Institute of Theoretical Physics
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有效场论观点下的中微子质量和0vbb

EFT Perspective on Neutrino Masses and 0vbb

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Outline

- Why EFT description for neutrino mass and 0vbb?

- EFT operators for neutrino mass and 0vbb

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2201.04639]

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2012.09188]

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2007.07899]

[Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2206.07722]

[Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2206.07722]

[Hao Sun, Yi-Ning Wang, **J.H.Yu**, in préparation]

- UV completion of neutrino masses and 0vbb

[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2204.03660]

[Xu-Xiang Li, Zhe Ren, **J.H.Yu,** in preparation]

[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, in preparation]

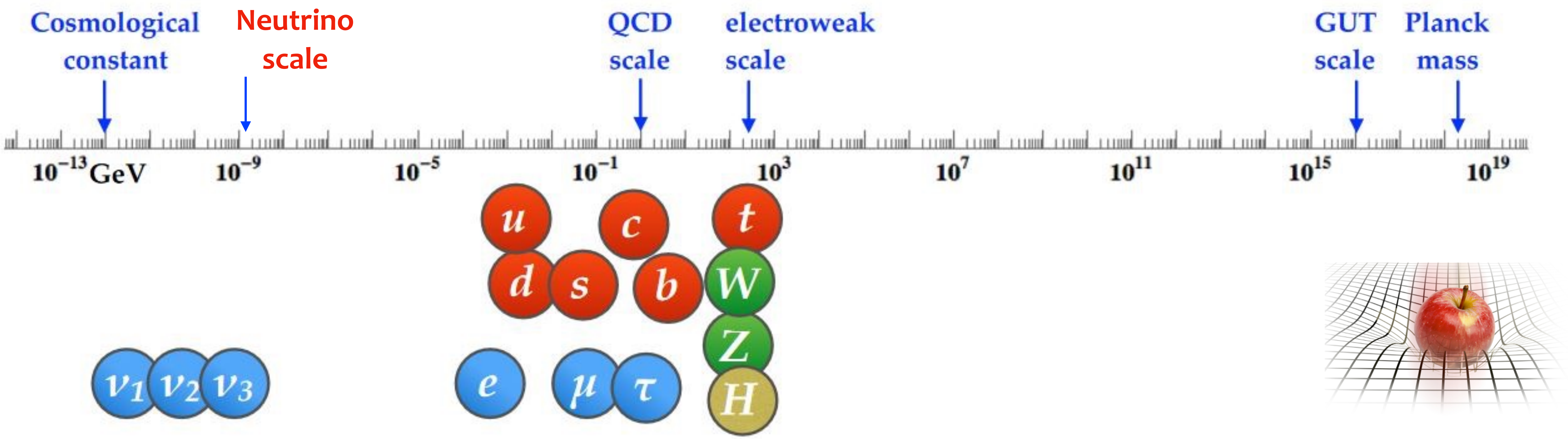
- Summary

[Gang Li, **J.H.Yu,** Xiang Zhao, in progress]

Why EFT description for nv mass and 0vbb?

Origin of Neutrino Mass

The existence of neutrino masses is the first evidence of new physics beyond Standard Model



Why neutrino masses so tiny? **Why Higgs mass so light?**

Dirac vs Majorana Neutrino

Extend standard model by introducing right-handed neutrino

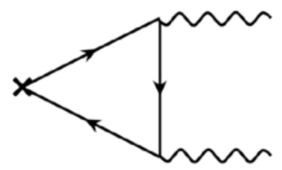
$$\mathcal{L}_m = \underbrace{m_D\, \overline{\psi_R}\psi_L}_{\text{Dirac term}} + \underbrace{\frac{1}{2}m_L\, \overline{\psi^c_L}\psi_L + \frac{1}{2}m_R\, \overline{\psi_R}\psi^c_R}_{\text{Majorana terms}} + \text{h.c.}$$

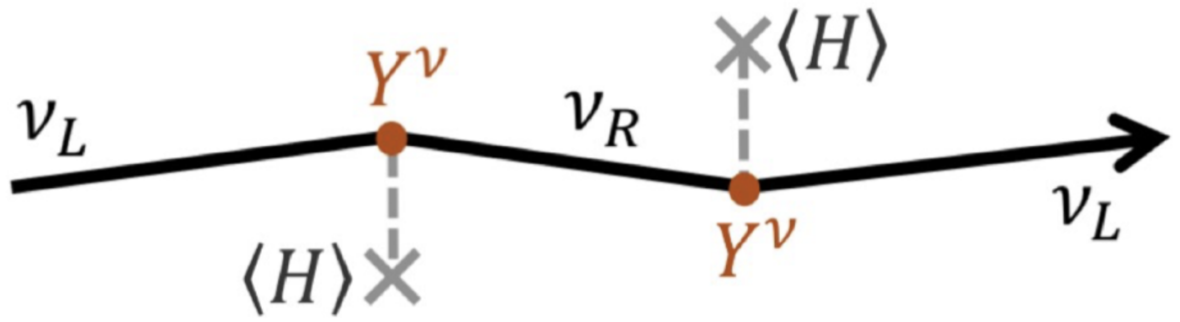
$$\mathbf{M} = \begin{pmatrix} 0 & m_D \\ m_D & 0 \end{pmatrix}$$

$$\mathbf{M} = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$$

How to forbid the Majorana term?

Lepton number conservation





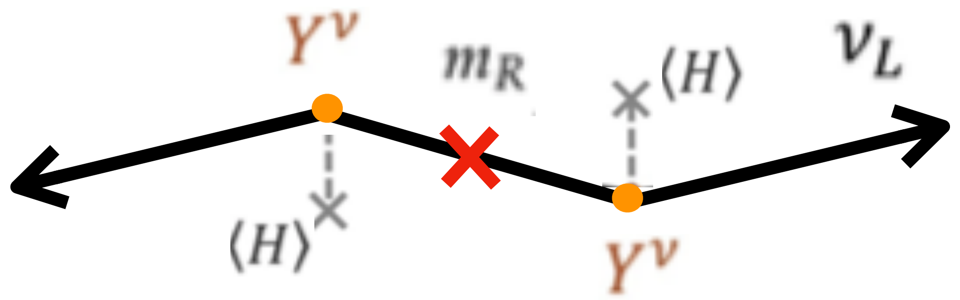
$$\frac{m_\nu}{v_{\text{EW}}} \leq 10^{-12}$$

$$m_\nu = Y^\nu v_{\text{EW}}$$

Tiny Yukawa coupling

The Majorana term is allowed

Lepton number violation

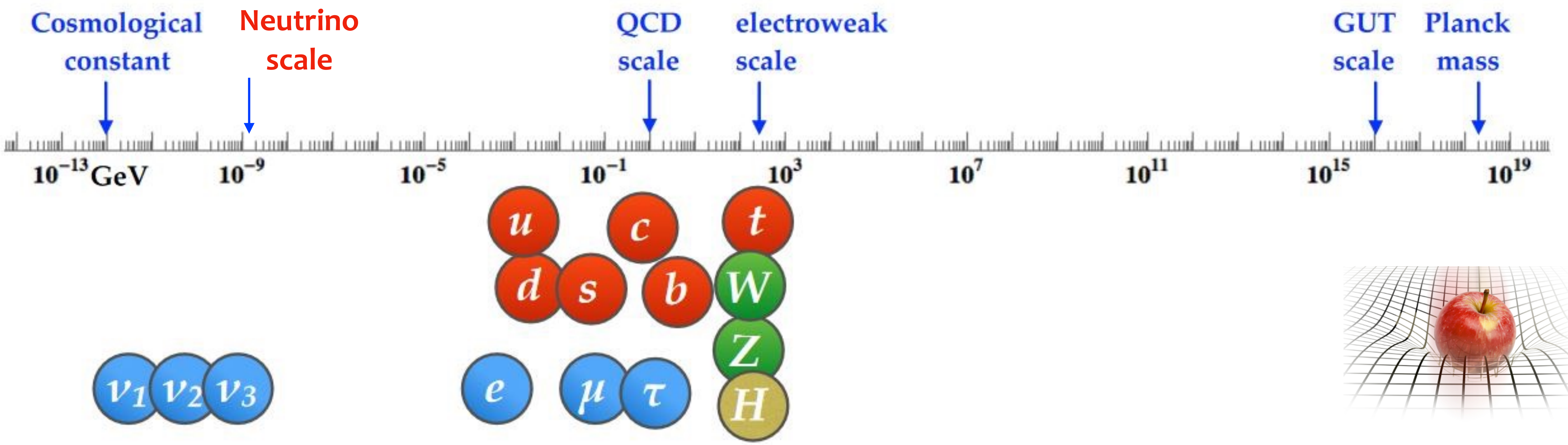


$$m_\nu = \frac{(Y^\nu v_{\text{EW}})^2}{m_R}$$

Yukawa coupling not small, but mR heavy

Majorana Neutrino: Origin of Matter

Majorana neutrino also explains matter-antimatter asymmetry



Why neutrino masses so tiny?

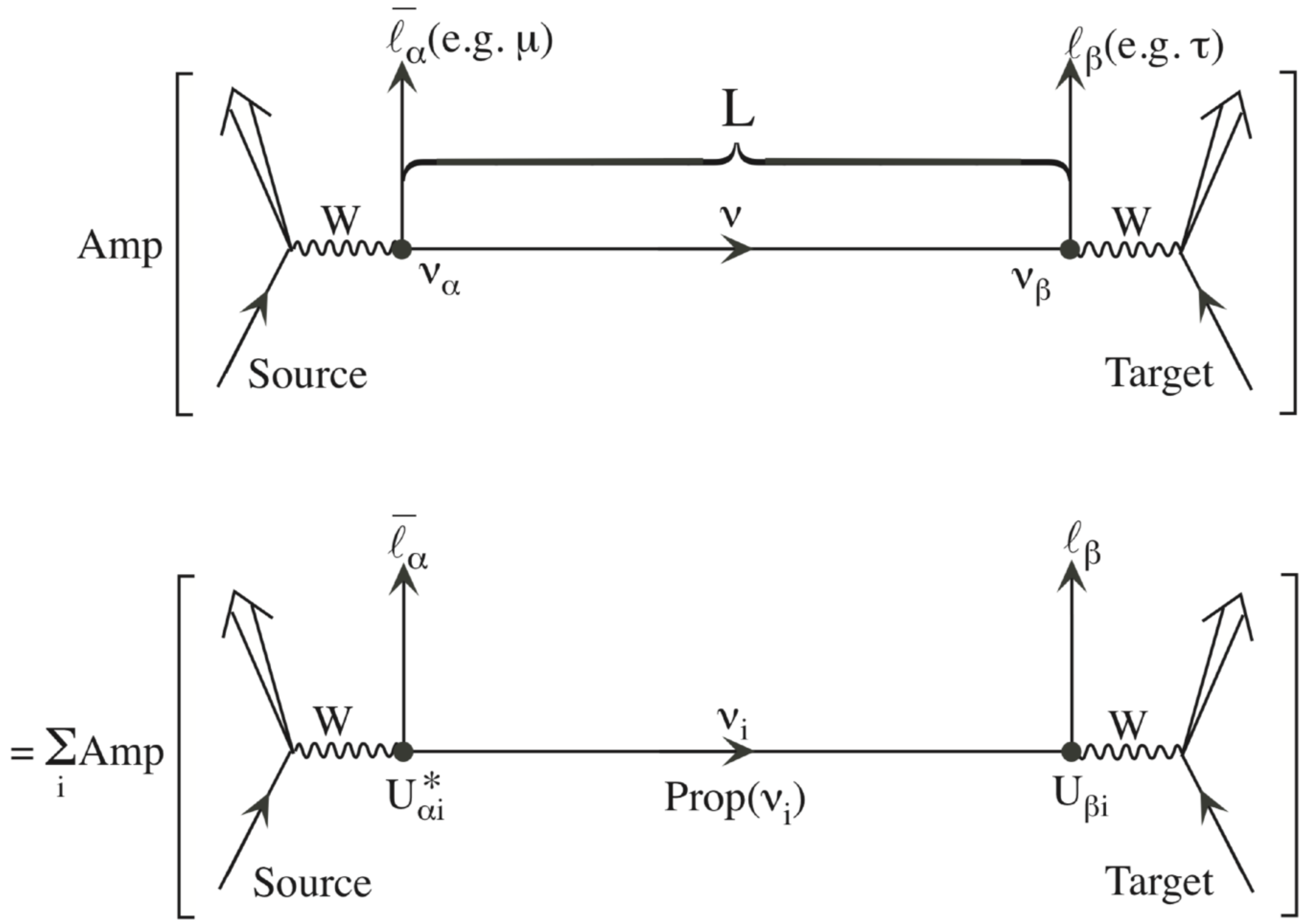
Why Higgs mass so light?

Leptogenesis

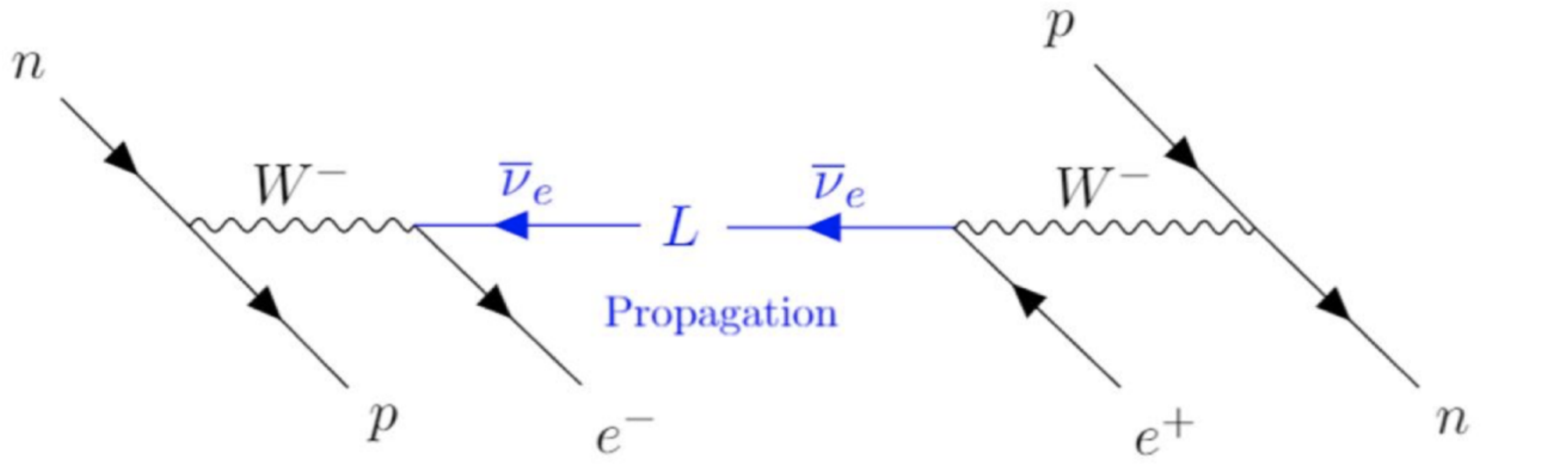
Electroweak baryogengesis

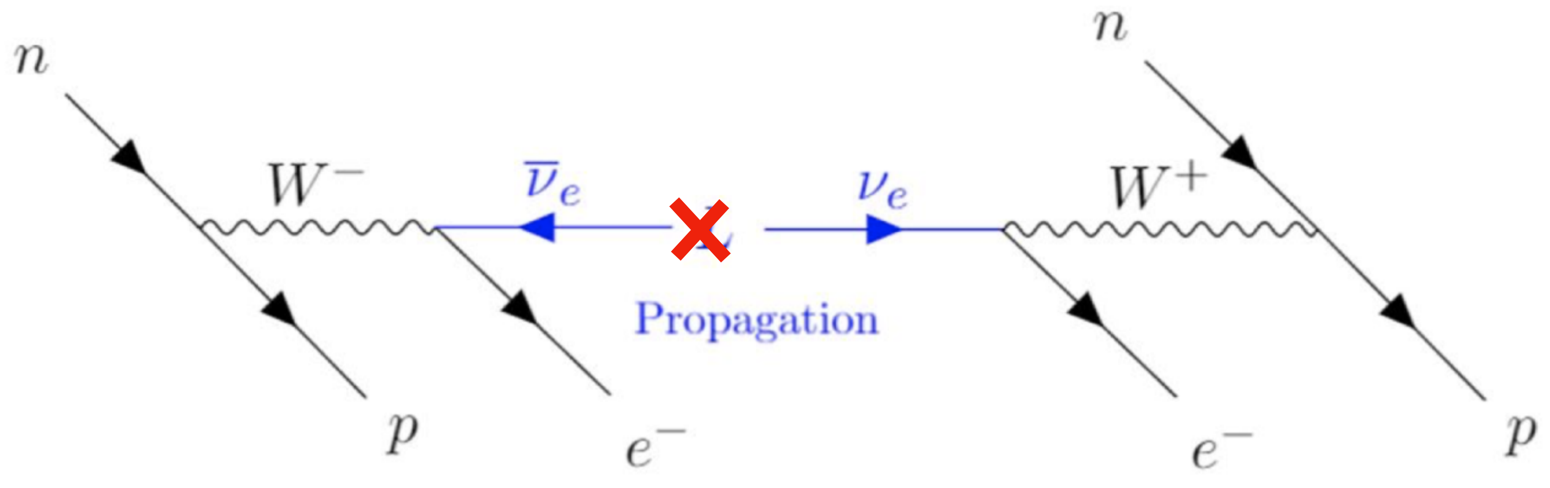
Nature of Majorana Neutrino

How to distinguish Dirac vs Majorana neutrino?



$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta) = \sum_{i=1}^{3} U^*_{\alpha i}\, e^{-i\frac{m_i^2}{2E}L}\, U_{\beta i}$$





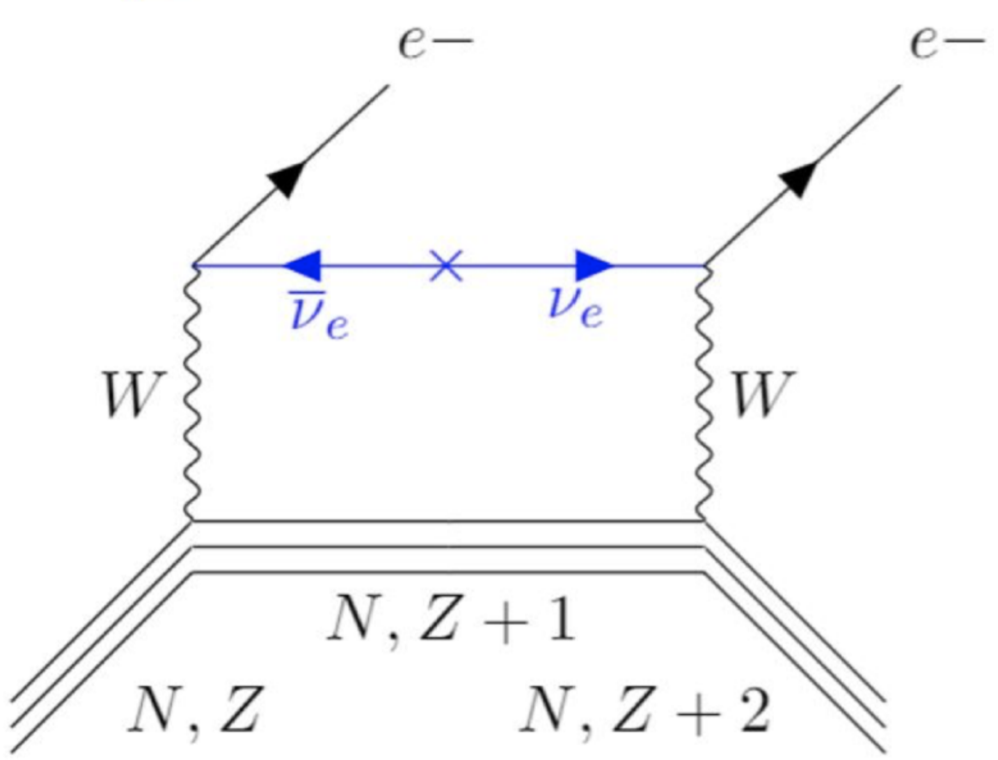
suppressed

by a factor m_ν^2/E^2

$$\mathcal{M} = \mathcal{A} \sum_i (U_{ei})^2 m_{\nu_i} = \mathcal{A}\, m_{\beta\beta}$$

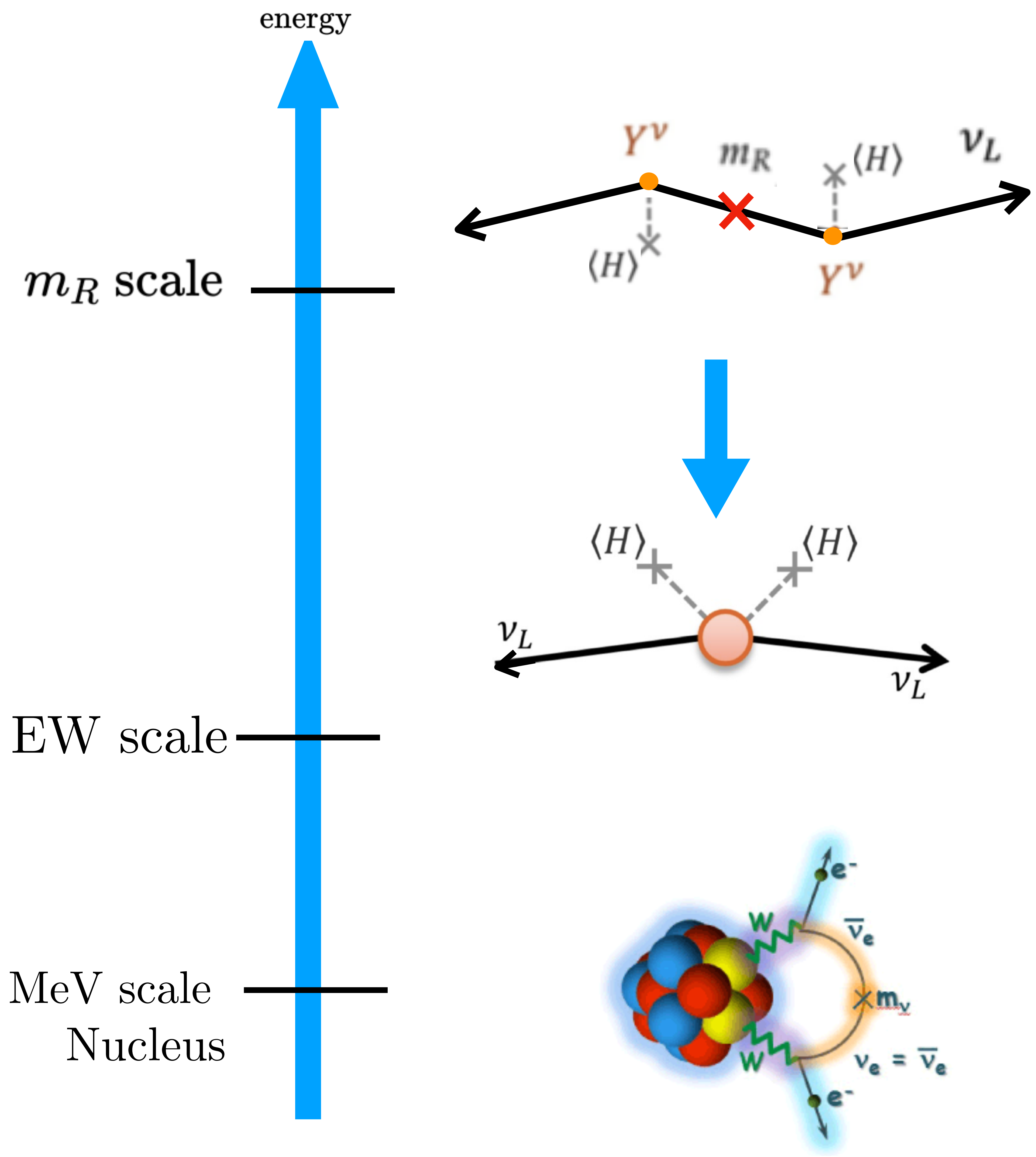
$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_1 e^{2i\lambda_a} + s_{12}^2 c_{13}^2 e^{2i\lambda_b}\sqrt{m_1^2 + \Delta m_{12}^2} + s_{13}^2\sqrt{m_1^2 \pm |\Delta m_{23}^2|}.$$

