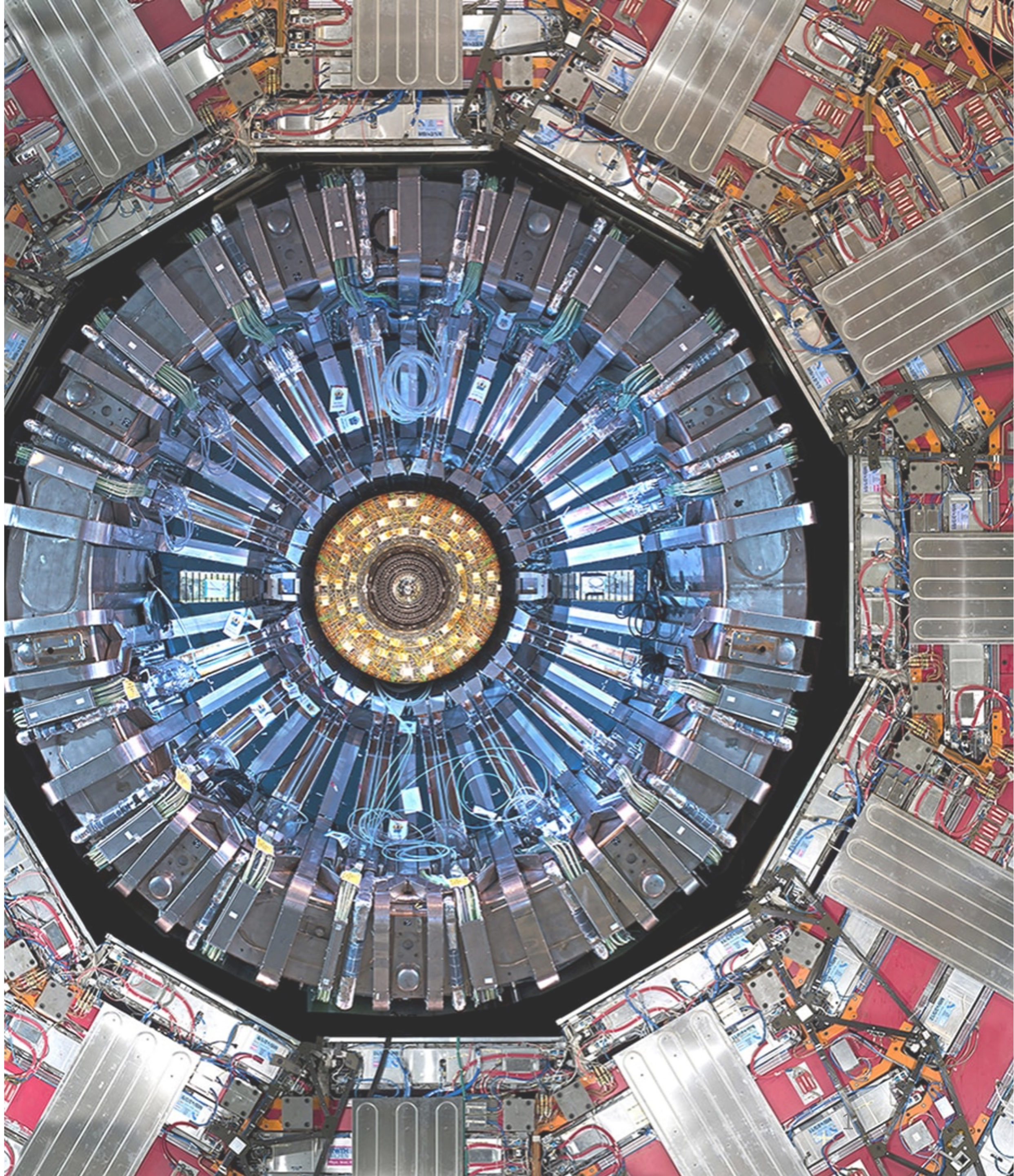
WW and HWW in Run 2 and Run 3

CPAN Days 2025

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

19/11/2024



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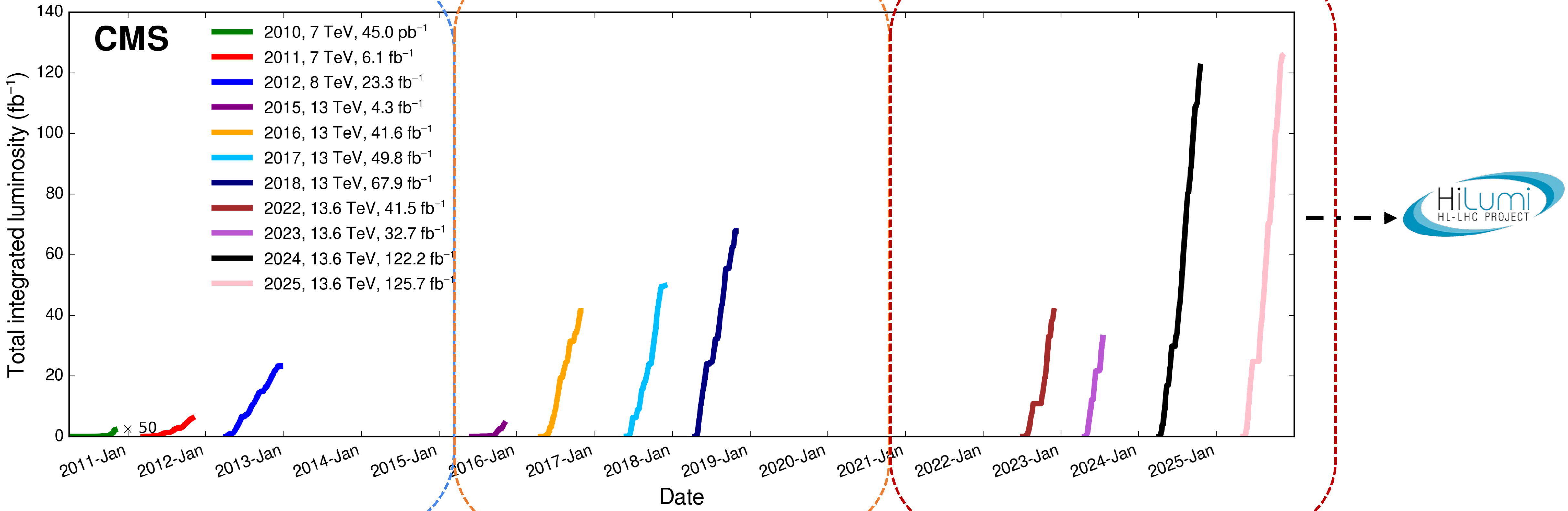
Introduction and motivation

Roadmap towards precision

Run-I
Higgs discovery

Run-II
Higgs couplings, κ_v, STXS, differential,…

Run-III
Prelude to the high-precision era

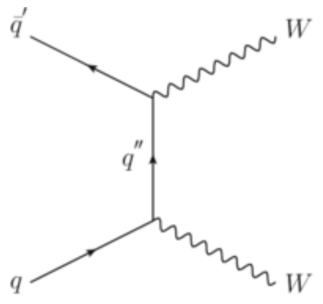


Introduction and motivation

Why do we measure WW/HWW final states?

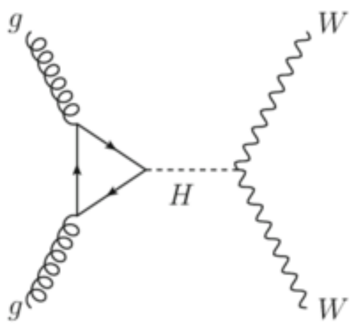
- The WW measurements provide information about the EWK boson self-couplings and the accuracy of perturbative QCD predictions
- The non-resonant WW production represents one of the largest backgrounds for $\mathrm{H} \rightarrow \mathrm{WW}$ measurements
- The Higgs decay to W boson is one of the flagships of CMS Higgs results

Non-resonant WW



- Large signal over background ratio
- Large cross-section
- High-precision analyses with Run-2 luminosity

$\mathrm{H} \rightarrow \mathrm{WW}$



- Challenging background control
- Second largest branching ratio
- From discovery to precision at the LHC era

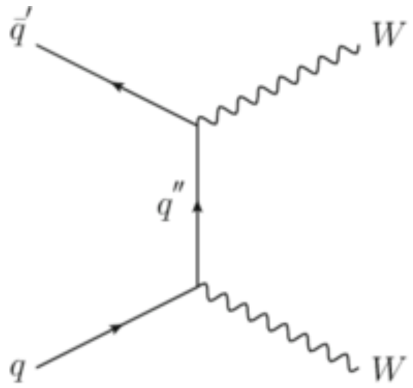
Non-resonant WW production

Measured from Run-1 to Run-3 (and even from LEP)

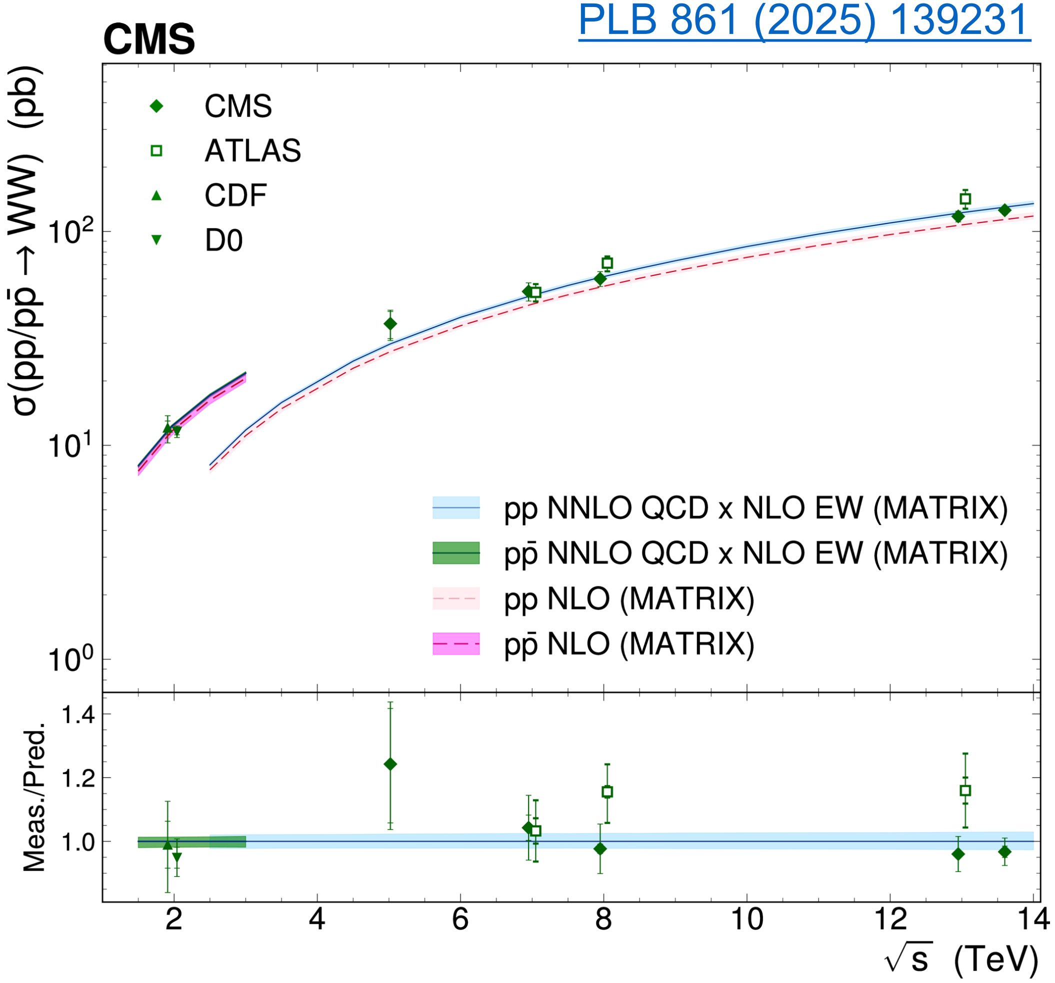
The non-resonant WW production is a key EWK di-boson process at the LHC

