Title: The few things we know, and some things that we are trying to understand about Higgs field spaces

Speakers: Michael Trott

Series: Quantum Fields and Strings

Date: May 30, 2023 - 2:00 PM

URL: https://pirsa.org/23050156

Abstract: It has long been known in studies of Pion physics, non-linear sigma models and cosmology that thinking in terms of field space metrics can be useful. Such an approach can help identify and define field redefinition invariant physics in observables. This approach is reemerging recently an a key organizing principle and calculational tool for interpreting collider physics data to study Higgs properties. I will review some known results and discuss outstanding issues being worked on in this area.

Zoom Link: https://pitp.zoom.us/j/96662488113?pwd=cGs0THQwWXRkcm9pVzcwVytnNjZ5Zz09

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)

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

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

In general terms: D. Volkov Sov. J. Particles Nucl. 4 (1973) 1–17.
G. A. Vilkovisky, Nucl. Phys. B234 (1984) 125.

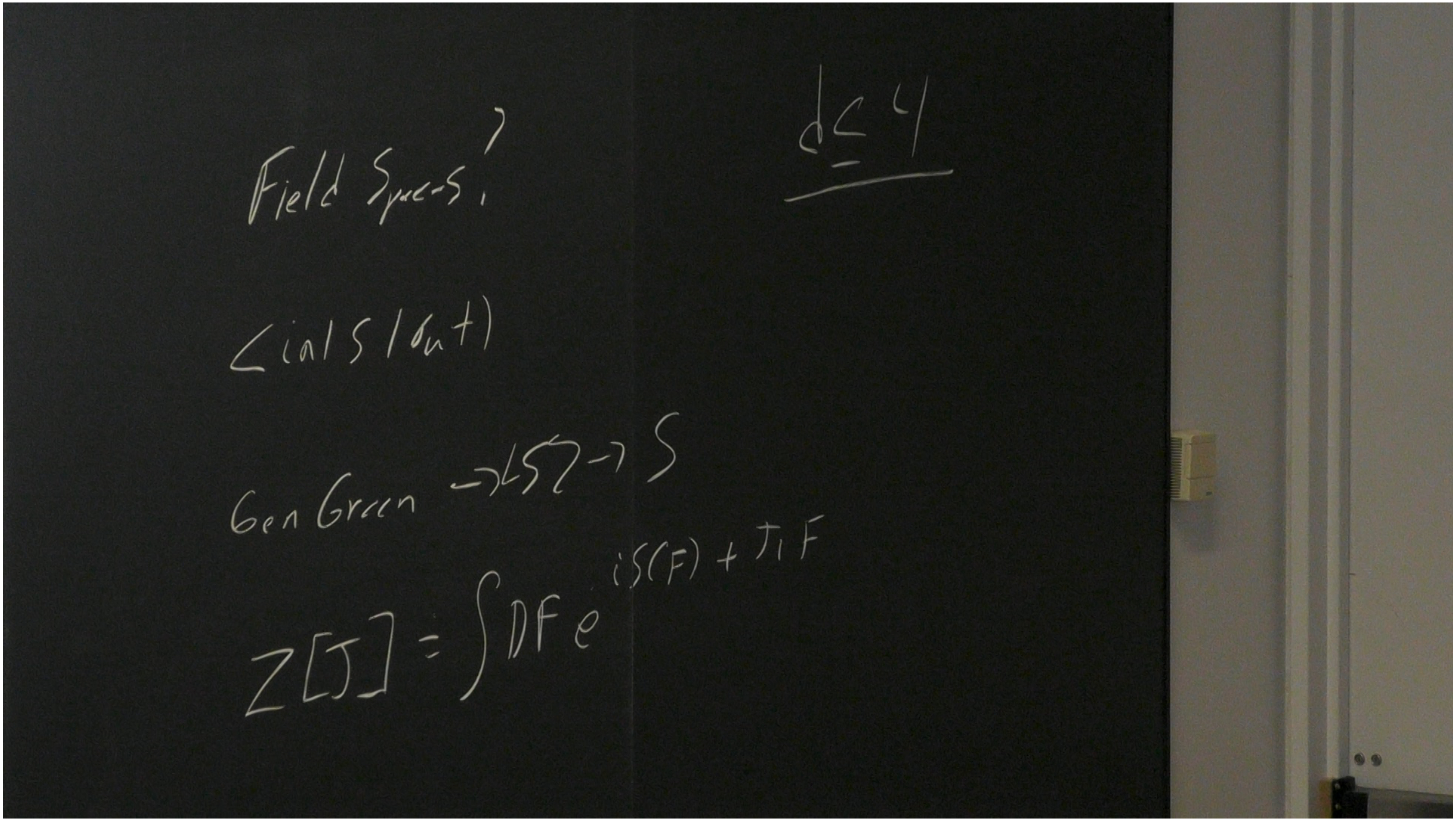
Modern uptake:

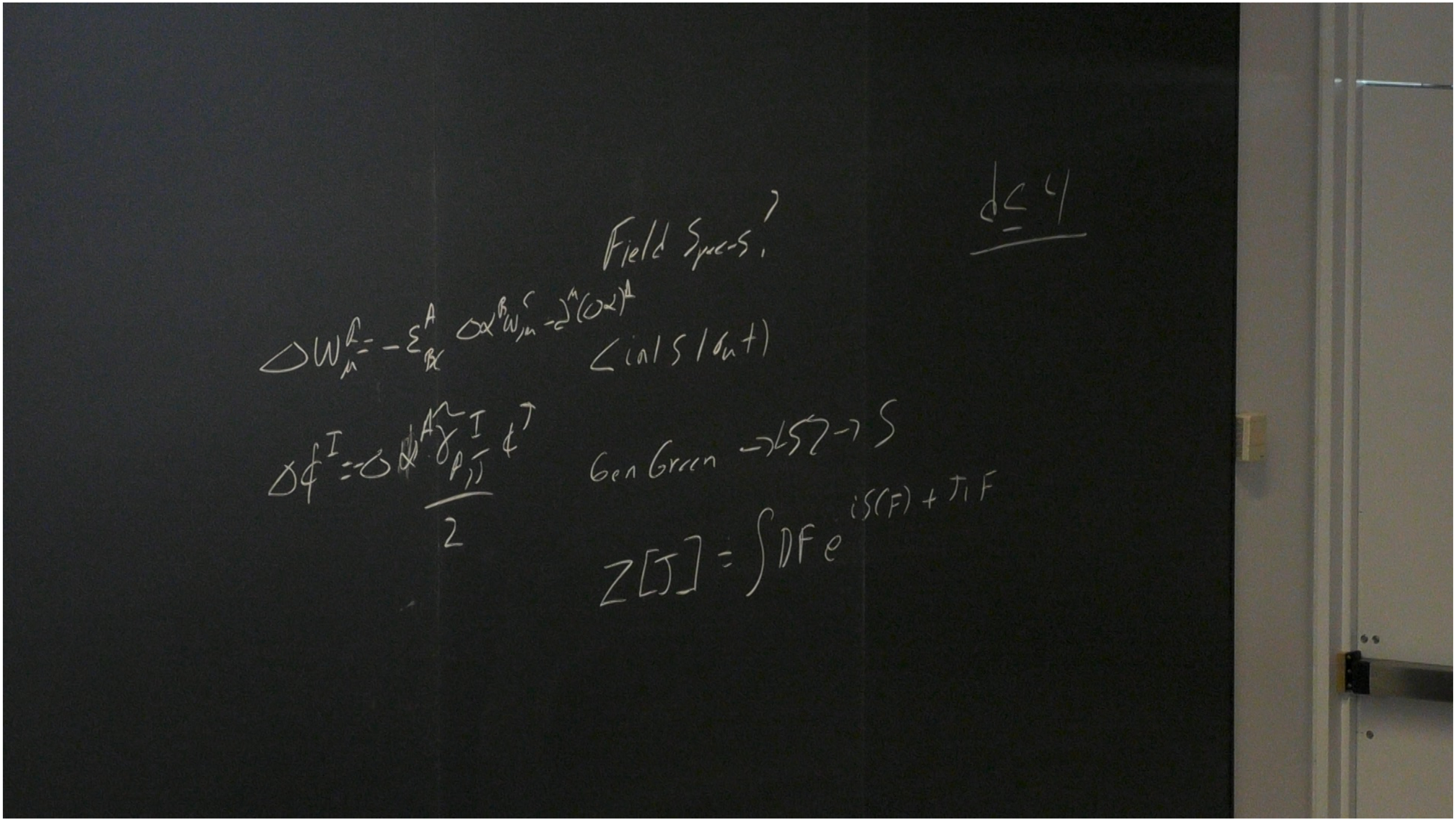
1002.2730 Burgess, Lee, Trott
1511.00724 Alonso, Jenkins, Manohar
1605.03602 Alonso, Jenkins, Manohar
1803.08001 Helset, Paraskevas, Trott.
1909.08470 Corbett, Helset, Trott

