Tri-boson Measurements at CMS

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on behalf of the CMS collaboration

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A brief history of the electroweak bosons

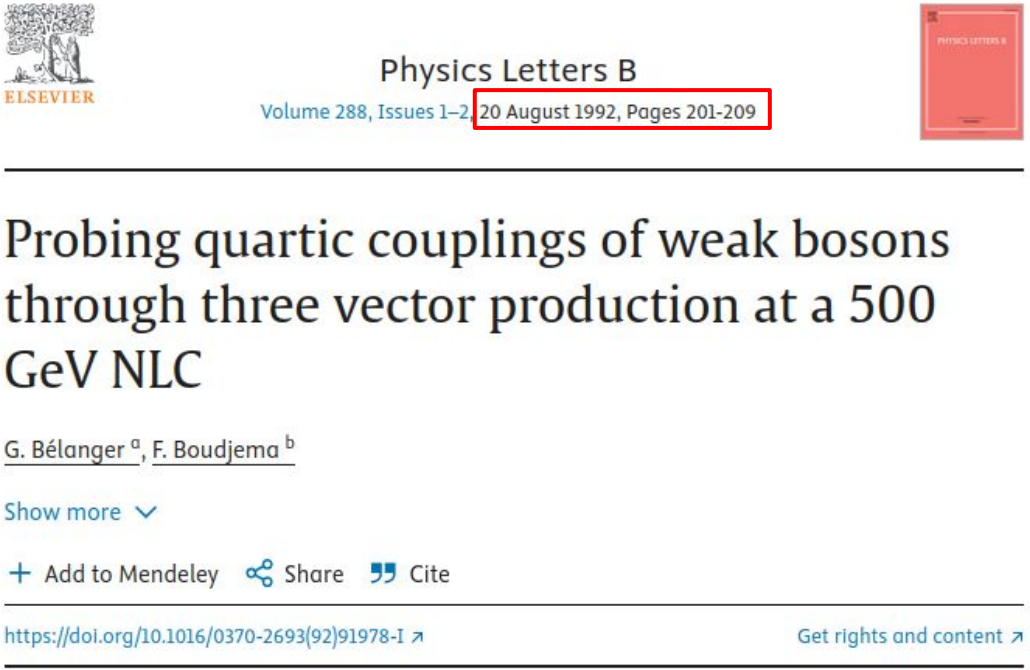
- 1967: Glashow, Salam, Weinberg propose unified electroweak theory
  - Nobel Prize (1979)
- 1983: W and Z bosons are discovered by UA1 collaboration (CERN)
  - Nobel Prize (1984): Carlo Rubbia (with S. van der Meer)
- 1980s: First precise measurements of W and Z properties, first measurements of multi-boson (VV) processes
- 1990s/2000s: CDF and D0 measure diboson processes at higher energies, providing indirect evidence for existence of SM Higgs boson
- Early 2010s: CMS and ATLAS can measure VV processes with high precision
- 2012: Discovery of the Higgs boson by ATLAS and CMS
  - Nobel Prize (2013): Peter Higgs, Francois Englert
- Late 2010s - 2020s: CMS and ATLAS are now sensitive to VVV processes!

What will the HL-LHC give us?

Some history on VVV

Interest in VVV has been around since (at least) the early 90s (https://doi.org/10.1016/0370-2693(92)91978-I)

Now we are capable of actually measuring these processes!

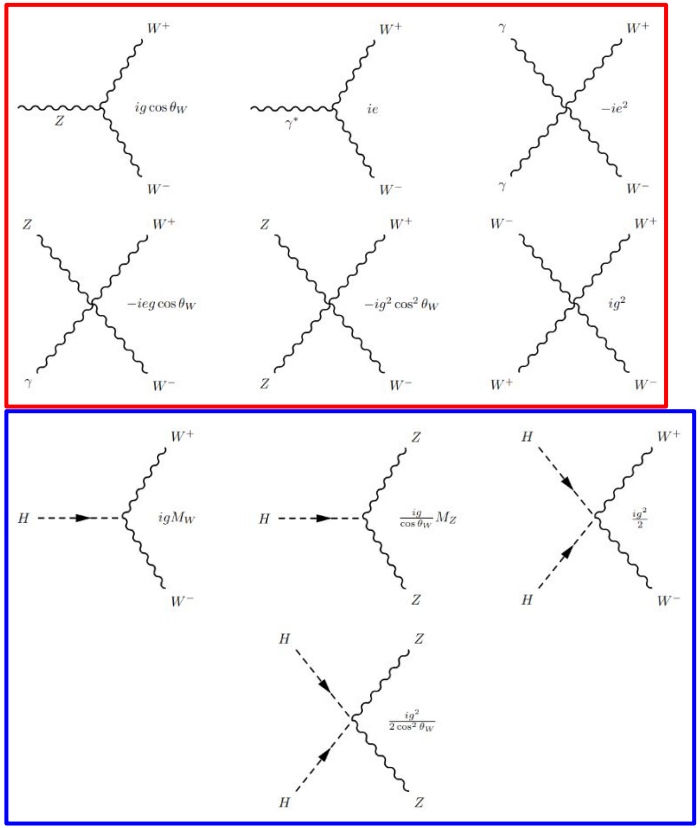


The need for multi-boson measurements

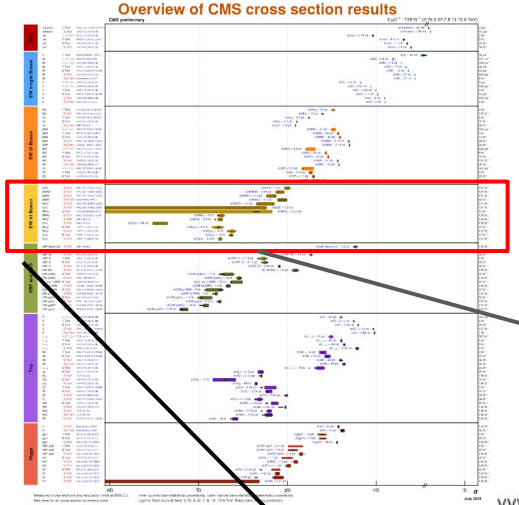
Why do we care?

