Dimension-eight Operator Basis for Universal Standard Model Effective Field Theory

Jay Desai

*T. Corbett, **J. Desai**, O. J. P. Éboli, M. C. Gonzalez-Garcia, M. Martines, and P. Reimitz*

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*T. Corbett, **J. Desai**, O. J. P. Éboli, M. C. Gonzalez-Garcia*

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Stony Brook University

C.N. YANG INSTITUTE for Theoretical Physics

Standard Model Effective field theory

- The Standard Model (SM) based on the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetry has been extensively tested at the LHC.
- Precision measurements of SM processes are an important tool to probe BSM physics and Effective Field Theory has become a standard tool employed.
- Assuming that the scalar particle detected in 2012 belongs to an electroweak doublet, the symmetry $SU(2)_L \otimes U(1)_Y$ can be realized linearly at low energies

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{f_i^{(d)}}{\Lambda^{d-4}} \left\{ O_i^{(d)} \right\}$$

Universal theories

- The advantage of the model-independent approach becomes a limitation as the number of Wilson coefficients becomes too large to handle.
- Identifying physically motivated hypotheses which reduce the EFT parameter space while still capturing a large class of BSM theories presents a motivated route to predictability.
- Universality, the assumption that NP mainly couples to SM bosons, is one such hypothesis. The low-energy effective operators can be chosen to involve exclusively SM bosons.

EWPO and TGC analysis

- We study the impact of Universal dimension eight operators on Electroweak Precision Observables and Triple Gauge Couplings[1].
- For dimension eight, the basis of operators for general SMEFT was constructed in [2]. In Universal theories only a subset of the fermionic operators from the general basis are generated.

Dimension 6

- $O_{WW} = \Phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi$
- $O_{BB} = \Phi^\dagger \widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi$
- $O_{BW} = \Phi^\dagger \widehat{W}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi$
- $O^{(1)}_{D^2\Phi^6} = (D_\mu \Phi)^\dagger \Phi \, \Phi^\dagger (D_\mu \Phi)$

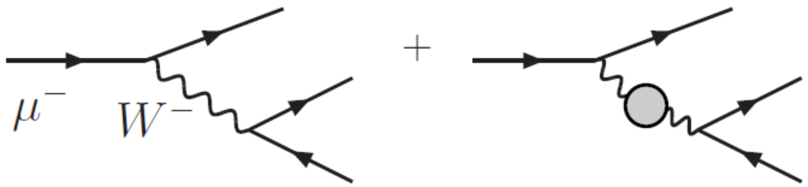
Dimension 8

- $O^{(1)}_{W^2\phi^4} = (\Phi^\dagger \Phi) \Phi^\dagger \widehat{W}_{\mu\nu} \widehat{W}^{\mu\nu} \Phi$
- $O^{(1)}_{B^2\phi^4} = (\Phi^\dagger \Phi) \Phi^\dagger \widehat{B}_{\mu\nu} \widehat{B}^{\mu\nu} \Phi$
- $O^{(1)}_{BW\phi^4} = (\Phi^\dagger \Phi) \Phi^\dagger \widehat{W}_{\mu\nu} \Phi \widehat{B}^{\mu\nu}$
- $O^{(3)}_{W^2\phi^4} = (\Phi^\dagger \widehat{W}_{\mu\nu} \Phi)(\Phi^\dagger \widehat{W}^{\mu\nu} \Phi)$
- $O^{(1)}_{D^2\Phi^6} = (\Phi^\dagger \Phi)^2 (D_\mu \Phi)^\dagger (D^\mu \Phi)$
- $O^{(2)}_{D^2\Phi^6} = (\Phi^\dagger \Phi)(\Phi^\dagger \tau^I \Phi)(D_\mu \Phi)^\dagger \tau^I (D^\mu \Phi)$

[1] arXiv:2304.03305 [2] Murphy, arXiv:2005.00059 [3] Wells, J.D., Zhang, Z. arXiv:1510.08462

Fermionic Operators: Finite Renormalization of G_F

- The muon decay observable $\hat{G}_F$ is computed from the lifetime of the muon,



