The SMEFT beyond leading order in $1/\Lambda^2$

Tyler Corbett

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Largely based on: TC, J. Desai, M. Martines, P. Reimitz, arXiv:2106.10284
O.J.P. Éboli, M.C. Gonzalez-Garcia – first fit @ $1/\Lambda^4$

TC, arXiv:2402.????? – convergence of the SMEFT expansion

See also: A. Helset, A. Martin, M. Trott arXiv:2001.01453 – "geoSMEFT"

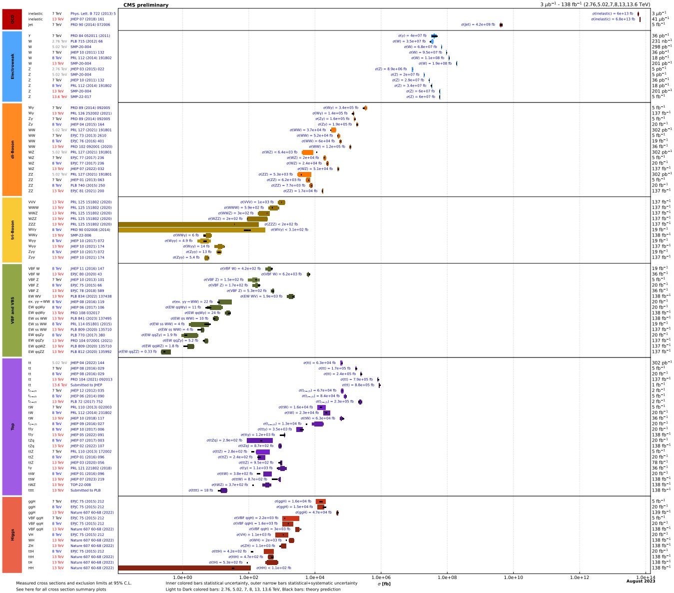
TC, A. Helset, M. Trott arXiv:1909.08470 – "Ward IDs in (geo)SMEFT"

TC, A. Martin, arXiv:2306.00053 – $pp \to h(V \to \bar{\psi}\psi)$ @ $1/\Lambda^4$

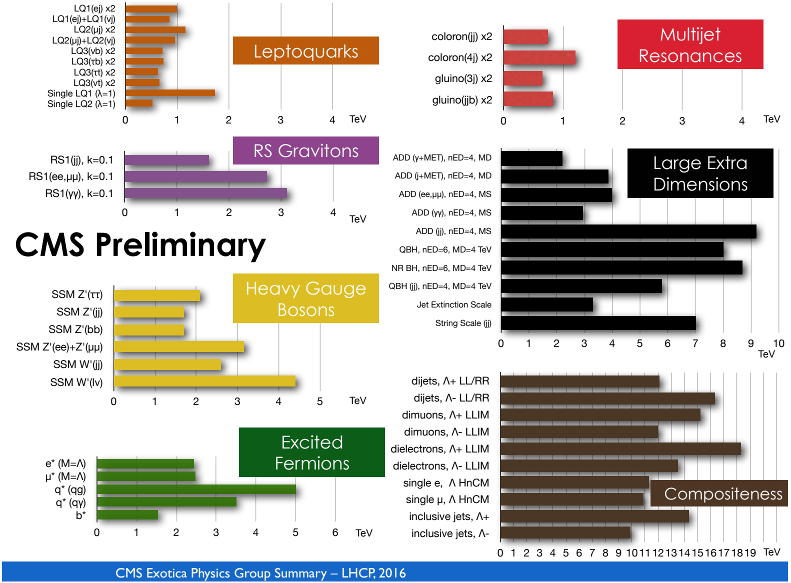
Outline

CMS SM Summary

Overview of CMS cross section results



CMS Exotics Summary



EFTs

$\Lambda_{\rm NP}$

The major underlying assumption of EFTs

$\Lambda_{\rm NP} \gg E$ of the scale of experiments/measurements

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.

E–scale of experiments

EFTs

Λ_{NP}

Top down EFTs:

- example: SM $\rightarrow$ Fermi theory
- Start w/ ultraviolet (UV)–model in mind (Seesaw, SUSY, etc)
- "integrate out" heavy degrees of freedom at UV scale
- model dependent relations between ops, $Q_i^{d>4}$
- Q_i are only in terms of IR degrees of freedom

E–scale of experiments

EFTs

Λ_{NP}

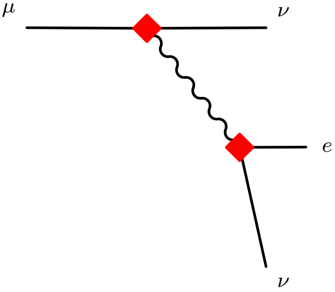
Bottom up EFTs:

- example: Fermi theory
- Start w/ infrared (IR)–model in mind (QED, SM)
- using symmetries of model put together ops, $Q^{d>4}$
- truncate EFT at some $\mathcal{O}(1/\Lambda)$
- constrain Q in experiment & infer properties of NP at Λ
- Qs are unrelated $\rightarrow$ model independent
- Qs are only in terms of IR degrees of freedom

E–scale of experiments

The Fermi-theory example

In the SM



$$\mathcal{M} \sim \frac{g_{\rm W}^2}{2} \frac{(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e)}{k^2 - M_W^2}$$

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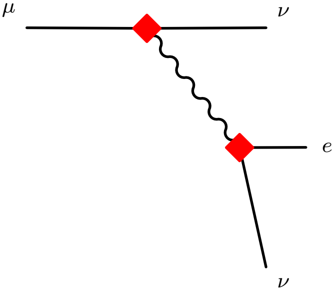
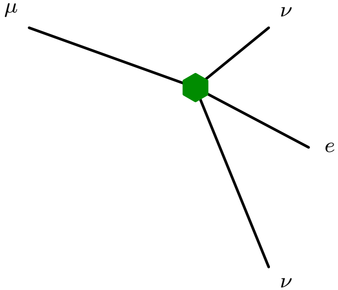


In the Fermi theory



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$$\frac{1}{M_W^2} (\bar{\psi}\gamma^\mu P_L \psi)^2$$

$$\mathcal{M} \sim -\frac{g_{\rm W}^2}{2 M_W^2} (\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e) + \cdots$$

The Fermi-theory example

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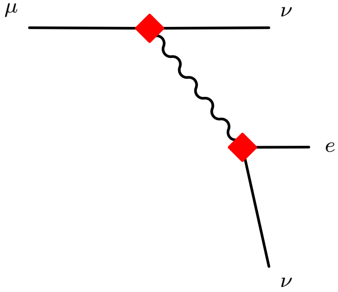

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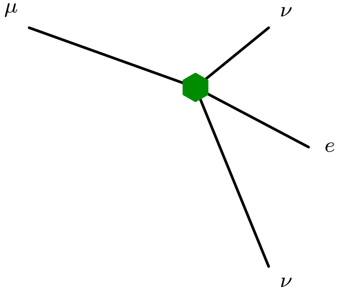

$\frac{1}{M_W^2}(\bar{\psi}\gamma^\mu P_L \psi)^2$ $\qquad$ $\frac{1}{M_W^4}\partial^2(\bar{\psi}\gamma^\mu P_L \psi)^2$

$$\mathcal{M} \sim -\frac{g_{\rm W}^2}{2M_W^2}(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e) - \frac{g_{\rm W}^2 k^2}{2M_W^4}(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma^\mu P_L \nu_e) + \cdots$$

SMEFT

In studying NP at $\Lambda_{\text{NP}} \gg v$, we employ the Standard Model EFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots \qquad \mathcal{L}_d = \sum_i c_i Q_i$$

The SMEFT is formed of $\mathcal{L}_{\text{SM}}$ and Q of $d > 4$ respecting SM symmetries & c_i embedding UV physics

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The SMEFT is:
a Taylor series in $\frac{v}{\Lambda}$, $\frac{p}{\Lambda} \ll 1$

