EFT and perturbation theory.
(SMEFT loops)

M. Trott, BSMPR 2018

"The greatest obstacle to discovery is not ignorance - it is the illusion of knowledge." - Daniel J. Boorstin

Michael Trott, Niels Bohr Institute, Copenhagen, Denmark.

In the BSMPR scientific program

This progress carries over to important models for Beyond the SM (BSM) physics in a straightforward way,

Specific BSM models involve new free parameters…. often fixed by MSbar renormalization conditions at some energy scale or other *unphysical renormalization conditions*.

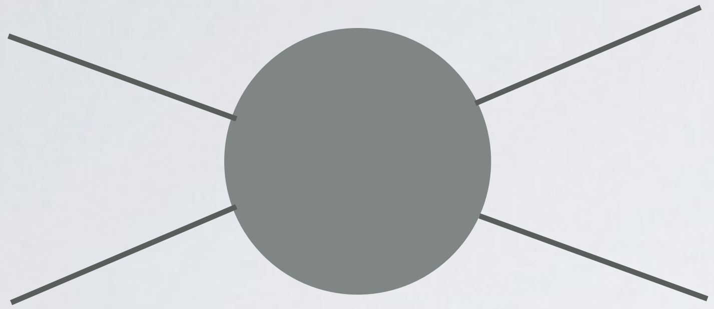
A proper choice of renormalization conditions may be nontrivial and model specific.

..precision calculations in the SMEFT require extensions of the existing tools and a thorough understanding of the corresponding renormalization …..

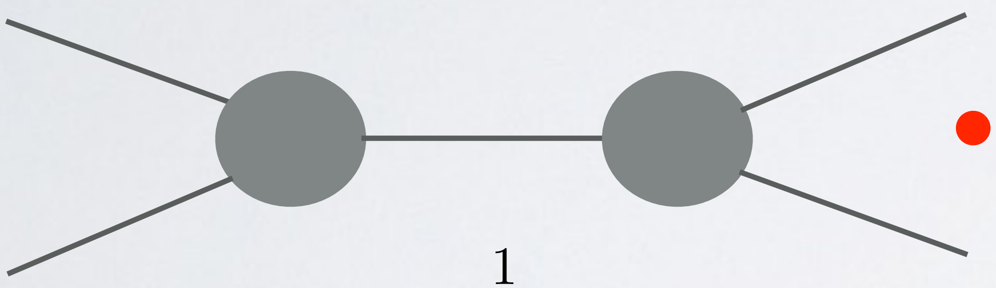
the link between electroweak corrections and an EFT Lagrangian is largely unexplored

Premise: SMEFT is a theory

When you do measurements below a particle threshold



- The observable is a function of the external Lorentz invariants: $f(s,t,u)$
- The observable is an analytic function of these invariants except in special regions of phase space where an internal state goes on-shell. This is the "Landau Principle".



$$\sim \frac{1}{s - m^2 + i\Gamma(s)\, m}$$

- IF the collision probe does not reach $\sim m^2_{heavy}$ THEN the observable's dependence on that scale is simplified
- No non-analytic behavior due to that state, and you can Taylor expand in LOCAL functions (operators)

$$\langle\rangle \sim O^0_{SM} + \frac{f_1(s,t,u)}{M^2_{heavy}} + \frac{f_2(s,t,u)}{M^4_{heavy}} + \cdots$$

- The locality is due to the uncertainty principle

See the review for the basics (1706.08945 Brivio,MT)

EFT approach not a guess, or a random model, its a powerful general approach that is motivated by the EXP situation that has appeared

General "BSM heavy" approach is SMEFT/HEFT

No BSM resonance seen → (Decoupling) → VERY! Efficient to constrain BSM/interpret the data in EFT

↓ no other (hidden) light states

SMEFT

observed scalar in doublet

HEFT

observed scalar not in doublet

Basics of the SMEFT formulation:

IR operator form

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

UV dependent Wilson coefficient and suppression scale

For SMEFT intro see ilaria's talk.

SM vs SMEFT theory precision

$\mathcal{L}_{SM}$

- UV incomplete, but a valid theory to calculate in, theoretical precision limited by

$$C_i \, \frac{v^2}{\Lambda^2}, \quad C_j \, \frac{p^2}{\Lambda^2}$$

If experimental and SM TH precision worse, then just fix that first (or at least prioritize).

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

- (usually) UV incomplete, but a valid theory to calculate in, theoretical precision limited by lack of loops usually. Metric on NP "theory space" also not defined. Good luck on guessing!

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

- UV incomplete, but a valid theory to calculate in, theoretical precision limited by in many cases

$$C_i \, \frac{v^2}{\Lambda^2} \frac{\alpha}{4\pi} \log\frac{\Lambda}{v^2}, \quad C_j \, \frac{p^2}{\Lambda^2} \frac{\alpha}{4\pi} \log\frac{\Lambda}{v^2}, \quad C_k \, \frac{p^2 \, q^2}{\Lambda^4}, \quad C_l \, \frac{p^2 \, v^2}{\Lambda^4}, \quad C_m \, \frac{v^4}{\Lambda^4}$$

We can systematically reduce these theory imprecisions in advance of a discovery or anomaly. This talk focussed on the first term above.

$\mathcal{L}_{SMEFT} \neq \mathcal{L}_{SM} + \mathcal{L}_{NP}$

- $\mathcal{L}_{SMEFT}$ a vast simplification studying the data on SM poles and below the (unknown) scale Λ

- NOT useful or predictive when studying the data above Λ .
The theory informs us of this with unitarity violation and the breakdown of the defining expansion

- These theories are different for their range of validity. And also due to the UV counter-terms being NOT THE SAME.

$$Z_{SMEFT} \neq Z_{SM} + Z_{NP}$$

- Counterterms are different, as is relation to asymptotic properties of S matrix to Lagrangian parameters.

The core question

For one loop in SMEFT..

- WHY should one loop calculations in SMEFT follow the same theoretical paradigm as renormalizable theories?
(In the technical execution of perturbative corrections.)

- Could be the case so long as the SM $\neq$ SMEFT basic features do not have subtleties related to renormalization/one loop calcs.

Is this true? No.

- Reason:

$\sqrt{2\,\langle H^\dagger H\rangle} \sim 246\,\mathrm{GeV}$	$+d \leq 4$	on-shell simplification
	$+d > 4$	local operator degeneracy

For one loop in SMEFT..

- WHY should one loop calculations in SMEFT follow the same theoretical paradigm as renormalizable theories?
  (In the technical execution of perturbative corrections.)

- Could be the case so long as the SM $\neq$ SMEFT basic features do not have subtleties related to renormalization/one loop calcs.

