Multiboson measurements at ATLAS and CMS

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On Behalf of ATLAS and CMS Collaborations

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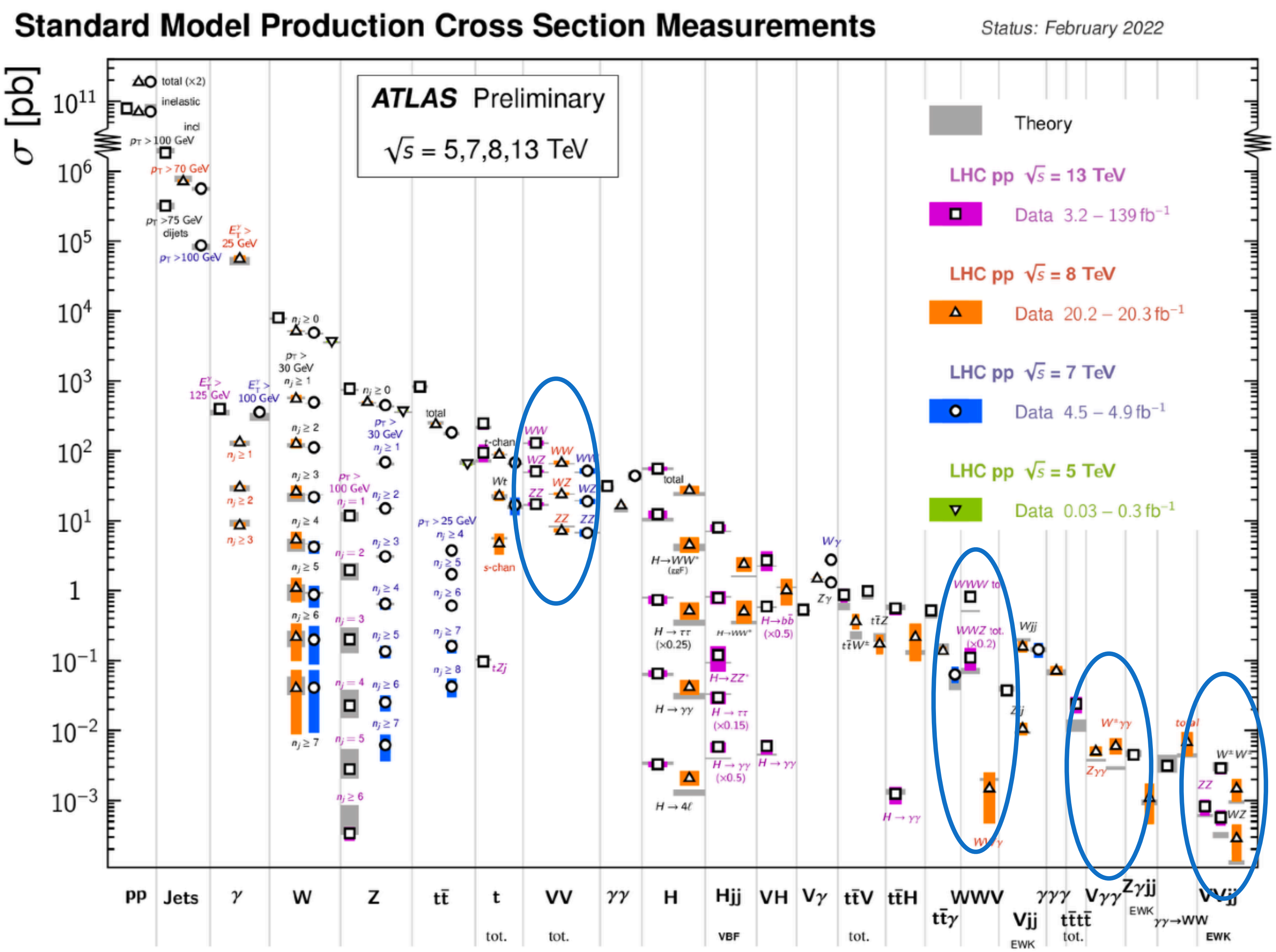
Motivation

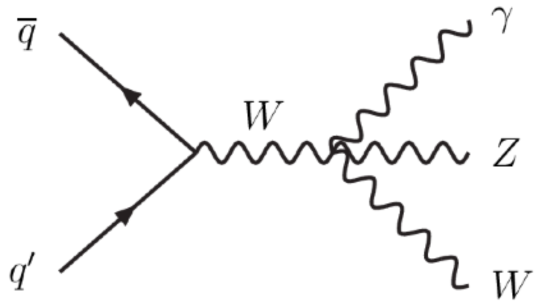
- Electroweak-boson self-interactions are rare processes that serve as:
  - an excellent probe to the Standard Model predictions
  - a portal to Physics Beyond the Standard Model, through the Effective Field Theories
- Going to focus to the newest results on **triboson, diboson** and processes that include **aQGCs**



Triboson processes and quartic couplings

- **Triboson**: probe of non-Abelian self couplings of the electroweak gauge bosons in the Standard Model (SM)
- Backgrounds to SM processes like ZH(γγ) and WH(γγ) that will become accessible at Run 3
- Sensitive to anomalous **Quartic Gauge Coupling** (aQGC) operators
- Serve as a probe for New Physics
- Vector boson scattering and triboson production processes-> aQGCs

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{\tilde{c}_i}{\Lambda^{d-4}} \mathcal{O}_i$$



	$WWWW$	$WWZZ$	$WW\gamma Z$	$WW\gamma\gamma$	$ZZZZ$	$ZZZ\gamma$	$ZZ\gamma\gamma$	$Z\gamma\gamma\gamma$	$\gamma\gamma\gamma\gamma$
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

Triboson processes and quartic couplings

Ana Cueto's talk on EFT's on Monday

- **Triboson**: probe of non-Abelian self couplings of the electroweak gauge bosons in the Standard Model (SM)
- Backgrounds to SM processes like ZH(γγ) and WH(γγ) that will become accessible at Run 3
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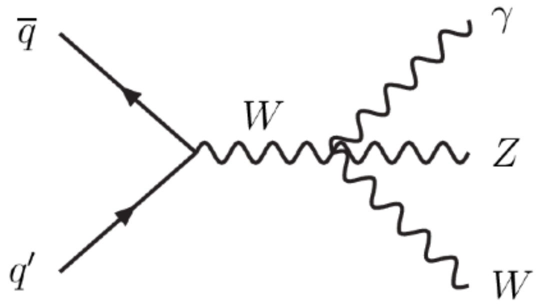
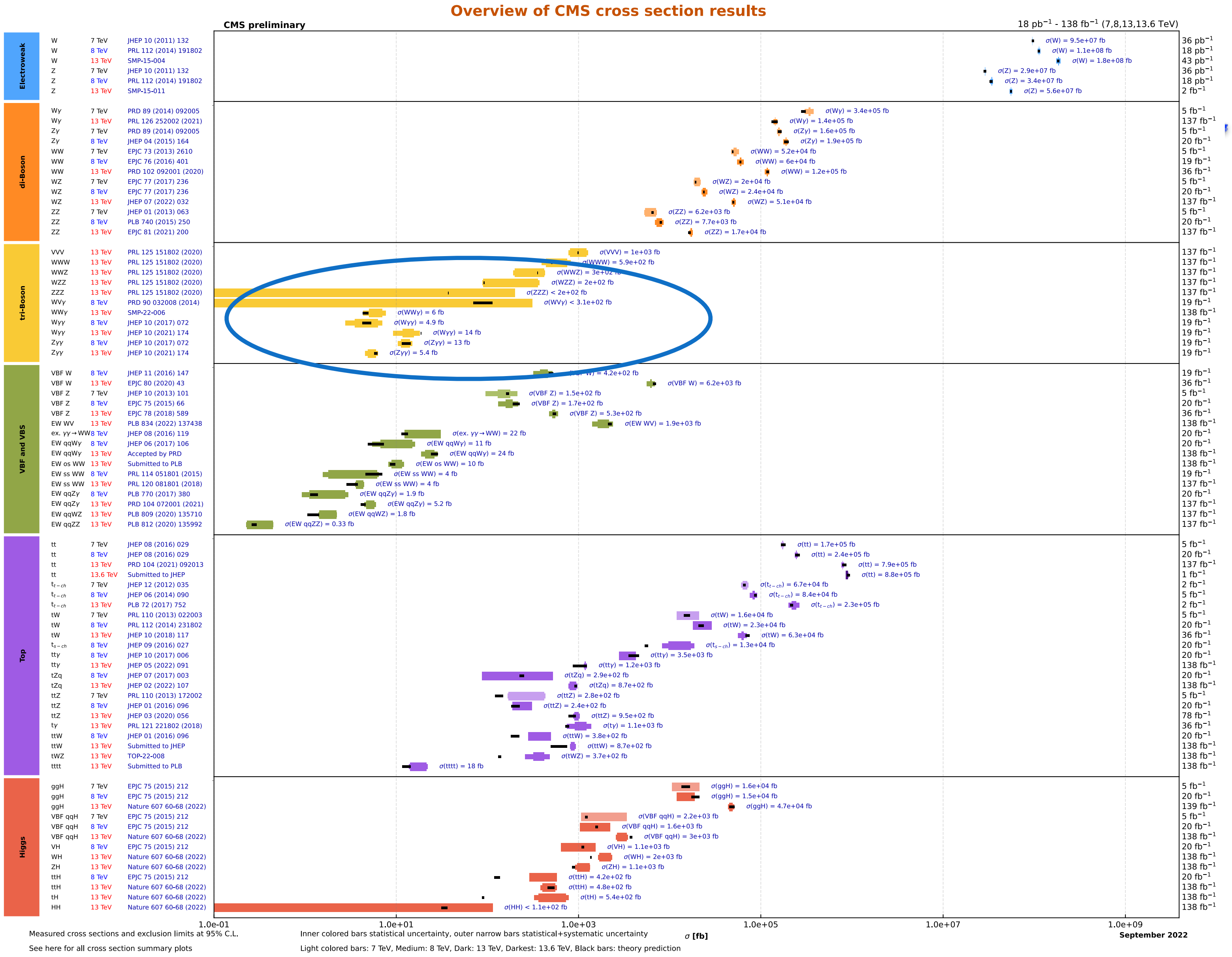