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The leading operator:

$$\mathcal{L}_5 = c_{\alpha\beta}(\bar{L}^c_\alpha \tilde{H})(\tilde{H}^\dagger L_\beta) \sim v^2 \bar{\nu}_\alpha \nu_\beta$$

$$\Rightarrow m_\nu \sim v^2/\Lambda$$

The SMEFT at dimension-six

D6 operators from SM field content ⇒ SMEFT @ D6

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}	$(H^\dagger H)G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{L}\sigma^{\mu\nu}e)\tau^I HW_{\mu\nu}^I$	$Q_{HL}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$
$Q_{H\tilde{G}}$	$(H^\dagger H)\tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{L}\sigma^{\mu\nu}e)\tau^I HB_{\mu\nu}$	$Q_{HL}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{L}\tau^I\gamma^\mu L)$
Q_{HW}	$(H^\dagger H)W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{Q}\sigma^{\mu\nu}T^A u)\tilde{H}G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$Q_{H\tilde{W}}$	$(H^\dagger H)\tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar{Q}\sigma^{\mu\nu}T^A d)HG_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
Q_{HWB}	$(H^\dagger\tau^I H)W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{Q}\sigma^{\mu\nu}d)\tau^I HW_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$Q_{H\tilde{W}B}$	$(H^\dagger\tau^I H)\tilde{W}_{\mu\nu}^I B^{\mu\nu}$	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: $5\times(\bar{L}L)(\bar{L}L)+7\times(\bar{R}R)(\bar{R}R)+8\times(\bar{L}L)(\bar{R}R)$
$+(\bar{L}R)(\bar{R}L)+4[(\bar{L}R)(\bar{L}R)+\text{h.c.}]=25(\bar{\Psi}\Psi)(\bar{\Psi}\Psi)$

SMEFT: Effective Vertices

T3: $Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$

T3: $Q_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D^\mu H)$

T4: $Q_{HV} = (H^\dagger H)V^{\mu\nu}V_{\mu\nu}$

T4: $Q_{HWB} = (H^\dagger \tau^I H)W^I_{\mu\nu}B^{\mu\nu}$

T5: $Q_{\psi H} = (H^\dagger H)(\bar{\Psi}H\psi)$

T7: $Q^{(3)}_{HL} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{L}\gamma^\mu L)$

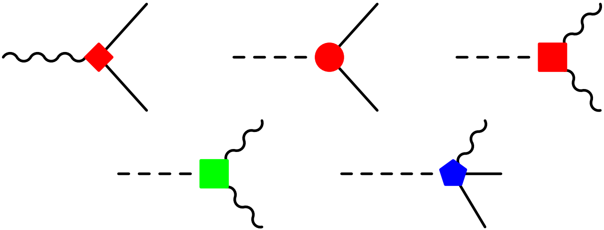
T7: $Q^{(1,3)}_{H\Psi} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{\Psi}\gamma^\mu \Psi)$

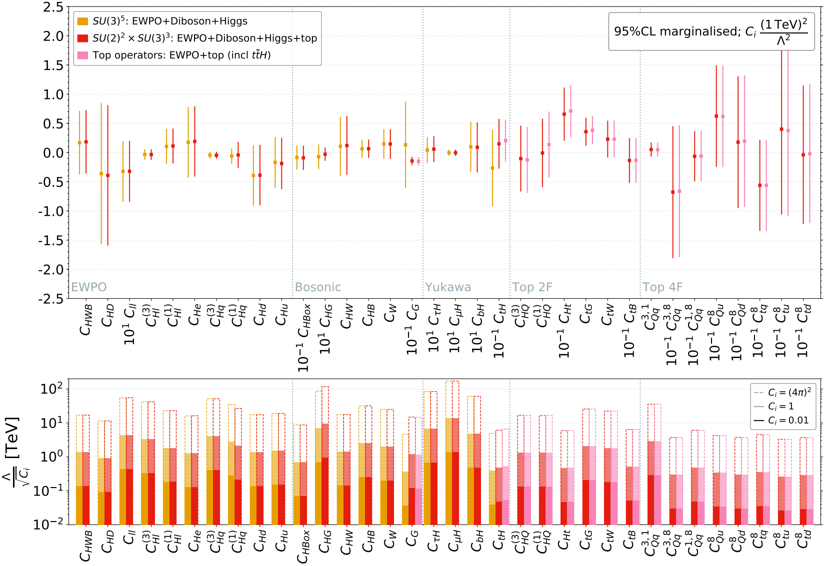
T7: $Q_{H\psi} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{\psi}\gamma^\mu \psi)$

T8: $Q_{LL} = (\bar{L}\gamma^\mu L)(\bar{L}\gamma^\mu L)$

SM–like

Non-SM-like kinematic structure





J. Ellis, M. Madigan, K. Mimasu, V. Sanz, T. You, arXiv:2012.02779

SMEFT@D6: state of the art

1. **Loops:**

   RGE – Alonso, Jenkins, Manohar, Trott, arXiv:1312.2014

   2 loop RGE – Fuentes-Martín, Palavrić, Thompsen, arXiv:2311.13630

   EW loops – e.g. $H\gamma\gamma$ – Harmann, Trott, arXiv:1507.03568

   e.g. Z-pole – Dawson, Giardino, arXiv:1909.02000

   QCD loops – e.g. W^+W^- – Baglio, Dawson, Lewis, arXiv:1812.00214

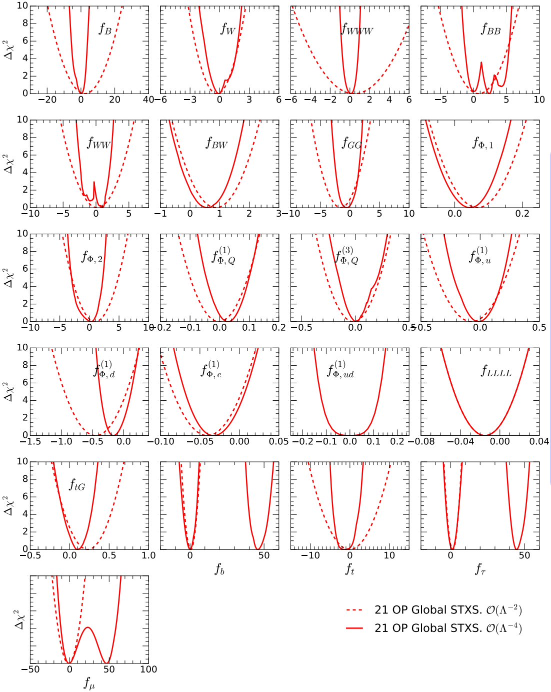
   SMEFT@NLO – Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, arXiv:2008.11743

2. **Global fits** – many groups (e.g. those cited in this talk)
3. **Matching to one-loop**
   Matchete (functional methods), arXiv:2212.04510
   Fuentes, König, Pagès, Thomsen, Wilsch

   Matchmakereft (amplitude based matching), arXiv:2112.10787
   Carmona, Lazopoulos, Olgoso, Santiago

   SMEFT→LEFT – Dekens, Stoffer, arXiv:1908.05295

4. **Improved tree-level calculations** (e.g. narrow width isn't always great)
5. **Channel specific studies**
6. **Myriad more** (this is a **biased list, though not on purpose**)



Almeida, Alves, Éboli, Gonzalez-Garcia
arXiv:2108.04828

Uses:

- EWPD
- EW diboson production
- Higgs data

dashed - $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)$

solid - $\sigma\left(\mathcal{O}\frac{1}{\Lambda^4}\right) \times \mathrm{BR}\left(\mathcal{O}\frac{1}{\Lambda^4}\right)$

D6, $D6^2$, and D8

- Big impact from $D6^2 \sim \left(\frac{1}{\Lambda^2}\right)^2$
- LHC EFT WG, Area 1 – Truncation, validity, uncertainties
  "although they only constitute a partial set of $1/\Lambda^4$ corrections, the squares of amplitudes featuring a single dimension-six operator insertion provide a convenient proxy to estimate $1/\Lambda^4$ corrections, as they are well defined and unambiguous. They are indeed gauge invariant and can be translated exactly from one dimension-six operator basis to the other."
- Cen Zhang, SMEFTs living on the edge, arXiv:2112.11665
  "Our results indicate that the dimension-8 operators encode much more information about the UV than one would naively expect, which can be used to reverse engineer the UV physics from the SMEFT."

