LHCP Boston 2024

The 12th Large Hadron Collider Physics Annual Conference

June 3-7, 2024 @ Northeastern University

http://lhcp2024.cos.northeastern.edu

Multiboson Measurements

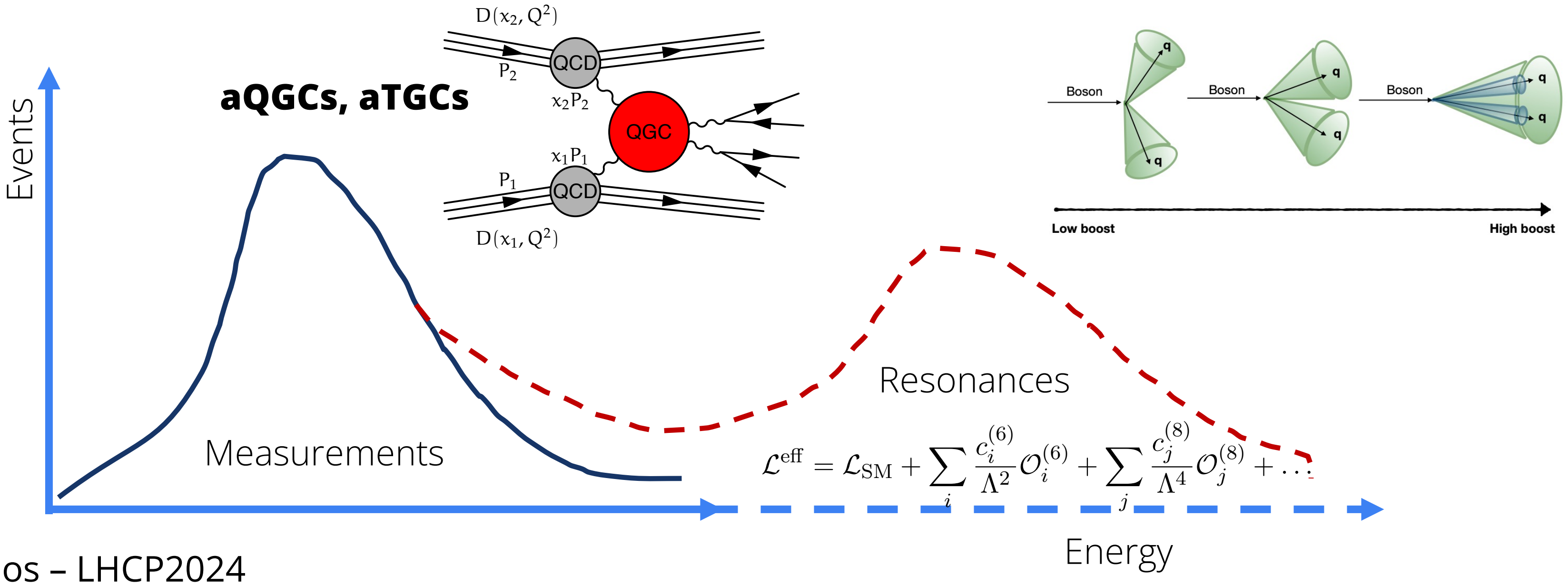
Karolos Potamianos, University of Warwick (GB)
on behalf of the ATLAS and CMS Collaborations

5 June 2024

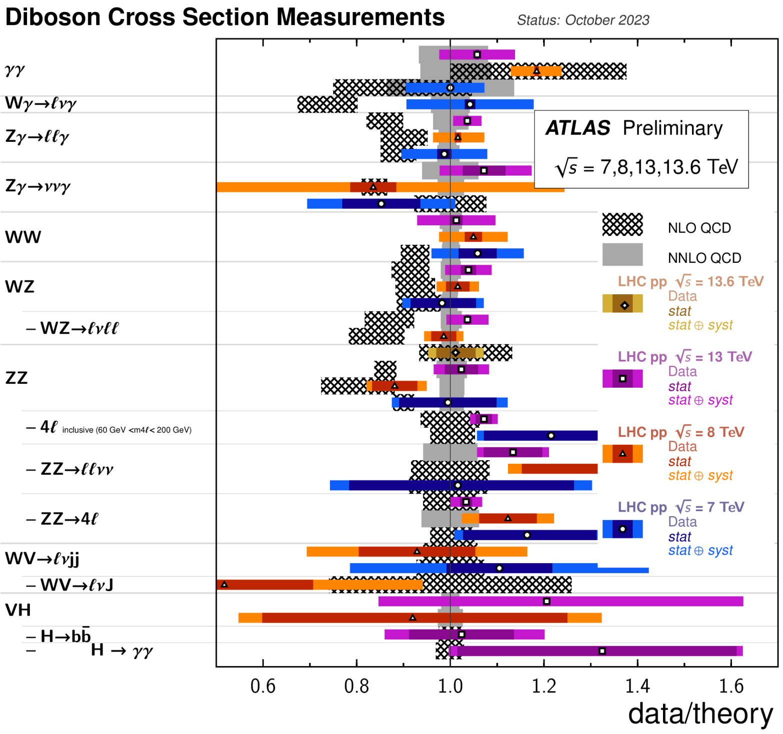
Photo credit: Alina Mak

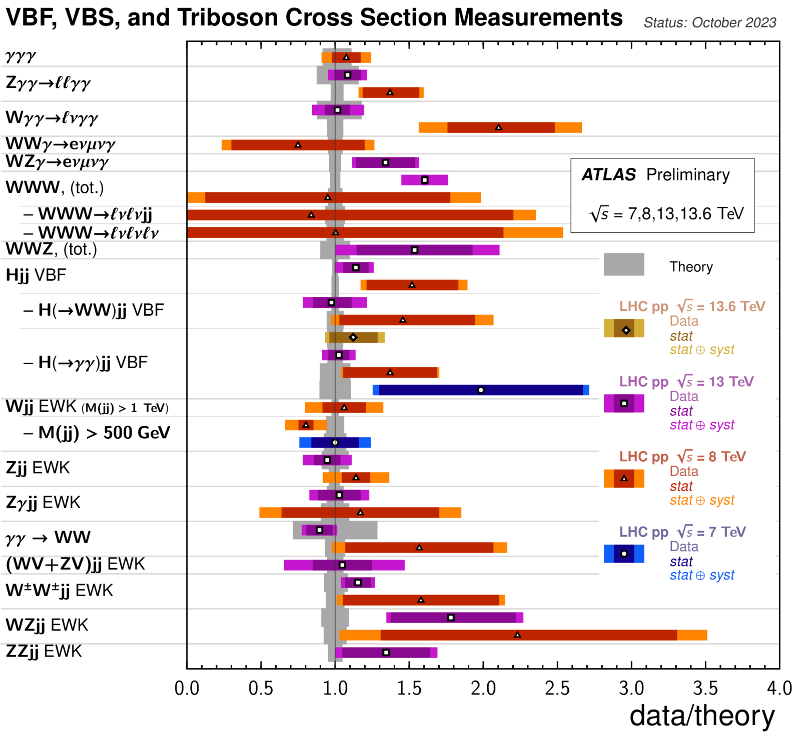
Multiboson Measurements – Motivation I

- Multiboson physics probes the nature of **Electroweak Symmetry Breaking**
- Wide range of processes: **diboson, triboson, vector boson scattering**
- Portal to BSM physics through interpretations: **EFT, resonant searches**
- Encompasses a broad range of measurements and searches



A wealth of measurements …





ATLAS summary multiboson measurements (10/23) – Also available from CMS (11/23)

Related Presentations This Week

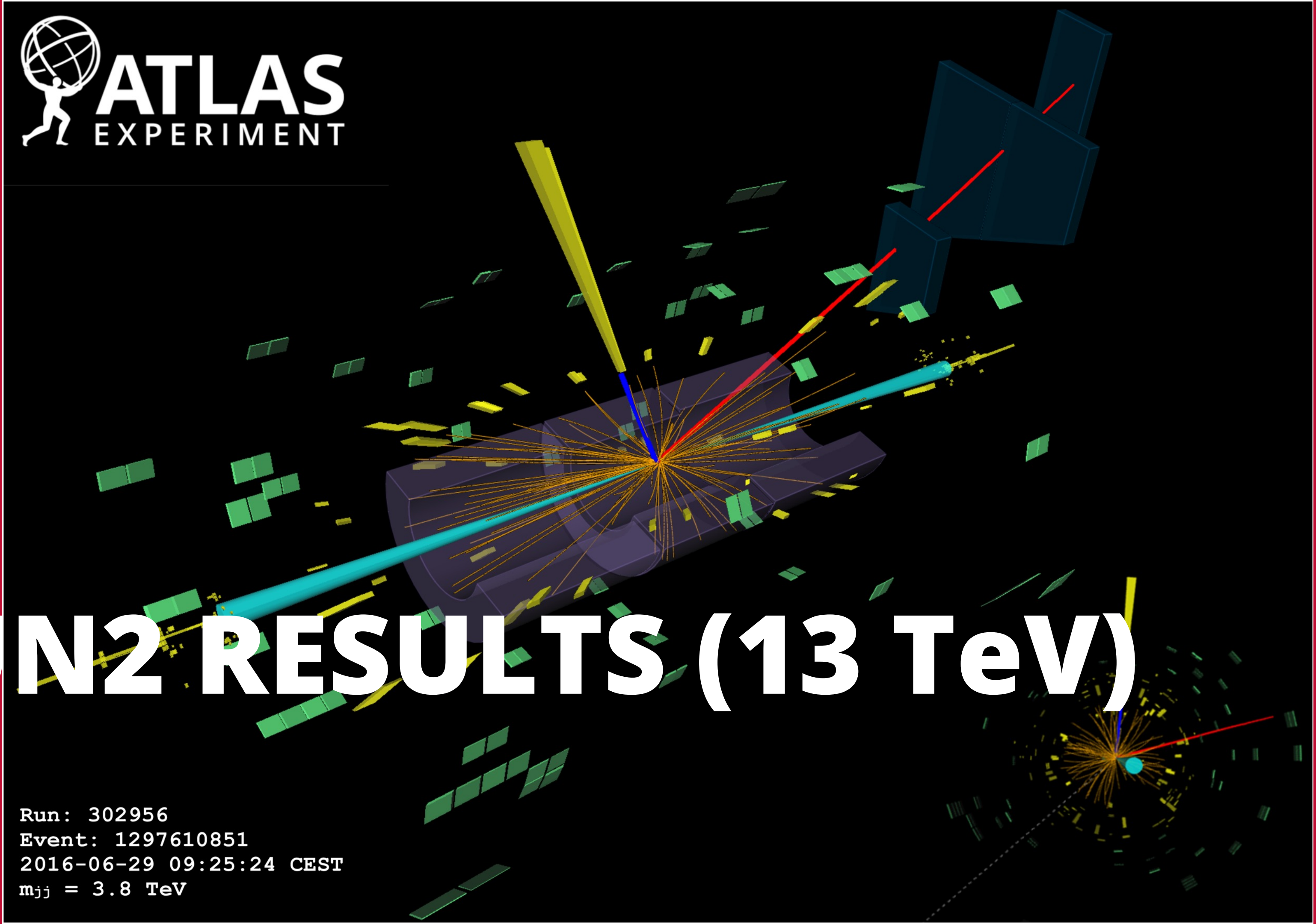
Friday, June 7, 2024

11:00 → 12:48 **Electroweak Physics** ISEC Room 138

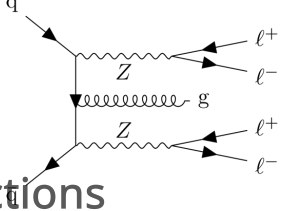
Conveners: Davide Napoletano (Universita & INFN, Milano-Bicocca (IT)), Francesca Cavallari (Sapienza Universita e INFN, Roma I (IT)), Garvita Agarwal (University of Notre Dame (US)), Oldrich Kepka (Czech Academy of Sciences (CZ))

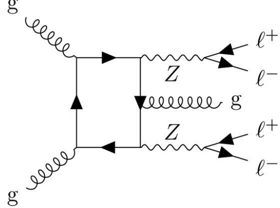
11:00	**Diboson and polarization measurements in ATLAS** **Speaker**: Prajita Bhattarai (SLAC National Accelerator Laboratory (US))	18m
11:18	**Dibosons and polarization measurements in CMS** **Speaker**: Giulia Sorrentino (Kansas State University (US))	18m
11:36	**Theory of diboson production** **Speaker**: Diana Mareen Hoppe (Technische Universitaet Dresden (DE))	18m
11:54	**Experimental overview of VBS/VBF measurements at the LHC** **Speaker**: Pietro Govoni (Universita & INFN, Milano-Bicocca (IT))	18m
12:12	**Theory overview of EFT in the electroweak sector** **Speaker**: Raquel Gomez Ambrosio	18m
12:30	**Experimental overview of EFT, including global fit (EWK+Higgs+Top)** **Speaker**: Aram Apyan (Brandeis University (US))	18m

RUN2 RESULTS (13 TeV)



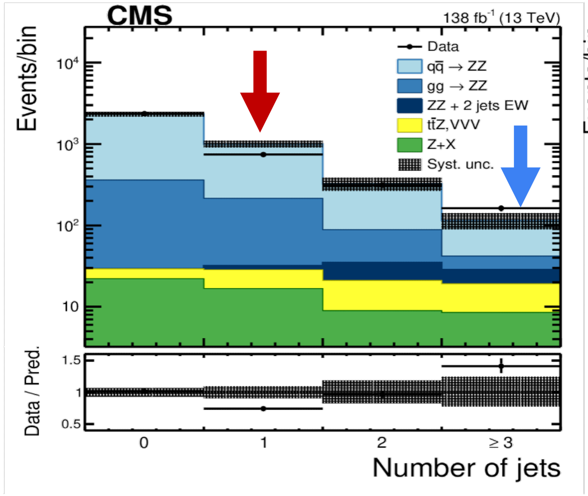
CMS ZZ+jets @ 13 TeV [138 fb^{-1}]

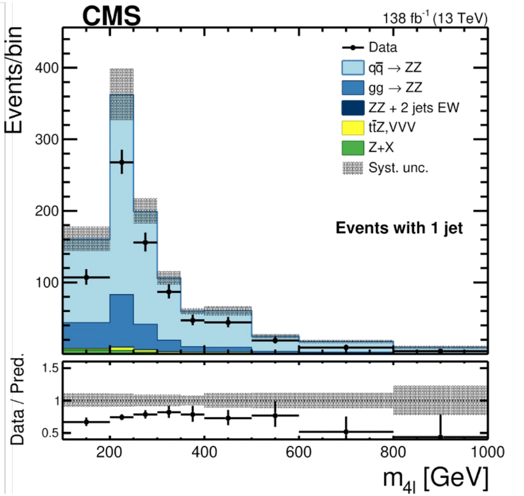




- **Differential distributions & normalised differential cross-sections**
- **Fully leptonic final state (e, μ)**, unfolding w/ iterative D'Agostini
- 40 < m_{Z1} < 120 GeV, 4 < m_{Z1} < 120 GeV; **On-shell req.: 60 < $m_{Z1,Z2}$ < 120 GeV**
- **Discrepancy in 1 jet bin**
- **Discrepancy in N >= 3 jets due to need for NNLO and higher order corrections**