- Multi-boson measurements probe the electroweak gauge couplings!
  - These couplings are highly sensitive to new physics lurking in the gauge sector
  - Triboson measurements can be sensitive to both triple and quartic gauge couplings!
- The electroweak bosons are predicted to have interactions with the Higgs
  - We can also study Higgs properties
  - Helps us to understand EWSB!

We can "kill 2 birds with one stone" by measuring multi-boson production



A Summary of CMS Triboson Results



A few analyses were from Run 1 at 8 TeV (19 fb-1)

Most analyses are from Run 2 at 13 TeV (~140 fb-1) → In this talk

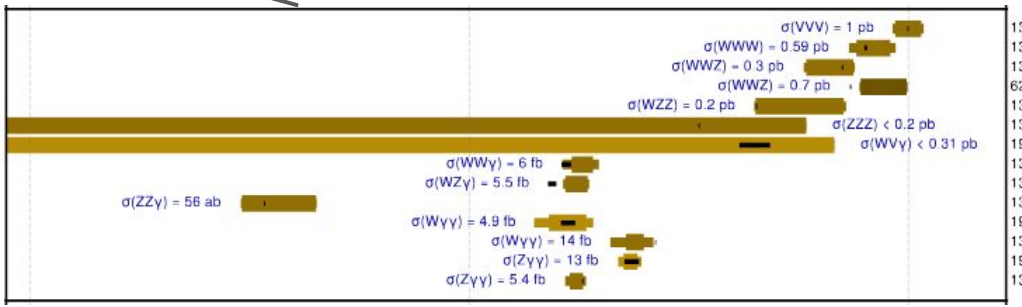
Currently only one public CMS result at 13.6 TeV (62 fb-1) → In this talk

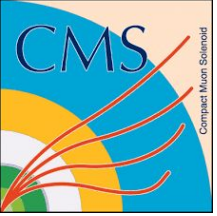
Lots of great work and effort has gone into obtaining these results!

[Source]

EW tri-Boson

VVV	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
WWW	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
WWZ	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
WWZ	13.6 TeV	Submitted to PRL	62 fb^{-1}
WZZ	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
ZZZ	13 TeV	PRL 125 151802 (2020)	137 fb^{-1}
WVγ	8 TeV	PRD 90 032008 (2014)	19 fb^{-1}
WWγ	13 TeV	PRL 132 (2024) 121901	138 fb^{-1}
WZγ	13 TeV	SMP-22-018	138 fb^{-1}
ZZγ	13 TeV	SMP-24-014	138 fb^{-1}
Wγγ	8 TeV	JHEP 10 (2017) 072	19 fb^{-1}
Wγγ	13 TeV	JHEP 10 (2021) 174	137 fb^{-1}
Zγγ	8 TeV	JHEP 10 (2017) 072	19 fb^{-1}
Zγγ	13 TeV	JHEP 10 (2021) 174	137 fb^{-1}





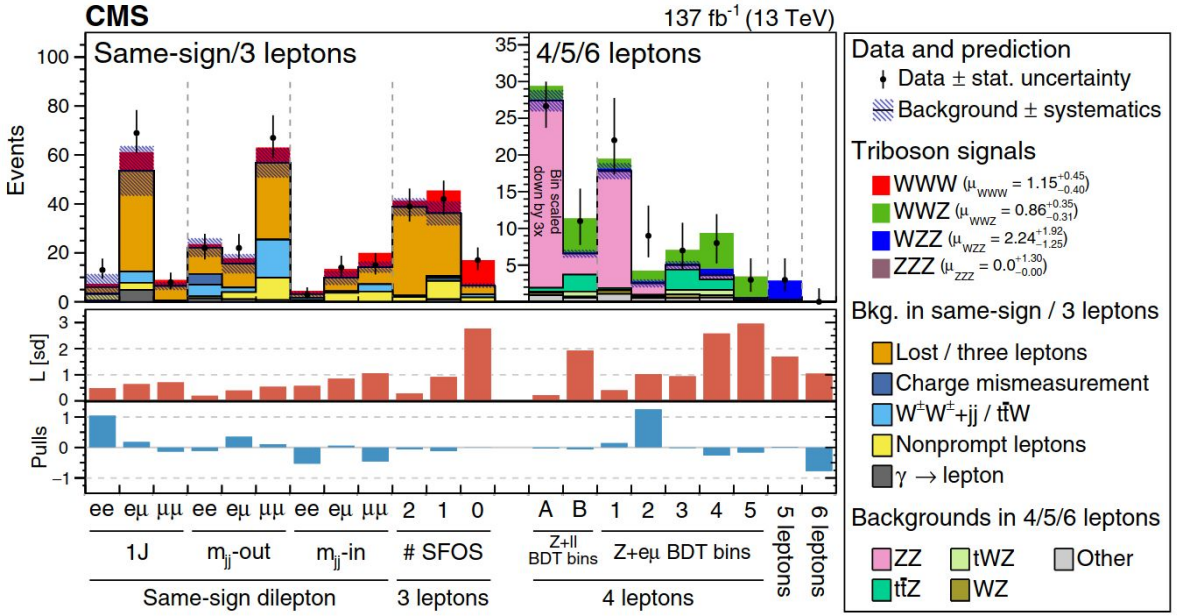
Run 2 Analyses

PRL 125, 151802 (2020)

Observation of Three Massive Gauge Bosons

Measurement of all VVV processes in 5 final states

- WWW
  - SS dilepton + jet
  - 3 lepton
- WWZ
  - 4 lepton
- WZZ
  - 5 lepton
- ZZZ
  - 6 lepton



