LIBERATING HIGGS/EW OBSERVABLES AT DIMENSION 8

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Based on: Bertuzzo, Grojean & RSG (in prep)
RSG, Pomarol & Riva (2014)

SMEFT: MODEL INDEPENDENT PARAMETRISATION

Vectorlike fermions   Superpartners   Composite states

Top partners   *W′,Z′*   Heavy Higgs bosons

1 TeV

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{84} \frac{c_i}{\Lambda^2} \mathcal{O}_i^6 + \sum_{i=1}^{993} \frac{c_i}{\Lambda^2} \mathcal{O}_i^8 \cdots$$

Deviations from SM in all possible low-energy measurements at the LHC/elsewhere

100 GeV

Mass

SMEFT: A PREDICTIVE FRAMEWORK

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{i=1}^{84} \frac{c_i}{\Lambda^2} \mathcal{O}_i^6 + \sum_{i=1}^{993} \frac{c_i}{\Lambda^2} \mathcal{O}_i^8 \cdots$$

- SMEFT not just a parametrisation but a predictive framework.
- At a given order in SMEFT fewer parameters than observables that it contributes to.
- These lead to predictions of some observable as a function of others

D4-PREDICTIONS

- Same SU(2)x U(1) invariant D4 operator gives rise to both LHS and RHS

$$m_W = m_Z \cos\theta_W \qquad g^h_{ff} = \frac{m_f}{v}$$

- Experimentally fermion mass and Yukawa completely different measurements. So are W and Z mass.

$$y_f \bar{Q} H f + h.c. \to m_f \left(1 + \frac{h}{v}\right) \bar{f} f$$

$$|D_\mu H|^2 \to \left(m_W^2 W^+ W^- + \frac{m_Z^2}{2} Z^2\right)$$

- But actually we are probing the same effect by two different measurements.

LIBERATING OBSERVABLES AT D6

$$m_W = m_Z \cos\theta_W \qquad g^h_{ff} = \frac{m_f}{v}$$

- At D6 level another SU(2)x U(1) invariant operator:

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

- Now 2 operators and 2 measurements so prediction is broken

$$(m_W^2 - m_Z^2 c_{\theta_W}^2) = c_T \frac{v^2}{\Lambda^2} m_Z^2$$

- At $O(v^2/\Lambda^2)$, *W* and *Z* mass independent couplings. We liberated an observable/ opened a new BSM primary at D6.

BSM PRIMARIES

Up to a given order

No of independent observables = No of operators=N

The subset of N observables that are all independent and can be best measured are called BSM Primaries

RSG, Pomarol & Riva (2014)

LIBERATING OBSERVABLES AT D8

$$m_W = m_Z \cos\theta_W \qquad g^h_{ff} = \frac{m_f}{v}$$

- At D6 level another SU(2)x U(1) invariant operator:

$$\mathcal{O}_y = y_f |H|^2 \bar{F} H f$$

- Now 2 operators and 2 observables so prediction is broken.

$$\left(g^h_{ff} - \frac{m_f}{v}\right) = c_y \frac{v^2}{\Lambda^2}\frac{m_f}{v}$$

- At $O(v^2/\Lambda^2)$, *hff* coupling and mass independent couplings. We liberated an observable/opened a new BSM primary at D6.

D4 AND D6 PREDICTION EXAMPLE

- At D4 level *Zff, Wff* couplings can be completely determined as a function of (g,g',v) which can be determined by W/Z mass and fine structure constant measurements.

$$g_f^Z = \frac{g}{c_{\theta_W}}(T_3 - Q s^2_{\theta_W}), \qquad g_F^W = \frac{g}{\sqrt{2}}$$

- At D6 level following operators break these D4 predictions at $O(v^2/\Lambda^2)$

$$\mathcal{O}_{e_R} = iH^\dagger \overleftrightarrow{D}_\mu H \bar{e}_R \gamma^\mu e_R \qquad \mathcal{O}_L = iH^\dagger \overleftrightarrow{D}_\mu H \bar{L} \gamma^\mu L \qquad \mathcal{O}_L^{(3)} = iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{L} \sigma^a \gamma^\mu L.$$

- But (considering only leptons) there are four couplings and only 3 operators so 1 prediction:

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

↓

$$\delta g^W_{\nu e} - \frac{c_{\theta_W}(\delta g^Z_{\nu_l} - \delta g^Z_{e_l})}{\sqrt{2}} = 0$$

LIBERATING OBSERVABLES AT D8

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

$$O_{3L}^{(3)Q} = iH^\dagger \overleftrightarrow{D}_\mu H (H^\dagger \sigma^a H) \bar{L} \sigma^a \gamma^\mu L$$

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

$$\delta^8 g^W_{\nu e} = \delta g^W_{\nu e} - \frac{c_{\theta_W}(\delta g^Z_{\nu_l} - \delta g^Z_{e_l})}{\sqrt{2}} = -\frac{c^{(3)}_{3L} g}{2\sqrt{2}} \frac{v^4}{\Lambda^4}$$

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

Bertuzzo, Grojean & RSG (in prep)

ANOMALOUS COUPLINGS AS 'OBSERVABLES'

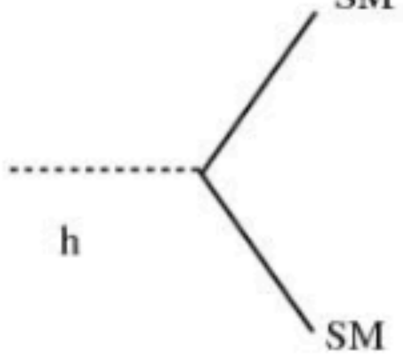
So far all 'observables' we have considered were **QCD & EM invariant vertices/ anomalous couplings**

More examples:

(1) Higgs observables (20):

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

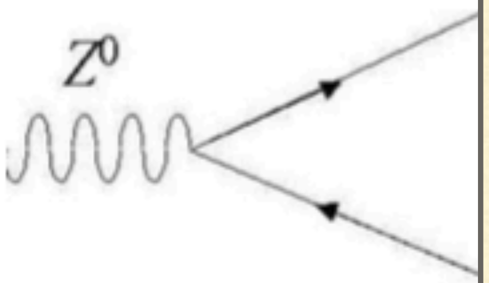
$$hZ_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$$



(2) Electorweak precision observables (9):

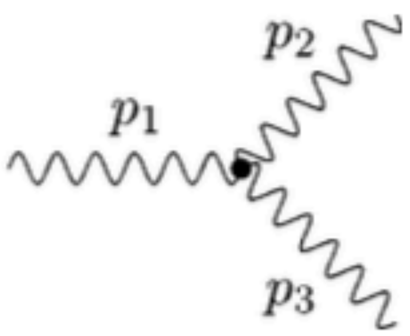
$$Z_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$$

$$W^+_\mu \bar{\nu}_L \gamma^\mu e_L$$



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

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



SMEFT: A PREDICTIVE FRAMEWORK

No of operators (No of free parameters)	<	No of 'observables' (anomalous couplings)
Eg. $iH^\dagger \overleftrightarrow{D}_\mu H \,\bar{f}\gamma^\mu f, (H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu}$		**Eg.** $Z_\mu \bar{f}\gamma^\mu f,\; hZ_\mu \bar{f}\gamma^\mu f,\; hZ_{\mu\nu}Z^{\mu\nu}$
Invariant under full electroweak group		Invariant under $U(1)_{em}$
Smaller number More Symmetry		Larger number Less Symmetry

No of SMEFT Predictions = No of observables - No of Operators

WHAT ABOUT THE HEFT?

- So far we have considered lagrangian terms in broken EW phase as they are can be thought of as ‘observables’ that can be separately measured.

- But these can be promoted to invariant terms where EW symmetry is non-linearly realised, i.e. HEFT operators.

$$D_\mu U = U^\dagger \partial_\mu U - iU^\dagger [gW^a_\mu T_a + g' B_\mu Y] U$$

$$\begin{aligned} e\mathcal{A}_\mu &= 2i\ \mathrm{Tr}[X_{em} D_\mu U] \\ \frac{g}{2c_w}\mathcal{Z}_\mu &= i\ \mathrm{Tr}[X_3 D_\mu U] \\ g\mathcal{W}^\pm_\mu &= i\sqrt{2}\ \mathrm{Tr}[T_\pm D_\mu U] \end{aligned}$$

↓

Unitary gauge: U=1

↓

$$\{\mathcal{A},\ \mathcal{Z},\ \mathcal{W}^\pm\} \to \{A, Z, W^\pm\}$$

Chanowitz, Holden & Georgi (1987)

WHAT ABOUT THE HEFT?

- HEFT equivalent to lagrangian of EM invariant operators.
- All anomalous couplings independent
- No predictions apart from those that test EM invariance

$$D_\mu U = U^\dagger \partial_\mu U - iU^\dagger [g W_\mu^a T_a + g' B_\mu Y] U$$

$$\begin{aligned} e\mathcal{A}_\mu &= 2i\ \mathrm{Tr}[X_{em} D_\mu U] \\ \frac{g}{2c_w}\mathcal{Z}_\mu &= i\ \mathrm{Tr}[X_3 D_\mu U] \\ g\mathcal{W}_\mu^\pm &= i\sqrt{2}\ \mathrm{Tr}[T_\pm D_\mu U] \end{aligned}$$

↓

Unitary gauge: U=1

↓

$$\{\mathcal{A},\ \mathcal{Z},\ \mathcal{W}^\pm\} \to \{A, Z, W^\pm\}$$

Chanowitz, Holden & Georgi (1987)

WHICH OBSERVABLES DO WE INCLUDE ?

- We focus on vertices involved in the following processes: →

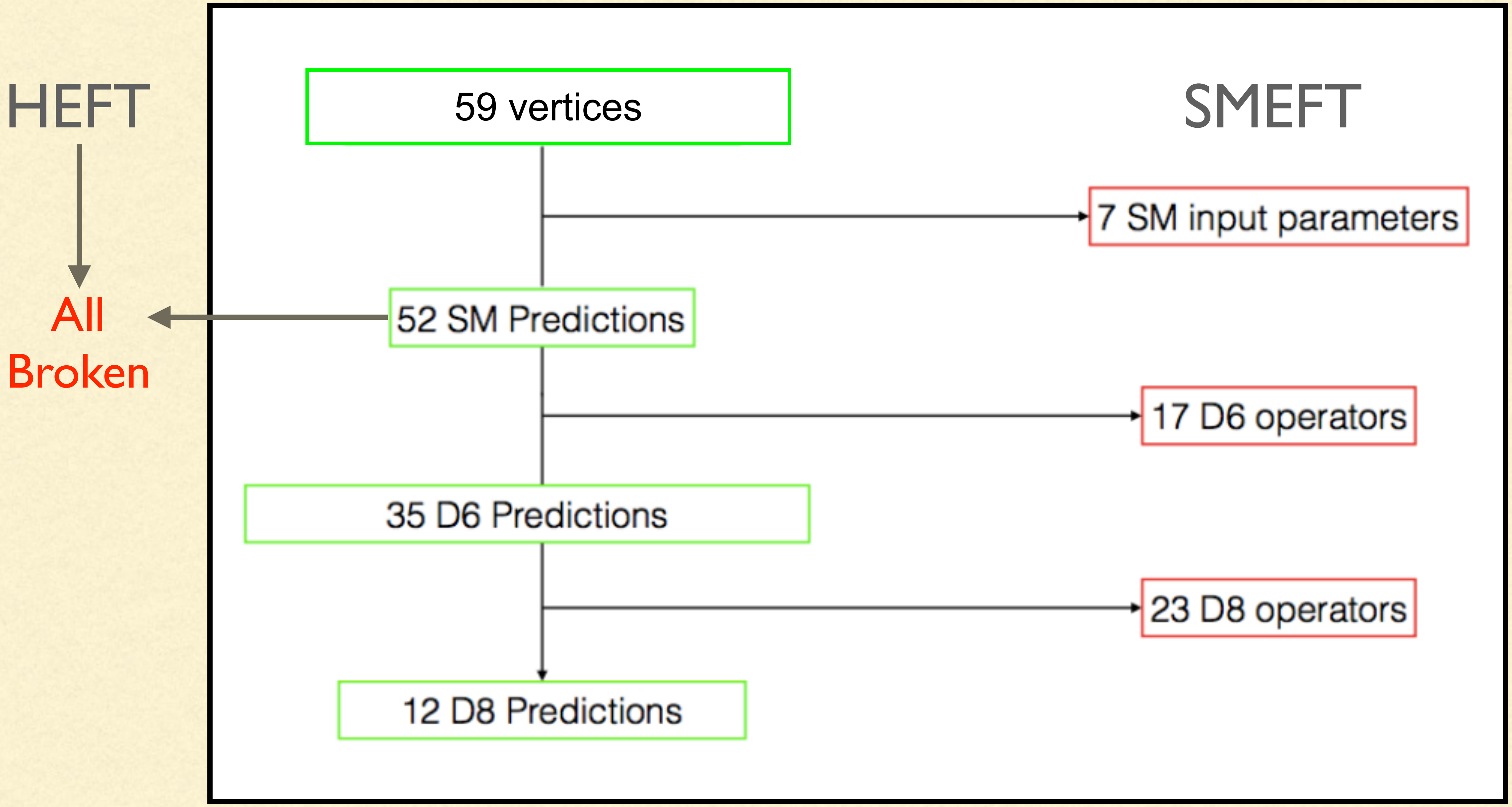
$$pp/ee/VV \rightarrow VV/Vh$$
$$pp/VV \rightarrow h$$
$$h \rightarrow Vff/\ \gamma\gamma\ /ff$$

$$pp \rightarrow hh, hhh$$

- Let us focus up to dimension 4 vertices, i.e. the lowest order of HEFT. These are almost all the 'observables' of D6 SMEFT in Higgs/EW Physics
- For these O(1) deviations from predictions in HEFT
- Dimension 6 operators with more than or equal to 2 Higgs doublets can contribute
- Dimension 8 operators with more than or equal to 4 Higgs doublets can contribute

$$\mathcal{O}_6 = |H|^2 \mathcal{O}_4 \rightarrow v^2 \mathcal{O}_4$$
$$\mathcal{O}_8 = |H|^4 \mathcal{O}_4 \rightarrow v^4 \mathcal{O}_4$$

