# 有效场论观点下的中微子0vbb

## EFT Perspective on Neutrino 0vbb

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# Outline

- EFT description for neutrino 0vbb

- Quark level EFTs: SMEFT and LEFT

- Nucleon level EFTs: ChPT and ChEFT

- UV completion of neutrino masses and 0vbb

- Summary

[ Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2404.15047 ]

[ Xuan-He Li, Hao Sun, Feng-Jie Tang, **J.H.Yu**, 2404.14152 ]

[ Hao Sun, Yi-Ning Wang, **J.H.Yu**, 2501.14018 ]

[ Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2501.09787 ]

[ Gang Li, Chuan-Qiang Song, **J.H.Yu**, 2507.02538 ]

[ Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, in preparation ]

[ Xu-Xiang Li, Zhe Ren, **J.H.Yu,** 2307.10380 ]

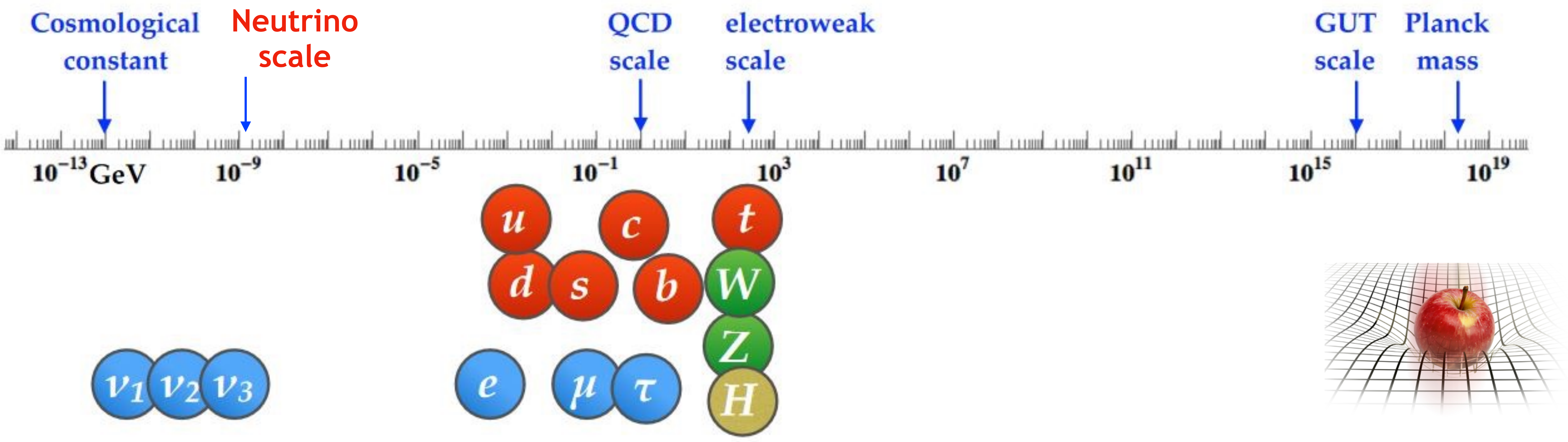
[ Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **J.H.Yu**, in preparation ]

[ Gang Li, **J.H.Yu,** Xiang Zhao, 2311.1

# EFT description for neutrino 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?**

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Decipher the Quantum Realm

# Dirac vs Majorana Neutrino

Simplest way to give neutrino masses is introducing the right-handed neutrino

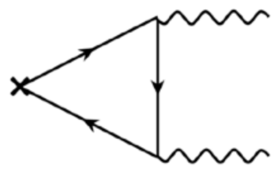
$$\mathcal{L}_m = \underbrace{m_D\, \overline{\psi_R}\psi_L}_{\text{Dirac term}} + \underbrace{\frac{1}{2}m_L\, \overline{\psi_L^c}\psi_L + \frac{1}{2}m_R\, \overline{\psi_R}\psi_R^c}_{\text{Majorana terms}} + \text{h.c.}$$

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

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

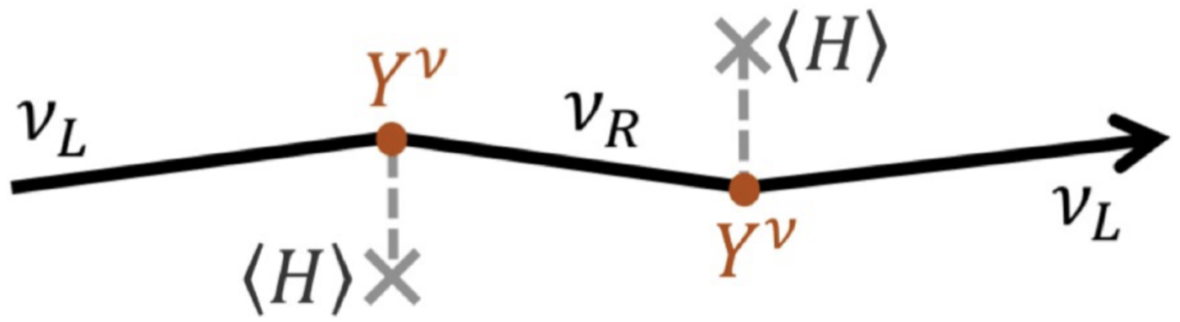
**How to forbid the Majorana term?**

**Lepton number conservation**



**The Majorana term should be there**

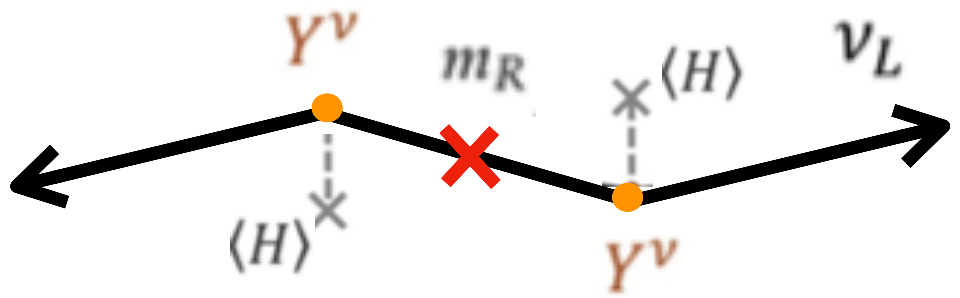
**Lepton number violation**




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

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

**Tiny Yukawa coupling**



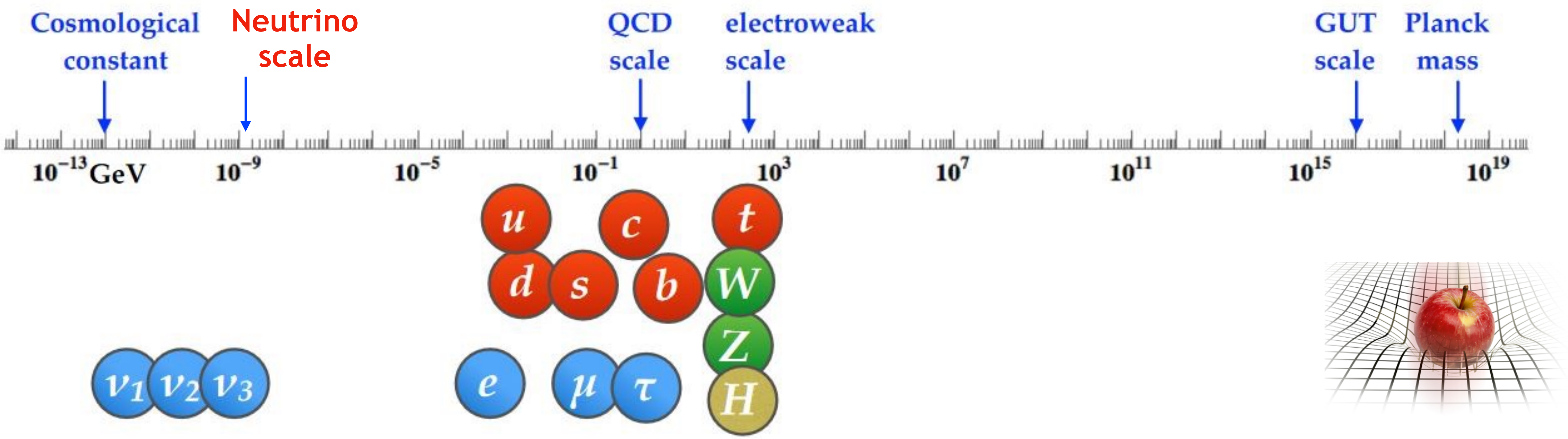

$$m_\nu = \frac{(Y^\nu v_{\text{EW}})^2}{m_R}$$

**Yukawa coupling not small, but mR heavy**

[ See Zhi-Zhong Xing's talk ]

# 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

Elucidate the Mysteries of Neutrinos

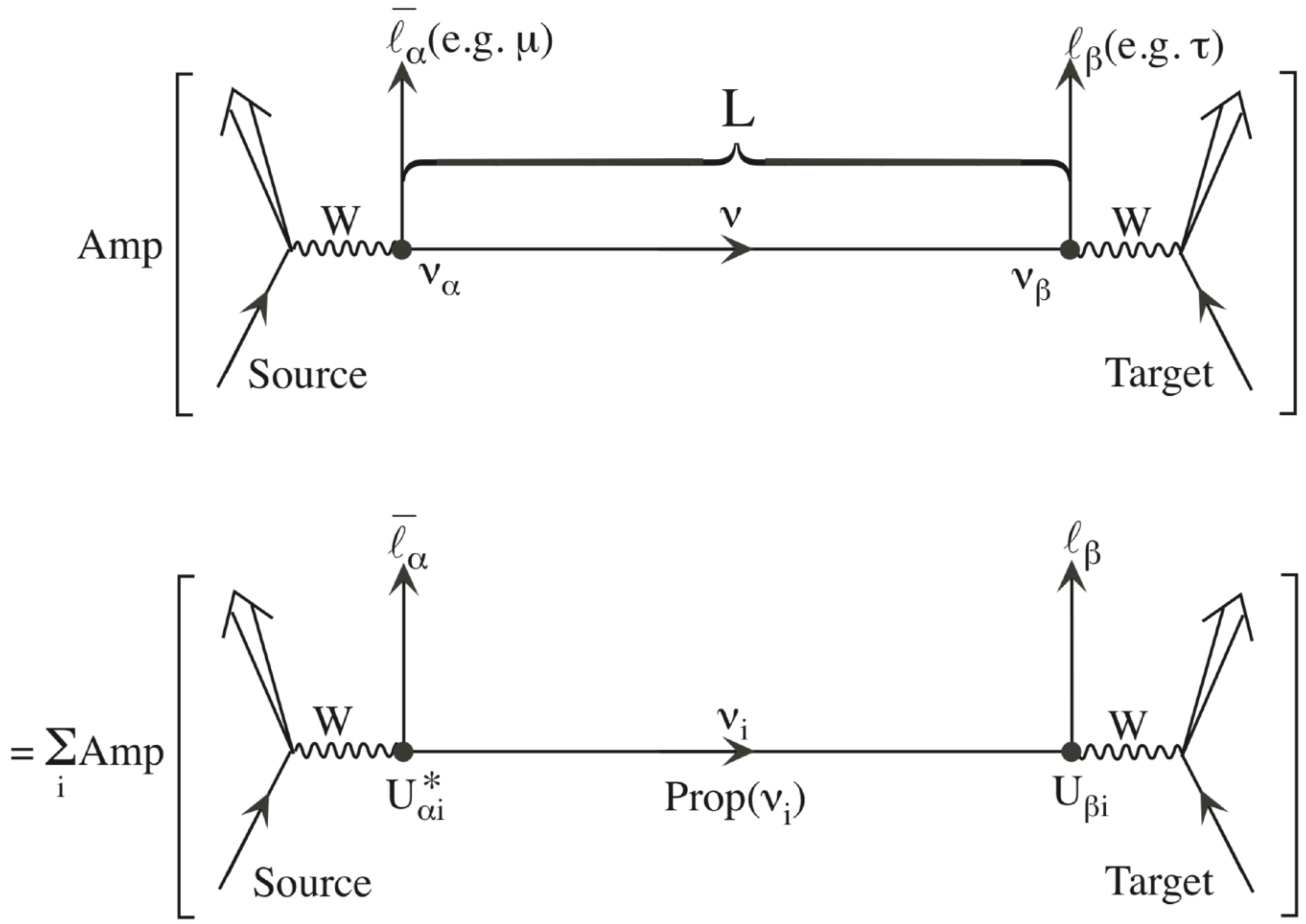
Reveal the Secrets of the Higgs Boson

Decipher the Quantum Realm

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

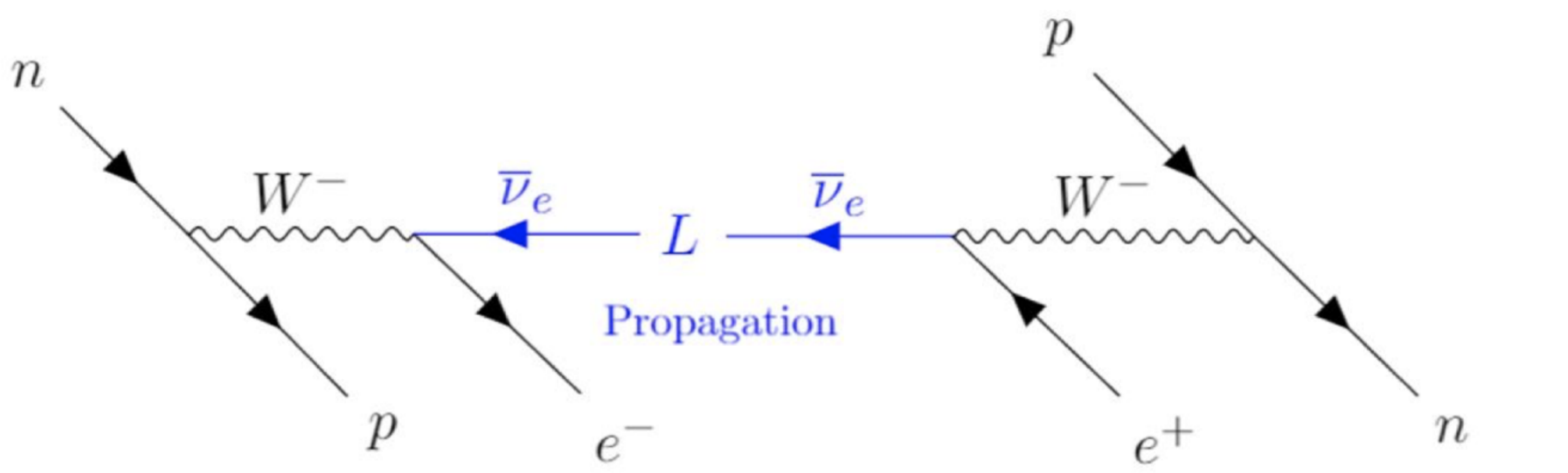
# Nature of Majorana Neutrino

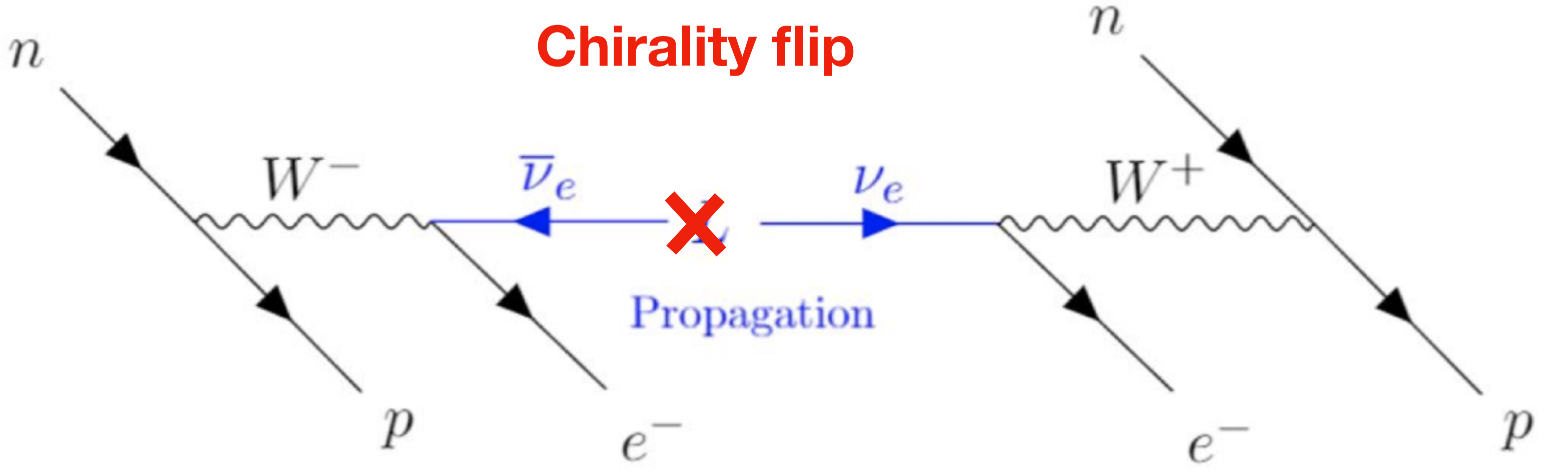
How to distinguish Dirac vs Majorana neutrino?




