# Latest Results on VBF and VBS Processes at CMS

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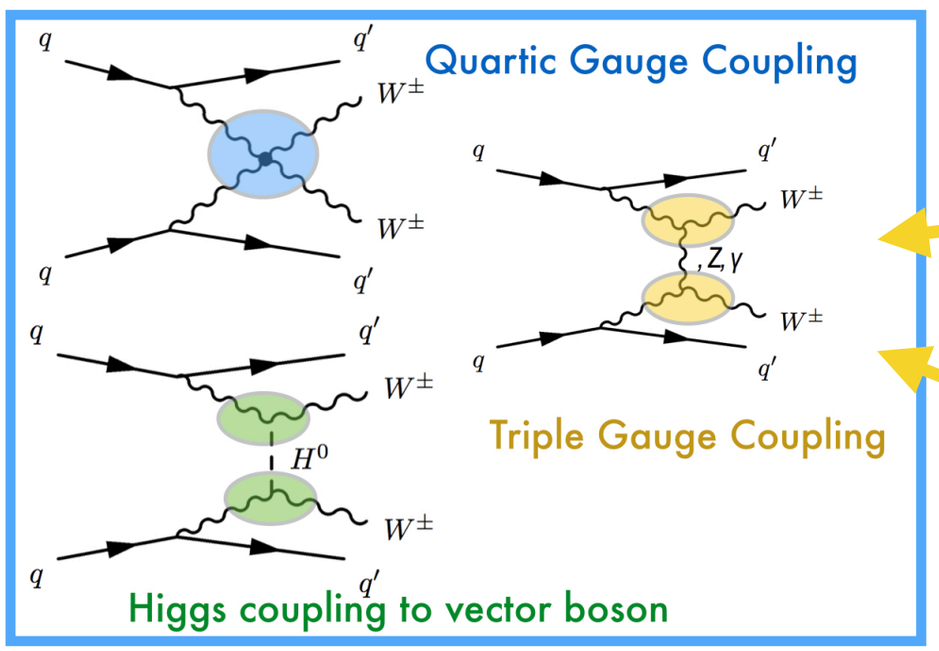
# Overview

- **Introduction**
  - Triple- and Quartic Gauge Couplings
- **Single Boson Production via Vector Boson Fusion**
  - EW Z production at 13 TeV
- **Electroweak Diboson Production and Vector Boson Scattering**
  - EW same-sign WW production at 13 TeV
  - EW ZZ production at 13 TeV
  - EW WZ production at 13 TeV
- **Conclusions**

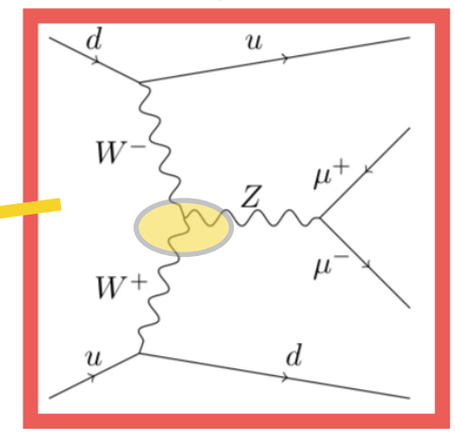
# Introduction

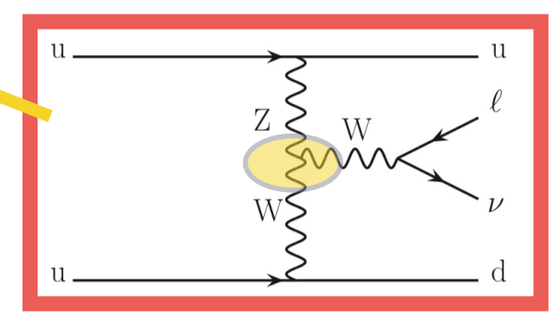
- **Electroweak single- and diboson production modes are important measurements at LHC to precisely explore EWSB mechanism**

Electroweak Diboson Production (VBS)




Electroweak Single Boson Production (VBF)



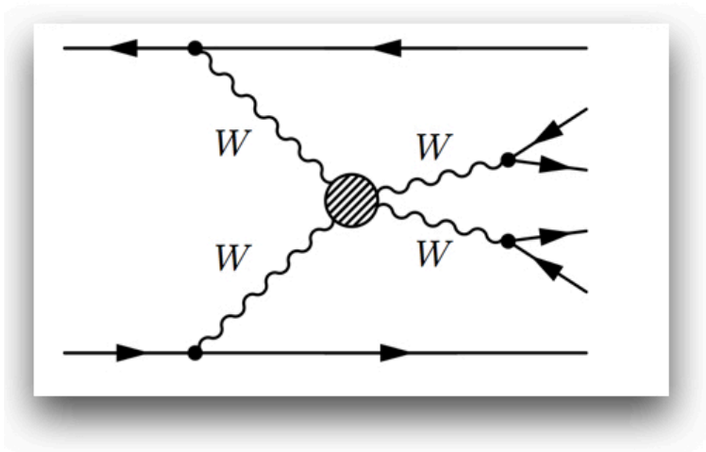


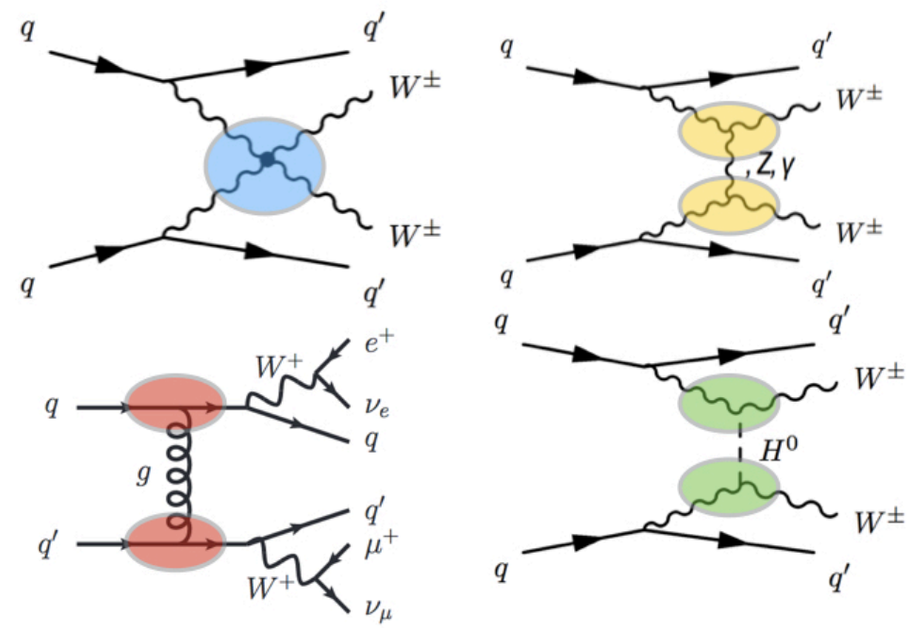
Note: Complementary access to Triple Gauge Couplings via inclusive diboson production

- **TGC and QGC precisely predicted in Standard Model**
  - **Slightest deviation from SM prediction leads to unitarity violation and thereby hints for New Physics**
  - **QGC: first measurements performed at LHC, TGC: studied at LEP and Tevatron**
- **VBS and VBF processes important background for New Physics**

# Electroweak (Di-)Boson Production

- **VBS and VBF signal processes defined via EW and strong coupling constants involved at LO, e.g.**




- **NLO EW corrections for VBS can be as large as 10-20% on cross section**
  - See Mathieus talk

**VBF**

| $\sigma_{EW} \propto \mathcal{O}(\alpha_{EW}^4)$ | $\sigma_{EW\times QCD} \propto \mathcal{O}(\alpha_{EW}^3 \alpha_S)$ | $\sigma_{QCD} \propto \mathcal{O}(\alpha_{EW}^2 \alpha_S^2)$ |
|---|---|---|
| EW Signal | Interference, added to background or scaled according to signal O(10%) | Background (QCD induced) |

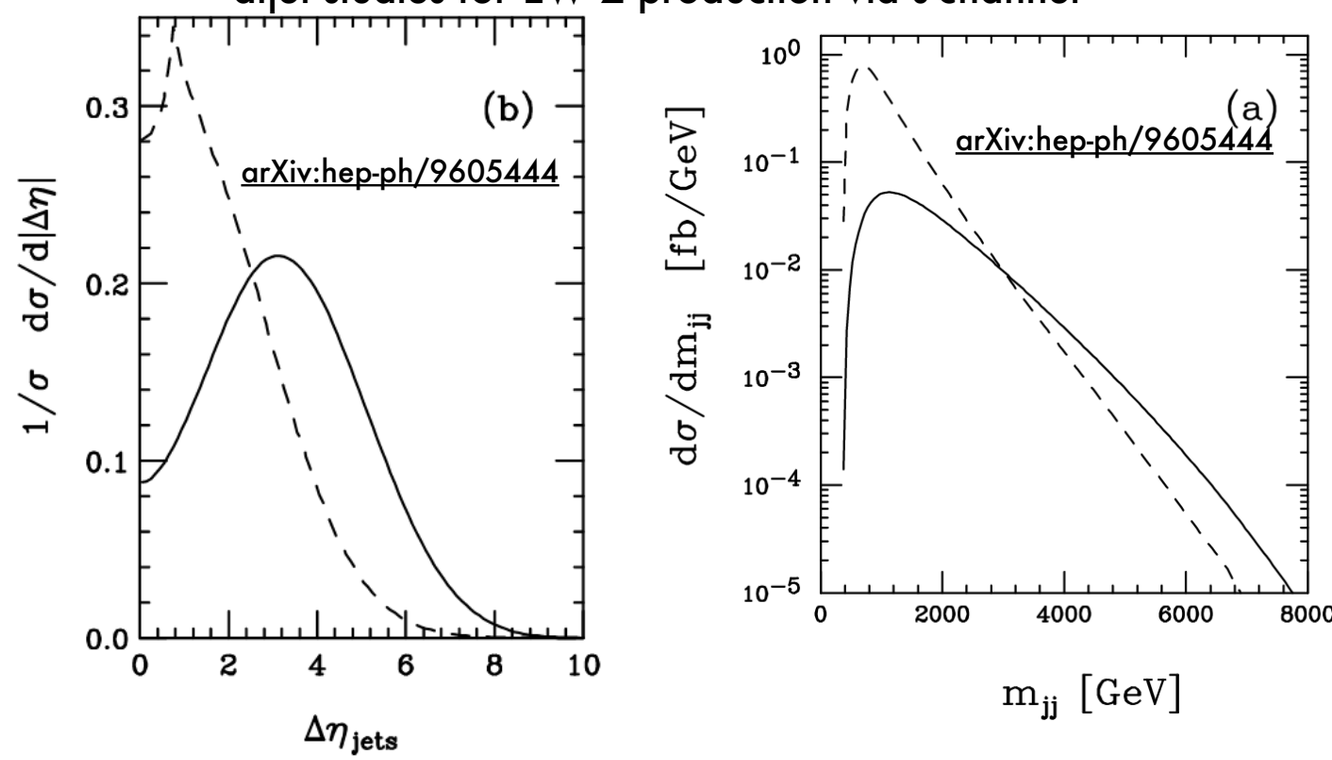
**VBS**

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

# Experimental Signature

- **VBF and VBS type events at LHC have distinct event topology in the detector**
  - **Two high-pT forward jets, with:**
    - **large pseudorapidity separation**
    - **high di-jet invariant mass**
  - **Suppressed central hadronic acitivity**
  - **"Centrality" of (di-)boson system with respect to dijet-system**