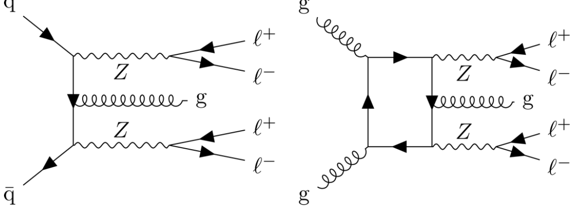
Systematic source	$m_{4\ell}$ with all jets	0 jet	1 jet	2 jets	3 and more jets
Electron efficiency	0.42%	0.38%	0.66%	0.36%	0.26%
Muon efficiency	0.05%	0.06%	0.07%	0.09%	0.08%
Jet energy resolution	—	0.07%	1.72%	1.65%	0.80%
JES correction	—	0.17%	1.77%	1.95%	0.97%
Reducible background	0.18%	0.18%	0.32%	0.33%	0.96%
Pileup	0.02%	0.05%	0.11%	0.13%	0.35%
Luminosity	0.01%	0.01%	0.02%	0.02%	0.05%
$q\bar{q} \rightarrow ZZ$ MC choice	0.35%	0.65%	0.94%	0.48%	0.35%
$gg \rightarrow ZZ$ cross section	0.02%	0.03%	0.09%	0.06%	0.09%
QCD scales	0.15%	0.16%	0.58%	0.54%	0.62%
PDF	0.05%	0.05%	0.15%	0.15%	0.21%
PDF α_S	0.02%	0.01%	0.05%	0.03%	0.02%



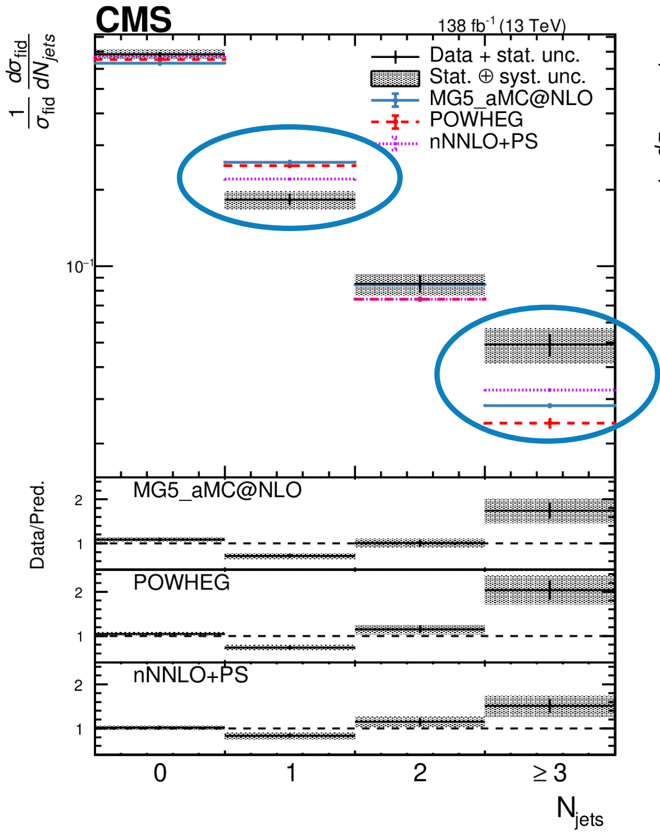


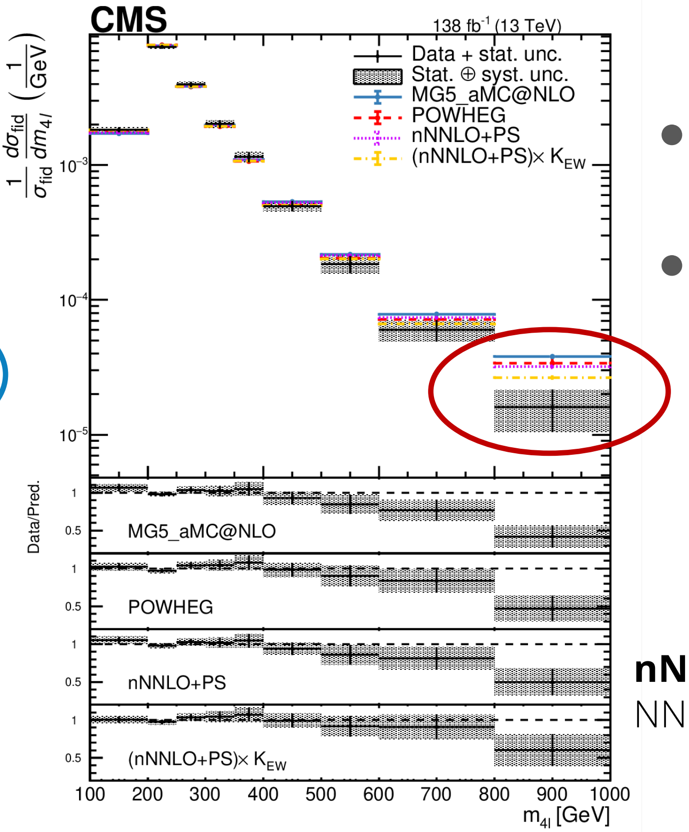
arXiv:2404.02711, submitted JHEP

CMS ZZ+jets @ 13 TeV [138 fb^{-1}]



60 < $m_{Z1,Z2}$ < 120 GeV





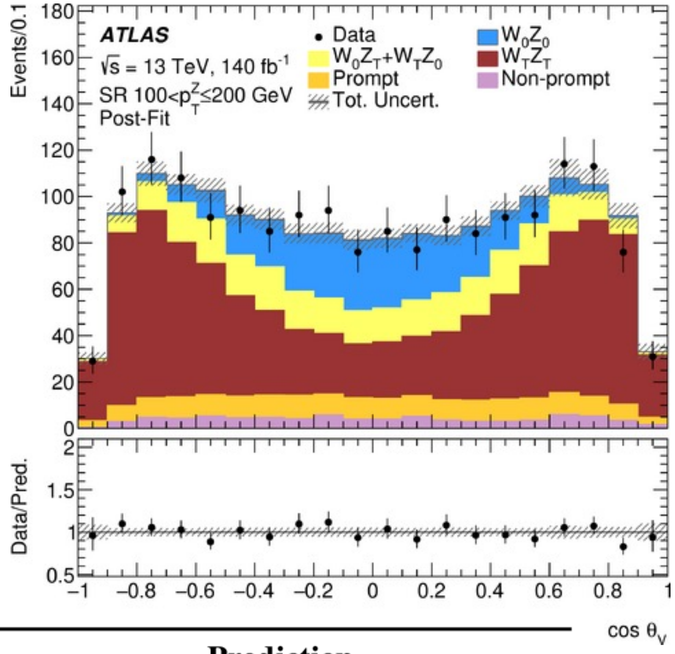
- Better Njet description with nNNLO+PS
- Better description of m_{4l} with EW-corrected nNNLO+PS, but negligible effect on other distributions

nNNLO+PS:
NNLO qq w/ $MiNNLO_{PS}$ + NLO ggF

arXiv:2402.16365, submitted to Phys. Rev. Lett.

ATLAS high-p_T^Z WZ @ 13 TeV [140 fb^{-1}]

- Study of polarisation states sensitive to Electroweak Symmetry Breaking
- BDT (7 variables) trained to measure polarisation fractions f_{WZ}: f_{00}, f_{0T+T0} & f_{TT}
- Fractions measured in **high p_T^Z and low p_T^{WZ}** yields **20-30% enhancement of f_{00}**
- 5.2σ (4.3σ) obs. (exp.) for 100 < p_T^Z < 200 GeV
  - 1.6σ (2.5σ) obs. (exp.) for p_T^Z > 200 GeV

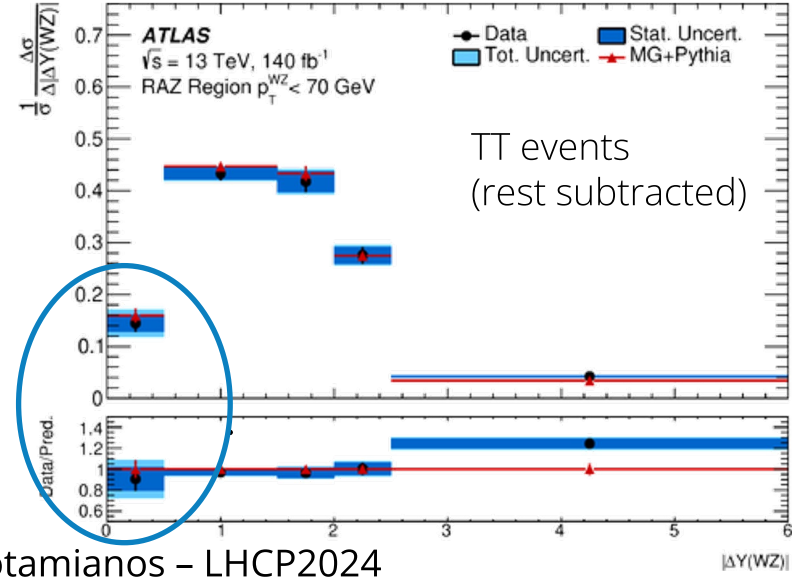


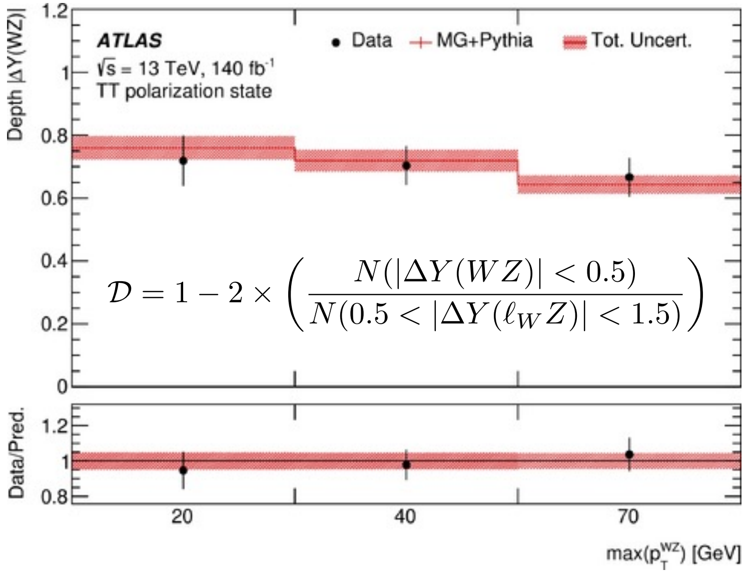
	Measurement $100 < p_T^Z \leq 200$ GeV	Measurement $p_T^Z > 200$ GeV		Prediction $100 < p_T^Z \leq 200$ GeV	Prediction $p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ	f_{TT}	0.619 ± 0.007	0.646 ± 0.008

arXiv:2402.16365, submitted to Phys. Rev. Lett.

ATLAS high-p_T^Z WZ @ 13 TeV [140 fb^{-1}]

- Radiation Amplitude Zero Effect: drop at 0 in ΔY(WZ) and $\Delta Y(l_W Z)$ for TT events
  - Scattering angle of the W in the WZ frame ~90° w.r.t. incoming antiquark
- **First observation of RAZ effect in WZ production** (previously seen in Wγ by CMS)
  - Challenges due to longitudinally-polarised W and NLO QCD corrections diluting effect (hadronic activity reduced by p_T^{WZ} requirement)

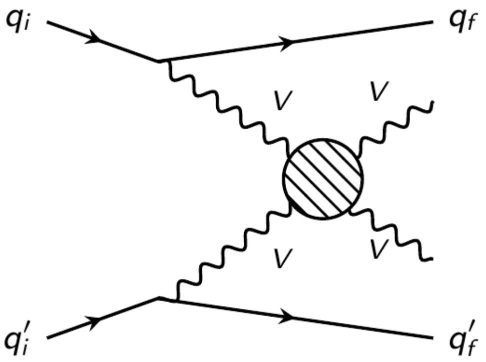




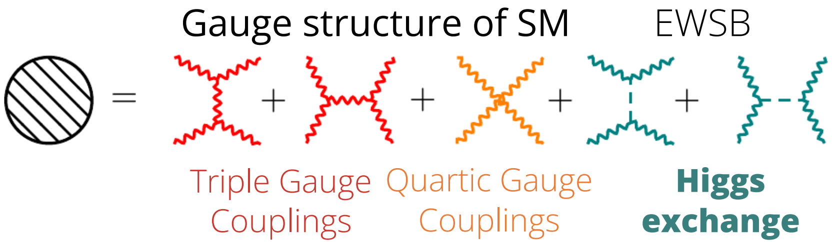
$$\mathcal{D} = 1 - 2 \times \left(\frac{N(|\Delta Y(WZ)| < 0.5)}{N(0.5 < |\Delta Y(\ell_W Z)| < 1.5)} \right)$$

See talk by P. Govoni, June 7

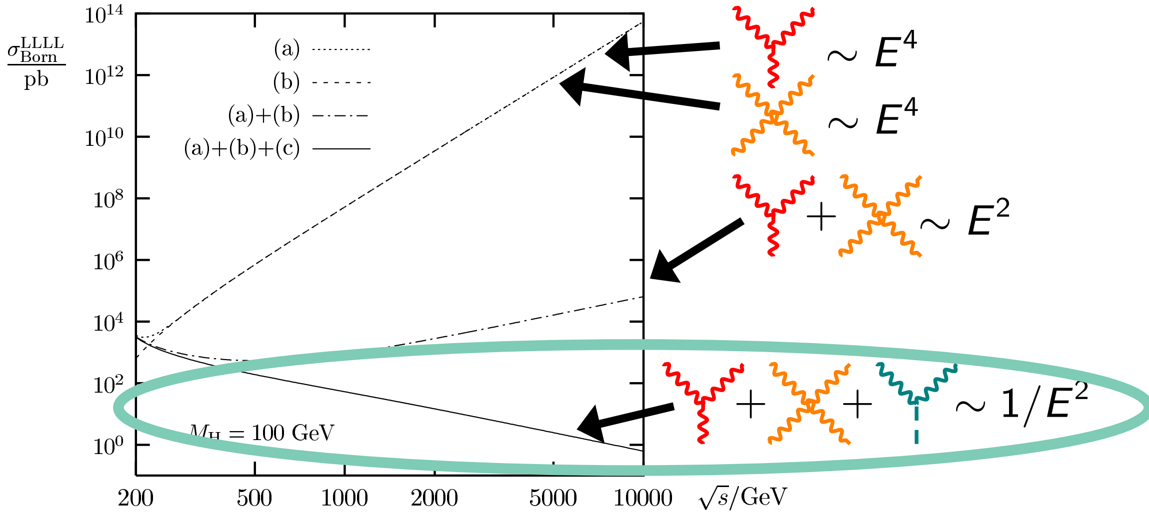
Vector Boson Scattering



Complementary probe to direct Higgs measurements



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



A light Higgs boson **prevents cross-section of VBS processes from becoming unphysical (diverging)**

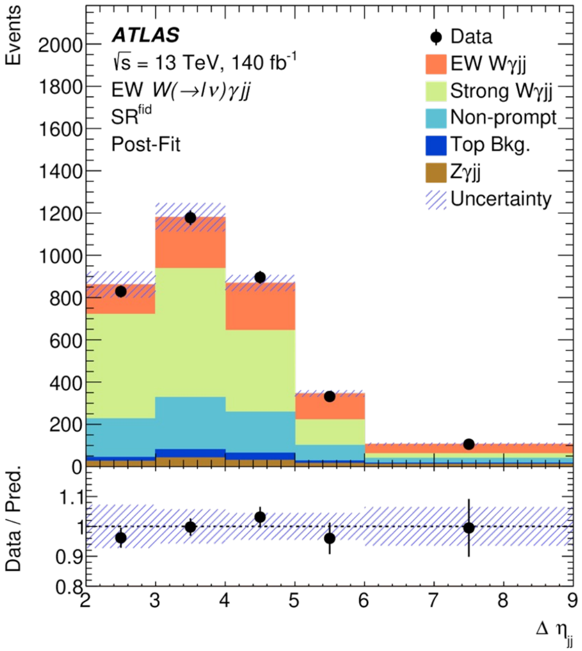
VBS measurements test the consistency of the SM and is sensitive to New Physics

