# Vector Boson Scattering EW WG

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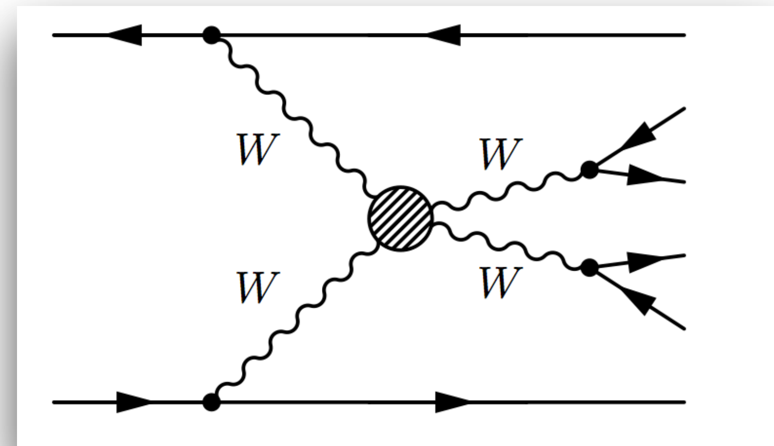
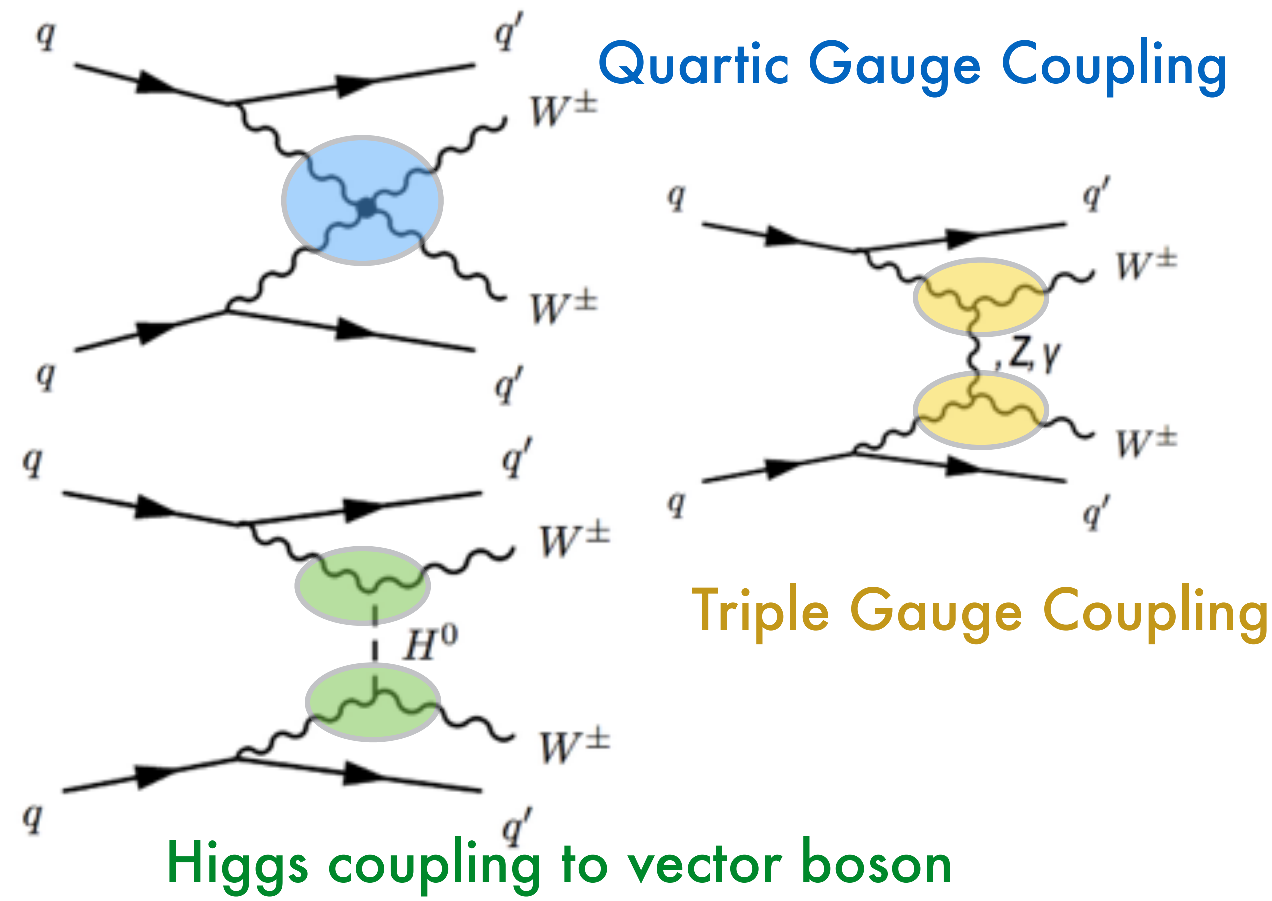
For CMS Collaboration
April 18th, 2018

# Quartic Gauge Couplings

- **LHC can probe W and Z quartic couplings in Standard Model for the first time**



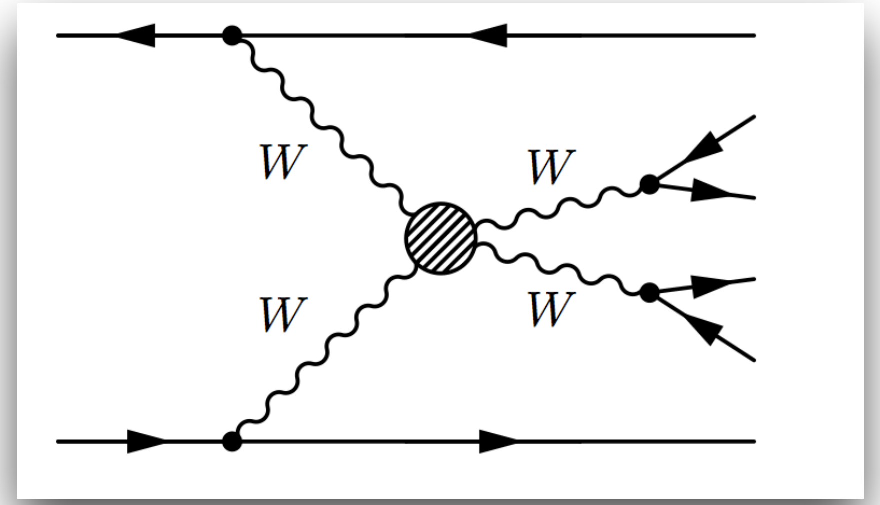

- **SM predicts couplings:**
  - **tree-level QGC: WWWW, WWZZ, WWZγ,WWγγ**
  - **tree-level TGC: WWZ,WWγ**
  - **ZZZ, ZZγ Zγγ, γγγ, ZZZZ, ZZZγ, ZZγγ, Zγγγ, γγγγ absent in SM**