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

- Reason:

$\sqrt{2\,\langle H^\dagger H\rangle} \sim 246\,\mathrm{GeV}$ $\quad +d \leq 4$ on-shell simplification
$\quad +d > 4$ local operator degeneracy

SM one loop subtleties

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

(blue circle) wavefunction renormalization and renormalization condition on two point function quite straightforward

(red circle) wavefunction renormalization and renormalization condition on two point functions more subtle. WHY? Asymptotic properties of S matrix elements not as trivially related to Lagrangian parameters. Due to rotation between weak and mass eigenbasis.

SM one loop subtleties

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

Subtleties - light quarks not asymptotic particle states, but we use Hadronization models and factorization, and light quarks inferred through chiral pert theory relations

- b quark is a special case extracted in HQET

- top quark decays rapidly, not asymptotic particle state leads to the endless top mass debates.

Not directly measured yet. And certainly not to accuracy of one loop EW corrections.

The basic issues I: Degeneracy

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \cdots + C_1 \mathcal{Q}_1 + C_2 \mathcal{Q}_2 + \cdots$$

$$\sqrt{2\langle H^\dagger H \rangle} \sim 246\,\mathrm{GeV}$$

$$\mathcal{L}_{SMEFT} = \mathcal{L}^1_{SM}\left(g_{SM} + C_1 \frac{v^2}{\Lambda^2} + C_2 \frac{v^2}{\Lambda^2} + \cdots\right) + \cdots + \mathcal{L}^2_{SM}\left(g_{SM} + C_n \frac{p^2}{\Lambda^2} + C_m \frac{p^2}{\Lambda^2} + \cdots\right) +$$

- On-shell renormalization schemes for renormalizable theories are convenient to the degree degeneracies of this form are avoided.
- More parameter degeneracy in particular observable is a structural feature of the SMEFT.

The basic problems 2: Structure

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

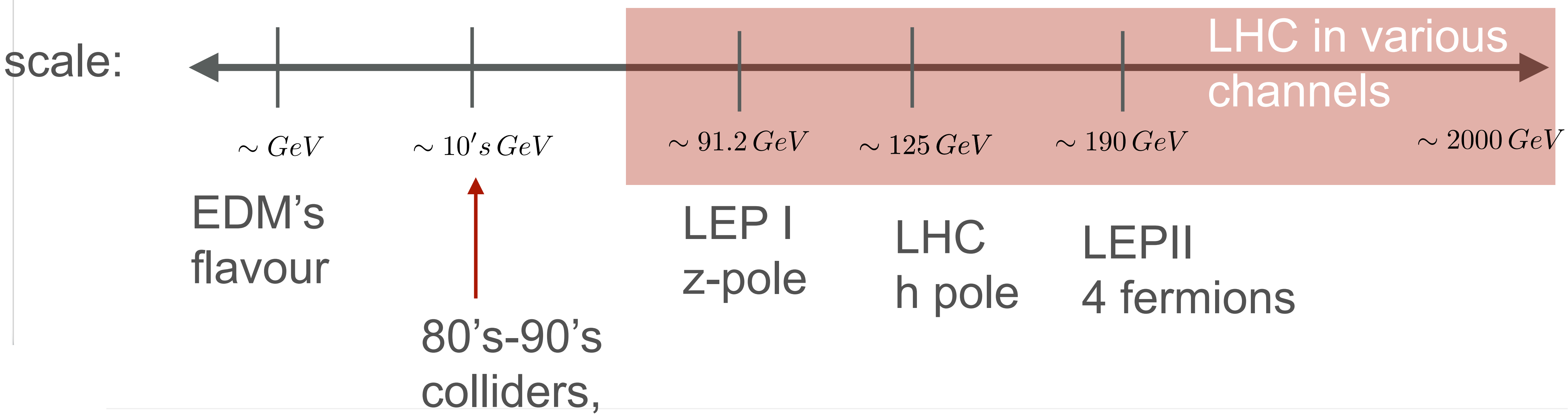
- Background field gauge fixing is convenient (awesome). By not breaking the global symmetry structure of the theory in gauging, a whole series of technical simplifications.
- All the experts are in the audience! For a nice discussion see 9410338 Denner,Weiglein, Dittmaier
- The problem is that the structure of the SMEFT is different than the SM even though the global symmetry is the same. And differences complicate the standard BFM techniques.

The basic problems 2: Structure

- Keep all operators at fixed operator dimension required. True at tree level and one loop. CAN neglect terms numerically suppressed due to IR physics (such as a smeft loop) once dependence of observable is known.

- EOM reductions of the SMEFT extensive compared to renormalizable theories. This + $\sqrt{2\,\langle H^\dagger H \rangle} \sim 246\,\mathrm{GeV}$ = degeneracy. Need to combine data sets in global fits.

- Experimental scales distinct/hierarchy in experimental precision



Two examples.

- One loop SMEFT result of $h \to \gamma\,\gamma$
- Partial one loop results of $Z \to \bar{\psi}\,\psi$

SM Higgs to di-photon reminder

- Very well known in the literature:

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

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

- Full 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 $|\Delta_{EW} + \Delta_{QCD}| \sim 1.5\%$

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

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

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

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.

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

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

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

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

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

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

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

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.

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

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 (and checked, all typos/bugs ironed out)

  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" (buyer beware)

  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

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

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

- 3x3 sub-matrix of ops that contribute at tree level and first at one loop

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

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

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_ξ 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:

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

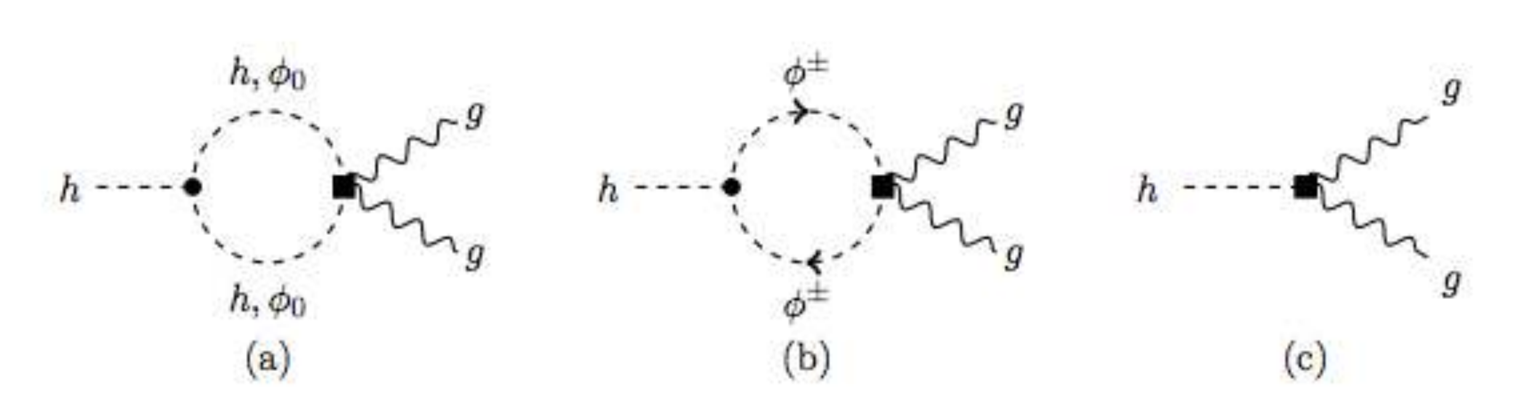
Also need the Higgs wavefunction and vev renorm

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

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

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

The ggh trick



The $h \to g\, g$ trick relies on lack of mixing of the G gauge field. Calc diagrams above.