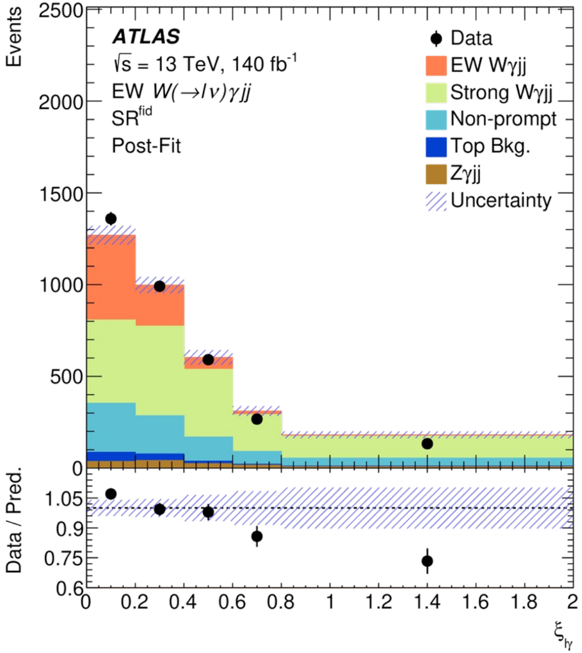
arXiv:2403.02809, submitted to EPJC

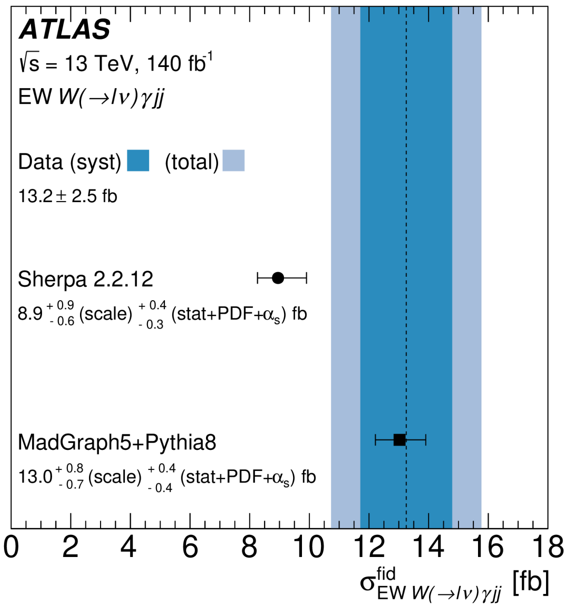
ATLAS Wγjj VBS @ 13 TeV [140 fb^{-1}]

- Observation of EW Wγjj with 6.3σ
- NN (13 variables) to enhance EW Wγjj (inclusive)

Uncertainty Source	Fractional Uncertainty [%]
Statistics	11
Jets	8
Lepton, photon, pile-up	8
EW $W\gamma jj$ modelling	7
Strong $W\gamma jj$ modelling	6
Non-prompt background	2
Luminosity	2
Other Background modelling	2
E_T^{miss}	1



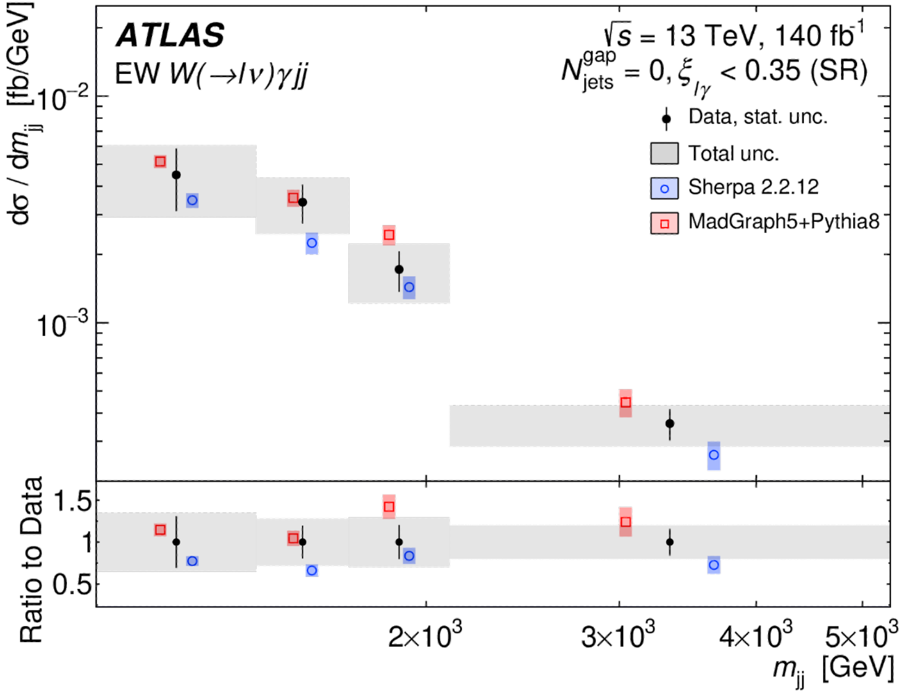


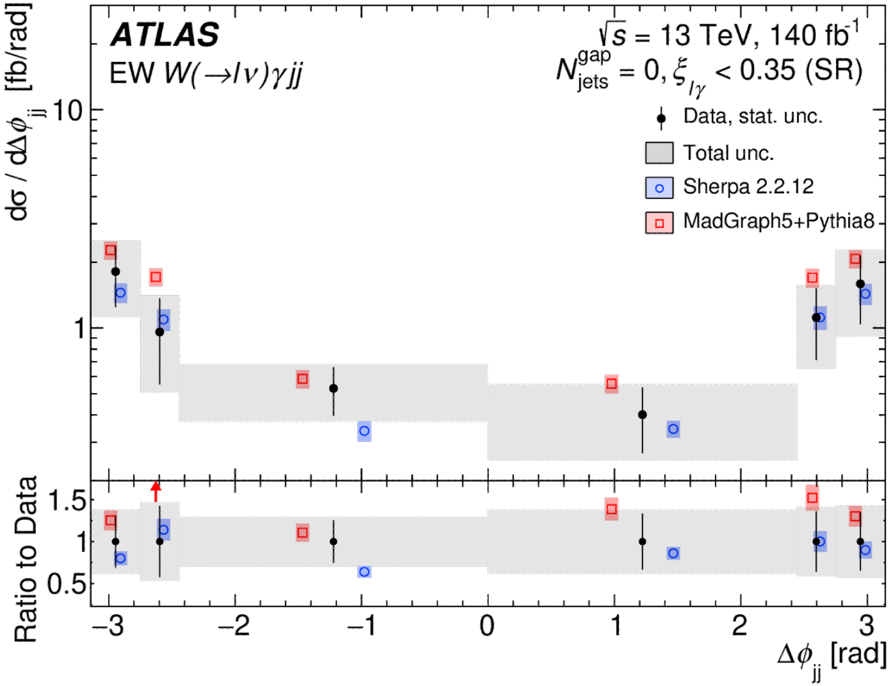


$$\xi_{l\gamma} = |(y_{l\gamma} - \frac{(y_{j_1}+y_{j_2})}{2})/(y_{j_1} - y_{j_2})|$$

ATLAS Wγjj VBS @ 13 TeV [140 fb^{-1}]

- Particle-level fiducial and differential cross-sections as a function of m_{jj}, p_T^{jj}, $\Delta_{\phi jj}$, p_T^{l}, $m_{l\gamma}$ and $\Delta_{\phi l\gamma}$ corrected for detector effects (efficiency and resolution)





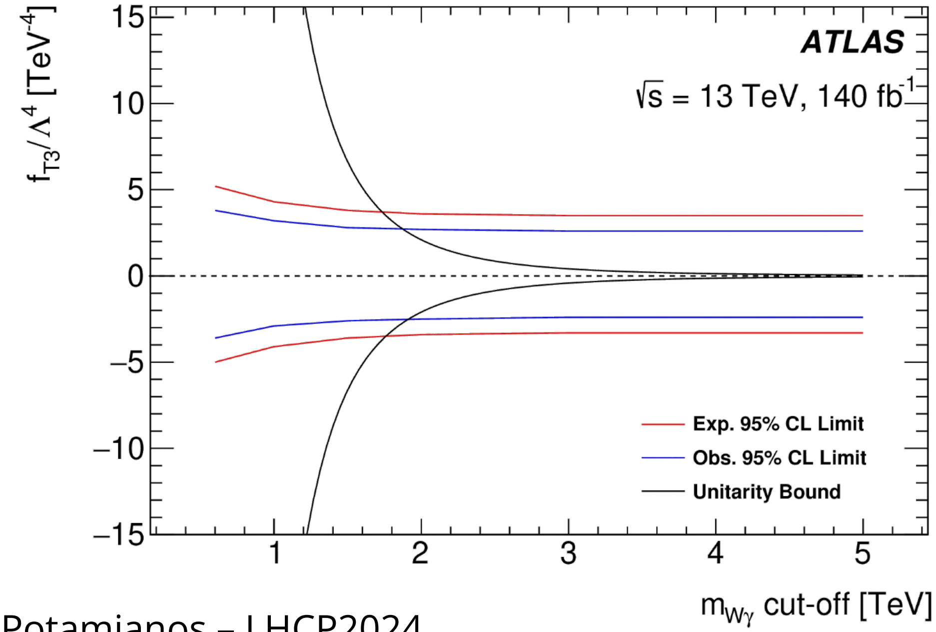
arXiv:2403.02809, submitted to EPJC

ATLAS Wγjj VBS @ 13 TeV [140 fb-1]

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

- EFT Interpretation
  - Pure dim-8 terms have higher impact than interference

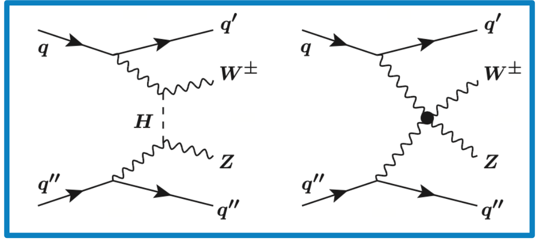
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2Re(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{D-8}}) + \boxed{|\mathcal{M}_{\mathrm{D-8}}|^2}$$



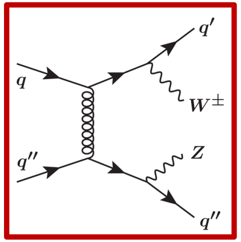
Cofficients [TeV^{-4}]	Observable	$M_{W\gamma}$ cut-off [TeV]	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	p_T^{jj}	1.4	[-2.5, 2.6]	[-1.9, 1.9]
f_{T1}/Λ^4	p_T^{jj}	1.9	[-1.6, 1.6]	[-1.1, 1.2]
f_{T2}/Λ^4	p_T^{jj}	1.6	[-4.9, 5.3]	[-3.6, 4.0]
f_{T3}/Λ^4	p_T^{jj}	1.9	[-3.4, 3.6]	[-2.5, 2.7]
f_{T4}/Λ^4	p_T^{jj}	2.2	[-3.1, 3.1]	[-2.2, 2.3]
f_{T5}/Λ^4	p_T^{jj}	1.8	[-1.8, 1.8]	[-1.3, 1.3]
f_{T6}/Λ^4	p_T^{jj}	2.1	[-1.5, 1.5]	[-1.1, 1.1]
f_{T7}/Λ^4	p_T^{jj}	2.1	[-4.0, 4.1]	[-2.9, 3.0]
f_{M0}/Λ^4	p_T^{l}	1.1	[-45, 44]	[-32, 31]
f_{M1}/Λ^4	p_T^{l}	1.4	[-60, 62]	[-43, 44]
f_{M2}/Λ^4	p_T^{l}	1.4	[-15, 15]	[-11, 11]
f_{M3}/Λ^4	p_T^{l}	1.8	[-22, 22]	[-16, 16]
f_{M4}/Λ^4	p_T^{l}	1.5	[-28, 27]	[-20, 20]
f_{M5}/Λ^4	p_T^{l}	1.9	[-21, 23]	[-14, 17]
f_{M7}/Λ^4	p_T^{l}	1.5	[-100, 99]	[-73, 71]

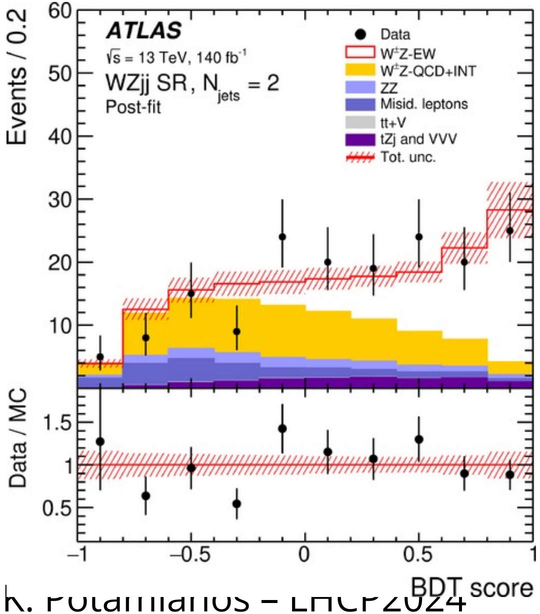
arXiv:2403.15296, submitted to JHEP

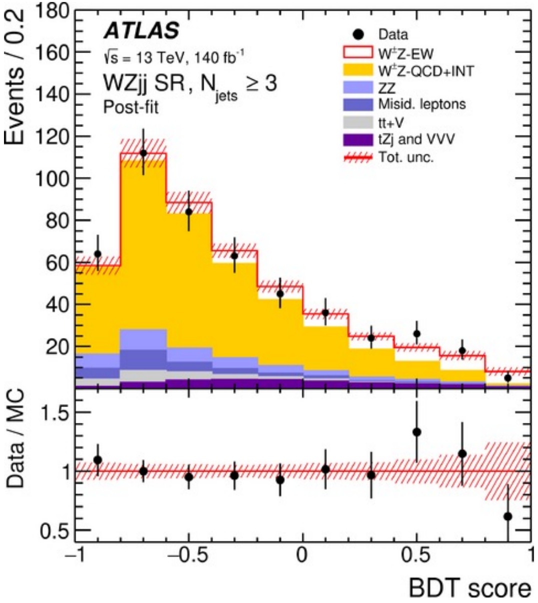
ATLAS WZjj VBS @ 13 TeV [140 fb^{-1}]



- Simultaneous extraction of EW and strong WZjj
  - In Njet = 2 and ≥ 3 & m_{jj} in [500, 1300, 2000]
- Enhanced sensitivity using BDT discriminant
- Adverserial NN to separate EW and QCD w/o m_{jj} bias







	$\sigma_{WZjj-\mathrm{EW}}$
Measured	0.368 ± 0.037 (stat.) ± 0.059 (syst.) ± 0.003 (lumi.) fb
MadGraph+Pythia8	0.370 ± 0.001 (stat.) ± 0.006 (PDF)$^{+0.030}_{-0.026}$ (scale) fb
	$\sigma_{WZjj-\mathrm{strong}}$
Measured	1.093 ± 0.066 (stat.) ± 0.131 (syst.) ± 0.009 (lumi.) fb
MadGraph+Pythia8	1.537 ± 0.009 (stat.) ± 0.016 (PDF)$^{+0.087}_{-0.149}$ (scale) fb