$0\nu\beta\beta$



Neutrinoless Double Beta Decay

Low energy probe of high energy new physics



[Weinberg, 1979]

Weinberg operator

$$\mathcal{L}_{\text{Weinberg}} = \frac{c_{ij}}{\Lambda}(L_i H)(L_j H) + \text{h.c.}$$

$$\rightarrow c_{ij}\frac{\text{v}^2}{\Lambda}\nu_i\nu_j + \text{h.c.}$$

… the effective field theory point view had predicted the neutrino masses

[Weinberg, 2021]

Standard Model Effective Field Theory

Standard model is viewed as the leading renormalizable terms of most general effective field theory

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \dots$$

[Weinberg, 1980]

Standard Model — Weinberg Operator

$$\frac{c_{ij}}{\Lambda}(L_i H)(L_j H) + \mathrm{h.c.}$$

Scale separation: series expansion can be performed and truncated

Crucial difference between model and eft

Decoupling theorem: EFT does not depend on details of UV scale

Provide modern understanding of renormalization

DOF
SM fields

Symmetry
SM gauge and Lorentz symmetry

Power Counting
Canonical dimension

Standard Model Effective Field Theory (SMEFT) provides systematic parameterization of all possible Lorentz-inv. new physics

SMEFT Dimension-6 Operators

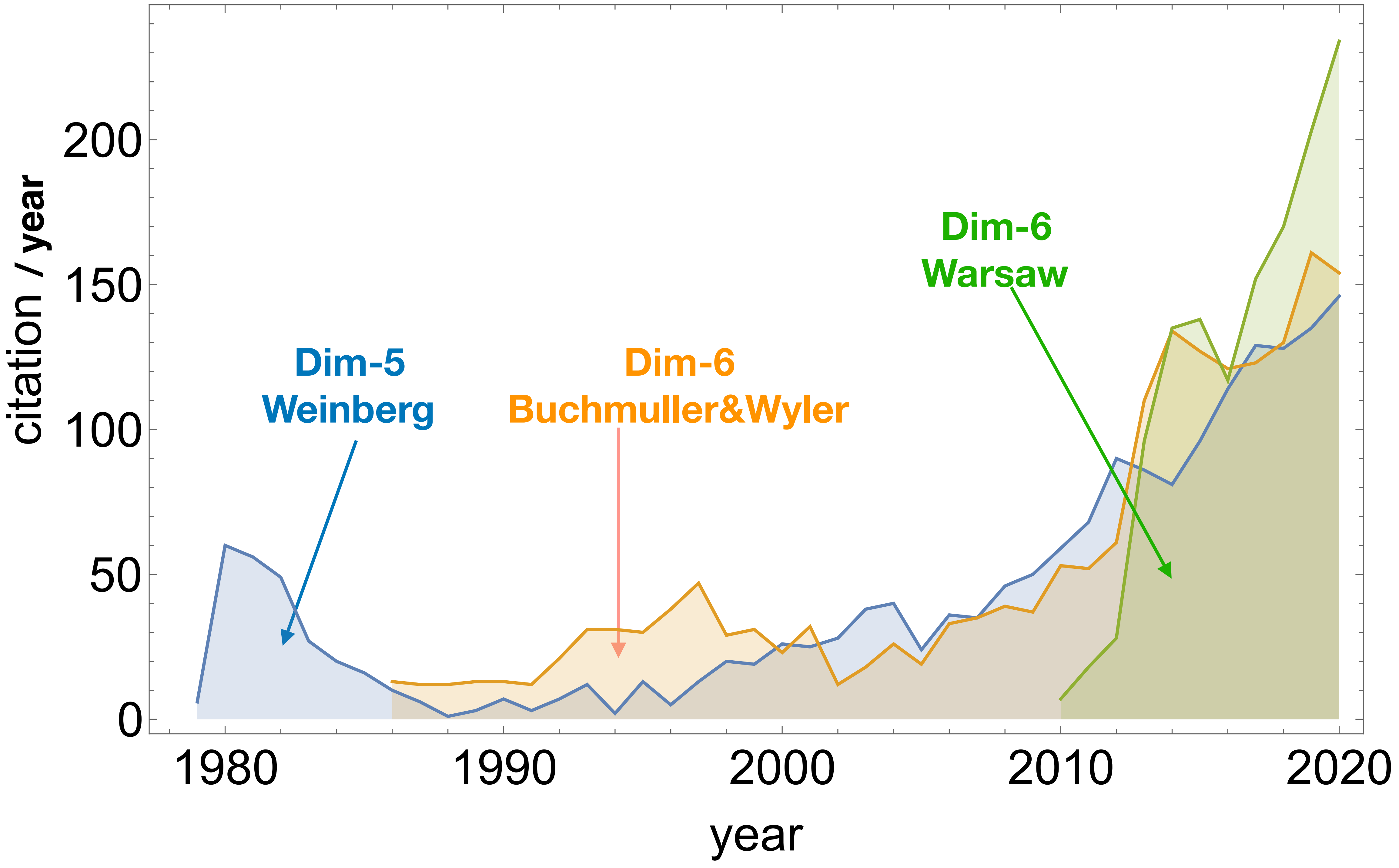
Dimension-6 operators parametrize new physics effects at low energy, electroweak precision, and Higgs boson physics, etc

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \cdots$$

[Buchmuller and Wyler, 1986]

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

One important task of LHC run-3 : dim-6 operator Wilson coefficients



Why take 25 years to write down complete and independent dimension-6 operators?

SMEFT Dimension-6 Operators

[Buchmuller and Wyler, 1986]

$O_\varphi = \frac{1}{3}(\varphi^\dagger\varphi)^3$,
$O_{\partial\varphi} = \frac{1}{2}\partial_\mu(\varphi^\dagger\varphi)\,\partial^\mu(\varphi^\dagger\varphi)$.

$O_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu}$,
$O_{\tilde G} = f_{ABC} \tilde G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu}$,
$O_W = \varepsilon_{IJK} W_\mu^{I\nu} W_\nu^{J\lambda} W_\lambda^{K\mu}$,
$O_{\tilde W} = \varepsilon_{IJK} \tilde W_\mu^{I\nu} W_\nu^{J\lambda} W_\lambda^{K\mu}$.

$O_{e\varphi} = (\varphi^\dagger\varphi)(\bar\ell e\varphi)$,
$O_{u\varphi} = (\varphi^\dagger\varphi)(\bar q u\tilde\varphi)$,
$O_{d\varphi} = (\varphi^\dagger\varphi)(\bar q d\varphi)$,

$O_{\ell B} = i\bar\ell\gamma_\mu D_\nu \ell B^{\mu\nu}$,
$O_{qB} = i\bar q\gamma_\mu D_\nu q B^{\mu\nu}$,

$O_{\varphi G} = \frac{1}{2}(\varphi^\dagger\varphi) G_{\mu\nu}^A G^{A\mu\nu}$,
$O_{\varphi \tilde G} = (\varphi^\dagger\varphi) \tilde G_{\mu\nu}^A G^{A\mu\nu}$,
$O_{\varphi W} = \frac{1}{2}(\varphi^\dagger\varphi) W_{\mu\nu}^I W^{I\mu\nu}$,
$O_{\varphi \tilde W} = (\varphi^\dagger\varphi) \tilde W_{\mu\nu}^I W^{I\mu\nu}$,
$O_{\varphi B} = \frac{1}{2}(\varphi^\dagger\varphi) B_{\mu\nu} B^{\mu\nu}$,
$O_{\varphi \tilde B} = (\varphi^\dagger\varphi) \tilde B_{\mu\nu} B^{\mu\nu}$,
$O_{WB} = (\varphi^\dagger\tau^I\varphi) W_{\mu\nu}^I B^{\mu\nu}$,
$O_{\tilde W B} = (\varphi^\dagger\tau^I\varphi) \tilde W_{\mu\nu}^I B^{\mu\nu}$,
$O_\varphi^{(1)} = (\varphi^\dagger\varphi)(D_\mu\varphi^\dagger D^\mu\varphi)$,
$O_\varphi^{(3)} = (\varphi^\dagger D^\mu\varphi)(D_\mu\varphi^\dagger\varphi)$.

$O_{\ell W} = i\bar\ell\tau^I\gamma_\mu D_\nu \ell W^{I\mu\nu}$,
$O_{eB} = i\bar e\gamma_\mu D_\nu e B^{\mu\nu}$,
$O_{qG} = i\bar q\lambda^A\gamma_\mu D_\nu q G^{A\mu\nu}$,
$O_{qW} = i\bar q\tau^I\gamma_\mu D_\nu q W^{I\mu\nu}$,
$O_{uG} = i\bar u\lambda^A\gamma_\mu D_\nu u G^{A\mu\nu}$,
$O_{uB} = i\bar u\gamma_\mu D_\nu u B^{\mu\nu}$,
$O_{dG} = i\bar d\lambda^A\gamma_\mu D_\nu d G^{A\mu\nu}$,
$O_{dB} = i\bar d\gamma_\mu D_\nu d B^{\mu\nu}$.

$O_{\varphi\ell}^{(1)} = i(\varphi^\dagger D_\mu\varphi)(\bar\ell\gamma^\mu\ell)$,
$O_{\varphi\ell}^{(3)} = i(\varphi^\dagger D_\mu\tau^I\varphi)(\bar\ell\gamma^\mu\tau^I\ell)$,
$O_{\varphi e} = i(\varphi^\dagger D_\mu\varphi)(\bar e\gamma^\mu e)$,
$O_{\varphi q}^{(1)} = i(\varphi^\dagger D_\mu\varphi)(\bar q\gamma^\mu q)$,
$O_{\varphi q}^{(3)} = i(\varphi^\dagger D_\mu\tau^I\varphi)(\bar q\gamma^\mu\tau^I q)$,
$O_{\varphi_u} = i(\varphi^\dagger D_\mu\varphi)(\bar u\gamma^\mu u)$,
$O_{\varphi_d} = i(\varphi^\dagger D_\mu\varphi)(\bar d\gamma^\mu d)$,

$O_{D_e} = (\bar\ell D_\mu e) D^\mu\varphi$,
$O_{\bar D_e} = (D_\mu\bar\ell e) D^\mu\varphi$,
$^\dagger\varepsilon D_\mu\varphi)(\bar u\gamma^\mu d)$.
$O_{Du} = (\bar q D_\mu u) D^\mu\tilde\varphi$,
$O_{\bar Du} = (D_\mu\bar q u) D^\mu\tilde\varphi$,
$O_{Dd} = (\bar q D_\mu d) D^\mu\varphi$,
$O_{\bar Dd} = (D_\mu\bar q d) D^\mu\varphi$,
$O_{eW} = (\bar\ell\sigma^{\mu\nu}\tau^I e)\varphi W_{\mu\nu}^I$,
$O_{eB} = (\bar\ell\sigma^{\mu\nu} e)\varphi B_{\mu\nu}$,
$O_{uG} = (\bar q\sigma^{\mu\nu}\lambda^A u)\tilde\varphi G_{\mu\nu}^A$,
$O_{uW} = (\bar q\sigma^{\mu\nu}\tau^I u)\tilde\varphi W_{\mu\nu}^I$,
$O_{uB} = (\bar q\sigma^{\mu\nu} u)\tilde\varphi B_{\mu\nu}$,
$O_{dG} = (\bar q\sigma^{\mu\nu}\lambda^A d)\varphi G_{\mu\nu}^A$,
$O_{dW} = (\bar q\sigma^{\mu\nu}\tau^I d)\varphi W_{\mu\nu}^I$,
$O_{dW} = (\bar q\sigma^{\mu\nu} d)\varphi B_{\mu\nu}$.

$O_{\ell\ell}^{(1)} = \frac{1}{2}(\bar\ell\gamma_\mu\ell)(\bar\ell\gamma^\mu\ell)$,
$O_{\ell\ell}^{(3)} = \frac{1}{2}(\bar\ell\gamma_\mu\tau^I\ell)(\bar\ell\gamma^\mu\tau^I\ell)$,
$O_{qq}^{(1,1)} = \frac{1}{2}(\bar q\gamma_\mu q)(\bar q\gamma^\mu q)$,
$O_{qq}^{(8,1)} = \frac{1}{2}(\bar q\gamma_\mu\lambda^A q)(\bar q\gamma^\mu\lambda^A q)$,
$O_{qq}^{(1,3)} = \frac{1}{2}(\bar q\gamma_\mu\tau^I q)(\bar q\gamma^\mu\tau^I q)$,
$O_{qq}^{(8,3)} = \frac{1}{2}(\bar q\gamma_\mu\lambda^A\tau^I q)(\bar q\gamma^\mu\lambda^A\tau^I q)$,
$O_{\ell q}^{(1)} = (\bar\ell\gamma_\mu\ell)(\bar q\gamma^\mu q)$,
$O_{\ell q}^{(3)} = (\bar\ell\gamma_\mu\tau^I\ell)(\bar q\gamma^\mu\tau^I q)$.

$O_{ee} = \frac{1}{2}(\bar e\gamma_\mu e)(\bar e\gamma^\mu e)$,
$O_{uu}^{(1)} = \frac{1}{2}(\bar u\gamma_\mu u)(\bar u\gamma^\mu u)$,
$O_{uu}^{(8)} = \frac{1}{2}(\bar u\gamma_\mu\lambda^A u)(\bar u\gamma^\mu\lambda^A u)$,
$O_{dd}^{(1)} = \frac{1}{2}(\bar d\gamma_\mu d)(\bar d\gamma^\mu d)$,
$O_{dd}^{(8)} = \frac{1}{2}(\bar d\gamma_\mu\lambda^A d)(\bar d\gamma^\mu\lambda^A d)$,
$O_{eu} = (\bar e\gamma_\mu e)(\bar u\gamma^\mu u)$,
$O_{ed} = (\bar e\gamma_\mu e)(\bar d\gamma^\mu d)$,
$O_{ud}^{(1)} = (\bar u\gamma_\mu u)(\bar d\gamma^\mu d)$,
$O_{ud}^{(8)} = (\bar u\gamma_\mu\lambda^A u)(\bar d\gamma^\mu\lambda^A d)$.

$O_{\ell e} = (\bar\ell e)(\bar e\ell)$,
$O_{\ell u} = (\bar\ell u)(\bar u\ell)$,
$O_{\ell d} = (\bar\ell d)(\bar d\ell)$,
$O_{qe} = (\bar q e)(\bar e q)$,
$O_{qu}^{(1)} = (\bar q u)(\bar u q)$,
$O_{qd}^{(1)} = (\bar q d)(\bar d q)$,
$O_{qde} = (\bar\ell e)(\bar d q)$.

$O_{qq}^{(1)} = (\bar q u)(\bar q d)$,
$O_{qq}^{(8)} = (\bar q\lambda^A u)(\bar q\lambda^A d)$,
$O_{\ell q} = (\bar\ell e)(\bar q u)$.
$O_{qu}^{(8)} = (\bar q\lambda^A u)(\bar u\lambda^A q)$,
$O_{qd}^{(8)} = (\bar q\lambda^A d)(\bar d\lambda^A q)$,

Equation of motion (field redefinition)

$$(D^\mu D_\mu\varphi)^j = m^2\varphi^j - \lambda(\varphi^\dagger\varphi)\varphi^j - \bar e\,\Gamma_e^\dagger l^j + \varepsilon_{jk}\bar q^k\,\Gamma_u u - \bar d\,\Gamma_d^\dagger q^j$$

$$i\not{D} l = \Gamma_e e\varphi, \quad i\not{D} e = \Gamma_e^\dagger\varphi^\dagger l, \quad i\not{D} q = \Gamma_u u\tilde\varphi + \Gamma_d d\varphi, \quad i\not{D} u = \Gamma_u^\dagger\tilde\varphi^\dagger q,$$

$$(D^\rho W_{\rho\mu})^I = \frac{g}{2}\left(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi + \bar l\gamma_\mu\tau^I l + \bar q\gamma_\mu\tau^I q\right),$$

Covariant derivative commutator

$$[D_\rho, D_\alpha] \sim X_{\rho\alpha}$$

80 → 59

Bianchi identity $D_{[\rho}X_{\mu\nu]} = 0$

Integration by part (total derivatives)

$$(D^n\varphi)^\dagger(D^m\varphi) = -(D^{n+1}\varphi)^\dagger(D^{m-1}\varphi) + \partial\left[(D^n\varphi)^\dagger(D^{m-1}\varphi)\right]$$

Fierz identity

$$T_{\alpha\beta}^A T_{\kappa\lambda}^A = \frac{1}{2}\delta_{\alpha\lambda}\delta_{\kappa\beta} - \frac{1}{6}\delta_{\alpha\beta}\delta_{\kappa\lambda}$$

$$\tau_{jk}^I\tau_{mn}^I = 2\delta_{jn}\delta_{mk} - \delta_{jk}\delta_{mn}$$

80-1-16-5+1 = 59

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$		

Higher Dim Operators for nv mass and 0vbb

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2201.04639]

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2012.09188]

[Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2007.07899]

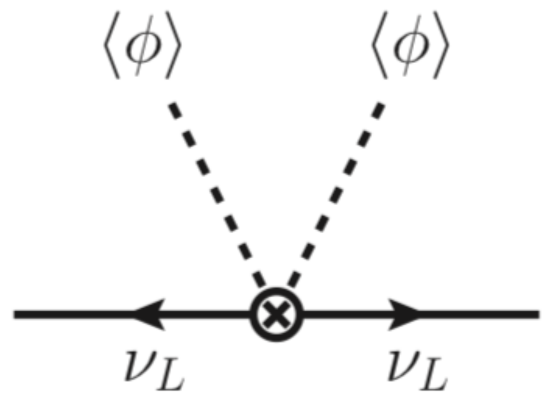
[Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2206.07722]

[Hao Sun, Ming-Lei Xiao, **J.H.Yu**, 2206.07722]

[Hao Sun, Yi-Ning Wang, **J.H.Yu**, in préparation]

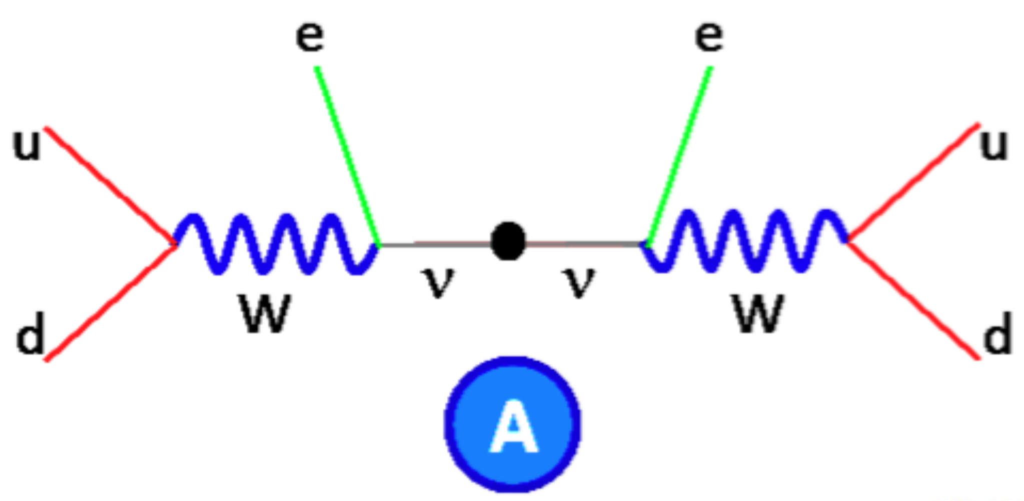
Why Higher Dim Operators?

