Effective Field theory in the high luminosity/ energy era

Beyond the Dim-6 SMEFT

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PRECISION HIGGS PHYSICS

- Studying the properties of the Higgs and other electroweak states is an obvious goal for particle physicists today.
- Precision Higgs physics has matured into a sophisticated field in the last 11 years since Higgs discovery
- The theoretical framework that has become standard is the dimension 6 Standard Model Effective Theory (SMEFT)

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{59} \frac{c_i}{\Lambda^2} \mathcal{O}_i^6 + \cdots$$

model independent way to parametrise effect of heavy particles

OVERVIEW

- EFTs in the context of BSM studies have seen intense activity recently on both the theory and experimental side.

- Many new theoretical developments:

  1. HEFT vs SMEFT
  2. Dimension 8
  3. Amplitude approach
  4. Differential/multivariate signatures of EFT operators
  5. Positivity bounds
  6. Many technical breakthroughs in operator counting, matching, RG etc

- I will cover the first 4 topics

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HIGHER LUMINOSITIES/ENERGIES AT FUTURE COLLIDERS

- We are now entering the era of higher luminosities/energies with many proposed future colliders.
- These have the potential to achieve a new level of precision in Higgs physics

- Can we say anything qualitatively new with all this new data ?
- Or just improve our existing constraints on EFT couplings ?

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- Or just improve our existing constraints on EFT couplings ?

PRESENT STATUS → HIGHER LUMINOSITIES/ ENERGIES

Experimental observables used:

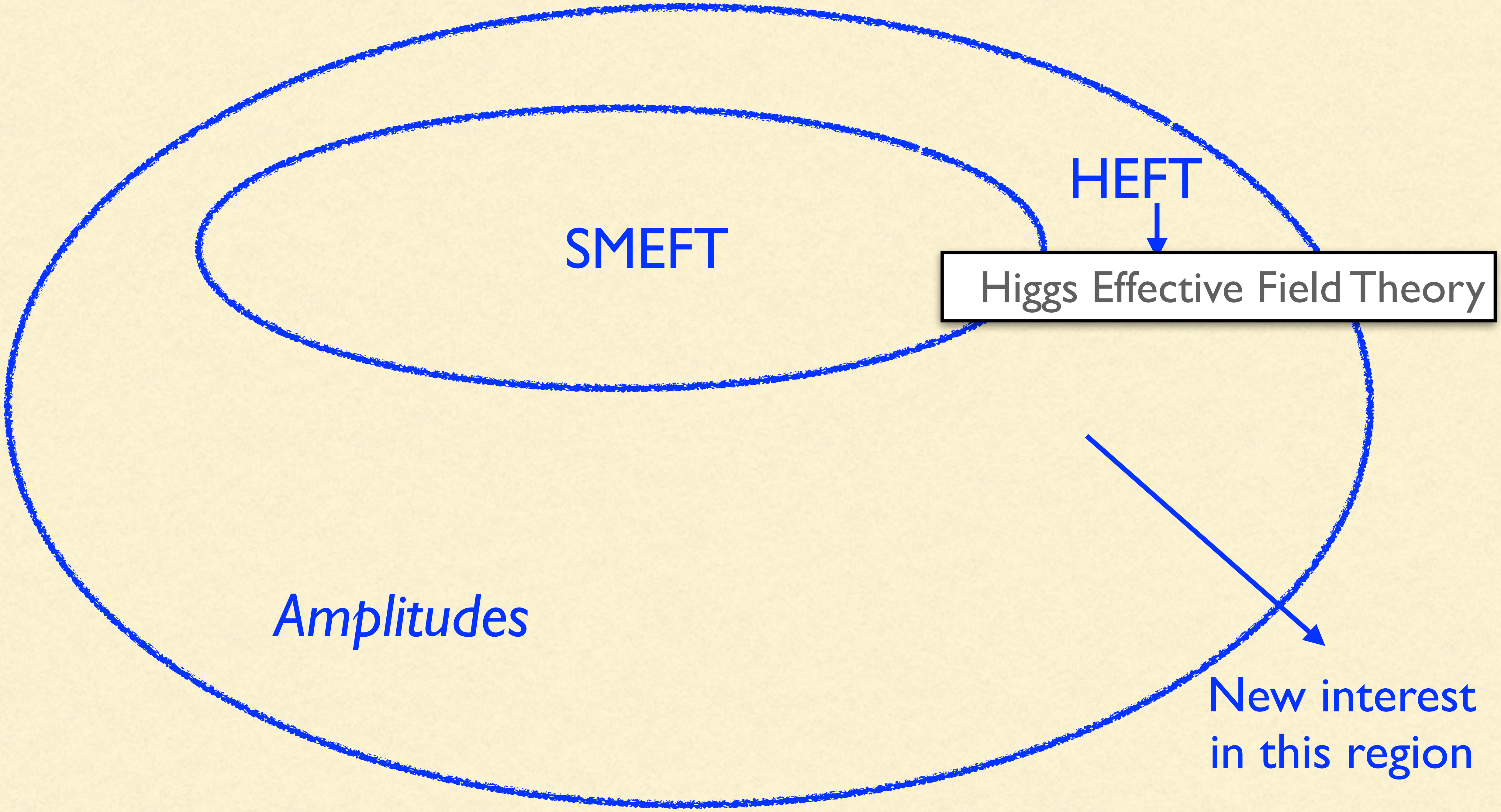
Mostly rates & some one dimensional distributions → Fully differentiable observables, Multivariate distributions, Machine learning

Theoretical framework used:

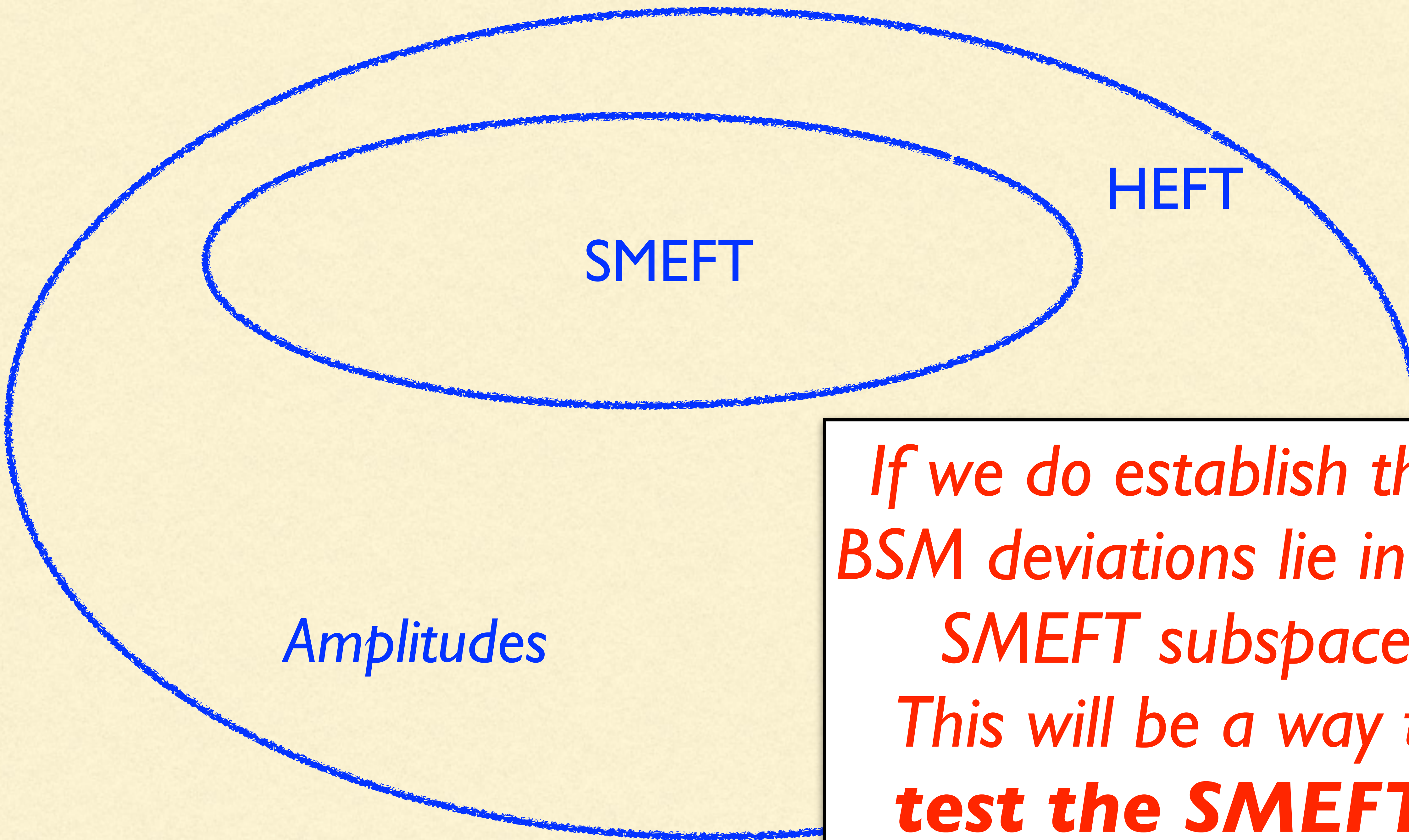
Dimension 6 SMEFT → Dimension 8 SMEFT, HEFT, Amplitudes

Go beyond SMEFT assumptions, test them !

BEYOND SMEFT



BEYOND SMEFT



If we do establish that BSM deviations lie in the SMEFT subspace

This will be a way to ***test the SMEFT!***

BEYOND SMEFT 1: HEFT

- SMEFT not always the right choice.

- SMEFT: Observed 125 GeV *h* and goldstones eaten by W,Z make a doublet.

$$\begin{pmatrix} G^{\pm} \\ iG_0 + v + h/\sqrt{2} \end{pmatrix}$$

Essence of Higgs mechanism!

- HEFT: More general, includes SMEFT as a special case. No connection assumed between *h* and goldstones/VEV.

$$\left(G^{\pm}, v + iG_0\right) + h$$

$$U = \exp(2iX_i\pi_i/v)$$

BEYOND SMEFT 1: HEFT

Lot of recent work:

1. Alonso, Jenkins & Manohar(2016)
2. Alonso, Jenkins & Manohar(2016)
3. Fallkowski & Rattazzi (2019)
4. Cohen, Craig, Lu & Sutherland (2020)
5. Banta, Cohen, Craig, Lu & Sutherland (2021)
6. Alonso & West (2021)
7. Alonso & West (2022)
8. Bertuzzo, Grojean & RSG (in prep)

HEFT BUT NOT SMEFT: UV SCENARIOS

- Recent work shows that UV theories that map to HEFT and not SMEFT are ubiquitous. Whenever we integrate out states that get a majority of their mass from electroweak VEV, theory maps to HEFT. Eg. 4th generation fermions, 2HDMS etc

- Such particles were dubbed 'Loryons' by Cohen et al.

- Parameter space for many such UV scenarios wide open.

Fallkowski & Rattazzi (2019),
Cohen, Craig, Lu & Sutherland (2020)

But what is the difference between these 2 expansions ?

How do we distinguish these 2 possibilities experimentally ?

Answer: The difference becomes clear at the level of anomalous couplings

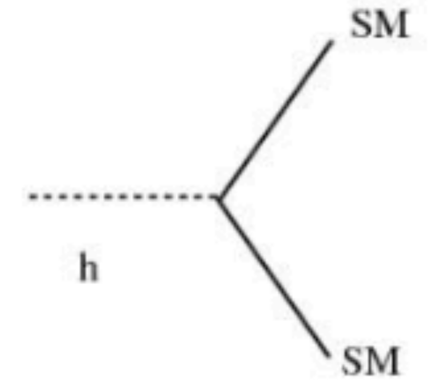
ANOMALOUS COUPLINGS

Anomalous couplings are QCD & EM invariant Lagrangian terms

(1) Higgs observables (20):

$$hW^{+}_{\mu\nu}\, W^{-\mu\nu}$$

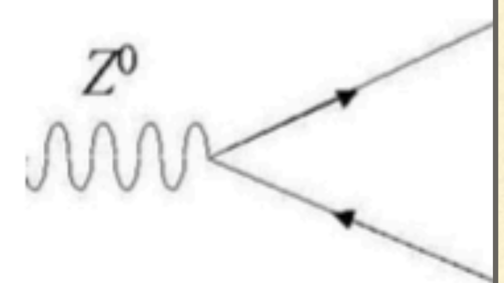
$$hZ_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}$$



(2) Electorweak precision observables (9):

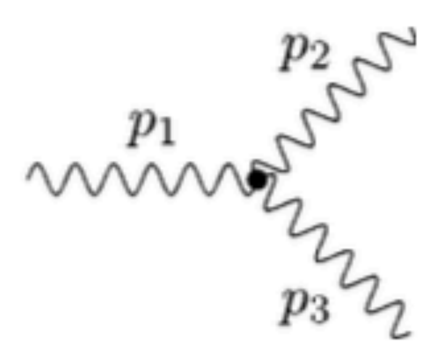
$$Z_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}$$

$$W^{+}_{\mu}\bar{\nu}_{L}\gamma^{\mu}e_{L}$$



(3) Triple and Quartic Gauge couplings (3+4):

$$g_1^Z c_{\theta_W} Z^{\mu}\left(W^{+\nu}\hat{W}^{-}_{\mu\nu} - W^{-\nu}\hat{W}^{+}_{\mu\nu}\right)$$
$$\kappa_\gamma s_{\theta_W}\hat{A}^{\mu\nu}W^{+}_{\mu}W^{-}_{\nu}$$
$$\lambda_\gamma s_{\theta_W}\hat{A}^{\mu\nu}\hat{W}^{-\rho}_{\mu}\hat{W}^{+}_{\rho\nu}$$



ANOMALOUS COUPLINGS: HEFT VS SMEFT

- In SMEFT some linear combination of anomalous couplings are suppressed by powers of wrt HEFT.

- Eg. : *Vll* couplings (*l* is a lepton)

$$SM + \delta g^Z_{e_L} Z_\mu \bar{e}_L \gamma^\mu e_L + \delta g^Z_{e_R} Z_\mu \bar{e}_R \gamma^\mu e_L + \delta g^Z_{\nu_L} Z_\mu \bar{\nu}_L \gamma^\mu \nu_L + \delta g^W_L (W^+_\mu \bar{\nu}_L \gamma^\mu e_L + h.c.)$$

4 anomalous couplings

- In HEFT all these arise independently at $\mathcal{O}(v^2/\Lambda^2)$

- In SMEFT 3 are $\mathcal{O}(v^2/\Lambda^2)$ and $\delta g^W_L = \dfrac{\cos\theta_W(\delta g^Z_{\nu_L} - \delta g^Z_{e_L})}{\sqrt{2}} = \mathcal{O}(v^4/\Lambda^4)$

CORRELATIONS BETWEEN W/Z COUPLING DEVIATIONS

- 4 anomalous couplings related to *Zff, Wff* deviations

$$SM + \delta g^Z_{e_L} Z_\mu \bar{e}_L \gamma^\mu e_L + \delta g^Z_{e_R} Z_\mu \bar{e}_R \gamma^\mu e_L + \delta g^Z_{\nu_L} Z_\mu \bar{\nu}_L \gamma^\mu \nu_L + \delta g^W_L (W^+_\mu \bar{\nu}_L \gamma^\mu e_L + h.c.)$$

- At D6 level only 3 operators break these D4 predictions at $\mathcal{O}(v^2/\Lambda^2)$

$$\mathcal{O}_{e_R} = iH^\dagger \overleftrightarrow{D} H \; \bar{e}_R \gamma^\mu e_R \qquad \mathcal{O}_{L1} = iH^\dagger \overleftrightarrow{D} H \; \bar{L} \gamma^\mu L \qquad \mathcal{O}_{L3} = iH^\dagger \sigma^a \overleftrightarrow{D} H \; \bar{L} \sigma^a \gamma^\mu L$$

- For leptons four anomalous couplings and only 3 operators so 1 prediction:

$$\delta g^W_L = \frac{\cos\theta_W (\delta g^Z_{\nu_L} - \delta g^Z_{e_L})}{\sqrt{2}} = 0$$

RSG, Pomarol & Riva (2014)

BREAKING OF D6 CORRELATION AT D8

- At D8 level another SU(2)x U(1) invariant operator breaks D6 prediction at $\mathcal{O}(v^4/\Lambda^4)$

$$\mathcal{O}_{L3'} = iH^\dagger \overleftrightarrow{D}_\mu H \; (H^\dagger \sigma^a H) \bar{L} \sigma^a \gamma^\mu L$$

- So of the 4 D4 predictions 3 are broken at $\mathcal{O}(v^2/\Lambda^2)$ and 1 at $\mathcal{O}(v^4/\Lambda^4)$

$$\delta g_L^W - \frac{\cos\theta_W (\delta g^Z_{\nu_L} - \delta g^Z_{e_L})}{\sqrt{2}} = \mathcal{O}(v^4/\Lambda^4)$$

- At D6 level there were 3 independent couplings, at D8 we unblock a further observable/ open a 4th BSM primary

Bertuzzo, Grojean & RSG (in prep)

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$$\mathcal{O}$$

D6 SMEFT Prediction: Once Z coupling deviations are measured, W coupling deviation completely fixed!