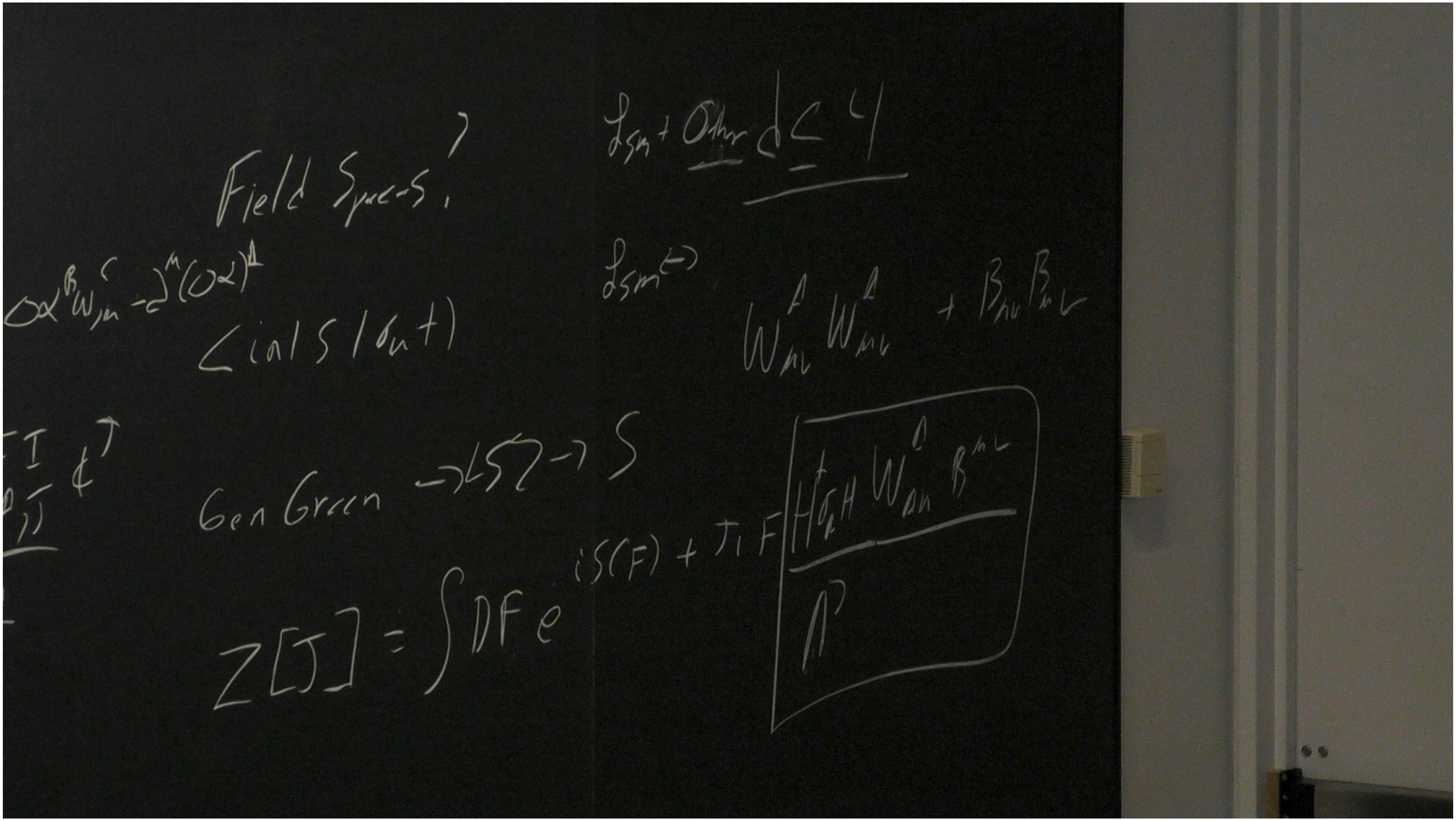
General Relativity.

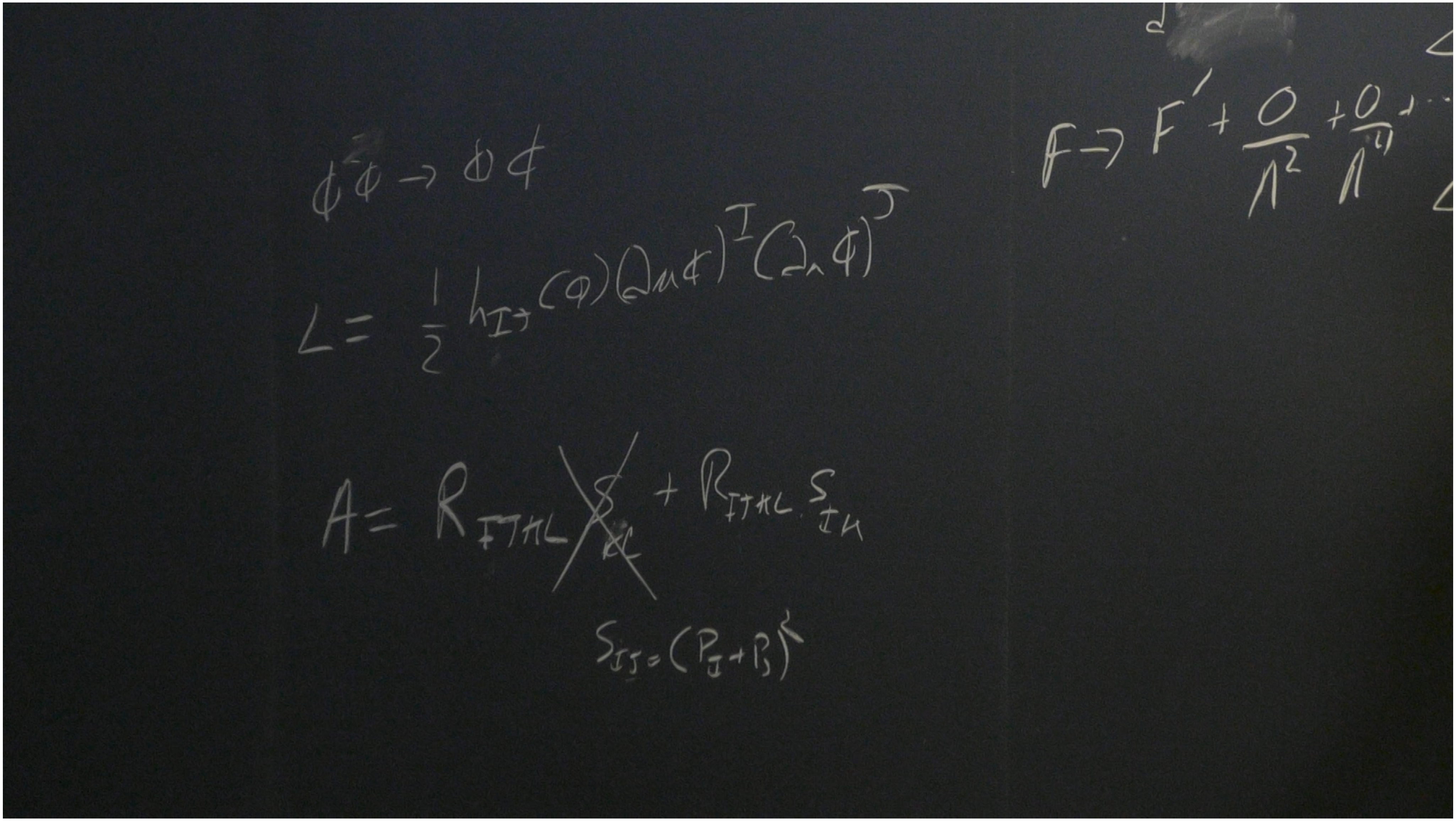
- Space-time coordinate general covariance
- Mathematical quantities: metrics, Curvature, tensors for SPACE TIME

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


Field Spaces?
d ≤ 4
⟨in|S|out⟩
Gen Green → ⟨S⟩ → S
Z[J] = ∫DF e^{iS(F) + J_i F}


Field Spaces?
d ≤ 4
⟨in|S|out⟩
Gen Green → ⟨S⟩ → S
$Z[J] = \int DF\, e^{iS(F) + J_i F}$


Field Species?
Gen Green
Z[J] = ∫DF e
iS(F) + J_i F


$\phi^I \to \phi^I$
$\mathcal{L} = \frac{1}{2} h_{IJ}(\phi)(\partial_\mu \phi)^I (\partial^\mu \phi)^J$
$A = R_{IJKL}\, S_{IK} + R_{IJKL}\, S_{IK}$
$S_{IJ} = (P_I + P_J)^2$
$F \to F' + \frac{O}{\Lambda^2} + \frac{O}{\Lambda^4} + \dots$

Basics of the pure scalar interaction geometry

- As usual: $$\Gamma^i_{jk} = \frac{1}{2} h^{il} \left(h_{jl,k} + h_{lk,j} - h_{jk,l} \right)$$

$$R_{ijkl} = h_{im} \left(\partial_k \Gamma^m_{lj} - \partial_l \Gamma^m_{kj} + \Gamma^m_{kn} \Gamma^n_{lj} - \Gamma^m_{ln} \Gamma^n_{kj} \right)$$

- For pure scalar metric (ungauged) case can go to Riemannian normal coordinates $$\mathcal{L} = \frac{1}{2} h_{ij} \partial_\mu \phi^i \partial_\mu \phi^j$$

Then $\Gamma^i_{jk}, \Gamma^i_{jk \cdots n}$ Vanish evaluated at origin.

