WZ measurements Inclusive and differential

4th Red LHC Workshop

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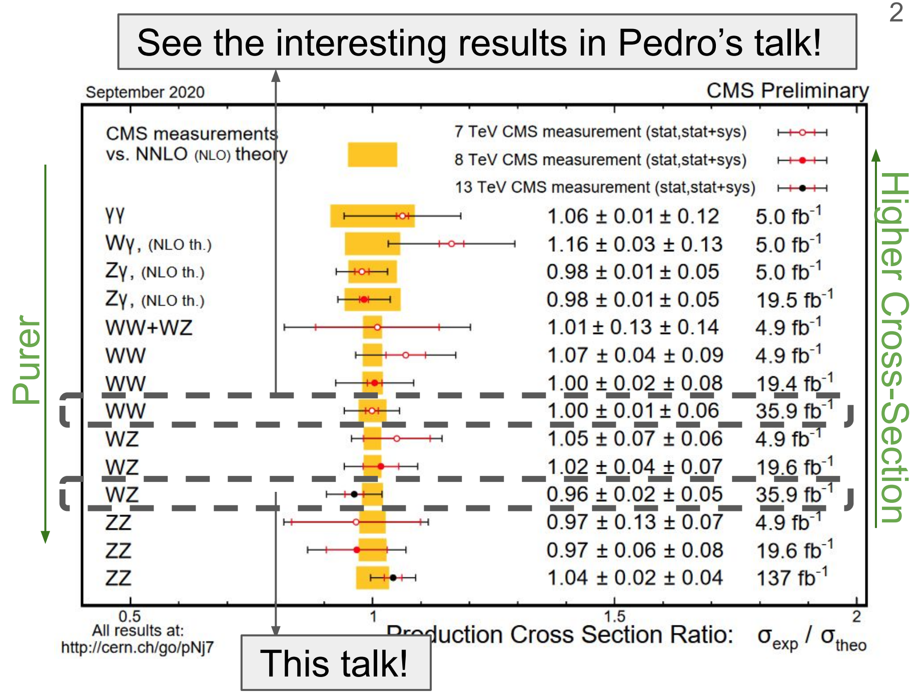
CMS Compact Muon Solenoid

Dibosons at the LHC

⇢ Processes that have typically **high cross-sections**, leading to sizable statistics (~thousands of events for the Run II of the LHC).

⇢ Multileptonic final states lead to **high purities** which translates into small systematic uncertainties.



⇢ Fully differential theoretical predictions cover effects up to NNLO QCD + NLO EWK (arxiv:1912.00068) leading to **high precision predictions**.

⇢ All together this is an **excellent setup to look for** deviations pointing to **new physics**!

Why measure WZ?

⇢ Dominant SM process in 3l final states: any analysis looking at multileptons needs to take WZ into account.

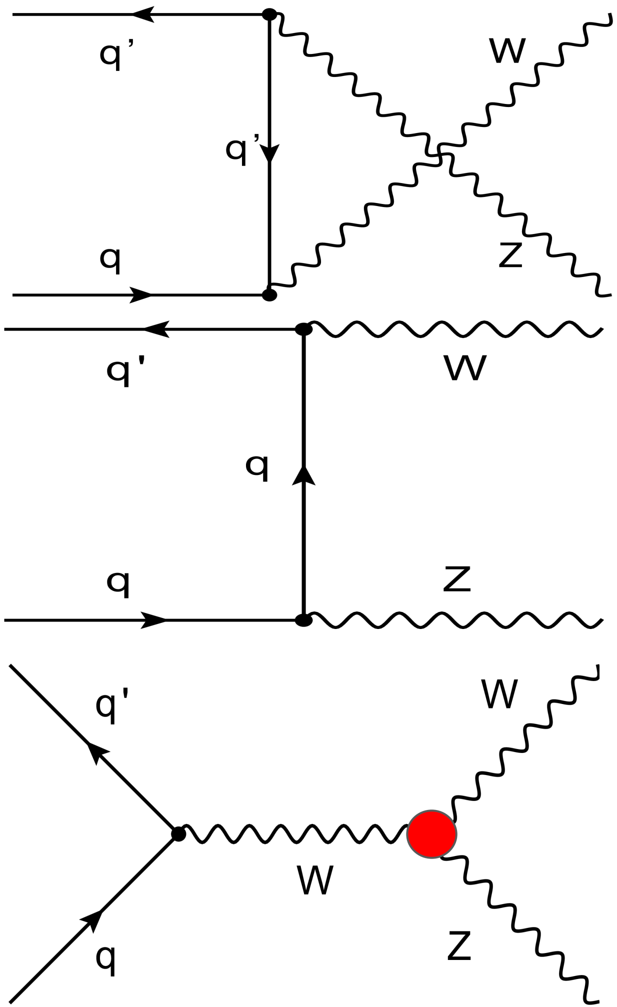
⇢ A door to several (relevant) points of high energy physics:

⇢ qq dominated initial state, leading to sensitivity to variations of the u/d quark PDFs.