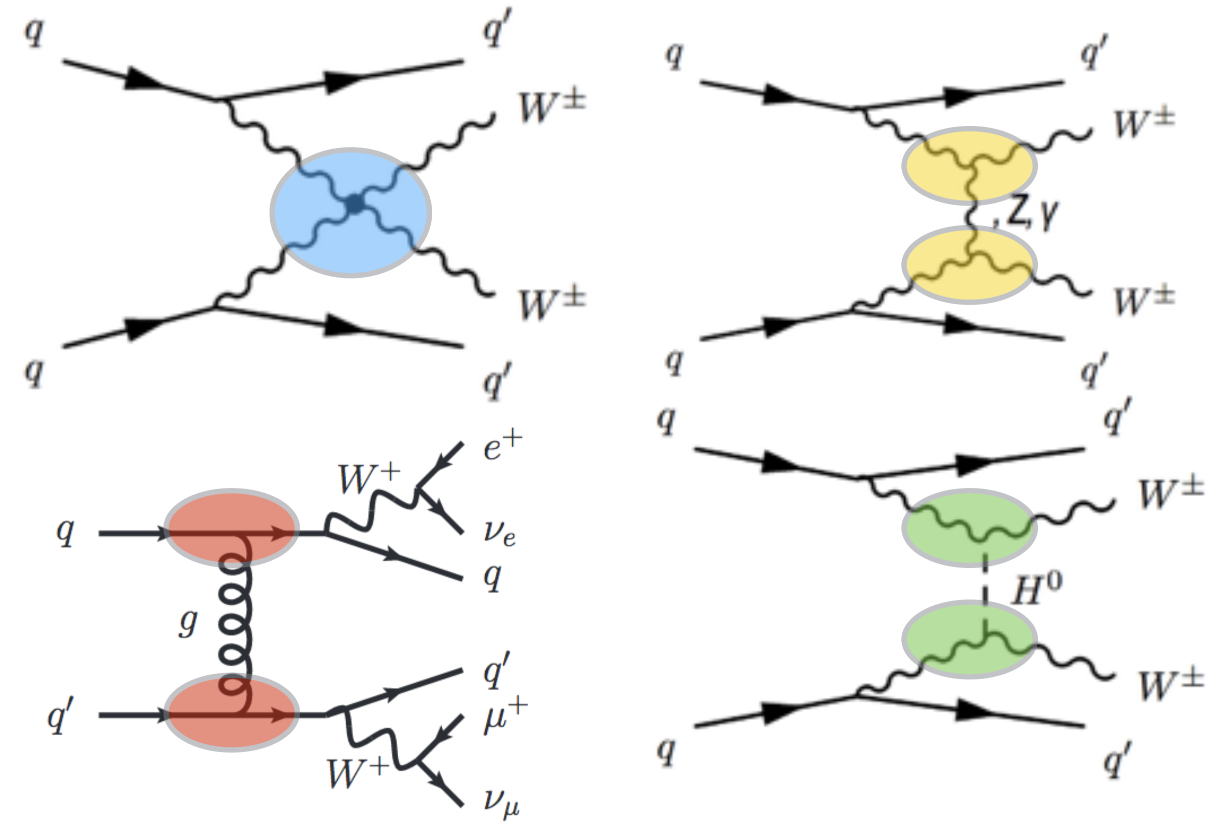
- **TGC and QGC (involving photons) studied at LEP and Tevatron**

**t-channel Z,γ and H exchange cancel divergent quartic coupling of massive gauge bosons**

# Electroweak Diboson Production

- **LHC can probe W and Z quartic couplings in Standard Model for the first time (massive bosons)**




- **At LO production cross section is sum of terms also involving strong coupling constant**

| $\sigma_{EW} \propto \mathcal{O}(\alpha_{EW}^6)$ | $\sigma_{EW \times QCD} \propto \mathcal{O}(\alpha_{EW}^5 \alpha_S)$ | $\sigma_{QCD} \propto \mathcal{O}(\alpha_{EW}^4 \alpha_S^2)$ |
|---|---|---|
| **EW Signal** | **Interference, uncertainty or added to background, usually O(1%)** | **Background (QCD induced)** |

- $\frac{\sigma_{EW}(VV+jj)}{\sigma_{QCD}(VV+jj)}$ **largest for W±W± production**
  - **most sensitive to probe quartic gauge coupling**

# Beyond The SM Interpretation

- **1.) Effective Field Theory (Eboli basis, orthogonal to aTGC)**
  - **Operators ordered terms of covariant derivatives only (Scalar), field strength tensors only (Tensor) or both (Mixed)**

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{i=WWW,W,B,\Phi W,\Phi B} \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_{j=1,2} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0,\dots,9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j} + \sum_{j=0,\dots,7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j}$$

**possible to map onto specific model**

| | $J=0$ | $J=1$ | $J=2$ |
|---|---|---|---|
| $I=0$ | $\sigma^0$ ("Higgs") | $[\omega^0]$ $(\gamma'/Z')$ | $f^0$ (KK graviton) |
| $I=1$ | $[\pi^\pm, \pi^0]$ (2HDM) | $\rho^\pm, \rho^0$ $(W'/Z')$ | $[a^\pm, a^0]$ |
| $I=2$ | $\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet) | — | $t^{\pm\pm}, t^\pm, t^0$ |

arxiv.1307.8170

| | WWWW | WWZZ | ZZZZ | WWAZ | WWAA | ZZZA | ZZAA | ZAAA | AAAA |
|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$ | X | X | X | | | | | | |
| $\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$ | X | X | X | X | X | X | X | | |
| $\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$ | | X | X | X | X | X | X | | |
| $\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$ | X | X | X | X | X | X | X | X | X |
| $\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$ | | X | X | X | X | X | X | X | X |
| $\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$ | | | X | | | X | X | X | X |

arxiv:1309.7890

- **2.) Direct diboson resonance searches reach ($M_X$ ~1-2 TeV)**
  - **Depends on: spin 0/1/2, charge, fermion/boson couplings**

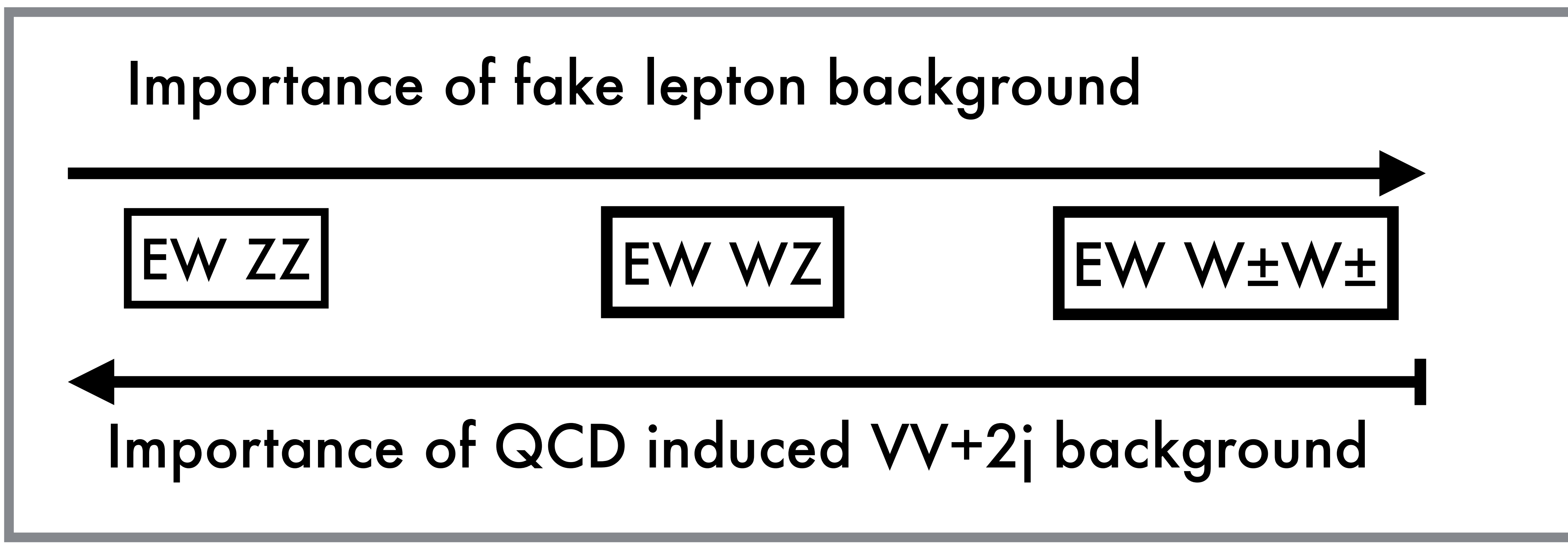
# LHC VBS Studies

- **WW largest EW cross section and signal to background ratio**
  - **So far the only VBS process experiementally confirmed**
- **WZ and ZZ processes become feasible with the full Run-2 dataset**
  - **larger QCD VV background, controlled in 2-jet side bands**
- **Semi-leptonic final states sensitive to BSM**

| sqrt(s) | VBS process | ATLAS | CMS | Comment |
|---|---|---|---|---|
| 8 TeV | EW W±W± (lνlν) | PRL 113, 141803<br>PRD 96, 012007 | PRL 114 (2015) 051801 | ATLAS finds evidence |
| | EW Zγ (νν/llγ) | JHEP07(2017)107 | Phys.Lett. B770 (2017) 380-402 | CMS finds evidence |
| | EW Wγ (lνγ) | x | JHEP 1706 (2017) 106 | CMS finds 2.7 σ |
| | EW WZ (3lν) | PRD 93, 092004 (2016) | PRL 114 (2015) 051801 | ATLAS places limits on aQGC, CMS meas. QCD+EW xsec |
| | EW WV (lνjj) | PRD 95 (2017) 032001 | x | limits on aQGC |
| 13 TeV | EW W±W± | x | PRL 120, 081801 | CMS first observation |
| | EW ZZ (4l) | x | Phys. Lett. B 774 (2017) 682 | CMS finds 2.7 σ |
| | EW WZ (3lν) | x | PRL 119 (2017), 141802 | VBF charged Higgs analysis (same phase space, no cross section measurement, yet) |

