First look at $W^{\pm}W^{\pm}$ and $W^{\pm}Z$ vector boson scattering at $\sqrt{s}$=13.6 TeV in CMS

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La Thuile (Italy)

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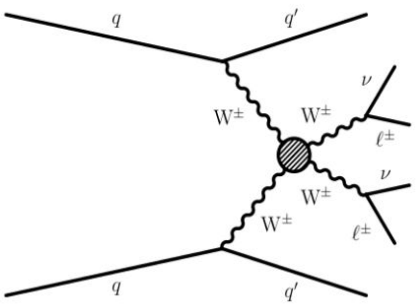
Introduction

Motivation

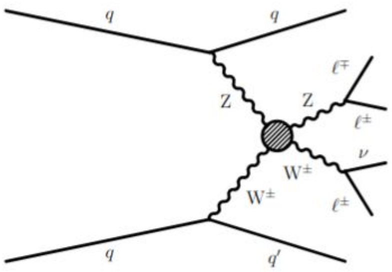
- Vector boson scattering (VBS) directly probes the electroweak sector and quartic gauge couplings.
- Measurements of VBS with same-sign $W^{\pm}W^{\pm}$ and WZ using pure leptonic channels.
- Run 1-2 : Observation beyond 5 standard deviations. Link



$W^{\pm}W^{\pm}$ process

Goals

- Measure inclusive and differential cross-sections using data collected during 2022-24 with Luminosity = 171 fb^{-1} →getting into precision measurements. CMS-PAS-SMP-25-013

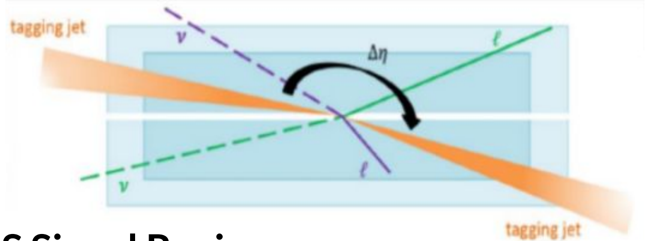


WZ process

Run-3 improvements

  - Larger dataset.
  - Improved lepton identification with MVA-based IDs.
  - Refined signal extraction with an updated fitting strategy.
  - More robust non-prompt background estimation.
    - second alternative method for estimation.

Event selection and backgrounds



VBS Signal Region

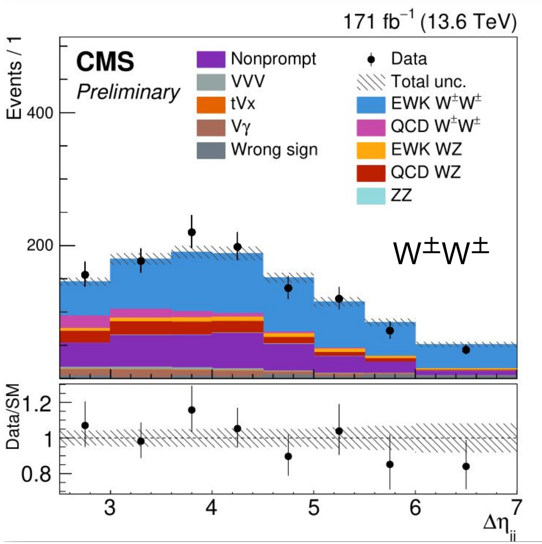
- 2 “tagging” jets with m_{jj} >500 GeV and $\Delta\eta_{jj}$>2.5.
- 2 ($W^{\pm}W^{\pm}$) or 3 (WZ) central leptons.
- $p_T^{miss} > 30$ GeV.
- b-jet veto (top suppression).

Considering several Control and Validation Regions

- Non-prompt CR
  - $W^{\pm}W^{\pm}$ with b-jet veto inverted
- WZb CR
  - WZ with b-jet veto inverted
- QCD enriched VR
  - $W^{\pm}W^{\pm}$ with b-jet veto inverted+relaxed VBS cuts

Backgrounds Sources

- QCD WZ ⟶ major background for WZ.
- Non-prompt leptons ⟶ major background for $W^{\pm}W^{\pm}$.
- Other minor backgrounds.



