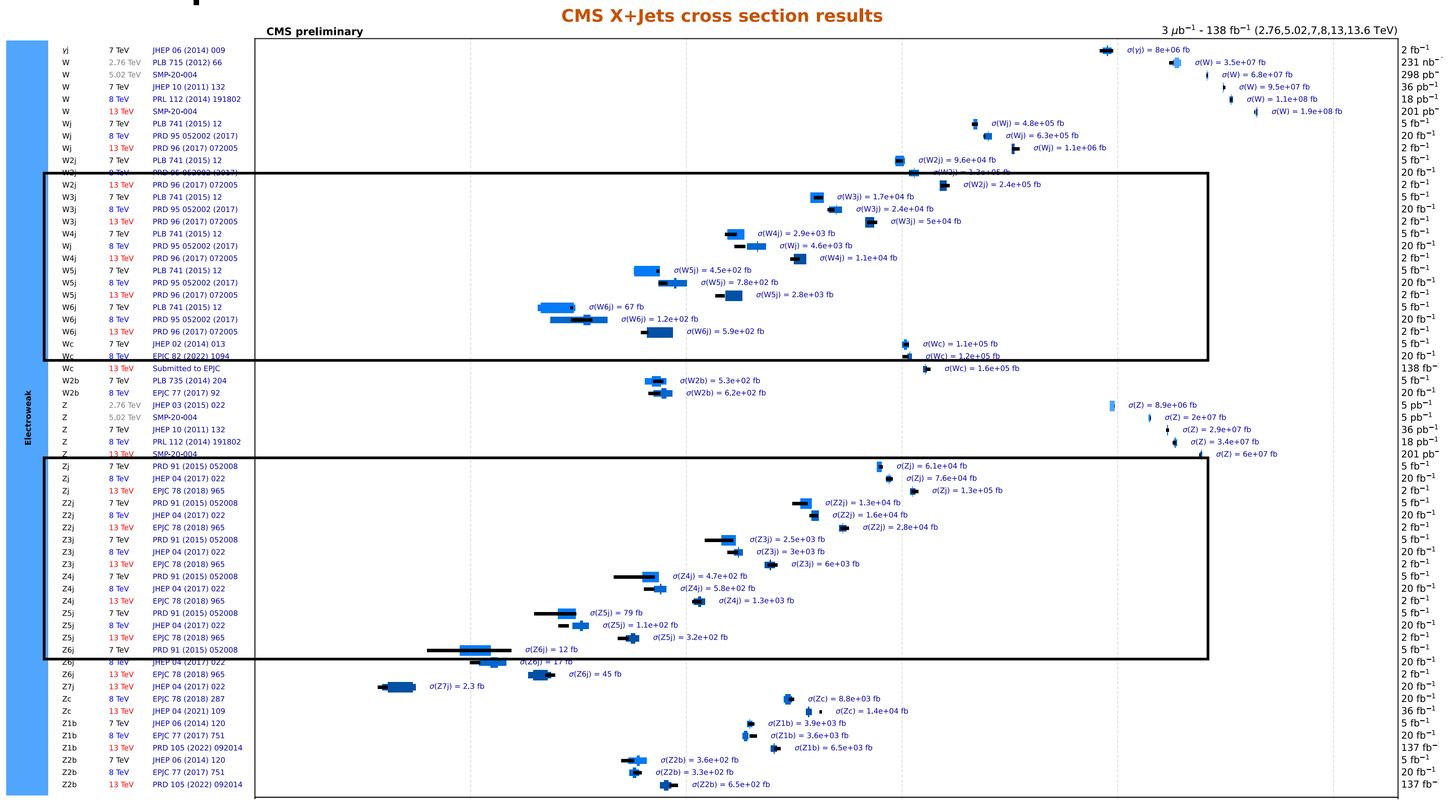
V + light jets summary in ATLAS and CMS

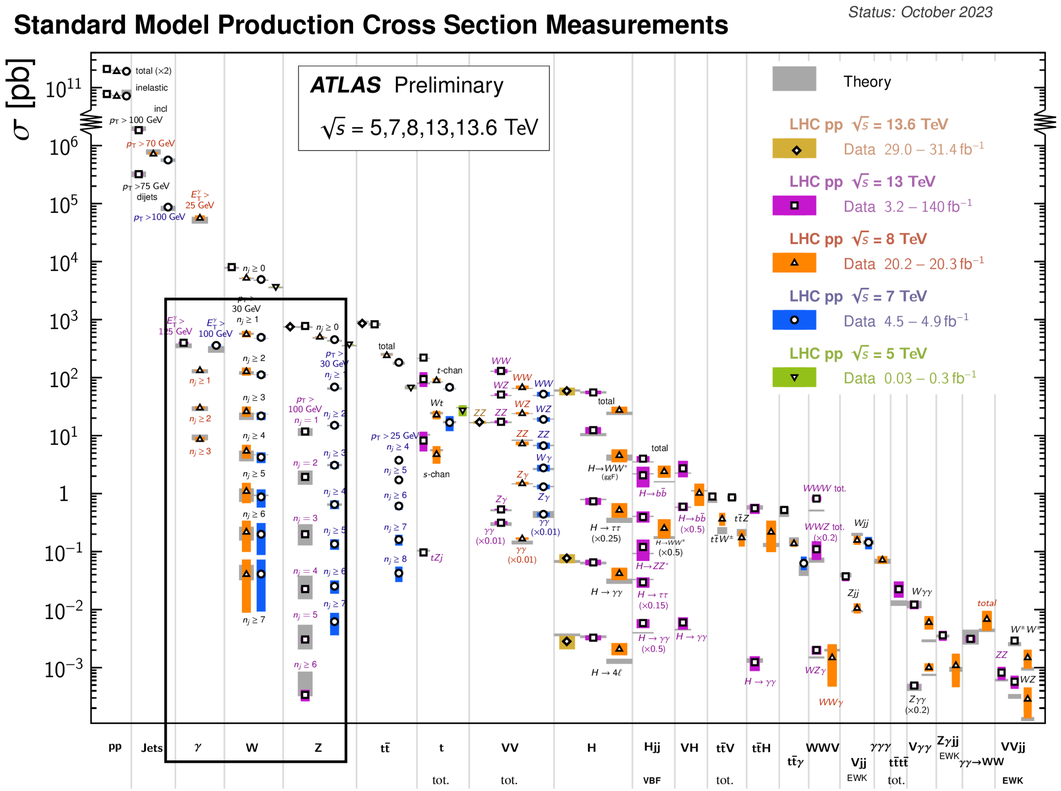
LHC EW WG General Meeting, CERN 10/07/24

Giorgio Pizzati on behalf of ATLAS and CMS Collaborations

Outline of V+Jets (QCD) results in ATLAS and CMS

A plethora of differential measurements!





