Multiboson production in CMS

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on behalf of the CMS Collaboration

Deep Inelastic Scattering 2022 - Santiago de Compostela

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Multiboson production in CMS

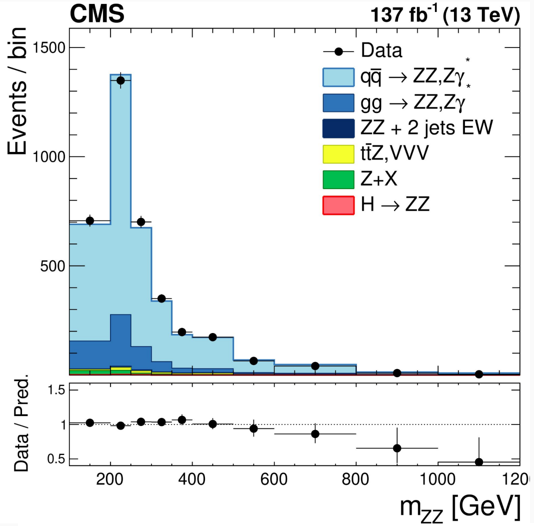
- Many CMS analyses targeting multiboson final states
- Rare processes, high energies
- Di- and triboson production allow probing the EW symmetry breaking mechanism, in parallel to the study of the Higgs boson
- Triple and quartic gauge couplings are sensitive to BSM physics
  - Limits on new operators, often in the Effective Field Theories framework or in terms of anomalous quartic couplings
- Diboson production is in the precision regime
- Triboson production measured in increasingly more channels
- I will discuss analyses targeting inclusive diboson and triboson production, since Vector Boson Scattering is the focus of another talk

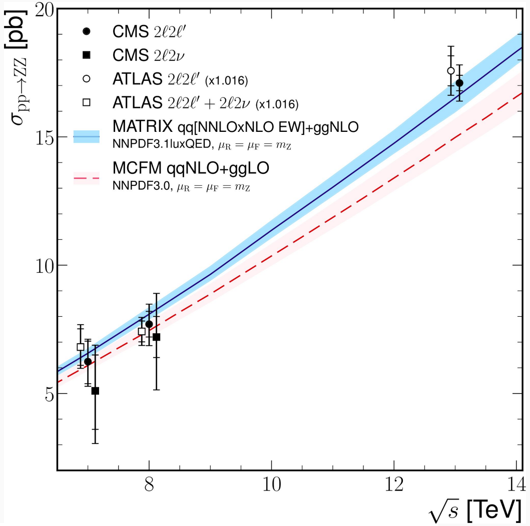
$ZZ \rightarrow 4\ell$ ($\ell = e, \mu$)

SMP-19-001

- Produced mainly via qq t- and u-channel (~ 90 %) and gg → loop (~ 10 %)
- No tree-level contribution from TGC in SM → probe aTGC
- Overall a very clean channel
  - Main background: nonprompt leptons → from data CRs
  - Rare backgrounds (from MC): ttZ, VVV

- Measurement of the fiducial cross section
- Total cross section
- Compare different MC generator predictions





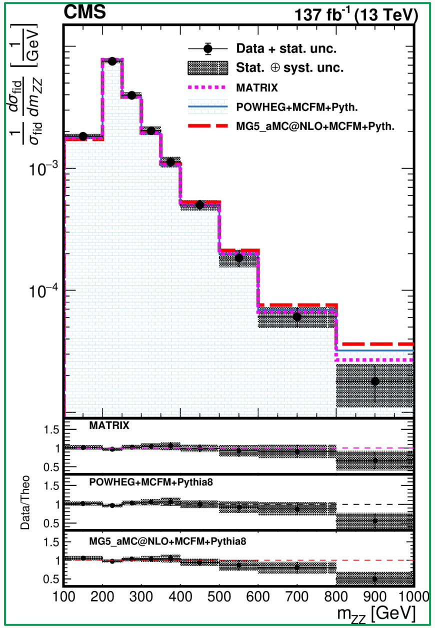
σ_{fid} = 40.5 ± 0.7 (stat) ± 1.1 (syst) ± 0.7 (lumi)

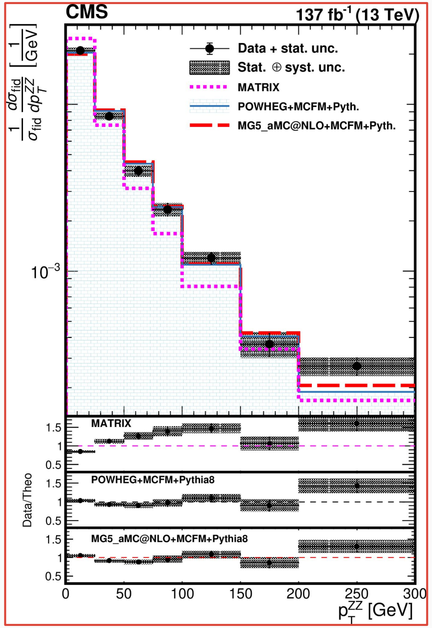
σ_{tot} = 17.4 ± 0.3 (stat) ± 0.5 (syst) ± 0.4 (theo) ± 0.3 (lumi)

$ZZ \rightarrow 4\ell$ ($\ell = e, \mu$) - results

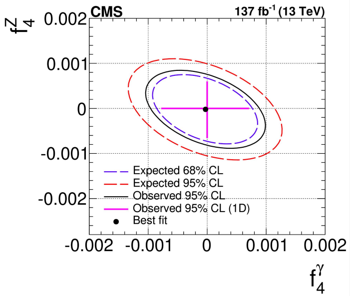
SMP-19-001

- Differential cross sections for **m_{ZZ}**, p_T^{ℓ}, p_T^{Z}, **p_T^{ZZ}**, $\Delta\varphi(Z_1,Z_2)$, $\Delta R(Z_1,Z_2)$
- Background correction and detector response unfolded with MC

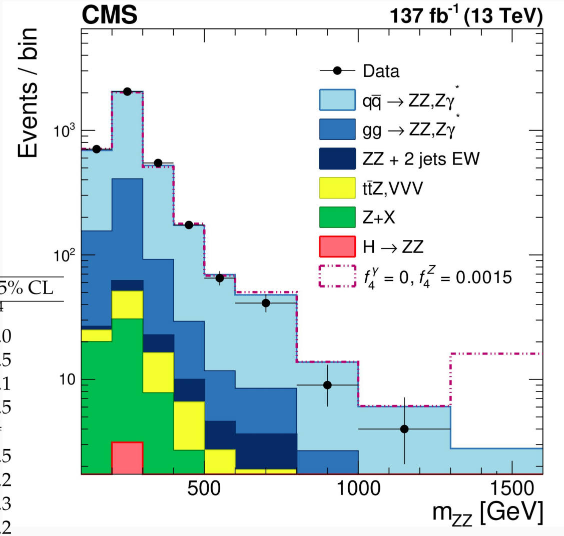




- Limits from fit to the m_{ZZ} distribution
- Mostly high energy tail (m_{ZZ} > 1300 GeV) affected
- 1D and 2D limits with all other coupling set to 0
  - CP-conserving (f_4^{γ}, f_4^{Z})
  - CP-violating (f_5^{γ}, f_5^{Z})



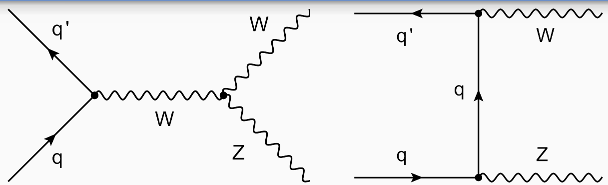
	Expected 95% CL	Observed 95% CL
aTGC parameter	$\times 10^{-4}$	$\times 10^{-4}$
f_4^Z	-8.8 ; 8.3	-6.6 ; 6.0
f_5^Z	-8.0 ; 9.9	-5.5 ; 7.5
f_4^{γ}	-9.9 ; 9.5	-7.8 ; 7.1
f_5^{γ}	-9.2 ; 9.8	-6.8 ; 7.5
EFT parameter	TeV^{-4}	TeV^{-4}
$C_{\tilde{B}W}/\Lambda^4$	-3.1 ; 3.3	-2.3 ; 2.5
C_{WW}/Λ^4	-1.7 ; 1.6	-1.4 ; 1.2
C_{BW}/Λ^4	-1.8 ; 1.9	-1.4 ; 1.3
C_{BB}/Λ^4	-1.6 ; 1.6	-1.2 ; 1.2

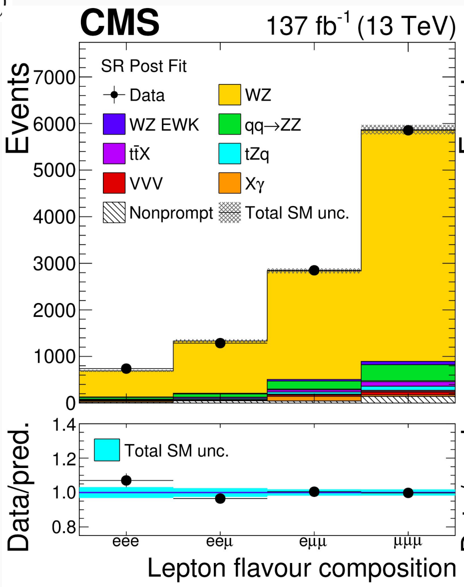


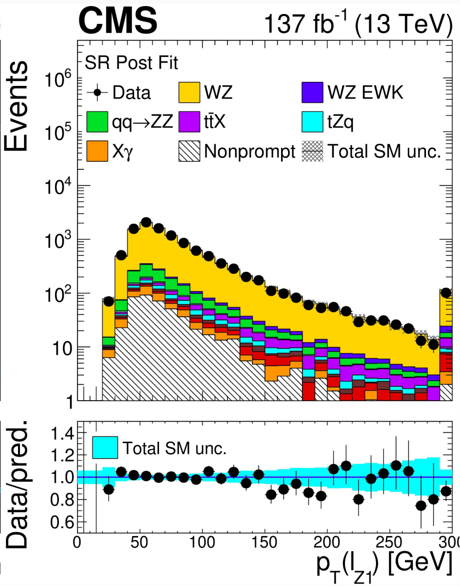
$WZ \rightarrow 3\ell\,\nu$

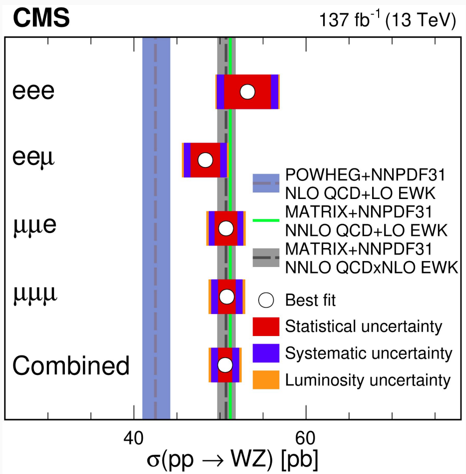
SMP-20-014

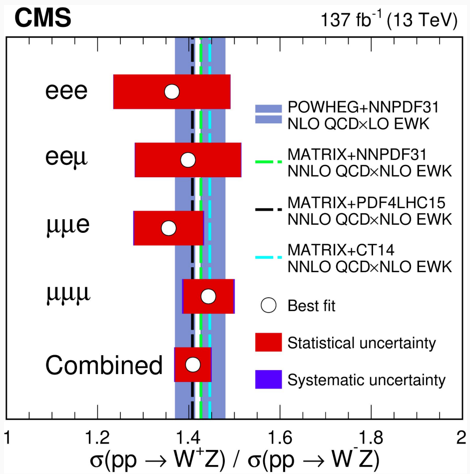
- Produced only by qq’ at tree level
- Sensitive to the WWZ TGC and to charge asymmetry → $A^{+-}_{WZ} = \frac{\sigma_{fid}(pp \rightarrow W^{+}Z)}{\sigma_{fid}(pp \rightarrow W^{-}Z)}$
- Nonprompt leptons: tight-to-loose
- Irreducible bkg: MC shape + normalization in CRs
  - ZZ (~6% of yield in SR), ttZ and tZq (~3.2%), X+γ (~1.5 %)











σ_{fid} = 40.5 ± 0.7 (stat) ± 1.1 (syst) ± 0.7 (lumi) fb

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

$W^+W^- \to \ell^+\ell^- 2\nu$

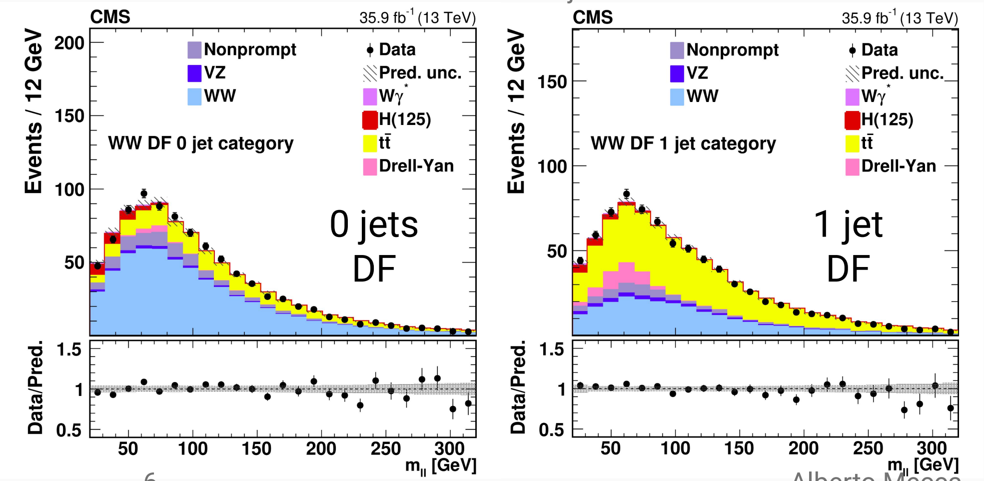
SMP-18-004

- Produced via qq annihilation (~95 %), gg-induced loop (~5 %) and H → WW (background)
- Signature: 2 isolated leptons and large p_T^{miss}
- Main background processes: tt, DY and **W+jets**
  - Lepton FR(p_T, η) is measured in QCD-enriched data
  - Applied in CR with 1 passing and 1 failing lepton
- Two analysis: sequential cut (σ_{tot}, $\sigma_{0/1j}$, $d\sigma_{0j}/dp_t^{THR}$) and Random Forest (σ_{tot} , $d\sigma/dn_j$)

Quantity	Sequential Cut DF	Sequential Cut SF
Number of leptons	Strictly 2	
Lepton charges	Opposite	
$p_T^{\ell\,max}$	>25	
$p_T^{\ell\,min}$	>20	
$m_{\ell\ell}$	>20	>40
Additional leptons	0	
$\lvert m_{\ell\ell} - m_Z \rvert$	—	>15
$p_T^{\ell\ell}$	>30	>30
p_T^{miss}	>20	>55
$p_T^{miss,proj}$, $p_T^{miss,track\ proj}$	>20	>20
Number of jets	≤1	
Number of b-tagged jets	0	
DYMVA score	—	>0.9
Drell–Yan RF score S_{DY}	—	—
$t\bar{t}$ RF score $S_{t\bar{t}}$	—	—

suppress DY

suppress ttbar

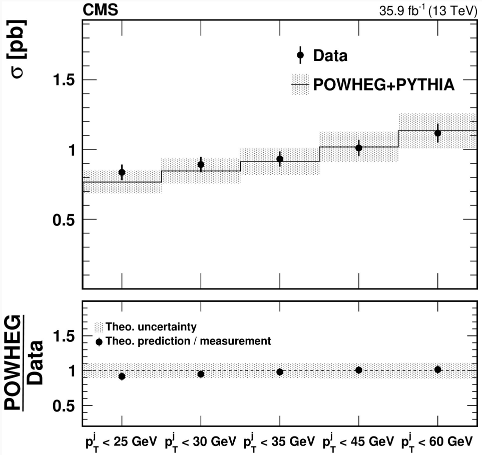


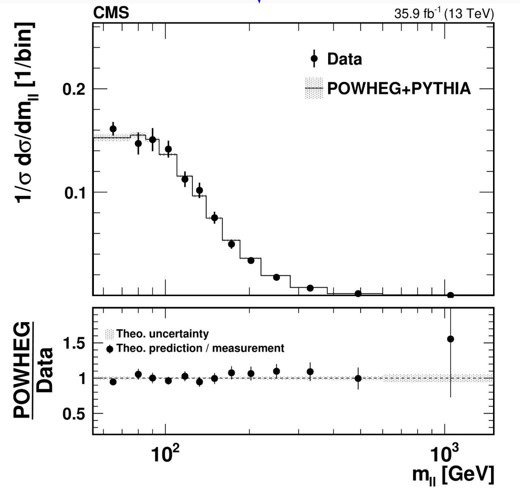
DYMVA: see arXiv:1806.05246

$W^+W^- \to \ell^+\ell^- 2\nu$ - results

SMP-18-004

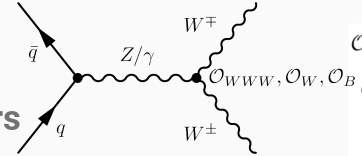
- **Fiducial cross section** (SEQ): Two e or μ with $p_T^{\ell} > 20$ GeV, $|\eta^{\ell}| < 2.5$, $m_{\ell\ell} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV, $E_T^{miss} > 20$ GeV, **0-1 jets**
  - **Change** in 0-jets with p_T threshold of vetoed jets
- **Total cross section** measurement with both analyses
- **Differential cross section** measurement in $\mathbf{m_{\ell\ell}}$, $p_T^{\ell 1}$, $p_T^{\ell 2}$, $\Delta\varphi_{\ell\ell}$



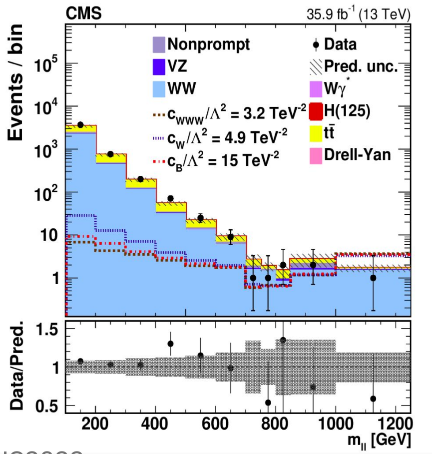


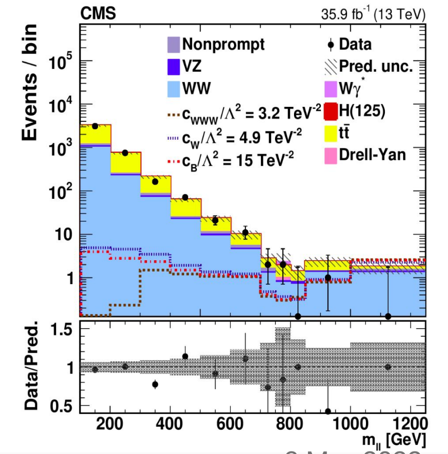
- <u>Theoretical prediction</u>: $\sigma_{tot}^{NNLO} = 118.8 \pm 3.6$ pb
- $\sigma_{tot}^{Seq} = 117.6 \pm 1.4$ (stat) ± 5.5 (syst) ± 1.9 (theo) ± 3.2 (lumi) pb $= 117.6 \pm 6.8$ pb
- $\sigma_{tot}^{RF} = 131.4 \pm 1.3$ (stat) ± 6.0 (syst) ± 5.1 (theo) ± 3.5 (lumi) pb $= 131.4 \pm 8.7$ pb