COUNTING



(considering only 1 generation for the purpose of counting)

Bertuzzo, Grojean & RSG (in prep)

COUNTING

HI

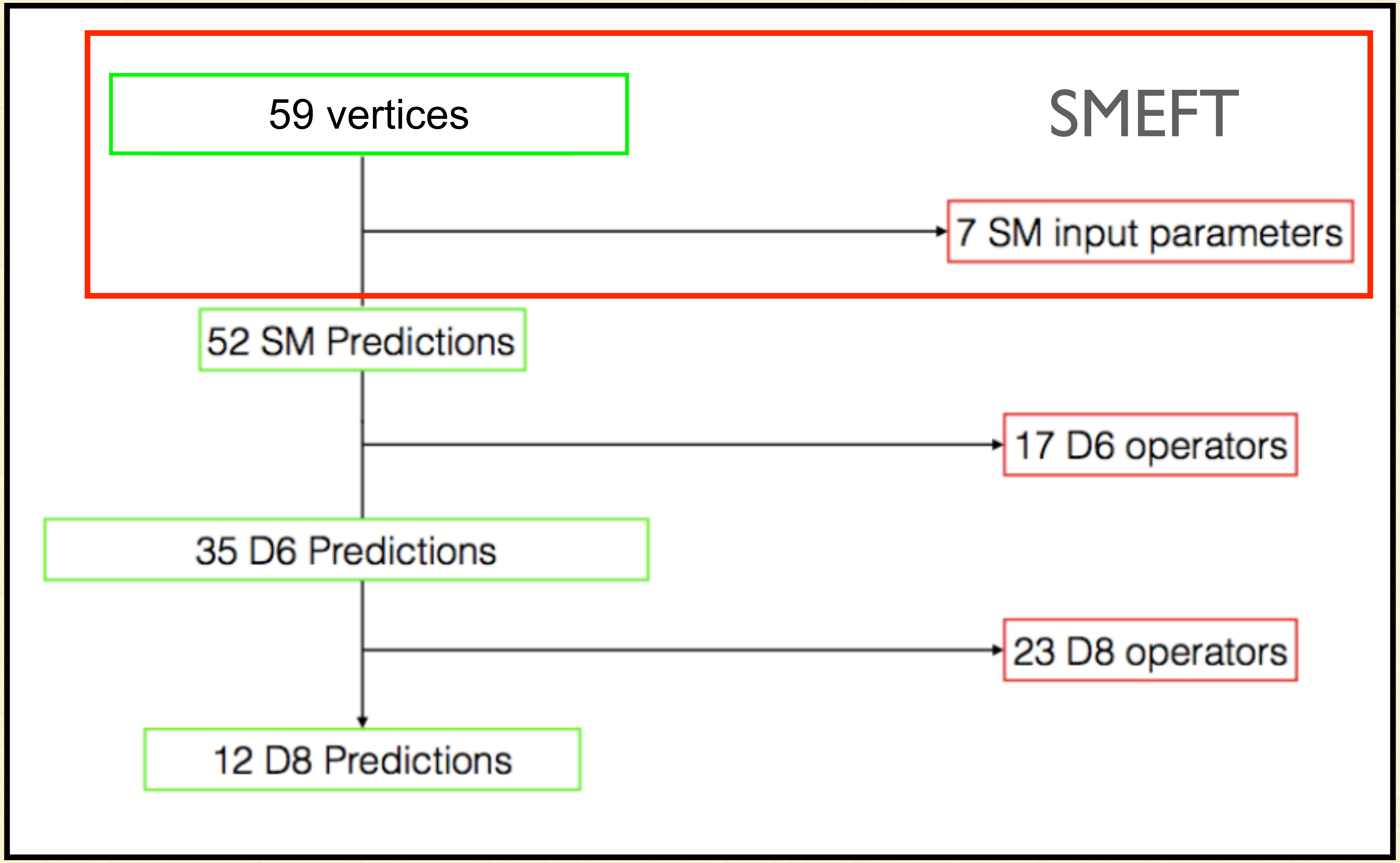
br

Pattern of breaking of these predictions distinguishes between HEFT and SMEFT:

1. HEFT: O(1) breaking
2. SMEFT: Breaking order by order in v^2/Λ^2
3. With sufficient no of Higgs doublets all predictions broken in SMEFT too at high D

Bertuzzo, Grojean & RSG (in prep)

COUNTING


59 vertices
SMEFT
7 SM input parameters
52 SM Predictions
17 D6 operators
35 D6 Predictions
23 D8 operators
12 D8 Predictions

59 VERTICES

7 input parameters

$$\alpha_{em}, m_W^2, m_Z^2, m_u, m_d, m_e, \text{ and } m_h$$

52 deformations

$$\Delta\mathcal{L}_{Vff} = \sum_f \delta g_f^Z Z_\mu \bar{f}\gamma^\mu f_{L,R} + \delta g_{e\nu}^W (W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + h.c.)L + \delta g_{ud}^W (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.)$$

$$\Delta\mathcal{L}_{TGC} = \mathrm{i} g c_W \left[\delta g_1^Z Z_\mu \left(W_\nu^+ \mathcal{W}^{-\mu\nu} - W_\nu^- \mathcal{W}^{+\mu\nu}\right) + \delta\kappa^Z W_\mu^+ W_\nu^- Z^{\mu\nu}\right] + \mathrm{i} e\, \delta\kappa^\gamma W_\mu^+ W_\nu^- A^{\mu\nu} + g_5 \epsilon^{\mu\nu\rho\sigma} W_\mu^+ \overleftrightarrow{D}_\rho W_\nu^- Z_\sigma$$

$$\Delta\mathcal{L}_{QGC} = g^2 {c_W}^2 \left[\delta g_{Q1}^{ZZ} Z^\mu Z^\nu W_\mu^- W_\nu^+ - \delta g_{Q2}^{ZZ} Z^\mu Z_\mu W^{-\nu} W_\nu^+\right] + \frac{g^2}{4{c_W}^4} h_Q^{ZZ} (Z^\mu Z_\mu)^2 + \frac{g^2}{2}\left[\delta g_{Q1}^{WW} W^{-\mu} W^{+\nu} W_\mu^- W_\nu^+ - \delta g_{Q2}^{WW} \left(W^{-\mu} W_\mu^+\right)^2\right]$$

$$\Delta\mathcal{L}_h = g_{VV}^h\, h \left[W^{+\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + g_{ff}^h \left(h \bar{f}_L f_R + h.c.\right) + \delta g_{ZZ}^h\, h \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2} + \sum_f g_{Zff}^h \frac{h}{v}\left(Z_\mu \bar{f}\gamma^\mu f + h.c.\right) + g_{Wud}^h \frac{h}{v}\left(W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.\right) + g_{W\nu e}^h \frac{h}{v}\left(W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + \right. + \kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} + \kappa_{\gamma\gamma} \frac{h}{2v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \kappa_{WW} \frac{h}{v} \mathcal{W}^{+\mu\nu} \mathcal{W}_{\mu\nu}^- + \kappa_{GG} \frac{h}{2v} G^{A\,\mu\nu} G_{\mu\nu}^A$$

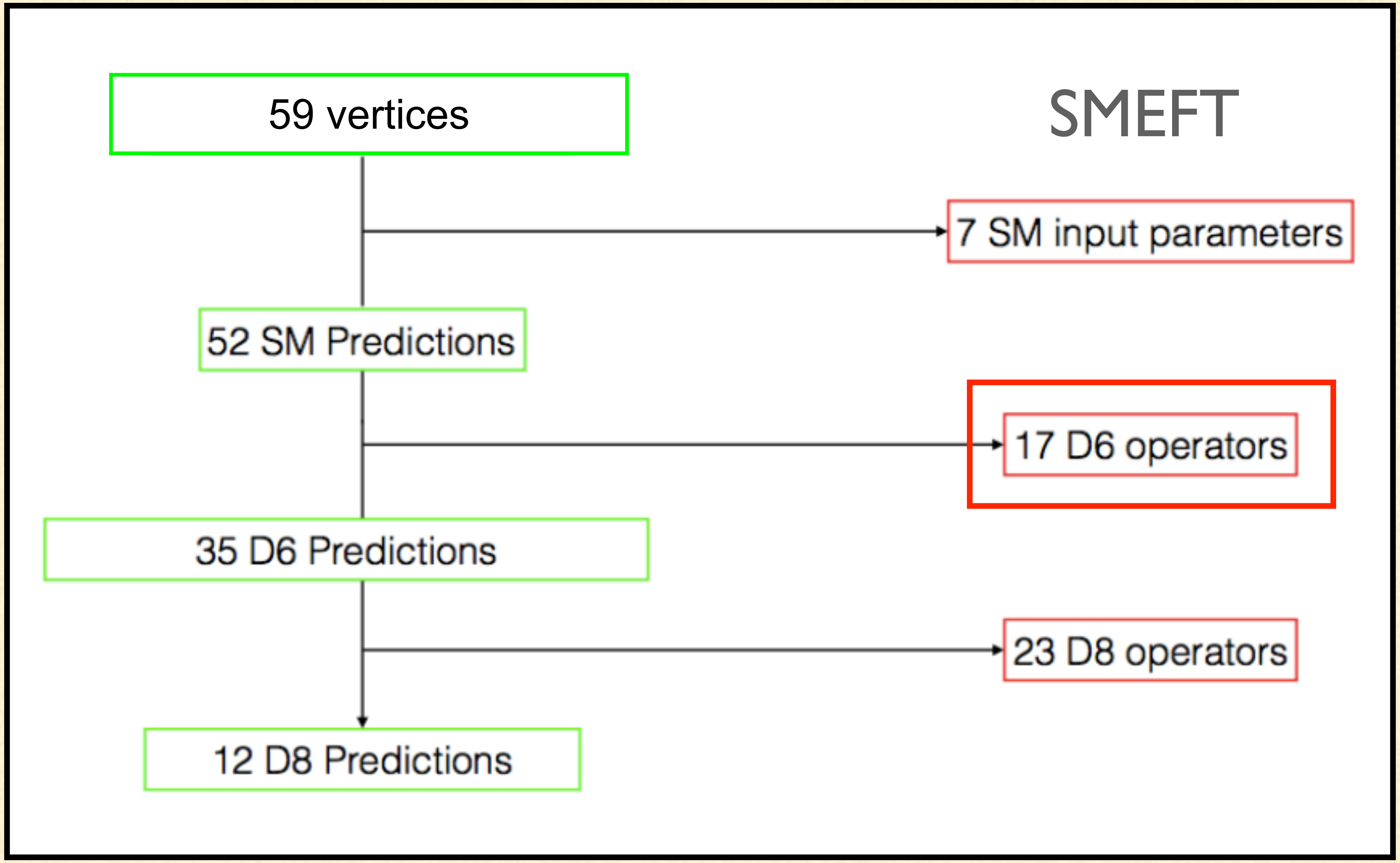
$$\Delta\mathcal{L}_{h^2,h^3}^{gg} = \kappa_{GG}^{hh} \frac{h^2}{4v^2} G^{A\,\mu\nu} G_{\mu\nu}^A - g_{3h}\, v h^3 - g_{4h}\, h^4$$

$$\Delta\mathcal{L}_{hh}^{V^2} = g_{VV}^{hh} \frac{h^2}{2}\left[W^{+\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + \delta g_{ZZ}^{hh} \frac{h^2}{2} \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2} + g_{hh2}^Z \frac{\partial_\mu h \partial_\nu h}{2v^2} \frac{Z^\mu Z'^\nu}{c_{\theta_W}^2} + g_{hh3}^Z \frac{(\partial_\nu h)^2}{v^2} \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2} + g_{hh2}^W \frac{\partial_\mu h \partial_\nu h}{2v^2}\left(W^{+\mu} W^{-\nu} + h.c.\right) + g_{hh3}^W \frac{(\partial_\nu h)^2}{v^2} W^{+\mu} W_\mu^- + \kappa_{WW}^{hh} \frac{h^2}{2v^2} \mathcal{W}^{+\mu\nu} \mathcal{W}_{\mu\nu}^- + \kappa_{ZZ}^{hh} \frac{h^2}{4v^2} Z^{\mu\nu} Z_{\mu\nu}.$$

$$\Delta\mathcal{L}_{hV^3} = \mathrm{i} g c_W \frac{h}{v}\left[g_1^{hZ} Z_\mu \left(W_\nu^+ \mathcal{W}^{-\mu\nu} - W_\nu^- \mathcal{W}^{+\mu\nu}\right) + \kappa^{hZ} W_\mu^+ W_\nu^- Z^{\mu\nu}\right] + \mathrm{i} e\, \kappa^{h\gamma} \frac{h}{v} W_\mu^+ W_\nu^- A^{\mu\nu} + \mathrm{i} g^{\partial h Z} \frac{g}{2c_{\theta_W}} \frac{\partial_\mu h}{v} Z_\nu \left(W_\mu^+ W^{-\nu} - W_\mu^- W^{+\nu}\right).$$

