The Geometric SMEFT...

VILLUM FONDEN

DET FRIE FORSKNINGSRÅD
DANISH COUNCIL FOR INDEPENDENT RESEARCH

Key collaborators and developments in geoSMEFT:

geoSMEFT talk online at All Things EFT







A. Helset	T. Corbett	A. Martin	C. Hays	J. Talbert
1803.08001 Helset, Paraskevas, Trott.		1909.08470	Corbett, Helset, Trott	
2001.01453 Helset, Martin, Trott.		2007.00565	Hays, Helset, Martin, Trott	
2010.08451	Corbett, Trott	2102.02819	Helset, Corbett, Martin, Trott	
2010.15852	Corbett,	2106.13794	Trott	
2107.03951	Talbert, Trott.	2107.07470	Corbett, Martin, Trott	
2106.10284	Corbett,	2109.05595	Martin, Trott	
2110.03694	Corbett, Rasmussen			
Other groups joining in:				
2202.06965	Cohen, Craig, Lu, Sutherland	2111.03045	Cheung, Helset, Parra-Martinez	
2202.06972	Cheung, Helset, Parra-Martinez			

SMEFT challenges.

Parameters in the SMEFT

In Warsaw basis arXiv:1008.4884 (SMEFT standard basis)

$$\frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6$$

Class		$N_{\rm op}$	CP-even			CP-odd		
			n_g	1	3	n_g	1	3
1	g^3X^3	4	2	2	2	2	2	2
2	H^6	1	1	1	1	0	0	0
3	H^4D^2	2	2	2	2	0	0	0
4	$g^2X^2H^2$	8	4	4	4	4	4	4
5	$y\psi^2H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6	$gy\psi^2XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7	ψ^2H^2D	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
ψ^4	$8:(\overline{L}L)(LL)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
	$8:(\overline{R}R)(\overline{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
	$8:(\overline{L}L)(\overline{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
	$8:(\overline{L}R)(\overline{R}L)$	1	n_g^4	1	81	n_g^4	1	81
	$8:(\overline{L}R)(\overline{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
	8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total		59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

2499

1312.2014 Alonso, Jenkins, Manohar, Trott

- Thats a lot of parameters in general.
- Linearly realised symmetries (exact or softly broken) of the SMEFT relate parameters

Dim 6 SMEFT EW Lagrangian terms

- SMEFT at dimension 6 with all operators is already complicated.
- EW sector parameters redefined in the SMEFT

$$\begin{bmatrix} \mathcal{W}^3_\mu \\ \mathcal{B}_\mu \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2}\, v_T^2\, C_{HWB} \\ -\frac{1}{2}\, v_T^2\, C_{HWB} & 1 \end{bmatrix} \begin{bmatrix} \cos\overline{\theta} & \sin\overline{\theta} \\ -\sin\overline{\theta} & \cos\overline{\theta} \end{bmatrix} \begin{bmatrix} \mathcal{Z}_\mu \\ \mathcal{A}_\mu \end{bmatrix},$$

Mass redefinitions

$$M_W^2 = \frac{\overline{g}_2{}^2 v_T^2}{4},$$

$$M_Z^2 = \frac{v_T^2}{4}(\overline{g}_1{}^2 + \overline{g}_2{}^2) + \frac{1}{8} v_T^4 C_{HD}(\overline{g}_1{}^2 + \overline{g}_2{}^2) + \frac{1}{2} v_T^4 \overline{g}_1 \overline{g}_2 C_{HWB}.$$

Mixing angle redefinitions

$$\sin\overline{\theta} = \frac{\overline{g}_1}{\sqrt{\overline{g}_1{}^2 + \overline{g}_2{}^2}} \left[1 + \frac{v_T^2}{2} \frac{\overline{g}_2}{\overline{g}_1} \frac{\overline{g}_2{}^2 - \overline{g}_1{}^2}{\overline{g}_2{}^2 + \overline{g}_1{}^2} C_{HWB}\right]$$

$$\cos\overline{\theta} = \frac{\overline{g}_2}{\sqrt{\overline{g}_1{}^2 + \overline{g}_2{}^2}} \left[1 - \frac{v_T^2}{2} \frac{\overline{g}_1}{\overline{g}_2} \frac{\overline{g}_2{}^2 - \overline{g}_1{}^2}{\overline{g}_2{}^2 + \overline{g}_1{}^2} C_{HWB}\right]$$

Interactions to remaining SM fields via:

$$D_\mu = \partial_\mu + i\,\frac{\overline{g}_2}{\sqrt{2}}\left[\mathcal{W}^+_\mu T^+ + \mathcal{W}^-_\mu T^-\right] + i\,\overline{g}_Z\left[T_3 - \overline{s}^2 Q\right]\mathcal{Z}_\mu + i\,\overline{e}\,Q\,\mathcal{A}_\mu,$$

$$\overline{e} = \frac{\overline{g}_1 \overline{g}_2}{\sqrt{\overline{g}_2{}^2 + \overline{g}_1{}^2}} \left[1 - \frac{\overline{g}_1 \overline{g}_2}{\overline{g}_2{}^2 + \overline{g}_1{}^2} v_T^2 C_{HWB}\right]$$

$$\overline{g}_Z = \sqrt{\overline{g}_2{}^2 + \overline{g}_1{}^2} + \frac{\overline{g}_1 \overline{g}_2}{\sqrt{\overline{g}_2{}^2 + \overline{g}_1{}^2}} v_T^2 C_{HWB}$$

$$\overline{s}^2 = \sin^2\overline{\theta} = \frac{\overline{g}_1{}^2}{\overline{g}_2{}^2 + \overline{g}_1{}^2} + \frac{\overline{g}_1 \overline{g}_2 (\overline{g}_2{}^2 - \overline{g}_1{}^2)}{(\overline{g}_1{}^2 + \overline{g}_2{}^2)^2} v_T^2 C_{HWB}.$$

1312.2014 Alonso, Jenkins, Manohar, Trott

- Note the complications are proportional to the vev.

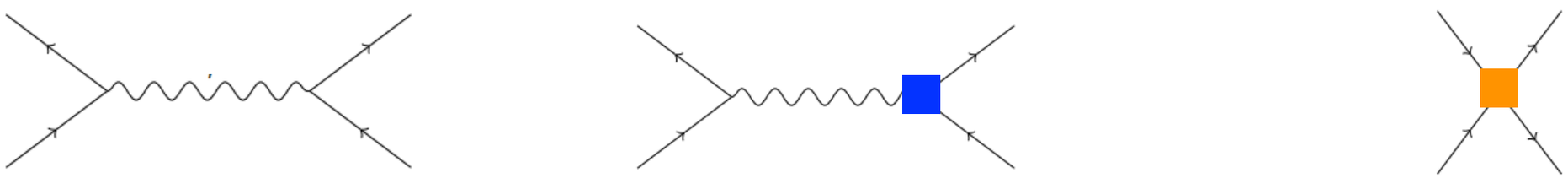
Inputs also needed -SMEFT Muon decay

- Decay of $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ still measured far below the W pole.

1312.2014 Alonso, Jenkins, Manohar, Trott

- Still probes the effective lagrangian

$$\mathcal{L}_{G_F} = -\frac{4\mathcal{G}_F}{\sqrt{2}} \left(\bar{\nu}_\mu \gamma^\mu P_L \mu\right) \left(\bar{e} \gamma_\mu P_L \nu_e\right)$$



So now $$-\frac{4\mathcal{G}_F}{\sqrt{2}} = -\frac{2}{v_T^2} + \left(C_{\substack{ll \\ \mu ee \mu}} + C_{\substack{ll \\ e\mu\mu e}}\right) - 2\left(C^{(3)}_{\substack{Hl \\ ee}} + C^{(3)}_{\substack{Hl \\ \mu\mu}}\right)$$

$$\delta G_F$$

- Tons of work to redefine things at dim 6, can we go to dim 8?

Automation of this approach

- Need to keep all operators and carefully compute S matrix elements avoiding uncontrolled approximations (and human error) - hard even at $\mathcal{L}_6$
- Automation of $\mathcal{L}_6$ SMEFT in the SMEFTsim package has enabled The experimental program to do this 1709.06492 Brivio, Jiang ,Trott.

feynrules.irmp.ucl.ac.be/wiki/SMEFT

SMEFTsim is consistent with the geoSMEFT at leading order

wiki: SMEFT

Standard Model Effective Field Theory -- The SMEFTsim package

Authors

Ilaria Brivio, Yun Jiang and Michael Trott

brivio@thphys.uni-heidelberg.de, yunjiang@nbi.ku.dk, michael.trott@cern.ch

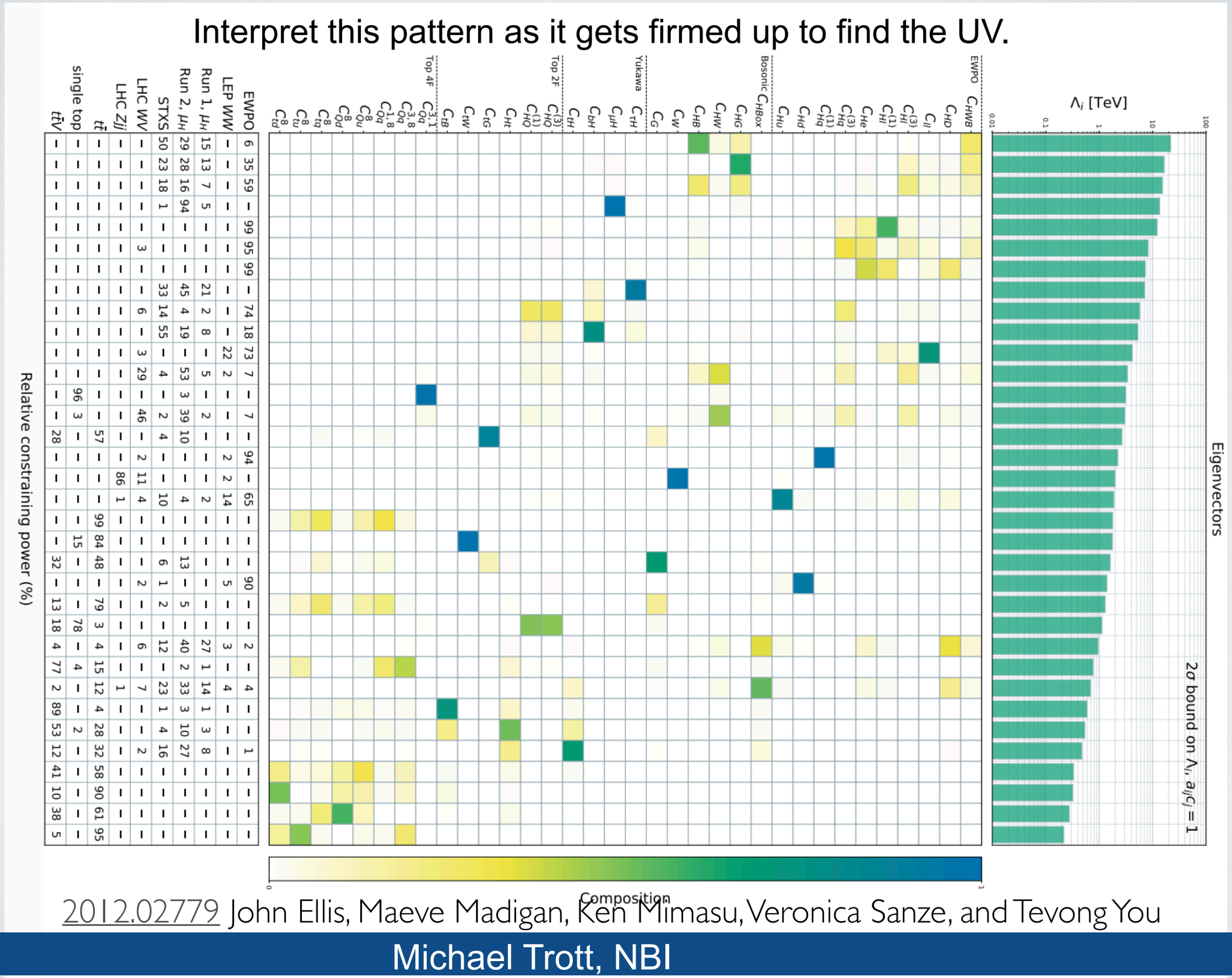
NBIA and Discovery Center, Niels Bohr Institute, University of Copenhagen

References

- I. Brivio, Y. Jiang and M. Trott, *The SMEFTsim package, theory and tools*, JHEP **1712** (2017) 070 arXiv:1709.06492

Keep all operators gives eigenvectors of constraint

Interpret this pattern as it gets firmed up to find the UV.

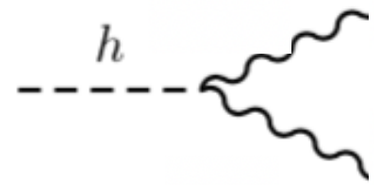


2012.02779 John Ellis, Maeve Madigan, Ken Mimasu, Veronica Sanze, and Tevong You

Can we do better re basis independence? Yes.

More basis independent results are possible!

All orders expression for Higgs to gamma gamma can be defined in closed form as:



Yes! Its a Vielbein of a Higgs space defining asy. particle states in SMEFT

$$\langle h|\mathcal{A}(p_1)\mathcal{A}(p_2)\rangle = -\langle hA^{\mu\nu}A_{\mu\nu}\rangle \frac{\sqrt{h}^{44}}{4}\left[\langle\frac{\delta g_{33}(\phi)}{\delta\phi_4}\rangle\frac{\overline{e}^2}{g_2^2} + 2\langle\frac{\delta g_{34}(\phi)}{\delta\phi_4}\rangle\frac{\overline{e}^2}{g_1 g_2} + \langle\frac{\delta g_{44}(\phi)}{\delta\phi_4}\rangle\frac{\overline{e}^2}{g_1^2}\right],$$

Kinematic structure

Geometric Dressings

No explicit SMEFT expansion op forms. *But all orders in vev expansion*

How do we get to such results?

Why all the geoSMEFT stuff.

We needed a physics principle that is active at $\mathcal{L}_6$ and $\mathcal{L}_8$ to efficiently organise the physics. Is there one?

YES THERE IS - THE MOST BASIC ONE.

Field coord. invariance leads to field space geometry

geoSMEFT

- Field coordinate choice invariance in amplitudes
- Mathematical quantities: metrics, Curvature, tensors of INTERACTION TERMS (field spaces)

$$\mathcal{L}_{SMEFT} = \frac{1}{2} h_{IJ}(\phi)(D_\mu \phi)^I (D_\mu \phi)^J - \frac{1}{4} g_{AB}(\phi) \mathcal{W}^A_{\mu\nu} W^{B,\mu\nu} + \cdots$$

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{bmatrix} \qquad \mathcal{W}^A = (W^1, W^2, W^3, B)$$

General Relativity.

- Space-time coordinate general covariance
- Mathematical quantities: metrics, Curvature, tensors for SPACE TIME

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

Field coord. invariance leads to field space geometry

geoSMEFT

- Field coordinate choice invariance in amplitudes
- Mathematical quantities: metrics, Curvature, tensors of INTERACTION TERMS (field spaces)

$$\mathcal{L}_{SMEFT} = \frac{1}{2} h_{IJ}(\phi)(D_\mu \phi)^I (D_\mu \phi)^J - \frac{1}{4} g_{AB}(\phi) \mathcal{W}^A_{\mu\nu} W^{B,\mu\nu} + \cdots$$

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{bmatrix} \qquad \mathcal{W}^A = (W^1, W^2, W^3, B)$$

In general terms: G. A. Vilkovisky, Nucl. Phys. B234 (1984) 125.

Modern uptake:

1002.2730 Burgess, Lee, Trott
1511.00724 Alonso, Jenkins, Manohar
1605.03602 Alonso, Jenkins, Manohar
1803.08001 Helset, Paraskevas, Trott.
1909.08470 Corbett, Helset, Trott

General Relativity.

- Space-time coordinate general covariance
- Mathematical quantities: metrics, Curvature, tensors for SPACE TIME

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

Field coord. invariance leads to field space geometry

$$\mathcal{L}_{SMEFT} = \frac{1}{2} h_{IJ}(\phi)(D_\mu \phi)^I (D_\mu \phi)^J - \frac{1}{4} g_{AB}(\phi) \mathcal{W}^A_{\mu\nu} W^{B,\mu\nu} + \cdots$$

- Dimensionless expansion into operator bases $\tilde{C}_i = \frac{\langle H^\dagger H \rangle}{\Lambda^2} C_i$

$$\sqrt{h}^{IJ} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 - \frac{1}{4}\tilde{C}_{HD} & 0 \\ 0 & 0 & 0 & 1 + \tilde{C}_{H\Box} - \frac{1}{4}\tilde{C}_{HD} \end{bmatrix}$$

$$\sqrt{g}^{AB} = \begin{bmatrix} 1+\tilde{C}_{HW} & 0 & 0 & 0 \\ 0 & 1+\tilde{C}_{HW} & 0 & 0 \\ 0 & 0 & 1+\tilde{C}_{HW} & -\frac{\tilde{C}_{HWB}}{2} \\ 0 & 0 & -\frac{\tilde{C}_{HWB}}{2} & 1+\tilde{C}_{HB} \end{bmatrix}$$

(Small perturbations so positive semi-definite matrix and unique square root)

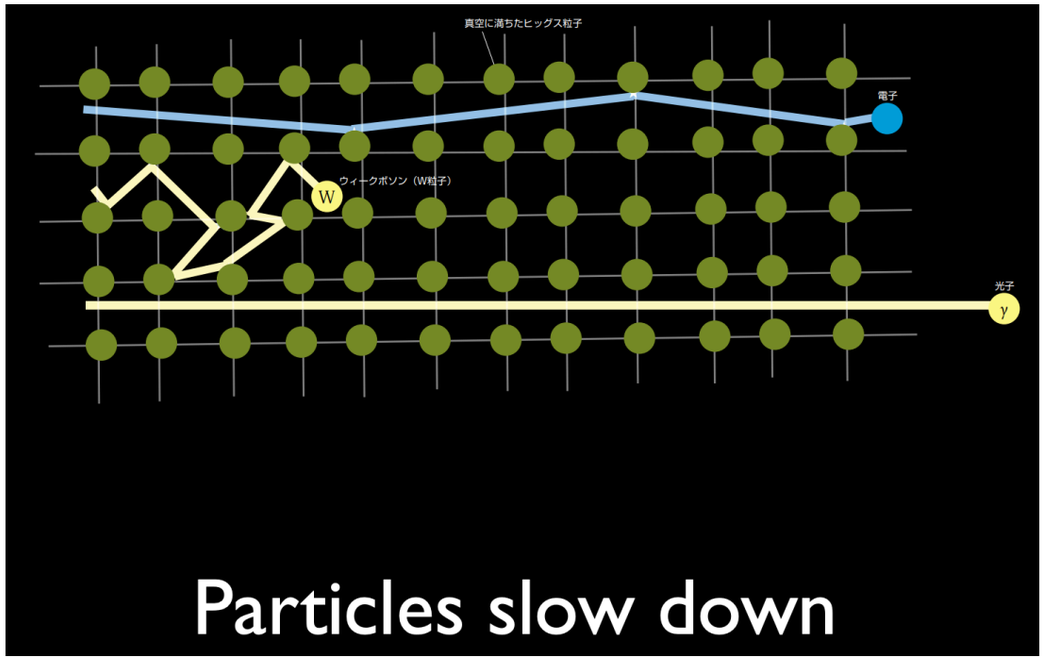
- Geometric field space quantities are useful (True independent of mass dimension of ops) Amp. perturb. are:

$$\mathcal{A} \simeq \mathcal{A}_{SM} + \langle \mathcal{O} \rangle_1 N_1 + \langle \mathcal{O} \rangle_2 N_2 + \cdots$$

Fun. of 4 vectors (kinematics)

Defined by field space geometries

What is the Geometric SMEFT?

