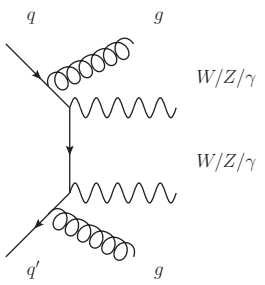
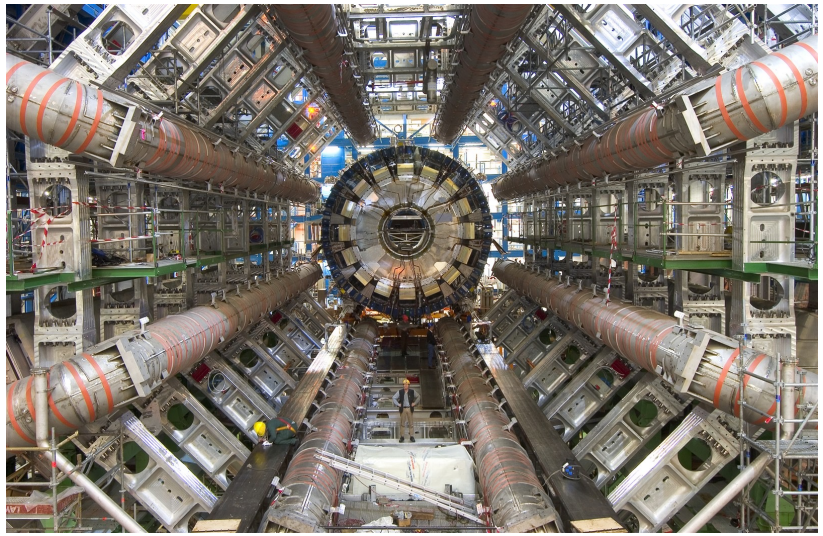
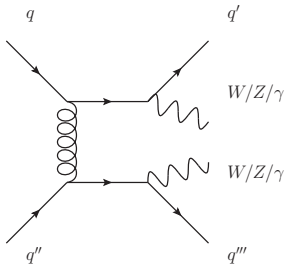
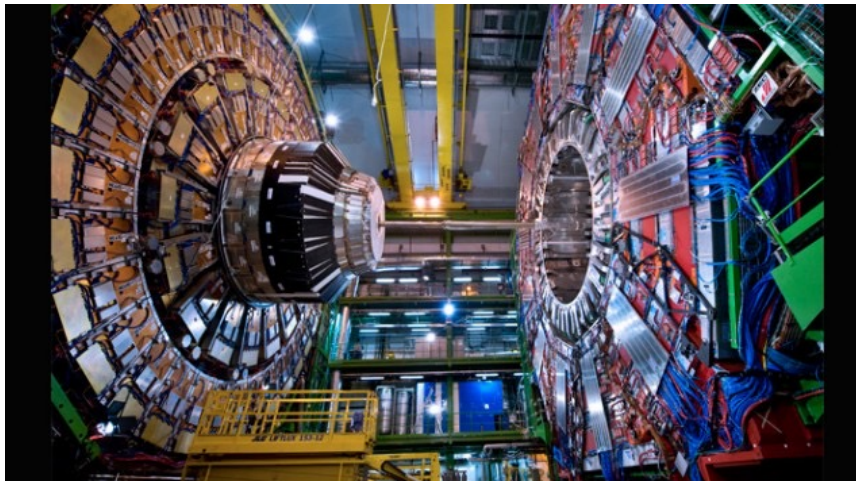




Recent Diboson Measurements





Darien Wood*, Northeastern University
On Behalf of the ATLAS and CMS Collaboration

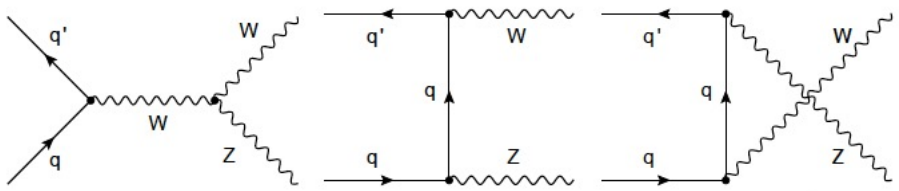
Brookhaven Forum 2021
3-5 November, 2021
Brookhaven National Laboratory (virtual)

*partially supported by NSF PHYS-2011848

Northeastern University

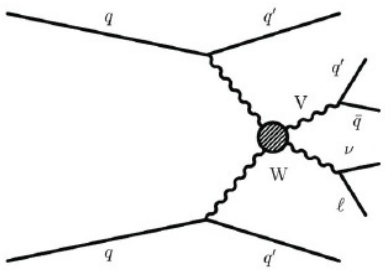
Outline

- Motivation and methods
  - Cross sections and couplings
- Inclusive production (non-VBS) – selected results



  - W-gamma
    - CMS SMP-19-002 (PhysRevLett 126,252002(2021))
    - ,CMS SMP-20-005
  - Gamma gamma production
    - ATLAS STDM-2017-30 (arXiv:2107.09330)
  - WW, WZ, ZZ cross sections at sqrt(s)=5.04 TeV
    - CMS SMP-20-012 (arXiv:2107.01137)
  - WZ (leptonic) differential cross sections including polarization
    - CMS SMP-20-014 (arXiv:2110.11231)
  - W+W- +>=1 jet xsec
    - ATLAS STDM-2018-34 (JHEP06 (2021)003)
  - Differential xsec of Z/g* Z/g*events to 4l
    - ATLAS STDM-2018-30 (JHEP07 (2021) 005)

- Electroweak (VBS) production – selected results



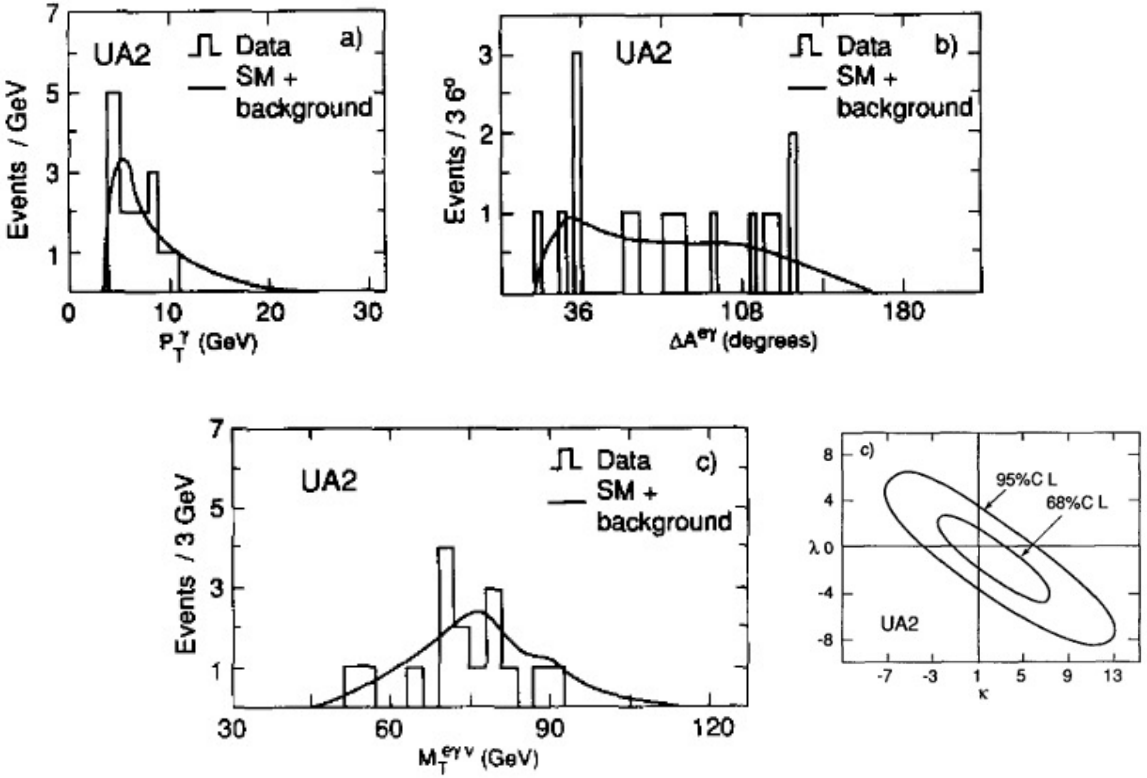
  - Zgamma + 2 jets
    - CMS SMP-20-016 (Phys. Rev. D, 104, 072001 (2021))
    - ATLAS STDM-2017-26 (Phys.Let.B 2020, 135341 (2020))
    - ATLAS EXOT-2021-17 (arXiv:2109.00925)
  - Polarization measurement in same-sign WW production
    - CMS SMP-20-006 (Phys. Let. B, 2020, 136018 (2021))
  - EWK ZZ production
    - ATLAS STDM-2017-19 (arXiv:2004.10612)
    - CMS SMP-20-001 (Phys. Let. B, 2020, 135992 (2021))
  - Photon induced WW production
    - ATLAS STDM-2017-21 (Phys. Let. B, 2021, 136190 (2021))

