SMEFT SPECTROSCOPY: HOW TO PROBE DIMENSION 8 OPERATORS ?

IPPP Internal Seminar

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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 BSM deviations /deformations that are generated
- These lead to predictions of some measurements as a function of others
- Here we will see how breaking of predictions at D6 level probes D8 operators

2 KINDS OF D8 OPERATORS

1. Those that give rise to vertex structures not present in D6 lagrangian. Can give leading contribution to new final states (neutral diboson production), new kinematic signatures. For e.g. they can contribute to new helicity amplitudes, faster energy growth not present in D6. $\longrightarrow$ ***Careful differential study required***

2. Those that give subleading contribution to vertex structures already present in D6 lagrangian. These can be probed by the breaking of D6 predictions. $\longrightarrow$ ***Focus of this talk***

PLAN OF TALK

1. SMEFT PREDICTION EXAMPLE
2. OVERVIEW OF WORK
3. PHENOMENOLOGICAL EXAMPLES
4. SMEFT VS HEFT

SMEFT PREDICTION EXAMPLE

D4-PREDICTIONS

- Same SU(2)x U(1) invariant D4 operator gives rise to both LHS and RHS
- Experimentally fermion mass and Yukawa completely different measurements. So are W and Z mass.
- But actually we are probing the same effect by two different measurements.

Proportional to Yukawa at D4

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

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

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

UNCONSTRAINING 'OBSERVABLES' AT D6

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

- 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 unconstrained an 'observable'/ opened a new BSM primary at D6.

BSM PRIMARIES

BSM Primary: Independent 'observable'

Up to a given order

No of independent 'observables' = No of operators=N

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

All other 'observables' can be predicted in terms of these.

RSG, Pomarol & Riva (2014)

UNCONSTRAINING 'OBSERVABLES' AT D8

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

- 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 unconstrained an 'observable'/opened a new BSM primary at D6.

D4 AND D6 PREDICTION EXAMPLE

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

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

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

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

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

$$\text{SM} + \boxed{\delta g_{e_L}^Z Z_\mu \bar{e}_L \gamma^\mu e_L + \delta g_{e_R}^Z Z_\mu \bar{e}_R \gamma^\mu e_R + \delta g_{\nu_L}^Z Z_\mu \bar{\nu}_L \gamma^\mu \nu_L + \delta g_L^W (W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + h.c.)}$$

$$\downarrow$$

$$\boxed{\delta g_{\nu e}^W - \frac{c_{\theta_W}(\delta g_{\nu_l}^Z - \delta g_{e_l}^Z)}{\sqrt{2}} = 0}$$

UNCONSTRAINING 'OBSERVABLES' AT D8

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

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

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

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

- 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)

OVERVIEW OF WORK

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

ANOMALOUS COUPLINGS AS 'OBSERVABLES'

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

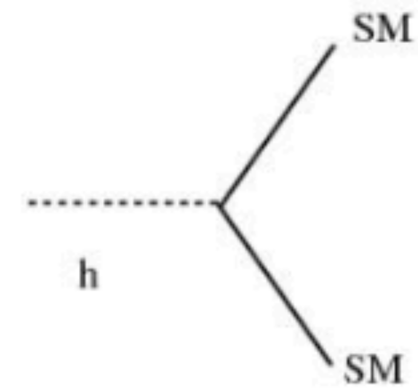
We will call these 'deformations' from now

More examples:

(1) Higgs observables (20):

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

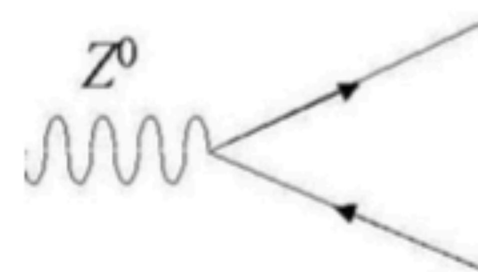
$$hZ_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$$



(2) Electorweak precision observables (9):

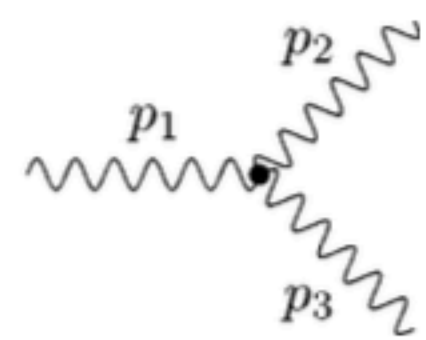
$$Z_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$$

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



(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 deformations (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 deformations - No of Operators

WHICH ‘OBSERVABLES’/ OPERATORS DO WE INCLUDE ?

- We focus on vertices involved in the following processes:

$$\boxed{\begin{aligned} pp/ee/VV &\to VV/Vh \\ pp/VV &\to h \\ h \to Vff/\ \gamma\gamma\ /ff \end{aligned}}$$

$$\boxed{pp \to hh, hhh}$$

- Let us focus up to CP dimension 4 deformations. These are almost all the ‘observables’ of D6 SMEFT in Higgs/EW Physics

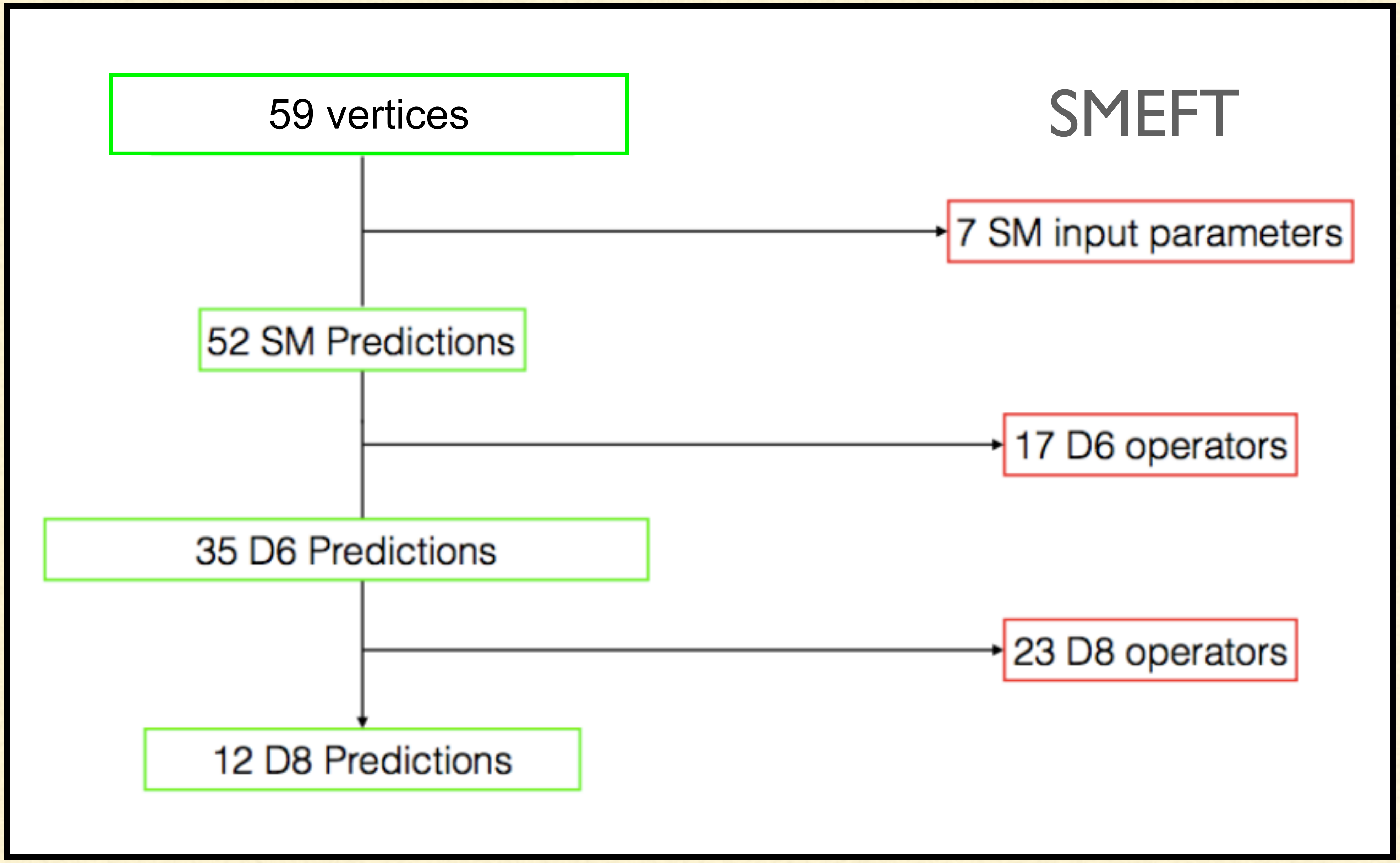
- For these largest deviations from predictions in HEFT

