On the convergence of the SMEFT expansion

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Based on: TC, arXiv:2405.04570

Is $1/\Lambda^4$ relevant?

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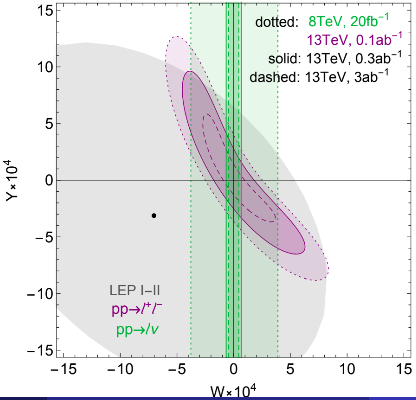
Some phenomenology occurs first at D8, such as neutral TGC
e.g. D. Liu, S. Li, J. Ellis, H-J He, arXiv:2404.15937 and many others

The energy helps accuracy paradigm

Recall: The SMEFT is a Taylor series in $\frac{v}{\Lambda}$ *and* $\frac{p}{\Lambda}$ $\Leftrightarrow$ $\langle H\rangle$ *and* ∂_μ
$\Rightarrow$ growth in p

"Energy helps accuracy: electroweak precision tests at hadron colliders"
M. Farina, G. Panico, D. Pappadopulo, J. Ruderman, R. Torre, arXiv:1609.08157

$$\mathcal{L}_{\rm eff} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$



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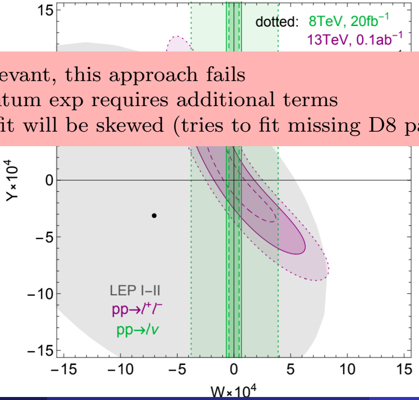

If D8 is relevant, this approach fails
i.e. momentum exp requires additional terms
or D6 fit will be skewed (tries to fit missing D8 part too)

Exploring concrete models

We can consider the following models to see how truncation affects this picture:

$$\Phi = (3,2)_{1/6} \qquad X_\mu = (1,1)_0$$

(D6 matching: J. de Blas, J.C. Criado, M. Perez-Victoria, J. Santiago, arXiv:1711.10391)

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1. write UV lagrangians
2. match to dimension 10
3. make field redefinitions and use IBP to simplify EFT
   → avoid Warsaw strategy, focus on a basis in which its easiest to calculate:
4. calculate Drell Yan cross section @ LHC in SM, UV, and IR
   ($d6$, $d6^2$, $d8$, $d6 \cdot d8$, $d10$)

$\Phi = (3, 2)_{1/6}$

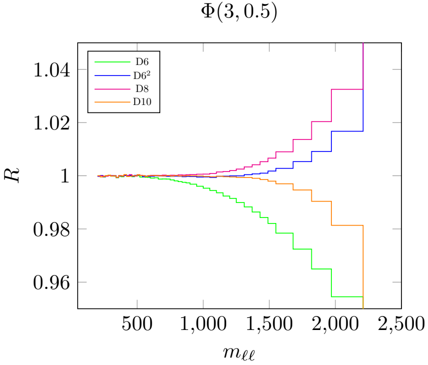
$$\Delta\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D_\mu \Phi) - M^2 \Phi^\dagger \Phi + Y_\Phi \left[\bar{d}\,(\Phi\, i\sigma_2 L) + h.c.\right]$$