Limits on EFT dim 6 operators



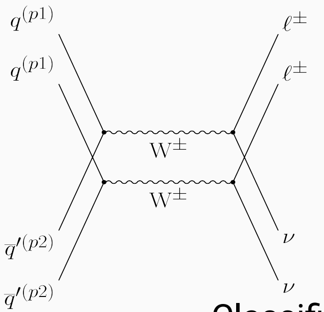
$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu},$$
$$\mathcal{O}_W = \frac{c_W}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} W_{\mu\nu} (D^{\nu}\Phi),$$
$$\mathcal{O}_B = \frac{c_B}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} B_{\mu\nu} (D^{\nu}\Phi),$$





$W^{\pm}W^{\pm} \to e^{\pm}\mu^{\pm}/\mu^{\pm}\mu^{\pm} + 2\nu$ Double Parton Scattering

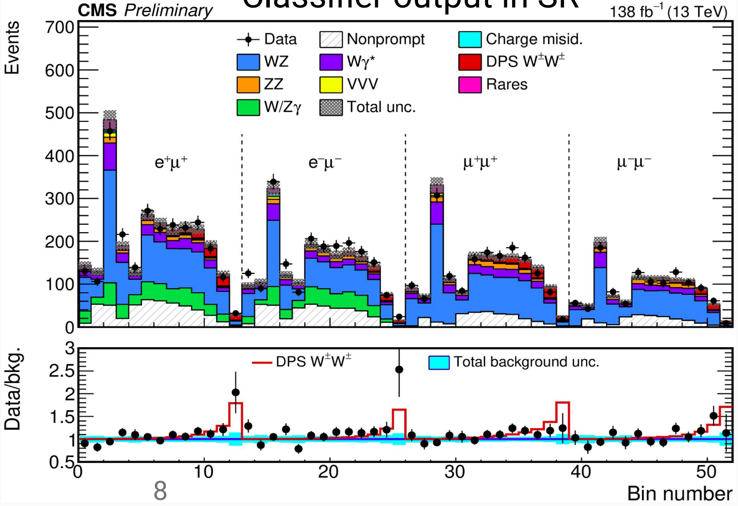
SMP-21-013



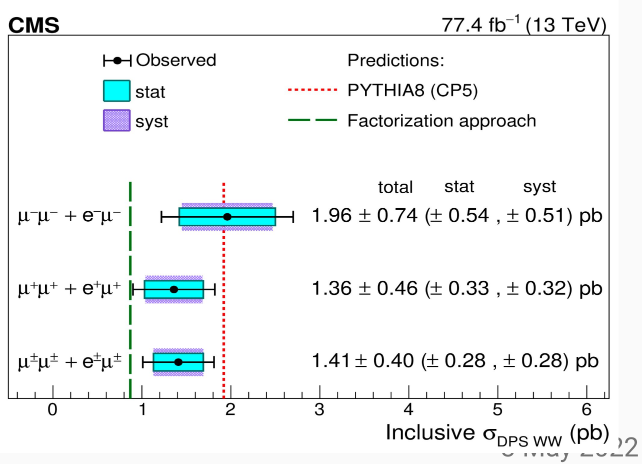
- Two hard parton-parton interaction within the same p-p collision
- For single hard scattering $\sigma^{SHS} = \sigma_{PDF} * \sigma_{parton}$; $\sigma_{PDF}{}^{DPS}$ depends on two partons
- A simplified formula can be written: $\sigma^{DPS}_{AB} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$ n = 1 if A = B, n = 2 otherwise
  - $\sigma_{eff} \in (15, 26)$ mb if there is a Vector Boson, ~2.2 mb for heavy flavour
- SHS $W^{\pm}W^{\pm}$ is mainly produced via VBS
  - suppressed by vetoing additional jets

	Value	Significance (standard deviations)
$\sigma^{PYTHIA}_{DPS\,WW,\,exp}$	1.92 pb	5.4
$\sigma^{factorized}_{DPS\,WW,\,exp}$	0.87 pb	2.5
$\sigma_{DPS\,WW,\,obs}$	$1.41 \pm 0.28\,(stat) \pm 0.28\,(syst)$ pb	3.9
σ_{eff}	$12.7^{+5.0}_{-2.9}$ mb	—

Classifier output in SR



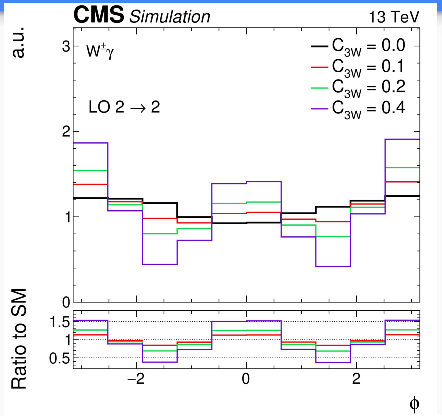
- Main background: **WZ**
  - Nonprompt leptons
  - Also Wγ, Zγ, ZZ
- 4 regions: {++, - -} x {eμ, μμ}
- Suppressed with BDTs
- Significance: 3.9σ
- $\sigma_{eff} = 12.7^{+5.0}_{-2.9}$ mb

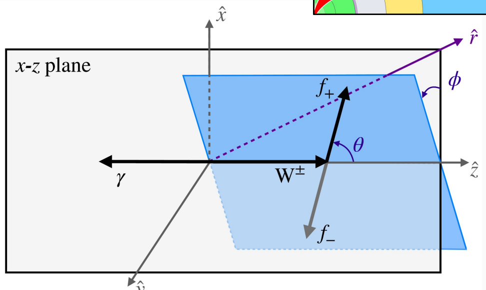


$W\gamma \rightarrow \ell\nu\,\gamma \quad (\ell = e, \mu)$

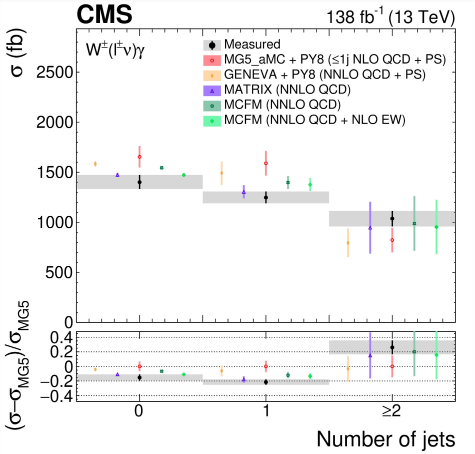
SMP-20-005

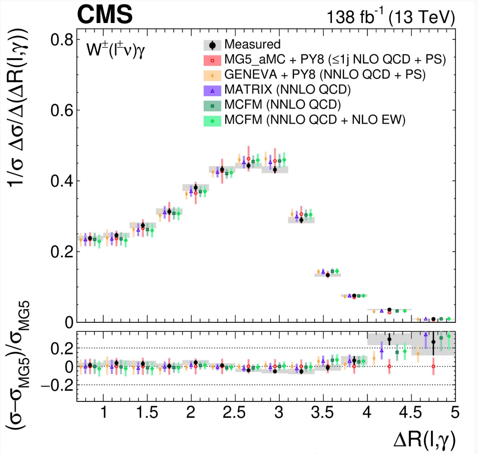
- $\sigma(C_{WWW}) = \sigma_{SM} + C_{WWW}\sigma_{int} + C_{WWW}^2\,\sigma_{BSM}$
- "Radiation amplitude zero": at LO destructive interference
- SM-EFT have different helicity for $ff \rightarrow W_T V_T$
- Use angular observables: ϕ
- Fiducial differential cross sections
- Constraints on $\mathcal{O}_{WWW}$ using p_T^{γ} and $|\phi_f|$

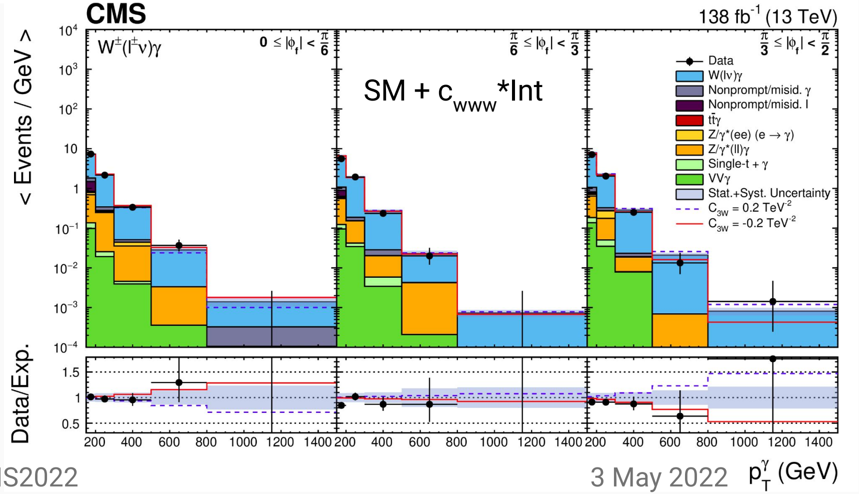




r = boost of Wγ



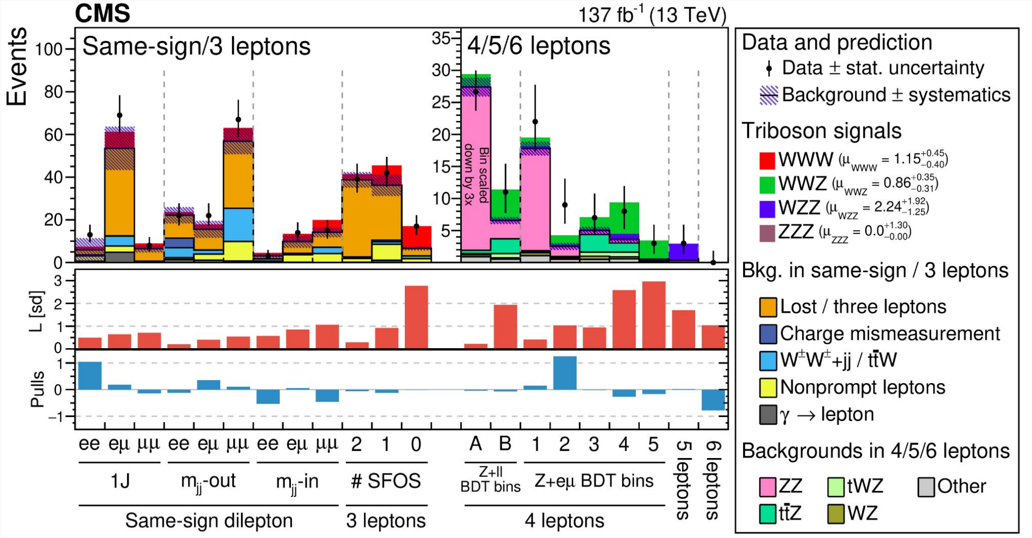




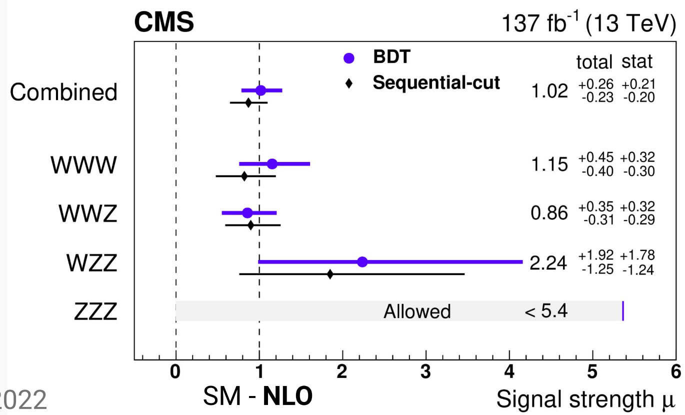
VVV (V = W,Z) - strategy

SMP-19-014

- $W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\nu \;\; \ell^{\pm}\nu \;\; qq' \rightarrow$ **2 $\ell^{\pm}$** 9 regions: {1J, m_{jj}-in, m_{jj}-out} x {ee, eμ, $\mu\mu$}
- // $\rightarrow \ell^{\pm}\nu \;\; \ell^{\pm}\nu \;\; \ell^{\mp}\nu \rightarrow$ **3 $\ell^{\pm}$** 3 regions: 0, 1, 2 SFOS
- $W^{\pm}W^{\pm}Z \rightarrow \ell^{\pm}\nu \;\; \ell^{\pm}\nu \;\; \ell^{\pm}\ell^{\mp} \rightarrow$ **4 $\ell^{\pm}$** 2 regions: BDT for ttZ, BDT for ZZ
- $W^{\pm}ZZ \rightarrow \ell^{\pm}\nu \;\; \ell^{\pm}\ell^{\mp} \;\; \ell^{\pm}\ell^{\mp} \rightarrow$ **5 $\ell^{\pm}$** 1 region
- $ZZZ \rightarrow \ell^{\pm}\ell^{\mp} \;\; \ell^{\pm}\ell^{\mp} \;\; \ell^{\pm}\ell^{\mp} \rightarrow$ **6 $\ell^{\pm}$** 1 region



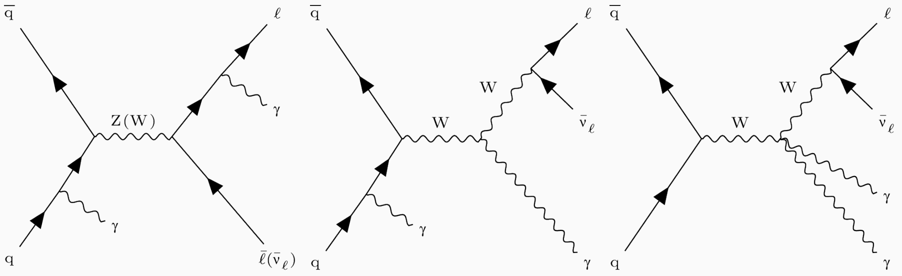
- Simultaneous fit with 4 signal strengths:
  - **WWW** → **2.5 σ**
  - **WWZ** → **3.5 σ**
  - **WZZ** → **1.6 σ**
  - **ZZZ** → **0.0 σ**
- Combined fit for **VVV** → **5.9σ**



Wγγ and Zγγ

SMP-19-013

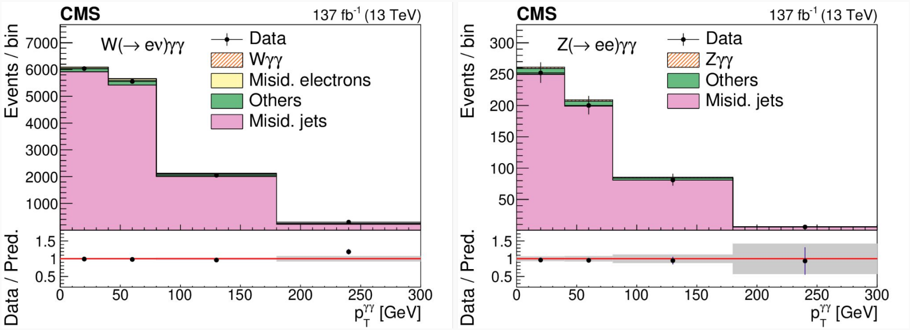
- Wγγ can be produced via a quartic coupling, while Zγγ cannot (in the SM)
- The photons can also be produced by initial or final state radiation



- Major backgrounds estimated from data
  - Electrons misidentified as photons - e.g. Zγ → eeγ [eγγ]
  - Jets misidentified as photons: CR = V+γ_{loose}
    - Subtract Zγ → eeγ (MC) before computing FR
- QCD: tγ, ttγ, ttγγ, VVγ → from MC

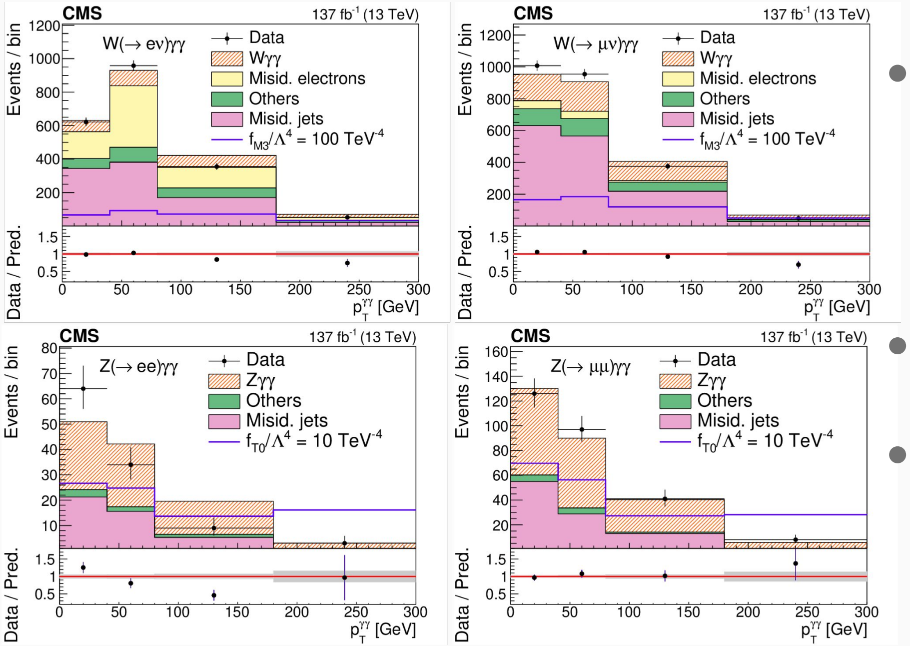
- Event selection: kinematic cuts
- Systematics
  - Mostly from data-driven background
  - Estimated by inverting lepton isolation and applying same strategy

