geoSMEFT and applications

Key collaborators on these developments:

More complete discussion see: **https://www.youtube.com/watch?v=9MRfqKhD7Qw&t=627s**

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Consequences of the Higgs field becoming a number

The Higgs field takes on a vev, recall what happens:

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu H^\dagger)(D^\mu H) + \sum_{\psi=q,u,d,l,e} \overline{\psi}\, i \not{D}\, \psi$$
$$- \lambda \left(H^\dagger H - \frac{1}{2}v^2\right)^2 - \left[H^{\dagger j}\overline{d}\, Y_d\, q_j + \widetilde{H}^{\dagger j}\overline{u}\, Y_u\, q_j + H^{\dagger j}\overline{e}\, Y_e\, l_j + \text{h.c.}\right],$$

$$D \leq 4$$

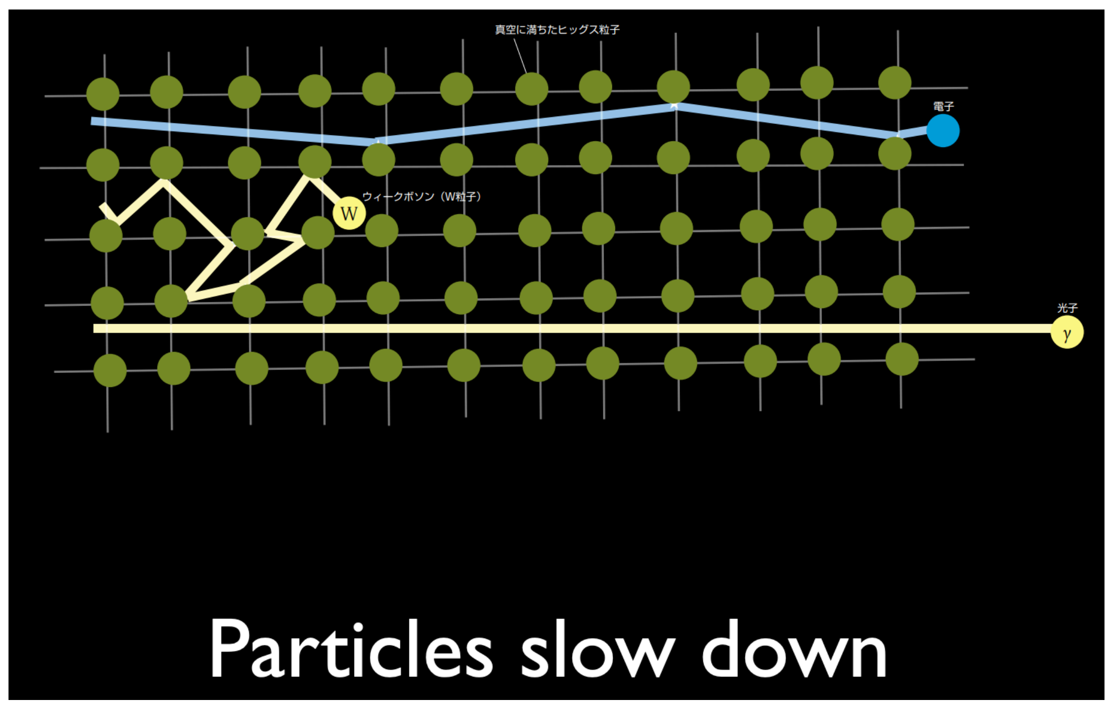


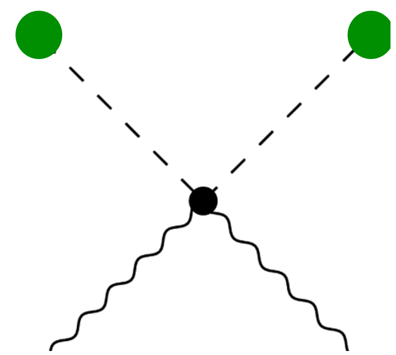
Image credit: Hitoshi's Higgs2020 talk

Gives masses, mass eigenstate fields, useful combinations of fields and couplings

