



# Status of Effective Field Theory and SMEFT



## Key collaborators and developments in geoSMEFT:



A. Helset



T. Corbett



A. Martin



C. Hays



J. Talbert

1803.08001 Helset, Paraskevas, Trott.

2001.01453 Helset, Martin, Trott.

2010.08451 Corbett, Trott

2010.15852 Corbett,

2107.03951 Talbert, Trott.

2106.10284 Corbett,

1909.08470 Corbett, Helset, Trott

2007.00565 Hays, Helset, Martin, Trott

2102.02819 Helset, Corbett, Martin, Trott

2106.13794 Trott

2107.07470 Corbett, Martin, Trott

VILLUM FONDEN

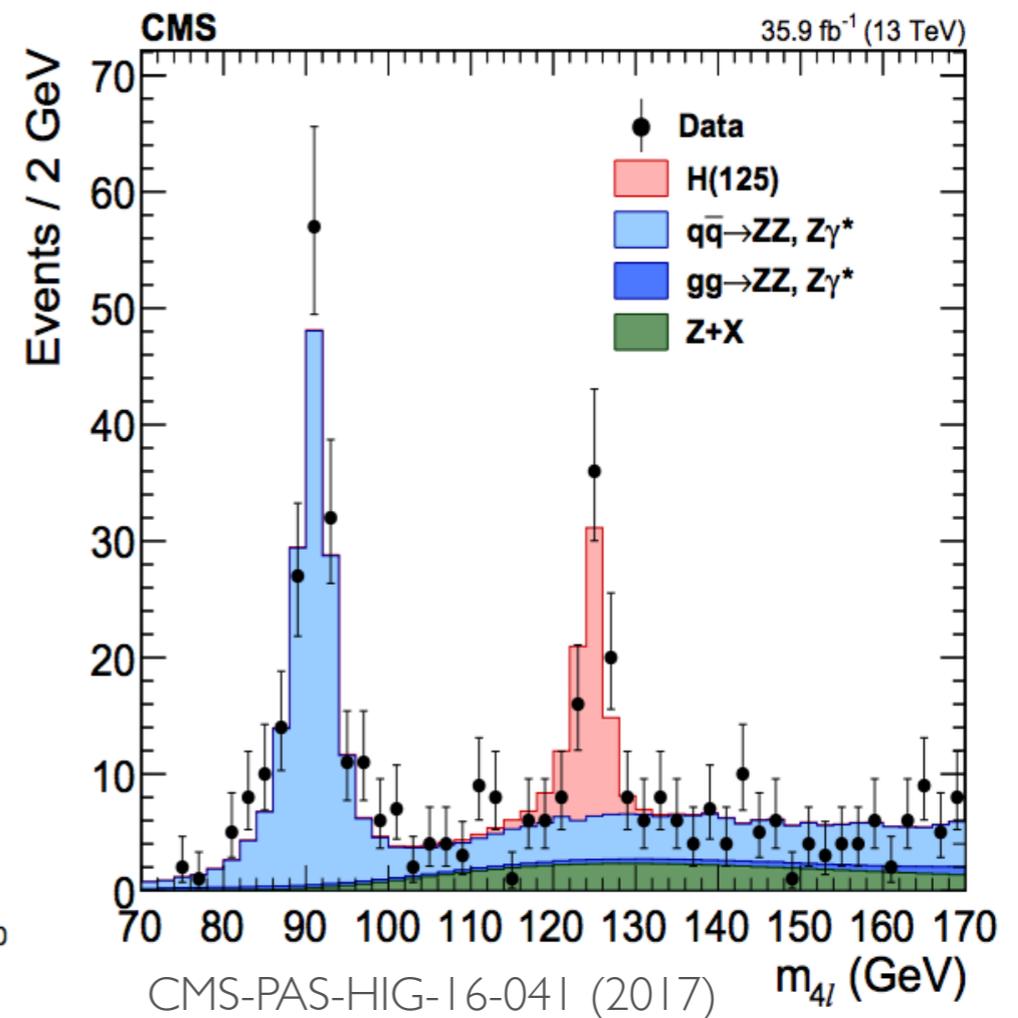
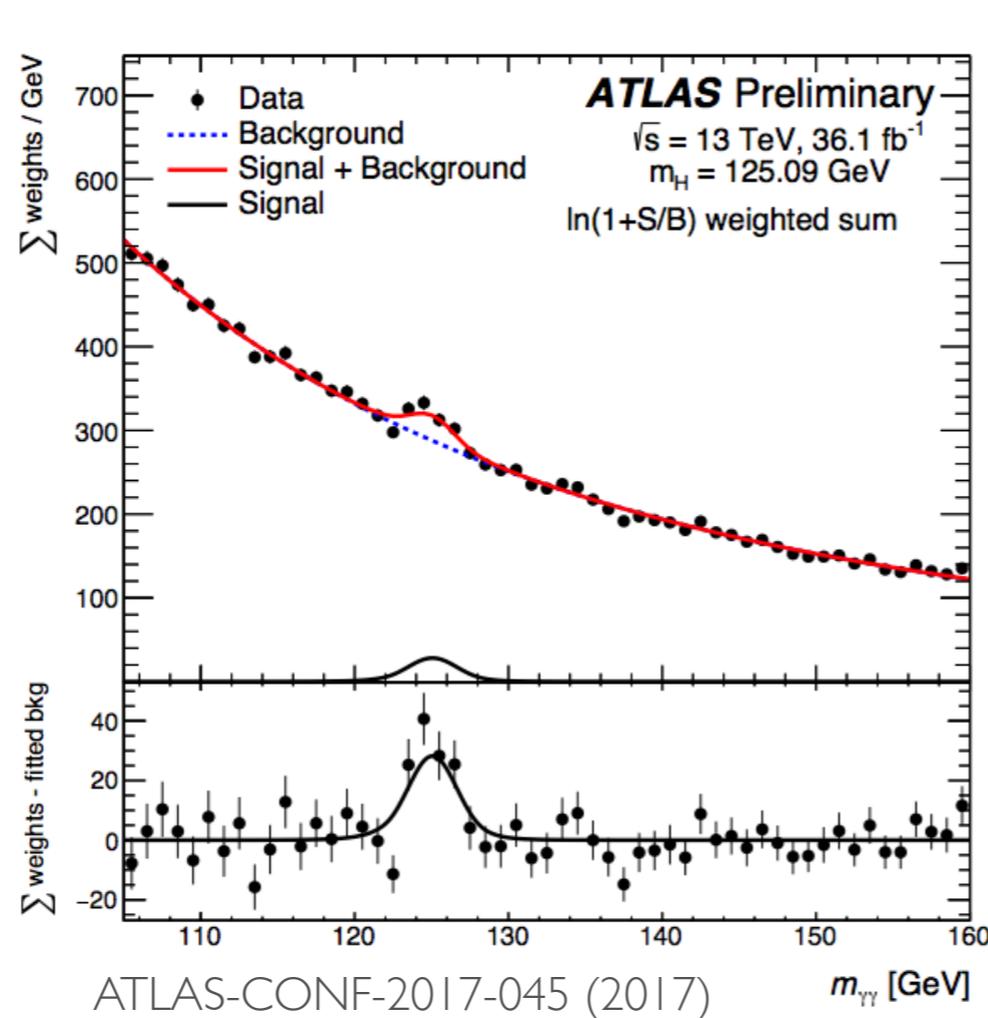