Jets control region

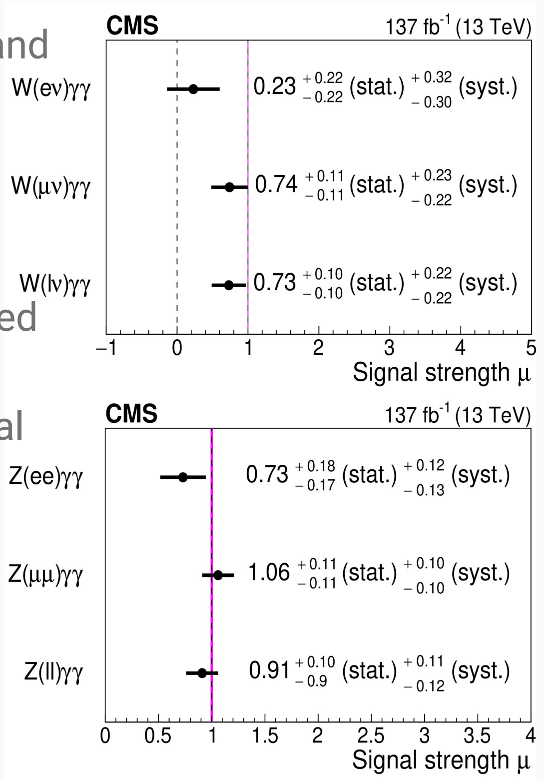


Wγγ and Zγγ - results

SMP-19-013



- Fit to $p_T^{\gamma\gamma}$ for electron and muon channels separately
  - Wγγ → **3.1 σ**
  - Zγγ → **4.8 σ**
- Uncertainty is dominated by systematics
- Extraction of the fiducial cross section



$$\sigma(W\gamma\gamma)_{SR} = \mathbf{13.6}^{+1.9}_{-1.9}\ (\text{stat})\ ^{+4.0}_{-4.0}(\text{syst})\ \pm 0.08\ (\text{PDF+scale})\ \text{fb}$$

$$\sigma(Z\gamma\gamma)_{SR} = \mathbf{5.41}^{+0.58}_{-0.55}\ (\text{stat})\ ^{+0.64}_{-0.70}(\text{syst}) \pm 0.06\ (\text{PDF+scale})\ \text{fb}$$

pWWp and pZZp

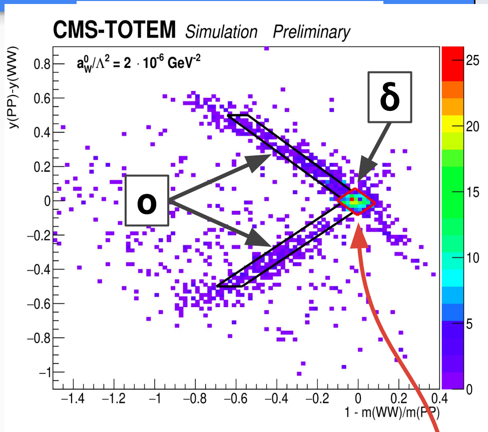
SMP-21-014

- The Precision Proton Spectrometer (PPS) allows to measure forward (intact) protons
- Access to the full kinematics of the event!
- 100 fb^{-1} of data (PPS in physics status)
- Search for pp → pp VV → pp j j , V = W, Z
  - Search for VBs decays into single large jets

$$M_X = \sqrt{s\xi_1\xi_2}$$

$$\xi = \Delta p_p/p_p$$

$$y = \frac{1}{2}\log\frac{\xi_1}{\xi_2}$$



Backgrounds

- Main: QCD multi jet
- Z+jet, W+Jet, tt production
- Diffractive pilup is not well modelled → data-driven

Protons

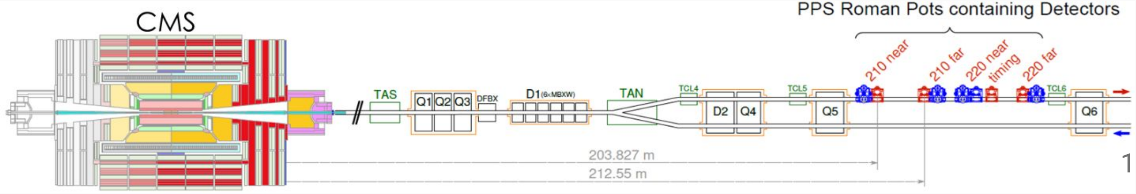
- multiRP → better ξ resolution
- 0.05 < ξ < ξ^{max} [depends on year]
  - 180 GeV < M_{pp} < 1.55-2.1 TeV → lower bound by jet trigger

Proton-jet matching

- m(VV) = m(pp)
- y(VV) = y(pp)

= In the diamond

- In the arms one proton is correctly matched, the other comes from pileup
- Still considered signal



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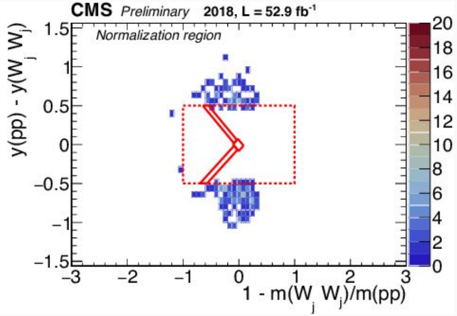
pWWp and pZZp - results

SMP-21-014

Pileup background

- 2D sideband in m - y plane
  - $|1 - m_{VV}/m_{pp}| > 1.0$
  - $|y_{pp} - y_{VV}| > 0.5$
  - Both δ and o are inside
- and in the acoplanarity

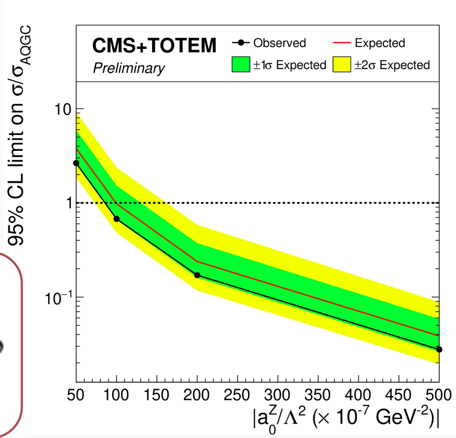
  $a = |1 - \Delta\varphi_{jj}| < 0.01$

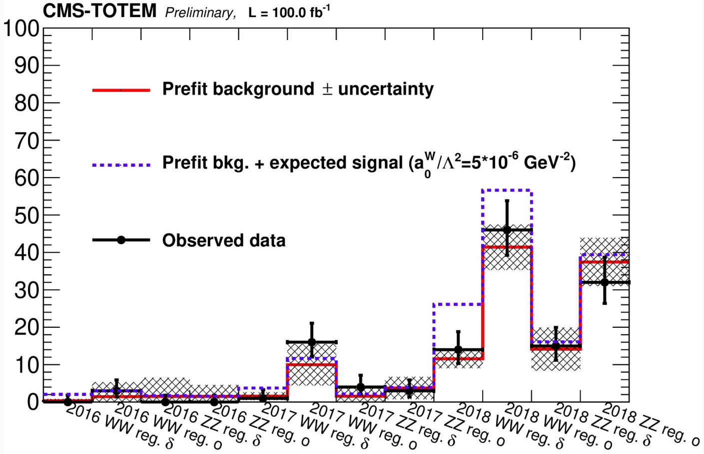


- Binned fit: {2016/17/18} ⊗ {WW / ZZ} ⊗ {fully [δ] / partial [o]}
- Limits to aQGC: first result on γγZZ
  - ~15 times better than Run1 on γγ → WW **without tagged protons**
- Limits on contribution from high mass resonance

- Divide WW and ZZ with cut on:

$$\cos(\pi/4) * M_{pruned}^{leading} + \sin(\pi/4) * M_{pruned}^{subleading}$$



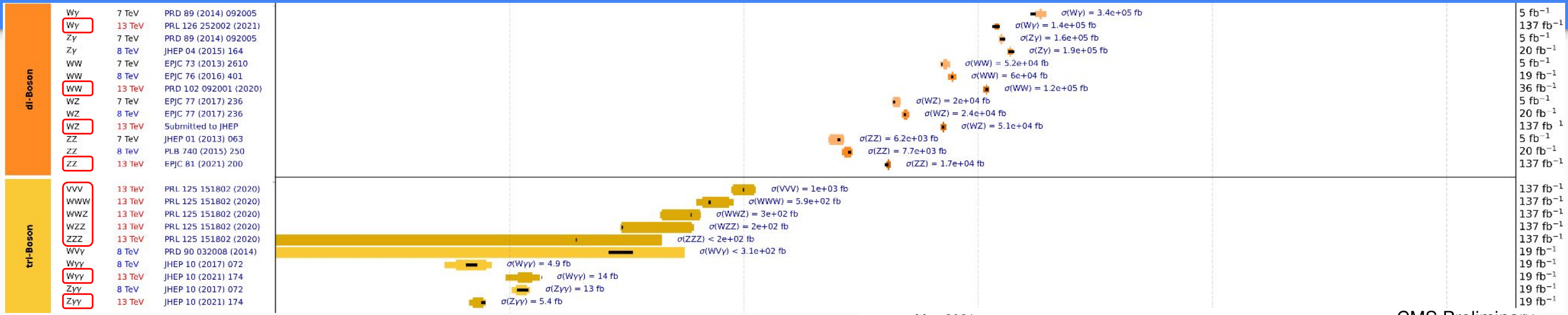


Fiducial cross section limits:

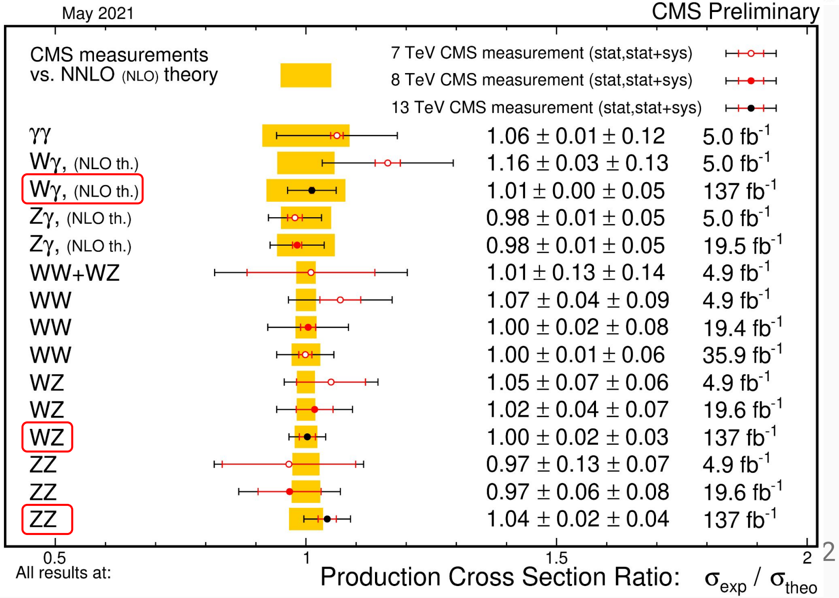
$$\sigma(pp \to pWWp)_{0.04<\xi<0.20, m>1000\ \mathrm{GeV}} < 67(53^{+34}_{-19})\ \mathrm{fb}$$

$$\sigma(pp \to pZZp)_{0.04<\xi<0.20, m>1000\ \mathrm{GeV}} < 43(62^{+33}_{-20})\ \mathrm{fb}$$

Summary



- Presented status of multiboson @CMS
- Diboson: precision era
  - Reach high precision → NNLO
  - Good agreement with MC predictions
- Triboson:
  - Can see (some) processes
  - Still much more to discover
- Stay tuned for Run3 and beyond!



References diboson [1]

- The CMS collaboration, “Measurement of $W^{\pm}\gamma$ differential cross sections in proton-proton collisions at $\sqrt{s}$ = 13 TeV and effective field theory constraints”, *Phys. Rev. D 105 (2022) 052003*, 9 March 2022, [doi:10.1103/PhysRevD.105.052003](https://doi.org/10.1103/PhysRevD.105.052003) **SMP-20-005**
- The CMS collaboration, “Measurement of the inclusive and differential WZ production cross sections, polarization angles, and triple gauge couplings in pp collisions at $\sqrt{s}$ = 13 TeV” **SMP-20-014**
- The CMS collaboration, “Measurements of the electroweak diboson production cross sections in proton-proton collisions at $\sqrt{s}$= 5.02 TeV using leptonic decays” SMP-20-012
- The CMS collaboration, “Measurement of Wγ production cross section in proton-proton collisions at $\sqrt{s}$ = 13 TeV and constraints on effective field theory coefficients” **SMP-19-002**
- Measurements of pp → ZZ production cross sections and constraints on anomalous triple gauge couplings at $\sqrt{s}$ = 13 TeV” **SMP-19-001**

References diboson [2]

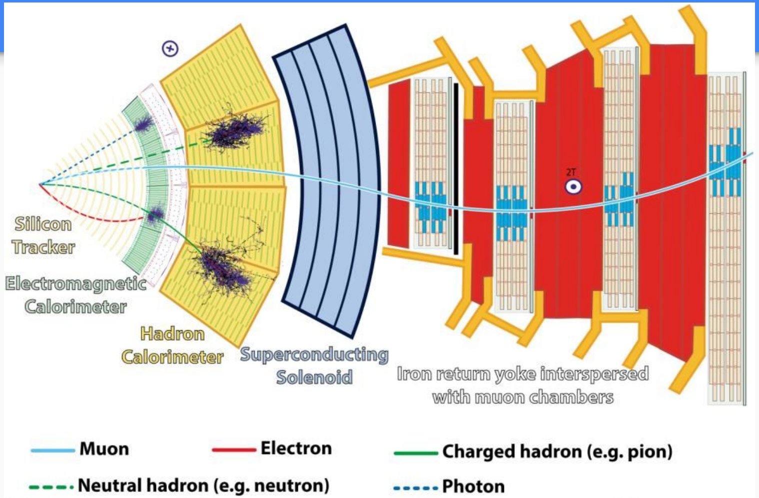
- The CMS Collaboration, “W+W− boson pair production in proton-proton collisions at √s = 13 TeV” **SMP-18-004**
- The CMS Collaboration, “Evidence for WW production from double-parton interactions in proton-proton collisions at √s = 13 TeV” **SMP-18-015**
- The CMS Collaboration, “Search for exclusive γγ → WW and γγ → ZZ production in final states with jets and forward protons”, CMS-PAS-SMP-21-014, March 2022 **SMP-21-014**
- The CMS Collaboration, “Search for anomalous triple gauge couplings in WW and WZ production in lepton + jet events in proton-proton collisions at √s = 13 TeV” SMP-18-008
- “Measurements of the pp→WZ inclusive and differential production cross section and constraints on charged anomalous triple gauge couplings at √s = 13 TeV” SMP-18-002
- “Measurements of the pp→ZZ production cross section and the Z→4ℓ branching fraction, and constraints on anomalous triple gauge couplings at √s = 13 TeV” SMP-16-017

References triboson

- The CMS collaboration, “Observation of the production of three massive gauge bosons at $\sqrt{s}$ = 13 TeV”, *Phys. Rev. Lett. 125 (2020) 151802*, 5 Oct 2020, 10.1103/PhysRevLett.125.151802 **VVV** **SMP-19-014**
- The CMS collaboration, “Measurements of the pp → $W^{\pm}\gamma\gamma$ and pp → $Z\gamma\gamma$ cross sections at $\sqrt{s}$ = 13 TeV and limits on anomalous quartic gauge couplings”, *J. High Energ. Phys. 2021, 174 (2021)*, 21 Oct 2021, doi:10.1007/jhep10(2021)174 **Wγγ,Zγγ** **SMP-19-013**
- The CMS Collaboration, “Search for the production of $W^{\pm}W^{\pm}W^{\mp}$ events at $\sqrt{s}$ = 13 TeV”, *Phys. Rev. D 100 (2019) 012004*, 26 Jul 2019, doi:10.1103/physrevd.100.012004 **WWW** **SMP-17-013**
- The CMS Collaboration, “Measurements of the pp→Wγγ and pp→Zγγ cross sections and limits on anomalous quartic gauge couplings at $\sqrt{s}$ = 8 TeV”, *J. High Energy Phys. 10 (2017) 072*, 11 Oct 2017, doi:10.1007/jhep10(2017)072 **8 TeV Wγγ,Zγγ** SMP-15-008
- The CMS Collaboration, “A search for WWγ and WZγ production and constraints on anomalous quartic gauge couplings in pp collisions at $\sqrt{s}$ = 8 TeV”, *Phys. Rev. D 90 (2014) 032008*, 25 Aug 2014, doi:10.1103/PhysRevD.90.032008 **8 TeV WWγ,WZγ** SMP-13-009

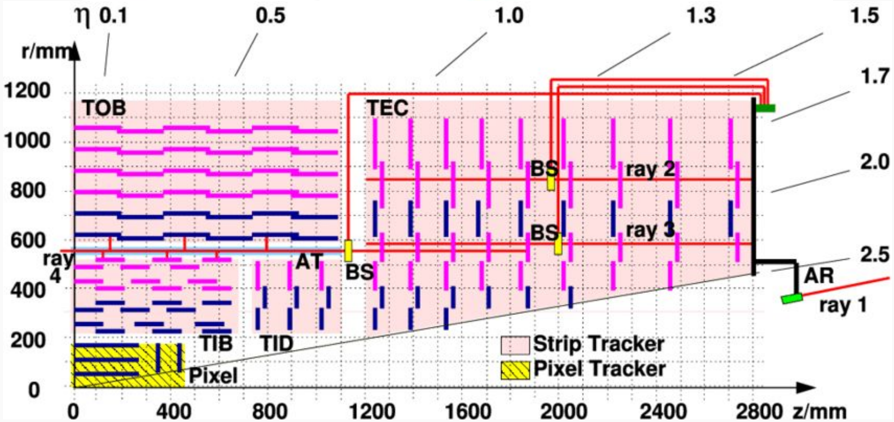
Backup

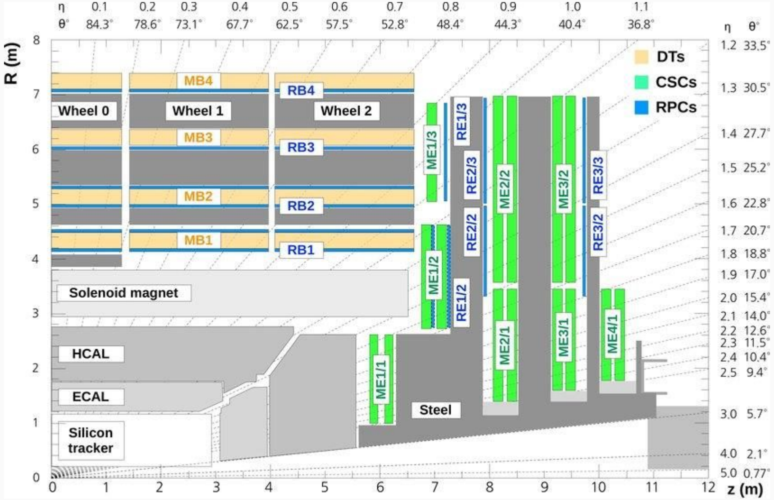
The CMS Detector



$$\eta = -\ln\left(\tan\left(\theta/_2\right)\right)$$

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$$





Cross section summary

Process	Fiducial cross section	Total cross section
$ZZ \rightarrow 4\ell$	40.5 ± 1.5 fb	17.4 ± 0.8 pb
$WZ \rightarrow 3\ell\,\nu$	299 ± 11 fb	50.6 ± 2.1 pb
$W^{+}W^{-} \rightarrow 2\ell\,2\nu$	1 592 ± 87 fb	117.6 ± 6.8 pb
$WW \rightarrow 2\ell\,2\nu$ DPS		1.41 ± 0.40 pb
Wγ	15 580 ± 750 fb	