- So of the 4 D4 predi... at $\mathcal{O}(v^4/\Lambda^4)$

$$\delta g_L^W - \frac{\cos\theta_W(\delta g^Z_{\nu_L} - \delta g^Z_{e_L})}{\sqrt{2}} = \mathcal{O}(v^4/\Lambda^4)$$

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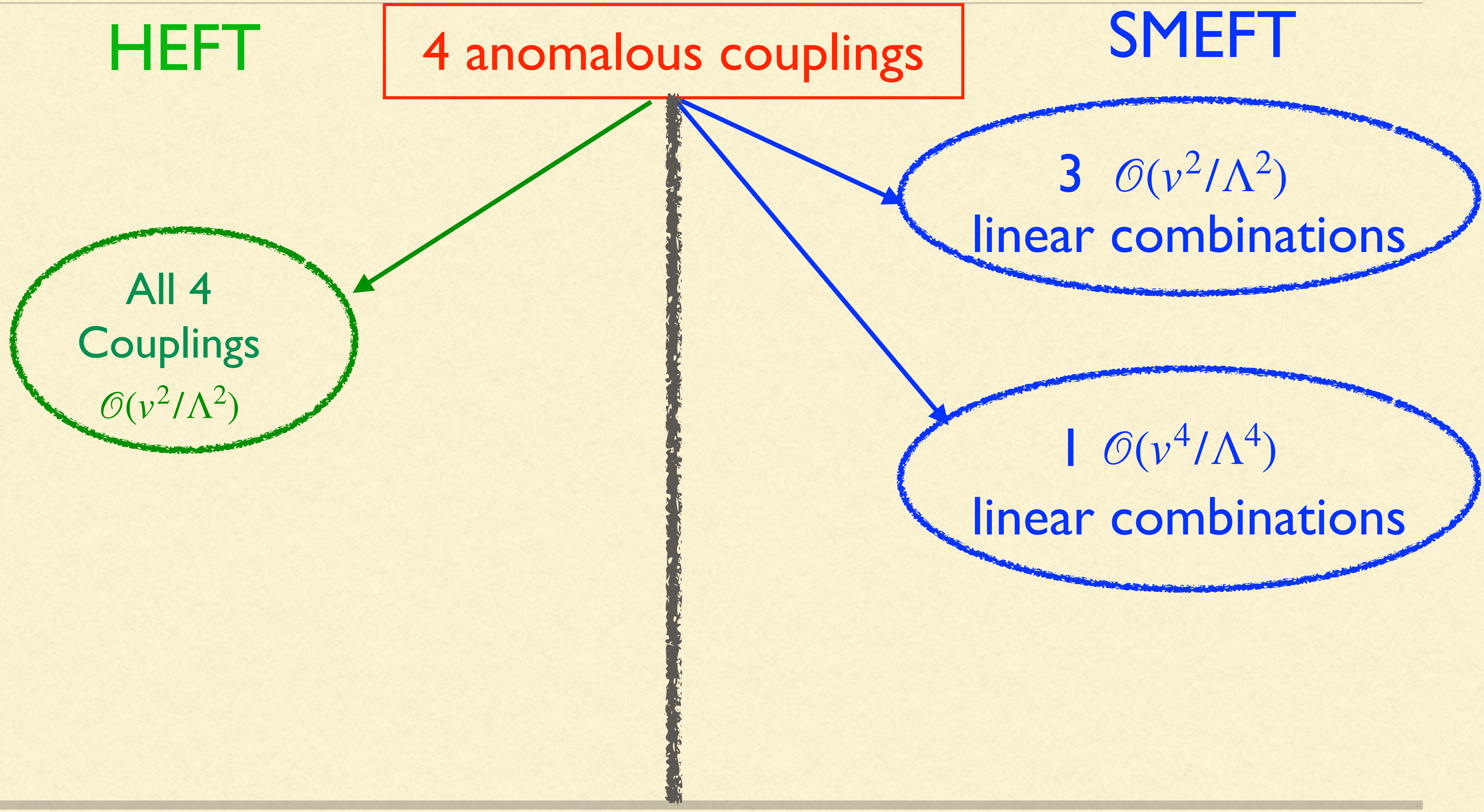
SMEFT VS HEFT



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CONSIDER ALL MAJOR HIGGS PROCESSES

We can extend this approach to all the anomalous couplings that contribute to these Higgs production/ decay processes

List of Processes
$gg \to h, hh, hhh$
$VV \to h, hh, hV$
$ff(ff') \to Zh(Wh)$
$h \to bb, cc, \tau\tau, \mu\mu$
$h \to \gamma\gamma, Z\gamma$
$h \to Wl\nu, Wjj, Zll, Zjj$

Bertuzzo, Grojean & RSG (in prep)

52 ANOMALOUS COUPLINGS

We find that these anomalous couplings that contribute to these processes*

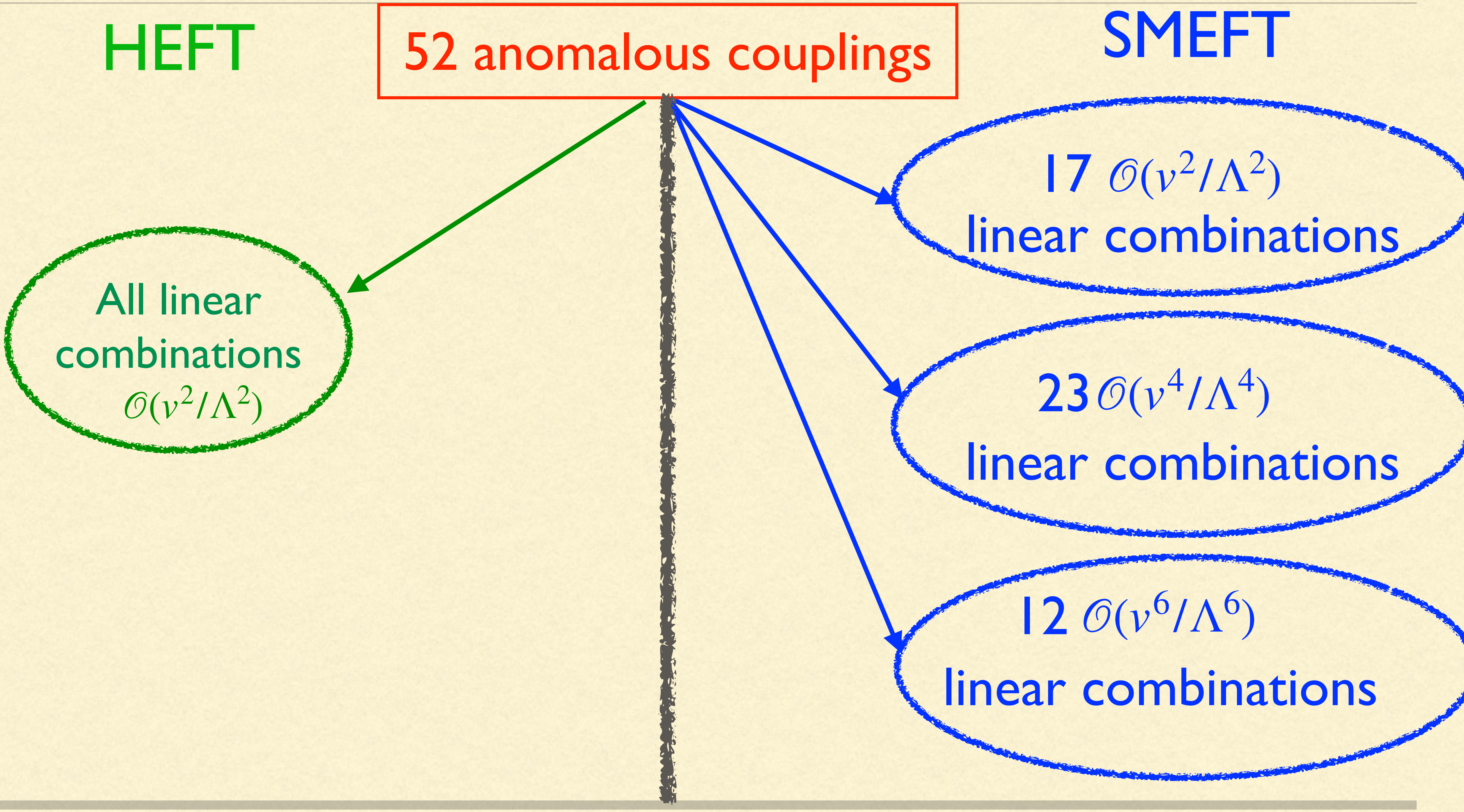
→

List of Anomalous Couplings
Vff couplings (9)
$\Delta\mathcal{L}_{Vff} = \sum_f \delta g_f^Z Z_\mu \bar{f}\gamma^\mu f_{L,R} + \delta g_{e\nu}^W (W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + h.c.) + \delta g_{ud}^W (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.$
Anomalous TGC (4)
$\Delta\mathcal{L}_{TGC} = \mathrm{i}gc_{\theta_W} \left[\delta g_1^Z Z_\mu (W_\nu^+ \mathcal{W}^{-\mu\nu} - W_\nu^- \mathcal{W}^{+\mu\nu}) + \delta\kappa^Z W_\mu^+ W_\nu^- Z^{\mu\nu}\right]$ $+\mathrm{ie}\ \delta\kappa^\gamma W_\mu^+ W_\nu^- A^{\mu\nu} + g_5 \epsilon^{\mu\nu\rho\sigma} W_\mu^+ \overleftrightarrow{D}_\rho W_\nu^- Z_\sigma$
Anomalous QGC (5)
$\Delta\mathcal{L}_{QGC} = g^2 c_{\theta_W}^2 \left[\delta g_{ZZ1}^Q Z^\mu Z^\nu W_\mu^- W_\nu^+ - \delta g_{ZZ2}^Q Z^\mu Z_\mu W^{-\nu} W_\nu^+\right] + \frac{g^2}{4c_{\theta_W}^4} h_{ZZ}^Q (Z^\mu Z_\mu)^2$ $+\frac{g^2}{2}\left[\delta g_{WW1}^Q W^{-\mu} W^{+\nu} W_\mu^- W_\nu^+ - \delta g_{WW2}^Q \left(W^{-\mu} W_\mu^+\right)^2\right]$
Single Higgs (19)
$\Delta\mathcal{L}_h = \delta g_{VV}^h\, h \left[W^{+\,\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + \delta g_{ff}^h\ (h \bar{f}_L f_R + h.c.) + \delta g_{ZZ}^h\, h \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2}$ $\sum_f g_{Zff}^h \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g_{WQ}^h \frac{h}{v} (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.) + g_{WL}^h \frac{h}{v} (W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + h.c.)$ $+\kappa_{ZZ}^h \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} + \kappa_{\gamma\gamma}^h \frac{h}{2v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \kappa_{WW}^h \frac{h}{v} \mathcal{W}^{+\,\mu\nu} \mathcal{W}_{\mu\nu}^-$ $+\kappa_{GG}^h \frac{h}{2v} G^{A\,\mu\nu} G_{\mu\nu}^A$
hV^3 couplings (5)
$\Delta\mathcal{L}^{hV^3} = \mathrm{i}gc_{\theta_W} \frac{h}{v} \left[g_{Z1}^{hV^3} Z_\mu (W_\nu^+ \mathcal{W}^{-\mu\nu} - W_\nu^- \mathcal{W}^{+\mu\nu}) + \kappa_Z^{hV^3} W_\mu^+ W_\nu^- Z^{\mu\nu}\right]$ $+\mathrm{ie}\ \kappa_\gamma^{hV^3} \frac{h}{v} W_\mu^+ W_\nu^- A^{\mu\nu} + g_5^{hV^3} \frac{h}{v} \epsilon^{\mu\nu\rho\sigma} W_\mu^+ \overleftrightarrow{D}_\rho W_\nu^- Z_\sigma$ $+\mathrm{i}g_{\partial hZ}^{hV^3} \frac{g}{2c_{\theta_W}} \frac{\partial_\mu h}{v} Z_\nu \left(W_\mu^+ W^{-\nu} - W_\mu^- W^{+\nu}\right).$
h^2V^2 couplings (8)
$\Delta\mathcal{L}_{V^2}^{hh} = \delta g_{VV}^{hh}\ \frac{h^2}{2} \left[W^{+\,\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + \delta g_{ZZ}^{hh}\ \frac{h^2}{2} \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2}$ $+g_{Z1}^{hh} \frac{(\partial_\nu h)^2}{v^2} + g_{Z2}^{hh} \frac{\partial_\mu h \partial_\nu h}{2v^2} \frac{Z^\mu Z^\nu}{c_{\theta_W}^2}$ $+g_{W1}^{hh} \frac{(\partial_\nu h)^2}{v^2} W^{+\mu} W_\mu^- + g_{W2}^{hh} \frac{\partial_\mu h \partial_\nu h}{2v^2} (W^{+\mu} W^{-\nu} + h.c.)$ $+\kappa_{WW}^{hh}\ \frac{h^2}{2v^2} \mathcal{W}^{+\,\mu\nu} \mathcal{W}_{\mu\nu}^- + \kappa_{ZZ}^{hh}\ \frac{h^2}{4v^2} Z^{\mu\nu} Z_{\mu\nu}.$
h^2G^2 couplings (1)
$\Delta\mathcal{L}_{GG}^{hh} = \kappa_{GG}^{hh}\ \frac{h^2}{4v^2} G^{A\,\mu\nu} G_{\mu\nu}^A$
Higgs potential corrections (2)
$\Delta\mathcal{L}^{h^n} = -\delta\lambda_3\, v h^3 - \delta\lambda_4\, \frac{h^4}{4}$

*under certain assumptions

Bertuzzo, Grojean & RSG (in prep)

SMEFT VS HEFT



Bertuzzo, Grojean & RSG (in prep)

