# Higgs decay to two Photons (in the SMEFT to one loop.)

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“Absence of evidence is not evidence of absence.” -The BSM physics mantra.

# SUMMARY

- The signal $h \to \gamma\gamma$ is a very powerful probe of Higgs substructure

  An amazing probe of the point-like "elementary" nature of the $J^p = 0^+$ scalar

- A consistent field theory of deviations in place to one loop in this signal (SMEFT) to interpret very small deviations in this observable. (this talk)

- We can gain maximum benefit from even small improvements in precision in bounds on anomalous $h \to \gamma\gamma$. I am personally begging you for every fraction of a precent in accuracy you can get.

# SUMMARY

- The signal $h \to \gamma\gamma$ is a very powerful probe of Higgs substructure

  An amazing probe of the point-like "elementary" nature of the $J^p = 0^+$ scalar

- 

  Work reported here is the result reported in the excellent Ph.D. thesis of C Hartmann. Well done!

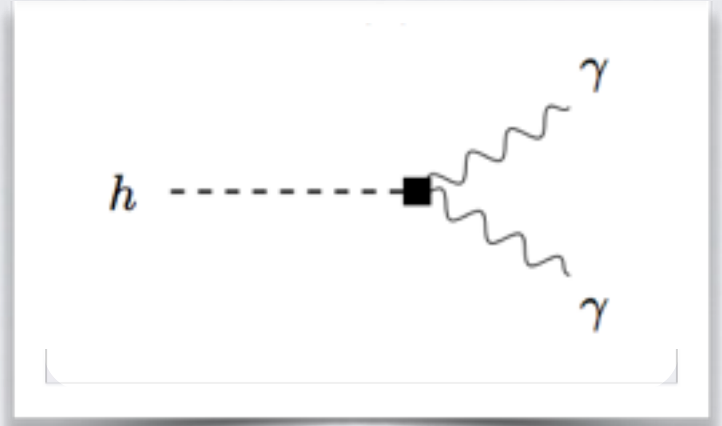
  arXiv:1505.02646 C. Hartmann, MT JHEP 1507 (2015) 151

  arXiv:1507.03568 C. Hartmann, MT Phys.Rev.Lett. 115 (2015) no.19, 191801

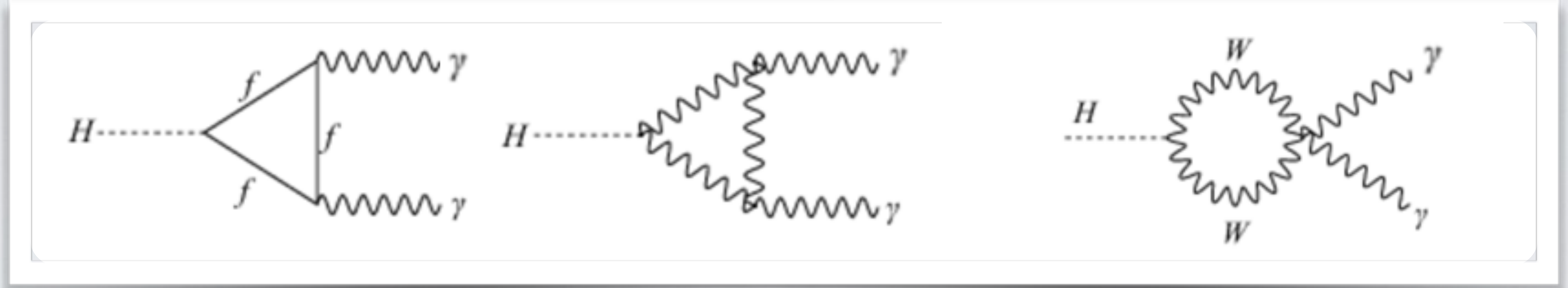
- Overlap with results reported in

  arXiv:1505.03706 M. Ghezzi et al, JHEP 1507 (2015) 175

# Precision on $\frac{\Gamma_{meas}(h \to \gamma\,\gamma)}{\Gamma_{SM}(h \to \gamma\,\gamma)}$ matters.




- In the SM, at one loop due to a renormalizability:

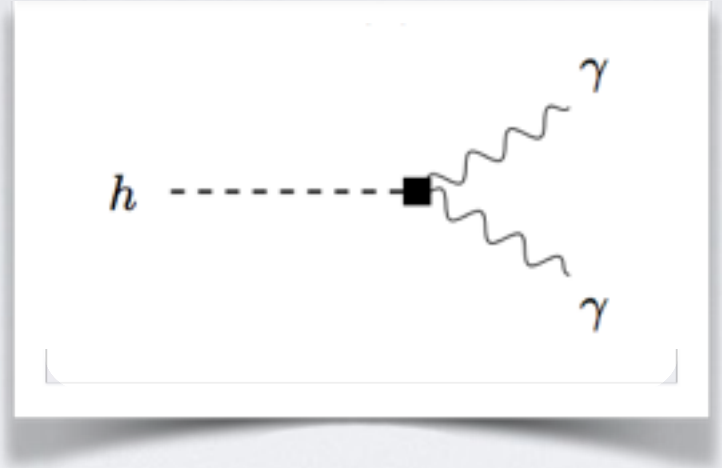



Lorentz indicies: $A^{\alpha\,\beta}_{h\gamma\,\gamma} = \langle h|h\, A^{\sigma\,\rho} A_{\sigma\,\rho}|\gamma(p_a\,\alpha)\,\gamma(p_b\,\beta)\rangle$

$$i\,\mathcal{A} = \frac{i g_2\, e^2}{16\,\pi^2 m_W} \int_0^1 dx \int_0^{1-x} dy \left( \frac{-4m_W^2 + 6xym_W^2 + x\,ym_h^2}{m_W^2 - xymh^2} + \Sigma_f\, N_c\, Q_f\, \frac{m_f^2(1-4xy)}{m_f^2 - xym_h^2} \right) A^{\alpha\,\beta}_{h\gamma\,\gamma}\, \epsilon_\alpha\, \epsilon_\beta$$


J. R. Ellis, M. K. Gaillard and D.V. Nanopoulos, Nucl. Phys. B 106 (1976) 292;
M. A. Shifman, A. I. Vainshtein, M. B. Voloshin and V. I. Zakharov, Sov. J. Nucl. Phys. 30 (1979) 711 [Yad. Fiz. 30 (1979) 1368].

# Precision on $\frac{\Gamma_{meas}(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)}$ matters.




- Full SM two loop result also known:

Complete two-loop QCD corrections to one-loop top contribution
Djouadi et al Phys. Lett. B 257, 187 (1991), Phys. Rev. D 47 (1993) 1264,Phys. Lett. B 311 (1993) 255
Melnikov et al Phys. Lett. B 312 (1993) + …

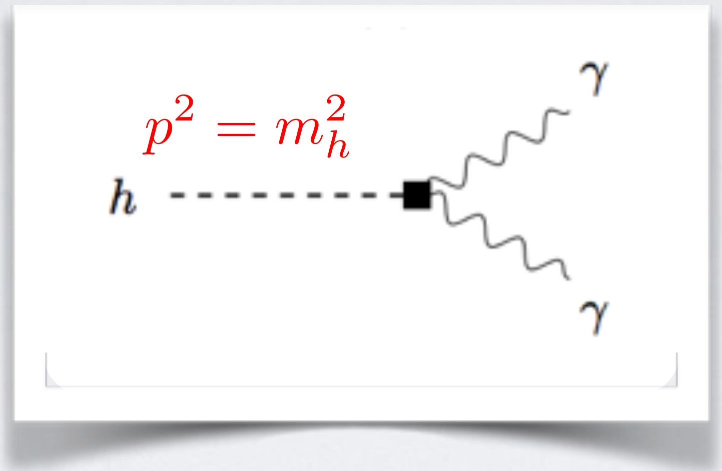
Two-loop electroweak corrections evaluated in the large top-mass
Djouadi et al arXivhep-ph/9712330, Liao at al. arXivhep-ph/9605310

Two-loop contribution induced by the light fermions
Aglietti et al arXivhep-ph/0404071, arXivhep-ph/0407162

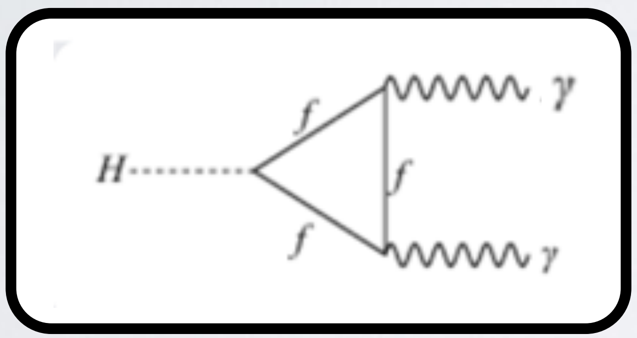
Two-loop electroweak corrections involving the weak bosons
Degrassi, Maltoni arXivhep-ph/0504137

- Two loop shift of one loop result $|\Delta_{EW} + \Delta_{QCD}| \sim 1.5\%$
- If deviations show up at the few % level, can be possible signal of BSM.