- 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

$$\boxed{\begin{aligned} \mathcal{O}_6 &= |H|^2\mathcal{O}_4 \to v^2\mathcal{O}_4 \\ \mathcal{O}_8 &= |H|^4\mathcal{O}_4 \to v^4\mathcal{O}_4 \end{aligned}}$$

COUNTING



(considering only 1 generation for the purpose of counting)

Bertuzzo, Grojean & RSG (in prep)

COUNTING

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

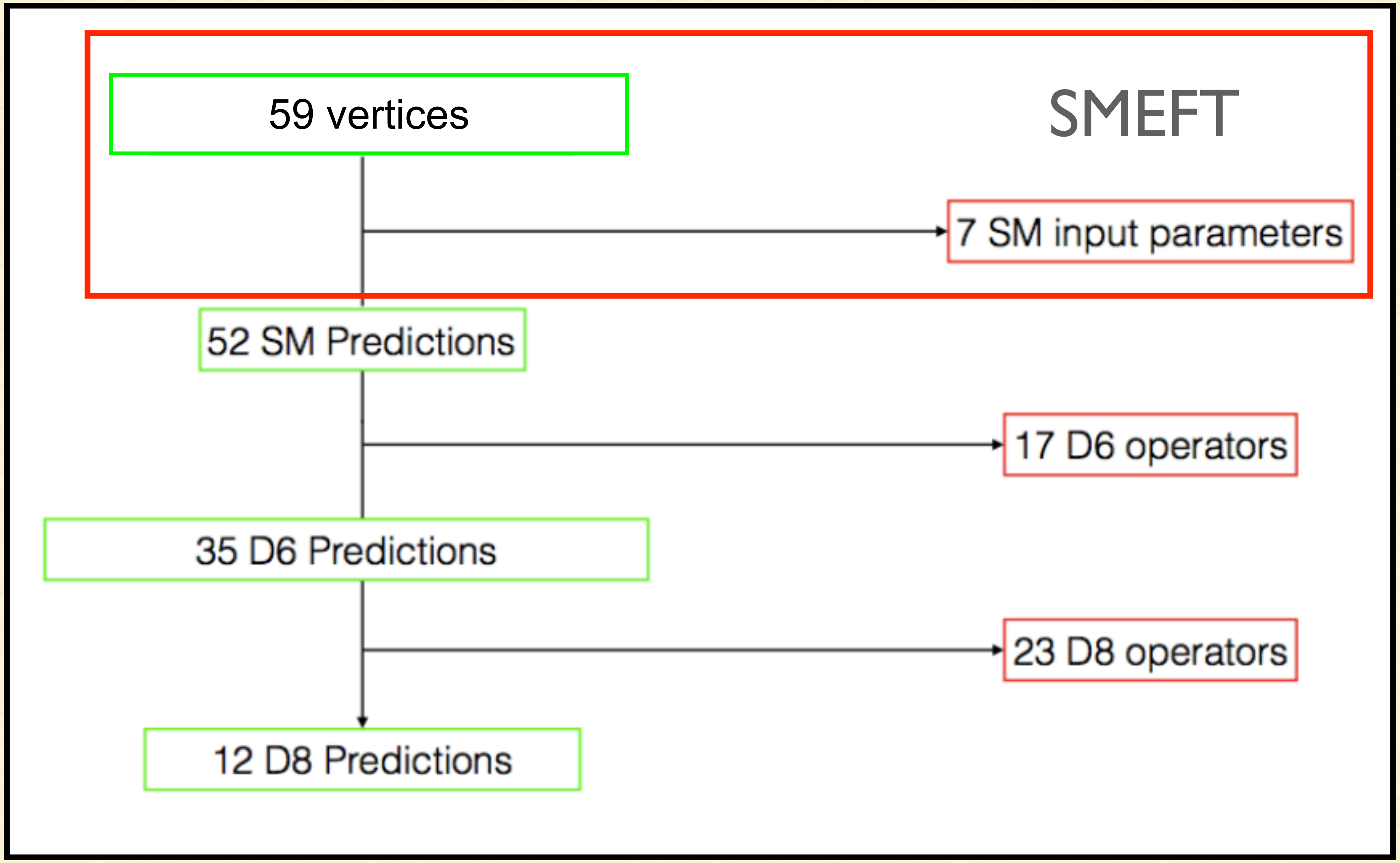
1. HEFT: Simultaneous Breaking at $O(v^2/\Lambda^2)$ for all predictions

