EFT operators to constraint in the Higgs property fits

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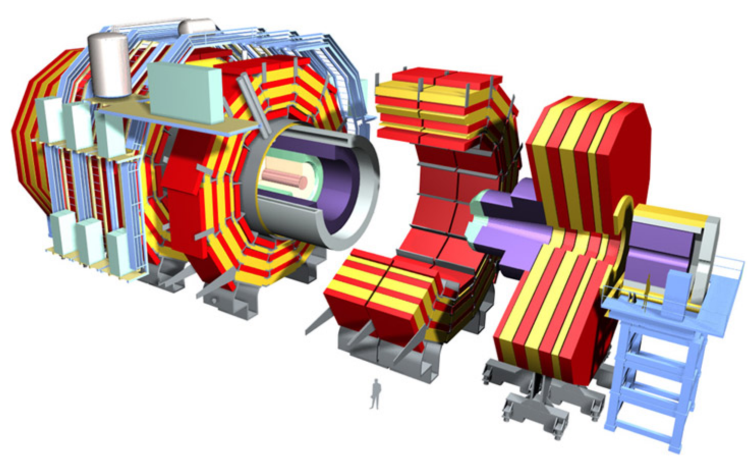


November 15, 2023

The 20th Workshop of the LHC Higgs Working Group

Introduction

- This report is based on experience in dedicated EFT-targeted analyses of LHC data
  - — but discuss concepts, do not expect numerical rigor
  - — biased by $H \to VV$ targets due to personal experience, but ideas are general

- In EFT a set of Wilson coefficients θ_i appears in certain **processes**

- Essential to limit the set of θ_i **before** building the analysis
  - — **optimal observables** are tuned to θ_i - number of dimensions N_D
  - — **number of templates** N_T grows quickly with the number of θ_i
  - — N_D and N_T may grow out of control with θ_i
  - — particular issue in dedicated (full detector simulation of EFT) analyses

- Goal:
  - — determine sensitive θ_i **in advance**
  - — rotate operators to remove flat directions **in advance** (based on physics)

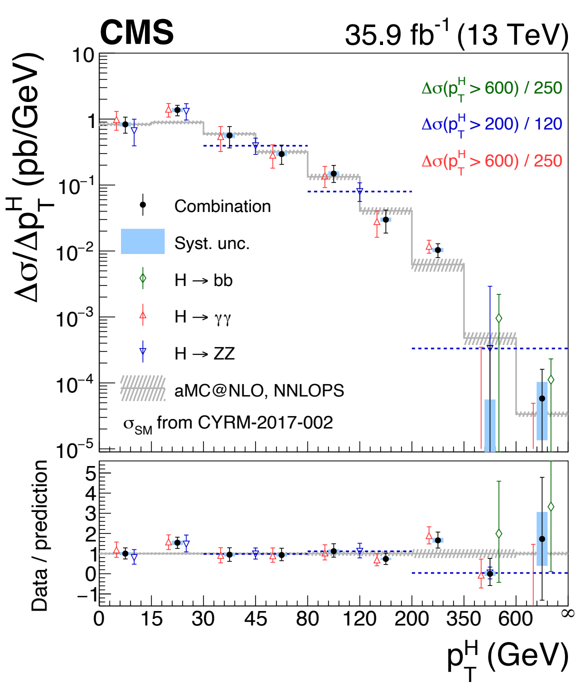
LHC EFT Analysis

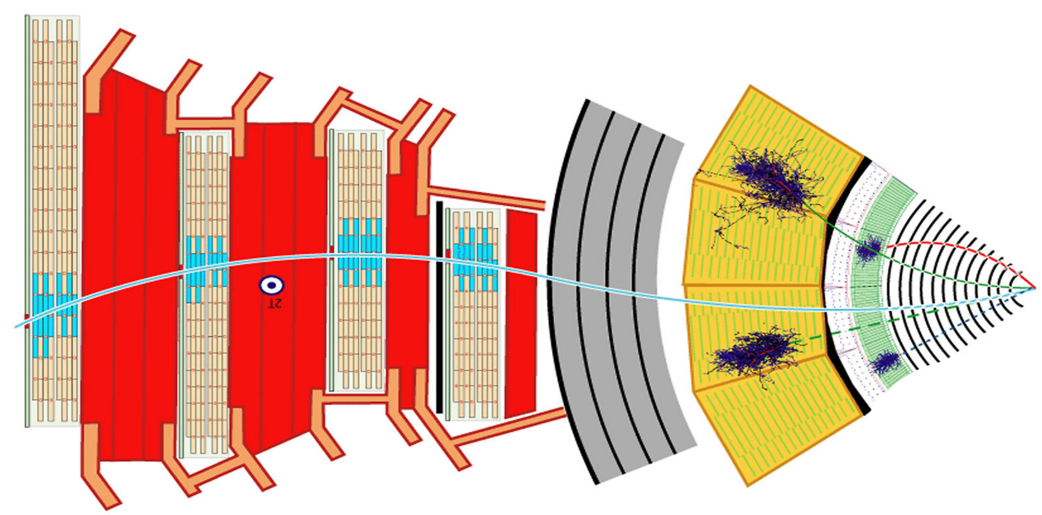
$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) = \int d\vec{x}_{\rm part} \quad p(\vec{x}_{\rm reco}\,|\,\vec{x}_{\rm part}) \; \mathscr{P}(\vec{x}_{\rm part}\,|\,\vec{\theta})$$

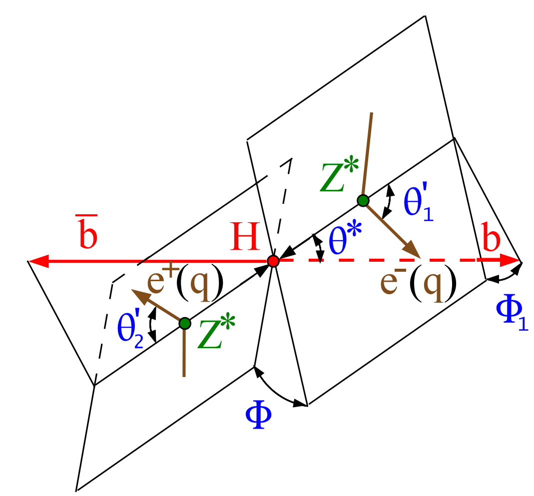
observables
measurement
(Fits)

parton shower
detector effects
reconstruction
(Pythia, GEANT, reco)

hard process
EFT params $\vec{\theta}$
parton mom $\vec{x}_{\rm part}$
(MC Generator)





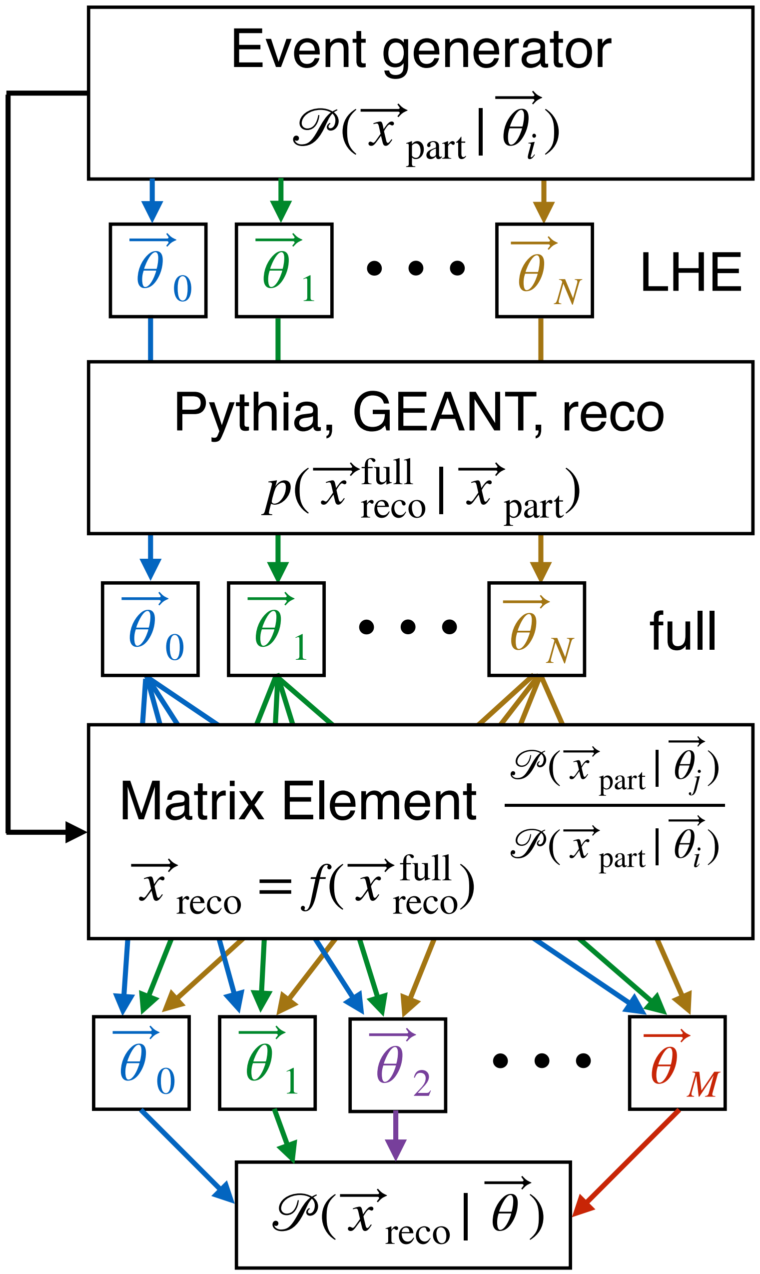


$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) \propto \mathscr{P}_0(\vec{x}_{\rm reco}) + \sum_k \left(\frac{2\theta_k}{\theta_0}\right) \mathscr{P}_{0k}(\vec{x}_{\rm reco}) + \sum_k \left(\frac{\theta_k}{\theta_0}\right)^2 \mathscr{P}_k(\vec{x}_{\rm reco}) + \sum_{i<j} \left(\frac{2\theta_i\theta_j}{\theta_0^2}\right) \mathscr{P}_{ij}(\vec{x}_{\rm reco})$$