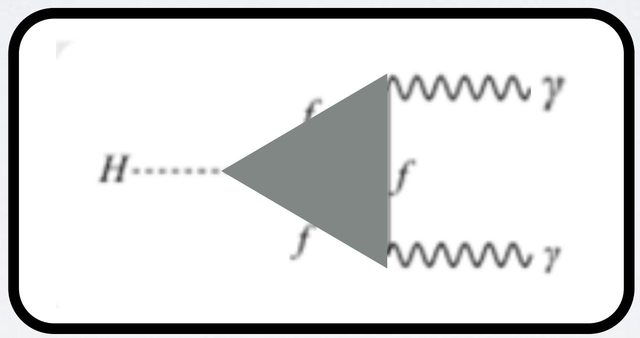
# Precision on $\frac{\Gamma_{meas}(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)}$ matters.



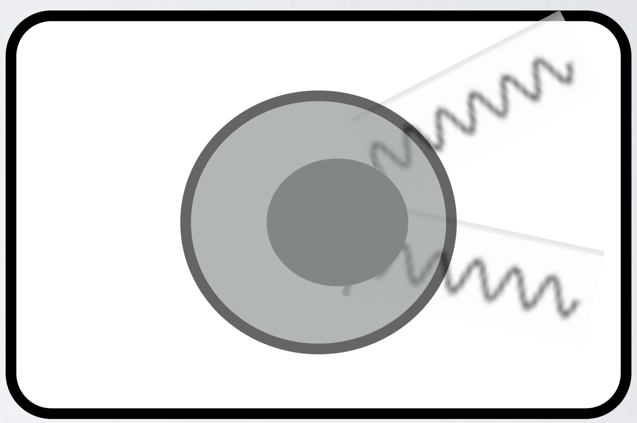

- Beyond the SM




Perturbative mediators




Non-perturbative couplings
at loop level (not a diagram sum)



Bound state substructure
(see backup slides)

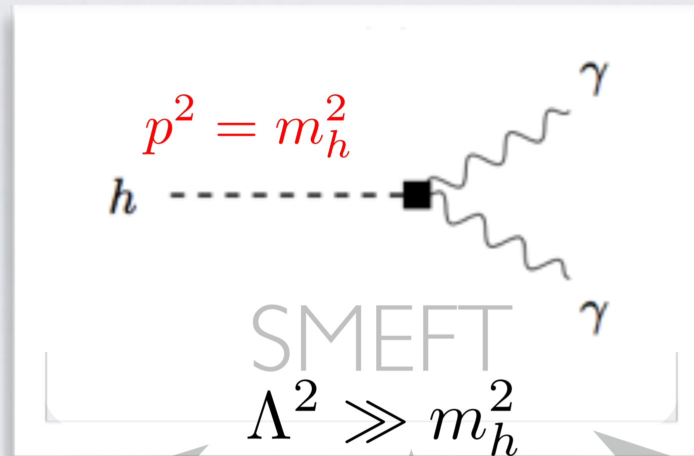
$h \to \gamma\gamma$

$$\lambda_{Mul}^2 \simeq \left\{\frac{C_{H\Box}}{\Lambda^2}, \frac{C_{HD}}{\Lambda^2}, \frac{C_{HWB}}{\Lambda^2}, \frac{C_{HW}}{\Lambda^2}, \frac{C_{HB}}{\Lambda^2}\right\}.$$

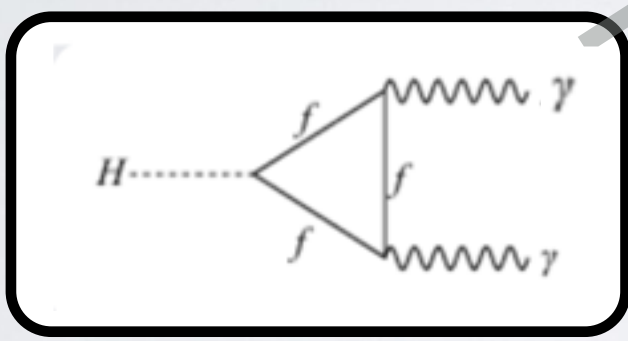
Are these substructure coefficients:

$$\lambda_{mul} \ll \hbar/m_h c$$

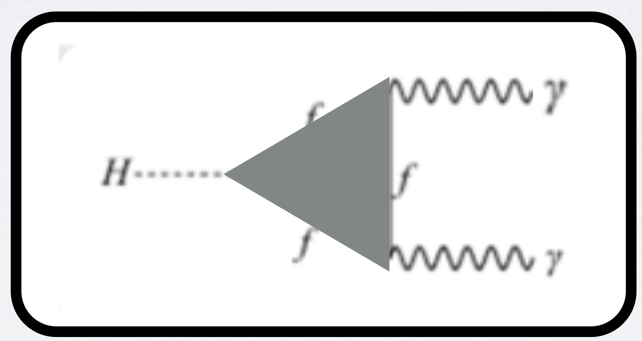
# Precision on $\frac{\Gamma_{meas}(h \to \gamma\gamma)}{\Gamma_{SM}(h \to \gamma\gamma)}$ matters.



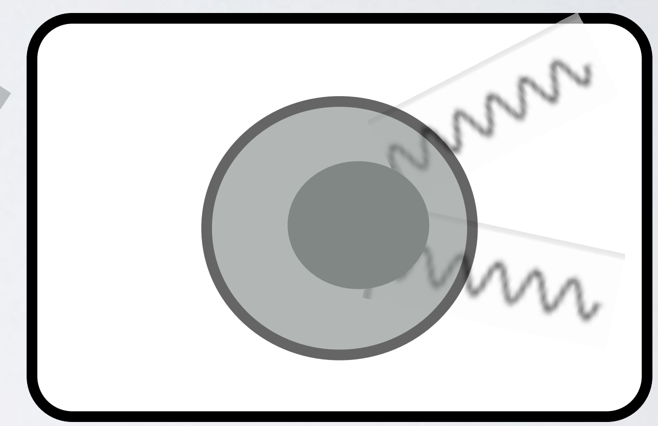

- Beyond the SM




Perturbative mediatiors




Non-perturbative couplings
tree/loop level (not a diagram sum)



Bound state substructure

✔ Can calculate

✘ Cannot calculate (honestly)

✘ Cannot calculate (honestly)

- Key point of EFT so long as characteristic scale is large we CAN parameterize in all 3 cases in a systematically improvable way for measurements

# What is the SMEFT?

Built of H doublet + higher D ops  (due to uncertainty principle+ scale separation)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B\neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots$$

Glashow 1961, Weinberg 1967 (Salam 1967)

Weinberg 1979, Zee, Wilczek 1979

Leung, Love, Rao 1984, Buchmuller Wyler 1986,
Grzadkowski, Iskrzynski, Misiak,Rosiek 2010

Weinberg 1979, Abbott Wise 1980

Lehman 1410.4193, Henning et al. 1512.03433

Lehman,Martin 1510.00372, Henning et al. 1512.03433

The Lagrangian expansion technology is essentially a solved problem

# Bases choice and Dim 6.

- Warsaw basis: 1008.4884  Grzadkowski, Iskrzynski, Misiak,Rosiek

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |

| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
|---|---|---|---|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$ |

Table 2: Dimension-six operators other than the four-fermion ones.

6 gauge dual ops

28 non dual operators

25 four fermi ops

59 + h.c. operators

**Notation:**

$$\widetilde X_{\mu\nu} = \tfrac{1}{2}\varepsilon_{\mu\nu\rho\sigma} X^{\rho\sigma} \quad (\varepsilon_{0123} = +1)$$

$$\widetilde\varphi^j = \varepsilon_{jk}(\varphi^k)^\star \qquad \varepsilon_{12} = +1$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi \equiv i\varphi^\dagger\left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi \equiv i\varphi^\dagger\left(\tau^I D_\mu - \overleftarrow{D}_\mu\tau^I\right)\varphi$$

# Bases choice and Dim 6.

- Four fermion operators: 1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek

| $8:(\bar{L}L)(\bar{L}L)$ | | $8:(\bar{R}R)(\bar{R}R)$ | | $8:(\bar{L}L)(\bar{R}R)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |

| $8:(\bar{L}R)(\bar{R}L)+\text{h.c.}$ | | $8:(\bar{L}R)(\bar{L}R)+\text{h.c.}$ | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$ | $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$ |
| | | $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$ |
| | | $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$ |
| | | $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$ |

Over 20 years?!
700 citations before full EOM reduction?
Our priorities were elsewhere.

