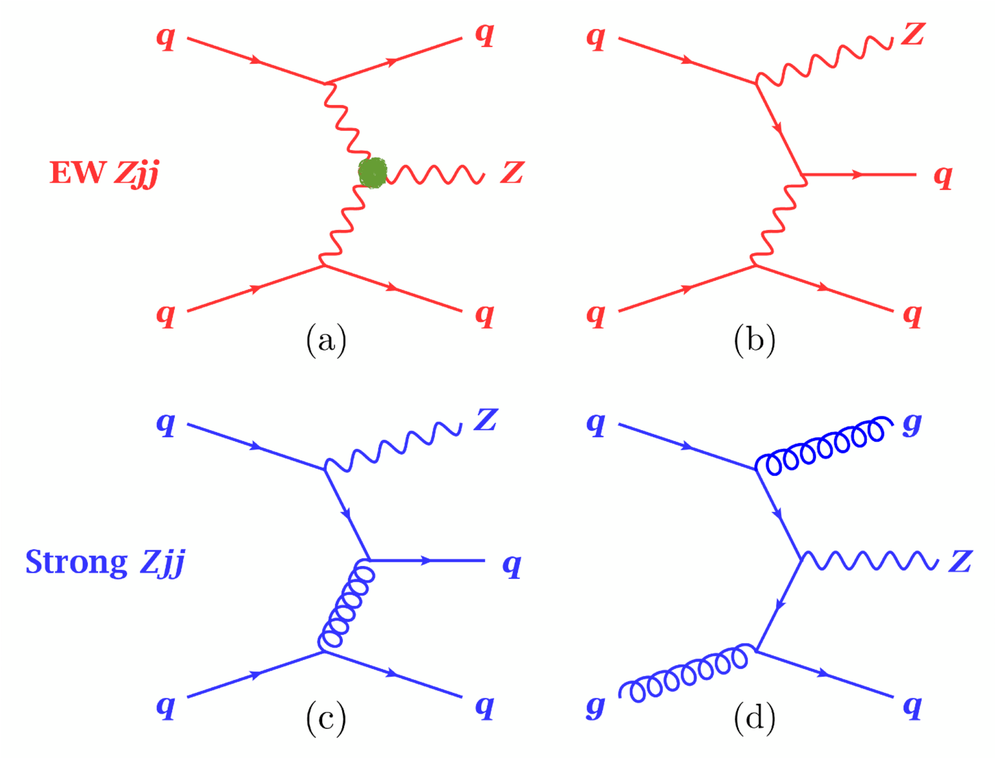
Andrew Pilkington - University of Manchester

EW Zjj differential cross-sections at ATLAS

- Issues with strong Zjj modelling
- EW Zjj: extraction method
- EW Zjj: results
- EFT constraints using measured spectra

Electroweak Zjj production at the LHC



- Why Electroweak Vjj production is interesting:
  - Study the kinematic of VBF-like processes. Use this as a ‘standard candle’ for VBF/VBS simulations
  - Sensitive to anomalous weak-boson self-interactions
  - Rare process. Typically O(1%) of the inclusive Vjj final state, which is dominated by the strong Zjj process

MC generators used in the analysis

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 topology preselection

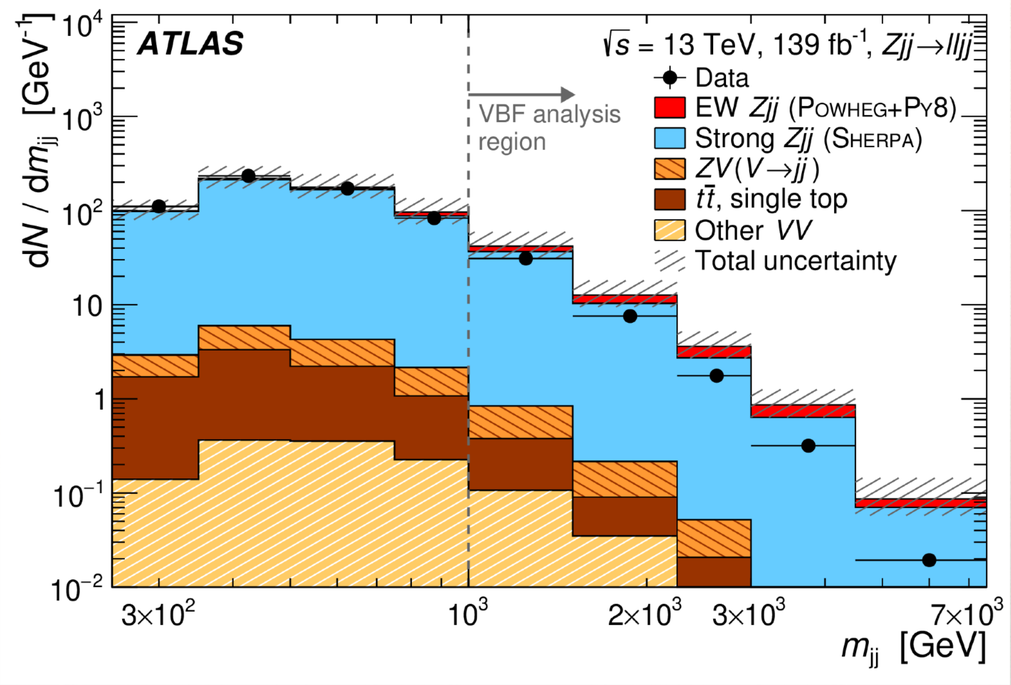
Dressed muons	$p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.4$
Dressed electrons	$p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.37$ (excluding $1.37 < \lvert\eta\rvert < 1.52$)
Jets	$p_{\mathrm{T}} > 25$ GeV and $\lvert y\rvert < 4.4$
VBF topology	$N_\ell = 2$ (same flavour, opposite charge),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