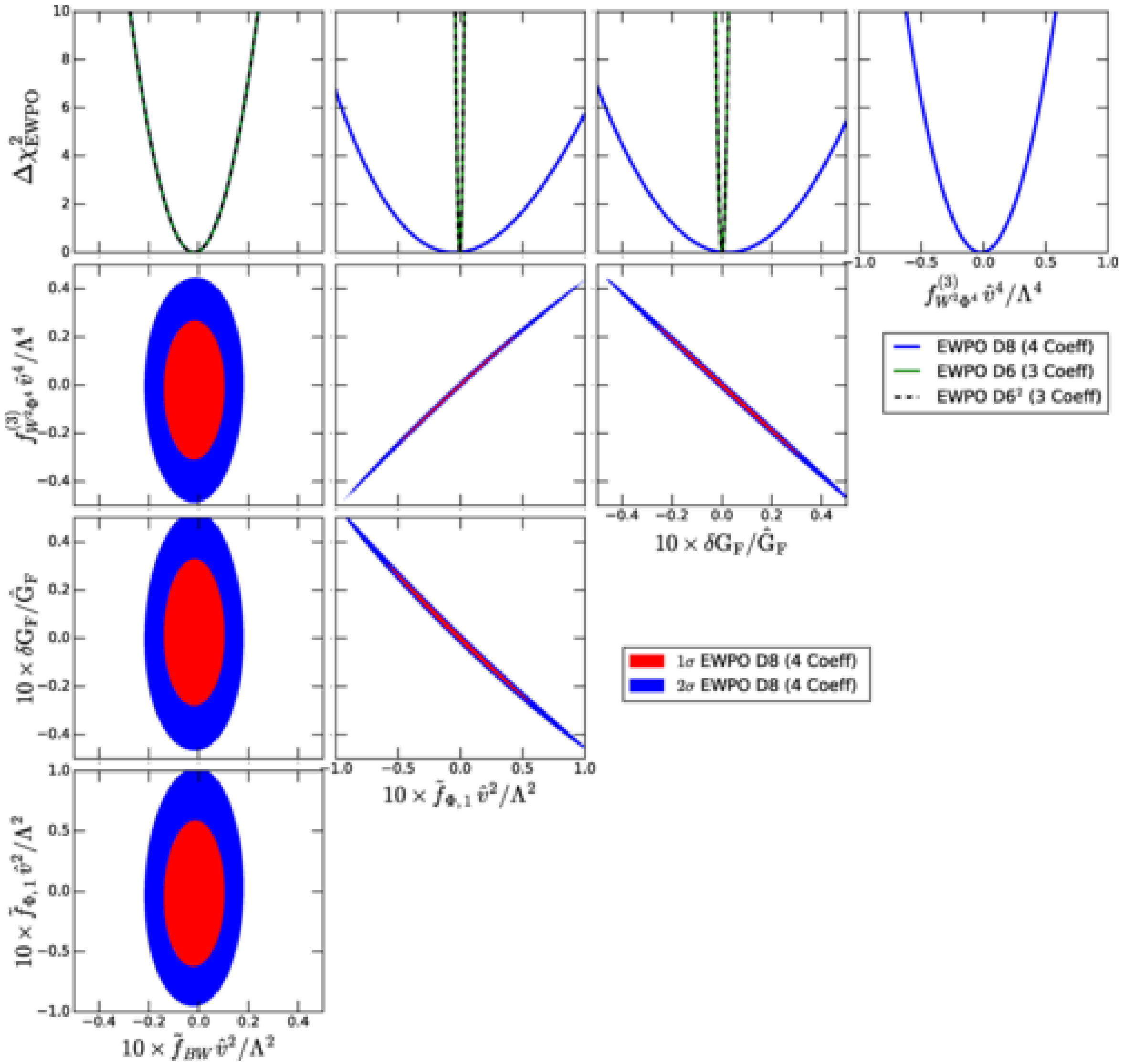
$$\left[2\langle\Phi^\dagger\Phi\rangle - \frac{1}{\sqrt{2}\hat{G}_F}\right]_{fermionic} \equiv \frac{\hat{v}^4}{\Lambda^2}\Delta_{4F} + \frac{\hat{v}^6}{\Lambda^4}\Delta_{4F}^{(8)}$$

$$\Delta_{4F} \sim O_{2JW} = \sum_{f,f' \epsilon \{Q,L\}} \left(\bar{f}\gamma_\mu \frac{\tau^I}{2} f\right)\left(\bar{f}'\gamma^\mu \frac{\tau^I}{2} f'\right)$$