# Assume deviation: then what?

- Maybe a part of the 3 loop result in the SM is needed. It will be checked out.
- Maybe an operator that contributes at tree level or one loop has modified the decay.

Signal strength modified as: $\mu_{\gamma\gamma} = |1 + \frac{A_{h\gamma\gamma}}{A^{SM}_{h\gamma\gamma}}|^2$

$$\frac{A_{h\gamma\gamma}}{A^{SM}_{h\gamma\gamma}} \simeq 16\,\pi^2 \left(\Sigma_i\, f_i\, C^{tree}_{NP,i} + \frac{\Sigma_j\, f_j\, C^{loop}_{NP,j}}{16\,\pi^2}\right) \frac{v^2}{\Lambda^2}$$

Three operators in chosen basis.

Thirteen more operators in chosen basis in the U(3)^5 limit

$$C^{tree,NP}_{\gamma\gamma} = C_{HW} + C_{HB} - C_{HWB}$$

$$\begin{aligned}
\mathcal{O}^{(0)}_{HB} &= g_1^2\, H^\dagger\, H\, B_{\mu\nu}\, B^{\mu\nu}, \\
\mathcal{O}^{(0)}_{HW} &= g_2^2\, H^\dagger\, H\, W^a_{\mu\nu}\, W_a^{\mu\nu}, \\
\mathcal{O}^{(0)}_{HWB} &= g_1\, g_2\, H^\dagger\, \sigma^a H\, B_{\mu\nu}\, W_a^{\mu\nu},
\end{aligned}$$

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$$C^{tree,NP}_{\gamma\gamma} = C_{HW} + C_{HB} - C_{HWB}$$

Thirteen more operators in chosen basis in the U(3)^5 limit

$$\mathcal{O}^{(0)}_{\substack{eW\\rs}} = g_2\, \bar{l}_{r,a}\sigma^{\mu\nu}\, e_s\, \tau^I_{ab}\, H_b\, W^I_{\mu\,\nu}, \quad \mathcal{O}^{(0)}_{\substack{eB\\rs}} = g_1\, \bar{l}_{r,a}\sigma^{\mu\nu}\, e_s\, H_a\, B_{\mu\,\nu}, \quad \mathcal{O}^{(0)}_{\substack{uW\\rs}} = g_2\, \bar{q}_{r,a}\sigma^{\mu\nu}\, u_s\, \tau^I_{ab}\, \tilde{H}_b\, W^I_{\mu\,\nu},$$

$$\mathcal{O}^{(0)}_{\substack{uB\\rs}} = g_1\, \bar{q}_{r,a}\sigma^{\mu\nu}\, u_s\, \tilde{H}_a\, B_{\mu\,\nu}, \quad \mathcal{O}^{(0)}_{\substack{dW\\rs}} = g_2\, \bar{q}_{r,a}\sigma^{\mu\nu}\, d_s\, \tau^I_{ab}\, H_b\, W^I_{\mu\,\nu}, \quad \mathcal{O}^{(0)}_{\substack{dB\\rs}} = g_1\, \bar{q}_{r,a}\sigma^{\mu\nu}\, d_s\, H_a\, B_{\mu\,\nu},$$

$$\mathcal{O}^{(0)}_{\substack{eH\\pr}} = H^\dagger H(\bar{l}_p e_r H), \quad \mathcal{O}^{(0)}_{\substack{uH\\pr}} = H^\dagger H(\bar{q}_p u_r \tilde{H}), \quad \mathcal{O}^{(0)}_{\substack{dH\\pr}} = H^\dagger H(\bar{q}_p d_r H),$$

$$\mathcal{O}^{(0)}_{H} = (H^\dagger H)^3, \quad \mathcal{O}^{(0)}_{H\Box} = H^\dagger H \Box (H^\dagger H), \quad \mathcal{O}^{(0)}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H),$$

$$\mathcal{O}^{(0)}_{W} = g_2^3\, \epsilon_{abc} W^{a\nu}_{\mu} W^{b\rho}_{\nu} W^{c\mu}_{\rho}.$$

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Three operators in chosen basis.

$$C^{tree,NP}_{\gamma\gamma} = C_{HW} + C_{HB} - C_{HWB}$$

Thirteen more operators in chosen basis in the U(3)^5 limit

To be able to robustly follow a hint in the SMEFT we want to be able to accommodate

$$C^{tree}_{NP} \sim C^{loop}_{NP}, \qquad C^{tree}_{NP} \lesssim C^{loop}_{NP}, \qquad C^{loop}_{NP} \lesssim C^{tree}_{NP}$$

So we need to do the one loop correction to capture some of these cases.
Idea of SMEFT: avoid theory bigotry, treat all possible SM deviations equally as a consistent EFT to avoid missing anything.

# One loop in the SMEFT.

- The Algorithm: Use SMEFT RGE results to renormalize.

  Also use SM counter term subtractions.

  Define a scheme that fixes that asymptotic properties of states in the S matrix, this fixes the finite terms in renormalization conditions.

  Gauge fix, calculate, and then check gauge independence.

- We know the Warsaw basis is self consistent at one loop as it has been completely renormalized - DONE!

  arXiv:1301.2588 Grojean, Jenkins, Manohar, Trott
  arXiv:1308.2627, 1309.0819, 1310.4838 Jenkins, Manohar, Trott
  arXiv: 1312.2014 Alonso, Jenkins, Manohar, Trott

  See also Ghezzi et al. 1505.03706 for Warsaw basis results

  Some partial results were also obtained in a "SILH basis"

  arXiv:1302.5661, 1308.1879 Elias-Miro, Espinosa, Masso, Pomarol
  1312.2928 Elias-Miro, Grojean, Gupta, Marzocca

# SMEFT counter-terms feeding in.

- Here is how this works in $\Gamma(h \to \gamma\,\gamma)$ , need mixing with the "tree" level operators
  Defining the basis of operators as

$$\mathcal{O}_i = (\mathcal{O}_{HB}, \mathcal{O}_{HW}, \mathcal{O}_{HWB}, \mathcal{O}_W, \mathcal{O}_{eB}, \mathcal{O}^*_{eB}, \mathcal{O}_{uB}, \mathcal{O}^*_{uB}, \mathcal{O}_{dB}, \mathcal{O}^*_{dB}, \mathcal{O}_{eW}, \mathcal{O}^*_{eW}, \mathcal{O}_{uW}, \mathcal{O}^*_{uW}, \mathcal{O}_{dW}, \mathcal{O}^*_{dW})$$

$$\begin{aligned} \mathcal{L}_6^{(0)} &= Z_{SM}\, Z_{i,j}\, C_i\, \mathcal{O}_j^{(r)}, \\ &= Z_{SM}\, \mathcal{N}_{HB}\, \mathcal{O}_{HB}^{(r)} + Z_{SM}\, \mathcal{N}_{HW}\, \mathcal{O}_{HW}^{(r)} + Z_{SM}\, \mathcal{N}_{HWB}\, \mathcal{O}_{HWB}^{(r)}. \end{aligned}$$

- 3x3 sub-matrix of ops that contribute at tree level

$$Z_{i,j} = \frac{1}{16\,\pi^2} \begin{pmatrix} \frac{g_1^2}{4} - \frac{9g_2^2}{4} + 6\lambda + Y & 0 & g_1^2 \\ 0 & -\frac{3g_1^2}{4} - \frac{5g_2^2}{4} + 6\lambda + Y & g_2^2 \\ \frac{3g_2^2}{2} & \frac{g_1^2}{2} & -\frac{g_1^2}{4} + \frac{9g_2^2}{4} + 2\lambda + Y \end{pmatrix}$$

and first at one loop

$$\begin{pmatrix} 0 & -\frac{15}{2}\, g_2^4 & \frac{3}{2}\, g_2^4 \\ -(y_l + y_e)\, Y_e & 0 & -\frac{1}{2}\, Y_e \\ -(y_l + y_e)\, Y_e^\dagger & 0 & -\frac{1}{2}\, Y_e^\dagger \\ -N_c\,(y_q + y_u)\, Y_u & 0 & \frac{1}{2}\, N_c\, Y_u \\ -N_c\,(y_q + y_u)\, Y_u^\dagger & 0 & \frac{1}{2}\, N_c\, Y_u^\dagger \\ -N_c\,(y_q + y_d)\, Y_d & 0 & -\frac{1}{2}\, N_c\, Y_d \\ -N_c\,(y_q + y_d)\, Y_d^\dagger & 0 & -\frac{1}{2}\, N_c\, Y_d^\dagger \\ 0 & -\frac{1}{2}\, Y_e & -(y_l + y_e)\, Y_e \\ 0 & -\frac{1}{2}\, Y_e^\dagger & -(y_l + y_e)\, Y_e^\dagger \\ 0 & -\frac{1}{2}\, N_c\, Y_u & N_c\,(y_q + y_u)\, Y_u \\ 0 & -\frac{1}{2}\, N_c\, Y_u^\dagger & N_c\,(y_q + y_u)\, Y_u^\dagger \\ 0 & -\frac{1}{2}\, N_c\, Y_d & -N_c\,(y_q + y_d)\, Y_d \\ 0 & -\frac{1}{2}\, N_c\, Y_d^\dagger & -N_c\,(y_q + y_d)\, Y_d^\dagger \end{pmatrix}$$

arXiv:1301.2588,1308.2627,
1310.4838, 1312.2014

- note that this counter-term subtraction is proportional to $v$

# SM counter-term structure

- To define the SM counter terms use background field , use $R_\xi$ gauge

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} i \phi^+ \\ h + v + \delta v + i \phi_0 \end{pmatrix}$$

