UV-HEFT Matching

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2412.00355(*JHEP* 06 (2025) 021), 2503.00707(*JHEP* 06 (2025) 249), 2602.14418(*PRD* 114 (2026) 1,015013), 2607.XXXXX

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TeV物理和超出标准模型新物理分会场

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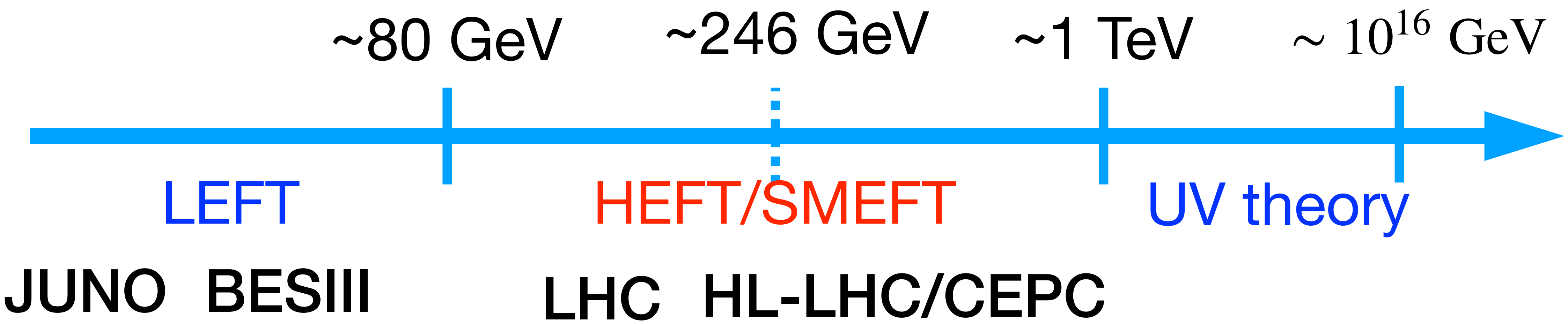
Effective Field Theory (EFT) for New Physics



- A systematic framework to describe the low-energy effects of new physics.
- Heavy degrees of freedom are integrated out via matching.
- New-physics effects are encoded in higher-dimensional operators.
- Different energy scales are described by different EFTs, each probed by corresponding experiments.
- Enables model-independent searches for new physics.

SMEFT v.s. HEFT

- SMEFT, linear realization

Decoupling   Symmetric phase

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix}, \mathscr{L}_{\rm SMEFT} \supset \frac{1}{2} D_\mu H^\dagger D^\mu H + \frac{m^2}{2} H^\dagger H - \lambda (H^\dagger H)^2 + \frac{C_H}{\Lambda^2}(H^\dagger H)^3 + \cdots$$