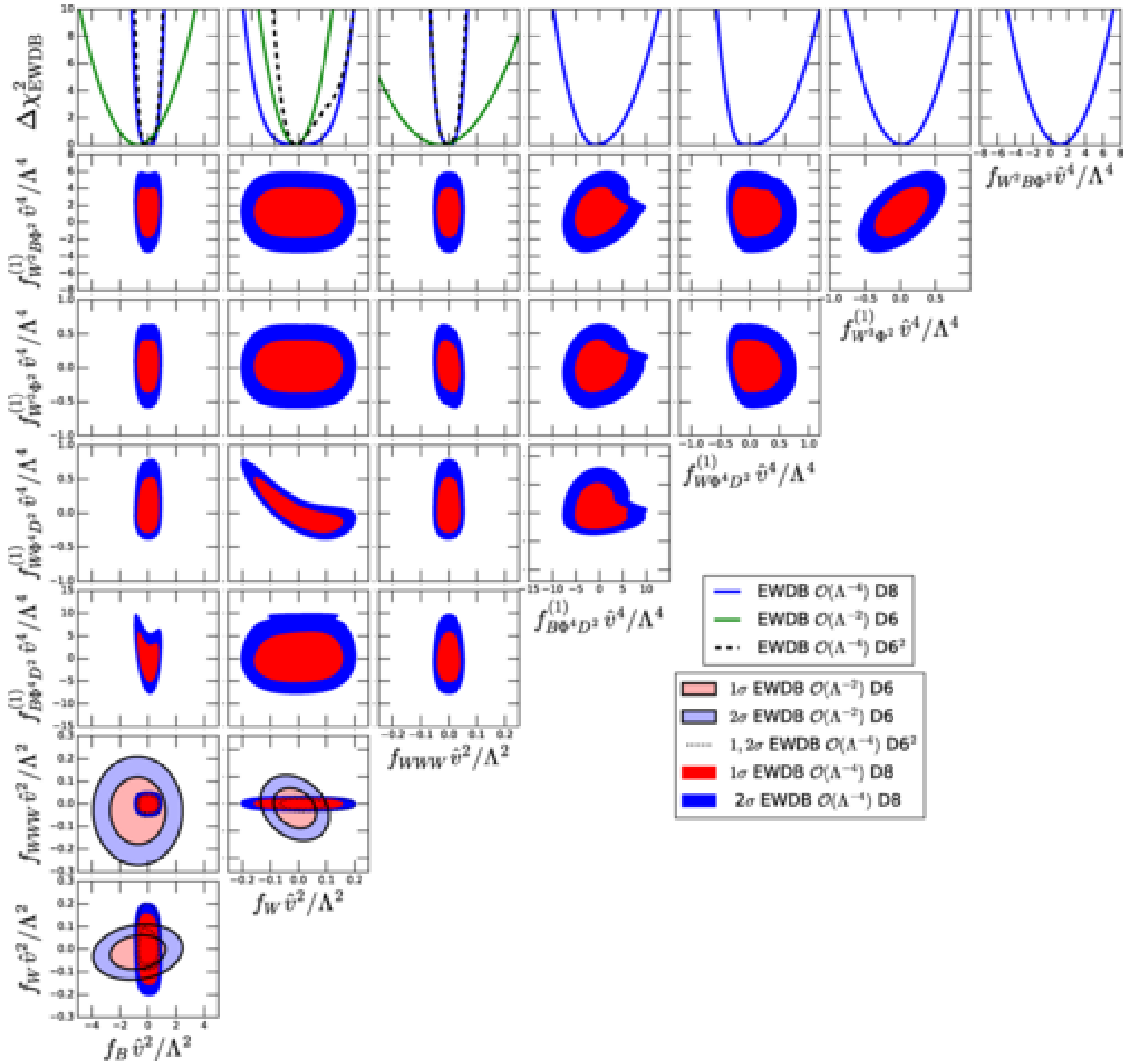
- We encapsulate all the relevant Universal four-fermionic operators at dimension 8 into a new Wilson coefficient $\Delta_{4F}^{(8)}$.

ref: *Wells, J.D., Zhang, Z.* [*arXiv:1510.08462*]

