Universiteit Antwerpen

Vector Boson Scattering measurements at CMS

X. Janssen

Be.HEP Annual Meeting

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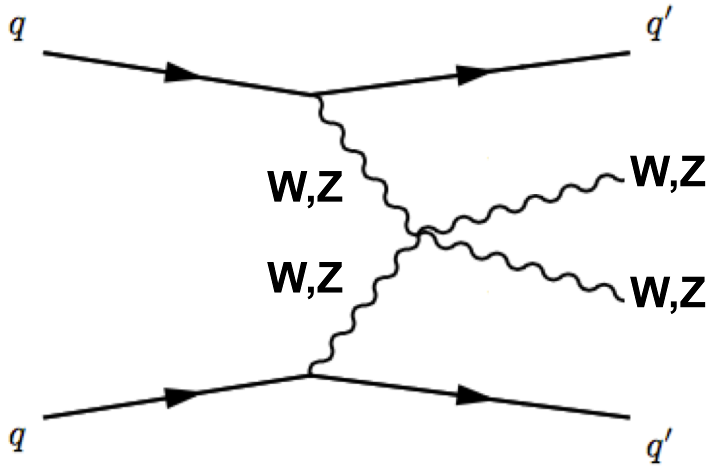
Vector Boson Scattering

Diboson production proceeding purely through EW interaction at tree level:



- ☐ **Precision measurement in the electroweak sector with sensitivity to the new physics**
  → EFT approach: Triple/Quartic Gauge Couplings

- ☐ **Test of the Higgs boson nature: $V_L V_L$ scattering unitarity relies on strong cancellations with Higgs diagrams**

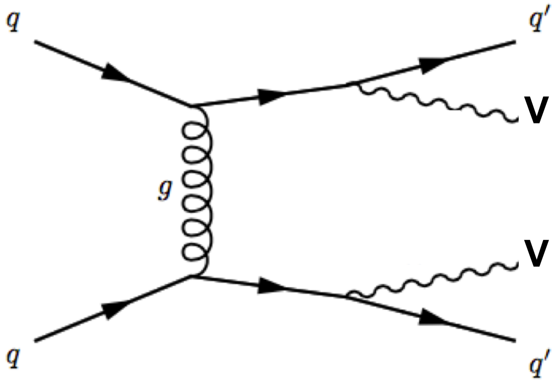
→ LHC Run-2 data @ $\sqrt{s}$ = 13 TeV allows to explore VBS with precision

VBS signature:

- ☐ **Two highly energetic (high p_T) forward jets**
  → High di-jet invariant mass: m_{jj}
  → Large pseudo-rapidity jet separation: $\Delta\eta_{jj}$

- ☐ **Central rapidity region void except VV decays**

QCD ($\alpha_s^2\ \alpha^2$) VV production threated mostly as background:



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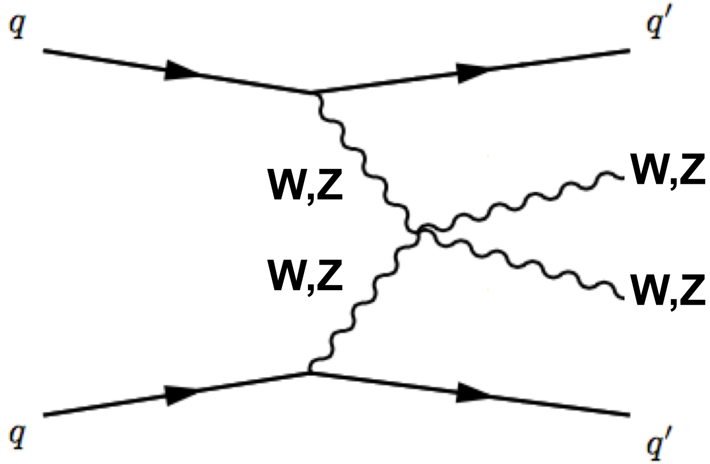
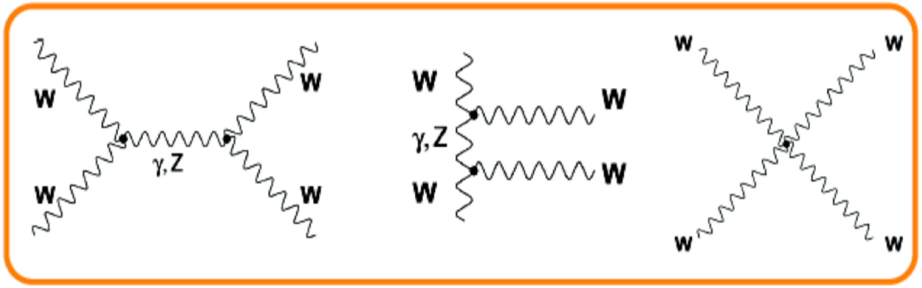
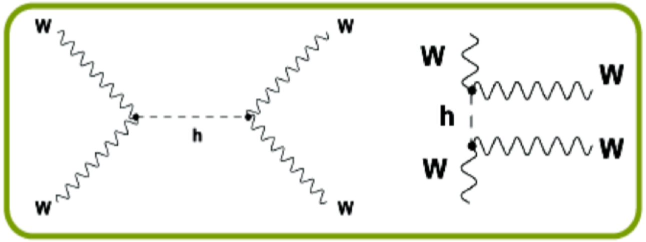


- **Precision measurement in the electroweak sector with sensitivity to the new physics**
  → EFT approach: Triple/Quartic Gauge Couplings
- **Test of the Higgs boson nature: $V_L V_L$ scattering unitarity relies on strong cancellations with Higgs diagrams**



S channel **T channel** **QGC**

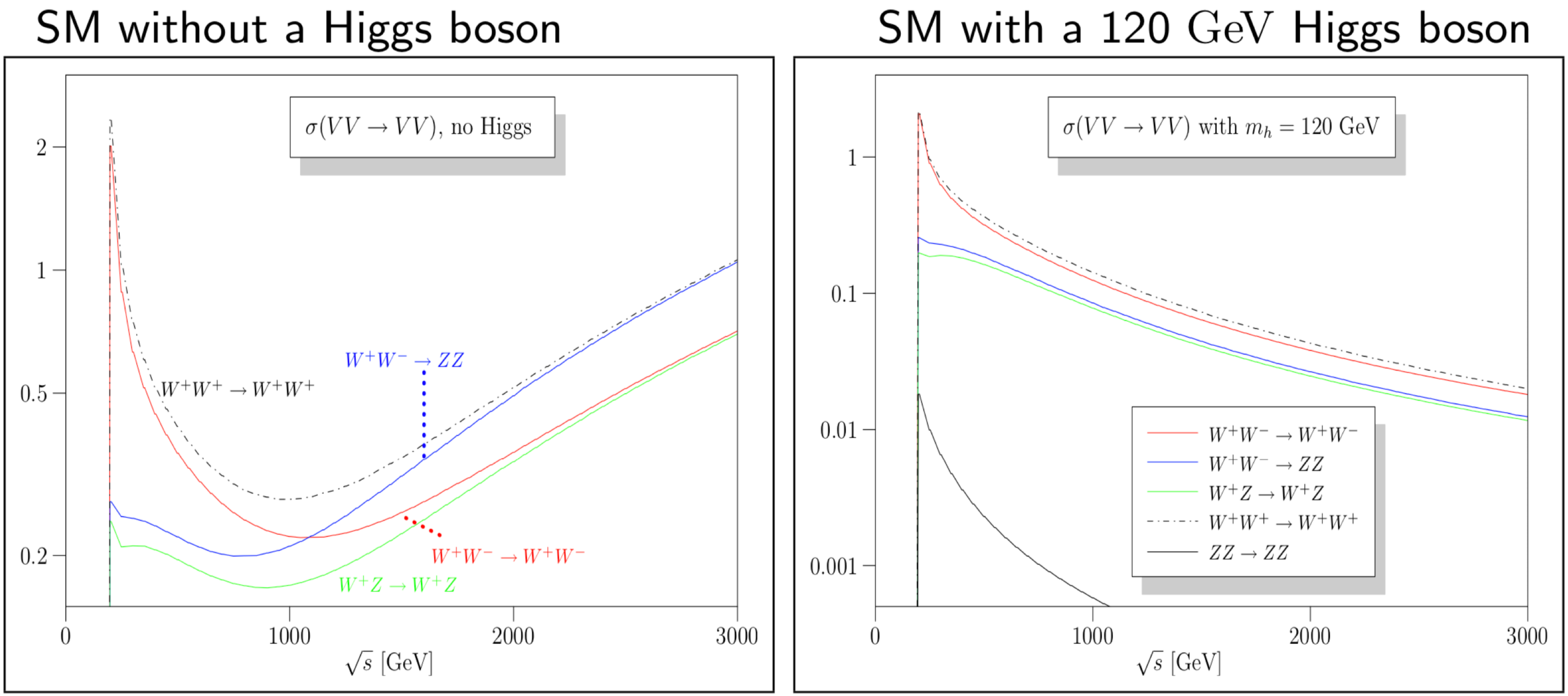


W, Z masses arrises in the EWSB mechanism from longitudinal d.o.f. of the BEH boson

$$\sigma_{V_L V_L \to V_L V_L} \propto \left[- s - t - \frac{s^2}{s - m_{\mathrm{H}}^2} - \frac{t^2}{t - m_{\mathrm{H}}^2} \right]$$

→ VBS at the LHC is the key process to experimentally probe the SM nature of EWSB complementary to direct Higgs measurements

Unitary Violation in VBS

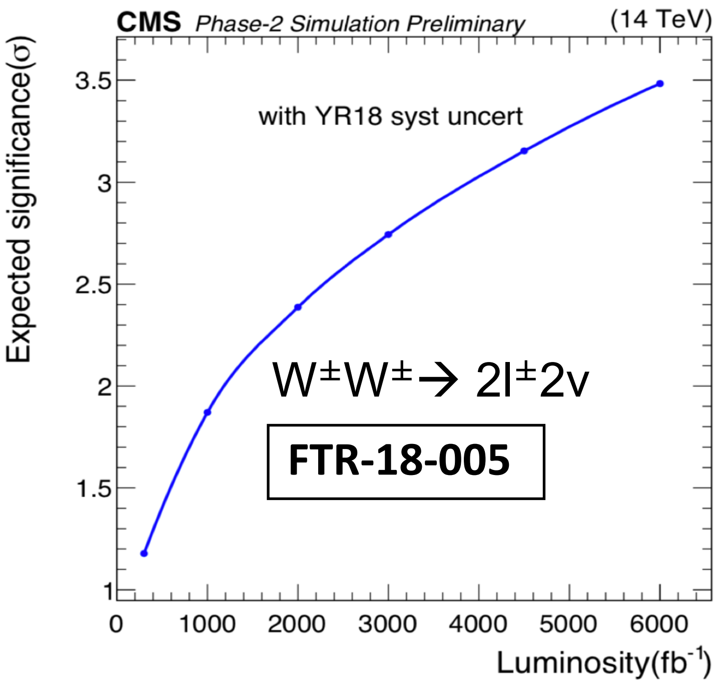


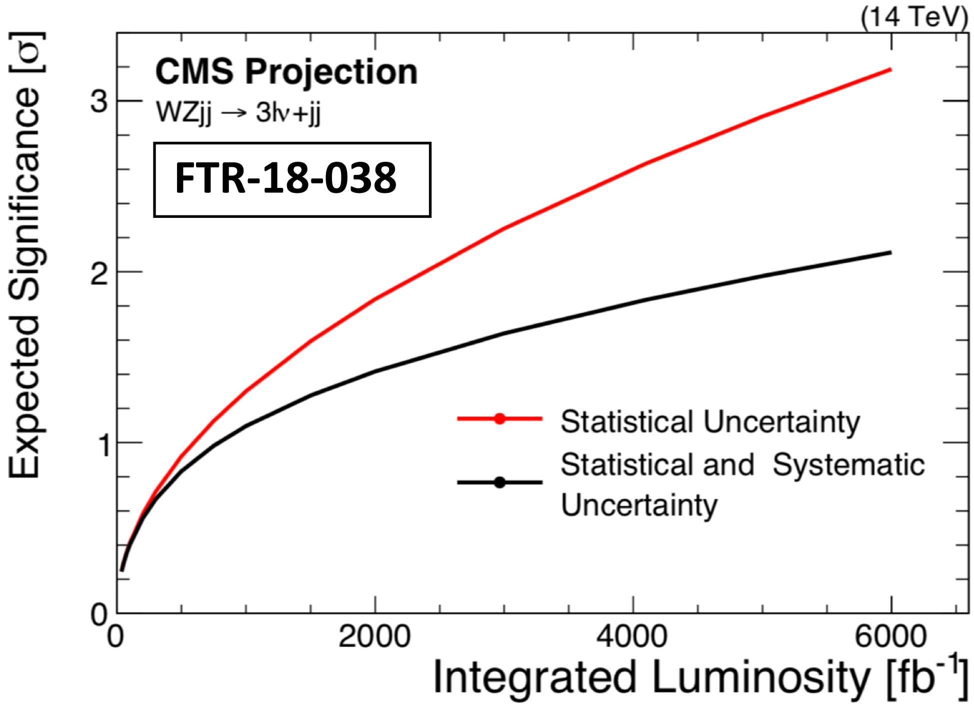
from arXiv:0806.4145

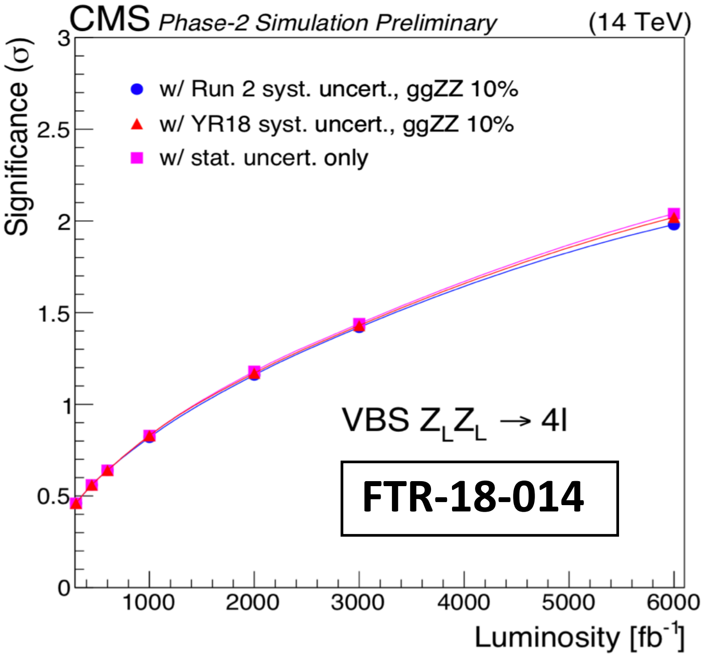
- **Without the SM Higgs boson VBS would violate unitarity**
- **Higgs boson contribution cancels the VBS cross section increase for large $\sqrt{s}$**

→ One of the key measurements in VBS is precise determination of the V_LV_L component (but it require large statistic → HL-LHC)

$\sigma(V_L V_L)$ projections at HL-LHC







For a luminosity of 3 ab-1 (HL-LHC) :

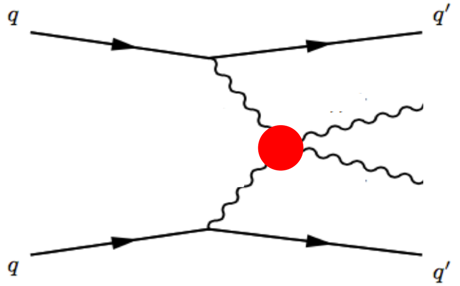
W±W±→2l±2v	2.7 σ
WZ→3lv	1.6 σ
ZZ→4l	1.4 σ

→ Other channels, machine learning and combination with ATLAS will also help.

