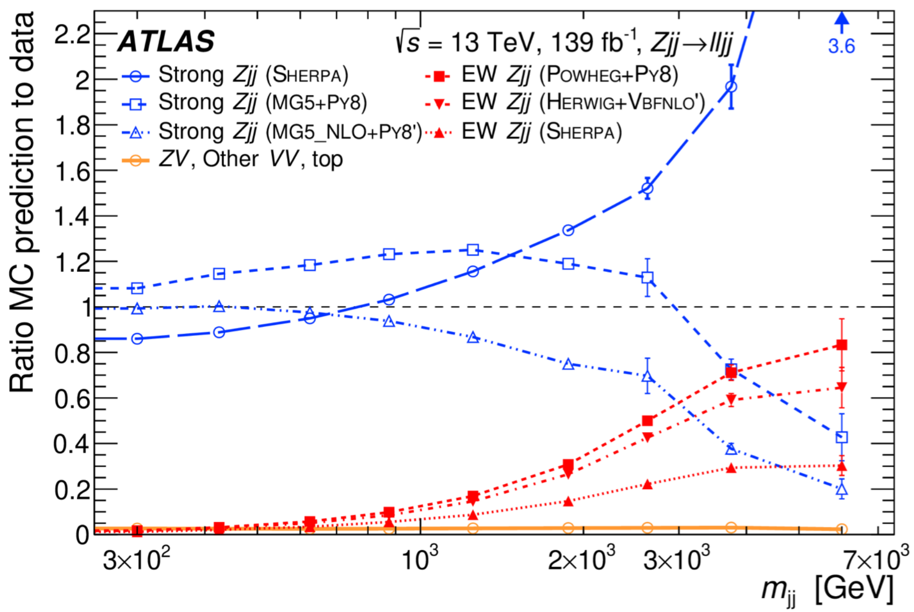
- Large spread of EW and strong Zjj prediction among different generators
- Large uncertainty of strong Zjj prediction, due to theory
- Disagreement between data and MC in event yields. In addition, key variables distributions also indicate the shape differences

Modelling

arxiv.org/abs/2006.15458

- **Modelling:**
  - **Poor data/MC agreement prohibits extracting signal by simply subtracting background prediction**
  - **Mismodelling also correlates with generators**
- **Data-driven method is used to constrain shape and normalization of strong Zjj while extracting EW Zjj**





Signal Extraction

arxiv.org/abs/2006.15458

- **Four regions are defined based on ξ_Z and jet multiplicity in the rapidity interval between leading and subleading jet** $\xi_Z = |y_{\ell\ell} - 0.5(y_{j1} + y_{j2})| \,/\, |\Delta y_{jj}|$
- **EW Zjj event yield is extracted in SR by binned maximum-likelihood fit, in all 4 regions simultaneously.**

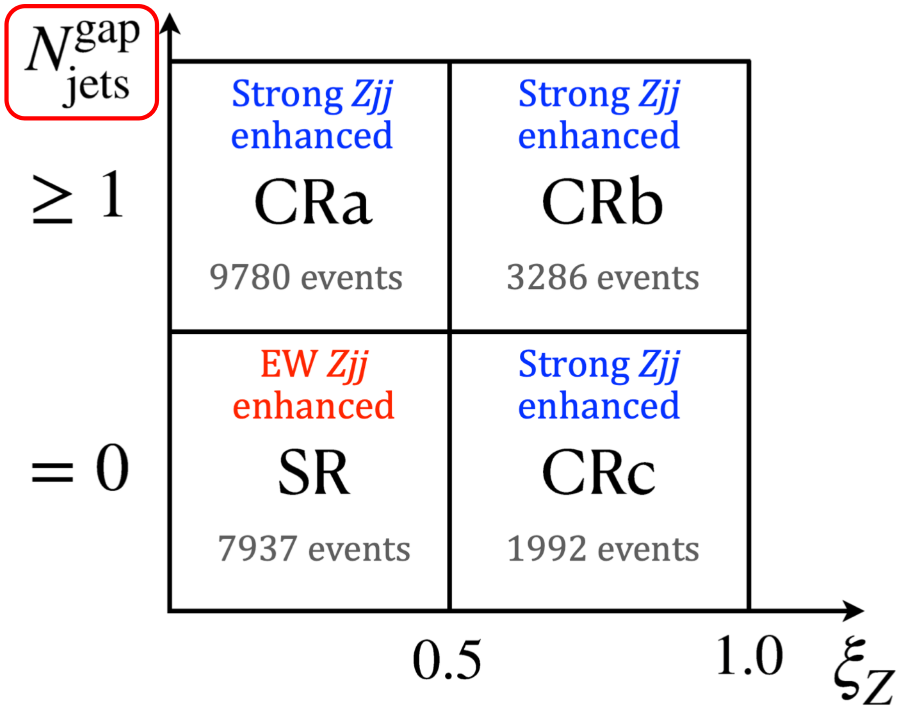
$$\ln \mathcal{L} = -\sum_{r,i} \nu_{ri}(\boldsymbol{\theta}) + \sum_{r,i} N_{ri}^{\text{data}} \ln \nu_{ri}(\boldsymbol{\theta}) - \sum_{s} \frac{\theta_s^2}{2}$$

$$\nu_{ri} = \mu_i \, \nu_{ri}^{\text{EW,MC}} + \nu_{ri}^{\text{strong}} + \nu_{ri}^{\text{other,MC}}$$

$$\nu_{\text{CRa},i}^{\text{strong}} = b_{\text{L},i} \, \nu_{\text{CRa},i}^{\text{strong,MC}}, \qquad \nu_{\text{CRb},i}^{\text{strong}} = b_{\text{H},i} \, \nu_{\text{CRb},i}^{\text{strong,MC}},$$

$$\nu_{\text{SR}i}^{\text{strong}} = b_{\text{L},i} \, f(x_i) \, \nu_{\text{SR},i}^{\text{strong,MC}}, \qquad \nu_{\text{CRc},i}^{\text{strong}} = b_{\text{H},i} \, f(x_i) \, \nu_{\text{CRc},i}^{\text{strong,MC}}$$

