# VBF-V EFT studies @ LHE


Flavia Cetorelli[2], Giorgio Pizzati[1,2], Andrea Claudio Maria Bulla[1,2]

1. Università degli Studi di Milano - Bicocca
2. Sezione INFN di Milano - Bicocca


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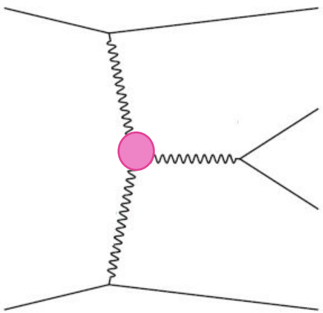
# Outline and motivation



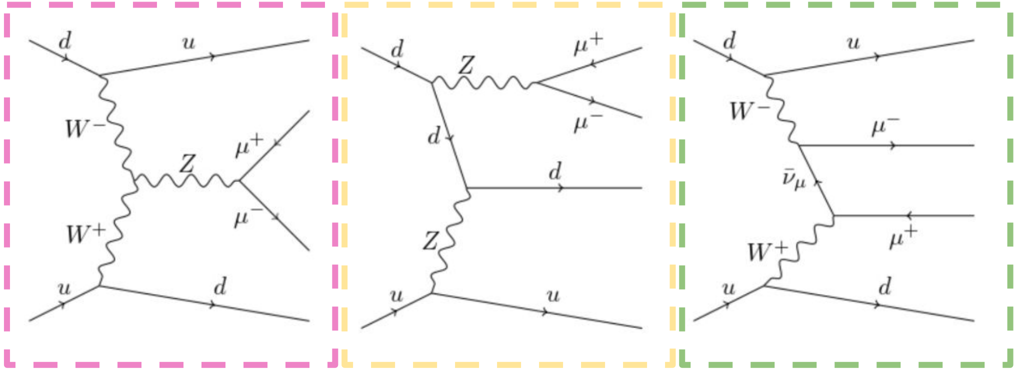
**VBF-V:** EFT dimension 6 studies @ LHE.

- ★ Based on **previous** studies in the field:
  - ○ W+2j : 35.9 $fb^{-1}$ 13 TeV CMS analysis
  - ○ Z+2j: 35.9 $fb^{-1}$ 13 TeV CMS analysis
- ★ **Preliminary** analysis at parton level:
  - ○ no detector effects, no backgrounds;
  - ○ describe analysis set up and strategy;
  - ○ show some preliminary **results**.
- ★ Outlook:
  - ○ show some possibilities for **future** studies.

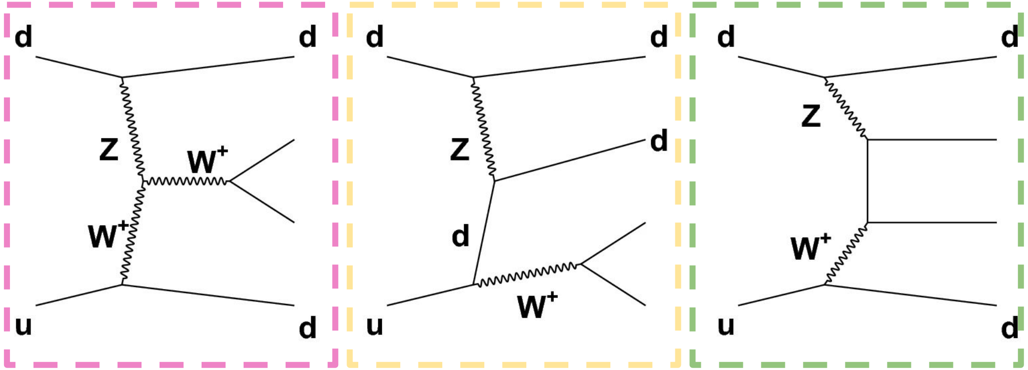
**Why VBF → V?**
Interesting process for testing the standard model (**SM**), **complementary** to Higgs boson measurements.
Sensitive to anomalous trilinear gauge couplings (**ATGCs**): indirect search for **beyond-the-SM** physics at mass scales not directly accessible at the LHC.

# VBF - V

```
generate p p > l+ l- j j SMHLOOP=0 QCD =0 QED=4 NP=1
```




```
generate p p > l+ vl j j SMHLOOP=0 QED=4 QCD=0 NP=1
```




Production of a V boson from a purely **electroweak process** @LO O($\alpha^4\alpha^0_S$):

**Vector boson fusion**

**Bremsstrahlung-like**

**Multiperipheral**

Including **non-resonant** diagrams

# SMEFT

Valid up to a certain energy scale of New Physics **Λ**

The **SM** could be interpreted as an **effective** low energy approximation of a more complete **theory**.

