Bridging Flavor Physics and Effective Field Theories

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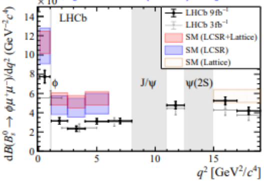
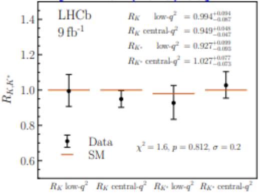
Research Directions in the Flavor Sector

1. $b \to sll$

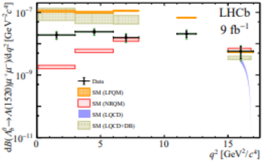
[PRL 127 (2021) 15]



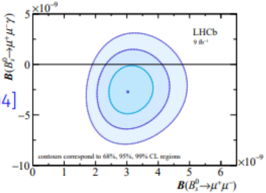
[PRL 131 (2023) 05]

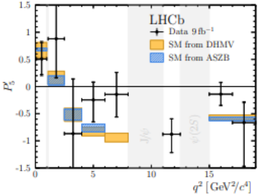


[PRL 131 (2023) 15]



[PRL 128 (2022) 04]

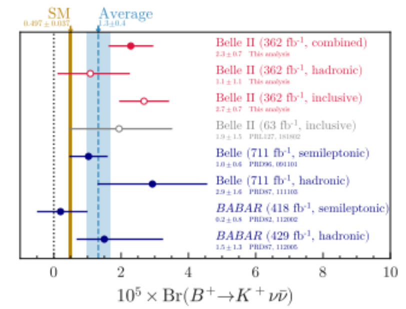




[PRL 126 (2021) 16]

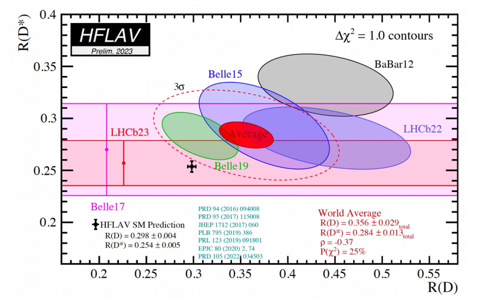
$B^+ \to K^{*+}\mu^+\mu^-$

2. $b \to s\nu_l\bar{\nu}_l$



Evidence@3.5σ & Deviation@2.7σ

3. $b \to c\tau\bar{\nu}_\tau$



Observables	Experimental values	SM Predictions
R_D	0.342 ± 0.026	0.298 ± 0.004
R_{D*}	0.287 ± 0.012	0.254 ± 0.005
$R_{J/\psi}$	$0.71 \pm 0.17 \pm 0.18$	0.289 ± 0.01
R_{Λ_c}	0.285 ± 0.073	0.324 ± 0.004
P_τ^D	NA	0.331 ± 0.004
$P_\tau^{D^*}$	$-0.38^{+0.53}_{-0.55}$	-0.497 ± 0.007
$F_L^{D^*}$	0.60 ± 0.09	0.464 ± 0.003
$\mathrm{Br}(B_c \to \tau\nu)$	$< 30\%$ (B_c lifetime) or $< 10\%$ (LEP)	$(3.6 \pm 0.14) \times 10^{-2}$

4. $b \to u\tau\bar{\nu}_\tau$

Observables	Experimental values	SM Predictions
R_π^l	0.699 ± 0.156	0.583 ± 0.055
$\mathrm{Br}(B_u \to \tau\nu)$	$(1.09 \pm 0.24) \times 10^{-4}$	$(8.48 \pm 0.5) \times 10^{-5}$
$\mathrm{Br}(B^0 \to \pi^+\tau\nu)$	$< 2.5 \times 10^{-4}$	$(9.40 \pm 0.75) \times 10^{-5}$

5. Others

- $b \to dl^+l^-$ decay modes
- Baryonic decay modes
- Rare decay modes of K meson
- Rare decay modes of D meson
- Lepton flavor violating decay modes
- Lepton number violating decay modes
- New physics in electron
- τ decay processes
- Muon anomalous magnetic moment
- Electron dipole moment
- Nonleptonic channels

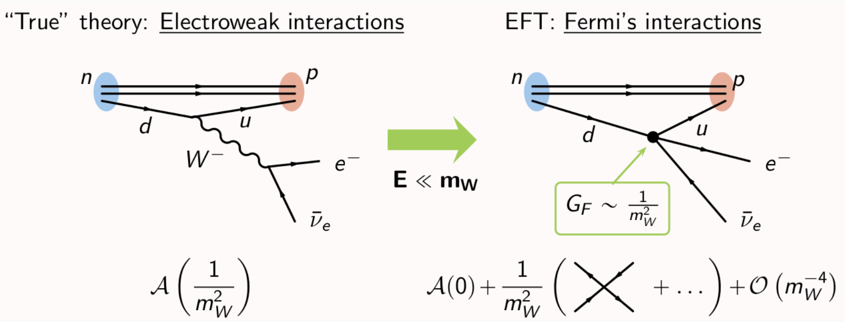
What can this new physics be?