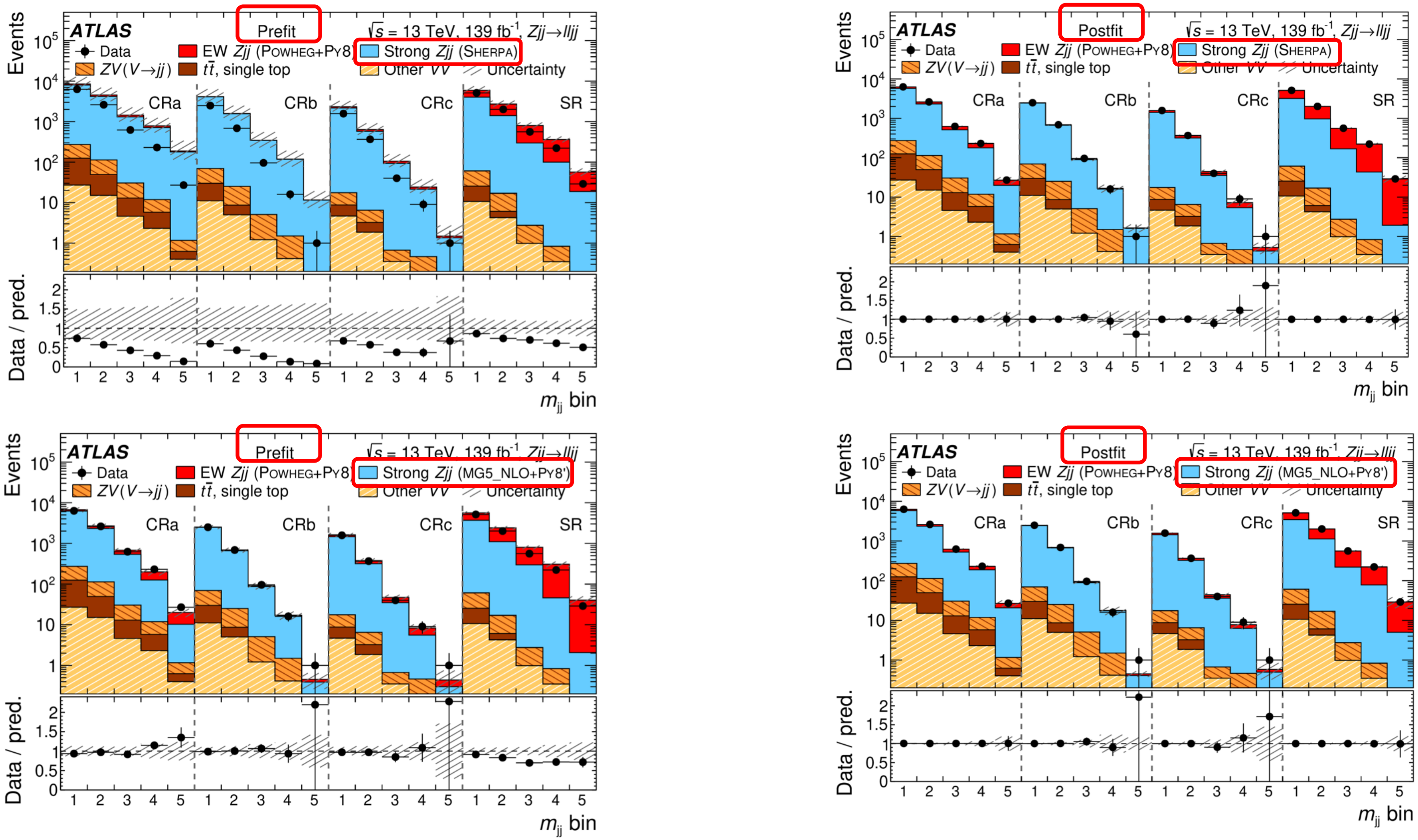
- μ_i : EW Zjj signal strength
- $b_{\text{L},i}$ and $b_{\text{H},i}$: adjusted to match prediction in CRa and CRb with data.
- $f(x_i)$ provides residual correction for extrapolation from CRa to SR



Signal Extraction

arxiv.org/abs/2006.15458

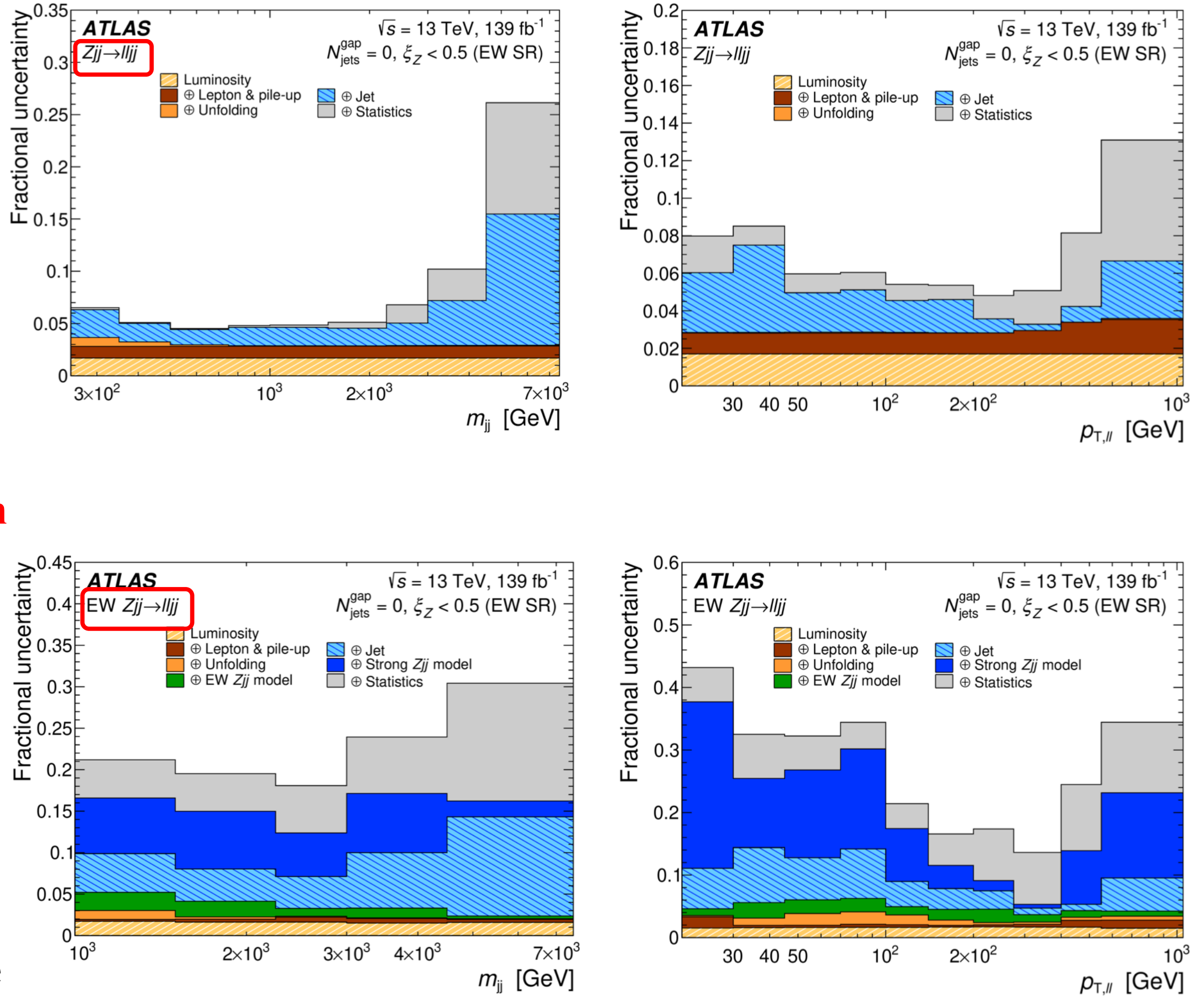
- EW Zjj is extracted by using different strong Zjj generators: Sherpa, NLO MG5_aMC, LO MG5
  - Different mismodelling before fits, but reach good data/MC agreement after fits
- Final EW Zjj signal is taken to be midpoint of the envelope of yields from the 3 different strong Zjj generators, which is also used to estimate the systematic.



