Consistency and prospects in the SMEFT

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

EFT for Collider Physics, Flavor Phenomena and EWSB

An Effective Field-Theory Assault on the Zeptometer Scale: Exploring the Origins of Flavour and EWSB(EFT4LHC)

Consistency...

- A foolish consistency is the hobgoblin of little minds, adored by little statesmen and philosophers and divines.
  -- Ralph Waldo Emerson
- The only completely consistent people are the dead. -- Aldous Huxley,
- Consistency is the last refuge of the unimaginative. -- Oscar Wilde
- Of course i am inconsistent! Only logicians and cretins are consistent. -- tim robbins
- A silly ass ... wrote a paper to prove me inconsistent.. inconsistency is the bugbear of fools! -- John “Jacky” Fisher, British admiral and first sea lord

and yet...

- You must do the best you can — if you know anything at all wrong, or possibly wrong — to explain it. If you make a theory, for example, and advertise it, or put it out, then you must also put down all the facts that disagree with it, as well as those that agree with it.

-- R.P. Feynman 1974 Caltech commencement “Cargo Cult science”

V.S.

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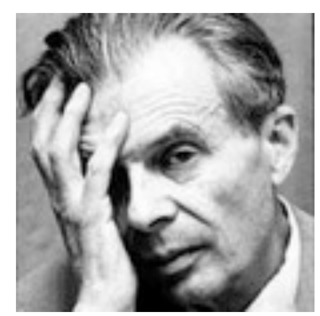

Outline

Two main aspects of consistency in the SMEFT in this talk.

- Consistency in the Higgs-Inflation story, considering recent knowledge of the SMEFT. Prospects for learning if Higgs inflation is right - ever.
- Consistency in bounding the SMEFT, with observables and “constructed observables”. The need to avoid redundancy in inconsistent procedures of fitting to the data - the later will be explained as “functional redundancy”.
- This will fit together much better than you expect!

Higgs Inflation - but as an EFT..

- The basic idea: $\mathcal{L}_{HI} = \mathcal{L}_{SM} - \sqrt{-g}\left[\frac{m_p^2}{2} + \xi\, H^\dagger H\right] R + \cdots$

Spokoiny Phys Lett B 147B 39 (1984)
Salopek, Bond, Bardeen Phys Rev D 40 1753 (1989)
Bezrukov, Shaposhnikov Phys Lett B 659, 703 (2008) arXiv:0710.3755

- Further interesting lesson:

THIS TERM EXISTS. (unless some unknown symmetry forces it to be 0)

Higgs Inflation: $\xi \simeq 5 \times 10^4 \left(\frac{m_h}{\sqrt{2}\, v}\right)$ Conformal symmetry: $\xi = -\frac{1}{6}$
(in the absence of a Higgs vev)

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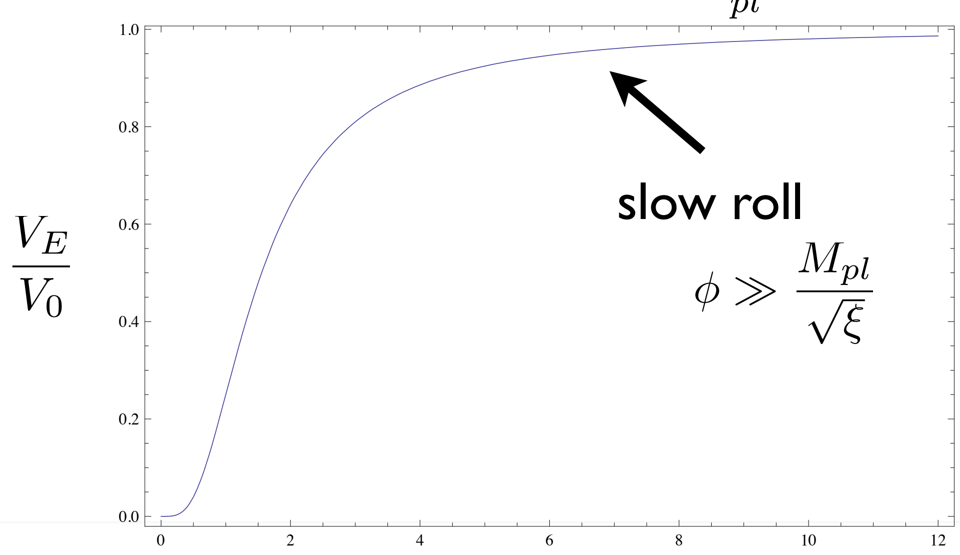
- Flatten the SM potential with a large non-minimal coupling.

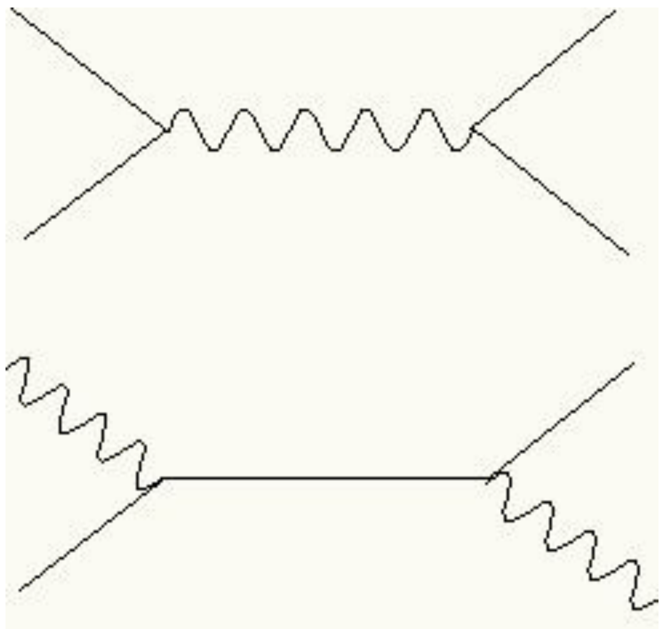
Weyl rescaling to the Einstein frame:

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \quad \text{where} \quad \Omega^2 = 1 + \frac{\xi\,\phi^2}{M_{pl}^2} \quad \text{and} \quad V_E(\phi) = \frac{V(\phi)}{(1 + \frac{\xi\,\phi^2}{M_{pl}^2})^2}$$



Higgs Inflation - but as an EFT..

- As $\xi \simeq 5 \times 10^4 \left(\frac{m_h}{\sqrt{2}\, v}\right)$ largest dependence on ξ origin of the scattering that violates unitarity.



$$h\, h \to h\, h$$
$$g\, h \to g\, h$$

$$A_4(E) \simeq \left(\frac{\xi E}{M_{pl}}\right)^2 \left(\frac{\xi E}{4\pi M_{pl}}\right)^{2L}$$

Insisting on unitarity ie $\sigma \propto 1/E^2$ we find

$$E < E_{max} \simeq \frac{M_{pl}}{\xi} \qquad M < \frac{M_{pl}}{\xi}$$

In the EW vacuum this is the case - old news. arXiv:0902.4465,arXiv:1002.2730
Burgess,Lee,Trott

See also arXiv:0903.0355 Barbon, Espinosa

Higgs Inflation - an important lesson.

- Cut off scales easy to understand (goldstone scattering)

$$\mathcal{A}(\sigma^i\,\sigma^j \to \sigma^k\,\sigma^l) = \left(1-(a_{sm}+\delta a)^2\right)\frac{s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}}{\bar{\chi}^2},$$

$$= \frac{2\,\xi^2}{M_{pl}^2}\left(s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}\right), \quad \text{small field}$$

$$\mathcal{A}(\sigma^i\,\sigma^j \to \sigma^k\,\sigma^l) = \frac{\xi}{M_p^2}\left[s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}\right], \quad \text{large field}$$

- Between the scales the cut off scale rises as $\Lambda \sim 4\,\pi\bar{\chi}$

  As in a theory with un-higgs massive vectors.

Higgs Inflation - an important lesson.

- Cut off scales easy to understand (goldstone scattering)

$$\mathcal{A}(\sigma^i\,\sigma^j \to \sigma^k\,\sigma^l) = \left(1-(a_{sm}+\delta a)^2\right)\frac{s\,\delta^{ij}\,\delta^{kl}+t\,\delta^{ik}\,\delta^{jl}+u\,\delta^{il}\,\delta^{jk}}{\bar{\chi}^2},$$

