Standard Model at LHC
Duhram (UK) – Apr. 2025

Recent Triboson measurements at the LHC

and interplay with VH production measurements

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on behalf of
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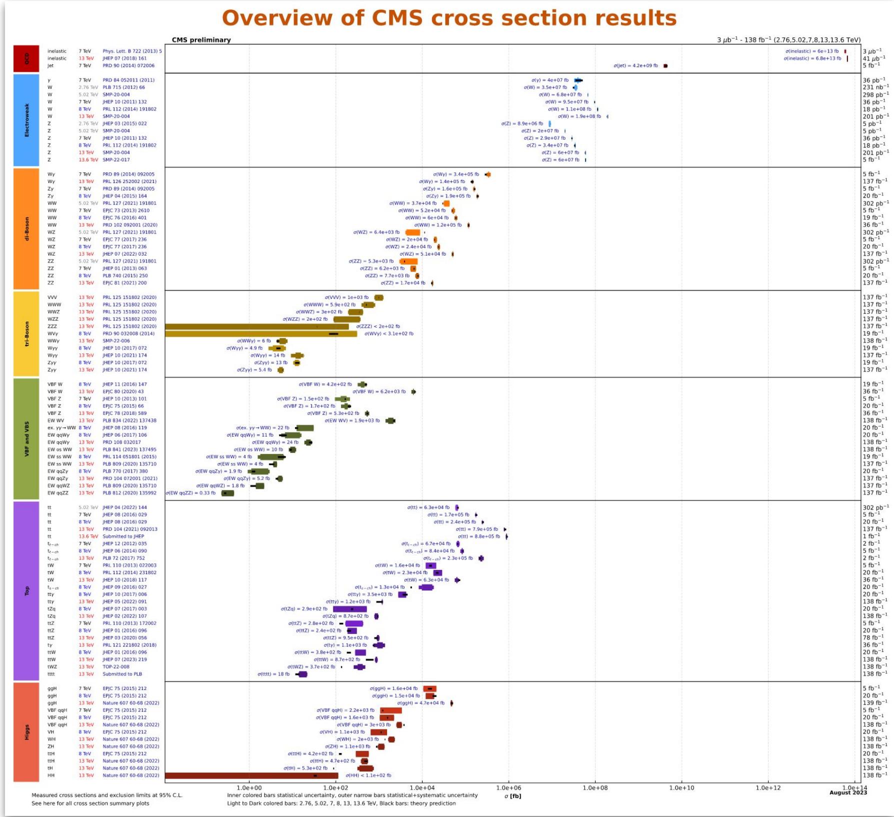
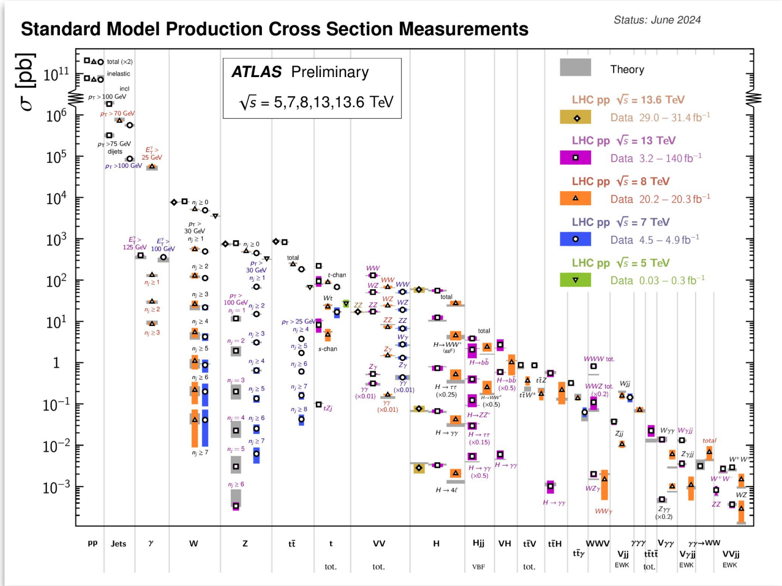
Triboson measurements at LHC



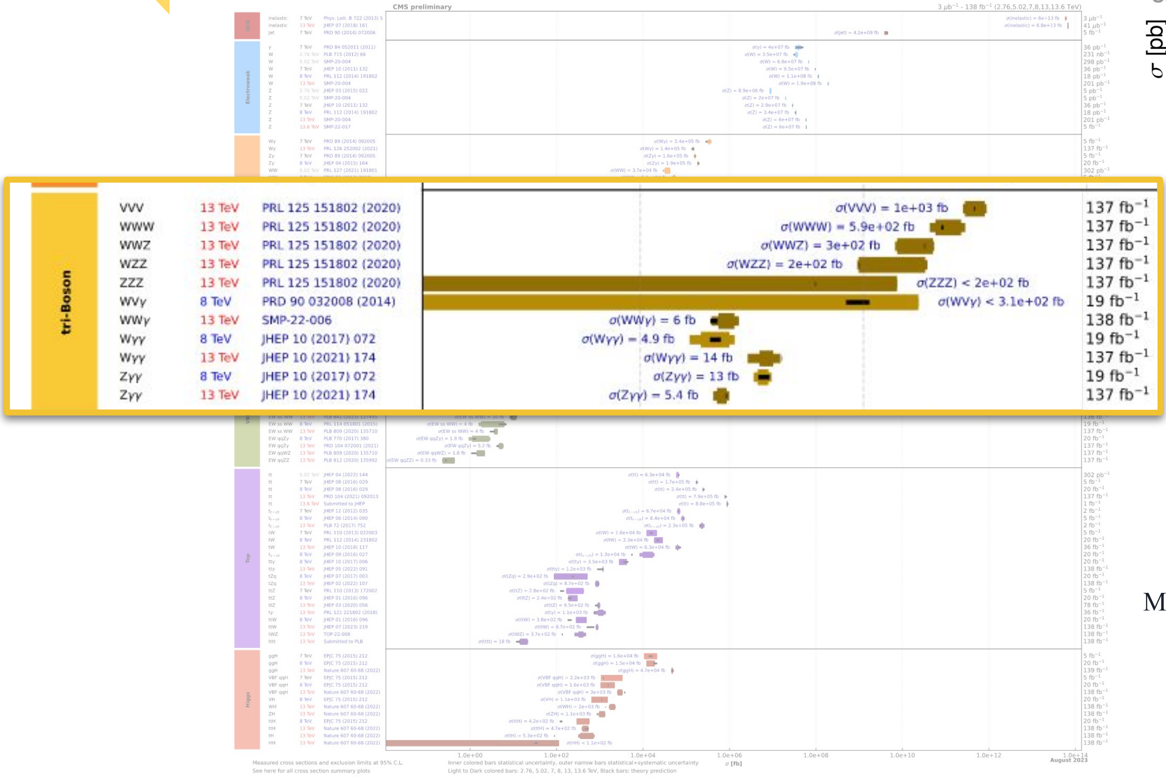


Measurement of the **cross section** of **triboson** production processes:

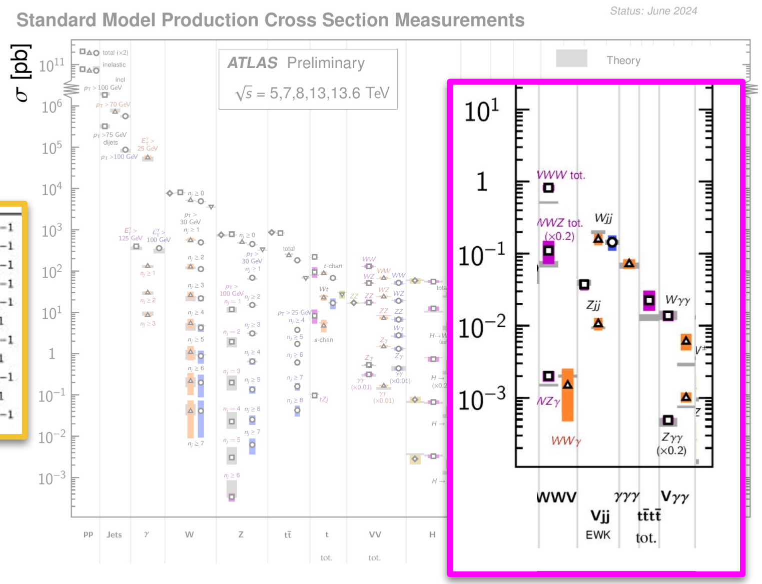
- valuable **precision tests** for the electroweak sector of the SM
- **novel observation** of **very rare** processes
- **TGCs** and **QGCs** involved

Triboson measurements at LHC

Overview of CMS cross section results



Standard Model Production Cross Section Measurements



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- valuable **precision tests** for the electroweak sector of the SM
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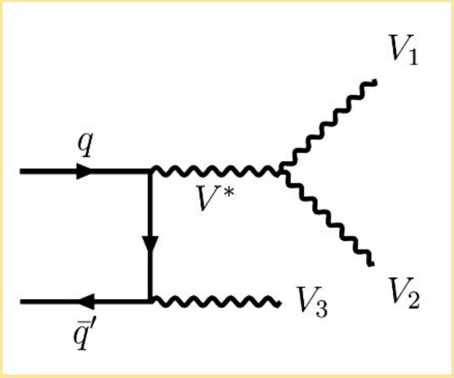
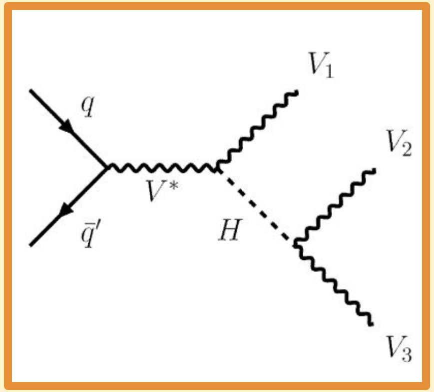
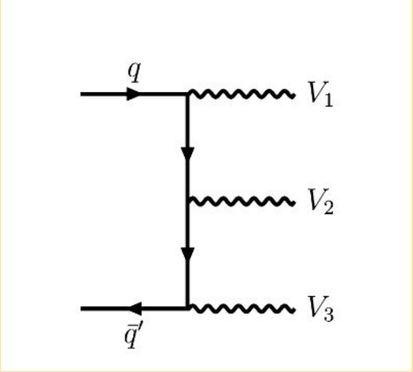


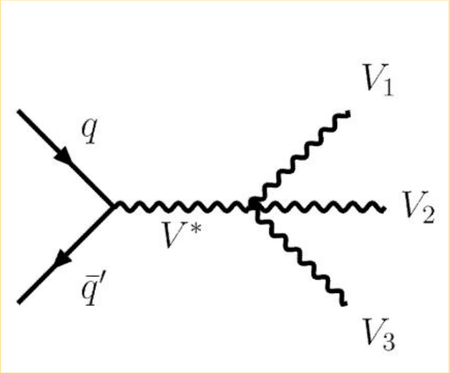
VVV searches

- ATLAS VVZ (STDM-2020-08)
- CMS WWZ (SMP-24-015)



and interplay with searches for VH production





Most recent VH results:
- ATLAS VH (H→ bb/cc) (HIGG-2020-20) arXiv:2410.19611 *
- CMS ZZ/ZH → 4b (HIG-22-011) *EPJC 84 (2024) 712*

*presented by G. D'Annibale on Monday

Previously on these channels…

First evidence of the ewk. production of WWW and WVZ (Nov. 2019)
First observation of the ewk. production of WWW (Aug. 2022)

Observed (expected) significance

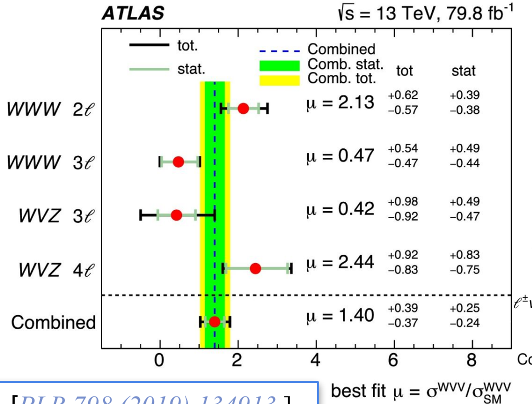
WWW	(2ℓ+2q)	**4.0 (1.7) S.D.**
	(3ℓ)	1.0 (2.0) S.D.