Systematic Uncertainties

arxiv.org/abs/2006.15458

- **Dominant Systematics:**
  - **Jet dominates inclusive Zjj result**
  - **Strong Zjj modelling dominates EW Zjj result**
    - **Generator choice**
    - **Renormalization and factorization scale**
    - **PDF**
  - **Statistics**
- **Various MC generators are used in SR and CR to estimate theory uncertainty**



EW Zjj Production

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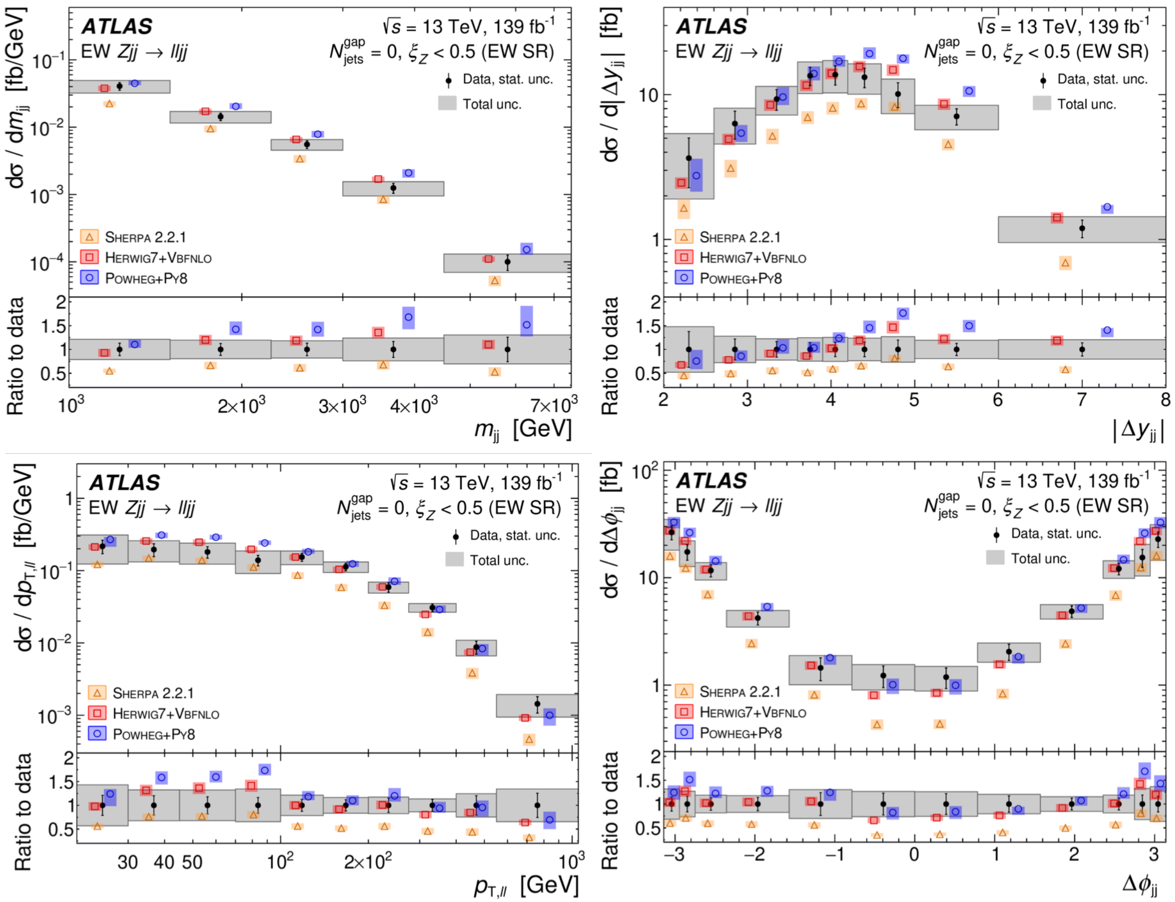
- **Differential x-sect as function of m_{jj}, $|\Delta y_{jj}|$, $p_{T,ll}$, $\Delta\phi_{jj}$, providing constraints on theory model to be used for future VBF and VBS measurements**
  - **Herwig7+VBFNLO reasonably agrees with data**
  - **Powheg+PY8 overestimates at high m_{jj}, high $|\Delta y_{jj}|$, intermediate $p_{T,ll}$**
  - **Sherpa significantly underestimates due to non-optimal setting of color flow**

$$\sigma_{EW} = 37.4 \pm 3.5\,(\text{stat}) \pm 5.5\,(\text{syst})\ \text{fb}$$

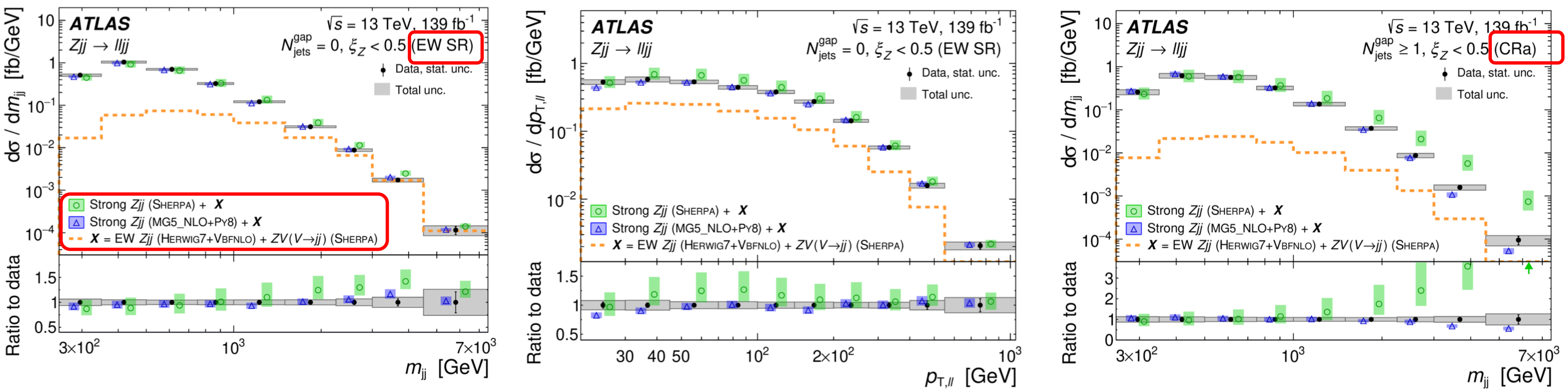
In excellent agreement with Herwig7+VBFNLO prediction:

39.5 ± 3.4 (scale) ± 1.2 (PDF) fb



Inclusive Zjj Production

- Differential x-sect as function of m_{jj}, $|\Delta y_{jj}|$, $p_{T,ll}$, $\Delta\phi_{jj}$, are measured in SR and CR, which can be used to re-evaluate EW Zjj when new Strong Zjj prediction is available
  - Strong Zjj: Sherpa and MG5_NLO+PY8
  - EW Zjj: Herwig7+VBFNLO
  - VZ: Sherpa, small contribution
- Overall, data is better described by MG5_NLO+PY8



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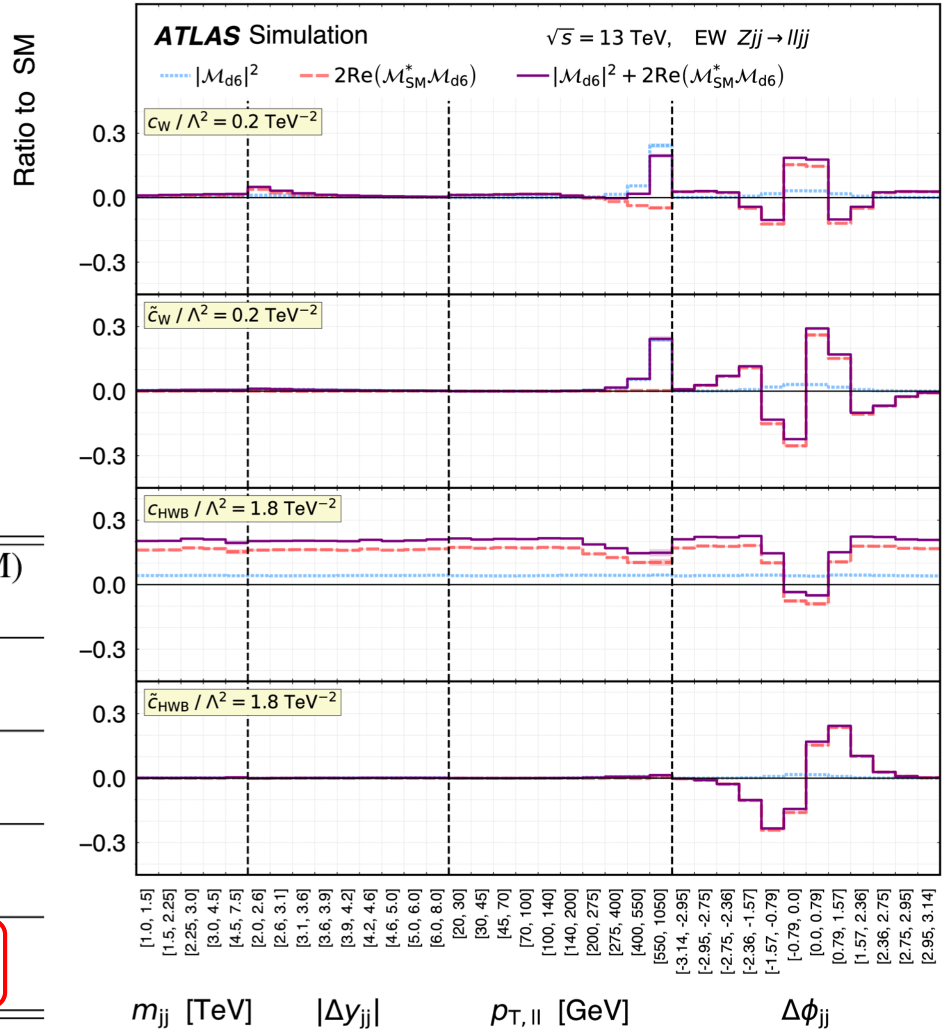
Anomalous Weak-boson Interactions

- **Constraints are placed on dimension-6 operators in Warsaw basis**
  - **CP-even: (O_W, O_{HWB})**
  - **CP-odd: ($\tilde{O}_W$, $\tilde{O}_{HWB}$)**
- **$\Delta\phi_{jj}$ is more sensitive to anomalous interactions and therefore used to constrain Wilson coefficients**
  - **Constraints on dimension-6 operators, derived with and without pure dimension-6 terms, show much less sensitivity from the pure dimension-6 terms**

EFT: $\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i$

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

Wilson coefficient	Includes $\lvert\mathcal{M}_{\mathrm{d6}}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%