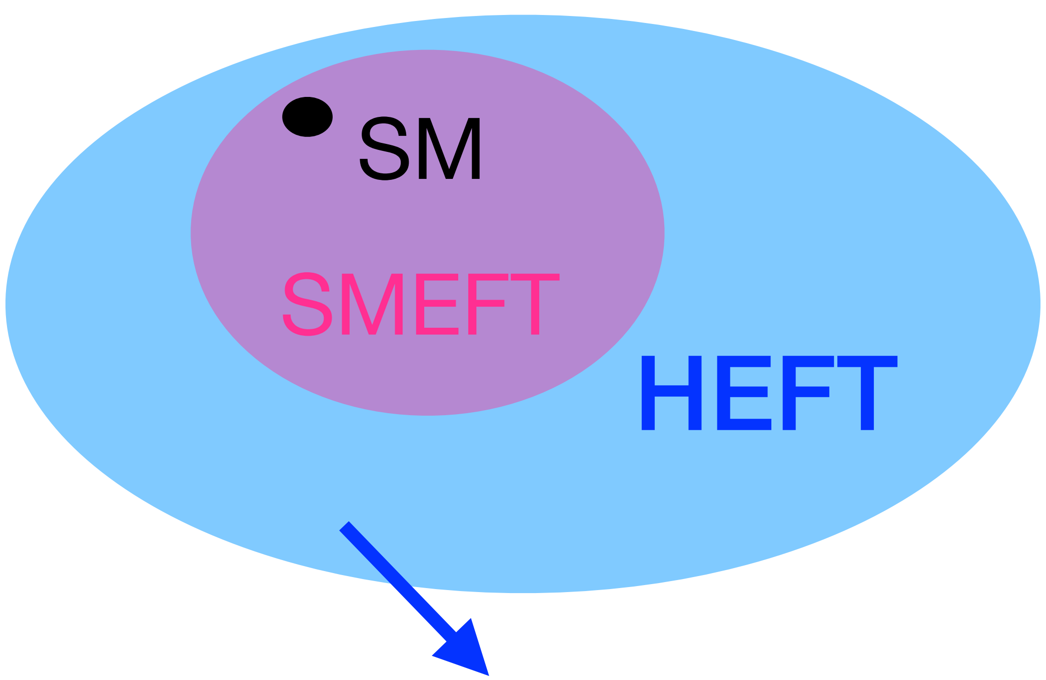
- HEFT, nonlinear realization

Non-decoupling   Broken phase

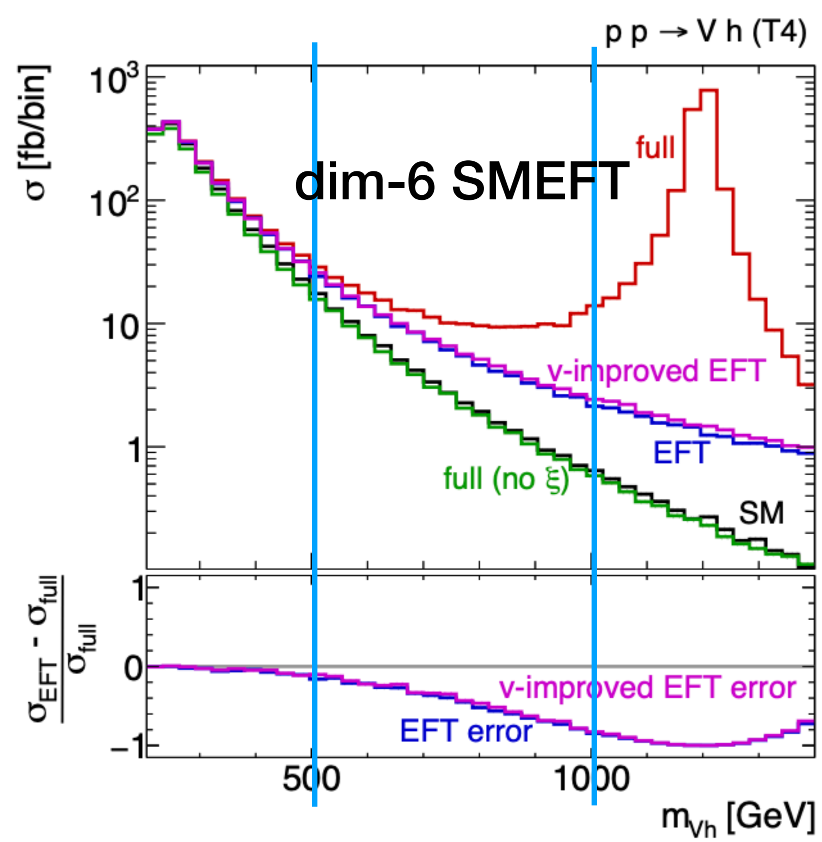
$$h, U \equiv \exp\left(\frac{i\pi_i \sigma_i}{v_{\rm EW}}\right), \mathscr{L}^{\rm LO}_{\rm HEFT} \supset \frac{1}{2} D_\mu h D^\mu h - V(h) + \frac{v_{\rm EW}^2}{4} F(h) {\rm Tr}(D_\mu U^\dagger D^\mu U) + \cdots$$

$$V(h) = \frac{1}{2} m_h^2 h^2 \left[1 + (1 + \Delta\kappa_3)\frac{h}{v_{\rm EW}} + \cdots\right], F(h) = 1 + 2(1 + \Delta a)\frac{h}{v_{\rm EW}} + \cdots$$