Consequences of the Higgs field becoming a number

The Higgs field takes on a vev, recall what happens:

$$(D_\mu H^\dagger)(D^\mu H)$$



4-point

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

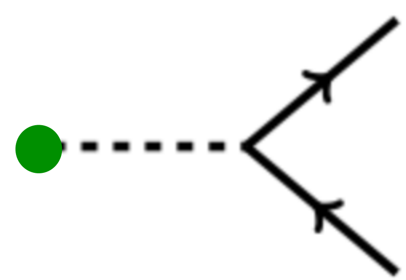
2-point (mass)

$$\mathcal{W}_B^\nu = U_{BC}\mathcal{A}^{C,\nu}$$

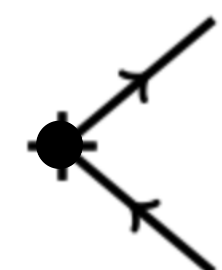
$$\mathcal{W}_B = \{W_1, W_2, W_3, B\}$$

$$\mathcal{A}_C = \{W^+, W^-, Z, A\}$$

$$\left[H^{\dagger j}\overline{d}\,Y_d\,q_j + \widetilde{H}^{\dagger j}\overline{u}\,Y_u\,q_j + H^{\dagger j}\overline{e}\,Y_e\,l_j + \text{h.c.}\right]$$