**The SMEFT  
is dead,  
long live  
the geoSMEFT!**

# What was discovered at LHC, a particle

- Discovery of a (Higgs like)  $J^P \sim 0^+$  particle in 2012



# What wasn't discovered at LHC

## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: July 2018

ATLAS Preliminary

$\int \mathcal{L} dt = (3.2 - 79.8) \text{ fb}^{-1}$

$\sqrt{s} = 8, 13 \text{ TeV}$

Model	$\ell, \gamma$	Jets <sup>†</sup>	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	$1-4 j$	Yes	36.1	$M_D$ 7.7 TeV	$n = 2$
	ADD non-resonant $\gamma\gamma$	$2 \gamma$	-	-	36.7	$M_S$ 8.6 TeV	$n = 3$ HLZ NLO
	ADD QBH	-	$2 j$	-	37.0	$M_{\text{th}}$ 8.9 TeV	$n = 6$
	ADD BH high $\Sigma p_T$	$\geq 1 e, \mu$	$\geq 2 j$	-	3.2	$M_{\text{th}}$ 8.2 TeV	$n = 6, M_D = 3 \text{ TeV}$ , rot BH
	ADD BH multijet	-	$\geq 3 j$	-	3.6	$M_{\text{th}}$ 9.55 TeV	$n = 6, M_D = 3 \text{ TeV}$ , rot BH
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \gamma$	-	-	36.7	$G_{KK}$ mass 4.1 TeV	$k/\bar{M}_{Pl} = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK}$ mass 2.3 TeV	$k/\bar{M}_{Pl} = 1.0$
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	$g_{KK}$ mass 3.8 TeV	$\Gamma/m = 15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$
	Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	36.1	$Z'$ mass 4.5 TeV
SSM $Z' \rightarrow \tau\tau$		$2 \tau$	-	-	36.1	$Z'$ mass 2.42 TeV	
Leptophobic $Z' \rightarrow bb$		-	$2 b$	-	36.1	$Z'$ mass 2.1 TeV	
Leptophobic $Z' \rightarrow tt$		$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	$Z'$ mass 3.0 TeV	$\Gamma/m = 1\%$
SSM $W' \rightarrow \ell\nu$		$1 e, \mu$	-	Yes	79.8	$W'$ mass 5.6 TeV	ATLAS-CONF-2018-017
SSM $W' \rightarrow \tau\nu$		$1 \tau$	-	Yes	36.1	$W'$ mass 3.7 TeV	1801.06992
HVT $V' \rightarrow WV \rightarrow qq\bar{q}\bar{q}$ model B		$0 e, \mu$	$2 J$	-	79.8	$V'$ mass 4.15 TeV	ATLAS-CONF-2018-016
HVT $V' \rightarrow WH/ZH$ model B		multi-channel	-	-	36.1	$V'$ mass 2.93 TeV	1712.06518
LRSM $W'_R \rightarrow tb$		multi-channel	-	-	36.1	$W'$ mass 3.25 TeV	CERN-EP-2018-142
CI		CI $qq\bar{q}\bar{q}$	-	$2 j$	-	37.0	$\Lambda$ 21.8 TeV $\eta_{LL}$
	CI $\ell\ell\bar{q}\bar{q}$	$2 e, \mu$	-	-	36.1	$\Lambda$ 40.0 TeV $\eta_{LL}$	1707.02424
	CI $tt\bar{t}\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$\Lambda$ 2.57 TeV	$ C_{4t}  = 4\pi$ CERN-EP-2018-174
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	$1-4 j$	Yes	36.1	$m_{\text{med}}$ 1.55 TeV	$g_q=0.25, g_\gamma=1.0, m(\chi) = 1 \text{ GeV}$
	Colored scalar mediator (Dirac DM)	$0 e, \mu$	$1-4 j$	Yes	36.1	$m_{\text{med}}$ 1.67 TeV	$g=1.0, m(\chi) = 1 \text{ GeV}$
	$VV\chi\chi$ EFT (Dirac DM)	$0 e, \mu$	$1 J, \leq 1 j$	Yes	3.2	$M_s$ 700 GeV	$m(\chi) < 150 \text{ GeV}$
LQ	Scalar LQ 1 <sup>st</sup> gen	$2 e$	$\geq 2 j$	-	3.2	LQ mass 1.1 TeV	$\beta = 1$
	Scalar LQ 2 <sup>nd</sup> gen	$2 \mu$	$\geq 2 j$	-	3.2	LQ mass 1.05 TeV	$\beta = 1$
	Scalar LQ 3 <sup>rd</sup> gen	$1 e, \mu$	$\geq 1 b, \geq 3 j$	Yes	20.3	LQ mass 640 GeV	$\beta = 0$
Heavy quarks	VLQ $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV	SU(2) doublet
	VLQ $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet
	VLQ $T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS) \geq 3 e, \mu \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$	
	VLQ $Y \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	3.2	Y mass 1.44 TeV	$\mathcal{B}(Y \rightarrow Wb) = 1, c(YWb) = 1/\sqrt{2}$
	VLQ $B \rightarrow Hb + X$	$0 e, \mu, 2 \gamma$	$\geq 1 b, \geq 1 j$	Yes	79.8	B mass 1.21 TeV	$\kappa_B = 0.5$
Excited fermions	Excited quark $q^* \rightarrow qg$	-	$2 j$	-	37.0	$q^*$ mass 6.0 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	$1 \gamma$	$1 j$	-	36.7	$q^*$ mass 5.3 TeV	only $u^*$ and $d^*$ , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow bg$	-	$1 b, 1 j$	-	36.1	$b^*$ mass 2.6 TeV	
	Excited lepton $\ell^*$	$3 e, \mu$	-	-	20.3	$\ell^*$ mass 3.0 TeV	$\Lambda = 3.0 \text{ TeV}$
	Excited lepton $\nu^*$	$3 e, \mu, \tau$	-	-	20.3	$\nu^*$ mass 1.6 TeV	$\Lambda = 1.6 \text{ TeV}$
Other	Type III Seesaw	$1 e, \mu$	$\geq 2 j$	Yes	79.8	$N^0$ mass 560 GeV	$m(W_R) = 2.4 \text{ TeV}$ , no mixing
	LRSM Majorana $\nu$	$2 e, \mu$	$2 j$	-	20.3	$N^0$ mass 2.0 TeV	DY production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2,3,4 e, \mu$ (SS)	-	-	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production, $\mathcal{B}(H^{\pm\pm} \rightarrow \ell\tau) = 1$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	$H^{\pm\pm}$ mass 400 GeV	$a_{\text{non-res}} = 0.2$
	Monotop (non-res prod)	$1 e, \mu$	$1 b$	Yes	20.3	spin-1 invisible particle mass 657 GeV	DY production, $ q  = 5e$
	Multi-charged particles	-	-	-	20.3	multi-charged particle mass 785 GeV	DY production, $ g  = 1g_D$ , spin 1/2
Magnetic monopoles	-	-	-	7.0	monopole mass 1.34 TeV		

\*Only a selection of the available mass limits on new states or phenomena is shown.

<sup>†</sup>Small-radius (large-radius) jets are denoted by the letter j (J).

# What wasn't discovered at LHC

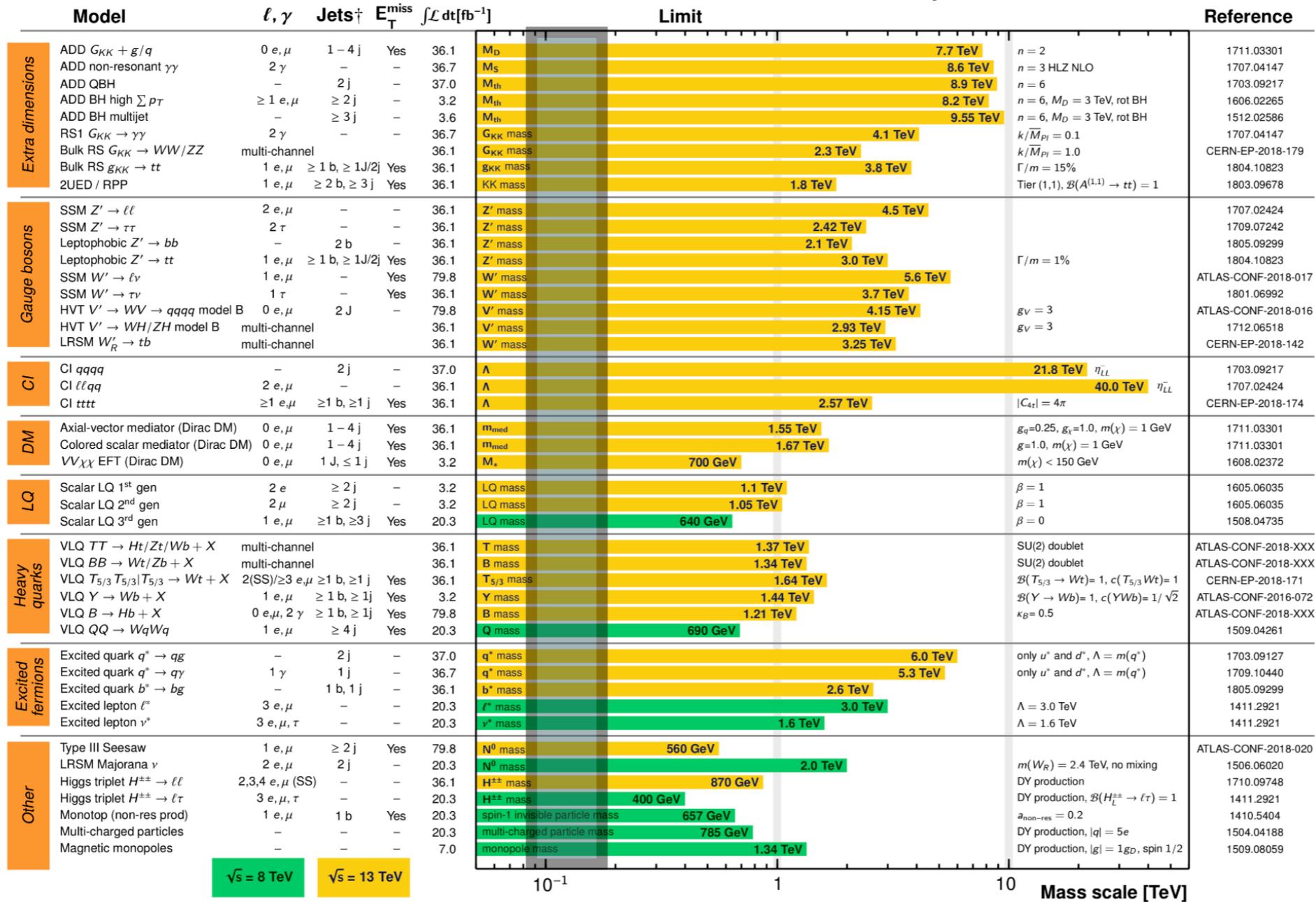
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Masses of EW scale ( $\sim gv$ ) states  $m_W, m_Z, m_t, m_h$