R. Alonso, E. Jenkins, A. Manohar [1511.00724,1605.03602]



Non-decoupling

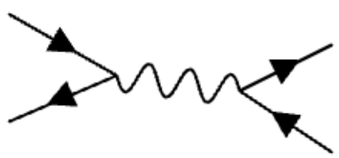


 Adapted from Brehmer, Freitas, López-Val, and Plehn, 1510.03443

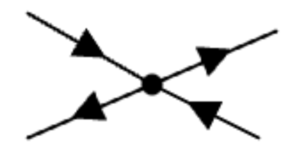
UV-EFT matching

$$\mathscr{L}_{\rm UV} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm BSM}\left(\phi_{\rm SM}, \Phi_{\rm BSM}\right) \Longleftrightarrow \mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_i C_i \mathcal{O}_i\left(\phi_{\rm SM}\right)$$

- Diagrammatic approach (amplitude)



$$\left\{\mathscr{A}_{\rm UV}\left(\lambda_{\rm UV}\right)\right\} = \left\{\mathscr{A}_{\rm SMEFT}\left(C_i\right)\right\}$$



- Need to know $\mathcal{O}_i$ in advance

Carmona, Lazopoulos, Olgoso & Santiago, *Matchmakereft*, 2112.10787
Gómez-Ambrosio,Quezada-Calonge, 2606.11170

- Functional method (action)

$$\Gamma_{\rm UV,1LPI}[\phi_{\rm SM}] = \Gamma_{\rm EFT,1PI}[\phi_{\rm SM}]$$

- Less intuitive
- Systematic operator generation
- Automation-friendly

Fuentes-Martín, König, Pagès, Thomsen & Wilsch, *Matchete*, 2212.04510
Brian Henning, Xiaochuan Lu, and Hitoshi Murayama, 1412.1837
Aleksandra Drozd, John Ellis, Jérémi Quevillon and Tevong You, 1512.03003
Timothy Cohen,[1] Xiaochuan Lu,[1] and Zhengkang Zhang, 2012.07851

Complication of UV-HEFT matching

in functional method

- While non-linear structure meets non-zero VEVs

$$\mathcal{L} \supset (D_\mu H)^\dagger (D^\mu H) + \langle D_\mu \Sigma^\dagger D^\mu \Sigma \rangle - V_S - V_Q,$$

The Real Triplet Model

$$V_S = Y_1^2 H^\dagger H + Z_1 (H^\dagger H)^2 + Y_2^2 \langle \Sigma^\dagger \Sigma \rangle + Z_2 \langle \Sigma^\dagger \Sigma \rangle^2 + Z_3 H^\dagger H \langle \Sigma^\dagger \Sigma \rangle + 2 Y_3 H^\dagger \Sigma H,$$

$$\mathrm{H} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_{\mathrm{H}} + h + iG^0) \end{pmatrix}, \Sigma = \frac{1}{2}\Sigma_i \sigma_i = \frac{1}{2}\begin{pmatrix} v_\Sigma + \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -v_\Sigma - \Sigma^0 \end{pmatrix}, i = 1, 2, 3$$

$$U \equiv \exp\left(\frac{i\pi_i \sigma_i}{v_{\mathrm{EW}}}\right)$$

- The broken phase $\{Z_1, Z_2, Z_3, Y_1, Y_2, Y_3\}$
  $\{m_h, m_K, m_{\phi^\pm}, s_\gamma, v_H, v_\Sigma\}$

Many effective parameters after symmetry breaking, e.g. multiple scalar masses, mixing angles.
$\Rightarrow$ **Multiple power-counting schemes.**

Is HEFT unique? [S. Dawson et al, 2311.16897]

Non-linear Representation

The Real Triplet Higgs Model (has an extra VEV v_Σ)

$$\mathrm{H} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v_\mathrm{H} + h + iG^0) \end{pmatrix}, \Sigma = \frac{1}{2}\Sigma_i \sigma_i = \frac{1}{2}\begin{pmatrix} v_\Sigma + \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -v_\Sigma - \Sigma^0 \end{pmatrix}, i = 1, 2, 3$$