Background field method (with particular operator normalization) gives:

$$Z_A Z_e = 1, \qquad Z_h = Z_{\phi_\pm} = Z_{\phi_0}, \qquad Z_W Z_{g_2} = 1.$$

Also need the Higgs wavefunction and vev renorm

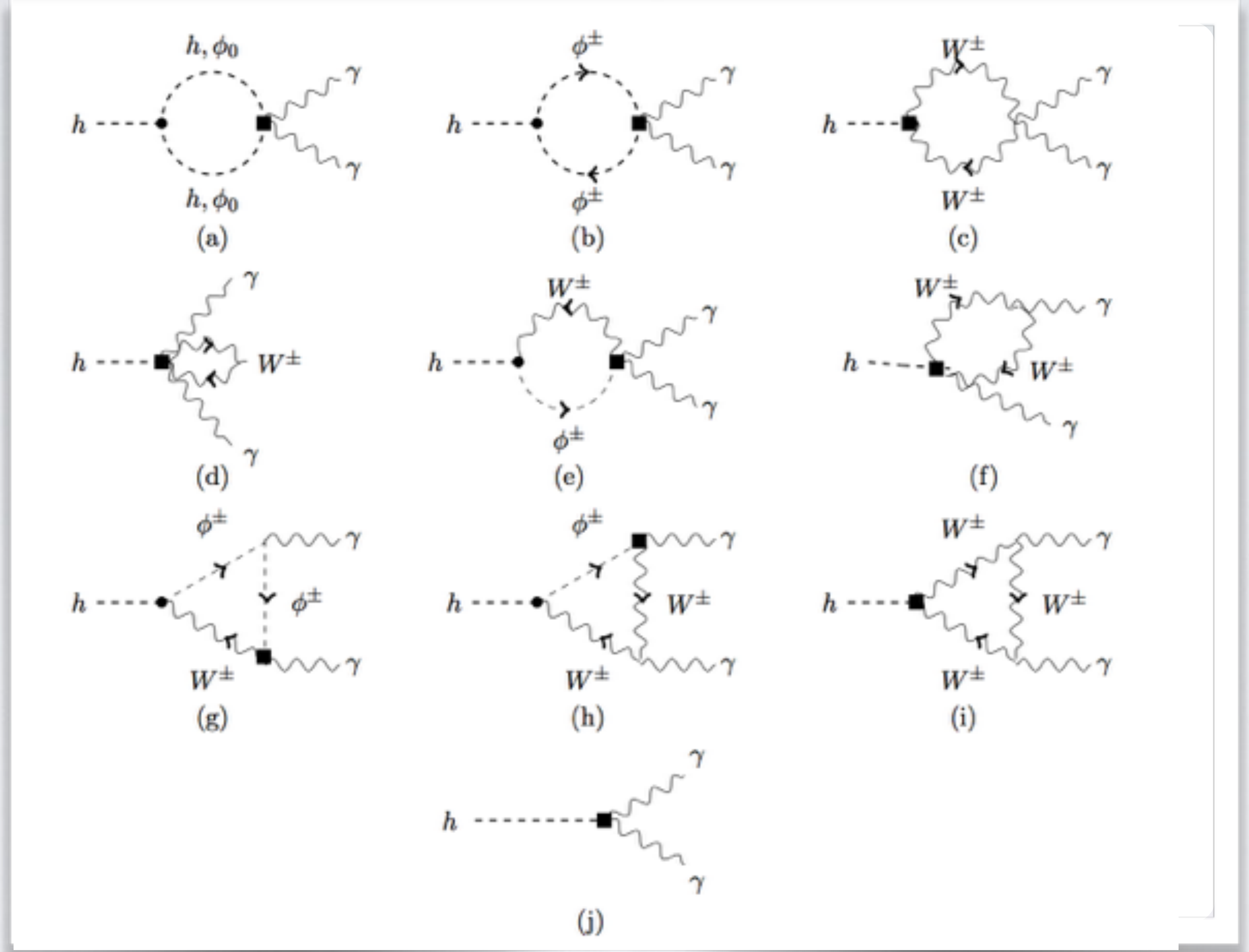
$$Z_h = 1 + \frac{(3+\xi)\,(g_1^2 + 3\,g_2^2)}{64\,\pi^2\,\epsilon} - \frac{Y}{16\,\pi^2\,\epsilon}.$$

$$(\sqrt{Z_v} + \frac{\delta v}{v})_{div} = 1 + \frac{(3+\xi)\,(g_1^2 + 3\,g_2^2)}{128\,\pi^2\,\epsilon} - \frac{Y}{32\,\pi^2\,\epsilon}.$$

We used a trick involving $h \to g\,g$ for the latter.

# The required loops.

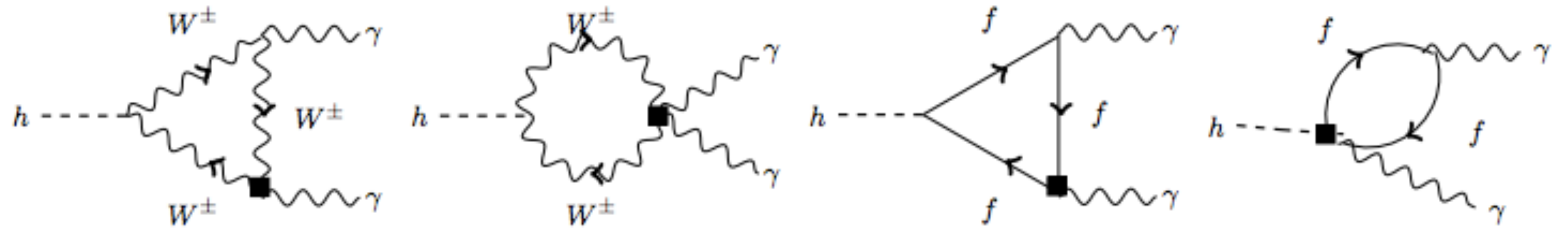
- Calculate in BF method, in $R_\xi$ gauge, for operators that contribute at tree level



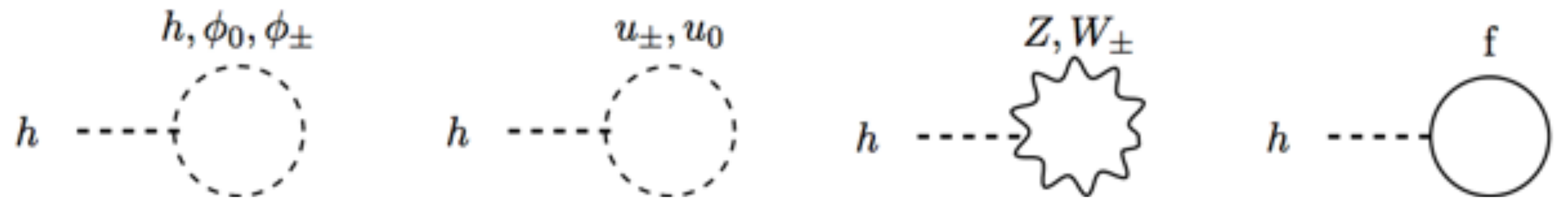

- Gauge dependence cancels ✓ remaining divergences cancel exactly ✓

# The required loops.

- Calculate in BF method, in $R_\xi$ gauge, for operators that contribute at loop level only




- Define vev of the theory as the one point function vanishing - fixes $\delta v$




$$T = m_h^2\, h\, v \frac{1}{16\pi^2}\left[-16\pi^2 \frac{\delta v}{v} + 3\,\lambda\left(1+\log\left[\frac{\mu^2}{m_h^2}\right]\right) + \frac{m_W^2}{v^2}\xi\left(1+\log\left[\frac{\mu^2}{\xi\, m_W^2}\right]\right),\right.$$
$$+\frac{1}{2}\frac{m_Z^2}{v^2}\xi\left(1+\log\left[\frac{\mu^2}{\xi\, m_Z^2}\right]\right) - \frac{1}{2}\sum_i y_i^4\, N_c \frac{1}{\lambda}\left(1+\log\left[\frac{\mu^2}{m_i^2}\right]\right),$$
$$\left. + \frac{g_2^2}{2}\frac{m_W^2}{m_h^2}\left(1+3\log\left[\frac{\mu^2}{m_W^2}\right]\right) + \frac{1}{4}(g_1^2+g_2^2)\frac{m_Z^2}{m_h^2}\left(1+3\log\left[\frac{\mu^2}{m_Z^2}\right]\right)\right].$$

# Renormalization conditions

- The finite terms that are fixed by renormalization conditions (at one loop) in the theory enter as

$$\langle h(p_h)|S|\gamma(p_a,\alpha),\gamma(p_b,\beta)\rangle_{BSM} = (1+\frac{\delta R_h}{2})\,(1+\delta R_A)\,(1+\delta R_e)^2\, i \sum_{x=a..o} \mathcal{A}_x.$$

Cancels!

