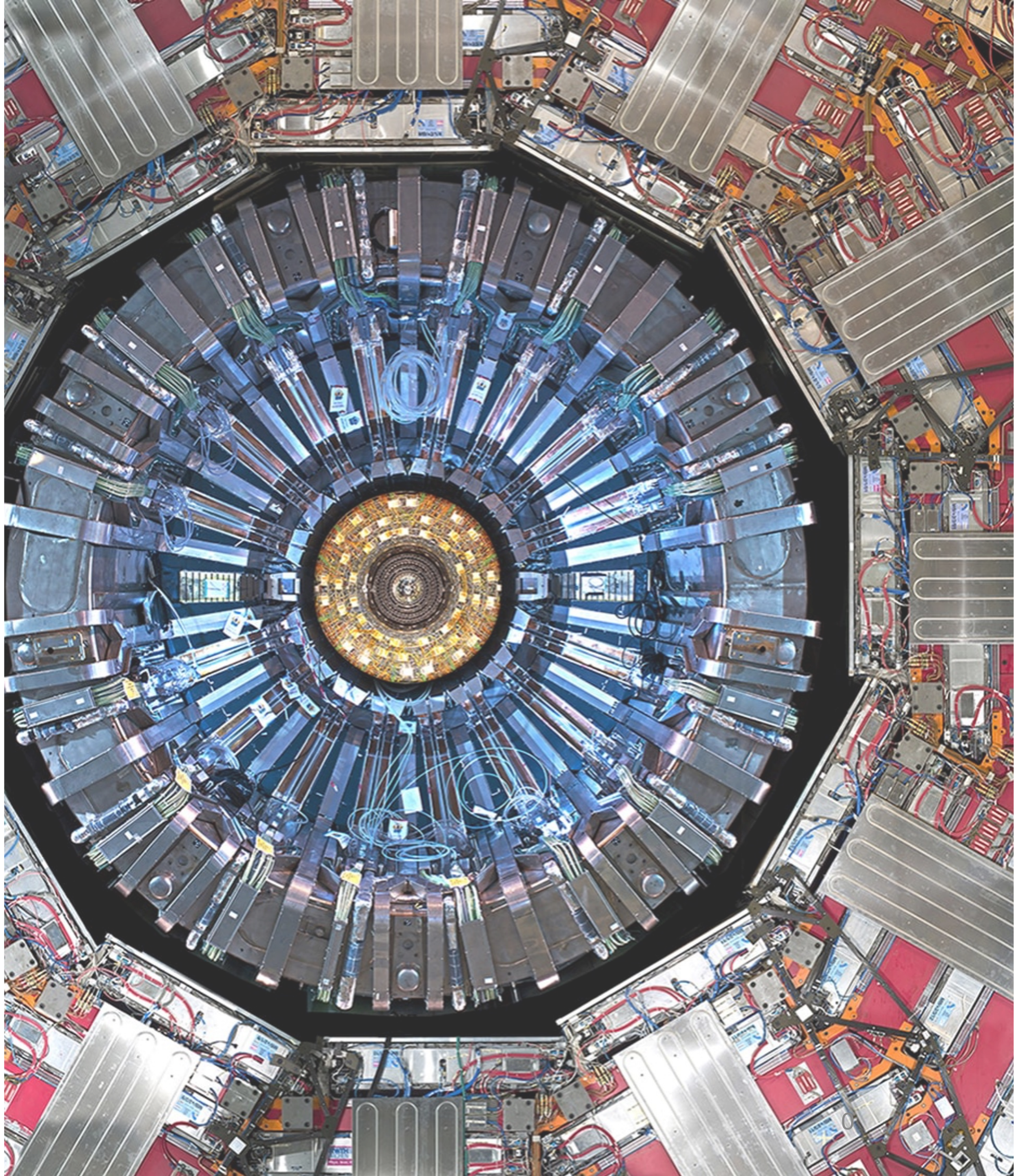
Run 3 multiboson measurements at CMS

Multiboson 2024

Sergio Blanco Fernandez on behalf of the CMS Collaboration
IFCA (CSIC – University of Cantabria)

25/09/2024



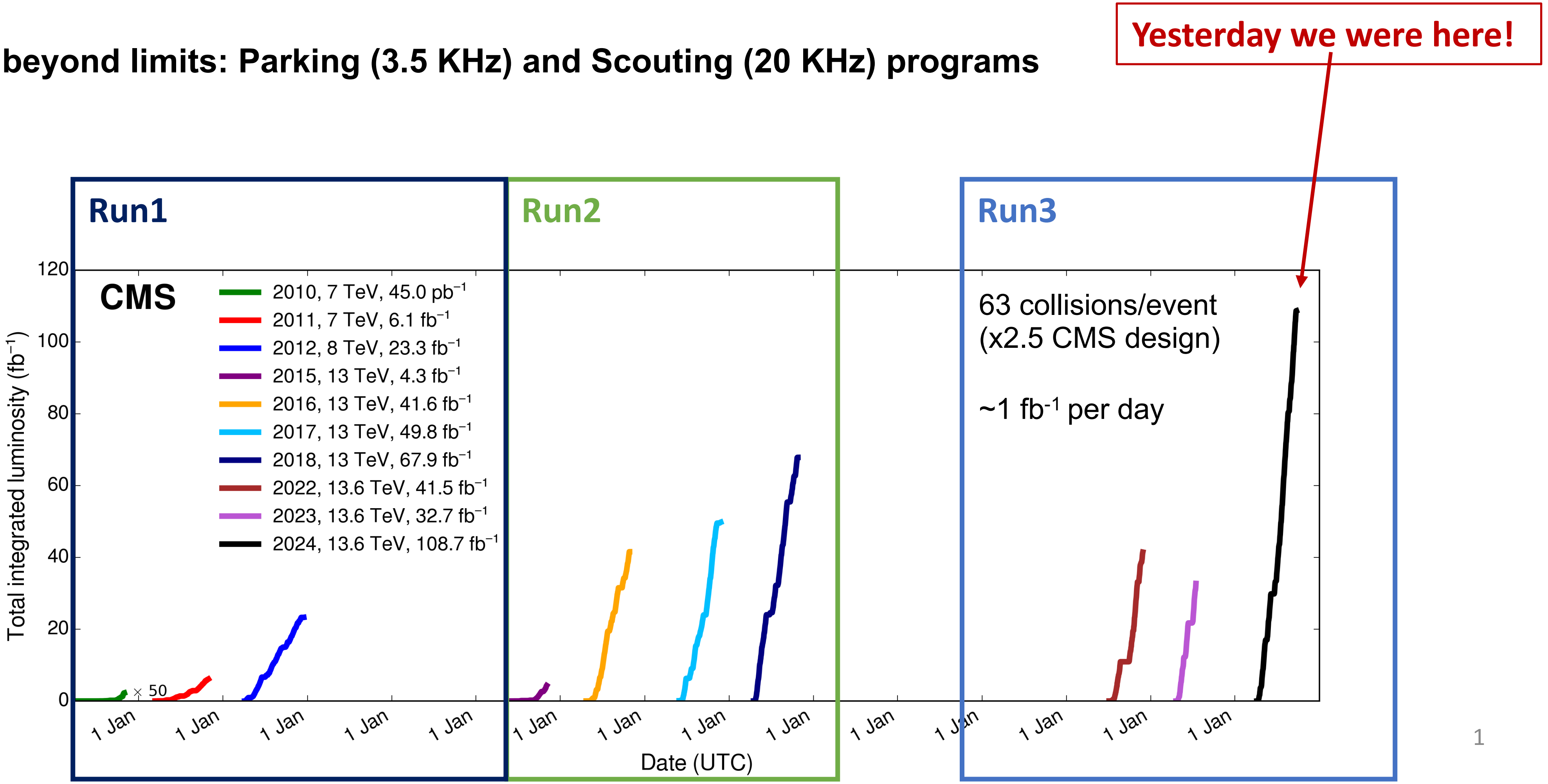
Research supported by PID2020-113304RB-100

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
AGENCIA ESTATAL DE INVESTIGACIÓN
UC
IFCA
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Introduction

Run 3 has exceeded Run 2 in a lot of aspects:

- **Integrated luminosity (>160 fb^{-1})**
- **Data quality: stable physics performance**
- **Push trigger beyond limits: Parking (3.5 KHz) and Scouting (20 KHz) programs**



CMS multiboson results using Run3 data

- Many measurements have already been performed with Run 3 data (Top, EWK, EXO, …)
- **Today, we focus on 4 multiboson analyses**

CMS-SMP-24-001

$\mathbf{pp \to W^{+}W^{-}}$

Available on the CERN CDS information server **CMS PAS SMP-24-001**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-smp@cern.ch 2024/03/22

Measurement of $W^{+}W^{-}$ inclusive and differential cross sections in pp collisions at $\sqrt{s} = 13.6$ TeV with the CMS detector

The CMS Collaboration

CMS-SMP-24-005

$\mathbf{pp \to W^{\pm}Z}$

Available on the CERN CDS information server **CMS PAS SMP-24-005**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-smp@cern.ch 2024/07/19

Measurement of the inclusive WZ production cross section in pp collisions at $\sqrt{s} = 13.6$ TeV with the CMS experiment

The CMS Collaboration

CMS-HIG-23-014

$\mathbf{pp \to H \to \gamma\gamma}$

Available on the CERN CDS information server **CMS PAS HIG-23-014**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch 2024/07/18

Measurements of inclusive and differential Higgs boson production cross sections at 13.6 TeV in the $H \to \gamma\gamma$ decay channel

The CMS Collaboration

CMS-HIG-24-013

$\mathbf{pp \to H \to ZZ}$

Available on the CERN CDS information server **CMS PAS HIG-24-013**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch 2024/07/19

Measurements of Higgs boson production cross sections in the four-lepton final state at 13.6 TeV

The CMS Collaboration

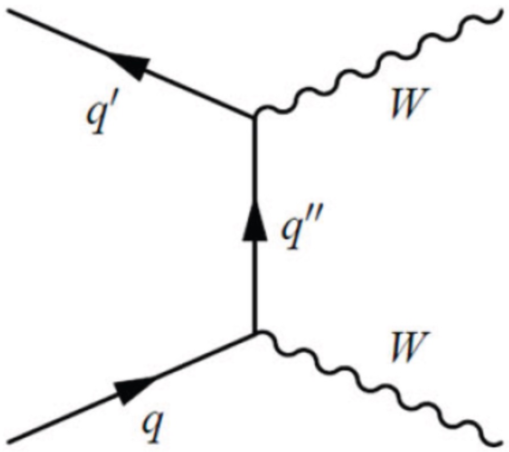
Measurements

[WW CMS-SMP-24-001]

W^+W^- Measurement

- **First Run 3 di-boson measurement** with the CMS detector
- It demonstrates the capacity of CMS to release analysis with complex topologies: **Muons, electrons, jets, b-jets, MET**
- **Some updates wrt 2016 measurement** and comparable luminosity but overall better sensitivity
- **Inclusive and fiducial results using 2022 data: 34.7 fb^{-1}**
- **Targets the different flavour leptonic decay channel**

$$\mathbf{pp \rightarrow W^+W^- \rightarrow e^{\pm}\mu^{\mp}\nu_e\nu_\mu}$$



W^+W^- Measurement

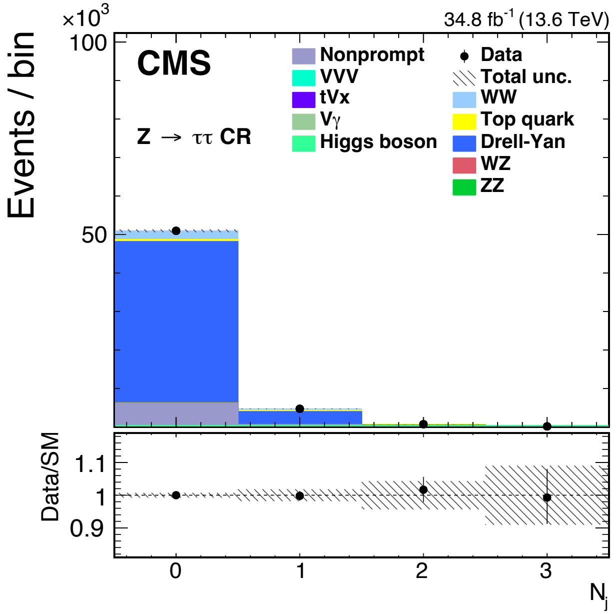
Several updates with respect to the 2016 analysis

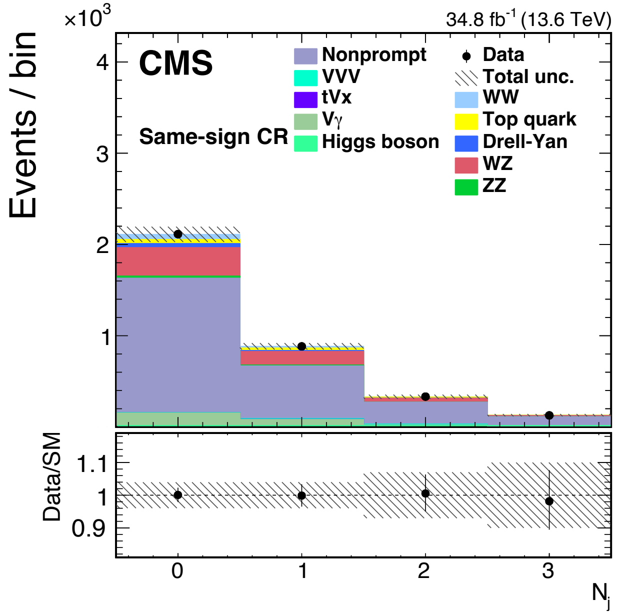
- More **control regions** introduced in the fit: **Top (2 regions), DY, Same-sign, WZ, and ZZ**
- **Object optimization** → lower uncertainties

Data-driven estimation of the **non-prompt lepton contamination**

Quantity	WW	One/two b tags	$Z \to \tau\tau$	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	





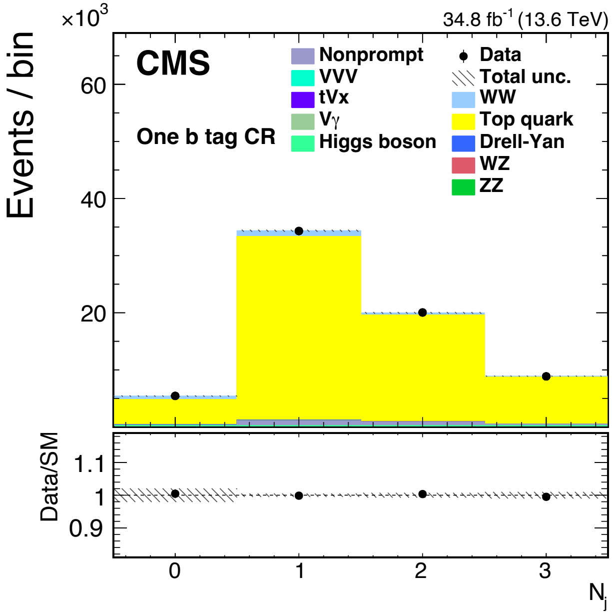
W^+W^- Measurement

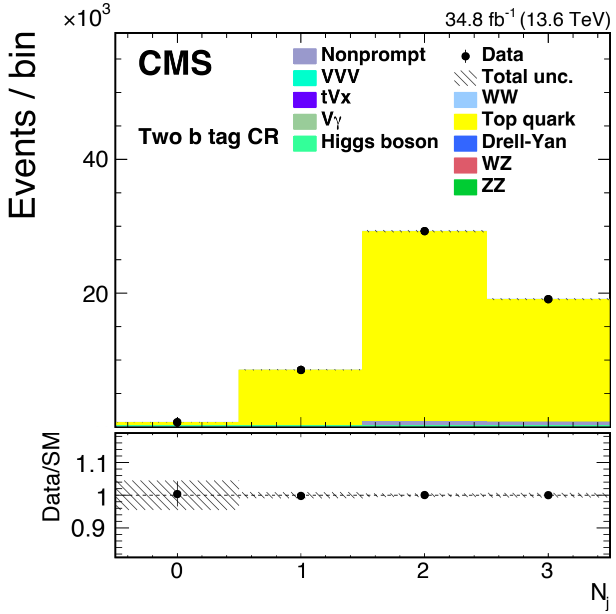
Several updates with respect to the 2016 analysis

- More **control regions** introduced in the fit: **Top (2 regions), DY, Same-sign, WZ, and ZZ**

- **Object optimization** → lower uncertainties

Data-driven estimation of the **non-prompt lepton contamination**





Quantity	WW	One/two b tags	$Z \to \tau\tau$	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	$0/1/2/\geq 3$			

