Study of VBF/VBS in the LHC at 13 TeV (and) the EFT approach

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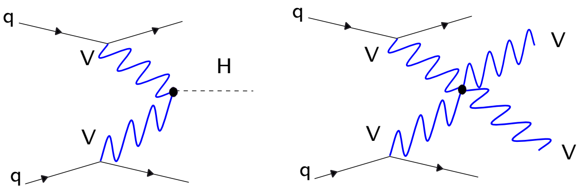
[1] In collaboration with G. Passarino

Outline

1. Introduction:
   - VBF/VBS motivation
2. Search for new physics: EFT
   - Searching for deviations
   - Top-Down approach
   - Bottom-up approach
   - Dim-6 LO EFT
   - NLO EFT
3. Tools used for simulation
   - Monte Carlo Generators
4. Next steps
   - Implementing EW corrections in the MC Generators

Vector Boson Fusion & Vector Boson Scattering



V $= W^+$, W^-, Z

Why look at this production channel? Mainly 2 reasons:

- Subleading channel for H production at LHC.
- Most important channel for EWSB and unitarity studies.[a]

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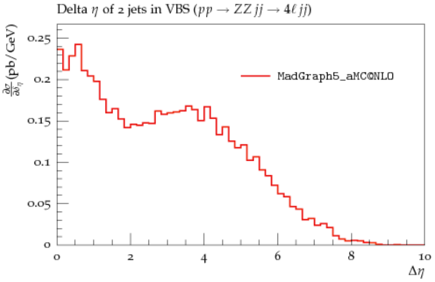
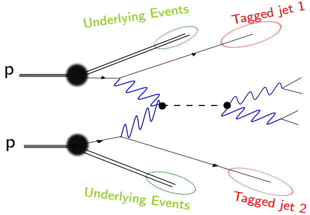
[a] For example, "delayed unitarity"

Why study VBF at LHC RUN-II ?

σ_{VBF} is suppressed with respect to σ_{ggF} but has many experimental advantages:

- Clean signature:
  - Two well defined tagged jets: large p_T
  - Big rapidity gap between jets
- Reasonable X-Section expected for Run-II luminosity





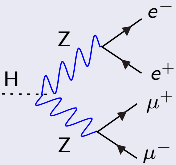
Which decay channel shall we study?

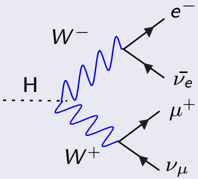
Experimentally: $pp \to ZZ \to 4\ell$

Cleanest channel: 4 leptons in the final state

Theoretically: $pp \to W^+W^- \to 2\ell 2\nu$

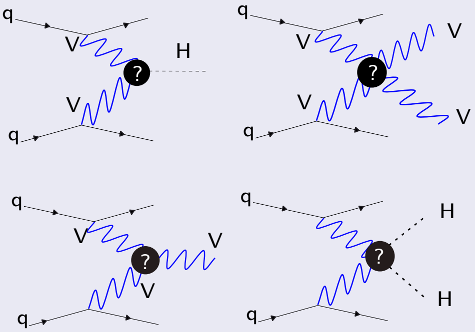
NLO EW corrections are easier to calculate (less diagrams)





From the theorist point of view . . .

VBF/VBS is much more than the previous 2 diagrams



- Portal to triple and quartic gauge couplings and to double Higgs production
- . . . and to *new physics* ?

Importance of NLO EW corrections

$pp \to ZZ \to 4\ell$

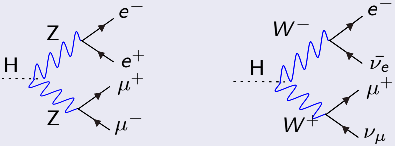
Pure EW corrections are of the order of 3.6 % (to the fiducial σ at 8-13TeV)

(Biedermann, Denner, Dittmaier, Hofer, Jäger : 1601.07787)

$pp \to W^+W^- \to 2\ell 2\nu$

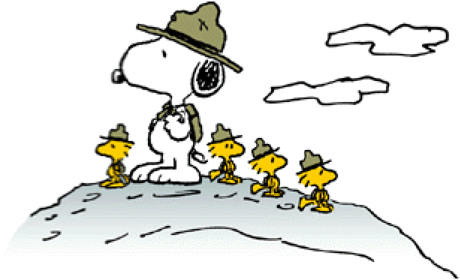
NLO EW corrections are of the order 2% (inclusive σ) and 3% (fiducial σ)

(Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder : 1605.03419)



EW corrections are needed for sensitive RUN-2 analyses

SEARCHING FOR NEW PHYSICS



The κ framework

Back in 2012 . . .