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

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

52 deformations

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

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

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

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

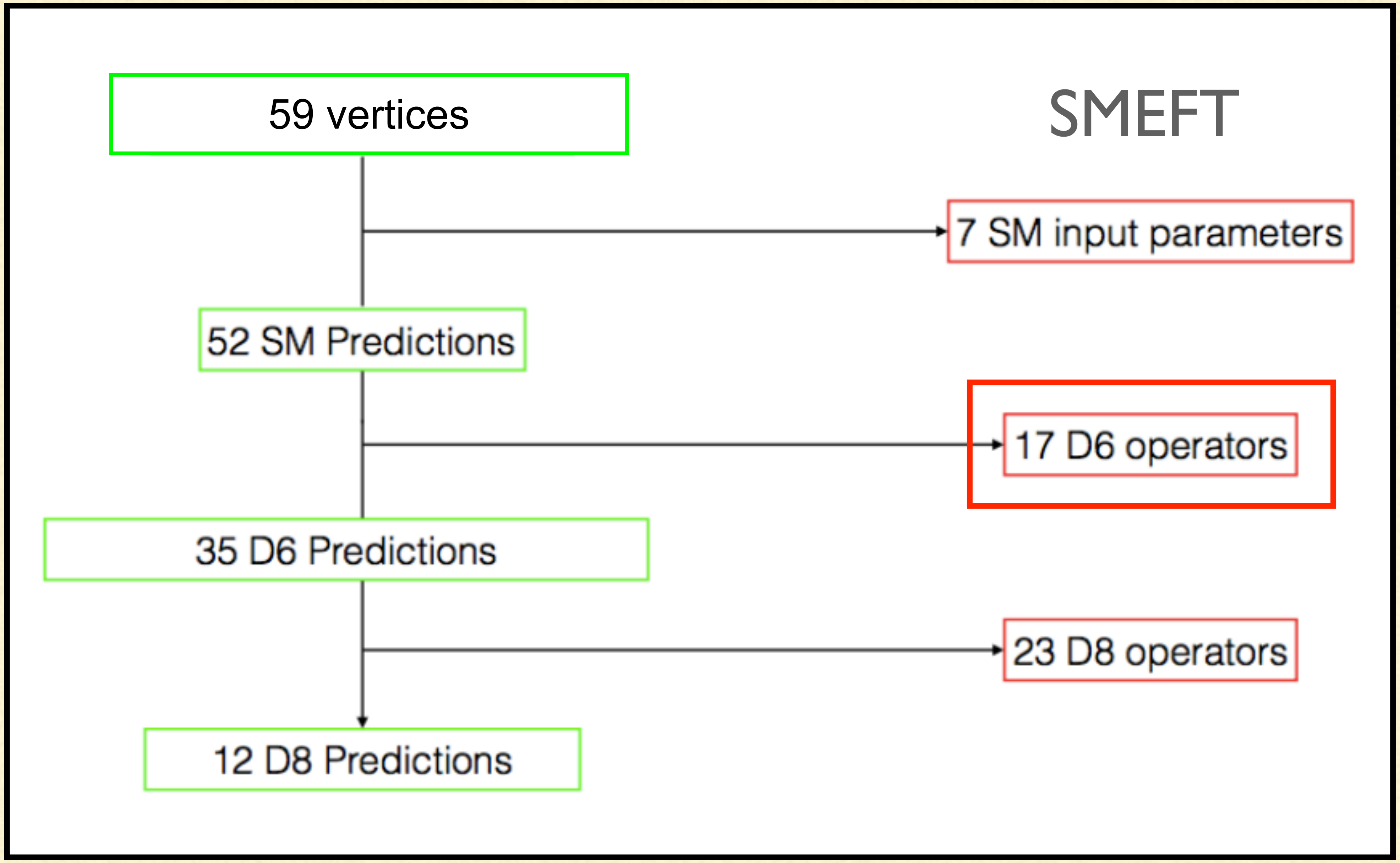
$$\Delta\mathcal{L}_{h^2,h^3}^{gg} = \kappa_{GG}^{hh} \frac{h^2}{4v^2} G^{A\,\mu\nu} G_{\mu\nu}^A - g_{3h} \, v h^3 - g_{4h} \, h^4$$

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

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

Bertuzzo, Grojean & RSG (in prep)

COUNTING

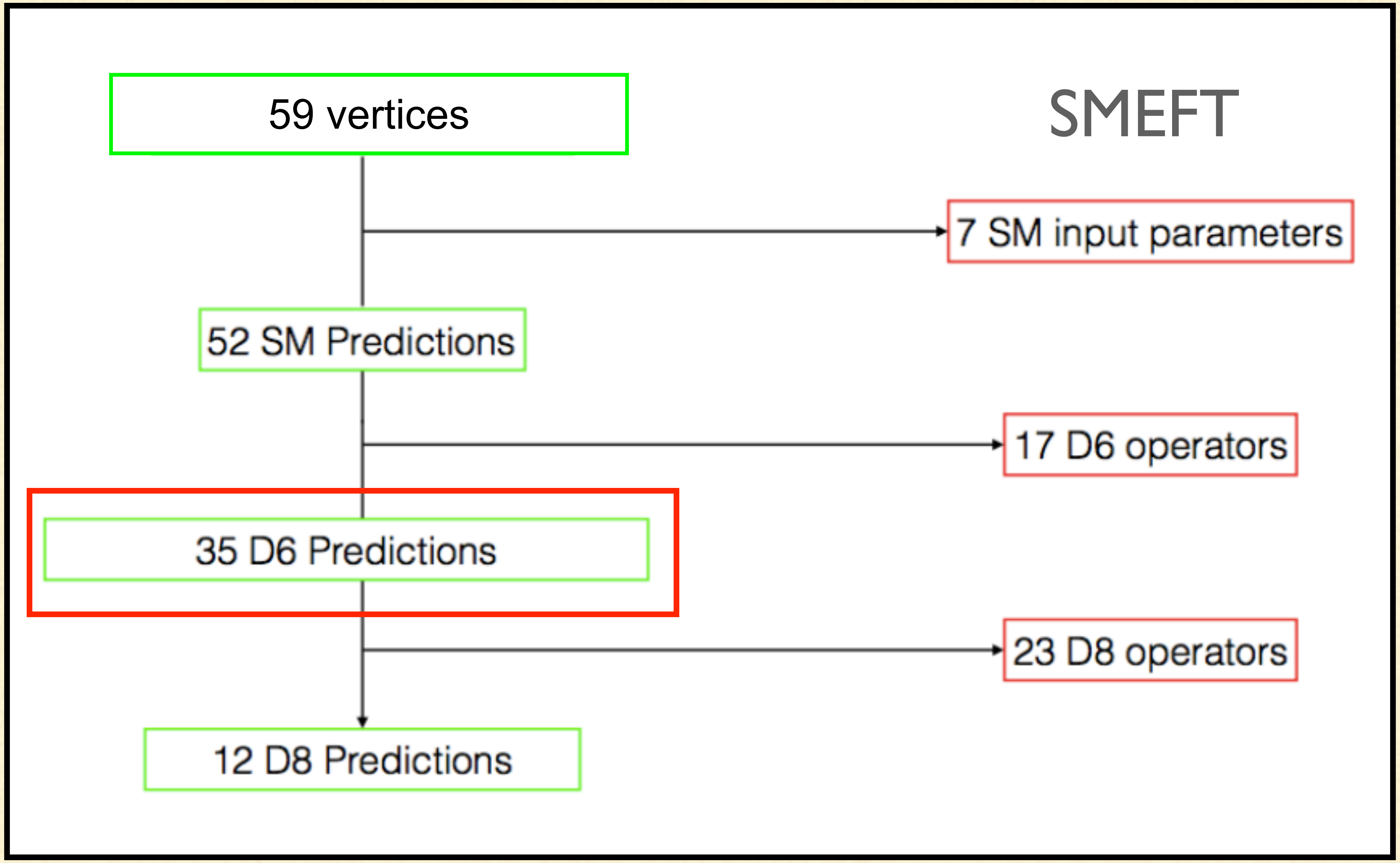


Bertuzzo, Grojean & RSG (in prep)