Interesting in its own, but also the main background for other searches

Precision at the order of 4-5%, with systematically limited results



PLB 861 (2025) 139231



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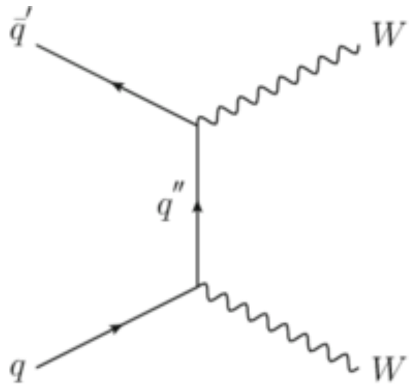

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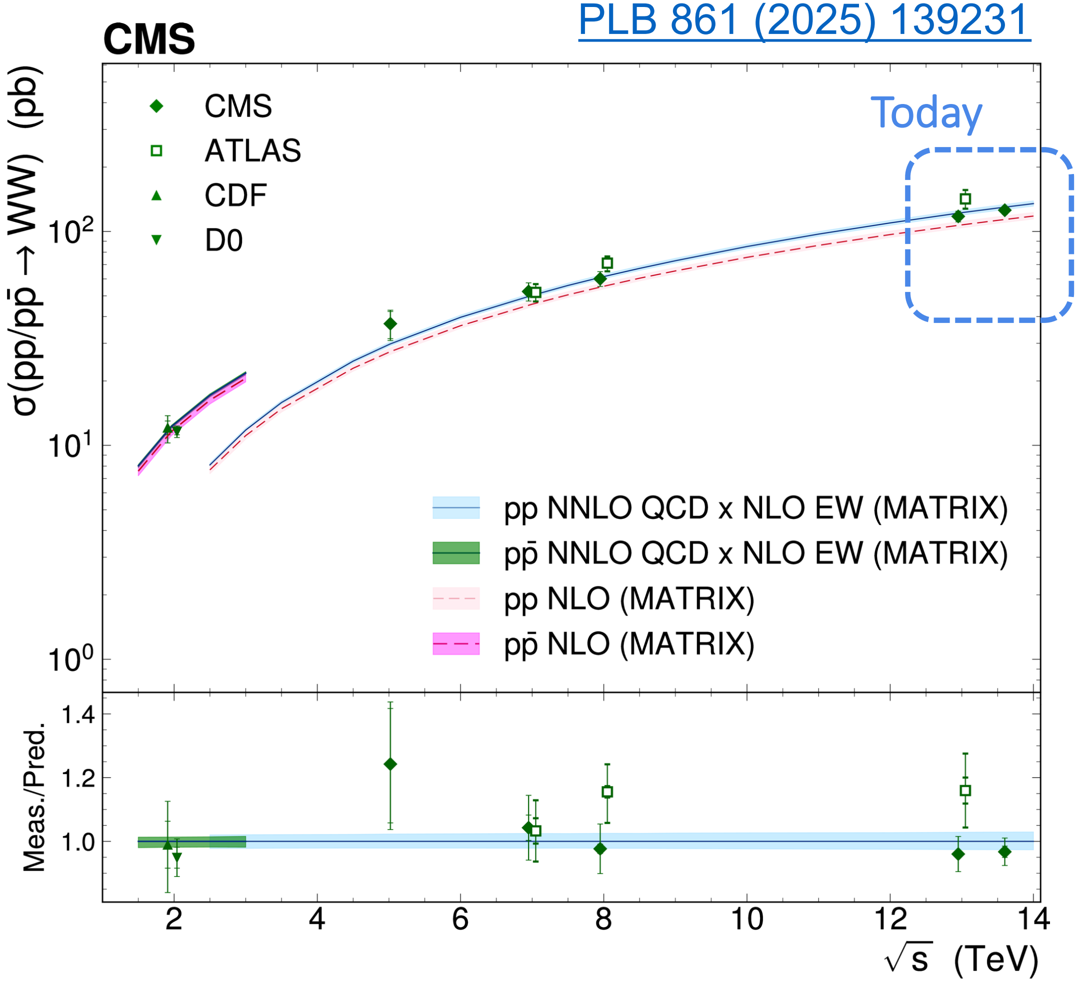


Non-resonant WW production

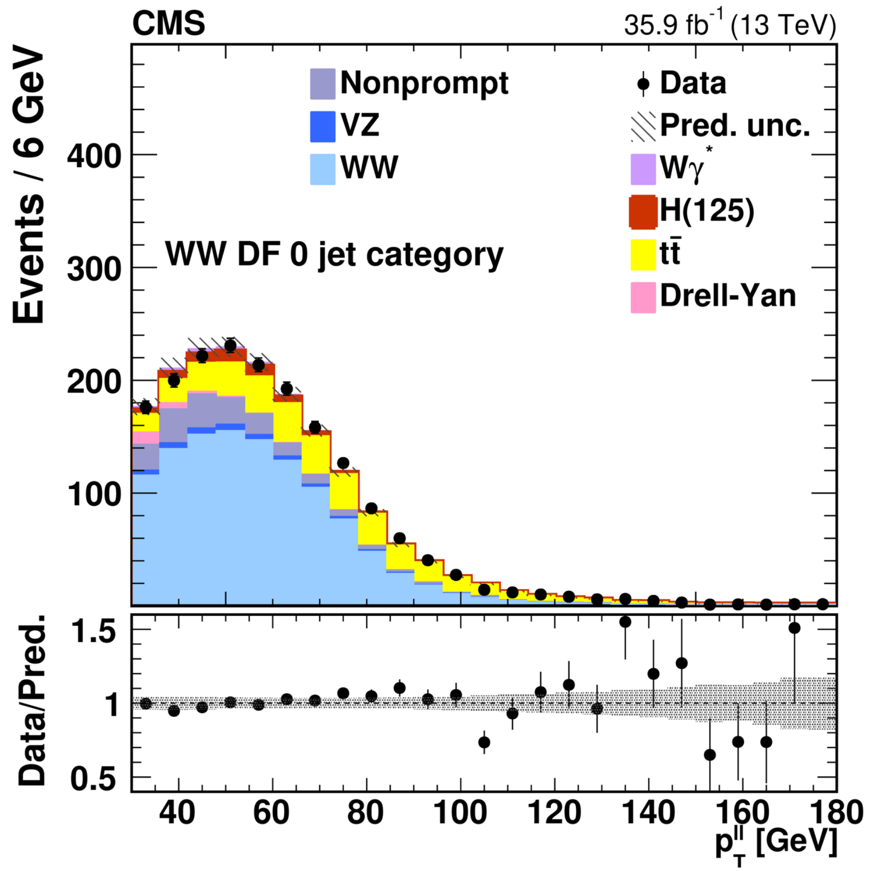
Run-2 result

- Inclusive and fiducial cross section measurements
- Data from 2016 only (systematically dominated) at $\sqrt{s} = 13$ TeV
- Interpretation in terms of Anomalous Triple Gauge couplings

Analysis strategy

- Main final state targeting $\mathbf{W^+W^- \to \mu^\pm e^\mp \nu_\mu \nu_e}$ (but also same-flavour)
- Relatively clean final state, with neutrinos as missing transverse energy
- Main background component from top quark pair production, rejected using b-jet taggers
- Cross section as a function of the number of jets

PRD 102 (2020) 092001



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The purity is reduced with the number of jets

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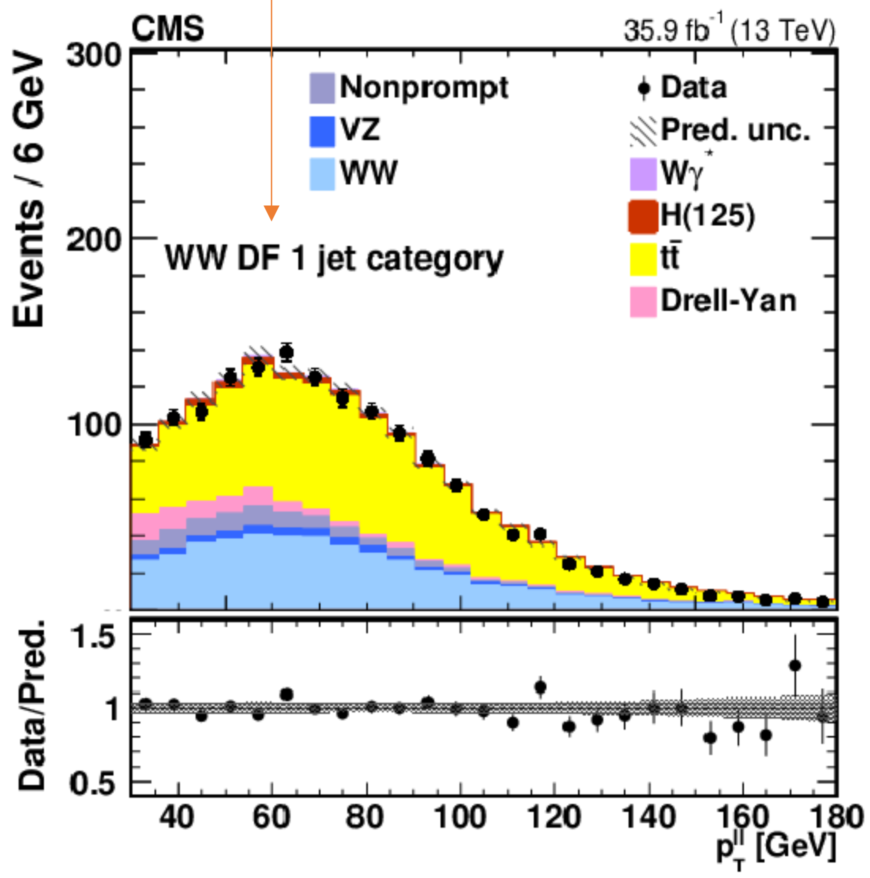


Non-resonant WW production

Run-2 result

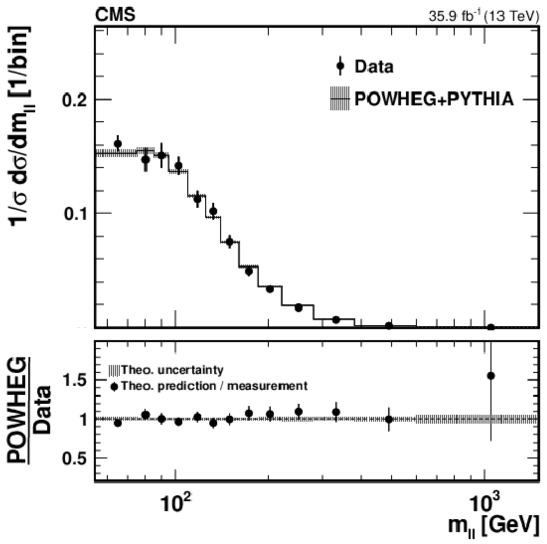
[PRD 102 (2020) 092001](PRD 102 (2020) 092001)

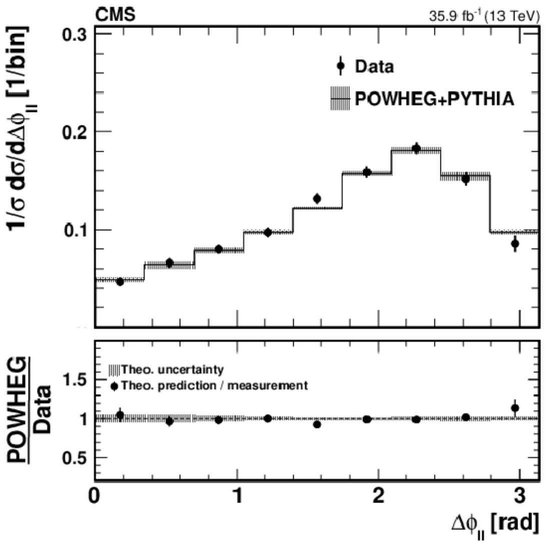
$$\boldsymbol{\sigma^{tot} = 117.6 \pm 6.8\ \mathrm{pb}}$$

