NLO SMEFT and global constraints.

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Chicago, USA

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Basic Outline

- The linear SMEFT - status and constraints, interplay with non LHC data and EWPD.

- Why we need to go beyond a LO treatment and theory developments in support of this effort.

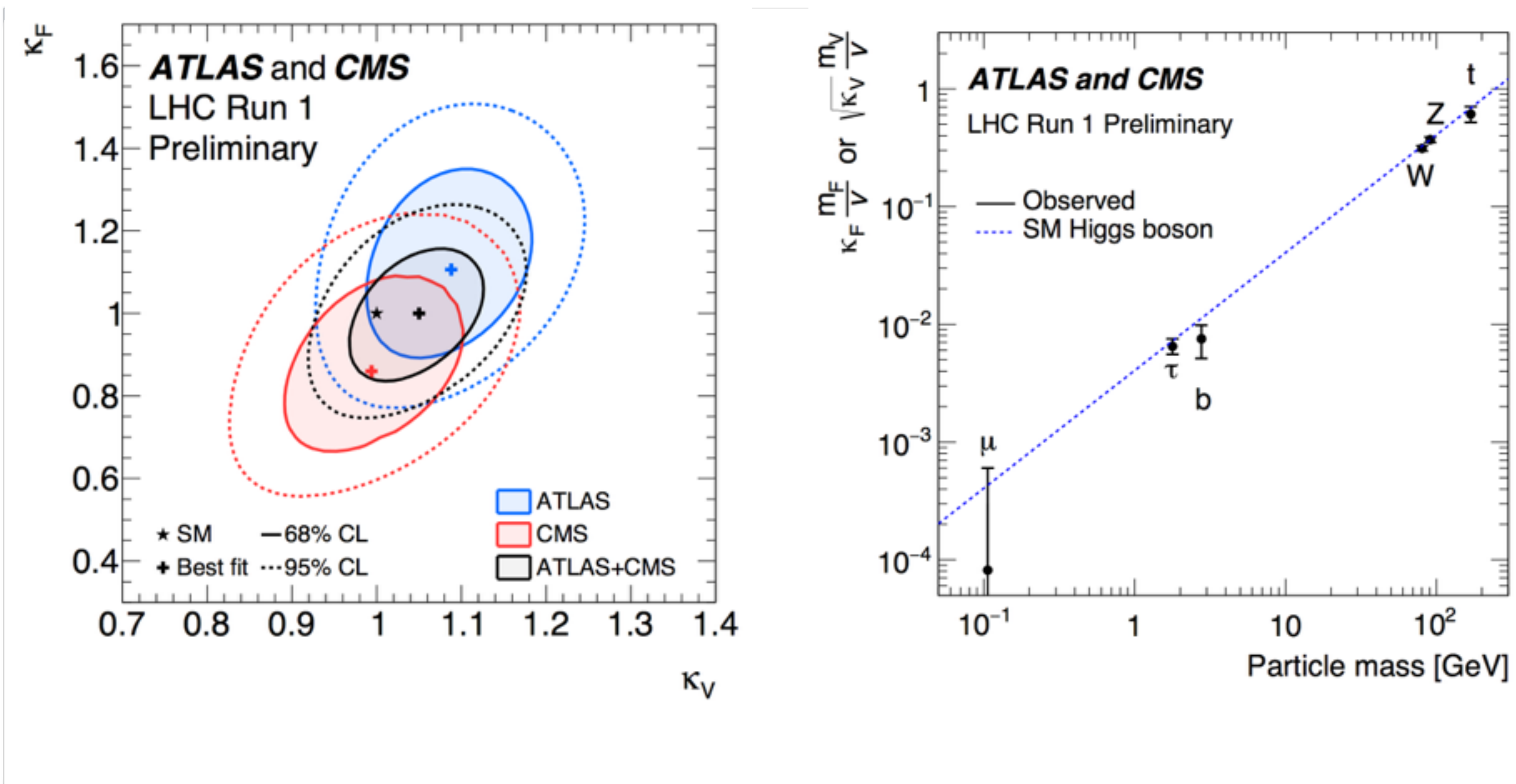
  This effort is only starting!

  The case of $h \to \gamma\,\gamma$ laying a path in the NLO jungle for this effort.

- Will discuss the case of $h \to \gamma\,\gamma$ in some detail and emphasize why the RGE part of the calc is not the whole story.

Run I Legacy

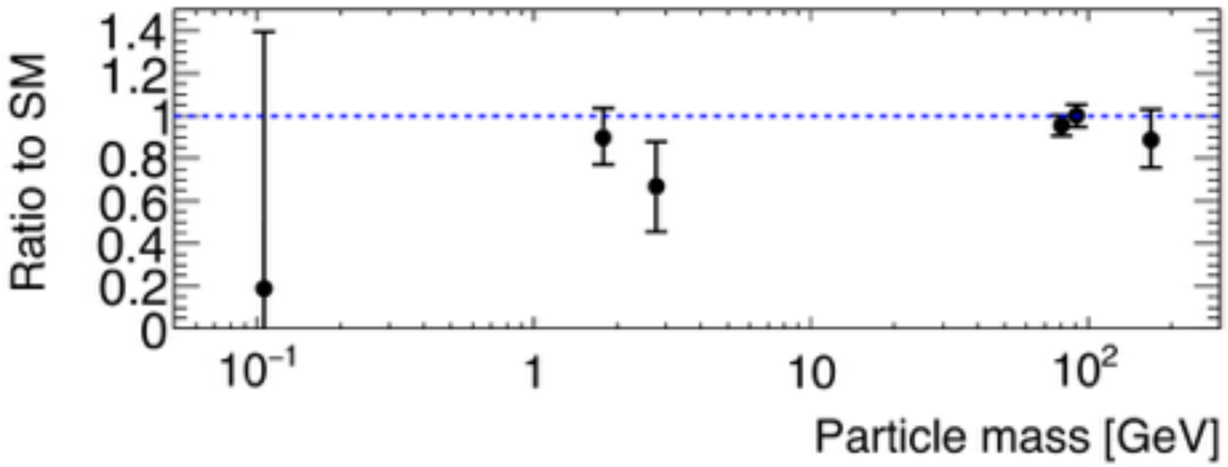
- What do we know? Without a doubt a very Higgs like boson.

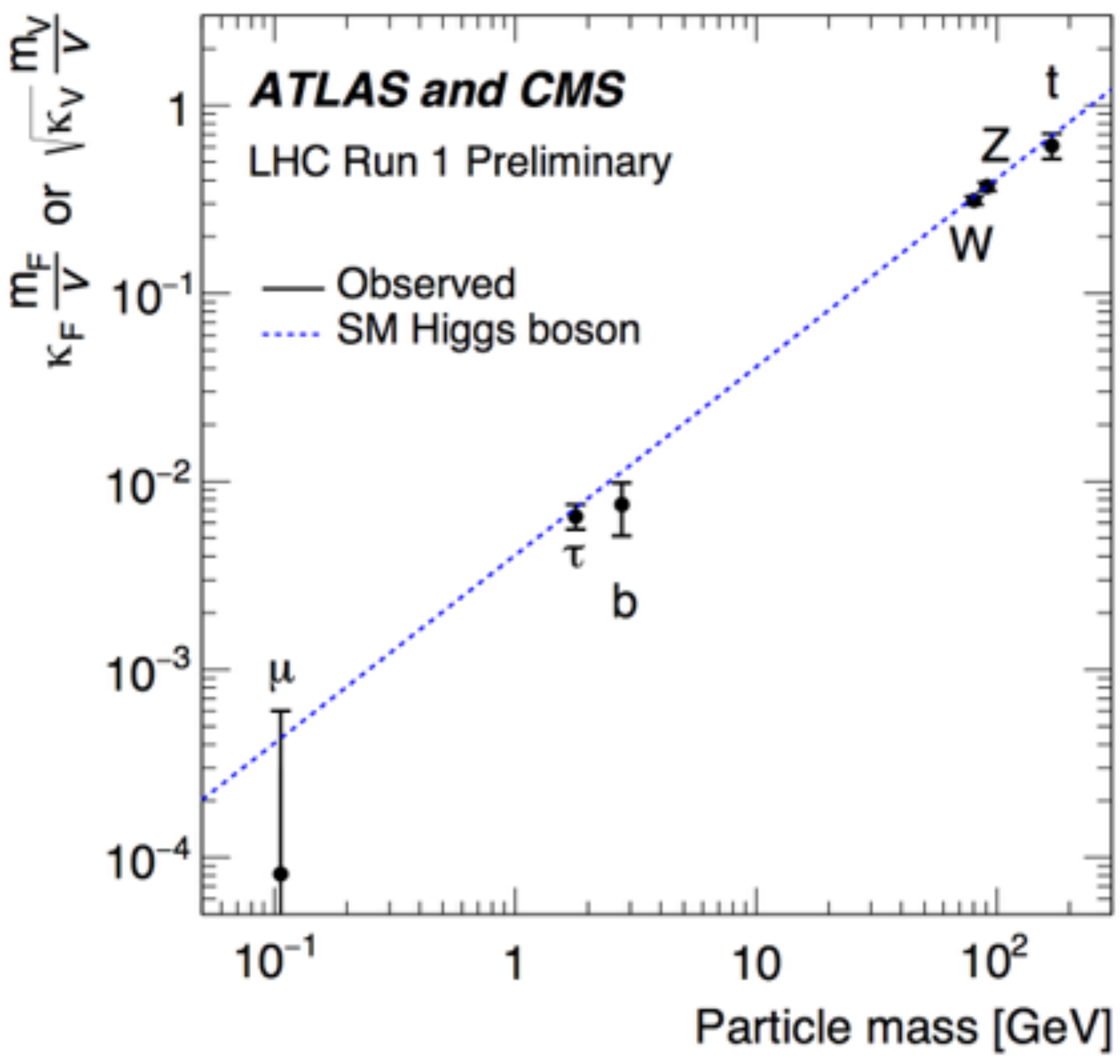


The Cut Off scale(s)

- What do we know? Without a doubt a very Higgs like boson.

However… recall.. didn't Feynman have something to say about log-log plots?





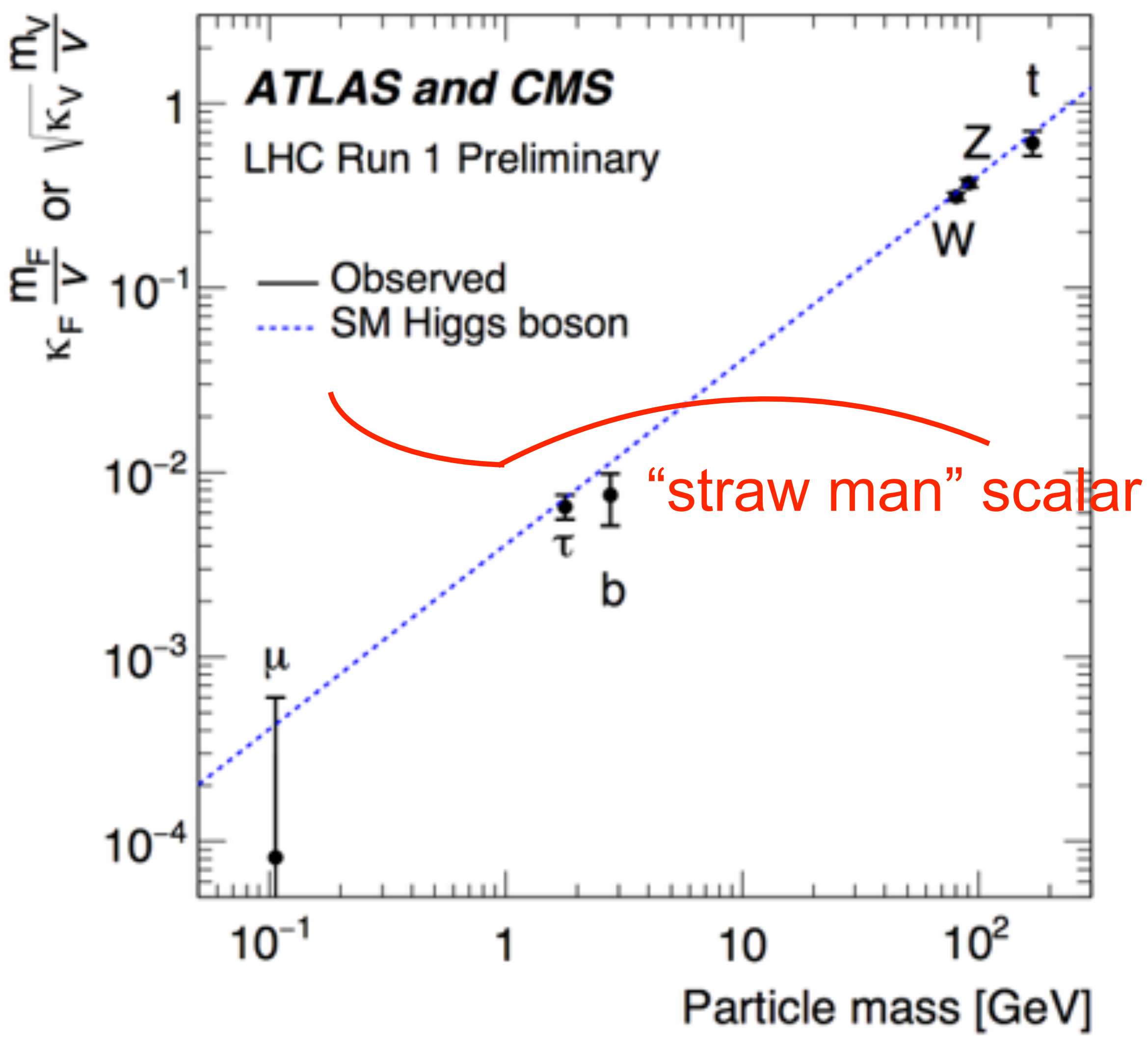
Thats a bit better..

The Cut Off scale(s)

- What do we know? Without a doubt a very Higgs like boson.

