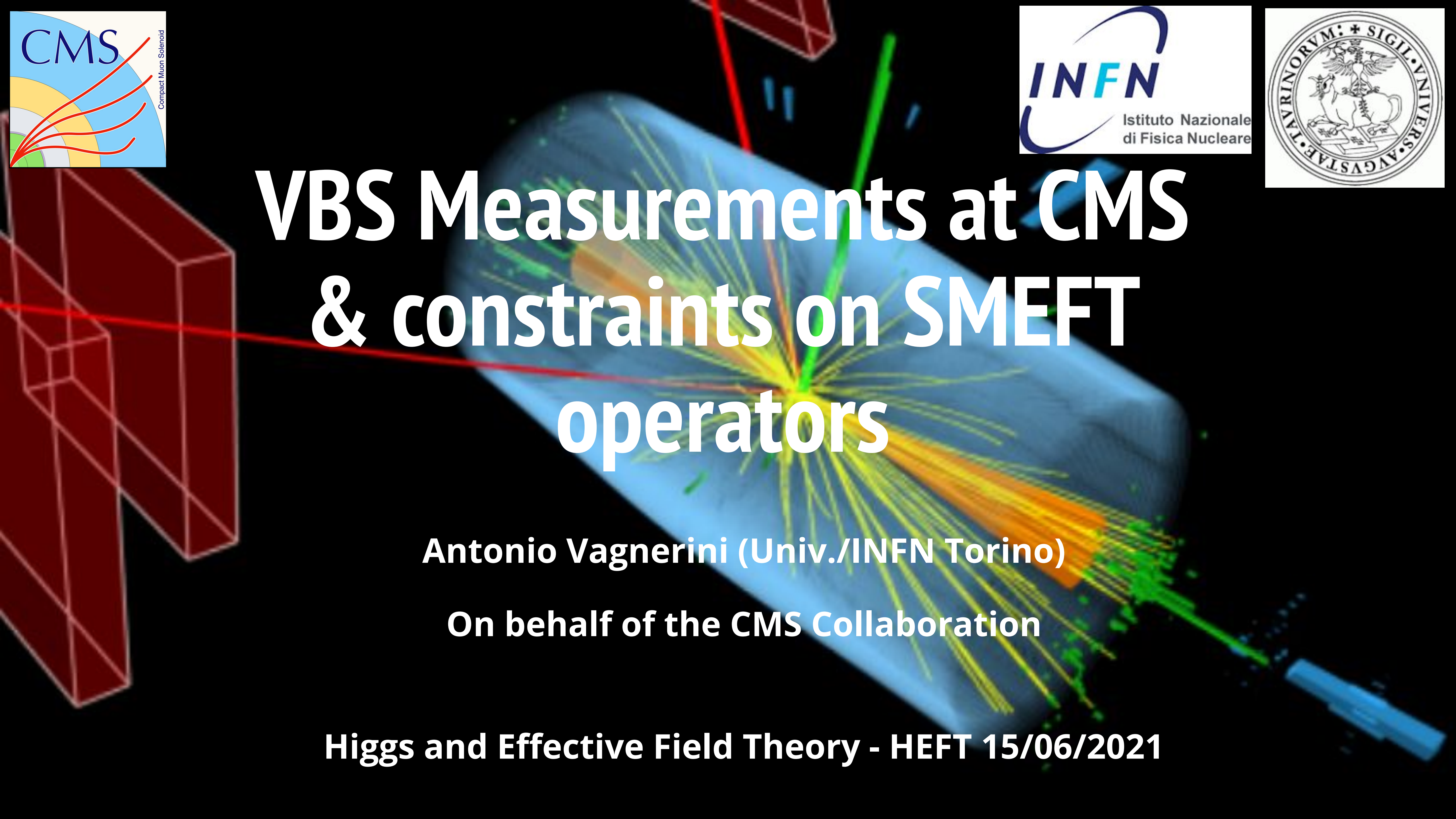


# VBS Measurements at CMS & constraints on SMEFT operators


**Antonio Vagnerini (Univ./INFN Torino)**

**On behalf of the CMS Collaboration**



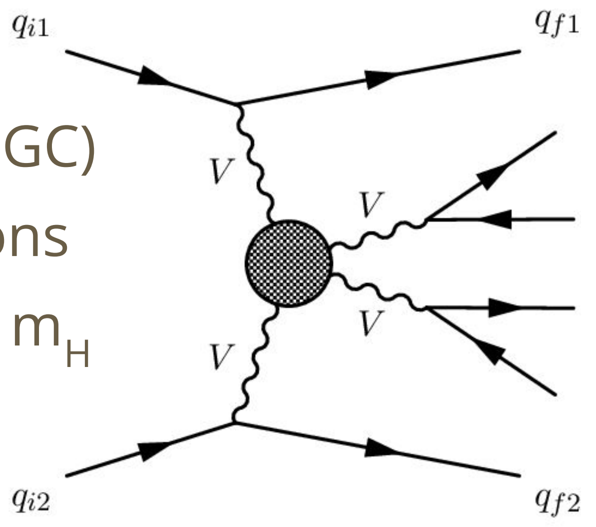
**Higgs and Effective Field Theory - HEFT 15/06/2021**

# Outline

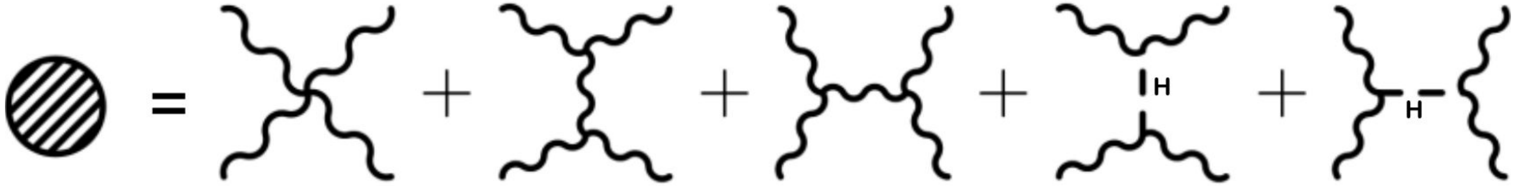
- This is a **VBS summary talk** of the most recent **CMS measurements**
  - **results** obtained with the **full Run 2 data (137fb$^{-1}$)**
- **Several final states** presented:
  - **fully-leptonic** : $W^{\pm}W^{\pm}\to 2l2\nu$; $WZ\to 3l\nu$; $ZZ\to 4l$; $W^{+}W^{-}\to 2l2\nu$
  - **semi-leptonic**: $WW/WZ\to l\nu jj$;
  - with **photons**: $Z\gamma\to 2l\gamma$; $W\gamma\to 2l\gamma$


- Inclusive/differential **cross-section measurements**
- **EFT interpretation** and latest constraints on **dim-8 SMEFT operators**
- **Sensitivity study** on **VBS+WW** combination to **dim-6 SMEFT** operators
- **Prospects** for VV scattering measurements with the CMS detector

# Motivation for VV scattering measurements




- **EW process probing** 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 > $m_H$




Phys.Rev.D 74 (2006) 073005

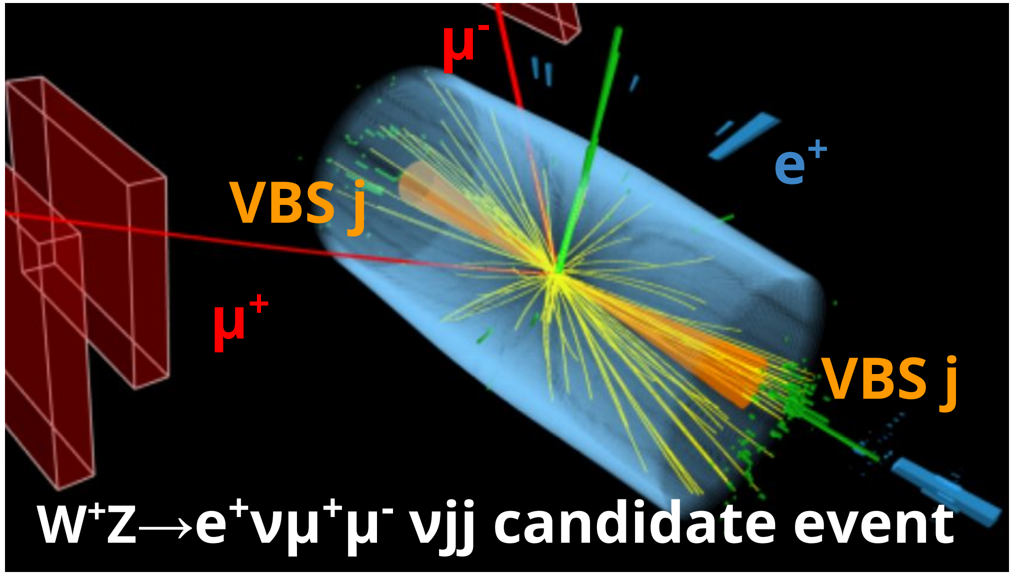
- **Portal to BSM physics:**
  - **model-independent** via **E**ffective **F**ield **T**heories (EFTs)
    - **18 bosonic** operators in **dim-8 EFT** tested
    - set constraints on anomalous gauge couplings, **aQGCs**

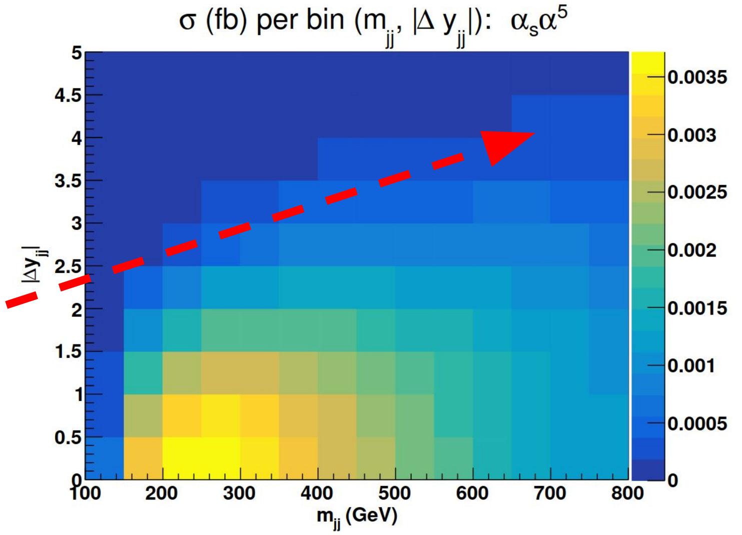
# VV scattering at the LHC

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

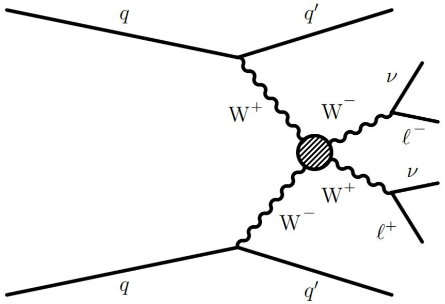
- **Signature** based on **diboson** final states:
  - **fully leptonic:** 4 e/μ ; 2 jets
  - **semi-leptonic/hadronic:** 1or 2 e/μ ; 4 jets
  - fully-hadronic: 4 or 6 jets