35 LINEAR COMBINATIONS $\leq \mathcal{O}(v^4/\Lambda^4)$

W/Z-decays (2)	
$\delta^8 g^W_Q$	$\delta g^W_Q - \frac{c_{\theta_W}}{\sqrt{2}}(\delta g^Z_{u_L} - \delta g^Z_{d_L})$
$\delta^8 g^W_L$	$\delta g^W_L - \frac{c_{\theta_W}}{\sqrt{2}}(\delta g^Z_{\nu_L} - \delta g^Z_{e_L})$
TGC (2)	
$\delta^8 \kappa^Z$	$\delta\kappa^Z - \delta g^Z_1 + t^2_{\theta_W}\delta\kappa^\gamma$
g_5	New Structure
QGC (5)	
$\delta^8 g^Q_{WW1}$	$\delta g^Q_{WW1} - 2c^2_{\theta_W}\delta g^Z_1$
$\delta^8 g^Q_{WW2}$	$\delta g^Q_{WW2} - 2c^2_{\theta_W}\delta g^Z_1$
$\delta^8 g^Q_{ZZ1}$	$\delta g^Q_{ZZ1} - 2\delta g^Z_1$
$\delta^8 g^Q_{ZZ2}$	$\delta g^Q_{ZZ2} - 2\delta g^Z_1$
h^{ZZ}	New Structure
Higgs Production and decay (12)	
$\delta^8 g^h_{ZZ}$	$\delta g^h_{ZZ} - (\delta g^Z_1 s^2_{\theta_W} - \delta\kappa^\gamma t^2_{\theta_W})g^2 v$
$\delta^8 \kappa^h_{WW}$	$\kappa^h_{WW} - \delta\kappa^\gamma - \frac{c_{\theta_W}}{s_{\theta_W}}\kappa^h_{Z\gamma} - \kappa^h_{\gamma\gamma}$
$\delta^8 \kappa^h_{ZZ}$	$\kappa^h_{ZZ} - \frac{1}{c^2_{\theta_W}}\delta\kappa^\gamma - \frac{c_{2\theta_W}}{c_{\theta_W}s_{\theta_W}}\kappa^h_{Z\gamma} - \kappa^h_{\gamma\gamma}$
$\delta^8 g^h_{WL}$	$g^h_{WL} - \sqrt{2}c_{\theta_W}(\delta g^Z_{\nu_L} - \delta g^Z_{e_L} - g c_{\theta_W}\delta g^Z_1) + 2\delta g^W_L \delta g^Z_1 c^2_{\theta_W}$
$\delta^8 g^h_{WQ}$	$g^h_{WQ} - \sqrt{2}c_{\theta_W}(\delta g^Z_{u_L} - \delta g^Z_{d_L} - g c_{\theta_W}\delta g^Z_1) + 2\delta g^W_Q \delta g^Z_1 c^2_{\theta_W}$
$\delta^8 g^h_{Zf}$	$g^h_{Zf} - \frac{2g}{c_{\theta_W}}Y_f t^2_{\theta_W}\delta\kappa^\gamma - 2\delta g^Z_f + \frac{2g}{c_{\theta_W}}(T^f_3 c^2_{\theta_W} + Y_f s^2_{\theta_W})\delta g^Z_1 + 2c_{2\theta_W}\delta g^Z_f \delta g^Z_1$
CorrectioNew Structure to Higgs potential (1)	
$\delta^8 \lambda_4$	$\delta\lambda_4 - 6\delta\lambda_3 + \frac{4}{g^2}\left(\frac{\delta g^h_{VV}}{v} + g^2 c^2_{\theta_W}\delta g^Z_1\right)\left(\frac{m^2_h}{3v^2} + 3\delta\lambda_3\right)$
h^2G^2 coupling (1)	
$\delta^8 \kappa^{hh}_{GG}$	$\kappa^{hh}_{GG} - \kappa^h_{GG} + \frac{\kappa^h_{GG}}{2}\alpha_r$
h^2V^2 couplings (8)	
$\delta^8 \kappa^{hh}_{WW}$	$\kappa^{hh}_{WW} - \delta\kappa^\gamma - \frac{c_{\theta_W}}{s_{\theta_W}}\kappa^h_{Z\gamma} - \kappa^h_{\gamma\gamma} + \frac{\kappa^h_{WW}}{2}\alpha_r$
$\delta^8 \kappa^{hh}_{ZZ}$	$\kappa^{hh}_{ZZ} - \frac{1}{c^2_{\theta_W}}\delta\kappa^\gamma - \frac{c_{2\theta_W}}{c_{\theta_W}s_{\theta_W}}\kappa^h_{Z\gamma} - \kappa^h_{\gamma\gamma} + \frac{\kappa^h_{ZZ}}{2}\alpha_r$
$\delta^8 g^{hh}_{VV}$	$\delta g^{hh}_{VV} - \frac{4\delta g^h_{VV}}{v} + g^2\delta g^Z_1 c^2_{\theta_W} + \frac{\delta g^h_{VV}}{2v}\alpha_r + 4\left(g^2\kappa^h_{WW} + 2\frac{\delta g^h_{VV}}{v}\right)\delta g^Z_1 c^2_{\theta_W}$
$\delta^8 g^{hh}_{ZZ}$	$\delta g^{hh}_{ZZ} - 5(\delta g^Z_1 s^2_{\theta_W} - \delta\kappa^\gamma t^2_{\theta_W})g^2 + \frac{\delta g^h_{ZZ}}{2v}\alpha_r + 4(\kappa^h_{Z\gamma}s_{2\theta_W} + \kappa^h_{ZZ}c_{2\theta_W} - \kappa^h_{WW})g^2\delta g^Z_1$
g^{hh}_{W1}	New Structure
g^{hh}_{W2}	New Structure
g^{hh}_{Z1}	New Structure
g^{hh}_{Z2}	New Structure
hV^3 couplings (5)	
$\delta^8 g^{hV^3}_{Z1}$	$g^{hV^3}_{Z1} + \frac{2}{c^2_{\theta_W}}\left(\frac{\kappa^h_{Z\gamma}}{t_{\theta_W}} + \delta\kappa^\gamma + \kappa^h_{\gamma\gamma}\right) + 4\left(\frac{c_{2\theta_W}}{2c^2_{\theta_W}} + 1\right)(\delta g^Z_1)^2 c^2_{\theta_W}$
$\delta^8 \kappa^{hV^3}_\gamma$	$\kappa^{hV^3}_\gamma + \frac{2}{t_{\theta_W}}\kappa^h_{Z\gamma} + 2\kappa^h_{\gamma\gamma} + 4\delta\kappa^\gamma\delta g^Z_1 c^2_{\theta_W}$
$\delta^8 \kappa^{hV^3}_Z$	$\kappa^{hV^3}_Z + \frac{2}{c^2_{\theta_W}}\delta\kappa_\gamma + \frac{2}{t_{\theta_W}}\kappa^h_{Z\gamma} + 2\kappa^h_{\gamma\gamma} + 4\left(\left(\frac{c_{2\theta_W}}{2c^2_{\theta_W}} + 1\right)\delta\kappa^Z + t^2_{\theta_W}\delta\kappa^\gamma\right)\delta g^Z_1 c^2_{\theta_W}$
$\delta^8 g^{hV^3}_{\partial hZ}$	$g^{hV^3}_{\partial hZ} + 4(\delta\kappa^Z c_{2\theta_W} + 2\delta\kappa^\gamma s^2_{\theta_W} - \delta g^Z_1 c^2_{\theta_W})\delta g^Z_1 c^2_{\theta_W}$
$g^{hV^3}_5$	New Structure

Bertuzzo, Grojean & RSG (in prep)

35 LINEAR COMBINATIONS=0

at $\mathcal{O}(v^2/\Lambda^2)$

D6 level SMEFT predictions !

W/Z-decays (2)	
$\delta^8 g^W_Q$	$\delta g^W_Q - \frac{c_{\theta_W}}{\sqrt{2}}(\delta g^Z_{u_L} - \delta g^Z_{d_L})$
$\delta^8 g^W_L$	$\delta g^W_L - \frac{c_{\theta_W}}{\sqrt{2}}(\delta g^Z_{\nu_L} - \delta g^Z_{e_L})$
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$\delta^8 g^h_{ZZ}$	$\delta g^h_{ZZ} - (\delta g^Z_1 s^2_{\theta_W} - \delta\kappa^\gamma t^2_{\theta_W})g^2 v$
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$\delta^8 g^h_{WL}$	$g^h_{WL} - \sqrt{2}c_{\theta_W}(\delta g^Z_{\nu_L} - \delta g^Z_{e_L} - gc_{\theta_W}\delta g^Z_1) + 2\delta g^W_L \delta g^Z_1 c^2_{\theta_W}$
$\delta^8 g^h_{WQ}$	$g^h_{WQ} - \sqrt{2}c_{\theta_W}(\delta g^Z_{u_L} - \delta g^Z_{d_L} - gc_{\theta_W}\delta g^Z_1) + 2\delta g^W_Q \delta g^Z_1 c^2_{\theta_W}$
$\delta^8 g^h_{Zf}$	$g^h_{Zf} - \frac{2g}{c_{\theta_W}}Y_f t^2_{\theta_W}\delta\kappa^\gamma - 2\delta g^Z_f + \frac{2g}{c_{\theta_W}}(T^f_3 c^2_{\theta_W} + Y_f s^2_{\theta_W})\delta g^Z_1 + 2c_{2\theta_W}\delta g^Z_f \delta g^Z_1$
CorrectioNew Structure to Higgs potential (1)	
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$\delta^8 \kappa^{hh}_{GG}$	$\kappa^{hh}_{GG} - \kappa^h_{GG} + \frac{\kappa^h_{GG}}{2}\alpha_r$
h^2V^2 couplings (8)	
$\delta^8 \kappa^{hh}_{WW}$	$\kappa^{hh}_{WW} - \delta\kappa^\gamma - \frac{c_{\theta_W}}{s_{\theta_W}}\kappa^h_{Z\gamma} - \kappa^h_{\gamma\gamma} + \frac{\kappa^h_{WW}}{2}\alpha_r$
$\delta^8 \kappa^{hh}_{ZZ}$	$\kappa^{hh}_{ZZ} - \frac{1}{c^2_{\theta_W}}\delta\kappa^\gamma - \frac{c_{2\theta_W}}{c_{\theta_W}s_{\theta_W}}\kappa^h_{Z\gamma} - \kappa^h_{\gamma\gamma} + \frac{\kappa^h_{ZZ}}{2}\alpha_r$
$\delta^8 g^{hh}_{VV}$	$\delta g^{hh}_{VV} - \frac{4\delta g^h_{VV}}{v} + g^2\delta g^Z_1 c^2_{\theta_W} + \frac{\delta g^h_{VV}}{2v}\alpha_r + 4\left(g^2\kappa^h_{WW} + 2\frac{\delta g^h_{VV}}{v}\right)\delta g^Z_1 c^2_{\theta_W}$
$\delta^8 g^{hh}_{ZZ}$	$\delta g^{hh}_{ZZ} - 5(\delta g^Z_1 s^2_{\theta_W} - \delta\kappa^\gamma t^2_{\theta_W})g^2 + \frac{\delta g^h_{ZZ}}{2v}\alpha_r + 4(\kappa^h_{Z\gamma}s_{2\theta_W} + \kappa^h_{ZZ}c_{2\theta_W} - \kappa^h_{WW})g^2\delta g^Z_1$
g^{hh}_{W1}	New Structure
g^{hh}_{W2}	New Structure
g^{hh}_{Z1}	New Structure
g^{hh}_{Z2}	New Structure
hV^3 couplings (5)	
$\delta^8 g^{hV^3}_{Z1}$	$g^{hV^3}_{Z1} + \frac{2}{c^2_{\theta_W}}\left(\frac{\kappa^h_{Z\gamma}}{t_{\theta_W}} + \delta\kappa^\gamma + \kappa^h_{\gamma\gamma}\right) + 4\left(\frac{c_{2\theta_W}}{2c^2_{\theta_W}} + 1\right)(\delta g^Z_1)^2 c^2_{\theta_W}$
$\delta^8 \kappa^{hV^3}_\gamma$	$\kappa^{hV^3}_\gamma + \frac{2}{t_{\theta_W}}\kappa^h_{Z\gamma} + 2\kappa^h_{\gamma\gamma} + 4\delta\kappa^\gamma\delta g^Z_1 c^2_{\theta_W}$
$\delta^8 \kappa^{hV^3}_Z$	$\kappa^{hV^3}_Z + \frac{2}{c^2_{\theta_W}}\delta\kappa_\gamma + \frac{2}{t_{\theta_W}}\kappa^h_{Z\gamma} + 2\kappa^h_{\gamma\gamma} + 4\left(\left(\frac{c_{2\theta_W}}{2c^2_{\theta_W}} + 1\right)\delta\kappa^Z + t^2_{\theta_W}\delta\kappa^\gamma\right)\delta g^Z_1 c^2_{\theta_W}$
$\delta^8 g^{hV^3}_{\partial hZ}$	$g^{hV^3}_{\partial hZ} + 4(\delta\kappa^Z c_{2\theta_W} + 2\delta\kappa^\gamma s^2_{\theta_W} - \delta g^Z_1 c^2_{\theta_W})\delta g^Z_1 c^2_{\theta_W}$
$g^{hV^3}_5$	New Structure

Bertuzzo, Grojean & RSG (in prep)

12 LINEAR COMBINATIONS $\leq \mathcal{O}(v^6/\Lambda^6)$

$$\delta^8\kappa_{WW} - c^2_{\theta_W}\delta^8\kappa_{ZZ} - 2c^2_{\theta_W}\delta^8\kappa_Z$$

$$\delta^8 g^h_{Wud} - \frac{c_{\theta_W}(\delta^8 g^h_{Zu_l} - \delta^8 g^h_{Zd_l})}{\sqrt{2}} - (4\delta^8 g^W_{ud} - \sqrt{2}gc^2_{\theta_W}\delta^8\kappa_Z)$$

$$\delta^8 g^h_{W\nu e} - \frac{c_{\theta_W}(\delta^8 g^h_{Z\nu_l} - \delta^8 g^h_{Ze_l})}{\sqrt{2}} - (4\delta^8 g^W_{\nu e} - \sqrt{2}gc^2_{\theta_W}\delta^8\kappa_Z)$$

$$\delta^8 g^{WW}_{Q2} - \delta^8 g^{WW}_{Q1} - 2c^4_{\theta_W}(\delta^8 g^{ZZ}_{Q2} - \delta^8 g^{ZZ}_{Q1})$$

$$h^{ZZ}_Q + c^4_{\theta_W}(\delta^8 g^{ZZ}_{Q2} - \delta^8 g^{ZZ}_{Q1})$$

$$g^Z_{hh2} - 4(\delta^8 g^{WW}_{Q1} - 2c^2_{\theta_W}\delta^8\kappa_Z)$$

$$g^Z_{hh3} + 4(\delta^8 g^{WW}_{Q1} - 2c^2_{\theta_W}\delta^8\kappa_Z + c^4_{\theta_W}(\delta^8 g^{ZZ}_{Q2} - \delta^8 g^{ZZ}_{Q1}))$$

$$g^W_{hh2} - 4c^4_{\theta_W}\delta^8 g^{ZZ}_{Q1}$$

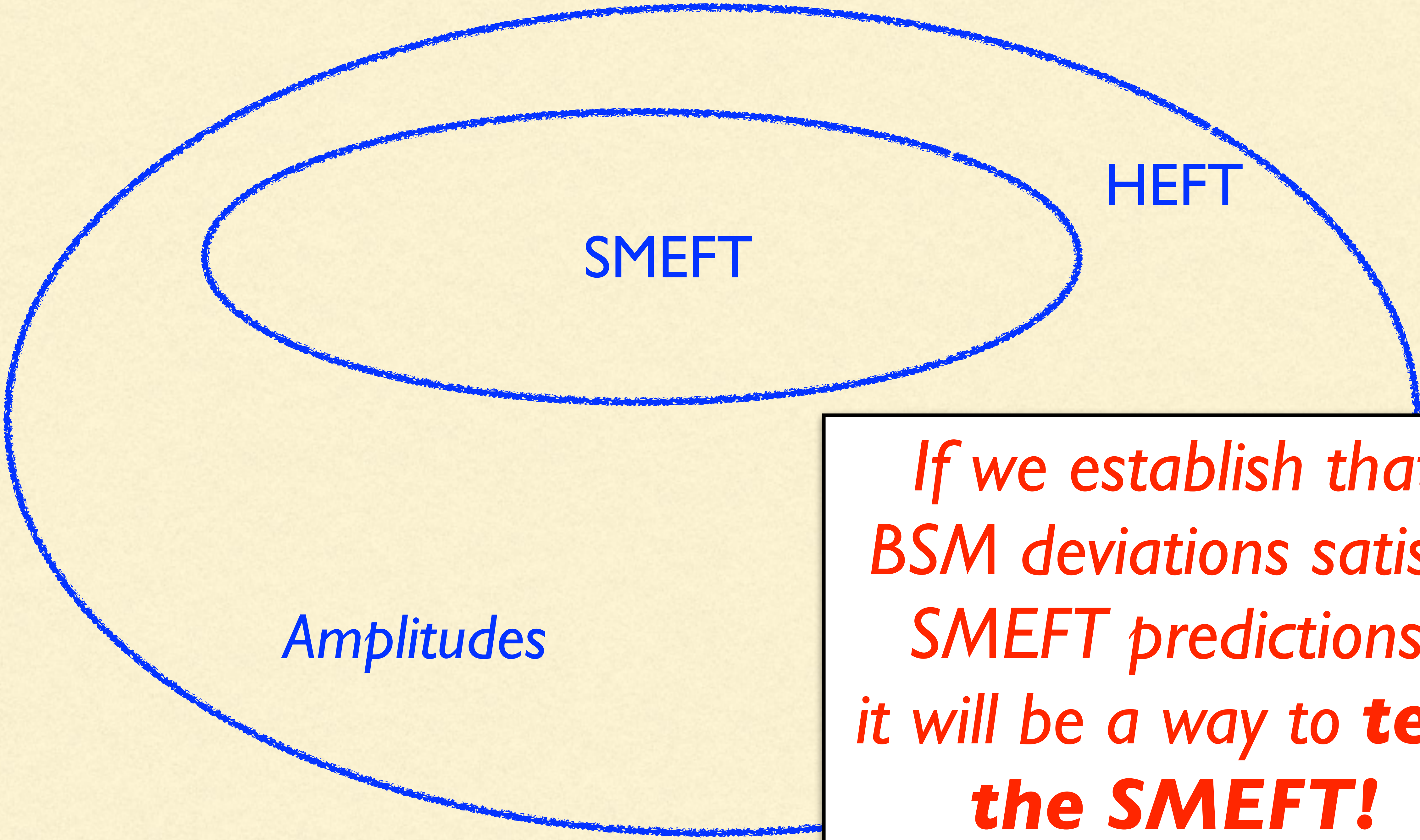
$$g^W_{hh3} + 4c^4_{\theta_W}\delta^8 g^{ZZ}_{Q2}$$

$$\delta^8\kappa^{hZ} - \frac{1}{3}\left(\frac{9\delta^8 g^h_{VV}/v - \delta^8 g^{h^2}_{ZZ}}{g^2} + 3\delta^8 g^{hZ}_1 - 3t^2_{\theta_W}(2\delta^8 g^{WW}_{Q1} + \delta^8\kappa^h_{WW} + g^{\partial hZ})\right.$$
$$\left. + 6\delta^8\kappa_Z + s^2_{\theta_W}(32\delta^8\kappa_Z + 15\delta^8\kappa_{ZZ} + 6\delta^8 g^{Q1}_{ZZ}c^2_{\theta_W})\right)$$

$$\delta^8\kappa^{h\gamma} + \frac{1}{3s^2_{\theta_W}}\left(\frac{9\delta^8 g^h_{VV}/v - \delta^8 g^{h^2}_{ZZ}}{g^2}c^2_{\theta_W} + 3\delta^8 g^{hZ}_1 - 3s^2_{\theta_W}(2\delta^8 g^{WW}_{Q1} + \delta^8\kappa^h_{WW} + g^{\partial hZ})\right.$$
$$\left. - 6\delta^8\kappa_Z c^4_{\theta_W} + s^2_{\theta_W}c^2_{\theta_W}(26\delta^8\kappa_Z + 15\delta^8\kappa_{ZZ} + 6\delta^8 g^{Q1}_{ZZ}c^2_{\theta_W})\right)$$