# CMS VBS Studies

- **$W^{\pm}W^{\pm}$ largest EW cross section and signal to background ratio**
  - **So far the only VBS process experiementally confirmed**
- **WZ and ZZ processes become feasible with the full Run-2 dataset**
  - **larger QCD VV background, controlled in 2-jet side bands**
- **Semi-leptonic final states sensitive to BSM**

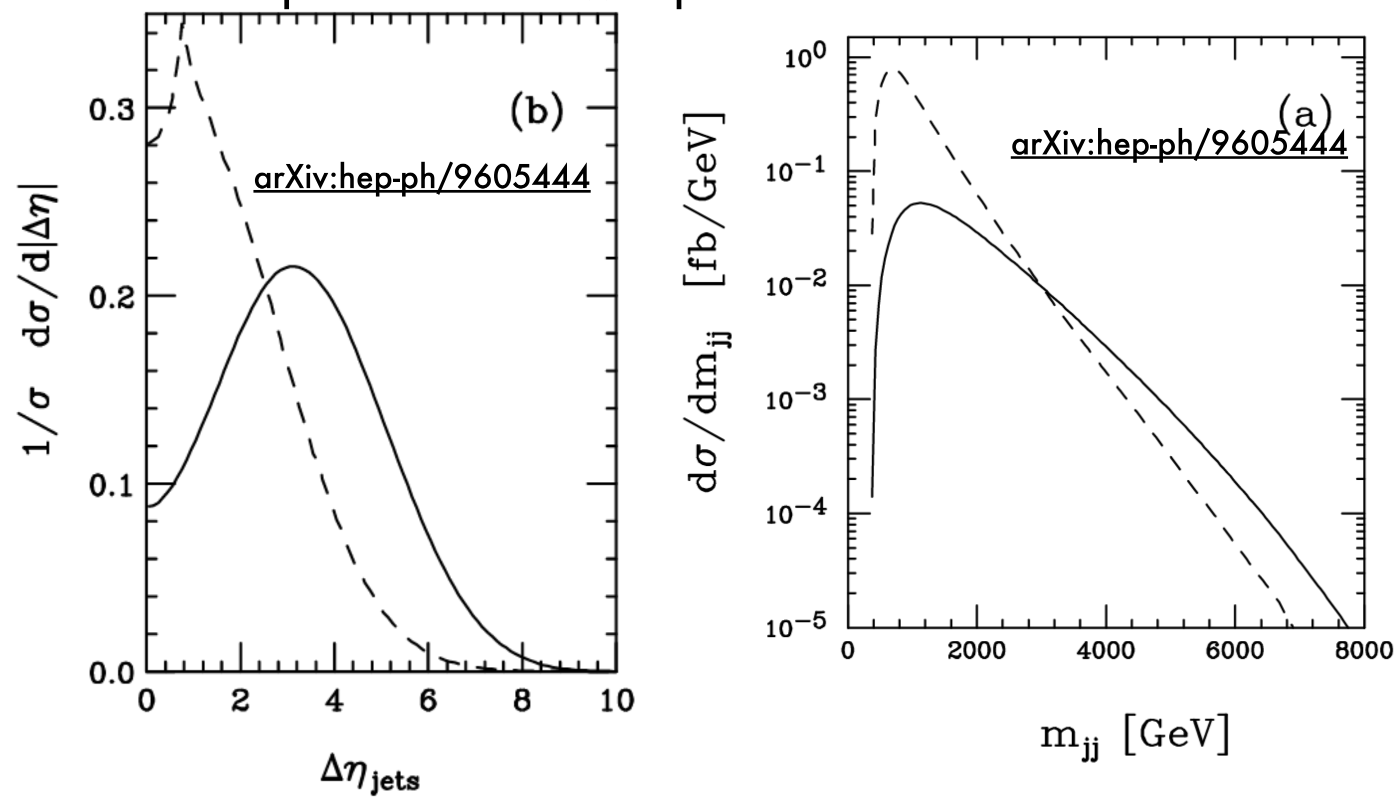



- **Both well validated in control regions, outside the signal region**
  - **e.g. inverted b-jet requirements (fake enriched) or dijet cuts (QCD VV enriched)**

# Experimental Signature and Predictions

- **VBS processes have distinct signature in the detector: two jets**
  - **large dijet invariant mass ($m_{JJ} > 500$ GeV)**
  - **large pseudorapidity separation**
  - **(di-)boson system central wrt dijets**

dijet studies for EW Z production via s-channel




- **SM processes mostly studied in fully leptonic final states**
  - **semi-leptonic decays affected by background, but sensitive to BSM physics**
  - **lepton: $p_T$\`s in general >20-30 GeV, I$\eta$I< 2.5 (2.4)**
  - **Jets $p_T > 30$ GeV**
- **Experiments do not always use similar theoretical tools**
  - **ATLAS: POWHEG/WHIZARD/SHERPA for Signal, WHIZARD for aQGCs, interference e.g. SHERPA**
  - **CMS: MadGraph for Signal and aQGCs, interference PHANTOM**
  - **Theoretical predicitions for EW production emerging at NLO (EW+QCD) (for $W^{\pm}W^{\pm}$ arXiv:1708.00268)**

# $W^{\pm}W^{\pm}$ VBS (Observation 13 TeV)

- **Measurement performed inclusively in ee, eμ, μμ channel, two same-sign leptons**
  - Major backgrounds estimated from the data: Fake leptons (60%), WZ (QCD+EW), charge flip (for electrons (sub) per mille level)
  - Major syst. unc.: jet energy scale, fake background
  - fiducial volume lepton: $|\eta| < 2.5$, $p_T > 20$ GeV, jets $|\eta| < 5$, $p_T > 30$ GeV, $m_{JJ} > 500$ GeV, $|\Delta\eta_{JJ}| > 2.5$
- **Fit performed in 2 dimensions ($m_{JJ}$ vs $m_{ll}$) to extract best-fit signal strength modifier**

