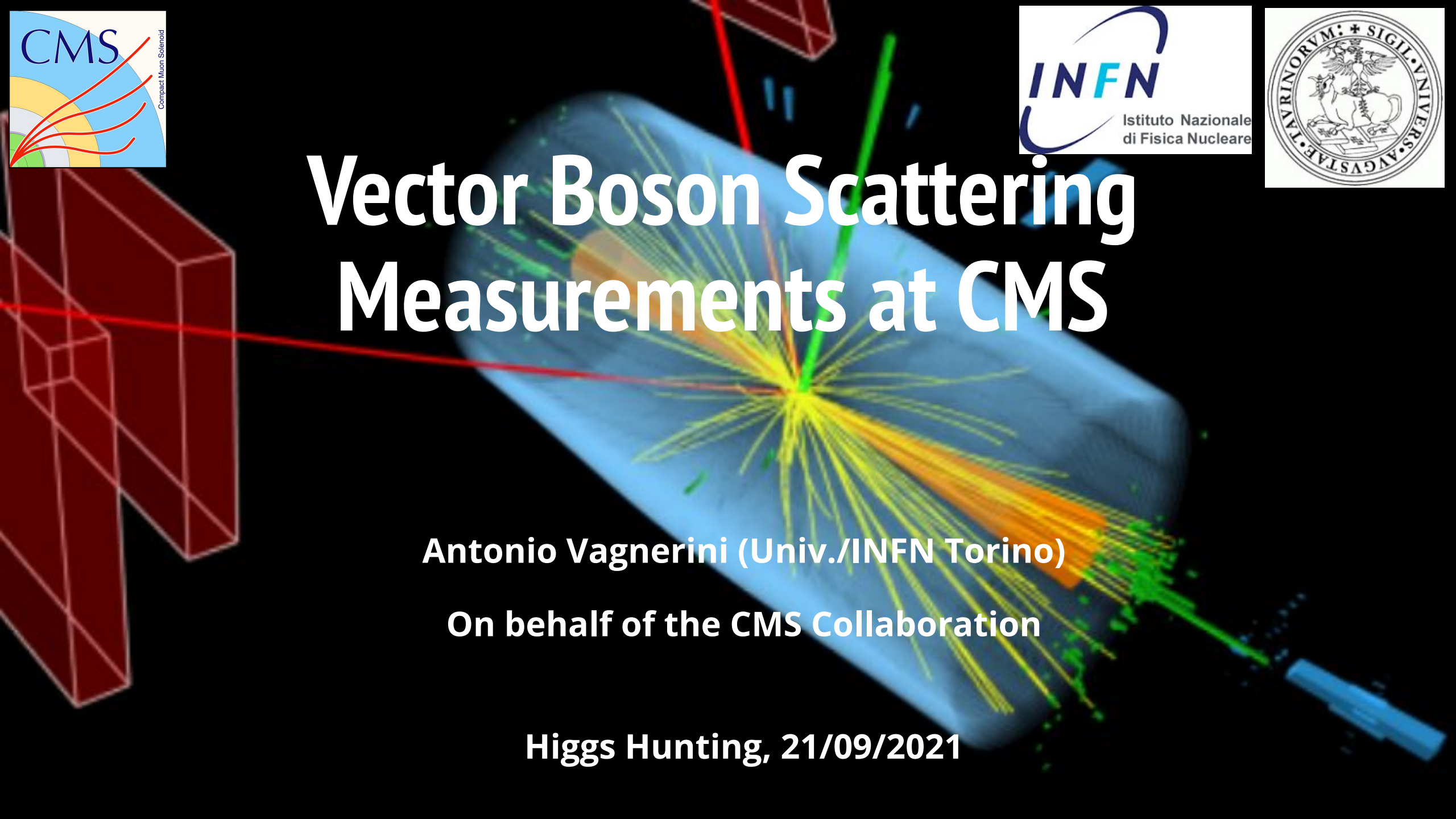


Vector Boson Scattering Measurements at CMS

Antonio Vagnerini (Univ./INFN Torino)

On behalf of the CMS Collaboration

Higgs Hunting, 21/09/2021

Outline

- This is a **VBS summary talk** of the most recent **CMS measurements**
  - only **results** obtained with the **full Run 2 data** are included

- **Several final states** presented:
  - **fully-leptonic** : $W^{\pm}W^{\pm} \rightarrow 2l2\nu$; $WZ \rightarrow 3l\nu$; $ZZ \rightarrow 4l$
  - **semi-leptonic**: $WW/WZ \rightarrow l\nu jj$;
  - **with photons**: $Z\gamma \rightarrow 2l\gamma$;

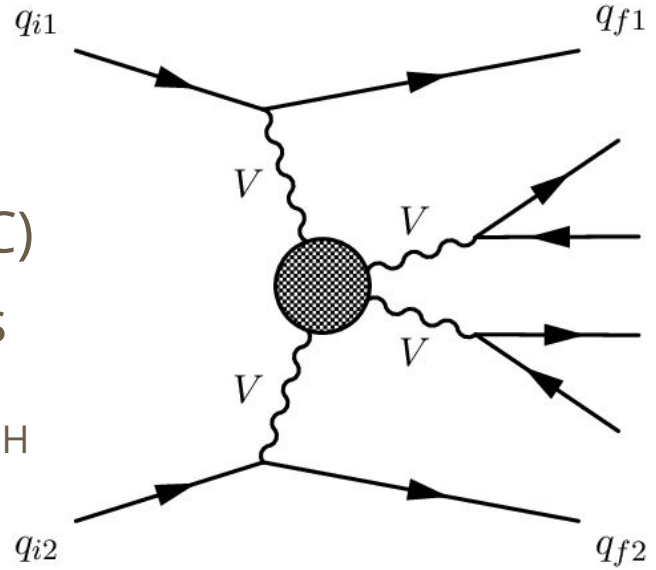
- Inclusive/differential **cross-section measurements**

- **EFT interpretation** and constraints on anomalous **quartic gauge couplings**
  - **VBS** targets **explicit models** e.g. VBF $H^{\pm}$ and $H^{\pm\pm}$, see talk by Attikis

- **Prospects** for VV scattering measurements **at the HL-LHC** with the CMS detector