0.7 factor between data and MG

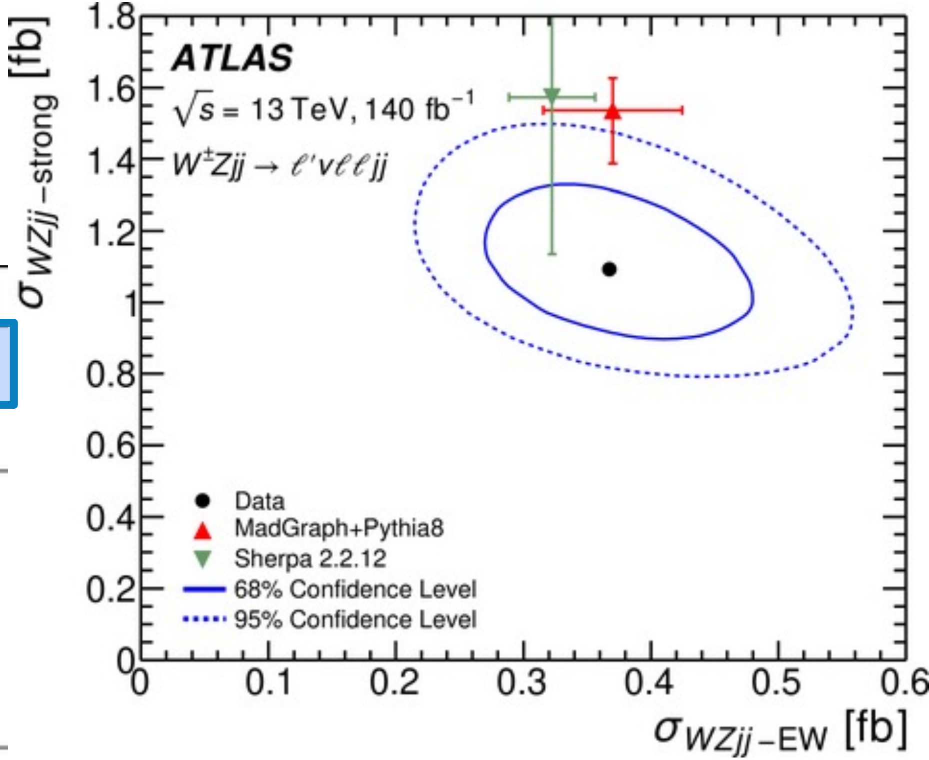
- within 1.8σ given unc. on MG

Also observed in W±W±jj and previous WZjj and WZ measurements by ATLAS

ATLAS WZjj VBS @ 13 TeV [140 fb^{-1}]

- Simultaneous extraction of EW and strong WZjj

Source	$\frac{\Delta\sigma_{WZjj-\mathrm{EW}}}{\sigma_{WZjj-\mathrm{EW}}}$ [%]	$\frac{\Delta\sigma_{WZjj-\mathrm{strong}}}{\sigma_{WZjj-\mathrm{strong}}}$ [%]
$WZjj$–EW theory modelling	7	1.8
$WZjj$–QCD theory modelling	2.8	8
$WZjj$–EW and $WZjj$–QCD interference	0.35	0.6
PDFs	1.0	0.06
Jets	2.3	5
Pile-up	1.1	0.6
Electrons	0.8	0.8
Muons	0.9	0.9
b-tagging	0.10	0.11
MC statistics	1.9	1.2
Misid. lepton background	2.3	2.3
Other backgrounds	0.9	0.23
Luminosity	0.7	0.9
All systematics	16	12
Statistics	10	6
Total	19	13



arXiv:2403.15296, submitted to JHEP

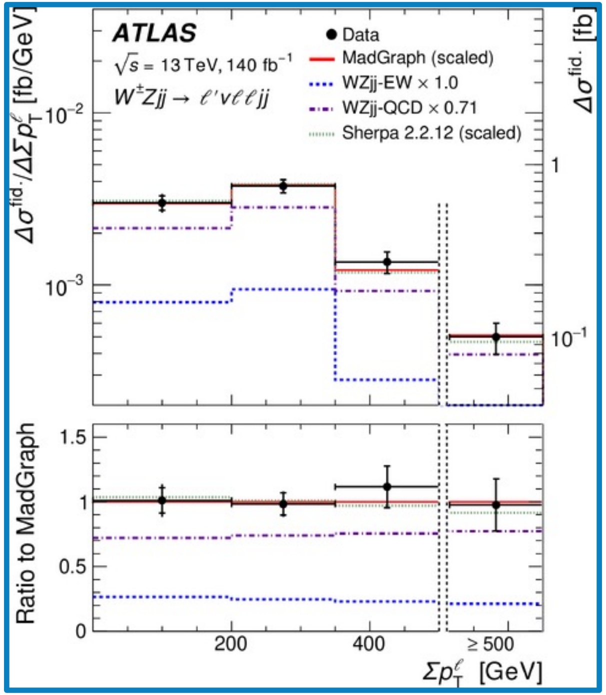
ATLAS WZjj VBS @ 13 TeV [140 fb^{-1}]

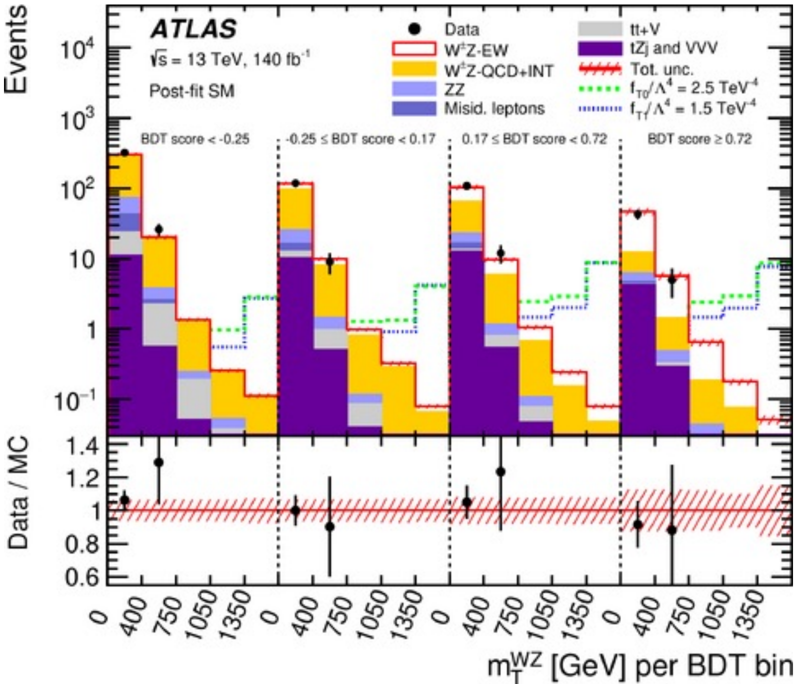
- Differential cross-sections and EFT interpretation

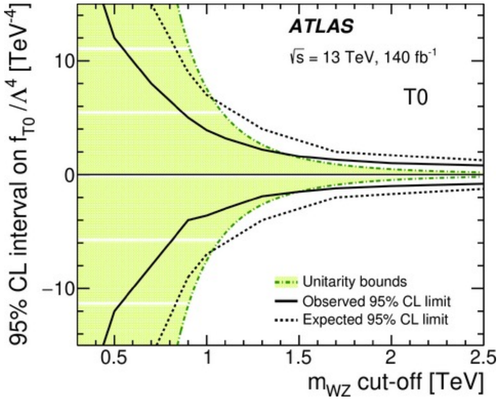
$$\left|A_{\rm SM} + \sum_i c_i A_i\right|^2 = |A_{\rm SM}|^2 + \sum_i c_i\, 2\,{\rm Re}(A^*_{\rm SM} A_i) + \sum_i c_i^2 |A_i|^2 + \sum_{ij, i\neq j} c_i c_j\, 2\,{\rm Re}(A_i A_j^*)$$

$$c_i = f_j^{(8)}/\Lambda^4$$

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





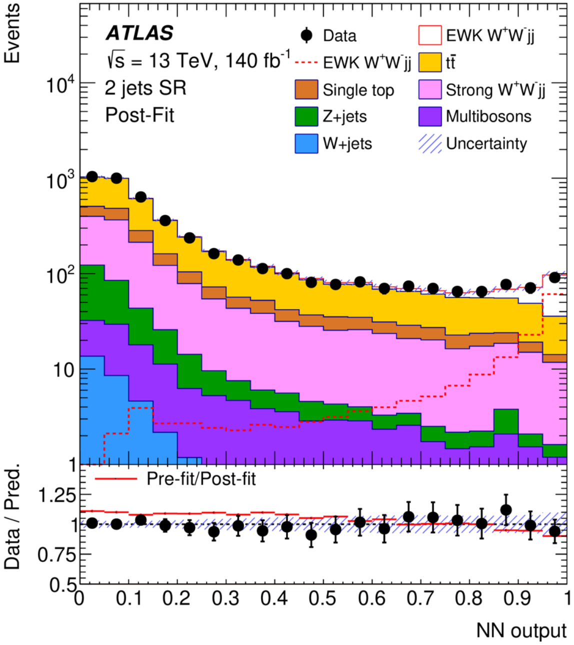


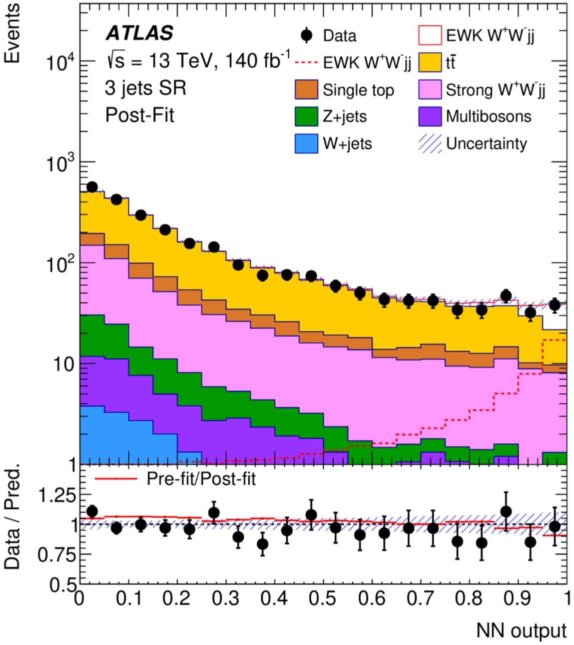
aXiv:2403.04869, submitted to JHEP

ATLAS OS WWjj VBS @ 13 TeV [138 fb^{-1}]

$$\sigma_{\mathrm{OBS}} = 2.65^{+0.49}_{-0.46}\ \mathrm{fb}$$
$$\sigma_{\mathrm{POWHEG}} = 2.20^{+0.14}_{-0.13}\ \mathrm{fb}$$

- Observation of EW $W^{\pm}W^{\mp}jj$
  - 7.1σ (6.2σ) obs. (exp.) in 2&3 jets
- 2 NNs trained to separate signal from top and QCD WWjj



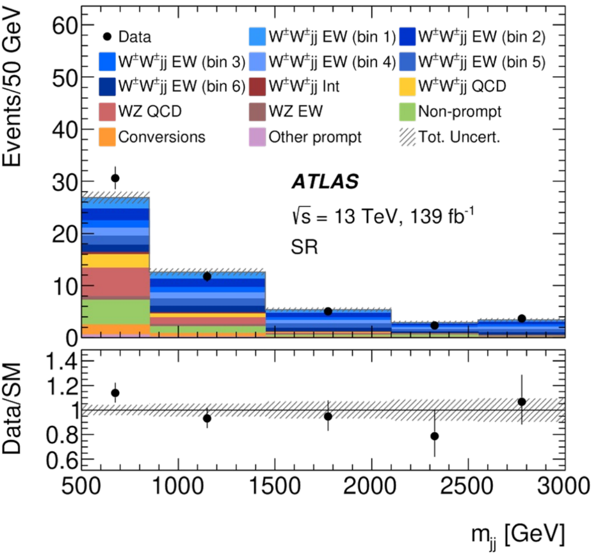


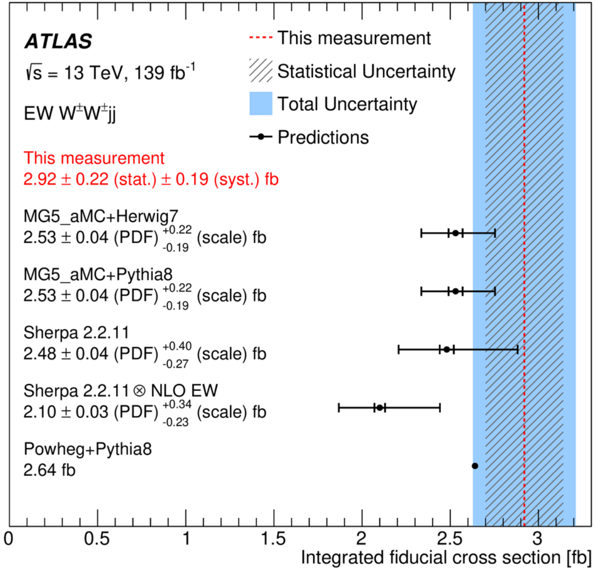
Sources	$\frac{\sqrt{(\Delta\mu)^2-(\Delta\mu')^2}}{\mu}$ [%]
MC statistical uncertainty	7.7
Top quark theoretical uncertainties	6.3
Signal theoretical uncertainties	5.8
Jet experimental uncertainties	4.9
Strong W^+W^-jj theoretical uncertainties	1.3
Luminosity	0.8
Misidentified lepton uncertainty	0.5
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

arXiv:2312.00420, JHEP 04 (2024) 026

ATLAS (SS) W±W±jj VBS @ 13 TeV [139 fb-1]

- Integrated EW and total W±W±jj fiducial cross-sections (most precise to date)