So can expand metric in terms of R.

K. Meetz, J. Math. Phys. 10 (1969) 589–593.
1002.2730 Burgess, Lee, Trott
1511.00724 Alonso, Jenkins, Manohar
1605.03602 Alonso, Jenkins, Manohar
2111.03045 Cheung, Helset, Parra-Maritinez
2108.03240 Cohen, Craig, Lu, Sutherland

Field coord. invariance leads to field space geometry

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

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

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

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

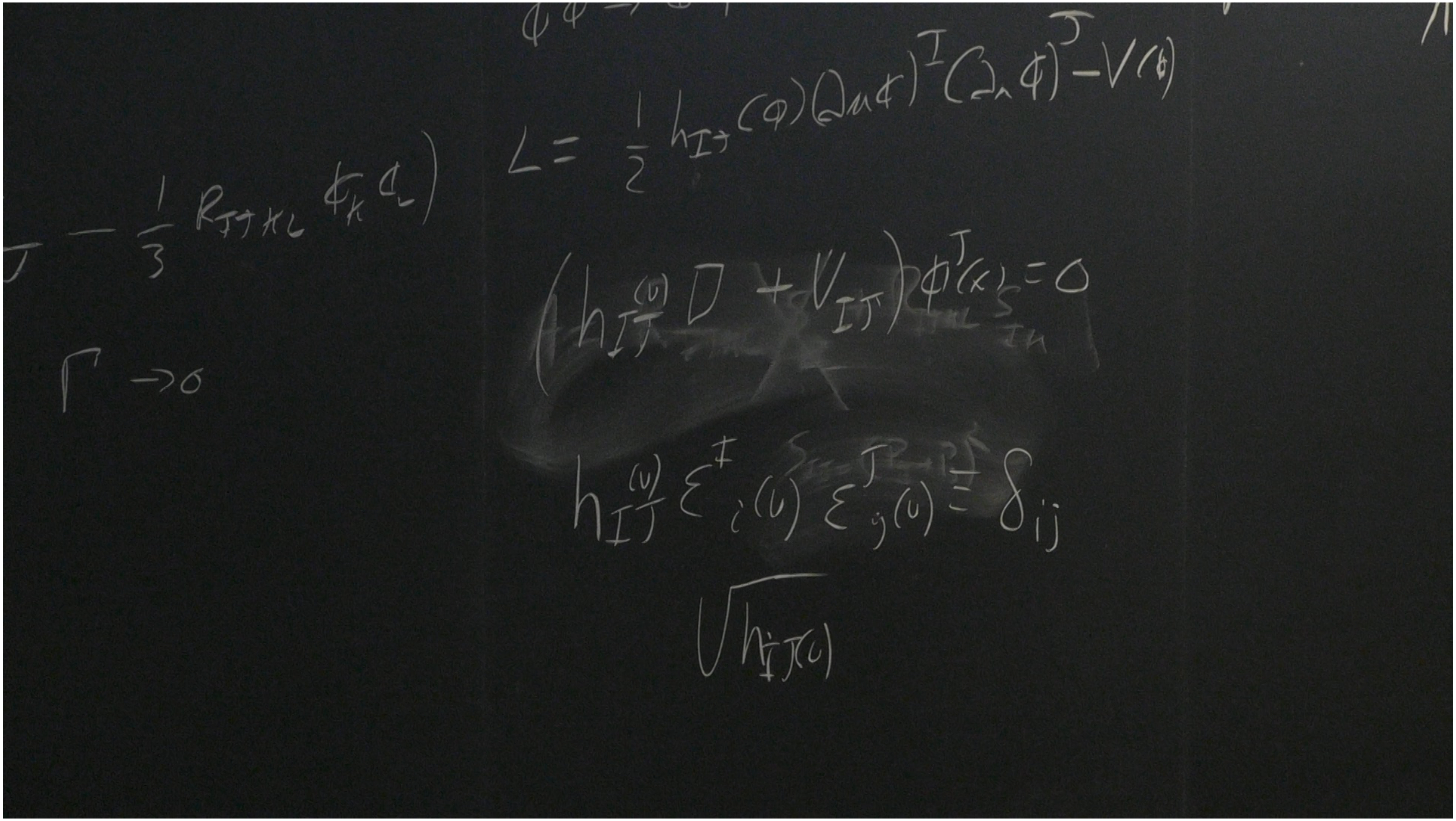
(Small perturbations so positive semi-definite matrix and unique square root)

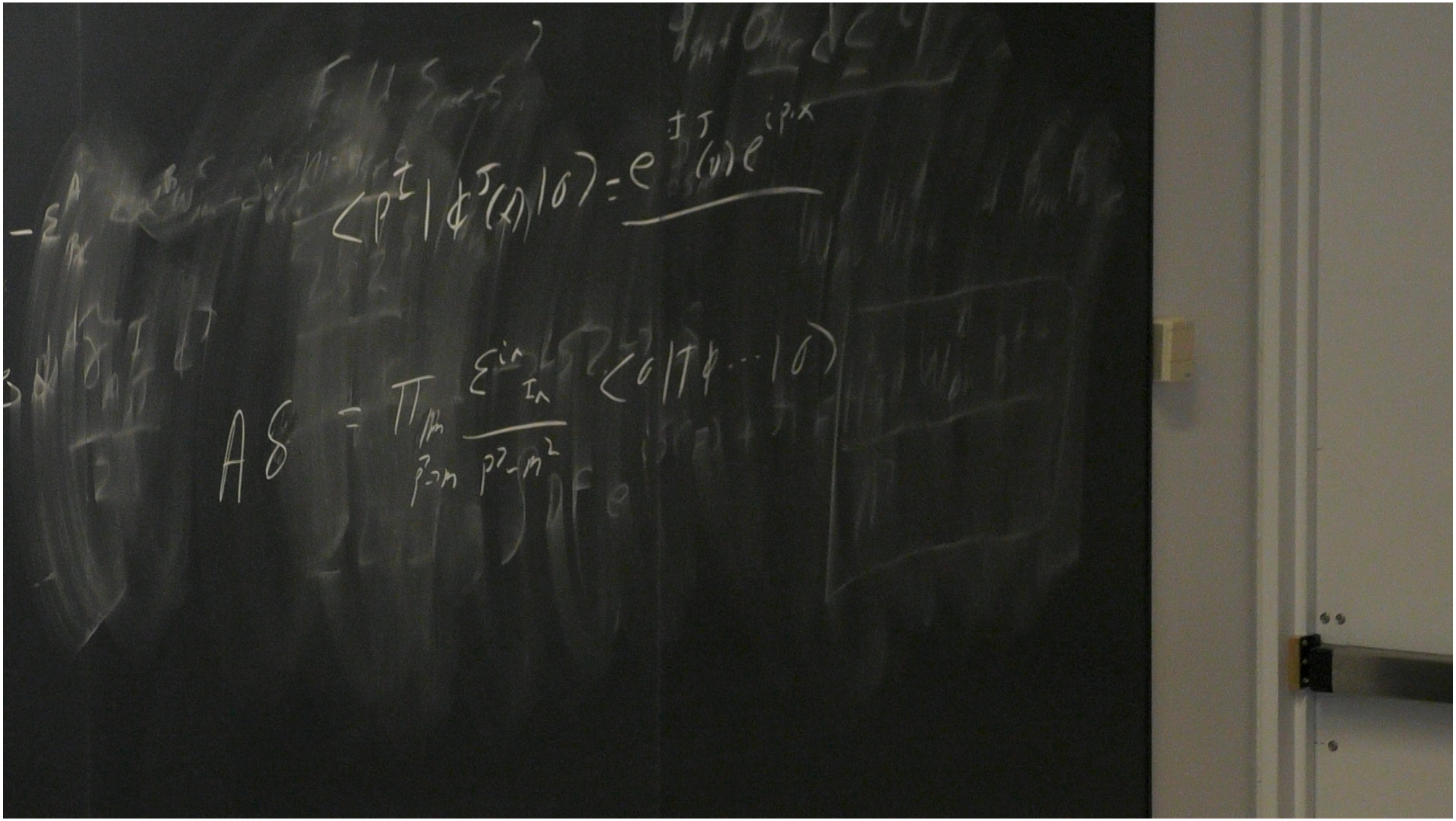
- Geometric field space quantities are useful (True independent of mass dimension of ops)
  Amp. perturb. are:

Fun. of 4 vectors (kinematics)

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

Defined by field space geometries


L = 1/2 h_IJ(φ)(∂_μ φ)^I (∂^μ φ)^J − V(φ)
− 1/3 R_IJKL φ^K φ^L)
(h_IJ^(0) □ + V_IJ) φ^J(x) = 0
Γ → 0
h_IJ^(0) ε^I_i(0) ε^J_j(0) = δ_ij
√h_IJ(0)



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:

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

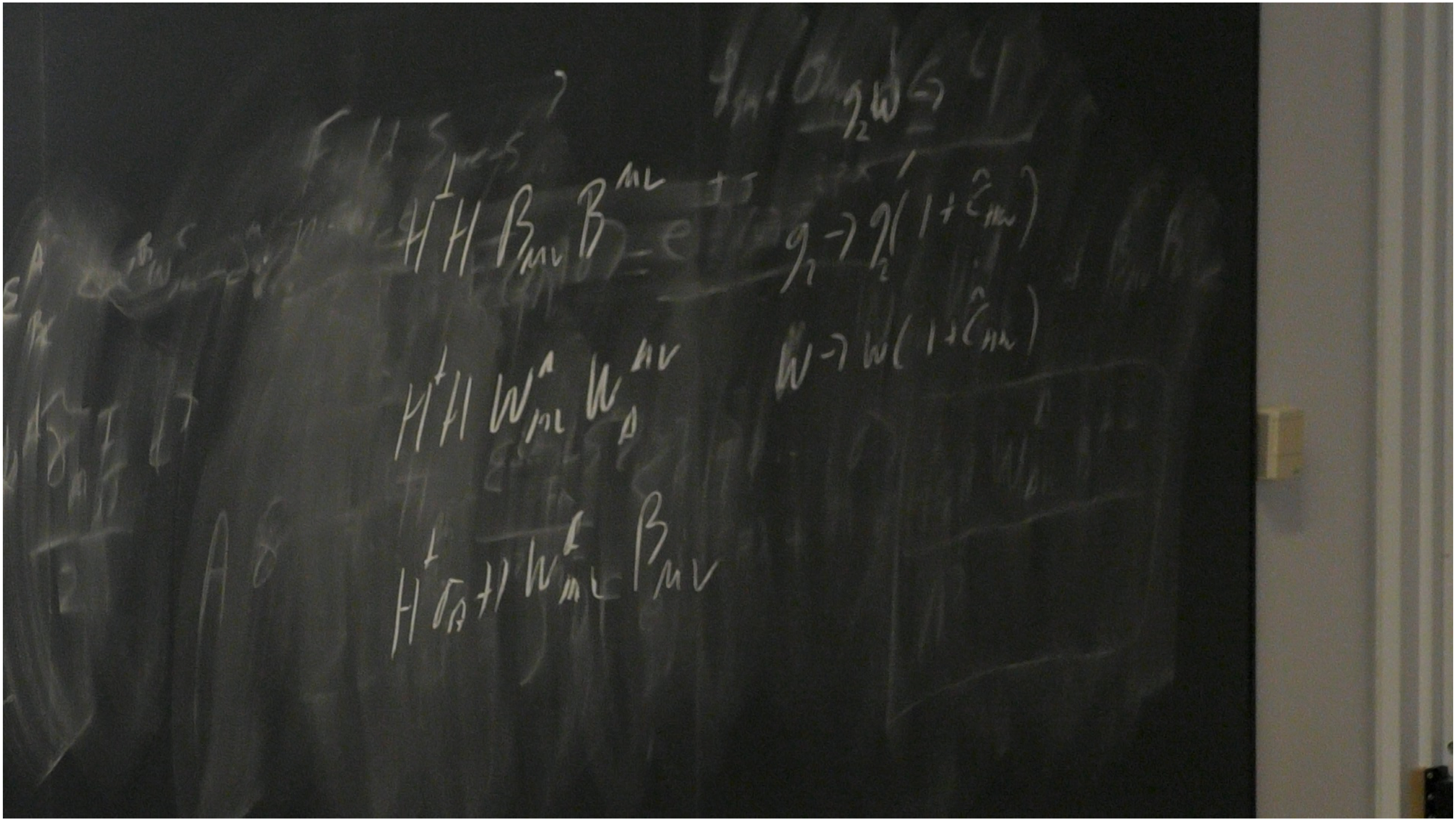
$$\overline{e} = \frac{\overline{g}_1 \overline{g}_2}{\sqrt{\overline{g}_2{}^2 + \overline{g}_1{}^2}} \left[1 - \frac{\overline{g}_1 \overline{g}_2}{\overline{g}_2{}^2 + \overline{g}_1{}^2} v_T^2 C_{HWB}\right]$$

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

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

1312.2014 Alonso, Jenkins, Manohar, Trott

- Note the complications are proportional to the vev.


H†H B_{μν} B^{μν}
g_1 → g_1(1+ε̂_{μν})
H†H W^A_{μν} W^{μν}_A
W → W(1+ε̂_{μν})
H† σ_A H W^A_{μν} B_{μν}

SM weak-mass eigenstate relations

- Weak eigenstates — Mass eigenstate

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

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

Rotations

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

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

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

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

What else could you write?

Dim 6 SMEFT EW Lagrangian terms

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

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

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

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

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

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

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

All orders SM Lagrangian parameters

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

1909.08470 Corbett, Helset, Trott

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

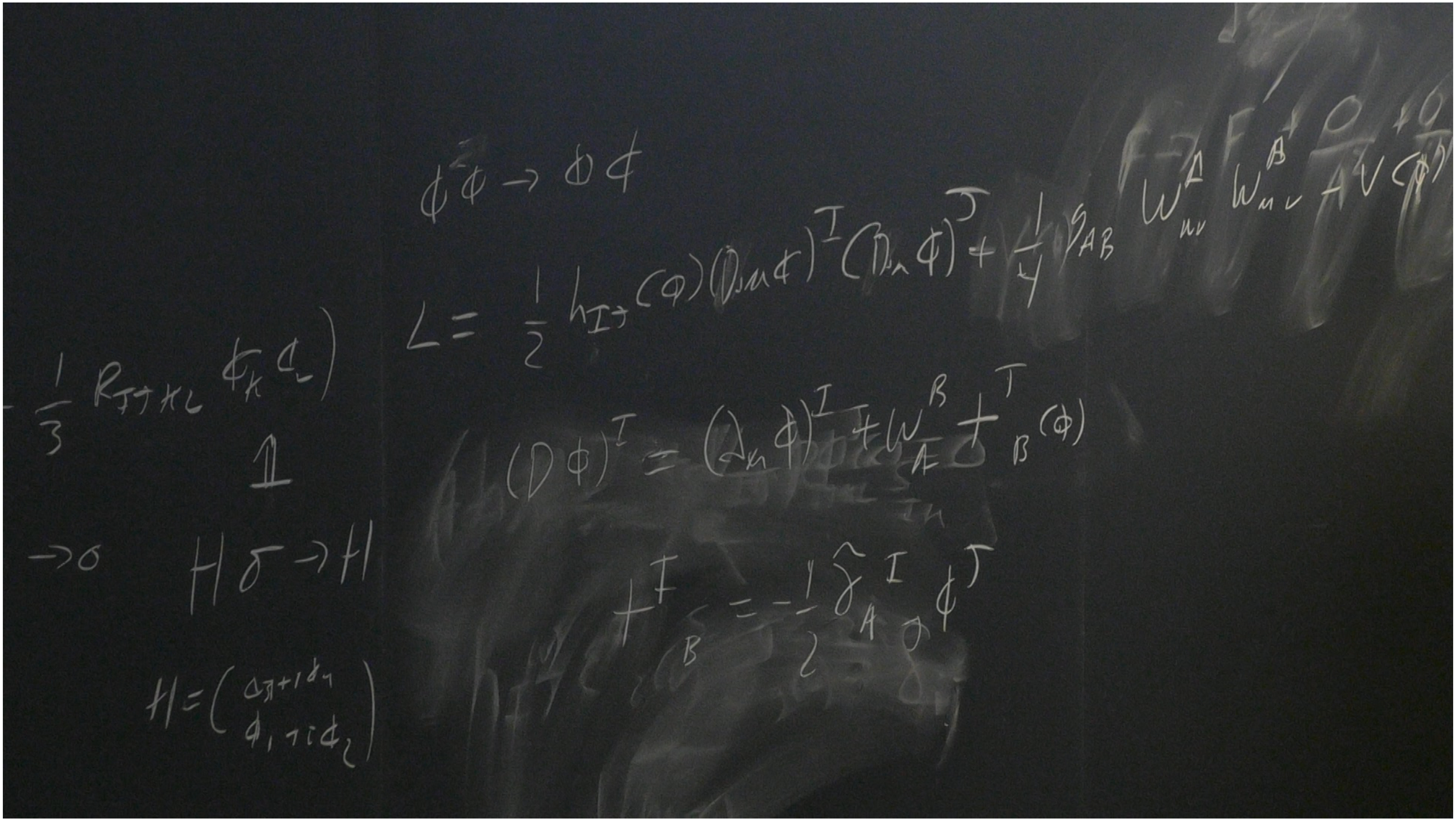
- Masses

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

- Mixing angles:

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

(Interesting way to think of the Weinberg angle)



All orders 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

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

- Mixing angles:

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

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

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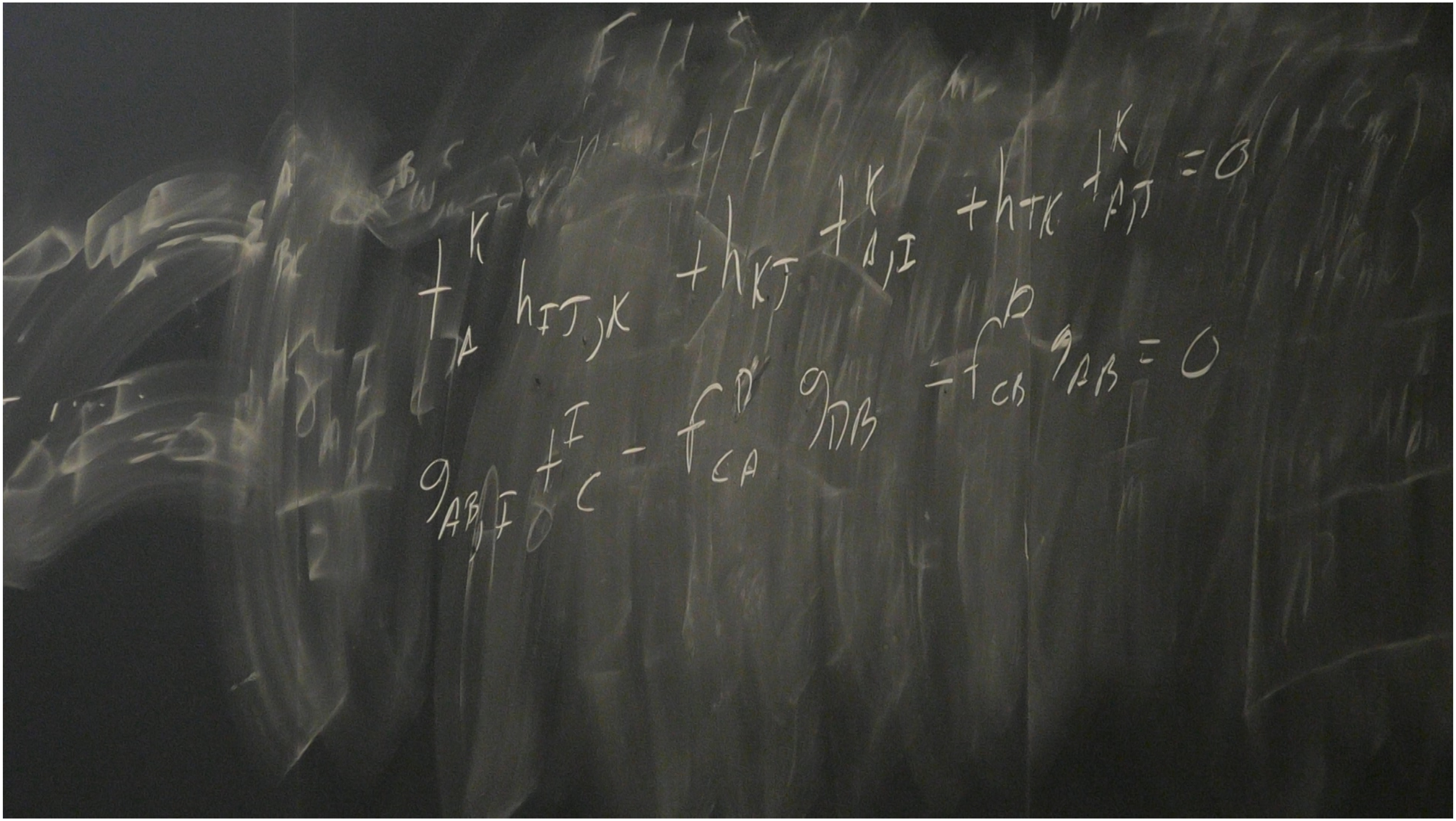

$f_A^K h_{IJ,K} + h_{KJ} f_{A,I}^K + h_{IK} f_{A,J}^K = 0$
$g_{AB,I} f_C^I - f_{CA}^D g_{DB} - f_{CB}^D g_{AB} = 0$

All orders expressions are known now

2001.01453 Helset, Martin, Trott

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

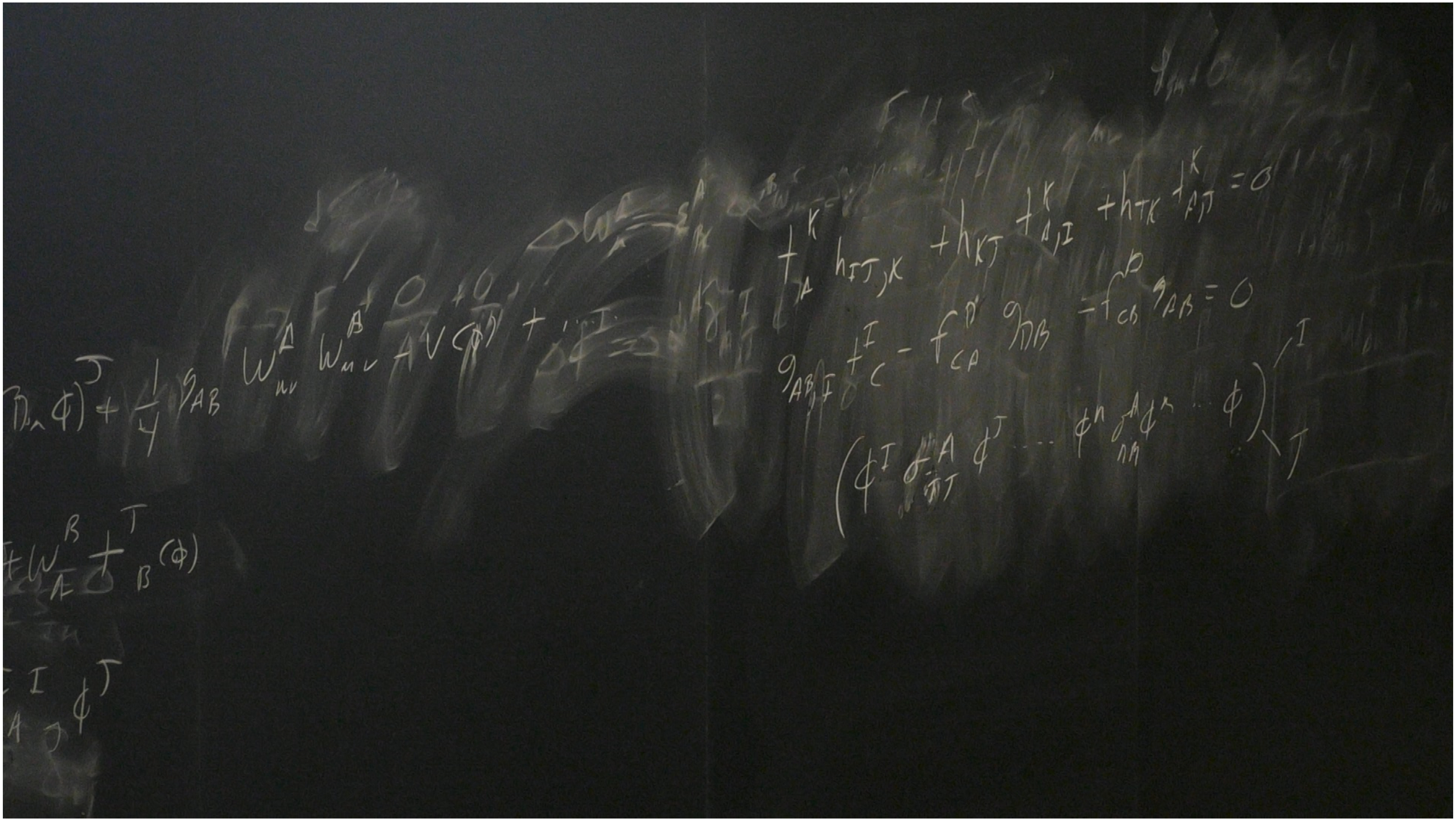
$$h_{IJ} = \left[1 + \phi^2 C^{(6)}_{H\Box} + \sum_{n=0}^{\infty}\left(\frac{\phi^2}{2}\right)^{n+2}\left(C^{(8+2n)}_{HD} - C^{(8+2n)}_{H,D2}\right)\right]\delta_{IJ} + \frac{\Gamma^I_{A,J}\phi_K\Gamma^K_{A,L}\phi^L}{2}\left(\frac{C^{(6)}_{HD}}{2} + \sum_{n=0}^{\infty}\left(\frac{\phi^2}{2}\right)^{n+1}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

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

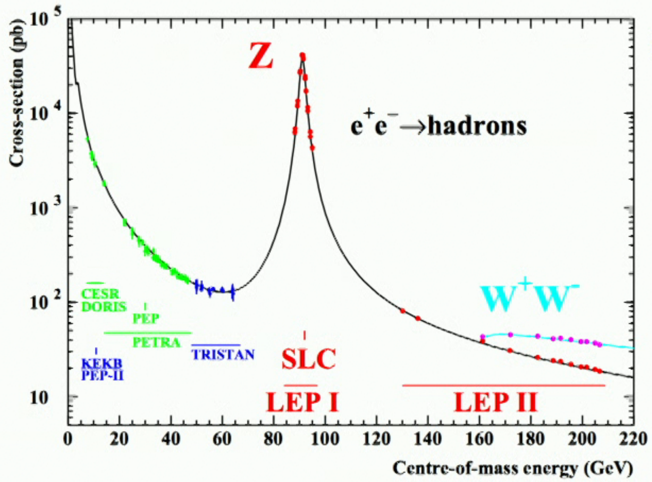
$$g_{AB}(\phi_I) = \left[1 - 4\sum_{n=0}^{\infty}\left(C^{(6+2n)}_{HW}(1-\delta_{A4}) + C^{(6+2n)}_{HB}\delta_{A4}\right)\left(\frac{\phi^2}{2}\right)^{n+1}\right]\delta_{AB} - \sum_{n=0}^{\infty} C^{(8+2n)}_{HW,2}\left(\frac{\phi^2}{2}\right)^n\left(\phi_I\Gamma^I_{A,J}\phi^J\right)\left(\phi_L\Gamma^L_{B,K}\phi^K\right)(1-\delta_{A4})(1-\delta_{B4})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