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



# VBS $W^+W^- \rightarrow 2\ell 2\nu$

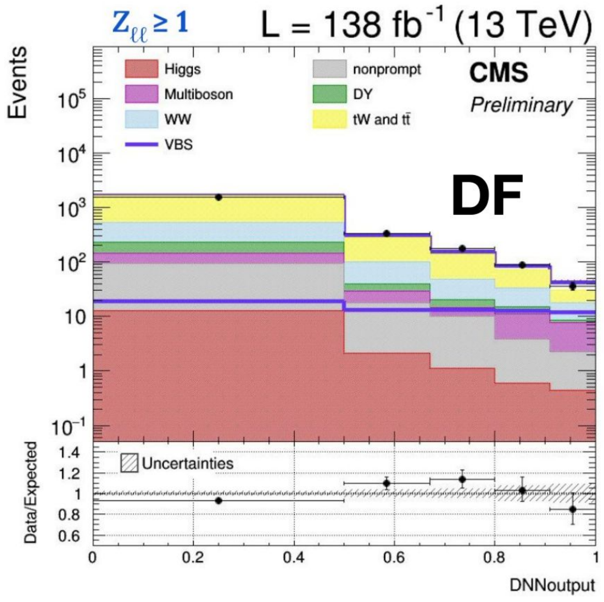


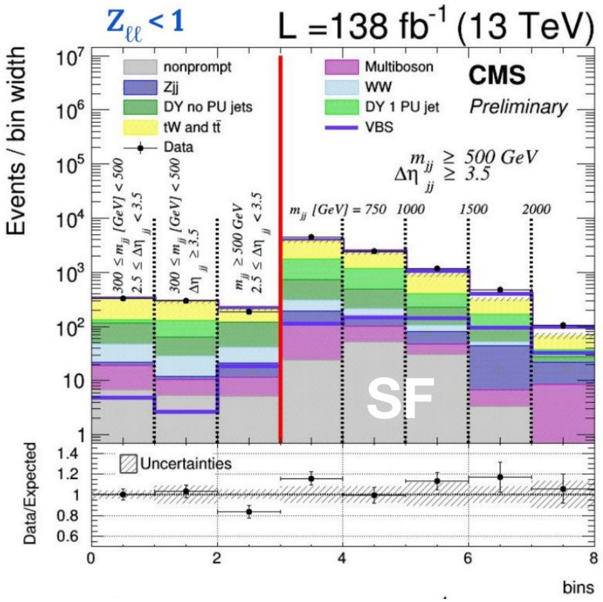
CMS-PAS-SMP-21-001
Submitted to PLB

- **OS WW fully leptonic** largest cross-section
  - but large irreducible QCD-induced bkg process
- **Event categories** based on **flavour** of lepton pair
  - **different/same** flavour: **eμ(DF)** vs **ee/μμ(SF)**
- **DNN** discriminant used in **DF signal region** while **SF region** sub-divided in $\mathbf{m_{jj}}$-$\mathbf{\Delta\eta_{jj}}$ bins
  - splitted by best var **Zeppenfeld**

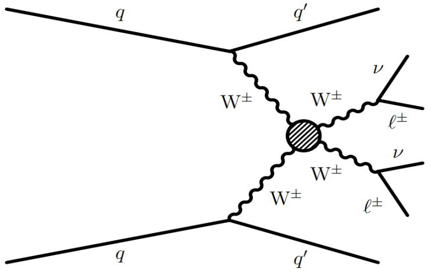
$$Z_{\ell_i} = \eta_{\ell_i} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$$

- **First observation** of **WW EWK** process: **5.6σ** significance



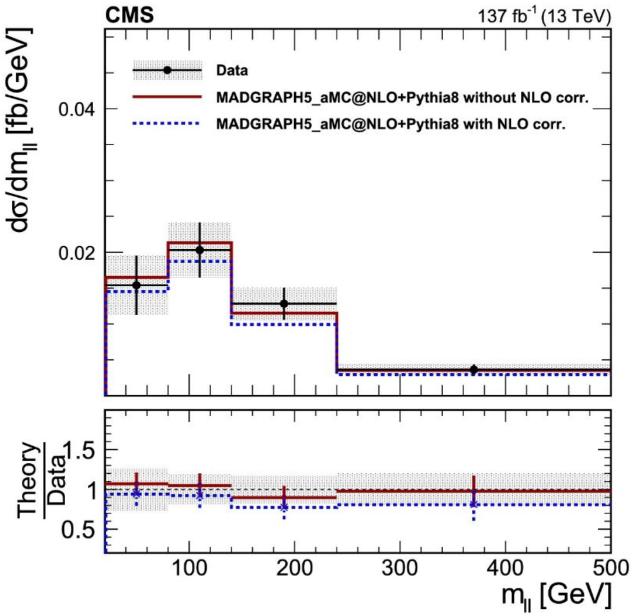



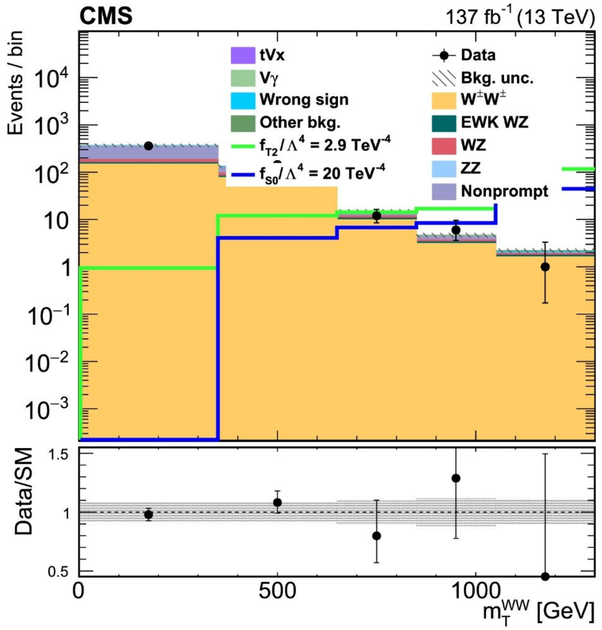
# VBS $W^{\pm}W^{\pm} \rightarrow 2l^{\pm}2\nu$



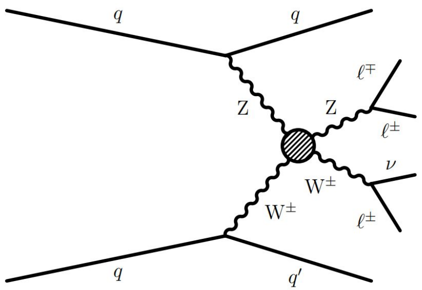

CMS, Phys. Lett. B 809, 135710 (2020)

- **Same-sign WW fully leptonic is a "golden channel"**
  - good separation EW/QCD components $\boldsymbol{\sigma_{EW}/\sigma_{QCD}}$**~4-6**
  - full tower of **NLO** corrections known
- **Simultaneous** measurement **of $W^{\pm}W^{\pm}$/WZ** production
  - advantage 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 $\rightarrow 3l1\nu$

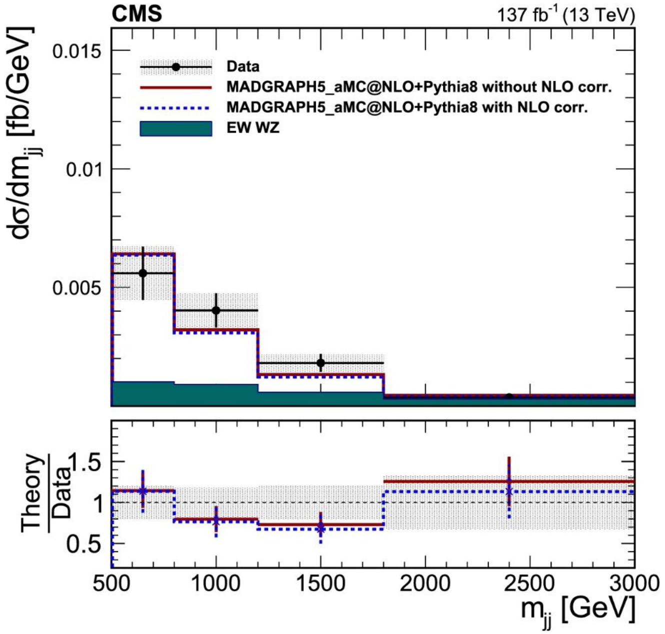


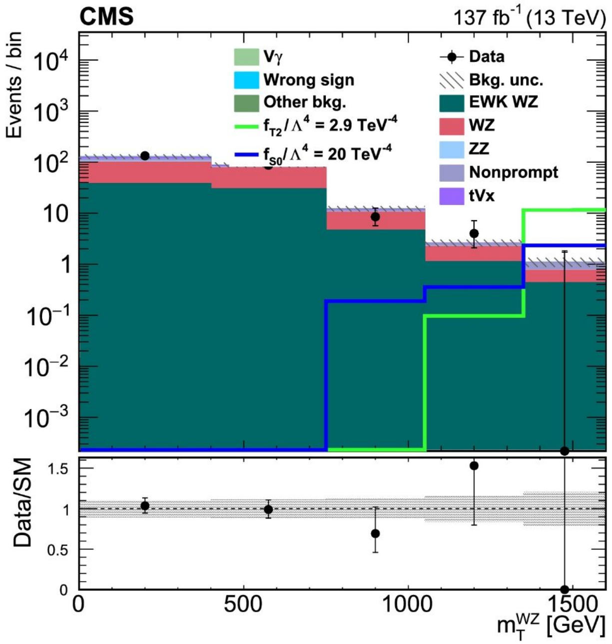

- **WZjj production** has **clean** 3-lepton **signature**
  - larger QCD bkg contribution since $\sigma_{EW}/\sigma_{QCD}$**~1/2**
- **BDT with lepton/jet kinematic** as input variables
  - sensitivity improvement wrt 2D fit by 20%
- Analysis methods in common with **W±W±**

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

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

Phys. Lett. B 809, 135710 (2020)



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

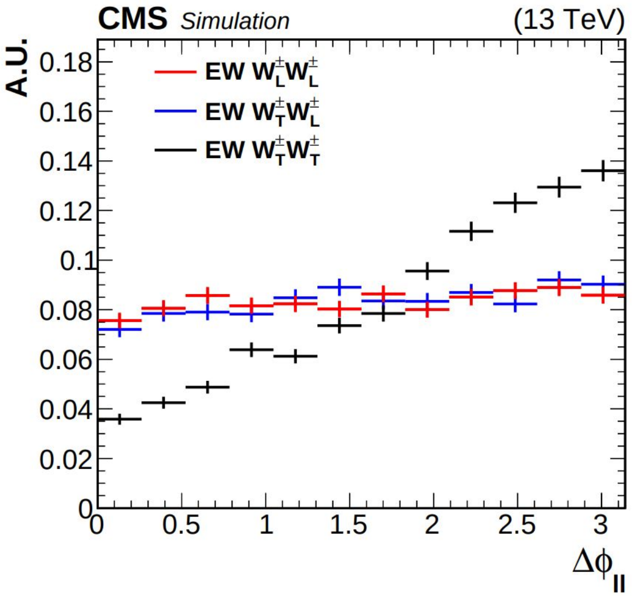
Phys. Lett. B 812, 136018 (2021)