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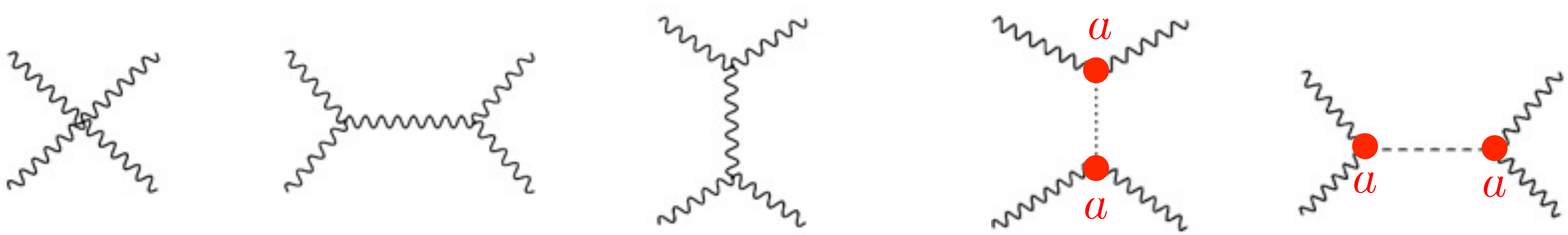
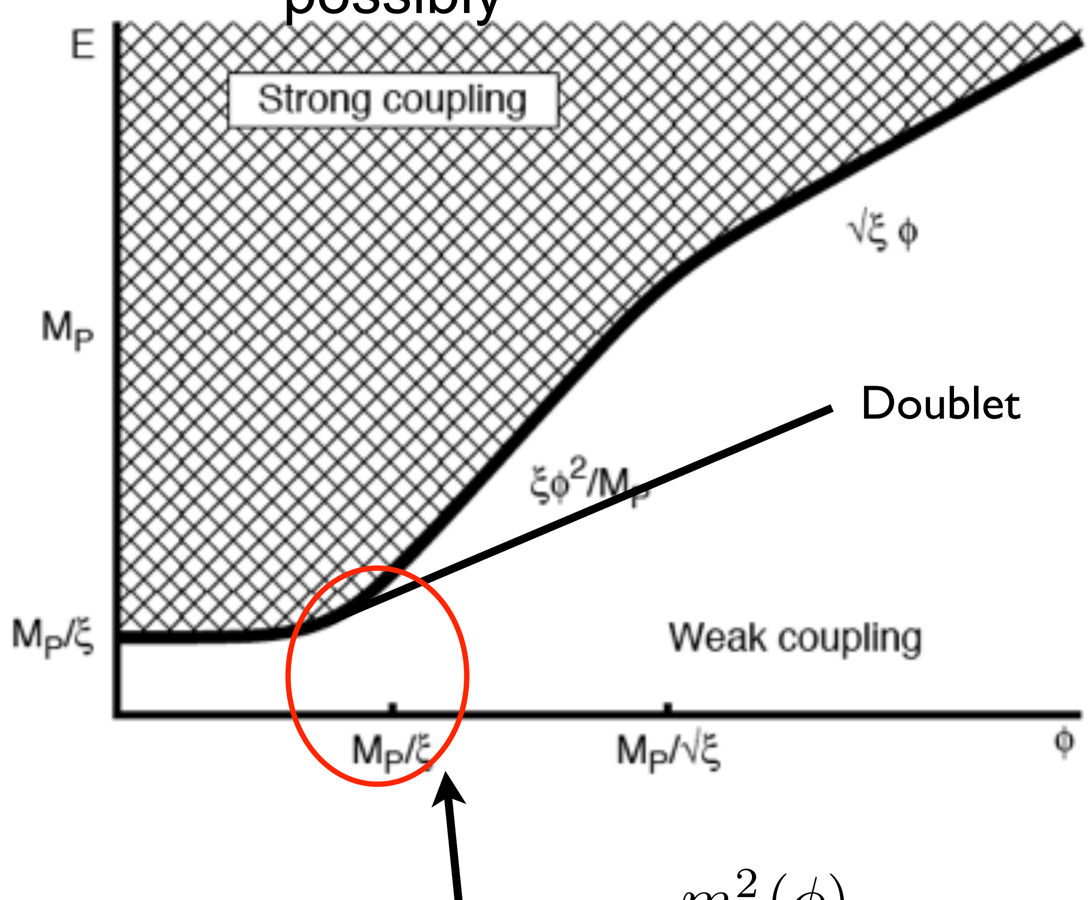


- Exactly the scattering physics of the nonlinear realization Higgs EFT.

Higgs Inflation - interesting wrinkles..

- Should add all higher D operators suppressed by this scale by the usual rules of EFT.



- Singlet vs doublet subtlety
  arXiv:1002.2730 Burgess,Lee,Trott

  See also arXiv:1002.2995 Hertzberg

- The cut off scale evolves with the background field!
  arXiv:1008.5157 Bezrukov et al.

- Right here $\dfrac{m_h^2(\phi)}{\Lambda^2(\phi)} \to 1$ threshold terms in the RGE introduce UV sensitivity

Higgs Inflation - interesting wrinkles..

- Threshold terms in the linear SMEFT - in a flat background:

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\lambda = \frac{m_H^2}{16\pi^2}\Big[12C_H + \left(-32\lambda + \frac{10}{3}g_2^2\right)C_{H\Box} + \left(12\lambda - \frac{3}{2}g_2^2 + 6g_1^2\mathsf{y}_H^2\right)C_{HD} + 2\eta_1 + 2\eta_2$$
$$+ 12g_2^2 c_{F,2}C_{HW} + 12g_1^2\mathsf{y}_H^2 C_{HB} + 6g_1 g_2 \mathsf{y}_H C_{HWB} + \frac{4}{3}g_2^2 C^{(3)}_{\substack{Hl\\tt}} + \frac{4}{3}g_2^2 N_c C^{(3)}_{\substack{Hq\\tt}}\Big],$$

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}m_H^2 = \frac{m_H^4}{16\pi^2}\left[-4C_{H\Box} + 2C_{HD}\right],$$

$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}[Y_u]_{rs} = \frac{m_H^2}{16\pi^2}\Big[3C^*_{\substack{uH\\sr}} - C_{H\Box}[Y_u]_{rs} + \frac{1}{2}C_{HD}[Y_u]_{rs} - [Y_u]_{rt}\left(C^{(1)}_{\substack{Hq\\ts}} + 3C^{(3)}_{\substack{Hq\\ts}}\right) + C_{\substack{Hu\\rt}}[Y_u]_{ts}$$
$$- C_{\substack{Hud\\rt}}[Y_d]_{ts} - 2\left(C^{(1)*}_{\substack{qu\\sptr}} + c_{F,3}C^{(8)*}_{\substack{qu\\sptr}}\right)[Y_u]_{tp} - C^{(1)*}_{\substack{lequ\\ptsr}}[Y_e^*]_{tp} + N_c C^{(1)*}_{\substack{quqd\\srpt}}[Y_d]^*_{tp}$$
$$+ \frac{1}{2}\left(C^{(1)*}_{\substack{quqd\\prst}} + c_{F,3}C^{(8)*}_{\substack{quqd\\prst}}\right)[Y_d]^*_{tp}\Big],$$

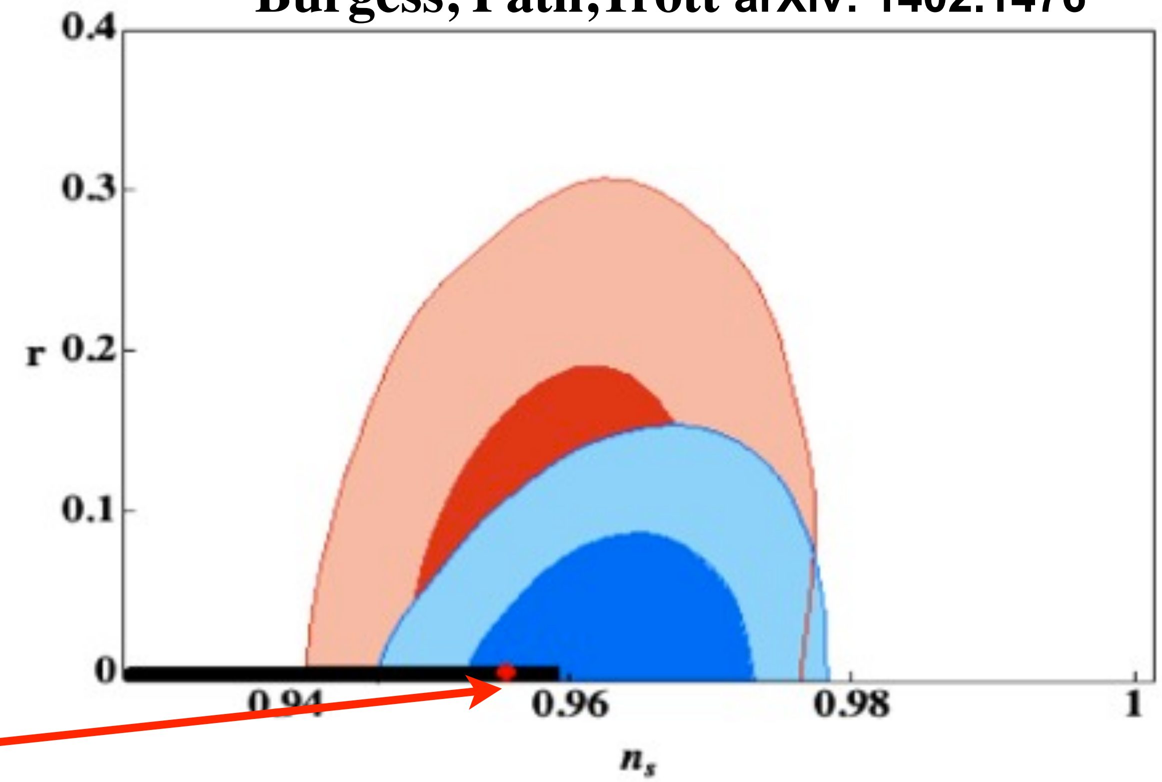
$$\mu\frac{\mathrm{d}g_3}{\mathrm{d}\mu} = -4\frac{m_H^2}{16\pi^2}g_3 C_{HG}, \qquad \mu\frac{\mathrm{d}g_2}{\mathrm{d}\mu} = -4\frac{m_H^2}{16\pi^2}g_2 C_{HW}, \qquad \mu\frac{\mathrm{d}g_1}{\mathrm{d}\mu} = -4\frac{m_H^2}{16\pi^2}g_1 C_{HB},$$
$$\mu\frac{\mathrm{d}}{\mathrm{d}\mu}\theta_3 = -\frac{4m_H^2}{g_3^2}C_{H\widetilde{G}}, \qquad \mu\frac{\mathrm{d}}{\mathrm{d}\mu}\theta_2 = -\frac{4m_H^2}{g_2^2}C_{H\widetilde{W}}, \qquad \mu\frac{\mathrm{d}}{\mathrm{d}\mu}\theta_1 = -\frac{4m_H^2}{g_1^2}C_{H\widetilde{B}},$$

- Extra dependence on ξ and Hubble parameter in EOM $\propto \dot{\mathcal{H}} + 3\,\mathcal{H}^2$

Higgs Inflation - interesting wrinkles..