17 D6 OPERATORS

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

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

as a function of

17 best measured 'observables' called BSM Primaries

D. de Florian *et al* (2016), RSG, Pomarol & Riva (2014)

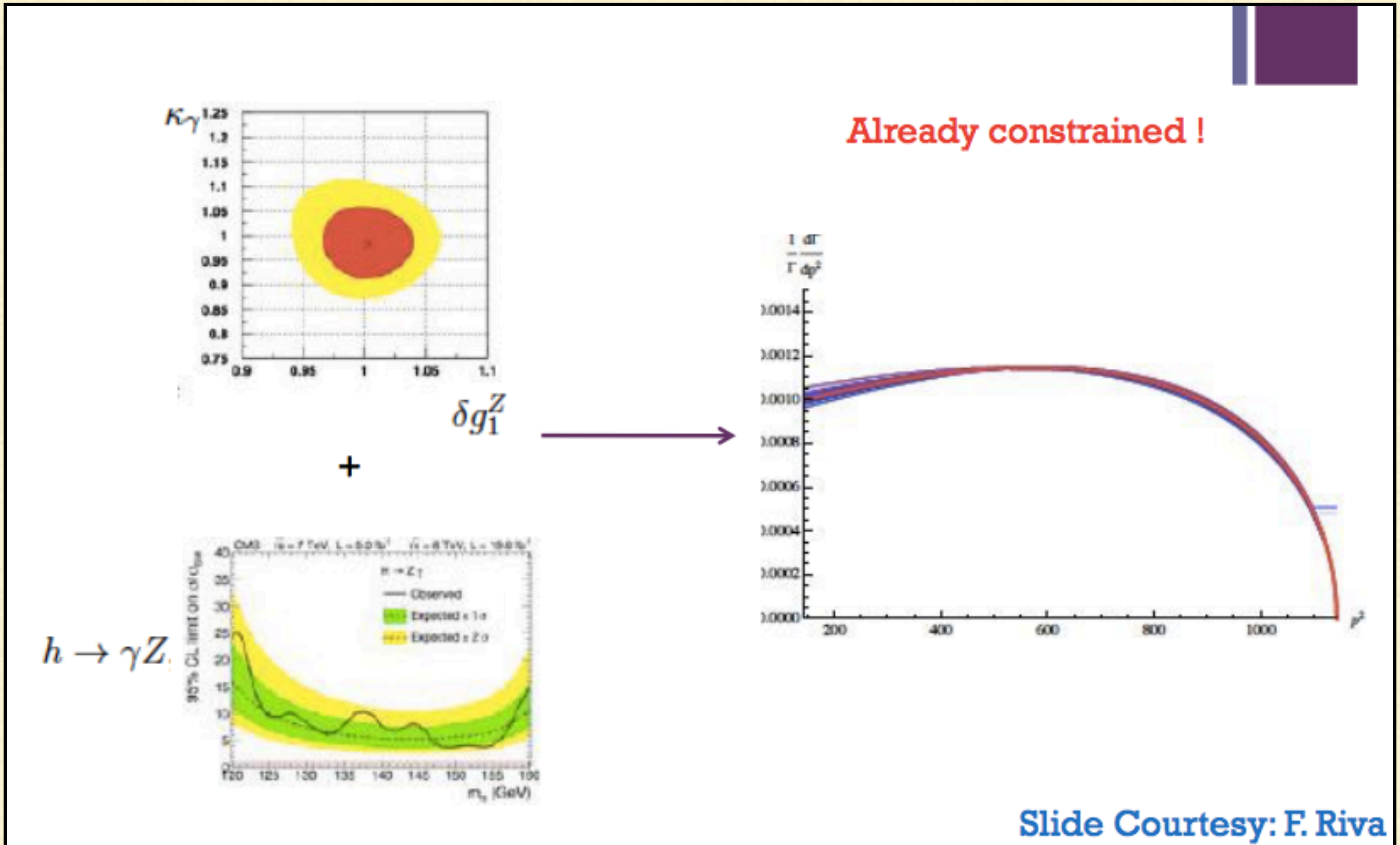
17 BSM PRIMARIES

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

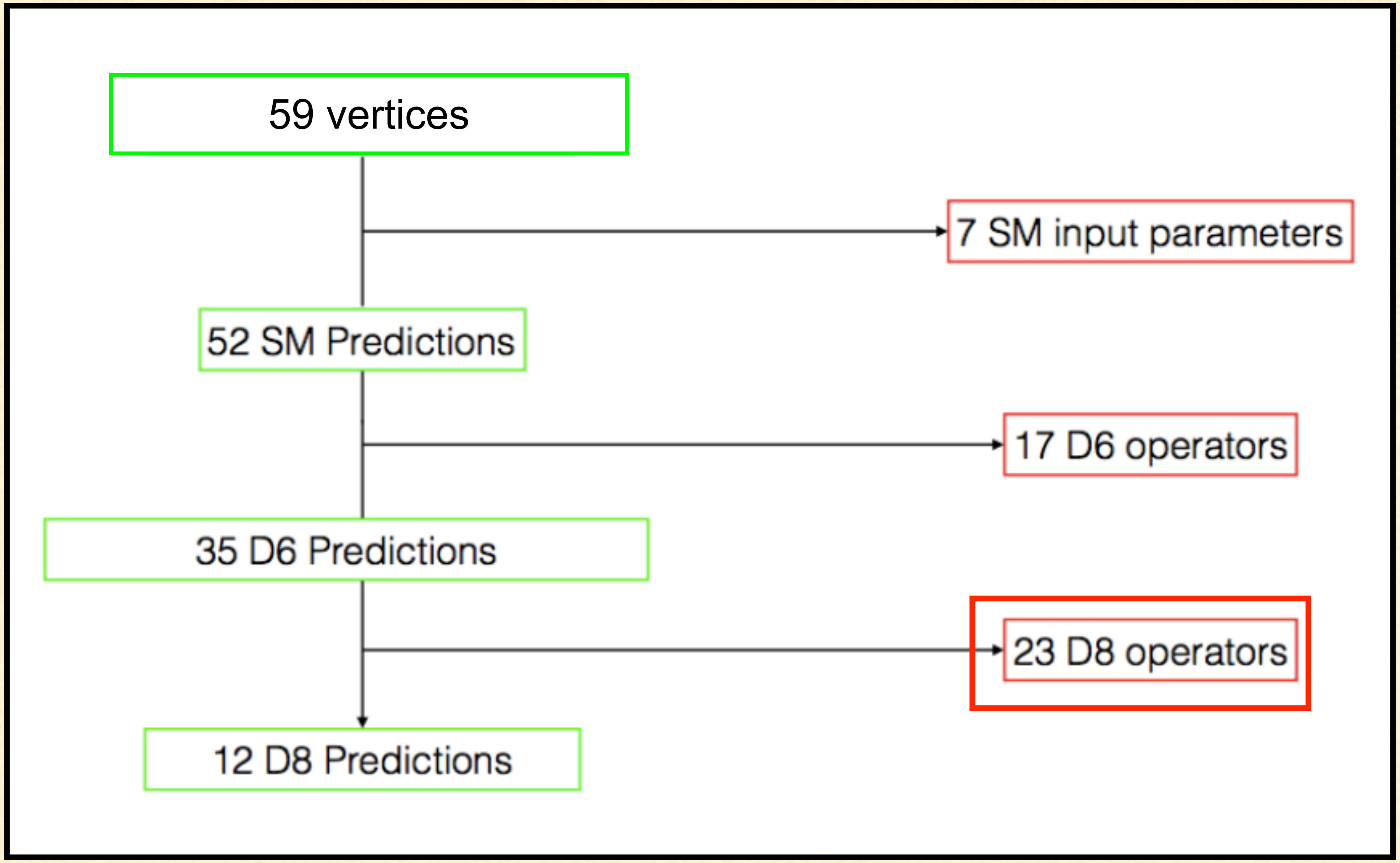
RSG, Pomarol & Riva (2014)

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

EXAMPLE OF D6 PREDICTION: *h>Vff*



COUNTING



D8 unconstrains 23 deformations and makes them primaries !