Use known counterterms for EW SM and SMEFT operator:

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

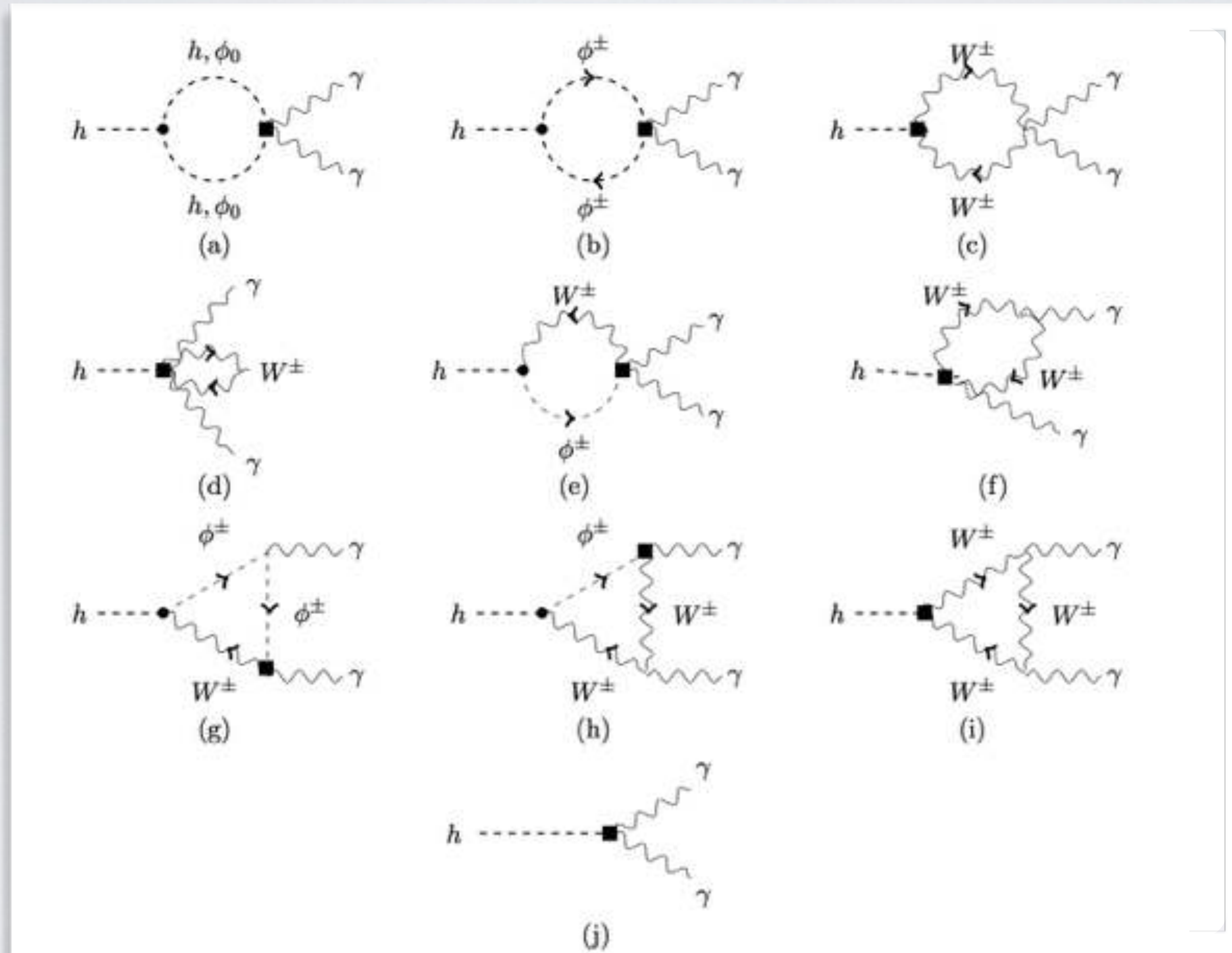
$$Z_{HG} = 1 + \frac{1}{16\,\pi^2\,\epsilon}\left[-\frac{3g_1^2}{4} - \frac{9g_2^2}{4} + 6\lambda + Y\right].$$

Remaining divergences defines:

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

The required loops.

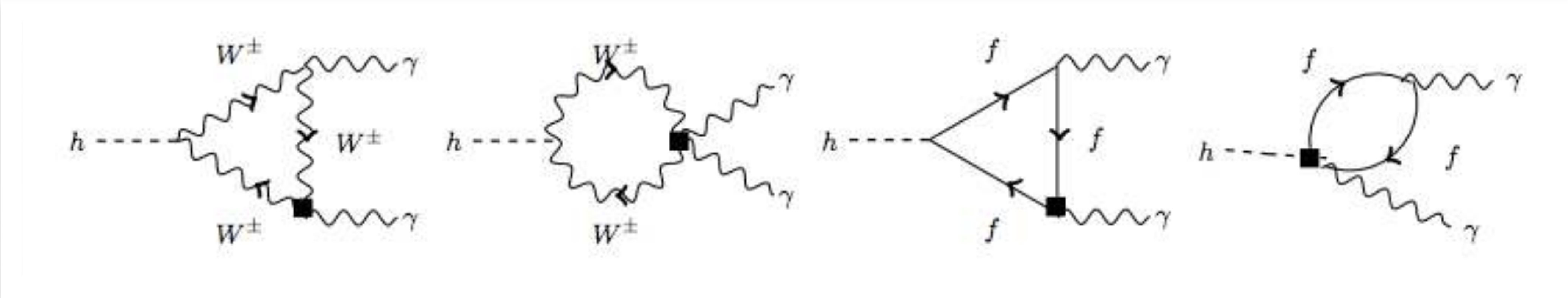
- Calculate in BF method, in R_ξ gauge, for operators that contribute at tree level