Combined all channels for a measurement of VVV cross section at 13 TeV

PRL 125, 151802 (2020)

Observation of Three Massive Gauge Bosons

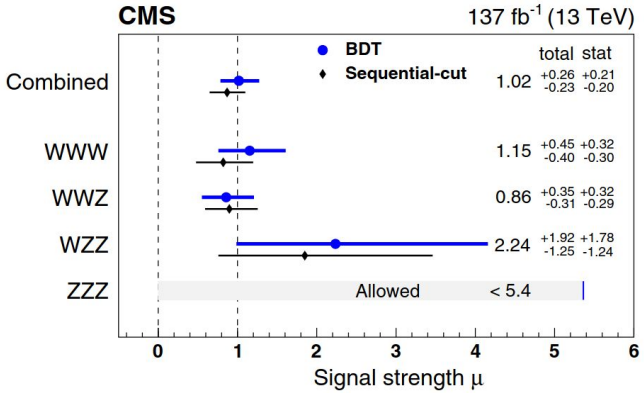
BDT and Cut-Based approaches were performed

First dedicated measurement of all VVV processes simultaneously

Observation of VVV with 5.7 s.d. significance

- Evidence for both WWW and WWZ

Observed (Expected) Significances
VVV: 5.7 (5.9)
WWW: 3.3 (3.1)
WWZ: 3.4 (4.1)



All measurements showed good agreement with the Standard Model

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

PRL 132, 121901 (2024)

Observation of WWγ and Search for Hγ

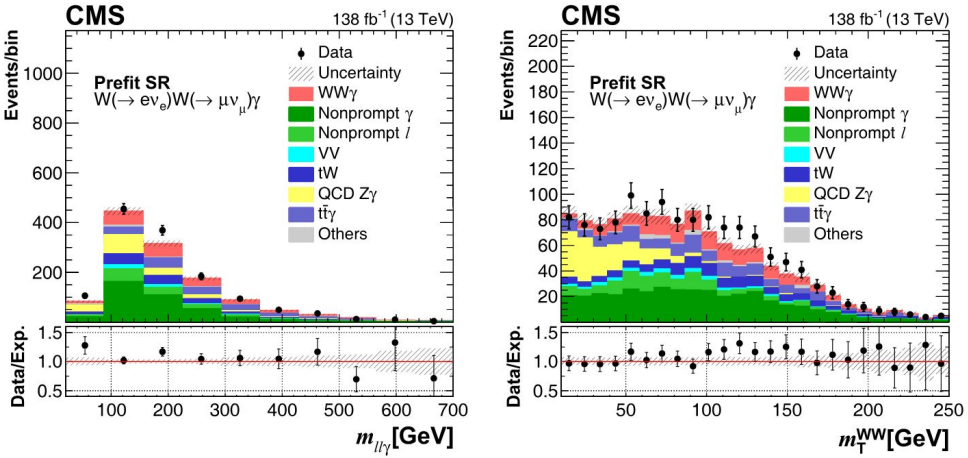
Measurement at 13 TeV with 138 fb-1

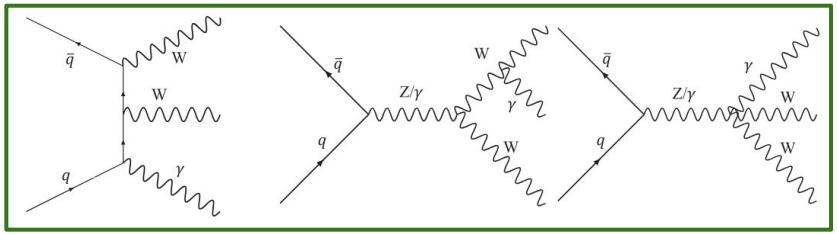
Cut based analysis

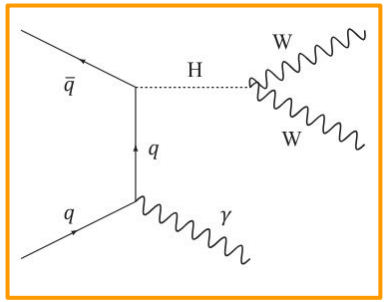
Final state: eμ (opposite sign) + photon (p_T > 20 GeV) + MET

Discriminating variables:

- Invariant mass of dilepton + gamma system (below left)
- Transverse mass of WW system (below right)







Major backgrounds
Same-sign WW + γ (CR)
Top + γ (CR)
QCD Vγ
Non-prompt lepton or γ

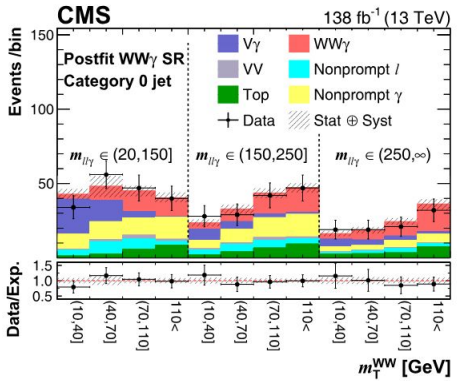
PRL 132, 121901 (2024)

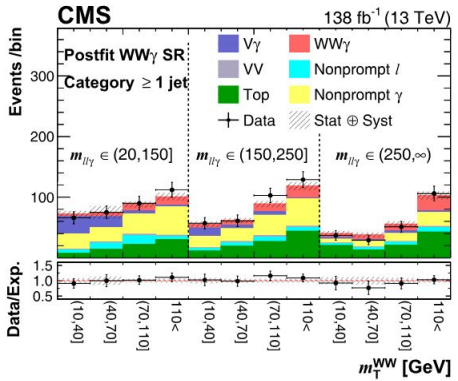
Observation of WWγ and Search for Hγ

Maximum-likelihood fit performed over signal region and control region bins in two categories:

- 0 jets
- 1 or more jets

Observation of WWγ with 5.6 s.d. significance





Process	SR (0 jet)	SR (≥1 jet)	SR (total)	SSWWγ CR	Topγ CR
$WW\gamma$	122 ± 22	134 ± 26	256 ± 47	1.3 ± 0.2	12.9 ± 2.7
QCD $V\gamma$	72.0 ± 6.0	94.6 ± 9.3	164 ± 14	12.2 ± 2.3	12.6 ± 1.2
VV	15.1 ± 1.2	21.6 ± 2.3	36.7 ± 3.5	24.9 ± 1.7	2.0 ± 0.3
Top	56.6 ± 6.5	271 ± 27	328 ± 32	2.4 ± 0.6	2434 ± 85
Nonprompt ℓ	45.7 ± 4.0	77.1 ± 6.2	122.9 ± 9.7	197 ± 14	40 ± 11
Nonprompt γ	109.0 ± 8.4	300 ± 24	410 ± 32	19.8 ± 1.6	792 ± 62
Total	420 ± 17	898 ± 26	1318 ± 43	257 ± 14	3294 ± 57
Data	414	916	1330	259	3287

Observed (Expected) Significance
WWγ: 5.6 (5.1)

Good agreement with Standard Model

$\sigma(WW\gamma) = 5.9 \pm 1.3$ fb

$\mu_{obs} = 1.11 \pm 0.16(stat) \pm 0.15(syst) \pm 0.13(modeling)$

PRD 112, 012009 (2025)

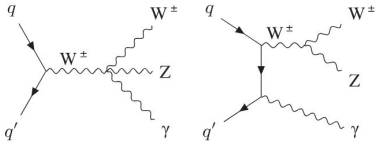
Observation of WZγ production at 13 TeV

Measurement at 13 TeV with 138 fb-1

Final states: 3 leptons (1 SFOS pair) + photon

Major backgrounds (Nonprompt lepton or photon, ZZ) estimated in dedicated control regions

Fit performed over Signal Region and Control Region bins



Process	SR	Nonprompt ℓ CR	Nonprompt γ CR	ZZ CR
$WZ\gamma$ signal	60.8 ± 3.5	0.66 ± 0.09	0.20 ± 0.04	0.017 ± 0.008
VV	12.99 ± 0.32	1.86 ± 0.12	0.164 ± 0.017	1016 ± 12
$V\gamma$	1.8 ± 0.9	4.7 ± 2.1	438 ± 27	0.011 ± 0.006
VVV	1.6 ± 0.4	0.36 ± 0.11	0.011 ± 0.007	0.10 ± 0.04
Top	3.3 ± 0.6	227 ± 15	27.0 ± 5.9	0.30 ± 0.04
Nonprompt ℓ	12.9 ± 2.8	1792 ± 34	<0.01	<0.01
Nonprompt γ	15.8 ± 2.2	<0.01	195 ± 19	<0.01
Total prediction	109 ± 5	2027 ± 33	660 ± 21	1016 ± 12
Observed	108	2029	658	1017

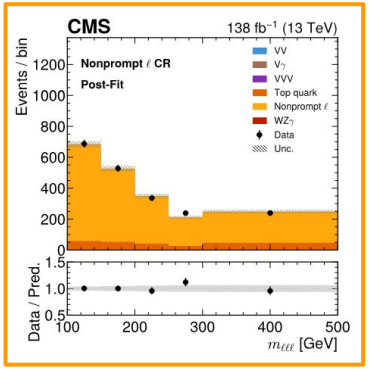
$\mu_{obs} = 1.47 \pm 0.31$
$\sigma_{obs} = 5.48 \pm 1.11$ fb
Observed (Expected) Significance: 5.4 (3.8)

