34th Rencontres of Blois
on Particle Physics
and Cosmology

Vector Boson production in CMS

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on behalf of
the **CMS Collaboration**

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Outline

Single Vector Boson production:

- $Z \to \tau\tau$
- $Z \to \tau\tau\mu\mu$
- W+ c-jets

Di-boson production:

- VBS Overview
- pVVp (CEP)
- SS–WW (DPS)

Tri-boson production:

- VVV
- $WW\gamma$

Additional contents in backup

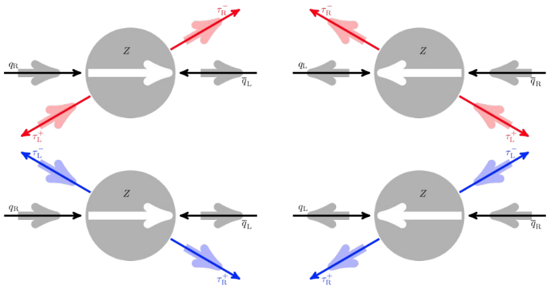
- Z/γ + jets
- Z + b-jets
- Z + jets (DPS)
- OS–WW (VBS)
- ZZ (VBS)
- $W\gamma$ (VBS)
- $V\gamma\gamma$

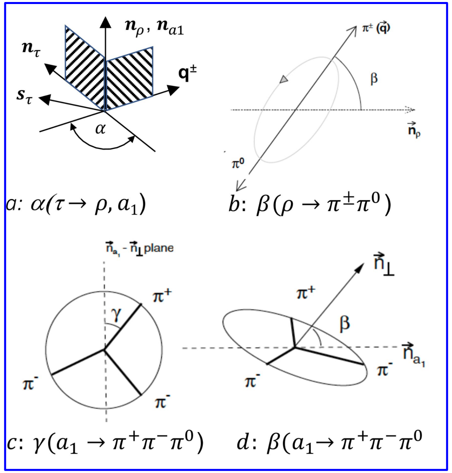
Single Vector Boson production

$Z \rightarrow \tau\tau$

- **Weak-mixing angle θ_W** leads to different coupl. for right- and left-handed fermions in **neutral weak currents**. → **polarization of fermion-antifermion pairs in the decay of the Z boson**.
- $Z \rightarrow \tau^+\tau^-$: τ polarization measurement:

$$\mathcal{P}_\tau = \frac{\sigma_{h^+} - \sigma_{h^-}}{\sigma_{h^+} + \sigma_{h^-}}$$

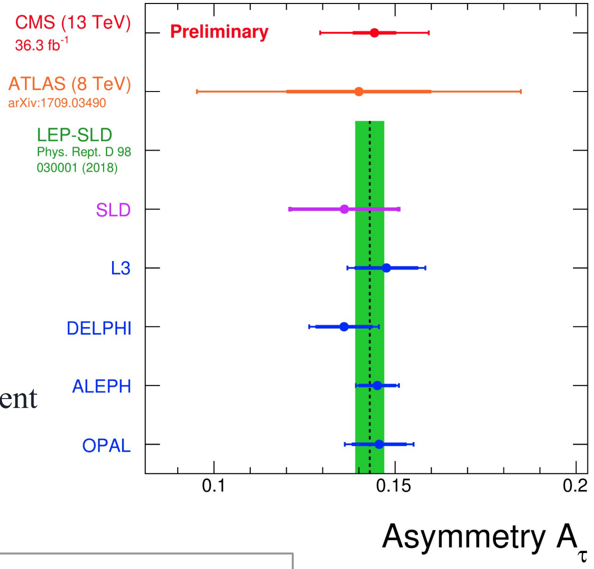




Main angular variables to measure the polarization

Test of **lepton universality** of weak neutral currents:

- from $P_\tau \rightarrow \sin^2\theta_W^{eff}$ measurement
- comparison to precise measurement @LEP from e^+e^-



Results for the weak-mixing angle:

$$\sin^2\theta_W^{eff.} = 0.2319 \pm 0.0008(stat.) \pm 0.0018(syst.)$$

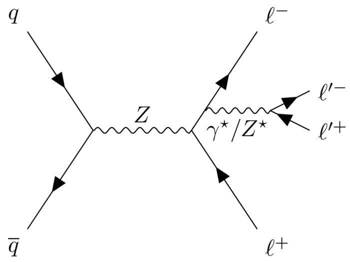
Combination of past results (LEP & SLD) :

$$\sin^2\theta_W^{eff.} = 0.2315 \pm 0.0002$$

CMS – SMP – 18 – 010 (Feb. 2023)

$Z \to \tau\tau\mu\mu$

- $Z \to \tau^+\tau^-\mu^+\mu^- \to \mu^+\mu^-(+2\nu)\mu^+\mu^-$: rare SM process
- Potential **BSM Z' boson** contribution
- Relative contamination from VV processes corrected via **multiplicative factors** in the final branching fraction extraction
- Bkg. from non-prompt μ characterized via data-driven techniques

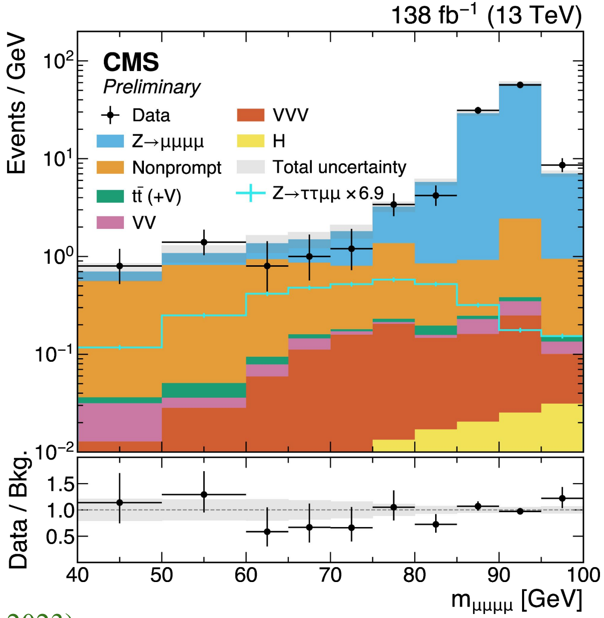


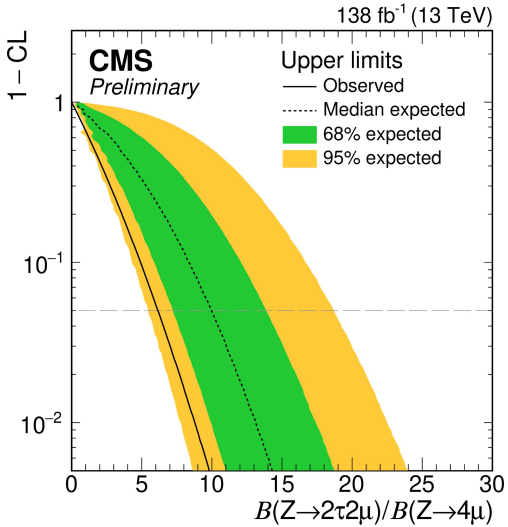
Yield extracted from a binned ML template fit with syst. unc. as nuisance parameters and 2 POIs:

- ❑ N($Z \to 4\mu$)
- ❑ r = N($Z \to 2\tau 2\mu \to 4\mu$) /N($Z \to 4\mu$)

→ ratio of the branching fractions given by:

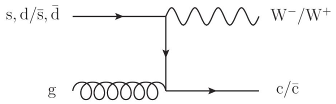
$$\mathcal{R}_{\tau^+\tau^-\mu^+\mu^-} = \frac{N_{Z\to\tau^+\tau^-\mu^+\mu^-}}{N_{Z\to\mu^+\mu^-\mu^+\mu^-}} \frac{(A\epsilon)_{Z\to\tau^+\tau^-\mu^+\mu^-}}{(A\epsilon)_{Z\to\mu^+\mu^-\mu^+\mu^-}} \frac{1}{\mathcal{B}^2_{\tau\to\mu\nu\bar{\nu}}} \frac{f_\tau}{f_\mu}$$



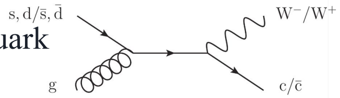


CMS – SMP – 22 – 016 (March 2023)

W+c-jet



W+c-jet → sensitive to strange-quark content of colliding protons



Remarkable improvement of heavy-flavour Jet-ID thanks to the 2017 Pixel tracking detector upgrade

INFN SEZIONE DI TORINO

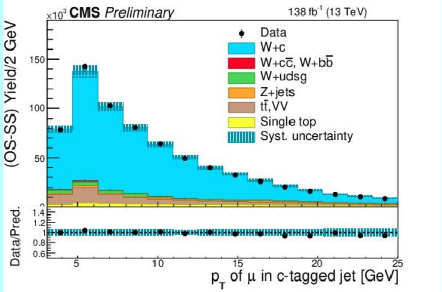
Yield after kin. selection

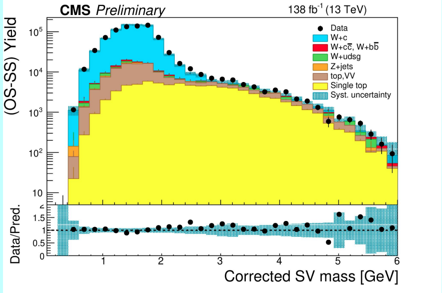
$$\sigma(W+c) = \frac{Y_{sel.}(1-f_{bkg.})}{\mathcal{CL}}$$

Bkg. fraction after OS-SS

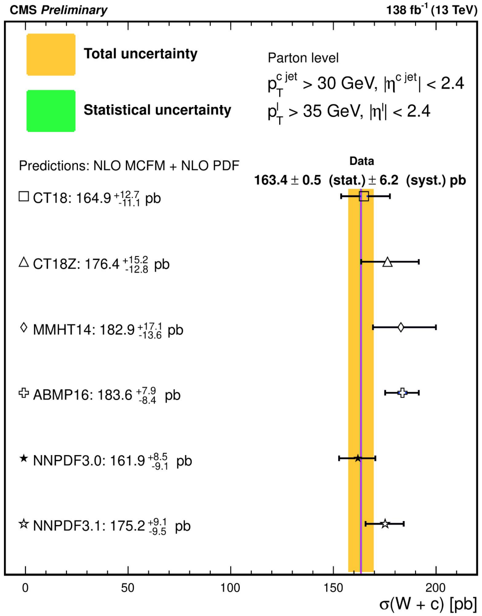
Correction factor for eff. loss in the selection

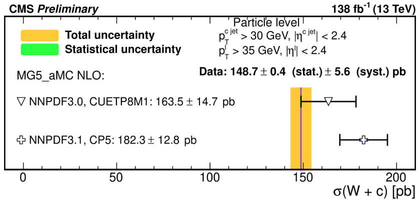
W and c are opposite-sign charge
→ ***OS-SS*** method enables bkg. suppression





<u>Strategy</u> 2 channels:
-Semileptonic (**SL**)
-Secondary Vertex (**SV**)



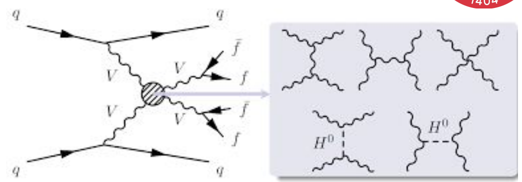


CMS – SMP – 21 – 005 (July 2022)

Novel results on Z+b-jet(s) channel (SMP-20-015) in backup.

Di-boson production

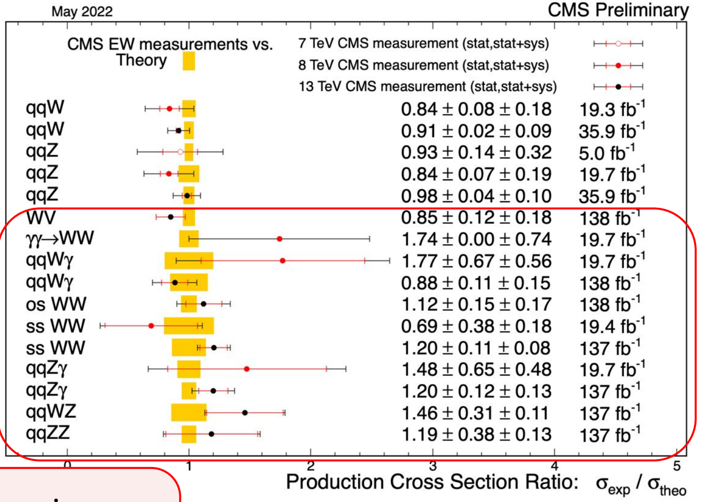
Vector Boson Scattering (VBS) in CMS



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.

