VECTOR-BOSON FUSION AND SCATTERING MEASUREMENTS

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ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS

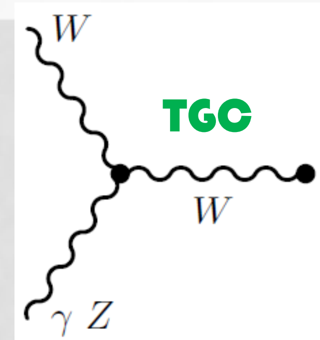
LHCP EW PLENARY SESSION, 9 JUNE 2021

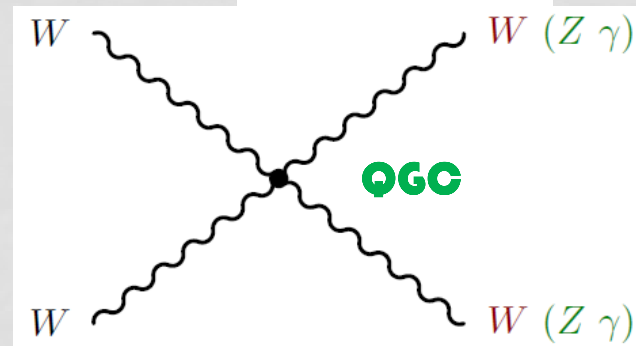
FOREWORD

- This is a VBS/VBF summary talk
- Only recent LHC Run2 results are included
- For those interested in more details, please refer to presentations (and watch recordings!) of the topical Monday session:
  - https://indico.cern.ch/event/905399/sessions/384934/#20210607

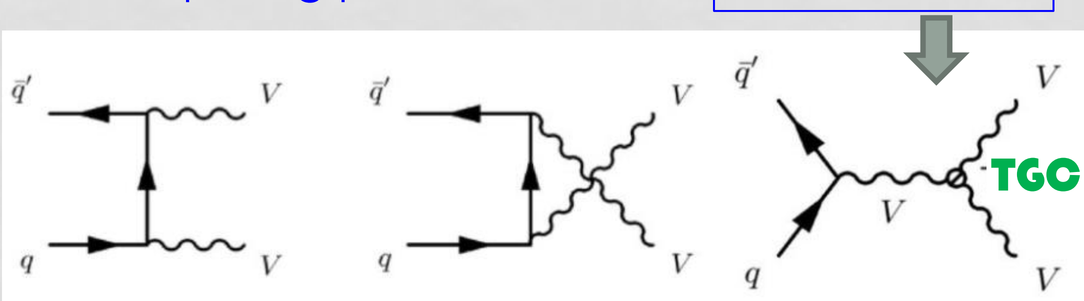
GAUGE SELF-COUPLINGS

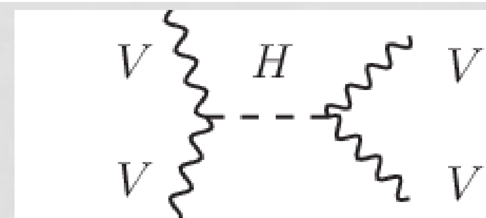
- Heavy gauge-bosons discovered decades before the Higgs boson
- Nevertheless, cubic and quartic gauge self-couplings yet among the least known SM structures
  - Theoretically very clean ← strengths determined by non-abelian SU(2)
  - Experimentally hard to investigate
    At the LHC final states:
    - with small cross-sections
    - and/or subdominant w.r.t. competing processes





Diboson production in pp collisions

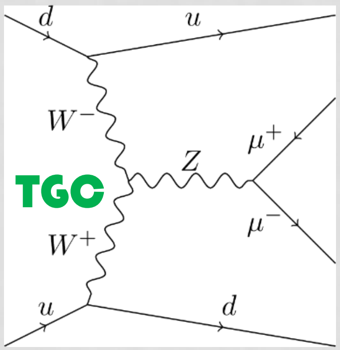


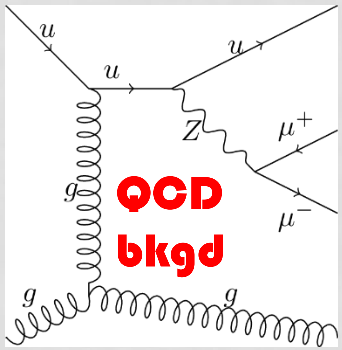


Interplay with Higgs sector

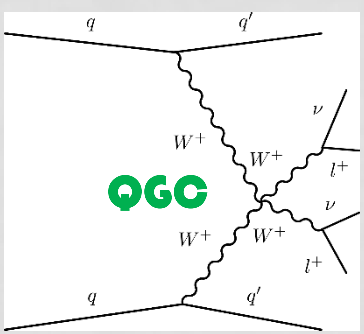
VBF AND VBS AT THE LHC

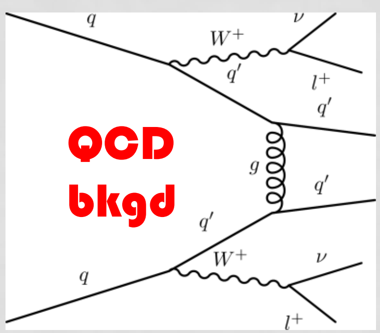
qq → Z qq (VBF)





qq → W⁺W⁺ qq (VBS)

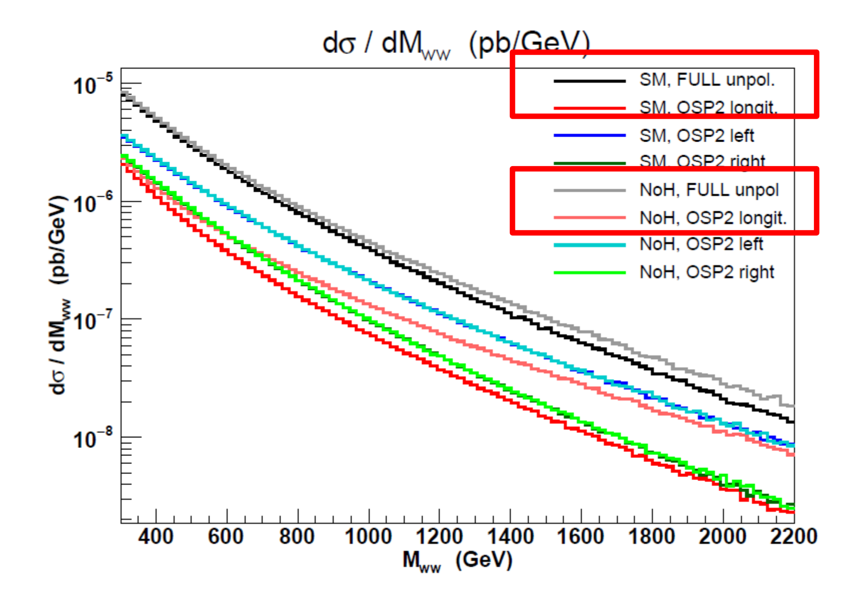




- EW process:
  - Experimental signature: V or VV and 2 jets from scattered quarks
- TGC and/or QGC diagrams at the LO (direct access to self-couplings)
- O(%) NLO QCD corrections on the EW component, unlike most LHC processes
  - Theory uncertainties very small
  - EW corrections become as important
- May have large SM backgrounds
  - Vjj or VVjj with jj from strong vertices
  - Top-quark production, for final states with many jets and/or W