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Beyond leading order in the SMEFT

At D6 in the SMEFT we have 59 operator forms, at D8 we have 895!
3,045 free parameters, 44k

Two complete bases have been formulated:

- Chris Murphy, arXiv:2005.00059
- Hao-Lin Li et al., arXiv:2005.00008

A *bit of a nightmare* to achieve, but some groups make predictions at D8 (e.g.):

- Hays et al., Assoc. Production of the Higgs, arXiv:1808.00442
- Boughezal et al., Dilepton production, arXiv:2106.05337
- Boughezal et al., Drell Yan, arXiv:2207.01703
- Asteriadis et al., Gluon fusion of Higgs, arXiv:2212.03258

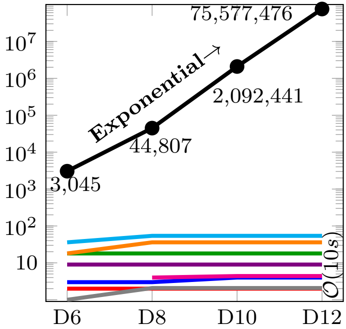
But this is greatly simplified by employing the geoSMEFT methodology, Helset et al. arXiv:2001.01453

- choice of basis that classifies all three-point functions
- (tree level) input parameters derived to all orders in $1/\Lambda^2$ (except G_F)
- naturally relates effective vertices to geometric formulation of SMEFT
  $\rightarrow$ constrain combinations of parameters

Saturation of number of operators

(This information is contained in the Hilbert Series)
(see e.g. Lehman & Martin 2015, Henning et al. 2015)

		Mass Dimension		
	Operator form:	6	8	10
(red)	$h_{IJ}(D_\mu\phi)^I(D^\mu\phi)^J$	2	2	2
(blue)	$g_{AB}W^A_{\mu\nu}W^{B,\mu\nu}$	3	4	4
(magenta)	$k_{IJA}(D^\mu\phi)^I(D^\nu\phi)^J W^A_{\mu\nu}$	0	3	4
(gray)	$f_{ABC}W^A_{\mu\nu}W^{B,\nu\rho}W^{C,\mu}_\rho$	1	2	2
(green)	$Y^\psi_{pr}\bar{\Psi}_L\psi_R + h.c.$	$2N_f^2$	$2N_f^2$	$2N_f^2$
(cyan)	$d^{\psi,pr}_A\bar{\Psi}_L\sigma_{\mu\nu}\psi_R W^{\mu\nu}_A + h.c.$	$4N_f^2$	$6N_f^2$	$6N_f^2$
(purple)	$L^{\psi_R}_{pr,J,A}(D^\mu\phi)^J(\bar{\psi}_{p,R}\gamma_\mu\sigma_A\psi_{r,R})$	N_f^2	N_f^2	N_f^2
(orange)	$L^{\Psi_L}_{pr,J,A}(D^\mu\phi)^J(\bar{\Psi}_{p,L}\gamma_\mu\sigma_A\Psi_{r,L})$	$2N_f^2$	$4N_f^2$	$4N_f^2$



Top down, revisited

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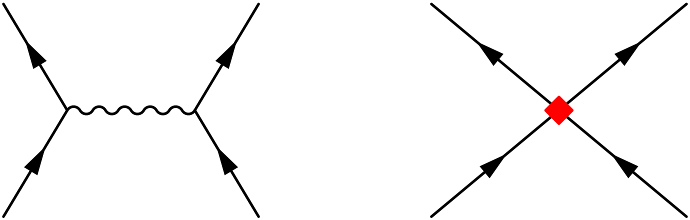
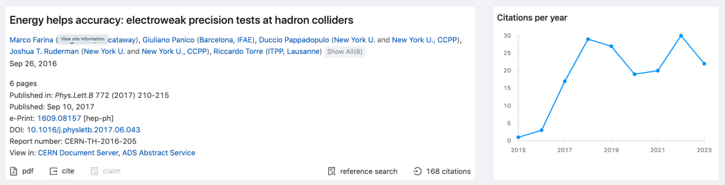
E–scale of experiments

Drell Yan



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



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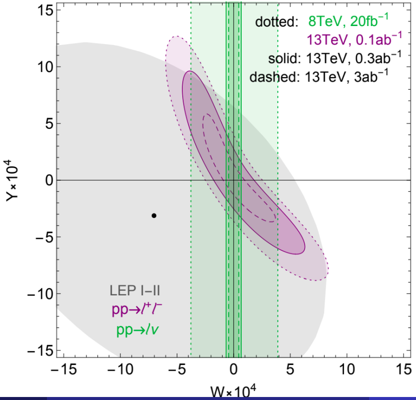
"Energy helps accuracy: electroweak precision tests at hadron colliders"
M. Farina, G. Panico, D. Pappadopulo, J. Ruderman, R. Torre, arXiv:1609.08157

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



Exploring concrete models

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

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

(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
   $\rightarrow$ 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
   ($d6$, $d6^2$, $d8$, $d6 \cdot d8$, $d10$)

$\phi = (1,3)_0$

$$\Delta\mathcal{L}_\phi = \frac{1}{2}(D_\mu\phi^a)^\dagger(D_\mu\phi^a) - \frac{1}{2}M^2(\phi^a)^2 + \kappa H^\dagger\sigma^a H\phi^a - \lambda_{\phi H}(\phi^a)^2(H^\dagger H) - \lambda_\phi(\phi^a)^4$$

$$\Downarrow$$

$$\begin{aligned}
\mathcal{L}_{\rm IR}^{\phi} \quad = \quad & \mathcal{L}_{\rm SM} - \frac{\kappa^2}{M^4}\left[\frac{1}{2}Q_{HD} - \frac{1}{4}Q_{HD2}\right] - \frac{\kappa^2}{8M^4}\left[|H|^2(H^\dagger D^2 H) + h.c.\right] \\
& + \frac{2\lambda_{\phi H}\kappa^2}{M^6}|H|^2 Q_{HD} - \frac{\lambda_{\phi H}\kappa^2}{M^6}|H|^2 Q_{HD2} + \frac{\lambda_{\phi H}\kappa^2}{2M^6}\left[|H|^4(H^\dagger D^2 H) + h.c.\right] \\
& + \frac{\kappa^2}{M^8}\left[\frac{\lambda_\phi\kappa^2}{M^2} - 6\lambda_{\phi H}^2\right]|H|^4 Q_{HD} + \frac{\kappa^2}{6M^8}\left[16\lambda_{\phi H}^2 - 3\frac{\lambda_\phi\kappa^2}{M^2}\right]|H|^4 Q_{HD2} \\
& + \frac{\kappa^2}{M^8}\left[\frac{\lambda_\phi\kappa^2}{4M^2} - \frac{5\lambda_{\phi H}^2}{3}\right]\left[|H|^6(H^\dagger D^2 H) + h.c.\right]
\end{aligned}$$

$\phi = (1,3)_0$

$$\Delta\mathcal{L}_\phi = \frac{1}{2}(D_\mu\phi^a)^\dagger(D_\mu\phi^a) - \frac{1}{2}M^2(\phi^a)^2 + \kappa H^\dagger\sigma^a H\phi^a - \lambda_{\phi H}(\phi^a)^2(H^\dagger H) - \lambda_\phi(\phi^a)^4$$

Only shifts m_Z, so no effect on Drell Yan (m_Z input scheme)
So truncation at dimension-six is clearly valid for Drell Yan
(we're measuring zero)

$$\begin{aligned}\mathcal{L}_{\rm IR}^\phi \quad = \quad & \mathcal{L}_{\rm SM} - \tfrac{\kappa^2}{M^4}\left[\tfrac{1}{2}Q_{HD} - \tfrac{1}{4}Q_{HD2}\right] - \tfrac{\kappa^2}{8M^4}\left[|H|^2(H^\dagger D^2 H) + h.c.\right] \\ & + \tfrac{2\lambda_{\phi H}\kappa^2}{M^6}|H|^2 Q_{HD} - \tfrac{\lambda_{\phi H}\kappa^2}{M^6}|H|^2 Q_{HD2} + \tfrac{\lambda_{\phi H}\kappa^2}{2M^6}\left[|H|^4(H^\dagger D^2 H) + h.c.\right] \\ & + \tfrac{\kappa^2}{M^8}\left[\tfrac{\lambda_\phi\kappa^2}{M^2} - 6\lambda_{\phi H}^2\right]|H|^4 Q_{HD} + \tfrac{\kappa^2}{6M^8}\left[16\lambda_{\phi H}^2 - 3\tfrac{\lambda_\phi\kappa^2}{M^2}\right]|H|^4 Q_{HD2} \\ & + \tfrac{\kappa^2}{M^8}\left[\tfrac{\lambda_\phi\kappa^2}{4M^2} - \tfrac{5\lambda_{\phi H}^2}{3}\right]\left[|H|^6(H^\dagger D^2 H) + h.c.\right]\end{aligned}$$