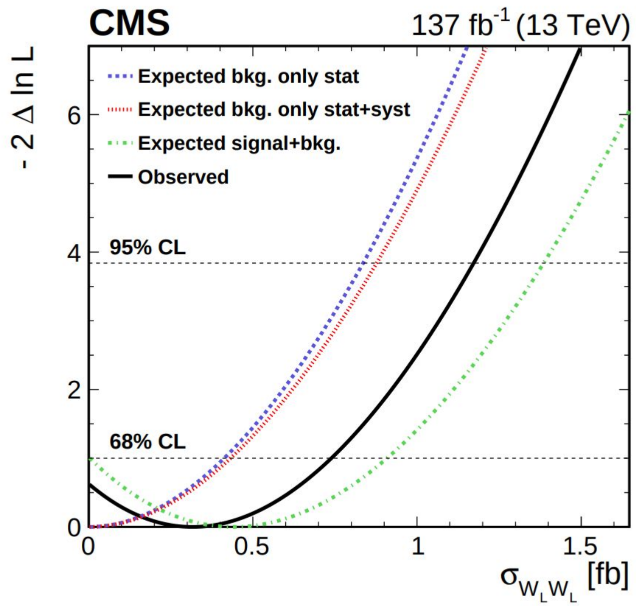
- First measurement of **polarization states** in VBS $\mathbf{W^{\pm}W^{\pm}}$
  - **challenging** since **low** expected **yields** for $\mathbf{W_L W_L}$
  - **four-momentum** of **W-boson unknown**
    - no direct access to helicity angles

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

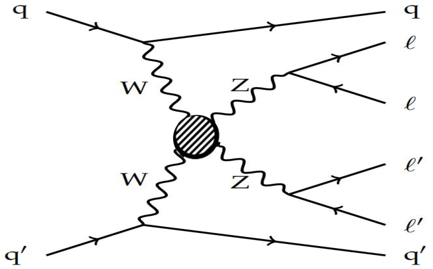
- **Two-dimensional fit** of two BDT output scores
  - **inclusive**: optimised to isolate EW WW from bkg
  - **signal** : designed to select $\mathbf{W_L W_L}$ or $\mathbf{W_L W_X}$ against other polarisation states

- Obs(exp) **2.6(2.9)σ** significance for EW $\mathbf{W_L W_X}$ production and 95% U.L. of **1.17(0.88) fb** for $\mathbf{W_L W_L}$



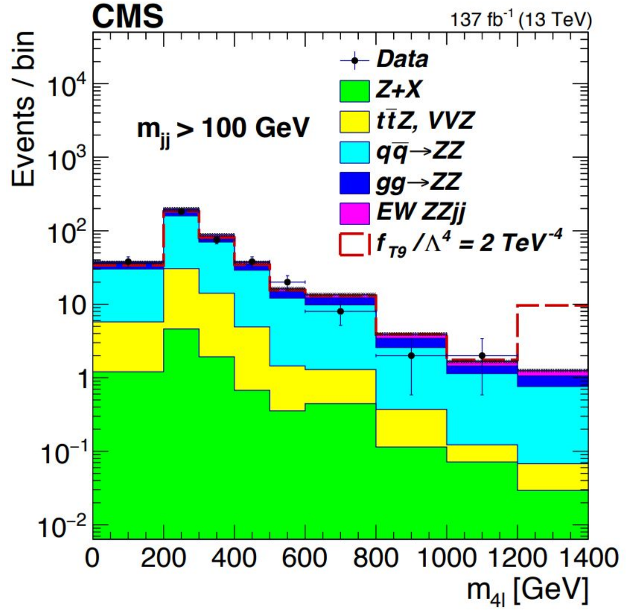
# VBS ZZ →4l



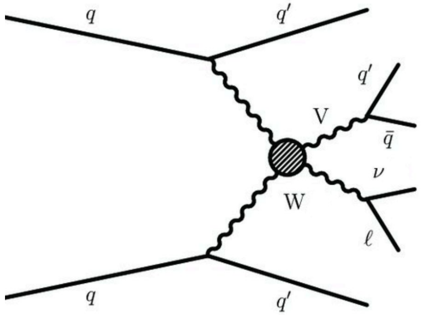

Phys. Lett. B 812, 135992 (2021)

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

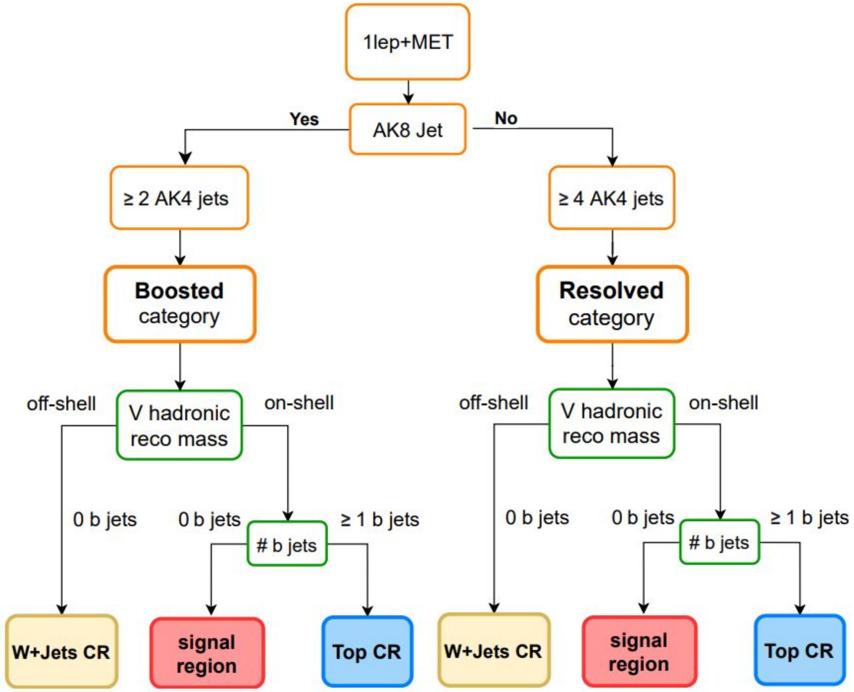


# VBS WW/WZ →lνjj

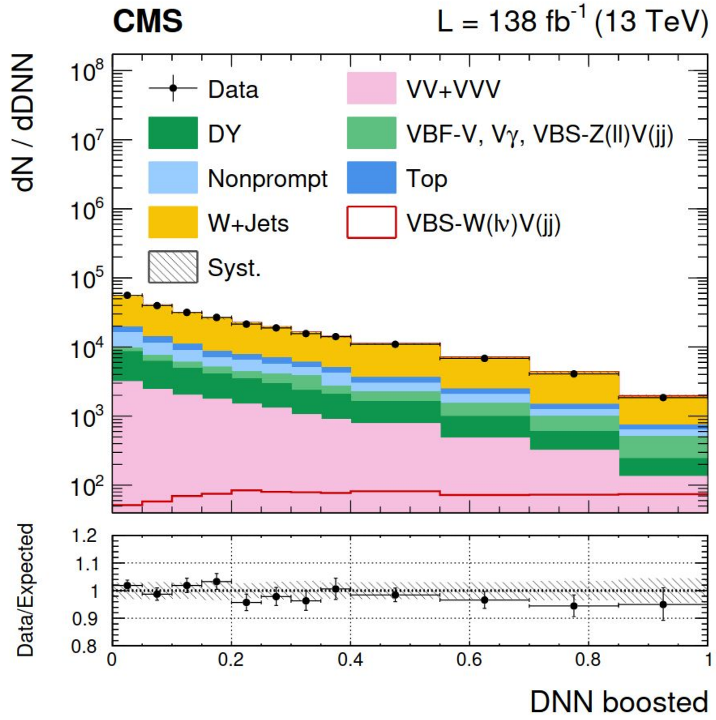



CMS-SMP-20-013 arXiv:2112.05259v1

- 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)**

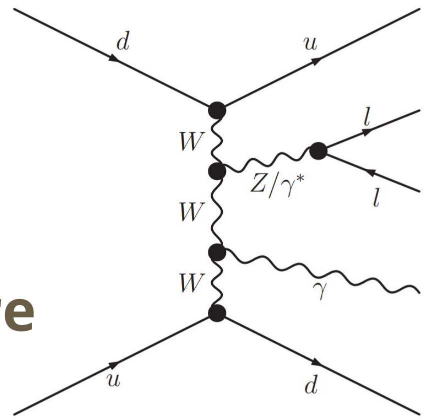



- **DNN discriminant** in signal region
- **W+jets /top-quark** control regions

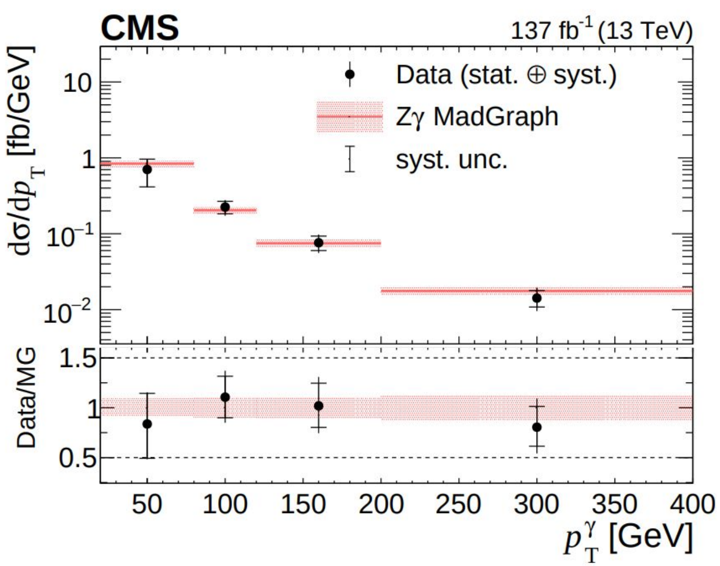



- Observed (expected) **4.4(5.1)σ** significance for EW WV production

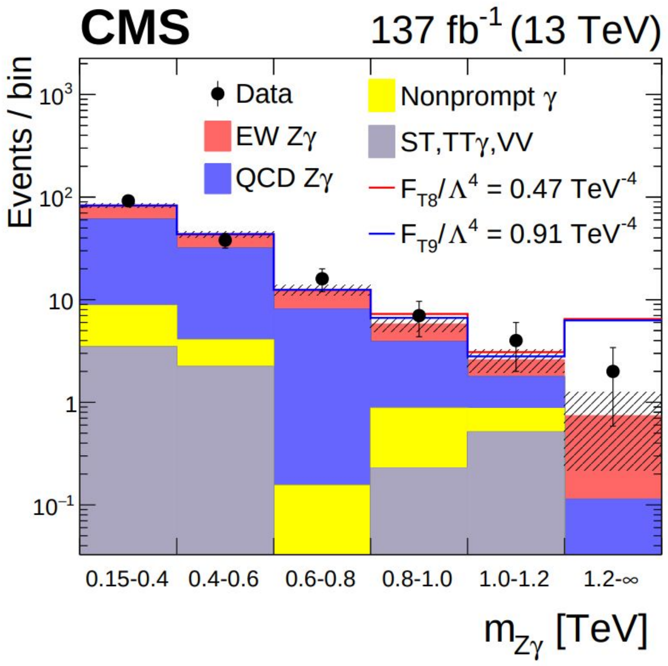
# VBS Zγ → 2lγ



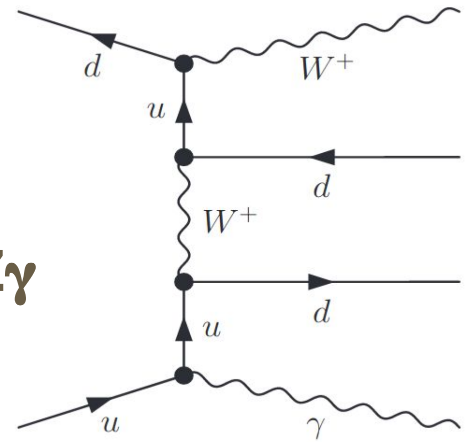

Phys. Rev. D 104, 072001 (2021)




