Multiboson production in CMS

The XXIX International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2022)

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27th June - 2nd July 2022

Work supported by DOE Award:
DE-SC0010103

Introduction

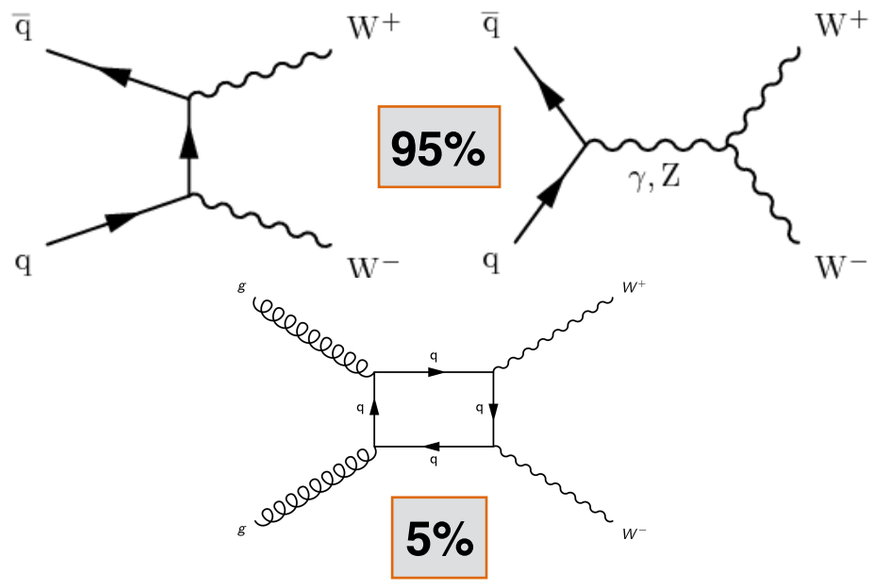
- Many CMS analyses have targeted Multiboson final states during the Run2 data-taking (2016-2018)
- **Motivation:**
    - Measurements of Multiboson final states provide excellent tests of the electroweak sector
    - Any deviation of the Multiboson production cross sections or kinematic distributions from the SM predictions may be an indication of anomalous couplings or the existence of new particles → Need precise measurements as well as reliable and accurate theoretical predictions for these processes
    - Multiboson final states represent a significant background to the measurements of the Higgs boson
- Latest published Multiboson results in the last ~couple of years by CMS:

Covered in this talk	**Not covered: dedicated talk on Friday**
WW (CMS-SMP-18-004)	VBS Wg (CMS-SMP-21-011)
WZ (CMS-SMP-20-014)	VBS WW OS (CMS-SMP-21-001)
Diboson xsecs at $\sqrt{s}$ = 5 TeV (CMS-SMP-20-012)	EW ZY+2jets (CMS-SMP-20-016)
WY differential (CMS-SMP-20-005)	WW VBS SS dilepton (CMS-SMP-20-006)
WW DPS (CMS-SMP-21-013)	ZZ VBS 4l+2j (CMS-SMP-20-001)
pWWp pZZp with PPS (CMS-SMP-21-014)	WV VBS semileptonic (CMS-SMP-20-013)

WW: strategy

- The Signal Region definition relies mainly on a set of **discrete requirements** on kinematic variables and on a multivariate analysis tool to suppress Drell-Yan background in same-flavour channel

Target signature: two opposite charged isolated leptons, and large transverse missing energy (MET) from the neutrinos



Signal Region definition:

Quantity	Sequential Cut	
	Different-flavor	Same-flavor
Number of leptons	Strictly 2	
Lepton charges	Opposite	
$p_{\mathrm{T}}^{\ell\,\mathrm{max}}$	>25	
$p_{\mathrm{T}}^{\ell\,\mathrm{min}}$	>20	
$m_{\ell\ell}$	>20	>40
Additional leptons	0	
$\lvert m_{\ell\ell} - m_{\mathrm{Z}}\rvert$	—	>15
$p_{\mathrm{T}}^{\ell\ell}$	>30	>30
$p_{\mathrm{T}}^{\mathrm{miss}}$	>20	>55
* $p_{\mathrm{T}}^{\mathrm{miss,proj}}$, $p_{\mathrm{T}}^{\mathrm{miss,track\ proj}}$	>20	>20
Number of jets	≤1	
Number of b-tagged jets	0	
DYMVA score	—	>0.9

for DY suppression

suppress ttbar

DYMVA: Developed for the CMS HWW analysis (arXiv:1806.05246)

* $$projected\ TrkE_T^{miss} = \begin{cases} TrkE_T^{miss} & \Delta\phi_{\min}(leptons, TrkE_T^{miss}) \geq \pi/2 \\ TrkE_T^{miss} \sin\Delta\phi_{\min} & \Delta\phi_{\min}(leptons, TrkE_T^{miss}) \leq \pi/2 \end{cases}$$

$$projected\ E_T^{miss} = \begin{cases} E_T^{miss} & \Delta\phi_{\min}(leptons, E_T^{miss}) \geq \pi/2 \\ E_T^{miss} \sin\Delta\phi_{\min} & \Delta\phi_{\min}(leptons, E_T^{miss}) \leq \pi/2 \end{cases}$$

WW: results

- The signal strength is extracted by fitting the predicted yields to the observed events (1-bin distributions). Information from the control regions is included in the fit
  - **Fit:** 4 Signal Regions, 4 Top Control Regions (2 flavour categories x 2 njets categories). Top normalization is measured

Inclusive cross-section:

Theoretical prediction: σ_{tot}^{NNLO} = 118.8 ± 3.6 pb

Category		Signal strength	Cross section [pb]
0-jet	DF	1.054 ± 0.083	125.2 ± 9.9
0-jet	SF	1.01 ± 0.16	120 ± 19
1-jet	DF	0.93 ± 0.12	110 ± 15
1-jet	SF	0.76 ± 0.20	89 ± 24
0-jet & 1-jet	DF	1.027 ± 0.071	122.0 ± 8.4
0-jet & 1-jet	SF	0.89 ± 0.16	106 ± 19
0-jet & 1-jet	DF & SF	0.990 ± 0.057	117.6 ± 6.8

σ_{tot} = 117.6 ± 1.4 (stat) ± 5.5 (syst) ± 1.9 (theo) ± 3.2 (lumi) pb
= **117.6 ± 6.8 pb**

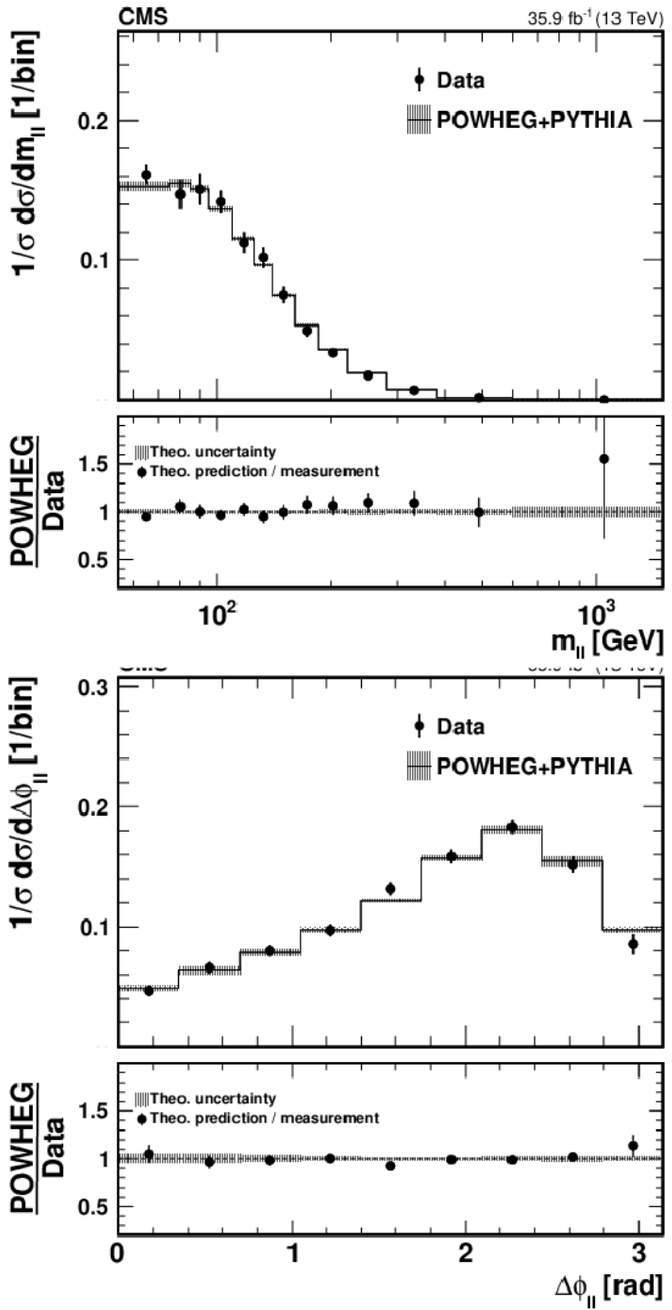
Fiducial cross-section:

Fiducial region definition at gen level: two dressed electrons or muons in the event with p_T > 20 GeV and |η|< 2.5, $m_{\ell\ell}$ > 20 GeV, $p_{T\ell\ell}$ > 30 GeV and MET > 20 GeV

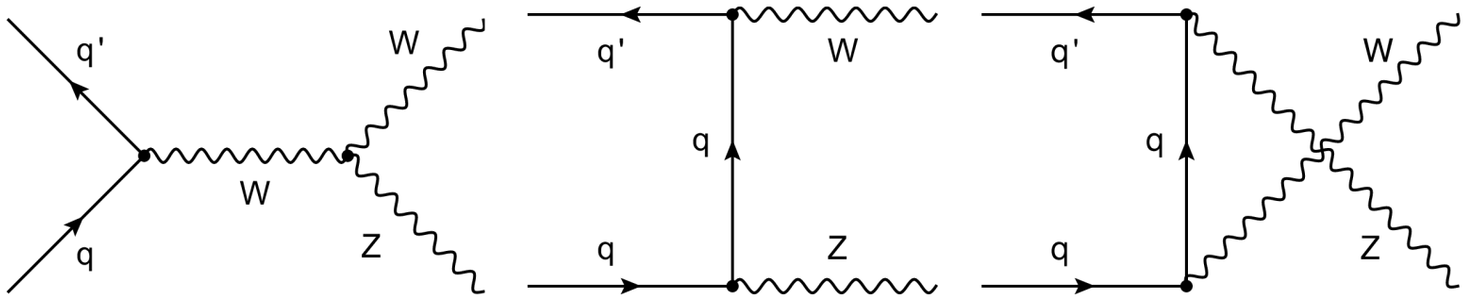
Theoretical prediction: σ_{fid}^{NNLO} = 1.531 ± 0.043 pb