1. SM is of course consistent with the data.

2. Scalar that has nothing to do with EWSB is not interesting as an “imposter” now.



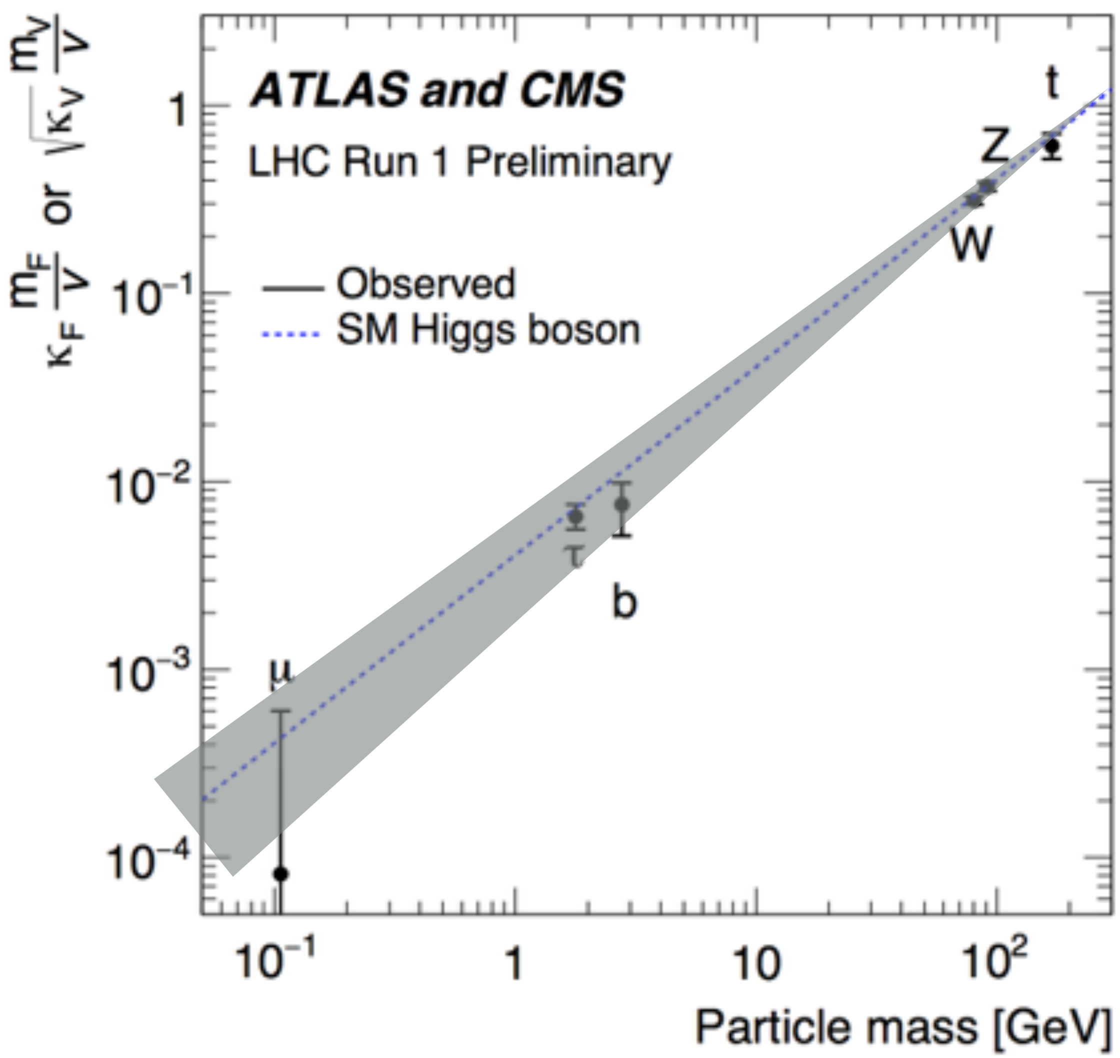
The Cut Off scale(s)

- What do we know? Without a doubt a very Higgs like boson.

1. SM is of course consistent with the data.

3. If one considers relevant scalars, and SMEFT deformations (linear and nonlinear) that are involved with separating the cut off scale from the scale "v" - different story.

Reason: The SM dependence is not random. The mission of the Higgs is to "solve" the unitarity problem of the Higgsless SM.



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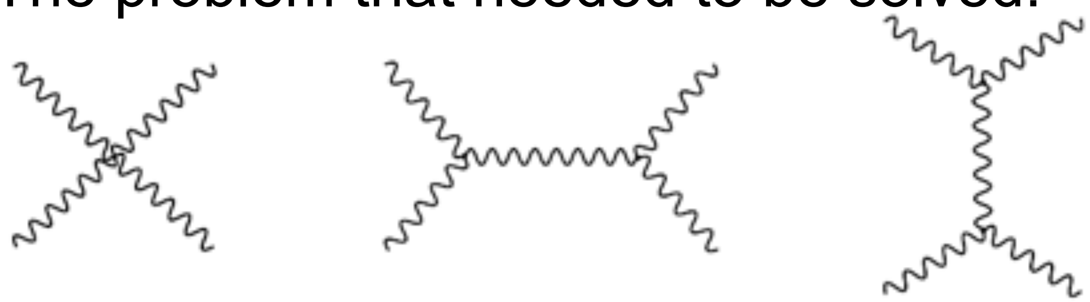
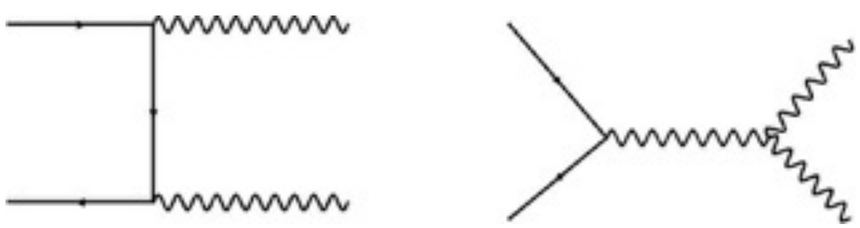
The problem that needed to be solved:

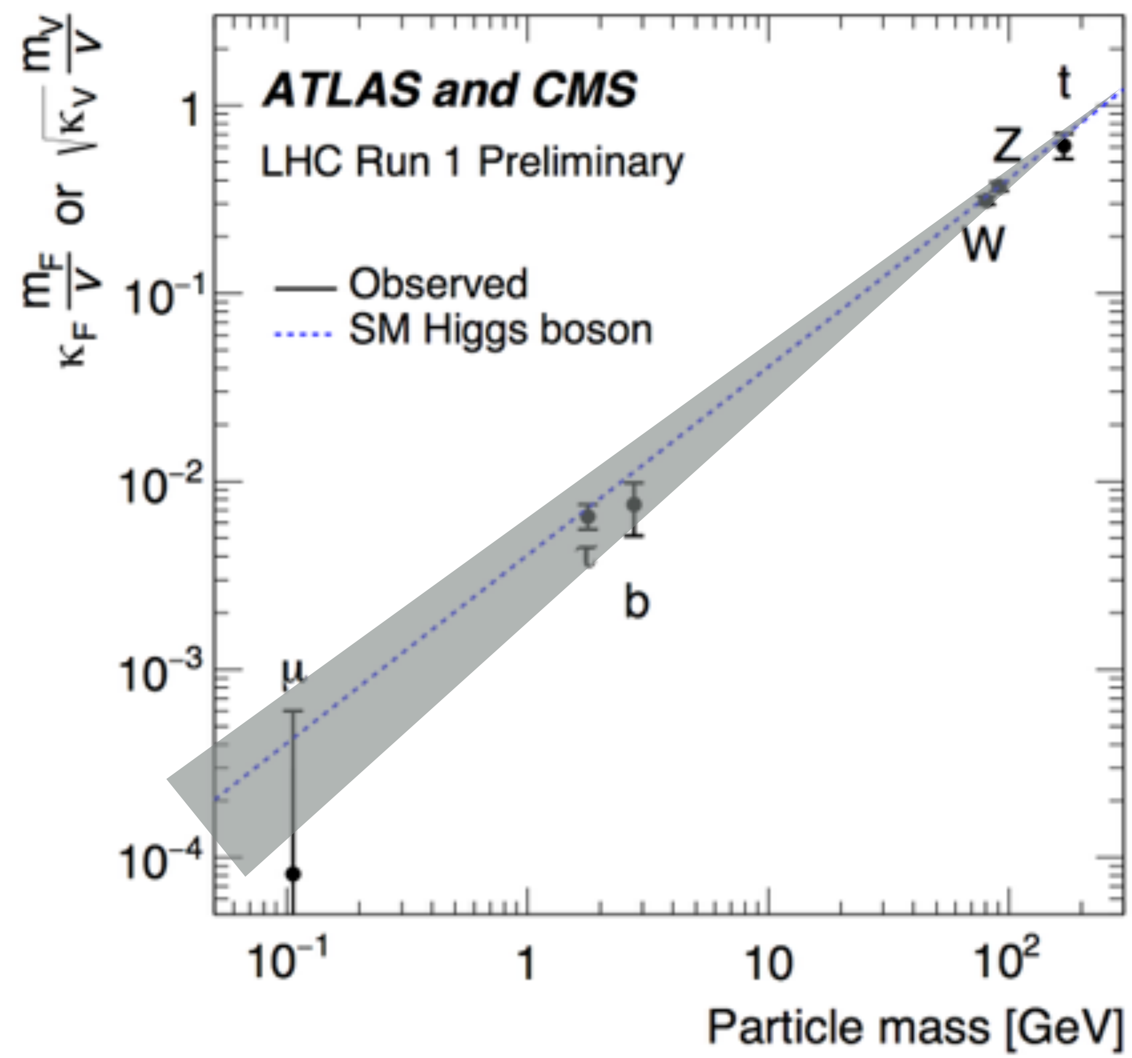


$$W_L^+ W_L^- \to W_L^+ W_L^- \; : \quad \mathcal{A} \simeq \frac{g^2}{4\, m_W^2}\,(s+t)$$

$$\epsilon_L^\mu \simeq p^\mu / m_W$$



$$\psi \bar{\psi} \to W_L^+ W_L^- \; : \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2}$$



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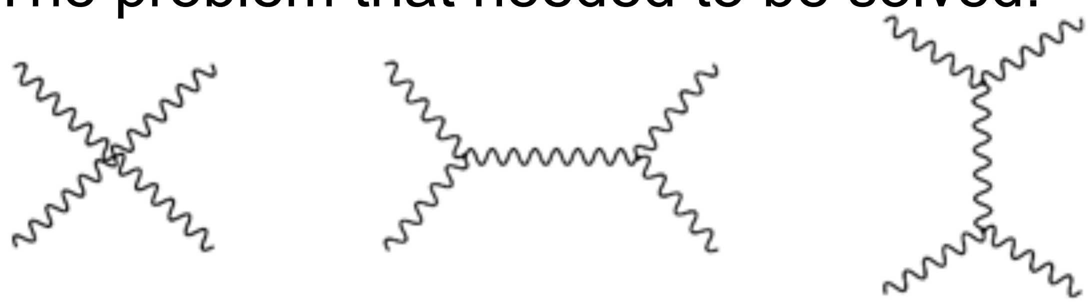

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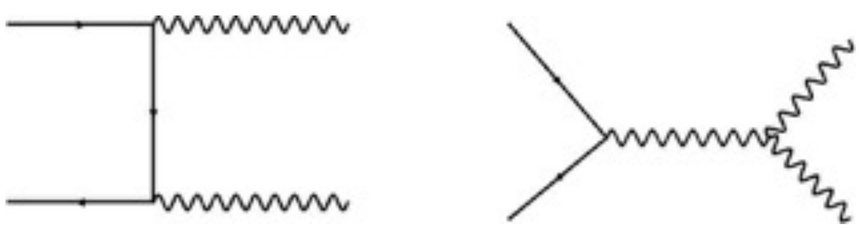

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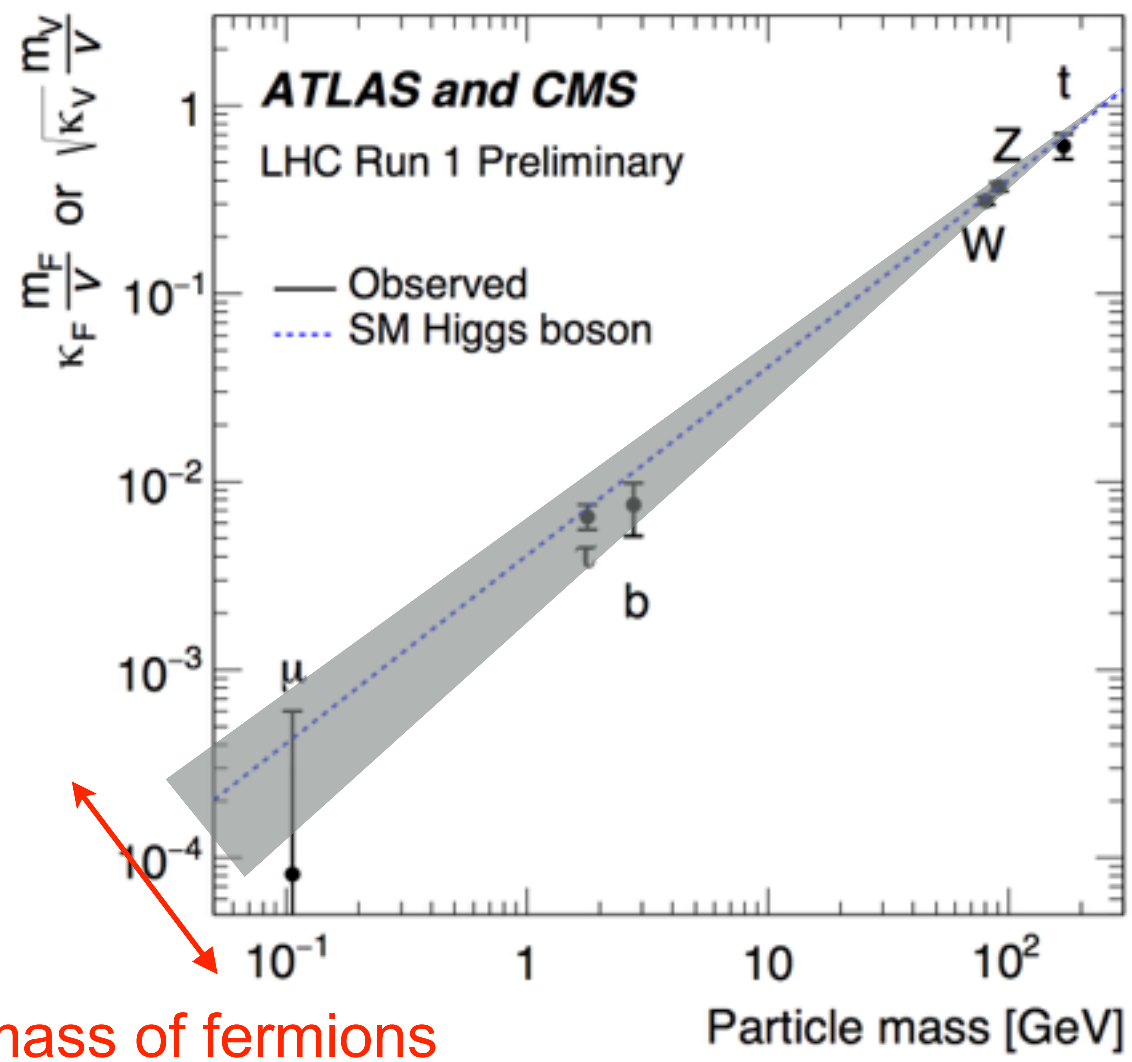