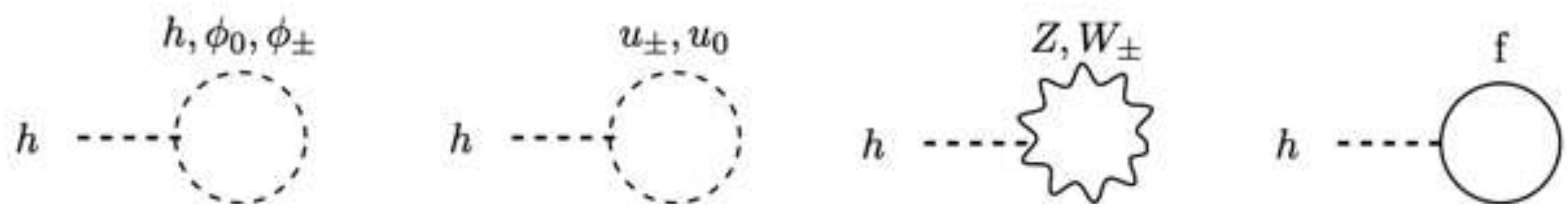
- Gauge dependence cancels ✓ remaining divergences cancel exactly ✓

The required loops.

- Calculate in BF method, in R_ξ gauge, for operators that contribute at loop level only



- Define vev of the theory as the one point function vanishing - fixes δv



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

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!

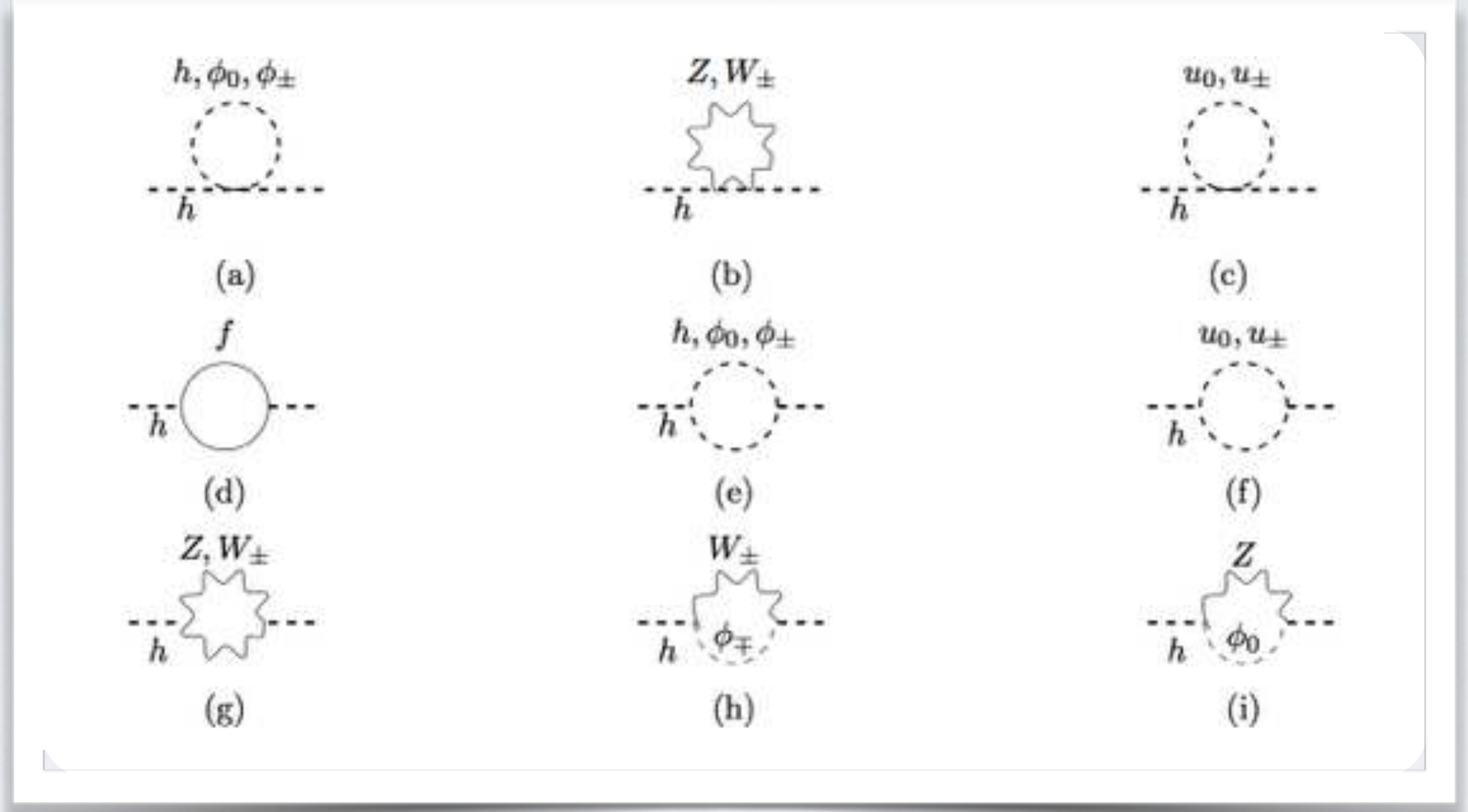
- Remaining finite terms fixed by defining in renormalization conditions on the couplings and two point function residues and poles

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

This relation follows from a Ward identity using BFM.

Higgs two point functions

- Required Higgs two point function results

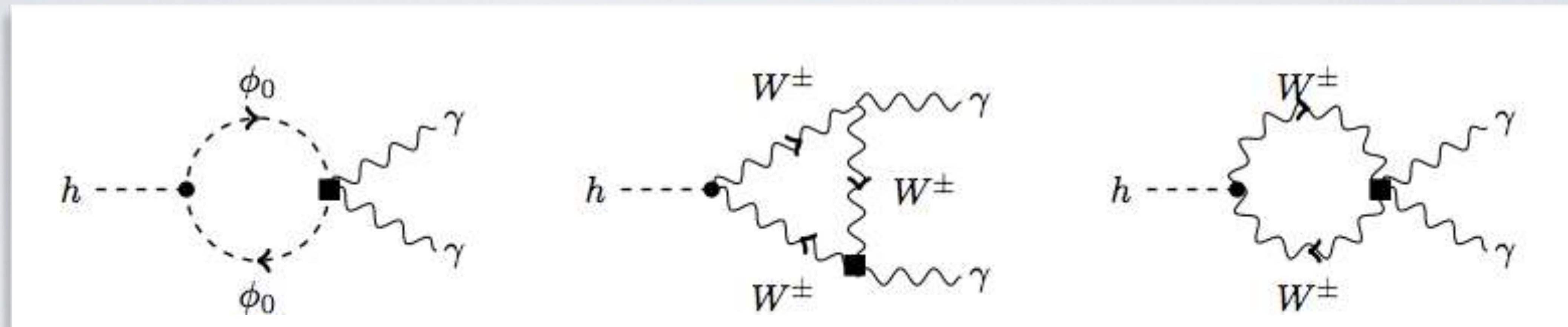


This result is pretty well known, but where is it ?! for finite terms in R_ξ gauge in BF method

We will supply it upon request for general ξ .