SMEFT dim-5,7,9 operators provides most general parametrization of new physics for neutrino masses and 0vbb

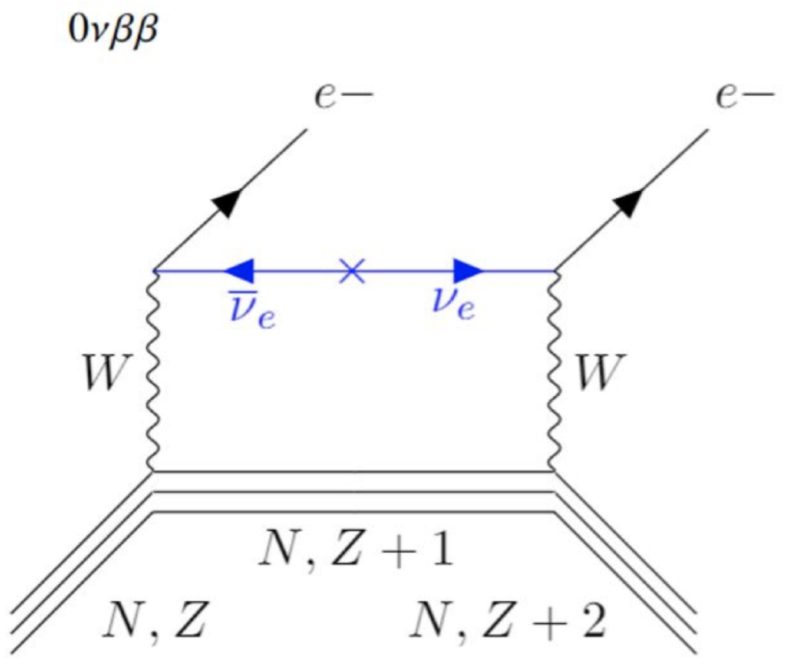


Dim-5, 7, 9 neutrino mass

Correlated between mv and 0vbb

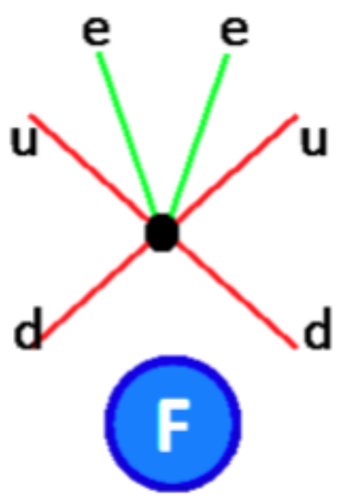


$\mathcal{O}_5$	$\epsilon^{ik}\epsilon^{jl}(\ell_i^T C\ell_j)H_k H_l$
$\mathcal{O}_{LH}$	$\epsilon^{ik}\epsilon^{jl}(\ell_i^T C\ell_j)H_k H_l(H^\dagger H)$

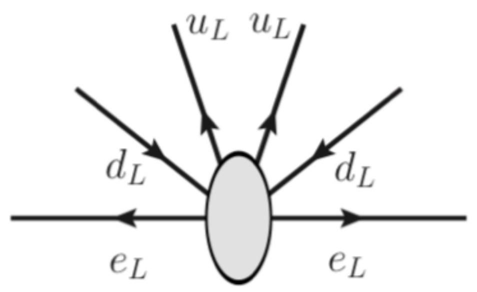


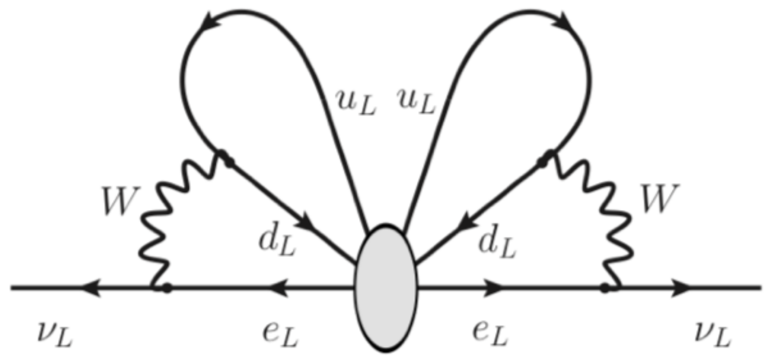
0vbb does not need to be related to the total neutrino masses

Lepton number violation operator



$dc^2\, L^2\, Q^2$, $dc^2\, dc^\dagger\, L^2\, uc^\dagger$, $dc\, L^2\, uc\, uc^{\dagger 2}$, $dc^2\, ec^\dagger\, L\, Q\, uc^\dagger$,
$dc^{\dagger 2}\, ec^2\, uc^2$, $dc\, L^2\, Q\, Q^\dagger\, uc^\dagger$, $dc^\dagger\, ec\, L^\dagger\, Q\, uc^2$, $L^{\dagger 2}\, Q^2\, uc^2$

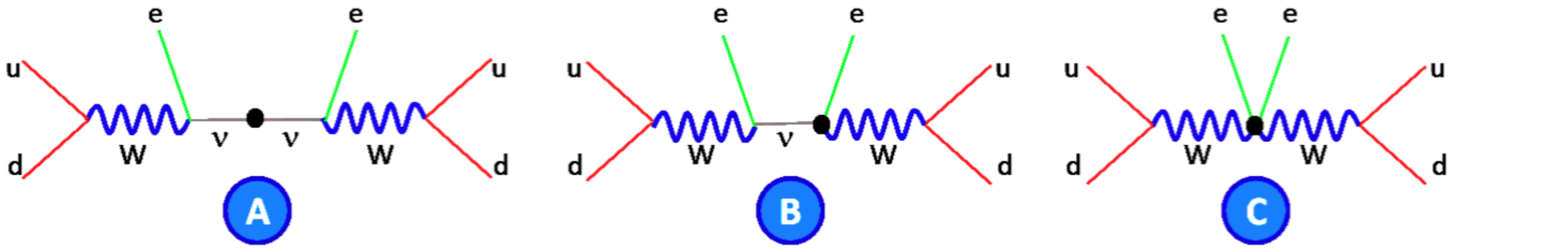


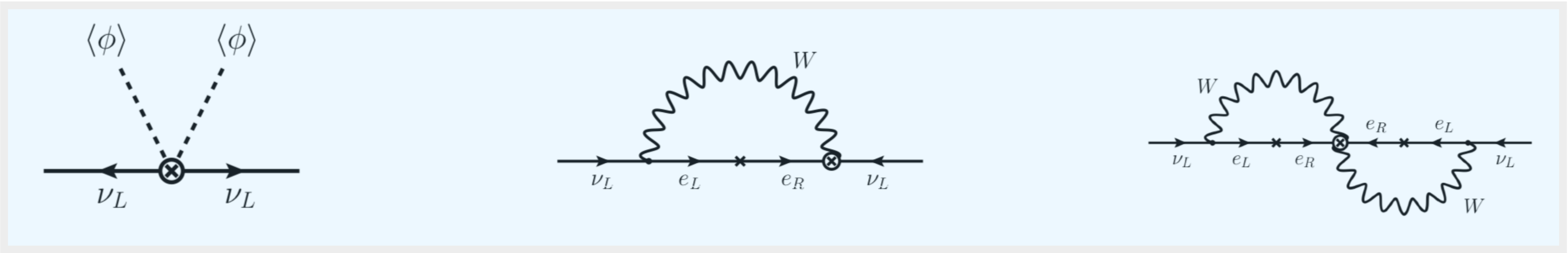


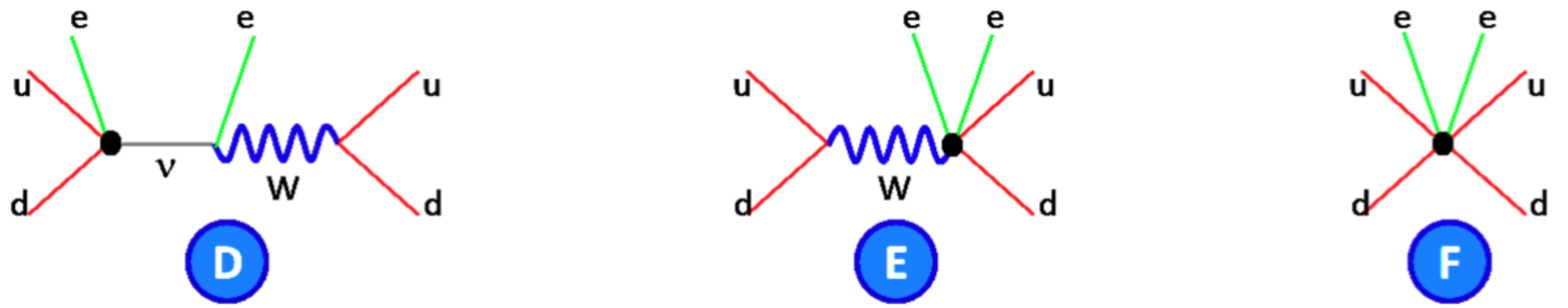
Very tiny loop-level neutrino mass

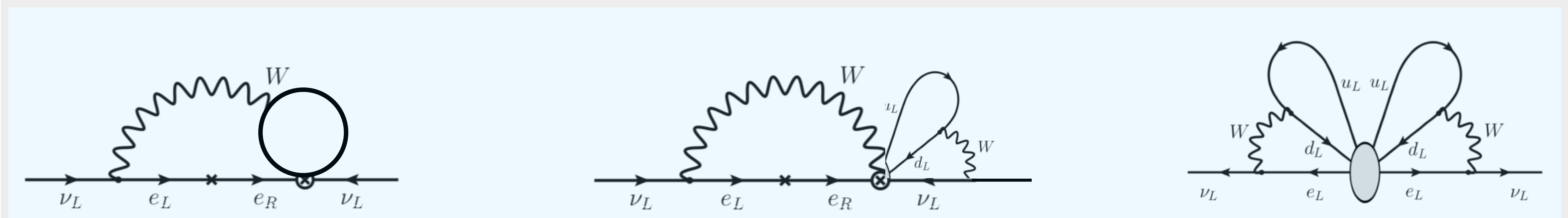
0vbb and Neutrino Masses

Schechter-Valle Theorem: Whatever processes cause 0vbb, its observation would imply existence of Majorana mass term



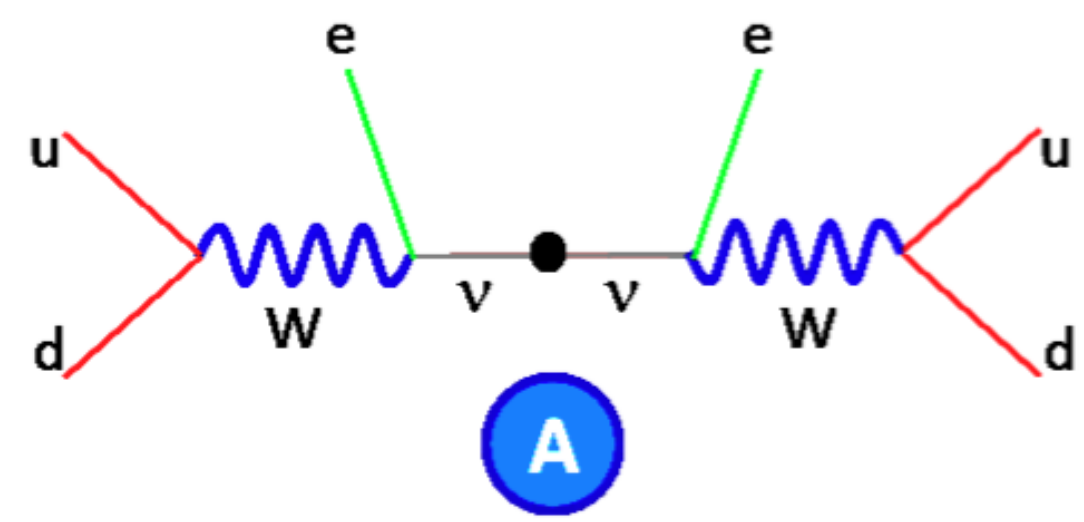


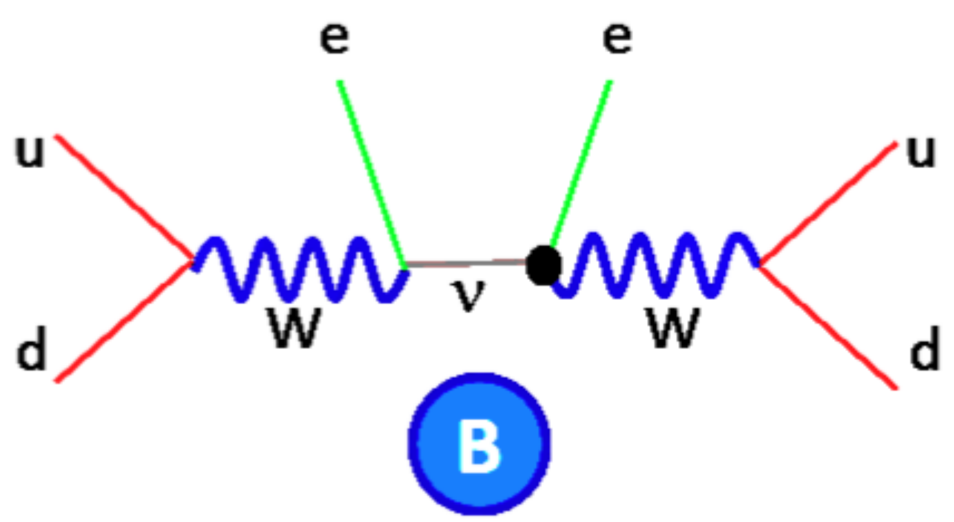


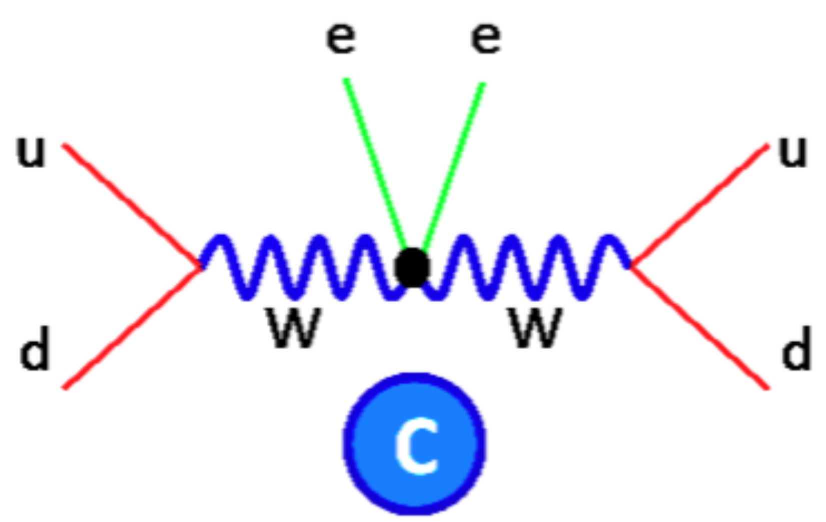


Why Higher Dim Operators?

SMEFT dim-5,7,9 operators provides most general parametrization of the new physics effects in 0vbb process







Dim-5, 7

$\mathcal{O}_5$	$\epsilon^{ik}\epsilon^{jl}(\ell_i^T C\ell_j)H_k H_l$
$\mathcal{O}_{LH}$	$\epsilon^{ik}\epsilon^{jl}(\ell_i^T C\ell_j)H_k H_l(H^\dagger H)$

Dim-7

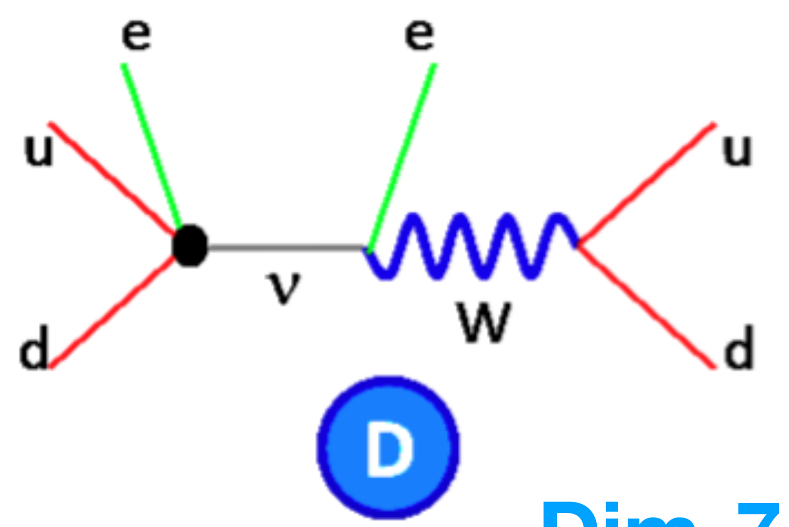
$\mathcal{O}_{LeHD}$	$\epsilon^{ij}\epsilon^{kl}(\ell_i^T C\gamma^\mu e)H_j H_k(iD_\mu H_l)$
$\mathcal{O}_{LHW}$	$-\epsilon^{ik}(\epsilon\tau^I)^{jl}(\ell_i^T Ci\sigma^{\mu\nu}\ell_j)H_k H_l W_{\mu\nu}^I$

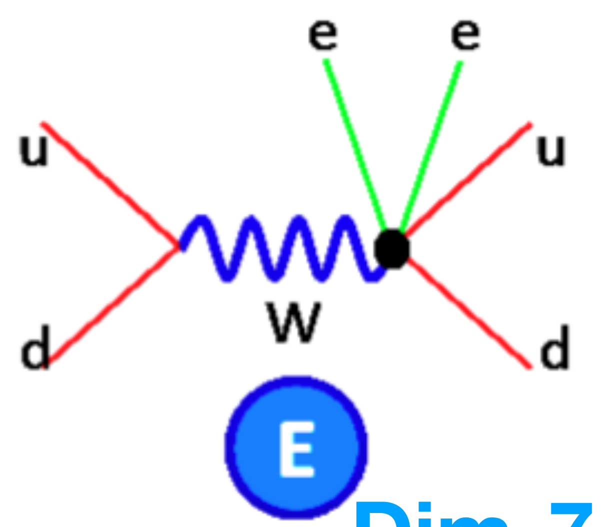
Dim-7, 9

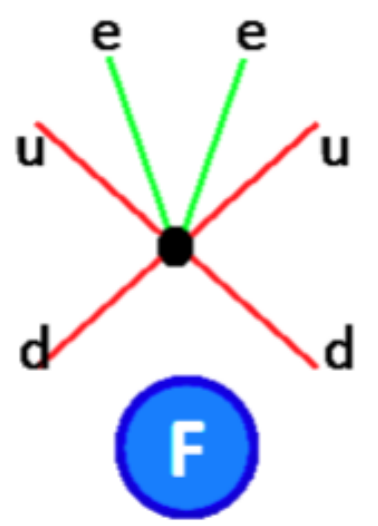
$D^2\ H^{\dagger 2}\ L^{\dagger 2}$

$\mathcal{O}_{LHD1}$ $\epsilon^{ij}\epsilon^{kl}(\ell_i^T CD_\mu\ell_j)(H_k D^\nu H_l)$

$D^2\ H^{\dagger 2}\ L^{\dagger 2}\ WL$







Dim-7

$\mathcal{O}_{dLQLH1}$	$\epsilon^{ij}\epsilon^{kl}(\bar{d}^a\ell_i)(q_{aj}^T C\ell_k)H_l$
$\mathcal{O}_{dLQLH2}$	$\epsilon^{ik}\epsilon^{jl}(\bar{d}^a\ell_i)(q_{aj}^T C\ell_k)H_l$
$\mathcal{O}_{dLueH}$	$\epsilon^{ij}(\bar{d}^a\ell_i)(u_a^T Ce)H_j$
$\mathcal{O}_{QuLLH}$	$\epsilon^{ij}(\bar{q}^{ak}u_a)(\ell_k^T C\ell_i)H_j$

Dim-7, 9

$\mathcal{O}_{duLLD}$ $\epsilon^{ij}(\bar{d}^a\gamma^\mu u_a)(\ell_i^T CiD_\mu\ell_j)$

$D\ dc^\dagger\ L^{\dagger 2}\ uc$

$dc^\dagger\ ec\ H^\dagger\ L^\dagger\ uc\ WL$

Dim-9

$dc^2\ L^2\ Q^2$, $dc^2\ dc^\dagger\ L^2\ uc^\dagger$, $dc\ L^2\ uc\ uc^{\dagger 2}$, $dc^2\ ec^\dagger\ L\ Q\ uc^\dagger$,
$dc^{\dagger 2}\ ec^2\ uc^2$, $dc\ L^2\ Q\ Q^\dagger\ uc^\dagger$, $dc^\dagger\ ec\ L^\dagger\ Q\ uc^2$, $L^{\dagger 2}\ Q^2\ uc^2$

How to obtain complete and independent higher dim operators?

Operator with Spinor Indices

Operator has more symmetries than what we expected

Field as irreducible rep of Lorentz group → **Field transforming under Little group of Poincare**

SO(3,1)	SL(2,C) $SU(2)_l \times SU(2)_r$	Spinor-helicity	Building blocks in spinor-helicity form
ϕ	$\phi \in (0,0)$		$D^{r_i}\phi_i \Leftrightarrow \lambda_i^{r_i}\tilde{\lambda}^{i,r_i}$,
ψ	$\psi_\alpha \in (1/2,0)$ $\psi^\dagger_{\dot\alpha} \in (0,1/2)$,	λ_α	$D^{r_i-1/2}\psi_i^{(\dagger)} \Leftrightarrow \lambda_i^{r_i\pm1/2}\tilde{\lambda}^{i,r_i\mp1/2}$,
$F_{\mu\nu}$	$F_{L\alpha\beta} = \frac{i}{2}F_{\mu\nu}\sigma^{\mu\nu}_{\alpha\beta} \in (1,0)$ $F_{R\dot\alpha\dot\beta} = -\frac{i}{2}F_{\mu\nu}\bar\sigma^{\mu\nu}_{\dot\alpha\dot\beta} \in (0,1)$.	$\lambda_\alpha\lambda_\beta$	$D^{r_i-1}F_{L/R\,i} \Leftrightarrow \lambda_i^{r_i\pm1}\tilde{\lambda}^{i,r_i\mp1}$,
$R_{\mu\nu\rho\sigma}$	$\mathcal{C}_{\alpha\beta\gamma\delta} = C_{\mu\nu\rho\sigma}\sigma^{\mu\nu}_{\alpha\beta}\sigma^{\rho\sigma}_{\gamma\delta} \in (2,0)$	$\lambda_\alpha\lambda_\beta\lambda_\gamma\lambda_\delta$	$D^{r_i-2}C_{L/R\,i} \Leftrightarrow \lambda_i^{r_i\pm2}\tilde{\lambda}^{i,r_i\mp2}$,
D_μ	$D_{\alpha\dot\alpha} = D_\mu\sigma^\mu_{\alpha\dot\alpha} \in (1/2,1/2)$.	$\lambda_\alpha\tilde\lambda_{\dot\alpha}$	

On-shell operator

$$\mathcal{O}_N^{(d)} = (\epsilon^{\alpha_i\alpha_j})^{\otimes n}(\tilde\epsilon_{\dot\alpha_i\dot\alpha_j})^{\otimes\tilde n}\prod_{i=1}^{N}(D^{r_i-|h_i|}\Psi_{i,a_i})^{\dot\alpha_i^{r_i+h_i}}_{\alpha_i^{r_i-h_i}}$$

$$F_{L1}{}^{\alpha\beta}F_{L2\alpha\beta}(D\phi_3)^\gamma{}_{\dot\alpha}(D\phi_4)_\gamma{}^{\dot\alpha}$$

$\mathcal{M} \to e^{ih_i\varphi}\mathcal{M}$

$\lambda_i \to e^{-i\varphi/2}\lambda_i, \quad \tilde\lambda^i \to e^{i\varphi/2}\tilde\lambda^i.$

$$(\epsilon^{\alpha_i\alpha_j})^{\otimes n}(\tilde\epsilon_{\dot\alpha_i\dot\alpha_j})^{\otimes\tilde n}\prod_{i=1}^{N}\lambda_i^{r_i-h_i}\tilde\lambda^{i,r_i+h_i}$$

$\langle ij\rangle = \epsilon^{\beta\alpha}\lambda_{i\alpha}\lambda_{j\beta}$

$[ij] = \tilde\lambda_{i\dot\alpha}\tilde\epsilon^{\dot\alpha\dot\beta}\tilde\lambda_{j\dot\beta}$

On-shell Brackets

$\langle12\rangle^2\langle34\rangle[34]$

EOM and CDC

$D^2\phi_i \Leftrightarrow p_i^2 = 0$

$[D_\mu, D_\nu] \Leftrightarrow [p_\mu, p_\nu] = 0$

Operator as On-shell Amplitude

[Li, Ren, Xiao, **Yu**, Zheng, 2201.04639]
[Li, Ren, Xiao, **Yu**, Zheng, 2012.09188]
[Li, Ren, Xiao, **Yu**, Zheng, 2007.07899]
[Li, Ren, Shu, Xiao, **Yu**, Zheng, 2005.00008]

Operator $W_{\mu\lambda}\left(e_{\mathbb{C}p}\sigma^{\nu\lambda}D^{\mu}L_r\right)D_{\nu}H^{\dagger}$

↓

Spinor Tensor → **Symmetrize indices**

$$\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_1\alpha_3}\epsilon_{\alpha_2\alpha_4}\epsilon^{\dot\alpha_3\dot\alpha_4}F_1^{\alpha_1^2}\psi_2^{\alpha_2}\left(D\psi_3\right)^{\alpha_3^2}_{\dot\alpha_3}\left(D\phi_4\right)^{\alpha_4}_{\dot\alpha_4}$$

$$D_{[\alpha\dot\alpha}D_{\beta]\dot\beta} = D_\mu D_\nu \sigma^\mu_{[\alpha\dot\alpha}\sigma^\nu_{\beta]\dot\beta} = -D^2\epsilon_{\alpha\beta}\epsilon_{\dot\alpha\dot\beta} + \frac{i}{2}[D_\mu, D_\nu]\epsilon_{\alpha\beta}(\bar\sigma^{\mu\nu})_{\dot\alpha\dot\beta},$$

$$D_{[\alpha\dot\alpha}\psi_{\beta]} = D_\mu\sigma^\mu_{[\alpha\dot\alpha}\psi_{\beta]} = -\epsilon_{\alpha\beta}(D_\mu\sigma^\mu\psi)_{\dot\alpha},$$

$$D_{[\alpha\dot\alpha}F_{L\beta]\gamma} = \frac{i}{2}D_\mu F_{L\nu\rho}\sigma^\mu_{[\alpha\dot\alpha}\sigma^{\nu\rho}_{\beta]\gamma} = iD^\mu F_{L\mu\nu}\epsilon_{\alpha\beta}\sigma^\nu_{\gamma\dot\alpha},$$