Motivation for VV scattering measurements

- **Electroweak process** characterised by **VVjj (V = W/Z) final state**



- **Probes** the **non-Abelian nature of SM:**
  - direct access to **triple/quartic gauge** couplings (TGC/QGC)
  - **sensitive** to **couplings** between **Higgs** and **gauge** bosons
    - complementary to **Higgs** measurements at scales > m_H

- **Portal to BSM physics:**
  - **model-independent** via **E**ffective **F**ield **T**heories (EFTs)
    - **18 bosonic** operators in **dim-8 EFT** tested
    - set constraints on anomalous gauge couplings, **aQGCs**

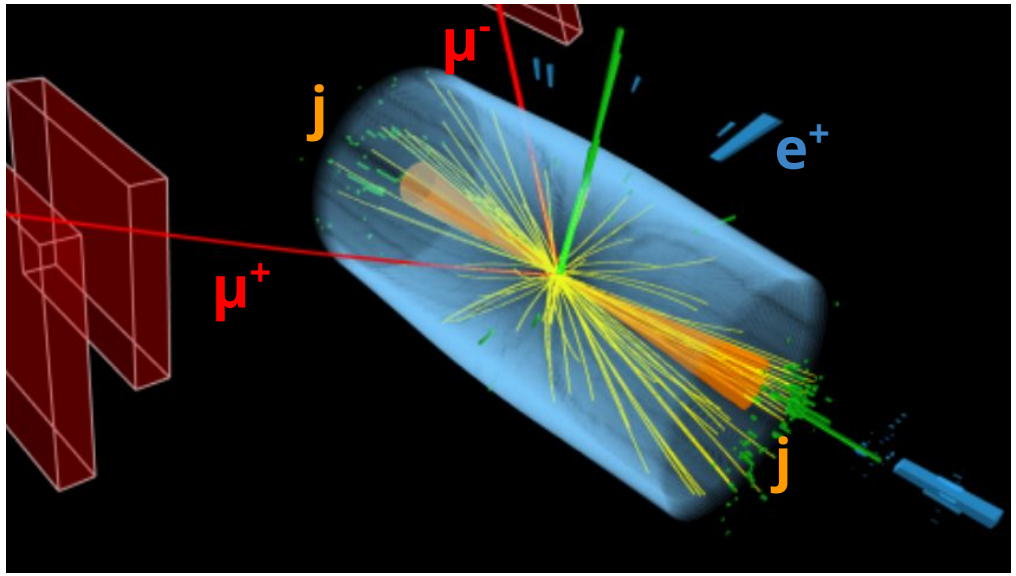
Phys.Rev.D 74 (2006) 073005

VV scattering at the LHC

- **Event topology**:
  - **2 vector bosons** produced **centrally**
  - **2 energetic tagging jets** emitted back-to-back

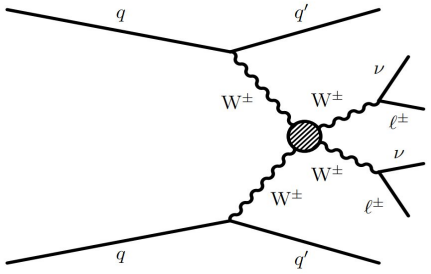
- **Signature** based on **diboson** final states:
  - **fully leptonic:** 4 e/μ & 2 jets
  - **semi-leptonic/hadronic:** 4 jets & 1 or 2 e/μ
  - fully-hadronic: 4 or 6 jets

$W^+Z \to e^+\nu\mu^+\mu^-\nu jj$ candidate event



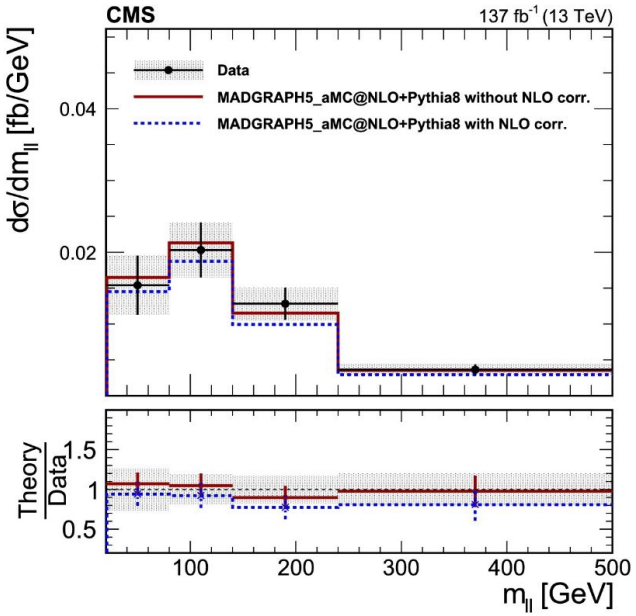
- Irreducible **tree-level contributions** to the final state:
  - **EW = $O(\alpha^6_{EW})$: signal** component
  - **QCD = $O(\alpha^4_{EW}\alpha^2_S)$ background : suppressed** in **high m_{jj}** and **high $|\Delta\eta_{jj}|$** region
  - **Interference = $O(\alpha^5_{EW}\alpha_S)$ term :** typically **O(%) of the signal**

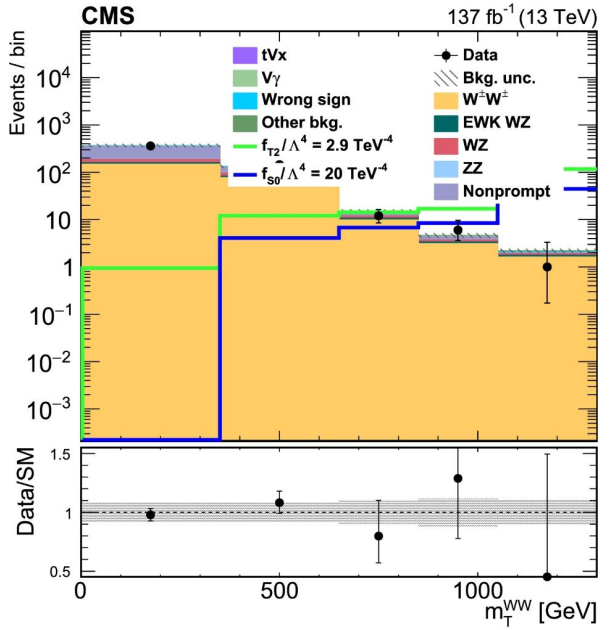
VBS $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$