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

**Neutrino Oscillation experiments**



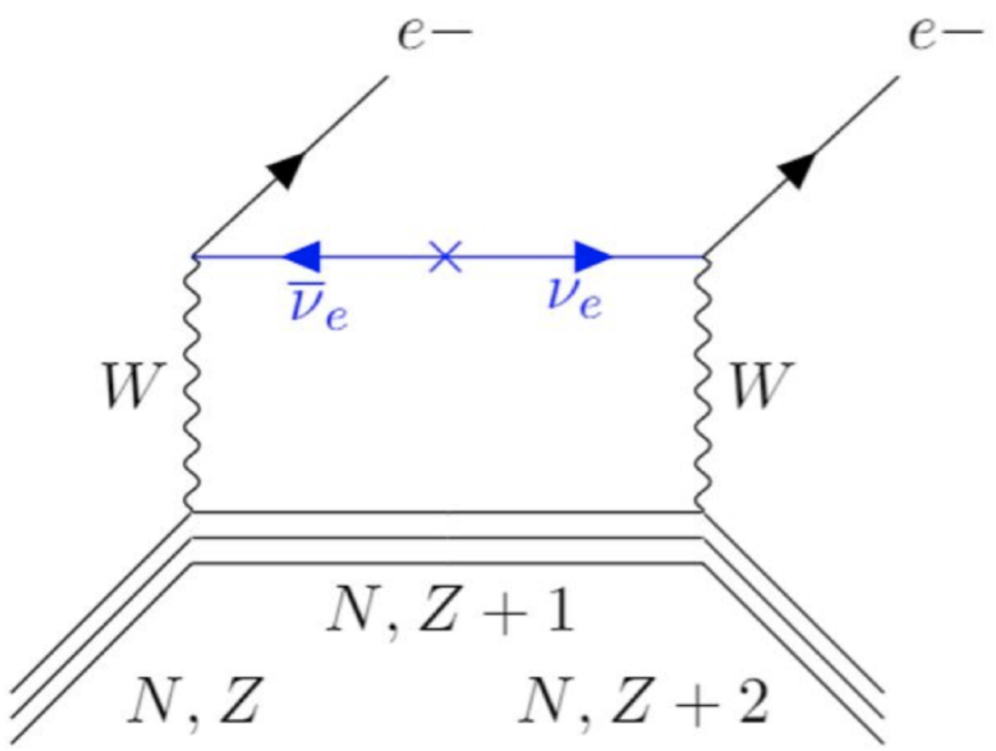

$$\mathcal{M} = \mathcal{A} \sum_i (U_{ei})^2 m_{\nu_i} = \mathcal{A}\, m_{\beta\beta}$$

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

suppressed

by a factor $m_\nu^2/E^2$

**0νββ exp.**



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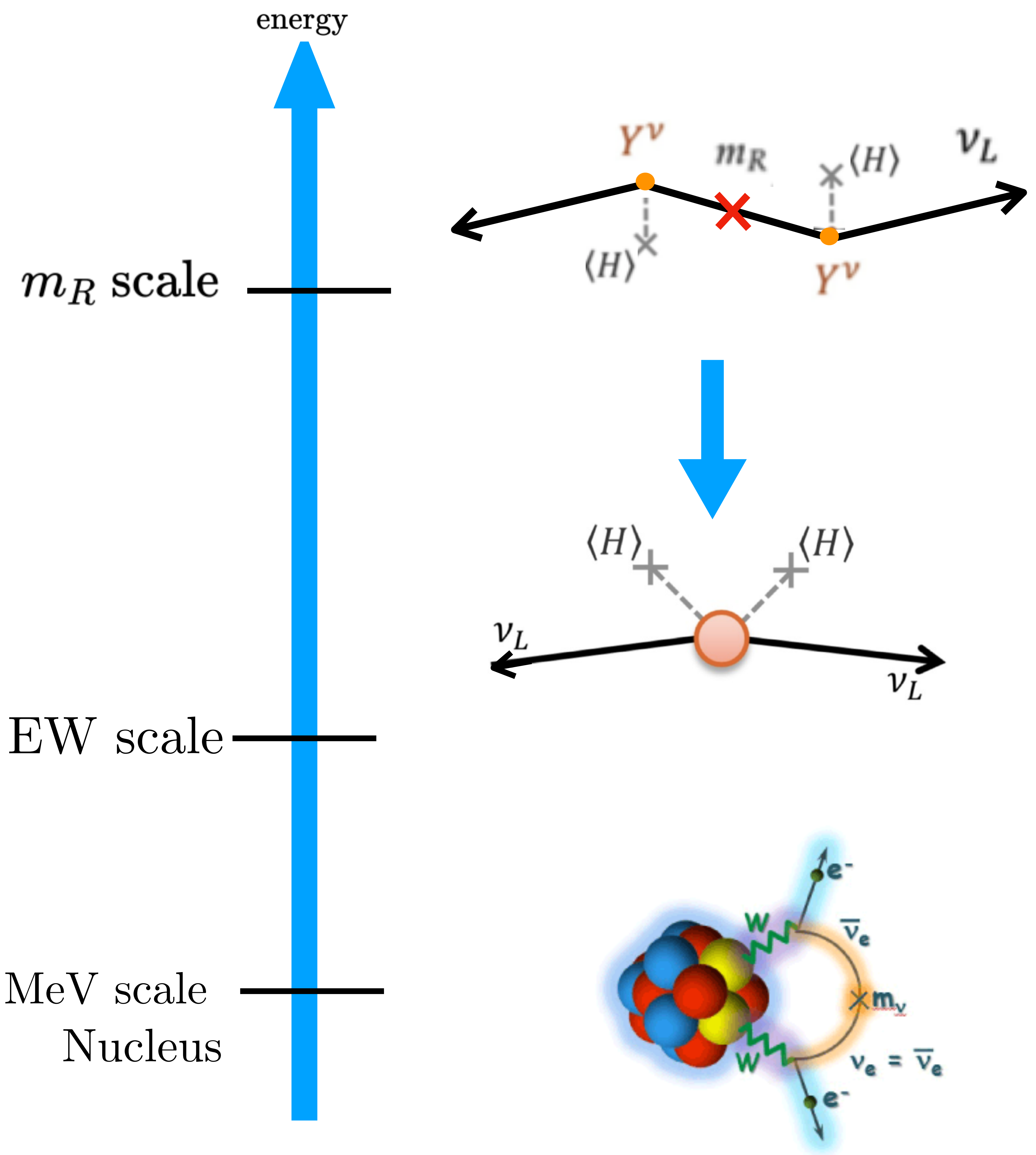
# Neutrinoless Double Beta Decay

Low energy probe of high energy new physics




[ Weinberg, 1979 ]

**Weinberg operator**

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

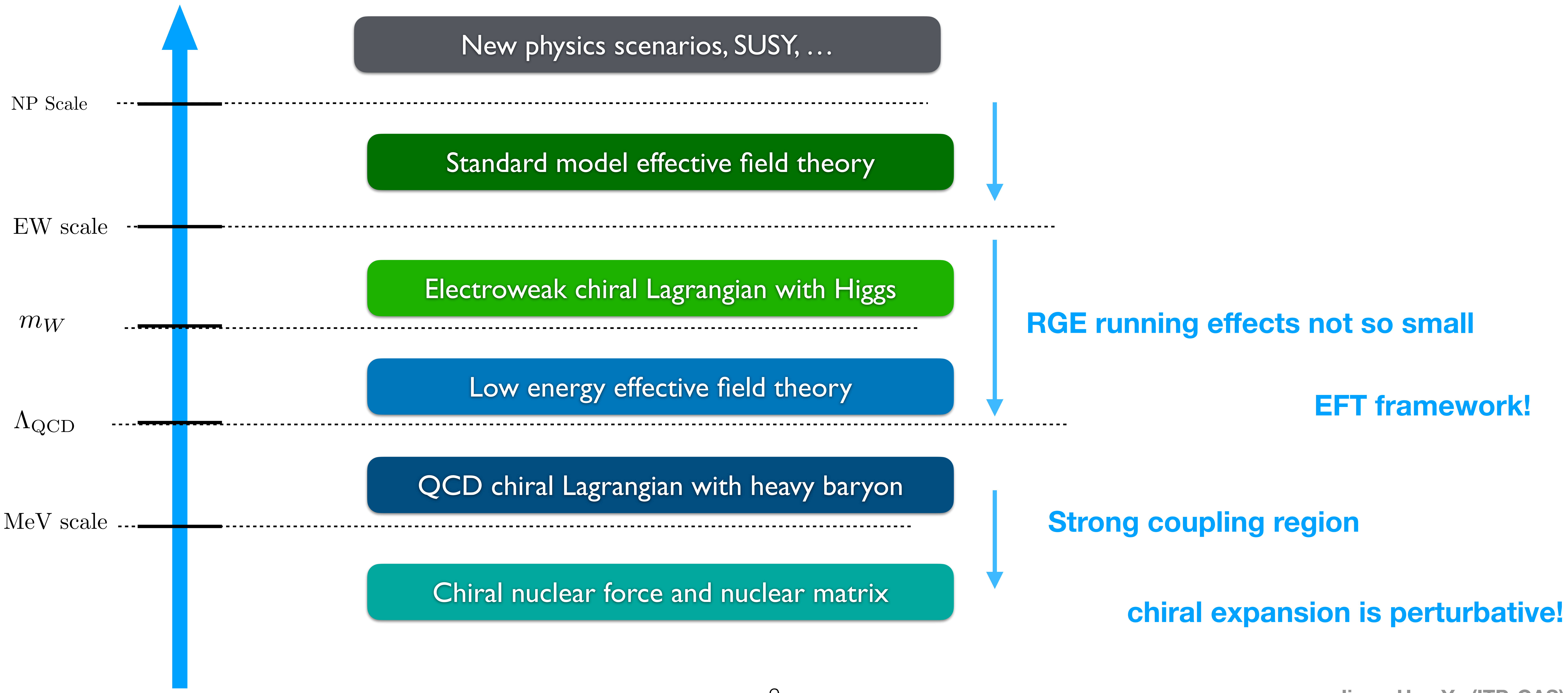
$$\to c_{ij}\frac{v^2}{\Lambda}\nu_i\nu_j + \text{h.c.}$$

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

[ Weinberg, 2021 ]

# Tower of effective field theories

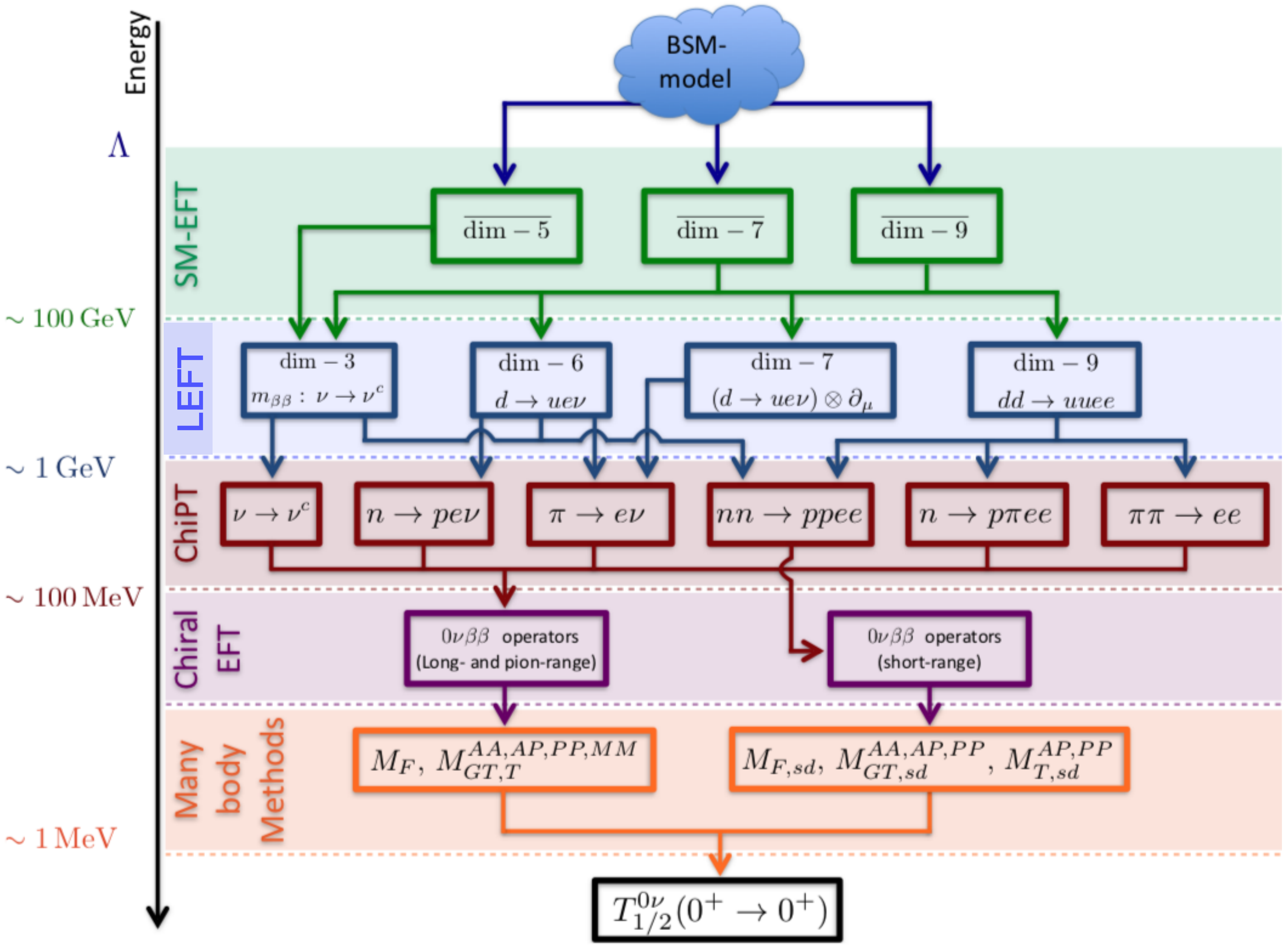
Why EFT framework? it is natural to consider different EFTs to avoid large Logs



# Complete EFT Framework for 0vbb

Operator bases for different EFTs are necessarily needed to provide most general description

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




[ See Shun Zhou's talk ]

# Complete EFT Framework for 0vbb

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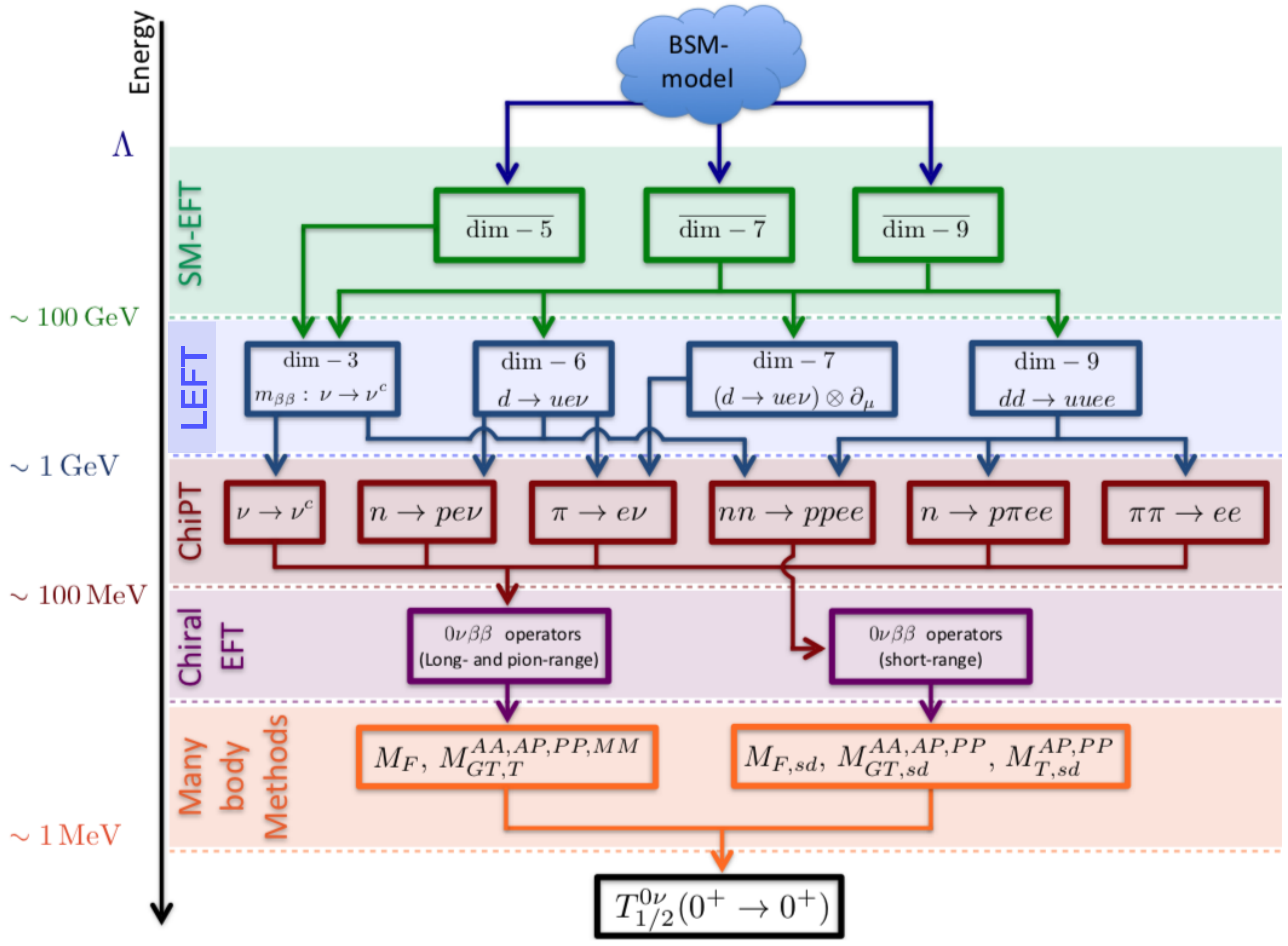



**UV models new particles**

[ See Shun Zhou and Jingyu Zhu's talk ]

**Quark level operators**

[ See Gang Li's talk ]

**Hadronic level operators**

[ See Bingwei Long and Tai-Xing Liu's talk ]

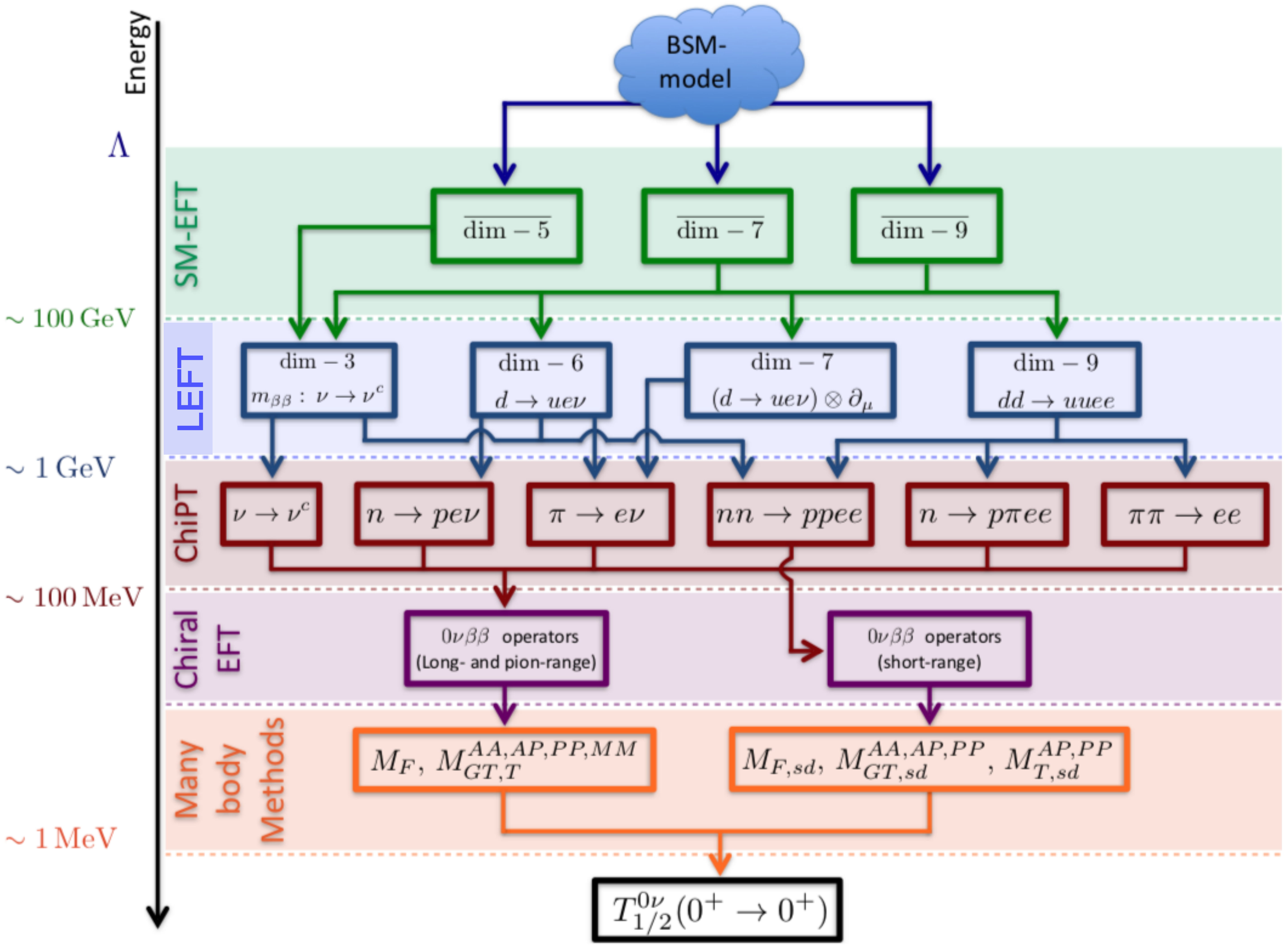
**Nuclear level operators**

[ See Pengwei Zhao and Chun-Lin Bai's talk ]

# Complete EFT Framework for 0vbb

Operator bases for different EFTs are necessarily needed to provide most general description