Ways to Address

- A model-independent effective-field-theory (EFT) approach
- Construct models of NP that reproduce the data.

Tell me the story of your favourite movie

Weak Effective Theory



- Effective Hamiltonian:

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_i V^i_{\mathrm{CKM}} C_i(\mu) Q_i \,.$$

Dimension-6 operators

Current-Current:

$$Q_1 = (\bar{c}_\alpha b_\beta)_{V-A} \, (\bar{s}_\beta c_\alpha)_{V-A} \qquad Q_2 = (\bar{c}b)_{V-A} \, (\bar{s}c)_{V-A}$$

QCD Penguins:

$$Q_3 = (\bar{s}b)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}q)_{V-A} \qquad Q_4 = (\bar{s}_\alpha b_\beta)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_\beta q_\alpha)_{V-A}$$

$$Q_5 = (\bar{s}b)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}q)_{V+A} \qquad Q_6 = (\bar{s}_\alpha b_\beta)_{V-A} \sum_{q=u,d,s,c,b} (\bar{q}_\beta q_\alpha)_{V+A}$$

Electroweak Penguins:

$$Q_7 = \frac{3}{2} \, (\bar{s}b)_{V-A} \sum_{q=u,d,s,c,b} e_q \, (\bar{q}q)_{V+A} \qquad Q_8 = \frac{3}{2} \, (\bar{s}_\alpha b_\beta)_{V-A} \sum_{q=u,d,s,c,b} e_q (\bar{q}_\beta q_\alpha)_{V+A}$$

$$Q_9 = \frac{3}{2} \, (\bar{s}b)_{V-A} \sum_{q=u,d,s,c,b} e_q (\bar{q}q)_{V-A} \qquad Q_{10} = \frac{3}{2} \, (\bar{s}_\alpha b_\beta)_{V-A} \sum_{q=u,d,s,c,b} e_q \, (\bar{q}_\beta q_\alpha)_{V-A}$$

Magnetic Penguin:

$$Q_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu}(1+\gamma_5) b_\alpha F_{\mu\nu} \qquad Q_{8G} = \frac{g}{8\pi^2} m_b \bar{s}_\alpha \sigma^{\mu\nu}(1+\gamma_5) T^a_{\alpha\beta} b_\beta G^a_{\mu\nu}$$

Mixing:

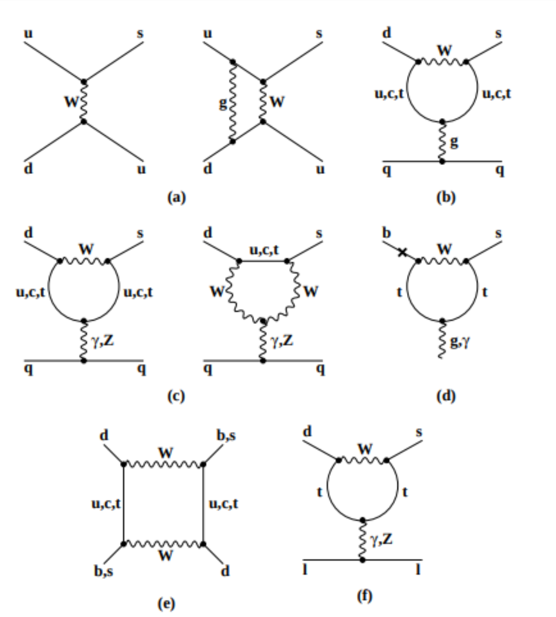
$$Q(\Delta S = 2) = (\bar{s}d)_{V-A}(\bar{s}d)_{V-A} \quad Q(\Delta B = 2) = (\bar{b}d)_{V-A}(\bar{b}d)_{V-A}$$

leptonic/semileptonic:

$$Q_{9V} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_V \quad Q_{10A} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_A$$

$$Q_{\nu\bar{\nu}} = (\bar{s}b)_{V-A}(\bar{\nu}\nu)_{V-A} \quad Q_{\mu\bar{\mu}} = (\bar{s}b)_{V-A}(\bar{\mu}\mu)_{V-A} \,.$$