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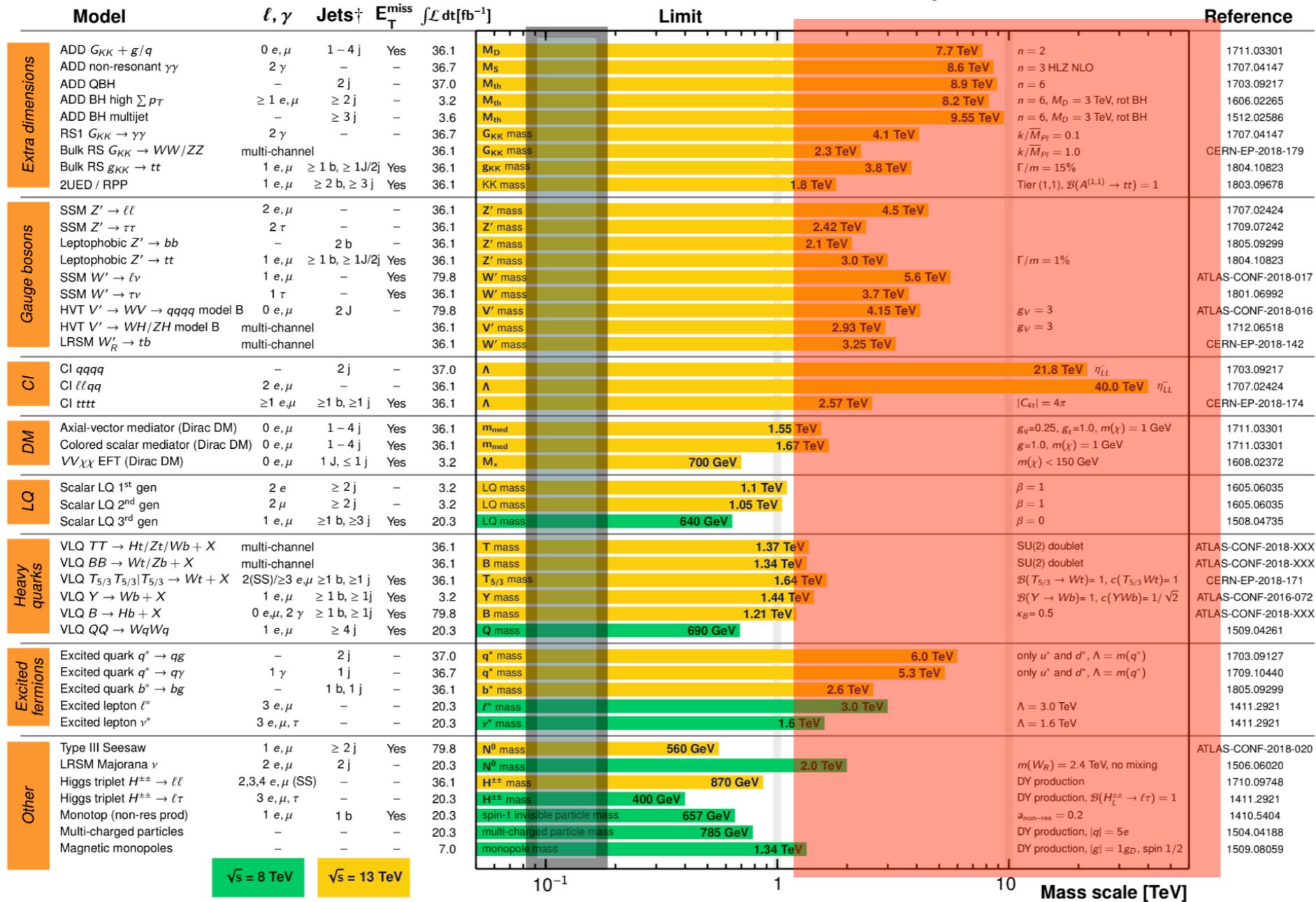
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These bounds have been pushed away from

$$v \sim m_h$$

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# EFT: Resonance limits to local operators

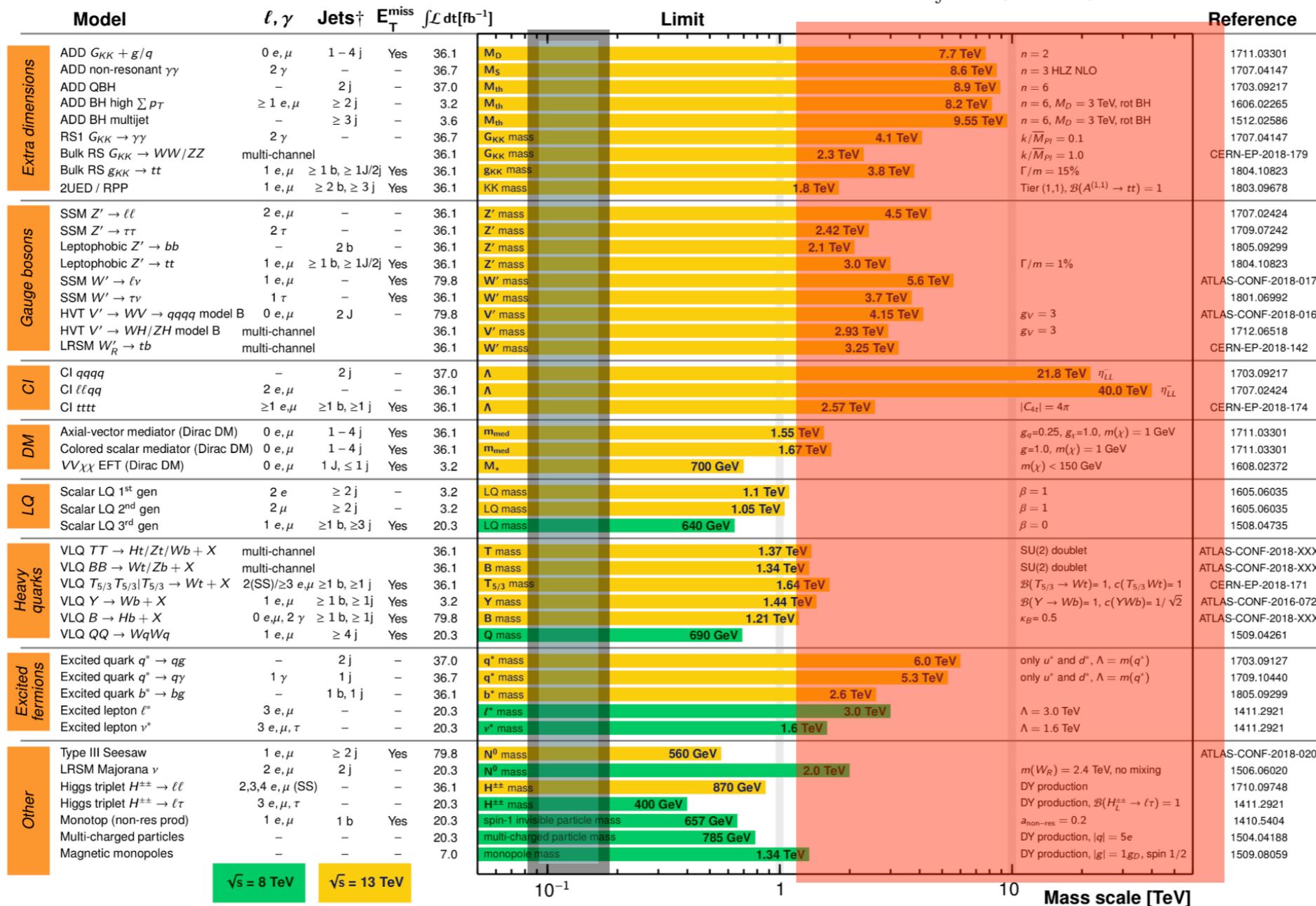
## ATLAS Exotics Searches\* - 95% CL Upper Exclusion Limits

Status: July 2018

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Now that these bounds have been pushed away from

$v$

USE that

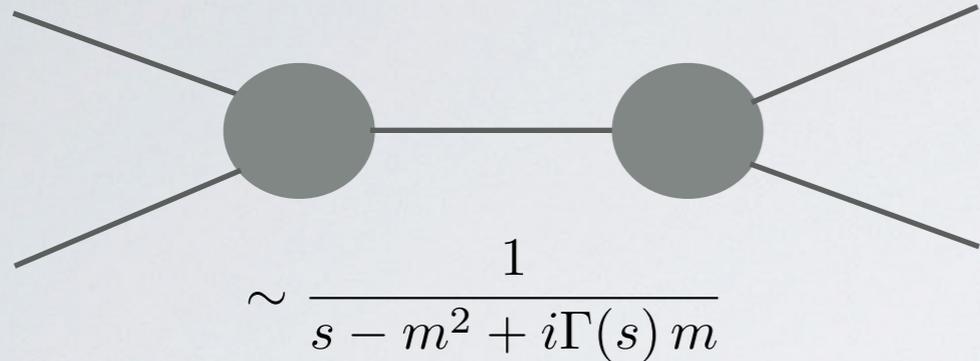
$$v/M < 1$$

to simplify/for more powerful conclusions:

- bound many models at once
- bound multiple resonances at same time

Deviations then look like local contact operator effects in EFT

# When you do measurements below a particle threshold



**IF** the collision probe does not reach  $\sim m_{heavy}^2$   
**THEN** observable's dependence on that scale simplified

- You can Taylor expand in LOCAL functions (operators)

$$\langle \rangle \sim O_{SM}^0 + \frac{f_1(s, t, u)}{M_{heavy}^2} + \frac{f_2(s, t, u)}{M_{heavy}^4} + \dots$$

This is the core idea of EFT interpretations of the data.