Process	Theoretical cross section (NLO)	σ x BR	Expected events for 137 fb^{-1}
WWW	509 fb	54.0 fb	7 400
WWZ	354 fb	4.12 fb	560
WZZ	91.6 fb	0.36 fb	50
ZZZ	37.1 fb	0.05 fb	6.9

$ZZ \to 4\ell$ SMP-19-001

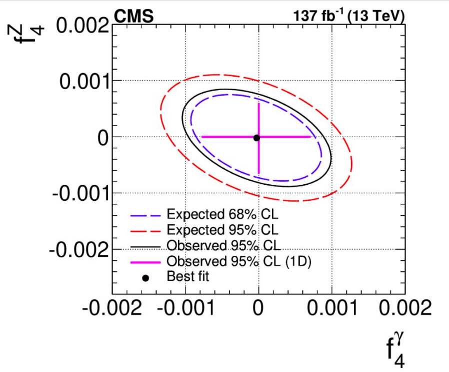
Uncertainty	Range of values
Lepton efficiency	2–5%
Trigger efficiency	1–2%
Background	0.6–1.3%
Pileup	1%
μ_R, μ_F	1%
PDF	1%
NNLO/NLO corrections	1%
Integrated luminosity	2.5% (2016), 2.3% (2017), 2.5% (2018)

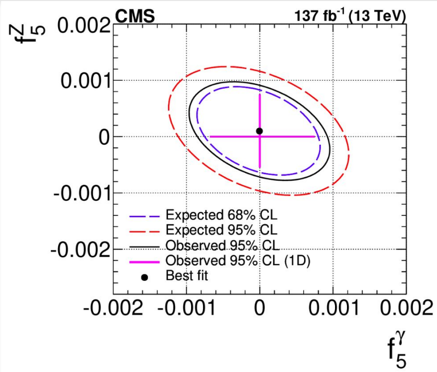
	Expected 95% CL	Observed 95% CL
aTGC parameter	$\times 10^{-4}$	$\times 10^{-4}$
f_4^Z	-8.8 ; 8.3	-6.6 ; 6.0
f_5^Z	-8.0 ; 9.9	-5.5 ; 7.5
f_4^γ	-9.9 ; 9.5	-7.8 ; 7.1
f_5^γ	-9.2 ; 9.8	-6.8 ; 7.5
EFT parameter	TeV^{-4}	TeV^{-4}
$C_{\tilde{B}W}/\Lambda^4$	-3.1 ; 3.3	-2.3 ; 2.5
C_{WW}/Λ^4	-1.7 ; 1.6	-1.4 ; 1.2
C_{BW}/Λ^4	-1.8 ; 1.9	-1.4 ; 1.3
C_{BB}/Λ^4	-1.6 ; 1.6	-1.2 ; 1.2

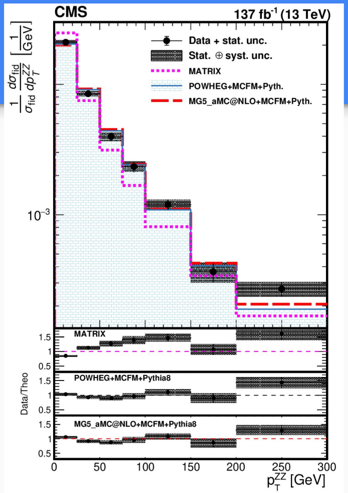
Year	Fiducial cross section, fb
2016	$41.6 \pm 1.4\,(\text{stat}) \pm 1.3\,(\text{syst})^{+1.1}_{-1.0}\,(\text{lumi})$
2017	$39.2 \pm 1.2\,(\text{stat})^{+1.3}_{-1.2}\,(\text{syst})^{+1.0}_{-0.9}\,(\text{lumi})$
2018	$39.3 \pm 1.0\,(\text{stat})^{+1.3}_{-1.1}\,(\text{syst}) \pm 1.0\,(\text{lumi})$
Combined	$40.1 \pm 0.7\,(\text{stat}) \pm 1.1\,(\text{syst}) \pm 0.7\,(\text{lumi})$

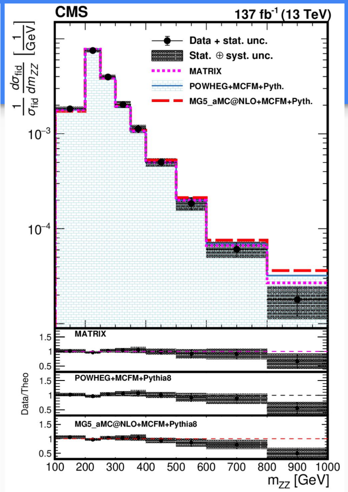
Year	Total cross section, pb
2016	$17.9 \pm 0.6\,(\text{stat})^{+0.6}_{-0.5}\,(\text{syst}) \pm 0.4\,(\text{theo})^{+0.5}_{-0.4}\,(\text{lumi})$
2017	$16.8 \pm 0.5\,(\text{stat})^{+0.6}_{-0.5}\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2018	$16.9 \pm 0.4\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
Combined	$17.2 \pm 0.3\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})$

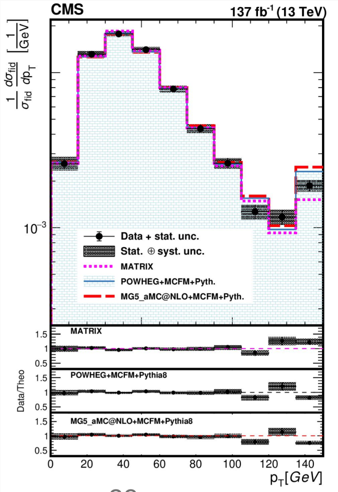
$ZZ \to 4\ell$ SMP-19-001

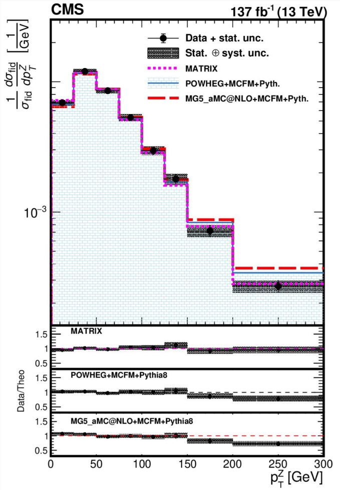






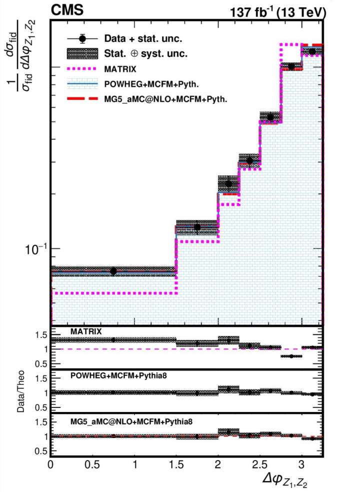


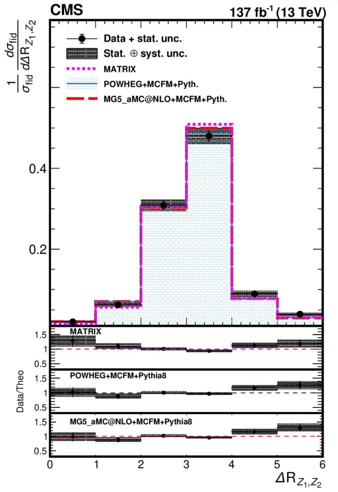




Matrix

- NNLO fixed order
- Differential predictions @NNLO QCD, NLO EW





WZ $\rightarrow 3\ell\,\nu$ SMP-20-014

- Fiducial region for cross section:
  - 3ℓ (no τ decay)
  - FRS-corrected for $\Delta R(\ell, \gamma)$ < **0.1**
  - $pT(\ell_{Z1})$ > **25** GeV
  - $pT(\ell_{Z2})$ > **10** GeV
  - $pT(\ell_{W})$ > **25** GeV
  - **60** GeV < $m(\ell_{Z1}, \ell_{Z2})$ < **120** GeV
  - $m(\ell\ell_{OSSF})$ > **4** GeV
  - $m(3\ell)$ > **100** GeV
- Free parameters: WZ, ZZ, ttZ, tZq and X+γ

b-tag WP
Mistag q-g jets: 0.1 %
Efficiency b-jets: 40 - 60 %

Systematics

Source	2016 %	2017 %	2018 %	Correlation scheme	Processes
Electron efficiency	0–3.3	0–3.0	0–2.8	Partially correlated	All MC
Muon efficiency	0–2.4	0–2.1	0–2.0	Partially correlated	All MC
Electron energy scale	0–5	0–5	0–5	Correlated	All MC
Muon energy scale	0–5	0–5	0–5	Correlated	All MC
Trigger efficiency	-1.0/+0.6	-0.7/+0.6	-0.7/+0.6	Partially correlated	All MC
Jet energy scale	0.9	0.7	1.1	Partially correlated	All MC
btagging	1.0	0.7	0.9	Correlated	All MC
bmistagging	0.5	0.4	0.3	Correlated	All MC
Pileup	0.9	0.8	0.8	Correlated	All MC
ISR	0.2–20	0.2–20	0.2–20	Correlated	WZ
Nonprompt shape	5–50	5–50	5–50	Correlated	Nonprompt
Nonprompt norm.	30	30	30	Correlated	Nonprompt
VVV norm.	50	50	50	Correlated	VVV
VH norm.	25	25	25	Correlated	VH
WZ EWK norm.	20	20	20	Correlated	WZ EWK
ZZ	Free	Free	Free	Correlated	ZZ
$t\bar{t}Z$ norm.	Free	Free	Free	Correlated	$t\bar{t}X$
tZq norm.	Free	Free	Free	Correlated	tZq
$X\gamma$ norm.	Free	Free	Free	Correlated	$X\gamma$
Integrated luminosity	1.2	2.3	2.5	Partially correlated	All MC
Statistical uncertainties	By bin	By bin	By bin	Uncorrelated	All MC
Theoretical (PDF + scale)	0.9	0.9	0.9	Correlated	WZ

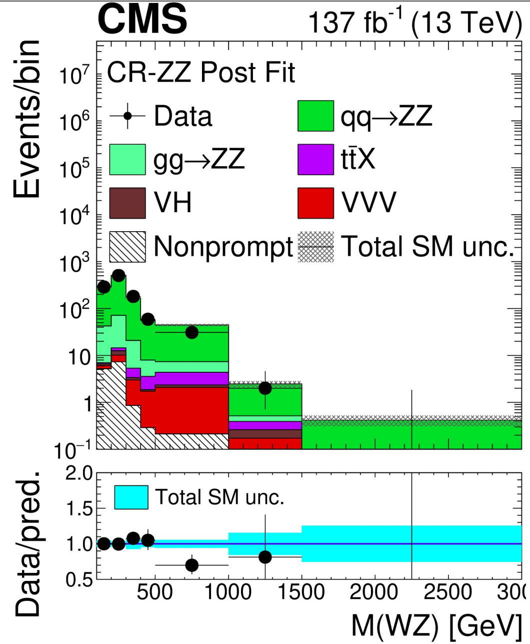
$WZ \rightarrow 3\ell\, \nu$ SMP-20-014

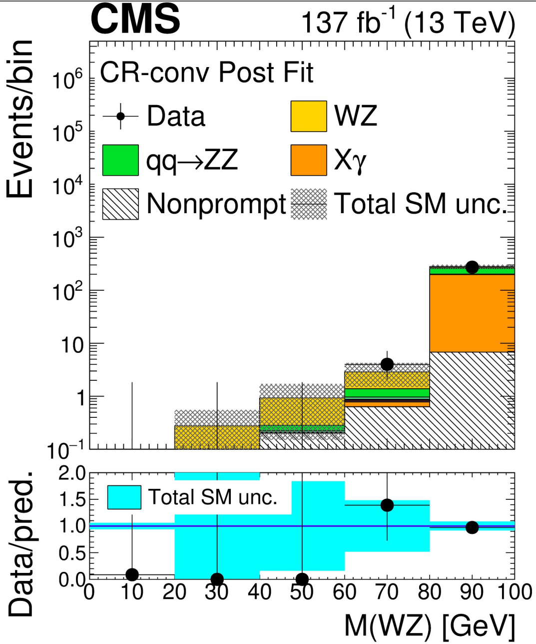
Cuts

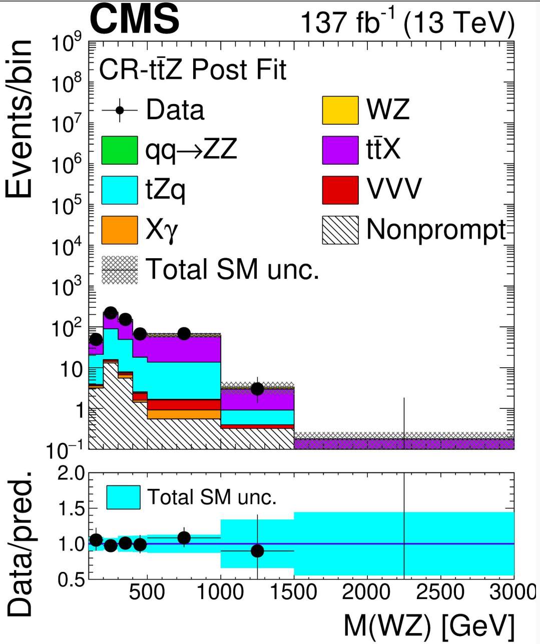
Zγ

$tt\ell_{fake}$, ttZ, tZq

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-$t\bar{t}$Z	$=3$	$>\{25, 10, 25, —\}$ 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



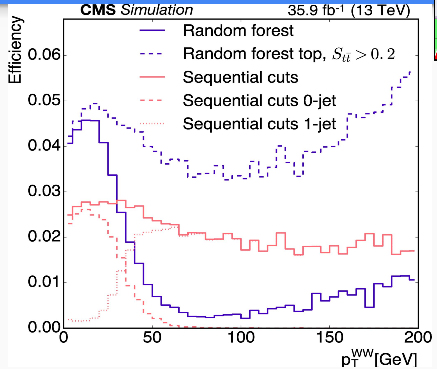




$W^+W^- \to \ell^+\ell^- 2\nu$ - Radom forest

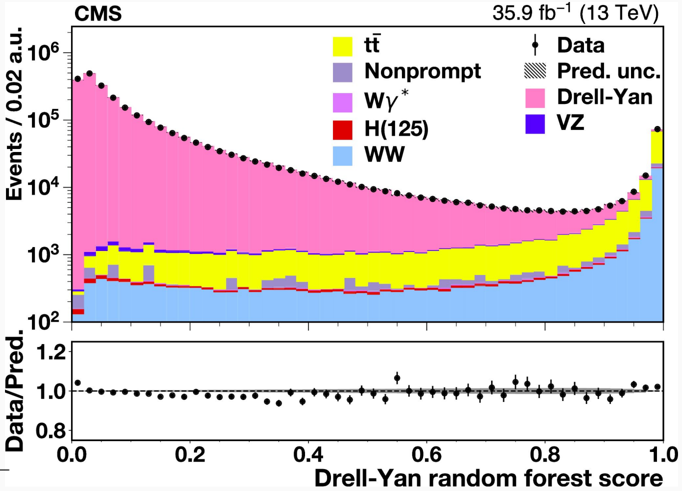
SMP-18-004

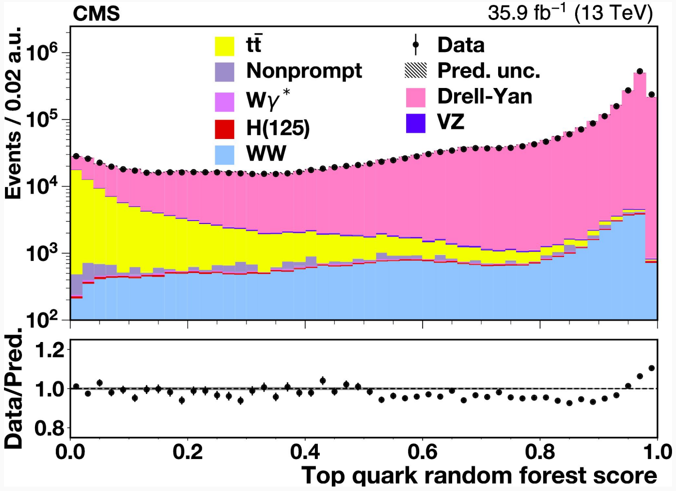
- Each tree uses a subset of the variables → reduces overfitting
- RF produces a purer SR, but it's more sensitive to p_T^{WW}
- σ_{tot}^{RF} = 131.4 ± 1.3 (stat) ± 6.0 (syst) ± 5.1 (theo) ± 3.5 (lumi) pb



Preselection

Quantity	Random Forest DF	Random Forest SF
Number of leptons	Strictly 2	
Lepton charges	Opposite	
$p_T^{\ell\,max}$	>25	
$p_T^{\ell\,min}$	>20	
$m_{\ell\ell}$	>30	>30
Additional leptons	0	
$\lvert m_{\ell\ell} - m_Z \rvert$	—	>15
$p_T^{\ell\ell}$	—	—
p_T^{miss}	—	—
$p_T^{miss,proj}$, $p_T^{miss,track\ proj}$	—	—
Number of jets	—	—
Number of b-tagged jets	0	
DYMVA score	—	—
Drell–Yan RF score S_{DY}	>0.96	
$t\bar{t}$ RF score $S_{t\bar{t}}$	>0.6	





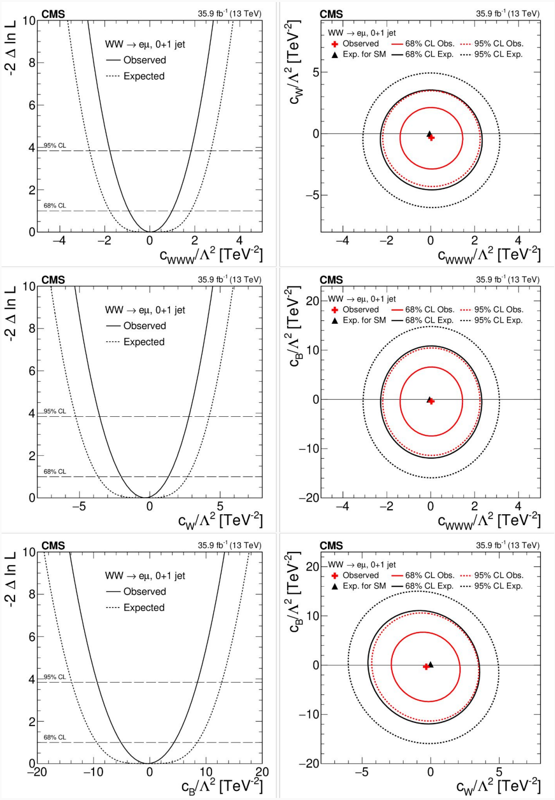
$W^+W^- \to \ell^+\ell^- 2\nu$ SMP-18-004

p_T threshold (GeV)	Signal strength	Cross section (pb)
25	1.091 ± 0.073	0.836 ± 0.056
30	1.054 ± 0.065	0.892 ± 0.055
35	1.020 ± 0.060	0.932 ± 0.055
45	0.993 ± 0.057	1.011 ± 0.058
60	0.985 ± 0.059	1.118 ± 0.067