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




**UV models new particles**

**Repeat for each model**

**Quark level operators**

**Operator correlation**

**How to do matching**

**Hadronic level operators**

**External source not enough**

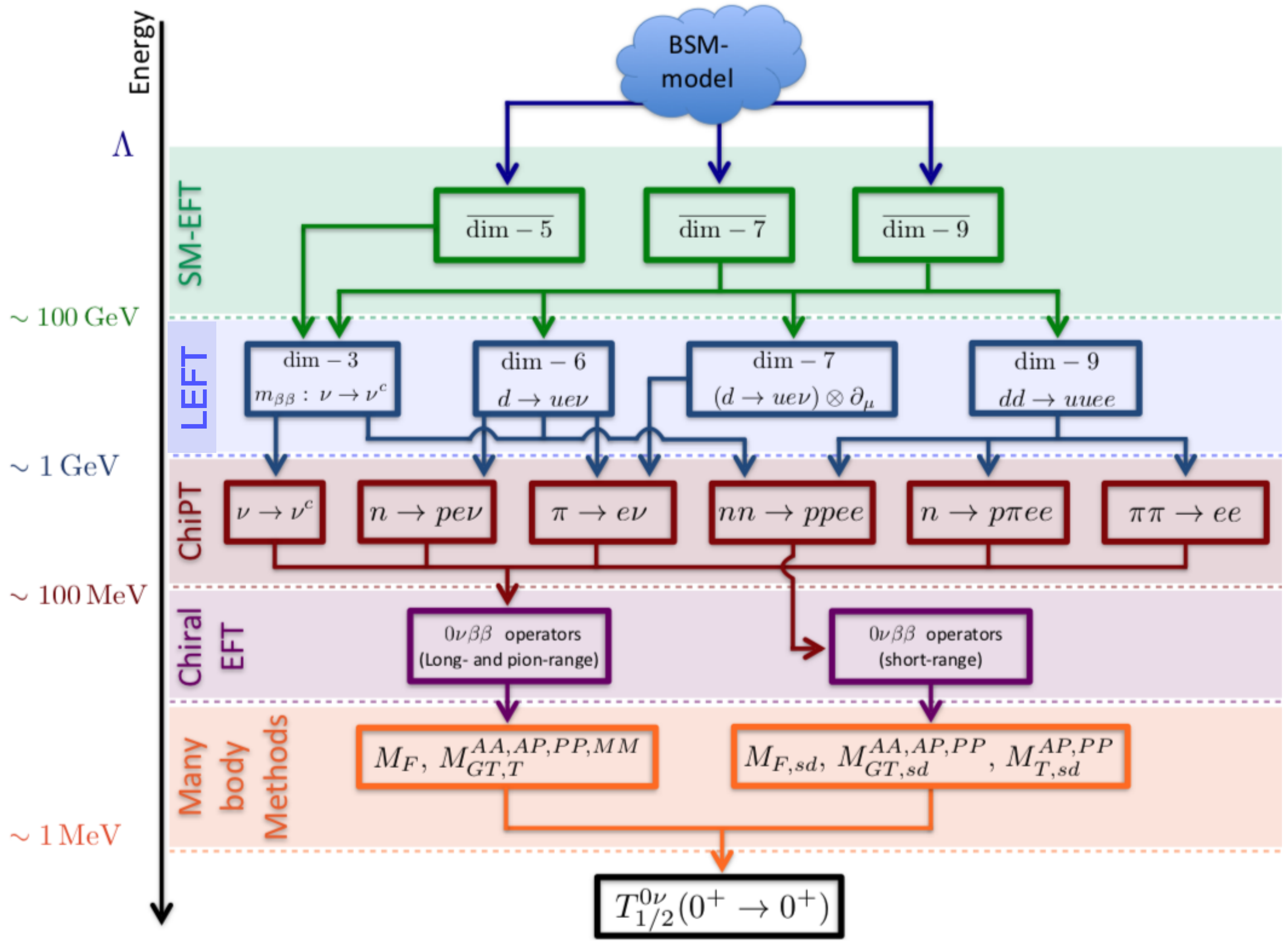
**Nuclear level operators**

**Nucleon matrix element incomplete**

# Complete EFT Framework for 0vbb

Operator bases for different EFTs are necessarily needed to provide most general description

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




**UV models new particles**

↓

**Quark level operators**

↓

**Hadronic level operators**

↓

**Nuclear level operators**

**Setup a general framework**

**Need complete operators at each level**

# Quark level EFTs: SMEFT and LEFT

[ 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-Lin Li, Jing Shu, Zhe Ren, Ming-Lei Xiao, **J.H.Yu**, Yu-Hui Zheng, 2005.00008 ]

# Standard Model Effective Field Theory

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

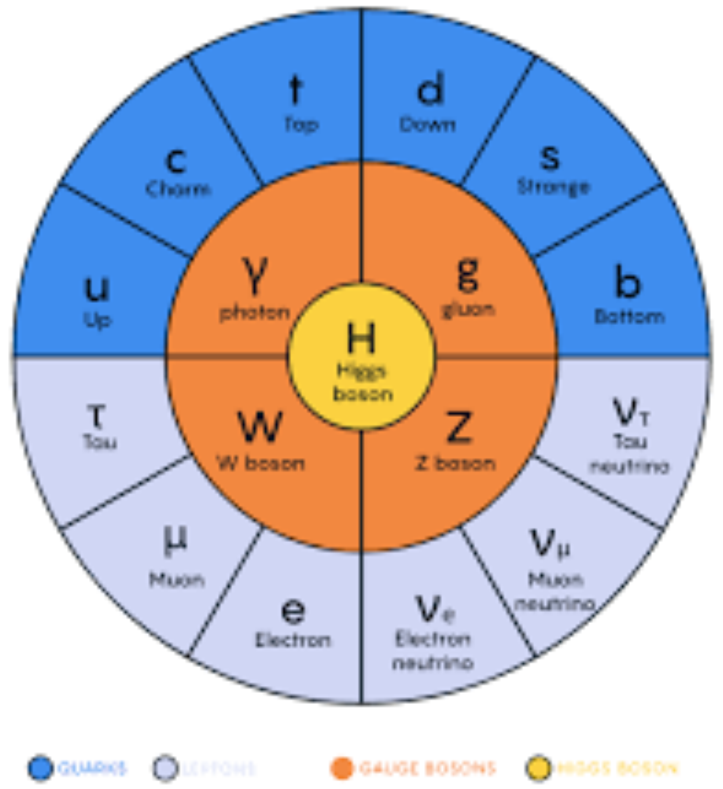
$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathscr{D}\leq 4} + \frac{\mathscr{L}_5}{\Lambda} + \frac{\mathscr{L}_6}{\Lambda^2} + \frac{\mathscr{L}_7}{\Lambda^3} + \frac{\mathscr{L}_8}{\Lambda^4} + \frac{\mathscr{L}_9}{\Lambda^5} + \ldots$$

[ Weinberg, 1980 ]

Standard Model

Weinberg Operator

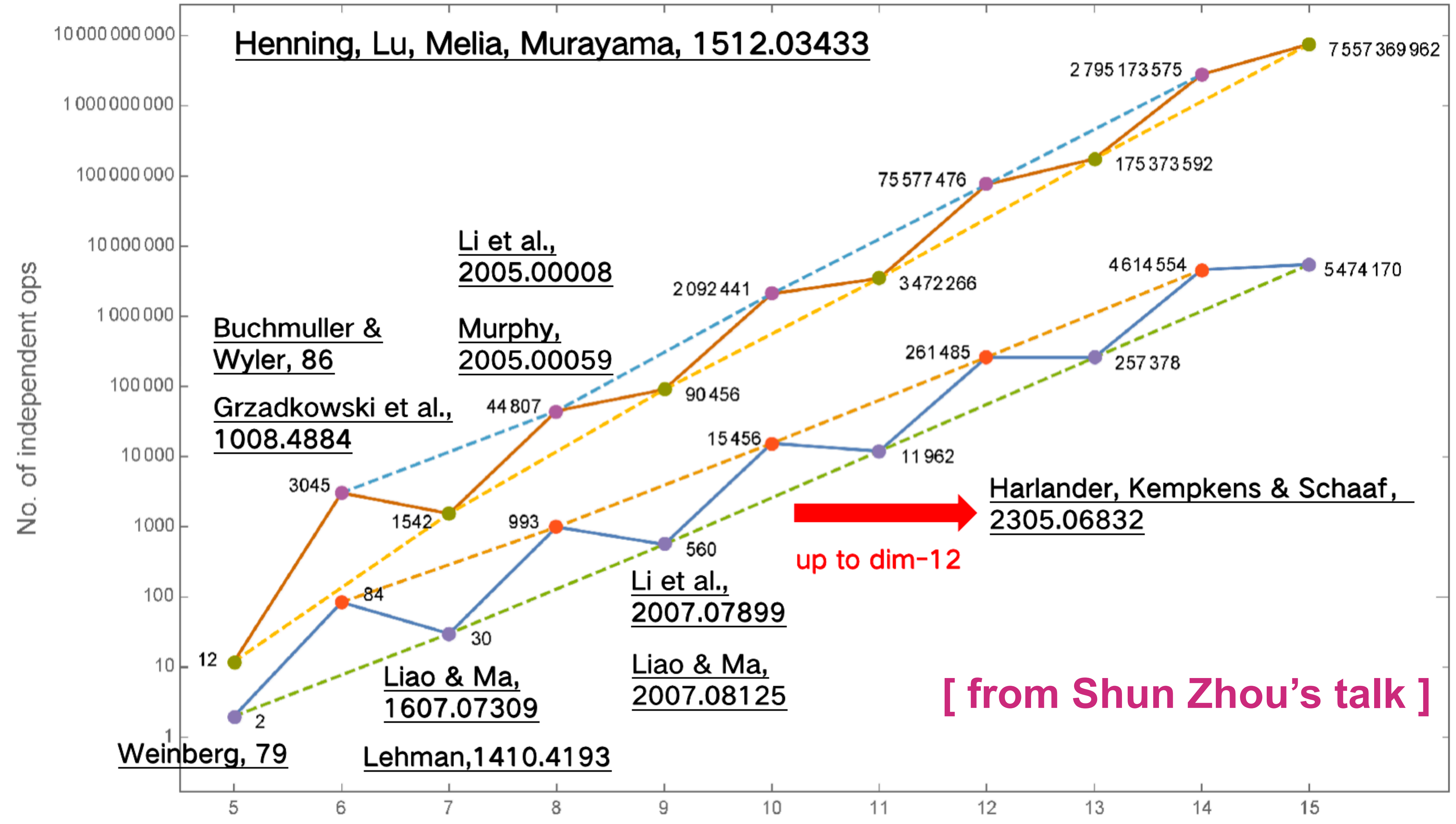
$$\frac{c_{ij}}{\Lambda}(L_i H)(L_j H) + \mathrm{h.c.}$$




17 elementary particles

$$\begin{aligned}\mathcal{L}_{SM} = & \underbrace{\frac{1}{4}W_{\mu\nu}\cdot W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}}_{\text{kinetic energies and self-interactions of the gauge bosons}} \\ & + \underbrace{\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)L + \bar{R}\gamma^{\mu}\left(i\partial_{\mu} - \frac{1}{2}g'YB_{\mu}\right)R}_{\text{kinetic energies and electroweak interactions of fermions}} \\ & + \underbrace{\frac{1}{2}\left|\left(i\partial_{\mu} - \frac{1}{2}g\tau\cdot W_{\mu} - \frac{1}{2}g'YB_{\mu}\right)\phi\right|^{2} - V(\phi)}_{W^{\pm},Z,\gamma \text{ and Higgs masses and couplings}} \\ & + \underbrace{g''\left(\bar{q}\gamma^{\mu}T_{a}q\right)G^{a}_{\mu}}_{\text{interactions between quarks and gluons}} + \underbrace{\left(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.\right)}_{\text{fermion masses and couplings to Higgs}}\end{aligned}$$

19 parameters, all measured but theta term




ing of independent operators up to dim-15

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



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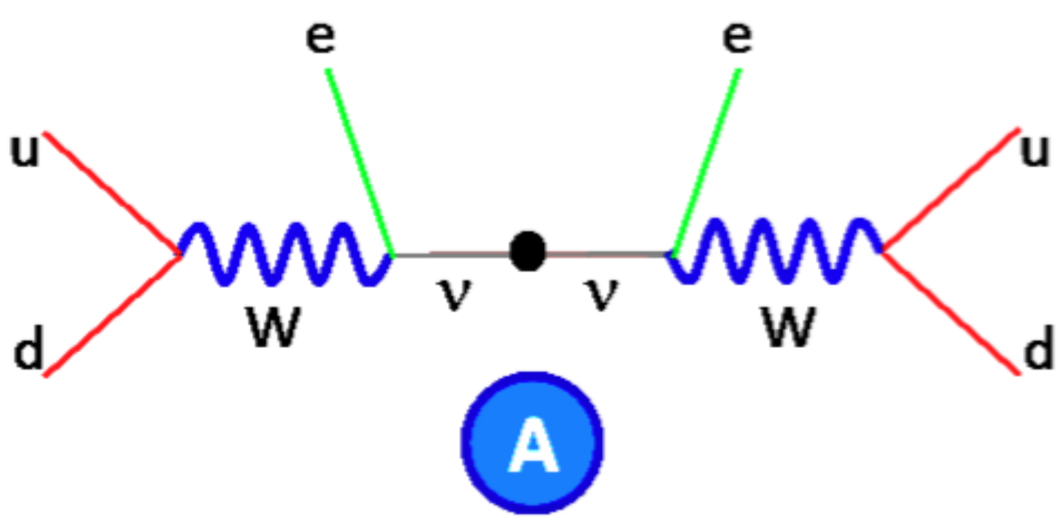
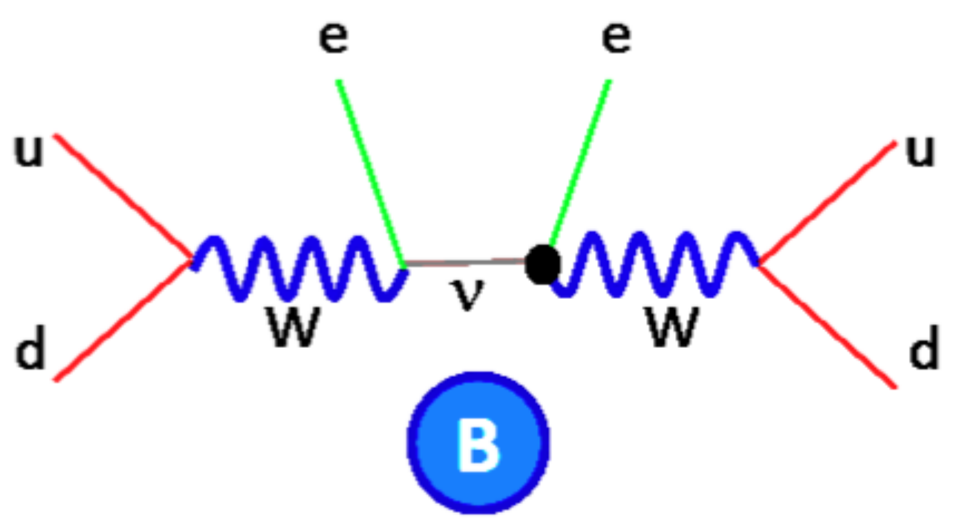
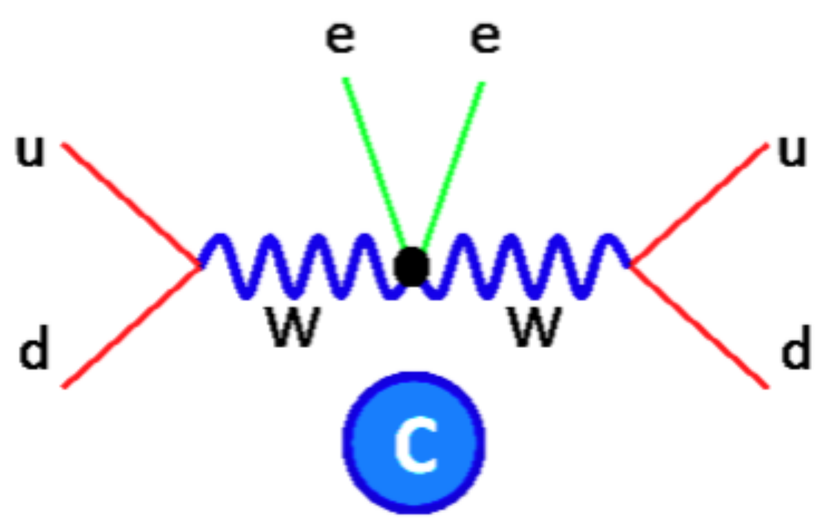
# Operators for 0vbb

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




**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**

$\mathcal{O}_{LeHD}$ $\epsilon^{ij}\epsilon^{kl}(\ell_i^T C\gamma^\mu e) H_j H_k (i D_\mu H_l)$

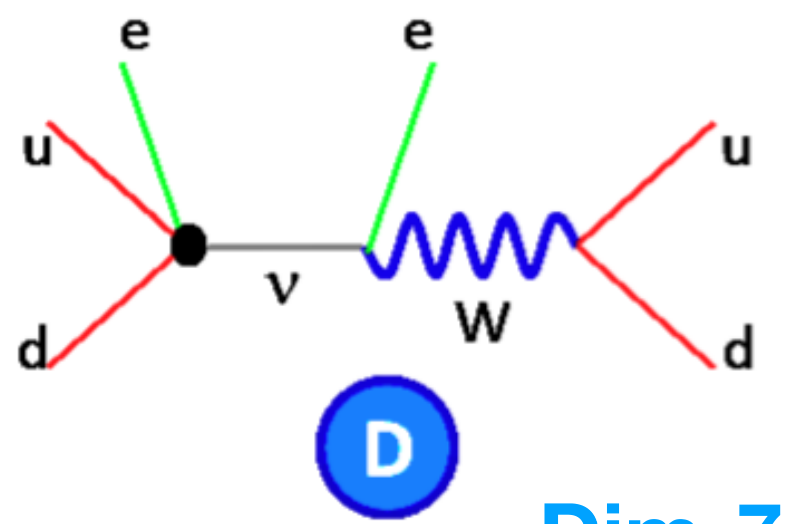
$\mathcal{O}_{LHW}$ $-\epsilon^{ik}(\epsilon\tau^I)^{jl}(\ell_i^T C i\sigma^{\mu\nu}\ell_j) H_k H_l W^I_{\mu\nu}$

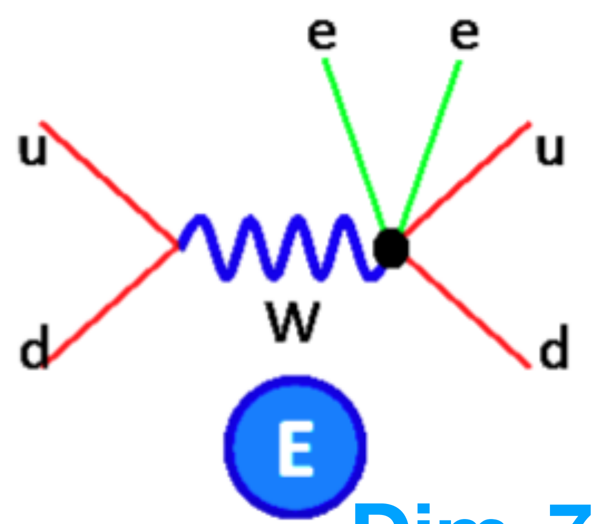
**Dim-7, 9**

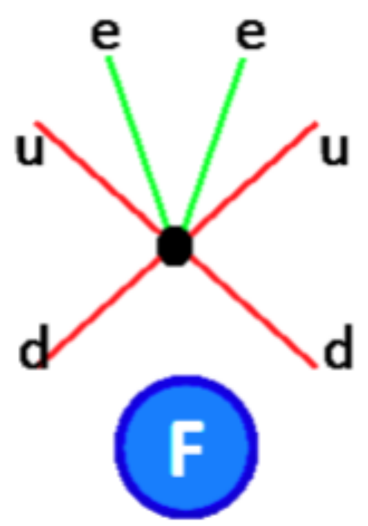
$D^2 H^{\dagger 2} L^{\dagger 2}$

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

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




**Dim-7**

$\mathcal{O}_{dLQLH1}$ $\epsilon^{ij}\epsilon^{kl}(\bar{d}^a \ell_i)(q_{aj}^T C \ell_k) H_l$

