Effective Field Theories for Vector Boson Scattering at LHC[1]

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[1]Work done in collaboration with I. Brivio

Outline

Introduction

- Parametrising new physics: EFTs
- EFT amplitudes and cross-sections

EFT for VBS

- Definition of the process
- Dim-6 effects Vs Dim-8 effects
- Differential distributions

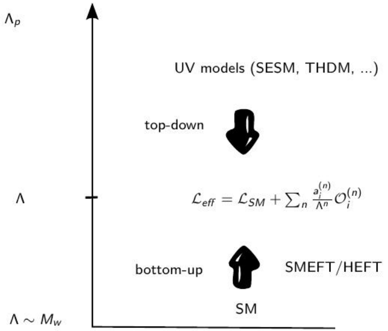
Conclusions

SMEFT

The SMEFT is born as an attempt to extend the Standard Model in the most general possible way. Any Lagrangian for SMEFT can be written as:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{a_5}{\Lambda}\mathcal{O}^{(5)} + \sum_i \frac{a_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{a_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

- The goal is to preform a fit the a_i coefficients, to understand the impact of each of the $\mathcal{O}_i$ operators.
- Each of these operators can be mapped and tested against different BSM scenatrios



See talks by E. Vryonidou, V. Sanz, D. Buttazzo, L. Silvestrini, et.al.

SMEFT. The Warsaw basis

- The most general set of dimension-6 operators respecting the SM symmetries has 81 operators (76 if we impose Baryon number conservation). These can be reduced to 59 using the equivalence theorem.
- These 59 operators, have 76 free parameters, if we consider only one generation of fermions. If we consider three independent generations, the number grows up to 2499 free parameters.
- The minimal basis of gauge-invariant non-redundant operators is called the "Warsaw Basis" *arXiv: 1008.4884*
- There are also other possible *parametrizations*: SILH, HISZ

In this work we will use the Warsaw Basis ($\dim = 6$) and

the $\mathrm{M_W}$ Input Parameter Scheme

SMEFT Amplitudes and cross-sections

The leading order for an EFT amplitude is unambiguous: $\mathcal{A} = \mathcal{A}_{\rm SM} + g_6\mathcal{A}_6^{(1)}$. Further terms in perturbation theory go as:

$$\mathcal{A}_{\rm EFT} = \mathcal{A}_{SM} + \underbrace{g_6\mathcal{A}_6^{(1)}}_{\text{LO EFT}} + \underbrace{g_6^2\mathcal{A}_6^{(1)} + g_8\mathcal{A}_8^{(1)}}_{\text{NLO EFT}} + \ldots$$

The first ambiguities appear when squaring the amplitude:

$$\begin{aligned} |\mathcal{A}_{\rm EFT}|^2 =& |\mathcal{A}_{\rm SM}|^2 + g_6\,|\mathcal{A}_{\rm SM} \times \mathcal{A}_6^{(1)}| + \\ & + g_6^2\,|\mathcal{A}_6^{(1)}|^2 + g_6^2\,|\mathcal{A}_{\rm SM} \times \mathcal{A}_6^{(2)}| + g_8\,|\mathcal{A}_{\rm SM} \times \mathcal{A}_8^{(1)}| + \ldots \end{aligned}$$

Hence,

$$|\mathcal{A}_{\rm EFT}|^2 = |\mathcal{A}_{SM}|^2 + \underbrace{|\mathcal{A}_{\rm SM} \times \mathcal{A}_6^{(1)}|}_{\text{“linear EFT”}} + \underbrace{|\mathcal{A}_6^{(1)}|^2}_{\text{“quadratic EFT”}} + \underbrace{|\mathcal{A}_{\rm SM} \times \mathcal{A}_6^{(2)}| + |\mathcal{A}_{\rm SM} \times \mathcal{A}_8^{(1)}|}_{\text{not available/th.uncertainty}} + \ldots$$