$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{\tilde{c}_i}{\Lambda^{d-4}} \mathcal{O}_i$$

	WWWW	WWZZ	WWγZ	WWγγ	ZZZZ	ZZZγ	ZZγγ	Zγγγ	γγγγ
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	✓	✓			✓				
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$					✓	✓	✓	✓	✓

First results

- First results of triboson processes in ATLAS and CMS using Run 2 datasets
  - First evidence for WWW and WWZ at ATLAS in 2019
    - Partial Run 2 dataset 80 fb-1
    - Observed:WWW 3.2σ
  - First observation of VVV at CMS in 2020
    - Full Run 2 dataset 137 fb-1
    - Observed: VVV 5.7σ



ATLAS WWW

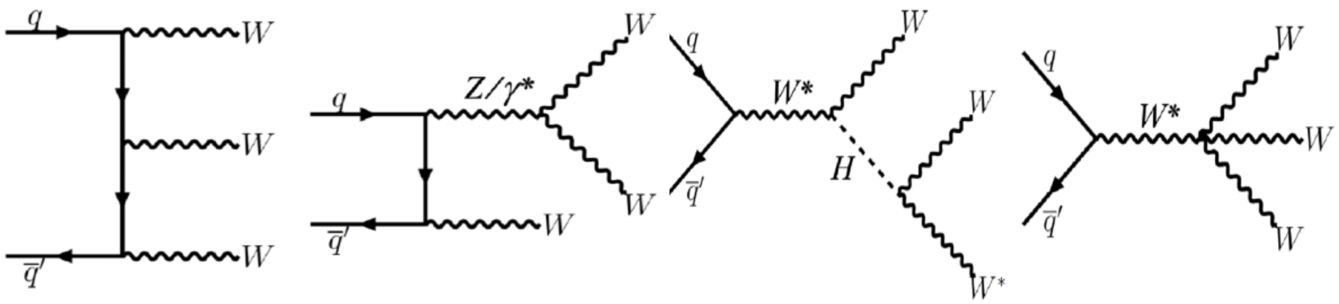
[Phys. Rev. Lett. 129 (2022) 061803]

- 2 final states:
  - W±W±W∓ —> 2l2ν2j :
    - Signature:

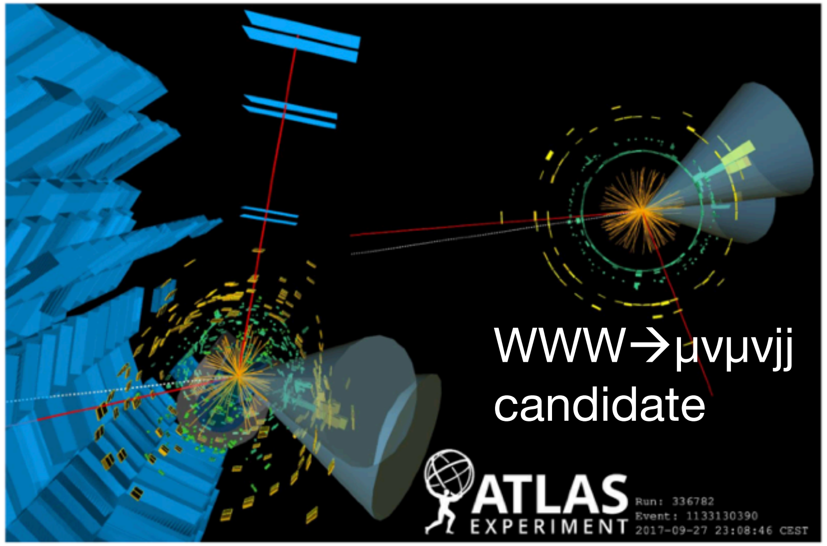
e± e± jj + ETmiss	e± μ± jj + ETmiss	μ± μ± jj + ETmiss

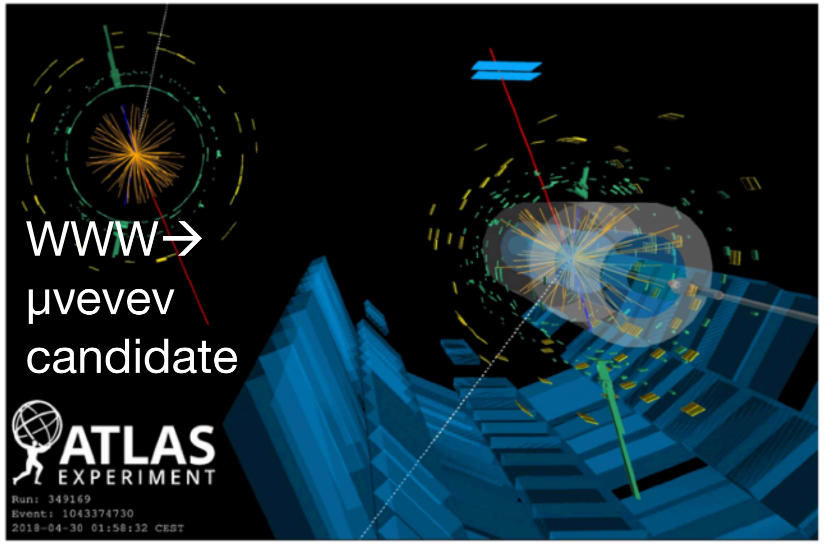
  - W±W±W∓ —> 3l3ν :
    - Signature:

e± e± μ∓ + ETmiss	μ± μ± e∓ + ETmiss



- Principle: avoiding opposite sign, same flavor pairs of leptons (OSSF) and SM processes that produce oppositely charged leptons pairs

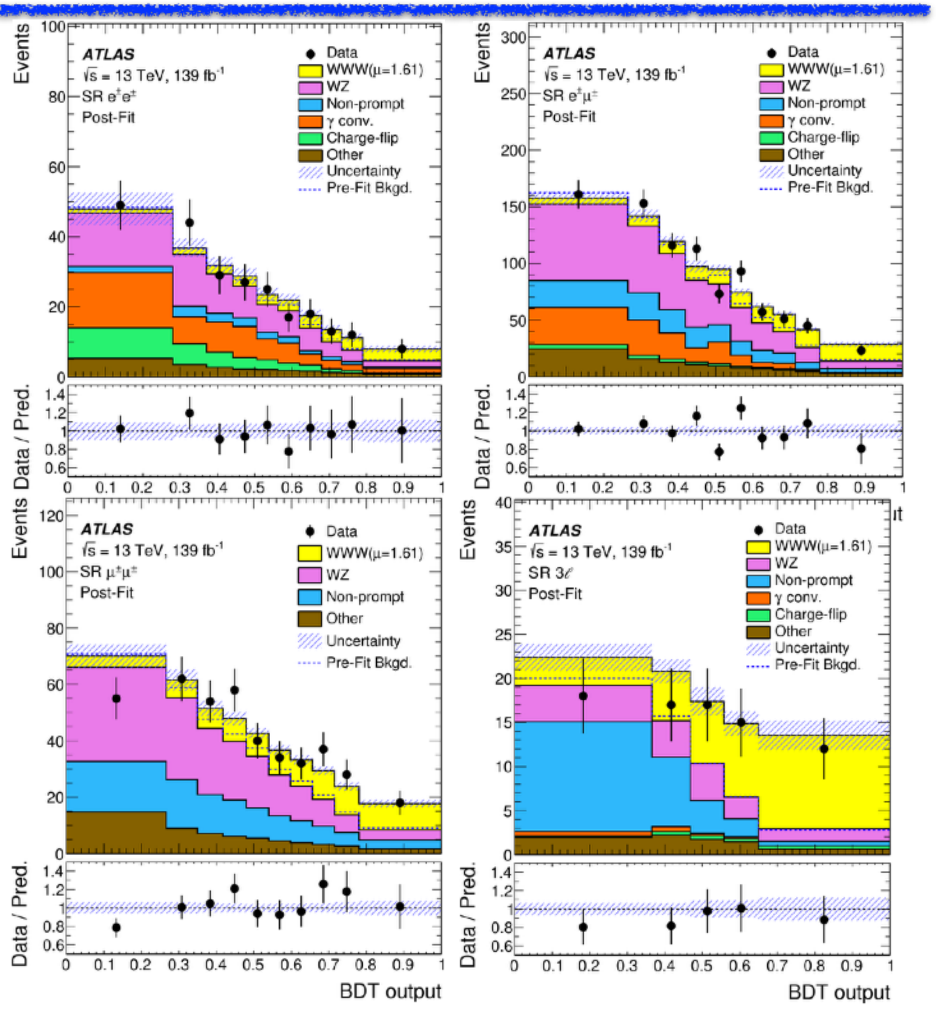




Phys. Rev. Lett. 129 (2022) 061803

WWW: Results

- Main background source is WZ: constrained using data from dedicated control regions (WZ+0,1,>1jets) to normalize the MC
- Data-driven methods to constrain:
  - Non-prompt leptons
  - Vγ events where the photon is misidentified as an electron
  - Prompt electron mis-identification (charge-flip)
- Fit strategy: simultaneous binned log-likelihood fit of BDT distributions in 2l and 3l signal regions