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

UV dependent Wilson coefficient  
and suppression scale

IR operator form

# Reasons for SMEFT-icide.

- 1a) Basis debates. (Are you sick of them yet?)

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

- This choice is not unique, and theorists are stubborn so they are converging asymptotically at best.
- The operators are defined in a BASIS, fixed by SM field redefinitions.

$$\begin{aligned} \mathcal{L}_{B'} = & -\frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - g_1 y_\psi \bar{\psi} \not{B}' \psi + (D^\mu H)^\dagger (D_\mu H) + C_B (H^\dagger \overleftrightarrow{D}^\mu H) (D^\nu B_{\mu\nu}), \\ & + C_{BH} (D^\mu H)^\dagger (D^\nu H) B'_{\mu\nu} + C_{Hl}^{(1)} Q_{Hl}^{(1)} + C_{He} Q_{He} + C_{Hq}^{(1)} Q_{Hq}^{(1)} + C_{Hu} Q_{Hu}, \\ & + C_{Hd} Q_{Hd} + C_{HB} Q_{HB} + C_T (H^\dagger \overleftrightarrow{D}^\mu H) (H^\dagger \overleftrightarrow{D}^\mu H). \end{aligned}$$

Over complete set of ops depending on

1706.08945 I. Brivio, MT

- Perform a field redefinition

$$B'_\mu \rightarrow B_\mu + b_2 \frac{H^\dagger i \overleftrightarrow{D}_\mu H}{\Lambda^2}$$

then

$$\mathcal{L}_{B'} - g_1 b_2 \Delta B$$

The physics is not changed by this choice of path integral variable.

# Reasons for SMEFT-icide.

- 1a) Basis debates. (Are you sick of them yet?)

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

- CHOOSE  $b_2 = C_B$  THEN

$$\begin{aligned} \mathcal{L}_{B'} = & -\frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - g_1 y_\psi \bar{\psi} \not{B}' \psi + (D^\mu H)^\dagger (D_\mu H) + \cancel{C_B (H^\dagger \overleftrightarrow{D}^\mu H) (D^\nu B_{\mu\nu})}, \\ & + C_{BH} (D^\mu H)^\dagger (D^\nu H) B'_{\mu\nu} + C_{Hl}^{(1)} Q_{Hl}^{(1)} + C_{He} Q_{He} + C_{Hq}^{(1)} Q_{Hq}^{(1)} + C_{Hu} Q_{Hu}, \\ & + C_{Hd} Q_{Hd} + C_{HB} Q_{HB} + C_T (H^\dagger \overleftrightarrow{D}^\mu H) (H^\dagger \overleftrightarrow{D}^\mu H). \end{aligned}$$

Non-redundant set of ops depending on  $B^\mu$

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- BUT terms that remain SHIFTED

$$\mathcal{L}_B - g_1 b_2 \Delta B$$

$$\Delta B = y_l Q_{Hl}^{(1)} + y_e Q_{He} + y_q Q_{Hq}^{(1)} + y_u Q_{Hu} + y_d Q_{Hd}, \quad + y_H (Q_{H\Box} + 4 Q_{HD}) + \frac{1}{g_1} B^{\mu\nu} \partial_\mu (H^\dagger \overleftrightarrow{D}_\nu H).$$

EWPD, diboson, Higgs data all modified globally

Keep all operators for basis independence

# Parameters in the SMEFT

In Warsaw basis arXiv:1008.4884 (SMEFT standard basis)

Class	$N_{\text{op}}$	$CP$ -even			$CP$ -odd		
		$n_g$	1	3	$n_g$	1	3
1 $g^3 X^3$	4	2	2	2	2	2	
2 $H^6$	1	1	1	1	1	1	
3 $H^4 D^2$	2	2	2	2	2	2	
4 $g^2 X^2 H^2$	8	4	4	4	4	4	
5 $y\psi^2 H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6 $gy\psi^2 XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7 $\psi^2 H^2 D$	8	$\frac{1}{2}n_g(9n_g + 7)$	8	51	$\frac{1}{2}n_g(9n_g - 7)$	1	30
8 : $(\bar{L}L)(LL)$	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 : $(\bar{R}R)(\bar{R}R)$	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
$\psi^4$ 8 : $(\bar{L}L)(\bar{R}R)$	8	$4n_g^2(n_g^2 + 1)$	8	360	$4n_g^2(n_g - 1)(n_g + 1)$	0	288
8 : $(\bar{L}R)(\bar{R}L)$	1	$n_g^4$	1	81	$n_g^4$	1	81
8 : $(\bar{L}R)(\bar{L}R)$	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**

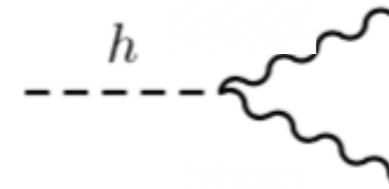
arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

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

# Can we do better re basis independence? Yes.

1b) More basis independent results are possible.

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



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

Kinematic structure



Geometric Dressings



(no explicit op forms!) How do we get to such results?

# Dim 6 SMEFT EW Lagrangian terms

2) SMEFT at dimension 6 with all operators is already complicated.

- EW sector parameters redefined in the SMEFT

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

Mass redefinitions

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

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

Mixing angle redefinitions

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

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

Interactions to remaining SM fields via:

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

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

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

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

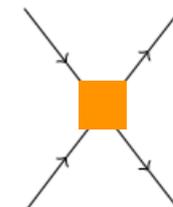
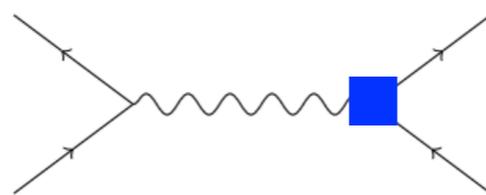
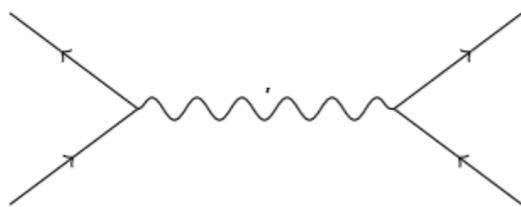
1312.2014 Alonso, Jenkins, Manohar, Trott

Note the complications are proportional to the vev.

# Inputs also needed - SMEFT Muon decay

- Decay of  $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$  still measured far below the W pole.
- Still probes the effective lagrangian