**This talk**

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k \cancel{C_k^{(5)}} Q_k^{(5)} + \boxed{\frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)}} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

**Renormalizable**
$SU(3)_C \times SU(2)_L \times U(1)_Y$

No L-conserving
**(removed)**

Dimension-six terms:
**$c_k$ Wilson coefficients**
**$Q_k$ gauge-invariant operators**

Defined in the **Warsaw basis**

Higher dimensional interaction terms
**(neglected)**

# Operators choice

★ **39 (25)** for Z(W)+2j dim-6 SMEFT operators with various field content from Warsaw basis.

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |

| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
|---|---|---|---|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger \tau^I \varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger \tau^I \varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$ |

| $(\bar LL)(\bar LL)$ | | $(\bar RR)(\bar RR)$ | | $(\bar LL)(\bar RR)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$ | $Q_{le}$ | $(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{dd}$ | $(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{ed}$ | $(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$ |

| $(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$ | | $B$-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar l_p^j e_r)(\bar d_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ |
| $Q_{quqd}^{(1)}$ | $(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{quqd}^{(8)}$ | $(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$ | $Q_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ |
| $Q_{lequ}^{(1)}$ | $(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ |
| $Q_{lequ}^{(3)}$ | $(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$ | | |

W+2j, Z+2j    Z+2j    W+2j

# SMEFT Monte Carlo generations

- **39 (25)** for Z(W)+2j dim-6 SMEFT operators with various field content from Warsaw basis.
- Generated at LO with SMEFTsim + `MadGraph5_aMC@NLO` (2.6.5).
  - Insertion of **one** operator per diagram in production/decay.
  - **U(3)$^5$** flavour symmetry, {mW,mZ, GF} input scheme, CP-even, $\Lambda$ = 1 TeV.
  - Used **LO MG re-weight**:
    - generate events once;
    - reweight to different Wilson coeff;
    - algebra to extract single components.

Faster than single components generation

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

# Phase space selections

Chose the **leptonic decay** mode:

- clearest signature;
- favorable signal to background ratio.

Reproduced **LHC-like** selections, based on the characteristic **signature** of VBF-V leptonic final state:

- **2** energetic **jets** well separated in pseudorapidity
- **1 (2)** charged **lepton(s)** (e or μ) from W(Z) decay

**W+2j**

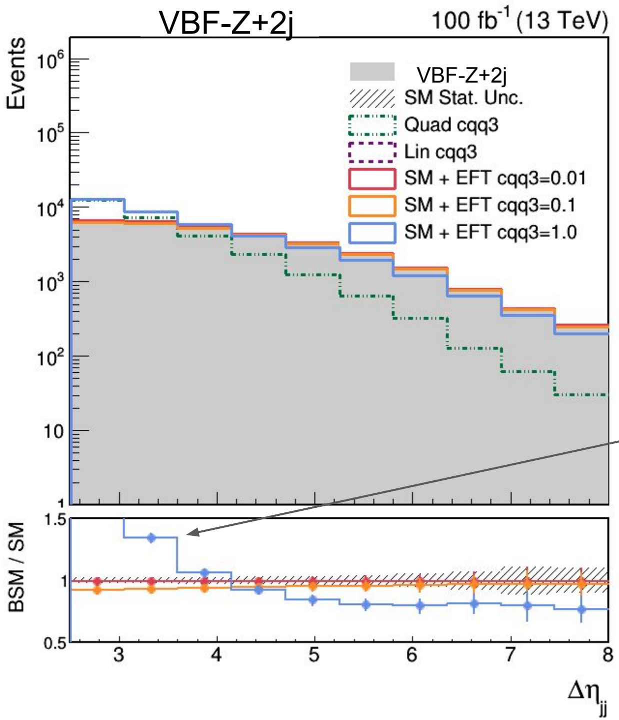
$p_{T,j1} > 70$ GeV and $p_{T,j2} > 70$ GeV
$\mathbf{m_{jj} > 400}$ **GeV and** $\mathbf{|\Delta\eta_{jj}| > 4}$
$p_{T,l1} > 25$ GeV and $|\eta_{l1}| < 2$