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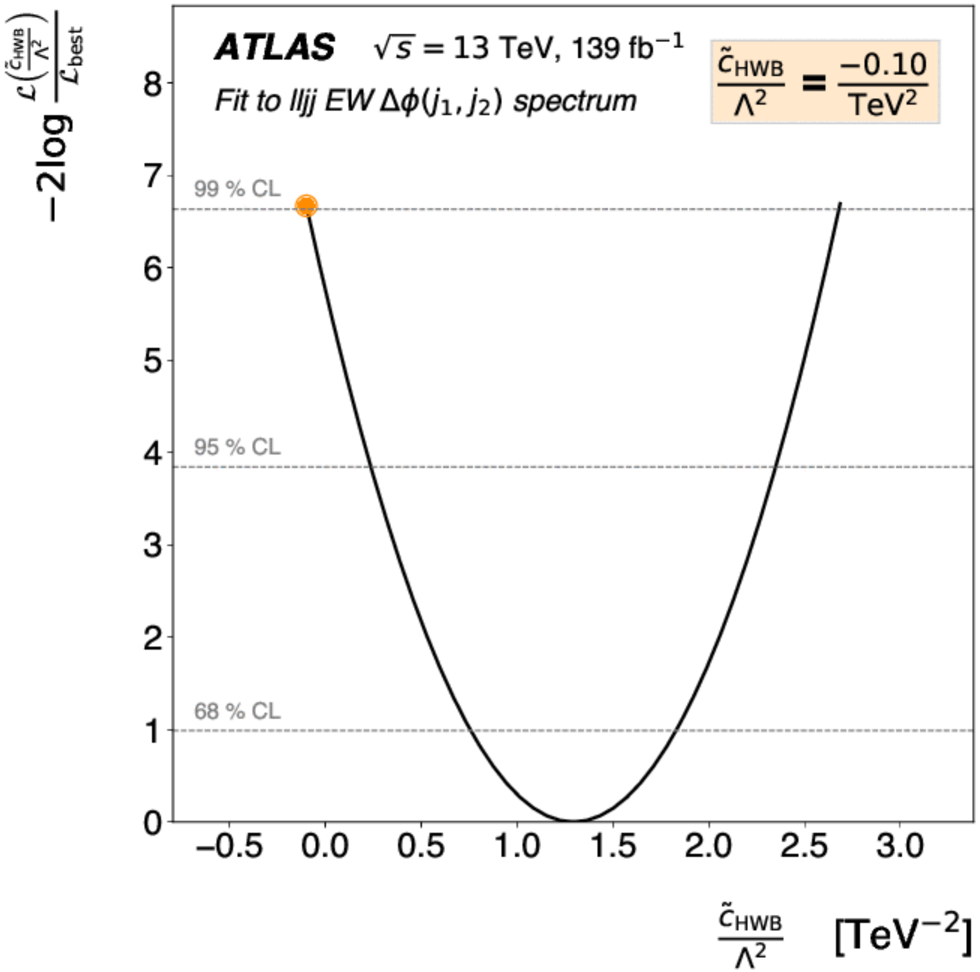
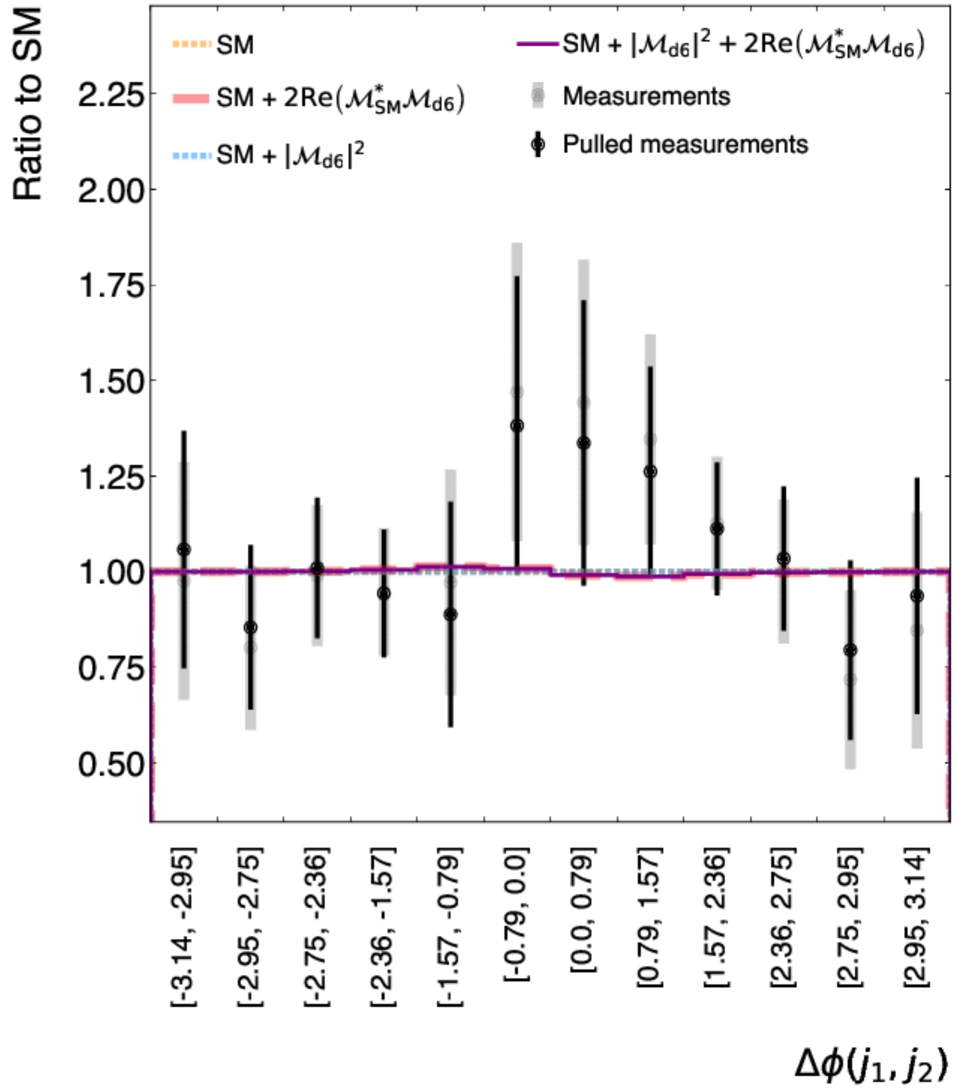
EFT Interpretation





https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-27/

Summary

- Full Run2 ATLAS data (139 fb^{-1}) is used to measure cross-sections of Zjj, to probe WWZ interaction and test $SU(2)_L \times U(1)_Y$ gauge symmetry of the SM

- Differential cross-sections are measured for EW and inclusive Zjj using 4 variables
  - Test different SM EW Zjj generators, under assumption of no BSM
  - Re-evaluate EW Zjj when new Strong Zjj prediction is available

- Search for anomalous weak-boson self-interactions, providing new avenue in search for BSM
  - Signed azimuthal angle between two jets ($\Delta\phi_{jj}$) is particularly sensitive to the interference between the SM and dimension-6 operators