$\chi = (1,1)_{-1}$

$$\Delta\mathcal{L}_\chi = i\bar{\chi}\not{D}\chi - M\bar{\chi}\chi - Y_\chi\left[H^\dagger\bar{\chi}L + h.c.\right]$$

$$\Downarrow$$

$$\begin{aligned}\mathcal{L}_{\rm IR}^{\chi} \;=\; & \mathcal{L}_{\rm SM} + i\frac{Y_\chi^2}{2M^2}\left[(H\bar{L})\gamma_\mu(D_\mu H)^\dagger L + (H\bar{L})\gamma_\mu(H^\dagger D_\mu L) - h.c.\right] \\ & -i\frac{Y_\chi^2}{2M^4}\Big[(H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\mu D_\nu D_\rho H)^\dagger L + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\mu D_\nu H)^\dagger(D_\rho L) \\ & \qquad + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\mu H)^\dagger(D_\nu D_\rho L) + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho H^\dagger(D_\mu D_\nu D_\rho L) \\ & \qquad + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\mu D_\rho H)^\dagger(D_\nu L) + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\nu H)^\dagger(D_\mu D_\rho L) \\ & \qquad + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\rho H)^\dagger(D_\mu D_\nu L) + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\nu D_\rho H)^\dagger(D_\mu L) - h.c.\Big] \\ & + D10\end{aligned}$$

$\chi = (1,1)_{-1}$

$$\Delta\mathcal{L}_\chi = i\bar{\chi}\not{D}\chi - M\bar{\chi}\chi - Y_\chi\left[H^\dagger\bar{\chi}L + h.c.\right]$$

$$\Downarrow$$

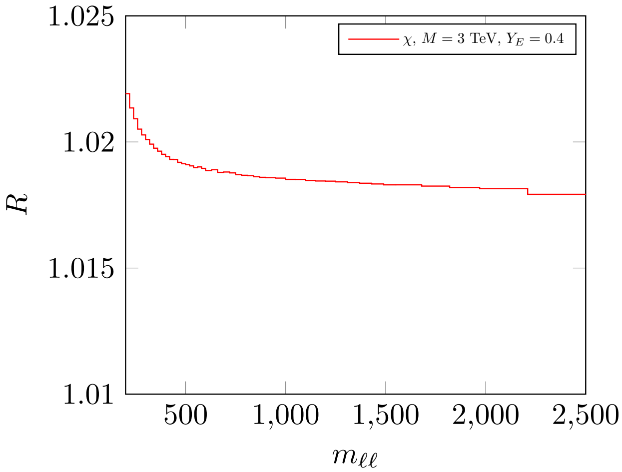
Shifts the $Z\bar{L}L$ couplings

D8+ operators appear to be momentum dependent,
but for on-shell leptons will not contribute ($m_\ell \to 0$)

This is actually an exact statement and doesn't require on-shell (geoSMEFT)

$$\begin{aligned}\mathcal{L}^\chi_{\rm IR} \;=\; & \mathcal{L}_{\rm S} \\ & -i \\ & \quad + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\mu H)^\dagger(D_\nu D_\rho L) + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho H^\dagger(D_\mu D_\nu D_\rho L) \\ & \quad + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\mu D_\rho H)^\dagger(D_\nu L) + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\nu H)^\dagger(D_\mu D_\rho L) \\ & \quad + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\rho H)^\dagger(D_\mu D_\nu L) + (H\bar{L})\gamma_\mu\gamma_\nu\gamma_\rho(D_\nu D_\rho H)^\dagger(D_\mu L) - h.c.\Big] \\ & + D10\end{aligned}$$

$\chi = (1,1)_{-1}$


χ, $M = 3$ TeV, $Y_E = 0.4$
1.025
1.02
1.015
1.01
R
500
1,000
1,500
2,000
2,500
$m_{\ell\ell}$

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

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

$$\Downarrow$$

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

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

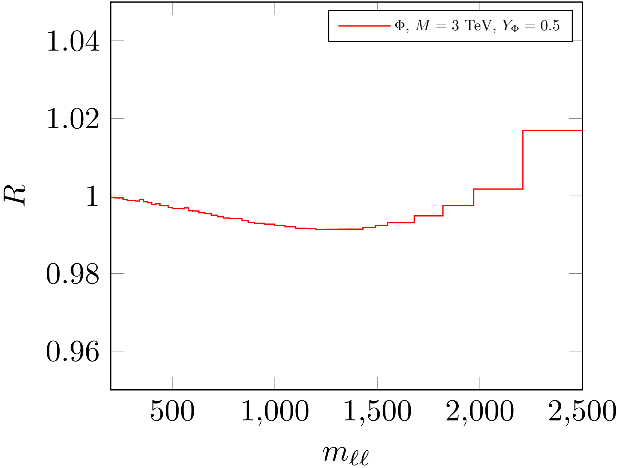
$$\Delta\mathcal{L}_\Phi = (D_\mu\Phi)^\dagger(D_\mu\Phi) - M^2\Phi^\dagger\Phi + Y_\Phi\ \left[\bar{d}\,(\Phi\, i\sigma_2 L) + h.c.\right]$$

$$\Downarrow$$

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

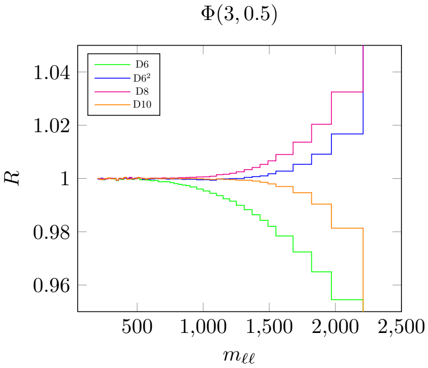
- A very clean example of the p expansion!
- No v expansion

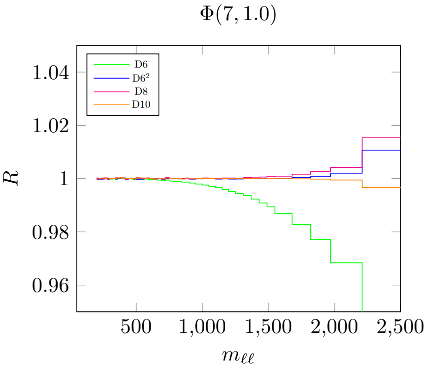
$\Phi = (3,2)_{1/6}$



Φ, $M = 3$ TeV, $Y_\Phi = 0.5$
1.04
1.02
1
0.98
0.96
R
500
1,000
1,500
2,000
2,500
$m_{\ell\ell}$

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


$\Phi(3, 0.5)$
D6
D6^2
D8
D10
1.04
1.02
1
0.98
0.96
R
500
1,000
1,500
2,000
2,500
$m_{\ell\ell}$


$\Phi(7, 1.0)$
D6
D6^2
D8
D10
1.04
1.02
1
0.98
0.96
R
500
1,000
1,500
2,000
2,500
$m_{\ell\ell}$

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

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

$$\Downarrow$$

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

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

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

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

$$\Downarrow$$

- 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

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

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

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

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

$$\Downarrow$$

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

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

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

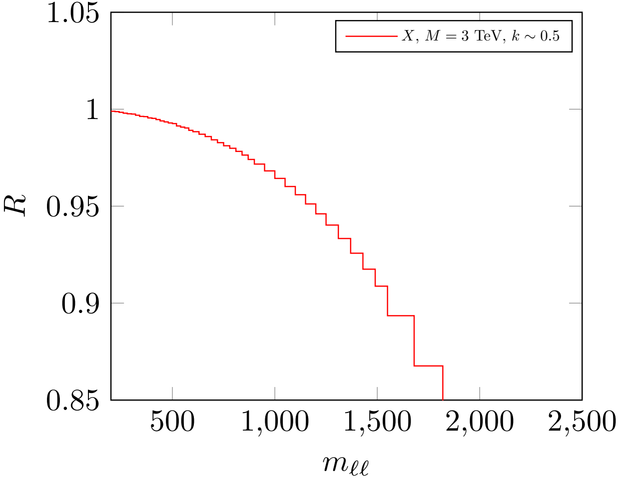
$$\begin{aligned}\Delta\mathcal{L}_V &= -\tfrac{1}{4}V_{\mu\nu}V^{\mu\nu} + \tfrac{1}{2}M^2 V_\mu V^\mu - \tfrac{k}{2}B_{\mu\nu}V^{\mu\nu} \\ &= -\tfrac{1}{4}X_{\mu\nu}X^{\mu\nu} + \tfrac{1}{2}M_X^2 X_\mu X^\mu - g_1 \textstyle\sum_\psi Y_\psi \beta(\bar\psi\gamma_\mu\psi)X^\mu\end{aligned}$$

- In this (massively) simplified version → 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: $\mathcal{O}(10^{-1.6}) \to \mathcal{O}(100)$ effect (bin-by-bin)

