Multiboson production in CMS

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On behalf of the CMS Collaboration

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Why study multiboson?

- Multiboson physics provide precise measurements of fundamental SM parameters

- Portal to New physics
  - Background for Higgs analysis or resonant searches
  - Indirect search through anomalous couplings

- A wide range of processes
  - **Diboson, triboson**, vector boson scattering

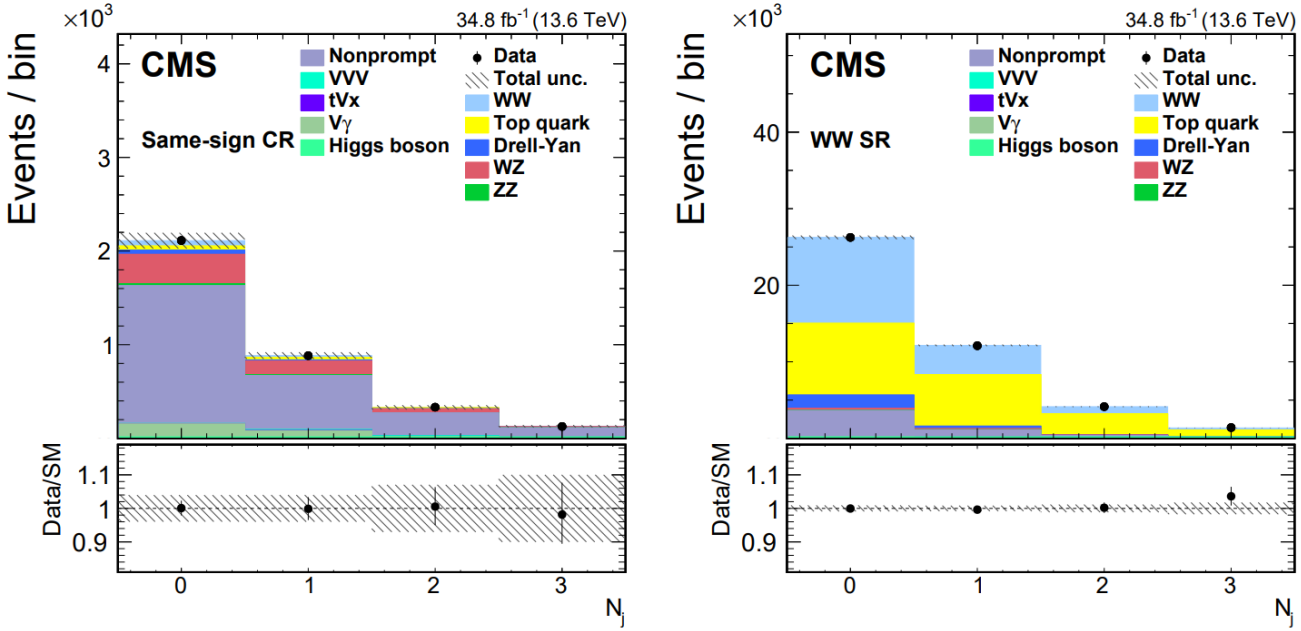
Multiboson measurement in CMS

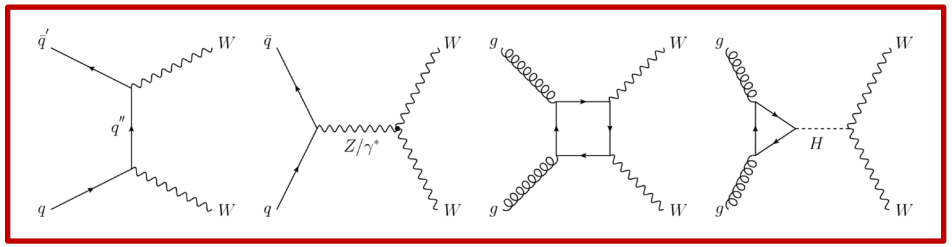
- **Diboson production**
  - WW inclusive @ 13.6 TeV *arXiv:2406.05101*
  - WZ cross section @ 13.6 TeV *CMS-PAS-SMP-24-005* NEW FOR ICHEP
  - $Z(\rightarrow \nu\bar{\nu})\gamma$ production @ 13 TeV *CMS-PAS-SMP-22-009*
- **Triboson production**
  - Observation of WWγ production @ 13 TeV *Phys. Rev. Lett. 132 (2024) 121901*
  - WZγ production @ 13 TeV *CMS-PAS-SMP-22-018* NEW FOR ICHEP
- **Vector boson scattering**
  - See presentations from Andrea Piccinelli

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

arXiv:2406.05101, submitted to PLB, CMS-SMP-24-001 Overview

- **First Measurement** of opposite-sign (OS) WW(+jets) production at $\sqrt{s}$ **= 13.6 TeV**
  - 2022 CMS Run 3 data → $\mathcal{L} = 34.8\ fb^{-1}$
- Inclusive and normalized cross-section measurement





- Events selected with **one electron** and **one muon** (OS) and categorized into WW Signal region (SR) + 6 Control regions (CRs)
- 3 production processes
  - qq→WW, gg→WW (corrected by a factor 1.4 for NLO/LO)
  - H→ WW (background for this analysis)