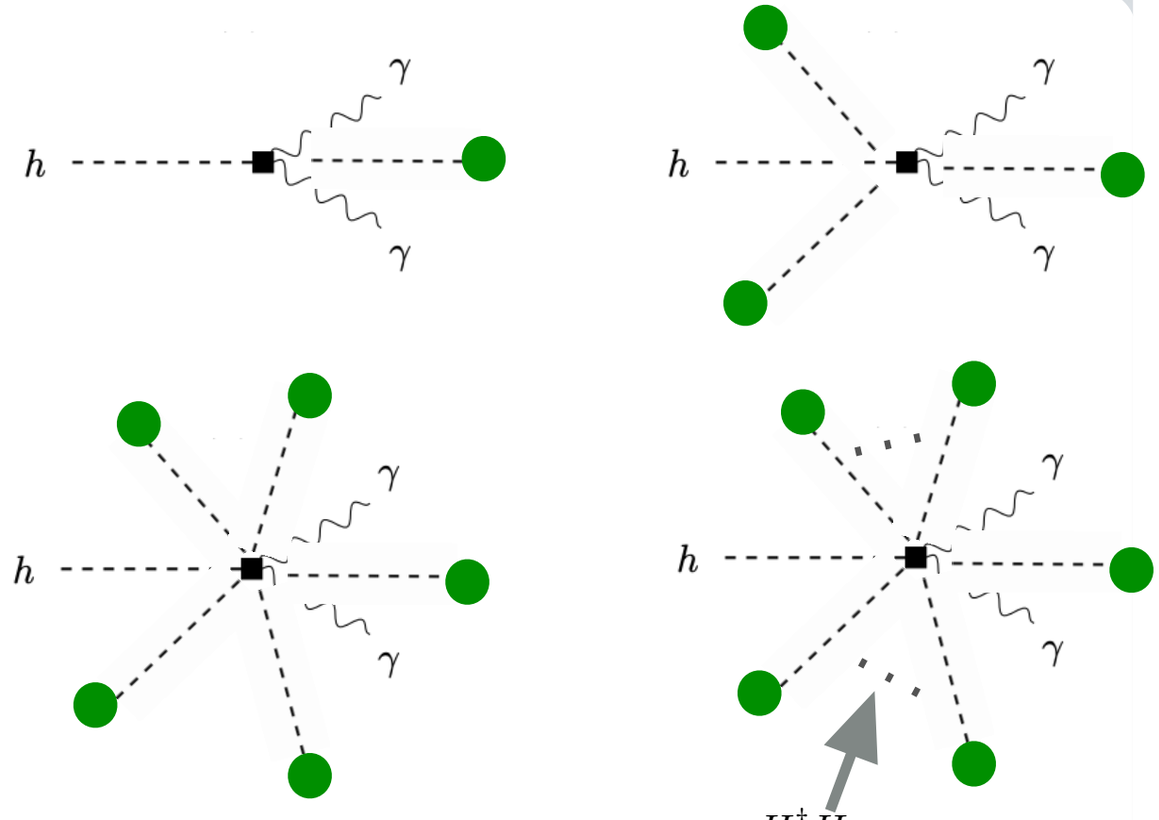


Particles slow down

$$\mathcal{L}_{SM}$$

$$D \leq 4$$

Gives masses, mass eigenstate fields.



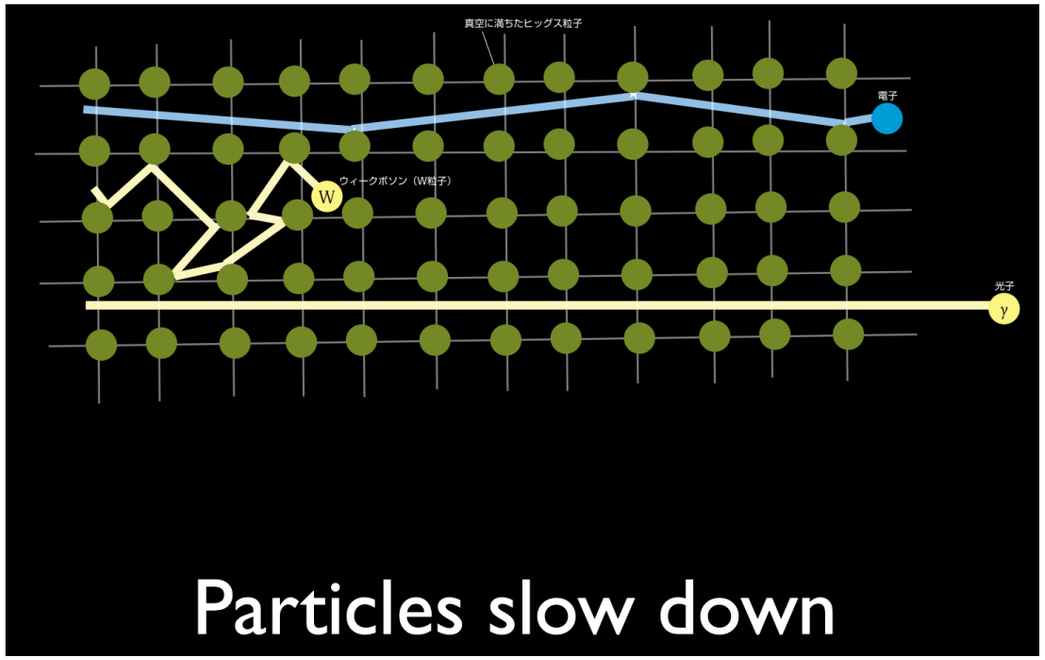
$$\mathcal{L}_{SMEFT}$$

Powers of $\frac{H^\dagger H}{\Lambda^2}$ and symmetry generators

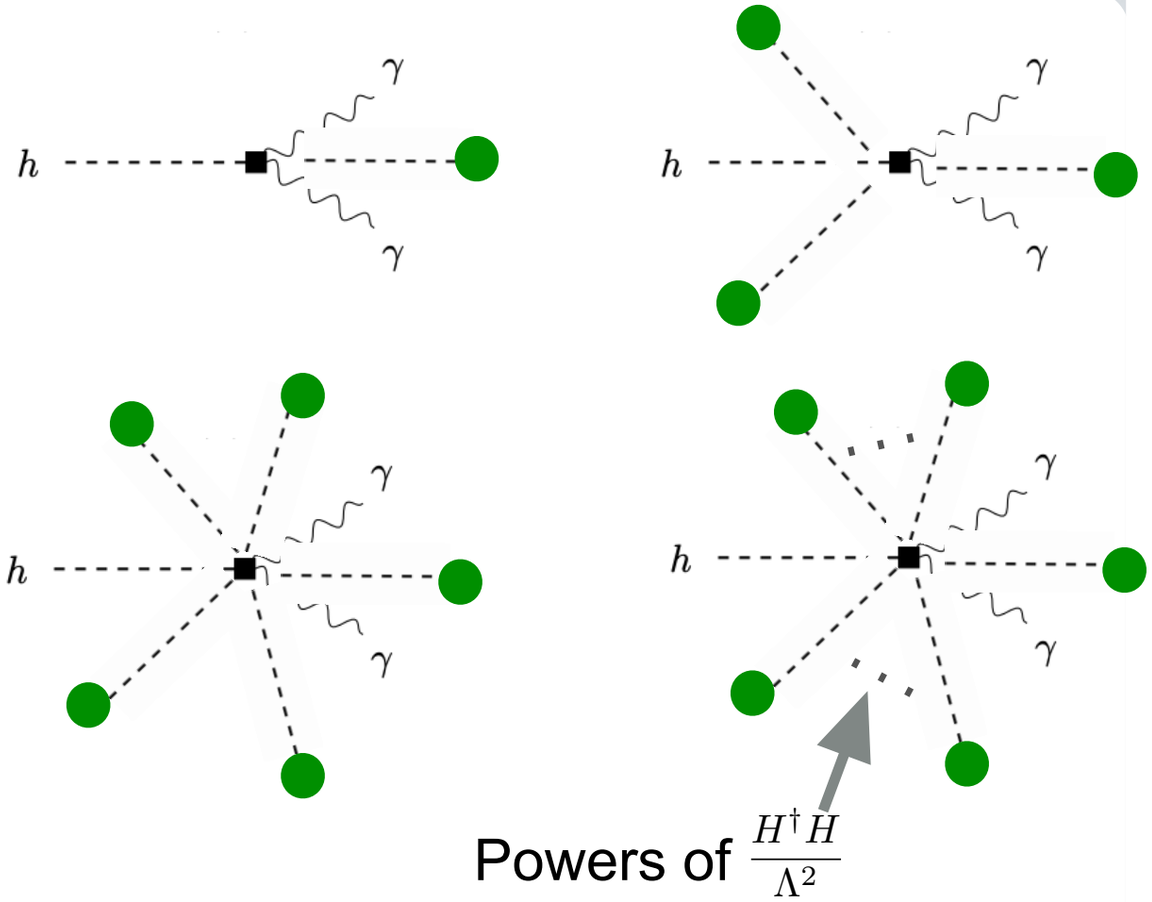
$$D > 4$$

Gives **<u>geometries</u>** that define the mass eigenstate fields and interactions in the EFT

What is the Geometric SMEFT?



Particles slow down



Powers of $\frac{H^\dagger H}{\Lambda^2}$
and symmetry generators

$$\langle h|\mathcal{A}(p_1)\mathcal{A}(p_2)\rangle = -\langle hA^{\mu\nu}A_{\mu\nu}\rangle \frac{\sqrt{h}^{44}}{4}\left[\langle\frac{\delta g_{33}(\phi)}{\delta\phi_4}\rangle\frac{\overline{e}^2}{g_2^2} + 2\langle\frac{\delta g_{34}(\phi)}{\delta\phi_4}\rangle\frac{\overline{e}^2}{g_1 g_2} + \langle\frac{\delta g_{44}(\phi)}{\delta\phi_4}\rangle\frac{\overline{e}^2}{g_1^2}\right],$$

Kinematic structure

Geometric Dressings

Geometric couplings

Curved SMEFT spaces: scalar fields

- Curved SMEFT field space manifest in background field formulation

In general terms: G. A. Vilkovisky, Nucl. Phys. B234 (1984) 125.

Metric on Higgs field space, SM a **FLAT** field space

$$\mathcal{L}_{\text{scalar,kin}} = \frac{1}{2} h_{IJ}(\phi) \left(D_\mu \phi\right)^I \left(D^\mu \phi\right)^J, \qquad \text{Where} \quad H = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{bmatrix}$$

$$\sqrt{h}^{IJ} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 - \frac{1}{4}\tilde{C}_{HD} & 0 \\ 0 & 0 & 0 & 1 + \tilde{C}_{H\Box} - \frac{1}{4}\tilde{C}_{HD} \end{bmatrix}$$

here $\tilde{C}_i = \dfrac{\langle H^\dagger H \rangle}{\Lambda^2} C_i$

Small perturbations so positive semi-definite Matrix and unique square root

(sqrt) Metric in SMEFT, a ***curved*** field space

$$R^I_{JKL} \neq 0$$

1002.2730 Burgess, Lee, Trott
1511.00724 Alonso, Jenkins, Manohar
1605.03602 Alonso, Jenkins, Manohar

Curved SMEFT space: gauge fields

- Similarly in the gauge coupling space a curved field space

Metric on gauge field space, SM a **FLAT** field space

$$\mathcal{L}_{\text{gauge,kin}} = -\frac{1}{4} g_{AB}(\phi) \mathcal{W}^A_{\mu\nu} \mathcal{W}^{B,\mu\nu},$$

Where $\mathcal{W}^A = (W^1, W^2, W^3, B)$

$$\sqrt{g}^{AB} = \begin{bmatrix} 1+\tilde{C}_{HW} & 0 & 0 & 0 \\ 0 & 1+\tilde{C}_{HW} & 0 & 0 \\ 0 & 0 & 1+\tilde{C}_{HW} & -\frac{\tilde{C}_{HWB}}{2} \\ 0 & 0 & -\frac{\tilde{C}_{HWB}}{2} & 1+\tilde{C}_{HB} \end{bmatrix}$$

here $\tilde{C}_i = \frac{\langle H^\dagger H \rangle}{\Lambda^2} C_i$

(sqrt) Metric in SMEFT, a *curved* field space

1803.08001 Helset, Paraskevas, Trott.
1909.08470 Corbett, Helset, Trott

Generators for SMEFT vs SM

Generators on scalar SMEFT space

- To think in a unified gauge space manifold need generators (reformulate SM generators)

$$(D^\mu\phi)^I = (\partial^\mu\delta^I_J - \tfrac{1}{2}\mathcal{W}^{A,\mu}\tilde{\gamma}^I_{A,J})\phi^J$$

$$\tilde{\epsilon}^A{}_{BC} = g_2\,\epsilon^A{}_{BC}, \qquad \text{with } \tilde{\epsilon}^1{}_{23} = +g_2,$$

$$\tilde{\gamma}^I_{A,J} = \begin{cases} g_2\,\gamma^I_{A,J}, & \text{for } A = 1,2,3 \\ g_1\gamma^I_{A,J}, & \text{for } A = 4. \end{cases}$$

$$\gamma^I_{1,J} = \begin{bmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \gamma^I_{2,J} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},$$

$$\gamma^I_{3,J} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad \gamma^I_{4,J} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}.$$

(this last one also “i”)

1803.08001 Helset, Paraskevas, Trott.

- Some interesting math here, we also define $\Gamma^I_{A,K} = \gamma^I_{A,J}\,\gamma^J_{4,K}$

$$\Gamma^I_{1,J} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix}, \quad \Gamma^I_{2,J} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \Gamma^I_{3,J} = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \Gamma^I_{4,J} = -\mathbb{I}_{4\times 4}.$$

Generators on scalar SMEFT space

- The mapping of operator forms works via:

$$
\begin{aligned}
H^\dagger \sigma_a H &= -\frac{1}{2}\phi_I \Gamma^I_{a,J}\phi^J, \\
H^\dagger \overleftrightarrow{iD^\mu} H &= -\phi_I\, \gamma^I_{4,J}(D^\mu\phi)^J = (D^\mu\phi)_I\, \gamma^I_{4,J}\phi^J, \\
H^\dagger \overleftrightarrow{iD^\mu_a} H &= -\phi_I\, \gamma^I_{a,J}(D^\mu\phi)^J = (D^\mu\phi)_I\, \gamma^I_{a,J}\phi^J, \\
2\tilde{H}^\dagger D^\mu H &= \tilde{\phi}_I(-\Gamma^I_{4,J} + i\,\gamma^I_{4,J})\,(D^\mu\phi)^J.
\end{aligned}
$$

It is useful to “real” the SM symmetry representation on the scalar manifold for lots of reasons. Makes more manifest possible contractions

$$
\phi_I \Gamma^I_{A,J}\phi^J \neq 0, \qquad \phi_I \gamma^I_{a,J}\phi^J = \phi_I \gamma^I_{4,J}\phi^J = 0.
$$

- All orders results follow, for example:

$$
\begin{aligned}
h_{IJ} = &\left[1 + \phi^2 C^{(6)}_{H\Box} + \sum_{n=0}^{\infty}\left(\frac{\phi^2}{2}\right)^{n+2}\left(C^{(8+2n)}_{HD} - C^{(8+2n)}_{H,D2}\right)\right]\delta_{IJ} \\
&+ \frac{\Gamma^I_{A,J}\phi_K\Gamma^K_{A,L}\phi^L}{2}\left(\frac{C^{(6)}_{HD}}{2} + \sum_{n=0}^{\infty}\left(\frac{\phi^2}{2}\right)^{n+1} C^{(8+2n)}_{H,D2}\right).
\end{aligned}
$$

All orders SM Lagrangian parameters

- Low n-point interactions of fields are parameterised in terms of couplings,

1909.08470 Corbett, Helset, Trott

$$\bar{g}_2 = g_2\sqrt{g}^{11} = g_2\sqrt{g}^{22},$$
$$\bar{g}_Z = \frac{g_2}{c^2_{\bar{\theta}_Z}}\left(c_{\bar{\theta}}\sqrt{g}^{33} - s_{\bar{\theta}}\sqrt{g}^{34}\right) = \frac{g_1}{s^2_{\bar{\theta}_Z}}\left(s_{\bar{\theta}}\sqrt{g}^{44} - c_{\bar{\theta}}\sqrt{g}^{34}\right),$$
$$\bar{e} = g_2\left(s_{\bar{\theta}}\sqrt{g}^{33} + c_{\bar{\theta}}\sqrt{g}^{34}\right) = g_1\left(c_{\bar{\theta}}\sqrt{g}^{44} + s_{\bar{\theta}}\sqrt{g}^{34}\right),$$