Burgess, Patil,Trott arXiv: 1402.1476

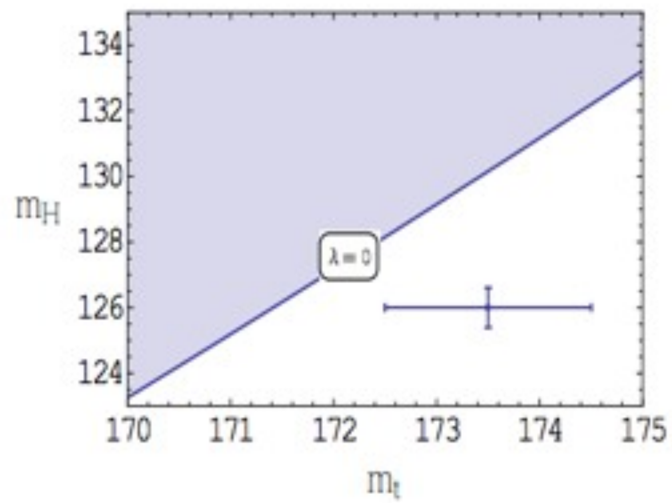
- NOT a predictive scenario. We can't know it is right by measurements of this form.

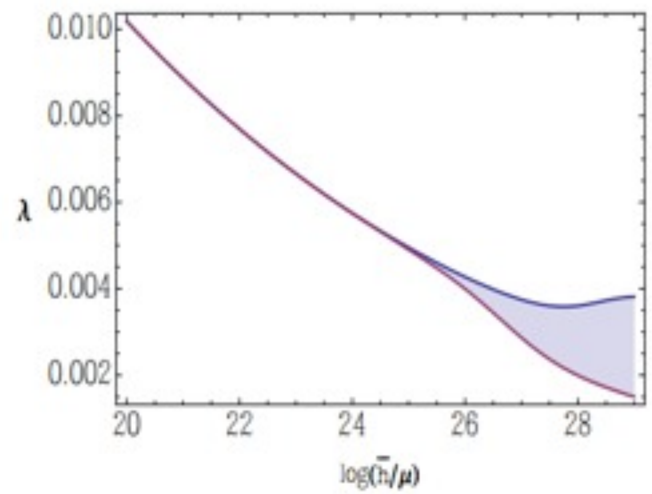


—— what you get due to the threshold terms in the RGE smearing predictions

Usual prediction for HI.

also...





The fundamental Higgs EFT is...

- NONLINEAR. Even when the Higgs mechanism and doublet is present.

- The right EFT has to reproduce the IR of the UV theory, and gravity introduces nonlinearities due to the singlet higgs field mixing with a scalar gravity component proportional to

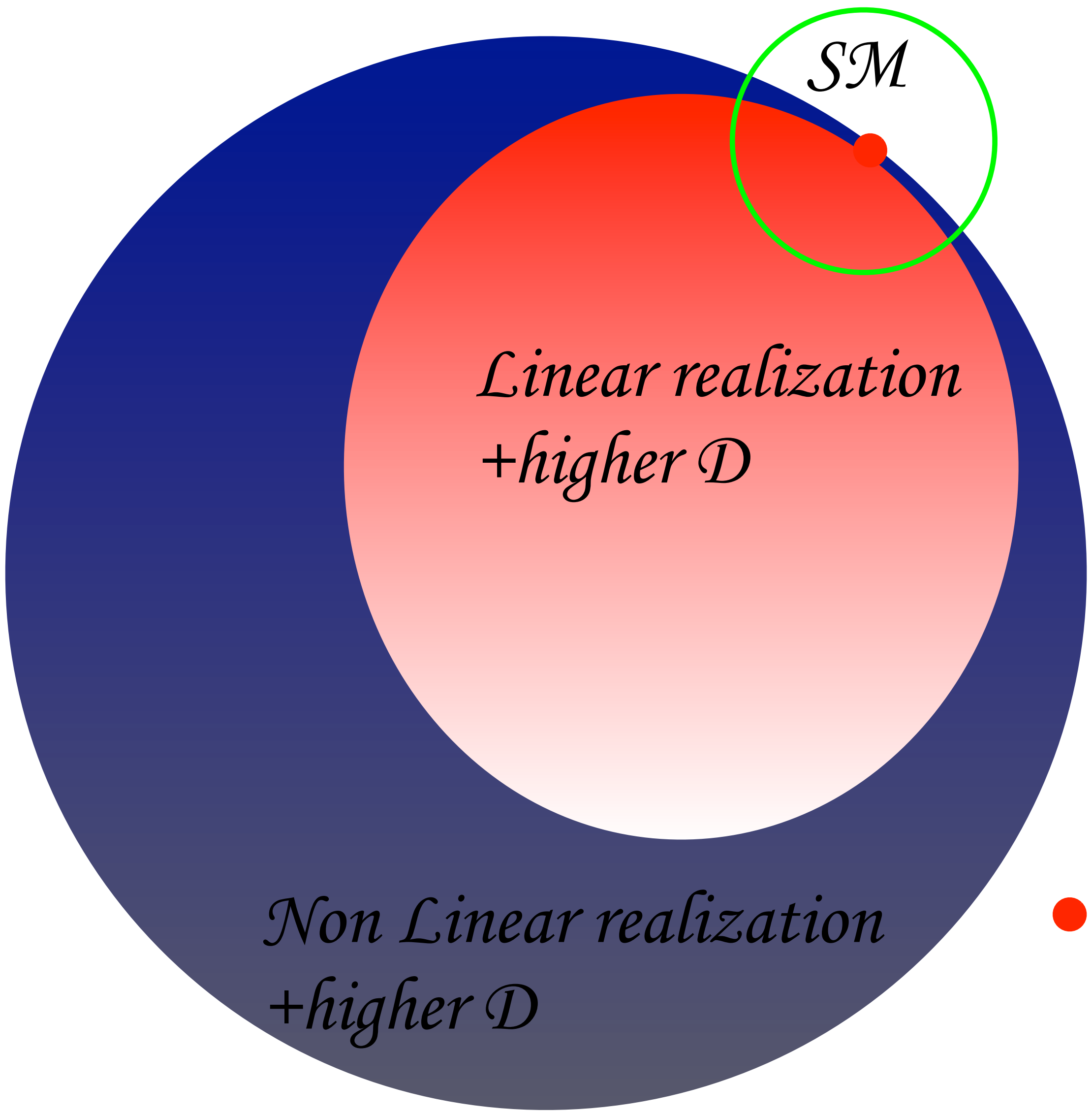
$$\xi \, \frac{\bar{X}}{M_{pl}}$$

- The question is not is the Higgs doublet or mechanism present.
The question is “do we have interactions in the UV that force us to use a nonlinear formalism to reproduce the IR”.

- Note that convergence on SM values of couplings implies the cut off scale is parametrically separated from the ew vev scale, not a linear EFT.

Consistency in bounding the SMEFT

- We need to bound the SMEFT consistently and precisely and look at patterns of deviations (if any found) and relations between observables to even know the right EFT formalism.



- Linear EFT $H \supset h$ and relations between measurements that follow from this hold

- Non-Linear EFT, singlet h. Broader range of relations between measurements.

- Non-Linear EFT not equivalent and more general arXiv:0704.1505 Grinstein Trott

- Non linear EFT developed Alonso,et al. arXiv:1212.3305,**arXiv:1409.1589** Contino et al. arXiv:1202.3415 Buchalla et al. arXiv:1203.6510, arXiv:1307.5017

Consistency in bounding the SMEFT

- USE full EFT (linear or nonlinear) without any other poorly defined extra assumptions.

- Do not use “minimal coupling” at an operator level in the EFT to argue “tree” and “loop” operators. This procedure is ill defined in a derivative expansion - i.e. an EFT.

$$i\partial_\mu \to iD_\mu = i\partial_\mu - eqA_\mu. \qquad [\partial^\mu, \partial^\nu] = 0, \text{ but } [D^\mu, D^\nu] = ieqF^{\mu\nu}$$

arXiv:1305.0017 Jenkins,Manohar Trott
(and weinberg 70’s, Weyl 1929)

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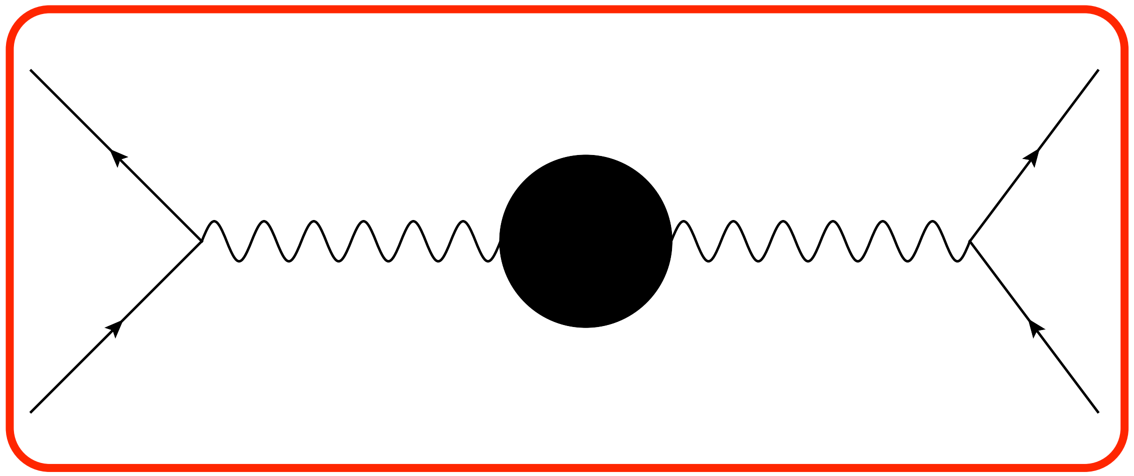
- Rigorously insist on basis independence of conclusions. And check this. No basis "better related to experiments" by definition.

- Related to this is the idea of observables vs constructed observables, and functional redundancy.

Observables vs constructed observables

- Observable directly related to an S matrix element. Relations between observables basis independent.
- Constructed observable related to measurements with defining conditions. Relations involving constructed observables are NOT basis independent -- unless the defining conditions are imposed on the field theory.
- The most well know constructed observable - the S parameter.