Feynman Diagram



Top-Down Vs Bottom-Up

Top-Down

- Start with full UV-complete theory
- Integrate out heavy fields (limit on possible vertices)
- Generate mathematically simpler theory
- Wilson coefficients defined by variables of full theory

$$G_F = \frac{\sqrt{2}g^2}{8M_W^2}$$

← Suppressed by "heavy" scale

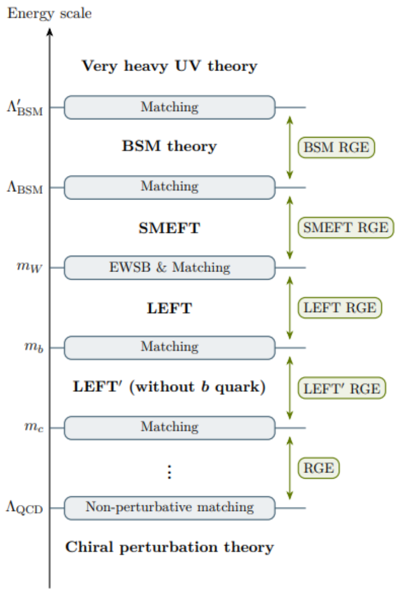
Bottom-Up

- Build basis of operators without making any connection to a UV complete theory
- Wilson coefficients entirely unspecified

Main Ingradients of EFTs

- Fields: Determine the relevant degrees of freedom.
- Symmetries: What interactions? Are there broken symmetries?
- Power counting: Expansion parameters, what is the leading order description?

EFT Tower



Energy scale
Very heavy UV theory
Λ'_{BSM}
Matching
BSM theory
BSM RGE
Λ_{BSM}
Matching
SMEFT
SMEFT RGE
m_W
EWSB & Matching
LEFT
LEFT RGE
m_b
Matching
LEFT′ (without b quark)
LEFT′ RGE
m_c
Matching
⋮
RGE
Λ_{QCD}
Non-perturbative matching
Chiral perturbation theory

Standard Model Effective Field Theory (SMEFT) :

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \frac{1}{\Lambda} C^{(5)} O^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right).$$

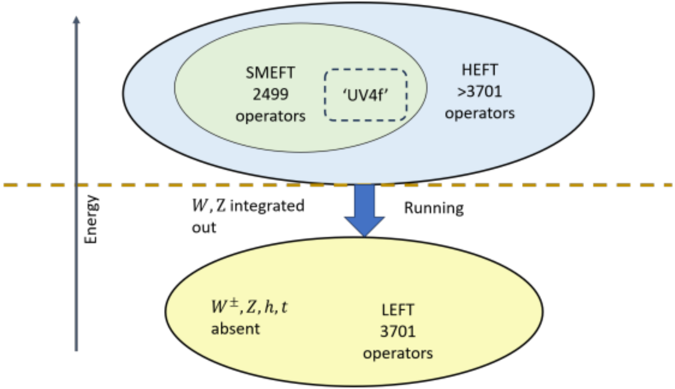
- Includes SM fields only.
- Follows $SU(3)_C \times SU(2)_L \times U(1)_Y$.
- Electroweak (EW) symmetry linearly realized.

Current uncertainties in Higgs coupling measurements can allow more generalized EFTs e.g. **Higgs Effective Field Therory (HEFT)**. In HEFT:

- $SU(2)_L \times U(1)_Y$ non-linearly realized.
- Higgs boson is not embedded in a $SU(2)_L$-doublet: $\longrightarrow$ More general coupling of Higgs.
- HEFT $\supset$ SMEFT $\supset$ SM

[G. Buchalla and O. Cata, JHEP 07 (2012) 101]
[A. Falkowski, R. Rattazzi, JHEP 10 (2019) 255]

- In the energy scale much below the EW symmetry breaking, the relevant EFT is **Low Energy Effective Field Theory (LEFT)**
- LEFT can be derived from HEFT by integrating out the heavier particles – $W^{\pm}$, Z, Higgs and top quark.



- More number of operator in HEFT/LEFT than in SMEFT $\Longrightarrow$ relations among HEFT/LEFT WCs
- Relations among HEFT/LEFT WCs $\Longrightarrow$ indirect bounds
- Violation of these relations $\Longrightarrow$ physics beyond SMEFT

What is SMEFT?

SMEFT is a "bottom up" effective field theory that describes SM interactions with new physics under certain assumptions

1) Assume that new physics is above some high energy scale
2) Assume that new physics Lorentz and gauge invariance

$\Rightarrow$ Build every possible operator at each order in mass dimension from the existing Standard Model fields

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\forall i, n \geq 5} \frac{C_i \mathcal{O}_i^{(n)}}{\Lambda^{n-4}}$$

Higher (mass) dimension operators suppressed by NP scale

Pro: We make no connection to any UV-complete model

Con: LARGE number of Wilson coefficients!