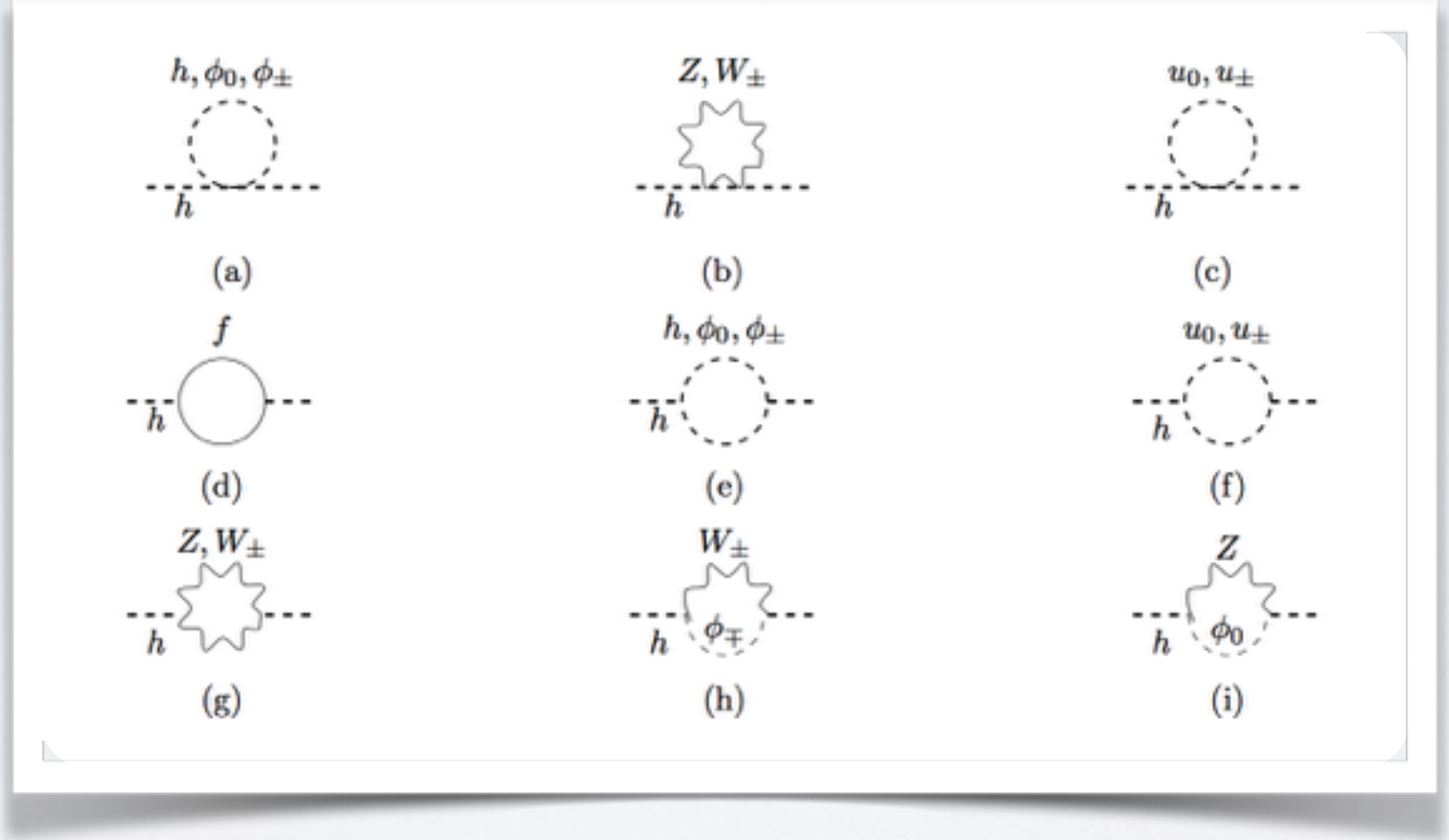
- Remaining finite terms fixed by defining in renormalization conditions on the couplings and two point function residues and poles

$$\delta R_h = -\frac{\partial \Pi_{hh}(p^2)}{\partial p^2}|_{p^2=m_h^2} \qquad \delta R_e = -\frac{1}{2}\delta R_A,$$

This relation follows from a Ward identity using BFM.

# Higgs two point functions

- Required Higgs two point function results

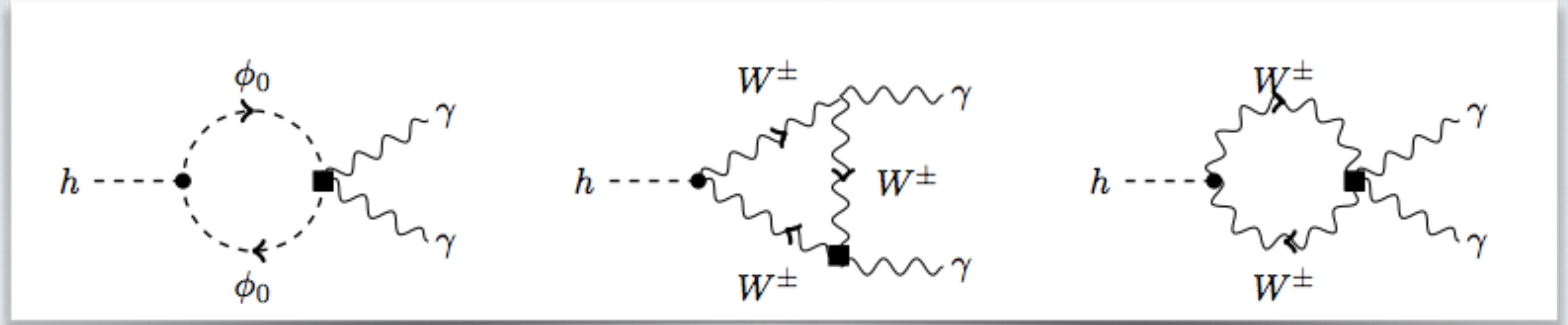



This result is pretty well known, but where is it ?! for finite terms in $R_\xi$ gauge in BF method

We will supply it upon request for general $\xi$ .

# SMEFT gauge fixing issues.

- Some interesting subtleties in the SMEFT. Consider




- These terms give divergences proportional to $v^2$ but counter-terms all come in proportional to $v$. So what is going on?