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)

Henning, Lu, Melia, and Murayama(2015)
Bertuzzo, Grojean & RSG (in prep)

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)
$\mathcal{O}^W_{F_Wf}$
$\mathcal{O}^D_{F_Wf}$
$\mathcal{O}^D_{F_BF}$
$\mathcal{O}^W_{F_BF}$
$\mathcal{O}^V_{F_WF}$
$\mathcal{O}^H_{F_WF}$
$\mathcal{O}^{W2}_{F_WF}$
$\mathcal{O}^{D2}_{F_WF}$
$\psi^2D^2H^2$:14
$\mathcal{O}^{T_f}_{D^2H^21} = T^f_{\mu\nu}(D^\mu H^\dagger D^\nu H + h.c.)$
$\mathcal{O}^{T_F}_{D^2H^22} = T^{Fa}_{\mu\nu}(D_\mu H^\dagger\sigma^a D_\nu H + h.c.)$
$\mathcal{O}^{A_f}_{D^2H^2} = A^f_{\mu\nu}(D^\mu H^\dagger D^\nu H - h.c.)$
$\mathcal{O}^{A_F^a}_{D^2H^2} = A^a_{F\mu\nu}(D^\mu H^\dagger\sigma^a D^\nu H - h.c.)$

X^4: 10 Henning: 10
$\mathcal{O}_{4B1} = g'^4 B_{\rho\sigma}B^{\rho\sigma}B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{4B2} = g'^4 B_{\mu\nu}B^{\nu\rho}B_{\mu\sigma}B^{\sigma\rho}$
$\mathcal{O}_{4W1} = g^4 W^I_{\rho\sigma}W^{I\rho\sigma}W^J_{\mu\nu}W^{J\mu\nu}$
$\mathcal{O}_{4W2} = g^4 W^I_{\mu\nu}W^{I\nu\rho}W^J_{\mu\sigma}W^{J\sigma\rho}$
$\mathcal{O}_{4W3} = g^4 W^I_{\mu\nu}W^I_{\rho\sigma}W^{J\mu\nu}W^{J\rho\sigma}$
$\mathcal{O}_{4W4} = g^4 W^I_{\mu\nu}W^I_{\rho\sigma}W^{J\nu\rho}W^{J\sigma\mu}$
$\mathcal{O}_{2WB1} = g'^2g^2 B_{\rho\sigma}B^{\rho\sigma}W^I_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{2WB2} = g'^2g^2 B_{\mu\nu}B^{\nu\rho}W^I_{\mu\sigma}W^{I\sigma\rho}$
$\mathcal{O}_{2WB3} = g'^2g^2 B_{\mu\nu}B_{\rho\sigma}W^{I\mu\nu}W^{I\rho\sigma}$
$\mathcal{O}_{2WB4} = g'^2g^2 B_{\mu\nu}B_{\rho\sigma}W^{I\nu\rho}W^{I\sigma\mu}$

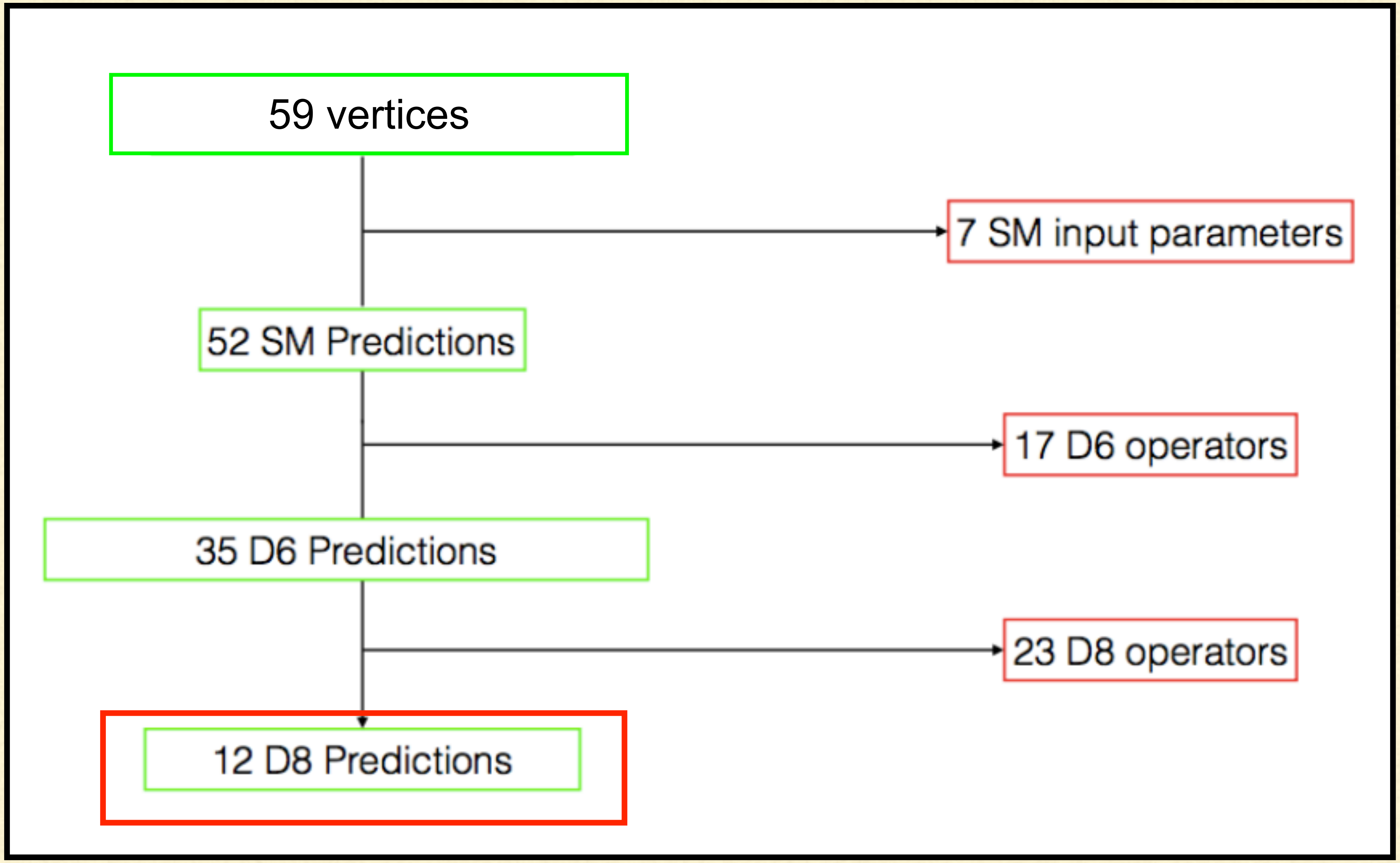
23 Dimension 8 operators with more than or equal to 4 Higgs doublets

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

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

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

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
$\mathcal{O}_{DHB1} = g'^2 D_\rho H^\dagger D^\rho H B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{DHW1} = g^2 D_\rho H^\dagger D^\rho H W^I_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{DHWB1} = gg' D_\rho H^\dagger\sigma^I D^\rho H B_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{DHB2} = g'^2 D_\mu H^\dagger D^\nu H B_{\mu\rho}B^{\nu\rho}$
$\mathcal{O}_{DHW2} = g^2 D_\mu H^\dagger D^\nu H W^I_{\mu\rho}W^{I\nu\rho}$
$\mathcal{O}_{DHWB2} = \frac{gg'}{2}(D_\mu H^\dagger\sigma^I D^\nu H + h.c.)W^I_{\mu\rho}B^{\nu\rho}$
$\mathcal{O}_{DHWB3} = \frac{igg'}{2}(D_\mu H^\dagger\sigma^I D^\nu H - h.c.)HW^I_{\mu\rho}\tilde{B}^{\nu\rho}$
$\mathcal{O}_{DHW3} = \frac{ig^2}{2}\epsilon_{IJK}D_\nu H^\dagger\sigma^I D_\rho H W^J_{\mu\nu}W^{K\mu\rho}$
$\mathcal{O}_{DHW4} = \frac{g^2}{2}\epsilon_{IJK}(D_\mu H^\dagger\sigma^I D_\nu H + h.c.)W^J_{\mu\rho}\tilde{W}^{K\nu\rho}$
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
$\mathcal{O}^V_{F_B f} = ig'H^\dagger \overleftrightarrow{D}_\mu H\bar{f}\gamma^\nu f\tilde{B}^{\mu\nu}$ (5)
$\mathcal{O}^H_{F_B f} = g'\partial_\mu(H^\dagger H)\bar{f}\gamma^\nu f B^{\mu\nu}$ (5)
$\mathcal{O}^{T_f}_{D^2H^2 2} = T^{Fa}_{\mu\nu}(D_\mu H^\dagger\sigma^a D_\nu H + h.c.)$
$\mathcal{O}^{A_f}_{D^2H^2} = A^f_{\mu\nu}(D^\mu H^\dagger D^\nu H - h.c.)$
$\mathcal{O}^{A^a_F}_{D^2H^2} = A^a_{F\mu\nu}(D^\mu H^\dagger\sigma^a D^\nu H - h.c.)$