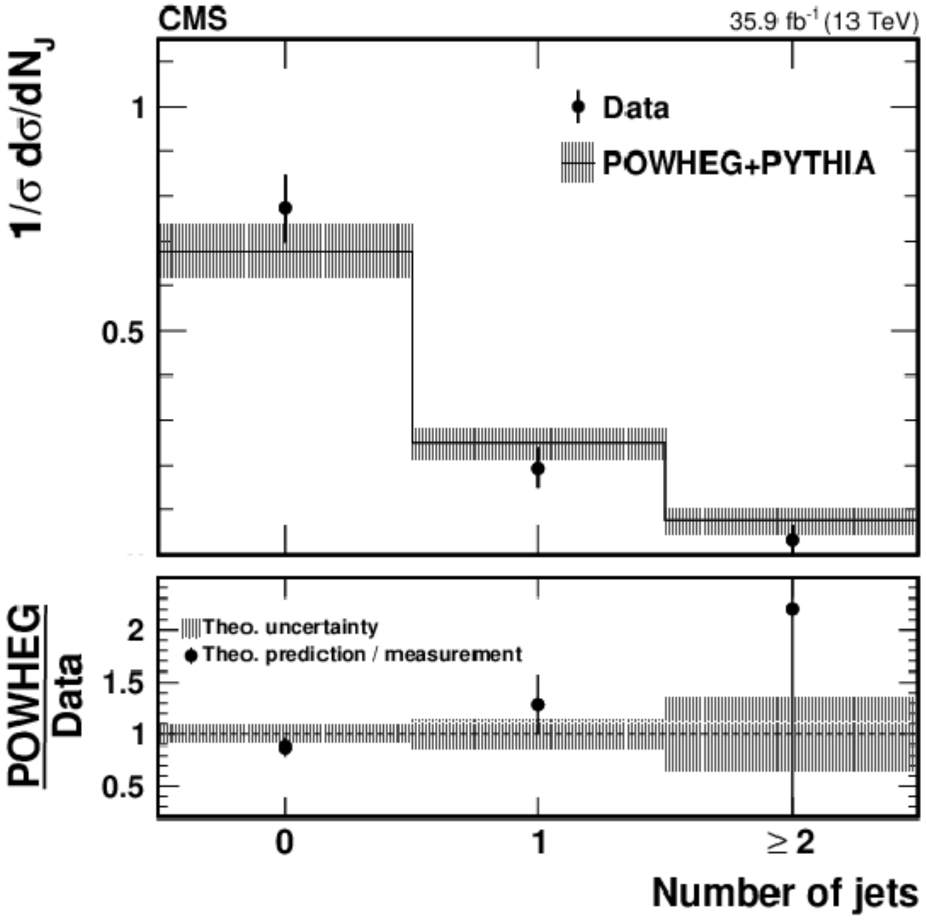
$$\sigma^{tot} = 117.6 \pm 1.4\ (stat) \pm 5.5(syst) \pm 1.9(theo) \pm 3.2(lumi)$$

- Results in good agreement with the SM NNLO expectation (118.8 ± 3.6 pb)

- Uncertainties already at 8% level using first part of Run-II







Non-resonant WW production

Run-3 result

$$\sigma^{tot} = 125.7 \pm 2.3\ (stat) \pm 4.8(syst) \pm 1.8(lumi)$$

- First analysis published using the full 2022 CMS dataset
- Requires excellent control of several objects: muon, electrons, jets, MET,…
- Uncertainty at 4.4% level using only the 2022 dataset

Analysis strategy

- Similar analysis strategy to Run-II analysis
- Target a different flavour leptonic decay channel
- Several control regions to normalize the background contributions from data

Inclusive in number of jets!

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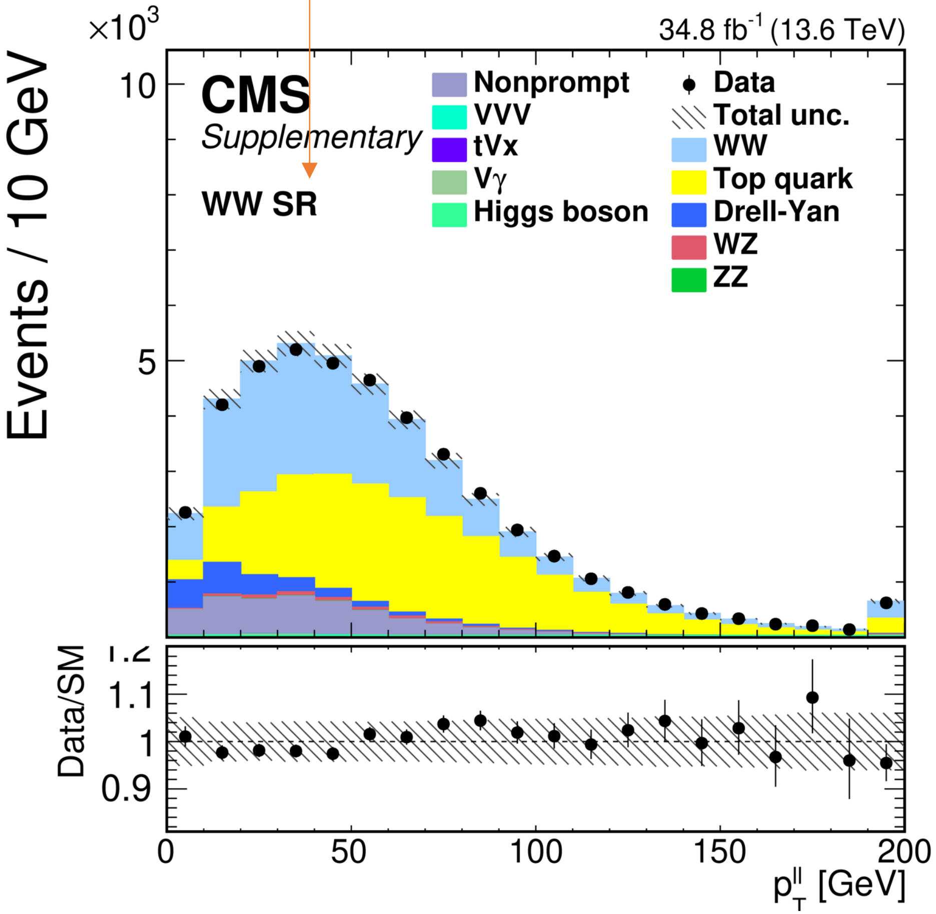

Non-resonant WW production

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Run-3 result

The analysis includes the measurement in the 2-jet signal region and provides results as a function of different generators. For the first time, including as well the Powheg-MiNNLO NNLOPS prediction for comparison

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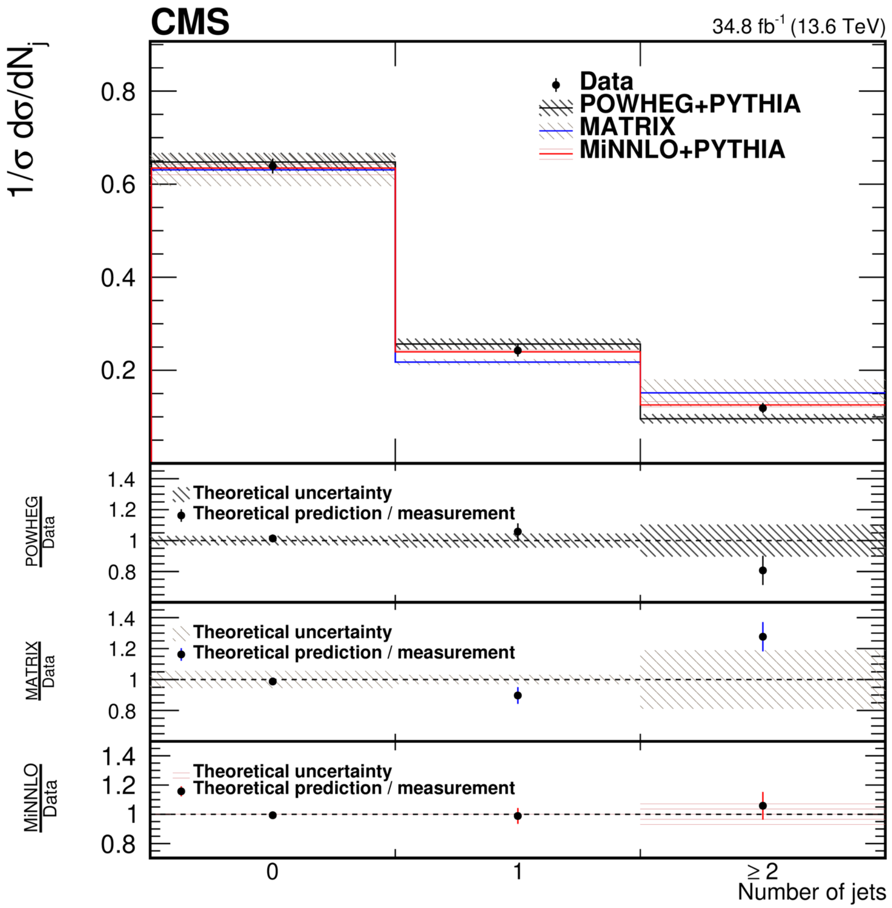
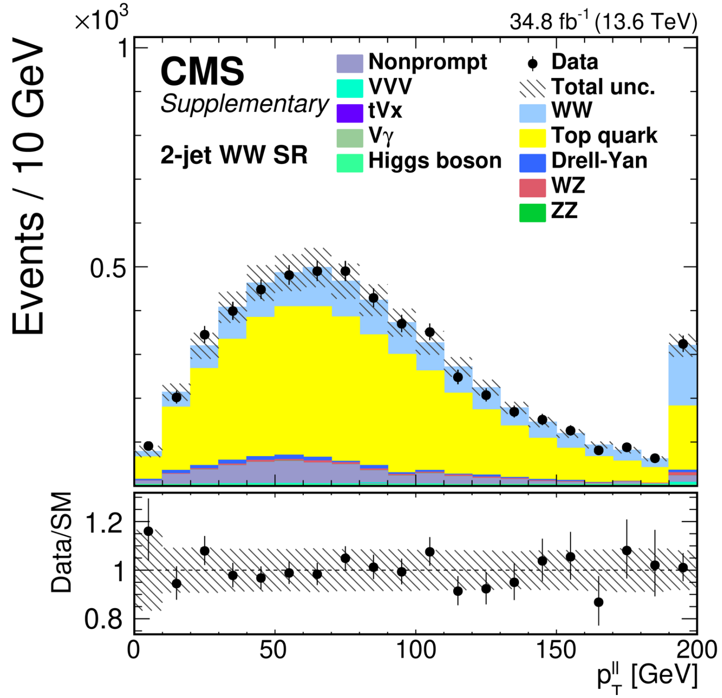
The integrated luminosity is lower than for the 2016 analysis:

Run-II: 35.9 fb^{-1}
Run-III: 34.6 fb^{-1}

Improved reconstruction, identification, and selections make it possible to measure the 2-jet category with less data.