Non-prompt leptons

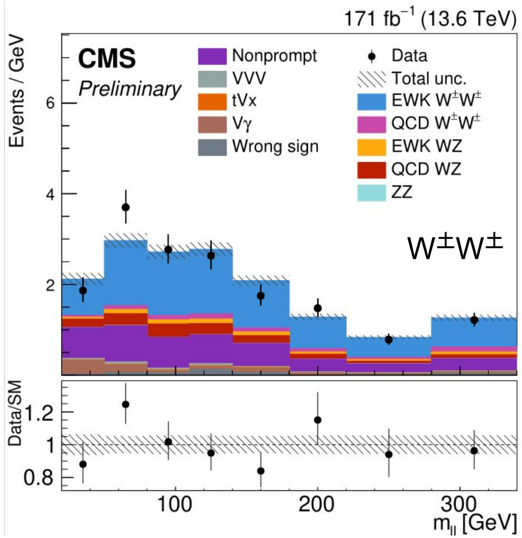
- Estimated using Data-Driven method.
- **Method I:** measured ε_{fake} (p_T, η)applied to data and MC samples.
- **Method II:** measured $\varepsilon_{prompt}(p_T, \eta)$, $\varepsilon_{fake}(p_T, \eta)$ applied to data(less MC dependence).

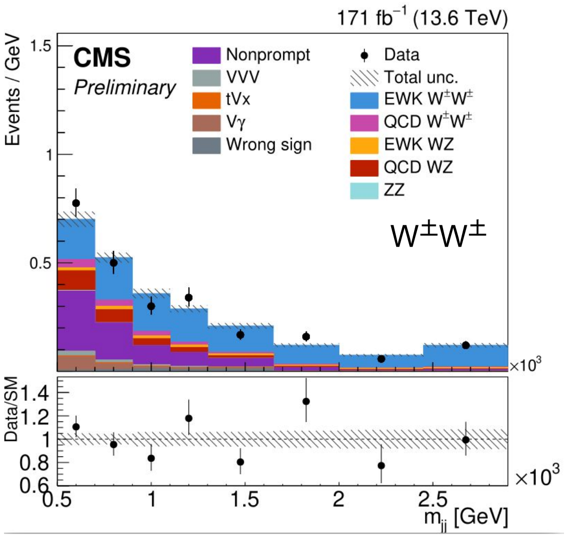
BDT for WZ QCD

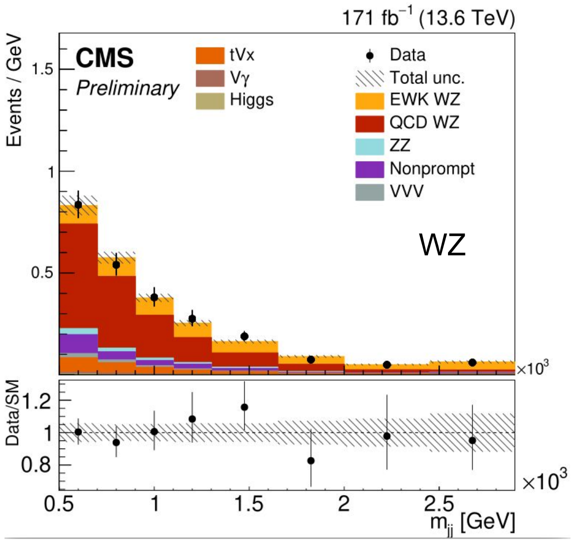
- Use Gradient BDT to separate EW WZ signal from QCD WZ background.

Measurement of inclusive fiducial and differential cross sections

- Simultaneous binned maximum likelihood fit across SRs ($W^{\pm}W^{\pm}$ and WZ) + CRs (non-prompt and WZb)
- For $W^{\pm}W^{\pm}$: Using 2-dimensional distributions m_{jj} vs m_{ll}, n_j, $\Delta\eta_{jj}$, $\Delta\Phi_{jj}$
- For WZ: Using BDT and Zeppenfeld variable.







Observed good Data vs prediction

Main uncertainties

- Lepton Identification and reconstruction, lumi, jets.
- Theory: PDF, PS and scale.
- Non-prompt uncertainty.

Analysis statistically dominated.

Results

- Unfolding: The measured distributions unfolded to particle level in a fiducial phase space to correct for detector effects.