dijet studies for EW Z production via s-channel

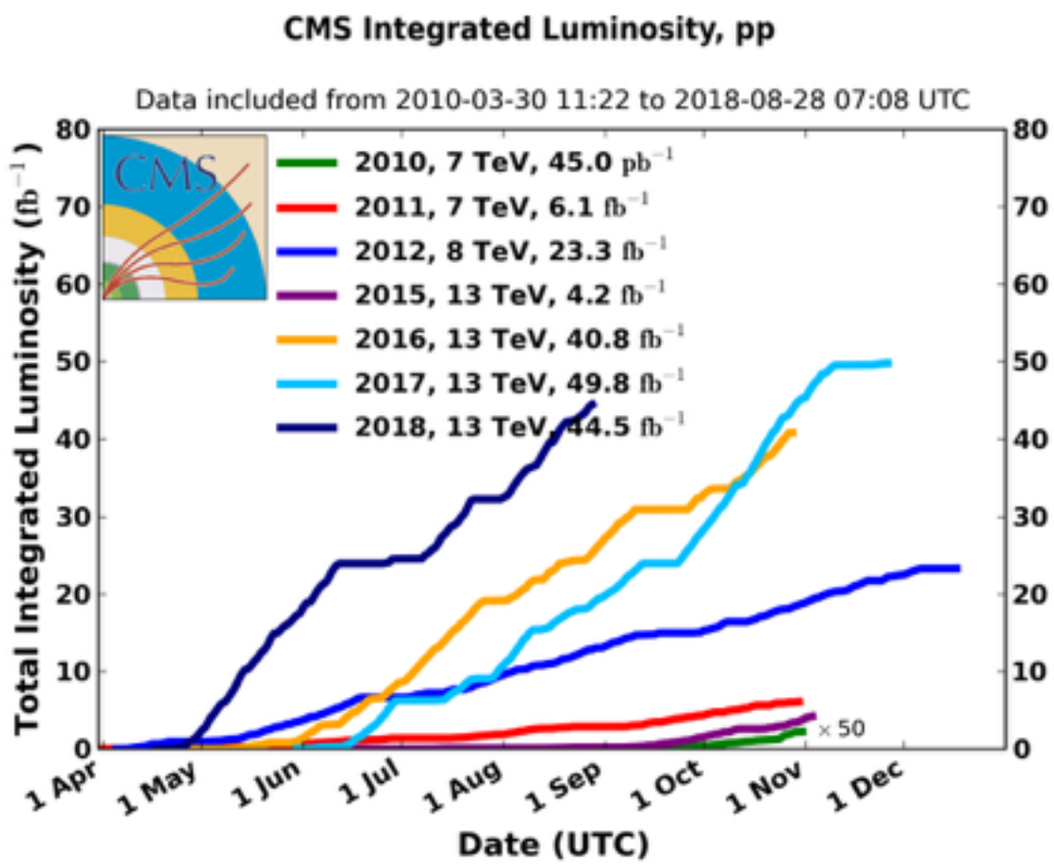


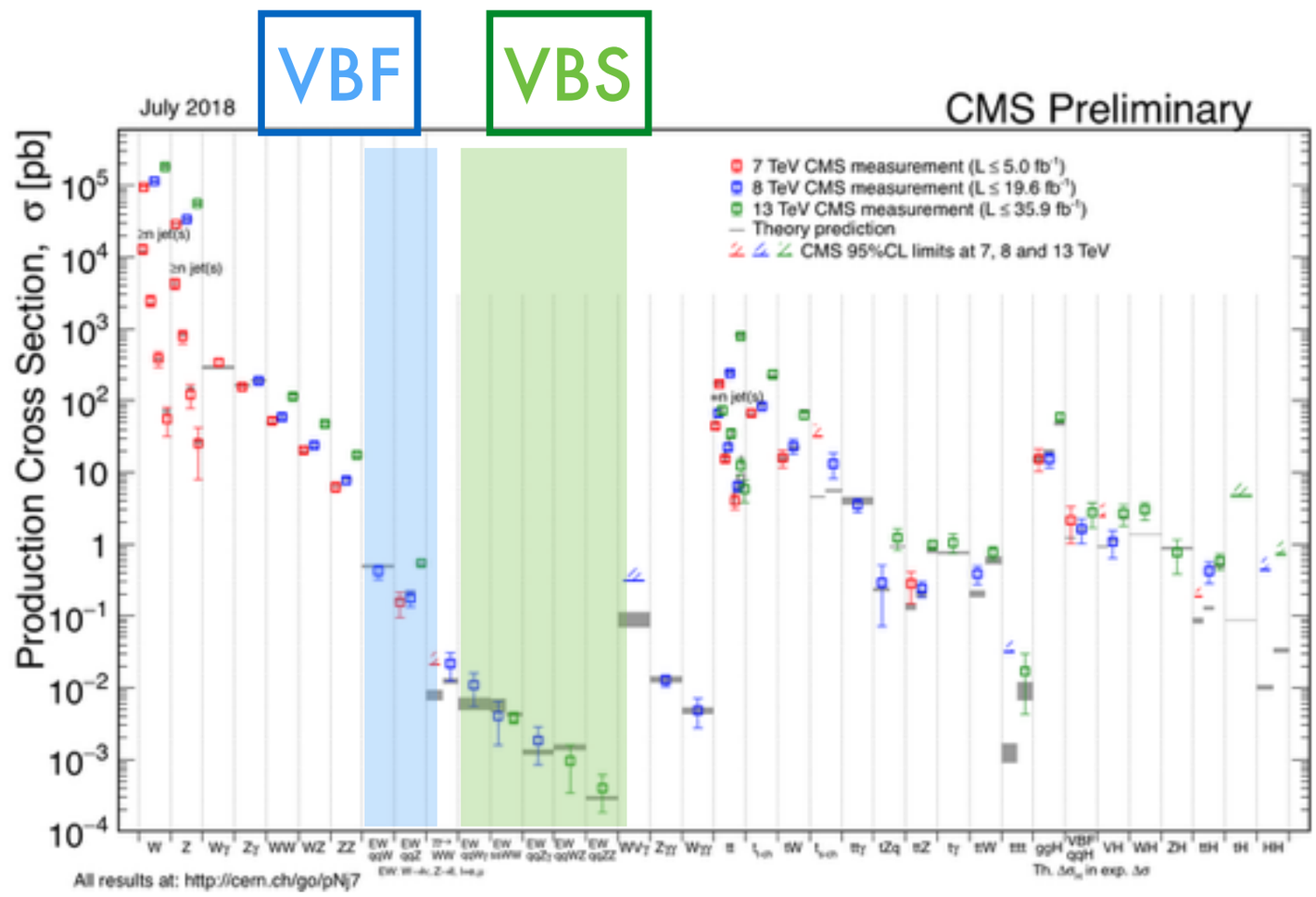

- **Observables used to EW from QCD induced processes**

- **In CMS, the QCD and EW production mechanisms are simulated with aMC@NLO**
  - **QCD⊗EW interference contributions are cross-checked using PHANTOM generator**

# LHC Experimental Status

- **Experiments have accumulated ~25 fb$^{-1}$ at 7/8 TeV and 130 fb$^{-1}$ at 13 TeV**
  - **expect ~150 fb$^{-1}$ at 13 TeV by end of 2018, full Run-2**
- **Measuring cross sections of *O*(1fb) for VBS, and *O*(100fb) for VBF**
  - **Current results based on Run-1 dataset and 36 fb$^{-1}$ of Run-2 collected in 2016**