EWPO RESULTS

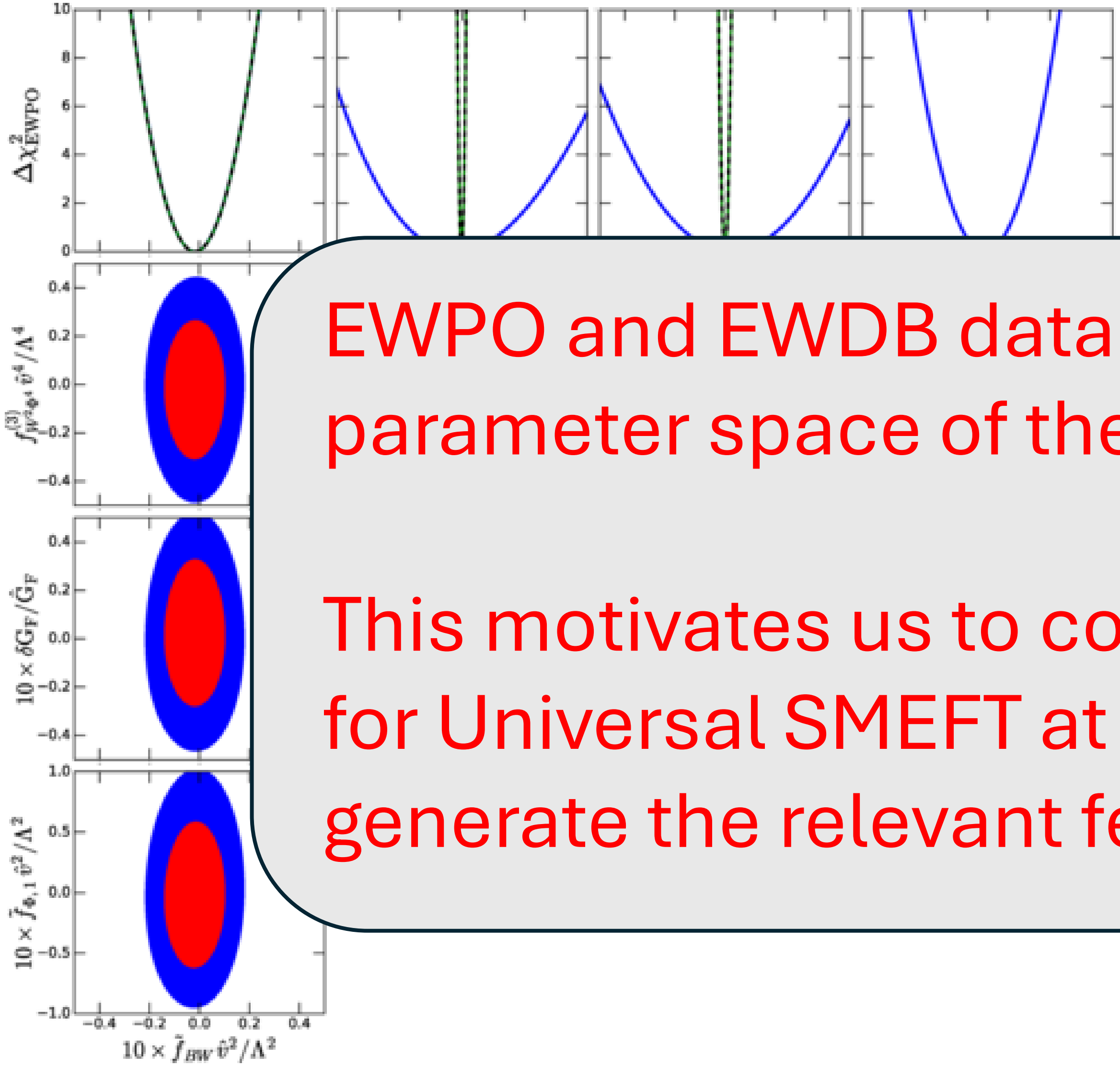


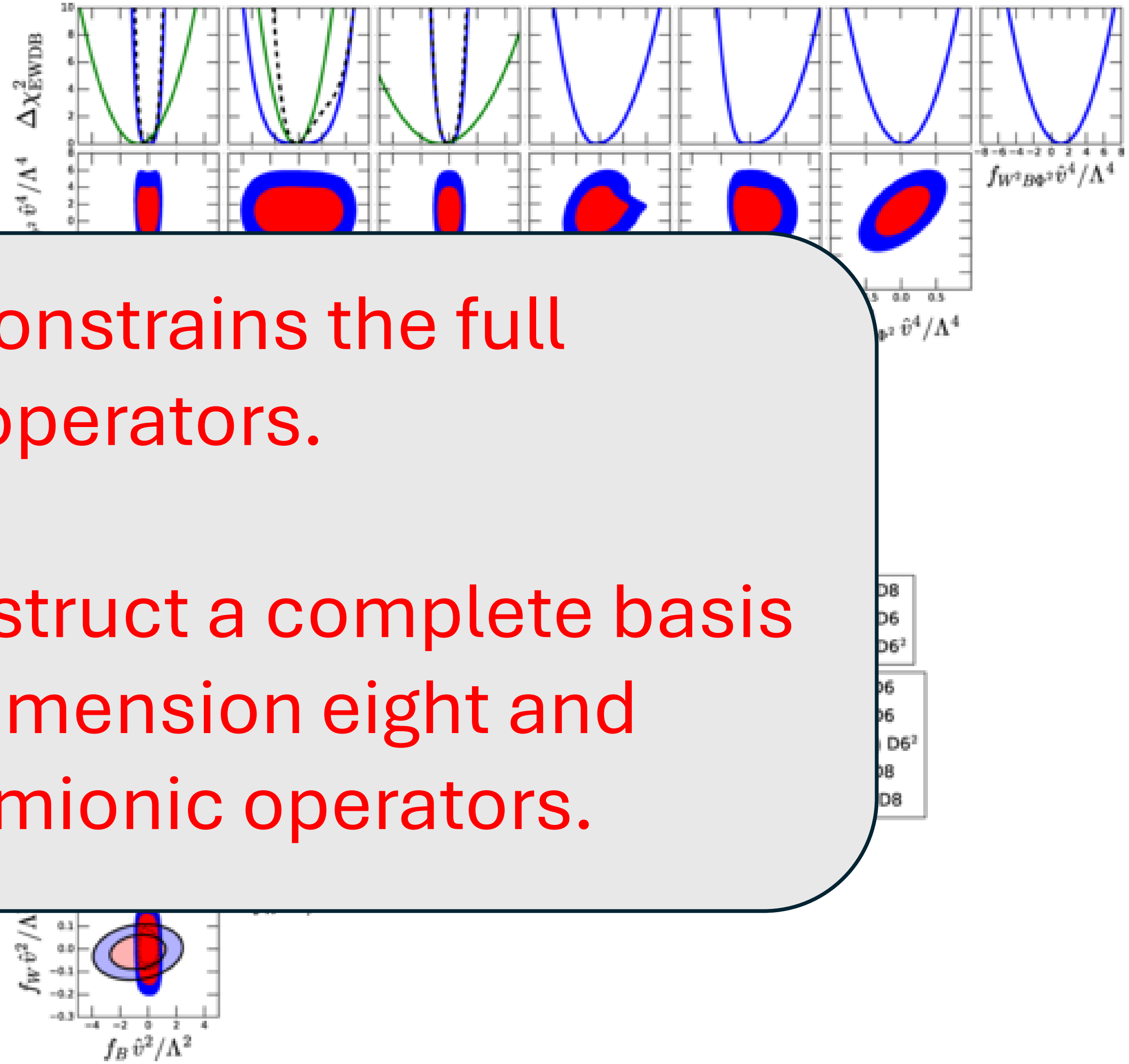
EWDB RESULTS



EWPO RESULTS

EWDB RESULTS





EWPO and EWDB data constrains the full parameter space of the operators.

This motivates us to construct a complete basis for Universal SMEFT at dimension eight and generate the relevant fermionic operators.

Construction of Universal basis at dim-8

- We create the complete SMEFT operator basis for Universal theories at dimension eight, and the relations implied among the Wilson coefficients of the general dimension eight basis*.

- Obtain the number of independent bosonic operators before applying EOM using packages BASISGEN and a modified version of ECO.

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- Use Fierz relations and IBP relations to construct independent dimension-eight operators involving only SM bosons.

*ref: Murphy, arXiv:2005.00059

Construction of Universal basis at dim-8

- We create the complete SMEFT operator basis for Universal theories, and the relations implied among the Wilson coefficients of the general dimension eight basis*.