SM　　linear terms　　quadratic terms

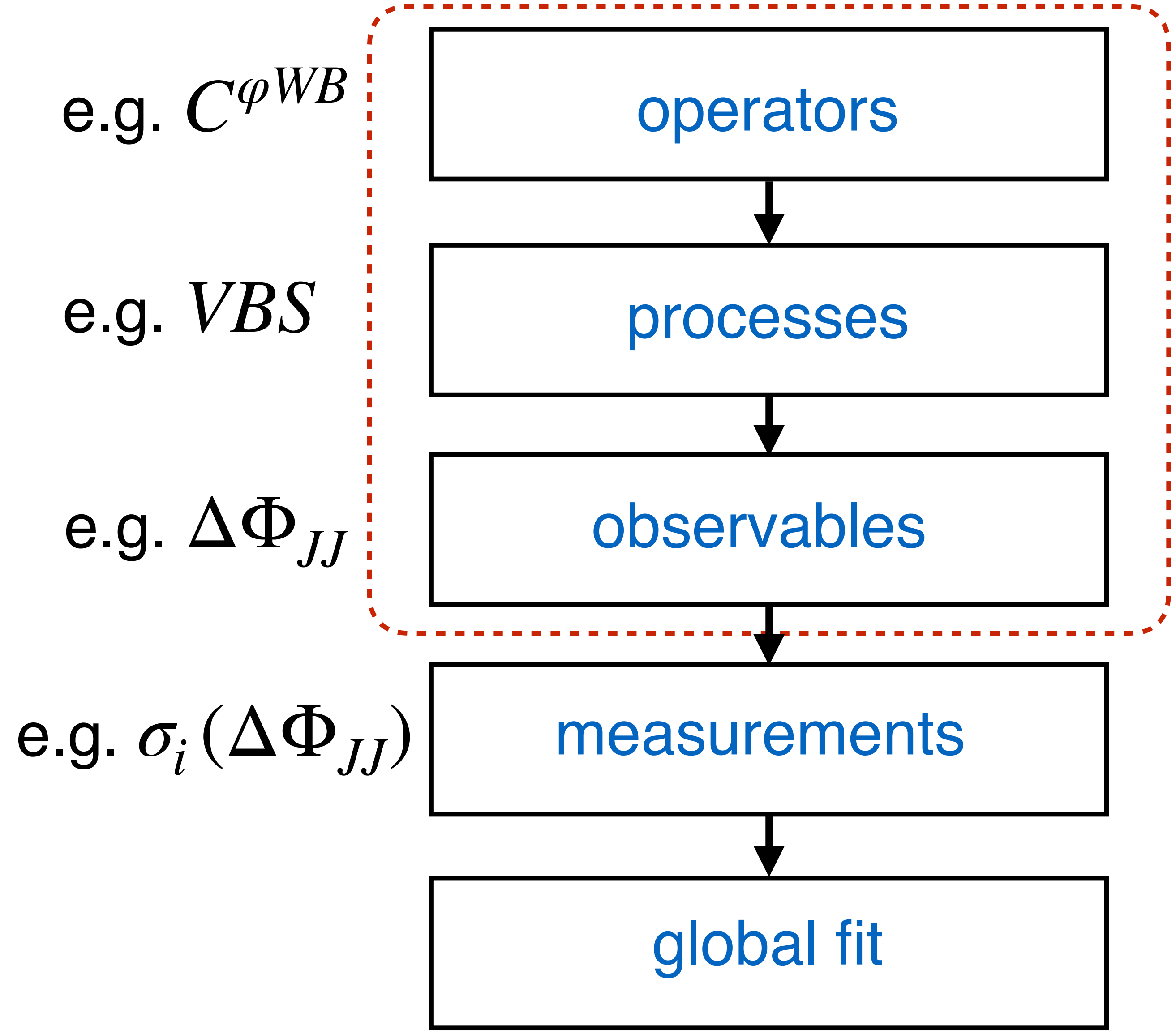
Measurements and Observables

- LHC-EFT-WG-2022-001: Experimental Measurements and Observables



(1) relate operators and observables

(2) define observables and measurements



$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) = \int {\rm d}\vec{x}_{\rm part}\, p(\vec{x}_{\rm reco}\,|\,\vec{x}_{\rm part})\,\mathscr{P}(\vec{x}_{\rm part}\,|\,\vec{\theta})$$

EFT Operators

operators

diagrams with page numbers from

SMEFT Feynman Rules arXiv:1704.03888

- Higgs potential:

$$\mathcal{L}_{\rm H} = (D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{2}(\varphi^\dagger\varphi)^2 + C^{\varphi}(\varphi^\dagger\varphi)^3 + C^{\varphi\Box}(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) + C^{\varphi D}(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)\,. \quad (3.1)$$

- Gauge bosons:

$$\mathcal{L}_{\rm EW} = -\frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\varphi)^\dagger(D^\mu\varphi) + C^{\varphi W}(\varphi^\dagger\varphi)W^I_{\mu\nu}W^{I\mu\nu} + C^{\varphi B}(\varphi^\dagger\varphi)B_{\mu\nu}B^{\mu\nu} + C^{\varphi WB}(\varphi^\dagger\tau^I\varphi)W^I_{\mu\nu}B^{\mu\nu} + C^{\varphi D}(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)\,, \quad (3.9)$$

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} + C^{\varphi G}(\varphi^\dagger\varphi)G^A_{\mu\nu}G^{A\mu\nu}\,, \quad (3.10)$$

- Target operators: $C^{\varphi D}, C^{\varphi\Box}, C^{\varphi W}, C^{\varphi B}, C^{\varphi WB}, C^{\varphi G}, C^{\varphi\tilde{W}}, C^{\varphi\tilde{B}}, C^{\varphi\tilde{W}B}, C^{\varphi\tilde{G}}, \ldots$ and so on…

- Use Warsaw basis of SMEFT

  most convenient for computation (e.g. min. derivatives)

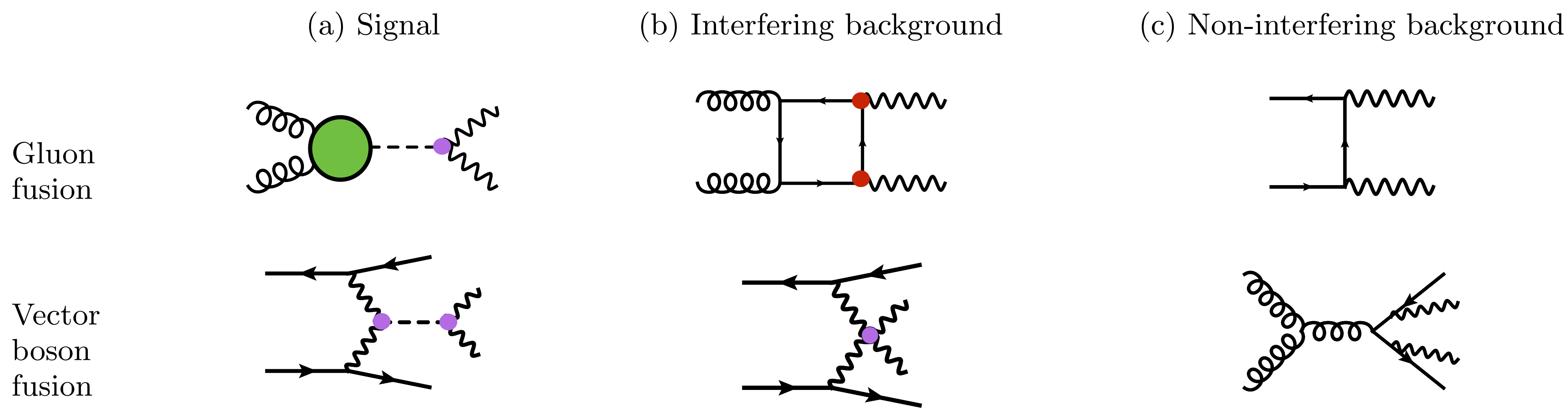
  operator "rotation" may be convenient in certain measurements (some call it "basis rotation")

  e.g. mass eigenstate "rotation" for direct map to observables (e.g. Z/γ instead of B^0/W^0)

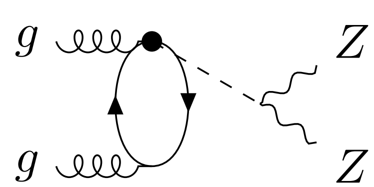
Processes: ggH, VBF, VH and VBS

processes

arXiv:2002.09888



arXiv:2203.02418



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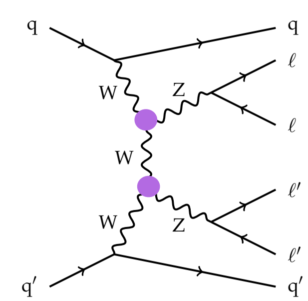
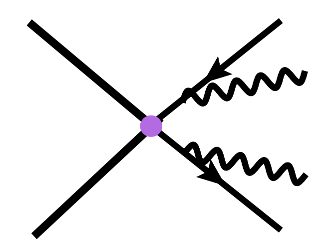
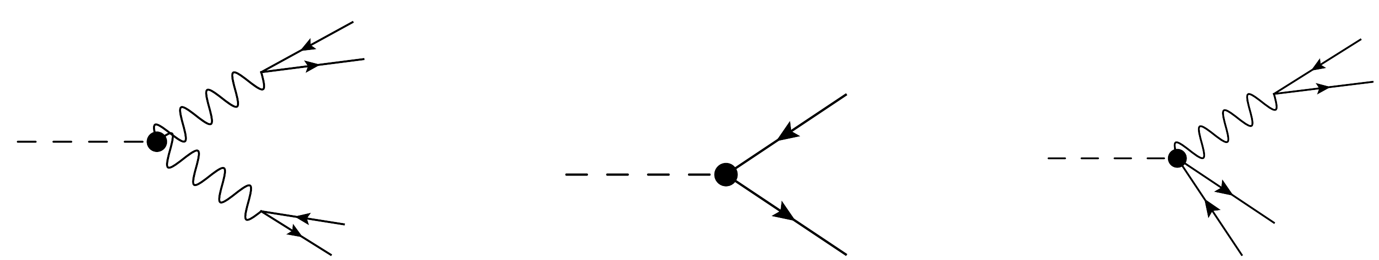


arXiv:1708.02812

four-fermion:



arXiv:2002.09888



(a) HVV (b) $Hf\bar{f}$ (c) $HVf\bar{f}$

- Left out (mostly) today: $t\bar{t}H, tqH, tWH, b\bar{b}H, HH$

Observables

observables

$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) = \int d\vec{x}_{\rm part}\;\; p(\vec{x}_{\rm reco}\,|\,\vec{x}_{\rm part})\;\; \mathscr{P}(\vec{x}_{\rm part}\,|\,\vec{\theta})$$

reco observables

Part 1a

— typical SM observables (to suppress background)

— EFT-sensitive observables (e.g. angular, q^2, etc)

— optimized observables (matrix element, machine learning)

— full accessible information $\vec{x}^{\rm full}_{\rm reco}$ (e.g. all four-vectors)

Example: VBF $\Delta\Phi_{JJ}$ (EFT-sensitive)

EFT:

— new tensor structures

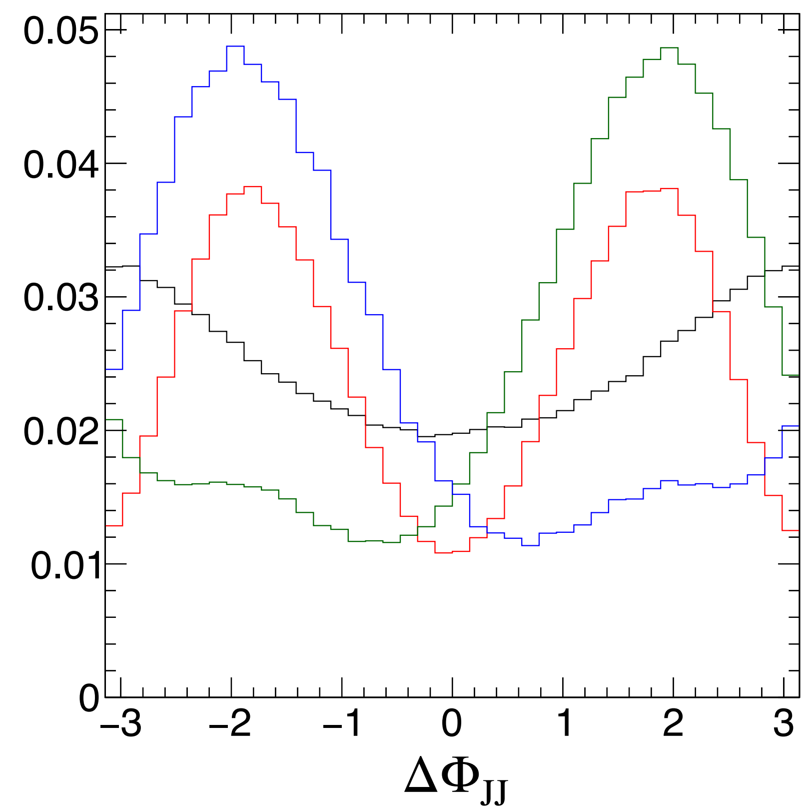
— higher q dimensions

SM — $(\theta_0, 0\,)$

CP-odd — $(\,0\,, \theta_1)$

+mix — $(\theta_0, +\theta_1)$

- mix — $(\theta_0, -\theta_1)$



Optimized Observables

$$\mathscr{P}(\vec{x}_{\rm reco}\,|\,\vec{\theta}) \propto \mathscr{P}_0(\vec{x}_{\rm reco}) + \sum_k \left(\frac{2\theta_k}{\theta_0}\right) \mathscr{P}_{0k}(\vec{x}_{\rm reco}) + \sum_k \left(\frac{\theta_k}{\theta_0}\right)^2 \mathscr{P}_k(\vec{x}_{\rm reco}) + \sum_{i<j} \left(\frac{2\theta_i\theta_j}{\theta_0^2}\right) \mathscr{P}_{ij}(\vec{x}_{\rm reco})$$

$$\mathcal{R}_{\rm opt,1} = \frac{2\mathcal{P}_{01}(\vec{x}^{\rm \,full}_{\rm reco})}{\mathcal{P}_0(\vec{x}^{\rm \,full}_{\rm reco}) + c\cdot\mathcal{P}_1(\vec{x}^{\rm \,full}_{\rm reco})} \qquad \mathcal{R}_{\rm opt,2} = \frac{\mathcal{P}_1(\vec{x}^{\rm \,full}_{\rm reco})}{\mathcal{P}_0(\vec{x}^{\rm \,full}_{\rm reco}) + c\cdot\mathcal{P}_1(\vec{x}^{\rm \,full}_{\rm reco})}$$