Bertuzzo, Grojean & RSG (in prep)

PROBING SMEFT VS TESTING SMEFT



If we establish that BSM deviations satisfy SMEFT predictions, it will be a way to ***test the SMEFT!***

PROBING SMEFT

Only 17 of these 52 anomalous couplings need to be measured

All other anomalous couplings can be predicted as a function of these 17

List of Anomalous Couplings
Vff couplings (9)
$\Delta\mathcal{L}_{Vff} = \sum_f \delta g^Z_f Z_\mu \bar{f}\gamma^\mu f_{L,R} + \delta g^W_{e\nu}(W^+_\mu \bar{\nu}_L \gamma^\mu e_L + h.c.) + \delta g^W_{ud}(W^+_\mu \bar{u}_L \gamma^\mu d_L + h.c.$
Anomalous TGC (4)
$\Delta\mathcal{L}_{TGC} = \mathrm{i}gc_{\theta_W}\left[\delta g^Z_1 Z_\mu (W^+_\nu \mathcal{W}^{-\mu\nu} - W^-_\nu \mathcal{W}^{+\mu\nu}) + \delta\kappa^Z W^+_\mu W^-_\nu Z^{\mu\nu}\right] + \mathrm{ie}\ \delta\kappa^\gamma W^+_\mu W^-_\nu A^{\mu\nu} + g_5 \epsilon^{\mu\nu\rho\sigma} W^+_\mu \overleftrightarrow{D}_\rho W^-_\nu Z_\sigma$
Anomalous QGC (5)
$\Delta\mathcal{L}_{QGC} = g^2 c^2_{\theta_W}\left[\delta g^Q_{ZZ1} Z^\mu Z^\nu W^-_\mu W^+_\nu - \delta g^Q_{ZZ2} Z^\mu Z_\mu W^{-\nu} W^+_\nu\right] + \frac{g^2}{4c^4_{\theta_W}} h^Q_{ZZ} (Z^\mu Z_\mu)^2 + \frac{g^2}{2}\left[\delta g^Q_{WW1} W^{-\mu} W^{+\nu} W^-_\mu W^+_\nu - \delta g^Q_{WW2}\left(W^{-\mu} W^+_\mu\right)^2\right]$
Single Higgs (19)
$\Delta\mathcal{L}_h = \delta g^h_{VV}\, h\left[W^{+\mu} W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \delta g^h_{ff}\ (h \bar{f}_L f_R + h.c.) + \delta g^h_{ZZ}\, h \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$ $\sum_f g^h_{Zff}\ \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g^h_{WQ}\ \frac{h}{v}\left(W^+_\mu \bar{u}_L \gamma^\mu d_L + h.c.\right) + g^h_{WL}\ \frac{h}{v}\left(W^+_\mu \bar{\nu}_L \gamma^\mu e_L + h.c.\right)$ $+\kappa^h_{ZZ}\ \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} + \kappa^h_{\gamma\gamma}\ \frac{h}{2v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \kappa^h_{WW}\ \frac{h}{v} \mathcal{W}^{+\,\mu\nu} \mathcal{W}^-_{\mu\nu}$ $+\kappa^h_{GG}\ \frac{h}{2v} G^{A\,\mu\nu} G^A_{\mu\nu}$
hV^3 couplings (5)
$\Delta\mathcal{L}^{hV^3} = \mathrm{i}gc_{\theta_W} \frac{h}{v}\left[g^{hV^3}_{Z1} Z_\mu (W^+_\nu \mathcal{W}^{-\mu\nu} - W^-_\nu \mathcal{W}^{+\mu\nu}) + \kappa^{hV^3}_Z W^+_\mu W^-_\nu Z^{\mu\nu}\right]$ $+\mathrm{ie}\ \kappa^{hV^3}_\gamma \frac{h}{v} W^+_\mu W^-_\nu A^{\mu\nu} + g^{hV^3}_5 \frac{h}{v} \epsilon^{\mu\nu\rho\sigma} W^+_\mu \overleftrightarrow{D}_\rho W^-_\nu Z_\sigma$ $+\mathrm{i}g^{hV^3}_{\partial hZ} \frac{g}{2c_{\theta_W}} \frac{\partial_\mu h}{v} Z_\nu \left(W^+_\mu W^{-\nu} - W^-_\mu W^{+\nu}\right).$
h^2V^2 couplings (8)
$\Delta\mathcal{L}^{hh}_{V^2} = \delta g^{hh}_{VV}\ \frac{h^2}{2}\left[W^{+\mu} W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \delta g^{hh}_{ZZ}\ \frac{h^2}{2} \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$ $+g^{hh}_{Z1} \frac{(\partial_\nu h)^2}{v^2} + g^{hh}_{Z2} \frac{\partial_\mu h \partial_\nu h}{2v^2} \frac{Z^\mu Z^\nu}{c^2_{\theta_W}}$ $+g^{hh}_{W1} \frac{(\partial_\nu h)^2}{v^2} W^{+\mu} W^-_\mu + g^{hh}_{W2} \frac{\partial_\mu h \partial_\nu h}{2v^2} (W^{+\mu} W^{-\nu} + h.c.)$ $+\kappa^{hh}_{WW}\ \frac{h^2}{2v^2} \mathcal{W}^{+\,\mu\nu} \mathcal{W}^-_{\mu\nu} + \kappa^{hh}_{ZZ}\ \frac{h^2}{4v^2} Z^{\mu\nu} Z_{\mu\nu}.$
h^2G^2 couplings (1)
$\Delta\mathcal{L}^{hh}_{GG} = \kappa^{hh}_{GG}\ \frac{h^2}{4v^2} G^{A\,\mu\nu} G^A_{\mu\nu}$
Higgs potential corrections (2)
$\Delta\mathcal{L}^{h^n} = -\delta\lambda_3\, v h^3 - \delta\lambda_4\ \frac{h^4}{4}$

RSG, Pomarol & Riva (2014)

TESTING SMEFT

1. Beyond D6 SMEFT
2. SMEFT at D8,D10.. level/HEFT
3. Testing SMEFT assumptions

All these 52 anomalous couplings need to be probed

List of Anomalous Couplings
Vff couplings (9)
$\Delta\mathcal{L}_{Vff} = \sum_f \delta g^Z_f Z_\mu \bar{f}\gamma^\mu f_{L,R} + \delta g^W_{e\nu}(W^+_\mu \bar{\nu}_L\gamma^\mu e_L + h.c.) + \delta g^W_{ud}(W^+_\mu \bar{u}_L \gamma^\mu d_L + h.c.$
Anomalous TGC (4)
$\Delta\mathcal{L}_{TGC} = \mathrm{i}gc_{\theta_W}\left[\delta g_1^Z Z_\mu (W^+_\nu \mathcal{W}^{-\mu\nu} - W^-_\nu \mathcal{W}^{+\mu\nu}) + \delta\kappa^Z W^+_\mu W^-_\nu Z^{\mu\nu}\right]$ $+\mathrm{ie}\ \delta\kappa^\gamma W^+_\mu W^-_\nu A^{\mu\nu} + g_5 \epsilon^{\mu\nu\rho\sigma} W^+_\mu \overleftrightarrow{D}_\rho W^-_\nu Z_\sigma$
Anomalous QGC (5)
$\Delta\mathcal{L}_{QGC} = g^2 c^2_{\theta_W}\left[\delta g^Q_{ZZ1} Z^\mu Z^\nu W^-_\mu W^+_\nu - \delta g^Q_{ZZ2} Z^\mu Z_\mu W^{-\nu} W^+_\nu\right] + \frac{g^2}{4c^4_{\theta_W}} h^Q_{ZZ}(Z^\mu Z_\mu)^2$ $+\frac{g^2}{2}\left[\delta g^Q_{WW1} W^{-\mu} W^{+\nu} W^-_\mu W^+_\nu - \delta g^Q_{WW2}\left(W^{-\mu} W^+_\mu\right)^2\right]$
Single Higgs (19)
$\Delta\mathcal{L}_h = \delta g^h_{VV}\, h\left[W^{+\mu} W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \delta g^h_{ff}\ (h\bar{f}_L f_R + h.c.) + \delta g^h_{ZZ}\, h\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$ $\sum_f g^h_{Zff}\ \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g^h_{WQ}\ \frac{h}{v}\left(W^+_\mu \bar{u}_L \gamma^\mu d_L + h.c.\right) + g^h_{WL}\ \frac{h}{v}\left(W^+_\mu \bar{\nu}_L \gamma^\mu e_L + h.c.\right)$ $+\kappa^h_{ZZ}\ \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} + \kappa^h_{\gamma\gamma}\ \frac{h}{2v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma}\frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \kappa^h_{WW}\ \frac{h}{v}\mathcal{W}^{+\,\mu\nu}\mathcal{W}^-_{\mu\nu}$ $+\kappa^h_{GG}\ \frac{h}{2v} G^{A\,\mu\nu} G^A_{\mu\nu}$
hV^3 couplings (5)
$\Delta\mathcal{L}^{hV^3} = \mathrm{i}gc_{\theta_W}\frac{h}{v}\left[g^{hV^3}_{Z1} Z_\mu (W^+_\nu \mathcal{W}^{-\mu\nu} - W^-_\nu \mathcal{W}^{+\mu\nu}) + \kappa^{hV^3}_Z W^+_\mu W^-_\nu Z^{\mu\nu}\right]$ $+\mathrm{ie}\ \kappa^{hV^3}_\gamma \frac{h}{v} W^+_\mu W^-_\nu A^{\mu\nu} + g^{hV^3}_5 \frac{h}{v}\epsilon^{\mu\nu\rho\sigma} W^+_\mu \overleftrightarrow{D}_\rho W^-_\nu Z_\sigma$ $+\mathrm{i}g^{hV^3}_{\partial hZ}\frac{g}{2c_{\theta_W}}\frac{\partial_\mu h}{v} Z_\nu\left(W^+_\mu W^{-\nu} - W^-_\mu W^{+\nu}\right).$
h^2V^2 couplings (8)
$\Delta\mathcal{L}^{hh}_{V^2} = \delta g^{hh}_{VV}\ \frac{h^2}{2}\left[W^{+\mu} W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \delta g^{hh}_{ZZ}\ \frac{h^2}{2}\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}$ $+g^{hh}_{Z1}\frac{(\partial_\nu h)^2}{v^2} + g^{hh}_{Z2}\frac{\partial_\mu h \partial_\nu h}{2v^2}\frac{Z^\mu Z^\nu}{c^2_{\theta_W}}$ $+g^{hh}_{W1}\frac{(\partial_\nu h)^2}{v^2} W^{+\mu} W^-_\mu + g^{hh}_{W2}\frac{\partial_\mu h\partial_\nu h}{2v^2}(W^{+\mu} W^{-\nu} + h.c.)$ $+\kappa^{hh}_{WW}\ \frac{h^2}{2v^2}\mathcal{W}^{+\,\mu\nu}\mathcal{W}^-_{\mu\nu} + \kappa^{hh}_{ZZ}\ \frac{h^2}{4v^2} Z^{\mu\nu} Z_{\mu\nu}.$
h^2G^2 couplings (1)
$\Delta\mathcal{L}^{hh}_{GG} = \kappa^{hh}_{GG}\ \frac{h^2}{4v^2} G^{A\,\mu\nu} G^A_{\mu\nu}$
Higgs potential corrections (2)
$\Delta\mathcal{L}^{h^n} = -\delta\lambda_3\, vh^3 - \delta\lambda_4\ \frac{h^4}{4}$

Bertuzzo, Grojean & RSG (in prep)

TESTING SMEFT

1. Beyo
2. SMEF
3. Testi

List of Anomalous Couplings
Vff couplings (9)
$\Delta\mathcal{L}_{Vff} = \sum_f \delta g_f^Z Z_\mu \bar{f}\gamma^\mu f_{L,R} + \delta g_{e\nu}^W (W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + h.c.) + \delta g_{ud}^W (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.$
Anomalous TGC (4)
$\Delta\mathcal{L}_{TGC} = igc_{\theta_W}\left[\delta g_1^Z Z_\mu (W_\nu^+ \mathcal{W}^{-\mu\nu} - W_\nu^- \mathcal{W}^{+\mu\nu}) + \delta\kappa^Z W_\mu^+ W_\nu^- Z^{\mu\nu}\right]$ $+ie\,\delta\kappa^\gamma W_\mu^+ W_\nu^- A^{\mu\nu} + g_5 \epsilon^{\mu\nu\rho\sigma} W_\mu^+ \overleftrightarrow{D}_\rho W_\nu^- Z_\sigma$
$\Delta\mathcal{L}_{V^2}^{hh} = \delta g_{VV}^{hh} \frac{h^2}{2}\left[W^{+\mu}W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + \delta g_{ZZ}^{hh} \frac{h^2}{2}\frac{Z^\mu Z_\mu}{2c_{\theta_W}^2}$ $+g_{Z1}^{hh}\frac{(\partial_\nu h)^2}{v^2} + g_{Z2}^{hh}\frac{\partial_\mu h \partial_\nu h}{2v^2}\frac{Z^\mu Z^\nu}{c_{\theta_W}^2}$ $+g_{W1}^{hh}\frac{(\partial_\nu h)^2}{v^2} W^{+\mu}W_\mu^- + g_{W2}^{hh}\frac{\partial_\mu h \partial_\nu h}{2v^2}(W^{+\mu}W^{-\nu} + h.c.)$ $+\kappa_{WW}^{hh}\frac{h^2}{2v^2}\mathcal{W}^{+\mu\nu}\mathcal{W}_{\mu\nu}^- + \kappa_{ZZ}^{hh}\frac{h^2}{4v^2} Z^{\mu\nu}Z_{\mu\nu}.$
h^2G^2 couplings (1)
$\Delta\mathcal{L}_{GG}^{hh} = \kappa_{GG}^{hh}\frac{h^2}{4v^2} G^{A\,\mu\nu} G_{\mu\nu}^A$
Higgs potential corrections (2)
$\Delta\mathcal{L}^{h^n} = -\delta\lambda_3\, v h^3 - \delta\lambda_4 \frac{h^4}{4}$

- Thus to go from probing to testing SMEFT many more measurements are required.
- This motivates the development of sophisticated differential observables, wrt energies, angles/Multivariate distributions/Machine learning
- High energies/high luminosities required for such studies

All th… couplings need to be probed

Bertuzzo, Grojean & RSG (in prep)

BEYOND SMEFT 2: AMPLITUDES

- Basic idea: one can try to find most general Lorentz invariant parameterisation of an amplitude for a process.
- There is a mapping between EFT Wilson coefficients and the parameters determining the amplitudes.
- No of parameters must equal no of Wilson coefficients.
- Amplitudes much more physical. No redundancies in amplitude parametrisation unlike Wilson coefficients.