- The building blocks of the operator basis for Universal theories are the Higgs field H, the SM field strengths ($X_{L,R}^{\mu\nu} \sim B_{L,R}^{\mu\nu}, W_{L,R}^{I,\mu\nu}, G_{L,R}^{A,\mu\nu}$) and covariant derivative D.

*ref: Murphy, arXiv:2005.00059

Consider class of operators of $D^2 B_L H^2$

$$x_1 = B_L^{\mu\nu}\left(D_\mu H^\dagger D_\nu H\right)\left(H^\dagger H\right)$$
$$x_2 = B_L^{\mu\nu}(D_\mu H^\dagger H)(H^\dagger D_\nu H)$$
$$x_3 = (D_\mu B_L^{\mu\nu})(D_\nu H^\dagger H)(H^\dagger H)$$
$$x_4 = (D_\mu B_L^{\mu\nu})(H^\dagger D_\nu H)(H^\dagger H)$$
$$x_5 = B_L^{\mu\nu}\left(D_\mu H^\dagger \tau^I D_\nu H\right)\left(H^\dagger \tau^I H\right)$$
$$x_6 = B_L^{\mu\nu}\left(D_\mu H^\dagger \tau^I H\right)\left(H^\dagger \tau^I D_\nu H\right)$$
$$x_7 = \left(D_\mu B_L^{\mu\nu}\right)\left(D_\nu H^\dagger \tau^I H\right)\left(H^\dagger \tau^I H\right)$$
$$x_8 = \left(D_\mu B_L^{\mu\nu}\right)\left(H^\dagger \tau^I D_\nu H\right)\left(H^\dagger \tau^I H\right)$$

Linear SU(2) Fierz relations

$$x_5 = 2x_2 - x_1$$
$$x_6 = 2x_1 - x_2$$
$$x_7 = x_3$$
$$x_8 = x_4$$

Consider class of operators of $D^2 B_L H^2$

$$x_1 = B_L^{\mu\nu}\left(D_\mu H^\dagger D_\nu H\right)\left(H^\dagger H\right)$$
$$x_2 = B_L^{\mu\nu}(D_\mu H^\dagger H)(H^\dagger D_\nu H)$$
$$x_3 = (D_\mu B_L^{\mu\nu})(D_\nu H^\dagger H)(H^\dagger H)$$
$$x_4 = (D_\mu B_L^{\mu\nu})(H^\dagger D_\nu H)(H^\dagger H)$$
$$x_5 = B_L^{\mu\nu}\left(D_\mu H^\dagger \tau^I D_\nu H\right)\left(H^\dagger \tau^I H\right)$$
$$x_6 = B_L^{\mu\nu}\left(D_\mu H^\dagger \tau^I H\right)\left(H^\dagger \tau^I D_\nu H\right)$$
$$x_7 = \left(D_\mu B_L^{\mu\nu}\right)\left(D_\nu H^\dagger \tau^I H\right)\left(H^\dagger \tau^I H\right)$$
$$x_8 = \left(D_\mu B_L^{\mu\nu}\right)\left(H^\dagger \tau^I D_\nu H\right)\left(H^\dagger \tau^I H\right)$$

$$y_1^\nu = B_L^{\mu\nu}\left(D_\mu H^\dagger H\right)\left(H^\dagger H\right)$$
$$y_2^\nu = B_L^{\mu\nu}\left(H^\dagger D_\mu H\right)\left(H^\dagger H\right)$$
$$y_3^\nu = \left(D_\mu B_L^{\mu\nu}\right)\left(H^\dagger H\right)^2$$

$$x_1 + x_2 + x_3 = 0$$
$$x_1 + x_2 + x_4 = 0$$
$$x_3 + x_4 = 0$$

Consider class of operators of $D^2 B_L H^2$

$$x_1 = B_L^{\mu\nu}(D_\mu H^\dagger D_\nu H)(H^\dagger H)$$
$$x_2 = B_L^{\mu\nu}(D_\mu H^\dagger H)(H^\dagger D_\nu H)$$
$$x_3 = (D_\mu B_L^{\mu\nu})(D_\nu H^\dagger H)(H^\dagger H)$$
$$x_4 = (D_\mu B_L^{\mu\nu})(H^\dagger D_\nu H)(H^\dagger H)$$
$$x_5 = B_L^{\mu\nu}(D_\mu H^\dagger \tau^I D_\nu H)(H^\dagger \tau^I H)$$
$$x_6 = B_L^{\mu\nu}(D_\mu H^\dagger \tau^I H)(H^\dagger \tau^I D_\nu H)$$
$$x_7 = (D_\mu B_L^{\mu\nu})(D_\nu H^\dagger \tau^I H)(H^\dagger \tau^I H)$$
$$x_8 = (D_\mu B_L^{\mu\nu})(H^\dagger \tau^I D_\nu H)(H^\dagger \tau^I H)$$