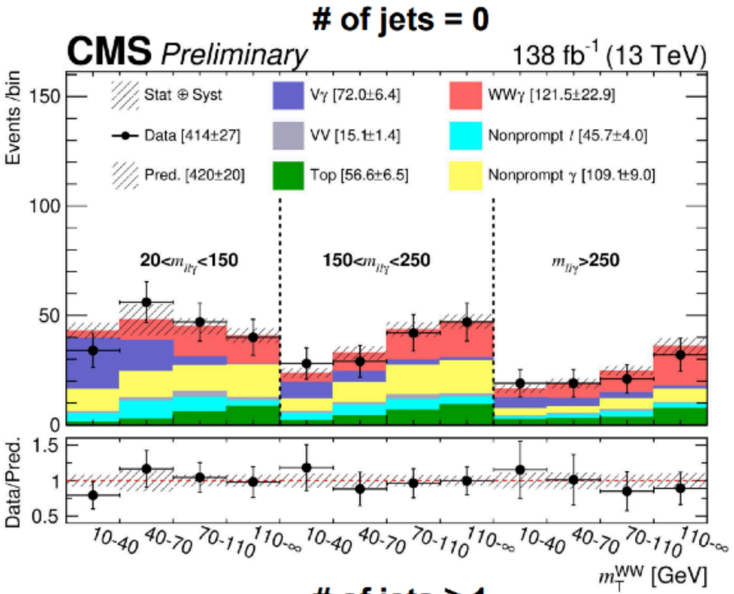
Observed cross-section with 8.2σ: 850 ± 100 (stat.) ± 80 (syst.) fb

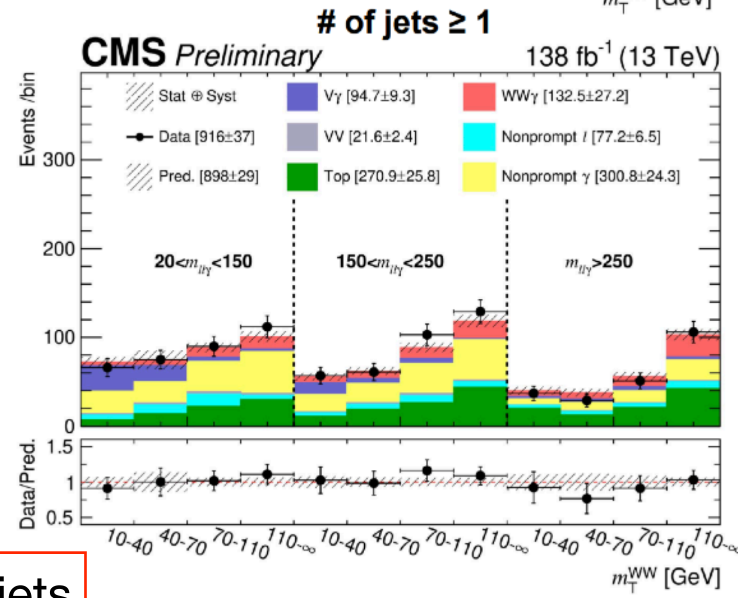
CMS-PAS-SMP-22-006

CMS: WWγ

- Leptonic final state OFOS (W+W- → eνμν)
- NLO QCD prediction
  - Non-prompt γ
    - Data-driven fake rate estimate in W+jets CR by fitting the photon shower width to extract non-prompt component
  - Non-prompt leptons
    - Data driven fake rate estimate in dijet CR
  - Top and SSWW CR :
    - ≥ 1 b-jet used to constrain non-prompt lepton and non-prompt γ backgrounds in fit

Process	Signal region	SSWWγ CR	Topγ CR
WWγ	254.0±47.3	1.2±0.2	12.8±2.7
QCD Vγ	166.7±13.8	12.2±2.2	12.6±1.2
VV	36.7±3.5	24.9±1.7	2.0±0.3
Top	327.5±32.2	2.4±0.6	2433.5±85.2
Nonprompt ℓ	122.9 ±9.7	196.6±13.6	39.8±10.7
Nonprompt γ	409.9 ±31.7	19.9±1.6	793.2±62.1
Expected	1318±43	257±14	3294±57
Observed	1330±46	259±20	3287±59





Fit: 2D fit mTWW-mllγ used in the CRs and the 3 SR regions in mllγ for 0 and >=1jets

First observation with 5.6σ: σ = 6.0 ± 1.0 (stat.) ± 1.0 (syst.) ± 0.9 (theo.) fb

CMS: WWγ

- Search for Hγ production with modified Higgs boson couplings to light quarks
- Hγ->WWγ: similar selection with EW, adding
  - $\Delta\phi ll < 2.5$
  - $\Delta Rll < 2.3$
  - $\Delta Rl\gamma > 0.8$
- Yukawa couplings limits using ΔRll and mTH distributions
- Expected and observed upper limits on the Hγ cross sections at 95%

Limits set on Higgs Yukawa couplings to u, d, s, c quarks

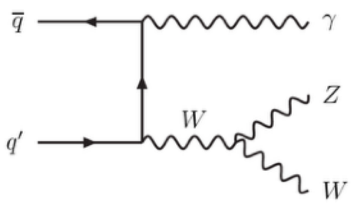
Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq 13000$ (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq 14000$ (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq 1300$ (1700)
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq 110$(200)

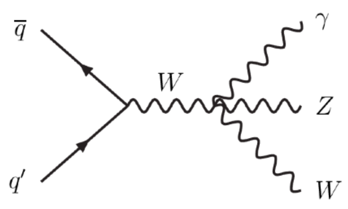
Under the assumption that that all other SM κ scale to give a signal strength of 1 for all other Higgs production decay processes

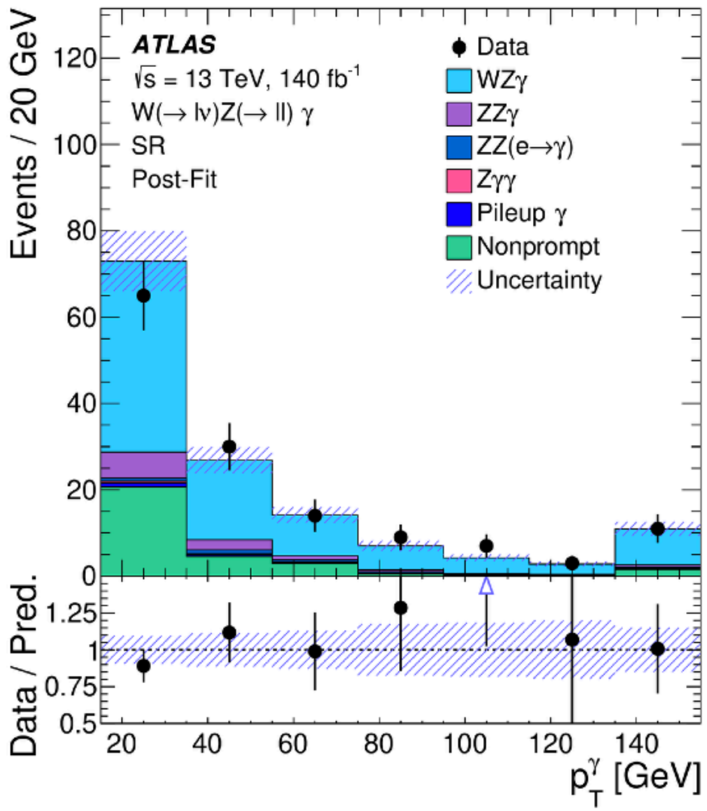
ATLAS WZγ

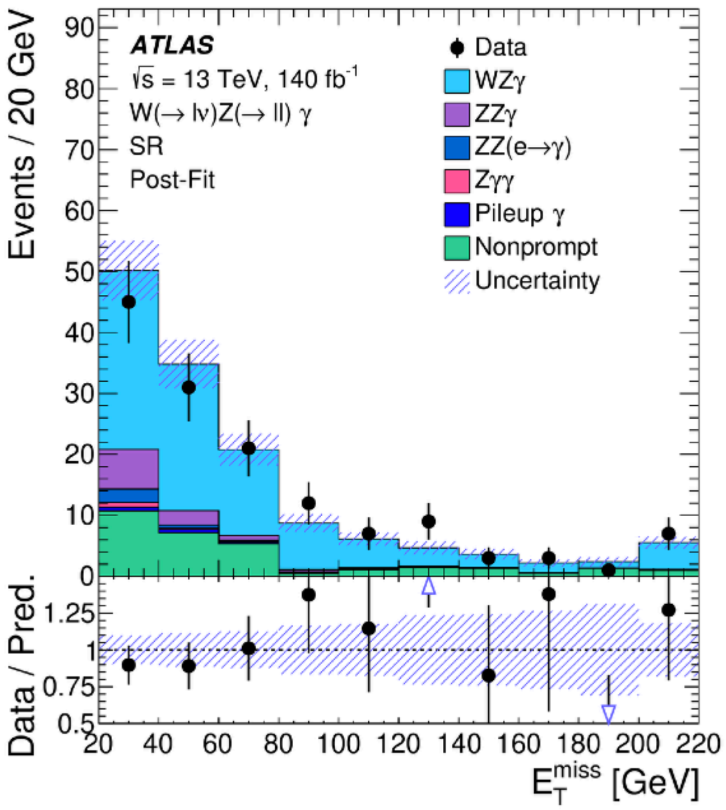
https://arxiv.org/abs/2305.16994

- Final state: 3 charged leptons (e, μ) + MET + 1 isolated photon
- Dominant BG:non-prompt γ and leptons
  - Estimated using data-driven calculation
- ZZγ and ZZ (e→ γ) bkg normalization from simultaneous fit in CRs
- Fit in SR and the 2 CRs for all leptonic final states