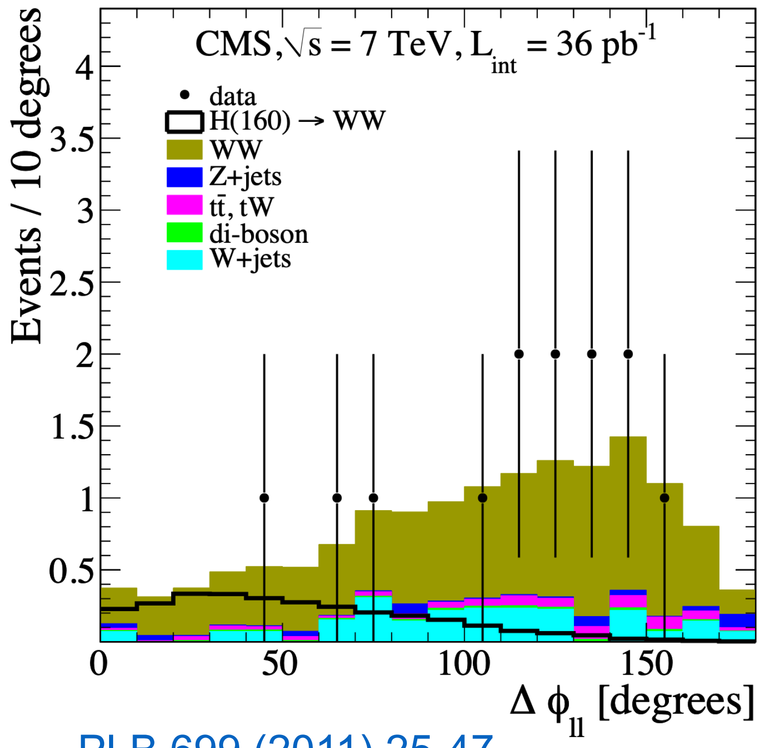
Higgs to WW measurements

From discovery to precision

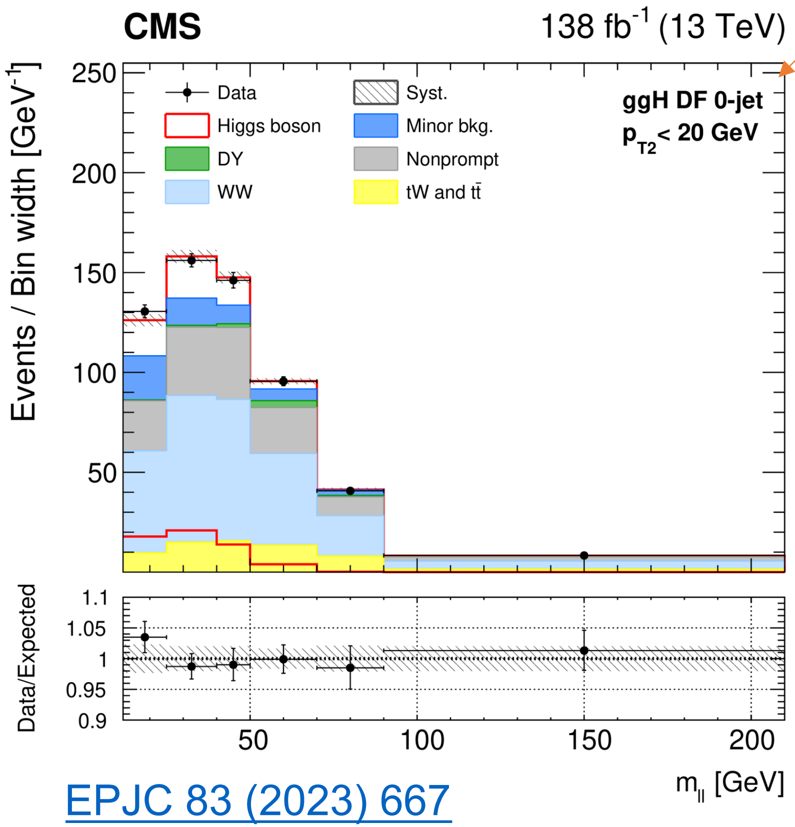
Over the past 10 years, the situation has evolved from a mild excess (in HWW) to systematically limited analyses, with an uncertainty of approximately 10%.

Less than 10 years

Only one category



[PLB 699 (2011) 25-47]

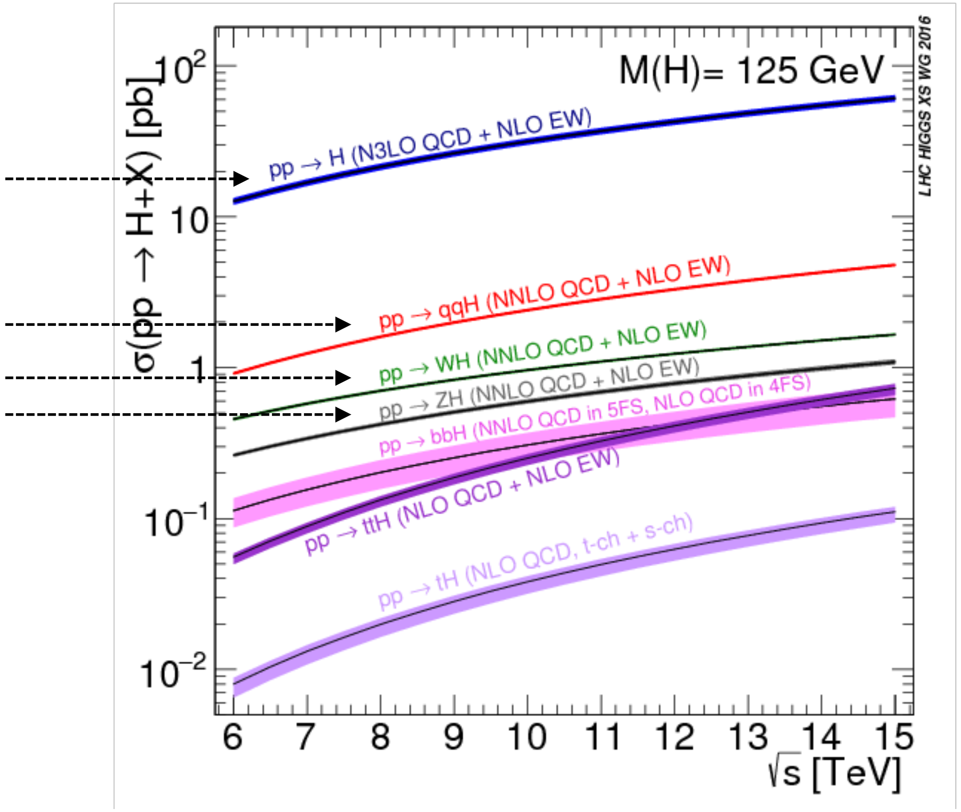


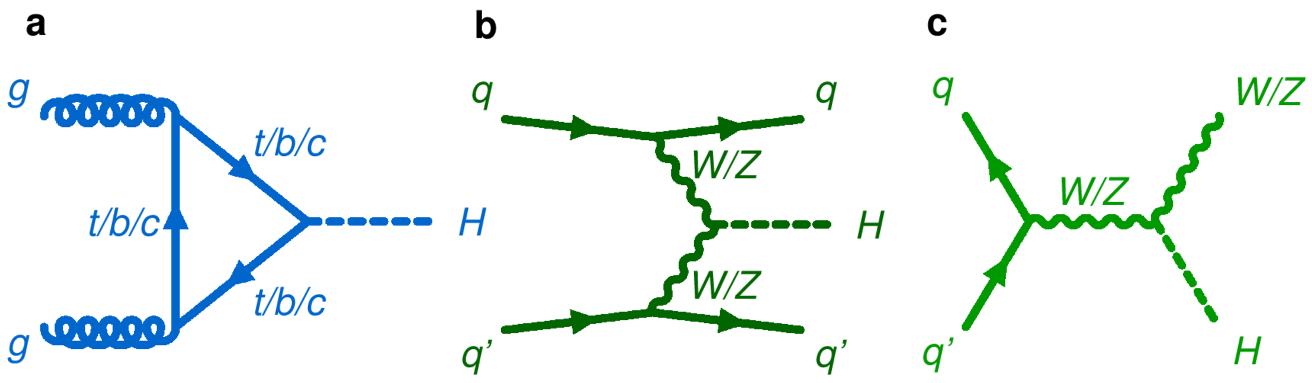
[EPJC 83 (2023) 667]

Higgs to WW measurements

Run-2 HWW result

- Ambitious analysis targeting the main Higgs production modes
- Target final state with at least two leptons, ggF and VBF dominated by $H \to W^+W^- \to \mu^\pm e^\mp \nu_\mu \nu_e$
- Inclusive and differential cross sections in the STXS framework





Some bins are merged due to the lack of statistics

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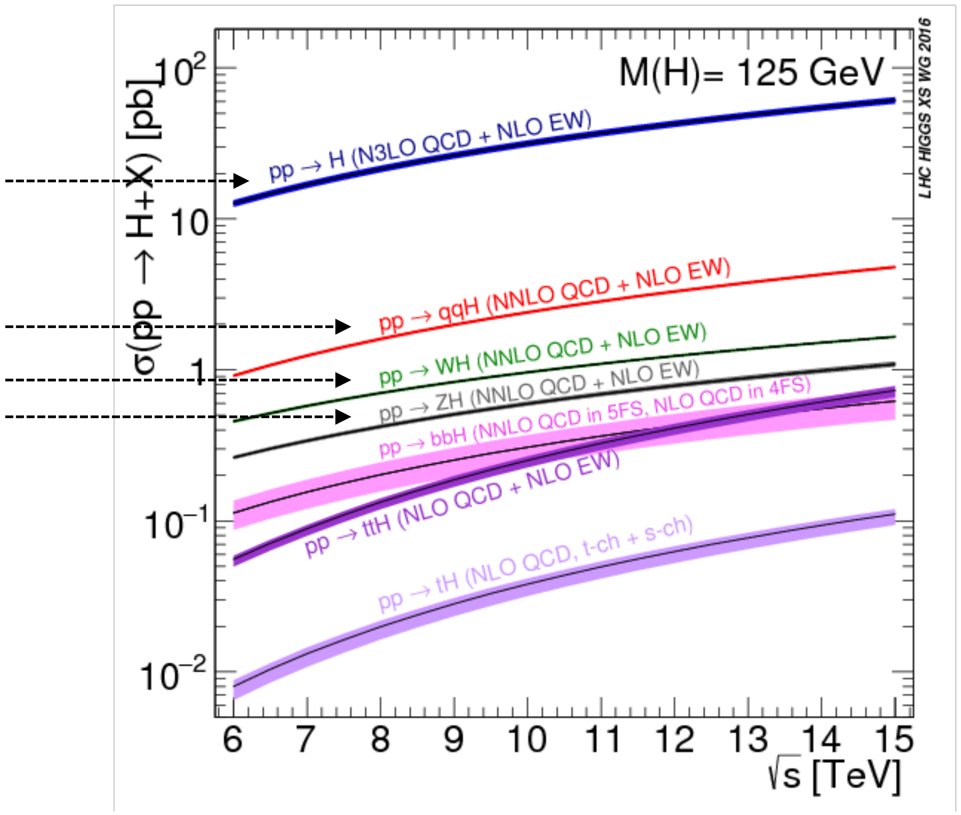

