59th Rencontres de Moriond on "Electroweak Interactions & Unified Theories"

Run 3 Standard Model cross section measurements

Carlos Vico Villalba on behalf of the CMS and ATLAS collaborations

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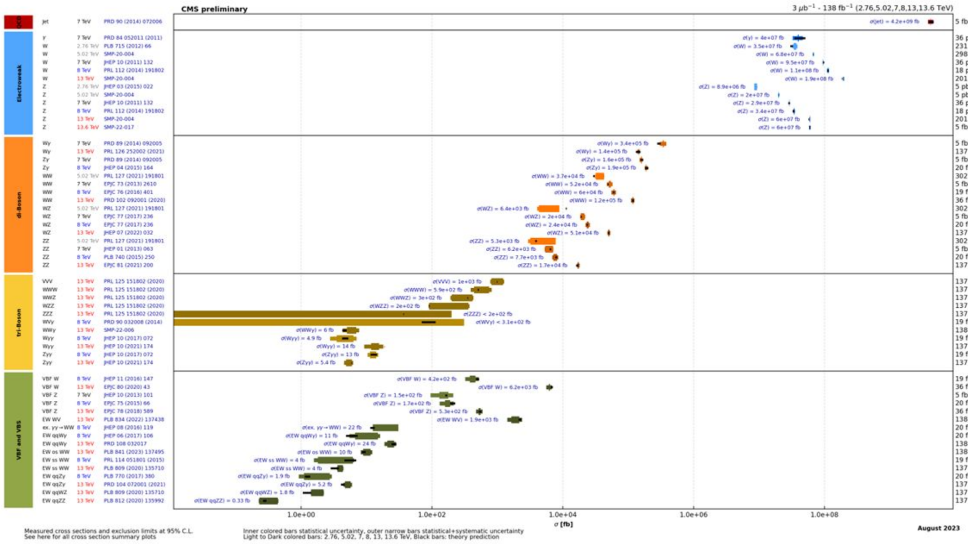
Introduction. Evolution of measurements at the LHC

- **A lot of aspects in electroweak** (**EW**) **physics** covered **during Run 2**.
  - ~ 140 fb^{-1} of data recorded by both **ATLAS** and **CMS**.
- **July 2022:** the new Run 3 of the LHC started.
  - At a new center of mass energy of 13.6 TeV!
- **LHC collaborations are targeting** (once again!) the **largest** ever recorded **dataset** in **High Energy Physics.**

*Plot from CMS. Note **ATLAS has also extensively explored the EW sector during Run 2**!*



- The largest dataset comes with great responsibility…
  - **Lessons from Run 2.**
  - Expected. **Stat unc reduced** by factor **~√2.**
  - Improved analysis techniques (**better systematic**).
  - **Improved detectors.**

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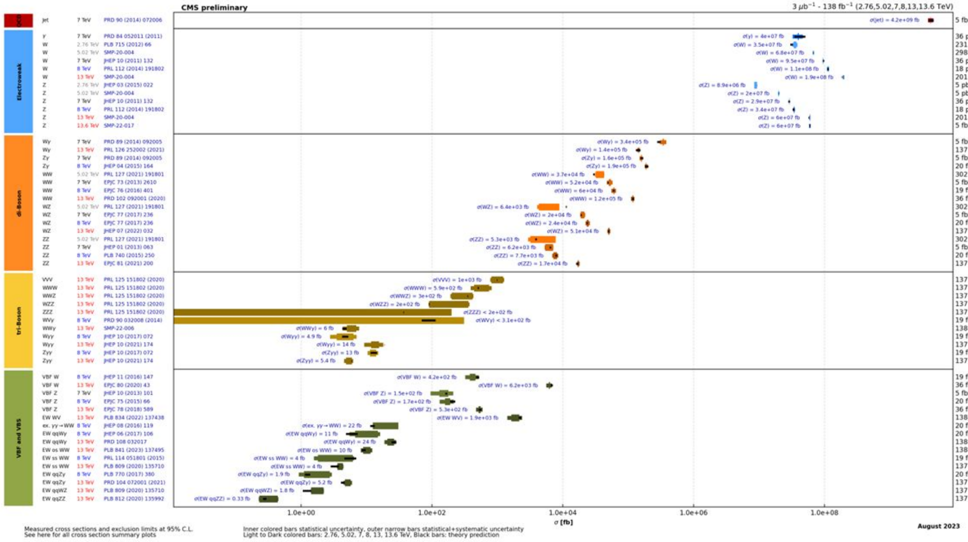

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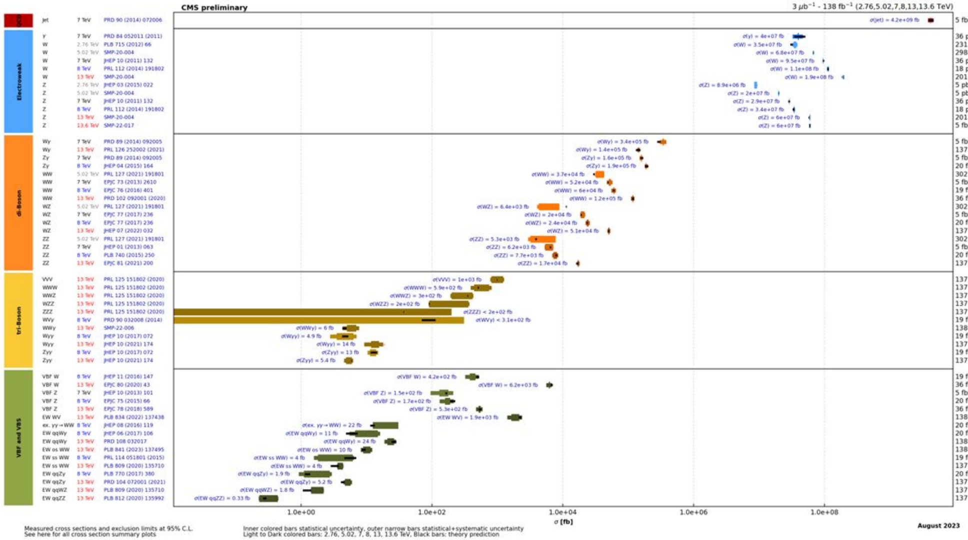

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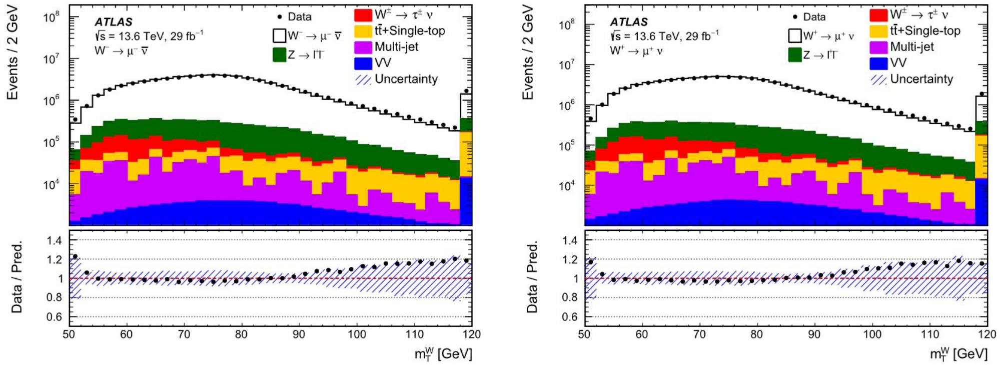
In my talk: **focus on EW sector measurements by ATLAS** and **CMS with Run 3 data.**

Single vector boson production measurements

Single vector boson production measurements

- Single-Z and W boson production is key for proper lepton calibration.
- **Z boson production:**
  - Measured by both CMS (SMP-22-017) and ATLAS (PLB. 854 (2024) 138725).
- **W boson production:**
  - Measured by ATLAS (PLB. 854 (2024) 138725), and recently by CMS (arXiv: 2503.09742 → superseeds **SMP-22-017**).

PLB. 854 (2024) 138725



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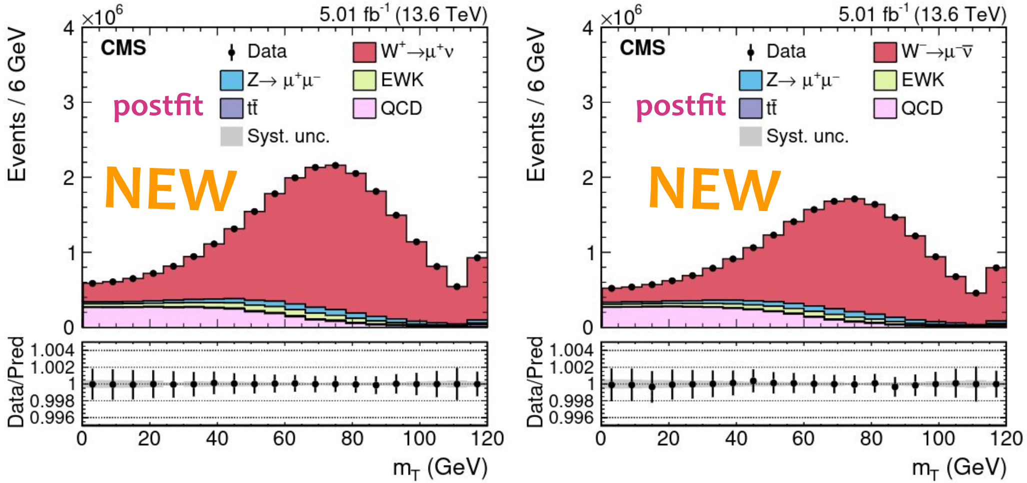
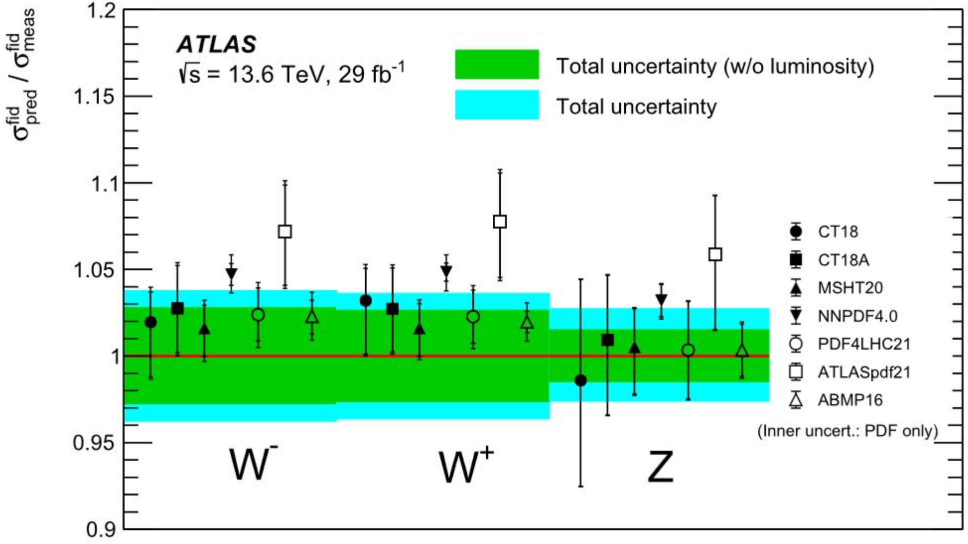
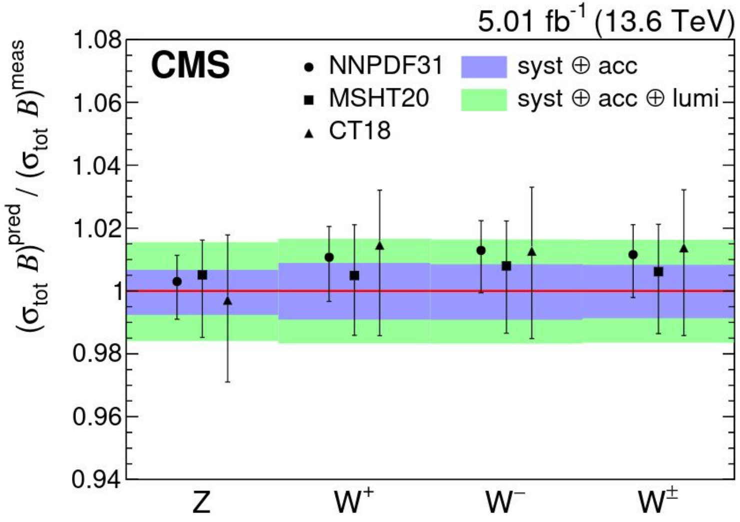