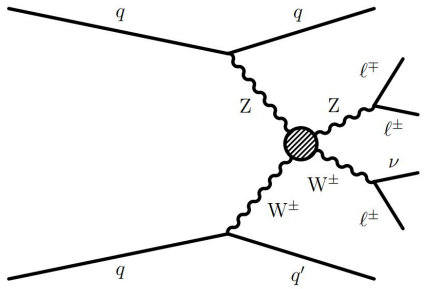
CMS, Phys. Lett. B 809, 135710 (2020)

- **Same-sign WW fully leptonic is a "golden channel"**
  - good separation EW/QCD components σ_{EW}/σ_{QCD}~4-6
  - full tower of NLO corrections known
- **Simultaneous** measurement **of $W^{\pm}W^{\pm}$/WZ** production
  - advantageous in definition signal/control region
- **Data-driven** estimation **of non-prompt background**
- **Cross section** measurement:
  - **inclusive** xsec from fit to the 2D m_{jj},-$m_{ll'}$ plane
  - **differential** in m_{jj},$m_{ll'}$ $p_{T,l1}$
- Stringent limits on **dim-8 EFT** operators from m_T(WW)

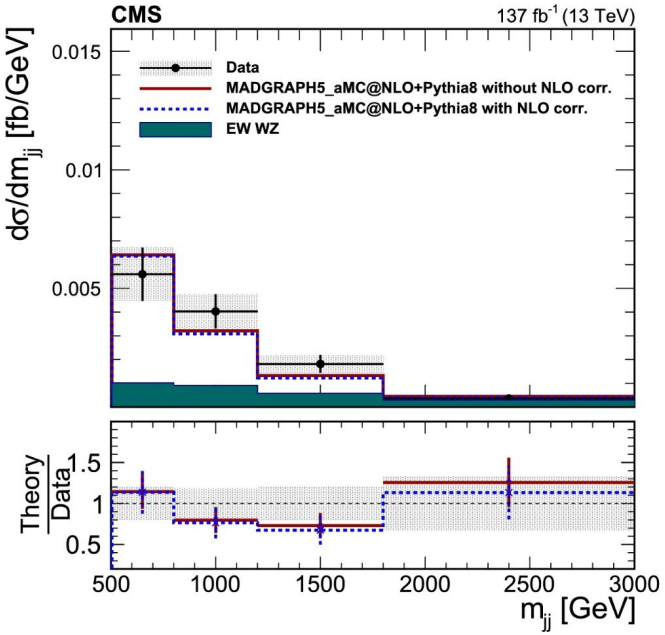




VBS WZ → 3l1ν

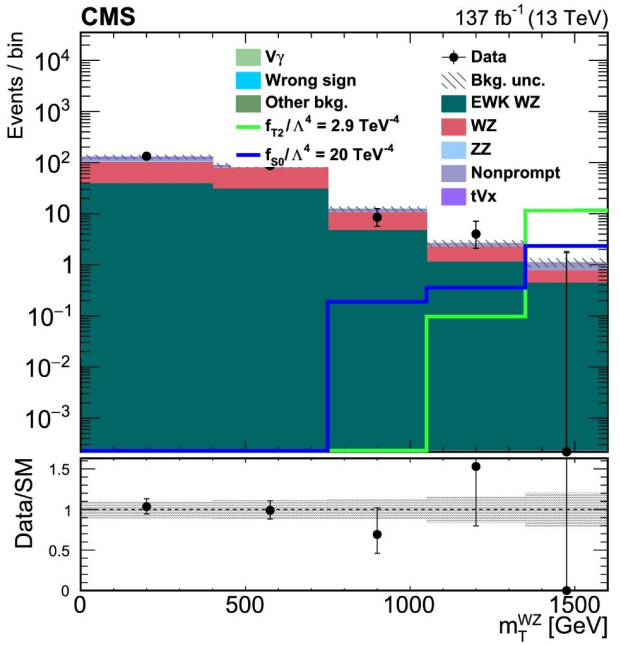


CMS, Phys. Lett. B 809, 135710 (2020)



- **WZjj production** has **clean** 3-lepton **signature**
  - larger QCD bkg contribution since σ_{EW}/σ_{QCD}~1/2
- **BDT with lepton/jet kinematic** as input variables
  - sensitivity improvement wrt 2D fit by 20%
- Analysis methods in common with **W±W±**

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 (stat) $\pm$ 0.25 (syst))	3.93 ± 0.57	3.31 ± 0.47
EW+QCD $W^{\pm}W^{\pm}$	4.42 ± 0.47 (0.39 (stat) $\pm$ 0.25 (syst))	4.34 ± 0.69	3.72 ± 0.59
EW WZ	1.81 ± 0.41 (0.39 (stat) $\pm$ 0.14 (syst))	1.41 ± 0.21	1.24 ± 0.18
EW+QCD WZ	4.97 ± 0.46 (0.40 (stat) $\pm$ 0.23 (syst))	4.54 ± 0.90	4.36 ± 0.88
QCD WZ	3.15 ± 0.49 (0.45 (stat) $\pm$ 0.18 (syst))	3.12 ± 0.70	3.12 ± 0.70



- Constraints on dim-8 EFT operators from m_T(WZ)

VBS $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$ Polarisation

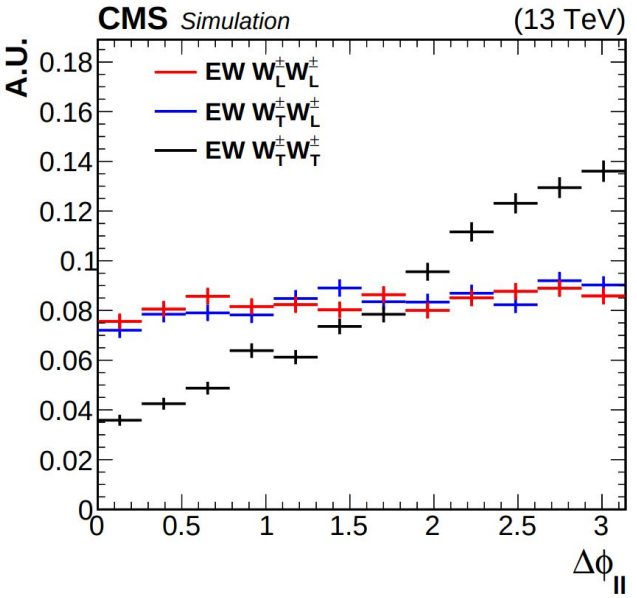
CMS, Phys. Lett. B 812, 136018 (2021)