Measured observable

Observables vs constructed observables

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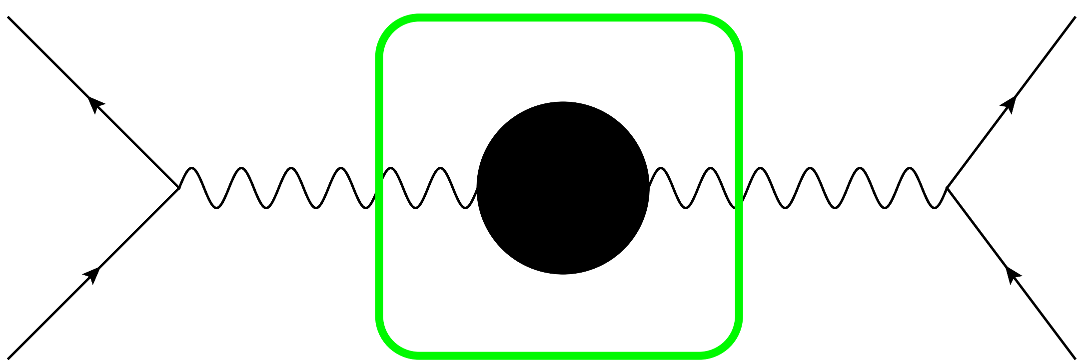

constructed observable

- Defining condition possible vertex corrections PHYSICALLY vanish.

S parameter defining conditions

- In terms of operators

$$Q_{HW} = H^\dagger H\, W^I_{\mu\nu} W_I^{\mu\nu}, \qquad \cancel{Q^{(1)}_{\substack{H\ell \\ pr}}} = (H^\dagger i \overleftrightarrow{D}_\mu H)\, \bar{\ell}_p \gamma^\mu \ell_r, \qquad Q_{HWB} = H^\dagger \tau_I H\, W^I_{\mu\nu} B^{\mu\nu},$$

$$\cancel{Q^{(3)}_{\substack{H\ell \\ pr}}} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)\, \bar{\ell}_p \tau^I \gamma^\mu \ell_r, \quad Q_{HD} = (H^\dagger D^\mu H)^\star (H^\dagger D_\mu H).$$

- However could also choose a basis:

$$\mathcal{O}_{HW} = -i\, g_2\, (D^\mu H)^\dagger \tau^I (D^\nu H)\, W^I_{\mu\nu}, \qquad \mathcal{O}_{HB} = -i\, g_1\, (D^\mu H)^\dagger (D^\nu H)\, B_{\mu\nu},$$

$$\mathcal{O}_W = -\frac{i\, g_2}{2} (H^\dagger \overleftrightarrow{D}^I_\mu H)(D^\nu W^I_{\mu\nu}), \qquad \mathcal{O}_B = -\frac{i\, g_1}{2} (H^\dagger \overleftrightarrow{D}^\mu H)(D^\nu B_{\mu\nu}),$$

$$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}^\mu H).$$

- Where has the defining condition gone as a constraint on the field theory?

S parameter defining conditions

- Operator relations

$$
\begin{aligned}
g_1\, g_2\, Q_{HWB} &= 4\,\mathcal{O}_B - 4\,\mathcal{O}_{HB} - 2\,\mathsf{y}_H\, g_1^2\, Q_{HB}, \\
g_2^2\, Q_{HW} &= 4\,\mathcal{O}_W - 4\,\mathcal{O}_B - 4\,\mathcal{O}_{HW} + 4\,\mathcal{O}_{HB} + 2\,\mathsf{y}_H\, g_1^2\, Q_{HB}, \\
g_1^2\, \mathsf{y}_\ell\, Q^{(1)}_{\substack{Hl\\tt}} &= 2\,\mathcal{O}_B + \mathsf{y}_H\, g_1^2\, \mathcal{O}_T - g_1^2 \left[\mathsf{y}_e Q_{\substack{He\\rr}} + \mathsf{y}_q Q^{(1)}_{\substack{Hq\\rr}} + \mathsf{y}_u Q_{\substack{Hu\\rr}} + \mathsf{y}_d Q_{\substack{Hd\\rr}} \right], \\
g_2^2\, Q^{(3)}_{\substack{Hl\\tt}} &= 4\,\mathcal{O}_W - 3\, g_2^2\, Q_{H\Box} + 2\, g_2^2 m_h^2\, (H^\dagger H)^2 - 8\, g_2^2\, \lambda\, Q_H - g_2^2\, Q^{(3)}_{Hq}, \\
&\quad - 2\, g_2^2 \left([Y_u^\dagger]_{rr} Q_{\substack{uH\\rr}} + [Y_d^\dagger]_{rr} Q_{\substack{dH\\rr}} + [Y_e^\dagger]_{rr} Q_{\substack{eH\\rr}} + h.c. \right).
\end{aligned}
$$

- Consistency in the field theory $\mathcal{L}^{(6)} = \sum_i C_i\, Q_i = \sum_i \mathcal{P}_i\, \mathcal{O}_i.$

$$
\mathcal{P}_B \to \frac{4}{g_1\, g_2} C_{HWB} - \frac{4}{g_2^2} C_{HW} + \frac{2}{g_1^2\, \mathsf{y}_\ell} \cancel{C^{(1)}_{\substack{H\ell\\tt}}}, \qquad \mathcal{P}_W \to \frac{4}{g_2^2} C_{HW} + \frac{4}{g_2^2} \cancel{C^{(3)}_{\substack{H\ell\\tt}}},
$$

$$
\mathcal{P}_{HB} \to -\frac{4}{g_1\, g_2} C_{HWB} + \frac{4}{g_2^2}\, C_{HW}, \qquad \mathcal{P}_{HW} \to -\frac{4}{g_2^2} C_{HW}.
$$

- Naively use S parameter bound $\mathcal{P}_{HB} = -\mathcal{P}_B \quad \mathcal{P}_{HW} = -\mathcal{P}_W$

S parameter defining conditions

- It (should) go without saying - no preferred operator basis for the oblique parameters

$$S_Q = -\frac{16\,\pi\,v_T^2}{g_1\,g_2}\,C_{HWB}. \qquad\qquad S_O = -4\,\pi\,v_T^2\,(\mathcal{P}_B + \mathcal{P}_W)$$

$$-4\,\pi\,v_T^2\,(\mathcal{P}_B + \mathcal{P}_W) \to -\frac{16\,\pi\,v_T^2}{g_1\,g_2}\,C_{HWB} - \frac{8\,\pi\,v_T^2}{g_1^2\,\mathsf{y}_\ell}\,C^{(1)}_{\substack{H\ell\\tt}} - \frac{16\,\pi\,v_T^2}{g_2^2\,\mathsf{y}_\ell}\,C^{(3)}_{\substack{H\ell\\tt}}.$$

hep-ph/0602154, Skiba, Terning et al.
(and others..)

- Does not follow that the EFT is less constrained due to an operator basis choice (obviously) if one is consistent.

Going forward S,T,U insufficient

- General analysis along the lines of Han, Skiba hep-ph/0412166 required

$$\mathcal{S} = \frac{v_T^2\, C_{HBW}}{\bar{g}_1\, \bar{g}_2}, \qquad \mathcal{T} = \frac{1}{2} v_T^2\, C_{HD}.$$

$$\frac{\delta\alpha_{ew}}{(\alpha_{ew})_{SM}} = -2\,(s_\theta^{SM})^2\, \bar{g}_2^2\, \mathcal{S},$$

$$\frac{\delta G_F}{(G_F)_{SM}} = -\frac{v_T^2}{2}\left(C_{\substack{ll\\ \mu e e \mu}} + C_{\substack{ll\\ e \mu \mu e}}\right) + v_T^2\left(C^{(3)}_{\substack{Hl\\ ee}} + C^{(3)}_{\substack{Hl\\ \mu\mu}}\right)$$

$$\frac{\delta m_Z^2}{(m_Z^2)_{SM}} = \mathcal{T} + 2\,(s_\theta^{SM})^2\, \bar{g}_2^2\, \mathcal{S}.$$

LEP data:

$$\frac{\delta\Gamma_Z^{L(t)}}{\Gamma_Z^L} = \frac{1}{\bar{c}_{2\theta}^2}\left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 4\bar{s}_\theta^2\, \bar{g}_2^2\, \mathcal{S}\right) + \frac{2\, v_T^2}{2\,\bar{s}_\theta^2 - 1}\left(C^{(1)}_{\substack{H\ell\\ tt}} + C^{(3)}_{\substack{H\ell\\ tt}}\right),$$

$$\frac{\delta\Gamma_Z^R}{\Gamma_Z^R} = -\frac{1}{\bar{c}_{2\theta}}\left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2\,\bar{g}_2^2\, \mathcal{S}\right) - \frac{v_T^2\, C_{He}}{\bar{s}_\theta^2},$$

$$\frac{\delta\Gamma_Z^\nu}{\Gamma_Z^L} = \mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2\, v_T^2\left(C^{(1)}_{\substack{H\ell\\ tt}} - C^{(3)}_{\substack{H\ell\\ tt}}\right),$$

$$\frac{\delta m_W}{m_W} = \frac{1}{2\,\bar{c}_{2\theta}}\left(\bar{c}_\theta^2\mathcal{T} + \bar{s}_\theta^2\left(\frac{\delta G_F}{(G_F)_{SM}} + 2\bar{g}_2^2\, \mathcal{S}\right)\right).$$

- For some recent works in this direction see Adam’s talk (arXiv:1411.0669), Pomarol, Riva arXiv:1308.2803, Ellis, Sanz You arXiv:1410.7703

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$$\frac{\delta G_F}{(G_F)_{SM}} = -\frac{v_T^2}{2} \left(C_{\underset{\mu e e \mu}{ll}} + C_{\underset{e \mu \mu e}{ll}} \right) + v_T^2 \left(C_{\underset{ee}{Hl}}^{(3)} + C_{\underset{\mu\mu}{Hl}}^{(3)} \right)$$

$$\frac{\delta m_Z^2}{(m_Z^2)_{SM}} = \mathcal{T} + 2 \, (s_\theta^{SM})^2 \, \bar{g}_2^2 \, \mathcal{S}.$$