$\mathcal{O}_{dLQLH2}$ $\epsilon^{ik}\epsilon^{jl}(\bar{d}^a \ell_i)(q_{aj}^T C \ell_k) H_l$

$\mathcal{O}_{dLueH}$ $\epsilon^{ij}(\bar{d}^a \ell_i)(u_a^T C e) H_j$

$\mathcal{O}_{QuLLH}$ $\epsilon^{ij}(\bar{q}^{ak} u_a)(\ell_k^T C \ell_i) H_j$

**Dim-7, 9**

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

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

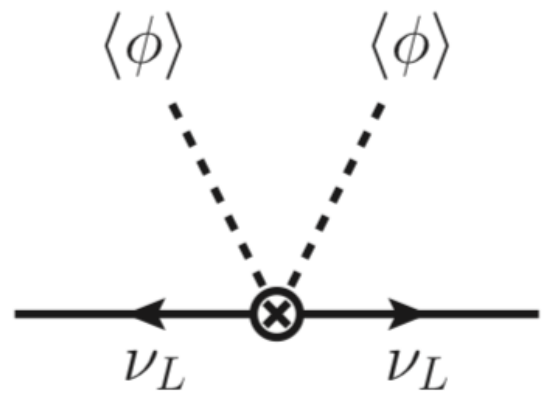
$dc^\dagger\, ec\, H^\dagger\, L^\dagger\, uc\, WL$

**Dim-9**

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

# Operator Correlation for nv mass/0vbb

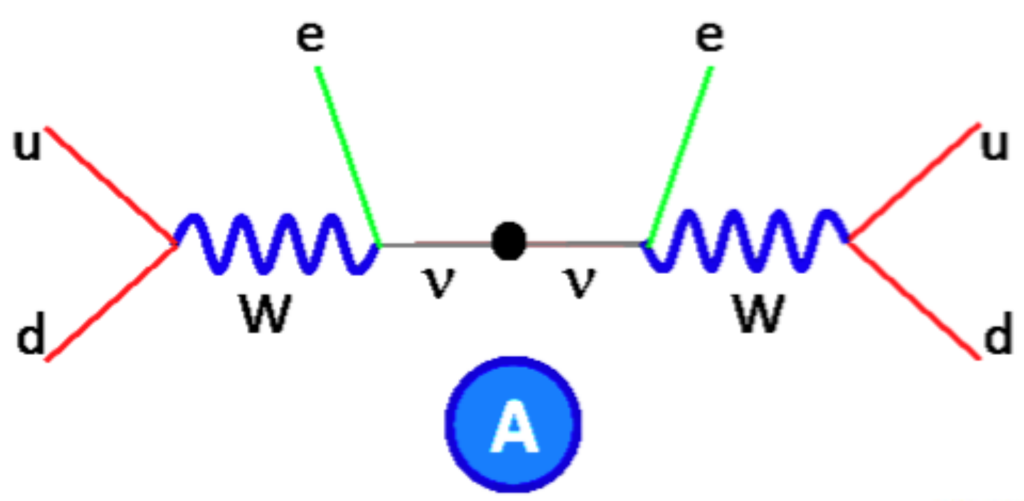
SMEFT dim-5,7,9 operators provides most general parametrization of new physics for neutrino masses and 0vbb

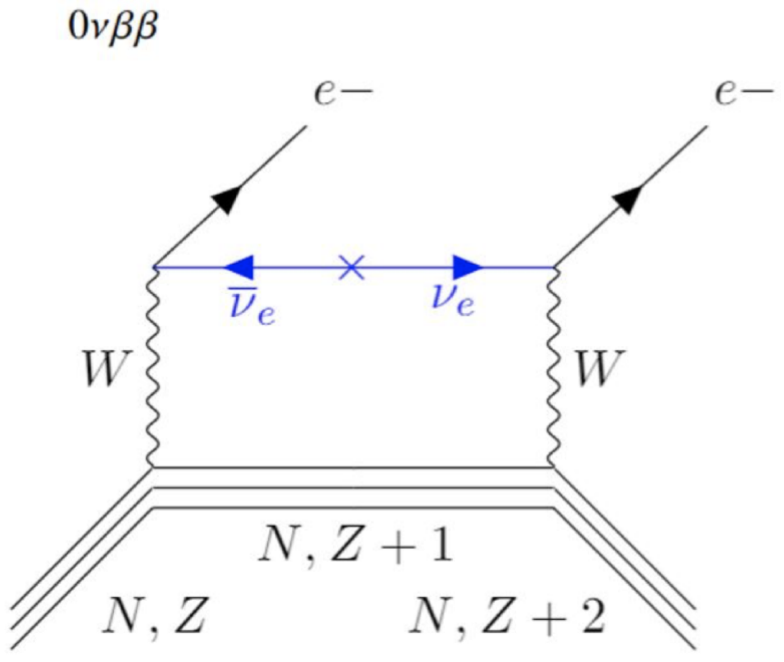



**Dim-5, 7, 9 neutrino mass**

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

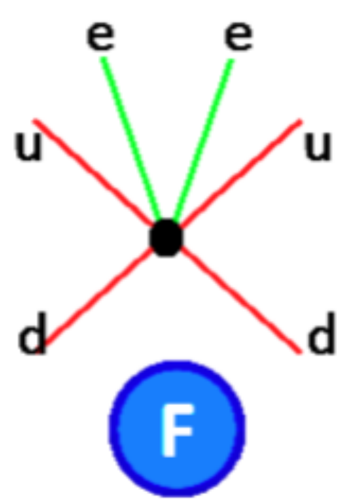
**Correlated between mv and 0vbb**



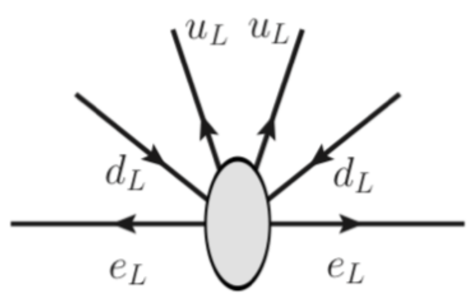



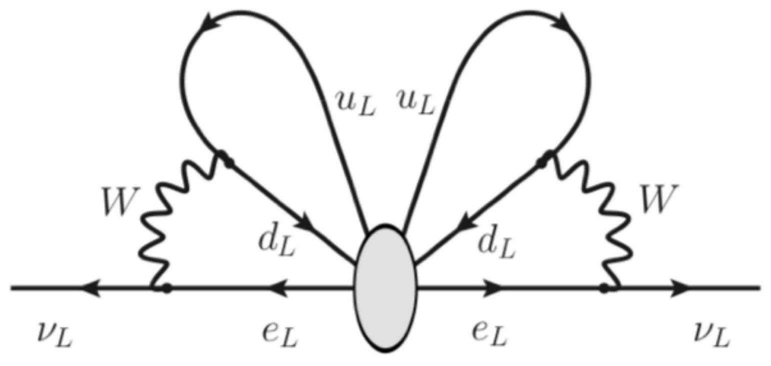

**0vbb does not need to be related to the total neutrino masses**

**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**



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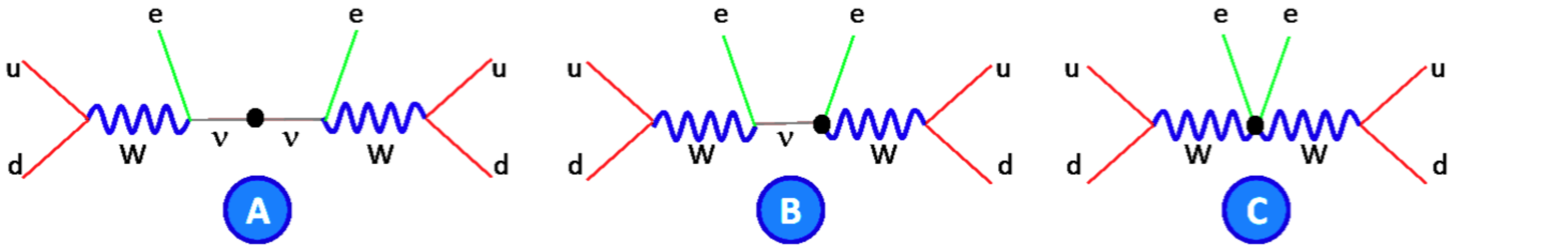
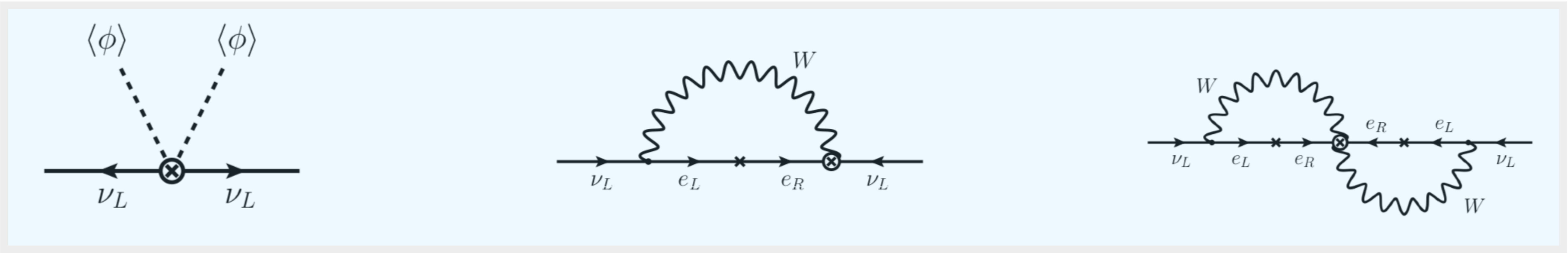
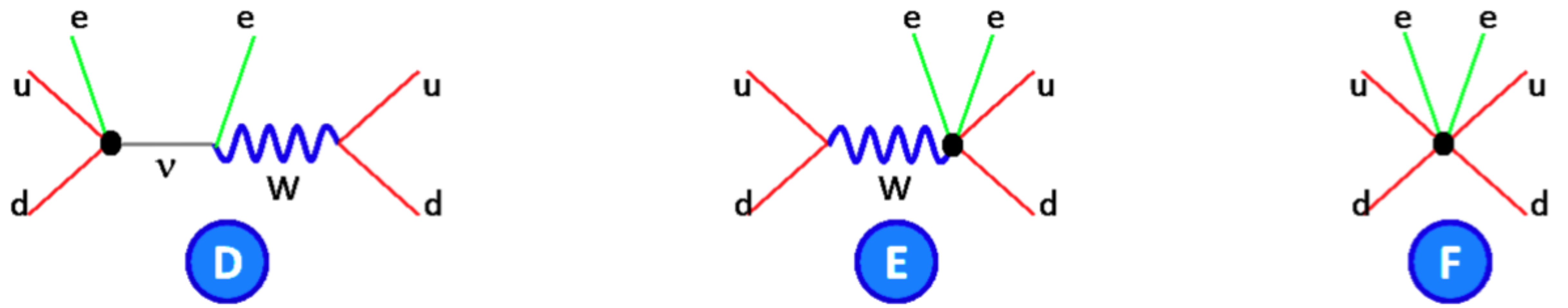
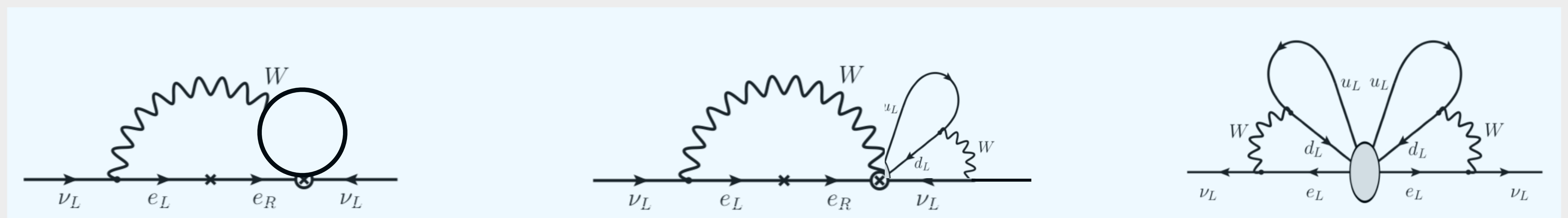
# 0vbb and Neutrino Masses

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







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# SMEFT Dimension-6 Operators

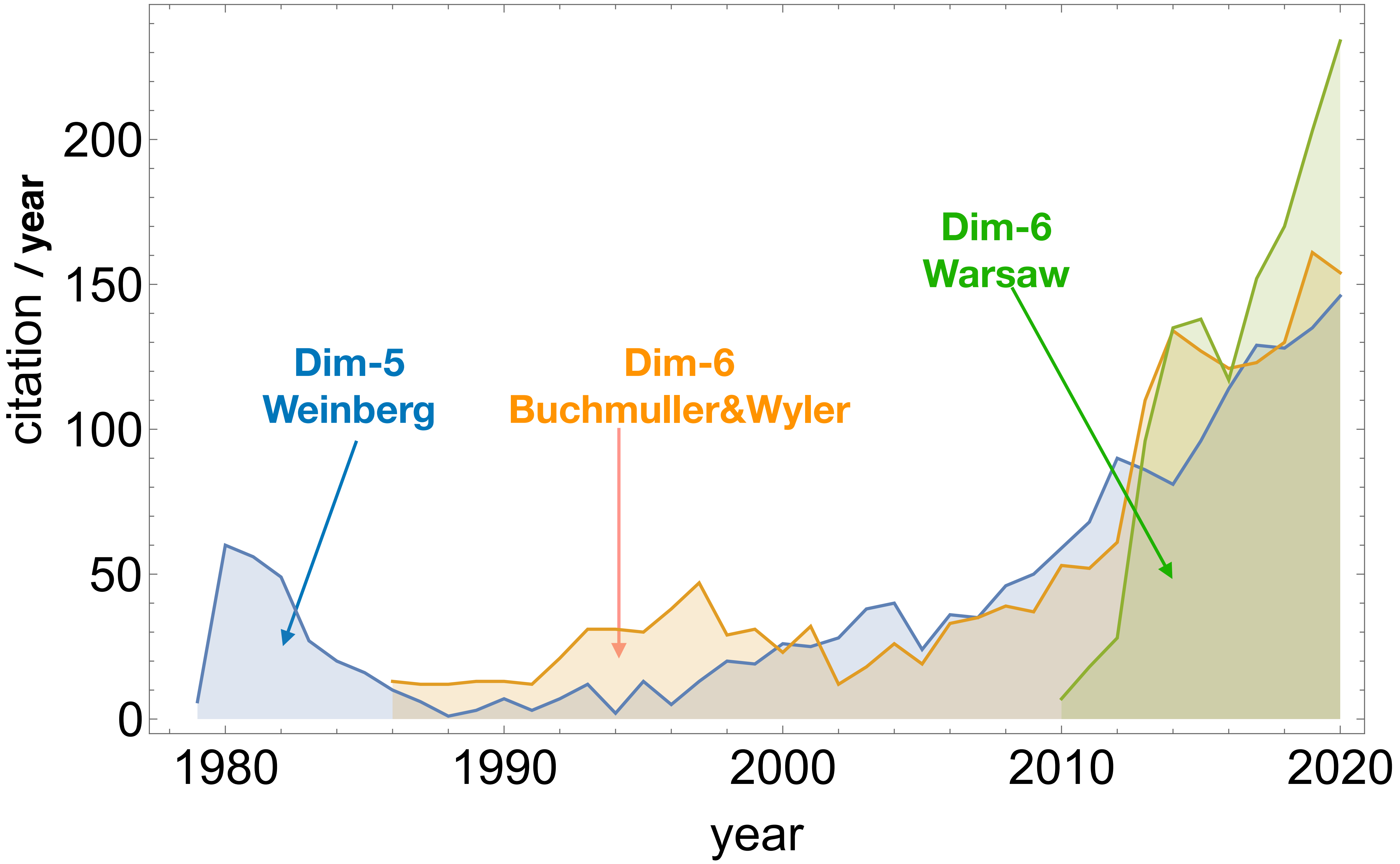
Dimension-6 operators parametrize new physics effects at low energy, electroweak precision, and Higgs boson physics, etc

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

[ Buchmuller and Wyler, 1986 ]

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

[ Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010 ]




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

# SMEFT Dimension-6 Operators

[ Buchmuller and Wyler, 1986 ]

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

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

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

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

$O_{\varphi G} = \frac{1}{2}(\varphi^\dagger\varphi)G^A_{\mu\nu}G^{A\mu\nu}$, $O_{\varphi W} = \frac{1}{2}(\varphi^\dagger\varphi)W^I_{\mu\nu}W^{I\mu\nu}$, $O_{\varphi B} = \frac{1}{2}(\varphi^\dagger\varphi)B_{\mu\nu}B^{\mu\nu}$, $O_{WB} = (\varphi^\dagger\tau^I\varphi)W^I_{\mu\nu}B^{\mu\nu}$, $O^{(1)}_\varphi = (\varphi^\dagger\varphi)(D_\mu\varphi^\dagger D^\mu\varphi)$,

$O_{\varphi\tilde G} = (\varphi^\dagger\varphi)\tilde G^A_{\mu\nu}G^{A\mu\nu}$, $O_{\varphi\tilde W} = (\varphi^\dagger\varphi)\tilde W^I_{\mu\nu}W^{I\mu\nu}$, $O_{\varphi\tilde B} = (\varphi^\dagger\varphi)\tilde B_{\mu\nu}B^{\mu\nu}$, $O_{\tilde WB} = (\varphi^\dagger\tau^I\varphi)\tilde W^I_{\mu\nu}B^{\mu\nu}$, $O^{(3)}_\varphi = (\varphi^\dagger D^\mu\varphi)(D_\mu\varphi^\dagger\varphi)$.

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

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

$O_{D_e} = (\bar\ell D_\mu e)D^\mu\varphi$, $O_{\bar D_e} = (D_\mu\bar\ell e)D^\mu\varphi$, $O_{Du} = (\bar q D_\mu u)D^\mu\tilde\varphi$, $O_{\bar Du} = (D_\mu\bar q u)D^\mu\tilde\varphi$, $O_{Dd} = (\bar q D_\mu d)D^\mu\varphi$, $O_{\bar Dd} = (D_\mu\bar q d)D^\mu\varphi$,

$O_{eW} = (\bar\ell\sigma^{\mu\nu}\tau^I e)\varphi W^I_{\mu\nu}$, $O_{eB} = (\bar\ell\sigma^{\mu\nu}e)\varphi B_{\mu\nu}$, $O_{uG} = (\bar q\sigma^{\mu\nu}\lambda^A u)\tilde\varphi G^A_{\mu\nu}$, $O_{uW} = (\bar q\sigma^{\mu\nu}\tau^I u)\tilde\varphi W^I_{\mu\nu}$, $O_{uB} = (\bar q\sigma^{\mu\nu}u)\tilde\varphi B_{\mu\nu}$, $O_{dG} = (\bar q\sigma^{\mu\nu}\lambda^A d)\varphi G^A_{\mu\nu}$, $O_{dW} = (\bar q\sigma^{\mu\nu}\tau^I d)\varphi W^I_{\mu\nu}$, $O_{dW} = (\bar q\sigma^{\mu\nu}d)\varphi B_{\mu\nu}$.