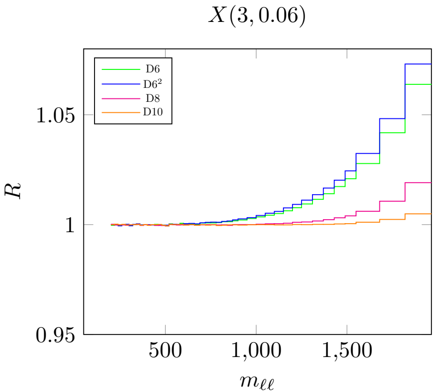
$$\begin{aligned}\mathcal{L}_{IR}^X = \; & \mathcal{L}_{\rm SM} - \frac{g_1^2\beta^2}{2M^2}\Psi_\mu\Psi^\mu \\ & + \frac{g_1^2\beta^2}{2M^4}\Psi_\mu\left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\Psi_\nu \\ & - \frac{g_1^2\beta^2}{2M^4}\Psi_\mu\left(\Box\eta^{\mu\nu} - \partial^\mu\partial^\nu\right)\left(\Box\eta_{\nu\rho}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

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

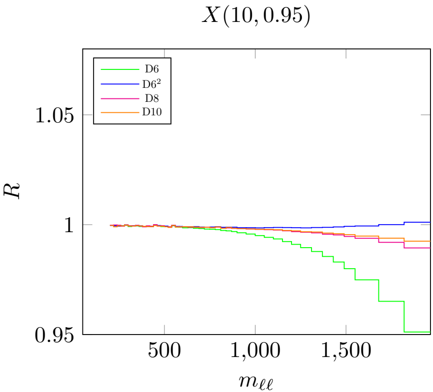
$X_\mu = (1,1)_0$



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



X(3, 0.06)
D6
D6²
D8
D10
1.05
1
0.95
R
500
1,000
1,500
mℓℓ



X(10, 0.95)
D6
D6²
D8
D10
1.05
1
0.95
R
500
1,000
1,500
mℓℓ

Convergence of the EFT

Two EFTs:

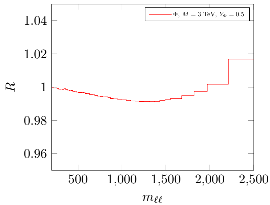
$$\mathcal{L}_{\rm IR}^{\Phi} = \mathcal{L}_{\rm SM} + c_6 \frac{Y_\Phi^2}{M^2} \left(\bar{d}L\right)\left(\bar{L}d\right) + c_8 \frac{Y_\Phi^2}{M^4}\Big[\left(\bar{d}D_\mu L\right)\left(\bar{L}D^\mu d\right) + \left(D_\mu \bar{d}\right) L \left(\bar{L}D_\mu d\right) + \left(\bar{d}D_\mu L\right)\left(D_\mu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

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

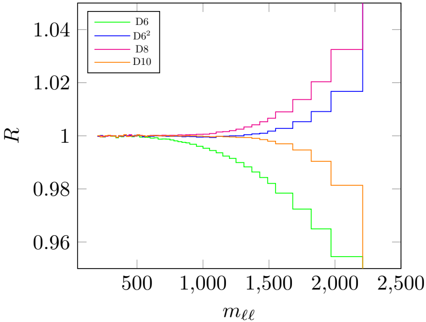
Minimize χ^2 to a given order in the EFT (including partial results, $(D6)^2$, $(D6 \cdot D8)$)

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

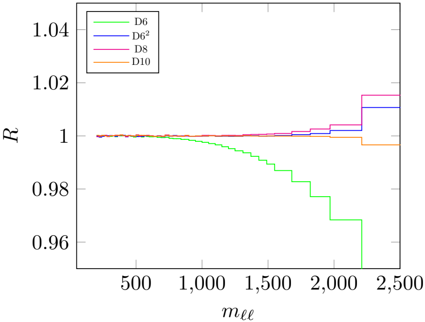
Convergence of the EFT: Φ



$\Phi(3, 0.5)$



$\Phi(7, 1.0)$



Convergence of the EFT: Φ

M_Φ	Y_Φ	fit up to	c_6	c_8	c_{10}	$\chi^2_{\min}$
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}

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}
		$(\mathrm{D6})^2$	0.94 ± 5.7	–	–	10^{-4}
		D8	0.99 ± 5.7	0.74 ± 57	–	10^{-6}
		$(\mathrm{D6} \cdot \mathrm{D8})$	1.0 ± 5.7	0.81 ± 61	–	10^{-6}
		D10	1.0 ± 5.7	0.97 ± 61	0.58 ± 253	10^{-8}
3	0.5	D6	0.74 ± 0.22	–	–	1
		$(\mathrm{D6})^2$	0.96 ± 0.30	–	–	10^{-2}
		D8	0.96 ± 0.30	-0.3 ± 2.3	–	10^{-2}
		$(\mathrm{D6} \cdot \mathrm{D8})$	0.99 ± 0.31	0.6 ± 2.8	–	10^{-4}
		D10	1.0 ± 0.31	0.7 ± 2.8	-0.4 ± 10	10^{-4}

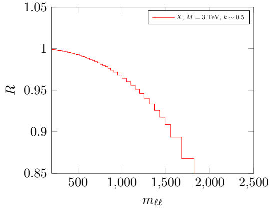
Convergence of the EFT: Φ

M_Φ	Y_Φ	fit up to	c_6	c_8	c_{10}	χ^2_{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}
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}
3	1.0	D6	0.16 ± 0.06	–	–	100
		$(\text{D6})^2$	0.84 ± 0.03	–	–	1
		D8	0.87 ± 0.03	-0.62 ± 0.62	–	1
		$(\text{D6} \cdot \text{D8})$	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}

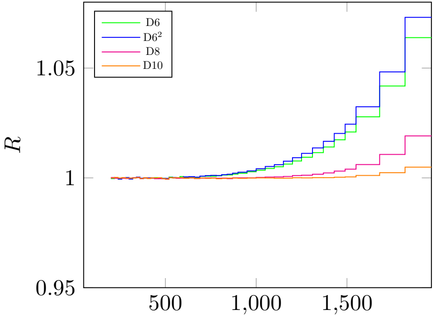
Convergence of the EFT: Φ

M_Φ	Y_Φ	fit up to	c_6	c_8	c_{10}	χ^2_{min}
3	1.0	D6	0.16 ± 0.06	–	–	100
		$(\text{D6})^2$	0.84 ± 0.03	–	–	1
		D8	0.87 ± 0.03	-0.62 ± 0.62	–	1
		$(\text{D6} \cdot \text{D8})$	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}
7	1.0	D6	0.8 ± 0.3	–	–	0.1
		$(\text{D6})^2$	0.99 ± 0.4	–	–	10^{-4}
		D8	0.99 ± 0.4	-0.2 ± 17	–	10^{-4}
		$(\text{D6} \cdot \text{D8})$	1.0 ± 0.4	0.9 ± 36	–	10^{-6}
		D10	1.0 ± 0.4	0.9 ± 36	-1 ± 400	10^{-7}

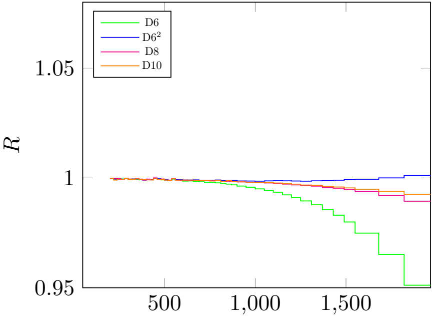
Convergence of the EFT: X_μ



$X(3, 0.06)$



$X(10, 0.95)$



Convergence of the EFT: X_μ

M_Φ	β	fit up to	c_6	c_8	c_{10}	χ^2_{min}
3	0.3	D6	1.13 ± 0.35	–	–	10^{-1}
		$(\text{D6})^2$	1.13 ± 0.36	–	–	10^{-1}
		D8	0.98 ± 0.36	1.5 ± 2.4	–	10^{-3}
		$(\text{D6} \cdot \text{D8})$	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}

Convergence of the EFT: X_μ

M_Φ	β	fit up to	c_6	c_8	c_{10}	χ^2_{min}
3	0.3	D6	1.13 ± 0.35	–	–	10^{-1}
		$(\text{D6})^2$	1.13 ± 0.36	–	–	10^{-1}
		D8	0.98 ± 0.36	1.5 ± 2.4	–	10^{-3}
		$(\text{D6} \cdot \text{D8})$	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}
3	1.2	D6	1.01 ± 0.02	–	–	100
		$(\text{D6})^2$	1.09 ± 0.02	–	–	10
		D8	1.05 ± 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