**Z+2j**

$p_{T,j1} > 50$ GeV and $p_{T,j2} > 30$ GeV
$\mathbf{m_{jj} > 200}$ **GeV** and $\mathbf{|\Delta\eta_{jj}| > 1}$
$p_{T,l1} > 25$ GeV and $p_{T,l2} > 20$ GeV
**77 GeV <** $\mathbf{m_{ll}}$ **< 107 GeV**
$p_{T,ll} > 30$ GeV
$p_T^{miss} < 100$ GeV

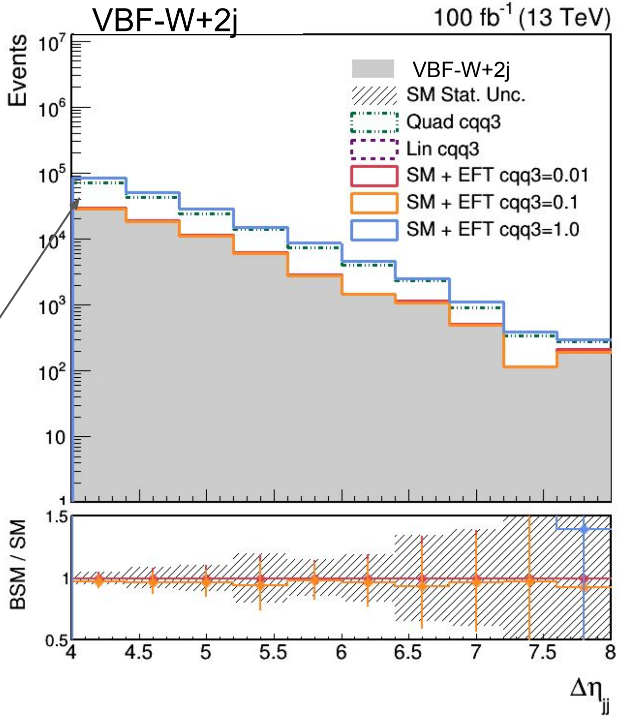
# Signal region

For each operator and channel distributions of **several observables** are investigated
→ looking for the most **discriminating** one



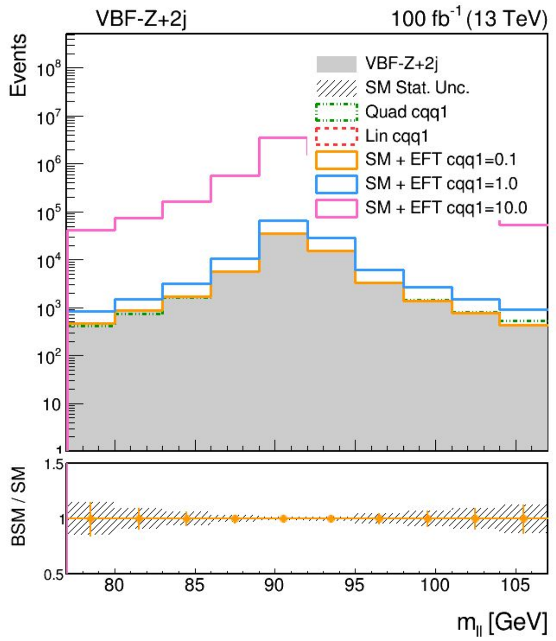

$Q_{qq}^{(3)}$

Departures from the **SM** are well visible for values of **cqq3 = 1**



# Shape analysis

Performed **shape analysis** with MC templates of **SM, lin, int, and quad** components to extract operators constraints at 68% and 95% c.l.:




**Poisson**

$$\mathcal{L}(c) = \boxed{\prod_{bin=k} \frac{(N_k(c))^{n_k}}{n_k!} e^{-N_k(c)}} \times \boxed{\prod_{syst=j} \pi(\tilde{\theta}|\theta)}$$

Systematic uncertainties as **nuisances**

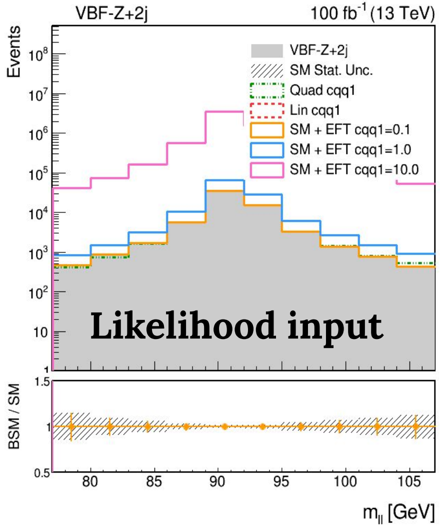
$$\boxed{N(c) = SM + \sum_c {}_\alpha c_\alpha Lin_\alpha + c_\alpha^2 Quad_\alpha + \sum_{\alpha\beta} c_\alpha c_\beta Mix_{\alpha\beta}}$$

Assumed **SM** scenario ⇨ $n = N(o)$

Considered only one **nuisance**: 2% on luminosity.