Anomalous Couplings / Effective Field Theory

- Generalized language for new physics searches
- Add generic terms to the SM Lagrangian of O(6) and/or O(8), i.e. effectives vertices:

$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_{i} \boxed{\frac{c_i^{(n)}}{\Lambda^n}} \mathcal{O}_i^{(n+4)}$$



- Limits on the Wilson coefficients of the extra terms
- Non-unitary as $\sqrt{\hat{S}} \longrightarrow \Lambda$: Either ignore or add a form factor which decrease the limits
- Up to now, we looked mostly at O(8) in VBS (but O(6) also contributes)

Examples of O(8) operators:

$$L_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi\right] \times \left[(D_\mu \Phi)^\dagger D_\nu \Phi\right]$$

$$L_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi\right] \times \left[(D_\nu \Phi)^\dagger D_\nu \Phi\right]$$

$$L_{M,0} = \mathrm{Tr}[W_{\mu\nu}W^{\mu\nu}] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi\right]$$

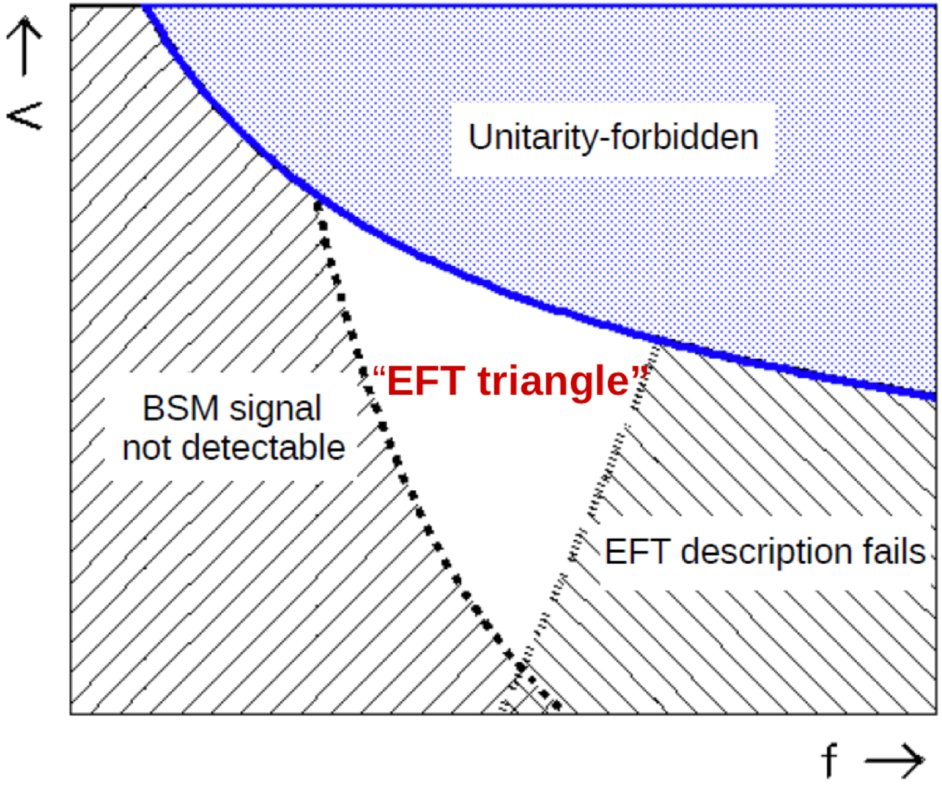
$$L_{M,1} = \mathrm{Tr}[W_{\mu\nu}W^{\nu\beta}] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi\right]$$

$$L_{T,0} = \mathrm{Tr}\,[W_{\mu\nu}W^{\mu\nu}] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

$$L_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right]$$

	WWWW	WWZZ	ZZZZ
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$,$\mathcal{O}_{M,7}$	X	X	X
$\mathcal{O}_{M,2}$,$\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$,$\mathcal{O}_{M,5}$		X	X
$\mathcal{O}_{T,0}$,$\mathcal{O}_{T,1}$,$\mathcal{O}_{T,2}$	X	X	X
$\mathcal{O}_{T,5}$,$\mathcal{O}_{T,6}$,$\mathcal{O}_{T,7}$		X	X
$\mathcal{O}_{T,8}$,$\mathcal{O}_{T,9}$			X

EFT Validity and Unitarity constraints



$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_{i} \boxed{\frac{c_i^{(n)}}{\Lambda^n}} \mathcal{O}_i^{(n+4)}$$

❑ **In practice too small effects, small f/Λ, are not distinguishable from SM (depend of luminosity)**

❑ **EFT validity stops at Λ, the scale of new physics**

❑ **When the coupling (f) is large, EFT description fails as well**

→ **EFT validity triangle is limited**

Unitarity bound in practice:

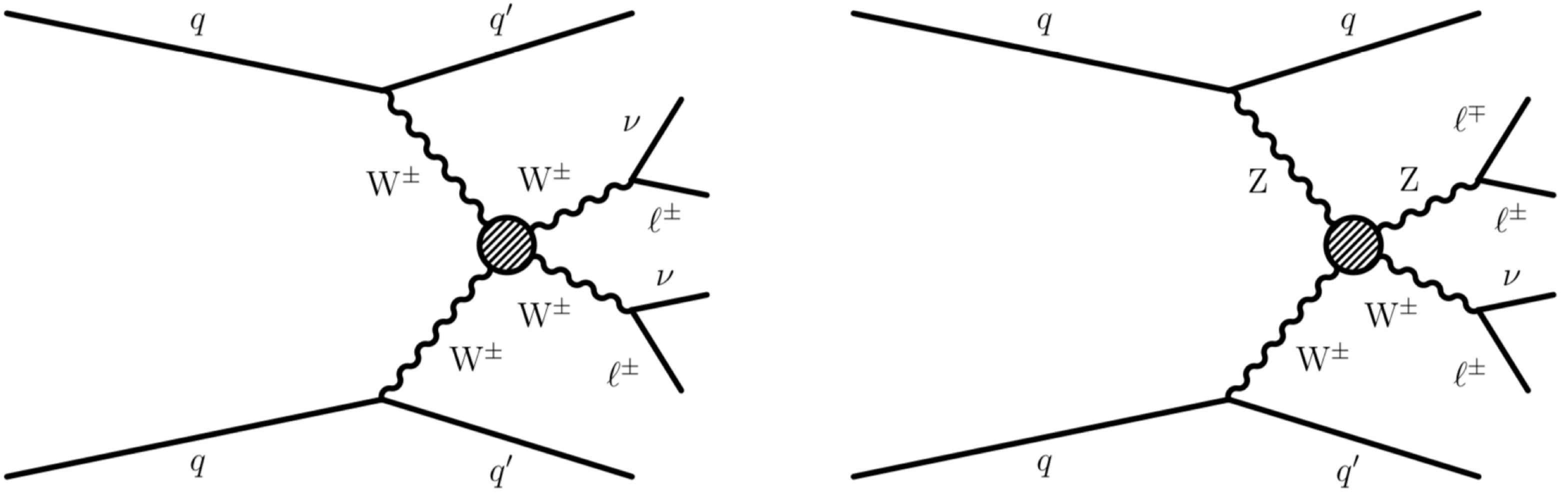
❑ CMS: Mostly do not include unitarity bounds in EFT results extraction
(or provide the unitarity bound separately from the limits)
❑ ATLAS: Cut-off the EFT effect for some value(s) of **Λ**

→ Ongoing discussion on how to present the results but this make comparison to theory and between experiments a bit difficult for now.

Same-sign $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$ and $WZ \rightarrow 3l\nu$

CMS-SMP-19-012

Full Run-II results with 137 fb^{-1} from CMS:



Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	>50 GeV	>50 GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	—
$m_{\ell\ell\ell}$	—	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
b quark veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	>500 GeV	>500 GeV
$\lvert\Delta\eta_{jj}\rvert$	>2.5	>2.5

>=2 jets:

Veto $Z \rightarrow ee$ charge-flip

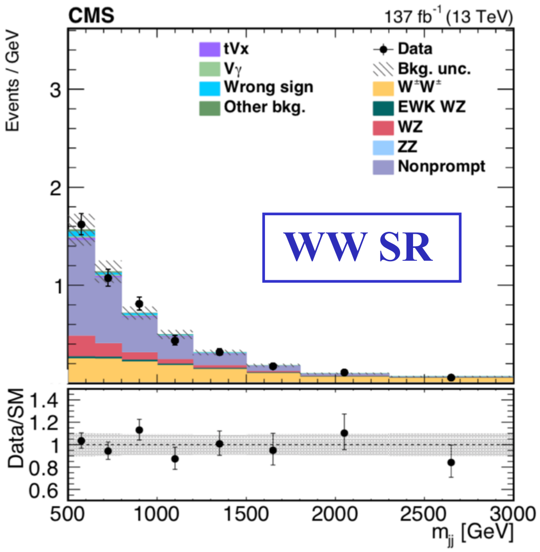
$Z \rightarrow l^+l^-$ pair

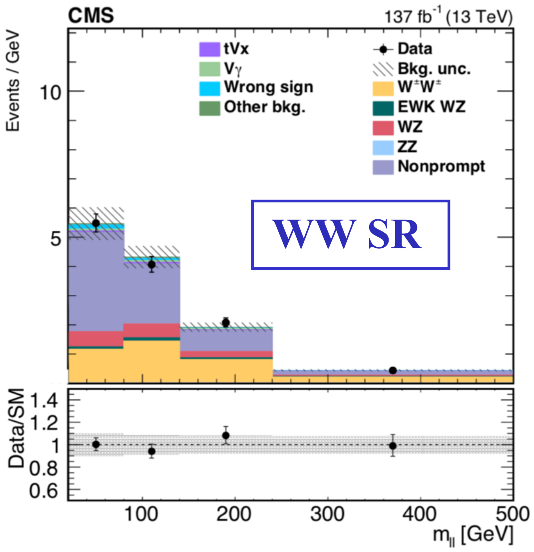
$$z_\ell^* = \left|\eta^\ell - \frac{\eta^{j_1} + \eta^{j_2}}{2}\right| / \lvert\Delta\eta_{jj}\rvert$$

Same-sign $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$ and $WZ \rightarrow 3l\nu$

Cross-sections extracted from simultaneous fit of:

- **3 CR: tZq, ZZ, non-ptompt**
  m_{jj} distribution

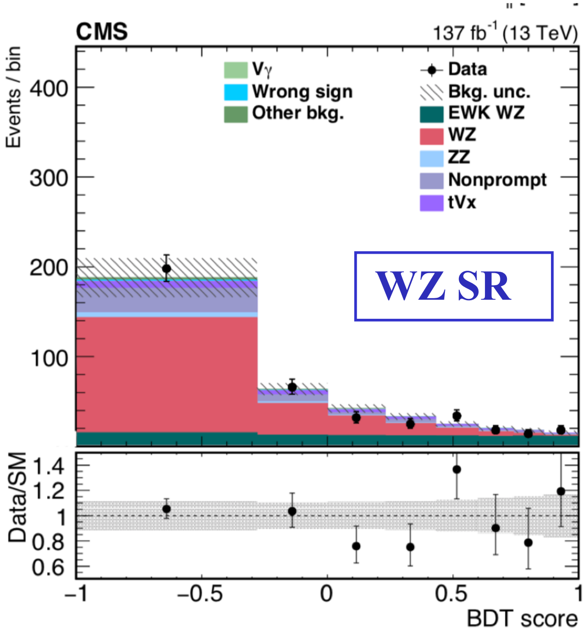




- **WW Signal Region:**
  2D fit of m_{ll} and m_{jj}

- **WZ Signal Region:**
  BDT trained to separate EW and QCD

Variable	Definition
m_{jj}	Mass of the leading and trailing jets system
$\lvert\Delta\eta_{jj}\rvert$	Absolute difference in rapidity of the leading and trailing jets
$\Delta\phi_{jj}$	Absolute difference in azimuthal angles of the leading and trailing jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the trailing jet
η^{j1}	Pseudorapidity of the leading jet
$\lvert\eta^W - \eta^Z\rvert$	Absolute difference between the rapidities of the Z boson and the charged lepton from the decay of the W boson
$z^*_{\ell_i} (i = 1-3)$	Zeppenfeld variable of the three selected leptons
$z^*_{3\ell}$	Zeppenfeld variable of the vector sum of the three leptons
$\Delta R_{j1,Z}$	ΔR between the leading jet and the Z boson
$\lvert\vec{p}_T^{\,tot}\rvert / \sum_i p_T^i$	Transverse component of the vector sum of the bosons and tagging jets momenta, normalized to their scalar p_T sum



Same-sign $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$ and $WZ \rightarrow 3l\nu$

Inclusive cross-sections in fiducial volumes:

WW fiducial region:

- ☐ 2 dressed leptons with $p_T > 20$ GeV, $|\eta| < 2.5$
- ☐ $m_{ll} > 20$ GeV
- ☐ 2 jets with $p_T > 50$ GeV, $|\eta| < 4.7$
- ☐ $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 2.5$

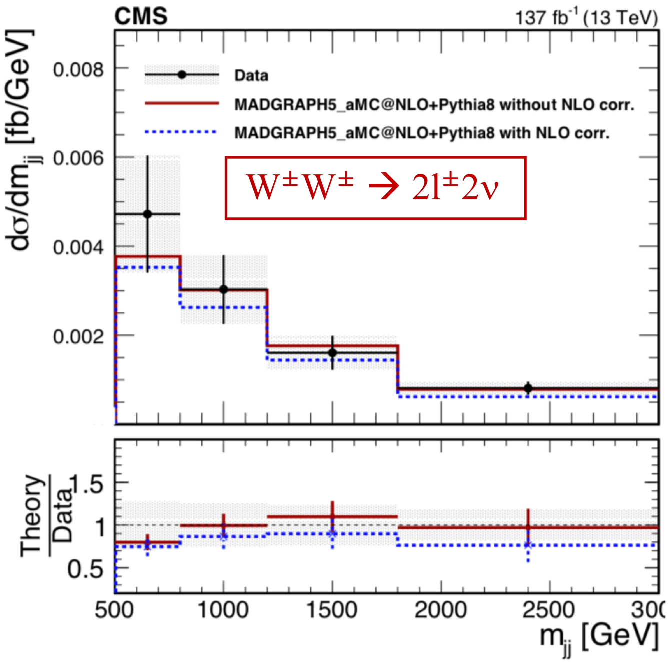
WZ fiducial region:

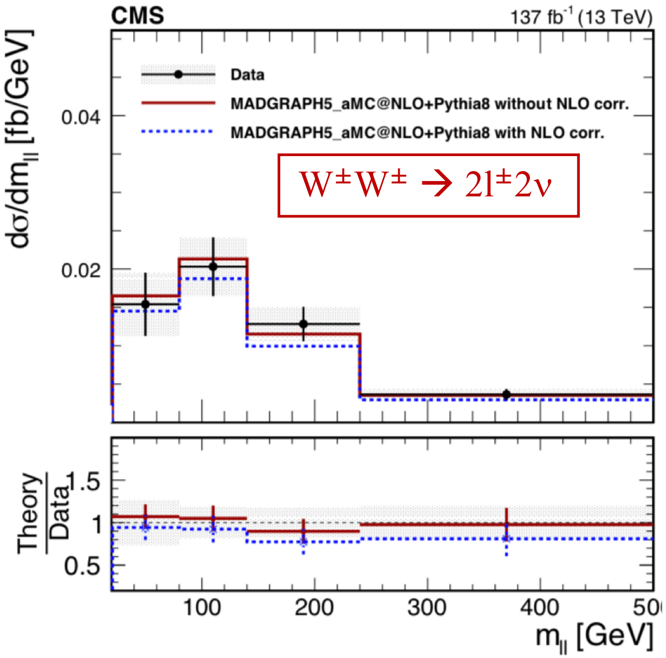
- ☐ 3 dressed leptons with $p_T > 20$ GeV, $|\eta| < 2.5$
- ☐ Z pair: $|m_{ll} - m_Z| < 15$ GeV
- ☐ 2 jets with $p_T > 50$ GeV, $|\eta| < 4.7$
- ☐ $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 2.5$

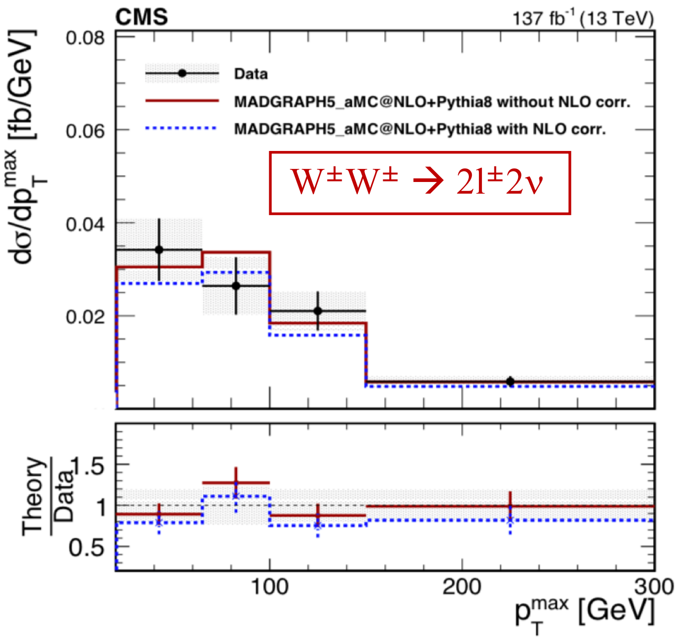
- ☐ **Dressed leptons** = e or μ dressed with photons in a $\Delta R=0.1$ cone
- ☐ Exclude e or μ from τ decays

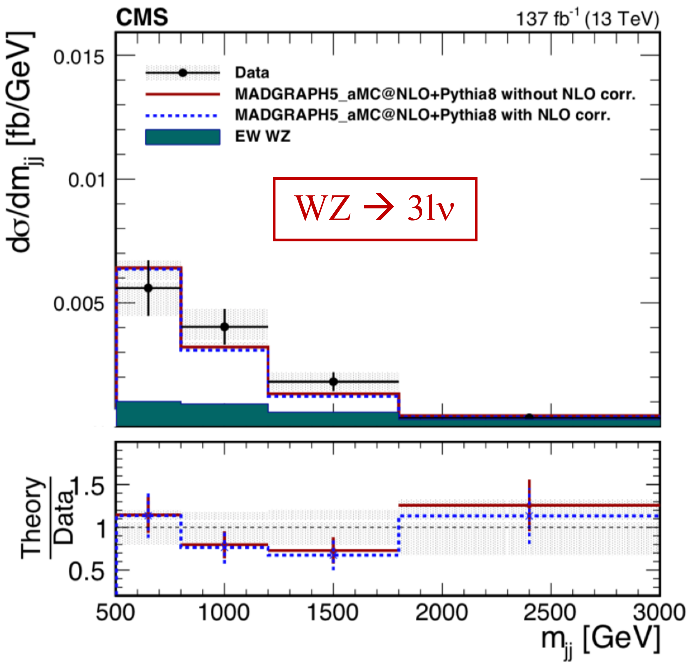
Process	$\sigma \mathcal{B}$ (fb)	Theoretical prediction without NLO corrections (fb)	Theoretical prediction with NLO corrections (fb)
EW $W^{\pm}W^{\pm}$	3.98 ± 0.45 $0.37\,(\text{stat}) \pm 0.25\,(\text{syst})$	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 $0.39\,(\text{stat}) \pm 0.25\,(\text{syst})$	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 $0.39\,(\text{stat}) \pm 0.14\,(\text{syst})$	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 $0.40\,(\text{stat}) \pm 0.23\,(\text{syst})$	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 $0.45\,(\text{stat}) \pm 0.18\,(\text{syst})$	3.12 ± 0.70	3.12 ± 0.70

Same-sign $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$ and $WZ \rightarrow 3l\nu$









Same-sign WW differential cross-sections in:

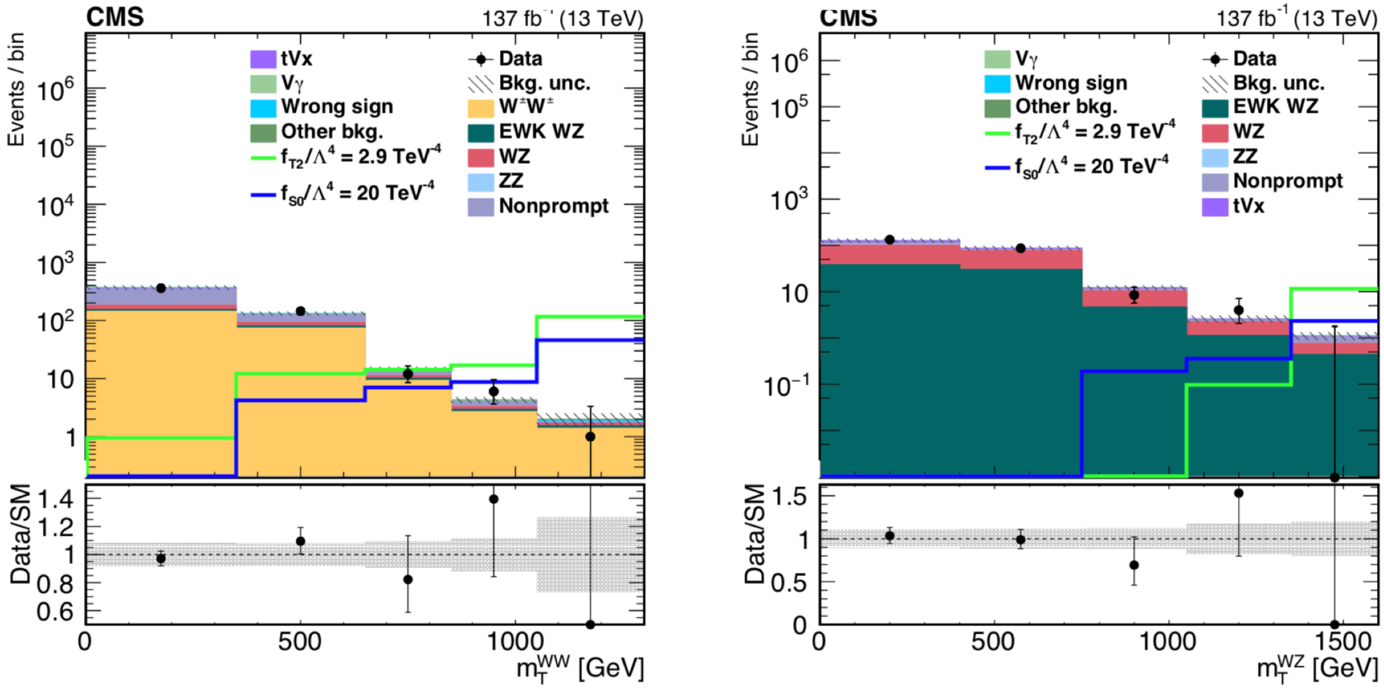
- ☐ m_{jj}
- ☐ m_{ll}
- ☐ p_T^{max} (leading lepton)

WZ cross-section in m_{jj}

→ Good description by MG_aMC with/without NLO

Same-sign $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$ and $WZ \rightarrow 3l\nu$

Quartic Gauge Couplings: Fit $m_{\mathrm{T}}(\mathrm{VV}) = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$, Σ leptons and MET



	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-0.28, 0.31]	[-0.36, 0.39]	[-0.62, 0.65]	[-0.82, 0.85]	[-0.25, 0.28]	[-0.35, 0.37]
f_{T1}/Λ^4	[-0.12, 0.15]	[-0.16, 0.19]	[-0.37, 0.41]	[-0.49, 0.55]	[-0.12, 0.14]	[-0.16, 0.19]
f_{T2}/Λ^4	[-0.38, 0.50]	[-0.50, 0.63]	[-1.0 , 1.3]	[-1.4, 1.7]	[-0.35, 0.48]	[-0.49, 0.63]
f_{M0}/Λ^4	[-3.0, 3.2]	[-3.7, 3.8]	[-5.8, 5.8]	[-7.6, 7.6]	[-2.7, 2.9]	[-3.6, 3.7]
f_{M1}/Λ^4	[-4.7, 4.7]	[-5.4, 5.8]	[-8.2, 8.3]	[-11, 11]	[-4.1, 4.2]	[-5.2, 5.5]
f_{M6}/Λ^4	[-6.0, 6.5]	[-7.5, 7.6]	[-12, 12]	[-15, 15]	[-5.4, 5.8]	[-7.2, 7.3]
f_{M7}/Λ^4	[-6.7, 7.0]	[-8.3, 8.1]	[-10, 10]	[-14, 14]	[-5.7, 6.0]	[-7.8, 7.6]
f_{S0}/Λ^4	[-6.0, 6.4]	[-6.0, 6.2]	[-19, 19]	[-24, 24]	[-5.7, 6.1]	[-5.9, 6.2]
f_{S1}/Λ^4	[-18, 19]	[-18, 19]	[-30, 30]	[-38, 39]	[-16, 17]	[-18, 18]

ZZjj→4ljj VBS @ 13 TeV

CMS: SMP-20-001

Full Run-II results with 137 fb^{-1} from CMS:

Topology: 4 isolated leptons (ee or $\mu\mu$ pairs) + 2 “forward” jets
→ Very clean channel but low cross-section
→ Full kinematic available, access to boson polarization

Event selection:

☐ 4 Isolated leptons:
$p_{T,1} > 20$ GeV
$p_{T,2} > 12$ (10) GeV if e (μ)
$p_{T,3/4} > 7$ (5) GeV if e (μ)
$|\eta| < 2.5$ (e), 2.4 (μ)
$60 < m_Z < 120$ GeV

Opposite sign pairs of ee and/or $\mu\mu$
$\Delta R_{ll} > 0.02$
$\Delta R\,(e, \mu) > 0.05$
m_{ll} of any opposite sign pair > 4 GeV
$m_{ZZ} > 180$ GeV

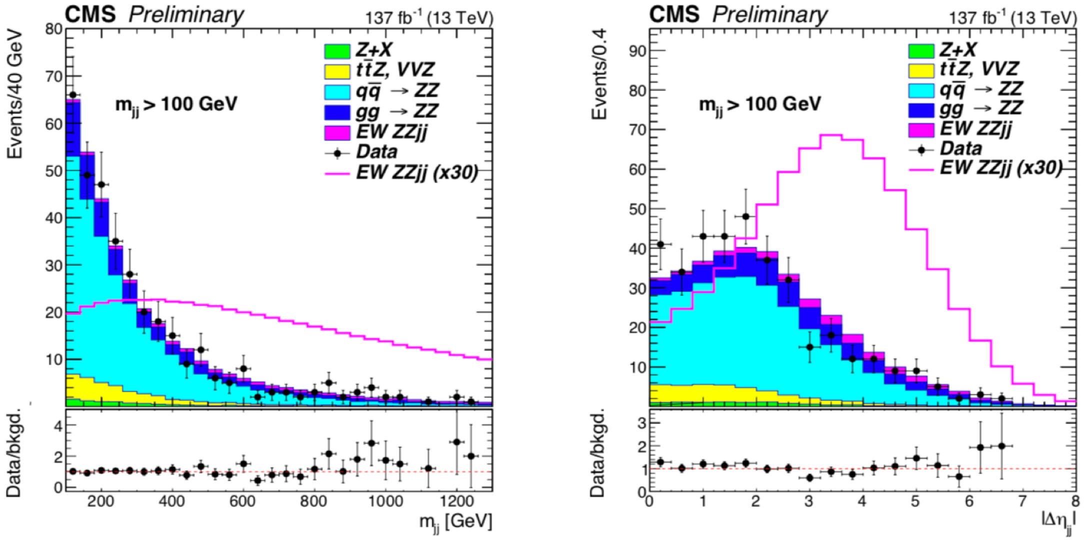
☐ >=2 Anti-k_T (ΔR=0.4) jets: $p_T > 30$ GeV and $|\eta| < 4.7$
→ Inclusive ZZjj region: $m_{jj} > 100$ GeV
→ loose VBS region: $m_{jj} > 400$ GeV and $|\Delta\eta_{jj}| > 2.4$ (signal purity ~15%)
→ tight VBS region: $m_{jj} > 400$ GeV and $|\Delta\eta_{jj}| > 5.0$ (signal purity ~30%)

Backgrounds:

☐ QCD ZZjj : Shape from MC, normalization from fit to data in sideband
☐ Non-prompt leptons measured from control region
☐ Z+jets: Charge flip probability measured in Z peak
☐ Others from MC: ttZ+jets, VVZ+jets, …