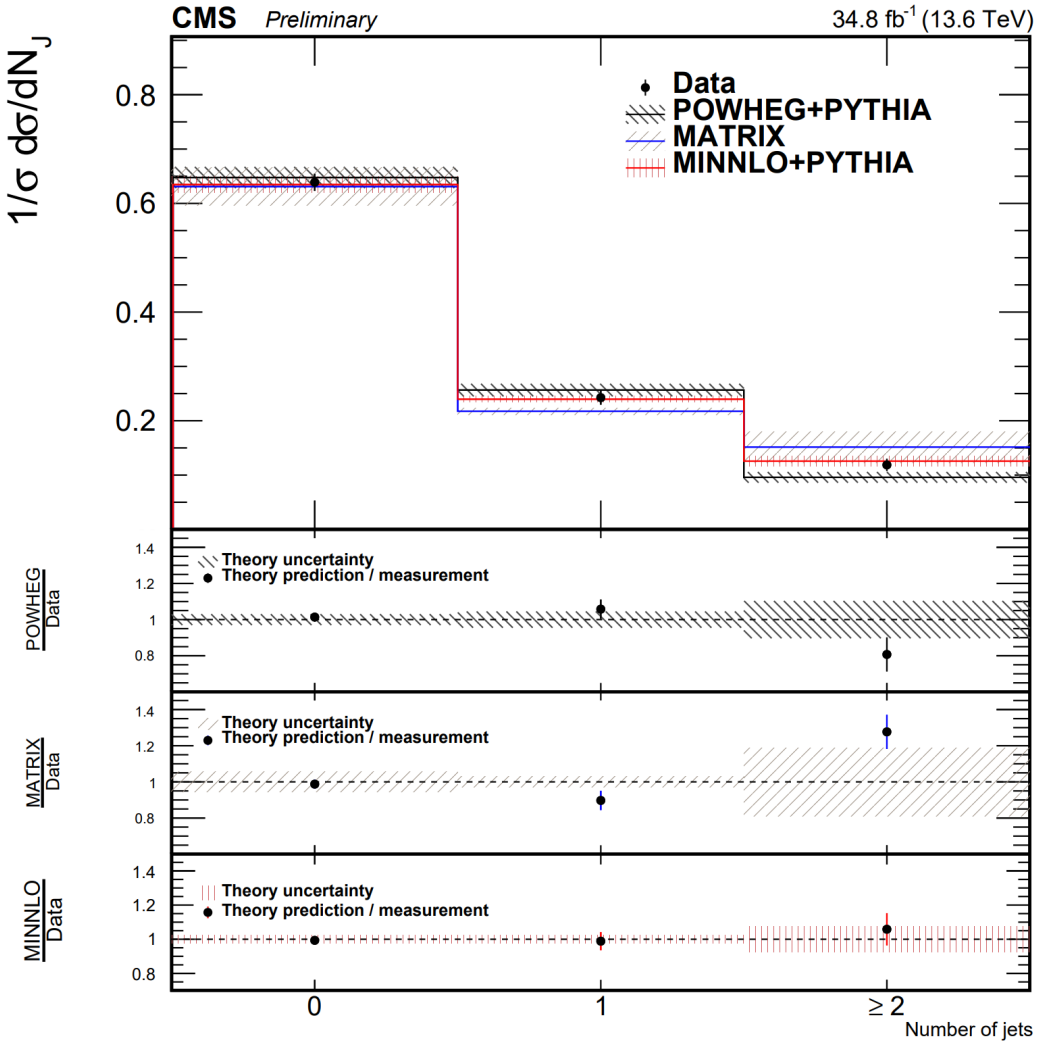
W^+W^- inclusive @ 13.6 TeV [34.8 fb^{-1}]

arXiv:2406.05101, submitted to PLB, CMS-SMP-24-001 results

- Inclusive cross section
  - Extracted from simultaneous Maximum Likelihood fits over SR+CRs with 1 POI
  - **$\sigma^{obs} = 125.7 \pm 2.3$ (stat.) ± 4.8 (syst.) ± 1.8 (lumi.) pb**
  - Compatible with predictions: **$\sigma^{exp} = 125.8 \pm 3.7$ pb** (QCD NNLO and EW NLO from MATRIX v2.1.0)
- Comparison of normalized fiducial cross sections

Observable	Requirement
Lepton origin	Direct decay of a W boson
Lepton definition	Dressed-leptons ($e^{\pm}\mu^{\mp}$)
Leading lepton p_T	$p_T^{\ell\,max} > 25$ GeV
Trailing lepton p_T	$p_T^{\ell\,min} > 20$ GeV
$\|\eta\|$ of leptons	$\|\eta\| < 2.5$
Dilepton mass	$m_{\ell\ell} > 85$ GeV
Jet p_T	$p_T^{j} > 30$ GeV
$\|\eta\|$ of jets	$\|\eta^{j}\| < 2.5$
Jet-lepton removal	$\Delta R(j, \ell) > 0.4$

Definition of the fiducial region

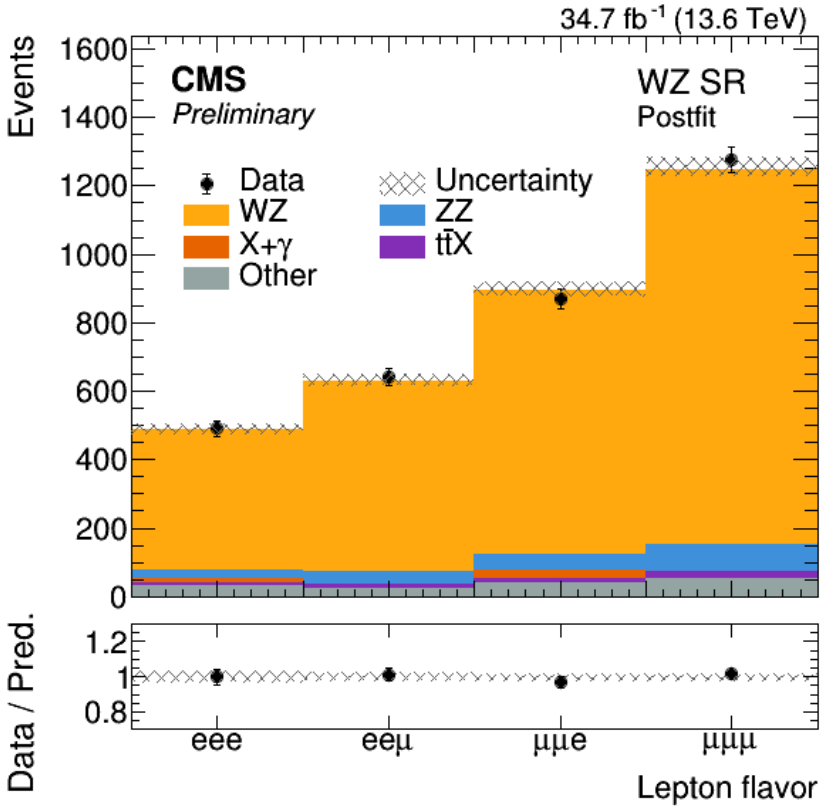


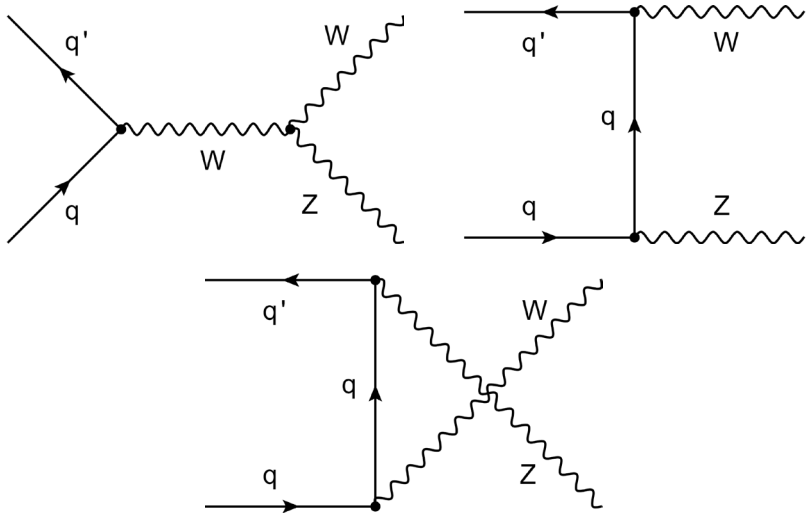
WZ cross section @ 13.6 TeV [34.7 fb^{-1}]