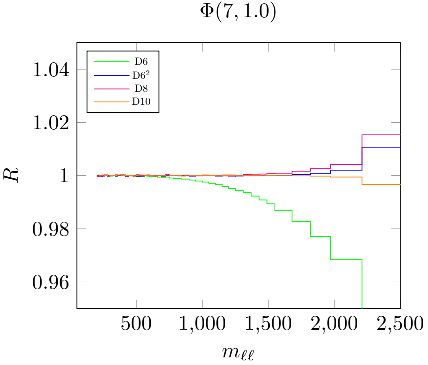
$$\Downarrow$$

$$\begin{aligned}\mathcal{L}_{\rm IR}^{\Phi} = \mathcal{L}_{\rm SM} &+ \tfrac{Y_\Phi^2}{M^2}\left(\bar{d}L\right)\left(\bar{L}d\right) \\ &+ \tfrac{Y_\Phi^2}{M^4}\Big[\left(\bar{d}D_\mu L\right)\left(\bar{L}D^\mu d\right) + \left(D_\mu \bar{d}\right)L\left(\bar{L}D_\mu d\right) + \left(\bar{d}D_\mu L\right)\left(D_\mu \bar{L}\right)d + \left(D_\mu \bar{d}\right)L\left(D_\mu \bar{L}\right)d\Big] \\ &+ \text{D10}\end{aligned}$$

- A very clean example of the p expansion!
- No v expansion

$\Phi = (3, 2)_{1/6} \qquad R = \sigma_{IR}/\sigma_{\text{full UV}}$





$X_\mu = (1,1)_0$

$$\begin{aligned}\Delta\mathcal{L}_V &= -\tfrac{1}{4}V_{\mu\nu}V^{\mu\nu} + \tfrac{1}{2}M^2 V_\mu V^\mu - \tfrac{k}{2}B_{\mu\nu}V^{\mu\nu} \\ &= -\tfrac{1}{4}X_{\mu\nu}X^{\mu\nu} + \tfrac{1}{2}M_X^2 X_\mu X^\mu - g_1 \textstyle\sum_\psi Y_\psi \beta(\bar{\psi}\gamma_\mu\psi)X^\mu\end{aligned}$$

$$\beta = -\frac{k}{\sqrt{1-k^2}}$$

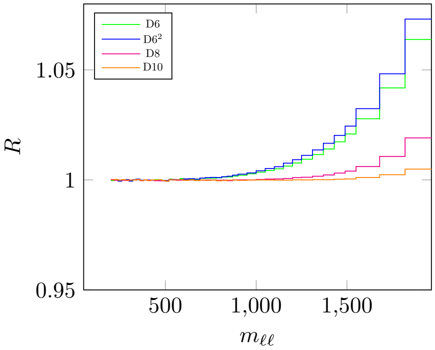
$$\Downarrow$$

$$\begin{aligned}\mathcal{L}_{IR}^X &= \mathcal{L}_{\rm SM} - \tfrac{g_1^2\beta^2}{2M^2}\Psi_\mu\Psi^\mu \\ &\quad + \tfrac{g_1^2\beta^2}{2M^4}\Psi_\mu\left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\Psi_\nu \\ &\quad - \tfrac{g_1^2\beta^2}{2M^4}\Psi_\mu\left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\left(\Box\eta_{\nu\rho} - \partial_\nu\partial_\rho\right)\Psi^\rho\end{aligned}$$

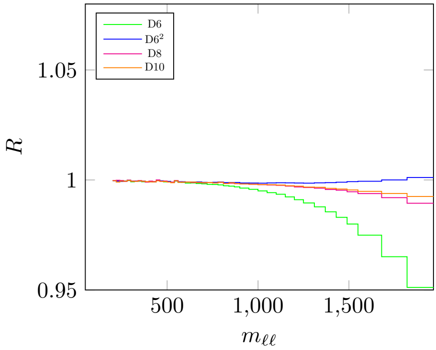
$$\mathcal{H}_\mu = Y_H(H^\dagger i\overleftrightarrow{D}_\mu H) \qquad \Psi_\mu = \textstyle\sum_\psi Y_\psi\bar{\psi}\gamma_\mu\psi$$