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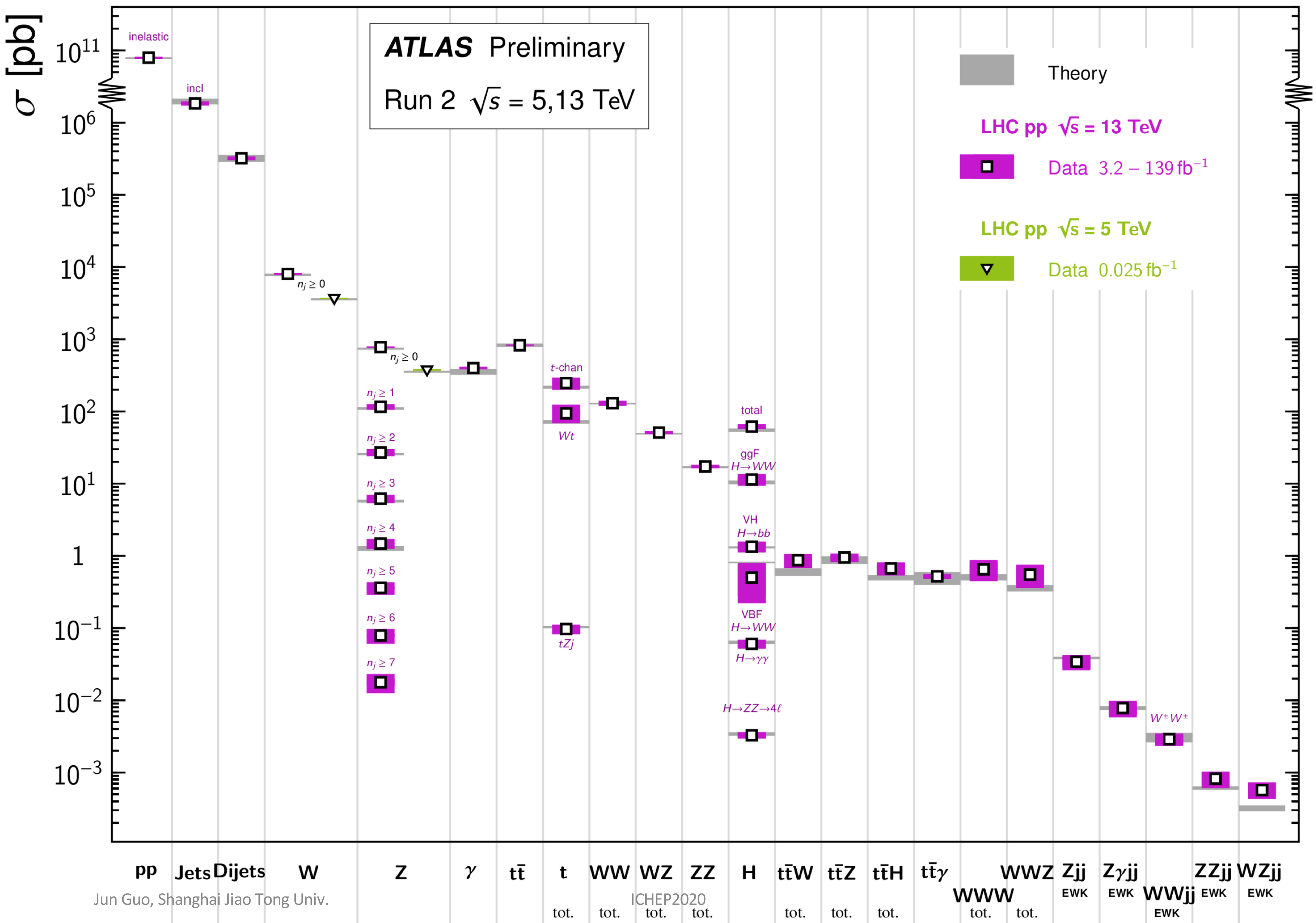
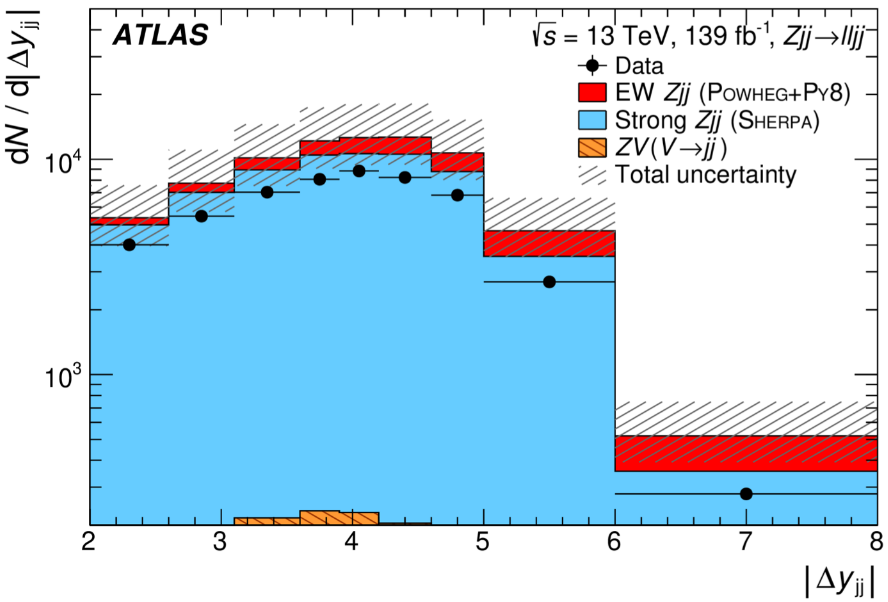
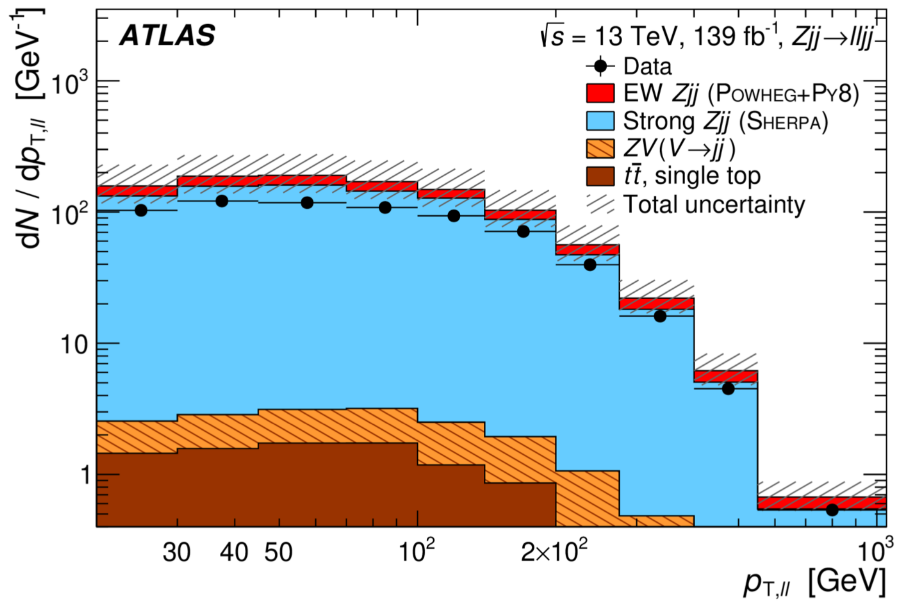
Standard Model Production Cross Section Measurements