Number of jets	0	1	≥ 2
Efficiency	0.555 ± 0.003	0.448 ± 0.004	0.290 ± 0.004

Number of jets	0	1	≥ 2
Before unfolding	$0.795 \pm 0.007 \pm 0.053$	$0.180 \pm 0.006 \pm 0.039$	$0.025 \pm 0.005 \pm 0.018$
After unfolding	$0.773 \pm 0.008 \pm 0.075$	$0.193 \pm 0.007 \pm 0.043$	$0.034 \pm 0.006 \pm 0.033$
Predicted	$0.677 \pm 0.007 \pm 0.058$	$0.248 \pm 0.007 \pm 0.033$	$0.075 \pm 0.006 \pm 0.026$

Coefficients	68% confidence interval		95% confidence interval	
(TeV^{-2})	expected	observed	expected	observed
c_{WWW}/Λ^2	$[-1.8, 1.8]$	$[-0.93, 0.99]$	$[-2.7, 2.7]$	$[-1.8, 1.8]$
c_W/Λ^2	$[-3.7, 2.7]$	$[-2.0, 1.3]$	$[-5.3, 4.2]$	$[-3.6, 2.8]$
c_B/Λ^2	$[-9.4, 8.4]$	$[-5.1, 4.3]$	$[-14, 13]$	$[-9.4, 8.5]$



$W^+W^- \to \ell^+\ell^- 2\nu$ SMP-18-004

Event yields in the SR

Process	Sequential Cut DF 0-jet	Sequential Cut DF 1-jet	Sequential Cut SF 0-jet	Sequential Cut SF 1-jet	Random Forest DF (all jet multiplicities)	Random Forest SF (all jet multiplicities)
Top quark	2110 ± 110	5000 ± 120	1202 ± 66	2211 ± 69	3450 ± 340	830 ± 82
Drell–Yan	129 ± 10	498 ± 38	1230 ± 260	285 ± 86	1360 ± 130	692 ± 72
VZ	227 ± 13	270 ± 12	192 ± 12	110 ± 7	279 ± 29	139 ± 10
V V V	11 ± 1	29 ± 2	4 ± 1	6 ± 1	13 ± 4	3 ± 2
$H \to W^+W^-$	269 ± 41	150 ± 25	50 ± 2	27 ± 1	241 ± 26	90 ± 10
$W\gamma^{(*)}$	147 ± 17	136 ± 13	123 ± 5	58 ± 6	305 ± 88	20 ± 6
Nonprompt leptons	980 ± 230	550 ± 120	153 ± 39	127 ± 32	940 ± 300	183 ± 59
Total background	3870 ± 260	6640 ± 180	2950 ± 270	2820 ± 120		
	$10\,510 \pm 310$		5780 ± 300		6600 ± 480	1960 ± 120
$q\bar{q} \to W^+W^-$	6430 ± 250	2530 ± 140	2500 ± 180	1018 ± 71	$12\,070 \pm 770$	2820 ± 180
$gg \to W^+W^-$	521 ± 66	291 ± 38	228 ± 32	117 ± 15	693 ± 44	276 ± 17
Total W^+W^-	6950 ± 260	2820 ± 150	2730 ± 190	1136 ± 72		
	9780 ± 300		3860 ± 200		$12\,770 \pm 820$	3100 ± 200
Total yield	$10\,820 \pm 360$	9460 ± 240	5680 ± 330	3960 ± 360		
	$20\,280 \pm 430$		9640 ± 490		$19\,360 \pm 950$	5060 ± 240
Purity	0.64	0.30	0.48	0.29		
	0.48		0.40		0.66	0.61
Observed	10 866	9404	5690	3914	19 418	5210

Features used

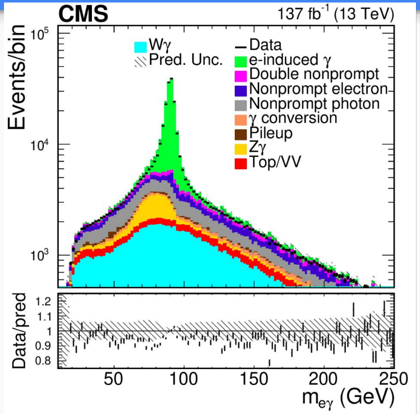
Feature	Classifier: Drell–Yan	Classifier: Top quark
Lepton flavor	✓	
Number of jets		✓
$p_T^{\ell\,\text{min}}$	✓	
p_T^{miss}	✓	✓
$p_T^{\text{miss,proj}}$	✓	
$p_T^{\ell\ell}$	✓	✓
$m_{\ell\ell}$	✓	
$m_{\ell\ell p_T^{\text{miss}}}$	✓	
$\Delta\phi_{\ell\ell p_T^{\text{miss}}}$	✓	✓
$\Delta\phi_{\ell J}$		✓
$\Delta\phi_{p_T^{\text{miss}} J}$		✓
$\Delta\phi_{\ell\ell}$	✓	
H_T		✓
Recoil	✓	✓

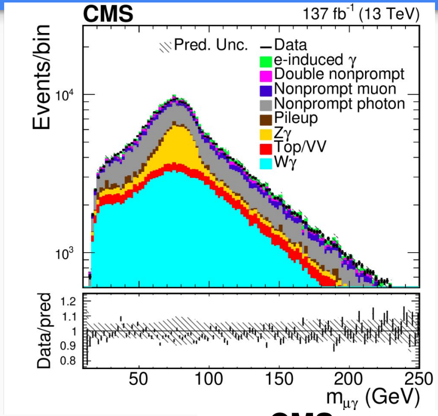
$W\gamma \rightarrow \ell\nu\,\gamma$ (ℓ = e, μ)

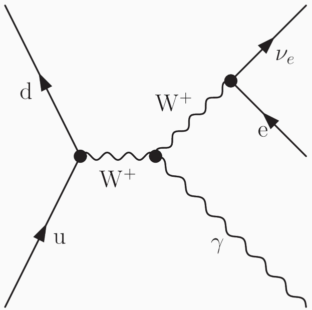
SMP-19-002

Backgrounds

- Prompt ℓ+γ: **Zγ**, **ttγ**, **VVγ** (V=W,Z) → MC
- Photon conversion (γ → ee) → MC
- **Electrons** faking photons → MC template, normalization from fit to $m_{\ell\gamma}$
- Nonprompt **leptons** (**photons**): data-driven from dijet (W+jets) CR





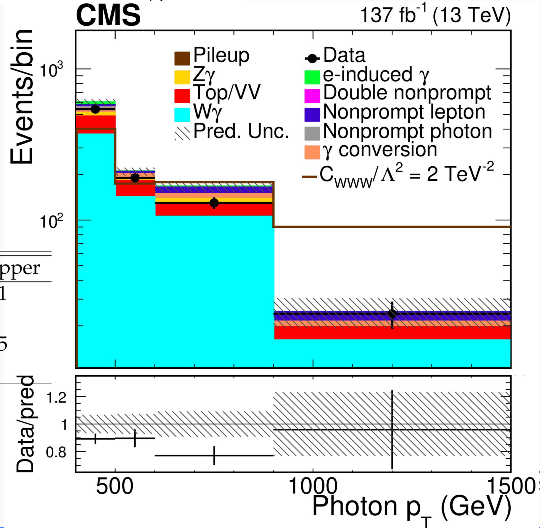


Measurement of the total cross section:

- σ = 15.58 ± 0.05 (stat) ± 0.73 (syst) ± 0.15 (theo) pb = 15.58 ± 0.75 pb
- $\sigma_{MadGraph}$ = 15.4 ± 1.2 (scale) ± 0.1 (PDF) pb
- σ_{Powheg} = 22.4 ± 3.2 (scale) ± 0.1 (PDF) pb

- Probe WWγ coupling → limits on EFT dimension 6 $\mathcal{O}_{WWW}$
  - Fit to photon p_T → mostly high energy bin (> 900 GeV)

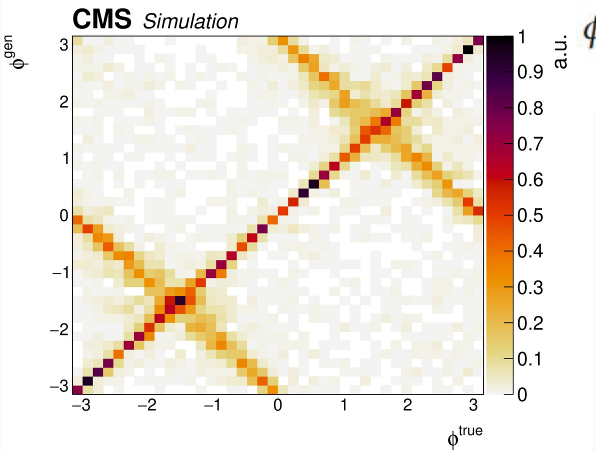
Coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper
c_{WWW}/Λ^2	−0.85	0.87	−0.90	0.91
c_B/Λ^2	−46	45	−40	41
$c_{\widetilde{W}WW}/\Lambda^2$	−0.43	0.43	−0.45	0.45
$c_{\widetilde{W}}/\Lambda^2$	−23	22	−20	20



$W\gamma \to \ell\nu\,\gamma$ ($\ell = e, \mu$) SMP-20-005

$$\eta^{\nu} = \eta^{\ell} \pm \ln\left[1 + \Delta\sqrt{2+\Delta^2} + \Delta^2\right]$$

$$\Delta = \sqrt{\frac{m_W^2 - m_T^2}{2 p_T^{\ell} p_T^{\nu}}}$$



Off-diagonal = wrong sign for $p_z(\nu)$

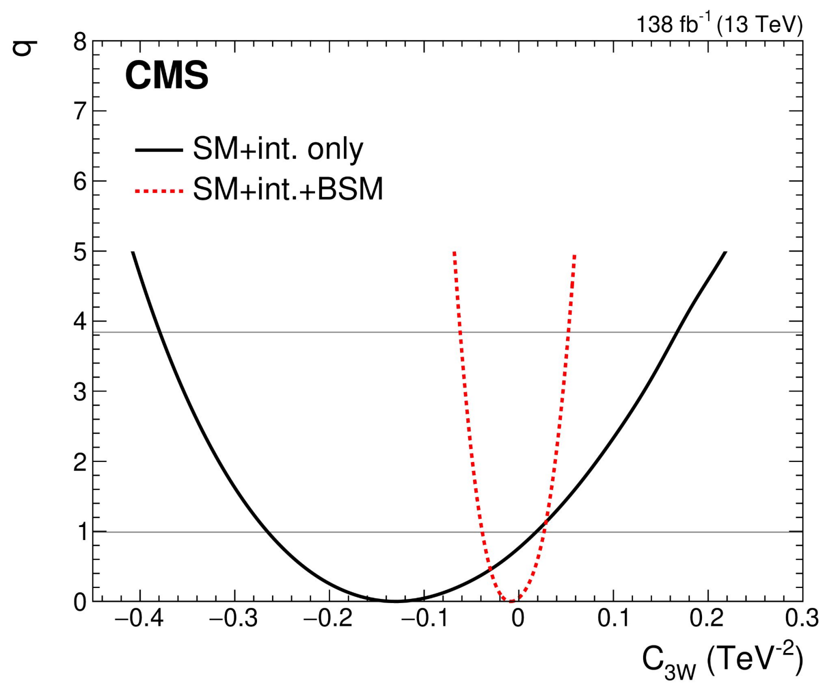
$$\phi_f = \begin{cases} -(\pi + \phi), & \text{for } \phi < -\frac{\pi}{2}; \\ \phi, & \text{for } |\phi| < \frac{\pi}{2}; \\ \pi - \phi, & \text{for } \phi > \frac{\pi}{2}. \end{cases}$$

Fiducial region

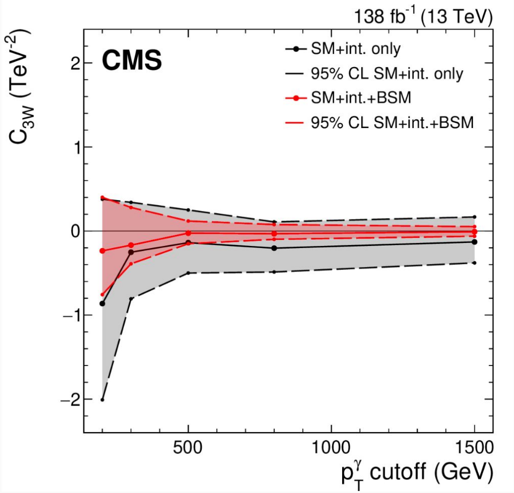
- $p_T^{\ell} > 30$ GeV, $|\eta^{\ell}| < 2.5$
- $p_T^{\gamma} > 30$ GeV, $|\eta^{\gamma}| < 2.5$
- $p_T^{miss} > 40$ GeV
- $\Delta R(\ell, \gamma) > 0.7$

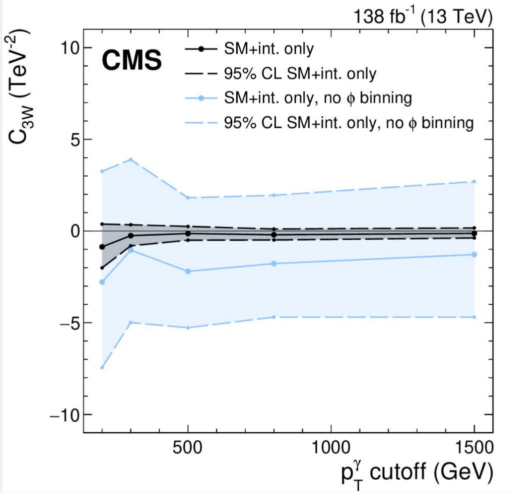
Uncertainty	Affects shape	Corr. years	Relative effect on expected yield
	Experimental		
Integrated luminosity	—	Partial	1.6%
Pileup modeling	✓	✓	0.2–3.1%
L1 trigger	✓	✓	0.3–1.1%
Electron ID	✓	✓	0.7–2.8%
Electron ID ($p_T^e > 200$ GeV)	✓	—	0.1–1.2%
Electron trigger	—	—	0.5%
Muon ID (stat)	✓	—	0.1–0.6%
Muon ID (syst)	✓	✓	0.2–0.7%
Muon trigger	✓	—	0.1–0.7%
Photon ID	✓	✓	0.6–6.0%
Photon ID ($p_T^{\gamma} > 200$ GeV)	✓	—	2.1–4.7%
Photon ID (high p_T extrapolation)	✓	—	Typically 3.0–9.0%, max. 14%
Photon (e veto)	—	—	1%
Photon energy scale	✓	✓	Typically 0.1–4.8%, max. 13%
Jet energy scale	✓	—	1–4%
p_T^{miss} scale	✓	Partial	0.1–10.1%
$e \to \gamma$ misidentification	✓	—	Typically 6.7–18%, max. 25%
Jet $\to \gamma$ misidentification	✓	—	10–45%
Misidentified e	✓	—	Typically 13–36%, max. 75%
Misidentified μ	✓	—	Typically 16–42%, max. 70%
	Theoretical		
γ acceptance (scale)	✓	✓	0.3–1.7%
γ acceptance (PDF)	✓	✓	Typically 0.5–2.2%, max. 7.6%
γ out-of-acceptance (scale)	✓	✓	5.2–12%
γ parton shower modeling	✓	✓	0.2–1.3%
Background normalization (scale)	—	✓	2.0–16%
Background normalization (PDF)	—	✓	4.2–4.8%

$W\gamma \rightarrow \ell\nu\gamma$ (ℓ = e, μ) SMP-20-005



p_T^γ bin (GeV)	$0 \leq \lvert\phi_f\rvert < \pi/6$		$\pi/6 \leq \lvert\phi_f\rvert < \pi/3$		$\pi/3 \leq \lvert\phi_f\rvert < \pi/2$	
	μ^{int}	μ^{BSM}	μ^{int}	μ^{BSM}	μ^{int}	μ^{BSM}
150–200	−0.19	0.52	0.03	0.50	0.23	0.44
200–300	−0.38	2.5	0.02	2.1	0.43	1.9
300–500	−0.95	10.7	0.06	10.3	1.0	11.0
500–800	−2.2	83.0	0.07	82.5	2.4	81.6
800–1500	−4.9	688.5	0.02	651.7	4.9	646.2





WW+pp and ZZ+pp

SMP-21-014

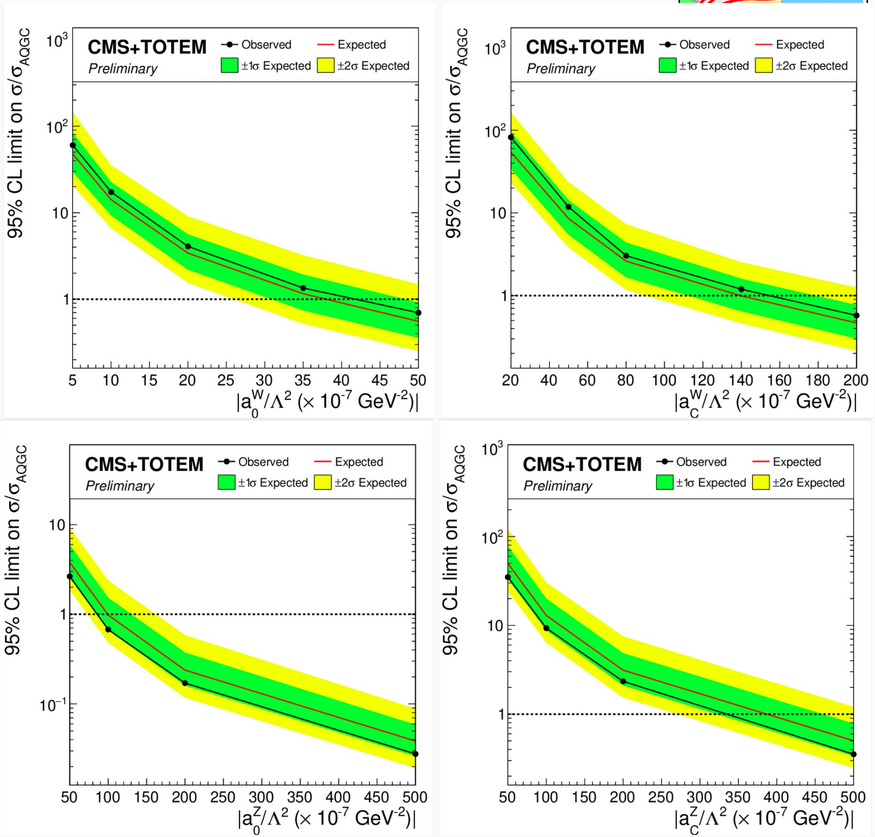
Jets

- $p_T^j > 200$ GeV, $|\eta_j| < 2.5$
- $m_j > 1126$ GeV (trigger)
- $|\Delta\eta_{jj}| < 1.3$
- acoplanarity:
  $a = |1 - \Delta\varphi_{jj}| < 0.01$
- $p_T^{j1}/p_T^{j2} < 1.3$
- $\tau_{21}^{DDT} < 0.75$ (*)

