The Universal SMEFT

Tyler Corbett

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Largely based on: TC, J. Desai, M. Martines, P. Reimitz, arXiv:2304.03305
O.J.P. Éboli, M.C. Gonzalez-Garcia – first fit @ $1/\Lambda^4$

TC, J. Desai, O.J.P. Éboli, M.C. Gonzalez-Garcia, arXiv:2404.03720
– the D8 Universal SMEFT

TC, J. Desai, M. Martines, P. Reimitz, arXiv:2503.XXXXX
O.J.P. Éboli, M.C. Gonzalez-Garcia – EWPD & Drell Yan @ D8

See also: J.D. Wells and Z. Zhang, arXiv:1510.08462 – The D6 Universal SMEFT

“Universal Theories”

For this talk, a Universal Theory is a theory of NP where,
the NP couples to SM fermions as in the SM:

$U(1)$ mixing model (matched to D10 TC arXiv:2405.04570):

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}M^2 X_\mu X^\mu - g_1 Y_H k (H^\dagger i\overleftrightarrow{D}_\mu H)X^\mu + g_1^2 Y_H^2 k^2 |H|^2 X_\mu X^\mu$$
$$- g_1 k \sum_\psi Y_\psi (\bar{\psi}\gamma_\mu\psi)X^\mu$$

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Other examples include:

- $\mathbb{R}$ Scalar singlet, (matched to D8, TC et al. arXiv:2404.03720)
- Scalar triplet with $Y = 0$, (matched to D8, TC et al. arXiv:2404.03720)
- Composite Higgs models,
  (e.g. ρ from $SO(5)/SO(4)$ matched to D8, TC et al. arXiv:2404.03720)
- Extra dimensions (5d see Barbieri et al. arXiv: hep-ph/0405040)
- Little Higgs models (see Barbieri et al. arXiv: hep-ph/0405040)
- Higgsless models (see Barbieri et al. arXiv: hep-ph/0405040)
- Any new scalar not coupling to fermions
- W' model (see e.g. arXiv:2307.10370)

Matching the $U(1)$ mixing model

Starting from the NP $\mathcal{L}$, we want to 'match' onto the low energy EFT (SMEFT):

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}M^2 X_\mu X^\mu - g_1 Y_H k (H^\dagger i \overleftrightarrow{D}_\mu H) X^\mu + g_1^2 Y_H^2 k^2 |H|^2 X_\mu X^\mu \\ &\quad - g_1 k \sum_\psi Y_\psi (\bar{\psi}\gamma_\mu \psi) X^\mu\end{aligned}$$

Derive the EOM, solve for X, plug back into original $\mathcal{L}$
(See Henning et al. arXiv:1412.1837)

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EOM:

$$\frac{\delta\mathcal{L}}{\delta X_\mu} = \partial_\mu \frac{\delta\mathcal{L}}{\delta\partial_\mu X_\nu}$$

$$\left[-\Box\delta_{\rho\mu} + \partial_\rho\partial_\mu - M^2\delta_{\rho\mu} - 2g_1^2 Y_H^2 k^2 |H|^2\delta_{\rho\mu}\right] X_\rho = -g_1 Y_H k(H^\dagger i\overleftrightarrow{D}_\mu H) + g_1 k \sum_\psi Y_\psi \bar{\psi}\gamma_\mu\psi$$

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Solve for X (in the limit M is large):

$$X_\rho \sim \frac{g_1 k}{M^2}\left[Y_H (H^\dagger i \overleftrightarrow{D}_\mu H) + \sum_\psi Y_\psi \bar{\psi}\gamma_\mu \psi\right] + \cdots$$

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Plug into $\mathcal{L}$:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} - \frac{g_1^2 k^2}{2M^2}(H^\dagger i\overleftrightarrow{D}_\mu H)^2 - \frac{g_1^2 k^2}{2M^2}\left(\sum_\psi Y_\psi\bar\psi\gamma_\mu\psi\right)^2 - \frac{g_1^2 k^2}{M^2}(H^\dagger i\overleftrightarrow{D}_\mu H)\left(\sum_\psi Y_\psi\bar\psi\gamma_\mu\psi\right)$$

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Plug into $\mathcal{L}$:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} - \frac{g_1^2 k^2}{2M^2} Q_T - \frac{g_1^2 k^2}{2M^2}\left(Q_{Hl}^{(1)} + Q_{He} + Q_{Hq}^{(1)} + Q_{Hu} + Q_{Hd}\right)$$
$$- \frac{g_1^2 k^2}{M^2}\left(Q_{ll} + 2Q_{lq}^{(1)} + 2Q_{le} + 2Q_{lu} + 2Q_{ld} + Q_{qq}^{(1)} + 2Q_{qe} + 2Q_{qu} + \cdots\right)$$

What is an EFT/what is the SMEFT?