Bertuzzo, Grojean & RSG (in prep)

COUNTING

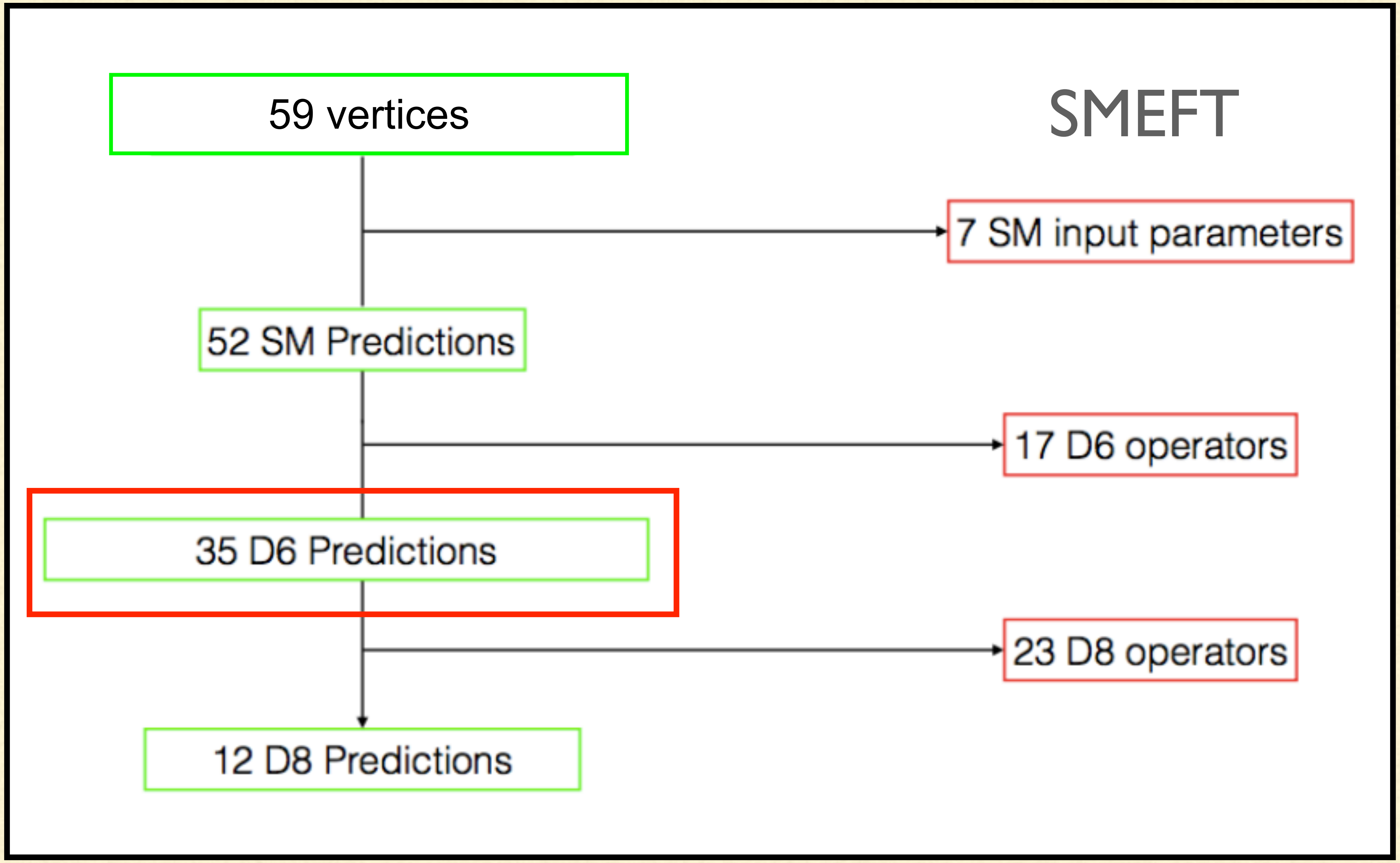


Bertuzzo, Grojean & RSG (in prep)

17 D6 OPERATORS

H^2-operators
$\mathcal{O}_{H\Box} = \|H\|^2 \Box \|H\|^2$
$\mathcal{O}_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$
$\mathcal{O}_6 = \lambda \|H\|^6$
$\mathcal{O}_y = \|H\|^2 \bar{F} H f$
$\mathcal{O}_f = i H^\dagger \overleftrightarrow{D}_\mu H \bar{f} \gamma^\mu f$
$\mathcal{O}_L = i H^\dagger \overleftrightarrow{D}_\mu H \bar{F} \gamma^\mu F$
$\mathcal{O}_L^{(3)} = i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{F} \sigma^a \gamma^\mu F$
$\mathcal{O}_{BB} = g'^2 \|H\|^2 B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{WW} = g^2 \|H\|^2 W^a_{\mu\nu} W^{a\mu\nu}$
$\mathcal{O}_{GG} = g_s^2 \|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$
H^0-operators
$\mathcal{O}_{3W} = \frac{\epsilon_{abc}}{3!} W^{a\mu\nu} W^{b\mu\rho} W^{c\nu\rho}$

COUNTING



59 vertices
SMEFT
7 SM input parameters
52 SM Predictions
17 D6 operators
35 D6 Predictions
23 D8 operators
12 D8 Predictions

35 D6 PREDICTIONS

35 Dependant couplings

$$
\begin{aligned}
\delta g^W_{ff'} &= \frac{c_{\theta_W}(\delta g^Z_f - \delta g^Z_{f'})}{\sqrt{2}} \\
\delta\kappa_Z &= \delta g^Z_1 - t^2_{\theta_W}\delta\kappa_\gamma \\
g^h_{Zf} &= \delta g^Z_f - 2\delta g^Z_1(g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y \frac{s_{\theta_W}}{c^2_{\theta_W}} \\
g^h_{WF} &= \sqrt{2}c_{\theta_W}(\delta g^Z_f - \delta g^Z_{f'}) - 2\delta g^Z_1 g^W_f c^2_{\theta_W} \\
\kappa_{WW} &= \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma} \\
\delta g^h_{ZZ} &= (\delta g^Z_1 e^2 - \delta\kappa_\gamma g'^2)v \\
\kappa_{ZZ} &= \frac{\delta\kappa_\gamma}{2c^2_{\theta_W}} + \kappa_{Z\gamma}\frac{c_{2\theta_W}}{2c^2_{\theta_W}} + \kappa_{\gamma\gamma} \\
\kappa^{h^2}_{WW} &= \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma} \\
\kappa^{h^2}_{ZZ} &= \frac{\delta\kappa_\gamma}{2c^2_{\theta_W}} + \kappa_{Z\gamma}\frac{c_{2\theta_W}}{2c^2_{\theta_W}} + \kappa_{\gamma\gamma} \\
\delta g^W_{hh1} &= \frac{5\delta g^h_{VV}}{4v} \\
\delta g^Z_{hh1} &= \frac{5\delta g^h_{VV}}{4v} \\
\delta g^{WW}_1 &= 2c_W{}^2\delta g^Z_1 \\
\delta g^{WW}_2 &= 2c_W{}^2\delta g^Z_1 \\
\delta g^{ZZ}_1 &= 2\delta g^Z_1 \\
\delta g^{ZZ}_2 &= 2\delta g^Z_1 \\
g^h_{Z1} &= -\frac{2\kappa_{Z\gamma}s_{\theta_W}}{c^2_{\theta_W}} - \frac{2\delta\kappa_\gamma}{c^2_{\theta_W}} - \frac{2\kappa_{\gamma\gamma}}{c^2_{\theta_W}} \\
\kappa^h_\gamma &= -\frac{2\kappa_{Z\gamma}}{t_{\theta_W}} - 2\kappa_{\gamma\gamma} \\
\kappa^h_Z &= -\frac{2\delta\kappa_\gamma}{c^2_{\theta_W}} - \frac{2\kappa_{Z\gamma}}{t_{\theta_W}} - 2\kappa_{\gamma\gamma}
\end{aligned}
$$

as a function of
17 best measured
'observables'
called
BSM Primaries

RSG, Pomarol & Riva (2014)

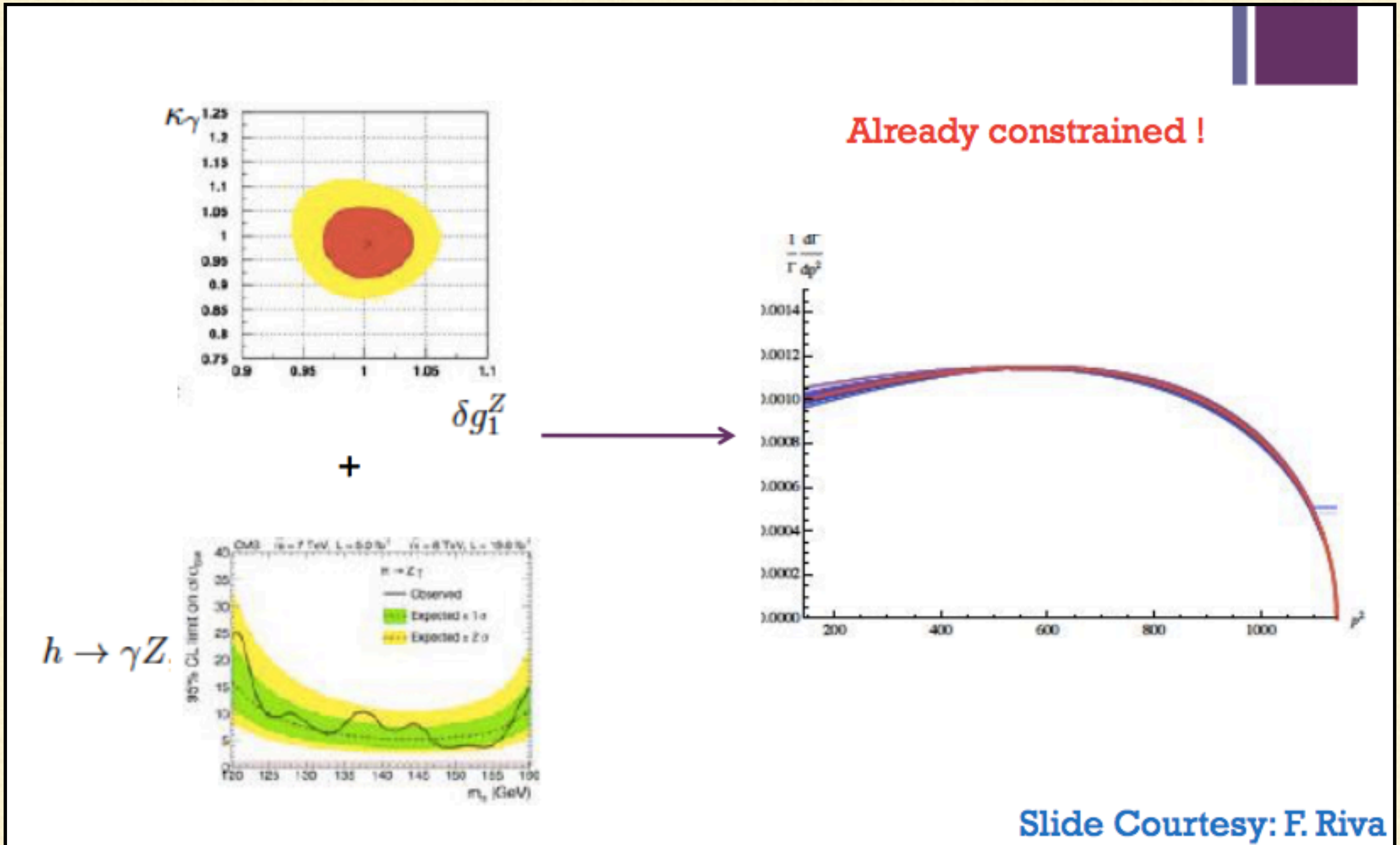
17 BSM PRIMARIES

	Process	Vertex
Higgs Physics (8)	$h \to \gamma\gamma,\ h \to \gamma Z,\ h \to gg$ $h \to VV, h \to ff, pp \to h^* \to hh$	$hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu}\ hG_{\mu\nu}G^{\mu\nu}$ $hW^{+\mu}W^{-}_{\mu},\ h\bar{f}f,\ h^3$
Z-pole(7)	$Z \to ff$ (2 can be traded for S,T)	$Z_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$
Triple Gauge Couplings(2)	$ee \to WW$	$g_1^Z c_{\theta_W} Z^\mu \left(W^{+\nu}\hat{W}^{-}_{\mu\nu} - W^{-\nu}\hat{W}^{+}_{\mu\nu}\right)$ $\kappa_\gamma s_{\theta_W} \hat{A}^{\mu\nu} W^{+}_{\mu} W^{-}_{\nu}$