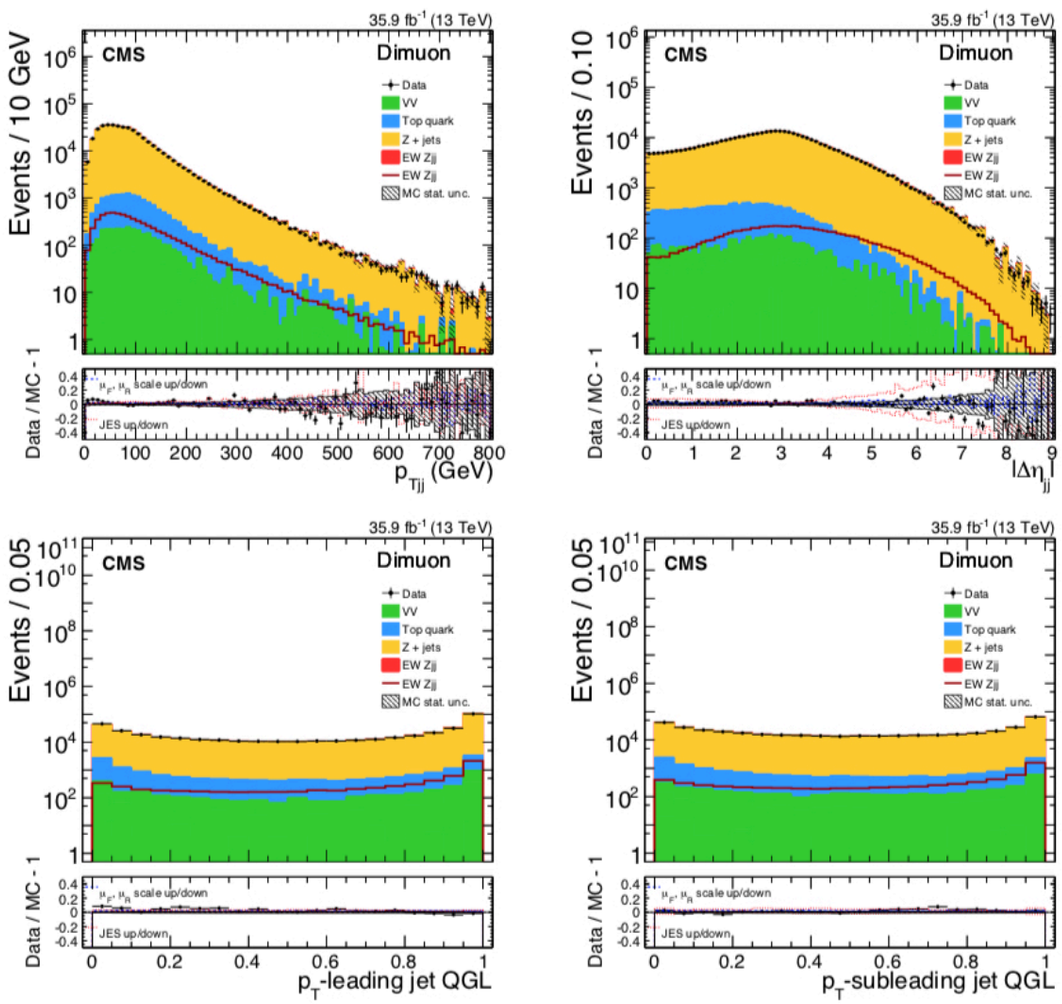


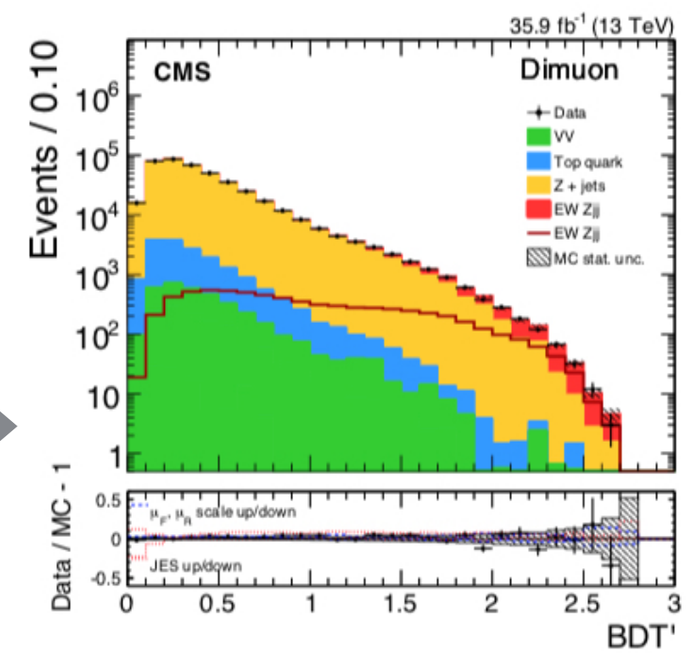



# VBF Z (13 TeV)

arxiv:1712.09814

- **CMS EW Z production cross section measurement performed on 2016 dataset, 36 fb$^{-1}$**
  - **Event selection: two same-flavour leptons (ee or μμ), mass within 15 GeV of Z, $p_T$>30/20 GeV, two jets with $p_T$>50/30 GeV, $m_{JJ}$ > 200 GeV**
  - **Signal extraction performed using dedicated boosted decision tree, usual VBF variables used ($m_{JJ}$, $|\Delta\eta_{JJ}|$,z*, $R_T$ and g/q discrimitator)**




| Sample | Initial | | BDT > 0.92 | |
|---|---|---|---|---|
| | ee | $\mu\mu$ | ee | $\mu\mu$ |
| WW | $62 \pm 16$ | $116 \pm 22$ | — | — |
| WZ | $914 \pm 38$ | $2151 \pm 63$ | $1.6 \pm 1.6$ | $1.8 \pm 1.8$ |
| ZZ | $522 \pm 17$ | $1324 \pm 29$ | $1.8 \pm 1.1$ | $2.7 \pm 1.3$ |
| $t\bar{t}$ | $5363 \pm 48$ | $12938 \pm 81$ | $7.1 \pm 1.9$ | $7.1 \pm 1.9$ |
| single top quark | $269 \pm 18$ | $723 \pm 31$ | — | — |
| W + jets | $34 \pm 5$ | $36 \pm 5$ | — | — |
| DY Zjj | $152750 \pm 510$ | $394640 \pm 880$ | $273 \pm 20$ | $493 \pm 31$ |
| Total backgrounds | $159890 \pm 510$ | $411890 \pm 890$ | $283 \pm 29$ | $505 \pm 43$ |
| EW Zjj signal | $2833 \pm 10$ | $6665 \pm 16$ | $194.9 \pm 2.6$ | $379.7 \pm 3.9$ |
| Data | 163640 | 422499 | 418 | 892 |

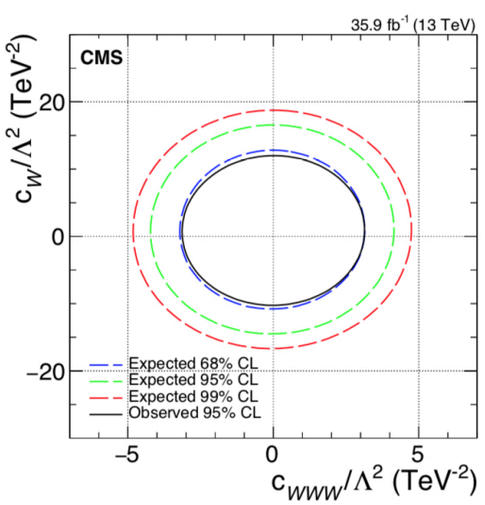
# VBF Z (13 TeV)

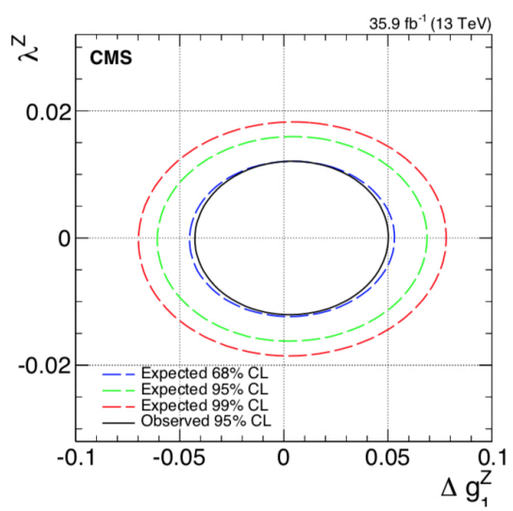
arxiv:1712.09814

- **Cross section measurement performed using template fit of BDT discriminant**
  - **excellent agreement with the SM prediction (MG LO), ee and μμ combined to find**

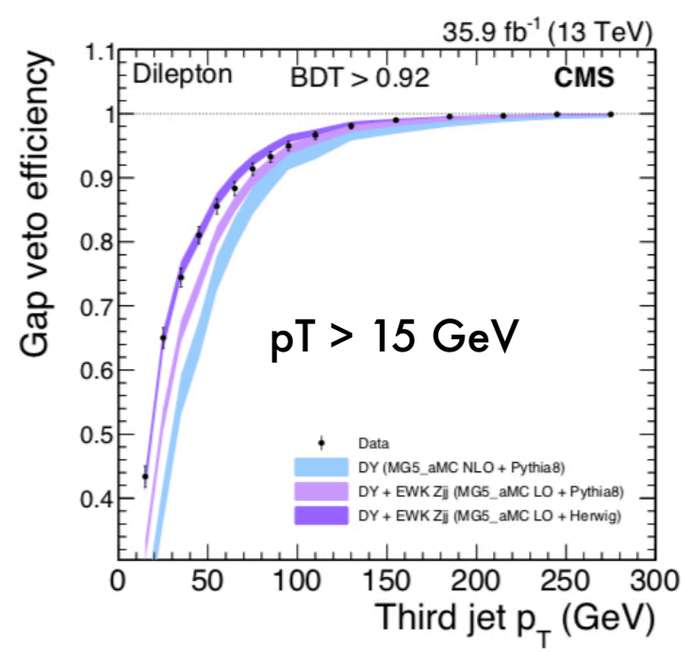
$$\mu = 0.98 \pm 0.04\,(\text{stat}) \pm 0.10\,(\text{syst}) = 0.98 \pm 0.11\,(\text{total})$$
$$\sigma(\text{EW}\ \ell\ell\text{jj}) = 534 \pm 20\,(\text{stat}) \pm 57\,(\text{syst})\,\text{fb} = 534 \pm 60\,(\text{total})\,\text{fb}$$

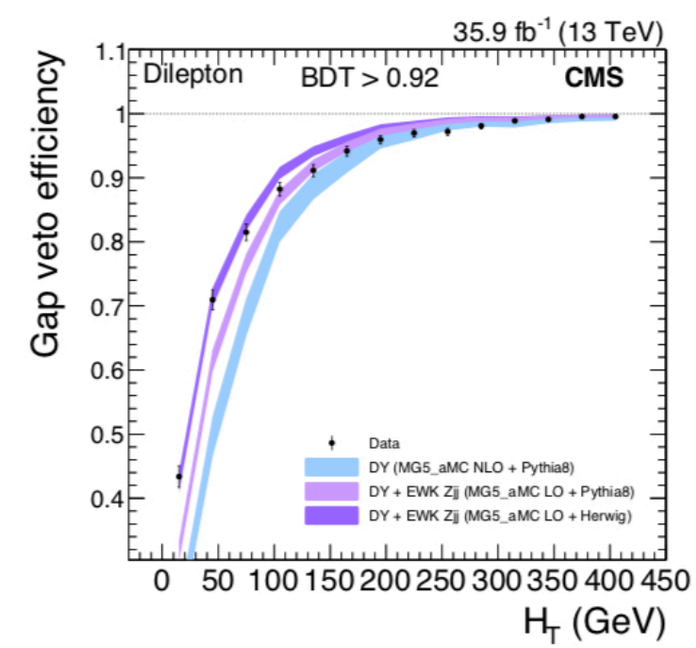
  - **Note interference term contribution scaled according to signal strength modifier**
- **Generator comparisons performed for hadronic activitiy, results interpreted in terms of dim-6 EFT operators (LEP parametrization)**




| Coupling constant | Expected 95% CL interval | Observed 95% CL interval |
|---|---|---|
| $\lambda^Z$ | $[-0.014, 0.014]$ | $[-0.010, 0.010]$ |
| $\Delta g_1^Z$ | $[-0.053, 0.061]$ | $[-0.035, 0.042]$ |




compatible with WZ inclusive sensitivity

# CMS 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**

| sqrt(s) | VBS process | CMS | Comment |
|---|---|---|---|
| 8 TeV | EW W±W± (lvlv) | PRL 114 (2015) 051801 | CMS finds 2.0 σ |
| | EW Zγ (vv/llγ) | Phys.Lett. B770 (2017) 380-402 | CMS finds evidence |
| | EW Wγ (lvγ) | JHEP 1706 (2017) 106 | CMS finds 2.7 σ |
| | EW WZ (3lv) | PRL 114 (2015) 051801 | CMS meas. QCD+EW xsec |
| 13 TeV | EW W±W± (2l2v) | PRL 120, 081801 | CMS first observation |
| | EW ZZ (4l) | Phys. Lett. B 774 (2017) 682 | CMS finds 2.7 σ |
| | EW WZ (3lv) | SMP-18-001 | CMS finds 1.9 σ, aQGC constraints and limits on H+ are derived |