⇢ Sensitive to **anomalies in the electroweak sector** in general, specifically the **triple gauge coupling WWZ**. Experimental leads to BSM physics:

⇢ **“Blind” searches** (EFTs) => Some today!

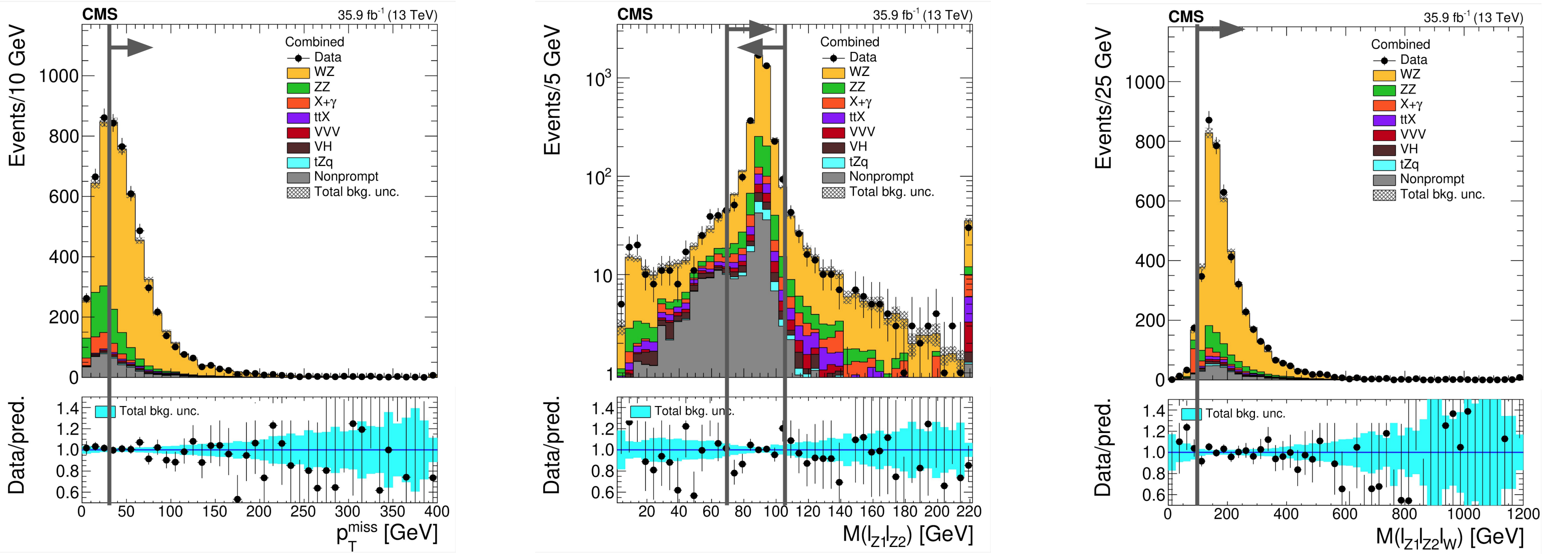
⇢ “Targeted” searches: SUSY, new resonances (i.e. exotic higgs), compositeness, etc.



WZ Inclusive cross-section

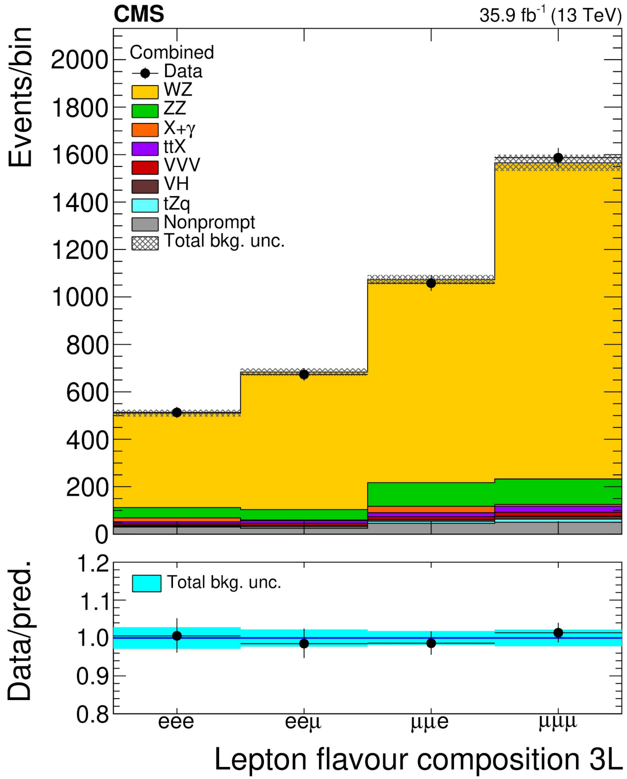
10.1007/JHEP04(2019)122

- Cross-section measured in the 3 lepton final state, both flavor-inclusive and flavor-exclusive.
- A signal-enriched region is designed to fit the WZ signal contribution
  - Per lepton non-prompt discriminant.
  - b-tag veto to reduce tt/ttZ presence.
  - **p_T^{miss} > 30 GeV** to reject ZZ/DY.
  - **$|m_{lZ1,lZ2} - m_Z^{pdg}| < 15$ GeV**; on-shell Z boson
  - **m_{3L} > 100 GeV**; against photon conversions