Flavour dependent
cancelation

LEP data:

$$\frac{\delta \Gamma_Z^{L(t)}}{\Gamma_Z^L} = \frac{1}{\bar{c}_{2\theta}^2} \left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 4 \bar{s}_\theta^2 \, \bar{g}_2^2 \, \mathcal{S} \right) + \frac{2 \, v_T^2}{2 \, \bar{s}_\theta^2 - 1} \left(C_{\underset{tt}{H\ell}}^{(1)} + C_{\underset{tt}{H\ell}}^{(3)} \right),$$

$$\frac{\delta \Gamma_Z^R}{\Gamma_Z^R} = -\frac{1}{\bar{c}_{2\theta}} \left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2 \, \bar{g}_2^2 \, \mathcal{S} \right) - \frac{v_T^2 \, C_{He}}{\bar{s}_\theta^2},$$

$$\frac{\delta \Gamma_Z^\nu}{\Gamma_Z^L} = \mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2 \, v_T^2 \left(C_{\underset{tt}{H\ell}}^{(1)} - C_{\underset{tt}{H\ell}}^{(3)} \right),$$

$$\frac{\delta m_W}{m_W} = \frac{1}{2 \, \bar{c}_{2\theta}} \left(\bar{c}_\theta^2 \mathcal{T} + \bar{s}_\theta^2 \left(\frac{\delta G_F}{(G_F)_{SM}} + 2 \bar{g}_2^2 \, \mathcal{S} \right) \right).$$

- As flavour matters, how many parameters for the leptons in general?

$$\frac{1}{4} \left(8 + 15 n_g^2 + 2 n_g^3 + 3 n_g^4 \right) = 110 \qquad \text{Set} \quad \Gamma_z^2 / M_z^2 \sim 10^{-3} \to 0 \quad \text{Then 22.}$$

- In the trivialized case we are talking about in general, 6 vs 10 for flavour symmetric lepton effects

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$$\mathcal{S} = \frac{v_T^2\, C_{HBW}}{\bar{g}_1\, \bar{g}_2}, \qquad \mathcal{T} = \frac{1}{2} v_T^2\, C_{HD}.$$

$$\frac{\delta\alpha_{ew}}{(\alpha_{ew})_{SM}} = -2\,(s_\theta^{SM})^2\, \bar{g}_2^2\, \mathcal{S},$$

$$\frac{\delta G_F}{(G_F)_{SM}} = -\frac{v_T^2}{2}\left(C_{\substack{ll\\ \mu e e \mu}} + C_{\substack{ll\\ e \mu \mu e}}\right) + v_T^2 \left(C^{(3)}_{\substack{Hl\\ ee}} + C^{(3)}_{\substack{Hl\\ \mu\mu}}\right)$$

$$\frac{\delta m_Z^2}{(m_Z^2)_{SM}} = \mathcal{T} + 2\,(s_\theta^{SM})^2\, \bar{g}_2^2\, \mathcal{S}.$$

Flavour dependent cancelation

LEP data:

$$\frac{\delta\Gamma_Z^{L(t)}}{\Gamma_Z^L} = \frac{1}{\bar{c}_{2\theta}^2}\left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 4\bar{s}_\theta^2\, \bar{g}_2^2\, \mathcal{S}\right) + \frac{2\, v_T^2}{2\,\bar{s}_\theta^2 - 1}\left(C^{(1)}_{\substack{H\ell\\ tt}} + C^{(3)}_{\substack{H\ell\\ tt}}\right),$$

$$\frac{\delta\Gamma_Z^R}{\Gamma_Z^R} = -\frac{1}{\bar{c}_{2\theta}}\left(\mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2\,\bar{g}_2^2\, \mathcal{S}\right) - \frac{v_T^2\, C_{He}}{\bar{s}_\theta^2},$$

$$\frac{\delta\Gamma_Z^\nu}{\Gamma_Z^L} = \mathcal{T} + \frac{\delta G_F}{(G_F)_{SM}} + 2\, v_T^2\left(C^{(1)}_{\substack{H\ell\\ tt}} - C^{(3)}_{\substack{H\ell\\ tt}}\right),$$

$$\frac{\delta m_W}{m_W} = \frac{1}{2\,\bar{c}_{2\theta}}\left(\bar{c}_\theta^2 \mathcal{T} + \bar{s}_\theta^2\left(\frac{\delta G_F}{(G_F)_{SM}} + 2\bar{g}_2^2\, \mathcal{S}\right)\right).$$

- Don't freak out!

$$\left[107 n_g^4 + 2 n_g^3 + 135 n_g^2 + 60\right]/4$$

$n_g = 1$ total parameters 76

$n_g = 3$ total parameters 2499

Alonso,Jenkins,Manohar Trott arXiv:1312.2014

We need on the order of hundreds of parameters, not thousands.

We need the real SMEFT constraints

- Flat directions in LEP care about flavour indicies, which is surprising. It might matter.

  In the trivialized case we are talking about in general, 6 parameters, not 10.

- Most LEP data is 1% precise, ***some*** data is even 0.1 % precise.

$$C^2 \frac{v^2}{\Lambda^2} = C^2 \frac{246^2}{2000^2} \sim C^2 0.015$$

If we are doing the SMEFT as we think the hierarchy problem means deviations to follow related to couple TeV physics, we should be doing the general analyses. (If we can.)

- Flavour physics probes much further for flavour violating effects. So U(3)^5 and MFV (Isidori et al. hep-ph/0207036) very important to think about. But flavour SYMMETRIC effects correspond to different constraints.

LEP is not blind to flat directions

- With some chosen flat directions the leading breaking is:

$$\mu \frac{d}{d\mu}(C_{HD} - 2\,C^{(3)}_{Hl}) = \frac{12\,\lambda}{16\,\pi^2}\,C_{HD} + \cdots$$

$$\mu \frac{d}{d\mu}(C_{HD} - C_{ll}) = \frac{3}{4\,\pi^2}\,(\lambda + y_t^2)\;C_{HD} + \cdots$$

(neglecting mixing)
Trott 1409.7605

- It actually can matter to treat the scale dependence carefully in global analyses. Percent level breaking of flat directions for precision observables doing so at LEP.

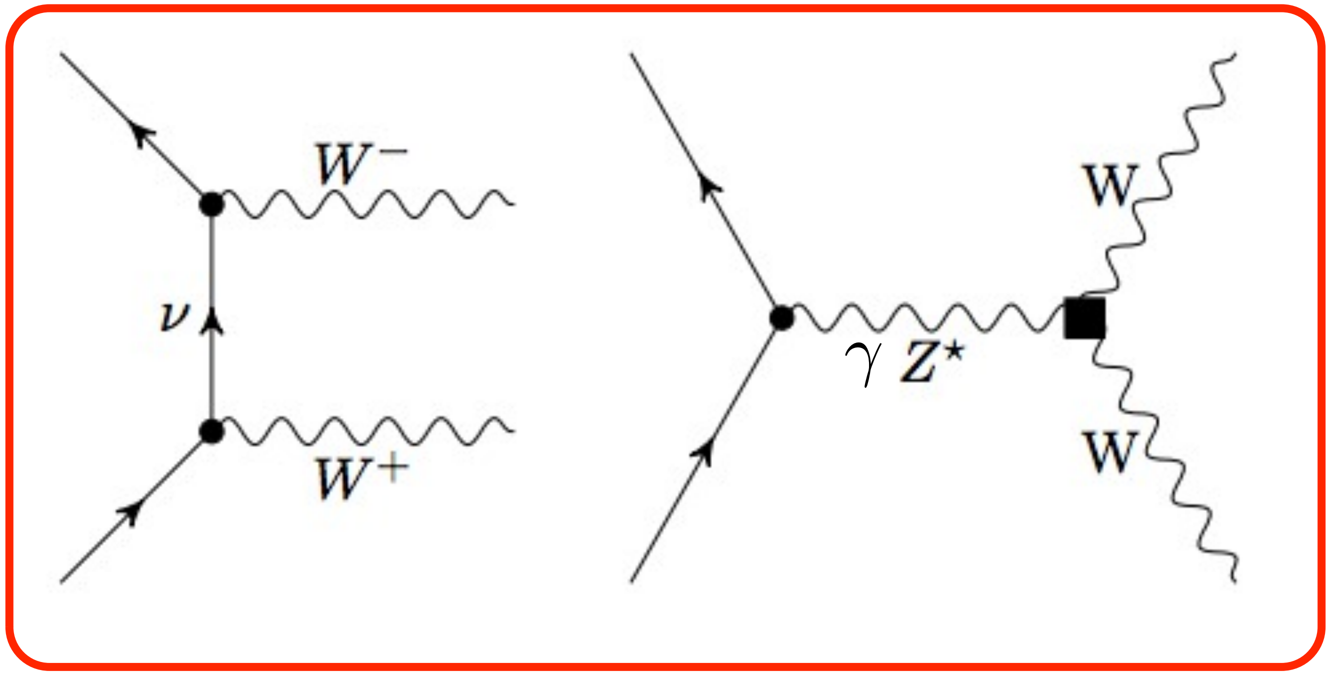
- In this sense, the LHC vector bosons are not your fathers (or mothers) vector bosons.

- Path is starting to emerge to globally constrain the SMEFT accounting for the scale dependence of the operators fully at one loop.

