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31st International Workshop on Deep Inelastic Scattering

Multiboson production in CMS

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the **CMS Collaboration**

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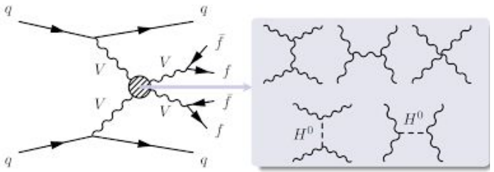
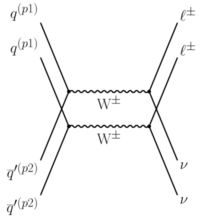
Diboson production

Diboson production

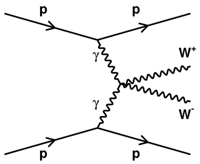


- Measurement of the **cross section** of **di-boson** production processes including
  - **vector boson scattering** (VBS)
    - valuable **precision tests** for the electroweak sector of the SM
    - **triple** and **quartic gauge couplings (TGC, QGC)** involved

Dedicated talk by C. Carrivale today



  - **double parton scattering (DPS)**
    - allows **precision tests** of **initial and final state radiation,** and **multi-parton interaction**



  - **central exclusive production (CEP)** processes e.g. p$\gamma\gamma$p → pVVp
    - $\gamma\gamma$→VV VBS processes involved as well, including $\gamma\gamma$VV QGCs

- The cross section measurements allowed to achieve more **stringent constraints** on **SM deviations** coming from anomalous gauge couplings (**aTGC**, **aQGC**) interpreted in the context of the SM-**effective field theory** (**SM-EFT**) framework.

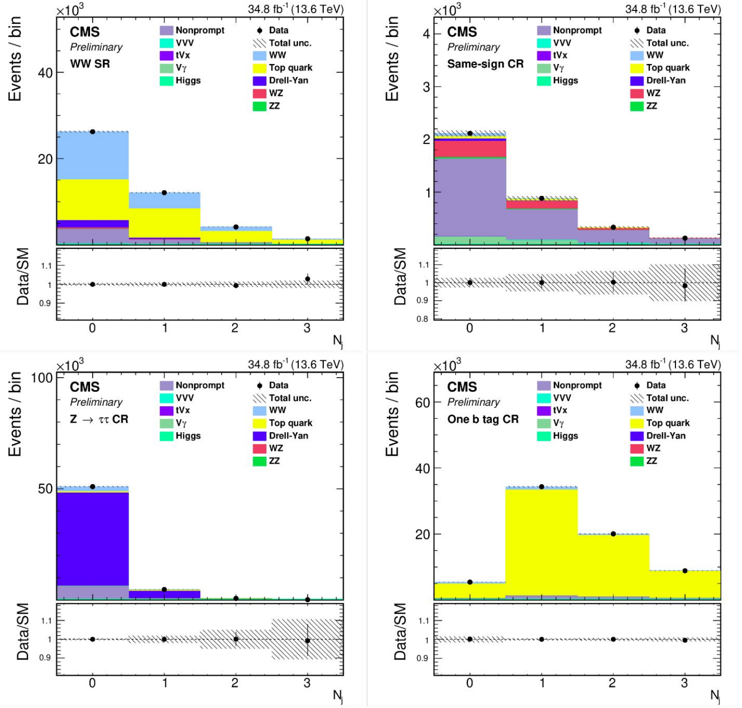
W^+W^- inclusive

First measurement of opposite-sign WW(+jets) production at $\sqrt{s}$ = 13.6 TeV

CMS Run 3 data (2022 only) →L = 34.8/fb

- Importance of OS-WW production
  - Sensitive to vector boson self-interactions
  - Test for perturbative-QCD & electroweak predictions
- 3 production processes
  - qq → WW
  - gg → WW
    → corrected by a factor 1.4 (X sec. NLO/LO)
  - H → WW
    ~10 times smaller → bkg. for this analysis
- Normalization of the main background constrained by data in Control Regions

Final state studied with this analysis:
e μ+2ν (+jets)



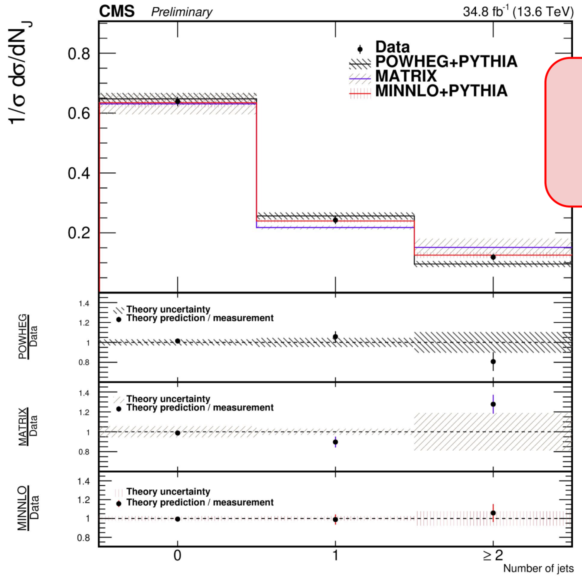
CMS – SMP – 24 – 001 **New CMS result!**

W^+W^- inclusive

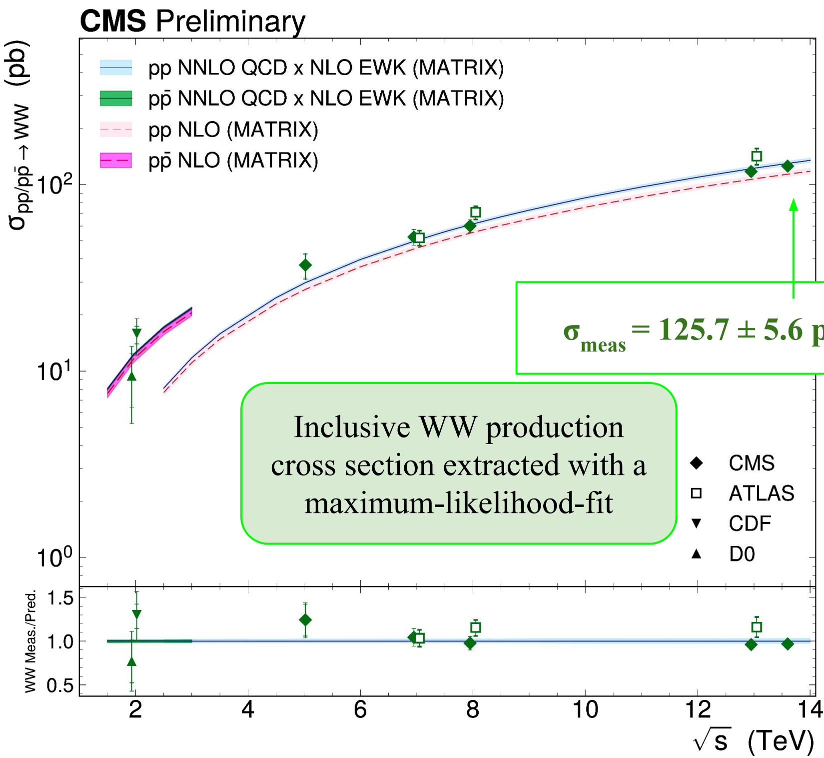
First measurement of opposite-sign WW(+jets) production at $\sqrt{s}$ = 13.6 TeV

CMS Run 3 data (2022 only) →L = 34.8/fb

Observable	Expected	Observed
Cross section (fb)	$812 \pm 34(31, 15)$	$813 \pm 35(32, 15)$
0-jet fraction	$0.648 \pm 0.015(0.012, 0.009)$	$0.640 \pm 0.016(0.013, 0.009)$
1-jet fraction	$0.256 \pm 0.013(0.008, 0.010)$	$0.243 \pm 0.013(0.009, 0.010)$
$\geq$ 2-jet fraction	$0.096 \pm 0.011(0.008, 0.008)$	$0.119 \pm 0.011(0.008, 0.008)$



Cross section measured in a fiducial region

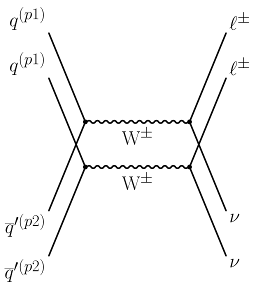


σ_{meas} = 125.7 ± 5.6 pb

Inclusive WW production cross section extracted with a maximum-likelihood-fit

CMS – SMP – 24 – 001 **New CMS result!** ⭐

$W^{\pm}W^{\pm}$ from DPS



Measurement of **Double Parton Scattering** (DPS) in WW channel for:

- Exploring **internal transversal structure** of **colliding protons** → information about **PDFs**
- Paramount goal: DPS as a bkg. (**contribution increasing with √s**)