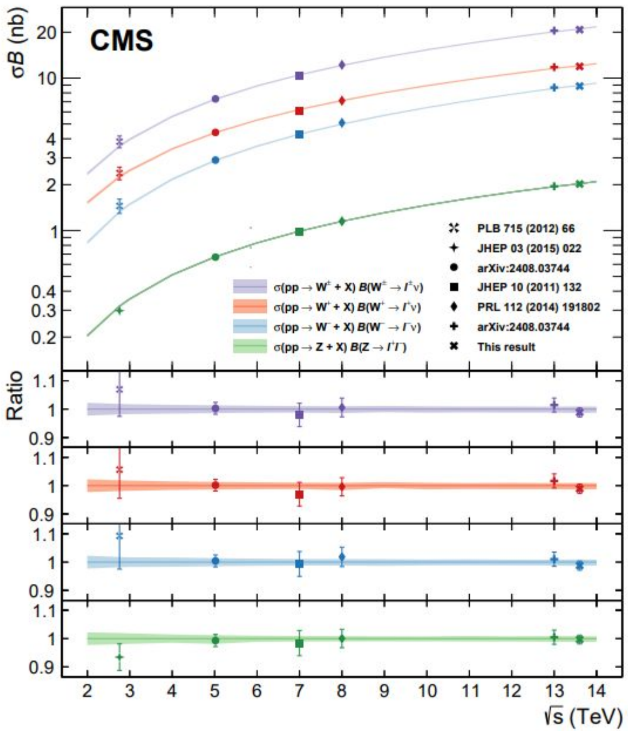
- Measurement of the Z and W boson production cross section at 13.6 TeV.





Good agreement with SM with competitive final uncertainty

arXiv: 2503.09742



NEW

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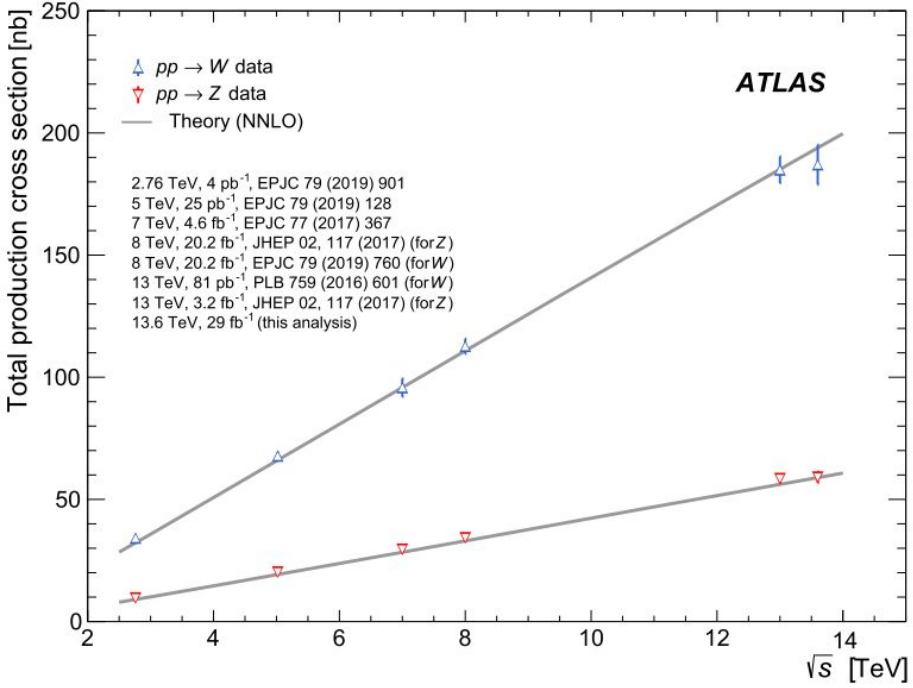
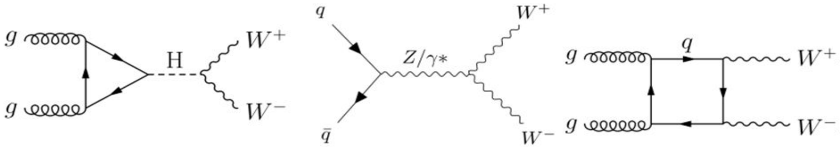
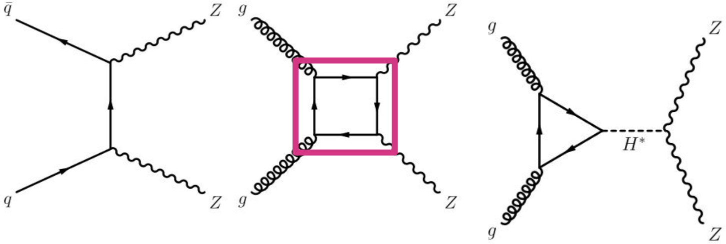


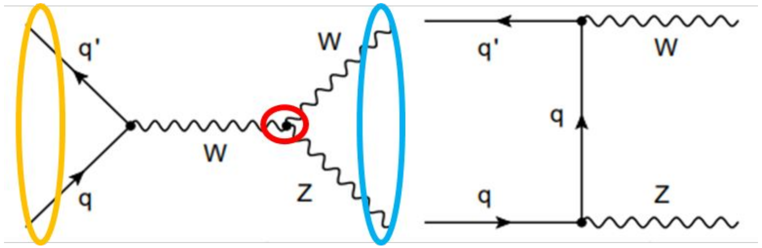
Diboson production

Diboson production measurements

- Diboson production processes are very interesting because of many reasons
- **From a theoretical point of view:**
  - **Relevant backgrounds in Higgs measurements.**
  - Sensitive to triple gauge couplings.
  - Boson polarization effects
  - Sensitive to proton PDFs
- **From a experimental point of view**
  - Relatively large cross section
  - Very clean final states.
  - **Already accessible with Run 3 data.**

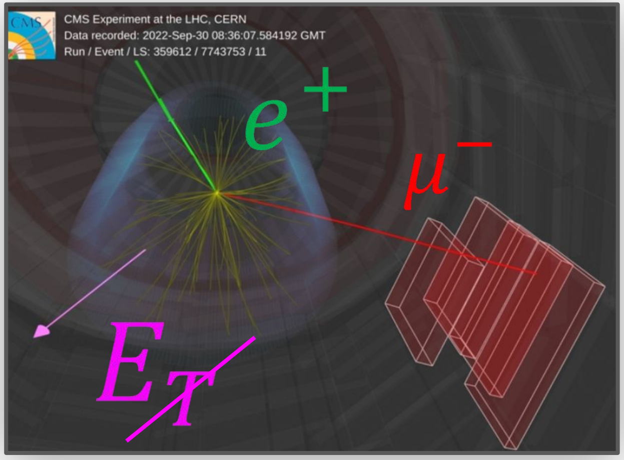






Diboson measurements at 13.6 TeV

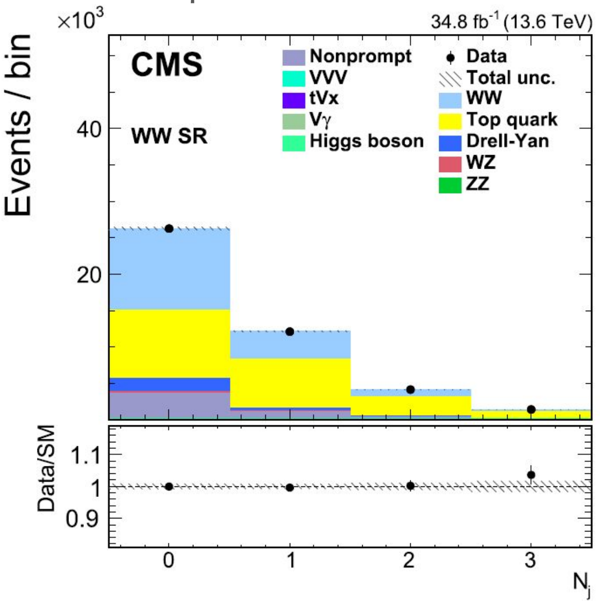
$WW \to e^{\pm}\mu^{\mp}$



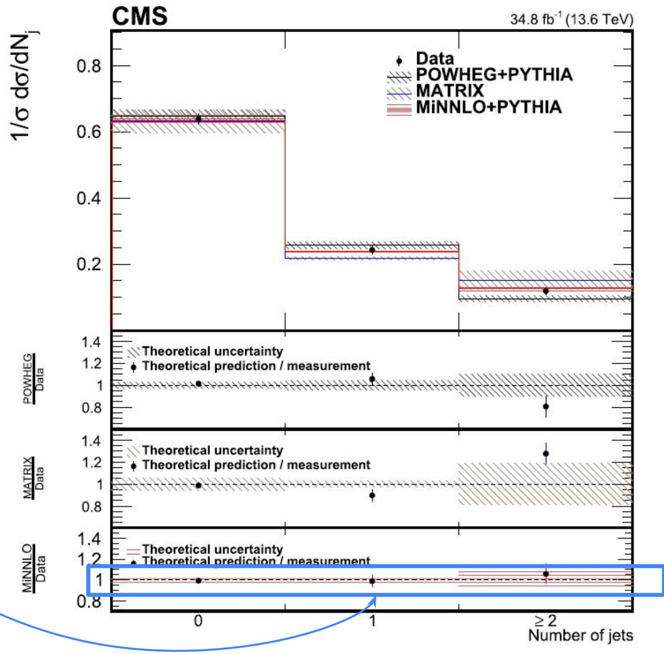
Run 3 provides standard model with new victory energy frontier

WW cross section measurements – PLB. 861 (2025) 139231

- Inclusive and differential cross sections are reported
  - **Extracted from a maximum likelihood fit to** the **observed yields** as a **function of the number of jets** to the signal region + multiple CRs.