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

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



LEP EWPD measurements in SMEFT



- EWPD is a scan through the Z pole

$\sim 40\, pb^{-1}$ off peak data

$\sim 155\, pb^{-1}$ on peak data

Simultaneous PO fit to

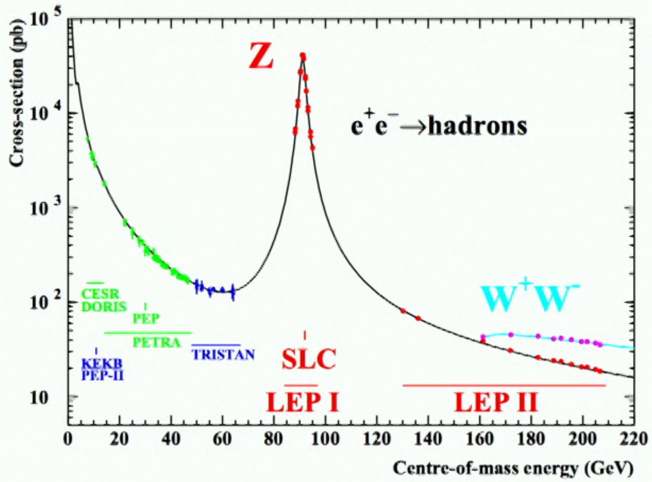
$$\sigma^Z_{\bar{f}f} = \sigma^{peak}_{\bar{f}f} \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

Peak shape is fit to:

$$\sigma^{peak}_{\bar{f}f} = \frac{\sigma^0_{\bar{f}f}}{R_{QED}} \qquad \sigma^0_{\bar{f}f} = \frac{12\pi\,\Gamma_{ee}\,\Gamma_{\bar{f}f}}{m_Z^2\,\Gamma_Z^2} \qquad R^0_\ell = \frac{\Gamma_{had}}{\Gamma_\ell}$$

Parameters extracted: $(m_Z^2, \Gamma_Z, R^0_\ell, \sigma^0_{had})$

LEP EWPD measurements in SMEFT



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$$\sigma^Z_{\bar{f}f} = \sigma^{peak}_{\bar{f}f} \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$$

Using geoSMEFT we have masses and widths to all orders

$$\langle \bar{\Gamma}_i^{\rm SMEFT} \rangle = \hat{\Gamma}_i^{\rm SM} + \langle \bar{\Gamma}_i \rangle_{\mathcal{O}(v^2/\Lambda^2)} + \langle \bar{\Gamma}_i \rangle_{\mathcal{O}(v^4/\Lambda^4)} + \dots$$

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

EWPD done to dim 8 …. ***for first time*** …in three weeks!

2102.02819 Corbett, Helset, Martin, Trott

Gauging the SMEFT/renorm

Aside on the BFM

Abbott Acta Phys.Polon.B 13 (1982) 33

- Here we are gauge fixing in the BFM: $F \to \hat{F} + F$

  Double the fields, introduce background fields that have gauge sym unbroken when gauge fixing quantum fields

$$\mathcal{L}_{GF} = -\frac{1}{2\,\xi_W}\sum_a \left[\partial_\mu W^{a,\mu} - g_2\,\epsilon^{abc}\hat{W}_{b,\mu}W^\mu_c + i\,g_2\,\frac{\xi}{2}\left(\hat{H}^\dagger_i\sigma^a_{ij}H_j - H^\dagger_i\sigma^a_{ij}\hat{H}_j\right)\right]^2, \\ -\frac{1}{2\,\xi_B}\left[\partial_\mu B^\mu + i\,g_1\,\frac{\xi}{2}\left(\hat{H}^\dagger_i H_i - H^\dagger_i\hat{H}_i\right)\right]^2.$$

From the gauge fixing term, choosing $\xi_B = \xi_W$, one directly finds

$$\mathcal{L}_{GF} = -\frac{1}{2\,\xi}\left[(G^A)^2 + (G^Z)^2 + 2\,G^+\,G^-\right],$$

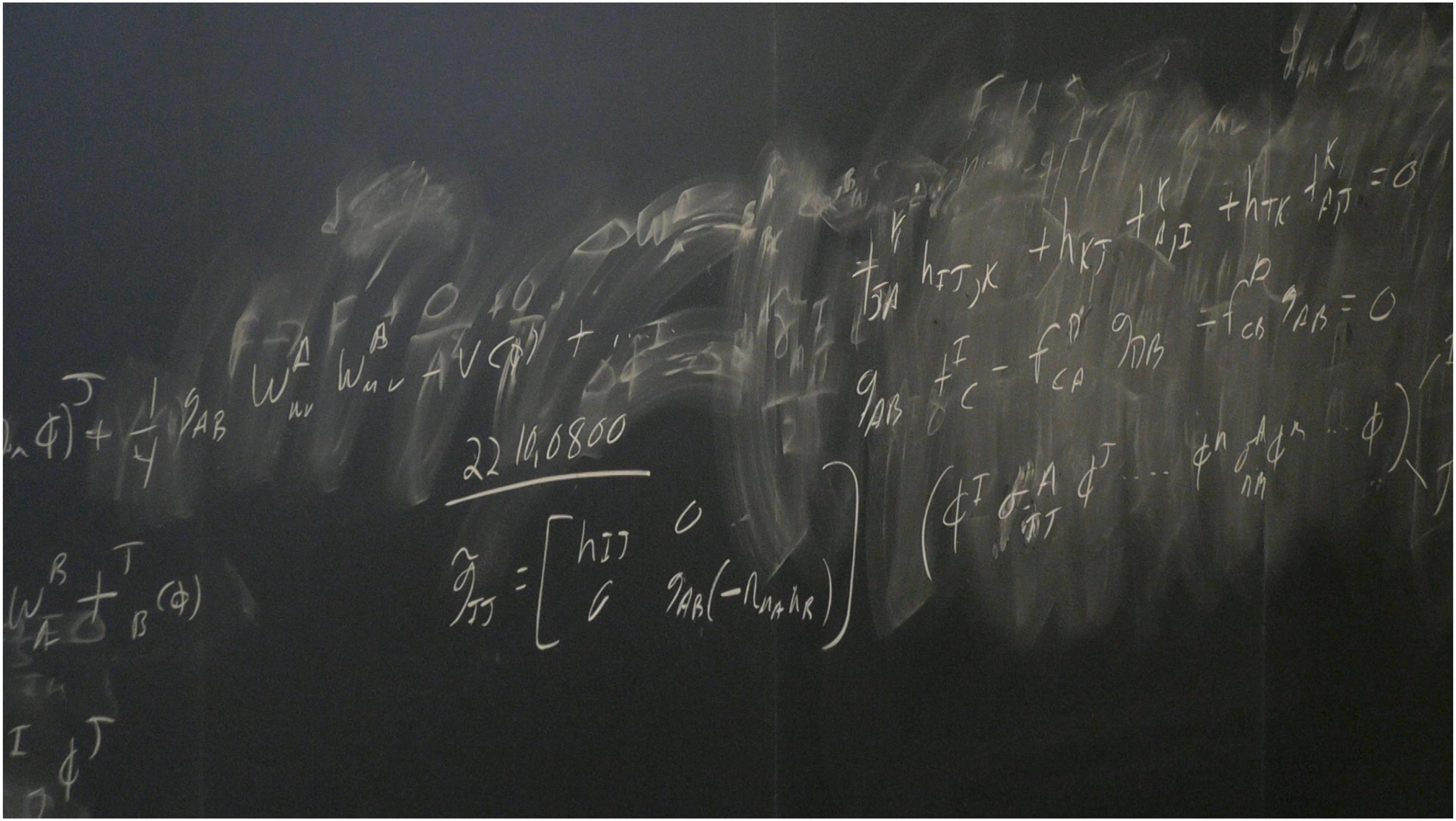
Counter terms then gauge Invariant. t'Hooft, Veltmann *Nucl.Phys.B* 44 (1972) 189-213

where

$$G^A = \partial_\mu A^\mu + ie\left(\hat{W}^+_\mu W^-_\mu - W^+_\mu\hat{W}^-_\mu\right) + ie\,\xi\left(\hat{\phi}^-\phi^+ - \hat{\phi}^+\phi^-\right),$$

$$G^Z = \partial_\mu Z^\mu + ie\frac{c_w}{s_w}\left(\hat{W}^+_\mu W^-_\mu - W^+_\mu\hat{W}^-_\mu\right) + ie\xi\frac{1}{2c_w\,s_w}(c_w^2 - s_w^2)\left(\hat{\phi}^-\phi^+ - \hat{\phi}^+\phi^-\right), \\ -e\,\xi\frac{1}{2\,c_w s_w}\left(\hat{\phi}_0\,h - \hat{h}\phi_0 - v\phi_0\right),$$