- $Z\gamma \to l^{\pm}l^{\mp}\gamma$ 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 **$m_{jj}$;$p_T l$;$p_T \gamma$;$p_T j_1$**
- **Strongest** constraints on **dim-8 EFT** operators (T8,T9)
  - using invariant mass di-lepton photon **m(Zγ)**

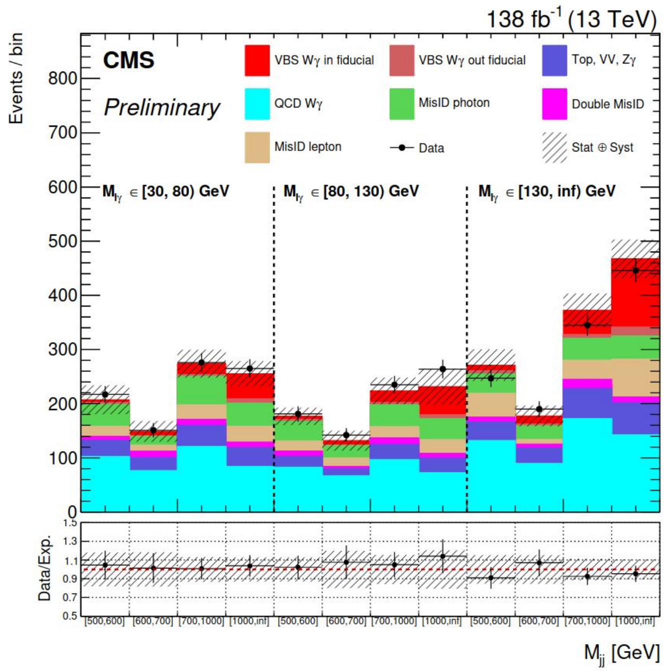


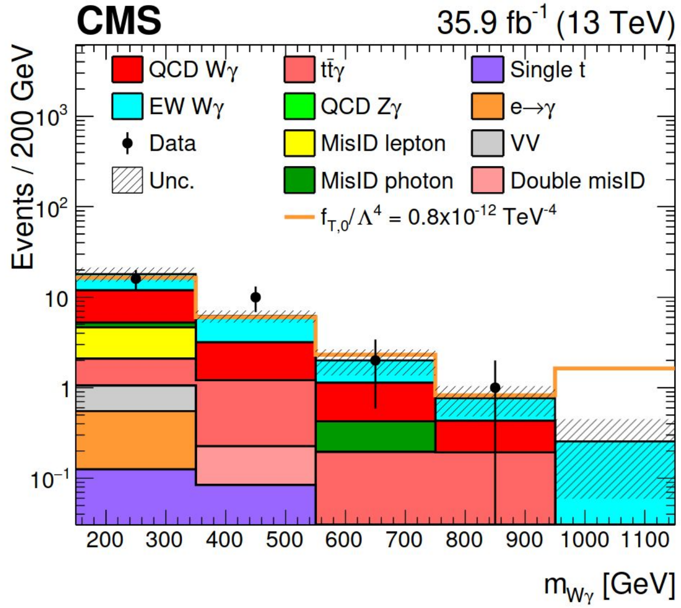
# VBS Wγ →lνγ




- **Wγ→lνγ** has larger signal than **Zγ**
  - except **QCD-induced** bkg
- **Data-driven** estimation **non-prompt background**
  - **2D $m_{jj}$-$m_{l\gamma}$** binned likelihood fit
- Obs (exp) **6.0(6.8)σ** significance for EW **Wγjj** process
  - **first measurement** of the EW+QCD process
- **Stringest** constraints on **M(2,3,4,5)** and **T(6,7)**
  - using invariant mass **m(Wγ)**