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

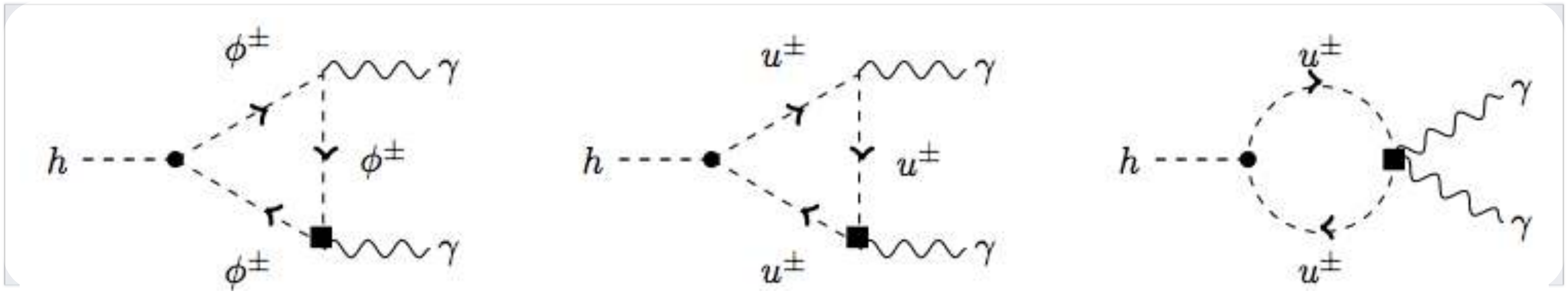
$$
\begin{aligned}
\mathcal{L}_{GF} = &-\frac{1}{2\,\xi_W}\sum_a \left[\partial_\mu W^{a,\mu} - g_2\,\epsilon^{abc}\hat{W}_{b,\mu}W_c^\mu + i\,g_2\,\frac{\xi}{2}\left(\hat{H}_i^\dagger \sigma^a_{ij} H_j - H_i^\dagger \sigma^a_{ij}\hat{H}_j\right)\right]^2, \\
&-\frac{1}{2\,\xi_B}\left[\partial_\mu B^\mu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

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

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

NLO EFT - Final tree result

- The final tree result is of the form

1505.02646 Hartmann, Trott

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

Where

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

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

NLO EFT - Final tree result

- The final tree result is of the form

1505.02646 Hartmann, Trott

Fixed by renorm conditions

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

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

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

NLO EFT - Final tree result

- The final tree result is of the form

1505.02646 Hartmann, Trott

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

← “(not so) Large” log terms consistent with RGE

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

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

NLO EFT - Final tree result

- The final tree result is of the form

1505.02646 Hartmann, Trott

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

Finite terms with associated logs terms

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

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

NLO EFT - Final tree result

- The final tree result is of the form

1505.02646 Hartmann, Trott

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

“Pure” finite terms not in $C_{\gamma\,\gamma}$ and no associated log

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

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

NLO EFT - 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)

- <u>The RGE is not a good proxy for the full one loop structure of the SMEFT in general.</u>

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

Full NLO SMEFT 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:

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

- SM rescalings: (only this in eHdecay)

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

In terms of usual loop functions of the SM.

Do we need this SMEFT NLO?

- 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, $C_i \sim 1$:

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

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

$\kappa_\gamma = 0.93^{+0.36}_{-0.17}$ 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 $[167, 21]\,\%$

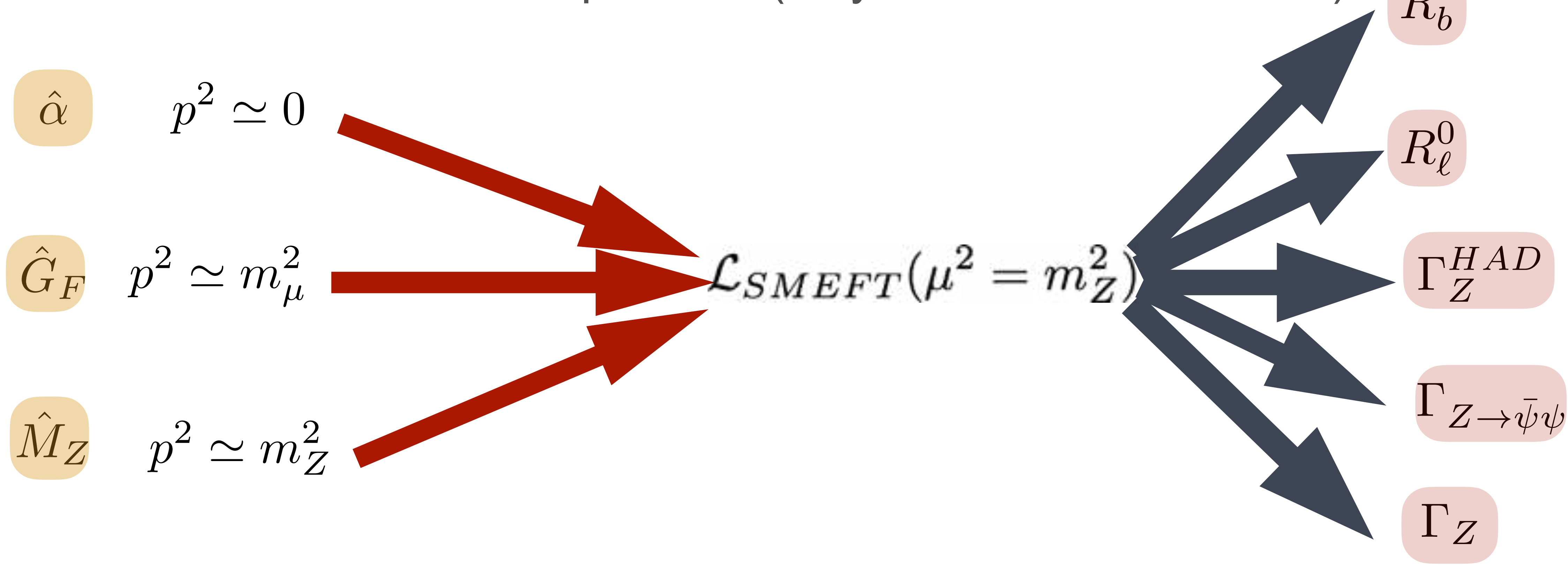
$\kappa_\gamma^{proj:HILHC} = 1 \pm 0.03$ $[250, 31]\,\%$

