Measurements of vector-boson scattering with the ATLAS experiment

Deep Inelastic Scattering (DIS) 2024
Grenoble

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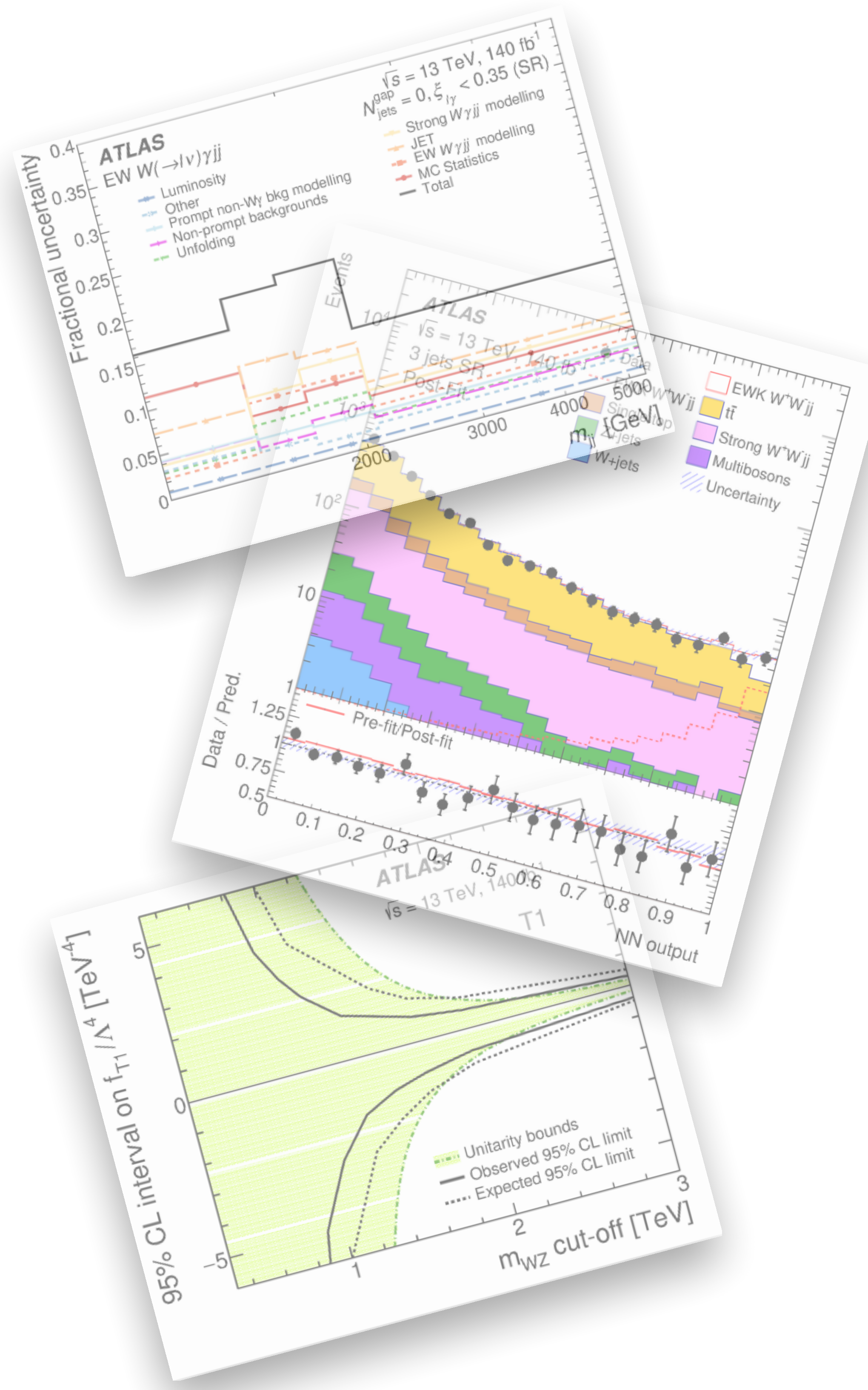
on behalf of the ATLAS collaboration

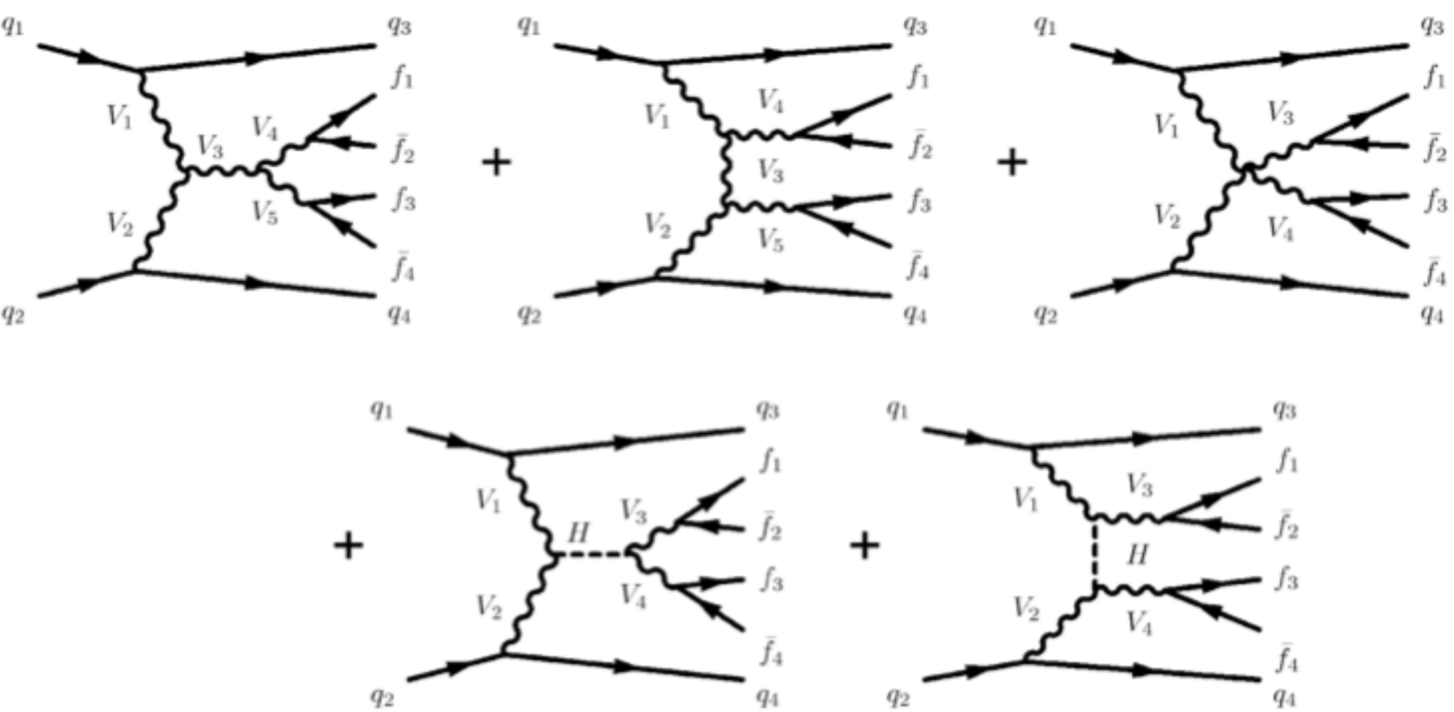
Outline

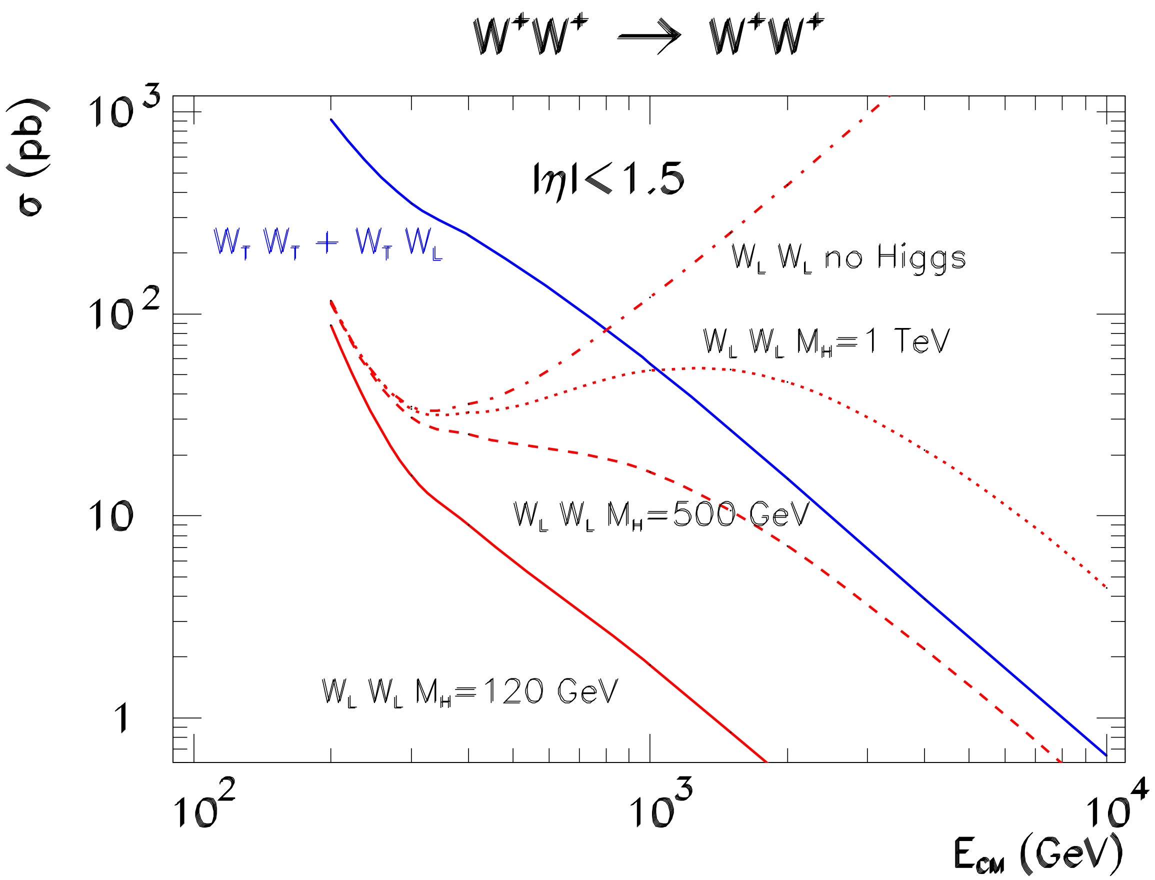
- ***Measurements of Vector Boson Scattering with the ATLAS experiment***
- Introduction
- Summary of ATLAS results
- Results’ highlights
- Final states
    - W(lν)γ + jj
    - opposite-sign W(lν)W(lν) + jj
    - W(lν)Z(ll) + jj
- ***Wrap-up***



Introduction: why VBS?

- ***Diboson physics has been a crucial test of the SM***
  - experimental constraints in many diboson channels
  - still huge interest in probing higher ranges
- ***Vector Boson Scattering (VBS)***
  - probe the Electroweak Symmetry Breaking
  - sensitive to New Physics



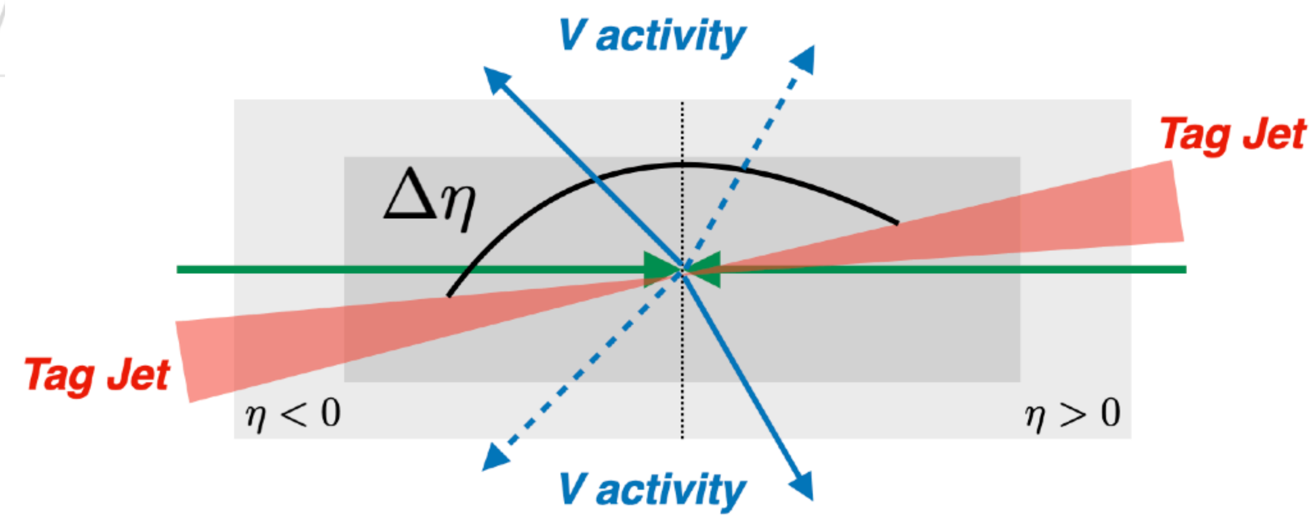


[arxiv.1412.8367](https://arxiv.org/abs/1412.8367)

Experimental perspective

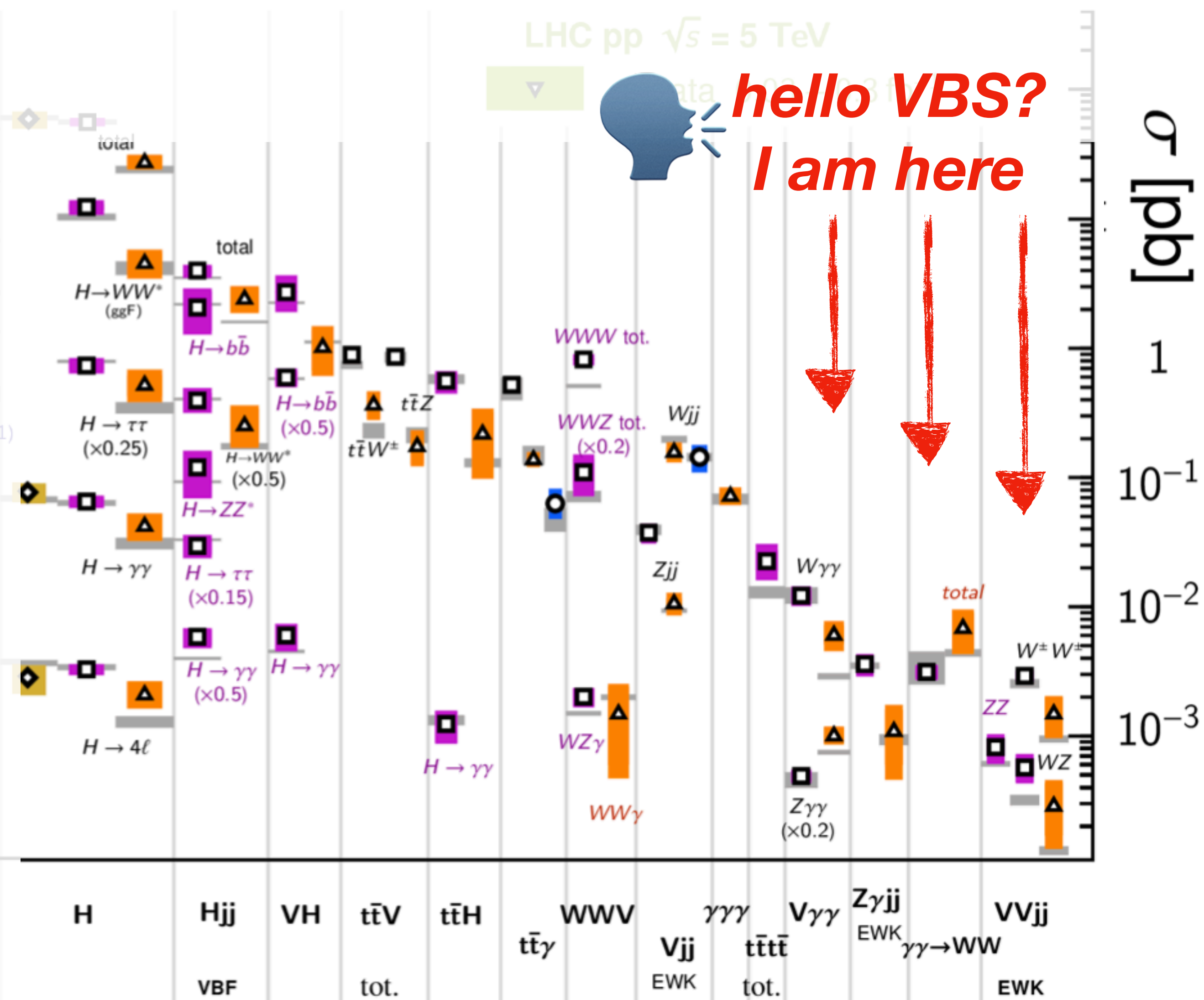
VBS experimental signature

- **Energetic and forward jets**
  - large rapidity separation, $\Delta\eta_{jj}$
  - large invariant mass, M_{jj}
- **Centrality**
  - low hadronic activity in the central region (color singlet exchange)
- Key discrimination for EWK VV+jj and VBS components



VBS experimental challenges

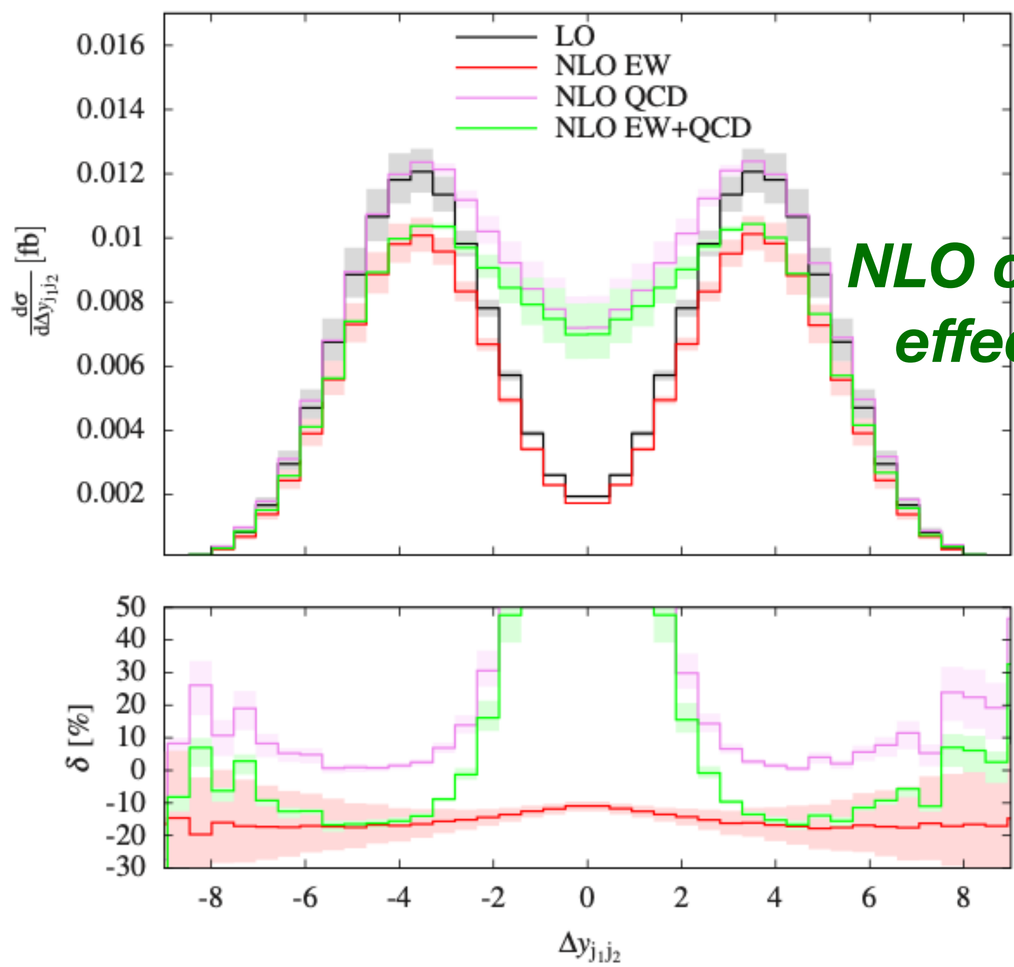
- Rare process and large variety of background processes
- Forward jets identification
- VBS can NOT be directly extracted to due gauge invariance —> EWK VV+jj in VBS-enhanced phase space
- Interference with QCD VV+jj production



Theoretical challenges

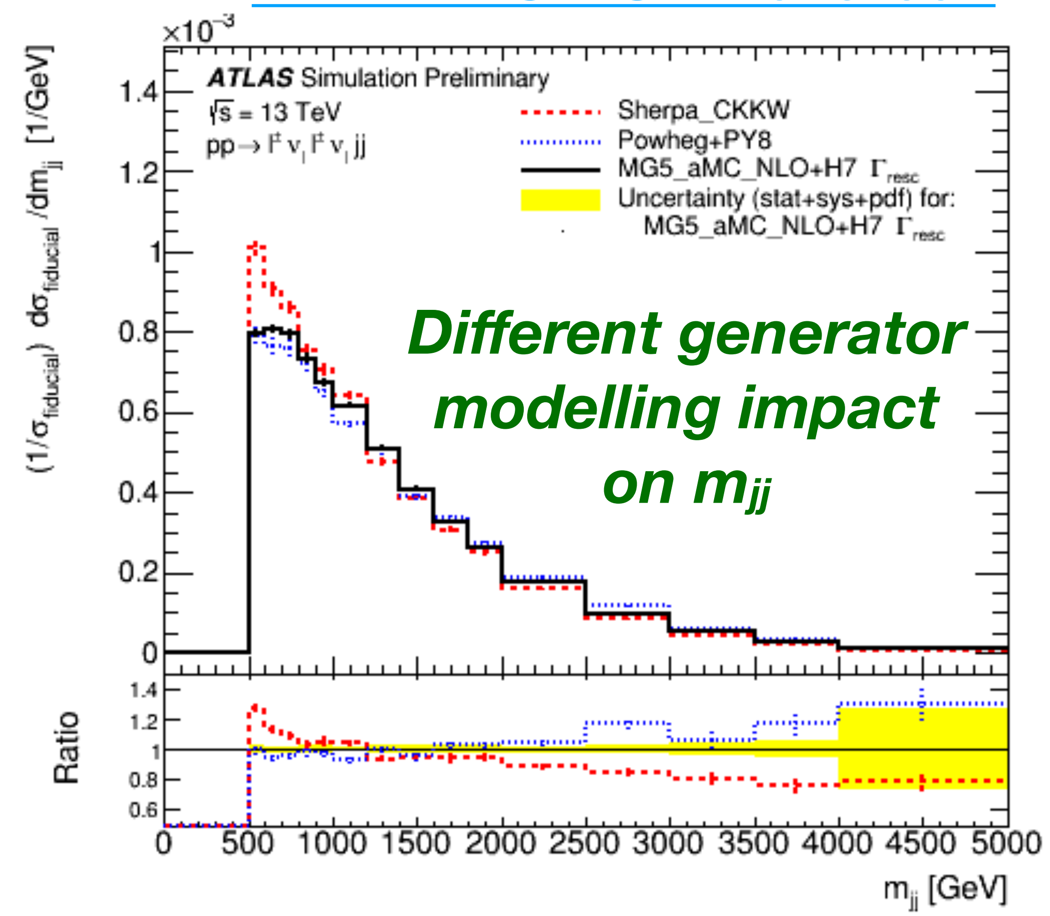
- ***Precise theory predictions to constraint QCD and EWK VV+jj productions***
  - generations can not distinguish between VBS and no-VBS components
  - non-VBS components: VVV and t-X diagrams
- ***Understand experimental data with theory predictions***
  - high-order corrections impact the phase space
  - modelling description plays a leading role in this phase space

[arxiv.2009.00411]



NLO correction effect on $\Delta\eta$

[ATL-PHYS-PUB-2019-004]



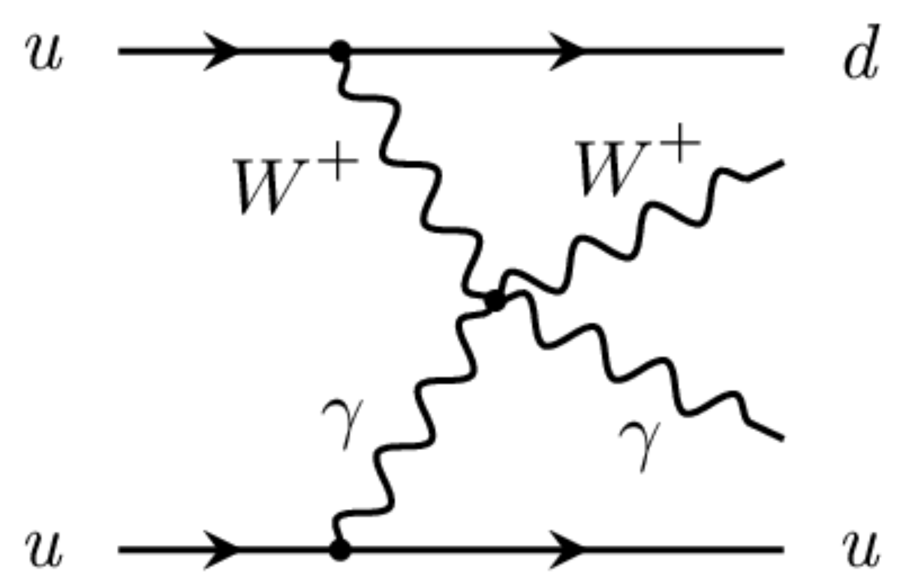
Different generator modelling impact on m_{jj}