$$G^\pm = \partial^\mu W^\pm_\mu \pm i\,e\left[\hat{A}^\mu + \frac{c_w}{s_w}\,\hat{Z}^\mu\right]W^\pm_\mu \mp ie\left(A^\mu + \frac{c_w}{s_w}Z^\mu\right)\hat{W}^\pm_\mu, \\ -e\,\xi\,\frac{1}{2s_w}\left((v + \hat{h} \mp i\hat{\phi}_0)\phi^\pm - (h \mp i\phi_0)\hat{\phi}^\pm\right).$$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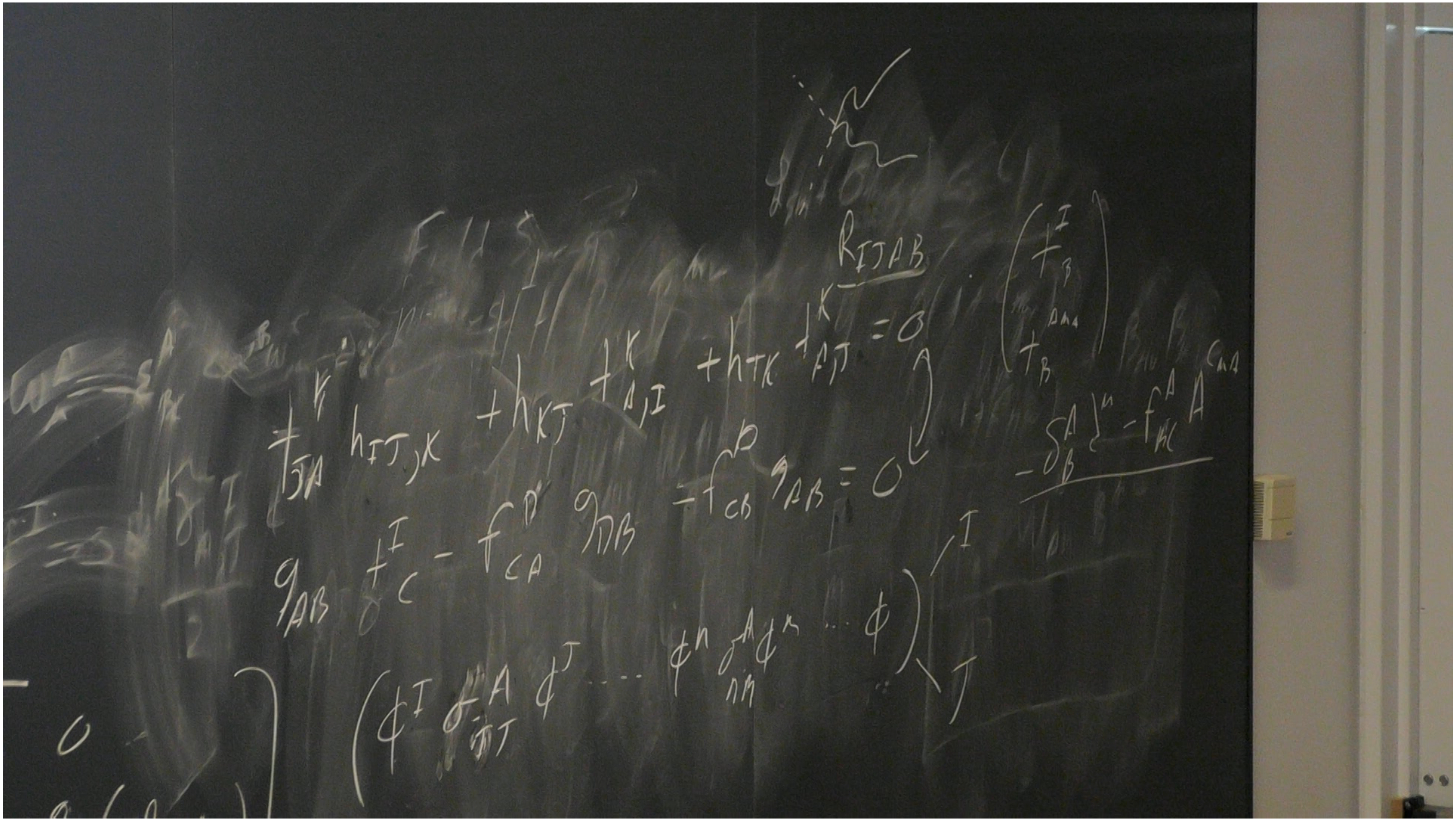
RIJAB

Aside on the BFM

Abbott Acta Phys.Polon.B 13 (1982) 33

- Here we are gauge fixing in the BFM: $F \to \hat{F} + F$

  Double the fields, introduce background fields that have gauge sym unbroken when gauge fixing quantum fields

$$\mathcal{L}_{GF} = -\frac{1}{2\,\xi_W}\sum_a \left[\partial_\mu W^{a,\mu} - g_2\,\epsilon^{abc}\hat{W}_{b,\mu}W_c^\mu + i\,g_2\,\frac{\xi}{2}\left(\hat{H}_i^\dagger\sigma_{ij}^a H_j - H_i^\dagger\sigma_{ij}^a\hat{H}_j\right)\right]^2,$$
$$-\frac{1}{2\,\xi_B}\left[\partial_\mu B^\mu + i\,g_1\,\frac{\xi}{2}\left(\hat{H}_i^\dagger H_i - H_i^\dagger\hat{H}_i\right)\right]^2.$$

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$$G^Z = \partial_\mu Z^\mu + ie\frac{c_w}{s_w}\left(\hat{W}_\mu^+ W_\mu^- - W_\mu^+\hat{W}_\mu^-\right) + ie\xi\frac{1}{2c_w\,s_w}(c_w^2 - s_w^2)\left(\hat{\phi}^-\phi^+ - \hat{\phi}^+\phi^-\right),$$
$$-\,e\,\xi\frac{1}{2\,c_w s_w}\left(\hat{\phi}_0\,h - \hat{h}\phi_0 - v\phi_0\right),$$
$$G^\pm = \partial^\mu W_\mu^\pm \pm i\,e\left[\hat{A}^\mu + \frac{c_w}{s_w}\,\hat{Z}^\mu\right]W_\mu^\pm \mp ie\left(A^\mu + \frac{c_w}{s_w}Z^\mu\right)\hat{W}_\mu^\pm,$$
$$-\,e\,\xi\,\frac{1}{2s_w}\left((v + \hat{h} \mp i\hat{\phi}_0)\phi^\pm - (h \mp i\phi_0)\hat{\phi}^\pm\right).$$

Counter terms then gauge Invariant. t'Hooft, Veltmann *Nucl.Phys.B* 44 (1972) 189-213

SMEFT gauge fixing solution!

- Problem: contact operators change mass and weak eigenstate relationship as seen. This can be understood as a "curved field space" due to the contact operators. So we should gauge fix the correctly redefined field. We need the tetrads.

- Solution:define a gauge fixing term on the "curved field space"

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

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

$$\int \mathcal{D}F \det\left[\frac{\Delta\mathcal{G}^A}{\Delta\alpha^B}\right] e^{i\left(S[F+\hat{F}]+\mathcal{L}_{\rm GF}+\hat{g}_{CD}J^C_\mu\mathcal{W}^{D,\mu}+\hat{h}_{IJ}J^I_\phi\phi^J\right)}.$$

arXiv:1803.08001 Helset, Paraskevas, Trott

SMEFT gauge fixing solution!

$$\mathcal{L}_{\rm scalar,kin} = (D_\mu H)^\dagger (D^\mu H) + C_{H\Box} (H^\dagger H) \Box (H^\dagger H) + C_{HD} (H^\dagger D_\mu H)^* (H^\dagger D^\mu H), \qquad \equiv \frac{1}{2} h_{IJ}(\phi) (D_\mu \phi)^I (D^\mu \phi)^J .$$

$$\mathcal{L}_{\rm WB} = -\frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{C_{HB}}{\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{C_{HW}}{\Lambda^2} H^\dagger H W^a_{\mu\nu} W^{a,\mu\nu} + \frac{C_{HWB}}{\Lambda^2} H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}, \qquad \equiv -\frac{1}{4} g_{AB}(H) \mathcal{W}^A_{\mu\nu} \mathcal{W}^{B,\mu\nu},$$

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

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

$$\int \mathcal{D}F \det \left[\frac{\Delta \mathcal{G}^A}{\Delta \alpha^B}\right] e^{i\left(S[F+\hat{F}] + \mathcal{L}_{\rm GF} + \hat{g}_{CD} J^C_\mu \mathcal{W}^{D,\mu} + \hat{h}_{IJ} J^I_\phi \phi^J\right)}.$$

$$\gamma^I_{1,J} = \begin{bmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, \quad \gamma^I_{2,J} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \quad \gamma^I_{3,J} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad \gamma^I_{4,J} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

Michael Trott

Another geoSMEFT clue

Goes back to arXiv:1505.02646 Hartmann, Trott

$$-\frac{c_w\, s_w}{\xi_B\, \xi_W}(\xi_B - \xi_W)\,(\partial^\mu A_\mu\, \partial^\nu Z_\nu) - \frac{C_{HWB} v^2 (s_w^2 - c_w^2)(s_w^2 \xi_B + c_w^2 \xi_W)}{\xi_B\, \xi_W}\,(\partial^\mu A_\mu\, \partial^\nu Z_\nu)\,.$$

The geometric BFM gauge fixing cancels this mixing at all orders in the vev expansion! Exactly as it should be. ***You need to gauge fix geometrically to have the usual BFM benefits.***

GeoSMEFT based loop corrections?