→ Combined fit for **WWW**: **3.2 (2.4) S.D.**

WVZ	(3ℓ)	0.5 (1.0) S.D.
	(4ℓ/4ℓ+2q)	**3.5 (1.8) S.D.**

→ Combined fit for **WVZ**: **4.1 (3.1) S.D.**

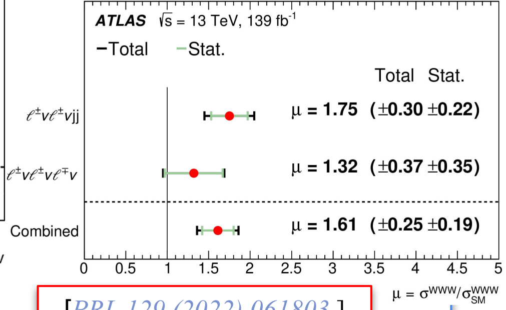
→ Combined fit for **WVV:** **4.1 (5.9) S.D.**



[PLB 798 (2019) 134913]

WWW	(2ℓ+2q)	**6.6 (4.0) S.D.**
	(3ℓ)	**4.8 (3.8) S.D.**

→ Combined fit: **8.0 (5.0) S.D.**



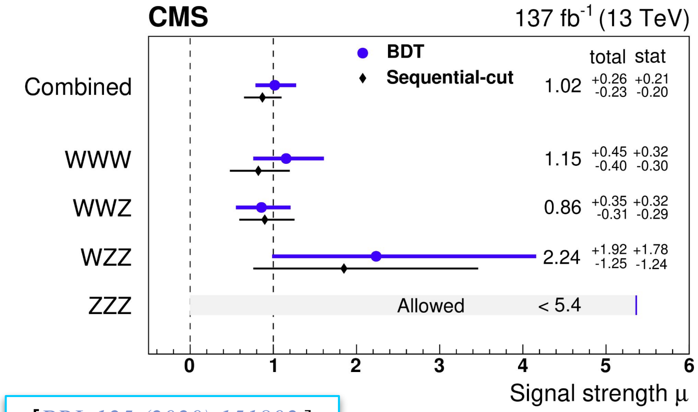
[PRL 129 (2022) 061803]

First observation of the **combined** electroweak production of **three massive vector bosons** VVV (Apr. 2020)

Observed (expected) significance
Simultaneous fit with 4 channels:

WWW	(2ℓ2q/3ℓ)	**3.3 (3.1) S.D.**
WWZ	(4ℓ)	**3.4 (4.1) S.D.**
WZZ	(5ℓ)	1.7 (0.7) S.D.
ZZZ	(6ℓ)	0.0 (0.9) S.D.

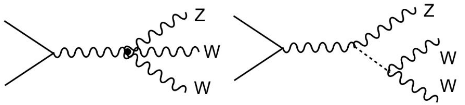
→ Combined fit for **VVV:** **5.7(5.9) S.D.**



[PRL 125 (2020) 151802]

VVZ combination

ATLAS Run 2 analysis



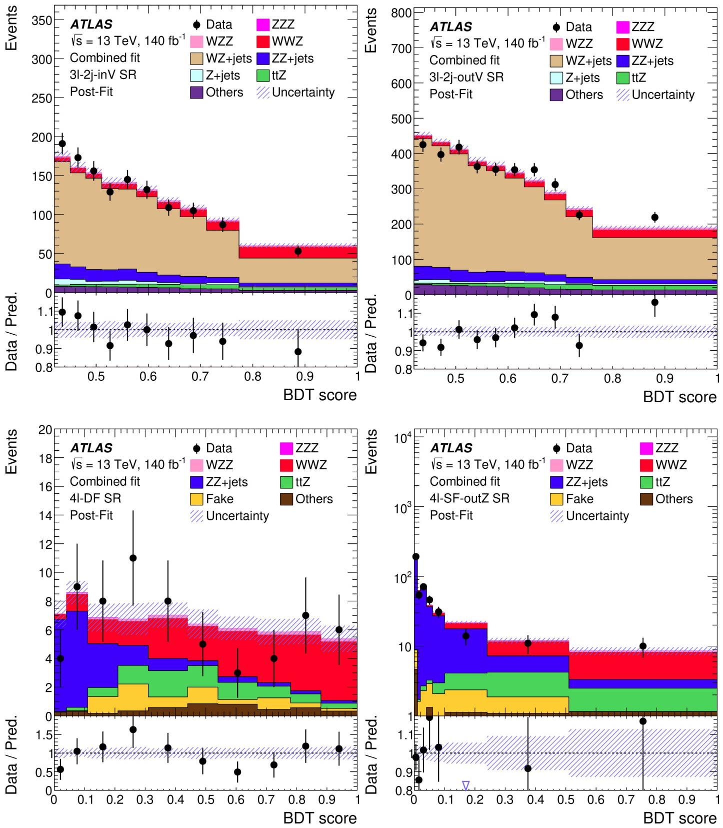
Include both non-resonant WWZ and ZH (H->WW) as signal

[ATLAS-STDM-2020-08, arXiv:2412.15123]

- Search for VVZ combined (WWZ+WZZ+ZZZ) observation at 13 TeV
  - ATLAS Run 2 dataset → 140 fb^{-1}
  - 3 different final states (3ℓ+jets, 4ℓ, ≥5ℓ)

3ℓ + jets	4ℓ	≥5ℓ
W/Z → qq W→ lν Z→ll	W→ lν W→ lν Z→ll	W/Z → ℓν/ℓℓ Z → ℓℓ Z → ℓℓ
Target processes: W^+W^-Z, $W^\pm ZZ$	Target process: W^+W^-Z	Target processes: $W^\pm ZZ$, ZZZ
Main backgrounds: $W^\pm Z$	Main backgrounds: $W^\pm Z$, ZZ	Main backgrounds: $W^\pm Z$, ZZ

- Analysis strategy:
  - MVA techniques to enhance the sensitivity
  - BDTs separately optimised per-SR and final states
  - Most discriminant observables region by region
    - H_T^{tot}, p_T^{j2}
    - m_{ll}^{Z2}, n_{jets}
    - MET, p_T^{lw}



VVZ combination

ATLAS Run 2 analysis

3ℓ required, two of which same-flavour opposite-sign (SFOS), such that $|m_{\ell\ell} - m_Z| < 20$ GeV

- ❖ **SR 3ℓ-1j** : one jet only
- ❖ **SR 3ℓ-2j-inV**: ≥ 2 jets with $60 < m_{jj} < 110$ GeV
- ❖ **SR 3ℓ-2j-outV**: ≥ 2 jets with $m_{jj} < 60$ GeV $\vee$ $m_{jj} > 110$ GeV
- ❖ **CRs**: **Z+jets**, **3ℓ-ttZ**, **WZ+jets**

4ℓ required,
with 1 SFOS di-lepton pair (Z Candidate)
such that $|m_{\ell\ell} - m_Z| < 20$ GeV

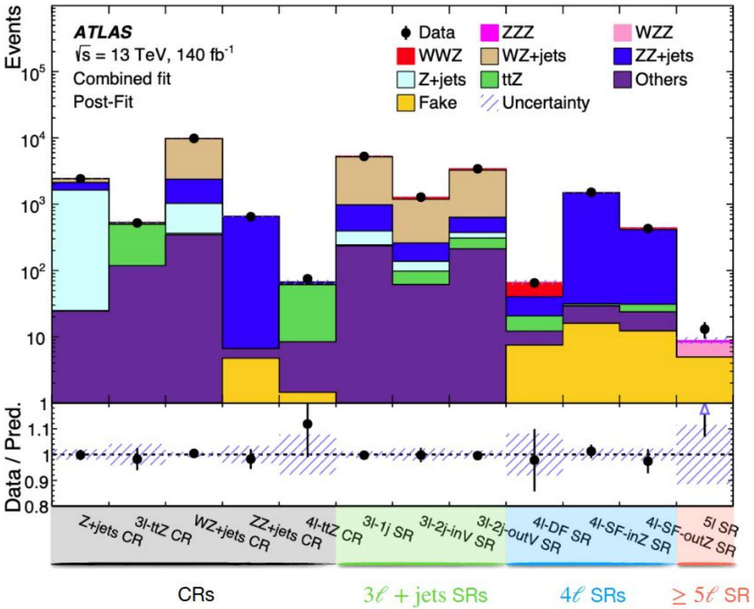
Categorisation wrt the flavour of the other 2ℓ ("W-leptons" $\ell_{3,4}$):

- ❖ **SR 4ℓ-DF** : different-flavour pair $\ell_3\ell_4$
- ❖ **SR 4ℓ-SF-inZ**: SF pair $\ell_3\ell_4$, $|m_{\ell 3,\ell 4} - m_Z| < 20$ GeV
- ❖ **SR 4ℓ-SF-outZ**: SF pair $\ell_3\ell_4$, $|m_{\ell 3,\ell 4} - m_Z| \geq 20$ GeV
- ❖ **CRs**: **ZZ+jets**, **4ℓ-ttZ**

At least 5ℓ required:

- ❖ **SR 5ℓ** : ≥ 2 SFOS di-lepton pairs with $|m_{\ell\ell} - m_Z| < 20$ GeV

[ATLAS-STDM-2020-08, arXiv:2412.15123]



<u>Observed (expected) significance</u>

Simultaneous fit across final states and regions:

WZZ 2.8 (1.6) S.D.

WWZ 4.4 (3.6) S.D.

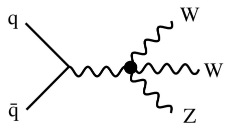
→ Combined fit for **VVZ:** **6.4 (4.7) S.D.**

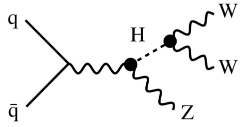
Treating **ZH as bkg.**: **5.5 (3.7) S.D.**

WWZ fully leptonic channel

CMS Run 2 (2016-2018) - 3 (2022-2023) analysis

[CMS-PAS-SMP-24-015]

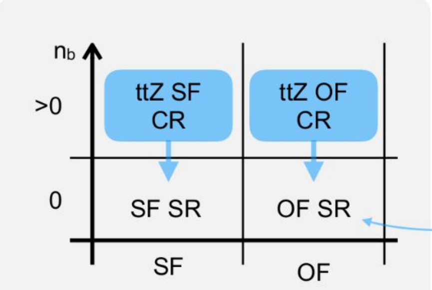




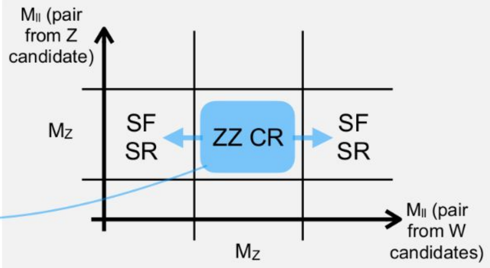
Measurement of W^+W^-Z and ZH signal strengths individually and together

- Final state selected with **4 charged leptons (e, μ)**
  - 2 charged leptons reconstructing the best **Z candidate**
  - The remaining 2 charged leptons must be **opposite-charge**, **same-flavor (SF) or opposite-flavor (OF)** defining 2 corresponding channels

- CRs to normalize the main backgrounds, i.e., ttZ and ZZ



The ttZ estimation



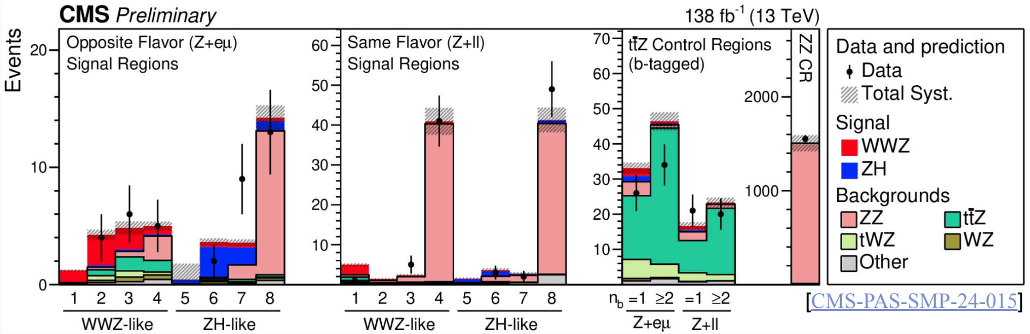
The ZZ estimation

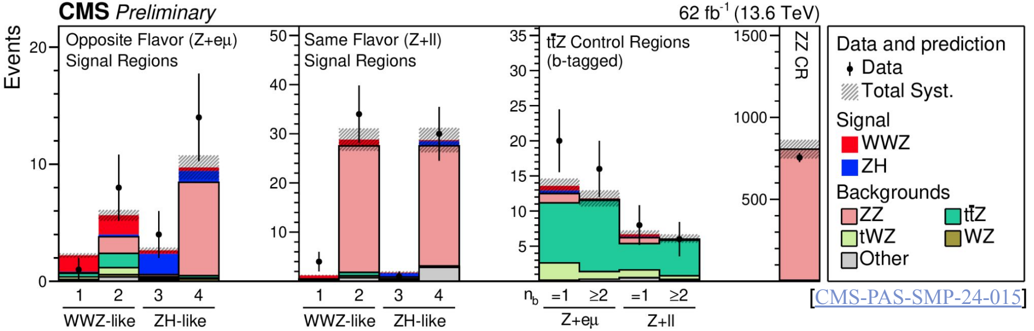
- **BDT multiclassifier** assigning three different scores (summed to 1)
  - non-resonant WWZ
  - ZH, H→WW*
  - background

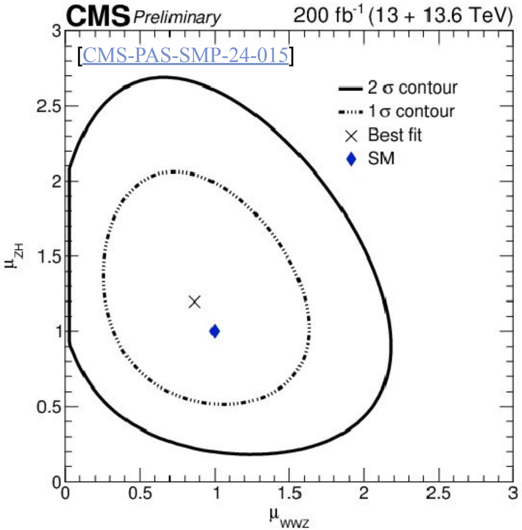
- Scores used to define several SRs
  - 8(4) SRs per channel, *i.e.*, SF and OF channels
  - Separately defined SRs per data set, *i.e.*, Run 2 (13 TeV, 138/fb) and Run 3 (13.6 TeV, 62/fb)