σ_{fid}^{tot} = 1.529 ± 0.0020 (stat) ± 0.069 (syst)
± 0.028 (theo) ± 0.041 (lumi) pb = **1.529 ± 0.087 pb**

Differential cross-sections:



WZ: strategy



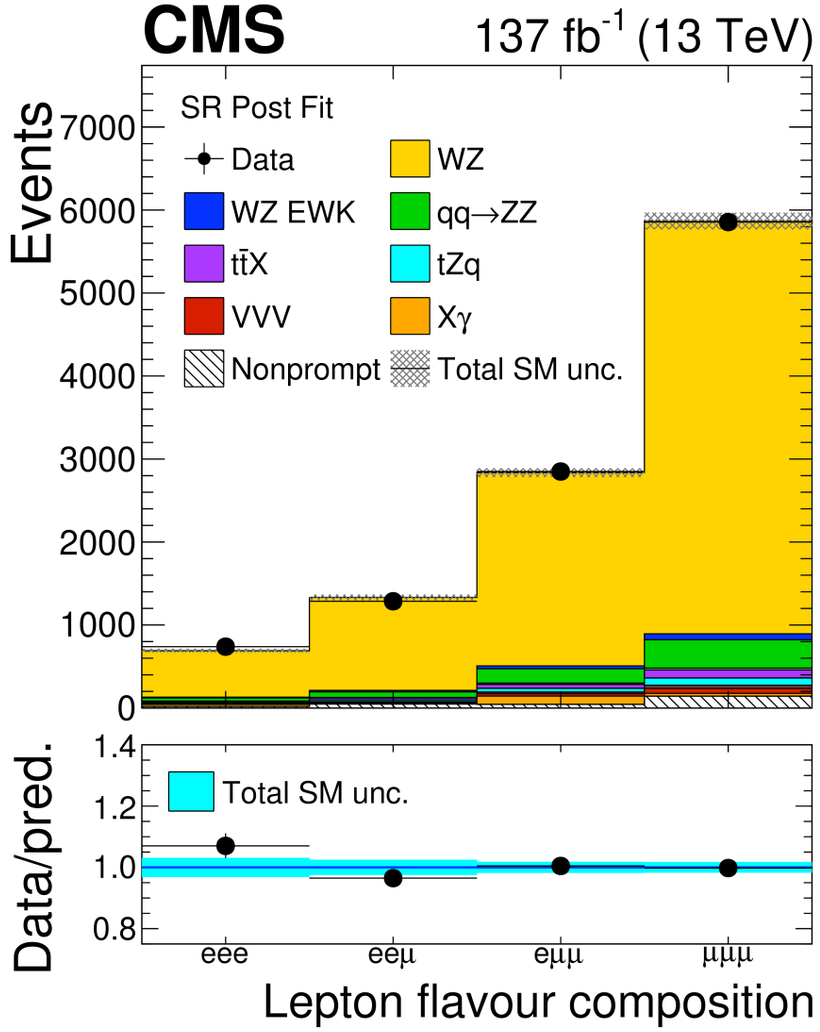
- Produced only via qq annihilation → sensitive to charge asymmetry measurements

Baseline selection:

- 3 isolated leptons
- The 2 OSSF leptons with closest $m_{\ell\ell}$ to m_Z are tagged as "Z leptons" (Z1, Z2)
- Remaining lepton is "W Lepton"
- $p_{T,\,Z1} > 25$ GeV, $p_{T,Z2} > 10$ GeV, $p_{T,W} > 25$ GeV
- $m\ell\ell > 4$ GeV

- On top of the baseline selection, a SR and CRs are defined to estimate the main backgrounds:

Target signature: three isolated leptons with an OSSF pair, and MET

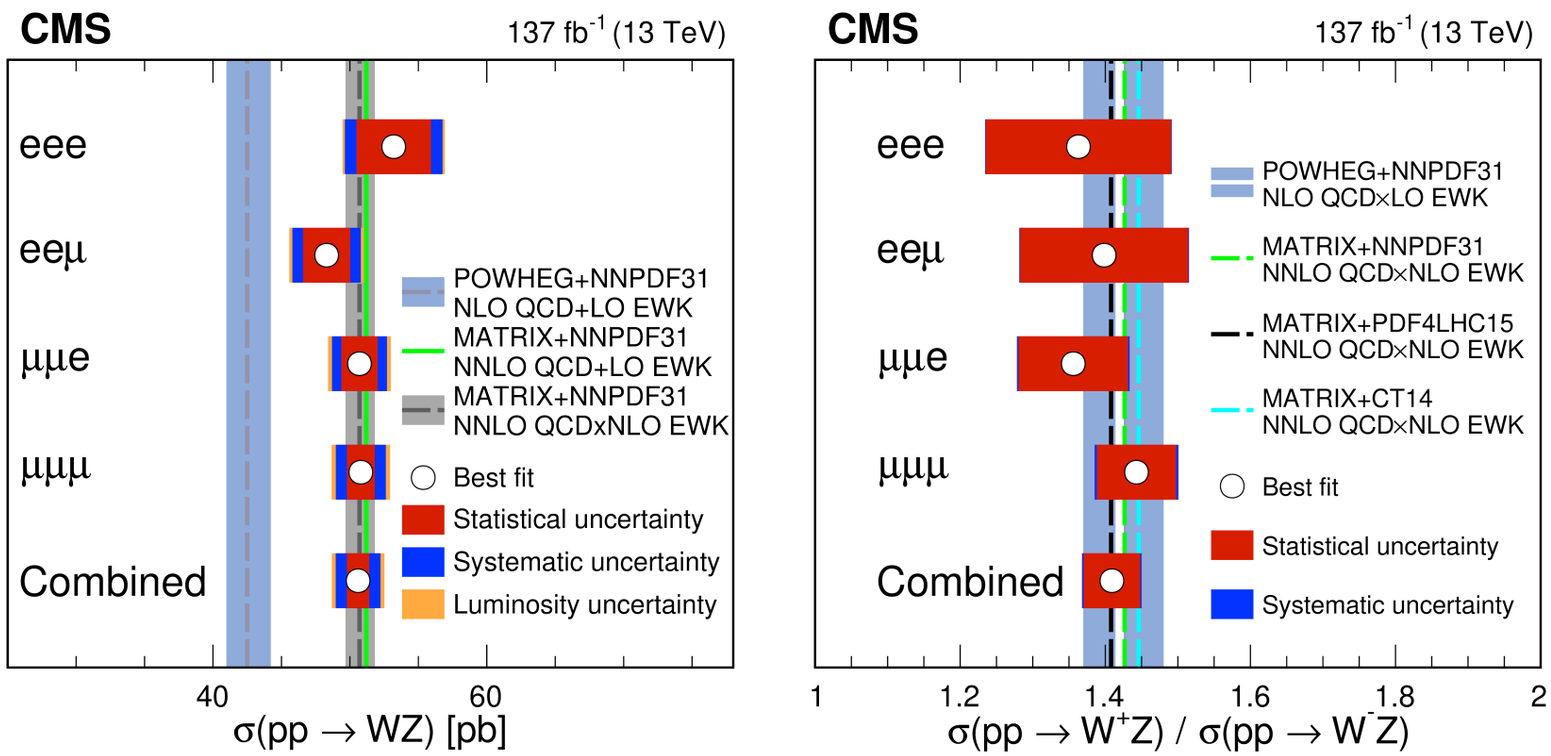


Region	N_ℓ	$p_T\{\ell_{Z1}, \ell_{Z2}, \ell_W, \ell_4\}$	N_{OSSF}	$\lvert M(\ell_{Z1}, \ell_{Z2}) - m_Z \rvert$	p_T^{miss}	N_{btag}	$\min(M(\ell\ell'))$	$M(\ell_{Z1}, \ell_{Z2}, \ell_W)$
SR	=3	$>\{25, 10, 25, —\}$ GeV	≥1	<15 GeV	>30 GeV	=0	>4 GeV	>100 GeV
CR-ZZ	=4	$>\{25, 10, 25, 10\}$ GeV	≥1	<15 GeV	—	=0	>4 GeV	>100 GeV
CR-tt̄Z	=3	$>\{25, 10, 25, —\}$ GeV	≥1	<15 GeV	>30 GeV	>0	>4 GeV	>100 GeV
CR-conv	=3	$>\{25, 10, 25, —\}$ GeV	≥1	—	≤30 GeV	=0	>4 GeV	<100 GeV

WZ: results

ML fit: flavour distribution in SR + ZZ CR + b-tagged ttZ - tZq CR + XΥ CR. Background normalizations are measured