Normalized differential cross-sections

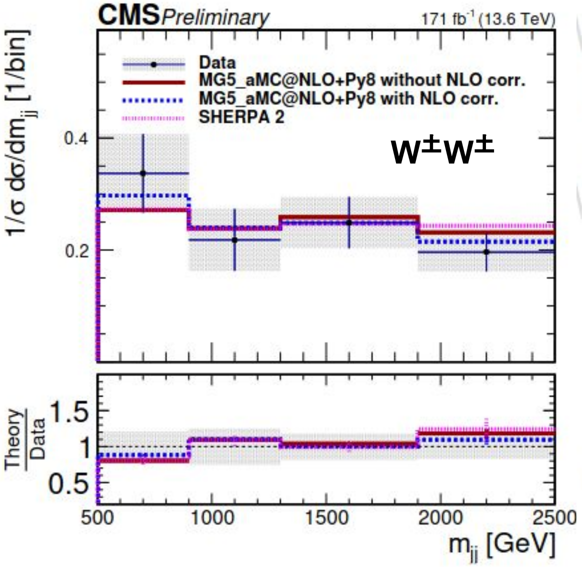
- For $W^{\pm}W^{\pm}$ also differential measurements wrt: m_{ll}, n_j, $\Delta\eta_{jj}$, $\Delta\Phi_{jj}$
- The accuracy of the measurement is 10% for $W^{\pm}W^{\pm}$ and 18% for WZ.

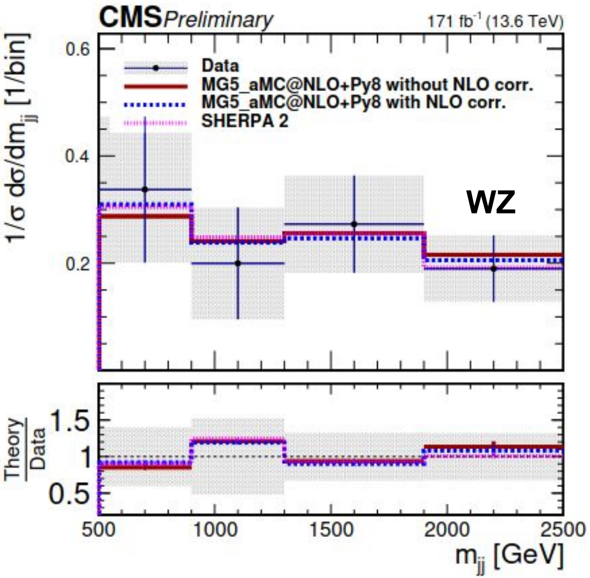
Compared to Run 2

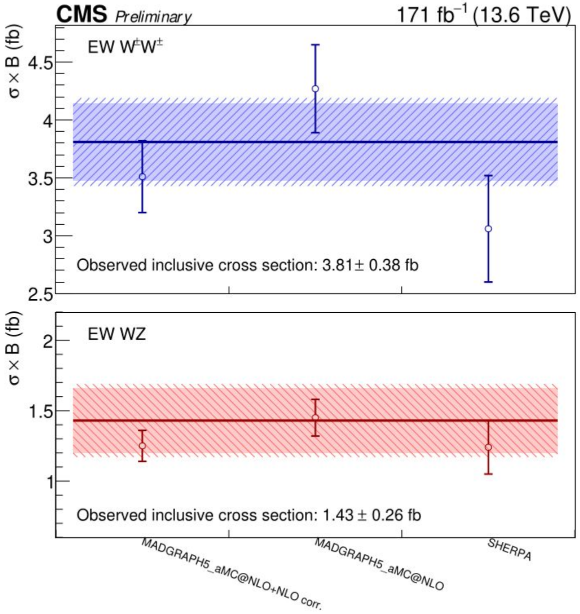
- Large reduction of non-prompt background.
- Smaller non-prompt uncertainty.
- Improved Lepton experimental, lumi unc.

Analysis still limited by statistics.