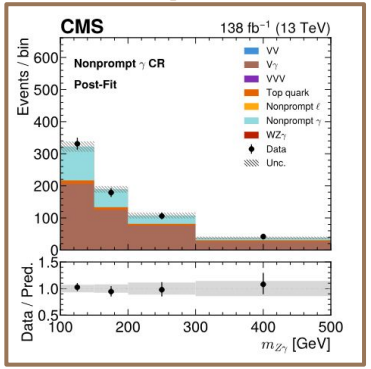
Nonprompt lepton CR

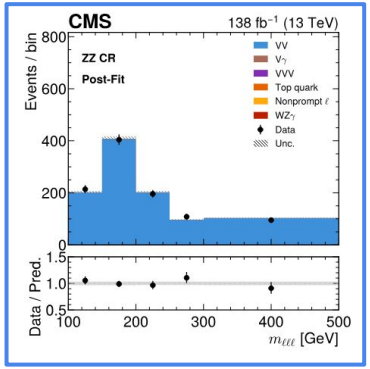
Nonprompt photon CR

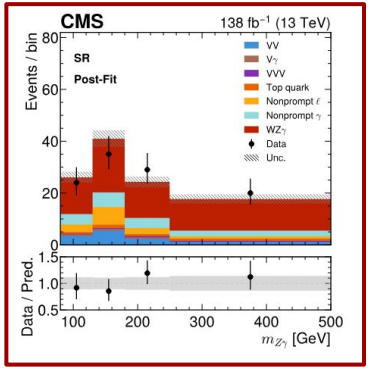
ZZ CR

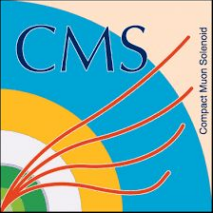
SR











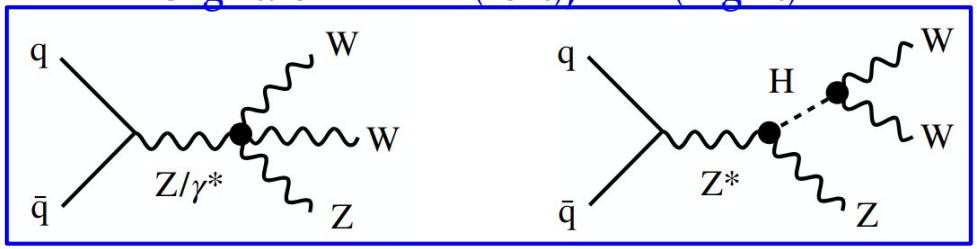
Run 3 Analyses

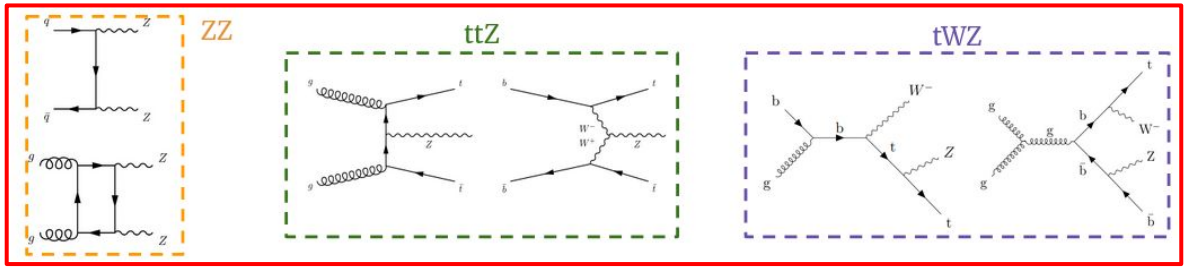
PRL 135, 091802 (2025)

WWZ and ZH Cross Section at 13 and 13.6 TeV

- Measured non-resonant WWZ and ZH(H→WW) production cross sections at both 13 and 13.6 TeV
  - First analysis to measure the two processes separately
- First CMS Triboson measurement at 13.6 TeV
- Datasets:
  - Run 2: 138 fb-1
  - Run 3: 62 fb-1
  - **Total: 200 fb-1**
- Final state: 4-leptons + MET

Signals: WWZ (left), ZH (right)



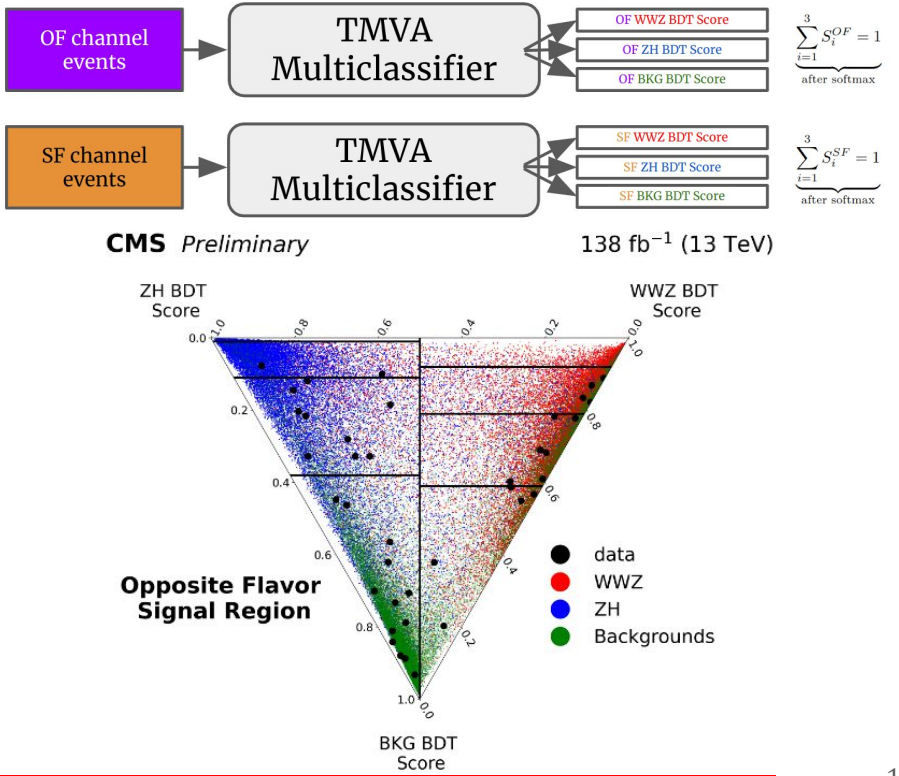


Major Backgrounds: ZZ, ttZ, tWZ

PRL 135, 091802 (2025)

WWZ and ZH Cross Section at 13 and 13.6 TeV

- Select 4 leptons
  - Require that 2 are same-flavor, opposite sign pair near the Z mass
- 2 channels based on lepton flavors from W decays
  - Opposite flavor: WW → eμ (+MET)
  - Same flavor: WW → ee or μμ (+MET)
- Train BDT multiclassifier for each channel
  - Scores visualized by Ternary Plots →
  - Signal regions obtained by binning in BDT scores



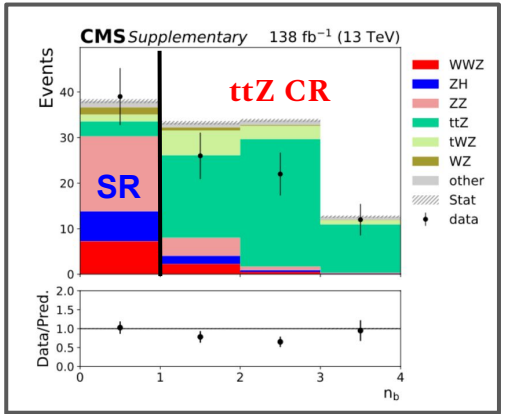
PRL 135, 091802 (2025)