CMS-PAS-SMP-21-011

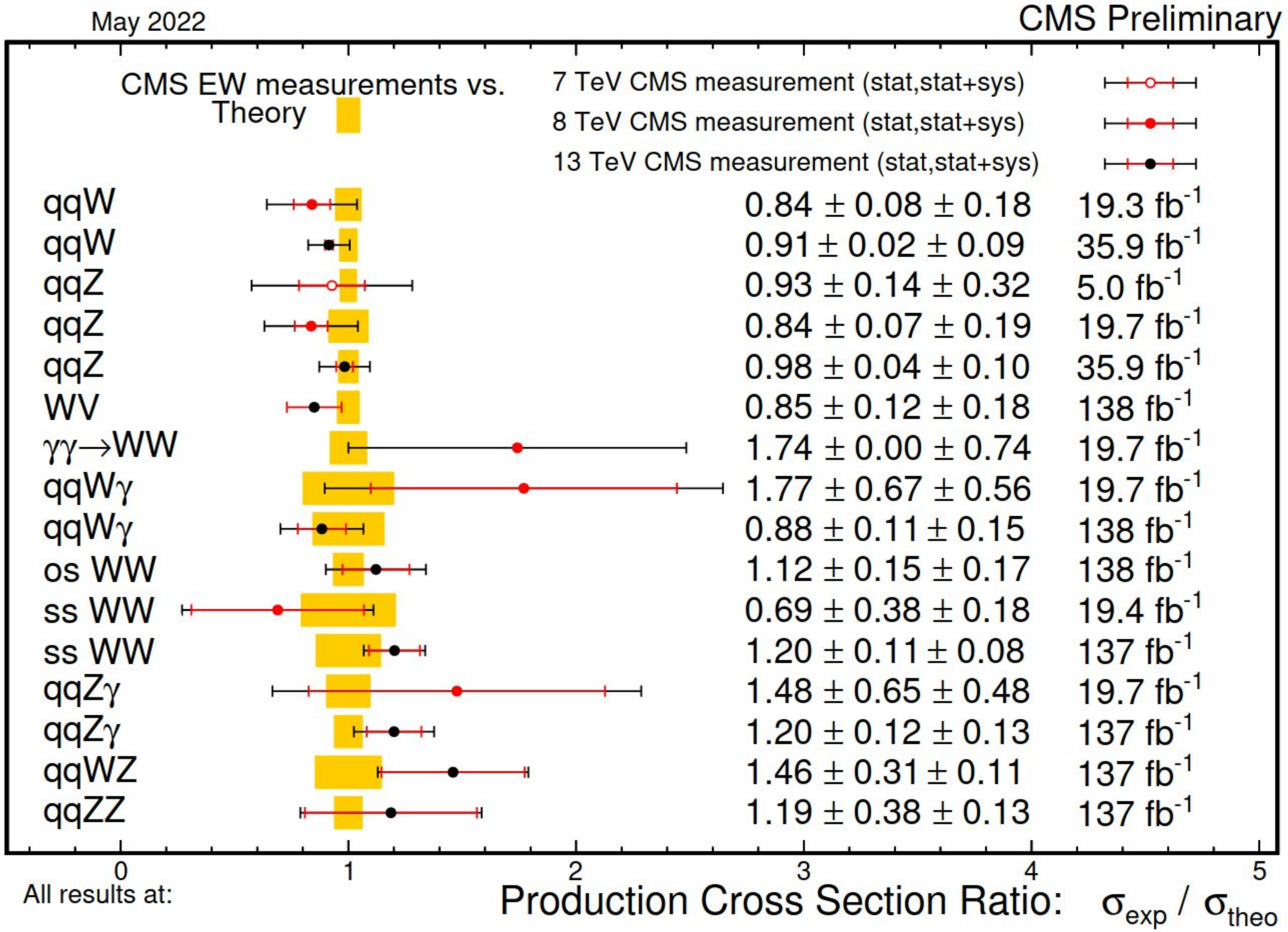


# Summary of Cross-section

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

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



# Summary of aQGCs limits

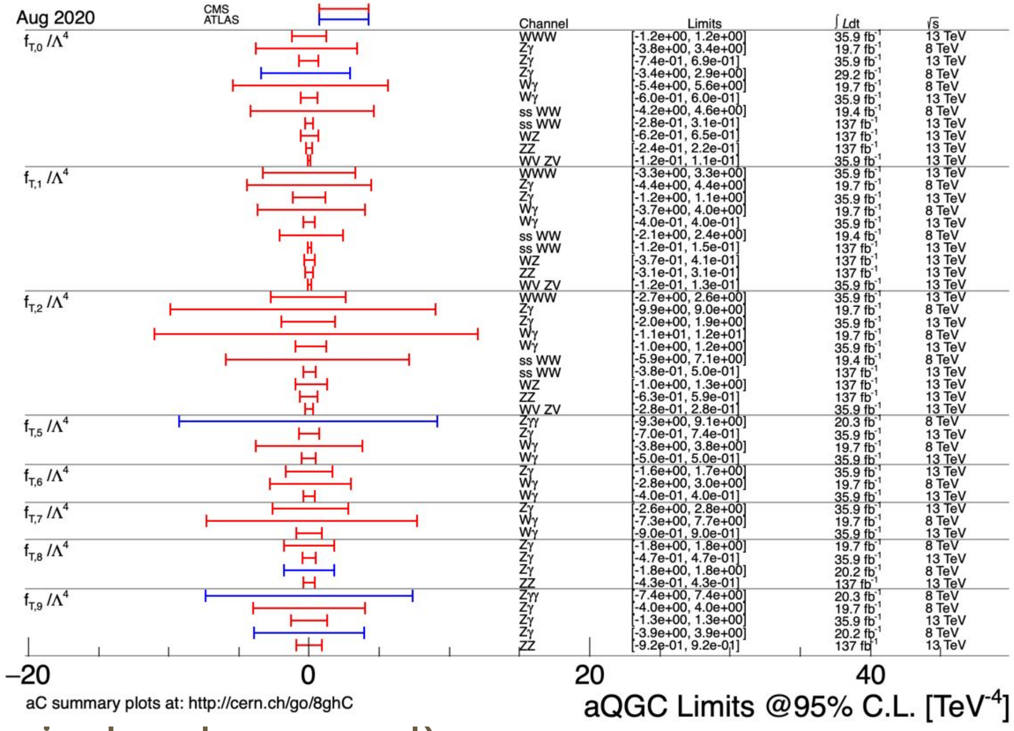
*L* = 35.9 $fb^{-1}$

| | | 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) | $f_{T0}/\Lambda^4$ | [-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] |
| | $f_{T1}/\Lambda^4$ | [-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] |
| | $f_{T2}/\Lambda^4$ | [-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] |
| | $f_{T5}/\Lambda^4$ | — | — | — | — | [-0.5, 0.5] | [-0.4, 0.4] | [-0.45,0.52] | [-0.58,0.64] |
| | $f_{T6}/\Lambda^4$ | — | — | — | — | [-0.4, 0.4] | [-0.3, 0.4] | [-1.02,1.07] | [-1.30,1.33] |
| | $f_{T7}/\Lambda^4$ | — | — | — | — | [-0.9, 0.9] | [-0.8, 0.9] | [-1.67,1.97] | [-2.15,2.43] |
| | $f_{T8}/\Lambda^4$ | — | — | [-0.43, 0.43] | [-0.68, 0.68] | — | — | [-0.36,0.36] | [-0.47,0.47] |
| | $f_{T9}/\Lambda^4$ | — | — | [-0.92, 0.92] | [-1.50, 1.50] | — | — | [-0.72,0.72] | [-0.91,0.91] |
| **Mixed** (2 Higgs-fields 2 gauge tensors) | $f_{M0}/\Lambda^4$ | [-2.7, 2.9] | [-3.6, 3.7] | — | — | [-8.1, 8.0] | [-7.7, 7.6] | [-12.5,12.8] | [-15.8,16.0] |
| | $f_{M1}/\Lambda^4$ | [-4.1, 4.2] | [-5.2, 5.5] | — | — | [-12, 12] | [-11, 11] | [-28.1,27.0] | [-35.0,34.7] |
| | $f_{M2}/\Lambda^4$ | — | — | — | — | [-2.8, 2.8] | [-2.7, 2.7] | [-5.21,5.12] | [-6.55,6.49] |
| | $f_{M3}/\Lambda^4$ | — | — | — | — | [-4.4, 4.4] | [-4.0, 4.1] | [-10.2,10.3] | [-13.0,13.0] |
| | $f_{M4}/\Lambda^4$ | — | — | — | — | [-5.0, 5.0] | [-4.7, 4.7] | [-10.2,10.2] | [-13.0,12.7] |
| | $f_{M5}/\Lambda^4$ | — | — | — | — | [-8.3, 8.3] | [-7.9, 7.7] | [-17.6,16.8] | [-22.2,21.3] |
| | $f_{M6}/\Lambda^4$ | [-5.4, 5.8] | [-7.2, 7.3] | — | — | [-16, 16] | [-15, 15] | — | — |
| | $f_{M7}/\Lambda^4$ | [-5.7, 6.0] | [-7.8, 7.6] | — | — | [-21, 20] | [-19, 19] | [-44.7,45.0] | [-56.6,55.9] |
| **Scalar** | $f_{S0}/\Lambda^4$ | [-5.7, 6.1] | [-5.9, 6.2] | — | — | — | — | — | — |
| | $f_{S1}/\Lambda^4$ | [-16, 17] | [-18, 18] | — | — | — | — | — | — |

- **Competitive** limits for different final states: **semi-leptonic** channels **more sensitive**
- Expected/observed limits are in good agreement **(no clipping)**

# Motivation for dimension-6 EFT sensitivity study

- **Interpretation** of **VBS results** traditionally in terms of **dim-8 SMEFT operators**
- **However, dim-6 operators** should not be neglected, see [arXiv:1809.04189]
- **First LHE sensitivity** study **of VBS+WW** including **O(Λ$^{-4}$) dim-6** terms, JHEP05(2022)039




- EFT analysis of **EWK+QCD-induced** processes (main background)
- **Assess sensitivity interplay** between **VBS** and **diboson analyses at LHC**
  - in the future **global EFT fit** will be necessary to provide the most stringent constraints to **SMEFT operators** (top, Higgs, EW, etc)

# SMEFT Monte Carlo Generations

- **Paramerisation** using **15 dim-6 SMEFT operators** from **Warsaw basis**
- **Generated** at **LO** with **SMEFTsim + MadGraph5_aMC@NLO (2.6.5)**
  - $U(3)^5$ flavour symmetry
  - $\{m_W, m_Z, G_F\}$ input scheme
  - CP-even
  - $\Lambda$ = 1TeV

$$Q_{Hl}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_p) \qquad Q_{Hl}^{(3)} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{l}_p \sigma^i \gamma^\mu l_p)$$

$$Q_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_p) \qquad Q_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}_p \sigma^i \gamma^\mu q_p)$$

$$Q_{qq}^{(1)} = (\bar{q}_p \gamma_\mu q_p)(\bar{q}_r \gamma^\mu q_r) \qquad Q_{qq}^{(1,1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_r \gamma^\mu q_p)$$

$$Q_{qq}^{(3)} = (\bar{q}_p \gamma_\mu \sigma^i q_p)(\bar{q}_r \gamma^\mu \sigma^i q_r) \qquad Q_{qq}^{(3,1)} = (\bar{q}_p \gamma_\mu \sigma^i q_r)(\bar{q}_r \gamma^\mu \sigma^i q_p)$$

$$Q_{HD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H) \qquad Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$Q_{HWB} = (H^\dagger \sigma^i H) W^i_{\mu\nu} B^{\mu\nu} \qquad Q_{HW} = (H^\dagger H) W^i_{\mu\nu} W^{i\mu\nu}$$

$$Q_W = \varepsilon^{ijk} W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho \qquad Q_{ll}^{(1)} = (\bar{l}_p \gamma_\mu l_r)(\bar{l}_r \gamma^\mu l_p)$$

- **Event yield:**

$$N \propto \overbrace{|\mathcal{A}_{SM}|^2}^{\text{SM}} + \sum_\alpha \frac{c_\alpha}{\Lambda^2} \cdot \underbrace{2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}^\dagger_{Q_\alpha})}_{\text{Lin}} + \frac{c_\alpha^2}{\Lambda^4} \cdot \overbrace{|\mathcal{A}_{Q_\alpha}|^2}^{\text{Quad}} + \sum_{\alpha,\beta} \frac{c_\alpha c_\beta}{\Lambda^4} \cdot \underbrace{\mathrm{Re}(\mathcal{A}_{Q_\alpha}\mathcal{A}^\dagger_{Q_\beta})}_{\text{Mix}}$$

# Processes of interest

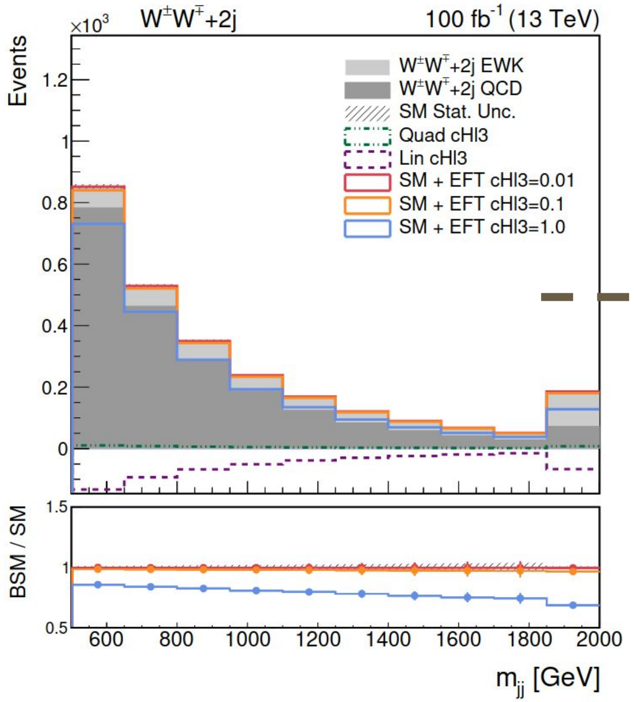
- **Modelling** of **VBS(diboson) 2→6(4) processes** including non-resonant diagrams
  - both **EWK** and **QCD-induced** contributions for **SM** and **EFT processes**

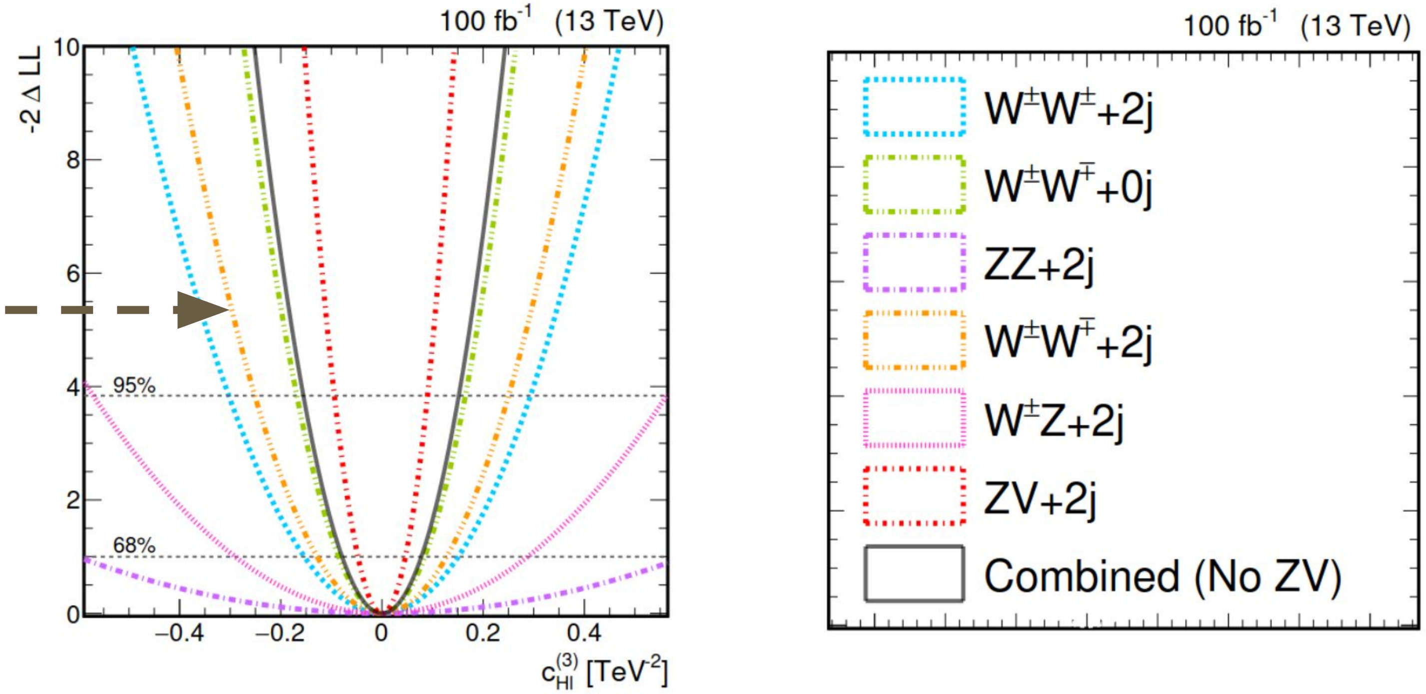
- **Same-sign WW**: $\mathrm{p\,p} > \mathrm{e}^+ \nu_\mathrm{e}\, \mu^+ \nu_\mu\, \mathrm{j\,j}$
- **Opposite-sign WW (QCD)**: $\mathrm{p\,p} > \mathrm{e}^+ \nu_\mathrm{e}\, \mu^- \bar{\nu_\mu}\, \mathrm{j\,j}$
- **WZ+2j(QCD)**: $\mathrm{p\,p} > \mathrm{e}^+ \mathrm{e}^- \mu^+ \nu_\mu\, \mathrm{j\,j}$
- **ZZ+2j(QCD)**: $\mathrm{p\,p} > \mathrm{e}^+ \mathrm{e}^- \mu^+ \mu^-$
- **ZV+2j(QCD)**: $\mathrm{p\,p} > \mathrm{z\,w}^+(\mathrm{w}^-, \mathrm{z}) > \mathrm{l}^+ \mathrm{l}^- \mathrm{j\,j\,j\,j}$
- **WW**: $\mathrm{p\,p} > \mathrm{e}^+ \nu_\mathrm{e}\, \mu^- \bar{\nu_\mu}$