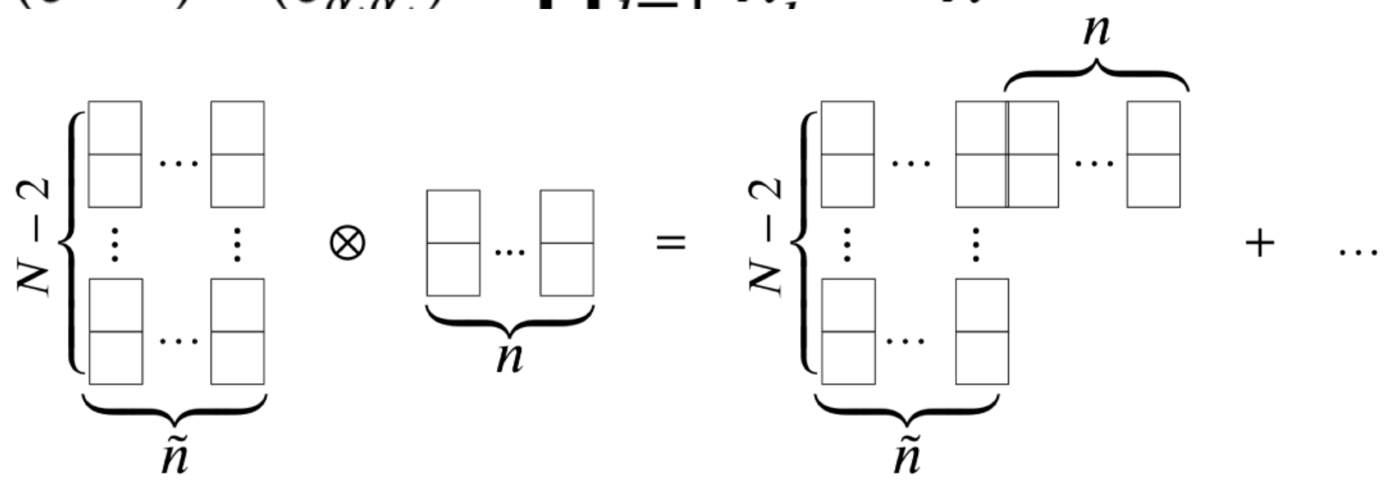
$$(D\psi)_{\alpha\beta\dot\alpha} = -\frac{1}{2}\epsilon_{\alpha\beta}(\not{D}\psi)_{\dot\alpha} + \frac{1}{2}(D\psi)_{(\alpha\beta)\dot\alpha}$$

↓

SL(2,C) x SU(N)

$$\lambda_i \to \sum_j U_i^j\lambda_j, \quad \tilde\lambda^i \to \sum_k U^{\dagger i}{}_k\tilde\lambda^k,$$

$$(\epsilon^{\alpha_i\alpha_j})^{\otimes n}(\tilde\epsilon_{\dot\alpha_i\dot\alpha_j})^{\otimes\tilde n}\prod_{i=1}^N \lambda_i^{r_i-h_i}\tilde\lambda^{i,r_i+h_i}$$



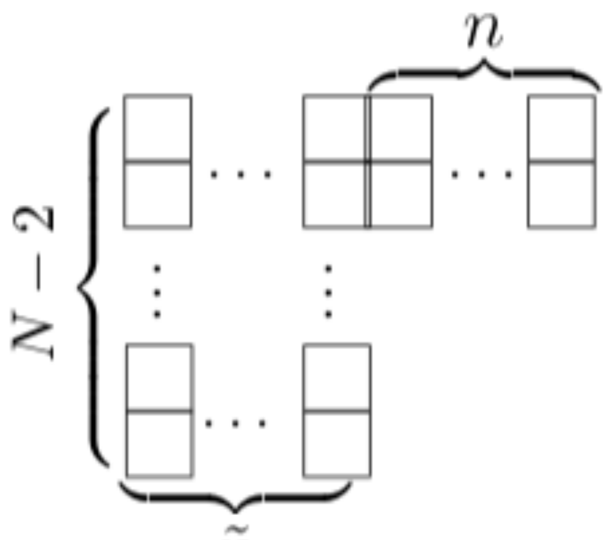
Momentum conservation

$$\delta^{(4)}\left(\sum_{i=1}^N \lambda_i\tilde\lambda_i\right)$$

$$\sum_i \lambda_i\tilde\lambda^i \to \sum_i\sum_j\sum_k U_i^j U^{\dagger i}{}_k\lambda_j\tilde\lambda^k = \sum_j \lambda_j\tilde\lambda^j$$

↓

SSYT



$$\overbrace{\{1,\ldots,1}^{\#1},\overbrace{2,\ldots,2}^{\#2},\ldots,\overbrace{N,\ldots,N\}}^{\#N}$$

$$\#i = \tilde n - 2h_i$$

→ **On-shell Amplitude**

$\begin{array}{|c|}\hline i \\ \hline j \\ \hline\end{array} \Leftrightarrow \langle ij\rangle$

1	1	1	2
2	3	3	4

$\langle 13\rangle\langle 13\rangle\langle 24\rangle[34]$ $\quad F_{L1}^{\alpha\beta}\psi_2^{\gamma}(D\psi_3)_{\alpha\beta\dot\alpha}(D\phi_4)_\gamma{}^{\dot\alpha}$

1	1	1	3
2	2	3	4

$\langle 12\rangle\langle 13\rangle\langle 34\rangle[34]$ $\quad F_{L1}^{\alpha\beta}\psi_{2\alpha}(D\psi_3)_\beta{}^\gamma{}_{\dot\alpha}(D\phi_4)_\gamma{}^{\dot\alpha}$

On-shell Amplitude correspondence

Operator as Spinor Young Tensor

Dim-8 operators: 993 (44807) operators for 1 (3) generations

Traditional method

$\boxed{BWHH^\dagger D^2}$ [Hays, Martin, Sanz, Setford, 2018]

$$(D^2H^\dagger)HB_{L\mu\nu}W_L^{\mu\nu},\ (D^\mu D_\nu H^\dagger)HB_{L\mu\rho}W_L^{\nu\rho},\ (D_\nu D^\mu H^\dagger)HB_{L\mu\rho}W_L^{\nu\rho},\ (D_\mu H^\dagger)(D^\mu H)B_{L\nu\rho}W_L^{\nu\rho},$$
$$(D_\mu H^\dagger)(D^\nu H)B_{L\nu\rho}W_L^{\mu\rho},\ (D^\nu H^\dagger)(D_\mu H)B_{L\nu\rho}W_L^{\mu\rho},\ (D_\mu H^\dagger)H(D^\mu B_{L\nu\rho})W_L^{\nu\rho},\ (D_\mu H^\dagger)H(D^\nu B_{L\nu\rho})W_L^{\mu\rho},$$
$$(D^\nu H^\dagger)H(D_\mu B_{L\nu\rho})W_L^{\mu\rho},\ (D_\mu H^\dagger)HB_{L\nu\rho}(D^\mu W_L^{\nu\rho}),\ (D_\mu H^\dagger)HB_{L\nu\rho}(D^\nu W_L^{\mu\rho}),\ (D^\nu H^\dagger)HB_{L\nu\rho}(D_\mu W_L^{\mu\rho}),$$
$$H^\dagger(D^2H)B_{L\mu\nu}W_L^{\mu\nu},\ H^\dagger(D^\mu D_\nu H)B_{L\mu\rho}W_L^{\nu\rho},\ H^\dagger(D_\nu D^\mu H)B_{L\mu\rho}W_L^{\nu\rho},\ H^\dagger(D^\mu H)(D_\mu B_{L\nu\rho})W_L^{\nu\rho},$$
$$H^\dagger(D^\nu H)(D_\mu B_{L\nu\rho})W_L^{\mu\rho},\ H^\dagger(D_\mu H)(D^\nu B_{L\nu\rho})W_L^{\mu\rho},\ H^\dagger(D^\mu H)B_{L\nu\rho}(D_\mu W_L^{\nu\rho}),\ H^\dagger(D^\nu H)B_{L\nu\rho}(D_\mu W_L^{\mu\rho}),$$
$$H^\dagger(D_\mu H)B_{L\nu\rho}(D^\nu W_L^{\mu\rho}),\ H^\dagger H(D^2B_{L\mu\nu})W_L^{\mu\nu},\ H^\dagger H(D^\mu D_\nu B_{L\mu\rho})W_L^{\nu\rho},\ H^\dagger H(D_\nu D^\mu B_{L\mu\rho})W_L^{\nu\rho},$$
$$H^\dagger H(D^\mu B_{L\nu\rho})(D_\mu W_L^{\nu\rho}),\ H^\dagger H(D^\nu B_{L\nu\rho})(D_\mu W_L^{\mu\rho}),\ H^\dagger H(D_\mu B_{L\nu\rho})(D^\nu W_L^{\mu\rho}),\ H^\dagger HB_{L\mu\nu}(D^2W_L^{\mu\nu}),$$
$$H^\dagger HB_{L\mu\rho}(D^\mu D_\nu W_L^{\nu\rho}),\ H^\dagger HB_{L\mu\rho}(D_\nu D^\mu W_L^{\nu\rho}). \quad (14)$$

30

EOM

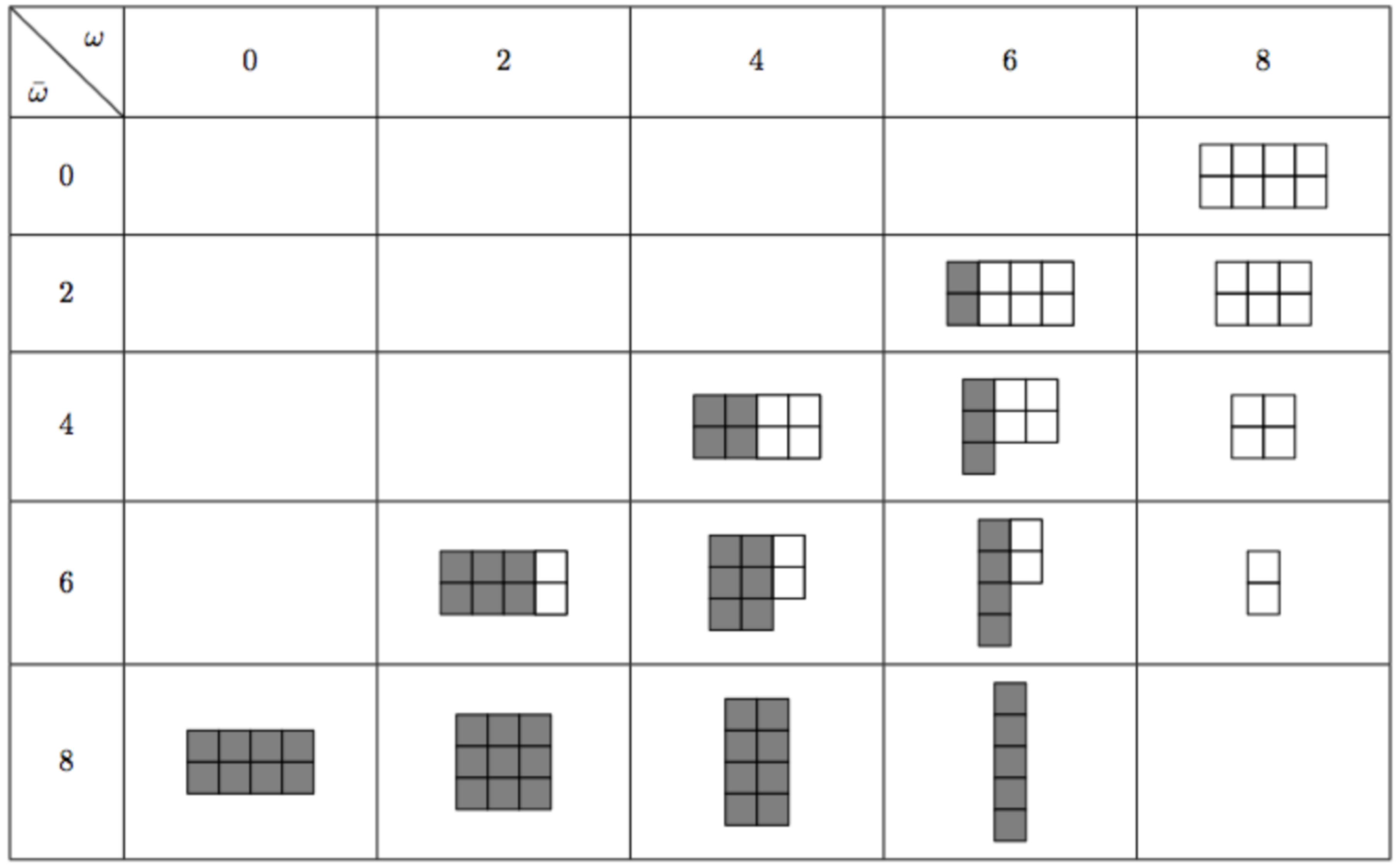
$$(DH^\dagger)_{\alpha\dot\alpha}(DH)_{\beta\dot\beta}B_{L\{\gamma\delta\}}W_{L\{\xi\eta\}}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$(DH^\dagger)_{\alpha\dot\alpha}(DH)_{\beta\dot\beta}B_{L\{\gamma\delta\}}W_{L\{\xi\eta\}}\,\tfrac{1}{2}\epsilon^{\dot\alpha\dot\beta}\epsilon^{\delta\xi}(\epsilon^{\alpha\gamma}\epsilon^{\beta\eta}+\epsilon^{\beta\gamma}\epsilon^{\alpha\eta})$$
$$(DH^\dagger)_{\alpha\dot\alpha}\,H\,(DB_L)_{\{\beta\gamma\delta\},\dot\beta}W_{L\{\xi\eta\}}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$(DH^\dagger)_{\alpha\dot\alpha}\,H\,B_{L\{\xi\eta\}}(DW_L)_{\{\beta\gamma\delta\},\dot\beta}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$H^\dagger\,(DH)_{\alpha\dot\alpha}\,(DB_L)_{\{\beta\gamma\delta\},\dot\beta}W_{L\{\xi\eta\}}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$H^\dagger\,(DH)_{\alpha\dot\alpha}\,B_{L\{\xi\eta\}}(DW_L)_{\{\beta\gamma\delta\},\dot\beta}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$H^\dagger H\,(DB_L)_{\{\alpha\beta\gamma\},\dot\alpha}(DW_L)_{\{\xi\eta\delta\},\dot\beta}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\xi}\epsilon^{\beta\eta}\epsilon^{\gamma\delta}$$

7

IBP

$$B_L{}^{\alpha\beta}W_{L\alpha\beta}\,(DH^\dagger)^{\gamma}{}_{\dot\alpha}\,(DH)_{\gamma}{}^{\dot\alpha}$$
$$B_L{}^{\alpha\beta}W_{L\alpha}{}^{\gamma}\,(DH^\dagger)_{\beta\dot\alpha}\,(DH)_{\gamma}{}^{\dot\alpha}$$

2



$\boxed{BWHH^\dagger D^2}$ $\#1=3, \#2=3, \#3=1, \#4=1$

1	1	1	3
2	2	2	4

1	1	1	2
2	2	3	4

2

$\langle 13\rangle\langle 13\rangle\langle 24\rangle[34]$ $\langle 12\rangle\langle 13\rangle\langle 34\rangle[34]$

$B_L{}^{\alpha\beta}W_{L\alpha\beta}\,(DH^\dagger)^{\gamma}{}_{\dot\alpha}\,(DH)_{\gamma}{}^{\dot\alpha}$, $B_L{}^{\alpha\beta}W_{L\alpha}{}^{\gamma}\,(DH^\dagger)_{\beta\dot\alpha}\,(DH)_{\gamma}{}^{\dot\alpha}$

EFT Operator Bases

$$\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \dots$$

Standard Model Effective Field Theory

SU(3) x SU(2) x U(1) gauge symmetry

Dim-5	[Weinberg, 1979]
Dim-6	[Buchmuller, Wyler, 1986] [Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]
Dim-7	[Lehman, 2014] [Henning, Lu, Melia, Murayama, 2015] [Liao, Ma, 2016]
Dim-8	[Li, Ren, Shu, Xiao, **Yu**, Zheng, **2020**] [Murphy, 2020]
Dim-9	[Li, Ren, Xiao, **Yu**, Zheng, **2020**] [Liao, Ma, 2020]

Low Energy Effective Field Theory

SU(3) x U(1) gauge symmetry

Dim-5	[Dirac, 1932]
Dim-6	[Fermi, 1934] [Lee, Yang, 1956] [Jenkins, Manohar, Stoffer, 2017]
Dim-7	[Liao, Ma, Wang, 2020] [Li, Ren, Xiao, **Yu**, Zheng, 2020]
Dim-8	[Li, Ren, Xiao, **Yu**, Zheng, 2020] [Murphy, 2020]
Dim-9	[Li, Ren, Xiao, **Yu**, Zheng, 2020]

EFTs in Broken Phase

Standard Model Effective Field Theory

Matching → Running

Low Energy Effective Field Theory

approximate custodial symmetry
SU(2) x SU(2)

$$\Sigma \equiv (\Phi^c, \Phi) = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^- & \phi^0 \end{pmatrix} \to g_L \, \Sigma \, g_R^\dagger$$

$$\langle \Sigma \rangle = \begin{pmatrix} v & 0 \\ 0 & v \end{pmatrix} \neq 0$$

approximate chiral symmetry
SU(3) x SU(3)

$$\mathbf{q}_L \to g_L \, \mathbf{q}_L \,, \quad \mathbf{q}_R \to g_R \, \mathbf{q}_R \,,$$

$$\langle 0 | \left(\bar{\mathbf{q}}_L \mathbf{q}_R + \bar{\mathbf{q}}_R \mathbf{q}_L \right) | 0 \rangle \neq 0$$

Electroweak Chiral Lagrangian

QCD Chiral Lagrangian

$$\boldsymbol{\Phi} \equiv \frac{1}{\sqrt{2}} \vec{\sigma} \cdot \vec{\varphi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \varphi^0 & \varphi^+ \\ \varphi^- & -\frac{1}{\sqrt{2}} \varphi^0 \end{pmatrix}$$

SM fields and Goldstone

$$\boldsymbol{\Phi} \equiv \frac{\vec{\lambda}}{\sqrt{2}} \vec{\phi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}} \pi^0 + \frac{1}{\sqrt{6}} \eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}} \eta \end{pmatrix}$$

meson and baryon

SM Fermion masses from Higgs VEV

Baryon masses around 1 GeV from Trace anomaly

CCWZ Chiral Lagrangian

Define the nonlinear Goldstone matrix

$$\Omega(\Pi) \equiv \exp\left[\frac{i}{2f}\Pi(x)\right] \rightarrow \Omega(\Pi^{(\mathfrak{g})}) = \mathfrak{g}\Omega(\Pi)\mathfrak{h}^{-1}(\Pi;\mathfrak{g})$$

[Callan, Coleman, Wess, Zumino, 1969]

CCWZ Coset

$$-i\Omega^\dagger\partial_\mu\Omega = d_\mu^{\hat{a}}T^{\hat{a}} + E_\mu^a T^a \equiv d_\mu + E_\mu$$

$$d_\mu \rightarrow \mathfrak{h}d_\mu\mathfrak{h}^{-1}, \quad E_\mu \rightarrow \mathfrak{h}E_\mu\mathfrak{h}^{-1} - ih\partial_\mu\mathfrak{h}^{-1}$$

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + iA_\mu$$
$$A_\mu = A_\mu^{\hat{a}}T^{\hat{a}} + A_\mu^a T^a$$

Building block

$$d_\mu(\Pi), \quad E_{\mu\nu}(\Pi) \quad \nabla_\mu \equiv \partial_\mu + iE_\mu$$
$$f_{\mu\nu} = \Omega^\dagger F_{\mu\nu}\Omega = f_{\mu\nu}^{-\hat{a}}T^{\hat{a}} + f_{\mu\nu}^{+a}T^a$$

$$[T_{\hat{a}}, T_{\hat{b}}] \propto T_c$$

Symmetric Coset

$$\Omega \rightarrow \mathfrak{g}\Omega\mathfrak{h}^{-1}, \quad \Omega \rightarrow \mathfrak{h}\Omega\mathfrak{g}_{\mathcal{R}}^{-1}$$

$$U \equiv \Omega^2 \rightarrow \mathfrak{g}\,U\mathfrak{g}_{\mathcal{R}}^{-1}$$

$$D_\mu U \equiv \partial_\mu U + iA_\mu U - iU A_\mu^{(R)}$$
$$A_\mu^{(R)} \equiv A_\mu^a T^a - A_\mu^{\hat{a}}T^{\hat{a}}$$

$$E_{\mu\nu} = -i[u_\mu, u_\nu] + f_{\mu\nu}^+$$
$$d_\mu = u_\mu$$

$$u_\mu = i\Omega(D_\mu U)^\dagger\Omega \qquad D_\mu$$
$$f_{\mu\nu}^\pm = \frac{1}{2}\left(f_{\mu\nu} \pm f_{\mu\nu}^{(R)}\right) = \Omega^\dagger F_{\mu\nu}\Omega \pm F_{\mu\nu}^{(R)}$$

Building block

$$\Omega(\Pi) \equiv \begin{bmatrix} u(\Pi) & 0 \\ 0 & u^\dagger(\Pi) \end{bmatrix} \qquad u \rightarrow \sqrt{\mathfrak{g}_L U \mathfrak{g}_R^\dagger} = \mathfrak{g}_L\, u\mathfrak{h}^{-1} = \mathfrak{h}^{-1}u\mathfrak{g}_R$$

$$U(\Pi) \equiv u^2(\Pi) \longrightarrow \mathfrak{g}_L \mathbf{U}(\Pi)\mathfrak{g}_R^\dagger$$

QCD Chiral Lag

$$u_\mu \rightarrow \mathfrak{h}\,u_\mu\,\mathfrak{h}^{-1}$$

$$u_\mu = \mathrm{i}\left[u^\dagger\left(\partial_\mu - \mathrm{i}r_\mu\right)u - u\left(\partial_\mu - \mathrm{i}l_\mu\right)u^\dagger\right]$$

$$\chi_\pm = u^\dagger\chi u^\dagger \pm u\chi^\dagger u\,,$$
$$f_{\mu\nu}^\pm = u f_{\mu\nu}^{\mathrm{L}} u^\dagger \pm u^\dagger f_{\mu\nu}^{\mathrm{R}} u\,,$$

EW Chiral Lag

$$\mathbf{V}_\mu \rightarrow \mathfrak{g}_L\,\mathbf{V}\,\mathfrak{g}_L^{-1}$$

$$\mathbf{V}_\mu(x) = i\mathbf{U}(x)D_\mu\mathbf{U}(x)^\dagger$$

$$\mathbf{T} = \mathbf{U}\mathcal{T}_R\mathbf{U}^\dagger \longrightarrow \mathfrak{g}_L\mathbf{T}\mathfrak{g}_L^\dagger \qquad \hat{W}_{\mu\nu} \longrightarrow \mathfrak{g}_L\hat{W}_{\mu\nu}\mathfrak{g}_L^\dagger$$

$$\mathbf{Y} = \mathbf{U}\mathcal{Y}_R\mathbf{U}^\dagger \longrightarrow \mathfrak{g}_L\mathbf{Y}\mathfrak{g}_L^\dagger \qquad \hat{B}_{\mu\nu} \longrightarrow \mathfrak{g}_R\hat{B}_{\mu\nu}\mathfrak{g}_R^\dagger$$