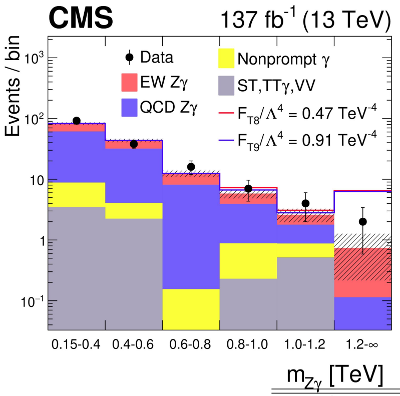


Several VBS channels are now well established and enable stringent constraints on BSM theories → **Effective Field Theory (EFT)**

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

Vector Boson Scattering (VBS) in CMS

Constraints on anomalous quartic gauge couplings (aQGCs)



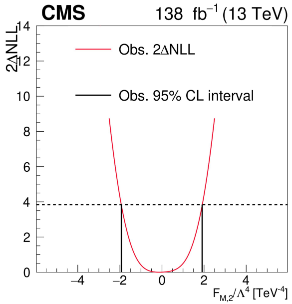
<u>Constraining on aQGCs</u>: typical procedure

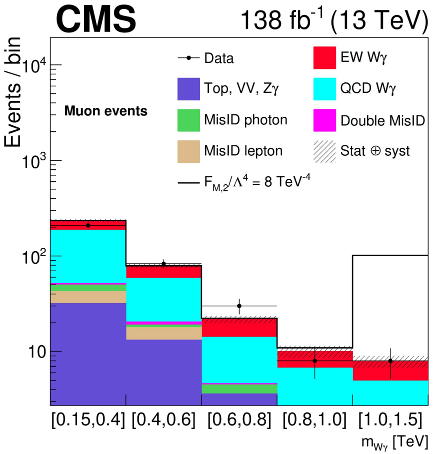
- ➔ **Dimension-8 EFT op.s**
- ➔ **m_{VV}** sensitive to deviations from SM
- ➔ **Maximum-likelihood fit profiling** the **syst. unc.**

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





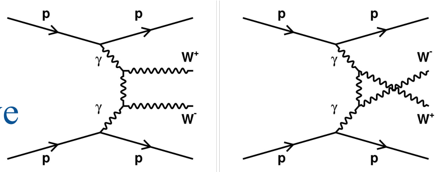
CMS – SMP – 21 – 001

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

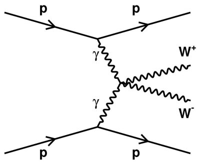
<u>Wγ analysis</u>: Among the best limits for $f_{M,2-5}/\Lambda^4$, $f_{T,5-7}/\Lambda^4$,

pVVp

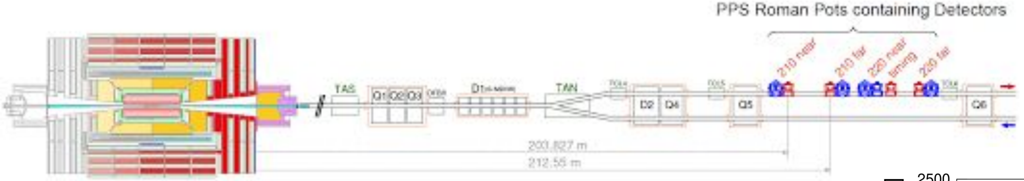
WW/ZZ Central Exclusive Production (CEP)



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)

Proton fractional momentum loss:

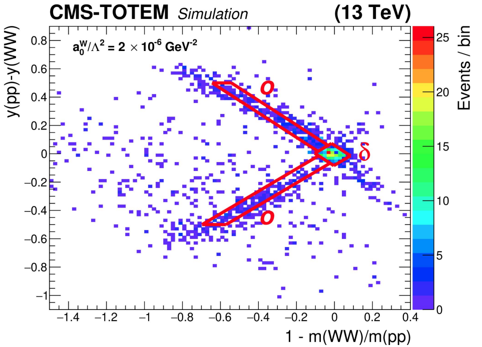
$$\xi = \frac{p_{nom} - p}{p_{nom}}$$

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**

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

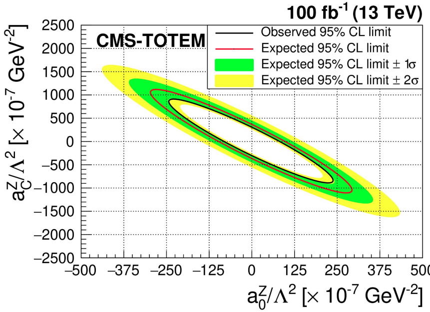


Limits on the fiducial cross section:

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

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

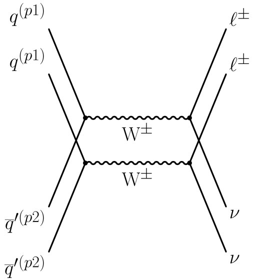
$\sigma_{pZZp} < 43(62^{+33}_{-20})$ fb



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   Submitted to JHEP

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



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

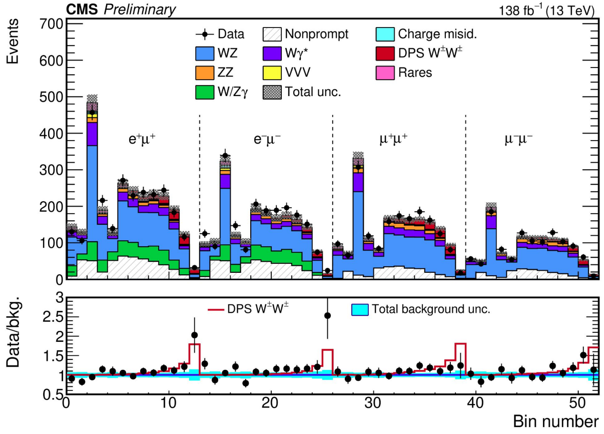
- Exploring **internal structure** of **colliding protons** → information about **PDFs** (unlike SPS)
- Paramount goal: DPS as a bkg. (**contribution increasing with √s**)

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 bkg.s

Novel results on **DPS in single VB production** in backup. (Z+jets, SMP-20-009)

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.

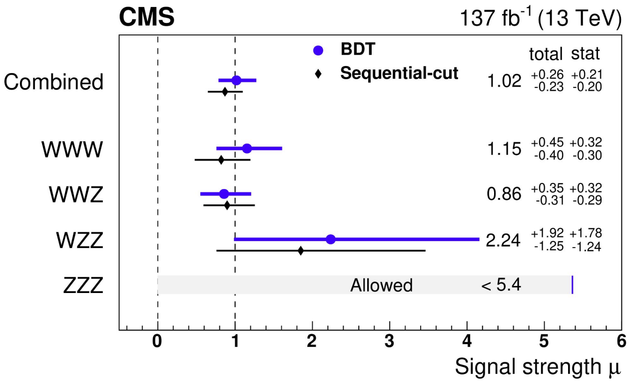
CMS – SMP – 21 – 013
Accepted by PRL

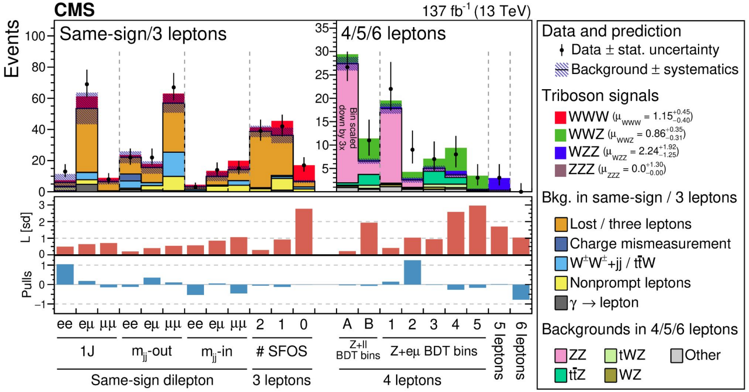
Tri-boson production

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





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

Simultaneous fit with 4 signal strengths:

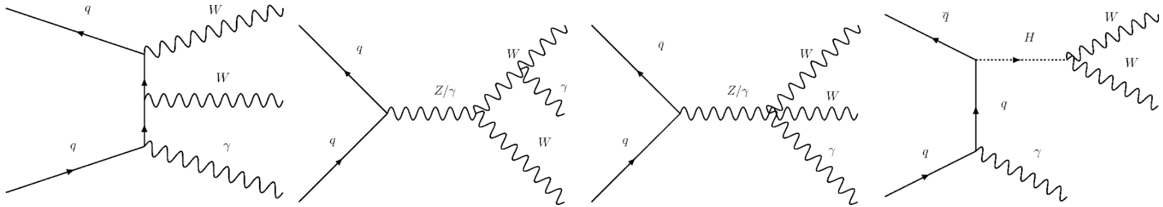
WWW	**3.3 (3.1) S.D.**
WWZ	**3.4 (4.1) S.D.**
WZZ	1.7 (0.7) S.D.
ZZZ	0.0 (0.9) S.D.

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

CMS – SMP – 19 – 014

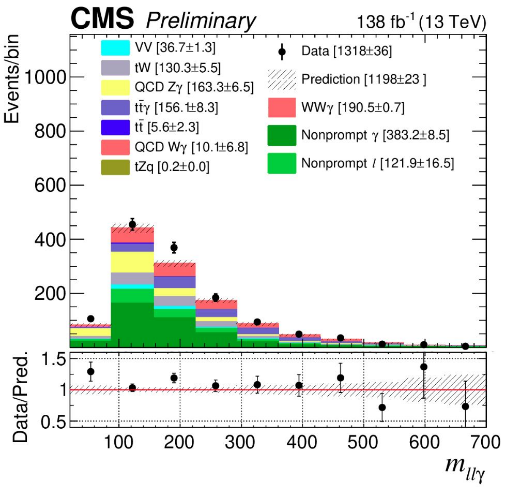
PRL 125 (2020) 151802

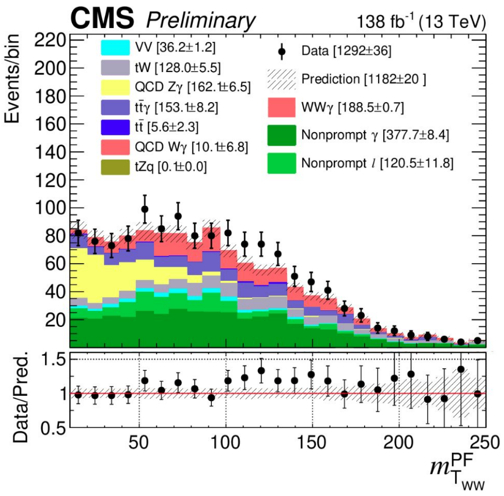
WWγ
Analysis strategy



- 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

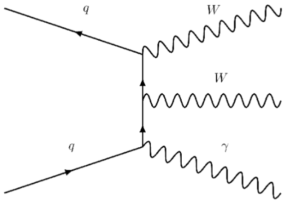


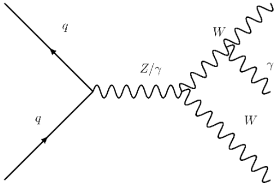


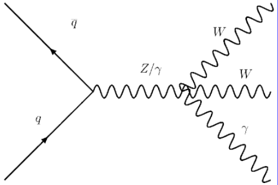
CMS – SMP – 22 – 006 (March 2023)

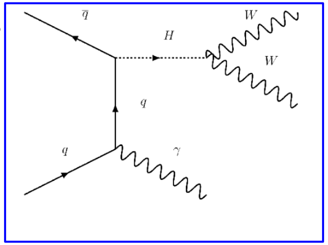
WWγ

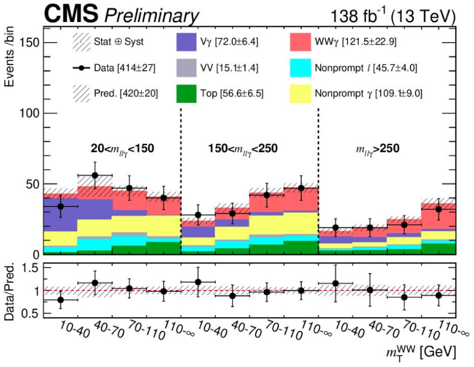
Results

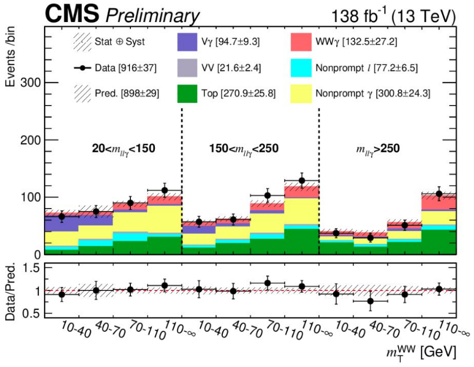












Extraction of limits on Higgs couplings with light quarks from $H\gamma \rightarrow WW\gamma$

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.