CMS-PAS-SMP-24-005 Overview

NEW FOR ICHEP

- First measurement of WZ production at $\sqrt{s}$ = 13.6 TeV
  - 2022 CMS Run 3 data → $\mathcal{L} = 34.7\ fb^{-1}$





- Experimentally: in its **multileptonic final state**

  $(W^{\pm} \to \ell^{\pm}\,\nu, Z \to \ell^{+}\,\ell^{-})$:

  - One of the **cleanest diboson channels** at the LHC (85% purity of signal over background after selections).
  - Reasonably high statistical power.
  - It is known to be compatible (with excellent accuracy) with the latest NNLO QCD x NLO EWK predictions (Computed with MATRIX).

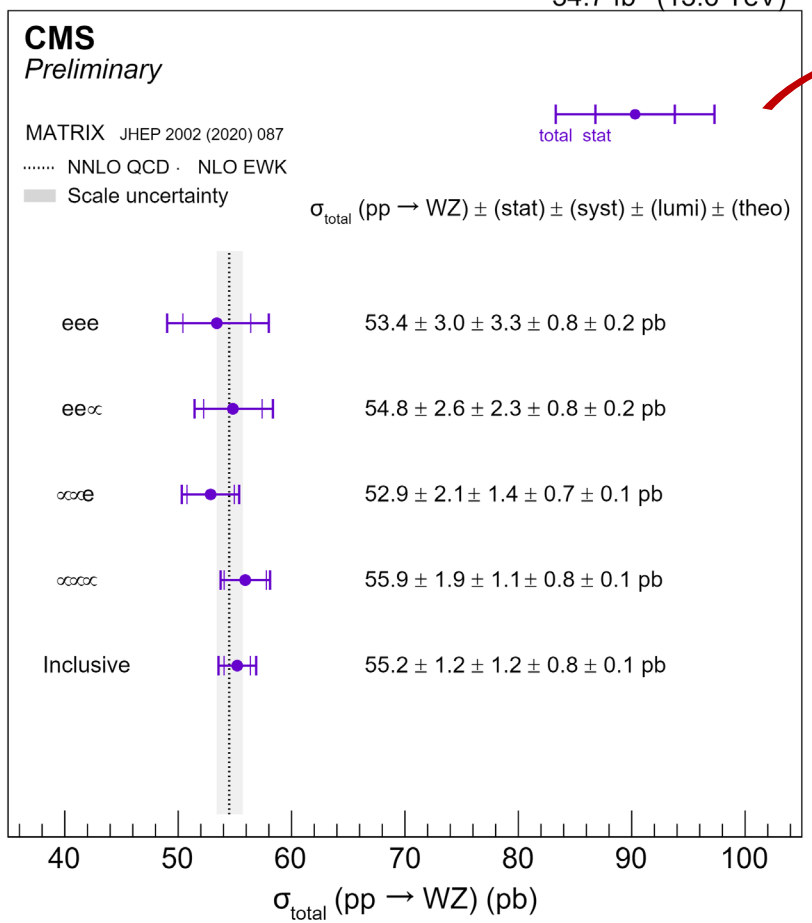
WZ cross section @ 13.6 TeV [34.7 fb^{-1}]

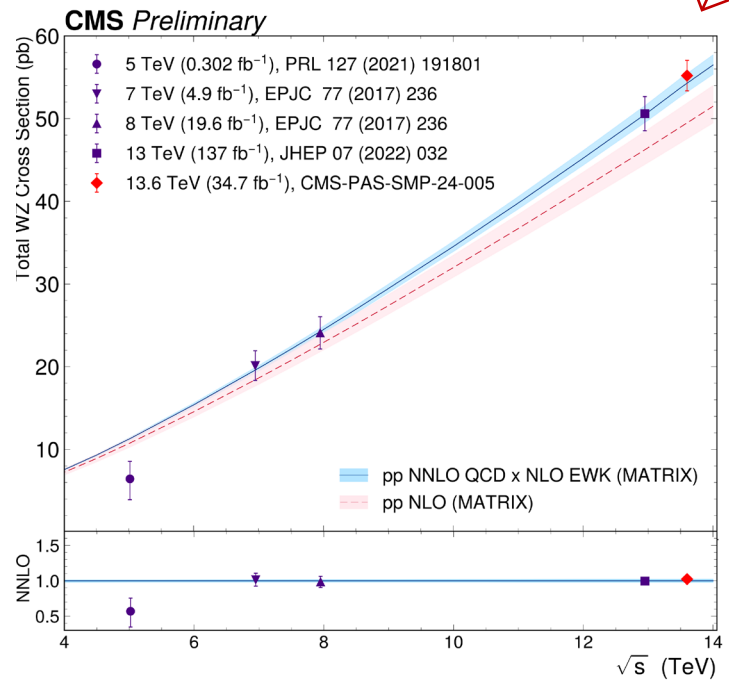
CMS-PAS-SMP-24-005 Results

NEW FOR ICHEP

- The WZ production cross section is measured in a phase space, defined around a 30 GeV window around the Z mass

- The results are shown to be in **good agreement with the NNLO QCD x NLO EWK** calculations (from MATRIX).

