Multibosons in ATLAS and CMS

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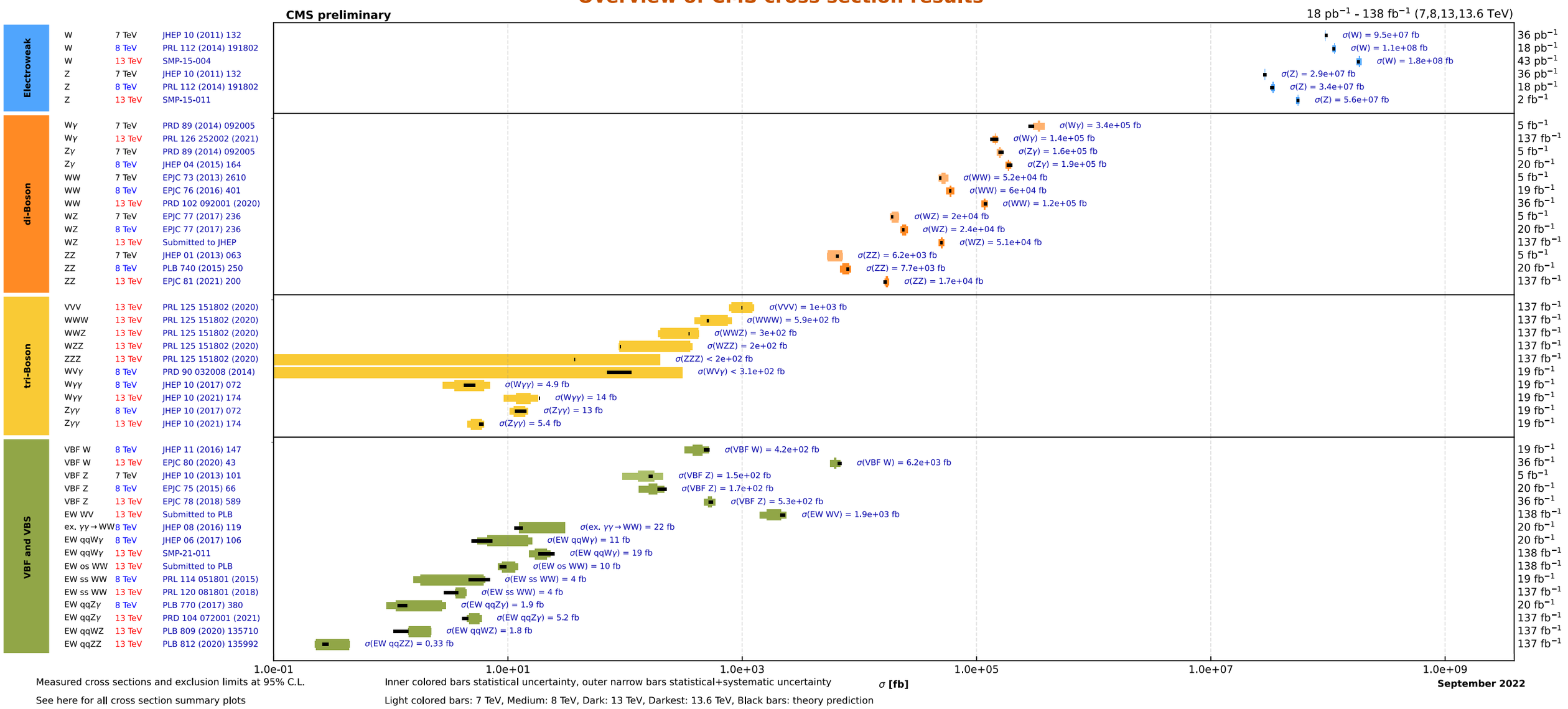
Fermilab

On behalf of the CMS and ATLAS Collaborations

Many EWK physics results from ATLAS and CMS precision measurements of cross sections spanning 9 orders of magnitude



CMS Summary plots

ATLAS Summary plots

Run 3 of the LHC is ongoing, will have doubled Run 2 luminosity mid-2024

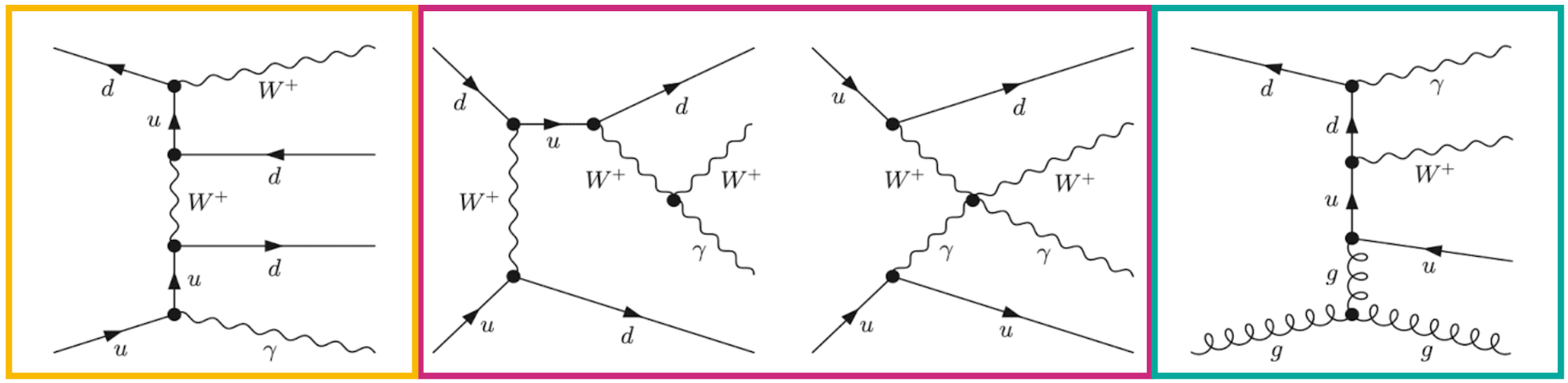
New EWK results from ATLAS and CMS are difficult analyses with full Run 2 dataset

I will present four of the most recent results today

WɣWɣ+2 jets

- Vector boson scattering (VBS) processes crucial to understanding EWK symmetry breaking

non VBS EWK process | EWK-induced VBS signal | QCD induced background



- Select events with leptonic W decay (e/μ + p_T^{miss}), photon, and two jets
  - Suppress QCD-induced and non-VBS contribution by
    - Jets required to have large separation in pseudorapidity and high di-jet mass
    - WɣWɣ system be balanced by the jet system in azimuthal angel

CMS SMP-21-011 2212.12592

Event Selection:

exactly 1 e/μ

$p_T^{\ell} > 35$ GeV

$p_T^{\gamma} > 25$ GeV

$p_T^{\text{miss}} > 30$ GeV

$m_T^W > 30$ GeV

$m_T^W = \sqrt{2 p_T^{\ell} p_T^{\text{miss}} [1 - \cos(\Delta\phi_{\ell, p_T^{\text{miss}}})]}$

$N_{\text{jets}} \geq 2$

$|\eta_{\text{jet}}| < 4.7$

$p_T^{\text{jet}} > 50$ GeV

$\Delta R(\text{any}) > 0.5$

if electron:

$|m_{\ell\gamma} - m_Z| > 10$GeV

$m_{jj} > 500$ GeV

$|\Delta\eta_{jj}| > 2.5$

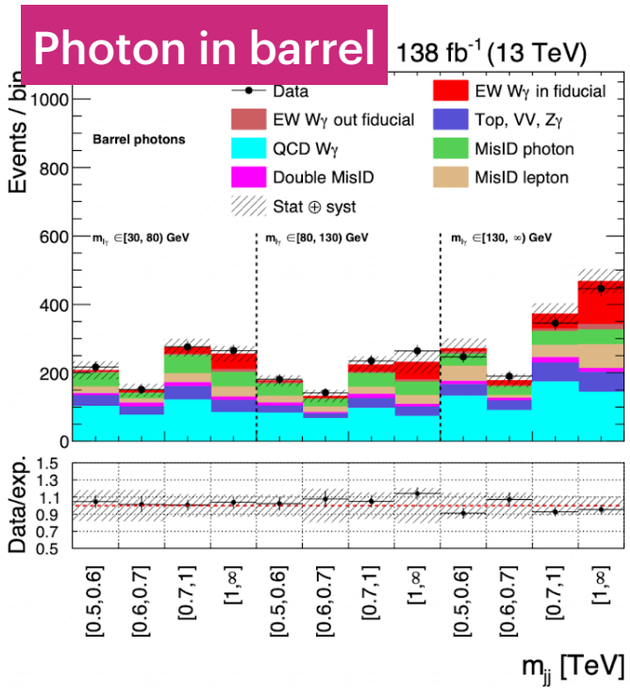
$m_{W\gamma} > 100$ GeV

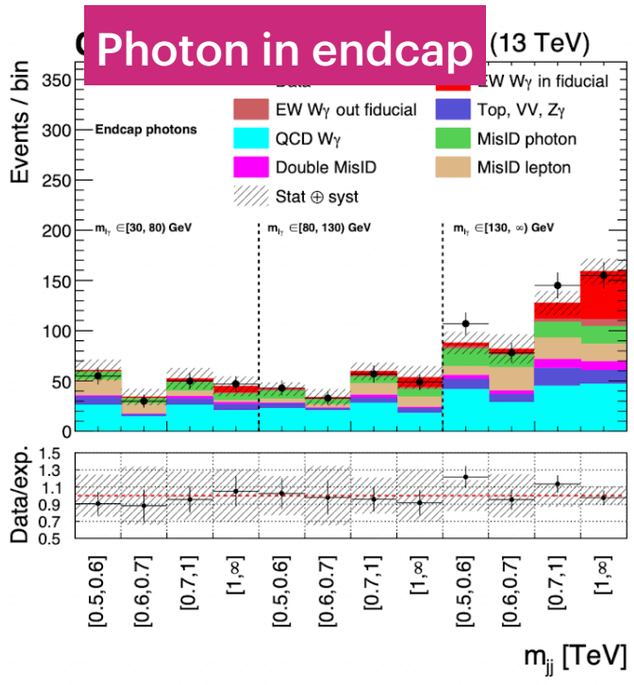
$|y_{W\gamma} - (y_{j1} + y_{j2})/2| < 1.2$

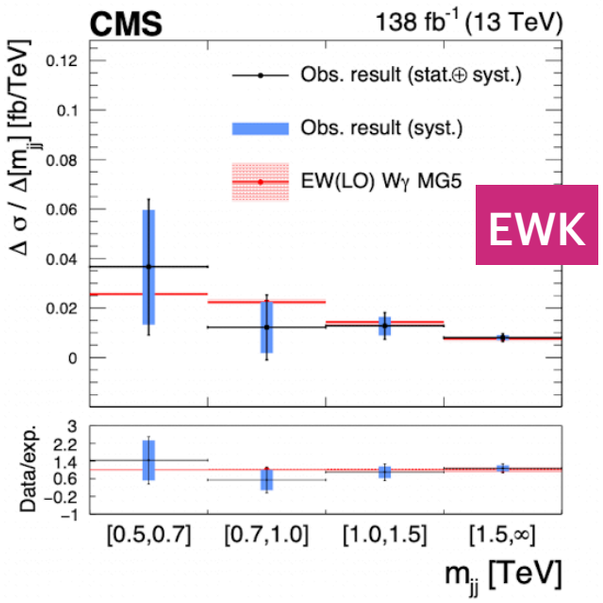
$|\phi_{W\gamma} - \phi_{jj}| > 2$

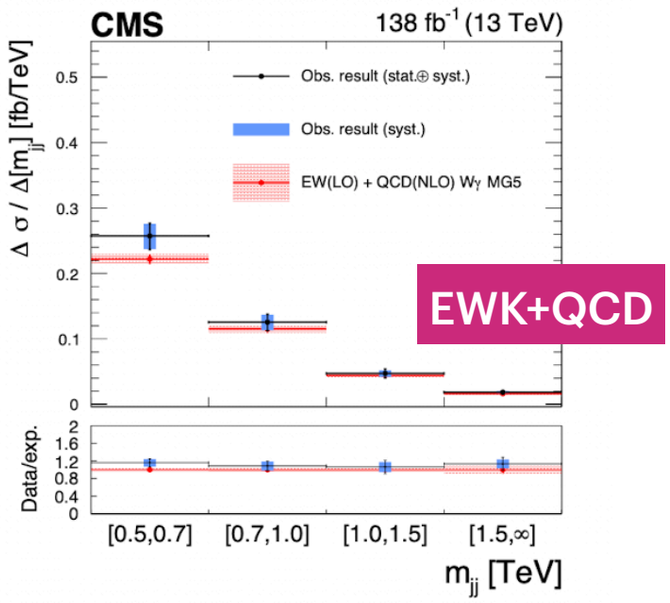
Wγ+2 jets

- Main background from mis-identified photons and/or leptons estimated from data
  - Separated into barrel and endcap to account for differences in photon performance
- Dominant systematic uncertainty from non-prompt photon/lepton data-driven background estimation
- Measure EWK-only and EWK+QCD fiducial and differential cross sections and observe good agreement with SM









Fiducial cross sections:

$$\sigma_{\mathrm{EW}}^{\mathrm{fid}} = 23.5 \pm 2.8\,(\mathrm{stat})^{+1.9}_{-1.7}\,(\mathrm{theo})^{+3.5}_{-3.4}\,(\mathrm{syst})\,\mathrm{fb} = 23.5^{+4.9}_{-4.7}\,\mathrm{fb}.$$

$$\sigma_{\mathrm{EW+QCD}}^{\mathrm{fid}} = 113 \pm 2.0\,(\mathrm{stat})^{+2.5}_{-2.3}\,(\mathrm{theo})^{+13}_{-13}\,(\mathrm{syst})\,\mathrm{fb} = 113 \pm 13\,\mathrm{fb}.$$

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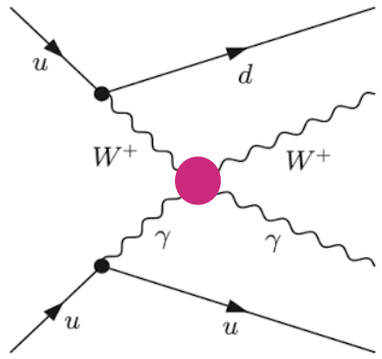
$|y_{W\gamma} - (y_{j1} + y_{j2})/2| < 1.2$