Convergence of the EFT: X_μ

M_Φ	β	fit up to	c_6	c_8	c_{10}	χ^2_{min}
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		$(\text{D6} \cdot \text{D8})$	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}
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
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

Convergence of the EFT: X_μ

M_Φ	β	fit up to	c_6	c_8	c_{10}	χ^2_{min}
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
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}
		$(\text{D6} \cdot \text{D8})$	0.98 ± 0.03	0.8 ± 1.6	–	10^{-3}
		D10	0.98 ± 0.03	0.9 ± 1.6	-1.0 ± 25	10^{-5}

Interim conclusions – the SMEFT expansion

1. We seem safe at D6 – except in the most extreme models (low M, or strong coupling)
2. Lack of inclusion of D8 results → D6 constraints shift away from true value
3. T-channel $\frac{1}{\Lambda^2} - \frac{1}{\Lambda^4} + \frac{1}{\Lambda^6}$
   S-channel $\frac{1}{\Lambda^2} + \frac{1}{\Lambda^4} + \frac{1}{\Lambda^6}$
   ⇒ Sometimes $(D6)^2$ is representative of NLO, sometimes it messes things up!
4. An interpretation:
   D6 fits are SM measurements w/ errors/nuisance params. consistent w/ SMEFT
   D8 fits are SMEFT fits at D6 w/ errors/nuisance params. consistent w/ SMEFT
   (but when, if ever, at the HL-LHC does the latter become possible/true?)

Bottom up revisited

$\Lambda_{\rm NP}$

Bottom up EFTs:

- example: Fermi theory
- Start w/ infrared (IR)–model in mind (QED, SM)
- using symmetries of model put together ops, $Q^{d>4}$
- truncate EFT at some $\mathcal{O}(1/\Lambda)$
- constrain Q in experiment & infer properties of NP at Λ
- Qs are unrelated → model independent
- Qs are only in terms of IR degrees of freedom

E–scale of experiments

The Universal SMEFT

How does flavor universal physics imprint on the SMEFT?
J. Wells, Z. Zhang, arXiv:1510.08462

1. purely bosonic operators
2. for convenience, trade a few for SM-like fermionic currents (field redefinitions) e.g.:

$$
\begin{aligned}
-\frac{1}{2}(\partial^\nu B_{\mu\nu})^2 \quad &\rightarrow \quad -\frac{ig_1}{2}(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)\partial^\nu B_{\mu\nu} - \frac{g_1^2}{8}(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)^2 - \frac{1}{2}J_{B\mu}J_B^\mu \\
J_B^\mu \quad &= \quad g_1 \sum_\psi Y_\psi \bar{\psi}\gamma^\mu\psi
\end{aligned}
$$

This procedure results in the universal D6 basis:

$$
\begin{array}{lll}
\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D^\mu\Phi), & \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi), & \\
\mathcal{O}_{BB} = \Phi^\dagger\Phi B_{\mu\nu}B_{\mu\nu} & \mathcal{O}_{WW} = \Phi^\dagger\Phi W^a_{\mu\nu}W^a_{\mu\nu} & \mathcal{O}_{BW} = \Phi^\dagger\sigma^a\Phi B_{\mu\nu}W^a_{\mu\nu} \\
O_B = (D_\mu\Phi)^\dagger(D_\nu\Phi)B_{\mu\nu} & O_W = (D_\mu\Phi)^\dagger\sigma^a(D_\nu\Phi)W^a_{\mu\nu} & O_{WWW} = f^{abc}W^a_{\mu\nu}W^b_{\nu\rho}W^c_{\rho\mu} \\
O_{2JB} = J_B^\mu J_{B,\mu} & O_{2JW} = J_W^{a,\mu}J^a_{W,\mu} &
\end{array}
$$

+ others not relevant for the upcoming analysis

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\end{array}
$$

+ others not relevant for the upcoming analysis
Note: operator normalizations are neglected in the above (and from here on) for simplicity

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1. purely bosonic operators
2. for convenience, trade a few for SM-like fermionic currents (field redefinitions) e.g.:

The Universal SMEFT

simplifying assumption
→ explore the SMEFT to dimension-eight (bottom up)

This procedu

$$
\begin{array}{lll}
\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D^\mu\Phi), & \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi), & \\
\mathcal{O}_{BB} = \Phi^\dagger\Phi B_{\mu\nu}B_{\mu\nu} & \mathcal{O}_{WW} = \Phi^\dagger\Phi W^a_{\mu\nu}W^a_{\mu\nu} & \mathcal{O}_{BW} = \Phi^\dagger\sigma^a\Phi B_{\mu\nu}W^a_{\mu\nu} \\
O_B = (D_\mu\Phi)^\dagger(D_\nu\Phi)B_{\mu\nu} & O_W = (D_\mu\Phi)^\dagger\sigma^a(D_\nu\Phi)W^a_{\mu\nu} & O_{WWW} = f^{abc}W^a_{\mu\nu}W^b_{\nu\rho}W^c_{\rho\mu} \\
O_{2JB} = J^\mu_B J_{B,\mu} & O_{2JW} = J^{a,\mu}_W J^a_{W,\mu} &
\end{array}
$$

+ others not relevant for the upcoming analysis
Note: operator normalizations are neglected in the above (and from here on) for simplicity

Beyond D6

no known D8 universal basis
$\rightarrow$ consider known full D8 basis (C. Murphy arXiv:2005.00059)
$\rightarrow$ drop operators without SM-like currents
$\rightarrow$ drop operators which don't allow for resonant physics
We arrive at the dimension-eight "universal" basis:

$$\mathcal{O}^{(1)}_{D^2\Phi^6} = (\Phi^\dagger\Phi)^2(D_\mu\Phi)^\dagger(D^\mu\Phi) \qquad \mathcal{O}^{(2)}_{D^2\Phi^6} = (\Phi^\dagger\Phi)(\Phi^\dagger\sigma^I\Phi)(D_\mu\Phi)^\dagger\sigma^I(D^\mu\Phi)$$

$$\mathcal{O}^{(1)}_{W^3\Phi^2} = (\Phi^\dagger\Phi)f^{abc}W^a_{\mu\nu}W^b_{\nu\rho}W^c_{\rho\mu} \qquad \mathcal{O}_{W^2B\Phi^2} = \epsilon^{IJK}\Phi^\dagger\sigma^I\Phi B_{\mu\nu}W^J_{\nu\rho}W^K_{\rho\mu}$$

$$\mathcal{O}^{(1)}_{B\Phi^4D^2} = (\Phi^\dagger\Phi)(D_\mu\Phi)^\dagger(D_\nu\Phi)B_{\mu\nu} \qquad \mathcal{O}^{(1)}_{W\Phi^4D^2} = (\Phi^\dagger\Phi)(D_\mu\Phi)^\dagger\sigma^I(D_\nu\Phi)W^I_{\mu\nu}$$

$$\mathcal{O}^{(1)}_{W^2\Phi^4} = (\Phi^\dagger\Phi)^2W^a_{\mu\nu}W^a_{\mu\nu} \qquad \mathcal{O}_{B^2\Phi^4} = (\Phi^\dagger\Phi)^2B_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}^{(1)}_{BW\Phi^4} = (\Phi^\dagger\Phi)\Phi^\dagger\sigma^I\Phi B_{\mu\nu}W^I_{\mu\nu} \qquad \mathcal{O}_{W^2\Phi^4} = (\Phi^\dagger\sigma^I\Phi)(\Phi^\dagger\sigma^J\Phi)W^I_{\mu\nu}W^J_{\mu\nu}$$

+4 fermion

Beyond D6 – on the Z- and W-poles

The tree-level all orders in $1/\Lambda^2$ result for Z-pole physics can be found in,
TC, A. Helset, A. Martin, M. Trott, arXiv:2102.02819

In the universal theory we have a simpler result,
as the Peskin-Takeuchi parameters (STU) are consistently defined:

$$\begin{aligned}
\alpha S &= -e^2 v^2 \tilde{f}_{BW} = -e^2 v^2 \left(f_{BW} + \frac{v^2}{2} f^{(1)}_{BW\Phi^4} \right) \\
\alpha T &= -\frac{v^2}{2} \tilde{f}_{BW} = -\frac{v^2}{2} \left(f_{\phi,1} + v^2 f^{(2)}_{D^2\Phi^6} \right) \\
\alpha U &= e^2 v^4 f^{(3)}_{W^2\Phi^4} \\
\delta G_F &= G_F v^2 \left(\Delta_{4F} + v^2 \Delta^{(8)}_{4F} \right)
\end{aligned}$$