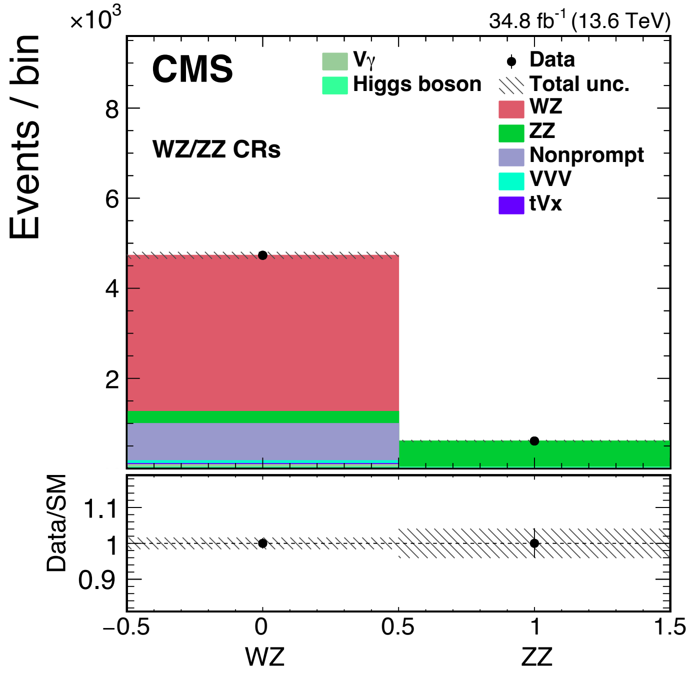
Variable	WZ	ZZ
Number of tight leptons	Strictly 3	Strictly 4
Additional loose leptons	0	
Lepton p_T	>25/10/20 GeV	>25/20/10/10 GeV (p_T ordered)
$\lvert m_{\ell\ell} - m_Z \rvert$	<15 GeV	<15 GeV (both pairs)
$m_{3\ell}$	>100 GeV	—
$m_{4\ell}$	—	>150 GeV
p_T^{miss}	>30 GeV	—
Number of b-tagged jets	0	

W^+W^- Measurement

Several updates with respect to the 2016 analysis

- More **control regions** introduced in the fit: **Top (2 regions), DY, Same-sign, WZ, and ZZ**
- **Object optimization** → lower uncertainties

Data-driven estimation of the **non-prompt lepton contamination**



Quantity	WW	One/two b tags	$Z \to \tau\tau$	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	$0/1/2/\geq 3$			

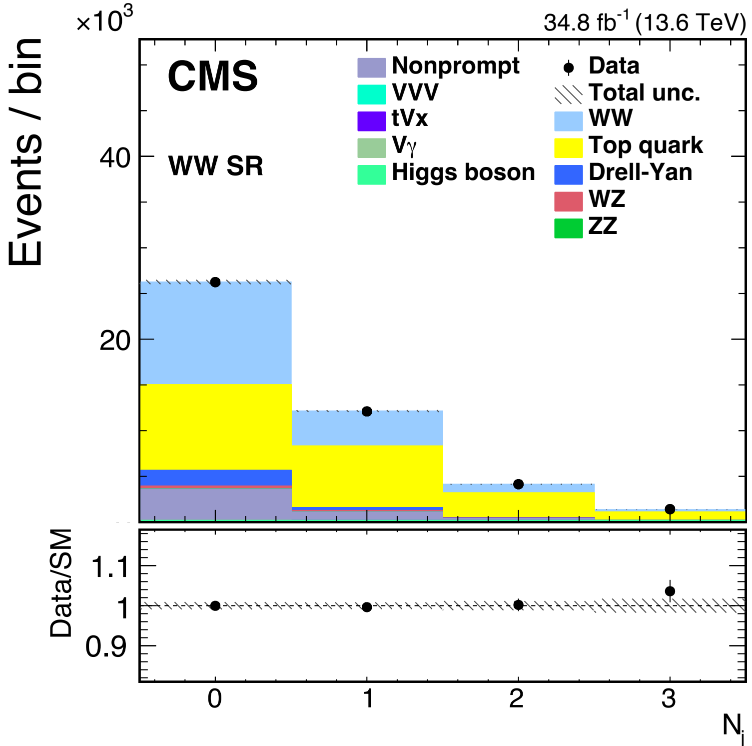
Variable	WZ	ZZ
Number of tight leptons	Strictly 3	Strictly 4
Additional loose leptons	0	
Lepton p_T	>25/10/20 GeV	>25/20/10/10 GeV (p_T ordered)
$\lvert m_{\ell\ell} - m_Z \rvert$	<15 GeV	<15 GeV (both pairs)
$m_{3\ell}$	>100 GeV	—
$m_{4\ell}$	—	>150 GeV
p_T^{miss}	>30 GeV	—
Number of b-tagged jets	0	

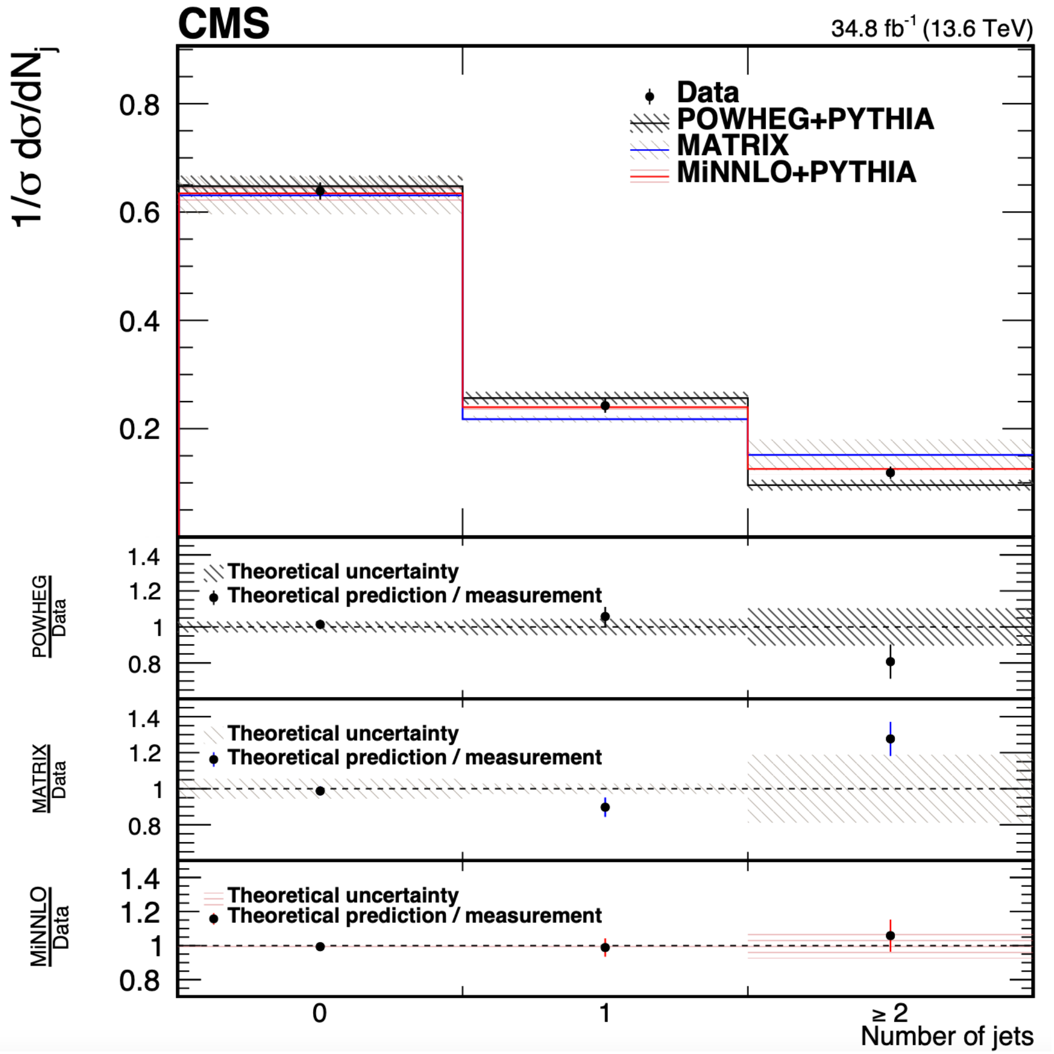
W^+W^- Measurement

Good agreement is found in all the jet bins

Results provided as a function of the **number of jets: 0, 1, or ≥2**

Data compared with **different MC generators**, MiNNLO provided the best agreement





W^+W^- Measurement

Results are also provided as a function of the centre-of-mass energy

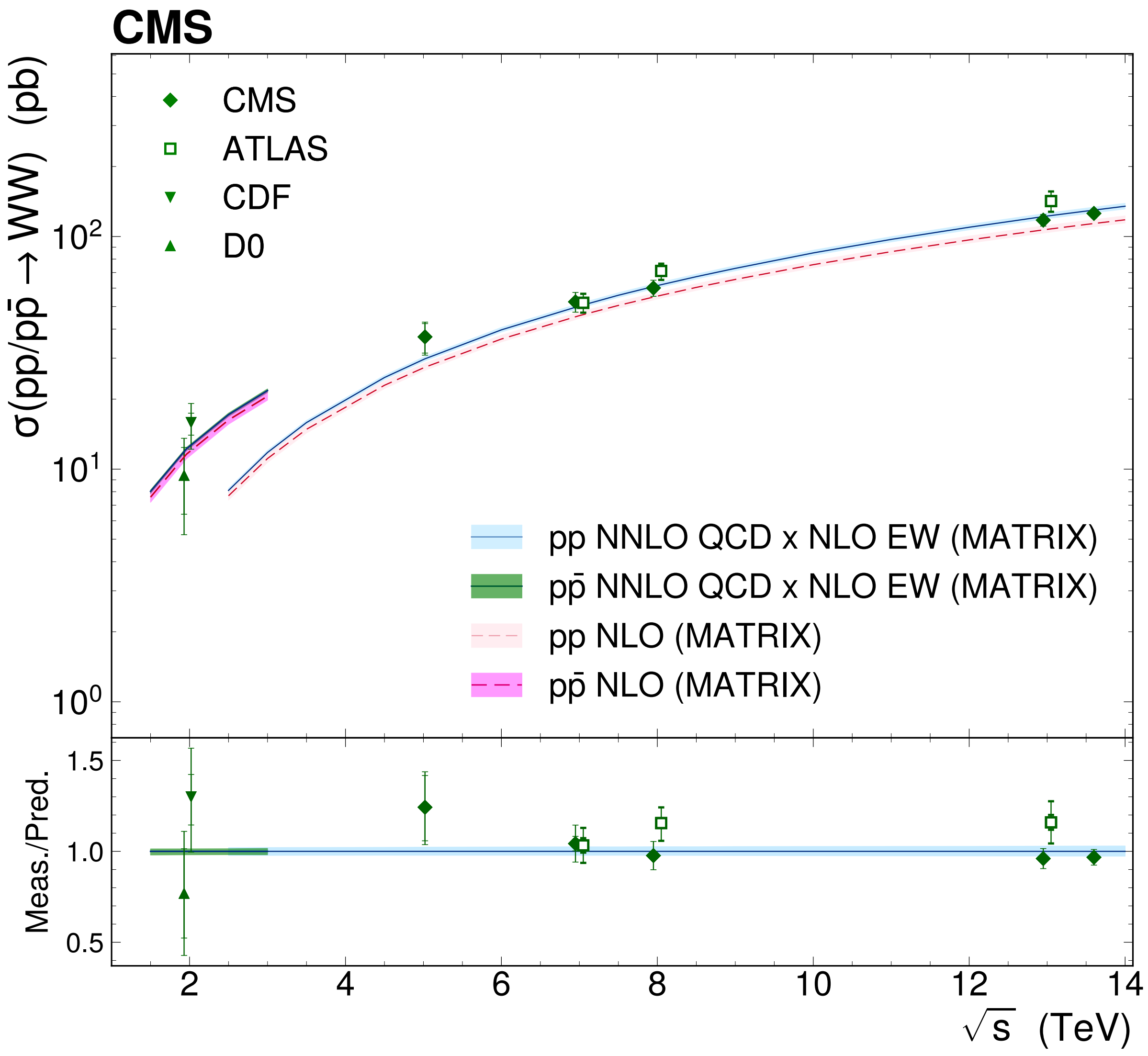
Inclusive result

$$\sigma_{Inc}^{WW} = 125.7 \pm 5.6 \text{ pb}$$

25% lower uncertainty wrt 2016

No particularly dominant uncertainty

Uncertainty source	$\Delta\mu$
Integrated luminosity	0.014
Lepton experimental	0.019
Jet experimental	0.008
b tagging	0.012
Nonprompt background	0.010
Limited sample size	0.017
Background normalization	0.018
Theory	0.011
Statistical	0.018
Total	0.044

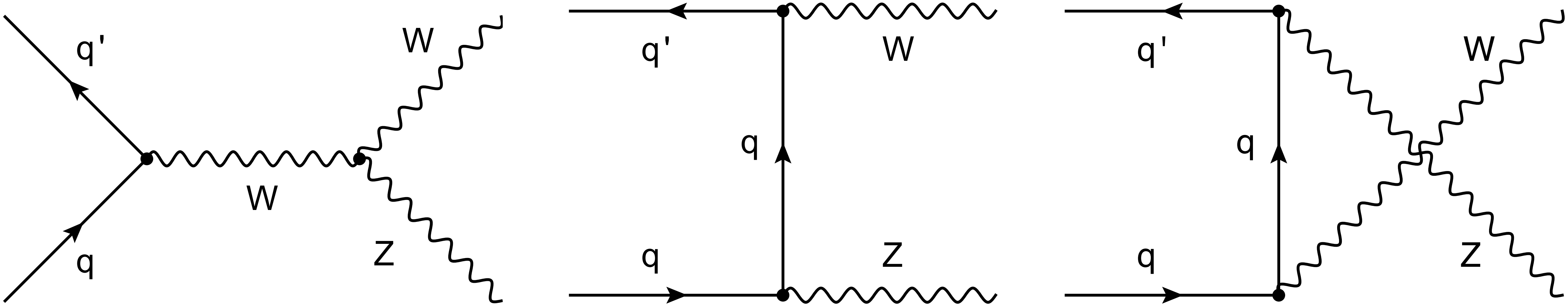


Measurements

[WZ CMS-SMP-24-005]

$W^{\pm}Z$ Measurement

- Measurement of the WZ production in the leptonic final state: $\mu\mu\mu$, $\mu\mu e$, μee, and eee
- **Data from 2022 period is used: 34.7 fb^{-1}**
- **Inclusive and fiducial** results are reported

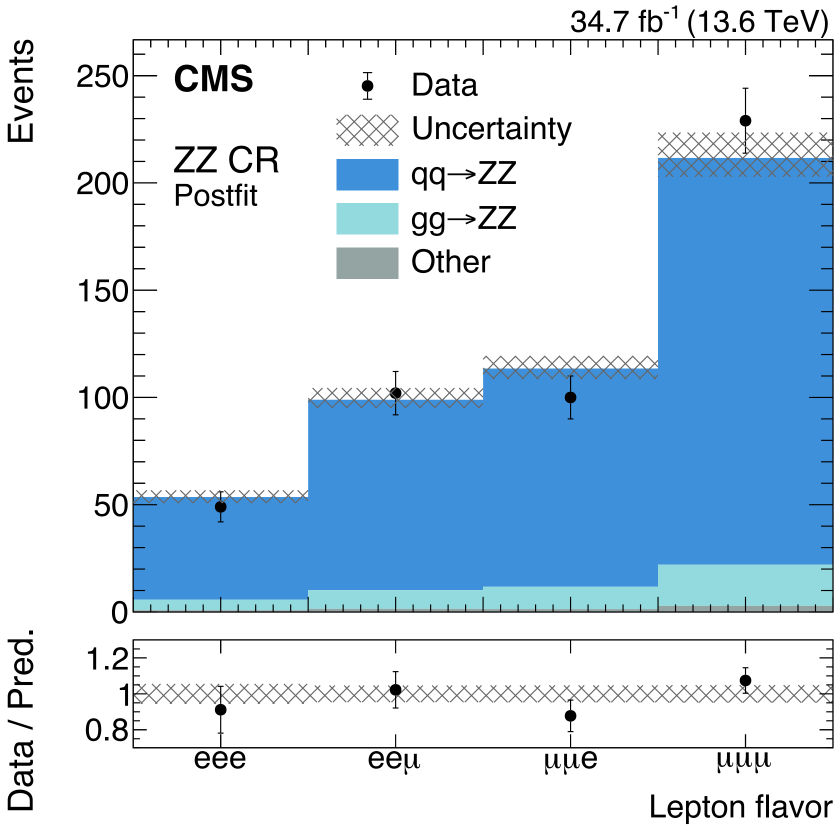


$W^{\pm}Z$ Measurement

- Measurement of the WZ production in the leptonic final state: $\boldsymbol{\mu\mu\mu}$, $\boldsymbol{\mu\mu e}$, $\boldsymbol{\mu ee}$, and $\boldsymbol{eee}$

- An **MVA approach** is performed to improve the **lepton identification**

- **Three control regions** are used to estimate the background contributions from data
  - $\boldsymbol{ZZ}$
  - $\boldsymbol{t\bar{t}Z}$
  - $\boldsymbol{V\gamma}$