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

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

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

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

$O^{(8)}_{qu} = (\bar q\lambda^A u)(\bar u\lambda^A q)$, $O^{(8)}_{qd} = (\bar q\lambda^A d)(\bar d\lambda^A q)$,

## Equation of motion (field redefinition)

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

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

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

## 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

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

$$\tau^I_{jk}\tau^I_{mn} = 2\delta_{jn}\delta_{mk} - \delta_{jk}\delta_{mn}$$

**80-1-16-5+1 = 59**

[ Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010 ]

| $X^3$ | | $\varphi^6$ and $\varphi^4D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r\varphi)$ |
| $Q_{\tilde G}$ | $f^{ABC}\tilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r\tilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$ |
| $Q_{\tilde W}$ | $\varepsilon^{IJK}\tilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$ | | | | |

| $X^2\varphi^2$ | | $\psi^2X\varphi$ | | $\psi^2\varphi^2D$ | |
|---|---|---|---|---|---|
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$ | $Q^{(1)}_{\varphi l}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$ |
| $Q_{\varphi\tilde G}$ | $\varphi^\dagger\varphi\,\tilde G^A_{\mu\nu}G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$ | $Q^{(3)}_{\varphi l}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p\sigma^{\mu\nu}T^A u_r)\tilde\varphi G^A_{\mu\nu}$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$ |
| $Q_{\varphi\tilde W}$ | $\varphi^\dagger\varphi\,\tilde W^I_{\mu\nu}W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\tilde\varphi W^I_{\mu\nu}$ | $Q^{(1)}_{\varphi q}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p\sigma^{\mu\nu}u_r)\tilde\varphi B_{\mu\nu}$ | $Q^{(3)}_{\varphi q}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$ |
| $Q_{\varphi\tilde B}$ | $\varphi^\dagger\varphi\,\tilde B_{\mu\nu}B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi G^A_{\mu\nu}$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi W^I_{\mu\nu}$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$ |
| $Q_{\varphi\tilde WB}$ | $\varphi^\dagger\tau^I\varphi\,\tilde W^I_{\mu\nu}B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p\sigma^{\mu\nu}d_r)\varphi B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\tilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$ |

| $(\bar LL)(\bar LL)$ | | $(\bar RR)(\bar RR)$ | | $(\bar LL)(\bar RR)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$ | $Q_{le}$ | $(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$ |
| $Q^{(1)}_{qq}$ | $(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$ |
| $Q^{(3)}_{qq}$ | $(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$ | $Q_{dd}$ | $(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$ |
| $Q^{(1)}_{lq}$ | $(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$ |
| $Q^{(3)}_{lq}$ | $(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$ | $Q_{ed}$ | $(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$ | $Q^{(1)}_{qu}$ | $(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$ |
| | | $Q^{(1)}_{ud}$ | $(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$ | $Q^{(8)}_{qu}$ | $(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$ |
| | | $Q^{(8)}_{ud}$ | $(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$ | $Q^{(1)}_{qd}$ | $(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$ |
| | | | | $Q^{(8)}_{qd}$ | $(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$ |

| $(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$ | | B-violating | |
|---|---|---|---|
| $Q_{ledq}$ | $(\bar l^j_p e_r)(\bar d_s q^j_t)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^TCu^\beta_r\right]\left[(q^{\gamma j}_s)^TCl^k_t\right]$ |
| $Q^{(1)}_{quqd}$ | $(\bar q^j_p u_r)\varepsilon_{jk}(\bar q^k_s d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^TCq^{\beta k}_r\right]\left[(u^\gamma_s)^TCe_t\right]$ |
| $Q^{(8)}_{quqd}$ | $(\bar q^j_p T^A u_r)\varepsilon_{jk}(\bar q^k_s T^A d_t)$ | $Q_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^TCq^{\beta k}_r\right]\left[(q^{\gamma m}_s)^TCl^n_t\right]$ |
| $Q^{(1)}_{lequ}$ | $(\bar l^j_p e_r)\varepsilon_{jk}(\bar q^k_s u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^TCu^\beta_r\right]\left[(u^\gamma_s)^TCe_t\right]$ |
| $Q^{(3)}_{lequ}$ | $(\bar l^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q^k_s\sigma^{\mu\nu}u_t)$ | | |



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# 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 |
|---|---|---|
| $\phi$ | $\phi \in (0,0)$ | |
| $\psi$ | $\psi_\alpha \in (1/2,0)$   $\psi^\dagger_{\dot\alpha} \in (0,1/2)$, | $\lambda_\alpha$ |
| $F_{\mu\nu}$ | $F_{L\alpha\beta} = \frac{i}{2} F_{\mu\nu}\sigma^{\mu\nu}_{\alpha\beta} \in (1,0)$   $F_{R\dot\alpha\dot\beta} = -\frac{i}{2} F_{\mu\nu}\bar\sigma^{\mu\nu}_{\dot\alpha\dot\beta} \in (0,1)$. | $\lambda_\alpha \lambda_\beta$ |
| $R_{\mu\nu\rho\sigma}$ | $\mathcal{C}_{\alpha\beta\gamma\delta} = C_{\mu\nu\rho\sigma}\sigma^{\mu\nu}_{\alpha\beta}\sigma^{\rho\sigma}_{\gamma\delta} \in (2,0)$ | $\lambda_\alpha\lambda_\beta\lambda_\gamma\lambda_\delta$ |
| $D_\mu$ | $D_{\alpha\dot\alpha} = D_\mu \sigma^\mu_{\alpha\dot\alpha} \in (1/2,1/2)$. | $\lambda_\alpha \tilde\lambda_{\dot\alpha}$ |

**Building blocks in spinor-helicity form**

$$D^{r_i}\phi_i \quad \Leftrightarrow \quad \lambda_i^{r_i}\tilde\lambda^{i,r_i},$$

$$D^{r_i-1/2}\psi_i^{(\dagger)} \quad \Leftrightarrow \quad \lambda_i^{r_i\pm 1/2}\tilde\lambda^{i,r_i\mp 1/2},$$

$$D^{r_i-1}F_{L/R\,i} \quad \Leftrightarrow \quad \lambda_i^{r_i\pm 1}\tilde\lambda^{i,r_i\mp 1},$$

$$D^{r_i-2}C_{L/R\,i} \quad \Leftrightarrow \quad \lambda_i^{r_i\pm 2}\tilde\lambda^{i,r_i\mp 2},$$

On-shell operator

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

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

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

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

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

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

→ **On-shell Brackets**

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

$$\langle 12\rangle^2\langle 34\rangle[34]$$

**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**

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

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

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

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

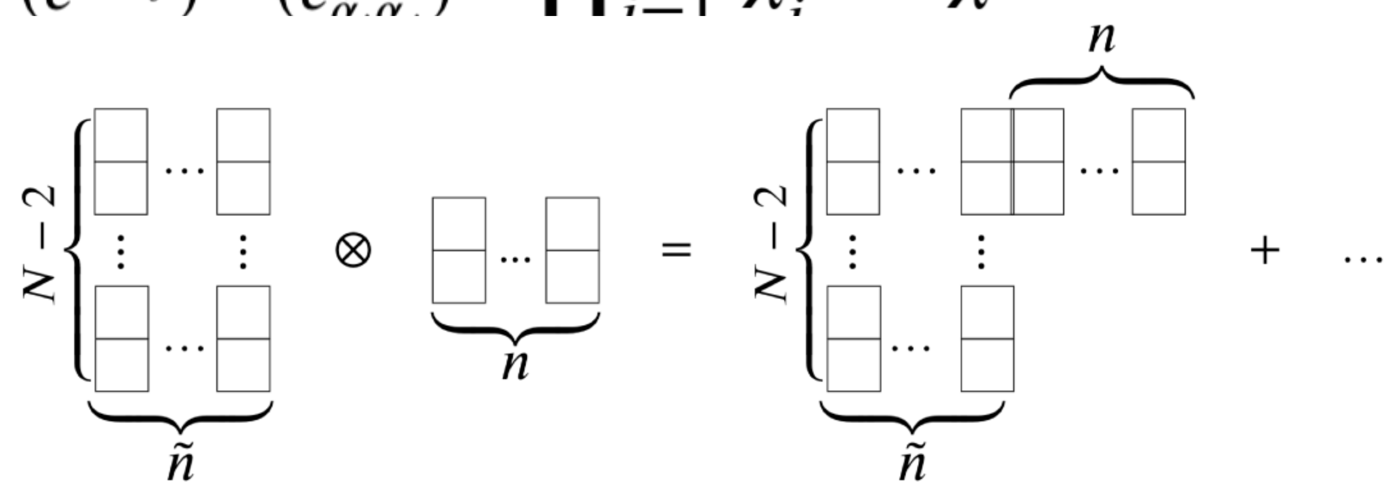
$$(D\psi)_{\alpha\beta\dot\alpha} = -\frac{1}{2}\epsilon_{\alpha\beta}(\not{D}\psi)_{\dot\alpha} + \frac{1}{2}(D\psi)_{(\alpha\beta)\dot\alpha}$$

↓

**SL(2,C) x SU(N)**

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

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




↓

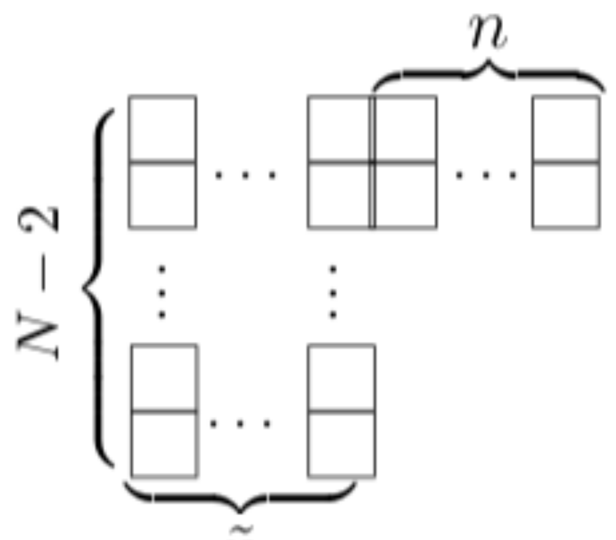
$\boxed{i \atop j} \Leftrightarrow \langle ij\rangle$

**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** → **On-shell Amplitude**




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

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

| 1 | 1 | 1 | 2 |
|---|---|---|---|
| 2 | 3 | 3 | 4 |

$\langle 13\rangle\langle 13\rangle\langle 24\rangle[34]$ $\quad F_{\mathrm{L}1}^{\alpha\beta}\psi_2^\gamma(D\psi_3)_{\alpha\beta\dot\alpha}(D\phi_4)_\gamma{}^{\dot\alpha}$

| 1 | 1 | 1 | 3 |
|---|---|---|---|
| 2 | 2 | 3 | 4 |

$\langle 12\rangle\langle 13\rangle\langle 34\rangle[34]$ $\quad F_{\mathrm{L}1}^{\alpha\beta}\psi_{2\alpha}(D\psi_3)_\beta{}^\gamma{}_{\dot\alpha}(D\phi_4)_\gamma{}^{\dot\alpha}$

**On-shell Amplitude correspondence**



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# 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]

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

30

EOM

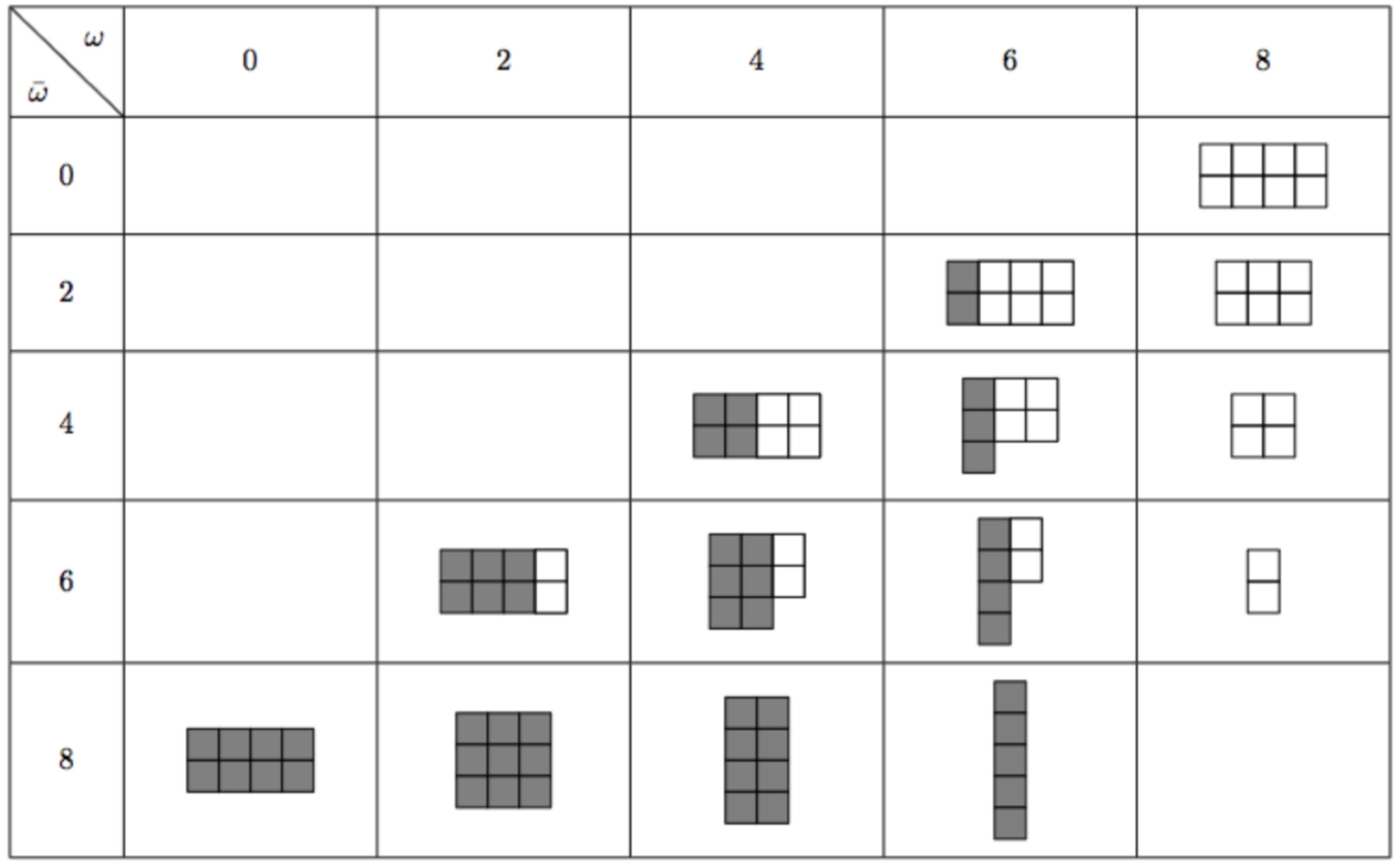
$$(DH^\dagger)_{\alpha\dot\alpha}(DH)_{\beta\dot\beta}B_{L\{\gamma\delta\}}W_{L\{\xi\eta\}}\,\epsilon^{\dot\alpha\dot\beta}\epsilon^{\alpha\beta}\epsilon^{\gamma\xi}\epsilon^{\delta\eta}$$
$$(DH^\dagger)_{\alpha\dot\alpha}(DH)_{\beta\dot\beta}B_{L\{\gamma\delta\}}W_{L\{\xi\eta\}}\,\tfrac{1}{2}\epsilon^{\dot\alpha\dot\beta}\epsilon^{\delta\xi}(\epsilon^{\alpha\ga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

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

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

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



Jiang-Hao Yu (ITP-CAS)

# EFT Operator Bases

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

## 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]

# ABC4EFT Package

**Amplitude Basis Construction for Effective Field Theory**

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

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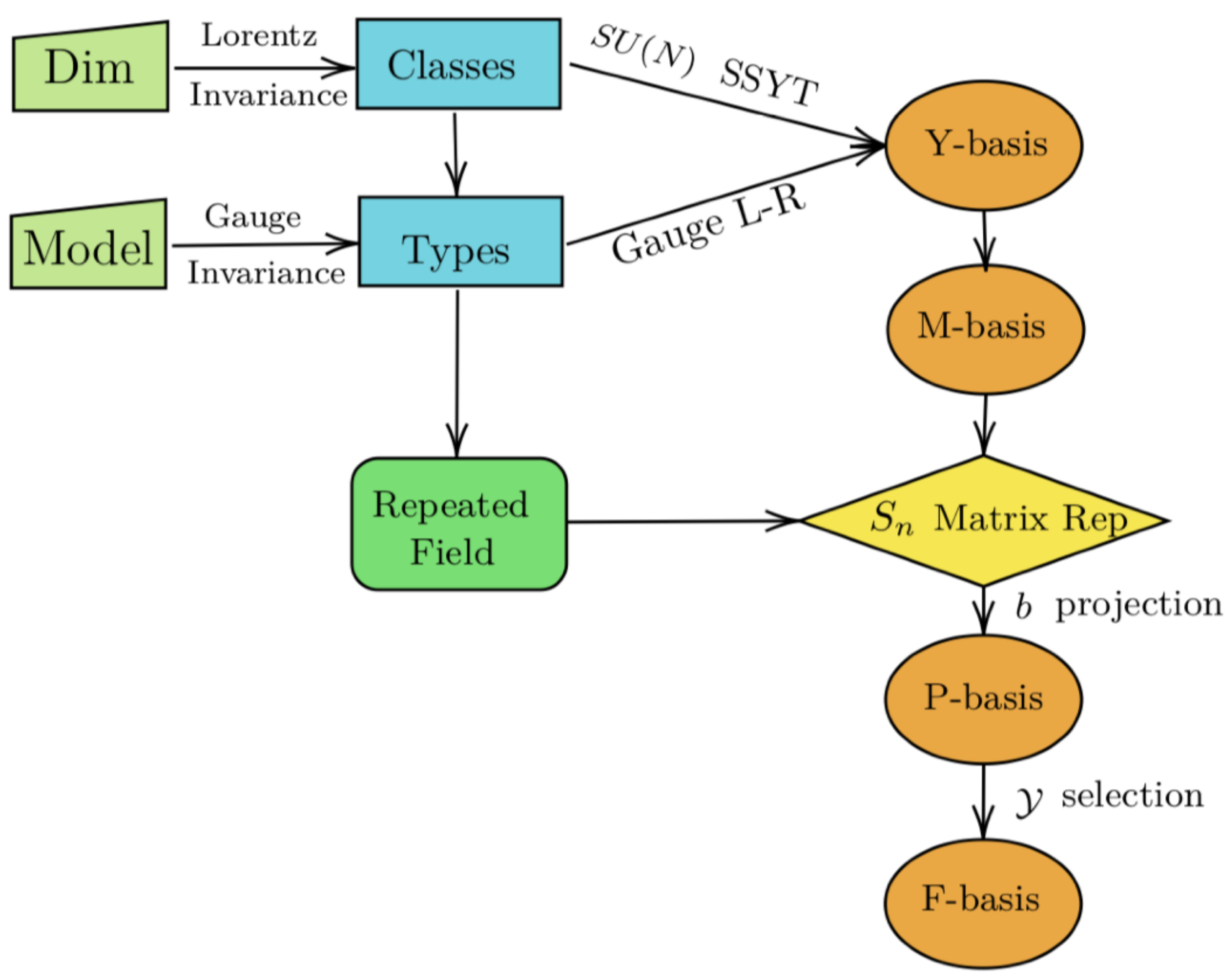
- Jiang-Hao Yu (professor at ITP-CAS)
- Yu-Hui Zheng (5th-year graduate student at ITP-CAS)

https://abc4eft.hepforge.org/




**Fully Automatic**

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

# Hadronic level EFTs: ChPT and ChEFT

[ Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2404.15047 ]

[ Xuan-He Li, Hao Sun, Feng-Jie Tang, **J.H.Yu**, 2404.14152 ]

[ Hao Sun, Yi-Ning Wang, **J.H.Yu**, 2501.14018 ]

[ Gang Li, Chuan-Qiang Song, **J.H.Yu**, 2507.02538 ]

[ Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2501.09787 ]

# 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

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

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

SM fields and Goldstone

meson and baryon

**SM Fermion masses from Higgs VEV**

**Baryon masses around 1 GeV from Trace anomaly**



Jiang-Hao Yu (ITP-CAS)