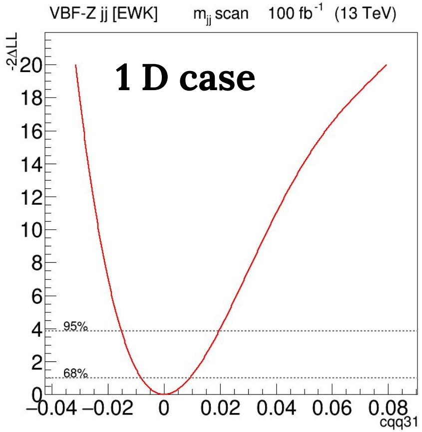
# Analysis strategy

Performed a 1D (2D) **likelihood scan** for each (pair of) operator(s) for each observable:

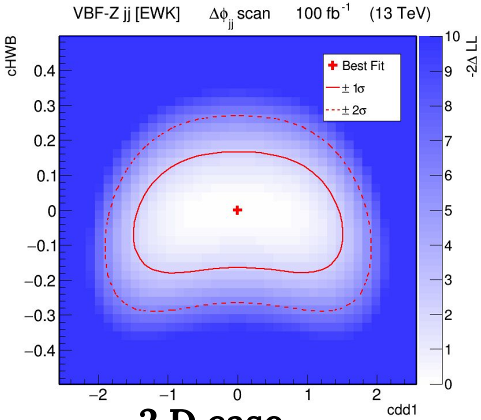



$$\mathcal{L}(c) = \prod_{bin=k} \frac{(N_k(c))^{n_k}}{n_k!} e^{-N_k(c)} \times \prod_{syst=j} \pi(\widetilde{\theta}|\theta)$$

NB: other operators are set to 0 during the scan.




**Sensitivity** estimated as:
68% c.l.: $-2\Delta\log L < 1$
95% c.l.: $-2\Delta\log L < 3.84$



2 D case

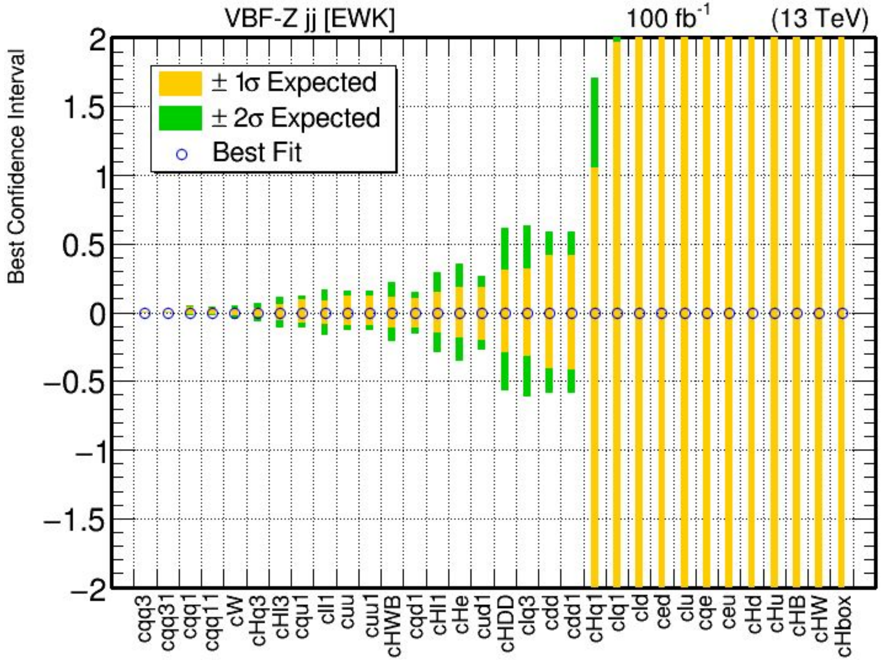
**Sensitivity** estimated as:
68% c.l.: $-2\Delta\log L < 2.30$
95% c.l.: $-2\Delta\log L < 5.99$