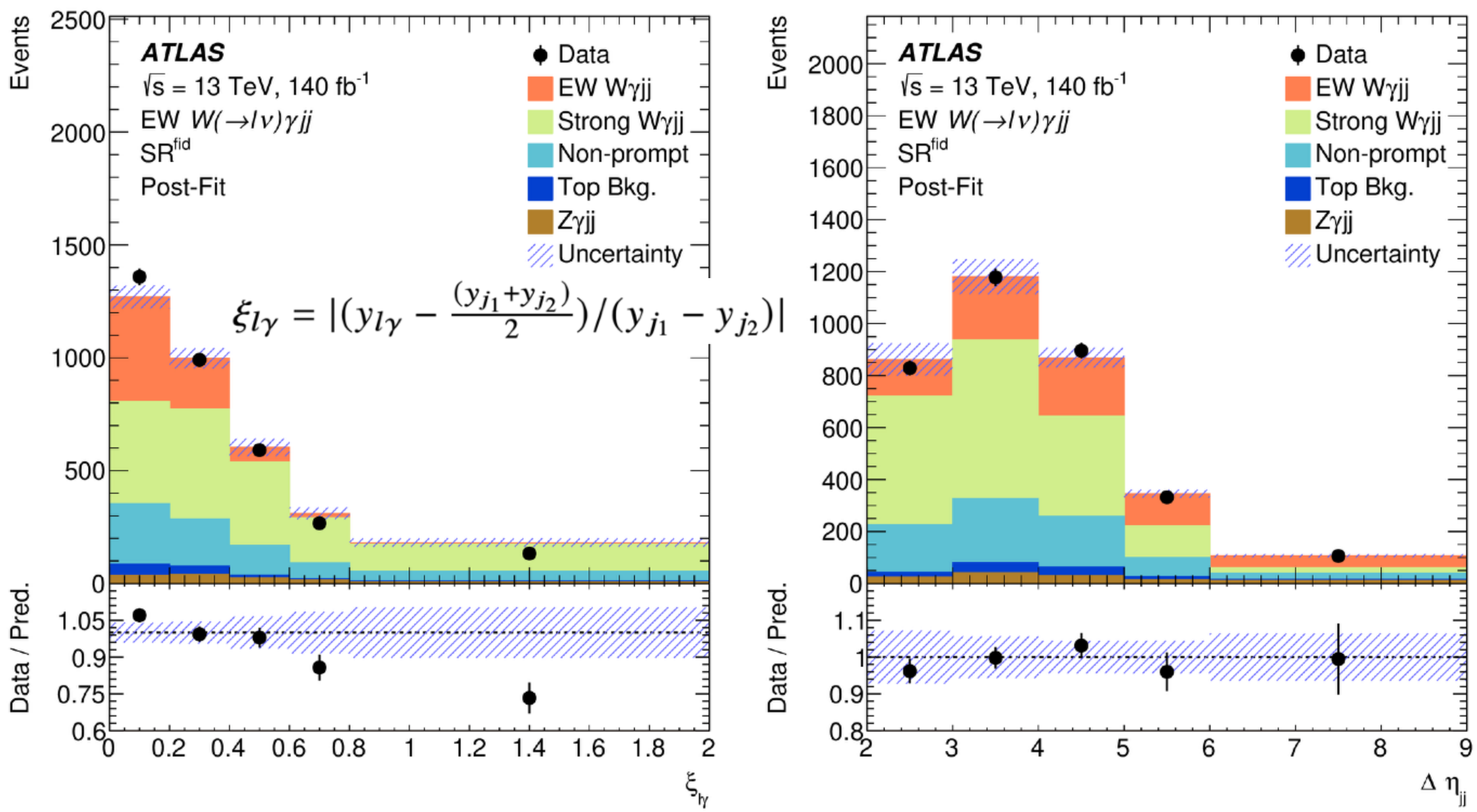
ATLAS results in a nutshell

Channel	Final state	Dataset	ATLAS paper
W^+W^- + jj	* $e\nu\mu\nu$ + jj	139/fb	Submitted to JHEP
$W^\pm W^\pm$ + jj	$l\nu l\nu$ + jj	140/fb	Submitted to JHEP
WZ + jj	* $l\nu ll$ + jj	140/fb	Submitted to JHEP
ZZ + jj	4l + jj	140/fb	JHEP 01 (2024) 004
	$2l2\nu$ + jj	139/fb	Nature Phys. 19 (2023) 237
VV + jj semi-leptonic	$\nu\nu qq/l\nu qq/llqq$ + jj	35/fb	Phys. Rev. D 100 (2019) 032007
$W\gamma$ + jj	* $l\nu\gamma$ + jj	140/fb	Submitted to EPJC
$Z\gamma$ + jj	$ll\gamma$ + jj	140/fb	Phys. Lett. B 846 (2023) 138222
	$\nu\nu\gamma$ + jj	139/fb	JHEP 06 (2023) 082
$\gamma\gamma$ —> WW (γ-induced)	$e\nu\mu\nu$ + X	139/fb	Phys. Lett. B 816 (2021) 136190

Wγ+jj production

- ***W and γ associated final state***
  - clean signal topology
  - both electron and muon channels explored
- ***Typical VBS-enhanced phase space selection***
- ***Source of background processes***
  - irreducible: QCD Wγ+jj production
  - others: non-prompt, top, fakes





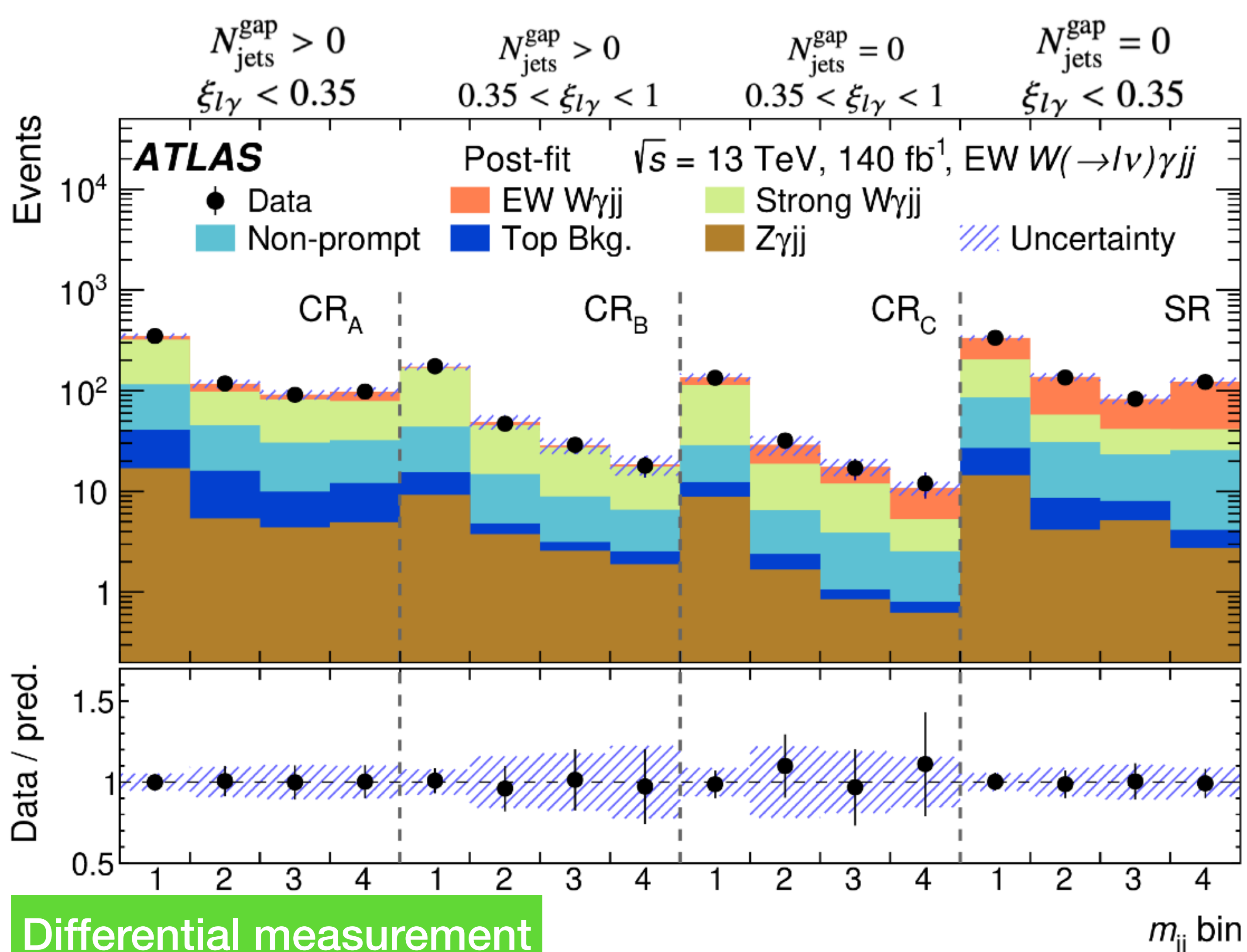
$$\xi_{l\gamma} = |(y_{l\gamma} - \frac{(y_{j_1}+y_{j_2})}{2})/(y_{j_1} - y_{j_2})|$$

Good separation power for the EWK signal against the other SM processes for relevant kinematics

How to: CRs and ML

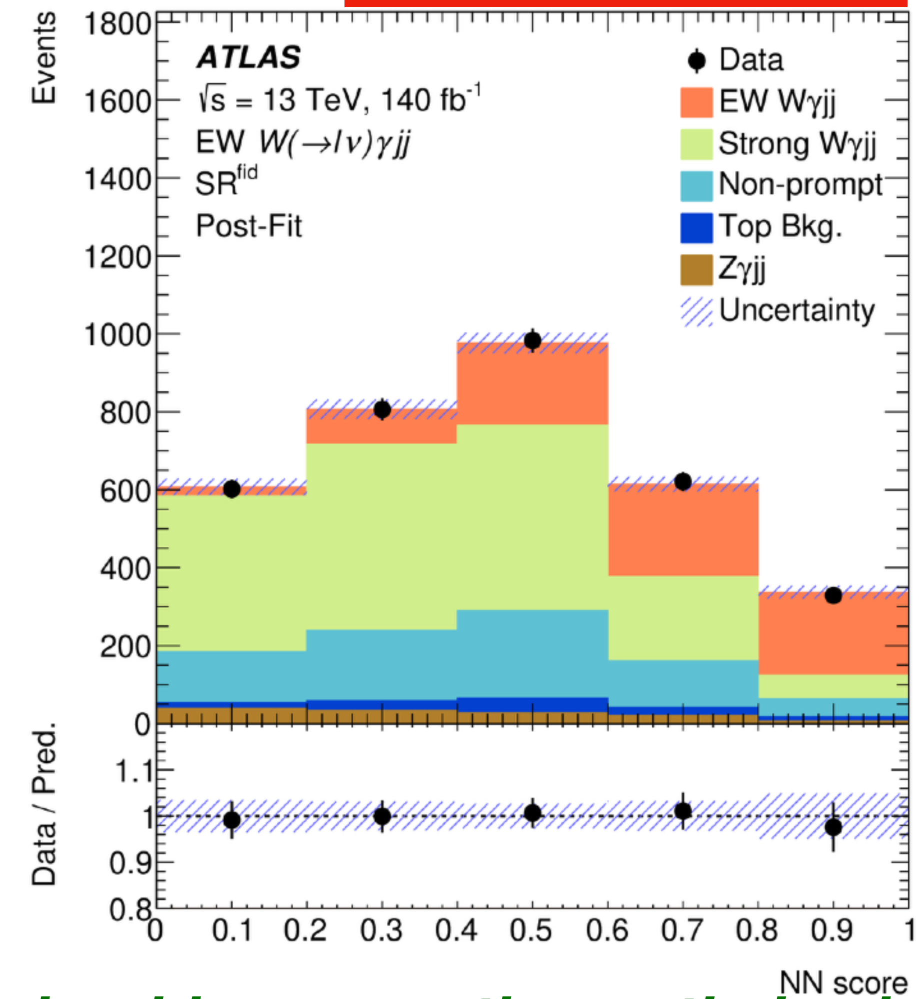
Submitted to EPJC
arxiv.2403.02809

- Events are ***categorised in Signal Region (SR) and Control Regions (CRs)***
  - constraint the main background, QCD $W\gamma$+jj
- ***Inclusive measurement***:
  - SR^{fid}: $N_{jets}^{gap} == 0$, CR^{fid}: $N_{jets}^{gap} > 0$
- ***Differential measurement***:
  - SR + 3 CRs based on N_{jets}^{gap} and $l\gamma$-centrality



Differential measurement

Inclusive measurement



- ***Signal vs bkg separation optimised using Machine Learning (ML)***
  - DNN with 13 kinematic variables
  - training in the SR phase space
- ***Observation of the EWK $W\gamma$+jj***
  - 6.3 σ, **μ** = 1.5 ± 0.5
  - σ_{EWK} = 13.2 ± 2.5 fb

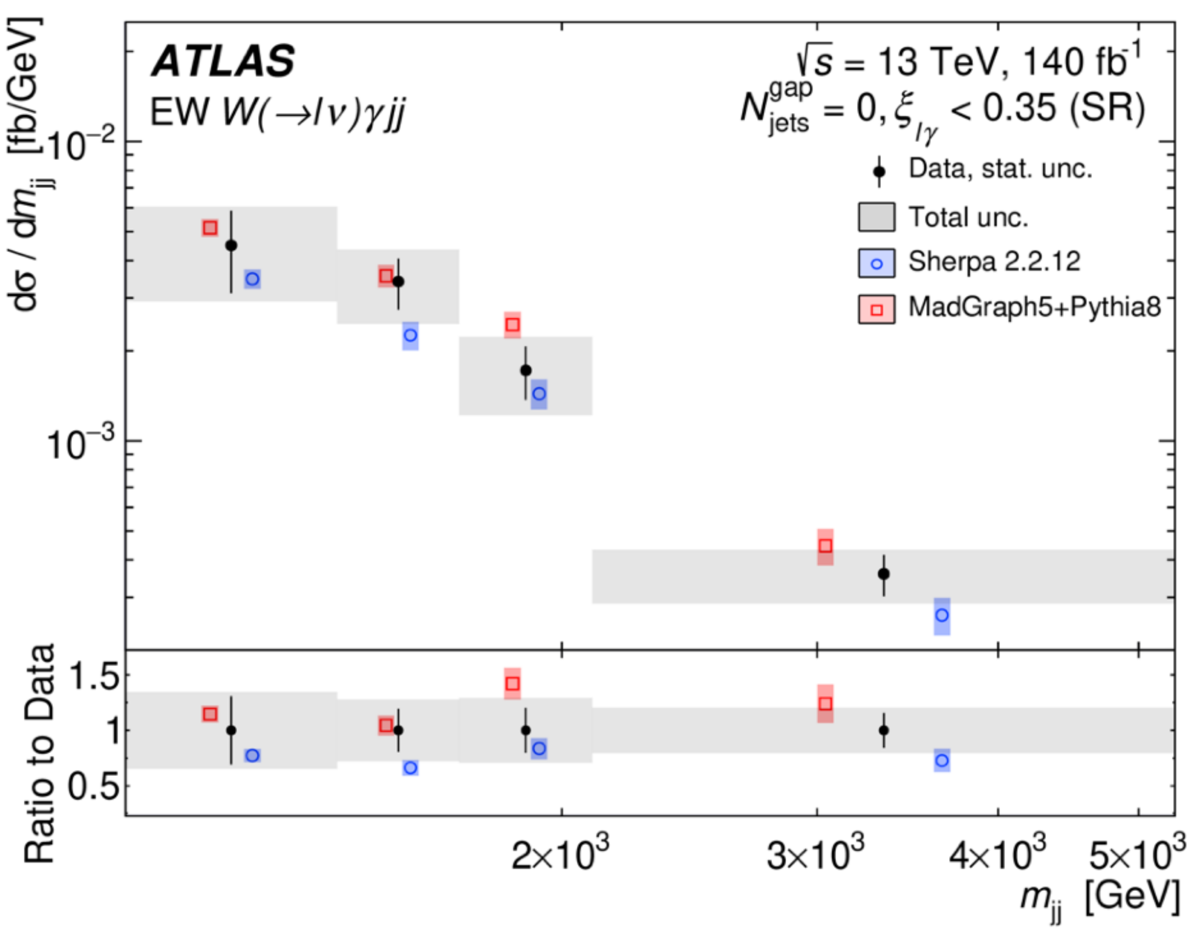
Goal: differential measurement

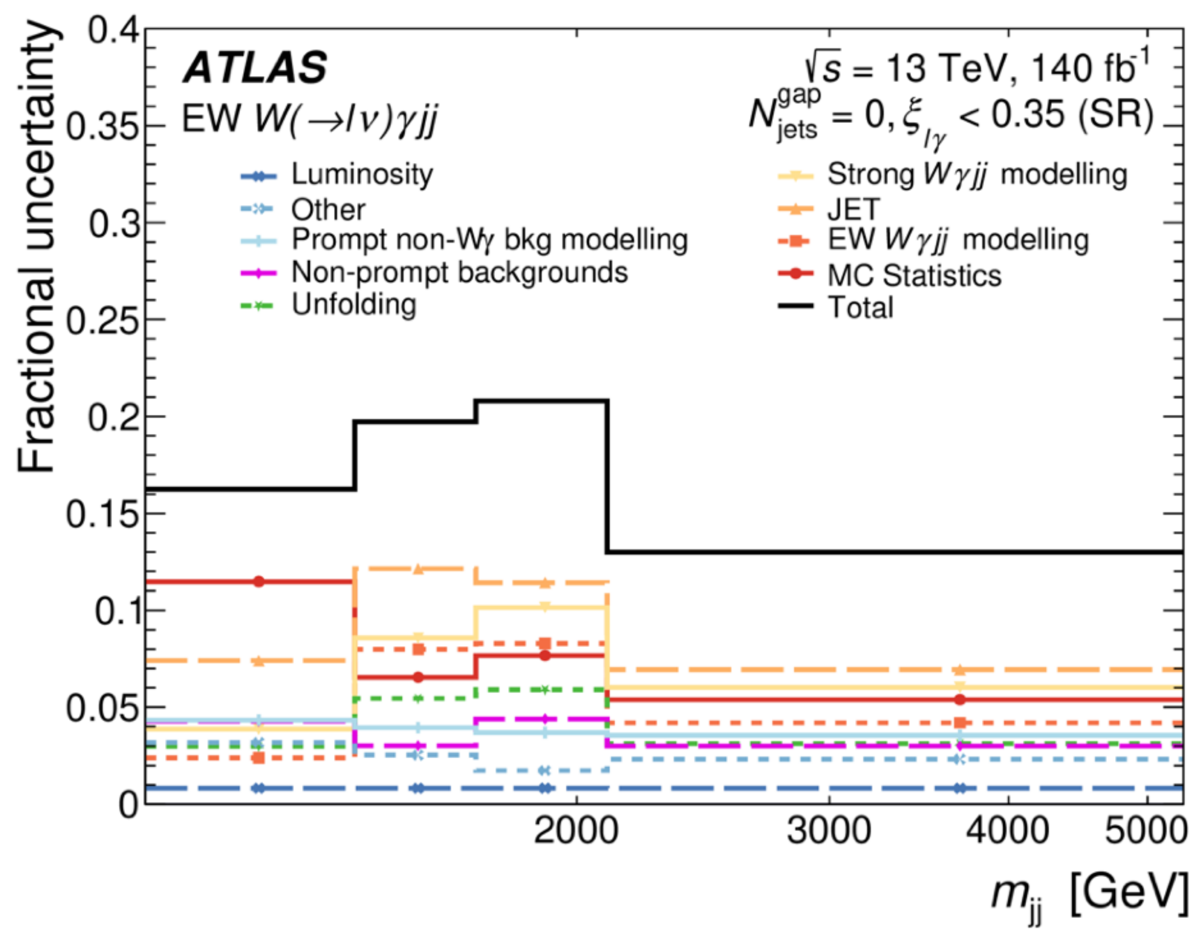
Submitted to EPJC [arxiv.2403.02809](https://arxiv.org/abs/2403.02809)

- Differential measurement performed in high m_{jj} (> 1 TeV) phase space
- ***Fiducial definition at particle level defined to mimic the reco level selection***
  - the C-factor estimated from Sherpa EWK Wγ+jj sample

$$\sigma^{\text{fid}}_{\text{EW } W\gamma jj} = \frac{N_{\text{EW } W\gamma jj}}{L \cdot C_{\text{EW } W\gamma jj}}$$

- ***Unfolding using iterative Bayesian procedure***
  - done for several variables, binning optimised to account for data statistics
- ***Modelling and jets uncertainties dominate the measurement***

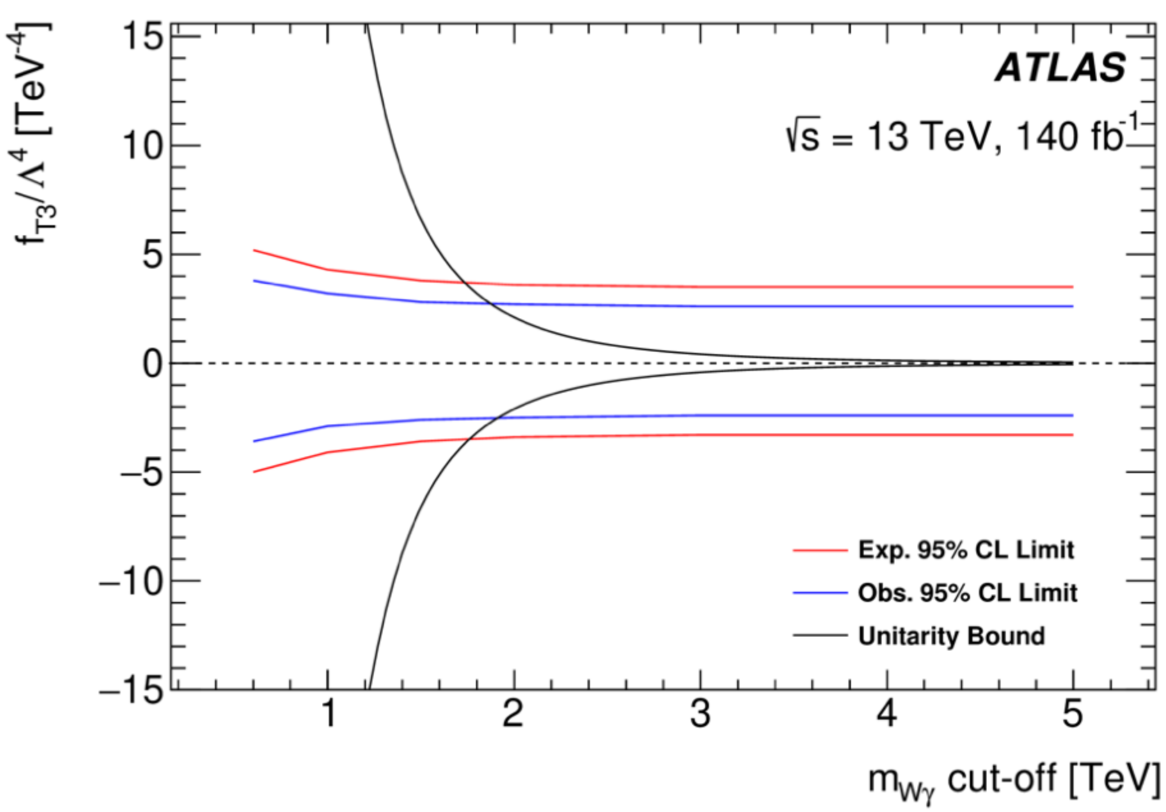




Another goal: dim-8 EFT

- The VBS component is directly sensitive to New Physics via a large variety of ***dim-8 Effective Field Theory (EFT) operators*** (Eboli model)
  - LO MG+Pythia8 predictions
  - constraint using p_T^l or p_T^{jj}
- ***Clipping scan compared with the unitarity bound***

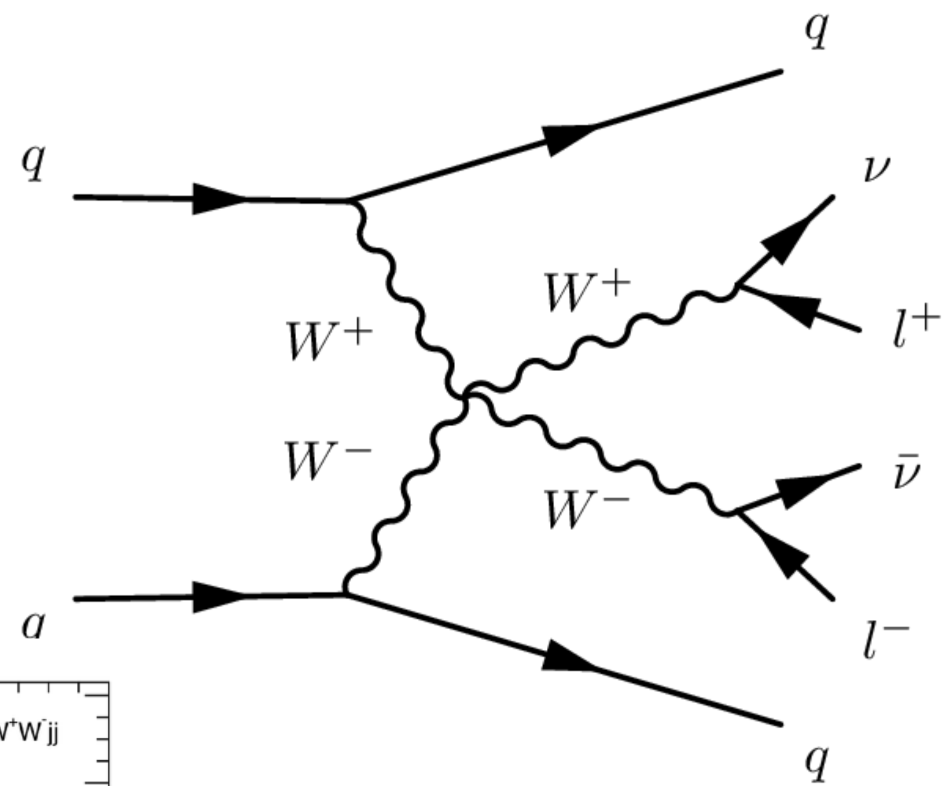
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_j \frac{f_j^{(8)}}{\Lambda^4} O_j^{(8)}$$