# CCWZ Chiral Lagrangian

Define the nonlinear Goldstone matrix

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

[Callan, Coleman, Wess, Zumino, 1969]

**CCWZ Coset**

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

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

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

Building block

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

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

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

**Symmetric Coset**

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

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

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

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

Building block

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

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

**QCD Chiral Lag**

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

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

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

**EW Chiral Lag**

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

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

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



Jiang-Hao Yu (ITP-CAS)

# Adler Zero Condition for Goldstone

**Chiral symmetry**

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

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)**

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

[ Adler, 1965 ]

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

[ 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 ]
[ Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2404.15047 ]

**nucleon-meson**
[ Krause, 1990 ]
[ Ecker, 1994 ]
[ Fettes, Meisner, Mojzis, Steininger, 2000 ]
[ Oller, Verbeni, Prades, 2006 ]
[ Frink, Meisner, 2006 ]
[ Jiang, Chen, Liu, 2017 ]
[ Xuan-He Li, Hao Sun, Feng-Jie Tang, **J.H.Yu**, 2404.14152 ]

**nucleon-nucleon**
[ Weinberg 1990 ]
[ van Kolck, Ordonez, 1992 ]
[ Petschauer, Kaiser, 2013 ]
[ Petschauer, Haidenbauer, Kaiser, Meisner, Weise, 2020 ]
[ Hao Sun, Yi-Ning Wang, **J.H.Yu**, 2501.14018 ]

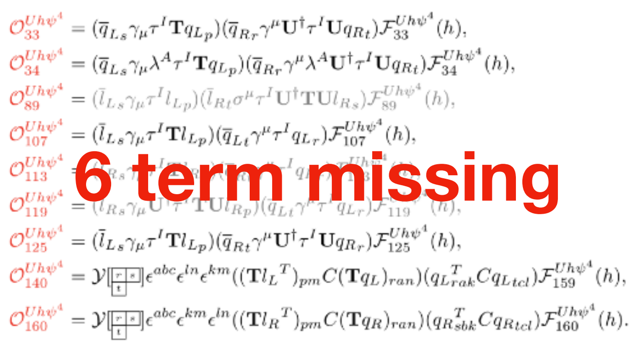
## EW Chiral Lagrangian = HEFT

**LO Lagrangian**
[ Weinberg, 1979 ]

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

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

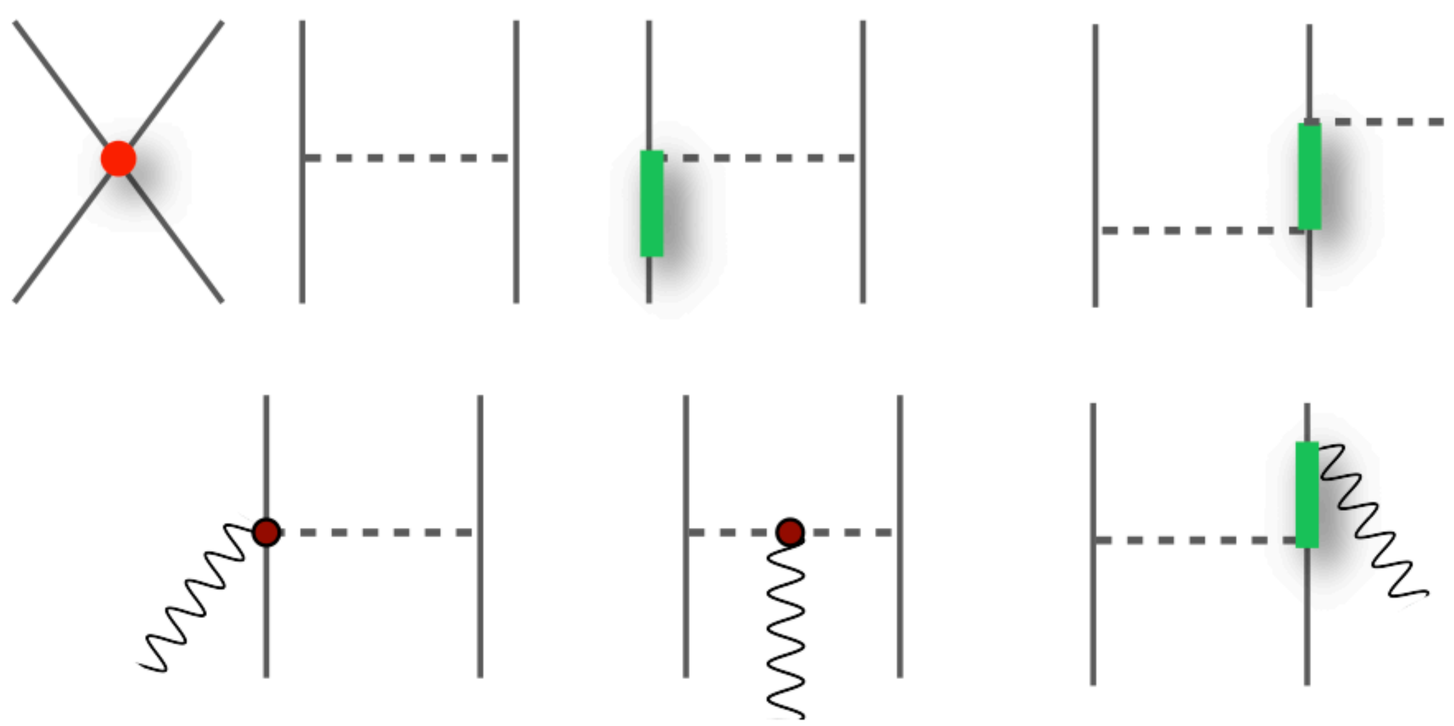
**NLO 4-fermion**
[ Buchalla, Cata, Krause, 2014 ]
[ Pich, Rosell, Santos, Sanz-Cillero, 2015, 2018 ]
[ Sun, Xiao, **Yu**, 2206.07722 ]




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

# Ab initio nuclear structure

Effective Hamiltonians and consistent currents

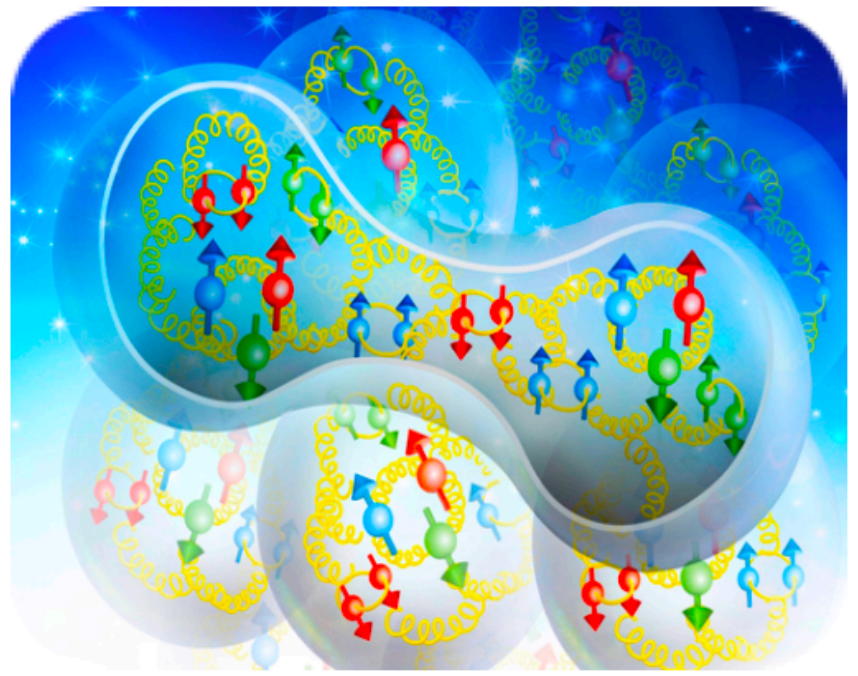


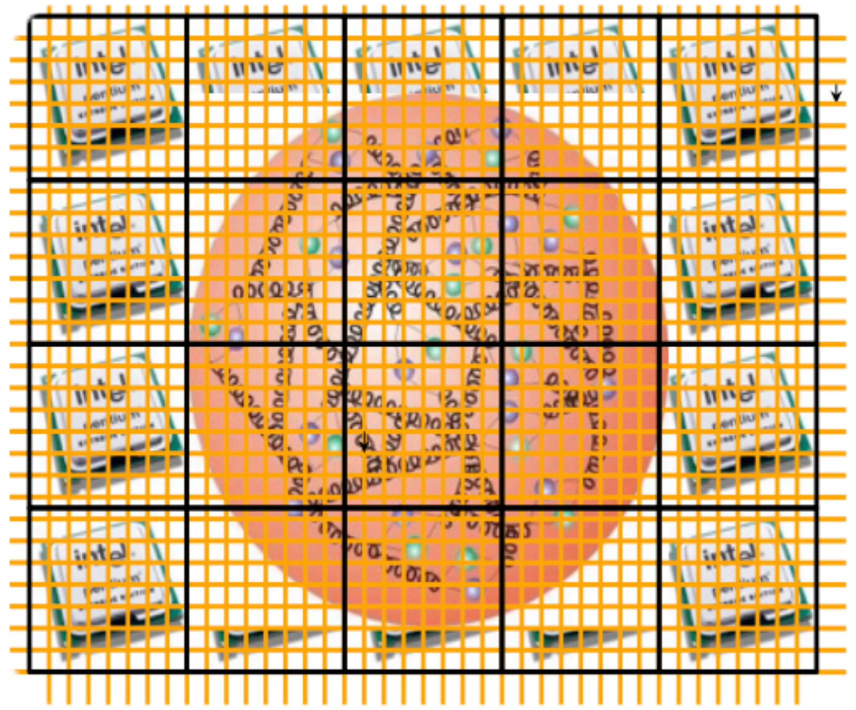
Accurate nuclear many-body methods


$$H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

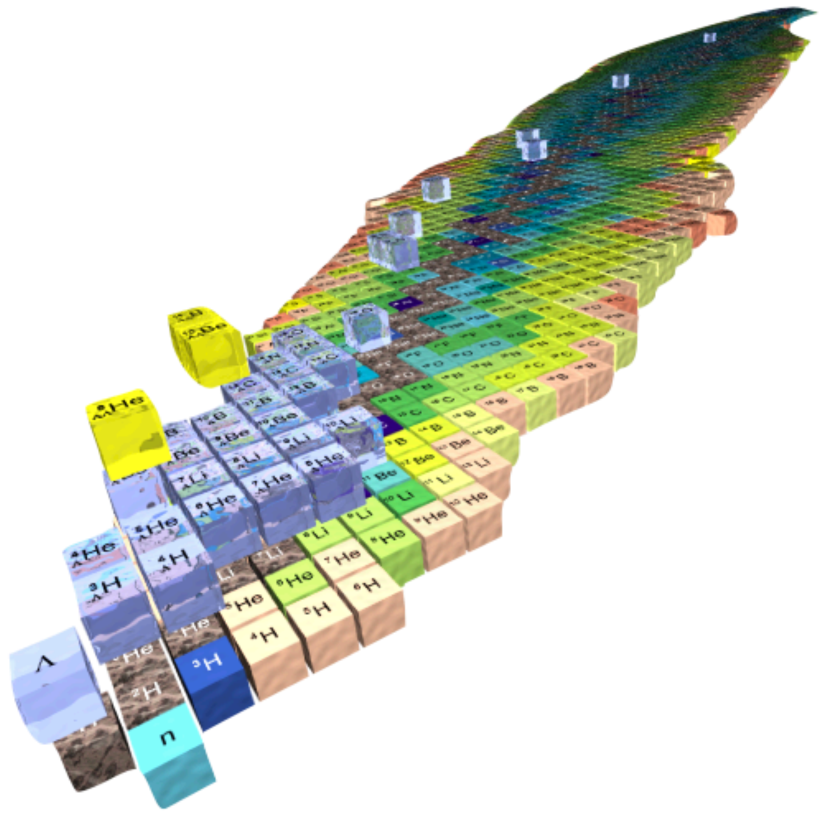
$$J_{mn} = \langle\Psi_m|J|\Psi_n\rangle$$

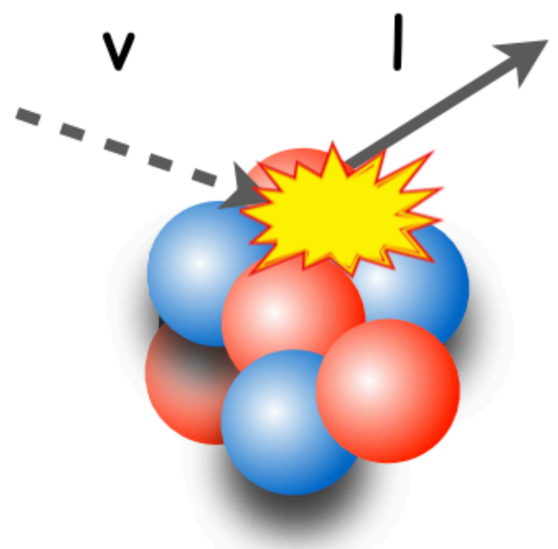
Quantum Chromodynamcs





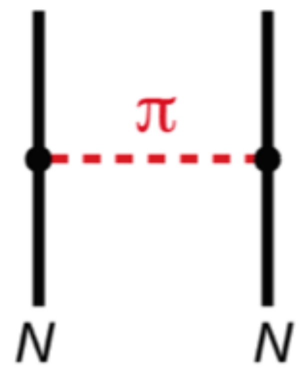
Nuclei and electroweak interactions



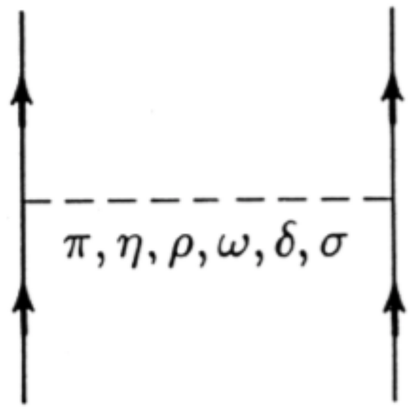



[ See Pengwei Zhao’s talk ]