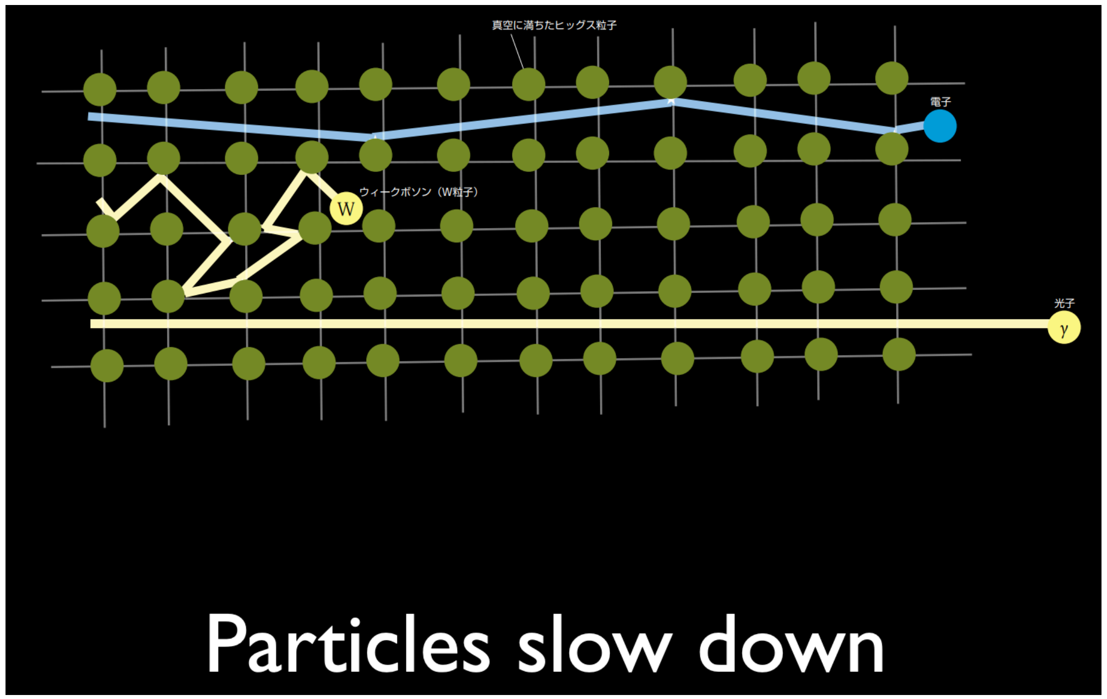


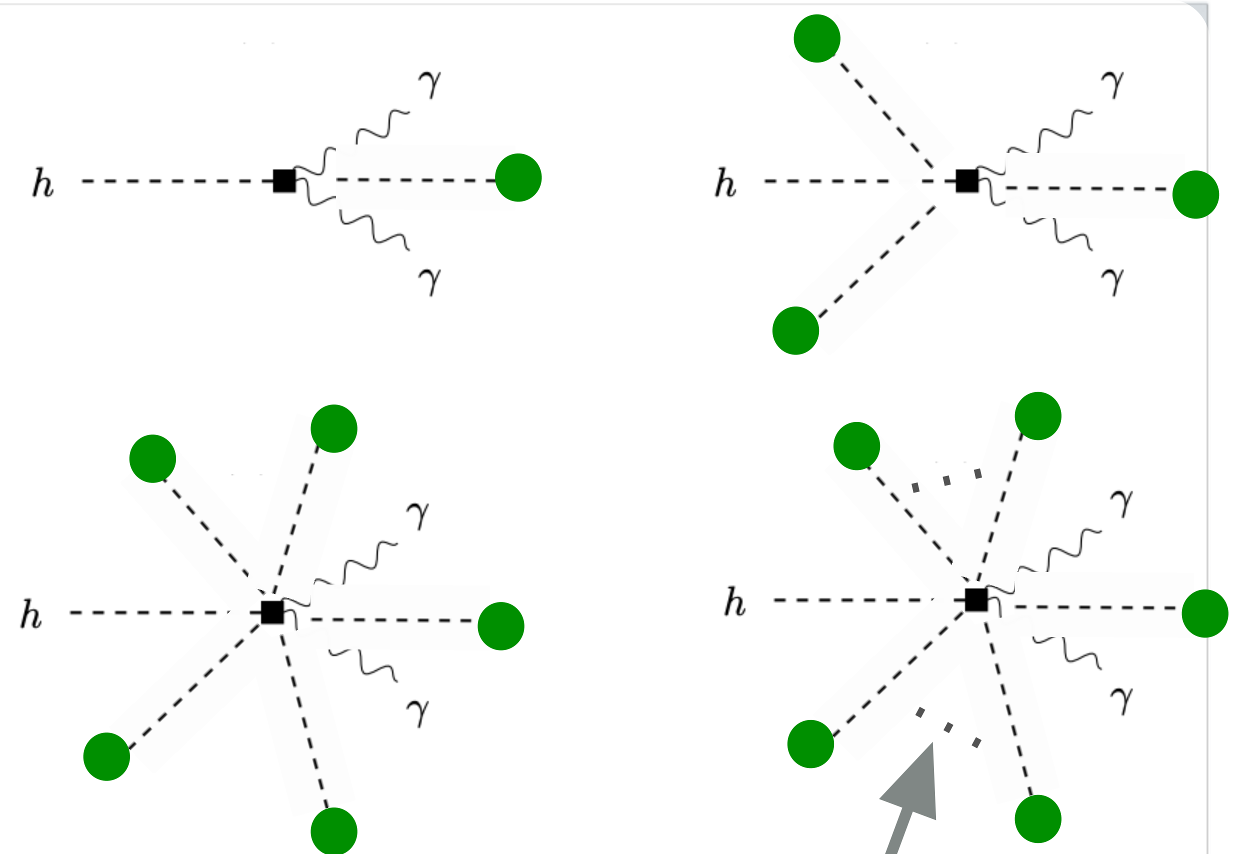
3-point



2-point (mass)

What is the Geometric SMEFT?





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

$$D \leq 4$$

$$D > 4$$

Gives masses, mass eigenstate fields.