(*) Designing Decorrelated Tagger. Goal: avoid mass sculpting. See arXiv:1603.00027

ABCD method	a < 0.01	a > 0.01
in rectangle	**A** (SR)	**B**
out rectangle	**C**	**D**

$$N_{BKG}^{A} = N^{B} * N^{C} / N^{D}$$



VVV (V = W,Z) SMP-19-014

Selection in the 2l and 3l regions

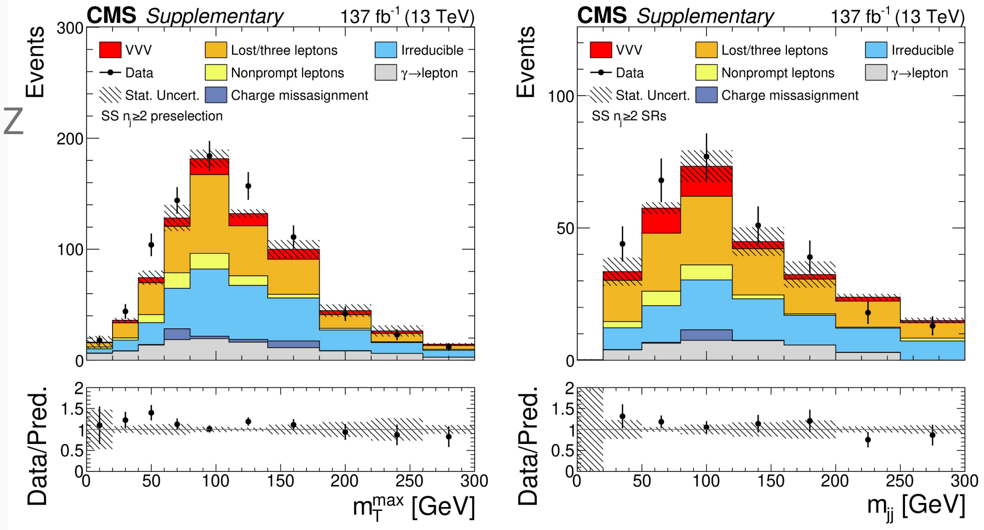
Features	Selections		
	SS + $\geq$2j	SS + 1j	3ℓ
Triggers	Select events passing dilepton triggers		
Number of leptons	Select events with 2 (3) leptons passing SS-ID (3ℓ-ID) for SS (3ℓ) final states		
Number of leptons	Select events with 2 (3) leptons passing veto-ID for SS (3ℓ) final states		
Isolated tracks	No additional isolated tracks		—
b-tagging	no b-tagged jets and soft b-tag objects		
Jets	$\geq$2 jets	1 jet	$\leq$1 jet
m_{JJ} (leading jets)	$<$500 GeV		—
$\Delta\eta_{JJ}$ (leading jets)	$<$2.5		—
$m_{\ell\ell}$	$>$20 GeV		—
$m_{\ell\ell}$	$\|m_{\ell\ell} - m_Z\| > 20\,\text{GeV}$ if $e^{\pm}e^{\pm}$		—
m_{SFOS}	—	—	$m_{SFOS} > 20\,\text{GeV}$
m_{SFOS}	—	—	$\|m_{SFOS} - m_Z\| > 20\,\text{GeV}$
$m_{\ell\ell\ell}$	—	—	$\|m_{\ell\ell\ell} - m_Z\| > 10\,\text{GeV}$

VVV (V = W,Z) - strategy

SMP-19-014

- $W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\nu\ \ \ell^{\pm}\nu\ \ qq' \rightarrow$ **2 $\ell^{\pm}$** 9 regions: {1J, m_{jj}-in, m_{jj}-out} x {ee, eμ, $\mu\mu$}
- // $\rightarrow \ell^{\pm}\nu\ \ \ell^{\pm}\nu\ \ \ell^{\mp}\nu \rightarrow$ **3 $\ell^{\pm}$** 3 regions: 0, 1, 2 SFOS
- $W^{\pm}W^{\pm}Z \rightarrow \ell^{\pm}\nu\ \ \ell^{\pm}\nu\ \ \ell^{\pm}\ell^{\mp} \rightarrow$ **4 $\ell^{\pm}$** 2 regions: BDT for ttZ, BDT for ZZ
- $W^{\pm}$ Z Z $\rightarrow \ell^{\pm}\nu\ \ \ell^{\pm}\ell^{\mp}\ \ell^{\pm}\ell^{\mp} \rightarrow$ **5 $\ell^{\pm}$** 1 region
- Z Z Z $\rightarrow \ell^{\pm}\ell^{\mp}\ \ell^{\pm}\ell^{\mp}\ \ell^{\pm}\ell^{\mp} \rightarrow$ **6 $\ell^{\pm}$** 1 region

- Backgrounds for same sign dilepton (**SS-2ℓ**):
  - Lost lepton: mostly WZ with a lost lepton from the Z
  - Nonprompt lepton: 1 prompt + 1 nonprompt from hadronic decays
  - Irreducible background: $W^{\pm}$ $W^{\pm}$ from VBS, double parton scattering
  - Charge misidentification: a lepton from Z is assigned the wrong charge; negligible for μ

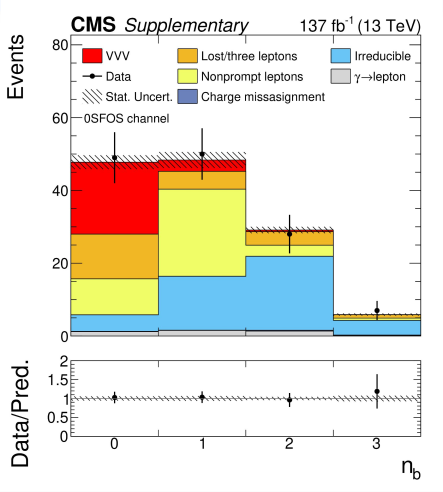


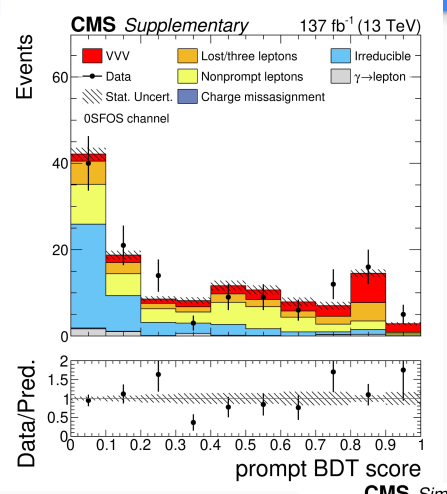
m_{jj}-in: 65 < m_{jj} < 95 GeV

$m_T^{max} = \max(m(p_T^{miss}, \ell_i))$

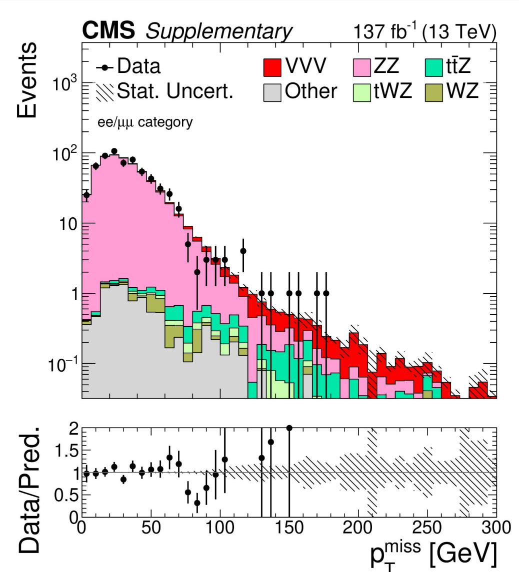
VVV (V = W,Z) - strategy [2]

SMP-19-014

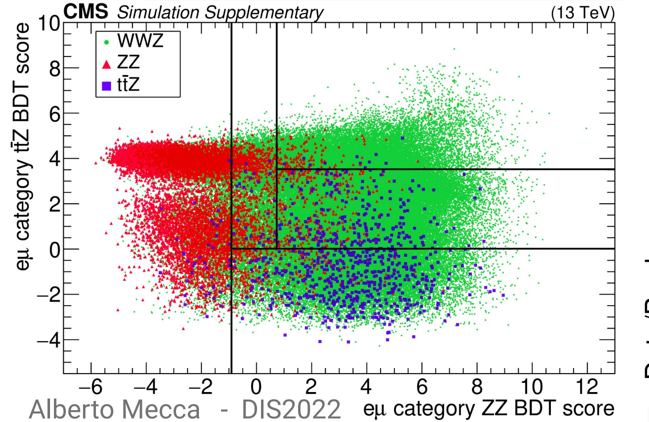




- Background fo four-lepton (**4ℓ**):
  ZZ, **ttZ**, tWZ, WZ+fake, Higgs
- Two BDTs: one for ZZ, one for ttZ



- Background for three-lepton (**3ℓ**):
  - WZ with off-shell Z
  - Nonprompt lepton: 2 prompt + 1 nonprompt from hadronic decays
  - Irreducible: ttW

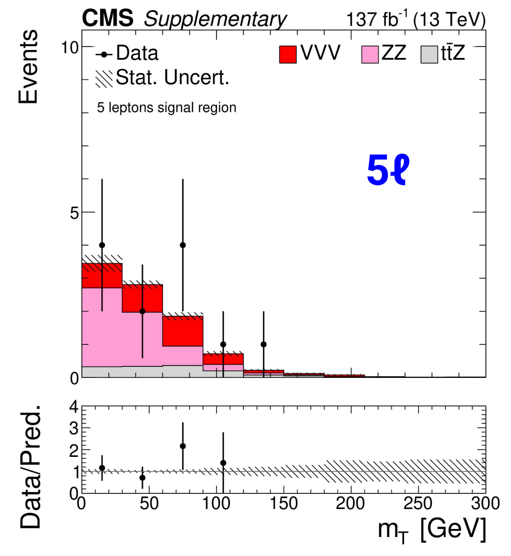


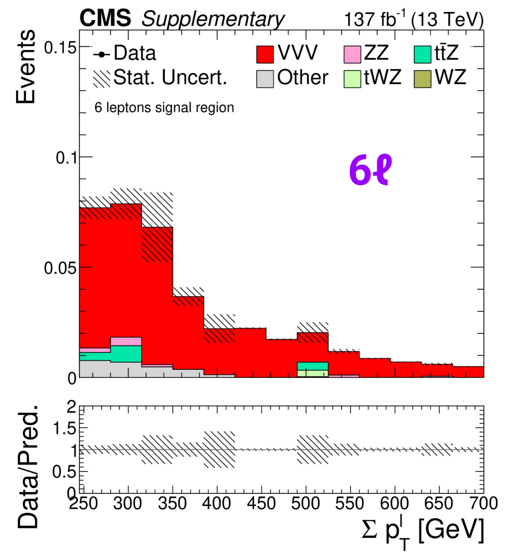
VVV (V = W,Z) - strategy [3]

SMP-19-014

5ℓ (WZZ)	6ℓ (ZZZ)
$p_T^{\ell 1,2} > 25$ GeV/c , $p_T^{\ell > 2} > 10$ GeV/c , no b-tagged jets	
2 SFOS pairs	3 SFOS pairs
$\lvert m_{SFOS} - m_Z \rvert < 15$ GeV	$\lvert m_{SFOS} - m_Z \rvert < 15$ GeV
ZZ+ℓ_{fake}: $m(\vec{p}_T^{miss} + \vec{p}_T^{e5}) > 50$ GeV	$\Sigma_{i=1}^{6} \lvert \vec{p}_T^{\ell i} \rvert > 250$ GeV (tt̄H, ZZ+ℓℓ)

- Background for five-lepton (**5ℓ**):
  - ZZ + fake lepton
- Background for six-lepton (**6ℓ**): negligible

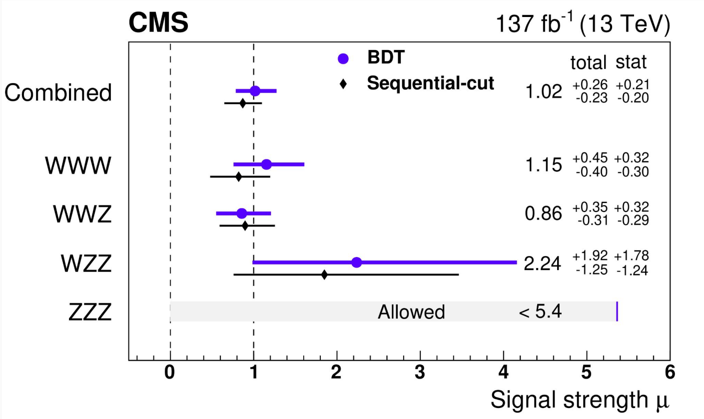




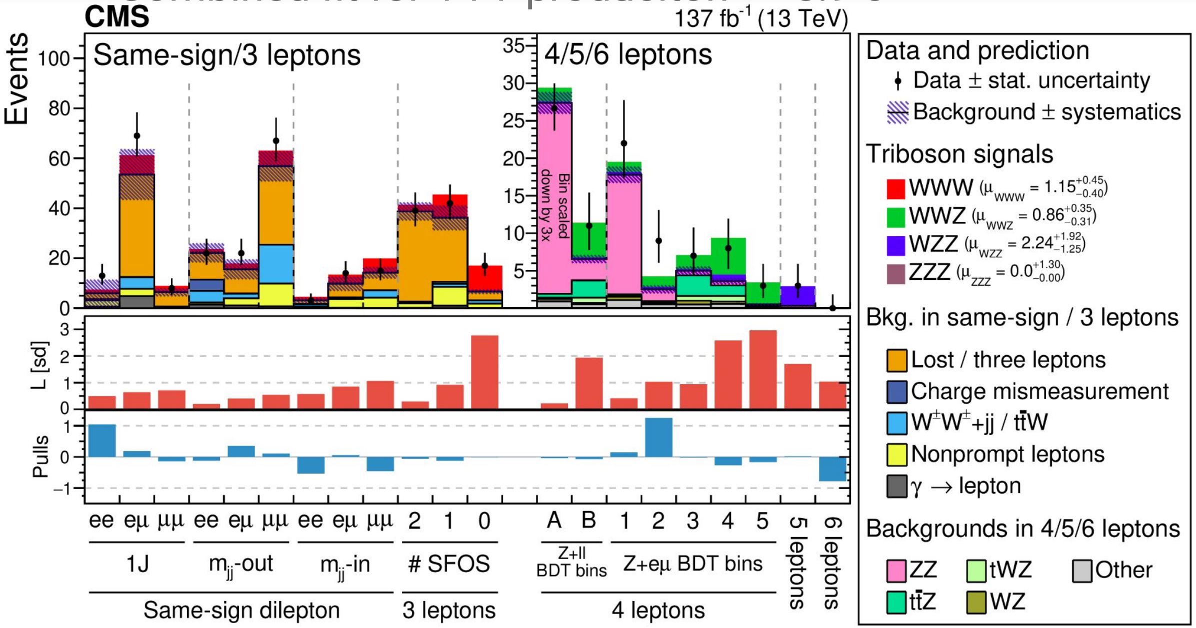
VVV (V = W,Z) - results

SMP-19-014

- Simultaneous fit with 4 signal strengths
  - WWW → 3.3 σ
  - WWZ → 3.4 σ
  - WZZ →
- Combined fit for VVV produciton → 5.9 σ



Process	Cross section (fb)
Treating Higgs boson contributions as signal	
VVV	$1010^{+210}_{-200}\,^{+150}_{-120}$
WWW	$590^{+160}_{-150}\,^{+160}_{-130}$
WWZ	$300^{+120}_{-100}\,^{+50}_{-40}$
WZZ	$200^{+160}_{-110}\,^{+70}_{-20}$
ZZZ	<200
Treating Higgs boson contributions as background	
VVV	$370^{+140}_{-130}\,^{+80}_{-60}$
WWW	$190^{+110}_{-100}\,^{+80}_{-70}$
WWZ	$100\,^{+80}_{-70}\,^{+30}_{-30}$
WZZ	$110^{+100}_{-70}\,^{+30}_{-10}$
ZZZ	<80



VVV (V = W,Z) SMP-19-014

selection for electrons

	SS-ID	Loose-SS-ID	3ℓ-ID	Loose-3ℓ-ID
Veto ID see Table 7	Common Veto ID		Common Veto ID	
POG MVA wp	MVA POG 80% No Iso		MVA POG 90% No Iso	
p_T	> 25 GeV		> 20 GeV	
$\lvert\eta\rvert$ (veto $1.4 < \lvert\eta\rvert < 1.6$)	< 2.4		< 2.4	
IP_{3D}	< 0.01 cm		< 0.015 cm	
$\lvert d_{xy}\rvert$	< 0.05 cm		< 0.05 cm	
$\lvert d_z\rvert$	< 0.1 cm		< 0.1 cm	
$I_{rel,R=0.3,EA,Lep}$	< 0.05	< 0.4	< 0.10	< 0.4
3-charge agreement	yes		not required	
Trigger safe cuts	yes		yes	

selection for muons

	SS-ID	Loose-SS-ID	3ℓ-ID	Loose-3ℓ-ID
Veto ID see Table 7	Common Veto ID		Common Veto ID	
POG ID	Medium		Medium	
p_T	> 25 GeV		> 20 GeV	
$\lvert\eta\rvert$	< 2.4		< 2.4	
IP_{3D}	< 0.015 cm		< 0.015 cm	
$IP_{3D}/\sigma_{IP_{3D}}$	< 4		< 4	
$\lvert d_{xy}\rvert$	< 0.05 cm		< 0.05 cm	
$\lvert d_z\rvert$	< 0.1 cm		< 0.1 cm	
$I_{rel,R=0.3,EA,Lep}$	< 0.04	< 0.4	< 0.15	< 0.4
$\sigma(p_T)/p_T^{track}$	< 0.2		< 0.2	

Lepton Flavor	Electron	Muon
ID	MVA POG NoIso	Loose
$\lvert\eta\rvert$	< 2.5	< 2.4
$\lvert d_z\rvert$	< 0.1 cm	
$\lvert d_{xy}\rvert$	< 0.05 cm	
I_{rel}(R=0.3,EA,Lep)	< 0.4	

Wγγ and Zγγ SMP-19-013

Selection for muons

Variable	Cut
Global muon	Yes
Particle-flow muon	Yes
Track fit χ^2/ndof < 10	Yes
Muon chamber hits	≥ 1
Muon station segments	≥ 2
d_{xy}	< 0.2
d_z	< 0.5
Pixel hits	> 1
Tracker layers hits	> 5