BEYOND SMEFT 2: AMPLITUDES

- Many recent papers with similar objectives:

1. Shadmi & Weiss (2018)
2. Durieux, Kitahara, Shadmi & Weiss (2019)
3. Durieux, Kitahara, Machado, Shadmi & Weiss (2020)
5. Ma, Shu & Xiao (2019)
6. Baratella, Fernandez & Pomarol (2020)
8. Jiang, Ma & Shu (2020)
9. Dong, Ma, Shu & Zhou (2022)
10. Chang, Chen, Liu and Luty (2022)

We will focus on this recent work in this talk

AMPLITUDES EXAMPLE: HIGGSTRAHLUNG

As an example take the most general amplitude for Higgstrahlung:

$$\mathcal{M}(f_1\bar{f}_2 \to Z_3 h_4) = \bar{u}_2 \Gamma^\mu u_1 \epsilon^*_{3\mu}$$

$$\begin{aligned}
\Gamma^\mu =& c_1 p_1^\mu + c_2 p_2^\mu + c_3 p_1^\mu \gamma_5 + c_4 p_2^\mu \gamma_5 + c_5 \gamma^\mu + c_6 p_1^\mu \not{p}_3 + c_7 p_2^\mu \not{p}_3 \\
&+ c_8 \gamma^\mu \gamma_5 + c_9 p_1^\mu \not{p}_3 \gamma_5 + c_{10} p_2^\mu \not{p}_3 \gamma_5 + c_{11} \gamma^{\mu\nu} p_{3\,\nu} \\
&+ \epsilon^{\mu\nu\rho\sigma} p_{1\,\nu} p_{2\,\rho} p_{3\,\sigma} \left(c_{12} + c_{13}\gamma_5 + c_{14}\not{p}_3\right) + \epsilon^{\mu\nu\rho\sigma} \gamma_\nu \left(c_{15} p_{1\,\rho} p_{2\,\sigma} + c_{16} p_{1\,\rho} p_{3\,\sigma} + c_{17} p_{2\,\rho} p_{3\,\sigma}\right) \\
&+ \epsilon^{\mu\nu\rho\sigma} p_{1\,\nu} p_{2\,\rho} p_{3\,\sigma} \left(c_{18} \not{p}_3 \gamma_5\right) + \epsilon^{\mu\nu\rho\sigma} \gamma_\nu \gamma_5 \left(c_{19} p_{1\,\rho} p_{2\,\sigma} + c_{20} p_{1\,\rho} p_{3\,\sigma} + c_{21} p_{2\,\rho} p_{3\,\sigma}\right) \\
&+ c_{22} \epsilon_{\nu\rho\sigma\gamma} \gamma^{\mu\nu} p_1^\rho p_2^\sigma p_3^\gamma + \epsilon^{\mu\nu\rho\sigma} \gamma_{\nu\gamma} p_3^\gamma \left(c_{23} p_{1\,\rho} p_{2\,\sigma} + c_{24} p_{1\,\rho} p_{3\,\sigma} + c_{25} p_{2\,\rho} p_{3\,\sigma}\right) \\
&+ \epsilon^{\mu\nu\rho\sigma} \gamma_{\nu\rho} \left(c_{26} p_{1\,\sigma} + c_{27} p_{2\,\sigma} + c_{28} p_{3\,\sigma}\right) \\
&+ \epsilon^{\alpha\beta\gamma\delta} \gamma_\alpha p_{1\,\beta} p_{2\,\gamma} p_{3\,\delta} \left(c_{29} p_1^\mu + c_{30} p_2^\mu + c_{31} p_1^\mu \gamma_5 + c_{32} p_2^\mu \gamma_5\right).
\end{aligned}$$

where $c_n = f(p_i \,.\, p_j)$

Chang, Chen, Liu and Luty (2022)

AMPLITUDES EXAMPLE: HIGGSTRAHLUNG

$$\mathcal{M}(f_1\bar{f}_2 \to Z_3 h_4) = \frac{1}{v}(\bar{u}_2 \not{\epsilon}_3^* u_1)\left[A + B\frac{s}{M^2} + C\frac{t}{M^2} + \cdots\right] + \frac{1}{v^3}(\bar{u}_2 \not{p}_4 u_1)(p_4 \cdot \epsilon_3^*)\left[A' + B'\frac{s}{M^2} + C'\frac{t}{M^2} + \cdots\right] + \cdots$$

Primary: $hZ_\mu \bar{f}\gamma^\mu f$ Descendant: $\partial_\rho h \partial^\rho Z_\mu \bar{f}\gamma^\mu f$ Primary: $ih\tilde{Z}_{\mu\nu}\bar{f}\gamma^\mu \overleftrightarrow{\partial_\nu} f$

- Most general amplitude can be rewritten in above form where there is are primaries in the amplitude with 'Mandelstam descendant' contributions (*B*,*C*,*B'*,*C'* etc) suppressed by powers of s/Λ^2, t/Λ^2 etc

- Each term in the above expansion corresponds to an anomalous coupling (HEFT operator). Higher order terms above are couplings/operators with more derivatives.

Chang, Chen, Liu and Luty (2022)

AMPLITUDES EXAMPLE: HIGGSTRAHLUNG

- While there are an infinite number of independent parameters/anomalous couplings there are only a finite number of primaries. These are all independent.
- Chang et al list all primary operators (up to arbitrary high dimension) for the important Higgs production and decay processes:

$$(\bar{f}f, gg, W^+W^-, ZZ) \to (h, hh, hZ, h\gamma, hg)$$
$$(\bar{f}f', ZW) \to hW,$$
$$(fg, f\gamma, fZ) \to hf,$$
$$fW \to f'h.$$

- These can be distinguished in angular measurements. Measuring these can become a target for experiments.

Ex: 12 primaries for Higgstrahlung:

i	$\mathcal{O}_i^{hZ\bar{f}f}$
1	$hZ^\mu \bar{\psi}_L \gamma_\mu \psi_L$
2	$hZ^\mu \bar{\psi}_R \gamma_\mu \psi_R$
3	$hZ^{\mu\nu} \bar{\psi}_L \sigma_{\mu\nu} \psi_R + \text{h.c.}$
4	$ih\widetilde{Z}_{\mu\nu} \bar{\psi}_L \sigma^{\mu\nu} \psi_R + \text{h.c.}$
5	$ihZ^\mu (\bar{\psi}_L \overleftrightarrow{\partial}_\mu \psi_R) + \text{h.c.}$
6	$hZ^\mu \partial_\mu (\bar{\psi}_L \psi_R) + \text{h.c.}$
7	$ihZ^\mu \partial_\mu (\bar{\psi}_L \psi_R) + \text{h.c.}$
8	$hZ^\mu (\bar{\psi}_L \overleftrightarrow{\partial}_\mu \psi_R) + \text{h.c.}$
9	$ih\widetilde{Z}_{\mu\nu} (\bar{\psi}_L \gamma^\mu \overleftrightarrow{\partial}^\nu \psi_L)$
10	$h\widetilde{Z}_{\mu\nu} \partial^\mu (\bar{\psi}_L \gamma^\nu \psi_L)$
11	$ih\widetilde{Z}_{\mu\nu} (\bar{\psi}_R \gamma^\mu \overleftrightarrow{\partial}^\nu \psi_R)$
12	$h\widetilde{Z}_{\mu\nu} \partial^\mu (\bar{\psi}_R \gamma^\nu \psi_R)$

PHYSICAL INTERPRETATION OF PRIMARIES

Work done in collaboration with:

Debsubhra

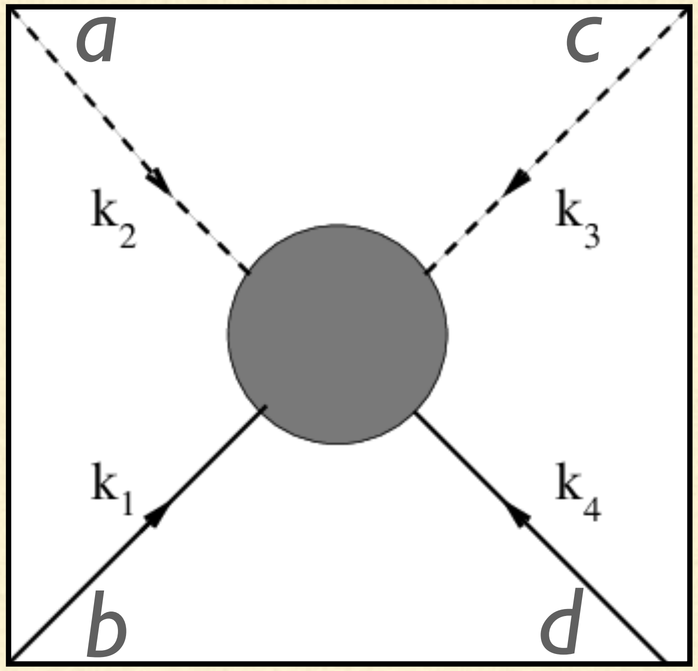
Sourav

Susobhan

PHYSICAL INTERPRETATION OF PRIMARIES

$$a(\lambda_a) + b(\lambda_b) \to c(\lambda_c) + d(\lambda_d)$$

- We use the **partial wave expansion** to get a more **physical interpretation of the primaries**
- For a given set of initial and final helicities the amplitude is given by an expansion in the total *J* :

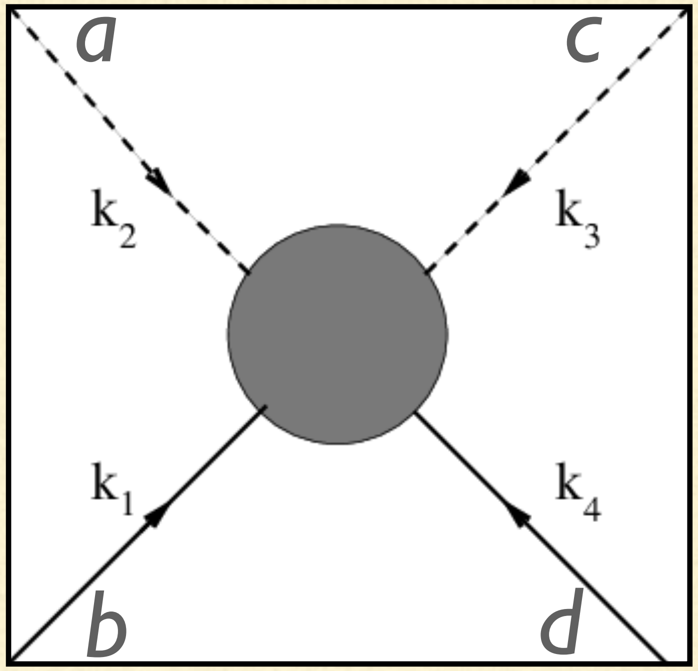


$$\mathscr{A}_{i\to f} = \sqrt{\frac{s}{p_i p_f}} \sum_J (2J+1) d^J_{\lambda_i,\lambda_f}(\theta) T^J_{\lambda_a\lambda_b\lambda_c\lambda_d}(s)$$

PHYSICAL INTERPRETATION OF PRIMARIES

- We use the partial wave expansion to get a more physical interpretation of the primaries

$$a(\lambda_a) + b(\lambda_b) \to c(\lambda_c) + d(\lambda_d)$$



- **For a given set of initial and final helicities the *primary amplitudes* are given by the lowest *J* terms:**

$$\mathscr{A}^{primary}_{i\to f} = \sqrt{\frac{s}{p_i p_f}}(2J_{lowest}+1)d^J_{\lambda_i,\lambda_f}(\theta)T^J_{\lambda_a\lambda_b\lambda_c\lambda_d}(s)$$

NUMBER OF PRIMARIES

- There is one primary amplitude (the lowest *J* contribution) for each different helicity configuration
- No of primary amplitudes:

$$N = n_{\lambda_1} \times n_{\lambda_2} \times n_{\lambda_3} \times n_{\lambda_4}$$

- Our approach enables us to **also construct these table** is a simple, intuitive way.

i	$\mathcal{O}_i^{hZ\bar{f}f}$
1	$hZ^\mu\bar{\psi}_L\gamma_\mu\psi_L$
2	$hZ^\mu\bar{\psi}_R\gamma_\mu\psi_R$
3	$hZ^{\mu\nu}\bar{\psi}_L\sigma_{\mu\nu}\psi_R + \text{h.c.}$
4	$ih\widetilde{Z}_{\mu\nu}\bar{\psi}_L\sigma^{\mu\nu}\psi_R + \text{h.c.}$
5	$ihZ^\mu(\bar{\psi}_L\overleftrightarrow{\partial}_\mu\psi_R) + \text{h.c.}$
6	$hZ^\mu\partial_\mu(\bar{\psi}_L\psi_R) + \text{h.c.}$
7	$ihZ^\mu\partial_\mu(\bar{\psi}_L\psi_R) + \text{h.c.}$
8	$hZ^\mu(\bar{\psi}_L\overleftrightarrow{\partial}_\mu\psi_R) + \text{h.c.}$
9	$ih\widetilde{Z}_{\mu\nu}(\bar{\psi}_L\gamma^\mu\overleftrightarrow{\partial}^\nu\psi_L)$
10	$h\widetilde{Z}_{\mu\nu}\partial^\mu(\bar{\psi}_L\gamma^\nu\psi_L)$
11	$ih\widetilde{Z}_{\mu\nu}(\bar{\psi}_R\gamma^\mu\overleftrightarrow{\partial}^\nu\psi_R)$
12	$h\widetilde{Z}_{\mu\nu}\partial^\mu(\bar{\psi}_R\gamma^\nu\psi_R)$

$$f + f \rightarrow Z + h$$

$$N = 2 \times 2 \times 3 \times 1 = 12$$

NUMBER OF PRIMARIES

- The set of primary amplitudes is simply the lowest J contribution to the set of different helicity configurations

- No of primary amplitudes:

$$N = n_{\lambda_1} \times n_{\lambda_2} \times n_{\lambda_3} \times n_{\lambda_4}$$

- Our approach enables us to construct these table is a simple, intuitive way.

1	$hG^{\mu\nu}G_{\nu\gamma}G^{\gamma}{}_{\mu}$
2	$hG^{\alpha\rho}G^{\beta}{}_{\rho}\widetilde{G}_{\alpha\beta}$
3	$hD^{\mu}G^{\nu\gamma}G_{\nu\rho}D^{\rho}G\ {}_{\gamma\mu}$
4	$hD^{\alpha}G^{\rho\sigma}\widetilde{G}_{\alpha\beta}D^{\beta}G_{\rho\sigma}$
5	$hD^{\mu}G^{\nu\gamma}\overleftrightarrow{D}_{\eta}G_{\nu\rho}D^{\eta\rho}G_{\gamma\mu}$
6	$hD^{\alpha}G^{\rho\sigma}\overleftrightarrow{D}_{\eta}\widetilde{G}_{\alpha\beta}D^{\eta\beta}G_{\rho\sigma}$
7	$hD^{\sigma\mu}G^{\nu\gamma}D_{\sigma}\overleftrightarrow{D}_{\eta}G_{\nu\rho}D^{\eta\rho}G_{\gamma\mu}$
8	$hD^{\chi\alpha}G^{\rho\sigma}D_{\chi}\overleftrightarrow{D}_{\eta}\widetilde{G}_{\alpha\beta}D^{\eta\beta}G_{\rho\sigma}$

$$g + g \to g + h$$

$$N = 2 \times 2 \times 2 \times 1 = 8$$

NUMBER OF PRIMARIES

- The set of primary amplitudes is simply the lowest J contribution to the set of different helicity configurations

- No of primary amplitudes:

$$N = n_{\lambda_1} \times n_{\lambda_2} \times n_{\lambda_3} \times n_{\lambda_4}$$

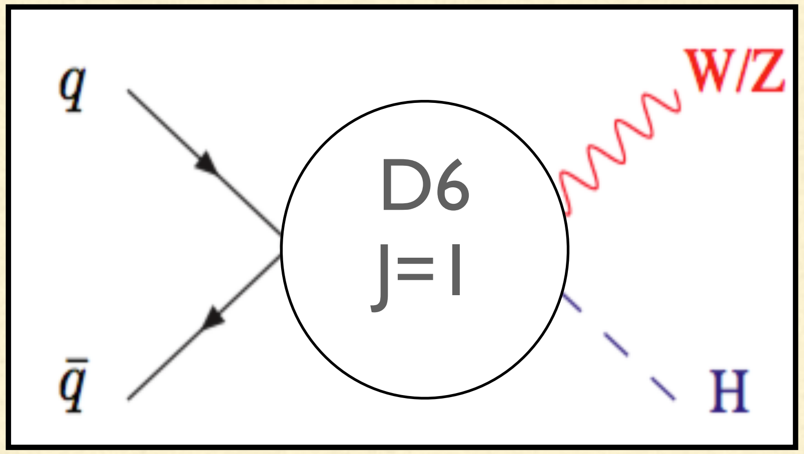
- Our approach enables us to construct these table is a simple, intuitive way.