- Masses

$$\bar{m}^2_W = \frac{\bar{g}^2_2}{4}\sqrt{h_{11}}^2\bar{v}^2_T, \qquad \bar{m}^2_Z = \frac{\bar{g}^2_Z}{4}\sqrt{h_{33}}^2\bar{v}^2_T \qquad \bar{m}^2_A = 0.$$

- Mixing angles:

$$s^2_{\bar{\theta}_Z} = \frac{g_1(\sqrt{g}^{44}s_{\bar{\theta}} - \sqrt{g}^{34}c_{\bar{\theta}})}{g_2(\sqrt{g}^{33}c_{\bar{\theta}} - \sqrt{g}^{34}s_{\bar{\theta}}) + g_1(\sqrt{g}^{44}s_{\bar{\theta}} - \sqrt{g}^{34}c_{\bar{\theta}})},$$
$$s^2_{\bar{\theta}} = \frac{(g_1\sqrt{g}^{44} - g_2\sqrt{g}^{34})^2}{g^2_1[(\sqrt{g}^{34})^2 + (\sqrt{g}^{44})^2] + g^2_2[(\sqrt{g}^{33})^2 + (\sqrt{g}^{34})^2] - 2g_1g_2\sqrt{g}^{34}(\sqrt{g}^{33} + \sqrt{g}^{44})}.$$

(Interesting way to think of the Weinberg angle)

All orders expressions are known now

- All orders scalar metric -leading to gauge boson masses in SMEFT

$$h_{IJ} = \left[1 + \phi^2 C_{H\Box}^{(6)} + \sum_{n=0}^{\infty} \left(\frac{\phi^2}{2}\right)^{n+2} \left(C_{HD}^{(8+2n)} - C_{H,D2}^{(8+2n)}\right)\right] \delta_{IJ} + \frac{\Gamma_{A,J}^{I} \phi_K \Gamma_{A,L}^{K} \phi^L}{2} \left(\frac{C_{HD}^{(6)}}{2} + \sum_{n=0}^{\infty} \left(\frac{\phi^2}{2}\right)^{n+1} C_{H,D2}^{(8+2n)}\right).$$

- All orders gauge metric - gives mass eigenstate couplings in SMEFT

$$g_{AB}(\phi_I) = \left[1 - 4\sum_{n=0}^{\infty} \left(C_{HW}^{(6+2n)}(1-\delta_{A4}) + C_{HB}^{(6+2n)}\delta_{A4}\right)\left(\frac{\phi^2}{2}\right)^{n+1}\right]\delta_{AB} - \sum_{n=0}^{\infty} C_{HW,2}^{(8+2n)} \left(\frac{\phi^2}{2}\right)^{n} \left(\phi_I \Gamma_{A,J}^{I} \phi^J\right)\left(\phi_L \Gamma_{B,K}^{L} \phi^K\right)(1-\delta_{A4})(1-\delta_{B4}) + \left[\sum_{n=0}^{\infty} C_{HWB}^{(6+2n)} \left(\frac{\phi^2}{2}\right)^{n}\right]\left[\left(\phi_I \Gamma_{A,J}^{I} \phi^J\right)(1-\delta_{A4})\delta_{B4} + (A \leftrightarrow B)\right],$$

- Number of operator forms saturate in geosmeft.
  This is due to reducing possible generator insertions on the Higgs manifold

$$T_{ij}^a T_{k\ell}^a = \frac{1}{2}\left(\delta_{i\ell}\delta_{jk} - \frac{1}{N}\delta_{ij}\delta_{k\ell}\right)$$

SM weak-mass eigenstate relations

- Weak eigenstates

Mass eigenstate

$$\hat{\mathcal{W}}^{A,\nu} = \delta^{AB} U_{BC} \hat{\mathcal{A}}^{C,\nu},$$
$$\hat{\alpha}^{A} = \delta^{AB} U_{BC} \hat{\beta}^{C},$$
$$\hat{\phi}^{J} = \delta^{JK} V_{KL} \hat{\Phi}^{L},$$

Rotations

Flat field space's.
Due to $D \leq 4$

$$U_{BC} = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{i}{\sqrt{2}} & \frac{-i}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & c_{\overline{\theta}} & s_{\overline{\theta}} \\ 0 & 0 & -s_{\overline{\theta}} & c_{\overline{\theta}} \end{bmatrix} \qquad V_{JK} = \begin{bmatrix} \frac{-i}{\sqrt{2}} & \frac{i}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\phi^J = \{\phi_1, \phi_2, \phi_3, \phi_4\}, \Phi^K = \{\Phi^-, \Phi^+, \chi, h\}$$

$$\alpha^A = \{g_2\, g_2, g_2, g_1\},$$

$$\beta^C = \left\{ \frac{g_2\,(1-i)}{\sqrt{2}}, \frac{g_2\,(1+i)}{\sqrt{2}}, \sqrt{g_1^2+g_2^2}(c_{\overline{\theta}}^2 - s_{\overline{\theta}}^2), \frac{2\,g_1\,g_2}{\sqrt{g_1^2+g_2^2}} \right\},$$

$$\mathcal{W}^A = \{W_1, W_2, W_3, B\},$$

$$\mathcal{A}^C = (\mathcal{W}^+, \mathcal{W}^-, \mathcal{Z}, \mathcal{A})\,.$$

What else could you write?

SMEFT weak-mass eigenstate relations

- Weak eigenstates

Mass eigenstate

$$\hat{\mathcal{W}}^{A,\nu} = \sqrt{g}^{AB} U_{BC} \hat{\mathcal{A}}^{C,\nu},$$
$$\hat{\alpha}^{A} = \sqrt{g}^{AB} U_{BC} \hat{\beta}^{C},$$
$$\hat{\phi}^{J} = \sqrt{h}^{JK} V_{KL} \hat{\Phi}^{L},$$

1909.08470 Corbett, Helset, Trott

Generator transform

$$\boldsymbol{\gamma}^{I}_{C,J} = \frac{1}{2} \tilde{\gamma}^{I}_{A,J} \sqrt{g}^{AB} U_{BC}.$$

SMEFT Field space metrics
(Now known to all orders)

Rotations

$$U_{BC} = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{i}{\sqrt{2}} & \frac{-i}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & c_{\overline{\theta}} & s_{\overline{\theta}} \\ 0 & 0 & -s_{\overline{\theta}} & c_{\overline{\theta}} \end{bmatrix} \qquad V_{JK} = \begin{bmatrix} \frac{-i}{\sqrt{2}} & \frac{i}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\phi^J = \{\phi_1, \phi_2, \phi_3, \phi_4\}, \Phi^K = \{\Phi^-, \Phi^+, \chi, h\}$$

$$\alpha^A = \{g_2\, g_2, g_2, g_1\}, \qquad \mathcal{W}^A = \{W_1, W_2, W_3, B\},$$

$$\beta^C = \left\{ \frac{g_2\,(1-i)}{\sqrt{2}}, \frac{g_2\,(1+i)}{\sqrt{2}}, \sqrt{g_1^2+g_2^2}(c_{\bar{\theta}}^2 - s_{\bar{\theta}}^2), \frac{2\,g_1\,g_2}{\sqrt{g_1^2+g_2^2}} \right\}, \qquad \mathcal{A}^C = (\mathcal{W}^+, \mathcal{W}^-, \mathcal{Z}, \mathcal{A})\,.$$

What else could you write? Nothing that generalises to all orders.

Dim 6 SMEFT EW Lagrangian terms

- EW sector parameters redefined in the SMEFT (already in SMEFTsim)

$$\begin{bmatrix} \mathcal{W}_\mu^3 \\ \mathcal{B}_\mu \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} v_T^2 C_{HWB} \\ -\frac{1}{2} v_T^2 C_{HWB} & 1 \end{bmatrix} \begin{bmatrix} \cos\overline{\theta} & \sin\overline{\theta} \\ -\sin\overline{\theta} & \cos\overline{\theta} \end{bmatrix} \begin{bmatrix} \mathcal{Z}_\mu \\ \mathcal{A}_\mu \end{bmatrix},$$

Mass redefinitions

$$M_W^2 = \frac{\overline{g}_2{}^2 v_T^2}{4},$$

$$M_Z^2 = \frac{v_T^2}{4}(\overline{g}_1{}^2 + \overline{g}_2{}^2) + \frac{1}{8} v_T^4 C_{HD} (\overline{g}_1{}^2 + \overline{g}_2{}^2) + \frac{1}{2} v_T^4 \overline{g}_1 \overline{g}_2 C_{HWB}.$$

Mixing angle redefinitions

$$\sin\overline{\theta} = \frac{\overline{g}_1}{\sqrt{\overline{g}_1{}^2 + \overline{g}_2{}^2}} \left[1 + \frac{v_T^2}{2} \frac{\overline{g}_2}{\overline{g}_1} \frac{\overline{g}_2{}^2 - \overline{g}_1{}^2}{\overline{g}_2{}^2 + \overline{g}_1{}^2} C_{HWB}\right]$$

$$\cos\overline{\theta} = \frac{\overline{g}_2}{\sqrt{\overline{g}_1{}^2 + \overline{g}_2{}^2}} \left[1 - \frac{v_T^2}{2} \frac{\overline{g}_1}{\overline{g}_2} \frac{\overline{g}_2{}^2 - \overline{g}_1{}^2}{\overline{g}_2{}^2 + \overline{g}_1{}^2} C_{HWB}\right]$$

Interactions to remaining SM fields via:

$$D_\mu = \partial_\mu + i \frac{\overline{g}_2}{\sqrt{2}} \left[\mathcal{W}_\mu^+ T^+ + \mathcal{W}_\mu^- T^-\right] + i \overline{g}_Z \left[T_3 - \overline{s}^2 Q\right] \mathcal{Z}_\mu + i \overline{e} Q \mathcal{A}_\mu,$$

$$\overline{e} = \frac{\overline{g}_1 \overline{g}_2}{\sqrt{\overline{g}_2{}^2 + \overline{g}_1{}^2}} \left[1 - \frac{\overline{g}_1 \overline{g}_2}{\overline{g}_2{}^2 + \overline{g}_1{}^2} v_T^2 C_{HWB}\right]$$

$$\overline{g}_Z = \sqrt{\overline{g}_2{}^2 + \overline{g}_1{}^2} + \frac{\overline{g}_1 \overline{g}_2}{\sqrt{\overline{g}_2{}^2 + \overline{g}_1{}^2}} v_T^2 C_{HWB}$$

$$\overline{s}^2 = \sin^2\overline{\theta} = \frac{\overline{g}_1{}^2}{\overline{g}_2{}^2 + \overline{g}_1{}^2} + \frac{\overline{g}_1 \overline{g}_2 (\overline{g}_2{}^2 - \overline{g}_1{}^2)}{(\overline{g}_1{}^2 + \overline{g}_2{}^2)^2} v_T^2 C_{HWB}.$$

- Dim 8,10 etc solved in closed form. Just expand.

Generalisation for composite ops

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \mathcal{L}^{(7)} + ..., \qquad \mathcal{L}^{(d)} = \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)} \quad \text{for } d > 4,$$

$$v/M < 1$$

$$\mathcal{L}_{\text{SMEFT}} = \sum_i f_i(\alpha \cdots) G_i(I, A \cdots),$$

Derivative expansion

Composite operator form
With minimal scalar field
coordinate dependence

Vev expansion

Scalar field coordinate dependence
And insertions of symmetry generators

$D^\mu \phi$

Mixes expansions, but grouped with derivative forms.

Generalisation for composite ops

- Such connections can be defined from the Lagrangian expansion constructively

$$h_{IJ}(\phi) = \frac{g^{\mu\nu}}{d} \frac{\delta^2 \mathcal{L}_{\text{SMEFT}}}{\delta(D_\mu\phi)^I \, \delta(D_\nu\phi)^J}\bigg|_{\mathcal{L}(\alpha,\beta\cdots)\to 0}.$$

non-trivial Lorentz-index-carrying Lagrangian terms and spin connections $\{\mathcal{W}^A_{\mu\nu}, (D^\mu\Phi)^K, \bar{\psi}\sigma^\mu\psi, \bar{\psi}\psi\cdots\}$

- Limited number of such connections for up to three point functions

$V(\phi)$ $h_{IJ}(\phi)(D_\mu\phi)^I(D_\mu\phi)^J$, $g_{AB}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\mu\nu}$, $k^A_{IJ}(\phi)(D_\mu\phi)^I(D_\nu\phi)^J\,\mathcal{W}^{\mu\nu}_A$, $f_{ABC}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\nu\rho}\mathcal{W}^{C,\mu}_\rho$,

With fermions $Y(\phi)\bar{\psi}_1\psi_2$, $L_{I,A}(\phi)\bar{\psi}_1\gamma^\mu\tau_A\psi_2(D_\mu\phi)^I$, $d_A(\phi)\bar{\psi}_1\sigma^{\mu\nu}\psi_2\mathcal{W}^A_{\mu\nu}$,

Gluon fields $k_{\mathcal{AB}}(\phi)G^{\mathcal{A}}_{\mu\nu}G^{\mathcal{B},\mu\nu}$, $k_{\mathcal{ABC}}(\phi)G^{\mathcal{A}}_{\nu\mu}G^{\mathcal{B},\rho\nu}G^{\mathcal{C},\mu\rho}$, $c(\phi)\bar{\psi}_1\sigma^{\mu\nu}T_{\mathcal{A}}\psi_2G^{\mathcal{A}}_{\mu\nu}$.

Generalisation for composite ops

- Such connections can be defined from the Lagrangian expansion constructively

$$h_{IJ}(\phi) = \frac{g^{\mu\nu}}{d} \frac{\delta^2 \mathcal{L}_{\text{SMEFT}}}{\delta(D_\mu\phi)^I \, \delta(D_\nu\phi)^J}\bigg|_{\mathcal{L}(\alpha,\beta\cdots)\to 0}.$$

non-trivial Lorentz-index-carrying Lagrangian terms and spin connections $\{\mathcal{W}^A_{\mu\nu}, (D^\mu\Phi)^K, \bar{\psi}\sigma^\mu\psi, \bar{\psi}\psi\cdots\}$

- Limited number of such connections for up to three point functions

  This is a non trivial fact proven in 2001.01453 Helset, Martin, Trott

  There is a theory choice here - its REMOVE DERIVATIVE OPS, USE EOM.

  Same reasoning built into, and led to the “Warsaw basis”.
  Also why we were able to renormalise the Warsaw basis completely in 2013.

  EFT Industry standard in flavour physics, chiral pert theory etc.

An instant pay off of this approach

- Growth in operator forms in connections
  Always saturate to fixed number, this is just the simplest organization exploiting this

	Mass Dimension				
Field space connection	6	8	10	12	14
$h_{IJ}(\phi)(D_\mu\phi)^I(D^\mu\phi)^J$	2	2	2	2	2
$g_{AB}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\mu\nu}$	3	4	4	4	4
$k_{IJA}(\phi)(D^\mu\phi)^I(D^\nu\phi)^J\mathcal{W}^A_{\mu\nu}$	0	3	4	4	4
$f_{ABC}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\nu\rho}\mathcal{W}^{C,\mu}_{\rho}$	1	2	2	2	2
$Y^u_{pr}(\phi)\bar{Q}u+$ h.c.	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$
$Y^d_{pr}(\phi)\bar{Q}d+$ h.c.	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$
$Y^e_{pr}(\phi)\bar{L}e+$ h.c.	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$	$2N_f^2$
$d_A^{e,pr}(\phi)\bar{L}\sigma_{\mu\nu}e\mathcal{W}_A^{\mu\nu}+$ h.c.	$4N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$
$d_A^{u,pr}(\phi)\bar{Q}\sigma_{\mu\nu}u\mathcal{W}_A^{\mu\nu}+$ h.c.	$4N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$
$d_A^{d,pr}(\phi)\bar{Q}\sigma_{\mu\nu}d\mathcal{W}_A^{\mu\nu}+$ h.c.	$4N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$	$6N_f^2$
$L^{\psi_R}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,R}\gamma_\mu\sigma_A\psi_{r,R})$	N_f^2	N_f^2	N_f^2	N_f^2	N_f^2
$L^{\psi_L}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,L}\gamma_\mu\sigma_A\psi_{r,L})$	$2N_f^2$	$4N_f^2$	$4N_f^2$	$4N_f^2$	$4N_f^2$