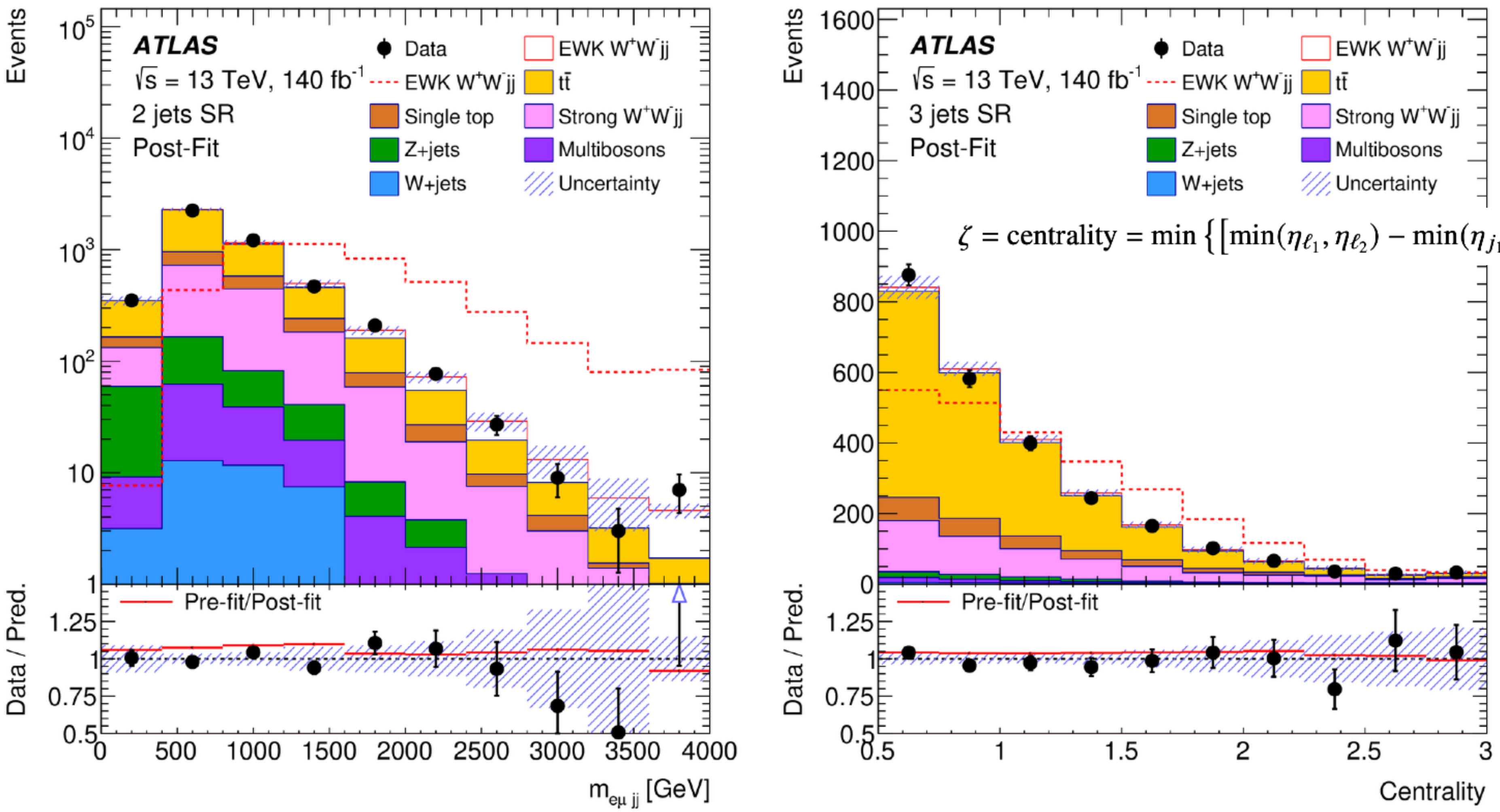


Coefficients [TeV^{-4}]	Observable	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	p_T^{jj}	[-2.4, 2.4]	[-1.8, 1.8]
f_{T1}/Λ^4	p_T^{jj}	[-1.5, 1.6]	[-1.1, 1.2]
f_{T2}/Λ^4	p_T^{jj}	[-4.4, 4.7]	[-3.1, 3.5]
f_{T3}/Λ^4	p_T^{jj}	[-3.3, 3.5]	[-2.4, 2.6]
f_{T4}/Λ^4	p_T^{jj}	[-3.0, 3.0]	[-2.2, 2.2]
f_{T5}/Λ^4	p_T^{jj}	[-1.7, 1.7]	[-1.2, 1.3]
f_{T6}/Λ^4	p_T^{jj}	[-1.5, 1.5]	[-1.0, 1.1]
f_{T7}/Λ^4	p_T^{jj}	[-3.8, 3.9]	[-2.7, 2.8]
f_{M0}/Λ^4	p_T^l	[-28, 28]	[-24, 24]
f_{M1}/Λ^4	p_T^l	[-43, 44]	[-37, 38]
f_{M2}/Λ^4	p_T^l	[-10, 10]	[-8.6, 8.5]
f_{M3}/Λ^4	p_T^l	[-16, 16]	[-13, 14]
f_{M4}/Λ^4	p_T^l	[-18, 18]	[-15, 15]
f_{M5}/Λ^4	p_T^l	[-17, 14]	[-14, 12]
f_{M7}/Λ^4	p_T^l	[-78, 77]	[-66, 65]

os-WW+jj production

- ***Phase space requiring opposite sign W pair***
  - one electron one muon
  - b-jets veto, centrality cut
- ***SM background processes***
  - top associated processes (dedicated CR)
  - QCD WW+jj production





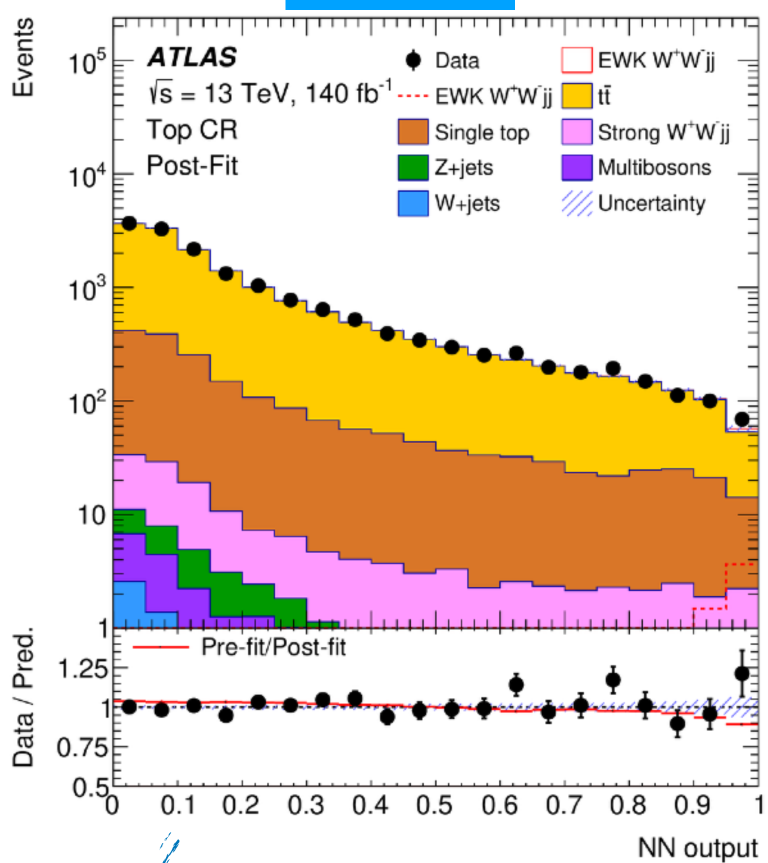
$$\zeta = \text{centrality} = \min\left\{\left[\min(\eta_{\ell_1},\eta_{\ell_2}) - \min(\eta_{j_1},\eta_{j_2})\right], \left[\max(\eta_{j_1},\eta_{j_2}) - \max(\eta_{\ell_1},\eta_{\ell_2})\right]\right\},$$

Good modelling description of the relevant kinematic distributions in the SRs

Good ML practice: looser phase space

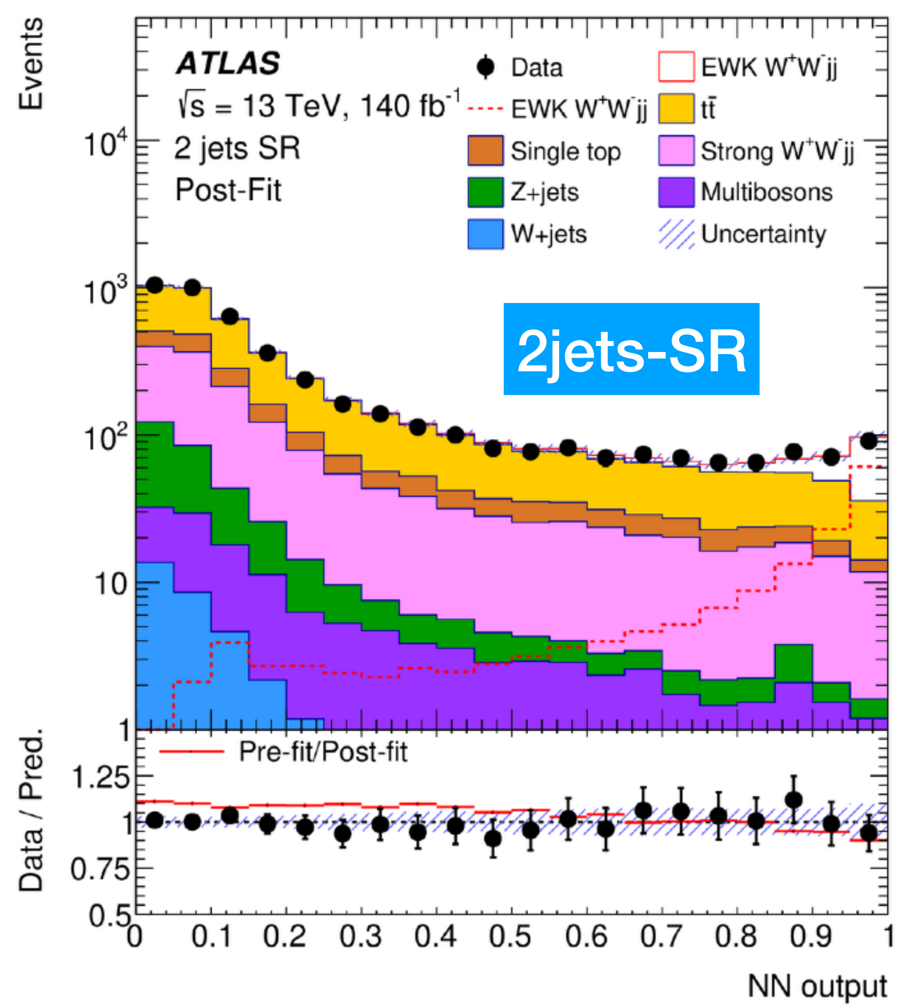
Submitted to JHEP
arxiv.2403.04869

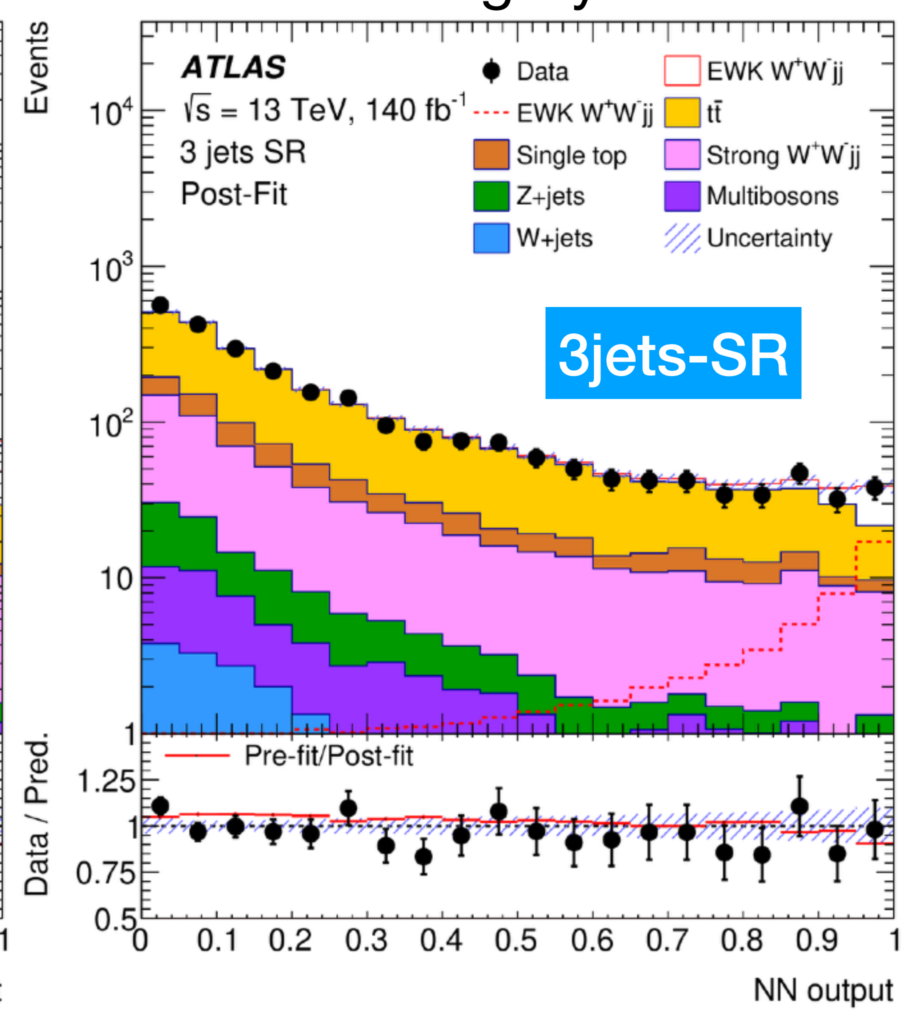
Top-CR



- ***Signal sensitivity enhanced with defining a dedicated DNN model***
    - 8 (2-jets) and 10 (3-jets) kinematic variables used as input features
- ***Dedicated models for 2-jets and 3-jets events***
    - recover signal efficiency
    - dedicated variables set for each category

Main top background constrained in CR and prediction extrapolated in the SR



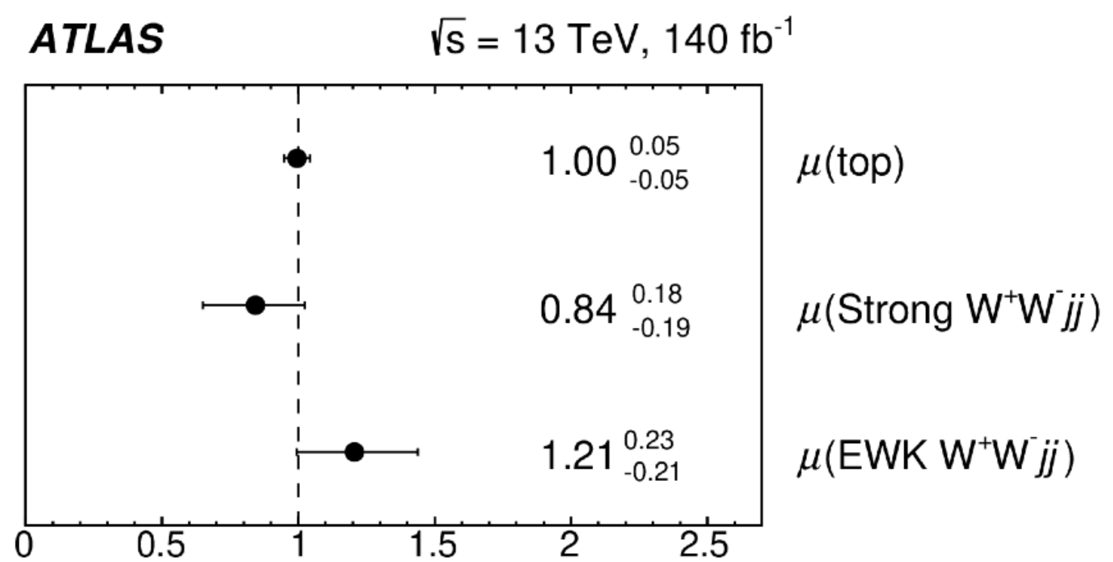


Goal: observation and measurement

Submitted to JHEP
[arxiv.2403.04869]

- ***Simultaneous CR+SRs fit to extract the signal component***
  - no dedicated QCD WW+jj CR —> floating
- ***Main uncertainties impact***
  - theory (top and EWK), MC stats, jets

Sources	$\frac{\sqrt{(\Delta\mu)^2-(\Delta\mu')^2}}{\mu}$ [%]
MC statistical uncertainty	7.7
Top quark theoretical uncertainties	6.3
Signal theoretical uncertainties	5.8
Jet experimental uncertainties	4.9
Strong W^+W^-jj theoretical uncertainties	1.3
Luminosity	0.8
Misidentified lepton uncertainty	0.5
b-tagging	0.4
Lepton experimental uncertainties	0.1
Others	0.3
Data statistical uncertainty	12.3
Top quark normalisation uncertainty	4.9
Strong W^+W^-jj normalisation uncertainty	2.2
Total uncertainty	18.5

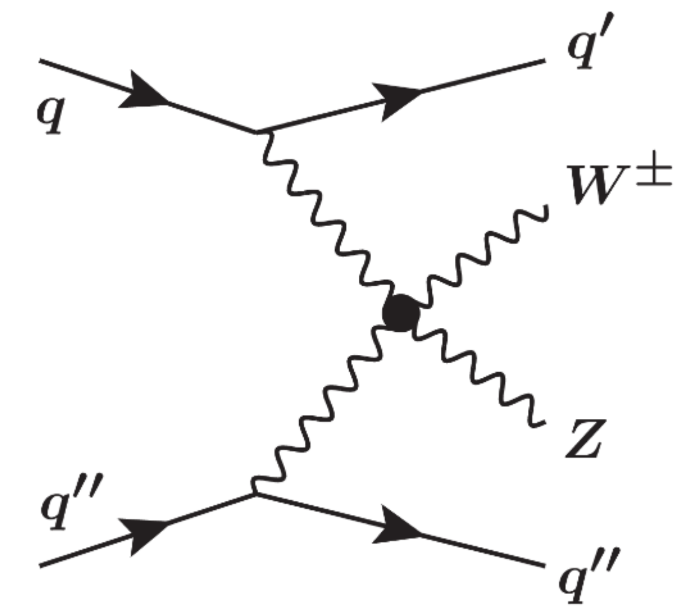


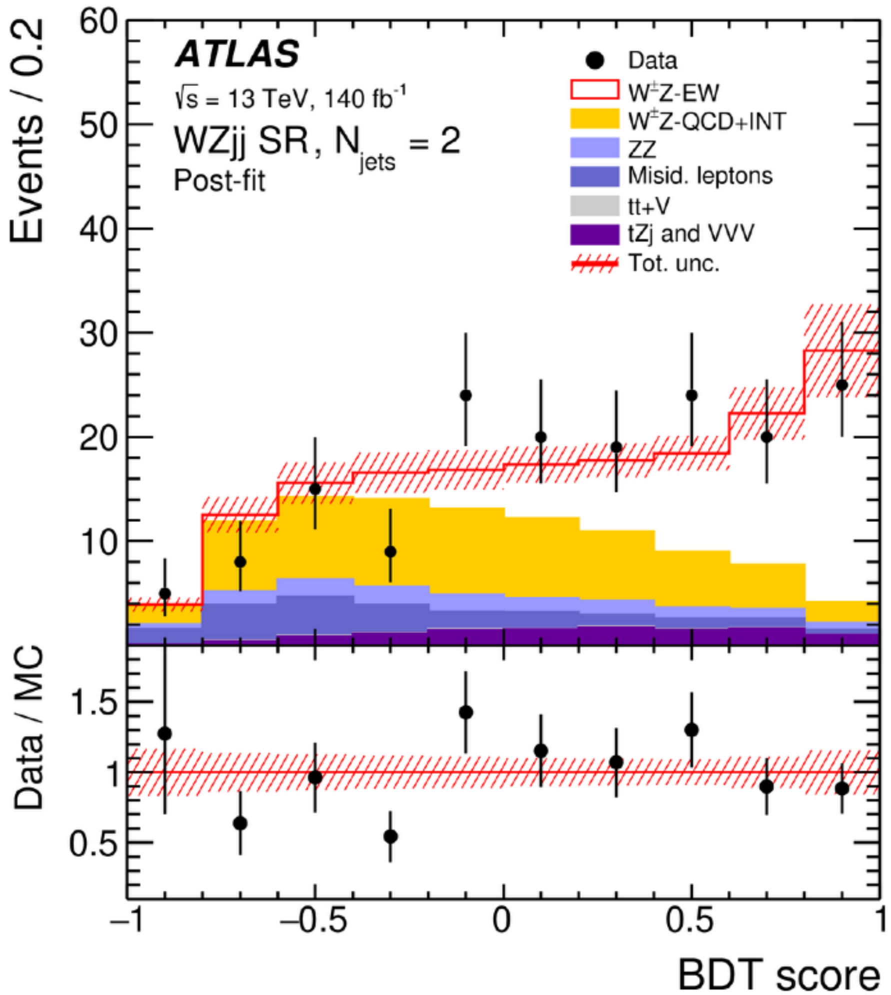
- ***Observation in this channel***
  - 7.1 σ (observed)
- ***Fiducial measurement of EWK WW+jj in VBS enhances phase space***
  - remove VVV contribution
  - $2.65\,^{+0.49}_{-0.46}$ fb

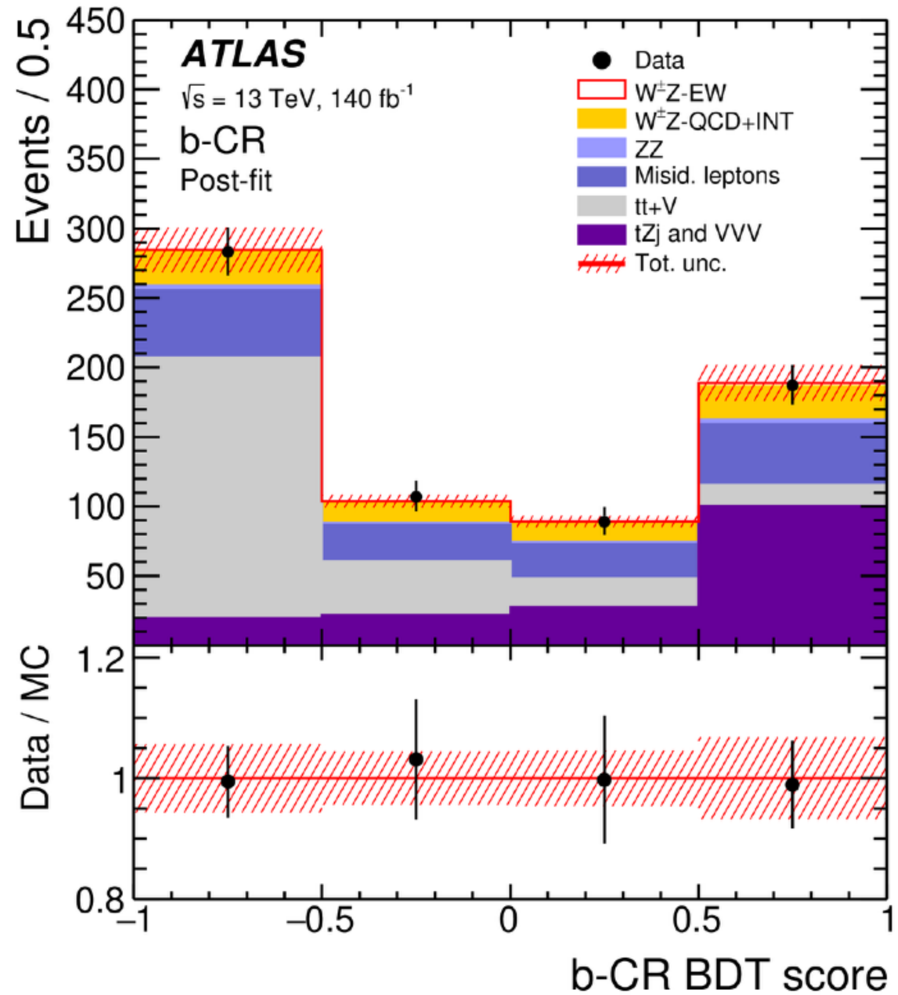
WZ + jj production

Submitted to JHEP
arxiv.2403.15296

- ***3 leptons, MET and additional jets final state***
  - additional lepton veto, loose $m_{jj} > 150$ GeV requirement
  - SR events divided in N_{jets} == 2 and >=3 categories
- ***Main SM backgrounds***
  - QCD WZ+jj production (irreducible)
  - dedicated ZZ CR (additional lepton)
  - b-CR to constraint tt+V process (additional b-jet)