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



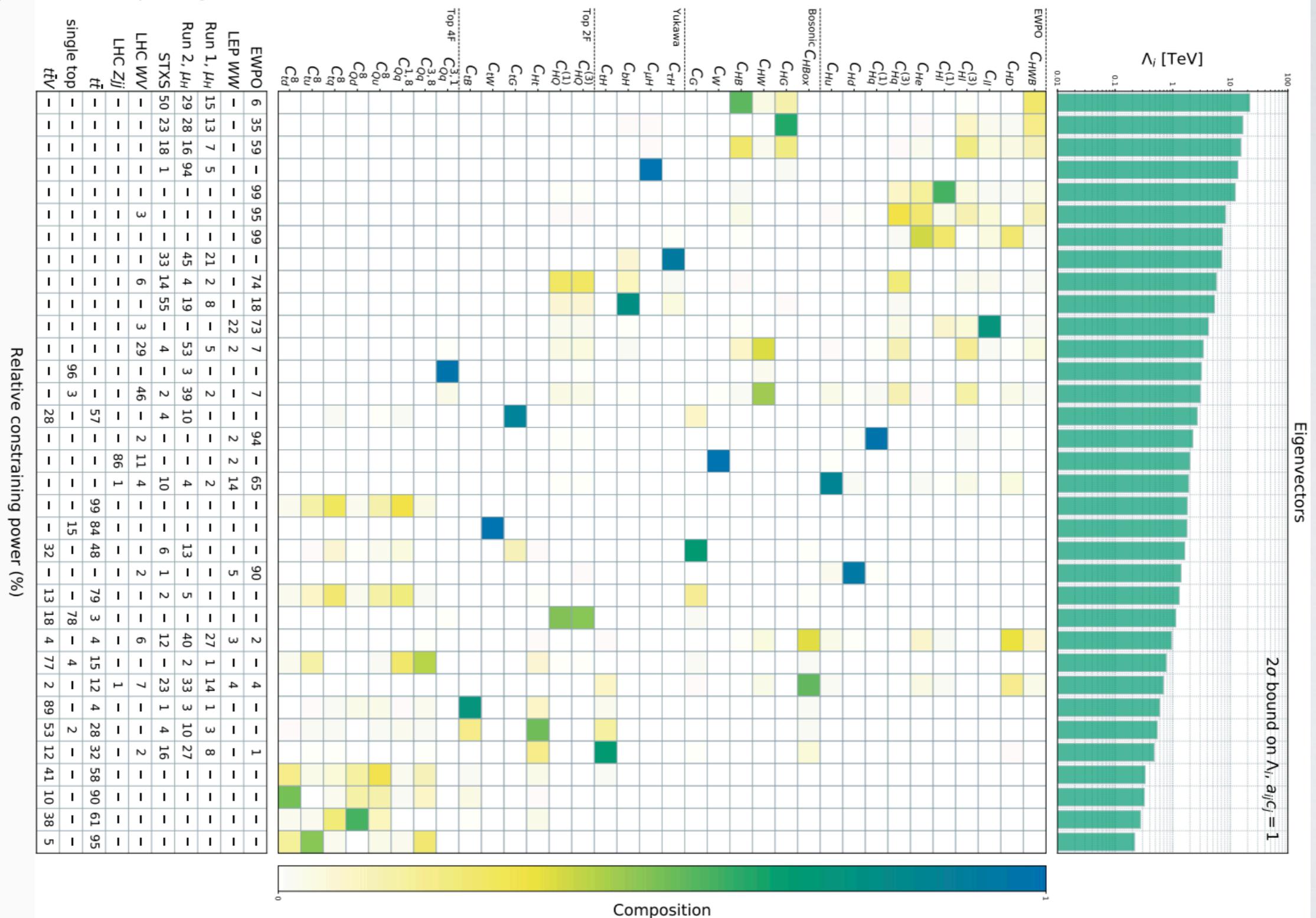
So now

$$-\frac{4G_F}{\sqrt{2}} = -\frac{2}{v_T^2} + \underbrace{\left( C_{\mu e e \mu}^{\mu} + C_{e \mu \mu e}^{\mu} \right)}_{\delta G_F} - 2 \left( C_{ee}^{(3)} + C_{\mu\mu}^{(3)} \right)$$

$\delta G_F$

# Keep all operators gives eigenvectors of constraint

3) Properly eigenvectors of constraint, not individual op limits - what are the spaces?



One can understand, and sort these issues geometrically

# Consequences of the Higgs field becoming a number

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

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

$$D \leq 4$$

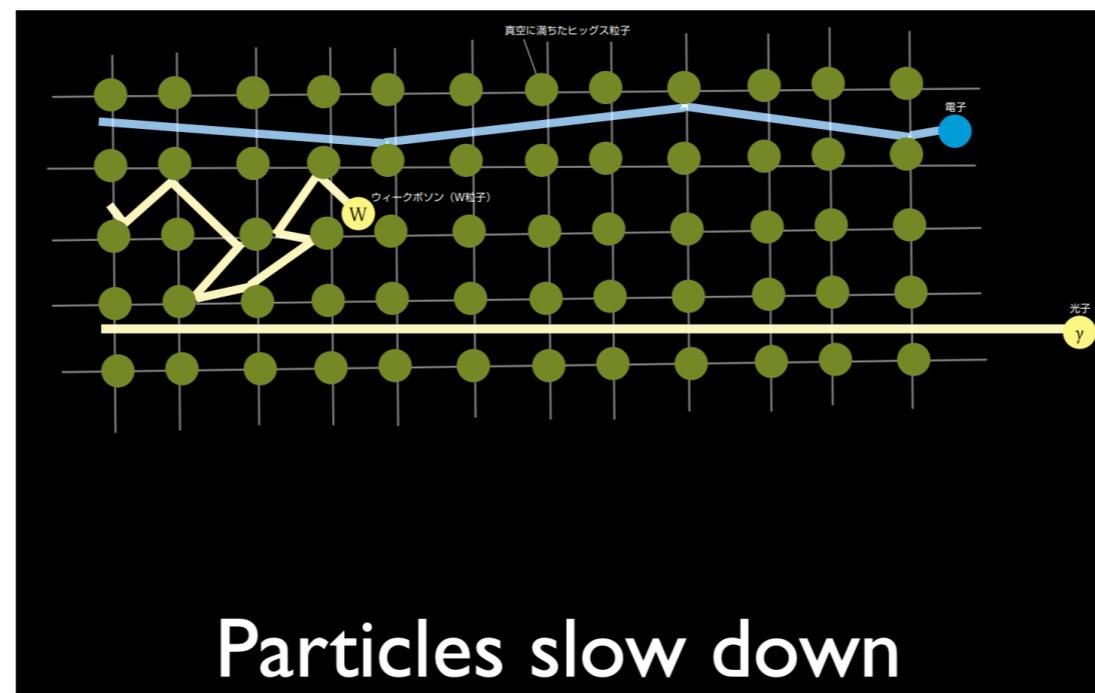


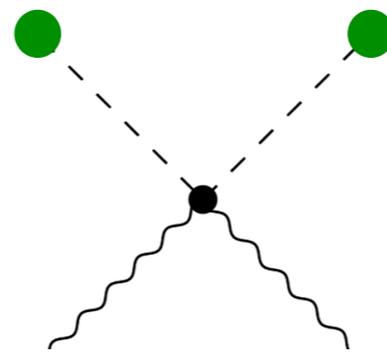
Image credit: Hitoshi's Higgs2020 talk

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

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



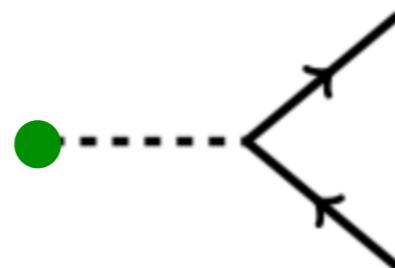
2-point (mass)

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

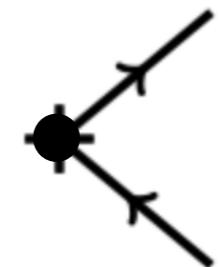
$$W_B = \{W_1, W_2, W_3, B\}$$

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

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



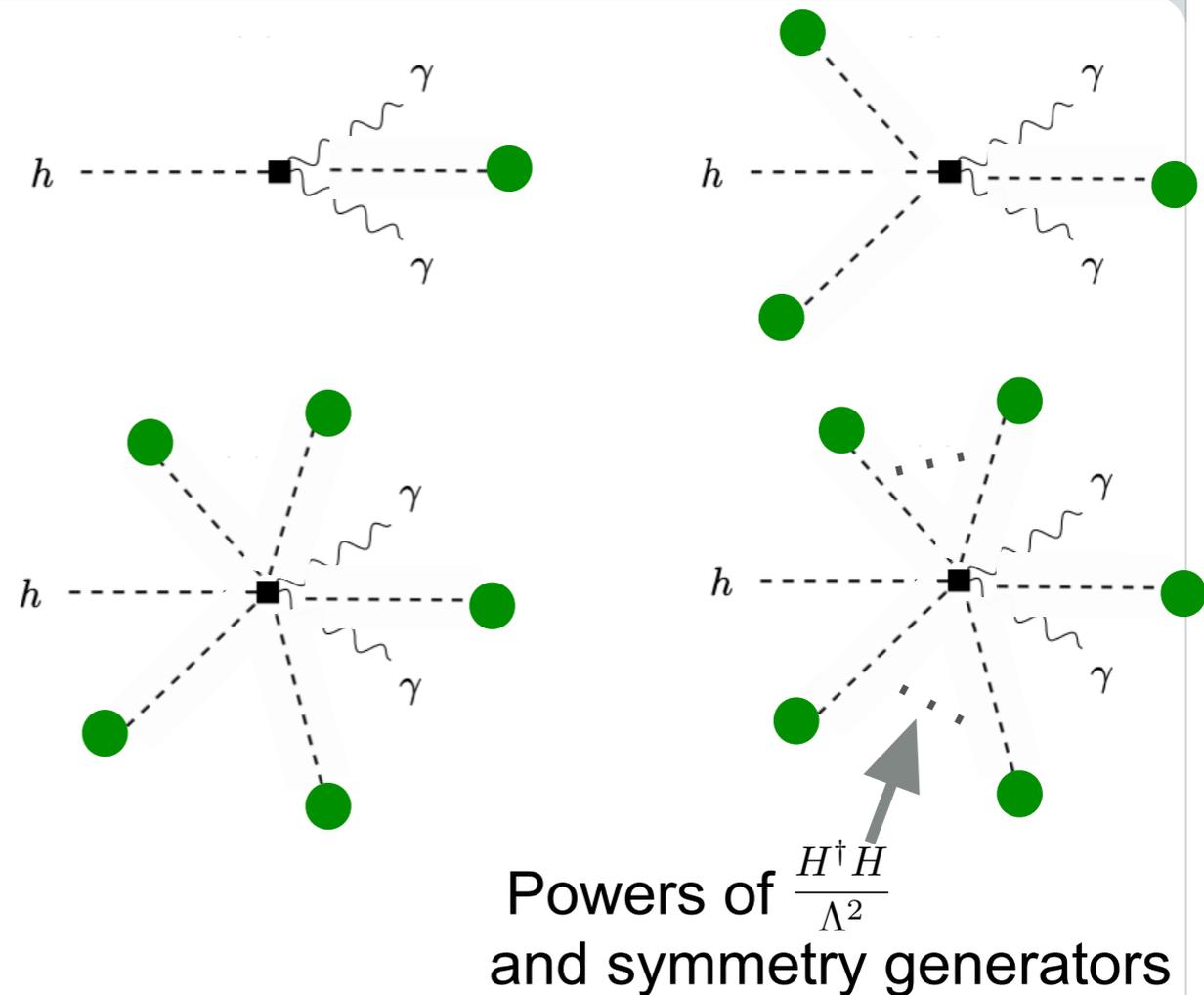
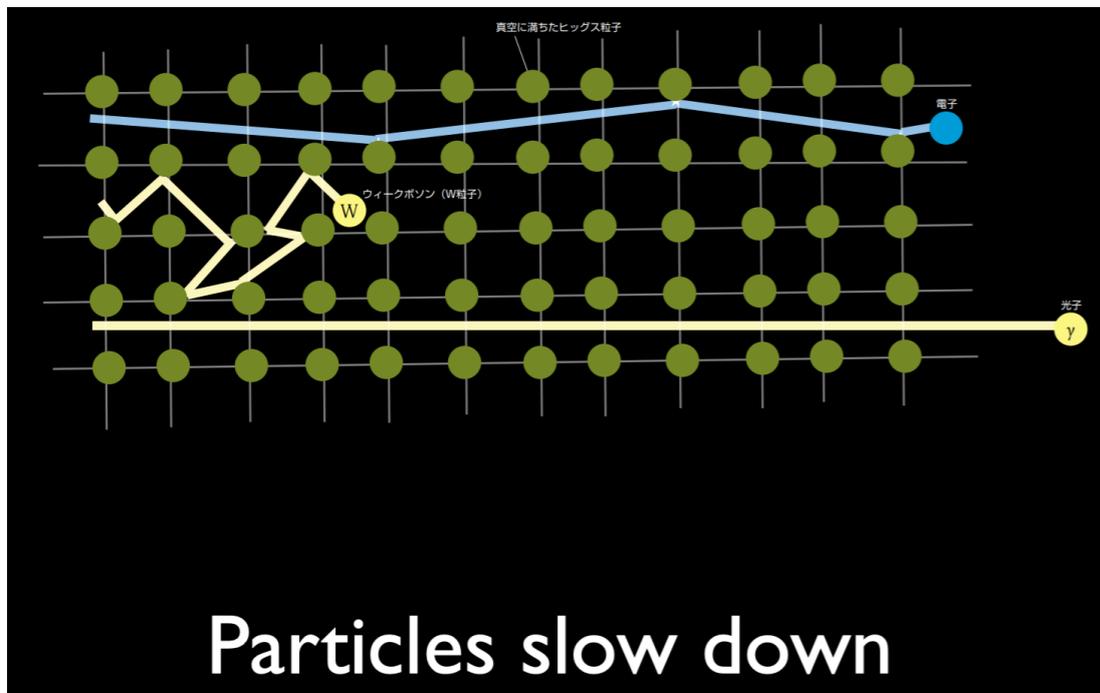
3-point