And,

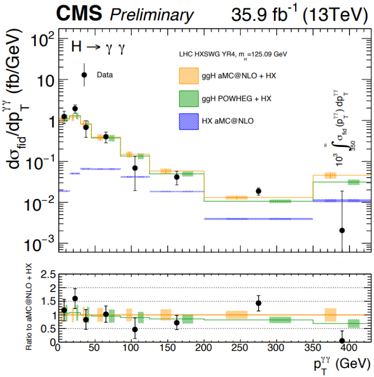
$$\sigma = \sigma_{SM} + \underbrace{\sigma_{int}\left(\frac{v^2}{\Lambda^2}\right)}_{\text{“linear EFT”}} + \underbrace{\sigma_{sq}\left(\frac{v^4}{\Lambda^4}\right)}_{\text{“quadratic EFT”}} + \ldots$$

A possible improvement: Differential Distributions

- EFT effects are expected to be larger in the tails of p_T distributions
- The Higgs width can be accessed mainly through off-shell measurements
- Unfolded p_T distributions allow for a bin-per-bin fit of the EFT effects:

$$\mathcal{A} = \mathcal{A}_{SM} + \frac{c_i}{\Lambda^2}\mathcal{A}_{dim=6} + \frac{d_i}{\Lambda^4}\mathcal{A}_{dim=8}$$

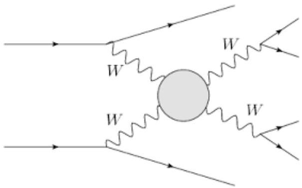
- The terms $\sim \frac{c_i}{\Lambda^2}$ can be added operator-by-operator and bin-by-bin to the SM predictions



Vector Boson Scattering

The set of VBS processes is interesting for many reasons:

- At the heart of EWSB: containing triple and quartic gauge couplings
- Studies of gauge invariance: this process is gauge invariant thanks to very delicate cancellations between diagrams
- Studies of Gauge Boson polarization: longitudinal modes couple to the Higgs while transverse don't, equivalence theorem
- Unitarity Studies: would violate unitarity without the Higgs (delayed unitarity?)



See talks by J. Cuevas, K. Lohwasser, et.al.

VBS in SMEFT

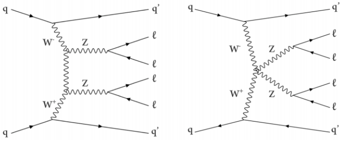
The motivations to study VBS in the context of EFT are mainly four

1. VBS processes were inaccesible til LHC Run-II, but they will become much more common soon
2. They give access to many more couplings than simple Higgs *production-times-decay* channels
3. There is no full "BSM" treatment of the process, beyond the *ad-hoc* anomalous couplings
4. There is some misunderstanding propagates refarding the EFT treatment: $(\mathrm{dim} = 6$ Vs $\mathrm{dim} = 8$ studies) , TGC Vs QGC

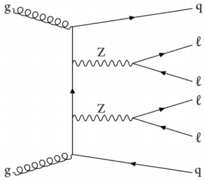
Searches for VBS in the experiment: $ZZ \to 4\ell$

- Low $\sigma \times BR$
- Large irreducible background (B $\approx$ 20 S)
- Final state selection:
  - Two charged-lepton pairs
  - Two tagged jets
- Additionally, VBS cuts:
  - $m_{jj} > 100\,\mathrm{GeV}$
  - Z on-shell
  - $\Delta\eta(jj) > 2.4$
- Very similar to $H \to ZZ \to 4\ell$ analysis.
- Evidence in CMS Run 2 data:
  - 2.7 σ observed (1.6 expected)