- Summary and prospects

Introduction

- 30 years of diboson studies
- Many advances
  - Enormous data samples
  - Rare production decay modes accessed
  - Multivariate techniques
  - Differential cross sections
  - Resolve EWK and QCD processes
  - Improved theoretical predictions
- Typical features of diboson studies
  - Rely on lepton triggers (with a few exceptions)
  - Likelihood fits to explore Triple and Quartic Gage Couplings

December 1991



PLB 277, 192 (1992)

$W\gamma$ production (2021)

CMS SMP-20-005

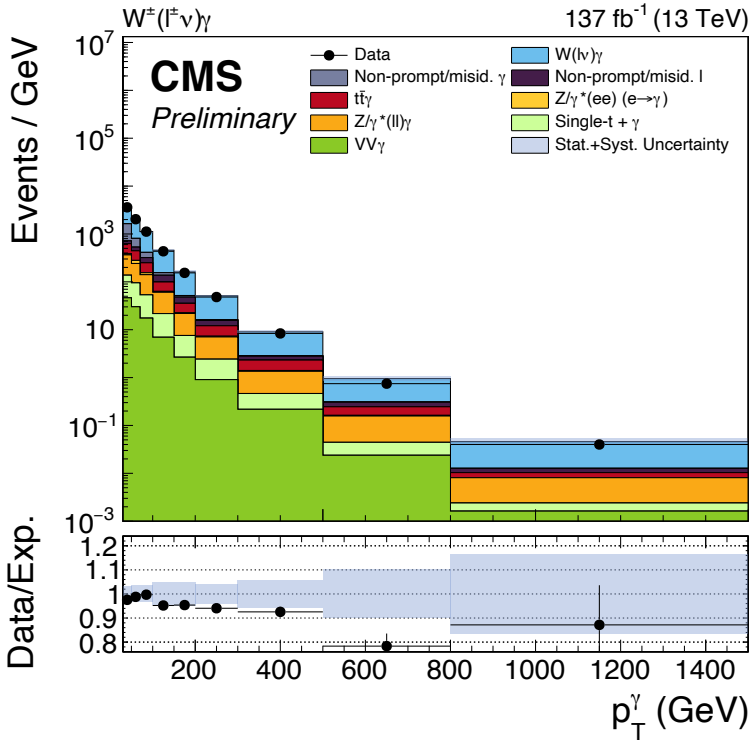
13 TeV, 137 fb^{-1}

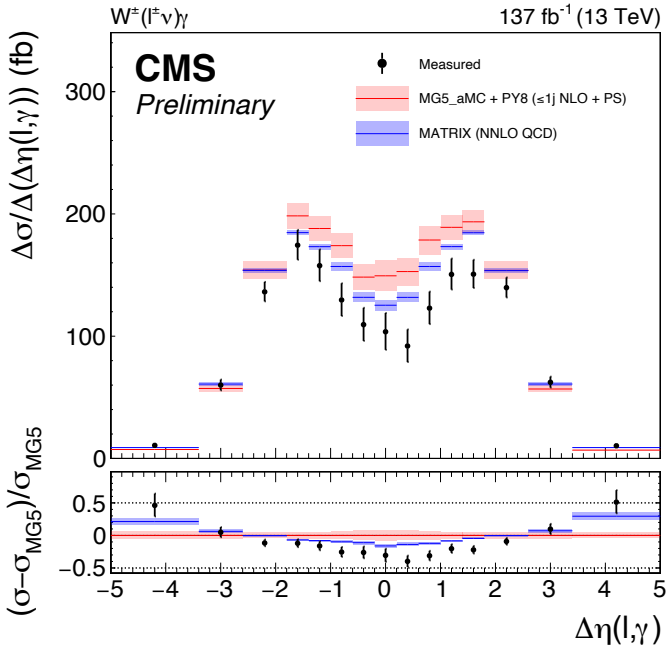
- $p_T(\gamma) > 25$ GeV
- $W \to e\nu, W \to \mu\nu$
- Sensitive to dimesion-6 anomalous triple gauge couplings:

$$\mathcal{O}_{3W} = \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}.$$

p_T^γ cutoff (GeV)	Best-fit C_{3W} (TeV^{-2})		Observed 95% CL (TeV^{-2})		Expected 95% CL (TeV^{-2})	
	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM	SM+int. only	SM+int.+BSM
200	−0.85	−0.22	[−2.02, 0.40]	[−0.76, 0.40]	[−1.17, 1.29]	[−0.82, 0.72]
300	−0.26	−0.17	[−0.83, 0.35]	[−0.39, 0.29]	[−0.57, 0.60]	[−0.33, 0.33]
500	−0.13	−0.026	[−0.50, 0.26]	[−0.15, 0.12]	[−0.36, 0.38]	[−0.17, 0.16]
800	−0.20	−0.034	[−0.48, 0.11]	[−0.10, 0.08]	[−0.29, 0.31]	[−0.097, 0.095]
1500	−0.13	−0.009	[−0.37, 0.17]	[−0.062, 0.053]	[−0.28, 0.30]	[−0.065, 0.065]

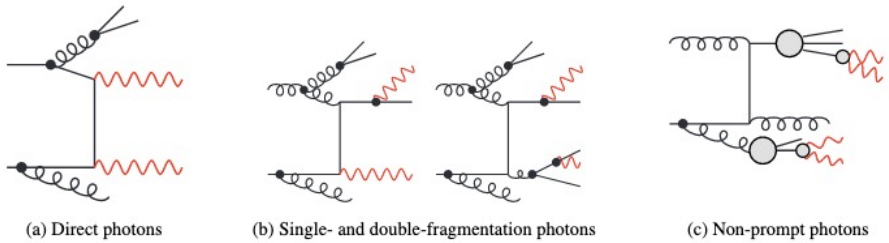
- >250 k signal events
- Among kinematic features: "radiation zero" in $\Delta\eta(\ell, \gamma)$ distribution





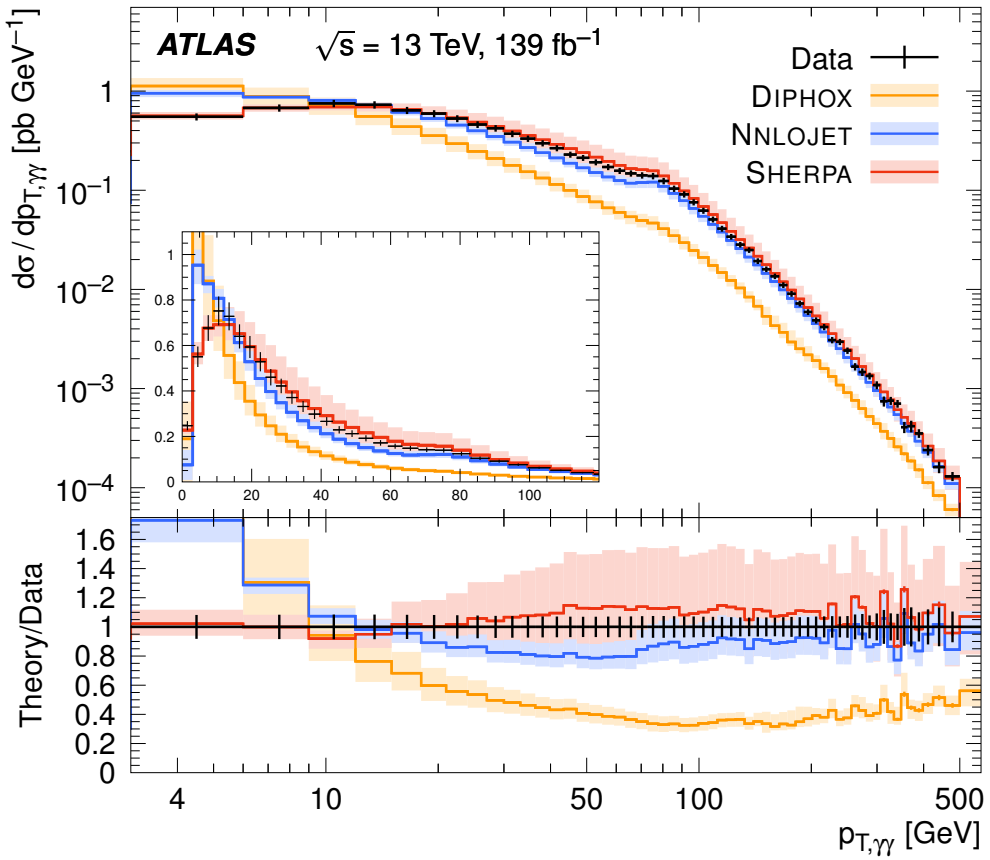
$\gamma\gamma$ Production

ATLAS STDM-2017-30 (arXiv:2107.09330)



- Production of two isolated photons
- $p_T > 40{,}30$ GeV
- data-driven background subtraction
- Differential cross section extracted as a function of many variables:
  - $p_{T(}\gamma_1), p_{T(}\gamma_2), m(\gamma\gamma), \cos\theta^*_{CS}$, acoplanarity, p_T with respect to thrust axis