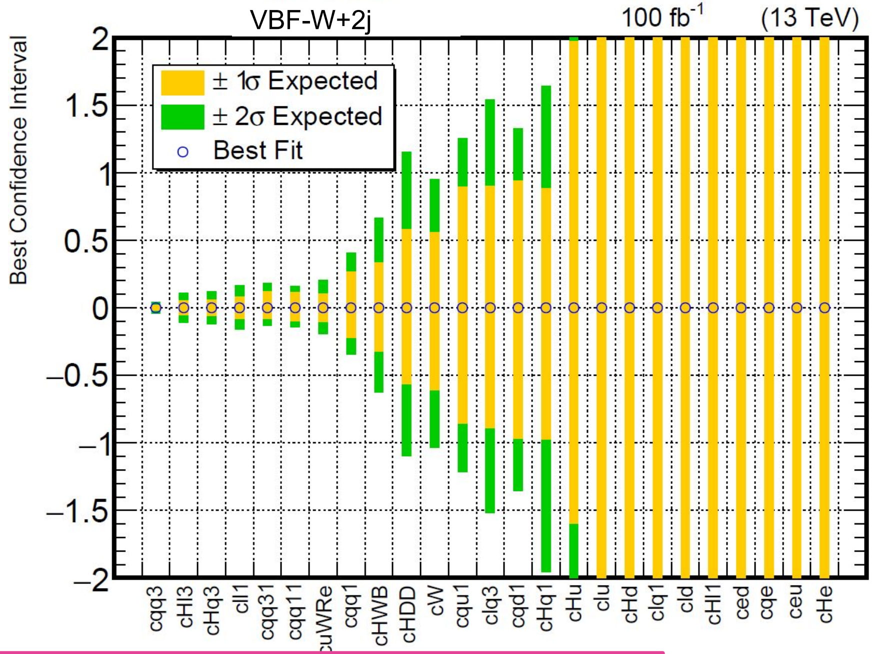
Ranking the **variables** wrt to 1 σ range (area).

# 1D Results: sensitivity

Between $\mathbf{Q_{qq}^{(3)}}$ and $\mathbf{Q_{He}}$ there are **seven orders** of magnitude difference in terms of sensitivity. Highlighting operators to which VBF-V channels are more sensitive put basis toward **LHC data analysis**! → final goal