Electroweak signal – α_{EW}^{6}

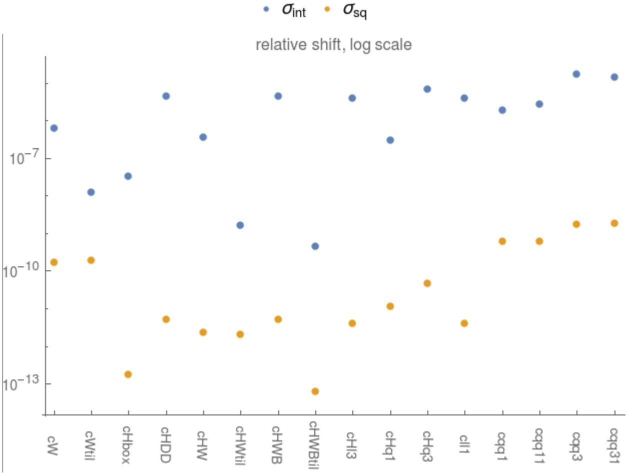


QCD background – $\alpha_{EW}^{4}\alpha^{2}$



Warsaw Operators giving non-zero contributions to $pp \to zzjj$ (Ewk)

$$\sigma = \sigma_{SM} + \sigma_{int}\left(\frac{v^2}{\Lambda^2}\right) + \sigma_{sq}\left(\frac{v^4}{\Lambda^4}\right) + \ldots$$



(anomalous) Triple and Quartic Gauge couplings

It is common in the experimental analysis to look for new physics in the *vertices*. Following this trend the gauge couplings analysis split in two directions:

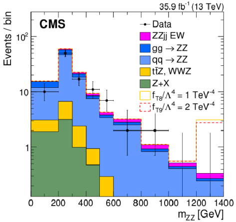
- Studies on Triple Gauge Couplings (TGCs) on diboson production channels
- Studies of Quartic Gauge Couplings (QGCs) on Vector Boson Scattering channels

EFT Triple and Quartic Gauge couplings

Analogously the EFT-gauge couplings analysis also split in two directions:

- Studies on Triple Gauge Couplings (TGCs) in terms of $\dim = 6$ operators
- Studies of Quartic Gauge Couplings (QGCs) in terms of $\dim = 8$ operators

This reasoning has two main flaws . . .



1) Perturbative power counting

- SMEFT amplitudes can be used as a tool to study the validity regime of the EFT perturbative expansion

$$
\begin{array}{lcccc}
\text{(1} \to \text{2 process)} & & & & \\
\text{Higher dim.} \to & & & & \\
\text{Higher order} \downarrow & g\mathcal{A}_1^{(4)} & gg_6\mathcal{A}_{1,1,1}^{(6)} & gg_8\mathcal{A}_{1,1,2}^{(8)} & \dots \\
 & g^3\mathcal{A}_3^{(4)} & g^3g_6\mathcal{A}_{3,1,1}^{(6)} & g^3g_8\mathcal{A}_{3,2,1}^{(8)} & \dots \\
 & \dots & \dots & \dots & \dots
\end{array}
$$

- It is a priori not correct to *skip* the calculation of certain perturbative orders and include only higher ones.

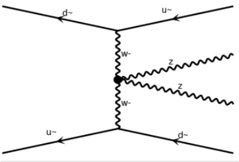
2) 4-Fermion and other operators

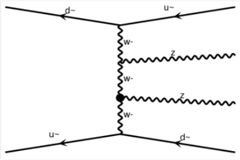
- New Physics might alter the triple and quartic gauge couplings, but a study of VBS processes must allow for EFT deviations in all the diagrams and not only in one vertex of one diagram.
- Moreover EFT-operators with only gauge bosons are expected to be suppressed by an order $\sim 16\pi^2$ with respect to four-fermion operators[2]

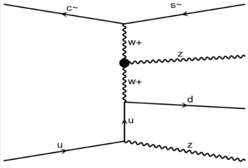
[2] Arzt, Einhorn, Wudka (9407334)

A few EFT diagrams

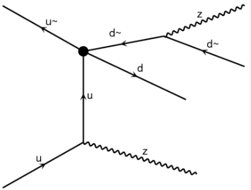
Only looking at TGCs and QGCs: C_W, C_{HW}, C_{HWB}

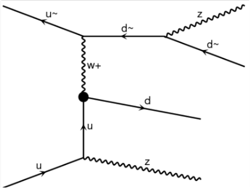


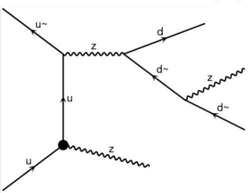




Including all the Warsaw Basis

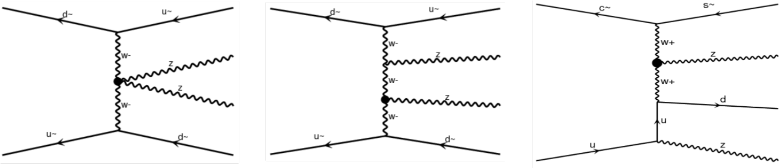






Off-shell couplings are not even well-defined ...