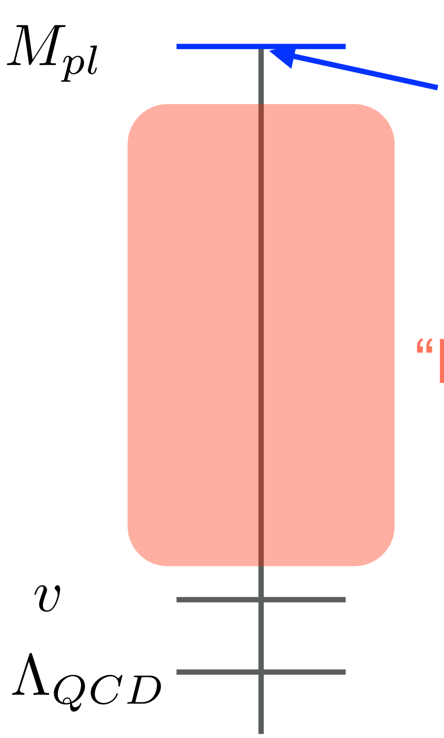
Lighter mass of fermions
suppress unitarity violation to
larger scales if couplings deviate from SM.

The Cut Off scale(s)

- What do we know? Without a doubt a very Higgs like boson.

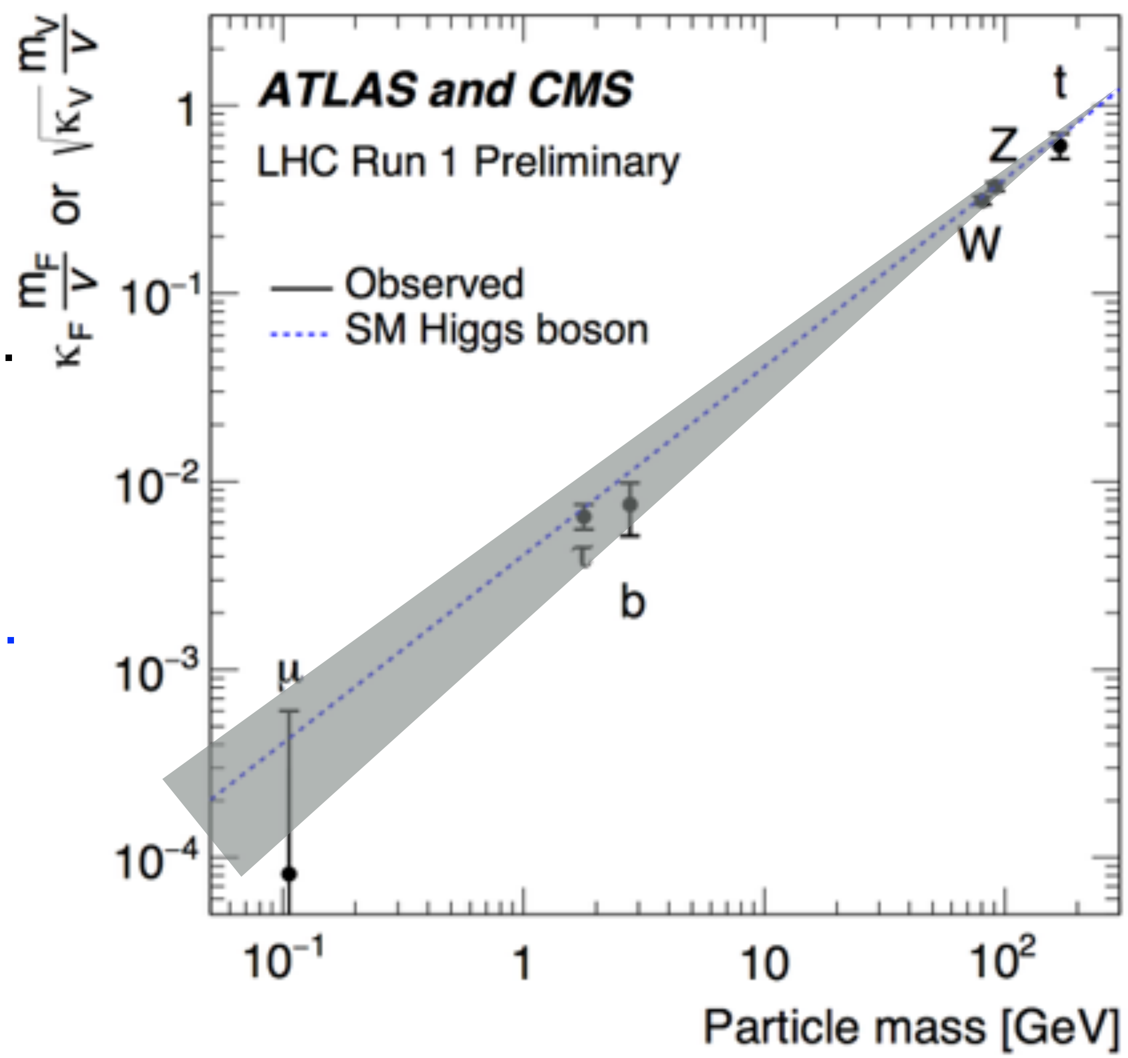
1. SM is of course consistent with the data.

Lesson: The observed Higgs like boson pushed the cut off scale away from the EW scale.



Exactly the SM Higgs.
Nothing else coupled to the SM.

“Higgs like scalar” cut off scales



Relevant question is - how far is the cut off scale?

What is the EFT: 1)Nonlinear EFT

Two options. Not obvious to choose between them for cut off scale reasons stated.

1) Nonlinear EFT - built of

$$\Sigma = e^{i\sigma_a \pi^a/v} \quad h$$

History of this idea is quite a story and a talk itself, see citing in 1504.01707, 1409.1571

$$\mathcal{L} = -\frac{1}{4}W^{\mu\nu}W_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}G^{\mu\nu}G_{\mu\nu} + \bar{\psi}iD\psi$$

$$+ \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma) - \frac{v}{\sqrt{2}}(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + h.c.,$$

"Higgs like boson" couplings are given by adding all possibly "h" interactions

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu\Sigma^\dagger D^\mu\Sigma)\left[1 + 2\,a_{W,Z}\frac{h}{v} + b_{Z,W}\frac{h^2}{v^2} + b_{3,Z,W}\frac{h^3}{v^3} + \cdots\right],$$

$$-\frac{v}{\sqrt{2}}(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c_i^{u,d}\frac{h}{v} + c_{2,j}^{u,d}\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + h.c.,$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + \frac{d_3}{6}\left(\frac{3\,m_h^2}{v}\right)h^3 + \frac{d_4}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \cdots.$$

SM mass scales then unrelated to scalar couplings - ***this is used in the "kappa" fits.***

What is the EFT: Assumptions

Here are my assumptions for the analyses in this talk.

- Assume linear SMEFT formalism. Neglect operators that violation Lepton and Baryon number.
- Power counting is most naive general power counting all operators suppressed by $\bar{v}_T^2/\Lambda^2$, W coefficients order 1 till constrained (implicitly interested in case $1\,\mathrm{TeV} \lesssim \Lambda \lesssim 3\,\mathrm{TeV}$)
- Fitting W coefficients, not absorbing some scale dependence into effective parameters, as no complete one loop analysis.
- In fits using a $U(3)^5$ and CP even assumption (for now)

What is the EFT: Assumptions

- NOT assuming any particular UV, no “minimal coupling”, no “universal theories”, no renormalizability of UV assumption, no $g^\star$.
- Although i agree that the physical regulation of the UV behavior in the EFT will be, well physics, the $g^\star$ thinking is avoided as it is not systematically improvable and not appropriate for all UV.
- That thinking IS a sub-case of interest clearly motivated by analogy to 4 fermi theory. This case is present in suppressed coupling dependence in the W coefficients, and the cut off scale.
  But it is not the only case.

What is the EFT: Linear SMEFT

Linear EFT - built of H doublet + higher D ops

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

- Glashow 1961, Weinberg 1967 (Salam 1967)
- Weinberg 1977
- Leung, Love, Rao 1984, Buchmuller Wyler 1986, Grzadkowski, Iskrzynski, Misiak,Rosiek 2010
- Weinberg 1979, Abbott Wise 1980
- Lehman 2014 (student at Notre Dame) arXiv:1410.4193
- Lehman,Martin 2015 (couple weeks ago!) arXiv:1510.00372.

We are up to one order a year!

Complexity is scaling up…

Linear EFT - built of H doublet + higher D ops

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

(red) 14 operators, or 18 parameters (+ 1 op and then 19 with strong CP)

(blue) 1 operator, and 7 extra parameters

Complexity is scaling up…

Dim 6 counting is a bit non trivial.

Class		$N_{\rm op}$	CP-even n_g	1	3	CP-odd n_g	1	3
	1 g^3X^3	4	2	2	2	2	2	2
	2 H^6	1	1	1	1	0	0	0
	3 H^4D^2	2	2	2	2	0	0	0
	4 $g^2X^2H^2$	8	4	4	4	4	4	4
	5 $y\psi^2H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
	6 $gy\psi^2XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
	7 ψ^2H^2D	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
	8 : $(\overline{L}L)(\overline{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
	8 : $(\overline{R}R)(\overline{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
ψ^4	8 : $(\overline{L}L)(\overline{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
	8 : $(\overline{L}R)(\overline{R}L)$	1	n_g^4	1	81	n_g^4	1	81
	8 : $(\overline{L}R)(\overline{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
	8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total		59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

Complexity is scaling up…

Linear EFT - built of H doublet + higher D ops

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

14 operators, or 18 parameters (+ 1 op and then 19 with strong CP)

1 operator, and 7 extra parameters

59 + h.c operators, or 2499 parameters (76 with $N_f = 1$)
arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

4 operators, or 408 parameters (all violate B number)
arXiv:1405.0486 Alonso, Cheng, Jenkins, Manohar, Shotwell

20 operators, (all violate L number, 7 violate B number)
arXiv:1410.4193 Lehman

535+h.c. operators (with $N_f = 1$), 49 violate B number
arXiv:1510.00372 Lehman, Martin

Complexity is scaling up…

Linear EFT - built of H doublet + higher D ops

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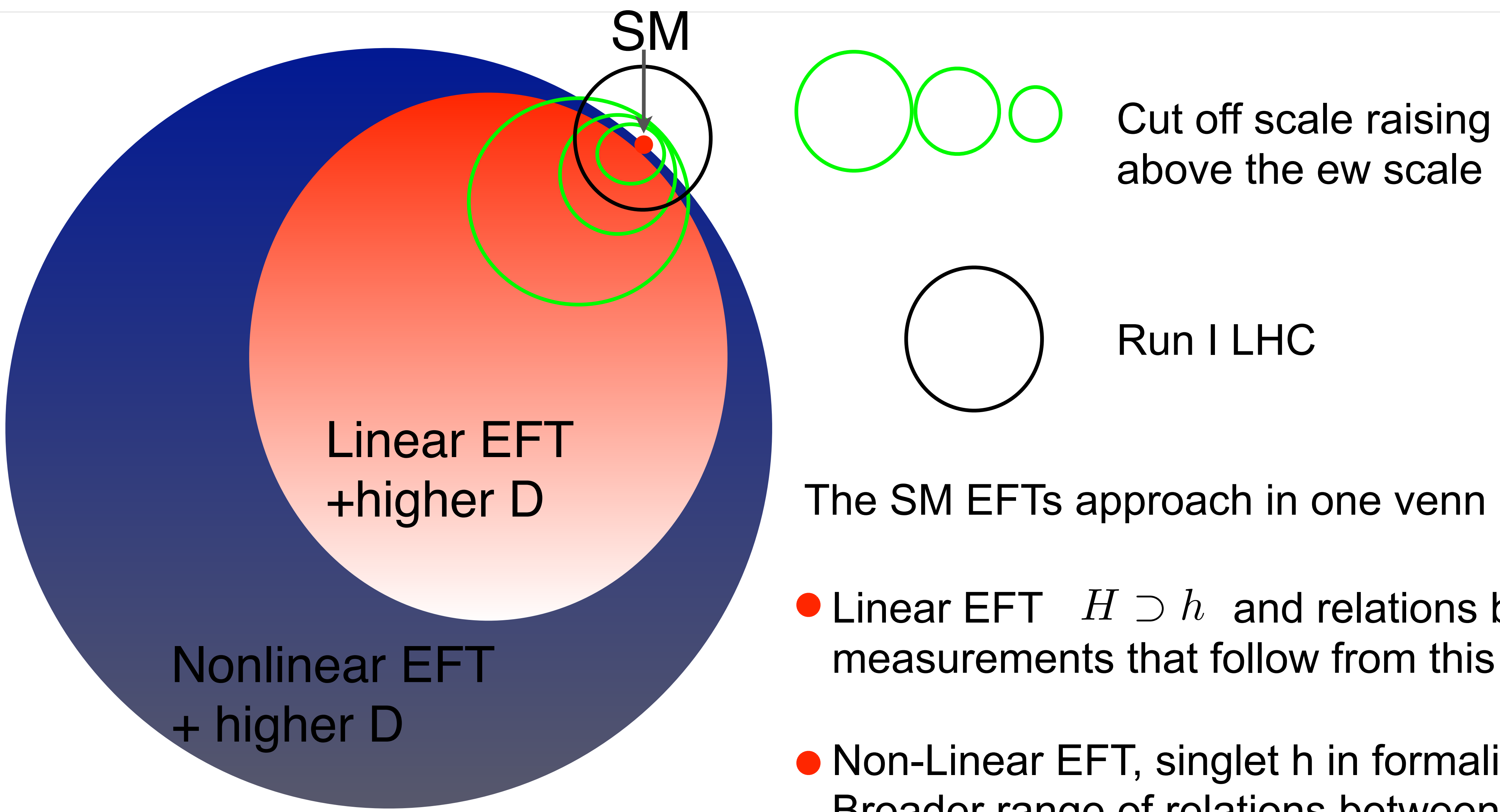
- Can reduce the number of relevant parameters to about 50 or so using flavour symmetry and neglecting CP violation, using scaling when near resonances..
  - WE CAN DO THE RELEVANT GENERAL CASE!
  - Consistent power counting can also be done.
  - There is no need for extra model dependence to be introduced or vague assumptions.