$\Longrightarrow$

- Already in the general SMEFT basis.

Consider class of operators of $D^2 B_L H^2$

$$x_1 = B_L^{\mu\nu}\left(D_\mu H^\dagger D_\nu H\right)\left(H^\dagger H\right)$$

$$x_2 = B_L^{\mu\nu}(D_\mu H^\dagger H)(H^\dagger D_\nu H)$$

$$x_3 = (D_\mu B_L^{\mu\nu})(D_\nu H^\dagger H)(H^\dagger H)$$

$$x_4 = (D_\mu B_L^{\mu\nu})(H^\dagger D_\nu H)(H^\dagger H)$$

$$x_5 = B_L^{\mu\nu}\left(D_\mu H^\dagger \tau^I D_\nu H\right)\left(H^\dagger \tau^I H\right)$$

$$x_6 = B_L^{\mu\nu}\left(D_\mu H^\dagger \tau^I H\right)\left(H^\dagger \tau^I D_\nu H\right)$$

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$$x_8 = \left(D_\mu B_L^{\mu\nu}\right)\left(H^\dagger \tau^I D_\nu H\right)\left(H^\dagger \tau^I H\right)$$

$\Longrightarrow$

- Already in the general SMEFT basis.

- Use EOM

$$D_\mu B^{\mu\nu} = -\frac{ig'}{2} H^\dagger \overleftrightarrow{D}_\nu H - J_B^\nu$$

where, $J_B^\nu = g' \sum_f Y_f \bar{f} \gamma^\nu f$

Consider class of operators of $D^2 B_L H^2$

$x_1 = B_L^{\mu\nu}(D_\mu H^\dagger D_\nu H)(H^\dagger H)$ $\Longrightarrow$ • Already in the general SMEFT basis.

$x_2 = B_L^{\mu\nu}(D_\mu H^\dagger H)(H^\dagger D_\nu H)$

$x_3 = (D_\mu B_L^{\mu\nu})(D_\nu H^\dagger H)(H^\dagger H)$ $\Longrightarrow$

$$\Delta - i\frac{1}{2} Q^{(1)}_{\psi^2 H^4 D} + i\frac{g'}{8}\left(Q^{(1)}_{\psi^2 H^5} + Q^{\dagger(1)}_{\psi^2 H^5}\right)$$

$$Q^{(1)}_{\psi^2 H^4 D} \equiv i\, J_B^\mu (H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$$

$$Q^{(1)}_{\psi^2 H^5} \equiv (H^\dagger H)^2 (J_H H)$$

$x_4 = (D_\mu B_L^{\mu\nu})(H^\dagger D_\nu H)(H^\dagger H)$

$x_5 = B_L^{\mu\nu}(D_\mu H^\dagger \tau^I D_\nu H)(H^\dagger \tau^I H)$

$x_6 = B_L^{\mu\nu}(D_\mu H^\dagger \tau^I H)(H^\dagger \tau^I D_\nu H)$

$x_7 = (D_\mu B_L^{\mu\nu})(D_\nu H^\dagger \tau^I H)(H^\dagger \tau^I H)$

$x_8 = (D_\mu B_L^{\mu\nu})(H^\dagger \tau^I D_\nu H)(H^\dagger \tau^I H)$

- Use EOM

$$D_\mu B^{\mu\nu} = -\frac{ig'}{2} H^\dagger \overleftrightarrow{D}_\nu H - J_B^\nu$$

where, $J_B^\nu = g' \sum_f Y_f \bar{f}\gamma^\nu f$

- Obtain the number of independent bosonic operators before applying EOM using packages BASISGEN and a modified version of ECO.

- Use Fierz relations and IBP relations to construct independent dimension-eight operators involving only SM bosons.