- Last slide: took M to be large
  $\Rightarrow$ the EFT describes a NP model with mass gap
- The EFT imprints on the IR (low E theory) in terms of the low energy field content
  $\Rightarrow$ All operators were formed of the SM fields, no Xs were left!
- The EFT is a Taylor expansion in $1/M$
  $\Rightarrow$ If we need better precision, we go to next order (this talk)
- Motivated by a specific UV (NP model) theory = "top down"
- All NP theories with (sufficient) mass gap described by enumerating all operators = "bottom up"

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Weinberg 1967:

> **This remark is based on a "theorem", which as far as I know has never been proven, but which I cannot imagine could be wrong. The "theorem" says that although individual quantum field theories have of course a good deal of content, quantum field theory itself has no content beyond analyticity, unitarity, cluster decomposition, and symmetry. This can be put more precisely in the context of perturbation theory: if one writes down the most general possible Lagrangian, including *all* terms consistent with assumed symmetry principles, and then calculates matrix elements with this Lagrangian to any given order of perturbation theory, the result will simply be the most general possible *S*-matrix consistent with analyticity, perturbative unitarity, cluster decomposition and the assumed symmetry principles. As I said, this has not been proved, but any counterexamples would be of great interest, and I do not know of any.**

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This is the SMEFT

Motivating the Universal SMEFT

Our example EFT was:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} - \frac{g_1^2 k^2}{2M^2}(H^\dagger \overleftrightarrow{D}_\mu H)^2 - \frac{g_1^2 k^2}{2M^2}\left(\sum_\psi Y_\psi \bar{\psi}\gamma_\mu \psi\right)^2 - \frac{g_1^2 k^2}{M^2}(H^\dagger \overleftrightarrow{D}_\mu H)\left(\sum_\psi Y_\psi \bar{\psi}\gamma_\mu \psi\right)$$

Purveyors of EFTs know we can use the SM EOM to change operator bases:

$$\partial_\nu B_{\mu\nu} = \frac{g_1}{2}(H^\dagger i\overleftrightarrow{D}_\mu H) + g_1 \sum_\psi Y_\psi \bar{\psi}\gamma_\mu \psi$$

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$$\partial_\nu B_{\mu\nu} = \frac{g_1}{2}(H^\dagger i \overleftrightarrow{D}_\mu H) + g_1 \sum_\psi Y_\psi \bar{\psi}\gamma_\mu \psi$$

Resulting in a purely bosonic operator basis:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} - \frac{g_1^2 k^2}{8M^2}(H^\dagger i\overleftrightarrow{D}_\mu H)^2 - \frac{k^2}{2M^2}(\partial_\nu B_{\mu\nu})(\partial_\rho B_{\mu\rho}) - \frac{g_1 k^2}{2M^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\partial_\nu B_{\mu\nu})$$

Universal NP can be described by a purely bosonic SMEFT:

- This basis needs to include “redundant operators”
- In practice we swap operators like $(\partial_\mu B_{\mu\nu})^2$ for fermionic (extra poles in propagators are’t fun, see: Brivio et al. arXiv:1405.5412)

The SMEFT vs Universal SMEFT at D6

In the general SMEFT at D6 we have 59 operator forms and 2,499 free parameters:

Type I: X^3		Type II, III: H^6, H^4D^2		Type V: Ψ^2H^3 + h.c.	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	Q_{eH}	$(H^\dagger H)(\bar{L}eH)$
$Q_{\tilde{G}}$	$f^{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{uH}	$(H^\dagger H)(\bar{Q}u\tilde{H})$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	Q_{HD}	$(H^\dagger D^\mu H)^*(H^\dagger D^\mu H)$	Q_{dH}	$(H^\dagger H)(\bar{Q}dH)$
$Q_{\tilde{W}}$	$\epsilon^{IJK}\tilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