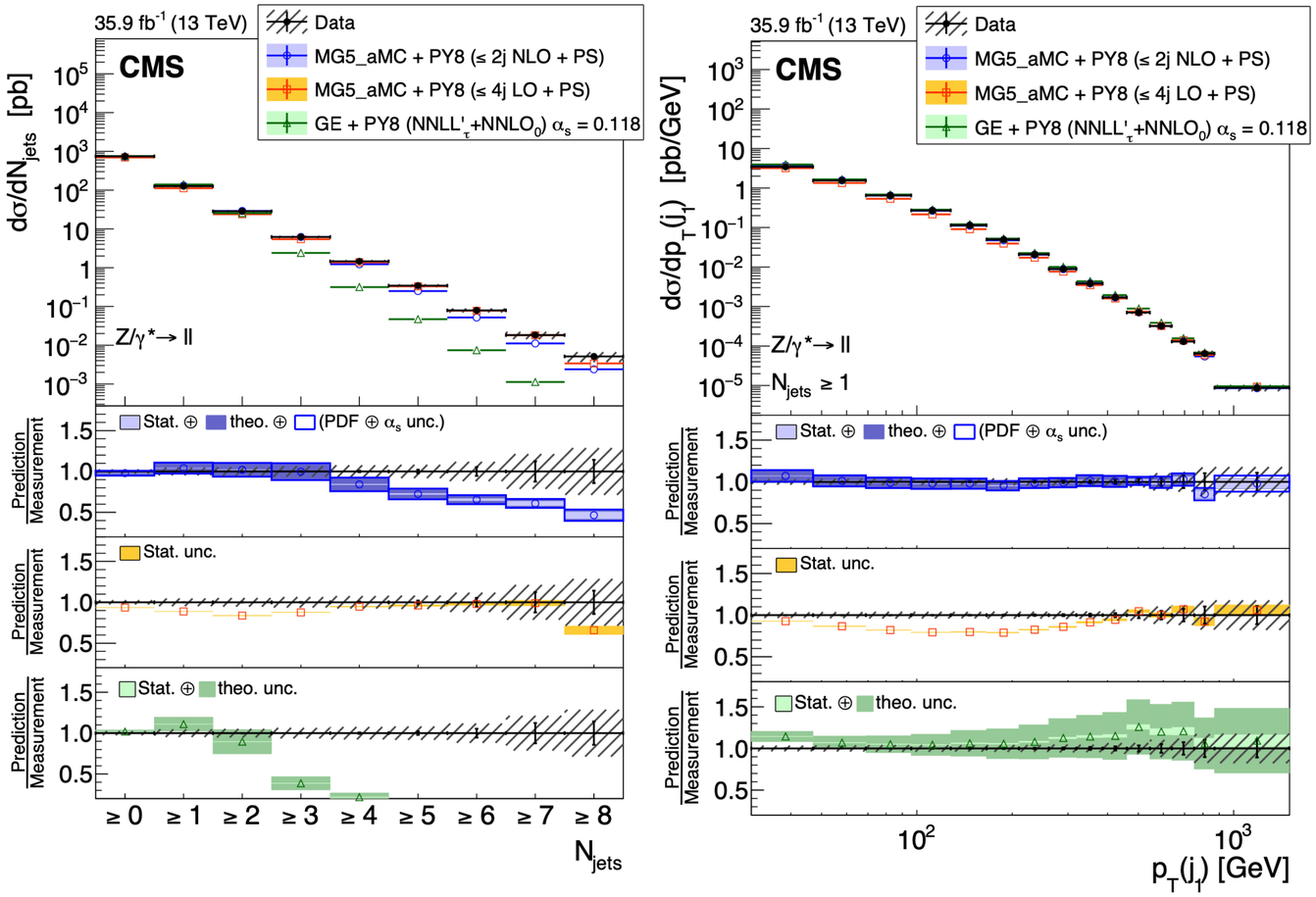
Outline

- Selected analysis with 13 TeV and at least 36 fb^{-1}
- First year of Run 2:
  - ATLAS photon + jets differential: arXiv: 1912.09866
  - CMS Z/γ + jets double differential: arXiv: 2205.02872
  - CMS Z/γ + jets azimuthal correlations double differential: arXiv: 2210.16139
  - CMS Z + jets and γ + jets ratio and collinear emission arXiv: 2102.02238
  - CMS $Z \to \nu\nu$ + jets: arXiv: 2012.09254
  - CMS EW Z + jets and W + jets: arXiv: 1712.09814 and arXiv: 1903.04040
- Full Run 2:
  - ATLAS Z with hight p_T jets: arXiv: 2205.02597
  - ATLAS Z+Jets 24 differential: arXiv: 2405.20041
  - ATLAS MET + jets: arXiv: 2403.02793
  - ATLAS EW Z + jets: arXiv: 2006.15458

Differential Z + Jets in CMS

arXiv: 2205.02872

- Proton–proton collision data collected by CMS at $\sqrt{s} = 13$ TeV and with an integrated luminosity of 35.9 fb^{-1}
- Differential cross-sections are measured in the $Z/\gamma\, jj \to l^+l^-jj$ with $l = e, \mu$ final state as a function of p_T^Z, and p_T, η of the 5 leading jets as well as double differential
- Unfolded data is compared with MG LO, MG NLO and Geneva + PY8



Results

- N_{jets}: GENEVA generator predicts a steeper spectrum than observed due to the lack of hard jets at ME level beyond two
- In NLO regions ($N_{\text{jets}} \leq 2$) MG NLO well describe the data with an agreement within 10% up to TeV scale

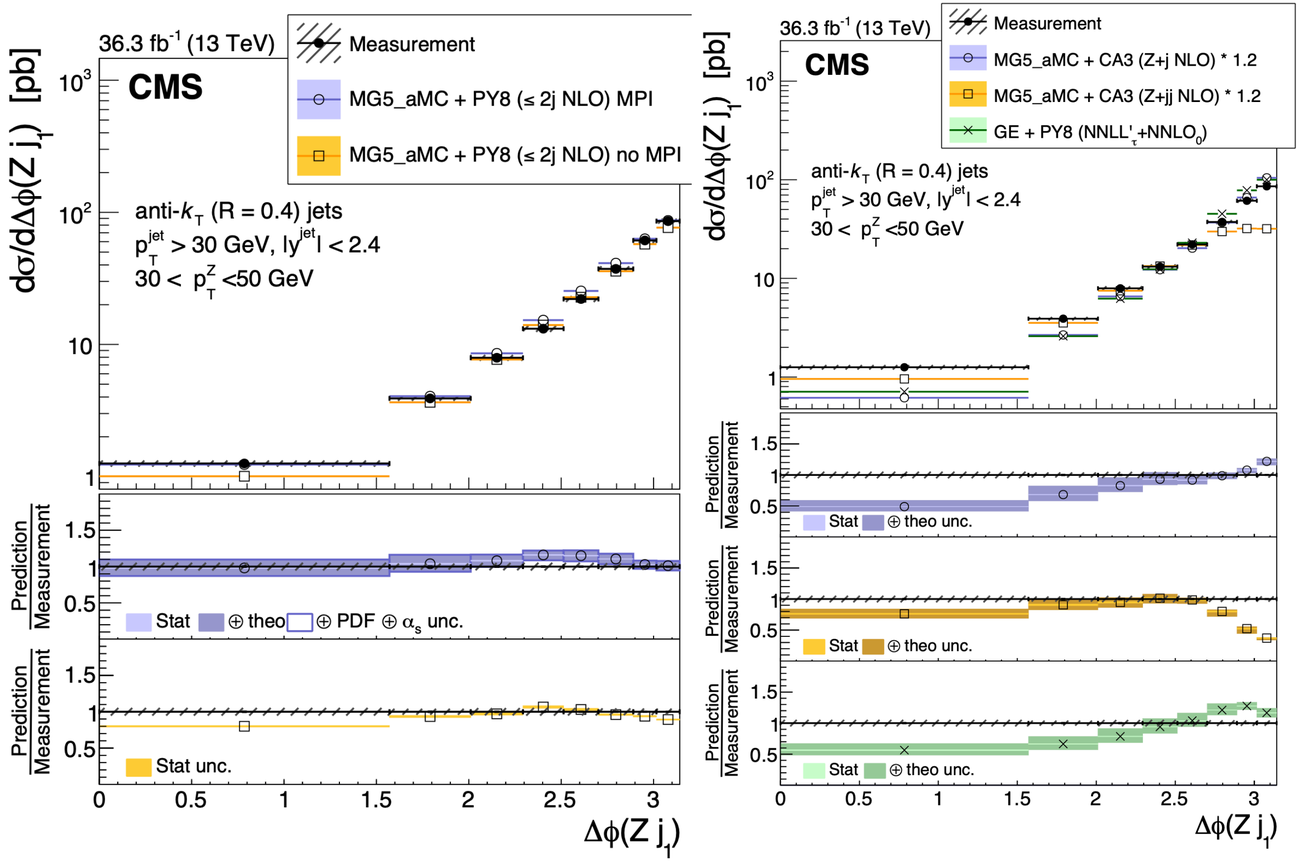
CMS: Azimuthal correlations in Z+jets

arXiv: 2210.16139

- Proton–proton collision data collected by CMS at $\sqrt{s} = 13$ TeV and with an integrated luminosity of 36.3 fb^{-1}
- Differential cross-sections are measured in the $Z \to l^+ l^-$ ($l = e, \mu$) decay channel as a function
  - $\Delta\phi_{Z,j1}$, $\Delta\phi_{j1,j2}$ measured in three regions of $p_T(Z)$ (low, mid and high)
- Comparison of unfolded that with predictions of
  - MadGraph5_aMC@NLO at NLO (≤2j NLO MG_aMC_FxFx)
  - Parton branching method with **transverse-momentum dependent** PDFs together with a TMD-based Parton Shower: MG5_aMC+CA3 (Z+1 NLO and Z+2 NLO)
  - Geneva (Z+0 NNLO)

Results

- Predictions based on transverse-momentum dependent parton distributions and corresponding parton showers give a good description when MPI effects are negligible