Status: May 2020

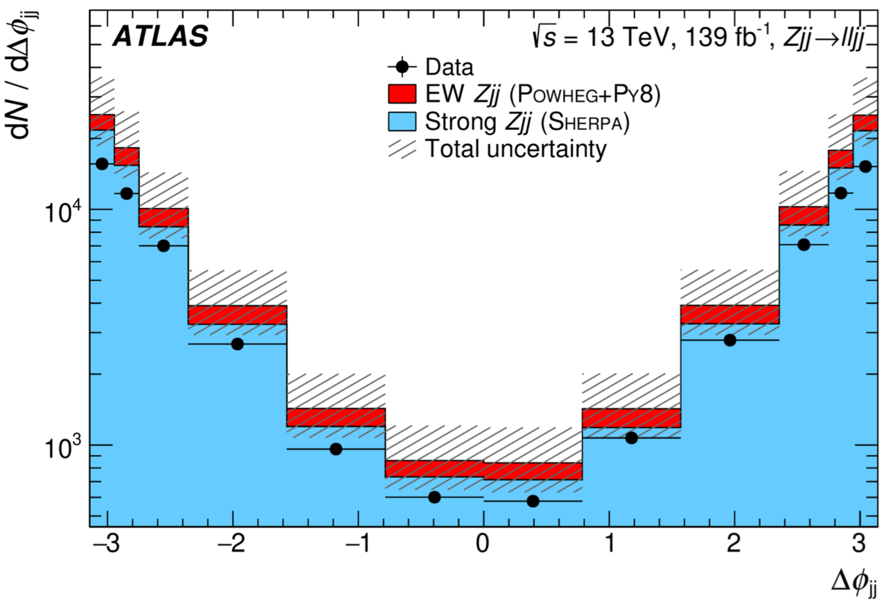




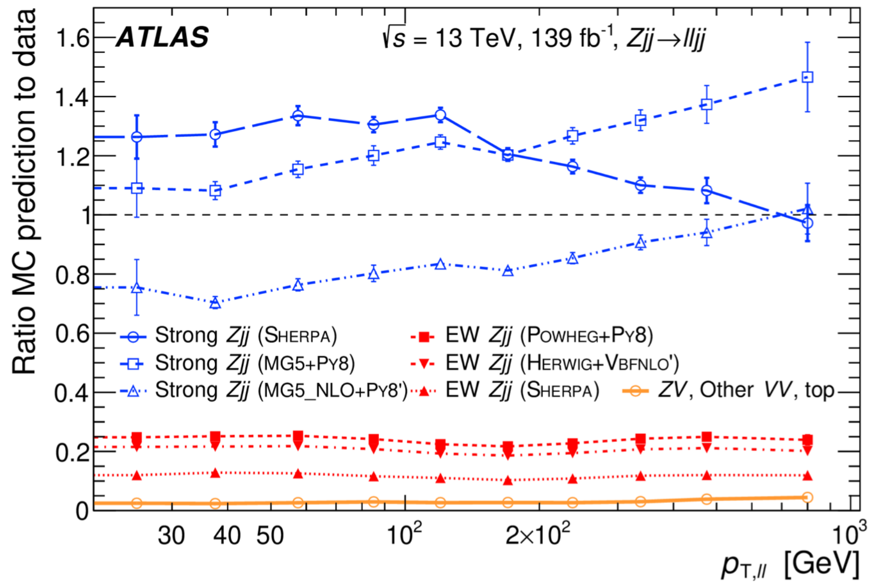
ATLAS
√s = 13 TeV, 139 fb-1, Zjj→lljj
Data
EW Zjj (POWHEG+PY8)
Strong Zjj (SHERPA)
ZV(V→jj)
Total uncertainty
dN / d|Δyjj|
|Δyjj|



ATLAS
√s = 13 TeV, 139 fb-1, Zjj→lljj
Data
EW Zjj (POWHEG+PY8)
Strong Zjj (SHERPA)
ZV(V→jj)
tt̄, single top
Total uncertainty
dN / dpT,ll [GeV-1]
pT,ll [GeV]