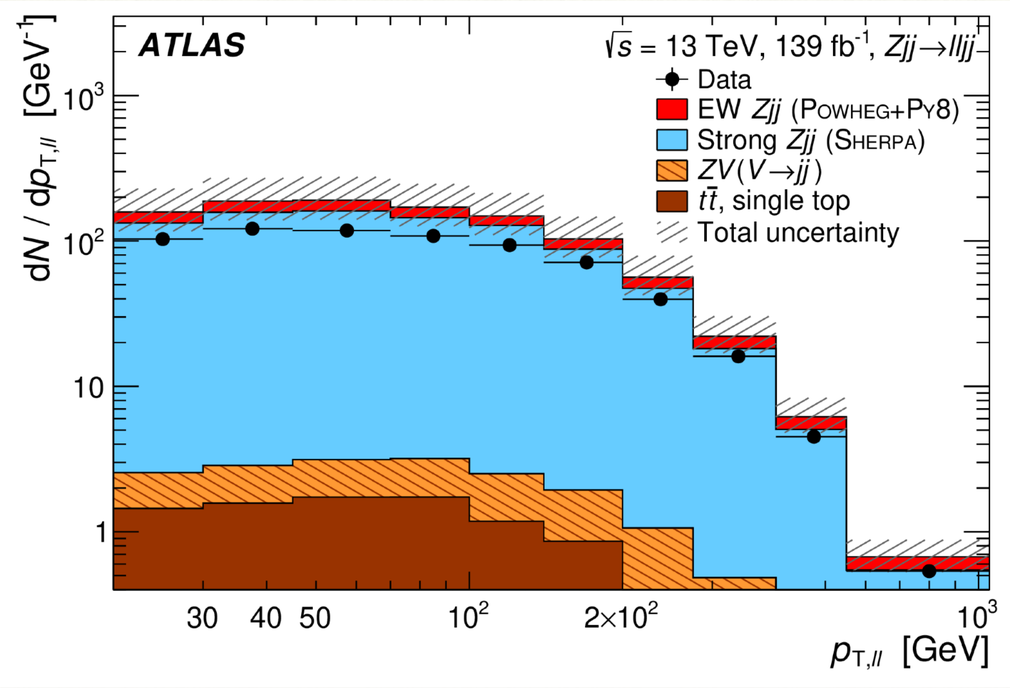
- Detector-level analysis has identical kinematic selection, with additional isolation of leptons using tracks and calorimeter deposits in region around lepton in η x ϕ

Events passing Zjj topology preselection

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

Strong Zjj modelling issues

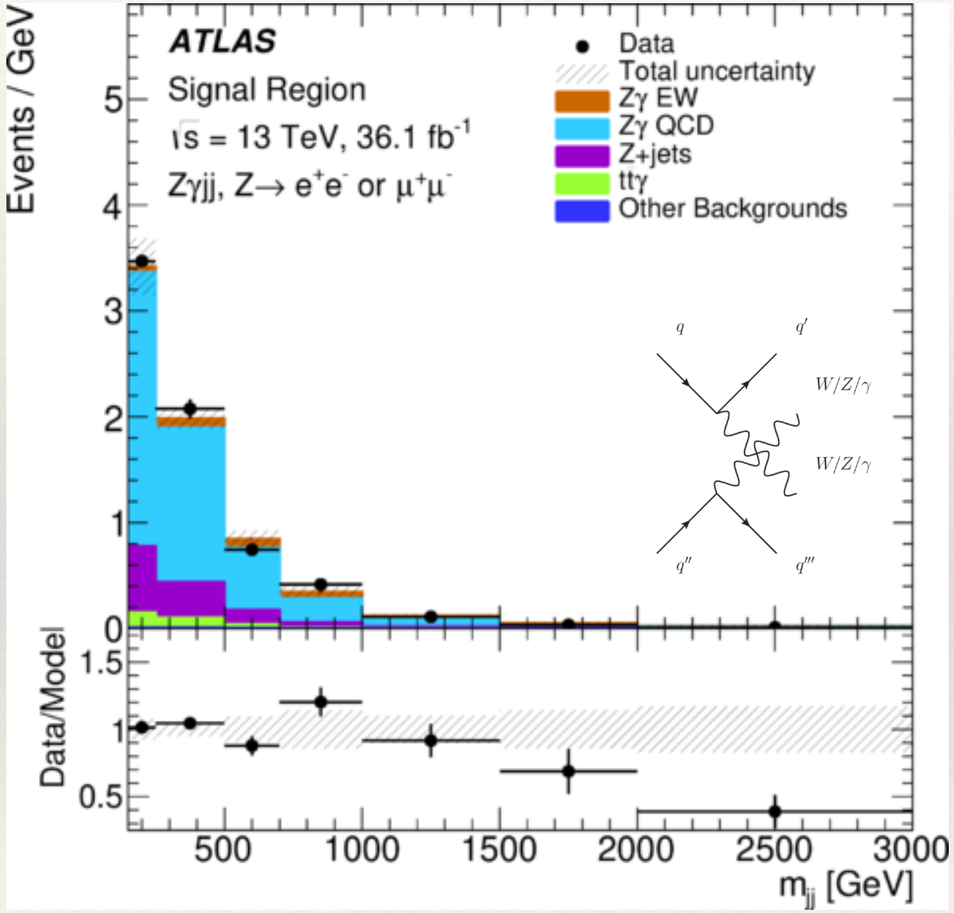




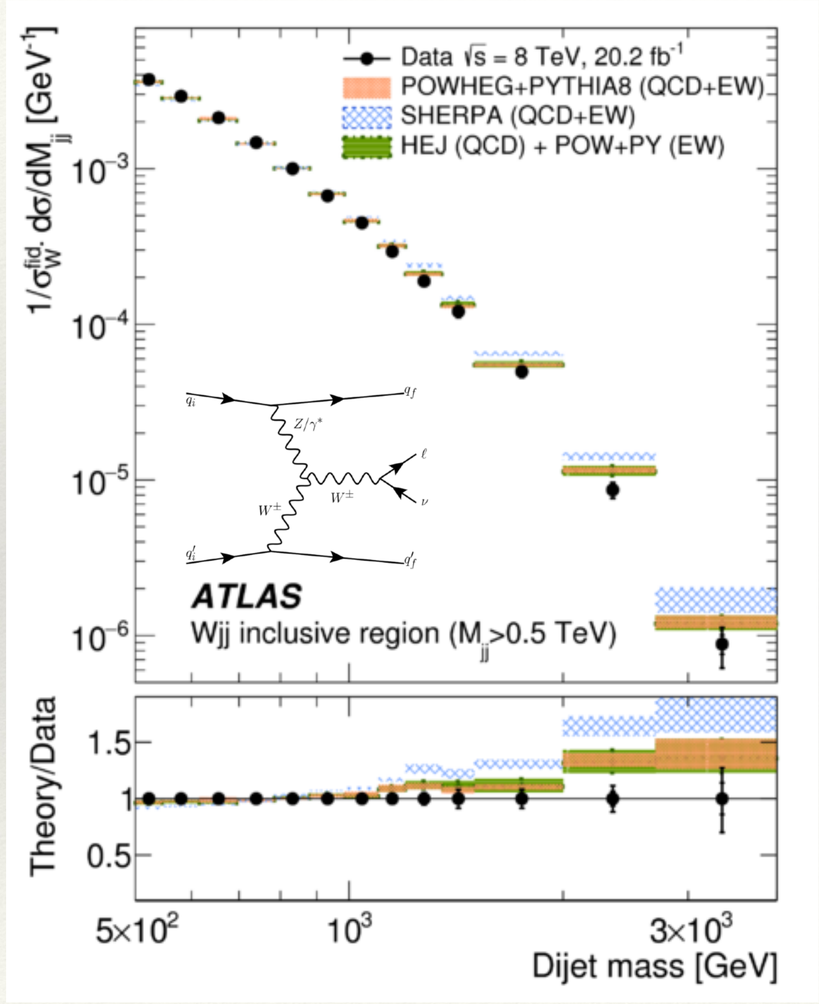
- Data not well modelled by simulation at the highest m_{jj}
  - SHERPA strong Zjj predicts more events than the data by itself.
  - Makes it difficult to extract the electroweak component