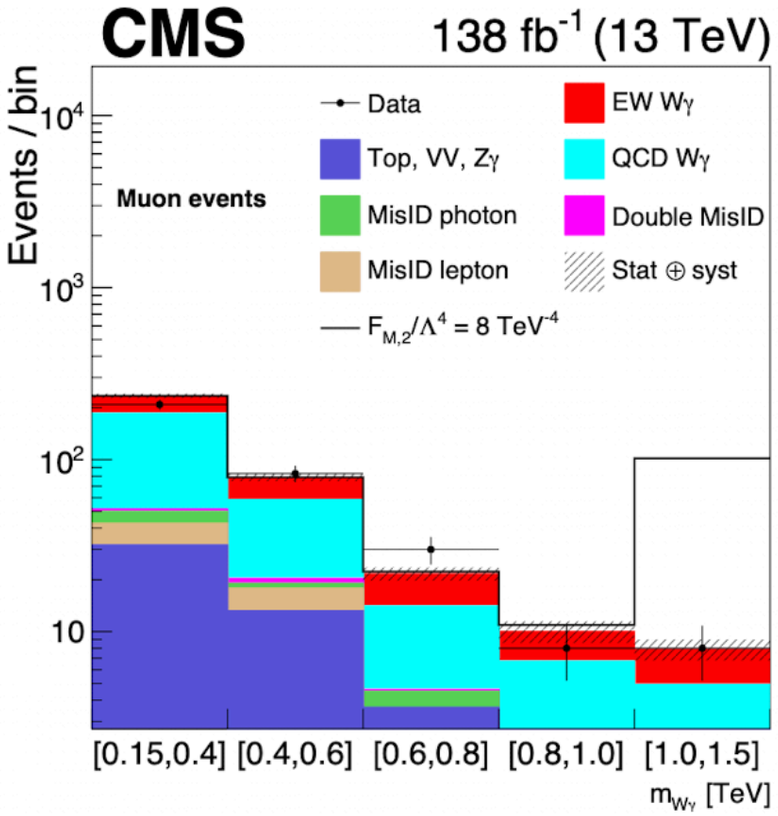
$|\phi_{W\gamma} - \phi_{jj}| > 2$

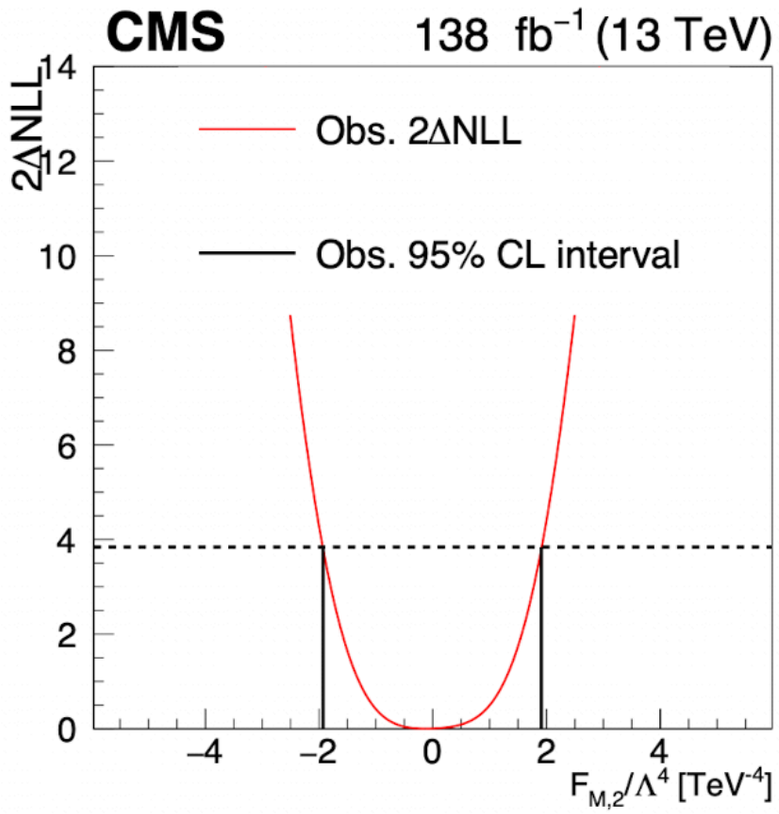
WɣWɣ+2 jets

- VBS very powerful to study anomalous quartic gauge couplings (aQGC)
  - Add additional selection to enhance VBS process even further — increase di-jet mass requirement and require more separation of jets
  - aQGC signal would enhance production at high m(Wɣ)



- Sets most stringent limits on $f_{M,2-4}/\Lambda^4$ and $f_{T,6-7}/\Lambda^4$





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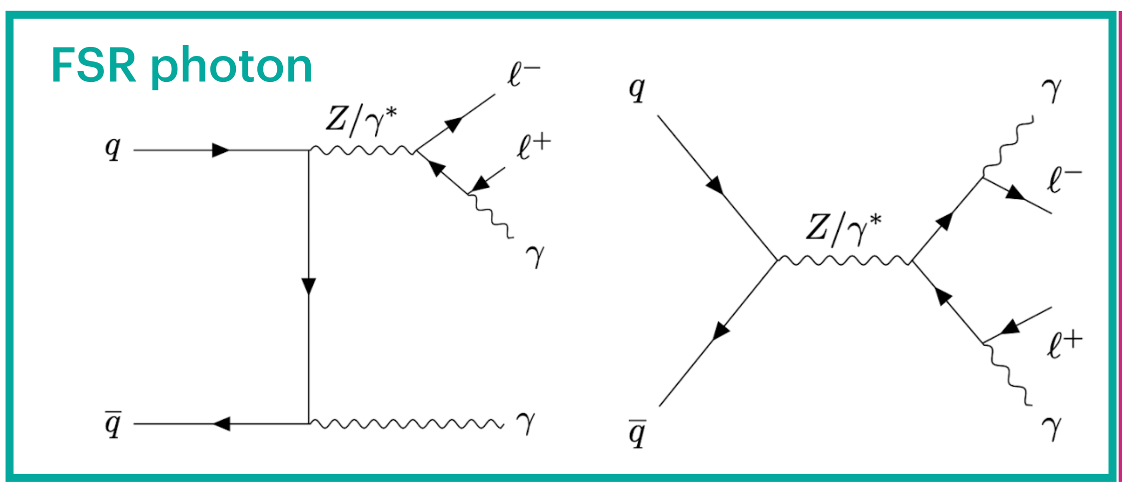
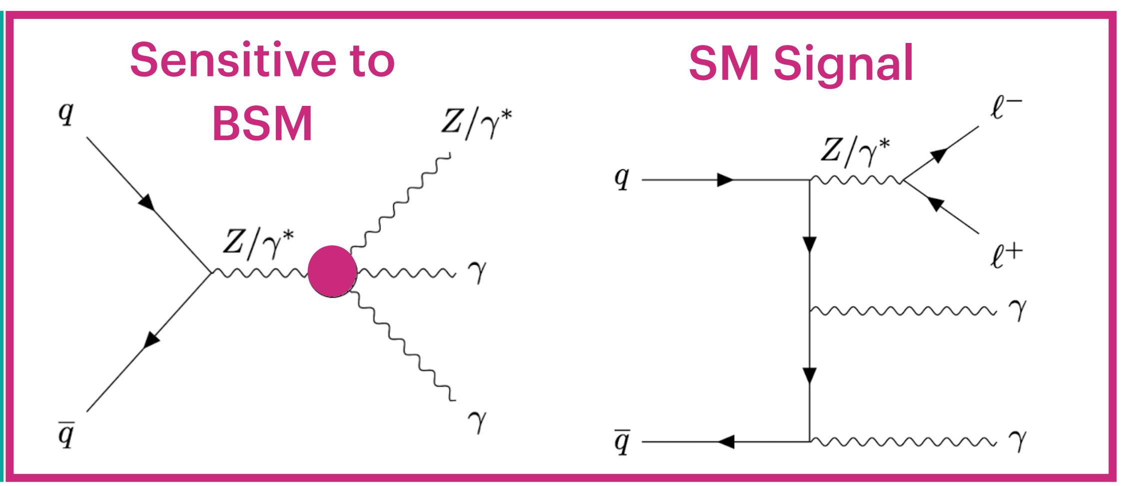
ZƔƔ

- Study triboson process that is only accessible with Run 2 luminosity → test EWK SM and constrain anomalous couplings
- Precision ZƔƔ measurement also important because it is an irreducible background in $Z(\rightarrow \ell\ell)H(\rightarrow \gamma\gamma)$ production, as well as to searches for resonances in $\ell\ell\gamma\gamma$ final state
- FSR diagrams are suppressed in event selection to make a cleaner interpretation





ATLAS STDM-2021-09
2211.14171

Event Selection:

≥1 SFOS e/μ pair
one trigger-matched l

leading lepton:
$p_T^\ell > 30$ GeV
pass *Tight* ID

$m_{\ell\ell} > 40$ GeV

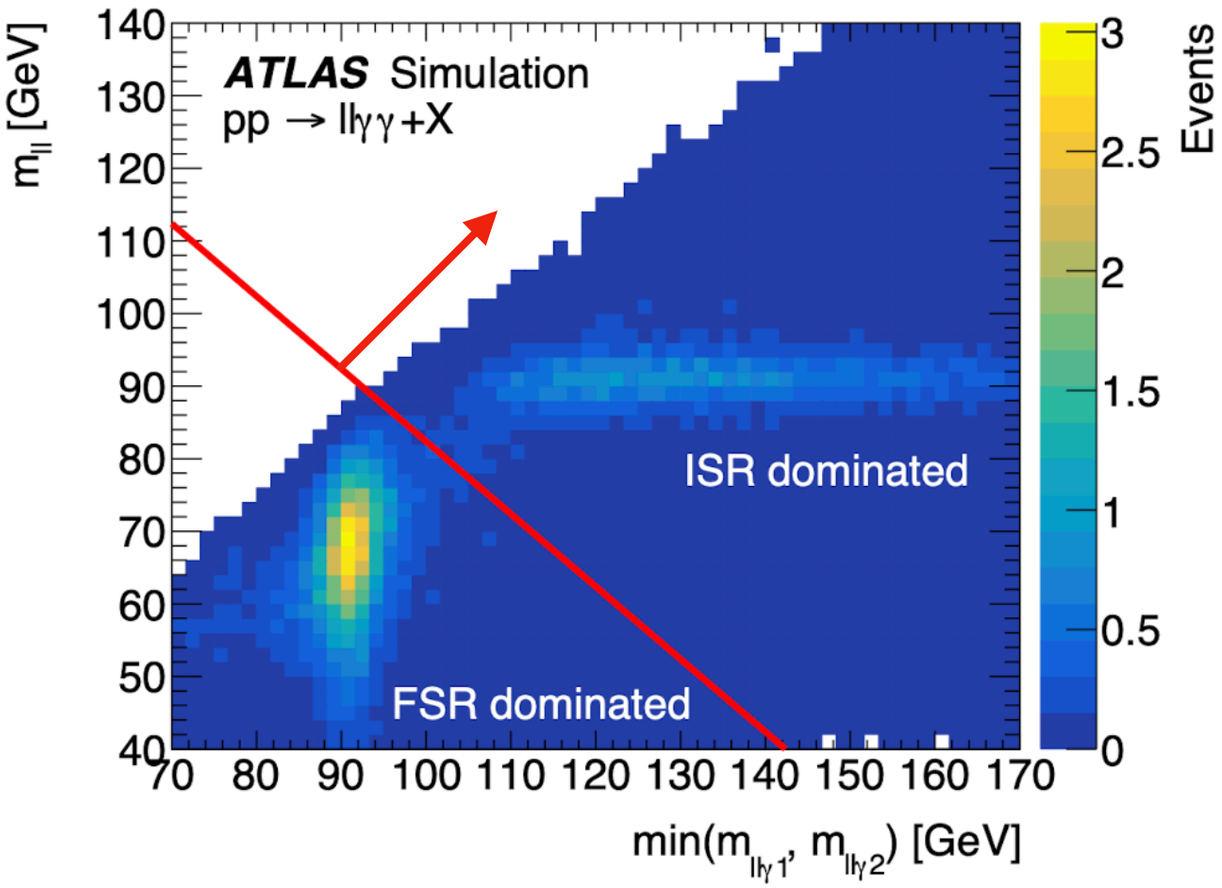
Select two highest p_T photons that pass *Tight* ID and *Loose* isolation