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

SMEFT decay widths of the Z at one loop

arXiv:1611.09879 One Loop Z C. Hartmann, W. Shepherd, MT

- This is a multi-scale hard problem (only $\propto y_t, \lambda$ sorted to date)



- LSZ defn: $\langle Z|S|\bar{\psi}_i\,\psi_i\rangle = (1 + \frac{\Delta R_Z}{2})(1 + \Delta R_{\psi_i})\, i\, \mathcal{A}_{Z\bar{\psi}_i\psi_i}.$

- Need to loop improve the extraction of parameters AND the decay process of interest.

input shifts decay process (wavefunction&process)

see also : Passarino et al arXiv:1607.01236 , arXiv:1505.03706

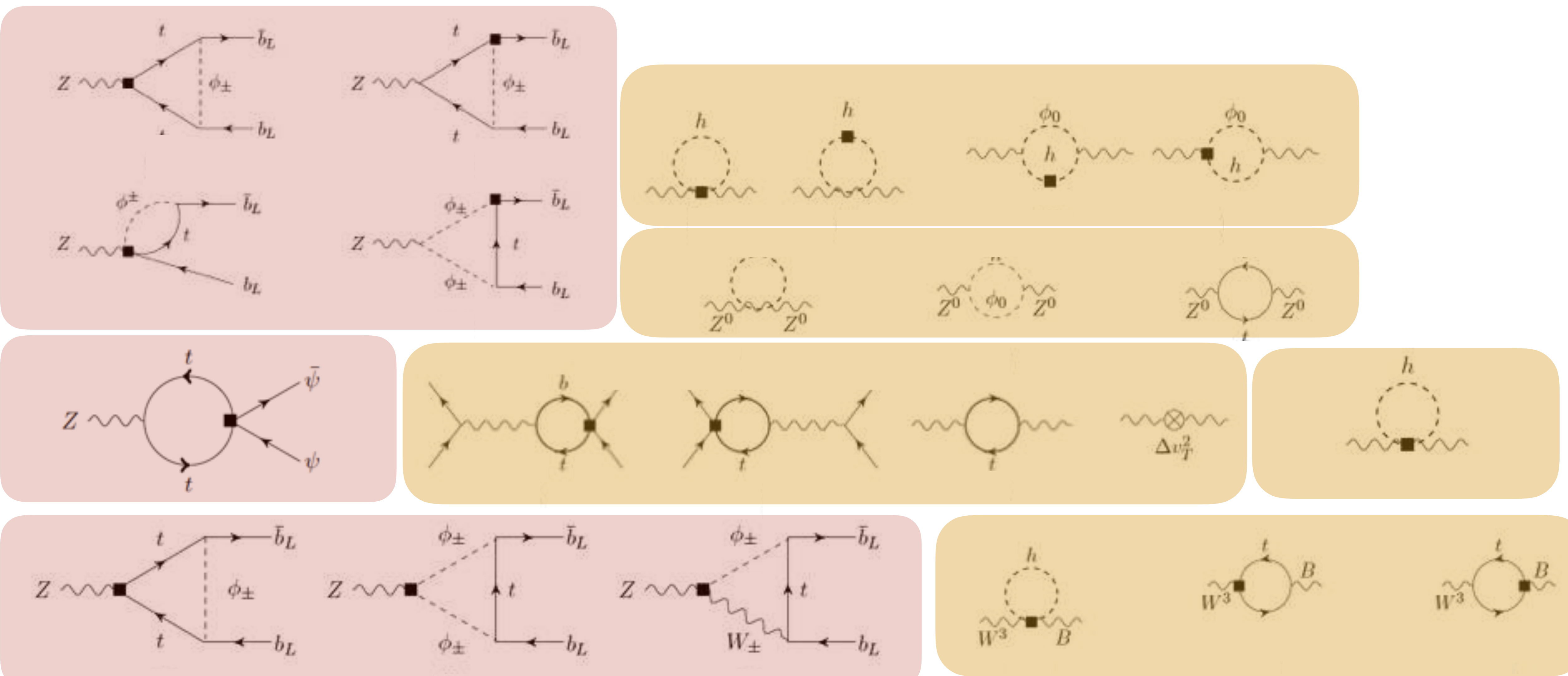
Loops present

- ~ 30 massive loops in addition to the RGE dim reg results of

arXiv:1301.2588 Grojean, Jenkins, Manohar, Trott

arXiv:1308.2627, 1309.0819, 1310.4838 Jenkins, Manohar, Trott

arXiv: 1312.2014 Alonso, Jenkins, Manohar, Trott

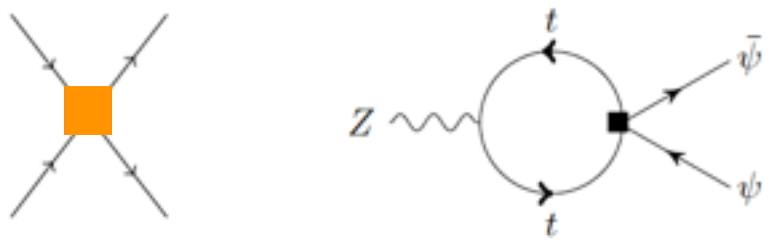


Again we need to combine data sets.

- (At least) the following operators contribute at one loop to EWPD, that are not present at tree level

$$\{C_{qq}^{(1)}, C_{qq}^{(3)}, C_{qu}^{(1)}, C_{uu}, C_{qd}^{(1)}, C_{ud}^{(1)}, C_{\ell q}^{(1)}, C_{\ell q}^{(3)}, C_{\ell u}, C_{qe}, C_{HB} + C_{HW}, C_{uB}, C_{uW}, C_{uH}\}.$$

- Distinctions between operators made at LO not relevant



- Corrections reported as:

$$\bar{\Gamma}\left(Z \to \psi\bar{\psi}\right) = \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3\, N_c}{6\pi}\left(|\bar{g}_L^{\psi}|^2 + |\bar{g}_R^{\psi}|^2\right),$$

$$\delta\bar{\Gamma}_{Z\to\ell\bar{\ell}} = \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3}{6\pi}\left[2\, g_R^{\ell}\, \delta g_R^{\ell} + 2\, g_L^{\ell}\, \delta g_L^{\ell}\right] + \delta\bar{\Gamma}_{Z\to\bar{\ell}\ell,\psi^4},$$

$$\Delta\bar{\Gamma}_{Z\to\ell\bar{\ell}} = \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3}{6\pi}\left[2\, g_R^{\ell}\, \Delta g_R^{\ell} + 2\, g_L^{\ell}\, \Delta g_L^{\ell} + 2\,\delta g_R^{\ell}\, \Delta g_R^{\ell} + 2\,\delta g_L^{\ell}\, \Delta g_L^{\ell}\right],$$