$X_\mu = (1,1)_0 \qquad R = \sigma_{IR}/\sigma_{\text{full UV}}$

$X(3, 0.6)$



$X(10, 3.0)$



Convergence of the EFT

Two EFTs:

$$\mathcal{L}_{\rm IR}^{\Phi} = \mathcal{L}_{\rm SM} + c_6 \frac{Y_\Phi^2}{M^2} \left(\bar{d}L\right)\left(\bar{L}d\right) + c_8 \frac{Y_\Phi^2}{M^4}\left[\left(\bar{d}D_\mu L\right)\left(\bar{L}D^\mu d\right) + \left(D_\mu \bar{d}\right) L \left(\bar{L}D_\mu d\right) + \left(\bar{d}D_\mu L\right)\left(D_\mu \bar{L}\right) d + \left(D_\mu \bar{d}\right) L \left(D_\mu \bar{L}\right) d\right] + c_{10} D10$$

$$\begin{aligned} \mathcal{L}_{IR}^{X} = & \mathcal{L}_{\rm SM} - c_6 \frac{g_1^2\beta^2}{2M^2} \Psi_\mu \Psi^\mu \\ & + c_8 \frac{g_1^2\beta^2}{2M^4} \Psi_\mu \left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\Psi_\nu \\ & - c_{10} \frac{g_1^2\beta^2}{2M^4} \Psi_\mu \left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\left(\Box\eta_{\nu\rho} - \partial_\nu\partial_\rho\right)\Psi^\rho \end{aligned}$$

Minimize χ^2 to a given order in the EFT (including partial results, $(\mathrm{D6})^2$, $(\mathrm{D6}\cdot\mathrm{D8})$)

$$\chi^2(c_6, c_8, c_{10}) = \sum_{m_{\ell\ell}} \left(\frac{N_{m_{\ell\ell}}^{\rm UV} - N_{m_{\ell\ell}}^{\rm IR}}{\sqrt{N_{m_{\ell\ell}}^{\rm UV}}}\right)^2$$

Pseudodata

More or less:
Matchete→Feynrules→Feynarts→Formcalc→ Vegas + NNPDF3.0
3/ab 13 TeV LHC, Invariant mass binning from CMS arXiv:2103.02708

Does Feynarts/Formcalc still not work with four-fermion ops?
(Did it by hand for vector currents)

Convergence of the EFT: Φ

M_Φ	Y_Φ	fit up to	c_6	c_8	c_{10}	$\chi^2_{\rm min}$
3	0.1	D6	0.93 ± 5.6	–	–	10^{-4}
		$(\text{D6})^2$	0.94 ± 5.7	–	–	10^{-4}
		D8	0.99 ± 5.7	0.74 ± 57	–	10^{-6}
		$(\text{D6} \cdot \text{D8})$	1.0 ± 5.7	0.81 ± 61	–	10^{-6}
		D10	1.0 ± 5.7	0.97 ± 61	0.58 ± 253	10^{-8}

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		D10	1.0 ± 5.7	0.97 ± 61	0.58 ± 253	10^{-8}
3	0.5	D6	0.74 ± 0.22	–	–	1
		$(\text{D6})^2$	0.96 ± 0.30	–	–	10^{-2}
		D8	0.96 ± 0.30	-0.3 ± 2.3	–	10^{-2}
		$(\text{D6} \cdot \text{D8})$	0.99 ± 0.31	0.6 ± 2.8	–	10^{-4}
		D10	1.0 ± 0.31	0.7 ± 2.8	-0.4 ± 10	10^{-4}

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3	1.0	D6	0.16 ± 0.06	–	–	100
		$(\mathrm{D6})^2$	0.84 ± 0.03	–	–	1
		D8	0.87 ± 0.03	-0.62 ± 0.62	–	1
		$(\mathrm{D6} \cdot \mathrm{D8})$	0.97 ± 0.03	0.61 ± 0.11	–	10^{-2}
		D10	0.98 ± 0.03	0.38 ± 0.11	6.6 ± 2.8	10^{-2}

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7	1.0	D6	0.8 ± 0.3	–	–	0.1
		$(\mathrm{D6})^2$	0.99 ± 0.4	–	–	10^{-4}
		D8	0.99 ± 0.4	-0.2 ± 17	–	10^{-4}
		$(\mathrm{D6} \cdot \mathrm{D8})$	1.0 ± 0.4	0.9 ± 36	–	10^{-6}
		D10	1.0 ± 0.4	0.9 ± 36	-1 ± 400	10^{-7}