Simplest theoretical model:
2 parton-parton interactions
A and B **entirely uncorrelated**

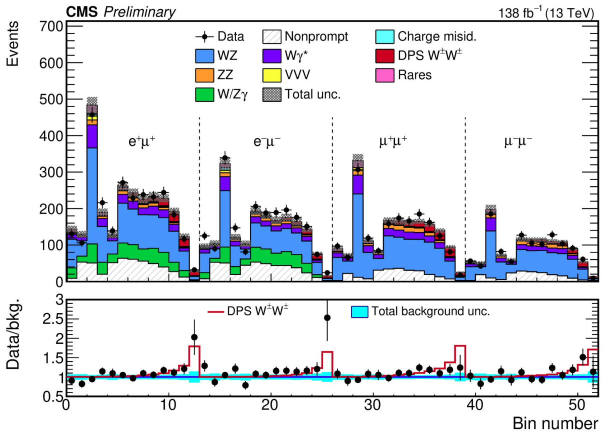
$$\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}$$

↓

Inter-parton correlation introduced via **double-PDFs (dPDF)**

↓

First dPDF-based MC generator for DPS events: dShower



Two different BDT classifiers trained to separate the signal from the WZ and non-prompt lepton backgrounds

First observation of DPS WW production

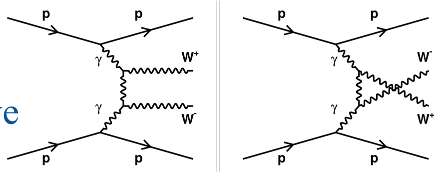
Measured (expected) inclusive cross section
0.16 ± 0.02 (stat.)
± 0.02 (syst.)
± 0.02 (model) pb

Significance observed (expected):
6.2 (6.7) S.D.

CMS – SMP – 21 – 013 *PRL 131 (2023) 091803*

pVVp

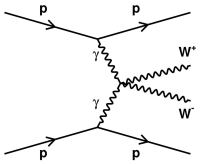
WW/ZZ Central Exclusive Production (CEP)



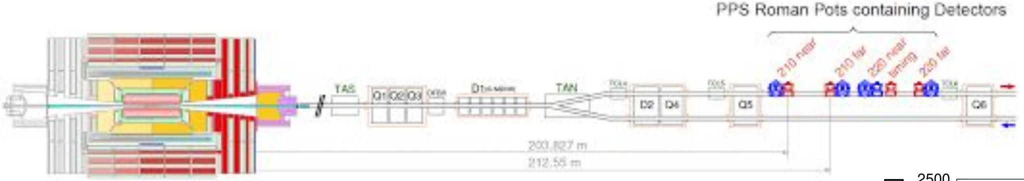
Proton fractional momentum loss:

$$\xi = \frac{p_{nom} - p}{p_{nom}}$$

WW/ZZ CEP (pp→pVVp)



- Measurement of forward (intact) protons possible in CMS via the **Precision Proton Spectrometer (PPS)** → access to the full kinematics of the events!



- Search for VBs decays into **single large jets**
- 100/fb of data (PPS in physics status)

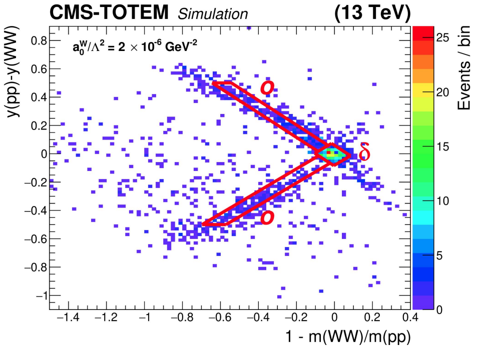
Main bkg.: **diffractive PU** → data-driven method

Defined two SRs:

- in m - y plane: ***δ* region**
  - ○ $|1 - m_{VV}/m_{pp}| > 1.0$
  - ○ $|y_{pp} - y_{VV}| > 0.5$
- PU p as a sig. p: ***O* region**

Requirement on **acoplanarity**

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

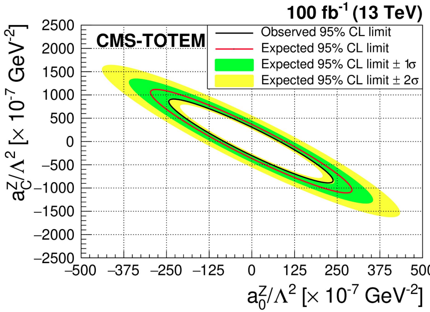


Limits on the fiducial cross section:

$$(0.04 < \xi < 0.20\ ,\ m > 1000\ \text{GeV})$$

$\sigma_{pWWp} < 67(53^{+34}_{-19})$ fb

$\sigma_{pZZp} < 43(62^{+33}_{-20})$ fb

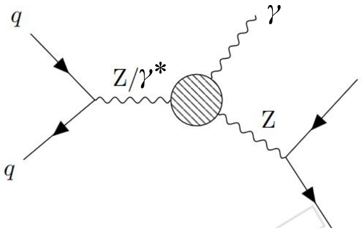


Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4 \rvert$	66.0 (60.0) TeV^{-4}	79.8 (78.2) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4 \rvert$	245.5 (214.8) TeV^{-4}	306.8 (306.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4 \rvert$	9.8 (9.0) TeV^{-4}	11.9 (11.8) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4 \rvert$	73.0 (64.6) TeV^{-4}	91.3 (92.3) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4 \rvert$	36.0 (32.9) TeV^{-4}	43.5 (42.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4 \rvert$	67.0 (58.9) TeV^{-4}	83.7 (84.1) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4 \rvert$	490.9 (429.6) TeV^{-4}	613.7 (613.7) TeV^{-4}

CMS – SMP – 21 – 014 JHEP07(2023)229

$Z(\rightarrow\nu\nu)\gamma$

$Z(\rightarrow 2\nu)+\gamma$
$\rightarrow$ suitable to detect **anomalous Neutral Triple Gauge Coupling (aNTGC)** as an excess or a deficit relative to the SM production

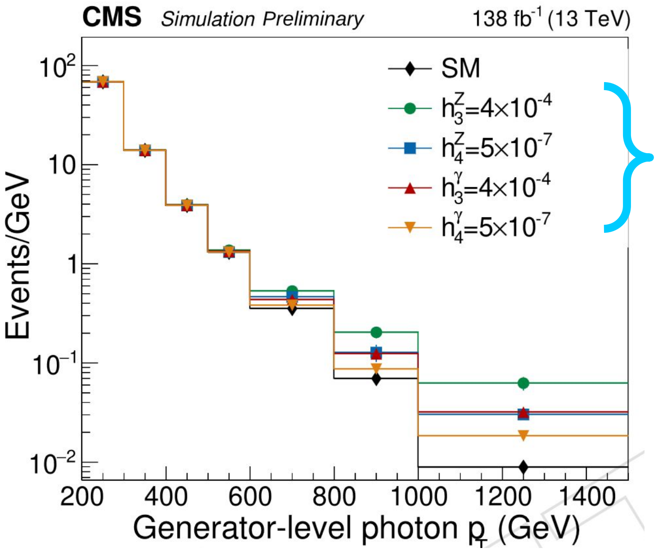


Note: **clean final state signature** with **high branching fraction** (2 times the charged lepton signature)

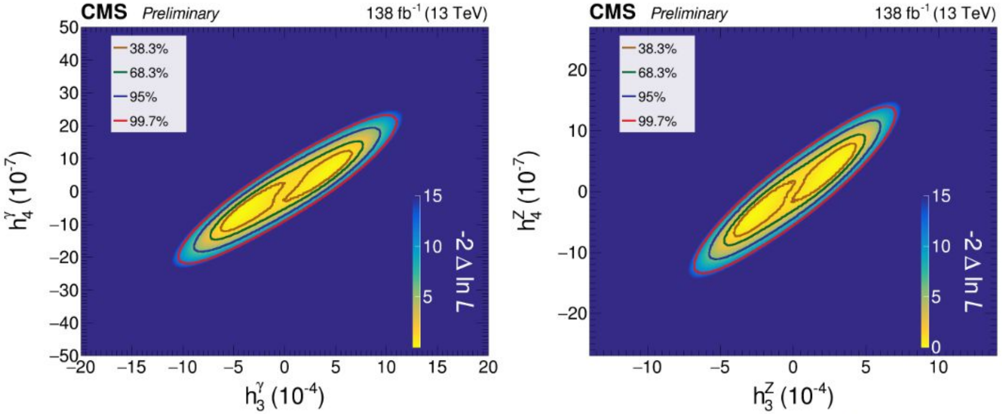
New CMS result!