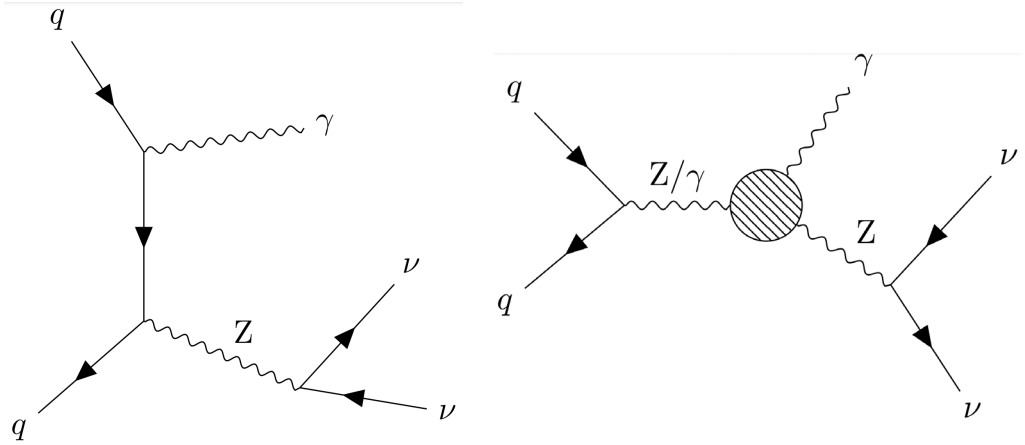


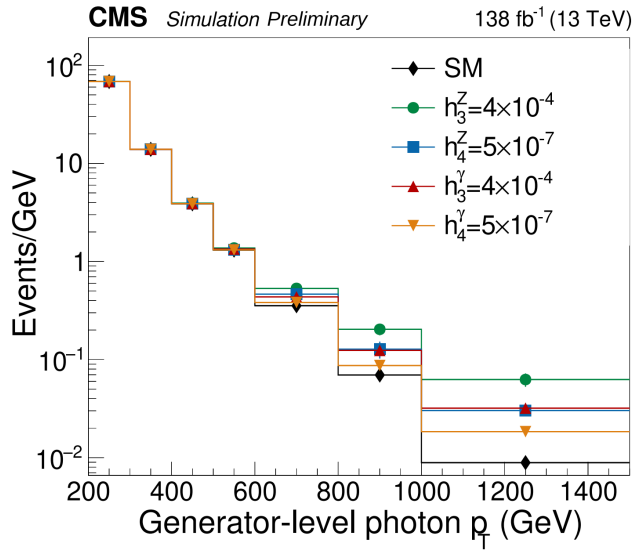


$Z(\rightarrow \nu\bar{\nu})\gamma$ @ 13 TeV [138 fb^{-1}]

CMS-PAS-SMP-22-009 Overview

- Fiducial and differential cross section measurement
- Limits on **anomalous Neutral Triple Gauge Coupling (aNTGC)** $h_3^{Z,\gamma}$ and $h_4^{Z,\gamma}$
- BDT algorithm to identify high-p_T photons (92% efficiency)
- Exact 1 high-p_T photon + E_T^{miss}





- True photons backgrounds:
  - γ+jets, VV (from MC), $W(\rightarrow \ell\nu)\gamma$ (from CR to data)
- Fake photons backgrounds:
  - $e \rightarrow \gamma$, jet→ γ (data-driven)
  - Particles interacting with ECAL barrel's electronics (data-driven)
  - Beam Halo in ECAL endcaps (data-driven)

$Z(\rightarrow \nu\bar{\nu})\gamma$ @ 13 TeV [138 fb^{-1}]

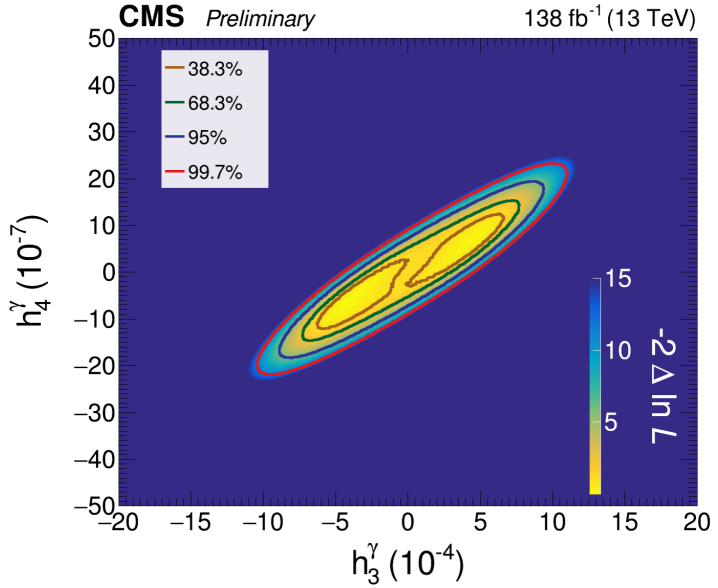
CMS-PAS-SMP-22-009 Results

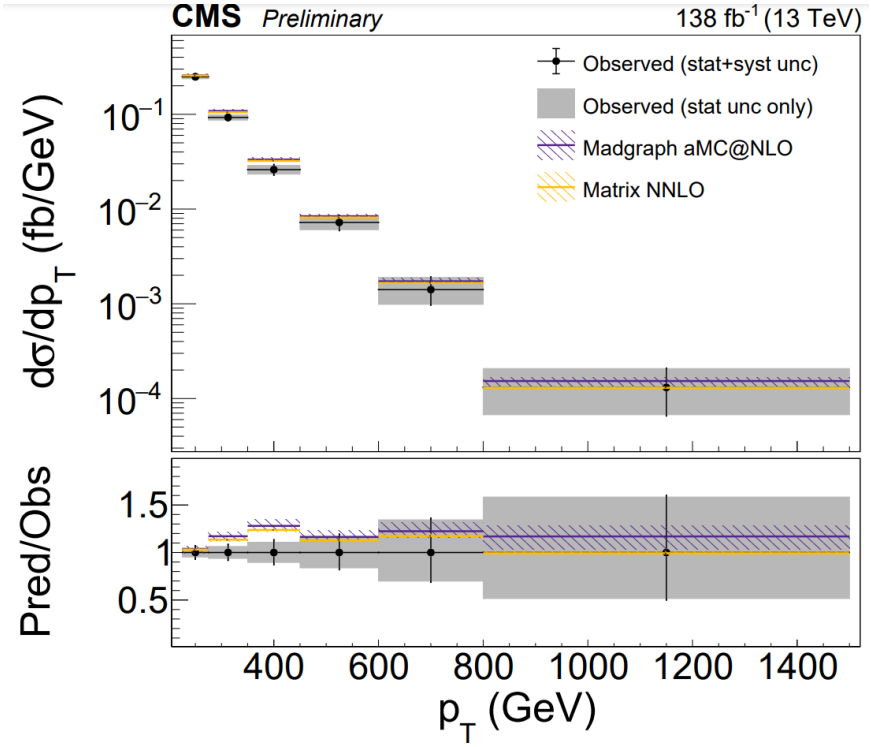
- Fiducial (left) and differential cross section (right) (fb)