- Two types from first principles: (matrix elements for models θ_0, θ_1)
- Machine learning equivalent (parton shower, detector effects)

  $\mathscr{R}_{\rm opt,1}$: train +mix vs -mix

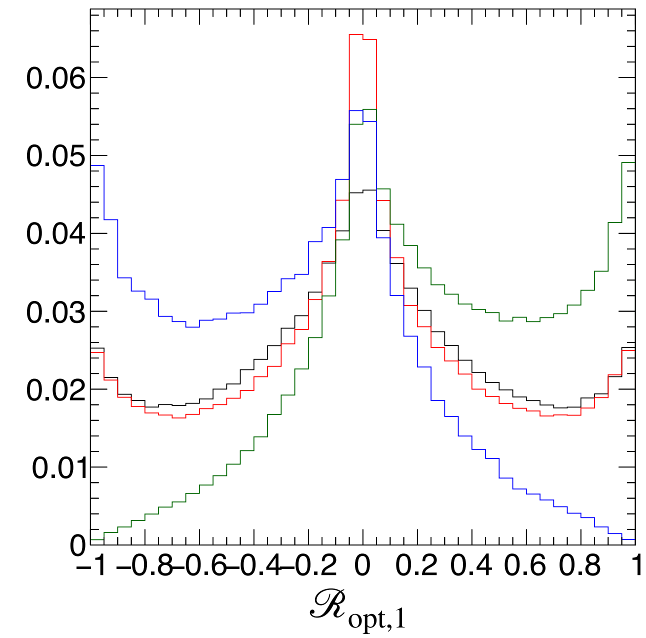
  $\mathscr{R}_{\rm opt,2}$: train θ_1 vs θ_0 (SM)

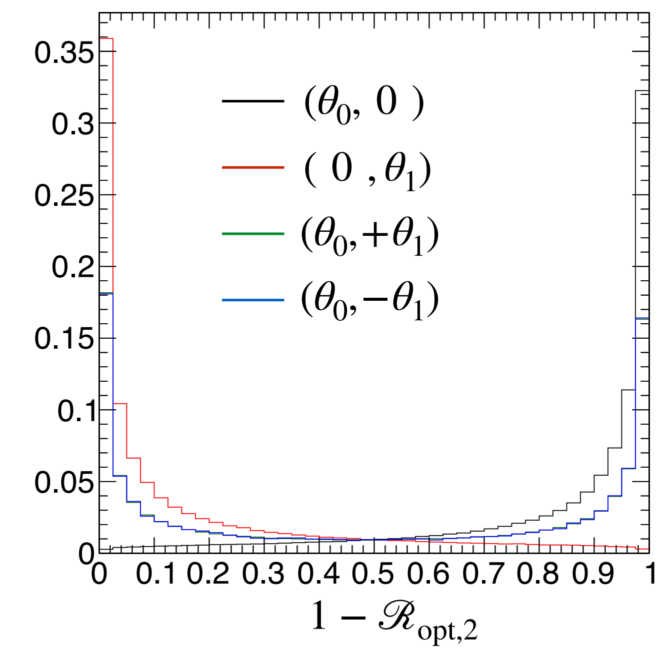
- Essential to limit the set of θ_i

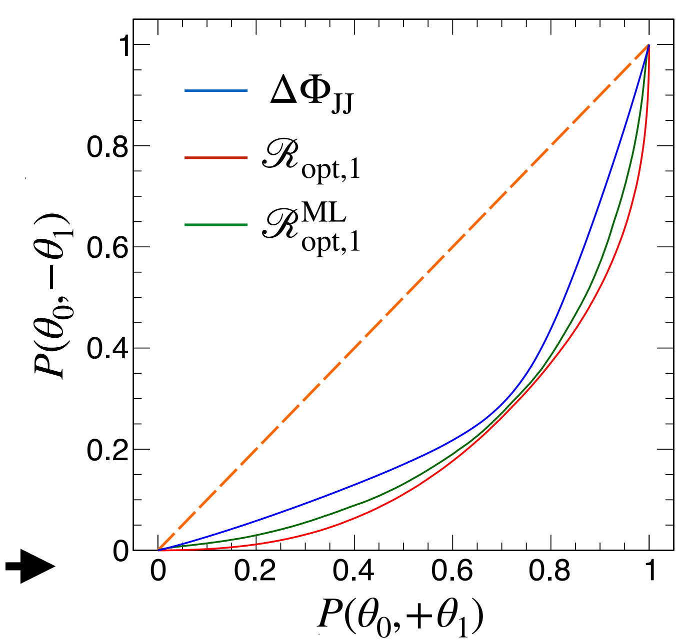
— determine sensitive θ_i in advance

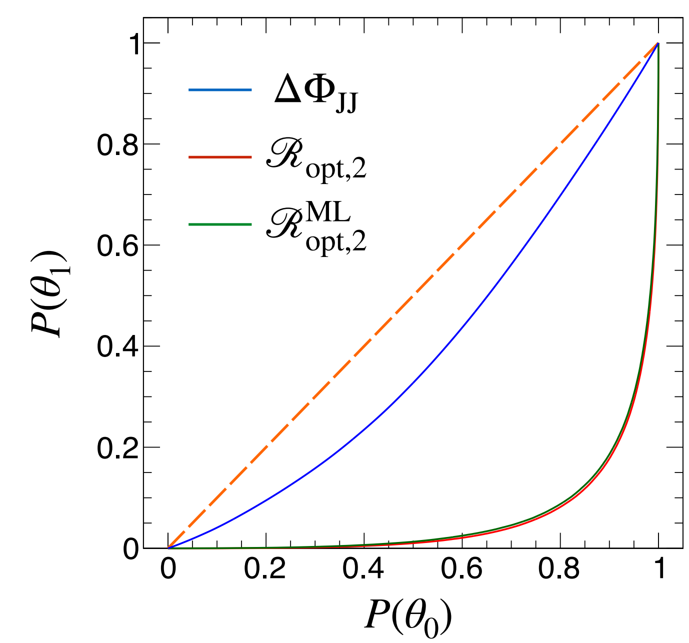
— rotate operators to remove flat directions

e.g. in VBF: rotate to $\theta_1 = \tilde{c}_{zz}$



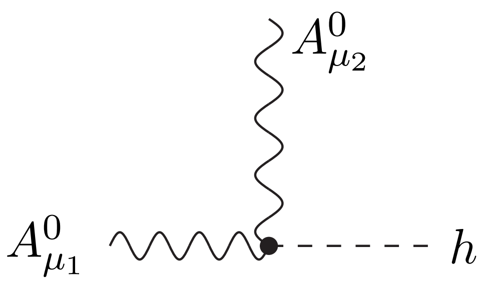






LHC EFT Analysis

- Feynman rules for SMEFT
  - — relate processes and operators



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arXiv:1704.03888

$$
\begin{aligned}
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi W}(p_1^{\mu_2}p_2^{\mu_1} - p_1\cdot p_2\eta_{\mu_1\mu_2}) \\
&+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi B}(p_1^{\mu_2}p_2^{\mu_1} - p_1\cdot p_2\eta_{\mu_1\mu_2}) \\
&-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} C^{\varphi WB}(p_1^{\mu_2}p_2^{\mu_1} - p_1\cdot p_2\eta_{\mu_1\mu_2}) \\
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{W}} p_1^{\alpha_1}p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1} + \frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{B}} p_1^{\alpha_1}p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1} \\
&-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{W}B} p_1^{\alpha_1}p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}
\end{aligned}
$$

$C^{\varphi W}, C^{\varphi B}, C^{\varphi WB} \rightarrow c_{\gamma\gamma}$

$C^{\varphi \tilde{W}}, C^{\varphi \tilde{B}}, C^{\varphi \tilde{W}B} \rightarrow \tilde{c}_{\gamma\gamma}$

rotate operators

- In the end relate to observables $\vec{x}_{\text{reco}}$
  - — kinematic effects
  - — experimental choice

  } affect sensitivity to EFT parameters $\vec{\theta}$

- For an optimal analysis — optimize target set of operators in advance

  - — determine sensitive θ_i in advance
  - — rotate operators to remove flat directions

Target set of operators

Main HVV:

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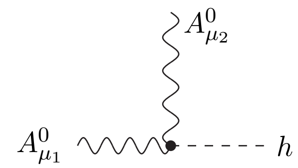
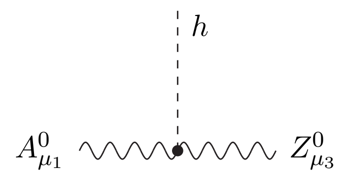


$$+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2}C^{\varphi W}\left(p_1^{\mu_2}p_2^{\mu_1}-p_1\cdot p_2\eta_{\mu_1\mu_2}\right)$$
$$+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2}C^{\varphi B}\left(p_1^{\mu_2}p_2^{\mu_1}-p_1\cdot p_2\eta_{\mu_1\mu_2}\right)$$
$$-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2}C^{\varphi WB}\left(p_1^{\mu_2}p_2^{\mu_1}-p_1\cdot p_2\eta_{\mu_1\mu_2}\right)$$
$$+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2}C^{\varphi\widetilde{W}}p_1^{\alpha_1}p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2}C^{\varphi\widetilde{B}}p_1^{\alpha_1}p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}$$
$$-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2}C^{\varphi\widetilde{W}B}p_1^{\alpha_1}p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}$$

$$C^{\varphi W}, C^{\varphi B}, C^{\varphi WB} \rightarrow c_{\gamma\gamma}$$
$$C^{\varphi \tilde{W}}, C^{\varphi \tilde{B}}, C^{\varphi \tilde{W}B} \rightarrow \tilde{c}_{\gamma\gamma}$$

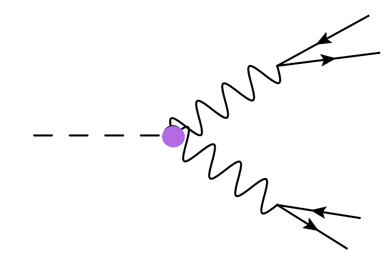
rotate operators

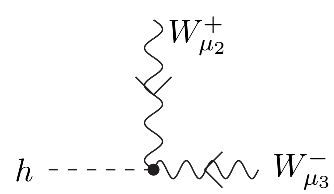


$$+\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2}C^{\varphi W}\left(p_1^{\mu_3}p_3^{\mu_1}-p_1\cdot p_3\eta_{\mu_1\mu_3}\right)$$
$$-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2}C^{\varphi B}\left(p_1^{\mu_3}p_3^{\mu_1}-p_1\cdot p_3\eta_{\mu_1\mu_3}\right)$$
$$+\frac{2iv\left(\bar{g}'^2-\bar{g}^2\right)}{\bar{g}^2+\bar{g}'^2}C^{\varphi WB}\left(p_1^{\mu_3}p_3^{\mu_1}-p_1\cdot p_3\eta_{\mu_1\mu_3}\right)$$
$$+\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2}C^{\varphi\widetilde{W}}p_1^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_1\mu_3\alpha_1\beta_1}-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2}C^{\varphi\widetilde{B}}p_1^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_1\mu_3\alpha_1\beta_1}$$
$$+\frac{2iv\left(\bar{g}'^2-\bar{g}^2\right)}{\bar{g}^2+\bar{g}'^2}C^{\varphi\widetilde{W}B}p_1^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_1\mu_3\alpha_1\beta_1}$$