CMS – SMP – 22 – 009

Parameter	Expected	Observed
$h_3^\gamma \times 10^4$	(-2.8, 2.9)	(-3.4, 3.5)
$h_4^\gamma \times 10^7$	(-5.9, 6.0)	(-6.8, 6.8)
$h_3^Z \times 10^4$	(-1.8,1.9)	(-2.2, 2.2)
$h_4^Z \times 10^7$	(-3.7, 3.7)	(-4.1, 4.2)



aNTGC parameters constrained

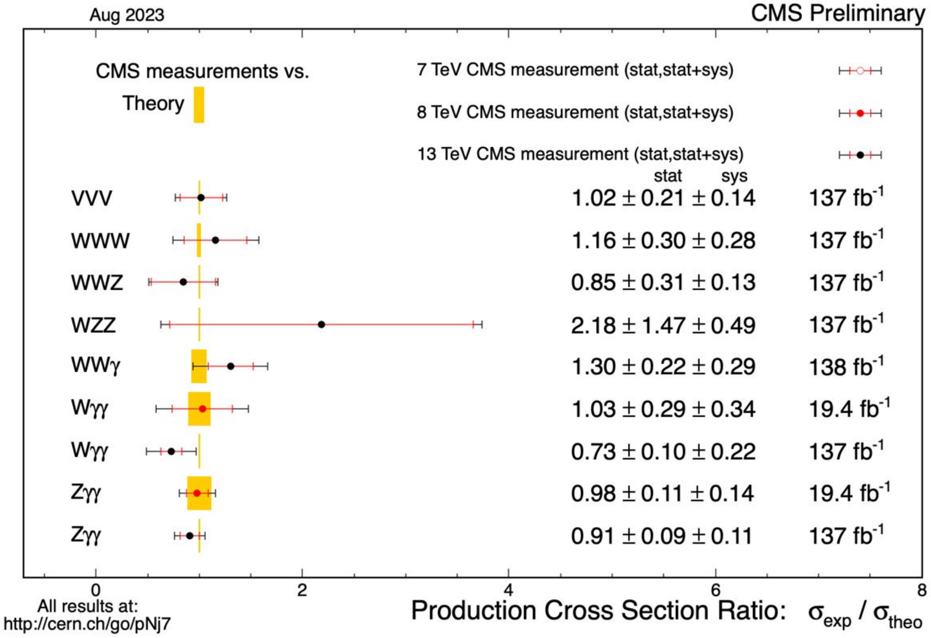


Triboson production

Tri-boson production

- Measurement of the **cross section** of **tri-boson** production processes
  - valuable **precision tests** for the electroweak sector of the SM
  - **novel observation** of **very rare** processes
  - **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.



VVV

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

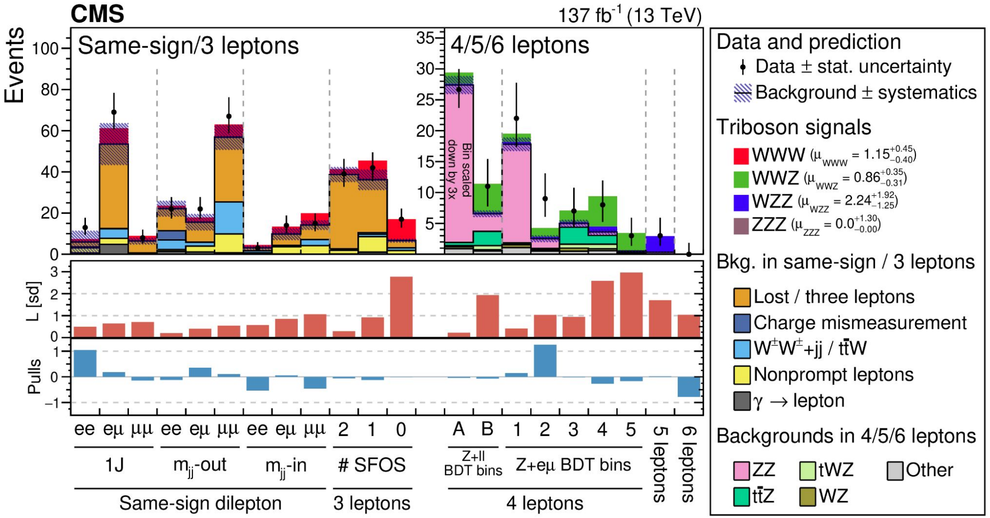
$W^{\pm}W^{\pm}W^{\mp}$	$\ell^{\pm}\nu\ \ell^{\pm}\nu\ qq'$	$2\ \ell$
$W^{\pm}W^{\pm}W^{\mp}$	$\ell^{\pm}\nu\ \ell^{\pm}\nu\ \ell^{\mp}\nu$	$3\ \ell$
$W^{\pm}W^{\pm}Z$	$\ell^{\pm}\nu\ \ell^{\pm}\nu\ \ell^{\pm}\ell^{\mp}$	$4\ \ell$
$W^{\pm}ZZ$	$\ell^{\pm}\nu\ \ell^{\pm}\ell^{\mp}\ \ell^{\pm}\ell^{\mp}$	$5\ \ell$
ZZZ	$\ell^{\pm}\ell^{\mp}\ \ell^{\pm}\ell^{\mp}\ \ell^{\pm}\ell^{\mp}$	$6\ \ell$

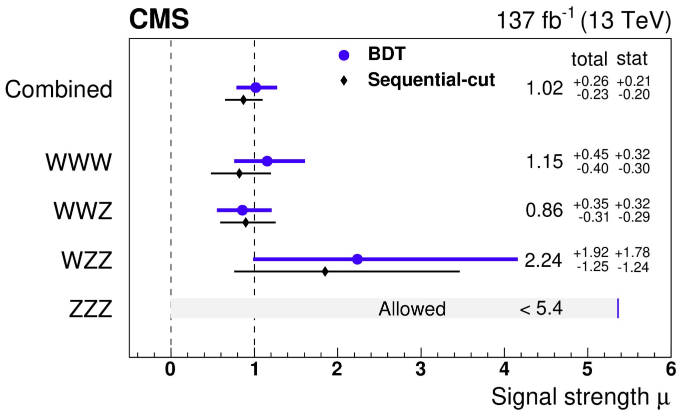
Observed (expected) significance

Simultaneous fit with 4 signal strengths:

WWW	**3.3 (3.1) S.D.**
WWZ	**3.4 (4.1) S.D.**
WZZ	1.7 (0.7) S.D.
ZZZ	0.0 (0.9) S.D.

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





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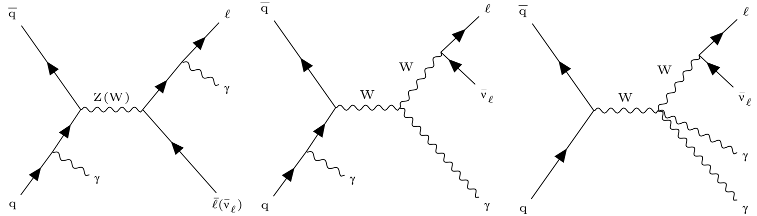
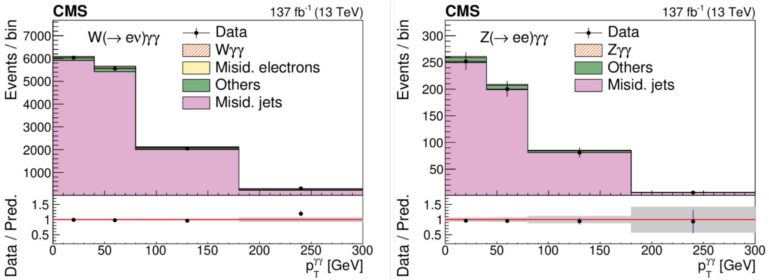
PRL 125 (2020) 151802

Vγγ
Analysis strategy



- 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:
  - Jets misid. as γ → CR : V+γloose
  - Electrons misid. as γ, *e.g.* Zγ → eeγ [eγγ] →subtract Zγ → eeγ (MC) before computing FR
  - QCD: tγ, ttγ, ttγγ, VVγ → from MC
- Systematics from data-driven background estimated by inverting lepton isolation and applying same strategy



Process	$e\nu_e\gamma\gamma$	$\mu\nu_\mu\gamma\gamma$
Misid. jets	918 ± 23 (stat) ± 180 (syst)	1441 ± 27 (stat) ± 280 (syst)
Misid. electrons	669 ± 28 (stat) ± 34 (syst)	107 ± 9 (stat) ± 7 (syst)
Others	217 ± 11 (stat) ± 20 (syst)	286 ± 11 (stat) ± 25 (syst)
Total backgrounds	1804 ± 38 (stat) ± 180 (syst)	1834 ± 30 (stat) ± 280 (syst)
Expected signal	248 ± 6 (stat) ± 17 (syst)	500 ± 8 (stat) ± 33 (syst)
Total prediction	2052 ± 38 (stat) ± 180 (syst)	2334 ± 31 (stat) ± 280 (syst)
Data	1987	2384