WWZ fully leptonic channel

CMS Run 2 (2016-2018) - 3 (2022-2023) analysis







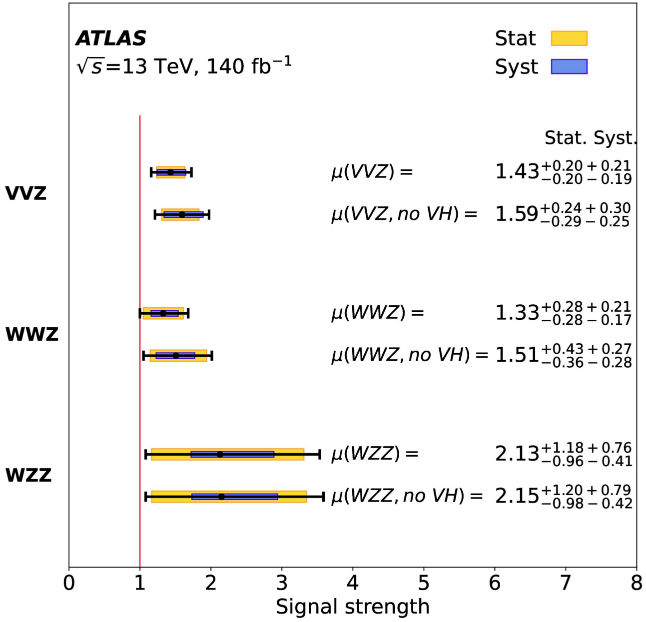
Era	Total	WWZ	ZH
Run 2	2.9 (4.4)	1.3 (3.1)	2.0 (2.6)
Run 3	3.8 (2.5)	2.5 (1.3)	2.5 (1.7)
Total	4.5 (5.0)	2.4 (3.3)	3.1 (3.1)

Observed (expected) significance per era

- Scores used to define several SRs
  - 8(4) SRs per channel, *i.e.*, SF and OF channels
  - Separately defined SRs per data set, *i.e.*, Run 2 (13 TeV, 138/fb) and Run 3 (13.6 TeV, 62/fb)

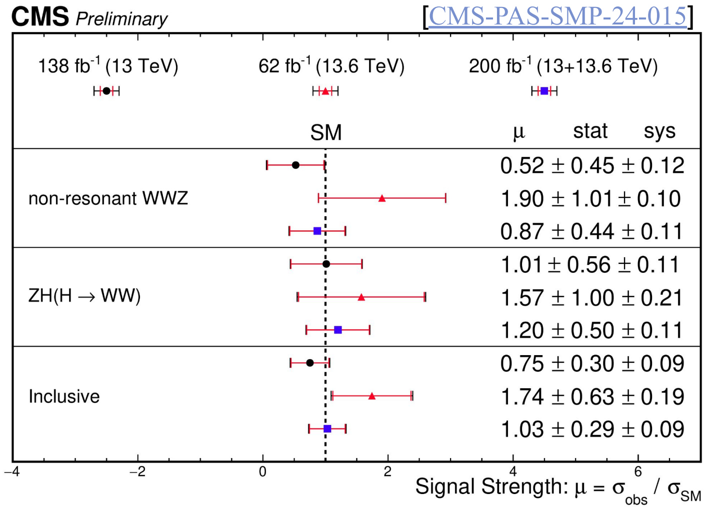
Summary of VVZ LHC analyses

[ATLAS-STDM-2020-08, arXiv:2412.15123]

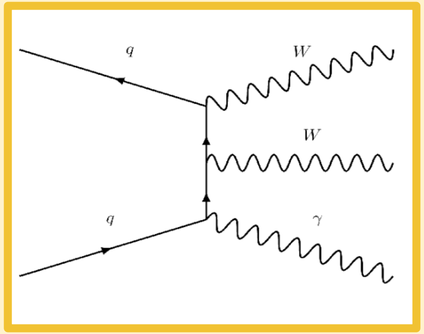


Process	Signal strength	Cross section (fb)
VVZ	$1.43 \pm 0.20(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$	$660^{+93}_{-90}(\text{stat.})^{+88}_{-81}(\text{syst.})$
WWZ	$1.33 \pm 0.28(\text{stat.})^{+0.21}_{-0.17}(\text{syst.})$	$442 \pm 94(\text{stat.})^{+60}_{-52}(\text{syst.})$
WZZ	$2.13^{+1.18}_{-0.96}(\text{stat.})^{+0.76}_{-0.41}(\text{syst.})$	$200^{+111}_{-91}(\text{stat.})^{+65}_{-37}(\text{syst.})$

[CMS-PAS-SMP-24-015]

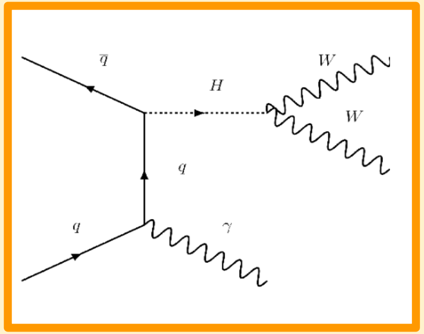


Era	Process	σ_{obs} (fb)	σ_{SM} (fb)
Run 2 ($\sqrt{s}$ = 13 TeV)	WWZ only	$97^{+91}_{-75}(\text{stat.})^{+24}_{-21}(\text{syst.})$	184 [8]
	ZH only	$190^{+120}_{-100}(\text{stat.})^{+30}_{-20}(\text{syst.})$	189 [9]
	Inclusive	$280^{+120}_{-110}(\text{stat.})^{+40}_{-30}(\text{syst.})$	373
Run 3 ($\sqrt{s}$ = 13.6 TeV)	WWZ only	$380^{+220}_{-190}(\text{stat.})^{+10}_{-30}(\text{syst.})$	200 [8]
	ZH only	$320^{+230}_{-180}(\text{stat.})^{+60}_{-30}(\text{syst.})$	202 [9]
	Inclusive	$700^{+270}_{-230}(\text{stat.})^{+90}_{-60}(\text{syst.})$	402



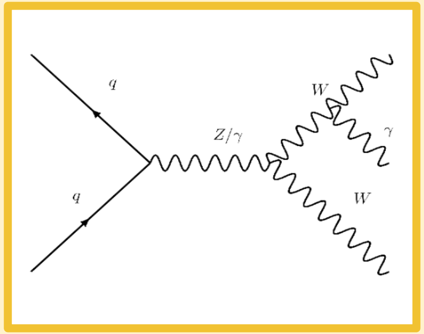
VVγ searches

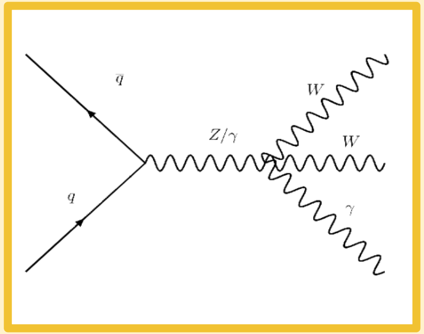
- ATLAS WZγ (STDM-2019-17)
- CMS WZγ (SMP-22-018)



and limits on Higgs couplings with light quarks

- CMS WWγ (SMP-22-006)





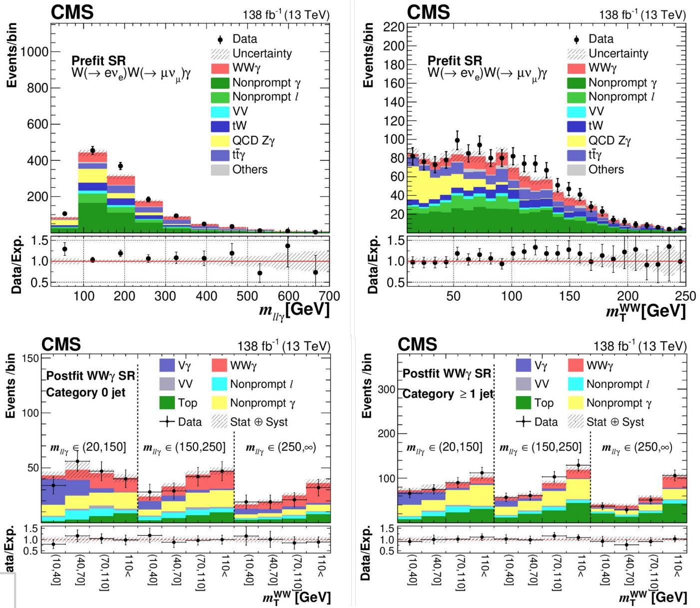
WWγ

CMS Run 2 analysis

[PRL 132 (2024) 121901]

- Measurement of WWγ with fully leptonic final state
- Data-driven method for estimating bkg. processes containing a prompt lepton/photon
  - Zγ
  - ttbar+γ
  - single-top
- Control Regions to validate the bkg. estimations:
  - SSWWγ
  - Top γ

→ m_T^{WW} > 10 GeV cut not applied in the CR

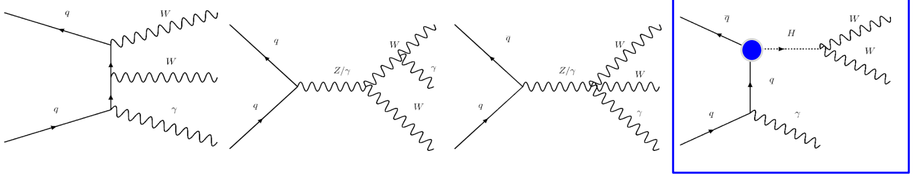


2D binned fit in m_T^{WW} vs $m_{ll\gamma}$

Measured fiducial cross section:

$$\sigma = 6.0 \pm 1.0(\text{stat}) \pm 1.0(\text{syst}) \pm 0.9(\text{theo})\ \text{fb}$$

$$\mu = 1.31 \pm 0.17(\text{stat}) \pm 0.21(\text{syst}) \quad 5.6(4.7)\ \text{S.D.}$$



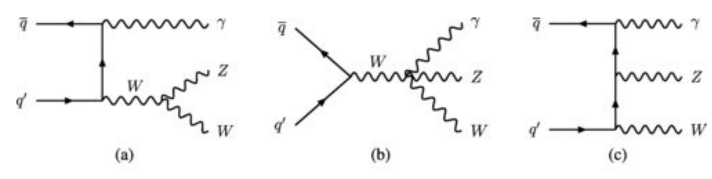
Extraction of limits on Higgs couplings with light quarks from $H\gamma \to WW\gamma$

Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\bar{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\bar{u} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (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)
$s\bar{s} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	68 (49)	$\lvert\kappa_s\rvert \leq 1700$ (1300)	$\lvert\bar{\kappa}_s\rvert \leq 32.8$ (25.2)
$c\bar{c} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	87 (67)	$\lvert\kappa_c\rvert \leq 200$ (110)	$\lvert\bar{\kappa}_c\rvert \leq 45.4$ (25.0)

WZγ

ATLAS Run 2 analysis

[PRL 132 (2024) 021802]

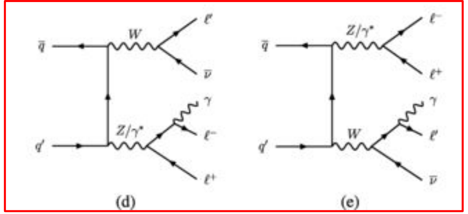


- Measurement of WZγ with fully leptonic final state

- Fiducial phase-space region requiring
  - high-p_T leptons and photons
  - isolated photons

  → **to enhance** the relative contribution of processes with **γ produced from initial hard-scattering**

  → **to mitigate** the relative contribution of **final state radiation (FSR)**



- Dominant backgrounds from non-prompt l/γ from hadron decay or jets misidentified as prompt l/γ:
  - Zγ+X
  - ttγ+X
  - VZ+X

  → Data-driven technique to extract the corresponding fake rate factors

$$N^{\text{nonprompt}} = \sum_i F_i^{\ell}(N_{\text{B},i}^{\text{data}} - N_{\text{B},i}^{\text{prompt}}) + \sum_j F_j^{\gamma}(N_{\text{C},j}^{\text{data}} - N_{\text{C},j}^{\text{prompt}}) - \sum_{i,j} F_i^{\ell} F_j^{\gamma}(N_{\text{D},i,j}^{\text{data}} - N_{\text{D},i,j}^{\text{prompt}}),$$

estimate of nonprompt bkg. events in SR

in CR l loose

in CR γ loose

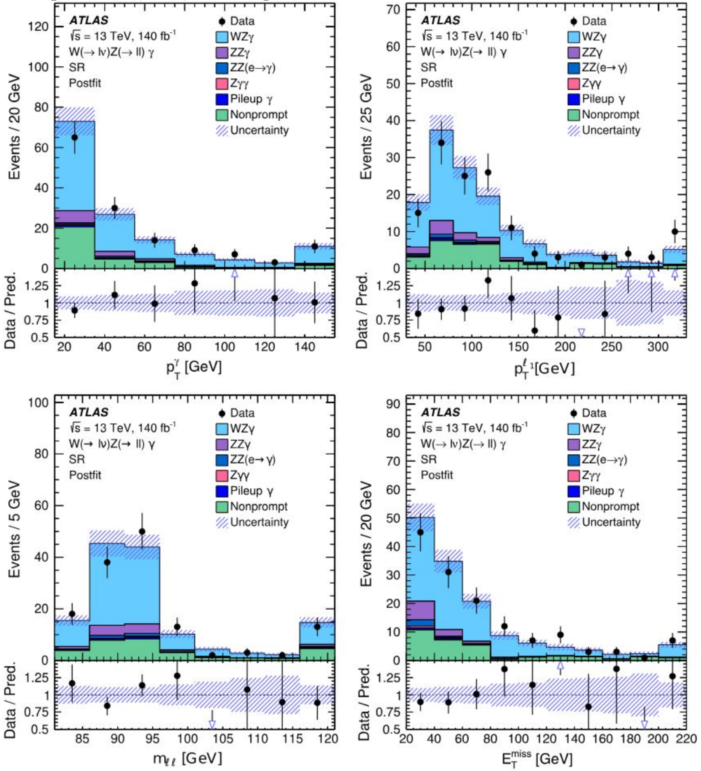
in CR l loose & γ loose

ratio of the probability that a leptonlike (photonlike) jet meets the signal selection criteria to the probability that it meets the loose selection criteria, determined in bin i (j) of the loose lepton (photon) p_T