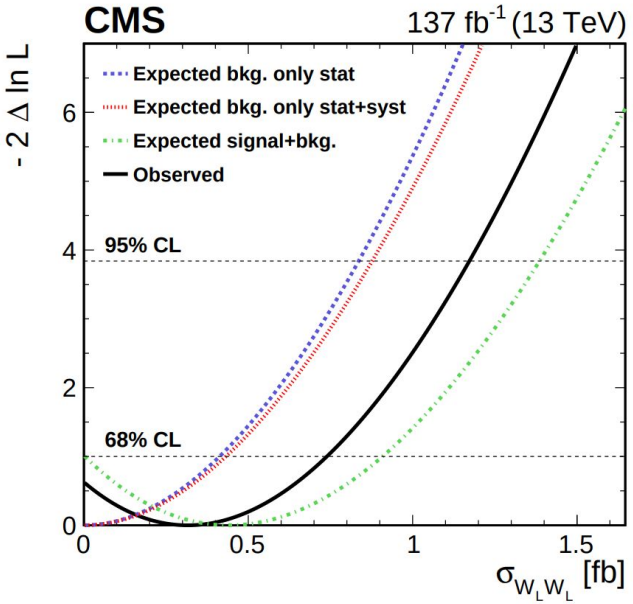
- First measurement of **polarization states** in VBS $W^{\pm}W^{\pm}$
  - **challenging** since **low** expected **yields** for W_LW_L
  - **four-momentum** of **W-boson unknown**
    - no direct access to helicity angles

- Similar **strategy** but different variables in BDT training
  - separately for WW & parton-parton rest frame

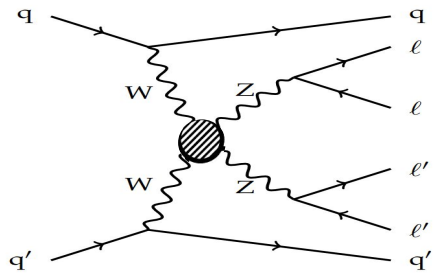
- **Two-dimensional fit** of two BDT output scores
  - **inclusive**: optimised to isolate EW WW from bkg
  - **signal** : designed to select W_LW_L or W_LW_X against other polarisation states

- Obs (exp) **2.6(2.9)σ** significance for EW W_LW_X productior and 95% U.L. of **1.17(0.88) fb** for W_LW_L





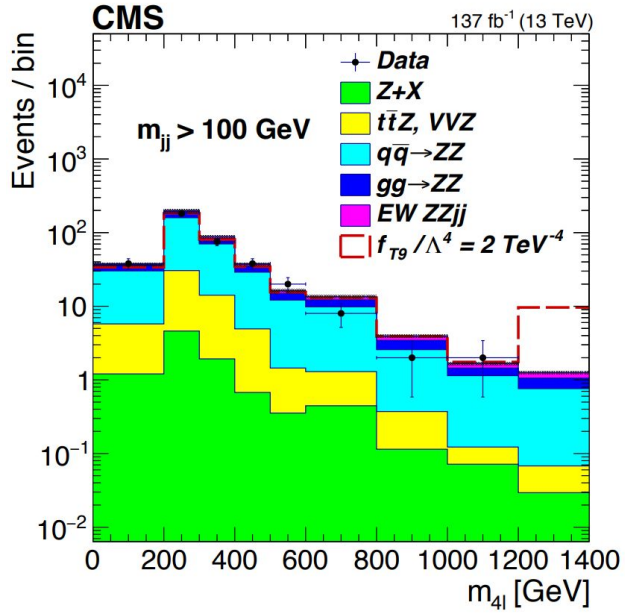
VBS ZZ →4l



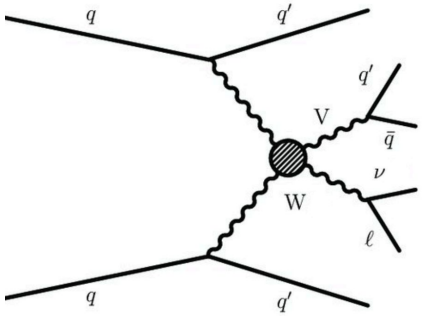
CMS, Phys. Lett. B 812, 135992 (2021)

- **One of the rarest SM processes observed to date:**
  - **4l+2j clean channel** with two $l^{\pm}l^{\mp}$ pairs
  - **NLO QCD correction available** matched to PS
- **Evidence of EW ZZjj** production at **4.0σ**
- **Matrix element analysis with discriminant K_D**
  - to better distinguish signal from QCD ZZ (main bkg)
- **Fiducial** cross-section in **3** regions differing in **EW-purity**
- Constraints on **dim-8 EFT** operators (T8,T9)
  - from **m(4l)** involving only neutral fields