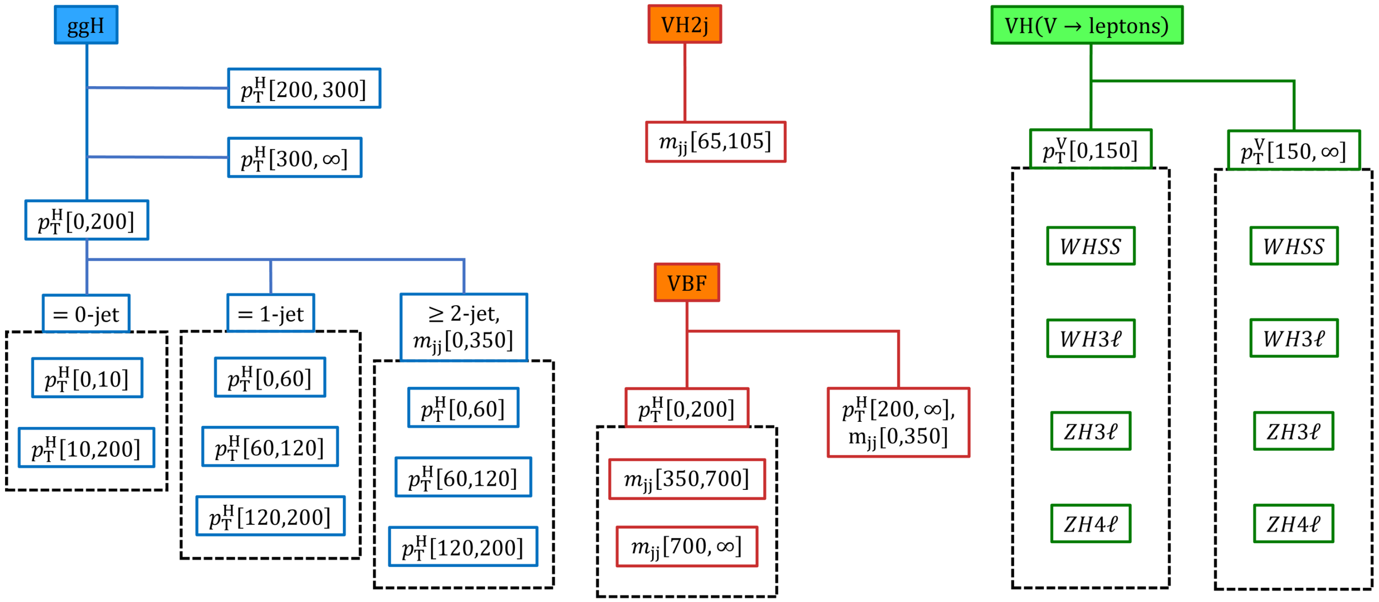

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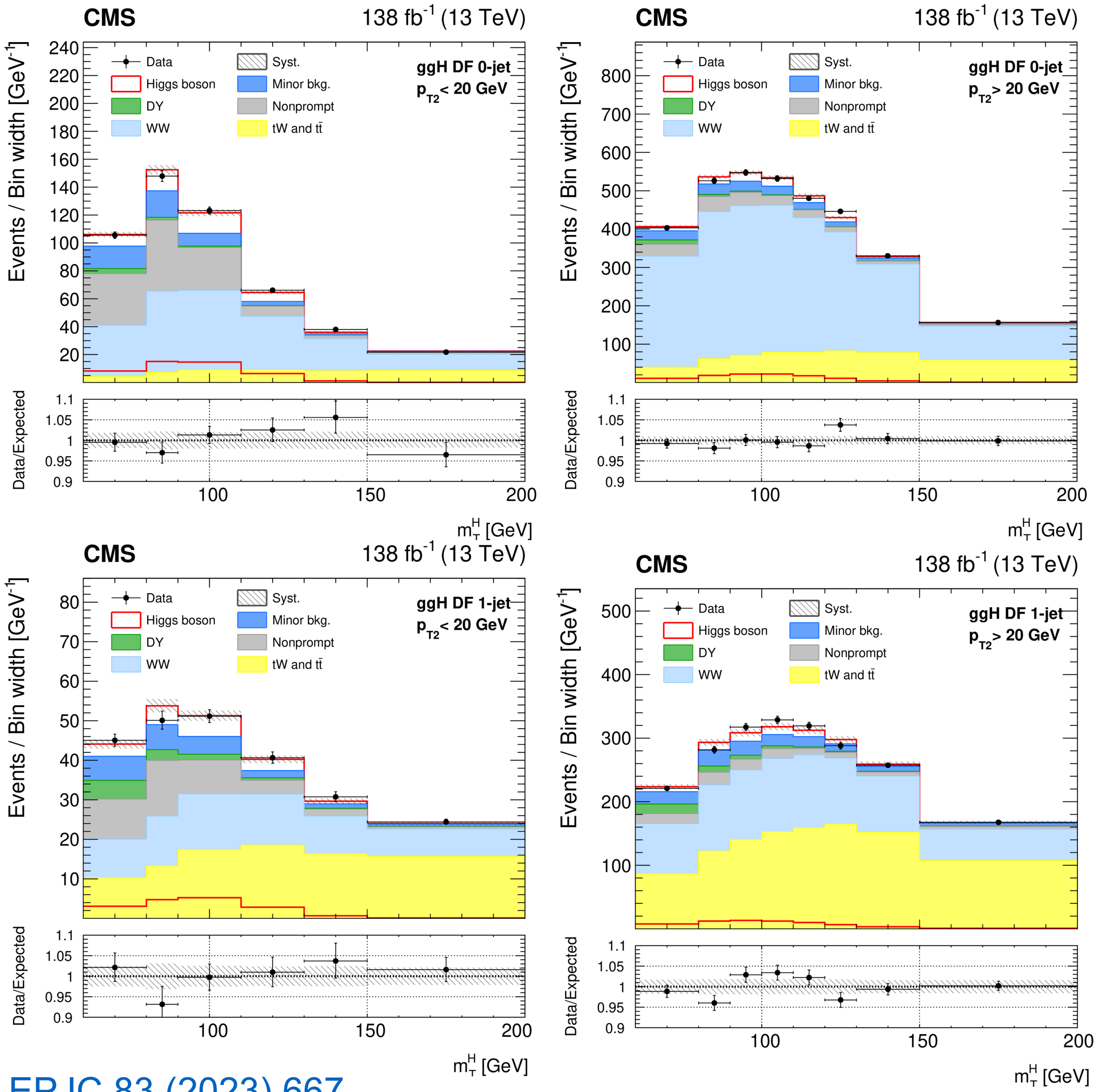
Higgs to WW measurements

Run-2 HWW result

- Full Run-II luminosity employed
- Data-driven techniques to estimate major backgrounds

Gluon fusion production

- Already dominated by systematics
- Categorized by $N_{jet}, p_T^{lep_2}$ to enhance sensitivity
- Fit performed to a 2D distribution of m_{ll} and m_T^H



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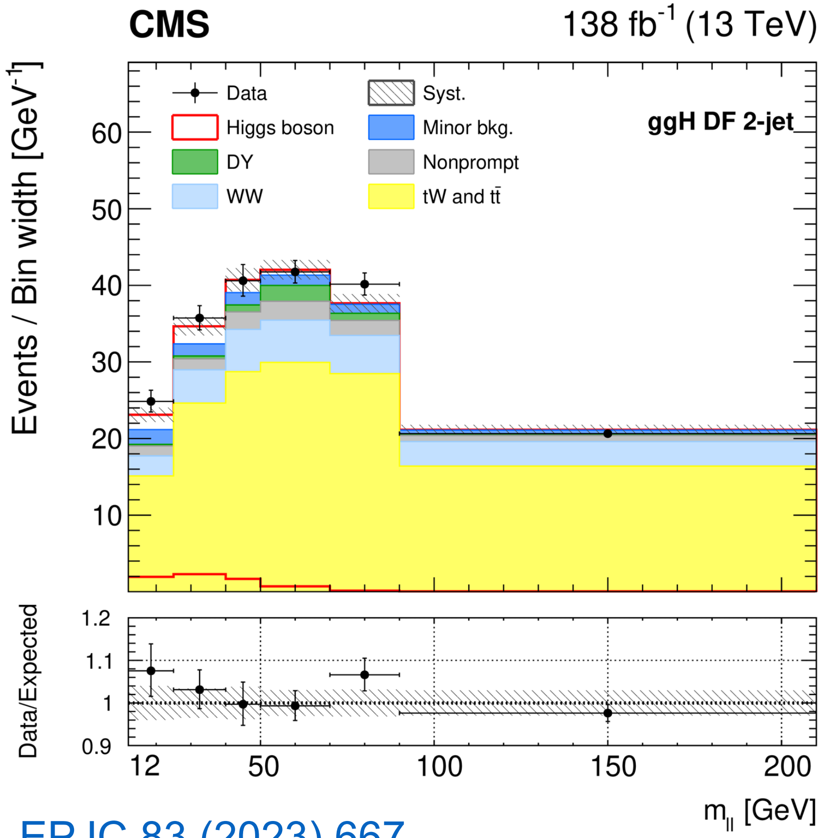

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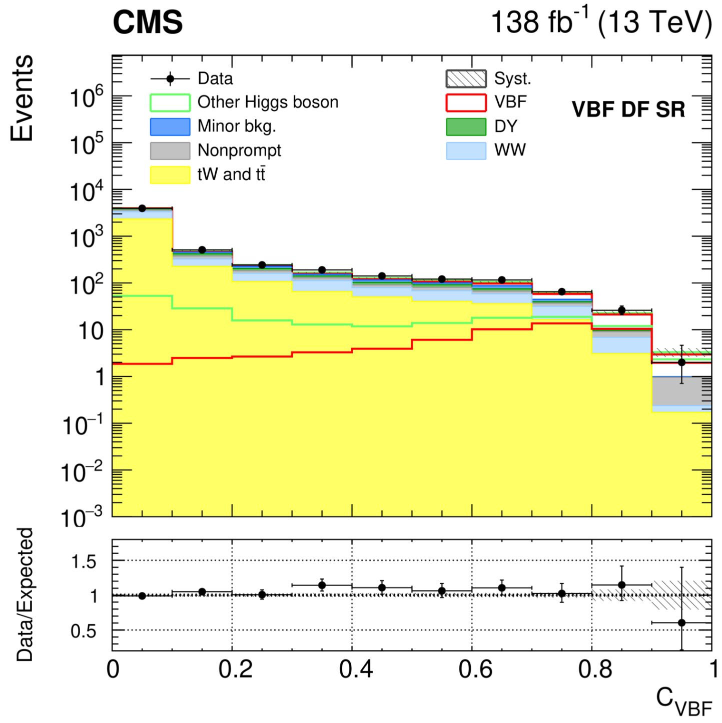
Higgs to WW measurements

Run-2 HWW result

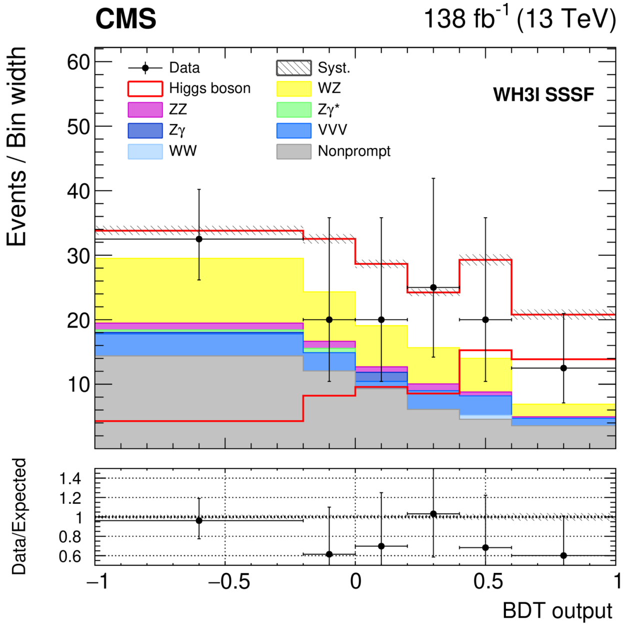
Vector boson fusion production

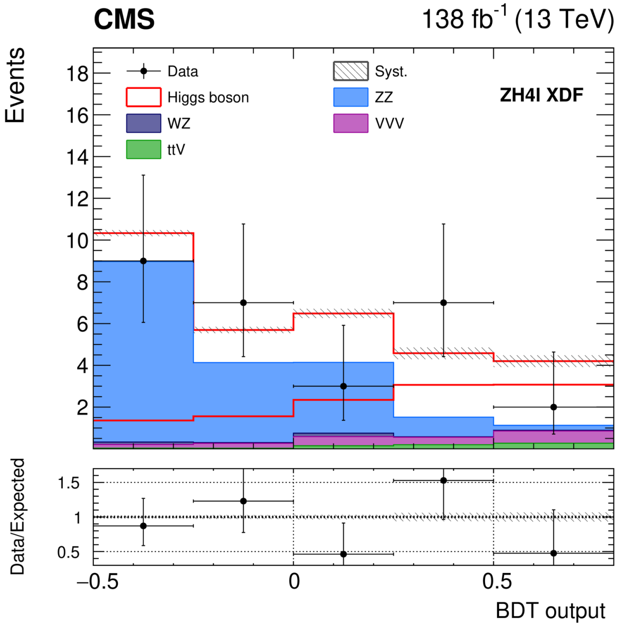
- Dominated by the statistics
- DNN to extract the signal
- The fit is performed simultaneously for all regions



Vector boson associated production

- Several categories depending on vector boson decay
- At least two leptons in the final state
- Extensive use of MVAs per category
- Very limited by the statistics