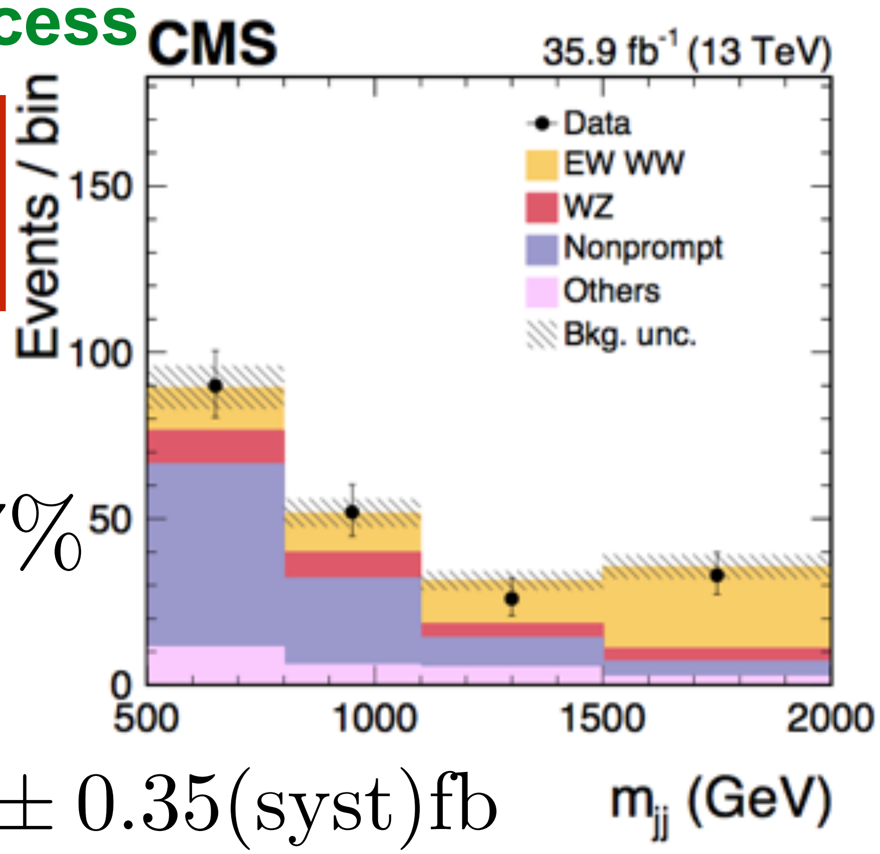
PRL 120, 081801

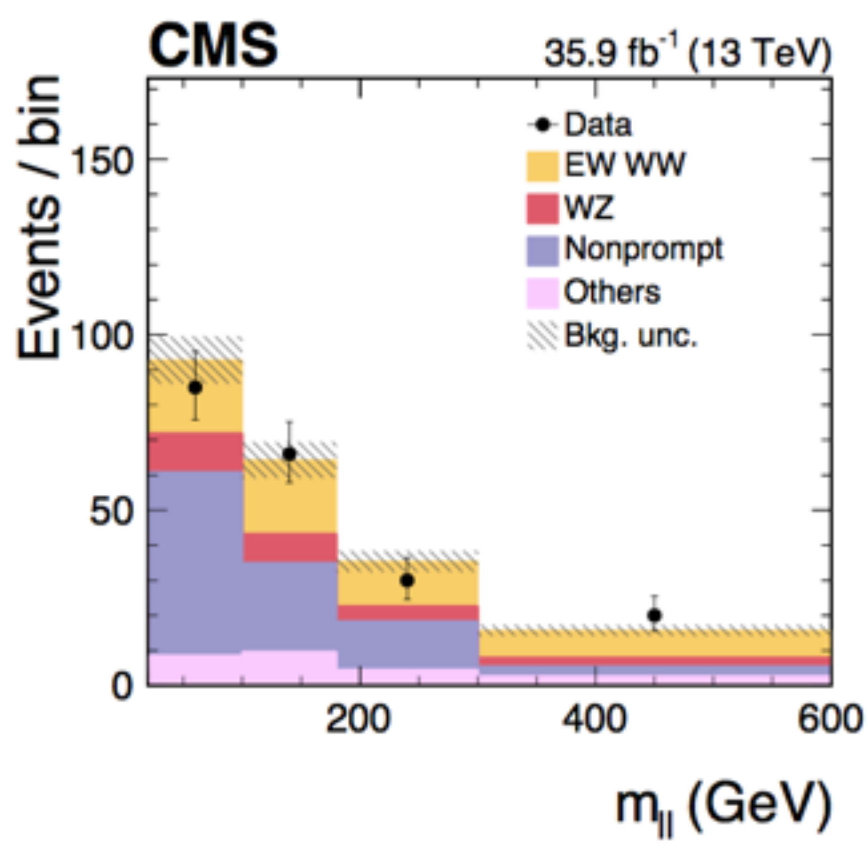
**First observation of VBS process**

5.5 (5.7) observed (expected) significance

$$\sigma_{LO}^{EW} = 4.25 \pm 0.27\text{fb}$$

$$\sigma_{NLO-EW} \approx \sigma_{LO} - 17\%$$



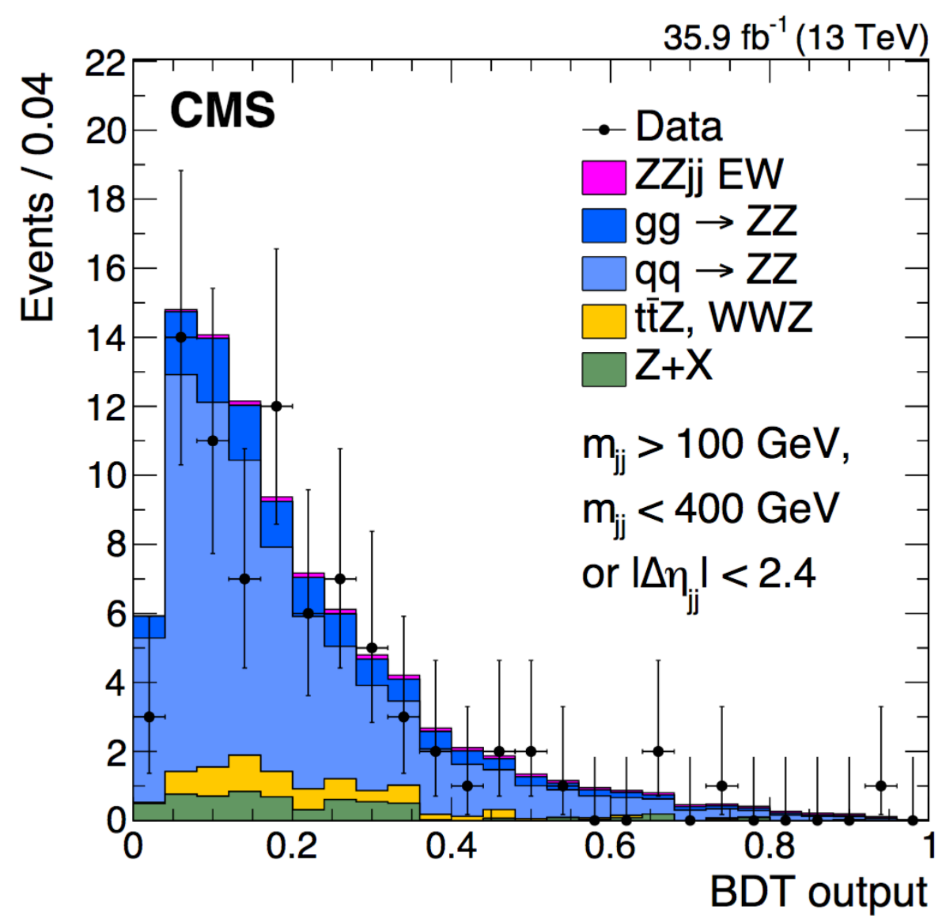




$$\sigma^{\text{meas.}} = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst})\text{fb}$$

# ZZ VBS (13 TeV)

Phys. Lett. B 774 (2017) 682

- **ZZjj production measurement performed in fully leptonic final state**
  - BDT used as final discriminant
  - Jets $p_T$ > 30 GeV, lepton: $p_T$ >5(7) GeV muon (electron) ,20/10(12) GeV (leading subleading muon (electron))
  - $m_{JJ}$ >100 GeV, Z candidates 60 < $m_{ll}$ < 120 GeV
  - for fiducial volume only change lepton kinematics |η|< 2.5, $p_T$ > 5 GeV
- **Leading background QCD-induced ZZ+jets production**
  - produced at NLO aMC@NLO
  - loop induced (gg->ZZ) with MCFM
- **ZZ background validated in control region**
  - inverted dijet cuts: $m_{JJ}$ < 400 GeV OR |$\Delta\eta_{JJ}$|< 2.4