Only looking at TGCs and QGCs: C_W, C_{HW}, C_{HWB}



TGC/QGC operators (only CP-even)

- $C_W = \epsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$
- $C_{HW} = H^\dagger H W_{\mu\nu}^I W^{\mu\nu I}$
- $C_{HWB} = H^\dagger \tau^I H W_{\mu\nu}^I B^{\mu\nu}$

Two - paradigmatic - four fermion operators

- $C_{ll} = (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{\ell}_s \gamma^\mu \ell_t) \to$ Purely leptonic, but enters through G_F !
- $C_{qq} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$

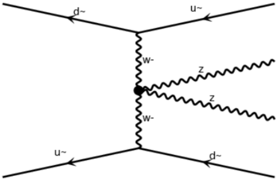
Dim-6 Vs Dim-8 Vs Quadratic

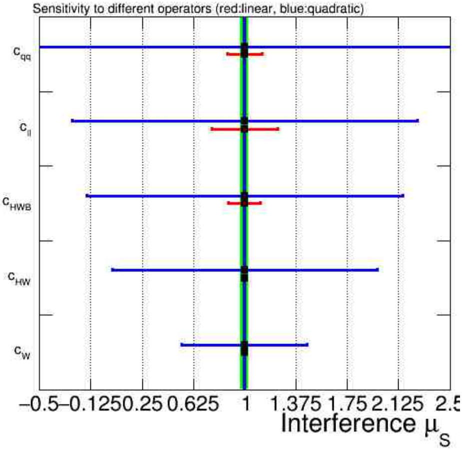
- The cross-section can be decomposed:

$$\sigma = \sigma_{SM} + c_i \frac{E^2}{\Lambda^2}\sigma_6 + \frac{E^4}{\Lambda^4}(d_i\sigma_8 + c_i^2\sigma_{6;sq})$$

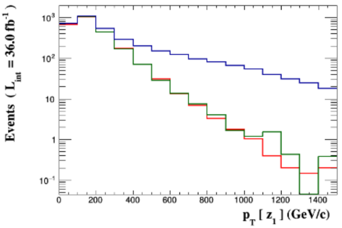
- With the condition $E << \Lambda$. Where E is the typical energy scale of our process (v or $2\mathrm{M_z}$)
- Corrections to the vertices enter as:

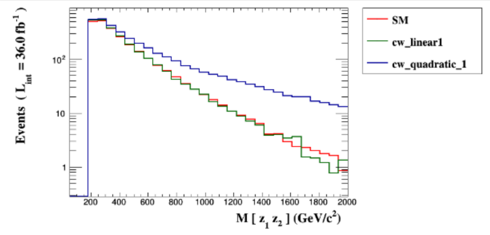
$$V = g + \frac{c_i v^2}{\Lambda^2} g_6 + \frac{c_i v^4}{\Lambda^4} g_8 + \ldots$$