WZ Inclusive cross-section

⇢ Signal yields are obtained from a fit to the lepton flavor distribution in the signal region:



⇢ And then extrapolated to the "total" phase space, defined as **60 < m_Z < 120 GeV**. All W/Z decays included:

Category	$\sigma_{tot}(pp \to WZ)$ [pb]
eee	$47.11^{+5.01}_{-4.63}$ (total) $= 47.11^{+2.88}_{-2.79}$ (stat)$^{+0.46}_{-0.41}$ (theo)$^{+3.89}_{-3.47}$ (syst) ± 1.41 (lumi)
eeμ	$47.16^{+3.87}_{-3.61}$ (total) $= 47.16^{+2.31}_{-2.29}$ (stat)$^{+0.45}_{-0.38}$ (theo)$^{+2.83}_{-2.52}$ (syst) ± 1.33 (lumi)
e$\mu\mu$	$47.70^{+3.58}_{-3.55}$ (total) $= 47.70^{+2.00}_{-1.96}$ (stat)$^{+0.45}_{-0.39}$ (theo)$^{+2.66}_{-2.61}$ (syst) ± 1.42 (lumi)
$\mu\mu\mu$	$49.00^{+3.18}_{-3.03}$ (total) $= 49.00^{+1.57}_{-1.53}$ (stat)$^{+0.41}_{-0.35}$ (theo)$^{+2.42}_{-2.22}$ (syst) ± 1.39 (lumi)

⇢ Biggest uncertainties arise from lepton and b-tag efficiencies (~2-3%).

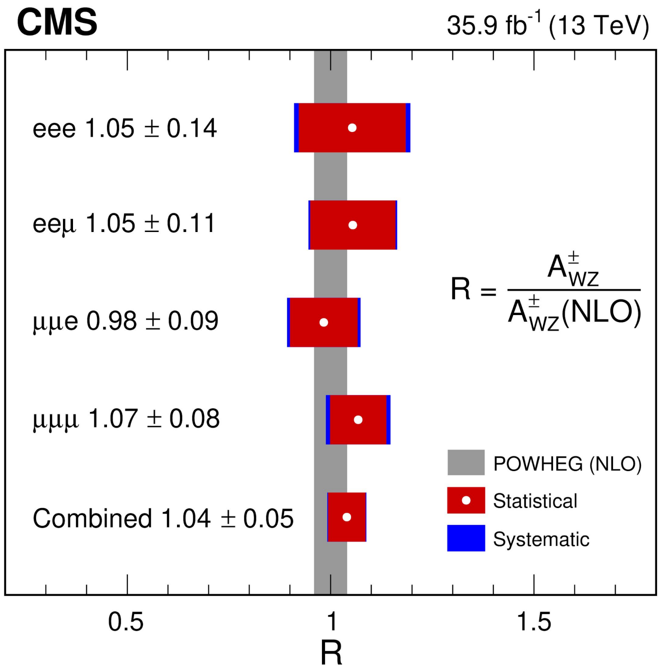
⇢ Measurement is closer to the MATRIX **σ_{NNLO} = 49.9±2.5 pb** than the POWHEG **σ_{NLO}= 42.5±1.7 pb** prediction.

Charge asymmetry measurements

⇢ We split all flavor channels based on final state charge and perform the same strategy to obtain charge split cross-sections. Then compute the **asymmetry ratio**:

$$A_{WZ}^{+-} = \frac{\sigma_{tot}(pp \to W^+Z)}{\sigma_{tot}(pp \to W^-Z)} = 1.48 \pm 0.06\,(stat) \pm 0.02\,(syst) \pm 0.01\,(theo)$$

⇢ Most uncertainties "cancel out", so result is **driven by statistical uncertainties**. Thus, the uncertainty scales directly with ~the square root of the luminosity.



⇢ Measurements already close to the level of theoretical uncertainties so we are already **close to be able to provide feedback to the PDF community in this channel**.