- **Fully-leptonic** and **semi-leptonic final states** studied with **LHC-like selections**
  - **determine** which **observables most sensitive** to EFT-induced anomalies

# Template fit analysis

- **Dependence** of **EFT-**induced kinematic **anomalies** on **Wilson coefficients**
- **Likelihood fit** for each **variable** based on **1σ** range (**area** for **2D** fit)

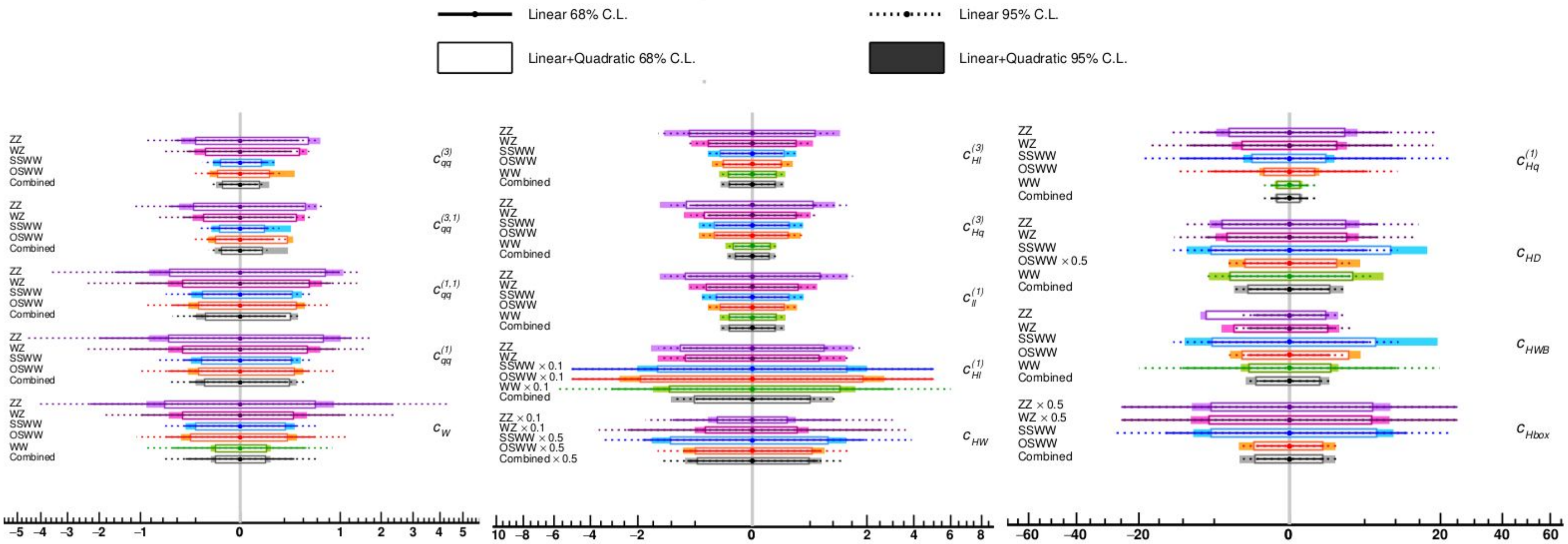



- **Optimal variable** extracted per **operator** used in **combination**

# Individual constraints - VBS + WW combination

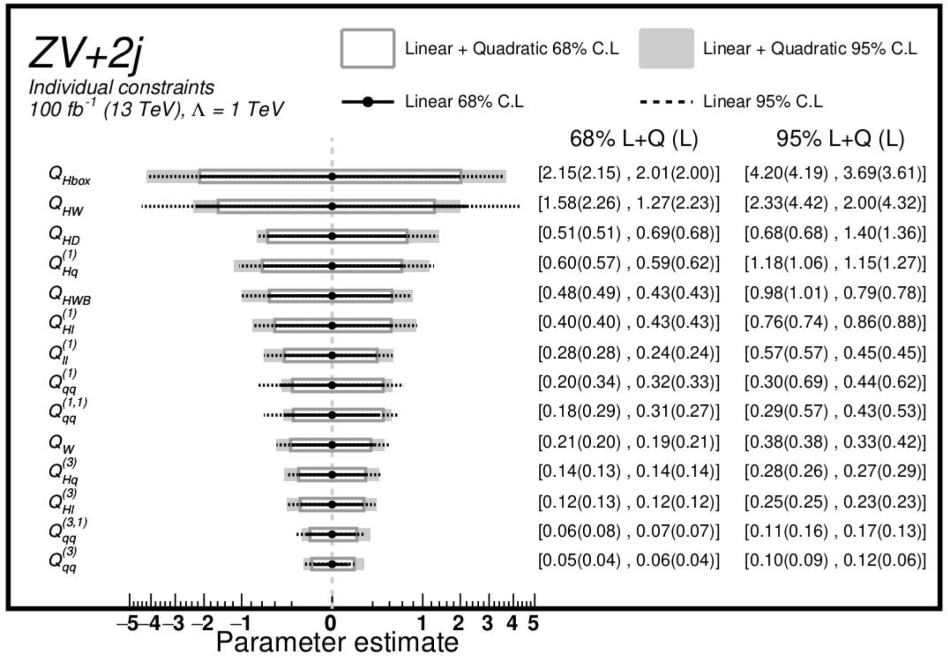
- **Individual operator constraints** with(without) **O($\Lambda^{-4}$)** quadratic **terms**

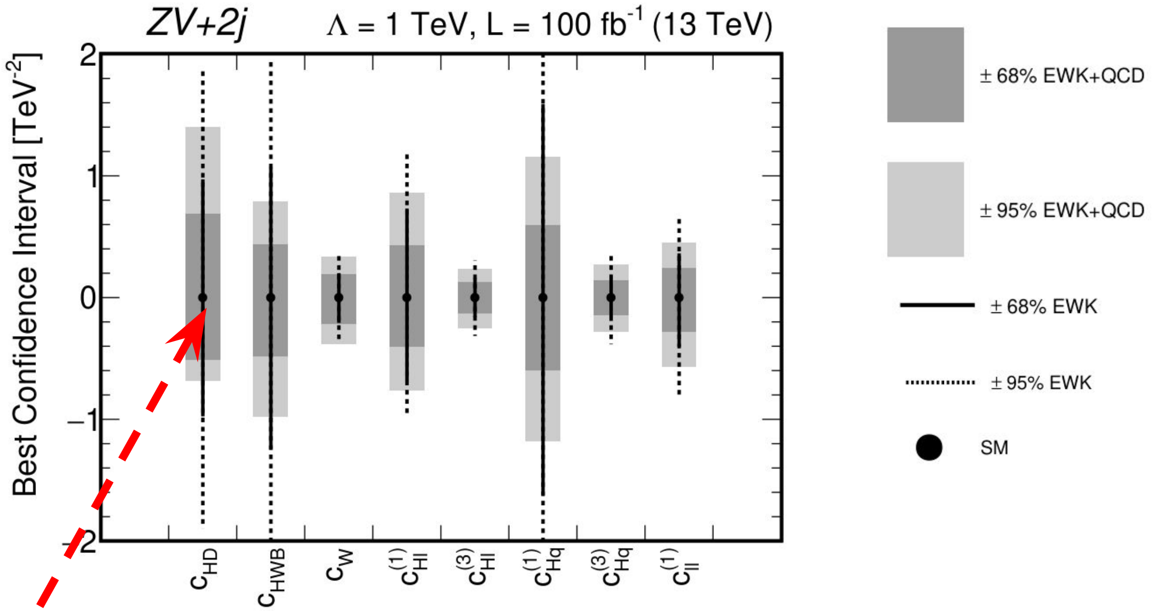



- **Large impact** of **quadratic terms** on **half** of the **single operator** constraints
- **Strongest constraints** on **four-fermion** ops as expected
- $Q_{Hl}^{(1)}$, $Q_{HW}$, $Q_{H\square}$, $Q_{HD}$ ops constrained solely by **VBS processes**

# Individual constraints - VBS semileptonic

- Separate treatment for **ZVjj process** as main bkg **Z+jets** not accounted for
    - not included in combination

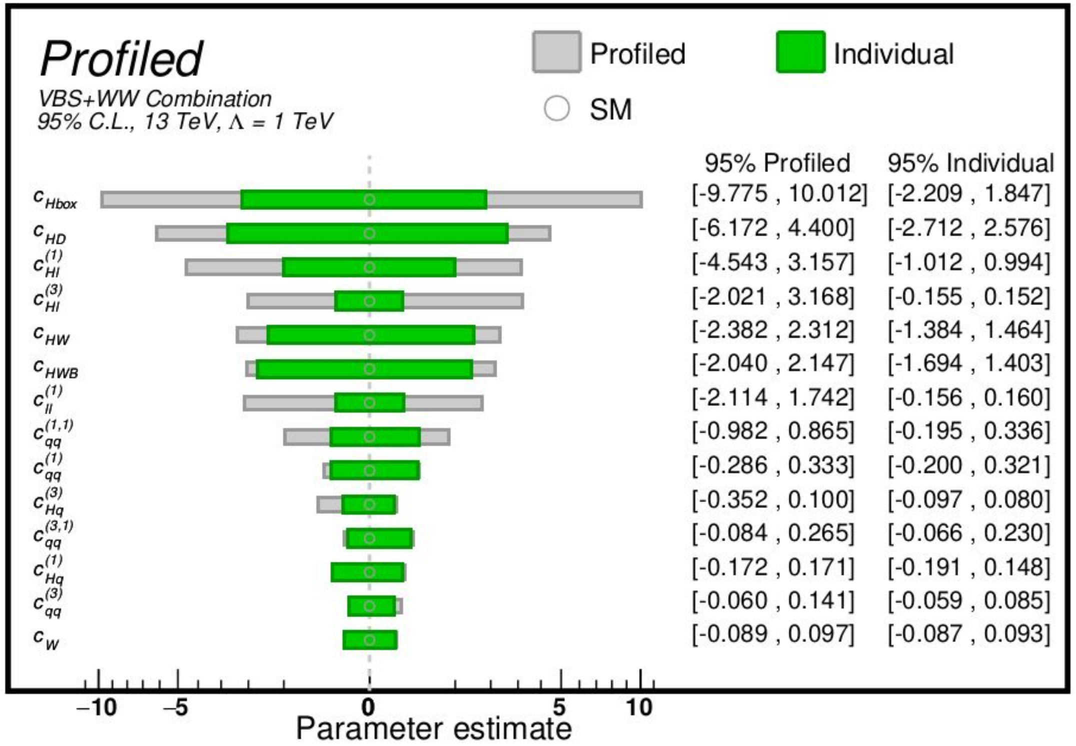



- **Competitive constraints** with **WW di-boson** process, lower impact of **$O(\Lambda^{-4})$** term
- Inclusion of **QCD** term **enhances** the **sensitivity** to EFT effects (as in other channels)