i	$\mathcal{O}_i^{hWWZ}$
1	$h\widetilde{W}^+_{\mu\nu} W^{-\mu} Z^\nu + \text{h.c.}$
2	$ih\widetilde{W}^+_{\mu\nu} W^{-\mu} Z^\nu + \text{h.c.}$
3	$ih\widetilde{Z}_{\mu\nu} W^{+\mu} W^{-\nu} + \text{h.c.}$
4	$ihD^\mu W^{+\nu} W^-_\mu Z_\nu + \text{h.c.}$
5	$hD^\mu W^{+\nu} W^-_\mu Z_\nu + \text{h.c.}$
6	$ihD^\mu W^{+\nu} W^-_\nu Z_\mu + \text{h.c.}$
7	$hD^\mu W^{+\nu} W^-_\nu Z_\mu + \text{h.c.}$
8	$ihZ^{\mu\nu} W^+_\mu W^-_\nu$
9	$h\partial^\mu Z^\nu W^+_\mu W^-_\nu + \text{h.c.}$
10	$h\partial_\mu W^+_{\alpha\beta} \widetilde{W}^{-\alpha\beta} Z^\mu + h.c.$
11	$ih\partial_\mu W^+_{\alpha\beta} \widetilde{W}^{-\alpha\beta} Z^\mu + \text{h.c.}$
12	$h\partial^\mu W^+_{\alpha\beta} \widetilde{Z}^{\alpha\beta} W^-_\mu + h.c.$
13	$ih\partial^\mu W^+_{\alpha\beta} \widetilde{Z}^{\alpha\beta} W^-_\mu + \text{h.c.}$
14	$h\partial^\mu Z_{\alpha\beta} \widetilde{W}^{+\alpha\beta} W^-_\mu + h.c.$
15	$ih\partial^\mu Z_{\alpha\beta} \widetilde{W}^{+\alpha\beta} W^-_\mu + \text{h.c.}$
16	$h\partial^\mu W^{+\alpha} \widetilde{W}^-_{\alpha\beta} \partial^\beta Z_\mu + \text{h.c.}$
17	$ih\partial^\mu W^{+\alpha} \widetilde{W}^-_{\alpha\beta} \partial^\beta Z_\mu + \text{h.c.}$
18	$ih\partial^\alpha W^+_\mu \widetilde{W}^-_{\alpha\beta} \partial^\mu Z^\beta + \text{h.c.}$
19	$ih\partial^\delta W^+_\mu \widetilde{W}^-_{\beta\delta} \partial^\beta Z^\mu + \text{h.c.}$
20	$ih\partial^{\mu\nu} W^+_\rho \partial^\rho W^-_\mu Z_\nu + \text{h.c.}$
21	$h\partial^{\mu\nu} W^+_\rho \partial^\rho W^-_\mu Z_\nu + \text{h.c.}$
22	$ih\partial^{\mu\nu} W^+_\rho \partial^\rho Z_\mu W^-_\nu + \text{h.c.}$
23	$h\partial^{\mu\nu} W^+_\rho \partial^\rho Z_\mu W^-_\nu + \text{h.c.}$
24	$ih\partial^{\mu\nu} Z_\rho \partial^\rho W^+_\mu W^-_\nu + \text{h.c.}$
25	$h\partial^{\mu\nu} Z_\rho \partial^\rho W^+_\mu W^-_\nu + \text{h.c.}$
26	$ih\partial^\mu W^+_\nu \partial^\nu W^-_\rho \partial^\rho Z_\mu + \text{h.c.}$
27	$h\partial^\mu W^+_\nu \partial^\nu W^-_\rho \partial^\rho Z_\mu + \text{h.c.}$

$$W + W \to Z + h$$

$$N = 3 \times 3 \times 3 \times 1 = 27$$

PRIMARIES IN HIGGSTRAHLUNG PROCESS

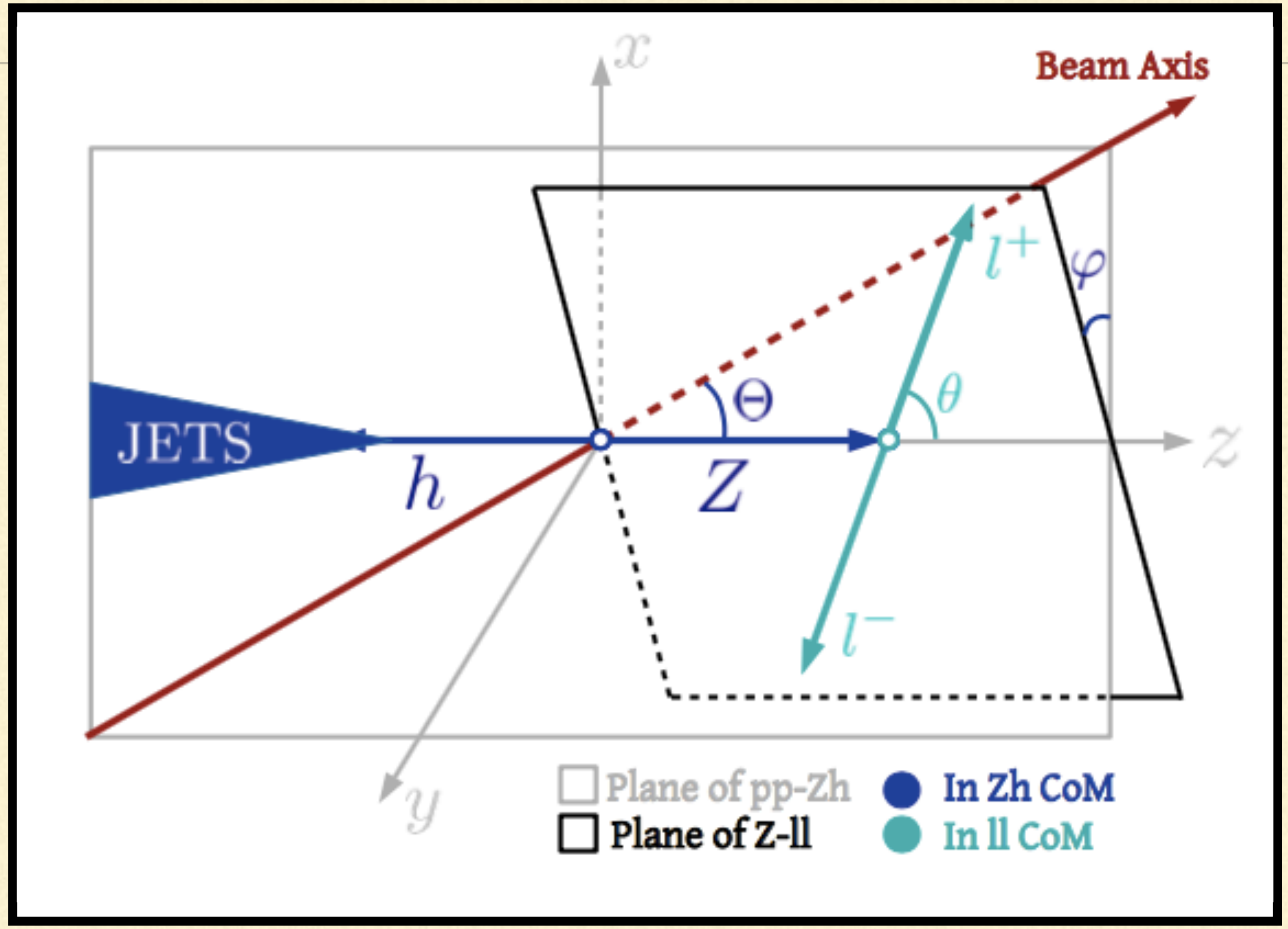


Z-helicity
{0, +, -}

$\mathscr{A}^0_{BSM}, \mathscr{A}^+_{BSM}, \mathscr{A}^-_{BSM}$

- To interfere with SM we must have initial fermions with same chirality (LL or RR).
- Averaging over initial spins this gives us 3 primary amplitudes corresponding to the 3 Z helicities

Z decays as a polarisation analyser



- The lepton decay angular distribution in θ, φ tells us about Z helicity

AZIMUTHAL DISTRIBUTIONS AS DISCRIMINANTS

3 interference amplitudes:

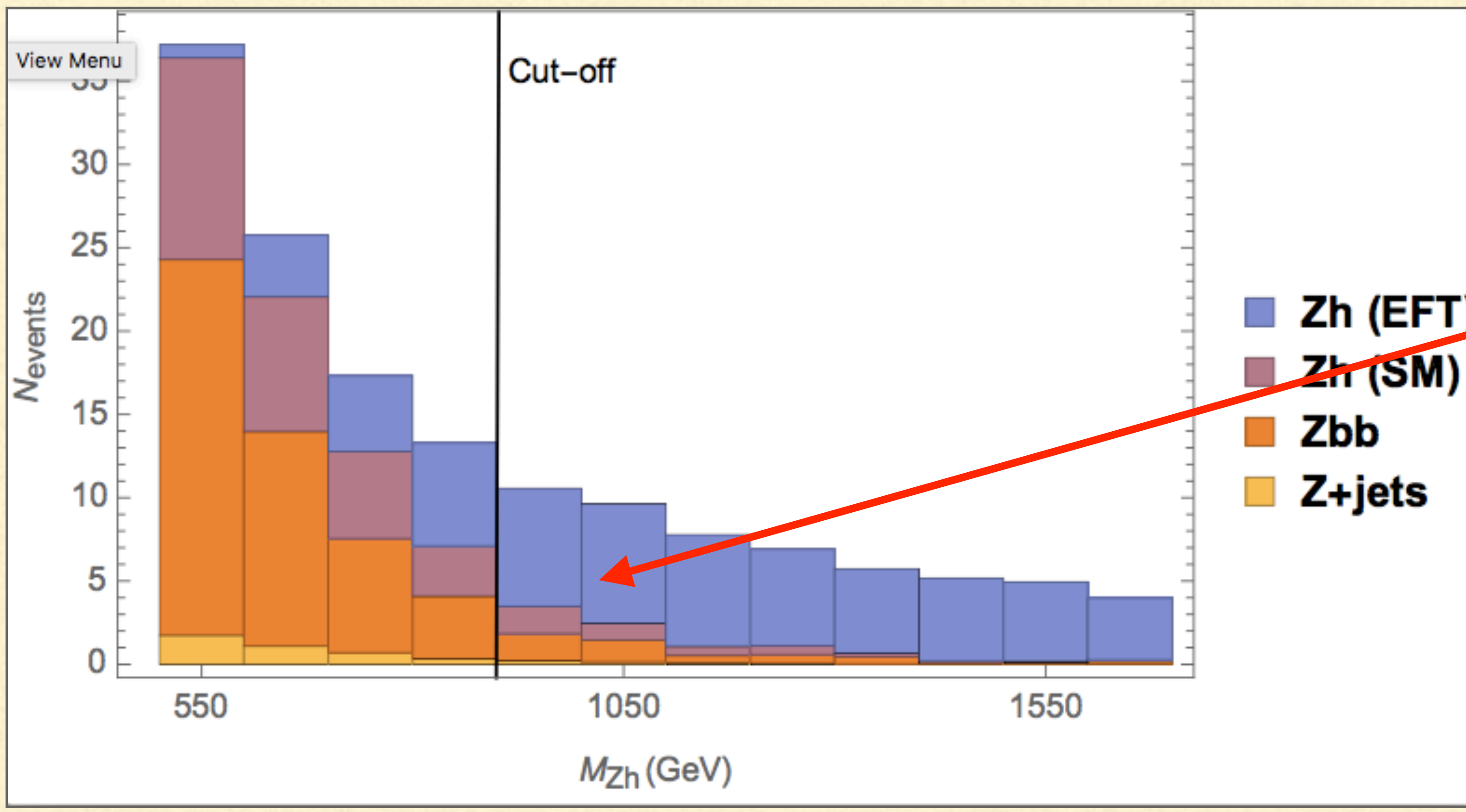
Dominant effect at high energies

$$\mathscr{A}^*_{SM}\mathscr{A}^0_{BSM} \longrightarrow \frac{\hat{s}}{m_Z^2}\sin^2\Theta\sin^2\theta \longleftarrow hZ_\mu\bar{q}\gamma^\mu q$$

$$\left.\begin{matrix}\mathscr{A}^*_{SM}\mathscr{A}^+_{BSM}\\ \pm \\ \mathscr{A}^*_{SM}\mathscr{A}^-_{BSM}\end{matrix}\right\} \rightarrow \begin{cases}\frac{\sqrt{\hat{s}}}{m_Z}\sin(\Theta/2)\sin(\theta/2)\cos\varphi \longleftarrow hZ_{\mu\nu}Z^{\mu\nu} \\ \frac{\sqrt{\hat{s}}}{m_Z}\sin(\Theta/2)\sin(\theta/2)\sin\varphi \longleftarrow hZ_{\mu\nu}\tilde{Z}^{\mu\nu}\end{cases}$$

Azimuthal distributions act as a discriminant between these 3 primaries

ENERGY GROWING EFFECTS



$hZ_\mu \bar{q}\gamma^\mu q$

- We studied *Z(ll)H(bb)* at high energies using boosted Higgs reconstruction techniques to obtain per-mille level bounds on *hVff* couplings that are competitive with LEP: $|g^h_{Z\mathbf{p}}| < 5 \times 10^{-4}$.

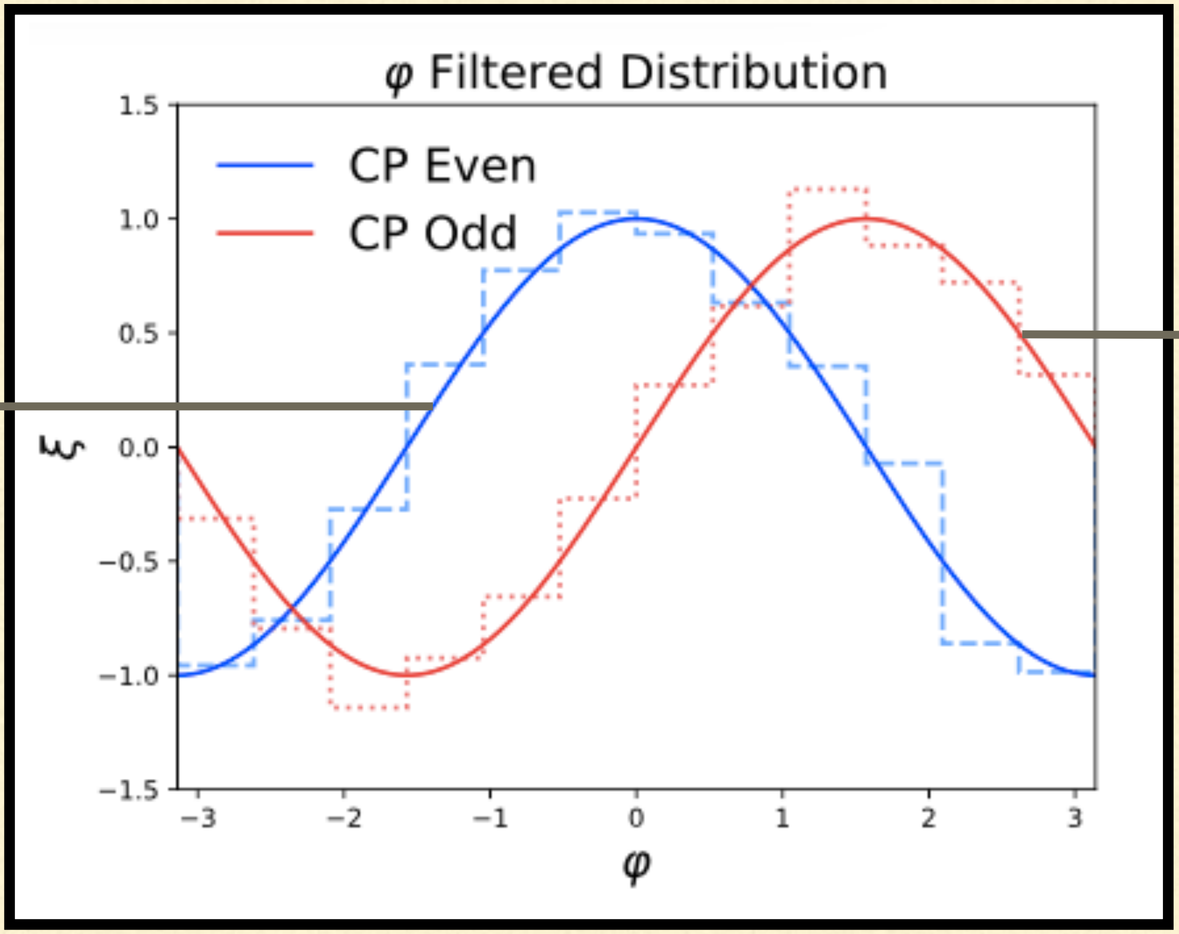
Banerjee, Englert, RSG & Spannowsky (2018)

A TRIPLE DIFFERENTIAL OBSERVABLE

$$\kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu}$$

$$g^5 = C_\varphi S_\Theta S_\theta C_\Theta C_\theta$$

Vanishes when integrated over any of the 3 angles



Events weighted by sign of $S_\Theta S_\theta C_\Theta C_\theta$

$$\tilde{\kappa}_{ZZ} \frac{h}{2v} Z^{\mu\nu} \tilde{Z}_{\mu\nu}.$$

$$g^7 = S_\varphi S_\Theta S_\theta C_\Theta C_\theta$$

Vanishes when integrated over any of the 3 angles

Interference resurrection!