OBSERVABLES / BSM MODELS (1)

- Observables
  - Cross-sections in detector-fiducial regions
    - EW only and/or total QCD+EW (theoretically cleaner, although interference terms are typically o(%) of the signal)
    - Usually requiring large di-jet rapidity separation (Δy_{jj}) and/or mass (m_{jj}) → enhances EW-only component
    - Differential, if data allows
  - Polarization
    - In the VBS case may be measured for both VV or be inclusive in one
- Constraints on concrete BSM models
  - A prominent example: alternative/additional sources of EWSB other than the Higgs boson modify significantly double-longitudinal component in VBS ($qq \rightarrow V_L V_L qq$)



Ballestrero, Maina, Pellicciolli, JHEP 03, 170 (2018)

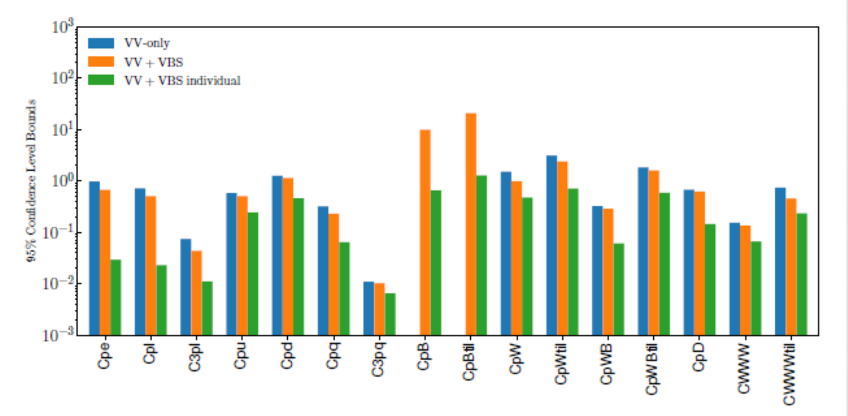
BSM MODELS (2): EFT

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

- VBF processes setting competitive limits on d=6 operator coefficients
  - Usually given using SILH or Warsaw bases
- VBS case more complex, as it receives similar-size BSM contributions from both d=6 and d=8. Two alternative approaches:
  - Neglect d=6, as constrained by many other LHC data (Higgs, dibosons…) → set limits on d=8 coefficients using gauge-boson-specific basis by Eboli et al.

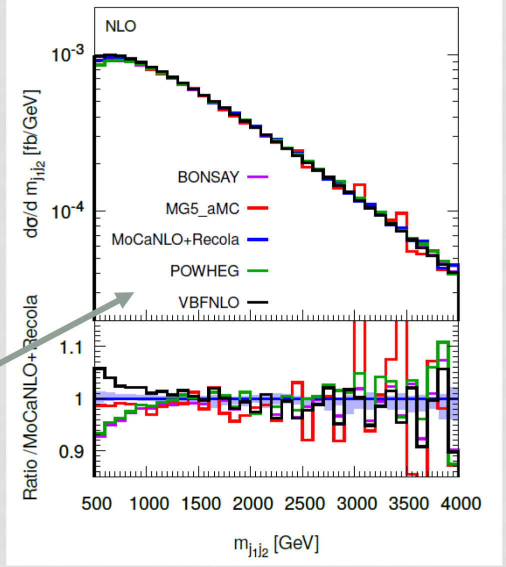
    Phys.Rev.D 74 (2006) 073005
  - Include d=6 VBS constraints (although weaker) in combinations

    arXiv:2011.07367
    arXiv:2101.03180



MEASUREMENT CHALLENGES

- Experimental:
  - Large QCD backgrounds: matrix-element techniques or machine-learning
  - Missing neutrinos in $W \rightarrow l\nu$ final states: p_L^ν reconstruction (1ν) or use approximations (2ν)
  - Jet systematic uncertainties in forward regions
- Physics modeling:
  - EW signals
    - Large theory-experimental efforts to cross-validate MC generators
    - Parton-shower schemes very important
  - VVjj QCD
    - Very expensive computations at NLO and/or matched+merged (MG5_aMC@NLO/Sherpa)
    - Need careful validation in data control regions
  - EFT QGCs
    - Avoid unitarity violation by setting energy cut-offs



Ballestrero et al.,
Eur. Phys. J. C 78, 671 (2018)

Jaeger et al.
Eur. Phys. J. C 80, 756 (2020)

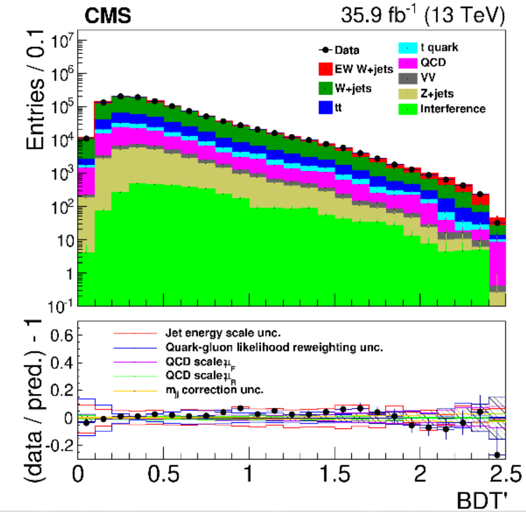
VBSCan

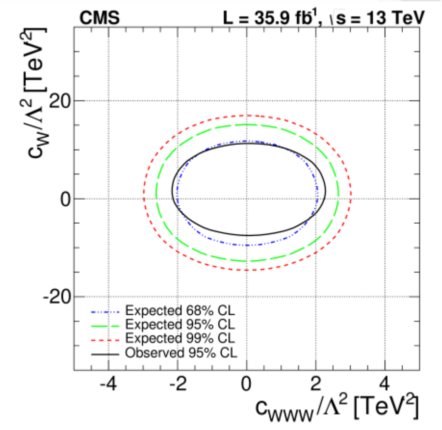
LPCC
LHC Physics Centre at CERN
Electroweak WG

VBF W $\rightarrow \ell\nu$

CMS, Eur. Phys. J. C 80 (2020) 43

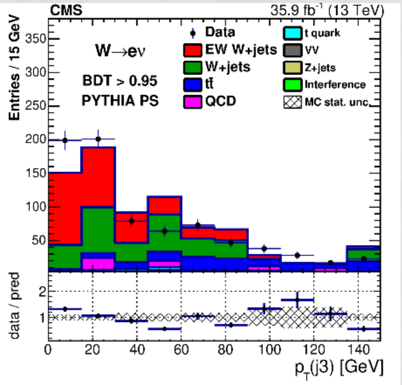
- CMS:
  - BDT-based analysis for EW extraction
    - Input variables: $p_{T,miss}$, $m_T(W)$, m_{jj}, Δy_{jj}, W Zeppenfeld variables…
    - Include quark-gluon discrimination for jets
  - Results:
    - Fiducial cross-section
    - EFT d=6 constraints (also combined with VBF Z, next slide)
    - Dedicated studies of extra jet activity with different PS programs