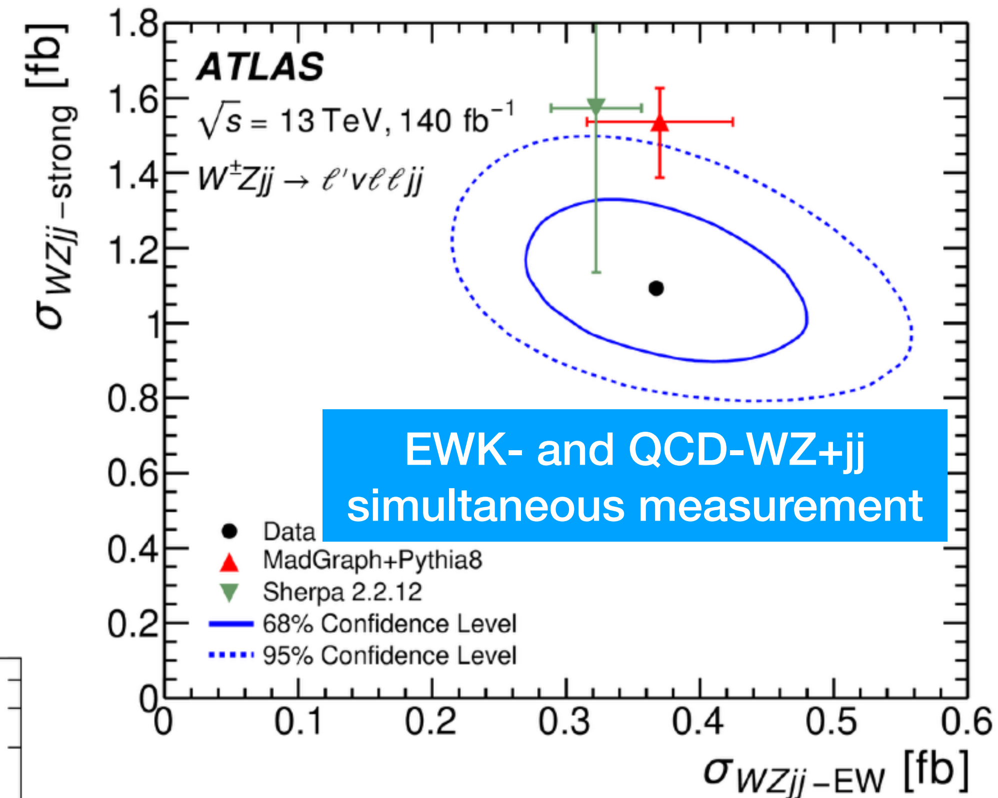


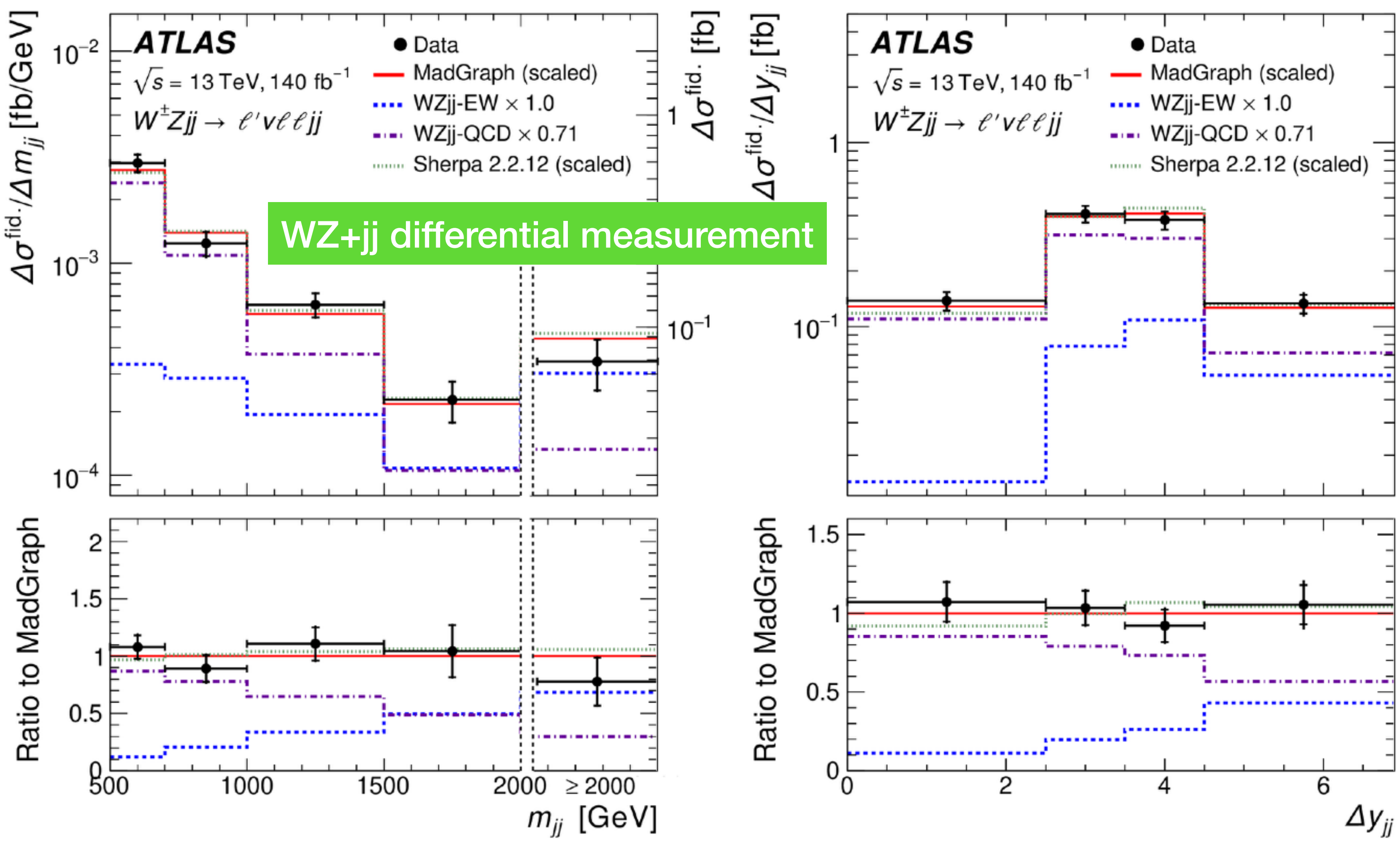


- ***BDT as final discriminant***
  - 15 inputs variables to separate EWK WZjj vs other backgrounds in SR
  - 16 inputs variables to separate ttV and tZj in b-CR
- ***Adversarial-NN***
  - to enhance QCD WZjj production in SR

EWK vs QCD production

- ***EWK- and QCD-WZ+jj production measured simultaneously; measurement in bins of:***
  - n_{Jets} {== 2; >= 3} bins and 3 m_{jj} bins
  - ***QCD-WZ+jj cross section measured by factor 0.71 lower than MC prediction***
- ***WZ+jj differential measurement***
  - SR events, predictions scaled by the integrated EWK- and QCD-WZ+jj measurements





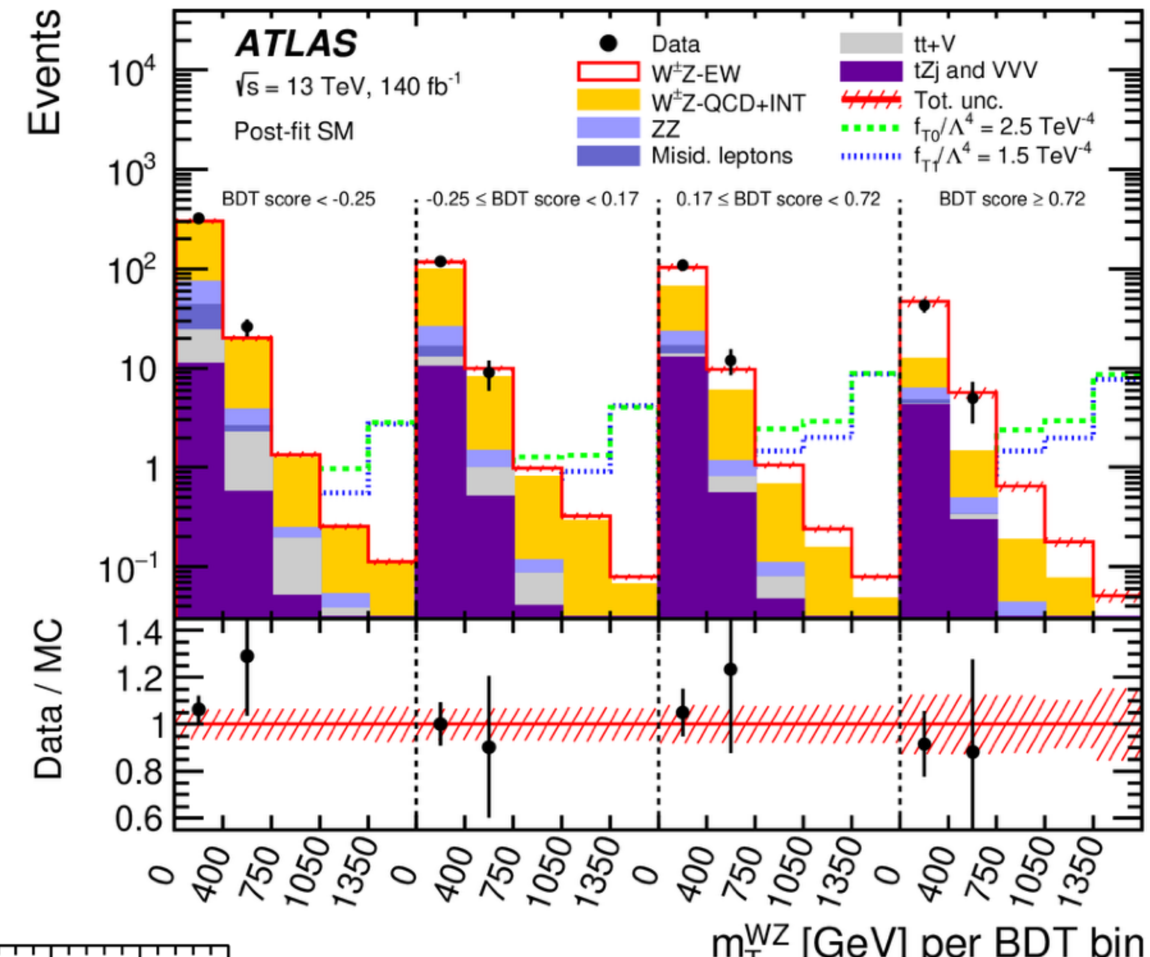
- ***Unfolding of several kinematics variables***
  - compared with the MadGraph and Sherpa predictions
  - BDT unfolded as well
- ***Measurements dominated by statistical uncertainty, followed by jets experimental uncertainties***

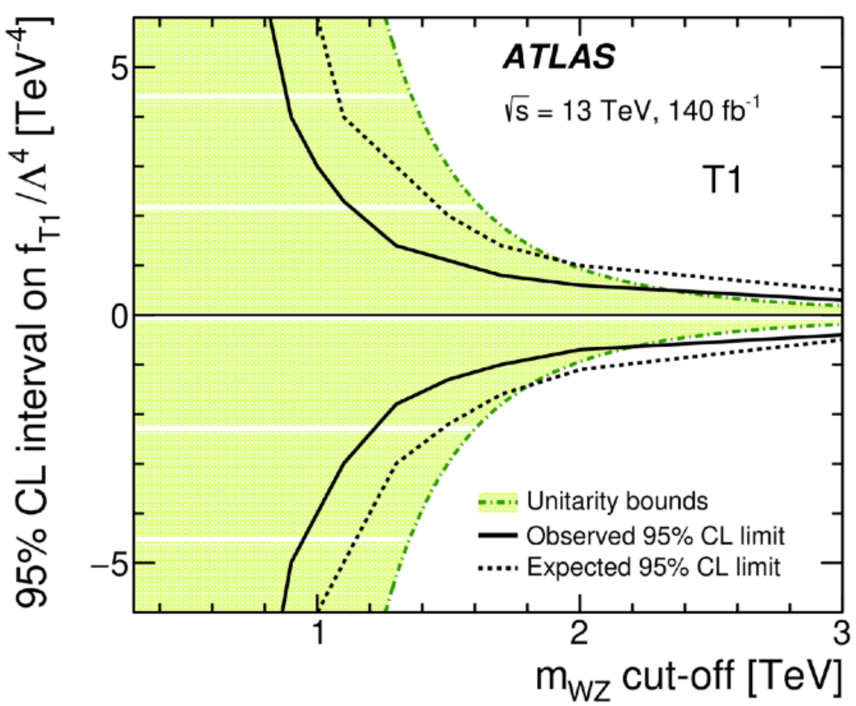
Goal: dim-8 EFT limits

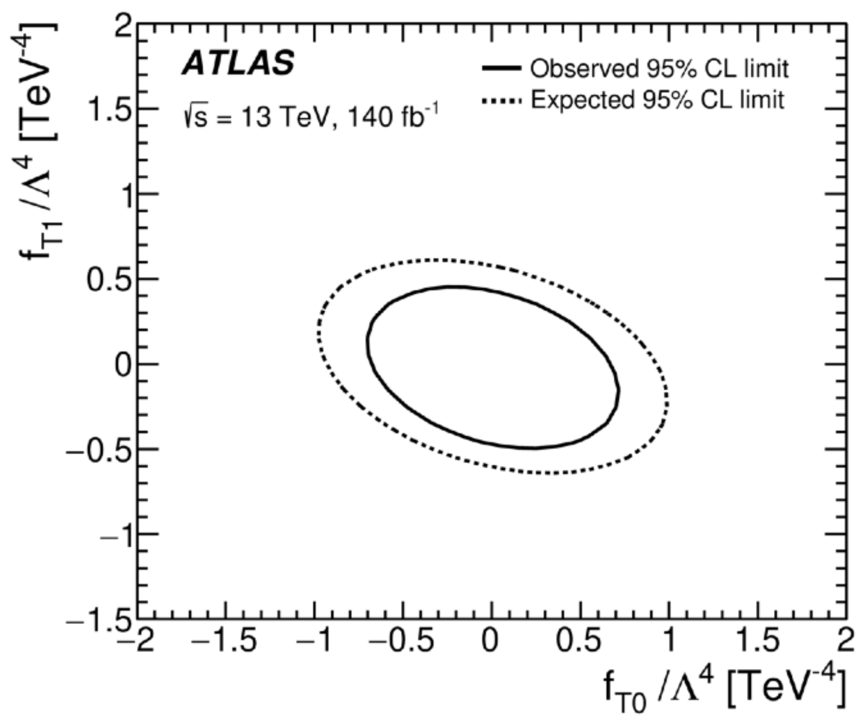
Submitted to JHEP
[arxiv.2403.15296](https://arxiv.org/abs/2403.15296)

- Effects from ***dim-8 EFT operators*** are expected at high invariant mass for the WZ+jj production
  - constraint a set of operators sensitive to
- 2-dim fit based on the BDT and m_T^{WZ} transverse mass

Limits overall better than the Wγ+jj final state, that is actually covering complementary operators







	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
f_{T0}/Λ^4	[-7.0, 7.0]	[-1.5, 1.6]
f_{T1}/Λ^4	[-1.1, 1.0]	[-0.7, 0.6]
f_{T2}/Λ^4	[-12, 6]	[-2.4, 1.8]
f_{M0}/Λ^4	[-60, 60]	[-12, 12]
f_{M1}/Λ^4	[-32, 32]	[-15, 15]
f_{M7}/Λ^4	[-30, 30]	[-15, 15]
f_{S02}/Λ^4	[-41, 41]	[-18, 18]
f_{S1}/Λ^4	—	—

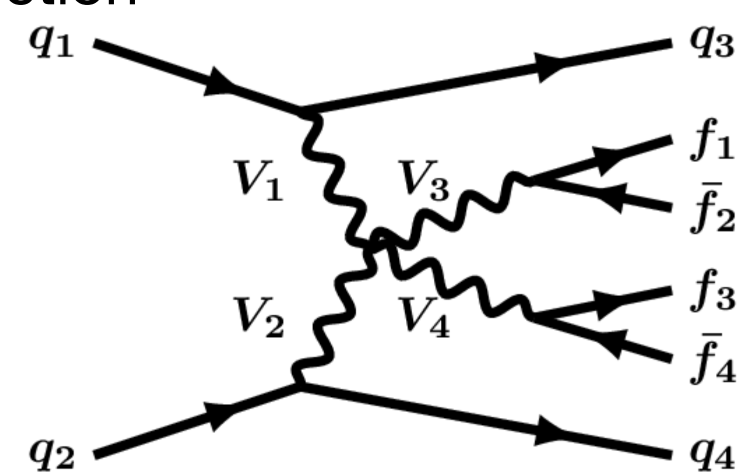
Summary

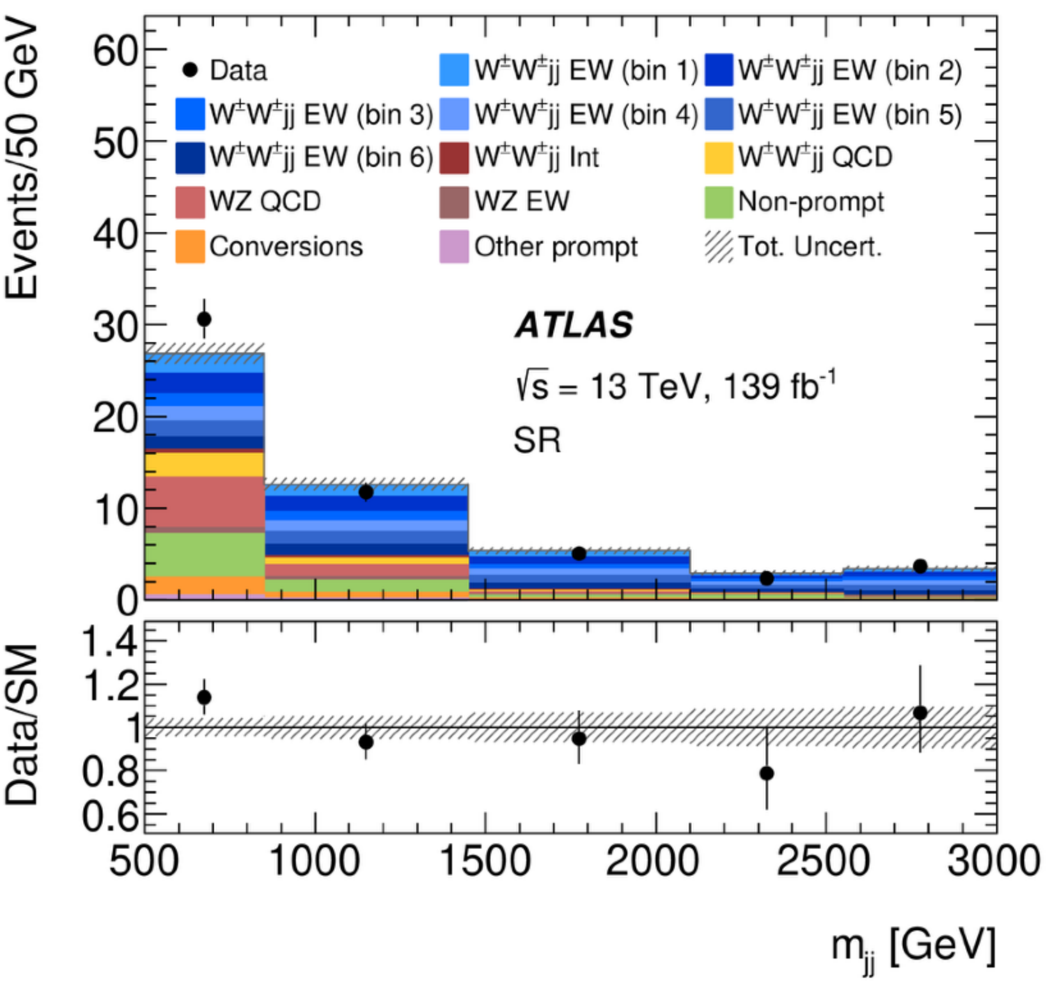
- ***Measurements of Vector Boson Scattering with the ATLAS experiment***
- Measurement of EWK diboson + jj production in VBS-enhanced phase space quite interesting
  - crucial test of the EWK-sector of the SM
  - challenges from theory/experimental side that push us to new strategies
- Additional and new final states covered along the years
  - new measurements released
  - all diboson final states have been observed by ATLAS
  - EFT interpretations performed in this sector
- ***Stay tuned for new ATLAS results with Run-2 and Run-3 datasets!!!***

backup

ss-WW+jj production

- Final state with the largest ratio (~5) for EWK/QCD WW+jj production
  - qg and gg initiated diagrams not allowed at LO
  - qq/qanti-q suppressed at LO
- Usual VBS selection; same-sign electrons/muons pair
  - veto on additional leptons veto and b-jets
- QCD WZ+jj estimated via MC + data-driven corrections
  - large source of fakes/non-prompts estimated via data-driven





Summary of MC samples for signal and background processes

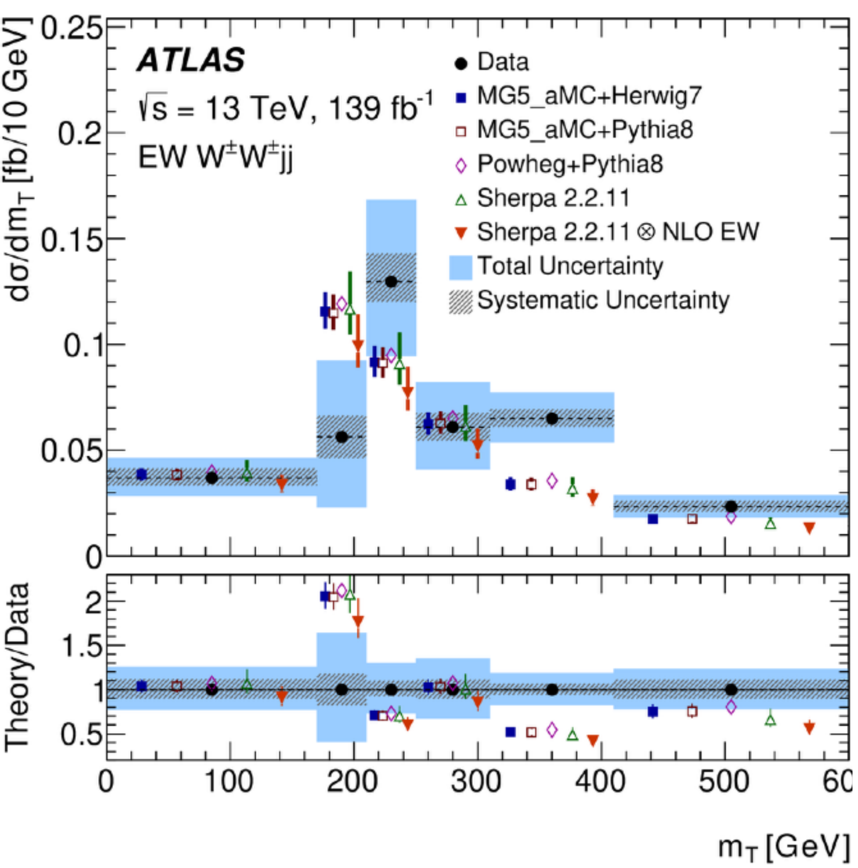
Process, short description	ME Generator + parton shower	Order	Tune	PDF set in ME
EW, Int, QCD $W^\pm W^\pm jj$, nominal signal	MadGraph5_aMC@NLO2.6.7 + Herwig7.2	LO	Herwig	NNPDF3.0nlo
EW, Int, QCD $W^\pm W^\pm jj$, alternative shower	MadGraph5_aMC@NLO2.6.7 + Pythia8.244	LO	A14	NNPDF3.0nlo
EW W^+W^+jj, NLO pQCD approx.	Sherpa2.2.11 & Sherpa2.2.2(WWW) & Powheg Box2+Pythia8.235 (WH)	+0,1j@LO NLO	Sherpa A14	NNPDF3.0nnlo
EW $W^\pm W^\pm jj$, NLO pQCD approx.	Powheg Boxv2 + Pythia8.230	NLO (VBS approx.)	AZNLO	NNPDF3.0nlo
QCD $W^\pm W^\pm jj$, NLO pQCD approx.	Sherpa2.2.2	+0,1j@LO	Sherpa	NNPDF3.0nnlo
QCD $VVjj$	Sherpa2.2.2	+0,1j@NLO; +2,3j@LO	Sherpa	NNPDF3.0nnlo
EW $W^\pm Z/\gamma^* jj$	MadGraph5_aMC@NLO2.6.2+Pythia8.235	LO	A14	NNPDF3.0nlo
EW $Z/\gamma^* Z/\gamma^* jj$	Sherpa2.2.2	LO	Sherpa	NNPDF3.0nnlo
QCD $V\gamma jj$	Sherpa2.2.11	+0,1j@NLO; +2,3j@LO	A14	NNPDF3.0nnlo
EW $V\gamma jj$	MadGraph5_aMC@NLO2.6.5+Pythia8.240	LO	A14	NNPDF3.0nlo
VVV	Sherpa2.2.1 (leptonic) & Sherpa2.2.2 (one $V \to jj$)	+0,1j@LO	Sherpa	NNPDF3.0nnlo
$t\bar{t}V$	MadGraph5_aMC@NLO2.3.3.p0 + Pythia8.210	NLO	A14	NNPDF3.0nlo
tZq	MadGraph5_aMC@NLO2.3.3.p1 + Pythia8.212	LO	A14	NNPDF2.3lo
$W^\pm W^\pm jj$ EFT	MadGraph5_aMC@NLO 2.6.5 + Pythia8.235	LO	A14	NNPDF3.0nlo
$H_5^{\pm\pm}$	MadGraph5_aMC@NLO 2.9.5 + Pythia8.245	LO	A14	NNPDF3.0nlo

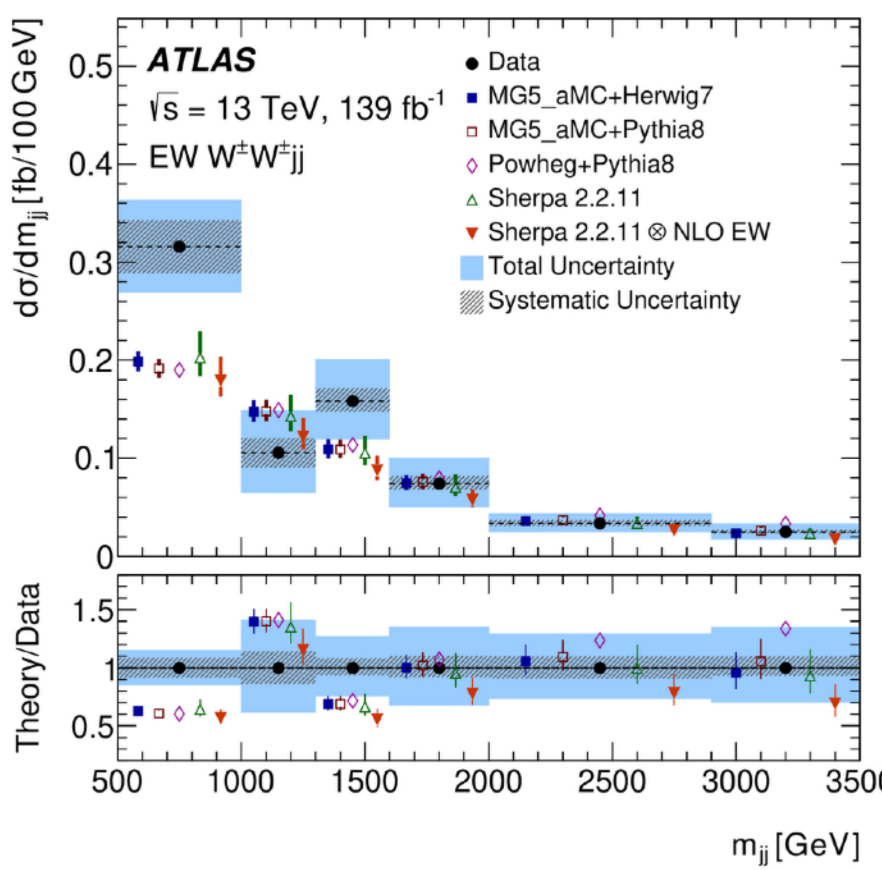
Differential measurement

Submitted to JHEP
arxiv.2312.00420

- SRs based on the lepton flavour (ee, eμ, μe, $\mu\mu$)
  - same for the low-mjj CR, one-bin for the WZ-CR
- mjj used to enhance the signal sensitivity in each bin of the measured variables
  - mll is instead used to measure the cross section as function of the mjj
- μ^{EW} = 1.15 ± 0.09 (stat.) ± 0.05 (mod. syst.) ± 0.05 (exp. syst.) ± 0.02 (lumi.)