Warsaw Basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

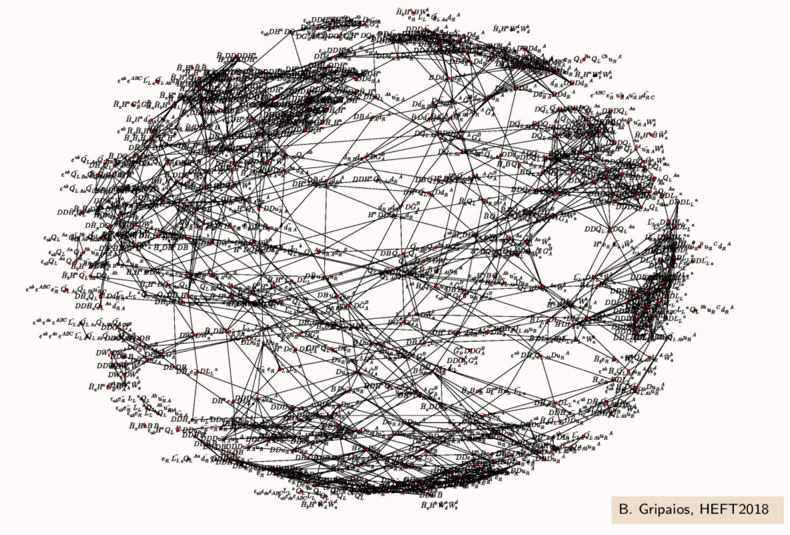
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Warsaw Basis

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

What’s a basis?



B. Gripaios, HEFT2018

1–4: Bosonic Operators

1: X^3 [LG]		2: H^6 [PTG]		4: X^2H^2 [LG]			
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	Q_{HG}	$(H^\dagger H)G^A_{\mu\nu}G^{A\mu\nu}$	Q_{HB}	$(H^\dagger H)B_{\mu\nu}B^{\mu\nu}$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	3: H^4D^2 [PTG]		$Q_{H\widetilde G}$	$(H^\dagger H)\widetilde G^A_{\mu\nu}G^{A\mu\nu}$	$Q_{H\widetilde B}$	$(H^\dagger H)\widetilde B_{\mu\nu}B^{\mu\nu}$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{HW}	$(H^\dagger H)W^I_{\mu\nu}W^{I\mu\nu}$	Q_{HWB}	$(H^\dagger\tau^I H)W^I_{\mu\nu}B^{\mu\nu}$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	Q_{HD}	$(H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$	$Q_{H\widetilde W}$	$(H^\dagger H)\widetilde W^I_{\mu\nu}W^{I\mu\nu}$	$Q_{H\widetilde WB}$	$(H^\dagger\tau^I H)\widetilde W^I_{\mu\nu}B^{\mu\nu}$

5–7: Fermion Bilinears (ψ^2)

non-hermitian ($\bar LR$)							
5: ψ^2H^3 + h.c. [PTG]		6: ψ^2XH + h.c. [LG]					
Q_{eH}	$(H^\dagger H)(\bar\ell_p e_r H)$	Q_{eW}	$(\bar\ell_p\sigma^{\mu\nu}e_r)\tau^I HW^I_{\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^Au_r)\widetilde HG^A_{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^Ad_r)HG^A_{\mu\nu}$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r\widetilde H)$	Q_{eB}	$(\bar\ell_p\sigma^{\mu\nu}e_r)HB_{\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde HW^I_{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I HW^I_{\mu\nu}$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$			Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde HB_{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)HB_{\mu\nu}$

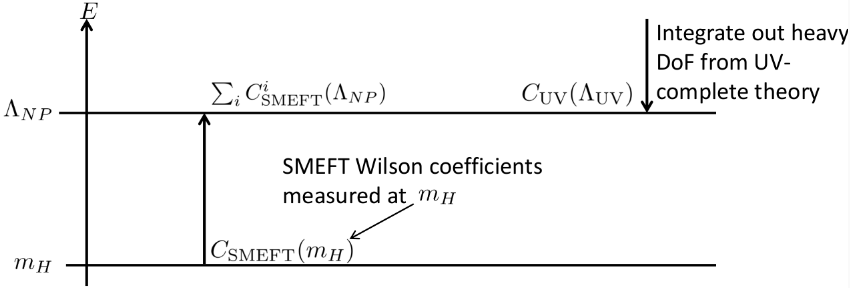
7: ψ^2H^2D – hermitian + Q_{Hud} [PTG]					
($\bar LL$)		($\bar RR$)		($\bar RR'$) + h.c.	
$Q^{(1)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar\ell_p\gamma^\mu\ell_r)$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$	Q_{Hud}	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$
$Q^{(3)}_{H\ell}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar\ell_p\tau^I\gamma^\mu\ell_r)$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$		
$Q^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$		
$Q^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p\tau^I\gamma^\mu q_r)$				