2001.01453 Helset, Martin, Trott

- Once we have things to dim eight it is sufficient in many observables

Mases
Couplings and mixing angles
TGC, Higgs to ZZ,WW
QGC,TGC + Higgs

Yukawas

Dipoles

W,Z couplings to fermions +higgs

Field space connections to all orders

2001.01453 Helset, Martin, Trott

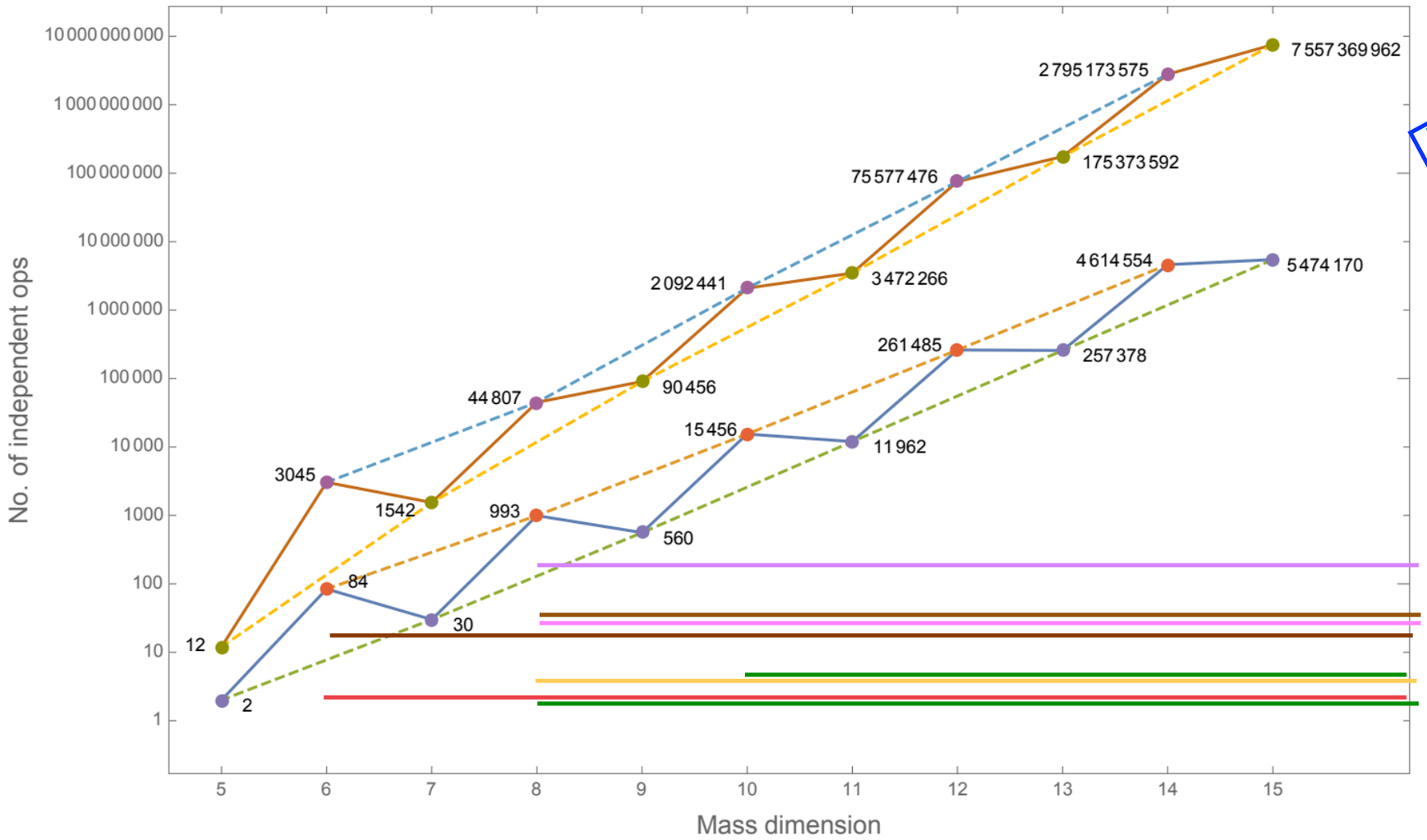
- Off shell operators contributing to three points $(D_\mu\phi)^I\sigma_A(D_\nu\phi)^J\mathcal{W}^A_{\mu\nu}$

$$
\begin{aligned}
Q^{(8+2n)}_{HDHB} &= i\,(H^\dagger H)^{n+1}(D_\mu H)^\dagger(D_\nu H)B^{\mu\nu},\\
Q^{(8+2n)}_{HDHW} &= i\delta_{ab}(H^\dagger H)^{n+1}(D_\mu H)^\dagger\sigma^a(D_\nu H)W^{\mu\nu}_b,\\
Q^{(8+2n)}_{HDHW,2} &= i\epsilon_{abc}(H^\dagger H)^{n}(H^\dagger\sigma^a H)(D_\mu H)^\dagger\sigma^b(D_\nu H)W^{\mu\nu}_c,\\
Q^{(10+2n)}_{HDHW,3} &= i\delta_{ab}\delta_{cd}(H^\dagger H)^{n}(H^\dagger\sigma^a H)(H^\dagger\sigma^c H)(D_\mu H)^\dagger\sigma^b(D_\nu H)W^{\mu\nu}_d.
\end{aligned}
$$

This connection saturates last in op dimension. This is due to EOM reduction. No entries at dim 6 in Warsaw basis.

$$
\begin{aligned}
k^A_{IJ}(\phi) = &-\frac{1}{2}\gamma^I_{4,J}\delta_{A4}\sum_{n=0}^{\infty}C^{(8+2n)}_{HDHB}\left(\frac{\phi^2}{2}\right)^{n+1} - \frac{1}{2}\gamma^I_{A,J}(1-\delta_{A4})\sum_{n=0}^{\infty}C^{(8+2n)}_{HDHW}\left(\frac{\phi^2}{2}\right)^{n+1}\\
&- \frac{1}{8}(1-\delta_{A4})\left[\phi_K\Gamma^K_{A,L}\phi^L\right]\left[\phi_M\Gamma^K_{B,L}\phi^N\right]\gamma^I_{B,J}\sum_{n=0}^{\infty}C^{(10+2n)}_{HDHW,3}\left(\frac{\phi^2}{2}\right)^{n}\\
&+ \frac{1}{4}\epsilon_{ABC}\left[\phi_K\Gamma^K_{B,L}\phi^L\right]\gamma^I_{C,J}\sum_{n=0}^{\infty}C^{(8+2n)}_{HDHW,2}\left(\frac{\phi^2}{2}\right)^{n}.
\end{aligned}
$$

Application to theory error



Tails are exponential

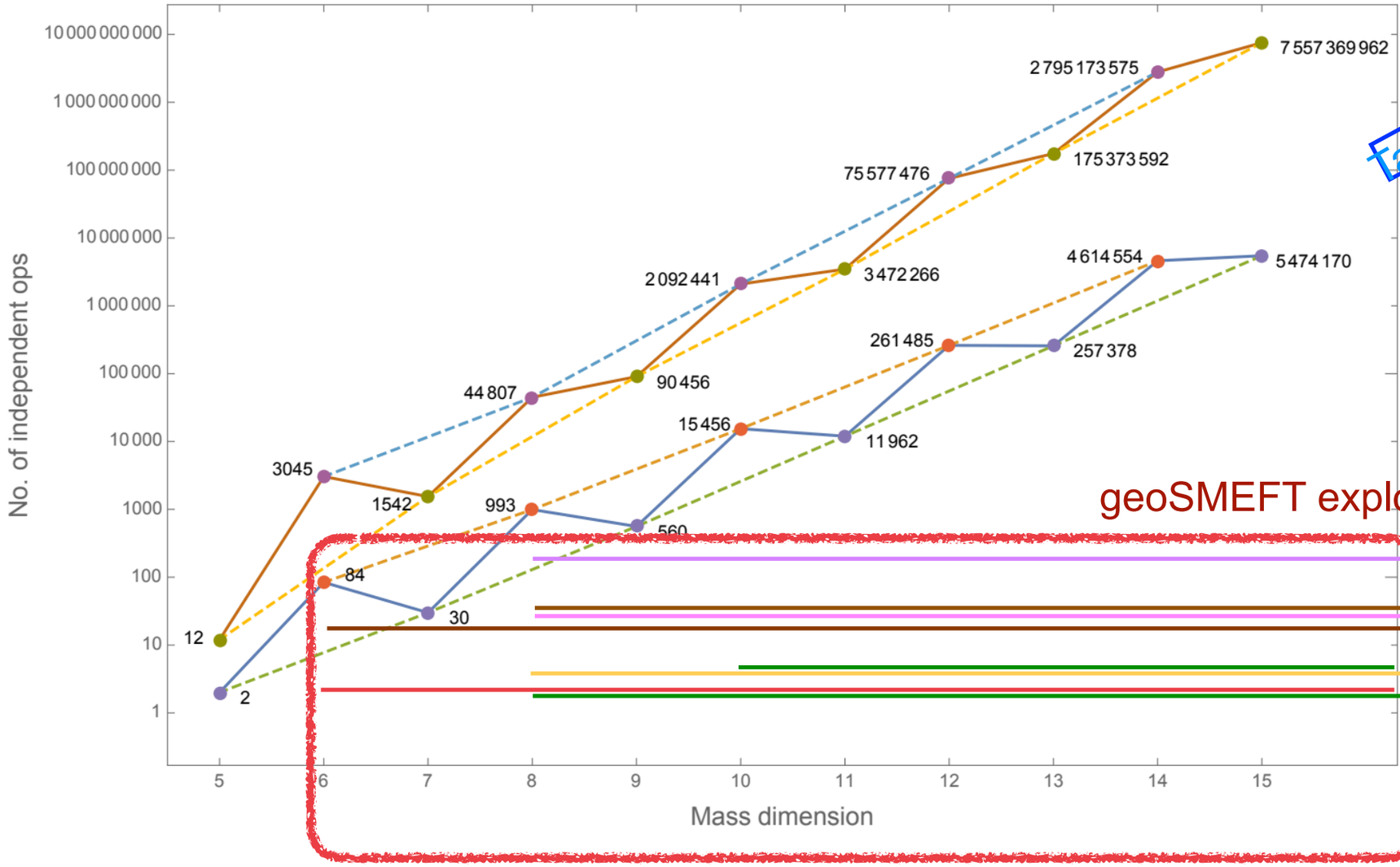
Pole parameters O(10's)

- General growth in operator forms from Hilbert series

1503.07537 Lehman, Martin. 1512.03433 Henning, Lu, Melia, Murayama

1510.00372 Lehman, Martin. 1706.08520 Henning, Lu, Melia, Murayama

Application to theory error



Tails built of 4pts/higher

Number of parameters
Grows with a factorial
In general with mass dim

geoSMEFT exploits this structure

Pole(s) built of 2,3 pts

Parameters O(10's)
Number of parameters
saturates to a constant
with mass dim

- General growth in operator forms from Hilbert series

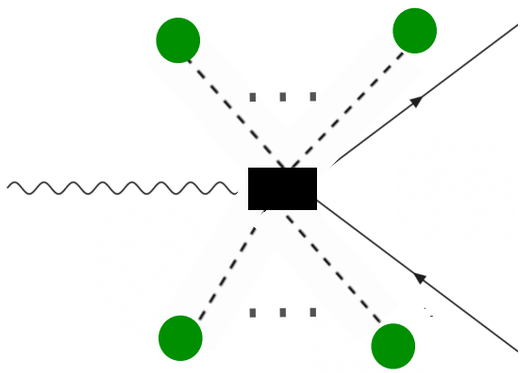
1503.07537 Lehman, Martin. 1512.03433 Henning, Lu, Melia, Murayama

1510.00372 Lehman, Martin. 1706.08520 Henning, Lu, Melia, Murayama

GeoSMEFT example

- What does this allow one to do?

2001.01453 Helset, Martin, Trott



Consider a $W^{\pm}, Z$ coupling to a fermion bilinear.

The all orders coupling in the SMEFT is a sum of two field space connections.

$\bar{\psi} i \not{D} \psi$:with a consistent change weak to mass eigenstates in SMEFT

Added to this is the scalar, fermion connection (with a background field expectation)

$$L^{\psi_R}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,R}\gamma_\mu\sigma_A\psi_{r,R})$$
$$L^{\psi_L}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,L}\gamma_\mu\sigma_A\psi_{r,L})$$

Field space connections to all orders

2001.01453 Helset, Martin, Trott

- Field space connection for W,Z coupling to fermion pairs $(D^\mu\phi)^I\,\bar\psi\,\Gamma_\mu\psi$

$$
\begin{aligned}
\mathcal{Q}^{1,(6+2n)}_{\substack{H\psi\\pr}} &= (H^\dagger H)^n H^\dagger \overleftrightarrow{iD}^\mu H \bar\psi_p \gamma_\mu \psi_r,\\
\mathcal{Q}^{3,(6+2n)}_{\substack{H\psi\\pr}} &= (H^\dagger H)^n\, H^\dagger \overleftrightarrow{iD}^\mu_a H \bar\psi_p \gamma_\mu \sigma_a \psi_r,\\
\mathcal{Q}^{2,(8+2n)}_{\substack{H\psi\\pr}} &= (H^\dagger H)^n (H^\dagger \sigma_a H)\, H^\dagger \overleftrightarrow{iD}^\mu H \bar\psi_p \gamma_\mu \sigma_a \psi_r,\\
\mathcal{Q}^{\epsilon,(8+2n)}_{\substack{H\psi\\pr}} &= \epsilon^a_{bc}\,(H^\dagger H)^n\,(H^\dagger \sigma_c H)\, H^\dagger \overleftrightarrow{iD}^\mu_b H \bar\psi_p \gamma_\mu \sigma_a \psi_r.
\end{aligned}
$$

Not that many op forms. Closed form field space connection.

$$
\begin{aligned}
L^{\psi,pr}_{J,A} = &-(\phi\,\gamma_4)_J \delta_{A4} \sum_{n=0}^{\infty} C^{1,(6+2n)}_{\substack{H\psi\\pr}} \left(\frac{\phi^2}{2}\right)^n - (\phi\,\gamma_A)_J (1-\delta_{A4}) \sum_{n=0}^{\infty} C^{3,(6+2n)}_{\substack{H\psi_L\\pr}} \left(\frac{\phi^2}{2}\right)^n\\
&+ \frac{1}{2}(\phi\,\gamma_4)_J (1-\delta_{A4})\,(\phi_K \Gamma^K_{A,L}\phi^L) \sum_{n=0}^{\infty} C^{2,(8+2n)}_{\substack{H\psi_L\\pr}} \left(\frac{\phi^2}{2}\right)^n\\
&+ \frac{\epsilon^A_{BC}}{2}(\phi\,\gamma_B)_J\,(\phi_K \Gamma^K_{C,L}\phi^L) \sum_{n=0}^{\infty} C^{\epsilon,(8+2n)}_{\substack{H\psi_L\\pr}} \left(\frac{\phi^2}{2}\right)^n .
\end{aligned}
$$

Notice the clean form due to generator structure and real fields.

Need input parameters defined at all orders

$\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

Sorted in

Hays, Helset, Martin Trott: 2007.00565

Input parameter dependence
Increased order by order
due to Lagrangian parameters
being redefined geometrically

D $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ input-parameter scheme at all orders in $(\bar{v}_T^2/\Lambda^2)^n$

In this scheme we can again use Eqn. (E.2) to define a shift to $\bar{g}_Z$. We also use

$$\bar{g}_2 = g_2\sqrt{g}^{11} = \frac{2\hat{m}_W}{\sqrt{h}_{11}\bar{v}_T}. \tag{D.1}$$

and

$$g_1 = g_2\frac{\left(s_{\bar{\theta}}\sqrt{g}^{33} + c_{\bar{\theta}}\sqrt{g}^{34}\right)}{\left(c_{\bar{\theta}}\sqrt{g}^{44} + s_{\bar{\theta}}\sqrt{g}^{34}\right)} \tag{D.2}$$

to solve for $s^2_{\bar{\theta}}$ via

$$s^2_{\bar{\theta}} = \frac{1}{\left[\left(\sqrt{g}^{44}\right)^2 + \left(\sqrt{g}^{34}\right)^2\right]^2}\left\{-\left(\frac{g_2\sqrt{g}_-}{\bar{g}_Z}\right)^2\left[\left(\sqrt{g}^{44}\right)^2 - \left(\sqrt{g}^{34}\right)^2\right] + \left(\sqrt{g}^{44}\right)^2\left[\left(\sqrt{g}^{44}\right)^2 + \left(\sqrt{g}^{34}\right)^2\right]\right.$$
$$\left. - 2\left(\frac{g_2\sqrt{g}_-}{\bar{g}_Z}\right)\sqrt{(\sqrt{g}^{44})^2(\sqrt{g}^{34})^2\left[\left(\sqrt{g}^{44}\right)^2 + \left(\sqrt{g}^{34}\right)^2 - \left(\frac{g_2\sqrt{g}_-}{\bar{g}_Z}\right)^2\right]}\right\}. \tag{D.3}$$

The remaining Lagrangian parameters can then be defined via

$$\bar{e} = \frac{\bar{g}_2}{\sqrt{g}^{11}}\left(s_{\bar{\theta}}\sqrt{g}^{33} + c_{\bar{\theta}}\sqrt{g}^{34}\right), \tag{D.4}$$

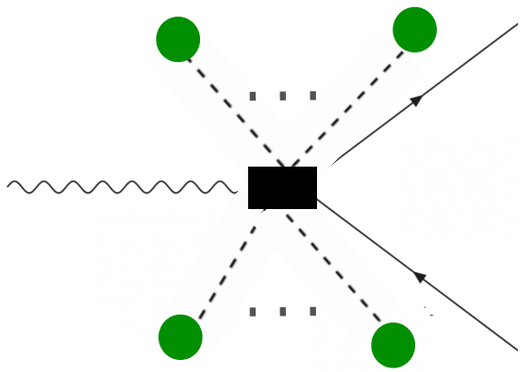
and

$$s^2_{\bar{\theta}_Z} = \frac{\bar{e}}{\bar{g}_Z}\frac{\left(s_{\bar{\theta}}\sqrt{g}^{44} - c_{\bar{\theta}}\sqrt{g}^{34}\right)}{\left(c_{\bar{\theta}}\sqrt{g}^{44} + s_{\bar{\theta}}\sqrt{g}^{34}\right)}. \tag{D.5}$$

In both schemes, $\bar{g}_Z$ and $s^2_{\bar{\theta}_Z}$ have the same definition in terms or other "barred" Lagrangian parameters.

GeoSMEFT example

- What does this allow one to do? 2001.01453 Helset, Martin, Trott



$\mathcal{A}^C = (\mathcal{W}^+, \mathcal{W}^-, \mathcal{Z}, \mathcal{A})$

Consider a $W^{\pm}, Z$ coupling to a fermion bilinear.

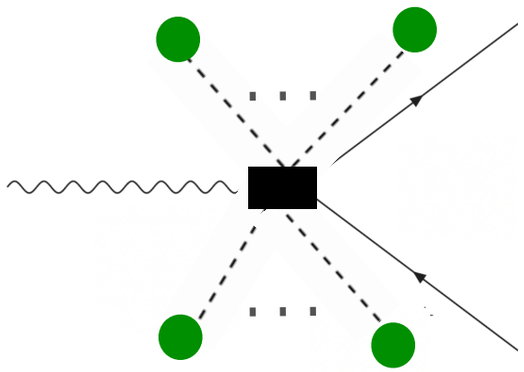
$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p \gamma_\mu \bar{\tau}_A \psi_r)\delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p \gamma_\mu \sigma_A \psi_r)\langle L^{\psi,pr}_{I,A}\rangle(-\boldsymbol{\gamma}^I_{C,4})\bar{v}_T,$$

Compact all $\bar{v}_T/\Lambda$ orders answer!

GeoSMEFT example

- What does this allow one to do?

2001.01453 Helset, Martin, Trott



Consider a $W^{\pm}, Z$ coupling to a fermion bilinear.