2-point (mass)



# What is the Geometric SMEFT?



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

Kinematic structure

Geometric Dressings

# 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

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

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

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

$$\mathcal{L}_{\text{gauge,kin}} = -\frac{1}{4} g_{AB}(\phi) \mathcal{W}_{\mu\nu}^A \mathcal{W}^{B,\mu\nu}, \quad \text{Where } \mathcal{W}^A = (W^1, W^2, W^3, B)$$

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

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

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

- Masses

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

- Mixing angles:

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

(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

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

- Number of operator forms saturate in geosmeft.

This is due to reducing possible generator insertions on the Higgs manifold

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

# SM weak-mass eigenstate relations

- Weak eigenstates

- Mass eigenstate

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

- Rotations

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

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

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

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

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

$$\beta^C = \left\{ \frac{g_2(1-i)}{\sqrt{2}}, \frac{g_2(1+i)}{\sqrt{2}}, \sqrt{g_1^2 + g_2^2}(c_{\bar{\theta}}^2 - s_{\bar{\theta}}^2), \frac{2g_1g_2}{\sqrt{g_1^2 + g_2^2}} \right\},$$

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

What else could you write?

# SMEFT weak-mass eigenstate relations

- Weak eigenstates

1909.08470 Corbett, Helset, Trott  
(True in any operator basis.)

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

SMEFT field space metrics  
(Now known to all orders)

- Mass eigenstate

Generator transform

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

Rotations

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

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

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

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

$$\beta^C = \left\{ \frac{g_2(1-i)}{\sqrt{2}}, \frac{g_2(1+i)}{\sqrt{2}}, \sqrt{g_1^2 + g_2^2}(c_{\bar{\theta}}^2 - s_{\bar{\theta}}^2), \frac{2g_1g_2}{\sqrt{g_1^2 + g_2^2}} \right\}, \quad \mathcal{A}^C = (\mathcal{W}^+, \mathcal{W}^-, \mathcal{Z}, \mathcal{A}).$$

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)

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

Mass redefinitions

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

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

Mixing angle redefinitions

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

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

Interactions to remaining SM fields via:

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

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

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

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

# Generalisation for composite ops

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

$$v/M < 1$$

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

## 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

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

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

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

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

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

Gluon fields  $k_{\mathcal{A}\mathcal{B}}(\phi) G_{\mu\nu}^{\mathcal{A}} G^{B,\mu\nu}, \quad k_{\mathcal{A}\mathcal{B}\mathcal{C}}(\phi) G_{\nu\mu}^{\mathcal{A}} G^{B,\rho\nu} G^{C,\mu\rho}, \quad c(\phi) \bar{\psi}_1 \sigma^{\mu\nu} T_{\mathcal{A}} \psi_2 G_{\mu\nu}^{\mathcal{A}}.$

# Generalisation for composite ops

- Such connections can be defined from the Lagrangian expansion constructively

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

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

- 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

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

- 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

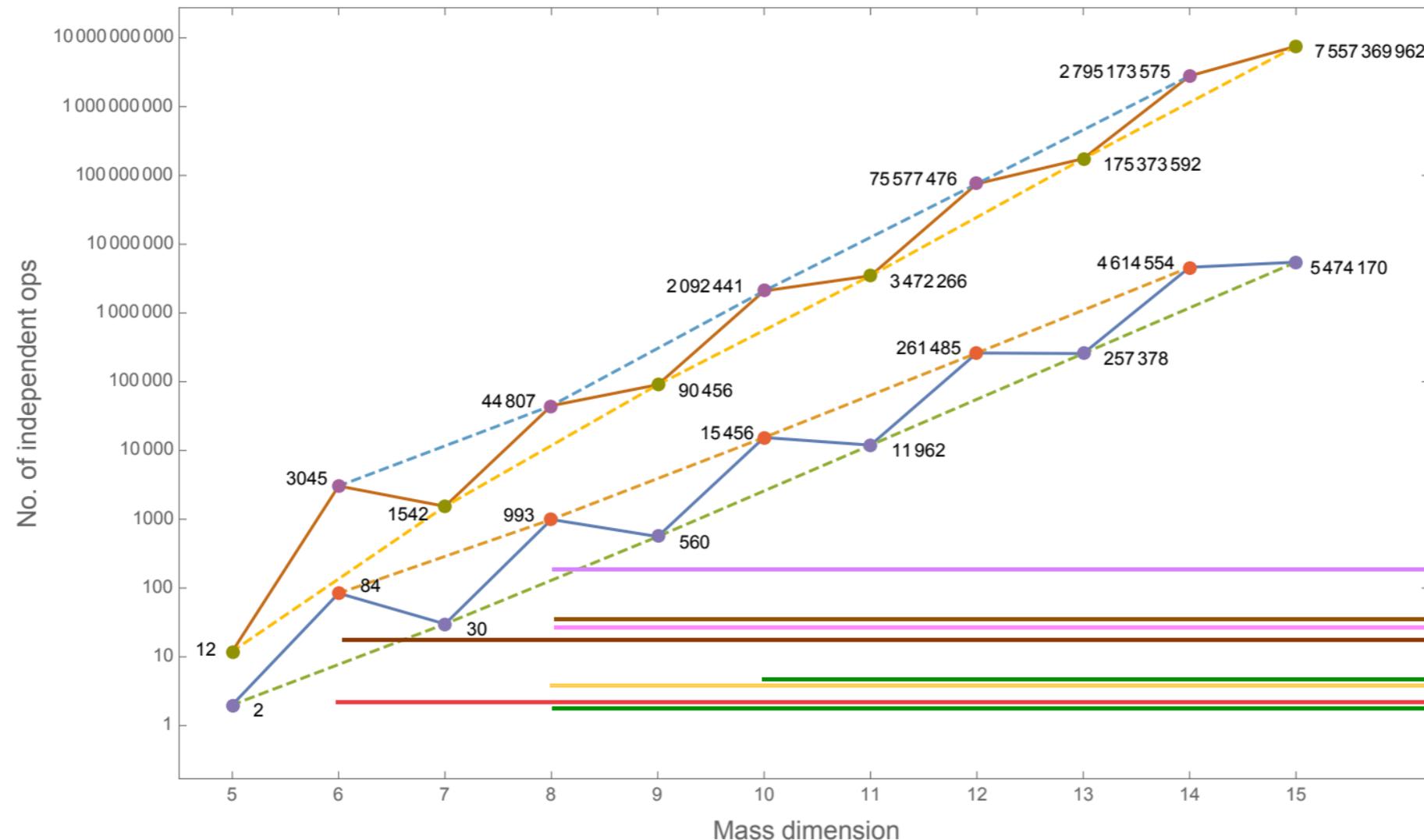
Dipoles

W,Z couplings to fermions + higgs

2001.01453 Helset, Martin, Trott

- 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.