Example of a differential distribution

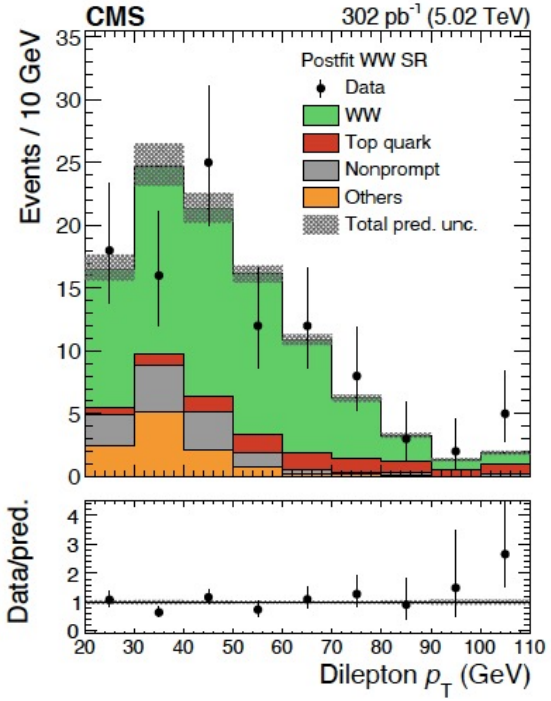


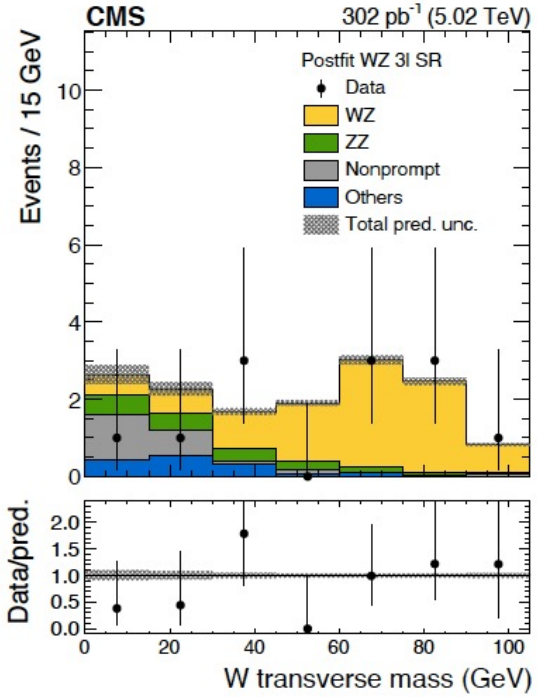
WW, WZ, ZZ at $\sqrt{s} = 5.08$ GeV

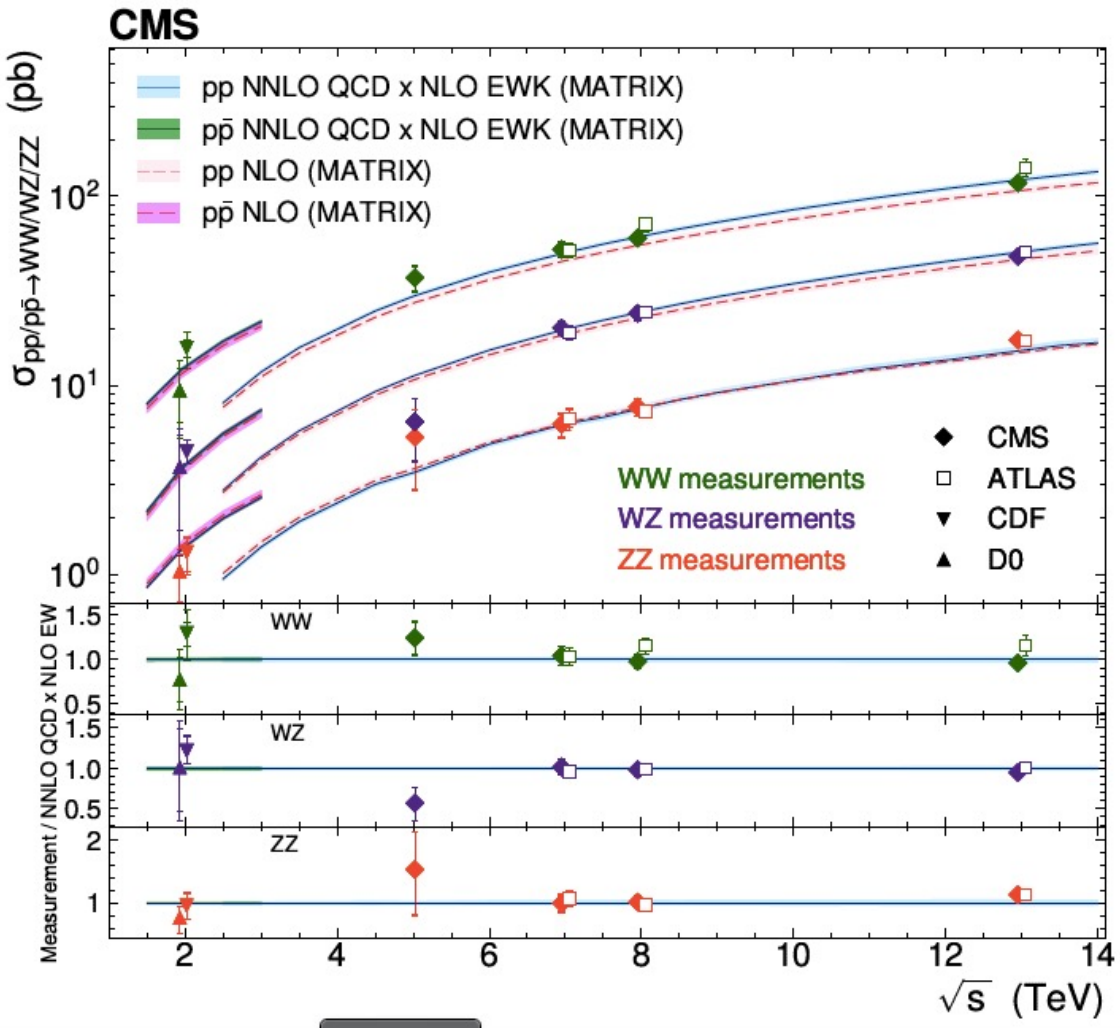
5.08 TeV, 302 pb^{-1}

- Fully leptonic decay modes

CMS SMP-20-012 (arXiv:2107.01137)