$\Delta R(\gamma_1, \gamma_2) \geq 0.4$

$m_{\ell\ell} + \min(m_{\ell\ell\gamma_1}, m_{\ell\ell\gamma_2}) > 2m_Z$

ZγγZγγ

- To suppress FSR,
  $m_{\ell\ell} + m_{\ell\ell\gamma} > 2m_Z$
- Small background, main contribution from jets faking photons
  - Measure fake rate in data



- No vertex requirement placed on photon → background from overlapping pp collisions producing llγγ system
  - Lack sufficient statistics to study in data → study by combining (@ particle level) simulated Zγ+γ and Z+γγ events
    - Kinematic distributions of combined events corrected to detector level using reweighting factors from signal simulation

ATLAS STDM-2021-09 2211.14171

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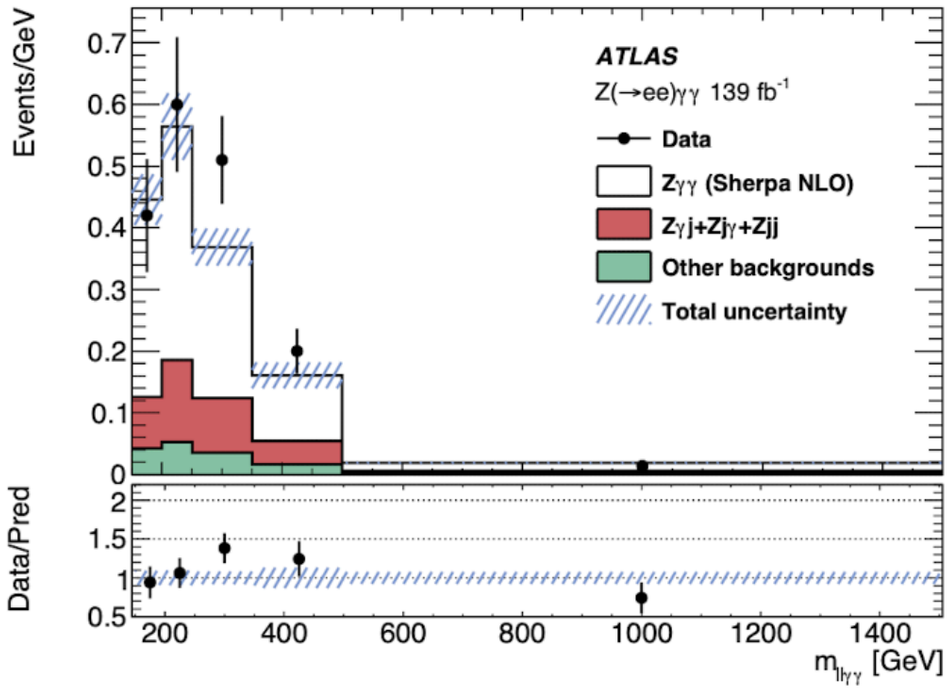
$Z\gamma\gamma$

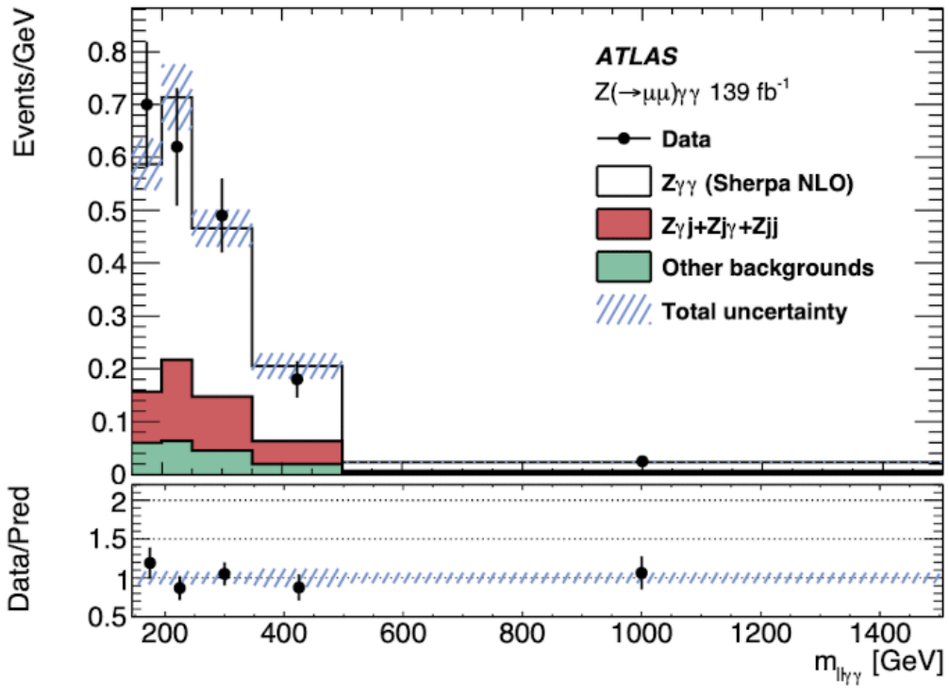
- Observe good agreement with SM cross section with 12% precision
- Main systematic uncertainty from data-driven estimation of jets identified as photons

$$\sigma_{\text{fid}}^{Z(\to\ell\ell)\gamma\gamma} = 2.45 \pm 0.20(\text{stat}) \pm 0.22(\text{syst}) \pm 0.04(\text{lumi}) \text{ fb}$$

$$\sigma_{\text{fid}}^{Z(\to ee)\gamma\gamma} = 2.65 \pm 0.31(\text{stat}) \pm 0.24(\text{syst}) \pm 0.05(\text{lumi}) \text{ fb}$$

$$\sigma_{\text{fid}}^{Z(\to\mu\mu)\gamma\gamma} = 2.29 \pm 0.25(\text{stat}) \pm 0.21(\text{syst}) \pm 0.04(\text{lumi}) \text{ fb}$$





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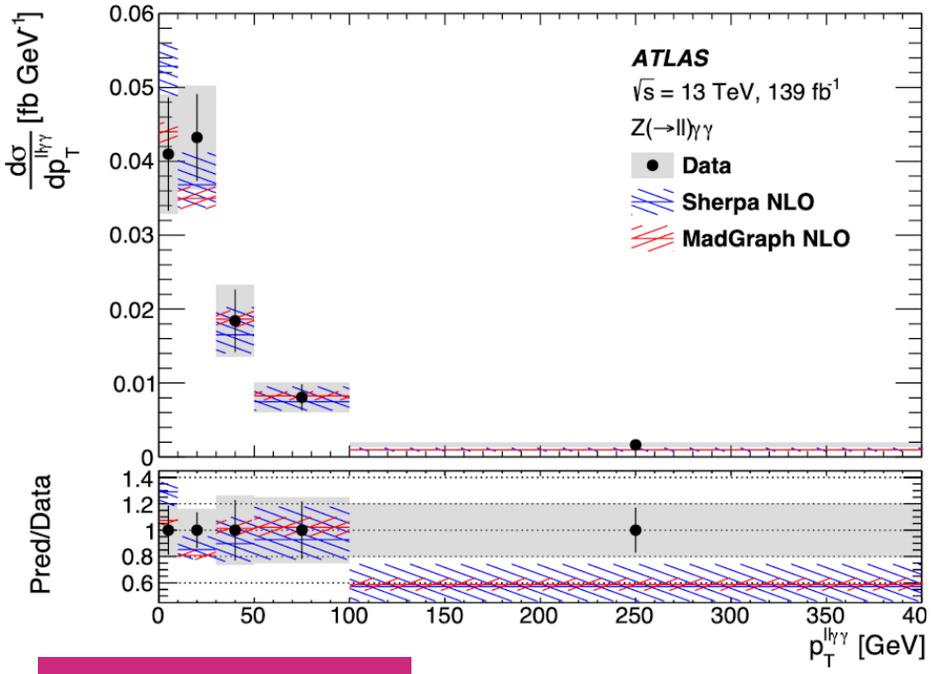
$\Delta R(\gamma_1, \gamma_2) \geq 0.4$