$30 < p_T^Z < 50$GeV

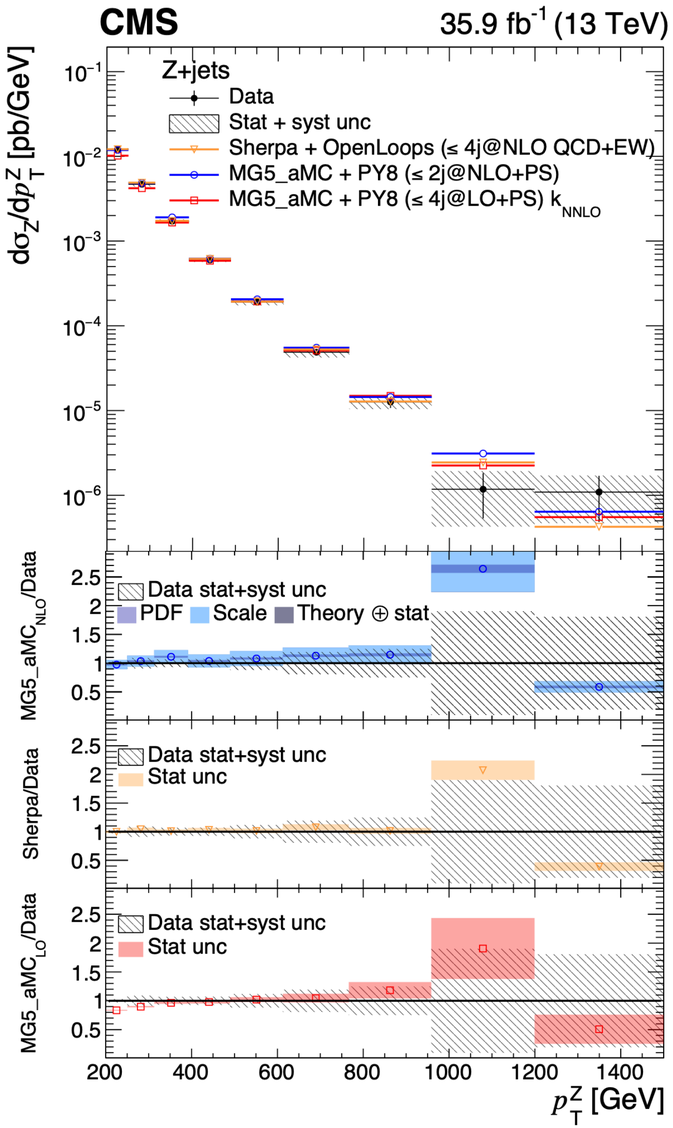
CMS Z/γ + jets ratio and collinear emission

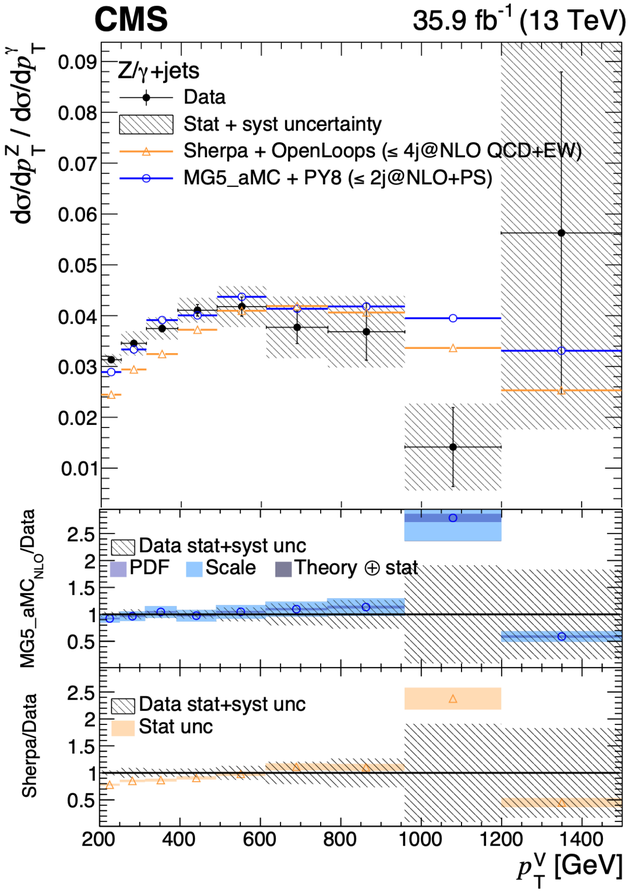
arXiv: 2102.02238

- Proton–proton collision data collected by CMS at $\sqrt{s} = 13$ TeV and with an integrated luminosity of 36.3 fb^{-1}
- Differential cross-sections are measured in the $Z \to l^+ l^-$ ($l = e, \mu$) decay channel as a function of $p_T(Z)$
- Comparison of unfolded that with predictions of
  - MadGraph5_aMC@NLO at NLO (≤2j NLO MG_aMC_FxFx)
  - MadGraph5_aMC@NLO at LO (≤4j NLO MG_aMC_MLM)
  - Sherpa + OpenLoops (≤4j NLO QCD+EW
- Measurement crucial for different searches at high mass (dark matter, SUSY)

Results

- Comparison with MG at NLO shows consistency within the uncertainties across the entire pT range
- SHERPA + OpenLoops ↓ the data by 10–20% at low pT, because of the ↑ in the photon p_T distribution, but consistent with data within uncertainties for $p_T > 300$ GeV





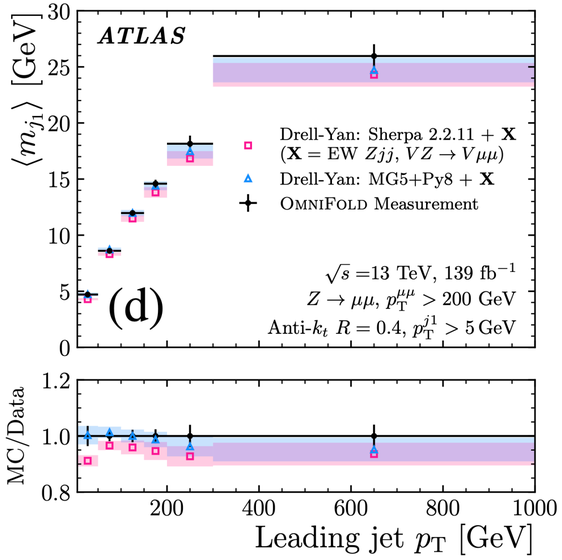
Unbinned differential Z+jets in ATLAS

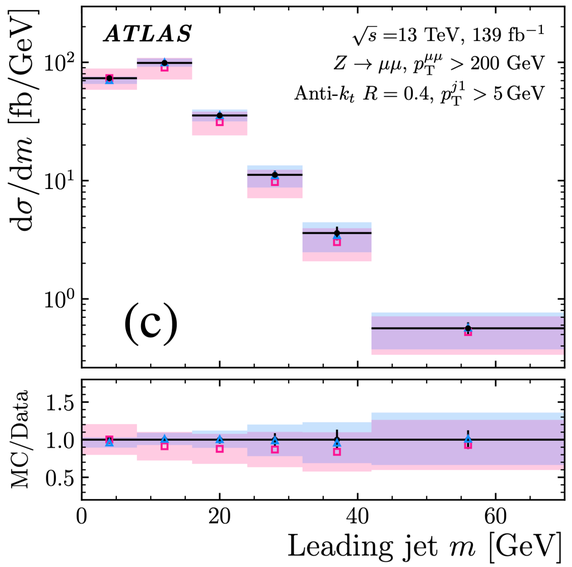
arXiv: 2405.20041

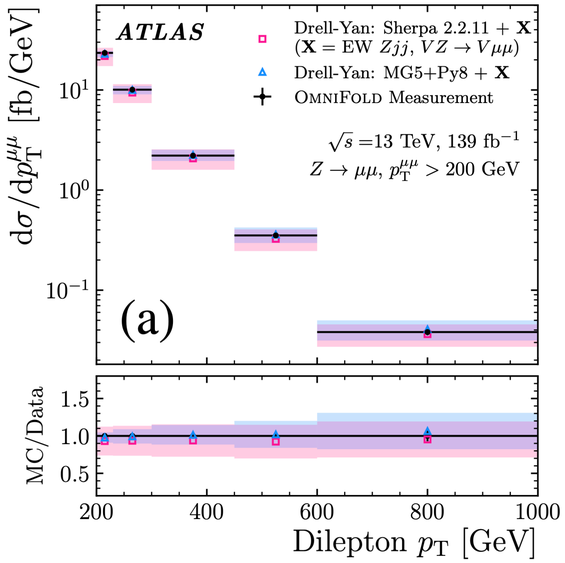
- Proton–proton collision data collected by ATLAS at $\sqrt{s} = 13$ TeV and with an integrated luminosity of 139 fb^{-1}
- Unbinned differential cross-sections are measured in the $Z +$ jets $\rightarrow \mu\mu +$ jets final state
- Result is presented unbinned as a dataset of particle-level events
- Unfolded data compared with SHERPA OpenLoops and MG NLO
- Region $p_T^{\mu\mu} > 200$ GeV and $m_{\mu\mu} \in (81, 101)$ GeV