EPJC 83 (2023) 667

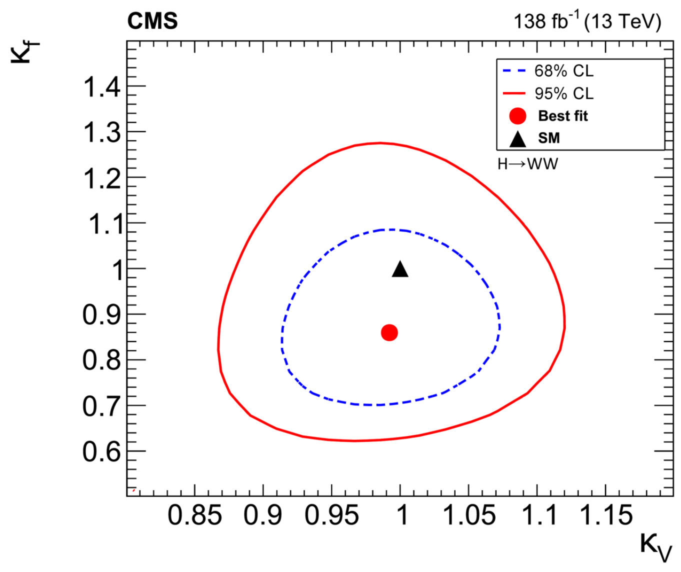
Higgs to WW measurements

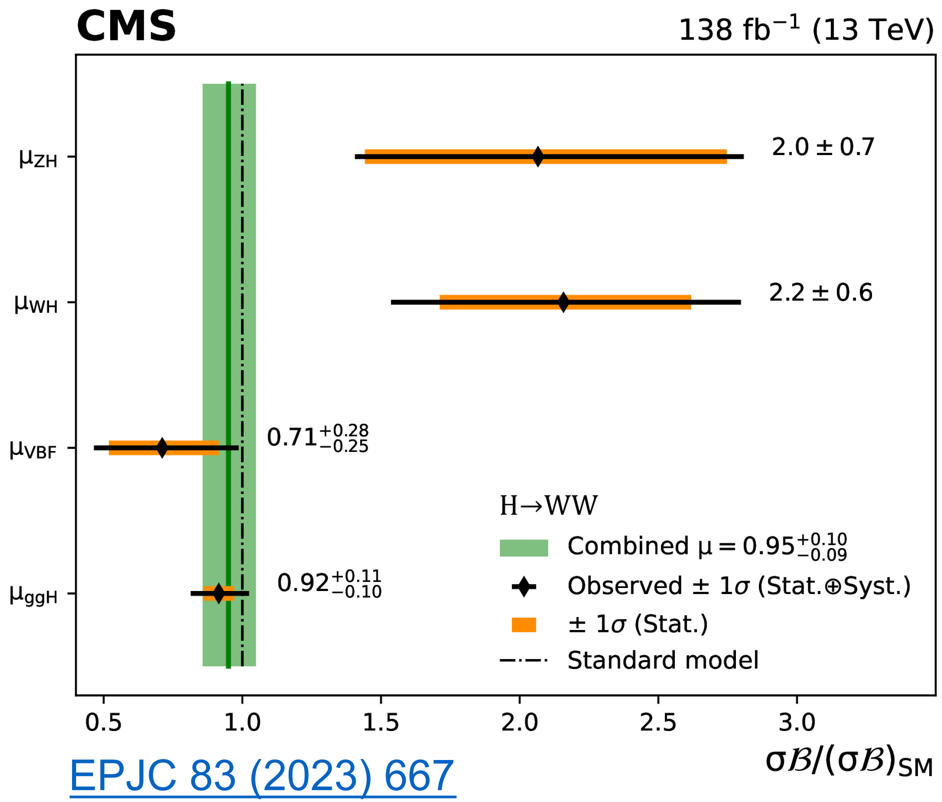
Run-2 HWW result

- Good agreement with SM prediction

$$\mu = \sigma/\sigma_{SM} = 0.95 \pm 0.05\ (stat) \pm 0.08(syst)$$

- VBF and VH dominated by statistics, to be improved with Run-III data





EPJC 83 (2023) 667

Higgs to WW measurements

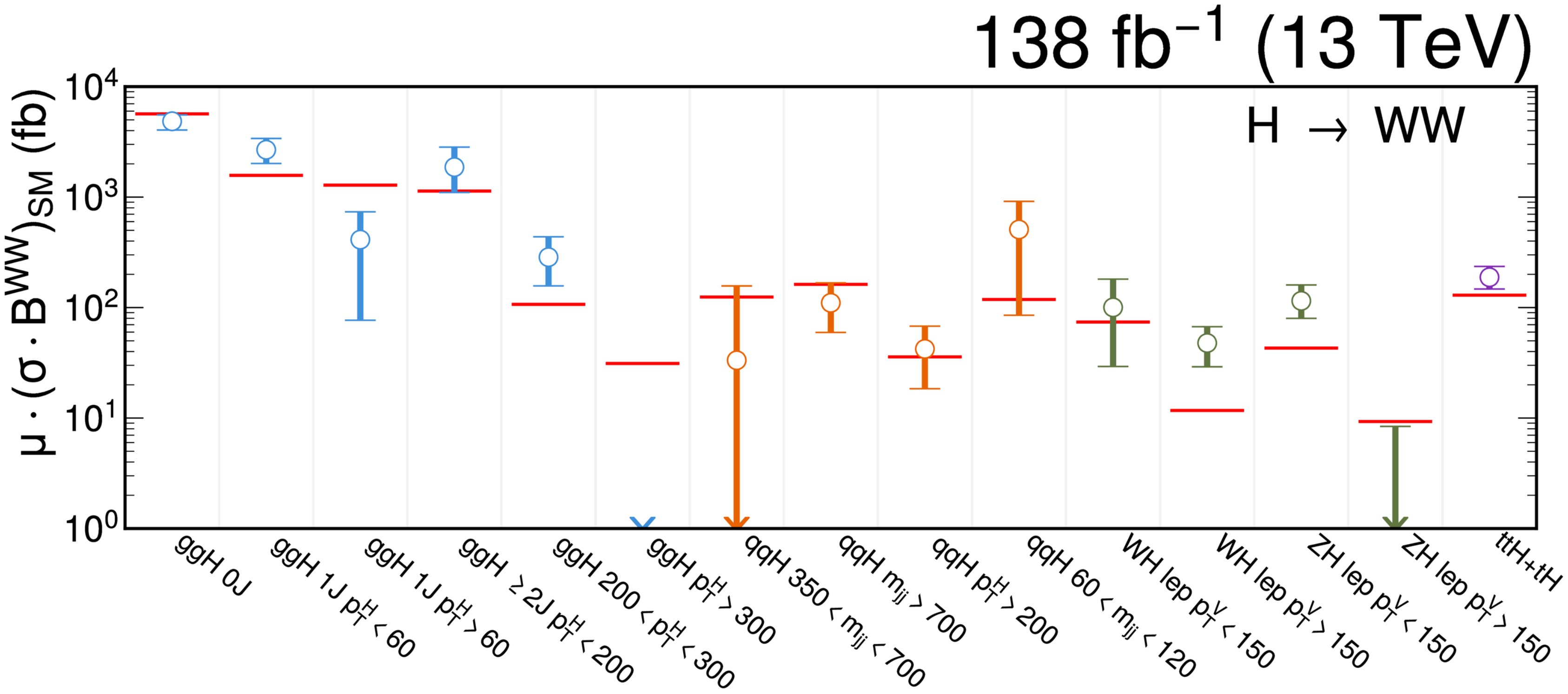
Run-2 HWW result

- Good agreement with SM prediction

$$\mu = \sigma/\sigma_{SM} = 0.95 \pm 0.05\ (stat) \pm 0.08(syst)$$

- Impressive granularity of STXS results

Nature 607 (2022) 60

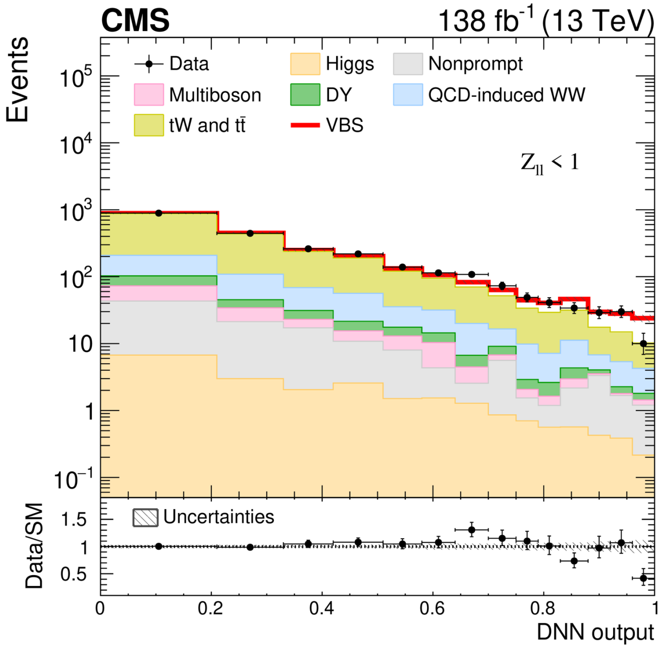


Other HWW/WW measurements (Run-II)

First observation of VBS W+W- production

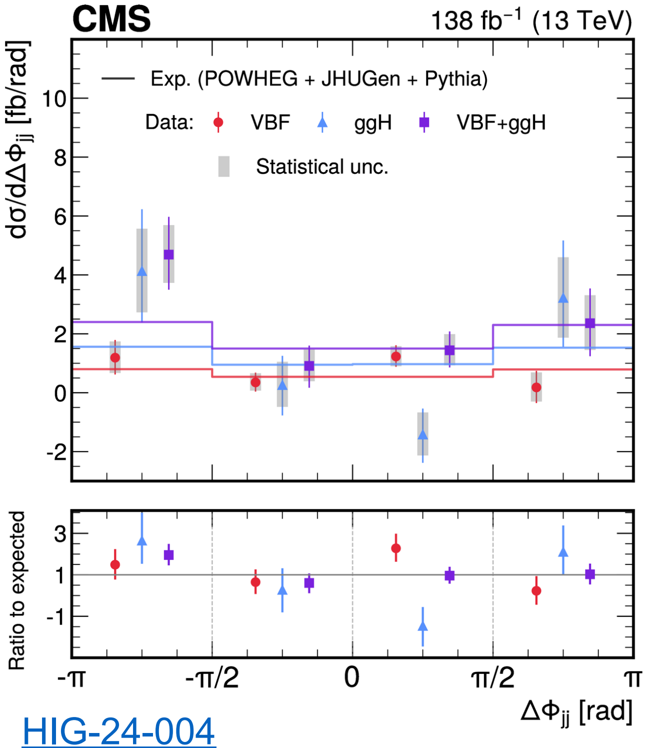
- First observation of VBS W^+W^- production by the CMS experiment
- DNN to improve the signal extraction
- Observed significance of 5.6

PLB 841 (2023) 137495



Model-independent VBF differential measurement

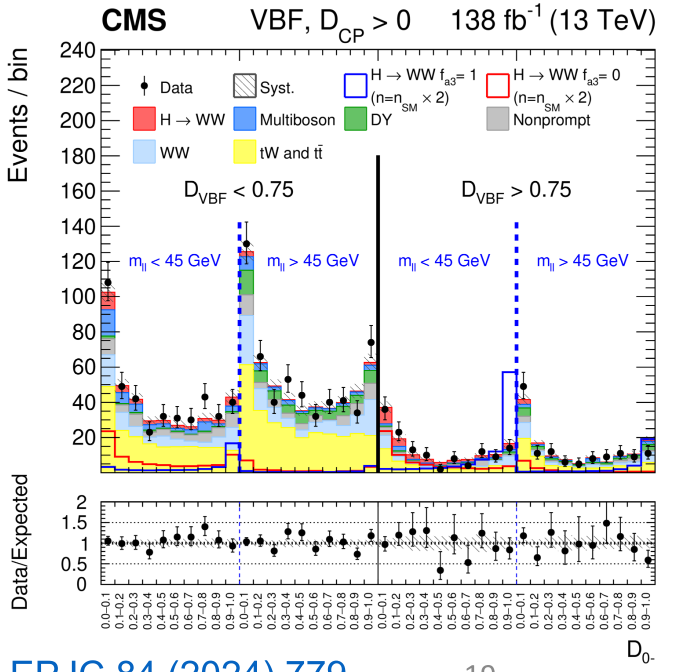
- Exploit an Adversarial-NN to preserve model independence
- Targets $\Delta\phi_{jj}$ differential measurement



HIG-24-004

Anomalous Higgs couplings from WW decay mode

- Include constraint on possible CP-violating effects
- Targets 2-jet final state
- Makes use of Matrix Element techniques



EPJC 84 (2024) 779

Conclusions and future

- So far, no significant deviations of the SM predictions are found
- There are a lot of analyses still dominated by the statistical uncertainties
- New ideas/proposals to test the SM: polarization, EFT, …
- The picture will greatly improve with Run-3 data
- And… a complete one to be achieved at the HL-LHC

Backup

W^+W^- Measurement

- **First Run 3 di-boson measurement** with the CMS detector

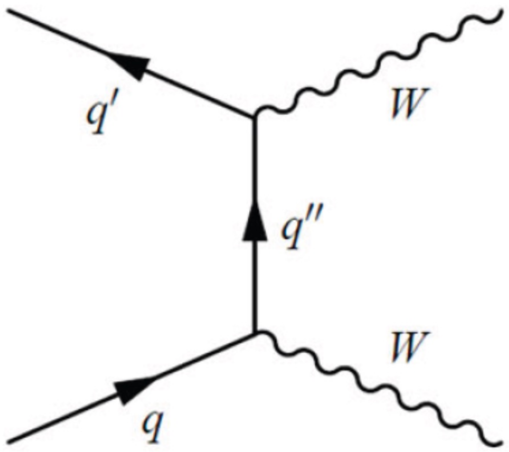
- It demonstrates the capacity of CMS to release analysis with complex topologies: **Muons, electrons, jets, b-jets, MET**