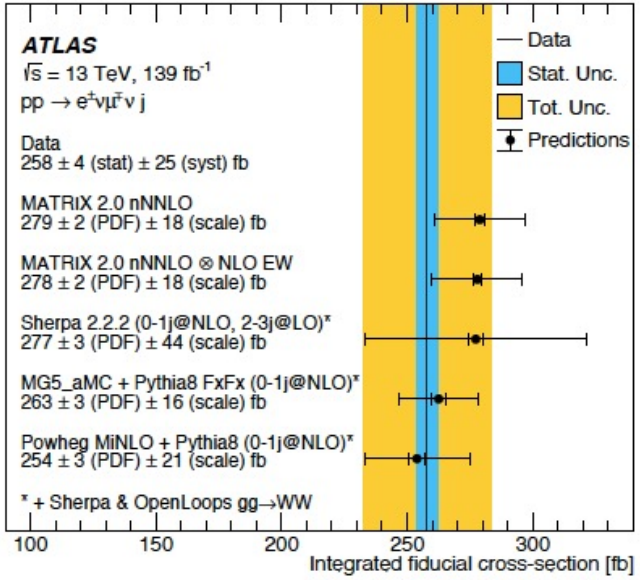


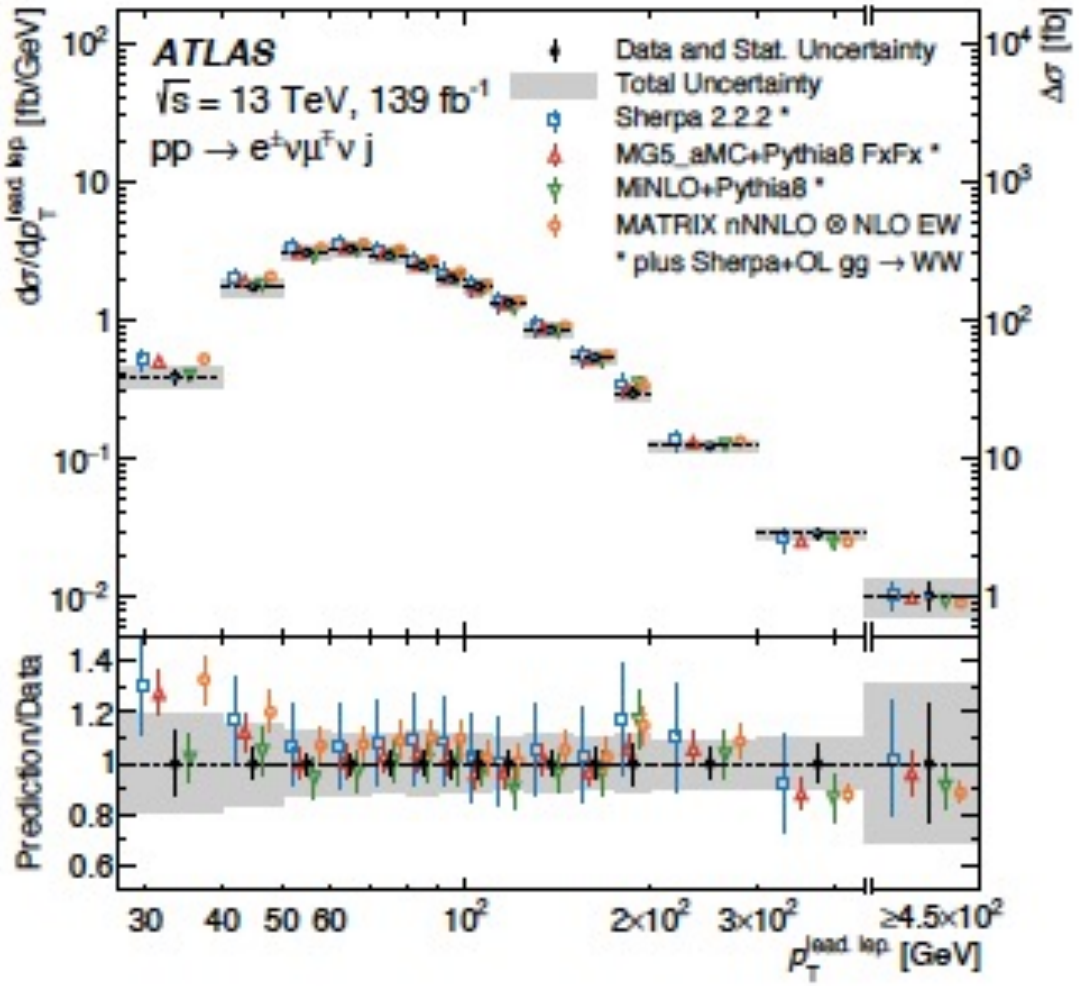


WW + 1 jet differential cross sections

ATLAS STDM-2018-34 (JHEP06 (2021)003)

- $pp \to e^{\pm}\nu\mu^{\mp}\nu j$

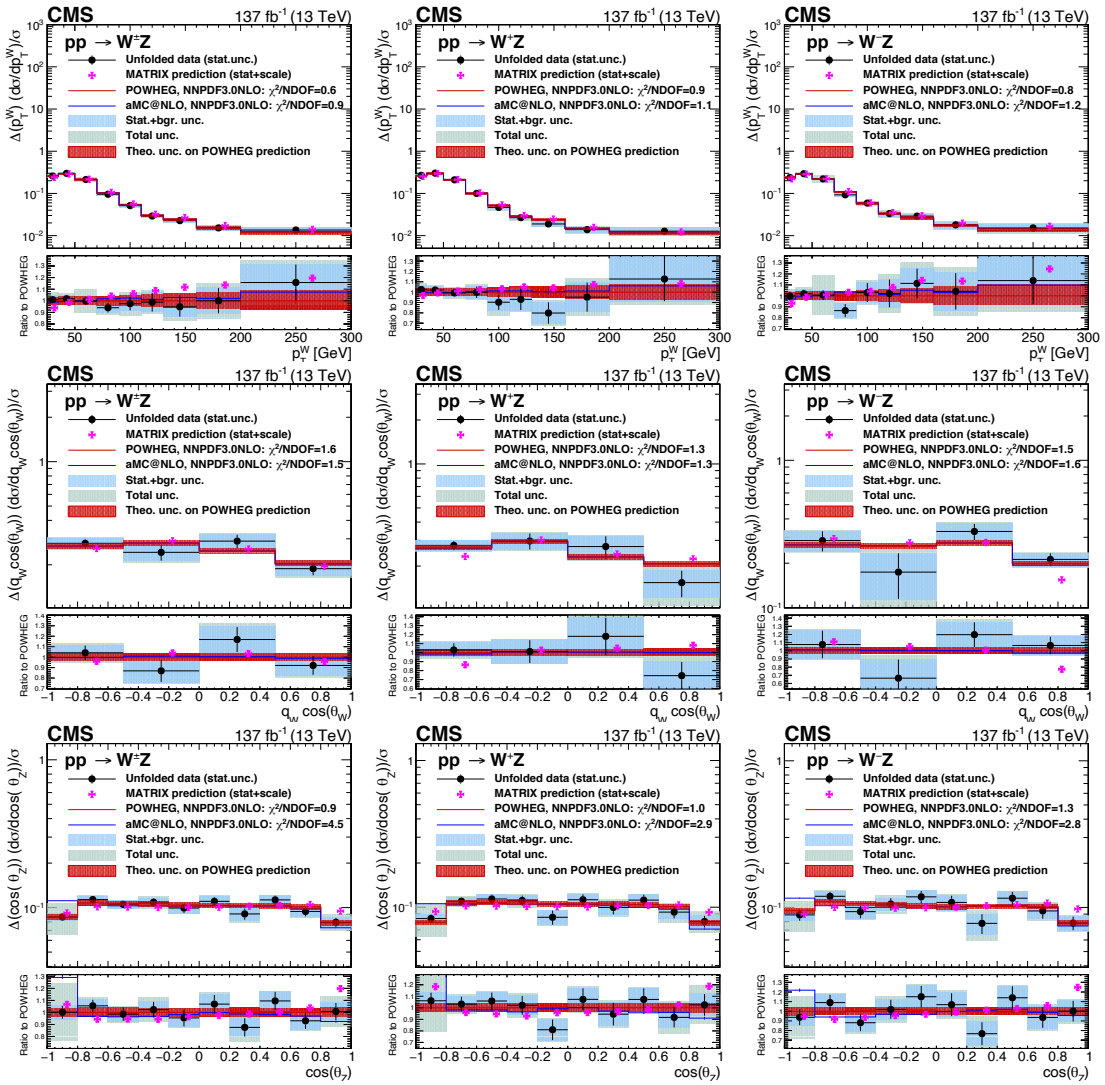


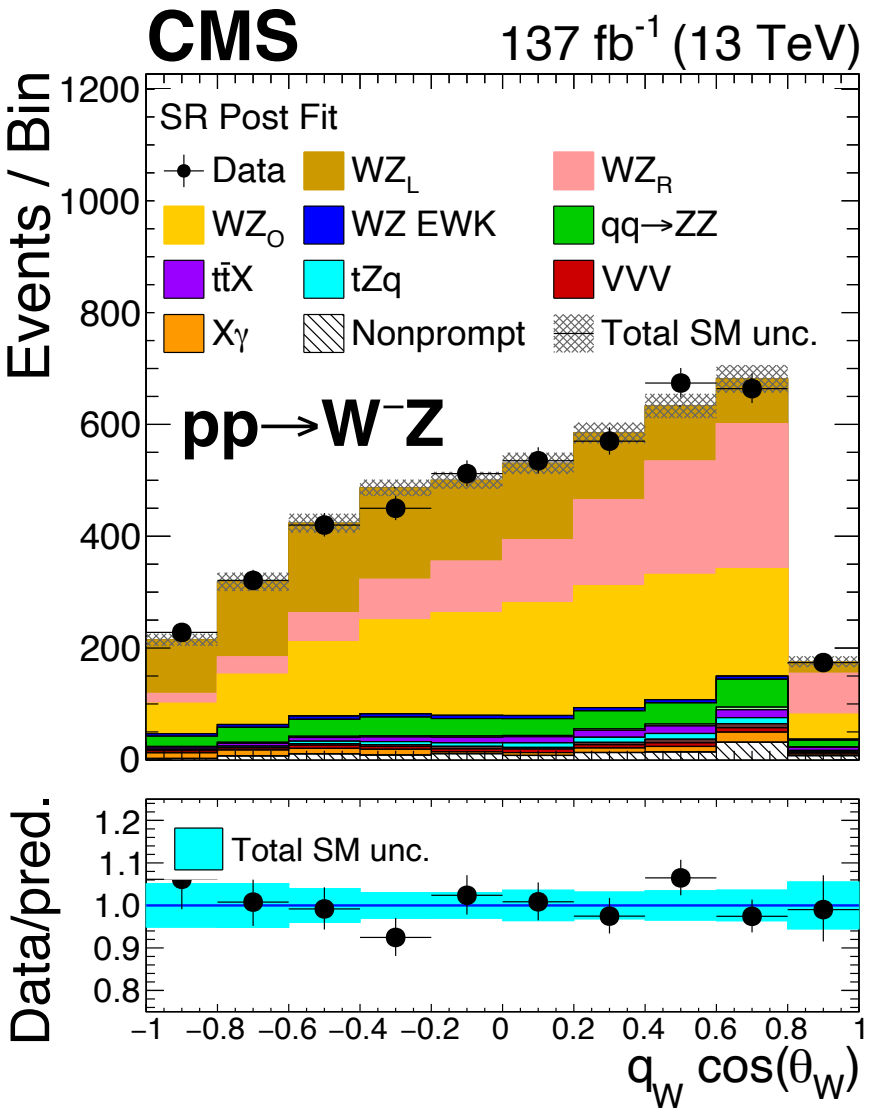


- Differential cross section measured as a function of
  - $p_T(\ell_1), p_T(\ell_2), p_T(j_1), m(e\mu),$
  - $H_T, S_T, p_T(e\mu), m_T(e\mu)$

WZ (leptonic) differential cross sections, and polarization

CMS SMP-20-014 (arXiv:2110.11231)

