EW precision measurements at CMS

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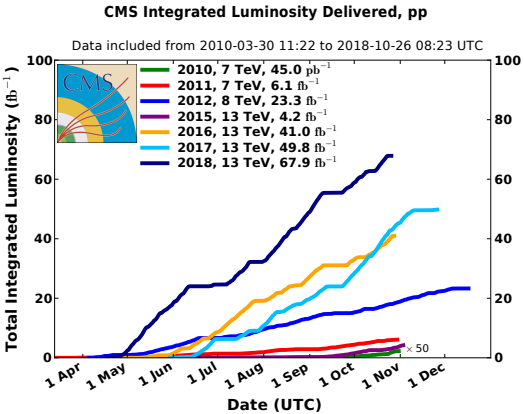
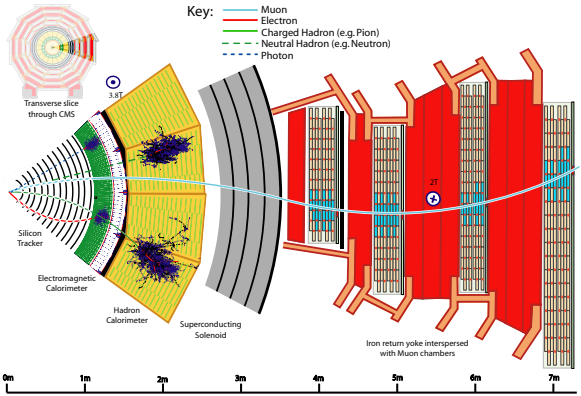
Introduction

- Unprecedented datasets, containing billions of vector bosons
- Precise instrumentation; in particular tracking, ECAL, and muon system





- Measurements of DY production (sensitive to QCD radiation and PDFs)
- Measurements of multi-boson processes, self-couplings could be modified by BSM physics

Differential Z boson production cross sections

CMS PAS-SMP-17-010

- Require 2 opposite-sign same-flavor isolated leptons, with $|\eta| < 2.4$, $p_T > 25$ GeV
- Z mass window $|m_{\ell\ell} - 91.2\,\text{GeV}| < 15$ GeV
- 1% background, estimated from MC or from OS-OF dilepton events

Fiducial cross section

Cross section	$\sigma\,\mathcal{B}$ [pb]
$\sigma_{Z\to\mu\mu}$	$694 \pm 6\,(\text{syst}) \pm 17\,(\text{lumi})$
$\sigma_{Z\to ee}$	$712 \pm 10\,(\text{syst}) \pm 18\,(\text{lumi})$
$\sigma_{Z\to\ell\ell}$	$699 \pm 5\,(\text{syst}) \pm 17\,(\text{lumi})$

FEWZ prediction (NNLO): $\sigma_{Z\to\ell\ell} = 719 \pm 8$ pb

Uncertainties

Source	$Z \to \mu\mu$ (%)	$Z \to ee$ (%)
Luminosity	2.5	2.5
Muon reconstruction efficiency	0.4	-
Muon selection efficiency	0.7	-
Muon momentum scale	0.1	-
Electron reconstruction efficiency	-	0.9
Electron selection efficiency	-	1.0
Electron momentum scale	-	0.2
Background estimation	< 0.1	< 0.1
Total (excluding luminosity)	0.8	1.4

Differential measurement

- Dilepton p_T, rapidity, p_T vs. rapidity, and $\phi^* \sim p_T/m_{\ell\ell}$
- Unfolded to the particle level, using dressed lepton definition