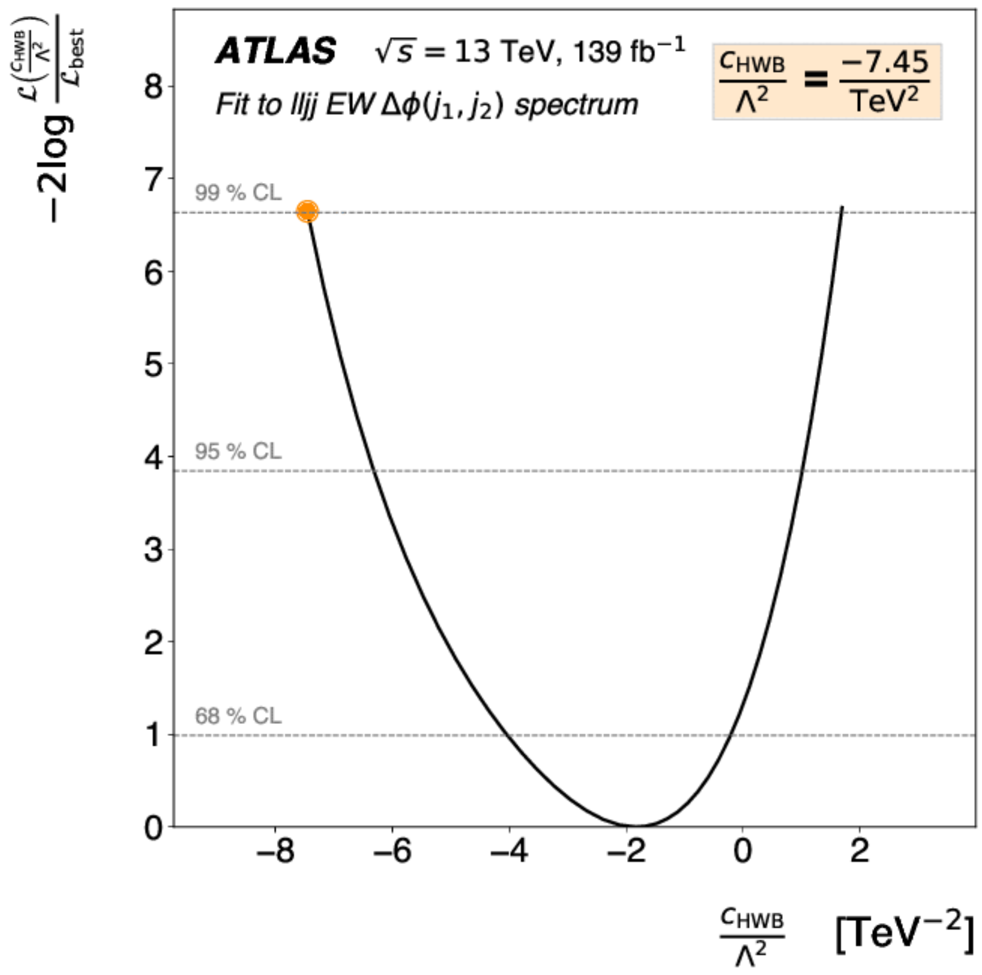


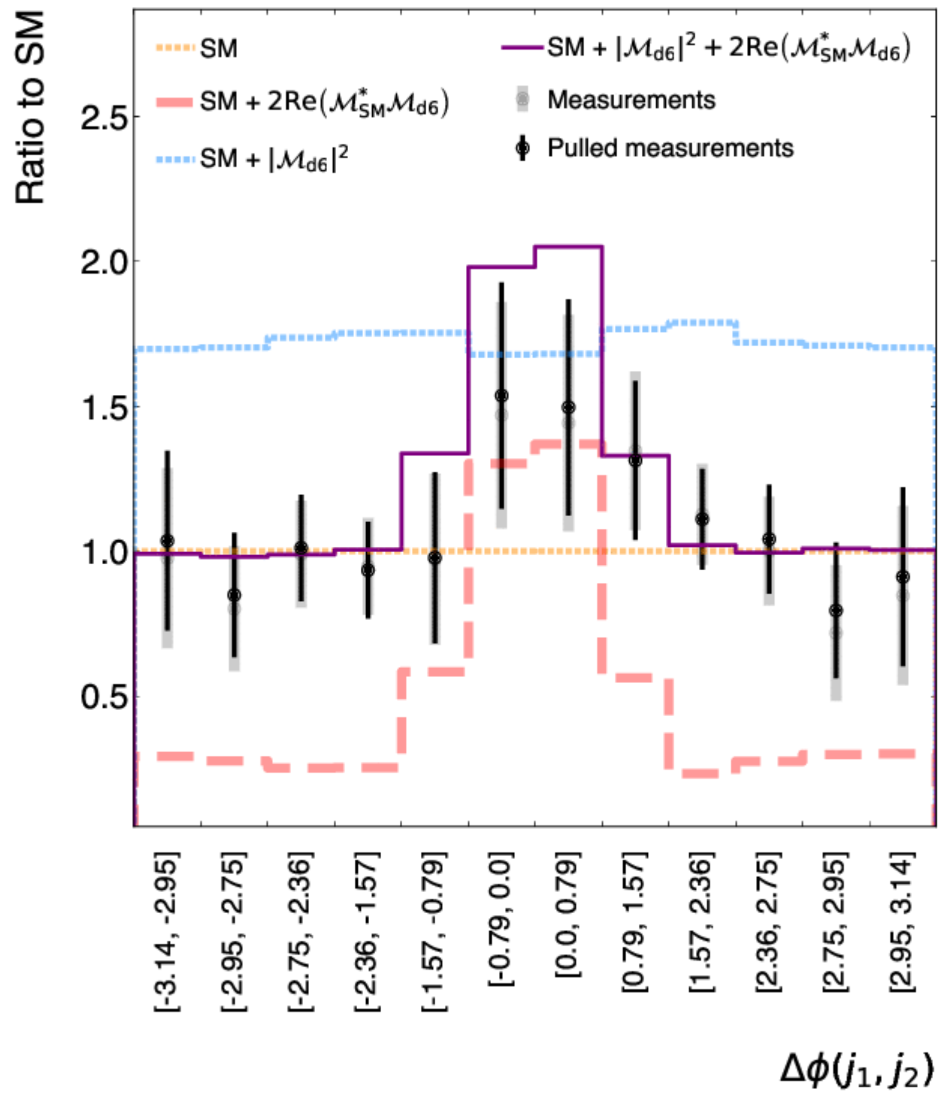
ATLAS
√s = 13 TeV, 139 fb-1, Zjj→lljj
Data
EW Zjj (POWHEG+PY8)
Strong Zjj (SHERPA)
Total uncertainty
dN / dΔφjj
Δφjj



ATLAS
√s = 13 TeV, 139 fb-1, Zjj→lljj
Ratio MC prediction to data
Strong Zjj (SHERPA)
Strong Zjj (MG5+PY8)
Strong Zjj (MG5_NLO+PY8')
EW Zjj (POWHEG+PY8)
EW Zjj (HERWIG+VBFNLO')
EW Zjj (SHERPA)
ZV, Other VV, top
pT,ll [GeV]

EW Zjj SR, m_{jj} cross-section measurements									
dσ / dm_{jj} [ab/GeV]	-	-	-	-	41	14	5.5	1.3	0.10
Stat. unc. [%]	-	-	-	-	13	13	13	17	26
Gen. choice [%]	-	-	-	-	11	11	9.4	14	7.6
Theory syst. [%]	-	-	-	-	8.1	6.6	4.3	3.1	1.2
Jet syst. [%]	-	-	-	-	8.4	6.9	6.3	9.4	14
Unfolding syst. [%]	-	-	-	-	2.3	1.1	0.7	0.6	0.6
Other syst. [%]	-	-	-	-	2.0	2.0	2.3	2.2	3.0
Inclusive Zjj SR, m_{jj} cross-section measurements									
dσ / dm_{jj} [ab/GeV]	510	1040	700	320	120	31	8.8	1.7	0.12
Stat. unc. [%]	1.6	1.0	0.9	1.3	1.5	2.3	4.5	7.2	21
Jet syst. [%]	5.2	3.8	3.3	3.6	3.6	3.5	4.1	6.6	15
Unfolding syst. [%]	2.3	1.6	0.9	0.6	0.5	0.4	0.5	0.6	0.6
Other syst. [%]	2.8	2.8	2.8	2.8	2.8	2.8	2.9	2.9	3.4
Inclusive Zjj CRa, m_{jj} cross-section measurements									
dσ / dm_{jj} [ab/GeV]	250	610	560	320	130	37	8.7	1.6	0.10
Stat. unc. [%]	2.2	1.2	1.0	1.3	1.3	2.1	4.4	7.3	22
Jet syst. [%]	11	11	9.4	8.6	8.6	8.1	9.9	11	14
Unfolding syst. [%]	6.7	5.3	4.1	3.3	2.7	2.6	3.0	3.9	5.3
Other syst. [%]	2.3	2.3	2.3	2.4	2.4	2.5	2.5	2.6	2.8
Inclusive Zjj CRb, m_{jj} cross-section measurements									
dσ / dm_{jj} [ab/GeV]	190	430	330	150	54	10	1.4	0.11	-
Stat. unc. [%]	2.5	1.4	1.2	1.8	2.2	4.2	11	28	-
Jet syst. [%]	11	9.0	7.6	8.0	7.4	7.9	9.0	8.9	-
Unfolding syst. [%]	2.3	2.4	2.4	2.1	1.8	2.1	3.0	3.8	-
Other syst. [%]	2.3	2.3	2.3	2.4	2.4	2.5	2.6	2.6	-
Inclusive Zjj CRc, m_{jj} cross-section measurements									
dσ / dm_{jj} [ab/GeV]	350	690	390	140	37	5.7	0.60	0.07	-
Stat. unc. [%]	1.9	1.2	1.2	2.0	2.7	5.8	18	36	-
Jet syst. [%]	6.7	3.6	3.3	5.0	2.3	4.7	5.5	4.0	-
Unfolding syst. [%]	1.2	1.0	0.8	0.9	1.1	1.6	2.1	2.3	-
Other syst. [%]	2.8	2.8	2.8	2.8	2.8	2.9	2.9	3.1	-
Low bin edge [TeV]	0.25	0.35	0.50	0.75	1.0	1.5	2.2	3.0	4.5
High bin edge [TeV]	0.35	0.50	0.75	1.0	1.5	2.2	3.0	4.5	7.5


ATLAS $\sqrt{s}$ = 13 TeV, 139 fb^{-1}
Fit to lljj EW $\Delta\phi(j_1, j_2)$ spectrum
$\frac{c_{HWB}}{\Lambda^2} = \frac{-7.45}{\mathrm{TeV}^2}$
99 % CL
95 % CL
68 % CL
$-2\log \frac{\mathcal{L}\left(\frac{c_{HWB}}{\Lambda^2}\right)}{\mathcal{L}_{best}}$
$\frac{c_{HWB}}{\Lambda^2}$ [TeV^{-2}]


SM
SM + 2Re($\mathcal{M}^*_{SM}\mathcal{M}_{d6}$)
SM + $|\mathcal{M}_{d6}|^2$
SM + $|\mathcal{M}_{d6}|^2$ + 2Re($\mathcal{M}^*_{SM}\mathcal{M}_{d6}$)
Measurements
Pulled measurements
Ratio to SM
[-3.14, -2.95]
[-2.95, -2.75]
[-2.75, -2.36]
[-2.36, -1.57]
[-1.57, -0.79]
[-0.79, 0.0]
[0.0, 0.79]
[0.79, 1.57]
[1.57, 2.36]
[2.36, 2.75]
[2.75, 2.95]
[2.95, 3.14]
$\Delta\phi(j_1, j_2)$