The κ framework postulates (*ad-hoc*) deviations from the SM couplings and decay widths, and proposes strategies to measure those “anomalous couplings”

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If there is something we learnt from the kappa framework is:

Deviations from the Standard Model are

SMALL

New Physics Quest's Agenda

Future Steps

1. Include EW corrections in the Monte Carlo Generators
2. Explore new scenarios → through Effective Field theory
    - Top- Down approach: Explore specific BSM models
    - Bottom- Up approach: studies the most general extensions of the SM

Bottom-Up approach

$$\mathcal{L}_{eff} = \underbrace{\mathcal{L}_{SM}}_{\text{dim 4}} + \underbrace{\frac{1}{\Lambda^2}\sum_k \alpha_k \mathcal{O}_k^{(6)}}_{\text{dim 6}} + \underbrace{\cdots}_{\text{higher dim. operators}}$$

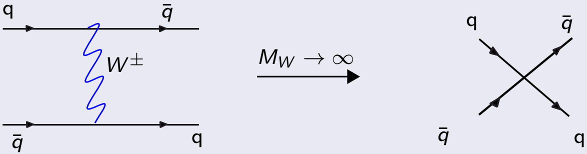
- Follows the SM spirit: Do the same calculations with (new) Feynman rules and a (new) renormalization
- For dim-6: "Warsaw Basis" → see backup slides

Effective field theory

Top-down approach

Take a BSM model and integrate out the heavy fields. i.e: The propagator becomes a point.

Recall Fermi theory:



Effective field theory

Top-Down approach

- Advantages: Straightforward and useful for Dark Matter and SUSY
- Model-dependent, therefore not very efficient

Low energy behaviour of standard model extensions

Michele Boggia[a,1], Raquel Gomez-Ambrosio[b,1], Giampiero Passarino[b,1]

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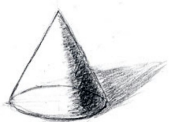
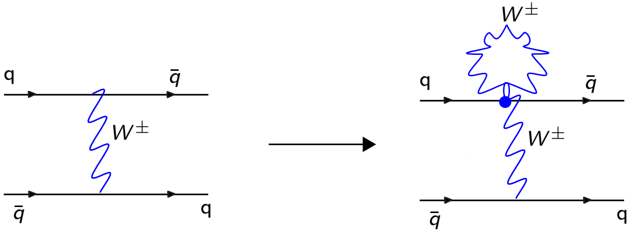
INFN, Sezione di Torino, Italy

arXiv: 1603.03660

Bottom-up approach



- In the bottom up approach we do exactly the opposite:



- **Observe:** Unlike in the top-down, the relation is not bijective: one low-energy operator might come from many different UV completions

Hierarchy of the corrections

Implementing EFT in Vector Boson Scattering

What is LO EFT? is it more relevant than NLO-SM? and NLO-EFT?

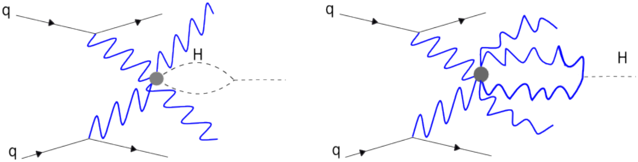
$$\mathcal{M} = \mathcal{M}_{SM}^{\mathrm{LO}} + \underbrace{\mathcal{M}_{SM}^{\mathrm{NLO}}}_{\substack{\text{all available}\\ \text{QCD, EW corrections}}} + \underbrace{\mathcal{M}_{dim=6}^{\mathrm{LO}} + \mathcal{M}_{dim=6}^{\mathrm{NLO}}}_{\substack{\kappa-\text{framework}\\ \text{and dim 6 EFT}}}$$

The answer depends on the scale of new physics Λ , the only way to be sure is to calculate the contributions and include them in the analysis.

Some words on NLO EFT and renormalization

NLO EFT corrections are quite involded to calculate:

1. Need to renormalize the new $\mathcal{L}_{eff}$ → *The SM renormalization is not recyclable.*
2. Many new contributions will appear, through non-SM loops:



Ongoing work ... More in future presentations


Tools

`PHANTOM` & `MadGraph5_aMC@NLO`

`PHANTOM`: Monte Carlo Event Generator for Six Parton Final States

- **Scope:** Six fermion final states: VBF, VBS, $t\bar{t}$ production . . .
- **Output:** Unweighted events (LHA) and Cross-Sections.
- Order $\mathcal{O}(\alpha^6) + \mathcal{O}(\alpha^4\alpha_s^2)$ + interferences

`MadGraph5_aMC@NLO`: “The MC generator that will calculate any process”

- Predecessors: `MadGraph`, `MadEvent`, `MadGraph5`, `MC@NLO`
- Also Lowest Order in the EW sector
- Highlight: Can accomodate Dim-6 EFT operators

`PHANTOM`: A. Ballestrero, A. Belhouari, G. Bevilacqua , V. Kashkan, E. Maina

`MadGraph5_aMC@NLO`: J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro

Implementing EW corrections in the Monte Carlo Generators

Challenges of the NLO EW calculation. In order of appearance:

1. There are more diagrams in a NLO EW process (photon emission!)
2. Each of them is more involved to calculate (massive particles!)
3. Renormalization