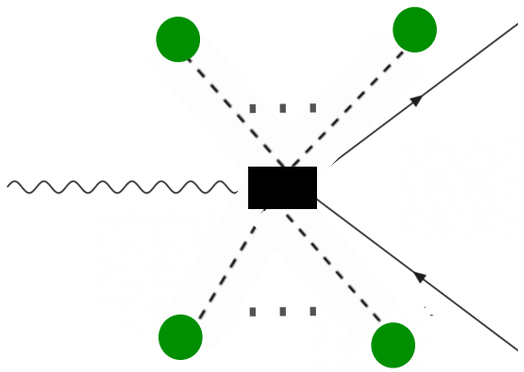
$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p\gamma_\mu\bar{\tau}_A\psi_r)\delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p\gamma_\mu\sigma_A\psi_r)\langle L^{\psi,pr}_{I,A}\rangle(-\boldsymbol{\gamma}^I_{C,4})\bar{v}_T,$$

The coupling of the canonically normalised mass eigenstate fields is then

$$\begin{aligned}
\langle \mathcal{Z}|\bar{\psi}_p\psi_r\rangle &= \frac{\bar{g}_Z}{2}\,\bar{\psi}_p\,\not{\epsilon}_{\mathcal{Z}}\,\left[(2s^2_{\theta_Z}Q_\psi - \sigma_3)\delta_{pr} + \sigma_3\bar{v}_T\langle L^{\psi,pr}_{3,3}\rangle + \bar{v}_T\langle L^{\psi,pr}_{3,4}\rangle\right]\,\psi_r,\\
\langle \mathcal{A}|\bar{\psi}_p\psi_r\rangle &= -\bar{e}\,\bar{\psi}_p\,\not{\epsilon}_{\mathcal{A}}\,Q_\psi\,\delta_{pr}\,\psi_r,\\
\langle \mathcal{W}_\pm|\bar{\psi}_p\psi_r\rangle &= -\frac{\bar{g}_2}{\sqrt{2}}\bar{\psi}_p(\not{\epsilon}_{\mathcal{W}^\pm})\,T^\pm\left[\delta_{pr} - \bar{v}_T\langle L^{\psi,pr}_{1,1}\rangle \pm i\bar{v}_T\langle L^{\psi,pr}_{1,2}\rangle\right]\,\psi_r.
\end{aligned}$$

GeoSMEFT example

- Can build up observable quantities, such as a decay width.



Consider a $W^{\pm}, Z$ coupling to a fermion bilinear.

$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p\gamma_\mu\bar{\tau}_A\psi_r)\delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p\gamma_\mu\sigma_A\psi_r)\langle L^{\psi,pr}_{I,A}\rangle(-\boldsymbol{\gamma}^I_{C,4})\bar{v}_T,$$

- Two body decay widths:

$$\bar{\Gamma}_{Z\to\bar{\psi}\psi} = \sum_\psi \frac{N_c^\psi}{24\pi}\sqrt{\bar{m}_Z^2}|g_{\text{eff}}^{Z,\psi}|^2\left(1-\frac{4\bar{M}_\psi^2}{\bar{m}_Z^2}\right)^{3/2}$$

$$g_{\text{eff}}^{Z,\psi} = \frac{\bar{g}_Z}{2}\left[(2s^2_{\theta_Z}Q_\psi - \sigma_3)\delta_{pr} + \bar{v}_T\langle L^{\psi,pr}_{3,4}\rangle + \sigma_3\bar{v}_T\langle L^{\psi,pr}_{3,3}\rangle\right]$$

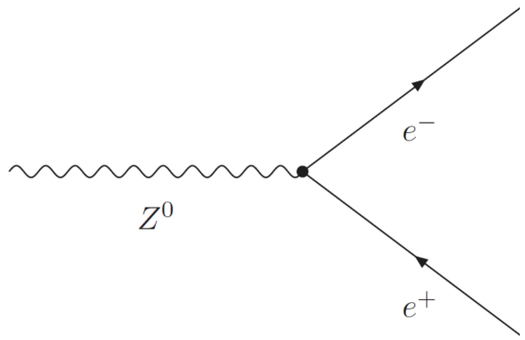
$$\bar{\Gamma}_{W\to\bar{\psi}\psi} = \sum_\psi \frac{N_c^\psi}{24\pi}\sqrt{\bar{m}_W^2}|g_{\text{eff}}^{W,\psi}|^2\left(1-\frac{4\bar{M}_\psi^2}{\bar{m}_W^2}\right)^{3/2}$$

$$g_{\text{eff}}^{W,q_L} = -\frac{\bar{g}_2}{\sqrt{2}}\left[V^{pr}_{\text{CKM}} - \bar{v}_T\langle L^{q_L,pr}_{1,1}\rangle \pm i\bar{v}_T\langle L^{q_L,pr}_{1,2}\rangle\right],$$

$$g_{\text{eff}}^{W,\ell_L} = -\frac{\bar{g}_2}{\sqrt{2}}\left[U^{pr,\dagger}_{\text{PMNS}} - \bar{v}_T\langle L^{\ell_L,pr}_{1,1}\rangle \pm i\bar{v}_T\langle L^{\ell_L,pr}_{1,2}\rangle\right],$$

SMEFT expansion correction error estimate by process.

- Process by process many of the dimension 8 corrections are also fully known now. We can examine process by process to be informed in defining the error. Ex. 2102.02819 Helset, Corbett, Martin, Trott



$$= \langle g^{Z,\psi}_{\mathrm{SM,pr}} \rangle + \langle g^{Z,\psi}_{\mathrm{eff,pr}} \rangle_{\mathcal{O}(v^2/\Lambda^2)} + \langle g^{Z,\psi}_{\mathrm{eff,pr}} \rangle_{\mathcal{O}(v^4/\Lambda^4)} + \cdots .$$

- LO SMEFT in SMEFTsim

SMEFT corrections in the $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}/\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme							
$\mathcal{O}(\frac{v^2}{\Lambda^2})$	$\langle g^{Z,u_R}_{\mathrm{eff,pp}} \rangle$	$\langle g^{Z,d_R}_{\mathrm{eff,pp}} \rangle$	$\langle g^{Z,\ell_R}_{\mathrm{eff,pp}} \rangle$	$\langle g^{Z,u_L}_{\mathrm{eff,pp}} \rangle$	$\langle g^{Z,d_L}_{\mathrm{eff,pp}} \rangle$	$\langle g^{Z,\ell_L}_{\mathrm{eff,pp}} \rangle$	$\langle g^{Z,\nu_L}_{\mathrm{eff,pp}} \rangle$
$\delta G_F^{(6)}$	-0.08/0.15	0.04/-0.07	0.12/-0.22	0.18/0.41	-0.22/-0.34	-0.15/-0.49	0.26/0.26
$\tilde{C}_{HD}^{(6)}$	-0.22/0.05	0.11/-0.03	0.33/-0.08	-0.13/0.15	0.02/-0.12	0.24/-0.17	0.09/0.09
$\tilde{C}_{HWB}^{(6)}$	-0.21/0.39	0.10/-0.19	0.31/-0.58	-0.21/0.39	0.10/-0.19	0.31/-0.58	
$\tilde{C}_{H\psi}^{(6)}$	0.37/0.37	0.37/0.37	0.37/0.37	0.37/0.37	0.37/0.37	0.37/0.37	0.37/0.37
$\tilde{C}_{H\psi}^{3,(6)}$				-0.37/-0.37	0.37/0.37	0.37/0.37	-0.37/-0.37

SMEFT expansion correction error estimate by process.

- EWPD to dim 8 now known in both input parameter schemes.
  2102.02819 Helset, Corbett, Martin, Trott

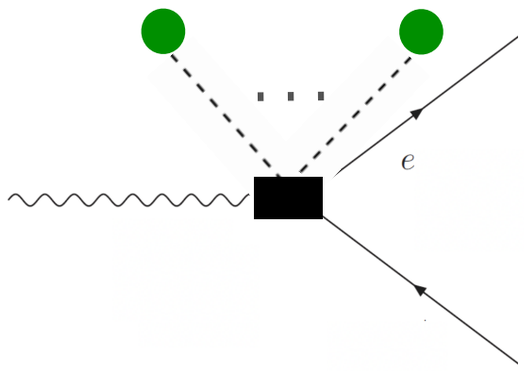
Many cross terms *NOT in quadratics* but known for error Estimates

Few new dimension Eight parameters

SMEFT corrections in $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}/\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme			
$\mathcal{O}(\frac{v^4}{\Lambda^4})$	$\langle g_{\rm eff,pp}^{\mathcal{Z},u_R}\rangle$	$\langle g_{\rm eff,pp}^{\mathcal{Z},d_R}\rangle$	$\langle g_{\rm eff,pp}^{\mathcal{Z},\ell_R}\rangle$
$\langle g_{\rm eff}^{\mathcal{Z},\psi}\rangle^2$	14/5.5	-27/-11	-9.1/-3.6
$\tilde{C}_{HB}\,\tilde{C}_{HWB}$	-0.21/0.39	0.10/-0.19	0.31/-0.58
$\tilde{C}_{HD}^2$	0.28/-0.026	-0.14/0.013	-0.42/0.040
$\tilde{C}_{HD}\,\tilde{C}_{H\psi}^{(6)}$	-0.83/-0.19	-0.83/-0.19	-0.83/-0.19
$\tilde{C}_{HD}\,\tilde{C}_{HWB}$	0.59/-0.19	-0.29/0.097	-0.88/0.29
$\tilde{C}_{HD}\langle g_{\rm eff}^{\mathcal{Z},\psi}\rangle$	4.0/0.50	4.0/0.50	4.0/0.50
$(\tilde{C}_{H\psi}^{(6)})^2$	0.62/1.4	-1.2/-2.8	-0.42/-0.93
$\tilde{C}_{HWB}\,\tilde{C}_{H\psi}^{(6)}$	-0.69/0.58	-0.69/0.58	-0.69/0.58
$\tilde{C}_{H\psi}^{(6)}\langle g_{\rm eff}^{\mathcal{Z},\psi}\rangle$	-6.7/-5.8	13/12	4.5/3.9
$\tilde{C}_{HWB}\,\langle g_{\rm eff}^{\mathcal{Z},\psi}\rangle$	3.7/0.26	3.7/0.26	3.7/0.26
$\tilde{C}_{HW}\,\tilde{C}_{HWB}$	-0.21/0.39	0.10/-0.19	0.31/-0.58
$\tilde{C}_{HD}^{(8)}$	-0.014/0.026	0.0069/-0.013	0.021/-0.040
$\tilde{C}_{HD,2}^{(8)}$	-0.21/0.026	0.10/-0.013	0.31/-0.040
$\tilde{C}_{H\psi}^{(8)}$	0.19/0.19	0.19/0.19	0.19/0.19
$\tilde{C}_{HW,2}^{(8)}$	-0.38/0	0.19/0	0.58/0
$\tilde{C}_{HWB}^{(8)}$	-0.10/0.19	0.051/-0.097	0.15/-0.29
$\delta G_F^{(8)}$	-0.078/0.15	0.039/-0.075	0.12/-0.22
$(\tilde{C}_{HWB}^{(6)})^2$	0.19/-0.35	-0.096/0.18	-0.29/0.53

GeoSMEFT directly informs theory error

- Can build up observable quantities, such as a decay width.



Consider a $W^{\pm}, Z$ coupling to a fermion bilinear.

$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p\gamma_\mu\bar{\tau}_A\psi_r)\delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p\gamma_\mu\sigma_A\psi_r)\langle L_{I,A}^{\psi,pr}\rangle(-\boldsymbol{\gamma}_{C,4}^{I})\bar{v}_T,$$

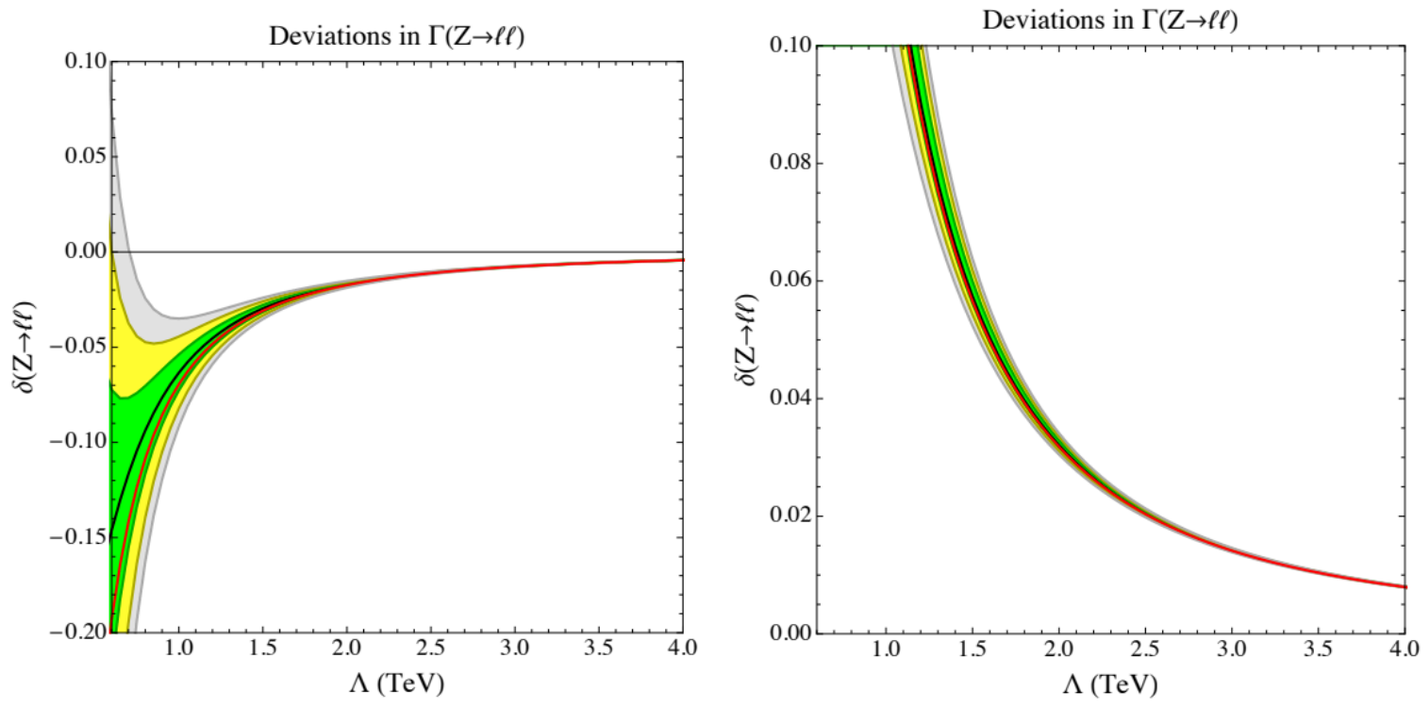


Figure 3. The deviations in $\mathcal{Z} \to \ell\ell$ from the $\mathcal{O}(v^2/\Lambda^2)$ (red line) and partial-square (black line) results, and the full $\mathcal{O}(v^4/\Lambda^4)$ results (green $\pm 1\,\sigma_\delta$, yellow $\pm 2\,\sigma_\delta$, and grey $\pm 3\,\sigma_\delta$ regions). In the left panel the coefficients determining the $\mathcal{O}(v^2/\Lambda^2)$ and partial-square results are $C_{H\ell}^{1,(6)} = -0.46, C_{H\ell}^{3,(6)} = 1.24, C_{He}^{(6)} = 1.53, C_{HD}^{(6)} = -0.79, C_{HWB}^{(6)} = 0.007$, and $\delta G_F^{(6)} = 0.16$. In the right panel they are $C_{H\ell}^{1,(6)} = 1.55, C_{H\ell}^{3,(6)} = -0.71, C_{He}^{(6)} = 0.23, C_{HD}^{(6)} = -0.51, C_{HWB}^{(6)} = -0.008$, and $\delta G_F^{(6)} = -0.44$.

- Dim 8 effects on Z decay now known

Yes people do over interpret EWPD.

- (Heretical) Doubts were raised years ago that dim 8 neglect and loop neglect In EWPD can significantly impact naive bounds with significant implications
  1502.02570, 1508.05060, Berthier, MT ,1606.06693 Berthier, Bjorn, MT , arXiv:1701.06424 Brivio, MT

2102.02819 Helset, Corbett, Martin, Trott

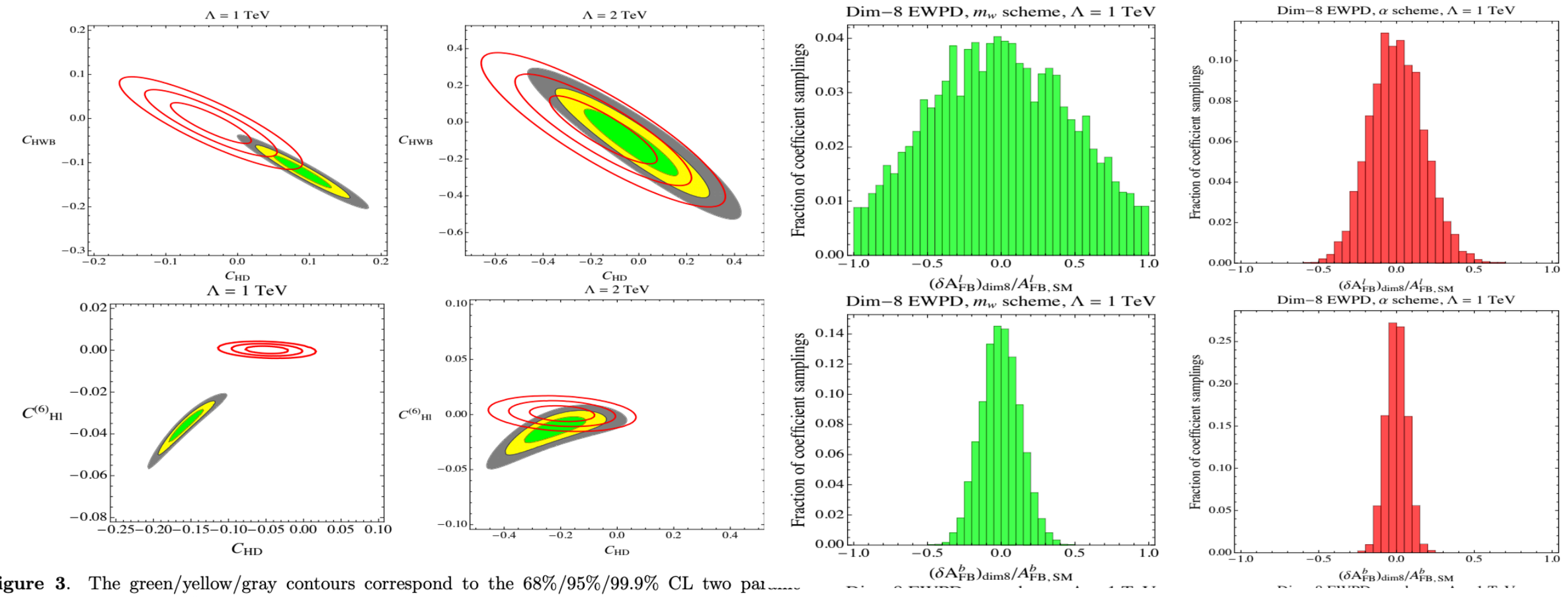
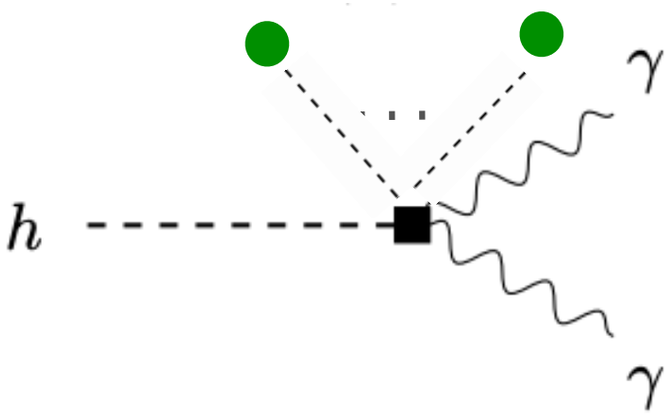


Figure 3. The green/yellow/gray contours correspond to the 68%/95%/99.9% CL two parameter fit determined by $\Delta\chi^2_{\mathcal{O}(v^4/\Lambda^4)}$, while the red rings correspond to the same CL determined using $\Delta\chi^2_{\mathcal{O}(v^2/\Lambda^2)}$. In the top panels the free parameters are C_{HD} and C_{HWB}, while in the bottom panels the free parameters are C_{HD} and $C^{(6)}_{H\ell}$. Note that the axes ranges vary from panel to panel. In the left panels, we have taken the scale $\Lambda = 1$ TeV, while in the right panels $\Lambda = 2$ TeV. All calculations use the $\hat{m}_W$ scheme.