Differential Z boson production cross sections: p_T

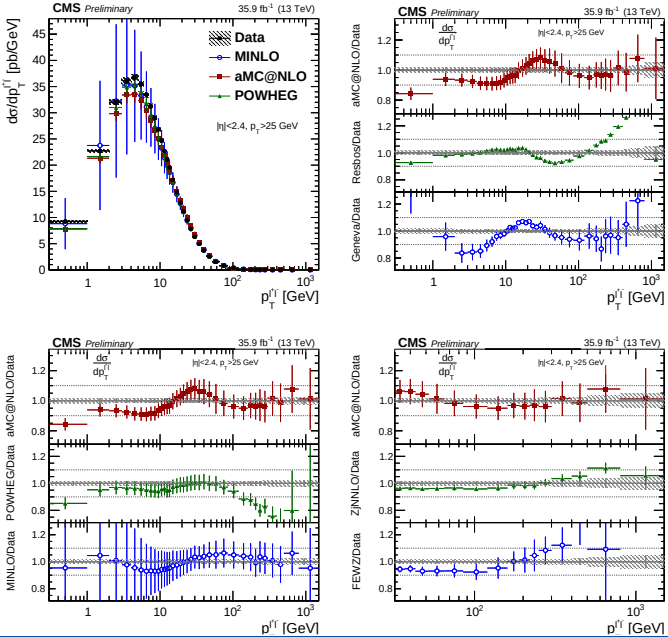
CMS PAS-SMP-17-010

- Showing absolute cross sections. Normalized versions have uncertainty $< 1\%$ in most bins

Comparison with

- lower left: aMC@NLO (Z+0,1,2j@NLO), Powheg (NLO), MiNLO (Z+0,1j@NLO, unc. overestimated at low p_T)
- upper right: aMC@NLO, ResBos, Geneva (both NNLO+NNLL)
- lower right: aMC@NLO, ZjNNLO, FEWZ (NNLO)

EW corrections expected to be relevant at $p_T > 500$ GeV



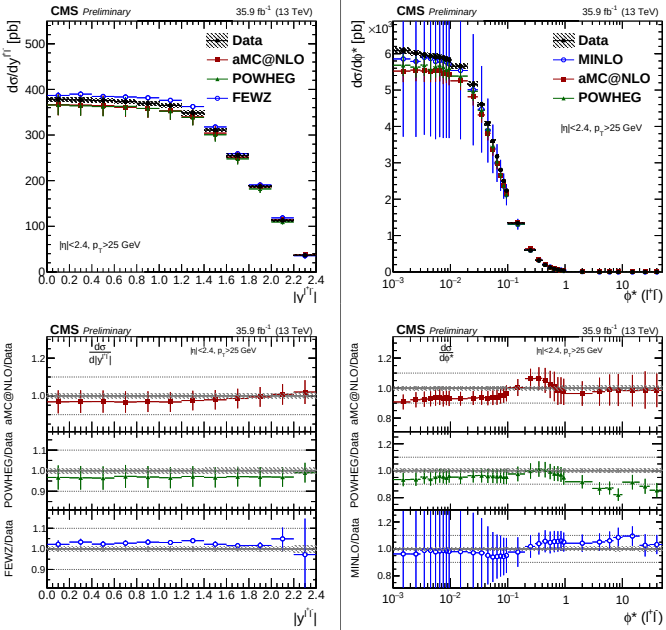
Differential Z boson production cross sections: y, ϕ^*

CMS PAS-SMP-17-010

- Showing absolute cross sections. Normalized versions have uncertainty $< 1\%$ in most bins

Comparison with

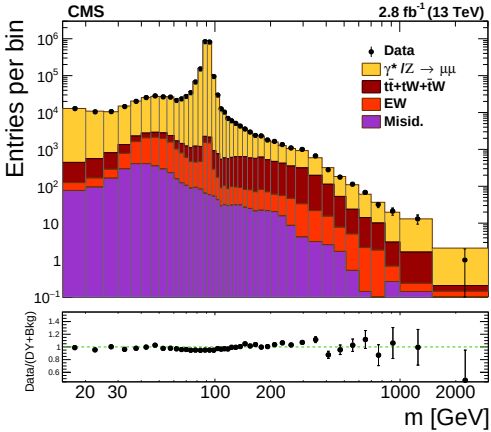
- y (left): aMC@NLO, Powheg, FEWZ
- ϕ^* (right): aMC@NLO, Powheg, Powheg MiNLO (MiNLO scale uncertainties overestimated at low p_T)