Process	$ee\gamma\gamma$	$\mu\mu\gamma\gamma$
Misid. jets	42 ± 4 (stat) ± 9 (syst)	98 ± 5 (stat) ± 27 (syst)
Others	6 ± 1 (stat) ± 1 (syst)	11 ± 2 (stat) ± 1 (syst)
Total backgrounds	48 ± 4 (stat) ± 9 (syst)	109 ± 6 (stat) ± 27 (syst)
Expected signal	68 ± 2 (stat) ± 5 (syst)	157 ± 3 (stat) ± 11 (syst)
Total prediction	116 ± 4 (stat) ± 8 (syst)	266 ± 6 (stat) ± 23 (syst)
Data	110	272

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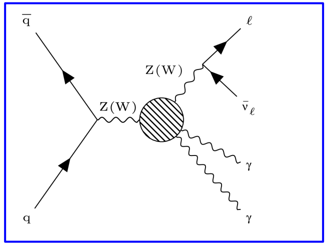
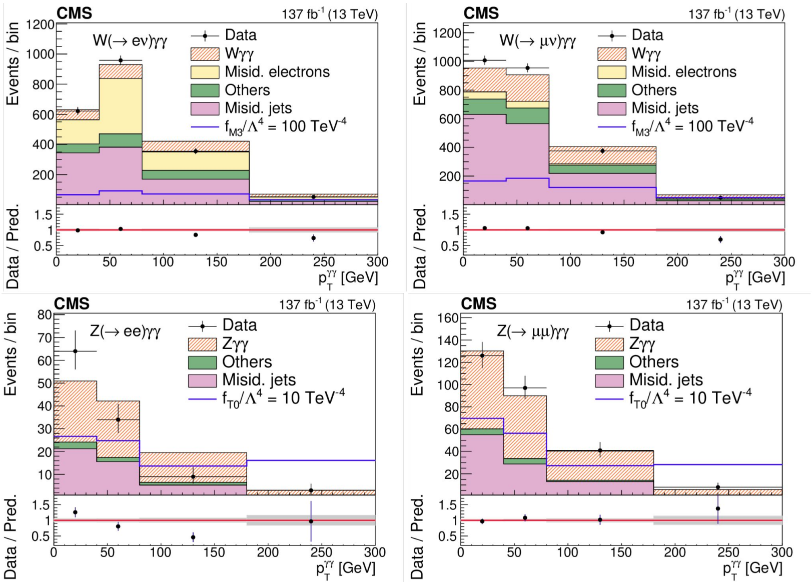
$V\gamma\gamma$

Results: SM & aQGCs



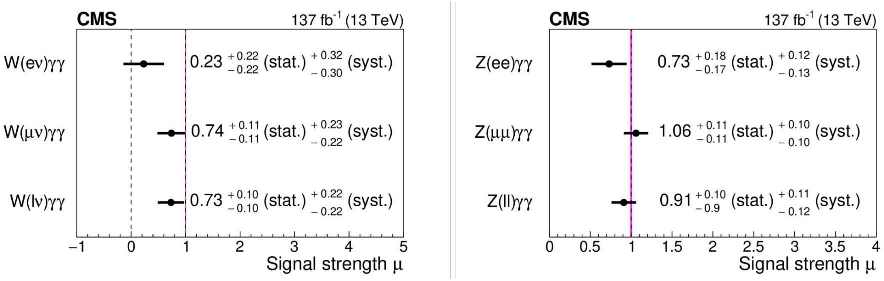
Example of BSM diagram affected by aQGC



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



Parameter	$W\gamma\gamma$ (TeV^{-4}) Expected	Observed	$Z\gamma\gamma$ (TeV^{-4}) 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]

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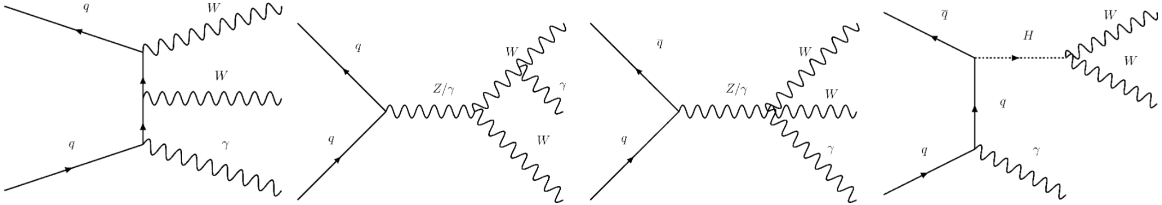
WWγ

Analysis strategy

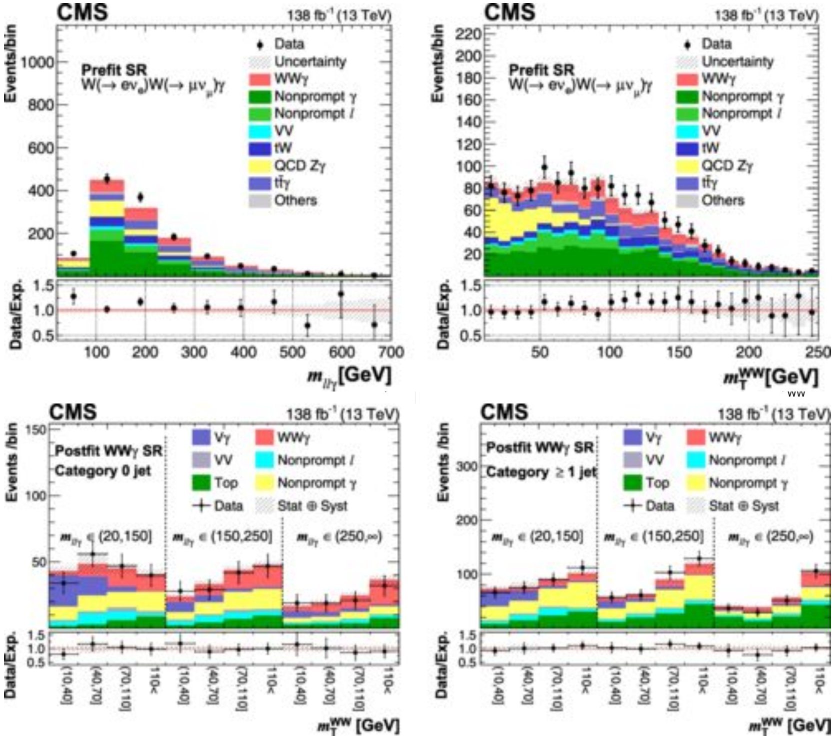


- Measurement of WWγ with fully leptonic final state sensitive to:
  - TGCs, QGCs
  - Higgs-gauge couplings
  - Higgs-light quarks couplings

- 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

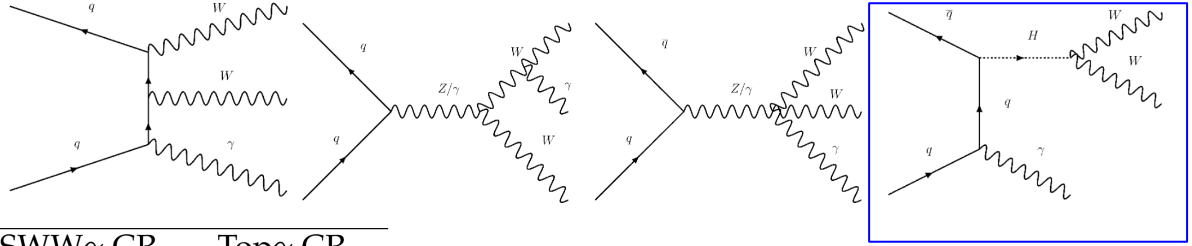
  Main difference to SR selection:
  → m_T^{WW} > 10 GeV cut not applied in the CR



CMS – SMP – 22 – 006   PRL 132 121901

WWγ

Results



Process	Signal region	SSWWγ CR	Topγ CR
WWγ	254.0$\pm$47.3	1.2$\pm$0.2	12.8$\pm$2.7
QCD Vγ	166.7$\pm$13.8	12.2$\pm$2.2	12.6$\pm$1.2
VV	36.7$\pm$3.5	24.9$\pm$1.7	2.0$\pm$0.3
Top	327.5$\pm$32.2	2.4$\pm$0.6	2433.5$\pm$85.2
Nonprompt ℓ	122.9 $\pm$9.7	196.6$\pm$13.6	39.8$\pm$10.7
Nonprompt γ	409.9 $\pm$31.7	19.9$\pm$1.6	793.2$\pm$62.1
Expected	1318$\pm$43	257$\pm$14	3294$\pm$57
Observed	1330$\pm$46	259$\pm$20	3287$\pm$59

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

Profile likelihood ratio test statistic built in bins of ΔR_{ll} (found to have good discrimination power) and m_T^H