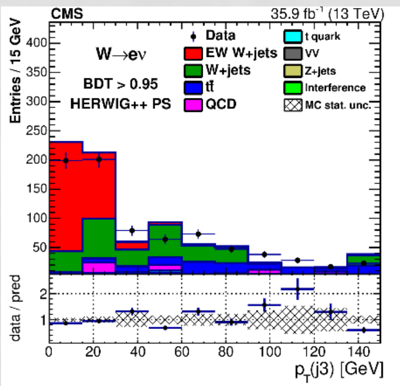




$$\sigma(\mathrm{EW}\ \ell\nu\mathrm{jj}) = 6.07 \pm 0.12\,(\mathrm{stat}) \pm 0.57\,(\mathrm{syst})\,\mathrm{pb}$$

$$\sigma_{\mathrm{NLO}}(\mathrm{EW}\ \ell\nu\mathrm{jj}) = 6.74^{+0.02}_{-0.04}\,(\mathrm{scale}) \pm 0.26\,(\mathrm{PDF})\,\mathrm{pb}.$$

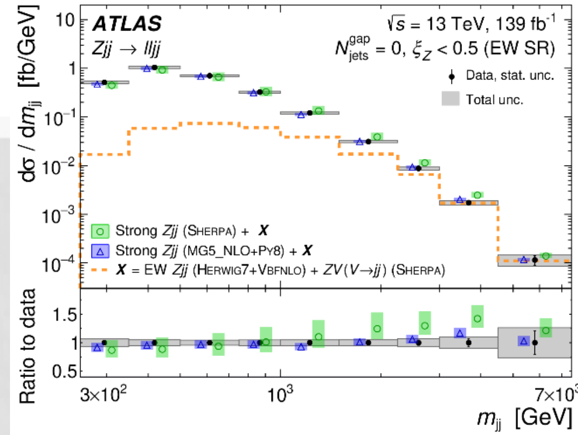




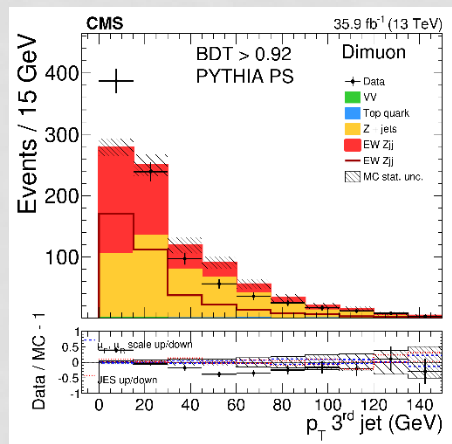
VBF Z → ℓℓ

CMS, Eur. Phys. J. C 78 (2018) 589
ATLAS, Eur. Phys. J. C 81 (2021) 163

- ATLAS:
  - Binned analysis in m_{jj}, in 1 signal and 3 control regions defined by ξ_Z and N_{jets} in Δy_{jj} gap
  - Focus on fiducial and differential cross-sections (EW and EW+QCD)
- CMS:
  - Similar to VBF W: BDT-based analysis for EW extraction
  - Cross-section in fiducial (but looser) region
  - Both: constraints on d=6 EFT



$$\sigma_{\mathrm{EW}} = 37.4 \pm 3.5\,(\mathrm{stat}) \pm 5.5\,(\mathrm{syst})\ \mathrm{fb}$$
$$\textsc{Herwig7+Vbfnlo}\ 39.5 \pm 3.4\,(\mathrm{scale}) \pm 1.2\,(\mathrm{PDF})\ \mathrm{fb}.$$



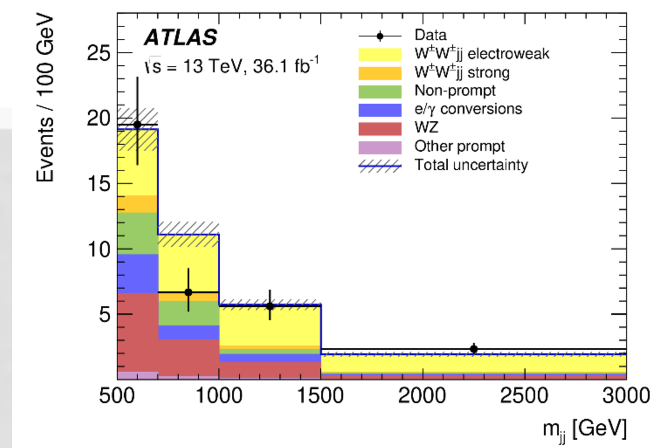
Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	interval [TeV^{-2}] Observed
c_W/Λ^2	no	[−0.19, 0.41]
	yes	[−0.19, 0.41]
$\tilde{c}_W/\Lambda^2$	no	[−0.11, 0.14]
	yes	[−0.11, 0.14]
c_{HWB}/Λ^2	no	[−3.78, 1.13]
	yes	[−6.31, 1.01]
$\tilde{c}_{HWB}/\Lambda^2$	no	[0.23, 2.34]
	yes	[0.23, 2.35]

$$\sigma(\mathrm{EW}\ \ell\ell\mathrm{jj}) = 534 \pm 20\,(\mathrm{stat}) \pm 57\,(\mathrm{syst})\ \mathrm{fb}$$
$$\sigma_{\mathrm{LO}}(\mathrm{EW}\ \ell\ell\mathrm{jj}) = 543 \pm 24\ \mathrm{fb}$$

VBS $W^{\pm}W^{\pm} \rightarrow 2\ell^{\pm}2\nu$

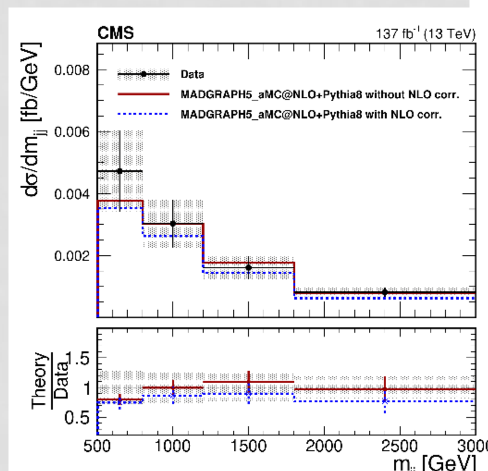
CMS, Phys. Lett. B 809, 135710 (2020)
ATLAS, Phys. Rev. Lett. 123, 161801 (2019)

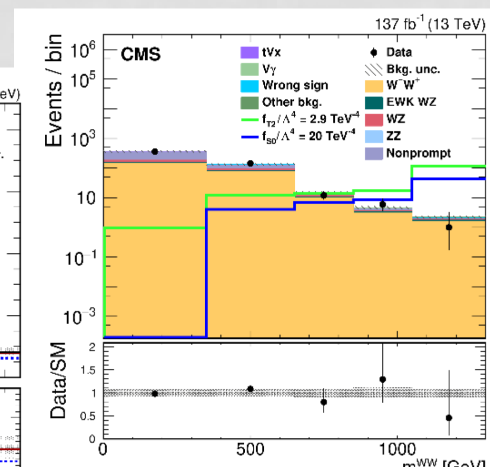
- «Golden channel» (σ_{EW}/σ_{QCD}~10)
- Non-prompt background estimates from data
- ATLAS (SM observation)
  - Signal-region data in four m_{jj} bins fit together with 3l and low-m_{jj} regions
- CMS (SM observation + EFT)
  - Fits of 2-dimensional distributions in bins of m_{jj} and $m_{\ell\ell}$ in signal and control regions (also differentially in m_{jj}, $m_{\ell\ell}$, and leading-lepton p_T)
  - Stringent limits on d=8 EFT from m_T(WW) distribution



$$\sigma^{\text{fid.}} = 2.89^{+0.51}_{-0.48}\,(\text{stat.})\,^{+0.24}_{-0.22}\,(\text{exp. syst.})\,^{+0.14}_{-0.16}\,(\text{mod. syst.})\,^{+0.08}_{-0.06}\,(\text{lumi.})\text{ fb,}$$