Strong process mismodelling: not a new feature

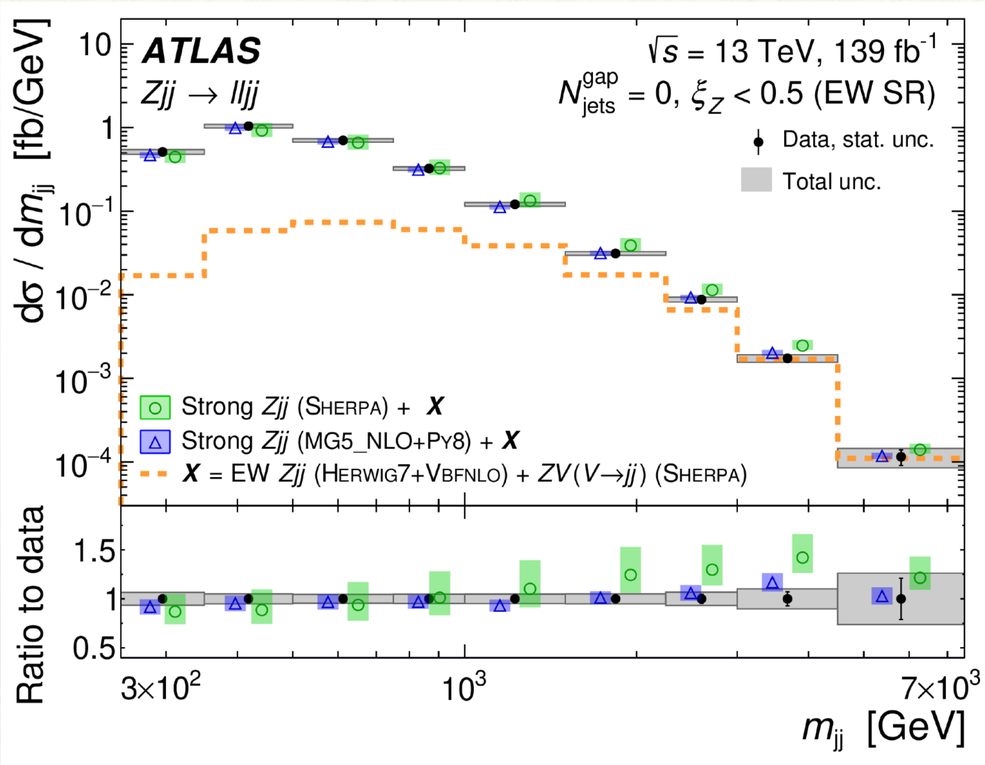
Phys.Lett.B 803 (2020) 135341

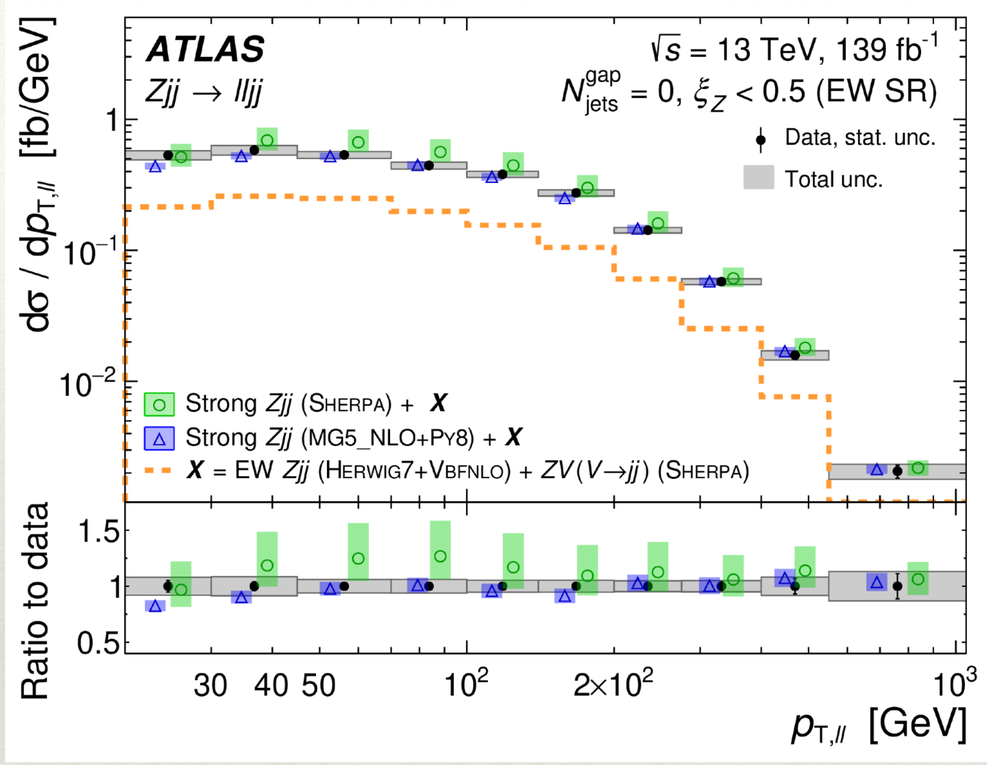


Eur.Phys.J C 77 (2017) 012007



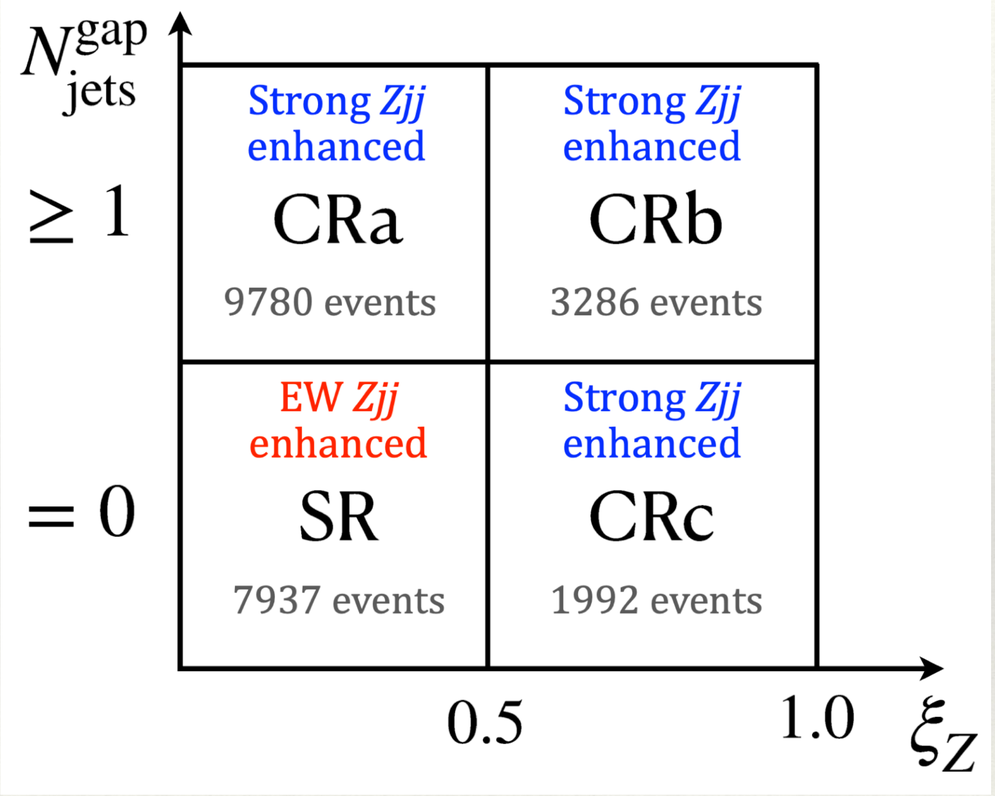
Inclusive Zjj differential cross section measurements





- Baseline approach: measure *inclusive Zjj* differential cross sections as a function of m_{jj}, $p_{T,ll}$, Δy_{jj}, signed-$\Delta\phi_{jj}$.
  - Provide measurements in EW-suppressed regions to help improve strong Vjj and strong VVjj modelling
  - Ensures EW extraction can be repeated with state-of-art generators in the future