Results

- MG generally models better the data than SHERPA except for N-subjettiness



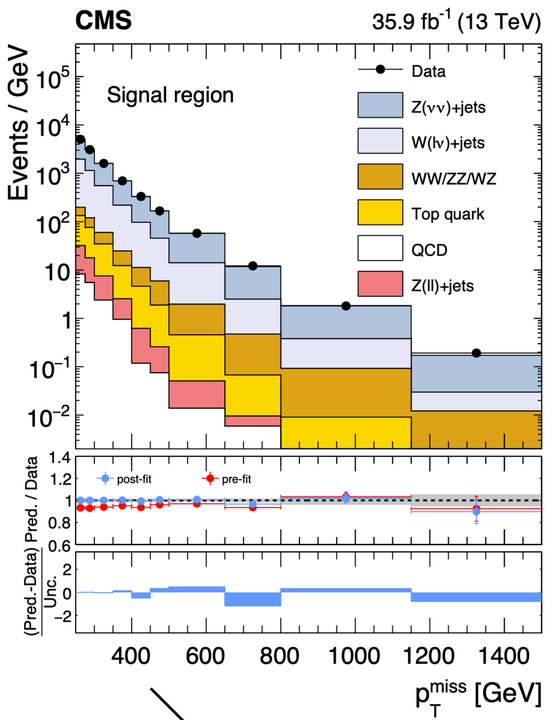


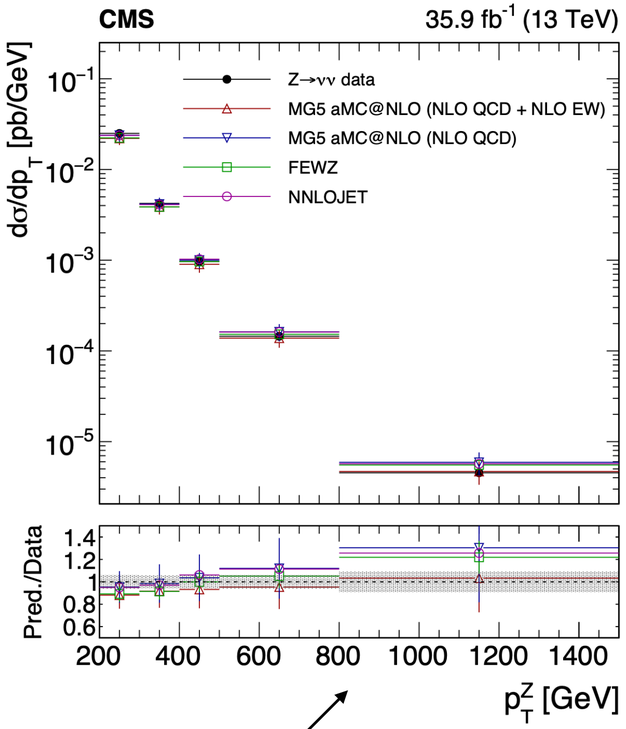


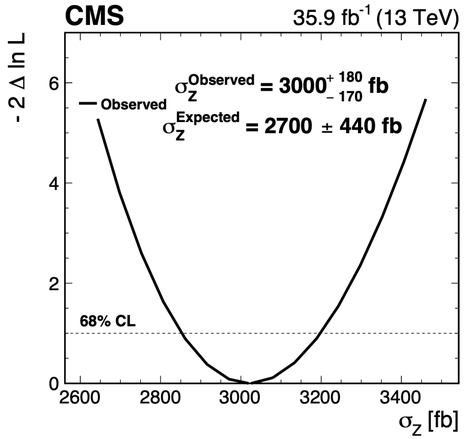
CMS $Z \rightarrow \nu\bar{\nu}$ + jets

arXiv: 2012.09254

- Proton–proton collision data collected by CMS at $\sqrt{s} = 13$ TeV and with an integrated luminosity of 35.9 fb^{-1}
- Events are selected containing an imbalance in transverse momentum and one or more energetic jets
- Fiducial differential cross section is measured as a function of p_T^Z
- Unfolded data compared with MG NLO (NLO QCD), MG NLO (NLO QCD + NLO EW), FEWZ and NNLOJET
- Results are combined with a previous measurement of charged-lepton decays of the Z boson
- Measured total fiducial cross section for events with Z boson transverse momentum greater than 200 GeV is 300^{+180}_{-170} fb^{-1}



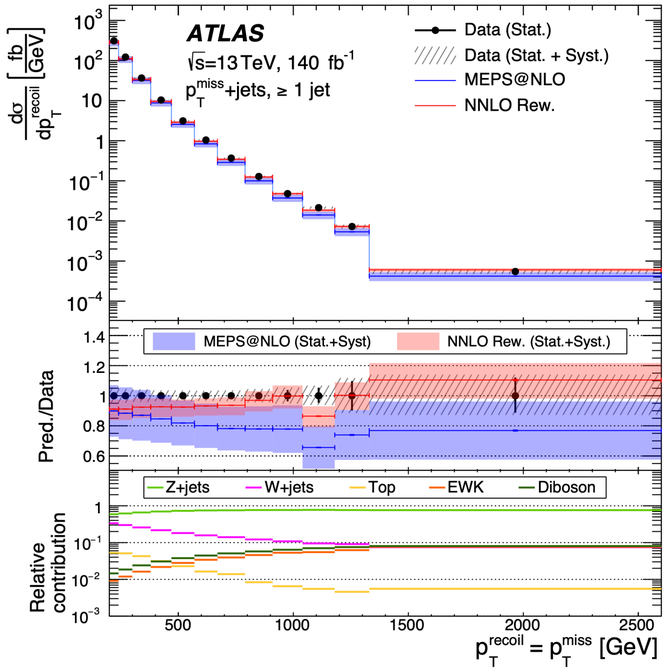


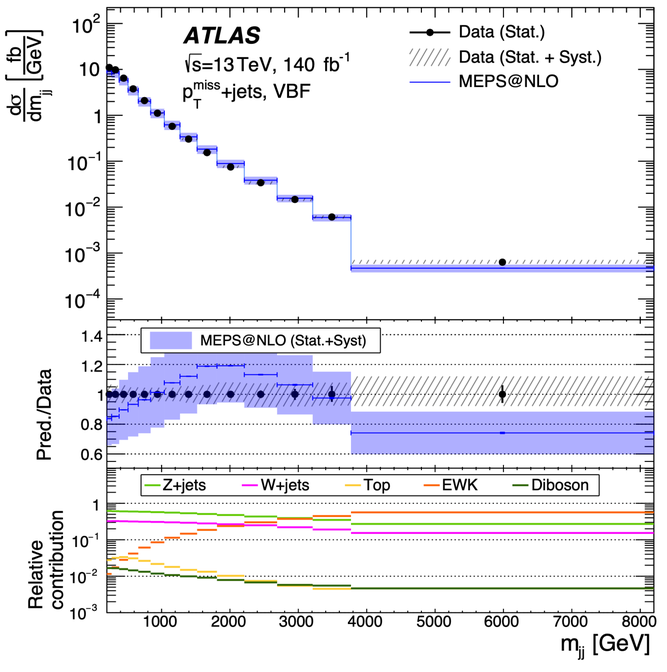


ATLAS MET + jets

arXiv: 2403.02793

- Proton–proton collision data collected by ATLAS at $\sqrt{s} = 13$ TeV and with an integrated luminosity of $140\ \text{fb}^{-1}$
- Main region is p_T^{miss} + jets, auxiliary measurements are $2e$ + jets, 2μ + jets, e + jets, μ + jets and γ + jets (the latter shows bad normalization)
  - Subregions are $N_{\text{jets}} \geq 1$ and VBF
- Unfolded data compared with
  - SHERPA OpenLoops NLO ME with CKKW extended to NLO using MEPS@NLO
  - In the $N_{\text{jets}} \geq 1$ region also with NNLO QCD reweighted sample
- Cross-section for $Z \to \nu\nu$ production is determined differential in the p_T^{miss}, $\Delta\phi_{jj}$ and m_{jj}
- The ratio, e.g. $R_{\text{miss}}(p_T^{\text{miss}}\text{ + jets}/2\mu\text{ + jets})$, is useful to cancel out some systematics





Bad modelling → cancels out in R^{miss}

Results

- Quantitative compatibility with SM predictions ✅
- Dark matter models studies and limits → usage of HEPData for reinterpretation