$WZ\gamma$

ATLAS Run 2 analysis

[PRL 132 (2024) 021802]



First observation, observed (expected) significance: **6.3 (5.0) S.D.**

Fitted parameters of interest

$$\mu_{ZZ\gamma} = 1.19 \pm 0.25$$
$$\mu_{ZZ} = 0.98 \pm 0.19,$$
$$\mu_{WZ\gamma} = 1.34 \pm 0.20(\text{stat}) \pm 0.10(\text{syst}) \pm 0.07(\text{theory})$$

Measured fiducial cross section:

$$\sigma^{\text{SM}}_{\text{fid}} = 1.50 \pm 0.01(\text{stat}) \pm 0.02(\text{PDF}+\alpha_s) \pm 0.06(\text{scale})\ \text{fb}$$

NLO correction [Cheng and Wackeroth, PRD 105 (2022) 096009]:

$$K_{\text{EW}} = \sigma^{\text{NLO EW}}_{\text{fid}} / \sigma^{\text{LO}}_{\text{fid}} = 1.05$$

Resulting production cross section:

$$\sigma_{WZ\gamma} = \mu_{WZ\gamma}\, \sigma^{\text{SM}}_{\text{fid}} = 2.01 \pm 0.30(\text{stat}) \pm 0.16(\text{syst})\ \text{fb}$$

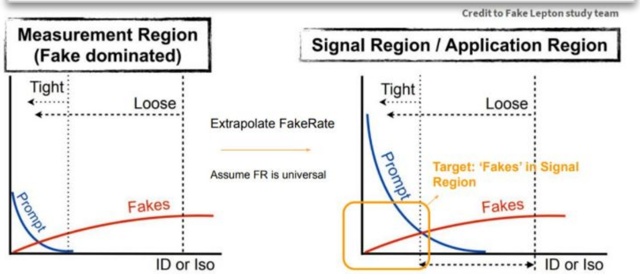
WZγ

CMS Run 2 analysis

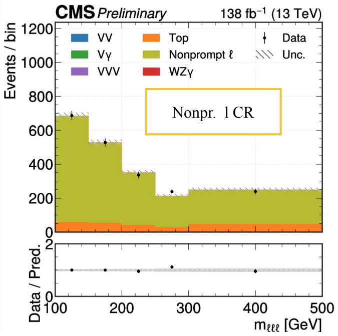
[arXiv:2503.21977, CMS-PAS-SMP-22-018]

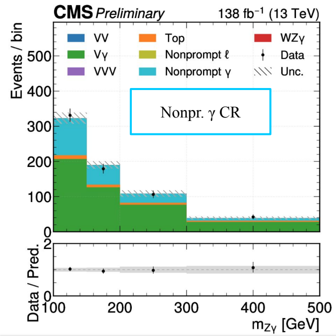
- Measurement of WZγ with fully leptonic final state

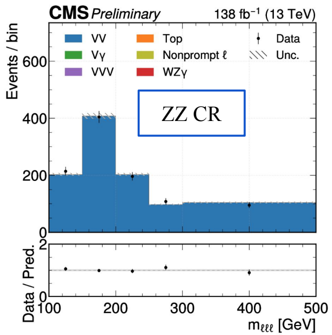
> CMS observation of the WZγ production process at 13 TeV
>
> Observed (expected) significance: **5.4 (3.8) S.D.**

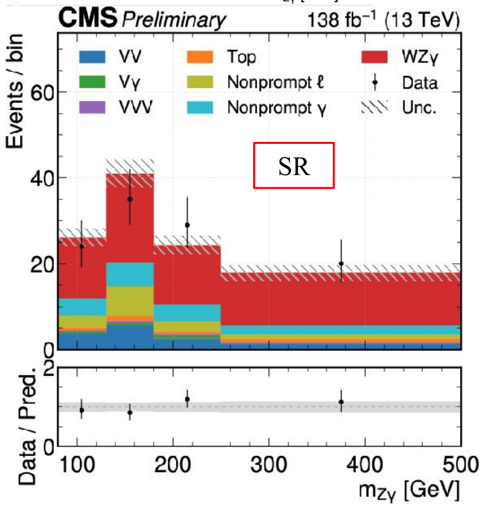


- Tight-to-loose method to extract the fake rates to apply in the SR from nonprompt lepton/γ-dominated CR (*measurement region*)





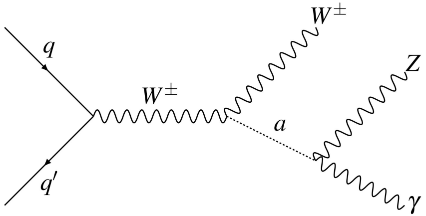




Region	N_ℓ	N_γ	N_{OSSF}	N_{btag}	MET [GeV]	$p_T\{\ell_{Z1},\ell_{Z2},\ell_W,\ell_4\}$ [GeV]	$\min(m(\ell\ell'))$ [GeV]	$\lvert m(\ell_{Z1},\ell_{Z2})-m_Z\rvert$ [GeV]	$m(\ell_{Z1},\ell_{Z2},\ell_W)$ [GeV]	$m(l_W,\gamma)$ [GeV]
SR	=3	≥ 1	≥ 1	=0	>30	>{25,15,25}	>4	<15	>100	<75 or >105
ZZ CR	=4	—	≥ 1	=0	<30	>{25,15,25,15}	>4	<15	>100	—
Nonprompt ℓ CR	=3	—	≥ 1	>0	>30	>{25,15,25}	>4	>15	>100	—
Nonprompt γ CR	=2	≥ 1	=1	>0	<30	>{25,15}	>4	>15	—	—

$WZ\gamma$

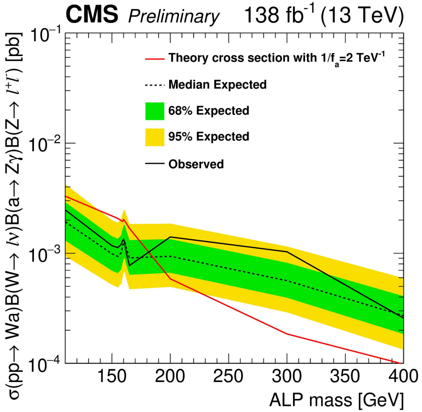
CMS Run 2 analysis

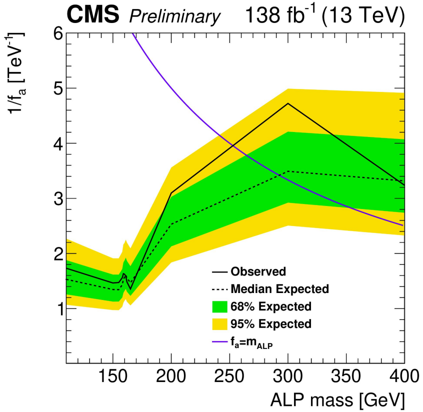


[arXiv:2503.21977, CMS-PAS-SMP-22-018]

- BSM interpretation using a specific model

  → neutral gauge bosons production (Zγ) from the decay of a **photophobic Axion-like particle (ALP)**
  - BSM process searched is $pp \to Wa,\ \ a \to Z\gamma$
  - Invariant mass $m_{ALP\ Cand.}$ as an observable for ALPs search
  - the SM WZγ contribution as a background whose normalization is determined in the simultaneous fit
- No significant excess observed → limits extracted via CLs criterion
  - single free parameter f_a → ALPs–vector bosons couplings
  - This directly affects the cross section → $(\sigma \times \mathcal{B}) \propto 1/f_a^2$
- Results
  - some of the most stringent constraints for m_a in the range [200, 400] GeV
  - first interpretation for m_a in the range 110 – 200 GeV





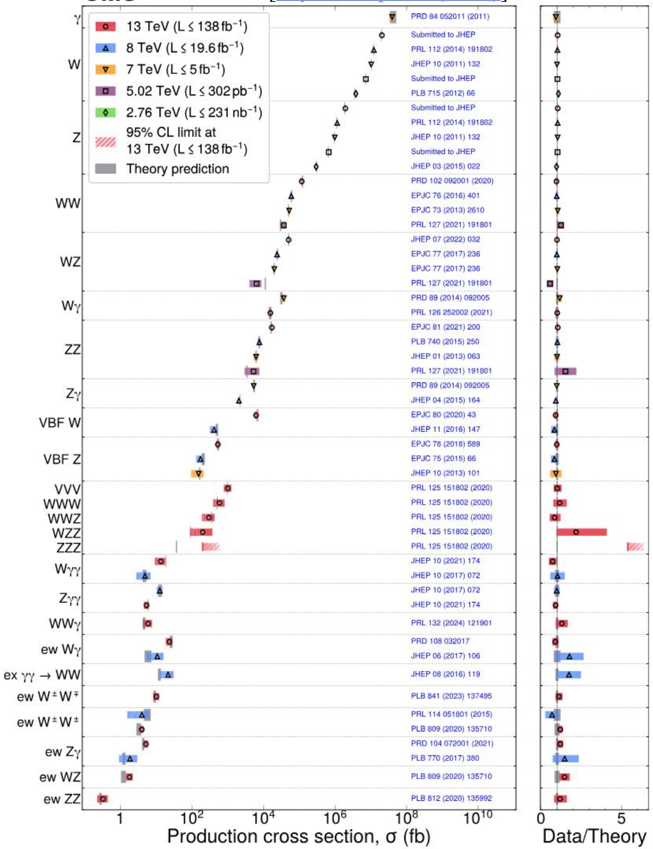
Small fluctuation near 160 GeV

→ due to the choice of bin boundaries in $m_{ALP\ Cand}$ used in the calculation

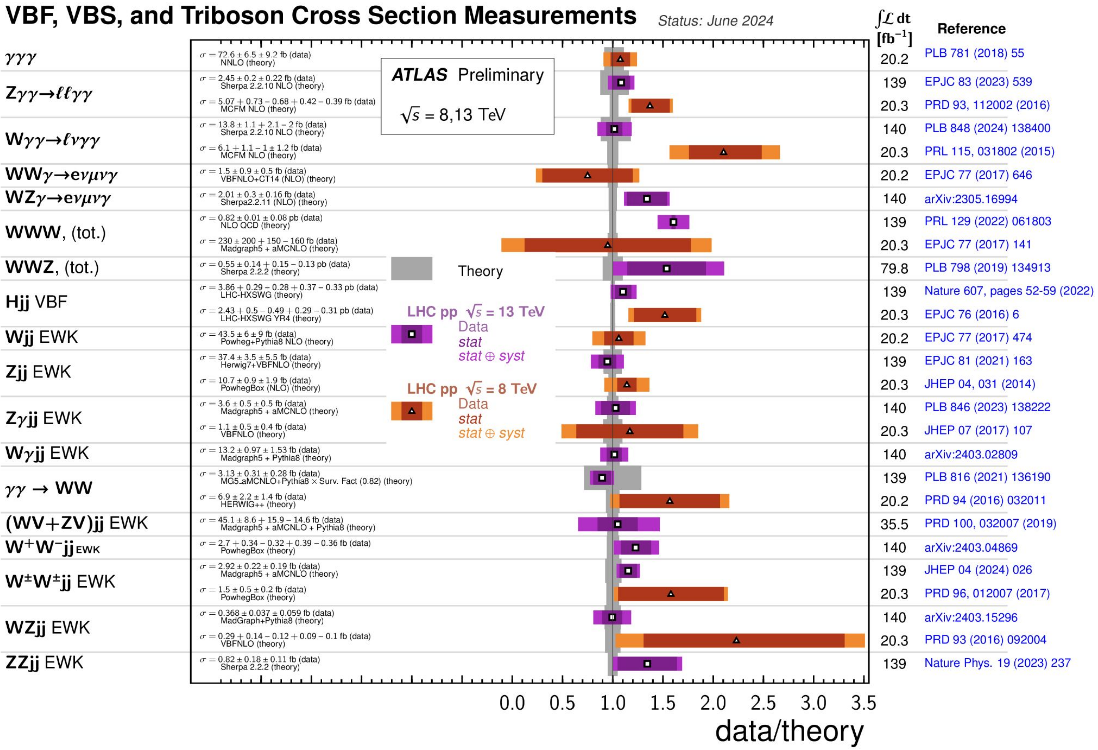
Summary and outlook

Stairway to discovery

[Physics Reports (2024)]



The most of the recent results achieved by the **ATLAS and CMS Collaboration** on **triboson** production push further our knowledge of the electroweak sector beyond



Stairway to discovery

The **triboson measurements** carried out **at LHC**, overall, seem to **confirm the Standard Model predictions**.

Nevertheless, **trends of theory underprediction** remain to be investigated, performing more precise measurements of **multiple gauge couplings** affecting triboson production processes.