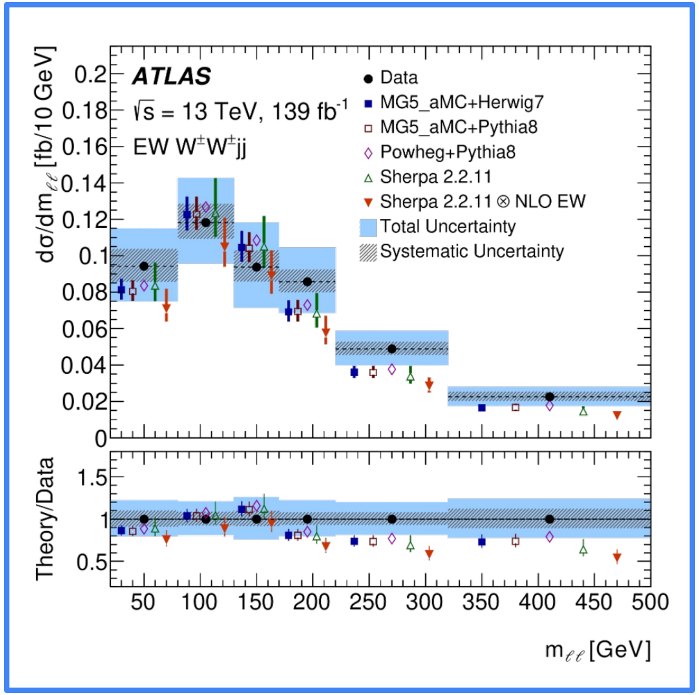


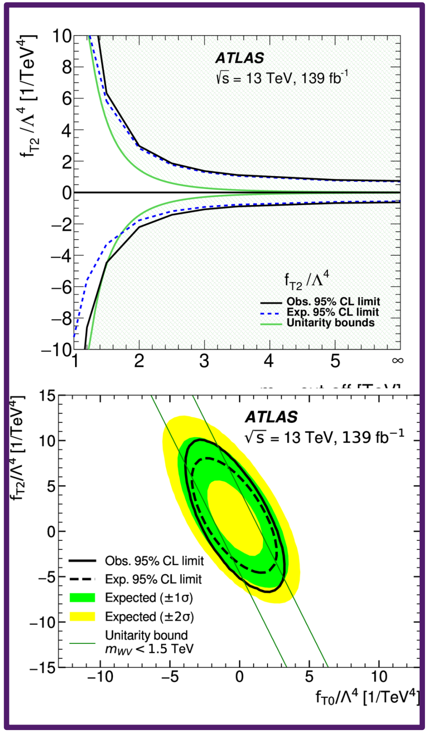
Source	Impact [%]
Experimental	4.5
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.7
E_T^{miss} scale and resolution	0.1
b-tagging inefficiency	0.7
Background, misid. leptons	3.5
Background, charge misrec.	0.8
Pileup modelling	0.1
Luminosity	1.8
Modelling	3.2
$W^\pm W^\pm jj$ shower, scale, PDF & α_s	0.4
EW $W^\pm W^\pm jj$, QCD corrections	2.1
EW $W^\pm W^\pm jj$, EW corrections	0.4
QCD $W^\pm W^\pm jj$, QCD corrections	0.0
Background, WZ scale, PDF & α_s	0.3
Background, WZ reweighting	1.2
Background, other	1.3
Model statistical	1.6
Experimental and modelling	5.5
Data statistical	6.6
Total	8.5

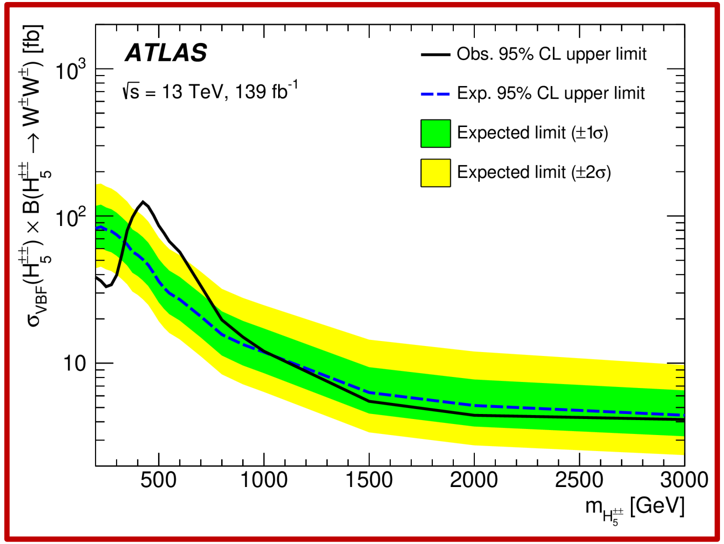
arXiv:2312.00420, *JHEP 04 (2024) 026*

ATLAS (SS) W±W±jj VBS @ 13 TeV [139 fb^{-1}]

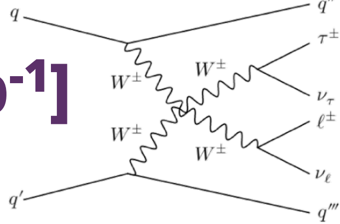
- Differential measurement with binned signal strength
- EFT dim-8 & GM $H^{\pm\pm}$ interpretations



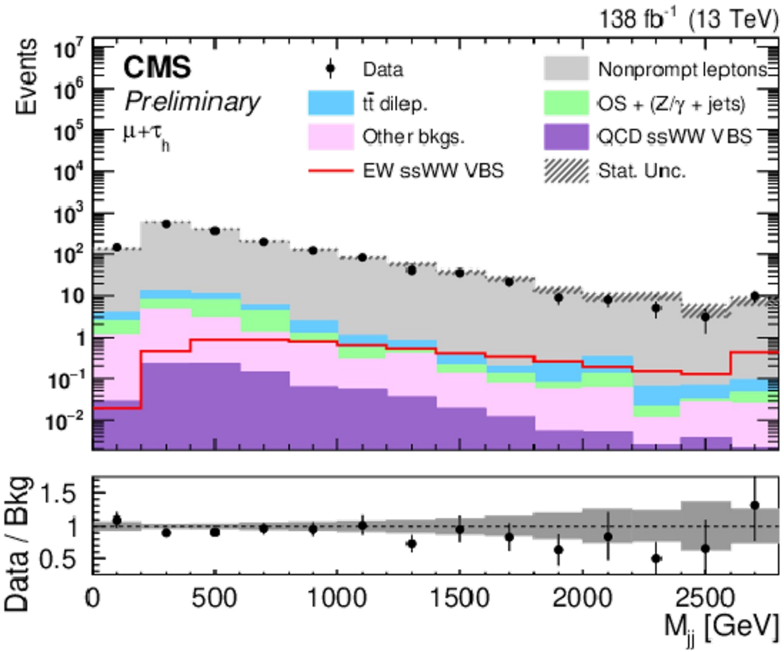


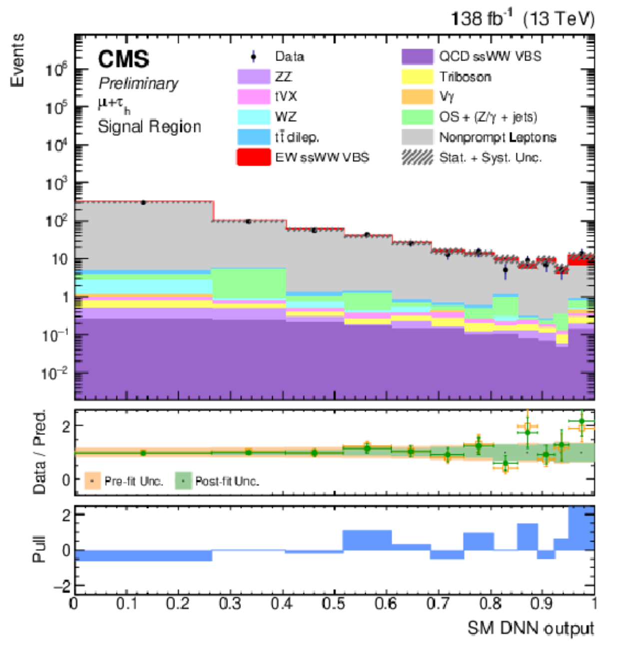


CMS (SS) $W^{\pm}W^{\pm}jj$ VBS with τ_h @ 13 TeV [138 fb^{-1}]



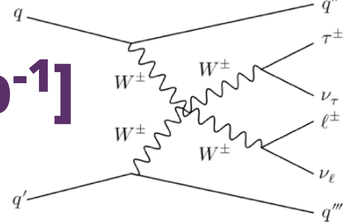
- **First study of VBS with a τ lepton decaying hadronically**
  - μ_{EW} = 1.44 +0.63 - 0.56, i.e. 2.7σ (1.9σ) obs. (exp.)
- **DNN (9 variables)** trained to separate signal from background





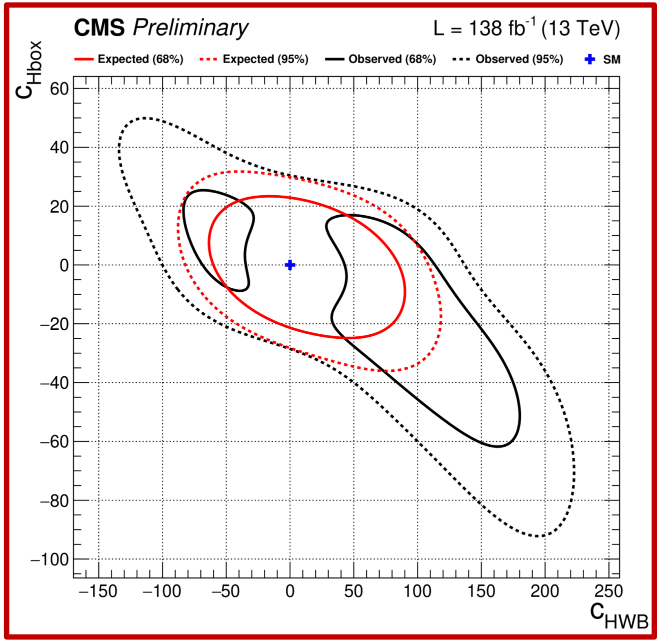
CMS-PAS-SMP-22-008

CMS (SS) $W^{\pm}W^{\pm}jj$ VBS with τ_h @ 13 TeV [138 fb^{-1}]



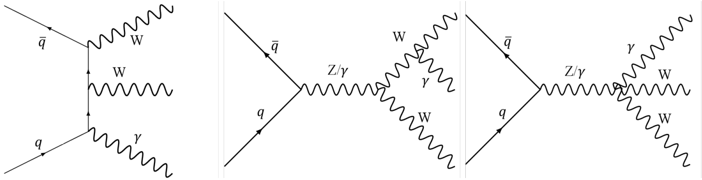
- Simultaneous extraction of dim-6 and dim-8 EFT operators
  - Dim-6: linear, BSM and mixed contributions
  - Dim-8: linear and BSM contributions

	Wilson coefficient	68% CL interval(s) Expected	68% CL interval(s) Observed	95% CL interval Expected	95% CL interval Observed
dim-6	$c_{ll}^{(1)}$	$[-12.9, -8.03] \cup [-2.95, 1.91]$	$[-11.6, 0.045]$	$[-14.6, 3.53]$	$[-13.5, 2.11]$
	$c_{qq}^{(1)}$	$[-0.501, 0.576]$	$[-0.341, 0.416]$	$[-0.742, 0.818]$	$[-0.605, 0.681]$
	c_W	$[-0.681, 0.669]$	$[-0.513, 0.481]$	$[-0.987, 0.974]$	$[-0.842, 0.818]$
	c_{HW}	$[-7.00, 6.09]$	$[-5.48, 4.31]$	$[-9.99, 9.05]$	$[-8.68, 7.60]$
	c_{HWB}	$[-41.7, 69.6]$	$[30.7, 89.2]$	$[-66.6, 96.4]$	$[-49.7, 110]$
	$c_{H\Box}$	$[-16.6, 18.1]$	$[-12.0, 14.0]$	$[-24.7, 26.3]$	$[-20.9, 22.7]$
	c_{HD}	$[-24.6, 34.7]$	$[-15.3, 31.5]$	$[-38.2, 48.8]$	$[-31.4, 45.5]$
	$c_{Hl}^{(1)}$	$[-28.8, 29.9]$	$[-38.2, 39.5]$	$[-49.4, 49.7]$	$[-69.3, 68.3]$
	$c_{Hl}^{(3)}$	$[-1.43, 2.23] \cup [5.88, 9.54]$	$[-0.045, 8.58]$	$[-2.64, 10.8]$	$[-1.59, 9.94]$
	$c_{Hq}^{(1)}$	$[-4.53, 4.42]$	$[-3.27, 3.44]$	$[-6.56, 6.44]$	$[-5.55, 5.60]$
	$c_{Hq}^{(3)}$	$[-2.39, 1.37]$	$[-1.88, 0.705]$	$[-3.24, 2.16]$	$[-2.82, 1.61]$
dim-8	f_{T0}	$[-1.02, 1.08]$	$[-0.774, 0.842]$	$[-1.52, 1.58]$	$[-1.32, 1.38]$
	f_{T1}	$[-0.426, 0.480]$	$[-0.319, 0.381]$	$[-0.640, 0.695]$	$[-0.552, 0.613]$
	f_{T2}	$[-1.15, 1.37]$	$[-0.851, 1.12]$	$[-1.75, 1.98]$	$[-1.51, 1.76]$
	f_{M0}	$[-9.89, 9.74]$	$[-8.07, 7.70]$	$[-14.6, 14.5]$	$[-13.1, 12.8]$
	f_{M1}	$[-12.5, 13.3]$	$[-9.54, 11.15]$	$[-18.7, 19.6]$	$[-16.4, 17.7]$
	f_{M7}	$[-20.3, 19.2]$	$[-17.6, 15.3]$	$[-29.9, 28.8]$	$[-27.6, 25.8]$
	f_{S0}	$[-11.6, 12.0]$	$[-9.60, 9.82]$	$[-17.4, 17.9]$	$[-15.9, 16.1]$
	f_{S1}	$[-37.4, 38.8]$	$[-40.9, 41.3]$	$[-57.2, 58.6]$	$[-60.9, 61.8]$
	f_{S2}	$[-37.4, 38.8]$	$[-40.9, 41.3]$	$[-57.2, 58.6]$	$[-60.9, 61.8]$



arXiv:2310.05164, Phys. Rev. Lett. 132 (2024) 121901

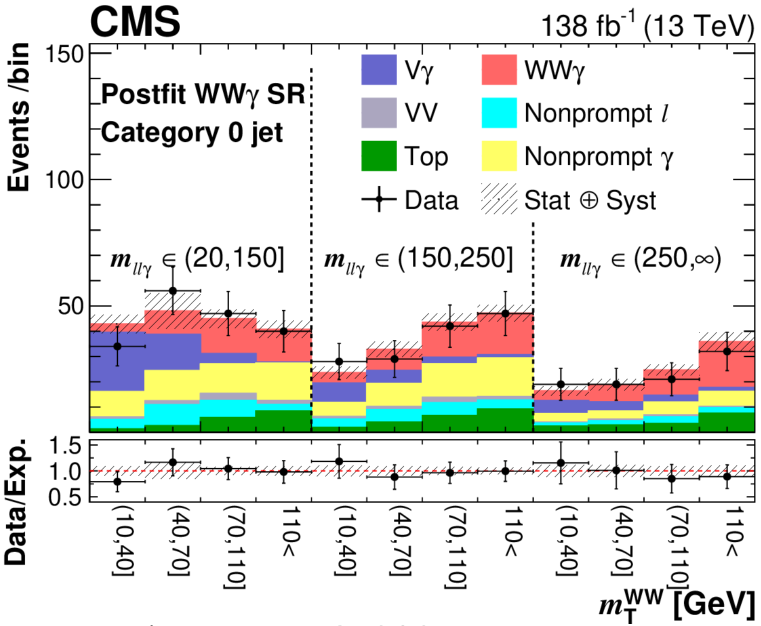
CMS WWγ @ 13 TeV [138 fb^{-1}]

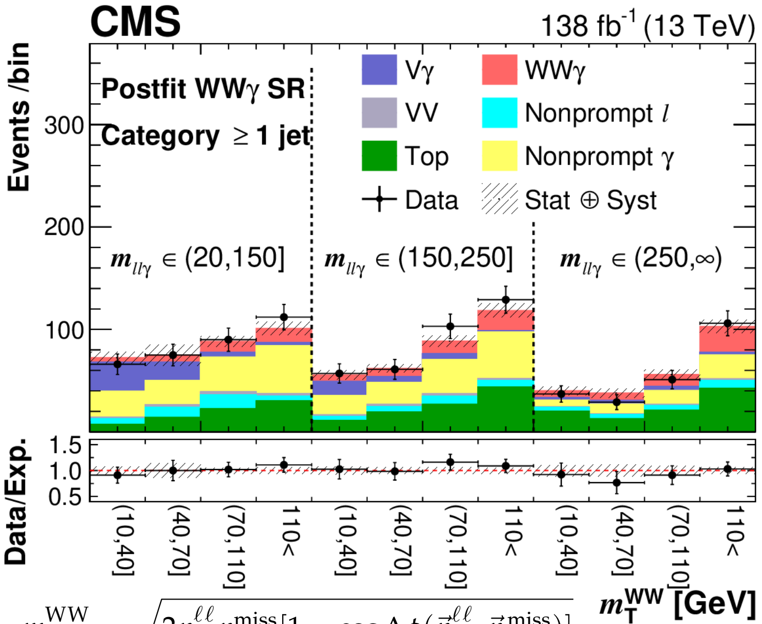


- Observation of WWγ: 5.6σ (4.7σ) obs. (exp.) & search for Hγ
  - Hγ fit on ΔR_{ll} [0.5, 1.8, 2.0, 2.3) and m_T^{WW} [0, 10, 40, 70, 110, ∞) [initiated by light quarks]