Thoughts on convergence of the EFT: Φ

- All central values are off for strictly D6 fit from theory prediction of 1
  → stats for weakly interacting models are bad, so consistent
  → strongly int. examples are interesting academically (probably already ruled out)

- Consider the trends:
  → D6 only fit → $c_6 \neq 1$
  → D6^2 improves convergence (model dependent)
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  ⇒ highest order of the EFT is absorbing our ignorance about higher orders

A fit at D6 is a SM fit with errors consistent with the SMEFT
A D8 fit is a D6 SMEFT fit where the "fit" c_8 are nuisance parameters
(but for weakly interacting NP we wont see the difference)

Convergence of the EFT: X_μ

M_Φ	β	fit up to	c_6	c_8	c_{10}	$\chi^2_{\rm min}$
3	0.3	D6	1.13 ± 0.35	–	–	10^{-1}
		$(\mathrm{D6})^2$	1.13 ± 0.36	–	–	10^{-1}
		D8	0.98 ± 0.36	1.5 ± 2.4	–	10^{-3}
		$(\mathrm{D6} \cdot \mathrm{D8})$	0.98 ± 0.36	1.5 ± 2.4	–	10^{-3}
		D10	1.00 ± 0.36	0.85 ± 2.4	1.9 ± 8.1	10^{-5}

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		D10	1.00 ± 0.36	0.85 ± 2.4	1.9 ± 8.1	10^{-5}
3	1.2	D6	1.01 ± 0.02	–	–	100
		$(\text{D6})^2$	1.09 ± 0.02	–	–	10
		D8	1.02 ± 0.02	0.18 ± 0.08	–	10
		$(\text{D6} \cdot \text{D8})$	1.01 ± 0.02	0.87 ± 0.18	–	1
		D10	0.98 ± 0.02	1.49 ± 0.17	-0.98 ± 0.26	1

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		D10	0.98 ± 0.02	1.49 ± 0.17	-0.98 ± 0.26	1
3	3.0	D6	0.612 ± 0.003	–	–	100
		$(\text{D6})^2$	1.165 ± 0.005	–	–	10
		D8	1.100 ± 0.004	-1.10 ± 0.04	–	10
		$(\text{D6} \cdot \text{D8})$	0.947 ± 0.003	2.27 ± 0.04	–	1
		D10	0.946 ± 0.004	1.98 ± 0.04	-1.5 ± 0.2	1

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		$(\text{D6})^2$	1.165 ± 0.005	–	–	10
		D8	1.100 ± 0.004	-1.10 ± 0.04	–	10
		$(\text{D6} \cdot \text{D8})$	0.947 ± 0.003	2.27 ± 0.04	–	1
		D10	0.946 ± 0.004	1.98 ± 0.04	-1.5 ± 0.2	1
8	3.0	D6	0.92 ± 0.03	–	–	1
		$(\text{D6})^2$	0.99 ± 0.03	–	–	0.1
		D8	0.98 ± 0.03	0.5 ± 1.1	–	10^{-3}
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A D8 fit is a D6 SMEFT fit where the "fit" c_8 are nuisance parameters
(but for weakly interacting NP we wont see the difference)

Same conclusions
Just D6^2 doesn't always improve agreement with theory

Top down vs bottom up?

So far just a top down study, what happens when more operators are included in the fit?
$\Rightarrow$ too hard for just Drell Yan...

Consider just four-fermion operators:

$$\begin{aligned}\mathcal{L}_{\text{SMEFT}}^{4-\text{ferm}} &= c_{LQ}^{(1)}(\bar{L}\gamma_\mu L)(\bar{Q}\gamma^\mu Q) + c_{LQ}^{(3)}(\bar{L}\gamma_\mu \tau^I L)(\bar{Q}\gamma^\mu \tau^I Q) \\ &\quad + c_{eu}(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u) + c_{ed}(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d) \\ &\quad + c_{Lu}(\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u) + c_{Ld}(\bar{L}\gamma_\mu L)(\bar{d}\gamma^\mu d) + c_{Qe}(\bar{Q}\gamma_\mu Q)(\bar{e}\gamma^\mu e)\end{aligned}$$