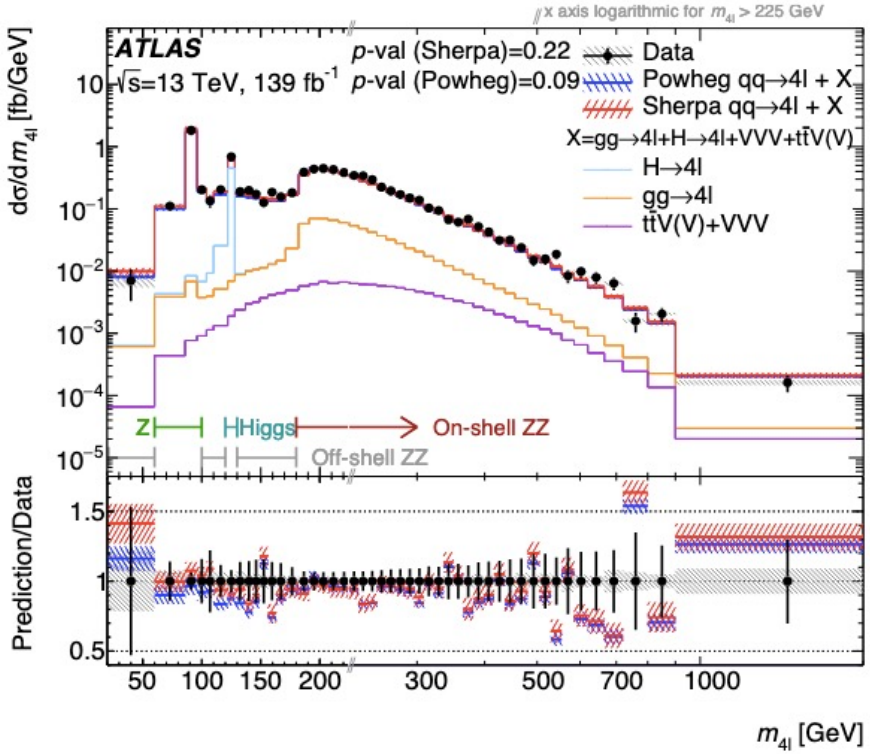


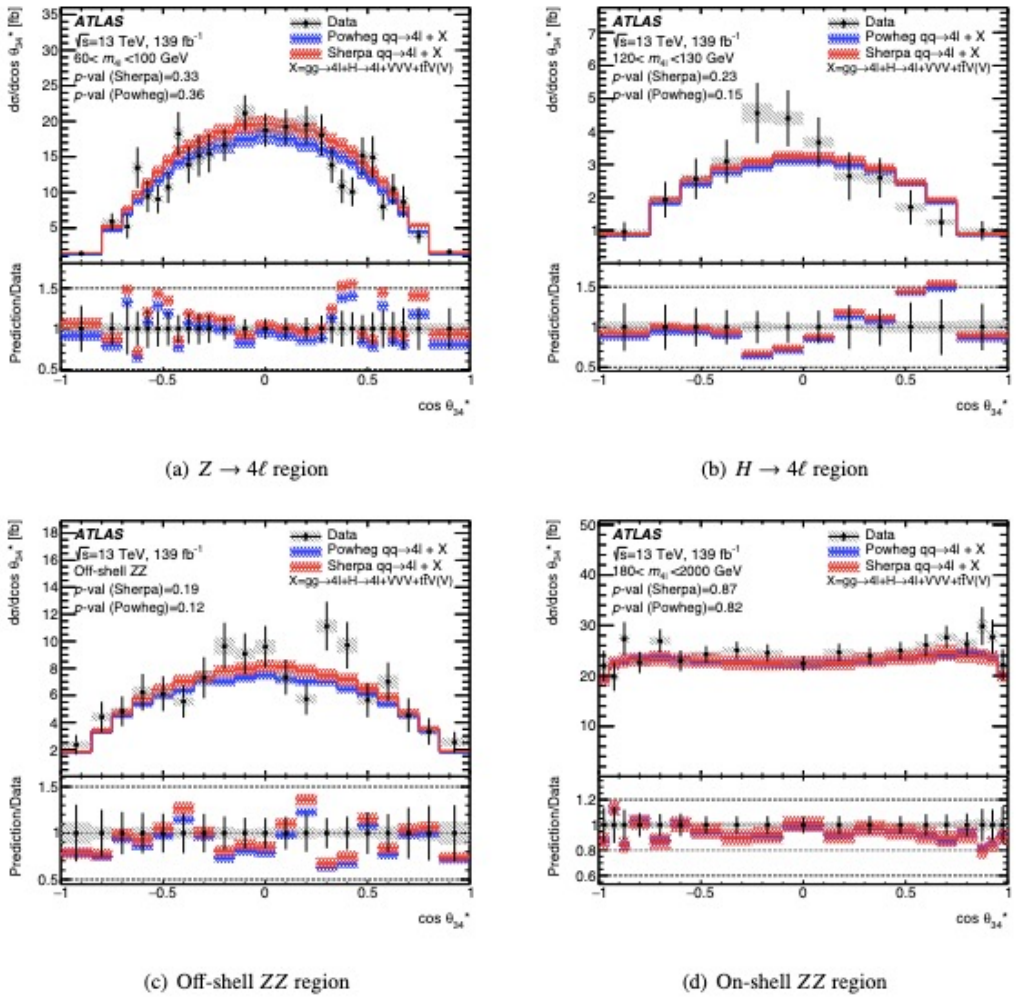


Differential Cross Section for $Z/\gamma^* Z/\gamma^* \rightarrow 4\ell$

ATLAS STDM-2018-30 (JHEP07 (2021) 005)

- Include at SM processes that can contribute to the 4ℓ final state
  - Including $Z \rightarrow 4\ell$ and $H \rightarrow ZZ^* \rightarrow 4\ell$