The stage for **Run 3** and **HL-LHC** analyses is settled…

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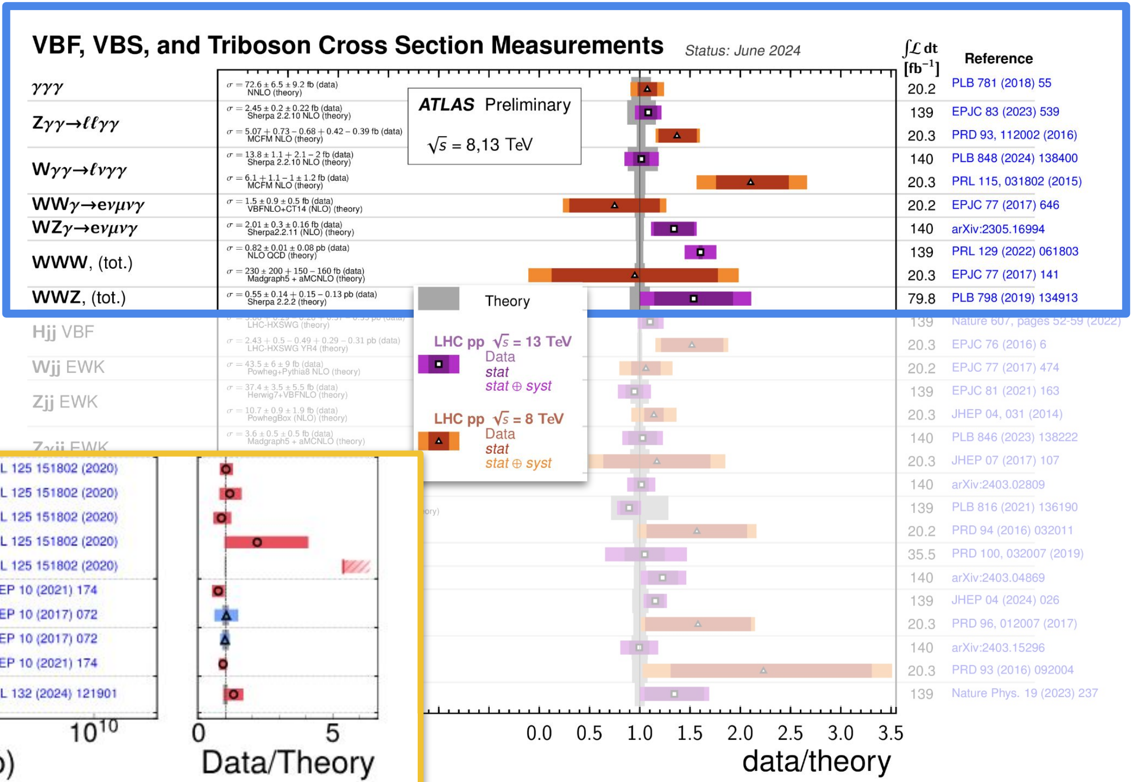
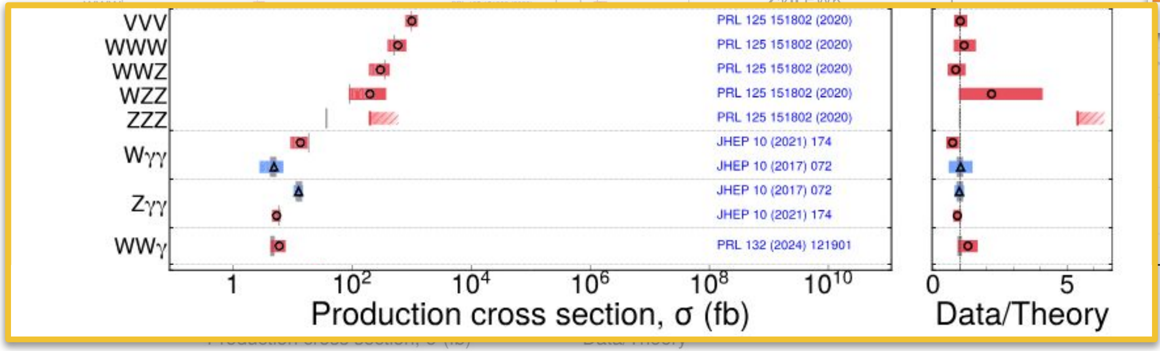




Thank you!

References

References

The ATLAS Collaboration

- The ATLAS Collaboration, "Observation of VVZ production at √s = 13 TeV with the ATLAS detector", arXiv:2412.15123, submitted to PLB — STDM-2020-08
- The ATLAS Collaboration, "Observation of $W\gamma\gamma$ triboson production in proton-proton collisions at √s = 13 TeV with the ATLAS detector", PLB 848 (2024) 138400 — STDM-2018-33
- The ATLAS Collaboration, "Observation of $WZ\gamma$ Production in Collisions at √s = 13 TeV with the ATLAS detector", PRL 132 (2024) 021802 — STDM-2019-17

References

The CMS Collaboration

- The CMS Collaboration, "Measurement of WWZ and ZH cross sections at $\sqrt{s}$ = 13 and 13.6 TeV in the four-lepton channel with the CMS detector $\sqrt{s}$ = 13 TeV", CMS-PAS-SMP-24-015

SMP – 24 – 015

- The CMS Collaboration, "Measurement of WZγ production and constraints on new physics scenarios in proton-proton collisions at $\sqrt{s}$ = 13 TeV", arXiv:2503.21977, submitted to PRD, CMS-PAS-SMP-22-018

SMP – 22 – 018

- The CMS Collaboration, "Observation of WWγ production and constraints on Higgs couplings to light quarks in proton-proton collisions at $\sqrt{s}$ = 13 TeV", PRL 132 (2024) 121901

SMP – 22 – 006

Other contents

Outline

VVV

- ATLAS VVZ (STDM-2020-08)
- CMS WWZ (SMP-24-015)

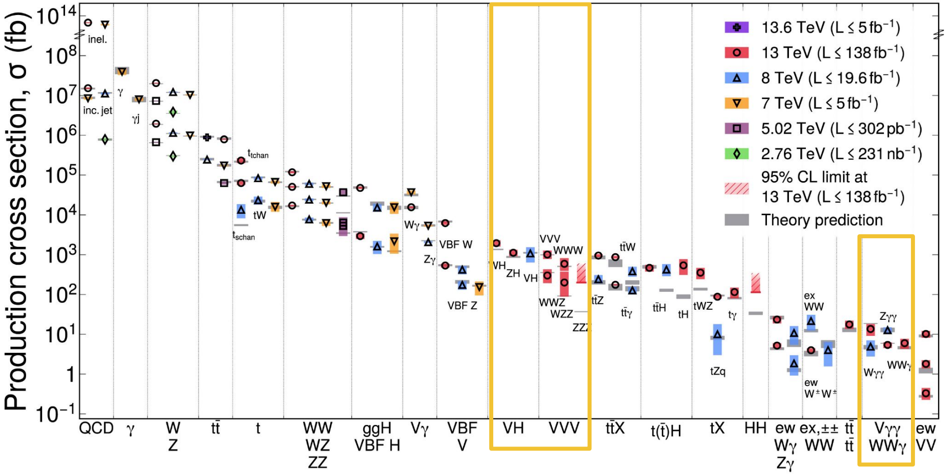
VV+γ

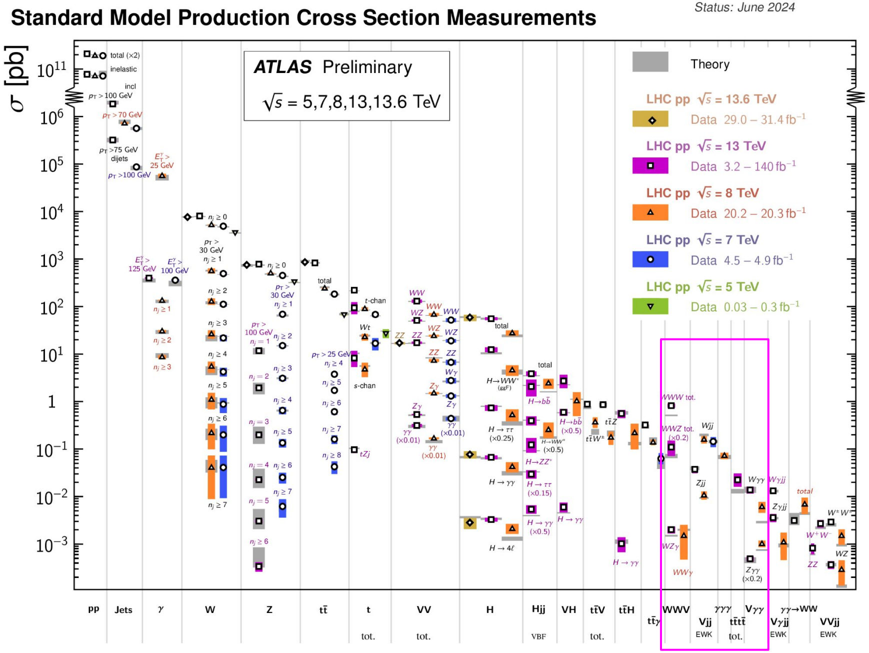
- ATLAS WZγ (STDM-2019-17)
- CMS WZγ (SMP-22-018)
- CMS WWγ (SMP-22-006)

Note:competitive **EFT constraints** extracted with triboson analyses.
→ not covered by this talk,
but already shown by T. Fitschen on Monday

Triboson measurements at LHC

CMS [Physics Reports (2024)]

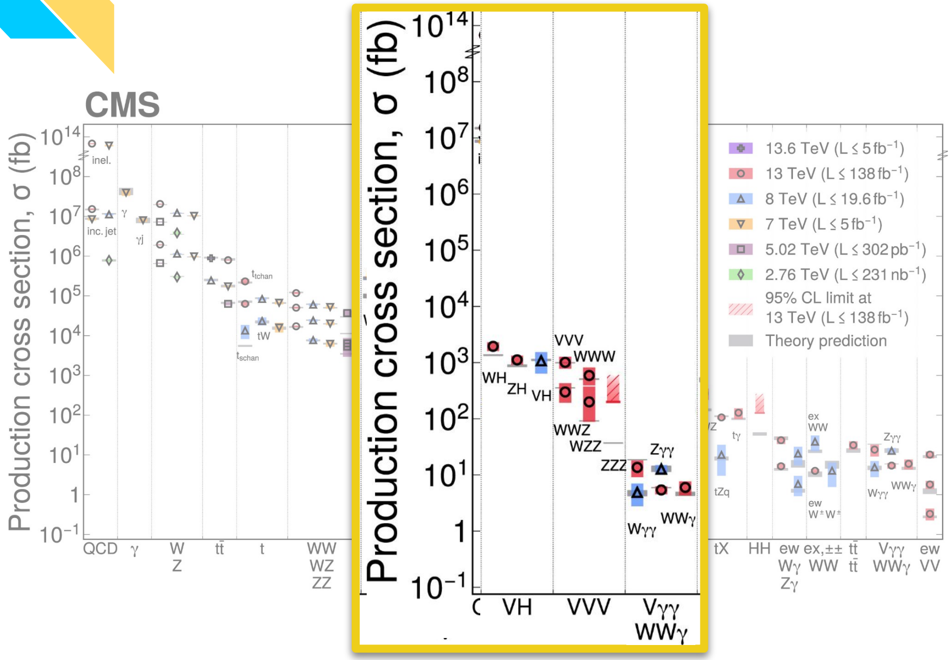


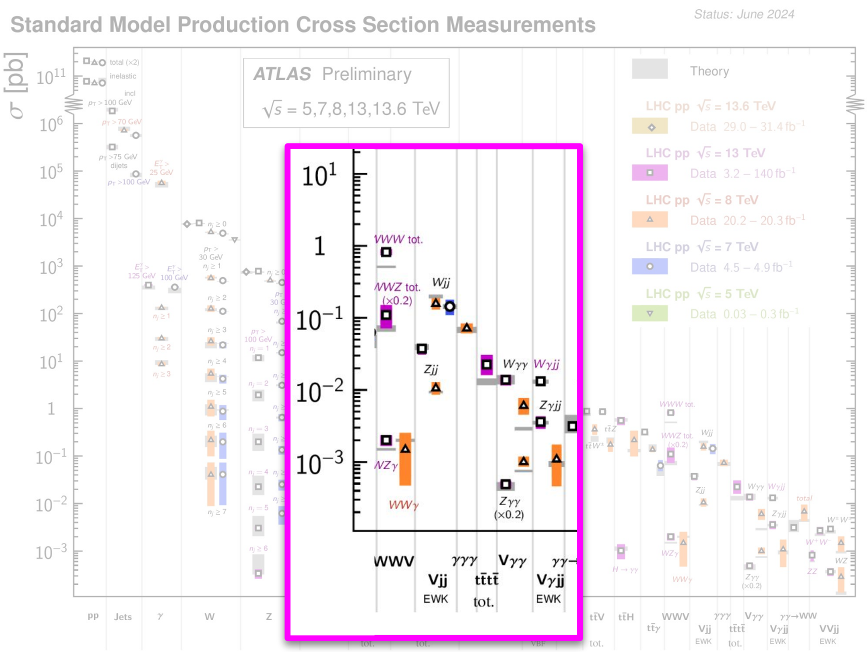


Measurement of the **cross section** of **triboson** production processes:

- valuable **precision tests** for the electroweak sector of the SM
- **novel observation** of **very rare** processes
- **TGCs** and **QGCs** involved