Type IV: $X^2\Phi^2$		Type VI: Ψ^2HX		Type VII: Ψ^2H^2D	
Q_{HG}	$(H^\dagger H)G_{\mu\nu}^AG^{A\mu\nu}$	Q_{eW}	$(\bar{L}\sigma^{\mu\nu}e)\tau^IHW_{\mu\nu}^I$	$Q_{HL}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$
$Q_{H\tilde{G}}$	$(H^\dagger H)\tilde{G}_{\mu\nu}^AG^{A\mu\nu}$	Q_{eW}	$(\bar{L}\sigma^{\mu\nu}e)\tau^IHB_{\mu\nu}$	$Q_{HL}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{L}\tau^I\gamma^\mu L)$
Q_{HW}	$(H^\dagger H)W_{\mu\nu}^IW^{I\mu\nu}$	Q_{uG}	$(\bar{Q}\sigma^{\mu\nu}T^Au)\tilde{H}G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$Q_{H\tilde{W}}$	$(H^\dagger H)\tilde{W}_{\mu\nu}^IW^{I\mu\nu}$	Q_{uW}	$(\bar{Q}\sigma^{\mu\nu}u)\tau^I\tilde{H}W_{\mu\nu}^I$	$Q_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
Q_{HB}	$(H^\dagger H)B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{Q}\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}$	$Q_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q)$
$Q_{H\tilde{B}}$	$(H^\dagger H)\tilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{Q}\sigma^{\mu\nu}T^Ad)HG_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
Q_{HWB}	$(H^\dagger\tau^IH)W_{\mu\nu}^IB^{\mu\nu}$	Q_{dW}	$(\bar{Q}\sigma^{\mu\nu}d)\tau^IHW_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$Q_{H\tilde{W}B}$	$(H^\dagger\tau^IH)\tilde{W}_{\mu\nu}^IB^{\mu\nu}$	Q_{dB}	$(\bar{Q}\sigma^{\mu\nu}d)\tilde{H}B_{\mu\nu}$	Q_{Hud}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu d)$

Type VIII: $5\times(\bar{L}L)(\bar{L}L)+7\times(\bar{R}R)(\bar{R}R)+8\times(\bar{L}L)(\bar{R}R)$
$+(\bar{L}R)(\bar{R}L)+4[(\bar{L}R)(\bar{L}R)+\text{h.c.}]=25(\bar{\Psi}\Psi)(\bar{\Psi}\Psi)$

In Blue: Operators generated by our $U(1)$ mixing model example, in this basis.

The SMEFT vs Universal SMEFT at D6

In the Universal SMEFT at D6 we have 16 operator forms and 16 free parameters:
Zhang and Wells arXiv:1510.08462

$Q_{\phi,1} = |D_\mu H^\dagger H|^2$ $\quad Q_{\phi,2} = \frac{1}{2}\left[\partial_\mu (H^\dagger H)\right]^2$ $\quad Q_{\phi^6} = (H^\dagger H)^3$

$Q_{WW} = (H^\dagger H) W^I_{\mu\nu} W^{I,\mu\nu}$ $\quad Q_{BB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$ $\quad Q_{BW} = (H^\dagger \sigma^I H) B_{\mu\nu} W^{I,\mu\nu}$

$Q_W = (D^\mu H)^\dagger \sigma^I (D^\nu H) W^I_{\mu\nu}$ $\quad Q_B = (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$ $\quad Q_{WWW} = \mathrm{Tr}\left[W^\nu_\mu W^\rho_\nu W^\mu_\rho\right]$

$Q_{GG} = (H^\dagger H) G^a_{\mu\nu} G^{a,\mu\nu}$ $\quad Q_{GGG} = f^{abc} G^{a,\nu}_\mu G^{b,\rho}_\nu G^{c,\mu}_\rho$

$Q_y = (H^\dagger H)(H_j J^j_H + h.c.)$ $\quad Q_{2y} = J^\dagger_{H,j} J^j_H$

$Q_{2JW} = \sum_{\psi,\psi'} \left(\bar{\psi}\gamma_\mu \frac{\sigma^a}{2}\psi\right)\left(\bar{\psi}'\gamma_\mu \frac{\sigma^a}{2}\psi'\right)$ $\quad Q_{2JB} = \sum_{\psi,\psi'} Y_\psi Y_{\psi'} \left(\bar{\psi}\gamma_\mu\psi\right)\left(\bar{\psi}'\gamma_\mu\psi'\right)$

$Q_{2JG} = \sum_{\psi,\psi'} \left(\bar{\psi}\gamma_\mu T^a\psi\right)\left(\bar{\psi}'\gamma_\mu T^a\psi'\right)$

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The SMEFT vs Universal SMEFT at D8