- Resolution of this issue is to rethink gauge fixing

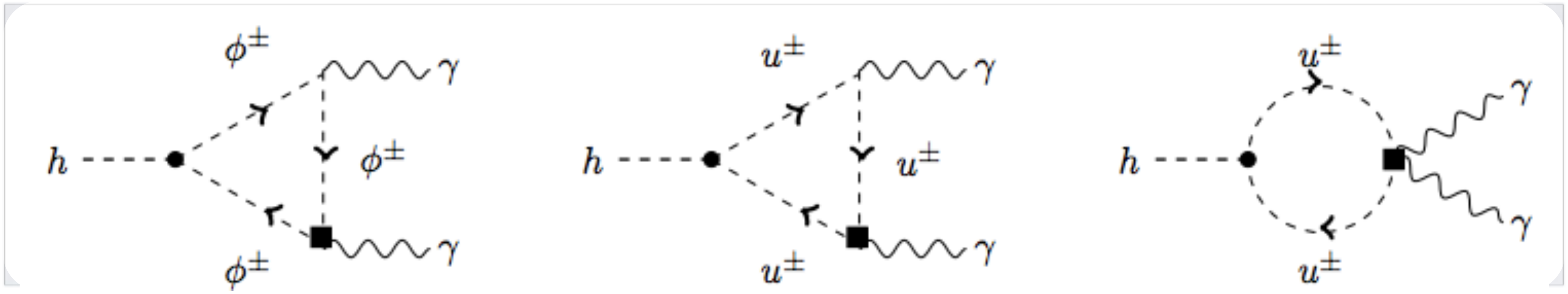
$$\mathcal{L}_{GF} = -\frac{1}{2\,\xi_W}\sum_a \left[\partial_\mu W^{a,\mu} - g_2\,\epsilon^{abc}\hat{W}_{b,\mu}W_c^\mu + i\,g_2\,\frac{\xi}{2}\left(\hat{H}_i^\dagger\sigma^a_{ij}H_j - H_i^\dagger\sigma^a_{ij}\hat{H}_j\right)\right]^2,$$
$$-\frac{1}{2\,\xi_B}\left[\partial_\mu B^\mu + i\,g_1\,\frac{\xi}{2}\left(\hat{H}_i^\dagger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

# SMEFT gauge fixing issues.

- The fields are redefined at each order in the power counting, this leads to the appearance of L6 Wilson coefficients in the gauge fixing term.

$$\mathcal{L}_{FP} = -\bar{u}^\alpha \frac{\delta G^\alpha}{\delta \theta^\beta} u^\beta.$$

Some operators in $\mathcal{L}_6$ then source ghosts!




- This cancels the unusual divergences exactly.
- The mismatch of the mass eigenstates in the SMEFT with the SM means gauge fixing in the former also results in some interesting local contact operators

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

# One loop SMEFT - Final result

- The final result for the 3 tree ops result is of the form

1505.02646 Hartmann, Trott

$$
\begin{aligned}
\frac{i\,\mathcal{A}^{NP}_{total}}{i\,v\,e^2\,A^{h\gamma\gamma}_{\alpha\beta}} = & \, C_{\gamma\gamma}\left(1+\frac{\delta R_h}{2}+\frac{\delta\,v}{v}\right), \\
& + \left(\frac{C_{\gamma\gamma}}{16\,\pi^2}\left(\frac{g_1^2}{4}+\frac{3\,g_2^2}{4}+6\,\lambda\right)+\frac{C_{HWB}}{16\,\pi^2}\left(-3\,g_2^2+4\,\lambda\right)\right)\log\left(\frac{m_h^2}{\Lambda^2}\right), \\
& + \frac{C_{\gamma\gamma}}{16\,\pi^2}\left(\left(\frac{g_1^2}{4}+\frac{g_2^2}{4}+\lambda\right)\mathcal{I}[m_Z^2]+\left(\frac{g_2^2}{2}+2\lambda\right)\mathcal{I}[m_W^2]+(\sqrt{3}\,\pi-6)\,\lambda\right), \\
& + \frac{C_{HWB}}{16\,\pi^2}\left(2e^2\left(1+6\frac{m_W^2}{m_h^2}\right)-2\,g_2^2\left(1+\log\left(\frac{m_W^2}{m_h^2}\right)\right)+(4\,\lambda-g_2^2)\,\mathcal{I}[m_W^2],\right. \\
& \qquad \left. +4\left(3e^2-g_2^2-6e^2\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right), \\
& - \frac{g_2^2\,C_{HW}}{4\,\pi^2}\left(3\,\frac{m_W^2}{m_h^2}+\left(4-\frac{m_h^2}{m_W^2}-6\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right). \qquad (3.6)
\end{aligned}
$$

Where

$$C^{NP}_{\gamma\gamma} = C_{HB} + C_{HW} - C_{HWB}$$

$$\mathcal{I}[m^2] \equiv \int_0^1 dx\,\log\left(\frac{m^2-m_h^2\,x\,(1-x)}{m_h^2}\right), \quad \mathcal{I}_y[m^2] \equiv \int_0^{1-x} dy \int_0^1 dx\,\frac{m^2}{m^2-m_h^2\,x\,(1-x-y)},$$

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$$+\left(\frac{C_{\gamma\gamma}}{16\pi^2}\left(\frac{g_1^2}{4}+\frac{3\,g_2^2}{4}+6\,\lambda\right)+\frac{C_{HWB}}{16\pi^2}\left(-3\,g_2^2+4\,\lambda\right)\right)\log\left(\frac{m_h^2}{\Lambda^2}\right),$$
$$+\frac{C_{\gamma\gamma}}{16\pi^2}\left(\left(\frac{g_1^2}{4}+\frac{g_2^2}{4}+\lambda\right)\mathcal{I}[m_Z^2]+\left(\frac{g_2^2}{2}+2\lambda\right)\mathcal{I}[m_W^2]+(\sqrt{3}\,\pi-6)\,\lambda\right),$$
$$+\frac{C_{HWB}}{16\pi^2}\left(2e^2\left(1+6\frac{m_W^2}{m_h^2}\right)-2\,g_2^2\left(1+\log\left(\frac{m_W^2}{m_h^2}\right)\right)+(4\,\lambda-g_2^2)\,\mathcal{I}[m_W^2],\right.$$
$$\left.+4\left(3e^2-g_2^2-6e^2\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right),$$
$$-\frac{g_2^2\,C_{HW}}{4\pi^2}\left(3\,\frac{m_W^2}{m_h^2}+\left(4-\frac{m_h^2}{m_W^2}-6\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right). \qquad (3.6)$$

Fixed by renorm conditions

Where $C^{NP}_{\gamma\gamma} = C_{HB} + C_{HW} - C_{HWB}$

$$\mathcal{I}[m^2] \equiv \int_0^1 dx\,\log\left(\frac{m^2-m_h^2\,x\,(1-x)}{m_h^2}\right),\quad \mathcal{I}_y[m^2] \equiv \int_0^{1-x} dy \int_0^1 dx\,\frac{m^2}{m^2-m_h^2\,x\,(1-x-y)},$$

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1505.02646 Hartmann, Trott

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$$+\frac{C_{\gamma\gamma}}{16\,\pi^2}\left(\left(\frac{g_1^2}{4}+\frac{g_2^2}{4}+\lambda\right)\mathcal{I}[m_Z^2]+\left(\frac{g_2^2}{2}+2\lambda\right)\mathcal{I}[m_W^2]+(\sqrt{3}\,\pi-6)\,\lambda\right),$$
$$+\frac{C_{HWB}}{16\,\pi^2}\left(2e^2\left(1+6\frac{m_W^2}{m_h^2}\right)-2\,g_2^2\left(1+\log\left(\frac{m_W^2}{m_h^2}\right)\right)+(4\,\lambda-g_2^2)\,\mathcal{I}[m_W^2],\right.$$
$$\left.+4\left(3e^2-g_2^2-6e^2\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right),$$
$$-\frac{g_2^2\,C_{HW}}{4\,\pi^2}\left(3\,\frac{m_W^2}{m_h^2}+\left(4-\frac{m_h^2}{m_W^2}-6\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right). \qquad (3.6)$$

"(not so) Large" log terms consistent with RGE

Where $C^{NP}_{\gamma\gamma} = C_{HB} + C_{HW} - C_{HWB}$

$$\mathcal{I}[m^2] \equiv \int_0^1 dx\,\log\left(\frac{m^2-m_h^2\,x\,(1-x)}{m_h^2}\right),\quad \mathcal{I}_y[m^2] \equiv \int_0^{1-x} dy\int_0^1 dx\,\frac{m^2}{m^2-m_h^2\,x\,(1-x-y)},$$

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1505.02646 Hartmann, Trott

$$
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&+\frac{C_{HWB}}{16\,\pi^2}\left(2e^2\left(1+6\frac{m_W^2}{m_h^2}\right)-2\,g_2^2\left(1+\log\left(\frac{m_W^2}{m_h^2}\right)\right)+(4\,\lambda-g_2^2)\,\mathcal{I}[m_W^2],\right.\\
&\qquad\left.+4\left(3e^2-g_2^2-6e^2\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right),\\
&-\frac{g_2^2\,C_{HW}}{4\,\pi^2}\left(3\,\frac{m_W^2}{m_h^2}+\left(4-\frac{m_h^2}{m_W^2}-6\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right).
\end{aligned}
\tag{3.6}
$$

Finite terms with associated logs terms

Where $C^{NP}_{\gamma\gamma}=C_{HB}+C_{HW}-C_{HWB}$

$$
\mathcal{I}[m^2]\equiv\int_0^1 dx\,\log\left(\frac{m^2-m_h^2\,x\,(1-x)}{m_h^2}\right),\quad \mathcal{I}_y[m^2]\equiv\int_0^{1-x}dy\int_0^1 dx\,\frac{m^2}{m^2-m_h^2\,x\,(1-x-y)},
$$

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1505.02646 Hartmann, Trott

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$$\left.+4\left(3e^2-g_2^2-6e^2\frac{m_W^2}{m_h^2}\right)\mathcal{I}_y[m_W^2]\right),$$
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"Pure" finite terms not in $C_{\gamma\,\gamma}$ and no associated log

Where $C^{NP}_{\gamma\gamma} = C_{HB} + C_{HW} - C_{HWB}$

$$\mathcal{I}[m^2] \equiv \int_0^1 dx\,\log\left(\frac{m^2-m_h^2\,x\,(1-x)}{m_h^2}\right),\quad \mathcal{I}_y[m^2] \equiv \int_0^{1-x} dy\int_0^1 dx\,\frac{m^2}{m^2-m_h^2\,x\,(1-x-y)},$$

# SMEFT - Physics developments

1505.02646 Hartmann, Trott

- Operators can contribute a “pure finite term” at NLO and not have a corresponding RGE log. This fact consistent with results in 1505.03706 Ghezzi et al.