7 d.o.f

$$\boxed{\mathrm{H} = U\frac{1}{\sqrt{2}}\begin{pmatrix} \underline{\chi^\pm} \\ v_\mathrm{H} + h^0 + \underline{i\chi^0} \end{pmatrix}, \quad \Sigma = U\Phi U^\dagger,\ \Phi = \frac{1}{2}\phi_i\sigma_i = \frac{1}{2}\begin{pmatrix} v_\Sigma + \phi^0 & \sqrt{2}\phi^+ \\ \sqrt{2}\phi^- & -v_\Sigma - \phi^0 \end{pmatrix}}$$

$$D_\mu H^\dagger D^\mu H \supset v_\mathrm{H}\epsilon_{3jk}D_\mu \chi_j D^\mu \pi_k/(2v_\mathrm{EW})$$
$$\langle D_\mu \Sigma^\dagger D^\mu \Sigma \rangle \supset -v_\Sigma \epsilon_{3jk} D_\mu \phi_j D^\mu \pi_k$$

$$\chi^\pm = 2\frac{v_\Sigma}{v_\mathrm{H}}\phi^\pm, \chi^0 = 0$$

U **matrix is separated from heavy scalars.**

H. Song, XW, 2412.00355(*JHEP* 06 (2025) 021)

Goldstone modes could also be excised in “Unitary basis”. (Cohen, Craig, Lu, and Sutherland 2021)

Similar ideas in the 2HDM .(P. Ciafaloni and D. Espriu,hep-ph/9612383; S. Dittmaier, et al, 2022)

Power Countings

$$\mathcal{P} = \{m^2_{\phi^\pm}, m^2_K, m_h, v_{\rm EW}, s_\gamma, \xi\},$$

$$\xi = v_\Sigma / v_H$$

$$\mathcal{P}_{Z_2} = \{m^2_{\phi^\pm}, m^2_K, m_h, v_{\rm EW}, Z_2, \xi\}$$

$$\mathcal{P}_\xi = \{Z_1, Z_2, Z_3, Y_3, v_H, \xi\}$$

$$\mathcal{P}_{Y_2} = \{Z_1, Z_2, Z_3, Y_1, Y_2, Y_3\}.$$

Power Countings

$\mathcal{P} = \{m^2_{\phi^\pm}, m^2_K, m_h, v_{\rm EW}, s_\gamma, \xi\},$ $\quad\quad \xi = v_\Sigma / v_H$

primary HEFT: $\sim 1/M^2$ **expansion**

Non-decoupling

$$\text{pHEFT:} \quad m^2_{\phi^\pm} \sim m^2_K \sim \mathcal{O}(t^{-1}), \quad m_h \sim v_{\rm EW} \sim s_\gamma \sim \xi \sim \mathcal{O}(t^0),$$

$$\text{dHEFT:} \quad m^2_{\phi^\pm} \sim m^2_K \sim \mathcal{O}(t^{-1}), \quad m_h \sim v_{\rm EW} \sim \mathcal{O}(t^0), \quad s_\gamma \sim \xi \sim \mathcal{O}(t^1).$$

Decoupling

$$\mathcal{P}_{Z_2} = \{m^2_{\phi^\pm}, m^2_K, m_h, v_{\rm EW}, Z_2, \xi\}$$

$$Z_2\text{-HEFT:} \quad m^2_{\phi^\pm} \sim m^2_K \sim \mathcal{O}(t^{-1}), \quad m_h \sim v_{\rm EW} \sim Z_2 \sim \xi \sim \mathcal{O}(t^0).$$

$$\mathcal{P}_\xi = \{Z_1, Z_2, Z_3, Y_3, v_H, \xi\}$$

$$\xi\text{-HEFT:} \quad Z_1 \sim Z_2 \sim Z_3 \sim Y_3 \sim v_H \sim \mathcal{O}(t^0), \quad \xi \sim \mathcal{O}(t^1).$$