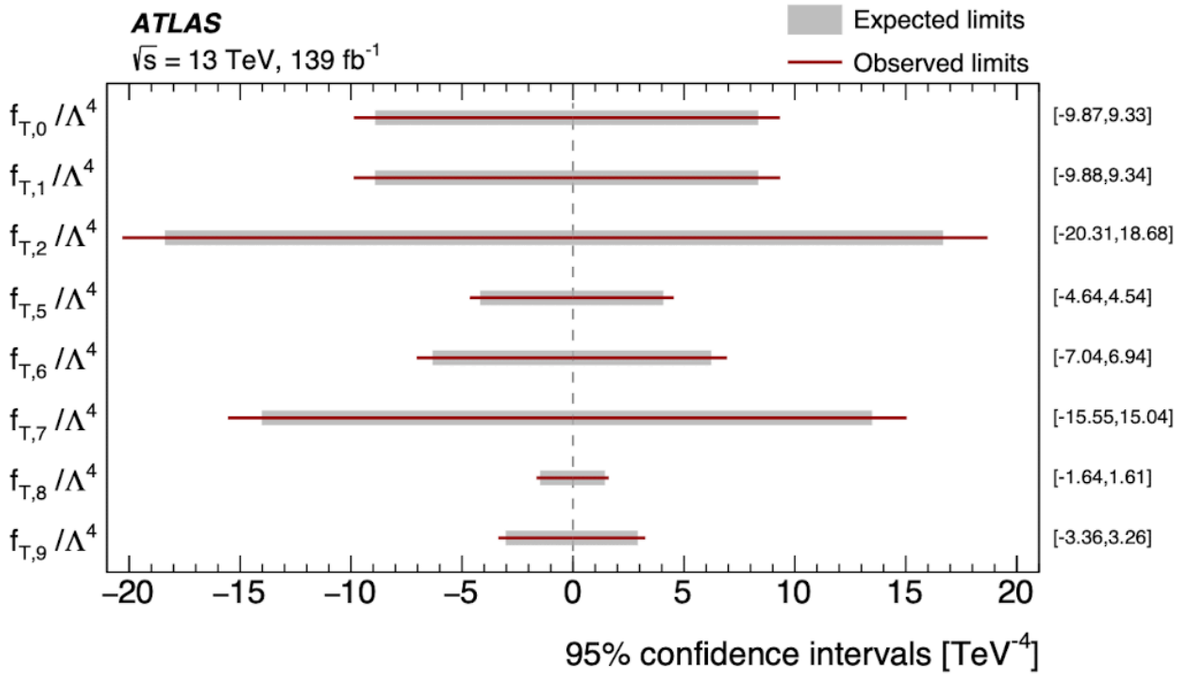
$m_{\ell\ell} + \min(m_{\ell\ell\gamma_1}, m_{\ell\ell\gamma_2}) > 2m_Z$

ZγγγZ

- Measure differential cross sections sensitive to important modeling parameters
- Set aQGC limits 100x more stringent than the previous analysis



$p_T^{\ell\ell\gamma\gamma}$ sensitive to QCD modeling



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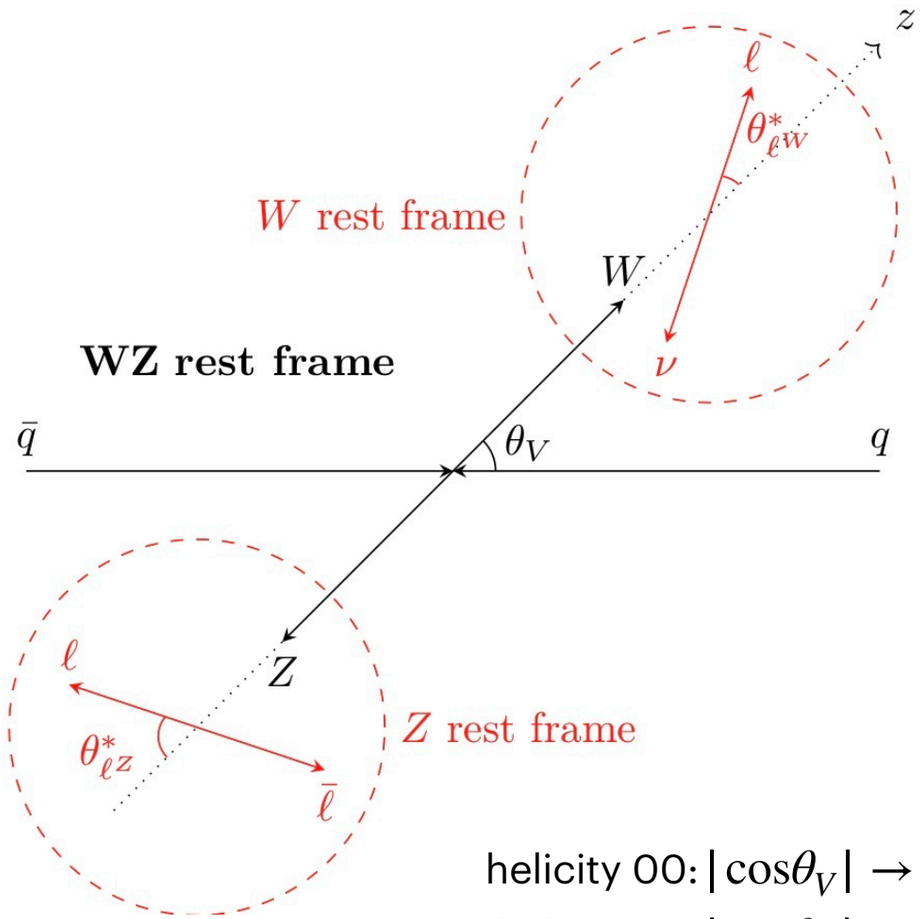
W±Z Polarization

- Many measurements of individual W and Z polarization from LEP, Tevatron, LHC, but this is the **first measurement of joint WZ polarization**
  - Polarization of in diboson production results from EWK symmetry breaking — probes triple gauge coupling and allows us to study structure of gauge symmetry and how it is broken
- Measure diagonal elements of joint spin-density matrix — probabilities of correlated helicity states of WZ
  - Measure fraction of events with different joint polarizations
    f_{00} — longitudinal-longitudinal
    f_{0T} — longitudinal-transverse
    f_{T0} — transverse-longitudinal
    f_{TT} — transverse-transverse



helicity 00: $|\cos\theta_V| \to 0$

helicity TT: $|\cos\theta_V| \to 1$

ATLAS STDM-2022-01 2211.09435

Event Selection:

≥3 e/μ passing medium ID, isolated

at least 1 with $p_T > 25(27)$ GeV in 2015 (2016-2018) and matched to trigger

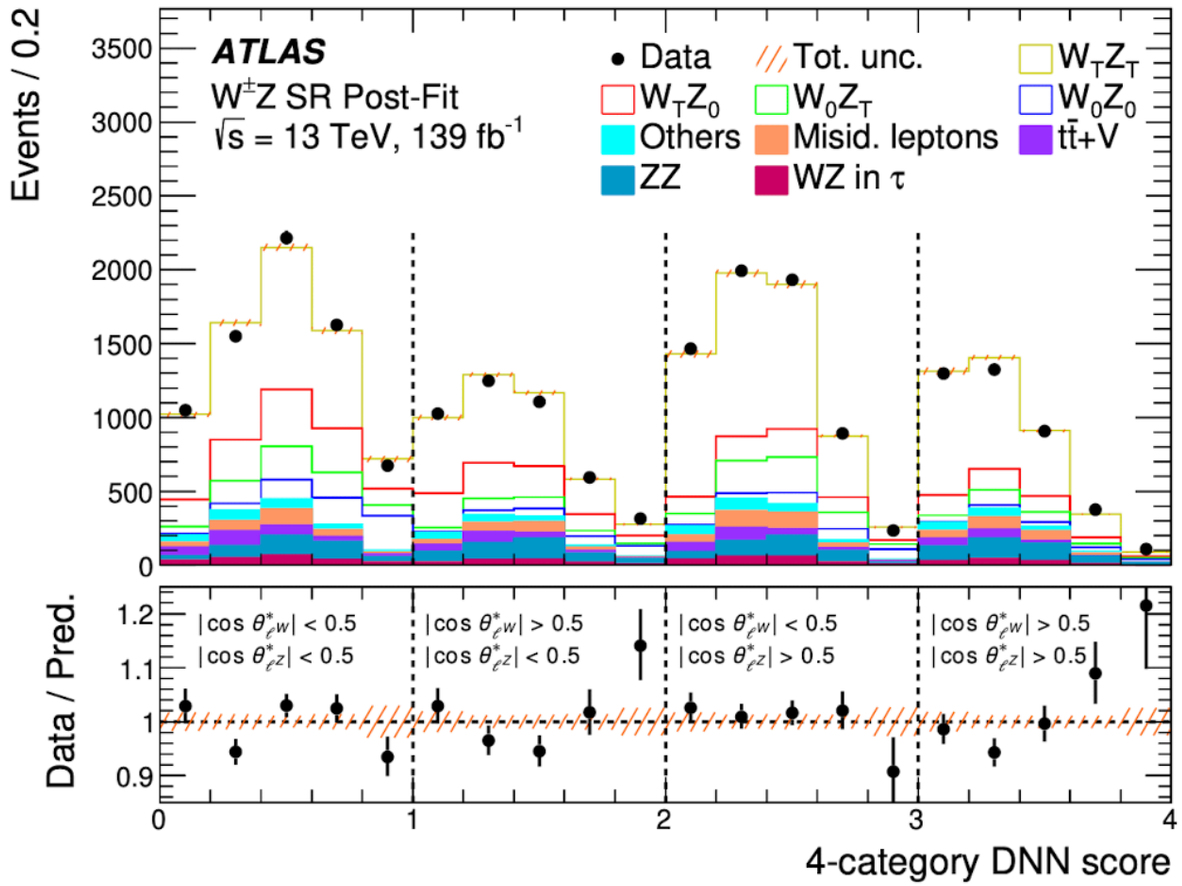
If ≥4 prompt e/μ, reject events with 4th lepton satisfying: $p_T > 5$ GeV, looser isolation

≥1 SFOS e/μ pair w/in 10 GeV of m_Z
Assign remaining lepton to W, and require $m_T^W > 30$ GeV
Lepton must also pass tight ID

W±Z Polarization

- To measure polarization, train Deep Neural Network (DNN) on lepton transverse momenta and angular variables
  - DNN: TT → TO/OT → OO (0 → 0.5 → 1)
  - Separate TO/OT by further defining 4 categories based on $|\cos\theta^*_{\ell Z}|$ and $|\cos\theta^*_{\ell W}|$

- NLO QCD corrections have a substantial impact on polarization, but polarized signal MC generated at LO — 10-50% difference
  - Use template fit to inclusive WZ generated at NLO, and use four DNNs to reweight to joint polarization states 1907.08209



ATLAS STDM-2022-01 2211.09435

Event Selection:

≥3 e/μ passing medium ID, isolated

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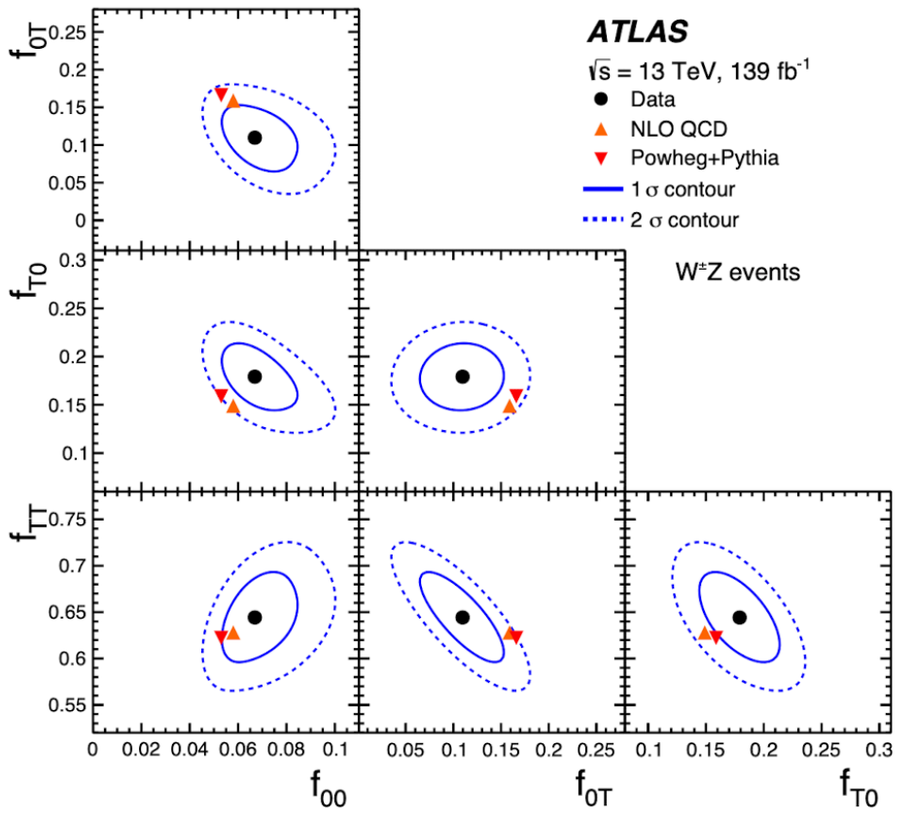
W±Z Polarization

- Measure WZ joint helicity fractions with observed (expected) significance of:
  - f_{00} 7.1 σ (6.2 σ)
    f_{0T} 3.4 σ (5.4 σ)
    f_{T0} 7.1 σ (6.6 σ)
    f_{TT} 11 σ (9.7 σ)
- Main uncertainties are statistical and from higher-order QCD corrections
- Measure individual W/Z polarizations and compare product to joint-polarization —
  $f_{00}/(f_0^W f_0^Z) = 1.54 \pm 0.35$
- Also measure
  - Helicity fractions for W^+Z and W^-Z separately
  - Inclusive fiducial cross section
  - Differential cross sections w.r.t polarization variables
- **All results are in agreement with NLO MC predictions**

	Data	POWHEG+PYTHIA	NLO QCD
		$W^{\pm}Z$	
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003
f_{T0}	0.179 ± 0.023	0.1465 ± 0.0017	0.149 ± 0.003
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	0.628 ± 0.004
		DNN re-weighted MC	Fixed-order computation from 2010.07149