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

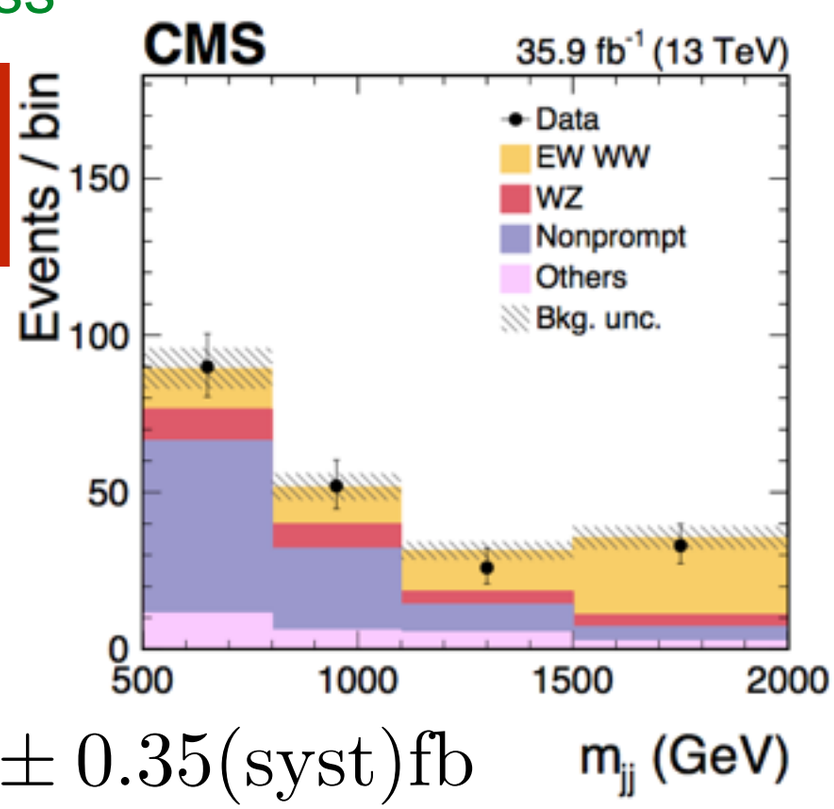
- **Measurement performed inclusively in ee, eμ, μμ channel, two same-sign leptons**
  - **Major backgrounds estimated from the data: Fake leptons (60%), WZ (QCD+EW), charge flip (for electrons (sub) per mille level)**
  - **Major syst. unc.: jet energy scale, fake background, theory unc. on the (factorization scale) signal modelling**
- **Fit performed to extract best-fit signal strength modifier with experimental and theoretical uncertainties, enhances sensitivity**

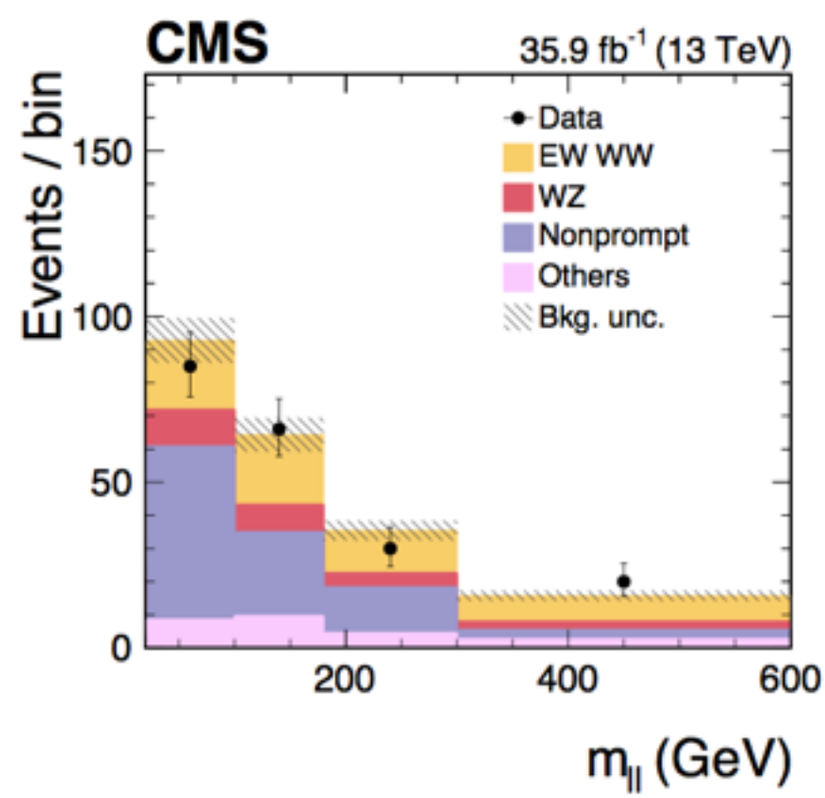
First observation of VBS process

5.5 (5.7) observed (expected) significance

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

$$\sigma_{NLO}^{EW} \approx \sigma_{LO}^{EW} - 13\%$$



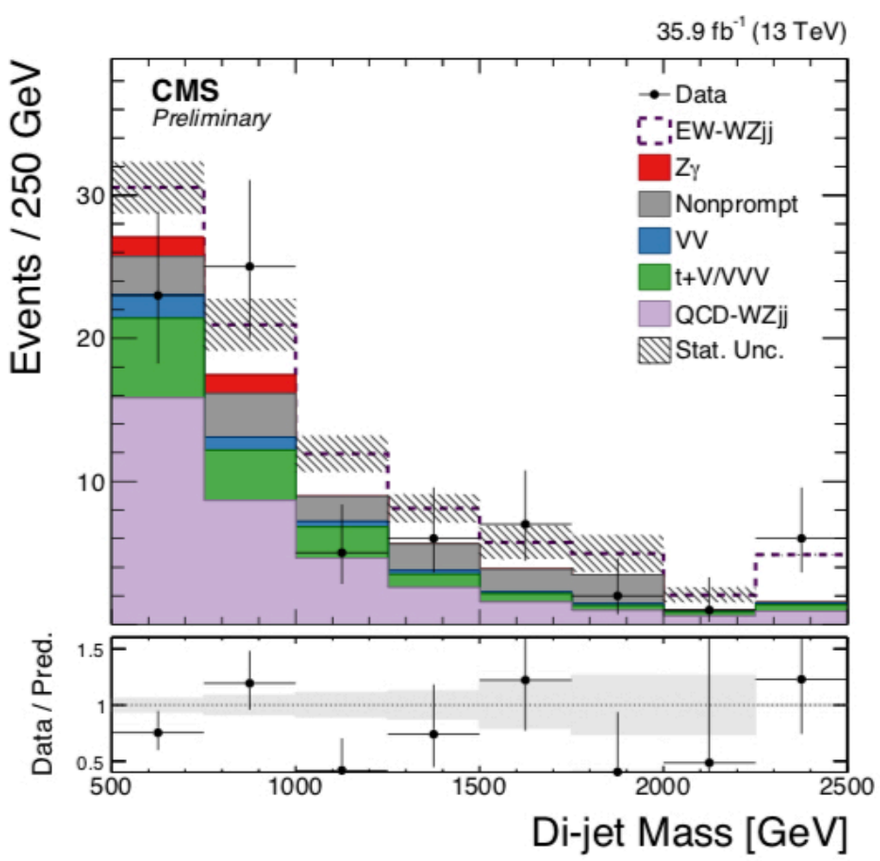



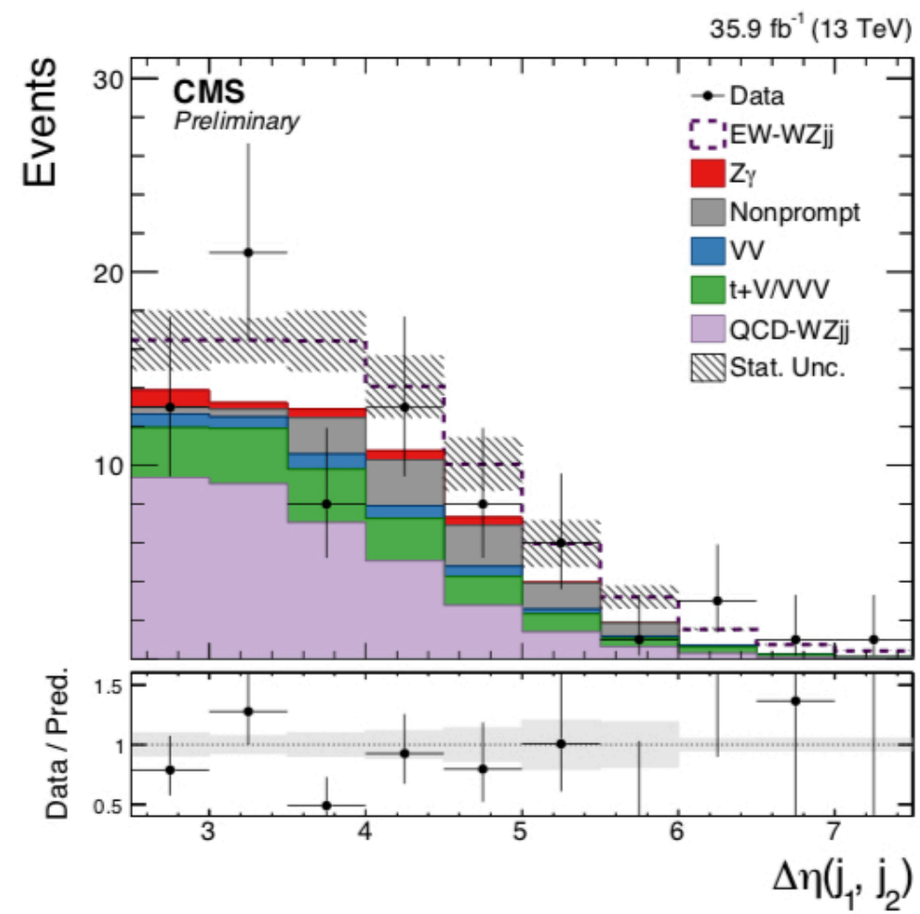

$$\sigma^{\text{meas.}} = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst})\text{fb}$$

# WZ VBS (13 TeV)

- **EW WZ cross section measurement performed on 2016 dataset, 36 fb$^{-1}$**
  - **3-lepton final-state (electron/muon)**
- **QCD WZ process controlled in background enriched side-band**
  - **Signal region: events pass the VBS cuts $m_{JJ} > 500$ GeV, $|\Delta\eta_{JJ}|>2.5$, $|z^*|<2.5$**
  - **Control region: events pass $m_{JJ} > 100$ GeV and fail either of the VBS cuts**

| | Electroweak Signal | Higgs Signal | Tight Fiducial | Loose Fiducial |
|---|---|---|---|---|
| $p_T(\ell_{Z,1})$ [GeV] | $> 25$ | $> 25$ | $> 25$ | $> 20$ |
| $p_T(\ell_{Z,2})$ [GeV] | $> 15$ | $> 15$ | $> 15$ | $> 20$ |
| $p_T(\ell_W)$ [GeV] | $> 20$ | $> 20$ | $> 20$ | $> 20$ |
| $\lvert\eta(\mu)\rvert$ | $< 2.4$ | $< 2.4$ | $< 2.5$ | $< 2.5$ |
| $\lvert\eta(e)\rvert$ | $< 2.5$ | $< 2.5$ | $< 2.5$ | $< 2.5$ |
| $\lvert m_Z - m_Z^{PDG}\rvert$ [GeV] | $< 15$ | $< 15$ | $< 15$ | $< 15$ |
| $m_{3\ell}$ [GeV] | $> 100$ | $> 100$ | $> 100$ | $> 100$ |
| $m_{\ell\ell}$ [GeV] | $> 4$ | $> 4$ | $> 4$ | $> 4$ |
| $p_T^{miss}$ [GeV] | $> 30$ | $> 30$ | - | - |
| $\lvert\eta(j)\rvert$ | $< 4.7$ | $< 4.7$ | $< 4.7$ | $< 4.7$ |
| $p_T(j)$ [GeV] | $> 50$ | $> 30$ | $> 50$ | $> 30$ |
| $\lvert\Delta R(j,\ell)\rvert$ | $> 0.4$ | $> 0.4$ | $> 0.4$ | $> 0.4$ |
| $n_j$ | $\geq 2$ | $\geq 2$ | $\geq 2$ | $\geq 2$ |
| $p_T(b)$ [GeV] | $> 30$ | $> 30$ | - | - |
| $n_{b-jet}$ | $= 0$ | $= 0$ | - | - |
| $m_{jj}$ | $> 500$ | $> 500$ | $> 500$ | $> 500$ |
| $\lvert\Delta\eta(j_1,j_2)\rvert$ | $> 2.5$ | $> 2.5$ | $> 2.5$ | $> 2.5$ |
| $\lvert\eta_{3\ell} - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})\rvert$ | $< 2.5$ | - | $< 2.5$ | - |