# The scalar expansion vs derivative expansion



Tails are exponential  
DERIVATIVE EXPANSION

Pole parameters  $O(10's)$

SCALAR EXPANSION

- Tails of distributions have significant sensitivity to the higher order terms.
- General growth in operator forms from Hilbert series

<https://arxiv.org/abs/1503.07537>

<https://arxiv.org/pdf/1512.03433.pdf>

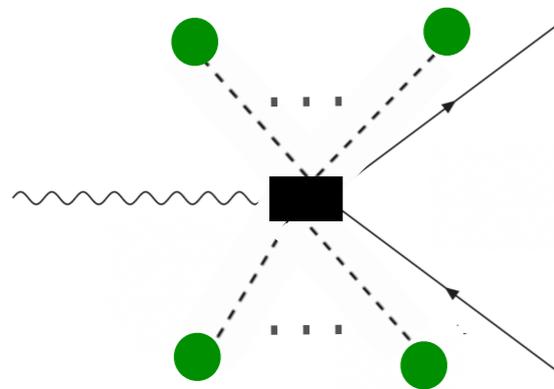
<https://arxiv.org/abs/1510.00372>

<https://arxiv.org/abs/1706.08520>

# GeoSMEFT example

2001.01453 Helset, Martin, Trott

- 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)

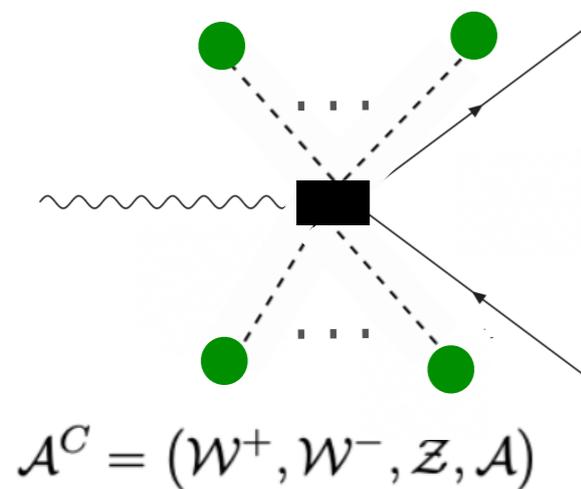
$$L_{pr,A}^{\psi_R}(\phi) (D^\mu \phi)^J (\bar{\psi}_{p,R} \gamma_\mu \sigma_A \psi_{r,R})$$

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

# GeoSMEFT example

2001.01453 Helset, Martin, Trott

- What does this allow one to do?



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

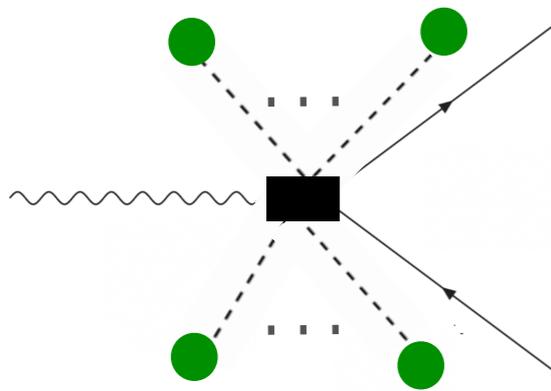
$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p \gamma_\mu \bar{\tau}_A \psi_r) \delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p \gamma_\mu \sigma_A \psi_r) \langle L_{I,A}^{\psi,pr} \rangle (-\gamma_{C,4}^I) \bar{v}_T,$$

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

# GeoSMEFT example

2001.01453 Helset, Martin, Trott

- What does this allow one to do?



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

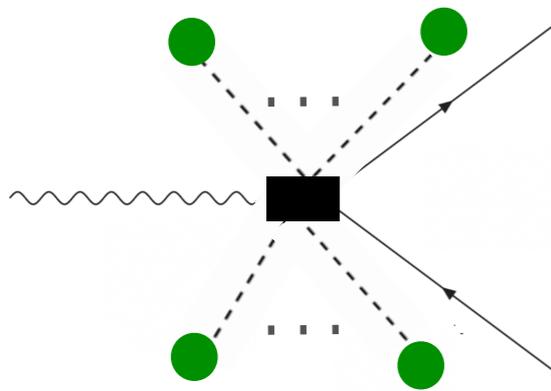
$$-\mathcal{A}^{A,\mu}(\bar{\psi}_p \gamma_\mu \bar{T}_A \psi_r) \delta_{pr} + \mathcal{A}^{C,\mu}(\bar{\psi}_p \gamma_\mu \sigma_A \psi_r) \langle L_{I,A}^{\psi,pr} \rangle (-\gamma_{C,4}^I) \bar{v}_T,$$

The coupling of the canonically normalised mass eigenstate fields is then

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

# GeoSMEFT example

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



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

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

- Two body decay widths:

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

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

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

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

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

# Need input parameters defined at all orders

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

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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

$$\bar{g}_2 = g_2 \sqrt{g^{11}} = \frac{2\hat{m}_W}{\sqrt{h_{11}} \bar{v}_T}. \quad (\text{D.1})$$

and

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

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

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

The remaining Lagrangian parameters can then be defined via

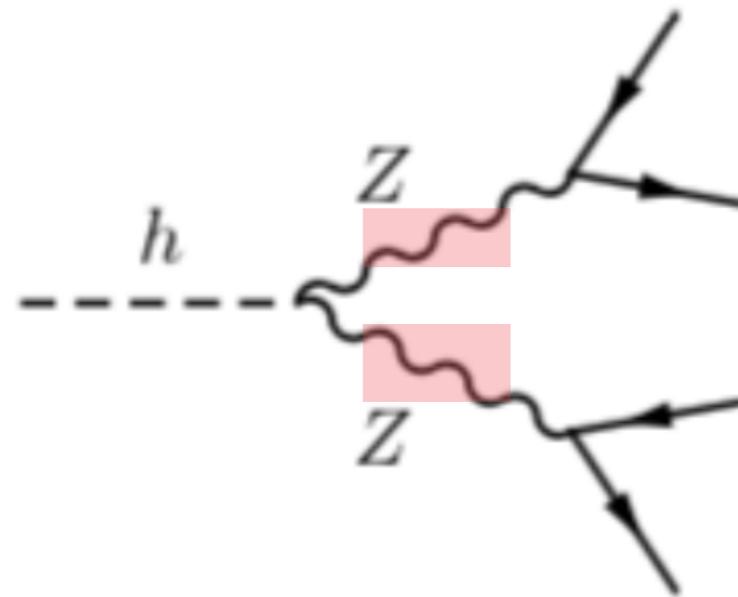
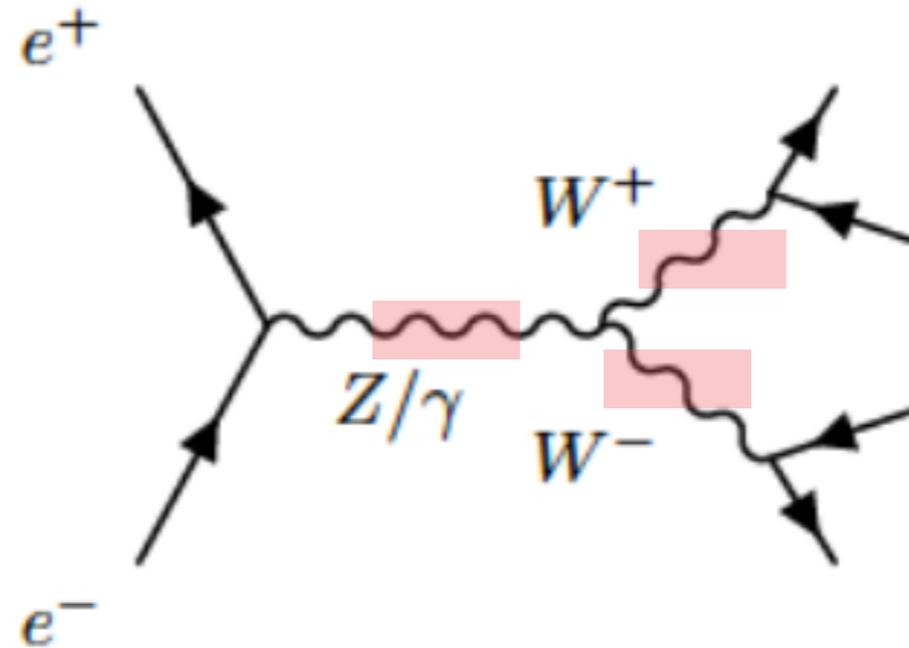
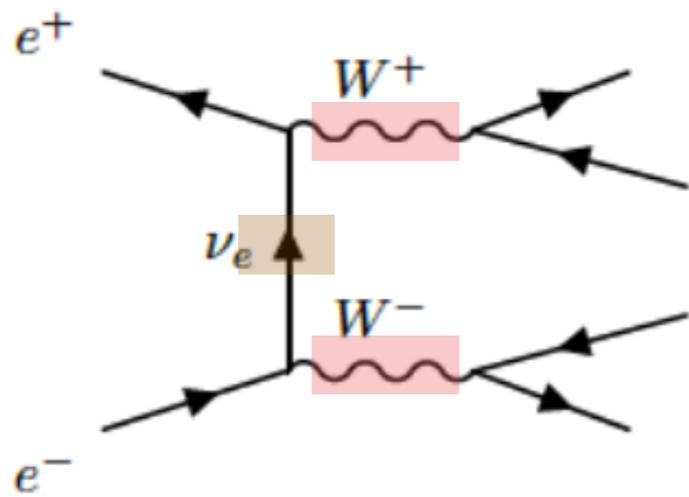
$$\bar{e} = \frac{\bar{g}_2}{\sqrt{g^{11}}} (s_{\bar{\theta}} \sqrt{g^{33}} + c_{\bar{\theta}} \sqrt{g^{34}}), \quad (\text{D.4})$$