Triboson measurements at LHC





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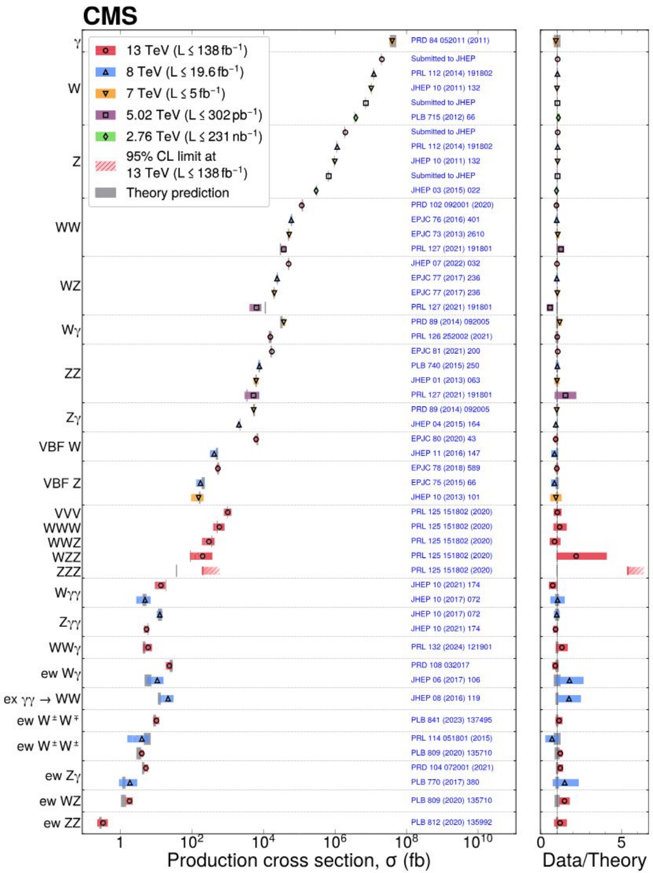
Stairway to discovery



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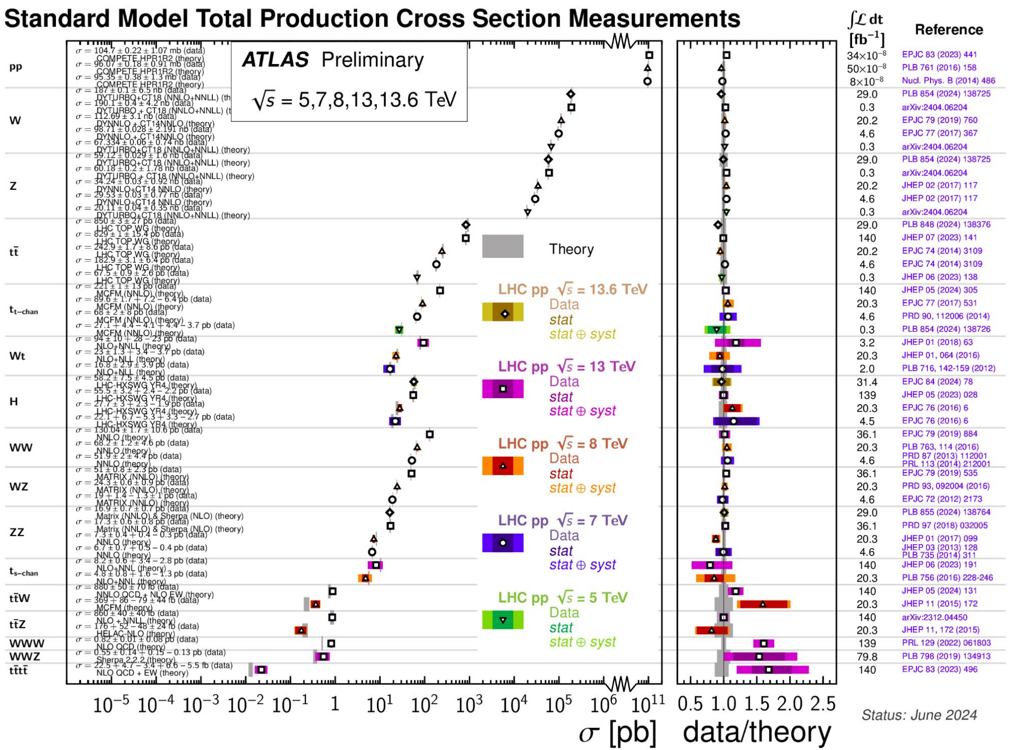

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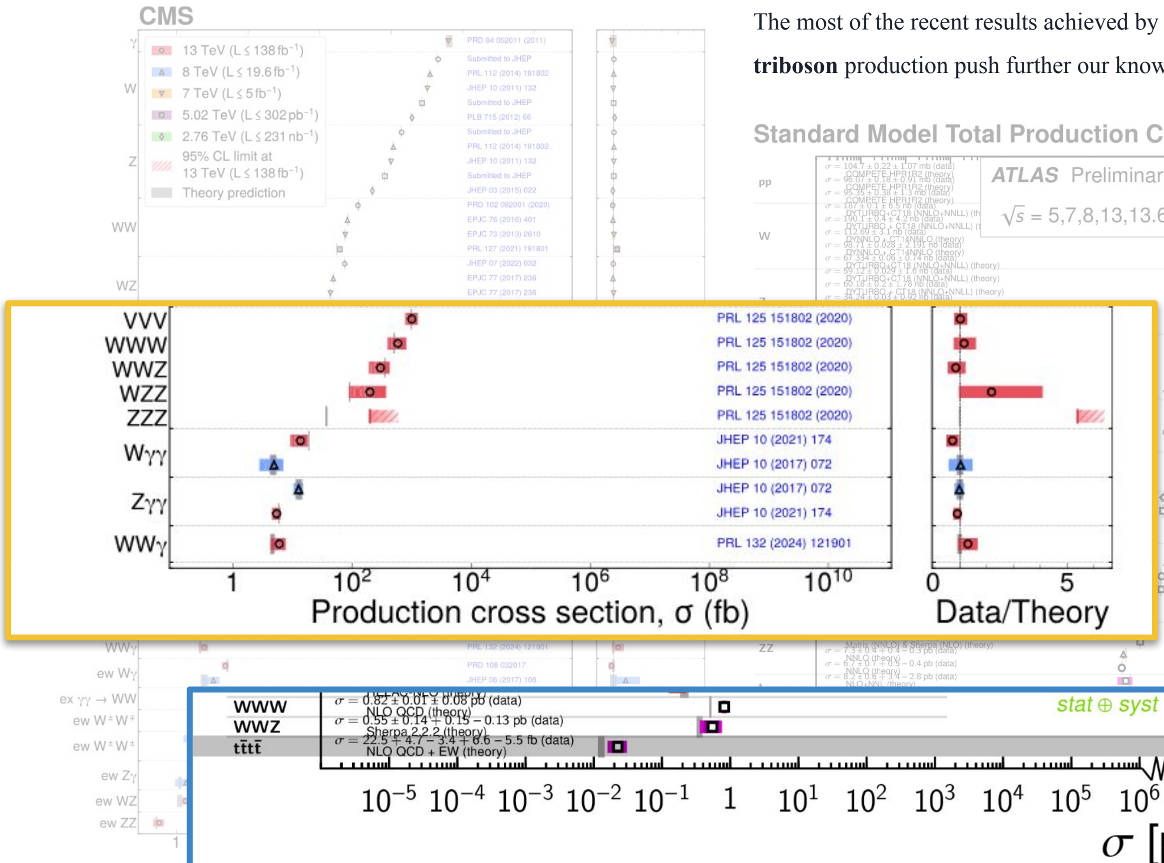

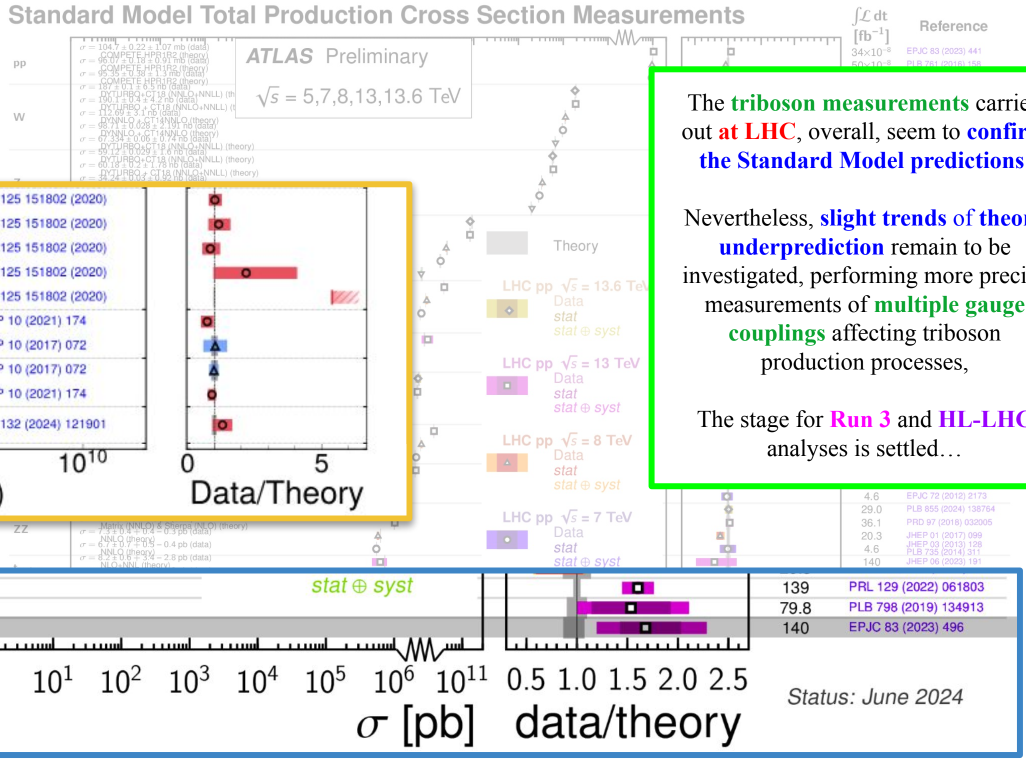

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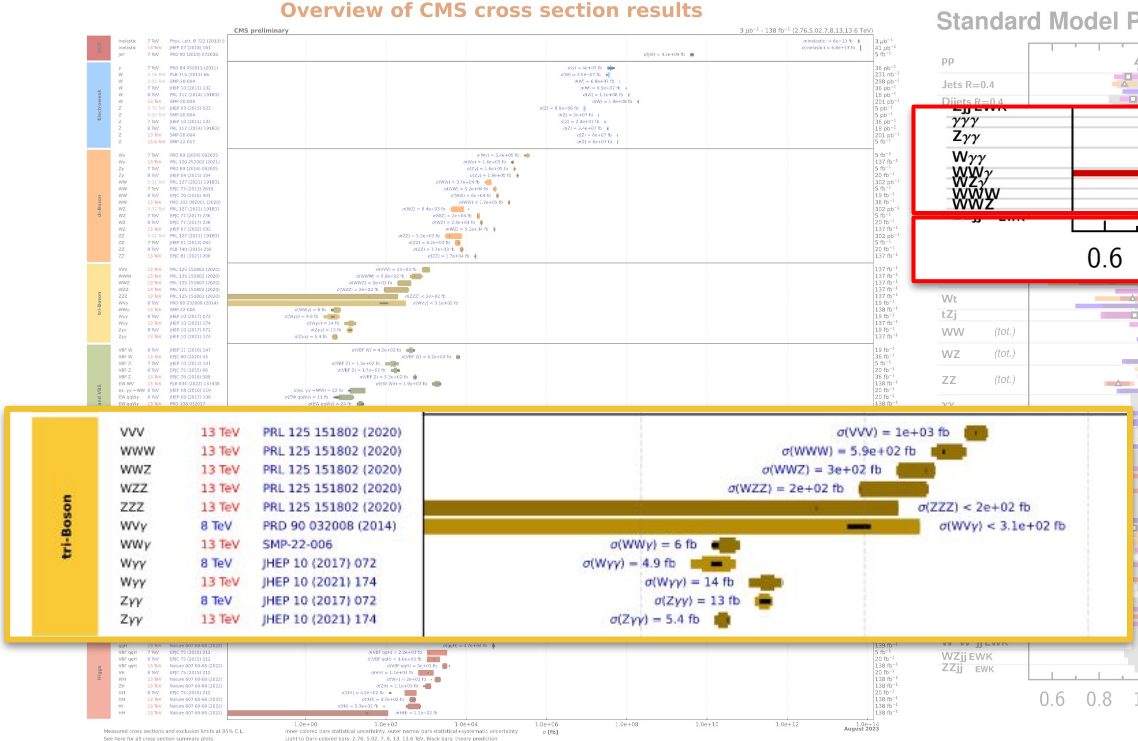
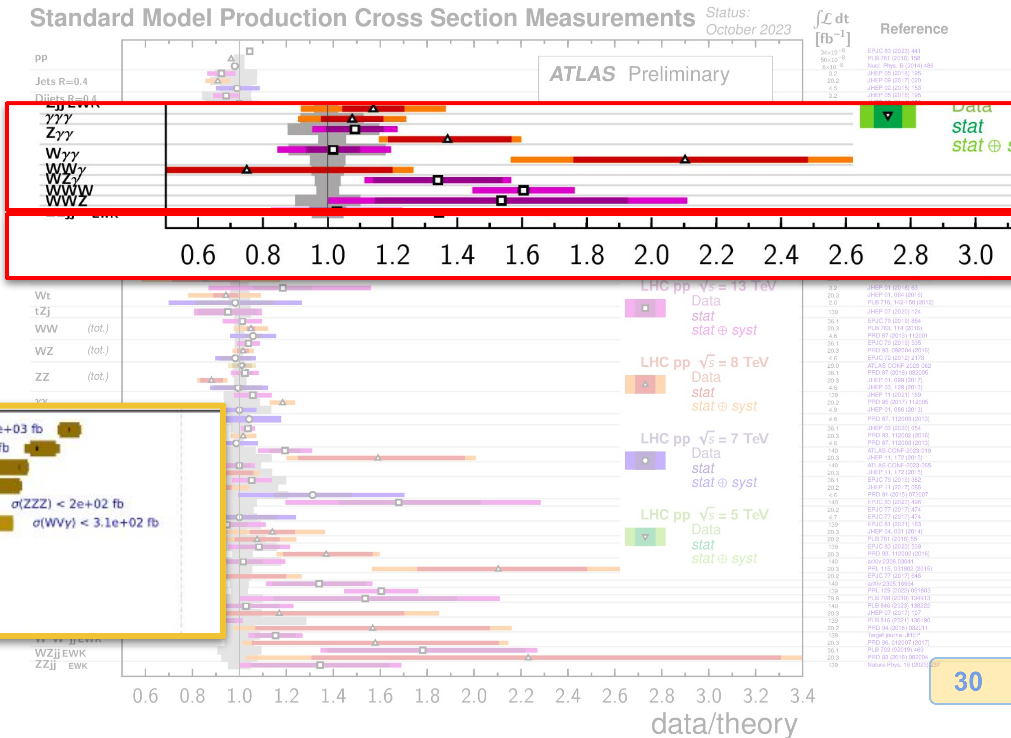
Nevertheless, **slight trends** of **theory underprediction** remain to be investigated, performing more precise measurements of **multiple gauge couplings** affecting triboson production processes,