Parameters exceeds LEP PO at one loop

- Structure of corrections at tree and loop level:

7.2 One loop corrections in the SMEFT

7.2.1 Charged Lepton effective couplings

For charged lepton final states the leading order (flavour symmetric) SMEFT effective coupling shifts are [11]

$$\delta(g_L^\ell)_{ss} = \delta\bar{g}_Z\,(g_L^\ell)_{ss}^{SM} - \frac{1}{2\sqrt{2}\hat{G}_F}\left(C^{(1)}_{\underset{ss}{H\ell}} + C^{(3)}_{\underset{ss}{H\ell}}\right) - \delta s_\theta^2, \quad (7.6)$$

$$\delta(g_R^\ell)_{ss} = \delta\bar{g}_Z\,(g_R^\ell)_{ss}^{SM} - \frac{1}{2\sqrt{2}\hat{G}_F}C_{\underset{ss}{He}} - \delta s_\theta^2, \quad (7.7)$$

where

$$\delta\bar{g}_Z = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{m}_Z^2} + s_{\hat{\theta}}^2\,c_{\hat{\theta}}^2\,4\,\hat{m}_Z^2\,C_{HWB}, \quad (7.8)$$

while the one loop corrections are

$$\Delta(g_L^\ell)_{ss} = \Delta\bar{g}_Z\,(g_L^\ell)_{ss}^{SM} + \frac{N_c\,\hat{m}_t^2}{8\,\pi^2}\log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\left[C^{(1)}_{\underset{ss33}{\ell q}} + C^{(3)}_{\underset{ss33}{\ell q}} - C_{\underset{ss33}{\ell u}}\right] - \Delta s_\theta^2, \quad (7.9)$$

$$\Delta(g_R^\ell)_{ss} = \Delta\bar{g}_Z\,(g_R^\ell)_{ss}^{SM} + \frac{N_c\,\hat{m}_t^2}{8\,\pi^2}\log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\left[-C^{(1)}_{\underset{ss33}{eu}} + C_{\underset{33ss}{qe}}\right] - \Delta s_\theta^2, \quad (7.10)$$

input shifts

decay process

arXiv:1611.09879 One Loop Z C. Hartmann, W. Shepherd, MT

One set of lots o numbers…

- Result for Γ_Z in tev units, RELATIVE 10% correction to the leading effects

$$\frac{\delta \bar{\Gamma}_Z}{10^{-2}} = \Big[-2.82\left(C_{Hd}+C_{He}+C^{(1)}_{H\ell}\right) - 9.87\,C_{HD} - 30.2\,C^{(3)}_{H\ell} + 6.97\,C^{(1)}_{Hq} + 23.6\,C^{(3)}_{Hq}, \\ +3.75\,C_{Hu} - 2.80\,C_{HWB} + 19.7\,C_{\ell\ell}\Big]. \quad (A.22)$$

$$\frac{\delta \Delta\bar{\Gamma}_Z}{10^{-3}} = \Big[(0.214\,\Delta\bar{v}_T + 0.603)\left(C_{Hd}+C_{He}+C^{(1)}_{H\ell}\right) - (1.09\,\Delta\bar{v}_T + 1.44)\,C_{HD}, \\ -(9.69\,\Delta\bar{v}_T + 9.11)\,C^{(3)}_{H\ell} + (0.174\,\Delta\bar{v}_T - 0.049)\,C^{(1)}_{Hq} + (1.73\,\Delta\bar{v}_T - 0.406)\,C^{(3)}_{Hq}, \\ -(0.286\,\Delta\bar{v}_T + 0.725)\,C_{Hu} - (0.560\,\Delta\bar{v}_T + 1.00)\,C_{HWB}, \quad (A.23) \\ +(5.20\,\Delta\bar{v}_T + 4.45)\,C_{\ell\ell} + 3.71\,C^{(3)}_{\ell q} + 1.28\,C^{(3)}_{qq}, \\ +0.101\,C_{uH} + 0.395\,(C_{HB}+C_{HW}) + 26.5\,\Delta\bar{v}_T\Big],$$

$$\frac{\delta \Delta\bar{\Gamma}_Z}{10^{-3}} = \Big[1.03\left(C_{Hd}+C_{He}+C^{(1)}_{H\ell}\right) - 2.56\,C_{HD} - 9.66\,C^{(3)}_{H\ell} - 0.749\,C^{(1)}_{Hq} + 0.590\,C^{(3)}_{Hq}, \quad (A.24) \\ -1.53\,C_{Hu} - 1.71\,C_{HWB} + 8.49\,C_{\ell\ell} - 5.69\,C^{(3)}_{\ell q} + 7.60\,C^{(3)}_{qq}, \\ +0.529\left(C^{(1)}_{\ell q} + C^{(1)}_{qd} + C_{qe} + C^{(1)}_{qd} - C_{\ell u} - C^{(1)}_{ud} - C_{eu}\right) \\ -2.62\,C^{(1)}_{qq} + 0.605\,C^{(1)}_{qu} + 0.067\,C_{uH} + 1.41\,C_{uu} - 0.651\,C_{uW} - 0.391\,C_{uB}\Big] \log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right], \\ + \Big[0.046\left(C_{Hd}+C_{He}+C^{(1)}_{H\ell}\right) + 1.60\times 10^{-4}\,C_{HD}, \; -0.114\,C^{(1)}_{Hq} - 0.386\,C^{(3)}_{Hq}, \\ -0.061\,C_{Hu} + 0.495\,C^{(3)}_{H\ell} - 0.323\,C_{\ell\ell} - 0.034\,C_{HWB}\Big] \log\left[\frac{\Lambda^2}{\hat{m}_h^2}\right].$$

Technical issues I : evanescent

- At one loop, the four fermion operators feeding into anomalous Z couplings have a scheme dependence due to needing to define gamma5 in d dimensions (evanescent)

$$i\mathcal{A}^{HV-NDR} = -\frac{i\,\delta_{pr}}{16\,\pi^2}\,(C^{(1)}_{\substack{qq\\33pr}} + C^{(1)}_{\substack{qq\\pr33}})\, m_z\, v\, y_t^2\, \bar{u}_p\, \tilde{\gamma}_\alpha\, P_L\, u_r.$$

- Diagrams above indicate that you need to do a one loop matching to contributions at one loop in same chosen scheme and feed it into predictions to cancel this scheme dependence

$$C^{(1)}_{\substack{Hq\\pr}} = C^{(1)}_{\substack{Hq\\pr}} + \frac{1}{48\pi^2}\left(C^{(1)}_{\substack{qq\\prst}} + C^{(1)}_{\substack{qq\\stpr}}\right)(2[Y_u^\dagger Y_u]^{st} + [Y_u Y_u^\dagger]^{st}).$$