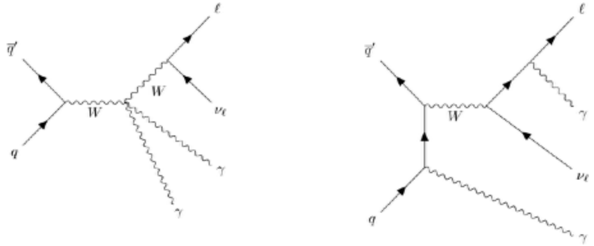






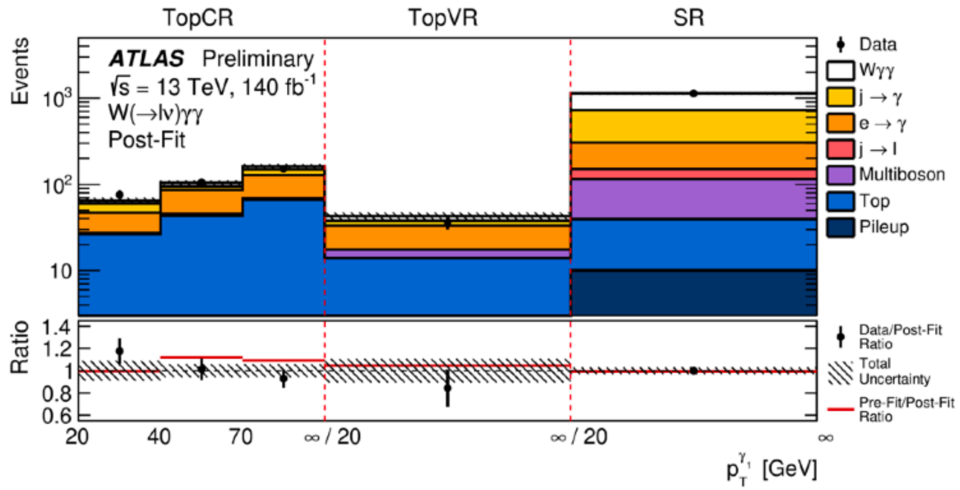
First observation with significance: 6.3σ!
Observed cross section σ= 2.01±0.30 (stat) ±0.16 (syst) fb

ATLAS: Wγγ



ATLAS-CONF-2023-005

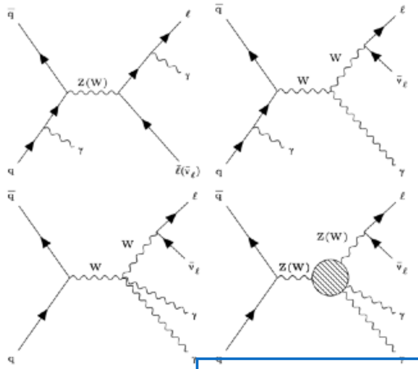
- Final state:lvγγ
- Dominant uncertainty: one or both signal photons originate from a misidentified jet or neutral hadron decay(j→γ)
  - Data-driven two-dimensional template fit method
- e→γ, second largest background in e channel
  - Data-driven fake rate estimate Z→ee/eγ CR
- Top background constrained in ≥ 1 b-jet CR simultaneously with SR
  - Validated in low ET miss region with ≥ 1 b-jet
- Dominant uncertainties : systematic on j→γ followed by stat. uncertainty



Source	SR	TopCR
$W\gamma\gamma$	410 ± 60	28 ± 5
Non-prompt $j \to \gamma$	420 ± 50	42 ± 20
Misidentified $e \to \gamma$	155 ± 11	120 ± 9
Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$)	76 ± 13	5.2 ± 1.7
Non-prompt $j \to \ell$	35 ± 10	–
Top ($tt\gamma$, $tW\gamma$, $tq\gamma$)	30 ± 7	136 ± 32
Pileup	10 ± 5	–
Total	$1\,136 \pm 34$	332 ± 18
Data	1 136	333

First observation with 5.6σ: Observed cross-section: 12.2 + 2.1 - 2.0fb

CMS Vγγ



JHEP 2021

- Final states: llγγ and lνγγ
- if |m(eγ) - m(Z)| or |m(eγγ) - m(Z)| < 5 GeV —> γ removed to reduce FSR
- Dominant background: misidentification of jets as photons —>Data-driven method
- Fit on distribution of diphoton pT system for all final states

Zγγ : 4.8σ obs
Wγγ : 3.1σ obs

$$\sigma(W\gamma\gamma)^{\text{meas}} = 13.6^{+1.9}_{-1.9}\,(\text{stat})^{+4.0}_{-4.0}\,(\text{syst}) \pm 0.08\,(\text{PDF + scale})\ \text{fb},$$
$$\sigma(Z\gamma\gamma)^{\text{meas}} = 5.41^{+0.58}_{-0.55}\,(\text{stat})^{+0.64}_{-0.70}\,(\text{syst}) \pm 0.06\,(\text{PDF + scale})\ \text{fb}.$$

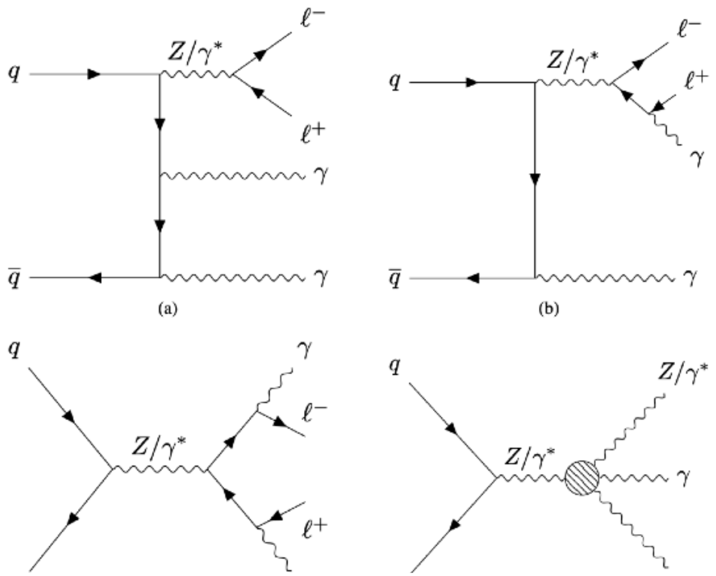
- Limits on Dim-8 EFT parameters
- pT of the diphoton system used as discriminating variable for the aQGCs
- Expected and observed constraints on the Dim-8 EFT parameters for both final states