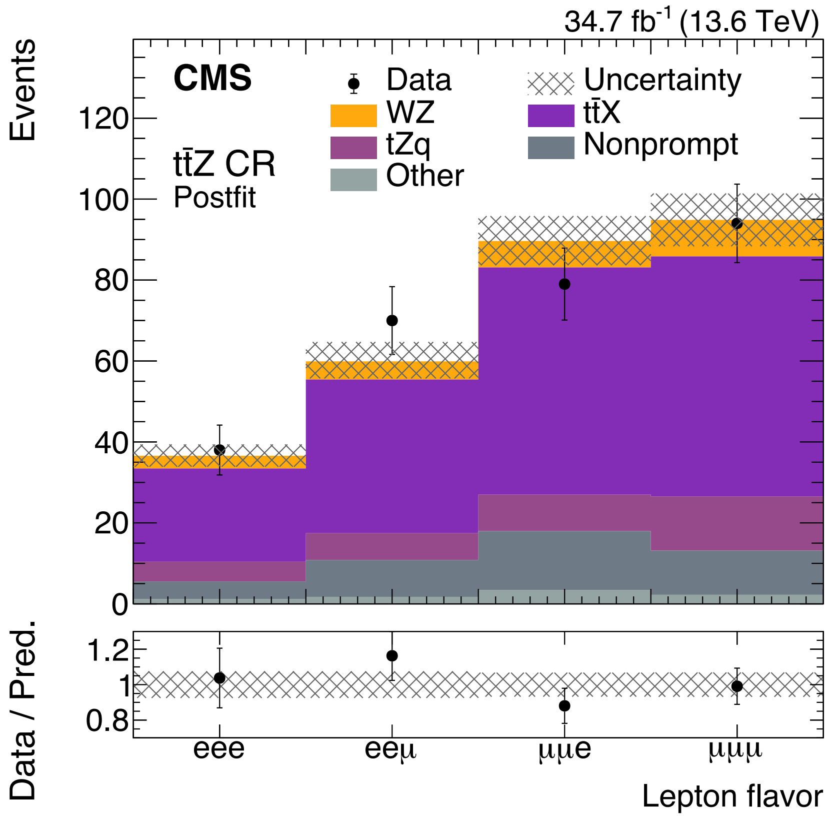
Region	N_ℓ	$p_T\{\ell_Z^1, \ell_Z^2, \ell_W\}$ (GeV)	N_{OSSF}	$\lvert m(\ell_Z^1, \ell_Z^2) - m_Z \rvert$ (GeV)	p_T^{miss} (GeV)	$N_{b\ tag}$	$\min(m(\ell, \ell'))$ (GeV)	$m(\ell_Z^1, \ell_Z^2, \ell_W)$ (GeV)
SR	=3	>{25, 15, 25}	≥1	<15	>35	=0	>4	>100
ZZ CR	=4	>{25, 15, 25, 15}	≥1	<15	-	=0	>4	>100
$t\bar{t}Z$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

$W^{\pm}Z$ Measurement

- Measurement of the WZ production in the leptonic final state: $\mu\mu\mu$, $\mu\mu e$, μee, and eee

- An **MVA approach** is performed to improve the **lepton identification**

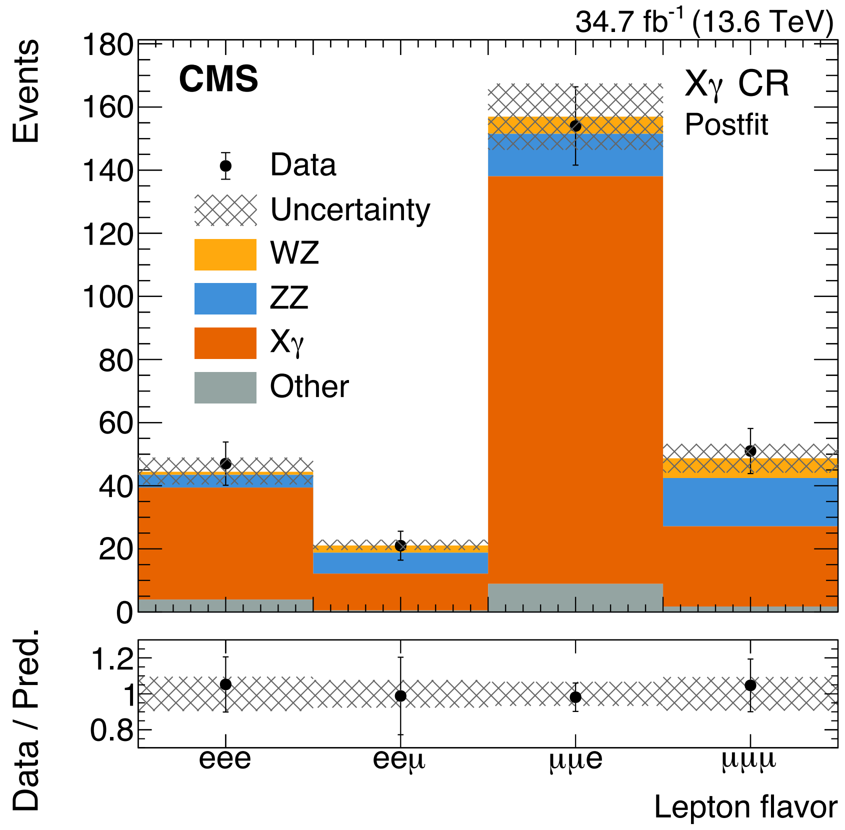
- **Three control regions** are used to estimate the background contributions from data
    - ZZ
    - $t\bar{t}Z$
    - $V\gamma$



Region	N_ℓ	$p_T\{\ell_Z^1, \ell_Z^2, \ell_W\}$ (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)	$m(\ell_Z^1, \ell_Z^2, \ell_W)$ (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

$W^{\pm}Z$ Measurement

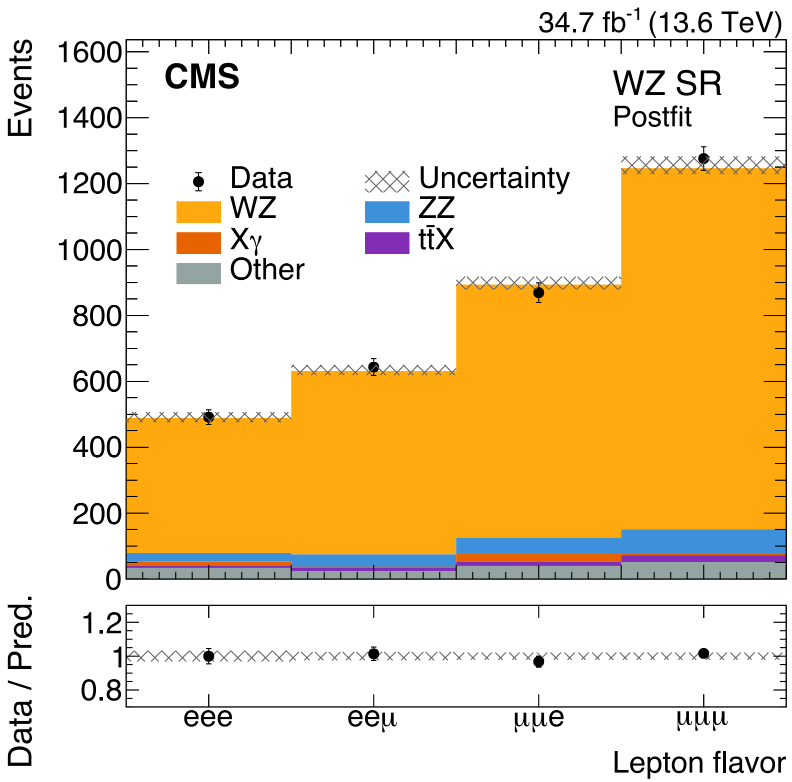
- Measurement of the WZ production in the leptonic final state: $\mu\mu\mu$, $\mu\mu e$, μee, and eee
- An **MVA approach** is performed to improve the **lepton identification**
- **Three control regions** are used to estimate the background contributions from data
  - ZZ
  - $t\bar{t}Z$
  - $V\gamma$

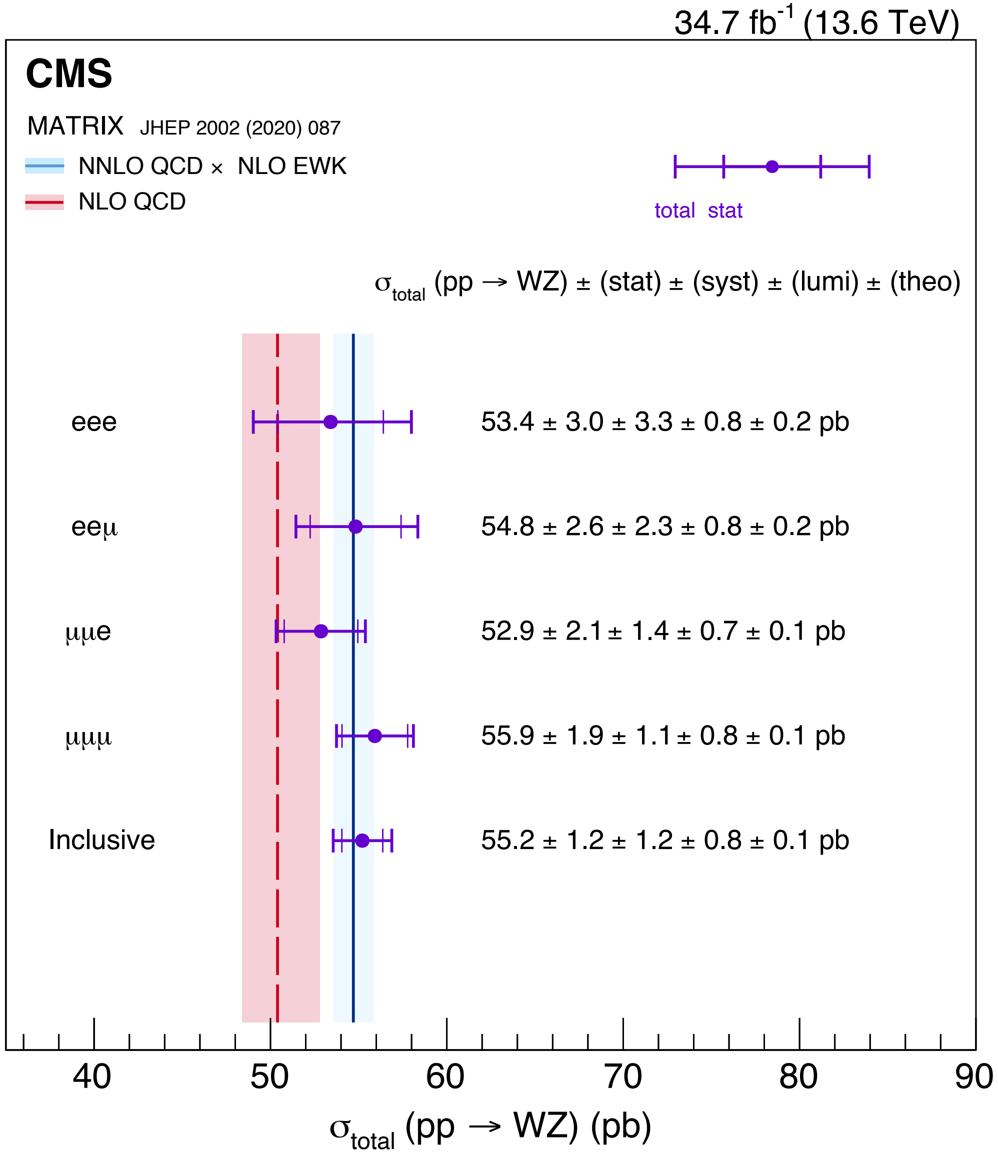


Region	N_ℓ	$p_T\{\ell_Z^1, \ell_Z^2, \ell_W\}$ (GeV)	N_{OSSF}	$\lvert m(\ell_Z^1, \ell_Z^2) - m_Z \rvert$ (GeV)	p_T^{miss} (GeV)	$N_{b\ tag}$	$\min(m(\ell, \ell'))$ (GeV)	$m(\ell_Z^1, \ell_Z^2, \ell_W)$ (GeV)
SR	=3	>{25, 15, 25}	≥1	<15	>35	=0	>4	>100
ZZ CR	=4	>{25, 15, 25, 15}	≥1	<15	-	=0	>4	>100
$t\bar{t}$Z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

$W^{\pm}Z$ Measurement

- Measurement of the WZ production in the leptonic final state: $\mu\mu\mu$, $\mu\mu e$, μee, and eee
- The agreement is found to be **excellent** in all the flavour categories
- Different generators are checked: **Powheg, MATRIX**





$W^{\pm}Z$ Measurement

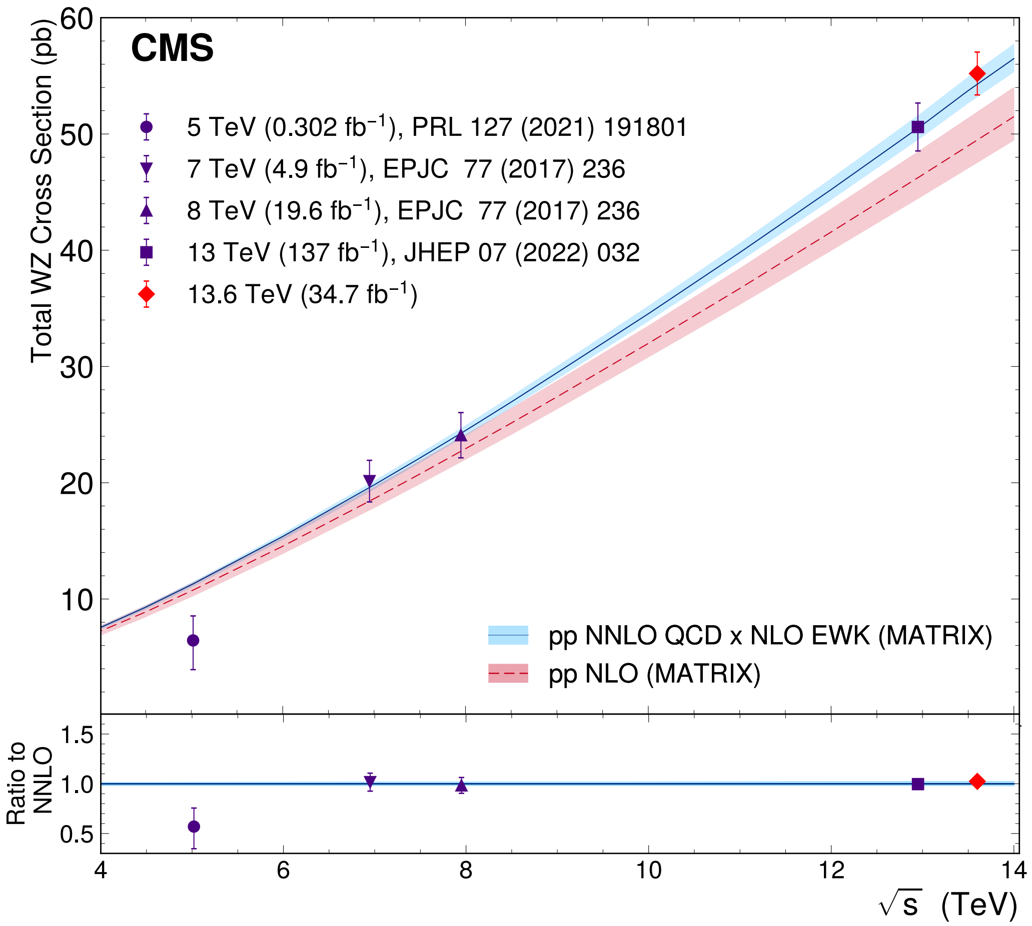
- Measurement of the WZ production in the leptonic final state: $\mu\mu\mu$, $\mu\mu e$, μee, and eee
- Fit performed in both flavour exclusive and inclusive regions
- Breakdown of systematic uncertainties per flavour
- **Dominated by statistical uncertainty**
- The picture may change with future datasets: 2023, 2024, 2025,…

Source	Inclusive	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Integrated luminosity	1.5	1.5	1.4	1.4	1.5
Trigger efficiencies	0.5	1.0	1.0	1.0	0.7
b tagging	0.1	0.1	0.1	0.1	0.1
Pileup	0.4	0.6	0.8	0.2	0.4
Jet energy scales	0.9	1.3	0.7	1.1	0.7
Electron ID efficiencies	0.7	3.6	2.4	1.1	-
Electron reconstruction	1.2	4.0	2.9	1.1	-
Electron energy scale	0.1	0.1	0.1	0.0	-
Muon efficiencies	0.7	-	0.3	0.8	1.2
Nonprompt normalization	0.7	1.6	0.5	0.7	0.7
VVV normalization	0.4	0.4	0.4	0.4	0.4
tZq normalization	0.1	0.1	0.1	0.1	0.1
ZZ normalization	0.3	0.8	0.7	0.5	0.5
$t\bar{t}Z$ normalization	0.3	0.7	0.6	0.4	0.5
$X+\gamma$ normalization	0.2	0.7	0.3	0.4	0.2
VH normalization	0.2	0.2	0.2	0.1	0.2
ISR/FSR	0.3	0.5	0.2	0.4	0.3
WZ theo (μ_R, μ_F, PDF)	0.2	0.2	0.2	0.2	0.2
MC statistical	0.5	1.9	0.9	1.0	0.9
Statistical	2.0	5.3	4.6	3.8	3.3
Total	3.3	8.4	6.4	5.0	4.2