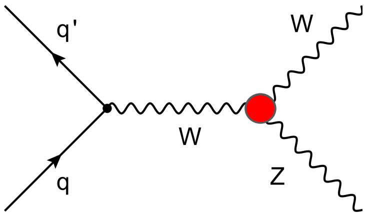
WZ in the EFT approach

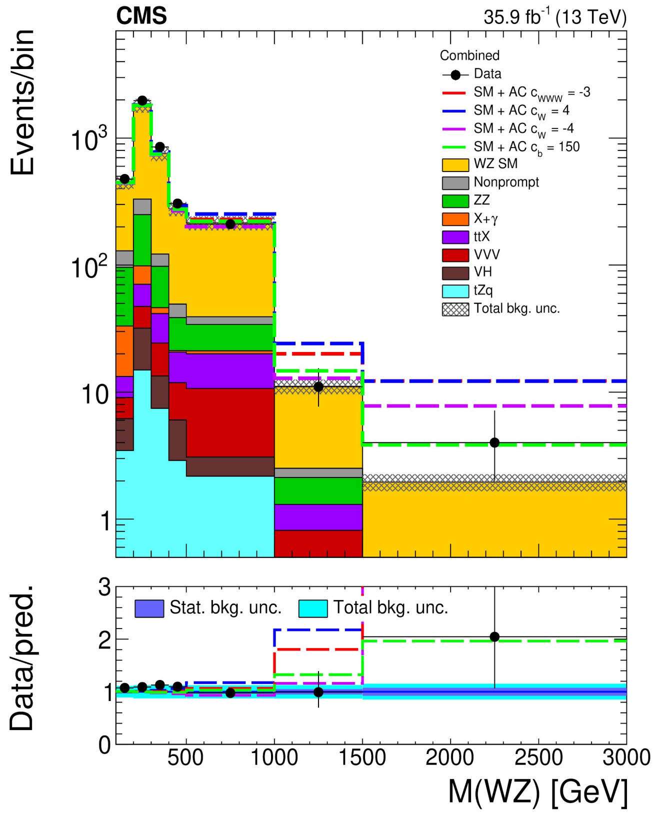
⇢ A reinterpretation of the measurements in terms of new physics searches is performed with BSM physics modelled through several **EFT CP even** terms (EWdim6, arXiv:1205.4231):

$$\delta\mathcal{L}_{AC} = c_{WWW}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}] + c_{W}\left(D_\mu H\right)^{\dagger} W^{\mu\nu}\left(D_\nu H\right) + c_{b}\left(D_\mu H\right)^{\dagger} B^{\mu\nu}\left(D_\nu H\right)$$

⇢ Greater signal sensitivities are obtained at the high momentum/invariant mass regions.

⇢ The **invariant mass of the WZ system** is a natural candidate for signal extraction as it also represents the energy scale of the process as well.





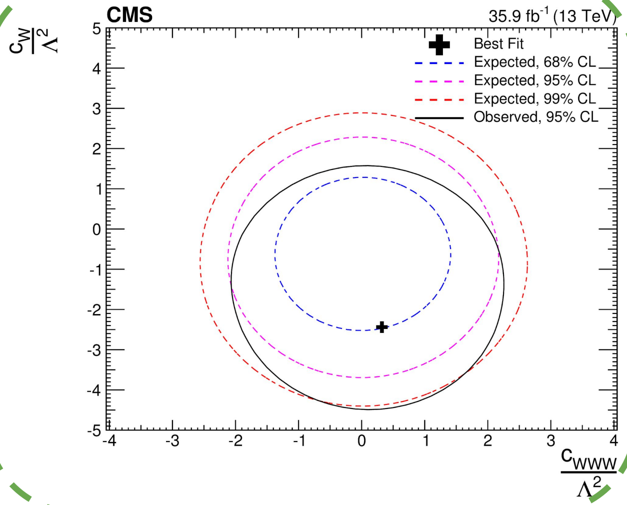
Anomalous Couplings searches (II)

⇢ Results have been obtained for 1D and 2D scans. Small deviations appear (**~1σ over SM**).

⇢ Also tested the "limitations" of the EFT approach:

⇢ Considering SM+BSM interference contributions only (as pure BSM is Λ^{-4} suppresed).

⇢ Applying mass cut-offs to the signal (no contribution beyond given values) we represent possible "breaks" of the EFT assumption at different energy scales.

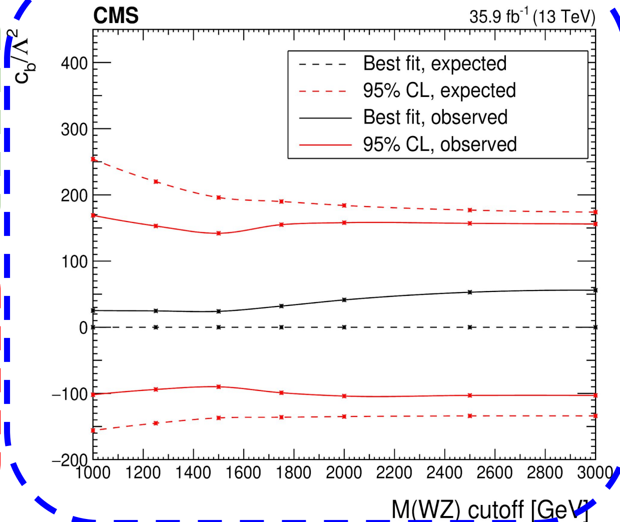


Parameter	95% CI (observed) $[\mathrm{TeV}^{-2}]$
c_W/Λ^2	$[-4.1, 1.1]$
c_{WWW}/Λ^2	$[-2.0, 2.1]$
c_b/Λ^2	$[-100, 160]$