	Electrons	Muons
Basic selection	$p_T > 15$ GeV $\lvert\eta\rvert < 1.442$ or $1.566 < \lvert\eta\rvert < 2.5$ Cut based Tight ID Impact parameter cuts	$p_T > 15$ GeV $\lvert\eta\rvert < 2.4$ Cut based Tight ID Rochester corrections
	photons	
	$p_T > 20$ GeV $\lvert\eta\rvert < 1.442$ or $1.566 < \lvert\eta\rvert < 2.5$ Cut based Medium ID Pixel seed veto $\lvert m_{e,\gamma} - 91.2\rvert > 5$ $Z\gamma \to ee\gamma\ (e\gamma\gamma)$ $\Delta R(\gamma, \gamma/l) > 0.4$	
Event selection	$W\gamma\gamma$	$Z\gamma\gamma$
	Exactly one selected lepton $p^{e(\mu)}_{T,\text{lead}} > 35(30)$ GeV At least two photons	At least two selected same flavour leptons $p^{e(\mu)}_{T,\text{lead}} > 35(30)$ GeV At least two photons $m_Z > 55$ GeV

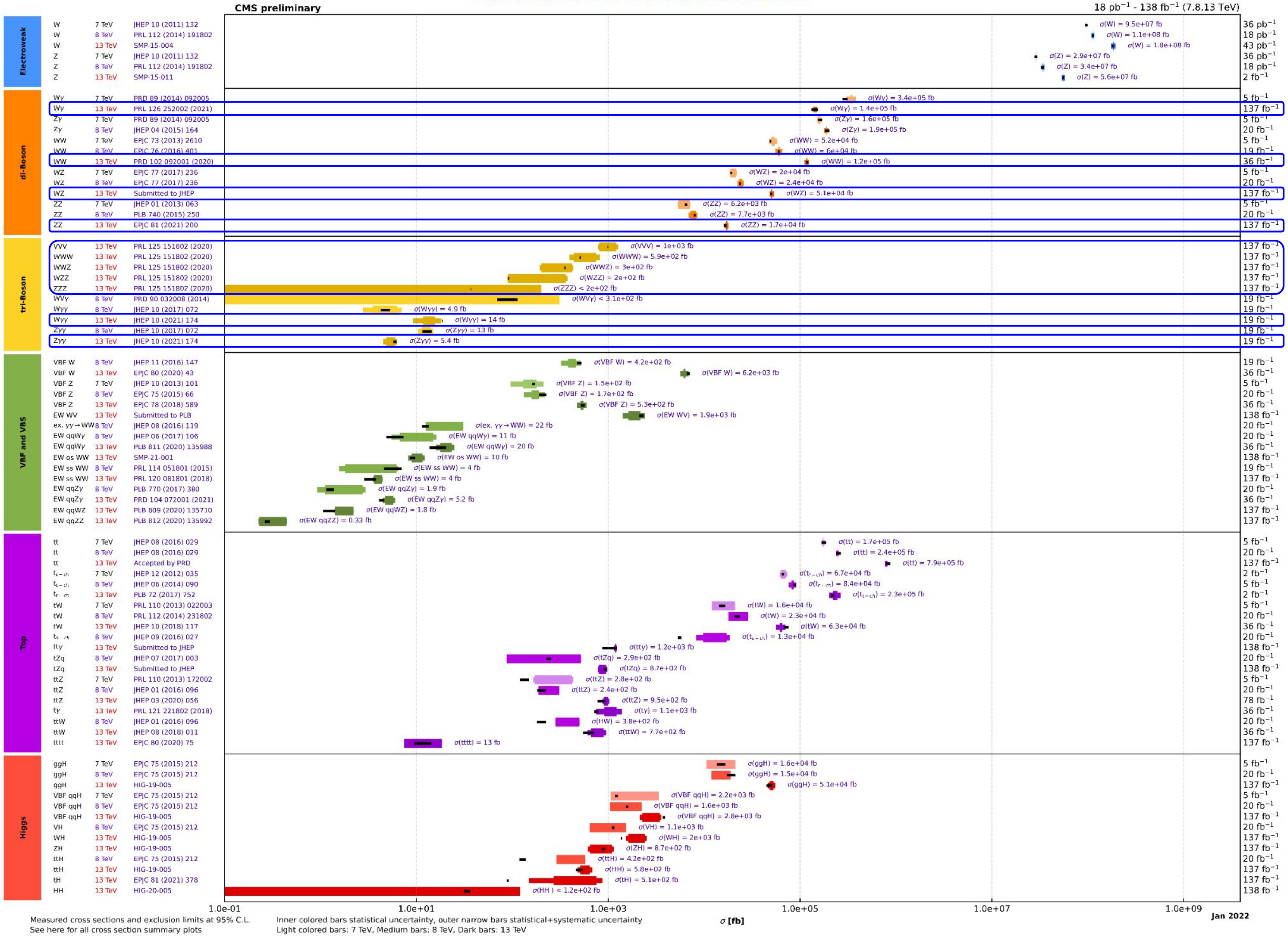
Selection for electrons

Variable	Barrel	Endcap
$\lvert\eta\rvert$	≤ 1.442	≥ 1.566 && ≤ 2.5
d_{xy}	< 0.05	< 0.10
d_z	< 0.10	< 0.20
$\sigma_{i\eta i\eta}$	< 0.0104	< 0.0353
$\lvert\Delta\eta\rvert$	< 0.00255	< 0.00501
$\lvert\Delta\phi\rvert$	< 0.022	< 0.0236
H/E	$< 0.026 + 1.15/E_{SC} + 0.0324\rho/E_{SC}$	$< 0.0188 + 2.06/E_{SC} + 0.183\rho/E_{SC}$
Iso_{rel}	$< 0.0287 + 0.506/p_T$	$< 0.0445 + 0.963/p_T$
$\lvert 1/E - 1/p\rvert$	< 0.159	< 0.0197
Missing hits	≤ 1	≤ 1
Pass conversion veto	Yes	Yes

Systematic source	$\ell\nu\gamma\gamma$ [%]	$\ell\ell\gamma\gamma$ [%]
Integrated luminosity	2	3
Pile-up	<1	1
Electron efficiencies	<1	1
Muon efficiencies	<1	1
Photon efficiencies	12	5
Jet-photon misid.	21	6
Electron-photon misid.	<1	—
Wγ theoretical cross section	3	<1
Zγ theoretical cross section	<1	6
Other bkgs theoretical cross section	2	<1
Simulated sample event count	8	4

TEMP

Overview of CMS cross section results



[motivations]?

Feynman diagrams for all the processes + some text?

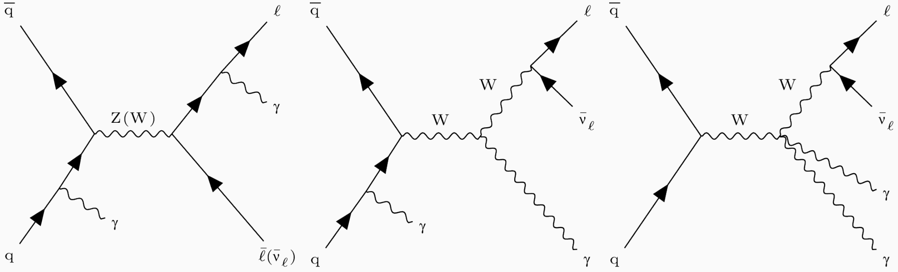
https://twiki.cern.ch/twiki/pub/CMSPublic/PhysicsResultsCombined/CMSCrossSectionSMPSummaryBarChart.pdf + illuminare area di questo talk

non parlerò di VBS. Per il tempo parlerò solo di risultati a 13 TeV

Wγγ and Zγγ

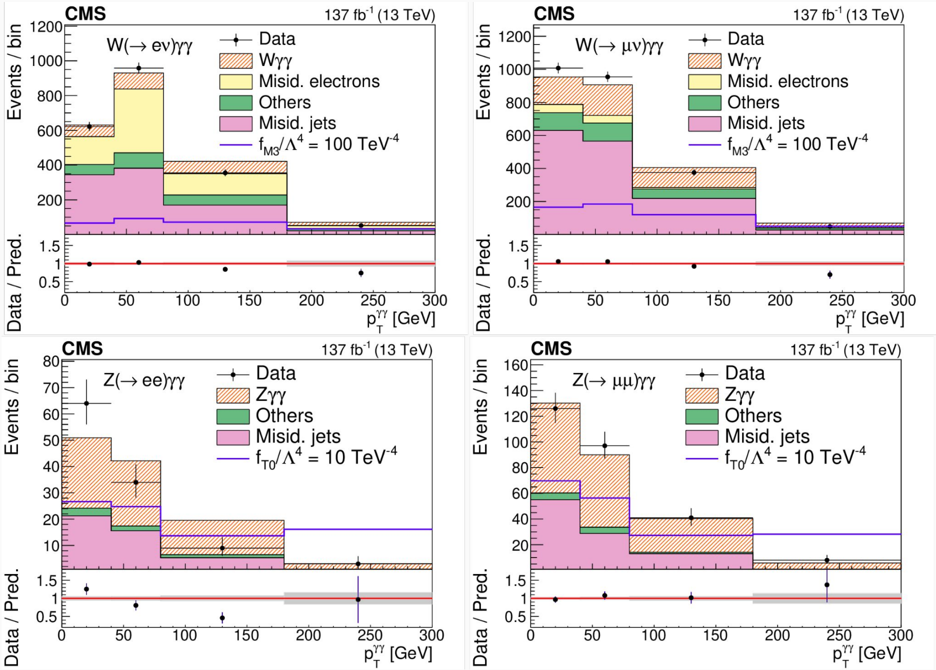
SMP-19-013

- Wγγ can be produced via a quartic coupling, while Zγγ cannot (in the SM)
- The photons can also be produced by initial or final state radiation



- Major backgrounds estimated from data
  - Electrons misidentified as photons - es Zγ → eeγ [eγγ]
  - **Jets** misidentified as photons: CR = V+γ_{loose}
    - Subtract Zγ → eeγ (MC) before computing FR
- QCD: tγ, ttγ, ttγγ, VVγ → from MC

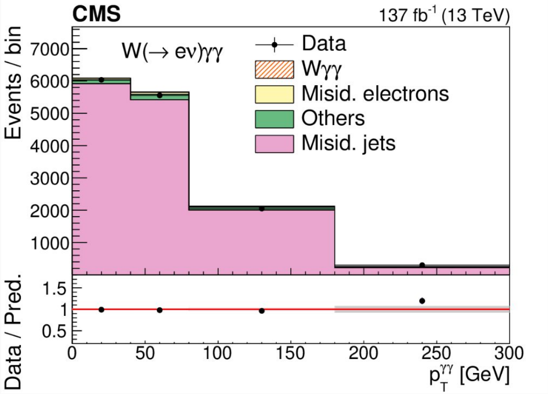
pre fit

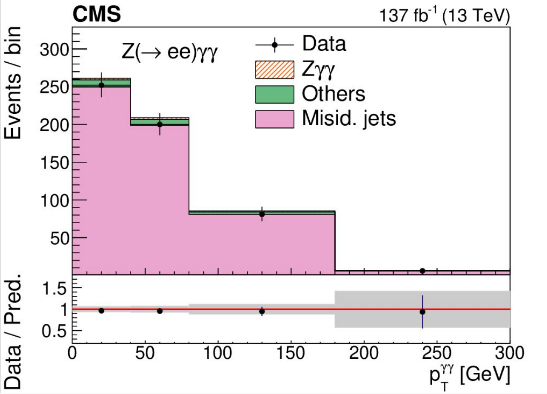


Wγγ and Zγγ - results

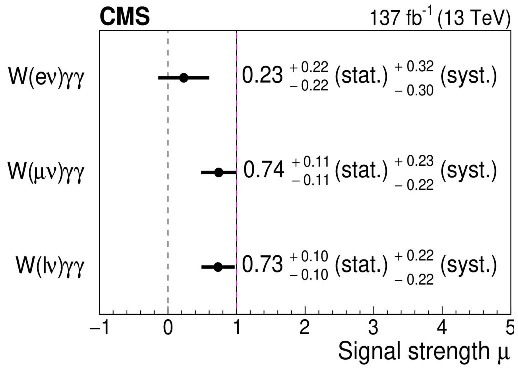
SMP-19-013

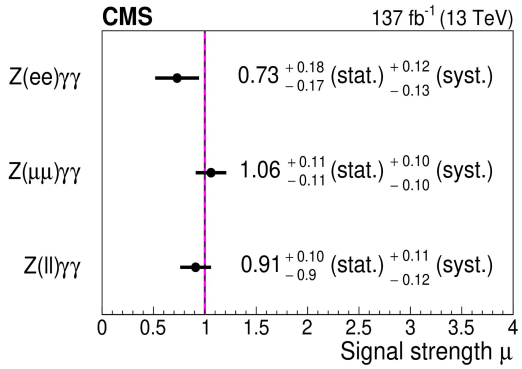
- Event selection: kinematic cuts
- Signal strength from fit to $p_T^{\gamma\gamma}$
- Uncertainty is dominated by systematics
  - Mostly from data-driven background
  - Estimated by inverting lepton isolation and applying same strategy





	Electrons	Muons
Basic selection	$p_T > 15$ GeV $\|\eta\| < 1.442$ or $1.566 < \|\eta\| < 2.5$ Cut based Tight ID Impact parameter cuts	$p_T > 15$ GeV $\|\eta\| < 2.4$ Cut based Tight ID Rochester corrections
	photons	
	$p_T > 20$ GeV $\|\eta\| < 1.442$ or $1.566 < \|\eta\| < 2.5$ Cut based Medium ID Pixel seed veto $\|m_{e,\gamma} - 91.2\| > 5$ ($Z\gamma \to ee\gamma$ ($e\gamma\gamma$)) $\Delta R(\gamma, \gamma/l) > 0.4$	
	$W\gamma\gamma$	$Z\gamma\gamma$
Event selection	Exactly one selected lepton $p_{T,\,lead}^{e(\mu)} > 35(30)$ GeV At least two photons	At least two selected same flavour leptons $p_{T,\,lead}^{e(\mu)} > 35(30)$ GeV At least two photons $m_Z > 55$ GeV

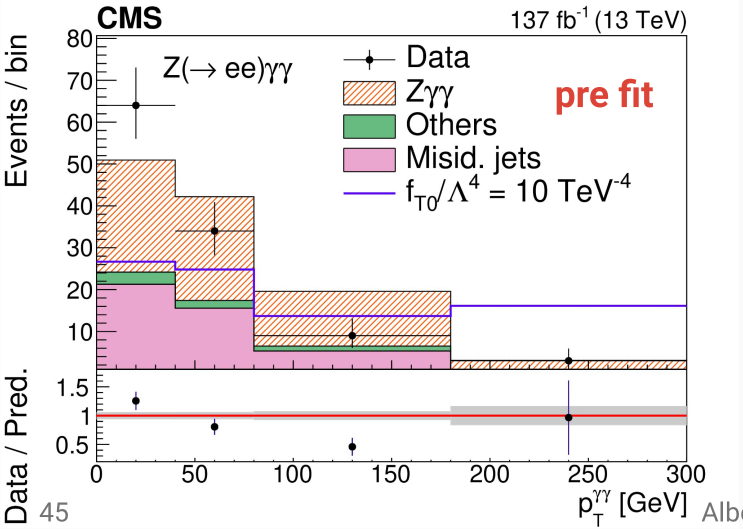




Wγγ and Zγγ - aQGC

SMP-19-013

- Both Wγγ and Zγγ are affected by dimension-6 and dimension-8 operators
  - Sensitivity to dim-6 is lower than diboson → omitted
- Fit to the $p_T^{\gamma\gamma}$ distribution
- Effects mostly in the high energy tail



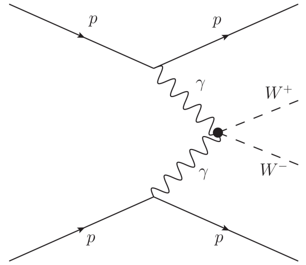
- Limits extracted for each operator with the others set to zero → 1D limits
  - Limits on f_{T5} and f_{T6} are comparable to results from Wγjj
  - f_{T0}, f_{T5}, f_{T8} and f_{T9} improve previous ATLAS analyses at 8 TeV
  - f_{T9} improves previous CMS result at 13 TeV

	Wγγ (TeV^{-4})		Zγγ (TeV^{-4})	
Parameter	Expected	Observed	Expected	Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T2}/Λ^4	[−5.16, 5.16]	[−3.64, 3.64]	[−9.72, 9.32]	[−11.4, 10.9]
f_{T5}/Λ^4	[−0.76, 0.84]	[−0.52, 0.60]	[−2.44, 2.52]	[−2.92, 2.92]
f_{T6}/Λ^4	[−0.92, 1.00]	[−0.60, 0.68]	[−3.24, 3.24]	[−3.80, 3.88]
f_{T7}/Λ^4	[−1.64, 1.72]	[−1.16, 1.16]	[−6.68, 6.60]	[−7.88, 7.72]
f_{T8}/Λ^4	—	—	[−0.90, 0.94]	[−1.06, 1.10]
f_{T9}/Λ^4	—	—	[−1.54, 1.54]	[−1.82, 1.82]

pWWp and pZZp

SMP-21-014

- The Precision Proton Spectrometer (PPS) allows to measure forward (intact) protons
- Access to the full kinematics of the event!
- 100 fb^{-1} of data (PPS in physics status)
- Search for pp → pp VV → pp j j , V = W, Z
  - Search for VBs decays into single large jets



Jets

- $p_T^j > 200$ GeV, $|\eta_j| < 2.5$
- $m_j > 1126$ GeV (trigger)
- $|\Delta\eta_{jj}| < 1.3$
- acoplanarity:
  $a = |1 - \Delta\varphi_{jj}| < 0.01$
- $p_T^{j1}/p_T^{j2} < 1.3$
- $\tau_{21}^{DDT} < 0.75$ (*)

Backgrounds

- Main: QCD multi jet
- Z+jet, W+Jet, tt production
- Diffractive pilup is not well modelled → data-driven

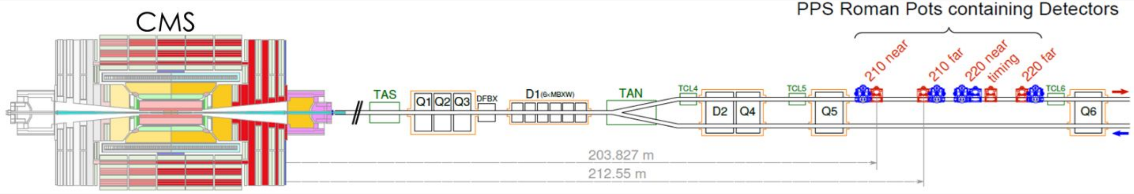
Protons

- multiRP → better ξ resolution
- $0.05 < \xi < \xi^{max}$
  - 180 GeV < M_{pp} < 1.55-2.1 TeV
    → lower bound by jet trigger