- **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

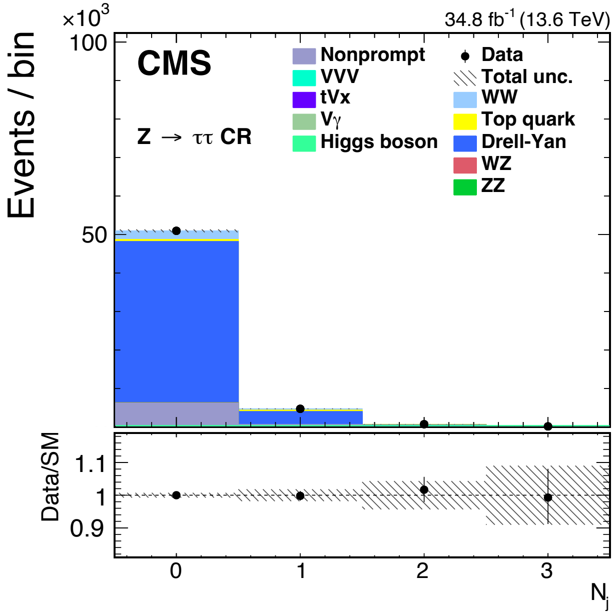
Several updates with respect to the 2016 analysis

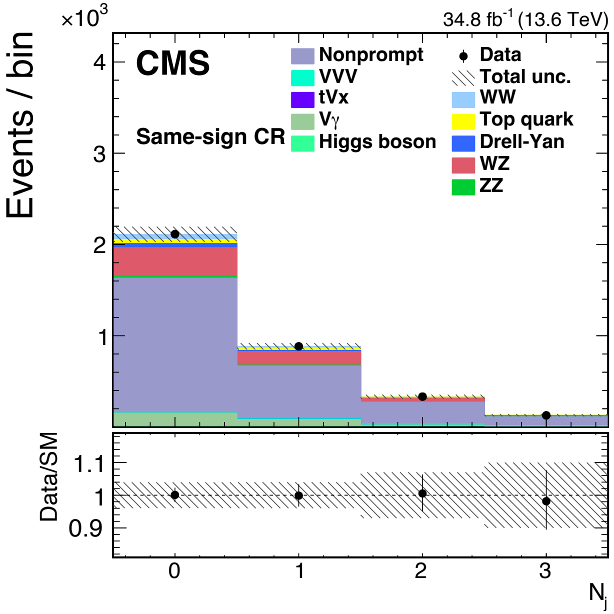
- More **control regions** introduced in the fit: **Top (2 regions), DY, Same-sign, WZ, and ZZ**
- **Object optimization** → lower uncertainties

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	





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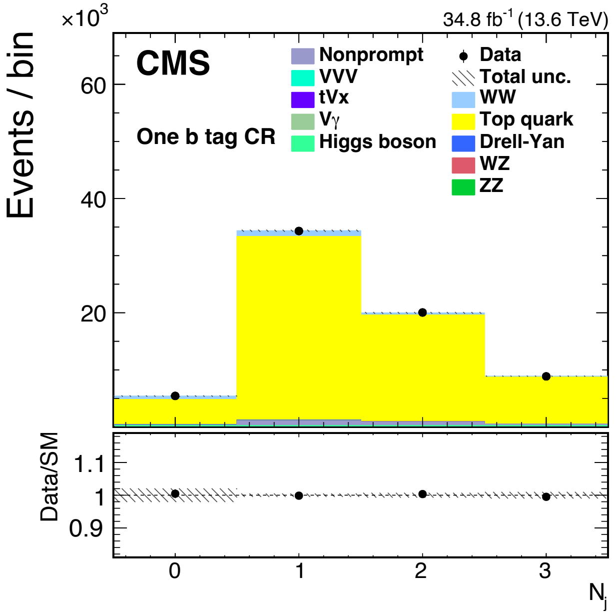

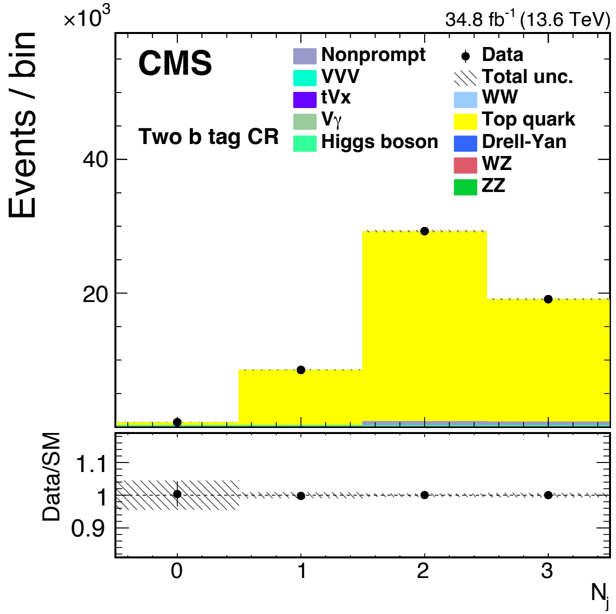

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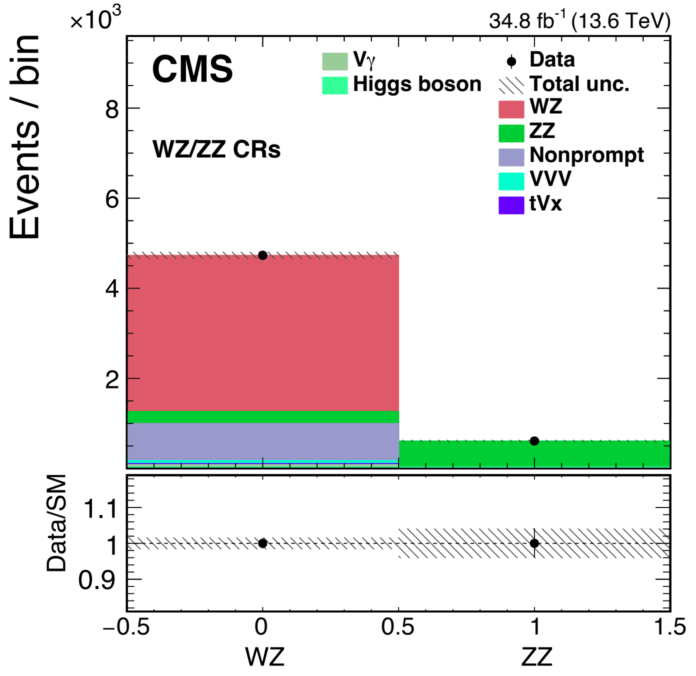

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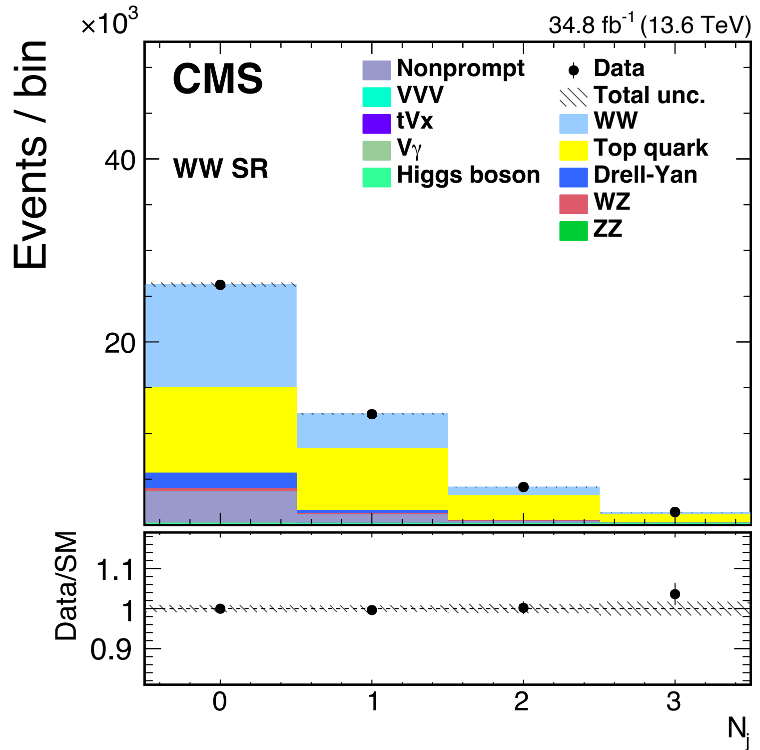
Number of b-tagged jets	0	