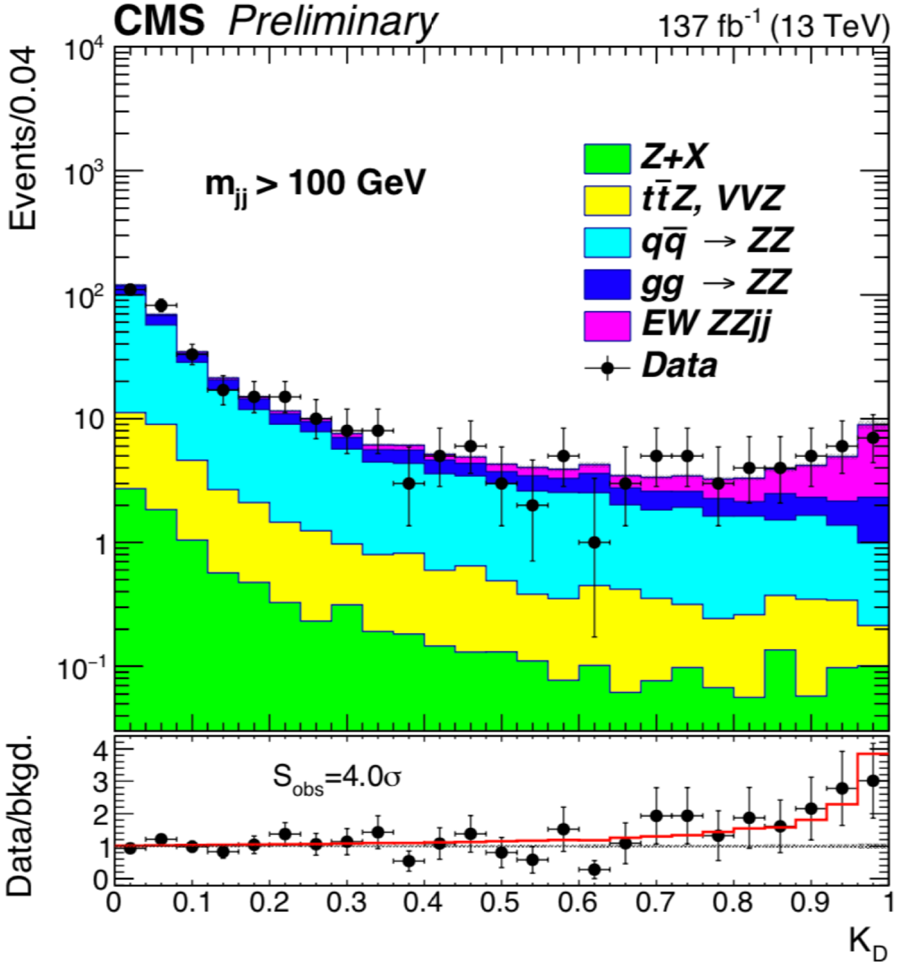
ZZjj→4ljj VBS: Cross section

For inclusive ZZjj, signal purity is ~6% but with 85% of QCD



→ **Build a Matrix Element discriminator K_D to separate the EW ZZjj component based on the event kinematic:**

	SM σ (fb)	Measured σ (fb)
	ZZjj inclusive	
EW	$0.275 \pm 0.021\,(\text{theo})$	$0.33\,^{+0.11}_{-0.10}\,(\text{stat})\,^{+0.04}_{-0.03}\,(\text{syst})$
EW+QCD	$5.35 \pm 0.51\,(\text{theo})$	$5.29\,^{+0.31}_{-0.30}\,(\text{stat}) \pm 0.46\,(\text{syst})$
	VBS-enriched (loose)	
EW	$0.186 \pm 0.015\,(\text{theo})$	$0.200\,^{+0.078}_{-0.067}\,(\text{stat})\,^{+0.023}_{-0.013}\,(\text{syst})$
EW+QCD	$1.21 \pm 0.09\,(\text{theo})$	$1.00\,^{+0.12}_{-0.11}\,(\text{stat})\,^{+0.06}_{-0.05}\,(\text{syst})$
	VBS-enriched (tight)	
EW	$0.050 \pm 0.005\,(\text{theo})$	$0.06\,^{+0.05}_{-0.04}\,(\text{stat}) \pm 0.01\,(\text{syst})$
EW+QCD	$0.171 \pm 0.012\,(\text{theo})$	$0.17 \pm 0.04\,(\text{stat}) \pm 0.01\,(\text{syst})$

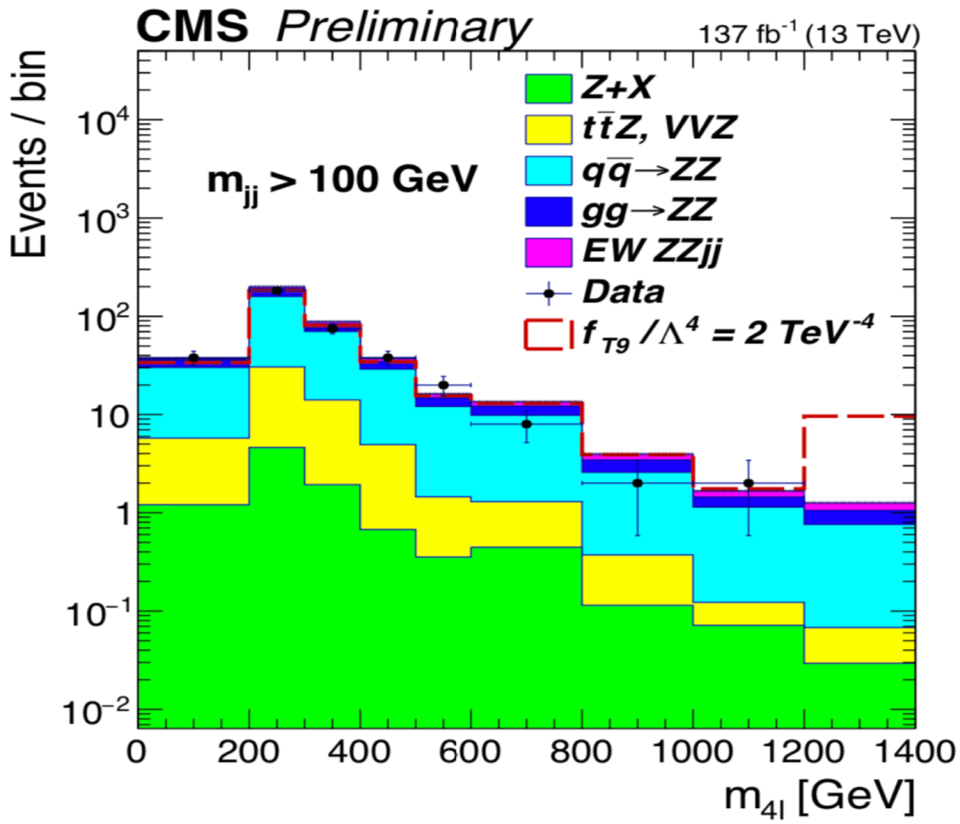


→ **4σ observed significance for EW ZZjj**
(exp. signif. 3.5 σ)

ZZjj→4ljj VBS: anomalous QGC

Use the di-Z invariant mass to set limits on aQGC:

- ❑ T0, T1, T2: close to WW+WZ results (or sligthly worse)
- ❑ T8, T9: Only accessible in ZZ



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	-0.37	0.35	-0.24	0.22	2.9
f_{T1}/Λ^4	-0.49	0.49	-0.31	0.31	2.7
f_{T2}/Λ^4	-0.98	0.95	-0.63	0.59	2.8
f_{T8}/Λ^4	-0.68	0.68	-0.43	0.43	3.3
f_{T9}/Λ^4	-1.46	1.46	-0.92	0.92	3.3

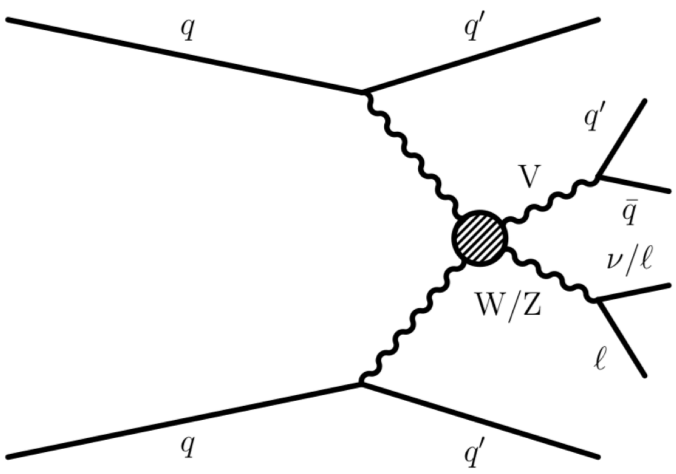
→ Most stringent limits on T8 & T9 up to now

Semi-leptonic VV VBS @ 13 TeV

CMS SMP-18-006

Study od WW, WZ and ZZ VBS in semi-leptonic decays: $V_1 \rightarrow qq$; $V_2 \rightarrow ll$ or $l\nu$

2016 data → 35.9 fb^{-1}



VBS jets: >= 2 Anti-K_T ($\Delta R=0.4$)
$p_T > 30$ GeV and $|\eta| < 5.$
$m_{jj} > 800$ GeV and $|\Delta\eta_{jj}| > 4.0$

$V_1 \rightarrow$ qq: Boosted topology → 1 Anti-K_T ($\Delta R=0.8$)
$p_T > 200$ GeV, $|\eta| < 2.4$
ΔR with leptons > 1.0
ΔR with VBS jets > 0.8
$\tau_2/\tau_1 < 0.55$ (N-subjettiness)
$65 < m_V < 105$ GeV (soft-drop mass)

V_2=Z→ll: e^+e^- or $\mu^+\mu^-$ pair with $p_T > 50$ and 30 GeV
$|m_{ll} - m_Z| < 15$ GeV

V_2=W→lν: e or μ with $p_T > 50$ GeV
no extra e or μ with $p_T > 20$ GeV
$p_T^{miss} > 50$ (80) GeV in the μ (e) case

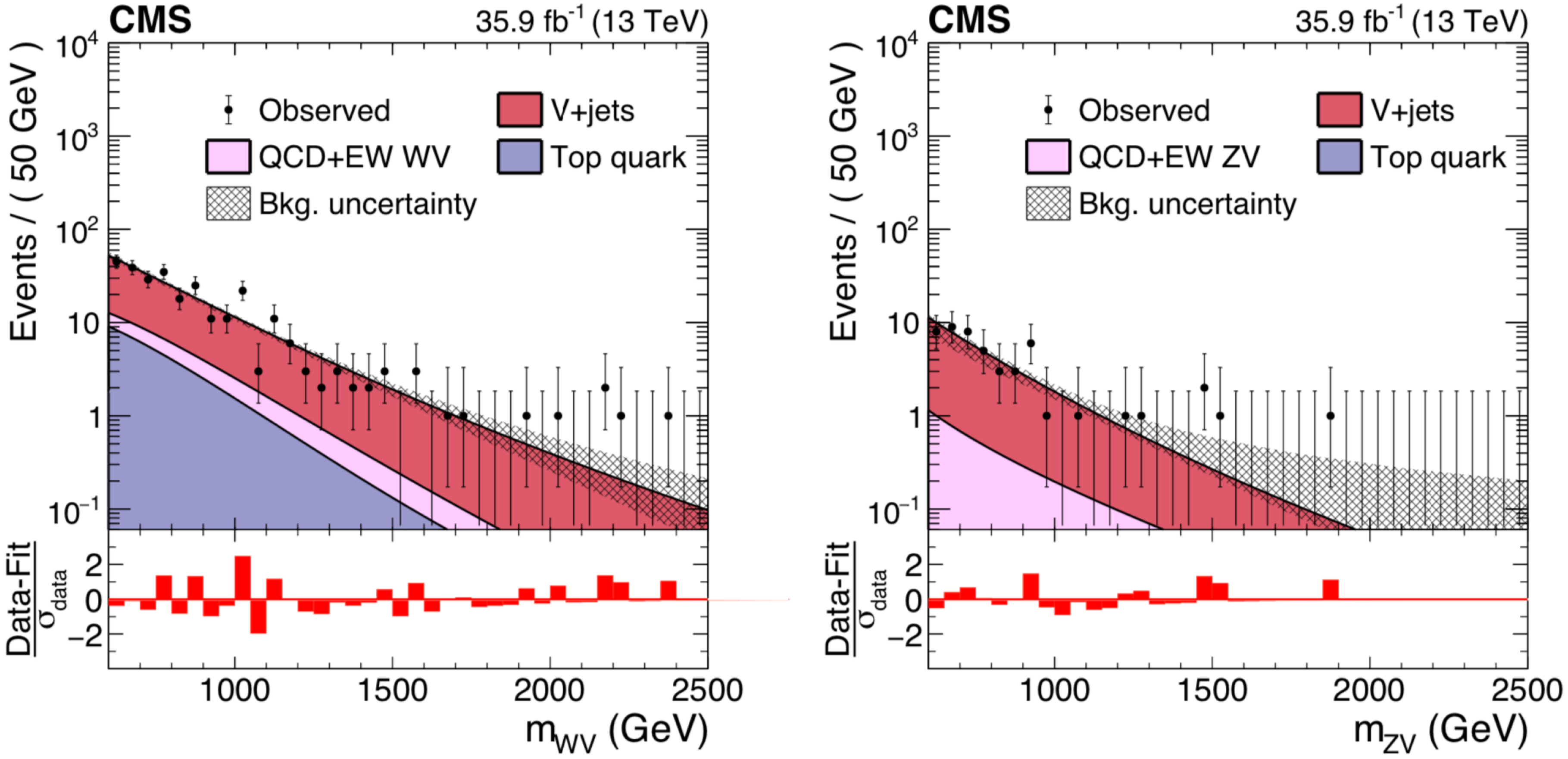
Centrality cuts on $V_{1,2}$
Zeppenfeld variable > 0.3 for V_1 and V_2
$\vartheta = \min(\min(\eta_W, \eta_V) - \min(\eta_{j1}, \eta_{j2}), \max(\eta_{j1}, \eta_{j2}) - \max(\eta_W, \eta_V)) > 1$

Semi-leptonic VV VBS: Backgrounds

V+jets background: estimated in $40 < m_{V,1} < 65$ GeV + $105 < m_{V,1} < 150$ GeV sideband