EW-enhanced and EW-suppressed regions



- Signal extracted with an ABCD-like method
- EW-enhanced signal region defined by lack of additional jet activity and centrally produced Z bosons (w.r.t the dijet system).
- Three EW-suppressed control regions defined by reversing these criteria.

Extraction of EW Zjj: methodology (I)

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

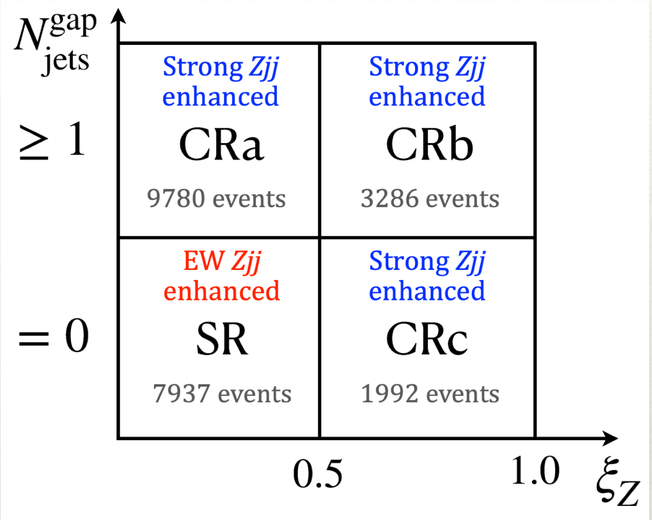
Standard likelihood

r=region, i=bin of observable

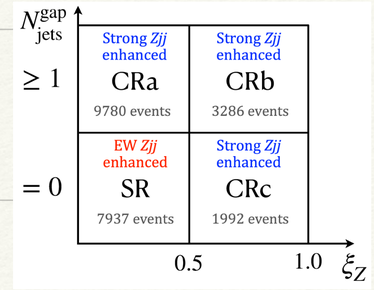
$$\nu_{ri} = \mu_i \, \nu_{ri}^{\text{EW,MC}} + \nu_{ri}^{\text{strong}} + \nu_{ri}^{\text{other,MC}};$$