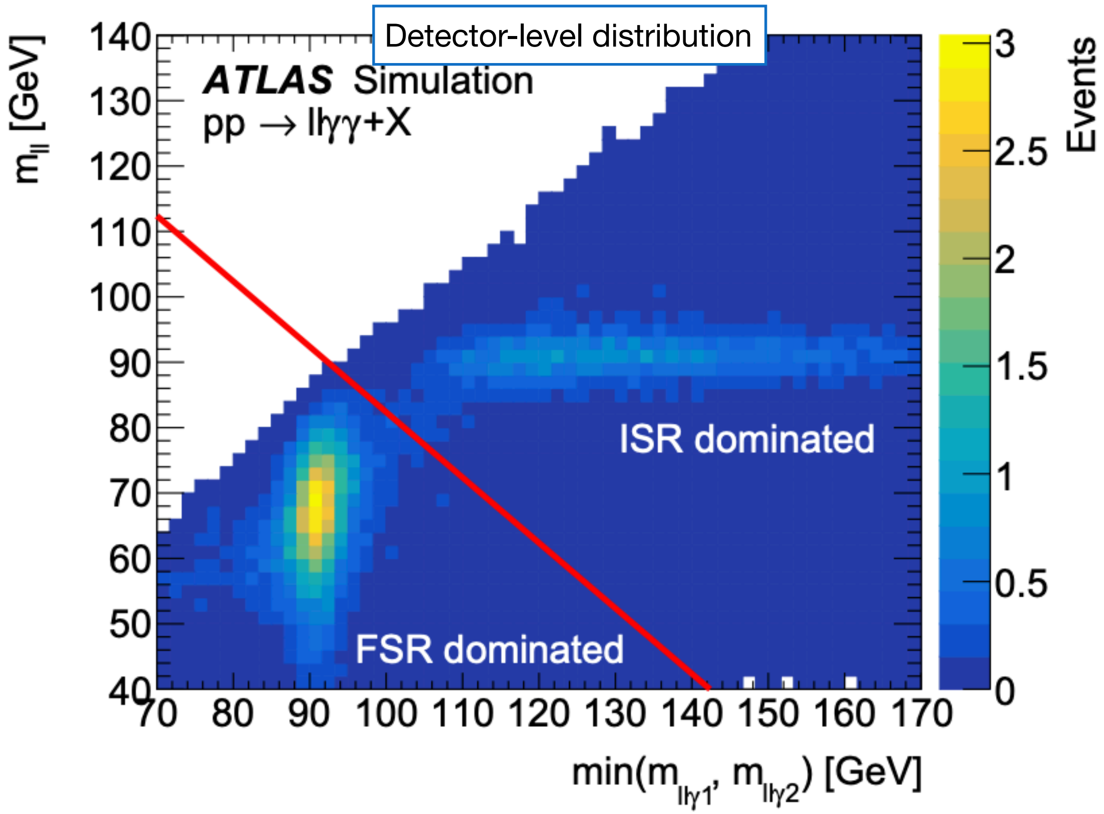
	Wγγ (TeV^{-4})		Zγγ (TeV^{-4})	
Parameter	Expected	Observed	Expected	Observed
$f_{M,2}/\Lambda^4$	[−57.3, 57.1]	[−39.9, 39.5]	-	-
$f_{M,3}/\Lambda^4$	[−91.8, 92.6]	[−63.8, 65.0]	-	-
$f_{T,0}/\Lambda^4$	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
$f_{T,1}/\Lambda^4$	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
$f_{T,2}/\Lambda^4$	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
$f_{T,5}/\Lambda^4$	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
$f_{T,6}/\Lambda^4$	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
$f_{T,7}/\Lambda^4$	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
$f_{T,8}/\Lambda^4$	-	-	[−0.90, 0.94]	[−1.06, 1.10]
$f_{T,9}/\Lambda^4$	-	-	[−1.54, 1.54]	[−1.82, 1.82]

accepted by EPJ C

ATLAS Zγγ

- e/μ channels, 13 TeV, 139 fb-1
  - Cut on m(ll) and min(m(llγ1), m(llγ2)) to minimize FSR
    - Enhance signal region (ISR): $m\ell\ell + \min(m\ell\ell\gamma1, m\ell\ell\gamma2) > 2mZ$
- Dominant BG: $jj \to \gamma$ mis-ID
  - Estimated using data-driven method
- Differential cross section along 6 kinematic variables



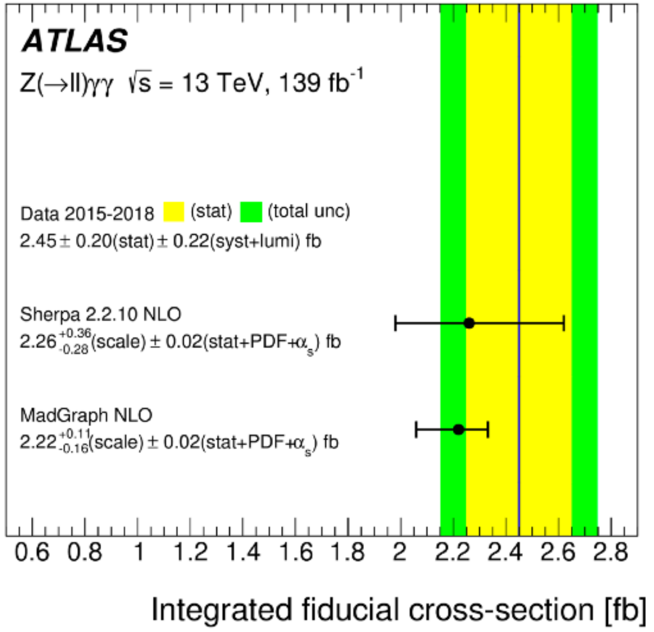


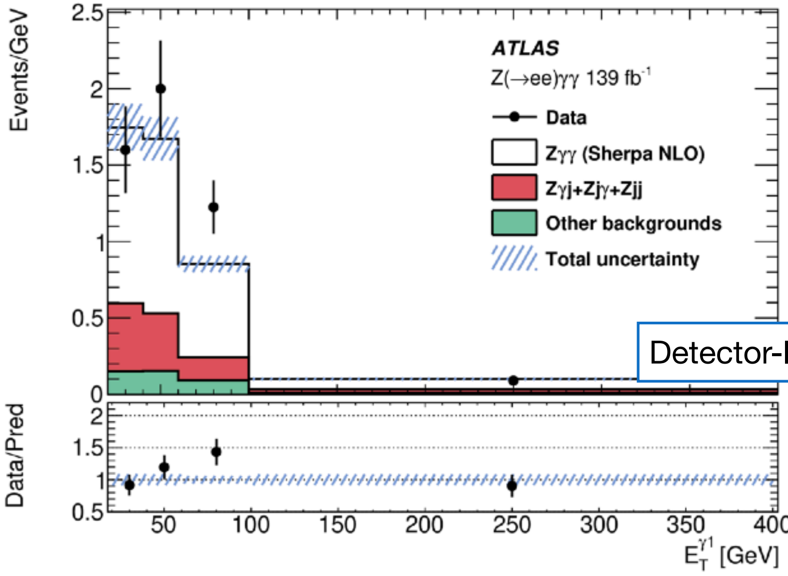
accepted by EPJ C

ATLAS Zγγ

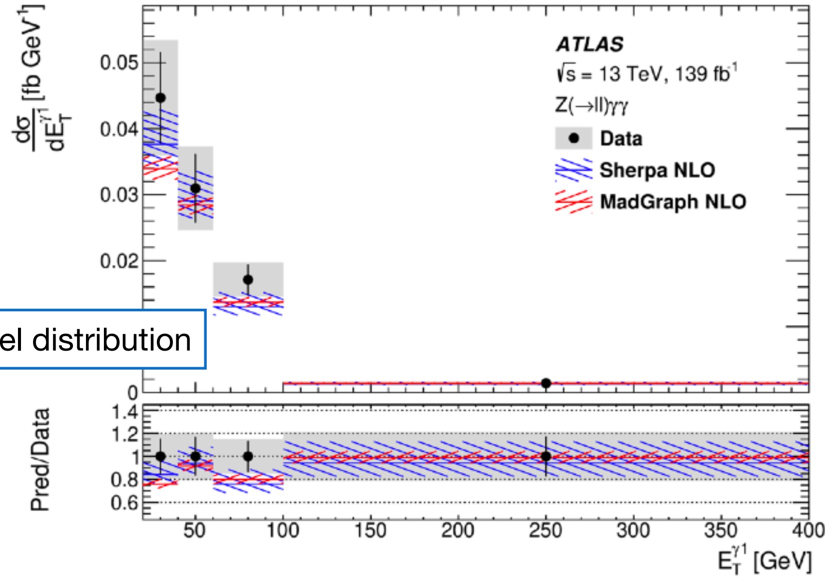
Measured cross section = 2.45 ± 0.20 (stat.) ± 0.22 (syst.) ± 0.04 (lumi) fb

- Integrated cross-section measurement precision: 12%
- Test SM predictions at up to NLO accuracy with Sherpa & MG5
- Differential distributions for the first time