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Fit the SM pseudo-data w Mathematica:

$$\begin{array}{ccccccccc} c^{(1)}_{LQ} & = & 0.20(1) & c^{(3)}_{LQ} & = & -0.10(1) & & & \\ c_{eu} & = & -0.023(2) & c_{ed} & = & 0.04(1) & & & \\ c_{Lu} & = & 0.57(3) & c_{Ld} & = & 0.57(3) & c_{Qe} & = & -0.38(1)\,, \end{array}$$

This is garbage (best fit point is actually $\{0,0,0,0,0,0,0\}$),
$\rightarrow$ because Mathematica's minimization routine is insufficient
(the parameter space is high dimensional and has narrow $\sim$ degenerate directions)

Faking bottom up, X_μ

Do it again for X w M=3 TeV and $\beta = 1.2$:

$$
\begin{aligned}
\mathcal{L}_{\text{IR}} &= \mathcal{L}_{\text{SM}} - \frac{g_1^2\beta^2}{2M^2}\sum_\psi \left(Y_\psi \bar{\psi}\gamma^\mu\psi\right)^2 \\
&\to \mathcal{L}_{\text{SM}} - c_6\frac{g_1^2\beta^2}{2M^2}\sum_\psi \left(Y_\psi \bar{\psi}\gamma^\mu\psi\right)^2 - c_{LQ}^{(3)}\frac{g_1^2\beta^2}{2M^2}Q_{LQ}^{(3)} + c_8 Q^{(8)}_{\text{actually generated}}
\end{aligned}
$$

Note: $c_6 = 1$, $c_{LQ}^{(3)} = 0$, and $c_8 = 1$ are predicted by the matching

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Fit strictly to D6:

$$c_6 = 3.4 \pm 0.4 \qquad c_{LQ}^{(3)} = -9.2 \pm 1.4$$

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Including D6^2:

$c_6 = 2.3 \pm 0.4$ $\qquad$ $c_{LQ}^{(3)} = -4.7 \pm 1.4$

Faking bottom up, X_μ

Do it again for X w M=3 TeV and $\beta = 1.2$:

$$\begin{aligned}\mathcal{L}_{\rm IR} &= \mathcal{L}_{\rm SM} - \frac{g_1^2\beta^2}{2M^2}\sum_\psi \left(Y_\psi\bar\psi\gamma^\mu\psi\right)^2 \\ &\to \mathcal{L}_{\rm SM} - c_6\frac{g_1^2\beta^2}{2M^2}\sum_\psi \left(Y_\psi\bar\psi\gamma^\mu\psi\right)^2 - c_{LQ}^{(3)}\frac{g_1^2\beta^2}{2M^2}Q_{LQ}^{(3)} + c_8 Q^{(8)}_{\text{actually generated}}\end{aligned}$$

Note: $c_6 = 1$, $c_{LQ}^{(3)} = 0$, and $c_8 = 1$ are predicted by the matching
Fit strictly to D6:

$c_6 = 3.4 \pm 0.4$ $\quad$ $c_{LQ}^{(3)} = -9.2 \pm 1.4$

Including D6^2:

$c_6 = 2.3 \pm 0.4$ $\quad$ $c_{LQ}^{(3)} = -4.7 \pm 1.4$

Drop D6^2 for c_{eu} but include D8 operators generated in UV:

$c_6 = 0.54 \pm 0.36$ $\quad$ $c_{LQ}^{(3)} = 1.7 \pm 1.4$

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Include all D6^2 and D8 ops generated in UV:

$$c_6 = 0.54 \pm 0.36 \qquad c_{LQ}^{(3)} = 1.7 \pm 1.4$$

- D6^2 gives a modest improvement
- D8$_{\text{actually realized}}$ does the heavy lifting to get us nearly consistent
- Again, we could guess the results are skewed as everything is working together to absorb missing relevant orders in expansion

Previous work

Of course other people have studied the SMEFT top down:

- J. Brehmer, A. Freitas, D. Lopez-Val and T. Plehn, arXiv:1510.03443
- S. Dawson, S. Homiller, M. Sullivan, arXiv:2110.06929
- C. Hays, A. Helset, A. Martin, M. Trott, arXiv:2007.00565
- TC, A. Helset, A. Martin, M. Trott, arXiv:2102.02819
- among others... (again, please forgive that this list is not comprehensive)