    Can always restrict to less general case AFTER general analysis.

What is the picture?

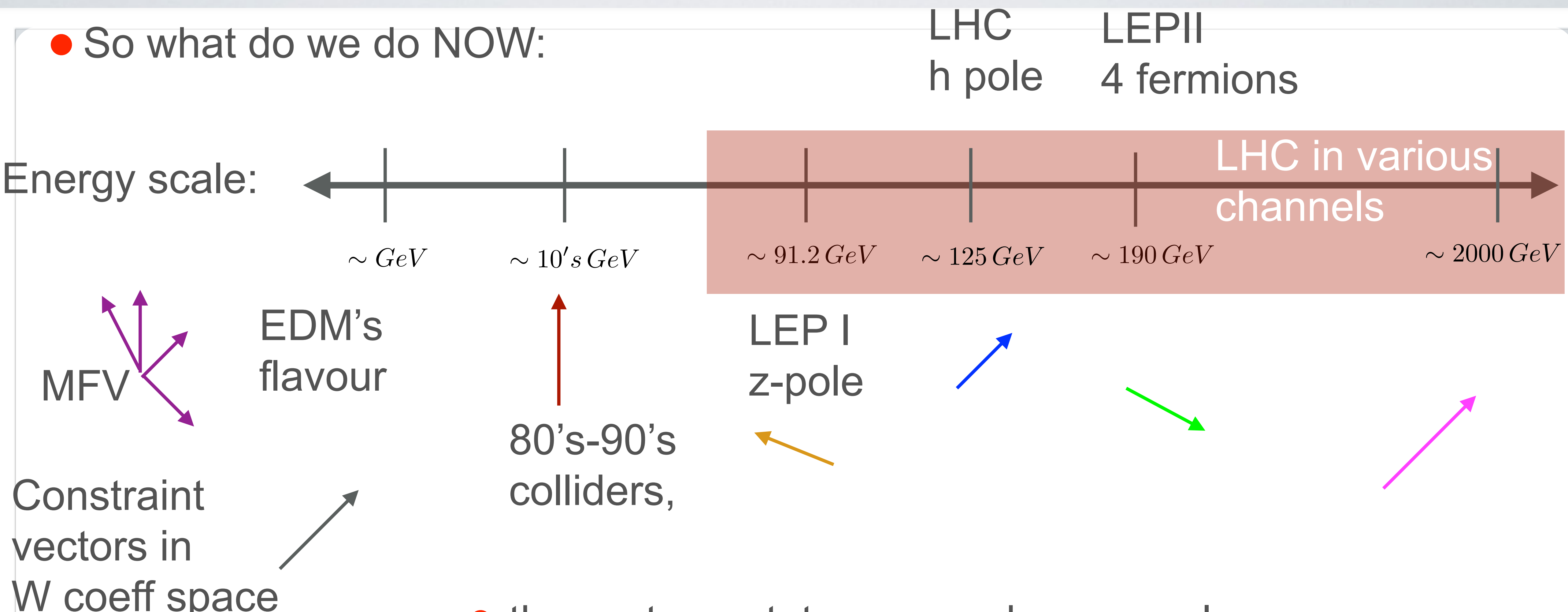


The SM EFTs approach in one venn diagram.

- Linear EFT $H \supset h$ and relations between measurements that follow from this hold
- Non-Linear EFT, singlet h in formalism. Broader range of relations between measurements.
- Want to have precise and well defined patterns of ALLOWED deviations in the linear EFT to know if more restricted formalism breaks.

Post Modern Discovery Physics

- So what do we do NOW:



- the vectors rotate as you change scale..

- To combine the various constraints consistently take into account they rotate as you change scale.. or introduce theory error.
- Any future discovery has to be projected back on these constraints to check consistency.

Bases choice and Dim 6.

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

X^3		φ^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_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$		$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
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.

Global constraints on dim 6.

Consider LEP I observables:

Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
$\hat{m}_Z$[GeV]	91.1875 ± 0.0021	[38]	-	-
$\hat{m}_W$[GeV]	80.385 ± 0.015	[39]	80.365 ± 0.004	[40]
σ_h^0 [nb]	41.540 ± 0.037	[38]	41.488 ± 0.006	[41]
Γ_Z[GeV]	2.4952 ± 0.0023	[38]	2.4942 ± 0.0005	[41]
R_ℓ^0	20.767 ± 0.025	[38]	20.751 ± 0.005	[41]
R_b^0	0.21629 ± 0.00066	[38]	0.21580 ± 0.00015	[41]
R_c^0	0.1721 ± 0.0030	[38]	0.17223 ± 0.00005	[41]
A_{FB}^ℓ	0.0171 ± 0.0010	[38]	0.01616 ± 0.00008	[42]
A_{FB}^c	0.0707 ± 0.0035	[38]	0.0735 ± 0.0002	[42]
A_{FB}^b	0.0992 ± 0.0016	[38]	0.1029 ± 0.0003	[42]

arXiv:1311.3107. Chen et al.

1211.1320 Masso, Sanz

1209.6382 Batell et al.

arXiv:1404.3667 Ellis et al.

arXiv:1501.0280. Petrov et al.

arXiv:1406.6070 Wells,Zhang

And Many others…

1308.2803 Pomarol, Riva. 1409.7605 Trott hep-ph/0412166] Han, Skiba
1411.0669 Falkowski, Riva. 1503.07872 Efrati et al. arXiv:1306.4644 Ciuchini et al.

Basic point is that STU is no longer sufficient in general.

Pioneering SMEFT works: Phys.Lett. B265 (1991) 326-334 Grinstein, Wise
hep-ph/0412166 Han, Skiba

Global constraints on dim 6.

Consider LEP I observables:

Observable	Experimental Value	Ref.	SM Theoretical Value	Ref.
$\hat{m}_Z$[GeV]	91.1875 ± 0.0021	[38]	-	-
$\hat{m}_W$[GeV]	80.385 ± 0.015	[39]	80.365 ± 0.004	[40]
σ_h^0 [nb]	41.540 ± 0.037	[38]	41.488 ± 0.006	[41]
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per-mille

percent!

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Note that theorists worked hard in SM for this to be the case.

Many 2 loop SM calculations

Global constraints on dim 6.

Consider LEP I observables:

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arXiv:1502.02570
Berthier, Trott

If you go beyond % constraints, LO SMEFT alone inconsistent.

Need of loops in SMEFT once measurements are 10% precise appears again and again in the literature

1209.5538 Passarino 1301.2588 Grojean, Jenkins, Manohar, Trott
1408.5147 Englert, Spannowsky many others..

Global constraints on dim 6.

Theory error defined by what you neglect in the calculation:

- All perturbative one loop corrections, LO → NLO

$$\Delta^i_{SMEFT}(\Lambda) = \sqrt{\Delta^2_{IFI,O_i} + \Delta^2_P + \Delta^2_{P,II} + \Delta^2_{\mathcal{L}_8} + \Delta^2_{\rm offshell,O_i}}.$$

Radiative corrections,i.e. emission, one loop, redefining input observables, correlations… in SMEFT.

- Higher order dim 8 terms in the SMEFT

$$\Delta^i_{SMEFT}(\Lambda) \simeq \sqrt{N_8}\, x_i \frac{\bar{v}_T^4}{\Lambda^4} + \frac{\sqrt{N_6}\, g_2^2}{16\,\pi^2}\, y_i \log\left[\frac{\Lambda^2}{\bar{v}_T^2}\right] \frac{\bar{v}_T^2}{\Lambda^2}.$$ (roughly)

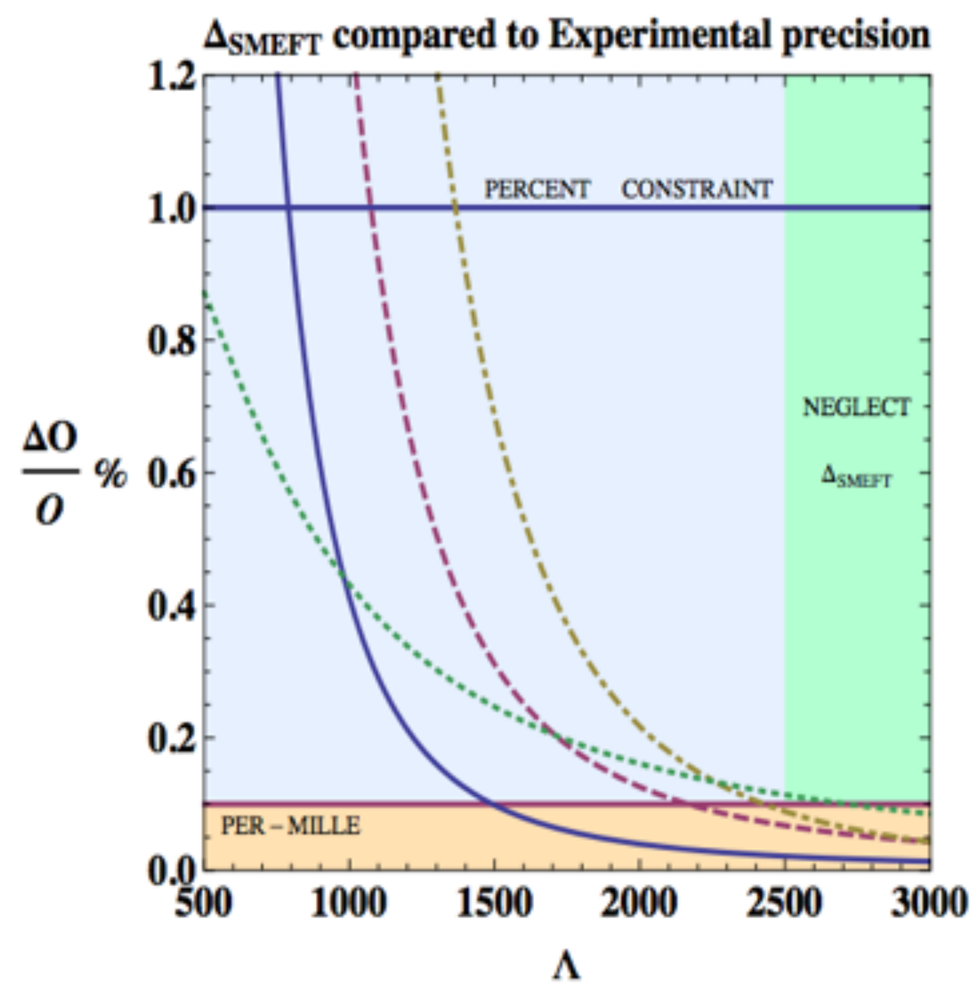
arXiv:1508.05060 Berthier, Trott

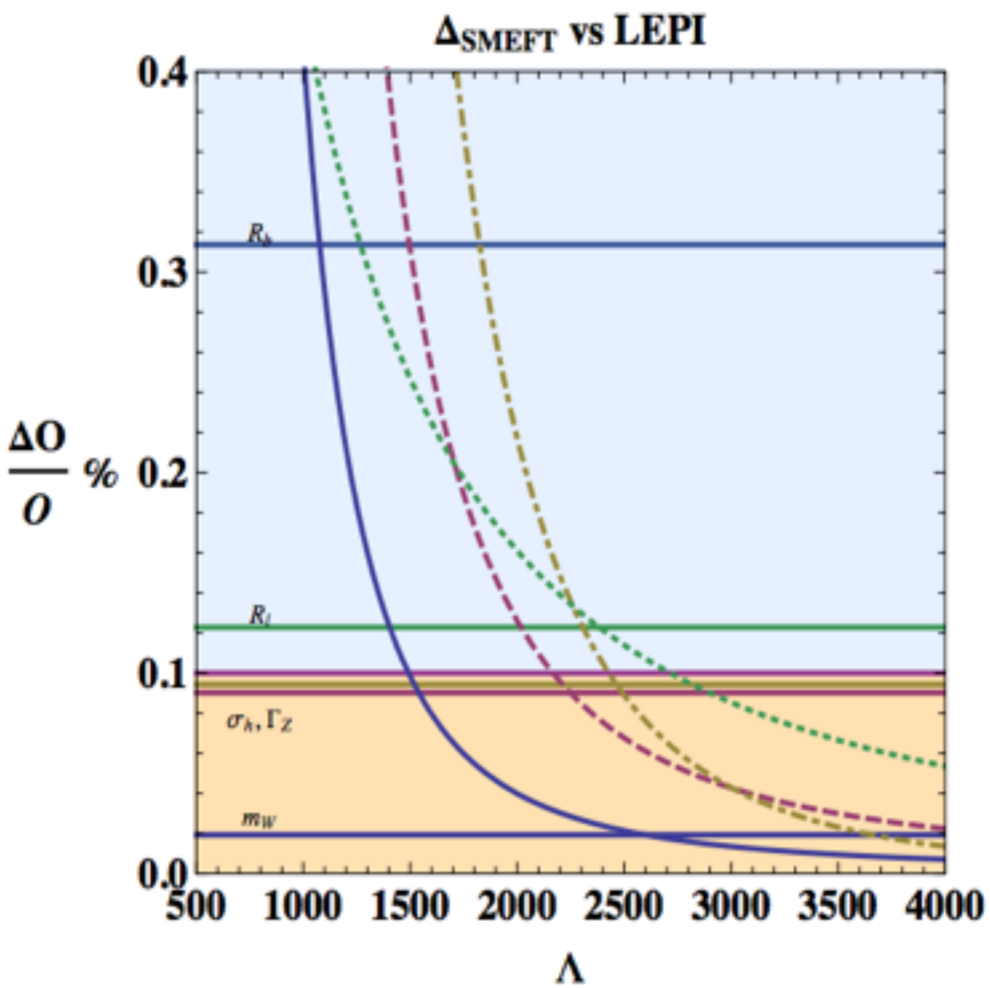
Error is roughly per-mille to percent level for cut off scales of interest.