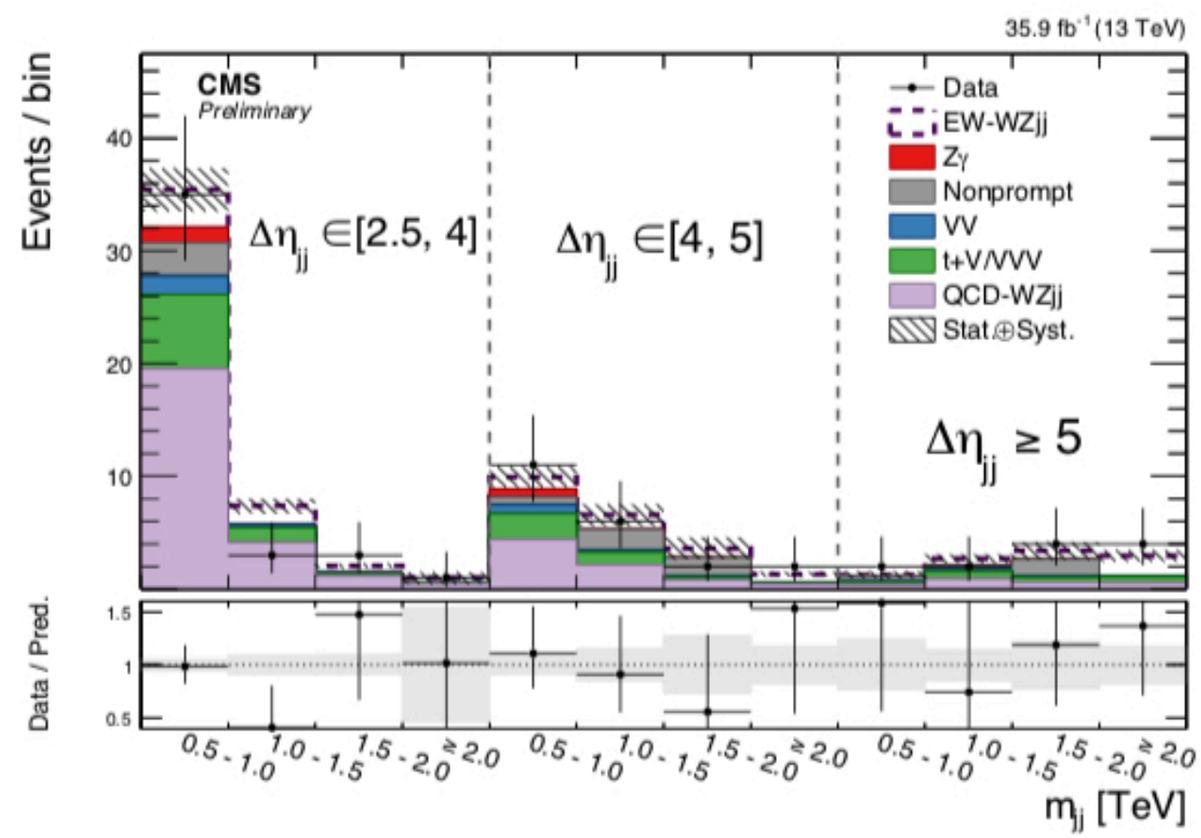



# WZ VBS (13 TeV)

- **Signal extraction using 2d $m_{JJ}$ vs $|\Delta\eta_{JJ}|$ distribution**
  - **Observed (Expected) significance: 1.9σ (2.7σ)** $\mu_{EW} = 0.64^{+0.45}_{-0.37}$
- **Also EW+QCD contribution measured in signal region**
  - **meas.:** $\sigma^{\text{fid}}_{\text{WZjj}} = 2.91^{+0.53}_{-0.49}\,(\text{stat})\ ^{+0.41}_{-0.34}\,(\text{syst}) = 2.91^{+0.67}_{-0.60}$ fb
  - **predicted:** $3.27\,^{+0.39}_{-0.32}(\text{scale}) \pm 0.15\,(\text{PDF})$ fb

| Process | $\mu\mu\mu$ | $\mu\mu e$ | $ee\mu$ | eee | Total Yield |
|---|---|---|---|---|---|
| QCD WZ | $14.1 \pm 0.9$ | $9.4 \pm 0.5$ | $7.1 \pm 0.4$ | $4.8 \pm 0.3$ | $35.4 \pm 1.1$ |
| t+V/VVV | $6.0 \pm 0.4$ | $3.4 \pm 0.2$ | $2.6 \pm 0.2$ | $1.8 \pm 0.1$ | $13.7 \pm 0.5$ |
| Nonprompt | $5.1 \pm 2.1$ | $2.3 \pm 1.0$ | $1.4 \pm 0.6$ | $0.7 \pm 0.3$ | $9.5 \pm 2.4$ |
| VV | $0.9 \pm 0.1$ | $1.7 \pm 0.2$ | $0.5 \pm < 0.1$ | $0.7 \pm 0.1$ | $3.7 \pm 0.2$ |
| $Z\gamma$ | $< 0.1$ | $2.2 \pm 0.8$ | $< 0.1$ | $< 0.1$ | $2.2 \pm 0.9$ |
| Pred. Background | $26.0 \pm 2.2$ | $18.9 \pm 1.6$ | $11.6 \pm 0.8$ | $8.0 \pm 0.5$ | $64.5 \pm 2.9$ |
| EW WZ | $5.1 \pm 1.1$ | $3.6 \pm 0.8$ | $2.5 \pm 0.5$ | $1.8 \pm 0.4$ | $13.0 \pm 1.5$ |
| Data | 38 | 15 | 12 | 10 | 75 |

| Source of systematic uncertainty | Relative systematic uncertainty [%] | |
|---|---|---|
| | $\sigma_{\text{WZ}jj}$ | EW WZ Significance |
| Jet energy scale | +9.8/-9.2 | 7.5 |
| Jet energy resolution | +1.1/-1.9 | $< 0.1$ |
| QCD WZ modeling | - | 0.9 |
| Other background theory | +2.5/-2.2 | 0.2 |
| Nonprompt normalization | +2.1/-2.4 | 1.1 |
| Nonprompt stat. | +6.1/-5.8 | 6.2 |
| Lepton energy scale and eff. | +3.5/-2.7 | $< 0.1$ |
| b-tagging | +1.7/-1.9 | $< 0.1$ |
| Luminosity | +3.1/-3.4 | $< 0.1$ |



# ZZ VBS (13 TeV)

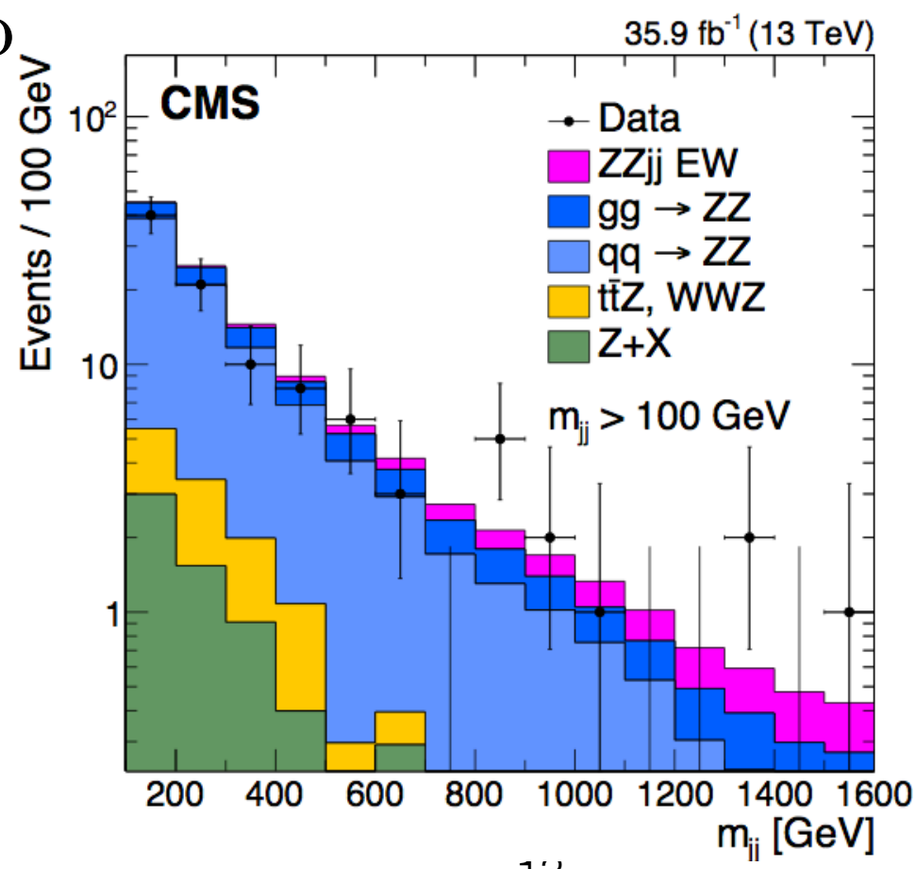
- **ZZjj production measurement performed in fully leptonic final state**
- **Exploit boosted decision tree to enhance sensitivity (7 most performant variables used)**
  - **$m_{JJ}$, $\Delta\eta_{JJ}$, $m_{ZZ}$, $Z_{1,2}$-centrality, vector/scalar sum of VBF-jets and of ZZ+jets**
- **2.7 (1.6) observed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