Disagreement with Sherpa from suboptimal MC configuration

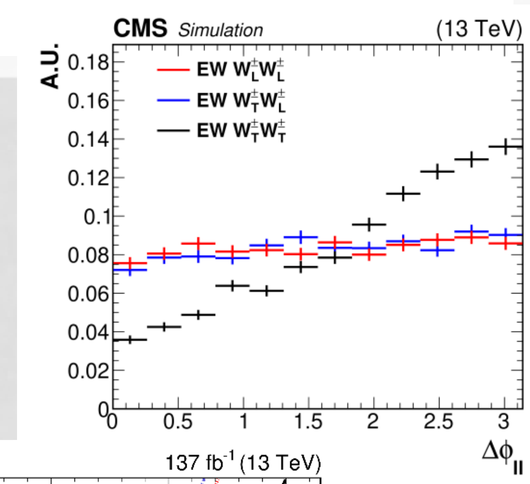


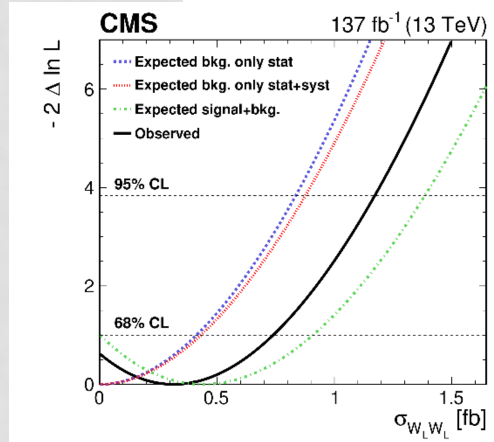


VBS $W^{\pm}W^{\pm} \rightarrow 2\ell^{\pm}2\nu$ POLARIZATION

CMS, Phys. Lett. B 812, 136018 (2021)

- Challenging measurement
  - Dedicated MC simulation (MG5_aMC@NLO)
  - Very low expected yields for $W_L W_L$
  - W four-momenta unknown (no direct access to helicity angles)
- CMS:
  - 2-dimensional fits of 2 BDT output scores
    - <u>Inclusive</u>: optimized to select EW WWjj over backgrounds
    - <u>Signal</u>: optimized to select $W_L W_L$ or $W_L W_X$ over other polarization states
  - 2.6σ observed significance for $W_L W_X$



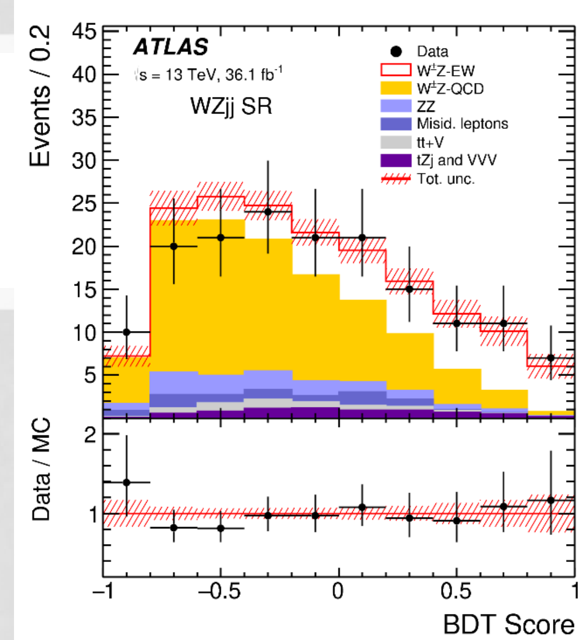


Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^{\pm}_{L}W^{\pm}_{L}$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
	< 1.17 @95% CL	
$W^{\pm}_{L}W^{\pm}_{X}$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18

VBS WZ → $3\ell 1\nu$

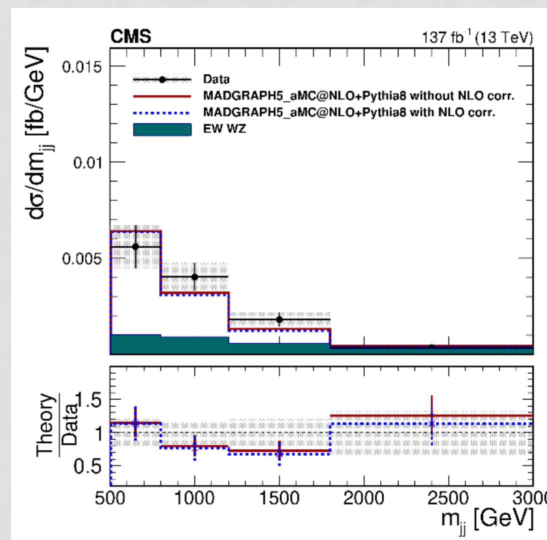
- QCD WZ ← largest background
  - Use of BDT-based analyses: inputs from lepton/jet kinematic variables and relative separation
  - W four-momentum by constraining m(W) to derive p_L^{ν}
- ATLAS (SM observation)
- CMS (SM observation + EFT)
  - Analysis methods shared with same-sign WW
  - Constraints on d=8 EFT from $m_T(WZ)$ distribution

ATLAS, Phys. Lett. B 793, 469 (2019)



$$\sigma^{\mathrm{fid.}}_{WZjj-\mathrm{EW}} = 0.57\,^{+0.14}_{-0.13}\,(\mathrm{stat.})\,^{+0.05}_{-0.04}\,(\mathrm{exp.\ syst.})\,^{+0.05}_{-0.04}\,(\mathrm{mod.\ syst.})\,^{+0.01}_{-0.01}\,(\mathrm{lumi.})\ \mathrm{fb}$$

$$\sigma^{\mathrm{fid.,\ Sherpa}}_{WZjj-\mathrm{EW}} = 0.321 \pm 0.002\,(\mathrm{stat.}) \pm 0.005\,(\mathrm{PDF})^{+0.027}_{-0.023}\,(\mathrm{scale})\ \mathrm{fb},$$