$W^{\pm}Z$ Measurement

- Measurement of the WZ production in the leptonic final state: $\boldsymbol{\mu\mu\mu}$, $\boldsymbol{\mu\mu e}$, $\boldsymbol{\mu ee}$, and $\boldsymbol{eee}$
- Similarly to the WW analysis, results are compared with previous **CMS measurements**

$$\boldsymbol{\sigma_{Inc}^{WZ} = 55.2 \pm 1.2(stat) \pm 1.2(syst) \pm 0.8(lumi) \pm 0.1(theo)}\ \textbf{pb}$$



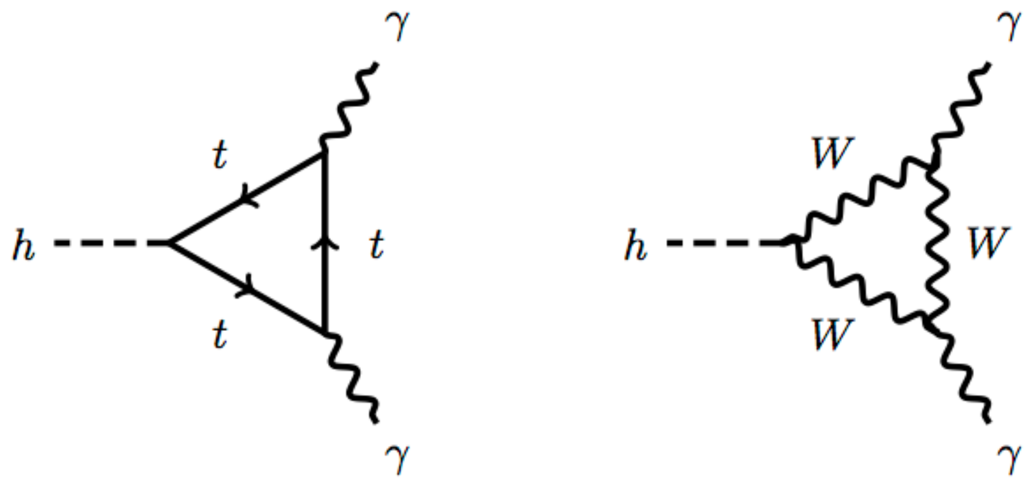
Measurements

HGG CMS-HIG-23-014

$\mathrm{H} \rightarrow \gamma\gamma$ Measurement

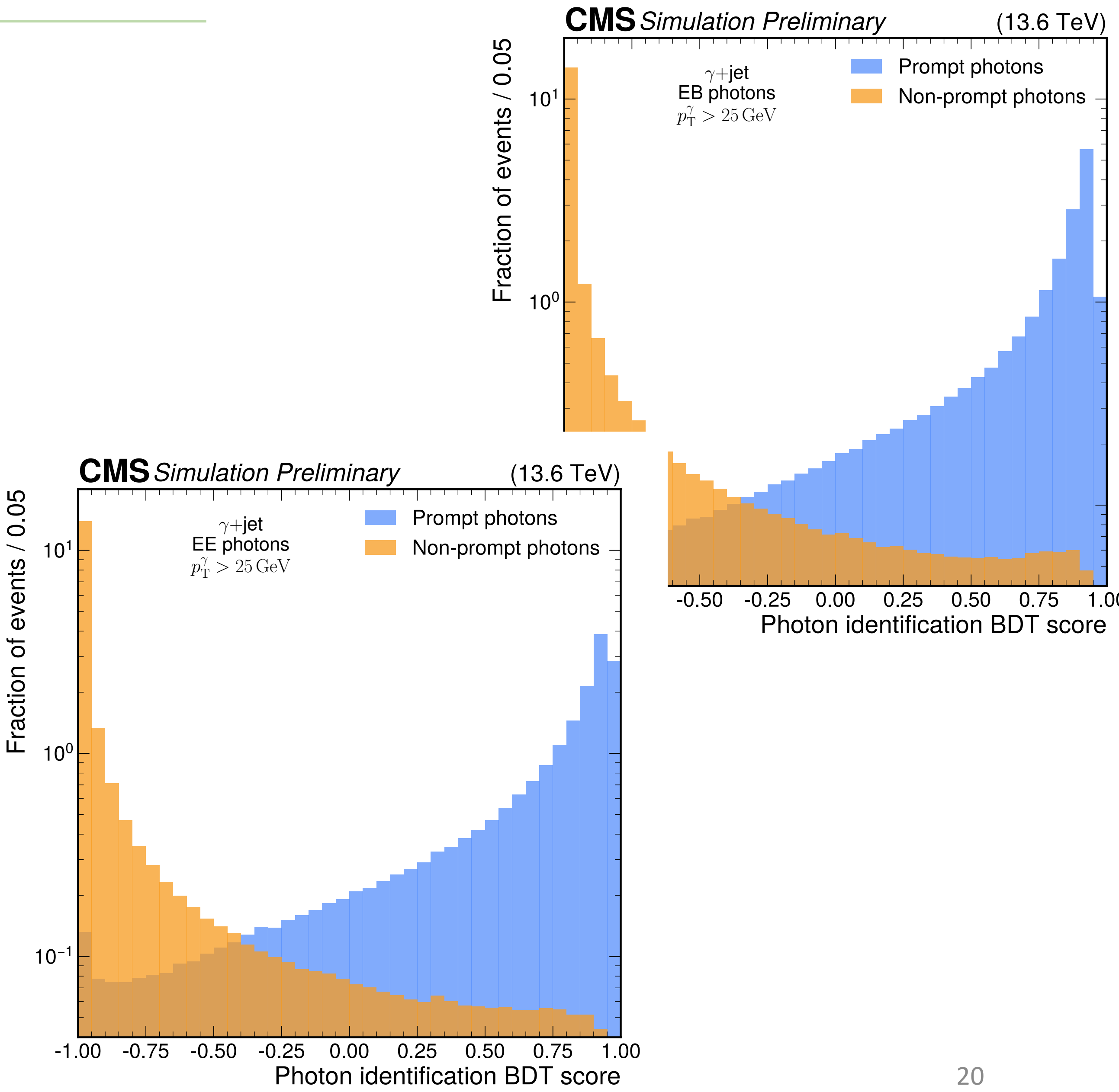
- **Measurement of inclusive and differential production cross sections**
- **Clean final state** topology, even with a low branching ratio. The invariant mass can be **precisely reconstructed**
- Overall **similar strategy than Full Run 2** result
- Again, data from 2022 is used: **34.7 fb^{-1}**

Fiducial phase space
$\sqrt{p_T^{\gamma_1} p_T^{\gamma_2}}/m_{\gamma\gamma} > 1/3$
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$
$I < 10$ GeV
$\|\eta\| < 2.5$



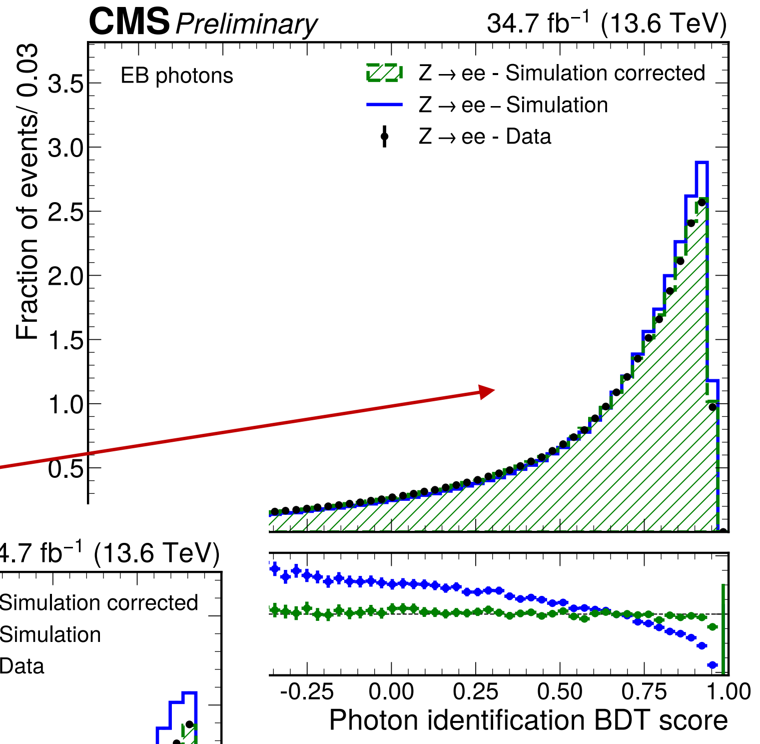
$H \rightarrow \gamma\gamma$ Measurement

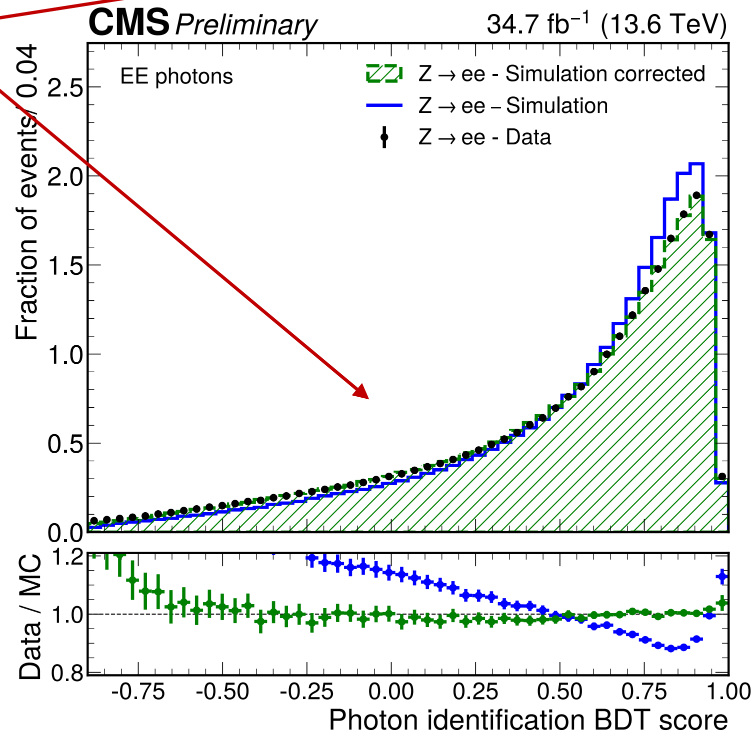
- **Photon resolution improved with a BDT**
- **Photon identification improved with a BDT →** reduce the non-prompt photon contamination
- The bad modelling of some photon reconstruction variables in MC is corrected using normalizing flows.
- **Data-driven estimation of the background** shape and normalization
- **Categorization** of the signal regions based on the **di-photon resolution**



H → γγ Measurement

- **Photon resolution improved with a BDT**
- **Photon identification improved with a BDT →** reduce the non-prompt photon contamination
- The bad modelling of some photon reconstruction variables in **MC is corrected** using normalizing flows.
- **Data-driven estimation of the background** shape and normalization
- **Categorization** of the signal regions based on the **di-photon resolution**