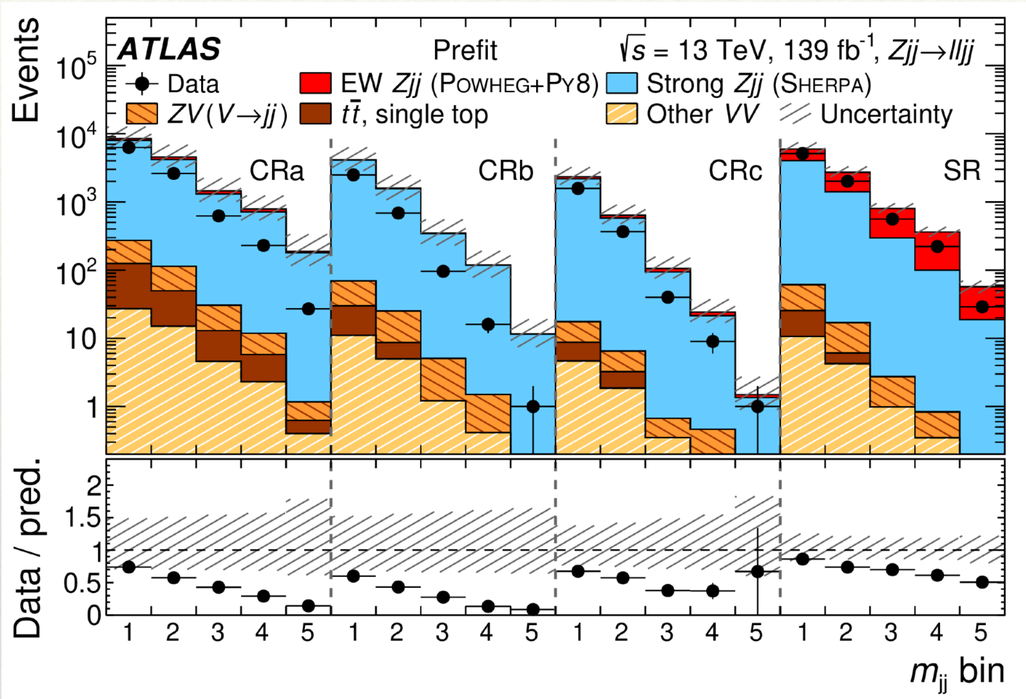
Constraints on strong Zjj production

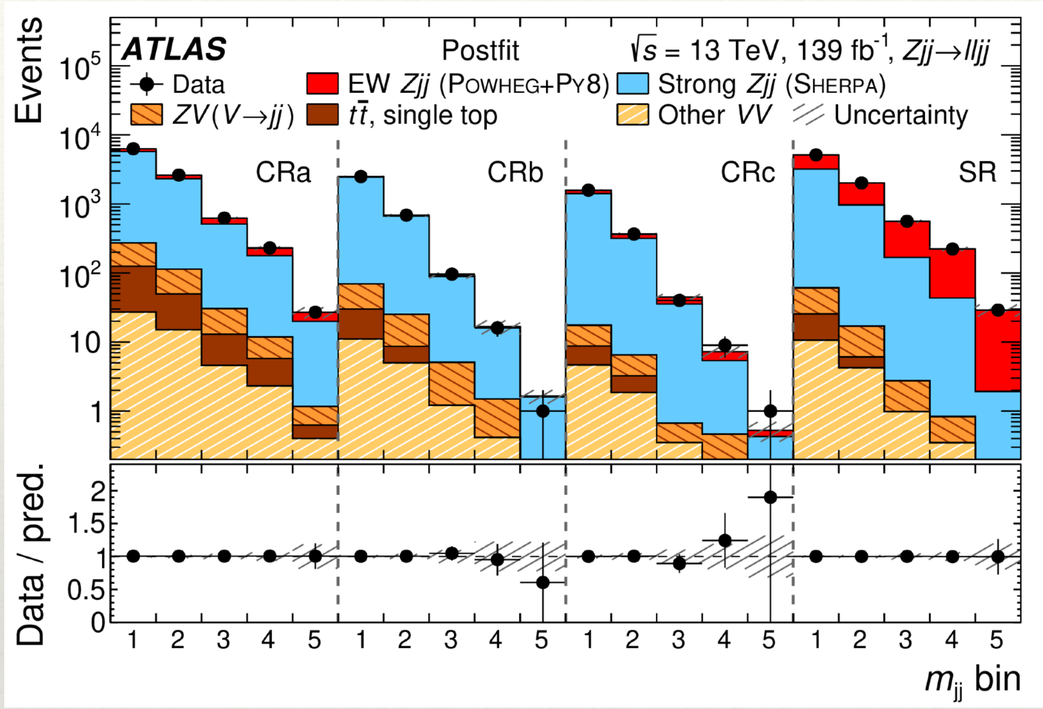
$$\nu_{\text{CRa},i}^{\text{strong}} = b_{\text{L},i} \, \nu_{\text{CRa},i}^{\text{strong,MC}}, \qquad \nu_{\text{CRb},i}^{\text{strong}} = b_{\text{H},i} \, \nu_{\text{CRb},i}^{\text{strong,MC}},$$
$$\nu_{\text{SR}i}^{\text{strong}} = b_{\text{L},i} \, f(x_i) \, \nu_{\text{SR},i}^{\text{strong,MC}},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



Extraction of EW Zjj: methodology (II)