- Finite terms are not small in general compared to the log terms

$$R_{C_{HWB}/C_{HW}} \simeq \frac{C_{HWB}}{C_{HW}} \left(0.5 + 0.7 \log \frac{m_h^2}{\Lambda^2}\right) \qquad R_{C_{HWB}} \simeq 1 + 0.7 \log^{-1} \frac{m_h^2}{\Lambda^2}$$

- Log mu dependence of RGE consistent with full one loop result, but important modification due to mass scales running (vev not 0) This is scheme dependent

- <u>The RGE is not a good proxy for the full one loop structure of the SMEFT. We need to calculate full one loop.</u>

(0’s in the rge do not mean 0’s guaranteed at one loop for finite terms)

# One loop SMEFT - Final result

1507.03568 Hartmann, Trott

- Remaining contributions are WWW operator

$$f_W = -9\,g_2^4 \log\left(\frac{m_h^2}{\Lambda^2}\right) - 9\,g_2^4\,\mathcal{I}[m_W^2] - 6\,g_2^4\,\mathcal{I}_y[m_W^2] + 6\,g_2^4\,\mathcal{I}_{xx}[m_W^2]\,(1 - 1/\tau_W) - 12\,g_2^4,$$

- dipole results:

$$f_{\substack{eB\\ss}} = 2\,Q_\ell\,[Y_\ell]_{ss}\left[-1 + 2\log\left(\frac{\Lambda^2}{m_h^2}\right) + \log\left(\frac{4}{\tau_s}\right)\right] - 2\,Q_\ell\,[Y_\ell]_{ss}\left[2\,\mathcal{I}_y[m_s^2] + \mathcal{I}[m_s^2]\right].$$

- SM rescalings: (only this in eHdecay)

$$f_{\substack{eH\\ss}} = \frac{Q_\ell^2}{2} A_{1/2}(\tau_s), \quad f_{\substack{uH\\ss}} = N_c\,\frac{Q_u^2}{2} A_{1/2}(\tau_s),$$

$$f_{\substack{dH\\ss}} = N_c\,\frac{Q_d^2}{2} A_{1/2}(\tau_s),$$

$$f_{H\Box} = -\frac{Q_\ell^2}{2} A_{1/2}(\tau_p) - N_c\,\frac{Q_u^2}{2} A_{1/2}(\tau_r) - N_c\,\frac{Q_d^2}{2} A_{1/2}(\tau_s) - \frac{1}{2}\,A_1(\tau_W),$$

In terms of usual loop functions of the SM.

# Do we need this SMEFT one loop?

- Developing the SMEFT lets you reduce theory errors in the future.
- For the current precision it is not a disaster to not have it:

Hartmann, Trott 1507.03568

Correcting tree level conclusion for 1 loop neglected effects errors introduced added in quadrature, $C_i \sim 1$ :

Data for: $-0.02 \leq \left(\hat{C}^{1,NP}_{\gamma\gamma} + \frac{\hat{C}^{NP}_i f_i}{16\,\pi^2}\right) \frac{\bar{v}_T^2}{\Lambda^2} \leq 0.02.$

$\Lambda = 800\,\mathrm{GeV}$    $\Lambda = 3000\,\mathrm{GeV}$

$\kappa_\gamma = 0.93^{+0.36}_{-0.17}$ ATLAS data - naive map to C corrected $[29, 4]\,\%$

$\kappa_\gamma = 0.98^{+0.17}_{-0.16}$ CMS data - naive map to C corrected $[52, 7]\,\%$

- The future precision Higgs phenomenology program clearly needs it:

$\kappa_\gamma^{proj:RunII} = 1 \pm 0.045$ - naive map to C (tree level) corrected $[167, 21]\,\%$

$\kappa_\gamma^{proj:HILHC} = 1 \pm 0.03$ $[250, 31]\,\%$

$\kappa_\gamma^{proj:TLEP} = 1 \pm 0.0145$ $[513, 64]\,\%$

# Conclusions

- Presented the complete one loop result for $\Gamma(h \to \gamma\gamma)$ in the (linear) SMEFT.

  Based on Hartmann, Trott 1505.02646, 1507.03568

  Some overlap of results in 1505.03706 Ghezzi et al. and builds on the RGE

- Results are numerically significant for interpretations of the data when precision descends below 10% experimentally. Results are not yet included in codes such as eHdecay.

- Era of one loop SMEFT results has now been kicked off:

  Pioneering full calculation $\mu \to e\gamma$ Pruna, Signer arXiv:1408.3565

  Other processes tacked in 1505.03706 Ghezzi et al. (partial EW precision)

  Partial $\Gamma(h \to f\bar{f})$ R. Gauld, B. D. Pecjak and D. J. Scott, arXiv:1512.02508

  QCD corrections partial SMEFT P. Artoisenet et. al., arXiv:1306.6464

  QCD NLO Higgs associated production K. Mimasu. et al. arXiv:1512.02572

  QCD NLO single top production C.Zhang, arXiv:1512.02508

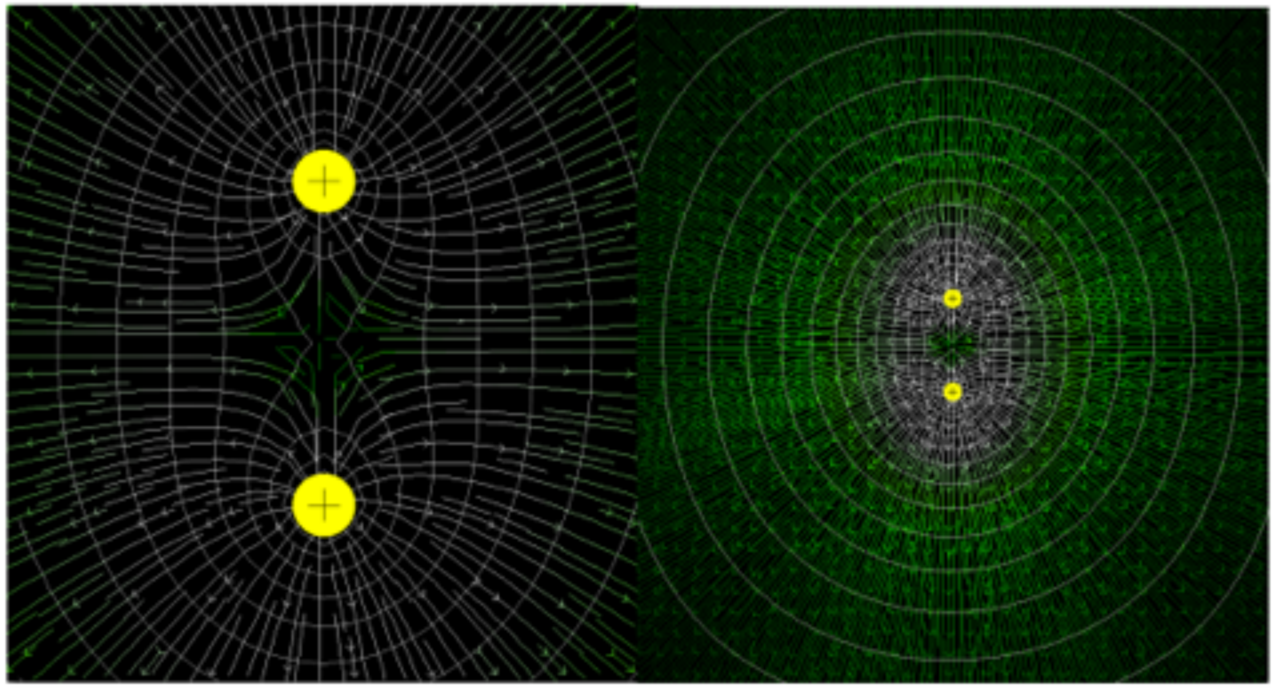
  QCD NLO Higgs pair production R. Grober et al. arXiv:1504.0657

  NLO Z decay widths $\mathcal{O}(y_T^2, \lambda)$ Hartmann, Shepherd, MT 1611.09879

# Backup stuff

# More scales, more possible signals

- What are we probing? Just for indirect mass scales of new states?