Adler Zero Condition for Goldstone

Chiral symmetry

$\alpha \to \beta$ $\xleftrightarrow{\text{At low energy}}$ $\alpha + n_1\pi \to \beta + n_2\pi$

Goldberger-Trieman, Callan-Trieman, Adler-Weisberger, etc

Adler Zero condition

$$T(\alpha+\phi(p),\beta) = -\frac{p_\mu}{F}R^\mu(p) \xrightarrow{p\to 0} 0$$

Amplitude (soft limit of external leg s)

$$\mathcal{A}(1,\ldots,N,s) \xrightarrow{p_s\to 0} \begin{cases} \left(S^{(0)}(s)+S^{(\text{sub})}(s)\right)\mathcal{A}(1,\ldots,N) \\ \mathcal{O}(p_s^\sigma) \quad \text{for Goldstone Boson} \end{cases}$$

[Adler, 1965]

$$\{-1/2,-1/2,1,0,0\} \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&4\\\hline 2&2&2&5\\\hline 4&5\\\cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\\hline 2&2&5&5\\\hline 4&4\\\cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\\hline 2&2&4&4\\\hline 5&5\\\cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\\hline 2&2&4&5\\\hline 4&5\\\cline{1-2}\end{array},$$

[Sun, Xiao, **Yu**, 2210.14939]
[Sun, Xiao, **Yu**, 2206.07722]
[Low, Shu, Xiao, Zheng, 2022]

Expand the soft-limit amplitude into the SSYT basis

Put constraints on the SSYT basis

$$\mathcal{B}_i^{(N)}(p_\pi\to 0) = \sum_{l=1}^{d_N}\mathcal{K}_{il}\mathcal{B}_l^{(N)}$$

$$\begin{array}{|c|c|c|c|}\hline 1&1&1&4\\\hline 2&2&2&5\\\hline 4&5\\\cline{1-2}\end{array}, \quad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\\hline 2&2&4&5\\\hline 4&5\\\cline{1-2}\end{array},$$

custodial/chiral symmetry breaking: spurion

Higher Order Chiral Lagrangian

$$\mathscr{L}_{\rm EFT} = \mathscr{L}_{p^2} + \mathscr{L}_{p^3} + \mathscr{L}_{p^4} + \mathscr{L}_{p^5} + \mathscr{L}_{p^6} + \ldots$$

ChPT and Chiral EFT

LO Lagrangian
[Weinberg, 1979]

Pure mesonic
[Gasser, Leutwyler, 1984, 1985]
[Fearing, Scherer 1994]
[Bijnens, Colangelo, Ecker, 1999]
[Jiang, Ge, Wang, 2014]
[Bijnens, Hermansson, Wang, 2018]

nucleon-meson
[Krause, 1990]
[Ecker, 1994]
[Fettes, Meisner, Mojzis, Steininger, 2000]
[Oller, Verbeni, Prades, 2006]
[Frink, Meisner, 2006]
[Jiang, Chen, Liu, 2017]

nucleon-nucleon
[Weinberg 1990]
[van Kolck, Ordonez, 1992]
[Petschauer, Kaiser, 2013]
[Petschauer, Haidenbauer, Kaiser, Meisner, Weise, 2020]

[Sun, Wang, **Yu**, in préparation]

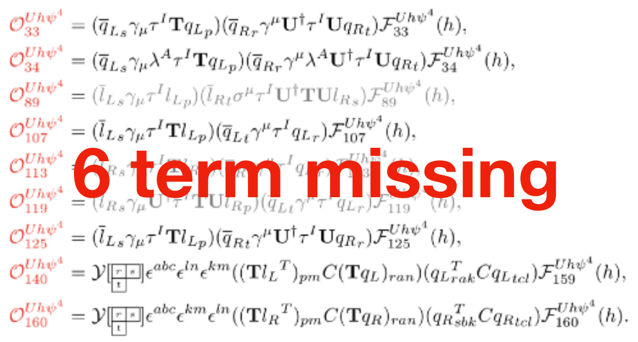
EW Chiral Lagrangian = HEFT

LO Lagrangian
[Weinberg, 1979]

NLO bosonic
[Appelquist, Bernard, 1980]
[Longhitano, 1980, 1981]
[Feruglio, 1993]

NLO 2-fermion
[Buchalla, Cata, Krause, 2014]

NLO 4-fermion
[Buchalla, Cata, Krause, 2014]
[Pich, Rosell, Santos, Sanz-Cillero, 2015, 2018]
[Sun, Xiao, **Yu**, 2206.07722]



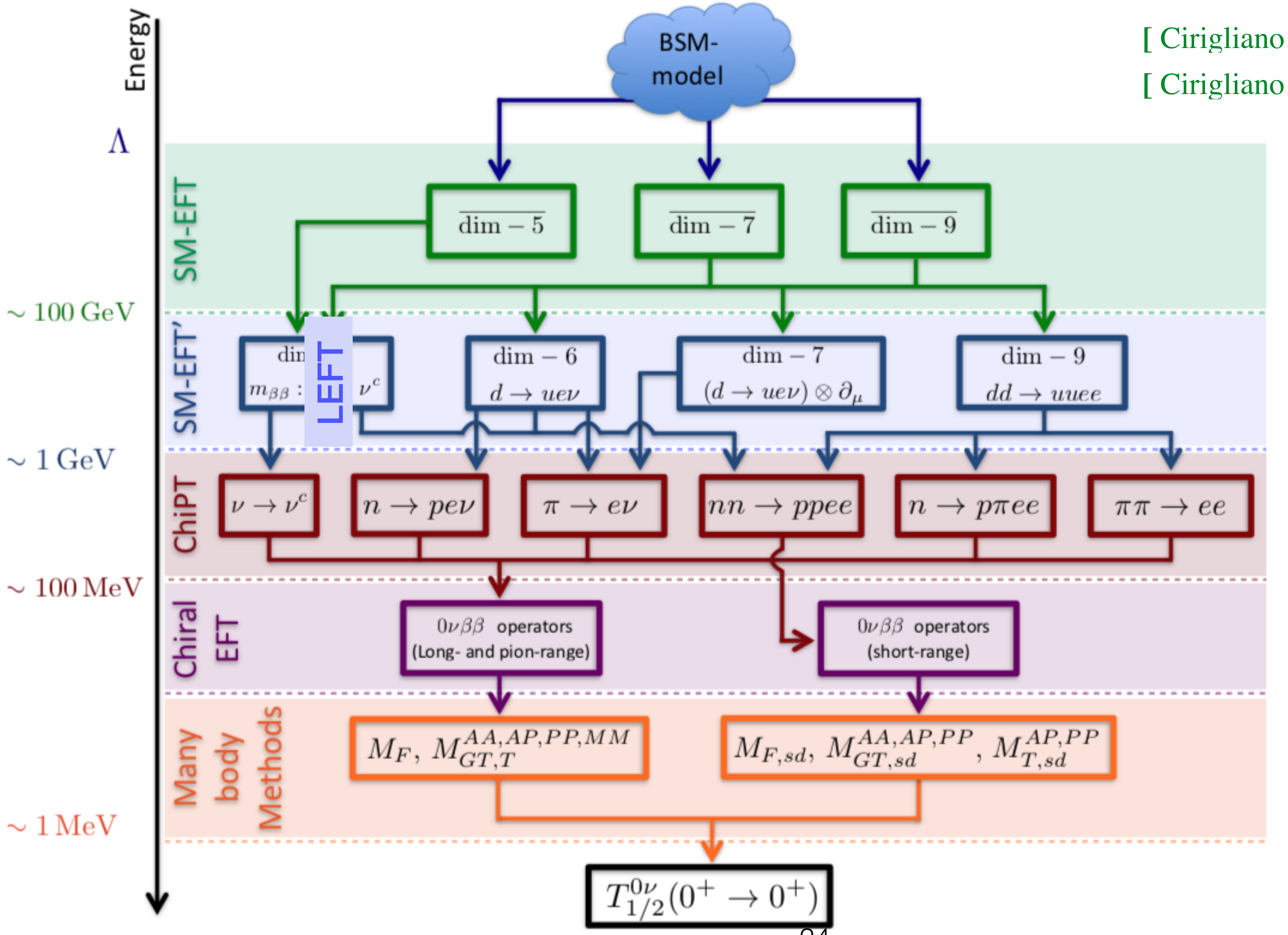
NNLO Basis
[Sun, Xiao, **Yu**, 2210.14939]

Complete EFT Framework for 0vbb

Operator bases for different EFTs are necessarily needed to provide most general description on 0vbb process

[Jordy de Vries's talk]

[Cirigliano, Dekens, de Vries, Graesser, Mereghetti, 2017]
[Cirigliano, Dekens, de Vries, Graesser, Mereghetti, 2018]



How to find complete UV?

ABC4EFT Package

Amplitude Basis Construction for Effective Field Theory

[Li, Ren, Xiao, **Yu**, Zheng, 2201.04639]

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Welcome to the HEPForge Project: ABC4EFT

This is the website for the Mathematica package: Amplitude Basis Construction for Effective Field Th

Package

This package has the following features:

- It provides a general procedure to construct the independent and complete operator bases for generic L invariant effective field theory, given any kind of gauge symmetry and field content, up to any mass dim
- Various operator bases have been systematically constructed to emphasize different aspects: operator independence (y-basis), flavor relation (p-basis) and conserved quantum number (j-basis).
- It provides a systematic way to convert any operator into our on-shell amplitude basis and the basis cor can be easily done.

Authors

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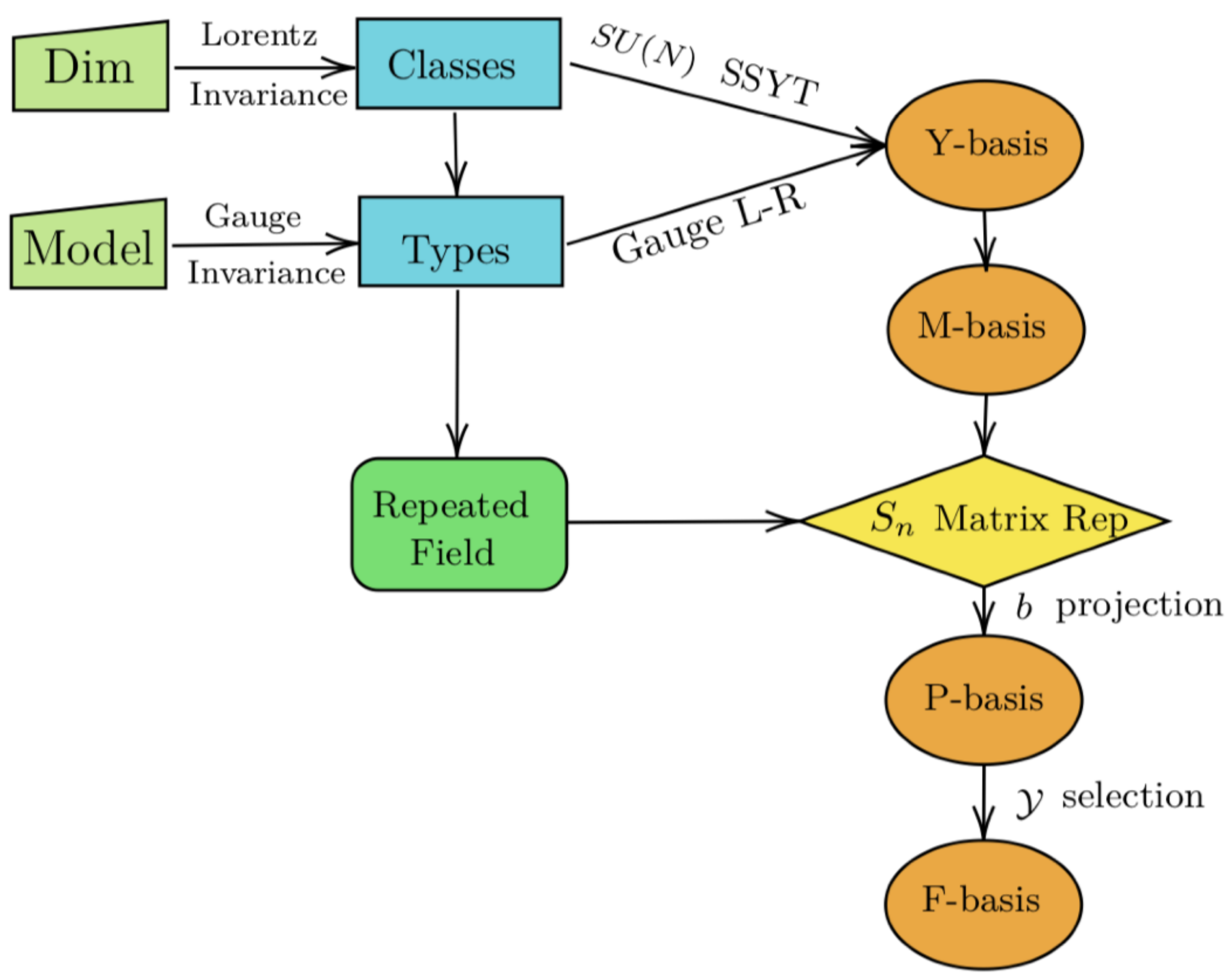
- Jiang-Hao Yu (professor at ITP-CAS)
- Yu-Hui Zheng (5th-year graduate student at ITP-CAS)

https://abc4eft.hepforge.org/



Fully Automatic

Dark matter EFT
Sterile neutrino EFT
Gravity EFT
Axion EFT
...

UV Completion for nv mass and 0vbb

[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, 2204.03660]

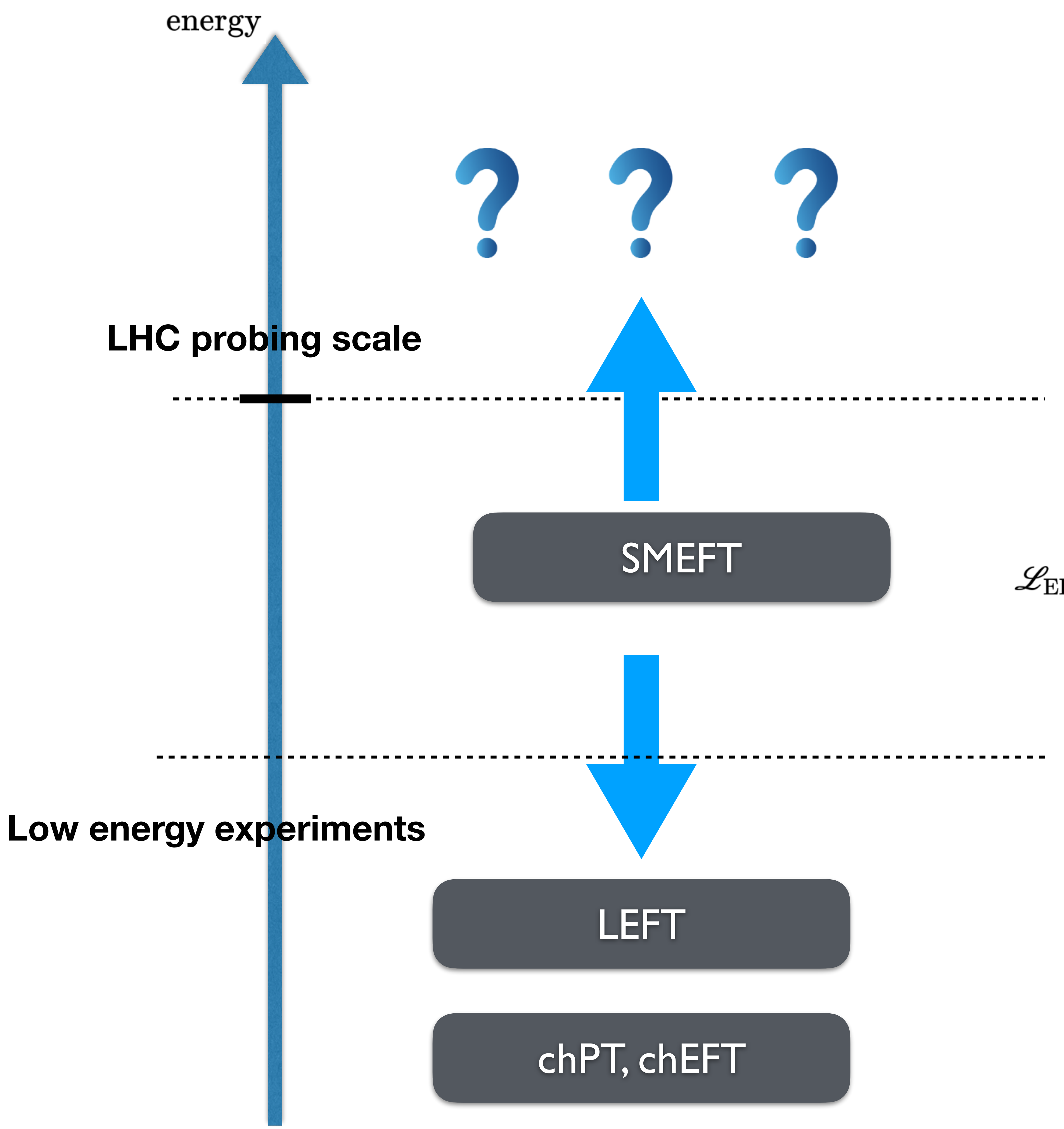
[Xu-Xiang Li, Zhe Ren, **J.H.Yu,** in preparation]

[Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, in preparation]

[Gang Li, **J.H.Yu,** Xiang Zhao, in progress]

SMEFT Inverse Problem

Given effective operators, how to find complete UV ?



$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \ldots$$

UV of Weinberg Operator

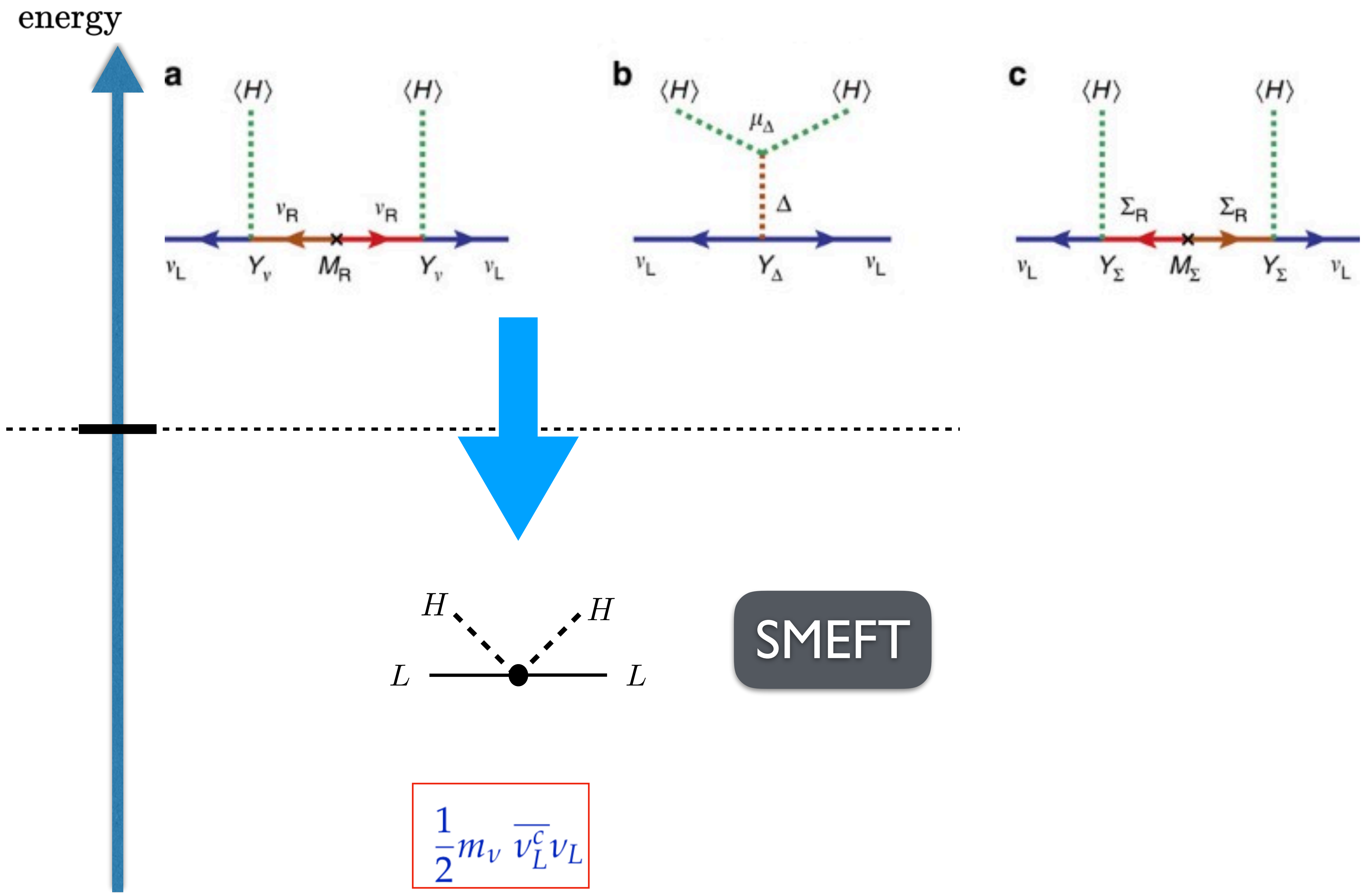
Top-down Approach

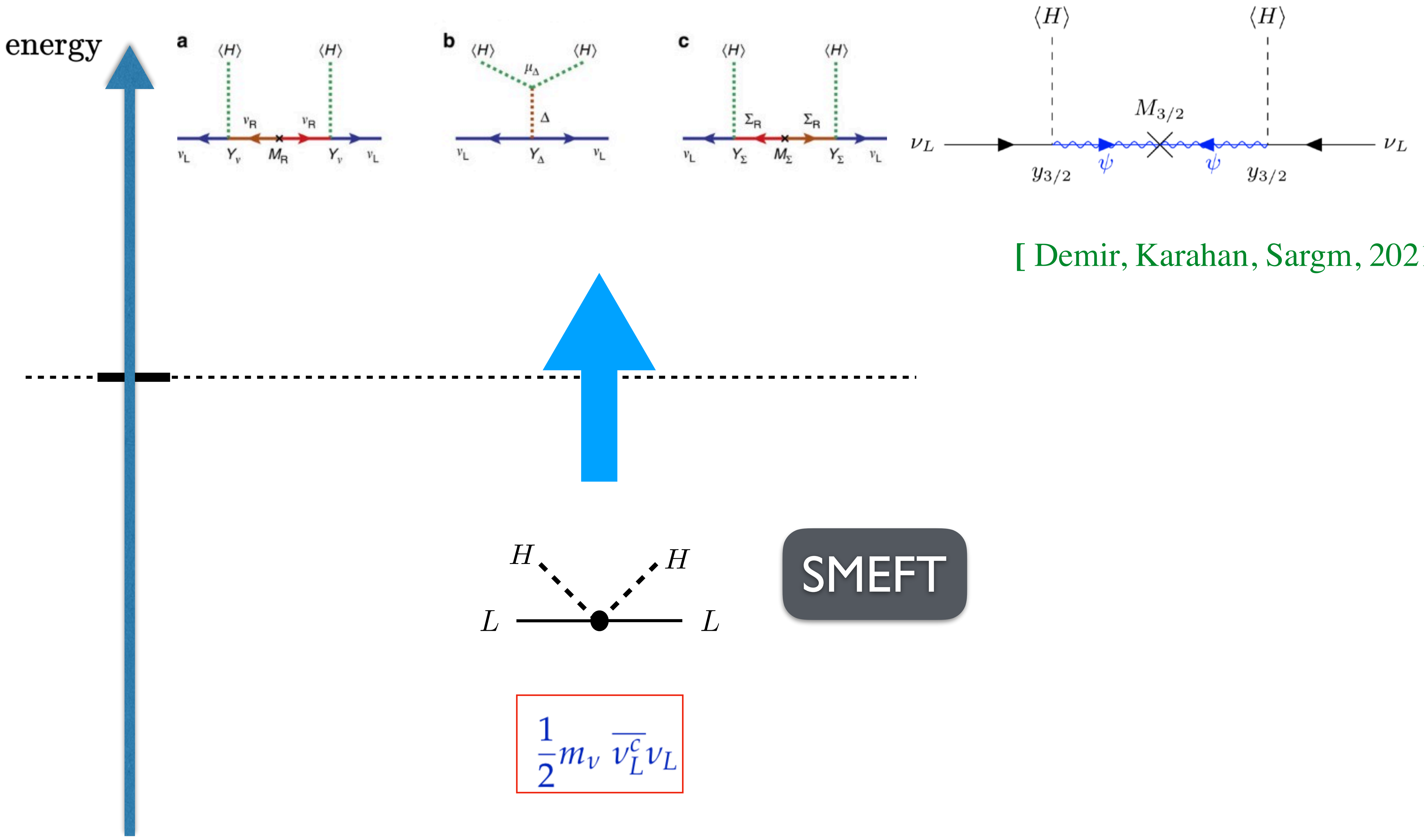
Bottom-up Approach

[Yanagida 1979, Gell-Mann, Ramond, Slansky1979, Mahapatra, Senjanovic, 1980]

[Schecheter, Walle, 1980, Cheng, Li 1980, Magg and Wetterich 1980]

[Foot, Lew, He, Joshi 1989]





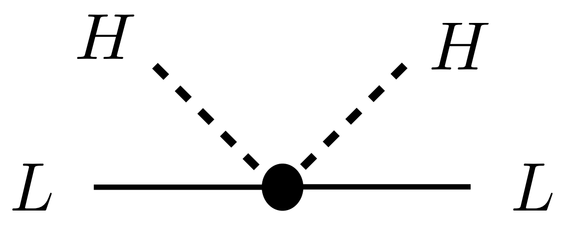
[Demir, Karahan, Sargm, 2021]

Consider Angular momentum conservation

Why only 3 Tree-level Seesaw?