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

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

OTHER D8 OPERATORS

- These give rise to vertices with more derivatives 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

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:

$$\delta_4 - 6\delta_3 - \left(\frac{\delta g_{VV}^h}{v} + g^2 c_{\theta_W}^2 \delta g_1^Z\right)\frac{m_h^2}{3m_W^2} \rightarrow \text{vanishes at D6 level}$$

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

EXAMPLE 1: SHAPE OF HIGGS POTENTIAL

Higgs potential:

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

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2 D4 Predictions:

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

D6 opens δ_3 but one Prediction remains:

stronger constraints

$$\boxed{\delta_4 - 6\delta_3 - \cancel{\left(\frac{\delta g_{VV}^h}{v} + g^2 c_{\theta_W}^2 \delta g_1^Z\right)\frac{m_h^2}{3m_W^2}}} \longrightarrow \text{vanishes at D6 level}$$

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

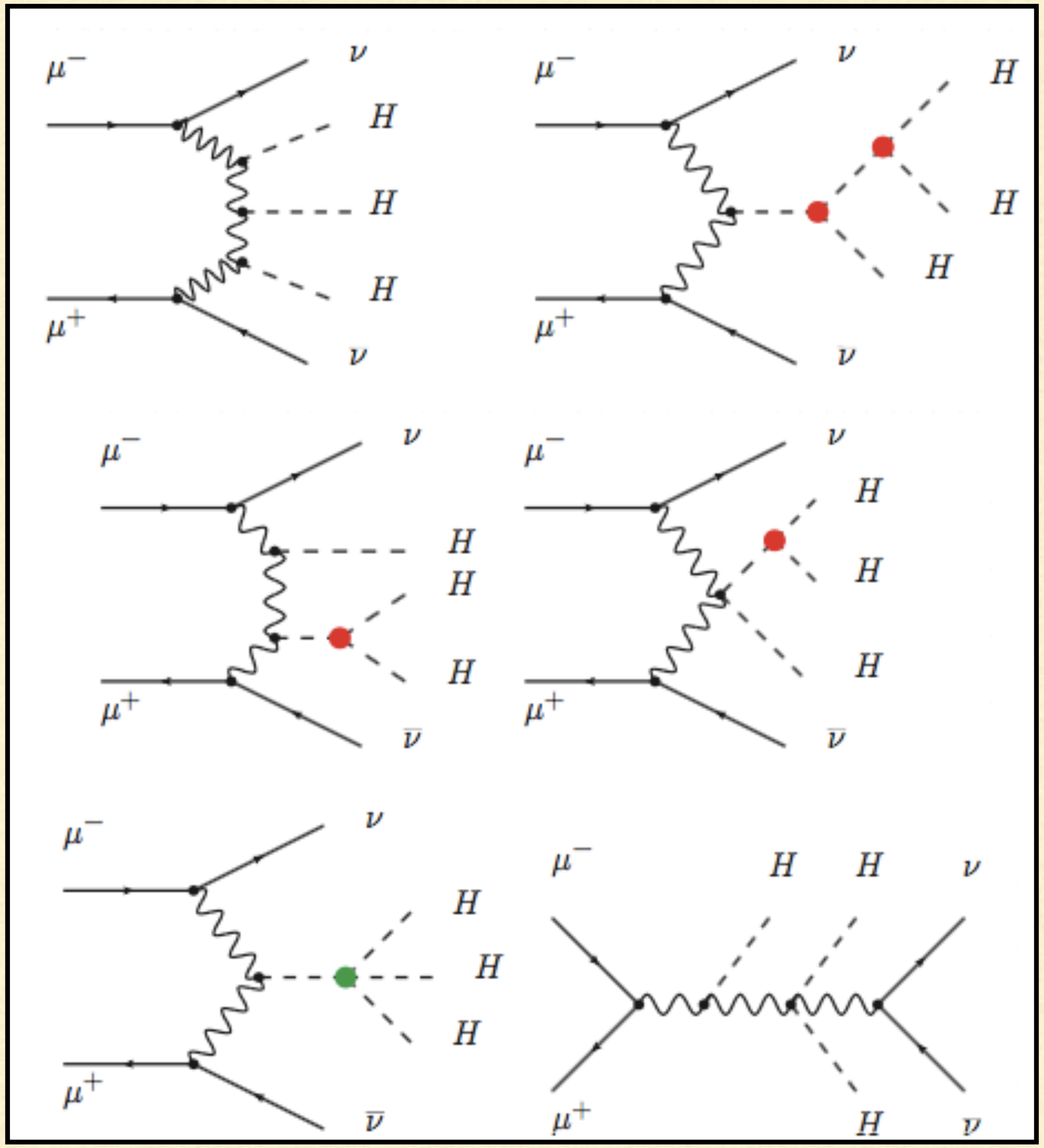
EXAMPLE 1: SHAPE OF HIGGS POTENTIAL

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

$$\boxed{\delta_4 - 6\delta_3 = 4c_8 \frac{v^4}{\Lambda^4} + c_{H^2r} \frac{m_h^2}{4v^2} \frac{v^4}{\Lambda^4}}$$