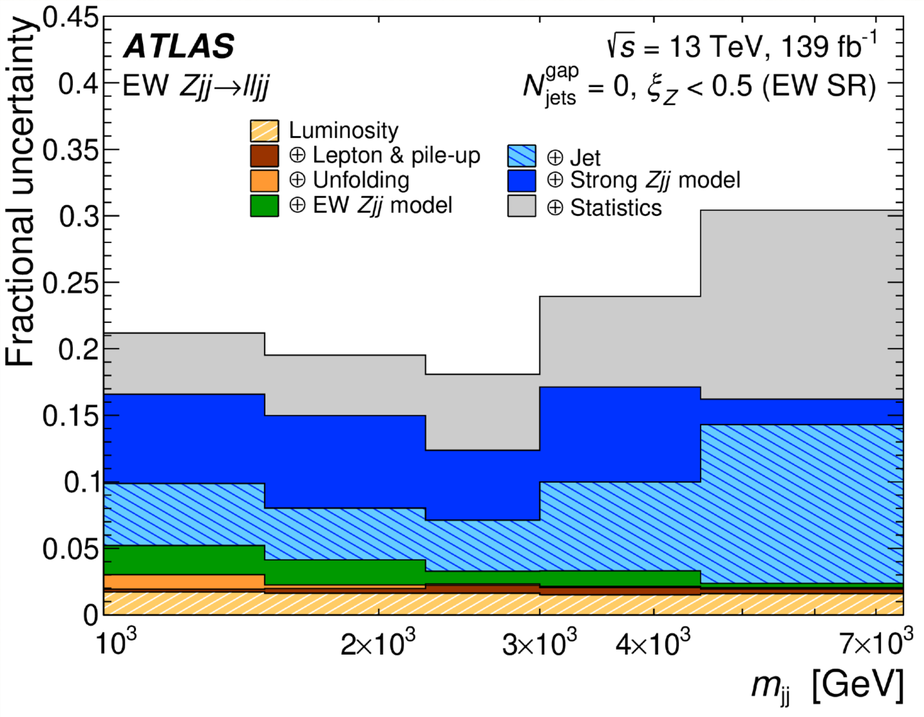


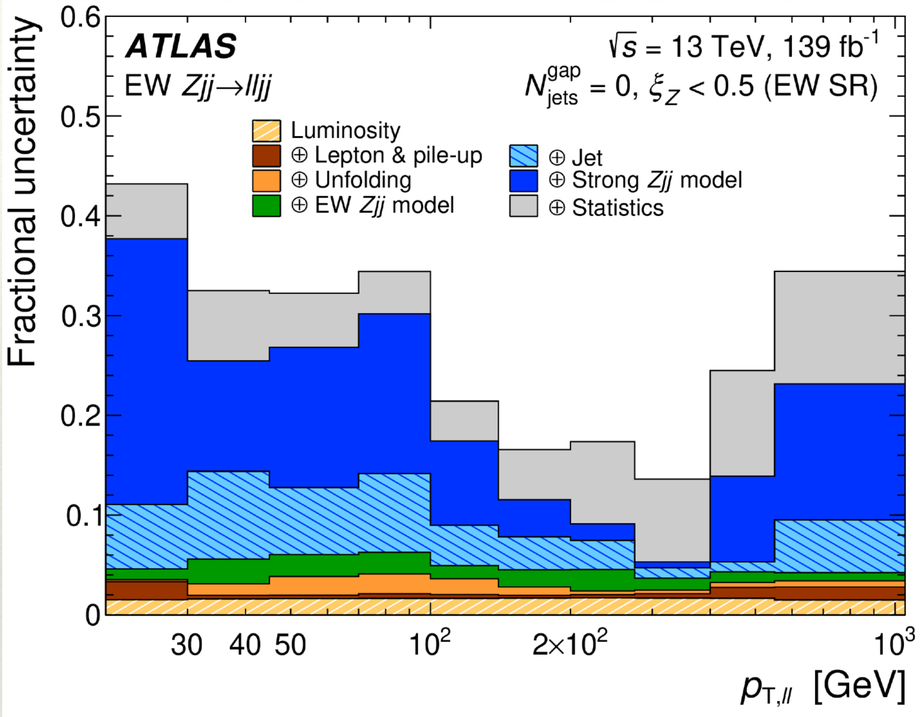




- Example: Poor agreement of SHERPA before constraint (left) is significantly improved after constraint (right).
- Uncertainties in method from choice of strong Zjj generator (Sherpa, Madgraph LO, Madgraph NLO) and scale variations of each generator.
- Cross-checks using simpler sequential method; variation of CRs; variation of functions used in constraint.