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

Immediate BFM Ward Identities have already been derived/verified:

1909.08470 Corbett, Helset, Trott

2010.08451 Corbett, Trott

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

Background field gauge transformation

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

$$0 = \partial^\mu \frac{\delta^2 \Gamma}{\delta \hat{\mathcal{A}}^{3\mu} \delta \hat{\mathcal{A}}^{Y\nu}} - \bar{M}_Z \frac{\delta^2 \Gamma}{\delta \hat{\Phi}^3 \delta \hat{\mathcal{A}}^{Y\nu}},$$

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

Second order variation of action

$$\mathcal{X} = \begin{bmatrix} [\mathcal{X}_{\eta\eta}]^I{}_J & [\mathcal{X}_{\eta\zeta}]^I{}_{(B\mu_B)} \\ [\mathcal{X}_{\eta\zeta}]^{(A\mu_A)}{}_J & [\mathcal{X}_{\zeta\zeta}]^{(A\mu_A)}{}_{(B\mu_B)} \end{bmatrix}$$

$$\left[\widetilde{\mathscr{D}}_\mu, \widetilde{\mathscr{D}}_\nu\right]^A{}_B = [\mathcal{Y}_{\mu\nu}]^A{}_B = \widetilde{R}^A{}_{BKL}(D_\mu\phi)^K(D_\nu\phi)^L + \widetilde{\nabla}_B \tilde{t}^A_C F^C_{\mu\nu}$$
$$= \widetilde{R}^A{}_{BKL}(D_\mu\phi)^K(D_\nu\phi)^L - f^A{}_{CB}F^C_{\mu\nu} + \Gamma^A_{LB}t^L_C F^C_{\mu\nu}\,.$$

2212.03253 Helset, Jenkins, Manohar

- Where after lie derivatives used action variation can be beat into form:

$$\delta_{\eta\eta}S = \frac{1}{2}\int d^4x \left\{h_{IJ}\left(\widetilde{\mathscr{D}}_\mu\eta\right)^I\left(\widetilde{\mathscr{D}}_\mu\eta\right)^J + \left[-\widetilde{R}_{IKJL}(D_\mu\phi)^K(D^\mu\phi)^L - (\nabla_I\nabla_J V)\right.\right.$$
$$\left.\left. - \frac{1}{4}\left(\widetilde{\nabla}_I\nabla_J g_{AB}\right)F^{A\mu\nu}F^B_{\mu\nu} - t_{IA}t^B_J\right]\eta^I\eta^J\right\}.$$

$$\delta_{\eta\zeta}S = \int d^4x \left\{\left[2(\nabla_I t_{JA}) + t^B_I(\nabla_J g_{AB}) - \frac{1}{2}t^B_J(\nabla_I g_{AB})\right](D_{\mu_A}\phi)^J\right.$$
$$\left. + \left(-\widetilde{R}_{(A\mu_A)I(B\mu_B)J} + 2\widetilde{R}_{IJ(A\mu_A)(B\mu_B)}\right)F^{B\mu_B\rho}(D_\rho\phi)^J\right\}\eta^I\zeta^{A\mu_A}$$

$$\delta_{\zeta\zeta}S = \frac{1}{2}\int \mathrm{d}^4x \left\{-g_{AB}\,\eta_{\mu_A\mu_B}(\widetilde{\mathscr{D}}_\mu\zeta)^{A\mu_A}(\widetilde{\mathscr{D}}^\mu\zeta)^{B\mu_B}\right.$$
$$+ \left[t_{IA}t^I_B\eta_{\mu\nu} - \widetilde{R}_{I(A\mu)J(B\nu)}(D_\alpha\phi)^I(D^\alpha\phi)^J + \frac{1}{2}g_{AB,I}\left((\widetilde{\mathscr{D}}_\mu D_\nu\phi)^I + (\widetilde{\mathscr{D}}_\nu D_\mu\phi)^I\right)\right.$$
$$+ \left(\nabla_I\nabla_J g_{AB} - g_{AD,I}g^{DG}g_{GB,J}\right)(D_\mu\phi)^I(D_\nu\phi)^J$$
$$+ \frac{1}{2}\left(g_{DB}f^D{}_{CA} - g_{DA}f^D{}_{CB} + 2g_{CD}f^D{}_{AB}\right)F^C_{\mu\nu} - \frac{1}{4}g_{DB,K}h^{KL}g_{CA,L}F^C_{\alpha\mu}F^D_{\alpha\nu}$$
$$\left.\left. + \frac{1}{8}h^{IM}g_{AB,M}g_{CD,I}F^C_{\alpha\beta}F^{D\alpha\beta}\eta_{\mu\nu} + \frac{1}{2}h^{IM}g_{AB,M}V_{,I}\eta_{\mu\nu}\right]\zeta^{A\mu}\zeta^{B\nu}\right\}.$$

- Here cov deriv and killing vectors are

$$\widetilde{\mathscr{D}}_\mu \begin{bmatrix}\eta^I \\ \zeta^A_\lambda\end{bmatrix} = \partial_\mu \begin{bmatrix}\eta^I \\ \zeta^A_\lambda\end{bmatrix} + \begin{bmatrix} t^I_{C,J}A^C_\mu + \Gamma^I_{LJ}(D_\mu\phi)^L & -\Gamma^I_{CB}F^C_{\mu\sigma} \\ \Gamma^A_{CJ}F^C_{\mu\lambda} & -f^A{}_{CB}A^C_\mu\eta_{\lambda\sigma} + \Gamma^A_{LB}(D_\mu\phi)^L\eta_{\lambda\sigma}\end{bmatrix}\begin{bmatrix}\eta^J \\ \zeta^B_\sigma\end{bmatrix},$$

$$\tilde{t}^i_B = \begin{bmatrix} t^I_B \\ -\delta^A_B\partial_{\mu_A} + f^A{}_{CB}A^C_{\mu_A}\end{bmatrix}.$$

$$\frac{1}{32\pi^2\epsilon}\left(\frac{1}{T_2}\,\mathrm{Tr}\left[Y_\mu Y^{\mu\nu}\right] + \frac{1}{2}\,\mathrm{Tr}(\chi^2)\right)$$

$$X^I{}_K = -R^I{}_{JKL}\,(D_\mu\phi)^J(D\phi)^L + g^{IJ}\,I_{JK}$$

GeoSMEFT based loop corrections.

- Further generalisation: 2212.03253 Helset, Jenkins, Manohar

$$S_{\rm g.f.} = -\frac{1}{2}\int {\rm d}^4x \; g_{AB}\mathcal{G}^A\mathcal{G}^B \,,$$

$$\begin{aligned}\mathcal{G}^A &= (\widetilde{\mathscr{D}}_\mu \zeta)^{A\mu} + \frac{1}{2} g^{AC} g_{CB,I} (D_\mu\phi)^I \zeta^{B\mu} - h_{IJ} g^{AB} t_B^J \eta^I \\ &= (\widetilde{\mathscr{D}}_\mu \zeta)^{A\mu} + \Gamma^A_{IB} (D_\mu\phi)^I \zeta^{B\mu} - t_I^A \eta^I \,.\end{aligned}$$

Where

$$\left(\widetilde{\mathscr{D}}_\mu \zeta\right)^{(A\mu_A)} = (D_\mu \zeta^{\mu_A})^A + \Gamma^A_{IB} (D_\mu\phi)^I \zeta^{B\mu_A} + \Gamma^A_{BI} F_\mu^{B\;\mu_A} \eta^I \,.$$

Generalisation used to clean up expressions and cancel cross term
In fluctuations, as well as lie derivative clean up

Cool running expressions for these also derived

$$\frac{d(\tilde{\nabla}_I \nabla_J g_{AB})}{d\log\mu} \qquad \frac{dR_{IKJL}}{d\log\mu}$$

Simple all orders results for the vev expansion

- Glue Glue higgs

$$\langle h|\mathcal{G}\mathcal{G}\rangle = -\frac{\sqrt{h}^{44}}{4}\langle h\,\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu}\rangle\frac{\delta\kappa_{AA}}{\delta\phi_4}$$

- Higgs to gamma gamma

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

- Where the geometric electric charge is $\bar{e} = g_2\left(s_{\bar{\theta}}\sqrt{g}^{33} + c_{\bar{\theta}}\sqrt{g}^{34}\right)$

$$s_{\bar{\theta}}^2 = \frac{(g_1\sqrt{g}^{44} - g_2\sqrt{g}^{34})^2}{g_1^2[(\sqrt{g}^{34})^2 + (\sqrt{g}^{44})^2] + g_2^2[(\sqrt{g}^{33})^2 + (\sqrt{g}^{34})^2] - 2g_1g_2\sqrt{g}^{34}(\sqrt{g}^{33} + \sqrt{g}^{44})}.$$

An instant pay off of "geoSMEFT"

- 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
$g_{AB}(\phi)\mathcal{W}^A_{\mu\nu}\mathcal{W}^{B,\mu\nu}$	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

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