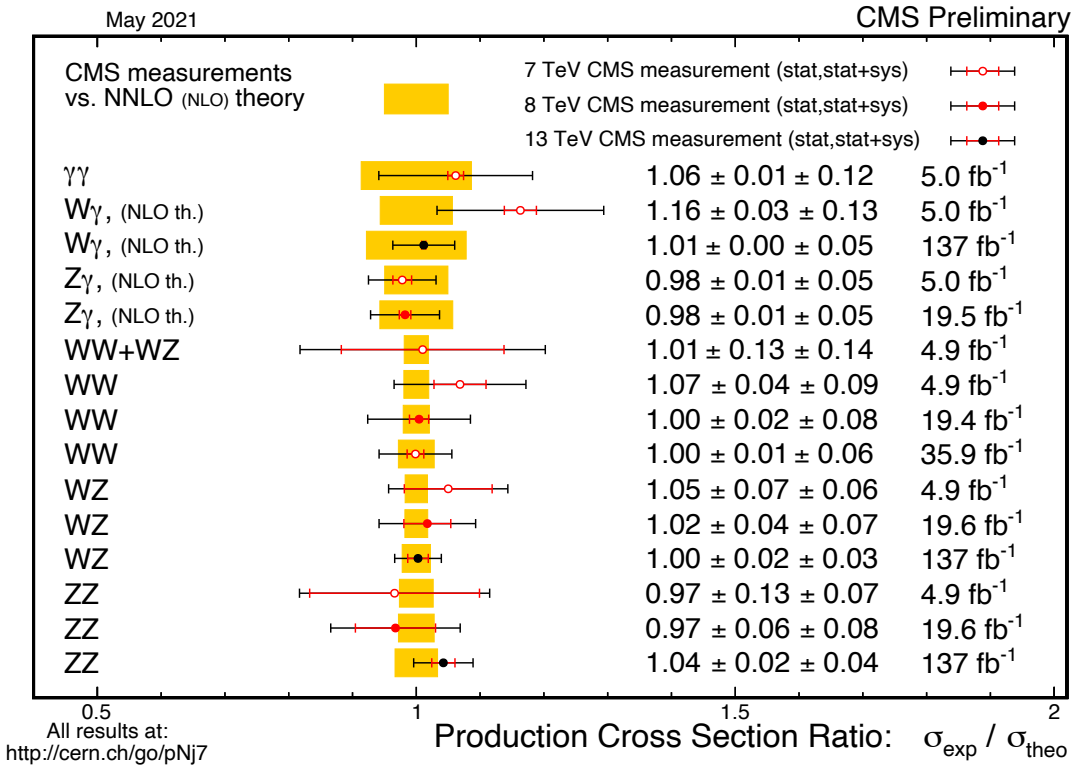
(a) $Z \rightarrow 4\ell$ region

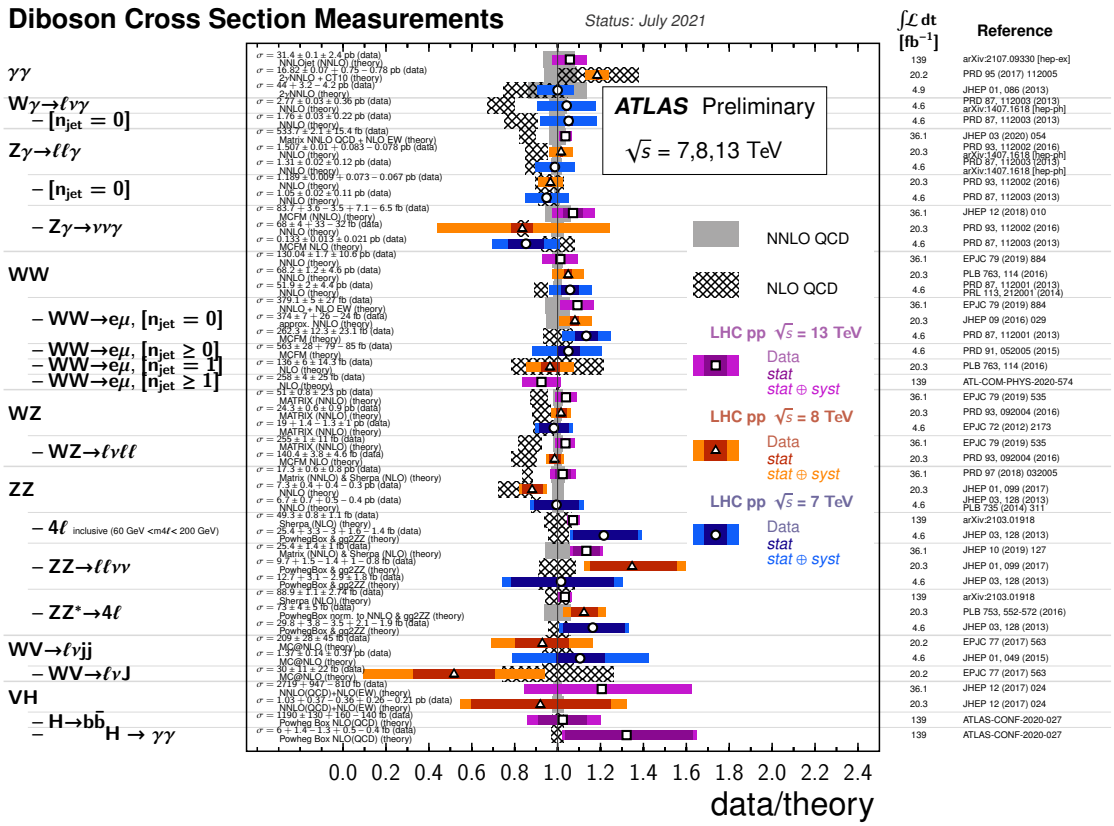
(b) $H \rightarrow 4\ell$ region

(c) Off-shell ZZ region

(d) On-shell ZZ region

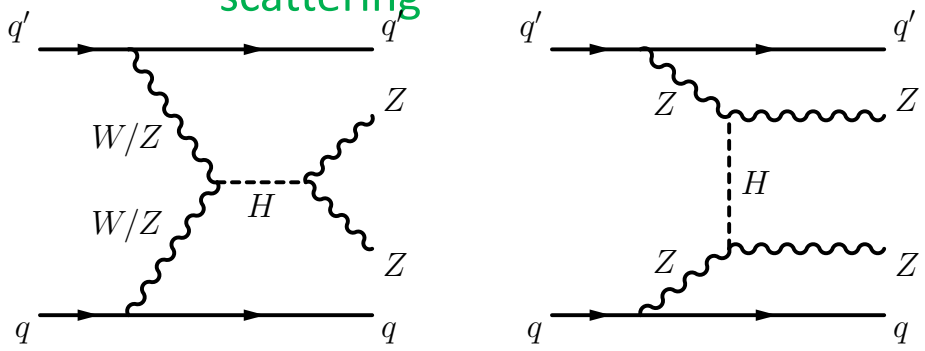
Summary plots of diboson cross sections





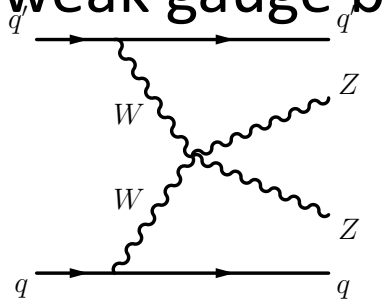
Vector Boson Scattering

- VBS process is particularly interesting
  - Pure Electroweak process ($\mathcal{O}(\alpha^6)$)
  - Connected with Electroweak symmetry breaking
    - Higgs diagrams are needed to avoid violation of unitarity
    - Longitudinal components of W and Z are expected to play a special role in the scattering



Feynman diagrams from ATLAS STDM-2017-19

- VBS is sensitive to quartic couplings of electroweak gauge bosons

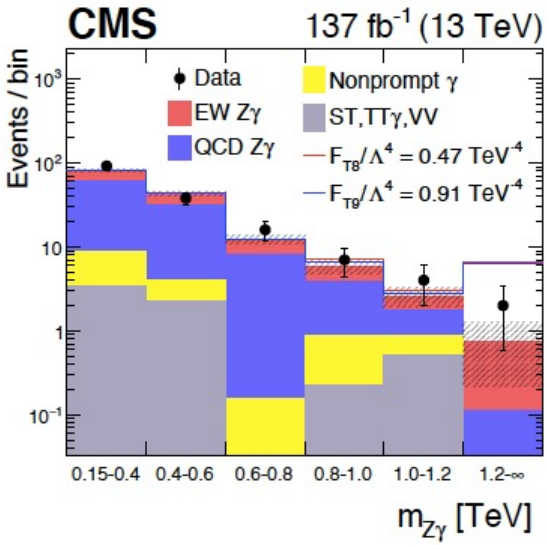


- Characterize couplings with effective field theory
  - $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4}\mathcal{O}_i^{(8)} + \cdots\right]$
- Dimension-8 operators can modify VVjj production through anomalous quartic gauge couplings (aQGCs)

Electroweak Production of $Z\gamma + 2$jets

CMS SMP-20-016 ([PhysRevD, 104, 072001 (2021)])

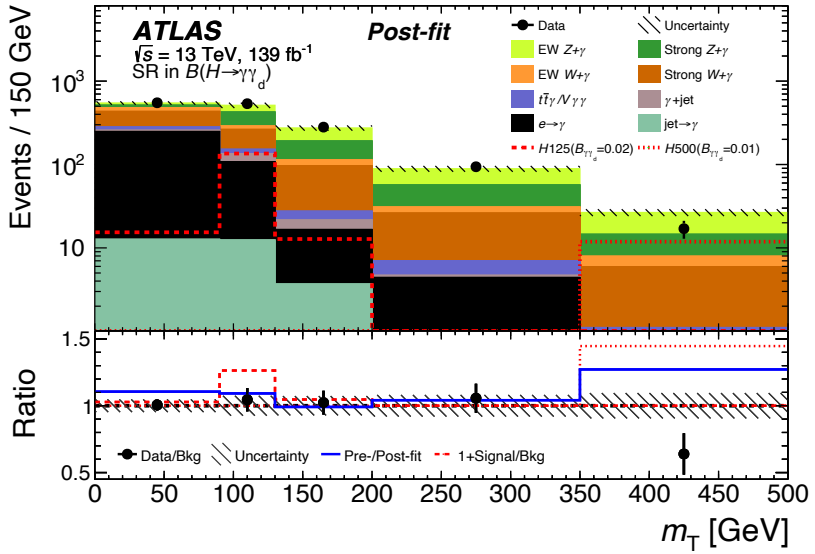
- First observation of electroweak production of $Z\gamma$
- $Z \to ee, \mu\mu \quad p_T(\gamma) > 20$ GeV
- $m(jj) > 500$ GeV, $|\Delta\eta_{jj}| > 2.5$



- Single and double differential distributions measured
- Most stringent limit to date on the aQGC parameter FT9/L4

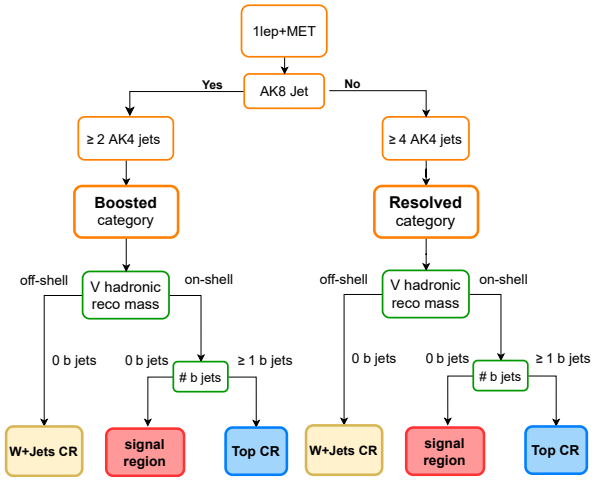
ATLAS EXOT-2021- 17 ((arXiv:2109.00925)

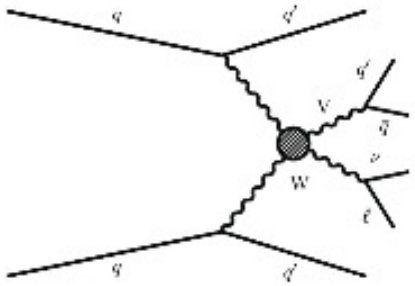
- Observation of electroweak production of $Z\gamma$ in $Z \to \nu\nu$