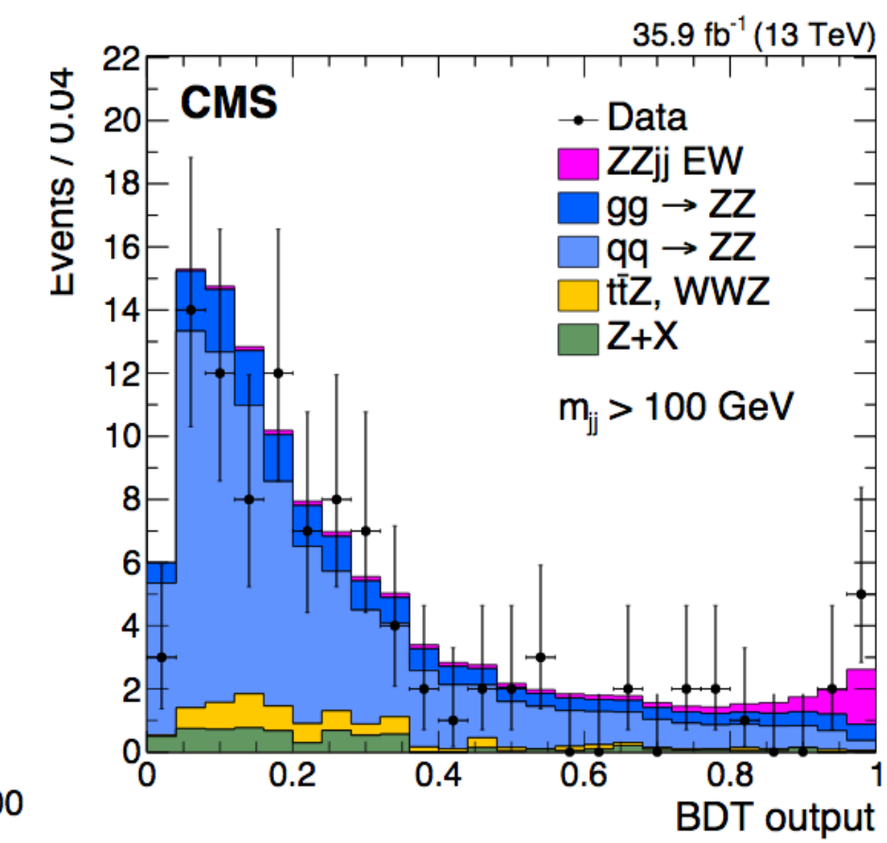
$$\sigma_{\mathrm{EW}}(\mathrm{pp} \to \mathrm{Z}\bar{\mathrm{Z}}\mathrm{jj} \to \ell\ell\ell'\ell'\mathrm{jj}) = 0.40^{+0.21}_{-0.16}\,(\mathrm{stat})\,^{+0.13}_{-0.09}\,(\mathrm{syst})\,\mathrm{fb}$$

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

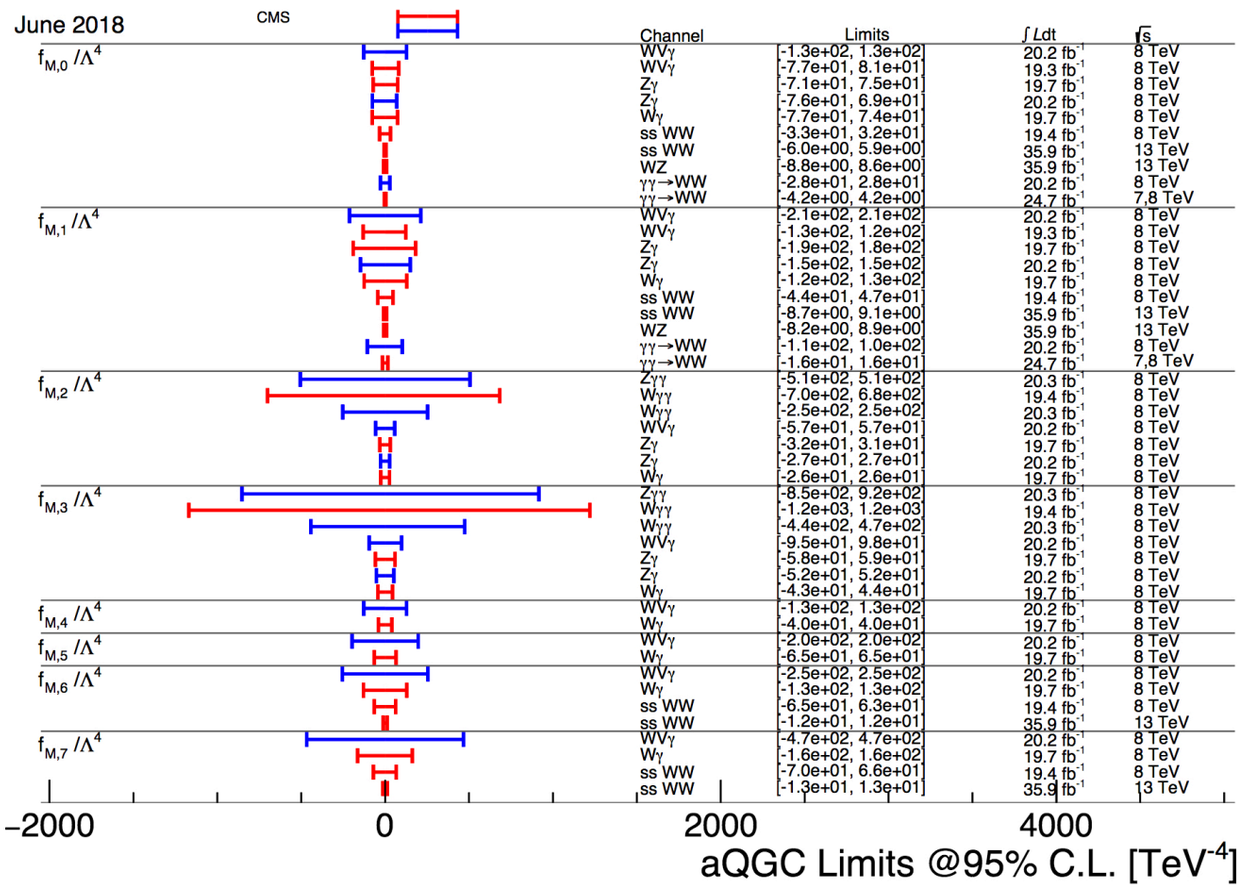
good sensitivity to EFT operators

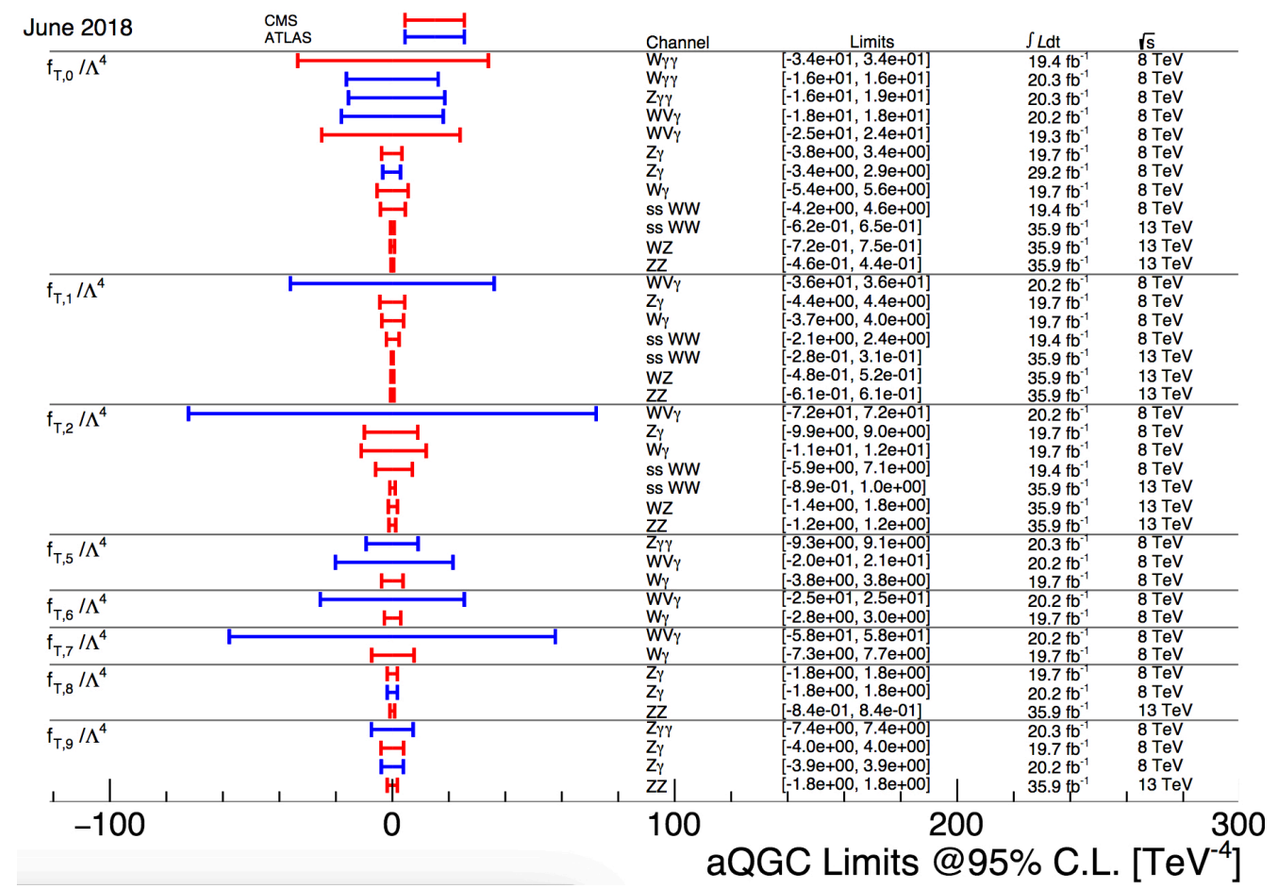
$$-0.46 < f_{\mathrm{T0}}/\Lambda^4 < 0.44$$
$$-0.61 < f_{\mathrm{T1}}/\Lambda^4 < 0.61$$
$$-1.2 < f_{\mathrm{T2}}/\Lambda^4 < 1.2$$
$$-0.84 < f_{\mathrm{T8}}/\Lambda^4 < 0.84$$
$$-1.8 < f_{\mathrm{T9}}/\Lambda^4 < 1.8$$



# Anomalous Quartic Gauge Couplings 2



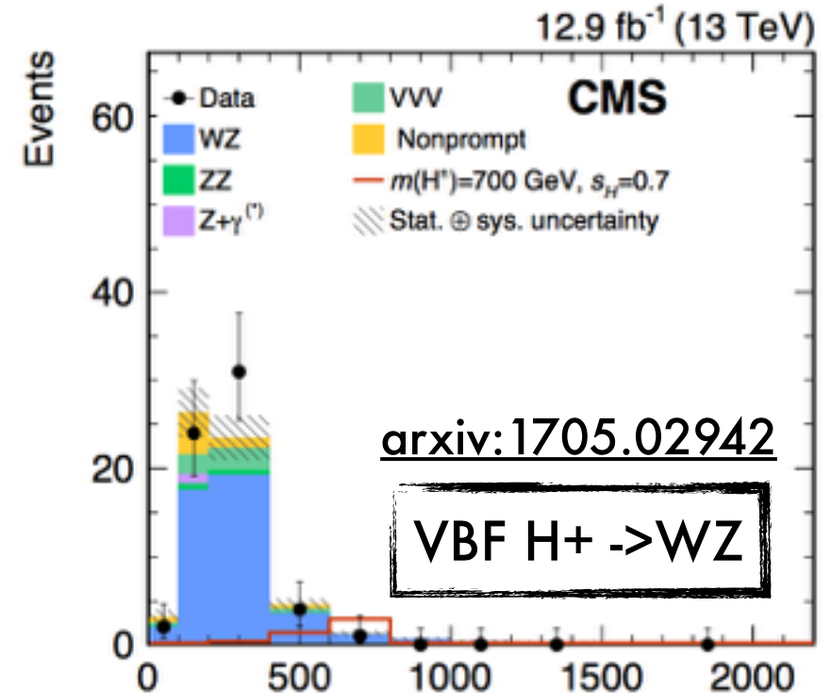

- **Important to probe all diboson processes to cover all possible EFT operators**
  - **Indirectly probing mass scales above 1 TeV**