- **Inclusive cross-section & charge asymmetry:**



σ_{tot} = 298.9 ± 4.8 (stat) ± 7.7 (syst) ± 5.4 (lumi) ± 2.7 (theo) fb

Theoretical prediction: $\sigma_{tot}^{NNLO \times NLO\ EW}$ = 298.1 ± 6.6 pb

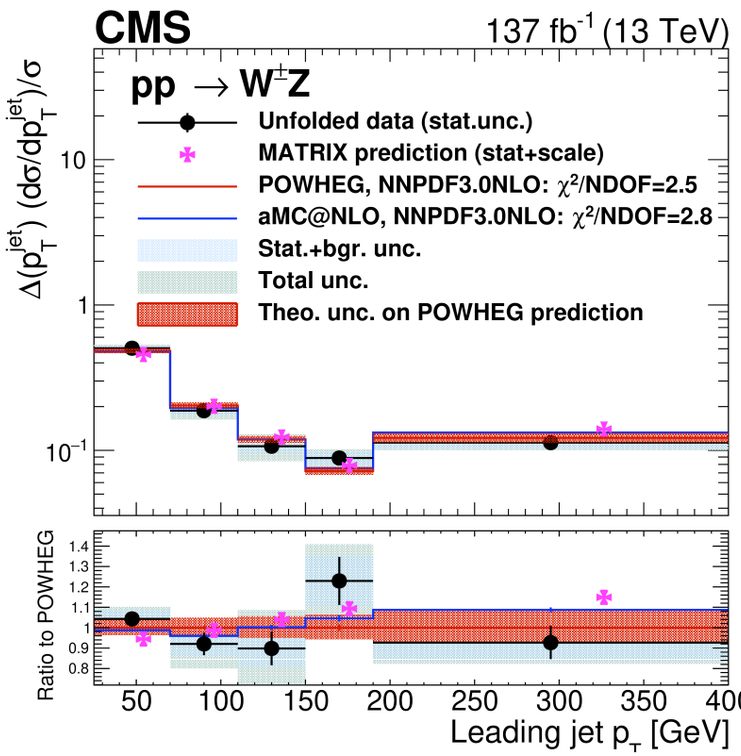
- **Fiducial cross-section:**

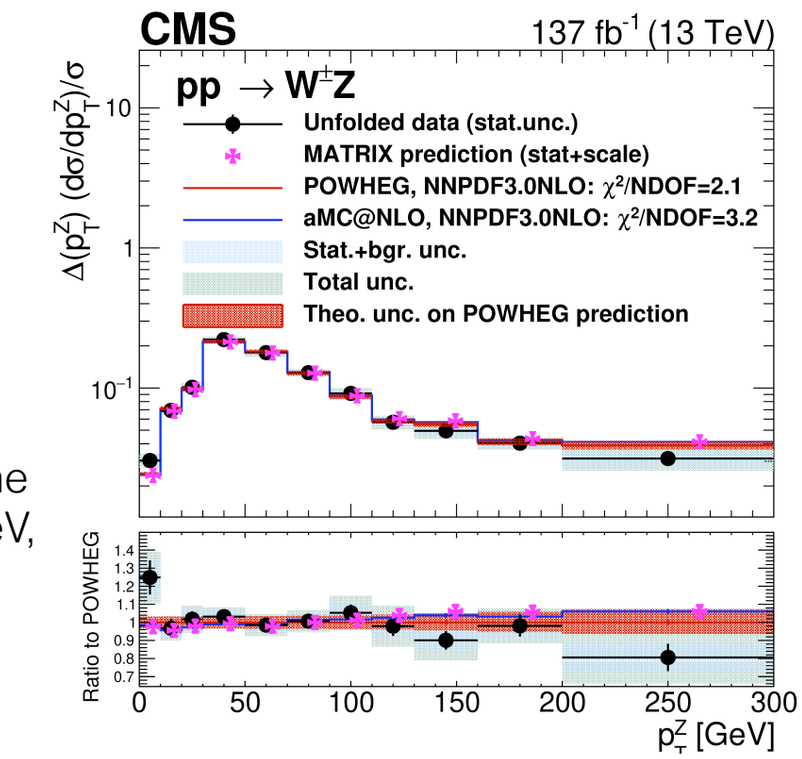
Fiducial region definition: three dressed electrons or muons in the event with at least one OSSF pair. $p_{T\ell Z1} > 25$ GeV, $p_{T\ell Z2} > 10$ GeV, $p_{T\ell W} > 25$ GeV, $|\eta| < 2.5$, $60 < m_{\ell Z1,\ell Z2} < 120$ GeV, $m_{\ell Z1,\ell Z2,\ell W} > 100$ GeV

σ_{fid} = 50.6 ± 0.8 (stat) ± 1.4 (syst) ± 1.1(lumi) ± 0.5 (theo) pb

Theoretical prediction: $\sigma_{fid}^{NNLO \times NLO\ EW}$ = 50.7 ± 1.1 pb

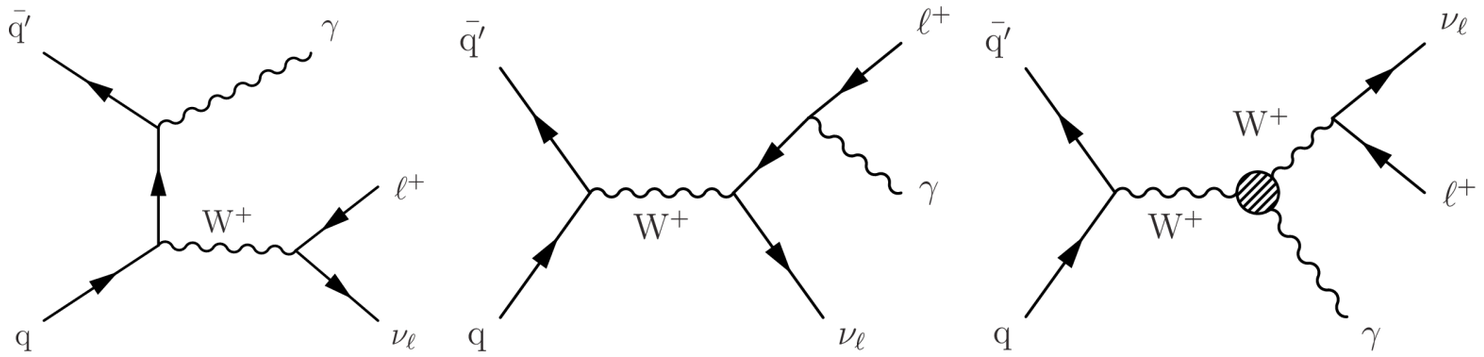
- **Differential cross-sections:**





WΥ differential: strategy

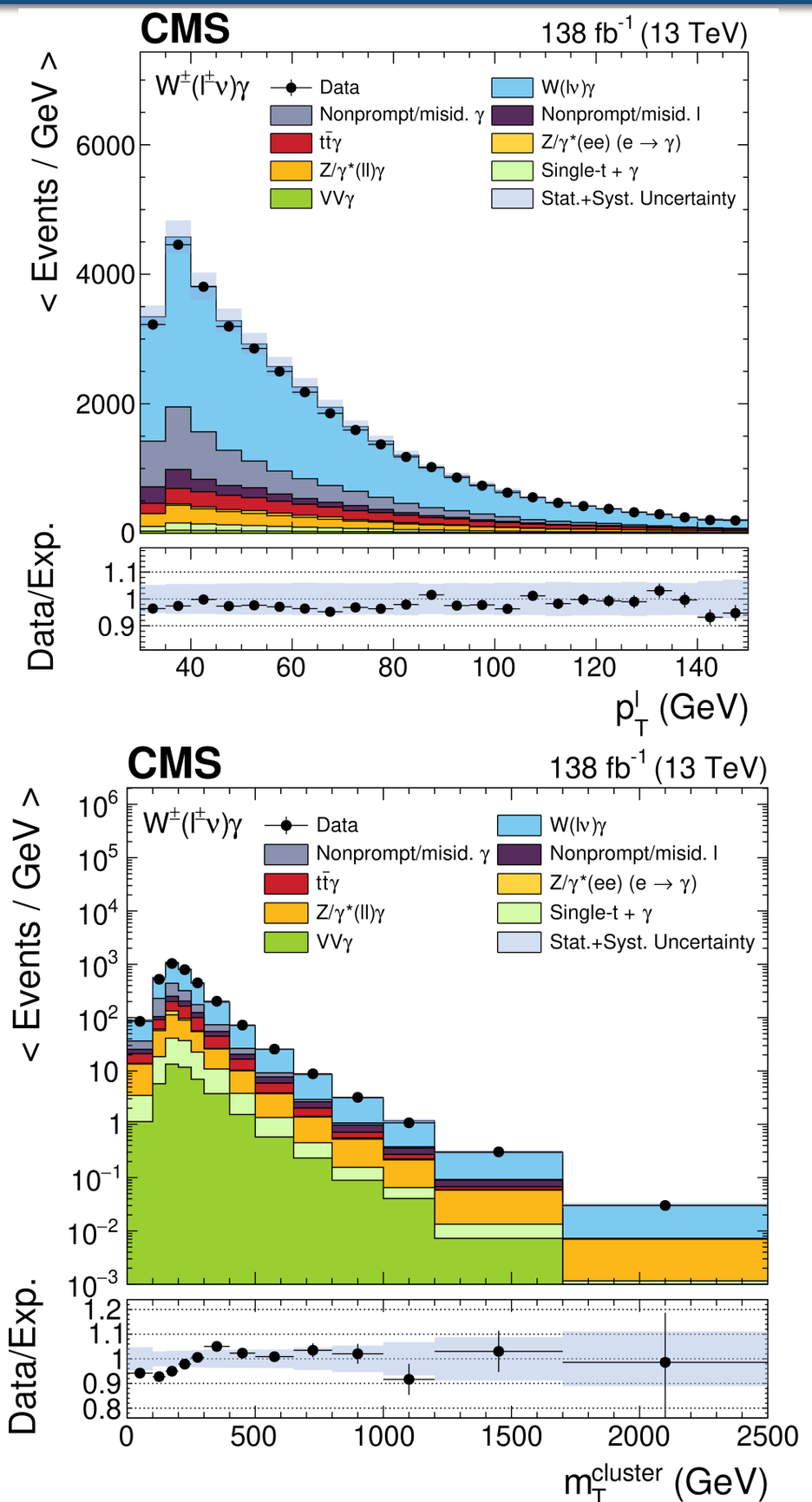
Target signature: one isolated lepton, one isolated photon, and MET



Event selection:

- pTe > 35 GeV / pTμ > 30 GeV / pTΥ > 30 GeV
- ΔR(ℓ,Υ) > 0.7
- MET > 40 GeV
- Vetoed events with $m_{\ell,\gamma}$ close to mZ
- Vetoed additional leptons & photons

- **Two flavour categories:** eΥ, μΥ
- **Main backgrounds:** W+jets (where a jets is misidentified as a photon, i.e., non-prompt photon) and events with a prompt photon but a nonprompt or misidentified lepton
    - Estimated from data using sidebands of the SR based on lepton and photon isolation requirements