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

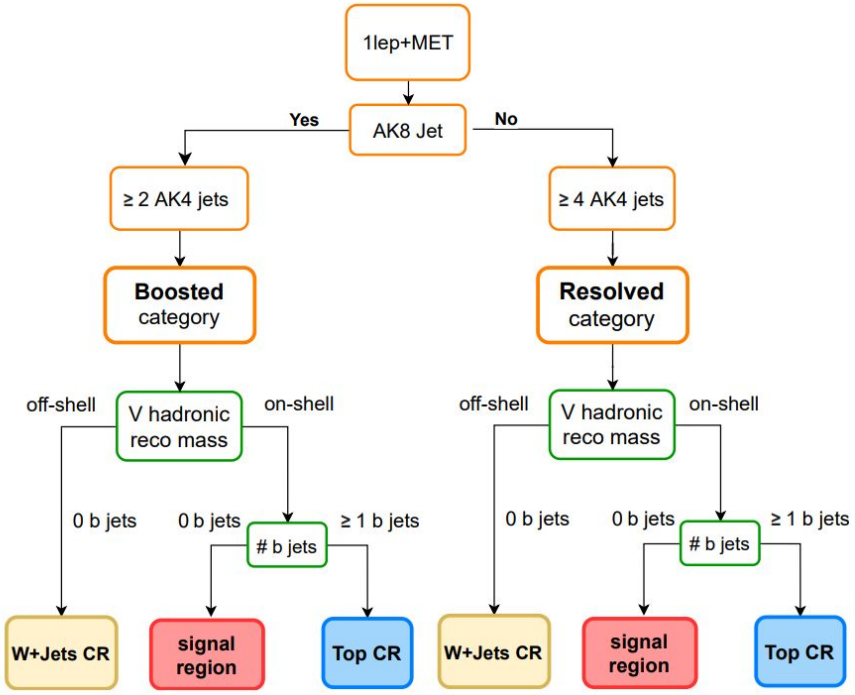


VBS WW/WZ →lνjj

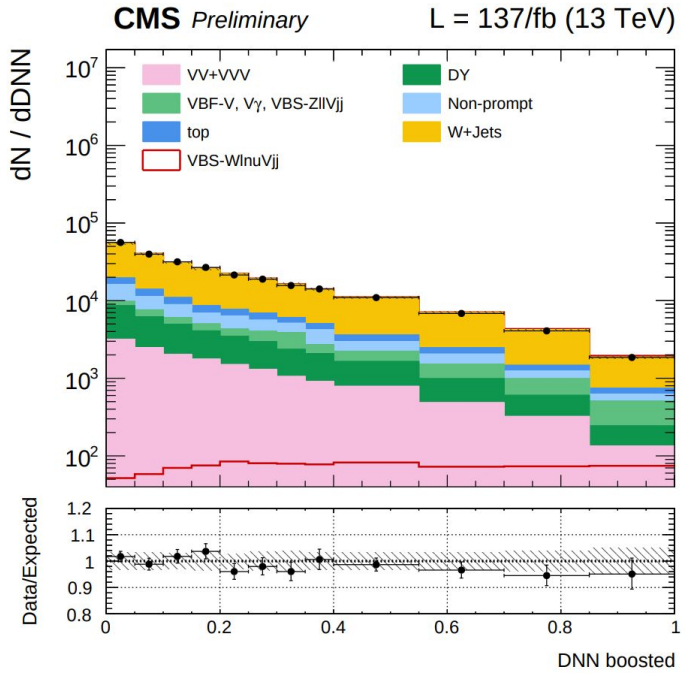


CMS-SMP-20-013
CDS:2776799

- Two vector bosons: **W→e/μν** and **V ≡W/Z →qq**
  - **large hadronic BR(V→qq)** compensates for **high irreducible** background
  - either **two jets** (**resolved** category) or one **merged jet (boosted)**

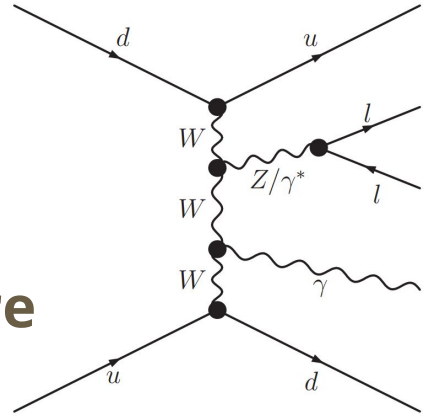


- **DNN discriminant** in signal region
- **W+jets /top-quark** control regions



- Observed (expected) **4.4(5.1)σ** significance for EW WV production

VBS Zγ →2lγ



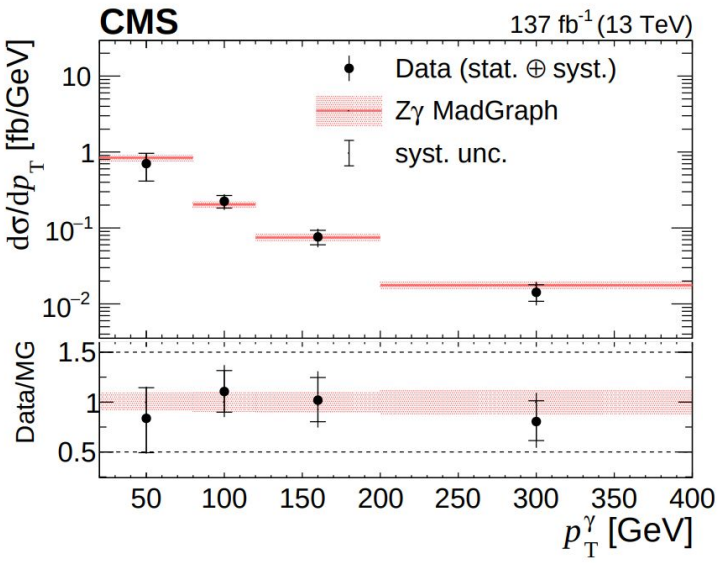
- **Zγ→l±l∓ γ** relatively **clean signature**
  - except **QCD-induced** bkg

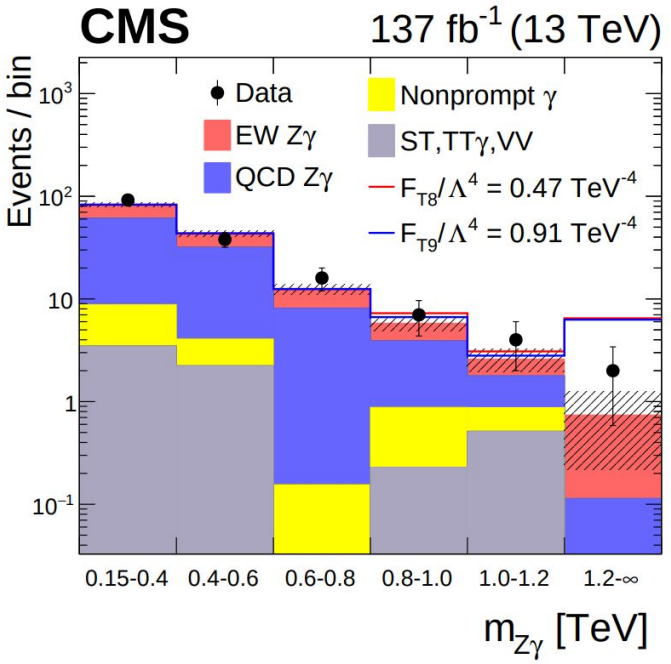
- **Data-driven** estimation **non-prompt background**
  - **2D $m_{jj'}$-$m_{ll'}$** distributions used for EW signal fit