- At D8 the full SMEFT has 44,807 free parameters (see e.g. Murphy arXiv:2005.00059)
- At D8 the Universal SMEFT has 175 free parameters (TC et al. arXiv:2404.03720)
- This is still kind of a lot so let's consider ops which are separately C & P even:

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Let H=Higgs, X=any field strength, D=covariant derivative of any given field

Fields	Tot.	Murphy + New
H^8:	1	=1+0
$H^6 D^2$:	3	=2+1
$H^4 D^4$:	9	=3+6
X^4:	26	=26+0
$X^3 H^2$:	3	=3+0
$X^2 H^4$:	5	=5+0
$X^2 H^2 D^2$:	23	=9+14
$X H^4 D^2$:	5	=2+3
$H^2 D^6$:	1	=0+1
$X^2 D^4$:	3	=0+3
$X^3 D^2$:	4	=0+4
$X H^2 D^4$:	4	=0+4
Sum:	87	=51+36

Universal SMEFT at D8 In practice

Again some of these operators aren't fun to work with in terms of Feynman rules
So we use EOM to replace with fermionic operator combinations:

$$
\begin{aligned}
(D^\mu D^2 H)^\dagger (D^\mu D^2 H) \quad \rightarrow \quad & (H^\dagger H)(\bar{\Psi}\psi H) + (D_\mu H)^\dagger (D^\mu H)(\bar{\Psi}\psi H) \\
& +(H^\dagger H)(\bar{\psi}\gamma_\mu \psi)(\bar{\chi}\gamma^\mu \psi) + D_\mu(\bar{\psi}\gamma_\nu \psi) D^\mu (\bar{\chi}\gamma^\mu \chi) \\
& +\text{in bosonic basis}
\end{aligned}
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& + \text{in bosonic basis}
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$$

EOM identities involve similar operators,

$$
\begin{aligned}
R_1 &= aQ_1 + bQ_2 \\
R_2 &= cQ_1 + dQ_2
\end{aligned}
$$

Allowing us to treat Q_1 and Q_2 separately instead of as correlated.

(Pro tip: The SM isn't C and P even, so Q_1 and Q_2 not necessarily C and P even)

Universal SMEFT: Ops for Z-pole and Drell Yan

The relevant subset of operators for Z-pole and Drell Yan processes are:
(D6: 6, D8: 11)

$$Q_{\phi,1} = |D_\mu H^\dagger H|^2 \qquad Q_{BW} = (H^\dagger \sigma^I H) W^I_{\mu\nu} B^{\mu\nu}$$

$$Q_{BB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu} \qquad Q_{WW} = (H^\dagger H) W^I_{\mu\nu} W^{I,\mu\nu}$$

$$Q_{2JB} = J_{B,\mu} J^\mu_B \qquad Q_{2JW} = J^I_{W,\mu} J^{I,\mu}_W$$

$$Q^{(2)}_{H^6} = |H|^2 (H^\dagger \sigma^I H)(D_\mu H)^\dagger \sigma^I (D^\mu H) \qquad Q^{(1)}_{WBH^4} = |H|^2 Q_{BW}$$

$$Q^{(3)}_{W^2H^4} = (H^\dagger \sigma^I H)(H^\dagger \sigma^J H) W^I_{\mu\nu} W^{J,\mu\nu}$$

$$Q^{(4)}_{\psi^2 H^4 D} = \epsilon^{IJK} J^{I,\mu}_W (H^\dagger \sigma^J H) D_\mu (H^\dagger \sigma^K H) \qquad Q^{(1)}_{\psi^2 H^4 D} = i|H|^2 J^\mu_B (H^\dagger \overleftrightarrow{D}_\mu H)$$

$$Q^{(2)}_{\psi^2 H^4 D} = i J^{I,\mu}_W \left[(H^\dagger \overleftrightarrow{D}^I_\mu H)|H|^2 - (H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \sigma^I H) \right]$$

$$Q^{(3)}_{\psi^4 D^2} = (D^\nu J^{I,\mu}_W)(D_\nu J^{I,\mu}_W) \qquad Q^{(2)}_{\psi^4 D^2} = (D^\nu J^\mu_B)(D_\nu J_{B,\nu})$$

$$Q^{(4)}_{\psi^4 H^2} = |H|^2 Q_{2JB} \qquad Q^{(5)}_{\psi^4 H^2} = |H|^2 Q_{2JW}$$

$$Q^{(7)}_{\psi^4 H^2} = (H^\dagger \sigma^I H) J^{I,\mu}_W J_{B,\mu}$$

$$J^\mu_B = g_1 \sum_\psi Y_\psi \bar\psi \gamma^\mu \psi \qquad J^{I,\mu}_W = \frac{g_2}{2} \sum_\psi \bar\psi \gamma^\mu \sigma^I \psi$$