They generally only look at the size of contributions from the theory prediction, not how/if a bottom up SMEFT fit reproduces the theory

Future work

I'd like to follow this up:

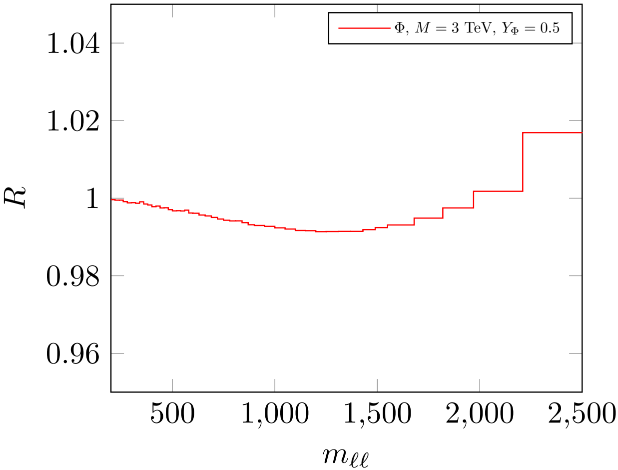
- Proper analyses with detector simulation and optimizing the search for the SMEFT
- More models, more channels, to get away from *faking* the bottom up approach
- Look at loop effects in UV and IR
  $\rightarrow$ Can LHC, other experiments, future experiments resolve loop effects in SMEFT
  $\rightarrow$ Obvious problem here, for disparate scales the EFT is the correct approach (resum some large logs)
- Look at effects of PDF fits,
  Hammou, Kassabov, Madigan, Mangano, Mantani, Moore, Morales Alvarado, arXiv:2307.10370
  Costantini, Hammou, Kassabov, Madigan, Mantani, Morales Alvarado, Moore, Ubiali, 2402.03308

Feel free to share thoughts and criticisms

Conclusions

- For more strongly decoupled theories, a D6 analysis appears to be sufficient (the errors were disappointingly large, hopefully a global fit helps with that)
- For models more strongly coupled to the SM (large coupling and/or low mass) the inclusion of D8 operators improves the accuracy of fit c_6.
  Here the D8 operators appear to behave as nuisance parameters
- $D6^2$ helps sometimes, hurts others, it's UV model dependent
- I made the probably controversial assertion:
  A D6 fit is a SM fit with errors consistent with the SMEFT framework
  A D8 fit is a SMEFT fit to D6, and the D8 WCs behave as nuisance parameters
- Didn't really talk about, but:
  It will hurt fits, but we should be including a cutoff in energy
  If including all bins, would be good to include extra fit w reasonable cutoff
- A bit more in the paper, arXiv:2405.04570

$\Phi = (3,2)_{1/6} \qquad R = \sigma_{\rm UV}/\sigma_{\rm SM}$



$X_\mu = (1,1)_0$

$$\begin{aligned}\Delta\mathcal{L}_V &= -\tfrac{1}{4}V_{\mu\nu}V^{\mu\nu} + \tfrac{1}{2}M^2 V_\mu V^\mu - \tfrac{k}{2}B_{\mu\nu}V^{\mu\nu} \\ &= -\tfrac{1}{4}X_{\mu\nu}X^{\mu\nu} + \tfrac{1}{2}M_X^2 X_\mu X^\mu - g_1 Y_H \beta (H^\dagger i \overleftrightarrow{D}_\mu H) X^\mu + g_1^2 Y_H^2 \beta^2 (H^\dagger H) X_\mu X^\mu \\ &\quad - g_1 \textstyle\sum_\psi Y_\psi \beta (\bar\psi \gamma_\mu \psi) X^\mu\end{aligned}$$