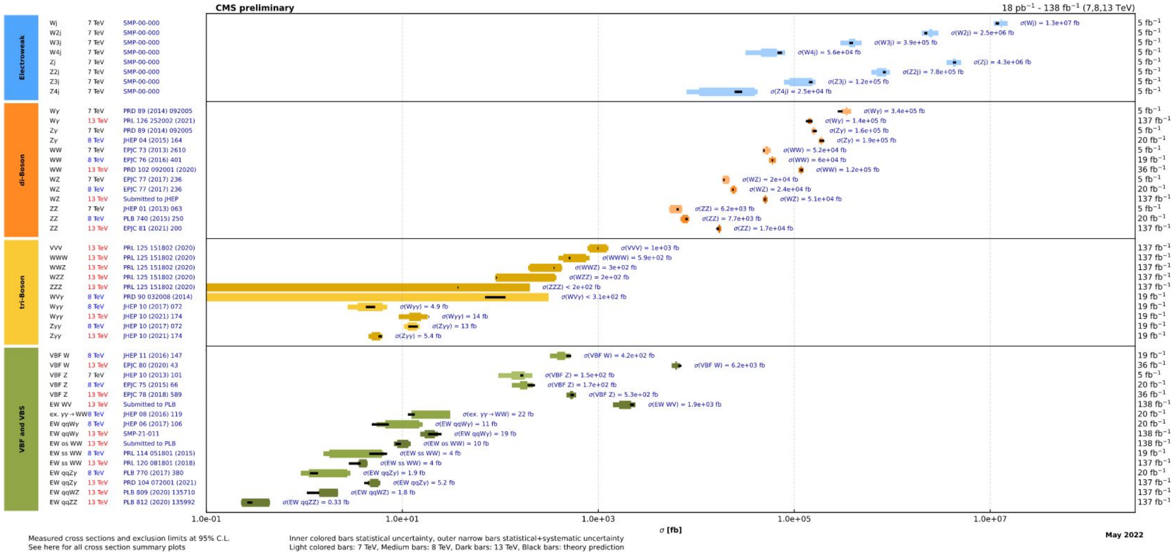
Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq$13000 (16000)
$d\bar{d} \rightarrow H + \gamma \rightarrow e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq$14000 (17000)
$s\bar{s} \rightarrow H + \gamma \rightarrow e\mu\gamma$	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 (March 2023)

Summary

The status report of electroweak vector boson(s) production at CMS was presented:

- Single & Di-boson: **precision era**
  - Reach **high precision** → NNLO
  - **Good agreement** with MC predictions



- Triboson:
  - Some processes already measured
  - Needs for higher sensitivity with future analyses

Stay tuned
for Run 3
and beyond!

Thank you for your attention!

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CMS Group – Turin University & INFN
cristiano.tarricone@cern.ch

CMS UNIVERSITÀ DI TORINO INFN SEZIONE DI TORINO

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Single vector boson production

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- The CMS Collaboration, "Search for the Z boson decay to $\tau^+\tau^-\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV", CMS-PAS-SMP-22-016, March 2023 — SMP – 22 – 016
- The CMS Collaboration, "Measurement of the production cross section of a W boson in association with a charm quark in proton-proton collisions at $\sqrt{s}$ = 13 TeV", CMS-PAS-SMP-21-005, July 2021 — SMP – 21 – 005
- The CMS Collaboration, "Measurement of Z+b jets cross section in proton-proton collisions at $\sqrt{s}$ = 13 TeV", PRD 105 (2022) 092014 — SMP – 20 – 015
- The CMS Collaboration, "Measurement of distributions sensitive to double parton scattering using Z bosons produced in association with jets at 13 TeV", JHEP 10 (2021) 176 — SMP – 20 – 009
- The CMS Collaboration, "Measurement of the differential Z+jets and γ+jets cross sections, their ratio, and collinear Z boson emission in pp collisions at $\sqrt{s}$ = 13 TeV", JHEP 05 (2021) 285 — SMP – 19 – 010

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- The CMS Collaboration, "First observation of the electroweak production of a leptonically decaying W^+W^- pair in association with two jets in √s = 13 TeV pp collisions", Accepted by PLB — SMP – 21 – 001
- The CMS Collaboration, "Evidence for vector boson scattering in events with four leptons and two jets in proton-proton collisions at √s = 13 TeV", PLB 812 (2020) 135992 — SMP – 20 – 001
- The CMS Collaboration, "Evidence for WW/WZ vector boson scattering in the decay channel $\ell\nu qq$ produced in association with two jets in proton-proton collisions at √s = 13 TeV", PLB 834 (2022) 137438 — SMP – 20 – 013
- The CMS Collaboration, "Measurement of electroweak production of $W\gamma$ with two jets in proton-proton collisions at √s = 13 TeV", Accepted by PRD — SMP – 21 – 011
- The CMS Collaboration, "Observation of WW from double-parton scattering in proton-proton collisions at √s = 13 TeV", Accepted by PRL — SMP – 21 – 013
- The CMS Collaboration, "Search for exclusive $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ production in final states with jets and forward protons", Submitted to JHEP — SMP – 21 – 014

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- The CMS Collaboration, “Observation of heavy triboson production in leptonic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”, PRL 125 (2020) 151802 — SMP – 19 – 014
- The CMS Collaboration, “Measurements of the pp→$W^{\pm}\gamma\gamma$ and pp→$Z\gamma\gamma$ cross sections and limits on anomalous quartic gauge couplings at $\sqrt{s} = 13$ TeV”, JHEP 10 (2021) 174 — SMP – 19 – 013
- The CMS Collaboration, “Observation of $WW\gamma$ production and constraints on Higgs couplings to light quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV”, CMS-PAS-SMP-22-006, March 2023 — SMP – 22 – 006

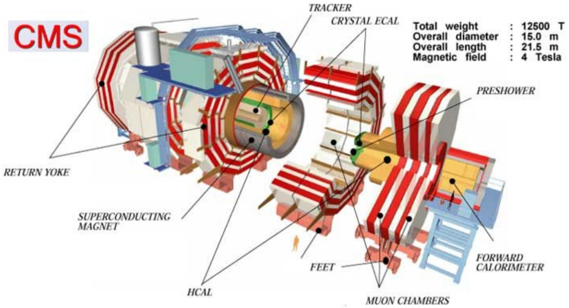
OTHER CONTENTS

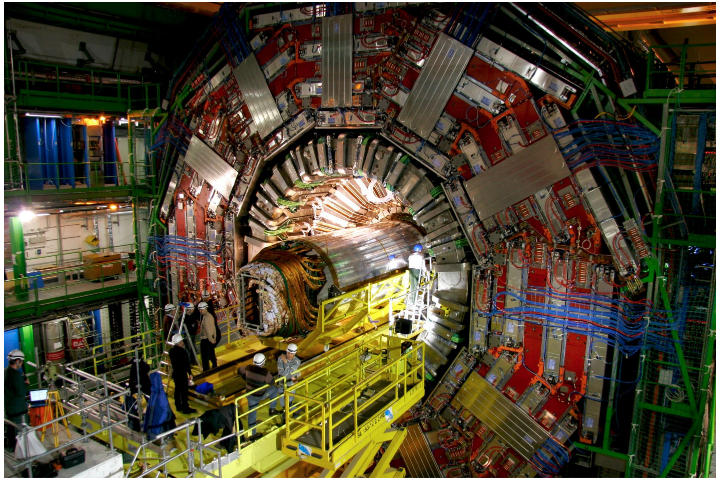
Introduction

- The production of **Vector Boson(s)** in proton-proton collisions is a valuable **precision test** of the **Standard Model (SM)**.

- The **high center-of-mass energy** of the LHC colliding protons and the **large amount of data** collected provides an extraordinary opportunity to constrain **Vector Boson(s) production** processes in **extreme region** of the phase space never accessible before.

- The **Compact Muon Solenoid (CMS)** allows accessing the proper physics scenario





Single Vector Boson production

- Z/γ + jets
- W+ c-jets
- Z+ b-jets
- $Z \to \tau\tau\mu\mu$
- $Z \to \tau\tau$
- Z + jet(s) (DPS)

Single vector boson production

- Measurement of the **cross section** of **single vector boson** production processes:
    - production of **neutral vector bosons (Z/γ)** associated with generic **jet(s)**
        - valuable **precision tests** of the SM
        - **relevant bkg**. for many **BSM** searches (DM, SUSY, invisible Higgs etc.)
    - production of **heavy vector bosons (W/Z)** associated with **b-/c-jet(s)**
        - information about **PDFs**
        - **dominant bkg.** for other **SM** analyses (e.g. ZH, $H \rightarrow$cc-bar/bb-bar)
    - production of a vector boson associated with jet(s) involving **double parton scattering (DPS)**
        - allows **precision tests** of **initial** and **final state radiation (ISR, FSR)** and **multi-parton interaction (MPI)**

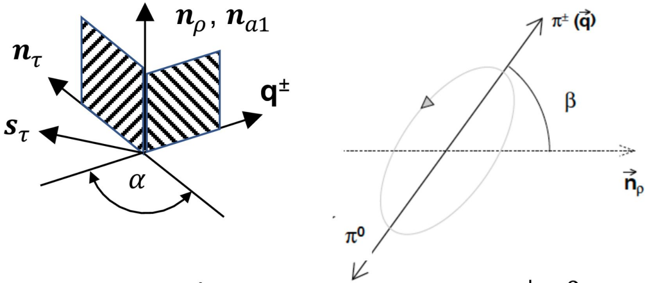
- Measurements of **branching fractions** targeting **precision tests** of the rarest vector boson decays

$Z \rightarrow \tau\tau$

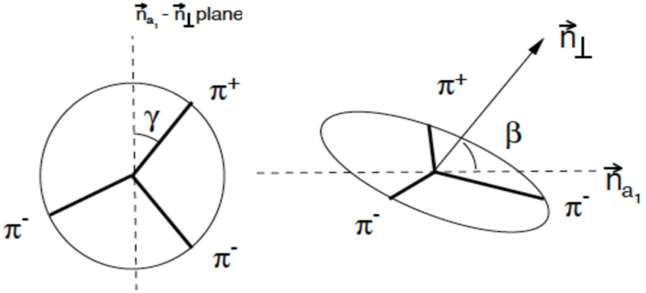
τ leptons decay rapidly inside the detector

→ polarization measured by analyzing the **energy** and **angular distributions** of the τ lepton decay products.

- α: between planes spanned by vectors ($\mathbf{n}_{a1/\rho}$, $\mathbf{n}_{\tau}$) and ($\mathbf{n}_{a1/\rho}$, $\mathbf{n}_{\pi}$)
- β: direction of $\pi^{\pm}$ wrt ρ rest frame and ρ direction
  or normal to the plane w/$3\pi^{\pm}$ (from a_1 decaying) and a_1 flight direction
- γ: relative π orientation in their decay plane



a: $\alpha(\tau \rightarrow \rho, a_1)$ b: $\beta(\rho \rightarrow \pi^{\pm}\pi^{0})$



c: $\gamma(a_1 \rightarrow \pi^+\pi^-\pi^0)$ d: $\beta(a_1 \rightarrow \pi^+\pi^-\pi^0$

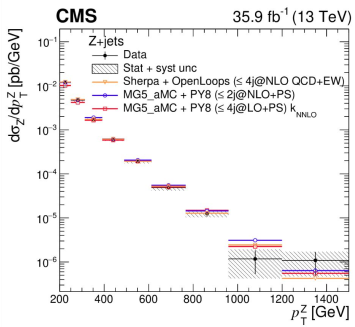
CMS – SMP – 18 – 010

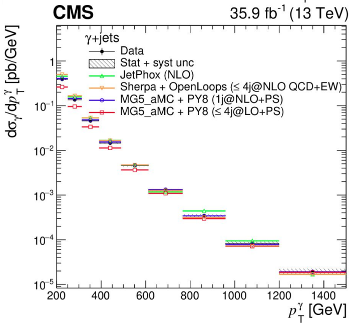
Z/γ + jets

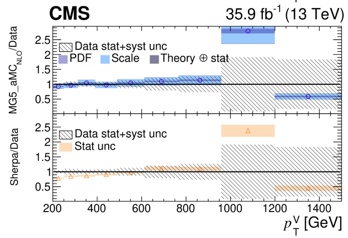
- Measurements of **Z/γ+(≥1)jets** processes ($Z \to \mu\mu$) precise tests for **p-QCD** and electroweak calculations

- **Differential cross sections** measured as a function of p_T^V → compared to different theory predictions.