$\Lambda \lesssim 3\mathrm{TeV}$

Global constraints on dim 6.

Because LEP I observables are so precise we can't ignore error in EFT:





Remember:

$$\frac{1}{\Lambda^4} \mathcal{L}_8 + \cdots$$ 535+h.c. operators!

arXiv:1508.05060 Berthier, Trott

Global constraints on dim 6.

Recent global SMEFT analysis on 103 observables (pre LHC data).

arXiv:1502.02570, 1508.05060 Berthier, Trott

Currently most comprehensive global fit of pre-LHC data in SMEFT

- LEP pole data + all these measurements below with clear theory errors

B 2 → 2 scattering observables at LEP, Tristan, Pep, Petra.
- B.1 $\ell^+ \ell^- \to f \bar{f}$ near and far from the Z pole.
  - B.1.1 Forward-Backward Asymmetries for u, d, ℓ
- B.2 Bhabba scattering, $e^+e^- \to e^+e^-$

C Low energy precision measurements
- C.1 ν lepton scattering
- C.2 ν Nucleon scattering
  - C.2.1 Neutrino Trident Production
- C.3 Atomic Parity Violation
- C.4 Parity Violating Asymmetry in eDIS
- C.5 Møller scattering

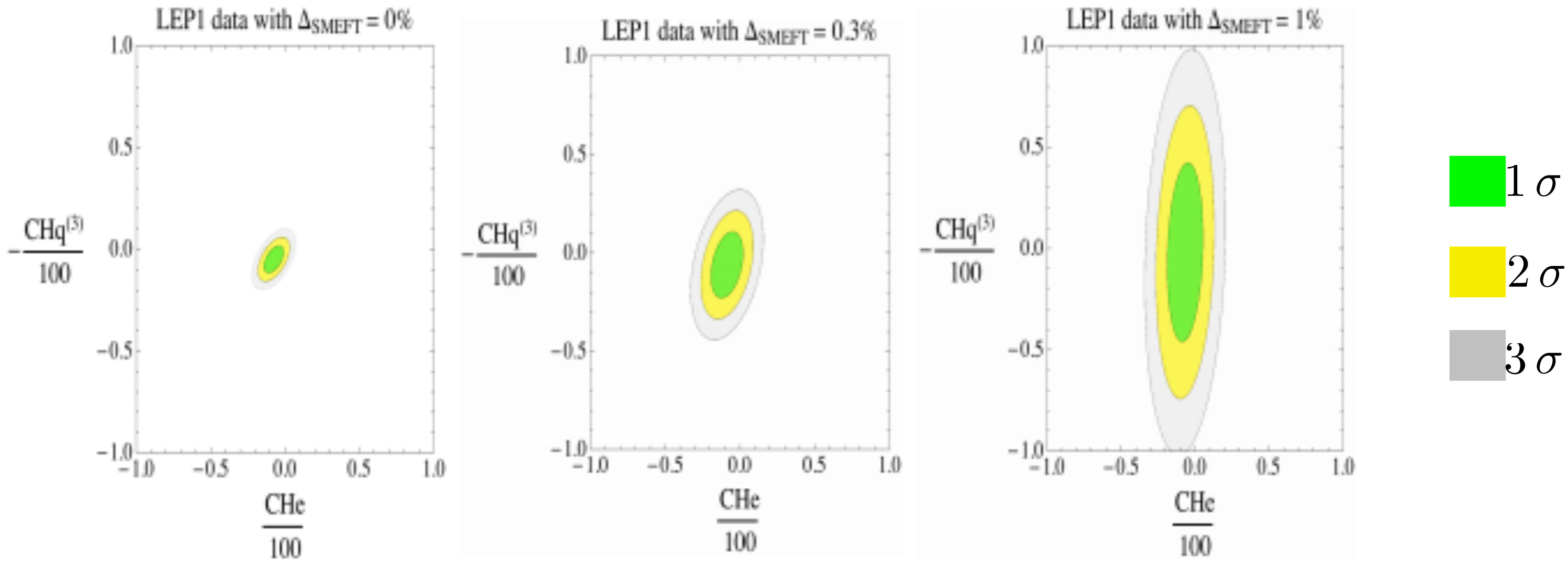
D Universality in β decays

- Global data analysis of data from PEP, PETRA, TRISTAN, SpS, Tevatron, SLAC, LEPI and LEP II

Global constraints on dim 6.

Recent global SMEFT analysis on 103 observables (pre LHC data).

arXiv:1502.02570, 1508.05060 Berthier, Trott



Theory errors effect subspace correlations and constraints.

Percent/per-mille precision need loops

We need loops for the SMEFT for future precision program to reduce theory error. So renormalize SMEFT as first step.

- We know the Warsaw basis is self consistent at one loop as it has been completely renormalized - DONE! Complete result, every index all couplings.

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

- 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

- Recent results obtained in alternate scheme approach:

  arXiv:1505.03706 Ghezzi, Gomez-Ambrosio, Passarino, Uccirati

It is the SMEFT not Higgs EFT.

- It does not really make sense to think of just RGE improving a sector like "the Higgs sector". We need the whole RGE evolution.
 Reality really does not care what basis you choose.

Consider the SM equations of motion:

Higgs:

$$D^2 H_k - \lambda v^2 H_k + 2\lambda (H^\dagger H) H_k + \overline{q}^j\, Y_u^\dagger\, u \epsilon_{jk} + \overline{d}\, Y_d\, q_k + \overline{e}\, Y_e\, l_k = 0$$

Gauge field:

$$i\not{D}\, q_j = Y_u^\dagger\, u\, \widetilde{H}_j + Y_d^\dagger\, d\, H_j\,, \qquad i\not{D}\, d = Y_d\, q_j\, H^{\dagger j}\,, \qquad i\not{D}\, u = Y_u\, q_j\, \widetilde{H}^{\dagger j}$$

$$i\not{D}\, l_j = Y_e^\dagger\, e H_j\,, \qquad i\not{D}\, e = Y_e\, l_j H^{\dagger j}\,,$$

Fermion:

$$[D^\alpha, G_{\alpha\beta}]^A = g_3 j_\beta^A\,, \qquad [D^\alpha, W_{\alpha\beta}]^I = g_2 j_\beta^I, \qquad D^\alpha B_{\alpha\beta} = g_1 j_\beta,$$

$$j_\beta^A = \sum_{\psi=u,d,q} \overline{\psi} T^A \gamma_\beta \psi\,,$$

$$j_\beta^I = \frac{1}{2}\overline{q}\,\tau^I \gamma_\beta q + \frac{1}{2}\overline{l}\,\tau^I \gamma_\beta l + \frac{1}{2} H^\dagger\, i \overleftrightarrow{D}_\beta^I H\,,$$

$$j_\beta = \sum_{\psi=u,d,q,e,l} \overline{\psi}\, \mathsf{y}_i \gamma_\beta \psi + \frac{1}{2} H^\dagger\, i \overleftrightarrow{D}_\beta H\,,$$

- We need to systematically improve the SMEFT to one loop, due to field redefinitions, do full one loop.
- I used to say Higgs EFT all the time. It is really SMEFT.

NLO EFT - Full one loop

- In SMEFT the cut off scale is not TOO high. So RGE log terms not expected to be much bigger than remaining one loop "finite terms"
- Further, no reason to expect that structure of the divergences in mixing will have to be preserved in finite terms. So - lets calculate finite terms for $\Gamma(h \to \gamma\,\gamma)$
- Initial calc - mirror initial RGE work, just use operators

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

Hartmann, Trott 1505.02646

Full calculation with all relevant operators was then performed:

$$\mathcal{O}^{(0)}_{H} = \lambda (H^\dagger H)^3,$$
$$\mathcal{O}^{(0)}_{HD} = (H^\dagger D_\mu H)^\star (H^\dagger D^\mu H),$$
$$\mathcal{O}^{(0)}_{uH} = y_u H^\dagger H (\bar{q}_p u_r \tilde{H}),$$
$$\mathcal{O}^{(0)}_{H\Box} = H^\dagger H \Box (H^\dagger H),$$
$$\mathcal{O}^{(0)}_{eH} = y_e H^\dagger H (\bar{l}_p e_r H),$$
$$\mathcal{O}^{(0)}_{dH} = y_d H^\dagger H (\bar{q}_p d_r H).$$

$$\mathcal{O}^{(0)}_{HW} = g_2^2\, H^\dagger\, H\, W^a_{\mu\nu}\, W_a^{\mu\nu},$$
$$\mathcal{O}^{(0)}_{W} = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu},$$
$$\mathcal{O}^{(0)}_{\substack{eB\\rs}} = \bar{l}_{r,a} \sigma^{\mu\nu}\, e_s\, H_a\, B_{\mu\nu},$$
$$\mathcal{O}^{(0)}_{\substack{uB\\rs}} = \bar{q}_{r,a} \sigma^{\mu\nu}\, u_s\, \tilde{H}_a\, B_{\mu\nu},$$
$$\mathcal{O}^{(0)}_{\substack{dB\\rs}} = \bar{q}_{r,a} \sigma^{\mu\nu}\, d_s\, H_a\, B_{\mu\nu},$$

$$\mathcal{O}^{(0)}_{HB} = g_1^2\, H^\dagger\, H\, B_{\mu\nu}\, B^{\mu\nu},$$
$$\mathcal{O}^{(0)}_{HWB} = g_1\, g_2\, H^\dagger\, \sigma^a H\, B_{\mu\nu}\, W_a^{\mu\nu},$$
$$\mathcal{O}^{(0)}_{\substack{eW\\rs}} = \bar{l}_{r,a} \sigma^{\mu\nu}\, e_s\, \tau^I_{ab}\, H_b\, W^I_{\mu\nu},$$
$$\mathcal{O}^{(0)}_{\substack{uW\\rs}} = \bar{q}_{r,a} \sigma^{\mu\nu}\, u_s\, \tau^I_{ab}\, \tilde{H}_b\, W^I_{\mu\nu},$$
$$\mathcal{O}^{(0)}_{dW} = \bar{q}_{r,a} \sigma^{\mu\nu}\, d_s\, \tau^I_{ab}\, H_b\, W^I_{\mu\nu},$$

Hartmann, Trott 1507.03568

NLO EFT - Subtract div.

- The Algorithm: Use 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!

Recent results:
Hartmann, Trott 1505.02646.pdf
Ghezzi et al. 1505.03706
Pruna, Signer 1408.3565 others..

- Here is how this works in $\Gamma(h \to \gamma\,\gamma)$

$$\mathcal{O}_i^{(0)} = Z_{i,j}\,\mathcal{O}_j^{(r)}, \qquad \mathcal{Z}_{i,j} = \begin{pmatrix} \frac{g_1^2}{4} - \frac{9g_2^2}{4} + 6\lambda + Y & 0 & g_1^2 \\ 0 & -\frac{3g_1^2}{4} - \frac{5g_2^2}{4} + 6\lambda + Y & g_2^2 \\ \frac{3g_2^2}{2} & \frac{g_1^2}{2} & -\frac{g_1^2}{4} + \frac{9g_2^2}{4} + 2\lambda + Y \end{pmatrix},$$

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

$$\begin{aligned} \mathcal{N}_{HB} &= \frac{1}{16\pi^2\epsilon}\left[\left(16\pi^2\epsilon + \frac{g_1^2}{4} - \frac{9g_2^2}{4} + 6\lambda + Y\right) C_{HB}(\Lambda) + \frac{3\,g_2^2}{2} C_{HWB}(\Lambda)\right], \qquad (2.8) \\ \mathcal{N}_{HW} &= \frac{1}{16\pi^2\epsilon}\left[\left(16\pi^2\epsilon - \frac{3g_1^2}{4} - \frac{5g_2^2}{4} + 6\lambda + Y\right) C_{HW}(\Lambda) + \frac{g_1^2}{2} C_{HWB}(\Lambda)\right], \\ \mathcal{N}_{HWB} &= \frac{1}{16\pi^2\epsilon}\left[\left(16\pi^2\epsilon - \frac{g_1^2}{4} + \frac{9g_2^2}{4} + 2\lambda + Y\right) C_{HWB}(\Lambda) + g_1^2\,C_{HB}(\Lambda) + g_2^2\,C_{HW}(\Lambda)\right]. \end{aligned}$$

NLO EFT - Subtract div.