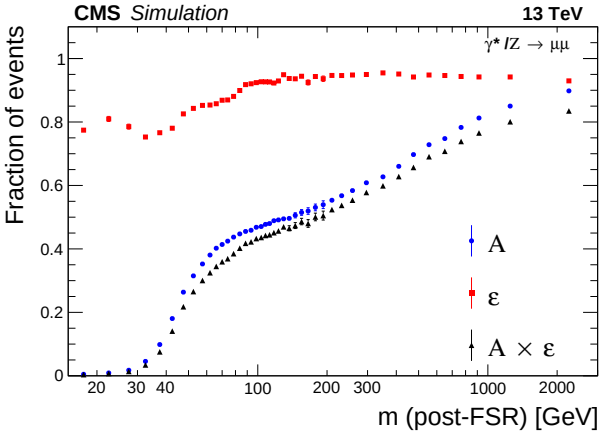


Differential Z boson production cross sections: $m(\ell\ell)$

CMS SMP-17-001

- Require leading muon (electron) $p_T > 22\,(30)$ GeV, $|\eta| < 2.4\,(2.5)$
  + additional opposite-sign muon (electron, w/o OS requirement) with $p_T > 10$ GeV



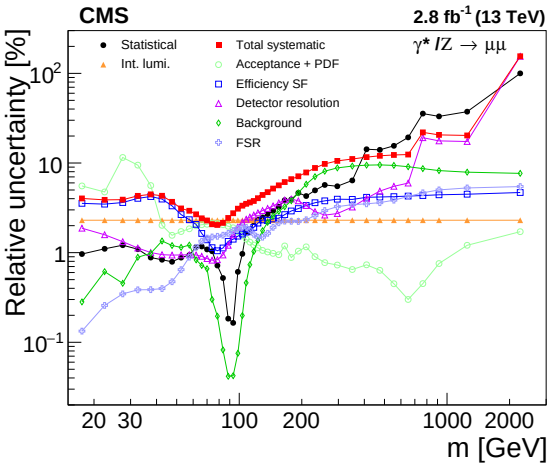


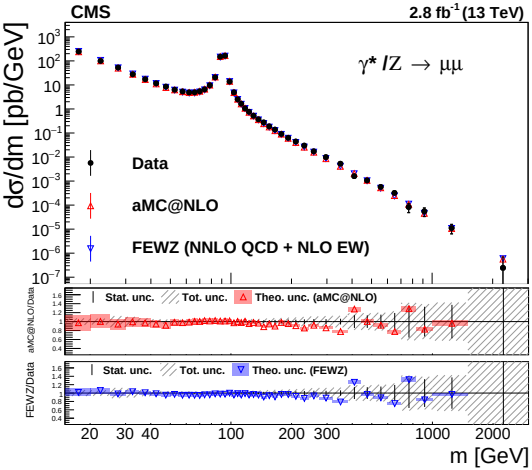
- Data unfolded to fiducial ($\propto 1/\varepsilon$) and full phase space ($\propto 1/(A \times \varepsilon)$)

Differential Z boson production cross sections: $m(\ell\ell)$

CMS SMP-17-001

- Most important uncertainties: acceptance at low mass, background and statistical at high mass; total uncertainty 2-10% up to 200 GeV



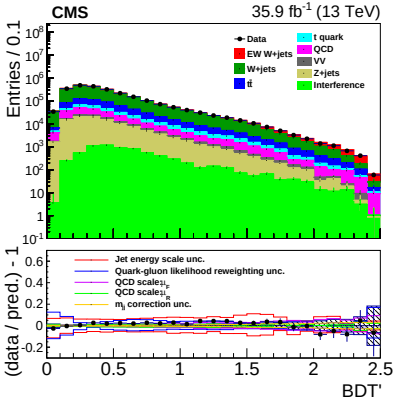


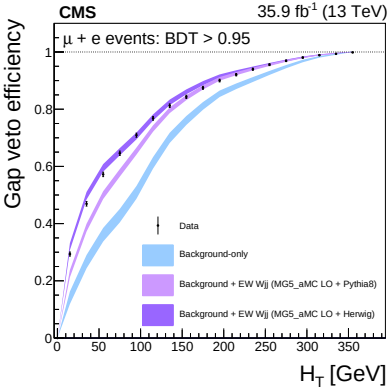
- Excellent agreement with aMCatNLO and FEWZ (NNLO)