Region	Measured	NLO (Madgraph5)	NNLO (MATRIX)
Barrel $\lvert\eta\rvert < 1.4442$	$16.74^{+1.05}_{-0.99}$	$19.61^{+0.73}_{-0.69}$	$19.33^{+0.27}_{-0.33}$
Endcaps $1.4442 < \lvert\eta\rvert < 2.5$	$7.84^{+0.76}_{-0.70}$	$6.45^{+0.27}_{-0.31}$	$6.21^{+0.07}_{-0.09}$
Combination of barrel and endcaps	$23.32^{+1.40}_{-1.32}$	$26.07^{+0.96}_{-0.97}$	$25.45^{+0.41}_{-0.33}$

p_T-range (GeV)	Measured	NLO (Madgraph5)	NNLO (MATRIX)
225-275	$12.45^{+0.91}_{-0.87}$	$12.88^{+0.42}_{-0.49}$	$12.83^{+0.17}_{-0.15}$
275-350	$6.95^{+0.60}_{-0.57}$	$8.14^{+0.31}_{-0.30}$	$7.89^{+0.16}_{-0.15}$
350-450	$2.61^{+0.35}_{-0.33}$	$3.34^{+0.17}_{-0.11}$	$3.22^{+0.07}_{-0.06}$
450-600	$1.08^{+0.21}_{-0.20}$	$1.26^{+0.08}_{-0.05}$	$1.22^{+0.02}_{-0.02}$
600-800	$(2.82^{+0.10}_{-0.09}) \times 10^{-1}$	$(3.45^{+0.26}_{-0.19}) \times 10^{-1}$	$(3.31^{+0.07}_{-0.05}) \times 10^{-1}$
800-1500	$(0.92^{+0.05}_{-0.05}) \times 10^{-1}$	$(1.07^{+0.11}_{-0.12}) \times 10^{-1}$	$(9.09^{+0.20}_{-0.14}) \times 10^{-2}$

- Limits on aNTGC

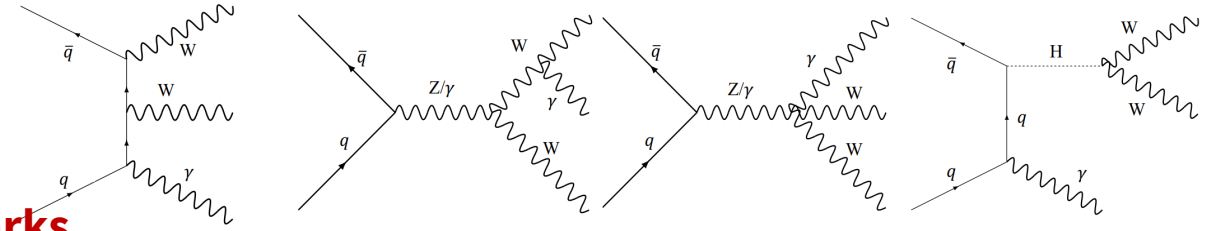




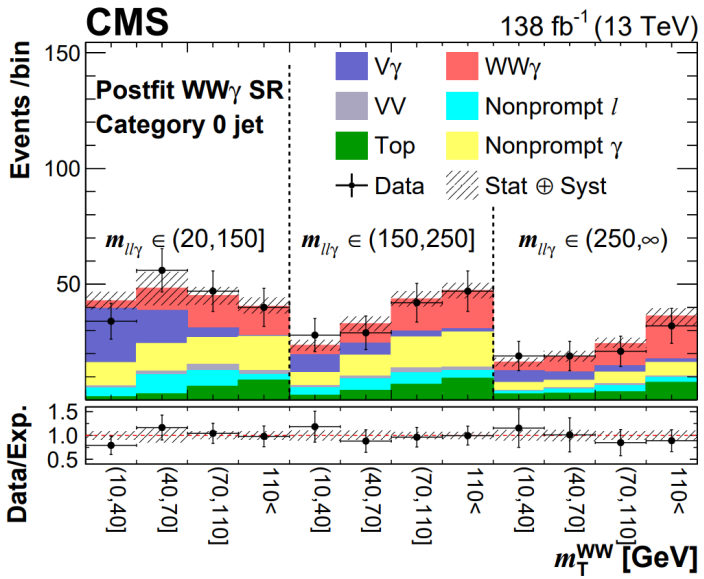
WWγ @ 13 TeV [138 fb^{-1}]

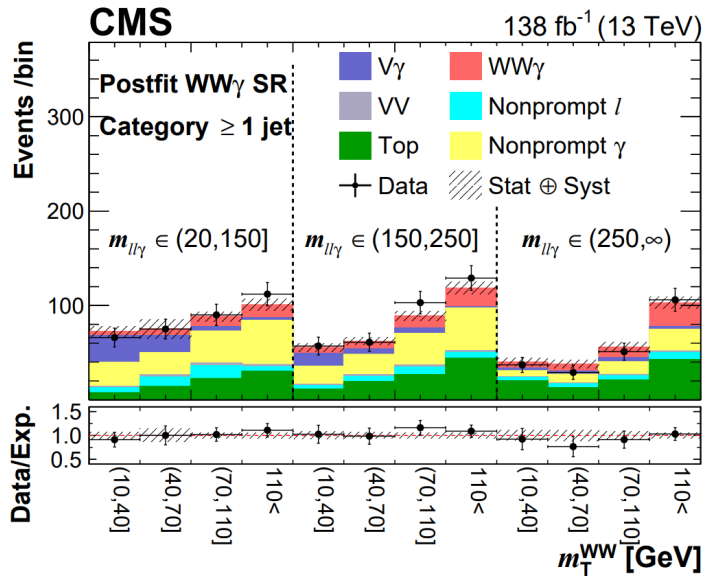
arXiv:2310.05164, PRL 132 (2024) 121901, CMS-SMP-22-006 overview

- **First observation** of WWγ: 5.6 σ (5.1 σ) obs. (exp.)
- Search for Hγ → WWγ
  - Extraction of limits on **higgs couplings with light quarks**



- Data-driven method for estimating background processes with non-prompt lepton/photon
- Focusing on fully leptonic final state: WWγ → $e\nu_e\ \mu\nu_\nu\ \gamma$





WWγ @ 13 TeV [138 fb^{-1}]

arXiv:2310.05164, PRL 132 (2024) 121901, CMS-SMP-22-006 results

- Measured fiducial cross section: **5.9 ± 0.8 (stat.) ± 0.8 (syst.) ± 0.7 (modeling) fb**
  - Theoretical predicted fiducial cross section (MadGraph5_aMC@NLO): **5.33 ± 0.34 (scale) ± 0.05 (PDF) fb**
  - fiducial region defined by applying the signal selection at particle level, without the requirements on b jets and additional leptons