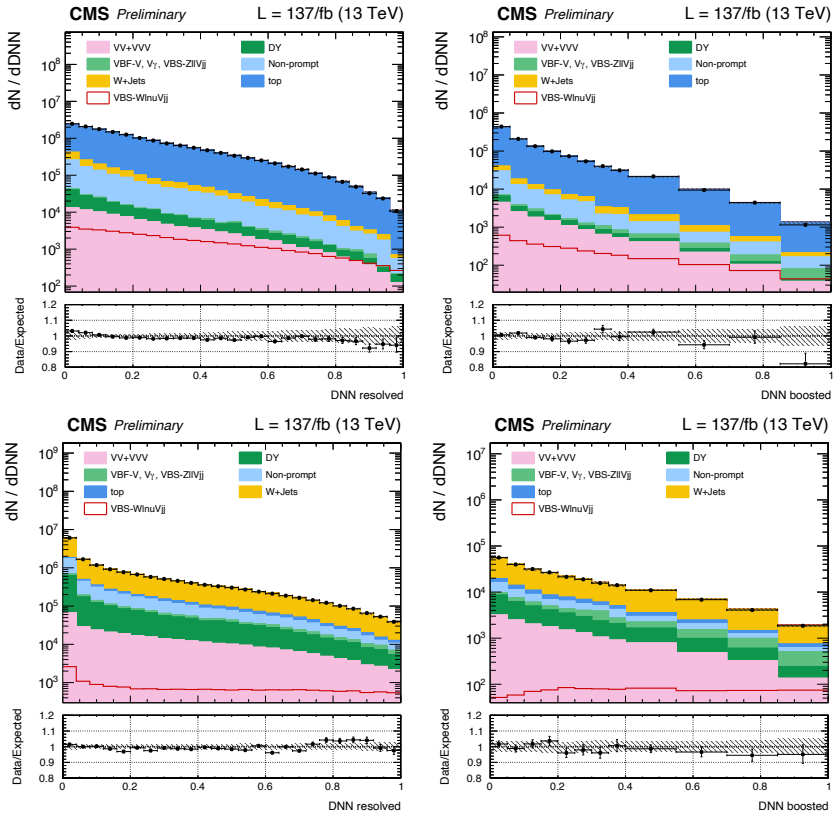


WZ (semileptonic) electroweak production

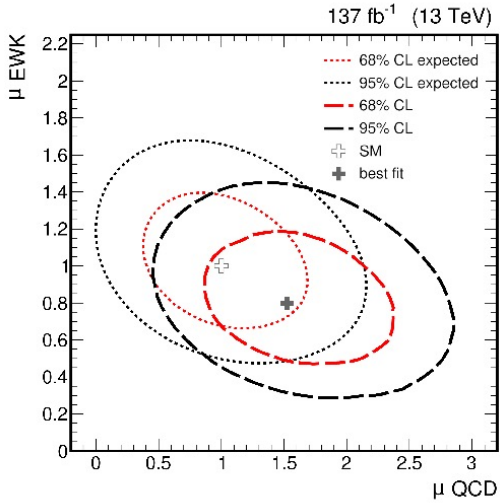
- $pp \to WVjj$ with $W \to \ell\nu$ and $V \to q\bar{q}^{(\prime)}$
- Uses either two resolved jets or one boosted jet for the $V \to q\bar{q}^{(\prime)}$ candidate
- Control regions in data used to assess main backgrounds: W +jets and top







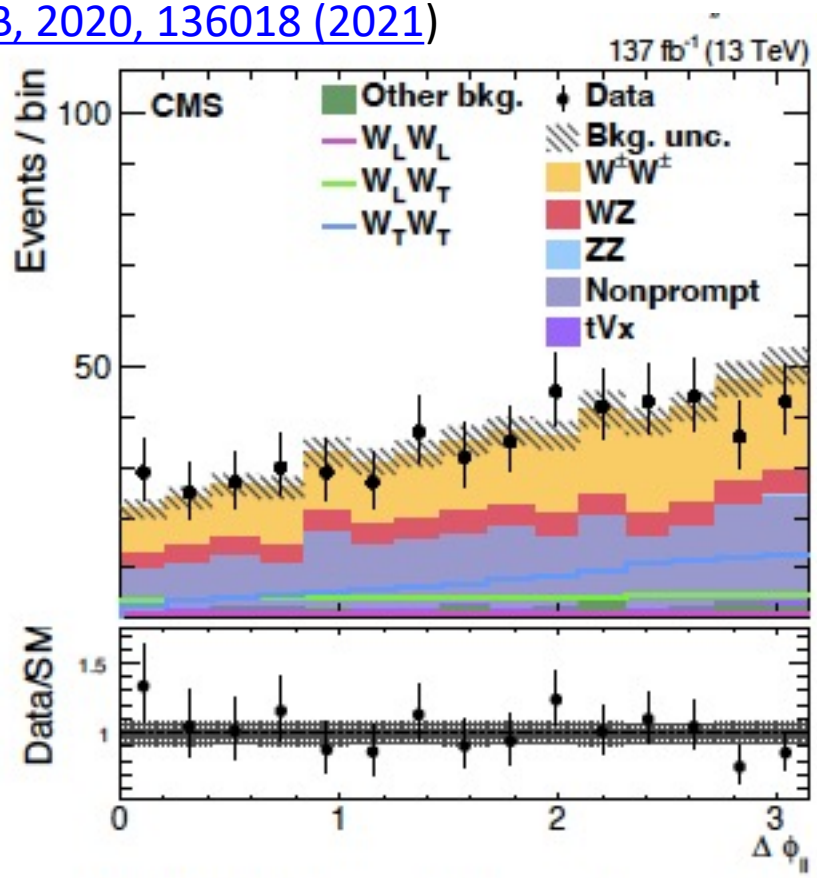
- Multivariate discriminator (DNN) used to separate QCD and EWK production
  - Simultaneous fit to QCD and EWK signal strengths



Polarization Measurement in $W^{\pm}\,W^{\pm}$

CMS SMP-20-006 (Phys. Let. B, 2020, 136018 (2021))

- $m(jj) > 500$ GeV, $|\Delta\eta_{jj}| > 2.5$
- Same sign lepton selection (further favors EWK production)
- three distinct polarization contributions: $W_L W_L$, $W_L W_T$, $W_T W_T$
- 14 variables sensitive to polarization included in BDT
  - $\Delta\phi_{\ell\ell}$, $\Delta\phi_{jj}$, $m(\ell\ell)$, etc.
- Significance for at least one W_L
  - 2.3 σ (3.1 σ) observed (expected)

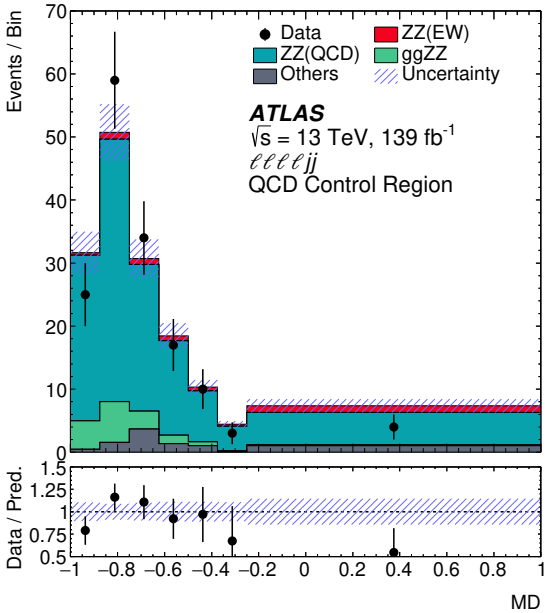


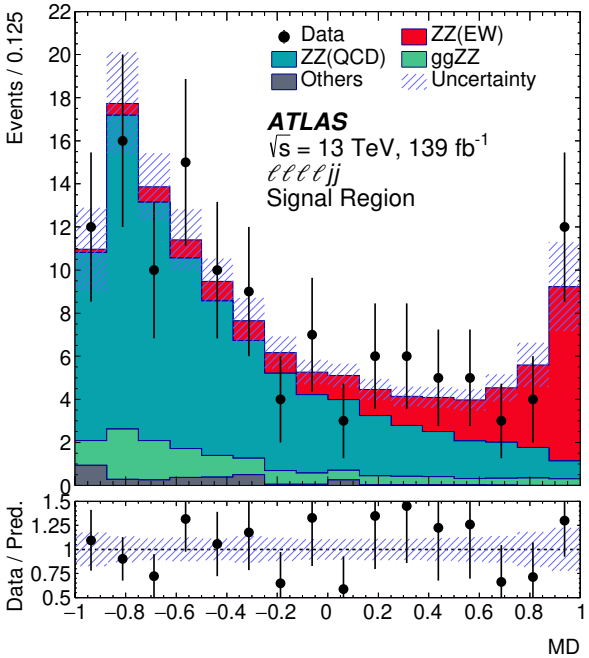
Process	$\sigma\,\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_L W^{\pm}_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^{\pm}_X W^{\pm}_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^{\pm}_L W^{\pm}_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^{\pm}_T W^{\pm}_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