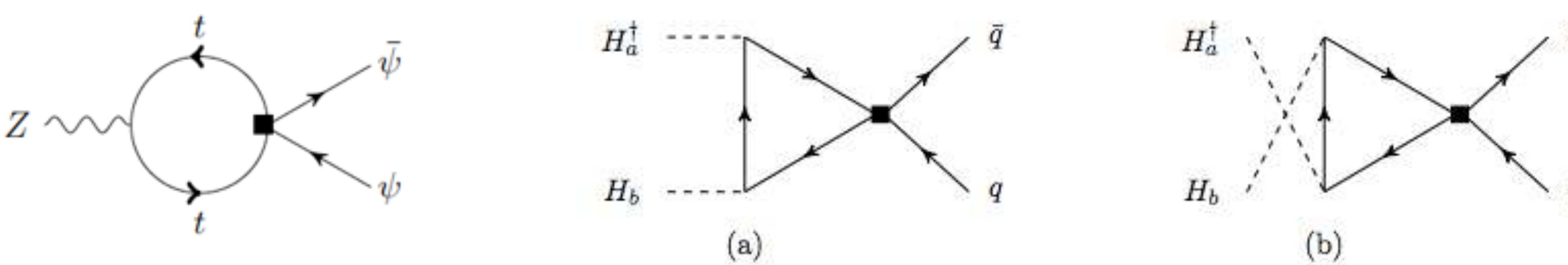


Figure 11: Evanescent one loop matching correction onto $C^{(1)}_{Hq}$.

Technical issues 2: Tadpoles

- In results shown, a combined MSbar scheme with R factors used to fix asymptotic states we have finite tadpole dependence, although the divergence defined to cancel.

$$\frac{i\,\mathcal{A}^{NP}_{total}}{i\,v\,e^2\,\mathcal{A}^{h\gamma\gamma}_{\alpha\beta}} = C_{\gamma\gamma}\left(1+\frac{\delta R_h}{2}+\frac{\delta v}{v}\right), \qquad \frac{\delta\Delta\bar{\Gamma}_Z}{10^{-3}} = \Big[(0.214\,\Delta\bar{v}_T+0.603)\left(C_{Hd}+C_{He}+C^{(1)}_{H\ell}\right)-(1.09\,\Delta\bar{v}_T+1.44)\,C_{HD},$$

Conclusions

- Loop results can be numerically significant for interpretations of the data when precision descends below 10% experimentally and when combining data sets which is required going forward.

- Era of NLO 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

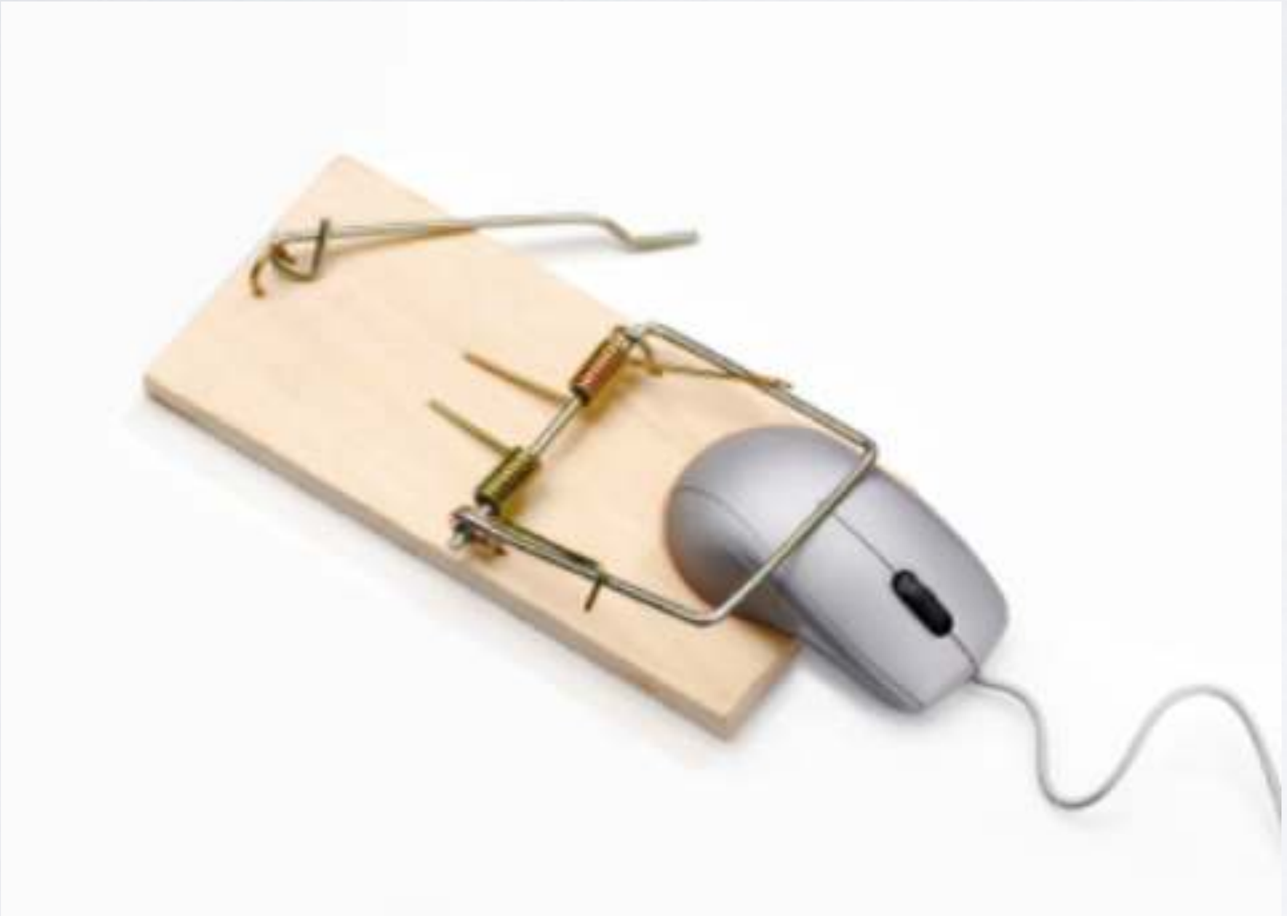
QCD NLO single top production C.Zhang, arXiv:1512.02508

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

- (many more works too many to list here)

NLO EW $h \to ZZ, h \to Z\gamma$ S. Dawson, P.P. Giardino 1801.01136

Proposition



- To make more rapid progress and have codes doing this efficiently (for EW) automatically we need a better BFM-SMEFT gauge fixing mouse trap.

Stay tuned!