- Upper limits on the cross section and derived limits in terms of **Yukawa coupling** for Hγ production initiated by light quarks

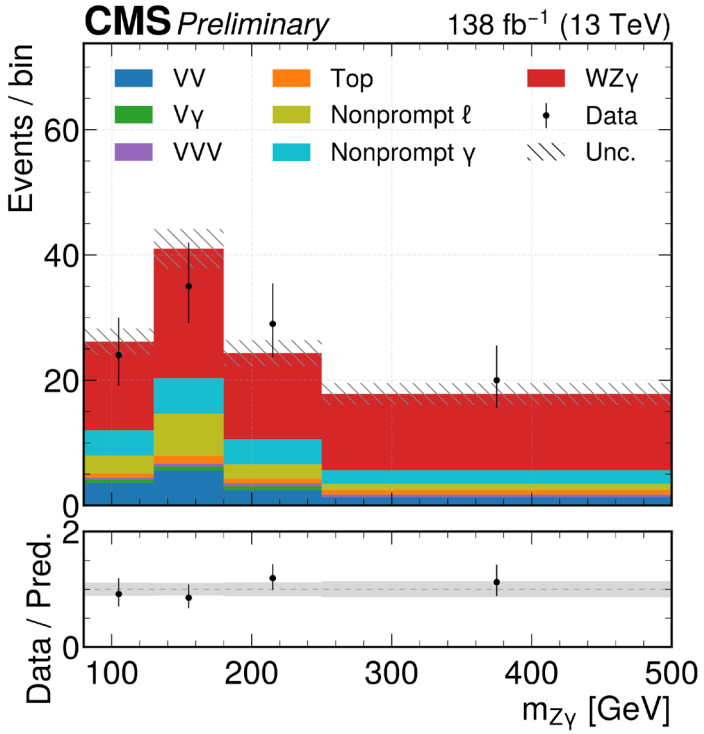
Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% C.L.	$\bar{\kappa}_q$ limits obs. (exp.) at 95% C.L.
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	86 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)	$\lvert\bar{\kappa}_u\rvert \leq 7.5$ (6.1)
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\lvert\kappa_d\rvert \leq 17000$ (14000)	$\lvert\bar{\kappa}_d\rvert \leq 16.6$ (14.7)
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	66 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)	$\lvert\bar{\kappa}_s\rvert \leq 32.8$ (25.2)
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	88 (66)	$\lvert\kappa_c\rvert \leq 190$ (110)	$\lvert\bar{\kappa}_c\rvert \leq 43.2$ (25.0)

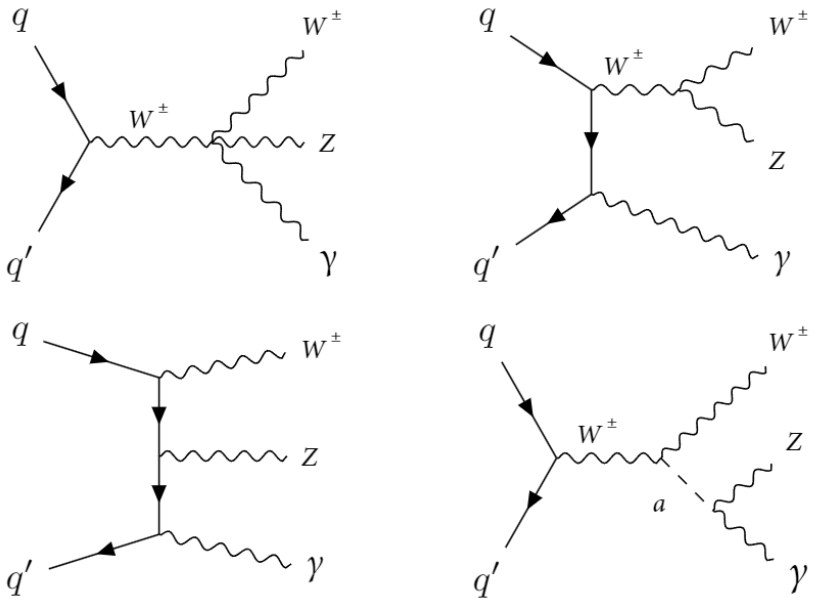
WZγ @ 13 TeV [138 fb^{-1}]

CMS-PAS-SMP-22-018 overview

NEW FOR ICHEP

- Measurement of WZγ production
- Limits on anomalous Quartic Gauge Coupling (aQGC)
- Limits on **photophobic axion-like particle** models





- Focusing on **fully leptonic final states** $WZ\gamma \rightarrow \ell^{\pm}\nu\,\ell'^{+}\ell'^{-}\gamma\ (\ell = e, \mu)$
- Data-driven method for estimating background processes with non-prompt lepton/photon. Validation is made with CRs
- Other backgrounds: Estimated by MC and constrained with the dedicated CR

WZγ @ 13 TeV [138 fb^{-1}]