- 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

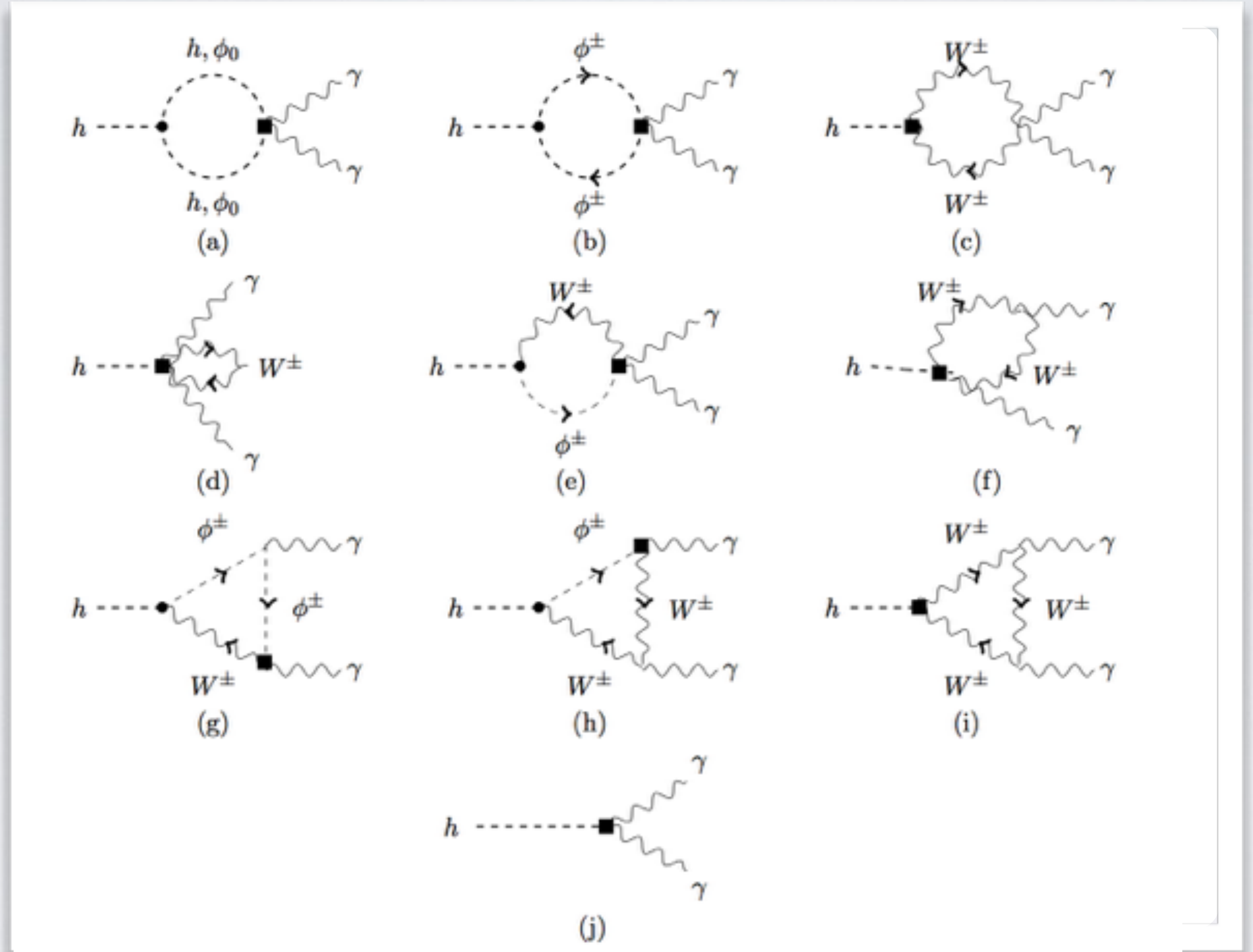
$$Z_h = 1 + \frac{(3+\xi)\,(g_1^2 + 3\,g_2^2)}{64\,\pi^2\,\epsilon} - \frac{Y}{16\,\pi^2\,\epsilon}.$$

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

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

NLO EFT - Loops such as this

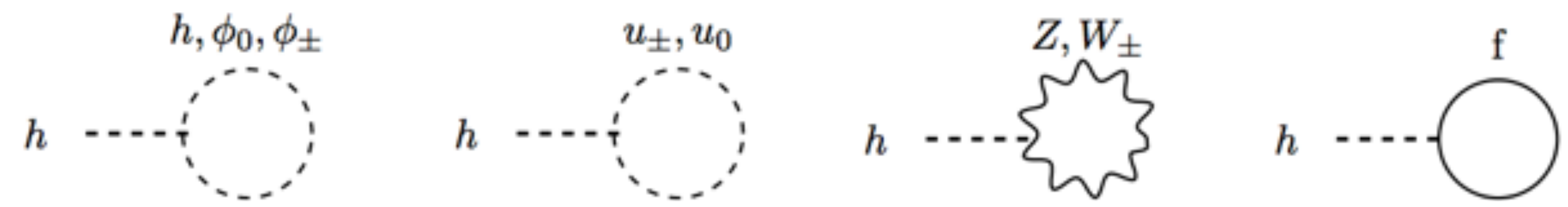
- Calculate in BF method, in R_ξ gauge



- Gauge dependence cancels ✓ remaining divergences cancel exactly ✓

NLO EFT - Fix finite terms

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



$$T = m_h^2\, h\, v\, \frac{1}{16\pi^2}\left[-16\pi^2\,\frac{\delta v}{v} + 3\,\lambda\left(1+\log\left[\frac{\mu^2}{m_h^2}\right]\right) + \frac{m_W^2}{v^2}\xi\left(1+\log\left[\frac{\mu^2}{\xi\, m_W^2}\right]\right)\right., \quad (3.3)$$

$$+\frac{1}{2}\frac{m_Z^2}{v^2}\xi\left(1+\log\left[\frac{\mu^2}{\xi\, m_Z^2}\right]\right) - \frac{1}{2}\sum_i y_i^4\, N_c\frac{1}{\lambda}\left(1+\log\left[\frac{\mu^2}{m_i^2}\right]\right),$$

$$\left.+\frac{g_2^2}{2}\frac{m_W^2}{m_h^2}\left(1+3\log\left[\frac{\mu^2}{m_W^2}\right]\right) + \frac{1}{4}(g_1^2+g_2^2)\frac{m_Z^2}{m_h^2}\left(1+3\log\left[\frac{\mu^2}{m_Z^2}\right]\right)\right].$$

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

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

Many interesting technicalities

- Closed form result now known.
- Running of vev important modification of RGE results.
- Gauge fixing modified by higher D ops, higher D ops source ghosts!

Recent results:
Hartmann, Trott 1505.02646.pdf
Hartmann, Trott 1507.03568.pdf
Ghezzi et al. 1505.03706
Pruna, Signer 1408.3565 others..

- Pure finite terms can be present for higher D operators at one loop.
- Finite terms not small compared to logs as cut off scale can't be too high.
- Two processes know to full one loop in SMEFT now:

$\mu \to e\gamma$ Pruna, Signer 1408.3565

$h \to \gamma\,\gamma$ Hartmann, Trott 1505.02646,1507.03568
Ghezzi et al. 1505.03706

But still need to redefine input observables to one loop in SMEFT to be more consistent. Lots more work to do.

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, $C_i \sim 1$:

Current 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 $[52, 7]\,\%$

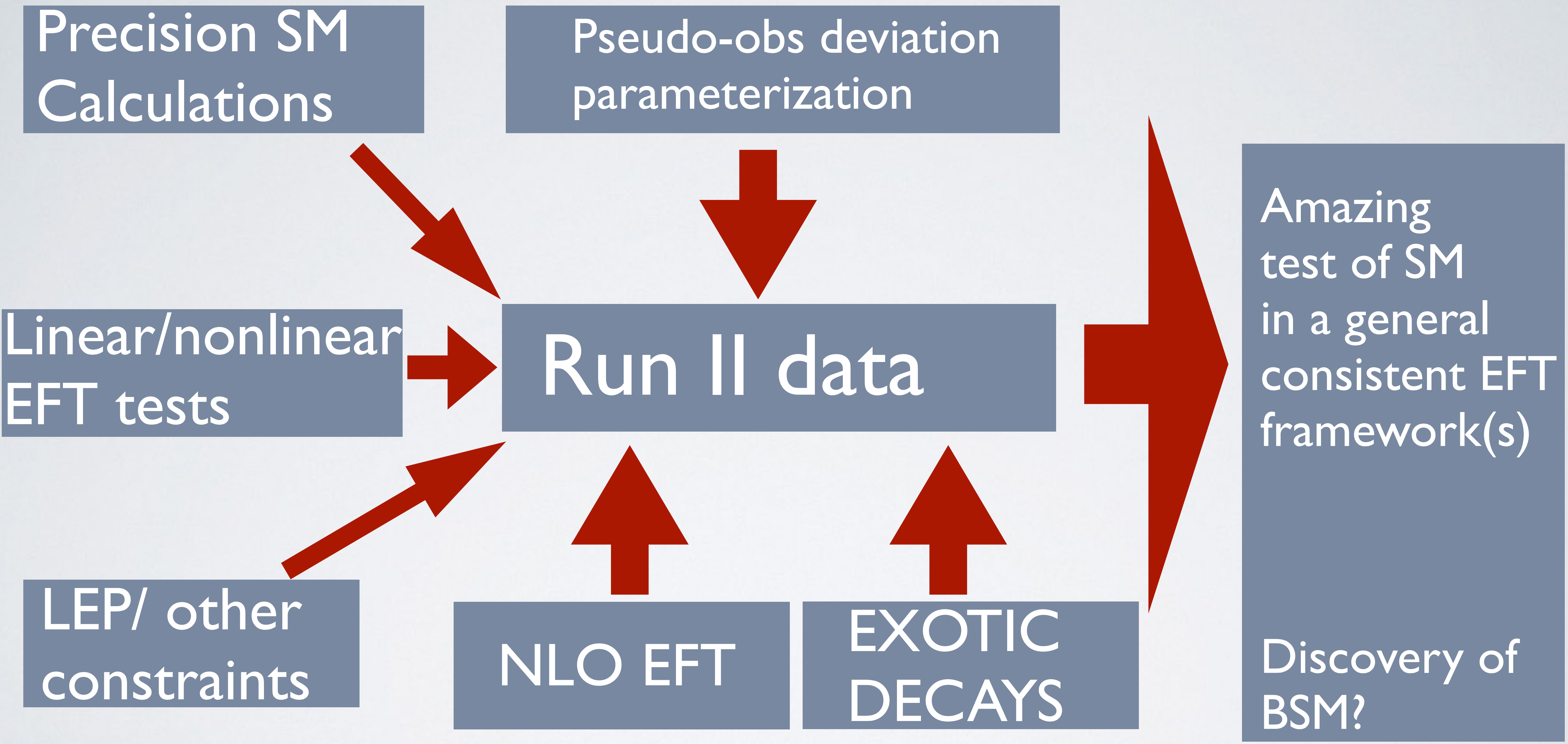
- The future precision Higgs phenomenology program clearly needs it:

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

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

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

The Big Picture going forward



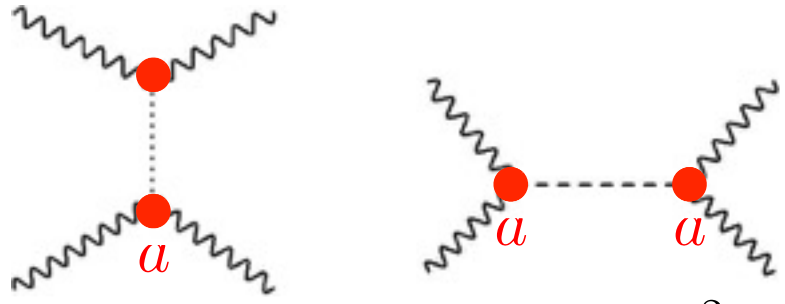
More slides.

The Cut Off scale(s)

- What do we know? Without a doubt a very Higgs like boson.

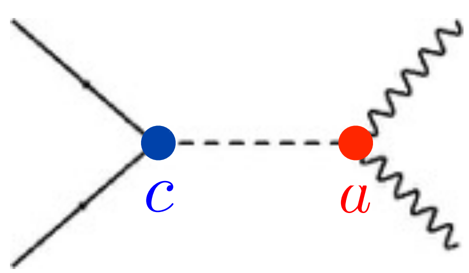
1. SM is of course consistent with the data.

The problem that needed to be solved:

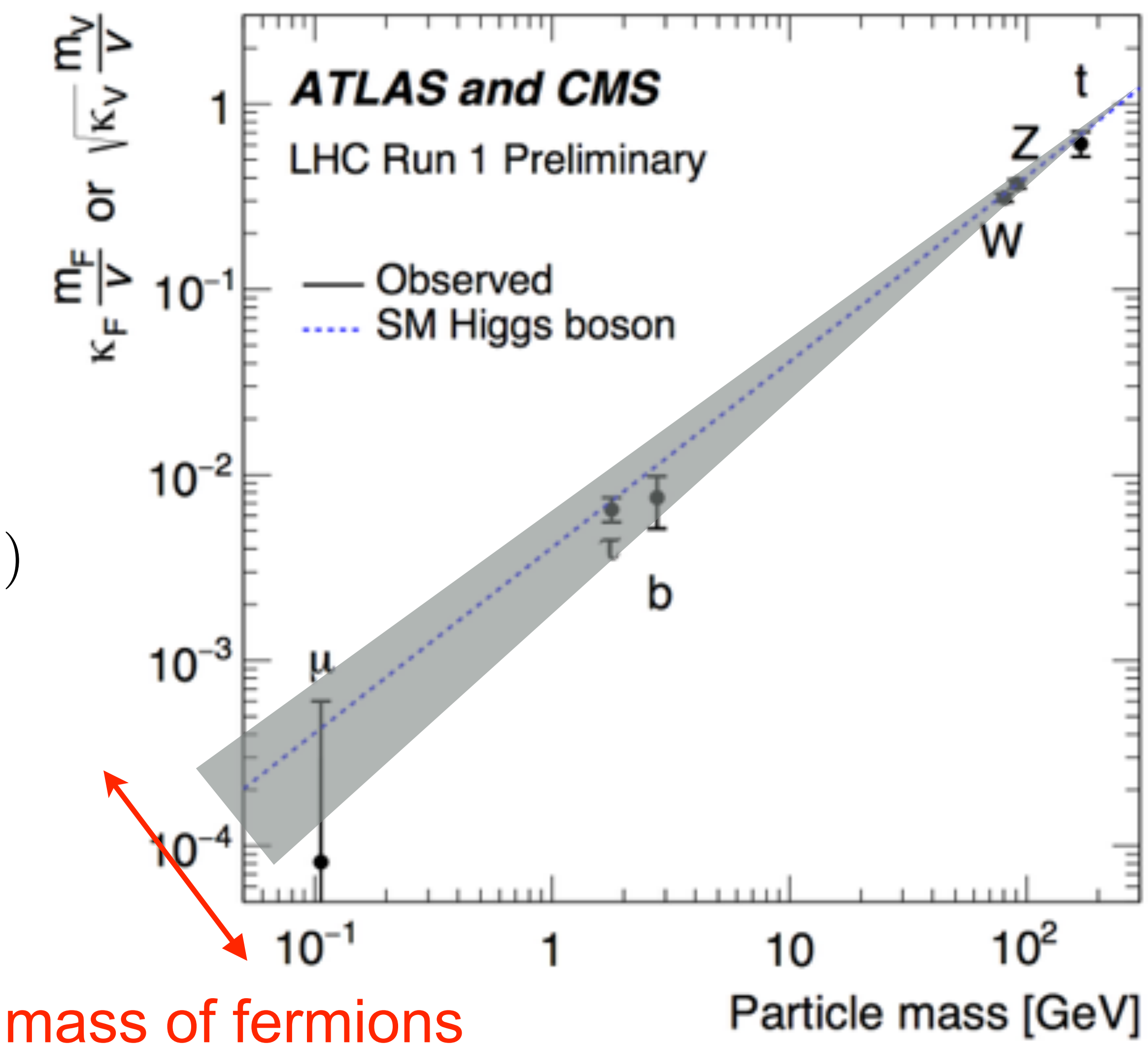


$$W_L^+ W_L^- \rightarrow W_L^+ W_L^- \; : \; \mathcal{A} \simeq \frac{g^2}{4\, m_W^2} (s+t)\,(1-a^2)$$

$$\epsilon_L^\mu \simeq p^\mu / m_W$$



$$\psi\,\bar{\psi} \rightarrow W_L^+ W_L^- \; : \quad \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2}\,(1 - a\,c)$$



Lighter mass of fermions suppress unitarity violation to larger scales if couplings deviate from SM.