Gives geometries that define the mass eigenstate fields and interactions in the EFT

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

$$\mathcal{L}_{\text{scalar,kin}} = \frac{1}{2} h_{IJ}(\phi) \left(D_\mu \phi\right)^I \left(D^\mu \phi\right)^J ,$$

Where $H = \frac{1}{\sqrt{2}} \begin{bmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{bmatrix}$

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

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

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

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

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

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

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

All orders SM Lagrangian parameters

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

2001.01453 Helset, Martin, 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

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

- Mixing angles:

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

(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

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

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

$$\begin{aligned} g_{AB}(\phi_I) = & \left[1 - 4\sum_{n=0}^{\infty} \left(C^{(6+2n)}_{HW}(1-\delta_{A4}) + C^{(6+2n)}_{HB}\delta_{A4}\right)\left(\frac{\phi^2}{2}\right)^{n+1}\right]\delta_{AB} \\ & - \sum_{n=0}^{\infty} C^{(8+2n)}_{HW,2}\left(\frac{\phi^2}{2}\right)^n \left(\phi_I \Gamma^I_{A,J}\phi^J\right)\left(\phi_L \Gamma^L_{B,K}\phi^K\right)(1-\delta_{A4})(1-\delta_{B4}) \\ & + \left[\sum_{n=0}^{\infty} C^{(6+2n)}_{HWB}\left(\frac{\phi^2}{2}\right)^n\right]\left[(\phi_I \Gamma^I_{A,J}\phi^J)(1-\delta_{A4})\delta_{B4} + (A \leftrightarrow B)\right], \end{aligned}$$

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

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

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 $D \leq 4$

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

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

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

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

What else could you write?

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
(True in any operator basis.)

Generator transform

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

SMEFT field space metrics
(Now known to all orders)

Rotations

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

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

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

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

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

Generalisation for composite ops

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

$$v/M < 1$$

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

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

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

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

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

With fermions $\quad Y(\phi)\bar\psi_1\psi_2, \quad L_{I,A}(\phi)\bar\psi_1\gamma^\mu\tau_A\psi_2(D_\mu\phi)^I, \quad d_A(\phi)\bar\psi_1\sigma^{\mu\nu}\psi_2\mathcal{W}^A_{\mu\nu},$

Gluon fields $\quad k_{\mathcal{A}\mathcal{B}}(\phi)G^{\mathcal{A}}_{\mu\nu}G^{\mathcal{B},\mu\nu}, \quad k_{\mathcal{A}\mathcal{B}\mathcal{C}}(\phi)G^{\mathcal{A}}_{\nu\mu}G^{\mathcal{B},\rho\nu}G^{\mathcal{C},\mu\rho}, \quad c(\phi)\bar\psi_1\sigma^{\mu\nu}T_{\mathcal{A}}\psi_2G^{\mathcal{A}}_{\mu\nu}.$

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

Field space connection	6	8	10	12	14
	Mass Dimension				
$h_{IJ}(\phi)(D_\mu\phi)^I(D^\mu\phi)^J$	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.	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$
$Y^d_{pr}(\phi)\bar{Q}d+$ h.c.	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$
$Y^e_{pr}(\phi)\bar{L}e+$ h.c.	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$	$2\,N_f^2$
$d^{e,pr}_A(\phi)\bar{L}\sigma_{\mu\nu}e\mathcal{W}^{\mu\nu}_A+$ h.c.	$4\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$
$d^{u,pr}_A(\phi)\bar{Q}\sigma_{\mu\nu}u\mathcal{W}^{\mu\nu}_A+$ h.c.	$4\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$
$d^{d,pr}_A(\phi)\bar{Q}\sigma_{\mu\nu}d\mathcal{W}^{\mu\nu}_A+$ h.c.	$4\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$	$6\,N_f^2$
$L^{\psi_R}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,R}\gamma_\mu\sigma_A\psi_{r,R})$	N_f^2	N_f^2	N_f^2	N_f^2	N_f^2
$L^{\psi_L}_{pr,A}(\phi)(D^\mu\phi)^J(\bar{\psi}_{p,L}\gamma_\mu\sigma_A\psi_{r,L})$	$2\,N_f^2$	$4\,N_f^2$	$4\,N_f^2$	$4\,N_f^2$	$4\,N_f^2$

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

- Basis choice changes entries in these geometric structures, but geometric organization exist in any basis. The trend of saturation of effects at dimension eight is a general feature.

GeoSMEFT All orders result ex.