  Recent excellent study on $\mu \to e\,\gamma$:Pruna, Signer arXiv:1408.3565

Constructed collider observables

- An observable in a collider environment is non trivial. Same lesson holds. Consider TGC bounds:



Measured observable(s)

$$\sigma(e^+e^- \to W^+W^-) \quad \frac{d\sigma}{d\Omega}$$

Constructed collider observables

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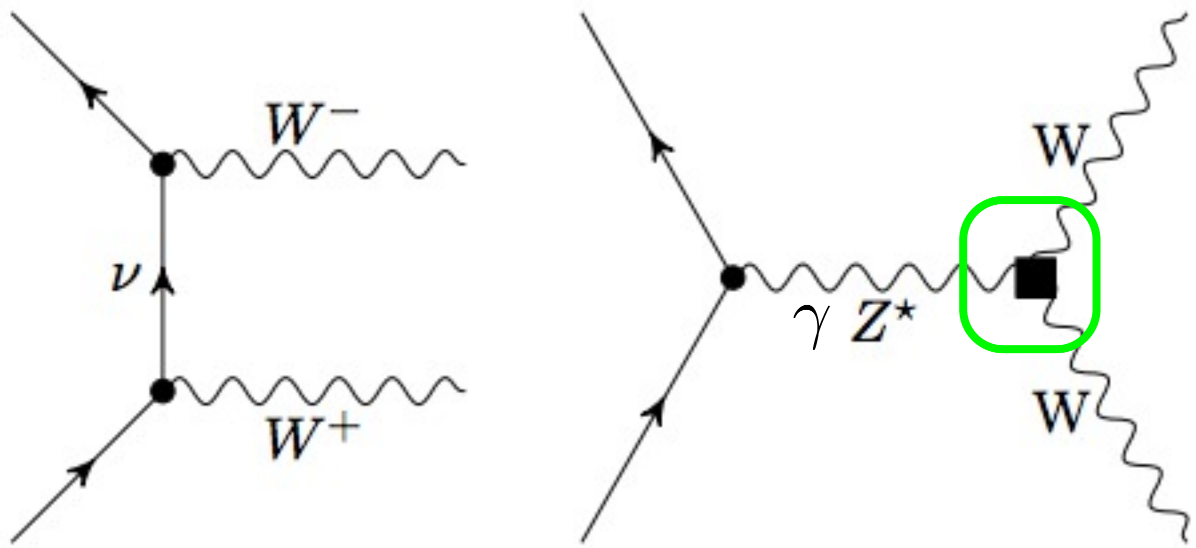

constructed observable(s)

$$\delta g_1^{Z,\gamma}, \delta\kappa^{Z,\gamma}, \delta\lambda^{Z,\gamma}$$

Reported by the LEP experiments! Be careful.

Constructed collider observables

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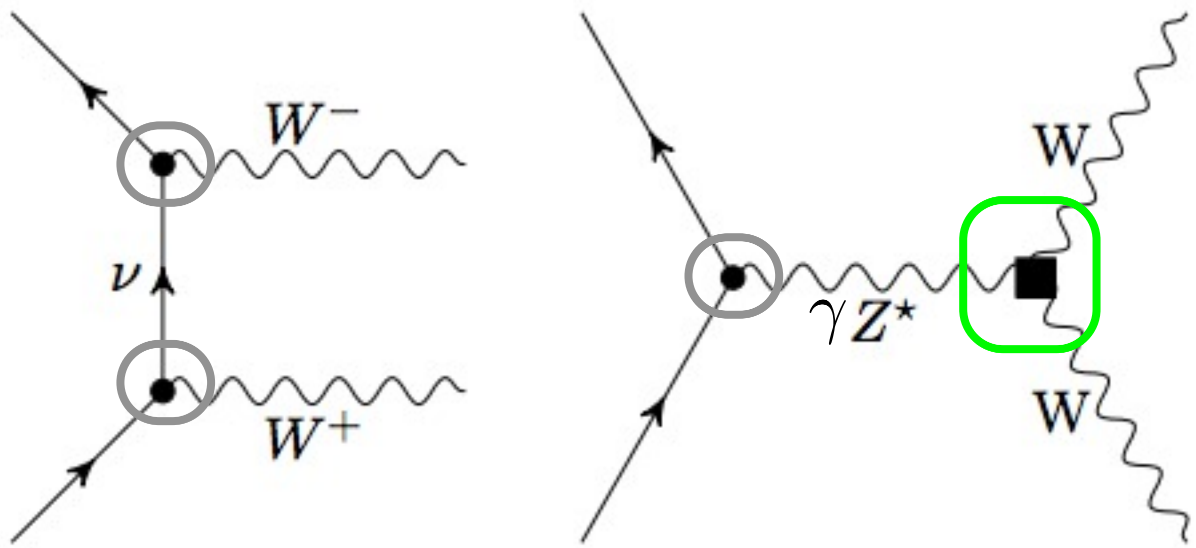


constructed observable(s)

$$\delta g_1^{Z,\gamma}, \delta\kappa^{Z,\gamma}, \delta\lambda^{Z,\gamma}$$

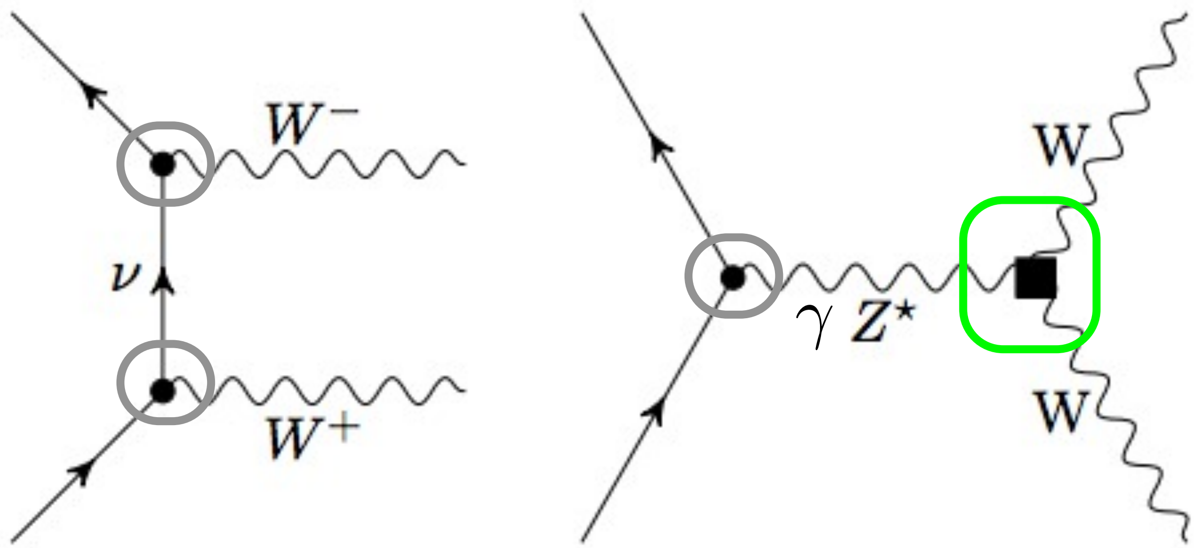
Reported by the LEP experiments! Be careful.

- Defining condition SM like coupling of W,Z to fermions.

physically as in the SM

"Functional redundancy"

- An observable in a collider environment is non trivial. Same lesson holds. Consider TGC bounds:



constructed observable(s)

$$\delta g_1^{Z,\gamma}, \delta\kappa^{Z,\gamma}, \delta\lambda^{Z,\gamma}$$

- Naively one can "extract" combinations of parameters such as

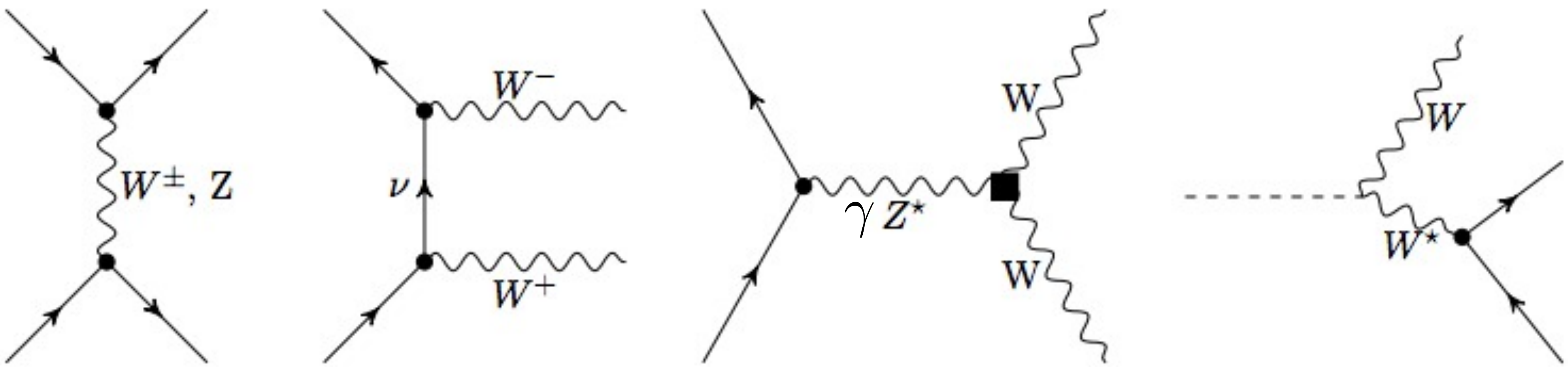
$$\mathcal{P}_{HW} + \mathcal{P}_W \qquad \mathcal{P}_{HW} + \mathcal{P}_{HB}$$

from TGC measurements - but the defining condition sets these contributions to 0.

- Taking into account the defining conditions restores the basis independence.

“Functional redundancy”

- This problem will lead to inconsistent global constraints when examining relations between observables and constructed observables:

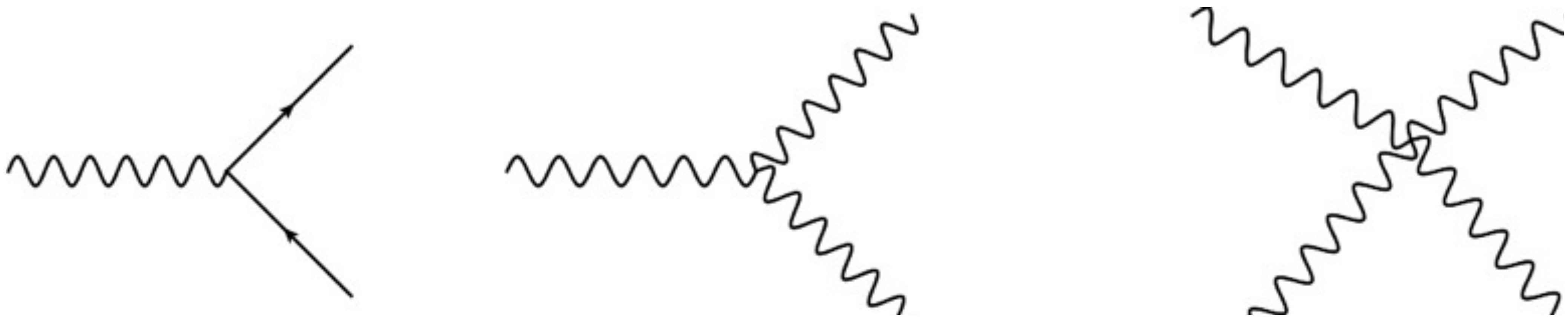


What NOT to do.