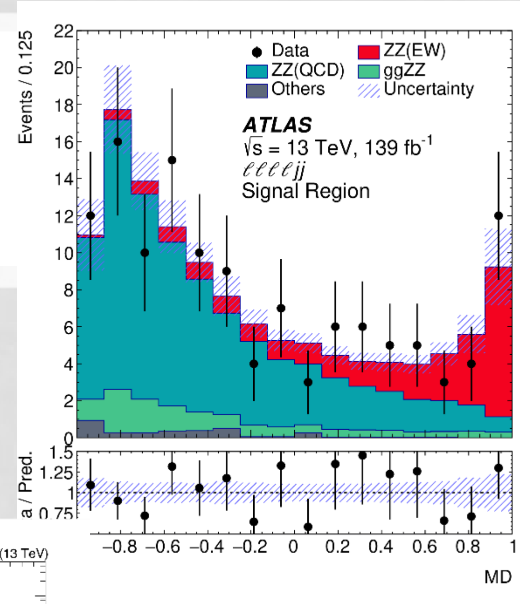


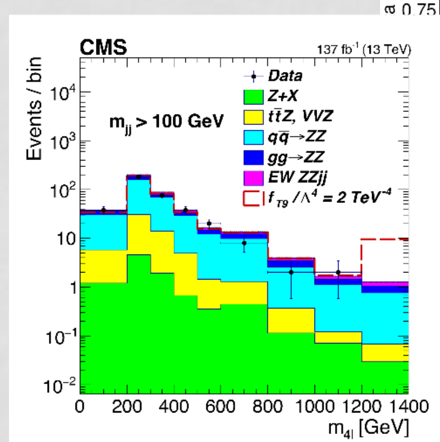
CMS, Phys. Lett. B 809, 135710 (2020)

VBS ZZ → 4ℓ

- QCD ZZ ← largest background
- ATLAS (5.5σ significance)
  - BDT analysis
  - Combination with 2l2ν channel
  - Focus on SM EW and EW+QCD cross-section
- CMS (4.0σ signif. + EFT)
  - Using advanced MC simulation for loop-induced QCD ZZ
  - Matrix-element analyses (MEs from MCFM program, at LO)
  - Fiducial cross-sections in different EW-purity regions
  - Constraints on d=8 EFT operators (T8, T9) from m(4l) distribution

ATLAS, arXiv: 2004.10612





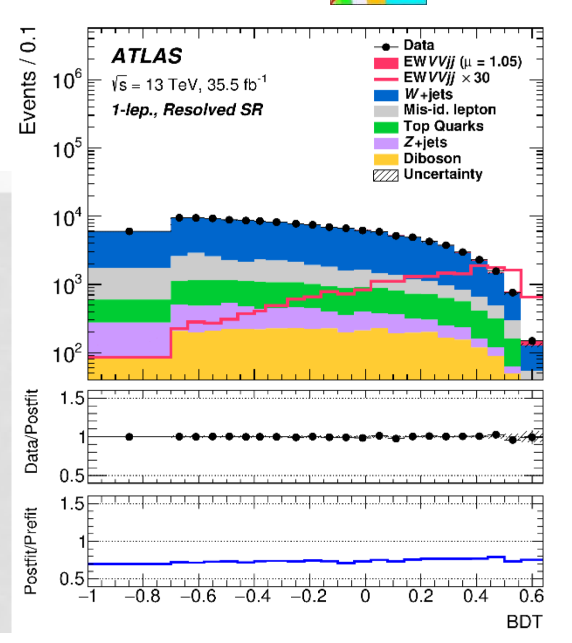
CMS, Phys. Lett. B 812, 135992 (2021)

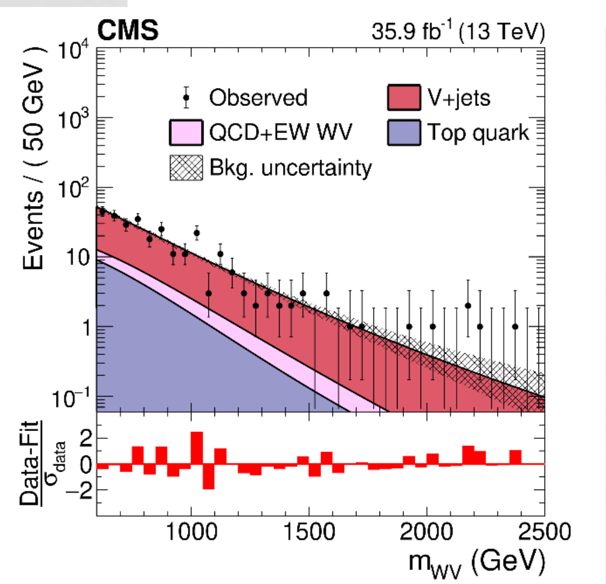
		SM σ (fb)	Measured σ (fb)
		inclusive	
EW	LO	0.275 ± 0.021	$0.33^{+0.11}_{-0.10}$ (stat) $^{+0.04}_{-0.03}$ (syst)
	NLO QCD	0.278 ± 0.017	
	NLO EW	$0.242^{+0.015}_{-0.013}$	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}$ (stat) ± 0.47 (syst)
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	$0.180^{+0.070}_{-0.060}$ (stat) $^{+0.021}_{-0.012}$ (syst)
	NLO QCD	0.197 ± 0.013	
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}$ (stat) ± 0.07 (syst)
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03}$ (stat) ± 0.02 (syst)
	NLO QCD	0.108 ± 0.007	
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04}$ (stat) ± 0.02 (syst)

SEMILEPTONIC VBS VV

- WVjj → $\ell\nu$ 4j or $\ell\nu$ 2j 1J
- ZVjj → $\ell\ell$ / $\nu\nu$ 4j
  or $\ell\ell$ / $\nu\nu$ 2j 1J
- ATLAS:
  - SM-targeted
  - BDT-based in a total of 9 event categories (number of charged leptons, low/high purity merged-jet reconstruction, resolved-jet reconstruction)
  - 2.7σ SM-VBS significance
- CMS:
  - cut-based analysis, optimized for VV high-invariant-mass regions
  - 2 categories: $\ell\nu$ or $\ell\ell$ plus a merged jet
  - Best limits on a large set of d=8 EFT operators

CMS, Phys. Lett. B 798, 134985 (2019)
ATLAS, Phys. Rev. D 100, 032007 (2019)

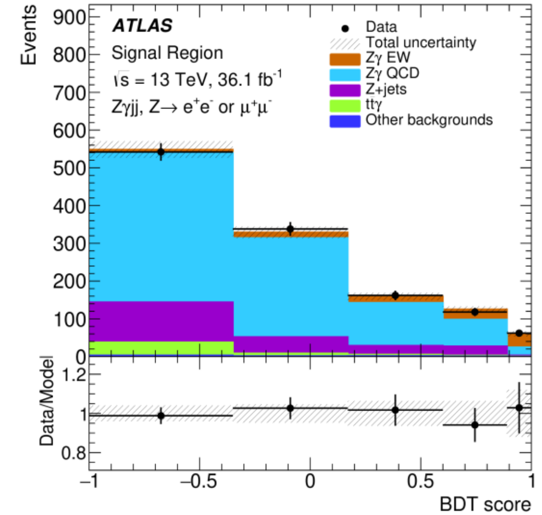


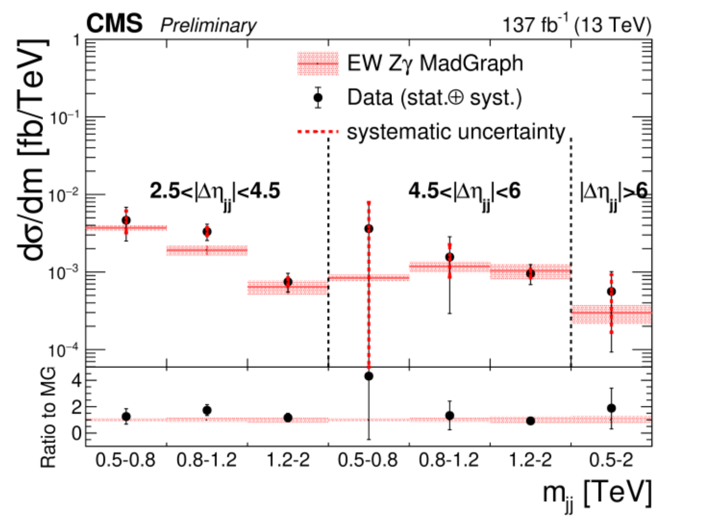


VBS WITH PHOTONS

CMS, Phys. Lett. B 811, 135988 (2020)
CMS-PAS-SMP-20-016
ATLAS collab., Phys. Lett. B 803, 135341 (2020)