Interference + pure BSM terms

Only interference terms

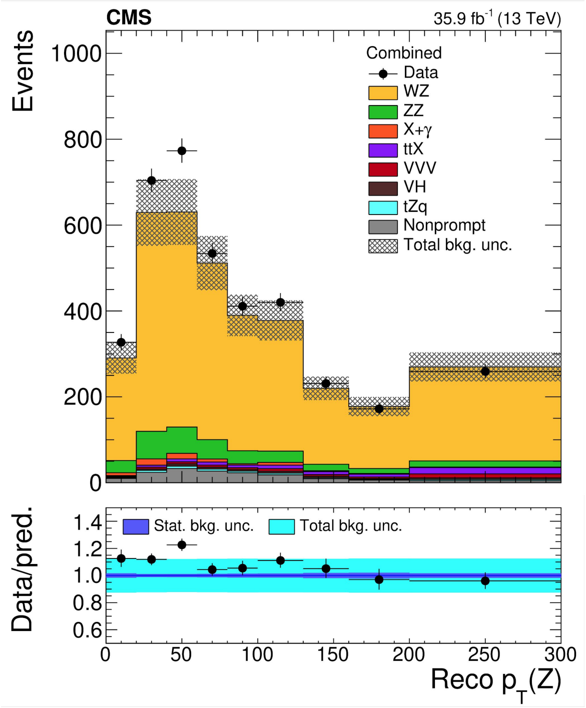
Parameter	95% CI (observed) $[\mathrm{TeV}^{-2}]$
c_W/Λ^2	$[-2.2, 2.7]$
c_{WWW}/Λ^2	$[-13.8, 41.2]$
c_b/Λ^2	$[-230, 390]$



Differential cross-section(s) measurements

⇢ Differential cross-sections are computed for several relevant observables: p_T(leading jet), p_T(W), p_T(Z), M(WZ).

⇢ A comparison with both POWHEG and aMC@NLO predictions shows consistent results.



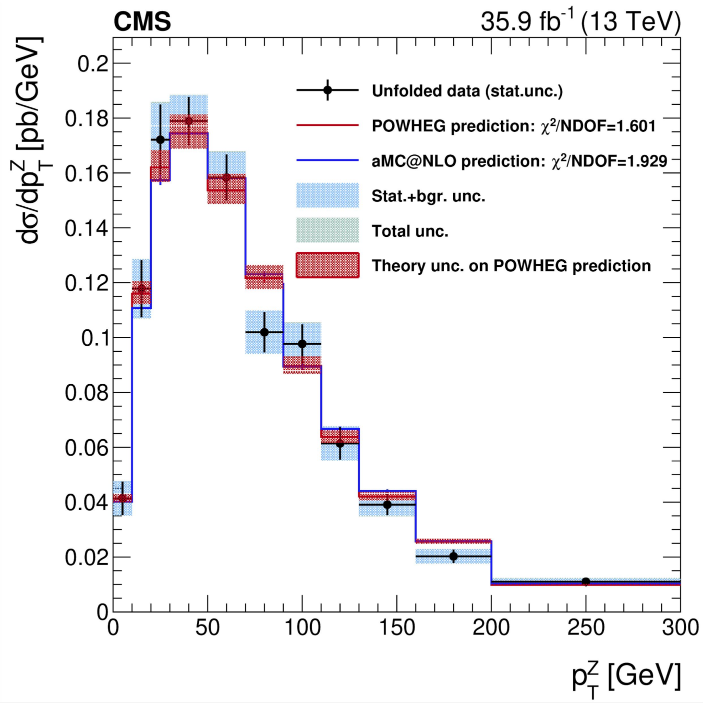
-Binning strategy designed to obtain near-diagonal response matrix (i.e. perfect detector response)

Unfolding using TUnfold and:

- Yields area constrain.

-Bias scale (towards measured total x-sec).

-No additional (i.e. Tikhonov) regularization terms.



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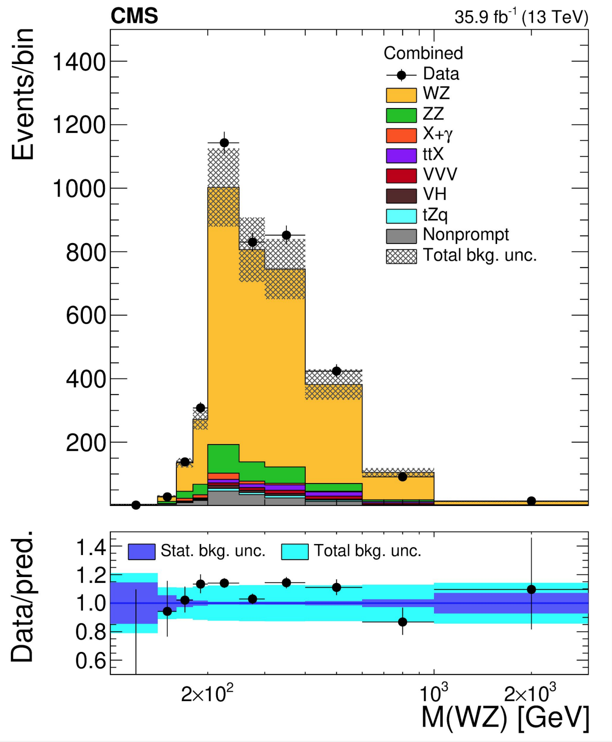