Measured fiducial cross section:

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

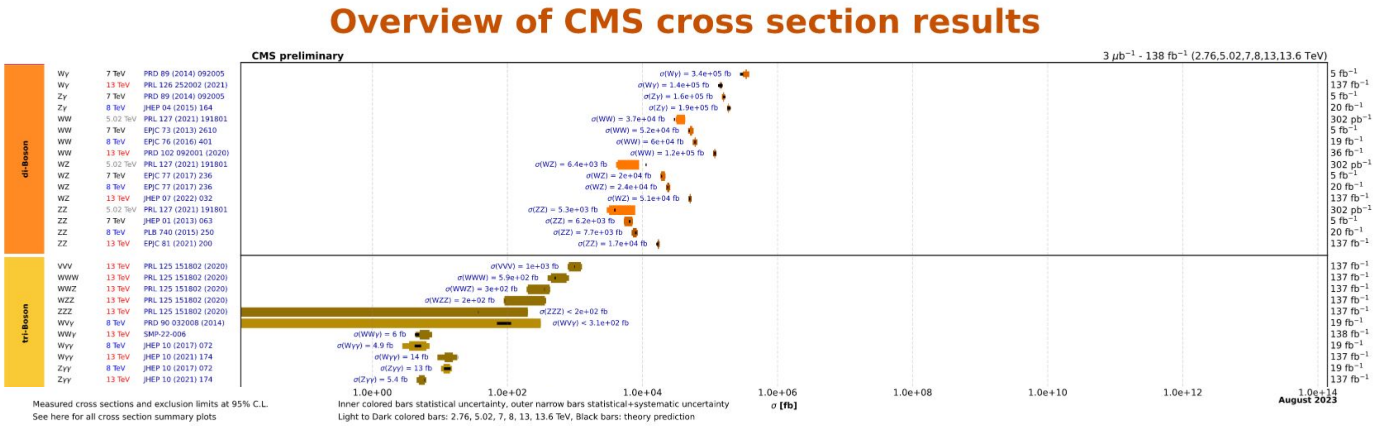
$\mu = 1.31 \pm 0.17(\text{stat}) \pm 0.21(\text{syst})$ 5.6(4.7) S.D.

Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq$13000 (16000)
$d\bar{d} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq$14000 (17000)
$s\bar{s} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq$1300 (1700)
$c\bar{c} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq$110(200)

CMS – SMP – 22 – 006

PRL 132 121901

Summary



- Most of the recent results achieved by the **CMS Collaboration** on **di-boson**, and **tri-boson** production processes including the most recent **constraints** on **SM deviations** coming from **anomalous couplings** in multi-boson processes were also reported

- Di-boson: **precision era** → NNLO. **Good agreement** with MC predictions ✅

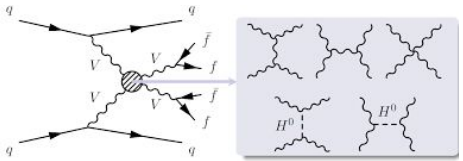
- Triboson: some processes already measured →need for higher sensitivity with future analyses

Stay tuned
for Run 3
and beyond!

Thank you!

BACKUP

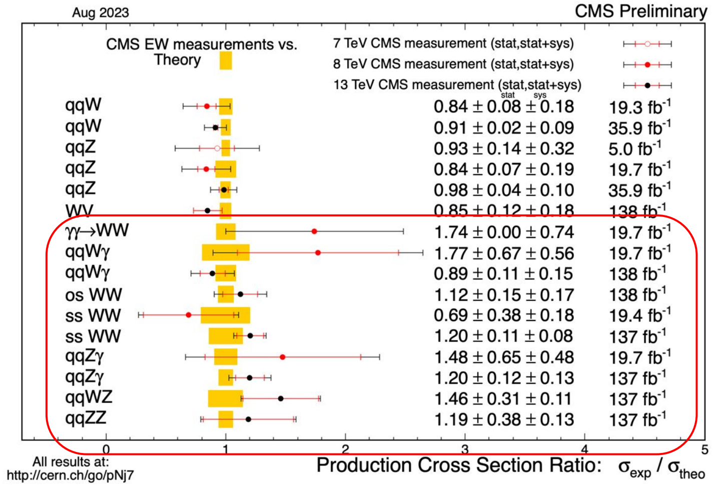
Vector Boson Scattering in CMS

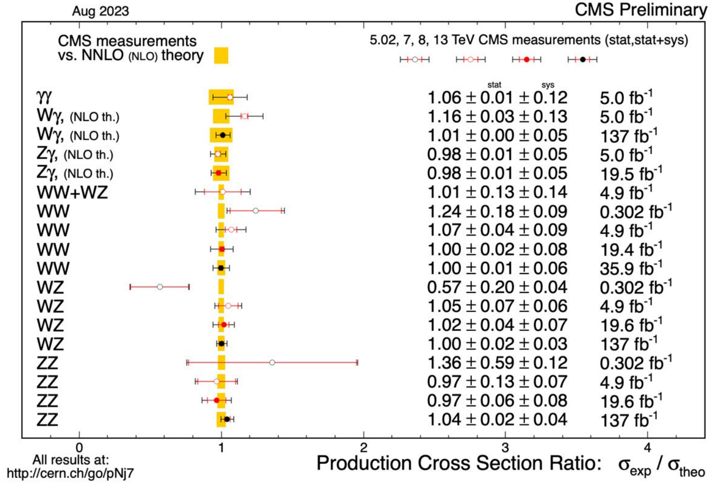


Plethora of results achieved with
full Run-2 dataset and still coming out:

- **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.





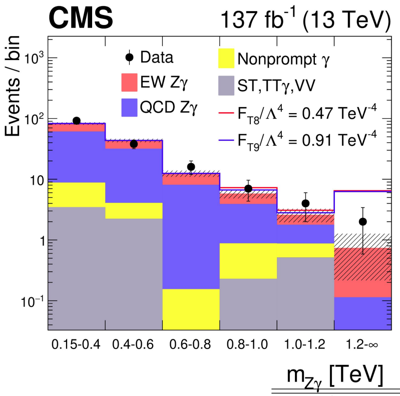
Several VBS channels are now well established and enable stringent constraints on BSM theories → **Effective Field Theory (EFT)**

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

Dedicated talk by C. Carrivale today

Vector Boson Scattering in CMS

Constraints on anomalous quartic gauge couplings (aQGCs)



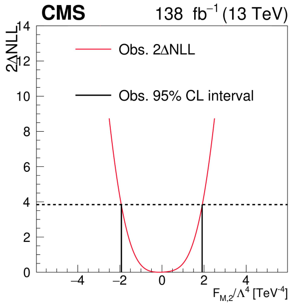
<u>Constraining on aQGCs</u>: typical procedure

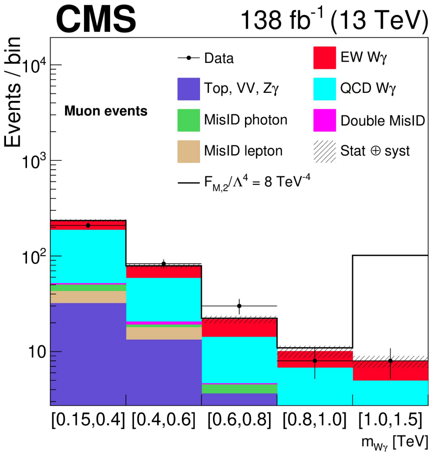
- ➔ **Dimension-8 EFT op.s**
- ➔ **m_{VV}** sensitive to deviations from SM
- ➔ **Maximum-likelihood fit profiling** the **syst. unc.**

CMS – SMP – 20 – 016

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

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





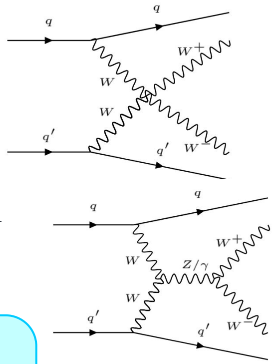
CMS – SMP – 21 – 011

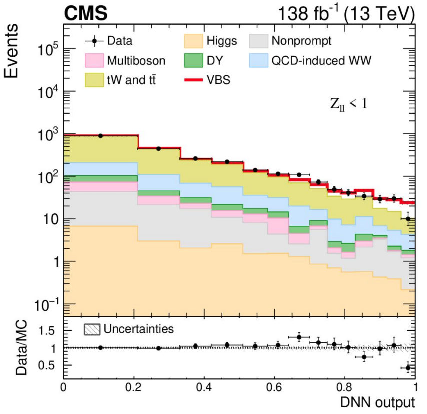
Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	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