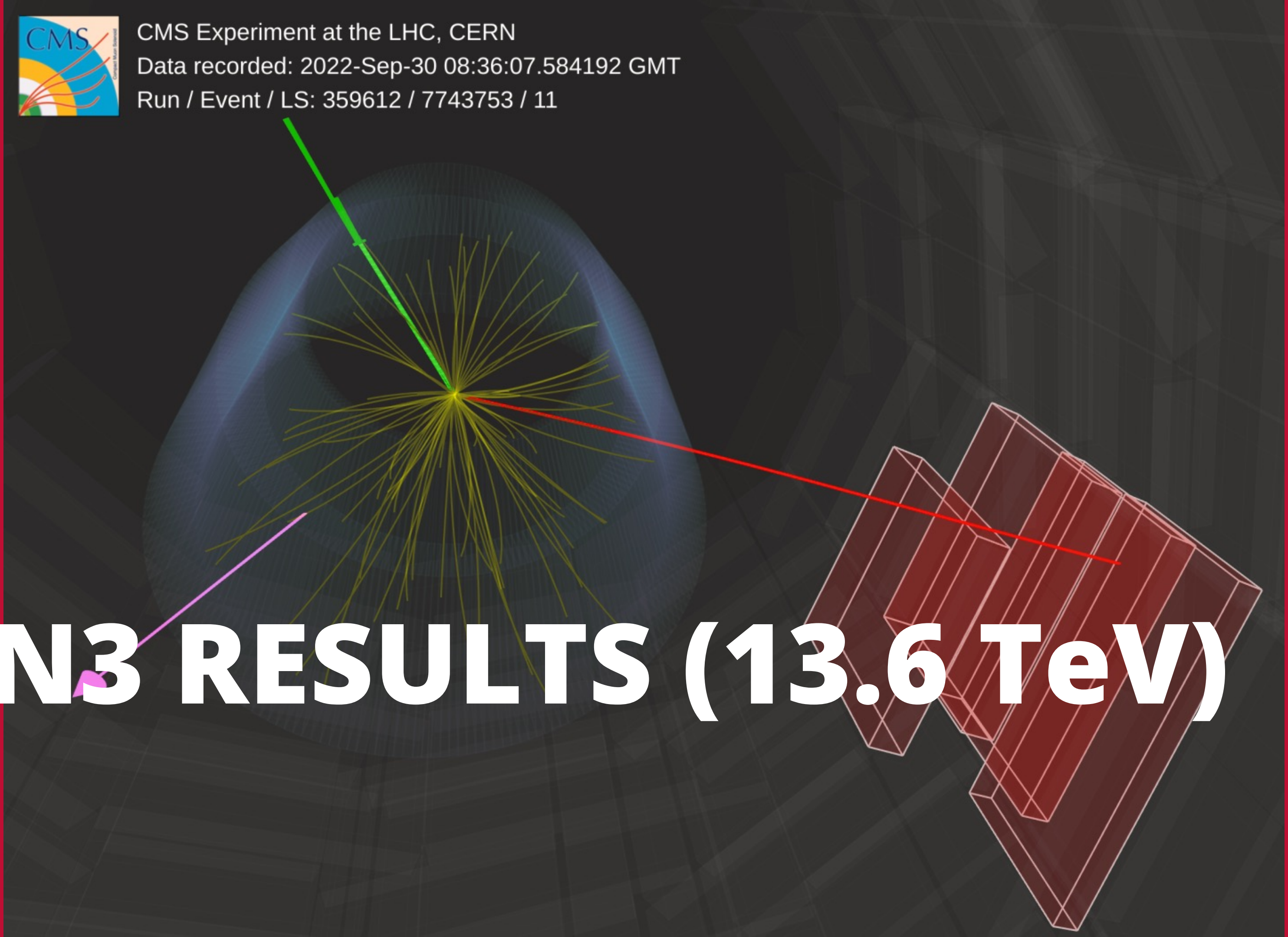
$$\sigma = 5.9 \pm 0.8\,(\text{stat}) \pm 0.8\,(\text{syst}) \pm 0.7\,(\text{modeling})\ \text{fb} = 5.9 \pm 1.3\,\text{fb}$$

MadGraph5_aMC@NLO $\sigma = 5.33 \pm 0.34\,(\text{scale}) \pm 0.05\,(\text{PDF})\ \text{fb}$





$$m_T^{WW} = \sqrt{2 p_T^{\ell\ell} p_T^{\text{miss}} [1 - \cos\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,\text{miss}})]}$$



RUN3 RESULTS (13.6 TeV)

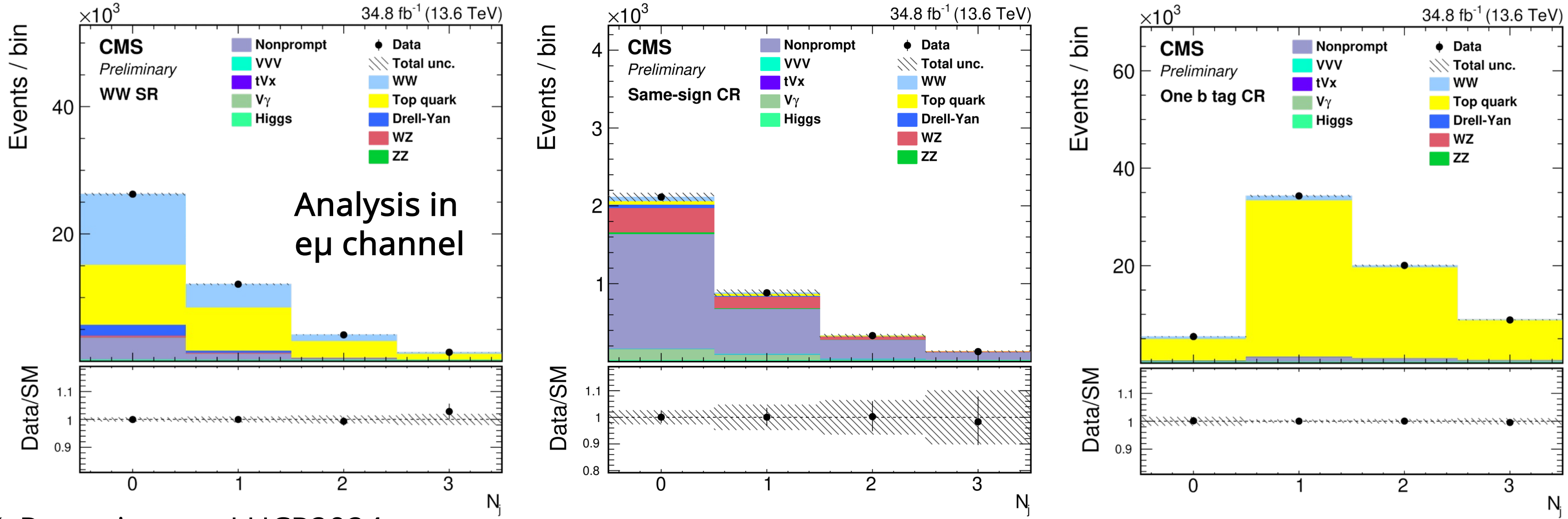
CMS W⁺W⁻ @ 13.6 TeV [34.8 fb⁻¹]

- **First measurement of W⁺W⁻ at 13.6 TeV w/2022 data**

$$125.7 \pm 2.3\,(\text{stat}) \pm 4.8\,(\text{syst}) \pm 1.8\,(\text{lumi})\,\text{pb} = 125.7 \pm 5.6\,\text{pb}$$

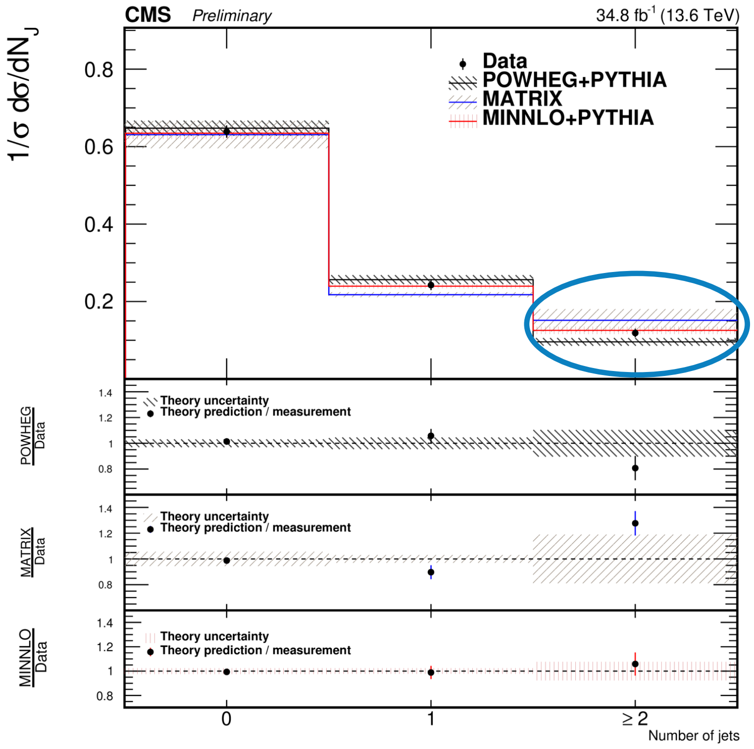
- In good agreement w/ SM: 125.8 ± 3.7 pb (MATRIX v2.1.0)

Uncertainty source	$\Delta\mu$
Integrated luminosity	0.014
Lepton experimental	0.019
Jet experimental	0.008
b tagging	0.012
Nonprompt background	0.010
Limited sample size	0.017
Background normalization	0.018
Theory	0.011
Statistical	0.018
Total	0.044



CMS W^+W^- @ 13.6 TeV [34.8 fb^{-1}]

- Comparison of normalised fiducial cross-sections using MiNNLO

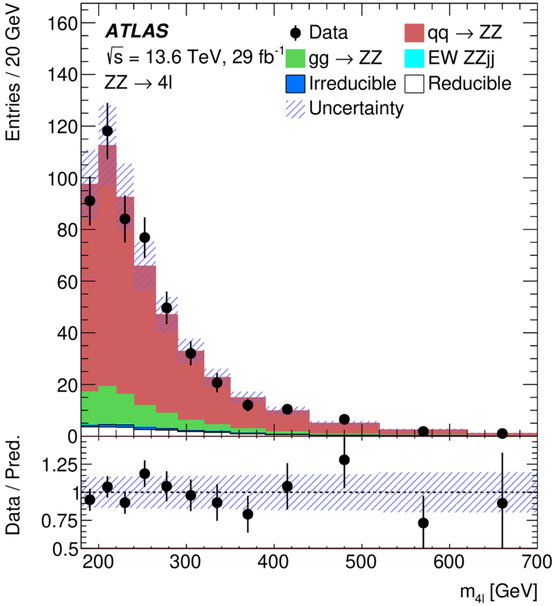


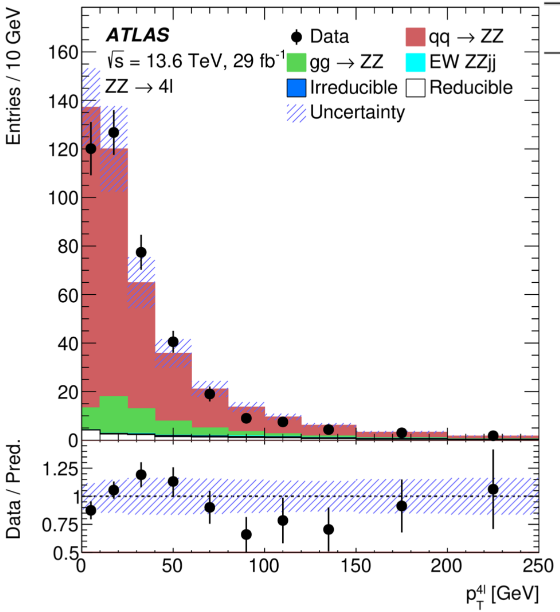
arXiv:2311.09715, submitted to Phys. Lett. B

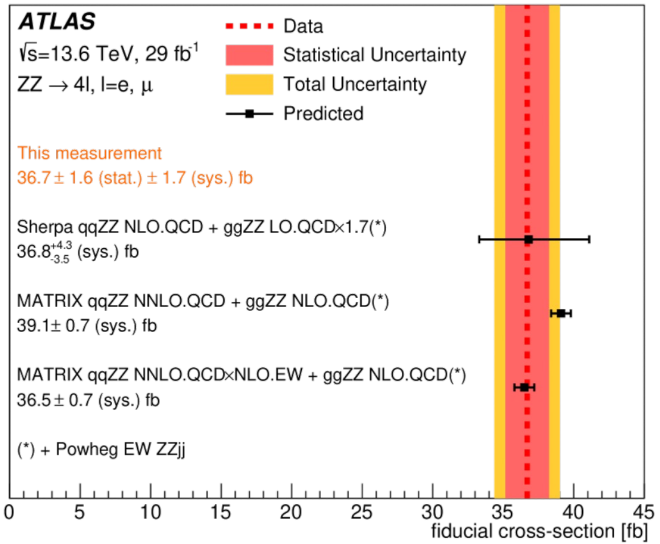
ATLAS ZZ @ 13.6 TeV [29 fb^{-1}]

- **Fiducial and total ZZ cross-sections**
  - First measurement of ZZ at 13.6 TeV w/2022 data

Source	Relative uncertainty (%)
Data statistical uncertainty	4.2
MC statistical uncertainty	0.3
Luminosity	2.2
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3