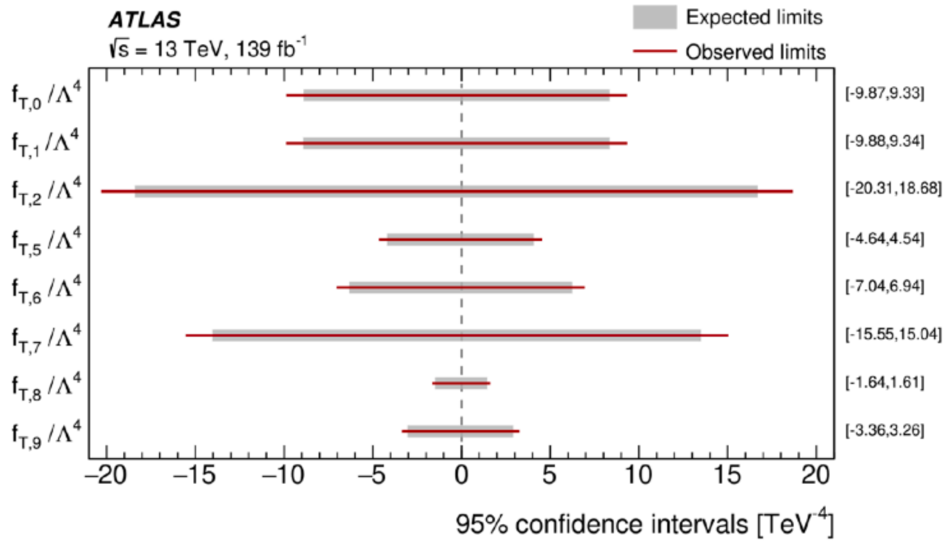
Detector-level distribution

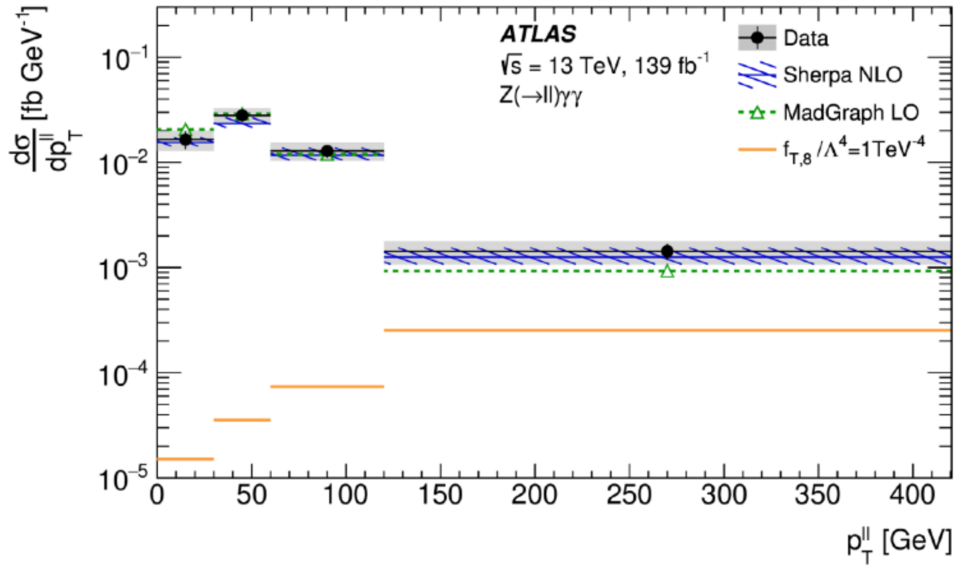


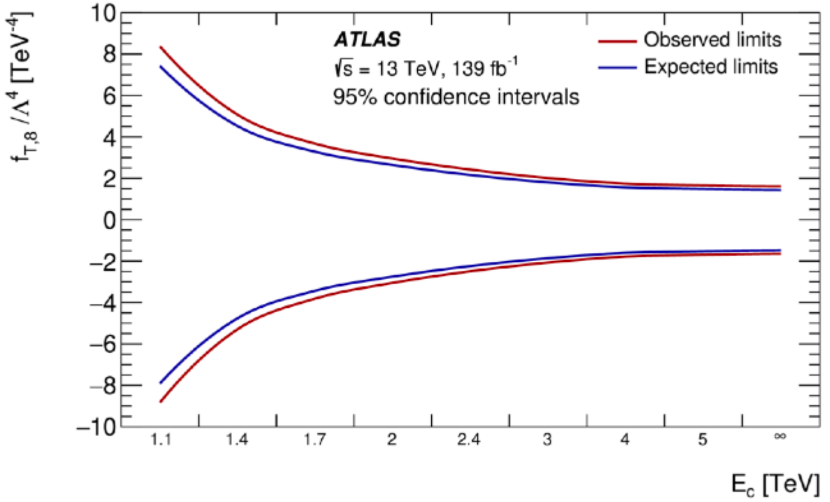
accepted by EPJ C

ATLAS Zγγ

- Dim-8 EFT limits on fT coefficients
- pT(ll) distribution used as discriminating variable
- Unitarized limits obtained
- Unitarization: Clipping method used
    - Limits as a function of Ec —> invariant mass of llγγ system
    - BSM events with E>Ec are removed from the signal MC



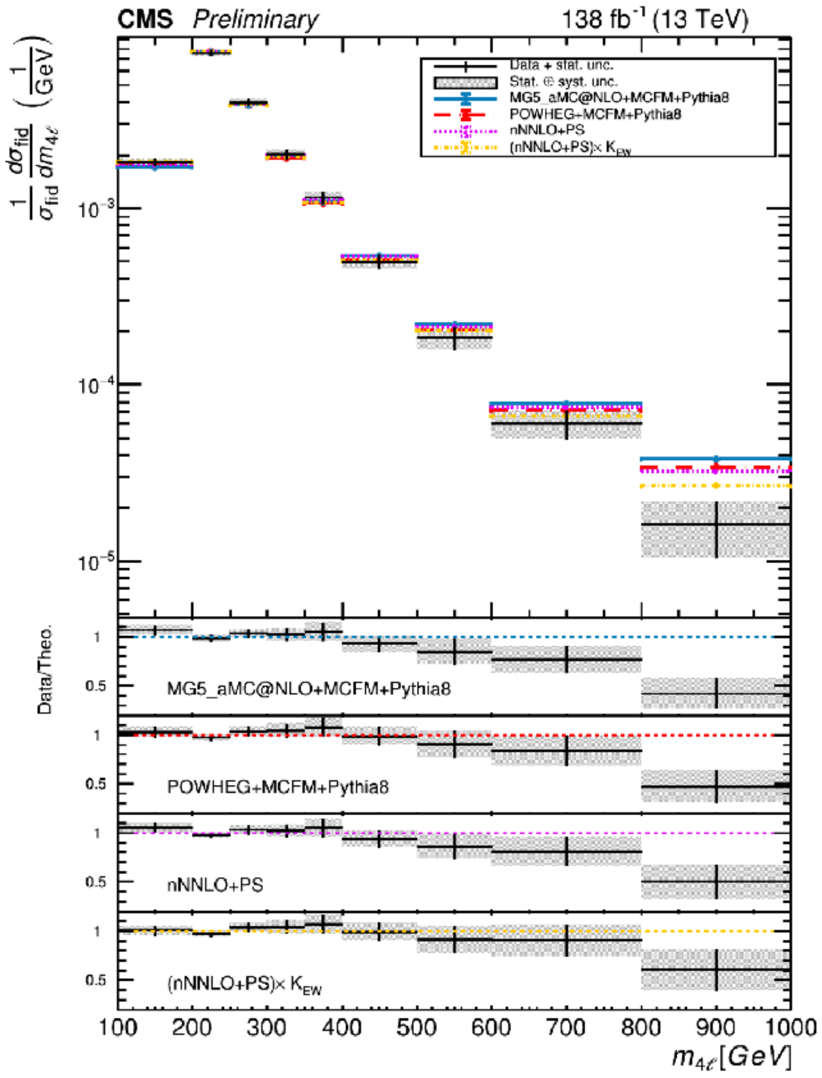


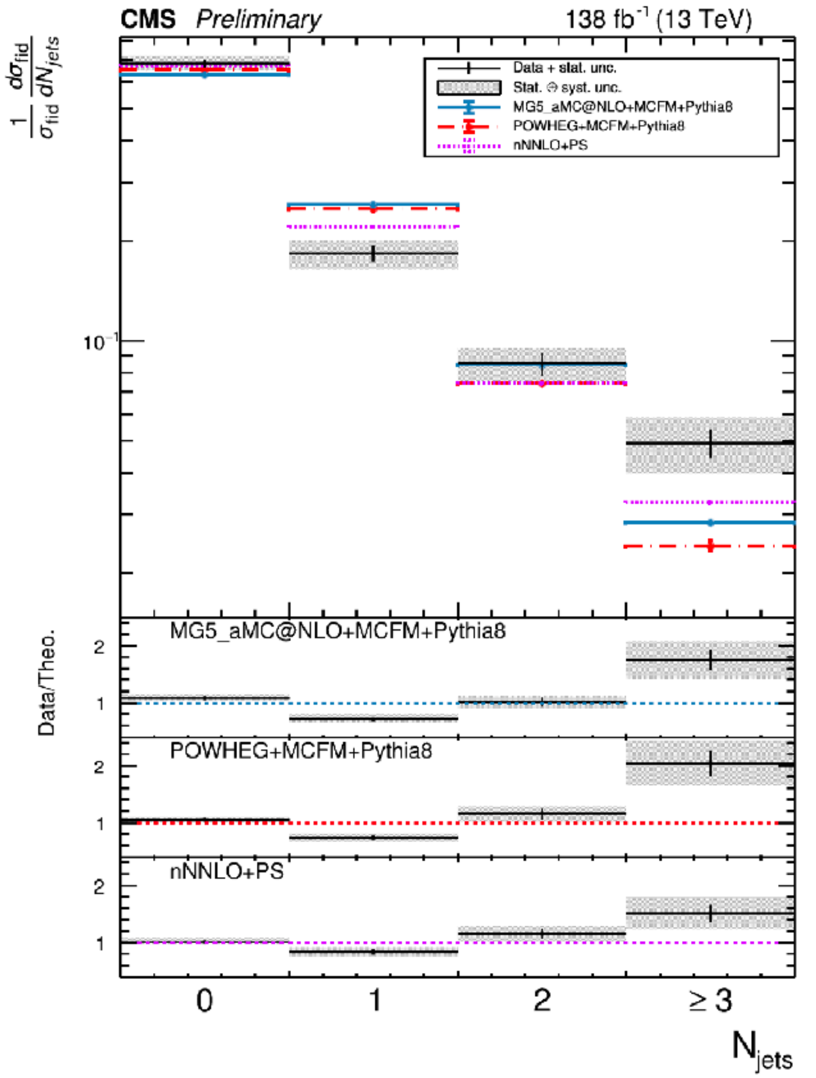


CMS ZZ+jets

[CMS-PAS-SMP-22-001]

- 139 fb-1, fully leptonic final state
- Diboson production in association with jets
- Differential distributions
- General agreement between theoretical predictions and data
- In some regions discrepancies between predicted and measured values
- nNNLO+PS prediction describes the distribution of jet multiplicities better than MadGraph5 aMC@NLO and POWHEG
- Inclusion of EW corrections improves the description of the m4l distribution.