- Should not deform only one coupling but both simultaneously

- Deviations from this line probe D8 effect



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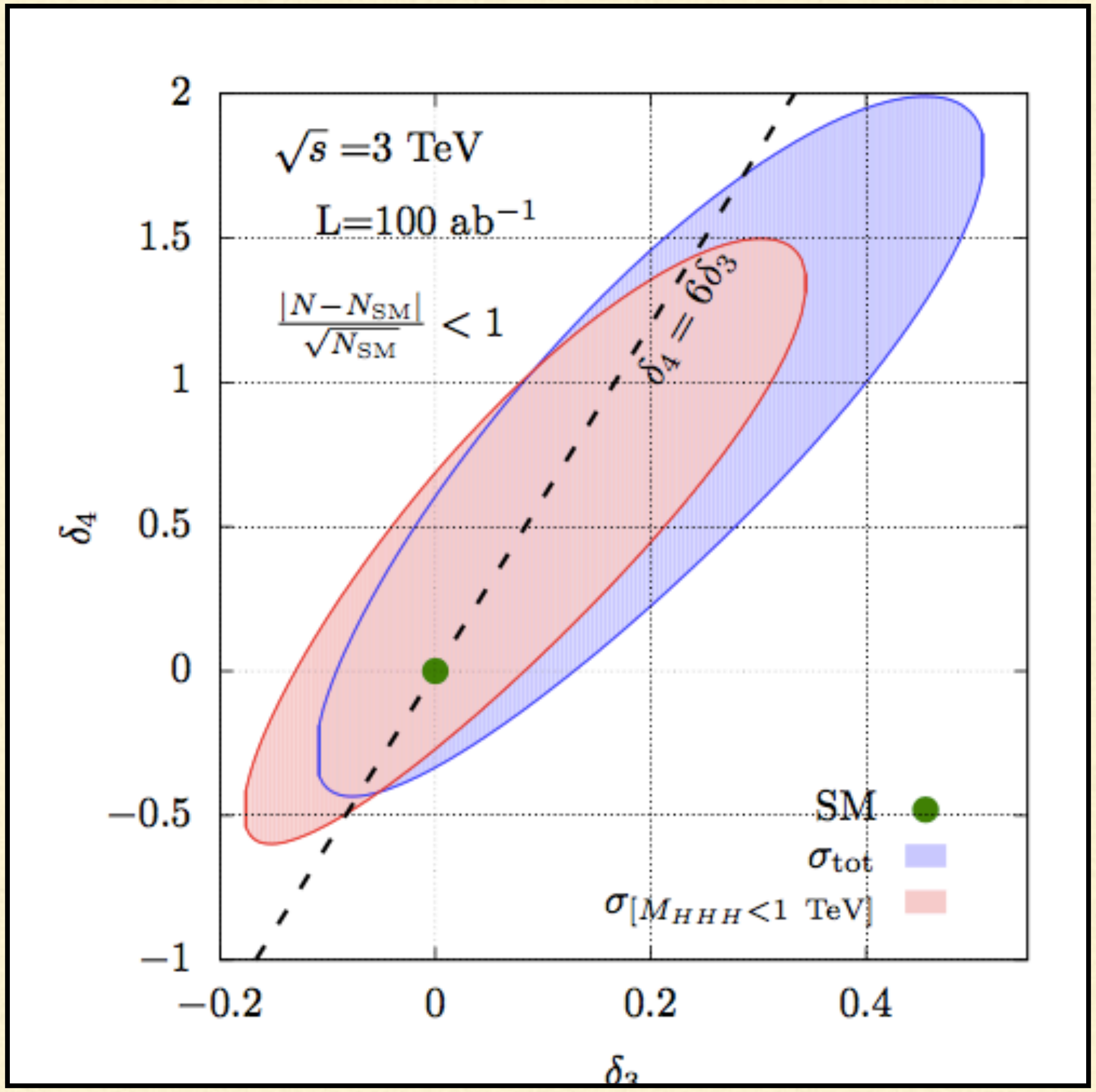


Chiesaa, Maltoni, Mantani, Melee, Piccinini & Zhao (2020)

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

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

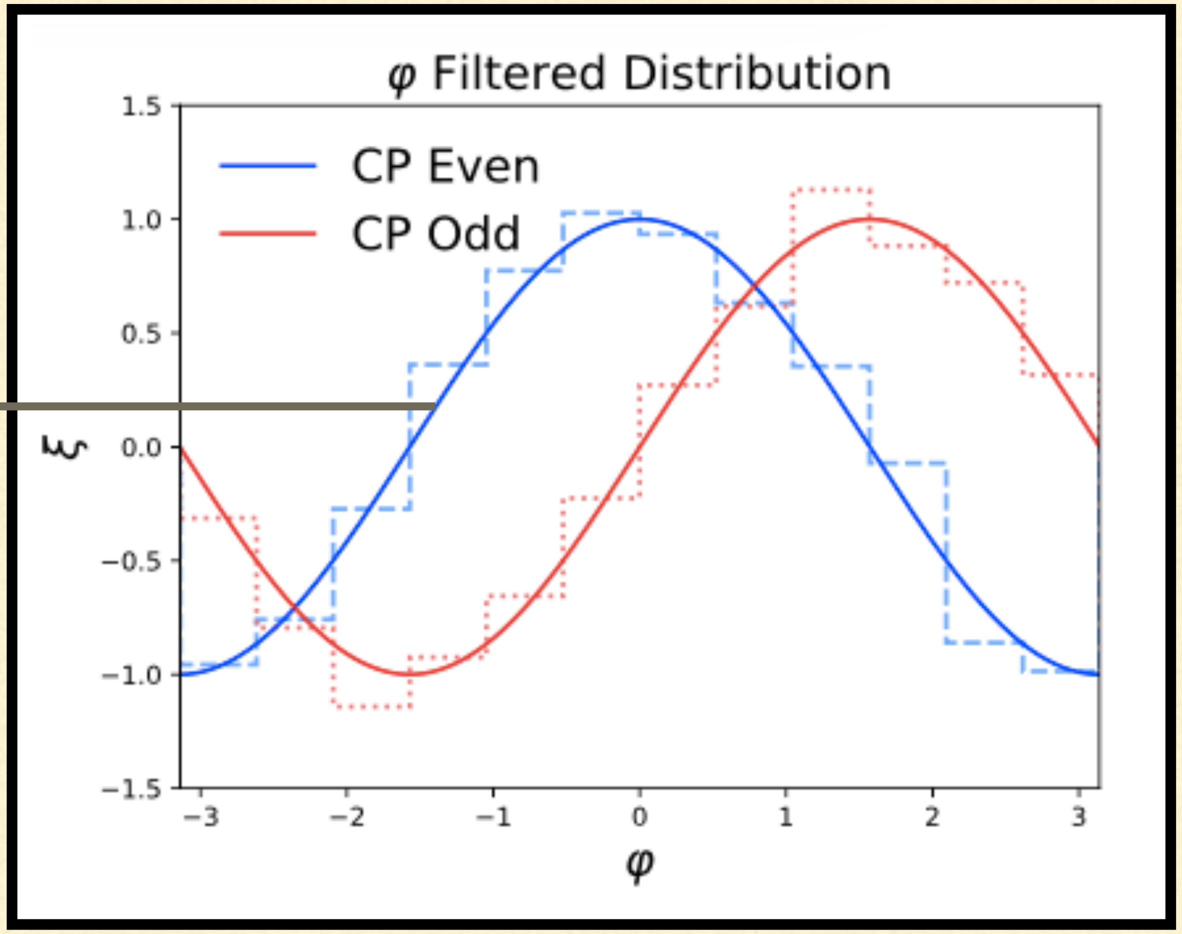
- κ_{ZZ} is already constrained at percent level due to this correlation. Is there any point in trying to measure this separately ?

YES !

- In HEFT this correlation broken at $O(v^2/\Lambda^2)$, i.e there is no correlation
- In SMEFT this correlation broken at $O(v^4/\Lambda^4)$(that is at D8)

EXAMPLE 2: TRANSVERSE GAUGE COUPLINGS

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



See Joey'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%

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

- 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

$$\boxed{VV} \xrightarrow{\text{D6 prediction}} \boxed{Vh}$$

Z-pole, TGCs   *hVff*

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

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

hWff   Z-pole   TGCs

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

EXAMPLE 3: HIGH ENERGY PRIMARIES

D6 prediction broken at D8 level:

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

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

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

$O(v^4/\Lambda^4)$=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)

SMEFT VS HEFT

HIGGS EFT (HEFT)

- *h* not part of doublet *H*. EW symmetry non-linearly realised.
- Goldstone bosons eaten by *W*, *Z*, written as follows,

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

- *h* does not unitarise WW scattering. Mass term of W, Z non renormalisable with cut off below 4πv, where a strong sector is often assumed

$$\boxed{\frac{v^2}{4}\mathrm{Tr}(D_\mu U^\dagger D^\mu U) \to (m_W^2 W^2 + m_Z^2 Z^2/2)}$$

HIGGS EFT (HEFT)

- *h* does not unitarise WW scattering. Mass term of W, Z non renormalisable with cut off below 4πv, often assumed to be a strong sector

$$\frac{v^2}{4}\mathrm{Tr}(D_\mu U^\dagger D^\mu U) \to (m_W^2 W^2 + m_Z^2 Z^2/2)$$

- *h* is a scalar, not necessarily related to goldstones, accidentally lighter than cut-off. Typical HEFT operator:

$$\frac{v^2}{4}\mathrm{Tr}(D_\mu U^\dagger D^\mu U)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + ...\right)$$

- No cost to additional *h* or *U* (goldstones) in HEFT. Each Higgs/goldstone accompanied by a 4π

$$\frac{4\pi h}{\Lambda} \to \frac{h}{v}, \quad \frac{4\pi\pi_i}{\Lambda} \to \frac{\pi_i}{v}$$

WHAT ABOUT THE HEFT?