$$\Downarrow$$

$$\begin{aligned}\mathcal{L}_{\rm IR}^X = \;& \mathcal{L}_{\rm SM} - \frac{g_1^2\beta^2}{2M^2}\mathcal{H}_\mu\mathcal{H}^\mu - \frac{g_1^2\beta^2}{2M^2}\Psi_\mu\Psi^\mu - \frac{g_1^2\beta^2}{M^2}\mathcal{H}_\mu\Psi^\mu \\ & + \frac{g_1^4 Y_H^2 \beta^4}{M^4}(H^\dagger H)\mathcal{H}_\mu\mathcal{H}^\mu \\ & + \frac{g_1^2\beta^2}{M^4}\mathcal{H}_\mu\left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\Psi_\nu + 2\frac{g_1^4 Y_H^2\beta^4}{M^4}(H^\dagger H)\mathcal{H}_\mu\Psi^\mu \\ & + \frac{g_1^2\beta^2}{2M^4}\Psi_\mu\left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\Psi_\nu + \frac{g_1^4 Y_H^2\beta^4}{M^4}(H^\dagger H)\Psi_\mu\Psi^\mu \\ & + \frac{g_1^4 Y_H^4\beta^4}{M^4}\left[4(H^\dagger H)Q_{HD} + (H^\dagger H)Q_{HD,2}\right] \\ & + \frac{g_1^4 Y_H^4\beta^4}{2M^4}\left[(H^\dagger H)^2(H^\dagger D^2 H) + h.c.\right] \\ & - \frac{g_1^2 Y_H^2\beta^2}{M^4}\left[\frac{g_1^2}{4}Q_{HB}^{(8)} + g_1 g_2 Q_{HWB}^{(8)} + g_2^2 Q_{HW,2}^{(8)}\right] + D10\end{aligned}$$

$$\mathcal{H}_\mu = Y_H(H^\dagger i\overleftrightarrow{D}_\mu H) \qquad \Psi_\mu = \textstyle\sum_\psi Y_\psi \bar\psi\gamma_\mu\psi$$

$X_\mu = (1,1)_0$

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$$= -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}M_X^2 X_\mu X^\mu - g_1 Y_H \beta (H^\dagger i \overleftrightarrow{D}_\mu H) X^\mu + g_1^2 Y_H^2 \beta^2 (H^\dagger H) X_\mu X^\mu$$
$$-g_1 \sum_\psi Y_\psi \beta (\bar{\psi}\gamma_\mu \psi) X^\mu$$

$$\Downarrow$$

- Mixing is a bit of a pain, but the effects are small (aside from δm_Z, only occur at D8+)
- For simplicity we drop the mixing (this is **bad** practice in QFT)
- No v expansion

$$+\frac{g_1^4 Y_H^4 \beta^4}{M^4}\left[4(H^\dagger H)Q_{HD} + (H^\dagger H)Q_{HD,2}\right]$$
$$+\frac{g_1^4 Y_H^4 \beta^4}{2M^4}\left[(H^\dagger H)^2 (H^\dagger D^2 H) + h.c.\right]$$
$$-\frac{g_1^2 Y_H^2 \beta^2}{M^4}\left[\frac{g_1^2}{4}Q_{HB}^{(8)} + g_1 g_2 Q_{HWB}^{(8)} + g_2^2 Q_{HW,2}^{(8)}\right] + D10$$

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$$\beta = -\frac{k}{\sqrt{1-k^2}}$$

- In this (massively) simplified version $\rightarrow$ only p expansion
- In full model, w/ $M_X = 3$ TeV & $k \sim 1 (\beta \sim 3)$
  Mixing: $\mathcal{O}(10^{-2})$ effect
  Momentum exp: $\mathcal{O}(10^{-1.6}) \rightarrow \mathcal{O}(100)$ effect (bin-by-bin)

$$\begin{aligned}\mathcal{L}_{IR}^X = \mathcal{L}_{\rm SM} &- \frac{g_1^2\beta^2}{2M^2}\Psi_\mu\Psi^\mu \\ &+ \frac{g_1^2\beta^2}{2M^4}\Psi_\mu\left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\Psi_\nu \\ &- \frac{g_1^2\beta^2}{2M^4}\Psi_\mu\left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\left(\Box\eta_{\nu\rho} - \partial_\nu\partial_\rho\right)\Psi^\rho\end{aligned}$$

$$\mathcal{H}_\mu = Y_H(H^\dagger i\overleftrightarrow{D}_\mu H) \qquad \Psi_\mu = \textstyle\sum_\psi Y_\psi\bar{\psi}\gamma_\mu\psi$$