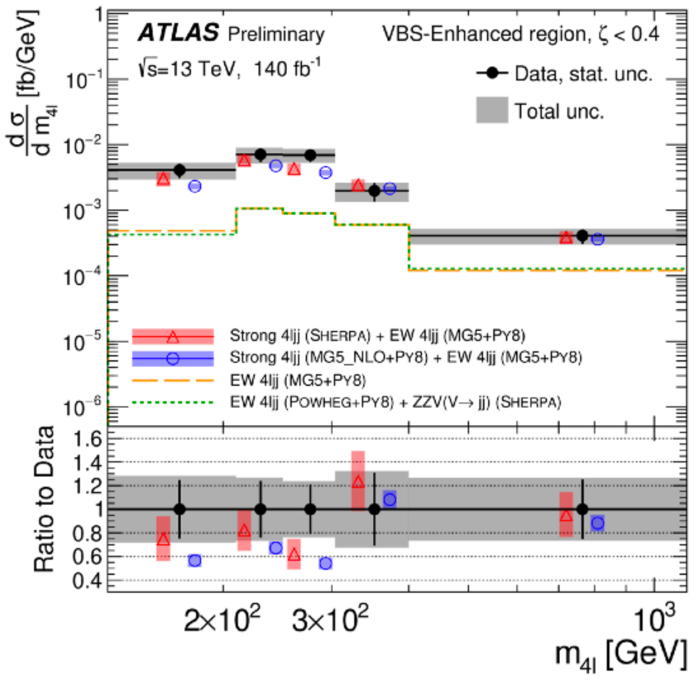


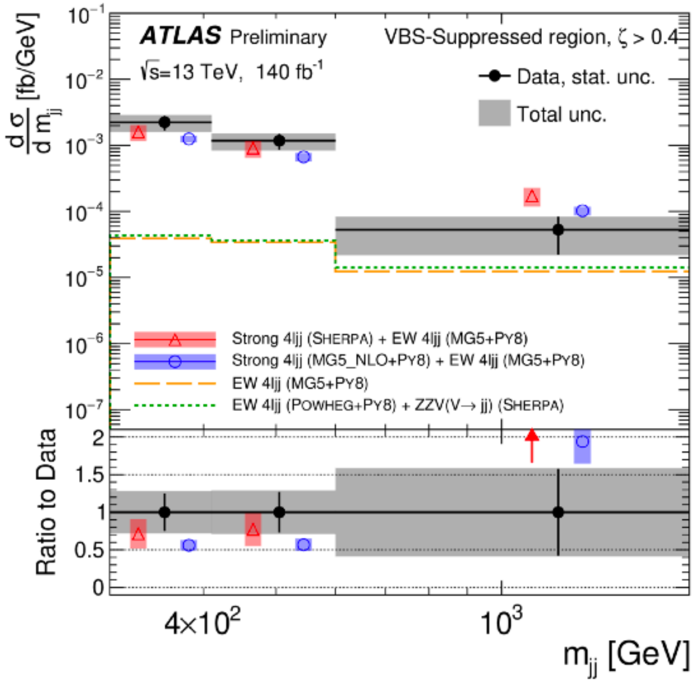


ATLAS ZZjj

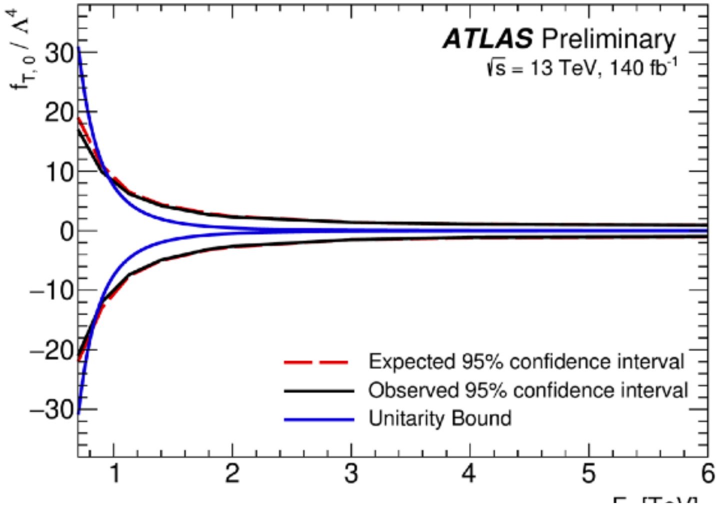
ATLAS-CONF-2023-024

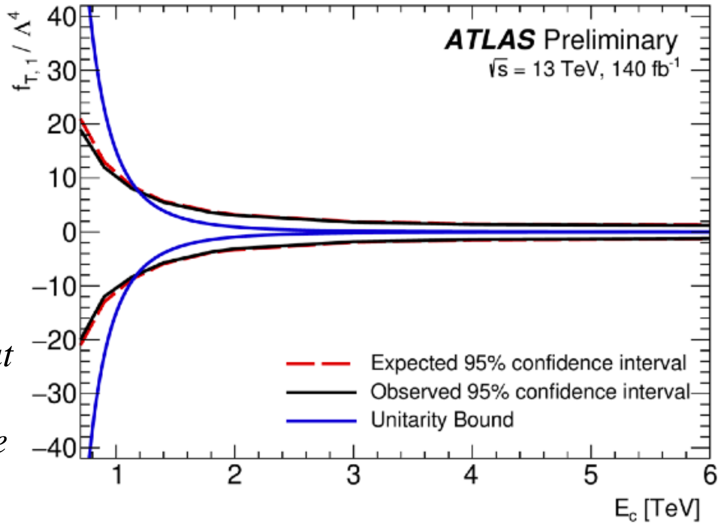
- EWK production of 4 leptons in association with two jets
- VBS enhanced and suppressed regions based on 4l system centrality
- Differential measurement of ZZjj with Full Run 2 dataset
- aQGC expected and observed limits as a function of energy cut-off





In full agreement with Sherpa,simulation of additional jet activity at LO in QCD whereas MG5+Py8 relies on the Pythia8 parton shower