Source	Impact [%]
Experimental	4.6
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.9
E_T^{miss} scale and resolution	0.2
b-tagging inefficiency	0.7
Background, misid. leptons	3.4
Background, charge misrec.	1.0
Pile-up modelling	0.1
Luminosity	1.9
Modelling	4.5
EW $W^\pm W^\pm jj$, shower, scale, PDF & α_s	0.7
EW $W^\pm W^\pm jj$, QCD corrections	1.9
EW $W^\pm W^\pm jj$, EW corrections	0.9
Int $W^\pm W^\pm jj$, shower, scale, PDF & α_s	0.6
QCD $W^\pm W^\pm jj$, shower, scale, PDF & α_s	2.6
QCD $W^\pm W^\pm jj$, QCD corrections	0.8
Background, WZ scale, PDF & α_s	0.3
Background, WZ reweighting	1.5
Background, other	1.3
Model statistical	1.8
Experimental and modelling	6.4
Data statistical	7.4
Total	9.8



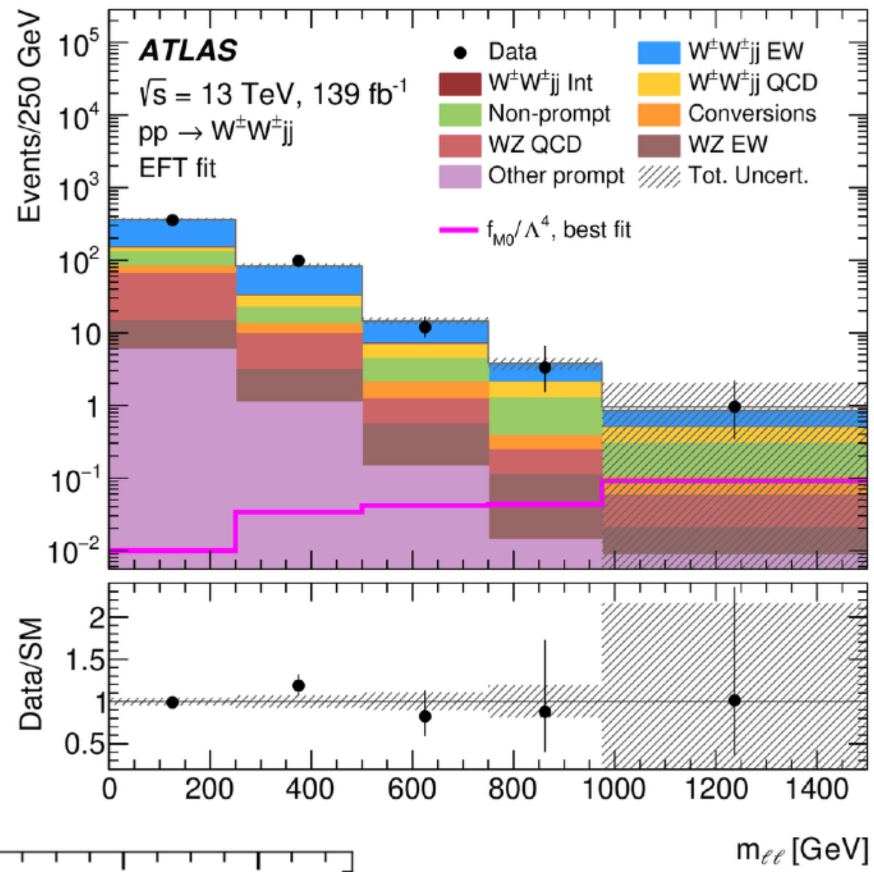


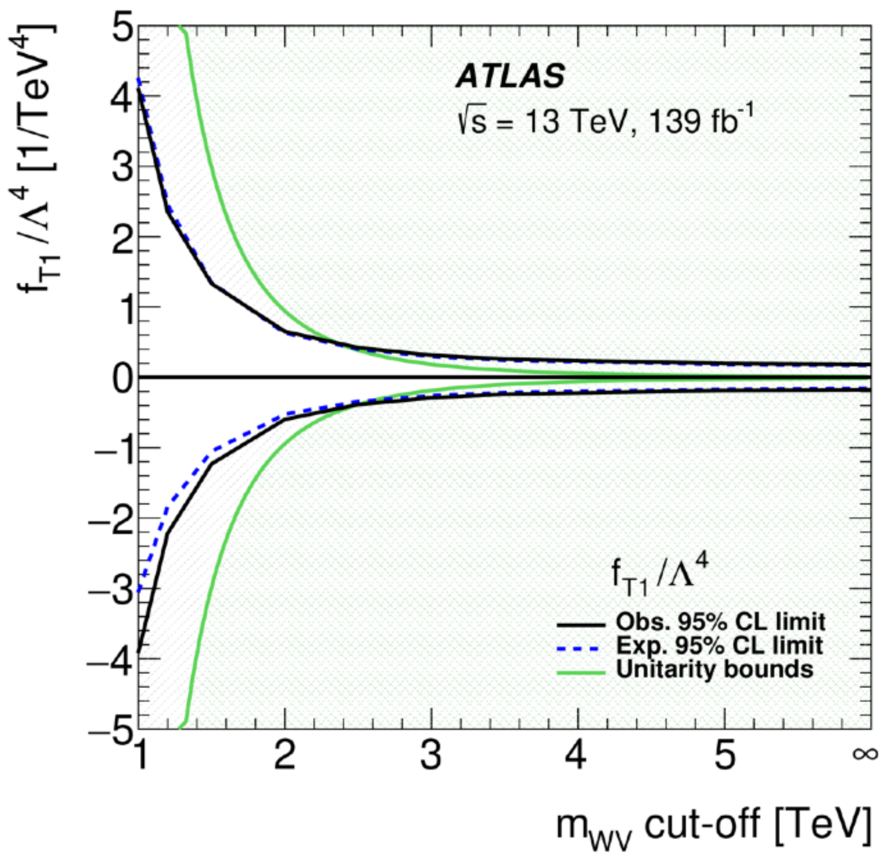
Description	σ_{fid}^{EW} [fb]
Measured cross section	2.92 ± 0.22 (stat.) ± 0.19 (syst.)
MG5_aMC+Herwig7	2.53 ± 0.04 (PDF) $^{+0.22}_{-0.19}$ (scale)
MG5_aMC+Pythia8	2.53 ± 0.04 (PDF) $^{+0.22}_{-0.19}$ (scale)
Sherpa	2.48 ± 0.04 (PDF) $^{+0.40}_{-0.27}$ (scale)
Sherpa ⊗ NLO EW	2.10 ± 0.03 (PDF) $^{+0.34}_{-0.23}$ (scale)
Powheg Box+Pythia	2.64

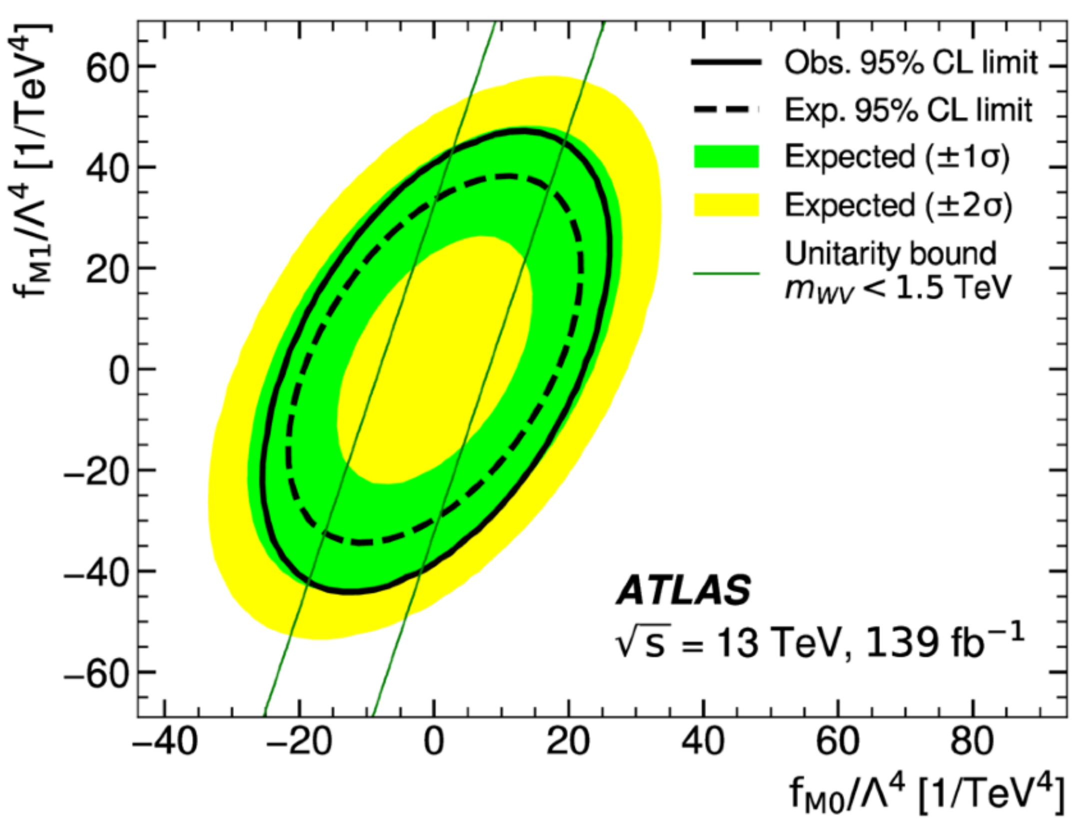
dim-8 EFT constraints

Submitted to JHEP
arxiv.2312.00420

- Phase space sensitive to a variety of dim-8 EFT operators
- 95% exclusion limits as a function of the clipping cut-off
  - tighter limit on T1 excluding up to 2.4 - 2.5 TeV
- 2-dimensional limits derived w/ a 1.5 TeV unitarisation cut-off and w/o it
  - interesting positive/negative correlation among the operators



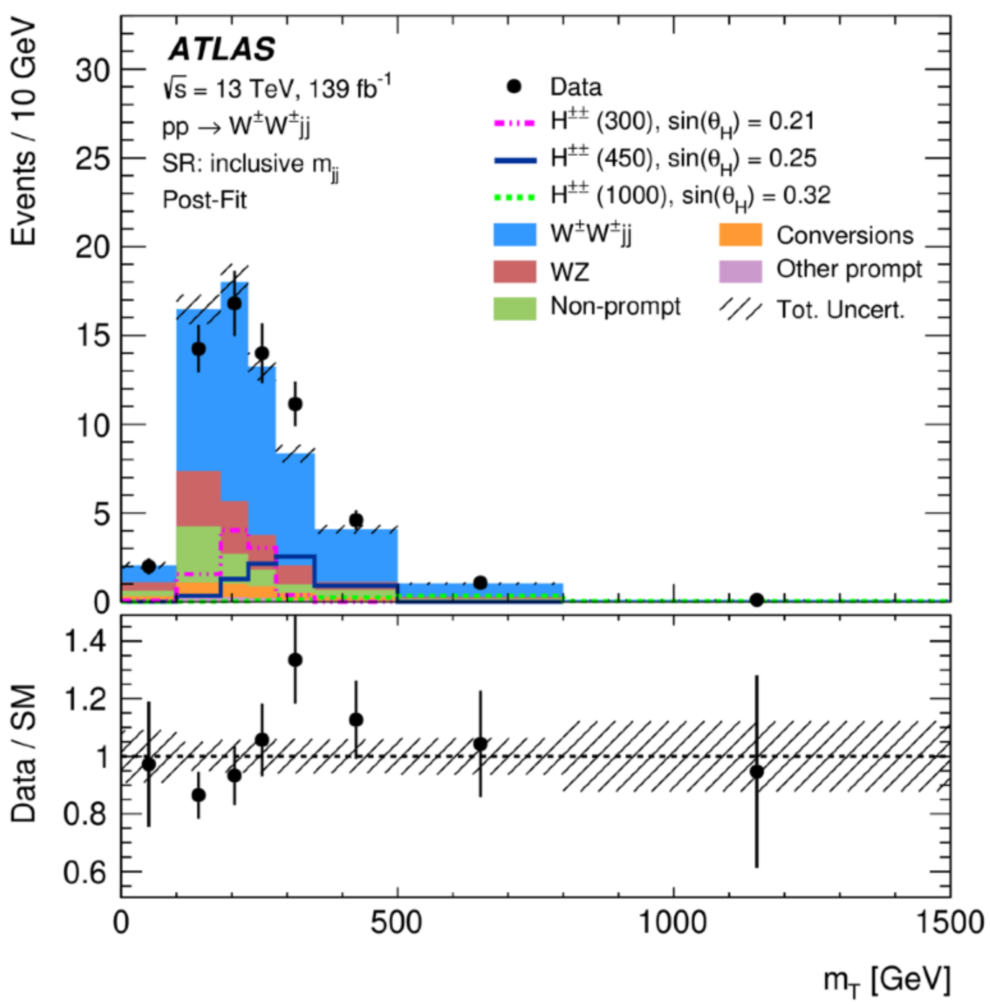


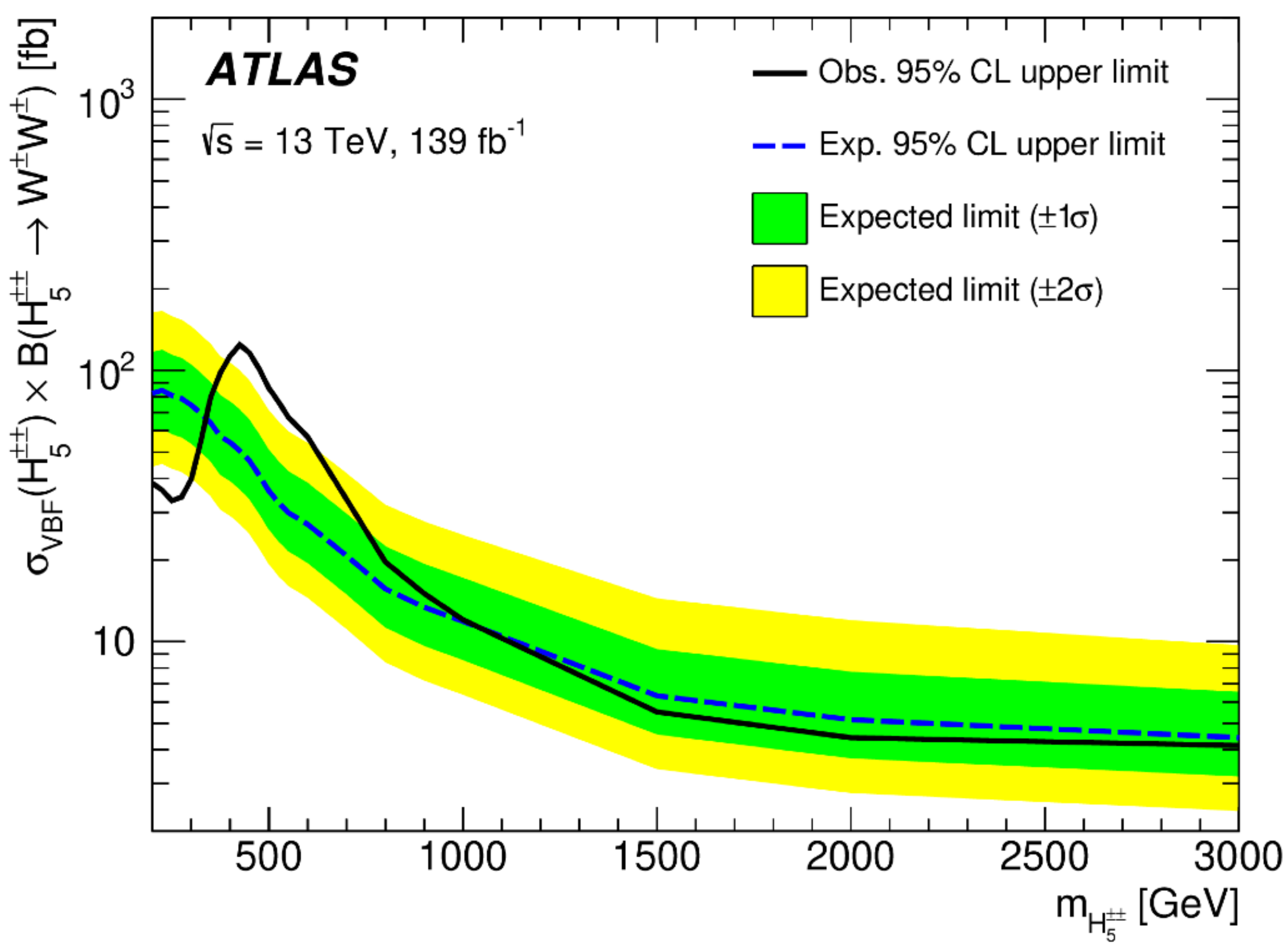


VBS: more than a measurement

- Limits on the production of doubly charged H++ via Vector Boson Fusion (VBF)
  - Georgi-Machacek model (*Nucl. Phys. B 262 (1985) 463*) foresees the presence of an additional quintuplet ($H^{\pm\pm}$, $H^{\pm}$, H^0) that couples to SM W/Z bosons
- Similar analysis strategy, 2-dim fit on m_{jj} and m_T variables
- Excess around 450 GeV: local 3.3, global 2.5