# Profiled constraints - VBS + WW combination

- Performed **global fit** of **VBS+WW profile** including all **O(Λ⁻⁴)** terms
  - **single operator** fit with all other **coefficients profiled** (free-floating in fit)

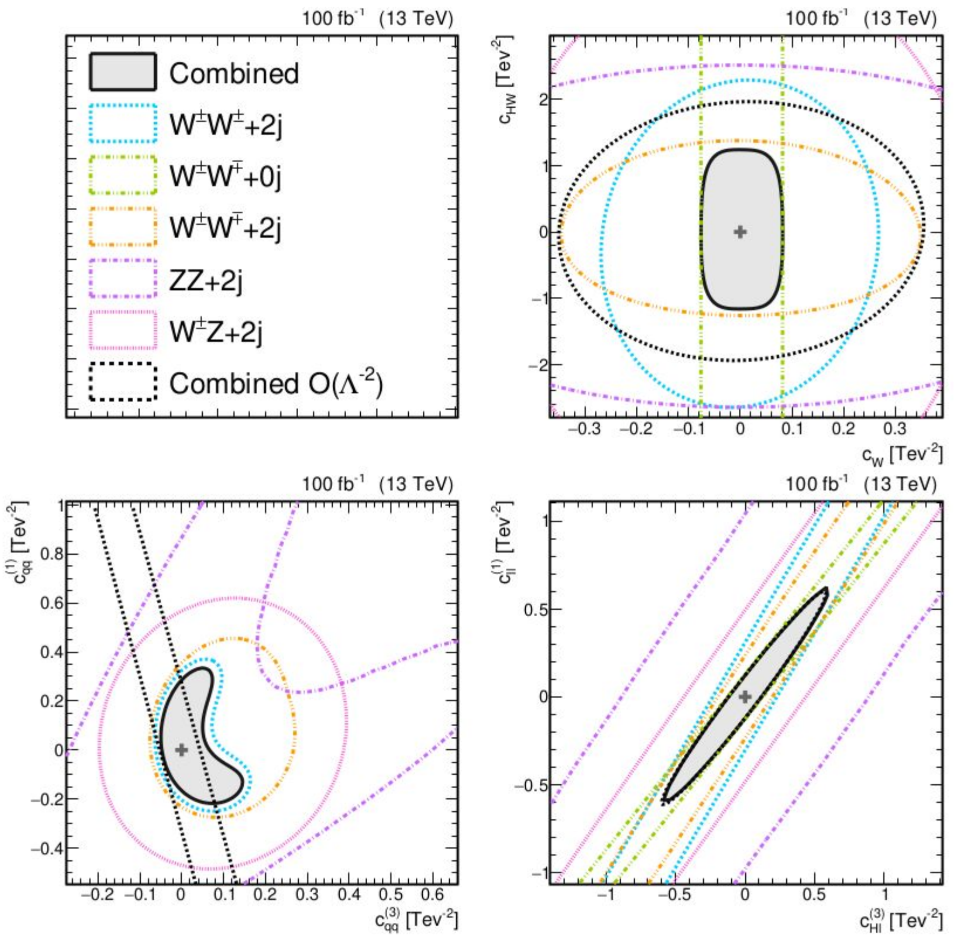



- **Profiled** constraints are up to **10x less stringent** wrt **individual** ones

# 2D constraints - VBS + WW combination

- Study **channel sensitivity** to **operator pairs** using 2D template fit
  - **contours** allow assessing **interplay** of **VBS** and **di-boson** measurements

1. **Orthogonal** constraints between **WW** and and **VBS** for **($Q_{HW}$,$Q_{HWB}$)**
2. **4-quark ops** constrained only by VBS
3. **flat directions $Q_{Hl}^{(3)}$~ $Q_{ll}^{(1)}$ resolved** thanks to **channel combination**

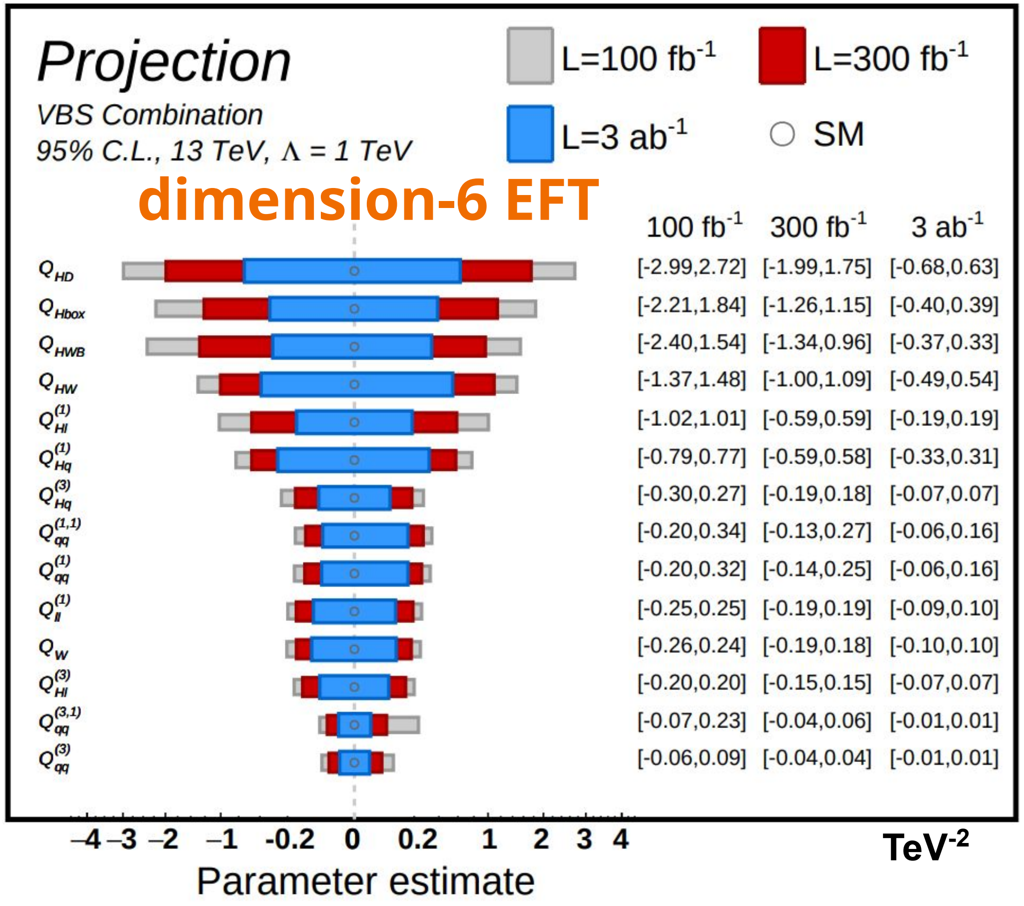


# Summary

- **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



# 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

| $\sqrt{s}$ | $\sigma^{\text{LO}}$ [fb] | $\sigma^{\text{NLO}}_{\text{EW}}$ [fb] | $\delta_{\text{EW}}$ [%] |
|---|---|---|---|
| 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 |

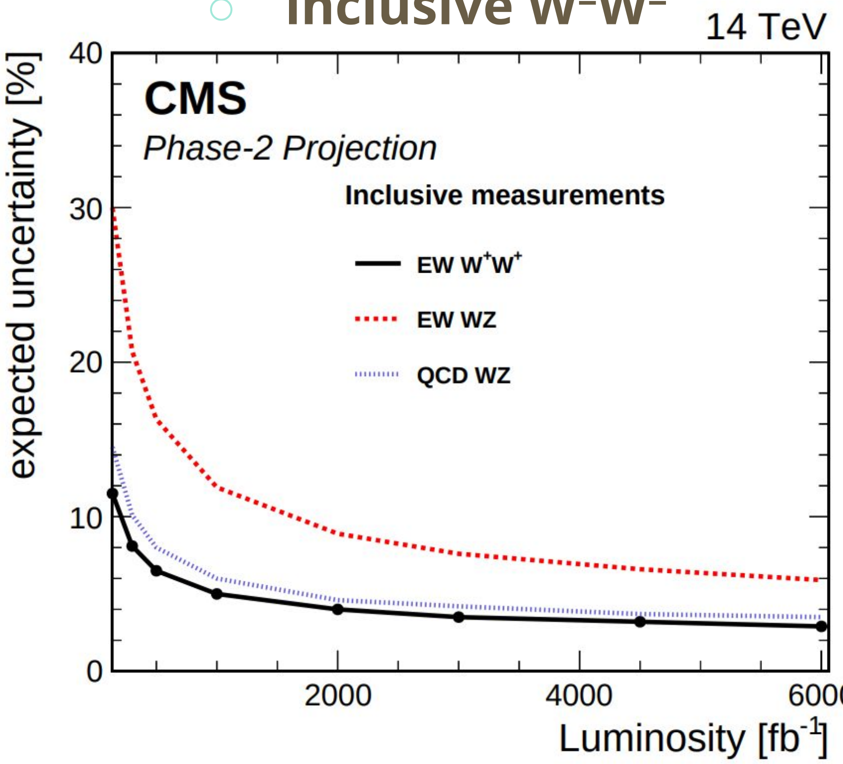
arXiv:2102.10991

- 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

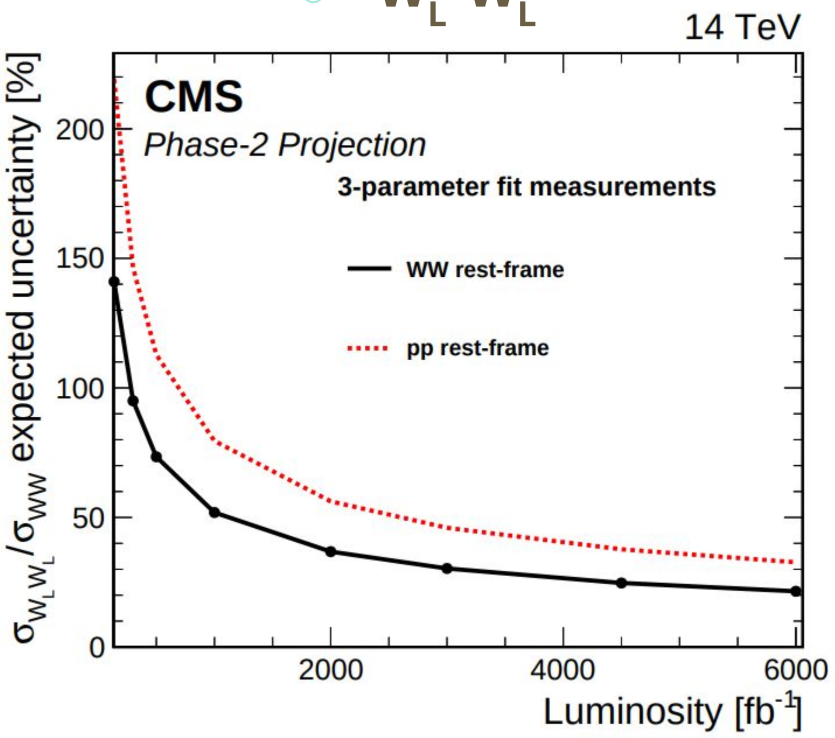
# Prospects for the VBS measurements at HL LHC