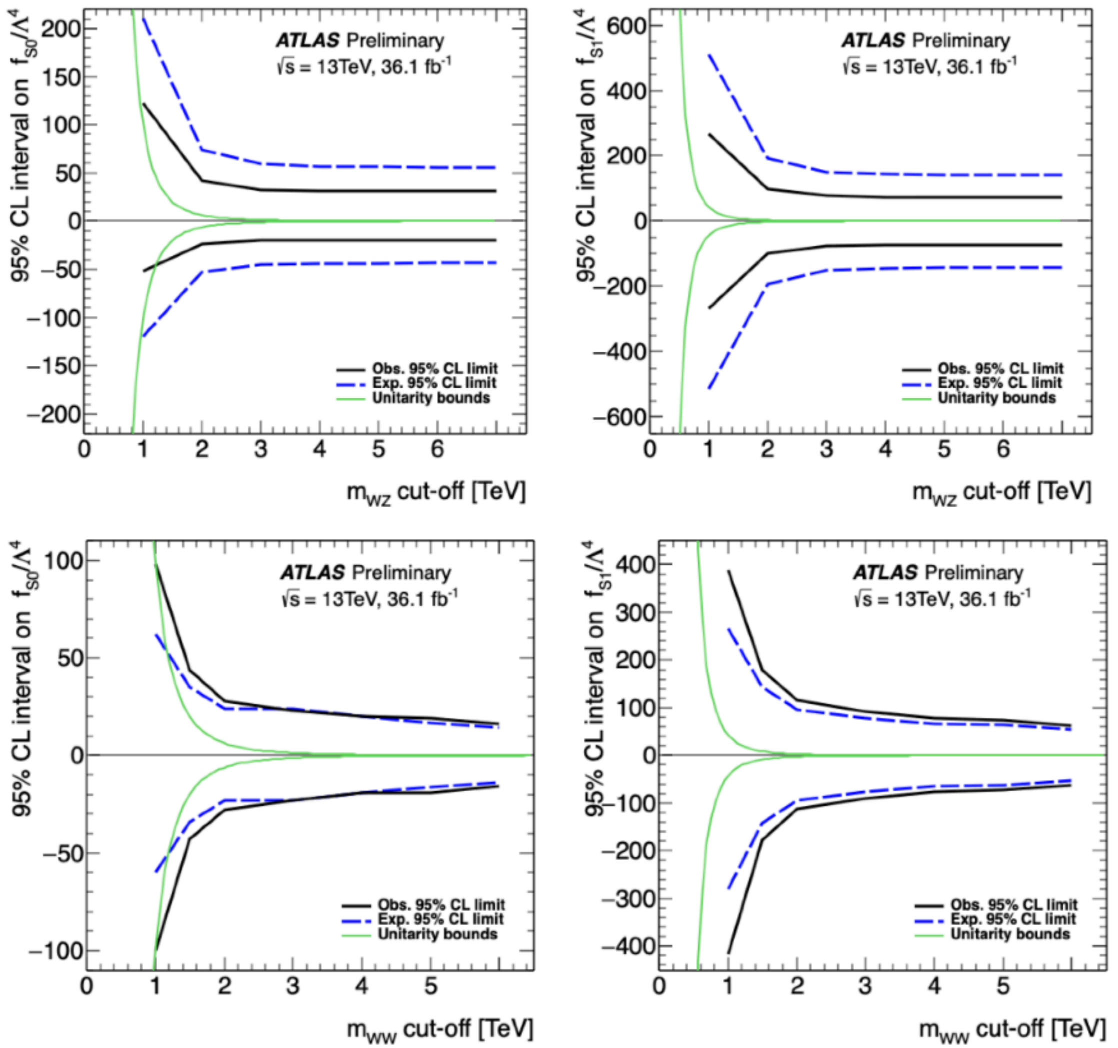




ATL-PHYS-PUB-2023-002

ATLAS ssWW+WZ

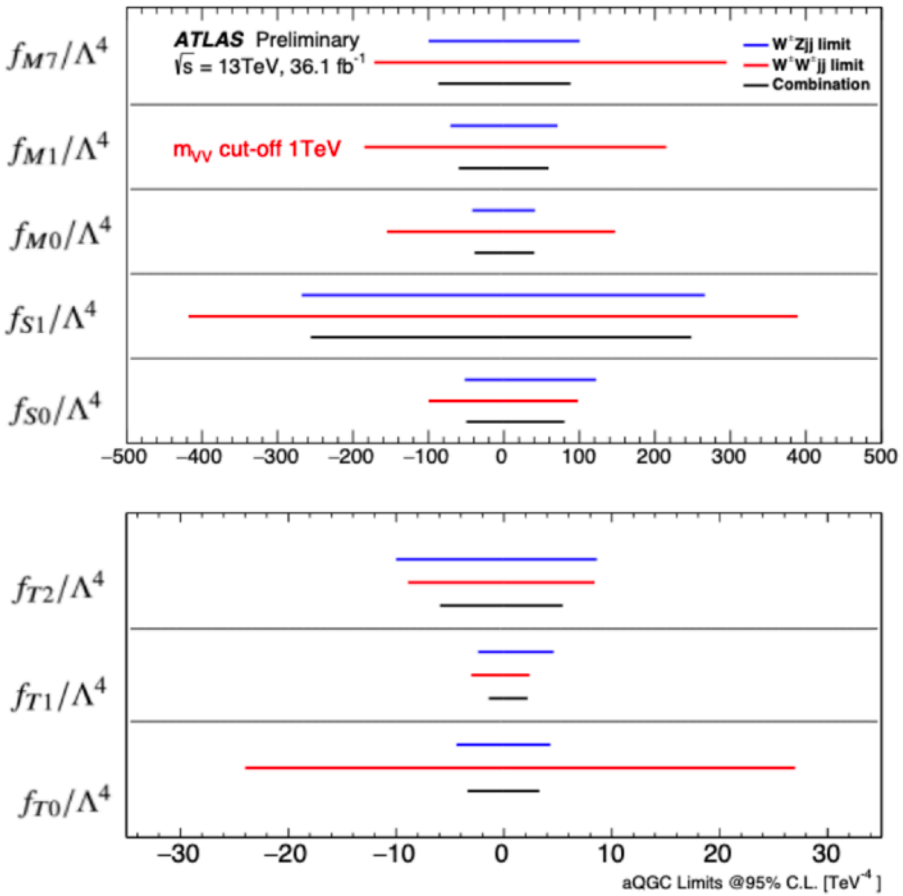
- Combined interpretation of ssWW and WZjj with Partial Run2 dataset
- Discriminating distributions:
  - ssWW: Reco-level mll
  - WZjj: Differential distribution of mTWZ
- Experimental systematic uncertainties treated correlated between the two measurements
- Unitarization: clipping method used, limits as a function of Ec
  - WZjj: Ec—>mWZ at generator level
  - ssWW: Ec—> mWW at generator level
- 1D and 2D limits



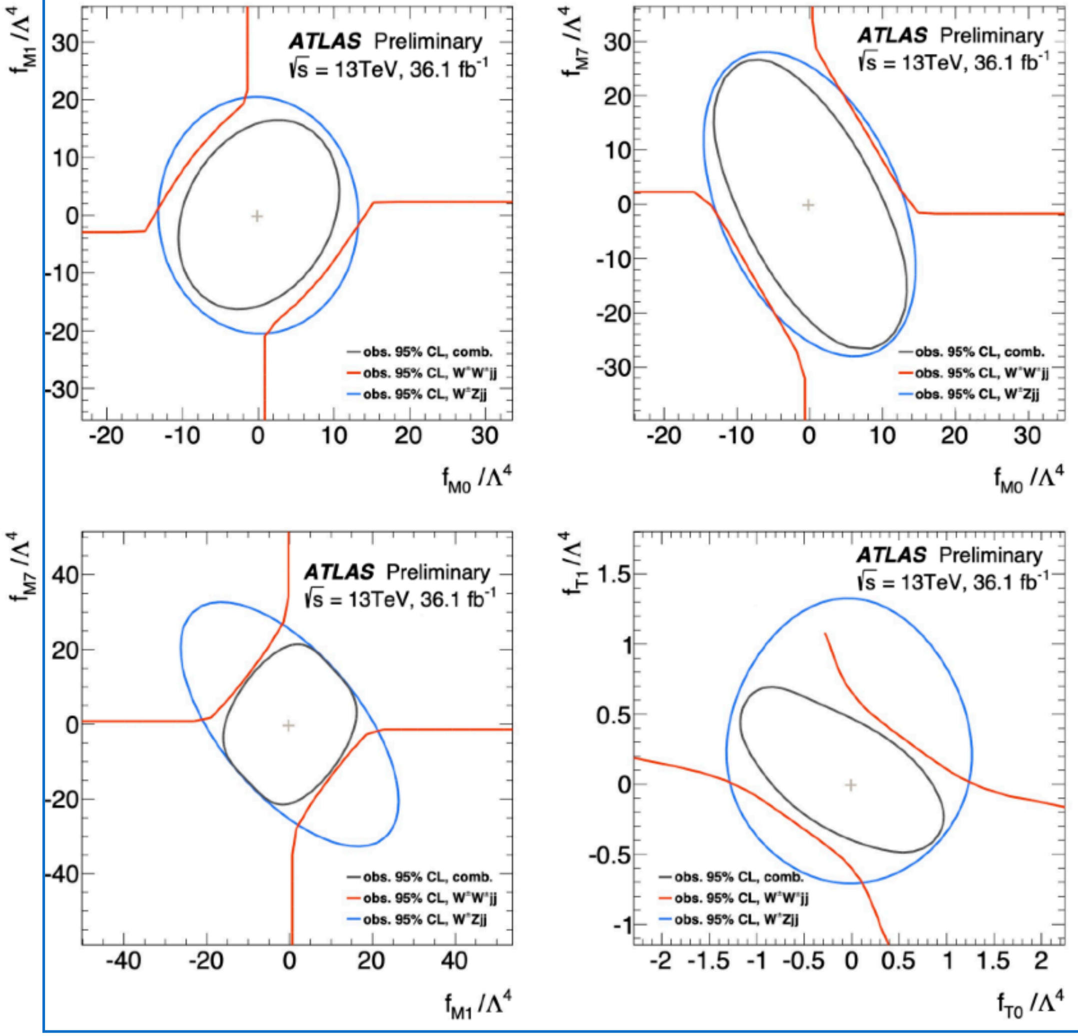
ATLAS ssWW and WZjj

ATL-PHYS-PUB-2023-002

Individual limits and combination



2D limits



Conclusion

- Precision measurements of triboson and diboson processes presented
- Exciting new first observations of triboson channels by ATLAS and CMS
- Improved limits set on aQGC operators with triboson and VBS analyses
- New limits on Higgs coupling to light quarks with $WW\gamma$ analysis by CMS
- Differential cross sections on diboson ZZ in association with jets from CMS discussed
- Run3 ongoing: increased statistics are promising for new measurements and BSM interpretations!

Thank you!

Backup-WWW

$\ell^{\pm}\nu\ell^{\pm}\nu jj$ **Signal Region**		
$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$
2 SS leptons with leading lepton-p_{T} > 27GeV		
veto 3$^{\mathrm{rd}}$ lepton		
$40 < m_{\ell\ell} < 80$ GeV $100 < m_{\ell\ell} < 400$ GeV	$40 < m_{\ell\ell} < 400$ GeV	
≥ 2 jets		
b-jet veto @ 85% DL1r		
$\lvert\Delta\eta_{jj}\rvert$ <1.5		
m_{jj} <160 GeV		
E_T^{miss}–significance > 3	None	

Table 14: Selection criteria for the $\ell^{\pm}\nu\ell^{\pm}\nu jj$ SRs.

$\ell^{\pm}\nu\ell^{\mp}\nu\ell^{\mp}\nu$ **Signal Region**	
$e^{\pm}\mu^{\mp}\mu^{\mp}$	$\mu^{\pm}e^{\mp}e^{\mp}$
3 leptons with leading lepton-p_{T} > 27GeV	
$\Sigma q_{\ell} = \pm 1$	
veto 4$^{\mathrm{th}}$ lepton	
no SFOS lepton pairs	
b-jet veto @ 85% DL1r	

Table 15: Selection criteria for the 3ℓ SR.