WWZ and ZH Cross Section at 13 and 13.6 TeV

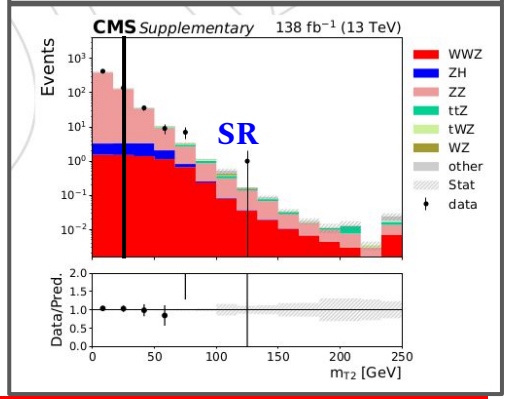
- Construct control regions to estimate major background contributions
  - ZZ (same-flavor channel):
    - **W lepton candidates are inside the Z-peak (within 10 GeV)**
  - ttZ + tWZ (same- and -opposite-flavor channels):
    - 2 bins (per channel)
      - $N_{btags} = 1$
      - $N_{btags} \geq 2$
    - SF channel has additional criteria applied:
      - W lepton candidates outside Z peak
      - MET > 80 GeV

ZZ and tXZ (ttZ & tWZ) normalizations float freely in fit

Opposite-flavor channel



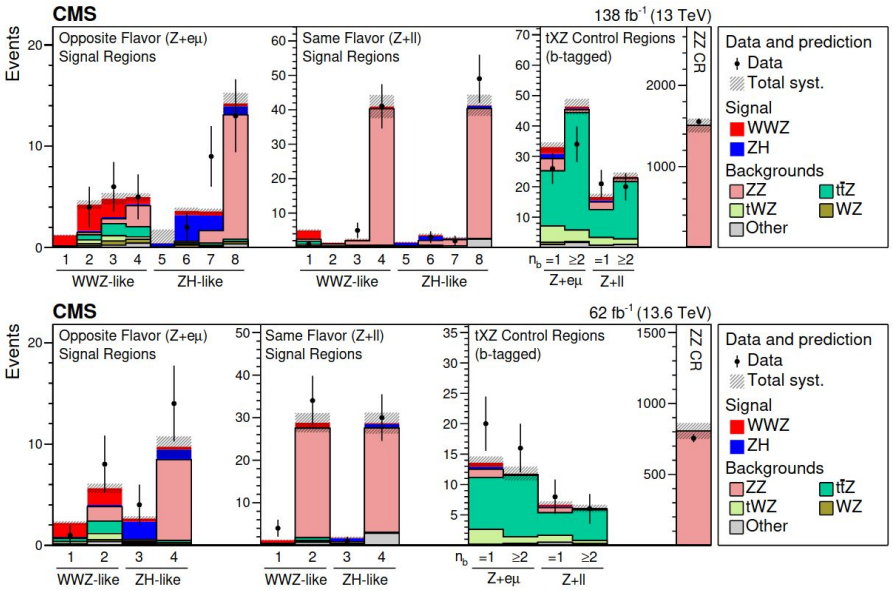
Same-flavor channel

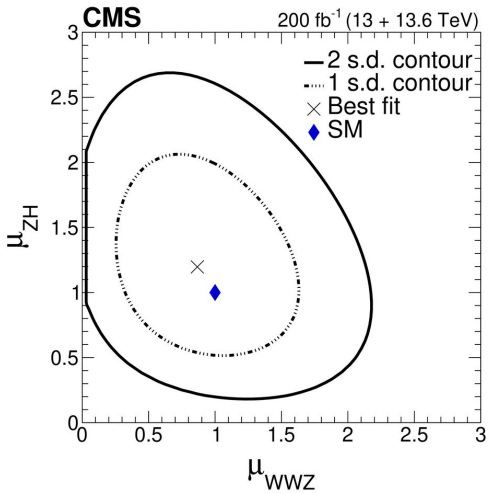


PRL 135, 091802 (2025)

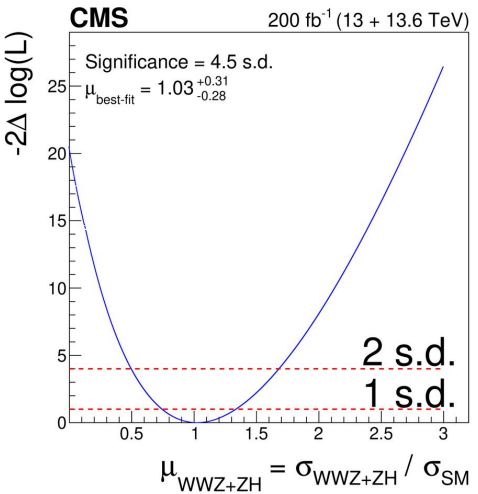
WWZ and ZH Cross Section at 13 and 13.6 TeV

- Use 34 total signal and control region bins (shown below) in fits for signal strengths →





2D Likelihood Scan



1D Likelihood Scan

Separate scans performed for combined (1D) and individual (2D) signal strengths

PRL 135, 091802 (2025)