Decoupling

H. Song, XW, 2503.00707(*JHEP* 06 (2025) 249)

$$\mathcal{P}_{Y_2} = \{Z_1, Z_2, Z_3, Y_1, Y_2, Y_3\}.$$

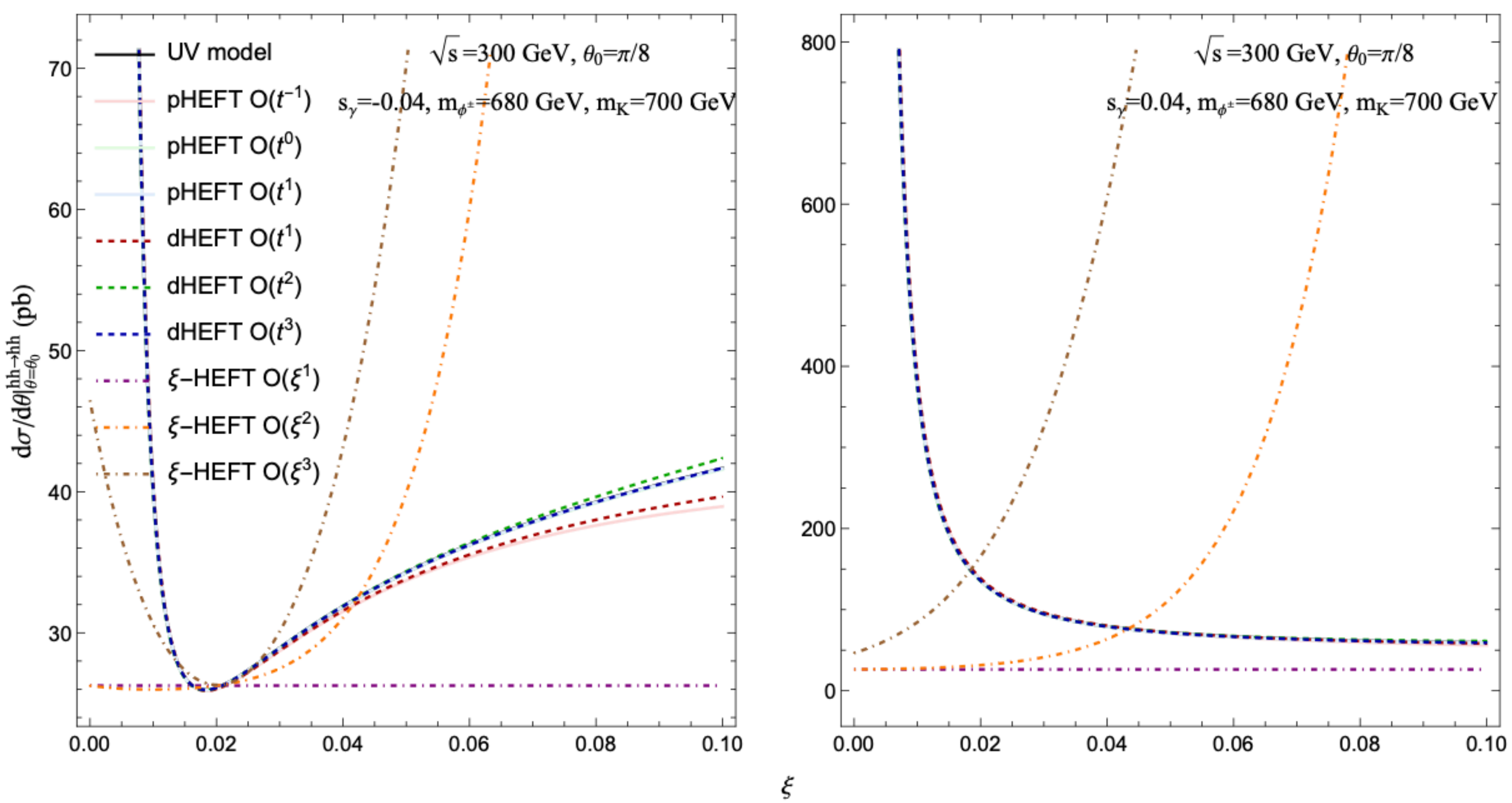
$$Y_2\text{-HEFT:} \quad Z_1 \sim Z_2 \sim Z_3 \sim Y_1 \sim Y_3 \sim \mathcal{O}(t^0), \quad Y_2^2 \sim \mathcal{O}(t^{-1}).$$