# Nuclear force

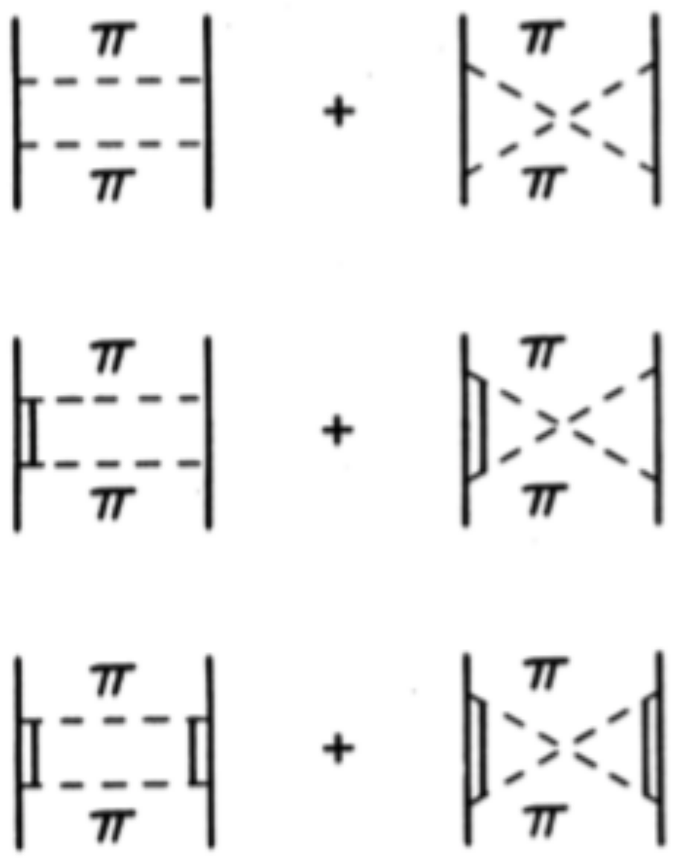



Yukawa Pion Theory
1935



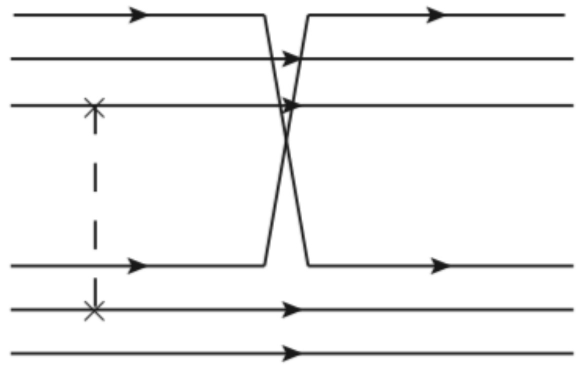

One-Boson Exchange Model
1936 - 1960

**Proca, Kemmer, Moller, Rosenfeld and Schwinger, Pauli, …**

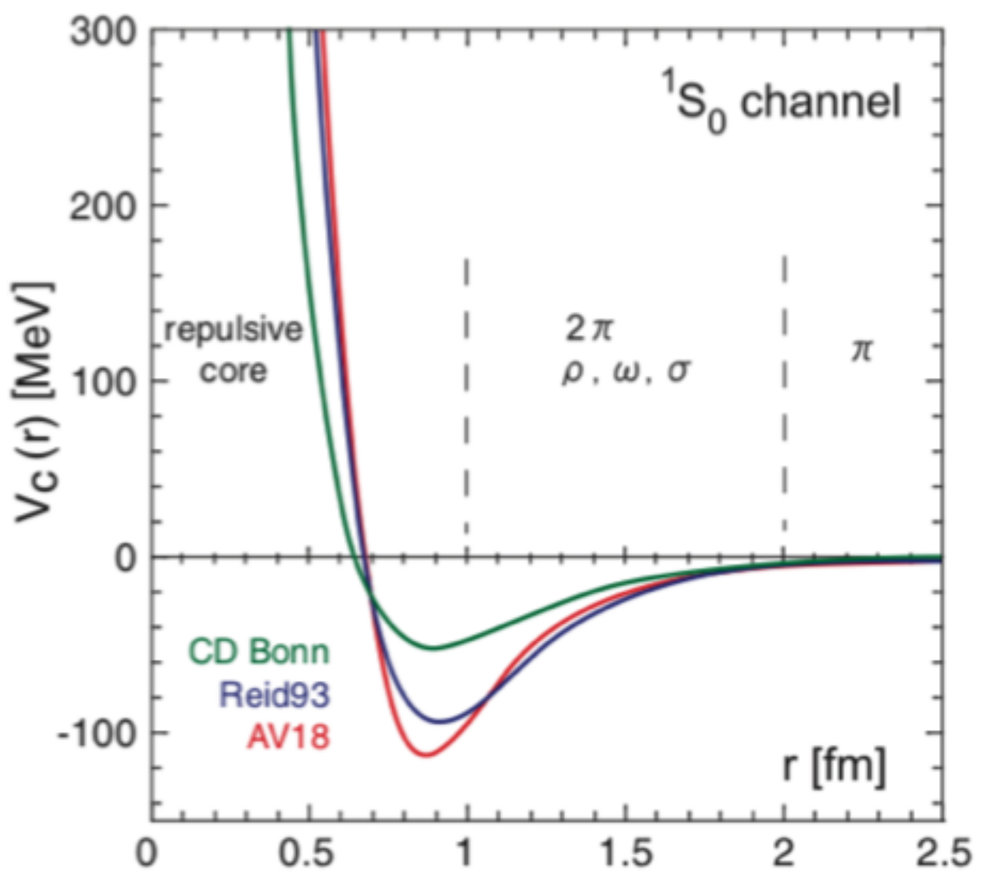



Two-Pion Exchange
1950 - 1980

**Taketani, Nakamura Sasaki, Bruckner, Watson, …**

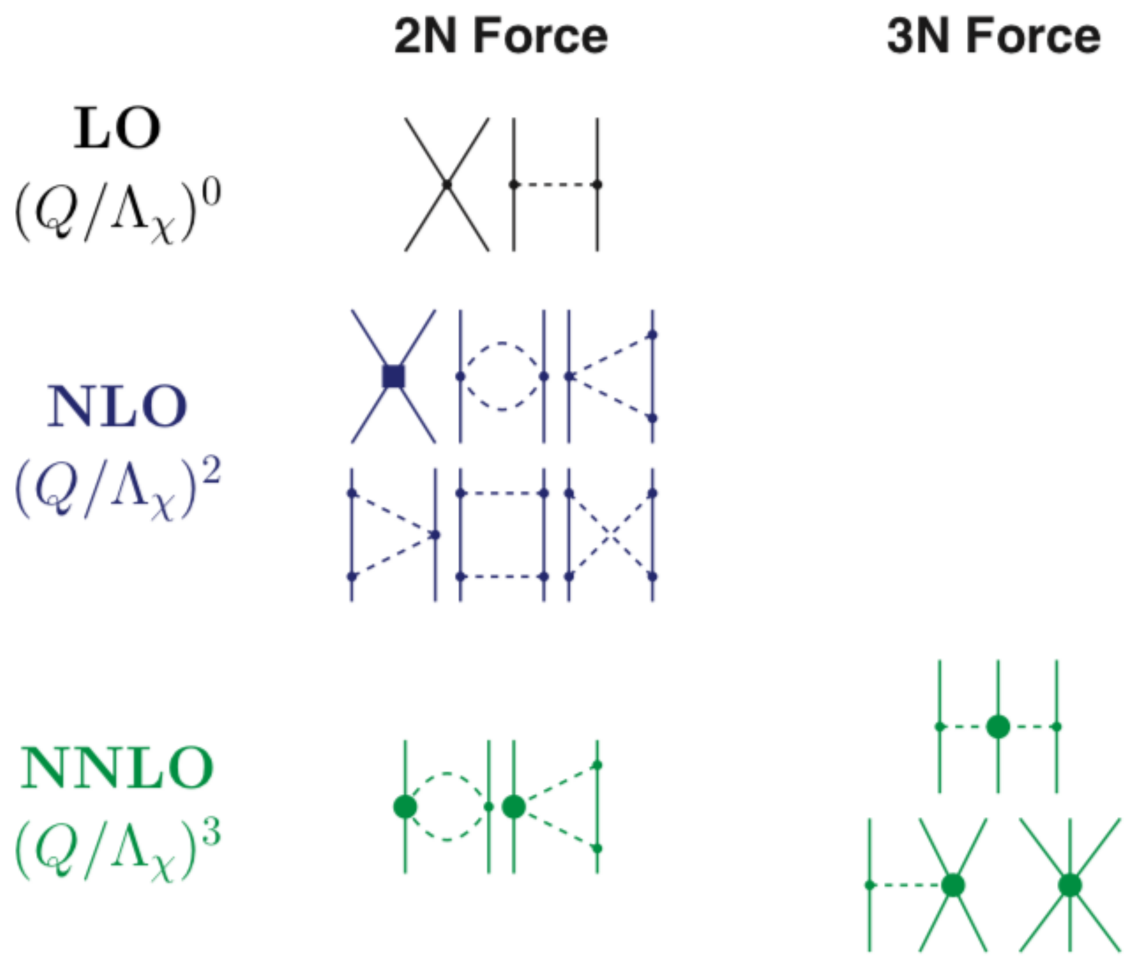


N-N from quark/chiral-bag model
1970 - 1980

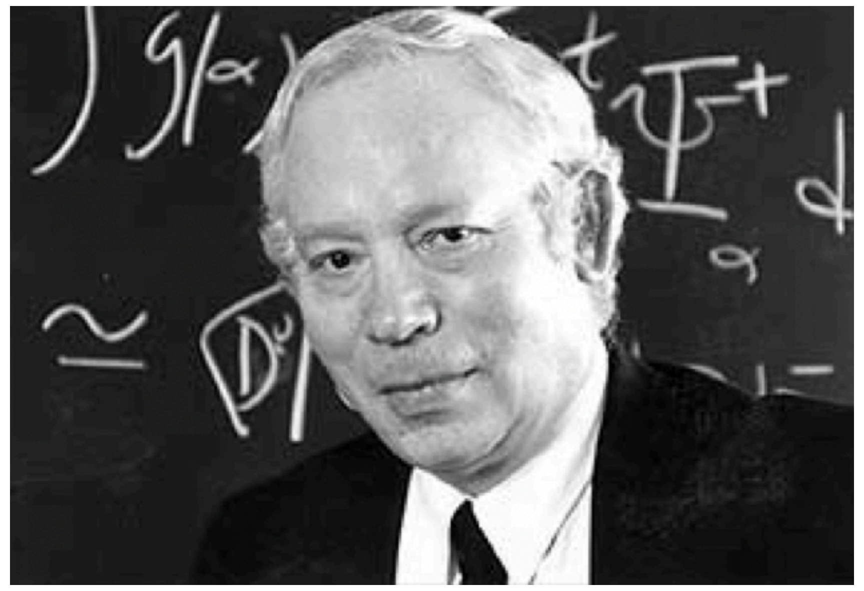



High precision potential
1990 -

**AV18, CD Bonn, Nijm, Reid93 …**




Weinberg nuclear chiral EFT
1990 -





Jiang-Hao Yu (ITP-CAS)

# Chiral nuclear force

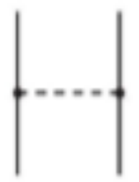
**Meson Exchange Model**

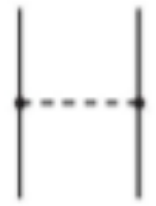
$$\mathcal{L}_\sigma = \overline{N_L}\, i\not{D}\, N_L + \overline{N_R}\, i\not{D}\, N_R - g\overline{N_R}\, \Sigma\, N_L - g\overline{N_L}\, \Sigma^\dagger\, N_R$$

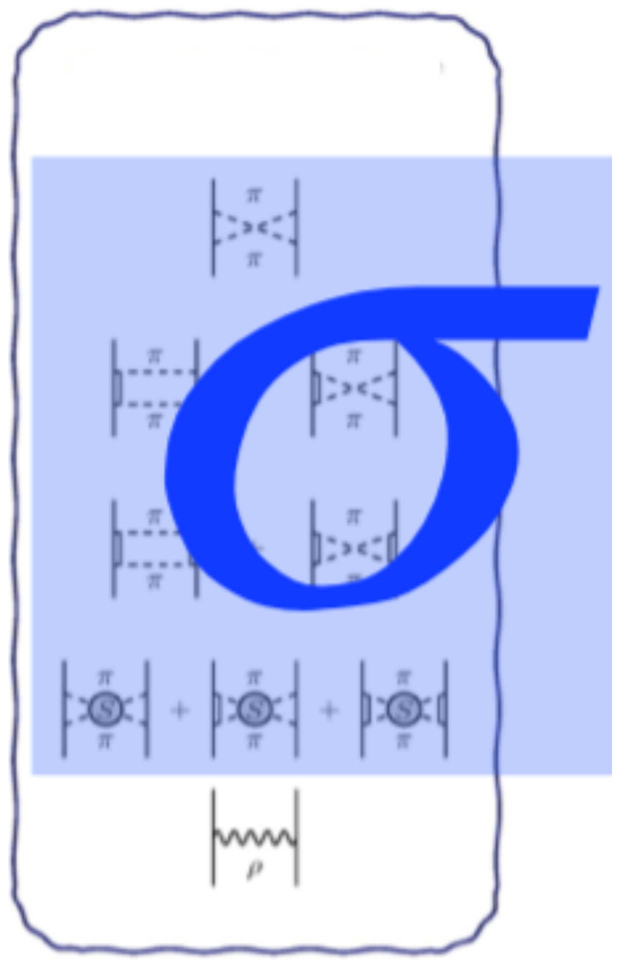
**Chiral EFT**

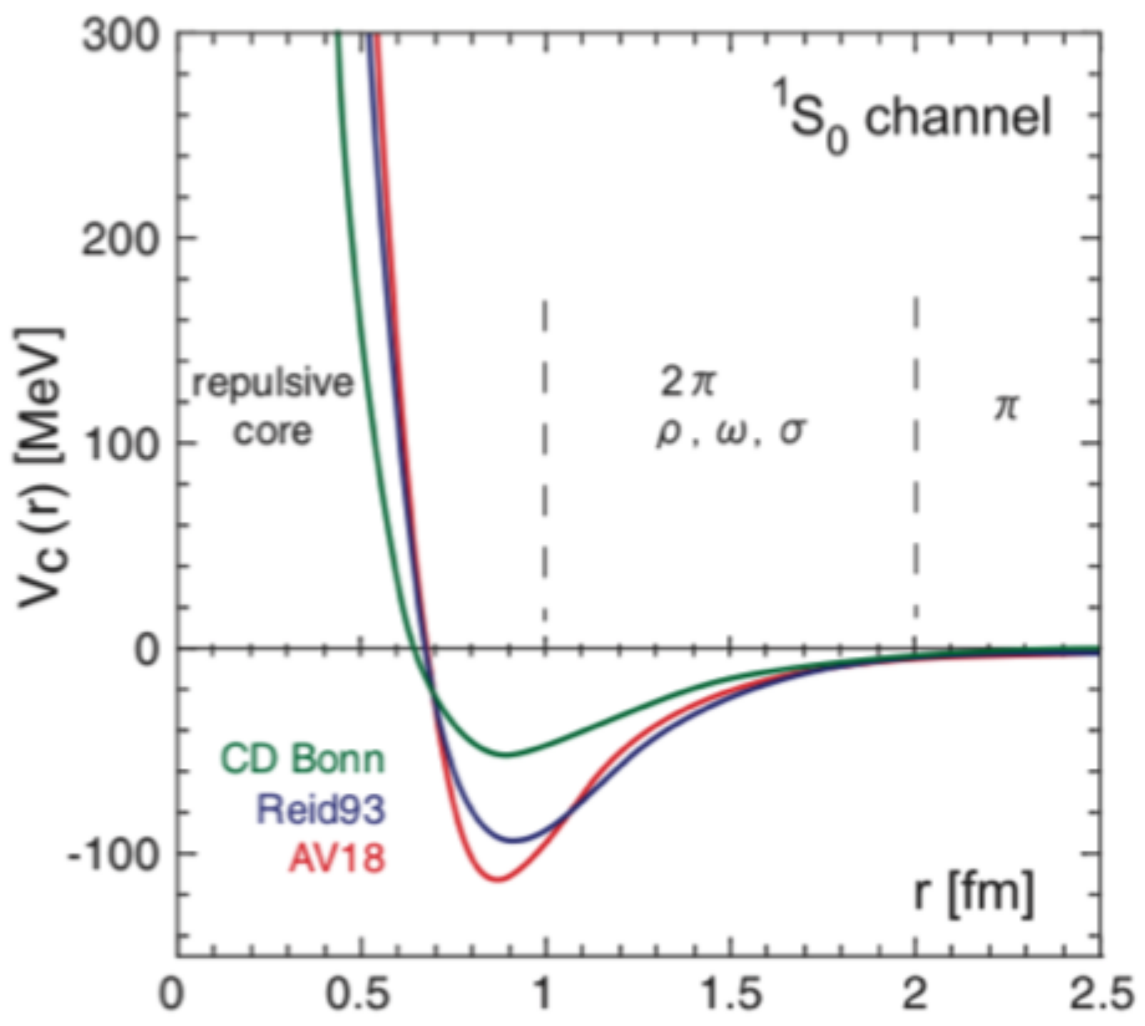
$$\mathcal{L}^{(1)}_{\pi N} = \bar{\psi}\left(i\not{D} - m_N + \tfrac{1}{2} g_A \gamma_\mu \gamma_5 u^\mu\right)\psi$$

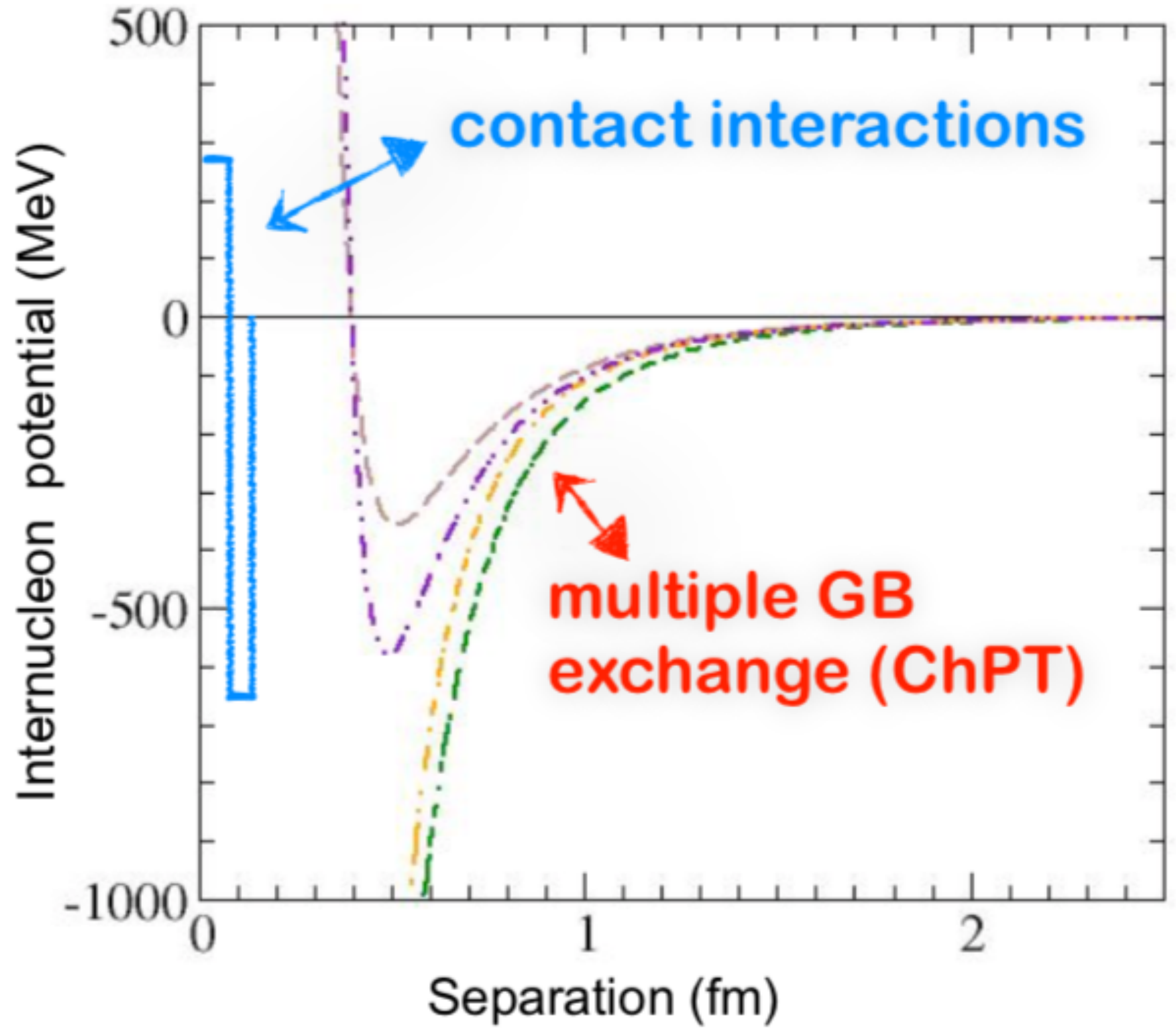
$$V(\mathbf{r}) = \left\{ C_c + C_\sigma \sigma_1 \cdot \sigma_2 + C_T \left(1 + \frac{3}{m_\alpha r} + \frac{3}{(m_\alpha r)^2}\right) S_{12}(\hat{r}) + C_{SL}\left(\frac{1}{m_\alpha r} + \frac{1}{(m_\alpha r)^2}\right) \mathbf{L}\cdot\mathbf{S} \right\} \frac{e^{-m_\alpha r}}{m_\alpha r} \quad (1,\ \tau_1 \cdot \tau_2)$$

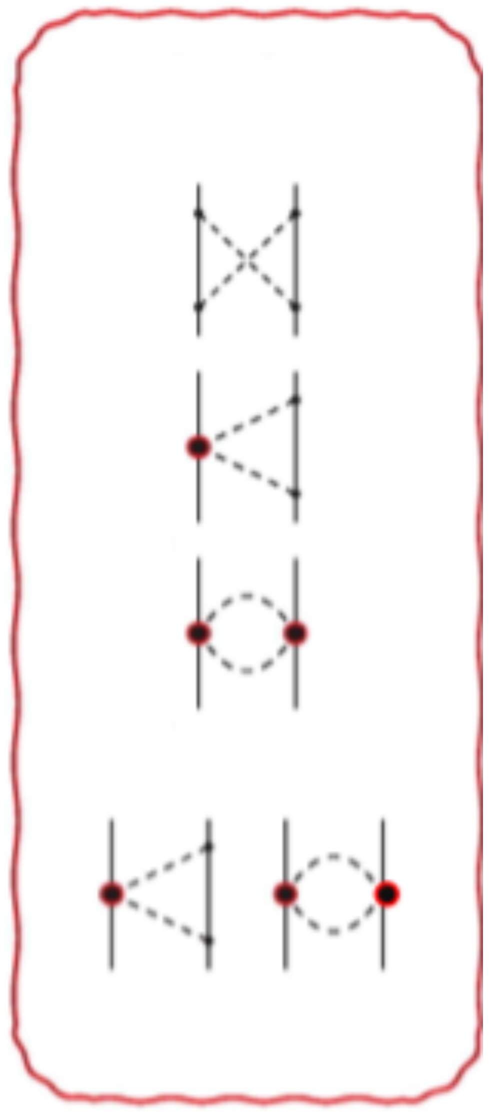








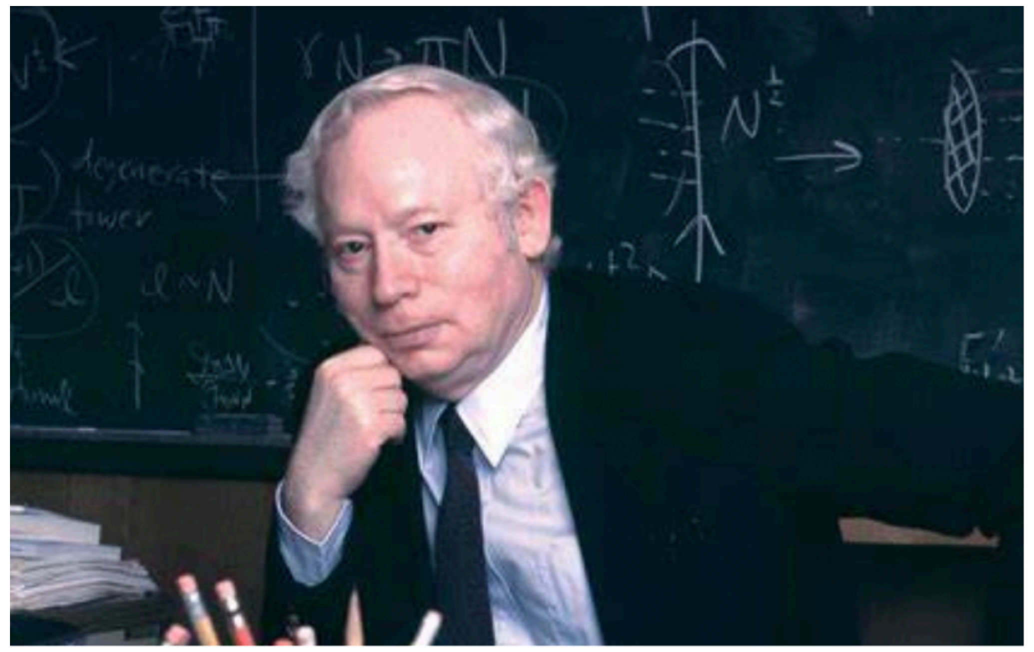




**Repulsive central**

CAS)