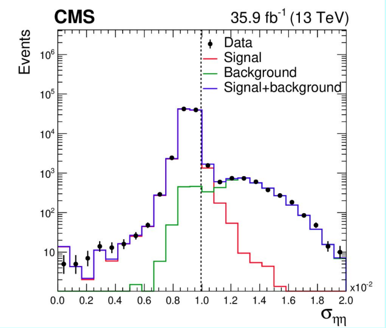
- **Differential cross section ratio** of Z+jets to γ+jets evaluated

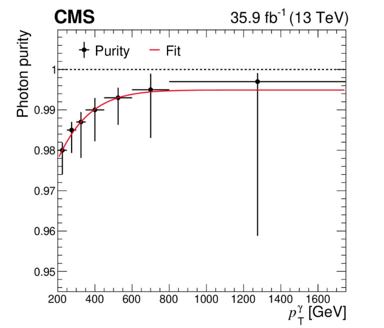






For the prompt-γ selection → $\sigma_{\eta\eta}$ measuring the extent of the shower along the ECAL crystal w/i a 5x5 array



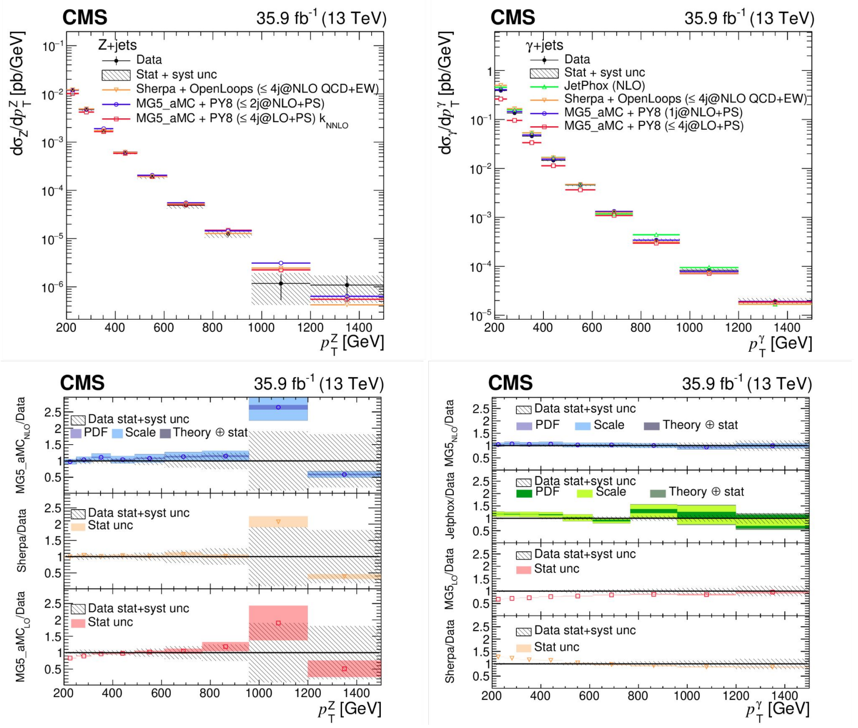


Overall, significant deviations are observed at LO → disappearing with more precise NLO predictions.

CMS – SMP – 19 – 010

Z/γ + jets

- Cross section measurements of Z/γ +jets processes ($Z\rightarrow\mu\mu$) precise tests for p-QCD and electroweak calculations
- Comparisons between unfolded data and several theory predictions.
- Differential cross sections measured as a function of $p_T^{\,V}$
- Study of the separation of the Z boson to the closest jet
- Overall, significant deviations are observed at LO → disappearing with more precise NLO predictions.



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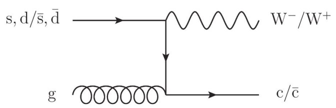
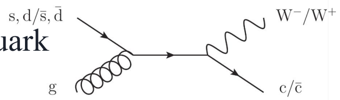
W+c-jet

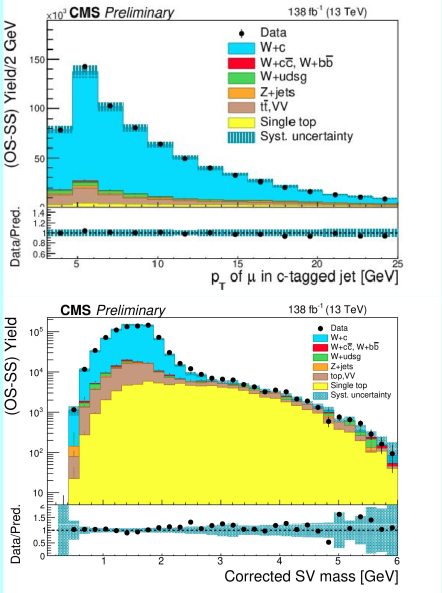


W+c-jet → sensitive to strange-quark content of colliding protons



Remarkable improvement of heavy-flavour Jet-ID thanks to the 2017 Pixel tracking detector upgrade

W and c are opposite-sign charge
→ ***OS-SS*** method enables bkg. suppression



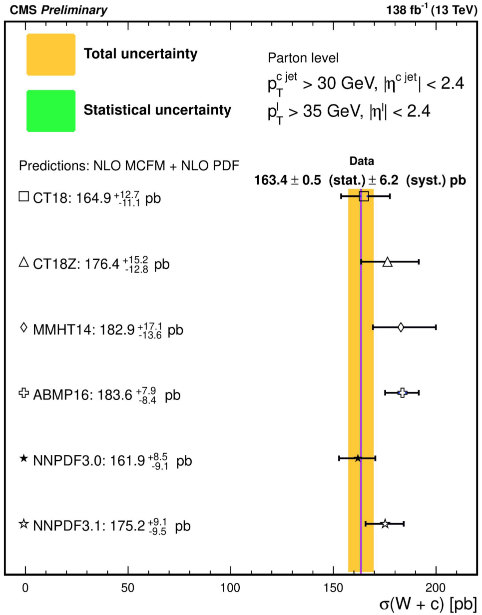
Strategy 2 channels:
- Semileptonic (**SL**)
- Secondary Vertex (**SV**)

Yield after kin. selection

$$\sigma(W+c) = \frac{Y_{sel.}(1-f_{bkg.})}{\mathcal{CL}}$$

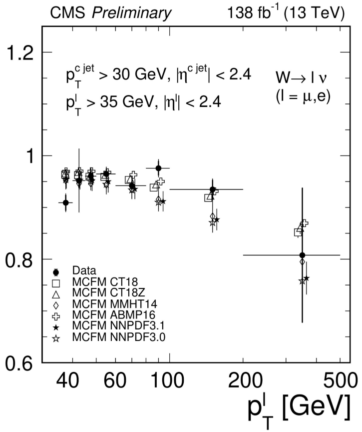
Bkg. fraction after OS-SS

Correction factor for eff. loss n the selection



$$R_c^{\pm} = \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)} = \frac{Y^+_{sel.}(1-f^+_{bkg.})}{Y^-_{sel.}(1-f^-_{bkg.})}$$

$R_c^{\pm}$ used to
- Constrain $R_s = \frac{s+\bar{s}}{u+\bar{d}}$
- Probe the asymm. $s/\bar{s}$



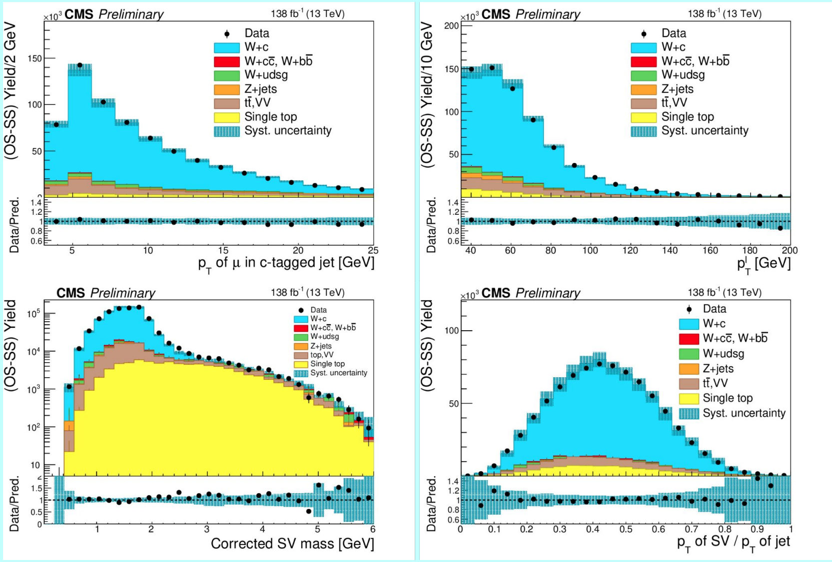
Novel results on Z+b-jet(s) channel (SMP-20-015) in backup.

CMS – SMP – 21 – 005

W+c-jet

Strategy 2 channels:
-Semileptonic (**SL**)
-Secondary Vertex (**SV**)

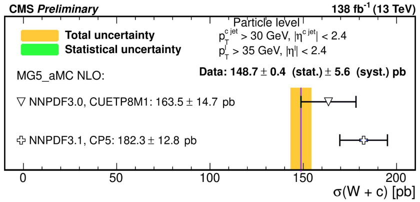
W and c are opposite-sign charge → ***OS-SS*** method enables bkg. suppression

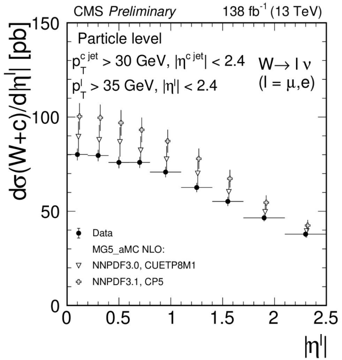


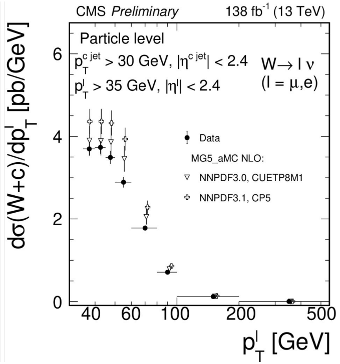
W+c-jets

CMS – SMP – 21 – 005

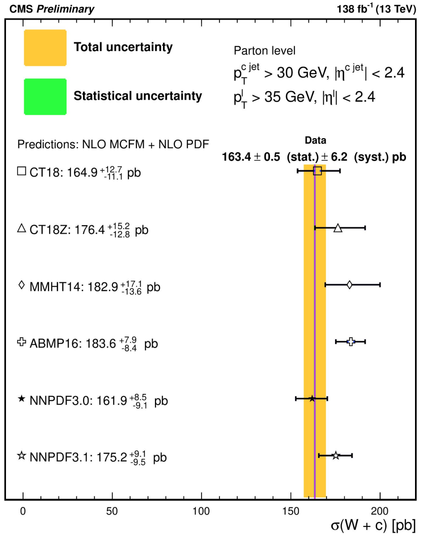
$$\sigma(W+c) = \frac{Y_{sel.}(1-f_{bkg.})}{\mathcal{CL}}$$

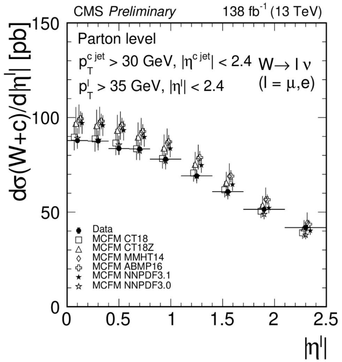


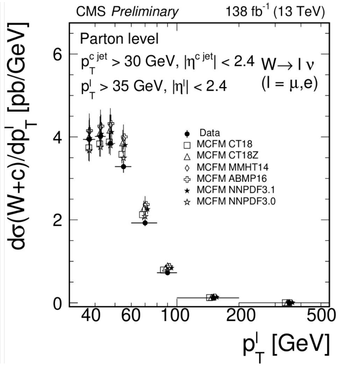




Channel	$Y_{\rm sel}(1-f_{\rm bkg})$	$\mathcal{C}(\%)$	$\sigma(W{+}c)$ [pb]
$W \to e\nu$, SL	341 316 ± 1294	1.568 ± 0.028 ± 0.073	158.7 ± 0.6 ± 8.3
$W \to \mu\nu$, SL	194 299 ± 934	0.946 ± 0.021 ± 0.037	149.8 ± 0.7 ± 8.0
$W \to e\nu$, SV	276 167 ± 1717	1.389 ± 0.026 ± 0.071	145.0 ± 0.9 ± 8.0
$W \to \mu\nu$, SV	397 555 ± 1876	1.966 ± 0.030 ± 0.087	147.4 ± 0.7 ± 7.3







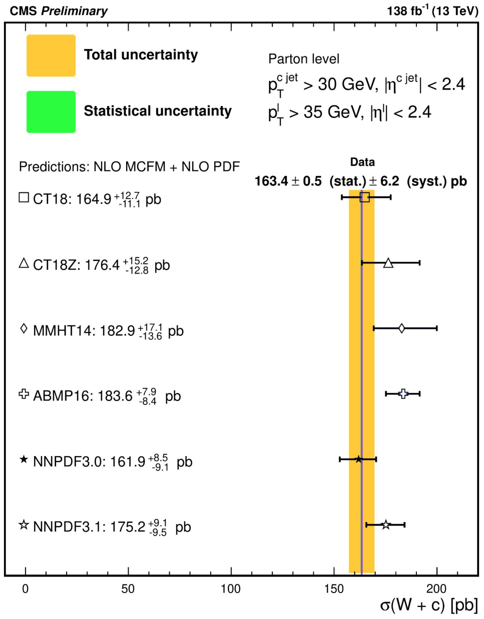
Channel	$N_{\rm sel}(1-f_{\rm bkg})$	$\mathcal{C}(\%)$	$\sigma(W{+}c)$ [pb]
$W \to e\nu$, SL	341 316 ± 1294	1.419 ± 0.025 ± 0.066	175.3 ± 0.7 ± 9.1
$W \to \mu\nu$, SL	194 299 ± 934	0.856 ± 0.019 ± 0.033	165.4 ± 0.8 ± 8.8
$W \to e\nu$, SV	276 167 ± 1717	1.261 ± 0.024 ± 0.062	159.6 ± 1.0 ± 8.6
$W \to \mu\nu$, SV	397 555 ± 1876	1.786 ± 0.028 ± 0.081	162.3 ± 0.8 ± 8.2