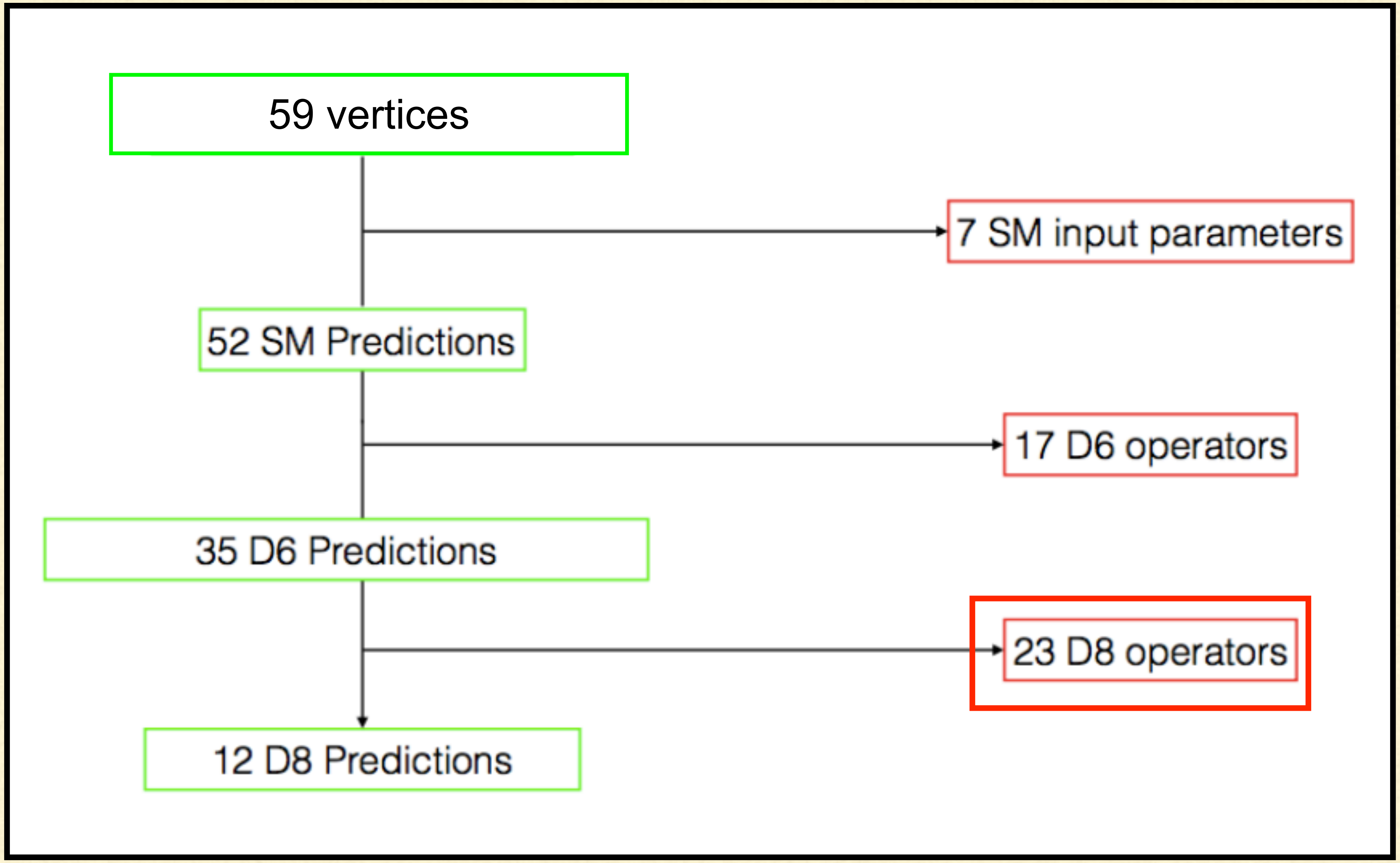
RSG, Pomarol & Riva (2014)

Do these 17 best measurements make the rest of the 52-17=35 ‘observables’ irrelevant ?

EXAMPLE OF D6 PREDICTION: *h>Vff*



COUNTING



D8 opens 23 new primaries liberates 23 observables !

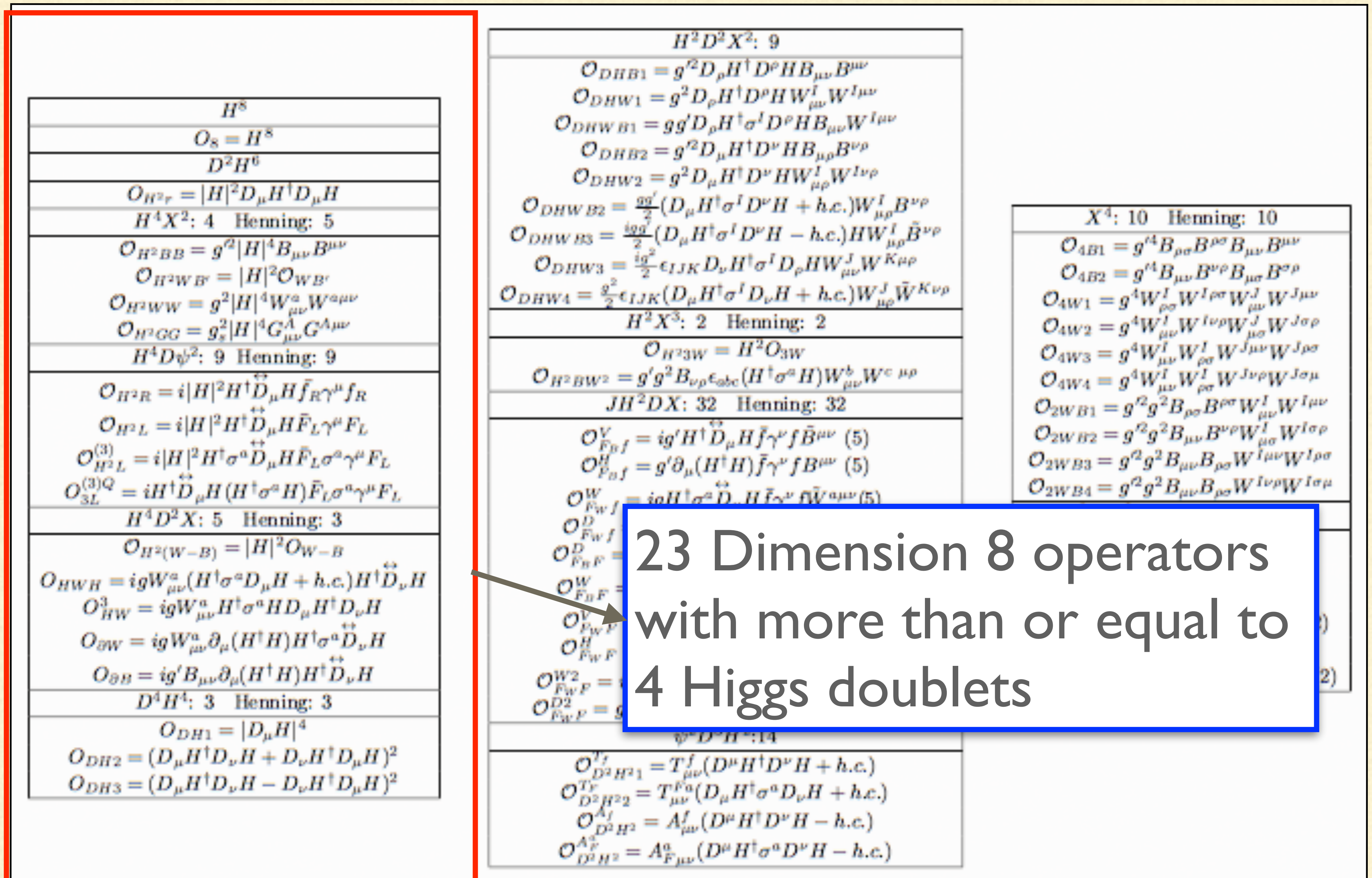
D8 OPERATORS

H^8
$O_8 = H^8$
D^2H^6
$O_{H^2r} = \lvert H\rvert^2 D_\mu H^\dagger D_\mu H$
H^4X^2: 4 Henning: 5
$\mathcal{O}_{H^2BB} = g'^2 \lvert H\rvert^4 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{H^2WB'} = \lvert H\rvert^2 \mathcal{O}_{WB'}$
$\mathcal{O}_{H^2WW} = g^2 \lvert H\rvert^4 W^a_{\mu\nu}W^{a\mu\nu}$
$\mathcal{O}_{H^2GG} = g_s^2 \lvert H\rvert^4 G^A_{\mu\nu}G^{A\mu\nu}$
$H^4D\psi^2$: 9 Henning: 9
$\mathcal{O}_{H^2R} = i\lvert H\rvert^2 H^\dagger \overleftrightarrow{D}_\mu H \bar{f}_R\gamma^\mu f_R$
$\mathcal{O}_{H^2L} = i\lvert H\rvert^2 H^\dagger \overleftrightarrow{D}_\mu H \bar{F}_L\gamma^\mu F_L$
$\mathcal{O}^{(3)}_{H^2L} = i\lvert H\rvert^2 H^\dagger\sigma^a \overleftrightarrow{D}_\mu H \bar{F}_L\sigma^a\gamma^\mu F_L$
$O^{(3)Q}_{3L} = iH^\dagger \overleftrightarrow{D}_\mu H(H^\dagger\sigma^a H)\bar{F}_L\sigma^a\gamma^\mu F_L$
H^4D^2X: 5 Henning: 3
$\mathcal{O}_{H^2(W-B)} = \lvert H\rvert^2 O_{W-B}$
$O_{HWH} = igW^a_{\mu\nu}(H^\dagger\sigma^a D_\mu H + h.c.)H^\dagger \overleftrightarrow{D}_\nu H$
$O^3_{HW} = igW^a_{\mu\nu}H^\dagger\sigma^a H D_\mu H^\dagger D_\nu H$
$O_{\partial W} = igW^a_{\mu\nu}\partial_\mu(H^\dagger H)H^\dagger\sigma^a \overleftrightarrow{D}_\nu H$
$O_{\partial B} = ig'B_{\mu\nu}\partial_\mu(H^\dagger H)H^\dagger \overleftrightarrow{D}_\nu H$
D^4H^4: 3 Henning: 3
$O_{DH1} = \lvert D_\mu H\rvert^4$
$O_{DH2} = (D_\mu H^\dagger D_\nu H + D_\nu H^\dagger D_\mu H)^2$
$O_{DH3} = (D_\mu H^\dagger D_\nu H - D_\nu H^\dagger D_\mu H)^2$