- ***Significant implications for future collider studies.***

GeoSMEFT for the Higgs



- SMEFT diphoton decay

$$\langle h|\mathcal{A}(p_1)\mathcal{A}(p_2)\rangle = -\langle hA^{\mu\nu}A_{\mu\nu}\rangle \frac{\sqrt{h}^{44}}{4}\left[\langle\frac{\delta g_{33}(\phi)}{\delta\phi_4}\rangle\frac{\overline{e}^2}{g_2^2} + 2\langle\frac{\delta g_{34}(\phi)}{\delta\phi_4}\rangle\frac{\overline{e}^2}{g_1 g_2} + \langle\frac{\delta g_{44}(\phi)}{\delta\phi_4}\rangle\frac{\overline{e}^2}{g_1^2}\right],$$

- What is the detailed difference between squaring the dimension 6 correction, and the full dimension 8 result?

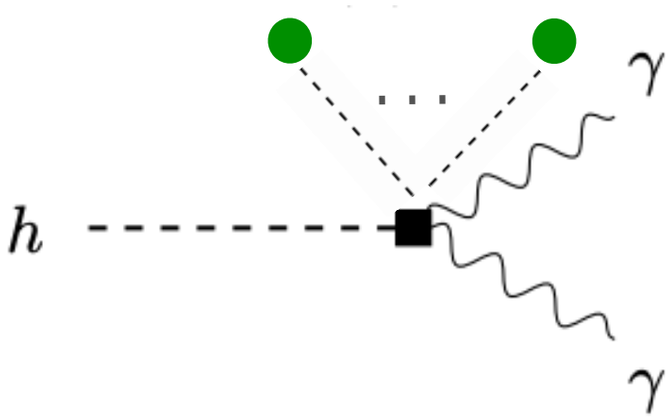
- Now we know. Using the expression above, just expand.

Correct result: 2007.00565 Hays, Helset, Martin, Trott

$$\left|\mathcal{A}_{SM}^{h\gamma\gamma}\right|^2 + 2\,\mathrm{Re}(\mathcal{A}_{SM}^{h\gamma\gamma})(1+\langle\sqrt{h}^{44}\rangle_{\mathcal{L}^{(6)}})\,\langle h|\gamma\gamma\rangle_{\mathcal{L}^{(6)}} + (1+4\,\bar{v}_T\,\mathrm{Re}(\mathcal{A}_{SM}^{h\gamma\gamma}))\,(\langle h|\gamma\gamma\rangle_{\mathcal{L}^{(6)}})^2,$$

$$+\,2\,\mathrm{Re}(\mathcal{A}_{SM}^{h\gamma\gamma})\left[\frac{g_2^2\,\tilde{C}_{HB}^{(8)} + g_1^2\,(\tilde{C}_{HW}^{(8)} - \tilde{C}_{HW,2}^{(8)}) - g_1\,g_2\,\tilde{C}_{HWB}^{(8)}}{(g_1^2+g_2^2)\,\bar{v}_T}\right].$$

GeoSMEFT for the Higgs



- How much does dim 8 effect things? Alot.
  2007.00565 Hays, Helset, Martin, Trott

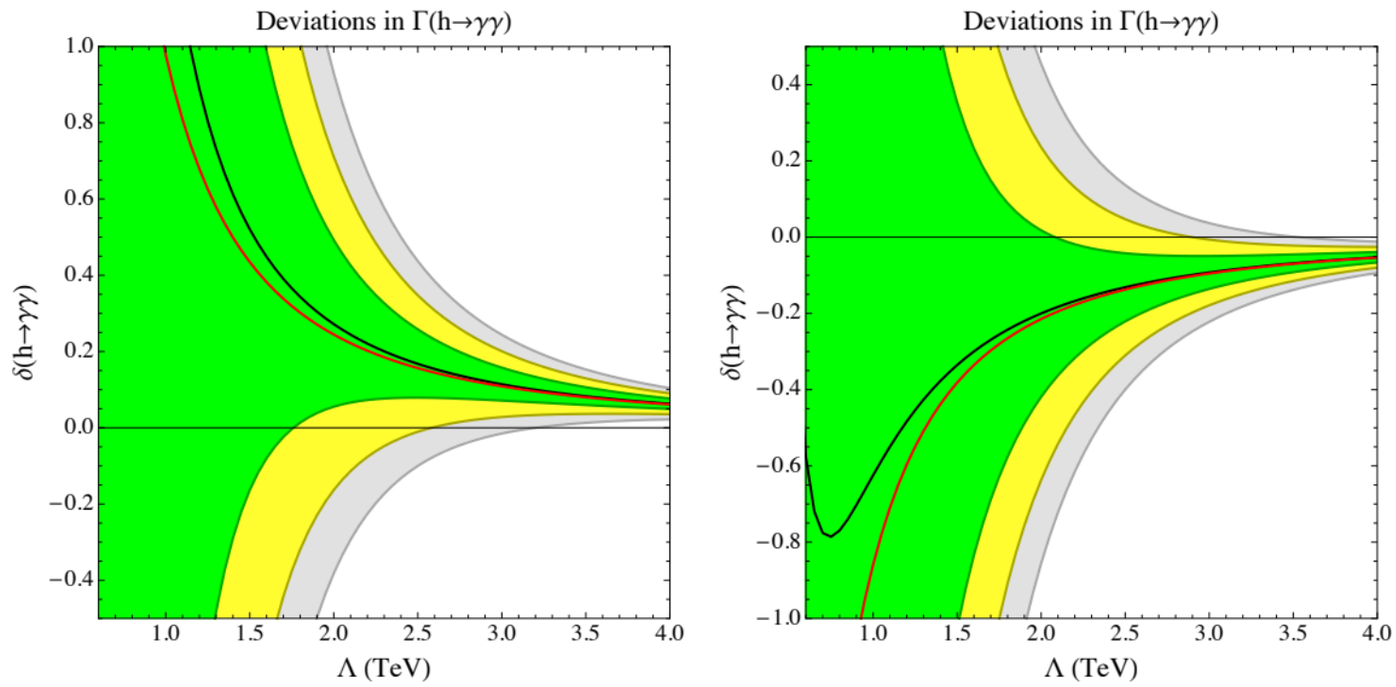
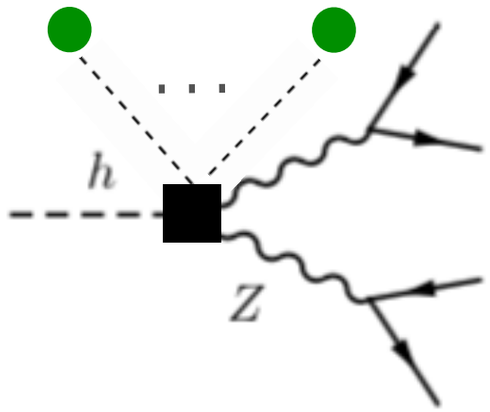


Figure 1. The deviations in $h \to \gamma\gamma$ from the $\mathcal{O}(v^2/\Lambda^2)$ (red line) and partial-square (black line) results, and the full $\mathcal{O}(v^4/\Lambda^4)$ results (green $\pm 1\,\sigma_\delta$, yellow $\pm 2\,\sigma_\delta$, and grey $\pm 3\,\sigma_\delta$ regions). In the left panel the coefficients determining the $\mathcal{O}(v^2/\Lambda^2)$ and partial-square results are $C_{HB}^{(6)} = -0.01$, $C_{HW}^{(6)} = 0.004, C_{HWB}^{(6)} = 0.007, C_{HD}^{(6)} = -0.74$, and $\delta G_F^{(6)} = -1.6$. In the right panel they are $C_{HB}^{(6)} = 0.007$, $C_{HW}^{(6)} = 0.007, C_{HWB}^{(6)} = -0.015, C_{HD}^{(6)} = 0.50$, and $\delta G_F^{(6)} = 1.26$.

- EFT studies that ignore this geoSMEFT enabled information can be misleading.

- Loop processes are more subject to SMEFT theoretical errors in the cases we looked at.

GeoSMEFT for the Higgs



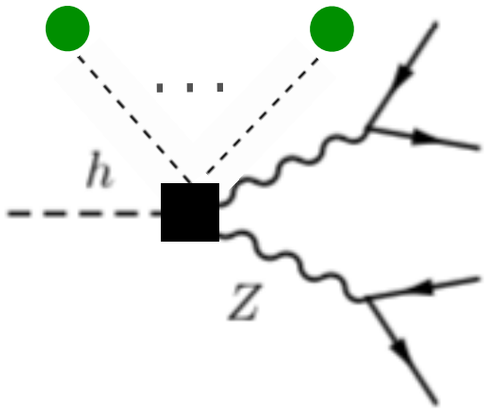
- All orders SMEFT higgs coupling to $W^{\pm}, Z$

  2001.01453 Helset, Martin, Trott

$$\langle h|\mathcal{Z}(p_1)\mathcal{Z}(p_2)\rangle = -\frac{\sqrt{h}^{44}}{4}\bar{g}_Z^2\left[\langle\frac{\delta g_{33}(\phi)}{\delta\phi_4}\rangle\frac{c_{\theta_Z}^4}{g_2^2} - 2\langle\frac{\delta g_{34}(\phi)}{\delta\phi_4}\rangle\frac{c_{\theta_Z}^2 s_{\theta_Z}^2}{g_1 g_2} + \langle\frac{\delta g_{44}(\phi)}{\delta\phi_4}\rangle\frac{s_{\theta_Z}^4}{g_1^2}\right]\langle h\mathcal{Z}_{\mu\nu}\mathcal{Z}^{\mu\nu}\rangle$$
$$+ \sqrt{h}^{44}\frac{\bar{g}_Z^2}{2}\left[\langle\frac{\delta h_{33}(\phi)}{\delta\phi_4}\rangle\left(\frac{\bar{v}_T}{2}\right)^2 + \langle h_{33}(\phi)\rangle\frac{\bar{v}_T}{2}\right]\langle h\mathcal{Z}_\mu\mathcal{Z}^\mu\rangle$$
$$+ \sqrt{h}^{44}\bar{g}_Z^2\bar{v}_T\left[\langle k_{34}^3\rangle\frac{c_{\theta_Z}^2}{g_2} - \langle k_{34}^4\rangle\frac{s_{\theta_Z}^2}{g_1}\right]\langle\partial^\nu h\mathcal{Z}_\mu\mathcal{Z}^{\mu\nu}\rangle,$$

$$\langle h|\mathcal{W}(p_1)\mathcal{W}(p_2)\rangle = -\frac{\sqrt{h}^{44}}{2}\bar{g}_2^2\left[\langle\frac{\delta g_{11}(\phi)}{\delta\phi_4}\rangle\frac{1}{g_2^2}\right]\langle h\mathcal{W}_{\mu\nu}\mathcal{W}^{\mu\nu}\rangle$$
$$+ \sqrt{h}^{44}\bar{g}_2^2\left[\langle\frac{\delta h_{11}(\phi)}{\delta\phi_4}\rangle\left(\frac{\bar{v}_T}{2}\right)^2 + \langle h_{11}(\phi)\rangle\frac{\bar{v}_T}{2}\right]\langle h\mathcal{W}_\mu\mathcal{W}^\mu\rangle$$
$$+ 2\sqrt{h}^{44}\frac{\bar{g}_2^2}{g_2}\frac{\bar{v}_T}{4}\left[i\langle k_{42}^1\rangle - \langle k_{42}^2\rangle\right]\langle(\partial^\mu h)(\mathcal{W}_{\mu\nu}^+ W_-^\nu + \mathcal{W}_{\mu\nu}^- W_+^\nu)\rangle.$$

GeoSMEFT for the Higgs



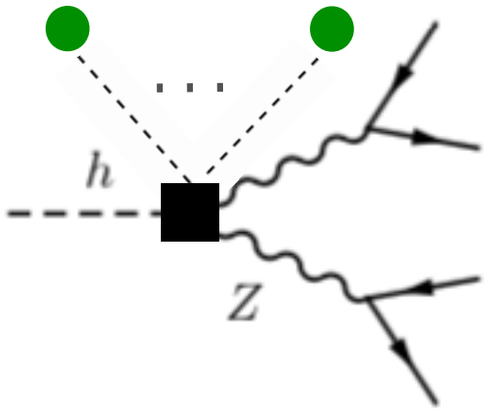
- All orders SMEFT higgs coupling to $W^{\pm}, Z$

2001.01453 Helset, Martin, Trott

$$\langle h|\mathcal{Z}(p_1)\mathcal{Z}(p_2)\rangle = -\frac{\sqrt{h}^{44}}{4}\bar{g}_Z^2\left[\langle\frac{\delta g_{33}(\phi)}{\delta\phi_4}\rangle\frac{c_{\theta_Z}^4}{g_2^2} - 2\langle\frac{\delta g_{34}(\phi)}{\delta\phi_4}\rangle\frac{c_{\theta_Z}^2 s_{\theta_Z}^2}{g_1 g_2} + \langle\frac{\delta g_{44}(\phi)}{\delta\phi_4}\rangle\frac{s_{\theta_Z}^4}{g_1^2}\right]\langle h\mathcal{Z}_{\mu\nu}\mathcal{Z}^{\mu\nu}\rangle$$
$$+ \sqrt{h}^{44}\frac{\bar{g}_Z^2}{2}\left[\langle\frac{\delta h_{33}(\phi)}{\delta\phi_4}\rangle\left(\frac{\bar{v}_T}{2}\right)^2 + \langle h_{33}(\phi)\rangle\frac{\bar{v}_T}{2}\right]\langle h\mathcal{Z}_\mu\mathcal{Z}^\mu\rangle \leftarrow \text{SM like kinematics}$$
$$+ \sqrt{h}^{44}\bar{g}_Z^2\bar{v}_T\left[\langle k_{34}^3\rangle\frac{c_{\theta_Z}^2}{g_2} - \langle k_{34}^4\rangle\frac{s_{\theta_Z}^2}{g_1}\right]\langle\partial^\nu h\mathcal{Z}_\mu\mathcal{Z}^{\mu\nu}\rangle,$$

$$\langle h|\mathcal{W}(p_1)\mathcal{W}(p_2)\rangle = -\frac{\sqrt{h}^{44}}{2}\bar{g}_2^2\left[\langle\frac{\delta g_{11}(\phi)}{\delta\phi_4}\rangle\frac{1}{g_2^2}\right]\langle h\mathcal{W}_{\mu\nu}\mathcal{W}^{\mu\nu}\rangle$$
$$+ \sqrt{h}^{44}\bar{g}_2^2\left[\langle\frac{\delta h_{11}(\phi)}{\delta\phi_4}\rangle\left(\frac{\bar{v}_T}{2}\right)^2 + \langle h_{11}(\phi)\rangle\frac{\bar{v}_T}{2}\right]\langle h\mathcal{W}_\mu\mathcal{W}^\mu\rangle$$
$$+ 2\sqrt{h}^{44}\frac{\bar{g}_2^2}{g_2}\frac{\bar{v}_T}{4}\left[i\langle k_{42}^1\rangle - \langle k_{42}^2\rangle\right]\langle(\partial^\mu h)(\mathcal{W}_{\mu\nu}^+ W_-^\nu + \mathcal{W}_{\mu\nu}^- W_+^\nu)\rangle.$$

GeoSMEFT for the Higgs



- All orders SMEFT higgs coupling to $W^{\pm}, Z$

  2001.01453 Helset, Martin, Trott

$$\langle h|\mathcal{Z}(p_1)\mathcal{Z}(p_2)\rangle = -\frac{\sqrt{h}^{44}}{4}\bar{g}_Z^2\left[\langle\frac{\delta g_{33}(\phi)}{\delta\phi_4}\rangle\frac{c_{\theta_Z}^4}{g_2^2} - 2\langle\frac{\delta g_{34}(\phi)}{\delta\phi_4}\rangle\frac{c_{\theta_Z}^2 s_{\theta_Z}^2}{g_1 g_2} + \langle\frac{\delta g_{44}(\phi)}{\delta\phi_4}\rangle\frac{s_{\theta_Z}^4}{g_1^2}\right]\langle h\mathcal{Z}_{\mu\nu}\mathcal{Z}^{\mu\nu}\rangle$$

$$+ \sqrt{h}^{44}\frac{\bar{g}_Z^2}{2}\left[\langle\frac{\delta h_{33}(\phi)}{\delta\phi_4}\rangle\left(\frac{\bar{v}_T}{2}\right)^2 + \langle h_{33}(\phi)\rangle\frac{\bar{v}_T}{2}\right]\langle h\mathcal{Z}_\mu\mathcal{Z}^\mu\rangle \leftarrow \text{SM like kinematics}$$

$$+ \sqrt{h}^{44}\bar{g}_Z^2\bar{v}_T\left[\langle k_{34}^3\rangle\frac{c_{\theta_Z}^2}{g_2} - \langle k_{34}^4\rangle\frac{s_{\theta_Z}^2}{g_1}\right]\langle\partial^\nu h\mathcal{Z}_\mu\mathcal{Z}^{\mu\nu}\rangle, \quad \text{Anomalous kinematic population correction factor - not many!}$$

$$\langle h|\mathcal{W}(p_1)\mathcal{W}(p_2)\rangle = -\frac{\sqrt{h}^{44}}{2}\bar{g}_2^2\left[\langle\frac{\delta g_{11}(\phi)}{\delta\phi_4}\rangle\frac{1}{g_2^2}\right]\langle h\mathcal{W}_{\mu\nu}\mathcal{W}^{\mu\nu}\rangle$$

$$+ \sqrt{h}^{44}\bar{g}_2^2\left[\langle\frac{\delta h_{11}(\phi)}{\delta\phi_4}\rangle\left(\frac{\bar{v}_T}{2}\right)^2 + \langle h_{11}(\phi)\rangle\frac{\bar{v}_T}{2}\right]\langle h\mathcal{W}_\mu\mathcal{W}^\mu\rangle$$

$$+ 2\sqrt{h}^{44}\frac{\bar{g}_2^2}{g_2}\frac{\bar{v}_T}{4}\left[i\langle k_{42}^1\rangle - \langle k_{42}^2\rangle\right]\langle(\partial^\mu h)(\mathcal{W}_{\mu\nu}^+ W_-^\nu + \mathcal{W}_{\mu\nu}^- W_+^\nu)\rangle.$$

In the hands of ATLAS for kinematic studies
Thx to Tyler Corbett for coding SMEFTsim mod.