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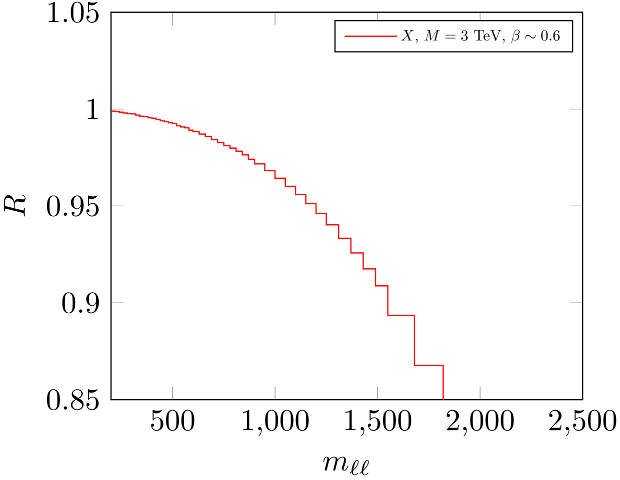

NLO in the SMEFT expansion

I've been working on calculating to order $1/\Lambda^4$:

- TC, J. Desai, O.J.P. Éboli, M.C. Gonzalez-Garcia, arXiv:2404.03720
- TC, A. Martin, arXiv:2306.00053
- TC, J. Desai, O.J.P. Éboli, M.C. Gonzalez-Garcia, M. Martines, P. Reimitz, arXiv:2304.03305
- TC, T. Rasmussen, arXiv:2110.03694
- TC, A. Martin, M. Trott, arXiv:2110.03694
- TC, arXiv:2107.07470
- TC, A. Helset, A. Martin, M. Trott, arXiv:2102.02819

As have many others...
C. Murphy, HL. Li, Z. Ren, J. Shu, M.L. Xiao, JH. Yu, Y.H. Zheng, C. Hays, V. Sanz, J. Setford, R. Boughezal, E. Mereghetti, F. Petriello, S. Alioli, F. Petriello, Y. Huang, T. Kim, L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, S. Dawson, S. Homiller, M. Sullivan, C. Degrande, J. Ellis, K. Mimasu, F. Zampedri, J. Talbert, M. Forslund, M. Schnubel, C. Grojean, G. Guedes, J. Roosmale, G. Salla, S. Das Bakshi, M. Chala, A. Díaz-Carmona, S. Alioli, W. cao, G. Durieux, L. Gràf, B. Henning, T. Kitahara, C. Machado, T. Melia, J. Roosmale Nepveu, S. Pal, Y. Shadmi, Y. Weiss, ML Xiao, probably many more (forgive me if your names not here)

Faking bottom up, Φ

Have to consider a subset of operators.
Really we have to drop down to just one extra operator
Consider Φ with $M = 3$ TeV and $Y_\Phi = 0.5$:

$$\begin{aligned}\mathcal{L}_{\rm IR} &= \mathcal{L}_{\rm SM} - \frac{Y_\Phi^2}{2M^2} Q_{Ld} \\ &\to \mathcal{L}_{\rm SM} - c_{Ld}\frac{Y_\Phi^2}{2M^2} Q_{Ld} - c_6 \frac{Y_\Phi^2}{2M^2} Q^{(6)}_{\text{something else}} + c_8 Q^{(8)}_{\text{actually generated}}\end{aligned}$$

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Include all D6^2 and D8 ops generated in UV:

$c_{Ld} = 0.8 \pm 0.3$ $\qquad$ $c_{eu} = 0.01 \pm 0.02$

(All other four-fermion operators result in similar results, included in paper)

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Include all $D6^2$ and D8 ops generated in UV:

$$c_{Ld} = 0.8 \pm 0.3 \qquad c_{eu} = 0.01 \pm 0.02$$

- $D6^2$ wins! (we saw from plots it would)
- D8 does worse, and actually skews $D6{+}D6^2{+}D8_{\text{actually generated}}$ though consistent statistically
- all ops are absorbing affects of NP? Maybe not a problem for a proper global fit