SMEFT-like

The primary HEFT (pHEFT)

$$\mathcal{L}^{p}_{\mathrm{HEFT}}(t^{-1}) = \frac{v_H^2\left[(4\xi^2+1)m_K^2(s_\gamma+\xi c_\gamma)^2-\xi^2 m_{\phi^\pm}^2\right]}{8(4\xi^2+1)} - \frac{h^3 m_{\phi^\pm}^2 s_\gamma^2(2\xi c_\gamma+s_\gamma)}{2\xi(4\xi^2+1)v_H}$$
$$-\frac{h^4}{8\xi^2(4\xi^2+1)^2 v_H^2 m_K^2}\Big\{m_{\phi^\pm}^2 s_\gamma^2\Big[(4\xi^2+1)m_K^2\Big(6(2\xi^2-1)c_\gamma^4+7c_\gamma^2+18\xi c_\gamma^3 s_\gamma-4\xi c_\gamma s_\gamma-1\Big)$$
$$+m_{\phi^\pm}^2\Big(9(1-4\xi^2)c_\gamma^4+3(8\xi^2-3)c_\gamma^2-36\xi c_\gamma^3 s_\gamma+12\xi c_\gamma s_\gamma-4\xi^2\Big)\Big]\Big\}+\mathcal{O}(h^5),$$

Non-decoupling effects are all kept.



pHEFT ⊃ dHEFT ⊃ ξ-**HEFT**

pHEFT ⊃ Z_2-**HEFT**

pHEFT ⊃ Y_2-**HEFT** ~ SMEFT

- The pHEFT preserves the maximal information from the UV theory.
- pHEFT can reduce to other HEFTs, serving as a common framework.

Why pHEFT keep maximal UV's information?

$$\mathcal{L}_{\text{mass}} = \frac{1}{2}\begin{pmatrix} h^0 & \phi^0 \end{pmatrix}\begin{pmatrix} 2Z_1 v_H^2 & v_H\left(Z_3 v_\Sigma - Y_3\right) \\ v_H\left(Z_3 v_\Sigma - Y_3\right) & 2Z_2 v_\Sigma^2 + \frac{Y_3 v_H^2}{2v_\Sigma} \end{pmatrix}\begin{pmatrix} h^0 \\ \phi^0 \end{pmatrix}$$

Masses are eigenvalues.

$$\begin{aligned} Y_3 &= \frac{2v_\Sigma}{v_H^2 + 4v_\Sigma^2} m_{\phi^\pm}^2 \\ Z_1 &= \frac{1}{2v_H^2}\left(c_\gamma^2 m_h^2 + s_\gamma^2 m_K^2\right) \\ Z_2 &= \frac{1}{2v_\Sigma^2}\left(s_\gamma^2 m_h^2 + c_\gamma^2 m_K^2 - \frac{v_H^2}{v_H^2 + 4v_\Sigma^2} m_{\phi^\pm}^2\right) \\ Z_3 &= \frac{1}{v_H v_\Sigma}\left[s_\gamma c_\gamma\left(m_K^2 - m_h^2\right) + \frac{2v_H v_\Sigma}{v_H^2 + 4v_\Sigma^2} m_{\phi^\pm}^2\right]. \end{aligned}$$

$\propto M^2$

The linear relation between the UV Lagrangian's couplings and heavy masses, expansion of $1/M^2$ cause no extra truncations except for the propagator structure.

Ge, Song, XW, 2602.14418(*PRD* 114 (2026) 1,015013)

The HEFT of Type-II Seesaw Model

Ge, Song, XW, in preparation

Based on the nonlinear framework and the primary power counting scheme, we get HEFT up to NLO (p^4 operators).

$V_\mu = U D_\mu U^\dagger$

$\langle V_\mu V^\mu \rangle \langle V_\nu V^\nu \rangle$
$\boldsymbol{\langle V_\mu V_\nu \rangle \langle V^\mu V^\nu \rangle}$
$\langle V_\mu \sigma_3 \rangle \langle V^\mu \sigma_3 \rangle \langle V_\nu V^\nu \rangle$
$\langle V_\mu \sigma_3 \rangle \langle V_\nu \sigma_3 \rangle \langle V^\mu V^\nu \rangle$
$\langle V_\mu \sigma_3 \rangle \langle V^\mu \sigma_3 \rangle \langle V_\nu \sigma_3 \rangle \langle V^\nu \sigma_3 \rangle$

- Sensitive to various EW processes, e.g. $WW \to WW$.
- Reproduce the results of [2504.02580] but retain higher-order terms.
- Complete basis of $\Delta L = 2$ lepton-number-violating operators.