# ZZ VBS (13 TeV)

Phys. Lett. B 774 (2017) 682

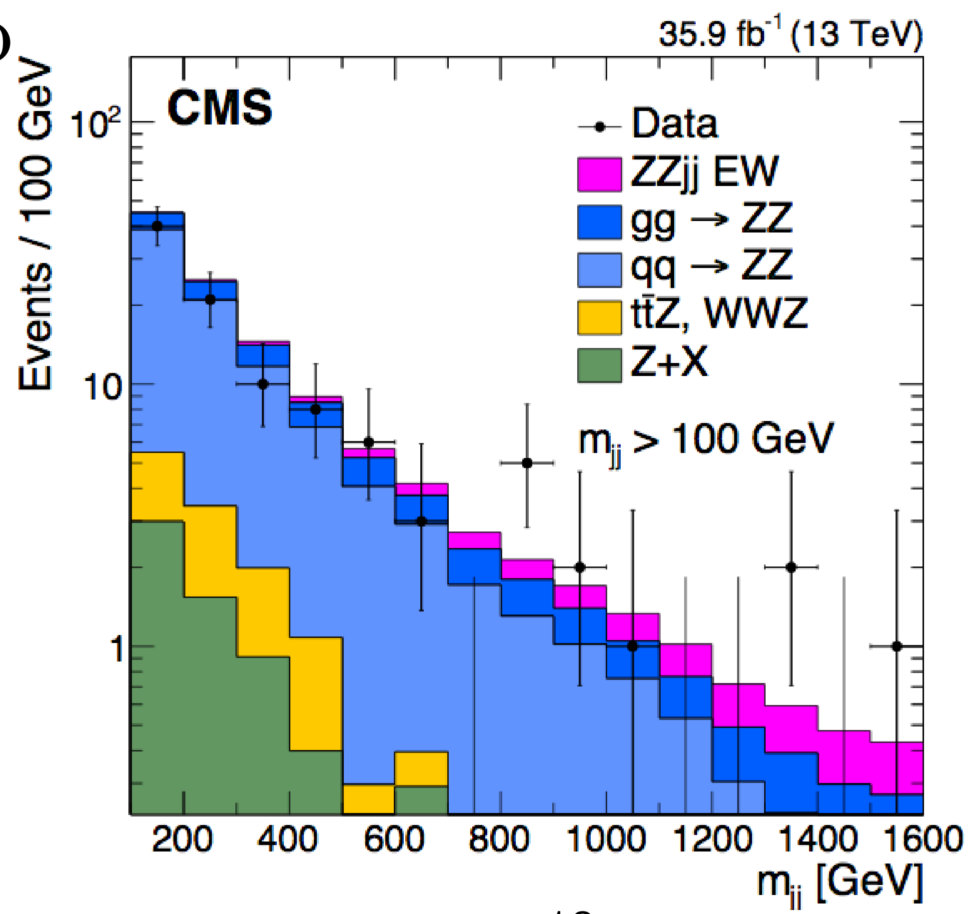
- **ZZjj production measurement performed in fully leptonic final state**
- **Exploit boosted decision tree to enhance sensitivity (7 most performant variables used)**
  - $m_{JJ}$, $\Delta\eta_{JJ}$, $m_{ZZ}$, $Z_{1,2}$-centrality, vector/scale sum of VBF-jets and of ZZ+jets
- **2.7 (1.6) observed (expected) over bkgd-only hypothesis**

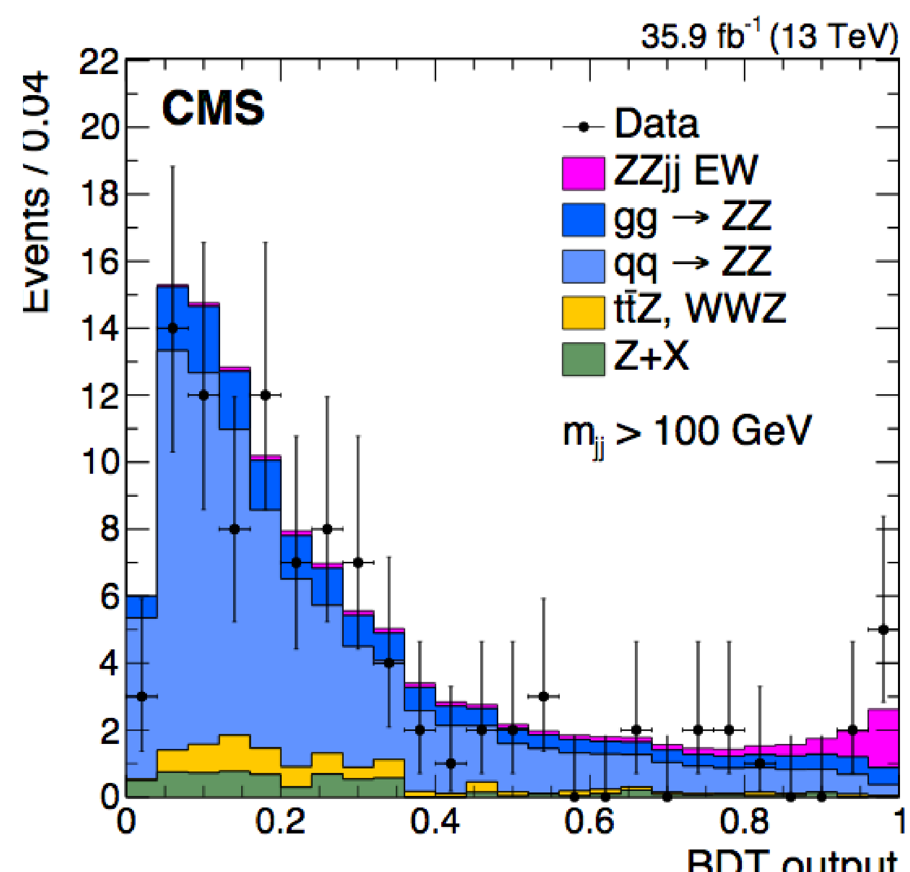
$$\sigma_{\mathrm{EW}}(\mathrm{pp} \to \mathrm{Z\bar{Z}jj} \to \ell\ell\ell'\bar{\ell}'\mathrm{jj}) = 0.40^{+0.21}_{-0.16}\,(\mathrm{stat})\,^{+0.13}_{-0.09}\,(\mathrm{syst})\,\mathrm{fb}$$