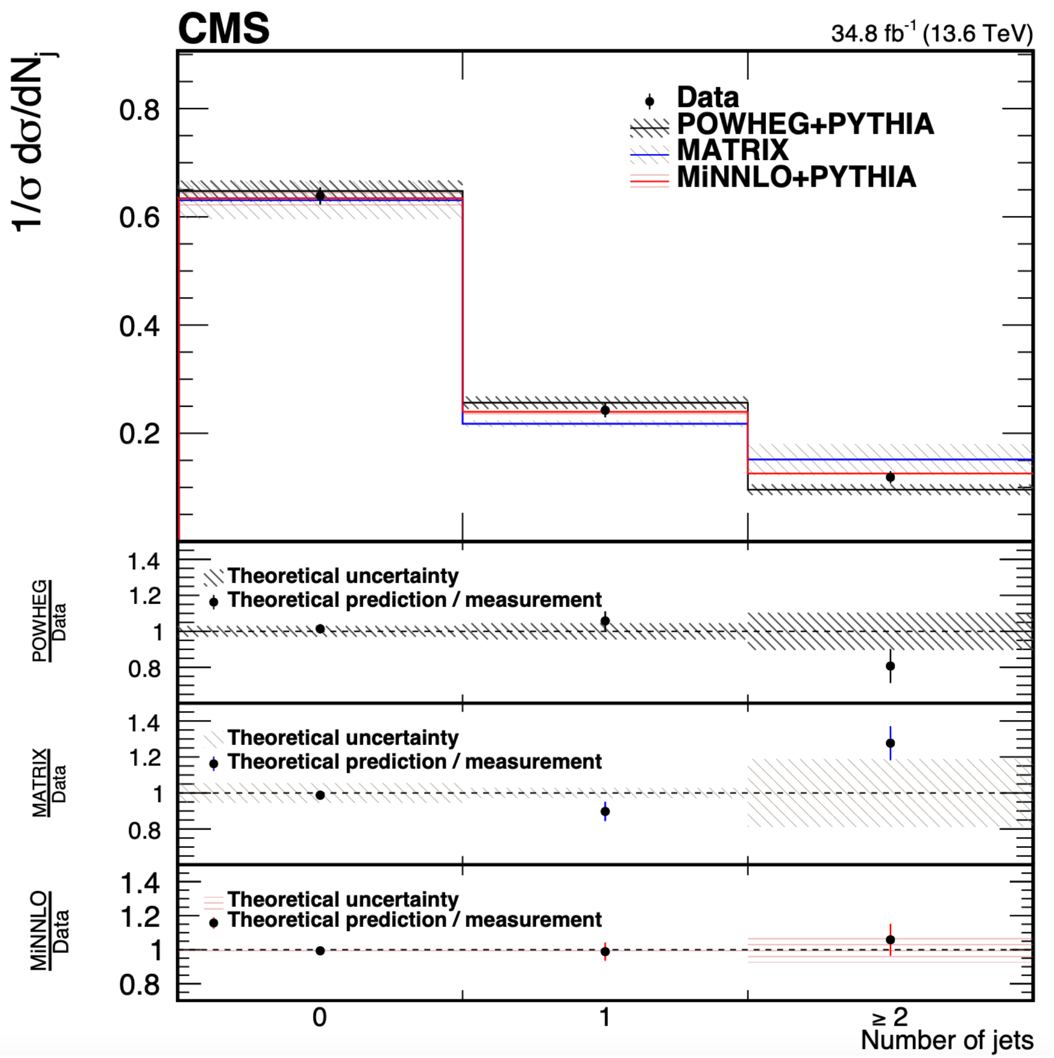
W^+W^- Measurement

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

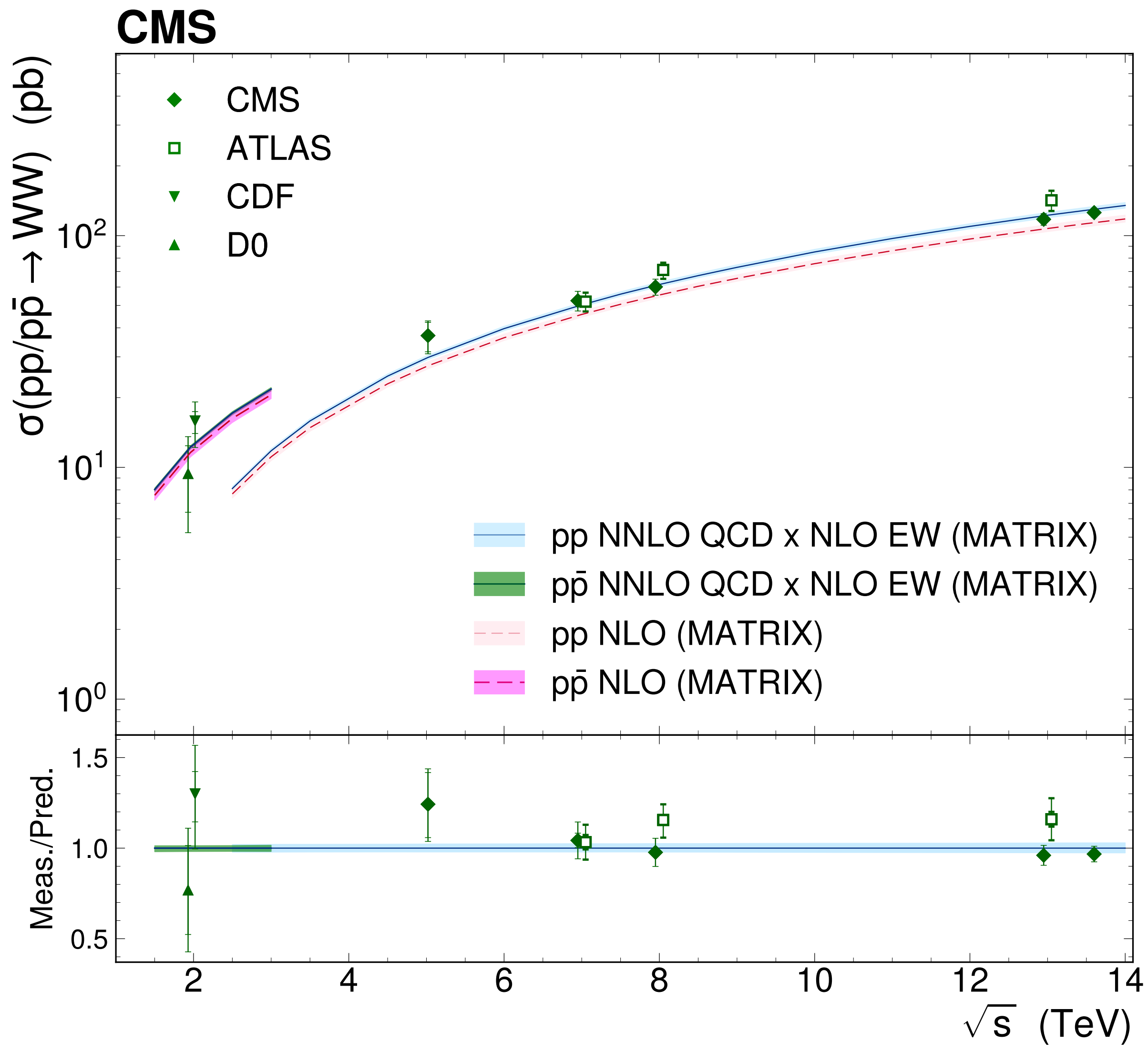
Inclusive result

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

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



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

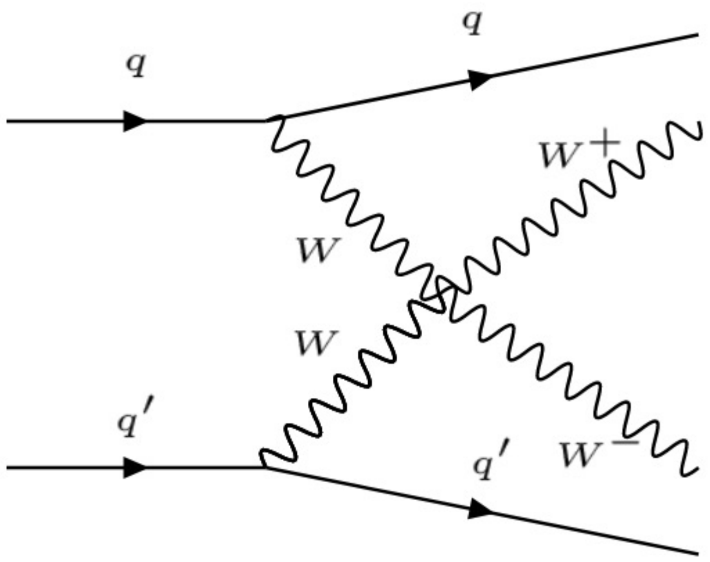
Uncertainty source	$\Delta\mu$
Integrated luminosity	0.014
Lepton experimental	0.019
Jet experimental	0.008
b tagging	0.012
Nonprompt background	0.010
Limited sample size	0.017
Background normalization	0.018
Theory	0.011
Statistical	0.018
Total	0.044

[SMP-21-001] VBS W^+W^- fully leptonic

First observation of VBS W^+W^- using the full Run 2 dataset collected by the CMS experiment at 13 TeV of pp collisions

Several categorizations in signal and control regions to fit the data:

- $e^\pm\mu^\mp$, $\mu^+\mu^-$, and e^+e^- signal regions further categorized as a function of Zeppenfeld (Z_{ll}) variable
- Normalization of Top and DY backgrounds from control region designed per lepton flavour
- QCD WW normalization included as well in the fit
- DNN used to separate signal from background



Predictions:

- Signal at LO using Madgraph
- Backgrounds at LO and NLO using Powheg

[SMP-21-001] VBS W^+W^- fully leptonic

First observation of VBS W^+W^- using the full Run 2 dataset collected by the CMS experiment at 13 TeV of pp collisions

Systematic and statistical uncertainties almost at same level. **Significance of 5.6** (5.2) standard deviations

$$\sigma_{Inc} = 99 \pm 20\ (89 \pm 5)\ \text{fb}$$

$$\sigma_{Fid} = 10.2 \pm 2.0\ (9.1 \pm 0.6)\ \text{fb}$$

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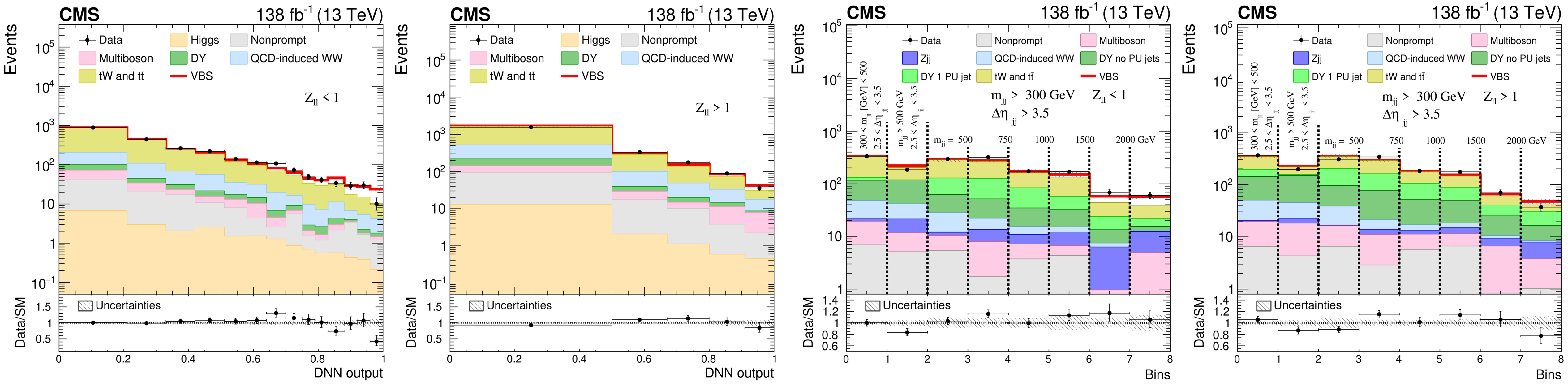
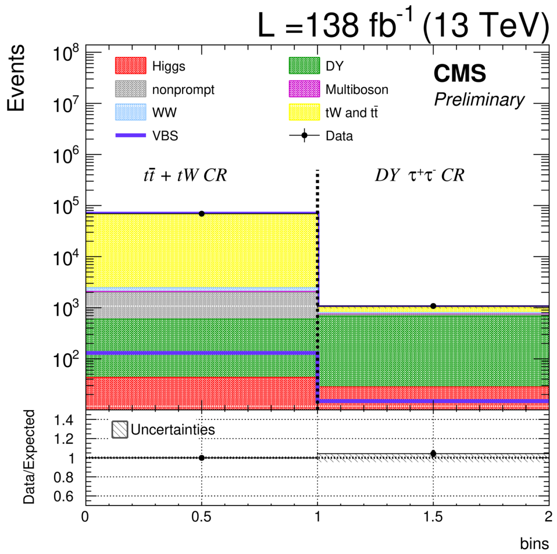
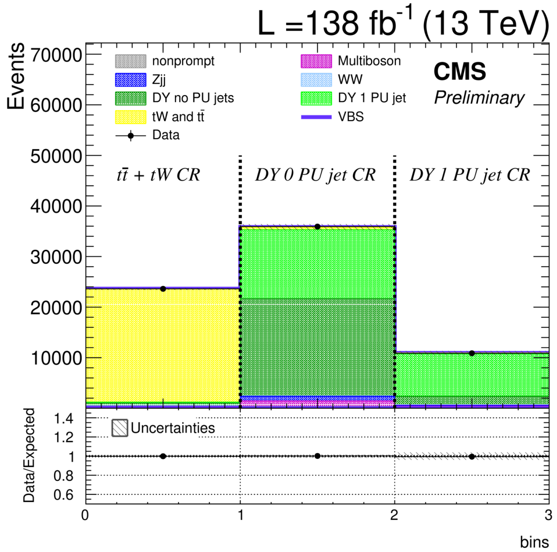


[SMP-21-001] VBS W^+W^- fully leptonic

The most impactful theoretical uncertainties are those corresponding to the choice of the QCD renormalization and factorization scales





Objects	Requirements
Leptons	$e\mu, ee, \mu\mu$ final state, opposite charge $p_T^\ell = p_T^{bare\,\ell} + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell,\gamma_i) < 0.1$ $p_T^{\ell_1} > 25\,\text{GeV}$, $p_T^{\ell_2} > 13\,\text{GeV}$, $p_T^{\ell_3} < 10\,\text{GeV}$ $\lvert\eta\rvert < 2.5$ $p_{T\ell\ell} > 30\,\text{GeV}$, $m_{\ell\ell} > 50\,\text{GeV}$
Jets	$p_T^j > 30\,\text{GeV}$ $\Delta R(j,\ell) > 0.4$ At least 2 jets, no b jets $\lvert\eta\rvert < 4.7$ $m_{jj} > 300\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$
MET	$p_T^{miss} > 20\,\text{GeV}$

Uncertainty source	Impact
QCD-induced W^+W^- normalization	5.3%
$t\bar{t}$ QCD scale	5.1%
QCD factorisation scale for VBS signal	5.0%
$t\bar{t}$ normalization	4.9%
b tagging	3.5%
Prefiring corrections	3.3%
DY normalization	2.9%
Jet energy scale + resolution	2.6%
p_T^{miss} energy scale	2.4%
QCD-induced W^+W^- QCD scale	2.1%
Luminosity	2.1%
Muon efficiency	2.0%
Pileup	1.8%
Electron efficiency	1.5%
Underlying event	1.3%
Parton shower	1.0%
Other	$< 1\%$
Total systematic uncertainty	13.1%
Total statistical uncertainty	14.9%
Total uncertainty	19.8%