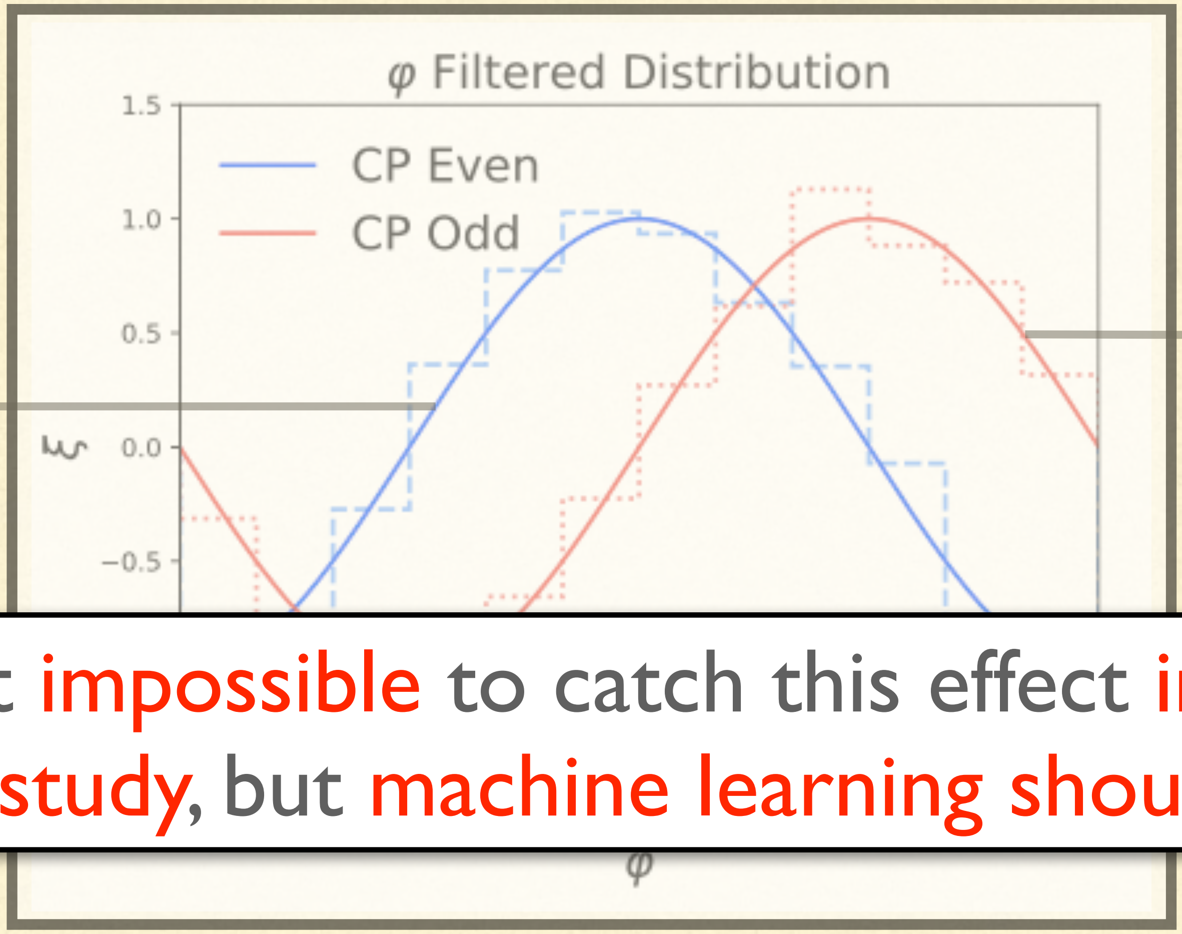
Banerjee, RSG, Reines & Spannowsky (2019)

Banerjee, RSG, Reines, Seth & Spannowsky (2019)

A TRIPLE DIFFERENTIAL OBSERVABLE

$\kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu}$

$g^5 = C$



$\tilde{\kappa}_{ZZ} \frac{h}{2v} Z^{\mu\nu} \tilde{Z}_{\mu\nu}$

$C_\Theta C_\theta$

Almost **impossible** to catch this effect **in regular cut based study**, but **machine learning should be useful!**

Vanishes when integrated over any of the 3 angles

Vanishes when integrated over any of the 3 angles

Events weighted by sign of $S_\Theta S_\theta C_\Theta C_\theta$

Gives few % level precision

Banerjee, RSG, Reines & Spannowsky (2019)

Banerjee, RSG, Reines, Seth & Spannowsky (2019)

AMPLITUDE TO ALL ORDERS!

$$\mathscr{A}^*_{SM}\mathscr{A}^+_{BSM} + \mathscr{A}^*_{SM}\mathscr{A}^-_{BSM} \longrightarrow \frac{\sqrt{\hat{s}}}{m_Z}\sin(\Theta/2)\sin(\theta/2)\cos\varphi \longleftarrow hZ_{\mu\nu}Z^{\mu\nu}$$

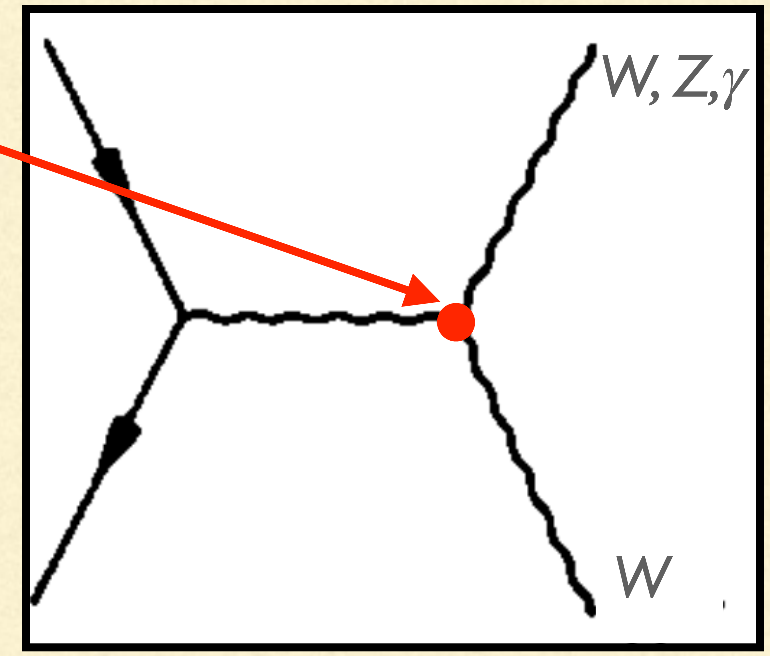
$$\frac{\sqrt{\hat{s}}}{m_Z}\left(1 + a_1\frac{\hat{s}}{M^2} + a_2\frac{\hat{s}^2}{M^4} + \cdots\right)\sin(\Theta/2)\left(1 + b_1\frac{t}{M^2} + b_2\frac{t^2}{M^4} + \cdots\right)\cos\varphi$$

CONCLUSIONS

- SMEFT not the most general EFT for LHC studies. Amplitudes/HEFT provide a more general framework.
- Many viable UV models, map to HEFT not SMEFT.
- SMEFT vs HEFT: In SMEFT different linear combinations of anomalous couplings suppressed wrt HEFT by powers of v^2/Λ^2.
- The 'Amplutudes' approach has identified a set of primary operators that give leading contribution to amplitudes in the EFT derivative expansion.
- Both approaches require new differential observables that can pinpoint these effects. Many require multivariate studies, high luminosities and high energies.

WW, WZ, Wγ PRODUCTION

$$\begin{aligned}\mathscr{L}_{WWV}/g_{WWV} = {} & i g_1^V\left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\ & + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) \\ & + g_5^V \varepsilon^{\mu\nu\rho\sigma}\left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu\right) V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} \\ & + \frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu \tilde{V}^{\nu\lambda}.\end{aligned}$$



s-channel contribution

anomalous triple gauge vertices
(11 ⟶ 6 CP even+5 CP odd)

How many of these 11 can we measure if we use all the energy/ angular information ?

Budhraja, Chattopadhyaya, RSG & Mukherjee (in preparation)

FULL ANGULAR INFORMATION FOR HIGGSTRAHLUNG

- These 9 coefficients carry full differential information in SM and D6 SMEFT
- Can be extracted using an analog of Fourier analysis called the 'Method of Moments'

ff->Z(ll)h matrix element squared

$$\sum_{L,R} |\mathcal{A}(\hat{s},\Theta,\theta,\varphi)|^2 = a_{LL}\sin^2\Theta\sin^2\theta + a^1_{TT}\cos\Theta\cos\theta + a^2_{TT}(1+\cos^2\Theta)(1+\cos^2\theta) + \cos\varphi\sin\Theta\sin\theta \times (a^1_{LT} + a^2_{LT}\cos\theta\cos\Theta) + \sin\varphi\sin\Theta\sin\theta \times (\tilde{a}^1_{LT} + \tilde{a}^2_{LT}\cos\theta\cos\Theta) + a_{TT'}\cos 2\varphi\sin^2\Theta\sin^2\theta + \tilde{a}_{TT'}\sin 2\varphi\sin^2\Theta\sin^2\theta.$$

Consider these 2 functions

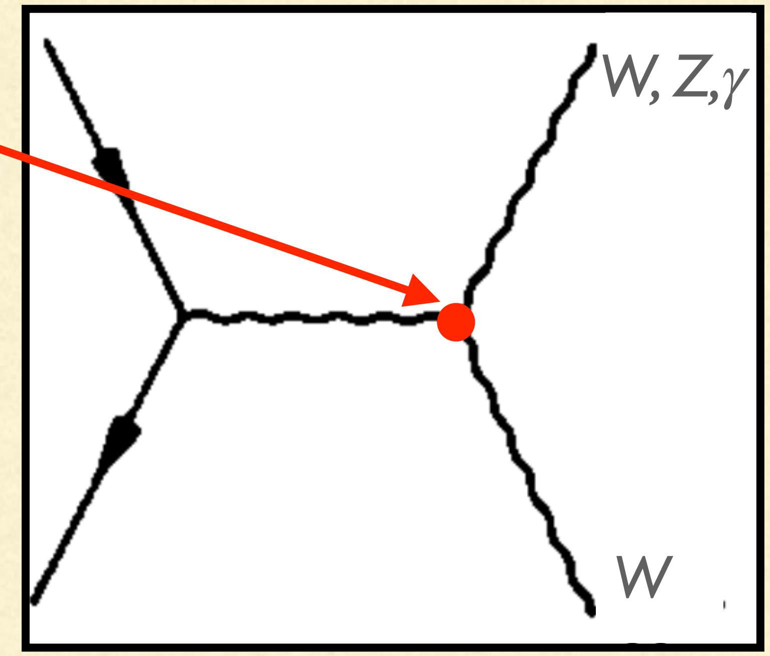
Vanish when integrated over any of the 3 angles

Dunietz, Quinn, Snyder, Toki & Lipkin (1991)

Diehl & Nachtmann (1994)

WW, WZ, Wγ PRODUCTION

$$\begin{aligned}\mathcal{L}_{WWV}/g_{WWV} = {} & i g_1^V\left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}\right) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\ & + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) \\ & + g_5^V \epsilon^{\mu\nu\rho\sigma}\left(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu\right) V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} \\ & + \frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu \tilde{V}^{\nu\lambda}.\end{aligned}$$



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How many of these 11 can we measure if we use all the energy/ angular information ?

Budhraja, Chattopadhyaya, RSG & Mukherjee (in preparation)

EG: PREDICTIONS IN CP EVEN CASE

- 3 D6 SMEFT operators:

$$ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

$$\frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$

$$\frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

- 6 CP even anomalous couplings. If we measure all of these in differential studies we can verify SMEFT predictions below.

- 3 D6 SMEFT predictions: $\delta\kappa_Z = \delta g_1^Z - t^2_{\theta_W}\delta\kappa_\gamma$ $\quad \lambda_Z = \lambda_\gamma$ $\quad g_5 = 0$

Budhraja, Chattopadhyaya, RSG & Mukherjee (in preparation)

SMEFT OPERATORS

$$\mathcal{O}_{H\Box} = |H|^2 \Box |H|^2$$
$$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$$
$$\mathcal{O}_6 = |H|^6$$
$$\mathcal{O}_y = \hat{y}_f |H|^2 \bar{F} H f_R$$
$$\mathcal{O}_f = i H^\dagger \overleftrightarrow{D}_\mu H \bar{f} \gamma^\mu f$$
$$\mathcal{O}_F^{(3)} = i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{F} \sigma^a \gamma^\mu F$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

Dimension 6

H^8
$\mathcal{O}_8 = \|H\|^8$
$H^6 D^2$:2 2
$\mathcal{O}_{H^2r} = \|H\|^4 \|D_\mu H\|^2$ $\mathcal{O}_{H^2T} = \frac{\|H\|^2}{2} (H^\dagger \overleftrightarrow{D}_\nu H)^2$
$H^4 X^2$: 3 4
$\mathcal{O}_{H^2BB} = g'^2 \|H\|^4 B_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_{H^2WB} = \|H\|^2 \mathcal{O}_{WB}$ $\mathcal{O}_{H^2WW} = g^2 \|H\|^4 W^a_{\mu\nu} W^{a\mu\nu}$ $\mathcal{O}_U = g^2 (H^\dagger \sigma^a H)(H^\dagger \sigma^b H) W^a_{\mu\nu} W^{b\mu\nu}$ $\mathcal{O}_{H^2GG} = g_s^2 \|H\|^4 G^A_{\mu\nu} G^{A\mu\nu}$
$H^4 D \psi^2$: 9 9
$\mathcal{O}_{H^2f} = i\|H\|^2 H^\dagger \overleftrightarrow{D}_\mu H \bar{f} \gamma^\mu f$ $\mathcal{O}_{H^2F} = i\|H\|^2 H^\dagger \overleftrightarrow{D}_\mu H \bar{F} \gamma^\mu F$ $\mathcal{O}^{(3)}_{H^2F} = i\|H\|^2 H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{F} \sigma^a \gamma^\mu F$ $\mathcal{O}^{(3)}_{3F} = i H^\dagger \overleftrightarrow{D}_\mu H (H^\dagger \sigma^a H) \bar{F} \sigma^a \gamma^\mu F$
$H^4 D^2 X$: 3 3
$O_{HWH} = i g W^a_{\mu\nu} (H^\dagger \sigma^a D_\mu H + h.c.) H^\dagger \overleftrightarrow{D}_\nu H$ $O_{\partial W} = i g W^a_{\mu\nu} \partial_\mu (H^\dagger H) H^\dagger \sigma^a \overleftrightarrow{D}_\nu H$ $O_{\partial B} = i g' B_{\mu\nu} \partial_\mu (H^\dagger H) H^\dagger \overleftrightarrow{D}_\nu H$
$H^4 D^4$: 3 3
$O_{DH1} = \|D_\mu H\|^4$ $O_{DH2} = (D_\mu H^\dagger D_\nu H + D_\nu H^\dagger D_\mu H)^2$ $O_{DH3} = (D_\mu H^\dagger D_\nu H - D_\nu H^\dagger D_\mu H)^2$

Dimension 8

PROBING D6 SMEFT

- Only 17 D6 operators contribute to the processes we are considering
- Only 17 measurements sufficient to constrain these