- We find 175 independent operators at dim8.
- 89 bosonic operators already in general SMEFT-8 basis.
- 86 operators rotated to fermionic ops using EOM.

- 86 bosonic operators → fermionic operators in general SMEFT-8 basis. → 86 independent combinations in Universal SMEFT-8 basis

Conclusions and Outlook

- Universal Effective field theories, present a physically motivated hypothesis which reduces the EFT parameter space while still capturing a large class of BSM theories.
- We studied the impact of Universal dimension-eight operators on Electroweak Precision Observables and Triple Gauge Couplings.
- In the following work, we constructed the dimension-eight Universal SMEFT operator basis which encodes the low-energy effects of Universal extensions of SM.
- Wish to study the impact of Universal dimension eight operators on Drell-Yan.

THANK YOU.

QUESTIONS?

BACKUP SLIDES

Universal Fermionic Operators

- Once, we apply the EOM, we identify 86 independent fermionic operators thereby completing our Universal "fermionic" basis.
- We derive relations between the 86 independent couplings of the Universal fermionic operators and the Wilson coefficients of the fermionic operators of the general SMEFT basis*.

$$\left(D_\mu B^{\mu\nu}\right)\left(D_\nu H^\dagger H\right)\left(H^\dagger H\right) \longrightarrow \Delta - i\,\frac{1}{2}\,Q^{(1)}_{\psi^2 H^4 D} + i\,\frac{g'}{8}\left(Q^{(1)}_{\psi^2 H^5} + Q^{\dagger(1)}_{\psi^2 H^5}\right)$$

$$Q^{(1)}_{\psi^2 H^4 D} \equiv i\, J_B^\mu \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(H^\dagger H\right)$$

$$Q^{(1)}_{\psi^2 H^5} \equiv \left(H^\dagger H\right)^2 \left(J_H H\right)$$

*ref: Murphy, arXiv:2005.00059

Future Phenomenology

- In our previous work*, we studied the impact of Universal dimension-eight operators on Electroweak Precision Observables and Triple Gauge Couplings.
- We assumed that only Four-fermion Universal operators contributed to muon decay, and thus modifying the Higgs field v.e.v.
- For future work, we wish to study the impact of the dimension eight Universal Operators on Drell-Yan.

*ref: arXiv:2304.03305

$$
\begin{aligned}
J_G^{A\mu} &= g_s \sum_{f\in\{q,u,d\}} \sum_a \overline{f}_a \gamma^\mu T^A f_a \ , \\
J_W^{I\mu} &= \frac{g}{2} \sum_{f\in\{q,l\}} \sum_a \overline{f}_a \gamma^\mu \tau^I f_a \ , \\
J_B^{\mu} &= g' \sum_{f\in\{q,l,u,d,e\}} \sum_a Y_f \overline{f}_a \gamma^\mu f_a \ , \\
J_H^{j} &= \sum_{ab} \left\{ y_{ab}^{u\dagger} \left(\overline{u}_a \, q_{bk}\right) \epsilon^{jk} \, + \, y_{ab}^{d}, \left(\overline{q}_a^j \, d_b\right) \, + \, y_{ab}^{e} \left(\overline{l}_a^j \, e_b\right) \right\} \ , \\
J_{H\,j}^{\dagger} &= \sum_{ab} \left\{ y_{ab}^{u} \left(\overline{q}_a^k \, u_b\right) \epsilon_{kj} \, + \, y_{ab}^{d\dagger}, \left(\overline{d}_a \, q_{bj}\right) \, + \, y_{ab}^{e\dagger} \left(\overline{e}_a \, l_{bj}\right) \right\} .
\end{aligned}
$$

$$x_3 = \left(D_\mu B^{\mu\nu}\right)\left(D_\nu H^\dagger H\right)\left(H^\dagger H\right)(\quad)$$

$$x_3 = \left(-\frac{ig'}{2} H^\dagger \overleftrightarrow{D_\nu} H - J_B^\nu\right)\left(D_\nu H^\dagger H\right)\left(H^\dagger H\right)$$

$$x_3 = \Delta - i\frac{1}{2} Q^{(1)}_{\psi^2 H^4 D} + i\frac{g'}{8}\left(Q^{(1)}_{\psi^2 H^5} + Q^{\dagger(1)}_{\psi^2 H^5}\right)$$