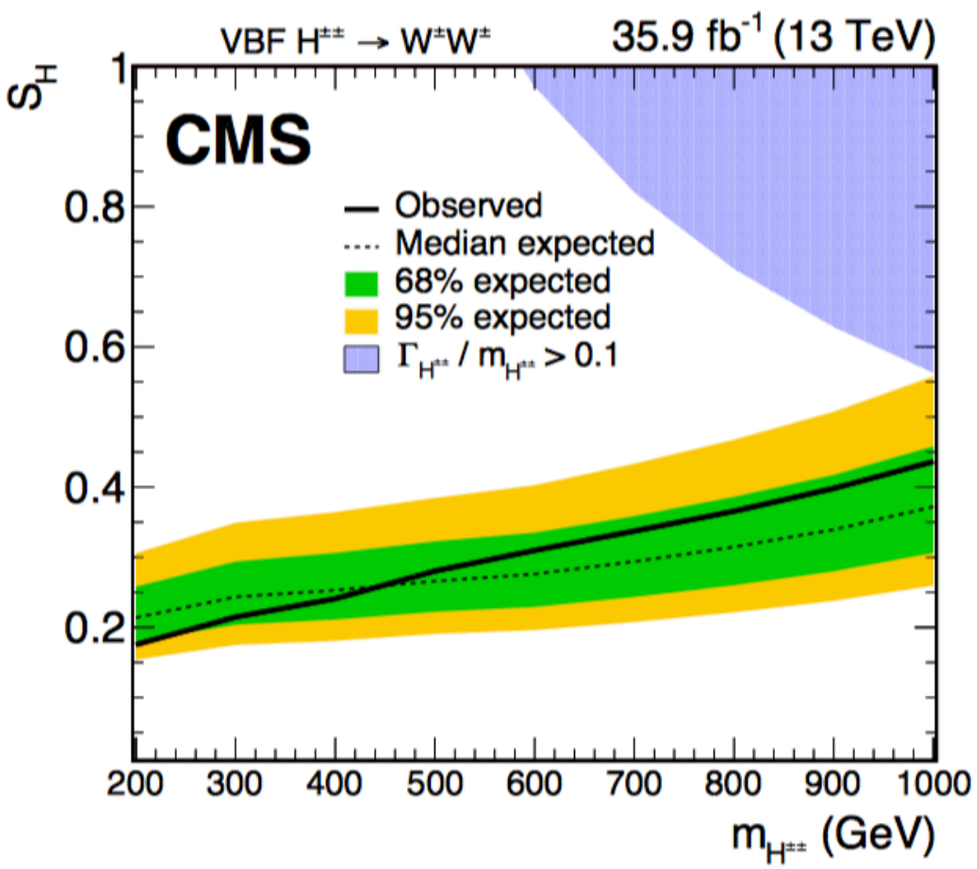
| | WWWW | WWZZ | ZZZZ | WWAZ | WWAA | ZZZA | ZZAA | ZAAA | AAAA |
|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$ | X | X | X | | | | | | |
| $\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$,$\mathcal{O}_{M,6}$ ,$\mathcal{O}_{M,7}$ | X | X | X | X | X | X | X | | |
| $\mathcal{O}_{M,2}$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

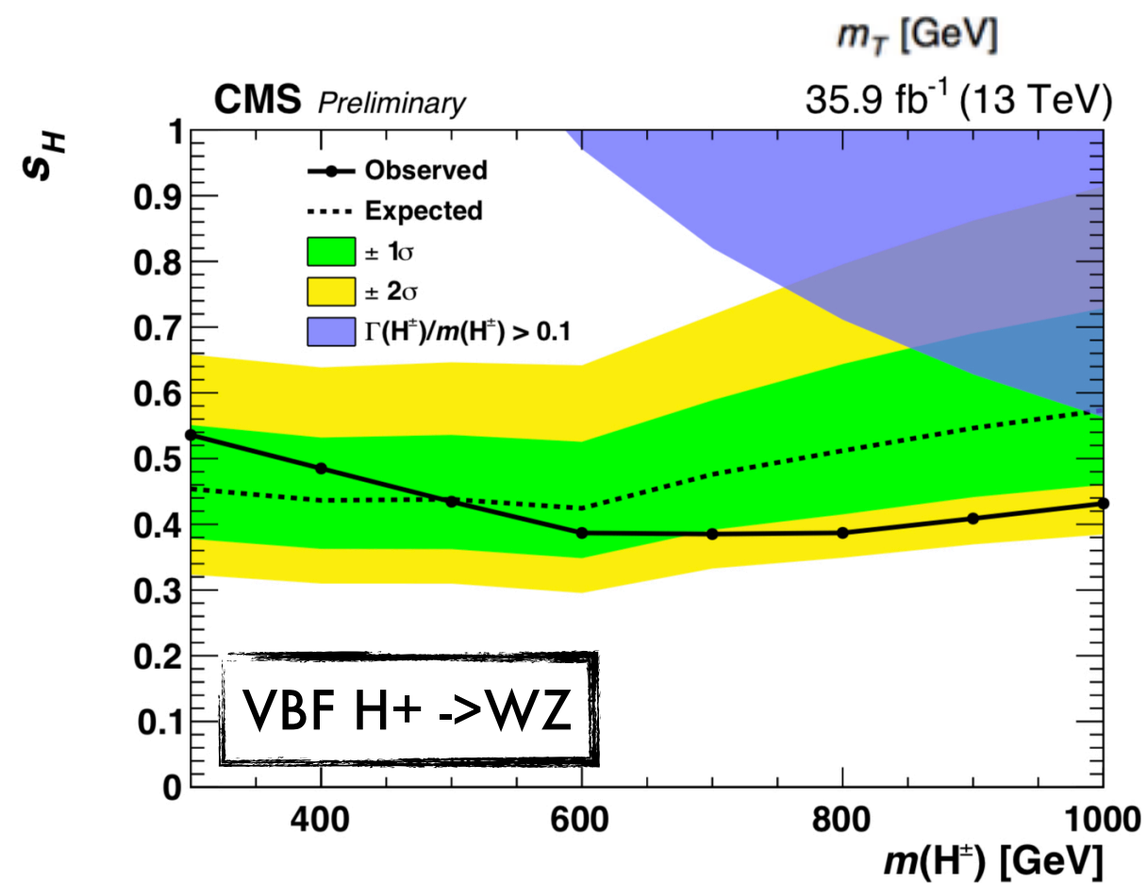
- **Gain in sensitivity can be obtained by combination, if two analyses have similar sensitivity**

# 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**

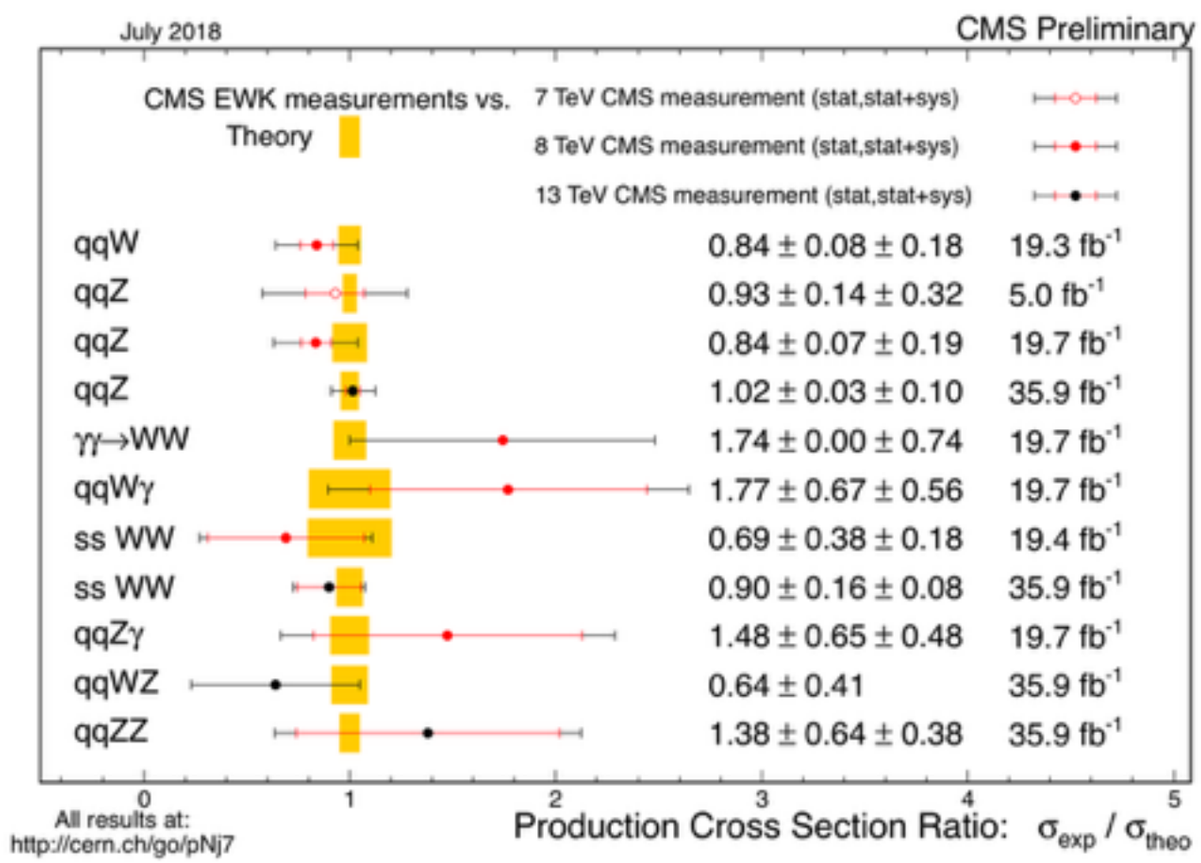


# The Summary

- **VBS and VBF processes key measurements to fully explore EWSB**
- **$W^{\pm}W^{\pm}$,WZ,ZZ VBS measurements performed at 13 TeV with 36 $fb^{-1}$**
  - **First VBS ($W^{\pm}W^{\pm}$) process observed directly with >5σ**
- **Expect 150 fb-1 by end of year => many more measurements**
  - **Clear evidence for WZ and ZZ VBS processes, and hadronic decays will be investigated**
- **VBS and VBF processes place strong limits on aTGCs and aQGCs**



# Additional Material

# 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)**

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

**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**

# VBF W at 8 TeV

arxiv:1607.06975

- **EW W boson production cross section measurement performed on 8 TeV dataset (19.2 fb$^{-1}$)**
  - **QCD W+2jet sample normalized in background control region**
  - **QCD⊗EW term treated as background (~12%)**