8: Fermion Quadrilinears (ψ^4) [PTG]

hermitian						non-hermitian	
($\bar LL$)($\bar LL$)		($\bar RR$)($\bar RR$)		($\bar LL$)($\bar RR$)		($\bar LR$)($\bar LR$) + h.c.	
$Q_{\ell\ell}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar\ell_s\gamma^\mu\ell_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	$Q_{\ell e}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar e_s\gamma^\mu e_t)$	$Q^{(1)}_{quqd}$	$(\bar q^i_p u_r)\varepsilon_{ij}(\bar q^j_s d_t)$
$Q^{(1)}_{qq}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	$Q_{\ell u}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar u_s\gamma^\mu u_t)$	$Q^{(8)}_{quqd}$	$(\bar q^i_p T^A u_r)\varepsilon_{ij}(\bar q^j_s T^A d_t)$
$Q^{(3)}_{qq}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	$Q_{\ell d}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar d_s\gamma^\mu d_t)$	$Q^{(1)}_{\ell equ}$	$(\bar\ell^i_p e_r)\varepsilon_{ij}(\bar q^j_s u_t)$
$Q^{(1)}_{\ell q}$	$(\bar\ell_p\gamma_\mu\ell_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$	$Q^{(3)}_{\ell equ}$	$(\bar\ell^i_p\sigma_{\mu\nu}e_r)\varepsilon_{ij}(\bar q^j_s\sigma^{\mu\nu}u_t)$
$Q^{(3)}_{\ell q}$	$(\bar\ell_p\gamma_\mu\tau^I\ell_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q^{(1)}_{qu}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$		
		$Q^{(1)}_{ud}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q^{(8)}_{qu}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$		
		$Q^{(8)}_{ud}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q^{(1)}_{qd}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$	($\bar LR$)($\bar RL$) + h.c.	
				$Q^{(8)}_{qd}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{\ell edq}$	$(\bar\ell^i_p e_r)(\bar d_s q_{ti})$

Making connection with UV-complete models

- When sufficient Wilson coefficients have been fitted, need to connect to UV complete models
- Integrate out heavy states of UV-Complete theory
- Run resulting Wilson coefficients of BSM theory and SMEFT theory to same scale
- Can compare consistency of (non) vanishing Wilson coefficients and general self-consistency
- Allow us to reject or support UV-complete theories



$b \to s l^+ l^-$ & $b \to c\tau\bar{\nu}_\tau$: SMEFT (dimension-6)

$b \to sll$

[2408.03380]

- SMEFT operators:

$$Q_{\ell q}^{(1)} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_\ell) \ , \quad Q_{\ell q}^{(3)} = (\bar{\ell}_i \gamma_\mu \tau^I \ell_j)(\bar{q}_k \gamma^\mu \tau^I q_\ell) \ ,$$
$$Q_{\ell d} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{d}_k \gamma^\mu d_\ell) \ , \quad Q_{qe} = (\bar{q}_i \gamma_\mu q_j)(\bar{e}_k \gamma^\mu e_\ell) \ ,$$
$$Q_{ed} = (\bar{e}_i \gamma_\mu e_j)(\bar{d}_k \gamma^\mu d_\ell) \ .$$

- The matching conditions between the WET and SMEFT operators are given by

$$C_{9,\ell} = \frac{1}{2\mathcal{N}} \left([C_{\ell q}^{(1)}]_{ll23} + [C_{\ell q}^{(3)}]_{ll23} + [C_{qe}]_{23ll} + \left[C_{\varphi q}^{(1)23} + C_{\varphi q}^{(3)23} \right] (-1 + 4\sin^2\theta_W) \right) \ ,$$
$$C_{10,\ell} = \frac{1}{2\mathcal{N}} \left([C_{qe}]_{23ll} - [C_{\ell q}^{(1)}]_{ll23} - [C_{\ell q}^{(3)}]_{ll23} + \left[C_{\varphi q}^{(1)23} + C_{\varphi q}^{(3)23} \right] \right) \ ,$$
$$C'_{9,\ell} = \frac{1}{2\mathcal{N}} \left([C_{\ell d}]_{ll23} + [C_{ed}]_{ll23} + C_{\varphi d}^{23}(-1 + 4\sin^2\theta_W) \right) \ ,$$
$$C'_{10,\ell} = \frac{1}{2\mathcal{N}} \left([C_{ed}]_{ll23} - [C_{\ell d}]_{ll23} + C_{\varphi d}^{23} \right) \ , \quad ($$

$b \to c\tau\bar{\nu}_\tau$

- WET operators:

$$\mathcal{N}' \, C_V^{33} \, (\bar{c}_L \gamma^\mu b_L) \, (\bar{\tau}_L \gamma_\mu \nu_{\tau L})$$

- Tree-level matching condition to SMEFT operator:

$$C_V^{33} = \frac{1}{2\mathcal{N}'} V_{2k} \, [C_{lq}^{(3)}]^*_{33k3} \ ,$$

$b \to s\nu_l\bar{\nu}_l$

- WET operators:

$$\mathcal{N}C_L(\bar{s}\gamma_\mu P_L b)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_i) + \mathcal{N}C_R(\bar{s}\gamma_\mu P_R b)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_i) + h.c.,$$

- The matching conditions between the WET and SMEFT operators are given by

$$C_L = \frac{1}{2\mathcal{N}}([C_{lq}^{(1)}]_{ii23} - [C_{lq}^{(3)}]_{ii23}) \ .$$