Z + 2j channel **more sensitive** than W+2j

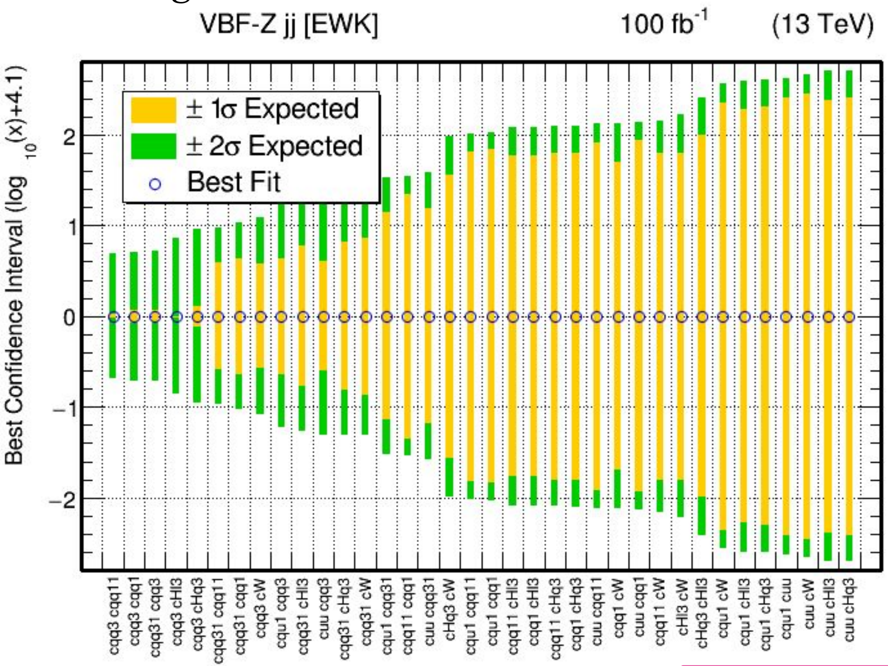


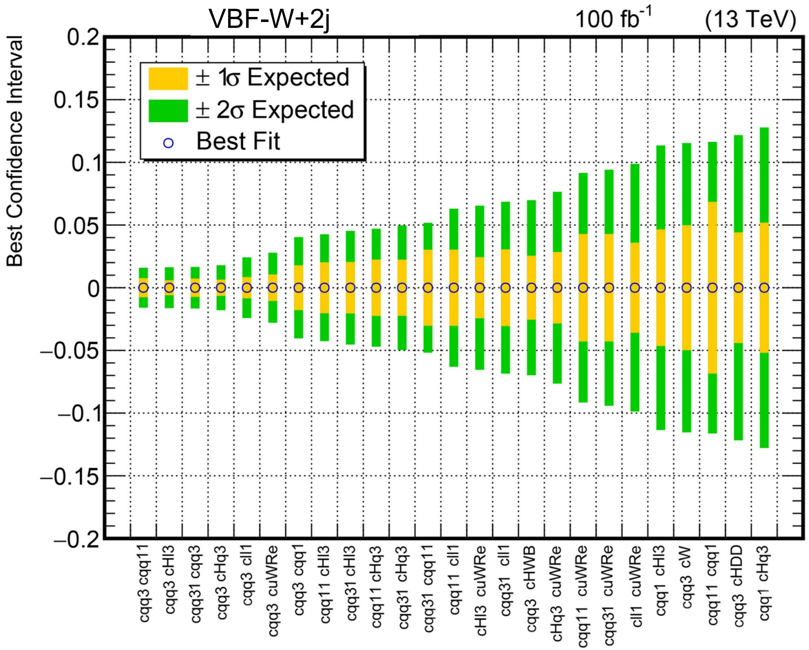




Most stringent constraints are on **4-fermions operators**

# 2D results: sensitivity

2D scan: **2** Wilson coefficients at time, all possible pairs tried with all possible variables.
Ranking wrt **area** of contour at 1 σ.



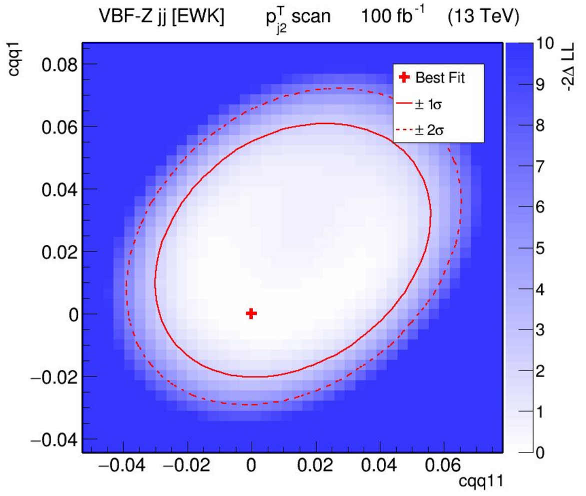

Most stringent constraints
include **4-fermions operators**

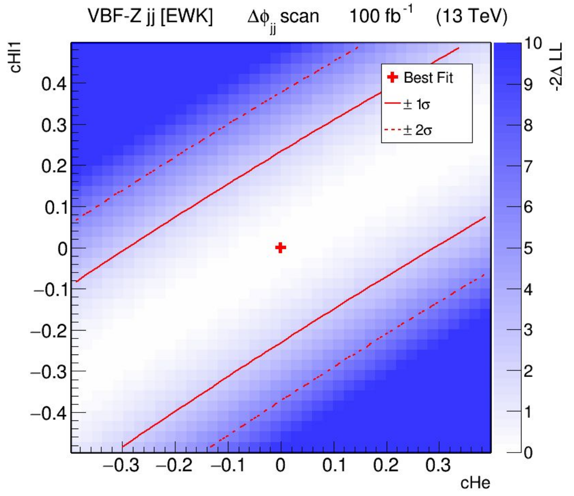
# 2D EFT studies: correlation

From 2D likelihood scan:

- **Area** (previous slide) → **sensitivity** and create ranking of most constrained operators (as for 1D case)
- **Shape** of the contour → indicate:
  - possible correlation between operators
  - flat directions

Useful info for **N-dimensional** studies:
flat directions must be avoided, since make fit fail!
Indication of STRONG correlation.



# Summary of results and outlook

VBF-V channels are good candidate to put constraints on **dimension 6 operators:**