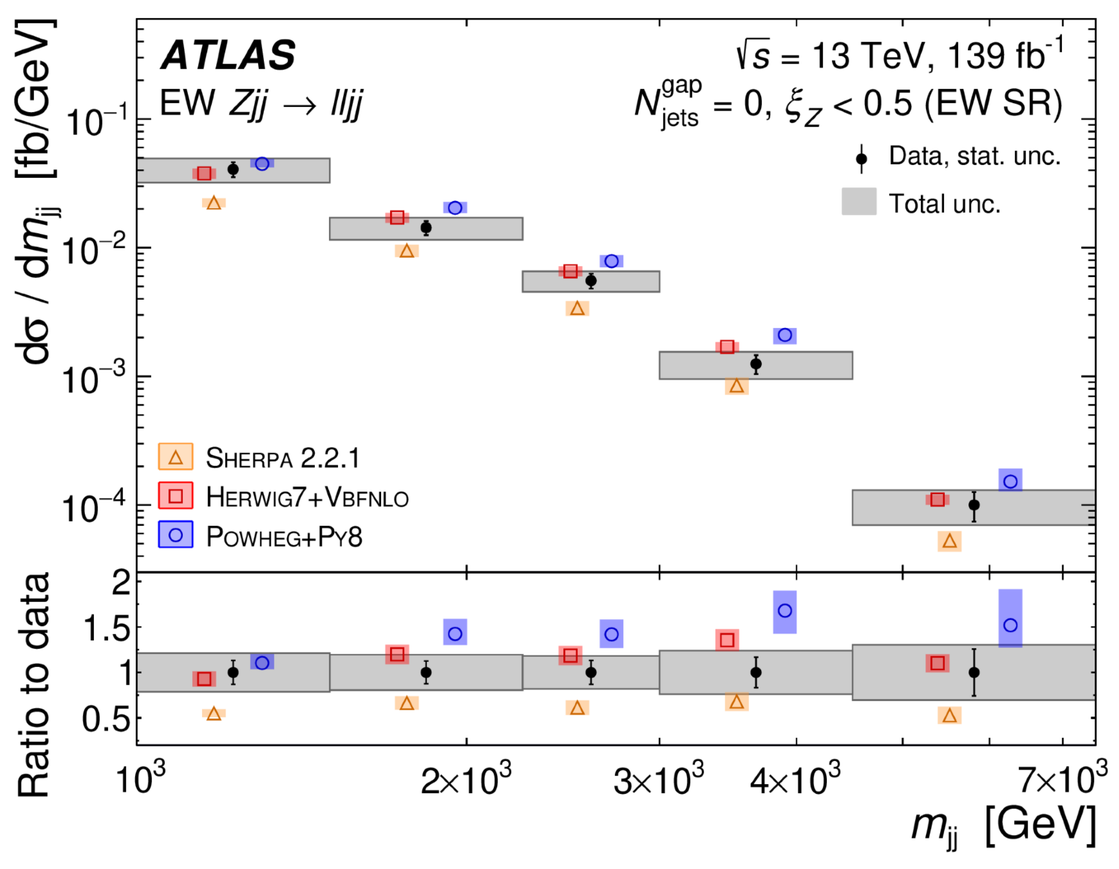
EW Zjj measurements: uncertainties

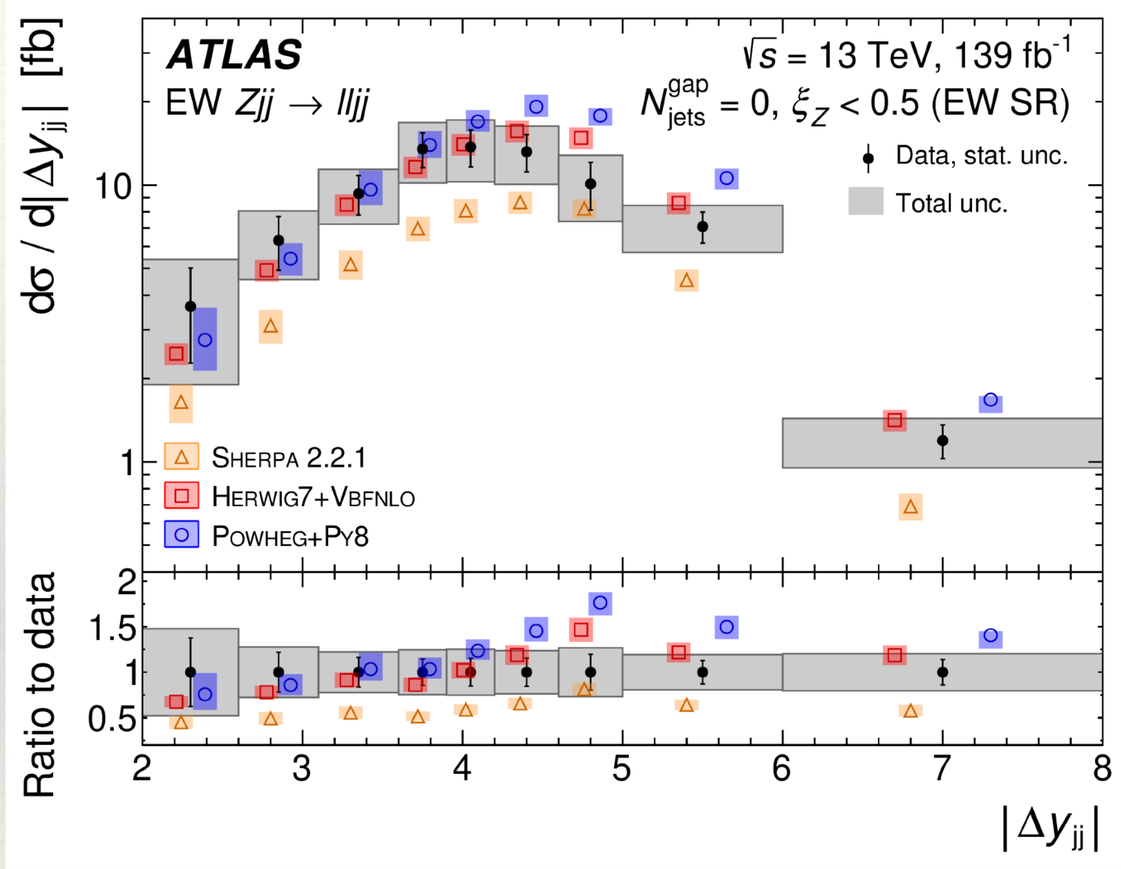




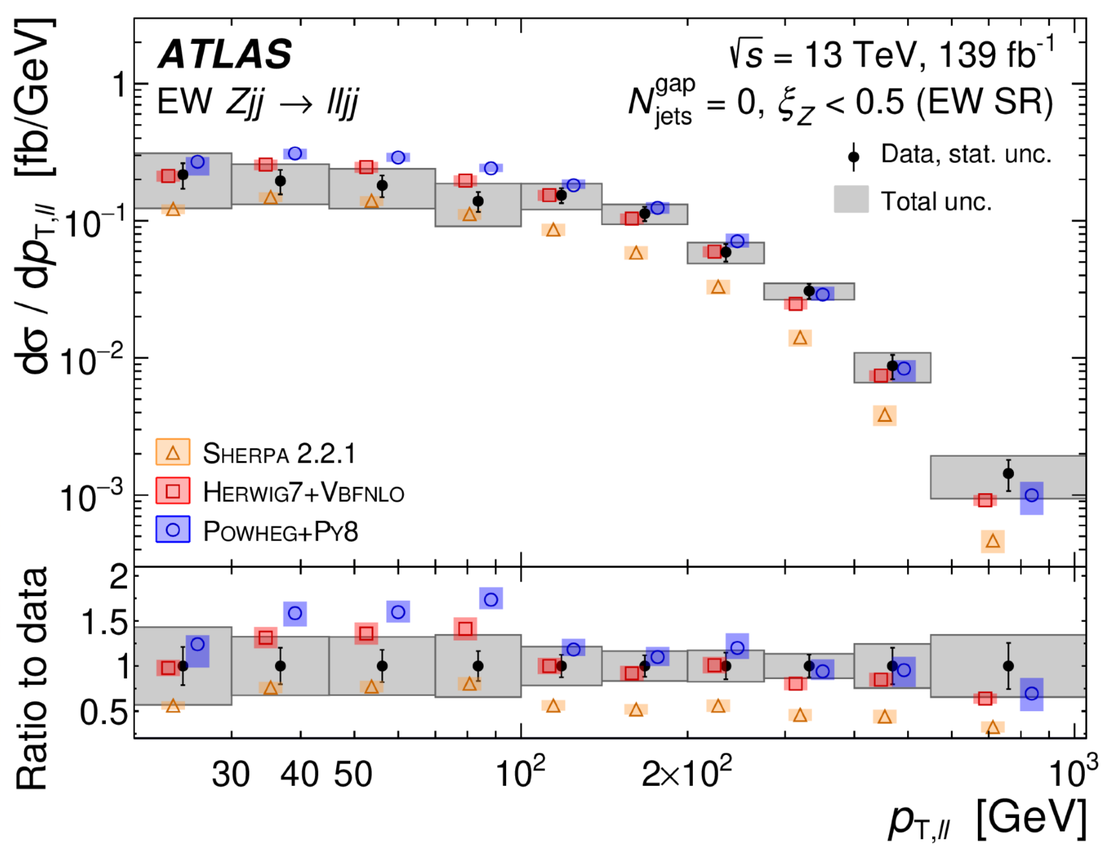
- Final measurement impacted by jet energy scale uncertainties and strong Zjj modelling uncertainties