$\Delta F = 2$ Observables

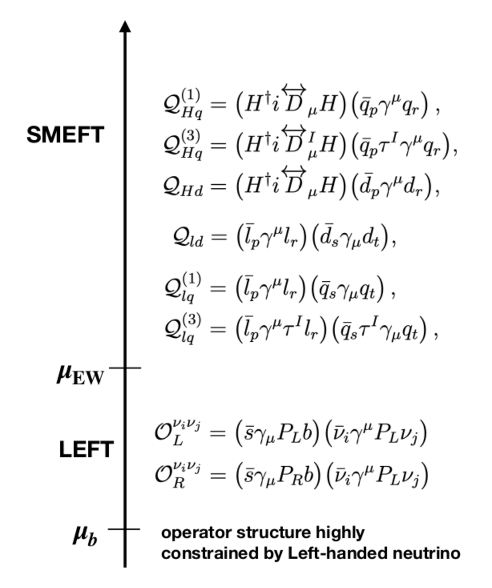
- WET operators:

$$\begin{aligned}
[O_{dd}^{V,LL}]_{ijij} &= (\bar{d}_i\gamma_\mu P_L d_j)(\bar{d}_i\gamma^\mu P_L d_j) \ , \\
[O_{dd}^{V,RR}]_{ijij} &= (\bar{d}_i\gamma_\mu P_R d_j)(\bar{d}_i\gamma^\mu P_R d_j) \ , \\
[O_{dd}^{V1,LR}]_{ijij} &= (\bar{d}_i\gamma_\mu P_L d_j)(\bar{d}_i\gamma^\mu P_R d_j) \ , \\
[O_{dd}^{V8,LR}]_{ijij} &= (\bar{d}_i\gamma_\mu P_L T^A d_j)(\bar{d}_i\gamma^\mu P_R T^A d_j) \ ,
\end{aligned}$$

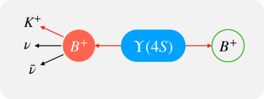
- Tree-level matching conditions to SMEFT operators

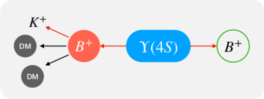
$$\begin{aligned}
[C_{dd}^{V,LL}]_{ijij} &= -([C_{qq}^{(1)}]_{ijij} + [C_{qq}^{(3)}]_{ijij}) \ , \\
[C_{dd}^{V1,LR}]_{ijij} &= -[C_{qd}^{(1)}]_{ijij} \ , \\
[C_{dd}^{V8,LR}]_{ijij} &= -[C_{qd}^{(8)}]_{ijij} \ , \\
[C_{dd}^{V,RR}]_{ijij} &= -[C_{dd}]_{ijij} .
\end{aligned}$$

$b \to s\nu\bar{\nu}$: SMEFT



$b \to s\nu\bar{\nu}$: DSMEFT





SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)\,,$$
$$\mathcal{Q}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r),$$
$$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r),$$
$$\mathcal{Q}_{ld} = (\bar{l}_p \gamma^\mu l_r)(\bar{d}_s \gamma_\mu d_t),$$
$$\mathcal{Q}_{lq}^{(1)} = (\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)\,,$$
$$\mathcal{Q}_{lq}^{(3)} = (\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \tau^I \gamma_\mu q_t)\,,$$

μ_{EW}

LEFT

$$\mathcal{O}_L^{\nu_i\nu_j} = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}_i \gamma^\mu P_L \nu_j)$$
$$\mathcal{O}_R^{\nu_i\nu_j} = (\bar{s}\gamma_\mu P_R b)(\bar{\nu}_i \gamma^\mu P_L \nu_j)$$

μ_b

Dark SMEFT

example

$$\mathcal{Q}_{d\phi^2} = (\bar{q}_p d_r H)\phi^2$$
$$\mathcal{Q}_{d\chi} = (\bar{d}_p \gamma_\mu d_r)(\bar{\chi}\gamma^\mu \chi)$$
$$\mathcal{Q}_{dX^2} = (\bar{q}_p d_r H) X_\mu X^\mu$$
$$\mathcal{Q}_{qa} = (\bar{q}_p \gamma_\mu q_r)\partial^\mu a$$

2011 Kamenik, Smith
2014 Duch, Grzadkowski, Wudka
2017 Brod, Gootjes-Dreesbach, Tammaro, Zupan
2021 Criado, Djouadi, Perez-Victoria, Santiago
2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)
2023 Song, Sun, Yu (basis@dim-8)

Axion-like particle, see also H.Y.Cheng, Phys.Rept 1988
2020 Bauer, Neubert, Renner, Schnubel, Thamm
2023 Song, Sun, Yu (basis@dim-8)