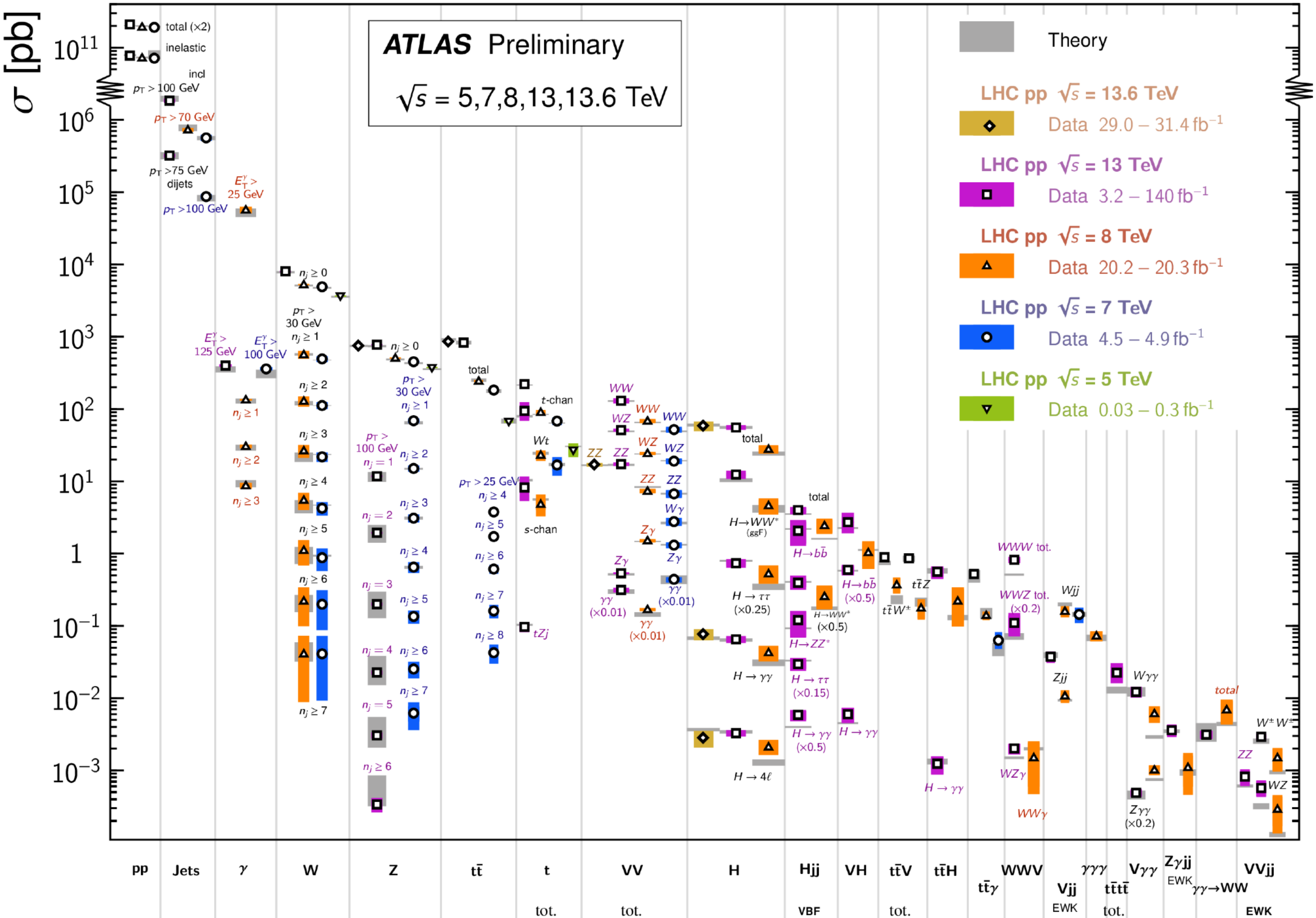
Submitted to JHEP
arxiv.2312.00420



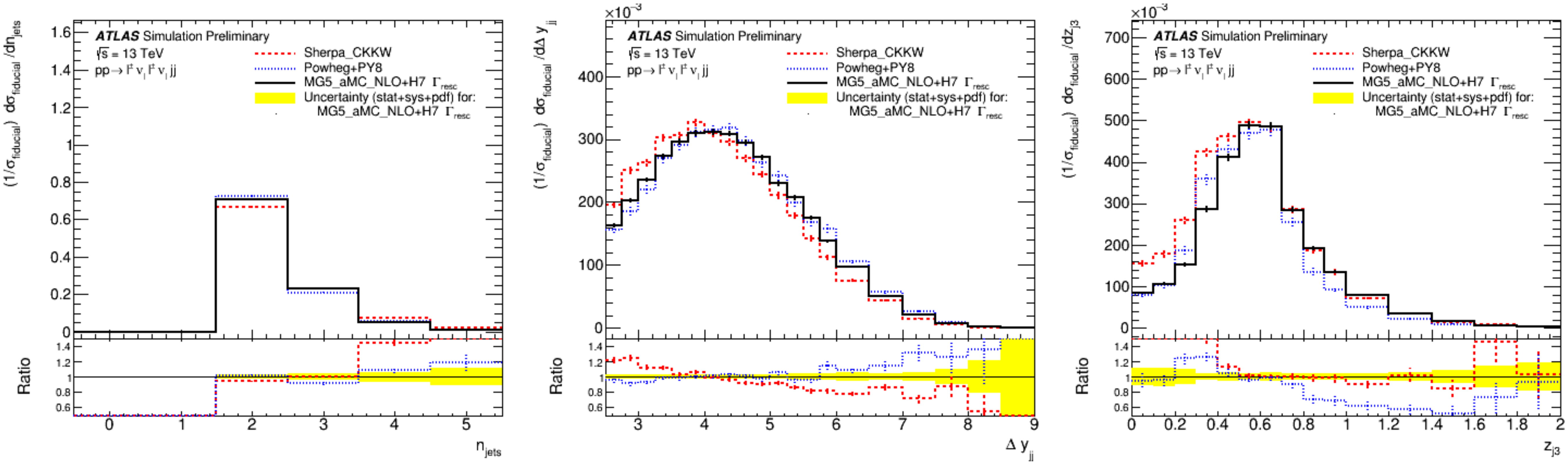


Standard Model Production Cross Section Measurements

Status: October 2023



More MC generator comparisons



Wγ+jj: diagrams

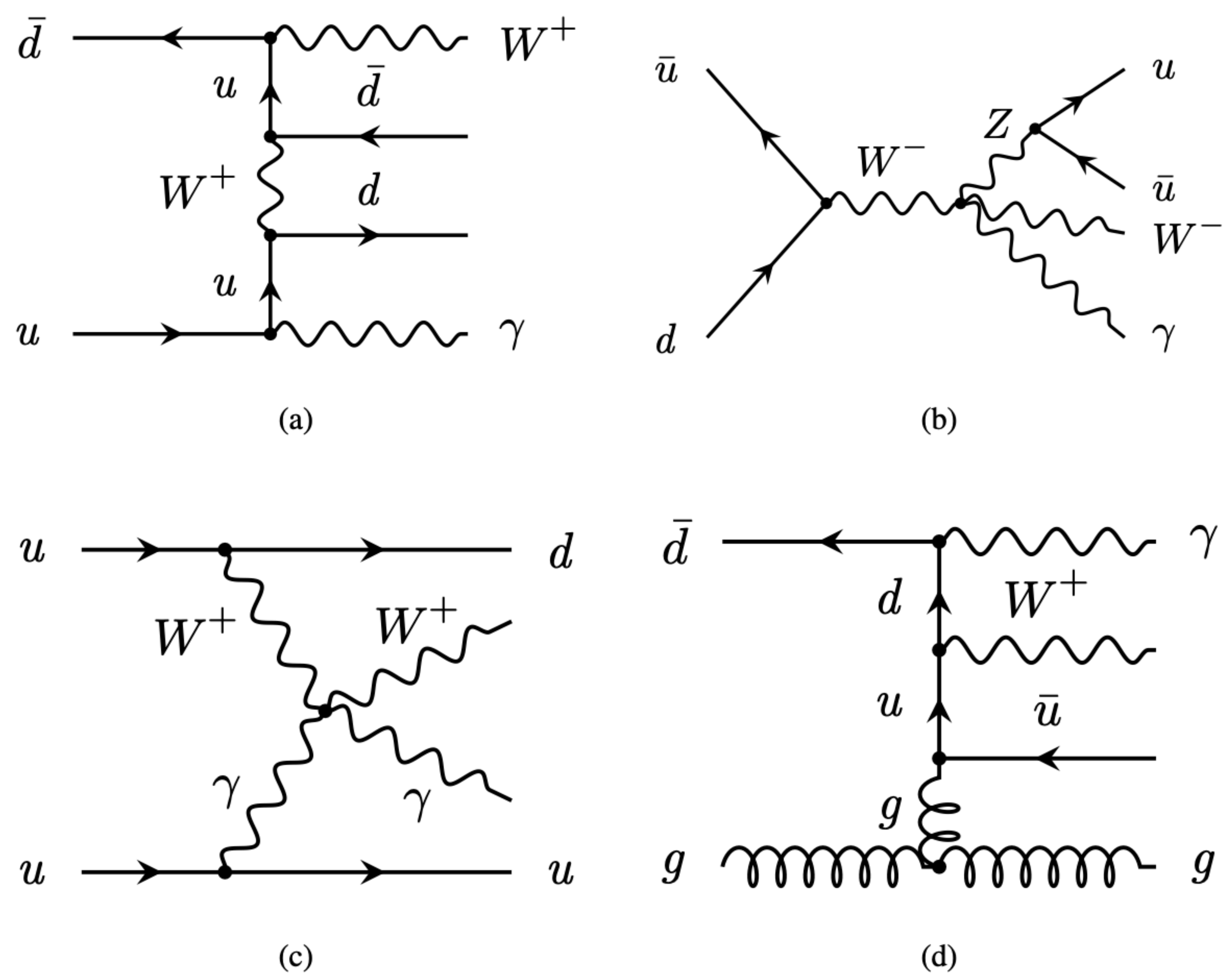


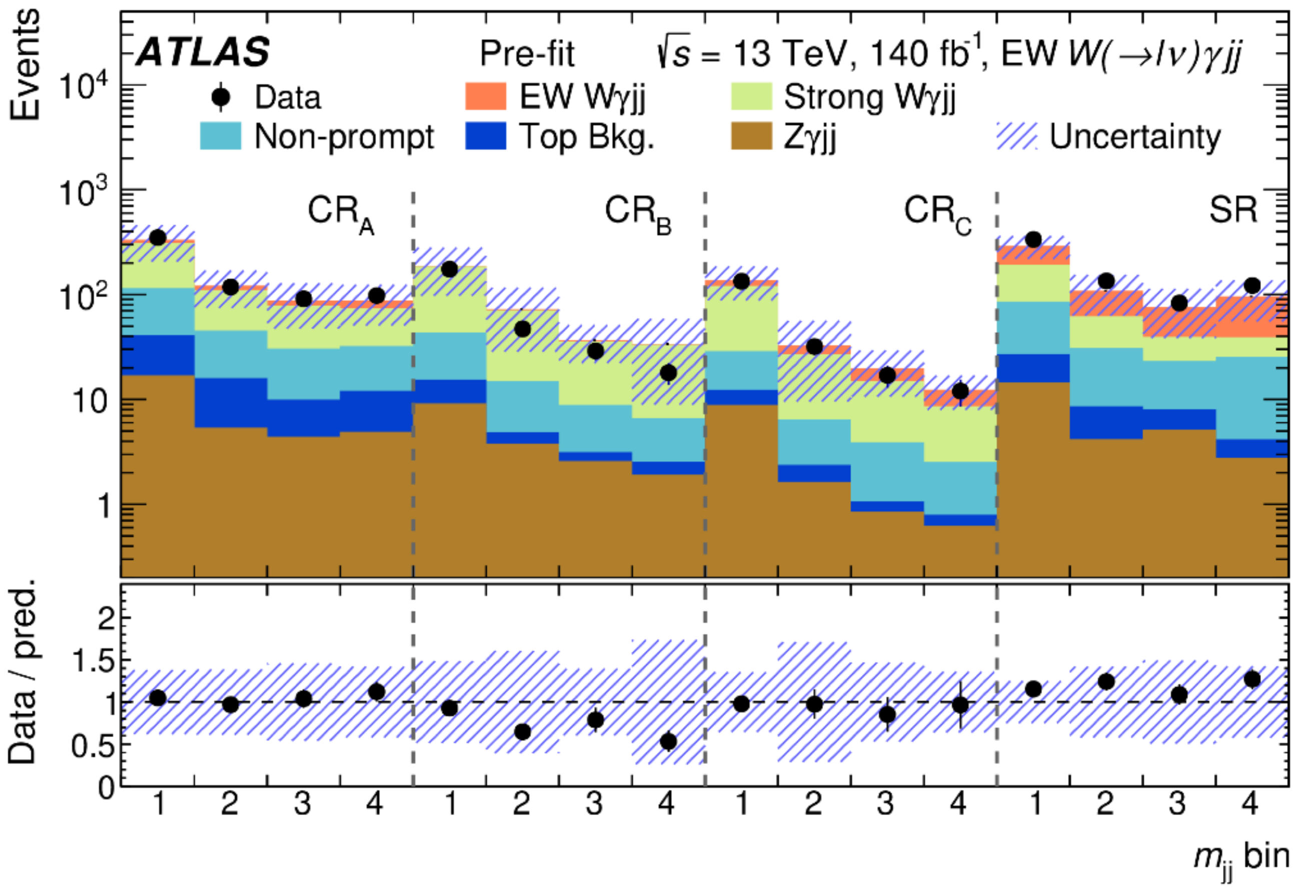
Figure 1: Representative Feynman diagrams for the $W\gamma jj$ final state: (a) EW $W\gamma jj$ production involving no gauge boson self-interactions, (b) bremsstrahlung EW $W\gamma jj$ non-VBS production involving quartic gauge boson interactions, (c) $W\gamma$ VBS involving quartic gauge boson interactions, and (d) Strong $W\gamma jj$ production.

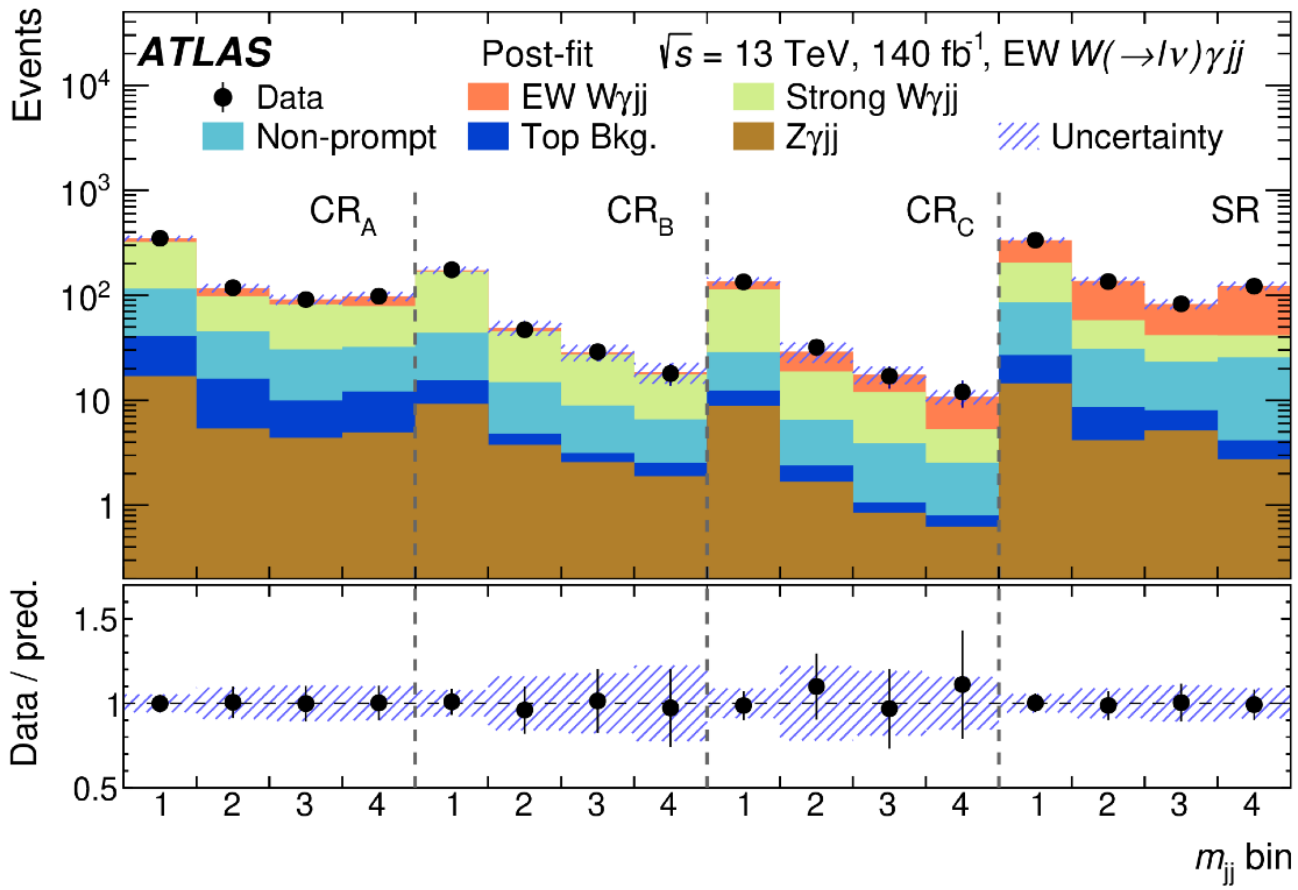
Wy+jj: event selection

Object	Selection requirements
Dressed muons	$p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 2.5$
Dressed electrons	$p_{\mathrm{T}} > 30$ GeV and $\lvert\eta\rvert < 2.47$ (excluding $1.37 < \lvert\eta\rvert < 1.52$)
Isolated photons	$E_{\mathrm{T}}^{\gamma} > 22$ GeV and $\lvert\eta\rvert < 2.37$ (excluding $1.37 < \lvert\eta\rvert < 1.52$) and $E_{\mathrm{T}}^{\mathrm{iso}} < 0.2E_{\mathrm{T}}^{\gamma}$
Jets	At least two jets with $p_{\mathrm{T}} > 50$ GeV and $\lvert y\rvert < 4.4$, b−jet veto
Missing transverse momentum	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV and $m_{\mathrm{T}}^{W} > 30$ GeV
VBS topology	$N_{\ell} = 1$, $N_{\gamma} \geq 1$, $\lvert m_{\ell\gamma} - m_{Z}\rvert > 10$ GeV
	$\Delta R_{\mathrm{min}}(\ell, j) > 0.4$, $\Delta R_{\mathrm{min}}(\gamma, j) > 0.4$, $\Delta R_{\mathrm{min}}(\ell, \gamma) > 0.4$
	$\Delta R_{\mathrm{min}}(j_1, j_2) > 0.4$, $\Delta\phi_{\mathrm{min}}(E_{\mathrm{T}}^{\mathrm{miss}}, j) > 0.4$
	$N_{\mathrm{jets}} \geq 2$, $p_{\mathrm{T}}^{j1}, p_{\mathrm{T}}^{j2} > 50$ GeV
	$m_{jj} > 500$ GeV, $\lvert\Delta y_{jj}\rvert > 2$
Fiducial measurement	VBS topology
Differential measurement	VBS topology $\oplus$ ($m_{jj} > 1000$ GeV, $N_{\mathrm{jets}}^{\mathrm{gap}} = 0$, and $\xi_{W\gamma} < 0.35$)

	$\mathrm{SR}^{\mathrm{fid}} \left(N_{\mathrm{jets}}^{\mathrm{gap}} = 0\right)$	$\mathrm{CR}^{\mathrm{fid}} \left(N_{\mathrm{jets}}^{\mathrm{gap}} > 0\right)$
EW $W\gamma jj$	520 ± 141	120 ± 49
Strong $W\gamma jj$	1550 ± 830	1970 ± 950
Non-prompt	692 ± 57	698 ± 58
Top quark processes	109 ± 18	183 ± 37
EW + strong $Z\gamma jj$	128 ± 34	163 ± 77
Total	3000 ± 830	3140 ± 960
Data	3341	3143

Wγ+jj: pre- vs post-fit





Wγ+jj: re-parameterisation

The fitted number of events in region r and bin i is expressed as

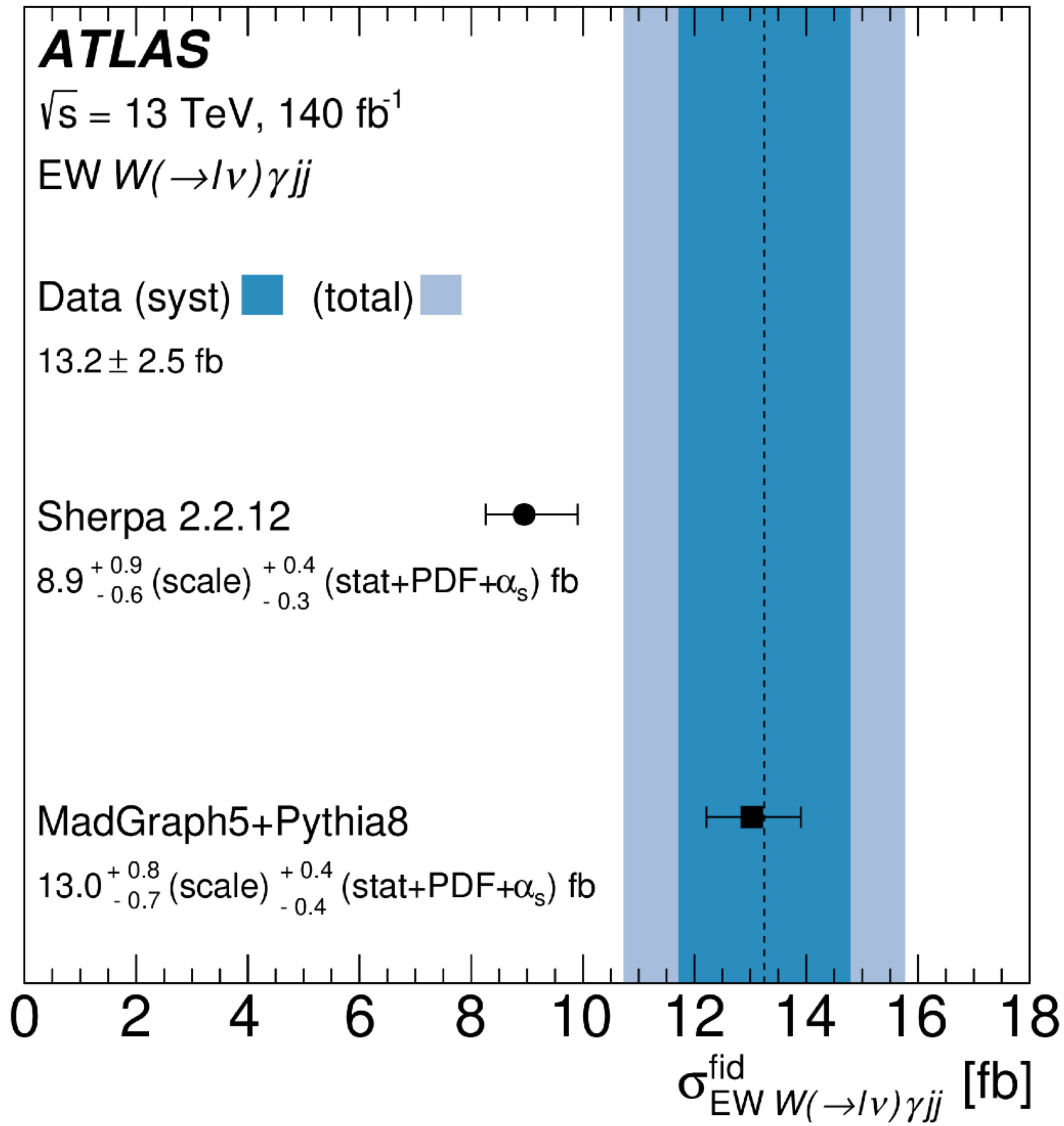
$$\nu_{ri} = \mu_{\mathrm{EW},i}\, \nu_{ri}^{\mathrm{EW,MC}} + \nu_{ri}^{\mathrm{strong}} + \nu_{ri}^{\mathrm{other,bkg}}, \tag{2}$$

where $\mu_{\mathrm{EW},i}$ is the signal strength of EW $W\gamma jj$ in bin i, and $\nu_{ri}^{\mathrm{EW,MC}}$ and $\nu_{ri}^{\mathrm{other,bkg}}$ correspond to the EW $W\gamma jj$ prediction and contributions from reducible background processes, respectively. The strong $W\gamma jj$ prediction is constrained using the signal-suppressed control regions based on the following four relations:

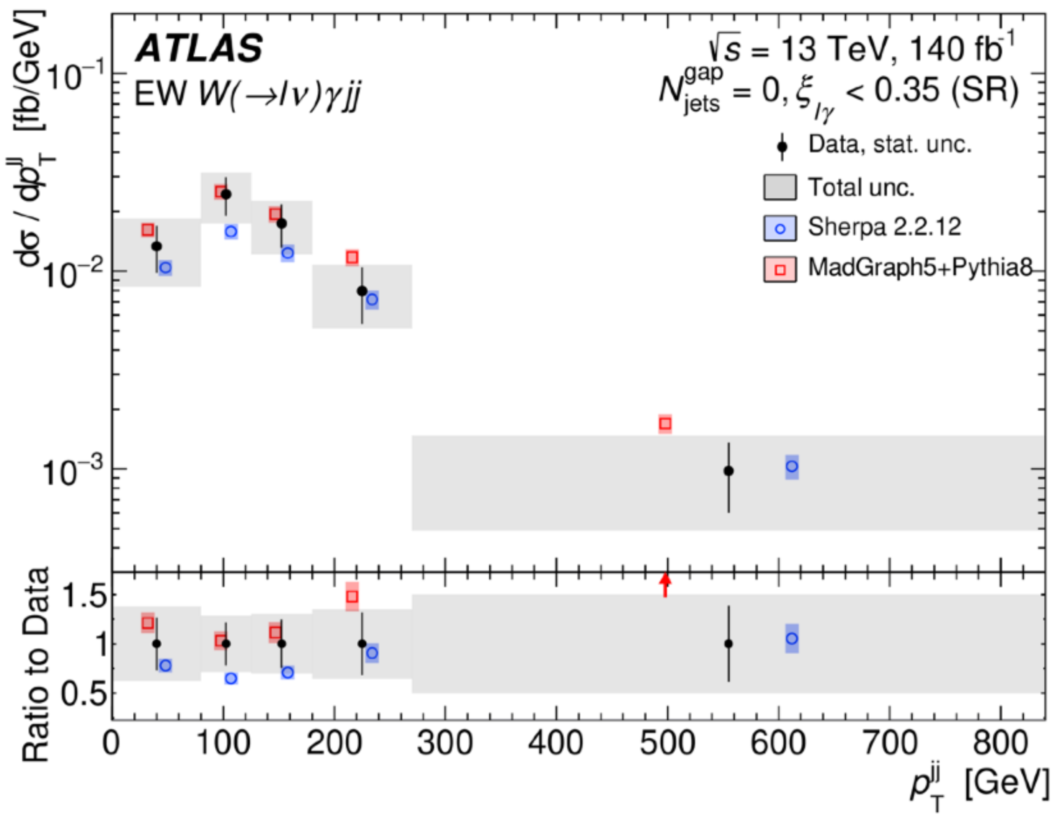
$$\begin{aligned} \nu_{\mathrm{CR_A},i}^{\mathrm{strong}} &= b_{\mathrm{L},i}\, \nu_{\mathrm{CR_A},i}^{\mathrm{strong,MC}}, & \nu_{\mathrm{CR_B},i}^{\mathrm{strong}} &= b_{\mathrm{H},i}\, \nu_{\mathrm{CR_B},i}^{\mathrm{strong,MC}}, \\ \nu_{\mathrm{SR},i}^{\mathrm{strong}} &= b_{\mathrm{L},i}\, c\, \nu_{\mathrm{SR},i}^{\mathrm{strong,MC}}, \quad \text{and} & \nu_{\mathrm{CR_C},i}^{\mathrm{strong}} &= b_{\mathrm{H},i}\, c\, \nu_{\mathrm{CR_C},i}^{\mathrm{strong,MC}}. \end{aligned} \tag{3}$$

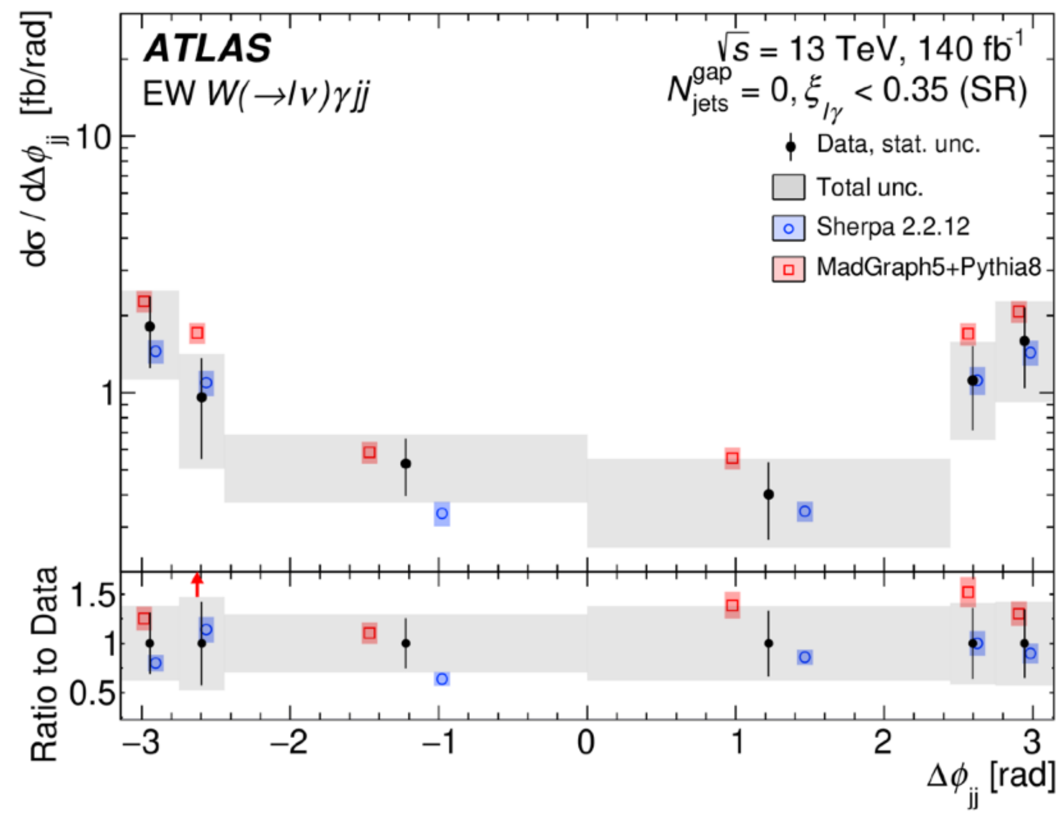
The parameters $b_{\mathrm{L},i}$ and $b_{\mathrm{H},i}$ are sets of bin-dependent free parameters that correspond to the $\xi_{l\gamma} < 0.35$ and $\xi_{l\gamma} > 0.35$ regions, respectively. The low-$\xi_{l\gamma}$ parameter, $b_{\mathrm{L},i}$, is primarily constrained by $\mathrm{CR_A}$, while $b_{\mathrm{H},i}$ is primarily constrained by $\mathrm{CR_B}$. These two sets of parameters introduce additional degrees of freedom to the predicted strong $W\gamma jj$ event yield to allow the fitted number of strong $W\gamma jj$ events to be more consistent with the observed data. A floating parameter c is used to provide a residual correction that can account for any mismodelling across $N_{\mathrm{jets}}^{\mathrm{gap}}$. This configuration is found to be more robust against