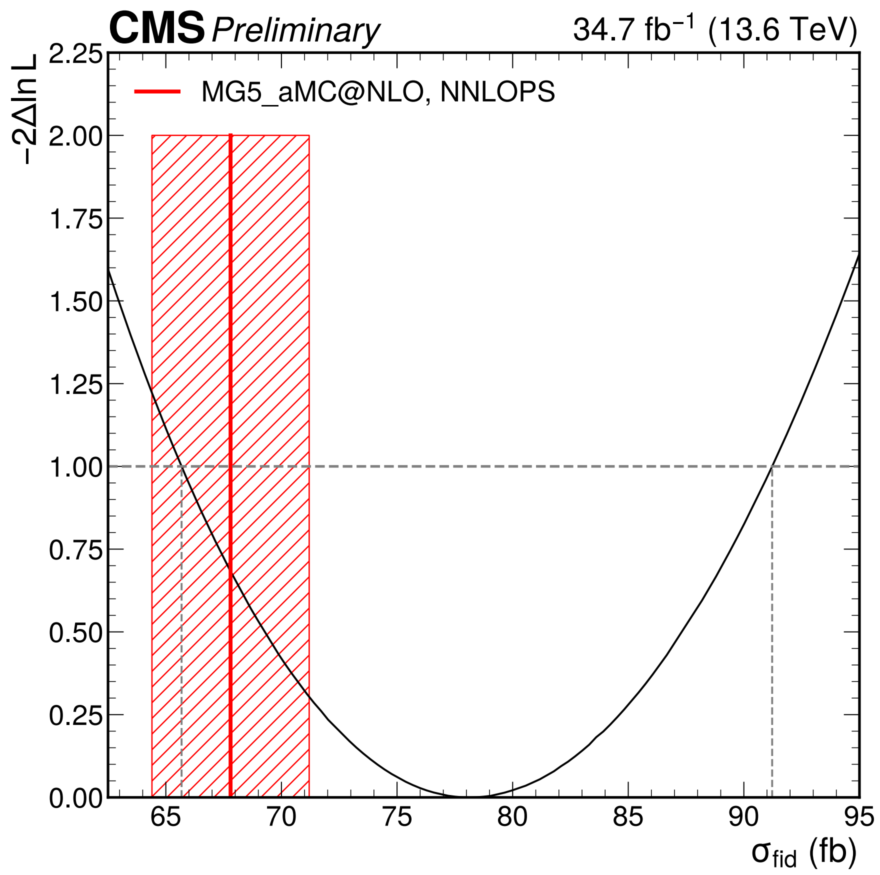


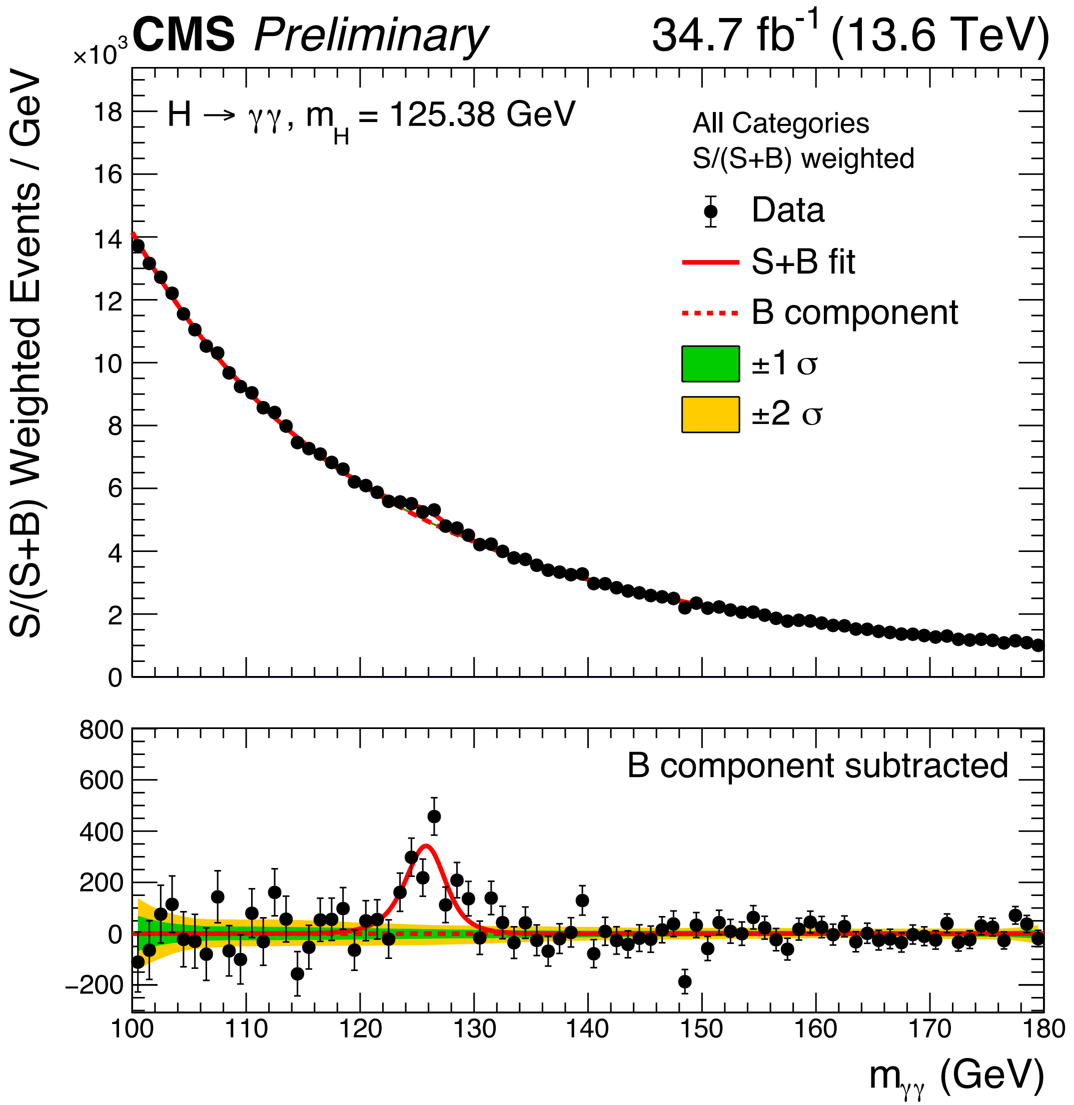


$H \to \gamma\gamma$ Measurement

Results in agreement with the SM expectation

$$\sigma_{fid} = 78 \pm 11(stat)^{+6}_{-5}(syst) = 78^{+13}_{-12}\ \text{fb}$$





H → γγ Measurement

Differential results provided as a function of p_T^H, $|y_H|$, N_{jets}

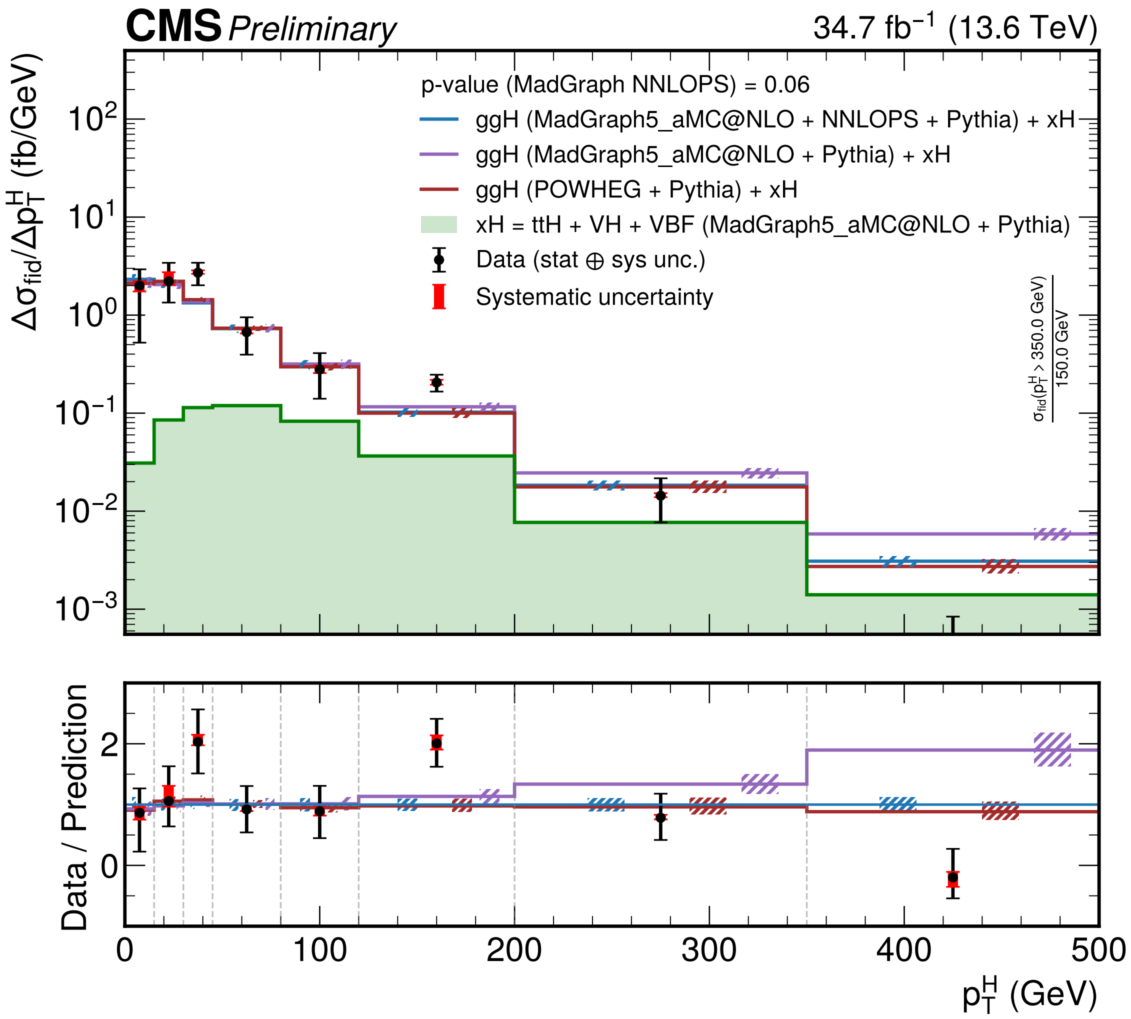
Results **dominated by the statistical uncertainties**

Within the **systematics**, the **photon scale and resolution** dominates

The results are compared with different MC generators

Room for improvement with more Run 3 data

Systematic uncertainty	Magnitude
Photon energy scale and resolution group	+5.8%/ − 4.9%
Category migration from energy resolution	+3.5%/ − 3.9%
Integrated luminosity	±1.4%
Photon preselection efficiency	±1.4%
Energy scale non-linearity	+0.8%/ − 1.6%
Photon identification efficiency	±1.0%
Pileup reweighting	±0.8%



$H \rightarrow \gamma\gamma$ Measurement

Differential results provided as a function of p_T^H, $|y_H|$, N_{jets}

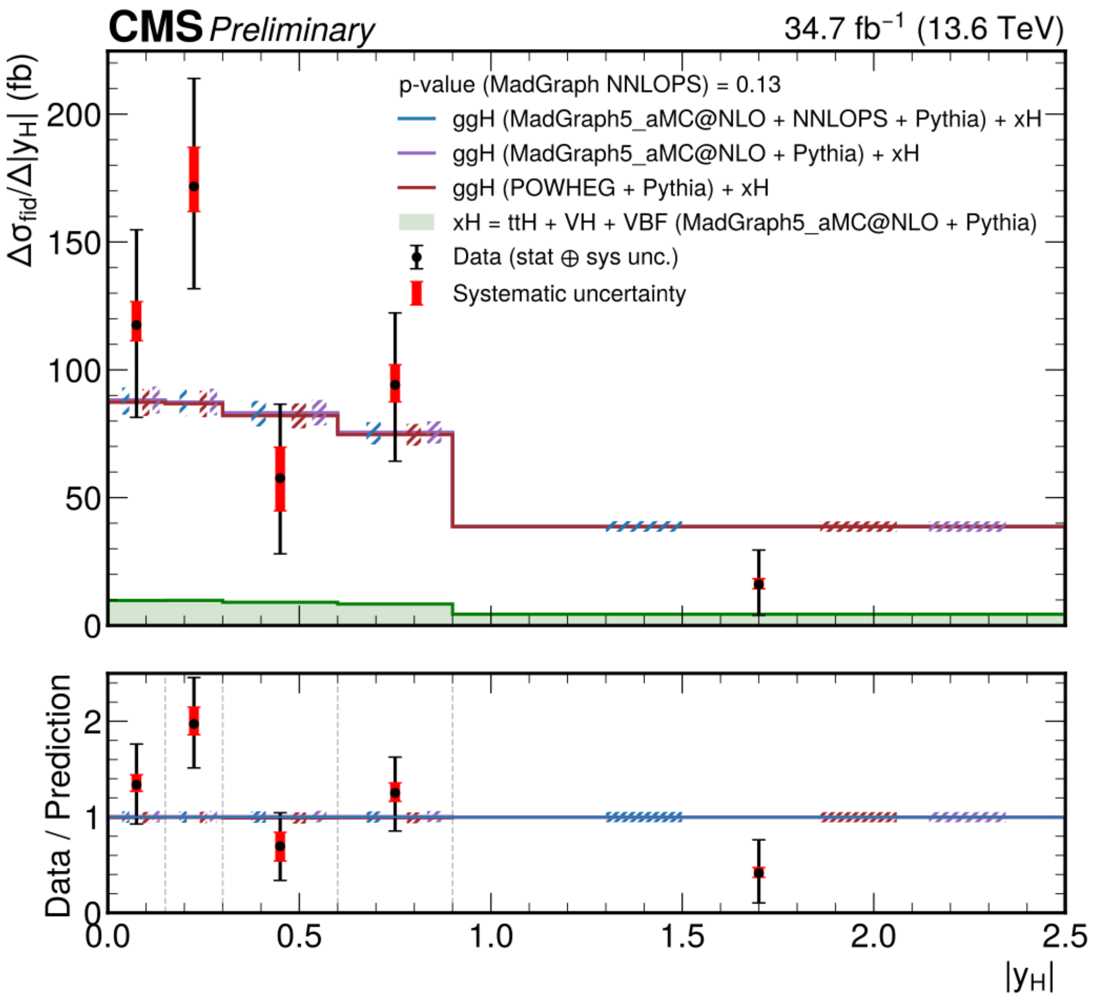
Results **dominated by the statistical uncertainties**

Within the **systematics**, the **photon scale and resolution** dominates

The results are compared with different MC generators

Room for improvement with more Run 3 data

Systematic uncertainty	Magnitude
Photon energy scale and resolution group	$+5.8\%/-4.9\%$
Category migration from energy resolution	$+3.5\%/-3.9\%$
Integrated luminosity	$\pm1.4\%$
Photon preselection efficiency	$\pm1.4\%$
Energy scale non-linearity	$+0.8\%/-1.6\%$
Photon identification efficiency	$\pm1.0\%$
Pileup reweighting	$\pm0.8\%$



$H \rightarrow \gamma\gamma$ Measurement

Differential results provided as a function of $\boldsymbol{p_T^H}$, $\boldsymbol{|y_H|}$, $\mathbf{N_{jets}}$

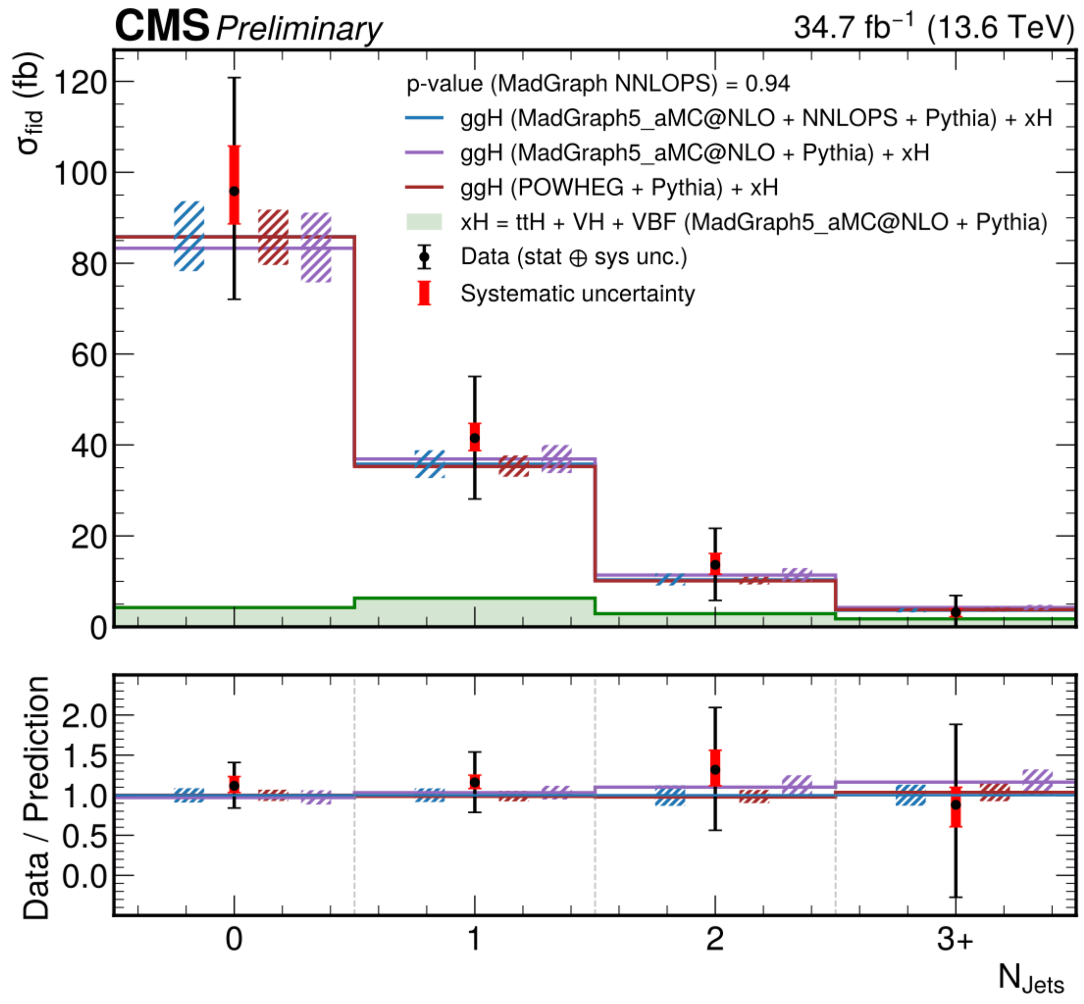
Results **dominated by the statistical uncertainties**

Within the **systematics**, the **photon scale and resolution** dominates

The results are compared with different MC generators

Room for improvement with more Run 3 data

Systematic uncertainty	Magnitude
Photon energy scale and resolution group	$+5.8\%/-4.9\%$
Category migration from energy resolution	$+3.5\%/-3.9\%$
Integrated luminosity	$\pm1.4\%$
Photon preselection efficiency	$\pm1.4\%$
Energy scale non-linearity	$+0.8\%/-1.6\%$
Photon identification efficiency	$\pm1.0\%$
Pileup reweighting	$\pm0.8\%$

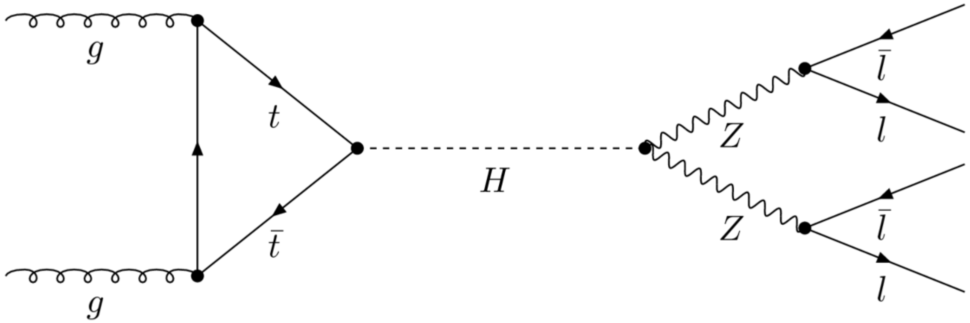


Measurements

HZZ CMS-HIG-24-013

H → ZZ Measurement

- **Measurement of inclusive fiducial cross section**
- **Clean final state** topology. The invariant mass can be **precisely reconstructed**
- **Irreducible background from qqZZ process**
- Overall **similar strategy than Full Run 2** result
- Again, data from 2022 is used: **34.7 fb^{-1}**

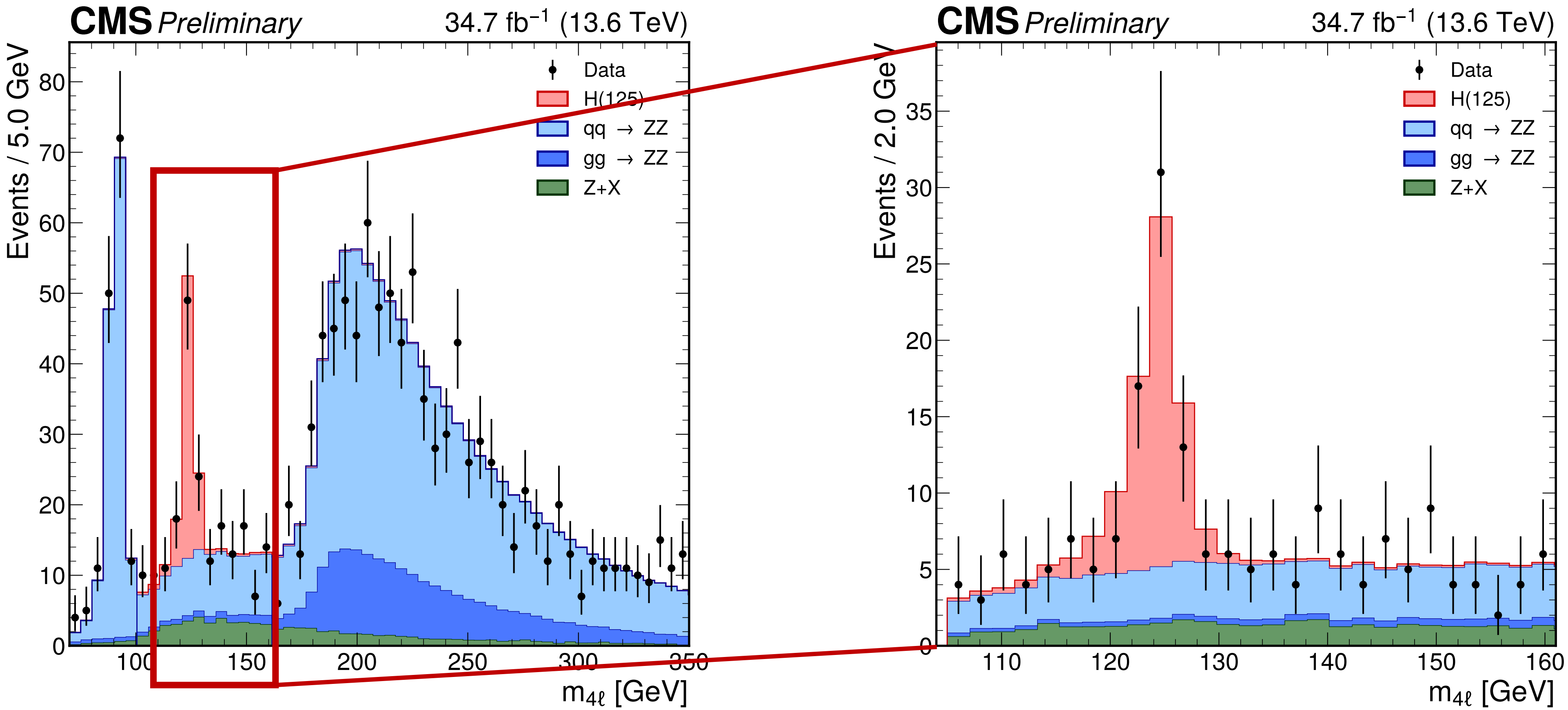


Requirements for the H → 4ℓ fiducial phase space	
Lepton kinematics and isolation	
leading lepton p_T	$p_T > 20$ GeV
next-to-leading lepton p_T	$p_T > 10$ GeV
additional electrons (muons) p_T	$p_T > 7(5)$ GeV
pseudorapidity of electrons (muons)	$\|\eta\| < 2.5(2.4)$
p_T sum of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 \cdot p_T$
Event topology	
existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
inv. mass of the Z_1 candidate	$40\,\text{GeV} < m(Z_1) < 120\,\text{GeV}$
inv. mass of the Z_2 candidate	$12\,\text{GeV} < m(Z_2) < 120\,\text{GeV}$
distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$ for any $i \neq j$
inv. mass of any opposite sign lepton pair	$m(\ell^+ \ell'^-) > 4\,\text{GeV}$
inv. mass of the selected four leptons	$105\,\text{GeV} < m_{4\ell} < 160\,\text{GeV}$
the selected four leptons must originate from the H → 4ℓ decay	