Dark LEFT

$$\mathcal{O}_{d\phi^2} = (\bar{d}_{Lp} d_{Rr})\phi^2$$
$$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})(\bar{\chi}_a \gamma^\mu \chi_b)$$
$$\mathcal{O}_{dXX}^{L} = (\bar{d}_{Lp}\gamma_\mu d_{Lr}) X^{\mu\nu} X_\nu$$
$$\mathcal{O}_{da}^{L} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})\partial^\mu a$$

example

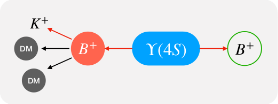
2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)
2022 He, Ma, Valencia (basis@dim-6)
2023 Liang, Liao, Ma, Wang (basis@dim-8)

12

$b \to s\nu\bar{\nu}$: DSMEFT

Can DSMEFT operators explain the Belle II excess, while satisfy other $b \to s$ bounds ?

Observable	SM	Exp	Unit
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
$\mathcal{B}(B^0 \to K^0\nu\bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	9.00 ± 0.87	< 18	10^{-6}
$\mathcal{B}(B_s \to \phi\nu\bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
$\mathcal{B}(B_s \to \nu\bar{\nu})$	≈ 0	< 5.9	10^{-4}
$\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
$\mathcal{B}(B^0 \to \pi^0\nu\bar{\nu})$	6.52 ± 0.85	< 900	10^{-8}
$\mathcal{B}(B^+ \to \rho^+\nu\bar{\nu})$	4.06 ± 0.79	< 300	10^{-7}
$\mathcal{B}(B^0 \to \rho^0\nu\bar{\nu})$	1.89 ± 0.36	< 400	10^{-7}
$\mathcal{B}(B^0 \to \nu\bar{\nu})$	≈ 0	< 1.4	10^{-4}
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	8.42 ± 0.61	$10.6^{+4.0}_{-3.4} \pm 0.9$	10^{-11}
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}



$\mu_{\rm EW}$

Dark SMEFT

$$\mathcal{Q}_{d\phi} = (\bar{q}_p d_r H)\phi + \text{h.c.}, \quad \mathcal{Q}_{d\phi^2} = (\bar{q}_p d_r H)\phi^2 + \text{h.c.},$$
$$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r)(i\phi_1 \overleftrightarrow{\partial^\mu} \phi_2), \quad \mathcal{Q}_{\phi d} = (\bar{d}_p \gamma_\mu d_r)(i\phi_1 \overleftrightarrow{\partial^\mu} \phi_2),$$

scalar: 4

$$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r)(\bar{\chi}\gamma^\mu \chi), \quad \mathcal{Q}_{d\chi} = (\bar{d}_p \gamma_\mu d_r)(\bar{\chi}\gamma^\mu \chi),$$

fermion: 2

$$\mathcal{Q}_{dHX} = (\bar{q}_p \sigma_{\mu\nu} d_r) H X^{\mu\nu} \quad \mathcal{Q}_{dX^2} = (\bar{q}_p d_r H) X_\mu X^\mu$$

vector: 1+13

$$\mathcal{Q}_{qa} = (\bar{q}_p \gamma_\mu q_r)\partial^\mu a \quad \mathcal{Q}_{da} = (\bar{d}_p \gamma_\mu d_r)\partial^\mu a$$

ALP: 2

Dark LEFT

$$\mathcal{O}_{d\phi} = (\bar{d}_{Lp} d_{Rr})\phi + \text{h.c.}, \quad \mathcal{O}^L_{\phi d} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})(i\phi_1 \overleftrightarrow{\partial^\mu} \phi_2),$$

scalar: 4

$$\mathcal{O}^{V,LR}_{d\chi} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})(\bar{\chi}_a \gamma^\mu \chi_b), \mathcal{O}^{V,RR}_{d\chi} = (\bar{d}_{Rp}\gamma_\mu d_{Rr})(\bar{\chi}_a \gamma^\mu \chi_b),$$

fermion: 5

$$\mathcal{O}^T_{dX} = (\bar{d}_{Lp}\sigma_{\mu\nu} d_{Rr}) X^{\mu\nu}_a \quad \mathcal{O}^L_{dXX} = (\bar{d}_{Lp}\gamma_\mu d_{Lr}) X^{\mu\nu} X_\nu$$

vector: 1+10

$$\mathcal{O}^L_{da} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})\partial^\mu a, \quad \mathcal{O}^R_{da} = (\bar{d}_{Rp}\gamma_\mu d_{Rr})\partial^\mu a$$

ALP:

μ_b

νSMEFT

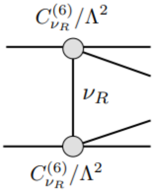
✦ Systematic Analysis based on Effective Field Theory with ν_R

$$\mathcal{L} = \mathcal{L}_{\rm SM} - Y_\nu L\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c}M_R\nu_R + \frac{1}{\Lambda^{n-4}}C^{(n)}_{\nu_R}\mathcal{O}^{(n)}_{\nu_R}$$

*Higher dimensional operators

✔ Contributions to 0N2B from non-standard (dim 6) interactions

New!