$H^2D^2X^2$: 9
$\mathcal{O}_{DHB1} = g'^2 D_\rho H^\dagger D^\rho H B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{DHW1} = g^2 D_\rho H^\dagger D^\rho H W^I_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{DHWB1} = gg' D_\rho H^\dagger\sigma^I D^\rho H B_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{DHB2} = g'^2 D_\mu H^\dagger D^\nu H B_{\mu\rho}B^{\nu\rho}$
$\mathcal{O}_{DHW2} = g^2 D_\mu H^\dagger D^\nu H W^I_{\mu\rho}W^{I\nu\rho}$
$\mathcal{O}_{DHWB2} = \frac{gg'}{2}(D_\mu H^\dagger\sigma^I D^\nu H + h.c.)W^I_{\mu\rho}B^{\nu\rho}$
$\mathcal{O}_{DHWB3} = \frac{igg'}{2}(D_\mu H^\dagger\sigma^I D^\nu H - h.c.)HW^I_{\mu\rho}\tilde{B}^{\nu\rho}$
$\mathcal{O}_{DHW3} = \frac{ig^2}{2}\epsilon_{IJK}D_\nu H^\dagger\sigma^I D_\rho H W^J_{\mu\nu}W^{K\mu\rho}$
$\mathcal{O}_{DHW4} = \frac{g^2}{2}\epsilon_{IJK}(D_\mu H^\dagger\sigma^I D_\nu H + h.c.)W^J_{\mu\rho}\tilde{W}^{K\nu\rho}$
H^2X^3: 2 Henning: 2
$\mathcal{O}_{H^23W} = H^2 O_{3W}$
$\mathcal{O}_{H^2BW^2} = g'g^2 B_{\nu\rho}\epsilon_{abc}(H^\dagger\sigma^a H)W^b_{\mu\nu}W^{c\,\mu\rho}$
JH^2DX: 32 Henning: 32
$\mathcal{O}^V_{F_Bf} = ig'H^\dagger \overleftrightarrow{D}_\mu H\bar{f}\gamma^\nu f\tilde{B}^{\mu\nu}$ (5)
$\mathcal{O}^H_{F_Bf} = g'\partial_\mu(H^\dagger H)\bar{f}\gamma^\nu f B^{\mu\nu}$ (5)
$\mathcal{O}^W_{F_Wf} = igH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\bar{f}\gamma^\nu f\tilde{W}^{a\mu\nu}$(5)
$\mathcal{O}^D_{F_Wf} = gD_\mu(H^\dagger\sigma^a H)\bar{f}\gamma^\nu f W^{a\mu\nu}$(5)
$\mathcal{O}^D_{F_BF} = g'D_\mu(H^\dagger\sigma^a H)\bar{F}\sigma^a\gamma^\nu F B^{\mu\nu}$(2)
$\mathcal{O}^W_{F_BF} = ig'H^\dagger\sigma^a \overleftrightarrow{D}_\mu H\bar{F}\sigma^a\gamma^\nu F\tilde{B}^{\mu\nu}$(2)
$\mathcal{O}^V_{F_WF} = igH^\dagger \overleftrightarrow{D}_\mu H\bar{F}\sigma^a\gamma^\nu F\tilde{W}^{a\mu\nu}$(2)
$\mathcal{O}^H_{F_WF} = g\partial_\mu(H^\dagger H)\bar{F}\sigma^a\gamma^\nu F W^{a\mu\nu}$(2)
$\mathcal{O}^{W2}_{F_WF} = ig\epsilon_{abc}H^\dagger\sigma^a \overleftrightarrow{D}_\mu H\bar{F}\sigma^b\gamma^\nu F W^{c\mu\nu}$(2)
$\mathcal{O}^{D2}_{F_WF} = g\epsilon_{abc}D_\mu(H^\dagger\sigma^a H)\bar{F}\sigma^b\gamma^\nu F\tilde{W}^{c\mu\nu}$(2)
$\psi^2D^3H^2$:14
$\mathcal{O}^{T_f}_{D^2H^21} = T^f_{\mu\nu}(D^\mu H^\dagger D^\nu H + h.c.)$
$\mathcal{O}^{T_F}_{D^2H^22} = T^{Fa}_{\mu\nu}(D_\mu H^\dagger\sigma^a D_\nu H + h.c.)$
$\mathcal{O}^{A_f}_{D^2H^2} = A^f_{\mu\nu}(D^\mu H^\dagger D^\nu H - h.c.)$
$\mathcal{O}^{A^a_F}_{D^2H^2} = A^a_{F\mu\nu}(D^\mu H^\dagger\sigma^a D^\nu H - h.c.)$

X^4: 10 Henning: 10
$\mathcal{O}_{4B1} = g'^4 B_{\rho\sigma}B^{\rho\sigma}B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{4B2} = g'^4 B_{\mu\nu}B^{\nu\rho}B_{\mu\sigma}B^{\sigma\rho}$
$\mathcal{O}_{4W1} = g^4 W^I_{\rho\sigma}W^{I\rho\sigma}W^J_{\mu\nu}W^{J\mu\nu}$
$\mathcal{O}_{4W2} = g^4 W^I_{\mu\nu}W^{I\nu\rho}W^J_{\mu\sigma}W^{J\sigma\rho}$
$\mathcal{O}_{4W3} = g^4 W^I_{\mu\nu}W^I_{\rho\sigma}W^{J\mu\nu}W^{J\rho\sigma}$
$\mathcal{O}_{4W4} = g^4 W^I_{\mu\nu}W^I_{\rho\sigma}W^{J\nu\rho}W^{J\sigma\mu}$
$\mathcal{O}_{2WB1} = g'^2g^2 B_{\rho\sigma}B^{\rho\sigma}W^I_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{2WB2} = g'^2g^2 B_{\mu\nu}B^{\nu\rho}W^I_{\mu\sigma}W^{I\sigma\rho}$
$\mathcal{O}_{2WB3} = g'^2g^2 B_{\mu\nu}B_{\rho\sigma}W^{I\mu\nu}W^{I\rho\sigma}$
$\mathcal{O}_{2WB4} = g'^2g^2 B_{\mu\nu}B_{\rho\sigma}W^{I\nu\rho}W^{I\sigma\mu}$
ψ^2DX^2: 18 Henning: 18
$\mathcal{O}_{TBB} = g'^2 T_{\mu\nu}B^{\mu\rho}B^{\nu\rho}$(5)
$\mathcal{O}_{TWB} = gg'T_{a\mu\nu}W^{a\mu\rho}B^{\nu\rho}$(2)
$\mathcal{O}^1_{TWW} = g^2 T_{\mu\nu}W^{a\mu\rho}W^{a\nu\rho}$(5)
$\mathcal{O}^2_{TWW} = g^2\epsilon_{abc}T^a_{\mu\nu}W^{b\mu\rho}\tilde{W}^{c\nu\rho}$(2)
$\mathcal{O}_{JWB} = gg'J^a_\nu W^{a\mu\rho}\partial_\nu\tilde{B}^{\mu\rho}$(2)
$\mathcal{O}_{JWW} = g^2\epsilon_{abc}J^a_\nu W^{b\mu\rho}D_\nu W^{c\mu\rho}$(2)

D8 OPERATORS



H^8

$\mathcal{O}_8 = H^8$

D^2H^6

$\mathcal{O}_{H^2_r} = |H|^2 D_\mu H^\dagger D_\mu H$

H^4X^2: 4 Henning: 5

$\mathcal{O}_{H^2BB} = g'^2|H|^4 B_{\mu\nu}B^{\mu\nu}$

$\mathcal{O}_{H^2WB'} = |H|^2\mathcal{O}_{WB'}$

$\mathcal{O}_{H^2WW} = g^2|H|^4 W^a_{\mu\nu}W^{a\mu\nu}$

$\mathcal{O}_{H^2GG} = g_s^2|H|^4 G^A_{\mu\nu}G^{A\mu\nu}$

$H^4D\psi^2$: 9 Henning: 9

$\mathcal{O}_{H^2R} = i|H|^2 H^\dagger \overleftrightarrow{D}_\mu H \bar{f}_R\gamma^\mu f_R$

$\mathcal{O}_{H^2L} = i|H|^2 H^\dagger \overleftrightarrow{D}_\mu H \bar{F}_L\gamma^\mu F_L$

$\mathcal{O}^{(3)}_{H^2L} = i|H|^2 H^\dagger\sigma^a \overleftrightarrow{D}_\mu H \bar{F}_L\sigma^a\gamma^\mu F_L$

$\mathcal{O}^{(3)Q}_{3L} = iH^\dagger \overleftrightarrow{D}_\mu H (H^\dagger\sigma^a H)\bar{F}_L\sigma^a\gamma^\mu F_L$

H^4D^2X: 5 Henning: 3

$\mathcal{O}_{H^2(W-B)} = |H|^2\mathcal{O}_{W-B}$

$\mathcal{O}_{HWH} = igW^a_{\mu\nu}(H^\dagger\sigma^a D_\mu H + h.c.)H^\dagger \overleftrightarrow{D}_\nu H$

$\mathcal{O}^3_{HW} = igW^a_{\mu\nu}H^\dagger\sigma^a H D_\mu H^\dagger D_\nu H$

$\mathcal{O}_{\partial W} = igW^a_{\mu\nu}\partial_\mu(H^\dagger H)H^\dagger\sigma^a \overleftrightarrow{D}_\nu H$

$\mathcal{O}_{\partial B} = ig'B_{\mu\nu}\partial_\mu(H^\dagger H)H^\dagger \overleftrightarrow{D}_\nu H$

D^4H^4: 3 Henning: 3

$\mathcal{O}_{DH1} = |D_\mu H|^4$

$\mathcal{O}_{DH2} = (D_\mu H^\dagger D_\nu H + D_\nu H^\dagger D_\mu H)^2$

$\mathcal{O}_{DH3} = (D_\mu H^\dagger D_\nu H - D_\nu H^\dagger D_\mu H)^2$

$H^2D^2X^2$: 9

$\mathcal{O}_{DHB1} = g'^2 D_\rho H^\dagger D^\rho H B_{\mu\nu}B^{\mu\nu}$

$\mathcal{O}_{DHW1} = g^2 D_\rho H^\dagger D^\rho H W^I_{\mu\nu}W^{I\mu\nu}$

$\mathcal{O}_{DHWB1} = gg' D_\rho H^\dagger\sigma^I D^\rho H B_{\mu\nu}W^{I\mu\nu}$

$\mathcal{O}_{DHB2} = g'^2 D_\mu H^\dagger D^\nu H B_{\mu\rho}B^{\nu\rho}$

$\mathcal{O}_{DHW2} = g^2 D_\mu H^\dagger D^\nu H W^I_{\mu\rho}W^{I\nu\rho}$

$\mathcal{O}_{DHWB2} = \frac{gg'}{2}(D_\mu H^\dagger\sigma^I D^\nu H + h.c.)W^I_{\mu\rho}B^{\nu\rho}$

$\mathcal{O}_{DHWB3} = \frac{igg'}{2}(D_\mu H^\dagger\sigma^I D^\nu H - h.c.)HW^I_{\mu\rho}\tilde{B}^{\nu\rho}$

$\mathcal{O}_{DHW3} = \frac{ig^2}{2}\epsilon_{IJK}D_\mu H^\dagger\sigma^I D_\nu H W^J_{\mu\nu}W^{K\mu\rho}$

$\mathcal{O}_{DHW4} = \frac{g^2}{2}\epsilon_{IJK}(D_\mu H^\dagger\sigma^I D_\nu H + h.c.)W^J_{\mu\rho}\tilde{W}^{K\nu\rho}$

H^2X^3: 2 Henning: 2

$\mathcal{O}_{H^23W} = H^2\mathcal{O}_{3W}$

$\mathcal{O}_{H^2BW^2} = g'g^2 B_{\nu\rho}\epsilon_{abc}(H^\dagger\sigma^a H)W^b_{\mu\nu}W^{c\,\mu\rho}$

JH^2DX: 32 Henning: 32

$\mathcal{O}^V_{F_Bf} = ig'H^\dagger \overleftrightarrow{D}_\mu H\bar{f}\gamma^\nu f\tilde{B}^{\mu\nu}$ (5)

$\mathcal{O}^H_{F_Bf} = g'\partial_\mu(H^\dagger H)\bar{f}\gamma^\nu f B^{\mu\nu}$ (5)

$\mathcal{O}^W_{F_Wf} = igH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\bar{f}\gamma^\nu f\tilde{W}^{a\mu\nu}$ (5)

$\mathcal{O}^D_{F_Wf}$

$\mathcal{O}^D_{F_BF}$

$\mathcal{O}^W_{F_BF}$

$\mathcal{O}^V_{F_WF}$

$\mathcal{O}^H_{F_WF}$

$\mathcal{O}^{W2}_{F_WF} =$

$\mathcal{O}^{D2}_{F_WF} =$

$\psi^2D^2H^2$:14

$\mathcal{O}^{T_f}_{D^2H^2_1} = T^f_{\mu\nu}(D^\mu H^\dagger D^\nu H + h.c.)$

$\mathcal{O}^{T_F}_{D^2H^2_2} = T^{Fa}_{\mu\nu}(D_\mu H^\dagger\sigma^a D_\nu H + h.c.)$

$\mathcal{O}^{A_f}_{D^2H^2} = A^f_{\mu\nu}(D^\mu H^\dagger D^\nu H - h.c.)$

$\mathcal{O}^{A_F}_{D^2H^2} = A^a_{F\mu\nu}(D^\mu H^\dagger\sigma^a D^\nu H - h.c.)$

X^4: 10 Henning: 10

$\mathcal{O}_{4B1} = g'^4 B_{\rho\sigma}B^{\rho\sigma}B_{\mu\nu}B^{\mu\nu}$

$\mathcal{O}_{4B2} = g'^4 B_{\mu\nu}B^{\nu\rho}B_{\mu\sigma}B^{\sigma\rho}$

$\mathcal{O}_{4W1} = g^4 W^I_{\rho\sigma}W^{I\rho\sigma}W^J_{\mu\nu}W^{J\mu\nu}$

$\mathcal{O}_{4W2} = g^4 W^I_{\mu\nu}W^{I\nu\rho}W^J_{\mu\sigma}W^{J\sigma\rho}$

$\mathcal{O}_{4W3} = g^4 W^I_{\mu\nu}W^I_{\rho\sigma}W^{J\mu\nu}W^{J\rho\sigma}$

$\mathcal{O}_{4W4} = g^4 W^I_{\mu\nu}W^I_{\rho\sigma}W^{J\nu\rho}W^{J\sigma\mu}$

$\mathcal{O}_{2WB1} = g'^2g^2 B_{\rho\sigma}B^{\rho\sigma}W^I_{\mu\nu}W^{I\mu\nu}$

$\mathcal{O}_{2WB2} = g'^2g^2 B_{\mu\nu}B^{\nu\rho}W^I_{\mu\sigma}W^{I\sigma\rho}$

$\mathcal{O}_{2WB3} = g'^2g^2 B_{\mu\nu}B_{\rho\sigma}W^{I\mu\nu}W^{I\rho\sigma}$

$\mathcal{O}_{2WB4} = g'^2g^2 B_{\mu\nu}B_{\rho\sigma}W^{I\nu\rho}W^{I\sigma\mu}$