- in particular 4-fermions and Vff

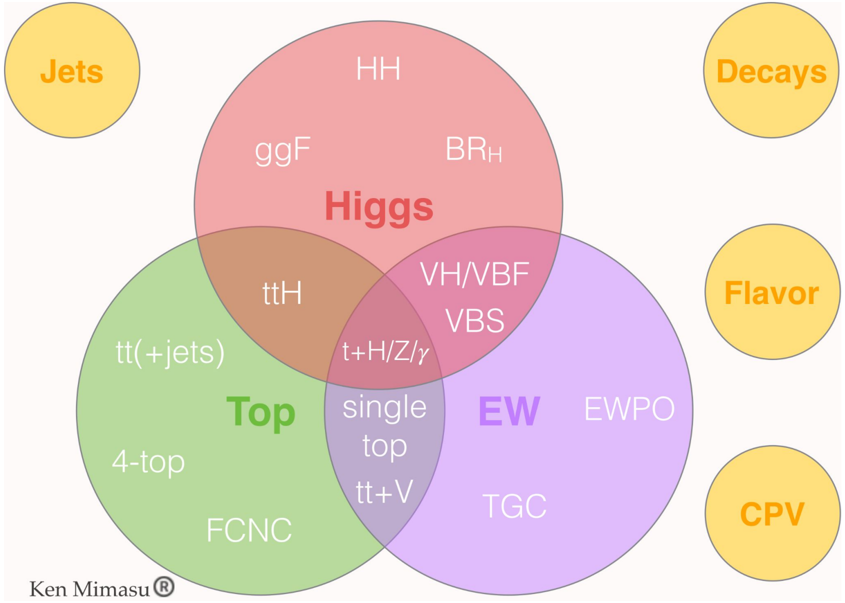
These LHE preliminary results are the inputs pointing towards an **LHC data analysis**, including all background, detector effects and systematic uncertainties.

Inclusion of **QCD** background:

- EFT dependence of the QCD induced sample (**$O(\alpha^2\alpha_s^2)$**) never weakens the sensitivity, as shown in VBS EFT paper.

**Combination:**

- of VBF-V channels, Z+2j and W+2j → to put tighter constraint (as shown in 2016 CMS reco analysis)
- with other VBS and triboson channels: → Towards **global EFT** combination in LHC!



# Backup

# Analysis framework

Comprehensive **framework** developed and maintained in **Milano-Bicocca**: from generations of events to datacard creation and fitting model!

Ntuples and LHE generation **framework**:
https://github.com/UniMiBAnalyses/D6EFTStudies

Post-processing, QCD merging, and shape maker based on:
https://github.com/GiacomoBoldrini/D6tomkDatacard

# Dimension 6 operators in SMEFT

## Bosons and 2 fermions operators

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |
| **$X^2\varphi^2$** | | **$\psi^2 X\varphi$** | | **$\psi^2\varphi^2 D$** | |
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$ |

## 4 fermions operators

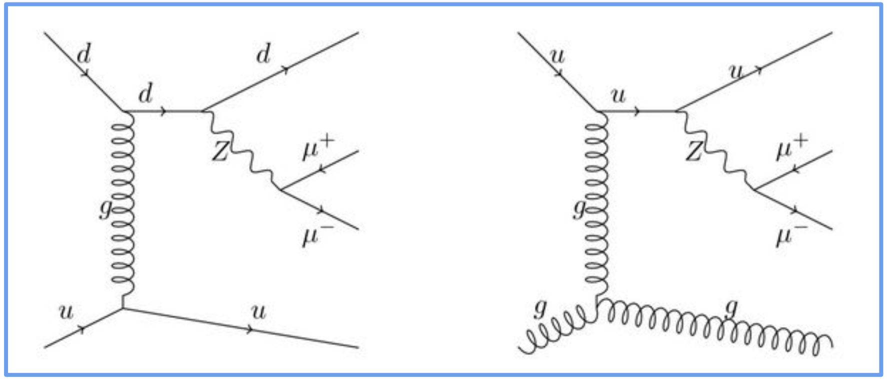
| $(\bar LL)(\bar LL)$ | | $(\bar RR)(\bar RR)$ | | $(\bar LL)(\bar RR)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$ | $Q_{le}$ | $(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{dd}$ | $(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{ed}$ | $(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$ |
| **$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$** | | **$B$-violating** | | | |
| $Q_{ledq}$ | $(\bar l_p^j e_r)(\bar d_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ | | |
| $Q_{quqd}^{(1)}$ | $(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ | | |
| $Q_{quqd}^{(8)}$ | $(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$ | $Q_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ | | |
| $Q_{lequ}^{(1)}$ | $(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ | | |
| $Q_{lequ}^{(3)}$ | $(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$ | | | | |