Photon + Jets in ATLAS

arxiv: 1912.09866

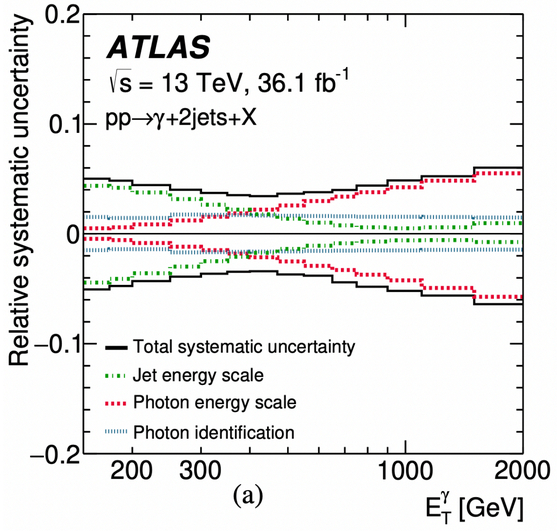
- Proton–proton collision data collected by ATLAS at $\sqrt{s} = 13$ TeV and with an integrated luminosity of 36.1 fb^{-1}
- Differential cross-sections are measured in the γ + jet + jet final state as a function of variety of observables, including angular correlations and invariant masses
- Unfolded data compared with SHERPA LO (including tree-level higher order ME), SHERPA NLO, PYTHIA LO

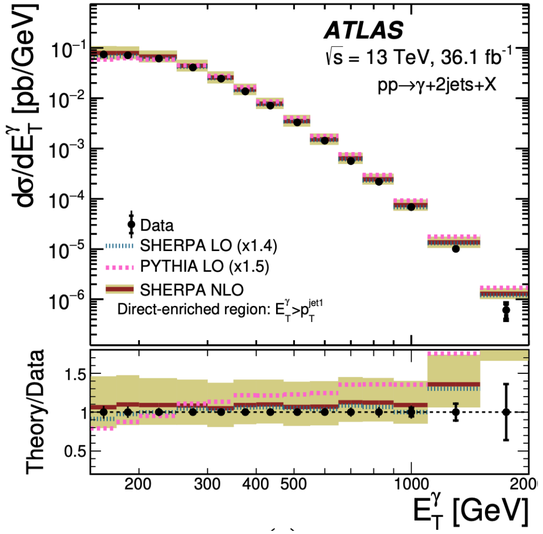
Two regions

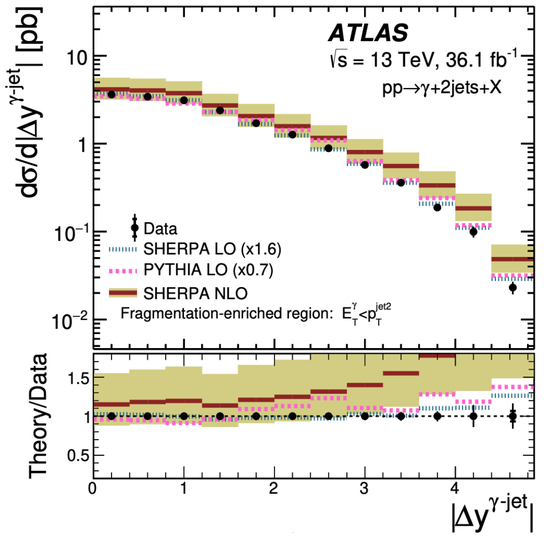
- **Direct**: photon from hard process
- **Fragmentation**: photon from fragmentation of high p_T parton

Results

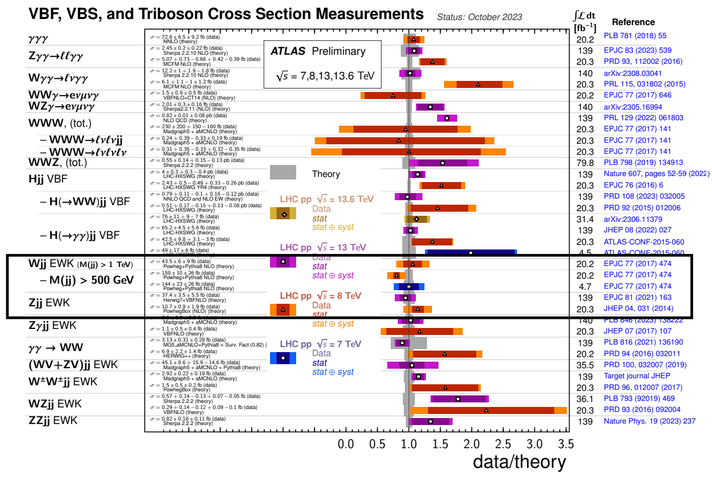
- Improved description of the data by the predictions from LO Sherpa thanks to the inclusion of tree-level higher-order matrix elements
- NLO predictions from Sherpa describe data adequately in shape and normalization except for fragmentation region
- Theoretical uncertainties are much larger than those of experimental nature, preventing a more precise test of the theory

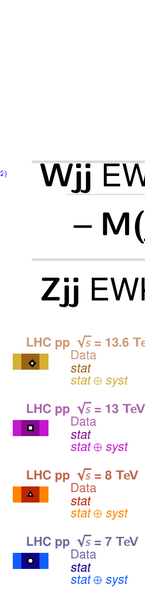




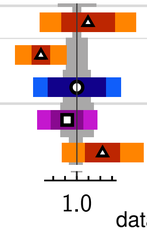


Current status of EW V+Jets ATLAS and CMS



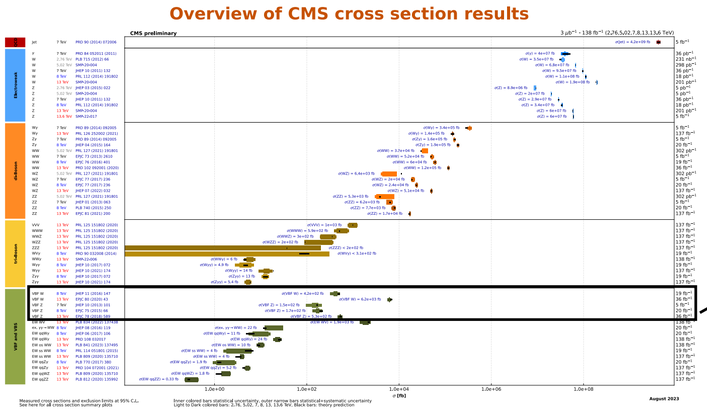


		$\int \mathcal{L}\,dt$ [fb^{-1}]	Reference
Wjj EWK (M(jj) > 1 TeV)	$\sigma = 43.5 \pm 6 \pm 9$ fb (data) Powheg+Pythia8 NLO (theory)	20.2	EPJC 77 (2017) 474
– M(jj) > 500 GeV	$\sigma = 159 \pm 10 \pm 26$ fb (data) Powheg+Pythia8 NLO (theory)	20.2	EPJC 77 (2017) 474
	$\sigma = 144 \pm 23 \pm 26$ fb (data) Powheg+Pythia8 NLO (theory)	4.7	EPJC 77 (2017) 474
Zjj EWK	$\sigma = 37.4 \pm 3.5 \pm 5.5$ fb (data) Herwig7+VBFNLO (theory)	139	EPJC 81 (2021) 163
	$\sigma = 10.7 \pm 0.9 \pm 1.9$ fb (data) PowhegBox (NLO) (theory)	20.3	JHEP 04, 031 (2014)

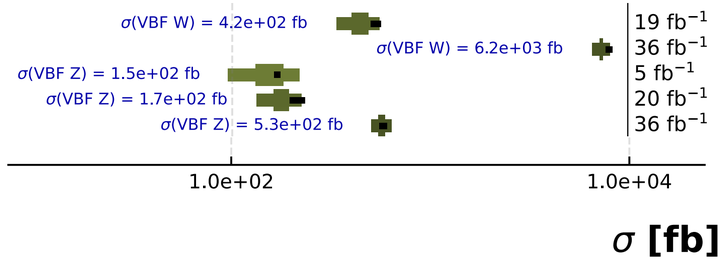


Run 2 VBF-V analysis:

- Zjj EW from ATLAS arxiv: 2006.15458
- VBF-Z and VBF-W from CMS arxiv: 1712.09814 and arxiv: 1903.04040



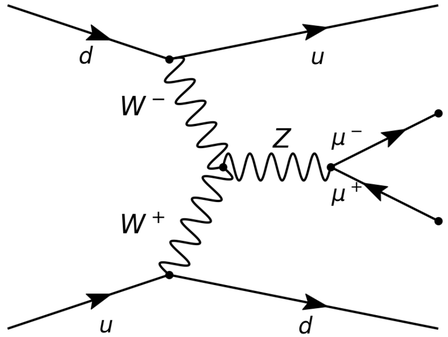
VBF W	8 TeV	JHEP 11 (2016) 147	
VBF W	13 TeV	EPJC 80 (2020) 43	
VBF Z	7 TeV	JHEP 10 (2013) 101	
VBF Z	8 TeV	EPJC 75 (2015) 66	
VBF Z	13 TeV	EPJC 78 (2018) 589	