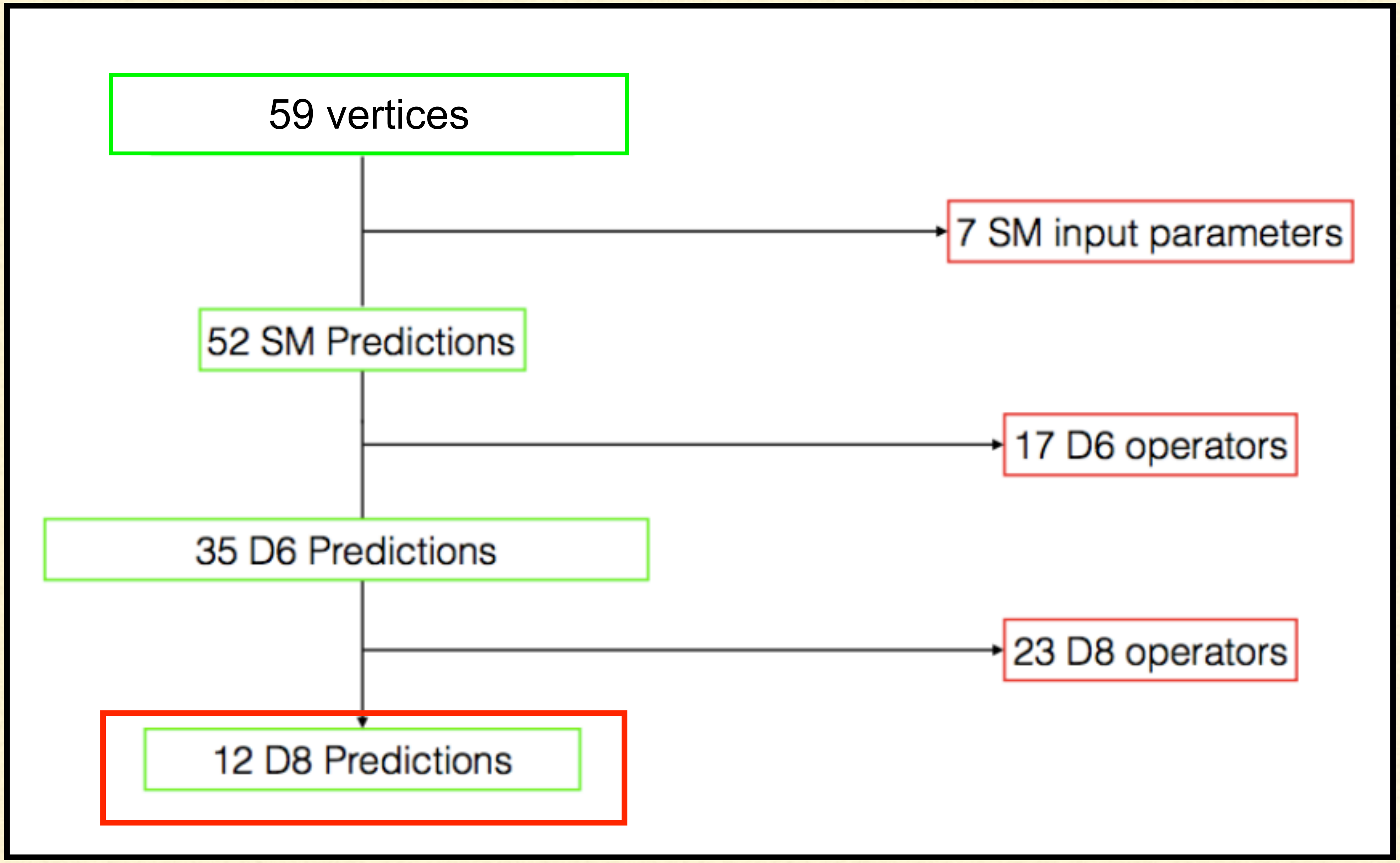
23 Dimension 8 operators with more than or equal to 4 Higgs doublets

VIOLATION OF D6 PREDICTION/ NEW D8 PRIMARY

Pure D8 observable	D8 Operators
$\sqrt{2}\delta g_F^W - c_{\theta_W}(\delta g_f^Z - \delta g_{f'}^Z)$	$-\frac{g\xi^2}{2\sqrt{2}} c_{3F}^3$
$\delta\kappa_Z - \delta g_1^Z + t_{\theta_W}^2 \delta\kappa_\gamma$	$\frac{g^2\xi^2}{8c_{\theta_W}^2}(c_{HW}^3 + 2c_{HWH})$
g_5	0
$\delta g_1^{WW} - 2{c_W}^2 \delta g_1^Z$	$\frac{g^2\xi^2}{4}(c_{HW}^3 + 2c_{HWH} + c_{DH2} + c_{DH3})$
$\delta g_2^{WW} - 2{c_W}^2 \delta g_1^Z$	$-\frac{g^2\xi^2}{8}(2c_{HW}^3 + 4c_{HWH} - c_{DH1} - 2c_{DH2} + 2c_{DH3})$
$\delta g_1^{ZZ} - 2\delta g_1^Z$	$\frac{g^2\xi^2}{4c_{\theta_W}^4} c_{DH2}$
$\delta g_2^{ZZ} - 2\delta g_1^Z$	$-\frac{g^2\xi^2}{16c_{\theta_W}^4} c_{DH1}$
h^{ZZ}	$\frac{g^2\xi^2}{16}(c_{DH1} + 4c_{DH2})$
$\delta g_{ZZ}^h - (\delta g_1^Z e^2 - \delta\kappa_\gamma g'^2)v$	$\frac{g^4 v\xi^2}{16c_{\theta_W}^2}(6c_{\partial B} - 2c_{H^2W'} - 8c_{H^2WB'} + (c_{\theta_W}^2 + 2)(c_{HW}^3 + 2c_{HWH}))$
$\kappa_{WW} - \delta\kappa_\gamma - \frac{c_{\theta_W}}{s_{\theta_W}}\kappa_{Z\gamma} - \kappa_{\gamma\gamma}$	$-\frac{g^2\xi^2}{4}(c_{\partial B} + c_{\partial W} - 2c_{H^2WB'} - c_{HWH})$
$\kappa_{ZZ} - \frac{1}{c_{\theta_W}^2}\delta\kappa_\gamma - \frac{c_{2\theta_W}}{c_{\theta_W}s_{\theta_W}}\kappa_{Z\gamma} - \kappa_{\gamma\gamma}$	$-\frac{g^2\xi^2}{4c_{\theta_W}^2}(c_{\partial B} + c_{\partial W} - 2c_{H^2WB'} + c_{HW}^3 + c_{HWH})$
$g_{WF}^h - \sqrt{2}c_{\theta_W}(\delta g_f^Z - \delta g_{f'}^Z - c_{\theta_W}\delta g_1^Z)$	$\frac{g\xi^2}{\sqrt{2}}((c_{H^2F}^3 - c_{3F}^3) + \frac{g^2}{4}(2c_{\partial W} + c_{H^2W} - 2c_{HWH}))$
$g_{Zf}^h - \frac{2g}{c_{\theta_W}}Y_f t_{\theta_W}^2 \delta\kappa_\gamma - 2\delta g_f^Z + \frac{2g}{c_{\theta_W}}(T_3^f c_{\theta_W}^2 + Y_f s_{\theta_W}^2)\delta g_1^Z$	$c_{3F}^3, c_{\partial W}, c_{\partial B}, c_{HW}^3 + 2c_{HWH}, c_{H^2W'}, c_{H^2WB'}$
$g_{4h} - \frac{3}{2}g_{3h}$	$xxxc_8\xi^2$
$\kappa_{GG}^{hh} - \kappa_{GG}$	$2c_{H^2GG}\xi^2$
$\kappa_{WW}^{h^2} - \delta\kappa_\gamma - \frac{c_{\theta_W}}{s_{\theta_W}}\kappa_{Z\gamma} - \kappa_{\gamma\gamma}$	$-\frac{g^2\xi^2}{4}(c_{\partial B} + 5c_{\partial W} - 16c_{H^2WW} - 2c_{H^2WB'} - c_{HWH})$
$\kappa_{ZZ}^{h^2} - \frac{1}{c_{\theta_W}^2}\delta\kappa_\gamma - \frac{c_{2\theta_W}}{c_{\theta_W}s_{\theta_W}}\kappa_{Z\gamma} - \kappa_{\gamma\gamma}$	$-\frac{g^2\xi^2}{4c_{\theta_W}^2}(c_{\partial B} + 5c_{\partial W} - 16c_{H^2WW} - 2c_{H^2WB'} - c_{HWH})$
$\delta g_{VV}^{hh} - \frac{5\delta g_{VV}^h}{v}$	$\frac{g^4\xi^2}{8}(46c_{H^2r} + 4c_{H^2W'})$
$\delta g_{ZZ}^{hh} - \frac{5\delta g_{ZZ}^h}{v}$	$\frac{g^4\xi^2}{16c_{\theta_W}^2}((10 + 5c_{\theta_W}^2)(c_{HW}^3 + 2c_{HWH}) + (30\, c_{\partial B} - 18(c_{H^2W'} + 4c_{H^2WB'})s_{\theta_W}^2)$
g_{hh2}^W	$g^2\xi^2 c_{DH2}$
g_{hh3}^W	$\frac{g^2\xi^2}{4}c_{DH1}$
g_{hh2}^Z	$g^2\xi^2(c_{DH2} + c_{DH3})$
g_{hh3}^Z	$\frac{g^2\xi^2}{4}(c_{DH1} - 4c_{DH3})$
$g_{Z1}^h + \frac{2}{s_{\theta_W}c_{\theta_W}}\kappa_{Z\gamma} + \frac{2}{c_{\theta_W}^2}\delta\kappa_\gamma + \frac{2}{c_{\theta_W}^2}\kappa_{\gamma\gamma}$	$\frac{g^2\xi^2}{2c_{\theta_W}^2}(c_{\partial B} - c_{\partial W} - 3c_{HWH} + 8c_{H^2WW} - 2c_{H^2WB'})$
$\kappa_\gamma^h + \frac{2}{t_{\theta_W}}\kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}$	$\frac{g^2\xi^2}{4}(c_{HW}^3 - 2c_{HWH} + 2c_{\partial B} - 2c_{\partial W} + 16c_{H^2WW} - 8c_{HWB'})$
$\kappa_Z^h + \frac{2}{c_{\theta_W}^2}\delta\kappa_\gamma + \frac{2}{t_{\theta_W}}\kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}$	$\frac{g^2\xi^2}{4c_{\theta_W}^2}((1 + c_{\theta_W}^2)c_{HW}^3 - 4c_{2\theta_W}c_{H^2WB'} + 2c_{\theta_W}^2(c_{\partial B} - c_{\partial W} + 8c_{H^2WW} - c_{HWH}))$
$g^{\partial hZ}$	$-\frac{g^2\xi^2}{4}(2c_{\partial W} + c_{HW}^3 + 2c_{HWH} + 2c_{DH3})$

Bertuzzo, Grojean & RSG (in prep)

COUNTING


59 vertices
7 SM input parameters
52 SM Predictions
17 D6 operators
35 D6 Predictions
23 D8 operators
12 D8 Predictions

12 D8 PREDICTIONS

$$g^5 = 0$$
$$\delta^8\kappa_{WW} - c_{\theta_W}^2\delta^8\kappa_{ZZ} - 2c_{\theta_W}^2\delta^8\kappa_Z = 0$$
$$\delta^8 g^h_{Wud} - \frac{c_{\theta_W}(\delta^8 g^h_{Zu_l} - \delta^8 g^h_{Zd_l})}{\sqrt{2}} - (4\delta^8 g^W_{ud} - \sqrt{2}gc_{\theta_W}^2\delta^8\kappa_Z) = 0$$
$$\delta^8 g^h_{W\nu e} - \frac{c_{\theta_W}(\delta^8 g^h_{Z\nu_l} - \delta^8 g^h_{Ze_l})}{\sqrt{2}} - (4\delta^8 g^W_{\nu e} - \sqrt{2}gc_{\theta_W}^2\delta^8\kappa_Z) = 0.$$

$$\delta^8 g^{WW}_{Q2} - \delta^8 g^{WW}_{Q1} - 2c_{\theta_W}^4(\delta^8 g^{ZZ}_{Q2} - \delta^8 g^{ZZ}_{Q1}) = 0$$
$$h^{ZZ}_Q + c_{\theta_W}^4(\delta^8 g^{ZZ}_{Q2} - \delta^8 g^{ZZ}_{Q1}) = 0$$
$$g^Z_{hh2} - 4(\delta^8 g^{WW}_{Q1} - 2c_{\theta_W}^2\delta^8\kappa_Z) = 0$$
$$g^Z_{hh3} + 4(\delta^8 g^{WW}_{Q1} - 2c_{\theta_W}^2\delta^8\kappa_Z + c_{\theta_W}^4(\delta^8 g^{ZZ}_{Q2} - \delta^8 g^{ZZ}_{Q1})) = 0$$
$$g^W_{hh2} - 4c_{\theta_W}^4\delta^8 g^{ZZ}_{Q1} = 0$$
$$g^W_{hh3} + 4c_{\theta_W}^4\delta^8 g^{ZZ}_{Q2} = 0$$
$$\delta^8\kappa^{hZ} - \frac{1}{3}\left(\frac{9\delta^8 g^h_{VV}/v - \delta^8 g^{h^2}_{ZZ}}{g^2} + 3\delta^8 g^{hZ}_1 - 3t_{\theta_W}^2(2\delta^8 g^{WW}_{Q1} + \delta^8\kappa^h_{WW} + g^{\partial hZ}) \right.$$
$$\left. + 6\delta^8\kappa_Z + s_{\theta_W}^2(32\delta^8\kappa_Z + 15\delta^8\kappa_{ZZ} + 6\delta^8 g^{Q1}_{ZZ}c_{\theta_W}^2)\right) = 0$$
$$\delta^8\kappa^{h\gamma} + \frac{1}{3s_{\theta_W}^2}\left(\frac{9\delta^8 g^h_{VV}/v - \delta^8 g^{h^2}_{ZZ}}{g^2}c_{\theta_W}^2 + 3\delta^8 g^{hZ}_1 - 3s_{\theta_W}^2(2\delta^8 g^{WW}_{Q1} + \delta^8\kappa^h_{WW} + g^{\partial hZ}) \right.$$
$$\left. - 6\delta^8\kappa_Z c_{\theta_W}^4 + s_{\theta_W}^2 c_{\theta_W}^2(26\delta^8\kappa_Z + 15\delta^8\kappa_{ZZ} + 6\delta^8 g^{Q1}_{ZZ}c_{\theta_W}^2)\right) = 0$$