- Obs (exp) **9.4(8.5)σ** significance for EW **Zγjj** process
  - **differential** measurement in **$m_{jj'}$; p_T,l ;p_Tγ ;$p_T j_1$**

- **Strongest** constraints on **dim-8 EFT** operators (T8,T9)
  - using invariant mass di-lepton photon **m(Zγ)**

arXiv:2106.11082 ; submitted to *Phys. Rev. D*

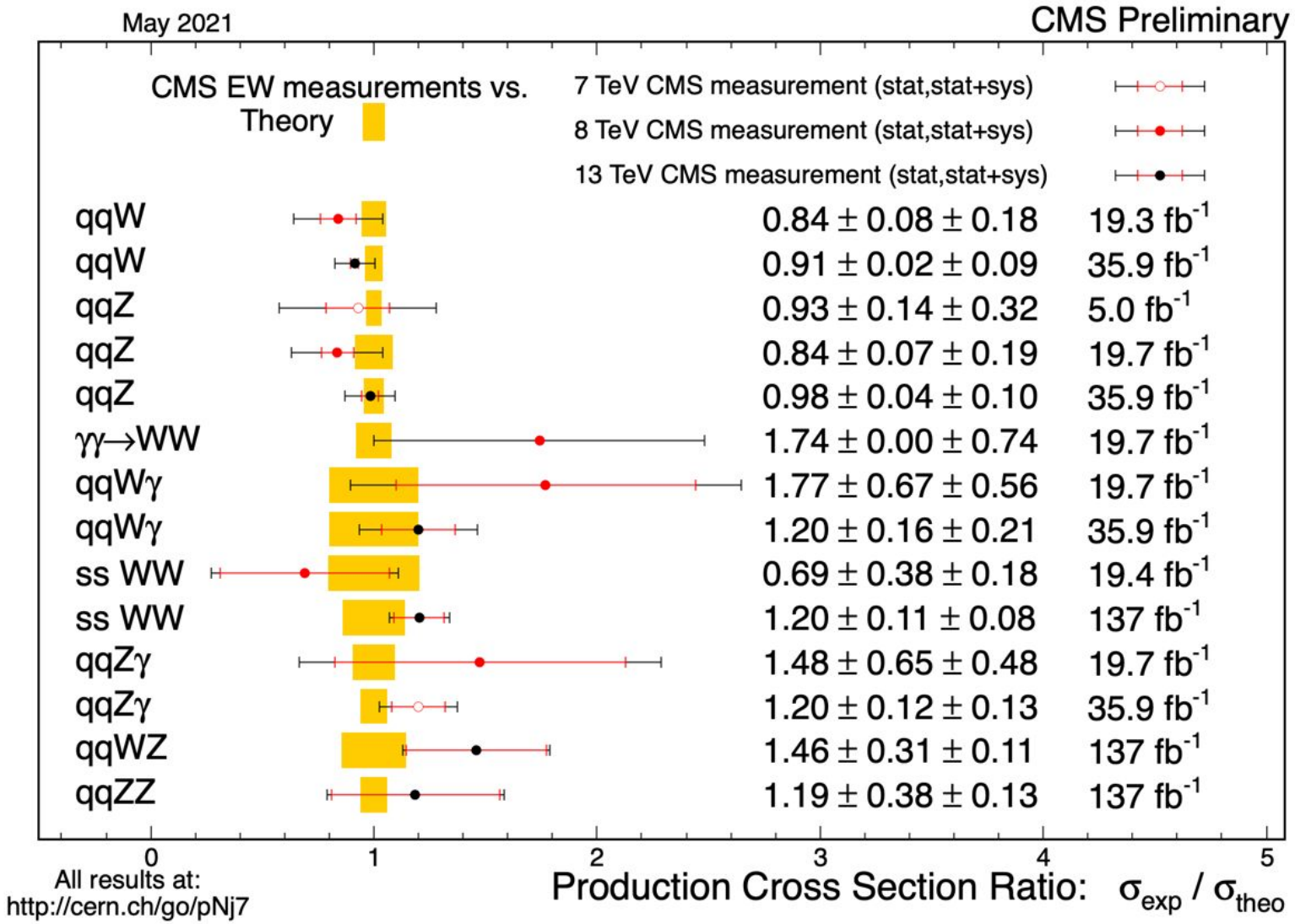




Summary Cross-section

- **Good agreement with SM**
- In some **VBS VV** scattering the EW measurements are ~1σ away from theory
- Accurate modelling of **VVjj** **non-VBS** contributions crucial