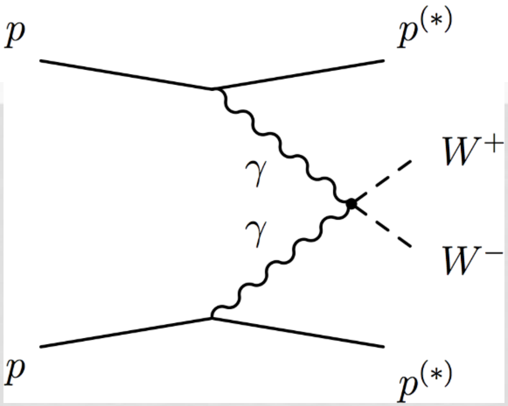
- Wγjj (CMS)and Zγjj analyses (CMS/ATLAS)
  - Leptonic heavy-boson decays combined with isolated photons (in ATLAS also converted γ considered)
  - <u>ATLAS</u>: BDT-based analysis
  - <u>CMS</u>: two dimensional fits using (m_{jj}, $\Delta\eta_{jj}$) for Zγjj and (m_{jj}, $m_{l\gamma}$) for Wγjj
- Significances:
  - 4.1σ (Zγjj ATLAS)
  - 5.3σ (Wγjj CMS)
  - Zγjj CMS: observation + differential cross-sections
- For Wγjj, best limits for certain d=8 operators (M/T5, 6, 7)

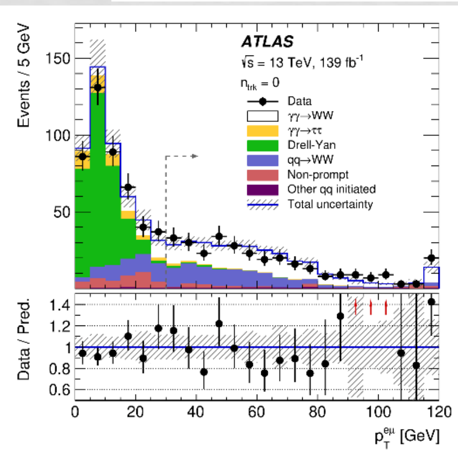


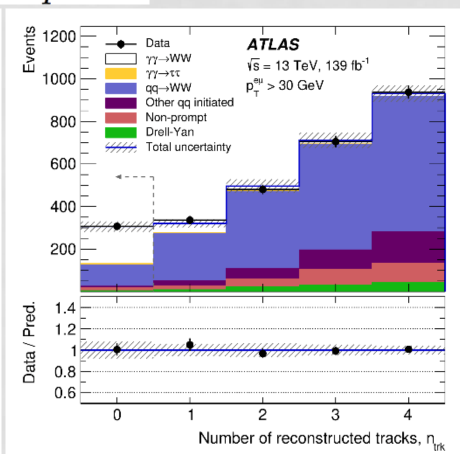


ATLAS, Phys. Lett. B 816 (2021) 136190

$\gamma\gamma \rightarrow W^+W^-$







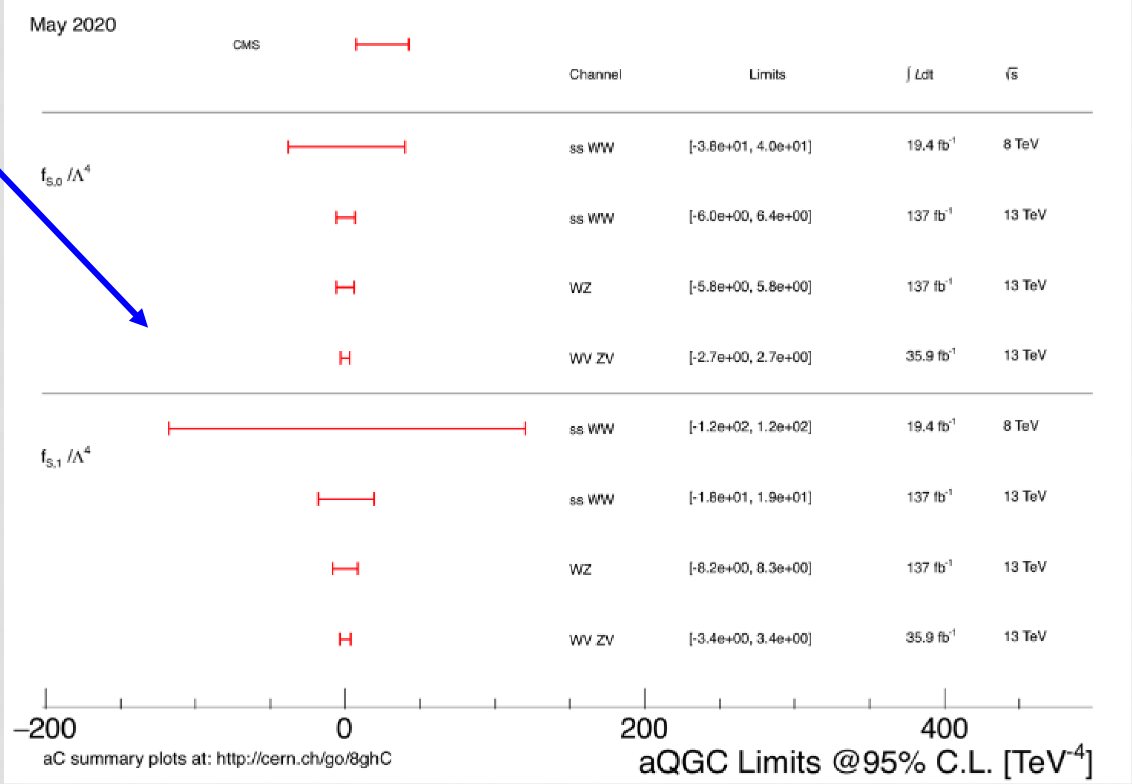
$$\sigma_{\text{meas}} = 3.13 \pm 0.31\,(\text{stat.}) \pm 0.28\,(\text{syst.})\ \text{fb}$$

- Exclusive production processes are mediated through $\gamma\gamma$ fusion
  - Use eμ final state
  - Large QCD WW background removed by requiring 0 extra tracks in the detector → implies control on:
    - QCD WW underlying event
    - Pile-up description
    - Proton rescattering effects

    achieved through control samples + transfer factors
- First observation of the process