Measured inclusive cross-section







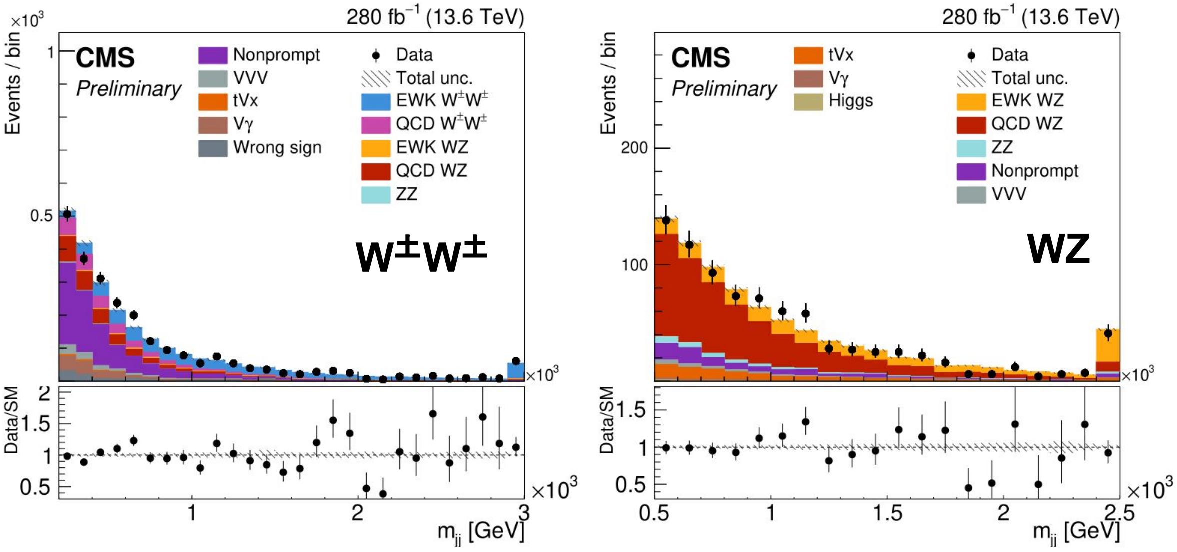
No evidence of deviation from SM.

Summary and Outlook

- Shown the first measurement of vector boson scattering in leptonic $W^{\pm}W^{\pm}$ and WZ diboson events at $\sqrt{s}$=13.6 TeV.
- Electroweak production of same-sign WW and WZ bosons is observed at a significance larger than five standard deviations each.
- Measured differential cross sections agree with MadGraph5_aMC@NLO and SHERPA predictions.
- Further details: PHY-Brief, CMS-PAS-SMP-25-013

Future Plans!

- Include 2025 and 2026 data.
- Improve sensitivity to aQGCs in Run 3.



First look at 2025 Data

Thank you

Backup Slides

Non-prompt background estimation

Non-prompt leptons

- Estimated using Data-Driven method.
- Define **Loose** and **Tight** selections
  - Loose leptons: to collect a sample dominated by non-prompt leptons.
  - Tight leptons:to define VBS signal.

Two methods to estimate non-prompt background:

- **Fakerate method:** measured ε_{fake} (pT, eta)applied to data and MC samples.

$$N^{\text{non-prompt}} = \sum_i w_i^{\text{data}} - \sum_i w_i^{\text{MC}} - \left(\sum_{i,j} w_{ij}^{\text{data}} - \sum_{i,j} w_{ij}^{\text{MC}} \right).$$

i (or j) is an index denoting the failing leg, and

$$w_i = \frac{\epsilon_{\text{fake}}(p_{T_i}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{T_i}, \eta_i)}, \; w_{ij} = \frac{\epsilon_{\text{fake}}(p_{T_i}, \eta_i)}{1 - \epsilon_{\text{fake}}(p_{T_i}, \eta_i)} \times \frac{\epsilon_{\text{fake}}\left(p_{T_j}, \eta_j\right)}{1 - \epsilon_{\text{fake}}\left(p_{T_j}, \eta_j\right)}.$$

NOTE

- failing leg: any lepton that passes loose but fails tight selection.
- ϵ_{fake}: Efficiency for a fake lepton to pass tight selection

- **Matrix method:** measured ε_{prompt}, ε_{fake} applied to data(less MC dependence).