Ex) Dimension 6 operator

$$\frac{1}{\Lambda^2}C^{(6)}_{\nu_R}\ \bar{L}^i d_R \epsilon_{ij}\bar{Q}\nu_R$$

*Work for production of sterile neutrino DM

νSMEFT Operator Basis

$$\mathscr{L} = \mathscr{L}_{SM+N} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \sum_{i}^{n_d} \alpha_i^{(d)} \mathscr{O}_i^{(d)}$$

$\mathscr{O}_i^{(d)}$ are invariant under $SU(3)_c \times SU(2)_L \times U(1)_Y$

Dimension 5 (LNV operators)

$$\mathscr{O}_{LH} = \left(\overline{L}\tilde{H}\right)\left(\tilde{H}^T L^c\right)$$

Weinberg, PRL **43** (1979) 1566

$$\mathscr{O}_{NNH} = \left(\overline{N^c}N\right)\left(H^\dagger H\right)$$

Aguila, Bar-Shalom, Soni, Wudka, 0806.0876
Aparici, Kim, Santamaria, Wudka, 0904.3244

$$\mathscr{O}_{NNB} = \left(\overline{N^c}\sigma^{\mu\nu}N\right)B_{\mu\nu}$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \qquad \sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]$$

$\mathscr{O}_{NNB} \equiv 0$ for $n_s = 1$ (n_s is # of Ns)

νSMEFT Operator Basis

Dimension 6

Initial set of operators (redundant) Aguila, Bar-Shalom, Soni, Wudka, 0806.0876
Complete set of independent operators (basis) Liao and Ma, 1612.04527

Higgs-N operators # (+h.c.) = 5 (9)

$1H$	$\mathcal{O}_{NB} = \overline{L}\sigma^{\mu\nu}N\tilde{H}B_{\mu\nu}$	$\mathcal{O}_{NW} = \overline{L}\sigma^{\mu\nu}N\sigma_I\tilde{H}W^I_{\mu\nu}$
$2H$	$\mathcal{O}_{HN} = \overline{N}\gamma^\mu N(H^\dagger i\overleftrightarrow{D}_\mu H)$	$\mathcal{O}_{HNe} = \overline{N}\gamma^\mu e(\tilde{H}^\dagger iD_\mu H)$
$3H$	$\mathcal{O}_{LNH} = \overline{L}\tilde{H}N(H^\dagger H)$	

4-fermions 11 (16)

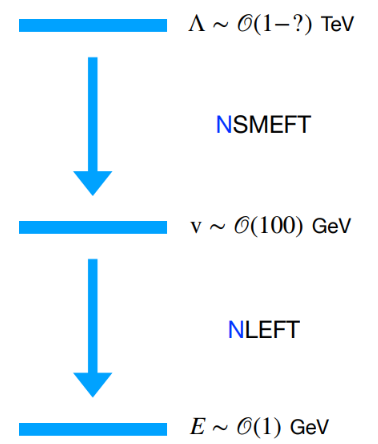
RRRR	$\mathcal{O}_{NN} = (\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$	
	$\mathcal{O}_{eN} = (\overline{e}\gamma_\mu e)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{uN} = (\overline{u}\gamma_\mu u)(\overline{N}\gamma^\mu N)$
	$\mathcal{O}_{dN} = (\overline{d}\gamma_\mu d)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{duNe} = (\overline{d}\gamma_\mu u)(\overline{N}\gamma^\mu e)$
LLRR	$\mathcal{O}_{LN} = (\overline{L}\gamma_\mu L)(\overline{N}\gamma^\mu N)$	$\mathcal{O}_{QN} = (\overline{Q}\gamma_\mu Q)(\overline{N}\gamma^\mu N)$
LRLR	$\mathcal{O}_{LNLe} = (\overline{L}N)\epsilon(\overline{L}e)$	$\mathcal{O}_{LNQd} = (\overline{L}N)\epsilon(\overline{Q}d)$
	$\mathcal{O}_{LdQN} = (\overline{L}d)\epsilon(\overline{Q}N)$	
LRRL	$\mathcal{O}_{QuNL} = (\overline{Q}u)(\overline{N}L)$	

3 (6)

$\not{L}$	$\mathcal{O}_{NNNN} = (\overline{N^c}N)(\overline{N^c}N)$
$\not{L}$ & $\not{B}$	$\mathcal{O}_{QQdN} = (\overline{Q^c}\epsilon Q)(\overline{d^c}N)$
	$\mathcal{O}_{uddN} = (\overline{u^c}d)(\overline{d^c}N)$

$n_f = 1\ (3):\ \ 29\ (1614)$
operators including h.c.

νSMEFT Scale



Takeaway

Thank You !