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

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

$\rightarrow$ Unitary gauge: U=1

$\downarrow$

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

$\downarrow$

$$\boxed{W_\mu^+ W_\nu^- Z^{\mu\nu} \to \mathcal{W}_\mu^+ \mathcal{W}_\nu^- \mathcal{Z}^{\mu\nu}}$$

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

- All deformations at a given HEFT order independent. All predictions broken all at once.

Chanowitz, Holden & Georgi (1987)

ALSO IN SMEFT!

$$-\frac{g(v+h)^2}{2c_{\theta_W}} Z_\mu \to iH^\dagger \overleftrightarrow{D}_\mu H$$

$$\frac{g(v+h)^2}{2}\{W_\mu^+, W_\mu^-, Z_\mu/c_{\theta_W}\} \to i\{H^\dagger\sigma^+\overleftrightarrow{D}_\mu H, H^\dagger\sigma^-\overleftrightarrow{D}_\mu H, H^\dagger\sigma^3\overleftrightarrow{D}_\mu H\}$$

$\boxed{W_\mu^+ W_\nu^- Z^{\mu\nu}} \longrightarrow$ But will Require 6 Higgs doublets.
A Dim 10 operator

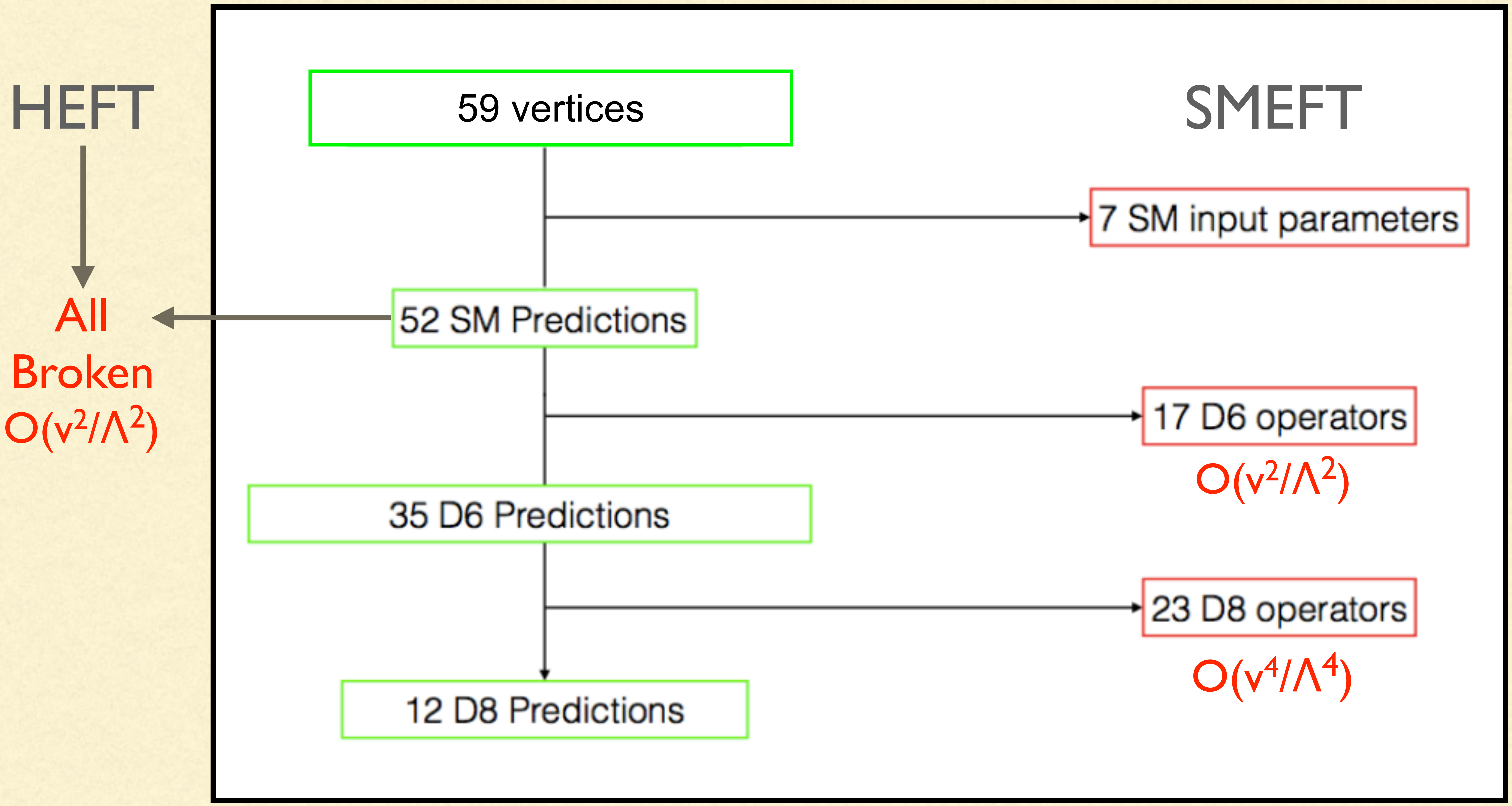
- Our deformations can be promoted to independent invariant terms SMEFT operators but at the cost of additional Higgs doublets.

- Have to go to higher and higher dimensions with more Higgs doublets to break all predictions. Predictions broken order by order in v^2/Λ^2 as these Higgs doublets et VEV

SMEFT VS HEFT: COST OF HIGGS DOUBLETS

- To generate each anomalous coupling independently need many Higgs doublets (up to 8 for QGCs), go to higher and higher dimension
- All SMEFT predictions broken eventually but order by order in v^2/Λ^2
- In HEFT all predictions at a given order broken simultaneously.
- SMEFT an expansion in v^2/Λ^2 and p^2/Λ^2
- HEFT an expansion only in p^2/Λ^2

SMEFT VS HEFT



(considering only 1 generation for the purpose of counting)

Bertuzzo, Grojean & RSG (in prep)

NON DECOUPLING NEW PHYSICS AND HEFT

- Another way of identifying physical scenarios that map to HEFT but not SMEFT

- Integrating out non-decoupled heavy physics getting mass from EWSB give non analytic terms:

4th generation fermions $\longrightarrow$ $\boxed{(H^\dagger H)\log(H^\dagger H)}$

Doublet Φ in $\boxed{V = \kappa\Phi^4 + \mu(\Phi^\dagger H + h.c.)}$ $\longrightarrow$ $\boxed{(H^\dagger H)^{2/3}}$

- Expanding these gives series an infinite series in powers of h/v not h/Λ
Maps to HEFT, not SMEFT.

Fallkowski & Rattazzi (2019)

CONCLUSIONS

- At any order in SMEFT more ‘observables’ than operators. This 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’ unconstrained. 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