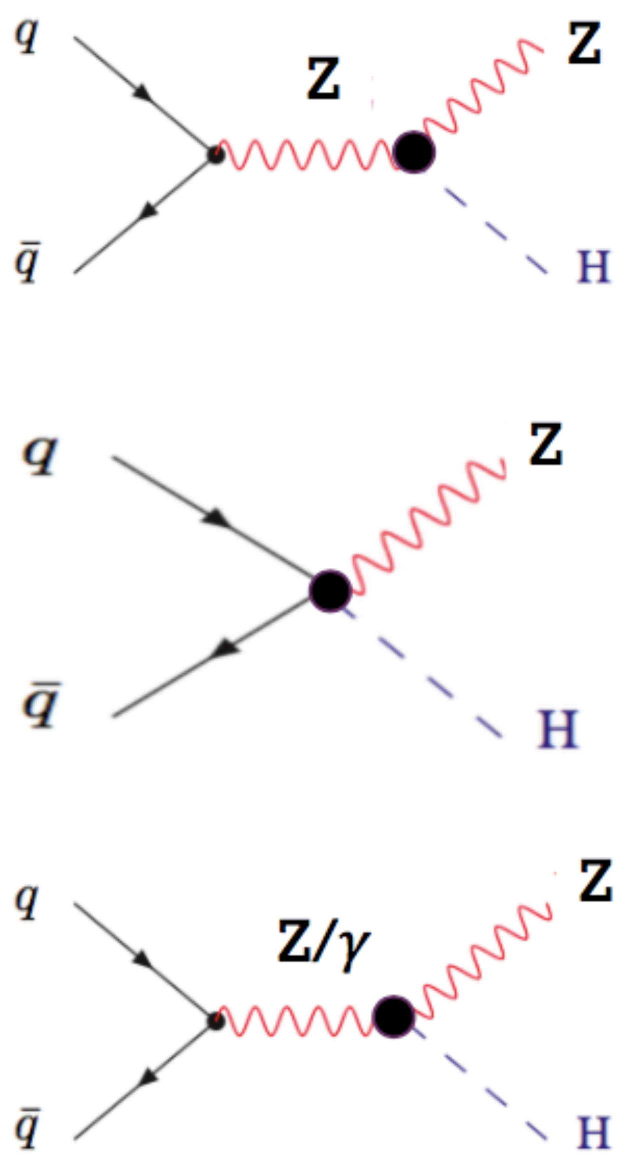
$$\mathcal{O}_{H\Box} = |H|^2 \Box |H|^2$$
$$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$$
$$\mathcal{O}_6 = |H|^6$$
$$\mathcal{O}_y = \hat{y}_f |H|^2 \bar{F} H f_R$$
$$\mathcal{O}_f = i H^\dagger \overleftrightarrow{D}_\mu H \bar{f} \gamma^\mu f$$
$$\mathcal{O}_F^{(3)} = i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{F} \sigma^a \gamma^\mu F$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

HIGGS ANOMALOUS COUPLINGS IN ZH PROD.

$$hZ_\mu Z^\mu$$

$$hZ_\mu \partial_\nu Z^{\mu\nu}$$

$$hZ_{\mu\nu}Z^{\mu\nu}, hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$$

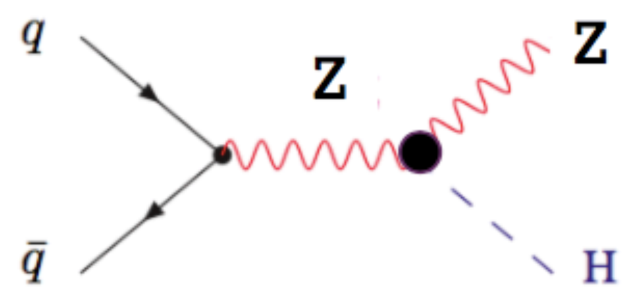


3 *hZZ* anomalous couplings

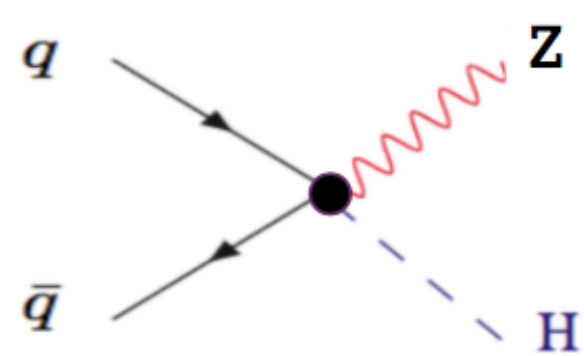
All these anomalous couplings can be completely predicted in terms of other more precise measurements, *if we assume D6 SMEFT.*

HIGGS ANOMALOUS COUPLINGS IN ZH PROD.

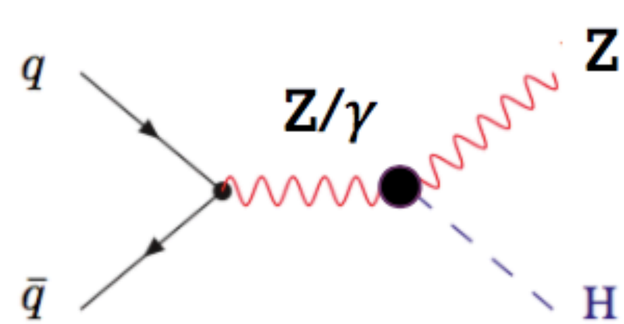
$$hZ_\mu Z^\mu$$



$$hZ_\mu \partial_\nu Z^{\mu\nu}$$



$$hZ_{\mu\nu}Z^{\mu\nu}, hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$$

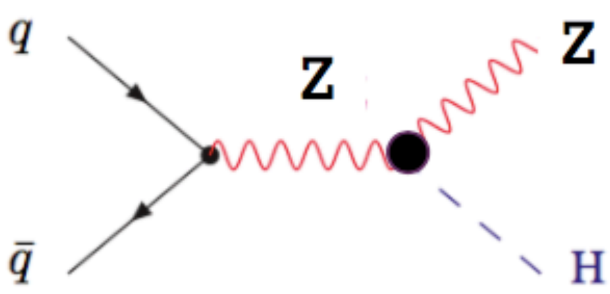


3 *hZZ* anomalous couplings

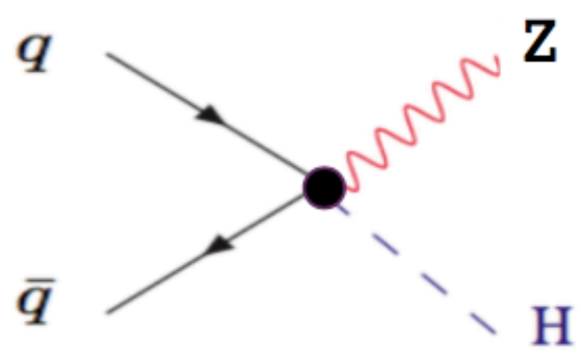
All these anomalous couplings must be measured, *if we want to test D6 SMEFT*

HIGGS ANOMALOUS COUPLINGS IN ZH PROD.

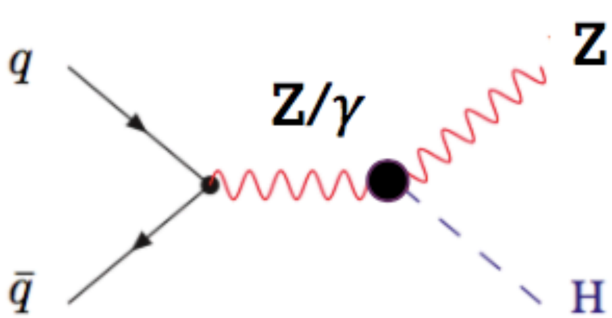
$$hZ_\mu Z^\mu$$



$$hZ_\mu \partial_\nu Z^{\mu\nu}$$



$$hZ_{\mu\nu} Z^{\mu\nu}, hZ_{\mu\nu} \tilde{Z}^{\mu\nu}$$

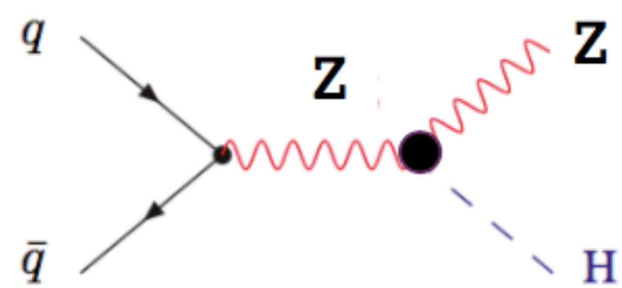


3 *hZZ* anomalous couplings

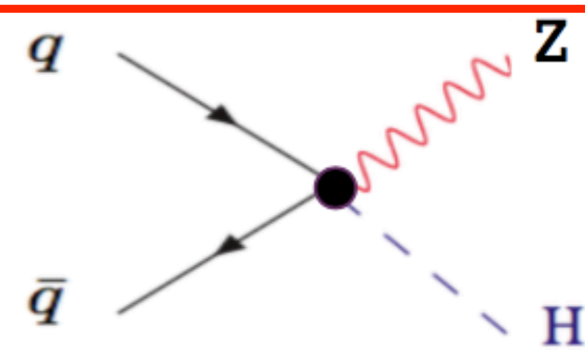
Rescales SM *hZZ* coupling.
No differential signature.
Only changes the rate.

HIGGS ANOMALOUS COUPLINGS IN ZH PROD.

$hZ_\mu Z^\mu$

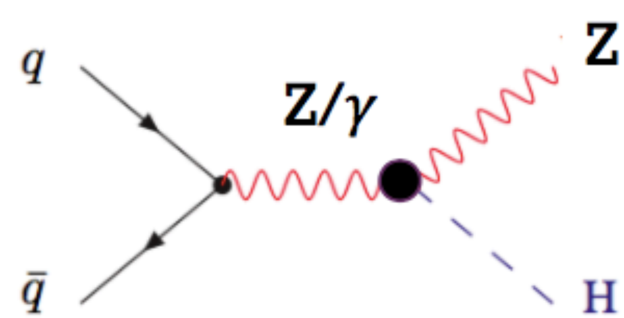


$hZ_\mu \partial_\nu Z^{\mu\nu}$



Grows with energy wrt SM.
Dominates at high energies.

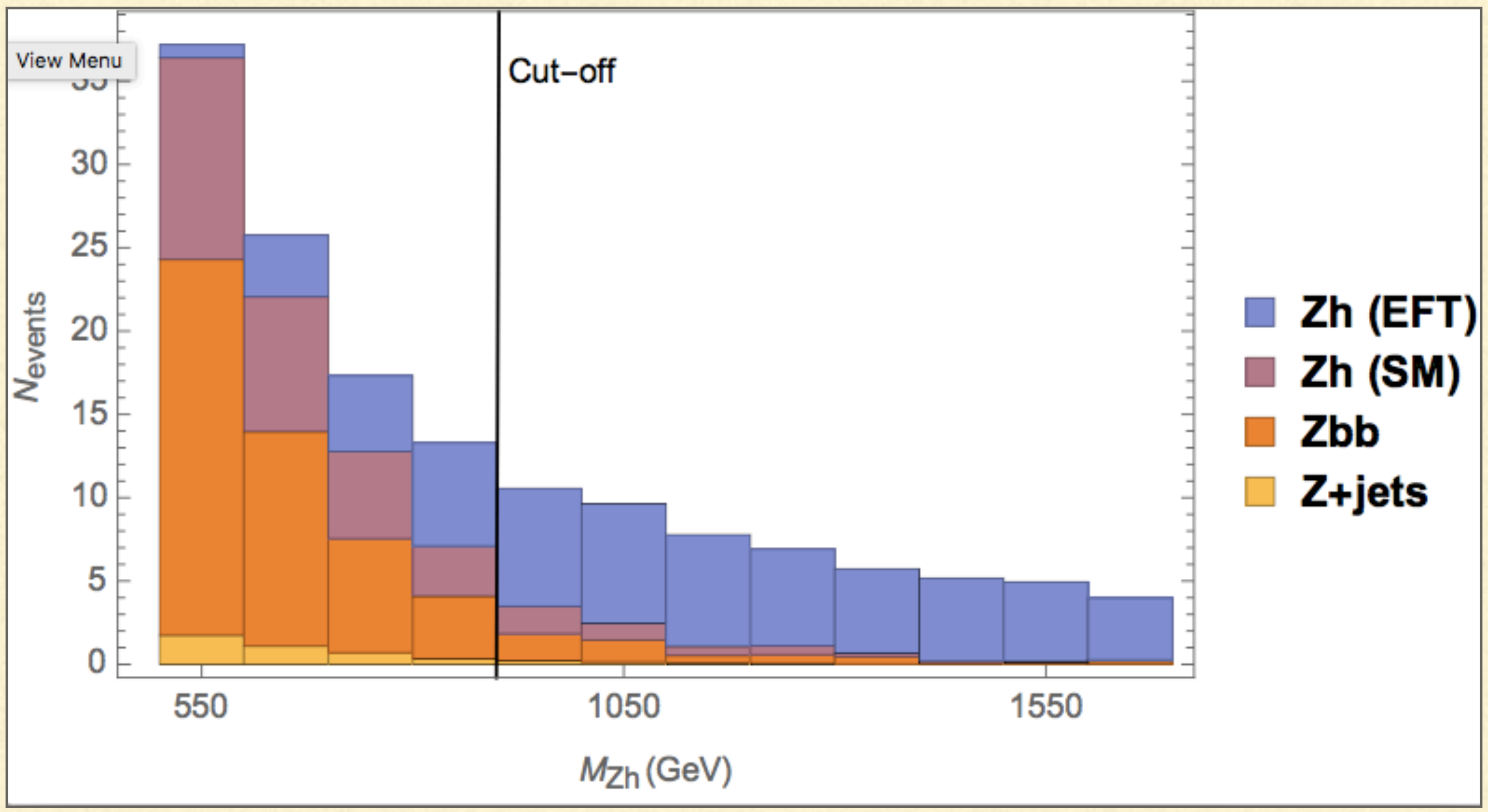
$hZ_{\mu\nu}Z^{\mu\nu}, hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$



3 *hZZ* anomalous couplings

Banerjee, Englert, RSG & Spannowsky (2018)

ENERGY GROWING EFFECTS

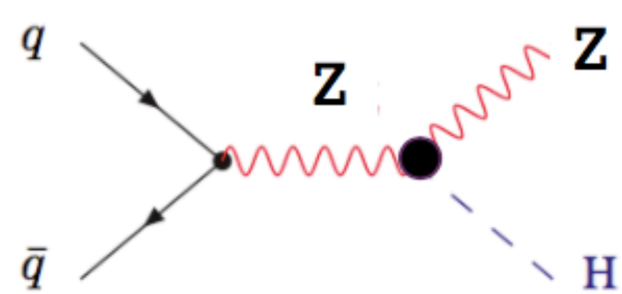


- We studied *Z(ll)H(bb)* at high energies using boosted Higgs reconstruction techniques to obtain per-mille level bounds on *hVff* couplings that are competitive with LEP: $|g^h_{Z\mathbf{p}}| < 5 \times 10^{-4}$.

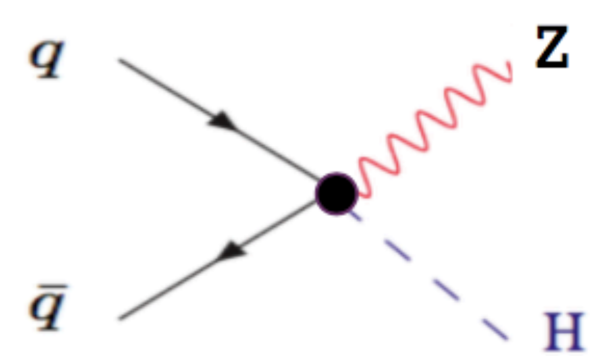
Banerjee, Englert, RSG & Spannowsky (2018)

HIGGS ANOMALOUS COUPLINGS IN ZH PROD.

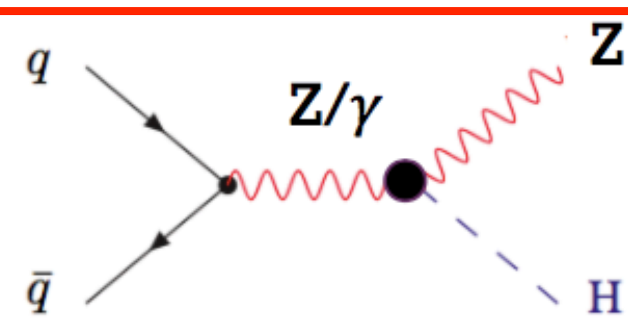
$hZ_\mu Z^\mu$



$hZ_\mu \partial_\nu Z^{\mu\nu}$



$hZ_{\mu\nu}Z^{\mu\nu}, hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$



Sophisticated angular variable required

3 *hZZ* anomalous couplings

Banerjee, RSG, Reines & Spannowsky (2019)

Banerjee, RSG, Reines, Seth & Spannowsky (2019)