$h^3 \subset -\frac{1}{3!} V^{(3)}(0)$	$-\frac{s^2 m_\eta^2 (2\xi c + s)}{2\xi(4\xi^2+1) v_H} + \frac{m_h^2 (s^3 - \xi c^3)}{2\xi v_H}$	$-\frac{\lambda}{2} v_{\rm ew} + \epsilon^2 v_{\rm ew} \left[\frac{(1-2\kappa^2)\lambda}{2} - \frac{1-\kappa+2\kappa^2-6\kappa^3}{2\kappa r_\Delta^2} \right]$
$h W_\mu^- W^{+\mu} \subset -\frac{1}{4} F'(0) \langle V_\mu V^\mu \rangle$	$\frac{g^2 v_H}{2}(c - 2\xi s)$	$\frac{g^2 v_{\rm ew}}{2} \times [1 - \epsilon^2(1 - 4\kappa + 2\kappa^2)]$
$h Z_\mu Z^\mu \subset -\frac{1}{4} F'(0) \langle V_\mu V^\mu \rangle - \frac{1}{4} G'(0) \langle T V_\mu \rangle \langle T V^\mu \rangle$	$\frac{g^2 v_H}{4 c_W^2}(c - 4\xi s)$	$\frac{g^2 v_{\rm ew}}{4 c_W^2} \times [1 - \epsilon^2(1 - 8\kappa + 2\kappa^2)]$

Yi Liao, Xiao-Dong Ma, Yoshiki Uchida, 2504.02580,

Class	Op. Name	Op. Structure	LEFT Matching	Matching Condition
		$\mathcal{O}(p^2)$		
ψ^2	$\mathcal{O}_L$	$L_{Lp}^T C \hat{\mathcal{S}} L_{Lr}$	$m_{\beta\beta}$	$m_{\beta\beta}^{pr} = -\mathcal{F}_L^{pr}(0)$
		$\mathcal{O}(p^3)$		
$\psi^2 V$	$\mathcal{O}_{LV}$	$L_{Lp}^T C \hat{\mathcal{S}} \gamma^\mu V_\mu U L_{Rr}$	$O_{VL}^{(6)}$	$C_{VL}^{(6)\,prst} \supset -2i V_{st} \mathcal{F}_{LV}^{rp*}(0)$
		$\mathcal{O}(p^4)$		
$\psi^2 W$	$\mathcal{O}_{LX,W}$	$L_{Lp}^T C \hat{\mathcal{S}} \sigma^{\mu\nu} W_{\mu\nu} L_{Lr}$	$O_{VL}^{(6)}, O_{VL}^{(7)}, O_{VL}^{(9)}$	$C_{VL}^{(6)\,prst} \supset -\frac{4}{g} V_{st} (M_e^\dagger)_{pu} \mathcal{F}_{LX,W}^{ru*}(0)$ $C_{VL}^{(7)\,prst} \supset -\frac{4v}{g} V_{st} \mathcal{F}_{LX,W}^{rp*}(0)$ $C_{1L}^{(9)\,prstuv} \supset -\frac{8v}{g} V_{st} V_{uv} \left[\mathcal{F}_{LX,W}^{rp*}(0) + \mathcal{F}_{LX,W}^{pr*}(0) \right]$

- Match LNV HEFT operators onto LEFT for $0\nu\beta\beta$.

Summary and outlook

- **Established the nonlinear framework for UV-HEFT matching.**
- **Developed the power-counting scheme of the primary HEFT.**
- **Completed the systematic tree-level matching of the Type-II seesaw model onto HEFT up to NLO precision, including the $\Delta L = 2$ LNV sector.**

Next:

- UV-HEFT matching for singlet, 2HDM, and scalar extensions such as the 4-plet, 5-plet, 7-plet, up to NLO precision
- 1-loop matching.

Thanks for your attention!