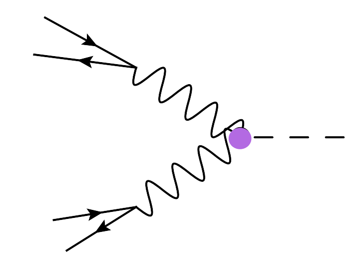
$$C^{\varphi W}, C^{\varphi B}, C^{\varphi WB} \rightarrow c_{z\gamma}$$
$$C^{\varphi \tilde{W}}, C^{\varphi \tilde{B}}, C^{\varphi \tilde{W}B} \rightarrow \tilde{c}_{z\gamma}$$

generate:





$$+\frac{1}{2}i\bar{g}^2 v\eta_{\mu_2\mu_3}+\frac{1}{2}i\bar{g}^2 v^3\eta_{\mu_2\mu_3}C^{\varphi\Box}-\frac{1}{8}i\bar{g}^2 v^3\eta_{\mu_2\mu_3}C^{\varphi D}$$
$$+4ivC^{\varphi W}\left(p_2^{\mu_3}p_3^{\mu_2}-p_2\cdot p_3\eta_{\mu_2\mu_3}\right)+4ivC^{\varphi\widetilde{W}}p_2^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_2\mu_3\alpha_1\beta_1}$$



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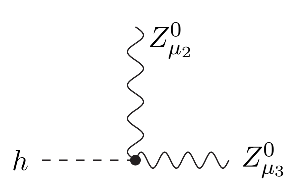

$$+\frac{iv}{2}\left(\bar{g}^2+\bar{g}'^2\right)\eta_{\mu_2\mu_3}+\frac{iv^3}{2}\left(\bar{g}^2+\bar{g}'^2\right)\eta_{\mu_2\mu_3}C^{\varphi\Box}$$
$$+\frac{3iv^3}{8}\left(\bar{g}^2+\bar{g}'^2\right)\eta_{\mu_2\mu_3}C^{\varphi D}+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2}C^{\varphi W}\left(p_2^{\mu_3}p_3^{\mu_2}-p_2\cdot p_3\eta_{\mu_2\mu_3}\right)$$
$$+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2}C^{\varphi B}\left(p_2^{\mu_3}p_3^{\mu_2}-p_2\cdot p_3\eta_{\mu_2\mu_3}\right)$$
$$+\frac{i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2}C^{\varphi WB}\left(\eta_{\mu_2\mu_3}\left(-4p_2\cdot p_3+\bar{g}^2v^2+\bar{g}'^2v^2\right)+4p_2^{\mu_3}p_3^{\mu_2}\right)$$
$$+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2}C^{\varphi\widetilde{W}}p_2^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_2\mu_3\alpha_1\beta_1}+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2}C^{\varphi\widetilde{B}}p_2^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_2\mu_3\alpha_1\beta_1}$$
$$+\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2}C^{\varphi\widetilde{W}B}p_2^{\alpha_1}p_3^{\beta_1}\epsilon_{\mu_2\mu_3\alpha_1\beta_1}$$

$$C^{\varphi W}, C^{\varphi B}, C^{\varphi WB} \rightarrow c_{zz}$$
$$C^{\varphi \tilde{W}}, C^{\varphi \tilde{B}}, C^{\varphi \tilde{W}B} \rightarrow \tilde{c}_{zz}$$

expect $Z\ell\ell$ and Zqq with light q to be well constrained elsewhere

Quark-gauge couplings:

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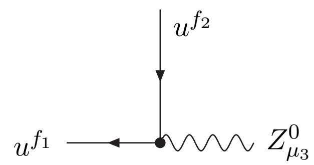
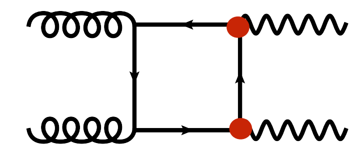


$$
\begin{aligned}
&+\frac{i}{6\sqrt{\bar g^2+\bar g'^2}}\delta_{f_1f_2}\left(\left(\bar g'^2-3\bar g^2\right)\gamma^{\mu_3}P_L+4\bar g'^2\gamma^{\mu_3}P_R\right)\\
&-\frac{i\bar g\bar g' v^2}{6\left(\bar g^2+\bar g'^2\right)^{3/2}}\delta_{f_1f_2}C^{\varphi WB}\left(\left(3\bar g'^2-\bar g^2\right)\gamma^{\mu_3}P_L-4\bar g^2\gamma^{\mu_3}P_R\right)\\
&-\frac{\sqrt{2}\bar g v}{\sqrt{\bar g^2+\bar g'^2}}p_3^\nu\left(C^{uW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{uW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)\\
&+\frac{\sqrt{2}\bar g' v}{\sqrt{\bar g^2+\bar g'^2}}p_3^\nu\left(C^{uB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{uB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)\\
&+\frac{1}{2}iv^2\sqrt{\bar g^2+\bar g'^2}K_{f_1g_2}K^*_{f_2g_1}C^{\varphi q1}_{g_2g_1}\gamma^{\mu_3}P_L\\
&-\frac{1}{2}iv^2\sqrt{\bar g^2+\bar g'^2}K_{f_1g_2}K^*_{f_2g_1}C^{\varphi q3}_{g_2g_1}\gamma^{\mu_3}P_L\\
&+\frac{1}{2}iv^2\sqrt{\bar g^2+\bar g'^2}C^{\varphi u}_{f_1f_2}\gamma^{\mu_3}P_R
\end{aligned}
$$

generate: Ztt coupling



consider C_L^{Ztt}, C_R^{Ztt} ?

"operator rotation"
to remove blind directions
(or "eigenvectors")

need to check if other processes, like ttZ, constrain it better…

(assuming no flavor symmetry for the top)

Expect the following to be better constrained elsewhere:

A.8 Quark-gluon vertices

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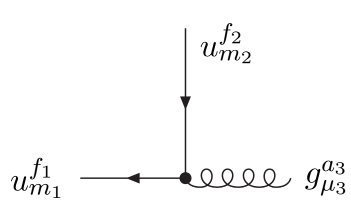
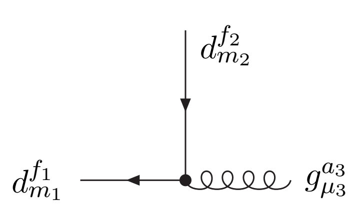
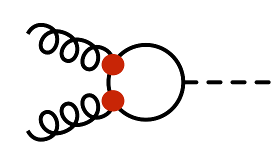


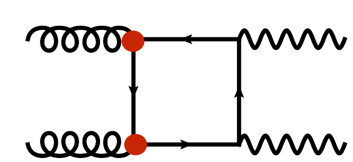
$$-i\bar g_s\delta_{f_1f_2}\mathcal{T}^{a_3}_{m_1m_2}\gamma^{\mu_3}-\sqrt{2}vp_3^\nu\mathcal{T}^{a_3}_{m_1m_2}\left(C^{uG*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{uG}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$



$$-i\bar g_s\delta_{f_1f_2}\mathcal{T}^{a_3}_{m_1m_2}\gamma^{\mu_3}-\sqrt{2}vp_3^\nu\mathcal{T}^{a_3}_{m_1m_2}\left(C^{dG*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{dG}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$

generate:





Contact terms with gluons:

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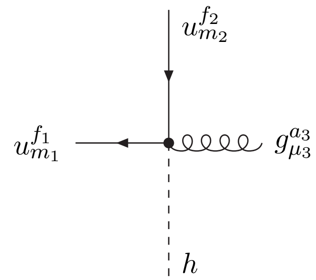
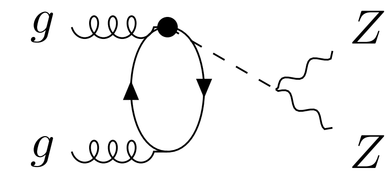


$$-\sqrt{2}p_3^{\nu}\mathcal{T}^{a_3}_{m_1m_2}\left(C^{uG*}_{f_2f_1}\sigma^{\mu_3\nu}P_L + C^{uG}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$

generate:



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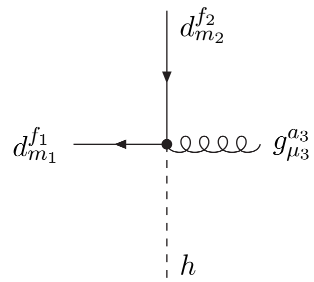

$$-\sqrt{2}p_3^{\nu}\mathcal{T}^{a_3}_{m_1m_2}\left(C^{dG*}_{f_2f_1}\sigma^{\mu_3\nu}P_L + C^{dG}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$

dipole operator

(also helicity structure and suppression may make linear terms vanish)

Constrained by:

(expecting these operators to be much better constrained in processes without Higgs)

A.8 Quark-gluon vertices

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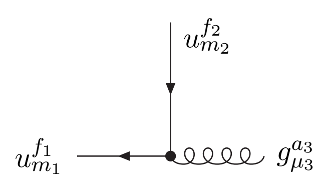
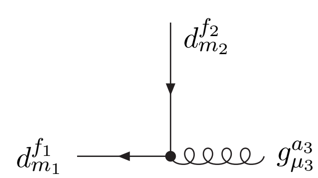


$$-i\bar{g}_s\delta_{f_1f_2}\mathcal{T}^{a_3}_{m_1m_2}\gamma^{\mu_3} - \sqrt{2}vp_3^{\nu}\mathcal{T}^{a_3}_{m_1m_2}\left(C^{uG*}_{f_2f_1}\sigma^{\mu_3\nu}P_L + C^{uG}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$



$$-i\bar{g}_s\delta_{f_1f_2}\mathcal{T}^{a_3}_{m_1m_2}\gamma^{\mu_3} - \sqrt{2}vp_3^{\nu}\mathcal{T}^{a_3}_{m_1m_2}\left(C^{dG*}_{f_2f_1}\sigma^{\mu_3\nu}P_L + C^{dG}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$

Contact terms with leptons:

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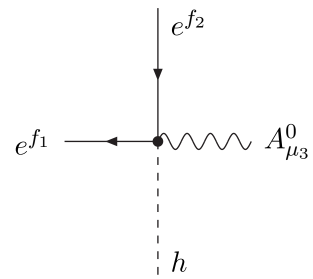
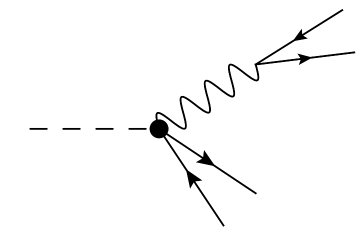


$$+\frac{\sqrt{2}\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{eW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{eW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$-\frac{\sqrt{2}\bar{g}}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{eB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{eB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$

generate $H(125)\to 4\ell$:



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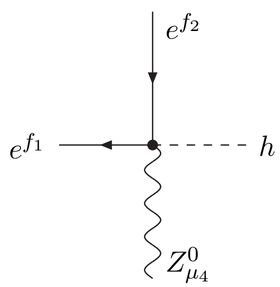

$$+\frac{\sqrt{2}\bar{g}}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_4^\nu\left(C^{eW*}_{f_2f_1}\sigma^{\mu_4\nu}P_L+C^{eW}_{f_1f_2}\sigma^{\mu_4\nu}P_R\right)$$
$$+\frac{\sqrt{2}\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_4^\nu\left(C^{eB*}_{f_2f_1}\sigma^{\mu_4\nu}P_L+C^{eB}_{f_1f_2}\sigma^{\mu_4\nu}P_R\right)$$
$$+iv\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi l1}_{f_1f_2}\gamma^{\mu_4}P_L+iv\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi l3}_{f_1f_2}\gamma^{\mu_4}P_L$$
$$+iv\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi e}_{f_1f_2}\gamma^{\mu_4}P_R$$

Constrained by:

(expecting these operators to be much better constrained in processes without Higgs outside of LHC)

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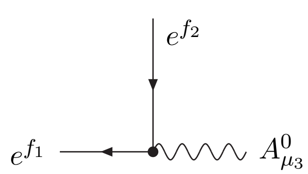
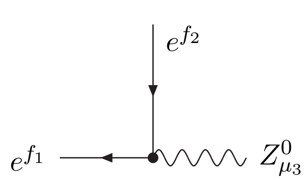