- A functionally redundant relation between observables and a constructed observable

Unphysical parameterizations

- It is tempting to try and parameterize NP in terms of some parts of Feynman diagrams:

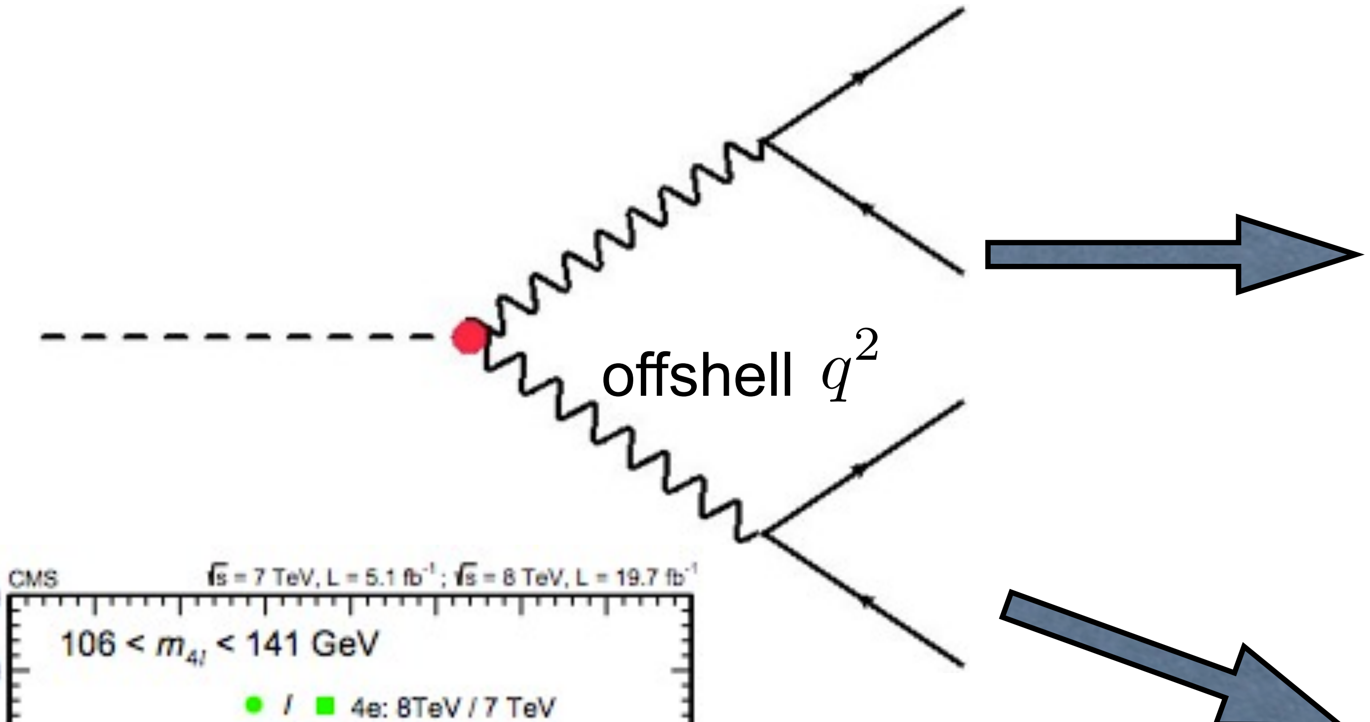


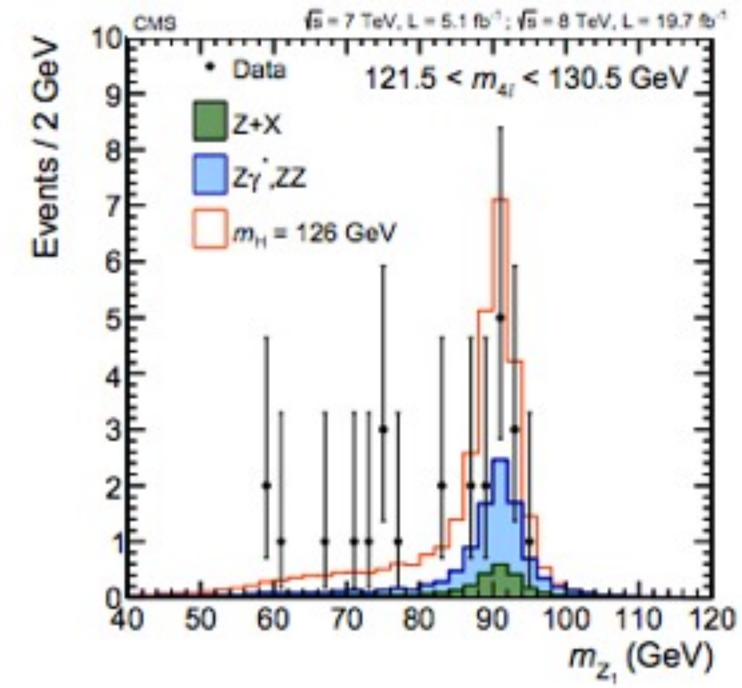
- In many cases the TGC and quartic couplings are offshell - unphysical.

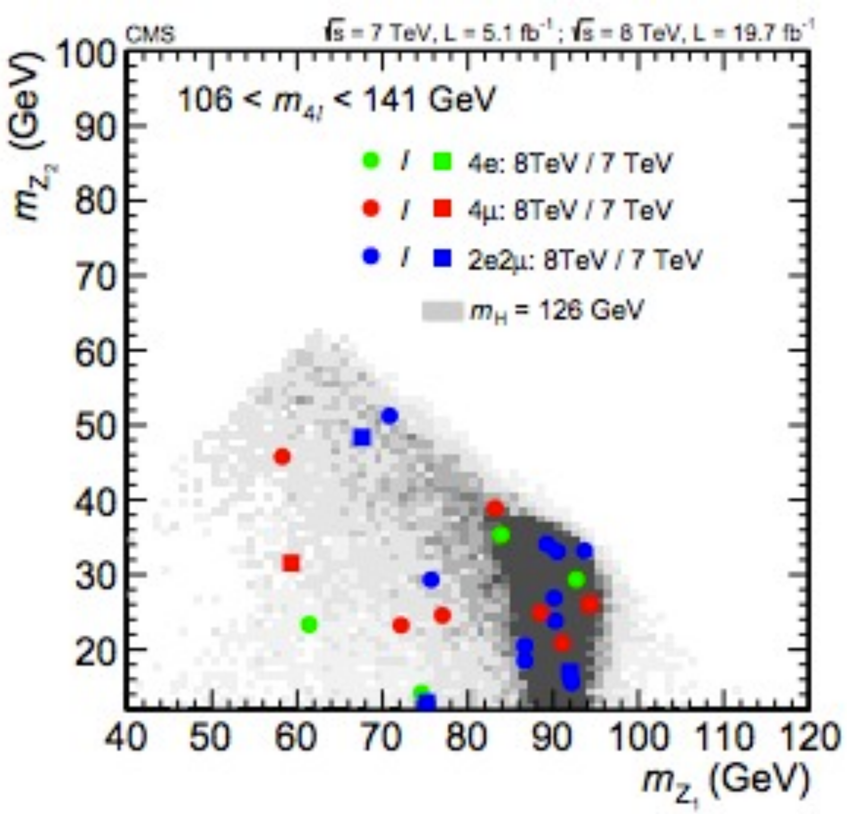
- This is a parameterization in constructed observables and you have to simultaneous impose the defining conditions trying to go this way.

Why care about being precise?

- Consider the following processes with non-SM interactions involving the “h”:

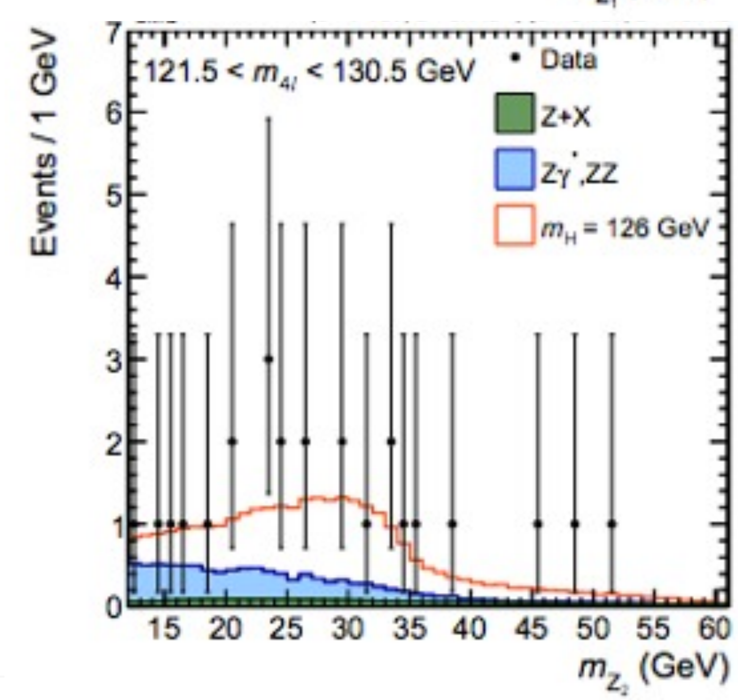




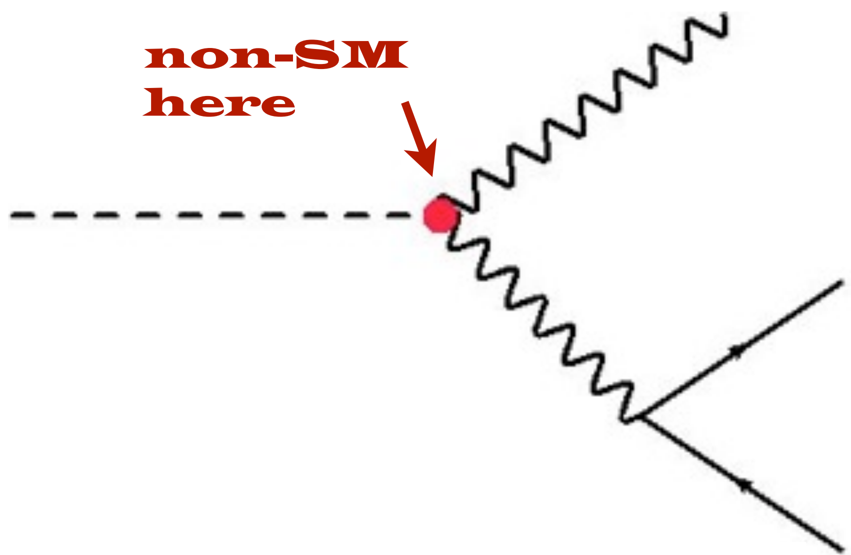


CMS
analysis 1312.5353

Event rate limited.

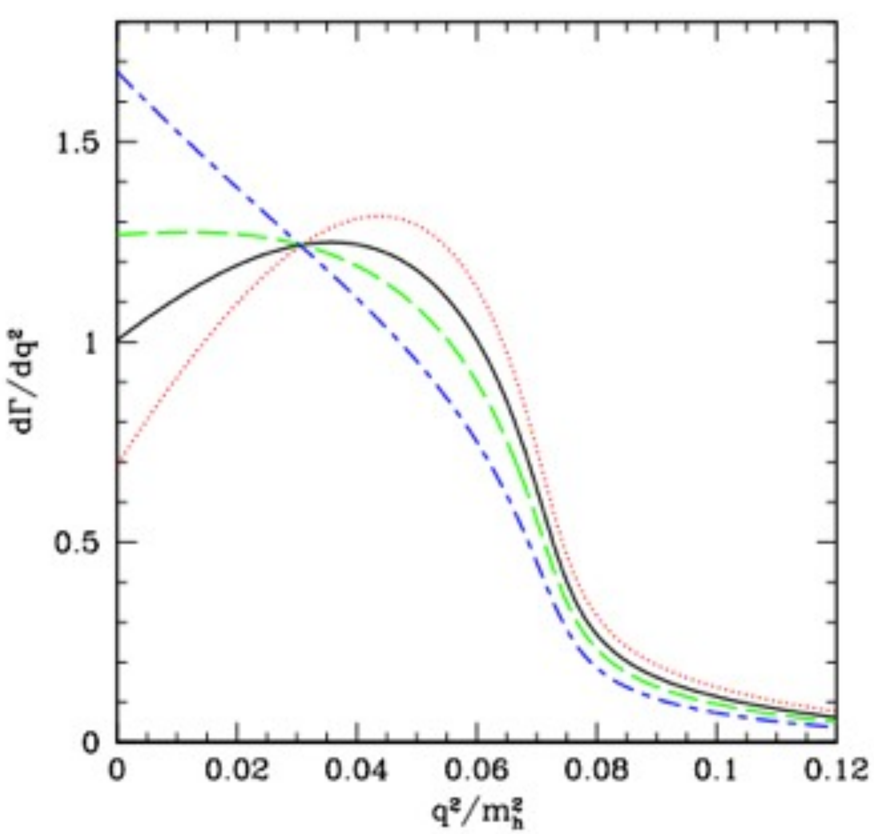


Establish the EFT in the golden channel



With sufficient data, a tight cut on the reconstructed on shell vector mass, study the 3 body distribution (can then combine vector decay modes)

shifted to minimal bi-lepton distribution (V reconstructed)



- Total signal strength the same, significant shape variations possible in offshell q^2 spec. (Photon pole neglected here).

Need more data!
But we are going to
get it!

- Another nice paper (light states focus)
M Gonzalez-Alonso, G Isidori **arXiv:1403.2648.**

Establish the EFT in the golden channel

- Generalized differential decay distributions:

Isidori, Manohar, Trott arXiv: 1305.0663
Grinstein et al. arXiv: 1305.6938
Buchalla et al. arXiv: 1310.2574

$$\frac{d^2\Gamma}{dq^2 dc_\theta} = \frac{C_V^2 g_V^4 m_V^2}{256\pi^3 m_h}\frac{\lambda(\hat{q}^2,\rho)}{(q^2-m_V^2)^2}\Big\{X_\ell q^2\left[\left|f_1+\frac{1}{2}\left(m_h^2-q^2-m_V^2\right)f_3\right|^2+\frac{1}{4}m_h^4\lambda^2(\hat{q}^2,\rho)\,|f_4|^2\right]$$
$$+\frac{1}{8}X_\ell m_h^4\lambda^2(\hat{q}^2,\rho)\left[\frac{|f_1|^2}{m_V^2}-q^2|f_3|^2-q^2|f_4|^2\right](1-c_\theta^2)-Y_\ell\,\mathrm{Im}\left[\left(f_1^*+\frac{1}{2}(m_h^2-q^2-m_V^2)f_3^*\right)f_4\right]m_h^2 q^2\lambda(\hat{q}^2,\rho)c_\theta\Big\}$$

where: $X_\ell = (g_R^\ell)^2 + (g_L^\ell)^2$, $Y_\ell = (g_R^\ell)^2 - (g_L^\ell)^2$.

- Why Form factors, just use operators. Form factors ill defined beyond L.O.
  Of course, but WHICH ONES? Which EFT linear or non-linear?

Non-Linear:

$$f_1^V(q^2) = c_1 + g_2^2(c_2+c_3)\left(1+\frac{q^2}{m_V^2}\right),$$
$$f_2^V(q^2) = -\frac{1}{m_V^2}\left[c_1 + 2g_2^2(c_2+c_3)\right]$$
$$f_3^V(q^2) = \frac{2g_2^2}{m_V^2}c_3,$$
$$f_4^V(q^2) = 0.$$

In terms of operators: (custodial)

$$\hat{O}_{LO} = \frac{v\,c_1}{2}\,h\,\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger D^\mu\Sigma\right],$$
$$\hat{O}_W = \frac{g_2\,c_2}{v}\,h\,D_\mu W_a^{\mu\nu}\mathrm{Tr}\left[\Sigma^\dagger i\tau^a\overleftrightarrow{D}_\nu\Sigma\right],$$
$$\hat{O}_{W\partial H} = \frac{g_2\,c_3}{v}\,(\partial_\nu h)\,W_a^{\mu\nu}\mathrm{Tr}\left[\Sigma^\dagger i\tau^a\overleftrightarrow{D}_\mu\Sigma\right],$$

Establish the EFT in the golden channel

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$$\left.+\frac{1}{8}X_\ell m_h^4\lambda^2(\hat{q}^2,\rho)\left[\frac{|f_1|^2}{m_V^2}-q^2|f_3|^2-q^2|f_4|^2\right](1-c_\theta^2)-Y_\ell\,\mathrm{Im}\left[\left(f_1^*+\frac{1}{2}(m_h^2-q^2-m_V^2)f_3^*\right)f_4\right]m_h^2q^2\lambda(\hat{q}^2,\rho)c_\theta\right\}$$

where: $X_\ell = (g_R^\ell)^2 + (g_L^\ell)^2,\ Y_\ell = (g_R^\ell)^2 - (g_L^\ell)^2.$

- Of course, but WHICH ONES? Which EFT linear or non-linear?

Linear:

$$f_1^V(q^2) = 1 + \frac{v^2 c_\Box}{\Lambda^2}\,,$$
$$f_2^V(q^2) = -\frac{1}{m_V^2}\left(1+\frac{v^2 c_\Box}{\Lambda^2}\right),$$
$$f_3^V(q^2) = \frac{g_2^2}{m_V^2}\left(\frac{v^2 c_{WW}^V}{\Lambda^2}\right)\,,$$
$$f_4^V(q^2) = 0\,.$$

q^2 dep.

In terms of operators: (custodial)

$$\mathcal{P}_\Box = \frac{2}{\Lambda^2}(H^\dagger H)\Box(H^\dagger H)\,,$$
$$\mathcal{P}_{WW} = \frac{g_2^2}{\Lambda^2}H^\dagger H\, W^a_{\mu\nu}W^{a\,\mu\nu},$$
$$\mathcal{P}_{HJ} = \frac{4}{\Lambda^2}\left(H^\dagger i\overleftrightarrow{D}^I_\mu H\right)J^\mu\,,$$
$$J^\mu = \{\bar{Q}_L\sigma_I\gamma^\mu Q_L\,,\quad \bar{Q}_L\sigma_3\gamma^\mu Q_L\,,\quad \bar{u}_R\gamma^\mu u_R\,,\quad \bar{d}_R\gamma^\mu d_R\,,$$
$$\bar{L}_L\sigma_I\gamma^\mu L_L\,,\quad \bar{L}_L\sigma_3\gamma^\mu L_L\,,\quad \bar{e}_R\gamma^\mu e_R\,\}.$$

Establish the EFT in the golden channel

- Different constraints on wilson coefficients inferred from other measurements in the EFT. Higgs and no Higgs processes related in linear case.
- In a restricted model analysis (not an EFT) with many symmetry assumptions, the deviations can easily be or order 10 %. This spectra is not particularly tightly constrained.
- If deviations larger than expected in linear EFT, can indicate nonlinear EFT
- Fairly clear that the deviations in either case will be small, but the pattern between measured quantities is relevant

Thank you!