$$\sigma_{LO}^{EW} = 0.29^{+0.02}_{-0.03}\mathrm{fb}$$

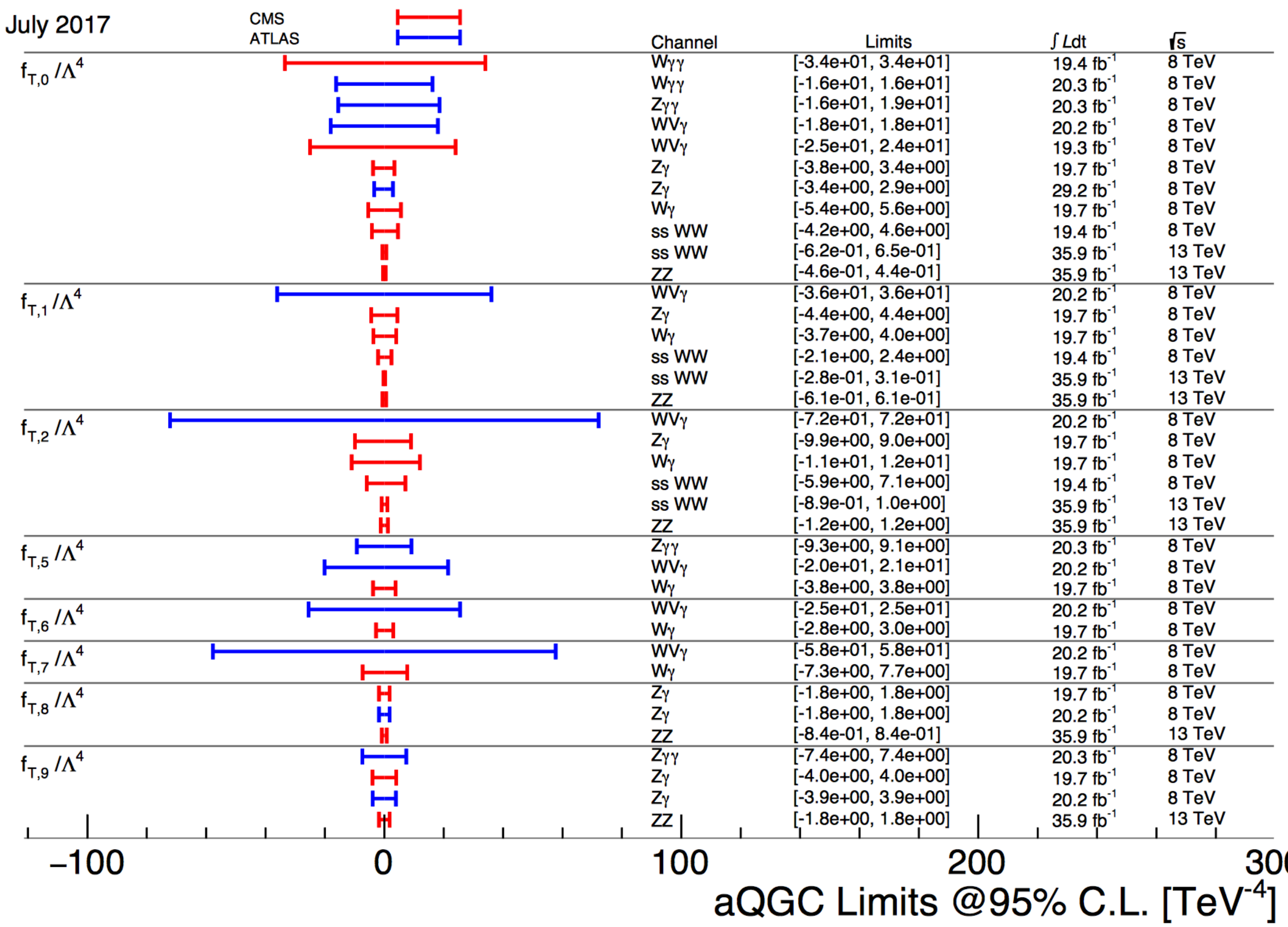
good sensitivity to EFT operators

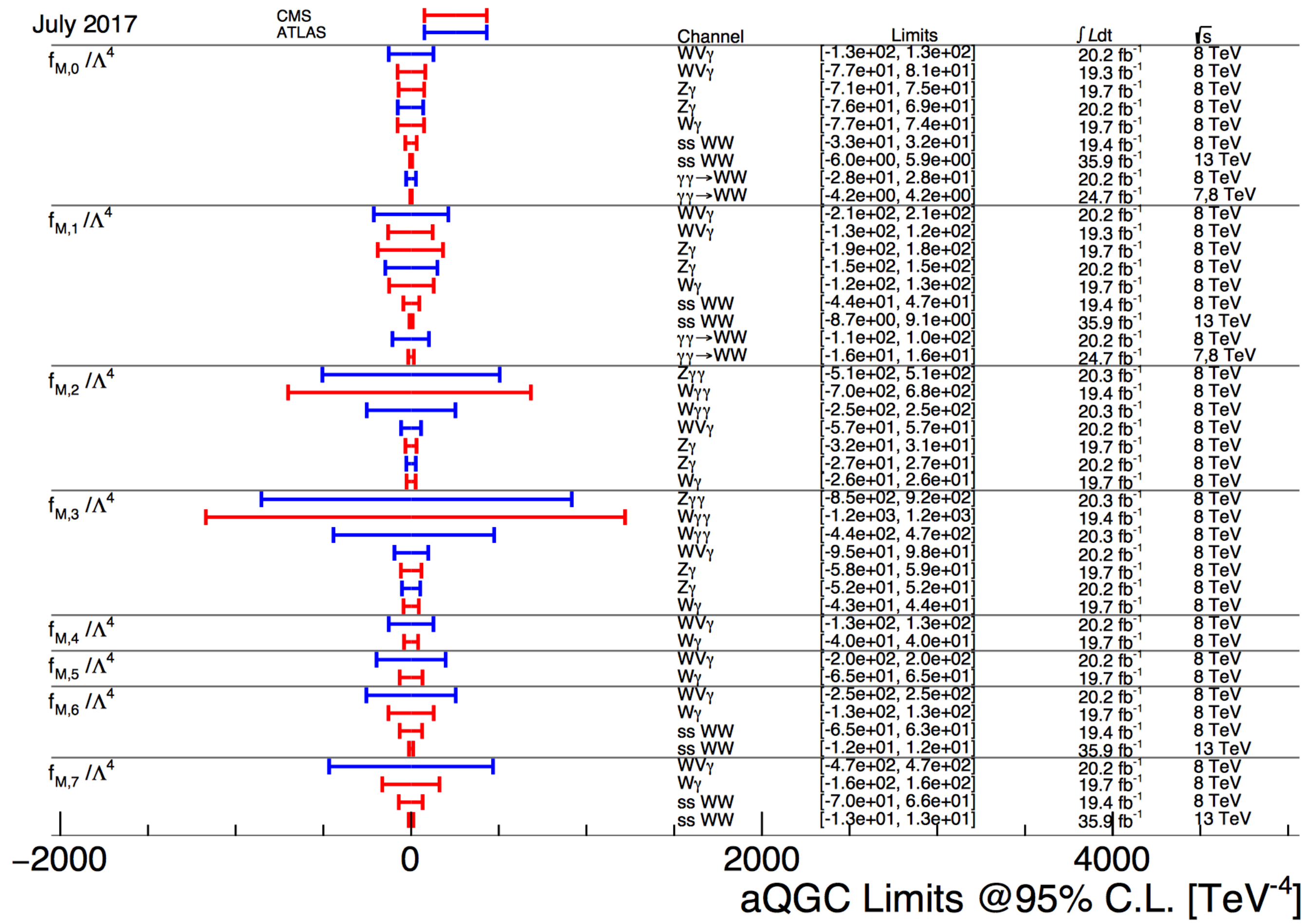
$$-0.46 < f_{T0}/\Lambda^4 < 0.44$$
$$-0.61 < f_{T1}/\Lambda^4 < 0.61$$
$$-1.2 < f_{T2}/\Lambda^4 < 1.2$$
$$-0.84 < f_{T8}/\Lambda^4 < 0.84$$
$$-1.8 < f_{T9}/\Lambda^4 < 1.8$$



# Anomalous Quartic Gauge Couplings 2




- **Important to probe all diboson processes to cover all possible EFT operators**

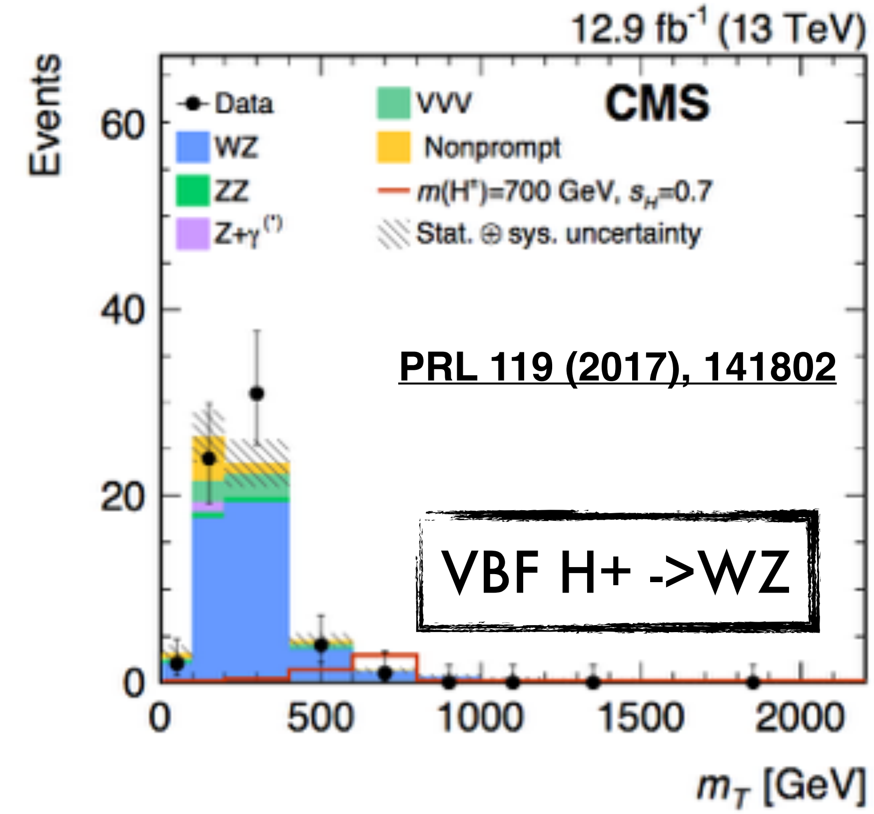
| | WWWW | WWZZ | ZZZZ | WWAZ | WWAA | ZZZA | ZZAA | ZAAA | AAAA |
|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$ | X | X | X | | | | | | |
| $\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$ | X | X | X | X | X | X | X | | |
| $\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$ | | X | X | X | X | X | X | | |
| $\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$ | X | X | X | X | X | X | X | X | X |
| $\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$ | | X | X | X | X | X | X | X | X |
| $\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$ | | | X | | | X | X | X | X |