The Cut Off scale(s)

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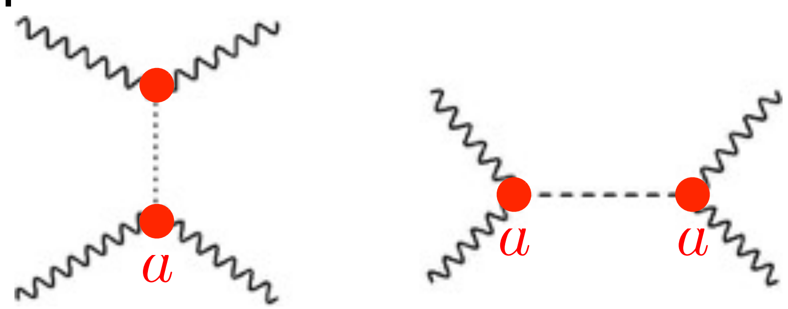
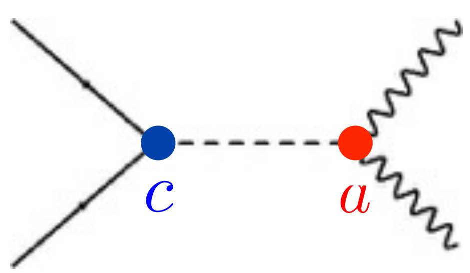


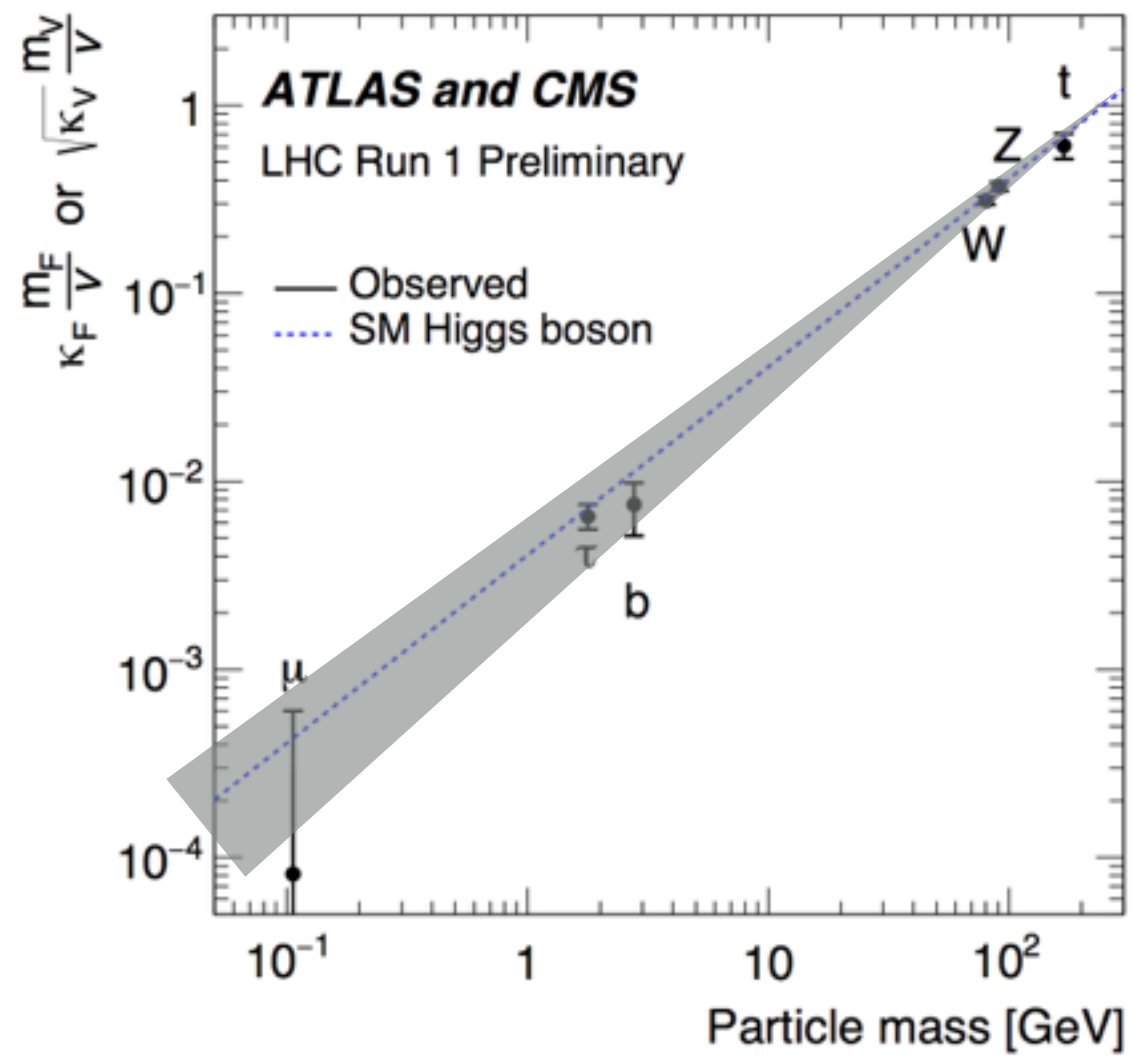
$$W_L^+ W_L^- \to W_L^+ W_L^- : \mathcal{A} \simeq \frac{g^2}{4\, m_W^2} (s+t)(1-a^2) \to 0$$

$$\epsilon_L^\mu \simeq p^\mu / m_W$$



Perfect solution to this problem is the SM Higgs.

$$\psi\, \bar{\psi} \to W_L^+ W_L^- : \quad \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2} (1 - a\, c) \to 0$$



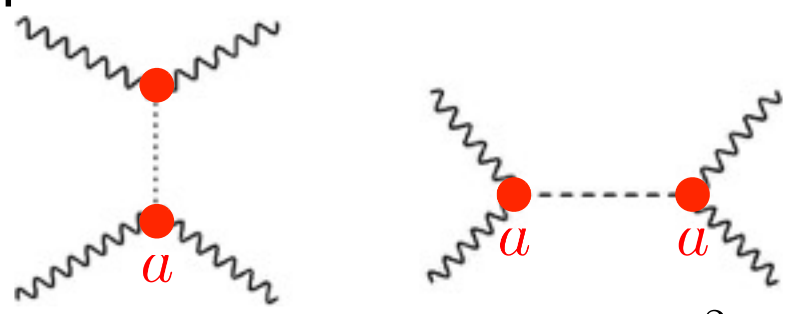
"Higgs like boson" is not a silly statement.
It has to look roughly like this as it is not raining NP particles near the EW scale.

The Cut Off scale(s)

- What do we know? Without a doubt a very Higgs like boson.

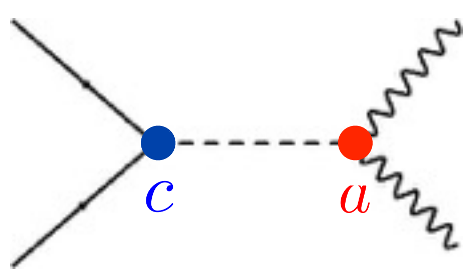
1. SM is of course consistent with the data.

The problem that needed to be solved:



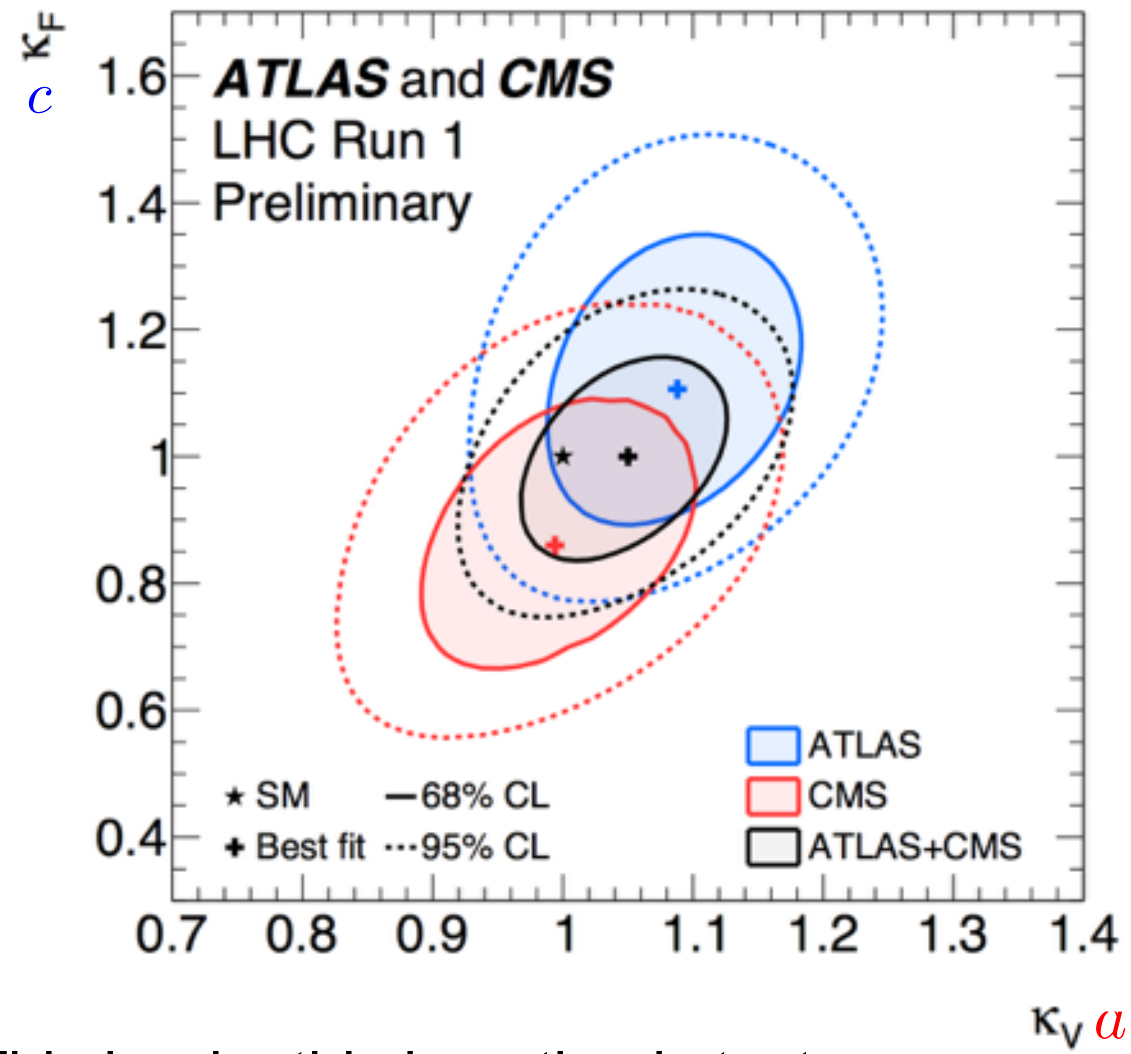
$$W_L^+ W_L^- \rightarrow W_L^+ W_L^- \, : \, \mathcal{A} \simeq \frac{g^2}{4\, m_W^2} \, (s+t)\,(1 - a^2) \rightarrow 0$$

$$\epsilon_L^\mu \simeq p^\mu / m_W$$



Perfect solution to this problem is the SM Higgs.

$$\psi \, \bar{\psi} \rightarrow W_L^+ W_L^- \, : \quad \mathcal{A} \simeq \frac{m_\psi \sqrt{s}}{v^2} \, (1 - a\, c) \rightarrow 0$$



This is why this hypothesis test makes sense to do now, and going forward.