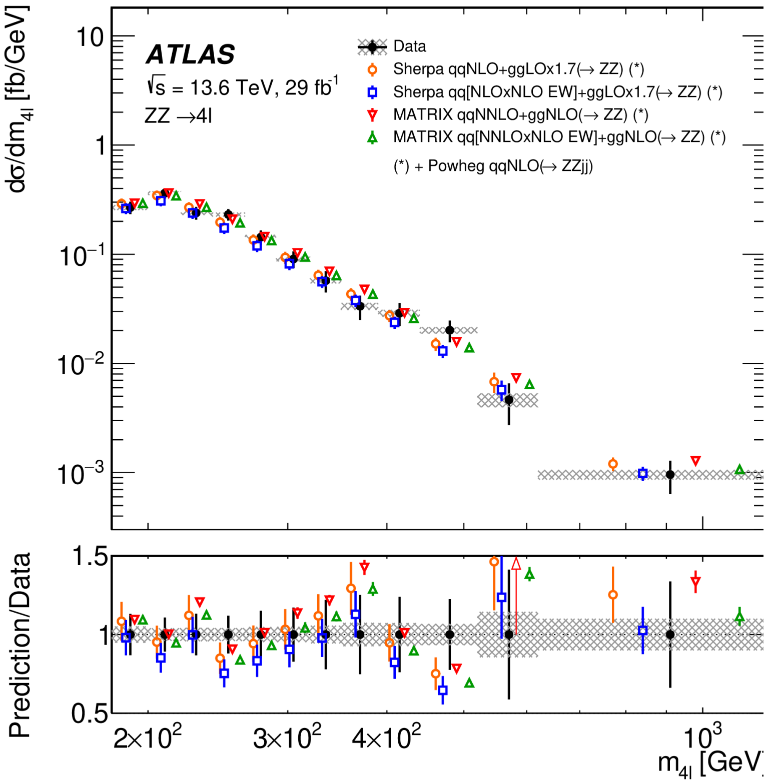


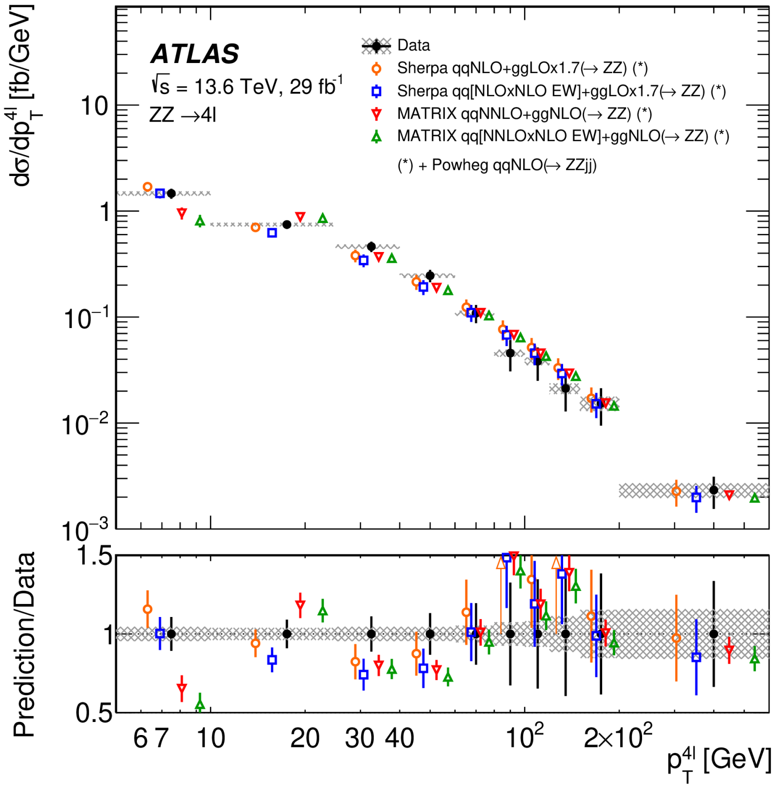
Process	$q\bar{q}\to ZZ$	$gg\to ZZ$	EW $qq\to ZZ+2j$	$t\bar{t}Z$	VVV	Reducible	Total	Data
Yield	515 ± 50	74 ± 44	4.7 ± 1.0	5.5 ± 0.8	2.1 ± 0.2	25.4 ± 8.1	626 ± 88	625

k

ATLAS ZZ @ 13.6 TeV [29 fb^{-1}]

- Differential cross-sections





Additional (Recent) Results Not Covered Here

- ATLAS Wγγ @ 13 TeV [140 fb^{-1}], arXiv:2308.03041, *Phys. Lett. B 848 (2024) 138400*
- ATLAS WZγ @ 13 TeV [140 fb^{-1}], arXiv:2305.16994, *Phys. Rev. Lett. 132 (2024) 021802*
- CMS Wγ @ 13 TeV [138 fb^{-1}], arXiv:2212.12592, Phys. Rev. D 108 (2023) 032017
- CMS osWWjj @ 13 TeV [138 fb-1], arXiv:2205.05711, *PLB 841 (2023) 137495*
- ATLAS $Z_L Z_L$ & CP prop. @ 13 TeV [140 fb^{-1}], arXiv:2310.04350, *JHEP 12 (2023) 107*
- ATLAS 4ljj @ 13 TeV [140 fb^{-1}], arXiv:2308.12324, *JHEP 01 (2024) 004*

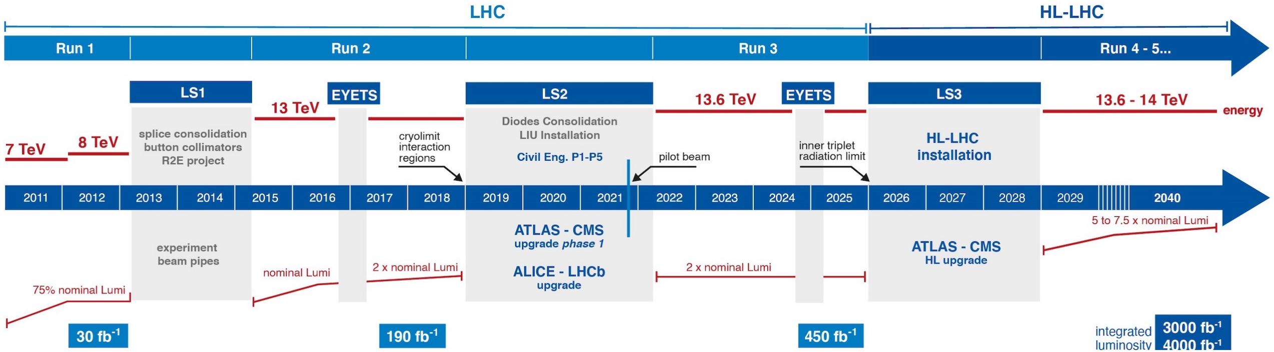
List of ATLAS results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

List of CMS results:
https://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/VV.html

Summary and Outlook

- **Rich potential from Multiboson Measurements & Searches/Probes**
  - Precision multiboson (diboson, VBS) measurements
  - Observation of triboson processes
  - Anomalous couplings, EFT, Higgs properties & extensions
- **Lots of opportunities with the Run-3 data coming in!**

Stay tuned !!!

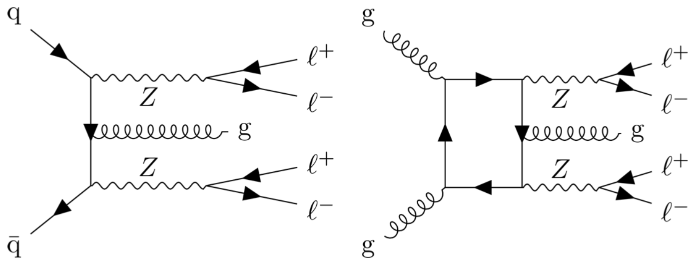


COMETA

Comprehensive Multiboson
Experiment-Theory Action
EU COST Action CA22130

ADDITIONAL MATERIAL

CMS ZZ+jets @ 13 TeV [138 fb^{-1}]



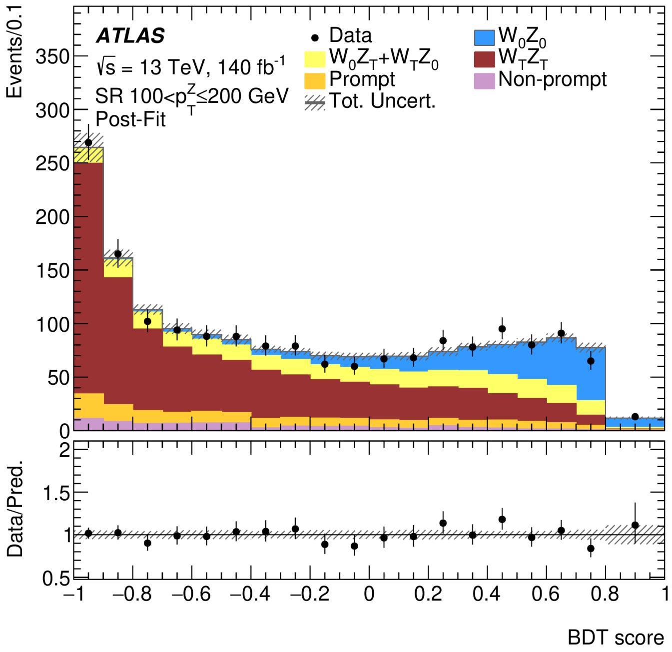
Particle type	Selection
	ZZ base selection
Leptons	$p_T(\ell_1) > 20$ GeV $p_T(\ell_2) > 10$ GeV $p_T(\ell) > 5$ GeV $\lvert\eta(\ell)\rvert < 2.5$
Z and ZZ	$40 < m_{Z_1} < 120$ GeV, $4 < m_{Z_2} < 120$ GeV $m_{\ell\ell} > 4$ GeV (any oppositely charged same-flavor pair)
Jets	$p_T(j) > 30$ GeV $\lvert\eta(j)\rvert < 4.7$ $\Delta R(\ell, j) > 0.4$ for each ℓ, j
	On-shell ZZ region
Z and ZZ	ZZ base selection + $60 < m_{Z_1,Z_2} < 120$ GeV
	Full $m_{4\ell}$ range
Z and ZZ	ZZ base selection + $m_{4\ell} > 80$ GeV

Process	eeee	$ee\mu\mu$	$\mu\mu\mu\mu$	$2\ell 2\ell'$
		$80 < m_{4\ell} < 100$ GeV		
Background	$4.6 \pm 0.5 \pm 1.8$	$15.5 \pm 1.6 \pm 6.2$	$22.8 \pm 2.1 \pm 9.1$	$43 \pm 3 \pm 17$
Signal	$216 \pm 1^{+40}_{-36}$	$731 \pm 2^{+66}_{-64}$	$841 \pm 2^{+59}_{-57}$	$1790 \pm 3^{+140}_{-140}$
Total expected	$220 \pm 1^{+40}_{-36}$	$747 \pm 3^{+66}_{-64}$	$864 \pm 3^{+59}_{-58}$	$1830 \pm 4^{+140}_{-140}$
Data	194	698	838	1730
		$60 < m_{Z_1,Z_2} < 120$ GeV		
Background	$22.9 \pm 0.9 \pm 5.7$	$46 \pm 2 \pm 10$	$28.9 \pm 1.3 \pm 6.5$	$98 \pm 2 \pm 23$
Signal	$716 \pm 2^{+63}_{-60}$	$1830 \pm 3^{+140}_{-140}$	$1138 \pm 3^{+85}_{-82}$	$3680 \pm 5^{+280}_{-270}$
Total expected	$739 \pm 2^{+63}_{-60}$	$1870 \pm 4^{+140}_{-140}$	$1167 \pm 3^{+85}_{-82}$	$3780 \pm 5^{+280}_{-270}$
Data	671	1805	1106	3582

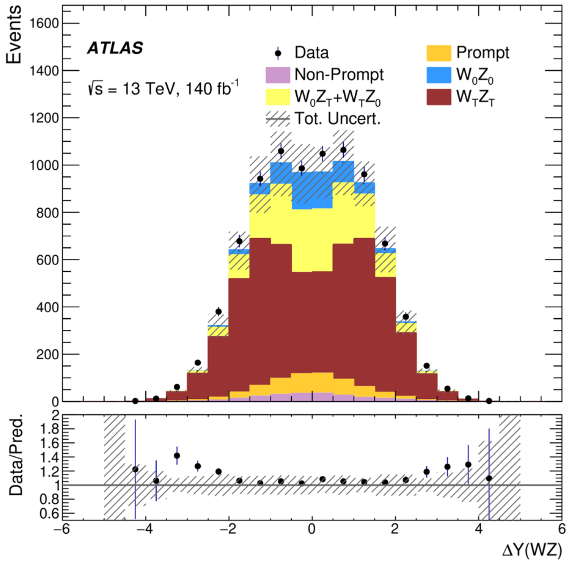
Systematic source	$m_{4\ell}$ with all jets	0 jet	1 jet	2 jets	3 and more jets
Electron efficiency	0.42%	0.38%	0.66%	0.36%	0.26%
Muon efficiency	0.05%	0.06%	0.07%	0.09%	0.08%
Jet energy resolution	—	0.07%	1.72%	1.65%	0.80%
JES correction	—	0.17%	1.77%	1.95%	0.97%
Reducible background	0.18%	0.18%	0.32%	0.33%	0.96%
Pileup	0.02%	0.05%	0.11%	0.13%	0.35%
Luminosity	0.01%	0.01%	0.02%	0.02%	0.05%
$q\bar{q} \to$ ZZ MC choice	0.35%	0.65%	0.94%	0.48%	0.35%
gg $\to$ ZZ cross section	0.02%	0.03%	0.09%	0.06%	0.09%
QCD scales	0.15%	0.16%	0.58%	0.54%	0.62%
PDF	0.05%	0.05%	0.15%	0.15%	0.21%
PDF α_S	0.02%	0.01%	0.05%	0.03%	0.02%

Systematic source	$m_{4\ell}$ with all jets	0 jet	1 jet	2 jets	3 and more jets
Electron efficiency	2.12%	2.55%	2.28%	1.77%	1.46%
Muon efficiency	0.71%	0.78%	0.92%	0.79%	0.42%
Jet energy resolution	—	0.11%	1.73%	2.63%	2.32%
JES correction	—	0.33%	1.64%	3.01%	2.02%
Reducible background	2.22%	2.19%	2.88%	3.40%	5.09%
Pileup	0.21%	0.28%	0.19%	0.32%	0.52%
Luminosity	0.12%	0.12%	0.16%	0.17%	0.25%
$q\bar{q} \to$ ZZ MC choice	0.57%	0.48%	1.22%	3.07%	4.21%
gg $\to$ ZZ cross section	0.10%	0.18%	0.61%	0.80%	0.46%
QCD scales	0.27%	0.25%	0.67%	1.25%	1.86%
PDF	0.07%	0.09%	0.20%	0.23%	0.28%
PDF α_S	0.08%	0.08%	0.15%	0.20%	0.28%

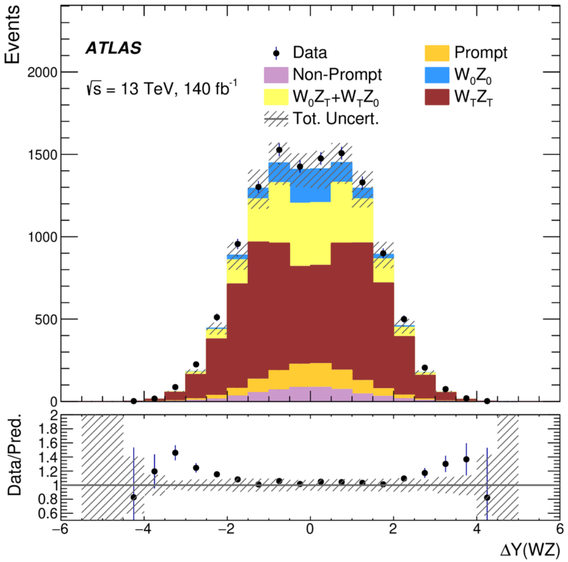
ATLAS high-p_T^Z WZ @ 13 TeV [140 fb^{-1}]