CMS-PAS-SMP-22-018 Results

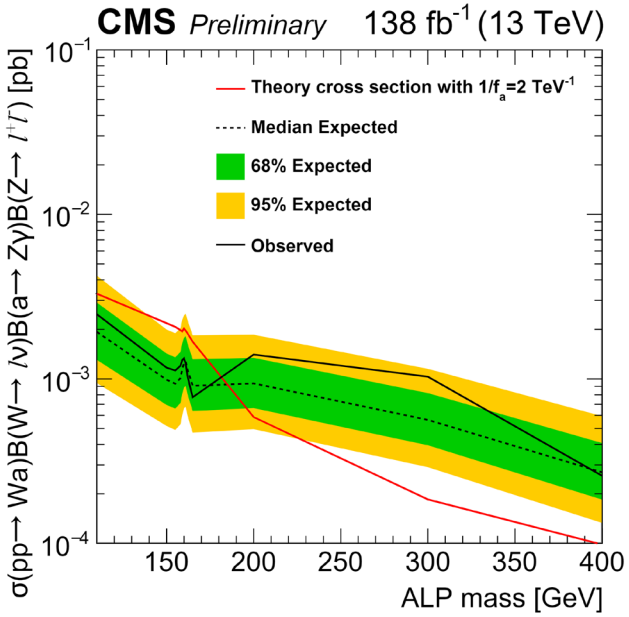
NEW FOR ICHEP

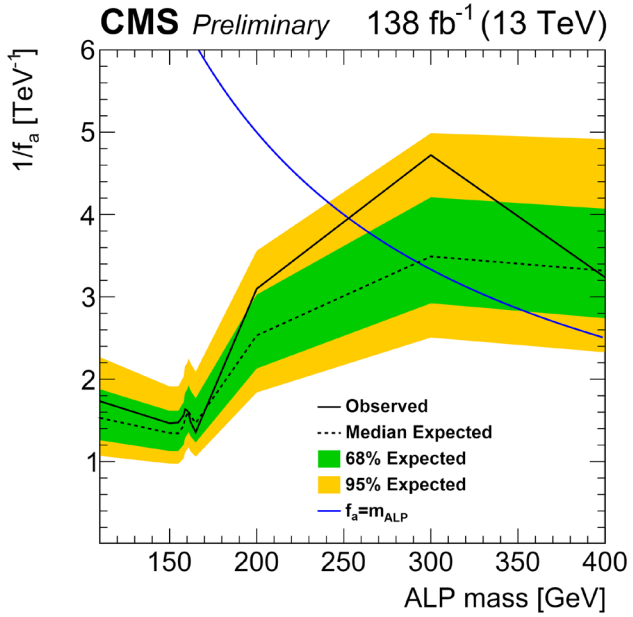
- Measured fiducial cross section: **5.48 ± 0.95 (stat.) ± 0.57 (syst.) ± 0.10 (theo.) fb**
  - Theoretical predicted fiducial cross section (MadGraph5_aMC@NLO): **3.69 ± 0.19 (scale) ± 0.15 (PDF) fb**
  - Particle-level selection: $p_T^{e,\mu,\gamma} > 15$ GeV, $|\eta^{e,\mu,\gamma}| < 2.5$, m_Z between [60, 120] GeV

- Exclusion limits at the 95% CL for each aQGC coefficient

Operators	Observed limits [TeV $^{-4}$]	Expected limits [TeV $^{-4}$]	Unitarity bound [TeV]
$F_{T,0}/\Lambda^4$	[-2.60, 2.60]	[-2.52, 2.52]	1.32
$F_{T,1}/\Lambda^4$	[-3.28, 3.24]	[-3.18, 3.14]	1.48
$F_{T,2}/\Lambda^4$	[-7.15, 7.05]	[-6.95, 6.85]	1.35
$F_{T,5}/\Lambda^4$	[-2.54, 2.56]	[-2.46, 2.50]	1.55
$F_{T,6}/\Lambda^4$	[-3.18, 3.22]	[-3.08, 3.14]	1.61
$F_{T,7}/\Lambda^4$	[-6.85, 7.05]	[-6.65, 6.85]	1.71

- The observed (expected) significance of the WZγ signal is 5.4 (3.8) standard deviations
- Photophobic ALPs [JHEP09(2018)028], suppressed ALP to photon couplings at tree level
  - Only one free parameter f_a that directly determines the couplings between ALPs and vector bosons, $(\sigma \times Br \propto \frac{1}{f_a^2})$





Summary of multiboson production in CMS

- CMS has a strong and comprehensive program of multiboson measurements & Searches/Probes
  - Precision multiboson measurements
  - Observation of triboson processes
  - Beyond Standard Model extensions: Anomalous couplings, EFT, Higgs properties, ALP etc.

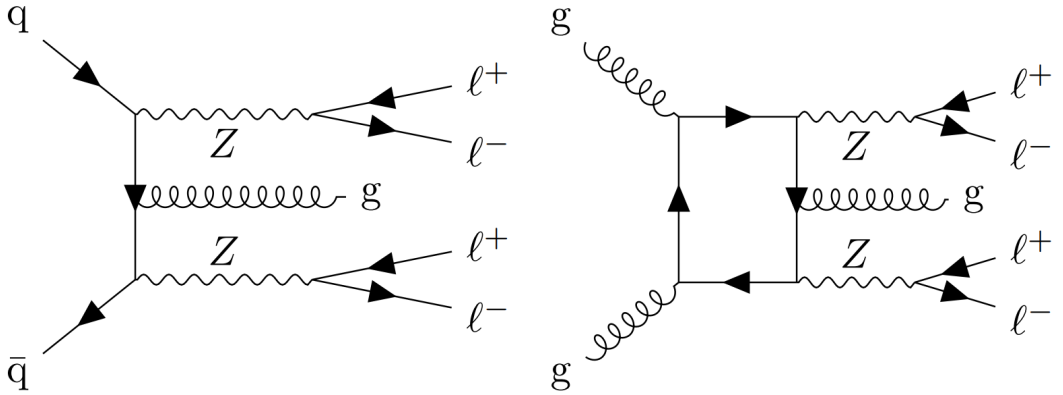
- Lots of opportunities with the Run-3 data coming in!
  - First measurement of opposite-sign WW(+jets) production at $\sqrt{s}$ = 13.6 TeV