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined



Summary of aQGCs limits

$L = 35.9\ \text{fb}^{-1}$

	Observed $W^{\pm}W^{\pm} + WZ$ (TeV^{-4})	Expected $W^{\pm}W^{\pm} + WZ$ (TeV^{-4})	Observed ZZ (TeV^{-4})	Expected ZZ (TeV^{-4})	Observed $W\gamma$ (TeV^{-4})	Expected $W\gamma$ (TeV^{-4})	Observed $Z\gamma$ (TeV^{-4})	Expected $Z\gamma$ (TeV^{-4})
Transverse (4 gauge tensors)								
f_{T0}/Λ^4	[-0.25, 0.28]	[-0.35, 0.37]	[-0.24, 0.22]	[-0.37, 0.35]	[-0.6, 0.6]	[-0.6, 0.6]	[-0.52,0.44]	[-0.64,0.57]
f_{T1}/Λ^4	[-0.12, 0.14]	[-0.16, 0.19]	[-0.31, 0.31]	[-0.49, 0.49]	[-0.4, 0.4]	[-0.3, 0.4]	[-0.65,0.63]	[-0.81,0.90]
f_{T2}/Λ^4	[-0.35, 0.48]	[-0.49, 0.63]	[-0.63, 0.59]	[-0.98, 0.95]	[-1.0, 1.2]	[-1.0, 1.2]	[-1.36,1.21]	[-1.68,1.54]
f_{T5}/Λ^4	—	—	—	—	[-0.5, 0.5]	[-0.4, 0.4]	[-0.45,0.52]	[-0.58,0.64]
f_{T6}/Λ^4	—	—	—	—	[-0.4, 0.4]	[-0.3, 0.4]	[-1.02,1.07]	[-1.30,1.33]
f_{T7}/Λ^4	—	—	—	—	[-0.9, 0.9]	[-0.8, 0.9]	[-1.67,1.97]	[-2.15,2.43]
f_{T8}/Λ^4	—	—	[-0.43, 0.43]	[-0.68, 0.68]	—	—	[-0.36,0.36]	[-0.47,0.47]
f_{T9}/Λ^4	—	—	[-0.92, 0.92]	[-1.50, 1.50]	—	—	[-0.72,0.72]	[-0.91,0.91]
Mixed (2 Higgs-fields 2 gauge tensors)								
f_{M0}/Λ^4	[-2.7, 2.9]	[-3.6, 3.7]	—	—	[-8.1, 8.0]	[-7.7, 7.6]	[-12.5,12.8]	[-15.8,16.0]
f_{M1}/Λ^4	[-4.1, 4.2]	[-5.2, 5.5]	—	—	[-12, 12]	[-11, 11]	[-28.1,27.0]	[-35.0,34.7]
f_{M2}/Λ^4	—	—	—	—	[-2.8, 2.8]	[-2.7, 2.7]	[-5.21,5.12]	[-6.55,6.49]
f_{M3}/Λ^4	—	—	—	—	[-4.4, 4.4]	[-4.0, 4.1]	[-10.2,10.3]	[-13.0,13.0]
f_{M4}/Λ^4	—	—	—	—	[-5.0, 5.0]	[-4.7, 4.7]	[-10.2,10.2]	[-13.0,12.7]
f_{M5}/Λ^4	—	—	—	—	[-8.3, 8.3]	[-7.9, 7.7]	[-17.6,16.8]	[-22.2,21.3]
f_{M6}/Λ^4	[-5.4, 5.8]	[-7.2, 7.3]	—	—	[-16, 16]	[-15, 15]	—	—
f_{M7}/Λ^4	[-5.7, 6.0]	[-7.8, 7.6]	—	—	[-21, 20]	[-19, 19]	[-44.7,45.0]	[-56.6,55.9]
Scalar								
f_{S0}/Λ^4	[-5.7, 6.1]	[-5.9, 6.2]	—	—	—	—	—	—
f_{S1}/Λ^4	[-16, 17]	[-18, 18]	—	—	—	—	—	—

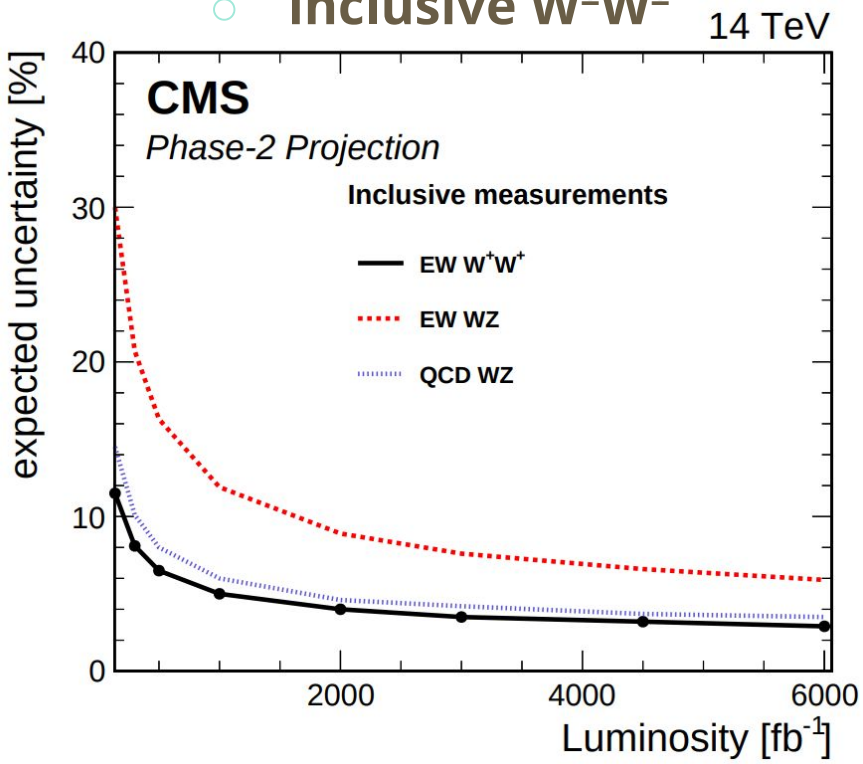
- **Competitive** limits for different final states: **semi-leptonic** channels **more sensitive**
- Expected/observed limits are in good agreement

Prospects for the VBS measurements at HL LHC

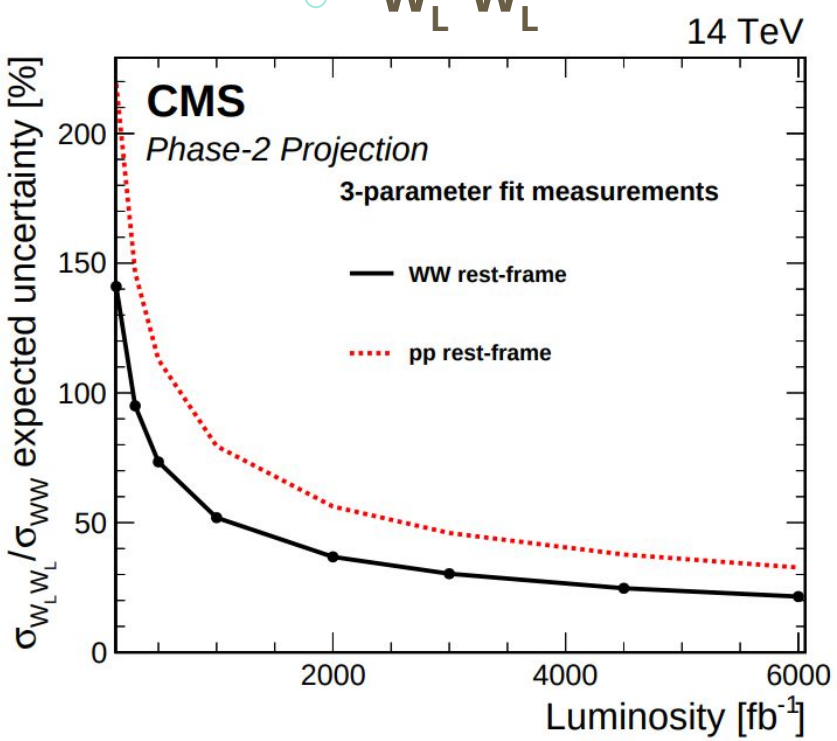
- **Prospects** for the study **of VBS $W^{\pm}W^{\pm}$/WZ** channels:
  - **EW production** and **polarized EW $W^{\pm}W^{\pm}$** production