→ Fit shape as $f(m) = \exp\left[-m/(c_0 + c_1 m)\right]$

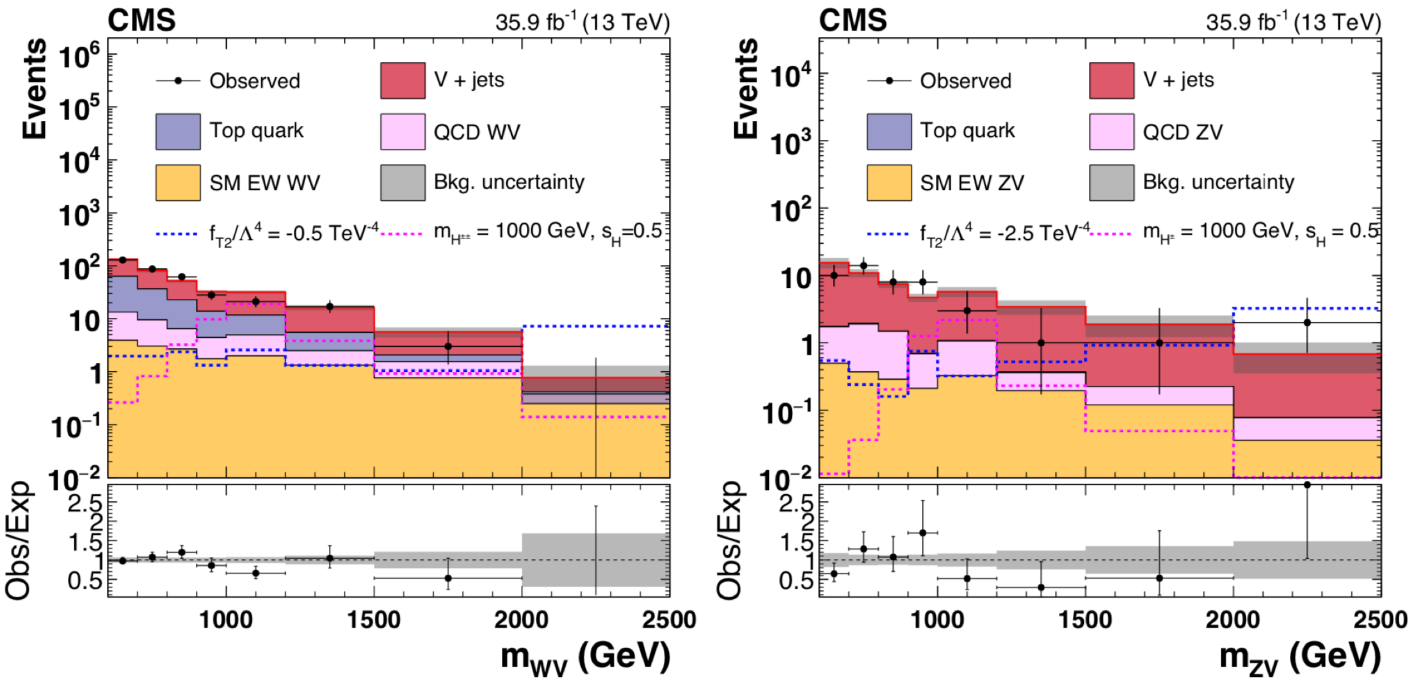
+ transfer functions from V+jet MC simulation



Other backgrounds: Top and QCD from MC simulations

Semi-leptonic VV VBS: QGC limits

SM signal yields are low (wrt Bkgd) → use this analysis only to set limits on aQGC

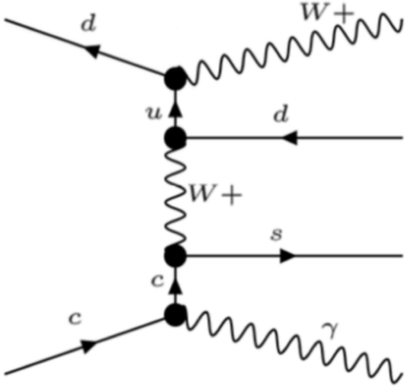


	Observed (WV) (TeV^{-4})	Expected (WV) (TeV^{-4})	Observed (ZV) (TeV^{-4})	Expected (ZV) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{S0}/Λ^4	$[-2.7, 2.7]$	$[-4.2, 4.2]$	$[-40, 40]$	$[-31, 31]$	$[-2.7, 2.7]$	$[-4.2, 4.2]$
f_{S1}/Λ^4	$[-3.3, 3.4]$	$[-5.2, 5.2]$	$[-32, 32]$	$[-24, 24]$	$[-3.4, 3.4]$	$[-5.2, 5.2]$
f_{M0}/Λ^4	$[-0.69, 0.69]$	$[-1.0, 1.0]$	$[-7.5, 7.5]$	$[-5.3, 5.3]$	$[-0.69, 0.70]$	$[-1.0, 1.0]$
f_{M1}/Λ^4	$[-2.0, 2.0]$	$[-3.0, 3.0]$	$[-22, 23]$	$[-16, 16]$	$[-2, 0, 2.1]$	$[-3.0, 3.0]$
f_{M6}/Λ^4	$[-1.4, 1.4]$	$[-2.0, 2.0]$	$[-15, 15]$	$[-11, 11]$	$[-1.3, 1.3]$	$[-1.4, 1.4]$
f_{M7}/Λ^4	$[-3.4, 3.4]$	$[-5.1, 5.1]$	$[-35, 36]$	$[-25, 26]$	$[-3.4, 3.4]$	$[-5.1, 5.1]$
f_{T0}/Λ^4	$[-0.12, 0.11]$	$[-0.17, 0.16]$	$[-1.4, 1.4]$	$[-1.0, 1.0]$	$[-0.12, 0.11]$	$[-0.17, 0.16]$
f_{T1}/Λ^4	$[-0.12, 0.13]$	$[-0.18, 0.18]$	$[-1.5, 1.5]$	$[-1.0, 1.0]$	$[-0.12, 0.13]$	$[-0.18, 0.18]$
f_{T2}/Λ^4	$[-0.28, 0.28]$	$[-0.41, 0.41]$	$[-3.4, 3.4]$	$[-2.4, 2.4]$	$[-0.28, 0.28]$	$[-0.41, 0.41]$

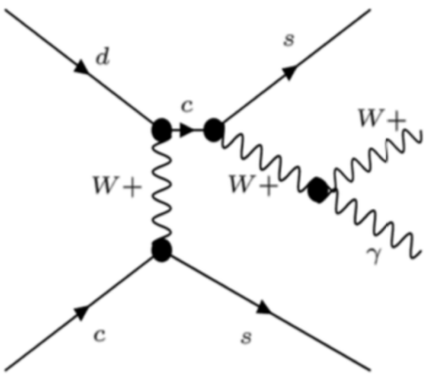
$W\gamma \rightarrow l\nu\gamma$ VBS @ 13 TeV

CMS SMP-19-008

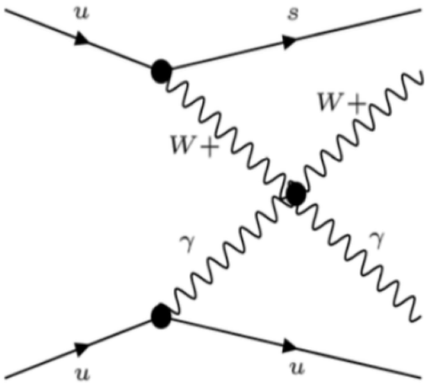
EW



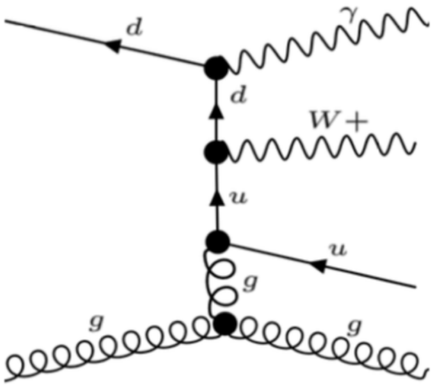
EW TGC



EW QGC



QCD



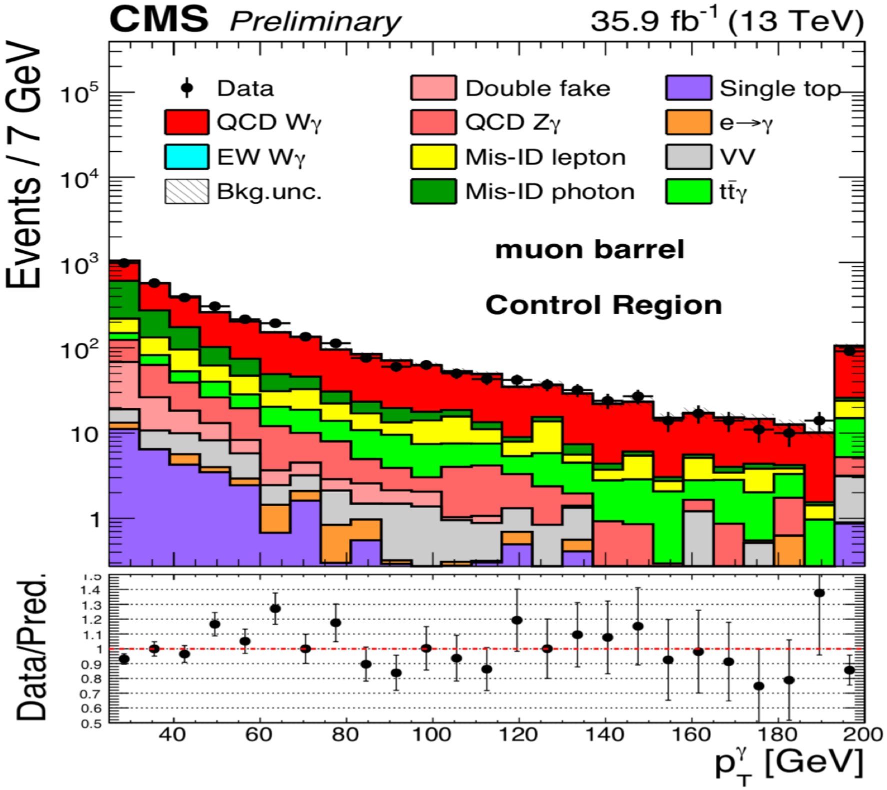
2016 data → 35.9 fb^{-1}

$W\gamma \rightarrow l\nu\gamma$: e or μ with $p_T > 30$ GeV
γ with $p_T > 25$ GeV
$\Delta R(l,\gamma) > 0.5$
$p_T^{miss} > 30$ GeV
$m_T(W) > 30$ GeV
if e: $|m_{e\gamma} - m_Z| > 10$ GeV (Z-→ee veto)

VBS jets: >= 2 Anti-K_T (ΔR=0.4)
$p_T > 40$ and 30 GeV and $|\eta| < 4.7$
$\Delta R(j,\gamma) > 0.5$ and $\Delta R(j,l) > 0.5$

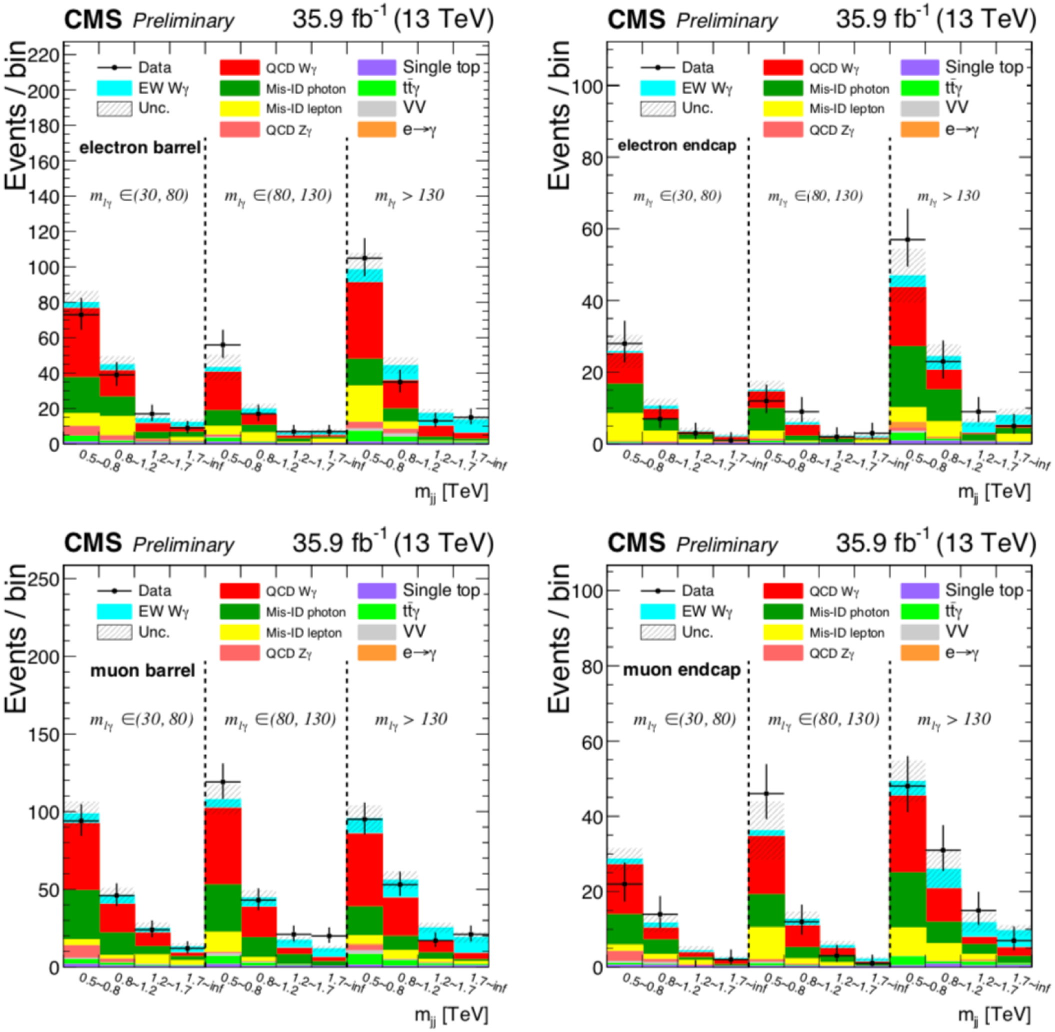
Signal Region: $m_{jj} > 500$ GeV and $|\Delta\eta_{jj}| > 2.5$
$m_{W\gamma} > 100$ GeV
$|y_{W\gamma} - (y_{j1} + y_{j2})/2| < 1.2$
$|\varphi_{W\gamma} - \varphi_{j1,j2}| > 2$

Control Region: $200 < m_{jj} < 400$ GeV



Wγ→lνγ VBS: EW Cross-section

Fit the 2D distribution of m_{jj} and $m_{l\gamma}$ in 4 catergories: e and μ in barrel and endcap



	electron barrel	electron endcap	muon barrel	muon endcap
Misidentified photon	81.0 ± 5.2	48.1 ± 4.9	134.8 ± 8.2	52.1 ± 4.8
Misidentified lepton	63.7 ± 12.3	27.8 ± 7.2	46.8 ± 10.6	23.1 ± 6.5
e → γ	1.5 ± 0.6	2.1 ± 0.8	1.7 ± 0.7	1.1 ± 0.6
QCD Zγ	18.0 ± 3.1	1.9 ± 0.9	16.2 ± 3.0	4.9 ± 1.3
Single top	4.9 ± 0.8	2.5 ± 0.5	6.8 ± 0.9	2.4 ± 0.5
VV	4.2 ± 1.6	0.6 ± 0.6	7.5 ± 2.1	1.4 ± 0.7
tt̄γ	20.6 ± 1.6	5.1 ± 0.6	28.3 ± 1.8	6.9 ± 0.8
QCD Wγjj	154.2 ± 12.0	41.1 ± 4.4	221.2 ± 15.8	72.1 ± 6.2
Total background	348.3 ± 18.4	129.1 ± 9.9	463.4 ± 21.2	163.8 ± 10.4
EW Wγjj	48.8 ± 2.2	16.1 ± 1.0	74.5 ± 2.8	24.4 ± 1.3
Data	393	159	565	201