GeoSMEFT based Theory error.

- GeoSMEFT efficiently organised the physics for dimension 8 calc that follow from rescaling dimension 6 results with the same kinematics.

- An algorithm to develop calc to dimension 8 efficiently to use, and also inform theory errors 2106.13794 Trott "Methodology…"

  SMEFT RGE is transparent to simulation chain. Thus infer logs of missing pert corrections for theory error.

  Use geoSMEFT to rescale dim 6 results with common kinematics to post-facto (avoid redundant Monte Carlo) get dim 8 from SMEFTsim

  Extra dim 8 bits with novel kinematics define in geoSMEFT consistent basis. Put in code. (SMEFTsim mod ongoing of this form with T Corbett)

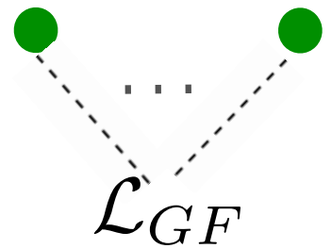
- Being applied to associated production, already done for $\Gamma(h \to \gamma\gamma)$ $\sigma(\mathcal{G}\,\mathcal{G} \to h)$, $\Gamma(h \to \mathcal{G}\,\mathcal{G})$

GeoSMEFT based loop corrections?

- The simplicity of the results for two and three point functions points to radiative corrections being more elegant than expected.

  The renormalisation follows the dependence on the Wilson coefficients.

- Do we have hints of this yet? Yes.



- Background field gauge fixing with preserved background Gauge invariance 1803.08001 Helset, Paraskevas, Trott.

$$\mathcal{L}_{\rm GF} = -\frac{\hat{g}_{AB}}{2\,\xi}\mathcal{G}^A\,\mathcal{G}^B,$$

$$\mathcal{G}^X \equiv \partial_\mu \mathcal{W}^{X,\mu} - \tilde{\epsilon}^X_{\ CD}\hat{\mathcal{W}}^C_\mu \mathcal{W}^{D,\mu} + \frac{\xi}{2}\hat{g}^{XC}\phi^I\,\hat{h}_{IK}\,\tilde{\gamma}^K_{C,J}\hat{\phi}^J.$$

- Gauge fixing confusion directly solved generalising to GeoSMEFT

GeoSMEFT based loop corrections?

- Will this simplify the NLO SMEFT radiative correction program?(Yes)

  Immediate BFM Ward Identities have already been derived:

$$\frac{\delta\Gamma[\hat{F},0]}{\delta\hat{\alpha}^B}=0.$$

Background field gauge transformation

1909.08470 Corbett, Helset, Trott

$$0=\left(\partial^\mu\delta^A_B-\tilde{\epsilon}^A_{\ BC}\,\hat{\mathcal{W}}^{C,\mu}\right)\frac{\delta\Gamma}{\delta\hat{\mathcal{W}}^\mu_A}-\frac{\tilde{\gamma}^I_{B,J}}{2}\hat{\phi}^J\frac{\delta\Gamma}{\delta\hat{\phi}^I}$$
$$+\sum_j\left(\bar{f}_j\bar{\Lambda}^j_{B,i}\frac{\delta\Gamma}{\delta\bar{f}_i}-\frac{\delta\Gamma}{\delta f_i}\Lambda^i_{B,j}f_j\right).$$

Photon identities:

$$0=\partial^\mu\frac{\delta^2\Gamma}{\delta\hat{\mathcal{A}}^{4\mu}\delta\hat{\mathcal{A}}^{Y\nu}},\qquad 0=\partial^\mu\frac{\delta^2\Gamma}{\delta\hat{\mathcal{A}}^{4\mu}\delta\hat{\Phi}^I}.$$

$$\Sigma^{\hat{\mathcal{A}},\hat{\mathcal{A}}}_{L,\mathrm{SMEFT}}(k^2)=0,\qquad \Sigma^{\hat{\mathcal{A}},\hat{\mathcal{A}}}_{T,\mathrm{SMEFT}}(0)=0.$$

One loop behaviour works!

Z identities:

Geometric mass

$$0=\partial^\mu\frac{\delta^2\Gamma}{\delta\hat{\mathcal{A}}^{3\mu}\delta\hat{\mathcal{A}}^{Y\nu}}-\bar{M}_Z\frac{\delta^2\Gamma}{\delta\hat{\Phi}^3\delta\hat{\mathcal{A}}^{Y\nu}},$$
$$0=\partial^\mu\frac{\delta^2\Gamma}{\delta\hat{\mathcal{A}}^{3\mu}\delta\hat{\Phi}^I}-\bar{M}_Z\frac{\delta^2\Gamma}{\delta\hat{\Phi}^3\delta\hat{\Phi}^I}$$
$$+\frac{\bar{g}_Z}{2}\frac{\delta\Gamma}{\delta\hat{\Phi}^4}\left(\sqrt{h}_{[4,4]}\sqrt{h}^{[3,3]}-\sqrt{h}_{[4,3]}\sqrt{h}^{[4,3]}\right)\delta^3_I$$
$$-\frac{\bar{g}_Z}{2}\frac{\delta\Gamma}{\delta\hat{\Phi}^4}\left(\sqrt{h}_{[4,4]}\sqrt{h}^{[3,4]}-\sqrt{h}_{[4,3]}\sqrt{h}^{[4,4]}\right)\delta^4_I,$$

Need for consistent dim 8 and loop

- <u>*Operator expansion and loop expansion are NOT independent.*</u>
  Can use geoSMEFT to get $\mathcal{L}_8$ in many cases

$$\frac{\sigma^{\hat{\alpha}}_{\rm SMEFT}(\mathcal{G}\mathcal{G}\to h)}{\sigma^{\hat{\alpha},1/m_t^2}_{\rm SM}(\mathcal{G}\mathcal{G}\to h)} \simeq 1 + 519\,\tilde{C}^{(6)}_{HG} + 504\,\tilde{C}^{(6)}_{HG}\left(\tilde{C}^{(6)}_{H\Box} - \frac{1}{4}\tilde{C}^{(6)}_{HD}\right) + 8.15\times 10^4\,(\tilde{C}^{(6)}_{HG})^2 + 504\,\tilde{C}^{(8)}_{HG}$$
$$+ 1.58\left(\tilde{C}^{(6)}_{H\Box} - \frac{1}{4}\tilde{C}^{(6)}_{HD}\right) + 362\,\tilde{C}^{(6)}_{HG} - 1.59\,\tilde{C}^{(6)}_{uH} - 12.6\,\mathrm{Re}\,\tilde{C}^{(6)}_{uG} - 1.12\,\delta G_F^{(6)} - 7.70\,\mathrm{Re}\,\tilde{C}^{(6)}_{uG}\,\log\left(\frac{\hat{m}_h^2}{\Lambda^2}\right)$$
$$- 0.19\,\mathrm{Re}\,\tilde{C}^{(6)}_{dG}\,\log\left(\frac{\hat{m}_h^2}{\Lambda^2}\right) - 0.09\,\mathrm{Re}\,\tilde{C}^{(6)}_{dG} + 3.54\,\tilde{C}^{(6)}_{dH}.$$

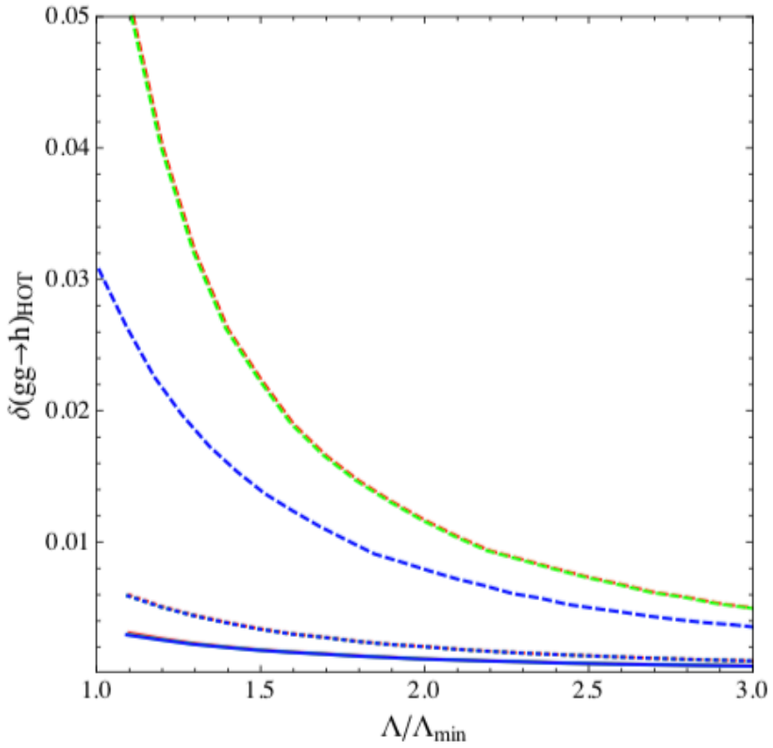


FIG. 1: Uncertainty on $\sigma(gg \to h)$ from higher order terms as a function of the new physics scale Λ relative to the min-

- Justified triage for the SMEFT global fit program with theory errors

- Otherwise

2109.05595 Martin, Trott

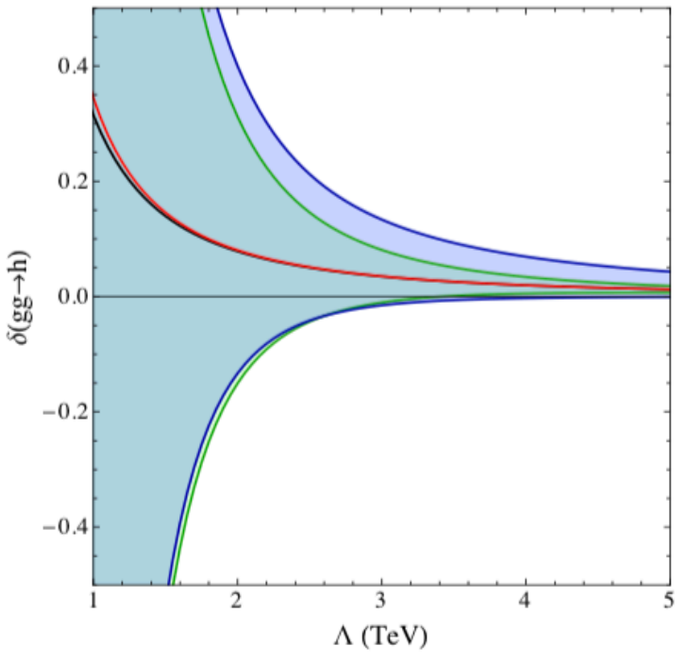
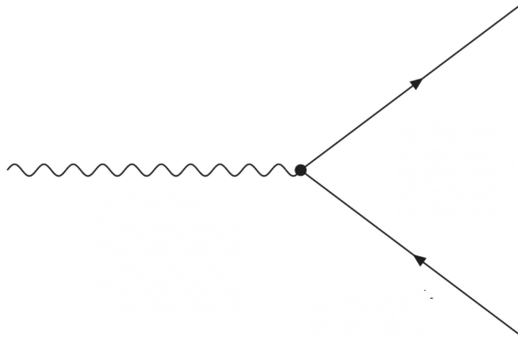


FIG. 4: Deviation in $\sigma(\mathcal{G}\mathcal{G} \to h)$ relative to the SM with $C^{(6)}_{HG} = 0.01$, and all other coefficients sampled according to gaussian distributions with zero mean and width of either 1.0 or .01 depending on whether the corresponding operator is generated at tree or loop level following the classification in Ref. [7–9]. The deviation is plotted as a function of Λ, and the color scheme for the lines and bands is the same as in Figs. 2, 3.

Current geosmeft limitations

GeoSMEFT Pushing to higher n points

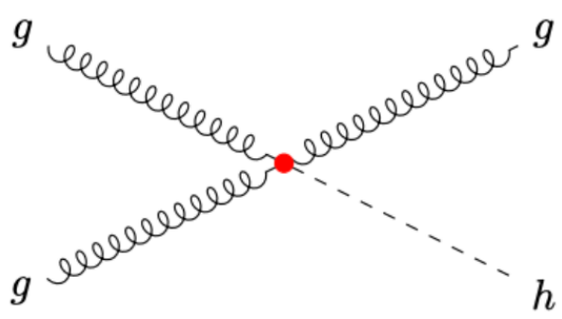
- Can build up observable quantities, such as a decay width.

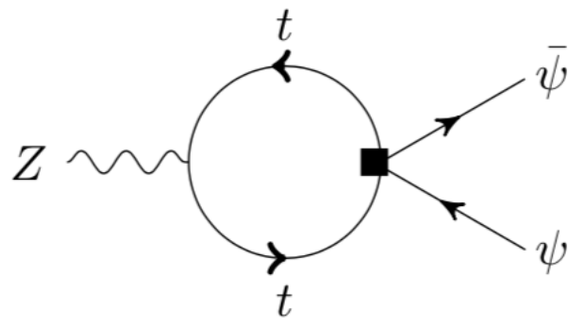


Consider a $W^{\pm}, Z$ coupling to a fermion bilinear.

$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p\gamma_\mu\bar{\tau}_A\psi_r)\delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p\gamma_\mu\sigma_A\psi_r)\langle L^{\psi,pr}_{I,A}\rangle(-\boldsymbol{\gamma}^I_{C,4})\bar{v}_T,$$

- Not all physics is derivable from two and three point functions





GeoSMEFT Pushing to higher n points

- Limited number of such connections for up to three point functions

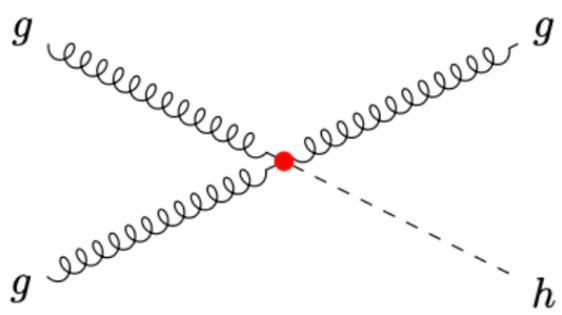
  This is a non trivial fact proven for: $F = \{H, \psi, \mathcal{W}^{\mu\nu}\}$ via the following:

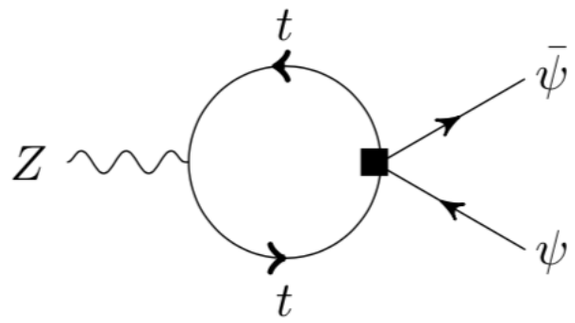
$$D^2 F \Rightarrow \boxed{\text{EOM}} \text{ and higher-points,}$$

2001.01453 Helset, Martin, Trott

$$f(H)(D_\mu F_1)(D_\nu F_2) D_{\{\mu\nu\}} F_3 \Rightarrow \boxed{\text{EOM}} \text{ and higher-points.}$$

$$f(\phi)\, F_1\, (D_\mu F_2)\, (D_\mu F_3) \Rightarrow (D_\mu f(\phi))\, (D_\mu F_1)\, F_2\, F_3 + \frac{1}{2}(D^2 f(\phi))\, F_1\, F_2\, F_3 + \boxed{\text{EOM}},$$





- How to incorporate such higher n-point effects is the key challenge.
- Pert corrections advancing fast- higher n points also moving.