Bertuzzo, Grojean & RSG (in prep)

OTHER D8 OPERATORS

H^8
$O_8 = H^8$
D^2H^6
$O_{H^2r} = \lvert H\rvert^2 D_\mu H^\dagger D_\mu H$
H^4X^2: 4 Henning: 5
$\mathcal{O}_{H^2BB} = g'^2 \lvert H\rvert^4 B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{H^2WB'} = \lvert H\rvert^2 \mathcal{O}_{WB'}$
$\mathcal{O}_{H^2WW} = g^2 \lvert H\rvert^4 W^a_{\mu\nu} W^{a\mu\nu}$
$\mathcal{O}_{H^2GG} = g_s^2 \lvert H\rvert^4 G^A_{\mu\nu} G^{A\mu\nu}$
$H^4D\psi^2$: 9 Henning: 9
$\mathcal{O}_{H^2R} = i\lvert H\rvert^2 H^\dagger \overleftrightarrow{D}_\mu H \bar{f}_R \gamma^\mu f_R$
$\mathcal{O}_{H^2L} = i\lvert H\rvert^2 H^\dagger \overleftrightarrow{D}_\mu H \bar{F}_L \gamma^\mu F_L$
$\mathcal{O}^{(3)}_{H^2L} = i\lvert H\rvert^2 H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{F}_L \sigma^a \gamma^\mu F_L$
$O^{(3)Q}_{3L} = iH^\dagger \overleftrightarrow{D}_\mu H (H^\dagger \sigma^a H) \bar{F}_L \sigma^a \gamma^\mu F_L$
H^4D^2X: 5 Henning: 3
$\mathcal{O}_{H^2(W-B)} = \lvert H\rvert^2 O_{W-B}$
$O_{HWH} = igW^a_{\mu\nu}(H^\dagger \sigma^a D_\mu H + h.c.) H^\dagger \overleftrightarrow{D}_\nu H$
$O^3_{HW} = igW^a_{\mu\nu} H^\dagger \sigma^a H D_\mu H^\dagger D_\nu H$
$O_{\partial W} = igW^a_{\mu\nu} \partial_\mu (H^\dagger H) H^\dagger \sigma^a \overleftrightarrow{D}_\nu H$
$O_{\partial B} = ig' B_{\mu\nu} \partial_\mu (H^\dagger H) H^\dagger \overleftrightarrow{D}_\nu H$
D^4H^4: 3 Henning: 3
$O_{DH1} = \lvert D_\mu H\rvert^4$
$O_{DH2} = (D_\mu H^\dagger D_\nu H + D_\nu H^\dagger D_\mu H)^2$
$O_{DH3} = (D_\mu H^\dagger D_\nu H - D_\nu H^\dagger D_\mu H)^2$

$H^2D^2X^2$: 9
$\mathcal{O}_{DHB1} = g'^2 D_\rho H^\dagger D^\rho H B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{DHW1} = g^2 D_\rho H^\dagger D^\rho H W^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{DHWB1} = gg' D_\rho H^\dagger \sigma^I D^\rho H B_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{DHB2} = g'^2 D_\mu H^\dagger D^\nu H B_{\mu\rho} B^{\nu\rho}$
$\mathcal{O}_{DHW2} = g^2 D_\mu H^\dagger D^\nu H W^I_{\mu\rho} W^{I\nu\rho}$
$\mathcal{O}_{DHWB2} = \frac{gg'}{2}(D_\mu H^\dagger \sigma^I D^\nu H + h.c.) W^I_{\mu\rho} B^{\nu\rho}$
$\mathcal{O}_{DHWB3} = \frac{igg'}{2}(D_\mu H^\dagger \sigma^I D^\nu H - h.c.) H W^I_{\mu\rho} \tilde{B}^{\nu\rho}$
$\mathcal{O}_{DHW3} = \frac{ig^2}{2} \epsilon_{IJK} D_\nu H^\dagger \sigma^I D_\rho H W^J_{\mu\nu} W^{K\mu\rho}$
$\mathcal{O}_{DHW4} = \frac{g^2}{2} \epsilon_{IJK} (D_\mu H^\dagger \sigma^I D_\nu H + h.c.) W^J_{\mu\rho} \tilde{W}^{K\nu\rho}$
H^2X^3: 2 Henning: 2
$\mathcal{O}_{H^23W} = H^2 O_{3W}$
$\mathcal{O}_{H^2BW^2} = g'g^2 B_{\nu\rho} \epsilon_{abc} (H^\dagger \sigma^a H) W^b_{\mu\nu} W^{c\,\mu\rho}$
JH^2DX: 32 Henning: 32
$\mathcal{O}^V_{F_Bf} = ig' H^\dagger \overleftrightarrow{D}_\mu H \bar{f} \gamma^\nu f \tilde{B}^{\mu\nu}$ (5)
$\mathcal{O}^H_{F_Bf} = g' \partial_\nu (H^\dagger H) \bar{f} \gamma^\nu f B^{\mu\nu}$ (5)
$\mathcal{O}^W_{F_Wf}$ …
$\mathcal{O}^D_{F_Wf}$ …
$\mathcal{O}^D_{F_BF}$ …
$\mathcal{O}^W_{F_BF}$ …
$\mathcal{O}^V_{F_WF}$ …
$\mathcal{O}^H_{F_WF}$ …
$\mathcal{O}^{W2}_{F_WF}$ …
$\mathcal{O}^{D2}_{F_WF}$ …
…
$\mathcal{O}^{T_f}_{D^2H^21}$ …
$\mathcal{O}^{T_F}_{D^2H^22} = T^{Fa}_{\mu\nu}(D_\mu H^\dagger \sigma^a D_\nu H + h.c.)$
$\mathcal{O}^{A_f}_{D^2H^2} = A^f_{\mu\nu}(D^\mu H^\dagger D^\nu H - h.c.)$
$\mathcal{O}^{A^a_F}_{D^2H^2} = A^a_{F\mu\nu}(D^\mu H^\dagger \sigma^a D^\nu H - h.c.)$

X^4: 10 Henning: 10
$\mathcal{O}_{4B1} = g'^4 B_{\rho\sigma} B^{\rho\sigma} B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{4B2} = g'^4 B_{\mu\nu} B^{\nu\rho} B_{\mu\sigma} B^{\sigma\rho}$
$\mathcal{O}_{4W1} = g^4 W^I_{\rho\sigma} W^{I\rho\sigma} W^J_{\mu\nu} W^{J\mu\nu}$
$\mathcal{O}_{4W2} = g^4 W^I_{\mu\nu} W^{I\nu\rho} W^J_{\mu\sigma} W^{J\sigma\rho}$
$\mathcal{O}_{4W3} = g^4 W^I_{\mu\nu} W^I_{\rho\sigma} W^{J\mu\nu} W^{J\rho\sigma}$
$\mathcal{O}_{4W4} = g^4 W^I_{\mu\nu} W^I_{\rho\sigma} W^{J\nu\rho} W^{J\sigma\mu}$
$\mathcal{O}_{2WB1} = g'^2 g^2 B_{\rho\sigma} B^{\rho\sigma} W^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{2WB2} = g'^2 g^2 B_{\mu\nu} B^{\nu\rho} W^I_{\mu\sigma} W^{I\sigma\rho}$
$\mathcal{O}_{2WB3} = g'^2 g^2 B_{\mu\nu} B_{\rho\sigma} W^{I\mu\nu} W^{I\rho\sigma}$
…

85 Dimension 8 operators with less than 4 Higgs doublets don't contribute to D4 vertices

PHENOMENOLOGICAL EXAMPLES

(1) Shape of Higgs potential

(2) Transverse Gauge boson couplings

(3) High energy primaries

EXAMPLE 1: SHAPE OF HIGGS POTENTIAL

Higgs potential:

$$V(h) = \frac{m_h^2}{2}h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4}h^4$$
$$\Delta V(h) = \delta_3 v h^3 + \frac{\delta_4}{4}h^4$$

2 D4 Predictions:

$$\lambda_3 = \lambda_4 = m_H^2/2v^2 \equiv \lambda_{SM}$$

D6 opens δ_3 (due to operator H^6) but one Prediction:

$$\delta_4 = 6\,\delta_3, \qquad \text{(SMEFT at dim} = 6\text{)}$$

Chiesaa, Maltoni, Mantani, Melee, Piccinini & Zhao (2020)

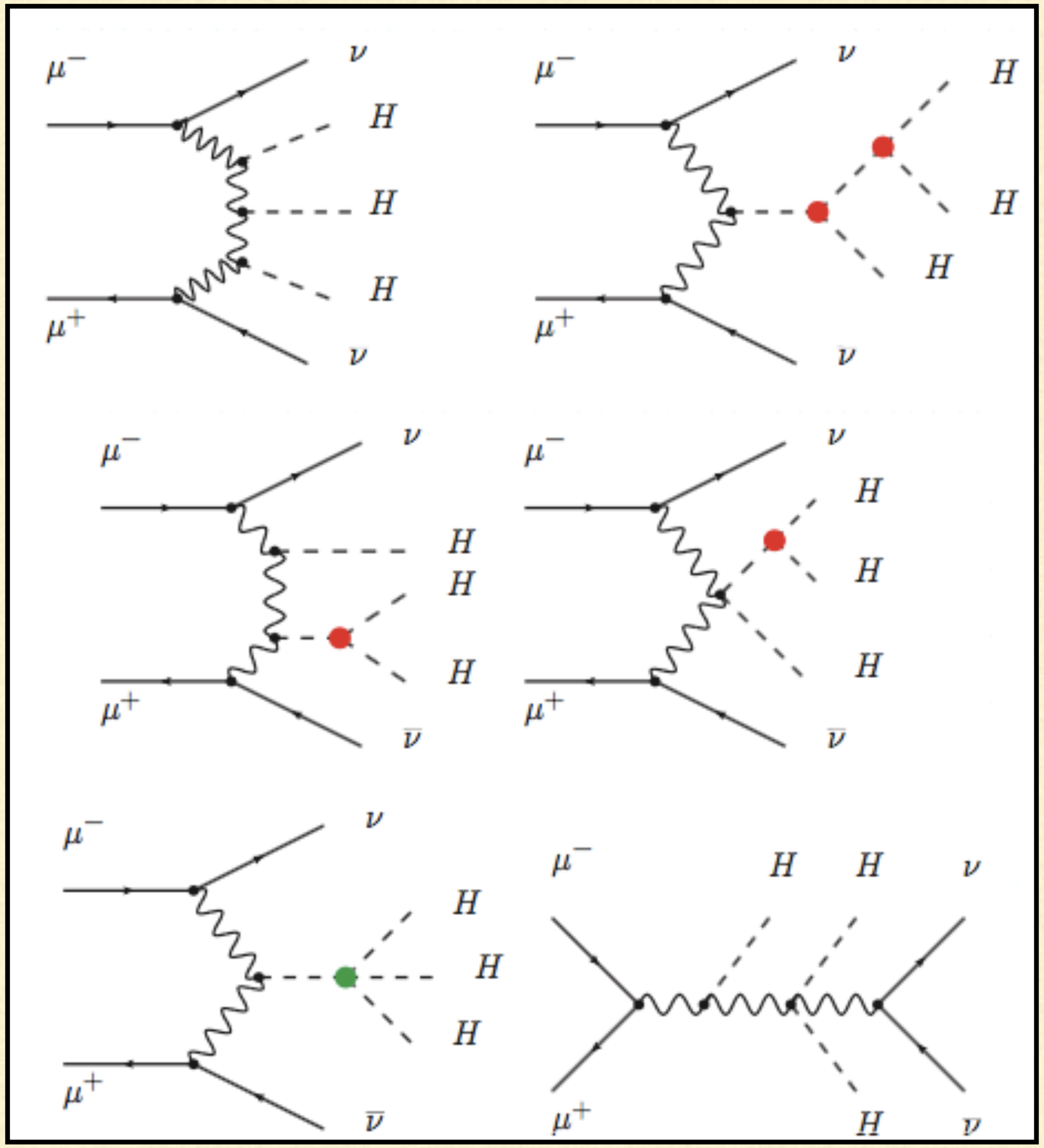
EXAMPLE 1: SHAPE OF HIGGS POTENTIAL

- D8 breaks D6 Prediction (due to operator H^8):