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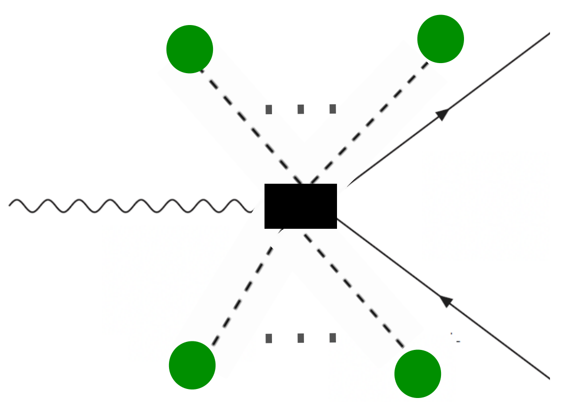
- What does this allow one to do?



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

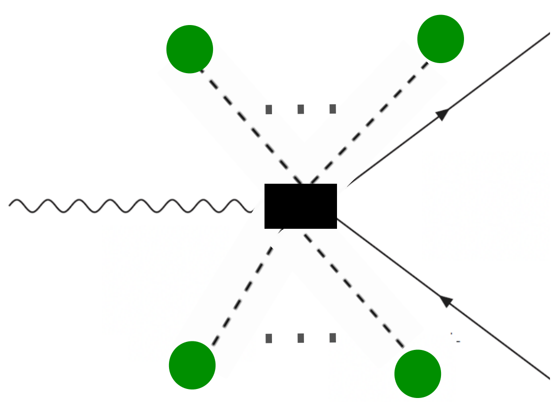
Added to this is the scalar, fermion connection (with a background field expectation)

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

GeoSMEFT All orders result ex.

2001.01453 Helset, Martin, Trott

- What does this allow one to do?



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

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

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

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

GeoSMEFT All orders result ex.

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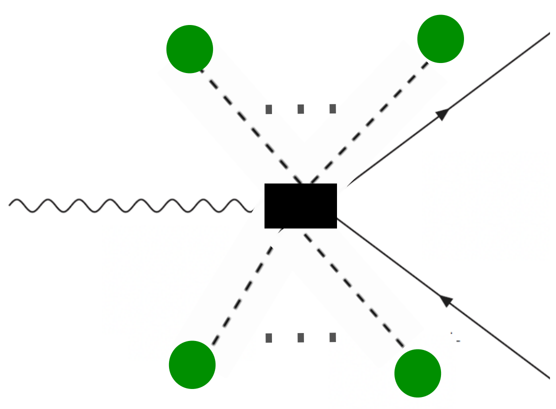
- What does this allow one to do?



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

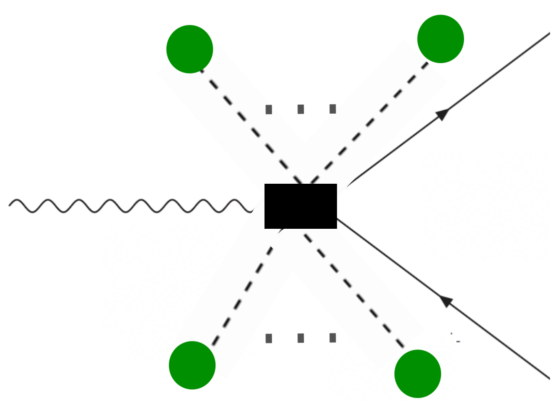
$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p\gamma_\mu\bar{\tau}_A\psi_r)\delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p\gamma_\mu\sigma_A\psi_r)\langle L_{I,A}^{\psi,pr}\rangle(-\gamma^{I}_{C,4})\bar{v}_T,$$

The coupling of the canonically normalised mass eigenstate fields is then

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

GeoSMEFT All orders result ex.

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



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

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

- Two body decay widths:

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

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

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

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

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

- Can do LEP to dim 8 in about 3 weeks of work if you learn this stuff.