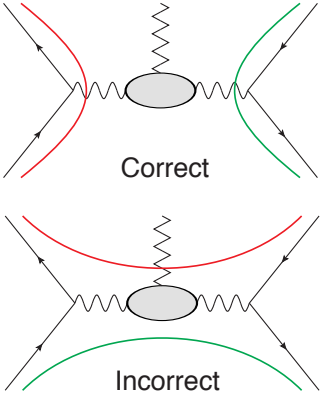
EW production of Wjj

CMS SMP-17-011

- $\mu\,(e)$ with $p_{\mathrm{T}} > 25\,(30)$ GeV, $|\eta| < 2.4$, $p_{\mathrm{T}}^{\mathrm{miss}} > 20(40)$ GeV, $m_{\mathrm{T}}\left(p_{\mathrm{T}}^{\mu}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right) > 40$ GeV
- 2 jets with $p_{\mathrm{T}} > 50/30$ GeV and $m_{jj} > 200$ GeV; event p_{T} balance $R\,(p_{\mathrm{T}}) < 0.2$
- Train BDT using m_{jj}, $\Delta\eta_{jj}$, z^*, quark-gluon likelihood: $f_{\mathrm{sig}} = 2 \rightarrow 43\%$ (BDT'> 2.185)





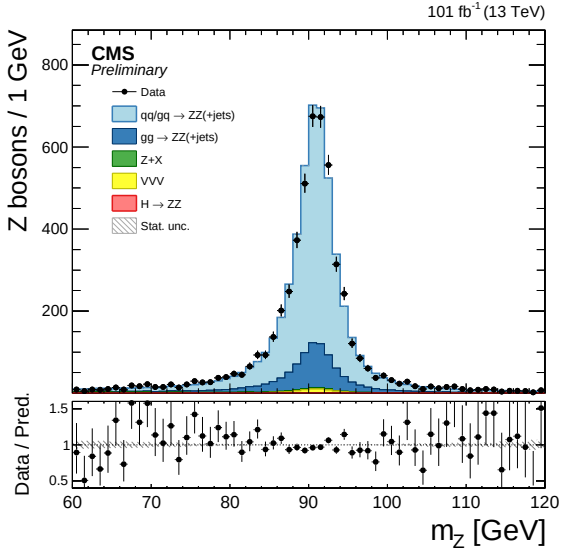


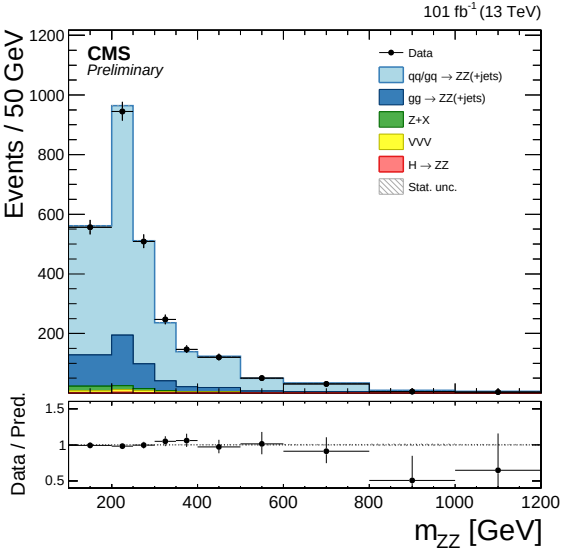
- Result: $\sigma\,(\mathrm{EW}\ \ell\nu jj) = 6.23 \pm 0.12\,(\mathrm{stat}) \pm 0.61\,(\mathrm{syst})$ pb, signal strength $\mu = 0.91 \pm 0.10$
- Additional jet observables sensitive to treatment of color connections

ZZ production

CMS PAS-SMP-19-001

- Require 2 Z/γ^* candidates with $60 < m_{Z1,2} < 120$ GeV, 2017+2018 data $\rightarrow 101\,\mathrm{fb}^{-1}$
- Backgrounds suppressed by $p_T^{miss} < 25$ GeV, $m_T < 30$ GeV, constrained in control regions





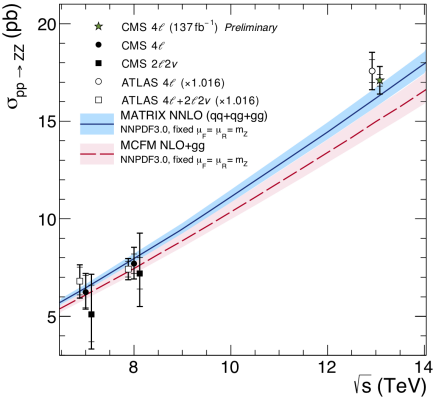
ZZ production

CMS PAS-SMP-19-001

- Fiducial: $p_T^{\ell 1} > 20, p_T^{\ell 2} > 10, p_T^{\ell 3,4} > 5\,\text{GeV}, \left|\eta^{\ell}\right| < 2.5, m_{\ell^+\ell^-} > 4\,\text{GeV}, 60 < m_{Z1,2} < 120\,\text{GeV}$
- Total: $m_{\ell^+\ell^-} > 4\,\text{GeV}, 60 < m_{Z1,2} < 120\,\text{GeV}$, in agreement with MATRIX NNLO