and

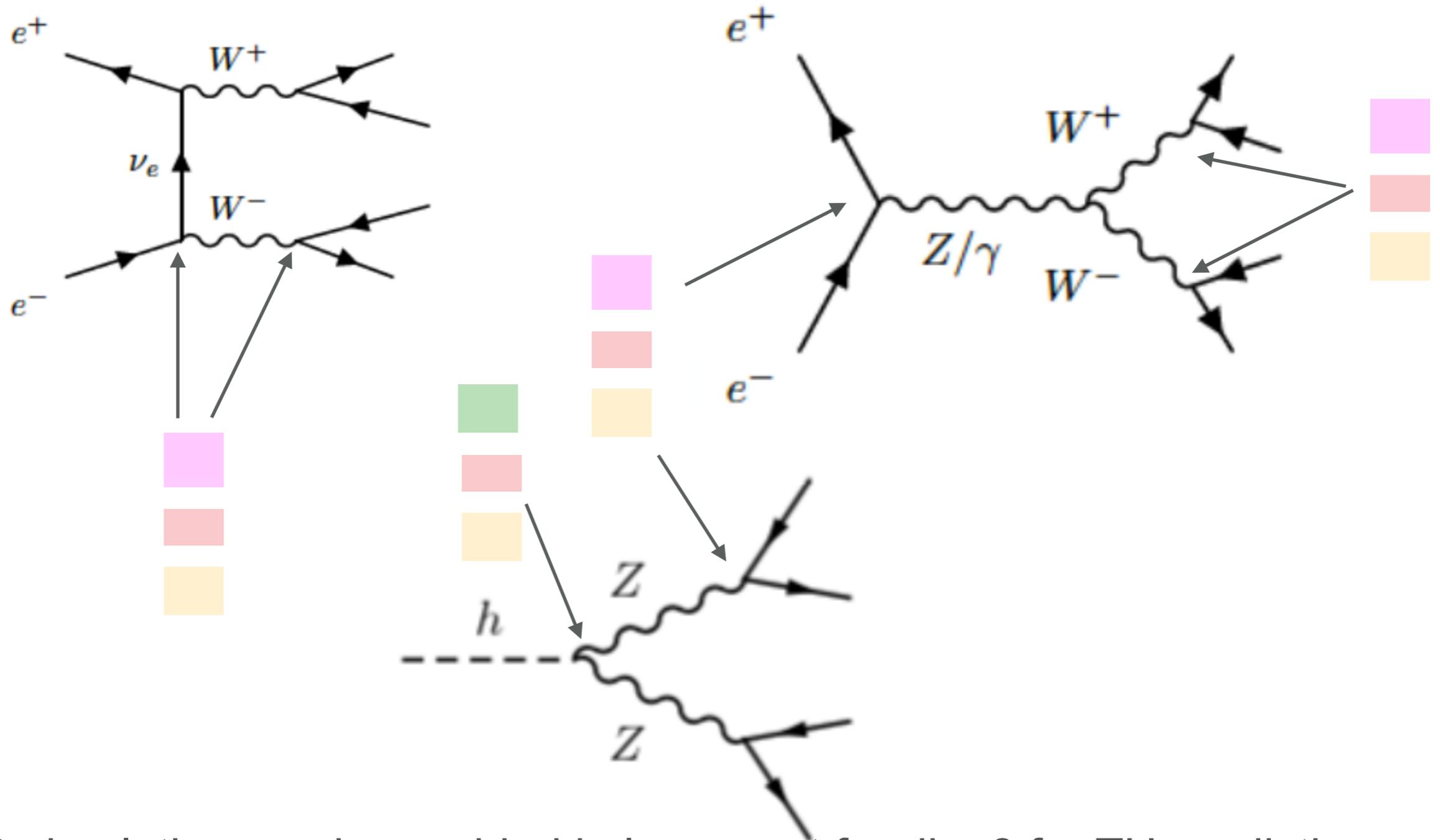
$$s_{\bar{\theta}_Z}^2 = \frac{\bar{e}}{\bar{g}_Z} \frac{(s_{\bar{\theta}} \sqrt{g^{44}} - c_{\bar{\theta}} \sqrt{g^{34}})}{(c_{\bar{\theta}} \sqrt{g^{44}} + s_{\bar{\theta}} \sqrt{g^{34}})}. \quad (\text{D.5})$$

In both schemes,  $\bar{g}_Z$  and  $s_{\bar{\theta}_Z}^2$  have the same definition in terms of other “barred” Lagrangian parameters.

# SMEFT reparameterization invariance



# Can build up processes with the info



- MC simulation can be avoided in large part for dim 8 for TH prediction Or TH error. Just rescale dim 6! -see 2106.13794

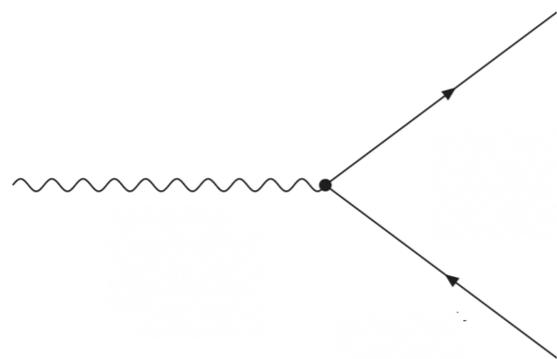
# Conclusions.

**Higgs physics is the physics  
of curved field space.**

# Current geosmeft limitations

# GeoSMEFT Pushing to higher n points

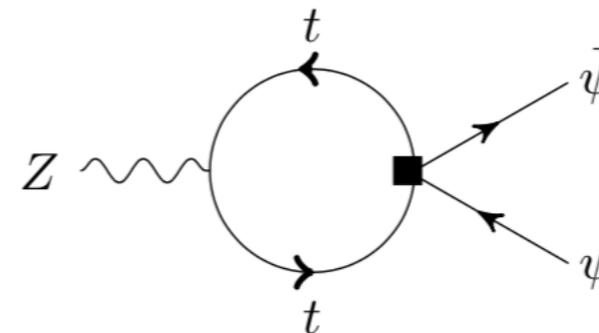
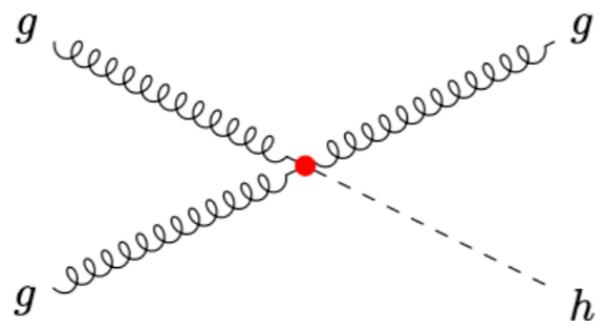
- Can build up observable quantities, such as a decay width.



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

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

- 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

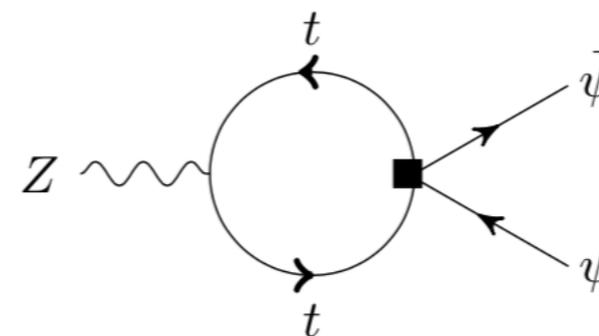
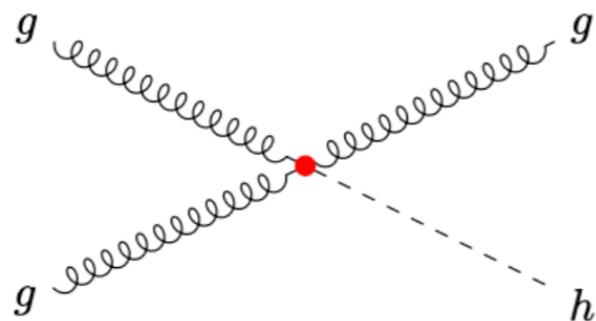
This is a non trivial fact proven for:  $F = \{H, \psi, \mathcal{W}^{\mu\nu}\}$  via the following:

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

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

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



- 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

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

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

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  $\{D_\mu \phi^I, D_{\{\mu,\nu\}} \phi^I, D_{\{\mu,\nu,\rho\}} \phi^I, \dots\}$ ,

*This is a problem for measurements away from SM resonances.*