The Cut Off scale(s)

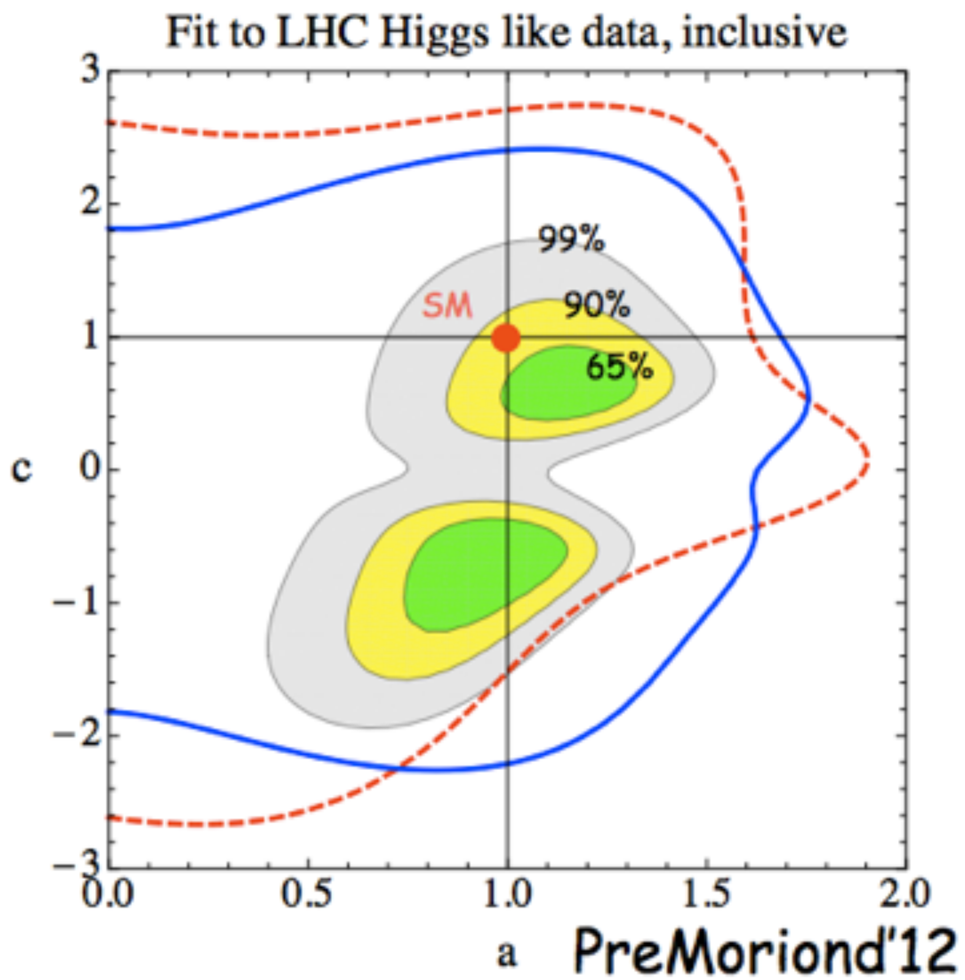
- What do we know? Without a doubt a very Higgs like boson.

1. SM is of course consistent with the data.

This is why this hypothesis test was introduced in these initial works, as soon as the signal strength data started to appear in 2012.

We want to do far more now - but it is a good idea to maintain this test going forward.

Espinosa,Grojean, Muhlleitner ,Trott arXiv:1202.3697



See also:

Azatov, Contino, Galloway arXiv:1202.3415

Carmi, Falkowski, Kuflik, Volansky arXiv:1202.3144 (v2)

There is a cut off scale.

- Where is dark matter in the SM?
- Where is inflation in the SM?

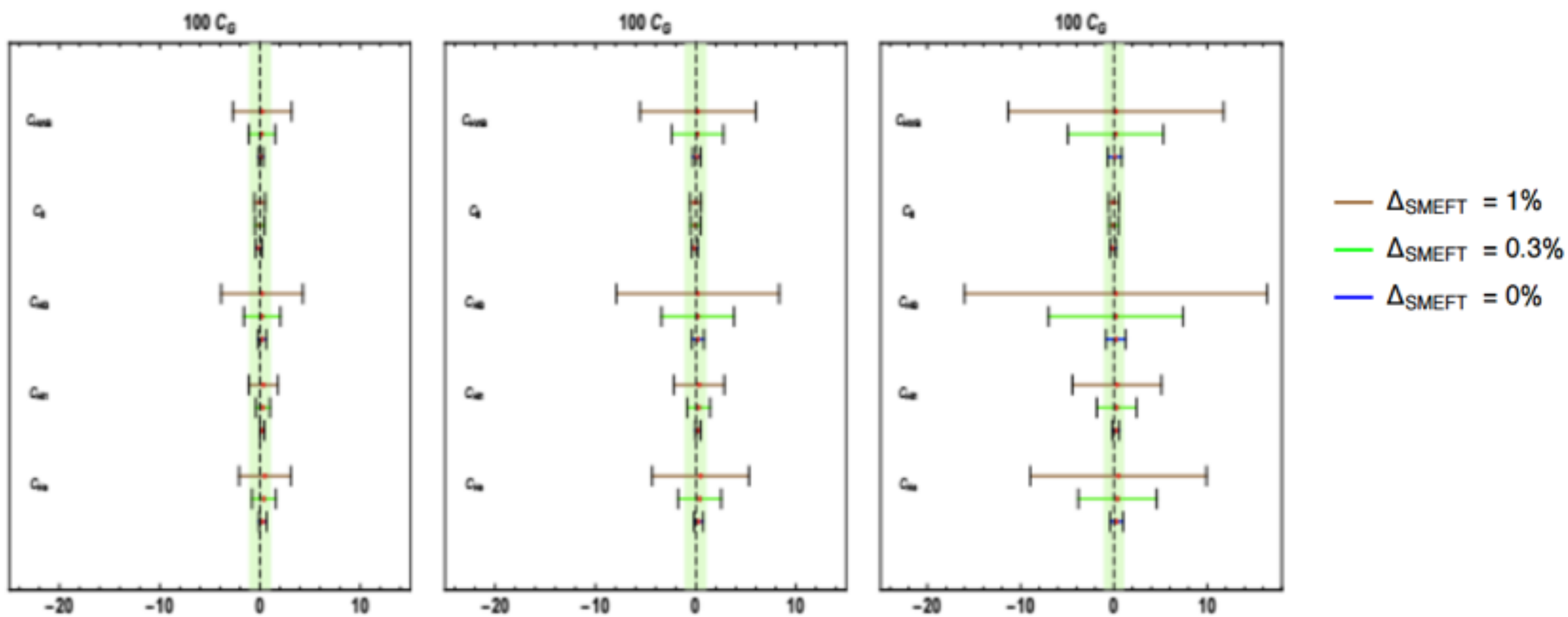
  re (minimal) Higgs inflation - ask me later.
- Minimal baryogenesis in the SM is out.

  Leptogenesis at a high scale might be right.
- What is the origin of neutrino mass? Beyond the dim 5 op.
- It is clear that the SM (if assumed) breaks down at some scale. Where are the corrections, where is everyone?

Global constraints on dim 6.

Recent global SMEFT analysis on 103 observables (pre LHC data).

Anomalous Z couplings in %: 95% CL shown. arXiv:1508.05060 Berthier, Trott



Difference compared to analyses that neglects SMEFT error, some bounds on individual parameters relaxed by factor of 10 or so. Three cases assume flat directions lifted by $\bar{v}_T^2/(2\Lambda^2), \bar{v}_T^2/(\Lambda^2), 2\,\bar{v}_T^2/(\Lambda^2)$ treated as an error.

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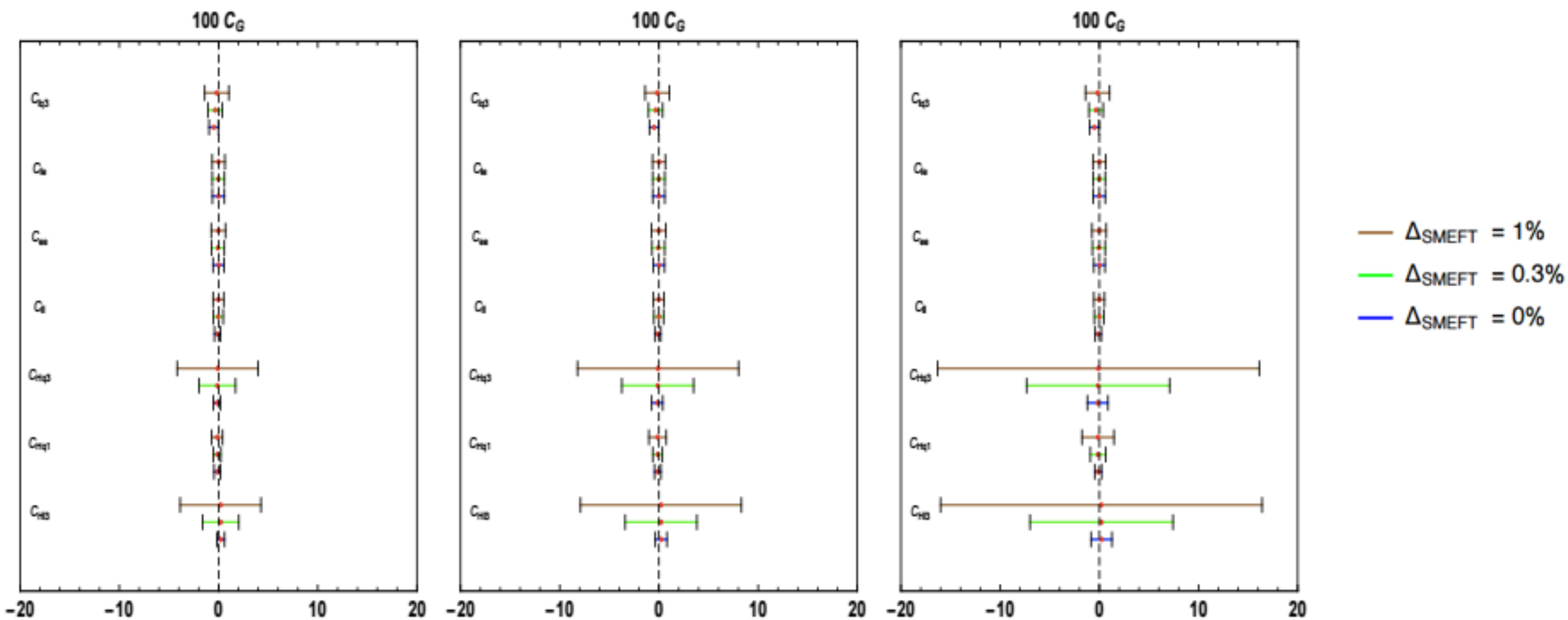

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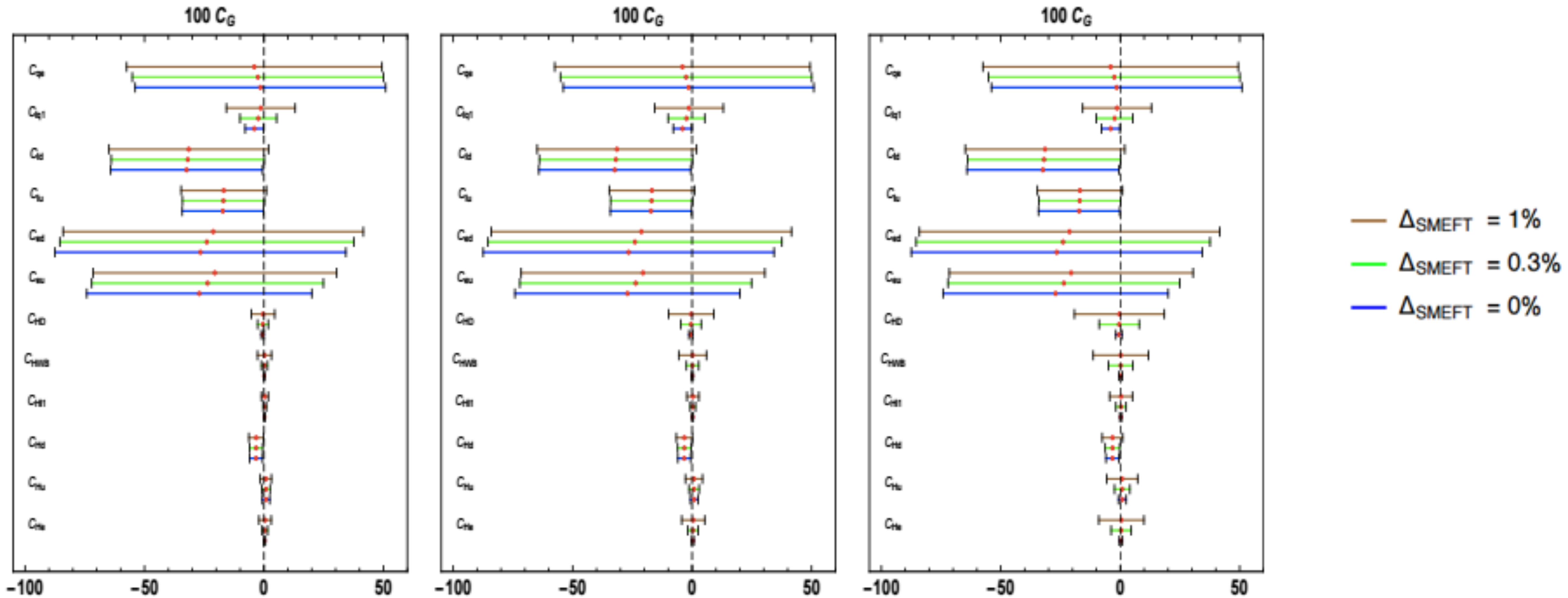

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NLO EFT - Step 2 Renormalize

- How was this renormalization done?

  Calculated in the unbroken phase of the theory, using the background field method.

G. 't Hooft, Acta Universitatis Wratislaviensis No.368, Vol.1*, Wroclaw 1976, 345-369

B. S. DeWitt, Phys.Rev. 162 (1967) 1195–1239

L. Abbott, Acta Phys.Polon. B13 (1982) 33

EW App. →

A. Denner, G. Weiglein, and S. Dittmaier, Nucl.Phys. B440 (1995) 95–128, hep-ph/9410338.

M. B. Einhorn and J. Wudka, Phys.Rev. D39 (1989) 2758.

A. Denner, Fortsch.Phys. 41 (1993) 307–420, [arXiv:0709.1075].

- Background field method not necessary, but a nice trick, and allowed US to succeed in avoiding gauge dependent results.
  (Some competition did not use the background field method.)

"Cool stuff" Addendum

- Gauge fixing in the SMEFT subtle compared to the SM. Consider:

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

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

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

- The mismatch of the mass eigenstates in the SMEFT with the SM means gauge fixing in the former results in some interesting local contact operators

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