Indistinguishable parameter combinations

Some operators are just $|H|^2$ times a D6 operator...

$$Q_{BW} = (H^\dagger \sigma^I H) W^I_{\mu\nu} B^{\mu\nu} \qquad \Leftrightarrow \qquad Q^{(1)}_{WBH^4} = (H^\dagger H)(H^\dagger \sigma^I H) W^I_{\mu\nu} B^{\mu\nu}$$

Without Higgs (and multiHiggs) processes we can't distinguish a lot of these
Introduce tilde (or bar) variables:

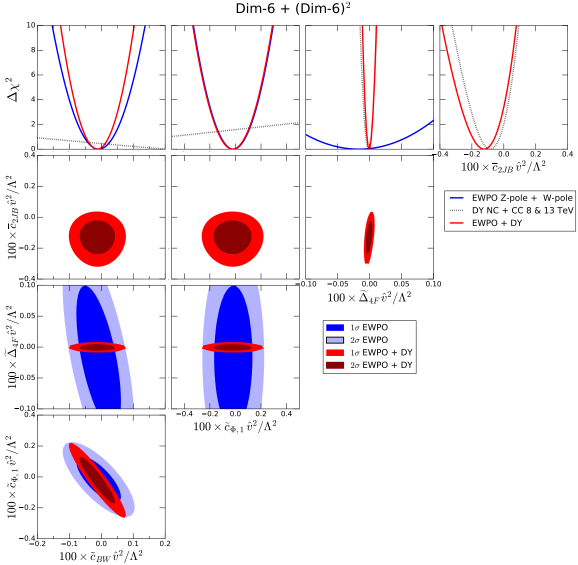
$$\tilde{c}_{BW} \sim \bar{c}_{BW} \sim c_{BW} + \frac{v^2}{2} c^{(1)}_{WBH^4}$$

This isn't consistent with the $1/M$ power counting...
Some justification can be found in the geoSMEFT/geometric methods for EFTs

See: Helset et al. arXiv:2007.00565

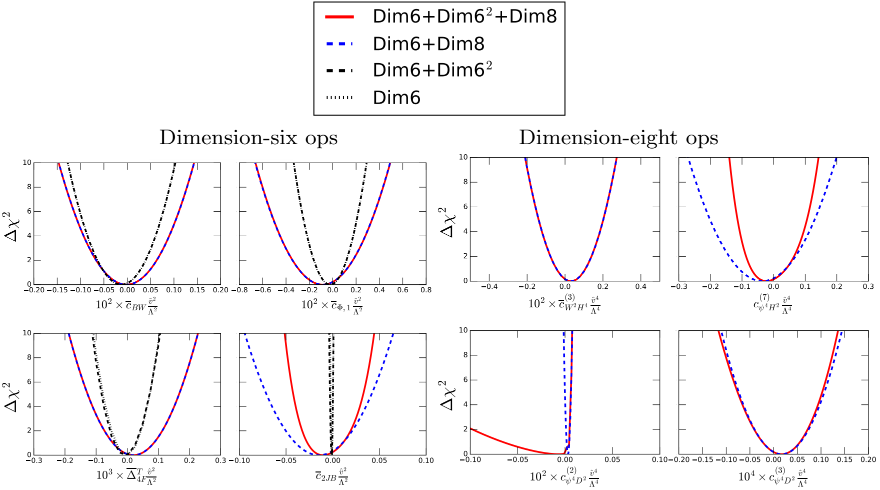
(Preliminary) Results D6

Including Z-pole, W decays, NC & CC Drell Yan:

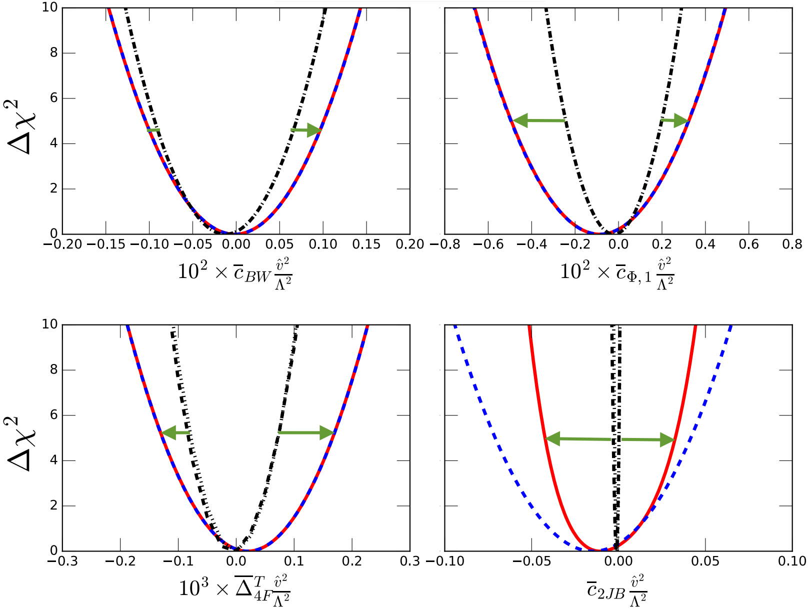


(Preliminary) Results D8

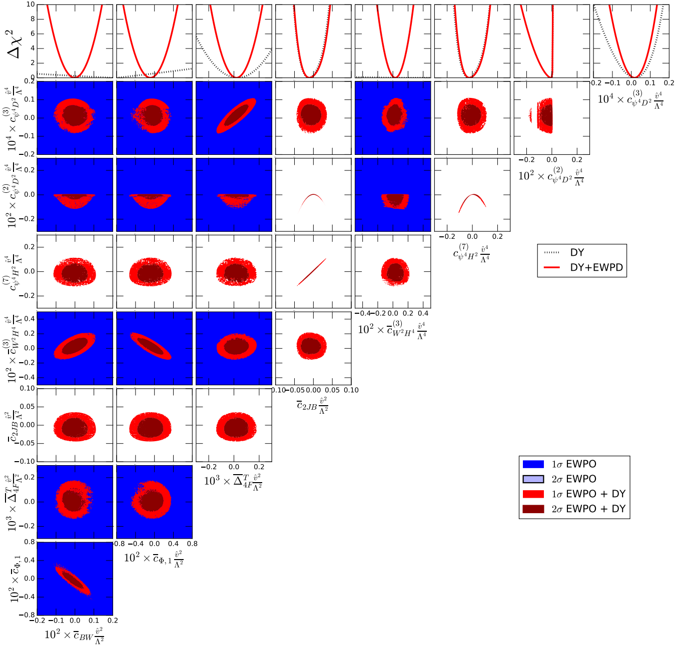
Including Z-pole, W decays, NC & CC Drell Yan:



(Preliminary) Theory/Truncation error



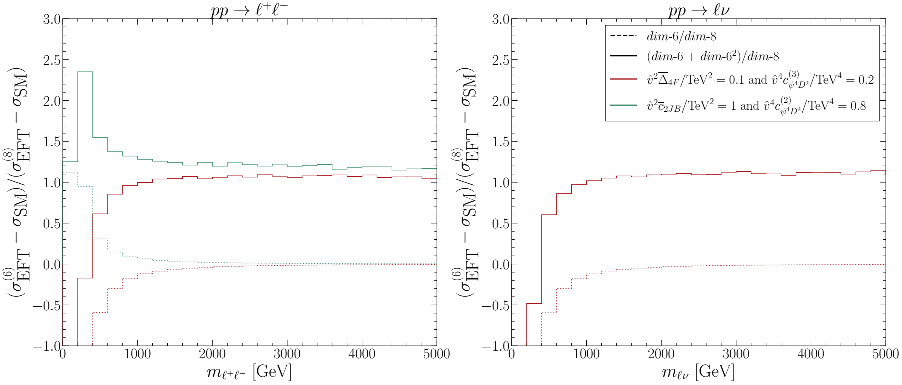
Dim-6 + (Dim-6)^2 + Dim-8



Truncation, more ops vs different mtm dep

The difference in D6 vs D8 fits shown in the last slide is driven by adding $c^{(3)}_{W^2H^4}$

not the momentum dep of $\Delta_{4F} \sim J^{I,\mu}_W J^I_{W,\mu}$ and $c^{(3)}_{\psi^4 D^2} \sim D_\nu J^{I,\mu}_W D^\nu J^I_{W,\mu}$



On the Oblique parameters (STU, and more)