EW Component:

σ_{fid} (EW)= 20.4 ± 0.4 (lumi) ± 2.8 (stat)
± 3.5 (syst) fb
= 20.4 ± 4.5 fb

→ **4.9 σ observation of EW Wγ**
→ **5.3 σ combining with 8 TeV results**

EW+QCD:

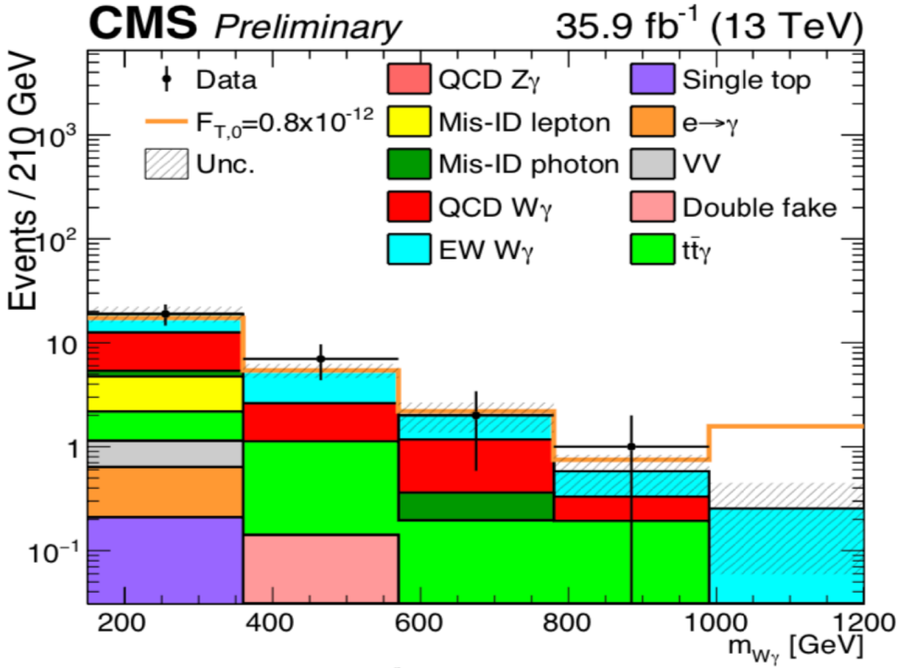
σ_{fid} (EW+QCD)= 108 ±2(lumi) ±5(stat)
±15(syst) fb
= 108±16fb

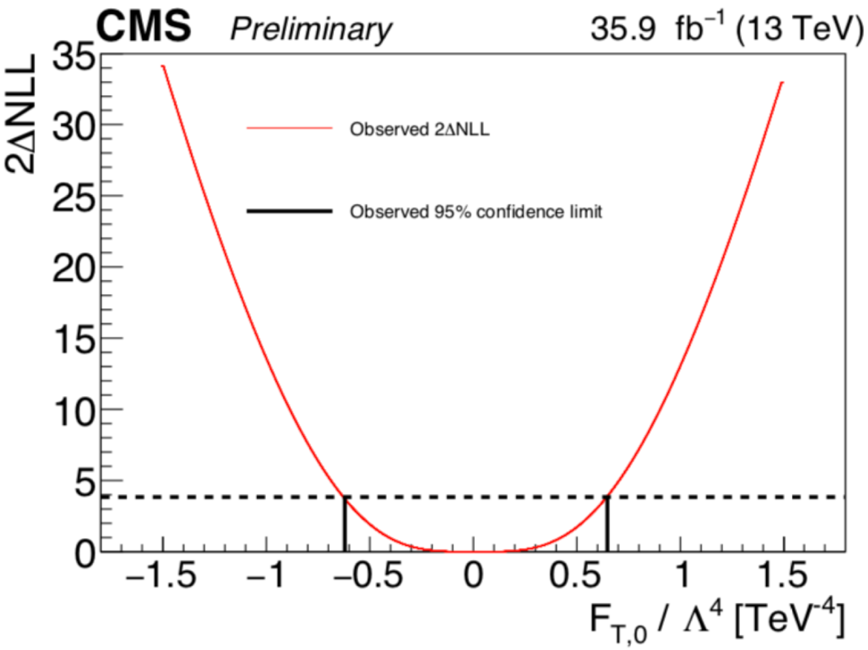
$W\gamma \rightarrow l\nu\gamma$ VBS: aQGC limits

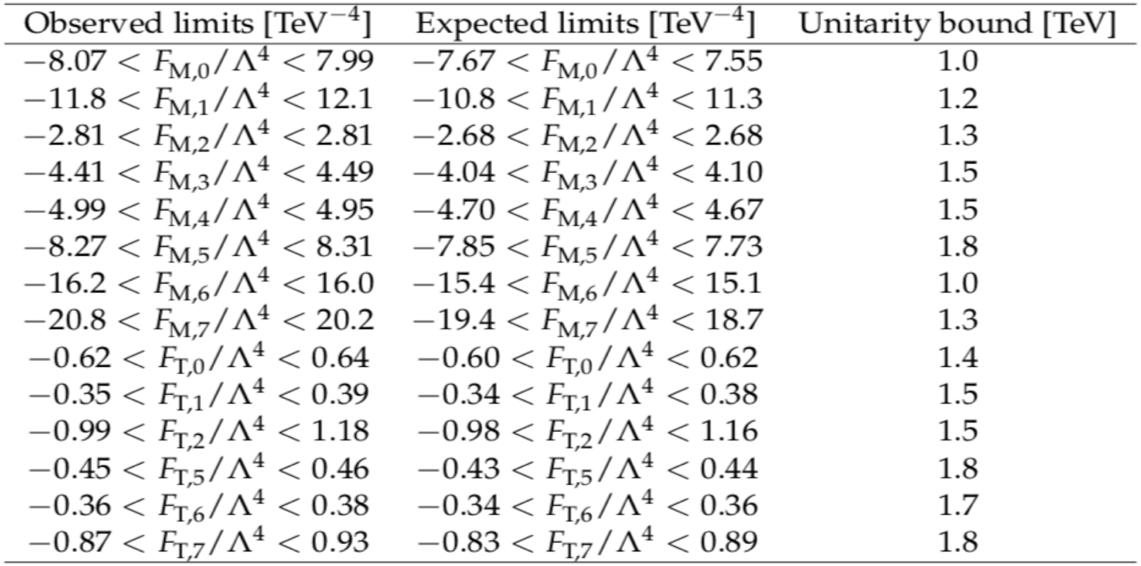
Further restrict the phase space:

m_{jj} > 800 GeV
$|\Delta\eta_{jj}|$ > 2.5
$m_{W\gamma}$ > 150 GeV
$p_{T\gamma}$ > 100 GeV

→ Use the $m_{W\gamma}$ distribution to set limits on the anomalous Quartic Gauge Couplings





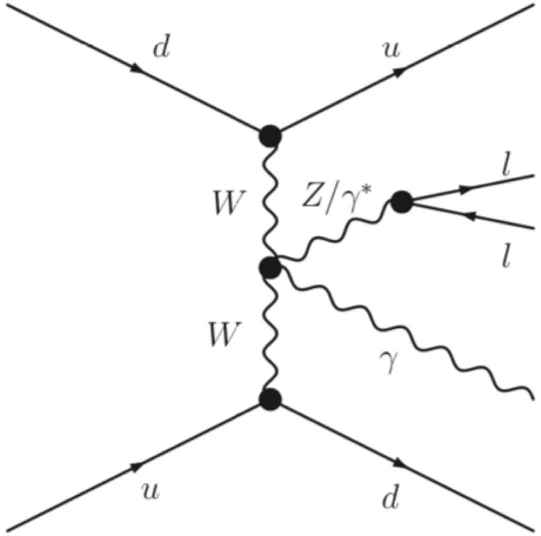


Observed limits [TeV^{-4}]	Expected limits [TeV^{-4}]	Unitarity bound [TeV]
$-8.07 < F_{M,0}/\Lambda^4 < 7.99$	$-7.67 < F_{M,0}/\Lambda^4 < 7.55$	1.0
$-11.8 < F_{M,1}/\Lambda^4 < 12.1$	$-10.8 < F_{M,1}/\Lambda^4 < 11.3$	1.2
$-2.81 < F_{M,2}/\Lambda^4 < 2.81$	$-2.68 < F_{M,2}/\Lambda^4 < 2.68$	1.3
$-4.41 < F_{M,3}/\Lambda^4 < 4.49$	$-4.04 < F_{M,3}/\Lambda^4 < 4.10$	1.5
$-4.99 < F_{M,4}/\Lambda^4 < 4.95$	$-4.70 < F_{M,4}/\Lambda^4 < 4.67$	1.5
$-8.27 < F_{M,5}/\Lambda^4 < 8.31$	$-7.85 < F_{M,5}/\Lambda^4 < 7.73$	1.8
$-16.2 < F_{M,6}/\Lambda^4 < 16.0$	$-15.4 < F_{M,6}/\Lambda^4 < 15.1$	1.0
$-20.8 < F_{M,7}/\Lambda^4 < 20.2$	$-19.4 < F_{M,7}/\Lambda^4 < 18.7$	1.3
$-0.62 < F_{T,0}/\Lambda^4 < 0.64$	$-0.60 < F_{T,0}/\Lambda^4 < 0.62$	1.4
$-0.35 < F_{T,1}/\Lambda^4 < 0.39$	$-0.34 < F_{T,1}/\Lambda^4 < 0.38$	1.5
$-0.99 < F_{T,2}/\Lambda^4 < 1.18$	$-0.98 < F_{T,2}/\Lambda^4 < 1.16$	1.5
$-0.45 < F_{T,5}/\Lambda^4 < 0.46$	$-0.43 < F_{T,5}/\Lambda^4 < 0.44$	1.8
$-0.36 < F_{T,6}/\Lambda^4 < 0.38$	$-0.34 < F_{T,6}/\Lambda^4 < 0.36$	1.7
$-0.87 < F_{T,7}/\Lambda^4 < 0.93$	$-0.83 < F_{T,7}/\Lambda^4 < 0.89$	1.8

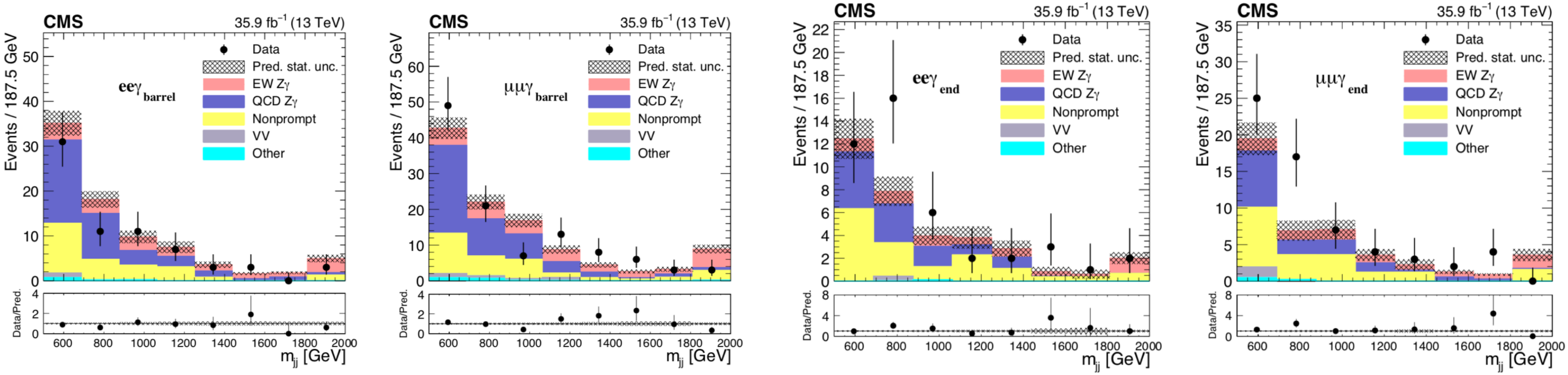
These are the most stringent limits to date on the aQGC parameters $F_{M,2-5}/\Lambda_4$ and $F_{T,6-7}/\Lambda_4$