Angular momentum conservation for **space-time Poincare symmetry** [Li, Ni, Xiao, **Yu**, 2204.03660]

Pauli-Lubanski Casimir $\mathbf{W}^2\langle p_L, h_L; p_H, h_H|P, J, J_z\rangle = -P^2 J(J+1)\langle p_L, h_L; p_H, h_H|P, J, J_z\rangle$



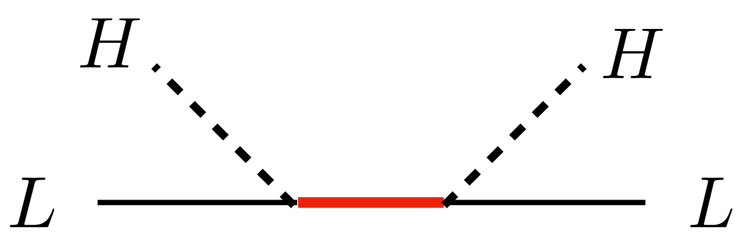
$\mathcal{O}^S = (HL)(HL)$

Generalized partial wave analysis for Poincare/Gauge Casimir

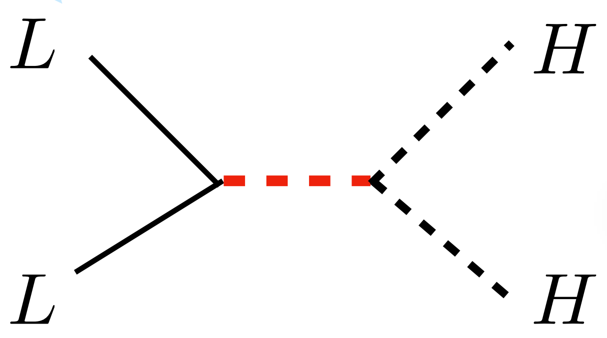
$$\mathbf{W}^2\mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$

$W^2_{\{1,3\}}\mathcal{B}^y = -\frac{3}{4}s_{13}\langle 12\rangle$ $LH \to LH$ channel

$LL \to HH$ channel $W^2_{\{1,2\}}\mathcal{B}^y = 0$



$J = \frac{1}{2}$



$J = 0$

Type-I and III: SU(2) **single and triplet**

Type-II: SU(2) **triplet,** or singlet (excluded by repeated field)

j-basis	Model
$\mathcal{O}^{(1/2,\mathbf{1})}_{HL\to HL} = \mathcal{O}^S + \mathcal{O}^A$	type I
$\mathcal{O}^{(1/2,\mathbf{3})}_{HL\to HL} = \mathcal{O}^S - 3\mathcal{O}^A$	type III

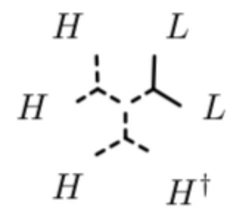
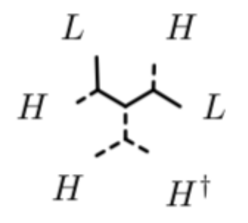
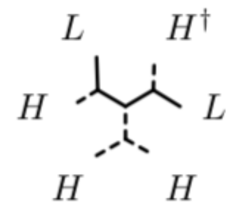
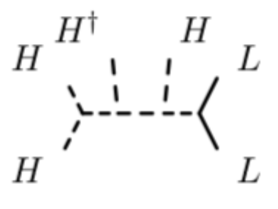
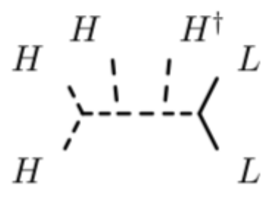
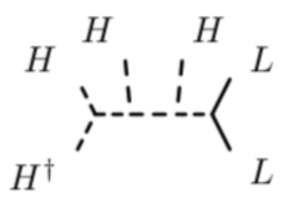
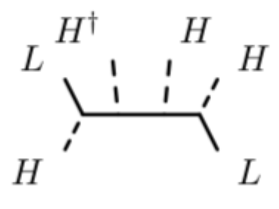
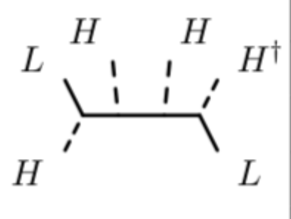
$\mathcal{O}^S = (HL)(HL), \quad \mathcal{O}^A = (HH)(LL)$

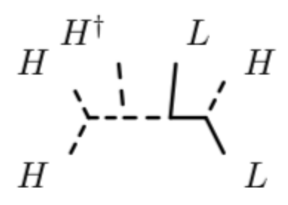
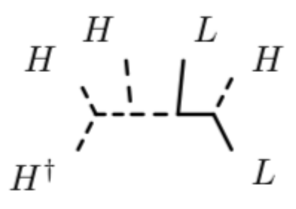
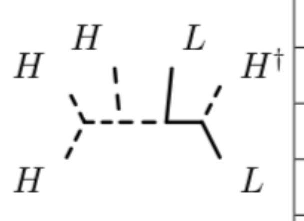
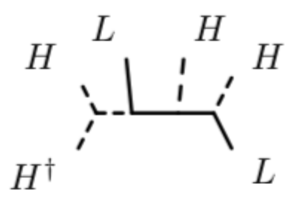
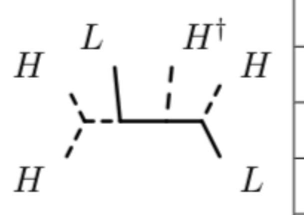
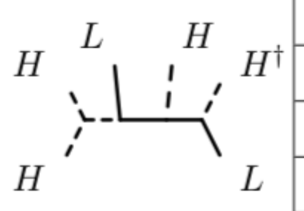
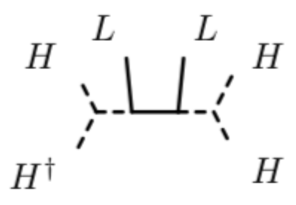
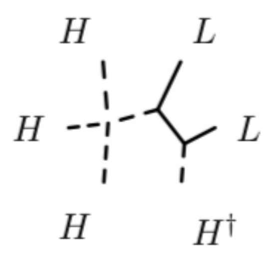
j-basis	Model
$\mathcal{O}^{(0,\mathbf{1})}_{HH\to LL} = \mathcal{O}^A$	N/A
$\mathcal{O}^{(0,\mathbf{3})}_{HH\to LL} = \mathcal{O}^S$	type II

Complete Dim-7 Tree-level Seesaw

59 UV tree-level models, 19 topologies, one genuine dim-7 seesaw

[Li, Ni, Xiao, **Yu**, 2204.03660]

Topology	j-basis	Quantum numbers $\{J, \mathbf{R}, Y\}$
	$\mathcal{O}_{\{12\|34\|56\},1} = 2\mathcal{O}^p_1 - 4\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,3,1\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|34\|56\},2} = 2\mathcal{O}^p_2 + 4\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,1,1\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|34\|56\},3} = 12\mathcal{O}^p_4,$	$\{0,1,-1\},\{0,3,1\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|34\|56\},4} = 4\mathcal{O}^p_1 + 4\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,3,1\},\{0,1,0\}$
	$\mathcal{O}_{\{12\|34\|56\},5} = 2\mathcal{O}^p_4 + 4\mathcal{O}^p_5.$	$\{0,1,-1\},\{0,1,1\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|24\|56\},1} = -\mathcal{O}^p_2 - 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|24\|56\},2} = -\mathcal{O}^p_1 + 3\mathcal{O}^p_2 + 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},1,0\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|24\|56\},3} = -\mathcal{O}^p_1 + \mathcal{O}^p_2 - 2\mathcal{O}^p_3 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|24\|56\},4} = -\mathcal{O}^p_1 - \mathcal{O}^p_2 + 3\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|24\|56\},5} = \mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},1,0\},\{0,1,0\}$
	$\mathcal{O}_{\{16\|23\|45\},1} = 2\mathcal{O}^p_1 - 2\mathcal{O}^p_2 - 2\mathcal{O}^p_3 + 6\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|23\|45\},2} = -2\mathcal{O}^p_1 - \mathcal{O}^p_2 - \mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},1,0\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|23\|45\},3} = 3\mathcal{O}^p_2 + 3\mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|23\|45\},4} = \mathcal{O}^p_2 - \mathcal{O}^p_3 - 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,1,1\}$
	$\mathcal{O}_{\{16\|23\|45\},5} = \mathcal{O}^p_2 - \mathcal{O}^p_3 + \mathcal{O}^p_4 - \mathcal{O}^p_5.$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},1,0\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|125\|34\},1} = \mathcal{O}^p_1 + 4\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|125\|34\},2} = -8\mathcal{O}^p_1 + 4\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|125\|34\},3} = -12\mathcal{O}^p_4,$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|125\|34\},4} = -2\mathcal{O}^p_2 - 4\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|125\|34\},5} = -2\mathcal{O}^p_4 - 4\mathcal{O}^p_5.$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|126\|34\},1} = 3\mathcal{O}^p_1,$	$\{0,3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|126\|34\},2} = 12\mathcal{O}^p_2,$	$\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|126\|34\},3} = -12\mathcal{O}^p_4,$	$\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{12\|126\|34\},4} = -2\mathcal{O}^p_2 - 4\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|126\|34\},5} = -2\mathcal{O}^p_4 - 4\mathcal{O}^p_5.$	$\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{12\|124\|36\},1} = -\mathcal{O}^p_1 - 4\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|124\|36\},2} = 2\mathcal{O}^p_1 + 6\mathcal{O}^p_2 + 2\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|124\|36\},3} = -6\mathcal{O}^p_4 - 6\mathcal{O}^p_5,$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{12\|124\|36\},4} = -2\mathcal{O}^p_1 + 2\mathcal{O}^p_2 + 2\mathcal{O}^p_3,$	$\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{12\|124\|36\},5} = -2\mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|135\|24\},1} = \mathcal{O}^p_1 - 2\mathcal{O}^p_3 - 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{13\|135\|24\},2} = -\mathcal{O}^p_1 - 3\mathcal{O}^p_2 - 4\mathcal{O}^p_3 + 9\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{13\|135\|24\},3} = \mathcal{O}^p_1 - \mathcal{O}^p_2 + 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{13\|135\|24\},4} = \mathcal{O}^p_1 - 3\mathcal{O}^p_2 - 2\mathcal{O}^p_3 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$
	$\mathcal{O}_{\{13\|135\|24\},5} = \mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$
	$\mathcal{O}_{\{16\|146\|23\},1} = -2\mathcal{O}^p_1 + 4\mathcal{O}^p_3 - 12\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{16\|146\|23\},2} = 2\mathcal{O}^p_1 - 3\mathcal{O}^p_2 - \mathcal{O}^p_3 + 9\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{16\|146\|23\},3} = 3\mathcal{O}^p_2 + 3\mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$
	$\mathcal{O}_{\{16\|146\|23\},4} = 2\mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_3 - 3\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$
	$\mathcal{O}_{\{16\|146\|23\},5} = -\mathcal{O}^p_2 + \mathcal{O}^p_3 - \mathcal{O}^p_4 + \mathcal{O}^p_5,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$

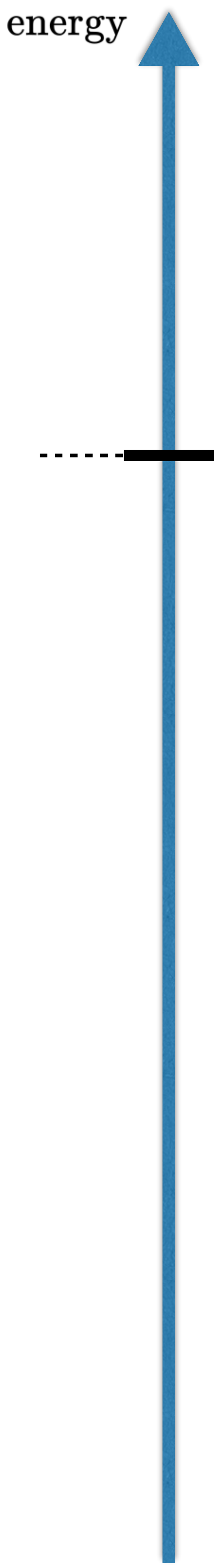
	$\mathcal{O}_{\{13\|123\|45\},1} = \mathcal{O}^p_1 - 4\mathcal{O}^p_2 - 4\mathcal{O}^p_3,$	$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|123\|45\},2} = 2\mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_3 - 9\mathcal{O}^p_4 - 9\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|123\|45\},3} = 2\mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|123\|45\},4} = \mathcal{O}^p_2 - \mathcal{O}^p_3 + 3\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{13\|123\|45\},5} = -\mathcal{O}^p_2 + \mathcal{O}^p_3 + \mathcal{O}^p_4 - \mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{13\|123\|46\},1} = \mathcal{O}^p_1 - 4\mathcal{O}^p_2 - 4\mathcal{O}^p_3,$	$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|123\|46\},2} = \mathcal{O}^p_1 + 2\mathcal{O}^p_2 - \mathcal{O}^p_3 - 9\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|123\|46\},3} = -\mathcal{O}^p_1 - 2\mathcal{O}^p_2 + \mathcal{O}^p_3 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{13\|123\|46\},4} = -\mathcal{O}^p_1 - \mathcal{O}^p_3 + 6\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|123\|46\},5} = -\mathcal{O}^p_1 - \mathcal{O}^p_3 - 2\mathcal{O}^p_4 - \mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{16\|126\|34\},1} = 6\mathcal{O}^p_1,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|126\|34\},2} = -3\mathcal{O}^p_2 + 9\mathcal{O}^p_4,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|126\|34\},3} = -3\mathcal{O}^p_2 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|126\|34\},4} = -\mathcal{O}^p_2 - 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|126\|34\},5} = \mathcal{O}^p_2 + 2\mathcal{O}^p_3 + \mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{23\|235\|46\},1} = \mathcal{O}^p_1 - 2\mathcal{O}^p_3 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{23\|235\|46\},2} = \mathcal{O}^p_1 - 6\mathcal{O}^p_2 - 5\mathcal{O}^p_3 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{23\|235\|46\},3} = \mathcal{O}^p_1 + 2\mathcal{O}^p_2 - \mathcal{O}^p_3 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{23\|235\|46\},4} = -\mathcal{O}^p_1 - \mathcal{O}^p_3 - 6\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{23\|235\|46\},5} = -\mathcal{O}^p_1 - \mathcal{O}^p_3 + 2\mathcal{O}^p_4 + \mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{13\|136\|45\},1} = \mathcal{O}^p_1 + 2\mathcal{O}^p_2 + 2\mathcal{O}^p_3 - 6\mathcal{O}^p_4 - 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|136\|45\},2} = 2\mathcal{O}^p_1 - 5\mathcal{O}^p_2 - 5\mathcal{O}^p_3 - 3\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|136\|45\},3} = 2\mathcal{O}^p_1 + \mathcal{O}^p_2 + \mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5,$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{13\|136\|45\},4} = \mathcal{O}^p_2 - \mathcal{O}^p_3 + 3\mathcal{O}^p_4 - 3\mathcal{O}^p_5,$	$\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{13\|136\|45\},5} = -\mathcal{O}^p_2 + \mathcal{O}^p_3 + \mathcal{O}^p_4 - \mathcal{O}^p_5.$	$\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{16\|156\|34\},1} = 2\mathcal{O}^p_1 - 4\mathcal{O}^p_2 + 12\mathcal{O}^p_4,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|156\|34\},2} = 4\mathcal{O}^p_1 + \mathcal{O}^p_2 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|156\|34\},3} = -3\mathcal{O}^p_2 - 3\mathcal{O}^p_4,$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$
	$\mathcal{O}_{\{16\|156\|34\},4} = -\mathcal{O}^p_2 - 2\mathcal{O}^p_3 + 3\mathcal{O}^p_4 + 6\mathcal{O}^p_5,$	$\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{16\|156\|34\},5} = \mathcal{O}^p_2 + 2\mathcal{O}^p_3 + \mathcal{O}^p_4 + 2\mathcal{O}^p_5.$	$\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$
	$\mathcal{O}_{\{34\|134\|56\},1} = -\mathcal{O}^p_1 + 2\mathcal{O}^p_2 + 6\mathcal{O}^p_4,$	$\{0,3,1\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{34\|134\|56\},2} = 4\mathcal{O}^p_1 - 8\mathcal{O}^p_2 + 12\mathcal{O}^p_4,$	$\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{34\|134\|56\},3} = 2\mathcal{O}^p_2 + 4\mathcal{O}^p_3,$	$\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$
	$\mathcal{O}_{\{34\|134\|56\},4} = -4\mathcal{O}^p_1 - 4\mathcal{O}^p_2,$	$\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{34\|134\|56\},5} = 2\mathcal{O}^p_4 + 4\mathcal{O}^p_5.$	$\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$
	$\mathcal{O}_{\{16\|126\|\},1} = 6\mathcal{O}^p_1,$	$\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\}$
	$\mathcal{O}_{\{16\|126\},2,3} = \begin{pmatrix} \mathcal{O}^p_2 - \mathcal{O}^p_3 - 3\mathcal{O}^p_4 + 3\mathcal{O}^p_5 \\ -2\mathcal{O}^p_2 - \mathcal{O}^p_3 + 6\mathcal{O}^p_4 + 3\mathcal{O}^p_5 \end{pmatrix},$	$\{\frac{1}{2},3,-1\},\{0,2,-\frac{3}{2}\}$
	$\mathcal{O}_{\{16\|126\},4,5} = \begin{pmatrix} -\mathcal{O}^p_2 - 2\mathcal{O}^p_3 - \mathcal{O}^p_4 - 2\mathcal{O}^p_5 \\ -2\mathcal{O}^p_2 - \mathcal{O}^p_3 - 2\mathcal{O}^p_4 - \mathcal{O}^p_5 \end{pmatrix}.$	$\{\frac{1}{2},1,-1\},\{0,2,-\frac{3}{2}\}$

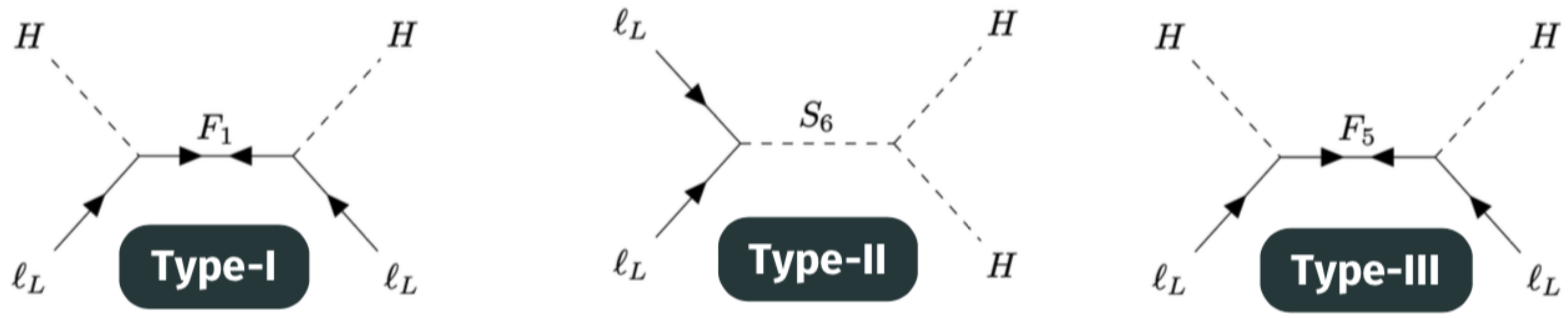
34/59

[Bonnet, Hernandez, Ota, Winter, 2009]

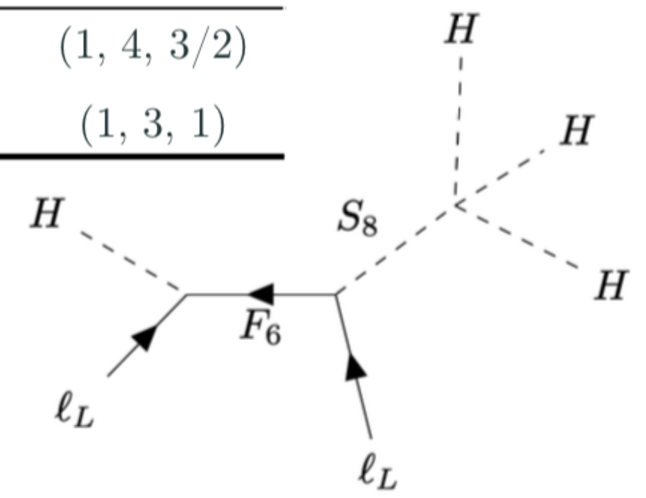
Top-Down from Bottom-up

[Li, Ren, **Yu**, in preparation]