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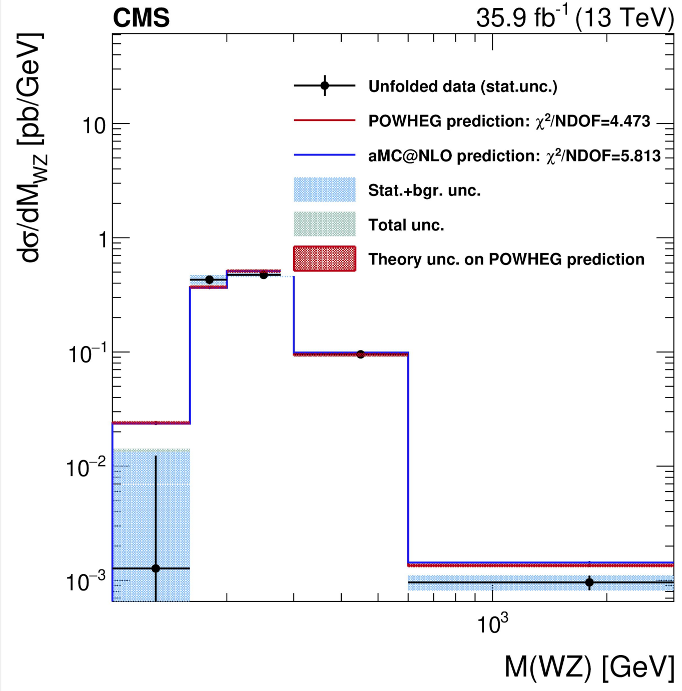

A look to the future

⇢ We have successfully studied WZ production with a subset of current LHC data, but many things can be improved with the Run II:

⇢ Increased statistics affect measurements both directly (data) and indirectly (systematic estimation). We might be able to reach **sub-5% precision**.

⇢ Plenty of new territories to explore:

⇢ Can we **increase our knowledge of the PDFs**?

⇢ High enough precision to study polarized cross-sections. What can we say about **longitudinally polarized bosons**?

⇢ So far we have assumed that possible BSM is CP even. What can we say about **CP odd EFTs**?

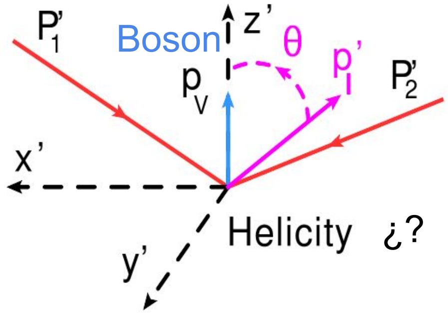

Figure from arXiv:1810.11034

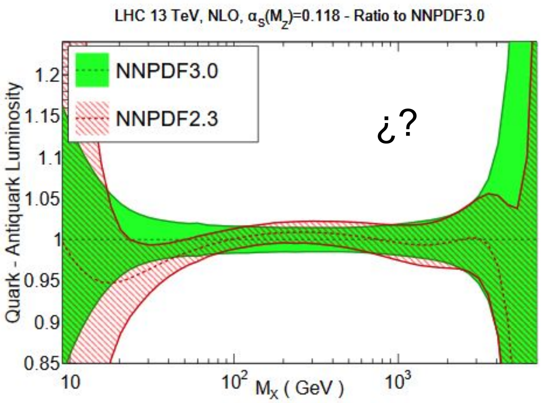

Figure from arXiv:1410.8849

Back-Up

Background control regions

⇢ Several control regions are designed to validate the MC background predictions and estimate normalization uncertainties:

Region	N_ℓ	$p_T\{\ell_{Z1}, \ell_{Z2}, \ell_W, \ell_4\}$ [GeV]	N_{OSSF}	$\lvert M(\ell_{Z1}\ell_{Z2}) - m_Z\rvert$ [GeV]	p_T^{miss} [GeV]	$N_{b\,tag}$	$\min(M(\ell\ell'))$ [GeV]	$M(\ell_{Z1}\ell_{Z2}\ell_W)$ [GeV]
SR	=3	>{25, 10, 25}	≥1	<15	>30	=0	>4	>100
CR-top	=3	>{25, 10, 25}	≥1	>5	>30	>0	>4	>100
CR-ZZ	=4	>{25, 10, 25, 10}	≥1	<15	>30	=0	>4	>100
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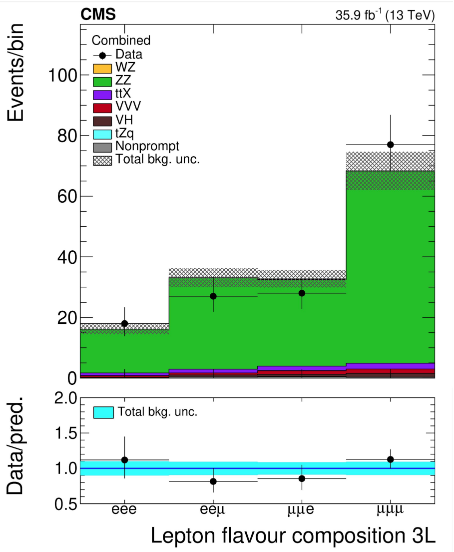