$H \to ZZ$ Measurement

- Measurement of **inclusive** fiducial cross section
- Dedicated **BDT for electron identification**
- Results in **agreement with the SM**

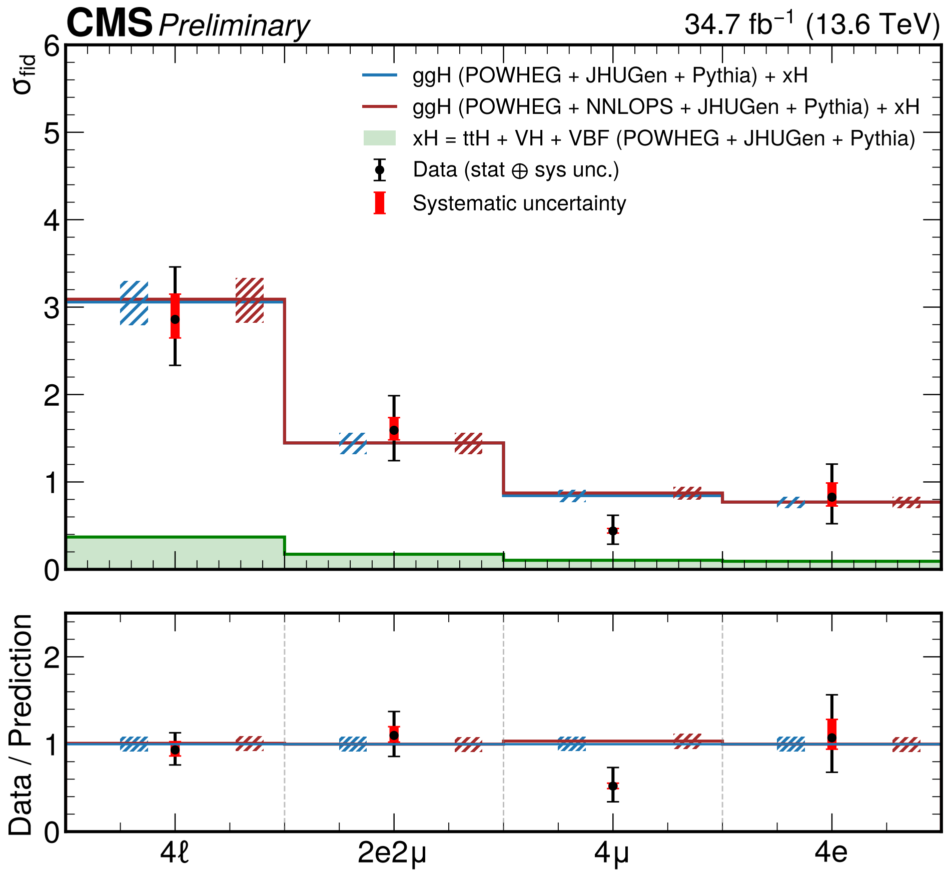
Fit range
$105 < m_{4l} < 160$ GeV

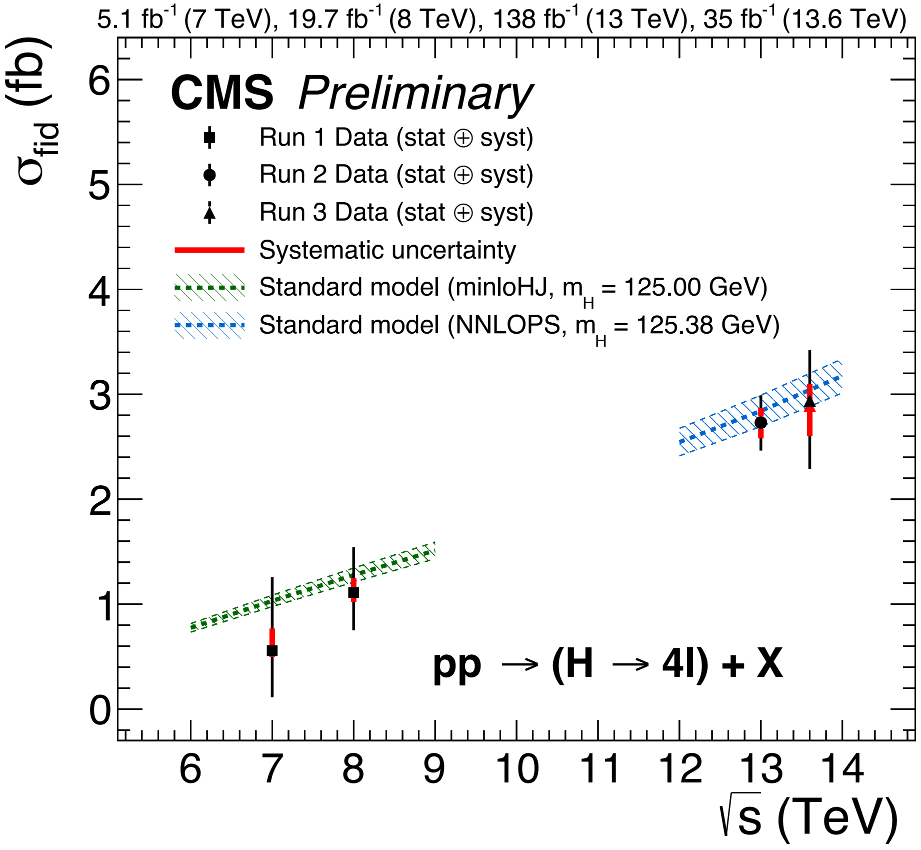


H → ZZ Measurement

- Results given as a function of the **lepton flavor**
- Among the systematics, the **4 muon channel is the most precise** one
- And as a function of the **center-of-mass energy**

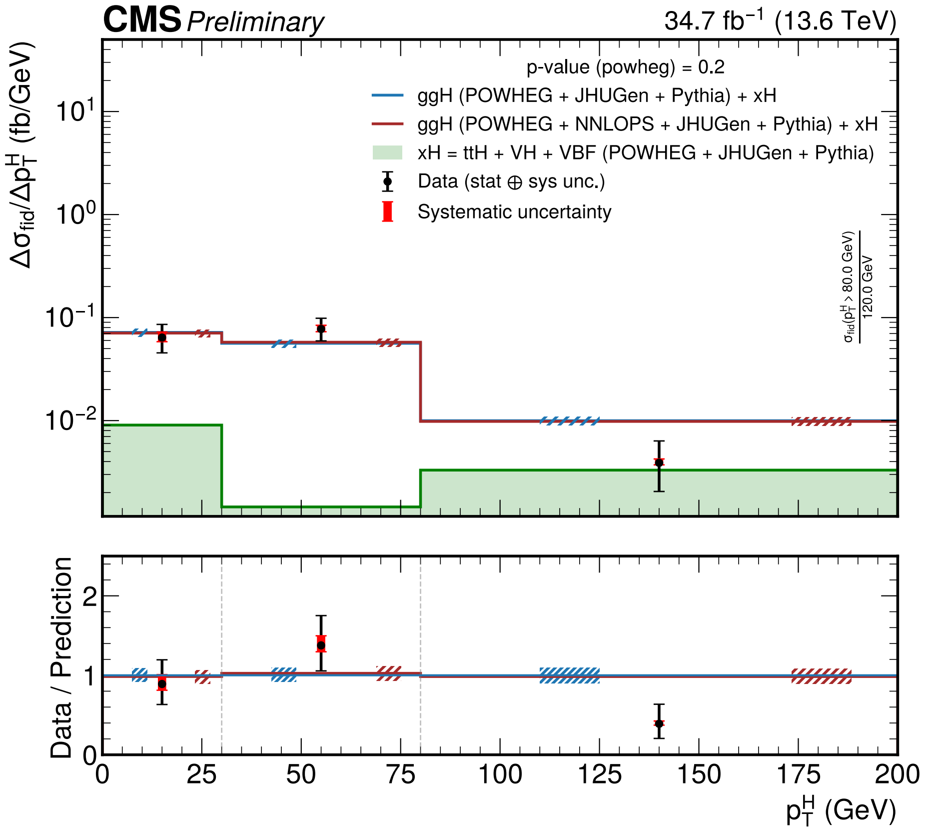
$$\sigma_{fid} = 2.94^{+0.53}_{-0.49}(stat)^{+0.29}_{-0.22}(syst)\ \text{fb}$$

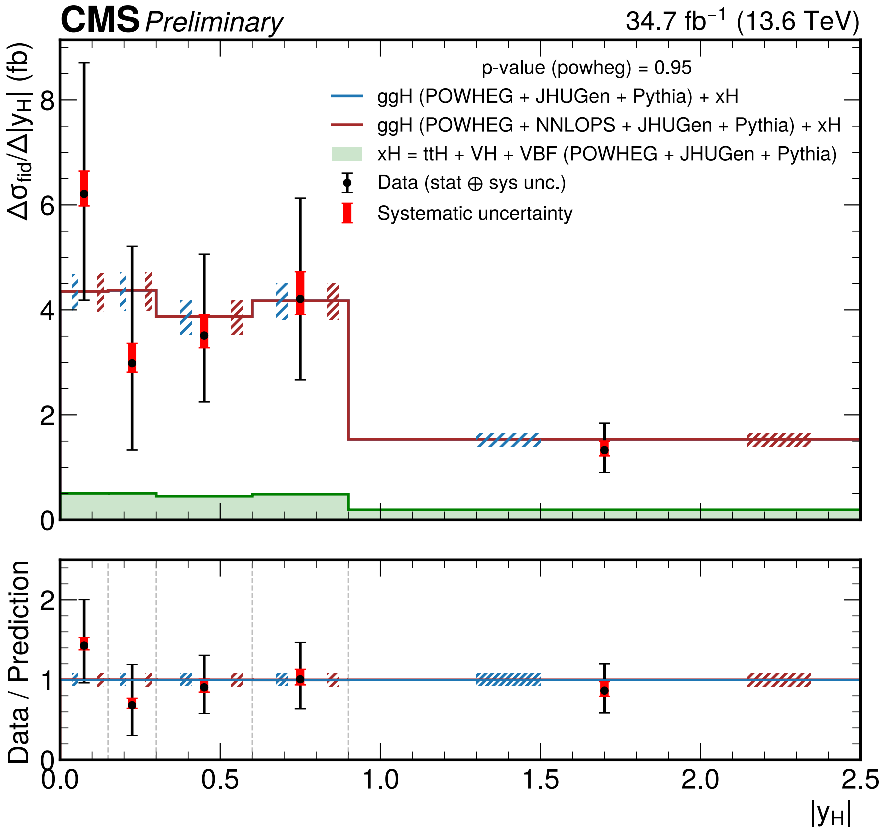




H → ZZ Measurement

- **Differential** cross section measurements are provided as a function of p_T^H, $|y_H|$
- Results **statistically dominated**, more precise results may come with larger datasets





Summary

- The **Run 3 data-taking** period is in good shape, today we have **>160 fb^{-1}**
- The **interest is slowly switching to Run 3 analysis**, so we expect more results to come out soon
- Today, **4 nice Multiboson results have been shown**
- **Stay tuned for more experimental measurements!**

BACKUP

W^+W^- Measurement (2016 / 2022)

Signal/control region yields

	WW SR	Same-sign CR	$Z \to \tau\tau$ CR	One b-tag CR	Two b-tag CR
WW	16220 ± 650	81.7 ± 9.5	2662 ± 94	2220 ± 180	248 ± 54
Top quark	19760 ± 480	87.3 ± 8.4	1126 ± 34	63340 ± 750	55610 ± 620
$Z \to \tau\tau$	2124 ± 72	57.0 ± 9.3	45630 ± 590	227 ± 27	19.6 ± 7.9
WZ	487 ± 21	512 ± 24	97.6 ± 4.9	96.9 ± 6.3	11.8 ± 1.7
ZZ	37.1 ± 1.7	33.6 ± 1.7	66.0 ± 3.9	6.9 ± 0.5	1.0 ± 0.1
Nonprompt	4860 ± 320	2390 ± 130	6550 ± 440	2630 ± 270	1640 ± 220
VVV	75.9 ± 3.7	25.8 ± 1.3	4.7 ± 0.4	33.7 ± 2.1	8.7 ± 0.8
tVx	10.7 ± 1.5	8.7 ± 2.7	0.7 ± 0.1	44.1 ± 3.2	52.1 ± 3.3
$V\gamma$	225 ± 18	232 ± 19	69.2 ± 7.6	43.2 ± 9.5	3.1 ± 0.9
Higgs	90 ± 14	27.5 ± 5.2	344 ± 52	29.3 ± 4.8	20.7 ± 3.2
Total	43890 ± 410	3460 ± 130	56550 ± 420	68670 ± 560	57610 ± 490
Data	43898	3456	56551	68656	57617

	WZ CR	ZZ CR
WZ	3470 ± 130	0.9 ± 0.1
ZZ	270 ± 29	599 ± 25
Nonprompt	820 ± 120	< 1
VVV	60.4 ± 3.7	5.4 ± 0.3
tVx	25.7 ± 3.1	2.3 ± 0.2
Higgs	55.4 ± 8.8	2.5 ± 0.9
$V\gamma$	28.3 ± 3.1	< 1
Total	4732 ± 78	610 ± 25
Data	4732	610

W^+W^- Measurement (2016 / 2022)

Fiducial cross section per N-jets

Table 7: Inclusive fiducial cross sections and normalized cross sections obtained in the analysis. The uncertainty listed is the total uncertainty obtained from the fit to the yields. The expected predictions are obtained from POWHEG+PYTHIA. In brackets, the split of systematic and statistical uncertainties are reported.