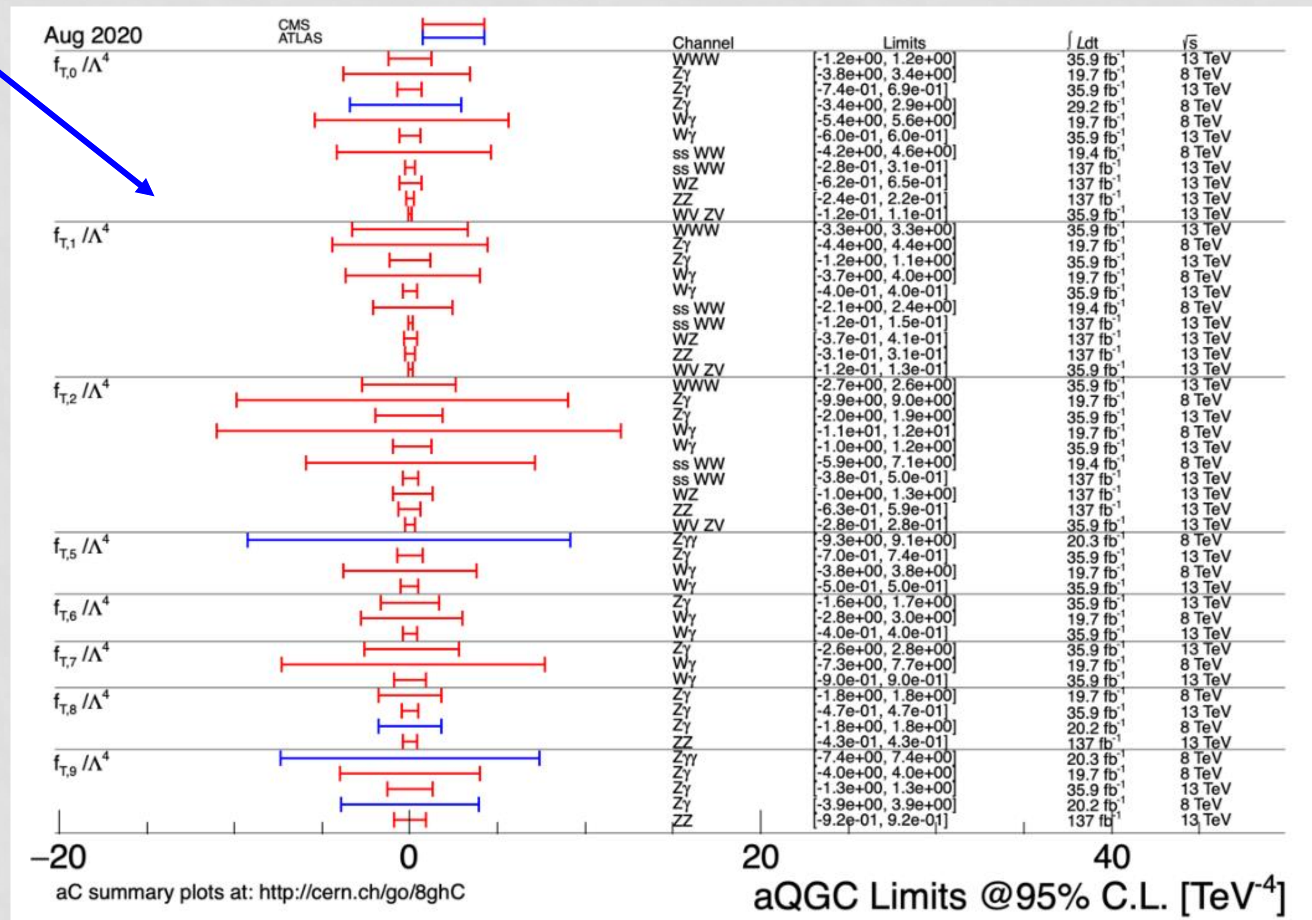
EFT D=8 SUMMARY

«Scalar» operators (4 Higgs-field derivatives)



EFT D=8 SUMMARY

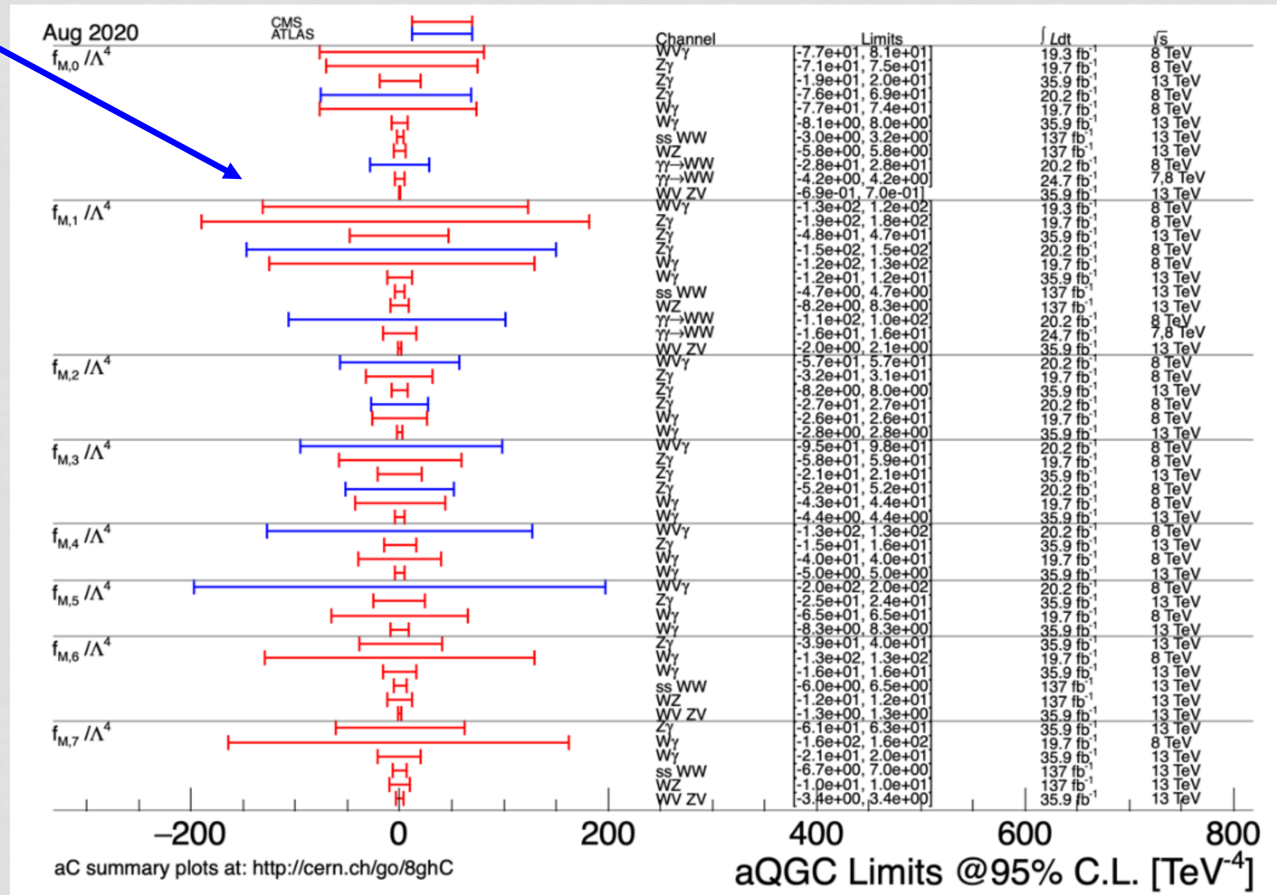
«Transverse» operators (4 gauge tensors)