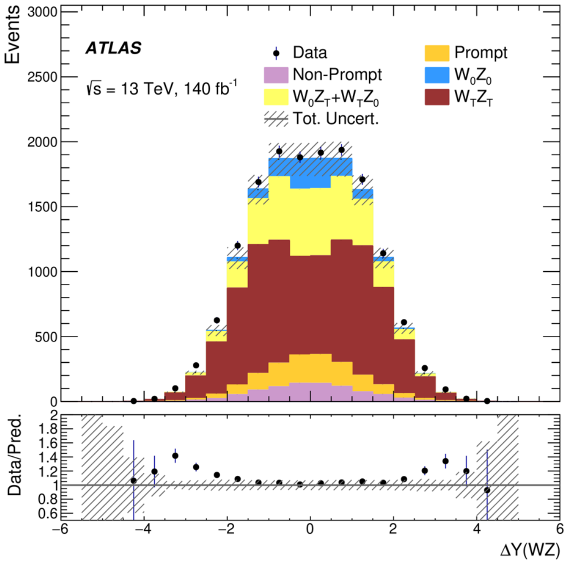
ATLAS high-p_T^Z WZ @ 13 TeV [140 fb^{-1}]



p_T^{WZ}<20 GeV



p_T^{WZ}<40 GeV

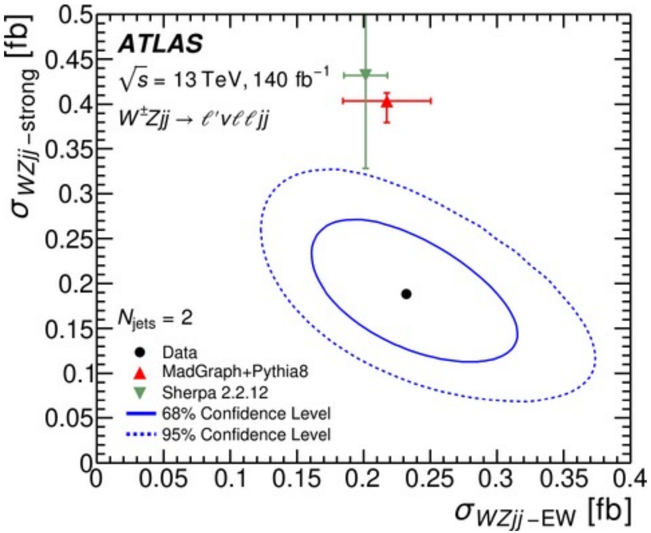


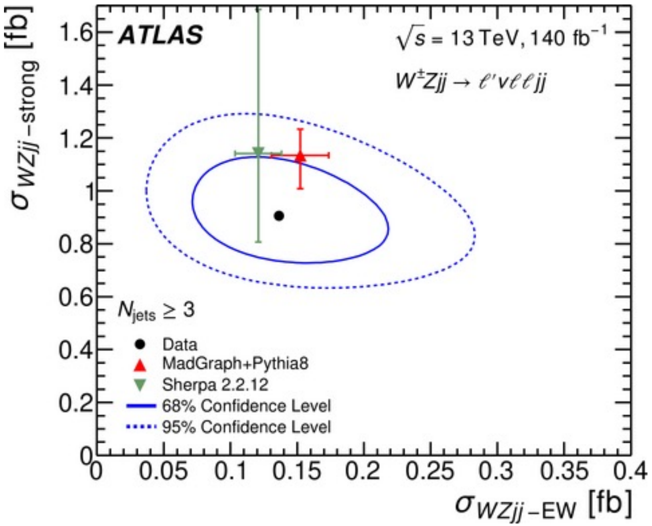
p_T^{WZ}<70 GeV

ATLAS Wγjj VBS @ 13 TeV [140 fb-1]

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 $\xi_{W\gamma} < 0.35$)

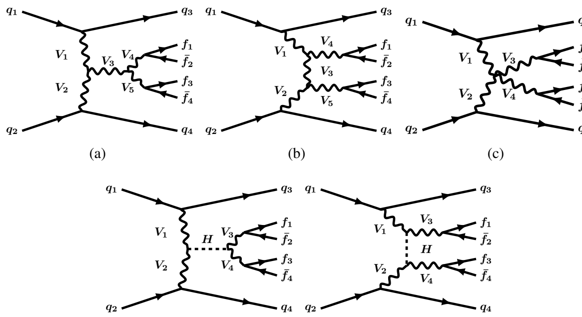
ATLAS WZjj VBS @ 13 TeV [140 fb^{-1}]





arXiv:2312.00420, *JHEP 04 (2024) 026*

ATLAS W±W±jj VBS @ 13 TeV [139 fb^{-1}]

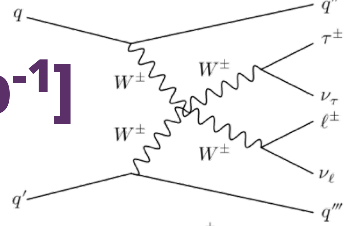


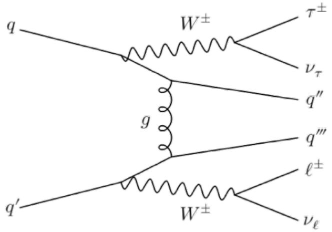
- Most precise fiducial and differential cross-section measurements
- Limits on dim-8 EFT operators to probe aQGC
- Limits on H±± decaying to pair of W± (GM model)

Process	ee	$e\mu$	μe	$\mu\mu$	Combined
$W^\pm W^\pm jj$ EW	32.9 ± 3.4	81 ± 8	73 ± 7	90 ± 9	277 ± 26
$W^\pm W^\pm jj$ QCD	1.7 ± 0.5	8.0 ± 2.4	7.1 ± 2.1	9.7 ± 2.9	27 ± 8
$W^\pm W^\pm jj$ Int	1.00 ± 0.22	2.4 ± 0.5	2.1 ± 0.4	2.7 ± 0.6	8.2 ± 1.7
$W^\pm Zjj$ QCD	5.5 ± 0.7	18.2 ± 2.1	18.2 ± 2.2	14.0 ± 1.7	56 ± 6
$W^\pm Zjj$ EW	1.69 ± 0.14	4.9 ± 0.4	4.1 ± 0.4	4.2 ± 0.4	14.9 ± 1.2
Non-prompt	8.4 ± 1.6	14.9 ± 2.4	10.2 ± 1.6	21 ± 5	55 ± 9
$V\gamma$	1.5 ± 0.7	6.1 ± 2.4	5.5 ± 2.8	—	13 ± 5
Charge misid.	4.3 ± 2.0	5.4 ± 1.2	1.4 ± 0.4	—	11 ± 4
Other prompt	0.99 ± 0.25	2.5 ± 0.5	1.9 ± 0.5	1.4 ± 1.4	6.8 ± 2.1
Total	58 ± 4	143 ± 7	123 ± 6	143 ± 8	468 ± 21
Data	52	149	127	147	475

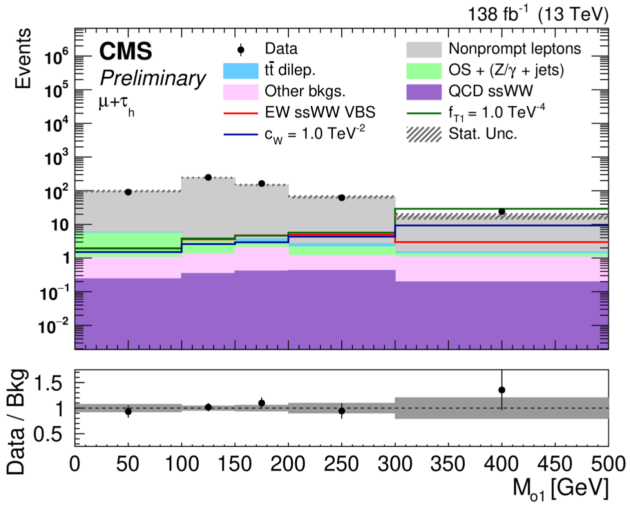
Source	Impact [%]
Experimental	4.6
Electron calibration	0.4
Muon calibration	0.5
Jet energy scale and resolution	1.9
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	0.2
b-tagging inefficiency	0.7
Background, misid. leptons	3.4
Background, charge misrec.	1.0
Pile-up modelling	0.1
Luminosity	1.9
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

CMS (SS) W±W±jj VBS with τ_h @ 13 TeV [138 fb^{-1}]



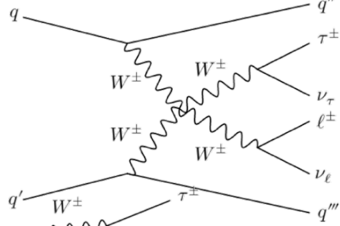


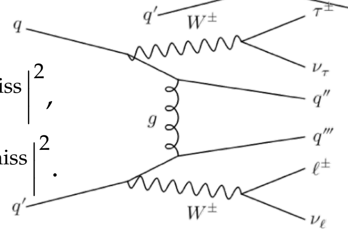
- First study of VBS with a τ lepton decaying hadronically
  - μ_{EW} = 1.44 +0.63 - 0.56, i.e. 2.7σ (1.9σ) obs. (exp.)
- **DNN (9 variables)** trained to separate signal from background



$$M_{\circ 1}^2 = \left(p_T^\tau + p_T^l + p_T^{\text{miss}}\right)^2 - \left|\vec{p_T}^\tau + \vec{p_T}^l + \vec{p}_T^{\text{miss}}\right|^2$$

CMS VBS $W^{\pm}W^{\pm}jj$ with τ_h @ 13 TeV [138 fb^{-1}]





Input variable	SM DNN	dim-6 DNN	dim-8 DNN
τ_h p_T	✓	✓	✓
ℓ p_T	✓	✓	✓
τ_h η		✓	
ℓ η		✓	
leading VBS jet p_T	✓	✓	✓
subleading VBS jet p_T	✓	✓	✓
leading VBS jet mass		✓	✓
subleading VBS jet mass		✓	✓
VBS jet pair $\Delta\phi$		✓	
M_{jj}	✓	✓	
M_{1T}	✓	✓	✓
M_{o1}	✓	✓	✓
$M_T(\tau_h, \vec{p}_T^{miss})$			✓
$M_T(\ell, \vec{p}_T^{miss})$	✓	✓	✓
$M_T(\ell, \tau_h, \vec{p}_T^{miss})$			✓
$p_T^{rel}(\ell, j_1)$		✓	
$p_T^{rel}(\ell, j_2)$		✓	
$p_T^{rel}(\tau_h, j_1)$		✓	
$p_T^{rel}(\tau_h, j_2)$		✓	
$\Delta\phi(\ell, j_1)$		✓	
$\Delta\phi(\ell, j_2)$		✓	
$\Delta\phi(\tau_h, j_1)$		✓	
$\Delta\phi(\tau_h, j_2)$		✓	
$p_{T,\text{leading } \tau_h \text{ track}} / p_{T,\tau_h}$	✓	✓	
Zeppenfeld variable		✓	

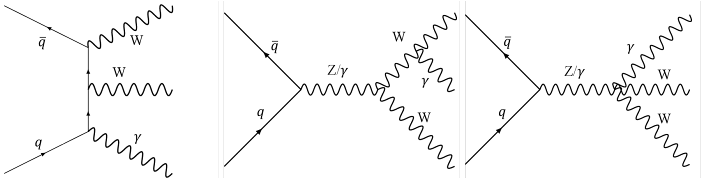
$$M_{1T}^2 = \left(\sqrt{M_{\tau l}^2 + p_T^{\tau l\,2}} + p_T^{miss}\right)^2 - \left|\vec{p_T}^{\tau l} + \vec{p}_T^{miss}\right|^2,$$
$$M_{\circ 1}^2 = \left(p_T^{\tau} + p_T^{l} + p_T^{miss}\right)^2 - \left|\vec{p_T}^{\tau} + \vec{p_T}^{l} + \vec{p}_T^{miss}\right|^2.$$

$$M_T(\ell, p_T^{miss}) \simeq \sqrt{2 p_T^{\ell} p_T^{miss} [1 - \cos\Delta\phi]},$$

The DNN implemented is optimized to discriminate signals from the main sources of background. It consists of one hidden layer with 200 neurons. The training is implemented with Adam Optimizer [32], and early stopping, dropout, and L2 regularization [33] techniques are used to avoid overfitting.

arXiv:2310.05164, Phys. Rev. Lett. 132 (2024) 121901

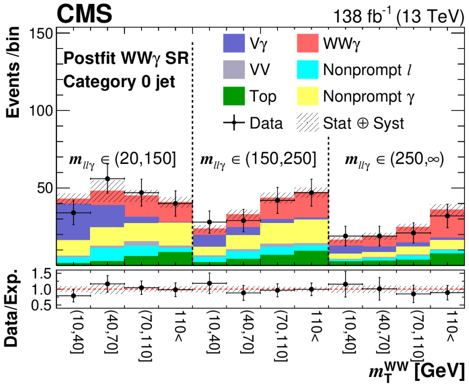
CMS WWγ @ 13 TeV [138 fb^{-1}]

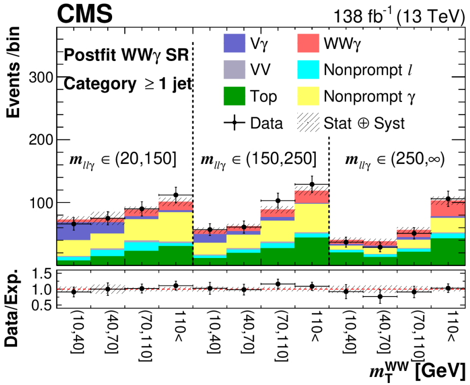


- Observation of WWγ: 5.6σ (4.7σ) obs. (exp.) & search for Hγ

$$\sigma = 5.9 \pm 0.8\,(\text{stat}) \pm 0.8\,(\text{syst}) \pm 0.7\,(\text{modeling})\ \text{fb} = 5.9 \pm 1.3\,\text{fb}$$

MadGraph5_aMC@NLO $\sigma = 5.33 \pm 0.34\,(\text{scale}) \pm 0.05\ (\text{PDF})\,\text{fb}$

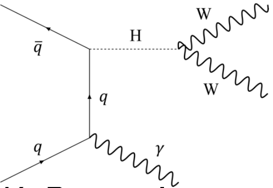




Process	SR (0 jet)	SR (≥1 jet)	SR (total)	SSWWγ CR	Topγ CR
WWγ	122 ± 23	132 ± 27	254 ± 47	1.0 ± 0.2	12.8 ± 2.7
QCD Vγ	72.0 ± 6.4	94.7 ± 9.3	167 ± 14	12.2 ± 2.2	12.6 ± 1.2
VV	15.1 ± 1.4	21.6 ± 2.4	36.7 ± 3.5	24.9 ± 1.7	2.0 ± 0.3
Top	56.6 ± 6.5	271 ± 26	328 ± 32	2.4 ± 0.6	2434 ± 85
Nonprompt ℓ	45.7 ± 4.0	77.2 ± 6.5	122.9 ± 9.7	197 ± 14	40 ± 11
Nonprompt γ	109.1 ± 9.0	301 ± 24	410 ± 32	19.9 ± 1.6	793 ± 62
Total	420 ± 20	898 ± 29	1318 ± 43	257 ± 14	3294 ± 57
Data	414	916	1330	259	3287

$$m_T^{WW} = \sqrt{2 p_T^{\ell\ell} p_T^{\text{miss}} [1 - \cos\Delta\phi(\vec{p}_T^{\,\ell\ell}, \vec{p}_T^{\,\text{miss}})]}$$

Hγ fit on ΔR_{ll} [0.5, 1.8, 2.0, 2.3) and m_T^{WW} [0, 10, 40, 70, 110, ∞)



Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\bar{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)	$\lvert\bar{\kappa}_u\rvert \leq 7.5$ (6.1)
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\lvert\kappa_d\rvert \leq 17000$ (14000)	$\lvert\bar{\kappa}_d\rvert \leq 16.6$ (14.7)
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	68 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)	$\lvert\bar{\kappa}_s\rvert \leq 32.8$ (25.2)
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	87 (67)	$\lvert\kappa_c\rvert \leq 200$ (110)	$\lvert\bar{\kappa}_c\rvert \leq 45.4$ (25.0)