  $\delta_4 - 6\delta_3 \sim c_8\, v^4/\Lambda^4$

- Should not deform only one coupling but both simultaneously

- Deviations from this line probe D8 effect



Chiesaa, Maltoni, Mantani, Melee, Piccinini & Zhao (2020)

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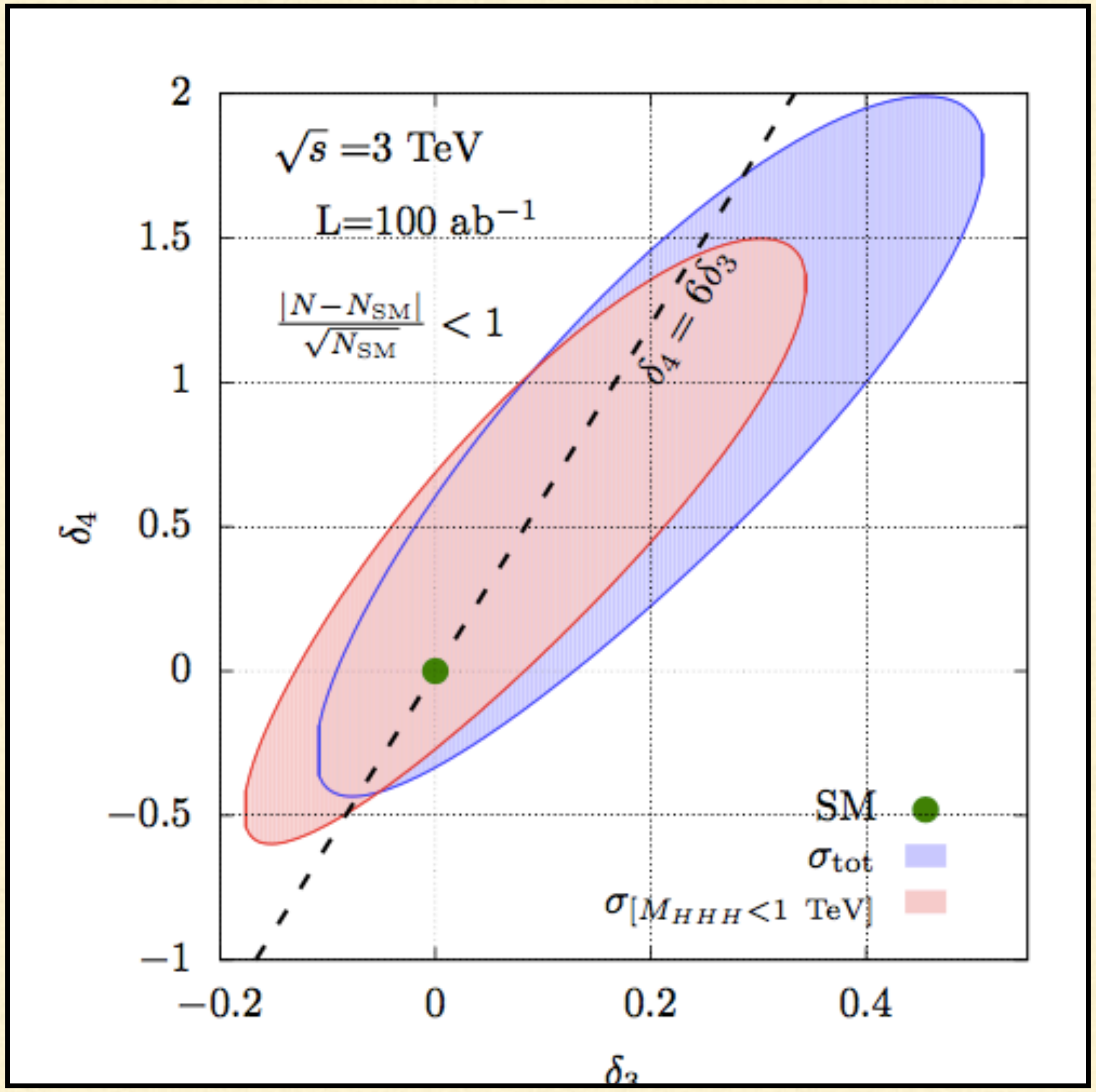


Chiesaa, Maltoni, Mantani, Melee, Piccinini & Zhao (2020)

EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

$$\delta\kappa^{\gamma} W^{+}_{\mu} W^{-}_{\nu} A^{\mu\nu}$$

$$\kappa_{ZZ}\,\frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu} + \kappa_{\gamma\gamma}\,\frac{h}{2v} A^{\mu\nu} A_{\mu\nu} + \kappa_{Z\gamma}\frac{h}{v} A^{\mu\nu} Z_{\mu\nu}$$

D6 Prediction: $$\kappa_{ZZ} = \frac{1}{c^2_{\theta_W}} \delta\kappa_{\gamma} + \frac{c_{2\theta_W}}{c_{\theta_W} s_{\theta_W}} \kappa_{Z\gamma} + \kappa_{\gamma\gamma}$$

Per-cent level constraint at HL LHC in WW production (Grojean, Montul & Riembau 2018)

Per-mille level constraint from Higgs decays

- κ_{ZZ} is already constrained at percent level due to this correlation. Is there any point in trying to measure this separately ?

EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

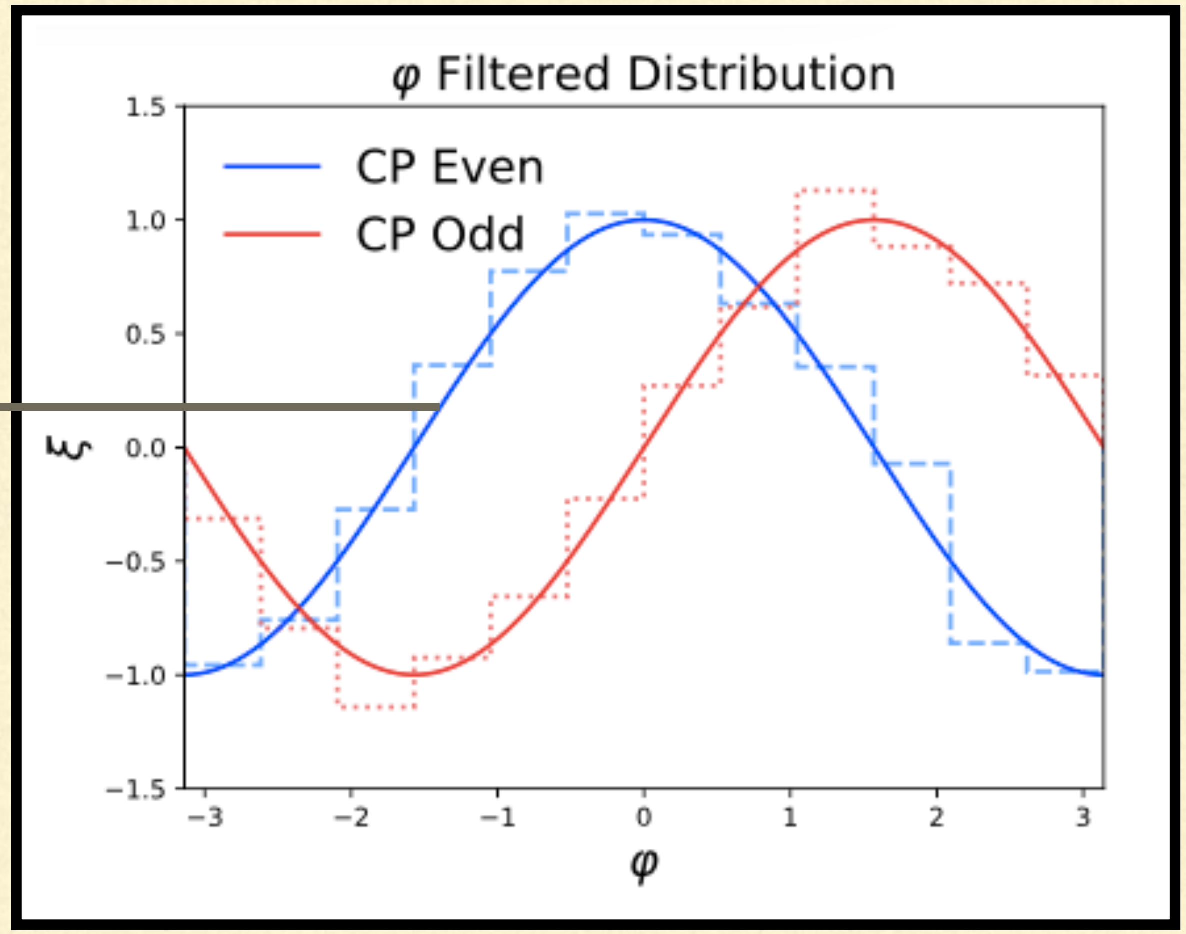
- κ_{ZZ} is already constrained at percent level due to this correlation. Is there any point in trying to measure this separately ?

YES !

- In HEFT this correlation broken at O(1), i.e there is no correlation
- In SMEFT this correlation broken at $O(v^2/\Lambda^2)$(that is at D8)

EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

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



See Shankha's Talk

Using our technique and combining with h>ZZ rate κ_{ZZ} can be measured at 1% level at HL-LHC

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

EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

$$\kappa_{ZZ} = \frac{1}{c^2_{\theta_W}}\delta\kappa_\gamma + \frac{c_{2\theta_W}}{c_{\theta_W}s_{\theta_W}}\kappa_{Z\gamma} + \kappa_{\gamma\gamma}$$

- In HEFT this correlation broken at O(1), i.e there is no correlation. We need to measure LHS and RHS at same level so Banerjee et al bound essential

EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

First 2 terms: $O(v^2/\Lambda^2)$=10% $O(v^4/\Lambda^4)$=1%

$$\kappa_{ZZ} - \frac{1}{c^2_{\theta_W}}\delta\kappa_\gamma - \frac{c_{2\theta_W}}{c_{\theta_W}\, s_{\theta_W}}\kappa_{Z\gamma} - \kappa_{\gamma\gamma} = -\frac{g^2 v^4}{4c^2_{\theta_W}\,\Lambda^4}\left(c_{\partial B} + c_{\partial W} - 2c_{H^2WB'} + c^3_{HW} + c_{HWH}\right)$$

- In SMEFT this correlation broken at $O(v^4/\Lambda^4)$
- Maximum size of each term on LHS: present bounds <10 %=$O(v^2/\Lambda^2)$
- $O(v^4/\Lambda^4)$= 1%= Required future sensitivity for measuring the full combination.
- Again Banerjee et al result can be used to measure this D8 effect.

EXAMPLE 3: HIGH ENERGY PRIMARIES

VV —D6 prediction→ Vh

Z-pole, TGCs — *hVff*

- Can be understood by Goldstone Boson Equivalence
- D6 Prediction for WZ—Wh case:

$$g^h_{WF} = \sqrt{2} c_{\theta_W} (\delta g^Z_f - \delta g^Z_{f'}) - 2\delta g^Z_1 g^W_f c^2_{\theta_W}$$

hWff — Z-pole — TGCs

Franceschini, Panico, Pomarol, Riva & Wulzer (2017)

EXAMPLE 3: HIGH ENERGY PRIMARIES

D6 prediction broken at D8 level:

$$g^h_{WF} - \sqrt{2} c_{\theta_W} (\delta g^Z_f - \delta g^Z_{f'} - c_{\theta_W} \delta g^Z_1) =$$

$$-\frac{g^2 v^4}{4 c^2_{\theta_W} \Lambda^4} (c_{\partial B} + c_{\partial W} - 2 c_{H^2 W B'} + c^3_{HW} + c_{HWH})$$

First and last term can be 10 %= O(v^2/Λ^2)

O(v^4/Λ^4)=1%

Future precision per mille level

so this D8 effect may be easily seen

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

Bishara, Englert, Grojean, Montull,Panico &. Rossia(2020)

CONCLUSIONS

- At any order in SMEFT more observables than operatorsThis leads to predictions of observables as a function of others
- Predictions broken as we go to higher order in EFT expansions for e.g. D6 to D8, i.e. order by order in v^2/Λ^2
- More and more observables liberated. Our work motivates more measurements
- Probing these violations of predictions only way to probe a certain class of D8 operators
- Predictions broken also in HEFT but all at once

OTHER D8 OPERATORS

- These give rise to vertices with more derivatives mostly not present in D6 lagrangian. Can give rise to new final states (neutral diboson production), new kinematic signatures. For e.g. they can contribute to new helicity amplitudes, faster energy growth
- The strategy required to probe these is very different as a careful differential study needs to be carried out to truly isolate their effect which is beyond the scope of our work