$\xi = \Delta p_p/p_p$

$$M_X = \sqrt{s\xi_1\xi_2}$$

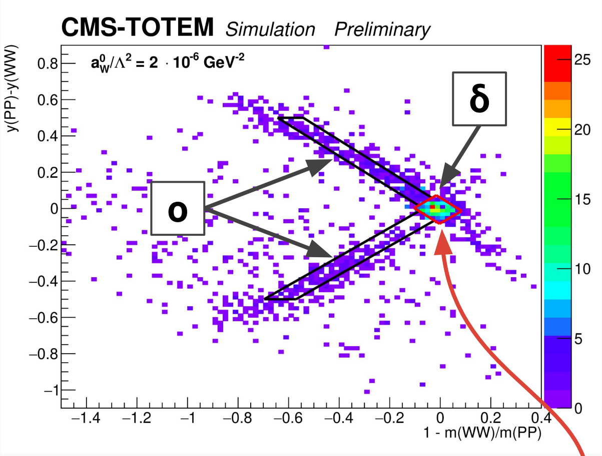
$$y = \frac{1}{2}\log\frac{\xi_1}{\xi_2}$$



(*) Designing Decorrelated Tagger. Goal: avoid mass sculpting. See arXiv:1603.00027

pWWp and pZZp - strategy

SMP-21-014



Proton-jet matching

- m(VV) = m(pp)
- y(VV) = y(pp)

= In the diamond

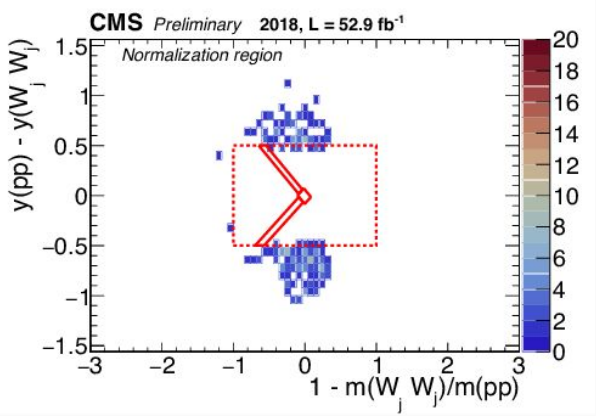
- In the arms one proton is correctly matched, the other comes from pileup
- Still considered signal

- Divide WW and ZZ with cut on:

$$\cos(\pi/4) * M^{leading}_{pruned} + sin(\pi/4) * M^{subleading}_{pruned}$$

Pileup background

- Use 2D sideband in m - y plane
  - $|1 - m_{VV}/m_{pp}| > 1.0$
  - $|y_{pp} - y_{VV}| > 0.5$
  - Note: both δ and o are inside
- and in the acoplanarity



ABCD method	a < 0.01	a > 0.01
in rectangle	**A** (SR)	**B**
out rectangle	**C**	**D**

$ZZ \to 4\ell$ ($\ell = e, \mu$) ex #3

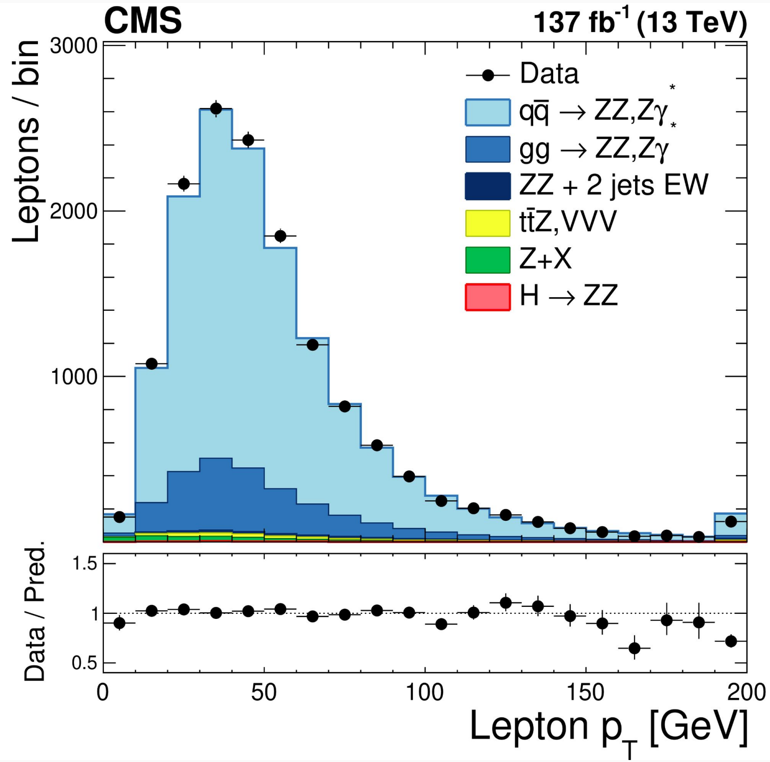
SMP-19-001

- Produced mainly via qq t- and u-channel (~ 90 %) and gg → loop (~ 10 %)
- No tree-level contribution from TGC in SM → probe aTGC
- Main background: nonprompt leptons
  - Two CR in data with a Z + $\ell^+\ell^-$ where both ℓ pass a loose ID
    - 2P2F: both fail tight ID
    - 3P1F: one fails tight ID
  - Measure lepton FR in CR with $Z+\ell_{loose}$ as $p(\ell_{loose} \to \ell_{tight})$
  - Scale each event in CRs by the lepton FR → contribution in SR
- Rare backgrounds: ttZ, VVV → MC

Variable	Cut
$p_T^{\ell 1}$	> 20 GeV
$p_T^{e2,\mu 2}$	> 12, 10 GeV
$p_T^{e,\mu,}$	> 7, 5 GeV
$\lvert \eta_{e,\mu} \rvert$	< 2.5, 2.4 GeV
$\Delta R(\ell, \ell)$	> 0.02
$\Delta R(e, \mu)$	> 0.05
$m(\ell\ell)$	$60 < m_{\ell\ell} < 120$ GeV
$m(\ell\ell')$	> 4 GeV

$Z+\ell_{loose}$ region

- $\lvert m_{\ell\ell} - m_Z \rvert < 10$ Gev
- $p_T^{miss} < 25$ GeV
- $m_T(\ell_3, p_T^{miss}) < 30$ GeV

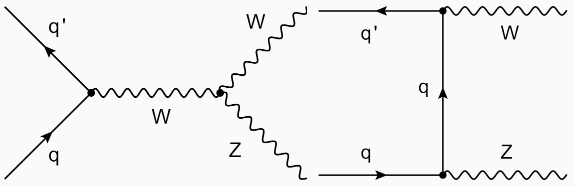


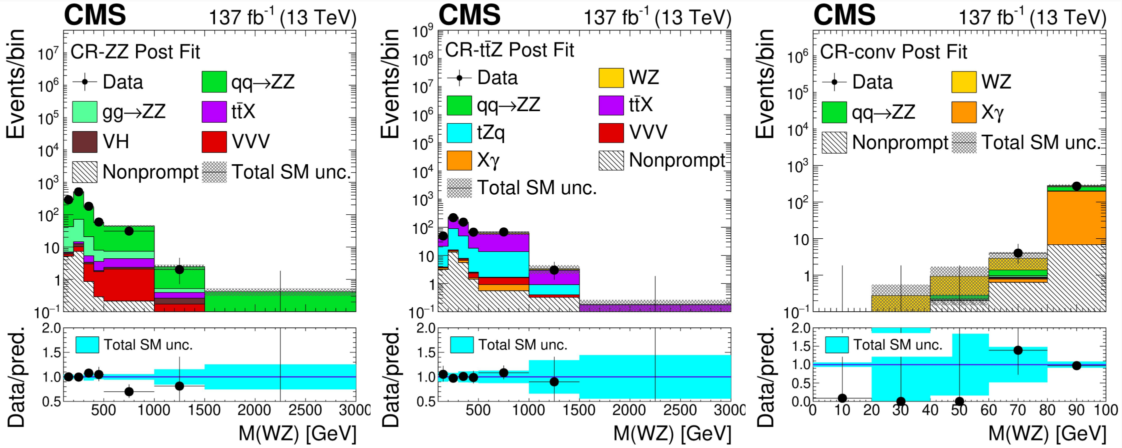
$WZ \rightarrow 3\ell\,\nu$

SMP-20-014

- Produced only by qq’ at tree level
- Sensitive to the WWZ TGC
- Sensitive to charge asymmetry

- Reducible bkg: tight-to-loose
- Irreducible bkg: MC (shape) + validation in CRs (norm)
  - ZZ (~6% of yield in SR), ttZ and tZq (~3.2%), X+γ (~1.5 %)





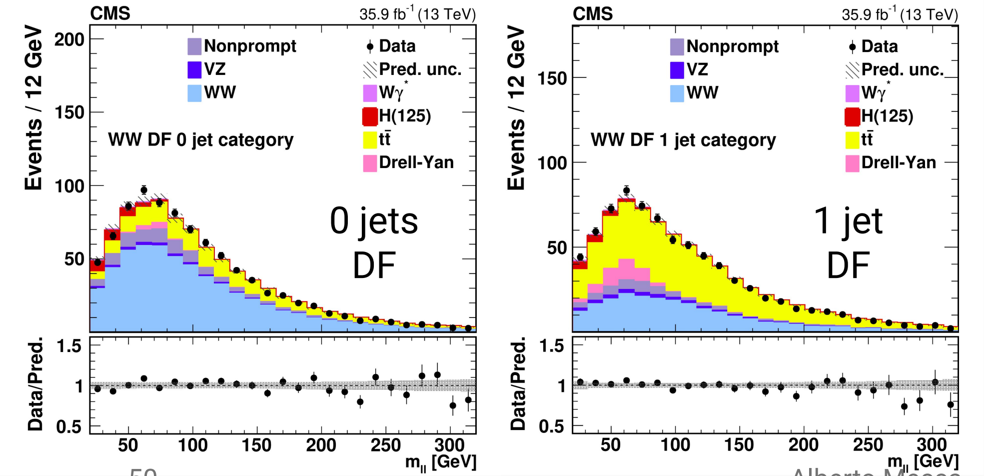
Region	N_ℓ	$p_T\{\ell_{Z1},\ell_{Z2},\ell_W,\ell_4\}$	N_{OSSF}	$\lvert M(\ell_{Z1},\ell_{Z2})-m_Z\rvert$	p_T^{miss}	N_{btag}	$\min(M(\ell\ell'))$	$M(\ell_{Z1},\ell_{Z2},\ell_W)$
SR	$=3$	$>\{25,10,25,—\}$ GeV	≥ 1	<15 GeV	>30 GeV	$=0$	>4 GeV	>100 GeV
CR-ZZ	$=4$	$>\{25,10,25,10\}$ GeV	≥ 1	<15 GeV	—	$=0$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

$tt\ell_{fake}$, ttZ, tZq

$W^+W^- \rightarrow \ell^+\ell^- 2\nu$

SMP-18-004

- Produced via qq annihilation (~95 %), gg-induced loop (~5 %) and H → WW (background)
- Signature: 2 isolated leptons and large p_T^{miss}
- Main background processes: tt, DY and **W+jets**
  - Lepton FR(p_T, η) is measured in QCD-enriched data
  - Applied in CR with 1 passing and 1 failing lepton
- Two analysis: sequential cut (measure σ_{tot}, $\sigma_{0/1j}$, $d\sigma_{0j}/dp_t^{THR}$) and Random Forest (σ_{tot} , $d\sigma/dn_j$)



Quantity	Sequential Cut DF	Sequential Cut SF
Number of leptons	Strictly 2	
Lepton charges	Opposite	
$p_T^{\ell\,max}$	>25	
$p_T^{\ell\,min}$	>20	
$m_{\ell\ell}$	>20	>40
Additional leptons	0	
$\lvert m_{\ell\ell} - m_Z \rvert$	—	>15
$p_T^{\ell\ell}$	>30	>30
p_T^{miss}	>20	>55
$p_T^{miss,proj}$, $p_T^{miss,track\ proj}$	>20	>20
Number of jets	≤1	
Number of b-tagged jets	0	
DYMVA score	—	>0.9
Drell–Yan RF score S_{DY}	—	—
$t\bar{t}$ RF score $S_{t\bar{t}}$	—	—

suppress DY

suppress ttbar

b jets: p_T > 20 GeV, medium WP

$p_T^{miss,\ proj} = proj_{\perp}(\mathbf{p}_T^{miss}, \mathbf{p}_T^{\ell,\ closest})$

DYMVA: developed for HWW analysis arXiv:1806.05246

$W^+W^- \rightarrow \ell^+\ell^- 2\nu$ - results [1]

SMP-18-004

Total cross section measurement with sequential analysis

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

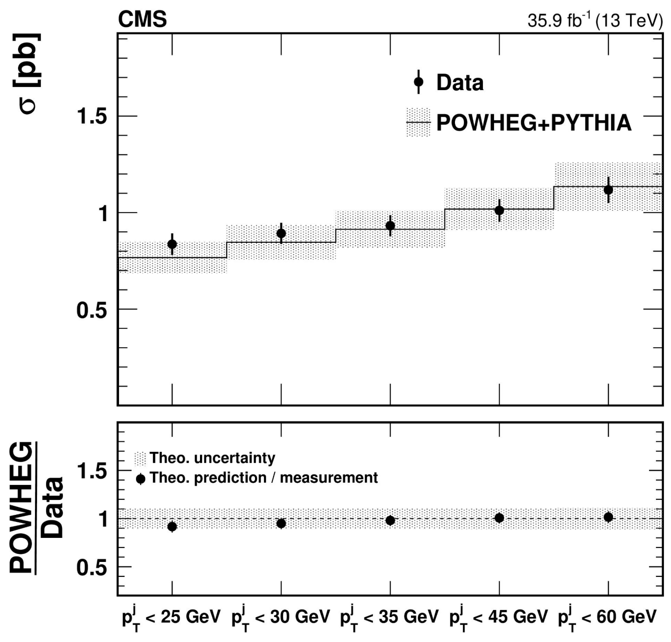
Theoretical prediction:

$\sigma_{tot}^{NNLO} = 118.8 \pm 3.6$ pb

Fiducial cross section: two dressed e or μ in the event with $p_T > 20$ GeV and $|\eta| < 2.5$, $m_{\ell\ell} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV and $E_T^{miss} > 20$ GeV

- Repeated for several pT thresholds for the jet veto

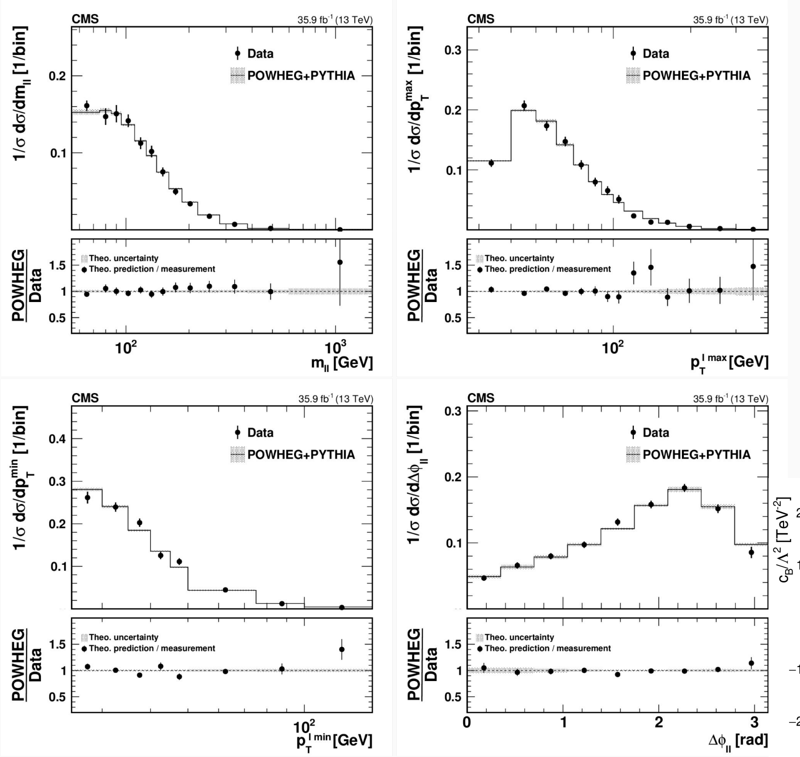
p_T threshold (GeV)	Signal strength	Cross section (pb)
25	1.091 ± 0.073	0.836 ± 0.056
30	1.054 ± 0.065	0.892 ± 0.055
35	1.020 ± 0.060	0.932 ± 0.055
45	0.993 ± 0.057	1.011 ± 0.058
60	0.985 ± 0.059	1.118 ± 0.067



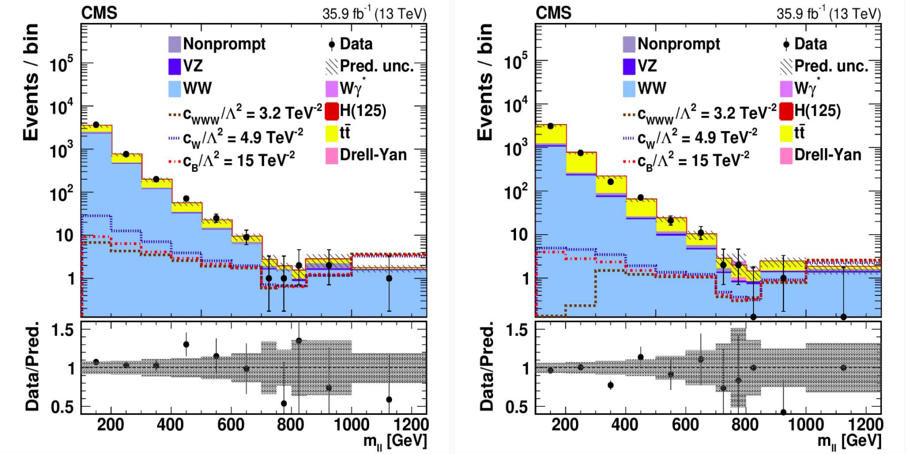
$W^+W^- \to \ell^+\ell^- 2\nu$ - results [2]

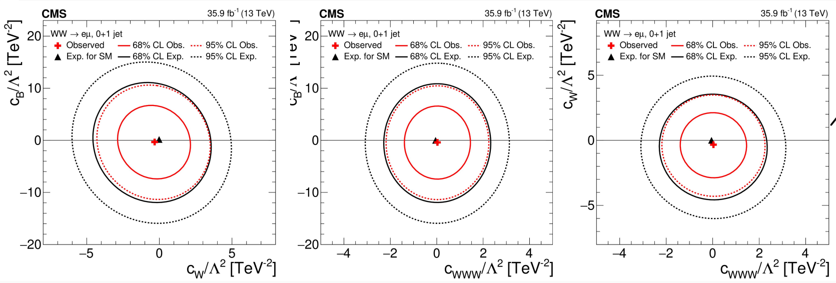
SMP-18-004

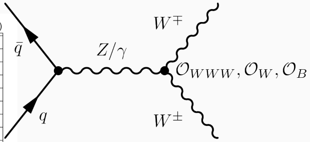
Differential cross section measurement



Limits on 3 Wilson coefficients







$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\ \mu},$$

$$\mathcal{O}_{W} = \frac{c_W}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^\nu \Phi),$$

$$\mathcal{O}_{B} = \frac{c_B}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^\nu \Phi),$$