WWZ and ZH Cross Section at 13 and 13.6 TeV

Era	Process	$\mu = \sigma_{obs}/\sigma_{SM}$	σ_{obs} (fb)	σ_{SM} (fb)
Run 2 ($\sqrt{s} = 13$ TeV)	WWZ only	$0.52^{+0.50}_{-0.41}\,(\text{stat})^{+0.13}_{-0.12}\,(\text{syst})$	$97^{+91}_{-75}\,(\text{stat})^{+24}_{-21}\,(\text{syst})$	184 [8]
	ZH only	$1.01^{+0.62}_{-0.51}\,(\text{stat})^{+0.14}_{-0.08}\,(\text{syst})$	$190^{+120}_{-100}\,(\text{stat})^{+30}_{-20}\,(\text{syst})$	189 [9]
	Inclusive	$0.75^{+0.32}_{-0.28}\,(\text{stat})^{+0.10}_{-0.08}\,(\text{syst})$	$280^{+120}_{-110}\,(\text{stat})^{+40}_{-30}\,(\text{syst})$	373
Run 3 ($\sqrt{s} = 13.6$ TeV)	WWZ only	$1.91^{+1.12}_{-0.94}\,(\text{stat})^{+0.25}_{-0.16}\,(\text{syst})$	$380^{+220}_{-190}\,(\text{stat})^{+50}_{-30}\,(\text{syst})$	200 [8]
	ZH only	$1.57^{+1.12}_{-0.89}\,(\text{stat})^{+0.29}_{-0.14}\,(\text{syst})$	$320^{+230}_{-180}\,(\text{stat})^{+60}_{-30}\,(\text{syst})$	202 [36]
	Inclusive	$1.74^{+0.67}_{-0.58}\,(\text{stat})^{+0.22}_{-0.15}\,(\text{syst})$	$700^{+270}_{-230}\,(\text{stat})^{+90}_{-60}\,(\text{syst})$	402

Significance

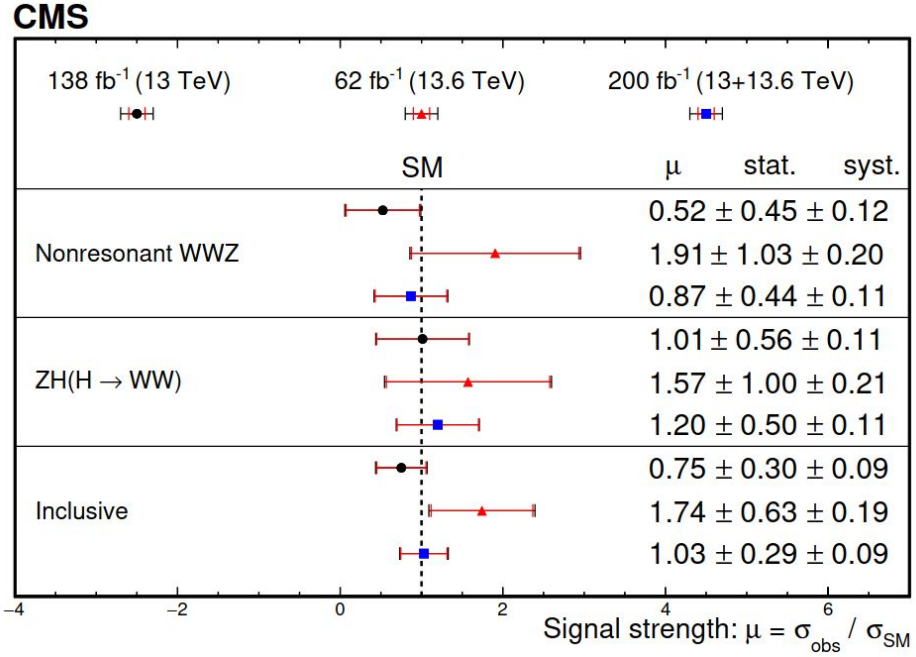
Era	Total	WWZ	ZH
Run 2	2.9 (4.4)	1.3 (3.1)	2.0 (2.6)
Run 3	3.8 (2.5)	2.5 (1.3)	2.5 (1.7)
Total	4.5 (5.0)	2.4 (3.3)	3.1 (3.1)

Significance (combined): 4.5σ

Significance (Run 3): 3.8σ

Evidence for WWZ at 13.6 TeV

Signal strengths consistent with SM



Combined signal strength: $\mathbf{1.03^{+0.31}_{-0.28}}$

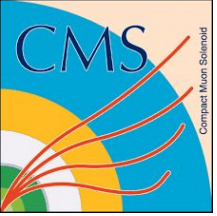
Summary

Triboson results from CMS

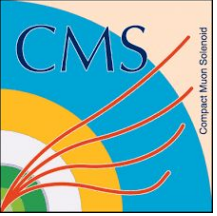
- One triboson result at 13.6 TeV thus far
  - Evidence for WWZ production (PRL)
- Run 2 results showed multiple observations of triboson processes
  - VVV observation (PRL)
  - WWγ (PRL)
  - WZγ (PRD)
  - ZZγ evidence (CMS-PAS-SMP-24-014)

We are excited to see more results at 13.6 TeV!

HL-LHC will also provide better statistics to study these rare processes!



Questions?



Backup

Evidence of ZZγ production at 13 TeV

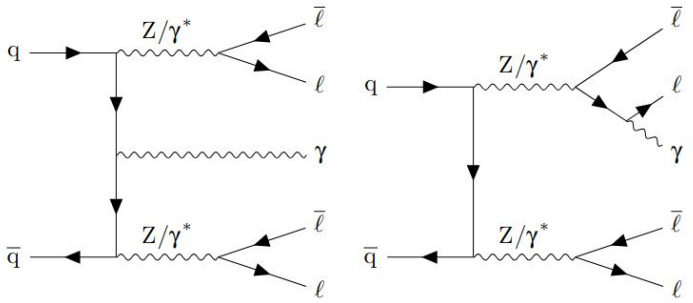
Measurement at 13 TeV with 138 fb-1

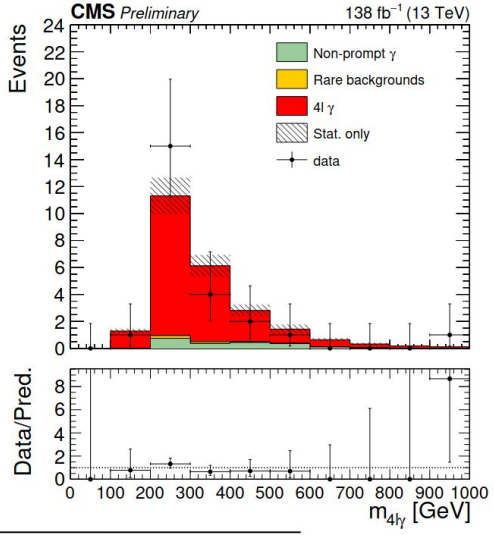
Final states: 4 leptons (2 SFOS pairs) + photon (> 20 GeV)