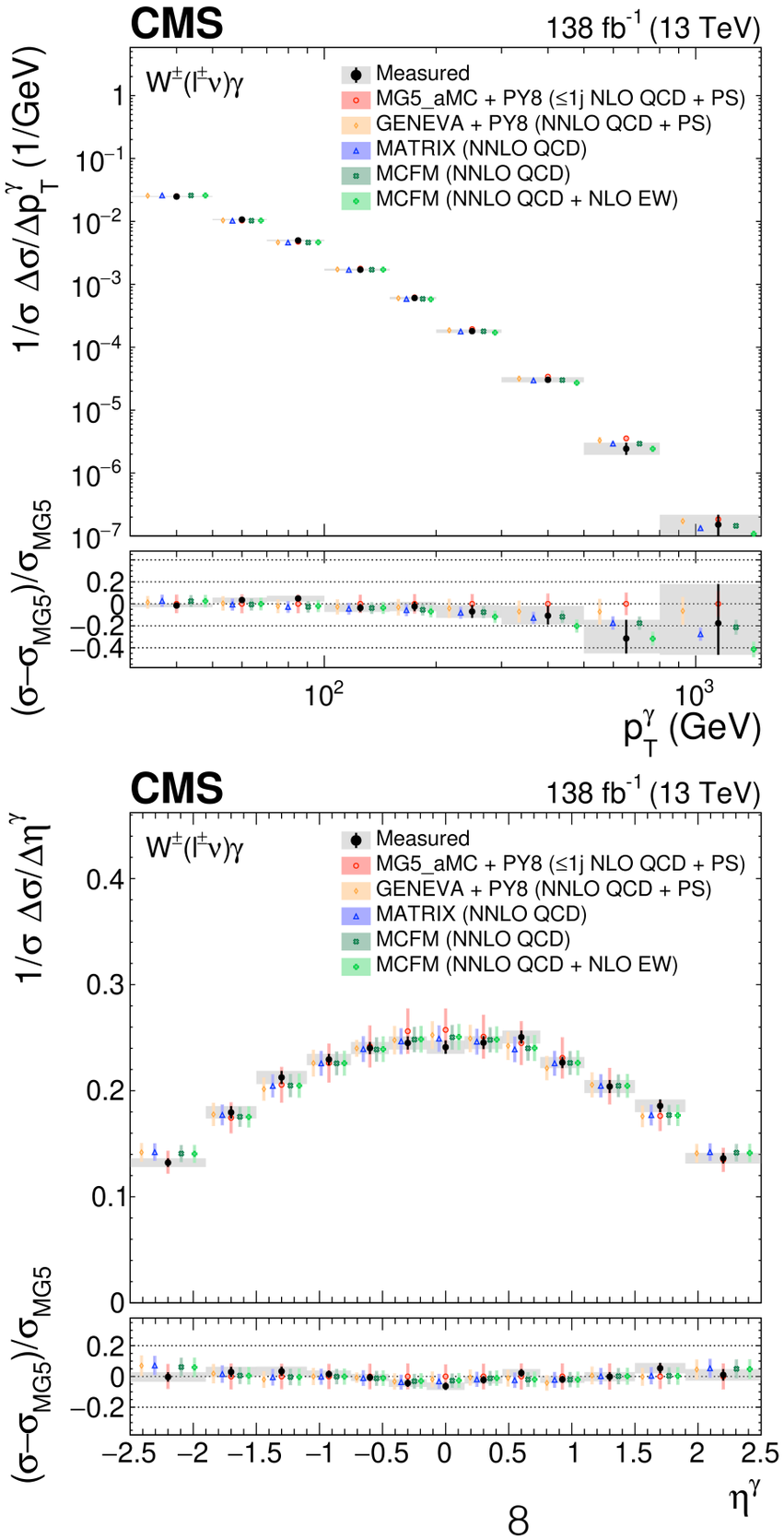
WΥ differential: results

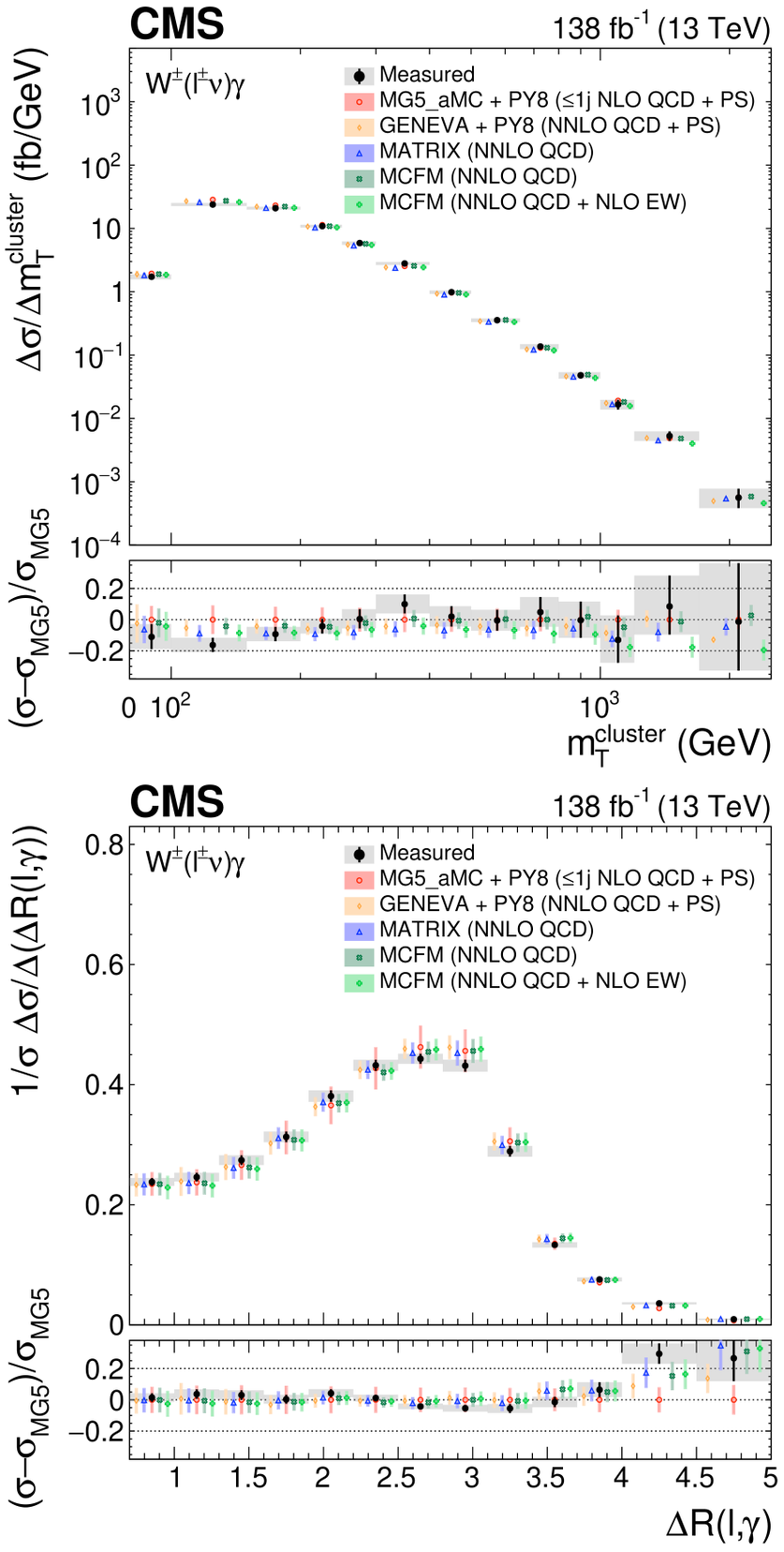
ML fit:

Fit to the RECO observables in each year for each electron and muon channels (6 categories: 2 flavour channels x 3 years)

Fiducial region definition:

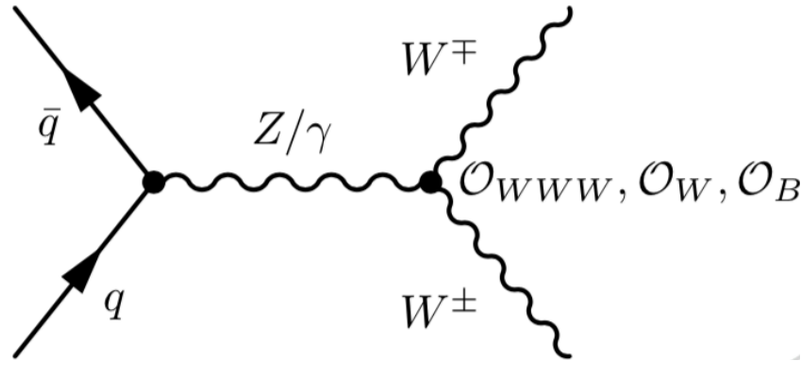
One gen dressed lepton and one photon in the event
- pTℓ > 30 GeV, |ηℓ| < 2.5
- pTΥ > 30 GeV, |ηΥ| < 2.5
- MET > 40 GeV
- ΔR(ℓ,Υ) > 0.7

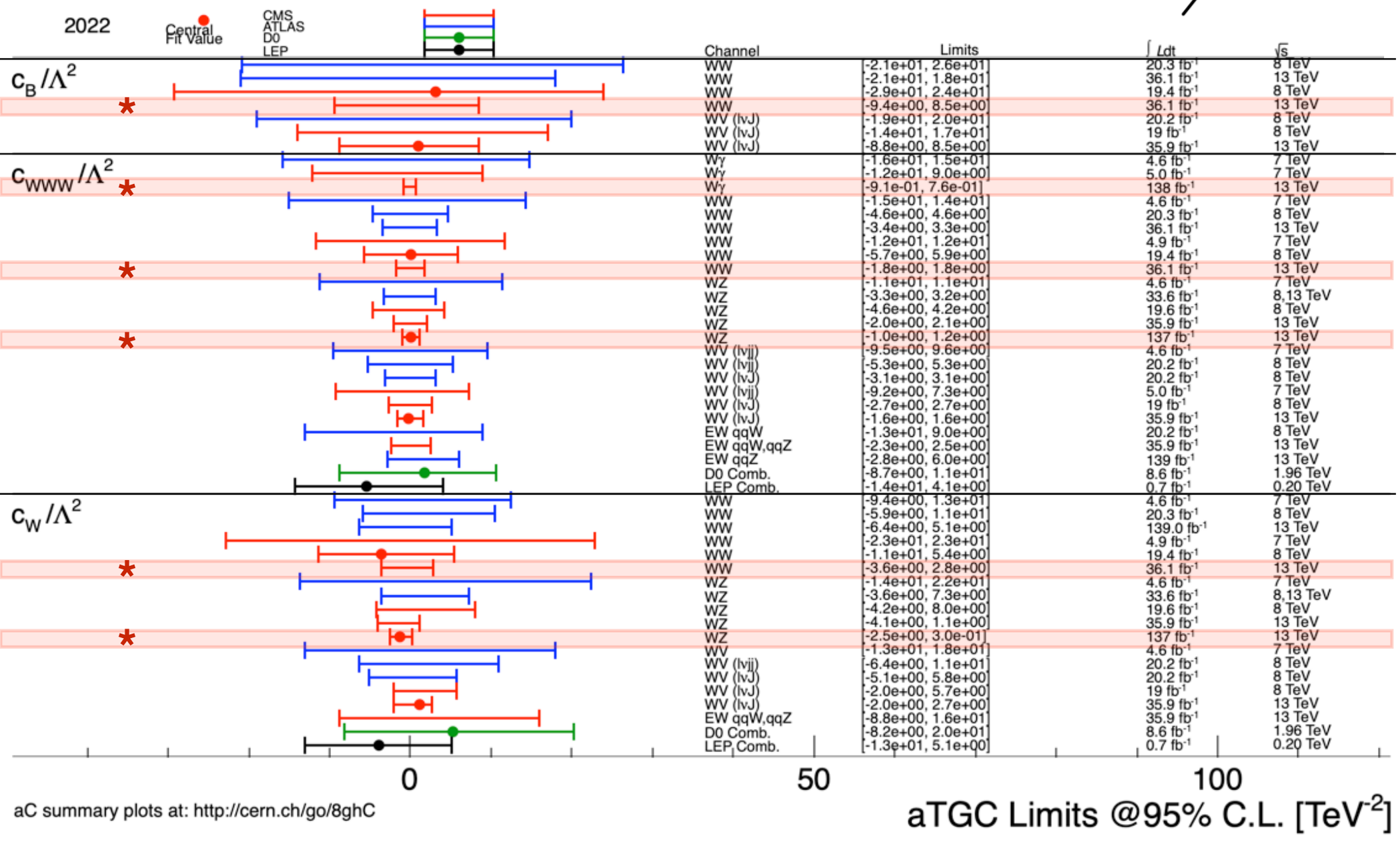




Limits on Wilson coefficients

- In the electroweak sector of the SM, the first higher-dimensional operators containing only massive boson fields are dimension-6
  - **EFT effects simulated with Madgraph5@NLO**