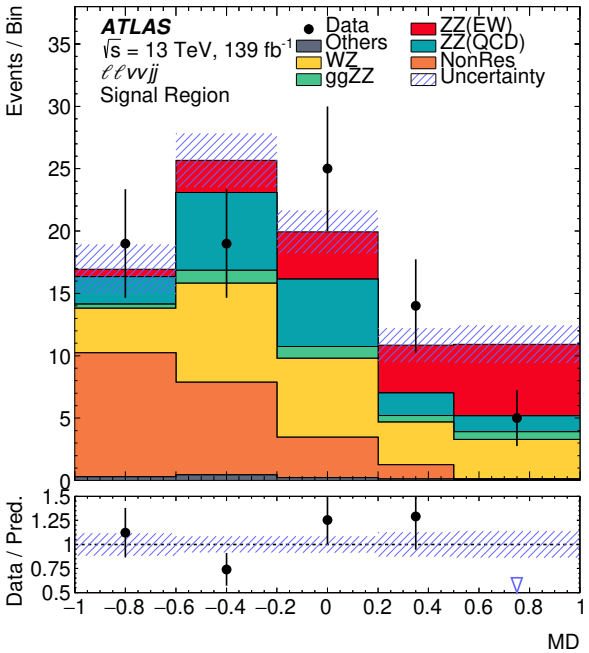
Electroweak ZZ production (ZZ + 2jets)

- ATLAS STDM-2017-19 (arXiv:2004.10612): First observation of EWK ZZ production (5.5 σ)
  - Previous CMS-20-001 (Phys. Let. B, 2020, 135992 (2021)) : 3.5 σ
- Uses both $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ channels

- Multivariate discriminator used to help separate QCD and EWK production



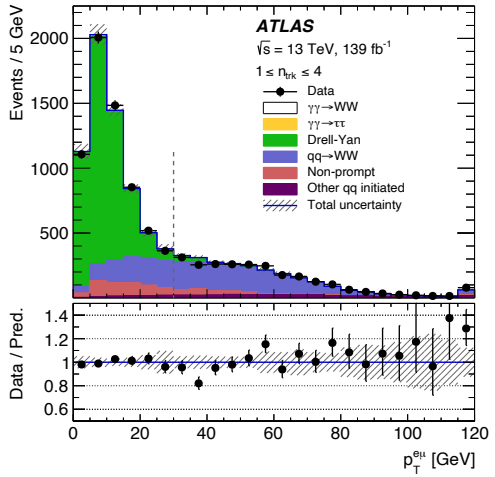


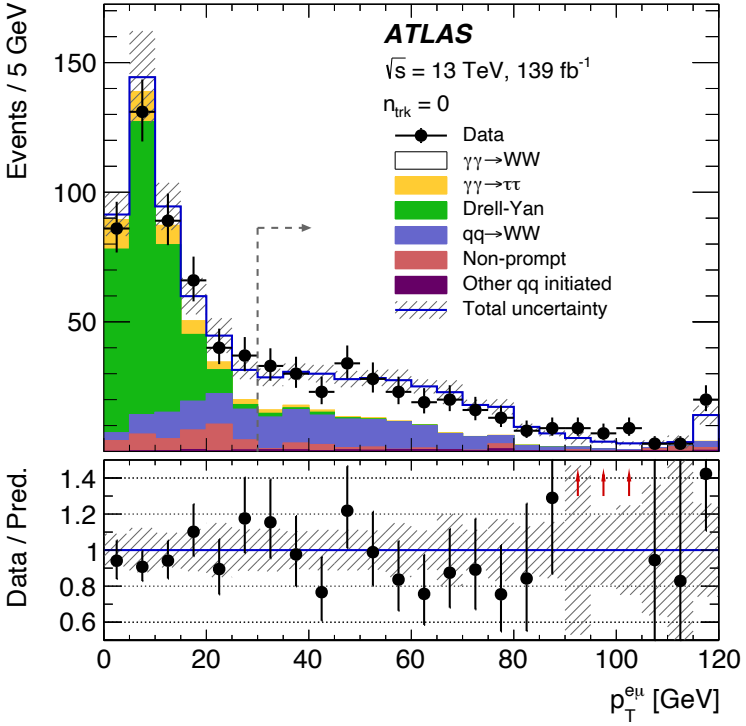


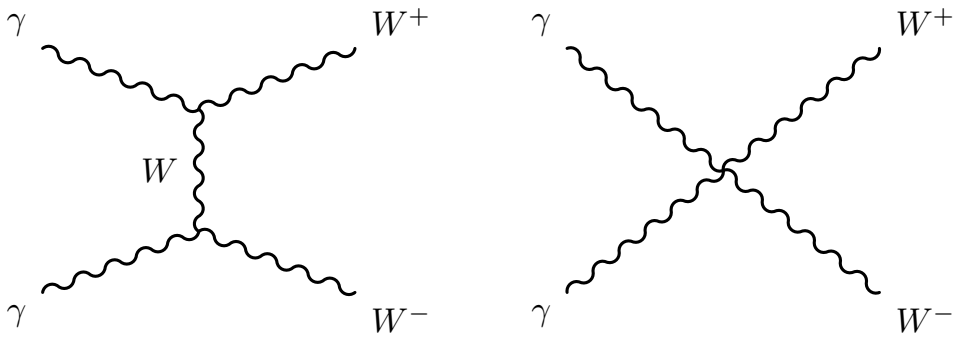
Photon-induced WW production

ATLAS STDM-2017-21 (Phys. Let. B, 2021, 136190 (2021))

- $WW \to e^{\pm}\nu\mu^{\mp}\nu$ with a requirement for no extra tracks associated with the production vertex
- Expect contributions from elastic production, as well as some diffractive
- Requires careful treatment of tracks from pileup vertices
- Significance: 8.4 σ

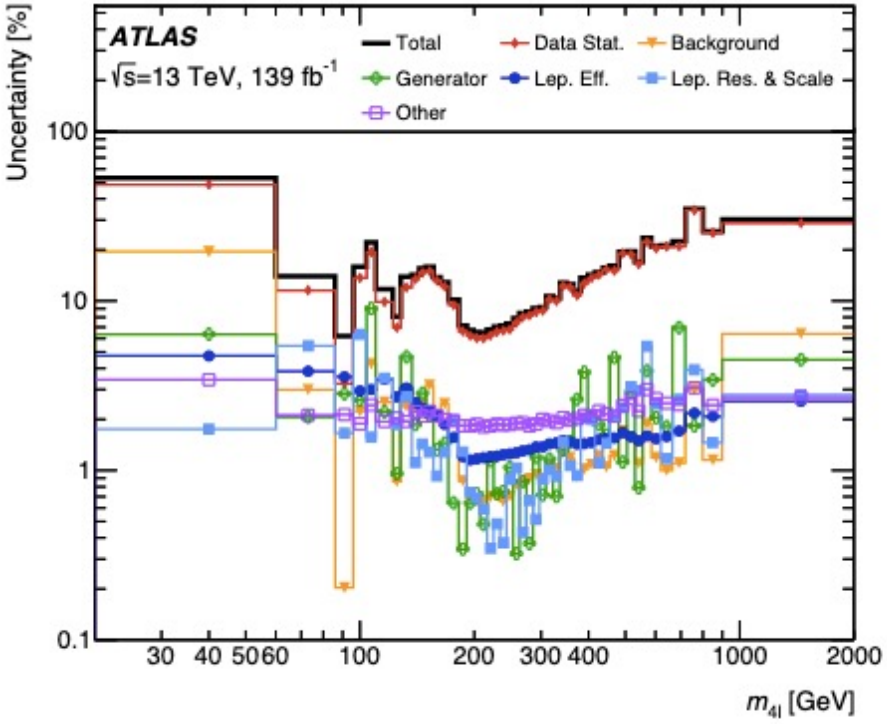






Diboson prospects

- Almost all analyses shown use the full LHC Run 2 data sets
  - Run 3 to begin next year (data sets approximately double)
- Large increase in LH-LHC
- Most diboson results are statistically limited



Example from ATLAS STDM-2018-30

BACKUPS

Selected recent ATLAS and CMS diboson results

Experiment	index	topic	status	link
CMS	SMP-19-002	W gamma	published	10.1103/PhysRevLett.126.252002
CMS	SMP-20-005	W gamma	preliminary	CMS-PAS-SMP-20-005
ATLAS	STDM-2017-30	Gamma-gamma	submitted	arXiv:2107.09330
CMS	SMP-20-012	WW, WZ, ZZ at sqrt(s)=5.08 TeV	submitted	arXiv:2107.01137
CMS	SMP-20-014	WZ (leptonic)	submitted	arXiv:2110.11231
ATLAS	STDM-2018-34	WW+1jet	published	10.1007/JHEP06(2021)003
ATLAS	STDM-2018-30	Z/g* Z/g* to 4l	published	10.1007/JHEP07(2021)005
ATLAS	STDM-2017-19	ZZjj VBS	submitted	arXiv:2004.10612
CMS	SMP-20-013	WZ VBS semieptonic	preliminary	https://cds.cern.ch/record/2776799
CMS	SMP-20-016	Z(ll)gamma+2jets	published	10.1103/PhysRevD.104.072001
ATLAS	STDM-2017-26	Z(ll)gamma+2jets	published	10.1016/j.physletb.2020.135341
ATLAS		Z(ll)gamam+2jets	preliminary	http://cdsweb.cern.ch/record/2779171
ATLAS	EXOT-2021-17	Z(vv)gamma+2jets	submitted	arXiv:2109.00925
CMS	SMP-20-006	W polarization in same-sign VBS	published	10.1016/j.physletb.2020.136018
CMS	SMP-20-001	ZZjj VBS	published	10.1016/j.physletb.2020.135992
ATLAS	STDM-2017-21	Photon-induced WW	published	10.1016/j.physletb.2021.136190