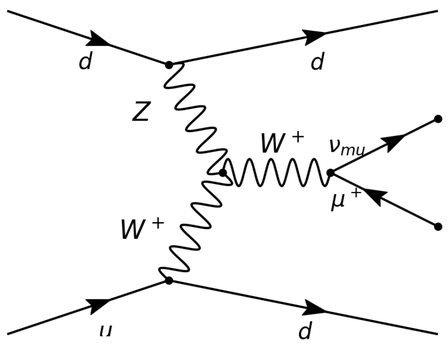
EW V + Jets production

- Very distinctive signature of VBF
- Access to Trilinear Gauge Coupling

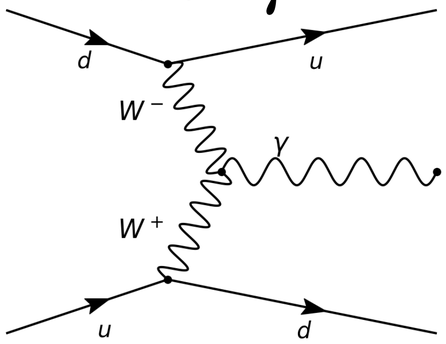
VBF-Z



VBF-W

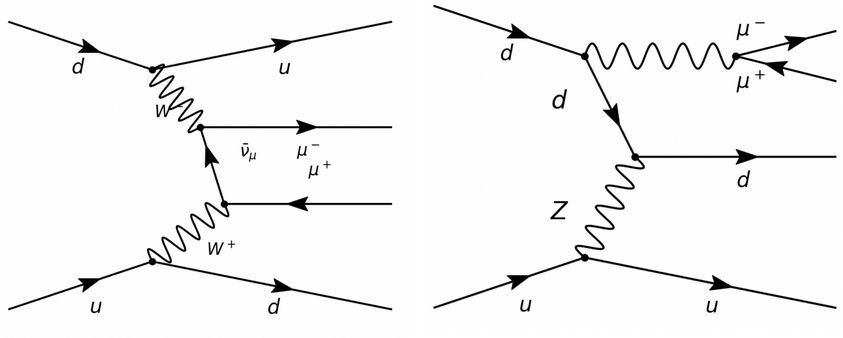


VBF-γ



Currently missing both in ATLAS and CMS

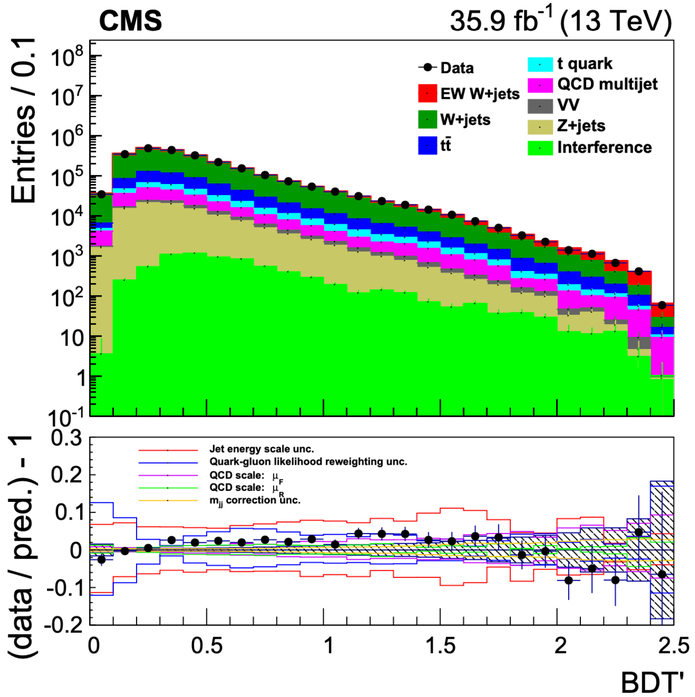
Non resonant diagrams

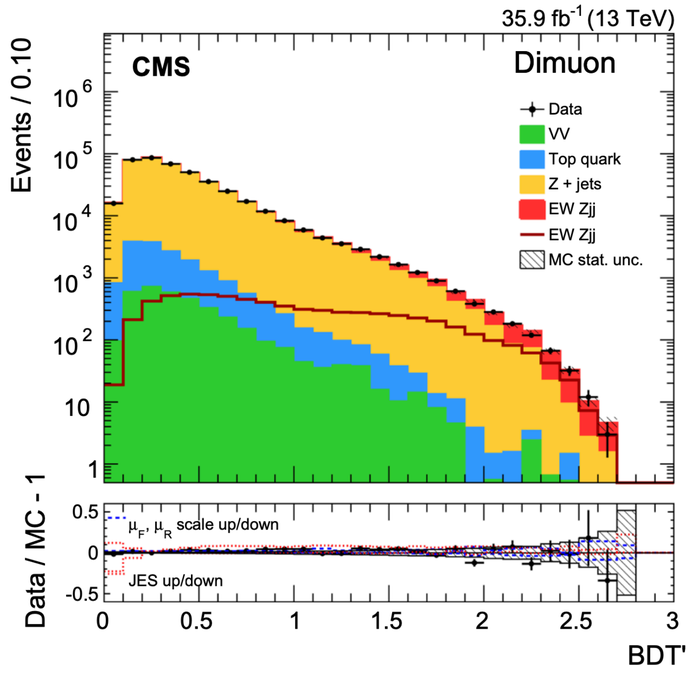


EW W + Jets and Z + Jets in CMS

arxiv: 1712.09814
arxiv: 1903.04040

- Proton–proton collision data collected by CMS at $\sqrt{s} = 13$ TeV and with an integrated luminosity of 35.9 fb^{-1}
- Two very similar analysis, with same analysis strategy and measurements: fit a BDT to measure ↓
- Inclusive cross-sections is measured in the $Z \rightarrow$ l+l− decay channel (l = e, μ) and in the $W \rightarrow l\nu$ (l = e, μ)
- Final state is also used to perform a **search for anomalous trilinear gauge** coupling for c_{WWW}, c_W, c_B, $c_{W\tilde{W}W}$, $c_{\tilde{W}}$
- Third jet activity studies