Field	(C, W, Y)
S_8	$(1,\ 4,\ 3/2)$
F_6	$(1,\ 3,\ 1)$



Operators	F_1	S_6	F_5	$S_8\&F_6$	$0\nu\beta\beta$	other
$\mathcal{O}_5$	✓	✓	✓	✗	✓	
$\mathcal{O}_H$	✗	✓	✗	✓		
$\mathcal{O}_{H\Box}$	✗	✓	✗	✗		
$\mathcal{O}_{HD}$	✗	✓	✗	✗		
$\mathcal{O}_{eH}$	✗	✓	✓	✗		
$\mathcal{O}_{uH}$	✗	✓	✗	✗		
$\mathcal{O}_{dH}$	✗	✓	✗	✗		
$\mathcal{O}_{Hl}^{(1)}$	✓	✗	✓	✓		
$\mathcal{O}_{Hl}^{(3)}$	✓	✗	✓	✓		
$\mathcal{O}_{ll}$	✗	✓	✗	✗		
$\mathcal{O}_{LH}$	✓	✓	✓	✓	✓	τ
$\mathcal{O}_{LeHD}$	✓	✗	✓	✗	✓	τ
$\mathcal{O}_{LHD1}$	✗	✓	✓	✗	✓	τ, K
$\mathcal{O}_{LHD2}$	✓	✓	✓	✗	✗	τ
$\mathcal{O}_{LHW}$	✓	✗	✓	✗	✓	τ, K, Dip
$\mathcal{O}_{LHB}$	✗	✗	✗	✗	✗	Dip
$\mathcal{O}_{eLLLH}$	✓	✗	✓	✗	✗	τ
$\mathcal{O}_{dLQLH1}$	✓	✗	✓	✗	✓	τ
$\mathcal{O}_{dLQLH2}$	✓	✗	✓	✗	✓	τ
$\mathcal{O}_{QuLLH}$	✓	✗	✓	✗	✓	τ

One-loop CDE

[Du, Li, **Yu,** 2201.04646]

[Zhang, Zhou, 2107.12133]

[Li, Zhang, Zhou, 2201.05082]

Operators	Seesaw models: Type-I	Type-II	Type-III	$Y_{\nu,\Sigma} \overset{?}{=} 0$
One-loop matching				
$\mathcal{O}_W$	✗	✓	✓$(-N_\Sigma)$	No
$\mathcal{O}_{HW}$	✗	✓	✗	Yes
$\mathcal{O}_{HB}$	✗	✓	✗	Yes
$\mathcal{O}_{HWB}$	✗	✓	✗	Yes
$\mathcal{O}_{eW}$	✓	✓$(-\frac{3}{5})$	✓$(\frac{9}{5})$	No
$\mathcal{O}_{eB}$	✓	✓(6)	✓(3)	No
$\mathcal{O}_{Hl}^{(1)}$	✗	✓	✗	Yes
$\mathcal{O}_{Hl}^{(3)}$	✗	✓	✓	Yes
$\mathcal{O}_{Hq}^{(1)}$	✗	✓	✗	Yes
$\mathcal{O}_{Hq}^{(3)}$	✗	✓	✓	Yes
$\mathcal{O}_{ll}$	✗	✓	✓	Yes
$\mathcal{O}_{qq}^{(1)}$	✗	✓	✗	No
$\mathcal{O}_{qq}^{(3)}$	✗	✓	✓$(4N_\Sigma)$	No
$\mathcal{O}_{lq}^{(1)}$	✗	✓	✗	Yes
$\mathcal{O}_{lq}^{(3)}$	✗	✓	✓$(4N_\Sigma)$	Yes
$\mathcal{O}_{ee}$	✗	✓	✗	No
$\mathcal{O}_{uu}$	✗	✓	✗	No
$\mathcal{O}_{dd}$	✗	✓	✗	No
$\mathcal{O}_{eu}$	✗	✓	✗	No
$\mathcal{O}_{ed}$	✗	✓	✗	No
$\mathcal{O}_{ud}^{(1)}$	✗	✓	✗	No
$\mathcal{O}_{le}$	✗	✓	✗	Yes
$\mathcal{O}_{lu}$	✗	✓	✗	Yes
$\mathcal{O}_{ld}$	✗	✓	✗	Yes
$\mathcal{O}_{qe}$	✗	✓	✗	No
$\mathcal{O}_{qu}^{(1)}$	✗	✓	✗	Yes
$\mathcal{O}_{qu}^{(8)}$	✗	✓	✗	Yes
$\mathcal{O}_{qd}^{(1)}$	✗	✓	✗	Yes
$\mathcal{O}_{qd}^{(8)}$	✗	✓	✗	Yes
$\mathcal{O}_{ledq}$	✗	✓	✗	Yes
$\mathcal{O}_{quqd}^{(1)}$	✗	✓	✗	Yes
$\mathcal{O}_{lequ}^{(1)}$	✗	✓	✗	Yes

Complete Dim-7 UV Resonances

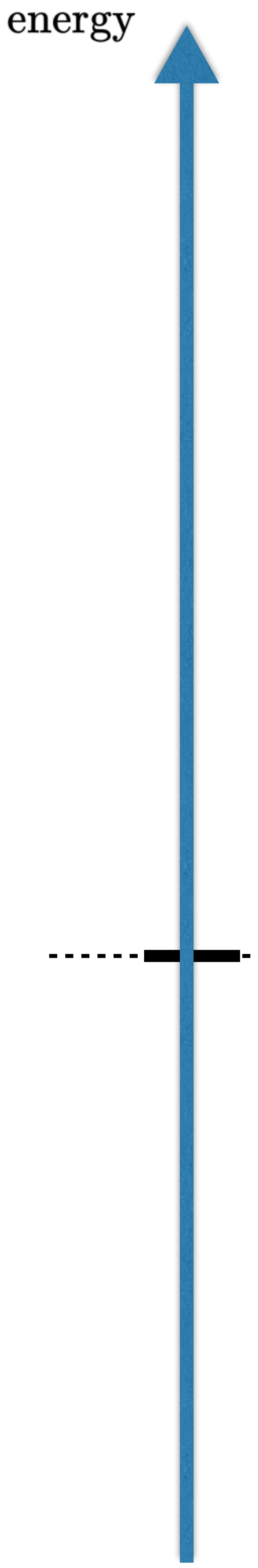
[Li, Ni, Xiao, **Yu**, 2204.03660]

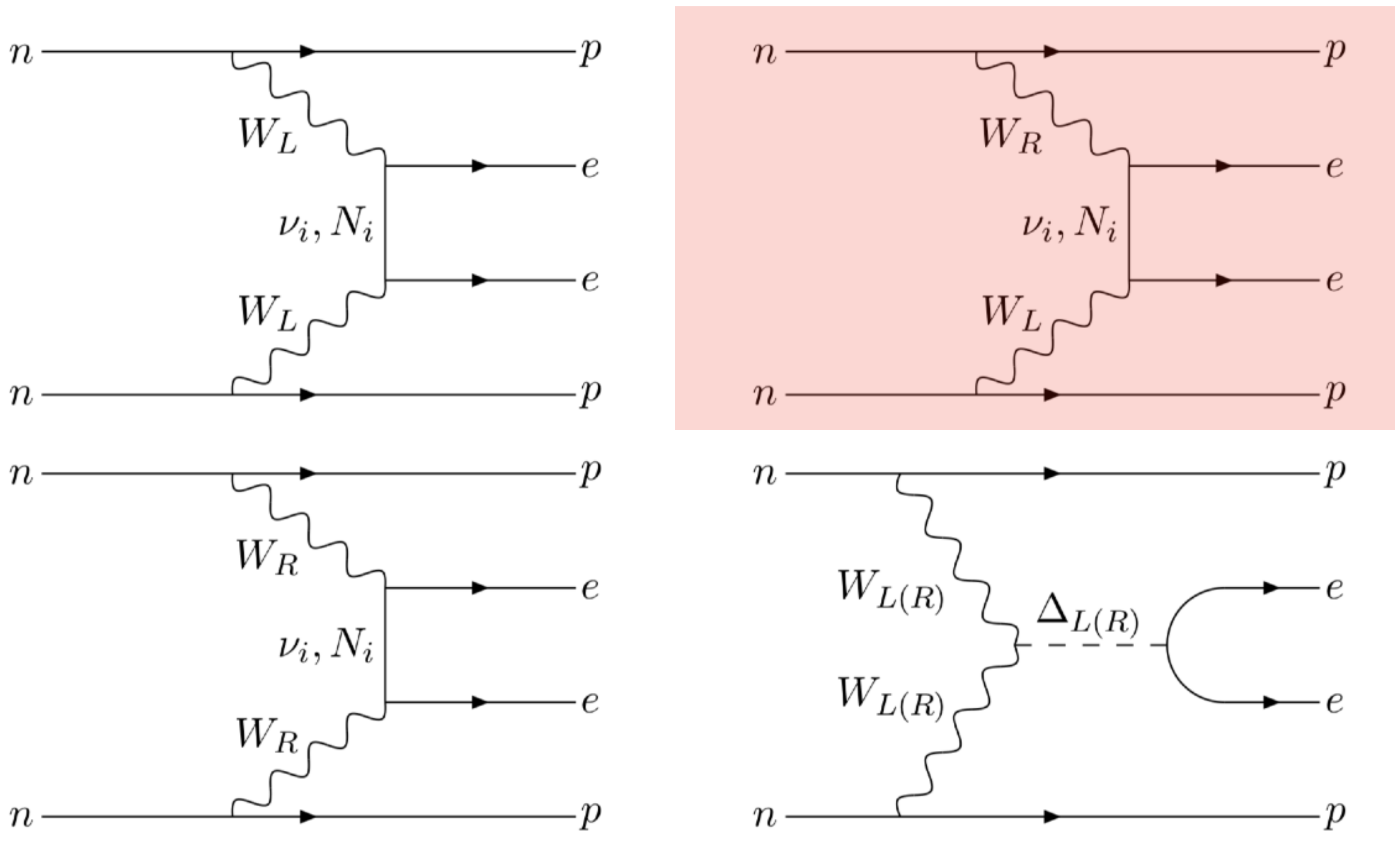
$(SU(3)_c, SU(2)_2, U(1)_y)$	Scalar
$S1\ (\mathbf{1},\mathbf{1},0)$	$H^3H^{\dagger}L^2[(S6),(F5),(F1),(S4,S6),$ $(S4,F5),(S4,F1),(F3,F5),(F1,F3),(S6,F3)]$
$S2\ (\mathbf{1},\mathbf{1},1)$	$e_{\mathbb{C}}HL^3[(S4),(F4),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S4),(F10),(F9)]$ $HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}[(S4),(F8),(F12)]$ $De_{\mathbb{C}}H^{\dagger 3}L^{\dagger}[(F1),(F3),(V3)]$
$S4\ \left(\mathbf{1},\mathbf{2},\frac{1}{2}\right)$	$e_{\mathbb{C}}HL^3[(S6),(S2),(F5),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S6),(S2),(F5),(F1)]$ $HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}[(S6),(S2),(F5),(F1)]$ $H^3H^{\dagger}L^2[(S6),(F5),(F1),(S5,S6),(S1,S6),$ $(S6,F5),(S6,F1),(S5,F5),(S5,F1),(S1,F5),(S1,F1)]$
$S5\ (\mathbf{1},\mathbf{3},0)$	$H^3H^{\dagger}L^2[(S6),(F1,F5),(S6,S7),(S4,S6),(S7,F5),$ $(S4,F5),(S4,F1),(F5,F7),(F3,F5),(F1,F3),(S6,F7),(S6,F3)]$
$S6\ (\mathbf{1},\mathbf{3},1)$	$D^2H^2L^2$ $e_{\mathbb{C}}HL^3[(S4),(F4),(F5)]$ $d_{\mathbb{C}}HL^2Q[(S4),(F10),(F14)]$ $HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}[(S4),(F13),(F12)]$ $De_{\mathbb{C}}H^{\dagger 3}L^{\dagger}[(F5),(F3),(V3)]$ $H^2L^2W_L[(F7)]$ $H^3H^{\dagger}L^2[(S4),(S8),(S7),(S5),(S1),(F5,F6),(F1,F6),$ $(S5,S7),(S4,S5),(S1,S4),(S7,F5),(S4,F5),(S4,F1),(F5,F7),(F3,F5),$ $(F1,F3),(S8,F6),(F6,F7),(F3,F6),(S5,F7),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^{\dagger}H^3L$
$S7\ \left(\mathbf{1},\mathbf{4},\frac{1}{2}\right)$	$H^3H^{\dagger}L^2[(S6),(F5),(S5,S6),(S6,F5),(S5,F5)]$
$S8\ \left(\mathbf{1},\mathbf{4},\frac{3}{2}\right)$	$H^3H^{\dagger}L^2[(S6),(F6),(S6,F6)]$
$S10\ \left(\mathbf{3},\mathbf{1},-\frac{1}{3}\right)$	$d_{\mathbb{C}}^{2}HLu_{\mathbb{C}}[(S12),(F10),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S12),(F10),(F1)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^{\dagger}HLu_{\mathbb{C}}^{\dagger}[(S12),(F10),(F1)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(S12),(F10),(F1)]$
$S11\ \left(\mathbf{3},\mathbf{1},\frac{2}{3}\right)$	$d_{\mathbb{C}}^{3}H^{\dagger}L[(S12),(F11),(F2)]$ $d_{\mathbb{C}}^{2}HLu_{\mathbb{C}}[(F11),(S13),(F1)]$ $d_{\mathbb{C}}^{2}e_{\mathbb{C}}^{\dagger}HQ^{\dagger}[(S13),(F3),(F8)]$
$S12\ \left(\mathbf{3},\mathbf{2},\frac{1}{6}\right)$	$d_{\mathbb{C}}^{3}H^{\dagger}L[(S11),(F11)]$ $d_{\mathbb{C}}^{2}HLu_{\mathbb{C}}[(F11),(S10),(F10)]$ $d_{\mathbb{C}}HL^2Q[(S10),(S14),(F5),(F1),(F14),(F9)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^{\dagger}HLu_{\mathbb{C}}^{\dagger}[(S10),(F3),(F12)]$
$S13\ \left(\mathbf{3},\mathbf{2},\frac{7}{6}\right)$	$d_{\mathbb{C}}^{2}HLu_{\mathbb{C}}[(S11),(F10)]$ $d_{\mathbb{C}}^{2}e_{\mathbb{C}}^{\dagger}HQ^{\dagger}[(S11),(F10)]$
$S14\ \left(\mathbf{3},\mathbf{3},-\frac{1}{3}\right)$	$d_{\mathbb{C}}HL^2Q[(S12),(F10),(F5)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(S12),(F10),(F5)]$

$(SU(3)_c, SU(2)_2, U(1)_y)$	Fermion
$F1\ (\mathbf{1},\mathbf{1},0)$	$D^2H^2L^2$ $e_{\mathbb{C}}HL^3[(S4),(S2)]$ $d_{\mathbb{C}}HL^2Q[(S4),(S10),(S12)]$ $HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}[(S4),(V5),(V8)]$ $De_{\mathbb{C}}H^{\dagger 3}L^{\dagger}[(F3),(V2)]$ $d_{\mathbb{C}}^{2}HLu_{\mathbb{C}}[(S11),(S10)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^{\dagger}HLu_{\mathbb{C}}^{\dagger}[(S10),(V5)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(S10),(V8)]$ $H^2L^2W_L[(F5)]$ $H^3H^{\dagger}L^2[(S4),(S5,F5),(S1),(S6,F6),(F3,F5),(F3),(F3,F6),$ $(S4,S6),(S6,F3),(S4,S5),(S1,S4),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^{\dagger}H^3L$
$F2\ (\mathbf{1},\mathbf{1},1)$	$d_{\mathbb{C}}^{3}H^{\dagger}L[(S11)]$
$F3\ \left(\mathbf{1},\mathbf{2},\frac{1}{2}\right)$	$De_{\mathbb{C}}H^{\dagger 3}L^{\dagger}[(F5),(F1),(S6),(V2)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^{\dagger}HLu_{\mathbb{C}}^{\dagger}[(S12),(V8)]$ $d_{\mathbb{C}}^{2}e_{\mathbb{C}}^{\dagger}HQ^{\dagger}[(V8),(S11)]$ $H^3H^{\dagger}L^2[(F5),(F1,F5),(F1),(F5,F6),(F1,F6),(S6,F5),$ $(S6,F1),(S5,F5),(S5,F1),(S1,F5),(S1,F1),(S6,F6),(S5,S6),(S1,S6)]$
$F4\ \left(\mathbf{1},\mathbf{2},\frac{3}{2}\right)$	$e_{\mathbb{C}}HL^3[(S6),(S2)]$
$F5\ (\mathbf{1},\mathbf{3},0)$	$e_{\mathbb{C}}HL^3[(S4),(S6)]$ $d_{\mathbb{C}}HL^2Q[(S4),(S12),(S14)]$ $HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}[(S4),(V9),(V8)]$ $D^2H^2L^2$ $De_{\mathbb{C}}H^{\dagger 3}L^{\dagger}[(S6),(F3),(V5)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(S14),(V8)]$ $H^2L^2W_L[(F7),(F1)]$ $H^3H^{\dagger}L^2[(S4),(S7),(S5,F1),(S1),(S6,F6),(F7),(F3),(F1,F3),$ $(F6,F7),(F3,F6),(S6,S7),(S4,S6),(S6,F7),(S6,F3),(S5,S7),$ $(S4,S5),(S1,S4),(S5,F7),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^{\dagger}H^3L$
$F6\ (\mathbf{1},\mathbf{3},1)$	$H^3H^{\dagger}L^2[(S8),(S6,F5),(S6,F1),(F5,F7),(F3,F5),(F1,F3),(S6,S8),(S6,F7),(S6,F3)]$
$F7\ \left(\mathbf{1},\mathbf{4},\frac{1}{2}\right)$	$H^2L^2W_L[(F5),(S6)]$ $H^3H^{\dagger}L^2[(F5),(S6,F5),(F5,F6),(S6,F6),(S5,F5),(S5,S6)]$
$F8\ \left(\mathbf{3},\mathbf{1},-\frac{1}{3}\right)$	$HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}[(S2),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(V8),(S12),(V5)]$ $d_{\mathbb{C}}^{2}e_{\mathbb{C}}^{\dagger}HQ^{\dagger}[(V5),(S11)]$
$F9\ \left(\mathbf{3},\mathbf{1},\frac{2}{3}\right)$	$d_{\mathbb{C}}HL^2Q[(S12),(S2)]$
$F10\ \left(\mathbf{3},\mathbf{2},-\frac{5}{6}\right)$	$d_{\mathbb{C}}^{2}HLu_{\mathbb{C}}[(S12),(S10),(S13)]$ $d_{\mathbb{C}}HL^2Q[(S10),(S6),(S2),(S14)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^{\dagger}HLu_{\mathbb{C}}^{\dagger}[(S10),(V3),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(S10),(S14),(V9),(V5)]$
$F11\ \left(\mathbf{3},\mathbf{2},\frac{1}{6}\right)$	$d_{\mathbb{C}}^{3}H^{\dagger}L[(S11),(S12)]$ $d_{\mathbb{C}}^{2}HLu_{\mathbb{C}}[(S11),(S12)]$
$F12\ \left(\mathbf{3},\mathbf{2},\frac{7}{6}\right)$	$HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}[(S6),(S2),(V9),(V5)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^{\dagger}HLu_{\mathbb{C}}^{\dagger}[(V5),(S12),(V3)]$
$F13\ \left(\mathbf{3},\mathbf{3},-\frac{1}{3}\right)$	$HL^2Q^{\dagger}u_{\mathbb{C}}^{\dagger}[(S6),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger 2}[(V8),(S12),(V9)]$
$F14\ \left(\mathbf{3},\mathbf{3},\frac{2}{3}\right)$	$d_{\mathbb{C}}HL^2Q[(S12),(S6)]$

Complete Dim-7 UV for 0vbb

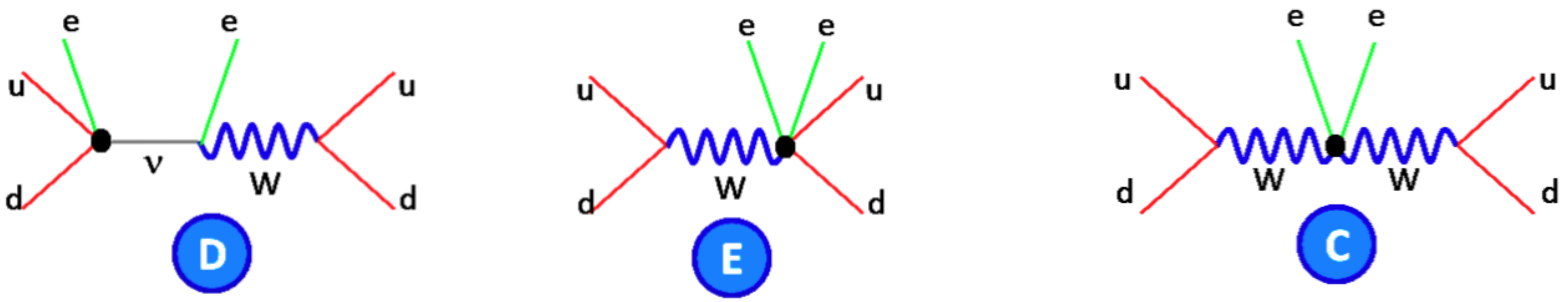
[Li, Ren, **Yu**, in preparation]





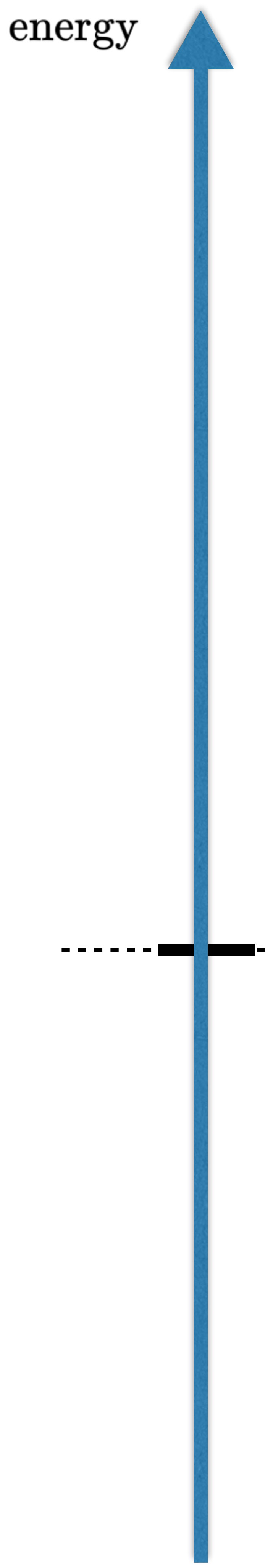
B preserving		B preserving		B violating	
$(S,1,1,1)$	$(S,1,2,1/2)$	$(S,3,2,1/6)$	$(F,3,2,7/6)$	$(S,3,1,-1/3)$	$(S,3,2,1/6)$
$(S,3,2,1/6)$	$(S,3,3,-1/3)$	$(S,3,2,1/6)$	$(F,3,3,2/3)$	$(S,3,1,-1/3)$	$(F,3,2,-5/6)$
$(S,1,1,1)$	$(F,3,1,-1/3)$	$(S,3,3,-1/3)$	$(F,3,2,-5/6)$	$(V,3,2,1/6)$	$(F,1,2,1/2)$
$(S,1,1,1)$	$(F,3,1,2/3)$	$(V,1,1,1)$	$(F,1,2,1/2)$	$(V,3,2,1/6)$	$(F,3,1,-1/3)$
$(S,1,1,1)$	$(F,3,2,-5/6)$	$(V,1,2,3/2)$	$(F,3,2,-5/6)$	$(V,3,2,1/6)$	$(F,3,2,-5/6)$
$(S,1,1,1)$	$(F,3,2,7/6)$	$(V,1,2,3/2)$	$(F,3,2,7/6)$	$(V,3,2,1/6)$	$(F,3,3,-1/3)$
$(S,1,2,1/2)$	$(F,1,3,0)$	$(V,3,1,2/3)$	$(F,3,2,7/6)$	$(V,3,1,2/3)$	$(V,3,2,1/6)$
$(S,3,2,1/6)$	$(F,1,2,1/2)$	$(V,3,3,3/2)$	$(F,3,2,7/6)$	$(V,3,2,1/6)$	$(V,3,3,2/3)$
$(S,3,2,1/6)$	$(F,3,1,2/3)$	$(V,1,1,1)$	$(V,1,2,3/2)$		