Year	Fiducial cross section, fb
2016 [?]	$40.9 \pm 1.3\,(\text{stat}) \pm 1.4\,(\text{syst}) \pm 1.0\,(\text{lumi})$
2017	$39.1 \pm 1.2\,(\text{stat}) \pm 1.2\,(\text{syst}) \pm 1.0\,(\text{lumi})$
2018	$39.2 \pm 1.0\,(\text{stat}) \pm 1.3\,(\text{syst}) \pm 1.0\,(\text{lumi})$
Combined	$39.9 \pm 0.7\,(\text{stat}) \pm 1.0\,(\text{syst}) \pm 0.7\,(\text{lumi})$

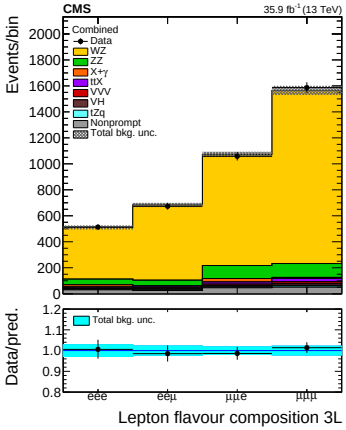
Year	Total cross section, pb
2016 [?]	$17.5^{+0.6}_{-0.5}\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2017	$16.8 \pm 0.5\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2018	$16.8 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
Combined	$17.1 \pm 0.3\,(\text{stat}) \pm 0.4\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})$

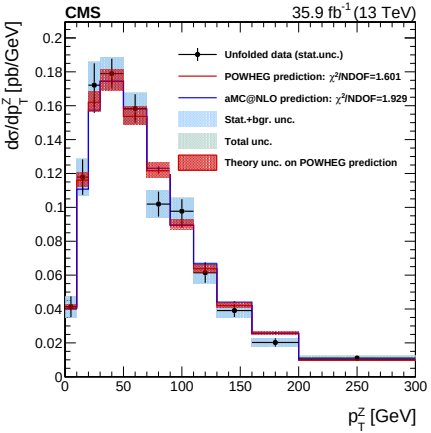


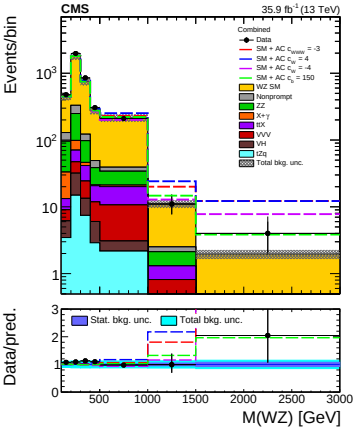
WZ inclusive and differential cross sections

CMS SMP-18-002

- Select events with 3 leptons $p_T^{\ell Z1} > 25$, $p_T^{\ell Z2} > 10$, $p_T^{\ell W} > 25$ GeV,
  signal region: $|m_{\ell\ell} - m_Z| < 15$ GeV, $p_T^{miss} > 30$ GeV, no b jet, $m_{\ell\ell\ell} > 100$ GeV, no $\ell 4$
- Inclusive result: $\sigma_{WZ} = 48.09^{+1.00}_{-0.96}\,(stat)^{+0.44}_{-0.37}\,(theo)^{+2.39}_{-2.17}\,(syst) \pm 1.39\,(lumi)$ pb,
  in agreement with MATRIX NNLO prediction of $49.98^{+1.10}_{-1.00}$ pb