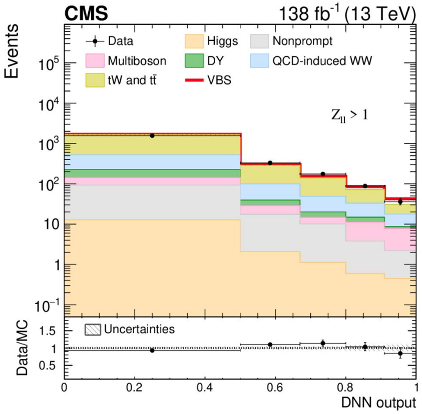
<u>Wγ analysis</u>: Among the best limits for $f_{M,2-5}/\Lambda^4$, $f_{T,5-7}/\Lambda^4$,

W^+W^-

OS-WW+2jets → VBS study crucial in investigating the **EWSB** mechanism







Analysis strategy:

- ➔ **Signal region** splitted in **2 regions** basing on the centrality of the *ll* system wrt the tagging jets
- ➔ **Ttbar** control region (inverted b-veto)
- ➔ **Drell-Yan** control region

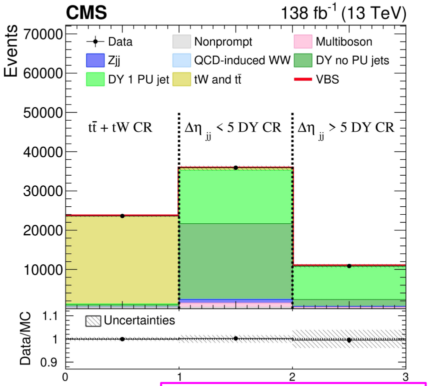
Zeppenfeld variable

$$Z_{\ell\ell} = \frac{1}{2}|Z_{\ell_1} + Z_{\ell_2}|$$

where $Z_\ell = \eta_\ell - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$

Use of a **DNN** to separate VBS signal from ttbar and QCD-induced WW bkg.s

Signal extraction based on a binned **maximum likelihood fit**



Nb. of events in the diffentent CRs

CMS – SMP – 21 – 001

Definition of a **fiducial volume** close to the reconstructed SR

Objects	Requirements
Leptons	$e\mu, ee, \mu\mu$ final state, opposite charge $p_T^\ell = p_T^{bare\,\ell} + \sum_i p_T^{\gamma_i}$ if $\Delta R(\ell, \gamma_i) < 0.1$ $p_T^{\ell_1} > 25$ GeV, $p_T^{\ell_2} > 13$ GeV, $p_T^{\ell_3} < 10$ GeV $\lvert\eta\rvert < 2.5$ $p_{T\ell\ell} > 30$ GeV, $m_{\ell\ell} > 50$ GeV
Jets	$p_T^j > 30$ GeV $\Delta R(j, \ell) > 0.4$ At least 2 jets, no b jets $\lvert\eta\rvert < 4.7$ $m_{jj} > 300$ GeV, $\Delta\eta_{jj} > 2.5$
MET	$p_T^{miss} > 20$ GeV

First observation of the EW production of a OS–WW pair (fully leptonic decay) in association with 2 jets

Measured (expected) fiducial cross section:

10.2 ± 2.0 fb

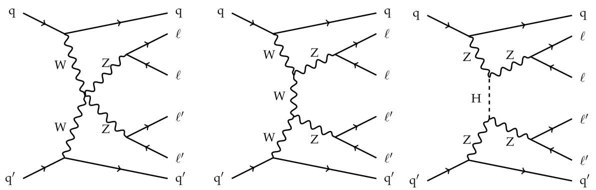
(9.1 ± 0.6 fb)

Significance observed (expected):

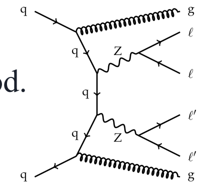
5.6 (5.2) S.D.

ZZ

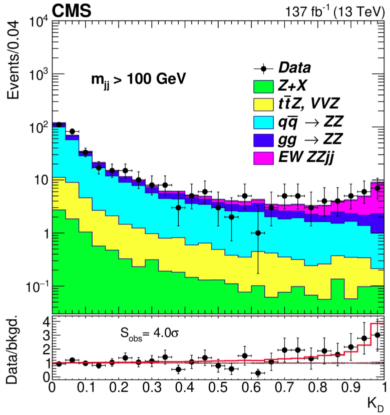
SM evidence and aQGC limits



- ZZ electroweak production (fully leptonic channel) associated with a jet pair



- Irreducible dominant bkg.: QCD-induced ZZjj prod.
- **MELA (Matrix Element Likelihood Approach) discriminant** used to extract the signal (performance checked vs. BDT w/28 inputs variables)



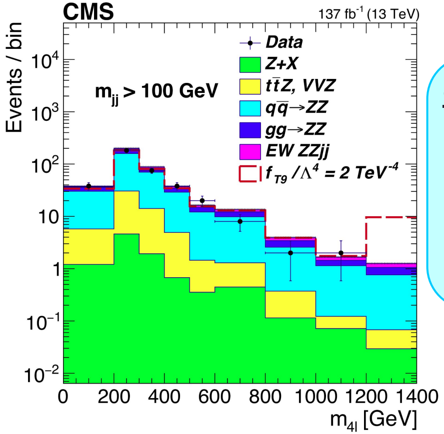
First evidence of the EW ZZ production (4ljj final state)

Observed (expected) signal strength:

$$\mu_{EW} = 1.21^{+0.47}_{-0.40} (1.00^{+0.43}_{-0.36})$$

Significance observed (expected):

4.0 (3.5) S.D.



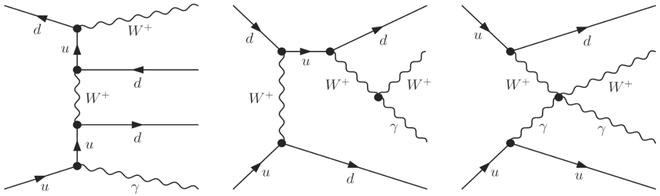
Constraining on aQGCs

- ➔ **Dimension-8 EFT op.s**
- ➔ **m_{zz}** used
- ➔ **Maximum-likelihood fit profiling** the **syst. unc.**

Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.37	0.35	−0.24	0.22	2.4
f_{T1}/Λ^4	−0.49	0.49	−0.31	0.31	2.6
f_{T2}/Λ^4	−0.98	0.95	−0.63	0.59	2.5
f_{T8}/Λ^4	−0.68	0.68	−0.43	0.43	1.8
f_{T9}/Λ^4	−1.5	1.5	−0.92	0.92	1.8

CMS – SMP – 20 – 001

$W\gamma$
aQGC limits



First observation (May 2020) of the EW $W\gamma$ production (ljj+MET final state) combining 8 TeV & (2016) 13 TeV center-of-mass-energy data collected by CMS

Combined observed (expected) significance: 5.3 (4.8) S.D.

CMS – SMP – 19 – 008

Constraining on aQGCs
- ➔ **Dimension-8 EFT op.s**
- ➔ **$m_{W\gamma}$** used
- ➔ **Maximum-likelihood fit profiling** the **syst. unc.**

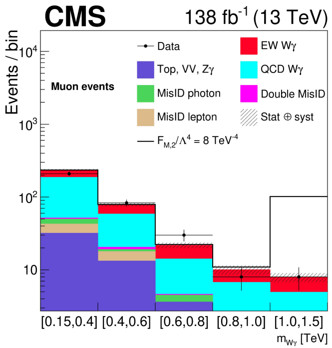
Improvement of constraints on aQGCs

CMS – SMP – 19 – 008

Parameters	Exp. limit	Obs. limit	U_{bound}
$f_{M,0}/\Lambda^4$	$[-8.1, 8.0]$	$[-7.7, 7.6]$	1.0
$f_{M,1}/\Lambda^4$	$[-12, 12]$	$[-11, 11]$	1.2
$f_{M,2}/\Lambda^4$	$[-2.8, 2.8]$	$[-2.7, 2.7]$	1.3
$f_{M,3}/\Lambda^4$	$[-4.4, 4.4]$	$[-4.0, 4.1]$	1.5
$f_{M,4}/\Lambda^4$	$[-5.0, 5.0]$	$[-4.7, 4.7]$	1.5
$f_{M,5}/\Lambda^4$	$[-8.3, 8.3]$	$[-7.9, 7.7]$	1.8
$f_{M,6}/\Lambda^4$	$[-16, 16]$	$[-15, 15]$	1.0
$f_{M,7}/\Lambda^4$	$[-21, 20]$	$[-19, 19]$	1.3
$f_{M,0}/\Lambda^4$	$[-0.6, 0.6]$	$[-0.6, 0.6]$	1.4
$f_{M,1}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.5
$f_{M,2}/\Lambda^4$	$[-1.0, 1.2]$	$[-1.0, 1.2]$	1.5
$f_{M,5}/\Lambda^4$	$[-0.5, 0.5]$	$[-0.4, 0.4]$	1.8
$f_{M,6}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.7
$f_{M,7}/\Lambda^4$	$[-0.9, 0.9]$	$[-0.8, 0.9]$	1.8