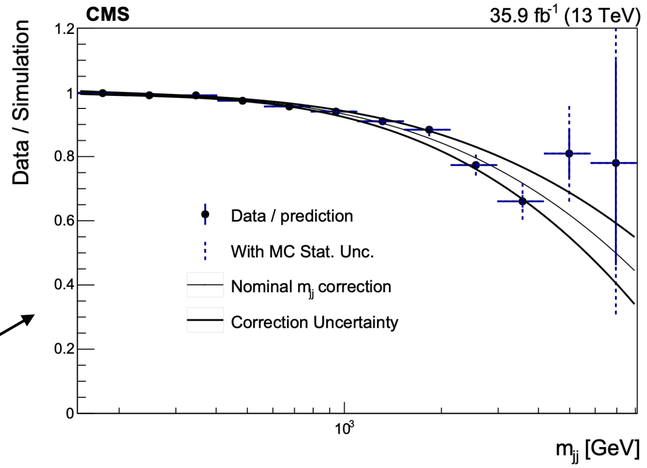


Muon channel

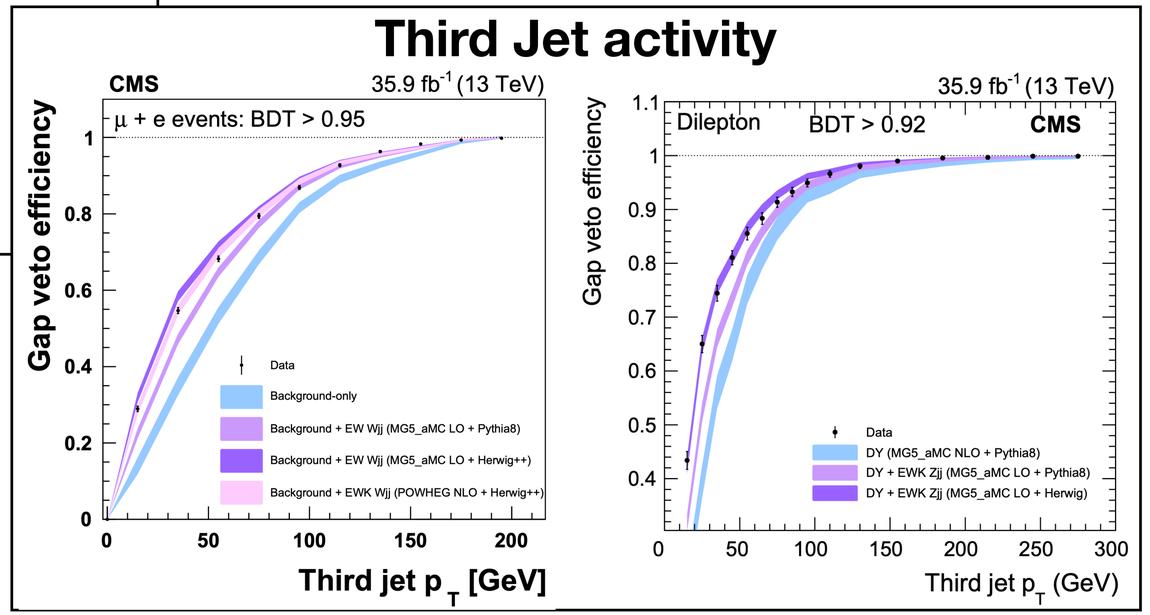
EW W + Jets and Z + Jets in CMS

arxiv: 1712.09814
arxiv: 1903.04040

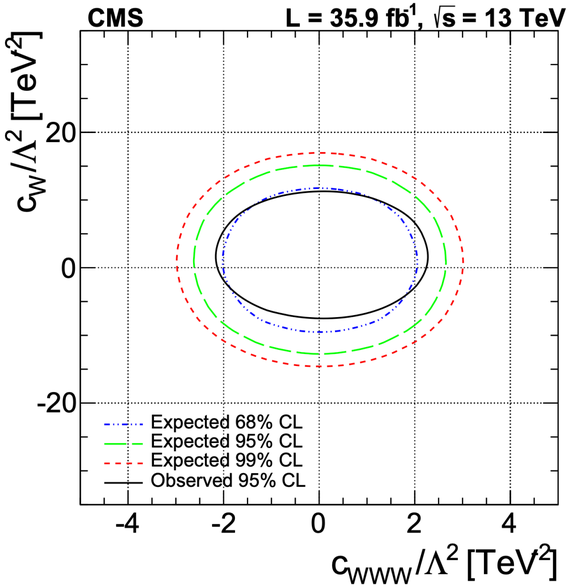
- $\sigma_{\mathrm{EW}}(Wjj)$ = 6.23 ± 0.12 (stat) ± 0.61 (syst) pb
- $\sigma^{\mathrm{EW}}(lljj)$ = 534 ± 20(stat) ± 57(syst)fb
- Both in agreement with LO
- Leading uncertainties:
  - limited statistics of simulated events
  - JES
  - for VBF-W m_{jj} correction
  - For theoretical uncertainty μ_R, μ_F scale uncertainties



m_{jj} correction



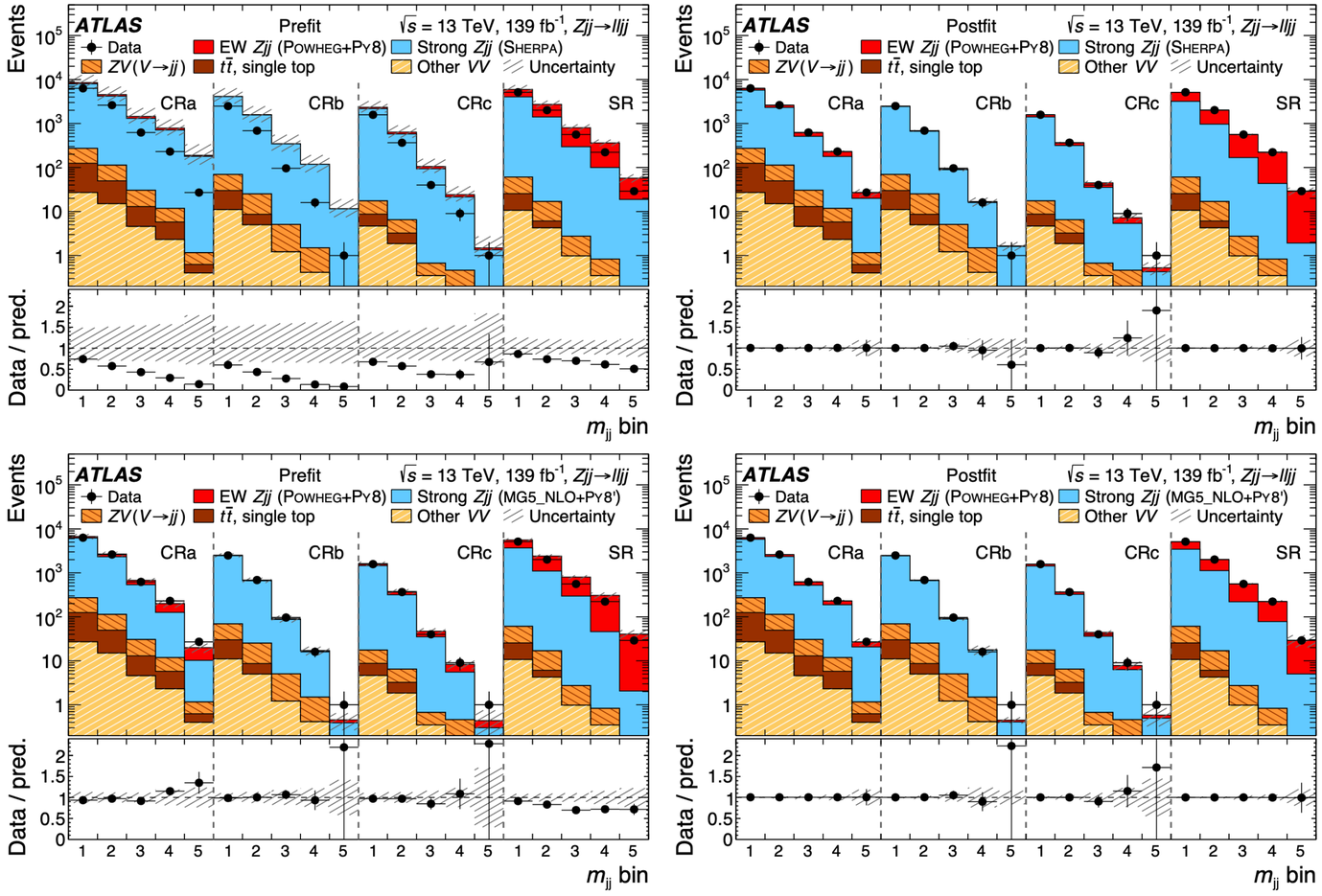
VBF-Z + VBF-W
combined EFT limits



EW Z + Jets in ATLAS

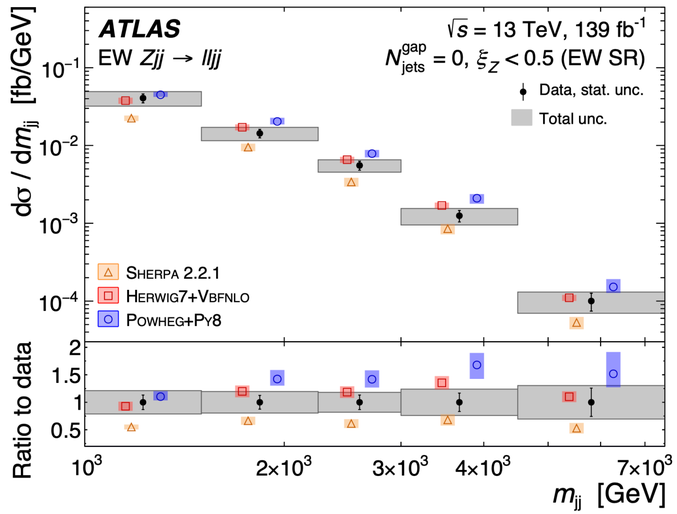
arxiv: 2006.15458

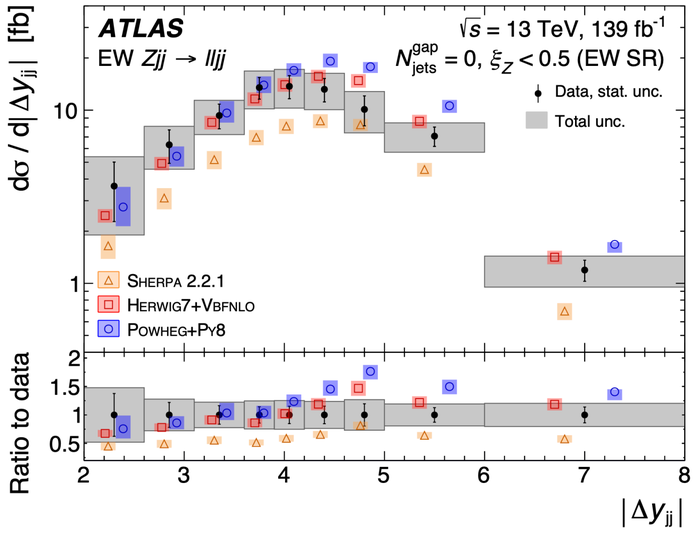
- Proton–proton collision data collected by ATLAS at $\sqrt{s} = 13$ TeV and with an integrated luminosity of 139 fb^{-1}
- Differential cross-sections are measured in the $Z \rightarrow$ l+l− decay channel (l = e, μ) as a function of m_{jj}, Δy_{jj}, $\Delta\phi_{jj}$, p_T^{ll}
- Unfolded data is compared with predictions of Herwig7+VBFNLO, Powheg+PY8 and Sherpa
- Differential cross-sections are used to search for anomalous weak-boson self-interactions using a dimension-six effective field theory (EFT also on QCD Z+Jets) for c_W, $\tilde{c}_W$, c_{HWB}, $\tilde{c}_{HWB}$