First ever comparison with MiNNLO+PS generator in WW!



Observable	Expected	Observed
Cross section (fb)	$812 \pm 34\,(31, 15)$	$813 \pm 35\,(32, 15)$
0-jet fraction	$0.648 \pm 0.015\,(0.012, 0.009)$	$0.640 \pm 0.016\,(0.013, 0.009)$
1-jet fraction	$0.256 \pm 0.013\,(0.008, 0.010)$	$0.243 \pm 0.013\,(0.009, 0.010)$
≥2-jet fraction	$0.096 \pm 0.011\,(0.008, 0.008)$	$0.119 \pm 0.011\,(0.008, 0.008)$

σ_{WW} = 125.7± 2.3 (stat) ± 4.8 (syst) ± 1.8 (lumi) pb

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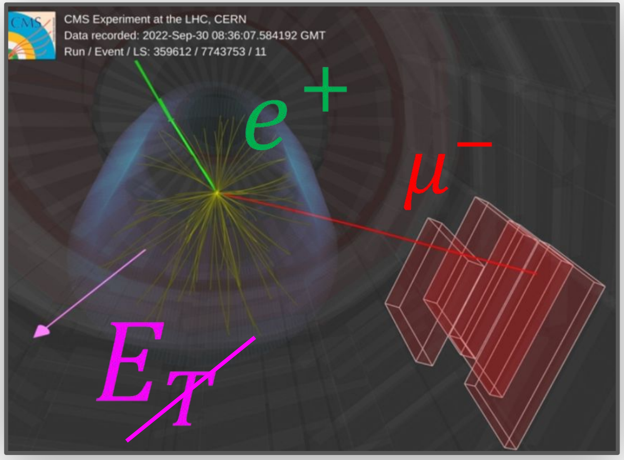
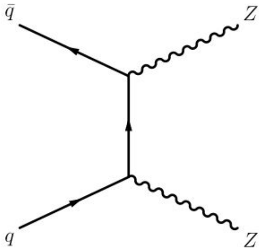


[Run 3 provides standard model with new victory energy frontier]

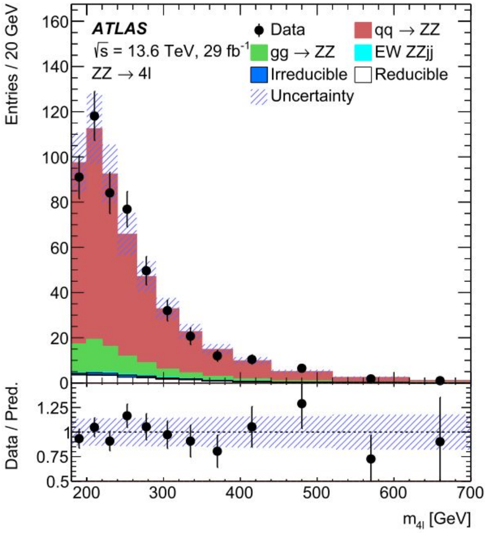
$ZZ \to 4\ell$

[ATLAS measures ZZ production using Run-3 data and a new slim data format]



ZZ cross section measurements – PLB. 855 (2024) 138764

- **Rarest diboson production mechanism** → target topology is **ZZ→ 4ℓ**.
  - The **measurements** are **reported in** a **fiducial volume** that mimics the requirements of the signal region.
  - The measurement is **also extrapolated to** a less theoretically constrained **total volume**.
- **The ZZ cross section is extracted through a cut & count procedure.**



	Fiducial phase space	Total lepton phase space
Muon selection	Bare, $p_T > 5$ GeV , $\|\eta\| < 2.5$	Born
Electron selection	Dressed, $p_T > 7$ GeV , $\|\eta\| < 2.47$	Born
Four-lepton signature	≥ 2 SFOC pairs	≥ 2 SFOC pairs
Lepton kinematics	$p_T > 27/10$ GeV	
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.05$	
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5$ GeV	$m_{ij} > 5$ GeV
Z mass window	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV
ZZ on-shell	$m_{4l} > 180$ GeV	

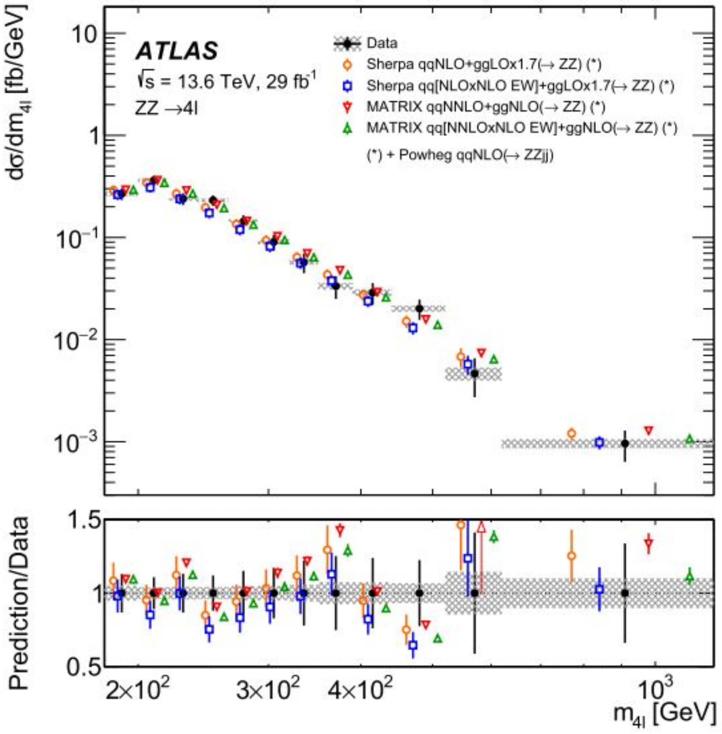
Source	Relative uncertainty (%)
Data statistical uncertainty	4.2
MC statistical uncertainty	0.3
Luminosity	2.2
Pile-up	0.3
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3

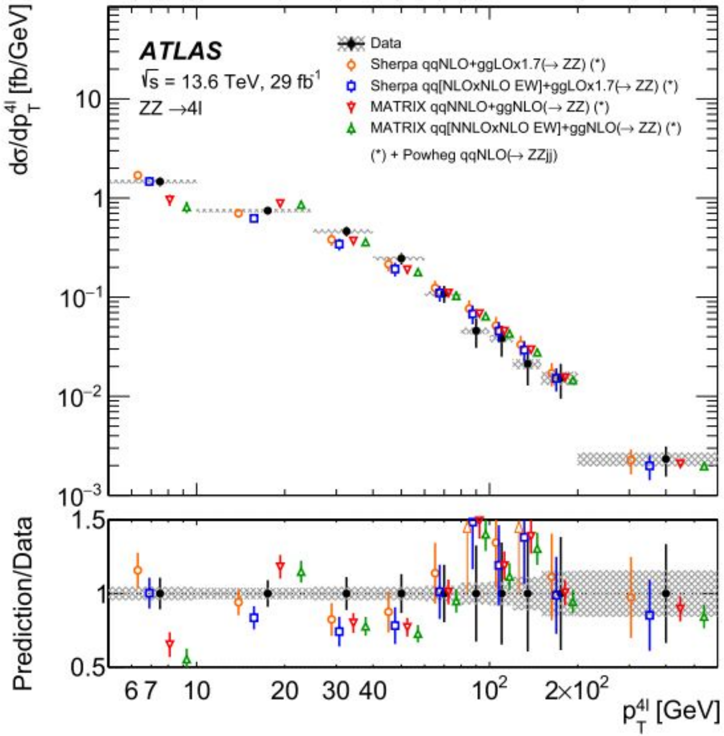
Better calibration to come in later Run 3!

	Measurement	MC prediction	MATRIX + EW $ZZjj$
Fiducial	$36.7 \pm 1.6(\text{stat}) \pm 1.5(\text{syst}) \pm 0.8(\text{lumi})$ fb	$36.8\ ^{+4.3}_{-3.5}$ fb	36.5 ± 0.7 fb
Total	$16.8 \pm 0.7(\text{stat}) \pm 0.7(\text{syst}) \pm 0.4(\text{lumi})$ pb	$17.0\ ^{+1.9}_{-1.4}$ pb	16.7 ± 0.5 pb

ZZ cross section measurements – PLB. 855 (2024) 138764

- **In addition** to the inclusive cross section measurements**, differential unfolding of observables is performed** using **background subtraction** techniques.