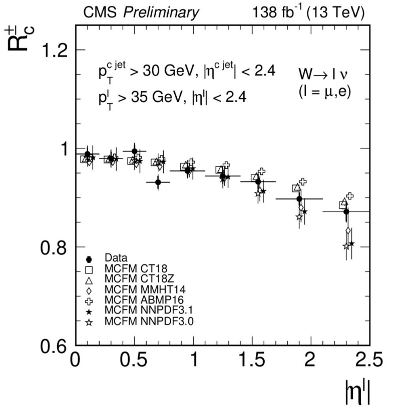
W+c-jets

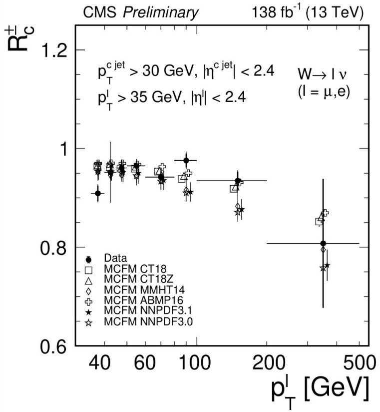
CMS – SMP – 21 – 005

$$R_c^{\pm} = \frac{\sigma(W^+ + \bar{c})}{\sigma(W^- + c)} = \frac{Y^+_{sel.}(1 - f^+_{bkg.})}{Y^-_{sel.}(1 - f^-_{bkg.})}$$

$R^{\pm}_c$ used to
- Constrain $R_s = \frac{s+\bar{s}}{u+\bar{d}}$
- Probe the asymm. $s/\bar{s}$

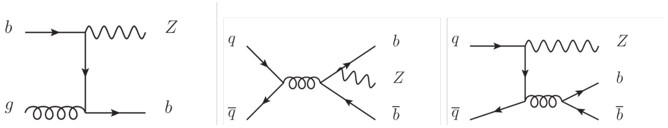






Channel	$R_c^{\pm}$
$W \to e\nu$, SL	$0.934 \pm 0.007 \pm 0.013$
$W \to \mu\nu$, SL	$0.940 \pm 0.009 \pm 0.015$
$W \to e\nu$, SV	$0.961 \pm 0.012 \pm 0.013$
$W \to \mu\nu$, SV	$0.974 \pm 0.009 \pm 0.015$

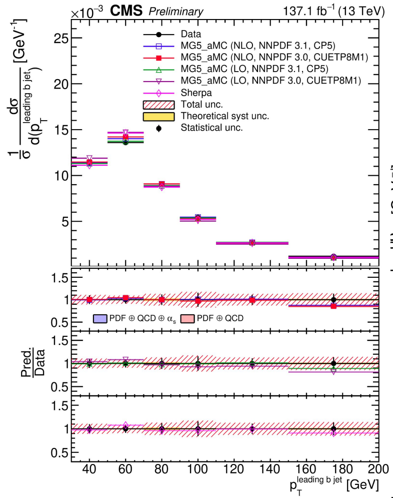
Z + b-jets

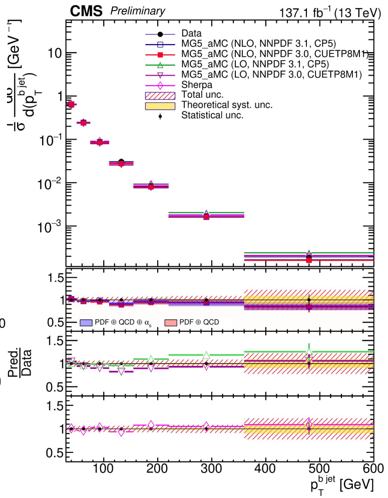


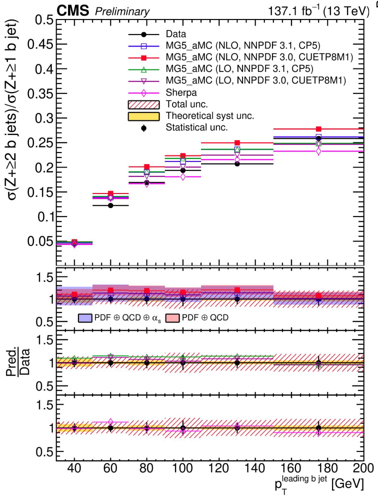
- Measurements of **Z+(≥1)b-jets** processes provide info on b-PDF → help estimation of unc. from **PDF choice** in the $\underline{m_W \text{ measurement}}$

- **Differential cross sections** measured as a function of six chosen kinematic variables

- **Differential cross section ratio** of Z+2b-jets to Z+1b-jet evaluated







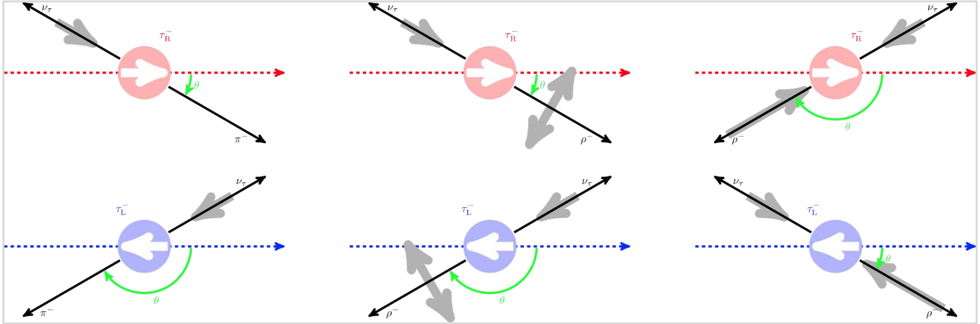
Differences of generators predictions LO vs. NLO on the normalized cross section are attributable to variations in shapes of observables and settings .

CMS – SMP – 20 – 015

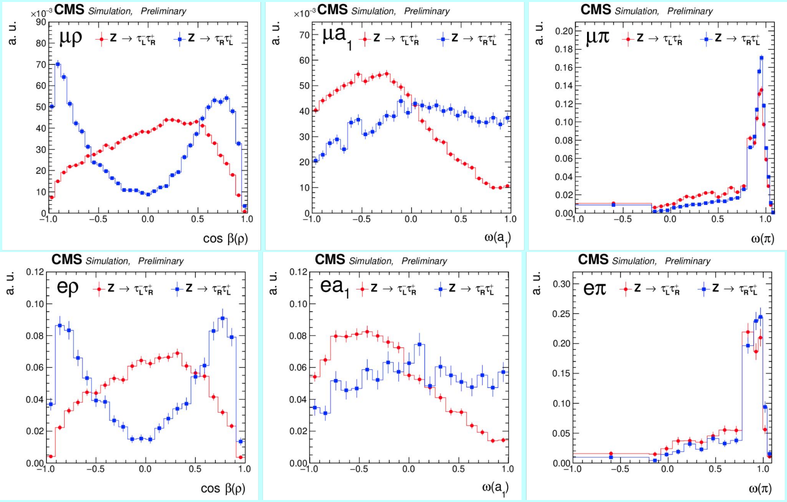
$Z \to \tau\tau$

$Z \to \tau^+\tau^-$: τ polarization measurement:

$$\mathcal{P}_\tau = \frac{\sigma_{h^+} - \sigma_{h^-}}{\sigma_{h^+} + \sigma_{h^-}}$$

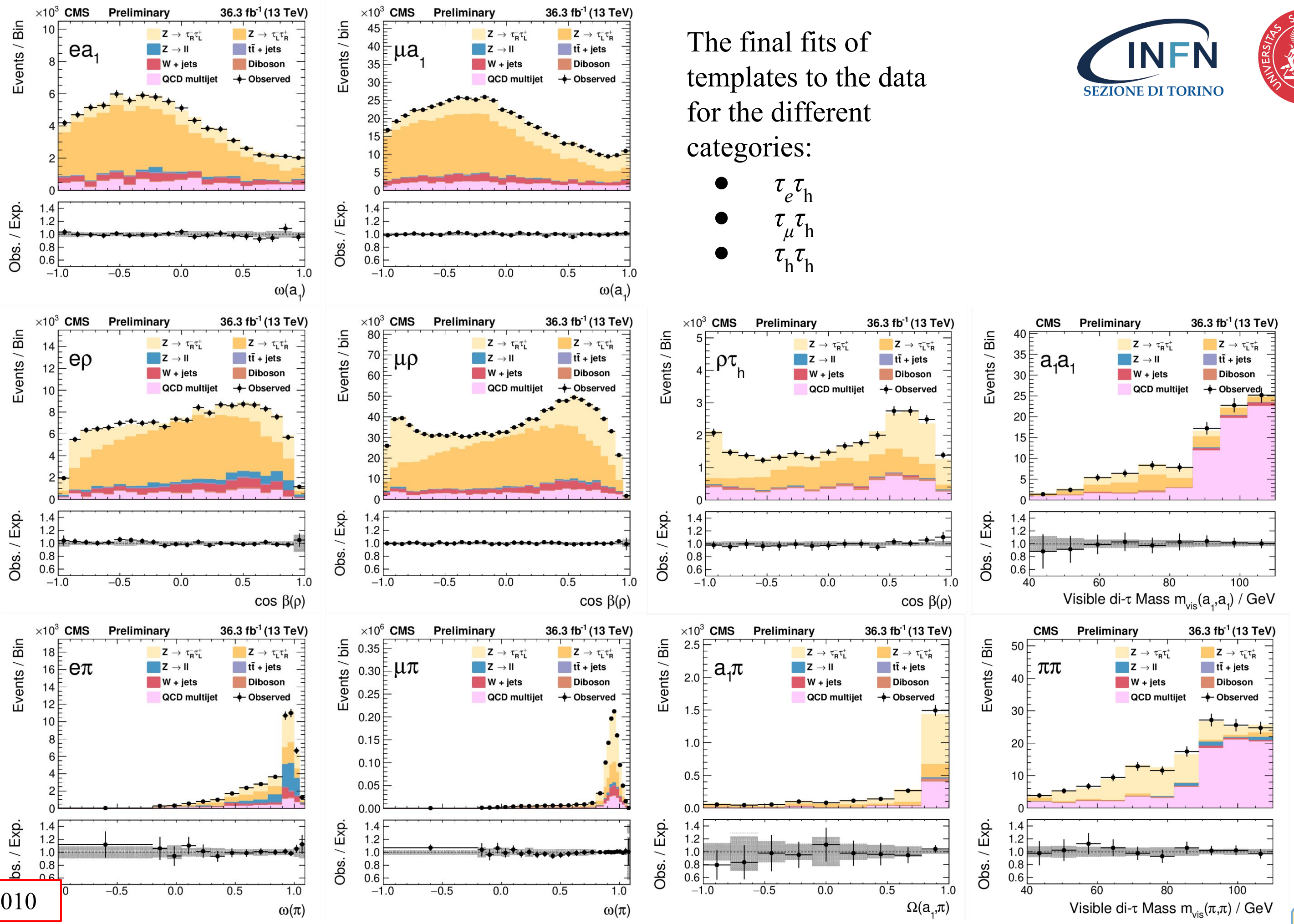


Representative templates for the channels μ+ρ, μ+a_1, μ+π and e+ρ, e+a_1, e+π.
Blue and red lines indicate right and left-handed τ leptons, respectively.
Error bars → statistical only



CMS – SMP – 18 – 010

$Z \rightarrow \tau\tau$

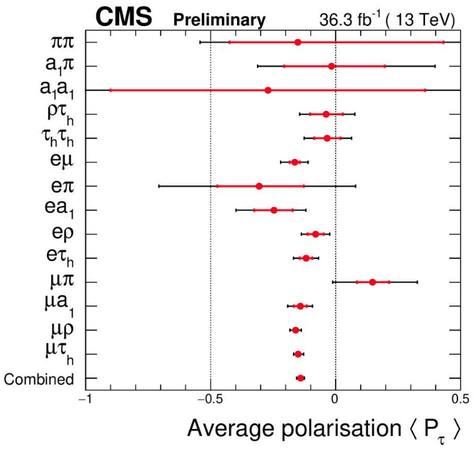


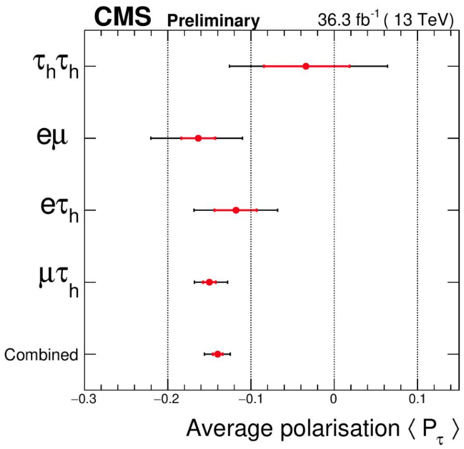
The final fits of templates to the data for the different categories:

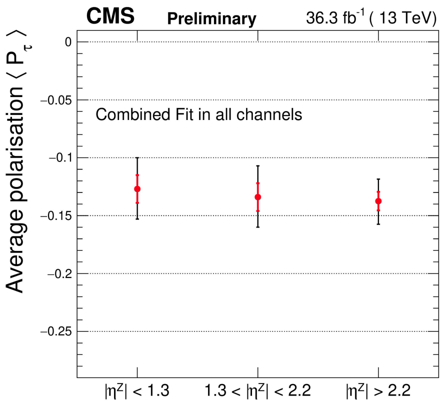
- $\tau_e \tau_h$
- $\tau_\mu \tau_h$
- $\tau_h \tau_h$

CMS – SMP – 18 – 010

$Z \rightarrow \tau\tau$
Results



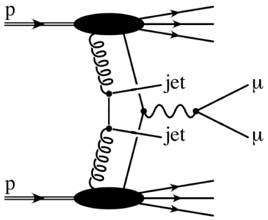


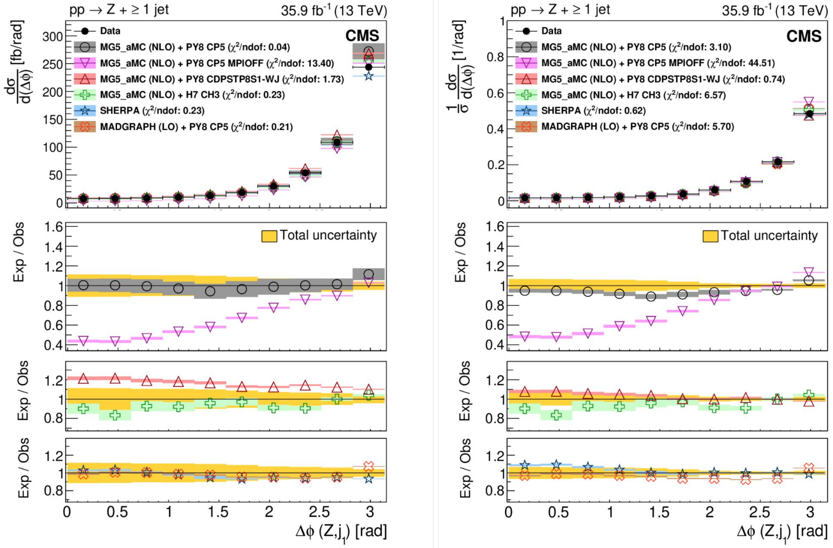


CMS – SMP – 18 – 010

DPS – Z+jet

Z boson production involving **double parton scattering (DPS) → precision tests** of **ISR, FSR**, and **MPI**

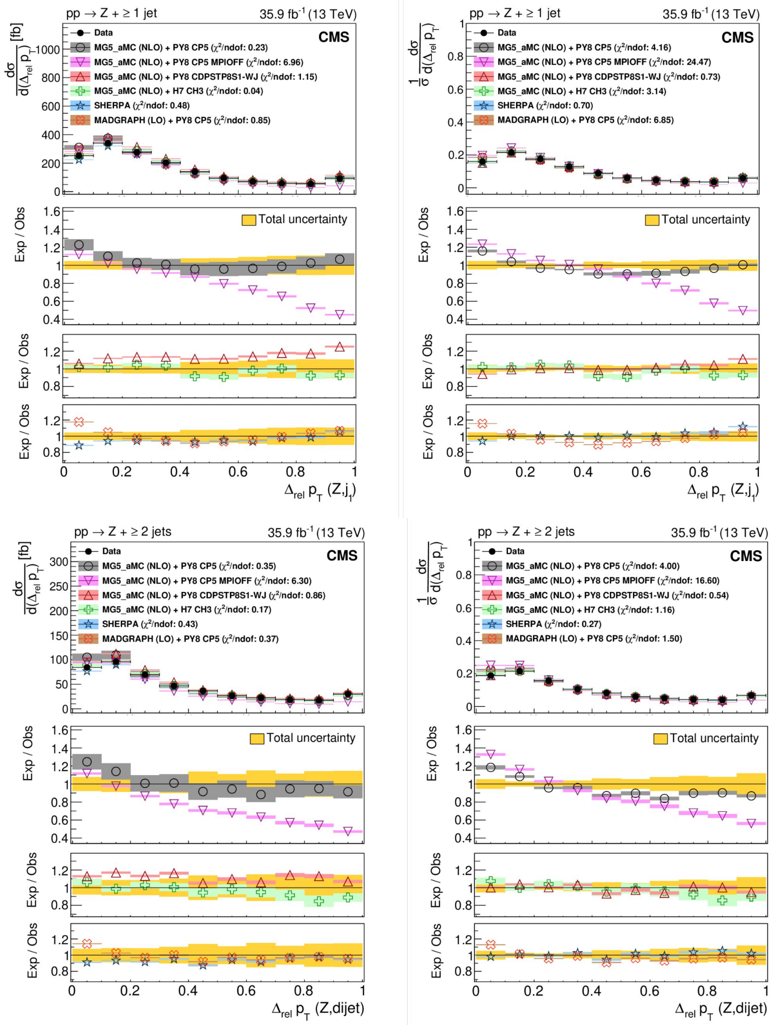




Cross section (pb)		Z+ ≥1 Jets	Z+ ≥2 Jets
Measured in data		158.5 ± 0.3 (stat)	44.8 ± 0.4 (sta
		±7.0 (syst)	±3.7 (syst)
		±1.2 (theo)	±0.5 (theo)
		±4.0 (lumi) pb	±1.1 (lumi) pl
Predicted by MC			
MG5_aMC (NLO)	PYTHIA8, CP5 tune	167.4 ± 9.7	47.0 ± 3.9
	PYTHIA8, CP5 tune MPIOFF	143.8 ± 0.3	37.7 ± 0.2
	PYTHIA8, CDPSTP8S1-WJ tune	178.4 ± 0.3	50.5 ± 0.2
	HERWIG7, CH3 tune	158.3 ± 1.1	44.4 ± 0.6
MG5_aMC (LO) + PYTHIA8, CP5 tune		161.2 ± 0.1	45.3 ± 0.1
SHERPA (NLO+LO)		149.8 ± 0.2	41.6 ± 0.1

CMS – SMP – 20 – 009

DPS – Z+jet



CMS – SMP – 20 – 009

Di-Boson production

• OS–WW (VBS)	**SMP – 21 – 001**
• ZZ (VBS)	**SMP – 20 – 001**
• Wγ	**SMP – 21 – 011**
• SS–WW (DPS)	**SMP – 21 – 013**
• $\gamma\gamma \rightarrow$ VV (CEP)	**SMP – 21 – 014**

Di-boson 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
  - **double parton scattering (DPS)**

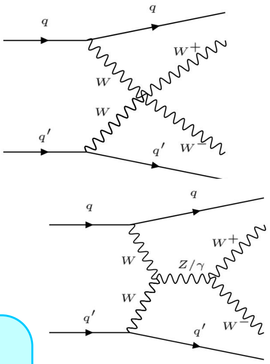
    - allows **precision tests** of **ISR**, **FSR**, and **MPI**
  - **central exclusive production (CEP)** processes e.g. $p\gamma\gamma p \rightarrow pVVp$

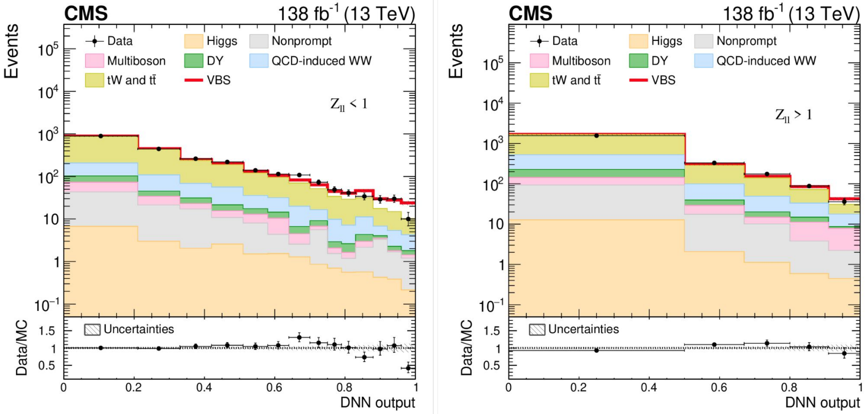
    - $\gamma\gamma \rightarrow VV$ VBS processes involved as well, including $\gamma\gamma VV$ QGCs

- 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^-

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





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**

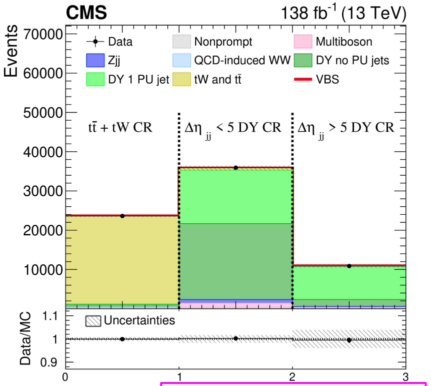
Analysis strategy:

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



Nb. of events in the diffrentent 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 $\Delta R(\ell, \gamma_i) < 0.1$ $p_T^{\ell_1} > 25\,\text{GeV}$, $p_T^{\ell_2} > 13\,\text{GeV}$, $p_T^{\ell_3} < 10\,\text{GeV}$ $\lvert\eta\rvert < 2.5$ $p_{T\ell\ell} > 30\,\text{GeV}$, $m_{\ell\ell} > 50\,\text{GeV}$
Jets	$p_T^j > 30\,\text{GeV}$ $\Delta R(j, \ell) > 0.4$ At least 2 jets, no b jets $\lvert\eta\rvert < 4.7$ $m_{jj} > 300\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$
MET	$p_T^{miss} > 20\,\text{GeV}$

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

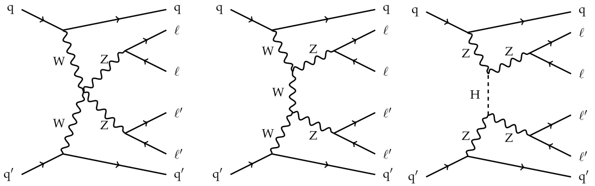
(9.1 ± 0.6 fb)

Significance observed (expected):

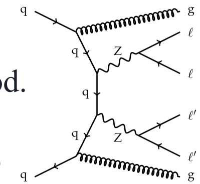
5.6 (5.2) S.D.

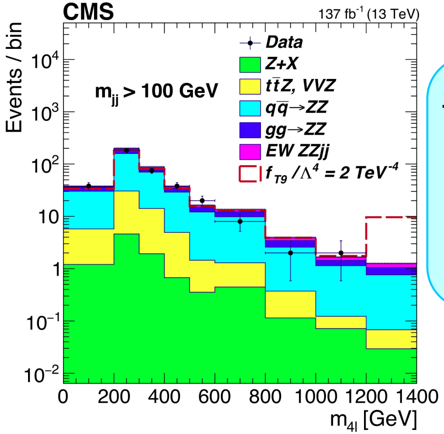
ZZ

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)



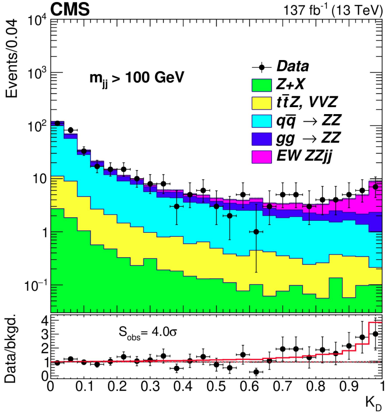


Constraining on aQGCs

→ **Dimension-8 EFT op.s**

→ **m_{ZZ}** used

→ **Maximum-likelihood fit profiling** the **syst. unc.**



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.

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

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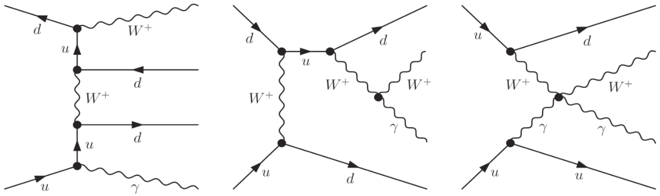
$W\gamma$
aQGC limits



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.**

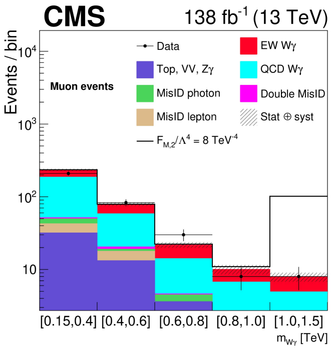
Improvement of constraints on aQGCs

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

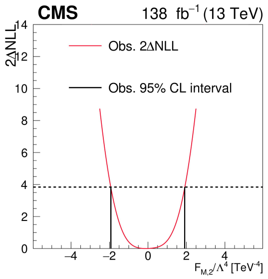
CMS – SMP – 21 – 011

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



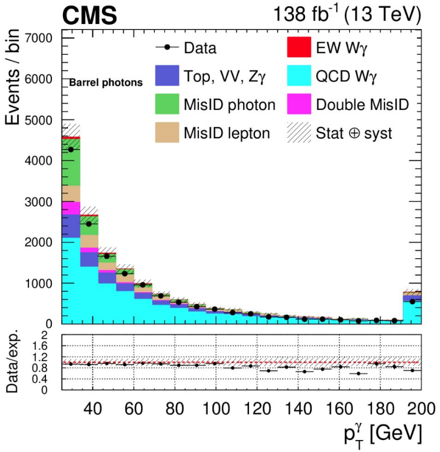
The $m_{W\gamma}$ distribution for muon events satisfying a selection used to set constraints on the aQGC parameters. The last bin includes overflow.