δ = promptrate: Efficiency for a prompt lepton to fail the tight selection

$$\begin{pmatrix} \mathrm{TT} \\ \mathrm{TF} \\ \mathrm{FT} \\ \mathrm{FF} \end{pmatrix} = \begin{pmatrix} (1-\delta_1)(1-\delta_2) & (1-\delta_1)\varepsilon_2 & \varepsilon_1(1-\delta_2) & \varepsilon_1\varepsilon_2 \\ \delta_2(1-\delta_1) & (1-\delta_1)(1-\varepsilon_2) & \varepsilon_1\delta_2 & \varepsilon_1(1-\varepsilon_2) \\ (1-\delta_2)\delta_1 & \delta_1\varepsilon_2 & (1-\varepsilon_1)(1-\delta_2) & (1-\varepsilon_1)\varepsilon_2 \\ \delta_1\delta_2 & \delta_1(1-\varepsilon_2) & (1-\varepsilon_1)\delta_2 & (1-\varepsilon_1)(1-\varepsilon_2) \end{pmatrix} \begin{pmatrix} \mathrm{PP} \\ \mathrm{PN} \\ \mathrm{NP} \\ \mathrm{NN} \end{pmatrix}$$

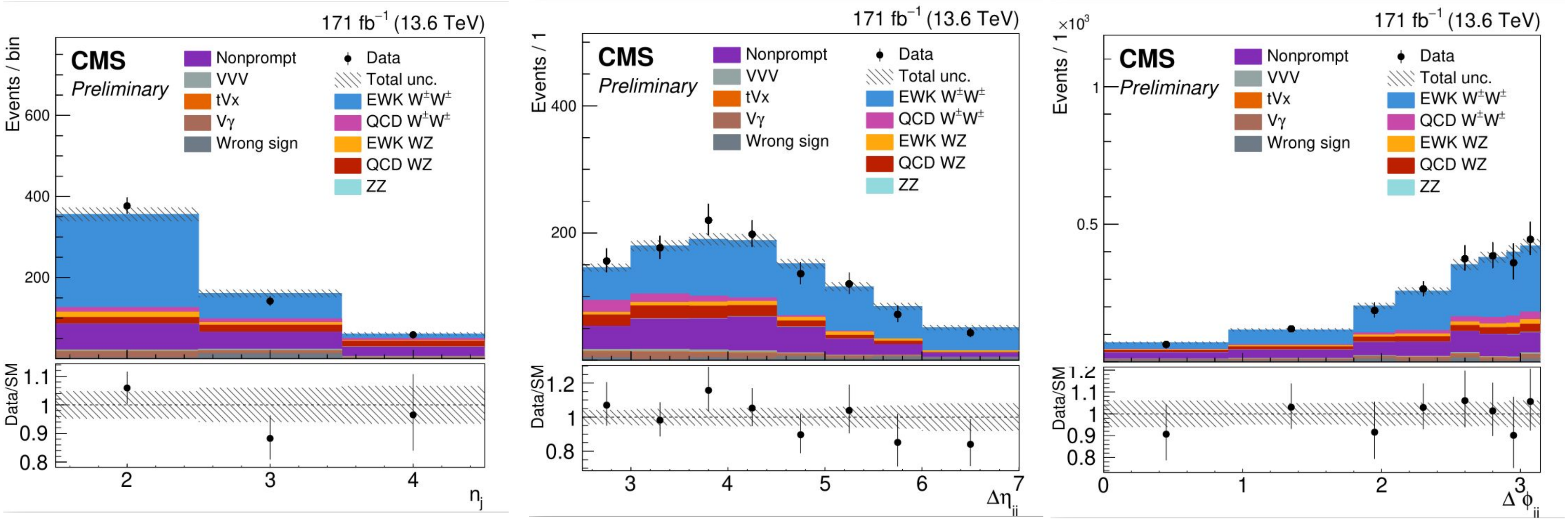
$$PP = \sum_{TT} \frac{(1-\varepsilon_1)(1-\varepsilon_2)}{(1-\varepsilon_1-\delta_1)(1-\varepsilon_2-\delta_2)} - \sum_{TF+FT} \frac{(1-\varepsilon_T)\varepsilon_F}{(1-\varepsilon_T-\delta_T)(1-\varepsilon_F-\delta_F)} + \sum_{FF} \frac{\varepsilon_1\varepsilon_2}{(1-\varepsilon_1-\delta_1)(1-\varepsilon_2-\delta_2)}$$

- The summation runs over the TT, TF+FT and FF events
- PP: prompt-prompt leptons
- After calculating PP, the signal can be estimated as:

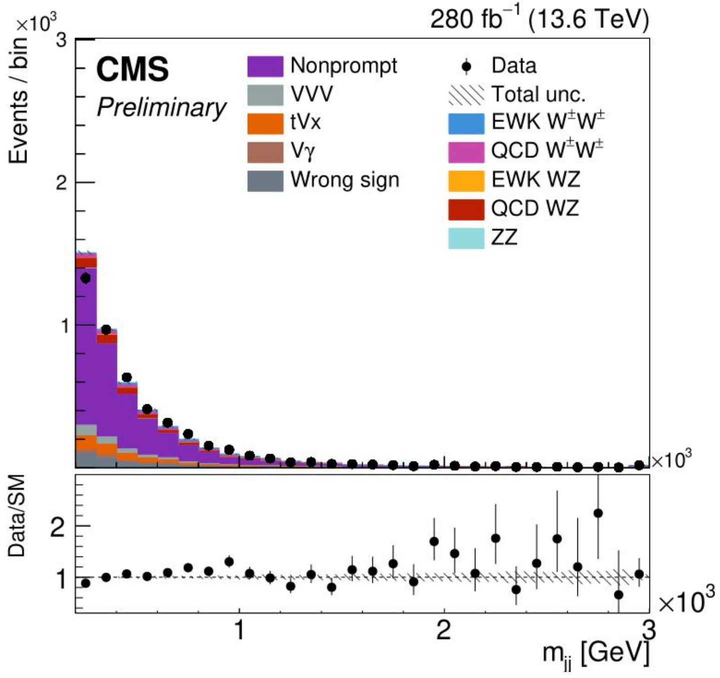
  $N_{signal} = (1-\delta)^2 PP$

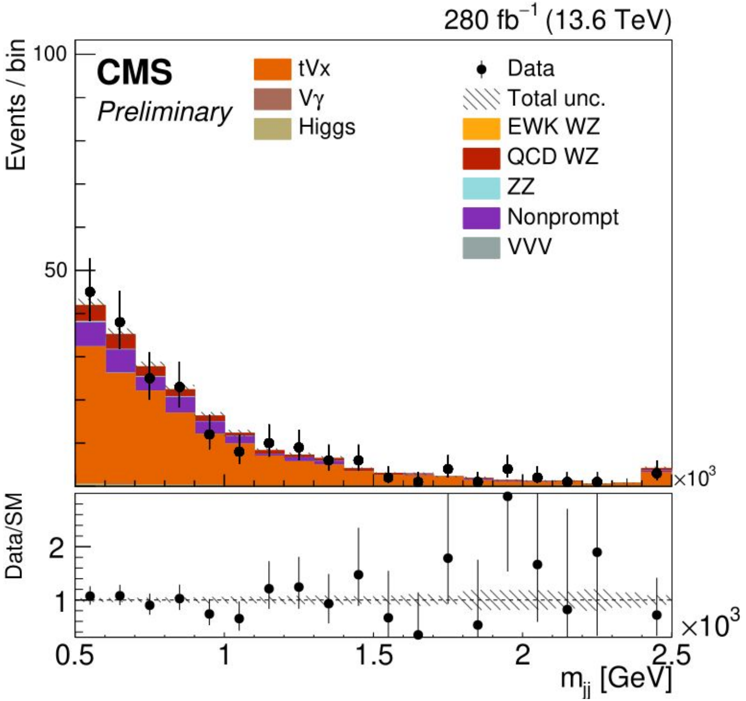
Closure: consistent results in validation regions.