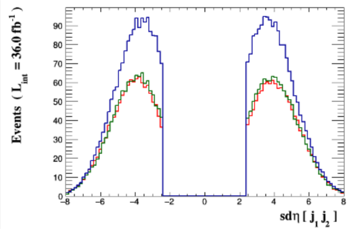


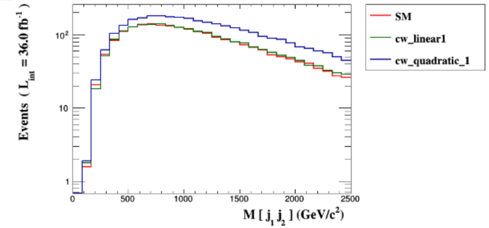


Differential Distributions: C_W

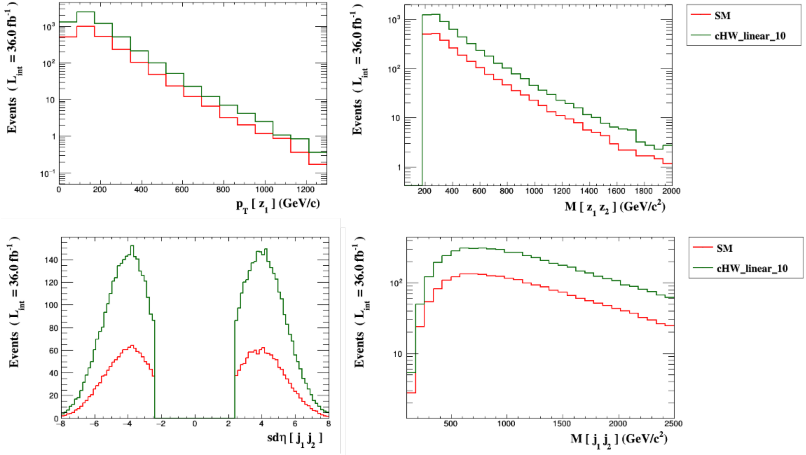






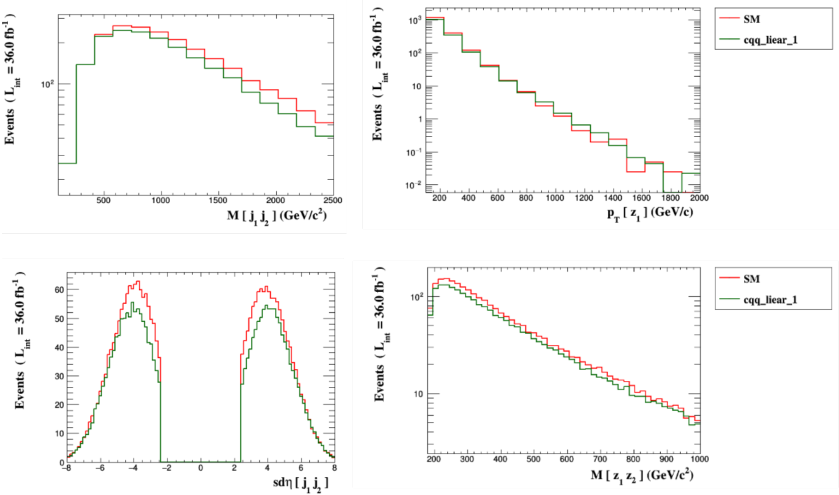


Differential Distributions: C_{HWB}



Differential Distributions: C_{qq}

Very sensitive to this operator: we reach the unitarity bound for $c_{qq} = 1$!

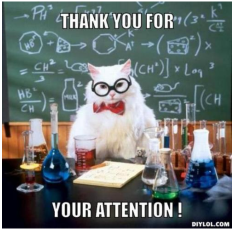


Conclusions

- There are other channels than the Higgs, to look for EFT effects.
- VBS due to the vast number of diagrams, is very sensitive to EFT operators
- Gauge invariance is carefully preserved in VBS $\rightarrow$ good stress-test for the EFT
- $\dim = 6$ effects should be introduced before the $\dim = 8$ ones.
- Measurements of differential distributions will be key for the EFT effects.

Thank you for your attention!

VBSCAN Cost Action
https://vbscanaction.web.cern.ch/



BACKUP

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}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Warsaw Basis. Fermionic Sector

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

EFT predictions: technical points

- Only one $\dim = 6$ operator insertion is allowed per diagram (renormalisation arguments and power counting)
- We expect that the inclusive σ, and (the bins of) differential distributions scale linearly on each of the Wilson Coefficients
- We can generate **only** the interference terms of the New Physics with the SM, with one operator insertion at a time. Speeding up the whole process

Example: some of the $qq \to hg$ diagrams