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$$\Pi_{VV'}(p^2) \sim \Pi_{VV'}(0) + p^2\Pi'_{VV'}(0) + \frac{1}{2!}p^4\Pi''_{VV'}(0) + \frac{1}{3!}p^6\Pi'''_{VV'}(0) + \cdots$$

$$\begin{aligned} S &= -\tfrac{c}{s}\Pi'_{3B}(0) &\sim\ & c_{BW} + \text{D8} \\ X &= -\tfrac{m_W^2}{2}\Pi''_{3B}(0) &\sim\ & r^{(13)}_{BWH^2D^2} \\ X' &= -\tfrac{m_W^4}{2}\Pi'''_{3B}(0) &=\ & 0 \end{aligned}$$

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X' &= -\tfrac{m_W^4}{2}\Pi'''_{3B}(0) &&= 0\\
T &= \tfrac{1}{m_W^2}\left[\Pi_{WW}(0) - \Pi_{33}(0)\right] &&\sim c_{\phi,1} + \text{D8}\\
U &= \left[\Pi'_{WW}(0) - \Pi'_{33}(0)\right] &&\sim c^{(3)}_{W^2H^4}\\
V &= \left[\Pi''_{WW}(0) - \Pi''_{33}(0)\right] &&= 0\\
V' &= \left[\Pi'''_{WW}(0) - \Pi'''_{33}(0)\right] &&= 0
\end{aligned}$$

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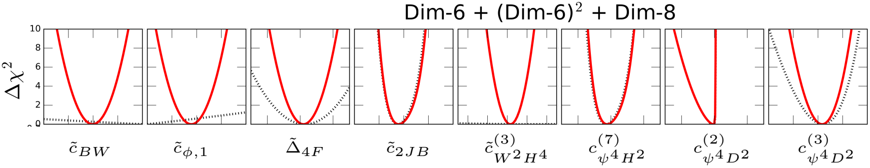
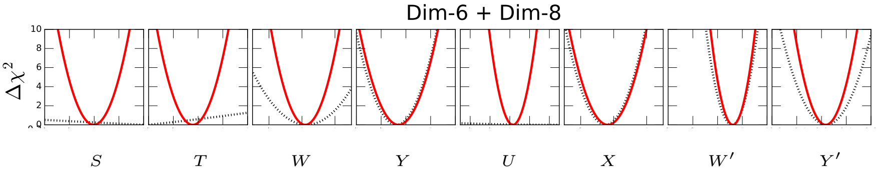
V' &= \left[\Pi'''_{WW}(0) - \Pi'''_{33}(0)\right] && = && 0 \\
\\
W &= -\tfrac{m_W^2}{2}\Pi''_{33}(0) && \sim && r_{2W} + \text{D8} \\
W' &= -\tfrac{m_W^4}{2}\Pi'''_{33}(0) && \sim && r^{(1)}_{W^2D^4} \\
\\
Y &= -\tfrac{m_W^2}{2}\Pi''_{BB}(0) && \sim && r_{2B} + \text{D8} \\
Y' &= -\tfrac{m_W^4}{2}\Pi'''_{BB}(0) && \sim && r^{(1)}_{B^2D^4}
\end{aligned}$$

Comparing full fit to “oblique parameter fit”





Conclusions

- The Universal basis is formed from purely bosonic operators
  ⇒ but we frequently prefer fermionic, use EOM
- The Universal SMEFT has far fewer parameters than the full SMEFT
  ⇒ It's less general though...
  ⇒ But provides an opportunity to see the impact of D8 operators on fits! (thry error)
- without multiHiggs processes can't distinguish some parameters
  ⇒ but tilde parameters help with this (similar to geoSMEFT approach)
- We can achieve D8 fits!
  ⇒ will provide a realistic estimate of theory/truncation error
- Oblique parameters are outdated, SMEFT is more consistent for decoupled NP

Backup

An older fit for triple gauge couplings

In TC et al. arXiv:2304.03305, before the D8 basis was determined:

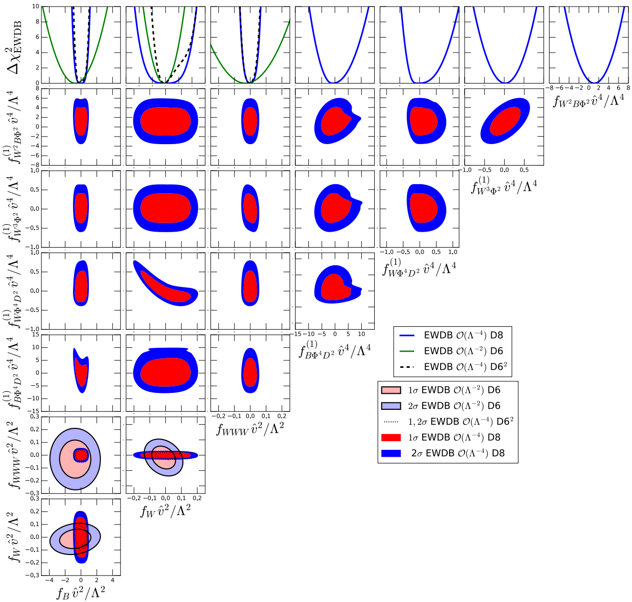
$$f_W Q_W \sim f_W (D^\mu H)^\dagger \sigma^I (D^\nu H) W^I_{\mu\nu} \qquad f_B Q_B \sim f_B (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$f_{WWW} Q_{WWW} \sim f_{WWW} \mathrm{Tr}[W^\nu_\mu W^\rho_\nu W^\mu_\rho]$$

& D8 counterparts ($f^{(1)}_{D^2\phi^6}, f^{(2)}_{D^2\phi^6}, f^{(1)}_{W^3\phi^2}, \cdots$)
All amplitudes grow with S (COM Energy),

so squares of D6 grow differently from linear in D6 or D8.

An older fit for triple gauge couplings



Matching the $U(1)$ mixing model

Starting from the NP $\mathcal{L}$, we want to 'match' onto the low energy EFT (SMEFT):

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}M^2 X_\mu X^\mu - g_1 Y_H k(H^\dagger i\overleftrightarrow{D}_\mu H)X^\mu + g_1^2 Y_H^2 k^2 |H|^2 X_\mu X^\mu$$
$$-g_1 k \sum_\psi Y_\psi (\bar{\psi}\gamma_\mu \psi) X^\mu$$

$$\begin{aligned}
\mathcal{L}_{\rm SMEFT} = \;& \mathcal{L}_{\rm SM} - \frac{g_1^2 k^2}{2M^2}(H^\dagger i\overleftrightarrow{D}_\mu H)^2 - \frac{g_1^2 k^2}{2M^2}\left(\sum_\psi Y_\psi \bar{\psi}\gamma_\mu\psi\right)^2 - \frac{g_1^2 k^2}{M^2}(H^\dagger i\overleftrightarrow{D}_\mu H)\left(\sum_\psi Y_\psi \bar{\psi}\gamma_\mu\psi\right) \\
&+ \frac{g_1^4 Y_H^2 k^2}{M^4}(H^\dagger H)(H^\dagger i\overleftrightarrow{D}_\mu H)^2 + \frac{g_1^2 k^2}{M^4}(H^\dagger i\overleftrightarrow{D}_\mu H)\left[\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right]\left(\sum_\psi Y_\psi \bar{\psi}\gamma_\mu\psi\right) \\
&+ \frac{2g_1^4 Y_H^2 k^4}{M^4}(H^\dagger H)(H^\dagger i\overleftrightarrow{D}_\mu H)\left(\sum_\psi Y_\psi \bar{\psi}\gamma_\mu\psi\right) \\
&+ \frac{g_1^2 k^2}{2M^4}\left(\sum_\psi Y_\psi \bar{\psi}\gamma_\mu\psi\right)\left[\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right]\left(\sum_\psi Y_\psi \bar{\psi}\gamma_\mu\psi\right) + \frac{g_1^4 Y_H^2 k^4}{M^4}(H^\dagger H)\left(\sum_\psi Y_\psi \bar{\psi}\gamma_\mu\psi\right)^2 \\
&+ \frac{g_1^4 Y_H^4 k^4}{M^4}\left[4(H^\dagger H)(H^\dagger D_\mu H)(D^\mu H)^\dagger H + (H^\dagger H)^2 (D_\mu H)^\dagger (D^\mu H)\right] \\
&+ \frac{g_1^4 Y_H^4 k^4}{2M^4}(H^\dagger H)^2\left(H^\dagger D^2 H + h.c.\right) \\
&- \frac{g_1^2 Y_H^2 k^2}{M^4}\left[\frac{g_1^2}{4}(H^\dagger H)^2 B_{\mu\nu}B^{\mu\nu} + g_2^2 (H^\dagger H)(H^\dagger \sigma^I H)W^I_{\mu\nu}B^{\mu\nu}\right] \\
&- \frac{g_1^2 Y_H^2 k^2}{M^4} g_1 g_2 (H^\dagger\sigma^I H)(H^\dagger \sigma^J H)W^{I,\mu\nu}W^J_{\mu\nu}
\end{aligned}$$