Big improvements have been published recently

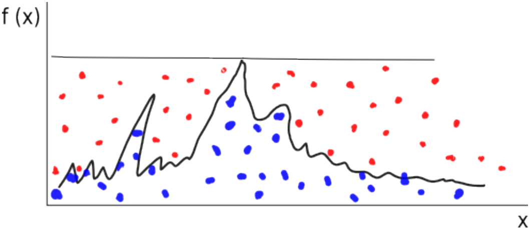
- `RECOLA`: REcursive Computation of One-Loop Amplitudes
- `COLLIER`: Complex One-Loop LIbrary in Extended Regularizations

`RECOLA` Ansgar Denner, Lars Hofer, Jean-Nicolas Lang, Sandro Uccirati
`COLLIER` Ansgar Denner, Stefan Dittmaier, Lars Hofer

Implementing EW corrections in the Monte Carlo Generators

Phase space integration:

The multichannel method has to be optimized for the EW sector: The peak distribution is much more involved than for QCD processes and in the case of VBS, we have more particles in the final state.



Implementing EW corrections in the Monte Carlo Generators

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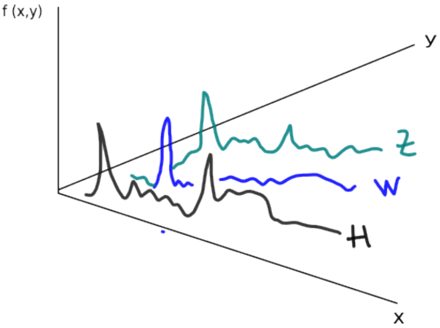

Implementing EW corrections in the Monte Carlo Generators

Other difficulties, well known from NLO QCD implementation:

- IR divergencies matching → not so bad, many methods are known from QCD: Antenna Substraction, q_T substraction, sector decomposition ...
- Matching to parton shower, double counting → Need to write a plug-in

The Message

- We live exciting times for particle physics, after LHC Run-II we will have a huge integrated luminosity
- Before the end of the summer we will have news from a new particle . . .
- Or a much better understanding of statistical fluctuations.
- There are new codes in the market able to provide us with all the SM corrections needed.
- The EFT framework is well established in the theoretical community and on its way to the experimental analyses.
- ENJOY IT! (and don't forget to do your calculations!)

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Thank You!

... Any Questions?

BACKUP

SM EFT (bottom-up approach)

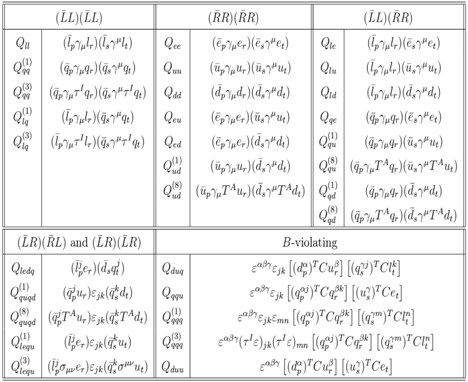
$$\mathcal{L}_{eff} = \underbrace{\mathcal{L}_{SM}}_{\text{dim 4}} + \underbrace{\frac{1}{\Lambda^2}\sum_k \alpha_k \mathcal{O}_k^{(6)}}_{\text{dim 6}} + \underbrace{\cdots}_{\text{higher dim. operators}}$$

- α_k is the Wilson coefficient of the k^{th} operator → needs to be calculated
- One can build 80 dim-6 operators (compatible with $SU(2) \times SU(3) \times U(1)$ and lepton/baryon conservation)
- Eqs. of motion, reduce this set to a 59-operator basis
  (for one generation of particles! for three → 2499 operators)
- "Warsaw Basis" → arXiv: 1008.4884

Warsaw Basis: 34 Bosonic + 25 (+5) fermionic operators

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

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

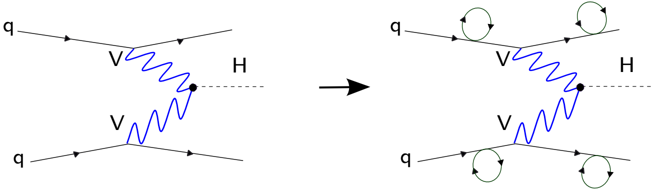


$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Warsaw Basis: Purely Fermionic Operators

At lowest order in VBF, these operators do not contribute. At NLO they should be taken on account during the renormalization process



Warsaw Basis: Bosonic Operators

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

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Vector Boson Fusion Lowest Order EFT

Amplitude with dim-6 insertions:

$$\mathcal{A} = \sum_{n=N}^{\infty} g^n \mathcal{A}_n^{(4)} + g_6 \sum_{n=N_6}^{\infty} \sum_{l=0}^{n} g^n g_6^l \mathcal{A}_{nl}^{(6)}, \qquad \text{with}: \quad \mathrm{g}_6 = \frac{1}{\sqrt{2}\mathrm{G_F}\Lambda^2}.$$

VBF Signal

At lowest order we don't have to consider loops originated by dimension 6 operators. Therefore only corrections to the actual SM vertices