Major backgrounds:

- qq → ZZ + non-prompt photon
- gg → ZZ + non-prompt photon
- Triboson processes

Highly dominated by statistics (~98% of the total uncertainty)





Observed (Expected) Significance: 3.7 (3.0)
→ Evidence for ZZγ

	2016	2017	2018	Run 2
$ZZ\gamma \to 4\ell\gamma$	2.18 ± 0.61	2.52 ± 0.99	3.58 ± 1.41	8.28 ± 1.83
$q\bar{q} \to ZZ$	0.18 ± 0.04	0.24 ± 0.06	0.34 ± 0.09	0.76 ± 0.12
$gg \to ZZ \to \ell\ell$	0.19 ± 0.03	0.20 ± 0.04	0.28 ± 0.05	0.67 ± 0.07
$ZZ\gamma \to 4\ell\gamma$ OOA	0.12 ± 0.02	0.12 ± 0.01	0.14 ± 0.02	0.38 ± 0.03
Non-prompt ℓ	0.17 ± 0.15	0.12 ± 0.11	0.08 ± 0.09	0.37 ± 0.21
Rare backgrounds	0.04 ± 0.01	0.13 ± 0.03	0.18 ± 0.04	0.35 ± 0.05
Predicted number of events	2.87 ± 0.64	3.34 ± 1.00	4.60 ± 1.41	10.80 ± 1.84
Observed number of events	2	3	6	11

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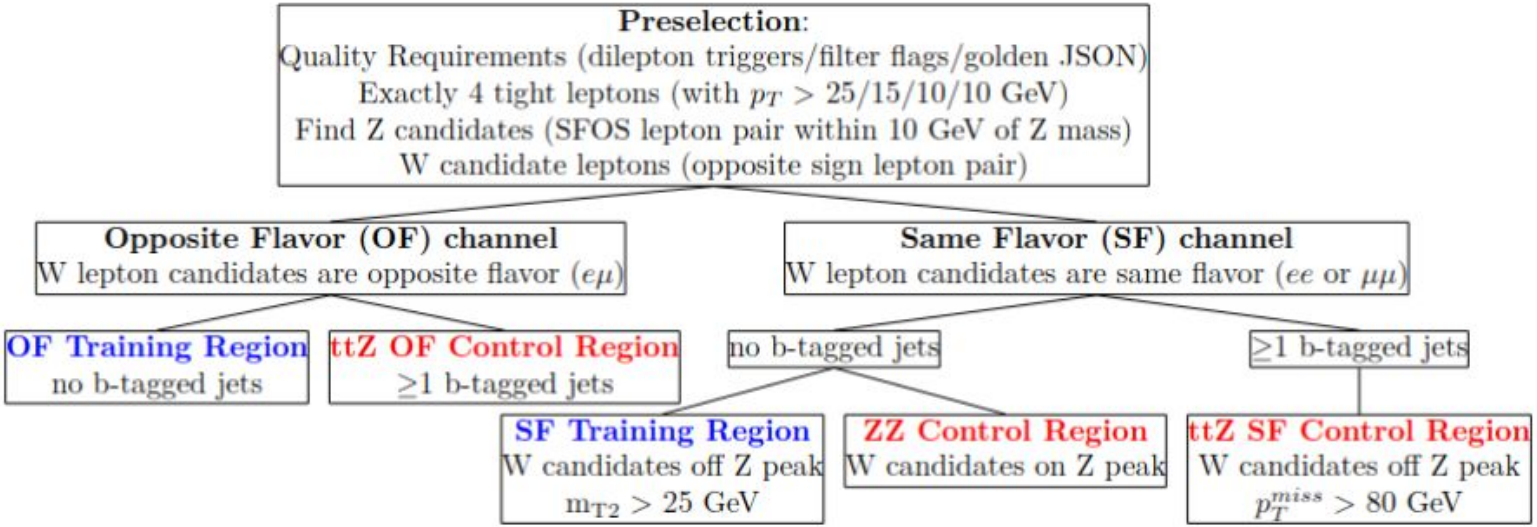
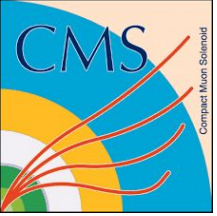
WWZ and ZH cross section at 13 and 13.6 TeV

Selection criteria





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Observation of WWγ and Search for Hγ

Set limits on the cross section and Yukawa couplings to light quarks for Hγ production

TABLE II. Upper limits on the cross section and derived limits in terms of Yukawa coupling at 95% C.L. for $H\gamma$ production initiated by light quarks.

Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% C.L.	$\bar{\kappa}_q$ limits obs. (exp.) at 95% C.L.
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	86 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)	$\lvert\bar{\kappa}_u\rvert \leq 7.5$ (6.1)
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\lvert\kappa_d\rvert \leq 17000$ (14000)	$\lvert\bar{\kappa}_d\rvert \leq 16.6$ (14.7)
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	66 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)	$\lvert\bar{\kappa}_s\rvert \leq 32.8$ (25.2)
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	88 (66)	$\lvert\kappa_c\rvert \leq 190$ (110)	$\lvert\bar{\kappa}_c\rvert \leq 43.2$ (25.0)

$$\bar{\kappa}_f \equiv \frac{m_f(\mu = 125\ \text{GeV})}{m_b(\mu = 125\ \text{GeV})}\kappa_f$$

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