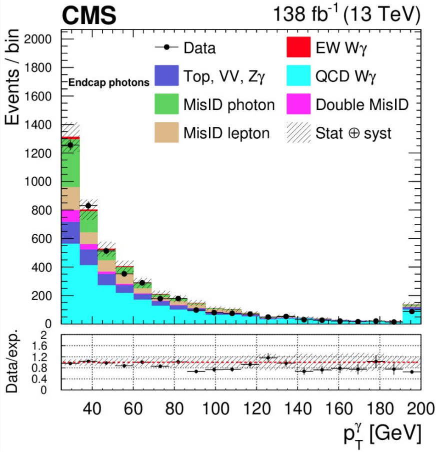
No statistically significant SM deviation is observed

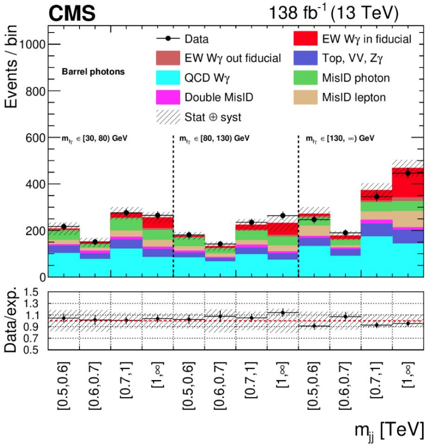


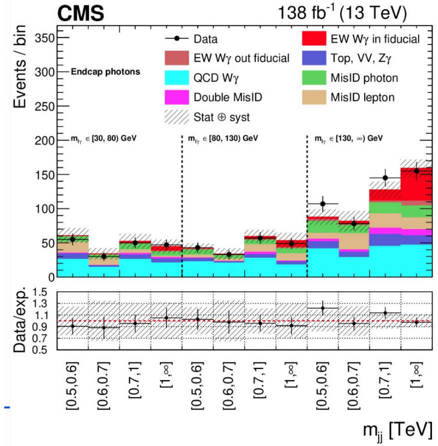
Wγ

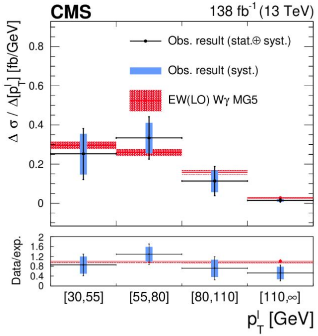
CMS – SMP – 21 – 011

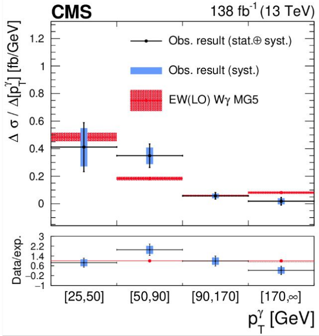


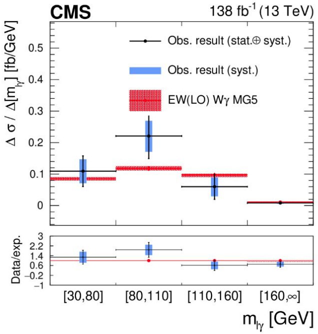


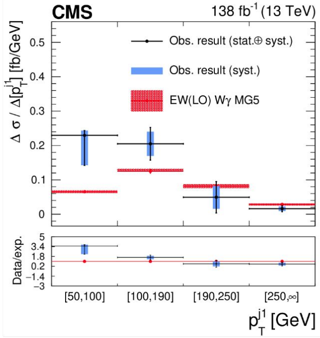


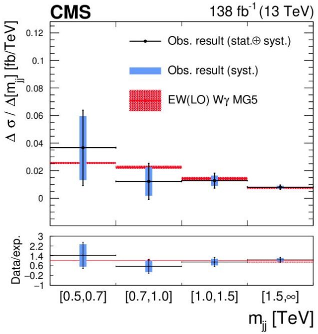


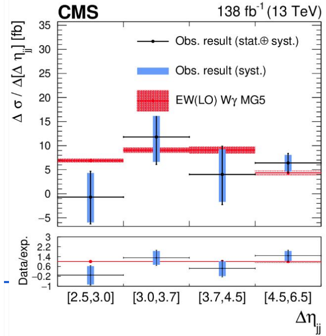




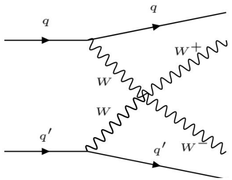


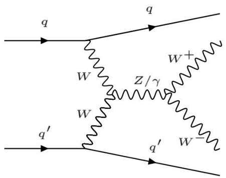






W^+W^-





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

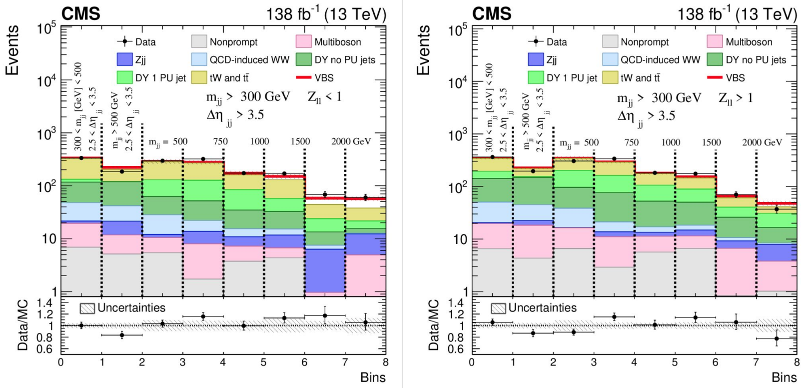
Analysis strategy:

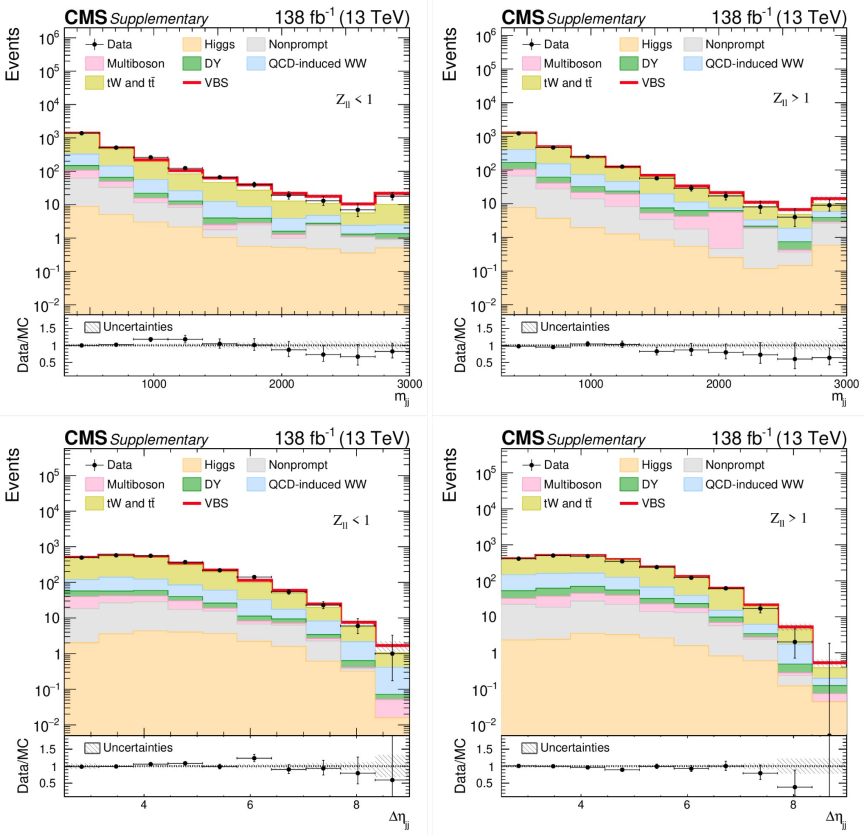
- ➔ **Signal region** splitted in **2 regions** basing on the centrality of the *ll* system wrt the tagging jets
- ➔ **Ttbar** control region (inverted b-veto)
- ➔ **Drell-Yan** control region

Zeppenfeld variable

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

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





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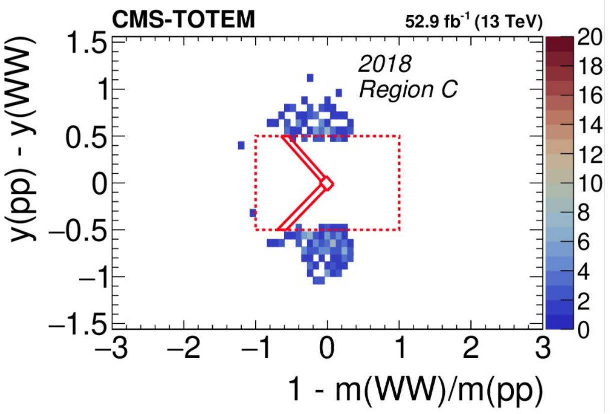
pVVp

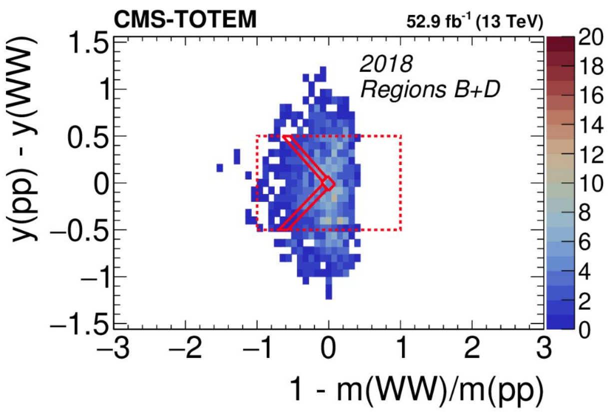
Important variables for this analysis:

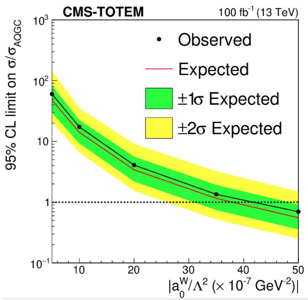
$\xi_i = \frac{\Delta p_i}{p_p}$ $M_{ij}\sqrt{s\xi_i\xi_j}$ $y_{ij} = \frac{1}{2}\log\frac{\xi_i}{\xi_j}$

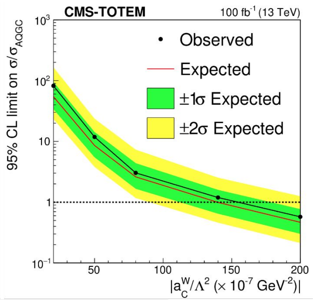
Main bkg.: **diffractive PU**
→ data-driven method

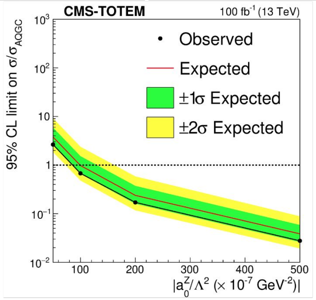
Defined CRs reverting the requirement on **acoplanarity**











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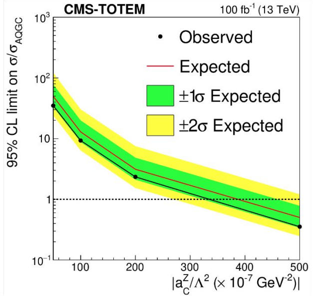

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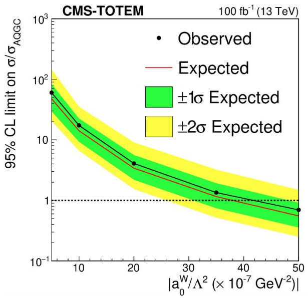
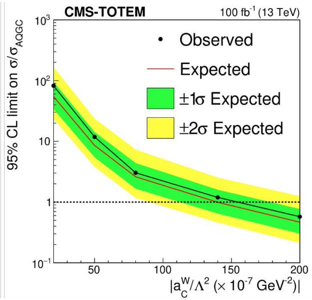
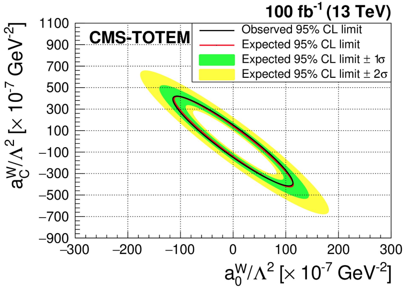
pVVp