The stage for **Run 3** and **HL-LHC** analyses is settled…

Triboson measurements at LHC

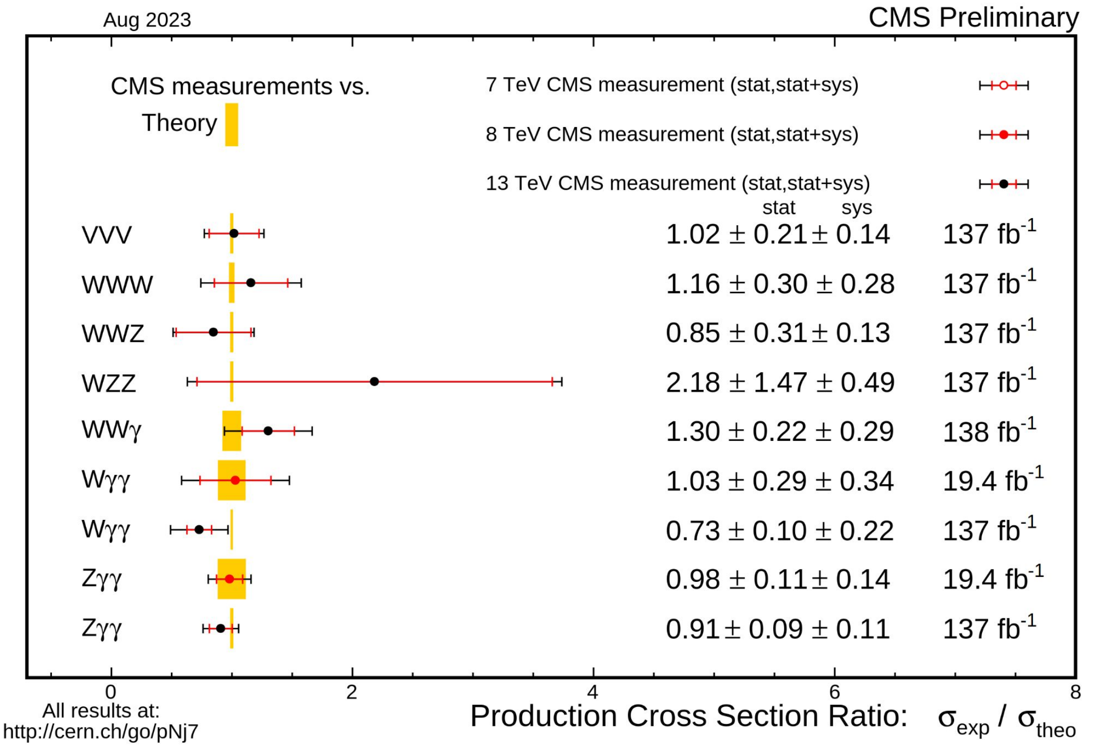
- The **ATLAS** and **CMS collaborations** have a **rich program** of **multi-boson** analyses
- Many **triboson** processes **have been studied** with at least a **photon** in final state





Triboson measurements at LHC

- **Extremely rare processes:** **$\sigma \times$ BR(to leptons) ~O(1fb)**
- **Observed three massive gauge** boson production and in **channels** with **a photon VVγ** and **two photons Vγγ**
- **BSM effects** as both **aTGC/aQGCs** and as anomalous **Higgs-gauge coupling**

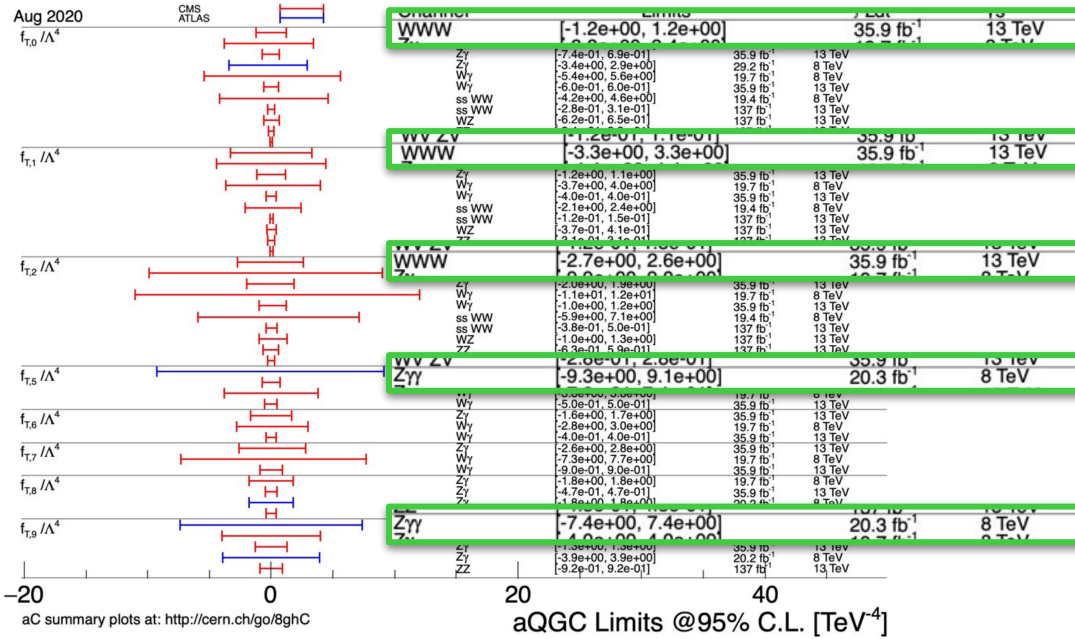


Motivation for dim.-6 EFT sensitivity study

- **Interpretation** of **triboson results** *traditionally* in terms of **dim-8 SMEFT operators (aQGCs)** at the LHC

- However, **dim-6 EFT operators** can have an impact on triboson production processes too!

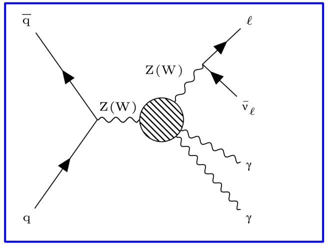
- **First LHE sensitivity** study **of triboson** [Bellan et al., JHEP08(2023)158] including **O(Λ^{-4}) dim-6** EFT terms
  → **Competitive expected constraints**



- Recently: [JHEP10(2021)174] → new stringent EFT constraints from CMS Vγγ analysis (more details in backup)

$V\gamma\gamma$

Results: SM & aQGCs

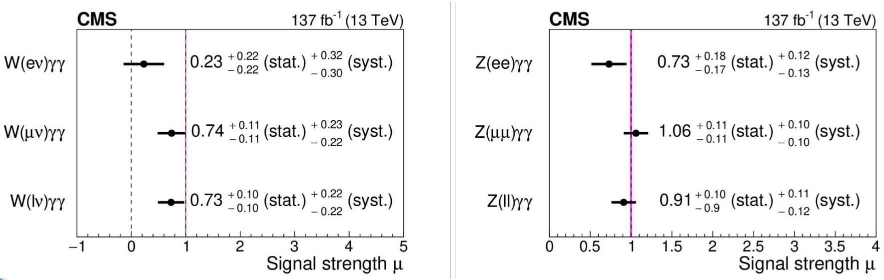


Example of BSM diagram affected by aQGC

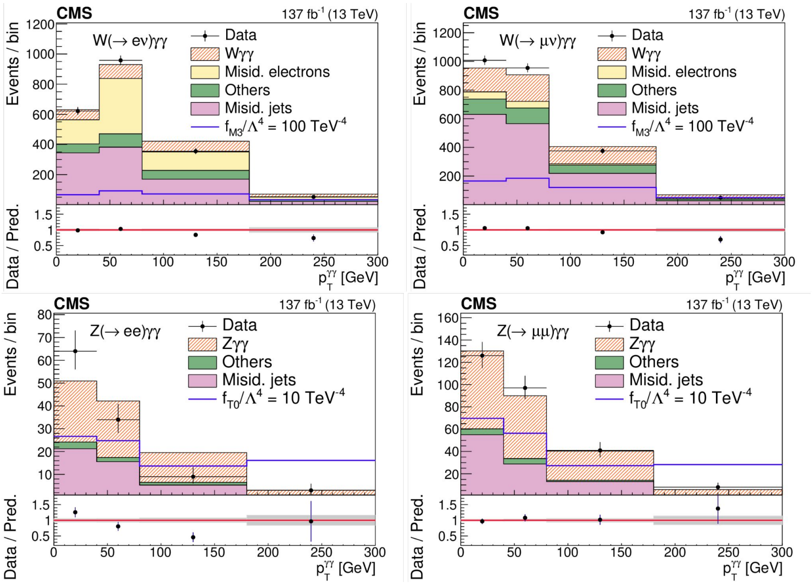
Measured cross section:

$\sigma_{W\gamma\gamma} = 13.63^{+1.93}_{-1.89}(\text{stat.})^{+4.04}_{-4.02}(\text{syst.}) \pm 0.08(\text{PDF+scale})$ — 3.1 S.D

$\sigma_{Z\gamma\gamma} = 5.41^{+0.58}_{-0.55}(\text{stat.})^{+0.64}_{-0.70}(\text{syst.}) \pm 0.06\ (\text{PDF+scale})$ — 4.8 S.D



JHEP 10 (2021) 174

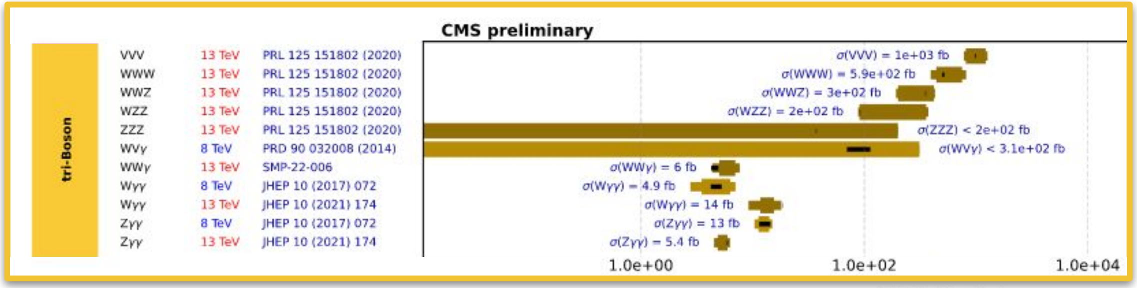


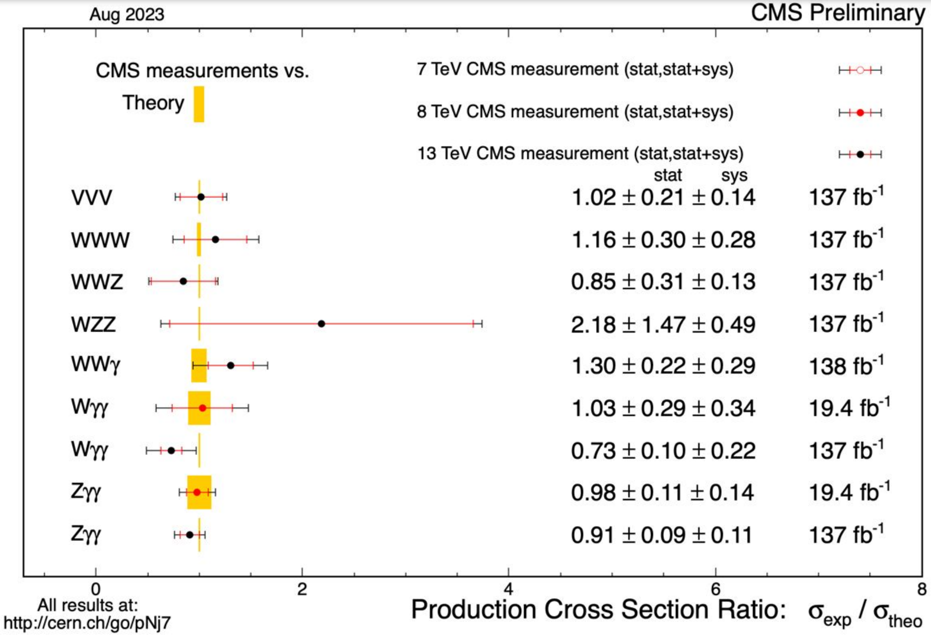
Parameter	$W\gamma\gamma$ (TeV^{-4}) Expected	$W\gamma\gamma$ (TeV^{-4}) Observed	$Z\gamma\gamma$ (TeV^{-4}) Expected	$Z\gamma\gamma$ (TeV^{-4}) Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 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]

Triboson measurements at LHC

- Measurement of the **cross section** of **triboson** production processes
  - valuable **precision tests** for the electroweak sector of the SM
  - **novel observation** of **very rare** processe
  - **TGCs** and **QGCs** involved

- Like VBS analyses, tri-boson processes measurements allow to achieve more **stringent limits** on **aTGCs** and **aQGCs** interpreted in the **SM-EFT** context.