Diboson measurements at 13.6 TeV

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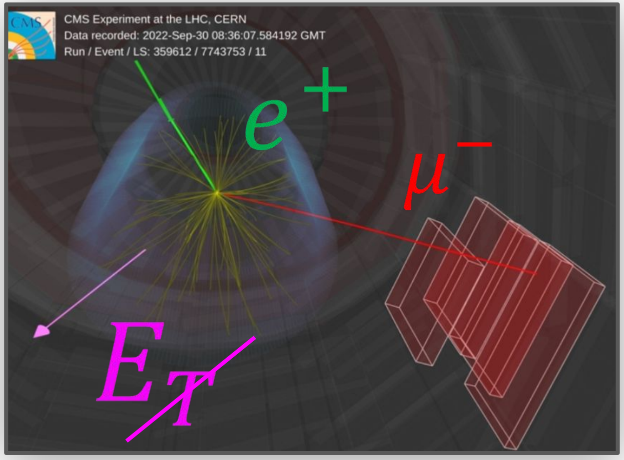

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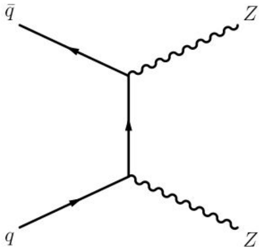
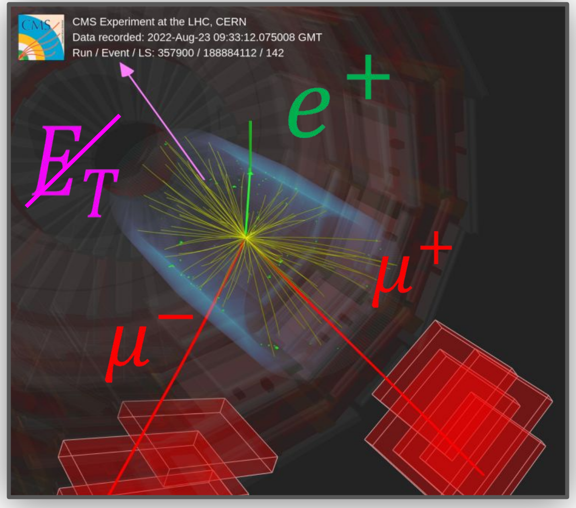


$WZ \to 3\ell+\nu$

The heavy force-carriers at record energy



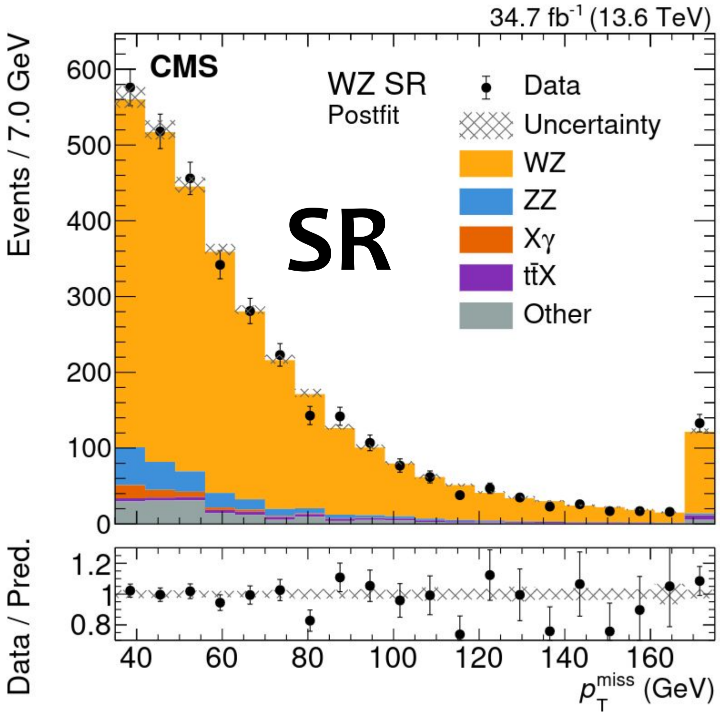
WZ cross section measurements – Arxiv. 2412.02477 Accepted by JHEP

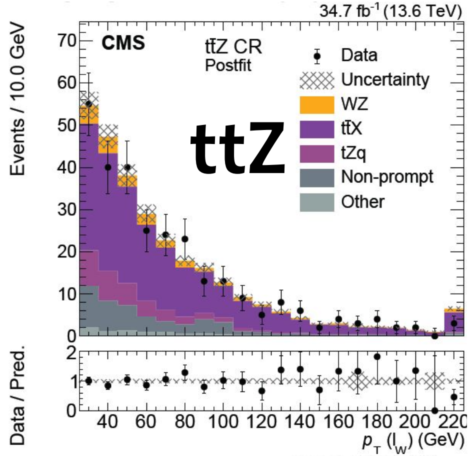
- In its multileptonic final state, this process has:
  - Very clean final state
  - **Reasonably high statistics and purity**
- The analysis is performed in these final state topologies ($WZ \to 3\ell + \nu$).

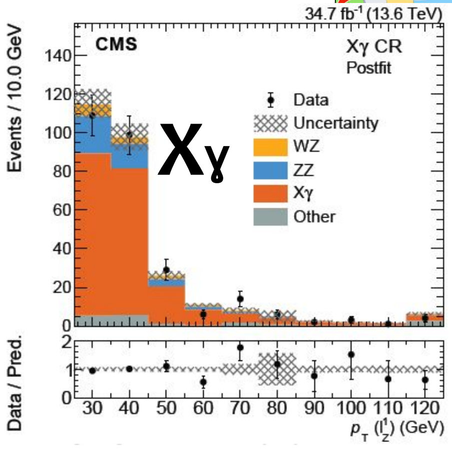
Region	N_ℓ	$p_T\{\ell_Z^1, \ell_Z^2, \ell_W(\ell_3), (\ell_4)\}$ (GeV)	N_{OSSF}	$\lvert m(\ell_Z^1, \ell_Z^2) - m_Z \rvert$ (GeV)	p_T^{miss} (GeV)	$N_{b\ tag}$	$\min(m(\ell, \ell'))$ (GeV)	$m(\ell_Z^1, \ell_Z^2, \ell_W(\ell_3))$ (GeV)
SR	=3	>{25, 15, 25}	≥1	<15	>35	=0	>4	>100
ZZ CR	=4	>{25, 15, 25, 15}	≥1	<15	—	=0	>4	>100
$t\bar{t}Z$ CR	=3	>{25, 15, 25}	≥1	<15	>35	>0	>4	>100
$X\gamma$ CR	=3	>{25, 15, 25}	≥1	—	≤35	=0	>4	<100

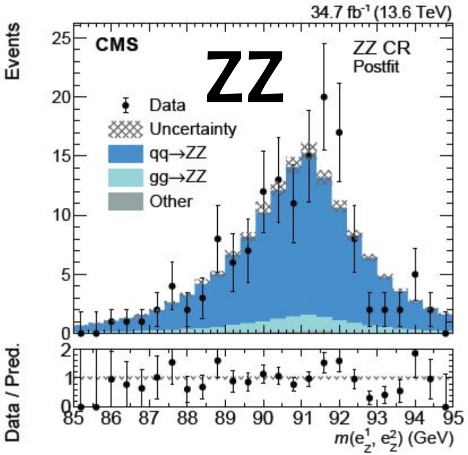
- **One signal region (SR)**.
- The main backgrounds (**ZZ**, **ttZ** and **conversions**) are controlled with three additional control regions (CRs).

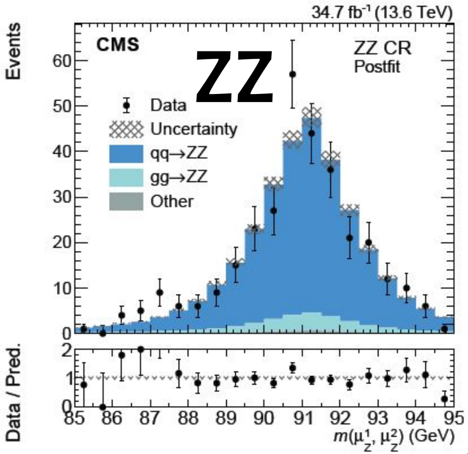
- The analysis also serves as a **proof** of the **performance of multiple objects in CMS** during Run 3!







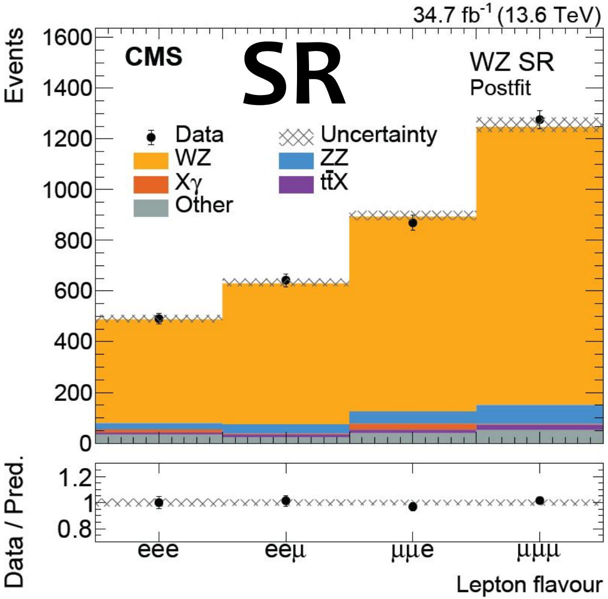




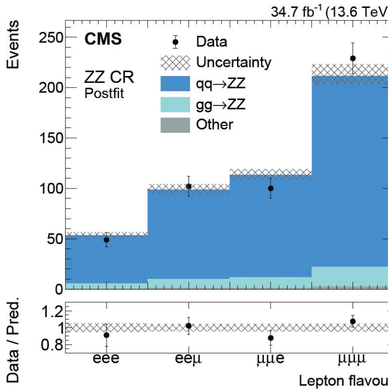
- The **WZ cross section** is extracted from a maximum likelihood **fit to** the number of **observed events** in **different lepton categories**.
  - The SR and all CRs are considered in the fit.

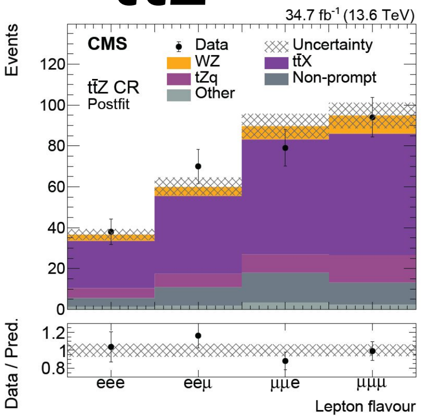
Measurements are reported in **fiducial** and **total regions** per lepton flavour channel.