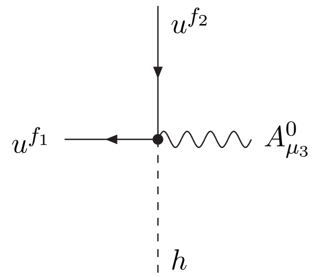
$$+\frac{i\bar{g}\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}\delta_{f_1f_2}\gamma^{\mu_3}-\frac{i\bar{g}^2\bar{g}'^2v^2}{\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}\delta_{f_1f_2}C^{\varphi WB}\gamma^{\mu_3}$$
$$+\frac{\sqrt{2}\bar{g}'v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{eW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{eW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$-\frac{\sqrt{2}\bar{g}v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{eB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{eB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$



$$-\frac{i}{2\sqrt{\bar{g}^2+\bar{g}'^2}}\delta_{f_1f_2}\left(\left(\bar{g}'^2-\bar{g}^2\right)\gamma^{\mu_3}P_L+2\bar{g}'^2\gamma^{\mu_3}P_R\right)$$
$$+\frac{i\bar{g}\bar{g}'v^2}{2\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}\delta_{f_1f_2}C^{\varphi WB}\left(\left(\bar{g}'^2-\bar{g}^2\right)\gamma^{\mu_3}P_L-2\bar{g}^2\gamma^{\mu_3}P_R\right)$$
$$+\frac{\sqrt{2}\bar{g}v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{eW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{eW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$+\frac{\sqrt{2}\bar{g}'v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{eB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{eB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi l1}_{f_1f_2}\gamma^{\mu_3}P_L+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi l3}_{f_1f_2}\gamma^{\mu_3}P_L$$
$$+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi e}_{f_1f_2}\gamma^{\mu_3}P_R$$

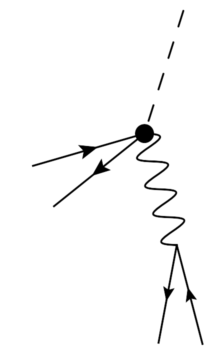
note 1/2…

Contact terms with up quarks:



$$-\frac{\sqrt{2}\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{uW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{uW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$-\frac{\sqrt{2}\bar{g}}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{uB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{uB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$

generate e.g. VH:



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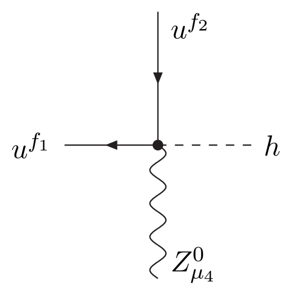
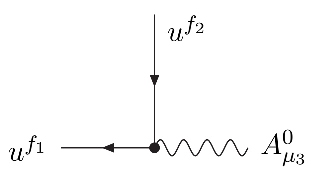


$$-\frac{\sqrt{2}\bar{g}}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_4^\nu\left(C^{uW*}_{f_2f_1}\sigma^{\mu_4\nu}P_L+C^{uW}_{f_1f_2}\sigma^{\mu_4\nu}P_R\right)$$
$$+\frac{\sqrt{2}\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_4^\nu\left(C^{uB*}_{f_2f_1}\sigma^{\mu_4\nu}P_L+C^{uB}_{f_1f_2}\sigma^{\mu_4\nu}P_R\right)$$
$$+iv\sqrt{\bar{g}^2+\bar{g}'^2}K_{f_1g_2}K^*_{f_2g_1}C^{\varphi q1}_{g_2g_1}\gamma^{\mu_4}P_L$$
$$-iv\sqrt{\bar{g}^2+\bar{g}'^2}K_{f_1g_2}K^*_{f_2g_1}C^{\varphi q3}_{g_2g_1}\gamma^{\mu_4}P_L+iv\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi u}_{f_1f_2}\gamma^{\mu_4}P_R$$

(also $q\bar{q}\to H\gamma$)

Constrained by:

(expecting these operators to be much better constrained in processes without Higgs outside of LHC)



$$-\frac{2i\bar{g}\bar{g}'}{3\sqrt{\bar{g}^2+\bar{g}'^2}}\delta_{f_1f_2}\gamma^{\mu_3}+\frac{2i\bar{g}^2\bar{g}'^2v^2}{3\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}\delta_{f_1f_2}C^{\varphi WB}\gamma^{\mu_3}$$
$$-\frac{\sqrt{2}\bar{g}'v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{uW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{uW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$-\frac{\sqrt{2}\bar{g}v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{uB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{uB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$

(see Ztt earlier)

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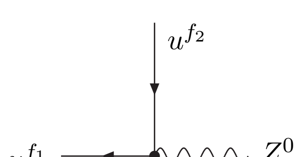
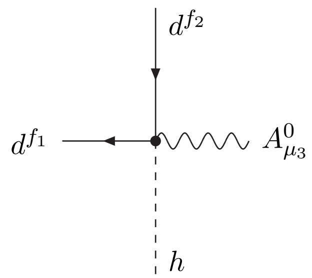


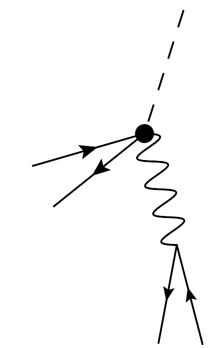
$$+\frac{i}{6\sqrt{\bar{g}^2+\bar{g}'^2}}\delta_{f_1f_2}\left(\left(\bar{g}'^2-3\bar{g}^2\right)\gamma^{\mu_3}P_L+4\bar{g}'^2\gamma^{\mu_3}P_R\right)$$
$$-\frac{i\bar{g}\bar{g}'v^2}{6\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}\delta_{f_1f_2}C^{\varphi WB}\left(\left(3\bar{g}'^2-\bar{g}^2\right)\gamma^{\mu_3}P_L-4\bar{g}^2\gamma^{\mu_3}P_R\right)$$
$$-\frac{\sqrt{2}\bar{g}v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{uW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{uW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$+\frac{\sqrt{2}\bar{g}'v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{uB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{uB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}K_{f_1g_2}K^*_{f_2g_1}C^{\varphi q1}_{g_2g_1}\gamma^{\mu_3}P_L$$
$$-\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}K_{f_1g_2}K^*_{f_2g_1}C^{\varphi q3}_{g_2g_1}\gamma^{\mu_3}P_L$$
$$+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi u}_{f_1f_2}\gamma^{\mu_3}P_R$$

Contact terms with down quarks:



$$+\frac{\sqrt{2}\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{dW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{dW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$-\frac{\sqrt{2}\bar{g}}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{dB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{dB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$

generate e.g. VH:



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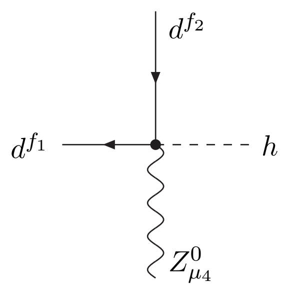

$$+\frac{\sqrt{2}\bar{g}}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_4^\nu\left(C^{dW*}_{f_2f_1}\sigma^{\mu_4\nu}P_L+C^{dW}_{f_1f_2}\sigma^{\mu_4\nu}P_R\right)$$
$$+\frac{\sqrt{2}\bar{g}'}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_4^\nu\left(C^{dB*}_{f_2f_1}\sigma^{\mu_4\nu}P_L+C^{dB}_{f_1f_2}\sigma^{\mu_4\nu}P_R\right)$$
$$+iv\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi q1}_{f_1f_2}\gamma^{\mu_4}P_L+iv\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi q3}_{f_1f_2}\gamma^{\mu_4}P_L$$
$$+iv\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi d}_{f_1f_2}\gamma^{\mu_4}P_R$$

Constrained by:

(expecting these operators to be much better constrained in processes without Higgs outside of LHC)

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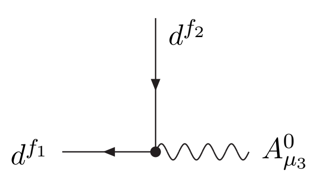

$$+\frac{i\bar{g}\bar{g}'}{3\sqrt{\bar{g}^2+\bar{g}'^2}}\delta_{f_1f_2}\gamma^{\mu_3}-\frac{i\bar{g}^2\bar{g}'^2v^2}{3\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}\delta_{f_1f_2}C^{\varphi WB}\gamma^{\mu_3}$$
$$+\frac{\sqrt{2}\bar{g}'v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{dW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{dW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$-\frac{\sqrt{2}\bar{g}v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{dB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{dB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$

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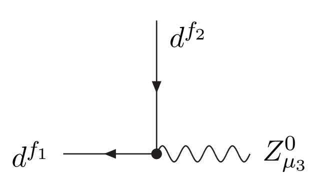

$$+\frac{i}{6\sqrt{\bar{g}^2+\bar{g}'^2}}\delta_{f_1f_2}\left(\left(3\bar{g}^2+\bar{g}'^2\right)\gamma^{\mu_3}P_L-2\bar{g}'^2\gamma^{\mu_3}P_R\right)$$
$$+\frac{i\bar{g}\bar{g}'v^2}{6\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}\delta_{f_1f_2}C^{\varphi WB}\left(\left(\bar{g}^2+3\bar{g}'^2\right)\gamma^{\mu_3}P_L-2\bar{g}^2\gamma^{\mu_3}P_R\right)$$
$$+\frac{\sqrt{2}\bar{g}v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{dW*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{dW}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$+\frac{\sqrt{2}\bar{g}'v}{\sqrt{\bar{g}^2+\bar{g}'^2}}p_3^\nu\left(C^{dB*}_{f_2f_1}\sigma^{\mu_3\nu}P_L+C^{dB}_{f_1f_2}\sigma^{\mu_3\nu}P_R\right)$$
$$+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi q1}_{f_1f_2}\gamma^{\mu_3}P_L+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi q3}_{f_1f_2}\gamma^{\mu_3}P_L$$
$$+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi d}_{f_1f_2}\gamma^{\mu_3}P_R$$

Gluon fusion with loop ○ and point-like ● interactions:

generate:

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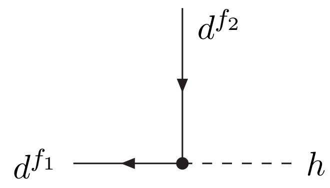
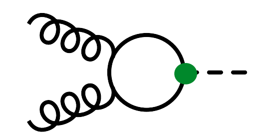


$$-\frac{i}{v}\delta_{f_1f_2}m_{d_{f_1}} - iv\delta_{f_1f_2}C^{\varphi\Box}m_{d_{f_1}} + \frac{iv}{4}\delta_{f_1f_2}C^{\varphi D}m_{d_{f_1}} + \frac{iv^2}{\sqrt{2}}\left(P_L C^{d\varphi *}_{f_2f_1} + P_R C^{d\varphi}_{f_1f_2}\right)$$



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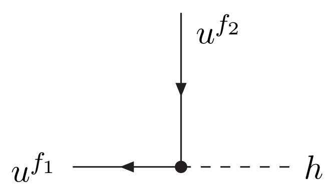

$$-\frac{i}{v}\delta_{f_1f_2}m_{u_{f_1}} - iv\delta_{f_1f_2}C^{\varphi\Box}m_{u_{f_1}} + \frac{iv}{4}\delta_{f_1f_2}C^{\varphi D}m_{u_{f_1}} + \frac{iv^2}{\sqrt{2}}\left(P_L C^{u\varphi *}_{f_2f_1} + P_R C^{u\varphi}_{f_1f_2}\right)$$

consider $(\kappa_t, \tilde{\kappa}_t)$, $(\kappa_b, \tilde{\kappa}_b)$

"operator rotation"
to remove blind directions
(or "eigenvectors")

use common NNNLO K factor?
(including off-shell H*+box)

A.11 Higgs-gluon vertices

generate:

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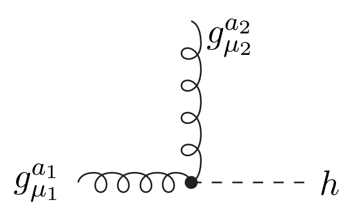
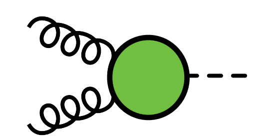


$$+4iv\delta_{a_1a_2}C^{\varphi G}\left(p_1^{\mu_2}p_2^{\mu_1} - p_1\cdot p_2\,\eta_{\mu_1\mu_2}\right) + 4iv\delta_{a_1a_2}C^{\varphi\widetilde{G}}p_1^{\alpha_1}p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}$$



no CP-odd contribution, further suppressed by α_s^2

generate:

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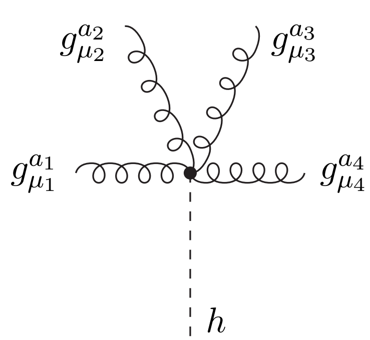
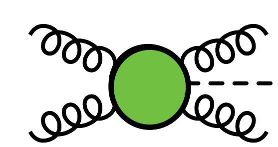
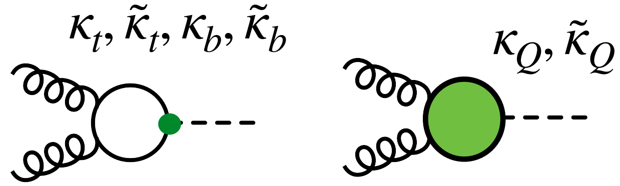
(like NNLO in QCD for the t loop)



$$-4iv\bar{g}_s^2C^{\varphi G}\left(\left(\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3} - \eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4}\right)f_{a_1a_2b_1}f_{a_3a_4b_1} + \left(\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3} - \eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}\right)f_{a_1a_3b_1}f_{a_2a_4b_1} + \left(\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4} - \eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}\right)f_{a_1a_4b_1}f_{a_2a_3b_1}\right)$$



More on the loops



$\Leftrightarrow \quad c^{\varphi G}, c^{\varphi \tilde G}$

at 125 GeV, and when kinematic distributions not tested (e.g. no 2 jets):

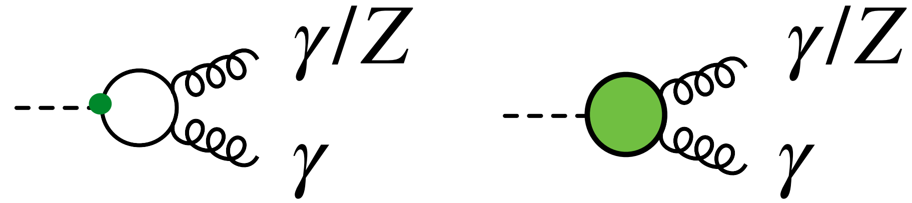
arXiv:2109.13363

$$\begin{aligned} R_{gg} = \; & 1.1068\,\kappa_t^2 + 0.0082\,\kappa_b^2 - 0.1150\,\kappa_t\kappa_b + 2.5717\,\tilde\kappa_t^2 + 0.0091\,\tilde\kappa_b^2 - 0.1982\,\tilde\kappa_t\tilde\kappa_b \\ & + 1.0298\,(N_c/3)^2\kappa_Q^2 + 2.1357\,(N_c/3)\kappa_Q\kappa_t - 0.1109\,(N_c/3)\kappa_Q\kappa_b \\ & + 2.3170\,(N_c/3)^2\tilde\kappa_Q^2 + 4.8821\,(N_c/3)\tilde\kappa_Q\tilde\kappa_t - 0.1880\,(N_c/3)\tilde\kappa_Q\tilde\kappa_b\,. \end{aligned} \qquad (13)$$

where $\kappa_Q, \tilde\kappa_Q$ from heavy particle in the loop, equivalent to $c^{\varphi G}, c^{\varphi \tilde G}$ (relationship in arXiv)

Both CP-odd and CP-even

Similarly:



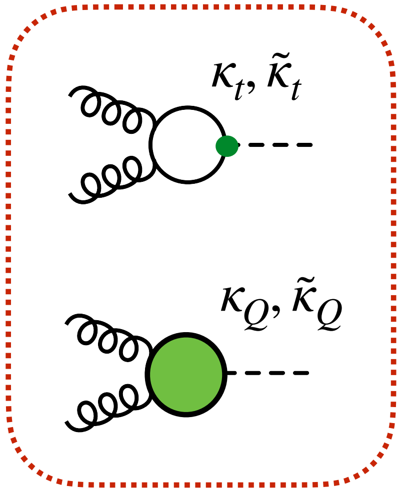
$\kappa_Q, \tilde\kappa_Q \quad \Leftrightarrow \quad c_{v\gamma}, \tilde c_{v\gamma}$

$$\begin{aligned} R_{\gamma\gamma} = \; & 1.60932\left(\frac{g_1^{WW}}{2}\right)^2 - 0.69064\left(\frac{g_1^{WW}}{2}\right)\kappa_t + 0.00912\left(\frac{g_1^{WW}}{2}\right)\kappa_b - 0.49725\left(\frac{g_1^{WW}}{2}\right)(N_c\,Q^2\,\kappa_Q) \\ & + 0.07404\,\kappa_t^2 + 0.00002\,\kappa_b^2 - 0.00186\,\kappa_t\kappa_b \\ & + 0.03841\,\left(N_c\,Q^2\,\kappa_Q\right)^2 + 0.10666\,\kappa_t\left(N_c\,Q^2\,\kappa_Q\right) - 0.00136\,\kappa_b\left(N_c\,Q^2\,\kappa_Q\right) \\ & + 0.20533\,\tilde\kappa_t^2 + 0.00006\,\tilde\kappa_b^2 - 0.00300\,\tilde\kappa_t\tilde\kappa_b \\ & + 0.10252\,\left(N_c\,Q^2\,\tilde\kappa_Q\right)^2 + 0.29018\,\tilde\kappa_t\left(N_c\,Q^2\,\tilde\kappa_Q\right) - 0.00202\,\tilde\kappa_b\left(N_c\,Q^2\,\tilde\kappa_Q\right)\,. \end{aligned}$$

$$\begin{aligned} R_{Z\gamma} = \; & 1.11965\left(\frac{g_1^{WW}}{2}\right)^2 - 0.12652\left(\frac{g_1^{WW}}{2}\right)\kappa_t + 0.00348\left(\frac{g_1^{WW}}{2}\right)\kappa_b - 0.13021\left(\frac{g_1^{WW}}{2}\right)(N_c\,\mathcal{R}_Q\kappa_Q) \\ & + 0.00357\,\kappa_t^2 + 0.000003\,\kappa_b^2 - 0.00018\,\kappa_t\kappa_b \\ & + 0.00377\,(N_c\,\mathcal{R}_Q\kappa_Q)^2 + 0.00734\,\kappa_t\,(N_c\,\mathcal{R}_Q\kappa_Q) - 0.00019\,\kappa_b\,(N_c\,\mathcal{R}_Q\kappa_Q) \\ & + 0.00849\,\tilde\kappa_t^2 + 0.000004\,\tilde\kappa_b^2 - 0.00025\,\tilde\kappa_t\tilde\kappa_b \\ & + 0.00883\,(N_c\,\mathcal{R}_Q\tilde\kappa_Q)^2 + 0.01723\,\tilde\kappa_t\,(N_c\,\mathcal{R}_Q\tilde\kappa_Q) - 0.00024\,\tilde\kappa_b\,(N_c\,\mathcal{R}_Q\tilde\kappa_Q)\,. \end{aligned}$$

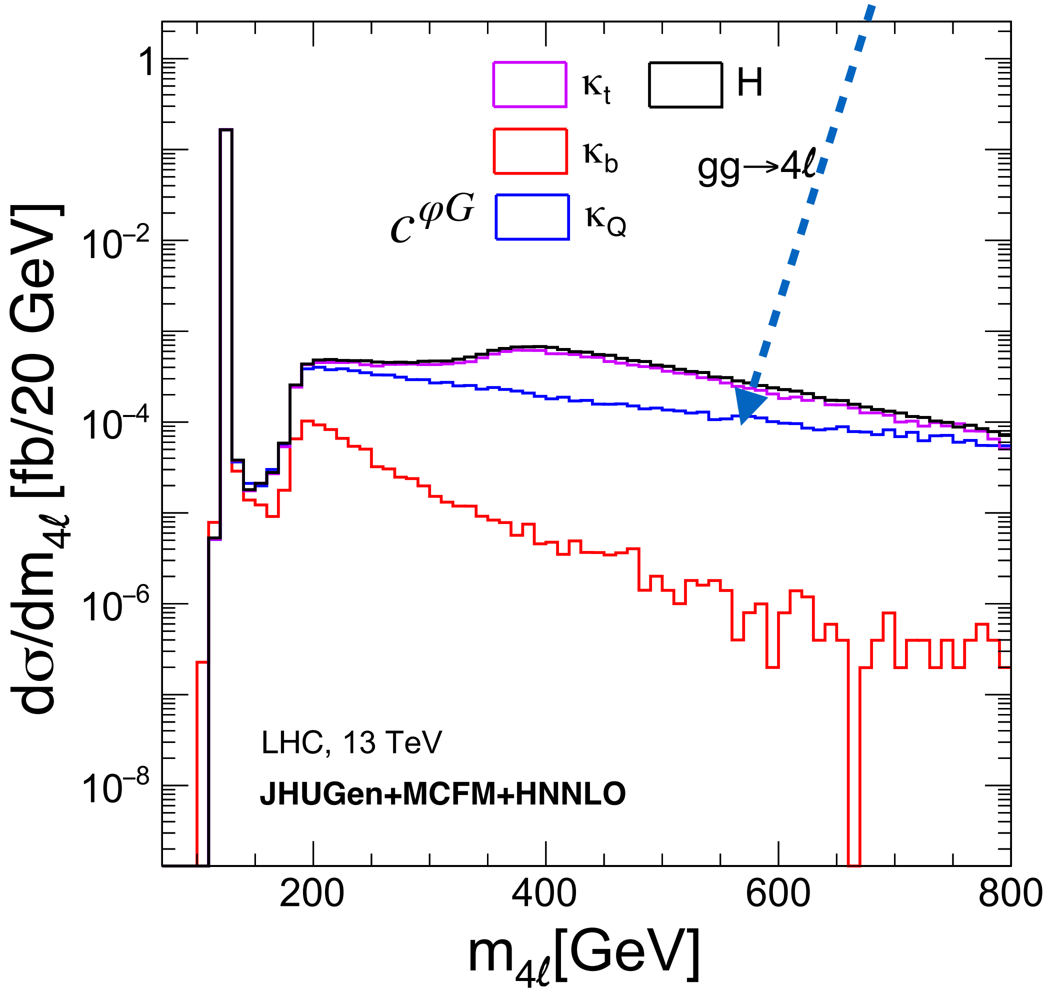
“VBS”: gluon fusion with off-shell H*

$\kappa_t, \tilde{\kappa}_t, c^{\varphi G}, c^{\varphi \tilde{G}}$



- off-shell H* is one possible place to disentangle
  - point-like interaction $\kappa_Q \sim c^{\varphi G}$
  - loop κ_t
  - neglect κ_b

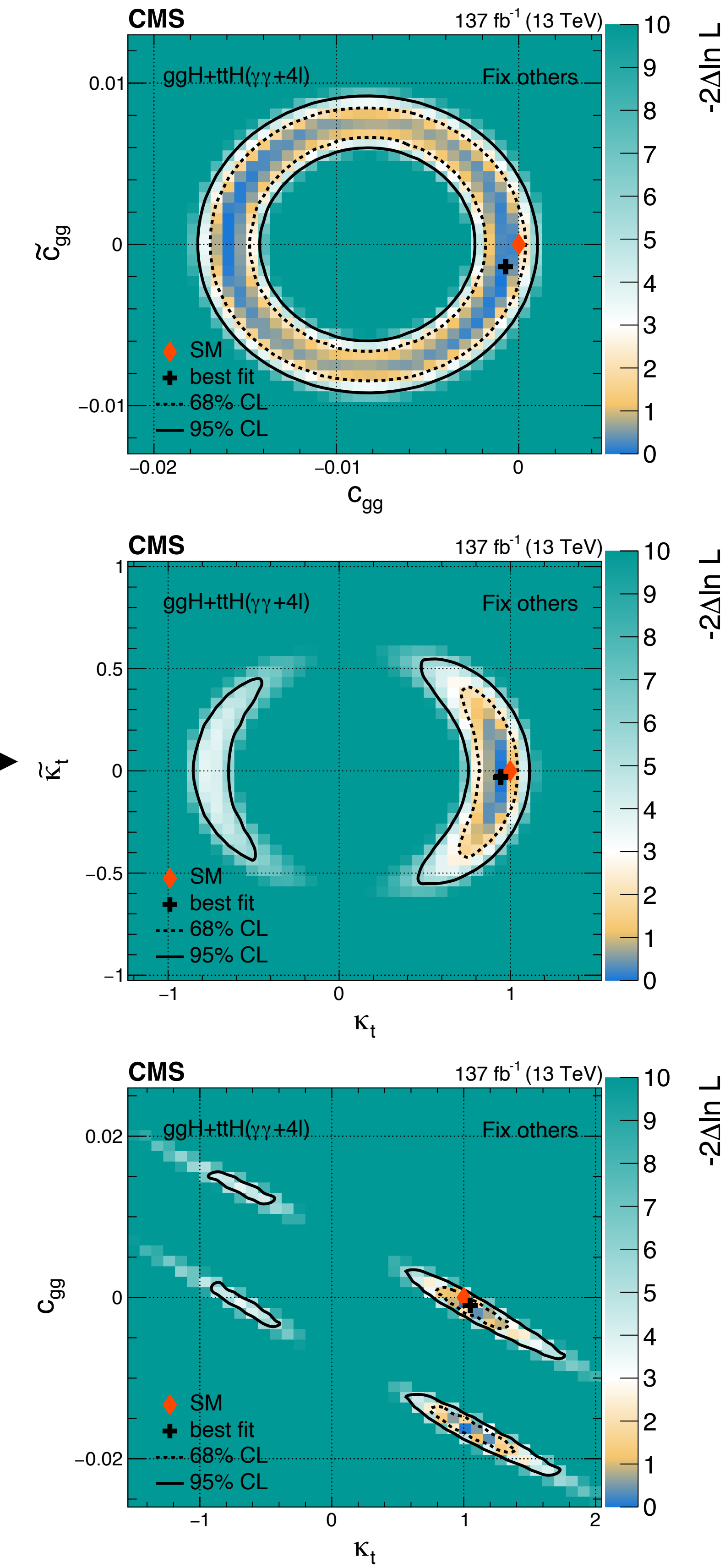
[arXiv:2002.09888](https://arxiv.org/abs/2002.09888)