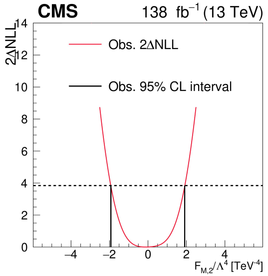
CMS – SMP – 21 – 011

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



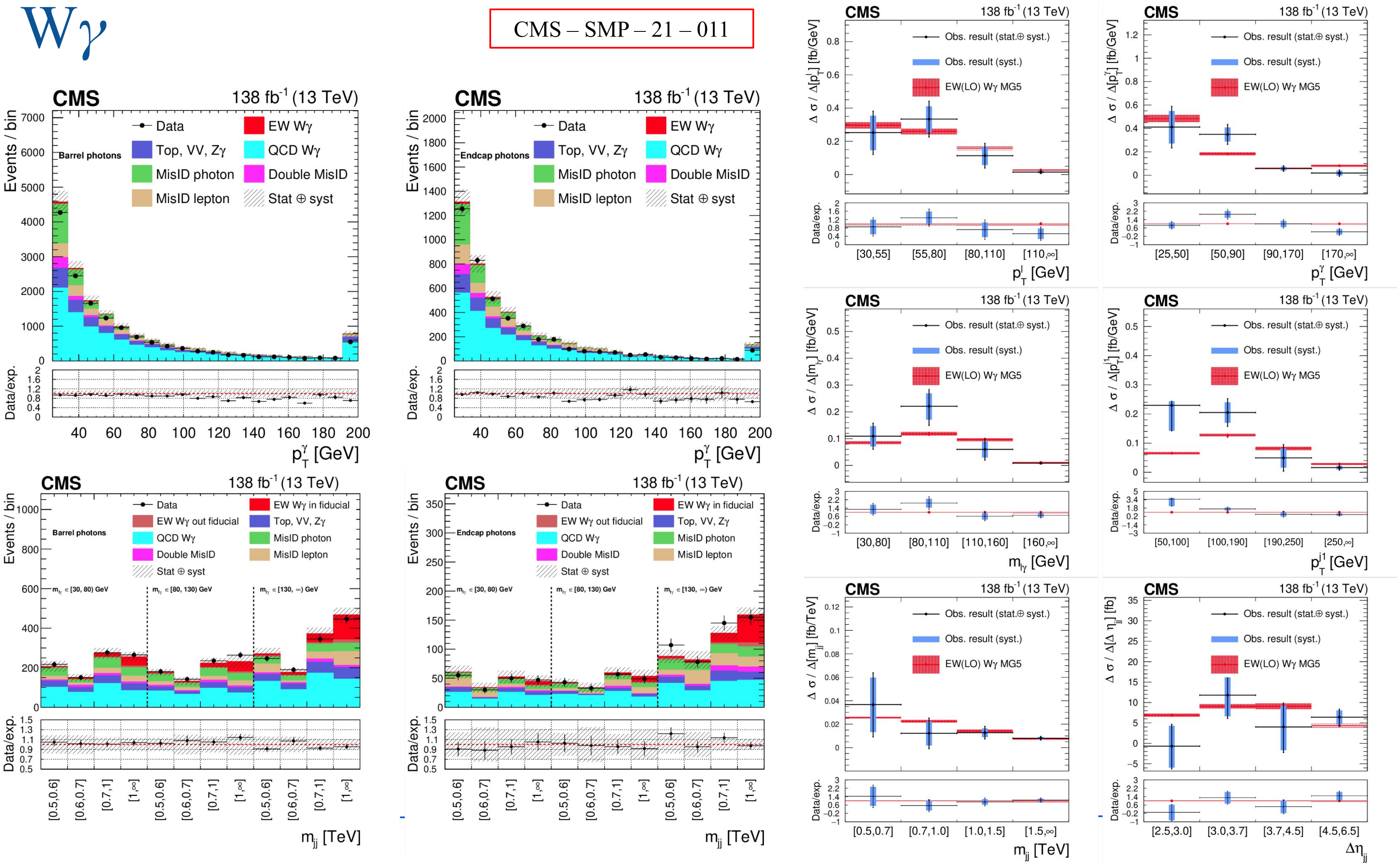
The $m_{W\gamma}$ distribution for muon events satisfying a selection used to set constraints on the aQGC parameters. The last bin includes overflow.

No statistically significant SM deviation is observed

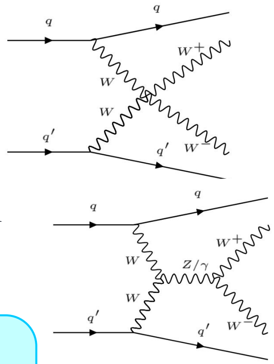


Wγ

CMS – SMP – 21 – 011



W^+W^-



OS-WW+2jets → VBS study crucial in investigating the **EWSB** mechanism

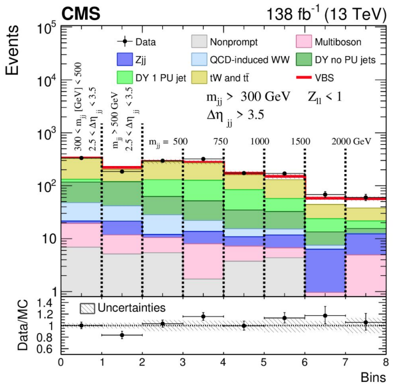
Analysis strategy:

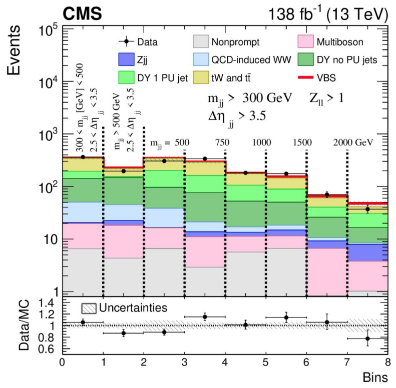
- ➔ **Signal region** splitted in **2 regions** basing on the centrality of the *ll* system wrt the tagging jets
- ➔ **Ttbar** control region (inverted b-veto)
- ➔ **Drell-Yan** control region

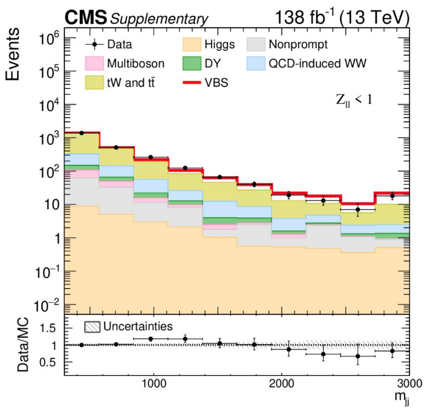
Zeppenfeld variable

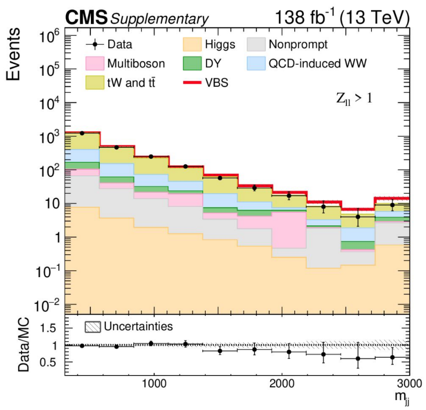
$$Z_{\ell\ell} = \frac{1}{2}|Z_{\ell_1} + Z_{\ell_2}|$$

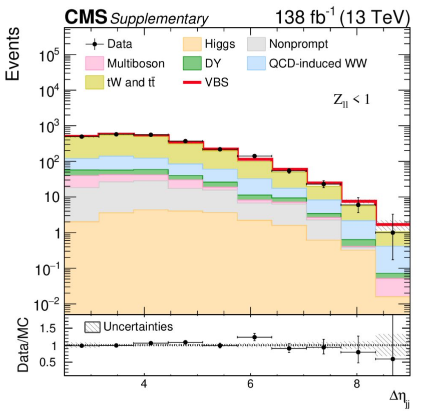
where $Z_{\ell} = \eta_{\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$