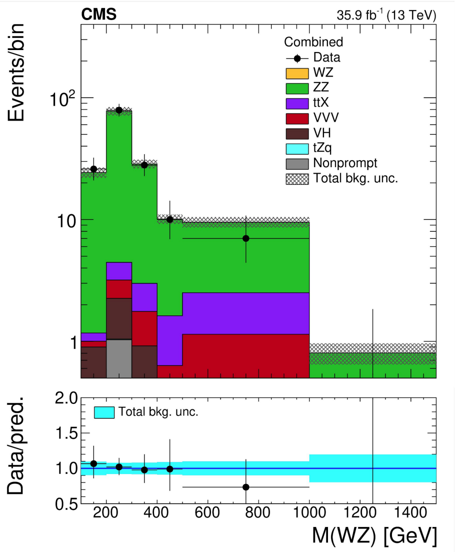

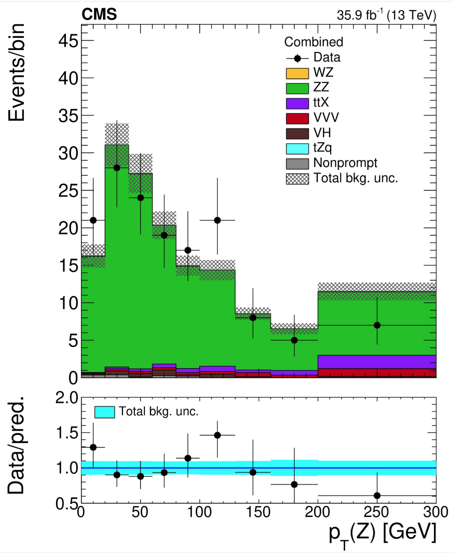

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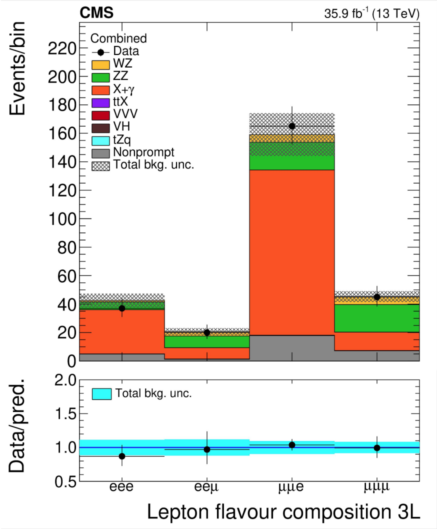

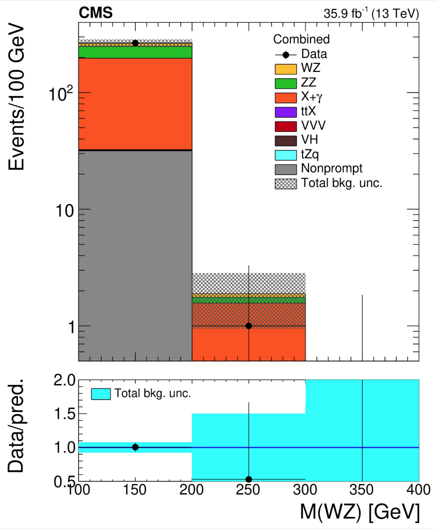

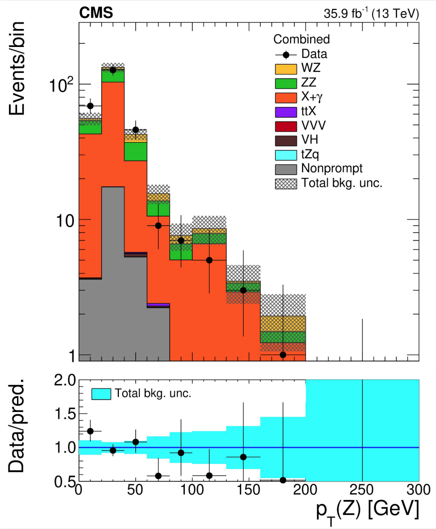

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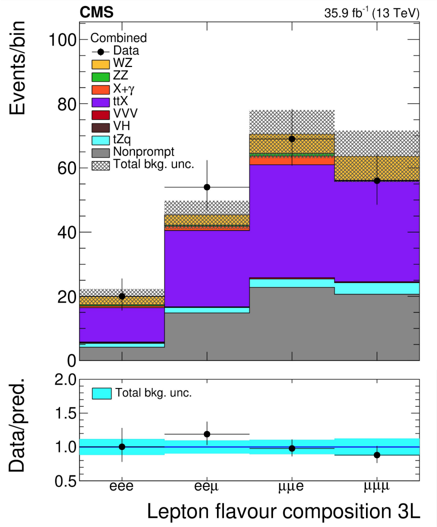