CMS-FTR-21-001 CDS:2776773

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



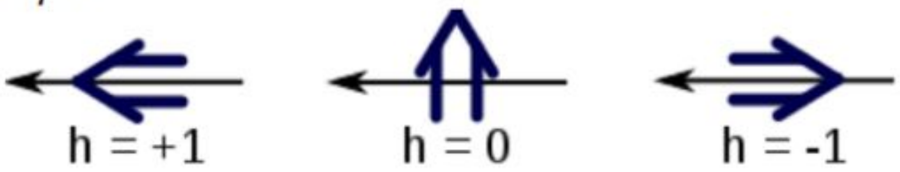

    - **$W_L^{\pm}W_L^{\pm}$**




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

# $W^{\pm}W^{\pm}$ Polarization components

Helicity: $h = \vec{p} \cdot \vec{\epsilon}$




Definition according to the **final state** of the scattering:

$$W^{\pm}W^{\pm} \rightarrow W^{\pm}_{L}W^{\pm}_{T}$$
$$W^{\pm}W^{\pm} \rightarrow W^{\pm}_{T}W^{\pm}_{L}$$
$$W^{\pm}W^{\pm} \rightarrow W^{\pm}_{T}W^{\pm}_{T}$$
$$W^{\pm}W^{\pm} \rightarrow W^{\pm}_{L}W^{\pm}_{L} \qquad = \text{SIGNAL}$$

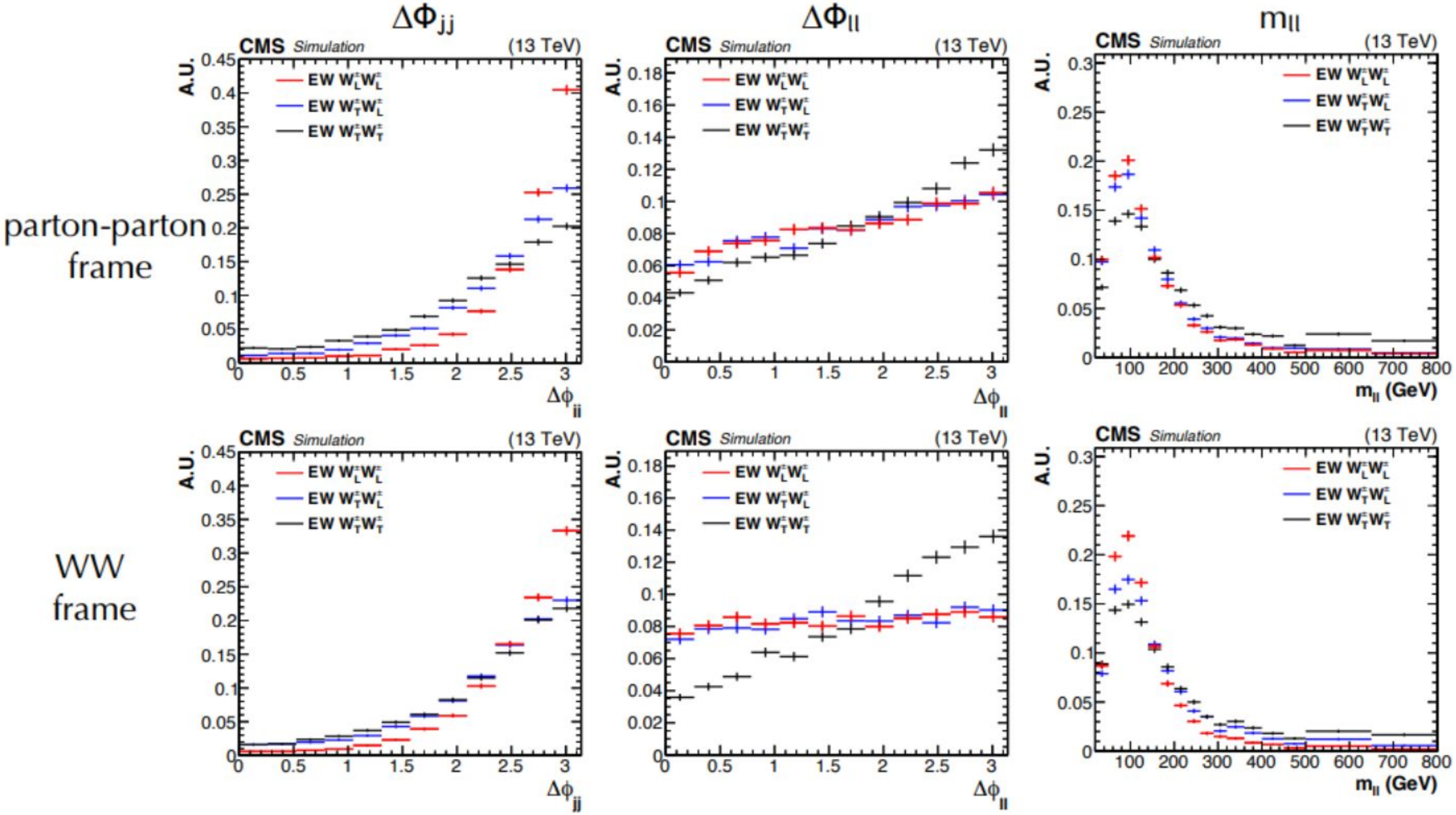
Summary of the fractions of the $W^{\pm}_{L}W^{\pm}_{L}$, $W^{\pm}_{L}W^{\pm}_{T}$, and $W^{\pm}_{T}W^{\pm}_{T}$ processes

| Cross sections with $m_{jj} > 200\text{GeV}$ and $p^{j}_{T} > 10\text{GeV}$ | | |
|---|---|---|
| Mode | WW rest-frame fraction (%) | Parton-parton rest-frame fraction (%) |
| $W^{\pm}_{L}W^{\pm}_{L}$ | 10.9 | 7.3 |
| $W^{\pm}_{L}W^{\pm}_{T}$ | 31.9 | 37.4 |
| $W^{\pm}_{T}W^{\pm}_{T}$ | 57.2 | 55.3 |

Each rest-frame produces different fractions, and hence different distributions

# $W^{\pm}W^{\pm}$ Polarization training variables

- Distributions of three variables with great separation power are shown
- Different between LL and XT, between LX and TT (X=L or T)



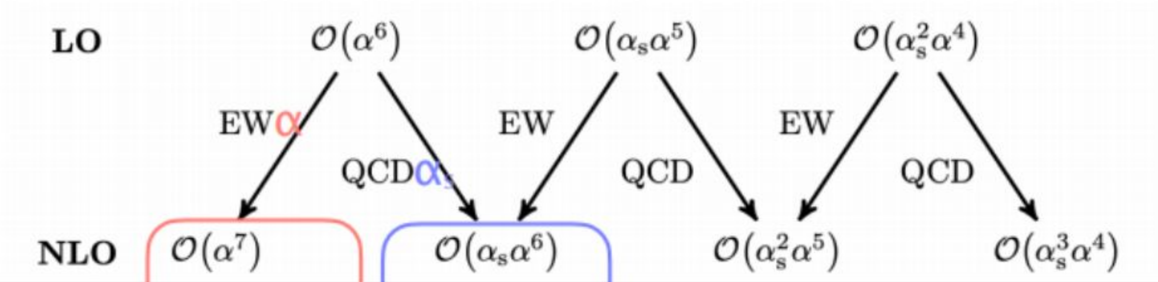
# $W^{\pm}W^{\pm}$ Polarization Systematic uncertainties

| Source of uncertainty | $W^{\pm}_{L}W^{\pm}_{L}$ (%) | $W^{\pm}_{X}W^{\pm}_{T}$ (%) | $W^{\pm}_{L}W^{\pm}_{X}$ (%) | $W^{\pm}_{T}W^{\pm}_{T}$ (%) |
|---|---|---|---|---|
| Integrated luminosity | 3.2 | 1.8 | 1.9 | 1.8 |
| Lepton measurement | 3.6 | 1.9 | 2.5 | 1.8 |
| Jet energy scale and resolution | 11 | 2.9 | 2.5 | 1.1 |
| Pileup | 0.9 | 0.1 | 1.0 | 0.3 |
| b tagging | 1.1 | 1.2 | 1.4 | 1.1 |
| Nonprompt lepton rate | 17 | 2.7 | 9.3 | 1.6 |
| Trigger | 1.9 | 1.1 | 1.6 | 0.9 |
| Limited sample size | 38 | 3.9 | 14 | 5.7 |
| Theory | 6.8 | 2.3 | 4.0 | 2.3 |
| Total systematic uncertainty | 44 | 6.6 | 18 | 7.0 |
| Statistical uncertainty | 123 | 15 | 42 | 22 |
| Total uncertainty | 130 | 16 | 46 | 23 |

Statistically limited measurements

# NLO correction

- The full NLO QCD and EW corrections for the leptonic unpolarized $W^{\pm}W^{\pm}$ scattering have been computed B.Biedermann, A.Denner, and M.Pellen arXiv:1611.02951 arXiv:1708.00268
- Reduce the LO cross section for the EW $W^{\pm}W^{\pm}$ process by approximately 10–15%
- Unknown for LL, LT, TT processes
  - $\alpha_s$ corrections expected to be the **same for all the 3** polarization modes
  - $\alpha$ corrections expected to be **small for the L** mode
  - Take the NLO corrections for the unpolarized EW $W^{\pm}W^{\pm}$ and apply
    - $\mathcal{O}(\alpha_s\alpha^6)$ and $\mathcal{O}(\alpha^7)$ to **TT**
    - Only $\mathcal{O}(\alpha_s\alpha^6)$ to **LL** and **LT**
    - $\mathcal{O}(\alpha^7)$ on the shapes of **LL** and **LT** considered as a systematic uncertainty




| Order | $\mathcal{O}(\alpha^7)$ | $\mathcal{O}(\alpha_s\alpha^6)$ | $\mathcal{O}(\alpha_s^2\alpha^5)$ | $\mathcal{O}(\alpha_s^3\alpha^4)$ | Sum |
|---|---|---|---|---|---|
| $\delta\sigma_{NLO}$ [fb] | −0.2169(3) | −0.0568(5) | −0.00032(13) | −0.0063(4) | −0.2804(7) |
| $\delta\sigma_{NLO}/\sigma_{LO}$ [%] | −13.2 | −3.5 | 0.0 | −0.4 | −17.1 |

# aQGCs: Unitarity issue

- EFT amplitudes grow with $m_{\mathrm{VV}}$ and this growth is unphysical above a certain scale $\Lambda$; this sets the limit of validity of EFT approach
- This scale derived from partial wave unitarity condition (as function of Wilson coefficients)
- Above $\Lambda$, since the data is consistent with SM, we replace prediction of EFT amplitudes with SM in that region; this leads to conservative bounds on EFT Wilson coefficients
- The technique is known as "Clipping", and essentially means using EFT only in the region it is valid
  - first time limits are also reported in this way
- See details in Arxiv.1906.10769 and Arxiv.1802.02366