Plus m_W and Γ_W (expressions not pretty)

Beyond D6 – on the Z- and W-poles

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$$\delta G_F = G_F v^2 \left(\Delta_{4F} + v^2 \Delta^{(8)}_{4F} \right)$$

Plus m_W and Γ_W (expressions not pretty)

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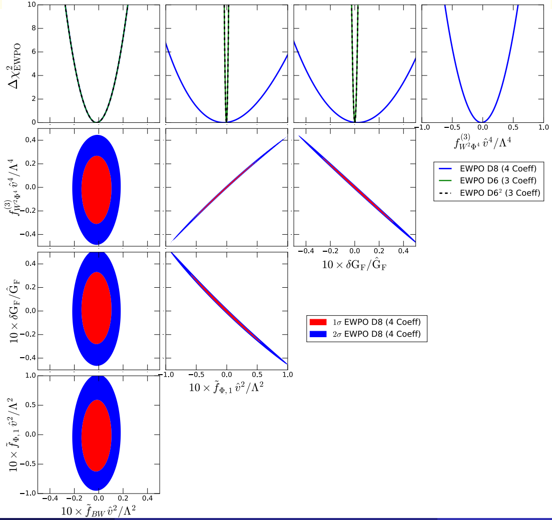
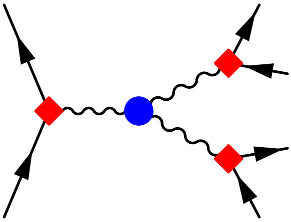


Beyond D6 – diboson production

	Channel (a)	Distribution	# bins	Data set	Int Lum
EWDB data	$WZ \to \ell^+\ell^-\ell'^{\pm}$	$M(WZ)$	7	CMS 13 TeV,	137.2 fb^{-1}
	$WW \to \ell^+\ell^{(\prime)-} + 0/1j$	$M(\ell^+\ell^{(\prime)-})$	11	CMS 13 TeV,	35.9 fb^{-1}
	$W\gamma \to \ell\nu\gamma$	$\frac{d^2\sigma}{dp_T d\phi}$	12	CMS 13 TeV,	137.1 fb^{-1}
	$WW \to e^{\pm}\mu^{\mp} + \not{E}_T$ $(0j)$	m_T	17 (15)	ATLAS 13 TeV,	36.1 fb^{-1}
	$WZ \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}	6	ATLAS 13 TeV,	36.1 fb^{-1}
	$Zjj \to \ell^+\ell^- jj$	$\frac{d\sigma}{d\phi}$	12	ATLAS 13 TeV,	139 fb^{-1}
	$WW \to \ell^+\ell^{(\prime)-} + \not{E}_T$ $(1j)$	$\frac{d\sigma}{dm_{\ell^+\ell^-}}$	10	ATLAS 13 TeV,	139 fb^{-1}

Feynrules→Madgraph→Pythia→Delphes (+fast jet)

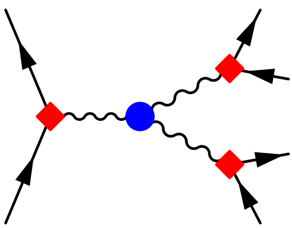
Beyond D6 – diboson production



EWPD constrains fermion couplings

$$\mathcal{L}_{WWV} = -ig_{WWV}\Big\{g_1^V\left(W^+_{\mu\nu}W^{-\,\mu}V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2}W^+_{\mu\nu}W^{-\,\nu\rho}V_\rho{}^\mu\Big\}$$

Beyond D6 – diboson production



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$$\Delta g_1^Z = \frac{e^2}{s^2c^2}\left[\frac{1}{8}v^2\left(f_W + \frac{v^2}{2}f^{(1)}_{W\Phi^4D^2}\right)\right]$$

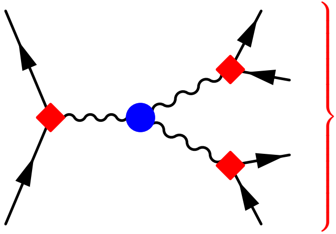
$$\Delta\kappa_\gamma = \frac{e^2}{s^2}\left[\frac{1}{8}\frac{v^2}{\Lambda^2}\left(f_W + \frac{v^2}{2}f^{(1)}_{W\Phi^4D^2} + f_B + \frac{v^2}{2}f^{(1)}_{B\Phi^4D^2}\right)\right]$$

$$\Delta\kappa_Z = \frac{e^2}{s^2}\left[\frac{1}{8}v^2\left(f_W + \frac{v^2}{2}f^{(1)}_{W\Phi^4D^2}\right) - \frac{s^2}{8c^2}v^2\left(f_B + \frac{v^2}{2}f^{(1)}_{B\Phi^4D^2}\right)\right]$$

$$\lambda_\gamma = \frac{3e^2}{2s^2}M_W^2\left[f_{WWW} + \frac{v^2}{2}f^{(1)}_{W^3\Phi^2}\right] - \frac{M_W^4}{2}f^{(1)}_{W^2B\Phi^2}$$

$$\lambda_Z = \frac{3e^2}{2s^2}M_W^2\left[f_{WWW} + \frac{v^2}{2}f^{(1)}_{W^3\Phi^2}\right] + \frac{M_W^4}{2}\frac{s^2}{c^2}f^{(1)}_{W^2B\Phi^2}$$

Beyond D6 – diboson production



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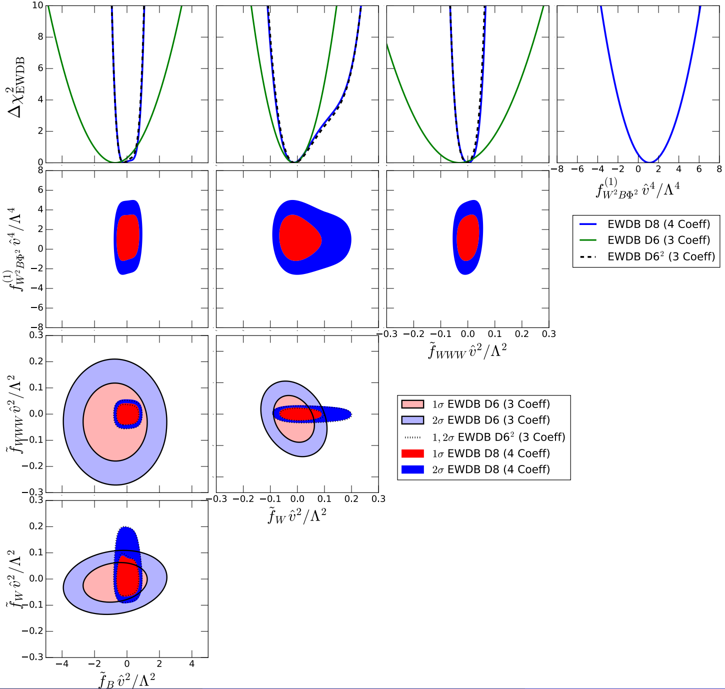
$$\begin{aligned}\Delta g_1^Z &= \frac{e^2}{s^2c^2}\left[\frac{1}{8}v^2\tilde f_W\right] \\ \Delta\kappa_\gamma &= \frac{e^2}{s^2}\left[\frac{1}{8}\frac{v^2}{\Lambda^2}\left(\tilde f_W + \tilde f_B\right)\right] \\ \Delta\kappa_Z &= \frac{e^2}{s^2}\left[\frac{1}{8}v^2\tilde f_W - \frac{s^2}{8c^2}\tilde f_B\right] \\ \lambda_\gamma &= \frac{3e^2}{2s^2}M_W^2\tilde f_{WWW} - \frac{M_W^4}{2}f^{(1)}_{W^2B\Phi^2} \\ \lambda_Z &= \frac{3e^2}{2s^2}M_W^2\tilde f_{WWW} + \frac{M_W^4}{2}\frac{s^2}{c^2}f^{(1)}_{W^2B\Phi^2}\end{aligned}$$



$\Delta\chi^2_{\rm EWDB}$
$f^{(1)}_{W^2B\Phi^2}\,\hat{v}^4/\Lambda^4$
$\tilde{f}_{WWW}\,\hat{v}^2/\Lambda^2$
$\tilde{f}_W\,\hat{v}^2/\Lambda^2$
$\tilde{f}_B\,\hat{v}^2/\Lambda^2$
EWDB D8 (4 Coeff)
EWDB D6 (3 Coeff)
EWDB D6^2 (3 Coeff)
1σ EWDB D6 (3 Coeff)
2σ EWDB D6 (3 Coeff)
$1,2\sigma$ EWDB D6^2 (3 Coeff)
1σ EWDB D8 (4 Coeff)
2σ EWDB D8 (4 Coeff)

On truncation...