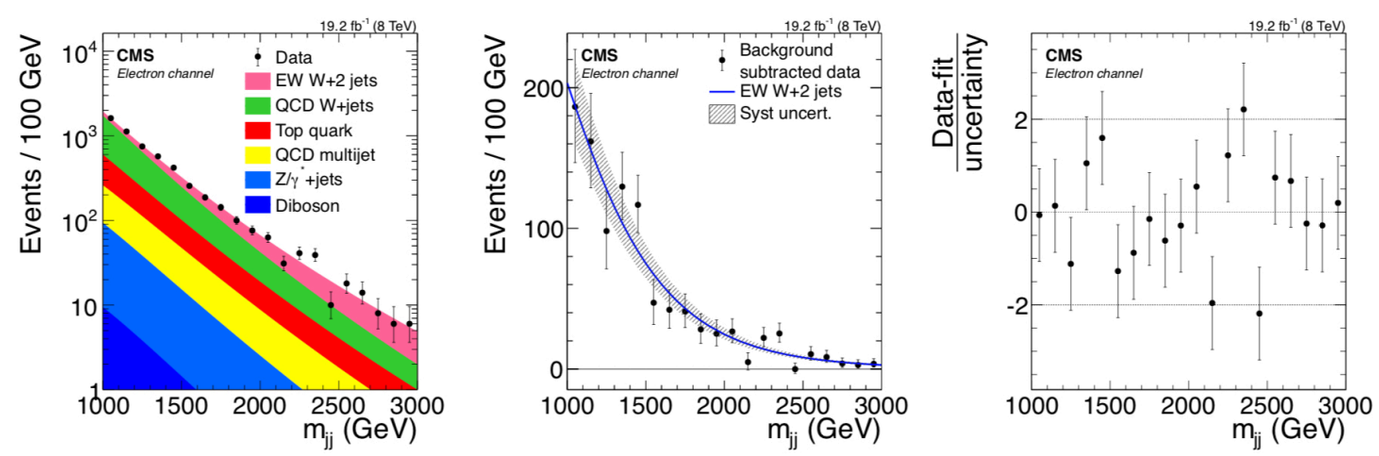
**Event Selection Criteria**

| $W \to \ell\nu$ Lepton requirements | Jet requirements |
|---|---|
| Single lepton trigger | $p_T^{j1} > 60$ GeV, $p_T^{j2} > 50$ GeV |
| High-quality lepton ID and isolation | $\lvert y_W - (y_{j1} + y_{j2})/2 \rvert < 1.2$ |
| Electron (muon) $p_T > 30$ (25) GeV | $m_{jj} > 1000$ GeV |
| $E_T^{miss} > 30$ (25) GeV for electron (muon) channels | |
| W transverse mass $> 30$ GeV | |
| Veto second lepton | |

- **Analytic fit to mJJ distribution performed to extract EW W production cross section**

| Channel | Measured cross section |
|---|---|
| Electron | $0.41 \pm 0.04$ (stat) $\pm 0.09$ (syst) $\pm 0.01$ (lumi) pb |
| Muon | $0.43 \pm 0.04$ (stat) $\pm 0.10$ (syst) $\pm 0.01$ (lumi) pb |
| Combined | $0.42 \pm 0.04$ (stat) $\pm 0.09$ (syst) $\pm 0.01$ (lumi) pb |

$$\mathcal{F} = \frac{1}{m_{jj}^{a_0 + a_1 \ln(m_{jj}/8000)}}$$

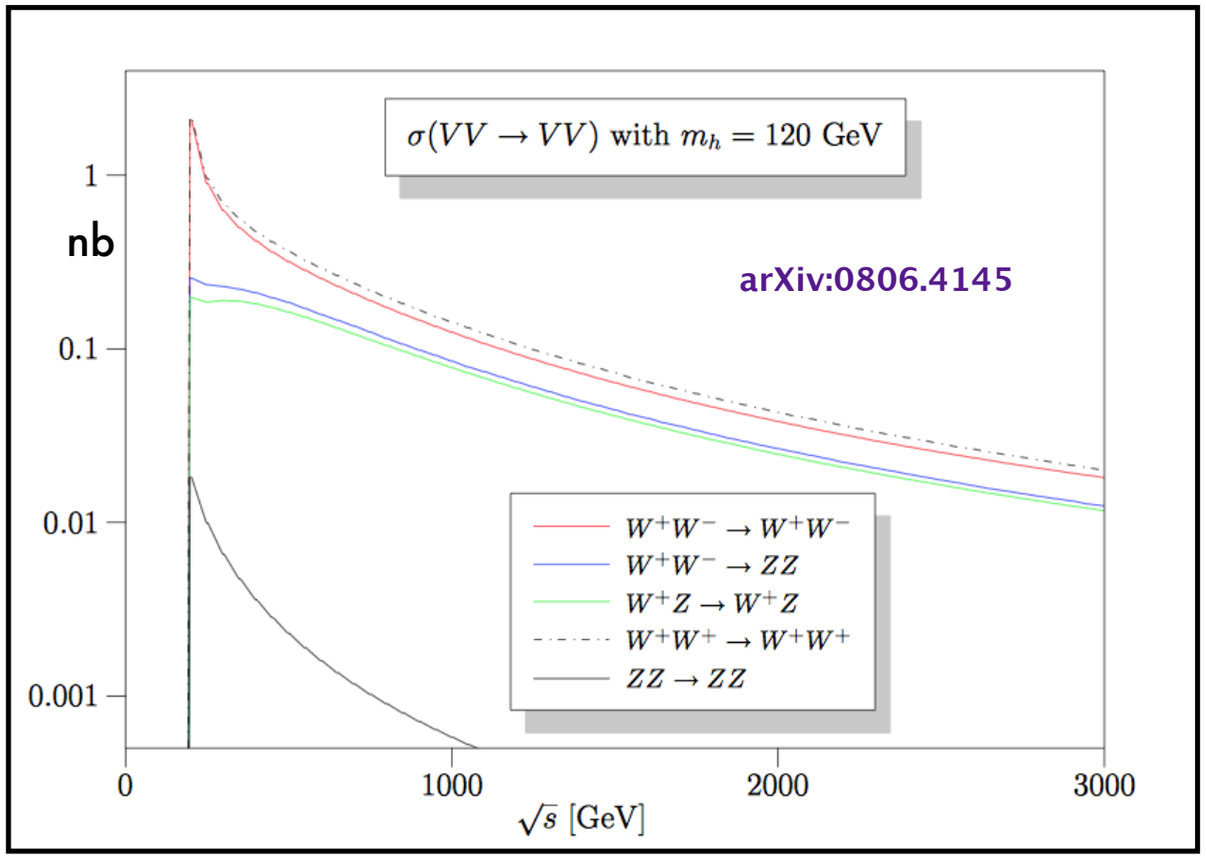


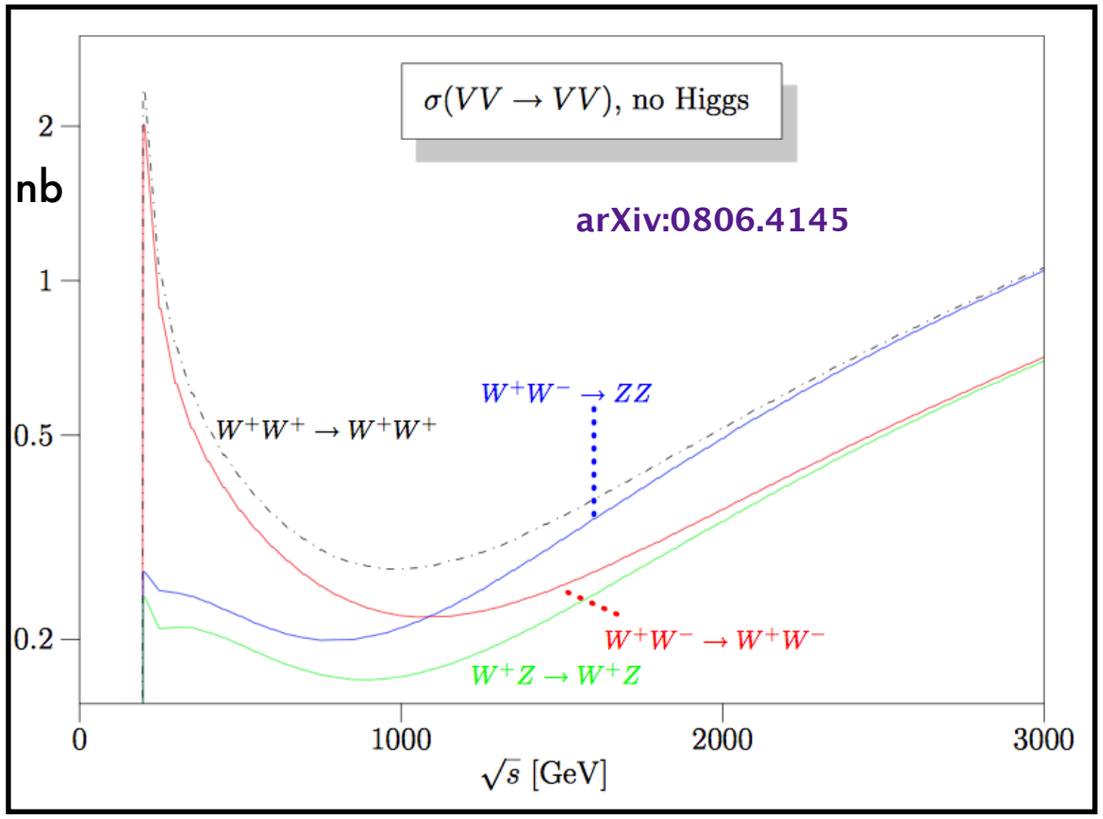

- **predicted LO cross section:**

$$0.50 \pm 0.02\,(\text{scale}) \pm 0.02\,(\text{PDF})\ \text{pb}$$

# Unitarity

- **After discovery of W and Z boson at SPS 1983**
  - **How to restore unitarity in quartic massive gauge boson interactions?**
  - **How do gauge bosons acquire mass?**




- **Without Higgs and/or BSM, unitarity violation in σ(VV→VV) above 1 TeV**
- **LHC was proposed in 1980`s to conclusively either find Higgs boson and/or yet unknown particles and interactions**

# aQGC EFT Operators

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

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

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

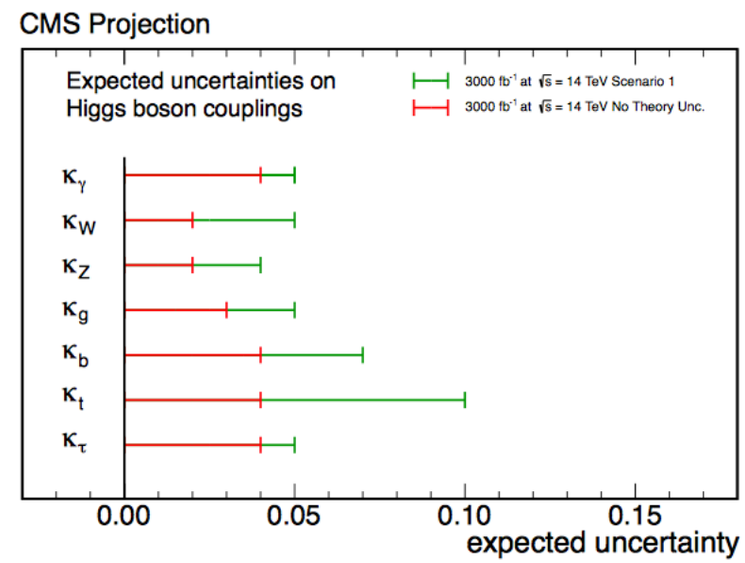
$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] ,$$
$$\mathcal{O}_{T,1} = \mathrm{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \times \mathrm{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] ,$$
$$\mathcal{O}_{T,2} = \mathrm{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right]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

# Higgs Couplings

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

- **Example: Two Higgs Doublet Models**

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




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