Signal Region Plots $W^{\pm}W^{\pm}$

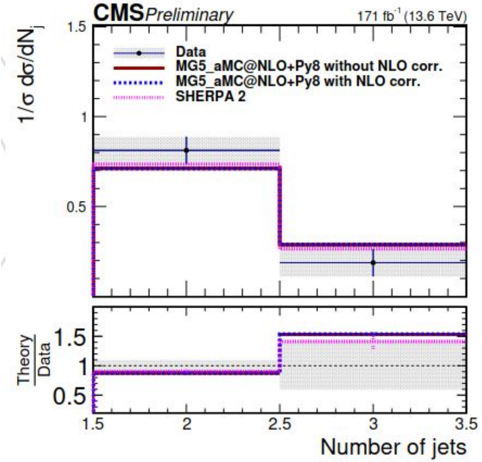


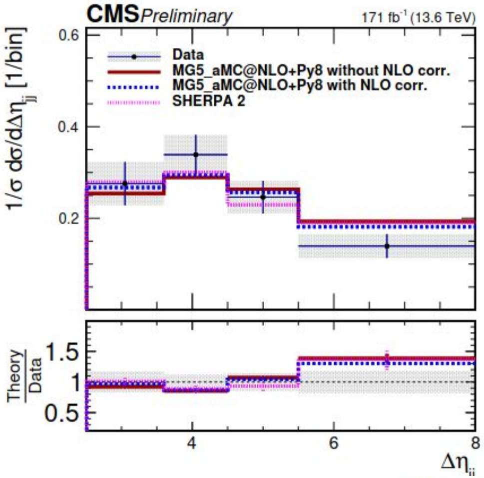
Plots using 2022- 2025 Data: W±W± and WZ CR

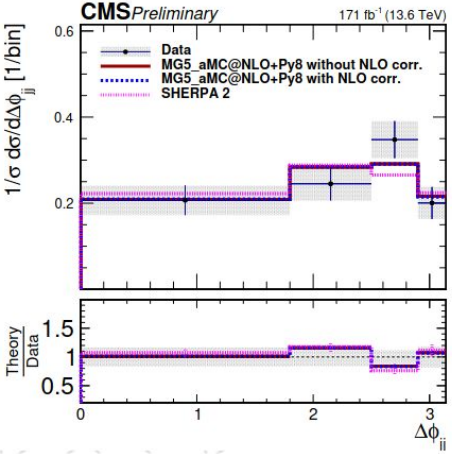


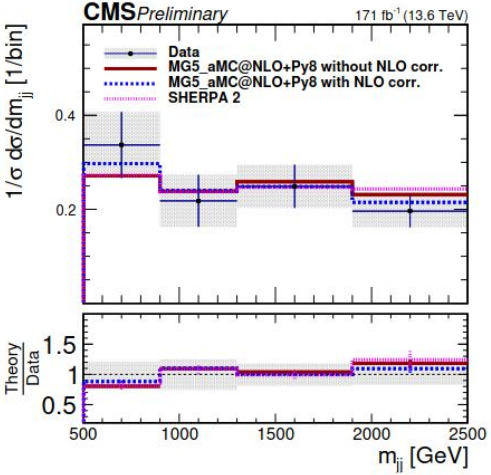


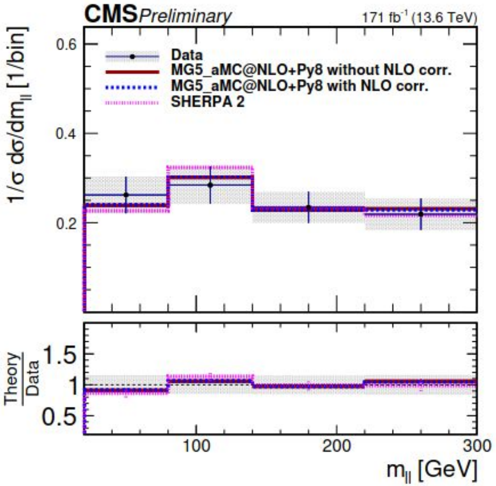
Normalized differential cross-sections for $W^{\pm}W^{\pm}$











List of Full Selections for SR

Variable	$W^{\pm}W^{\pm}$ SR	WZ SR
Leptons	2 leptons, $p_T > 25/20\,\text{GeV}$	3 leptons, $p_T > 25/10/20\,\text{GeV}$
$\lvert m_{\ell\ell} - m_Z \rvert$	$> 20\,\text{GeV}$ (ee)	$< 15\,\text{GeV}$
$m_{\ell\ell}$	$> 20\,\text{GeV}$	—
$m_{\ell\ell\ell}$	—	$> 100\,\text{GeV}$
p_T^{miss}	$> 30\,\text{GeV}$	$> 30\,\text{GeV}$
b quark veto	Required	Required
p_T^{j}	$> 50\,\text{GeV}$	$> 50\,\text{GeV}$
$\max(z_\ell^*)$	< 0.75	< 1.0
m_{jj}	$> 500\,\text{GeV}$	$> 500\,\text{GeV}$
$\Delta\eta_{jj}$	> 2.5	> 2.5