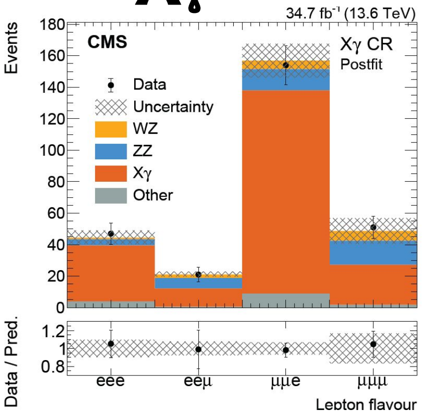
Region	Fiducial	Total
Lepton definition	Dressed (e, μ)	Dressed (e, μ, τ)
$N_\ell = 3$	✓	✓
$p_T\{\ell_Z^1, \ell_Z^2, \ell_W\} > \{25, 15, 25\}$ GeV	✓	—
$\lvert\eta\rvert\{\ell_Z^1, \ell_Z^2, \ell_W\} < \{2.5, 2.5, 2.5\}$	✓	—
$N_{OSSF} = 1$	✓	✓
$60 < m(\ell_Z^1, \ell_Z^2) < 120$ GeV	✓	✓
$\min(m(\ell, \ell')) > 4$ GeV	✓	✓
$m(\ell_Z^1, \ell_Z^2, \ell_W) > 100$ GeV	✓	—



All distributions are **postfit**







WZ cross section measurements – Arxiv. 2412.02477 Accepted by JHEP

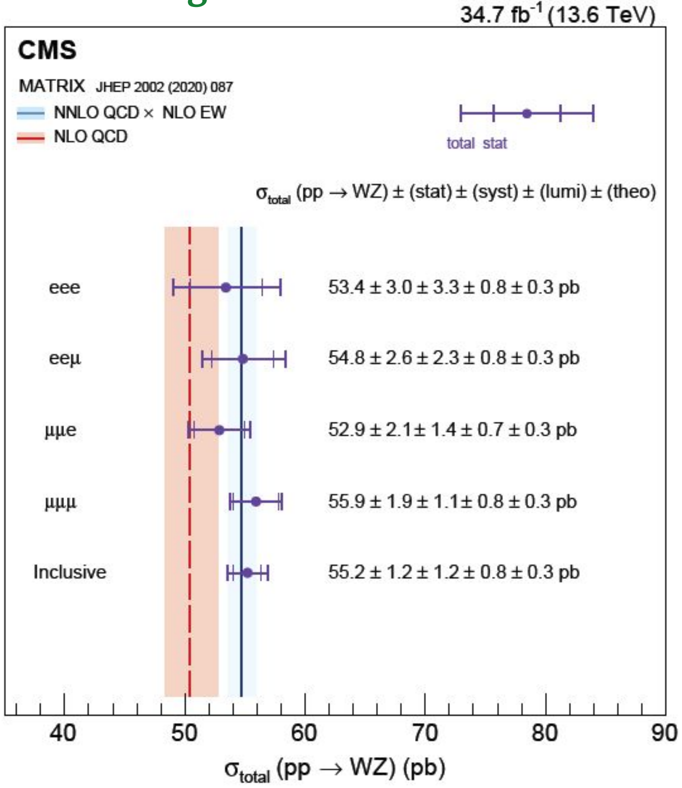
All results are compared to latest theoretical predictions computed with MATRIX.

Excellent agreement with SM!

Fiducial region results for the inclusive channel

Inclusive	POWHEG, NLO QCD	$271.9^{+9.0}_{-8.5}$ (scale) $\pm$ 3.8 (PDF)
	MATRIX, NLO QCD	$277.1^{+15.3}_{-12.3}$ (scale)
	MATRIX, NNLO QCD	$304.0^{+7.1}_{-6.6}$ (scale)
	MATRIX, NNLO QCD $\times$ NLO EW	$297.7^{+6.8}_{-6.3}$ (scale)
	Measured	297.6 $\pm$ 6.4 (stat) $\pm$ 6.4 (syst) $\pm$ 4.2 (lumi) $\pm$ 1.5 (theo)

Total region results



WWZ and ZH cross sections at 13 and 13.6 TeV

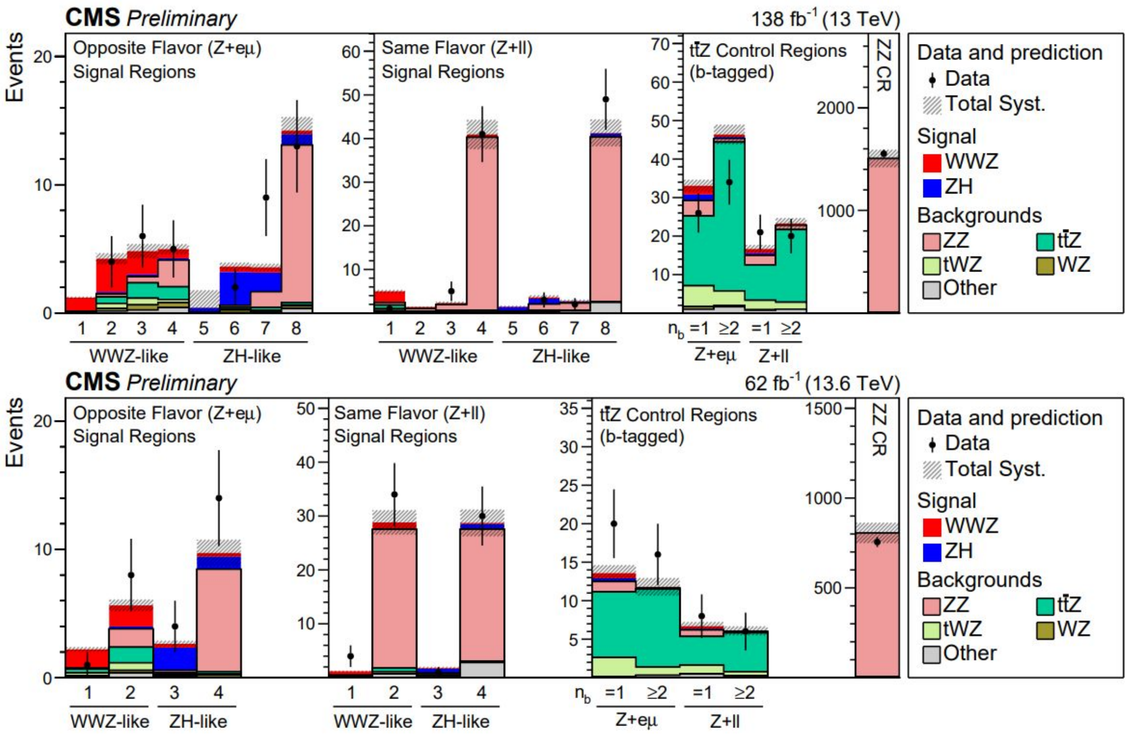
NEW

WWZ and ZH cross section measurements – SMP-24-015

NEW

- Events are categorized according to the flavors of the W-candidate leptons.
  - 2 channels
  - Opposite and same-flavour
- A BDT is used to further distinguish WWZ, ZH and other backgrounds.
  - (8 bins for Run 2) x 2 channels
  - (4 bins for Run 3) x 2 channels
- The post-fit yields are extracted from a maximum likelihood fit to signal region and other control regions.

Run 2



Run 3

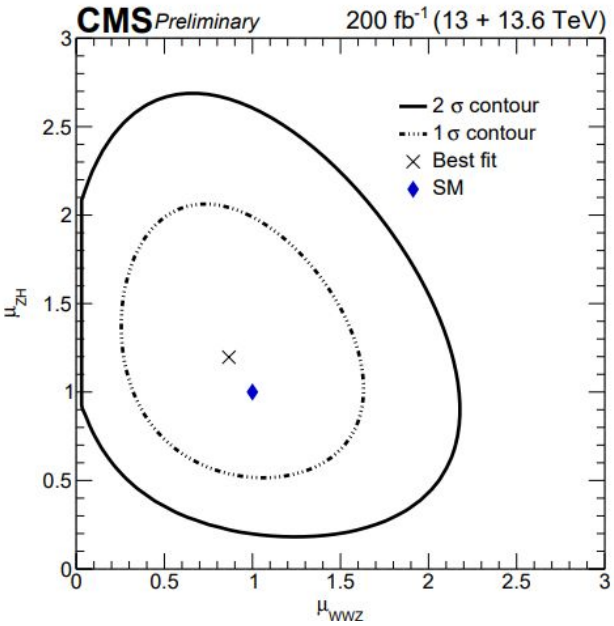
WWZ and ZH cross section measurements – SMP-24-015

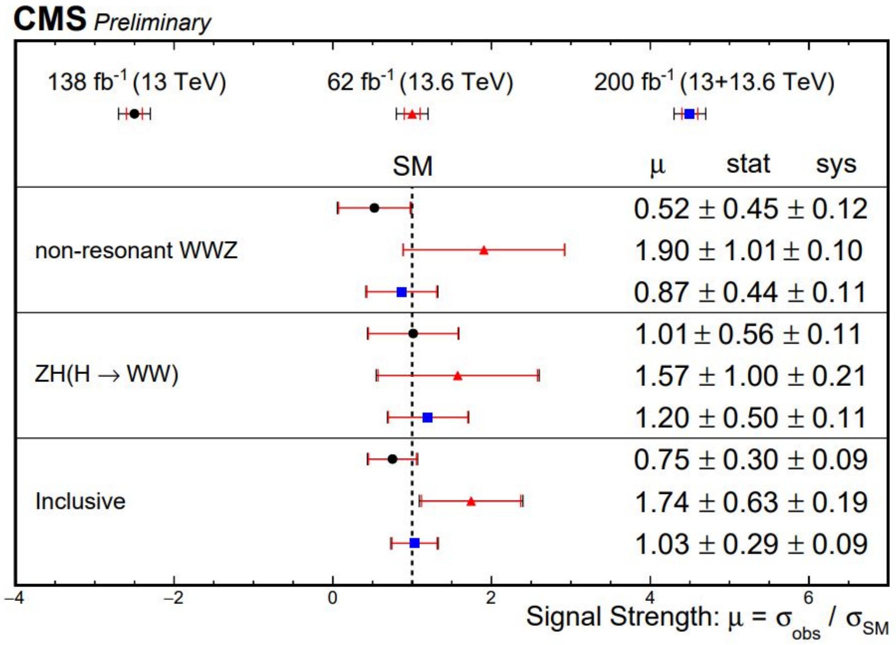
NEW

First evidence for a triboson production process at 13.6 TeV!