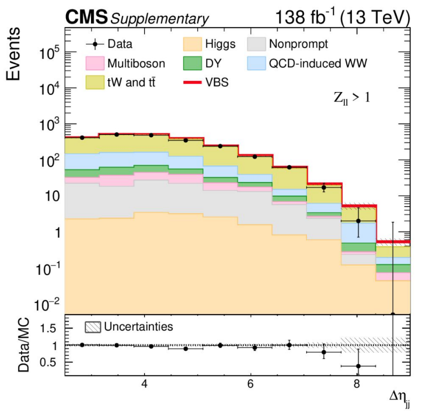












CMS – SMP – 21 – 001

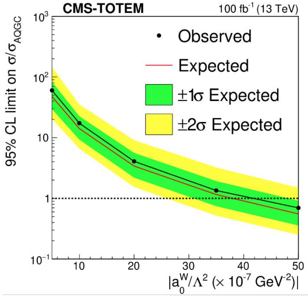
pVVp

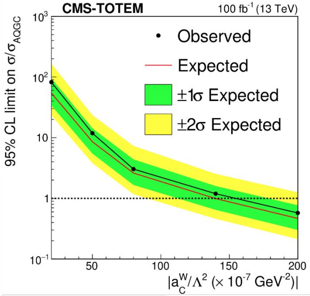
Important variables for this analysis:

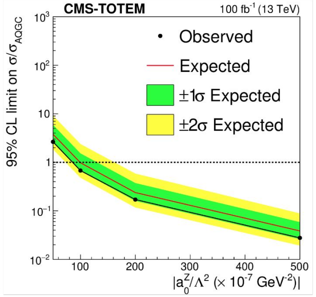
$$\xi_i = \frac{\Delta p_i}{p_p} \qquad M_{ij}\sqrt{s\xi_i\xi_j} \qquad y_{ij} = \frac{1}{2}\log\frac{\xi_i}{\xi_j}$$

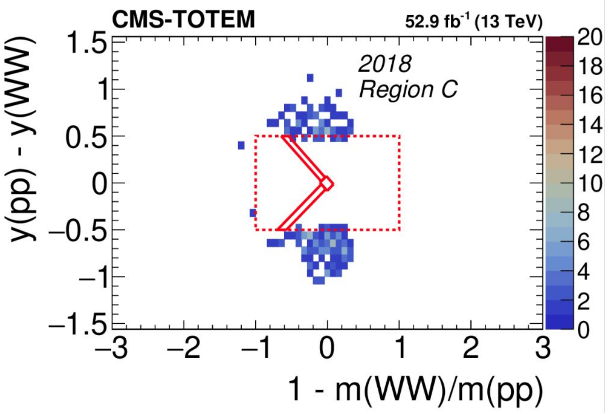
Main bkg.: **diffractive PU**
→ data-driven method

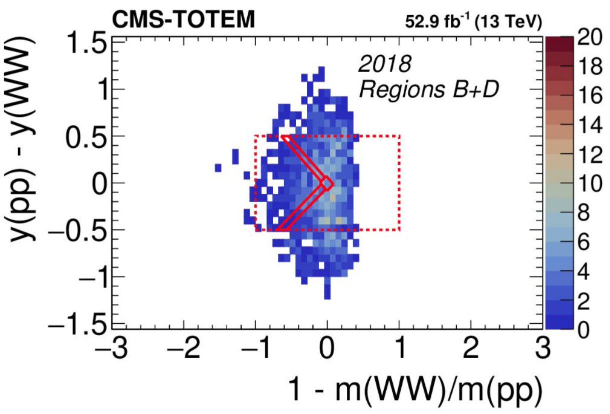
Defined CRs reverting the requirement on **acoplanarity**

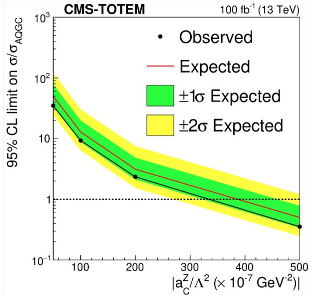






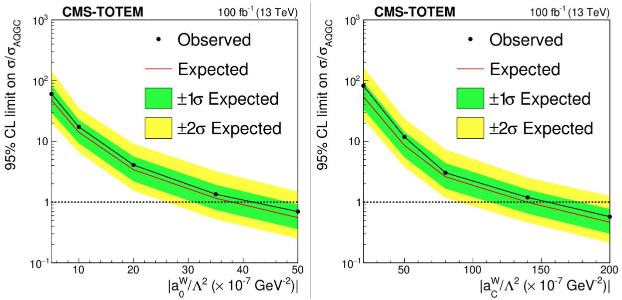


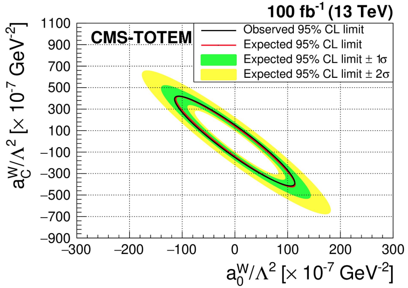




CMS – SMP – 21 – 014

pVVp



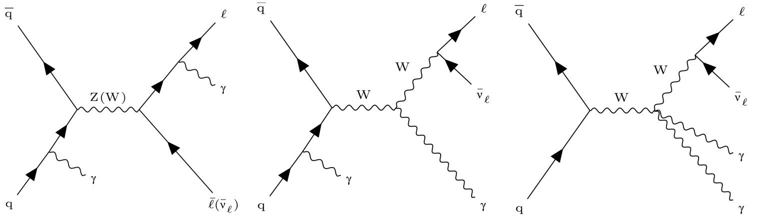


Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\|a_0^W/\Lambda^2\|$	$4.3\ (3.9) \times 10^{-6}$ GeV^{-2}	$5.2\ (5.1) \times 10^{-6}$ GeV^{-2}
$\|a_C^W/\Lambda^2\|$	$1.6\ (1.4) \times 10^{-5}$ GeV^{-2}	$2.0\ (2.0) \times 10^{-5}$ GeV^{-2}
$\|a_0^Z/\Lambda^2\|$	$0.9\ (1.0) \times 10^{-5}$ GeV^{-2}	—
$\|a_C^Z/\Lambda^2\|$	$4.0\ (4.5) \times 10^{-5}$ GeV^{-2}	—

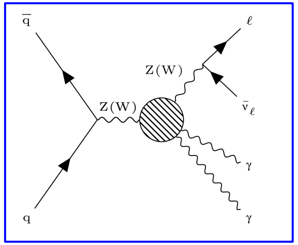
Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\|f_{M,0}/\Lambda^4\|$	66.0 (60.0) TeV^{-4}	79.8 (78.2) TeV^{-4}
$\|f_{M,1}/\Lambda^4\|$	245.5 (214.8) TeV^{-4}	306.8 (306.8) TeV^{-4}
$\|f_{M,2}/\Lambda^4\|$	9.8 (9.0) TeV^{-4}	11.9 (11.8) TeV^{-4}
$\|f_{M,3}/\Lambda^4\|$	73.0 (64.6) TeV^{-4}	91.3 (92.3) TeV^{-4}
$\|f_{M,4}/\Lambda^4\|$	36.0 (32.9) TeV^{-4}	43.5 (42.9) TeV^{-4}
$\|f_{M,5}/\Lambda^4\|$	67.0 (58.9) TeV^{-4}	83.7 (84.1) TeV^{-4}
$\|f_{M,7}/\Lambda^4\|$	490.9 (429.6) TeV^{-4}	613.7 (613.7) TeV^{-4}

CMS – SMP – 21 – 014

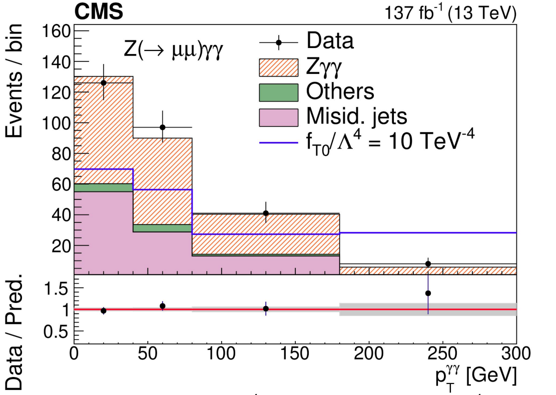
Vγγ



- 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

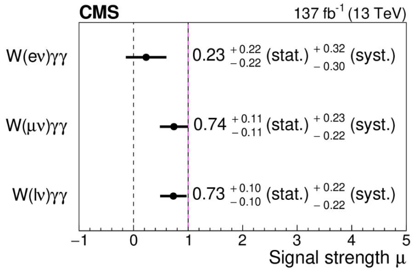


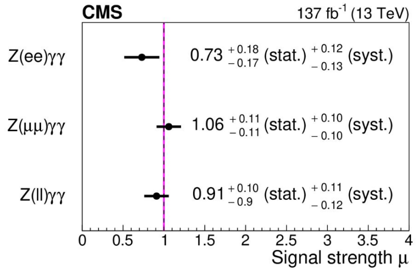
Parameter	Wγγ (TeV^{-4}) Expected	Wγγ (TeV^{-4}) Observed	Zγγ (TeV^{-4}) Expected	Zγγ (TeV^{-4}) Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 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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