List of Full Selections for CR

Variable	Nonprompt	WZb
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	> 50 GeV	> 50 GeV
$\|m_{\ell\ell} - m_Z\|$	> 20 GeV (ee)	< 15 GeV
$m_{\ell\ell}$	> 20 GeV	—
$m_{\ell\ell\ell}$	—	> 100 GeV
p_T^{miss}	> 30 GeV	> 30 GeV
b quark veto	Inverted	Inverted
$\max(z_\ell^*)$	< 0.75	< 1.0
m_{jj}	> 500 GeV	> 500 GeV
$\Delta\eta_{jj}$	> 2.5	> 2.5

Variables used for training BDT

Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$p_{\mathrm{T}}^{\mathrm{jj}}$	p_{T} of dijet system
$\Delta\eta_{\mathrm{jj}}$	Absolute difference in rapidity between the leading and trailing jets
$\Delta\phi_{\mathrm{jj}}$	Difference in azimuth angles between the leading and trailing jets
$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading jet
$p_{\mathrm{T}}^{\mathrm{j2}}$	p_{T} of the trailing jet
η^{j1}	η of the leading jet
η^{j2}	η of the trailing jet
$\max(z_{\ell}^{*})$	Maximum Zeppenfeld variable
$z_{3\ell}^{*}$	Zeppenfeld variable of the tri-lepton system
$p_{\mathrm{T}}^{\mathrm{VV}}$	p_{T} of the vectorial sum of all boson objects
p_{T}^{tot}	p_{T} of the vectorial sum of all boson objects and VBF jets
$\Delta\eta_{\mathrm{j1,VV}}$	$\Delta\eta$ between the leading jet and the tri-lepton system
$\Delta\eta_{\mathrm{j2,VV}}$	$\Delta\eta$ between the trailing jet and the tri-lepton system
$\lvert\vec{p_{\mathrm{T}}}^{\mathrm{tot}}\rvert / \sum_i p_{\mathrm{T}}^{i}$	Transverse component of the vector sum of the bosons and tagged jets momenta, normalized to their scalar p_{T} sum

Systematic Uncertainties

	EW WW		EW WZ	
Source of uncertainty	Run 2	Run 3	Run 2	Run 3
Integrated luminosity	1.5	1.3	1.6	1.3
Lepton experimental	2.1	1.6	3.1	3.0
Jet experimental	1.5	2.3	4.3	6.1
b tagging	1.0	1.6	1.0	0.4
non-prompt background	3.5	0.8	1.4	0.6
Limited sample size	2.6	3.3	3.7	3.4
Theory	1.9	1.6	3.8	3.8
Statistical	8.9	9.5	22	18
Total	11	10.7	23	20.4

- Values are shown in %.
- Non-prompt uncertainty is significantly reduced in Run 3 (improved lepton selections).
- Statistical uncertainty decreases with the larger Run 3 dataset (notably for EW WZ: 22% $\rightarrow$ 18%).
- The analysis is still statistically dominated.

Measured inclusive cross-section

Process	$\sigma \mathcal{B}$ (fb)	MADGRAPH5_aMC@NLO prediction without NLO corrections (fb)	MADGRAPH5_aMC@NLO prediction with NLO corrections (fb)	SHERPA prediction without NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.81 ± 0.38 $0.33\,(\text{stat}) \pm 0.18\,(\text{syst})$	4.27 ± 0.38	3.51 ± 0.31	3.06 ± 0.46
EW+QCD $W^{\pm}W^{\pm}$	4.32 ± 0.40 $0.36\,(\text{stat}) \pm 0.18\,(\text{syst})$	4.75 ± 0.52	3.99 ± 0.44	—
EW WZ	1.43 ± 0.26 $0.23\,(\text{stat}) \pm 0.12\,(\text{syst})$	1.45 ± 0.13	1.25 ± 0.11	1.24 ± 0.19
EW+QCD WZ	4.75 ± 0.35 $0.27\,(\text{stat}) \pm 0.22\,(\text{syst})$	4.59 ± 1.07	4.39 ± 1.05	—

- The inclusive cross-section is compared to the theoretical prediction from Madgraph and SHERPA