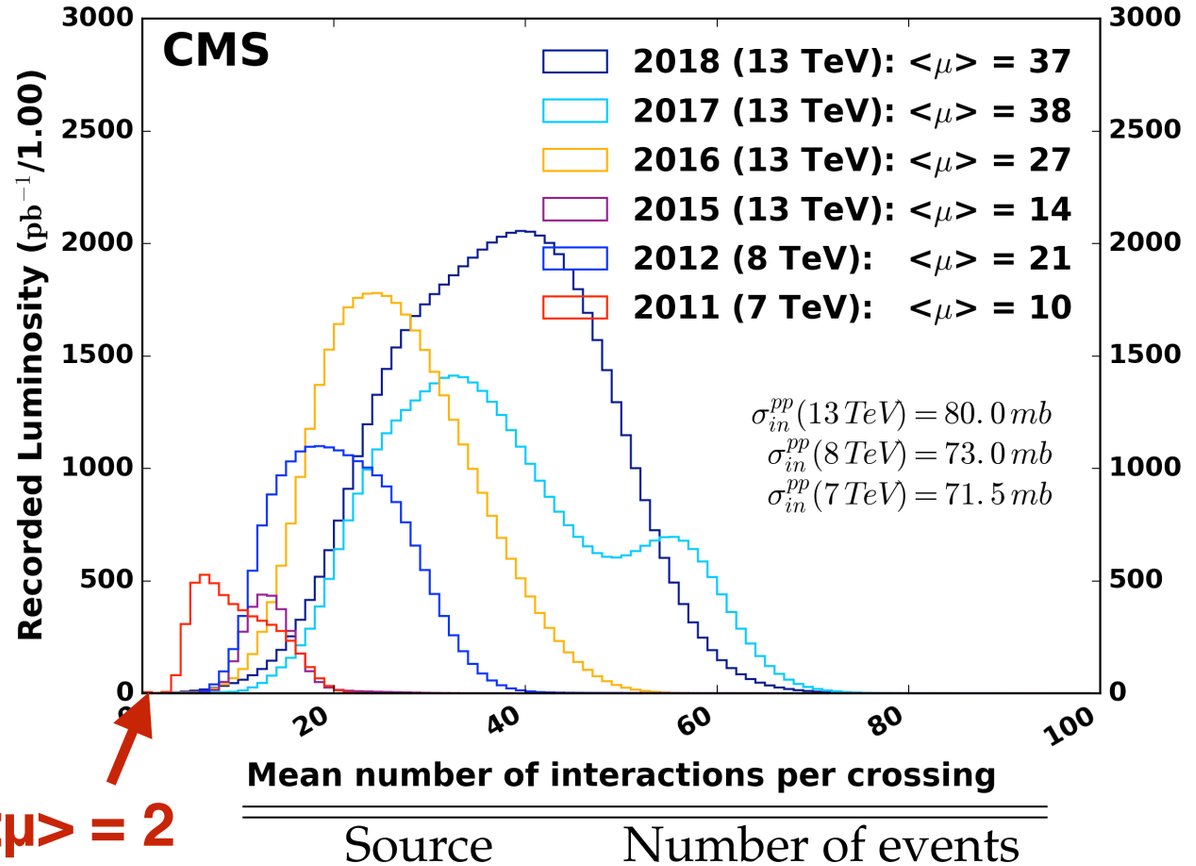


Channel	Limits	$\int L dt$	$\sqrt{s}$
WW	[-2.1e+01, 2.6e+01]	20.3 fb^{-1}	8 TeV
WW	[-2.1e+01, 1.8e+01]	36.1 fb^{-1}	13 TeV
WW	[-2.9e+01, 2.4e+01]	19.4 fb^{-1}	8 TeV
WW	[-9.4e+00, 8.5e+00]	36.1 fb^{-1}	13 TeV
WV (lvJ)	[-1.9e+01, 2.0e+01]	20.2 fb^{-1}	8 TeV
WV (lvJ)	[-1.4e+01, 1.7e+01]	19 fb^{-1}	8 TeV
WV (lvJ)	[-8.8e+00, 8.5e+00]	35.9 fb^{-1}	13 TeV
Wγ	[-1.6e+01, 1.5e+01]	4.6 fb^{-1}	7 TeV
Wγ	[-1.2e+01, 9.0e+00]	5.0 fb^{-1}	7 TeV
Wγ	[-9.1e-01, 7.6e-01]	138 fb^{-1}	13 TeV
WW	[-1.5e+01, 1.4e+01]	4.6 fb^{-1}	7 TeV
WW	[-4.6e+00, 4.6e+00]	20.3 fb^{-1}	8 TeV
WW	[-3.4e+00, 3.3e+00]	36.1 fb^{-1}	13 TeV
WW	[-1.2e+01, 1.2e+01]	4.9 fb^{-1}	7 TeV
WW	[-5.7e+00, 5.9e+00]	19.4 fb^{-1}	8 TeV
WW	[-1.8e+00, 1.8e+00]	36.1 fb^{-1}	13 TeV
WZ	[-1.1e+01, 1.1e+01]	4.6 fb^{-1}	7 TeV
WZ	[-3.3e+00, 3.2e+00]	33.6 fb^{-1}	8,13 TeV
WZ	[-4.6e+00, 4.2e+00]	19.6 fb^{-1}	8 TeV
WZ	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
WZ	[-1.0e+00, 1.2e+00]	137 fb^{-1}	13 TeV
WV (lvjj)	[-9.5e+00, 9.6e+00]	4.6 fb^{-1}	7 TeV
WV (lvjj)	[-5.3e+00, 5.3e+00]	20.2 fb^{-1}	8 TeV
WV (lvJ)	[-3.1e+00, 3.1e+00]	20.2 fb^{-1}	8 TeV
WV (lvjj)	[-9.2e+00, 7.3e+00]	5.0 fb^{-1}	7 TeV
WV (lvJ)	[-2.7e+00, 2.7e+00]	19 fb^{-1}	8 TeV
WV (lvJ)	[-1.6e+00, 1.6e+00]	35.9 fb^{-1}	13 TeV
EW qqW	[-1.3e+01, 9.0e+00]	20.2 fb^{-1}	8 TeV
EW qqW,qqZ	[-2.3e+00, 2.5e+00]	35.9 fb^{-1}	13 TeV
EW qqZ	[-2.8e+00, 6.0e+00]	139 fb^{-1}	13 TeV
D0 Comb.	[-8.7e+00, 1.1e+01]	8.6 fb^{-1}	1.96 TeV
LEP Comb.	[-1.4e+01, 4.1e+00]	0.7 fb^{-1}	0.20 TeV
WW	[-9.4e+00, 1.3e+01]	4.6 fb^{-1}	7 TeV
WW	[-5.9e+00, 1.1e+01]	20.3 fb^{-1}	8 TeV
WW	[-6.4e+00, 5.1e+00]	139.0 fb^{-1}	13 TeV
WW	[-2.3e+01, 2.3e+01]	4.9 fb^{-1}	7 TeV
WW	[-1.1e+01, 5.4e+00]	19.4 fb^{-1}	8 TeV
WW	[-3.6e+00, 2.8e+00]	36.1 fb^{-1}	13 TeV
WZ	[-1.4e+01, 2.2e+01]	4.6 fb^{-1}	7 TeV
WZ	[-3.6e+00, 7.3e+00]	33.6 fb^{-1}	8,13 TeV
WZ	[-4.2e+00, 8.0e+00]	19.6 fb^{-1}	8 TeV
WZ	[-4.1e+00, 1.1e+00]	35.9 fb^{-1}	13 TeV
WZ	[-2.5e+00, 3.0e-01]	137 fb^{-1}	13 TeV
WV	[-1.3e+01, 1.8e+01]	4.6 fb^{-1}	7 TeV
WV (lvjj)	[-6.4e+00, 1.1e+01]	20.2 fb^{-1}	8 TeV
WV (lvJ)	[-5.1e+00, 5.8e+00]	20.2 fb^{-1}	8 TeV
WV (lvJ)	[-2.0e+00, 5.7e+00]	19 fb^{-1}	8 TeV
WV (lvJ)	[-2.0e+00, 2.7e+00]	35.9 fb^{-1}	13 TeV
EW qqW,qqZ	[-8.8e+00, 1.6e+01]	35.9 fb^{-1}	13 TeV
D0 Comb.	[-8.2e+00, 2.0e+01]	8.6 fb^{-1}	1.96 TeV
LEP Comb.	[-1.3e+01, 5.1e+00]	0.7 fb^{-1}	0.20 TeV

$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_{\rho}{}^{\mu},$$
$$\mathcal{O}_W = \frac{c_W}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^\nu \Phi),$$
$$\mathcal{O}_B = \frac{c_B}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^\nu \Phi),$$

Diboson xsecs at √s = 5 TeV: strategy

- **First measurements** of diboson production cross sections at this center-of-mass energy. Reduce the gap between Tevatron and LHC measurements
- **Data collected in November 2017 under low pile-up conditions (302 pb^{-1})**
- Leptonic decays of the W/Z bosons with at least two leptons in the final state
- Dedicated lepton identification selection criteria based on a multivariate selection method, designed to separate prompt leptons from fakes