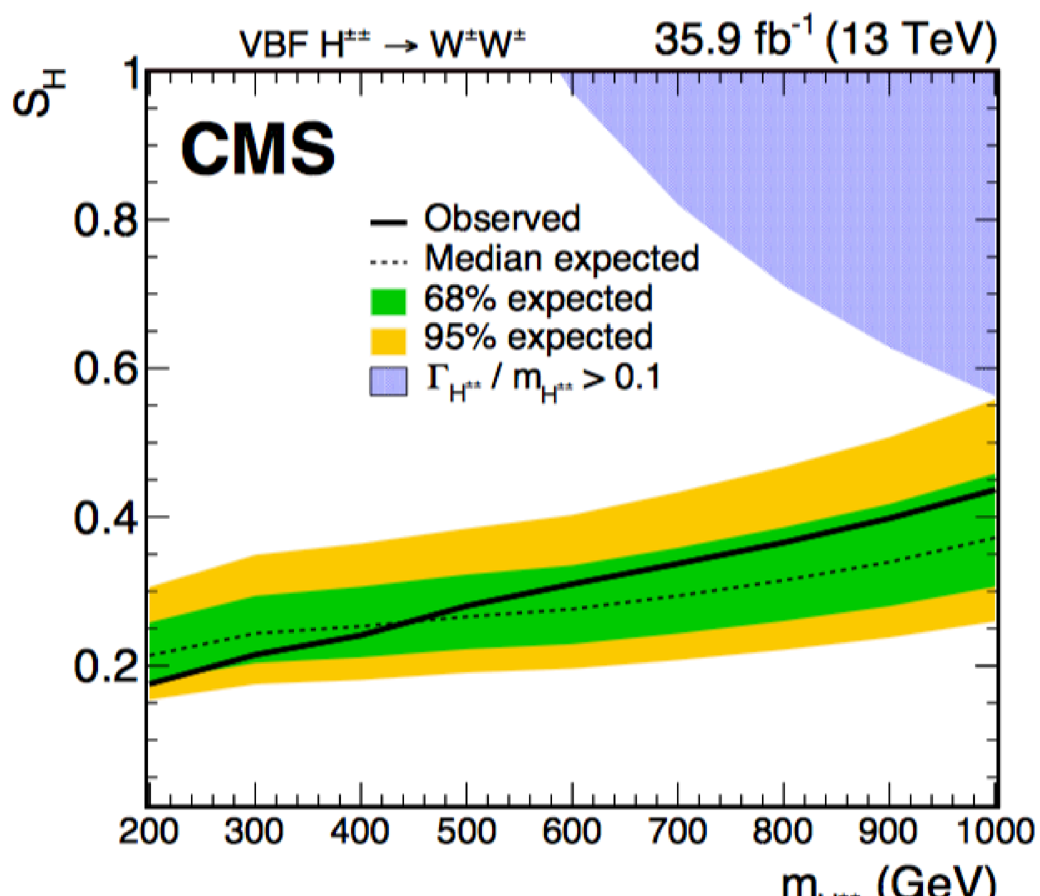
  - Indirectly probing mass scales ~1 TeV

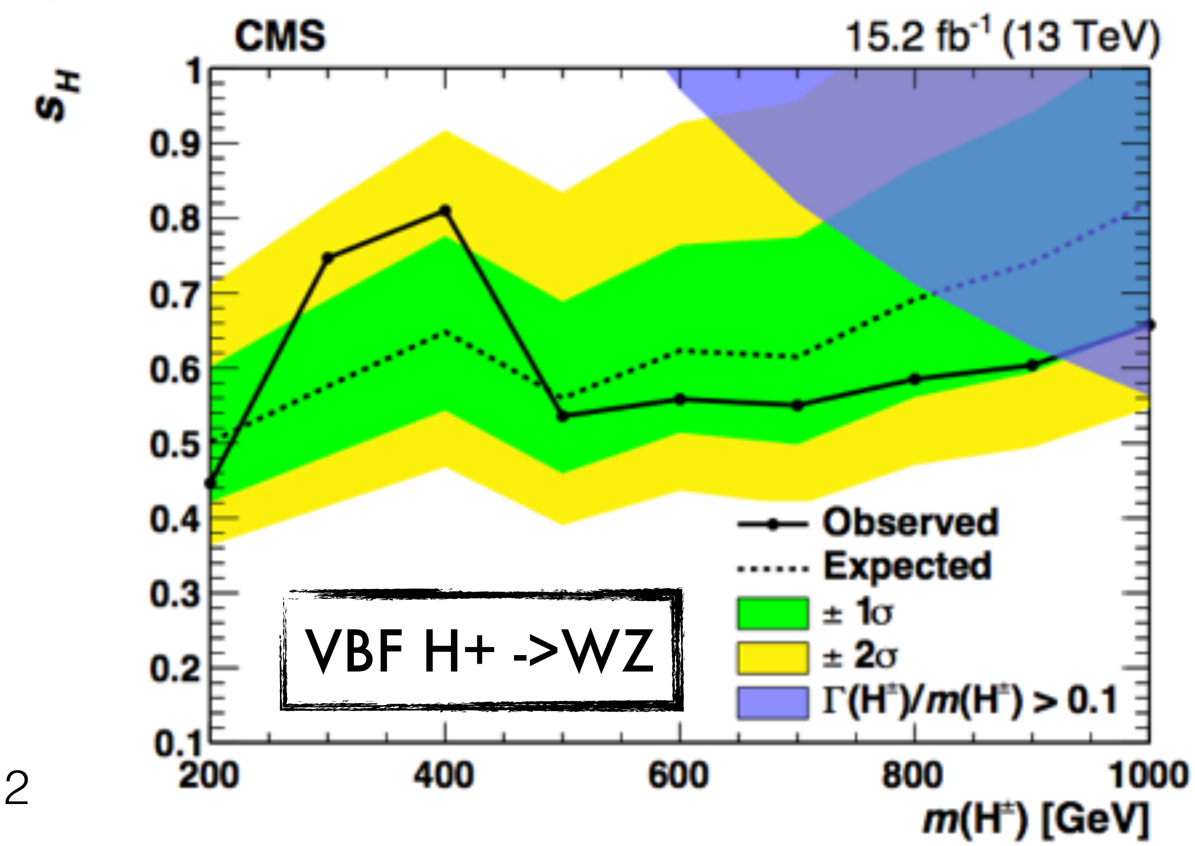
- **Gain in sensitivity can be obtained by combination, if two analyses have similar sensitivity**

# VBF Diboson Resonances (13 TeV)

- CMS performed searches for VBF $H^{++}$ and $H^{+}$ production at 13 TeV
  - Higgs triplet models give rise to doubly-charged Higgs bosons
- Search performed in fully leptonic final-states
  - VBF/VBS dijet topology cuts
- $W^{\pm}W^{\pm}$ analysis most performant when interpreted in Georgi-Machacek Model



# Inclusive VV BSM Searches

- **Many inclusive VV resonance searches performed**
  - Probing mainly qq->X production
    $c_f^X \times c_V^X$ **vs** $c_V^X \times c_V^X$
  - complemented with VBF searches, could improve measuring/probing resonance couplings to vector bosons and fermions