Zγ→llγ VBS @ 13 TeV

2016 data → 35.9 fb^{-1}

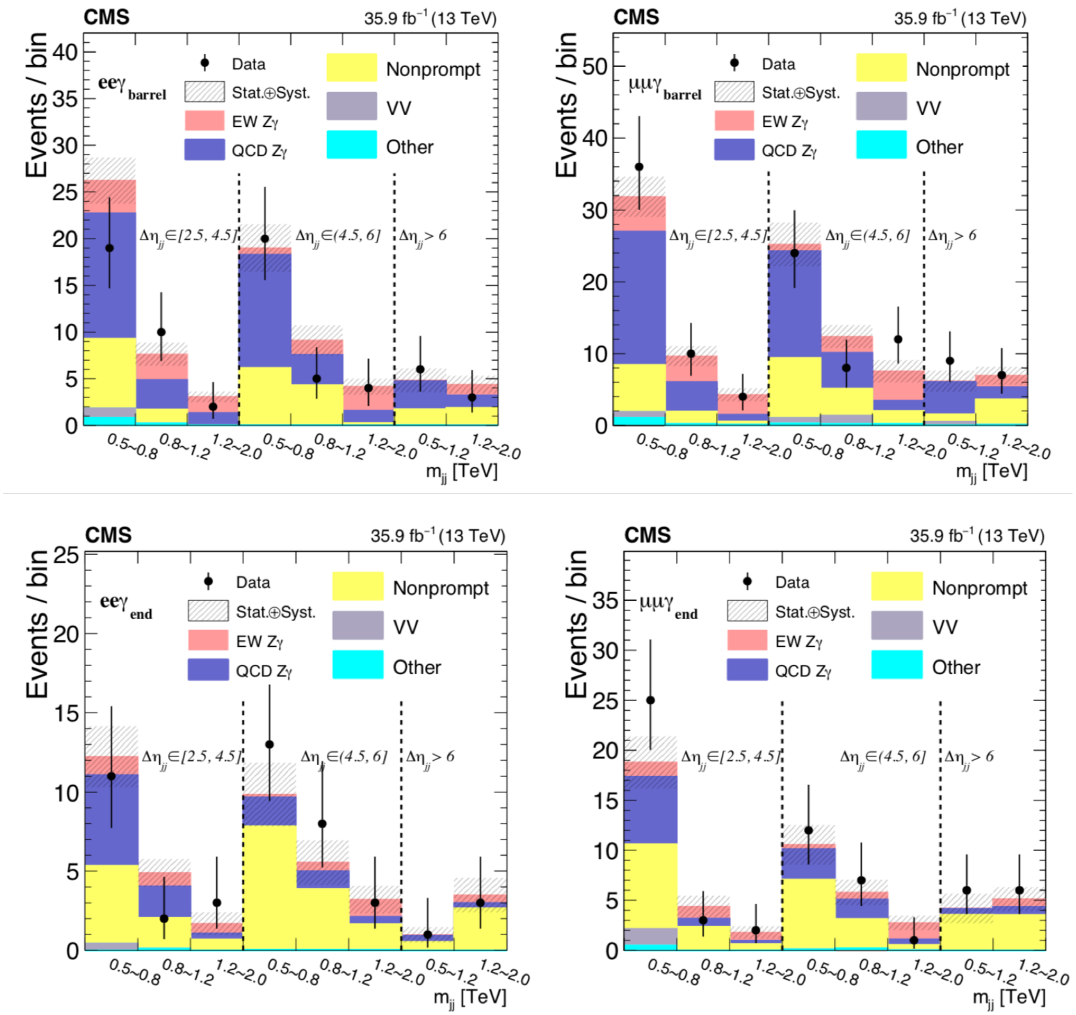


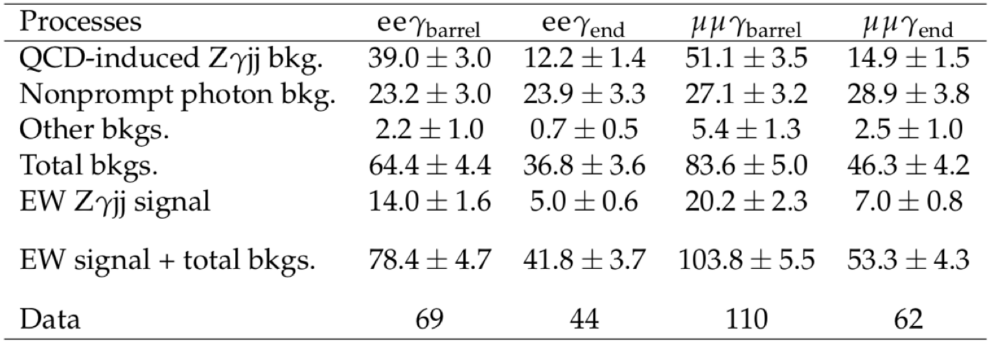
Common selection	$p_T^{\ell 1,\ell 2} > 25\,\text{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.5$ for electron channel $p_T^{\ell 1,\ell 2} > 20\,\text{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.4$ for muon channel $p_T^{\gamma} > 20\,\text{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.444$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_T^{j1,j2} > 30\,\text{GeV}$, $\lvert\eta^{j1,j2}\rvert 4.7$ $70 < m_{\ell\ell} < 110\,\text{GeV}$, $m_{Z\gamma} > 100\,\text{GeV}$ $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{j\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Control region	$150 < m_{jj} < 400\,\text{GeV}$, Common selection
EW signal region	$m_{jj} > 500\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$, $\eta^* < 2.4$, $\Delta\phi_{Z\gamma,jj} > 1.9$, Common selection
Fiducial region	$m_{jj} > 500\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$, Common selection, without requirement on $m_{Z\gamma}$
aQGC search region	$m_{jj} > 500\,\text{GeV}$, $\Delta\eta_{jj} > 2.5$, $p_T^{\gamma} > 100\,\text{GeV}$, Common selection, without requirement on $m_{Z\gamma}$



Zγ→llγ VBS: EW Cross-sections

Fit the 2D distribution of m_{jj} and $\Delta\eta_{jj}$ in 4 catergories: e and μ in barrel and endcap





Processes	$ee\gamma_{\mathrm{barrel}}$	$ee\gamma_{\mathrm{end}}$	$\mu\mu\gamma_{\mathrm{barrel}}$	$\mu\mu\gamma_{\mathrm{end}}$
QCD-induced Zγjj bkg.	39.0 ± 3.0	12.2 ± 1.4	51.1 ± 3.5	14.9 ± 1.5
Nonprompt photon bkg.	23.2 ± 3.0	23.9 ± 3.3	27.1 ± 3.2	28.9 ± 3.8
Other bkgs.	2.2 ± 1.0	0.7 ± 0.5	5.4 ± 1.3	2.5 ± 1.0
Total bkgs.	64.4 ± 4.4	36.8 ± 3.6	83.6 ± 5.0	46.3 ± 4.2
EW Zγjj signal	14.0 ± 1.6	5.0 ± 0.6	20.2 ± 2.3	7.0 ± 0.8
EW signal + total bkgs.	78.4 ± 4.7	41.8 ± 3.7	103.8 ± 5.5	53.3 ± 4.3
Data	69	44	110	62

EW Component:

σ_{fid} (EW) = 3.2 ±0.2(lumi) ±1.1(stat) ±0.6(syst) fb = 3.2 ±1.2 fb

→ **3.9 σ observed signif. of EW Zγ**

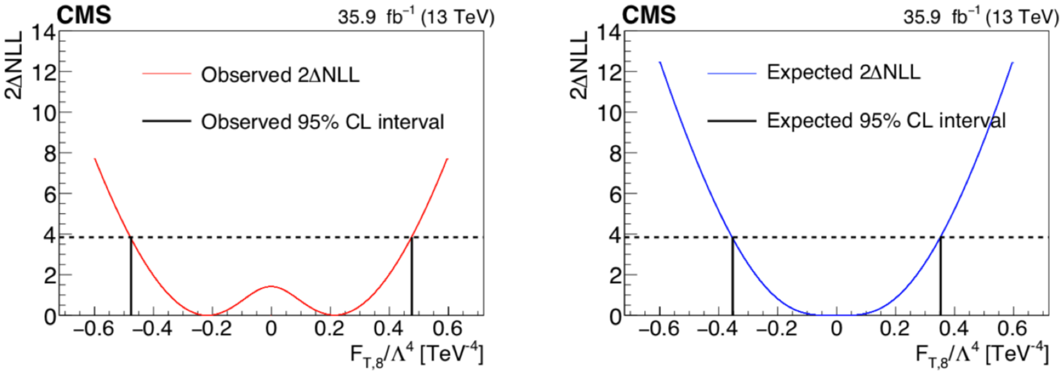
→ **4.7 σ combining with 8 TeV results**

EW+QCD:

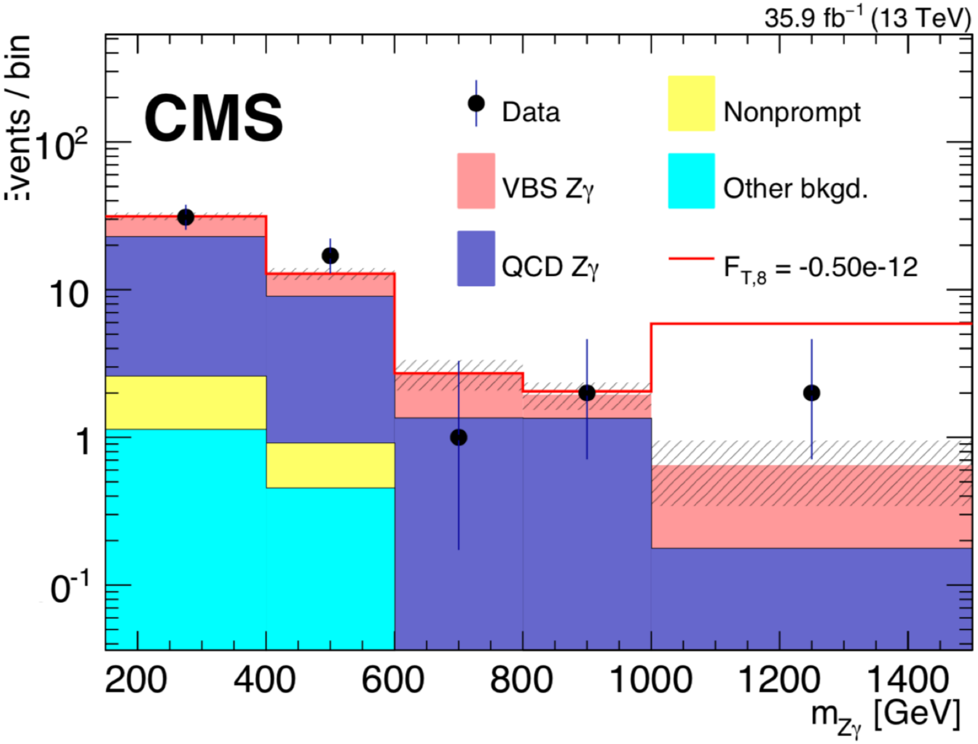
σ_{fid} (EW+QCD) = 14.3 ± 0.4 (lumi) ± 1.1 (stat) ± 2.7 (syst) fb = 14.3 ± 3.0 fb

$Z\gamma \rightarrow ll\gamma$ VBS: aQGC limits

Use the $m_{W\gamma}$ distribution to set limits on the anomalous Quartic Gauge Couplings:

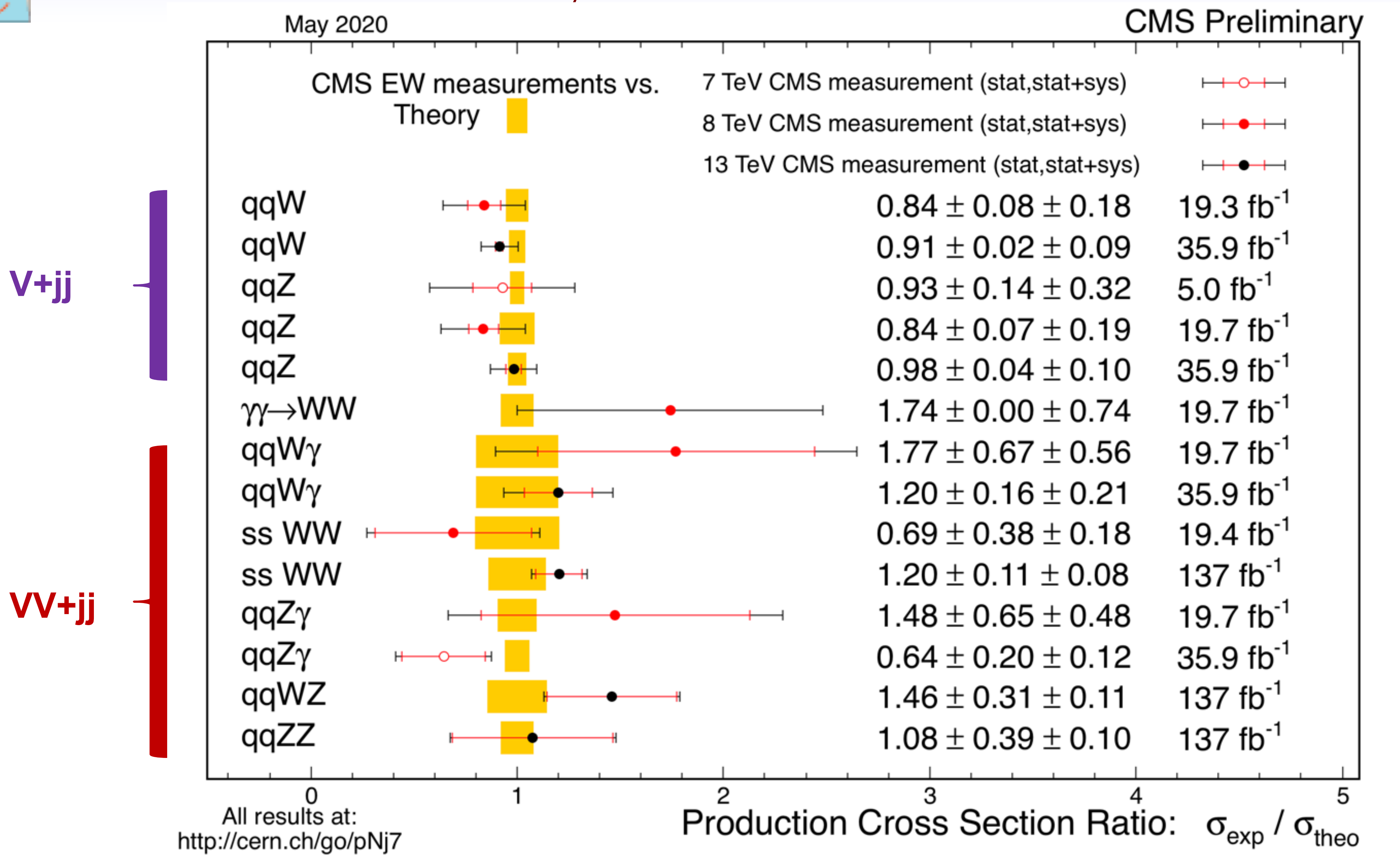


Observed limits [TeV^{-4}]	Expected limits [TeV^{-4}]	Unitarity bound [TeV]
$-19.5 < F_{M,0}/\Lambda^4 < 20.3$	$-15.0 < F_{M,0}/\Lambda^4 < 15.0$	1.0
$-40.5 < F_{M,1}/\Lambda^4 < 39.5$	$-30.0 < F_{M,1}/\Lambda^4 < 29.9$	1.2
$-8.22 < F_{M,2}/\Lambda^4 < 8.10$	$-6.09 < F_{M,2}/\Lambda^4 < 6.06$	1.3
$-17.7 < F_{M,3}/\Lambda^4 < 17.9$	$-13.1 < F_{M,3}/\Lambda^4 < 13.2$	1.4
$-15.3 < F_{M,4}/\Lambda^4 < 15.8$	$-11.7 < F_{M,4}/\Lambda^4 < 11.7$	1.4
$-25.1 < F_{M,5}/\Lambda^4 < 24.5$	$-19.0 < F_{M,5}/\Lambda^4 < 18.1$	1.8
$-38.9 < F_{M,6}/\Lambda^4 < 40.6$	$-29.9 < F_{M,6}/\Lambda^4 < 30.0$	1.0
$-60.3 < F_{M,7}/\Lambda^4 < 62.5$	$-45.9 < F_{M,7}/\Lambda^4 < 46.1$	1.3
$-0.74 < F_{T,0}/\Lambda^4 < 0.69$	$-0.56 < F_{T,0}/\Lambda^4 < 0.51$	1.4
$-0.98 < F_{T,1}/\Lambda^4 < 0.96$	$-0.72 < F_{T,1}/\Lambda^4 < 0.72$	1.4
$-1.97 < F_{T,2}/\Lambda^4 < 1.86$	$-1.47 < F_{T,2}/\Lambda^4 < 1.37$	1.4
$-0.70 < F_{T,5}/\Lambda^4 < 0.75$	$-0.51 < F_{T,5}/\Lambda^4 < 0.57$	1.7
$-1.64 < F_{T,6}/\Lambda^4 < 1.68$	$-1.23 < F_{T,6}/\Lambda^4 < 1.26$	1.6
$-2.59 < F_{T,7}/\Lambda^4 < 2.82$	$-1.91 < F_{T,7}/\Lambda^4 < 2.12$	1.7
$-0.47 < F_{T,8}/\Lambda^4 < 0.47$	$-0.36 < F_{T,8}/\Lambda^4 < 0.36$	1.5
$-1.27 < F_{T,9}/\Lambda^4 < 1.27$	$-0.94 < F_{T,9}/\Lambda^4 < 0.94$	1.5