Analysis Regions:

WW SR:
- Two OS leptons and DF channel
- pT(ℓℓ) > 20 GeV
- Δϕ(ℓ,ℓ) < 2.8
- mT(ℓ, MET) > 20 GeV
- Vetoed jets

WZ SRs:
- Three leptons and Two SS leptons channels
- Additional kinematic cuts

ZZ SRs:
- Two and four leptons channels
- Additional kinematic cuts

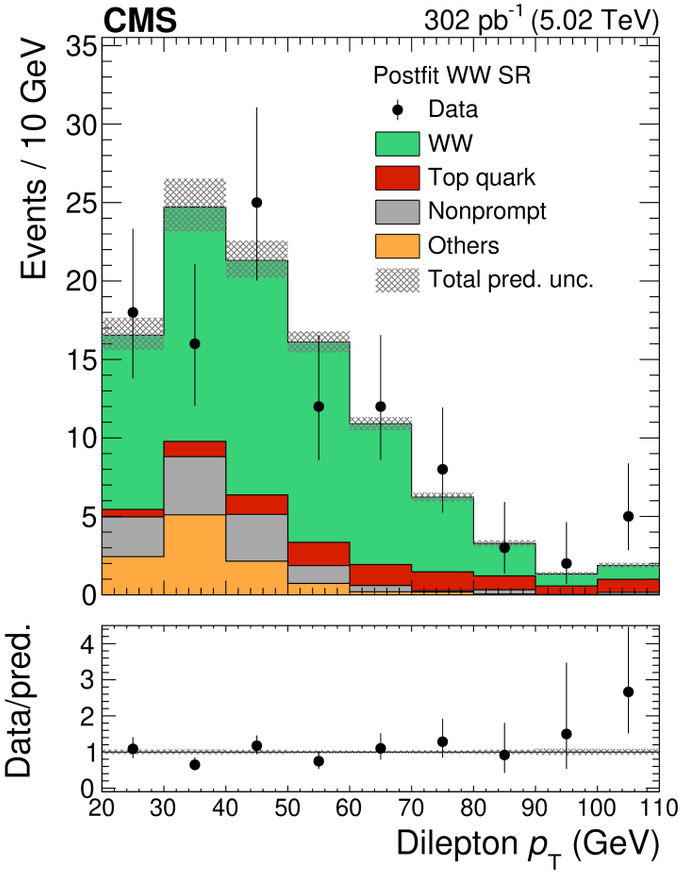
Source	Number of events
Top quark	$9.0 \pm 0.1 \pm 1.1$
WZ+ZZ	$5.6 \pm 1.0 \pm 1.1$
Drell–Yan	$1.8 \pm 0.5 \pm 0.2$
Conversions	$2.7 \pm 0.7 \pm 0.7$
Nonprompt ℓ	$11.2 \pm 1.3 \pm 3.4$
Background	$30.3 \pm 1.9 \pm 3.9$
WW signal	$55.2 \pm 0.3 \pm 1.8$
Data	101

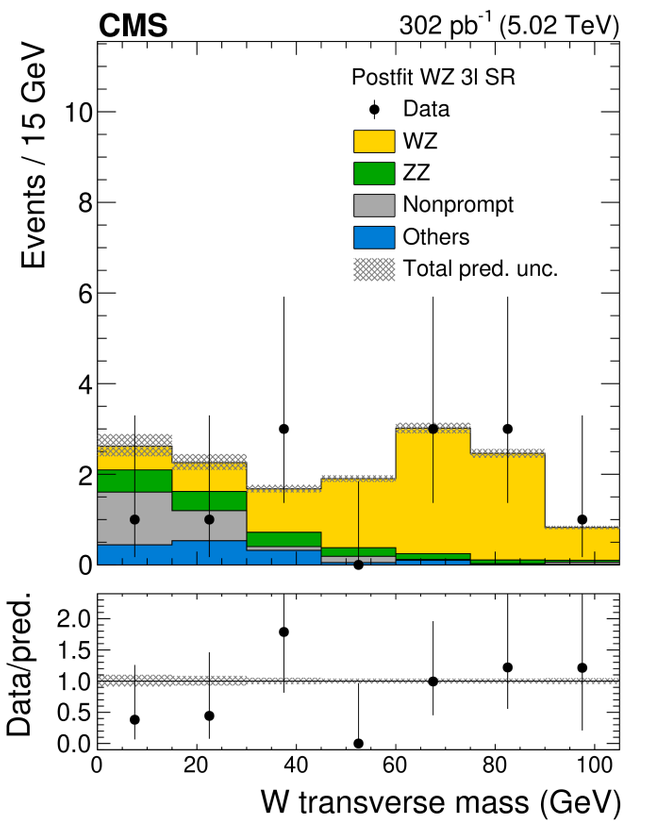
SR	Background	Signal	Data
WZ 3ℓ	$4.0 \pm 0.6 \pm 0.4$	$14.8 \pm 0.1 \pm 0.6$	12
WZ 2μss	$0.6 \pm 0.1 \pm 0.1$	$3.2 \pm 0.8 \pm 0.2$	4
ZZ 4ℓ	$0.5 \pm 0.2 \pm 0.1$	$2.5 \pm 0.0 \pm 0.1$	3
ZZ $2\ell 2\nu$	$4.8 \pm 0.3 \pm 0.7$	$3.8 \pm 0.0 \pm 0.2$	12

Diboson xsecs at √s = 5 TeV: results

ML fit: one for each SR, with a single free-floating parameter that corresponds to the normalization of the corresponding signal process

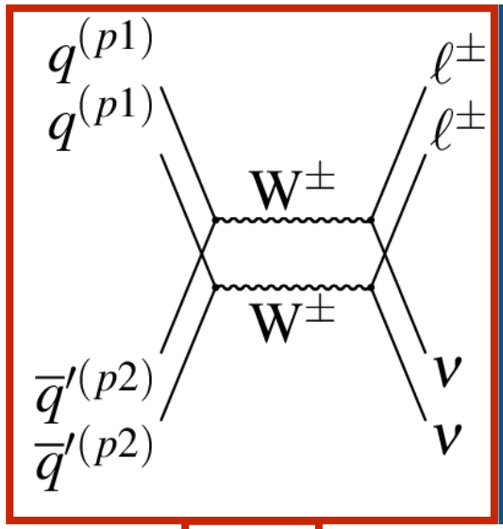
$$\sigma_{WW} = 37.0^{+5.5}_{-5.2}(\text{stat})^{+2.7}_{-2.6}(\text{syst}) = 37.0^{+6.2}_{-5.8}\ \text{pb},$$
$$\sigma_{WZ} = 6.4^{+2.5}_{-2.1}(\text{stat})^{+0.5}_{-0.3}(\text{syst}) = 6.4^{+2.5}_{-2.1}\ \text{pb},$$
$$\sigma_{ZZ} = 5.3^{+2.5}_{-2.1}(\text{stat})^{+0.5}_{-0.4}(\text{syst}) = 5.3^{+2.6}_{-2.1}\ \text{pb},$$



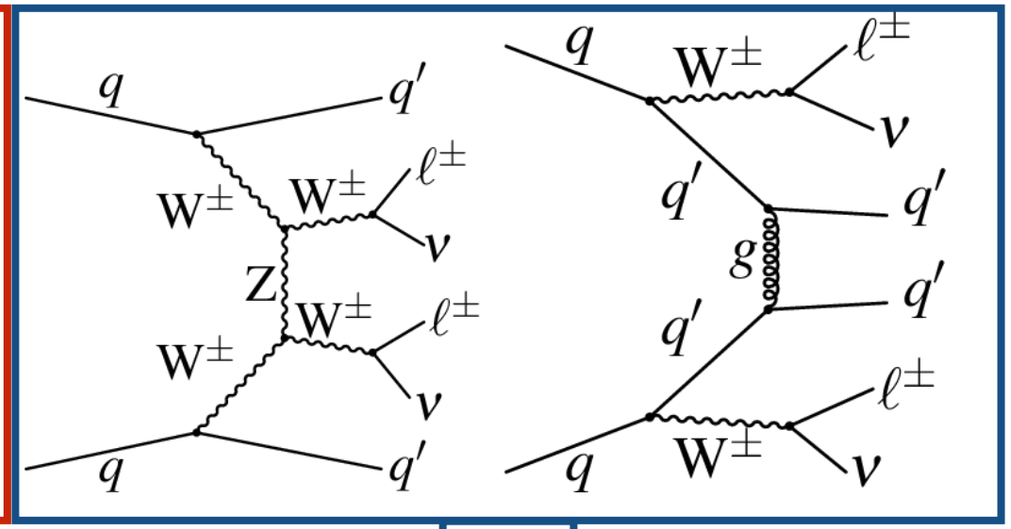


WW DPS: strategy

- **First observation** of WW production from Double Parton Scattering (DPS) process
- Two hard parton-parton occur in a single proton-proton collision
- Allow to know better the internal structure of the colliding protons by performing correlation studies among the partons



DPS



SPS

Analysis Regions:

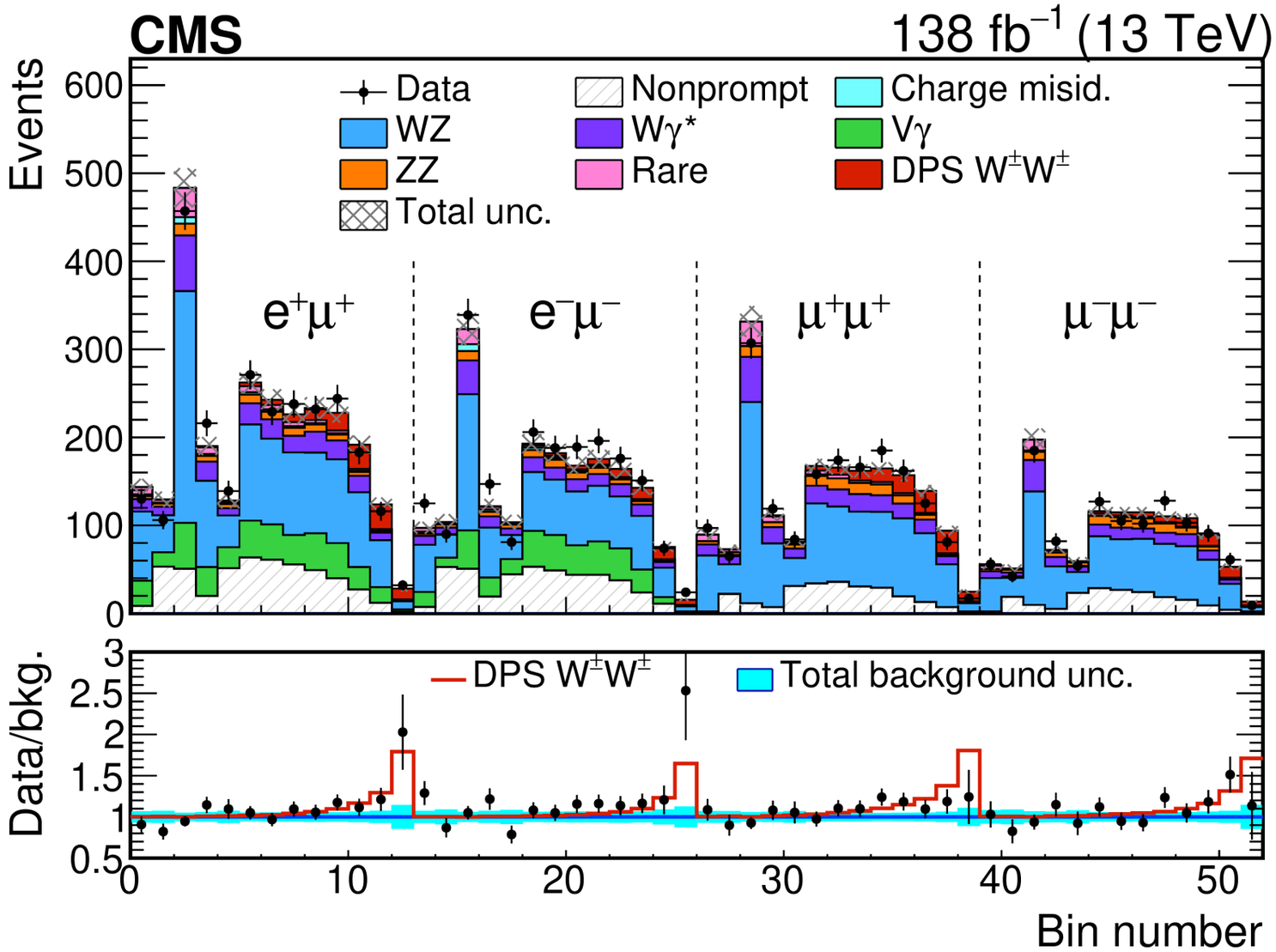
WW SS SR:	**WZ CR:**
-Two SS leptons (eμ, μμ), with pTℓ > 25 (20) GeV - MET > 15 GeV - njets ≤ 1 - mℓℓ > 20 GeV - bVeto and τh veto	- Three leptons, where the mℓℓ of the OSSF lepton pair must be consistent with mZ **ZZ CR:** - Four leptons, where the mℓℓ of both OSSF pairs must be consistent with mZ

- Non-prompt lepton background is estimated from data using a sideband of the SR to estimate the fake rate

- To enhance the sensitivity, events in the SR are split into four lepton-flavor and charge categories
- **Two BDTs are trained:** signal vs WZ, signal vs non-prompt. Kinematic and angular variables from leptons and pTmiss are used as training variables
- PYTHIA8 and HERWIG MC generators are used to simulate the signal process. PYTHIA8 is taken as nominal, and the difference in acceptance is accounted as systematic uncertainty in the measurements

WW DPS: results

ML fit: 2D map of the scores of the two BDTs from SRs, $m_{\ell\ell\ell}$ from WZ CR, $m_{\ell\ell\ell\ell}$ from ZZ CRs. WZ and ZZ normalizations are measured



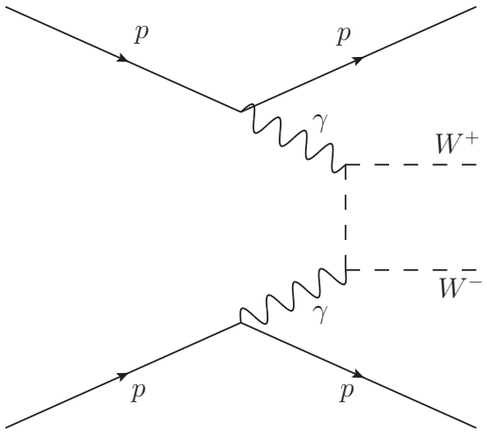
Fiducial region definition: two dressed electrons or muons in the event, with the same pT, η, $m\ell\ell$, $pT\ell\ell$ requirements as the SR

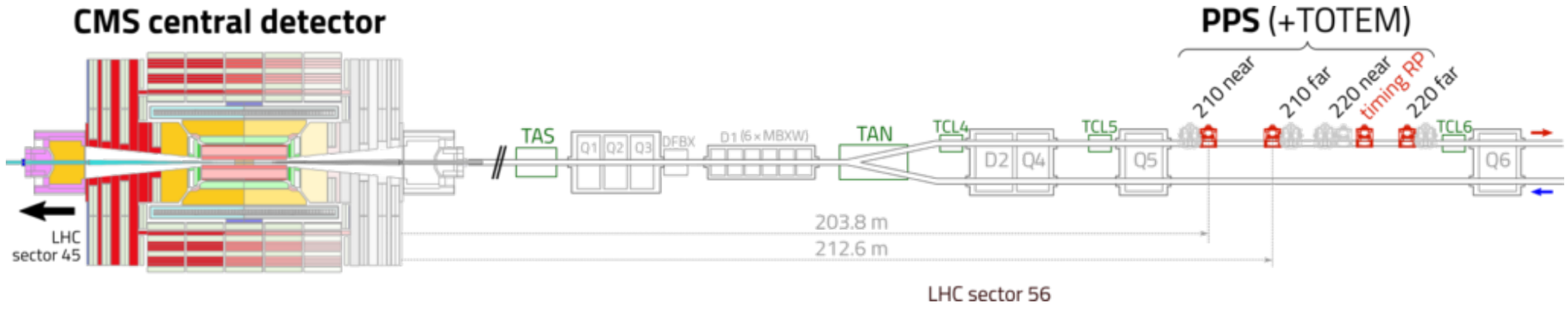
σ_{tot} = 0.16 ± 0.02 (stat) ± 0.02 (syst) ± 0.02 (model) pb

In agreement with predictions from Pythia and dShower

Observed significance of the signal above the background only hypothesis of 6.2σ

ϒϒ → VV with forward protons: strategy





- Search for anomalous **ϒϒ→WW and ϒϒ→ZZ** production, with reconstructed forward protons in PPS. Fully hadronic final states of W and Z into "fat" jets due to the large boost

Event selection:

Jets selection:
- Two "fat" jets with pT > 200 GeV, m > 1126 GeV
- $\Delta\eta(j1,j2) < 1.3$
- Jets balanced in ϕ and pT
  - $a = |1 - \Delta\phi / \pi| < 0.01$
  - $pTj1 / pTj2 < 1.3$

W and Z selection:
- Masses of the jets are used to separate WW and ZZ final states:

$$\cos(\pi/4)\times m_{j1} + \sin(\pi/4)\times m_{j2} = 117.8\ GeV$$

Proton selection:
- $\xi > 0.05$ to avoid large radiation-induced near the beam

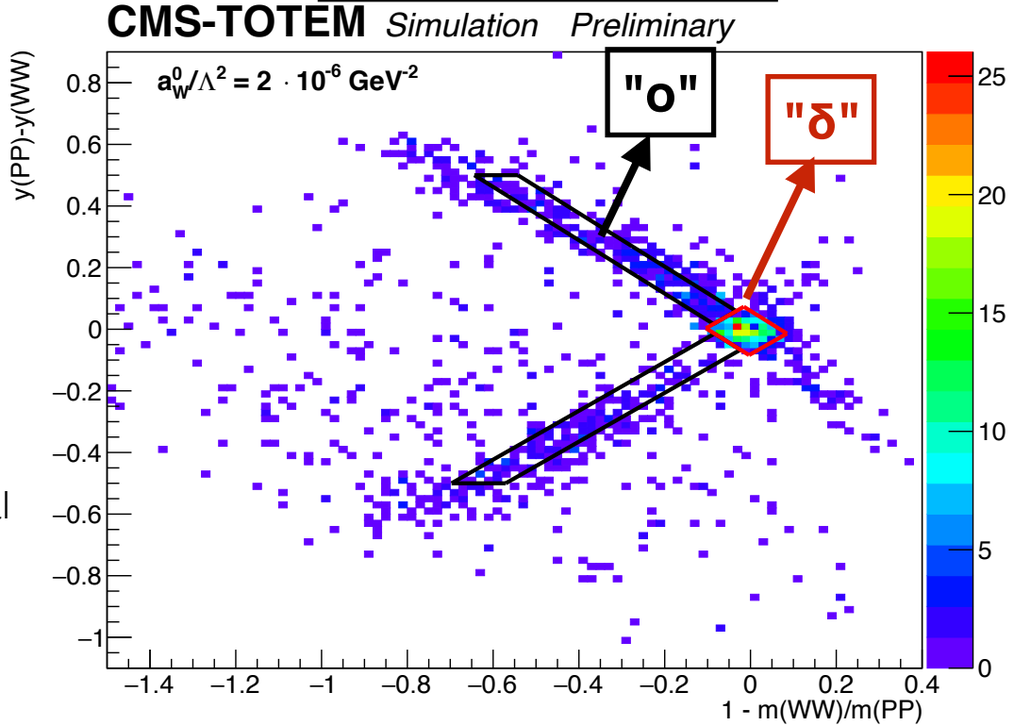
$$\xi_p = \frac{\Delta p_p}{p_p}$$

$$m(pp) = \sqrt{s} \times \sqrt{\xi_{p1} \times \xi_{p2}}$$

$$y(pp) = -\frac{1}{2} \times \ln\left(\frac{\xi_{p1}}{\xi_{p2}}\right)$$

Region "o": one signal proton is missed. A pileup proton is used instead

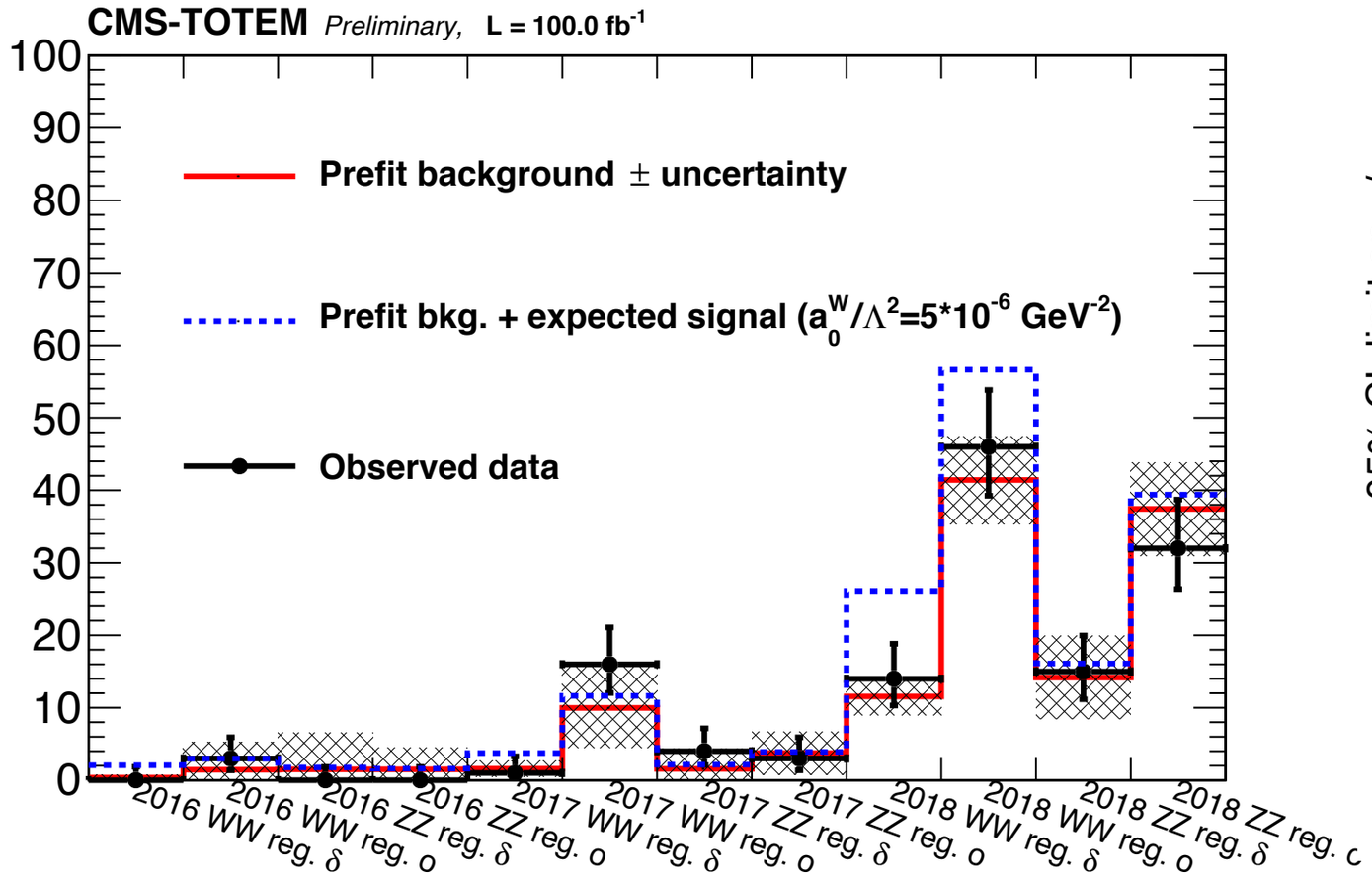
Proton-jet matching

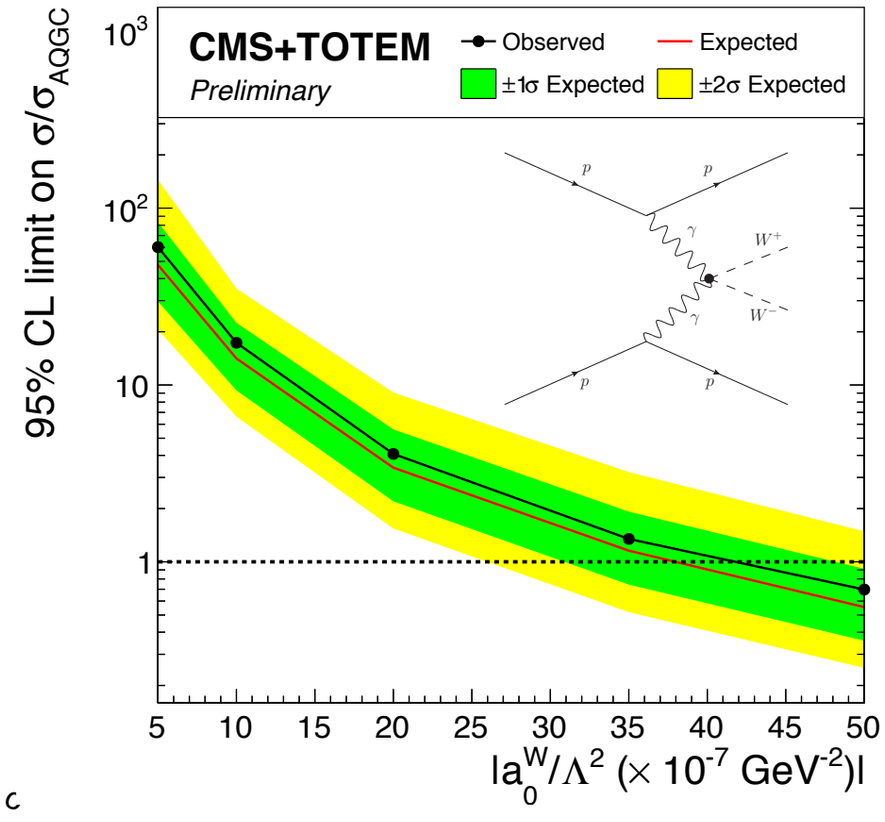


- **Main background:** jets coming from one interaction, combined with unrelated protons from pileup interactions in the same BX
  - Estimated from data using sidebands regions (inverted dijet acoplanarity and/or dijet-proton matching) through the ABCD method

ϒϒ → VV with forward protons: results

ML fit: Fully ("region δ") and partially ("region o") reconstructed events x 3 years x 2 SRs (WW and ZZ)

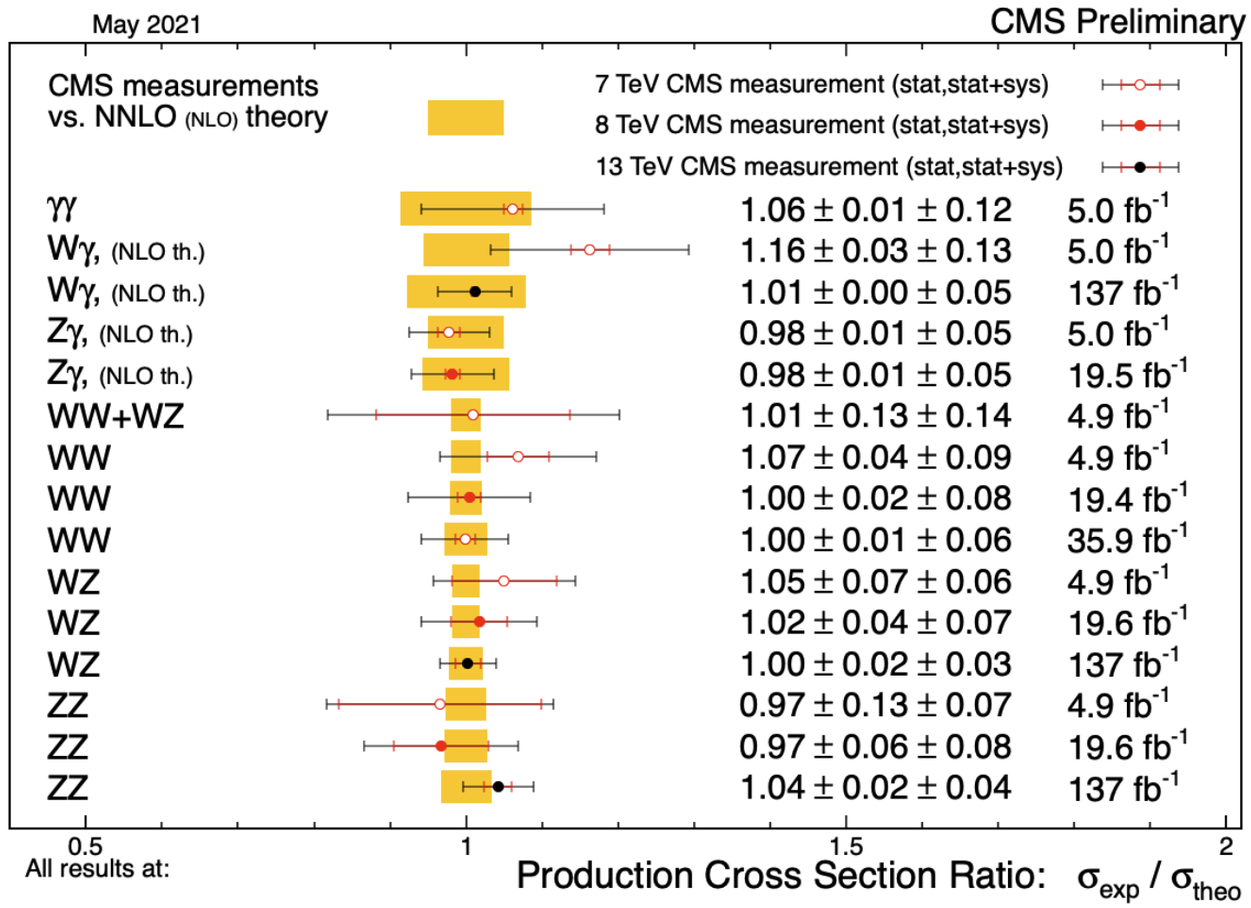




- Improved detectors in 2018 in PPS that allow to reconstruct more than 1 proton in each arm of the spectrometer per event. The one with with largest ξ is taken
    - **Sensitivity mostly relies on 2018 data**
- **No significant excess** is observed over the SM background prediction
- Limits are reinterpreted in terms of dimension-6 non-linear and dimension-8 **AQGC**. Limits on dimension-6 AQGC are 15-20x more stringent than the limits obtained in previous analysis performed in LHC Run1 (without proton tagging)

Summary

- Presented the latest CMS Mutiboson results in Run 2 era
- **Good agreement with SM predictions so far**
- The large amount of collected data is making possible to measure many rare processes predicted by the SM



- To have a complete overview of the latest Multiboson measurements at CMS, do not miss the VBS dedicated talk on Friday
- New data-taking era (Run 3) will start in August this year at $\sqrt{s}$ = 13.6 TeV
  → new interesting results will come. **Stay tuned!**