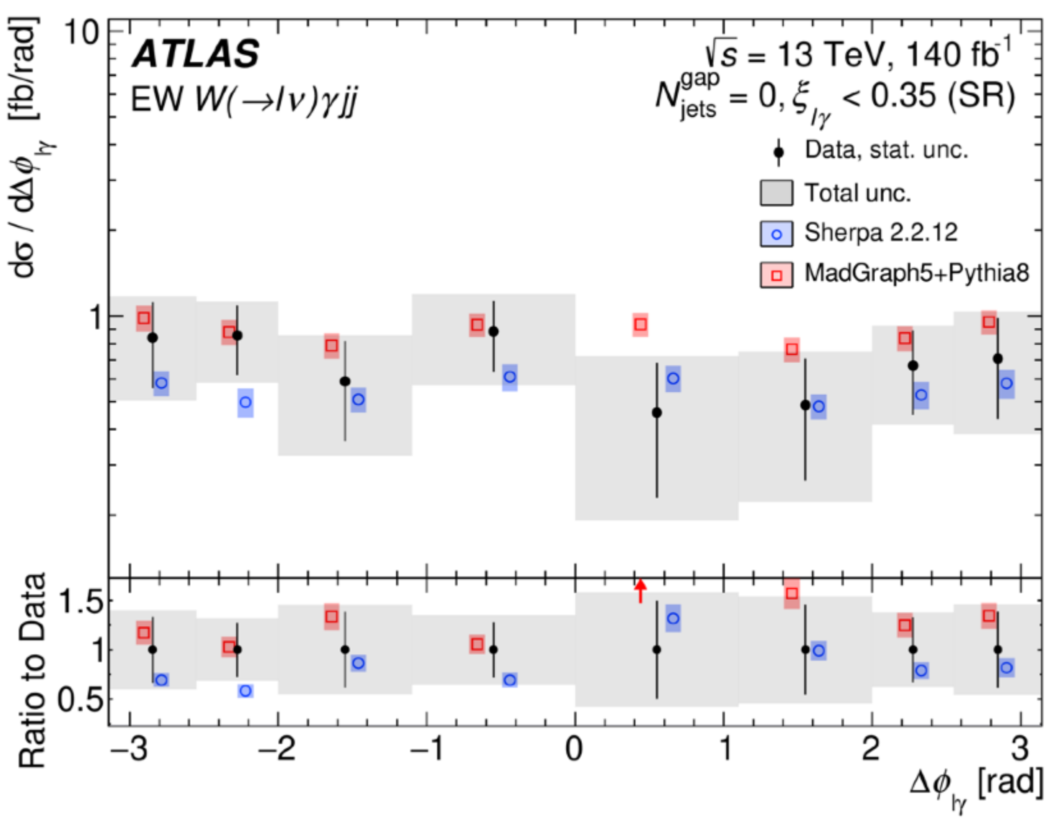
Wγ+jj: inclusive xSection

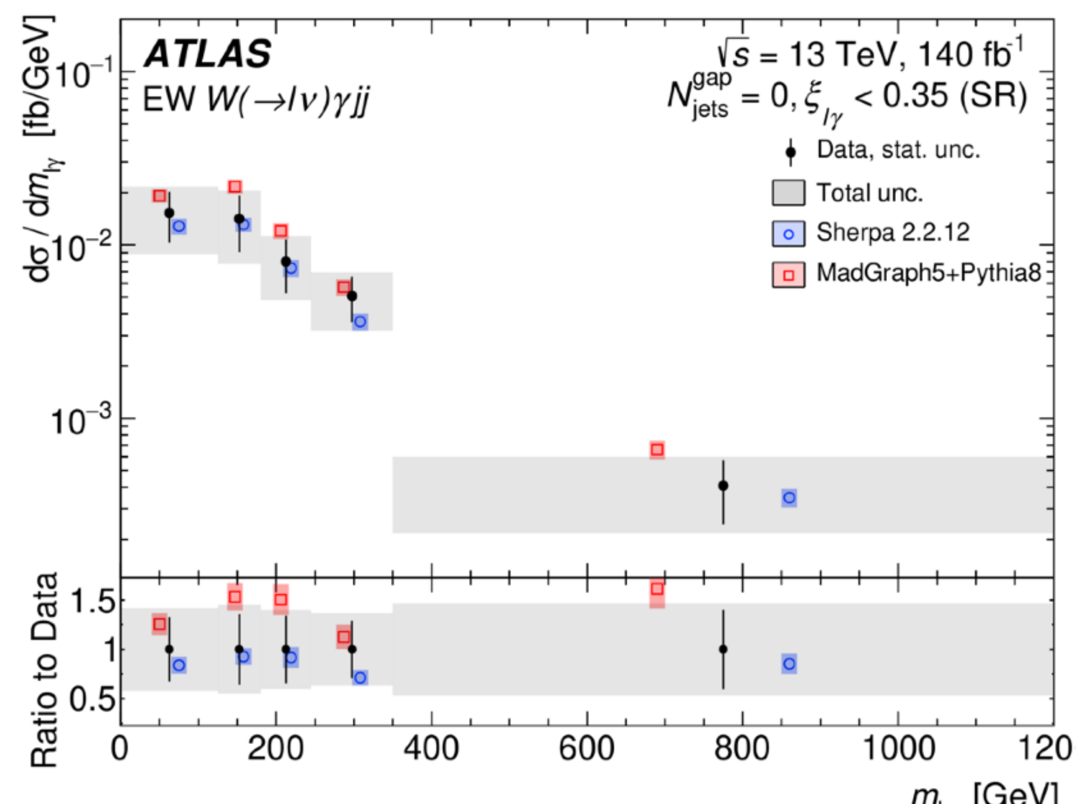


Wγ+jj: more differential plots

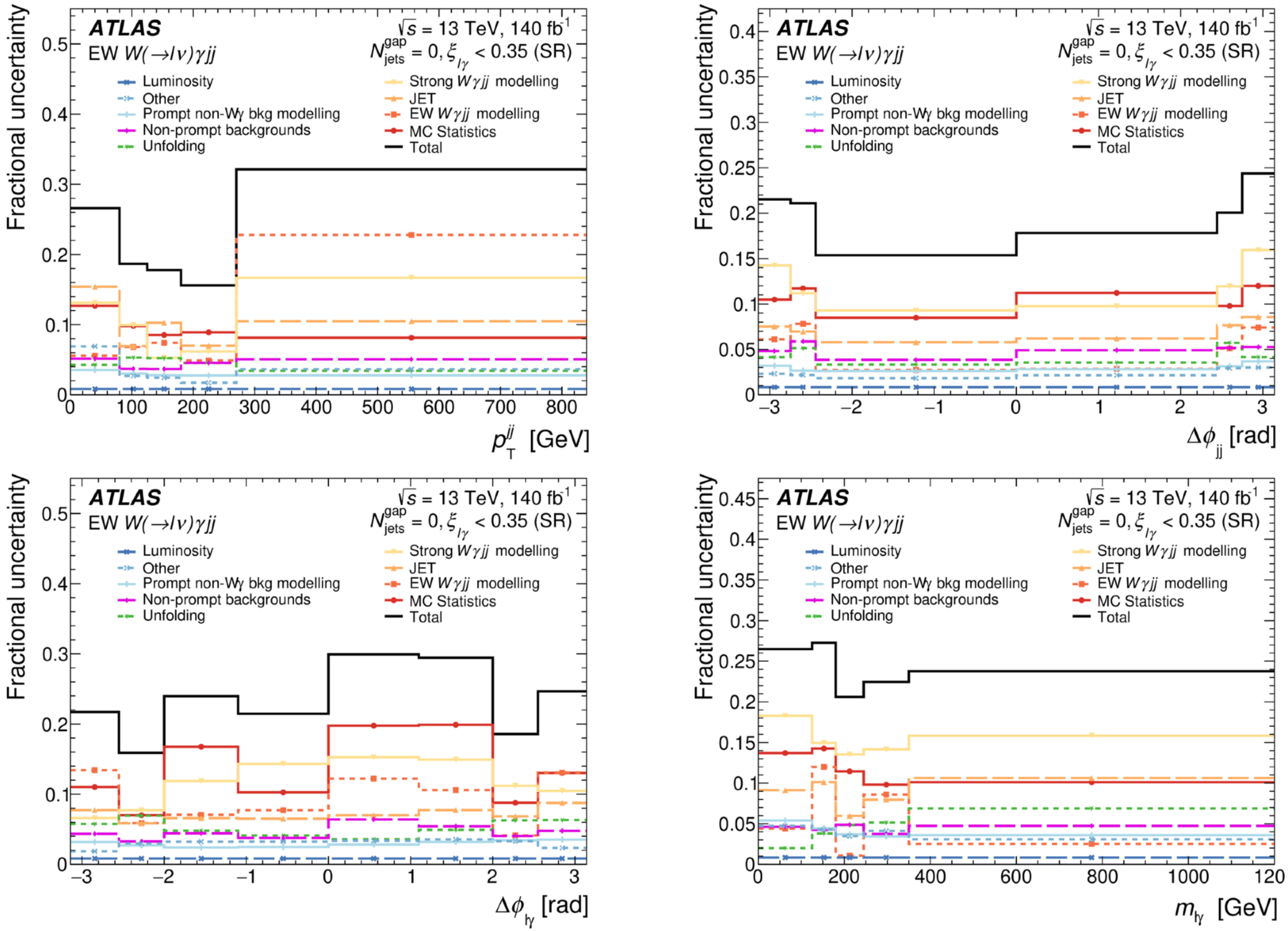








Wγ+jj: more differential plots



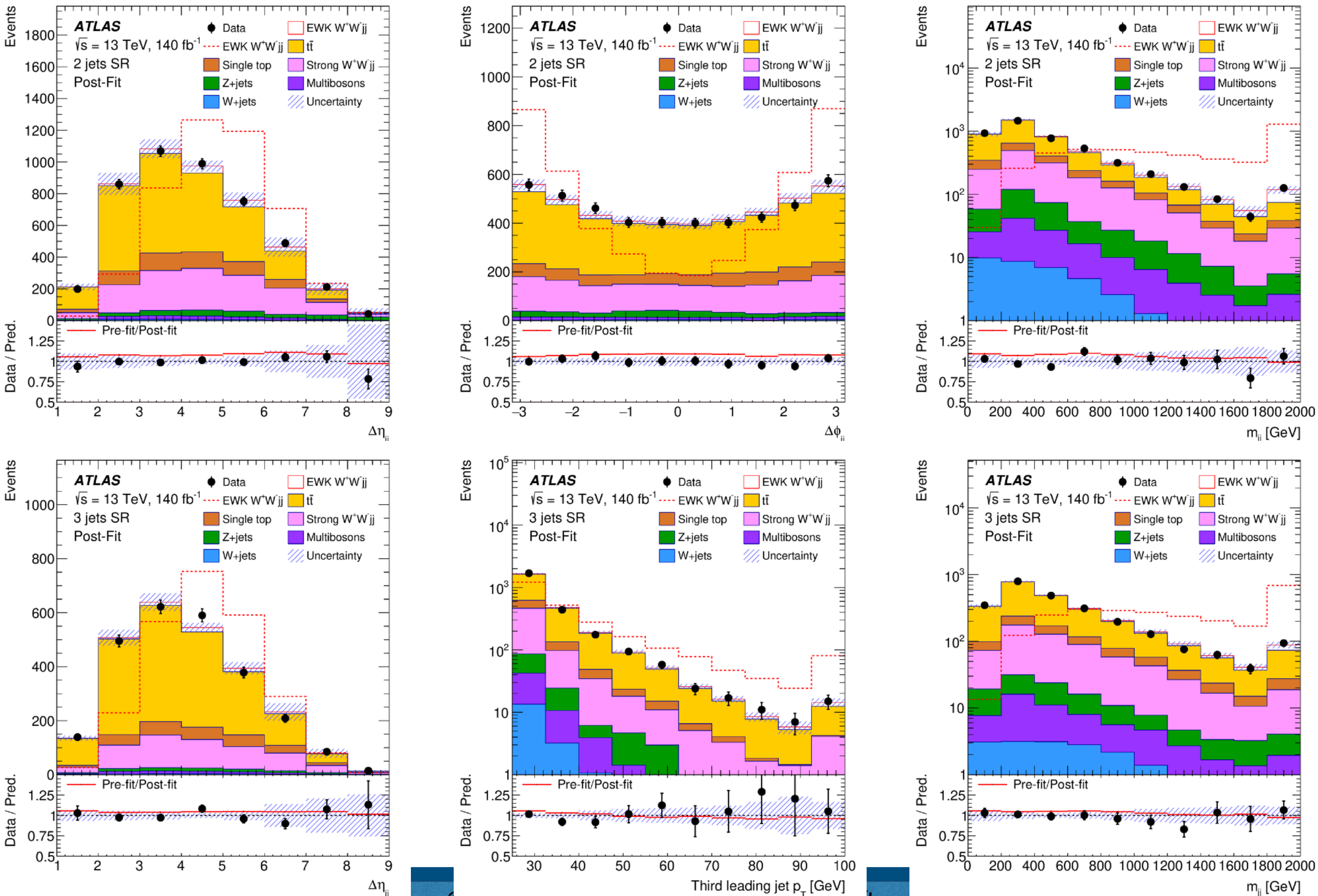
os-WW+jj: event selection

Category	Requirements
Leptons	$p_T > 27$ GeV $\lvert\eta\rvert < 2.47$ excluding $1.37 < \lvert\eta\rvert < 1.52$ (electrons) $\lvert\eta\rvert < 2.5$ (muons) Identification: `Tight` Isolation: `Gradient` (electrons), `Tight_FixedRad` (muons) $\lvert d_0/\sigma_{d_0}\rvert < 5$ (electrons), $\lvert d_0/\sigma_{d_0}\rvert < 3$ (muons) $\lvert z_0 \sin\theta\rvert < 0.5$ mm
b-jets	$p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$ (`DL1r` b-tagging with 85% efficiency)
Jets	$p_T > 25$ GeV and $\lvert\eta\rvert < 4.5$
Events	One electron and one muon with opposite electric charges No additional lepton with $p_T > 10$ GeV, `Loose` isolation, `Tight/Medium` (electrons) and `Loose` (muons) identification $m_{e\mu} > 80$ GeV $E_T^{miss} > 15$ GeV No b-jet Two or three jets $\zeta > 0.5$

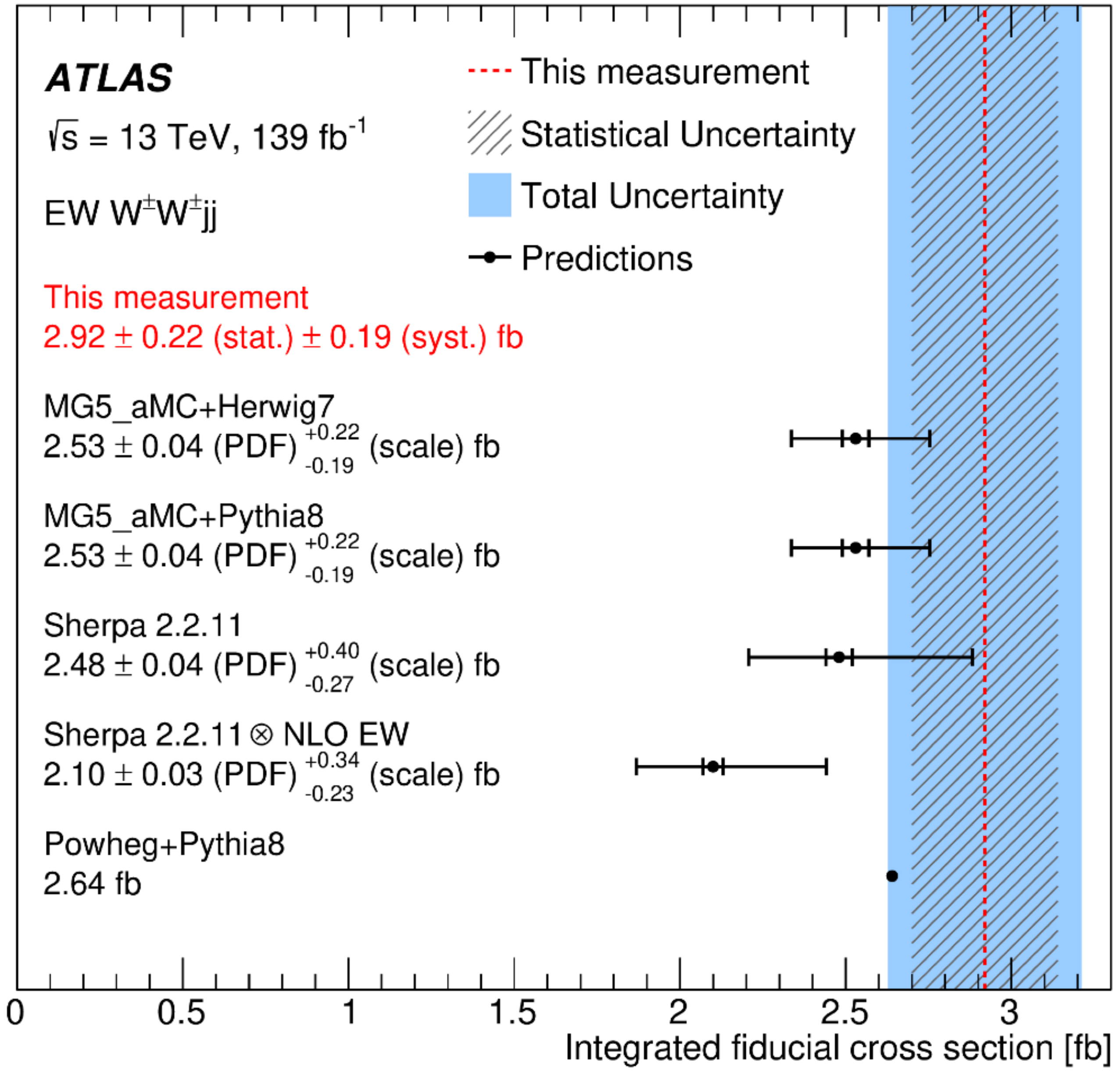
Process	Event yields $n_{jets} = 2$	$n_{jets} = 3$
EWK W^+W^-jj	158 ± 27	54 ± 13
$t\bar{t}$	2394 ± 194	1625 ± 125
Single top	491 ± 34	225 ± 21
Strong W^+W^-jj	1214 ± 256	514 ± 121
W+jets	37 ± 97	19 ± 48
Z + jets	216 ± 62	65 ± 25
Multiboson	101 ± 5	42 ± 3
SM prediction	4610 ± 77	2546 ± 48
Data	4610	2533

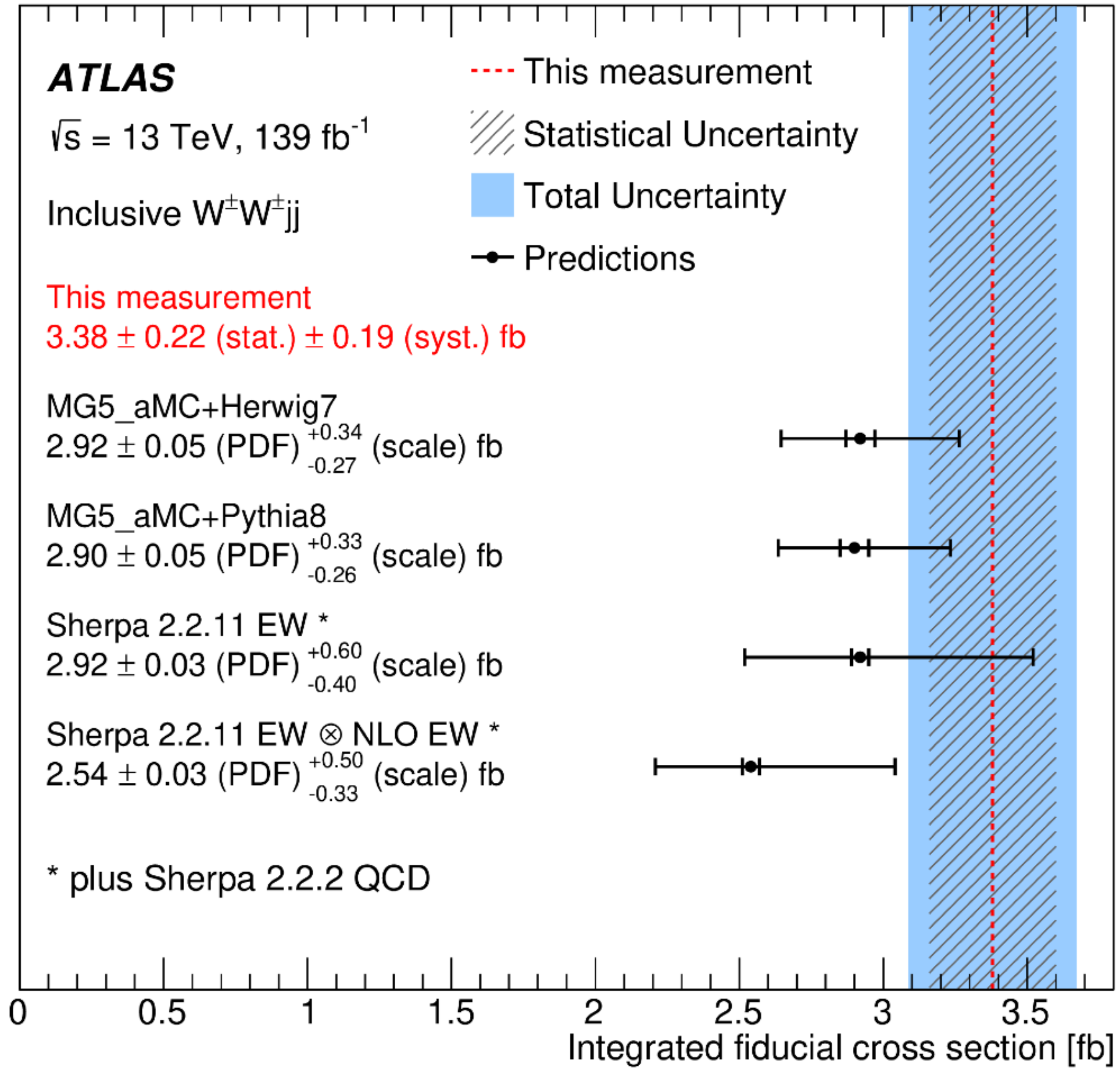
Sources	$\frac{\sqrt{(\Delta\mu)^2-(\Delta\mu')^2}}{\mu}$ [%]
MC statistical uncertainty	7.7
Top quark theoretical uncertainties	6.3
Signal theoretical uncertainties	5.8
Jet experimental uncertainties	4.9
Strong W^+W^-jj theoretical uncertainties	1.3
Luminosity	0.8
Misidentified lepton uncertainty	0.5
b-tagging	0.4
Lepton experimental uncertainties	0.1
Others	0.3
Data statistical uncertainty	12.3
Top quark normalisation uncertainty	4.9
Strong W^+W^-jj normalisation uncertainty	2.2
Total uncertainty	18.5

os-WW+jj: more post-fit plots



ssWW+jj: inclusive xSection





WZ lνll: diagrams

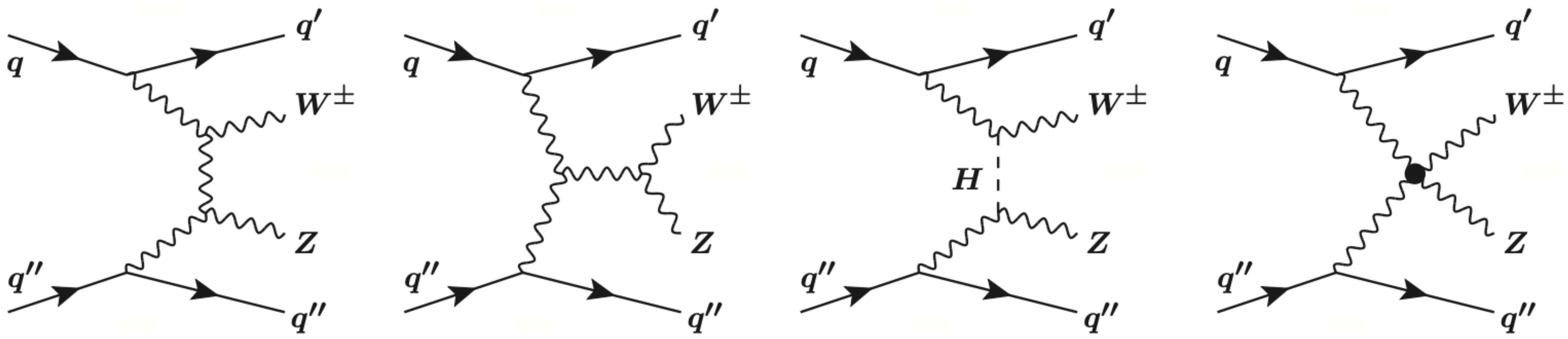


Figure 1: Representative diagrams at LO of the $WZjj$−EW production in pp collisions.

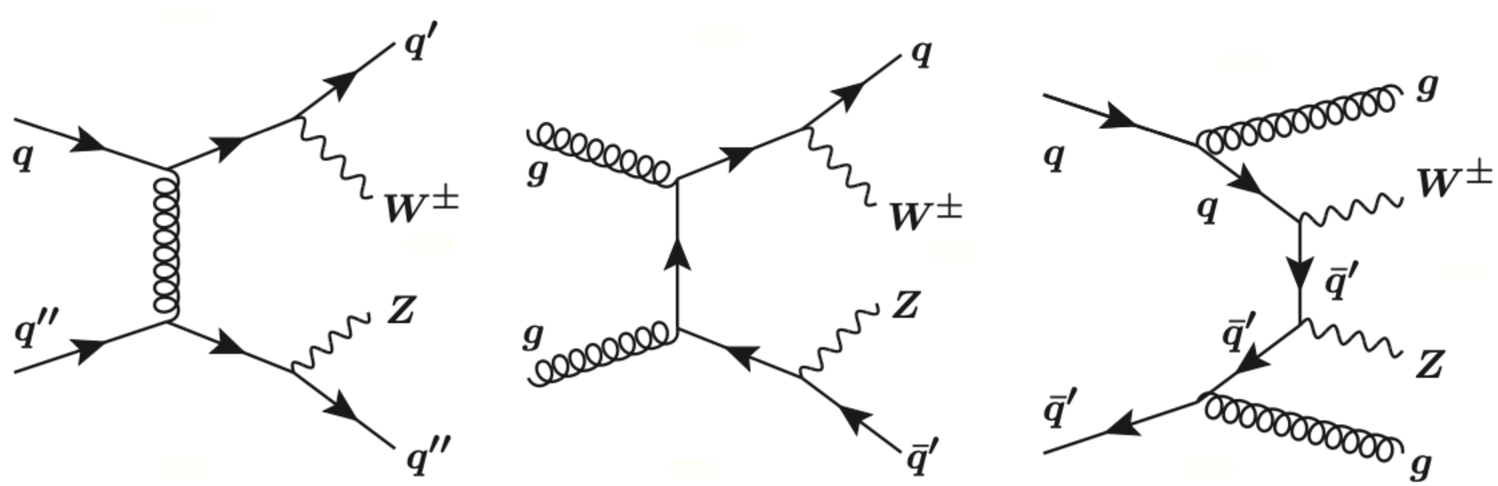
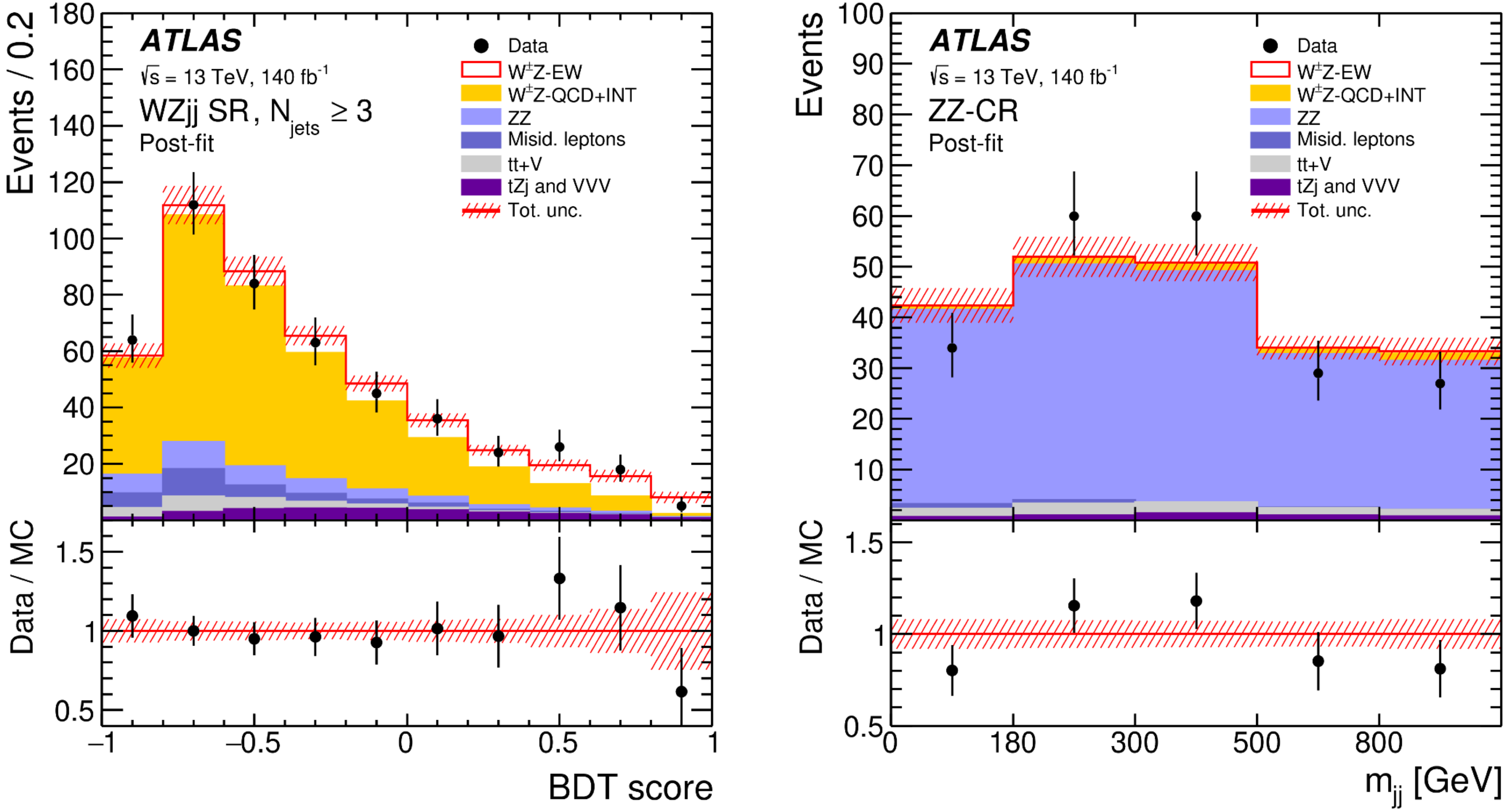


Figure 2: Representative diagrams at LO of the $WZjj$−QCD production in pp collisions.