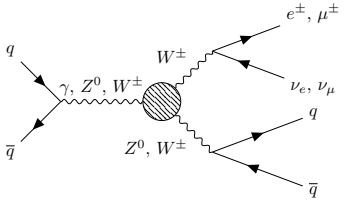


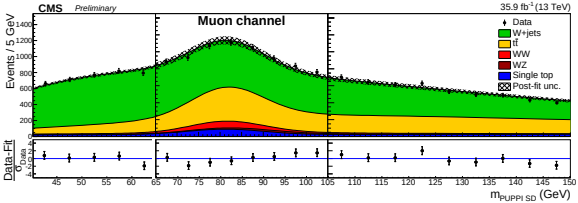
- Results also for fiducial cross section, split by charge, differential in $p_T^Z, p_T^W, p_T^j, m_{WZ}$

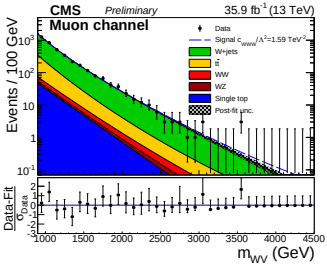
Anomalous couplings in semileptonic WW and WZ decays

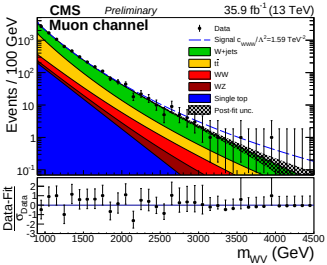
CMS **PAS-SMP-18-008**

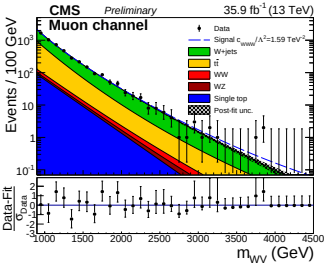
- Require muon (electron) with $p_\mathrm{T} > 53\,(50)$ GeV, $|\eta| < 2.4\,(2.5)$, $p_\mathrm{T}^{\mathrm{miss}} > 40\,(110)$ GeV
- $p_\mathrm{T}^{\mathrm{W}_\ell} > 200$ GeV; AK8 jet with $p_\mathrm{T} > 200$ GeV → hadronic V candidate, $m_{WV} > 900$ GeV
- Reject b jets ($\mathrm{t\bar{t}}$); apply PUPPI+SD on AK8, $\tau_{21} < 0.55$, W+jets from sidebands









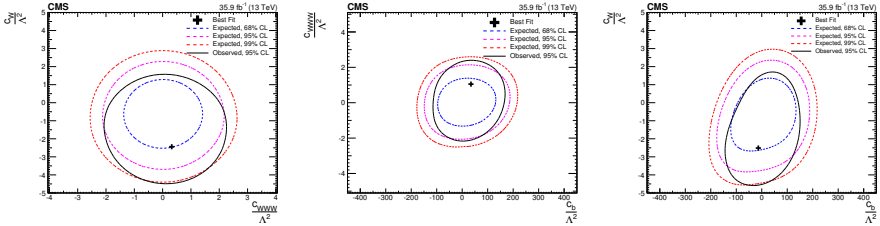


Limits on anomalous couplings

$$\delta\mathcal{L}_{\rm AC} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] + \frac{c_W}{\Lambda^2}\left(D_\mu H\right)^\dagger W^{\mu\nu}\left(D_\nu H\right) + \frac{c_B}{\Lambda^2}\left(D_\mu H\right)^\dagger B^{\mu\nu}\left(D_\nu H\right)$$

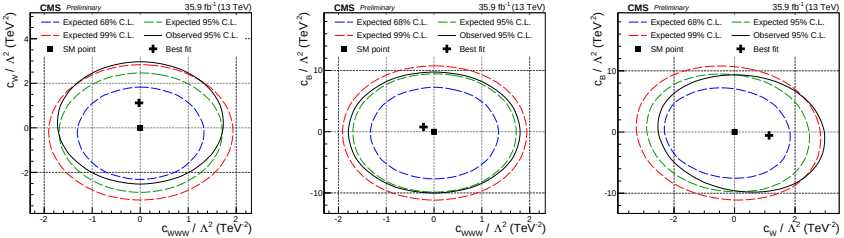
3-lepton analysis CMS SMP-18-002

- From M(WZ) up to 3 TeV
- No excess observed



Boosted analysis CMS PAS-SMP-18-008

- From M(WV) up to 4.5 TeV
- Gained factor >10 in $\mathcal{C}_B$ limit from WW component



Summary

- EW processes measured at CMS over 9 orders of magnitude
- No deviation from NNLO predictions → stringent limits on anomalous couplings