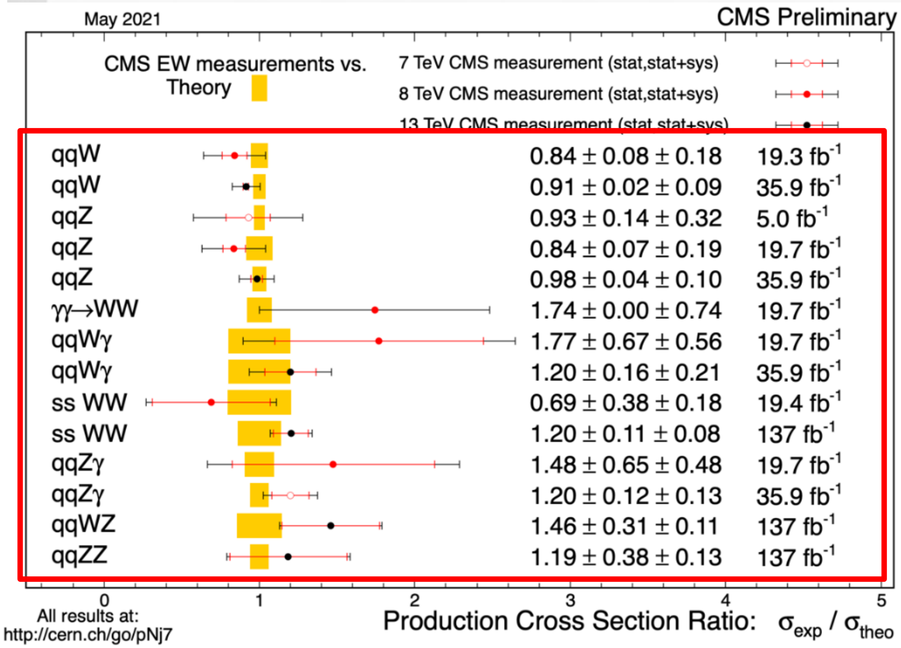
EFT D=8 SUMMARY

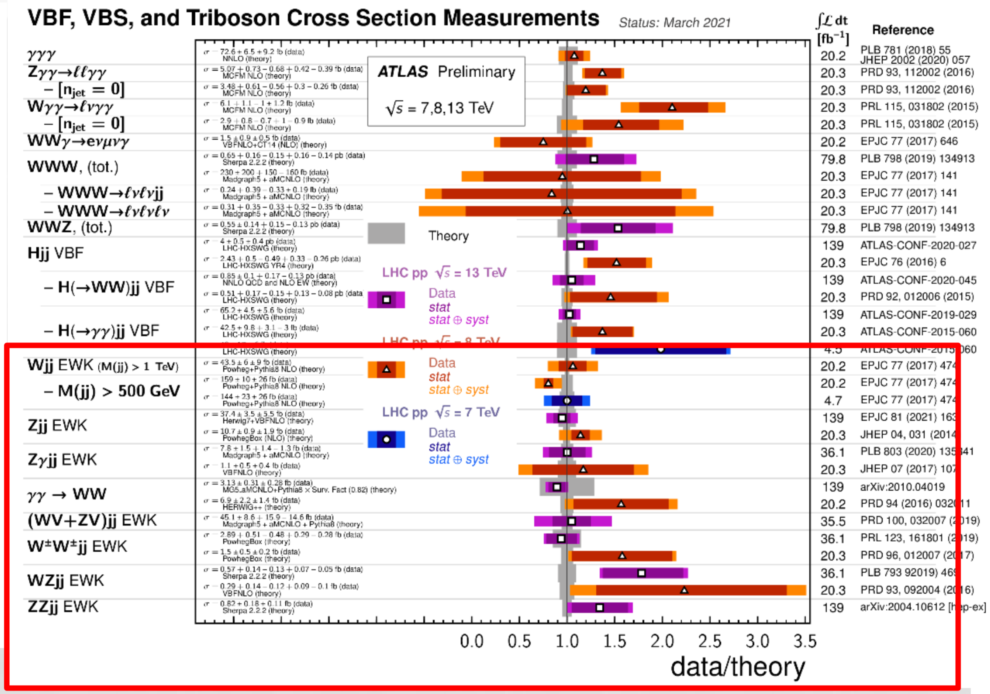
«Mixed» (2 and 2)

- In general <u>excellent agreement with expectations</u>



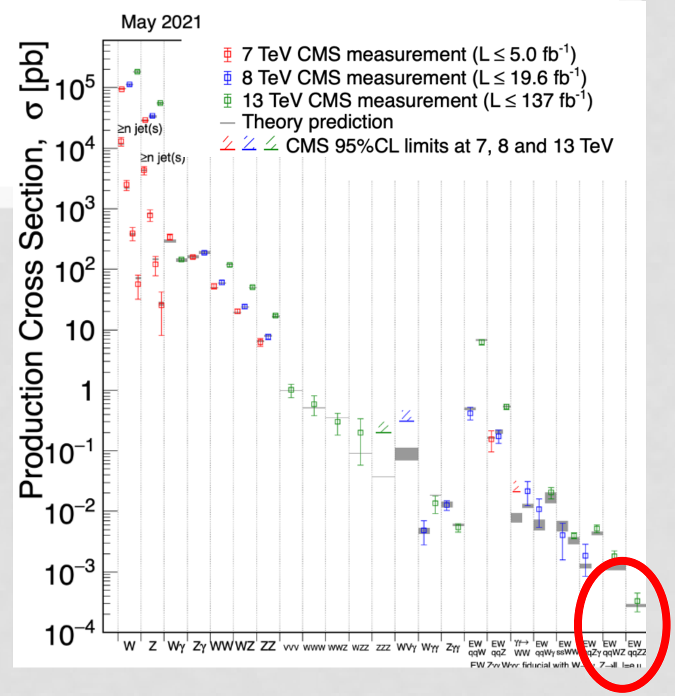
CROSS-SECTION SUMMARY





- Good agreement with SM
  - VBS VV exhibits a (not yet significant) «$\sigma > \sigma_{SM}$ trend», but not specifically at high energy ← EFT limits
  - Importance of modeling of all di-boson+2 jet QCD contributions at the best possible accuracy → very challenging task, large amount of theory literature in recent years

CONCLUSIONS



- VBF and VBS challenges
  - Low yields and in most cases large irreducible backgrounds, multivariate analyses are a must
  - Needs modeling of QCD with 2 extra jets with best possible accuracy
- VBS and VBS measurements
  - Among the rarest processes ever measured
  - Evidence/observation and first cross-section measurements only possible thanks to partial or full LHC 13-TeV data
  - Access to elusive gauge self-couplings and NP limits from EFTs
  - VBS VV investigating EWSB at scales different from Higgs mass
    - Polarization measurements crucial, we have just started

Full set of Run 2 results + LHC Run3 data essential to clarify global picture