- combination of $t\bar{t}H, tH, ggH$ at 125 GeV is the way to go

[arXiv:2104.12152](https://arxiv.org/abs/2104.12152)

- no CP structure in $H \to b\bar{b}$ but constrain $\kappa_b^2 + \tilde{\kappa}_b^2$



VBS: quartic gauge boson couplings

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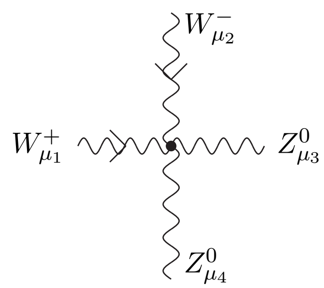
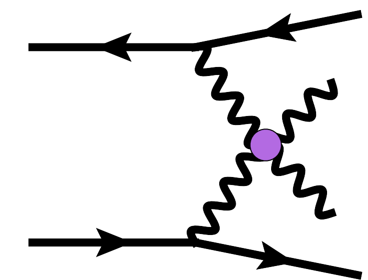


$$
\begin{aligned}
&+\frac{i\bar{g}^4}{\bar{g}^2+\bar{g}'^2}\left(\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3}+\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4}-2\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}\right)\\
&-\frac{6i\bar{g}^3}{\bar{g}^2+\bar{g}'^2}C^{W}\Big(\eta_{\mu_1\mu_3}\left(p_3^{\mu_2}p_1^{\mu_4}-p_1^{\mu_2}p_3^{\mu_4}-p_4^{\mu_2}p_1^{\mu_4}-p_3^{\mu_2}p_2^{\mu_4}\right)\\
&+\eta_{\mu_1\mu_4}\left(p_4^{\mu_2}p_1^{\mu_3}-p_1^{\mu_2}p_4^{\mu_3}-p_3^{\mu_2}p_1^{\mu_3}-p_4^{\mu_2}p_2^{\mu_3}\right)\\
&+\eta_{\mu_2\mu_3}\left(p_3^{\mu_1}p_2^{\mu_4}-p_2^{\mu_1}p_3^{\mu_4}-p_4^{\mu_1}p_2^{\mu_4}-p_3^{\mu_1}p_1^{\mu_4}\right)\\
&+\eta_{\mu_2\mu_4}\left(p_4^{\mu_1}p_2^{\mu_3}-p_2^{\mu_1}p_4^{\mu_3}-p_3^{\mu_1}p_2^{\mu_3}-p_4^{\mu_1}p_1^{\mu_3}\right)\\
&-\eta_{\mu_1\mu_2}\left(p_4^{\mu_3}(p_3+p_4)^{\mu_4}+(p_3+p_4)^{\mu_3}p_3^{\mu_4}\right)\\
&-\eta_{\mu_3\mu_4}\left(p_2^{\mu_1}(p_1+p_2)^{\mu_2}+(p_1+p_2)^{\mu_1}p_1^{\mu_2}\right)\\
&+\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4}\left(p_1\cdot p_4+p_2\cdot p_3\right)+\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3}\left(p_1\cdot p_3+p_2\cdot p_4\right)\\
&-\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}\left(p_1\cdot p_3+p_1\cdot p_4+p_2\cdot p_3+p_2\cdot p_4\right)\Big)\\
&+\frac{2i\bar{g}^3\bar{g}'^3v^2}{\left(\bar{g}^2+\bar{g}'^2\right)^2}C^{\varphi WB}\left(\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3}+\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4}-2\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}\right)\\
&-\frac{2i\bar{g}^3}{\bar{g}^2+\bar{g}'^2}C^{\widetilde{W}}\Big(\epsilon_{\mu_1\mu_3\mu_4\alpha_1}\left(p_1^{\mu_2}(p_3-p_4)^{\alpha_1}+(p_3-p_4)^{\mu_2}(p_1+p_2)^{\alpha_1}\right)\\
&+\epsilon_{\mu_2\mu_3\mu_4\alpha_1}\left(p_2^{\mu_1}(p_3-p_4)^{\alpha_1}+(p_3-p_4)^{\mu_1}(p_1+p_2)^{\alpha_1}\right)\\
&+\epsilon_{\mu_3\mu_1\mu_2\alpha_1}\left(p_3^{\mu_4}(p_1-p_2)^{\alpha_1}+(p_1-p_2)^{\mu_4}(p_3+p_4)^{\alpha_1}\right)\\
&+\epsilon_{\mu_4\mu_1\mu_2\alpha_1}\left(p_4^{\mu_3}(p_1-p_2)^{\alpha_1}+(p_1-p_2)^{\mu_3}(p_3+p_4)^{\alpha_1}\right)\\
&+\eta_{\mu_1\mu_3}\epsilon_{\mu_2\mu_4\alpha_1\beta_1}p_2^{\alpha_1}p_4^{\beta_1}+\eta_{\mu_1\mu_4}\epsilon_{\mu_2\mu_3\alpha_1\beta_1}p_2^{\alpha_1}p_3^{\beta_1}\\
&+\eta_{\mu_2\mu_3}\epsilon_{\mu_1\mu_4\alpha_1\beta_1}p_1^{\alpha_1}p_4^{\beta_1}+\eta_{\mu_2\mu_4}\epsilon_{\mu_1\mu_3\alpha_1\beta_1}p_1^{\alpha_1}p_3^{\beta_1}\\
&-2\eta_{\mu_1\mu_2}\epsilon_{\mu_3\mu_4\alpha_1\beta_1}p_3^{\alpha_1}p_4^{\beta_1}-2\eta_{\mu_3\mu_4}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}p_1^{\alpha_1}p_2^{\beta_1}\\
&+\epsilon_{\mu_1\mu_2\mu_3\mu_4}\left(p_1\cdot p_3+p_2\cdot p_4-p_1\cdot p_4-p_2\cdot p_3\right)\Big)
\end{aligned}
$$

generate:



VBS: triple gauge boson couplings

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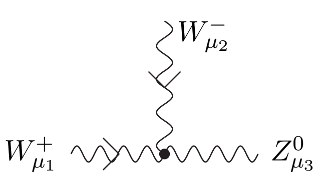
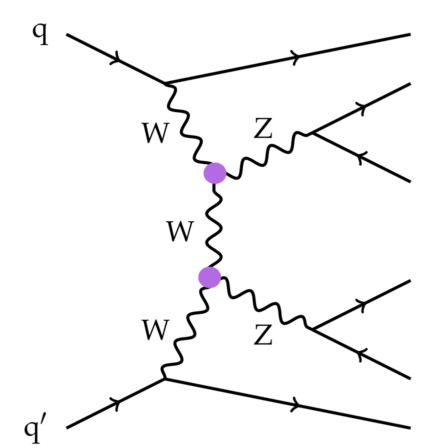


$$
\begin{aligned}
&+\frac{i\bar{g}^2}{\sqrt{\bar{g}^2+\bar{g}'^2}}\left(\eta_{\mu_1\mu_2}(p_1-p_2)^{\mu_3}+\eta_{\mu_2\mu_3}(p_2-p_3)^{\mu_1}+\eta_{\mu_3\mu_1}(p_3-p_1)^{\mu_2}\right)\\
&-\frac{6i\bar{g}}{\sqrt{\bar{g}^2+\bar{g}'^2}}C^{W}\Big(p_3^{\mu_1}p_1^{\mu_2}p_2^{\mu_3}-p_2^{\mu_1}p_3^{\mu_2}p_1^{\mu_3}+\eta_{\mu_1\mu_2}\left(p_1^{\mu_3}p_2\cdot p_3-p_2^{\mu_3}p_1\cdot p_3\right)\\
&+\eta_{\mu_2\mu_3}\left(p_2^{\mu_1}p_1\cdot p_3-p_3^{\mu_1}p_1\cdot p_2\right)+\eta_{\mu_3\mu_1}\left(p_3^{\mu_2}p_1\cdot p_2-p_1^{\mu_2}p_2\cdot p_3\right)\Big)\\
&+\frac{i\bar{g}\bar{g}'v^2}{\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}C^{\varphi WB}\Big(\eta_{\mu_1\mu_2}(\bar{g}'^2p_1^{\mu_3}-\bar{g}'^2p_2^{\mu_3})+\eta_{\mu_2\mu_3}(\bar{g}'^2p_2^{\mu_1}+\bar{g}^2p_3^{\mu_1})\\
&+\eta_{\mu_3\mu_1}(-\bar{g}^2p_3^{\mu_2}-\bar{g}'^2p_1^{\mu_2})\Big)\\
&-\frac{2i\bar{g}}{\sqrt{\bar{g}^2+\bar{g}'^2}}C^{\widetilde{W}}\Big(\epsilon_{\mu_1\mu_2\mu_3\alpha_1}\left(p_1^{\alpha_1}p_2\cdot p_3+p_2^{\alpha_1}p_1\cdot p_3+p_3^{\alpha_1}p_1\cdot p_2\right)\\
&+\epsilon_{\mu_1\mu_2\alpha_1\beta_1}(p_1-p_2)^{\mu_3}p_1^{\alpha_1}p_2^{\beta_1}+\epsilon_{\mu_2\mu_3\alpha_1\beta_1}(p_2-p_3)^{\mu_1}p_2^{\alpha_1}p_3^{\beta_1}\\
&+\epsilon_{\mu_3\mu_1\alpha_1\beta_1}(p_3-p_1)^{\mu_2}p_3^{\alpha_1}p_1^{\beta_1}\Big)\\
&-\frac{i\bar{g}\bar{g}'v^2}{\sqrt{\bar{g}^2+\bar{g}'^2}}C^{\varphi\widetilde{W}B}\epsilon_{\mu_1\mu_2\mu_3\alpha_1}p_3^{\alpha_1}
\end{aligned}
$$

generate:



$C^W, C^{\tilde{W}}$ ⟵ in VBS, but expect much better constraints in WW, WZ, or single-V production…
(without Higgs)

Four-fermion operators?

just one of several examples:

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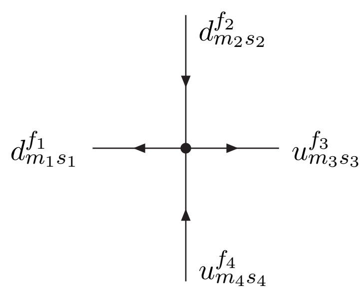
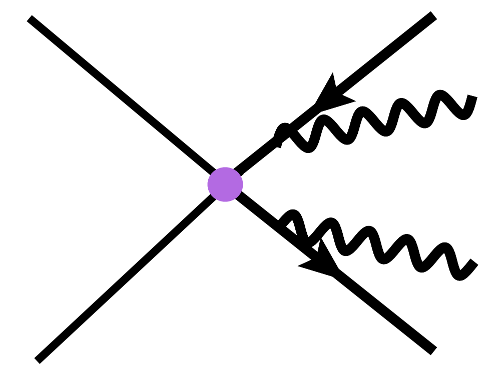


$$
\begin{aligned}
&+2i\delta_{m_1m_2}\delta_{m_3m_4}K_{f_3g_2}K^*_{f_4g_1}(\gamma^\mu P_L)_{s_1s_2}(\gamma^\mu P_L)_{s_3s_4}C^{qq1}_{f_1f_2g_2g_1}\\
&-2iK_{f_3g_2}K^*_{f_4g_1}\Big(\delta_{m_1m_2}\delta_{m_3m_4}(\gamma^\mu P_L)_{s_1s_2}(\gamma^\mu P_L)_{s_3s_4}C^{qq3}_{f_1f_2g_2g_1}\\
&+2\delta_{m_1m_4}\delta_{m_2m_3}(\gamma^\mu P_L)_{s_1s_4}(\gamma^\mu P_L)_{s_3s_2}C^{qq3}_{f_1g_1g_2f_2}\Big)\\
&+i\delta_{m_1m_2}\delta_{m_3m_4}C^{ud1}_{f_3f_4f_1f_2}(\gamma^\mu P_R)_{s_1s_2}(\gamma^\mu P_R)_{s_3s_4}\\
&+\frac{i}{6}\left(3\delta_{m_1m_4}\delta_{m_2m_3}-\delta_{m_1m_2}\delta_{m_3m_4}\right)C^{ud8}_{f_3f_4f_1f_2}(\gamma^\mu P_R)_{s_1s_2}(\gamma^\mu P_R)_{s_3s_4}\\
&+i\delta_{m_1m_2}\delta_{m_3m_4}C^{qu1}_{f_1f_2f_3f_4}(\gamma^\mu P_L)_{s_1s_2}(\gamma^\mu P_R)_{s_3s_4}\\
&+\frac{i}{6}\left(3\delta_{m_1m_4}\delta_{m_2m_3}-\delta_{m_1m_2}\delta_{m_3m_4}\right)C^{qu8}_{f_1f_2f_3f_4}(\gamma^\mu P_L)_{s_1s_2}(\gamma^\mu P_R)_{s_3s_4}\\
&+i\delta_{m_1m_2}\delta_{m_3m_4}K_{f_3g_2}K^*_{f_4g_1}(\gamma^\mu P_L)_{s_3s_4}(\gamma^\mu P_R)_{s_1s_2}C^{qd1}_{g_2g_1f_1f_2}\\
&+\frac{i}{6}\left(3\delta_{m_1m_4}\delta_{m_2m_3}-\delta_{m_1m_2}\delta_{m_3m_4}\right)K_{f_3g_2}K^*_{f_4g_1}(\gamma^\mu P_L)_{s_3s_4}(\gamma^\mu P_R)_{s_1s_2}C^{qd8}_{g_2g_1f_1f_2}\\
&+iK^*_{f_4g_1}\Big(\delta_{m_1m_2}\delta_{m_3m_4}(P_L)_{s_1s_2}(P_L)_{s_3s_4}C^{quqd1*}_{g_1f_3f_2f_1}\\
&+\delta_{m_1m_4}\delta_{m_2m_3}(P_L)_{s_1s_4}(P_L)_{s_3s_2}C^{quqd1*}_{f_2f_3g_1f_1}\Big)\\
&+iK_{f_3g_1}\Big(\delta_{m_1m_2}\delta_{m_3m_4}(P_R)_{s_1s_2}(P_R)_{s_3s_4}C^{quqd1}_{g_1f_4f_1f_2}\\
&+\delta_{m_1m_4}\delta_{m_2m_3}(P_R)_{s_1s_4}(P_R)_{s_3s_2}C^{quqd1}_{f_1f_4g_1f_2}\Big)\\
&+\frac{i}{6}K^*_{f_4g_1}\Big(\left(3\delta_{m_1m_4}\delta_{m_2m_3}-\delta_{m_1m_2}\delta_{m_3m_4}\right)(P_L)_{s_1s_2}(P_L)_{s_3s_4}C^{quqd8*}_{g_1f_3f_2f_1}\\
&+\left(3\delta_{m_1m_2}\delta_{m_3m_4}-\delta_{m_1m_4}\delta_{m_2m_3}\right)(P_L)_{s_1s_4}(P_L)_{s_3s_2}C^{quqd8*}_{f_2f_3g_1f_1}\Big)\\
&+\frac{i}{6}K_{f_3g_1}\Big((3\delta_{m_1m_4}\delta_{m_2m_3}-\delta_{m_1m_2}\delta_{m_3m_4})(P_R)_{s_1s_2}(P_R)_{s_3s_4}C^{quqd8}_{g_1f_4f_1f_2}\\
&+(3\delta_{m_1m_2}\delta_{m_3m_4}-\delta_{m_1m_4}\delta_{m_3m_2})(P_R)_{s_1s_4}(P_R)_{s_3s_2}C^{quqd8}_{f_1f_4g_1f_2}\Big)
\end{aligned}
$$

generate:



leave it to be constrained elsewhere?

List of operators of interest in Higgs processes with VBF, VH, ggH topology, including VBS:

$$C^{\varphi D}, C^{\varphi\Box}, C^{\varphi W}, C^{\varphi B}, C^{\varphi WB}, C^{\varphi\tilde{W}}, C^{\varphi\tilde{B}}, C^{\varphi\tilde{W}B}$$

$$C^{\varphi G}, C^{\varphi\tilde{G}}$$

$$\kappa_t, \tilde{\kappa}_t, \kappa_b, \tilde{\kappa}_b$$

← hard to separate without $t\bar{t}H, tH$, but “easy” with those

also unique in off-shell H

C_L^{Ztt}, C_R^{Ztt} ? ← may be important in the Higgs fits…

$C^W, C^{\tilde{W}}$? ← may be important in the Higgs fits…

Rotation of HVV basis, experimentally measurable "eigenvectors" a priori:

$C^{\varphi\tilde{W}}, C^{\varphi\tilde{B}}, C^{\varphi\tilde{W}B} \leftrightarrow \tilde{c}_{zz}, \tilde{c}_{z\gamma}, \tilde{c}_{\gamma\gamma}$

$C^{\varphi W}, C^{\varphi B}, C^{\varphi WB} \leftrightarrow c_{zz}, c_{z\gamma}, c_{\gamma\gamma}$

$C^{\varphi G}, C^{\varphi\tilde{G}}$

$C^{\varphi D}, C^{\varphi\Box}$

$\updownarrow$

$$c_H = -C^{\varphi\Box} + \frac{C^{\varphi D}}{4}$$

$$c_T = -\frac{C^{\varphi D}}{4}$$

$\updownarrow$

$\delta c_z, c_{z\Box}$

Constrained elsewhere

Rosetta arXiv:1508.05895

$$\begin{aligned}
\delta c_w &= -c_H - \frac{4g^2g'^2}{g^2-g'^2}c_{WB} + \frac{4g^2}{g^2-g'^2}c_T - \frac{3g^2+g'^2}{g^2-g'^2}\delta v\,,\\
\delta c_z &= -c_H - 3\delta v\,,\\
c_{gg} &= c_{GG}\,,\\
c_{ww} &= c_{WW}\,,\\
c_{zz} &= \frac{g^4c_{WW}+4g^2g'^2c_{WB}+g'^4c_{BB}}{(g^2+g'^2)^2}\,,\\
c_{z\gamma} &= \frac{g^2c_{WW}-2(g^2-g'^2)c_{WB}-g'^2c_{BB}}{g^2+g'^2}\,,\\
c_{\gamma\gamma} &= c_{WW}+c_{BB}-4c_{WB}\,,\\
c_{w\Box} &= \frac{2}{g^2-g'^2}\left[g'^2c_{WB}-c_T+\delta v\right],\\
c_{z\Box} &= -\frac{2}{g^2}\left[c_T-\delta v\right],\\
c_{\gamma\Box} &= \frac{2}{g^2-g'^2}\left[(g^2+g'^2)c_{WB}-2c_T+2\delta v\right].
\end{aligned} \tag{14}$$

Here, δv is defined by

$$\delta v = \frac{1}{2}\left[(c'_{H\ell})_{11}+(c'_{H\ell})_{22}\right] - \frac{1}{4}(c_{\ell\ell})_{1221} \tag{15}$$

Compare to:

arXiv:2108.03199

Thanks for discussion to
Ilaria B., Pietro G., Giacomo B., et al. !

also to Oscar Eboli!

A sensitivity study of VBS and diboson WW to dimension-6 EFT operators at the LHC

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$Q_{Hl}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_p)$	$Q_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}_p\sigma^i\gamma^\mu l_p)$
$Q_{Hq}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_p)$	$Q_{Hq}^{(3)} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_p\sigma^i\gamma^\mu q_p)$
$Q_{qq}^{(1)} = (\bar{q}_p\gamma_\mu q_p)(\bar{q}_r\gamma^\mu q_r)$	$Q_{qq}^{(1,1)} = (\bar{q}_p\gamma_\mu q_r)(\bar{q}_r\gamma^\mu q_p)$
$Q_{qq}^{(3)} = (\bar{q}_p\gamma_\mu\sigma^i q_p)(\bar{q}_r\gamma^\mu\sigma^i q_r)$	$Q_{qq}^{(3,1)} = (\bar{q}_p\gamma_\mu\sigma^i q_r)(\bar{q}_r\gamma^\mu\sigma^i q_p)$
$Q_{HD} = (H^\dagger D_\mu H)(H^\dagger D^\mu H)$	$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$
$Q_{HWB} = (H^\dagger\sigma^i H)W^i_{\mu\nu}B^{\mu\nu}$	$Q_{HW} = (H^\dagger H)W^i_{\mu\nu}W^{i\mu\nu}$
$Q_W = \varepsilon^{ijk}W^{i\nu}_\mu W^{j\rho}_\nu W^{k\mu}_\rho$	$Q_{ll}^{(1)} = (\bar{l}_p\gamma_\mu l_r)(\bar{l}_r\gamma^\mu l_p)$

Table 1. The subset of Warsaw basis operators considered in this work. Repeated indices are understood to be summed over. p, r are flavour indices, and a $U(3)^5$-invariant flavour structure is assumed.

Observations:

(1) $C^{\varphi B}$ and CP-odd operators can be added here

(2) $C^{\varphi\ell 1}, C^{\varphi\ell 3}, C^{\varphi q1}, C^{\varphi q3}$ suggested to constrain from Zff elsewhere

(3) four-fermion operator proliferation…

(4) QCD production cross-feed potentially to be added here (e.g. $C^{\varphi G}, C^{\varphi\tilde{G}}$)

Summary (EFT in dedicated Higgs fits)

- Optimizing the target set of EFT operators θ_i is important in advance:
  - — determine sensitive θ_i (optimal observables)
  - — rotate operators to remove flat directions

- Some work is needed to determine and/or agree on

  (1) main target operators ⇒ optimal / special observables

  (2) secondary operators ⇒ to be also considered in the fit

  (3) irrelevant operators ⇒ to be dropped (e.g. $Z \to \ell\ell$ well constrained)

- Rotation or removal of operators does not exclude later combination

$C^{\varphi D}, C^{\varphi\Box}$	$\leftrightarrow$	$\delta c_z, c_{z\Box}$	("a_1^{VV}")	$\kappa_t, \tilde{\kappa}_t, \kappa_b, \tilde{\kappa}_b$
$C^{\varphi W}, C^{\varphi B}, C^{\varphi WB}$	$\leftrightarrow$	$c_{zz}, c_{z\gamma}, c_{\gamma\gamma}$	("a_2^{VV}")	
$C^{\varphi\tilde{W}}, C^{\varphi\tilde{B}}, C^{\varphi\tilde{W}B}$	$\leftrightarrow$	$\tilde{c}_{zz}, \tilde{c}_{z\gamma}, \tilde{c}_{\gamma\gamma}$	("a_3^{VV}")	C_L^{Ztt}, C_R^{Ztt} ?
$C^{\varphi G}, C^{\varphi\tilde{G}}$	$=$	$c_{gg}, \tilde{c}_{gg}$	("$a_{2,3}^{\mathrm{gg}}$")	$C^W, C^{\tilde{W}}$?