Warsaw basis

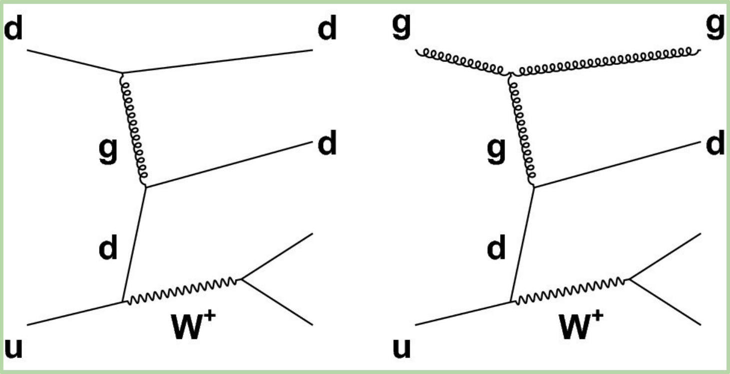
# Irreducible background

Irreducible bkg for VBF-V are all diagrams involving **QCD** interactions leading to same final state. They are of order **O($\alpha^2\alpha_s^2$)** @LO and **interfere** with the EW signal.

**Z+2j**




**W+2j**



# W+2j: operators and best observable

**Best** observables are usually **jet** related ones.

Between $Q_{qq}^{(3)}$ and $Q_{He}$ there are **seven orders** of difference in terms of sensitivity.
→ Strong indication for a possible additional study at the reco level!

| Operator | Best variable | 68% CL interval | 95% CL interval |
|---|---|---|---|
| $Q_{qq}^{(3)}$ | $m_{jj}$ | [-0.021,0.022] | [-0.041,0.043] |
| $Q_{Hl}^{(3)}$ | $\eta_{j^2}$ | [-0.056,0.055] | [-0.110,0.107] |
| $Q_{Hq}^{(3)}$ | $\eta_{j^1}$ | [-0.061,0.062] | [-0.119,0.121] |
| $Q_{ll}^{(1)}$ | $p_{T,j^2}$ | [-0.083,0.083] | [-0.161,0.164] |
| $Q_{qq}^{(3,1)}$ | $\eta_{j^1}$ | [-0.083,0.121] | [-0.133,0.183] |
| $Q_{qq}^{(1,1)}$ | $\eta_{l^1}$ | [-0.099,0.114] | [-0.143,0.158] |
| $Q_{uW\,Re}$ | $\eta_{j^2}$ | [-0.101,0.102] | [-0.196,0.203] |
| $Q_{qq}^{(1)}$ | $\eta_{j^1}$ | [-0.220,0.267] | [-0.346,0.406] |
| $Q_{HWB}$ | $\eta_{j^1}$ | [-0.323,0.333] | [-0.625,0.665] |
| $Q_{HDD}$ | $\eta_{j^1}$ | [-0.566,0.581] | [-1.096,1.156] |
| $Q_W$ | $m_{jj}$ | [-0.608,0.561] | [-1.035,0.951] |
| $Q_{qu}^{(1)}$ | $\eta_{j^1}$ | [-0.855,0.897] | [-1.213,1.255] |
| $Q_{lq}^{(3)}$ | $\|\Delta\phi_{jj}\|$ | [-0.889,0.902] | [-1.518,1.542] |
| $Q_{qd}^{(1)}$ | $\eta_{j^2}$ | [-0.966,0.939] | [-1.354,1.327] |
| $Q_{Hq}^{(1)}$ | $p_{T,j^2}$ | [-0.974,0.882] | [-1.955,1.641] |
| $Q_{Hu}^{(1)}$ | $\eta_{j^1}$ | [-1.595,1.973] | [-2.452,2.890] |
| $Q_{lu}$ | $\eta_{l^1}$ | [-2.151,2.137] | [-3.017,3.003] |
| $Q_{Hd}$ | $p_{T,j^2}$ | [-2.834,2.244] | [-3.883,3.288] |
| $Q_{lq}^{(1)}$ | $\eta_{l^1}$ | [-4.489,4.084] | [-6.453,6.012] |
| $Q_{ld}$ | $p_{T,j^2}$ | [-10.358,10.974] | [-14.661,15.278] |
| $Q_{Hl}^{(1)}$ | $\eta_{l^1}$ | [-52,45] | [-100,81] |
| $Q_{ed}$ | $m_{jj}$ | [-109,111] | [-154,156] |
| $Q_{qe}$ | $m_{jj}$ | [-132,130] | [-185,184] |
| $Q_{eu}$ | $\|\Delta\eta_{jj}\|$ | [-1438,1439] | [-2019,2020] |
| $Q_{He}$ | $\|\Delta\eta_{jj}\|$ | [-81429,80881] | [-160086,157980] |

# Variables ranking

Variables are sorted wrt to their 1 sigma interval (or area in the 2D case).