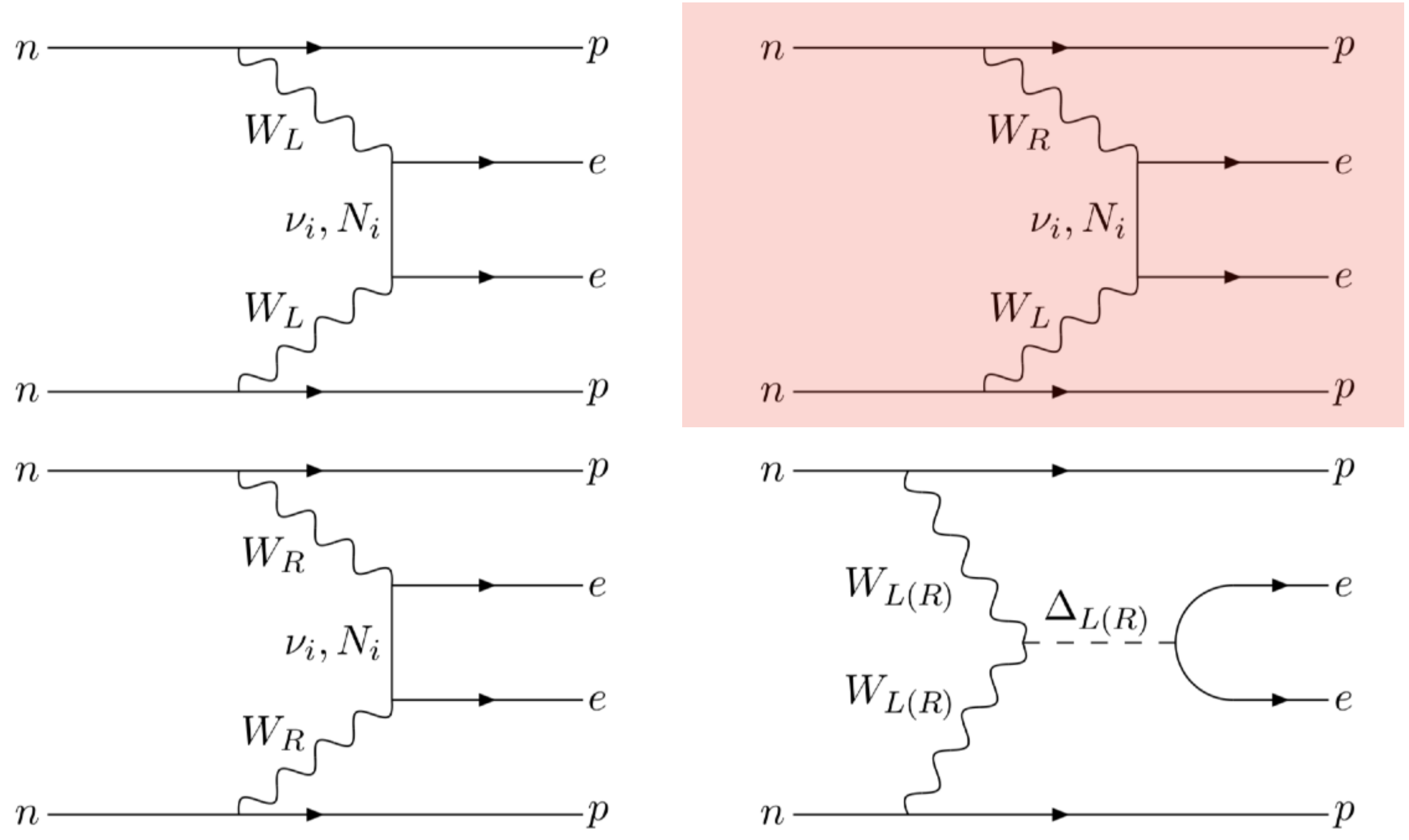
18 B preserving UV + 8 B violating UV
(0νββ w/ no tree ν-mass)



Complete Dim-7 UV for 0vbb

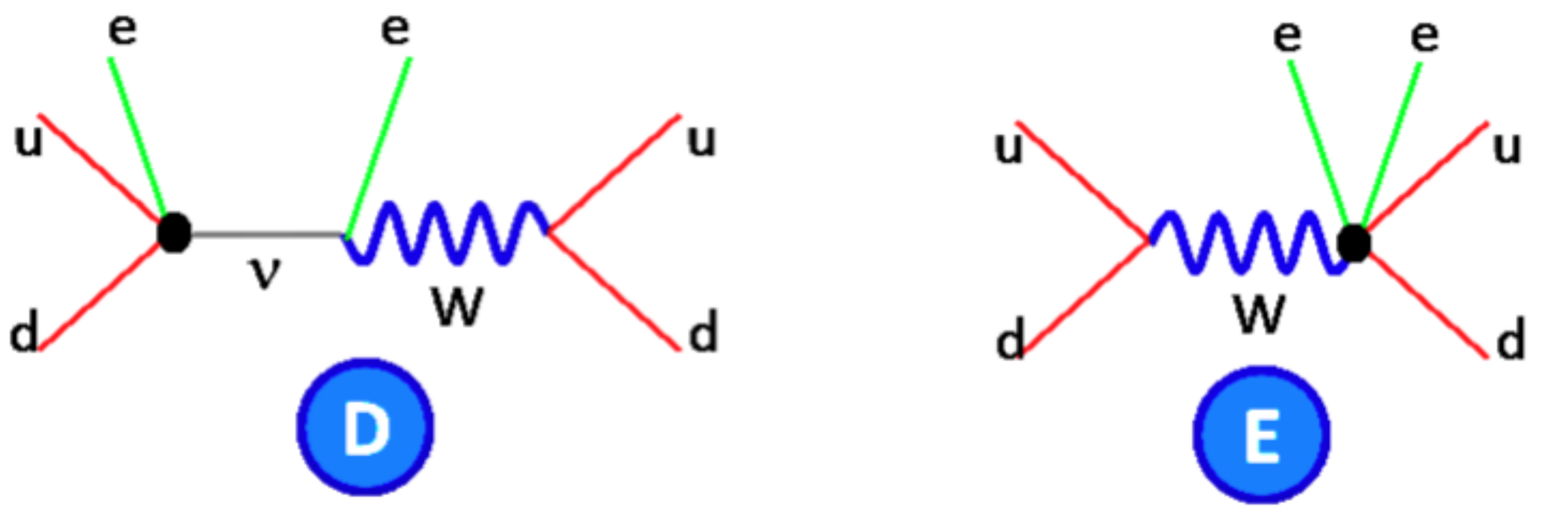
[Li, Ren, **Yu**, in preparation]





B preserving		B preserving		B violating	
$(S,1,1,1)$	$(S,1,2,1/2)$	$(S,3,2,1/6)$	$(F,3,2,7/6)$	$(S,3,1,-1/3)$	$(S,3,2,1/6)$
$(S,3,2,1/6)$	$(S,3,3,-1/3)$	$(S,3,2,1/6)$	$(F,3,3,2/3)$	$(S,3,1,-1/3)$	$(F,3,2,-5/6)$
$(S,1,1,1)$	$(F,3,1,-1/3)$	$(S,3,3,-1/3)$	$(F,3,2,-5/6)$	$(V,3,2,1/6)$	$(F,1,2,1/2)$
$(S,1,1,1)$	$(F,3,1,2/3)$	$(V,1,1,1)$	$(F,1,2,1/2)$	$(V,3,2,1/6)$	$(F,3,1,-1/3)$
$(S,1,1,1)$	$(F,3,2,-5/6)$	$(V,1,2,3/2)$	$(F,3,2,-5/6)$	$(V,3,2,1/6)$	$(F,3,2,-5/6)$
$(S,1,1,1)$	$(F,3,2,7/6)$	$(V,1,2,3/2)$	$(F,3,2,7/6)$	$(V,3,2,1/6)$	$(F,3,3,-1/3)$
$(S,1,2,1/2)$	$(F,1,3,0)$	$(V,3,1,2/3)$	$(F,3,2,7/6)$	$(V,3,1,2/3)$	$(V,3,2,1/6)$
$(S,3,2,1/6)$	$(F,1,2,1/2)$	$(V,3,3,3/2)$	$(F,3,2,7/6)$	$(V,3,2,1/6)$	$(V,3,3,2/3)$
$(S,3,2,1/6)$	$(F,3,1,2/3)$	$(V,1,1,1)$	$(V,1,2,3/2)$		

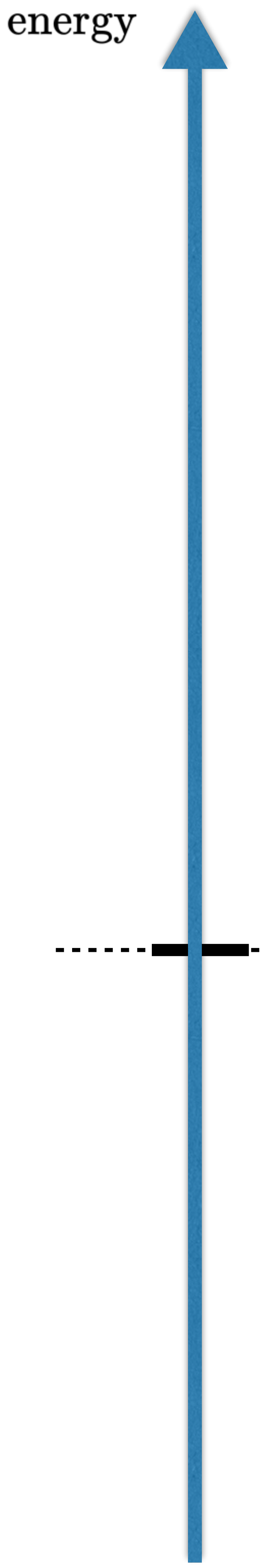
	$\mathcal{O}_{LeHD}$	$\mathcal{O}_{eLLLH}$	$\mathcal{O}_{dLQLH1}$	$\mathcal{O}_{dLQLH2}$	$\mathcal{O}_{dLueH}$	$\mathcal{O}_{QuLLH}$
S_2		$S_4/F_1/F_4$		$S_4/F_9/F_{10}$		$S_4/F_8/F_{12}$
S_4		$S_2/S_6/F_5$	$S_6/F_1/F_5$	$S_2/S_6/F_1/F_5$		$S_2/S_6/F_1/F_5$
S_6	F_3/F_5	$S_4/F_4/F_5$	$S_4/F_{10}/F_{14}$	$S_4/F_{10}/F_{14}$		$S_4/F_{12}/F_{13}$
S_{12}			$F_1/F_5/F_{14}$	$F_5/F_9/F_{14}$	F_3/F_{12}	
F_1	F_3/V_2	S_2	S_4/S_{12}	S_4	V_2/V_5	S_4/V_5
F_3	$S_6/F_1/F_5/V_2$				S_{12}/V_2	
F_4		S_2/S_6				
F_5	S_6/F_3	S_4/S_6	S_4/S_{12}	S_4/S_{12}		S_4/V_9
F_8						S_2
F_9				S_2/S_{12}		
F_{10}			S_6	S_2/S_6	V_3	
F_{12}					$S_{12}/V_3/V_5$	$S_2/S_6/V_5/V_9$
F_{13}						S_6
F_{14}			S_6/S_{12}	S_6/S_{12}		
V_2	$F_1/F_3/V_3$				$F_1/F_3/V_3$	
V_3	V_2				$F_{10}/F_{12}/V_2$	
V_5					F_1/F_{12}	F_1/F_{12}
V_9						F_5/F_{12}

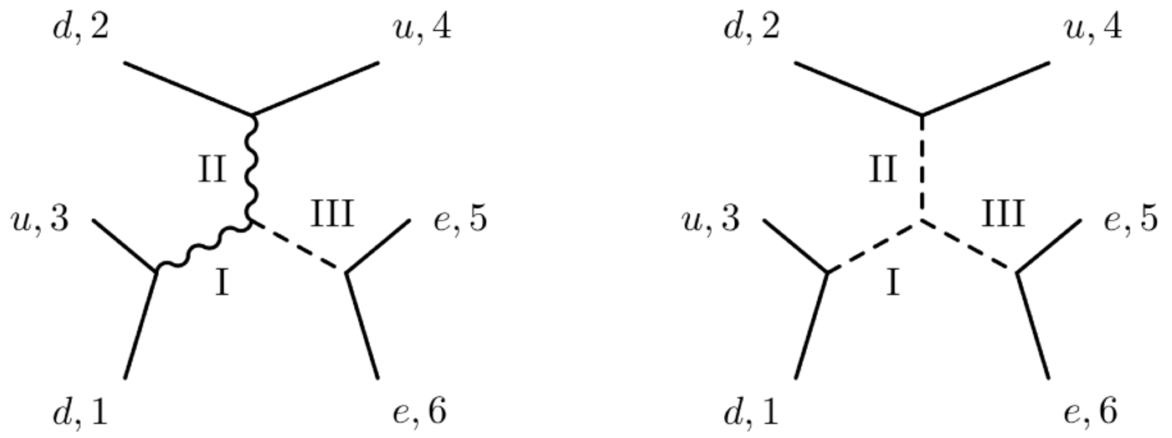


Complete Dim-9 UV for 0vbb

[Li, Ni, Xiao, **Yu**, in preparation]

[Li, **Yu**, Zhao, in progress]





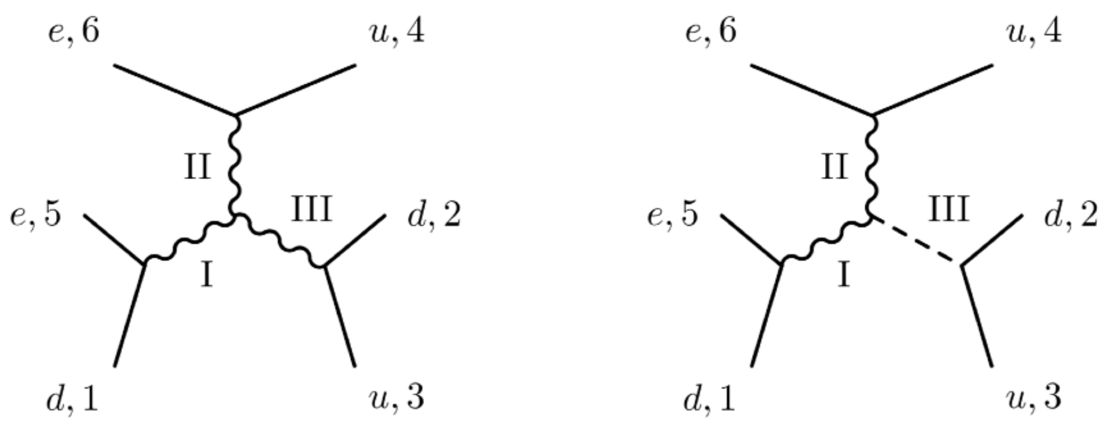
$(\mathbf{r}_i, J_i)$	$(1,1,0)$	$(0,0,0)$
$(\mathbf{8}_2, \mathbf{8}_2, \mathbf{1}_3)$	$\frac{4}{3}\mathcal{O}_1 + 2\mathcal{O}_2$	$-\frac{2}{3}\mathcal{O}_2$
$(\mathbf{8}_2, \mathbf{8}_2, \mathbf{1}_1)$	$-2\mathcal{O}_2$	$\frac{4}{3}\mathcal{O}_1 + \frac{2}{3}\mathcal{O}_2$
$(\mathbf{1}_2, \mathbf{1}_2, \mathbf{1}_3)$	$-4\mathcal{O}_1 - 6\mathcal{O}_2$	$2\mathcal{O}_2$
$(\mathbf{1}_2, \mathbf{1}_2, \mathbf{1}_1)$	$6\mathcal{O}_2$	$-4\mathcal{O}_1 - 2\mathcal{O}_2$

[**Michael Ramsey-Musolf's talk**]

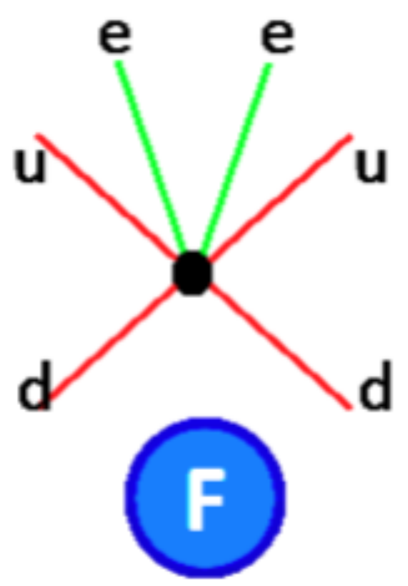
[Li, Ramsey-Musolf, Vasquez, 2020]

[Li, Ramsey-Musolf, Vasquez, 2021]

[Li, Ramsey-Musolf, Vasquez, 2022]



$(\mathbf{r}_i, J_i)$	$(1,1,1)$	$(1,1,0)$
$(\mathbf{3}_3, \mathbf{8}_2, \bar{\mathbf{3}}_2)$	$-\frac{8}{3}\mathcal{O}_1$	$\frac{4}{3}\mathcal{O}_1 + \frac{8}{3}\mathcal{O}_2$
$(\mathbf{3}_1, \mathbf{8}_2, \bar{\mathbf{3}}_2)$	$-\frac{8}{3}\mathcal{O}_1$	0
$(\mathbf{3}_3, \mathbf{1}_2, \bar{\mathbf{3}}_2)$	$-\frac{8}{3}\mathcal{O}_1$	$\frac{4}{3}\mathcal{O}_1 + \frac{8}{3}\mathcal{O}_2$
$(\mathbf{3}_1, \mathbf{1}_2, \bar{\mathbf{3}}_2)$	$-\frac{8}{3}\mathcal{O}_1$	0



$$\mathcal{O}_1 = \frac{1}{4}(L^\dagger{}_u{}^j L^\dagger{}_v{}^i)(Q_{pai} Q_{rbj})(u_{cs}{}^b u_{ct}{}^a)$$

$$\mathcal{O}_2 = -\frac{1}{4}(L^\dagger{}_u{}^j L^\dagger{}_v{}^i)(Q_{pai} u_{cs}{}^b)(Q_{rbj} u c_t{}^a).$$

[**Gui-Jun Ding's talk**]

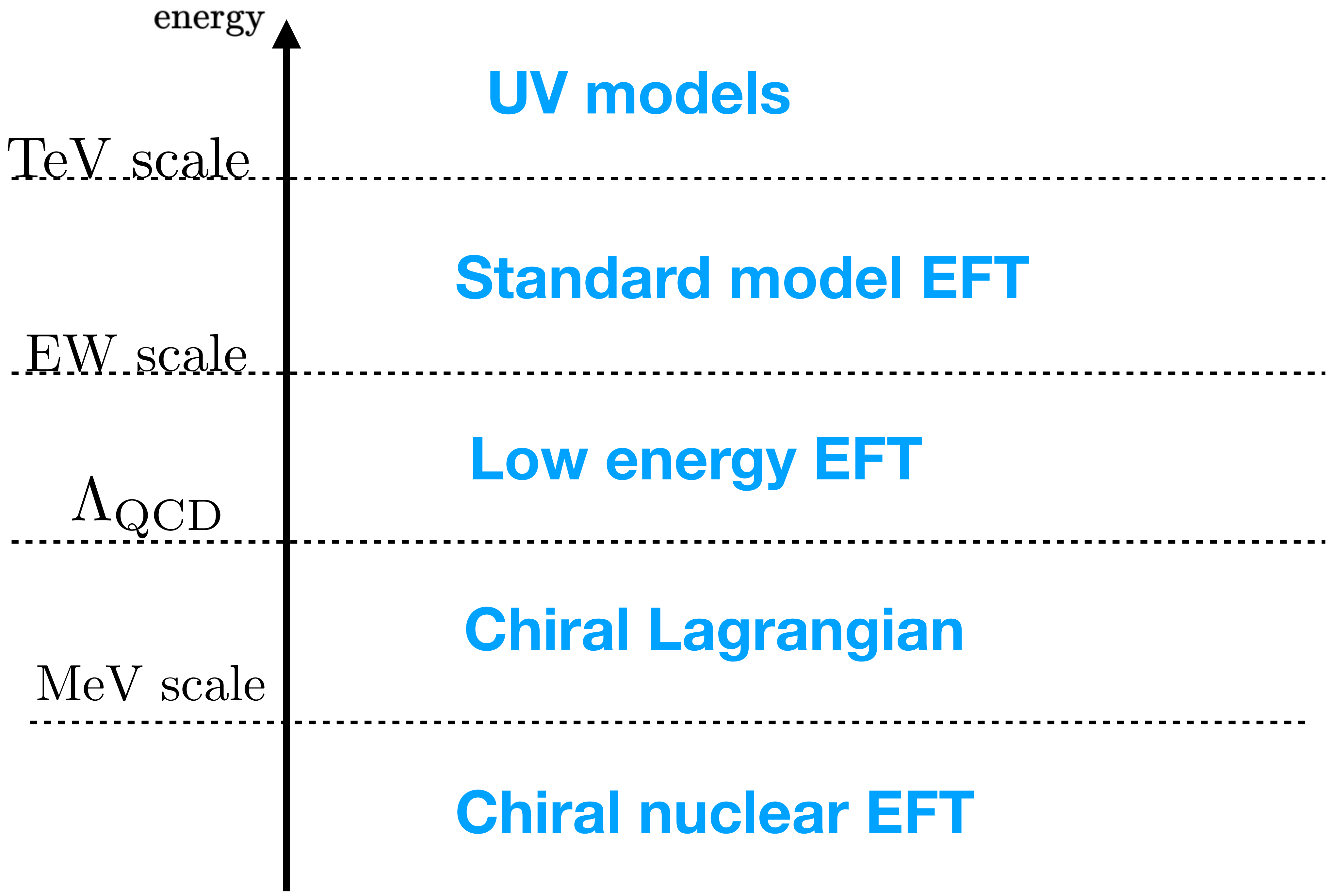
[Chen, Ding, Yao, 2021]

[Chen, Ding, Yao, 2023]

Summary

Neutrino experiments (0vbb, etc): low energy probe of high energy new physics

For physics involving in several energy scales, natural theoretical framework is EFT



EFT operators provide most general parametrization on new physics relevant to neutrino pheno

(Light sterile neutrino EFT not discussed in this talk)

The complete UV resonances can be explored using the Casimir projection

Thanks for your attention!