First simultaneous measurement of WWZ and ZH

Era	Total	WWZ	ZH
Run 2	2.9 (4.4)	1.3 (3.1)	2.0 (2.6)
Run 3	3.8 (2.5)	2.5 (1.3)	2.5 (1.7)
Total	4.5 (5.0)	2.4 (3.3)	3.1 (3.1)

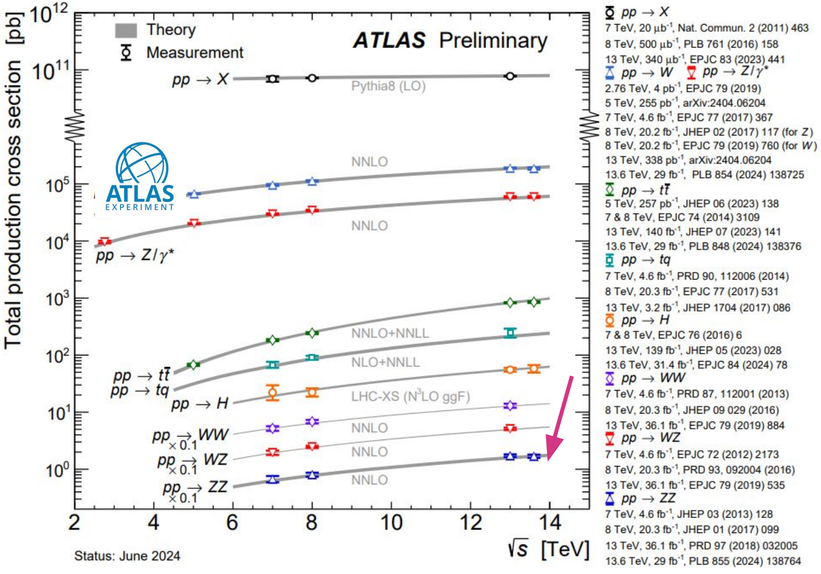


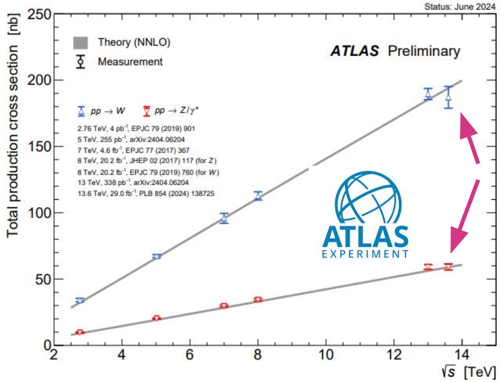


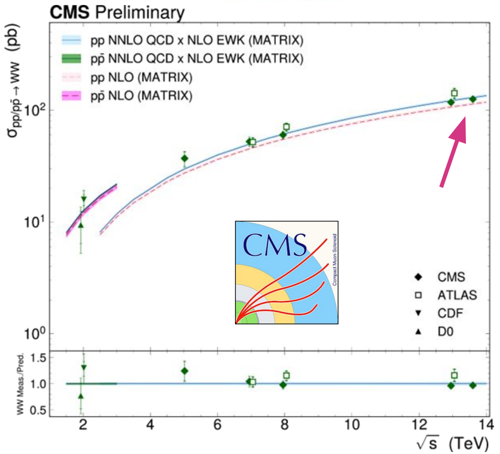
Conclusions (I)

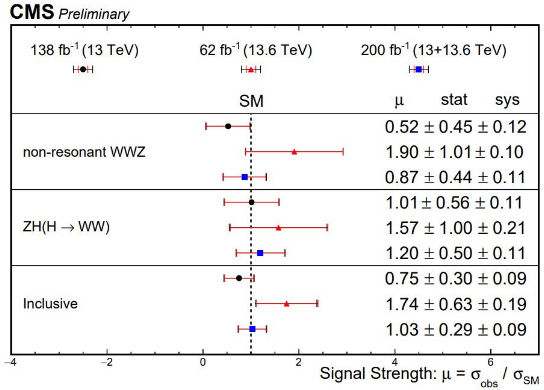
> 15 years of SM cross section measurements at LHC!

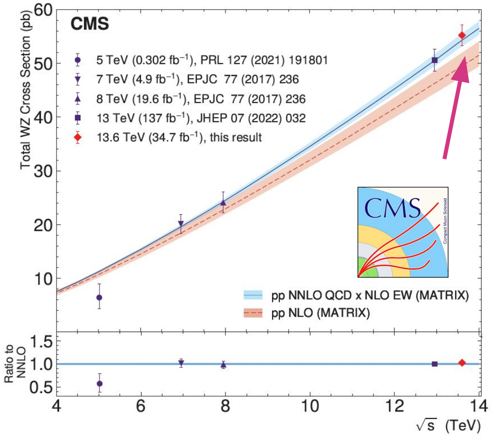
Excellent precision achieved, good agreement with the SM











Conclusions (II)

- **The CMS and ATLAS collaborations are analyzing Run 3 data**
  - **Physics analyses ramping up**
  - “Only” using ~10% of the total expected Run 3 dataset
  - Some ``serious'' competition with Run~2 analyses

- Run 3 should be seen as a **marathon** race, **not a sprint** race.
  - **Run 2 + Run 3** data samples will be **larger or comparable to Run 4**!
  - It will be our main dataset until ~2032.

- In this talk I’ve covered a handful of analyses developed by both CMS and ATLAS related to SM physics.
  - I’ve missed many other interesting results from both collaborations that anyone can checkout at the ATLAS and CMS webpages!

Stay tuned for more Run 3 Results!

Backup

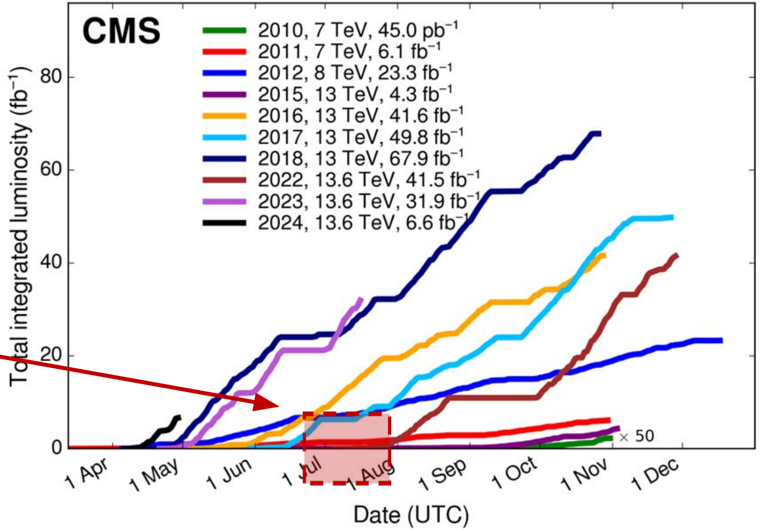
Z cross section measurement at 13.6 TeV (CMS) – SMP-22-017

- A measurement of the Z boson production cross section was performed by the CMS experiment at the beginning of Run 3.

- **Goal**: to measure the Z boson production rate at a brand new center of mass energy regime.

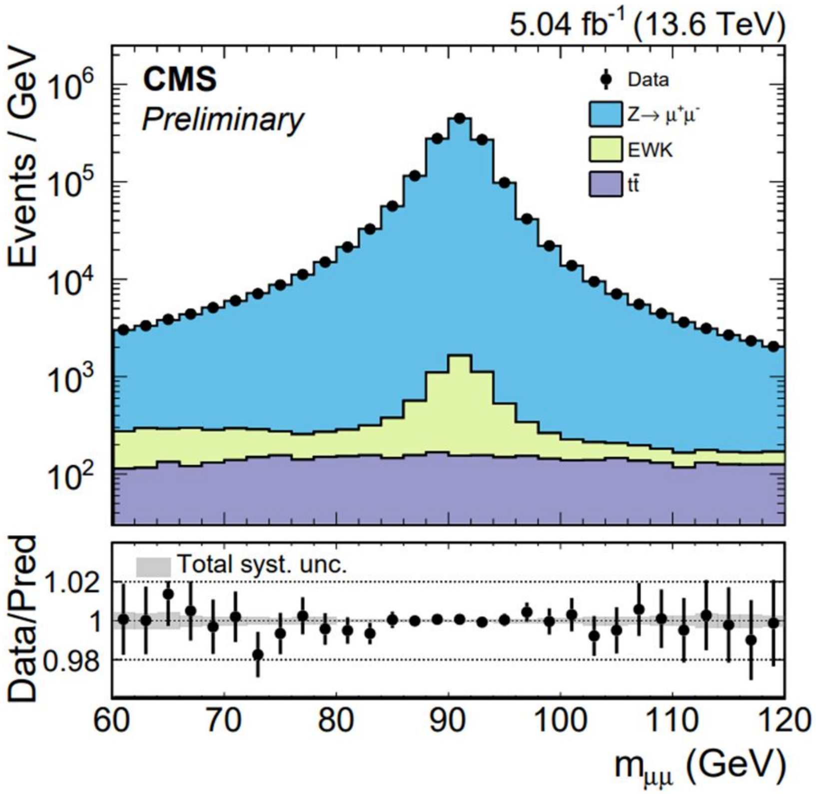
- **Dataset used**: first 5.04 fb^{-1} collected by CMS during 2022 data taking.

- **Target topology**: $Z \rightarrow \mu^+\mu^-$



Z cross section measurement at 13.6 TeV (CMS) – SMP-22-017

- **Object selection**: optimized for **$Z \to \mu^+\mu^-$**.
  - Exactly two reconstructed muons passing “tight” quality criteria [JINST 13 (2018) P06015].
  - Opposite sign
  - $p_T > 25$ GeV, $|\eta| < 2.4$
  - $m_{\mu\mu} \in [60, 120]$ GeV
  - Inclusive in jets and b tags.
- **Corrections**: particularly delicate in early analyses.
  - **Muon efficiency**
  - **Scale and energy.**
  - Trigger prefiring.
  - Pileup
- **Strategy**: maximum likelihood fit to the $m_{\mu\mu}$ distribution.