GeoSMEFT Pushing to higher n points

- Note these integration by parts steps were used

$$
\begin{aligned}
& f(H)(D_\mu F_1)(D_\nu F_2)D_{\{\mu\nu\}}F_3 \\
=& -f(H)\left[(D^2F_1)(D_\nu F_2)+(D_\mu F_1)(D_\mu D_\nu F_2)+(D_\mu D_\nu F_1)(D_\mu F_2)+(D_\nu F_1)(D^2F_2)\right](D_\nu F_3) \\
& -(D_\mu f(H))\left[(D_\mu F_1)(D_\nu F_2)+(D_\nu F_1)(D_\mu F_2)\right](D_\nu F_3)
\end{aligned}
$$

$$
f(\phi)\,F_1\,(D_\mu F_2)\,(D_\mu F_3) \Rightarrow (D_\mu f(\phi))\,(D_\mu F_1)\,F_2\,F_3+\frac{1}{2}(D^2 f(\phi))\,F_1\,F_2\,F_3+\boxed{\text{EOM}},
$$

These steps were critical to reducing the number of connections for two and three point functions. This just fails for four points and higher.

One knows that there are an infinite set of higher derivative terms lurking In higher n points, dependent on $\{D_\mu\phi^I, D_{\{\mu,\nu\}}\phi^I, D_{\{\mu,\nu,\rho\}}\phi^I, \cdots\}$,

This is a problem for measurements away from SM resonances.

Conclusions.

Higgs/SMEFT physics is the physics of curved field space(s).

Backup slides for discussion.

Model Example

Consider a kinetic mixing model to dim 8

- Lets see how this works in the simplest benchmark model to dim 8

$$\Delta\mathcal{L} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{1}{2}m_K^2 K_\mu K^\mu - \frac{k}{2}B^{\mu\nu}K_{\mu\nu},$$

Only has 2 parameters. Dimension 6 matching:

$H^2\psi^2 D$	
$C_{H\ell}^{1,(6)}$	$-\frac{y_\ell g_1^2}{2m_K^2}b_1$
$C_{He}^{(6)}$	$-\frac{y_e g_1^2}{2m_K^2}b_1$
$C_{Hq}^{1,(6)}$	$-\frac{y_q g_1^2}{2m_K^2}b_1$
$C_{Hu}^{(6)}$	$-\frac{y_u g_1^2}{2m_K^2}b_1$
$C_{Hd}^{(6)}$	$-\frac{y_d g_1^2}{2m_K^2}b_1$

$H^4 D^2$	
$C_{H\Box}^{(6)}$	$-\frac{g_1^2k^2}{8m_K^2}$
$C_{HD}^{(6)}$	$-\frac{g_1^2k^2}{2m_K^2}$

$\psi^4 : (\bar{L}L)(\bar{L}L)$	
$C_{\ell\ell}^{(6)}$	$-\frac{1}{8}\frac{g_1^2k^2}{m_K^2}$
$C_{qq}^{1,(6)}$	$-\frac{1}{72}\frac{g_1^2k^2}{m_K^2}$
$C_{\ell q}^{1,(6)}$	$\frac{1}{12}\frac{g_1^2k^2}{m_K^2}$

$\psi^4 : (\bar{R}R)(\bar{R}R)$	
$C_{ee}^{(6)}$	$-\frac{1}{2}\frac{g_1^2k^2}{m_K^2}$
$C_{uu}^{(6)}$	$-\frac{2}{9}\frac{g_1^2k^2}{m_K^2}$
$C_{dd}^{(6)}$	$-\frac{1}{18}\frac{g_1^2k^2}{m_K^2}$
$C_{eu}^{(6)}$	$\frac{2}{3}\frac{g_1^2k^2}{m_K^2}$
$C_{ed}^{(6)}$	$-\frac{1}{3}\frac{g_1^2k^2}{m_K^2}$
$C_{ud}^{1,(6)}$	$\frac{2}{9}\frac{g_1^2k^2}{m_K^2}$

$\psi^4 : (\bar{L}L)(\bar{R}R)$	
$C_{\ell e}^{(6)}$	$-\frac{1}{2}\frac{g_1^2k^2}{m_K^2}$
$C_{\ell u}^{(6)}$	$\frac{1}{3}\frac{g_1^2k^2}{m_K^2}$
$C_{\ell d}^{(6)}$	$-\frac{1}{6}\frac{g_1^2k^2}{m_K^2}$
$C_{qe}^{(6)}$	$\frac{1}{6}\frac{g_1^2k^2}{m_K^2}$
$C_{qu}^{1,(6)}$	$-\frac{1}{9}\frac{g_1^2k^2}{m_K^2}$
$C_{qd}^{1,(6)}$	$\frac{1}{18}\frac{g_1^2k^2}{m_K^2}$

Consider a kinetic mixing model to dim 8

- Lets see how this works in the simplest benchmark model to dim 8

$$\Delta\mathcal{L} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{1}{2}m_K^2 K_\mu K^\mu - \frac{k}{2}B^{\mu\nu}K_{\mu\nu},$$

Only has 2 parameters. Dimension 8 matching:

$H^4\psi^2 D$	
$C_{H\ell}^{1,(8)}$	$\frac{y_\ell g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_\ell}{m_K^4}(k^2-k^4)(2\lambda+\frac{g_1^2+g_2^2}{4})$
$C_{He}^{1,(8)}$	$\frac{y_e g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_e}{m_K^4}(k^2-k^4)(2\lambda+\frac{g_1^2+g_2^2}{4})$
$C_{Hq}^{1,(8)}$	$\frac{y_q g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_q}{m_K^4}(k^2-k^4)(2\lambda+\frac{g_1^2+g_2^2}{4})$
$C_{Hu}^{1,(8)}$	$\frac{y_u g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_u}{m_K^4}(k^2-k^4)(2\lambda+\frac{g_1^2+g_2^2}{4})$
$C_{Hd}^{1,(8)}$	$\frac{y_d g_1^4}{4m_K^4}k^4 - \frac{g_1^2 y_d}{m_K^4}(k^2-k^4)(2\lambda+\frac{g_1^2+g_2^2}{4})$
$C_{H\ell}^{2,(8)}$	$-\frac{g_1^2 g_2^2}{16m_K^4}(k^2-k^4)$
$C_{Hq}^{2,(8)}$	$-\frac{g_1^2 g_2^2}{16m_K^4}(k^2-k^4)$
$C_{H\ell}^{3,(8)}$	$-\frac{g_1^2 g_2^2}{16m_K^4}(k^2-k^4)$
$C_{Hq}^{3,(8)}$	$-\frac{g_1^2 g_2^2}{16m_K^4}(k^2-k^4)$

$H^6 D^2$	
$C_{H,D2}^{(8)}$	$\frac{g_1^4 k^4}{8m_K^4} - \frac{g_1^2 g_2^2}{2m_K^4}(k^2-k^4)$
$C_{HD}^{(8)}$	$\frac{3g_1^4 k^4}{16m_K^4} - \frac{g_1^2 g_2^2}{2m_K^4}(k^2-k^4)$

$X^2 H^4$	
$C_{HB}^{(8)}$	$-\frac{g_1^4}{16m_K^4}(k^2-k^4)$
$C_{HW}^{(8)}$	$\frac{g_1^2 g_2^2}{16m_K^4}(k^2-k^4)$

No loop suppression.

Consider a kinetic mixing model to dim 8

- Lets see how this works in the simplest benchmark model to dim 8

$$\Delta\mathcal{L} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{1}{2}m_K^2 K_\mu K^\mu - \frac{k}{2}B^{\mu\nu}K_{\mu\nu},$$

- Dimension 6 squared approximation:

$$\frac{\sum_\psi \bar{\Gamma}^{p.s.,\hat{\alpha}_{ew}}_{\mathcal{Z}\to\bar{\psi}_p\psi_p}}{\sum_\psi \bar{\Gamma}^{\mathrm{SM},\hat{\alpha}_{ew}}_{\mathcal{Z}\to\bar{\psi}_p\psi_p}} = 1 + 4.5\times10^{-3}\,\frac{\bar{v}_T^2\,k^2}{m_K^2} + 4.4\times10^{-3}\,k^4\,\frac{\bar{v}_T^4}{m_K^4},$$

$$\frac{\sum_\psi \bar{\Gamma}^{p.s.,\hat{m}_W}_{\mathcal{Z}\to\bar{\psi}_p\psi_p}}{\sum_\psi \bar{\Gamma}^{\mathrm{SM},\hat{m}_W}_{\mathcal{Z}\to\bar{\psi}_p\psi_p}} = 1 - 3.1\times10^{-2}\,\frac{\bar{v}_T^2\,k^2}{m_K^2} + 2.3\times10^{-4}\,k^4\,\frac{\bar{v}_T^4}{m_K^4}.$$

Consider a kinetic mixing model to dim 8

- Lets see how this works in the simplest benchmark model to dim 8

$$\Delta\mathcal{L} = -\frac{1}{4}K_{\mu\nu}K^{\mu\nu} + \frac{1}{2}m_K^2 K_\mu K^\mu - \frac{k}{2}B^{\mu\nu}K_{\mu\nu},$$

- To Dimension 8 consistently:

$$\frac{\sum_\psi \bar{\Gamma}^{\mathrm{SMEFT},\hat{\alpha}_{ew}}_{Z\to\bar{\psi}_p\psi_p}}{\sum_\psi \bar{\Gamma}^{\mathrm{SM},\hat{\alpha}_{ew}}_{Z\to\bar{\psi}_p\psi_p}} = 1 + 4.5\times10^{-3}\,\frac{\bar{v}_T^2\,k^2}{m_K^2} - 5.7\times10^{-3}\,(k^4 - 1.74k^2)\,\frac{\bar{v}_T^4}{m_K^4},$$

$$\frac{\sum_\psi \bar{\Gamma}^{\mathrm{SMEFT},\hat{m}_W}_{Z\to\bar{\psi}_p\psi_p}}{\sum_\psi \bar{\Gamma}^{\mathrm{SM},\hat{m}_W}_{Z\to\bar{\psi}_p\psi_p}} = 1 - 3.1\times10^{-2}\,\frac{\bar{v}_T^2\,k^2}{m_K^2} + 7.9\times10^{-3}\,(k^4 - 0.88k^2)\,\frac{\bar{v}_T^4}{m_K^4}.$$

Consider a kinetic mixing model to dim 8

- Strong input parameter dependence in any one observable:

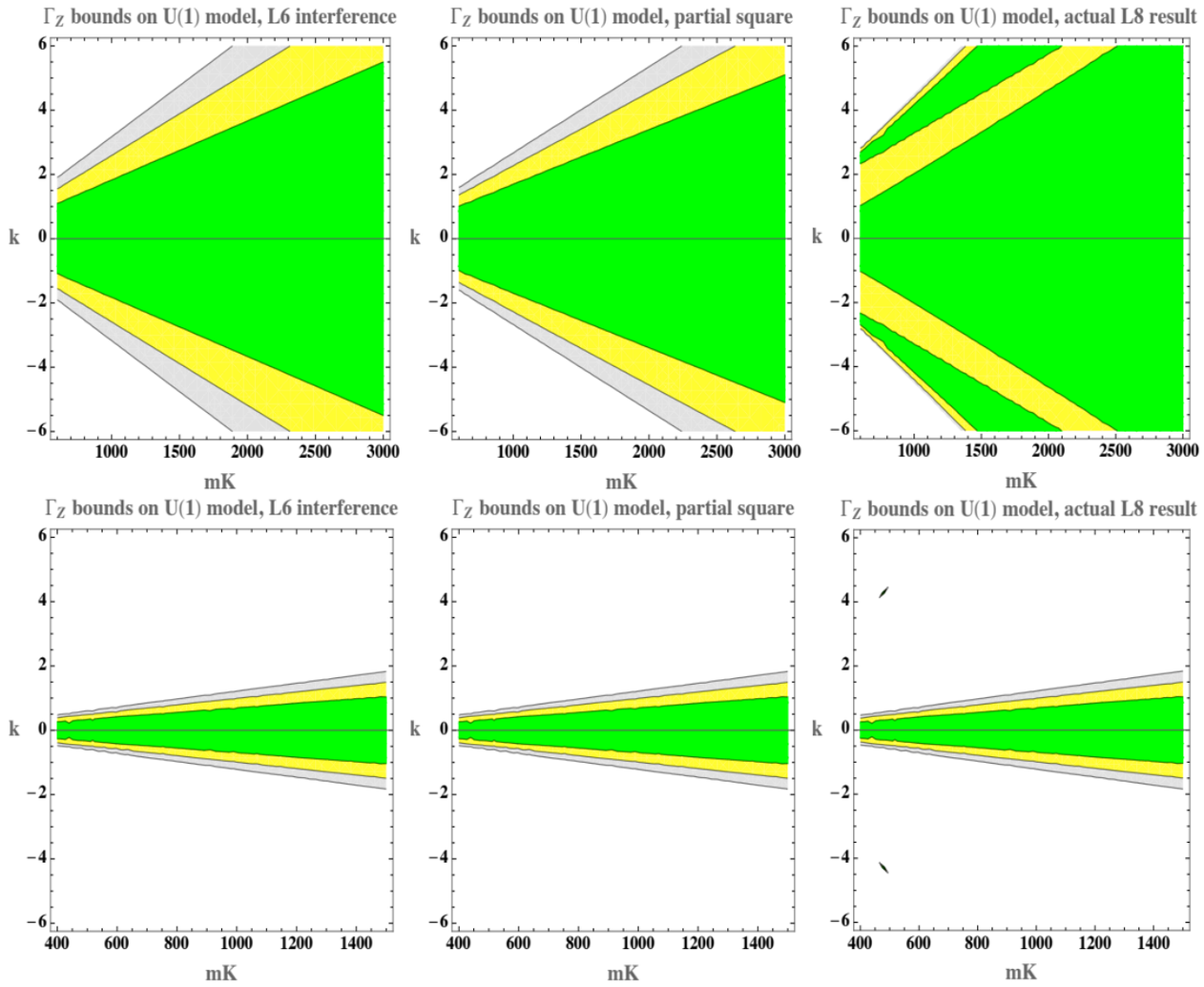


Figure 8. Illustrative bounds on a U(1) mixing model parameters due to bounds on Γ_Z. Shown is the $\{1, 2, 3\}\sigma$ allowed region in green, yellow, gray. Here 1σ for $\delta\Gamma_Z = 0.0023/2.4952$. Results shown are for the $\hat{\alpha}_{ew}$ input-parameter scheme in the first row. The results in the second row are in the $\hat{m}_W$ input-parameter scheme.

- L6^2 can manifestly mislead.
- Clearly need to go beyond quadratic. With geoSMEFT we can proceed efficiently to full dim 8.

Consider a kinetic mixing model to dim 8

- Strong input parameter dependence in any one observable:

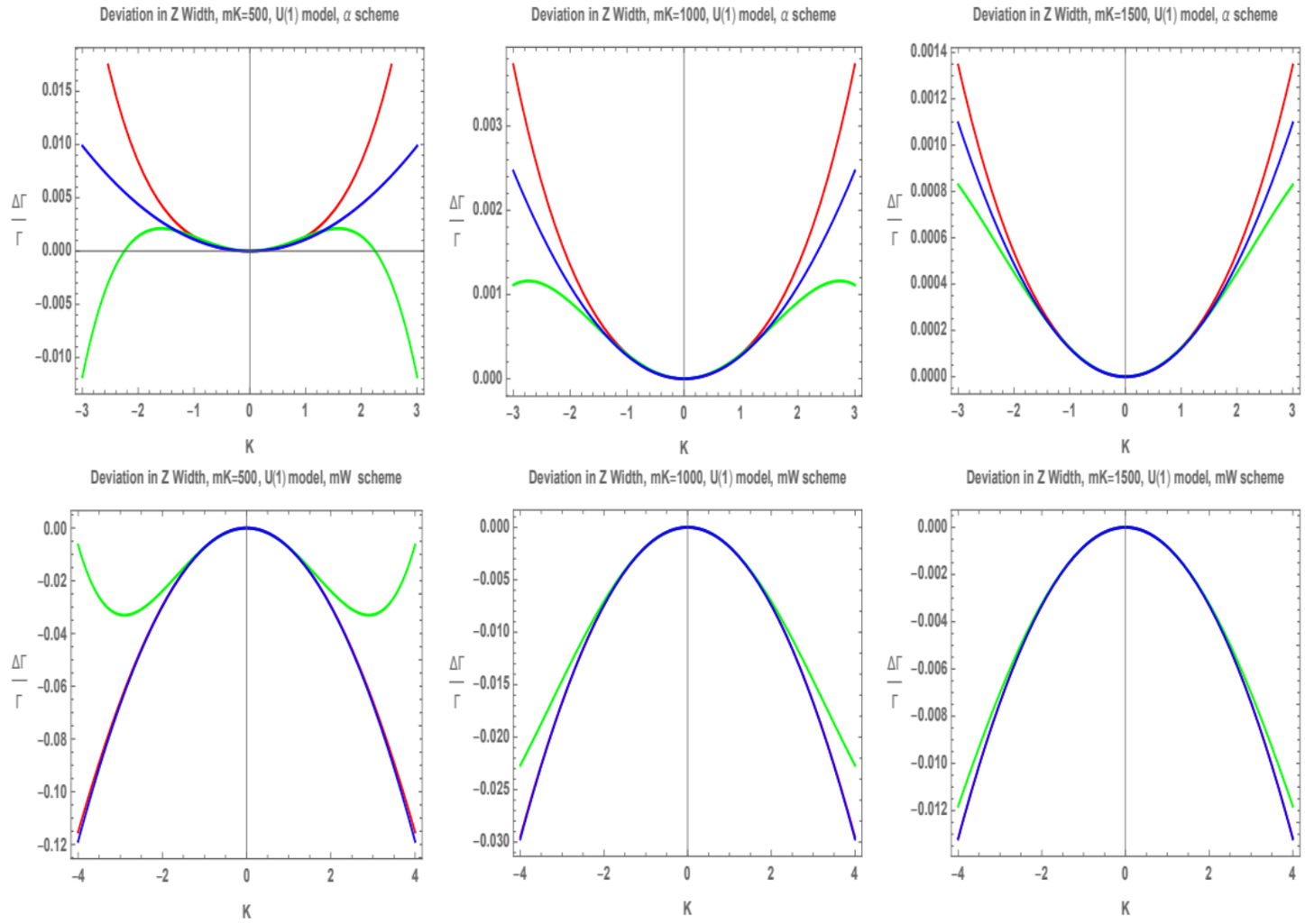


Figure 9. Deviation in the Z width in the U(1) mixing model for fixed m_K comparing the partial-square result in red and the full SMEFT result at $\mathcal{L}^{(8)}$ in green, and the full SMEFT result at $\mathcal{L}^{(6)}$ in blue.

- L6^2 can Mislead
- The power of the EFT is that you can combine observables and you have to do it