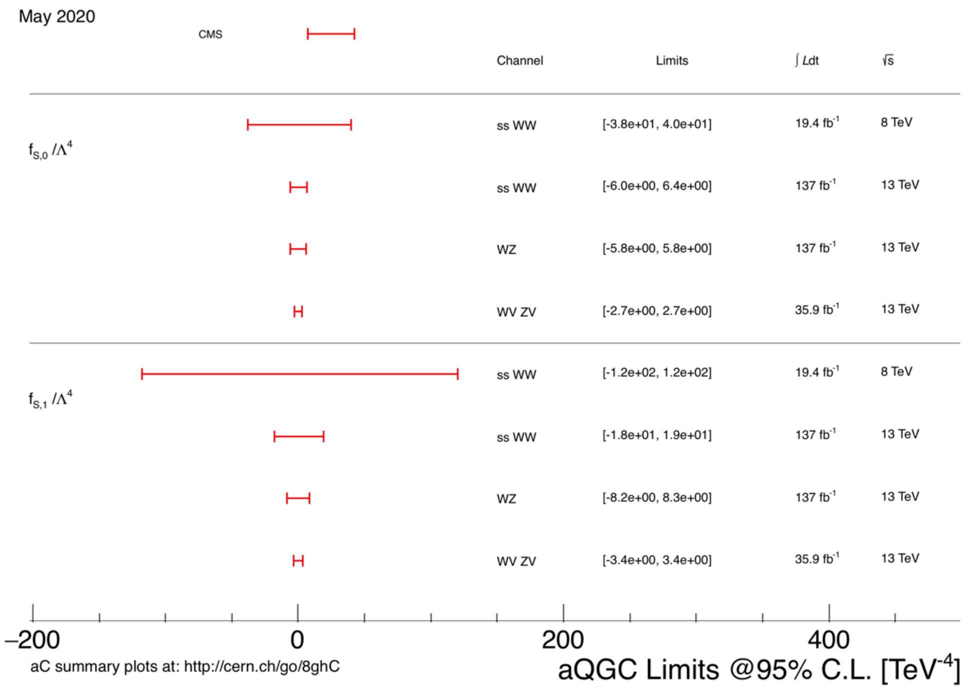
These results provide the most stringent limits to date on the aQGC parameters $F_{T,8}/\Lambda_4$ and $F_{T,9}/\Lambda_4$

Summary of Cross-sections



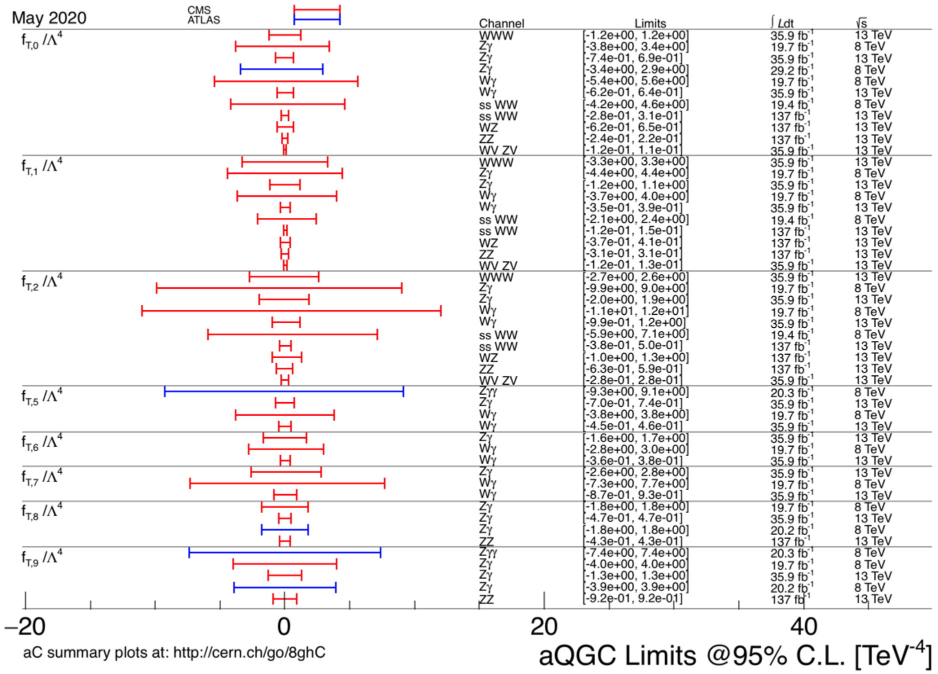
- → **Very large set of results on (V+jj and) VV+jj (VBS) by CMS with Run I/II data**
- → **Relatively good agreement with SM expectations**
- → **Vector Boson Scattering has been established by LHC Run II**
- → **Work on more channels & longitudinal XS ongoing in WW**

Summary of aQGC limits



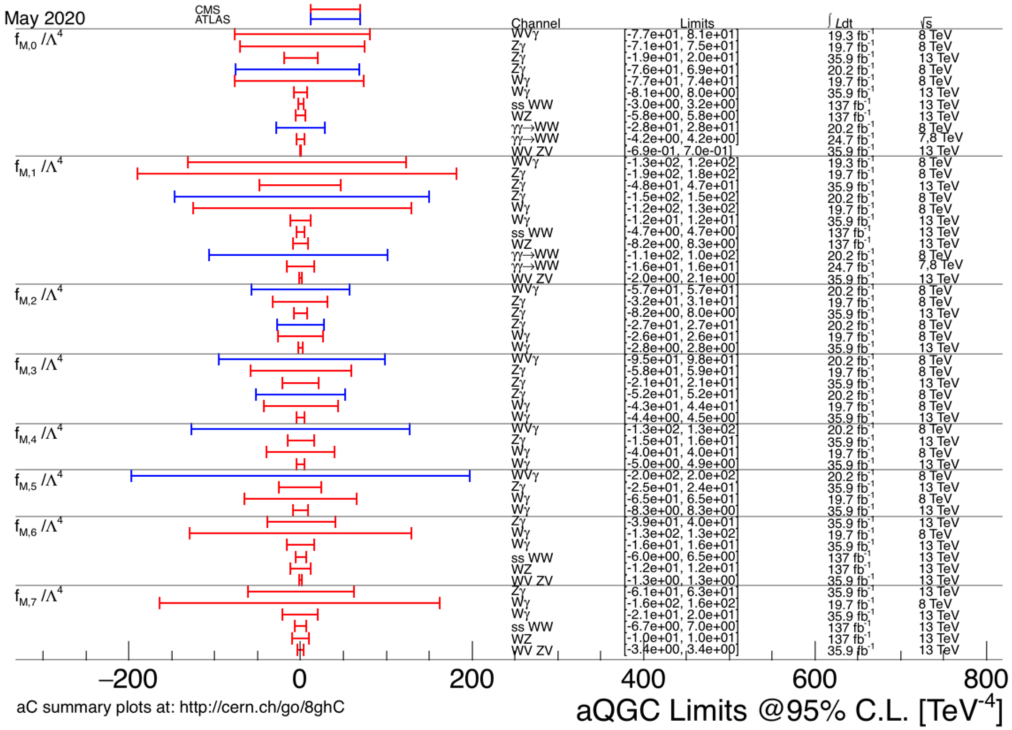
	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{S,0}/\Lambda^4$	ss WW	[-3.8e+01, 4.0e+01]	19.4 fb^{-1}	8 TeV
	ss WW	[-6.0e+00, 6.4e+00]	137 fb^{-1}	13 TeV
	WZ	[-5.8e+00, 5.8e+00]	137 fb^{-1}	13 TeV
	WV ZV	[-2.7e+00, 2.7e+00]	35.9 fb^{-1}	13 TeV
$f_{S,1}/\Lambda^4$	ss WW	[-1.2e+02, 1.2e+02]	19.4 fb^{-1}	8 TeV
	ss WW	[-1.8e+01, 1.9e+01]	137 fb^{-1}	13 TeV
	WZ	[-8.2e+00, 8.3e+00]	137 fb^{-1}	13 TeV
	WV ZV	[-3.4e+00, 3.4e+00]	35.9 fb^{-1}	13 TeV

aC summary plots at: http://cern.ch/go/8ghC



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	WWW	[-1.2e+00, 1.2e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-7.4e-01, 6.9e-01]	35.9 fb^{-1}	13 TeV
	Zγ	[-3.4e+00, 2.9e+00]	29.2 fb^{-1}	8 TeV
	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-6.2e-01, 6.4e-01]	35.9 fb^{-1}	13 TeV
	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-2.8e-01, 3.1e-01]	137 fb^{-1}	13 TeV
	WZ	[-6.2e-01, 6.5e-01]	137 fb^{-1}	13 TeV
	ZZ	[-2.4e-01, 2.2e-01]	137 fb^{-1}	13 TeV
	WV ZV	[-1.2e-01, 1.1e-01]	35.9 fb^{-1}	13 TeV
$f_{T,1}/\Lambda^4$	WWW	[-3.3e+00, 3.3e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.2e+00, 1.1e+00]	35.9 fb^{-1}	13 TeV
	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-3.5e-01, 3.9e-01]	35.9 fb^{-1}	13 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-1.2e-01, 1.5e-01]	137 fb^{-1}	13 TeV
	WZ	[-3.7e-01, 4.1e-01]	137 fb^{-1}	13 TeV
	ZZ	[-3.1e-01, 3.1e-01]	137 fb^{-1}	13 TeV
	WV ZV	[-1.2e-01, 1.3e-01]	35.9 fb^{-1}	13 TeV
$f_{T,2}/\Lambda^4$	WWW	[-2.7e+00, 2.6e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-2.0e+00, 1.9e+00]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-9.9e-01, 1.2e+00]	35.9 fb^{-1}	13 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
	ss WW	[-3.8e-01, 5.0e-01]	137 fb^{-1}	13 TeV
	WZ	[-1.0e+00, 1.3e+00]	137 fb^{-1}	13 TeV
	ZZ	[-6.3e-01, 5.9e-01]	137 fb^{-1}	13 TeV
	WV ZV	[-2.8e-01, 2.8e-01]	35.9 fb^{-1}	13 TeV
$f_{T,5}/\Lambda^4$	Zγγ	[-9.3e+00, 9.1e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-7.0e-01, 7.4e-01]	35.9 fb^{-1}	13 TeV
	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.5e-01, 4.6e-01]	35.9 fb^{-1}	13 TeV
$f_{T,6}/\Lambda^4$	Zγ	[-1.6e+00, 1.7e+00]	35.9 fb^{-1}	13 TeV
	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-3.6e-01, 3.8e-01]	35.9 fb^{-1}	13 TeV
$f_{T,7}/\Lambda^4$	Zγ	[-2.6e+00, 2.8e+00]	35.9 fb^{-1}	13 TeV
	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-8.7e-01, 9.3e-01]	35.9 fb^{-1}	13 TeV
$f_{T,8}/\Lambda^4$	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-4.7e-01, 4.7e-01]	35.9 fb^{-1}	13 TeV
	Zγ	[-1.8e+00, 1.8e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-4.3e-01, 4.3e-01]	137 fb^{-1}	13 TeV
$f_{T,9}/\Lambda^4$	Zγγ	[-7.4e+00, 7.4e+00]	20.3 fb^{-1}	8 TeV
	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.3e+00, 1.3e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-3.9e+00, 3.9e+00]	20.2 fb^{-1}	8 TeV
	ZZ	[-9.2e-01, 9.2e-01]	137 fb^{-1}	13 TeV

aC summary plots at: http://cern.ch/go/8ghC



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{M,0}/\Lambda^4$	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-1.9e+01, 2.0e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-7.6e+01, 6.9e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-8.1e+00, 8.0e+00]	35.9 fb^{-1}	13 TeV
	ss WW	[-3.0e+00, 3.2e+00]	137 fb^{-1}	13 TeV
	WZ	[-5.8e+00, 5.8e+00]	137 fb^{-1}	13 TeV
	γγ→WW	[-2.8e+01, 2.8e+01]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-4.2e+00, 4.2e+00]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-6.9e-01, 7.0e-01]	35.9 fb^{-1}	13 TeV
$f_{M,1}/\Lambda^4$	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	Zγ	[-4.8e+01, 4.7e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-1.5e+02, 1.5e+02]	20.2 fb^{-1}	8 TeV
	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.2e+01, 1.2e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-4.7e+00, 4.7e+00]	137 fb^{-1}	13 TeV
	WZ	[-8.2e+00, 8.3e+00]	137 fb^{-1}	13 TeV
	γγ→WW	[-1.1e+02, 1.0e+02]	20.2 fb^{-1}	8 TeV
	γγ→WW	[-1.6e+01, 1.6e+01]	24.7 fb^{-1}	7,8 TeV
	WV ZV	[-2.0e+00, 2.1e+00]	35.9 fb^{-1}	13 TeV
$f_{M,2}/\Lambda^4$	WVγ	[-5.7e+01, 5.7e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-8.2e+00, 8.0e+00]	35.9 fb^{-1}	13 TeV
	Zγ	[-2.7e+01, 2.7e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.8e+00, 2.8e+00]	35.9 fb^{-1}	13 TeV
$f_{M,3}/\Lambda^4$	WVγ	[-9.5e+01, 9.8e+01]	20.2 fb^{-1}	8 TeV
	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	Zγ	[-2.1e+01, 2.1e+01]	35.9 fb^{-1}	13 TeV
	Zγ	[-5.2e+01, 5.2e+01]	20.2 fb^{-1}	8 TeV
	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.4e+00, 4.5e+00]	35.9 fb^{-1}	13 TeV
$f_{M,4}/\Lambda^4$	WVγ	[-1.3e+02, 1.3e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-1.5e+01, 1.6e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-5.0e+00, 4.9e+00]	35.9 fb^{-1}	13 TeV
$f_{M,5}/\Lambda^4$	WVγ	[-2.0e+02, 2.0e+02]	20.2 fb^{-1}	8 TeV
	Zγ	[-2.5e+01, 2.4e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-8.3e+00, 8.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,6}/\Lambda^4$	Zγ	[-3.9e+01, 4.0e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.6e+01, 1.6e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-6.0e+00, 6.5e+00]	137 fb^{-1}	13 TeV
	WZ	[-1.2e+01, 1.2e+01]	137 fb^{-1}	13 TeV
	WV ZV	[-1.3e+00, 1.3e+00]	35.9 fb^{-1}	13 TeV
$f_{M,7}/\Lambda^4$	Zγ	[-6.1e+01, 6.3e+01]	35.9 fb^{-1}	13 TeV
	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.1e+01, 2.0e+01]	35.9 fb^{-1}	13 TeV
	ss WW	[-6.7e+00, 7.0e+00]	137 fb^{-1}	13 TeV
	WZ	[-1.0e+01, 1.0e+01]	137 fb^{-1}	13 TeV
	WV ZV	[-3.4e+00, 3.4e+00]	35.9 fb^{-1}	13 TeV

aC summary plots at: http://cern.ch/go/8ghC

→ aQGC (dim-8 EFT) has been explored In VBS at Run-II (also by ATLAS)

→ Stringent limits obtained

→ Ongoing work on adding the dim-6 on the picture in VBS (stay tuned)
+ need to incorporate effects of unitarity bounds coherently