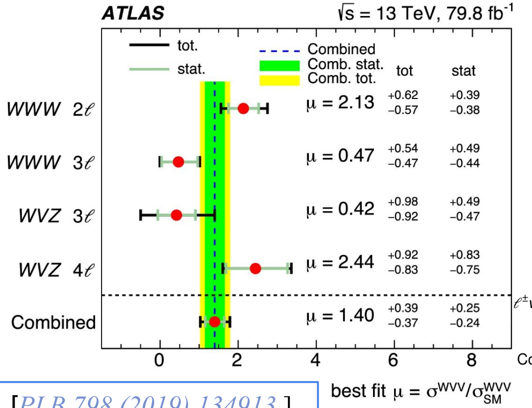
Previously on these channels…

First evidence of the **combined** electroweak production of WWW and WVZ (Nov. 2019)

<u>Observed (expected) significance</u>

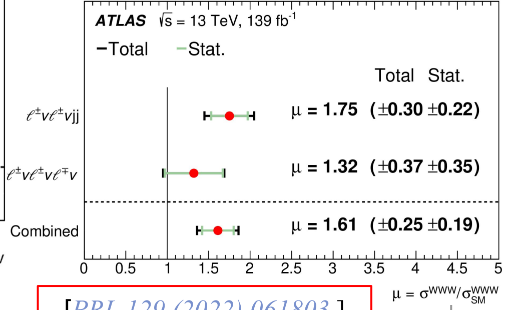
WWW	(2ℓ+2q)	**4.0 (1.7) S.D.**
	(3ℓ)	1.0 (2.0) S.D.
	→ Combined fit for **WWW**: **3.2 (2.4) S.D.**	
WVZ	(3ℓ)	0.5 (1.0) S.D.
	(4ℓ/4ℓ+2q)	**3.5 (1.8) S.D.**
	→ Combined fit for **WVZ**: **4.1 (3.1) S.D.**	

→ Combined fit for **WVV:** **4.1 (5.9) S.D.**



[PLB 798 (2019) 134913]

WWW	(2ℓ+2q)	**6.6 (4.0) S.D.**
	(3ℓ)	**4.8 (3.8) S.D.**
	→ Combined fit: **8.0 (5.0) S.D.**	



[PRL 129 (2022) 061803]

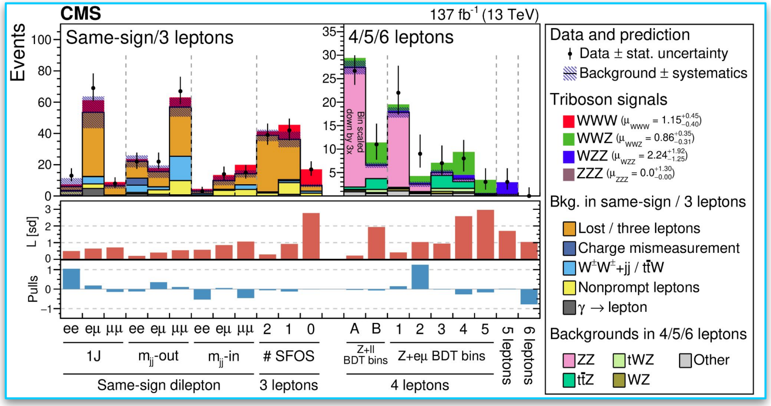
First observation of the **combined** electroweak production of **three massive vector bosons** VVV (Apr. 2020)

<u>Observed (expected) significance</u>

Simultaneous fit with 4 channels:

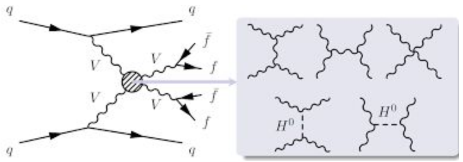
WWW	(2ℓ2q/3ℓ)	**3.3 (3.1) S.D.**
WWZ	(4ℓ)	**3.4 (4.1) S.D.**
WZZ	(5ℓ)	1.7 (0.7) S.D.
ZZZ	(6ℓ)	0.0 (0.9) S.D.

→ Combined fit for **VVV:** **5.7(5.9) S.D.**



[PRL 125 (2020) 151802]

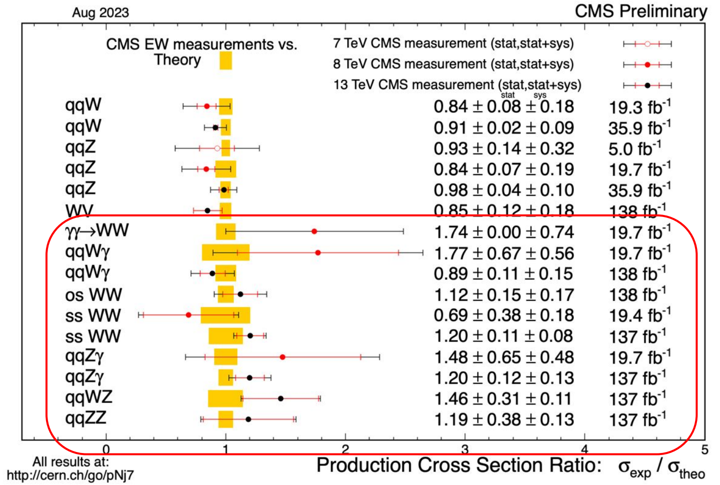
Vector Boson Scattering in CMS

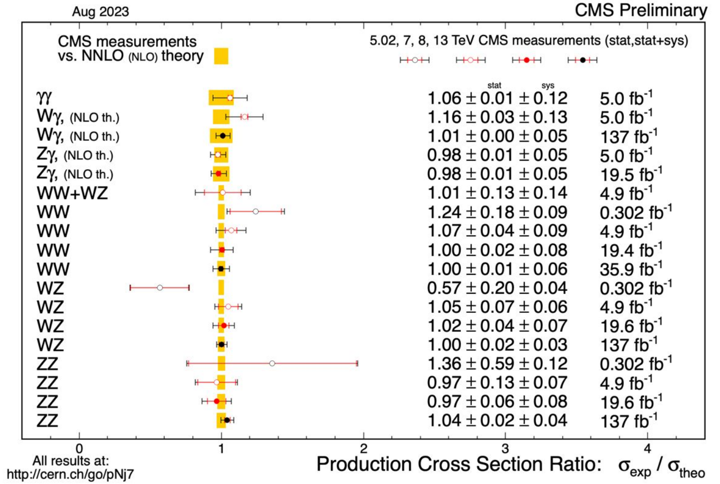


Plethora of results achieved with
full Run-2 dataset and still coming out:

- **Observation** of leptonic OS–WW VBS **5.6 (5.2) S.D.** CMS – SMP – 21 – 001
- **Evidence** of semi-leptonic WV VBS **4.4 (5.1) S.D.** CMS – SMP – 20 – 013
- **Observation** of Zγ **9.4 (8.5) S.D.** CMS – SMP – 20 – 016
- **Observation** of Wγ VBS **6.0 (6.8) S.D.** CMS – SMP – 21 – 011
- **Evidence** of fully leptonic ZZ **4.0 (3.5) S.D.** CMS – SMP – 20 – 001

.... many results already out and more are coming.



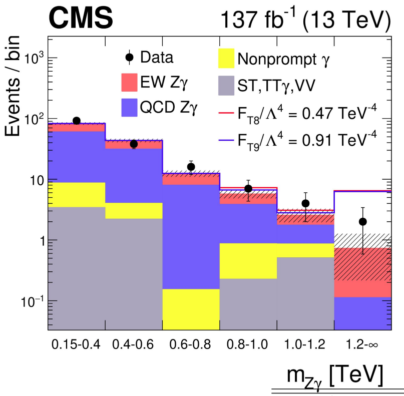


Several VBS channels are now well established and enable stringent constraints on BSM theories → **Effective Field Theory (EFT)**

VBS cross sections:
trend $\boldsymbol{\sigma}_{exp.} \geq \boldsymbol{\sigma}_{theo.}$
(not yet significant)

Vector Boson Scattering in CMS

Constraints on anomalous quartic gauge couplings (aQGCs)



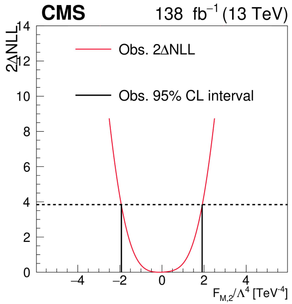
<u>Constraining on aQGCs</u>: typical procedure

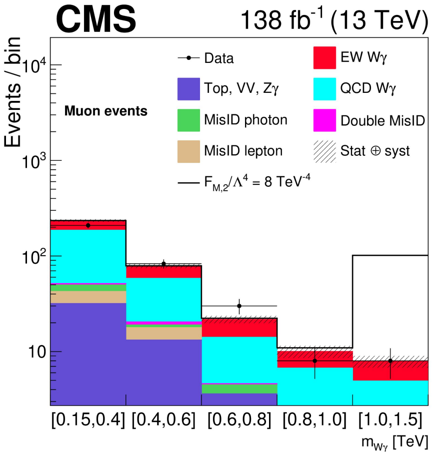
- ➔ **Dimension-8 EFT op.s**
- ➔ **m_{VV}** sensitive to deviations from SM
- ➔ **Maximum-likelihood fit profiling** the **syst. unc.**

CMS – SMP – 20 – 016

<u>Zγ analysis</u>: Strongest limits for dim.8 operators T8-9

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9



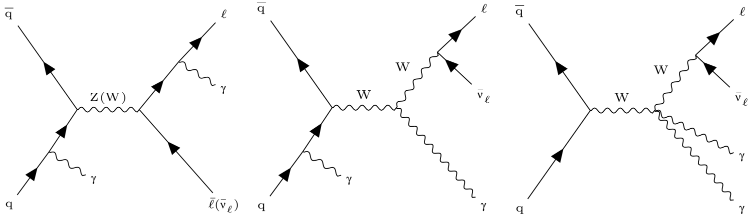


CMS – SMP – 21 – 011

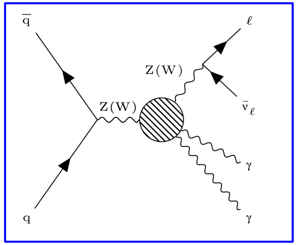
Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

<u>Wγ analysis</u>: Among the best limits for $f_{M,2-5}/\Lambda^4$, $f_{T,5-7}/\Lambda^4$,

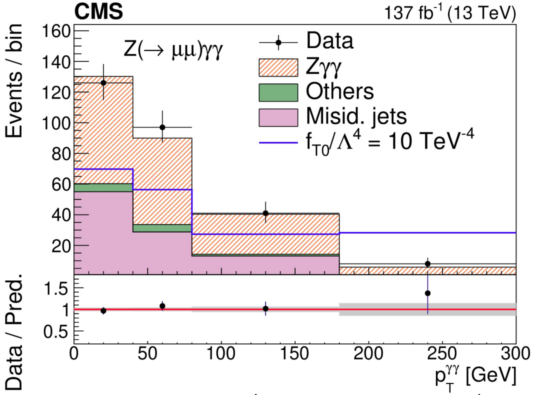
Vγγ



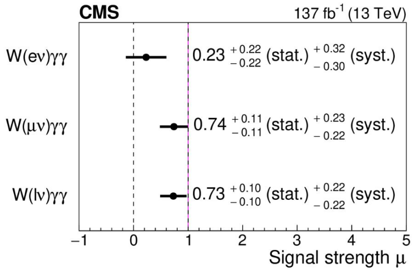
- Measurement of Vγγ fully leptonic channels
  - Wγγ can be produced via QGC
  - Zγγ does not involve QGCs (in the SM)
- γ can also be produced via ISR/FSR
- Data-driven method for major bkg.s estimation
- Systematics from data-driven background estimated by inverting lepton isolation and applying same strategy

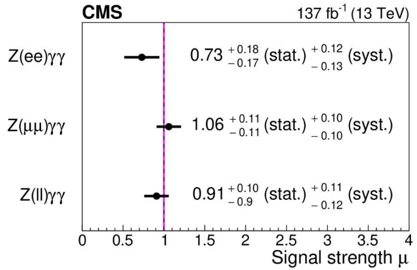


Representative BSM diagram affected by aQGC



Parameter	Wγγ (TeV^{-4}) Expected	Wγγ (TeV^{-4}) Observed	Zγγ (TeV^{-4}) Expected	Zγγ (TeV^{-4}) 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]





Measured cross section:

$\sigma_{W\gamma\gamma} = 13.63^{+1.93}_{-1.89}(\text{stat.})^{+4.04}_{-4.02}(\text{syst.}) \pm 0.08(\text{PDF+scale})$ — 3.1 S.D

$\sigma_{Z\gamma\gamma} = 5.41^{+0.58}_{-0.55}(\text{stat.})^{+0.64}_{-0.70}(\text{syst.}) \pm 0.06\,(\text{PDF+scale})$ — 4.8 S.D

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