Table 2,3 from T. Dorigo,arxix

| Expt. | CM energy (TeV) | Int. Lum. ($fb^{-1}$) | Year | Decay modes | Considered models | Ref. |
|---|---|---|---|---|---|---|
| ATLAS | 7 | 1.02 | 2012 | $l\nu l'l'$ | EGM $W'$, LSTC $\rho_T$ | [354] |
| ATLAS | 7 | 4.7 | 2013 | $l\nu q\bar{q}$ | EGM $W'$ | [318] |
| ATLAS | 8 | 20.3 | 2014 | $l\nu l'l'$ | EGM $W'$, HVT | [355] |
| ATLAS | 8 | 20.3 | 2014 | $llq\bar{q}'$ | EGM $W'$ | [356] |
| ATLAS | 8 | 20.3 | 2015 | $llq\bar{q}'$ | $H^\pm$, HTM | [357] |
| ATLAS | 8 | 20.3 | 2015 | $l\nu q\bar{q}$ | EGM $W'$ | [319] |
| ATLAS | 8 | 20.3 | 2015 | $q\bar{q}q\bar{q}'$ | EGM $W'$ | [320] |
| ATLAS | 8 | 20.3 | 2015 | Combination | EGM $W'$ | [322] |
| ATLAS | 13 | 3.2 | 2016 | Combination | HVT bosons | [323] |
| CMS | 7 | 5.0 | 2012 | $l\nu l'l'$ | SSM $W'$, $\rho_T$ | [358] |
| CMS | 7 | 5.0 | 2012 | $llq\bar{q}'$, $\nu\nu q\bar{q}'$ | SSM $W'$ | [359] |
| CMS | 7 | 5.0 | 2012 | $q\bar{q}q\bar{q}'$ | $W'$ | [325] |
| CMS | 8 | 19.7 | 2014 | $q\bar{q}q\bar{q}'$ | $W'$ | [326] |
| CMS | 8 | 19.7 | 2014 | Combination | model-independent | [327] |
| CMS | 8 | 19.5 | 2014 | $l\nu l'l'$ | EGM $W'$ | [360] |
| CMS | 13 | 2.7 | 2016 | Combination | HVT and model-independent | [328] |
| CMS | 13 | 15.2 | 2017 | $l\nu l'l'$ | $H^\pm$ | [361] |
| CMS | 8+13 | 19.7+2.7 | 2017 | Combination | HVT | [329] |

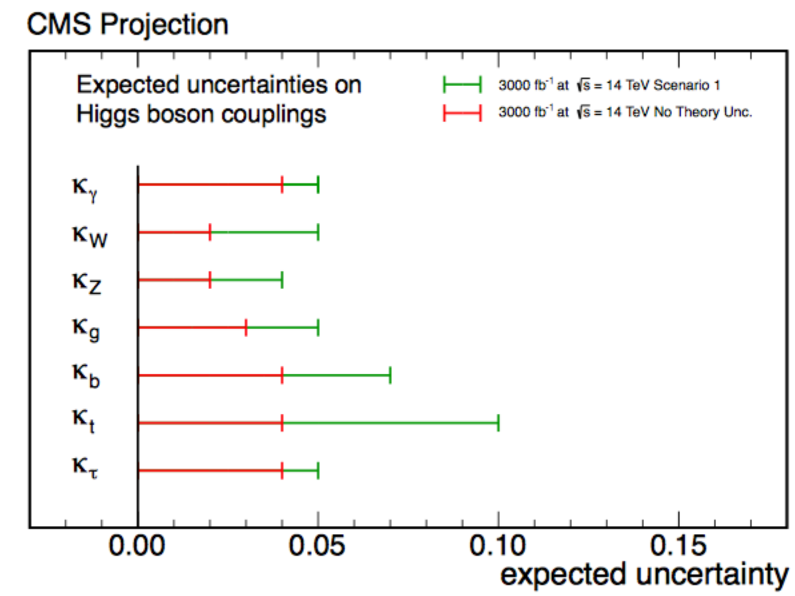
| Expt. | CM energy (TeV) | Int. Lum. ($fb^{-1}$) | Year | Decay modes | Considered models | Ref. |
|---|---|---|---|---|---|---|
| ATLAS | 7 | 4.7 | 2012 | $l\nu l\nu$ | RS $G^*$, $G^*_{bulk}$ | [317] |
| ATLAS | 7 | 4.7 | 2013 | $l\nu q\bar{q}'$ | RS $G^*$, $G^*_{bulk}$ | [318] |
| ATLAS | 8 | 20.3 | 2015 | $l\nu q\bar{q}'$ | RS $G^*_{bulk}$ | [319] |
| ATLAS | 8 | 20.3 | 2015 | $q\bar{q}'q\bar{q}'$ | RS $G^*_{bulk}$ | [320] |
| ATLAS | 8 | 20.3 | 2015 | $l\nu q\bar{q}'$, $l\nu l\nu$ | Heavy neutral Higgs | [321] |
| ATLAS | 8 | 20.3 | 2015 | Combination | RS $G^*_{bulk}$ | [322] |
| ATLAS | 13 | 3.2 | 2016 | $q\bar{q}'l\nu$, $q\bar{q}'q\bar{q}'$ | Scalar singlets, HVT bosons, $G^*_{bulk}$ | [323] |
| CMS | 7 | 5 | 2012 | Combination | Fermiophobic Higgs bosons | [324] |
| CMS | 7 | 5 | 2012 | $q\bar{q}'q\bar{q}'$ | RS $G^*$ | [325] |
| CMS | 8 | 19.7 | 2014 | $q\bar{q}'q\bar{q}'$ | RS $G^*$ and $G^*_{bulk}$ | [326] |
| CMS | 8 | 19.7 | 2014 | Combination | RS $G^*$ and $G^*_{bulk}$ | [327] |
| CMS | 13 | 2.7 | 2016 | $l\nu q\bar{q}'$, $q\bar{q}'q\bar{q}'$ | RS $G^*_{bulk}$, HVT bosons | [328] |
| CMS | 8+13 | 19.7+2.7 | 2017 | Combination | HVT Singlets and triplets, RS $G^*_{bulk}$ | [329] |

# Higgs Couplings

- **Cross section of VBS processes depend on Higgs vector boson couplings**

- **Example: Two Higgs Doublet Models**

$$g_{hVV}^{\rm 2HDM}/g_{hVV}^{\rm SM} = \sin(\beta-\alpha)$$
$$g_{HVV}^{\rm 2HDM}/g_{HVV}^{\rm SM} = \cos(\beta-\alpha)$$




arxiv:1307.7135

| | Cross Sections (fb) | | | |
|---|---|---|---|---|
| Channels | $\sin(\beta-\alpha)=0.5$ | 0.7 | 0.9 | SM ($C_v=1$) |
| $W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ | 0.51 | 0.46 | 0.40 | 0.39 |
| $W^+W^+ \to \ell^+\nu\ell^+\nu$ | 0.20 | 0.17 | 0.14 | 0.14 |
| $W^-W^- \to \ell^-\bar{\nu}\ell^-\bar{\nu}$ | 0.083 | 0.075 | 0.070 | 0.069 |
| $W^+Z \to \ell^+\nu\ell^+\ell^-$ | 0.016 | 0.013 | 0.011 | 0.010 |
| $W^-Z \to \ell^-\bar{\nu}\ell^+\ell^-$ | $1.0\times10^{-2}$ | $8.5\times10^{-3}$ | $7.6\times10^{-3}$ | $7.4\times10^{-3}$ |
| $ZZ \to \ell^+\ell^-\ell^+\ell^-$ | $8.4\times10^{-3}$ | $6.4\times10^{-3}$ | $4.6\times10^{-3}$ | $4.4\times10^{-3}$ |

arxiv:1303.6335

# Conclusions

- **Study of VBS processes complementary approach to study mechanism of electroweak symmetry breaking and the Higgs sector**
  - One of the reasons the LHC was built, slightest deviations of higgs couplings will lead to changes in cross sections and ultimately unitarity violation
- **Production cross section measurements involving quartic gauge couplings are progressing rapidly**
  - First electroweak diboson production mechanism experimentally confirmed with the analyses of $W^{\pm}W^{\pm}$ processes
- **Focussed on 13 TeV results, massive gauge bosons, see slide 5 details on VBS analysis at 8 TeV involving photons**
- **Many more results to appear on full Run-2 dataset ~ 150 $fb^{-1}$, exciting times ahead**
  - So far most results based on 20-40 $fb^{-1}$ on 8 and 13 TeV

# Additional Material

# aQGC EFT Operators

- **Grouped in covariant derivatives, Field Strength Tensors and both (mixed)**

$$\mathcal{O}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] ,$$
$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] ,$$

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] ,$$
$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] ,$$
$$\mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \times B^{\beta\nu} ,$$
$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \times B^{\beta\mu} ,$$
$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right] ,$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right] ,$$

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] ,$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] ,$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right] ,$$
$$\mathcal{O}_{T,5} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta} ,$$
$$\mathcal{O}_{T,6} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu} ,$$
$$\mathcal{O}_{T,7} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha} ,$$
$$\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} .$$

# Quartic Couplings at LHC

- At the LHC quartic vector boson couplings are studies in
  - Triboson production
  - And vector boson scattering
- $W^{\pm}W^{\pm}$ is the golden channel
  - Smallest largest EW-over-QCD ratio
- Number of leptons and VBF topology enhances sensitivity

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