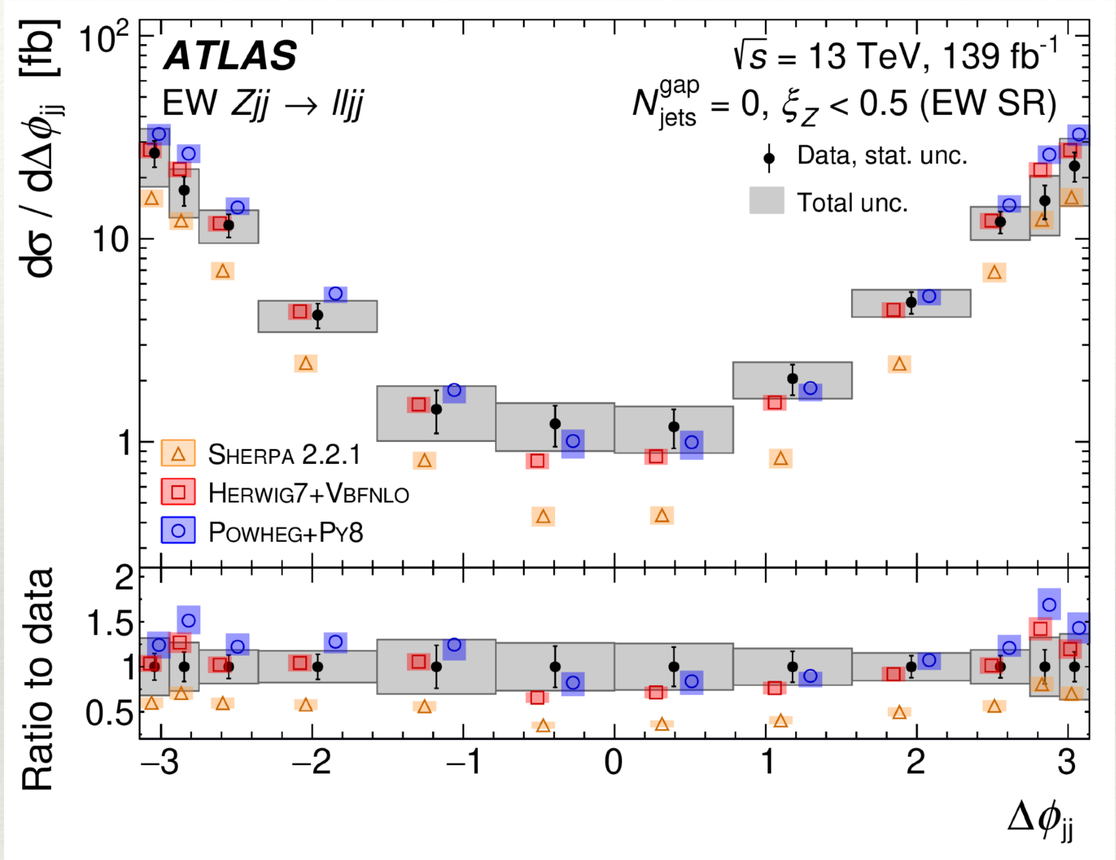
EW Zjj: differential cross sections (I)





EW Zjj: differential cross sections (II)





EFT reinterpretation

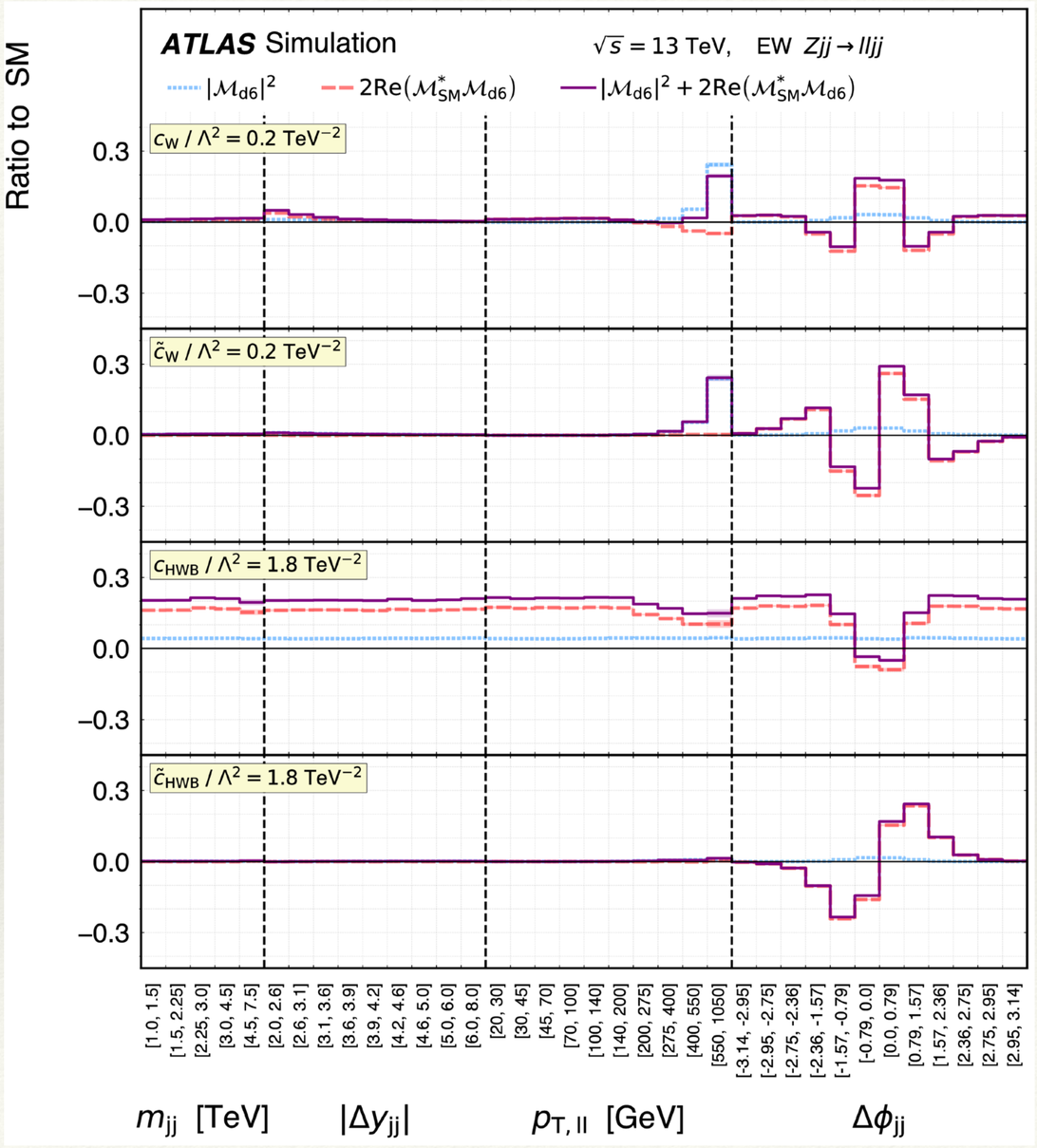
$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

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

SM-dim6 interference

pure dimension-6

- Excellent sensitivity from signed-$\Delta\phi_{jj}$ observable
  - Limits primarily driven by interference term.
  - CP-sensitive observable with asymmetric effects.



Constraints on Wilson coefficients in EFT

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%

Summary and outlook

- Electroweak Zjj differential cross sections presented as a function of m_{jj}, $p_{T,ll}$, Δy_{jj}, and signed-$\Delta\phi_{jj}$.
  - Useful for understanding kinematic properties of VBF- and VBS- like processes
  - sensitive to operators in dimension-6 EFT.
- Analysis requires data-driven methods to adequately constrain the strong Zjj background.
- Inclusive Zjj distributions measured in EW-enhanced and EW-suppressed regions will aid future modelling initiatives for V+jet production.

Paper: https://arxiv.org/abs/2006.15458

Hepdata: https://www.hepdata.net/record/ins1803608

Strong Zjj constraint with Madgraph