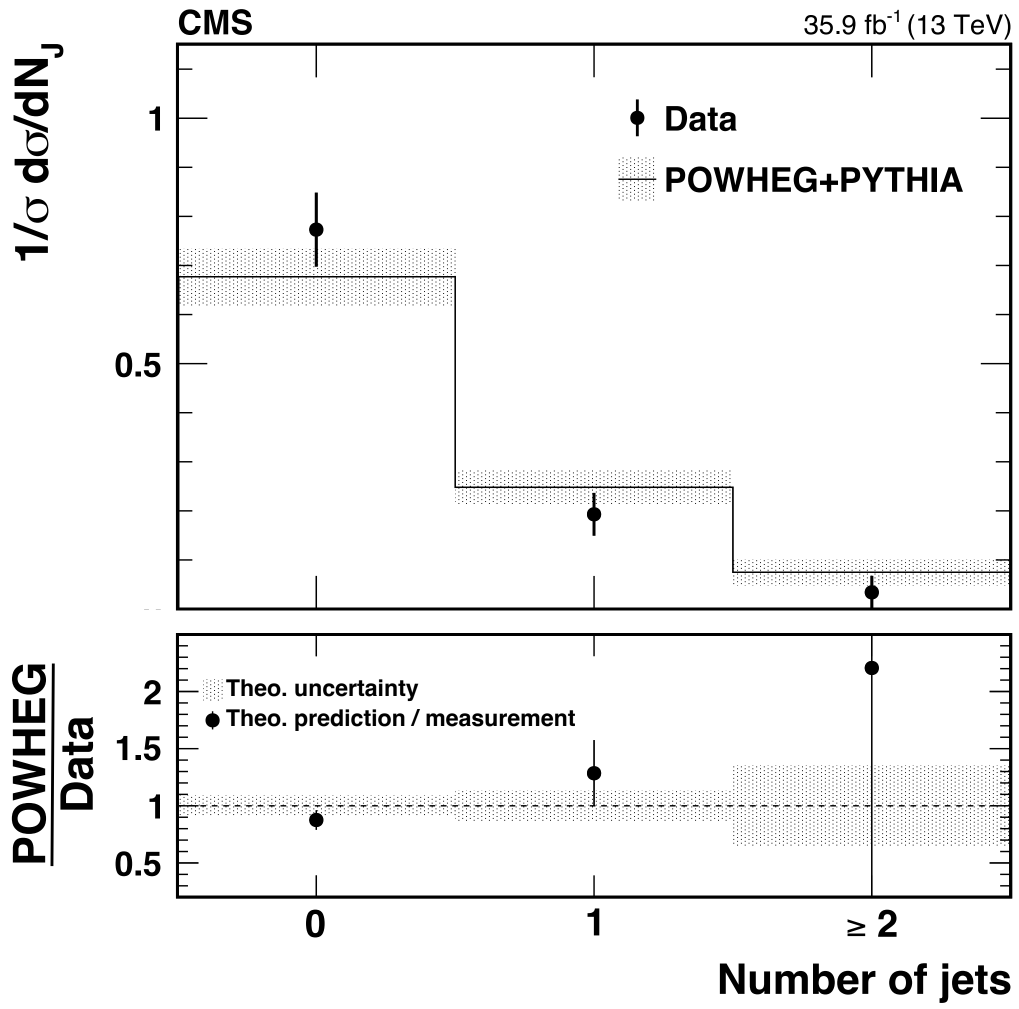
Observable	Expected	Observed
Cross section (fb)	$812 \pm 34(31, 15)$	$813 \pm 35(32, 15)$
0-jet fraction	$0.648 \pm 0.015(0.012, 0.009)$	$0.640 \pm 0.016(0.013, 0.009)$
1-jet fraction	$0.256 \pm 0.013(0.008, 0.010)$	$0.243 \pm 0.013(0.009, 0.010)$
$\geq$ 2-jet fraction	$0.096 \pm 0.011(0.008, 0.008)$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

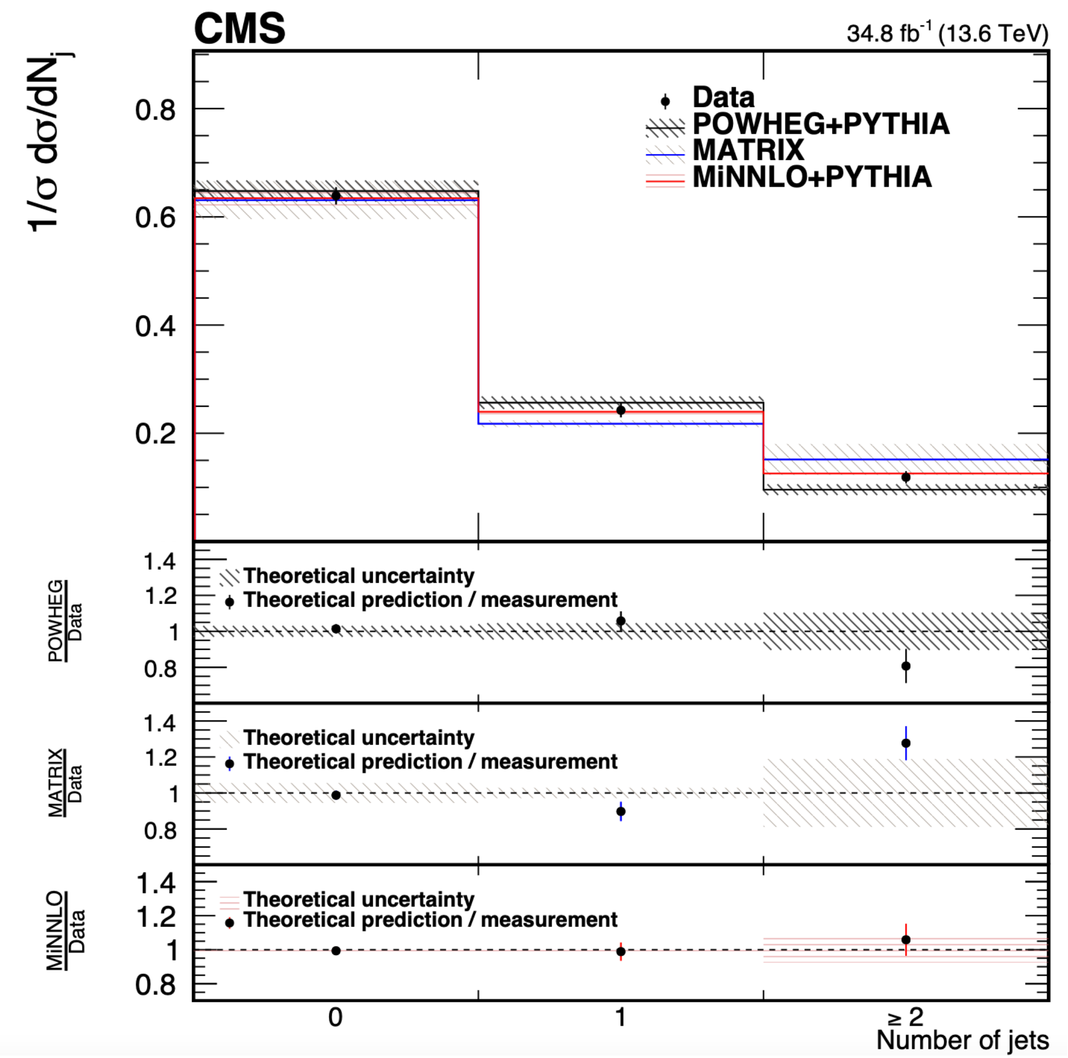
W^+W^- Measurement (2016 / 2022)

Uncertainty source	(%)
Statistical	1.2
$t\bar{t}$ normalization	2.0
Drell–Yan normalization	1.4
$W\gamma^*$ normalization	0.4
Nonprompt leptons normalization	1.9
Lepton efficiencies	2.1
b tagging (b/c)	0.4
Mistag rate (q/g)	1.0
Jet energy scale and resolution	2.3
Pileup	0.4
Simulation and data control regions sample size	1.0
Total experimental systematic	4.6
QCD factorization and renormalization scales	0.4
Higher-order QCD corrections and p_T^{WW} distribution	1.4
PDF and α_S	0.4
Underlying event modeling	0.5
Total theoretical systematic	1.6
Integrated luminosity	2.7
Total	5.7

Uncertainty source	$\Delta\mu$
Integrated luminosity	0.014
Lepton experimental	0.019
Jet experimental	0.008
b tagging	0.012
Nonprompt background	0.010
Limited sample size	0.017
Background normalization	0.018
Theory	0.011
Statistical	0.018
Total	0.044

W^+W^- Measurement (2016 / 2022)



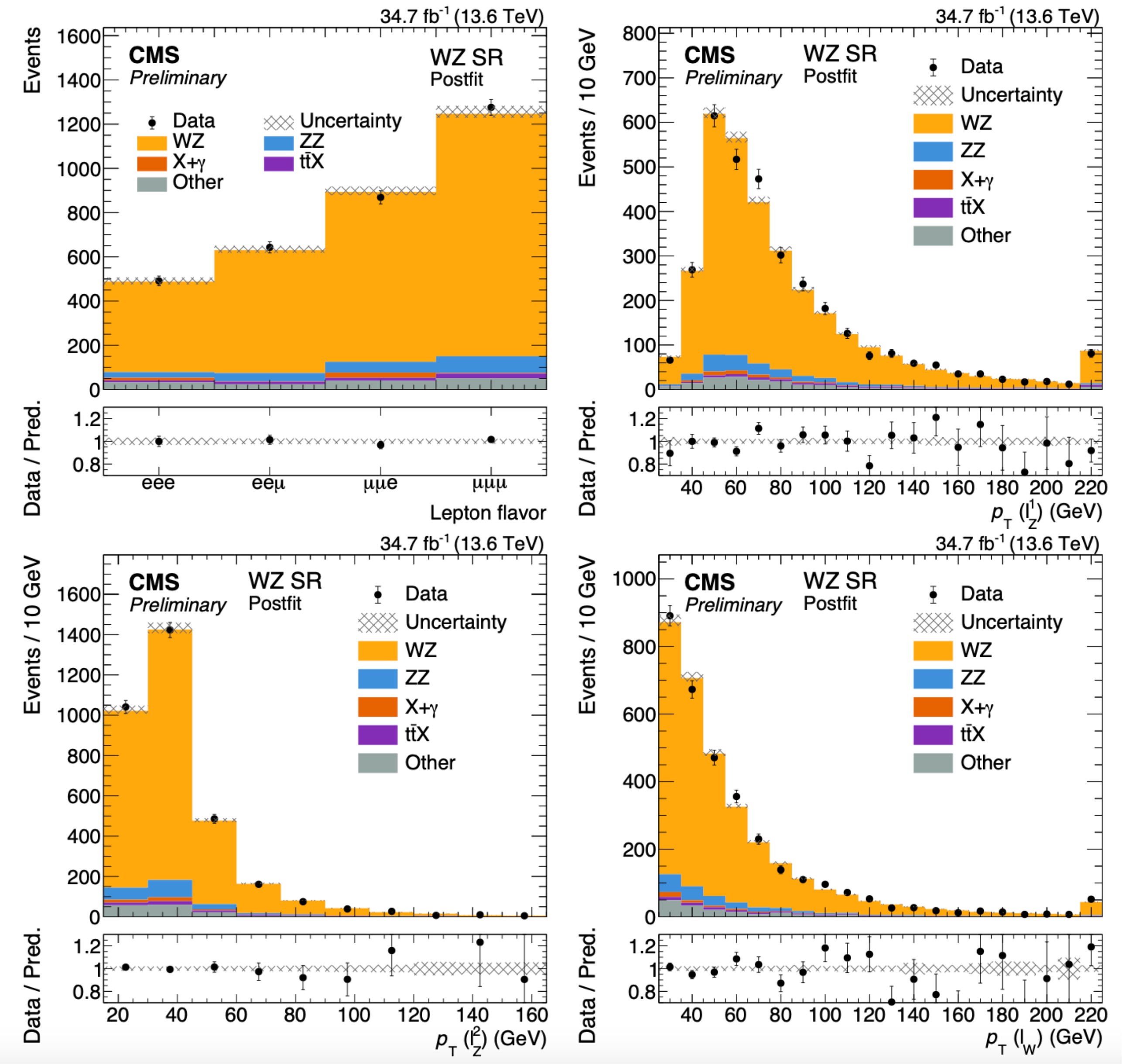


$W^{+}Z$ Measurement

Signal region yields

Process	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$	Inclusive
Non prompt	25 ± 7	13 ± 5	24 ± 7	30 ± 10	93 ± 15
ZZ	25 ± 2	37 ± 1	49 ± 3	75 ± 3	186 ± 5
$X + \gamma$	12 ± 2	2 ± 0	24 ± 2	3 ± 0	41 ± 3
$t\bar{t}X$	8 ± 1	11 ± 1	14 ± 1	21 ± 2	54 ± 3
VVV	4 ± 1	5 ± 2	7 ± 3	10 ± 4	27 ± 5
VH	3 ± 1	4 ± 1	5 ± 1	9 ± 2	20 ± 2
tZq	4 ± 1	5 ± 1	8 ± 1	11 ± 1	28 ± 2
Background	82 ± 8	78 ± 5	130 ± 9	160 ± 11	450 ± 17
WZ	410 ± 10	556 ± 12	768 ± 14	1096 ± 22	2830 ± 31
Data	491	643	869	1276	3279

W^+Z Measurement



W^+Z Measurement

Category	Accuracy	Fiducial cross section (fb)
eee	POWHEG	$68.0^{+2.3}_{-2.1}$ (scale) $\pm$ 1.0 (PDF)
	MATRIX, NNLO QCD	$77.0^{+1.8}_{-1.7}$ (scale)
	MATRIX, NNLO QCD $\times$ NLO EWK	$75.4^{+1.7}_{-1.6}$ (scale)
	Measured	72.0 $\pm$ 6.1 (stat) $\pm$ 6.1 (syst) $\pm$ 4.0 (lumi) $\pm$ 0.5 (theo)
eeμ	POWHEG	$68.0^{+2.3}_{-2.1}$ (scale) $\pm$ 1.0 (PDF)
	MATRIX, NNLO QCD	$75.0^{+1.8}_{-1.6}$ (scale)
	MATRIX, NNLO QCD $\times$ NLO EWK	$73.4^{+1.7}_{-1.5}$ (scale)
	Measured	73.9 $\pm$ 3.5 (stat) $\pm$ 3.1 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.3 (theo)
$\mu\mu$e	POWHEG	$68.0^{+2.3}_{-2.1}$ (scale) $\pm$ 1.0 (PDF)
	MATRIX, NNLO QCD	$75.0^{+1.8}_{-1.6}$ (scale)
	MATRIX, NNLO QCD $\times$ NLO EWK	$73.4^{+1.7}_{-1.5}$ (scale)
	Measured	71.2 $\pm$ 2.9 (stat) $\pm$ 2.0 (syst) $\pm$ 1.0 (lumi) $\pm$ 0.1 (theo)
$\mu\mu\mu$	POWHEG	$68.0^{+2.3}_{-2.1}$ (scale) $\pm$ 1.0 (PDF)
	MATRIX, NNLO QCD	$77.0^{+1.8}_{-1.7}$ (scale)
	MATRIX, NNLO QCD $\times$ NLO EWK	$75.4^{+1.7}_{-1.6}$ (scale)
	Measured	75.3 $\pm$ 2.5 (stat) $\pm$ 1.5 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.1 (theo)
Inclusive	POWHEG	$271.9^{+9.0}_{-8.5}$ (scale) $\pm$ 3.8 (PDF)
	MATRIX, NNLO QCD	$304.0^{+7.1}_{-6.6}$ (scale)
	MATRIX, NNLO QCD $\times$ NLO EWK	$298.1^{+6.9}_{-6.3}$ (scale)
	Measured	297.6 $\pm$ 6.4 (stat) $\pm$ 6.4 (syst) $\pm$ 4.2 (lumi) $\pm$ 0.5 (theo)

W^+Z Measurement (Run 2 / Run 3)

Run 3

Accuracy	Total cross section (pb)
POWHEG	$50.5^{+2.6}_{-2.1}$ (scale) $\pm$ 1.1 (PDF)
MATRIX, NNLO QCD	$55.0^{+1.2}_{-1.1}$ (scale)
MATRIX, NNLO QCD $\times$ NLO EWK	$54.7^{+1.2}_{-1.1}$ (scale)
eee (Measured)	53.4 $\pm$ 3.0 (stat) $\pm$ 3.3 (syst) $\pm$ 0.8 (lumi) $\pm$ 0.2 (theo)
eeμ (Measured)	54.8 $\pm$ 2.6 (stat) $\pm$ 2.3 (syst) $\pm$ 0.8 (lumi) $\pm$ 0.2 (theo)
$\mu\mu$e (Measured)	52.9 $\pm$ 2.1 (stat) $\pm$ 1.4 (syst) $\pm$ 0.7 (lumi) $\pm$ 0.1 (theo)
$\mu\mu\mu$ (Measured)	55.9 $\pm$ 1.9 (stat) $\pm$ 1.1 (syst) $\pm$ 0.8 (lumi) $\pm$ 0.1 (theo)
Inclusive (Measured)	55.2 $\pm$ 1.2 (stat) $\pm$ 1.2 (syst) $\pm$ 0.8 (lumi) $\pm$ 0.1 (theo)

Run 2

Category or source	Total cross section
POWHEG	$42.5^{+1.6}_{-1.4}$ (scale) $\pm$ 0.6 (PDF) pb
MATRIX, NNLO QCD	$51.2^{+1.2}_{-1.0}$ (scale) pb
MATRIX, NNLO QCD $\times$ NLO EWK	$50.7^{+1.1}_{-1.0}$ (scale) pb
eee (Measured)	53.2 $\pm$ 2.7 (stat) $\pm$ 2.3 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.5 (theo) pb
eeμ (Measured)	48.1 $\pm$ 1.7 (stat) $\pm$ 1.8 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.4 (theo) pb
$\mu\mu$e (Measured)	50.6 $\pm$ 1.3 (stat) $\pm$ 1.5 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.5 (theo) pb
$\mu\mu\mu$ (Measured)	50.8 $\pm$ 1.0 (stat) $\pm$ 1.5 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.5 (theo) pb
Combined (Measured)	50.6 $\pm$ 0.8 (stat) $\pm$ 1.5 (syst) $\pm$ 1.1 (lumi) $\pm$ 0.5 (theo) pb

W^+Z Measurement (Run 2 / Run 3)