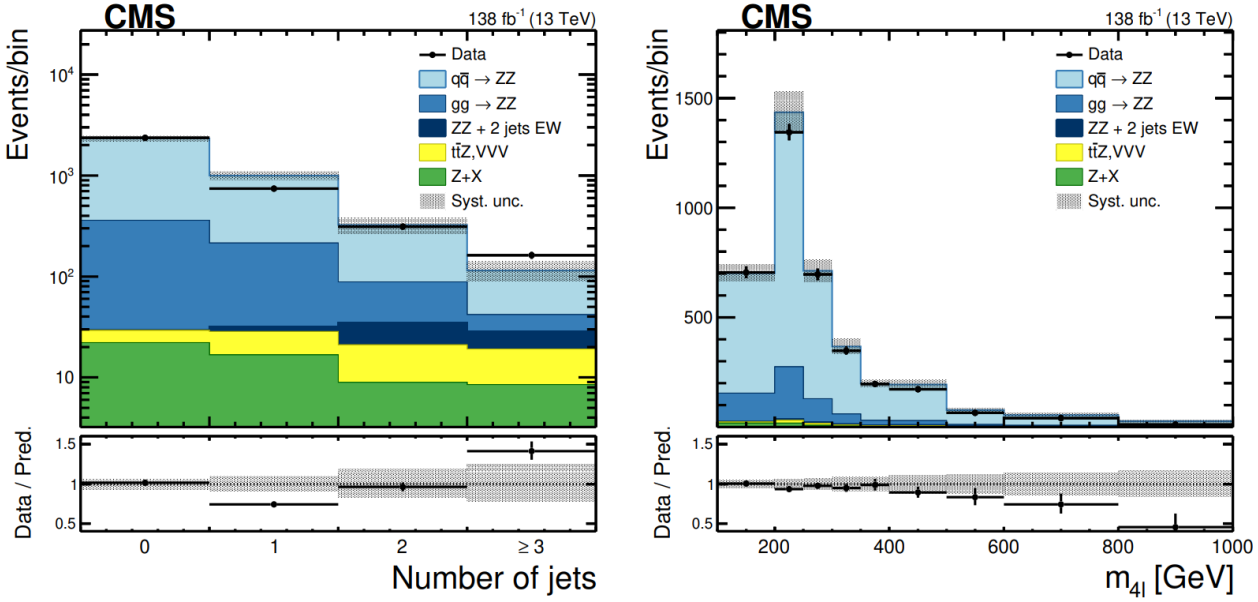
BACKUP

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

arXiv:2404.02711, submitted to JHEP, CMS-SMP-22-001 overview

- Differential distributions & normalised differential cross-sections
- Fully leptonic final state (e, μ), Four isolated leptons from PV + contribution

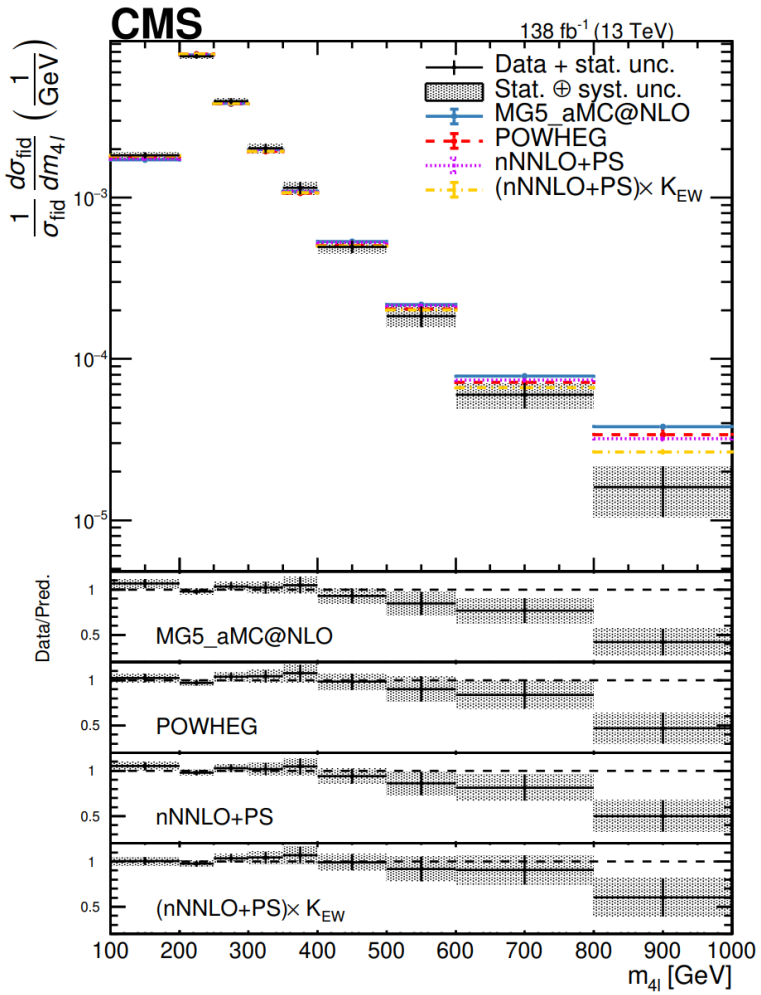


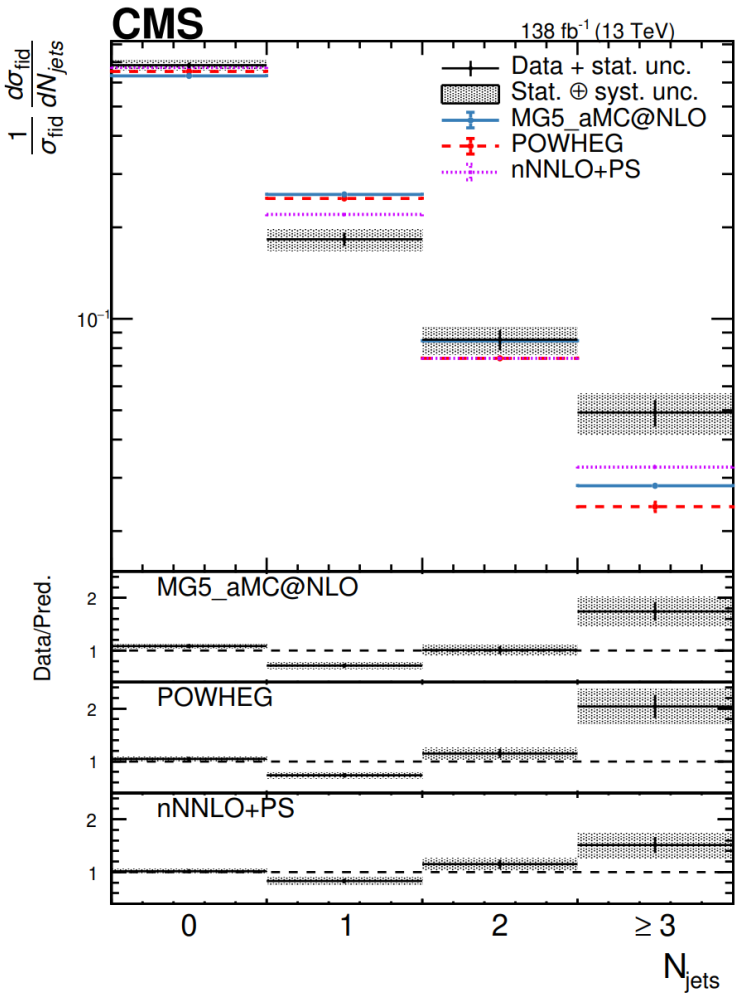


- from FSR photon with $\Delta R(\ell, \gamma) < 0.5$
- 2 on-shell Z candidates built from OS, same flavor leptons
- $40 < m_{Z1} < 120$ GeV, $4 < m_{Z2} < 120$ GeV
- $p_T^{jets} > 30$ GeV and $\Delta R(jet, \ell/\gamma) > 0.4$

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

arXiv:2404.02711, submitted to JHEP, CMS-SMP-22-001





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

- All predictions describe well data at low mass
- Discrepancy at high mass mitigated with EW corrections