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

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

CMS – SMP – 21 – 014   Submitted to JHEP

Tri-Boson production

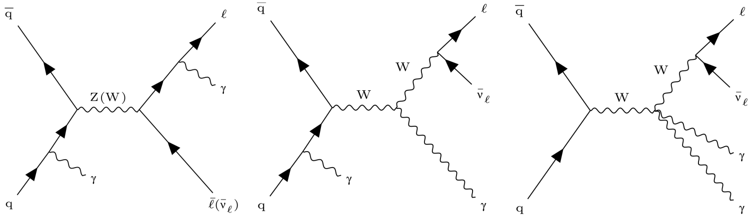
- Vγγ
- WWγ
- VVV

Tri-boson production

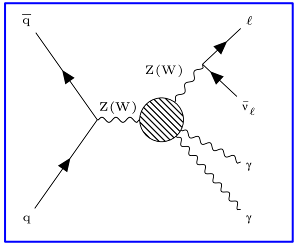
- Measurement of the **cross section** of **tri-boson** production processes
    - valuable **precision tests** for the electroweak sector of the SM
    - **novel observation** of **very rare** processes
    - **TGCs** and **QGCs** involved

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

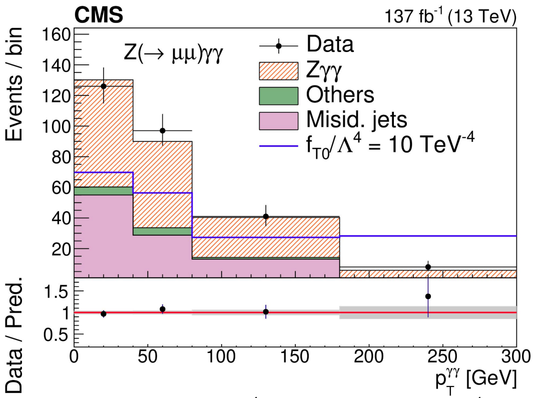
Vγγ



- 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

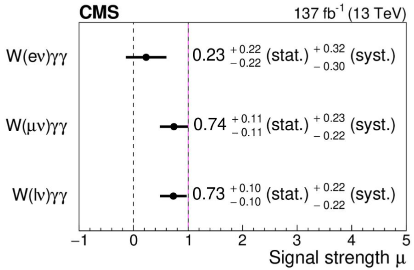


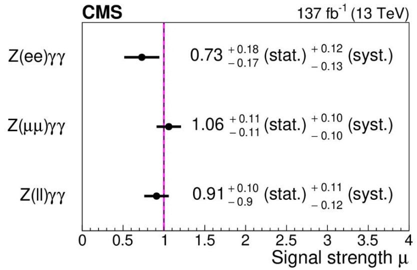
Parameter	Wγγ (TeV^{-4}) Expected	Wγγ (TeV^{-4}) Observed	Zγγ (TeV^{-4}) Expected	Zγγ (TeV^{-4}) Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86,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

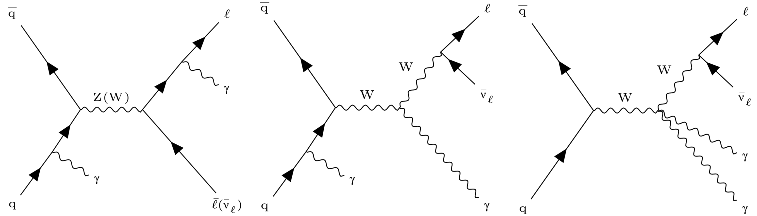
$\sigma_{Z\gamma\gamma} = 5.41^{+0.58}_{-0.55}(\text{stat.})^{+0.64}_{-0.70}(\text{syst.}) \pm 0.06\ (\text{PDF+scale})$ — 4.8 S.D



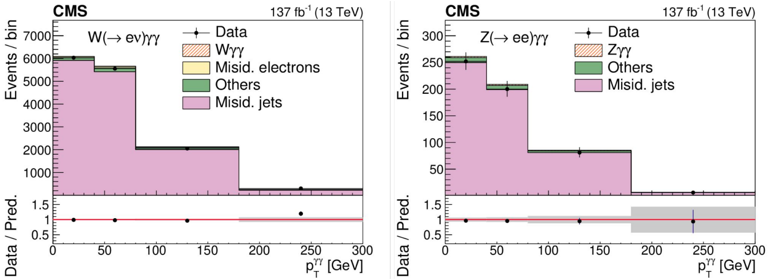


CMS – SMP – 19 – 013 JHEP 10 (2021) 174

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



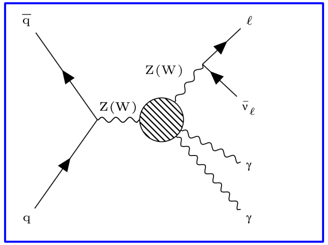
Process	$e\nu_e\gamma\gamma$	$\mu\nu_\mu\gamma\gamma$
Misid. jets	918 ± 23 (stat) ± 180 (syst)	1441 ± 27 (stat) ± 280 (syst)
Misid. electrons	669 ± 28 (stat) ± 34 (syst)	107 ± 9 (stat) ± 7 (syst)
Others	217 ± 11 (stat) ± 20 (syst)	286 ± 11 (stat) ± 25 (syst)
Total backgrounds	1804 ± 38 (stat) ± 180 (syst)	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

CMS – SMP – 19 – 013

Vγγ

Results: SM & aQGCs

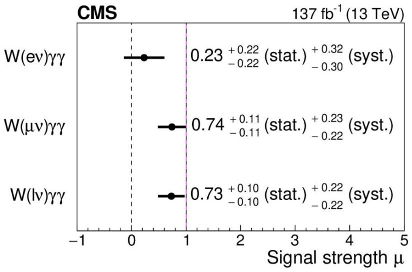


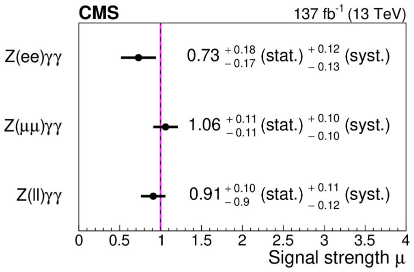
Example of BSM diagram affected by aQGC

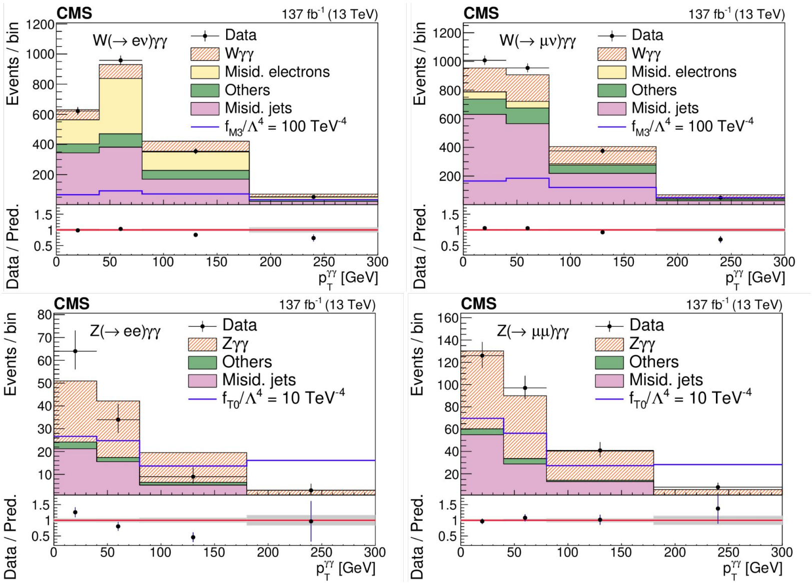
Measured cross section:

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





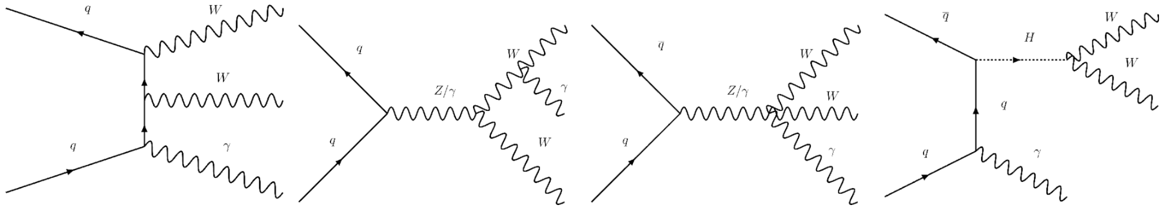


Parameter	$W\gamma\gamma$ (TeV^{-4}) Expected	Observed	$Z\gamma\gamma$ (TeV^{-4}) Expected	Observed
f_{M2}/Λ^4	[−57.3, 57.1]	[−39.9, 39.5]	—	—
f_{M3}/Λ^4	[−91.8, 92.6]	[−63.8, 65.0]	—	—
f_{T0}/Λ^4	[−1.86, 1.86]	[−1.30, 1.30]	[−4.86, 4.66]	[−5.70, 5.46]
f_{T1}/Λ^4	[−2.38, 2.38]	[−1.70, 1.66]	[−4.86, 4.66]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

CMS – SMP – 19 – 013

WWγ

Analysis strategy

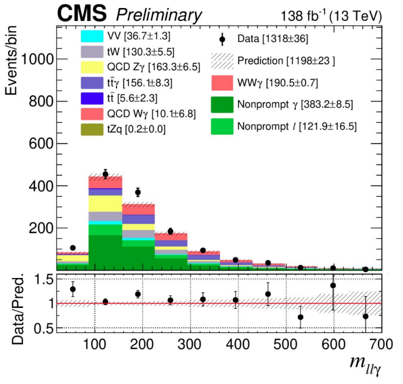


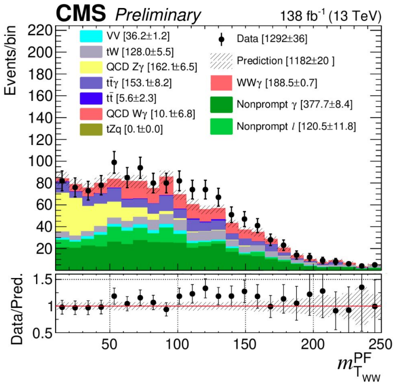
- Measurement of WWγ with fully leptonic final state sensitive to:
  - TGCs, QGCs
  - Higgs-gauge couplings
  - Higgs-light quarks couplings

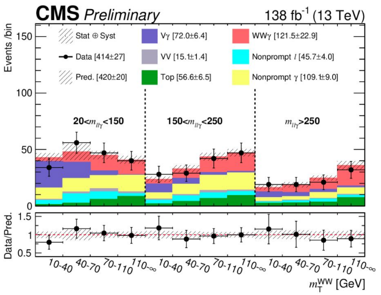
- Data-driven method for estimating bkg. processes containing a prompt lepton/photon
  - Zγ
  - ttbar+γ
  - single-top

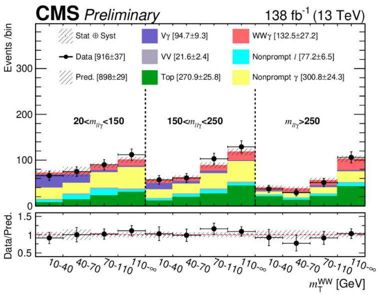
- Control Regions to validate the bkg. estimations:
  - SSWWγ
  - Top γ

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





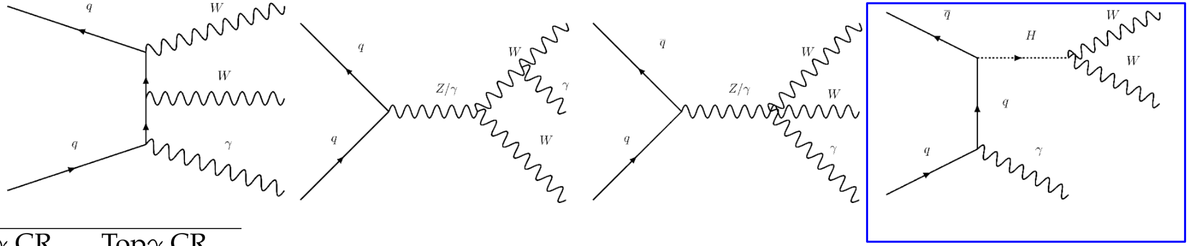




CMS – SMP – 22 – 006

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$\gamma \rightarrow$ WWγ

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

Summary

- The most of the recent results achieved by the **CMS Collaboration** on **single Vector Boson**, **di-boson**, and **tri-boson** production processes were presented.

- The most recent **constraints** on **SM deviations** coming from **anomalous couplings** in multi-boson processes were also reported.