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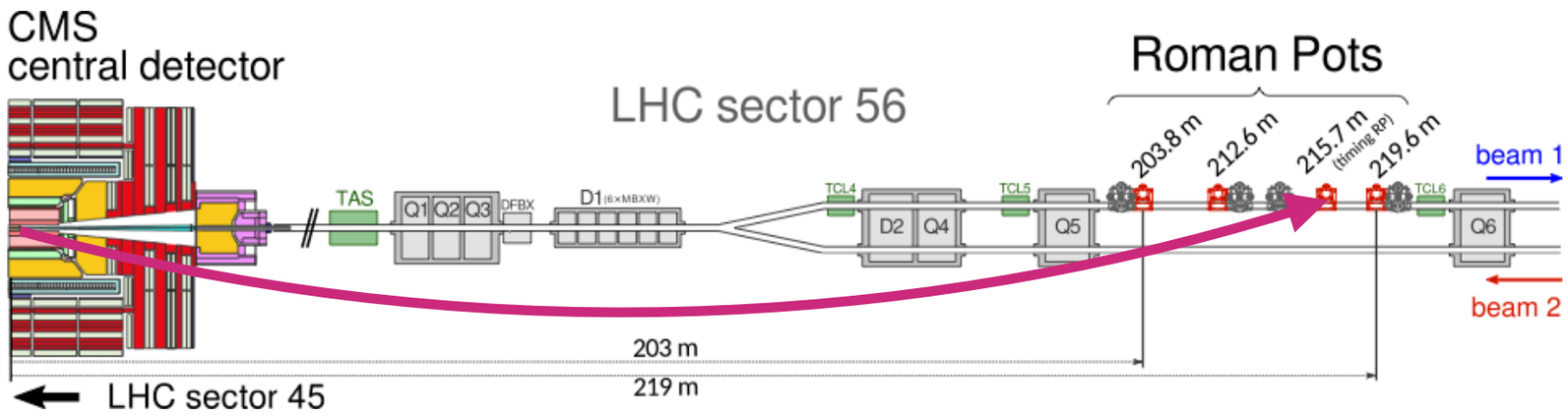
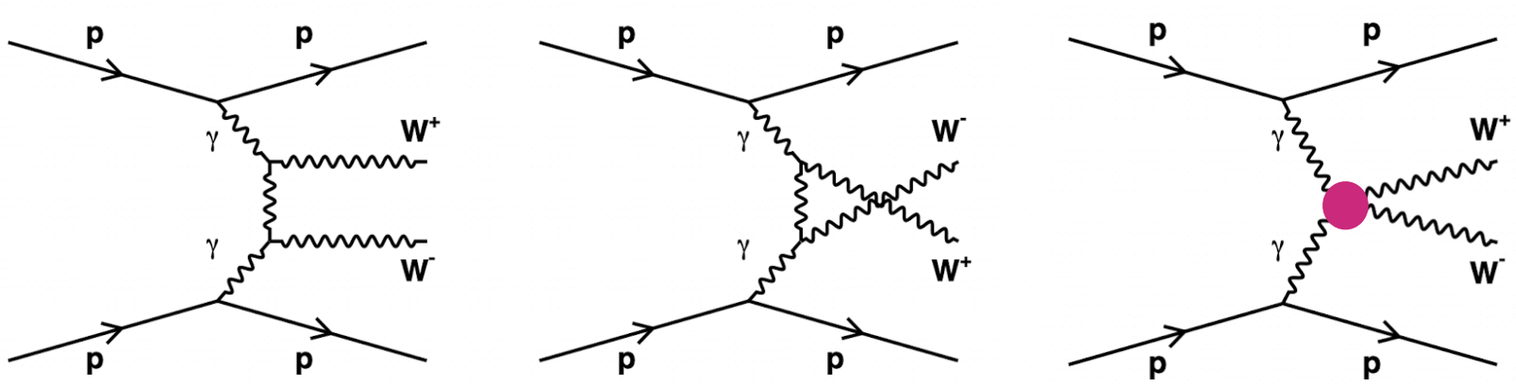
Lepton must also pass tight ID

γγ → VV

- PPS detects in-tact protons 200m from the CMS IP
  - Bent by LHC magnet between PPS and IP → measure proton momentum
- Use to measure pp scattering, where p emits γ and loses a small fraction of its momentum



- Measure exclusive VV production: tag hadronically decaying bosons in CMS, and scatted protons in PPS — SM cross sections: 50 fb (WW) 0.5 fb (ZZ)



CMS SMP-21-014 2211.16320

Event Selection:

Jet Selection

At least two jets with:

$p_T > 200$ GeV

$60 < m_{\text{pruned}} < 107$

$\tau_{21}^{\text{DDT}} < 0.75$

$m(jj) > 1126$ GeV

$|\Delta\eta_{jj}| < 1.3$

$|1 - (\phi_{j1} - \phi_{j2})/\pi) < 0.01$

$p_T(j_1)/p_T(j_2) < 1.3$

Proton selection

Two protons with:

$\xi = (p_{\text{norm}} - p)/p_{\text{norm}}$

$\xi > 0.05$

year-dependent upper limit, $0.12 \leq \xi \leq 0.20$

Matching

$m(\text{pp}) = \sqrt{s}\sqrt{\xi_{\text{p1}}\xi_{\text{p2}}}$

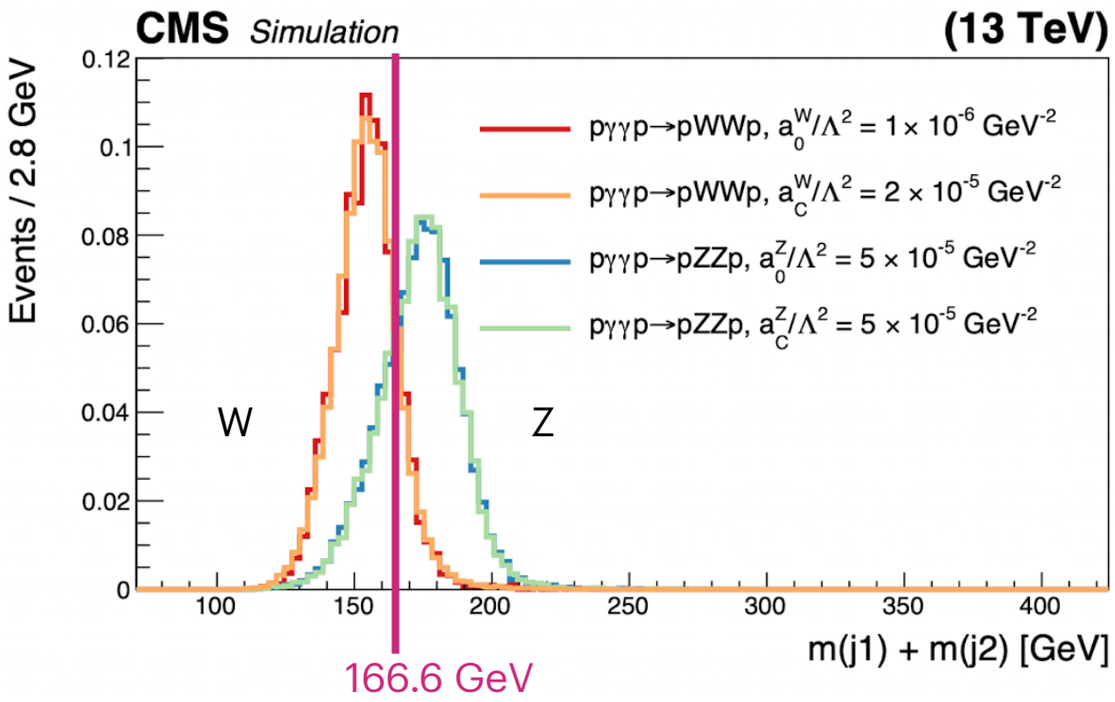
$y(\text{pp}) = -\frac{1}{2}\ln\left(\frac{\xi_{\text{p1}}}{\xi_{\text{p2}}}\right)$

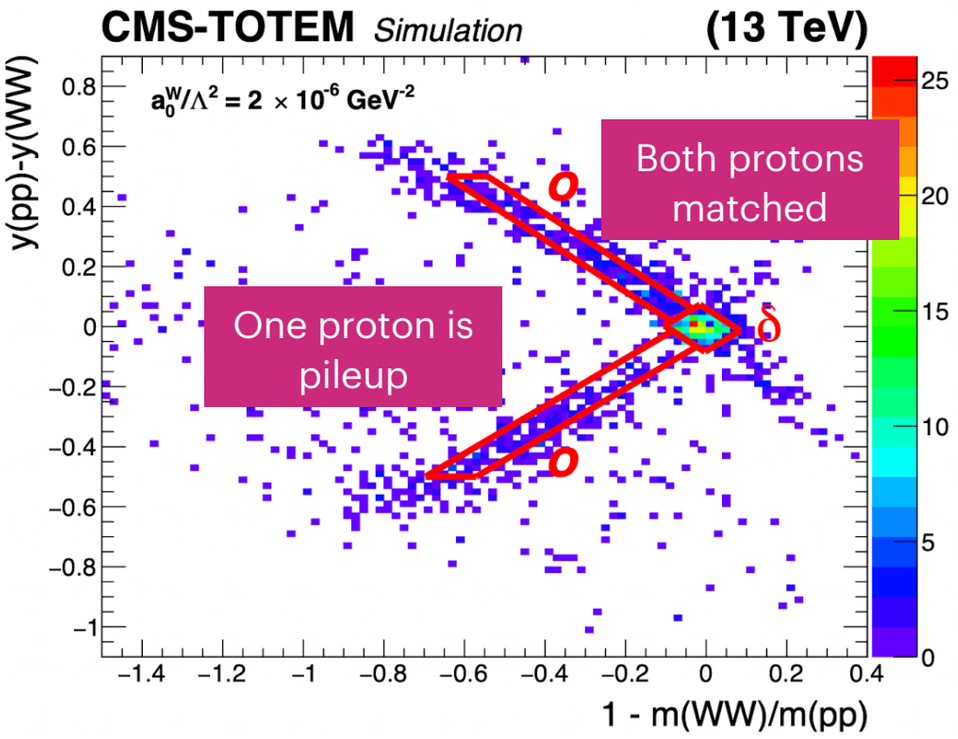
$|1 - m(\text{VV})/m(\text{pp})| < 1.0$

$|y(\text{pp}) - y(\text{VV})| < 0.5$

γγ → VV: Event Selection

- Forward protons reconstructed using "multi-RP" algorithm — combine tracks reconstructed in both Roman Pots in each arm
  - Reconstruct scattering angle, and fractional momentum loss using (known) beam momentum and scattered proton momentum
- Merged jets from V decays selected using N-subjettiness after pruning, where m(jj) > 1126 GeV
  - Further discriminate between WW and ZZ events using sum of jet masses
- **Match forward protons to jets** by comparing mass and rapidity of VV system to pp system → define two SR: if 1 (σ) or 2 (δ) protons are correctly matched