Run 2

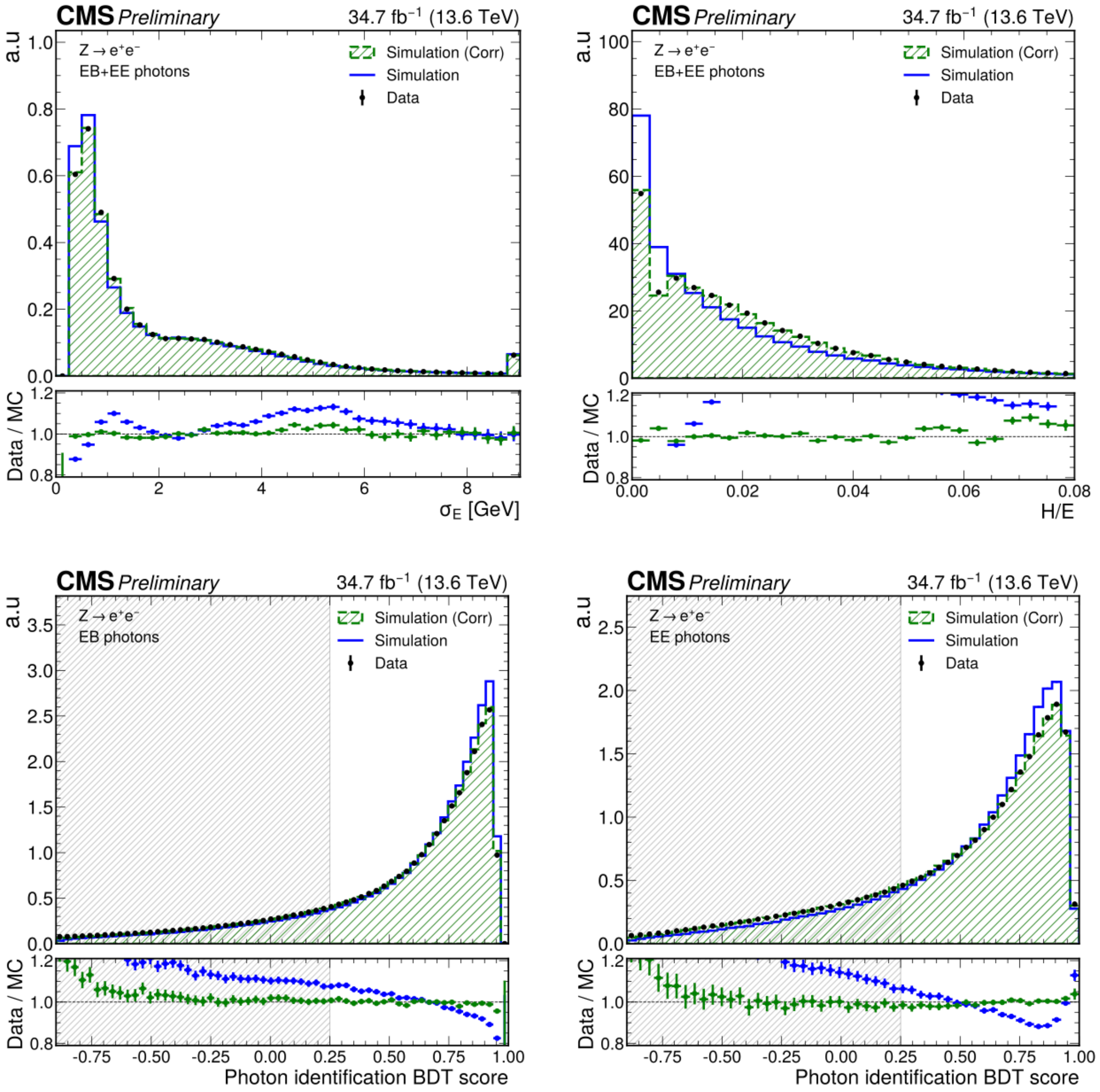
Source	Combined	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Electron efficiency	0.6	3.2	1.8	0.9	—
Muon efficiency	1.2	—	0.5	1.0	1.5
Electron energy scale	0.1	0.3	0.1	0.1	0.0
Muon energy scale	0.1	0.0	0.0	0.1	0.1
Trigger efficiency	0.7	0.7	0.8	0.7	0.7
Jet energy scale	0.9	0.8	0.7	1.0	0.9
b tagging	1.6	1.8	1.7	1.8	1.6
Pileup	0.9	1.0	1.2	0.8	0.7
ISR	0.2	0.2	0.2	0.2	0.2
Nonprompt normalization	0.6	0.7	0.8	0.6	0.7
Nonprompt shape	1.0	1.2	1.0	0.9	0.9
VVV normalization	0.5	0.6	0.5	0.5	0.5
VH normalization	0.2	0.1	0.2	0.2	0.2
WZ EWK normalization	0.2	0.2	0.2	0.2	0.2
ZZ normalization	0.3	0.3	0.3	0.3	0.3
$t\bar{t}Z$ normalization	0.3	0.4	0.4	0.4	0.3
tZq normalization	0.4	0.4	0.4	0.4	0.4
Xγ normalization	0.2	0.5	0.1	0.5	0.1
Total systematic uncertainties	2.8	4.3	3.7	3.0	3.0
Integrated luminosity	2.1	2.2	2.2	2.1	2.1
Statistical uncertainty	1.5	5.0	3.4	2.5	2.0
PDF+scale	0.9	0.9	0.9	0.9	0.9

Run 3

Source	Inclusive	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Integrated luminosity	1.5	1.5	1.4	1.4	1.5
Trigger efficiencies	0.5	1.0	1.0	1.0	0.7
b tagging	0.1	0.1	0.1	0.1	0.1
Pileup	0.4	0.6	0.8	0.2	0.4
Jet energy scales	0.9	1.3	0.7	1.1	0.7
Electron ID efficiencies	0.7	3.6	2.4	1.1	-
Electron reconstruction	1.2	4.0	2.9	1.1	-
Electron energy scale	0.1	0.1	0.1	0.0	-
Muon efficiencies	0.7	-	0.3	0.8	1.2
Nonprompt normalization	0.7	1.6	0.5	0.7	0.7
VVV normalization	0.4	0.4	0.4	0.4	0.4
tZq normalization	0.1	0.1	0.1	0.1	0.1
ZZ normalization	0.3	0.8	0.7	0.5	0.5
$t\bar{t}Z$ normalization	0.3	0.7	0.6	0.4	0.5
$X + \gamma$ normalization	0.2	0.7	0.3	0.4	0.2
VH normalization	0.2	0.2	0.2	0.1	0.2
ISR/FSR	0.3	0.5	0.2	0.4	0.3
WZ theo (μ_R, μ_F, PDF)	0.2	0.2	0.2	0.2	0.2
MC statistical	0.5	1.9	0.9	1.0	0.9
Statistical	2.0	5.3	4.6	3.8	3.3
Total	3.3	8.4	6.4	5.0	4.2

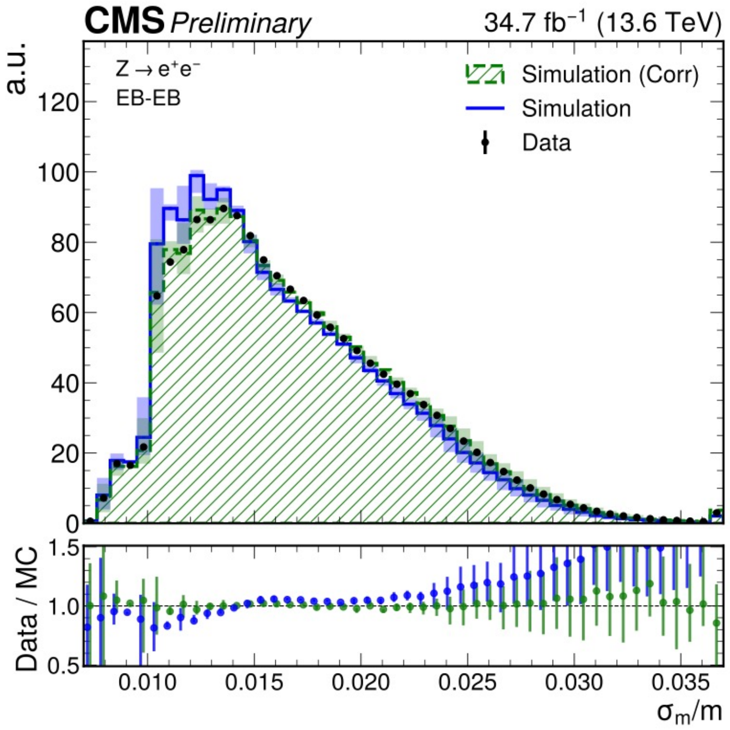
$H \to \gamma\gamma$ Measurement

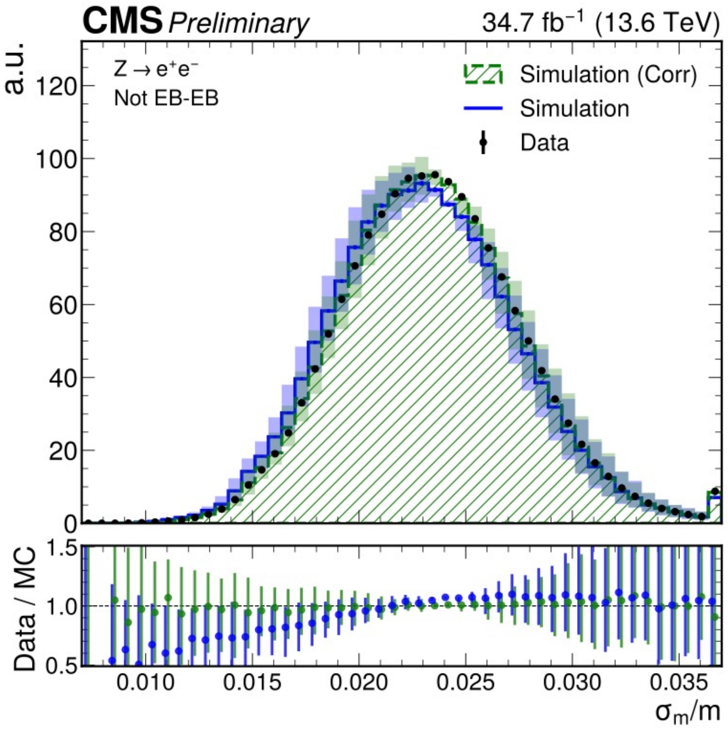
- The photon BDT regresses the parameters of the double-sided crystal ball function with the optimal energy resolution
- It improves the resolution to up to 1% in the barrel and 2.4% in the end-caps
- The CMS water leak during the 2022 data-taking period (solved issue) reduced the signal efficiency by 1.5%
- The mass resolution estimator is decorrelated to the invariant mass of the di-photon system using a quantile morphing algorithm



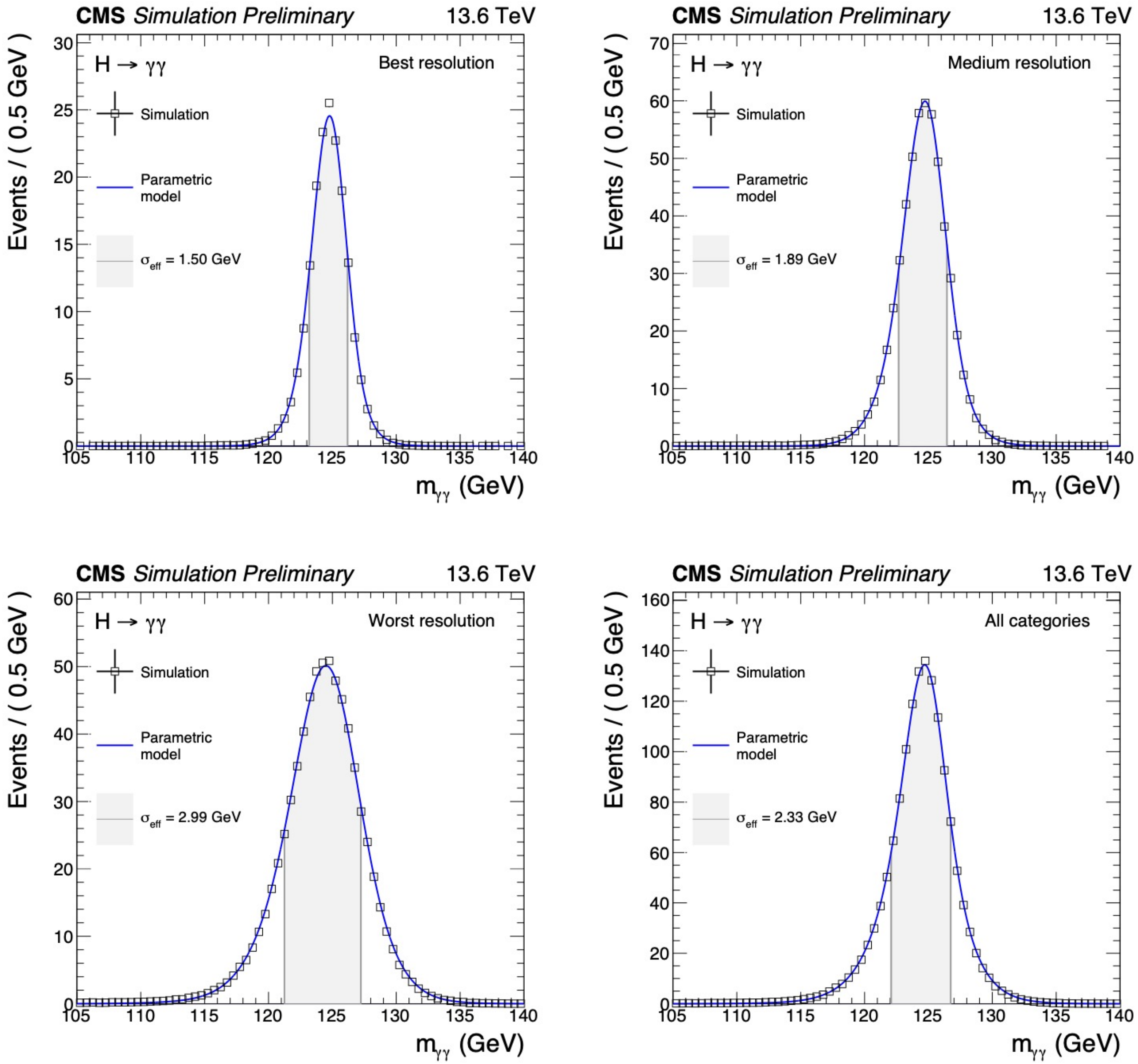
$\mathrm{H} \rightarrow \gamma\gamma$ Measurement

The resulting bin $\frac{\sigma_m}{m}$ categories are [0, 0.01), [0.01, 0.014) and [0.014, ∞).





$H \to \gamma\gamma$ Measurement



$H \rightarrow ZZ$ Measurement

	σ_{fid} (fb)
$2e2\mu$ (fb)	$1.63^{+0.37}_{-0.33}$(stat.)$^{+0.14}_{-0.12}$(syst.)
4μ (fb)	$0.46^{+0.18}_{-0.15}$(stat.)$^{+0.03}_{-0.02}$(syst.)
4e (fb)	$0.83^{+0.34}_{-0.29}$(stat.)$^{+0.16}_{-0.10}$(syst.)
Inclusive (fb)	$2.94^{+0.53}_{-0.49}$(stat.)$^{+0.29}_{-0.22}$(syst.)

Process	$4e$	4μ	$2e2\mu$	4ℓ
Signal(m_H =125.38 GeV)	$10.79^{+0.81}_{-1.44}$	$11.74^{+0.21}_{-0.26}$	$30.54^{+1.56}_{-2.63}$	$53.07^{+2.38}_{-4.14}$
nonfid	$0.35^{+0.03}_{-0.05}$	$0.26^{+0.00}_{-0.01}$	$0.32^{+0.02}_{-0.03}$	$0.93^{+0.04}_{-0.08}$
nonres	$0.11^{+0.01}_{-0.02}$	$0.22^{+0.00}_{-0.00}$	$0.33^{+0.02}_{-0.03}$	$0.65^{+0.03}_{-0.05}$
Total signal	$11.25^{+0.85}_{-1.50}$	$12.22^{+0.22}_{-0.27}$	$31.19^{+1.59}_{-2.69}$	$54.65^{+2.45}_{-4.26}$
qqZZ	$13.25^{+1.06}_{-1.96}$	$33.13^{+1.80}_{-1.78}$	$38.70^{+2.41}_{-4.06}$	$85.07^{+4.59}_{-7.20}$
ggZZ	$1.89^{+0.22}_{-0.34}$	$3.90^{+0.46}_{-0.40}$	$3.95^{+0.44}_{-0.56}$	$9.74^{+1.08}_{-1.24}$
ZX	$4.34^{+1.20}_{-1.54}$	$14.23^{+6.49}_{-2.22}$	$17.16^{+3.27}_{-3.60}$	$35.73^{+7.61}_{-4.35}$
Sum of backgrounds	$19.48^{+1.47}_{-2.97}$	$51.26^{+7.65}_{-2.30}$	$59.80^{+3.89}_{-5.84}$	$130.54^{+9.38}_{-8.27}$
Total expected	$30.72^{+2.10}_{-4.29}$	$63.48^{+7.73}_{-2.36}$	$90.99^{+4.67}_{-8.03}$	$185.19^{+9.66}_{-11.91}$

H → ZZ Measurement