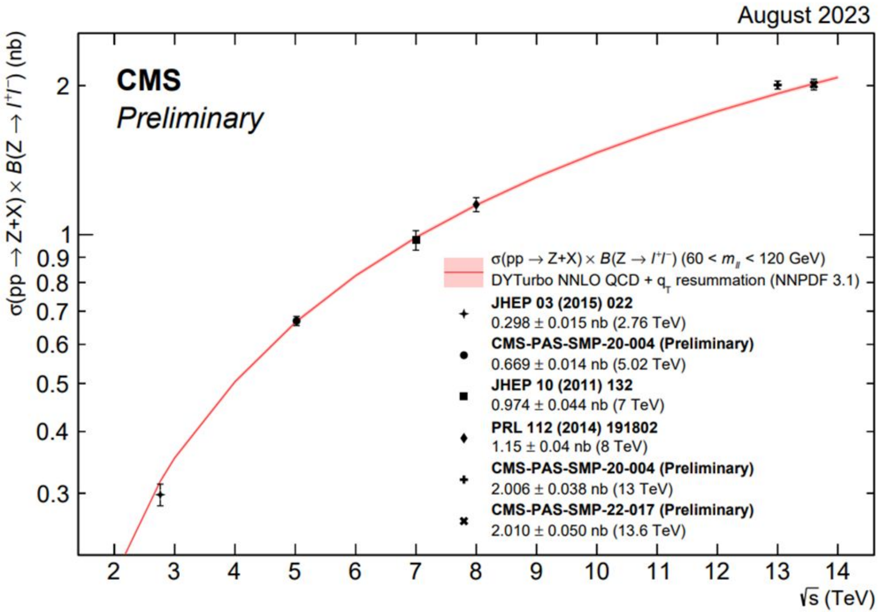
Z cross section measurement at 13.6 TeV (CMS) – SMP-22-017

- **Total cross sections times branching ratio** are **presented.**
  - **Measurement dominated by systematics.**
- Well in agreement with SM.

$$(\sigma_{\mathrm{fid}}\mathcal{B})_{\mathrm{measured}} = (0.7635 \pm 0.0004(\mathrm{stat}) \pm 0.0069(\mathrm{syst}) \pm 0.0176(\mathrm{lumi}))\,\mathrm{nb},$$
$$(\sigma_{\mathrm{fid}}\mathcal{B})_{\mathrm{predicted}} = (0.7666 \pm 0.0065(\mathrm{PDF})^{+0.0021}_{-0.0045}(\mathrm{scale}))\,\mathrm{nb},$$

$$(\sigma_{\mathrm{tot}}\mathcal{B})_{\mathrm{measured}} = (2.010 \pm 0.001(\mathrm{stat}) \pm 0.018(\mathrm{syst}) \pm 0.046(\mathrm{lumi}) \pm 0.007(\mathrm{theo}))\,\mathrm{nb},$$
$$(\sigma_{\mathrm{tot}}\mathcal{B})_{\mathrm{predicted}} = (2.018 \pm 0.012(\mathrm{PDF})^{+0.018}_{-0.023}(\mathrm{scale}))\,\mathrm{nb},$$

Source	Uncertainty (%)
Muon efficiencies	0.83
PDF, QCD scale and parton shower	0.53
Finite size of MC samples (bin-by-bin)	0.35
$t\bar{t}$ background	0.16
EWK background	0.12
Pileup	0.08
Muon momentum correction	0.08
Combined syst. uncertainty	0.92
Luminosity	2.3
Stat. uncertainty	0.06

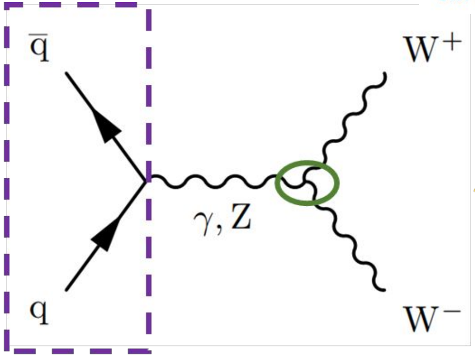


Vector boson production

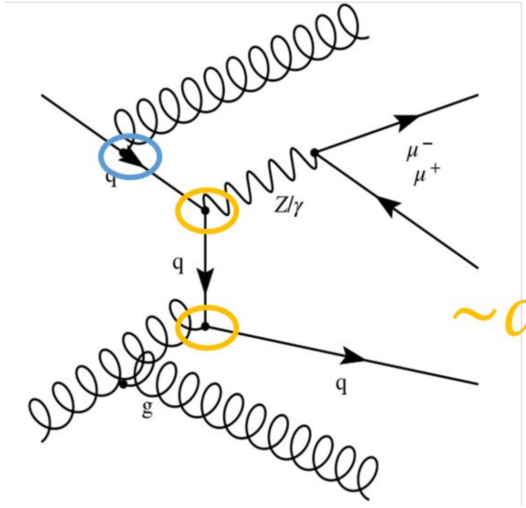
- **Isolated or simultaneous production of Z and W bosons** at the LHC is part of the core programme.

- **From a theoretical point of view:**
  - **Constraining of PDFs.**
  - **Anomalous triple gauge couplings.**
  - **Test perturbative effects of higher order contributions in QCD.**
  - **Parton shower effects.**

- **From a experimental point of view.**
  - The LHC is a Z and W bosons factory $\sigma_{Z/W} \simeq 10^2$ nb.
  - Ideal setup for calibration of many objects.
  - **Accessible already with rather low recorded luminosity.**



$\sim\alpha^2$



$\sim\alpha_s\alpha^2$

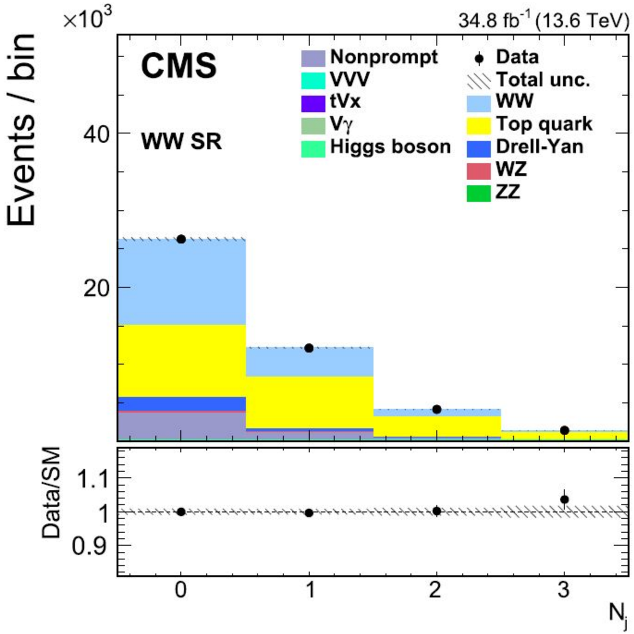
- **Measurement of W-boson pair production cross sections is an important test of the standard model.**
  - **First analysis using the full 2022 CMS dataset!**
- The target topology is WW $\rightarrow e^{\pm}\mu^{\mp}$:
  - **One signal region** is defined to maximize signal purity.
  - Several control regions are already defined to constraint effect of main backgrounds.
    - **TOP**, **ZZ $\rightarrow \tau\tau$**, **non prompt**, **WZ** and **ZZ $\rightarrow 4\ell$**

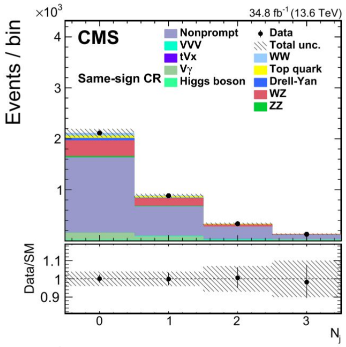
Quantity	WW	One/two b tags	$Z \rightarrow \tau\tau$	Same-sign
Number of tight leptons		Strictly 2		
Additional loose leptons		0		
Lepton charges		Opposite		Same
$p_T^{\ell\ max}$		>25 GeV		
$p_T^{\ell\ min}$		>20 GeV		
$m_{\ell\ell}$	>85 GeV	>85 GeV	<85 GeV	>85 GeV
$p_T^{\ell\ell}$	—	—	<30 GeV	—
Number of b-tagged jets	0	1/2	0	0
N_j		$0/1/2/\geq 3$		

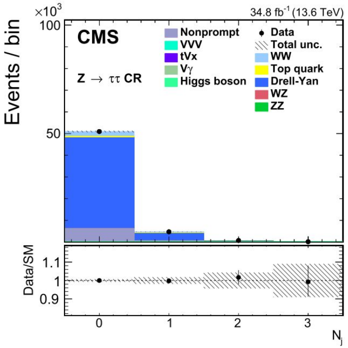
Variable	WZ	ZZ
Number of tight leptons	Strictly 3	Strictly 4
Additional loose leptons		0
Lepton p_T	$>25/10/20$ GeV	$>25/20/10/10$ GeV (p_T ordered)
$\lvert m_{\ell\ell} - m_Z \rvert$	<15 GeV	<15 GeV (both pairs)
$m_{3\ell}$	>100 GeV	—
$m_{4\ell}$	—	>150 GeV
p_T^{miss}	>30 GeV	—
Number of b-tagged jets	0	

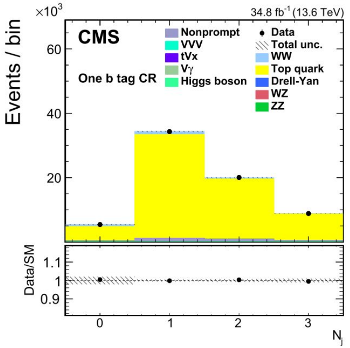
WW cross section measurements – PLB. 861 (2025) 139231

- **The inclusive WW cross** section is **extracted from a maximum likelihood fit to** the **observed yields** as a **function of the number of jets**.
- **The fit is performed simultaneously to the signal region and all control regions.**

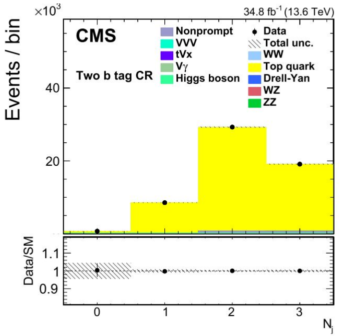


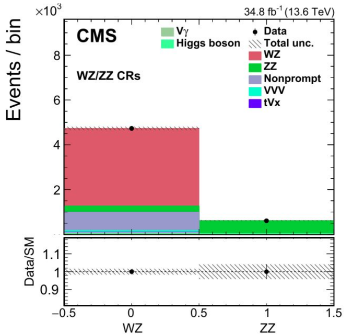






σ_{WW} = 125.7± 2.3 (stat) ± 4.8 (syst) ± 1.8 (lumi) pb





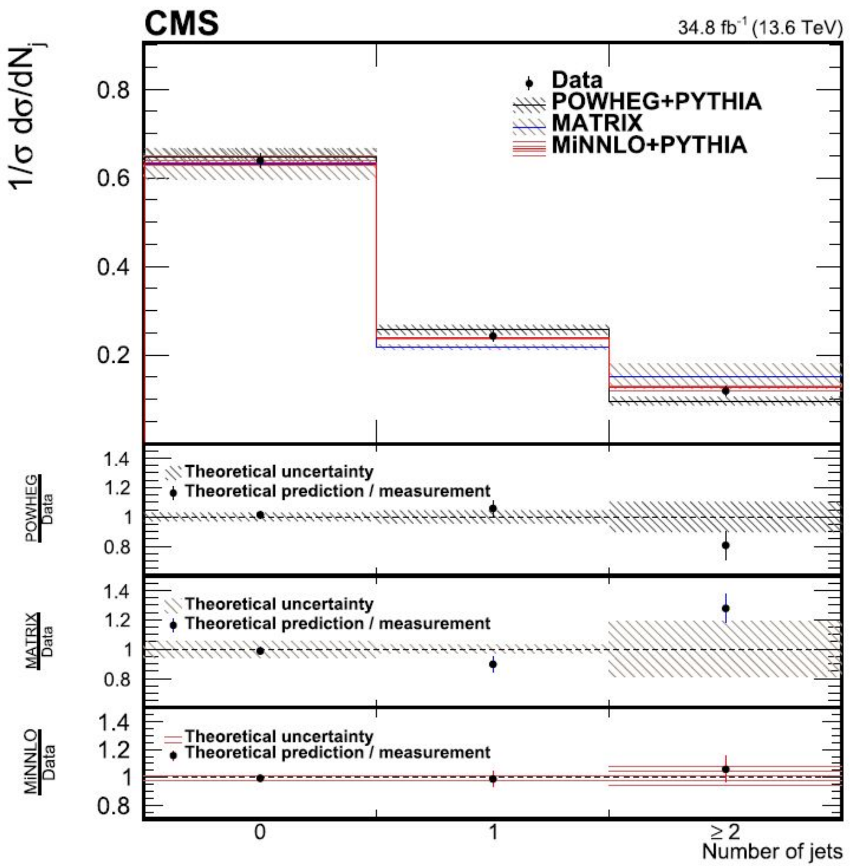
WW cross section measurements – PLB. 861 (2025) 139231

- In addition to the inclusive cross section, fiducial and inclusive and normalized cross sections are reported.