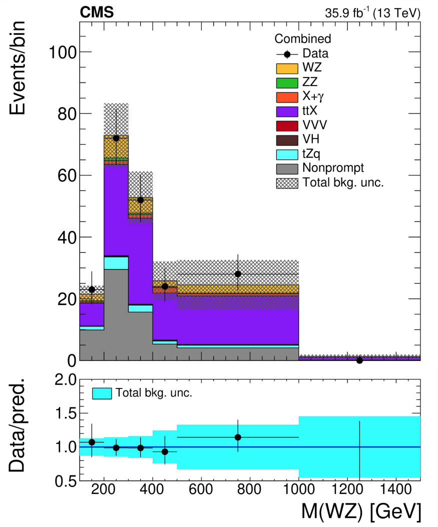

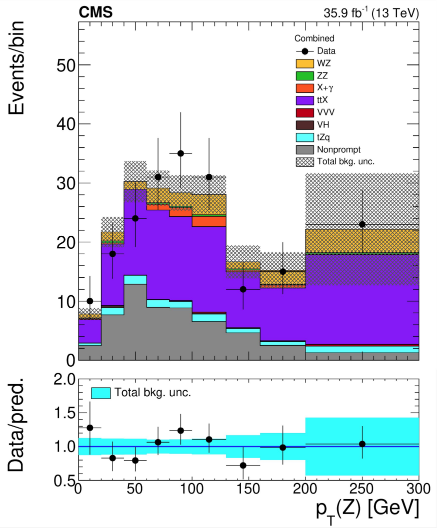

Inclusive measurement uncertainties and yields

Source	Combined	eee	eeμ	e$\mu\mu$	$\mu\mu\mu$
Electron efficiency	1.9	5.9	3.9	1.9	—
Electron energy scale	0.3	0.9	0.2	0.6	—
Muon efficiency	1.9	—	0.8	1.8	2.6
Muon momentum scale	0.5	—	0.7	0.3	0.9
Trigger efficiency	1.9	2.0	1.9	1.9	1.8
Jet energy scale	0.9	1.6	1.0	1.7	0.8
b-tagging (id.)	2.6	2.7	2.6	2.6	2.4
b-tagging (mis-id.)	0.9	1.0	0.9	1.0	0.7
Pileup	0.8	0.9	0.3	1.3	1.4
ZZ	0.6	0.7	0.4	0.8	0.5
Nonprompt norm.	1.2	2.0	1.2	1.5	1.0
Nonprompt (EWK subtr.)	1.0	1.5	1.0	1.3	0.8
VVV norm.	0.5	0.6	0.6	0.6	0.5
V H norm.	0.2	0.2	0.3	0.2	0.2
$t\bar{t}$ V norm.	0.5	0.5	0.5	0.5	0.5
tZq norm.	0.1	0.1	0.1	0.1	0.1
X+γ norm.	0.3	0.8	< 0.1	0.7	< 0.1
Total systematic	4.7	7.8	5.8	5.4	4.6
Integrated luminosity	2.8	2.9	2.8	2.9	2.8
Statistical	2.1	6.0	4.8	4.1	3.1
Total experimental	6.0	10.8	8.0	7.5	6.3
Theoretical	0.9	0.9	0.9	0.9	0.9

Process	eee	eeμ	e$\mu\mu$	$\mu\mu\mu$	Total
Nonprompt	30.0 ± 12.4	25.0 ± 10.4	45.7 ± 20.7	50.3 ± 19.3	151 ± 63
ZZ	43.4 ± 4.1	44.4 ± 3.4	100.1 ± 9.2	107.1 ± 8.3	295 ± 24
Xγ	16.8 ± 5.2	2.0 ± 0.7	26.9 ± 8.8	7.6 ± 2.0	53 ± 16
$t\bar{t}$ V	8.5 ± 2.8	11.6 ± 4.1	16.8 ± 5.5	25.8 ± 9.0	63 ± 21
VVV	6.2 ± 2.5	8.6 ± 3.4	11.4 ± 4.6	16.9 ± 6.8	43 ± 17
V H	3.3 ± 0.8	6.4 ± 1.6	7.7 ± 1.9	12.1 ± 3.0	29.6 ± 7.2
tZq	3.9 ± 1.30	5.7 ± 1.9	8.4 ± 2.8	12.6 ± 4.3	31 ± 10
Total background	112 ± 15	104 ± 15	217 ± 28	233 ± 29	666 ± 45
WZ	398 ± 18	579 ± 21	856 ± 29	1333 ± 47	3166 ± 62
Data	513 ± 23	673 ± 26	1058 ± 32	1587 ± 40	3831 ± 62

⇢ Yields are presented after the signal extraction fit is performed (to the lepton flavor distribution).

⇢ The contribution of each uncertainty is computed by freezing the associated nuisances, recomputing the best fit and its uncertainties, and subtracting quadratically.