Dimension 8 LEP effects

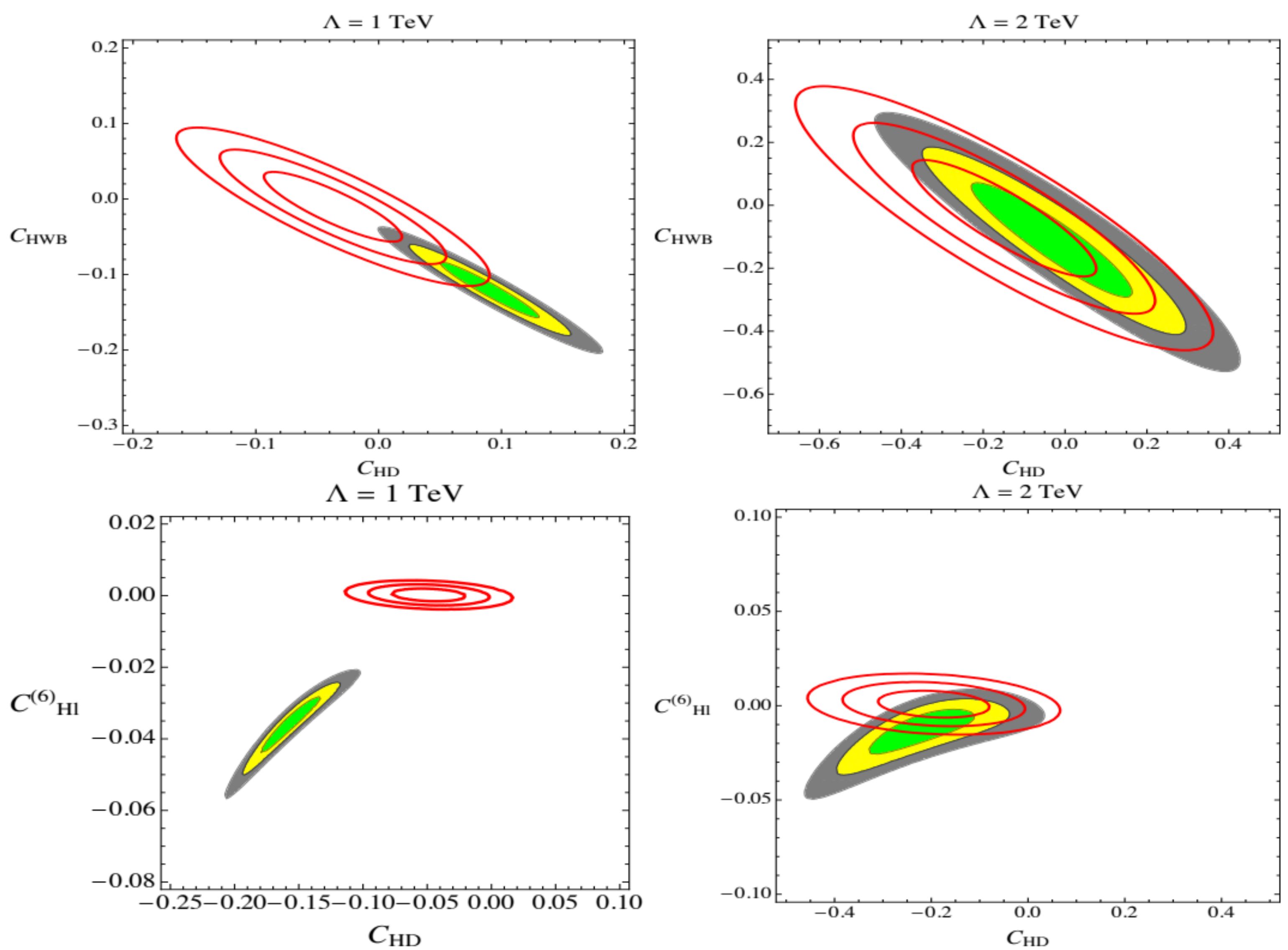


Figure 3. The green/yellow/gray contours correspond to the 68%/95%/99.9% CL two parameter fit determined by $\Delta\chi^2_{\mathcal{O}(v^4/\Lambda^4)}$, while the red rings correspond to the same CL determined using $\Delta\chi^2_{\mathcal{O}(v^2/\Lambda^2)}$. In the top panels the free parameters are 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.