Observable	Expected	Observed
Cross section (fb)	$812 \pm 34\,(31, 15)$	$813 \pm 35\,(32, 15)$
0-jet fraction	$0.648 \pm 0.015\,(0.012, 0.009)$	$0.640 \pm 0.016\,(0.013, 0.009)$
1-jet fraction	$0.256 \pm 0.013\,(0.008, 0.010)$	$0.243 \pm 0.013\,(0.009, 0.010)$
≥2-jet fraction	$0.096 \pm 0.011\,(0.008, 0.008)$	$0.119 \pm 0.011\,(0.008, 0.008)$

Fiducial definition in backup

- Differential measurements also performed.
  - Compared to alternative predictions.
  - **First ever comparison with `MiNNLO+PS` generator in WW!**
- Good agreement is observed



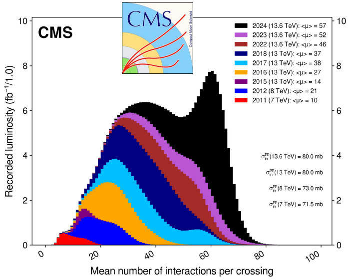
A quick word on CMS & ATLAS in Run 3

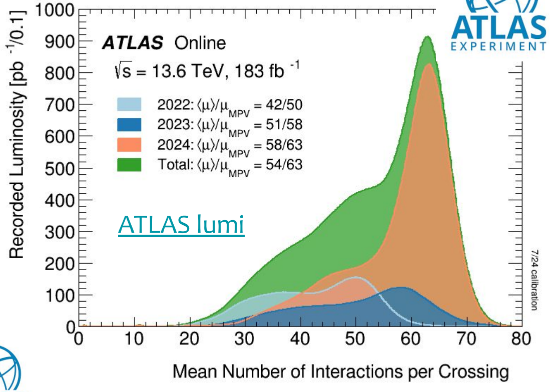
- **Both ATLAS and CMS have released several results** (**not covered in this talk**) showing **great performance** → Really critical for proper Run 3 analysis!

Check all these results and more at CMS & ATLAS

Luminosity calibration

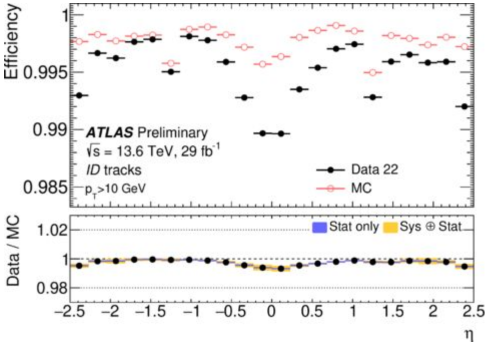
Source	Correction (%)	Uncertainty (%)
Calibration		
Beam current	3.4	0.2
Ghost and satellite charges	0.4	0.2
Orbit drift	0.1	0.1
Residual beam positions	0.0	0.3
Beam-beam effects	1.0	0.4
Length scale	-1.0	0.1
Factorization bias	1.0	0.8
Scan-to-scan variation	-	0.5
Bunch-to-bunch variation	-	0.1
Cross-detector consistency	-	0.4
Integration		
HFET OOT pileup corrections		0.2
Cross-detector stability		0.5
Cross-detector linearity		0.5
Calibration		1.2
Integration		0.8
Total		1.4

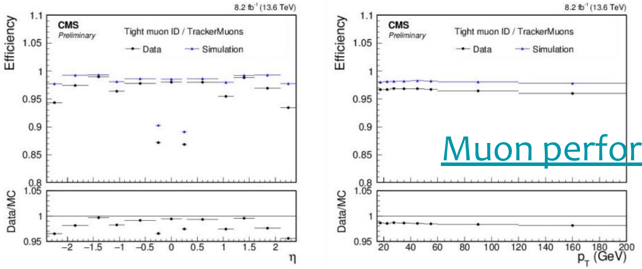




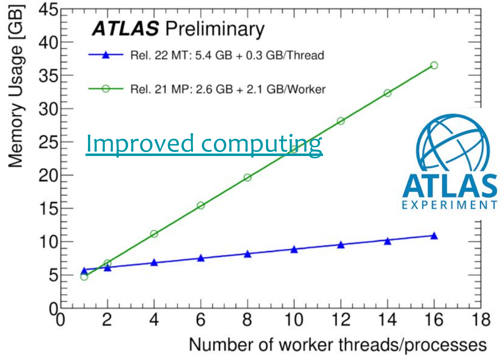
ATLAS lumi

Muon performance





Muon performance

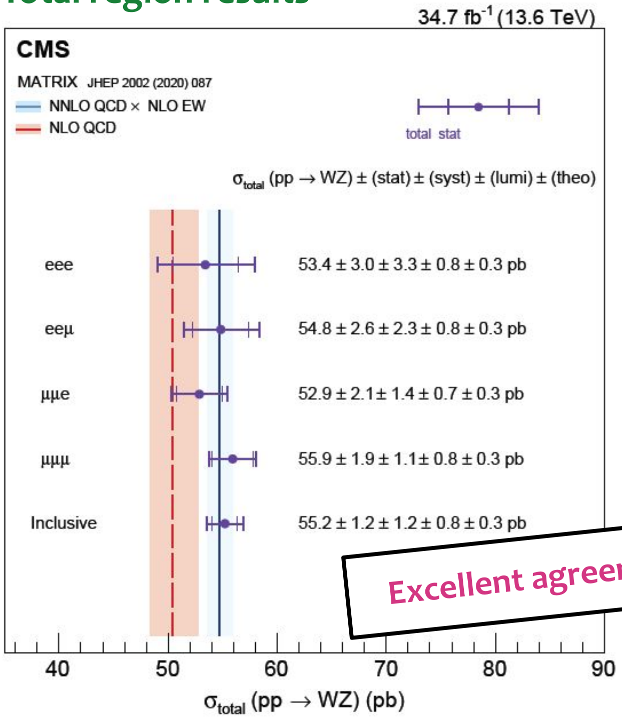


Improved computing

WZ cross section measurements – Arxiv. 2412.02477 Accepted by JHEP

All results are compared to latest theoretical predictions computed with MATRIX.

Total region results



Excellent agreement with SM!

Fiducial region results

Category	Accuracy	Fiducial cross section (fb)
eee	POWHEG, NLO QCD	$68.0^{+2.3}_{-2.1}$ (scale) ± 1.0 (PDF)
	MATRIX, NLO QCD	$69.9^{+3.9}_{-3.1}$ (scale)
	MATRIX, NNLO QCD	$77.0^{+1.8}_{-1.7}$ (scale)
	MATRIX, NNLO QCD × NLO EW	$75.4^{+1.7}_{-1.6}$ (scale)
	Measured	72.0 ± 4.0 (stat) ± 4.5 (syst) ± 1.0 (lumi) ± 0.4 (theo)
eeμ	POWHEG, NLO QCD	$68.0^{+2.3}_{-2.1}$ (scale) ± 1.0 (PDF)
	MATRIX, NLO QCD	$68.7^{+3.8}_{-3.0}$ (scale)
	MATRIX, NNLO QCD	$75.0^{+1.8}_{-1.6}$ (scale)
	MATRIX, NNLO QCD × NLO EW	$73.4^{+1.7}_{-1.5}$ (scale)
	Measured	73.9 ± 3.5 (stat) ± 3.1 (syst) ± 1.1 (lumi) ± 0.4 (theo)
$\mu\mu$e	POWHEG, NLO QCD	$68.0^{+2.3}_{-2.1}$ (scale) ± 1.0 (PDF)
	MATRIX, NLO QCD	$68.7^{+3.8}_{-3.0}$ (scale)
	MATRIX, NNLO QCD	$75.0^{+1.8}_{-1.6}$ (scale)
	MATRIX, NNLO QCD × NLO EW	$73.4^{+1.7}_{-1.5}$ (scale)
	Measured	71.2 ± 2.9 (stat) ± 2.0 (syst) ± 1.0 (lumi) ± 0.4 (theo)
$\mu\mu\mu$	POWHEG, NLO QCD	$68.0^{+2.3}_{-2.1}$ (scale) ± 1.0 (PDF)
	MATRIX, NLO QCD	$69.9^{+3.9}_{-3.1}$ (scale)
	MATRIX, NNLO QCD	$77.0^{+1.8}_{-1.7}$ (scale)
	MATRIX, NNLO QCD × NLO EW	$75.4^{+1.7}_{-1.6}$ (scale)
	Measured	75.3 ± 2.5 (stat) ± 1.5 (syst) ± 1.1 (lumi) ± 0.4 (theo)
Inclusive	POWHEG, NLO QCD	$271.9^{+9.0}_{-8.5}$ (scale) ± 3.8 (PDF)
	MATRIX, NLO QCD	$277.1^{+15.3}_{-12.3}$ (scale)
	MATRIX, NNLO QCD	$304.0^{+7.1}_{-6.6}$ (scale)
	MATRIX, NNLO QCD × NLO EW	$297.7^{+6.8}_{-6.3}$ (scale)
	Measured	297.6 ± 6.4 (stat) ± 6.4 (syst) ± 4.2 (lumi) ± 1.5 (theo)