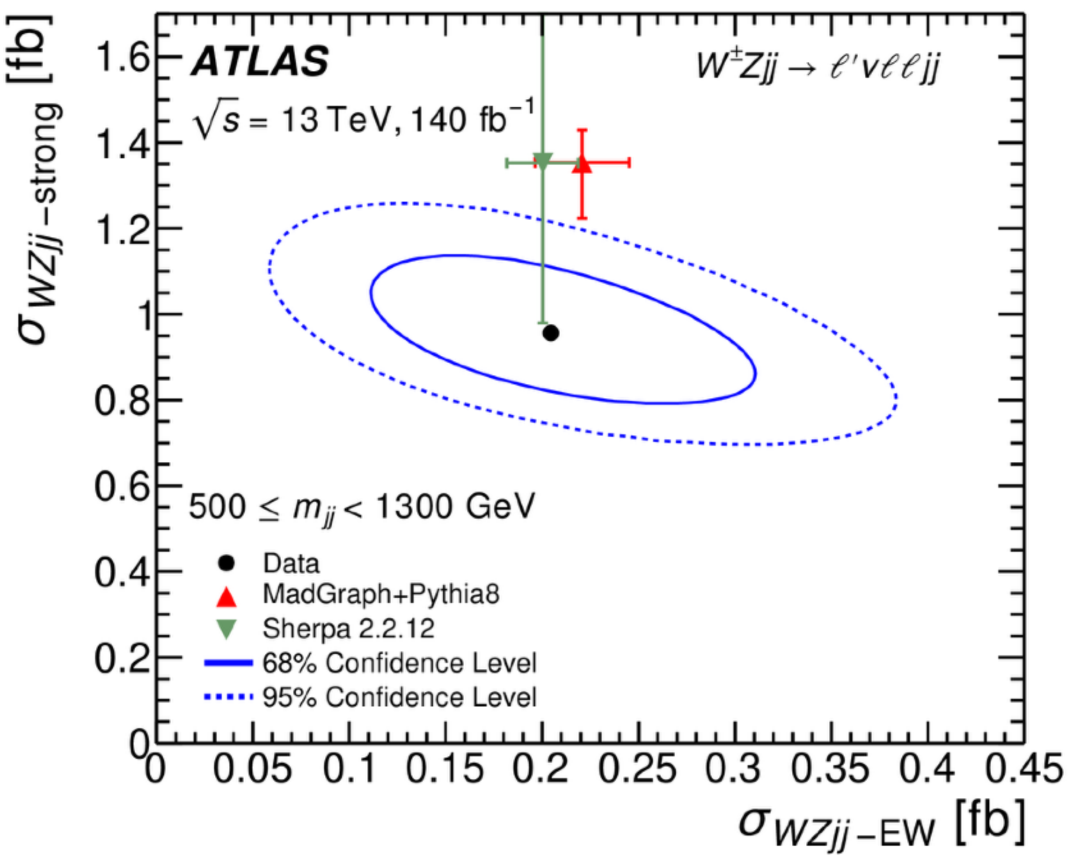
WZ lνll: more info

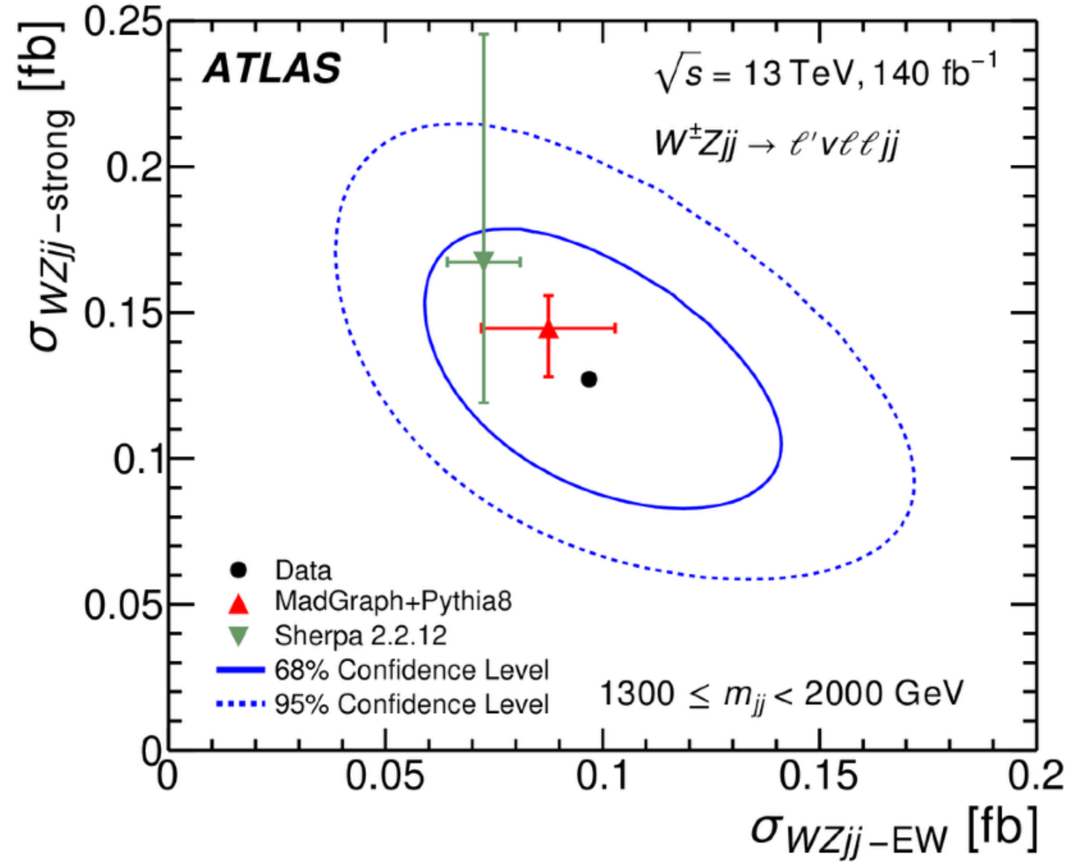
	SR, $N_{\text{jets}} = 2$	SR, $N_{\text{jets}} \geq 3$	b-CR	ZZ-CR
Data	169	477	666	210
Total pred.	231 ± 12	550 ± 50	660 ± 40	205 ± 11
$WZjj$-EW	65.0 ± 3.5	60 ± 6	4.82 ± 0.28	0.725 ± 0.014
$WZjj$-QCD	125 ± 9	380 ± 50	77 ± 18	6.2 ± 0.7
$WZjj$-INT	1.3 ± 0.6	5.3 ± 2.6	0.58 ± 0.29	0.22 ± 0.11
$t\bar{t} + V$	0.66 ± 0.04	20.2 ± 0.7	289 ± 10	9.89 ± 0.28
tZj	8.78 ± 0.34	19.7 ± 1.2	134 ± 4	0.432 ± 0.005
ZZ-QCD	9.6 ± 0.4	32.0 ± 2.5	10.1 ± 0.6	159 ± 9
ZZ-EW	2.2 ± 0.6	4.4 ± 1.1	0.25 ± 0.06	23 ± 6
VVV	0.41 ± 0.10	2.0 ± 0.5	0.39 ± 0.10	4.1 ± 1.1
Misid. leptons	18 ± 4	28 ± 7	150 ± 40	1.7 ± 0.5

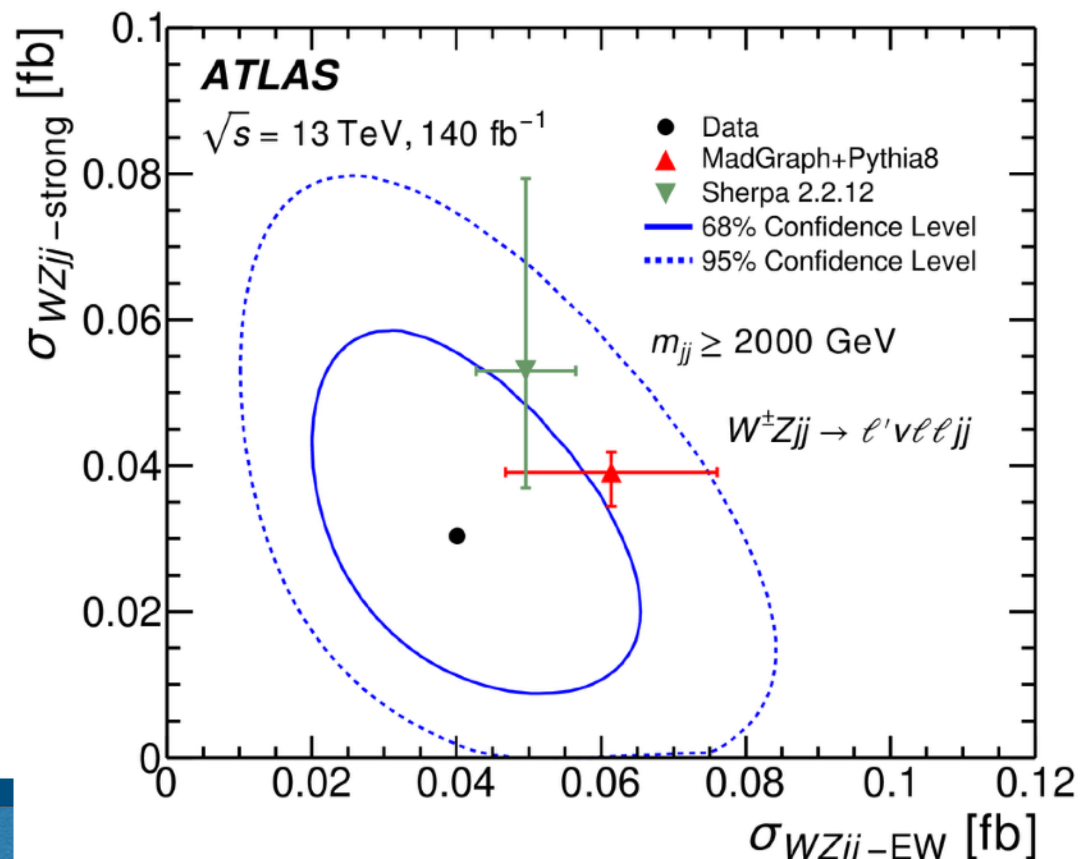
WZ lvll: other post-fits



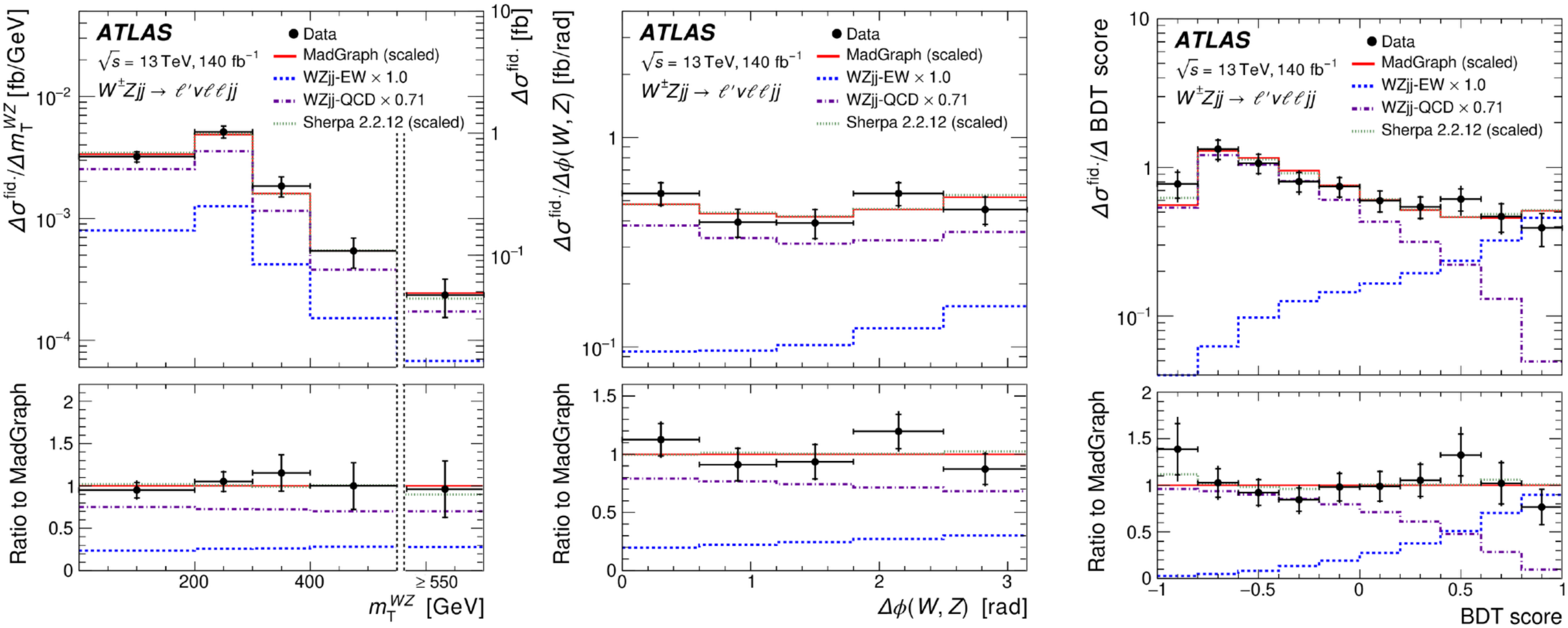
WZ lvll: mjj bins cross sections







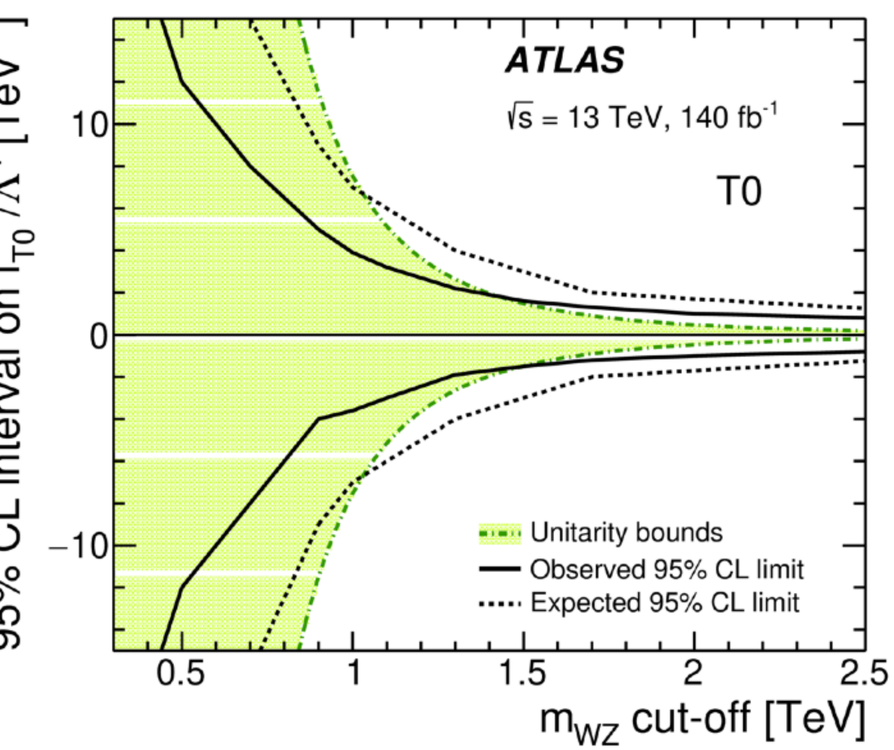
WZ lvll: more differential plots

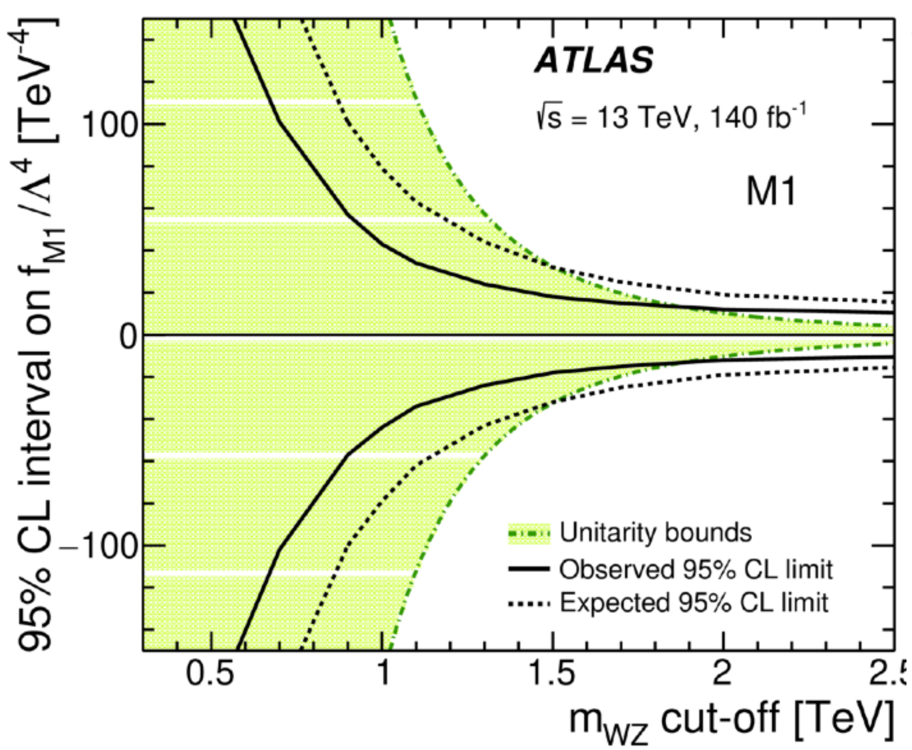


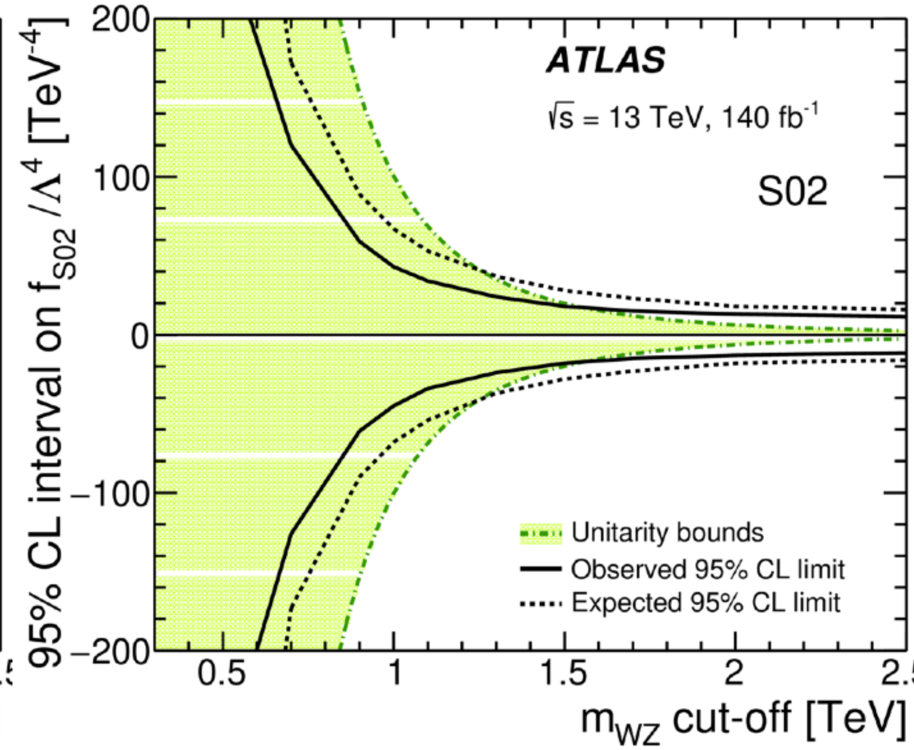
WZ lνll: other EFT plots

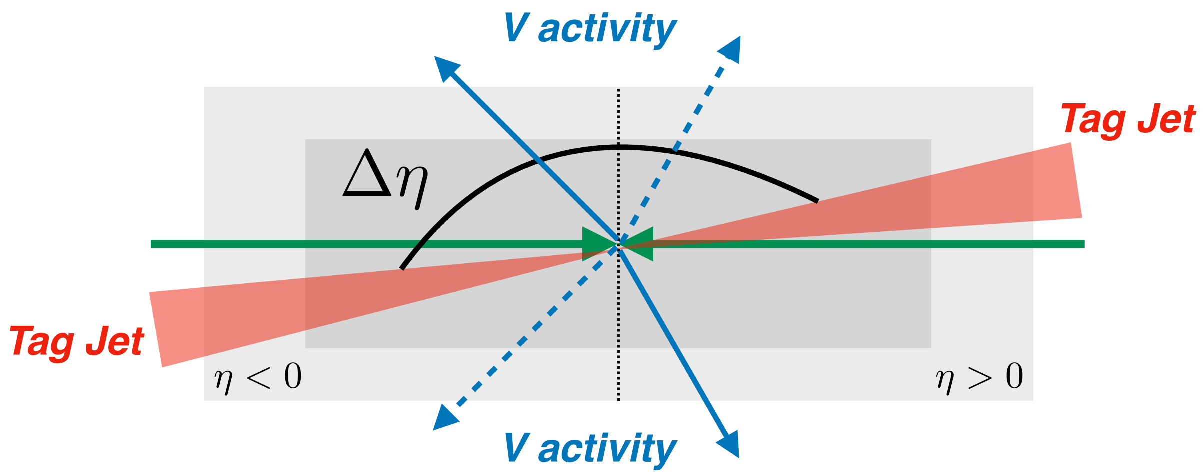
	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
$f_{\mathrm{T0}}/\Lambda^4$	[-0.80, 0.80]	[-0.57, 0.56]
$f_{\mathrm{T1}}/\Lambda^4$	[-0.52, 0.49]	[-0.39, 0.35]
$f_{\mathrm{T2}}/\Lambda^4$	[-1.6, 1.4]	[-1.2, 1.0]
$f_{\mathrm{M0}}/\Lambda^4$	[-8.3, 8.3]	[-5.8, 5.6]
$f_{\mathrm{M1}}/\Lambda^4$	[-12.3, 12.2]	[-8.6, 8.5]
$f_{\mathrm{M7}}/\Lambda^4$	[-16.2, 16.2]	[-11.3, 11.3]
$f_{\mathrm{S02}}/\Lambda^4$	[-14.2, 14.2]	[-10.4, 10.4]
$f_{\mathrm{S1}}/\Lambda^4$	[-42, 41]	[-30, 30]

	Expected [TeV $^{-4}$]	Observed [TeV $^{-4}$]
$f_{\mathrm{T0}}/\Lambda^4$	[-7.0, 7.0]	[-1.5, 1.6]
$f_{\mathrm{T1}}/\Lambda^4$	[-1.1, 1.0]	[-0.7, 0.6]
$f_{\mathrm{T2}}/\Lambda^4$	[-12, 6]	[-2.4, 1.8]
$f_{\mathrm{M0}}/\Lambda^4$	[-60, 60]	[-12, 12]
$f_{\mathrm{M1}}/\Lambda^4$	[-32, 32]	[-15, 15]
$f_{\mathrm{M7}}/\Lambda^4$	[-30, 30]	[-15, 15]
$f_{\mathrm{S02}}/\Lambda^4$	[-41, 41]	[-18, 18]
$f_{\mathrm{S1}}/\Lambda^4$	—	—








V activity
Tag Jet
$\Delta\eta$
Tag Jet
$\eta < 0$
$\eta > 0$
V activity