CMS-FTR-21-001 CDS:2776773

  - **inclusive $W^{\pm}W^{\pm}$**



  - **$W_L^{\pm}W_L^{\pm}$**



- Analysis based on existing **results at 13 TeV** extrapolated **to 14 TeV at HL-LHC**

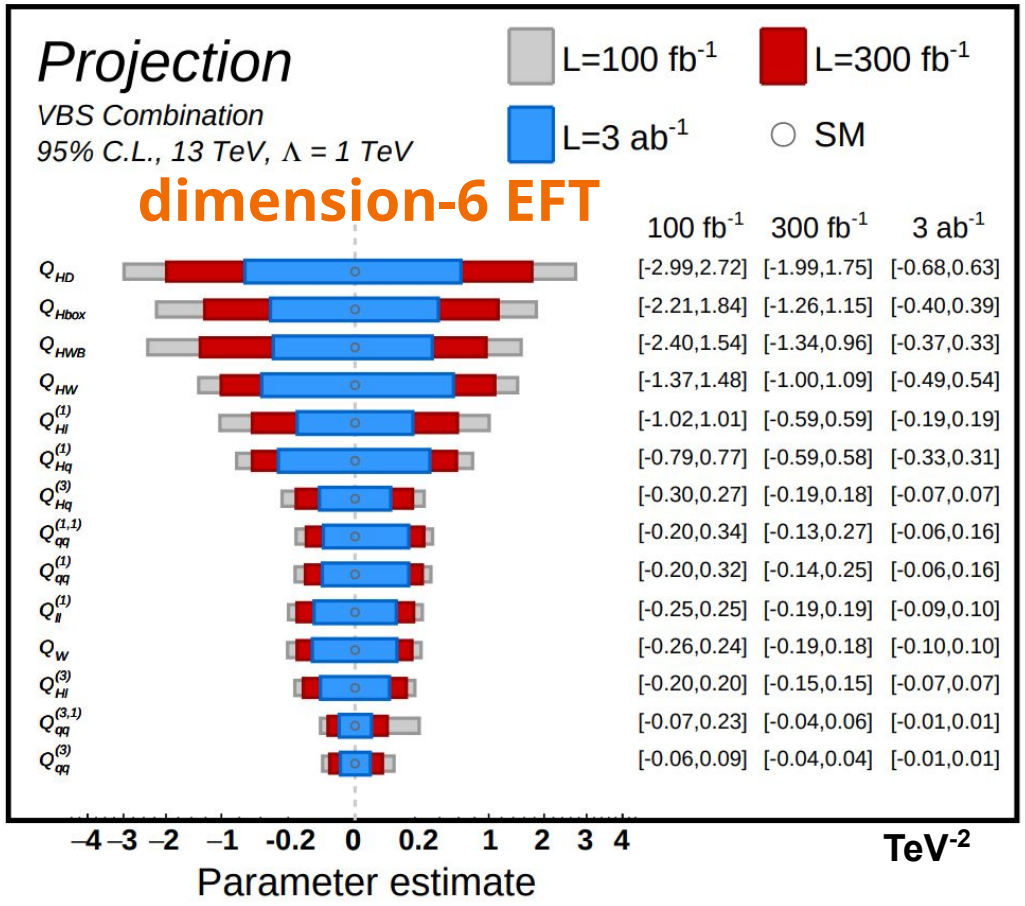
Summary

- **Highlights** from recent VBS **CMS measurements**: consistency tests of EW sector
- VBS **powerful tool** to explore BSM physics in "**UV-agnostic**" way
- **Extremely challenging** measurement:
  - very low yields as among **rarest processes** ever measured
  - require very accurate **modelling** of **QCD-induced background**
- **Full set of Run 2 and 3** needed to perform **polarisation measurements** and **high precision differential measurements**

Outlook

- **Extend scope** of **polarisation measurements** to other **VBS channels:**
  - **add WZ, ZZ, $W^{\pm}W^{\mp}$** production modes
- **High precision differential** measurements
  - test more variables
  - study variable cross-correlations
- **Expand scope of EFT analyses**
  - combination of **VBS channels to constrain** dimension 6 and 8 EFT operators

arXiv:2108.03199v1



Prospects for High-Luminosity LHC

- Cross sections at LO and NLO EW for W^+W^- scattering at **√s=14,27,100 TeV**
  - **σ increase** with **√s** while **EW corrections** become negatively **larger**
  - typical **scale** in the **Sudakov logarithms** is increasing

$\sqrt{s}$	σ^{LO} [fb]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [fb]	δ_{EW} [%]
14 TeV	1.4282(2)	1.213(5)	−15.1
27 TeV	4.7848(5)	3.881(7)	−18.9
100 TeV	25.485(9)	19.07(6)	−25.2

arXiv:2102.10991

- Simulations of **upgraded detectors** at √s=14 and total luminosity 3000 fb^{-1}
  - VBS $W^{\pm}W^{\pm}$ **- expected** total uncertainty on cross section is **4.5 (5-6)% for CMS(ATLAS)**
  - VBS $W_L^{\pm}W_L^{\pm}$ - **CMS+ATLAS combination** should yield **3σ discovery**
  - VBS $W^{\pm}Z$ **-** overall expected uncertainty **5.5 (5)%** for **CMS(ATLAS)**
  - VBS $W^{\pm}Z_L$ **-** expect **evidence** of **1.3-1.4σ** for CMS and **1.5-2.5σ** for ATLAS