The field far away looks just like a point charge.

Consider the electrostatics multipole expansion

$$V(r) = \frac{1}{r} \sum c_{lm} Y_{lm}(\Omega) \left(\frac{a}{r}\right)^l$$

- By adding a series of terms (operators) like the dipole quadrupole etc one approx the field

- "Non-minimal" coupling effects can be there, there is more than UV states to matching.

1305.0017 Jenkins,Manohar,Trott, Seminars at: - NBI Winter School lec 2015, MTCP Higgs 2015
also 1603.03064 Liu, Pomarol, Rattazzi, Riva

# More on scales

arXiv:1705.soon SMEFT, HEFT etc (review) Ilaria Brivio, MT

- We want to probe the multipole scales of the (fundamental?) scalar to determine if its effectively point-like

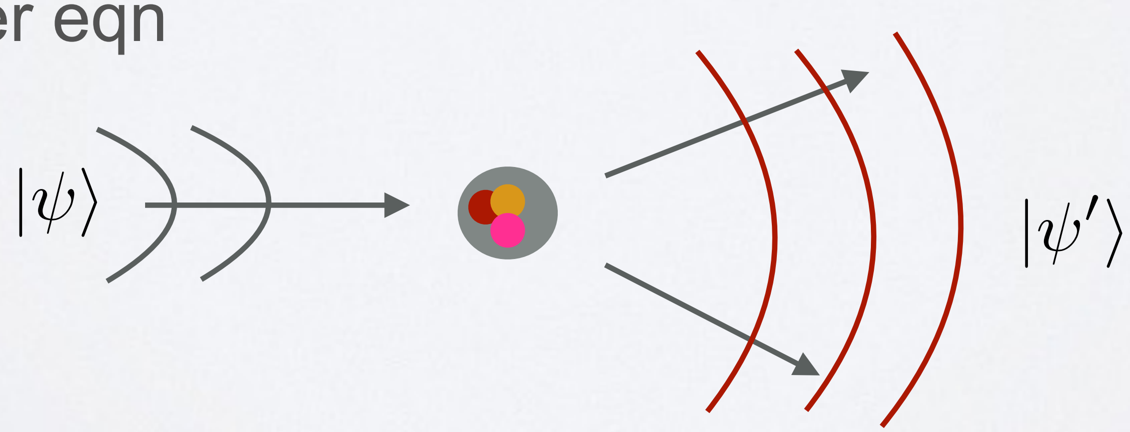
$$\lambda^2_{Mul} \simeq \{\frac{C_{H\Box}}{\Lambda^2}, \frac{C_{HD}}{\Lambda^2}, \frac{C_{HWB}}{\Lambda^2}, \frac{C_{HW}}{\Lambda^2}, \frac{C_{HB}}{\Lambda^2}\}.$$

Are these substructure coefficients:

$$\lambda_{mul} \ll \hbar/m_h c$$

Scattering lengths (i.e characteristic scales) can be larger than Compton wavelength), we are interested in a bit smaller but not vanishingly small.

- How can you think about the multipole expansion in SMEFT? Think of quantum mechanical scattering off of a non-local potential. With boundary conditions Lippman-Schwinger eqn



# The multipole expansion

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- Described as:

$$T_\ell(\mathbf{k},\mathbf{k}';E) = V_\ell(\mathbf{k},\mathbf{k}') + \frac{2}{\pi}\int_0^\infty d|\mathbf{q}|\, q^2 \frac{V_\ell(\mathbf{k}',\mathbf{q})T_\ell(\mathbf{q},\mathbf{k};E)}{E - q^2/\mu + i\epsilon}.$$

Transition matrix for non-local potential for Wavefunctions

- S matrix for partial wave scattering: $S_\ell(k) = e^{2i\delta_\ell(k)}$

(first introduced by wheeler)

- This is the effective range expansion:

$$k\cot\delta_0(k) = -\frac{1}{a_0} + \frac{1}{2} r_0\, k^2 - C_2 r_0^3\, k^4 + \cdots$$

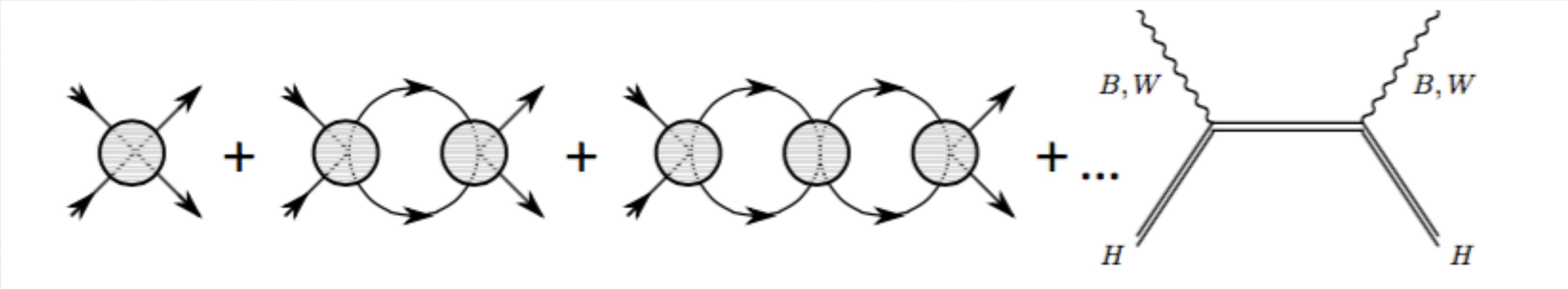
These are distinct scales to consider. We should think harder about them.

# Bound state physics = challenging

- How does it work in field theory? For NR bound states (see Kaplan et al 9605002, 9802075, manohar and luke 9610534, etc..)

$$i\mathcal{A} = -i\langle p|\hat{V} + \hat{V}G_E^0\hat{V} + \hat{V}(G_E^0\hat{V})^2 + \cdots|p'\rangle \rightarrow i\mathcal{A} = -i\langle p|(G_E^0)^{-1}\,G_E\,(G_E^0)^{-1}|p'\rangle$$

free g.f.      full g.f.



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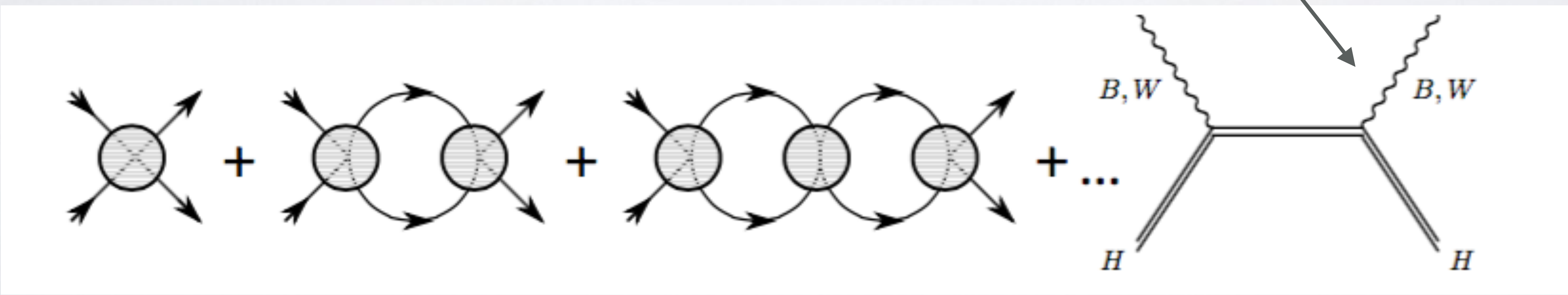
free g.f.

Satisfies Schrodinger. eqn

- In the end $|\mathbf{p}|\cot\delta(\mathbf{p}) = i|\mathbf{p}| + \frac{4\pi}{M}\frac{1}{\mathcal{A}}$

Problem is this is NOT NR



# SMEFT multipole expansion

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- In the end $|\mathbf{p}|\cot\delta(\mathbf{p}) = i|\mathbf{p}| + \frac{4\pi}{M}\frac{1}{\mathcal{A}}$

- We know, expansion of Higgs as a bound state in SMEFT case projects onto ops. Just because we have trouble calculating this physics of relativistic bound states does not make it 0.

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Test this without prejudice in $h \to \gamma\gamma$!