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Proton selection

Two protons with:

$\xi = (p_{\text{norm}} - p)/p_{\text{norm}}$

$\xi > 0.05$

year-dependent upper limit, $0.12 \leq \xi \leq 0.20$

Matching

$$m(\text{pp}) = \sqrt{s}\sqrt{\xi_{\text{p1}}\xi_{\text{p2}}}$$

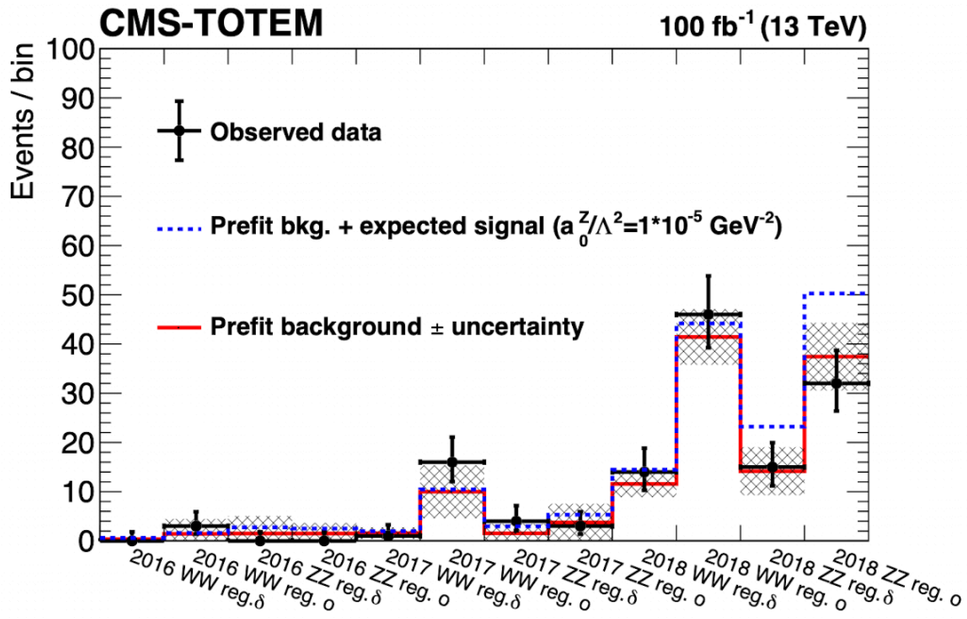
$$y(\text{pp}) = -\frac{1}{2}\ln\left(\frac{\xi_{\text{p1}}}{\xi_{\text{p2}}}\right)$$

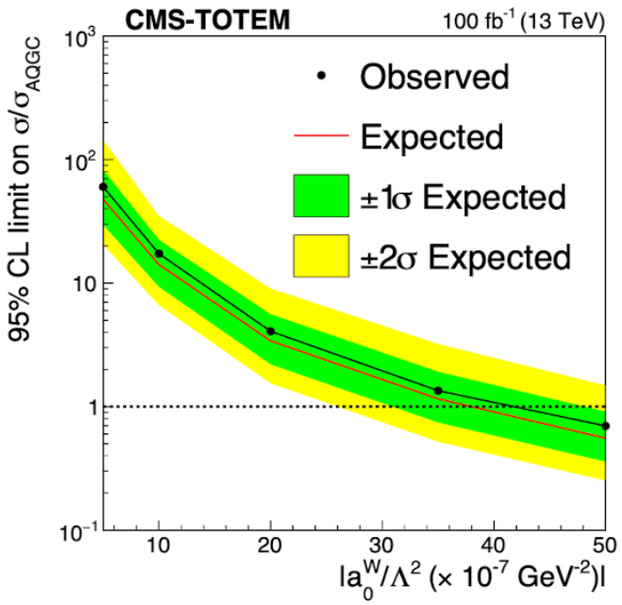
$|1 - m(\text{VV})/m(\text{pp})| < 1.0$

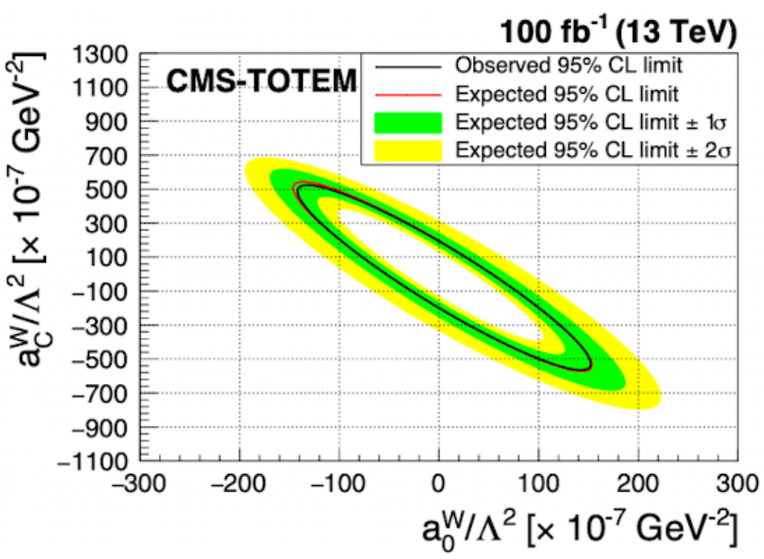
$|y(\text{pp}) - y(\text{VV})| < 0.5$

γγ → VV: Results

- No significant excess → set limits on dim-6 and dim-8 aQGC
- Dominant systematic uncertainty from limited statistics in data-driven background estimate
- Measure upper limits on fiducial cross sections
  $\sigma(\mathrm{pp} \to \mathrm{pWWp}) < 67\mathrm{fb}$
  $\sigma(\mathrm{pp} \to \mathrm{pZZp}) < 43\mathrm{fb}$
- Set limits with and without clipping (@ 1.4 TeV) applied → 15-20x more stringent limits than Run 1 analysis







CMS SMP-21-014 2211.16320

Event Selection:

Jet Selection
At least two jets with:
$p_T > 200$ GeV
$60 < m_{\text{pruned}} < 107$
$\tau_{21}^{\text{DDT}} < 0.75$

$m(jj) > 1126$ GeV
$|\Delta\eta_{jj}| < 1.3$
$|1 - (\phi_{j1} - \phi_{j2})/\pi) < 0.01$
$p_T(j_1)/p_T(j_2) < 1.3$

Proton selection
Two protons with:
$\xi = (p_{\text{norm}} - p)/p_{\text{norm}}$
$\xi > 0.05$
year-dependent upper limit, $0.12 \leq \xi \leq 0.20$

Matching
$m(\mathrm{pp}) = \sqrt{s}\sqrt{\xi_{\mathrm{p1}}\xi_{\mathrm{p2}}}$
$y(\mathrm{pp}) = -\frac{1}{2}\ln\left(\frac{\xi_{\mathrm{p1}}}{\xi_{\mathrm{p2}}}\right)$
$|1 - m(\mathrm{VV})/m(\mathrm{pp})| < 1.0$
$|y(\mathrm{pp}) - y(\mathrm{VV})| < 0.5$

Summary

- Many exciting multiboson results from ATLAS and CMS
  - Probe EWK physics, but also measure and validate important phenomena that are important to many other physics analyses
- **Wγ + 2 jets** targets vector boson scattering processes and sets most stringent limits on some aQGC operators
- **Zγγ** studies rare triboson process and measures its differential cross section for the first time
- **WZ joint polarization** measured for the first time
- **γγ→VV** probes the SM without hard scattering and uses the full potential of CMS detector

- Many many more results from ATLAS and CMS in Run 2 (and some first Run 3 results as well!)

ATLAS public results

CMS public results