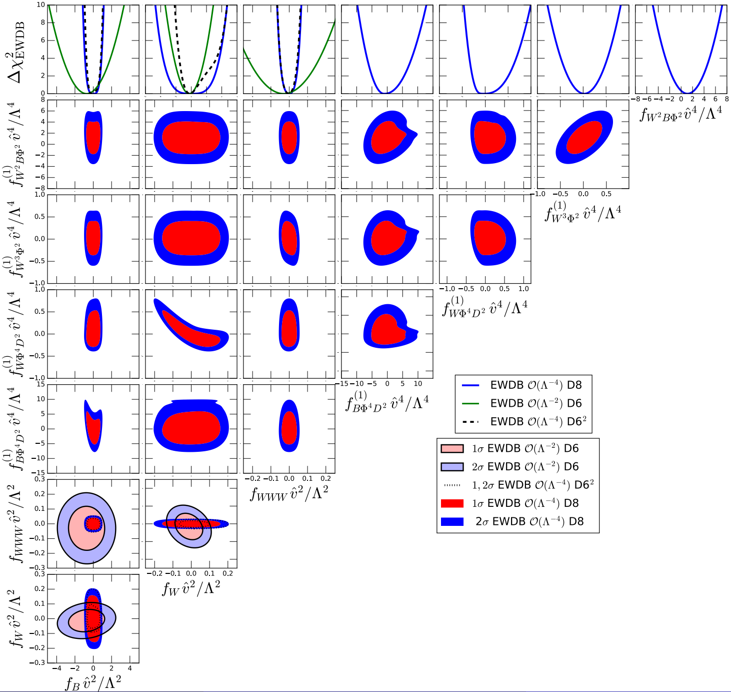
In the SMEFT the amplitudes for a given process may violate perturbative unitarity:

$$i\mathcal{M}\left(d_-\bar{d}_+ \to W_0^+ W_0^-\right) = \frac{e^2}{24 s^2 c^2}\hat{S}\sin\theta\left[3c^2\, f_W - s^2\, f_B + \frac{v^2}{2}\left(3c^2\, f^{(1)}_{W\Phi^4 D^2} - s^2\, f^{(1)}_{B\Phi^4 D^2}\right)\right]$$

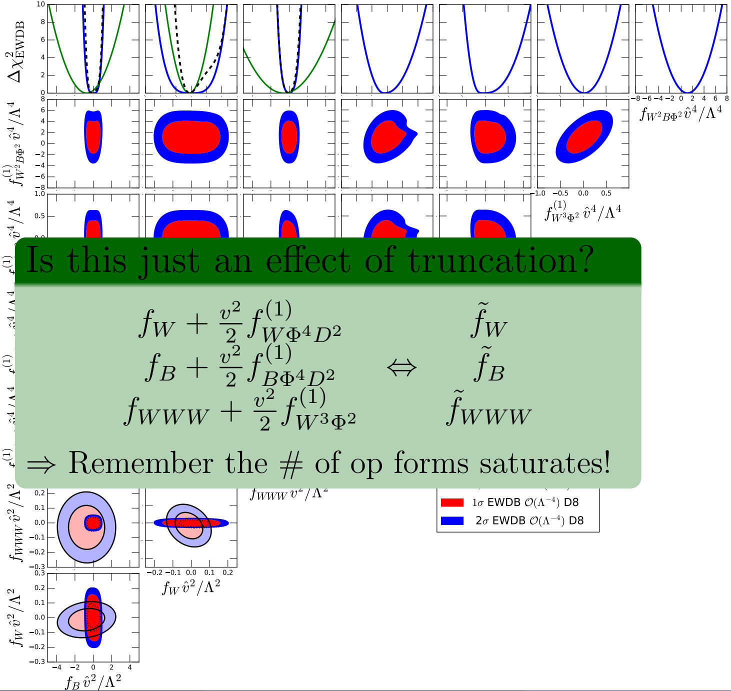
The combination of growth with COME, $\hat{S}$, and truncation at order $1/\Lambda^4$ gives:

$$|\mathcal{M}|^2 \sim |\mathrm{SM}|^2 + 2\mathrm{Re}\left[(\mathrm{D6})^*(\mathrm{SM})\right]\frac{\hat{S}}{\Lambda^2} + |\mathrm{D6}|^2\frac{\hat{S}^2}{\Lambda^4} + 2\mathrm{Re}\left[(\mathrm{D8})^*(\mathrm{SM})\right]\frac{\hat{S}}{\Lambda^4}$$

Using distributions for diboson data ⇒ separately constrain D6 and D8 operator coefficients



$\Delta\chi^2_{\mathrm{EWDB}}$
$f^{(1)}_{W^2B\Phi^2}\,\hat{v}^4/\Lambda^4$
$f^{(1)}_{W^3\Phi^2}\,\hat{v}^4/\Lambda^4$
$f^{(1)}_{W\Phi^4D^2}\,\hat{v}^4/\Lambda^4$
$f^{(1)}_{B\Phi^4D^2}\,\hat{v}^4/\Lambda^4$
$f_{WWW}\,\hat{v}^2/\Lambda^2$
$f_W\,\hat{v}^2/\Lambda^2$
$f_B\,\hat{v}^2/\Lambda^2$
$f_{W^2B\Phi^2}\,\hat{v}^4/\Lambda^4$
EWDB $\mathcal{O}(\Lambda^{-4})$ D8
EWDB $\mathcal{O}(\Lambda^{-2})$ D6
EWDB $\mathcal{O}(\Lambda^{-4})$ D6^2
1σ EWDB $\mathcal{O}(\Lambda^{-2})$ D6
2σ EWDB $\mathcal{O}(\Lambda^{-2})$ D6
$1,2\sigma$ EWDB $\mathcal{O}(\Lambda^{-4})$ D6^2
1σ EWDB $\mathcal{O}(\Lambda^{-4})$ D8
2σ EWDB $\mathcal{O}(\Lambda^{-4})$ D8



Is this just an effect of truncation?

$$
\begin{matrix}
f_W + \frac{v^2}{2} f^{(1)}_{W\Phi^4D^2} & & \tilde{f}_W \\
f_B + \frac{v^2}{2} f^{(1)}_{B\Phi^4D^2} & \Leftrightarrow & \tilde{f}_B \\
f_{WWW} + \frac{v^2}{2} f^{(1)}_{W^3\Phi^2} & & \tilde{f}_{WWW}
\end{matrix}
$$

$\Rightarrow$ Remember the # of op forms saturates!

On truncation...

So...

1. do we include $(D6)^2$? (or squares of whatever order we expand to?)
2. do we use something like geoSMEFT to sum all orders?
3. truncate and deal with the fact truncation effects are clearly there?

Interim conclusions – fitting D8

1. SMEFT folks are great at simplifying assumptions $\rightarrow$ possible to do prelim fits to D8 (and flavor universal isn't the worst assumption ever made)
2. Nature doesn't truncate, clear effects of truncation in our fits $\rightarrow$ a mistake? (seems we're safe, in the example above we have conservative constraints)
3. The geoSMEFT allows us to classify all orders vertices, and avoid this inconsistency (but only in some limited cases, ?for now?)

Conclusions

1. EFTs allow us to study the low energy impact of heavy decoupled new physics
2. The SMEFT is an excellent tool for precision BSM physics @ the LHC, HL-LHC, ++
3. The SMEFT expansion converges fairly well, even for low mass $M \sim 3$ TeV
   → We could measure a D6 WC off by more than 1σ (Strong int and/or low M)
   → $(D6)^2$ sometimes helps, sometimes hurts, not always obvious
   → Measure a D6 deviation → should see how it is affected by the inclusion of D8!
   REALLY! We could:
   - misinterpret the scale of NP! (next gen collider could miss its mark!)
   - miss a UV symmetry that's embedded in the IR!
4. D8 fits aren't impossible
   → Assumptions about the UV bring this into the realm of possibility
   → $(D6)^2$ is confusing, "apparent" better convergence, possibly skewing to bad results
5. Ways of summing higher order may help (geoSMEFT)
6. The clearest route is clarity in procedure
   → parallel work on D6, $(D6)^2$, poss. D8
   → results truncated at benchmark E scales (easier at HL-LHC)
   → (naive opinion) Theory should drive how to formulate analyses,
   Experiment could produce them by channel
   Constraints on combinations of parameters, can naively combine after