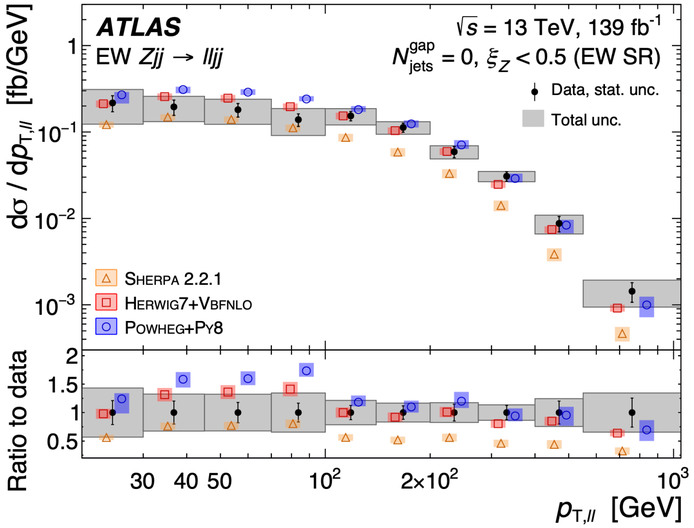


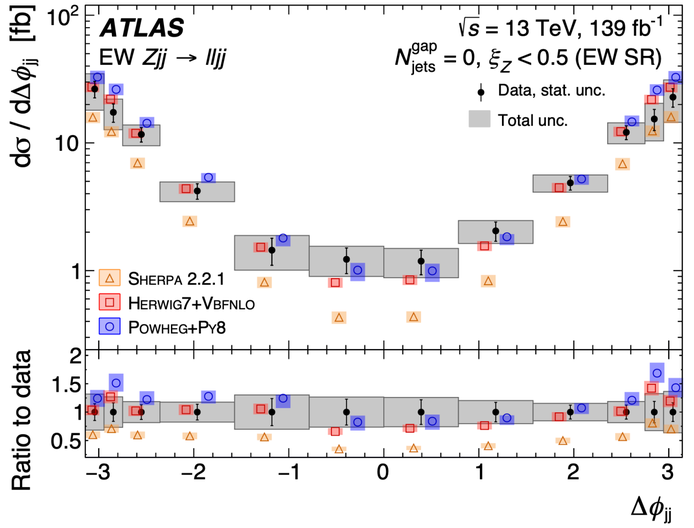
EW Z + Jets in ATLAS

arxiv: 2006.15458



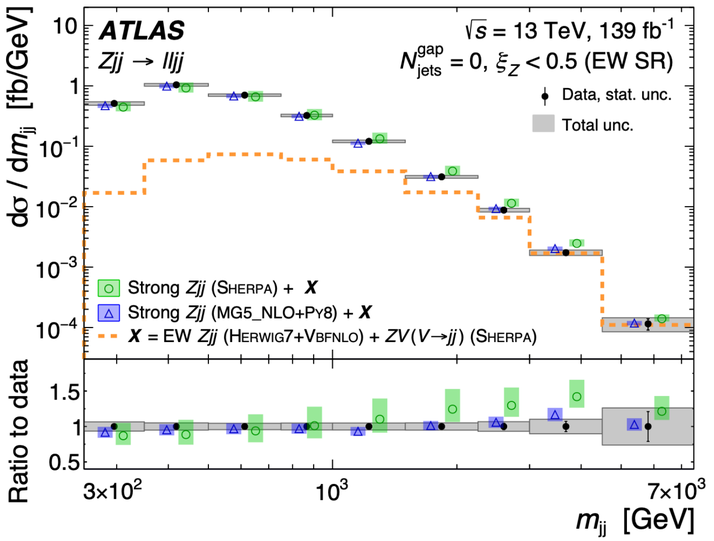


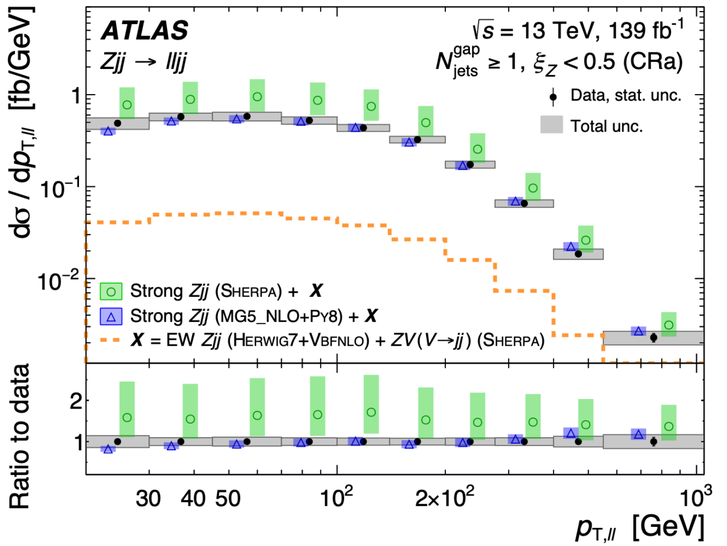


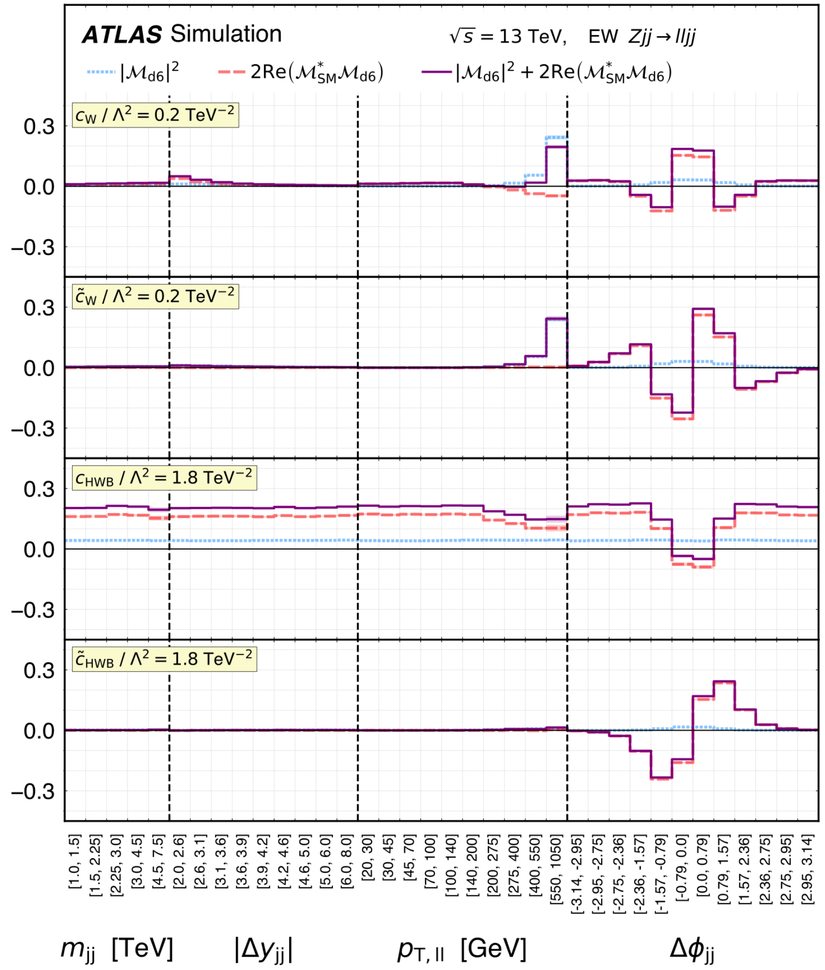


EW Z + Jets in ATLAS

arxiv: 2006.15458







Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	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

- Many measurements have been made by ATLAS and CMS at 13 TeV
  - Comparison of many different ME and PS with different tuning have been compared to differential measurements
  - The need for NLO EW and QCD corrections have been highlighted and possibly for NNLO QCD in V+jets
  - V+Jets measurements (and their correct prediction) are crucial for many analysis!
  - Missing differential measurements of VBF-Z and VBF-W by CMS (profit of Full Run 2 statistics and Run 3!)
  - There's currently no VBF-γ measurement at 13 TeV by neither ATLAS and CMS