# Weinberg's nuclear force

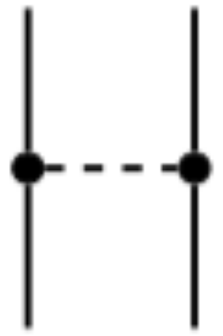
Hard-core nucleon-nucleon interaction



[ Weinberg 1933 - 2021 ]

**Weinberg power counting**

$$D = 2 - A + 2L + \sum_d V_d\left(d - 2 + \frac{f}{2}\right)$$



= 2(1-2+2/2) = 0

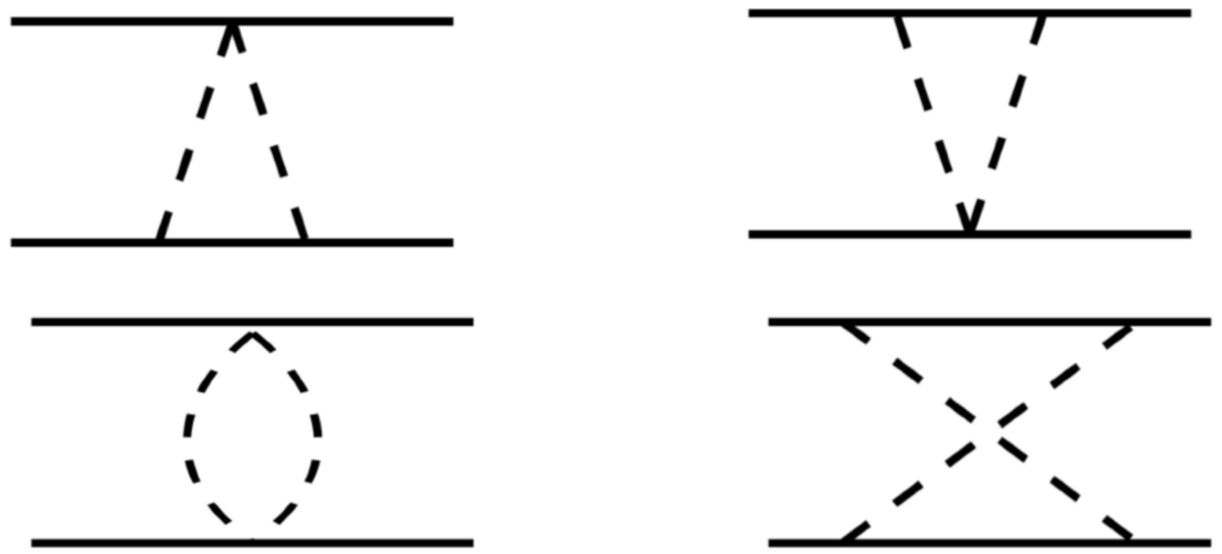
= (0-2+4/2) = 0

$$V_{1\pi} = -\left(\frac{g_A}{2F_\pi}\right)^2 \frac{\vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}}{q^2+M_\pi^2}\,\vec{\tau}_1\cdot\vec{\tau}_2 \sim \mathcal{O}(1)$$

It had taken me a decade to realize that four divided by two is two. This sort of interaction is just the kind of hard-core nucleon-nucleon interaction that nuclear physicists had always known would be needed to understand nuclear forces. But now we had a rationale for it.

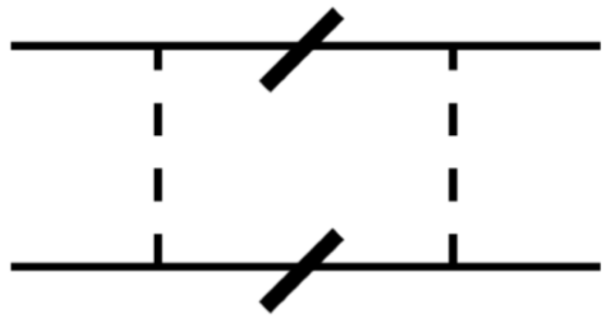
Weinberg 2021

**2PI Diagrams**



**Nuclear potential from Irre. 2PI only**

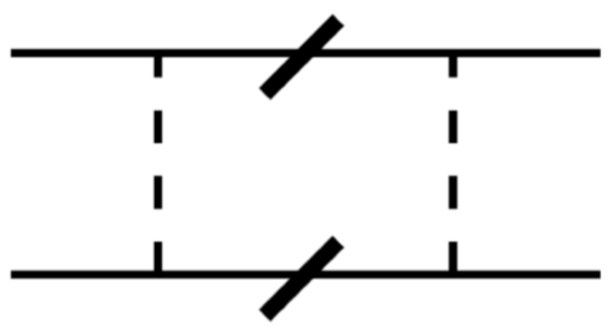
**2PR Diagrams**



**Breakdown in perturbation theory = nuclear bound states**

# Chiral effective field theory

**Chiral EFT with Pion** [ Weinberg, 1990 ]



$$\sim \left(\frac{g_A}{F_\pi}\right)^2 \frac{Q}{\Lambda_{NN}}$$

$$I \sim \int \frac{d^d q}{(2\pi)^d} \frac{1}{q^0 - \frac{\vec{p}^2 - \vec{q}^2}{2M} - i\epsilon} \frac{1}{-q^0 + \frac{\vec{p}^2 - \vec{q}^2}{2M} + i\epsilon} \frac{1}{(q+p)^2 + i\epsilon} \frac{1}{(q-p)^2 + i\epsilon}$$

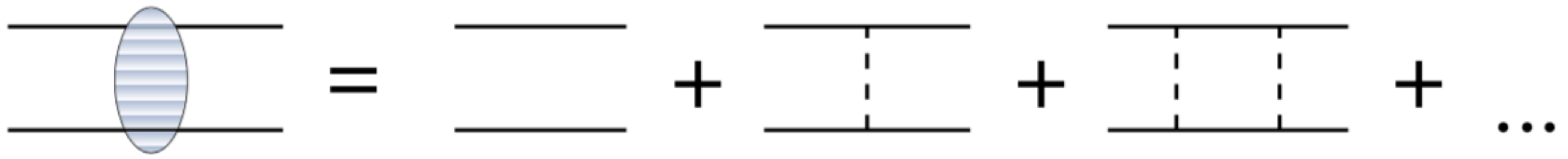
Pinch singularity

Infrared enhancement!

**1. calculate nuclear potential from irreducible diagrams**

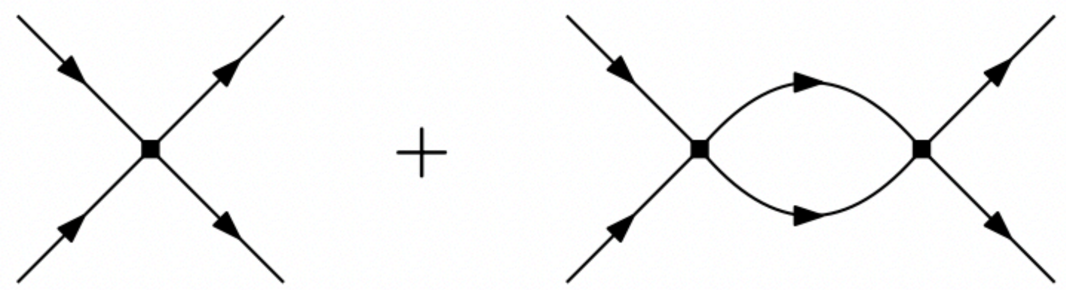
pinch diagrams subtracted

**2. Truncated nuclear potential is iterated to all order**



Solve Schrodinger equation

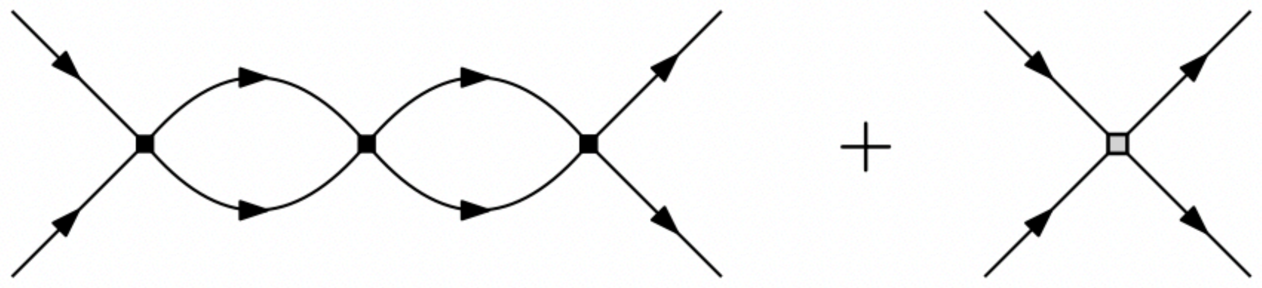
**Pionless EFT** Kaplan, Savage, Wise 1998



$-C_0$

$$\frac{Q^5}{4\pi M} \times C_0 \left(\frac{M}{Q^2}\right)\left(\frac{M}{Q^2}\right) C_0 \sim C_0^2 \frac{MQ}{4\pi}$$

Pinch singularity



$C_0^3 \left(\frac{Mp}{4\pi}\right)^2$ $\qquad -C_2 p^2$

$\sigma_{tot} \to 4\pi a^2$ as $p \to 0.$ $\quad a_0 \approx -23.7$ fm $\quad 1/m_\pi \approx 1.4$ fm

**a. Natural scattering length**

$$\mathcal{A} = -\frac{4\pi a}{M}\left[1 - iap + \left(\frac{1}{2} a r_0 - a^2\right) p^2 + O(p^3/\Lambda^3)\right]$$

$C_0 \sim 4\pi a/M$

Irrelevant

**b. Unnatural scattering length**

$$\mathcal{A} = -\frac{4\pi}{M} \frac{1}{(1/a + ip)}\left[1 + \frac{r_0/2}{(1/a + ip)} p^2 + \frac{(r_0/2)^2}{(1/a + ip)^2} p^4 + \dots\right]$$

$C_0 \sim 4\pi/MQ$ $\qquad$ Relevant

# Power counting schemes

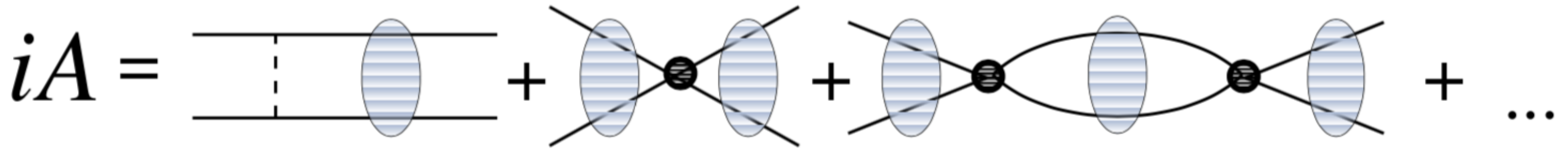
[ See Bingwei Long's talk ]

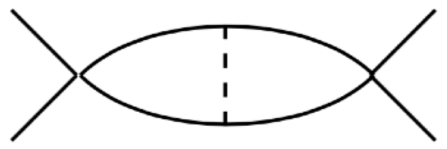
Complicated due to non-perturbative natures and renormalization problems

**Weinberg Scheme**

$V^{\mathrm{LO}}_{\mathrm{Weinberg}} \sim \mathcal{O}(1), \quad V^{\mathrm{NLO}}_{\mathrm{Weinberg}} \sim \mathcal{O}(p^2)$

[i.e. scaling of $C_{2n}$ according to NDA (~ O(1))]





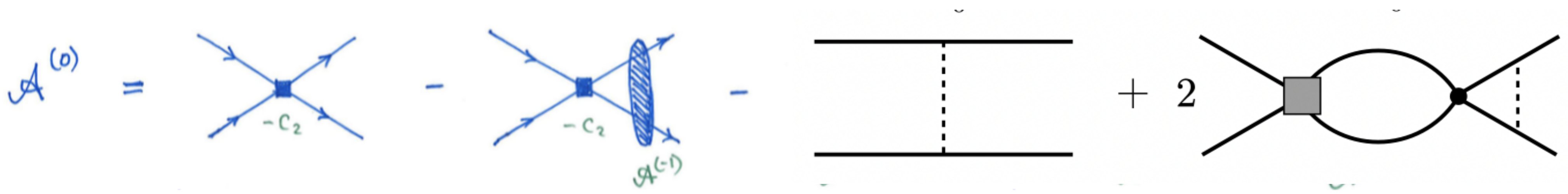
**Renormalization problem!**

**KSW Scheme**

$V^{\mathrm{LO}}_{\mathrm{KSW}} \sim \mathcal{O}(p^{-1}), \quad V^{\mathrm{NLO}}_{\mathrm{KSW}} \sim \mathcal{O}(1)$

[i.e. scaling of $C_{2n}$ as $C_{2n} \sim O(p^{-1-n})$]

**Pion are perturbative**



**Converge problem!**

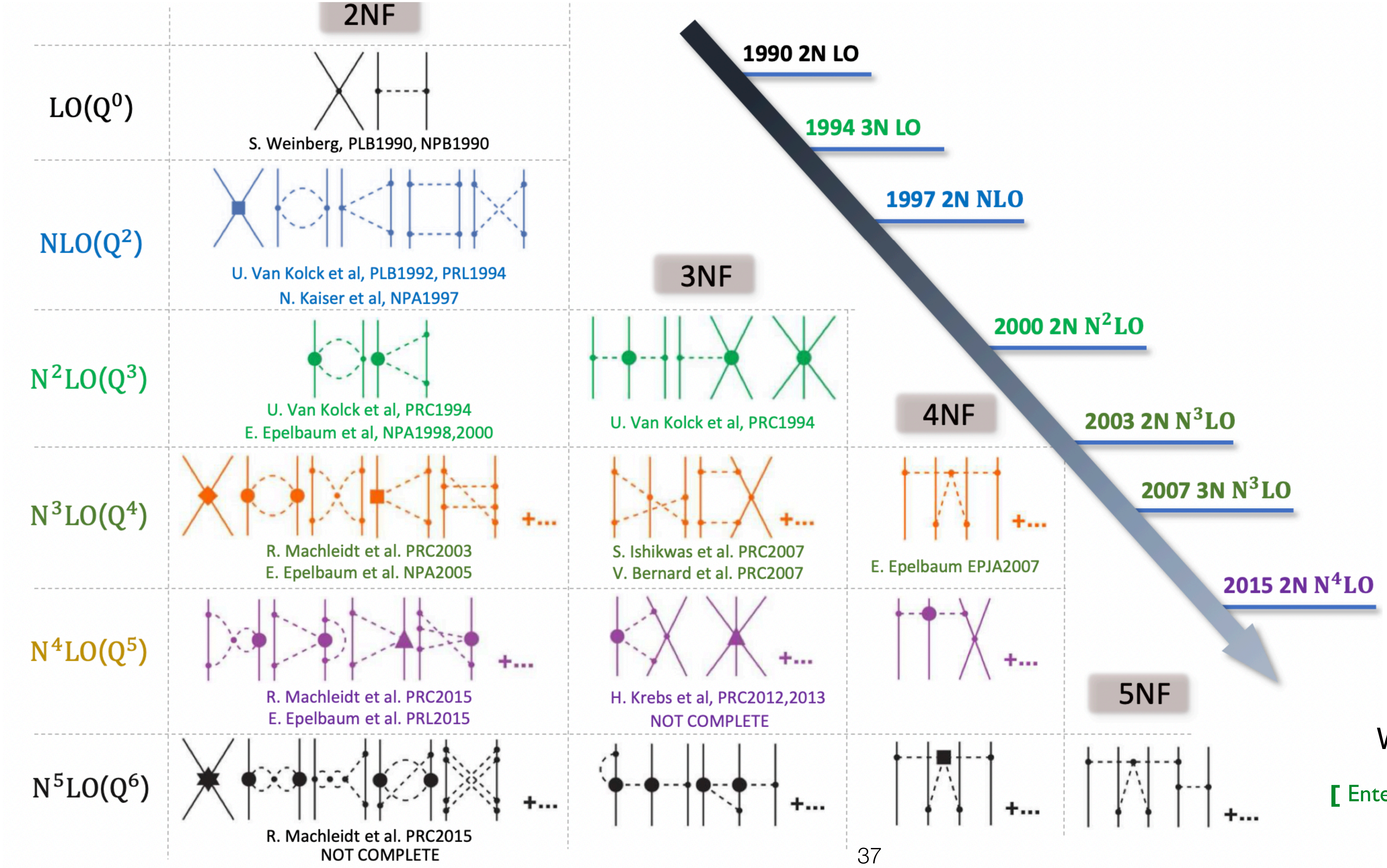
**Modified Weinberg**

[ Nogga, Timmermans, van Kolck, 2005 ]
[ Epelbaum, Gegelia, 2012 ]
[ S. Wu, B. W. Long, 2019 ]

$$V^{\mathrm{WPC}}_{\mathrm{LO}}(\mathbf{p},\mathbf{p}') = \frac{g_A^2}{4f_\pi^2}\tau_1\cdot\tau_2\frac{(\sigma_1\cdot\mathbf{q})(\sigma_2\cdot\mathbf{q})}{m_\pi^2+\mathbf{q}^2} + \tilde{C}_{^1S_0} + \tilde{C}_{^3S_1} \;\longrightarrow\; V^{\mathrm{MWPC}}_{\mathrm{LO}}(\mathbf{p},\mathbf{p}') = V^{\mathrm{WPC}}_{\mathrm{LO}}(\mathbf{p},\mathbf{p}') + (\tilde{C}_{^3P_0} + \tilde{C}_{^3P_2})pp'$$

**Solve both but why?**

# High precision nuclear force




Weinberg scheme

[ Entem, Machleidt, Nosyk, 2020 ]

# Non-relativistic operators

[ Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, in preparation ]

**Operator**

$$O=\epsilon^n \prod_{n_k}^{n_E}\prod_{n_l}^{n_B} N^\dagger(\nabla^{\omega_k}E_{n_k})(\nabla^{\omega_l}B_{n_l})\nabla^{\omega_j}N$$

$$(N^\dagger\sigma\cdot\overleftrightarrow{\nabla}N)(N^\dagger\sigma\cdot\overleftarrow{\nabla}N)$$

↓

**Spin Relation** → **EOM and CDC**

$$[s^I,s^J]=\sqrt{-1}\varepsilon^{IJK}s^K$$

↓

**Schouten Identity**

$$\nabla_{kj}\equiv\epsilon_{ki}\nabla_I(\sigma^I)^i_j. \quad +\langle ri\rangle\langle jk\rangle+\langle rj\rangle\langle ki\rangle=0,$$

↓

**IBP**

$$i(\nabla\times\vec{E})^i=Tr[\sigma^i\sigma^j\sigma^k]\nabla^jE^k=Tr[\sigma^i\sigma^k\sigma^j]\nabla^jE^k$$

↓

**SU(2) YD** → **On-shell Amplitude**

| | | | |
|---|---|---|---|
| $i_1$ | $j_3$ | $i_2$ | $k_2$ |
| $j_3$ | $i_3$ | $k_2$ | $i_4$ |

$$\epsilon^{i_1j_3}\epsilon^{j_3i_3}\epsilon^{i_2k_2}\epsilon^{k_2i_4}\sim\langle i_1j_3\rangle\langle j_3i_3\rangle\langle i_2k_2\rangle\langle k_2i_4\rangle$$

$$\Psi(x)=e^{-imv\cdot x}\Big[\underbrace{e^{imv\cdot x}P_v^+\Psi(x)}_{\equiv\mathcal{N}_v(x)}+\underbrace{e^{imv\cdot x}P_v^-\Psi(x)}_{\equiv\mathcal{H}_v(x)}\Big]$$

## Non-linearized Lorentz symmetry

$$SO(3,1)/SO(3)$$

$$v^\mu=L(\vec{\eta}(v))v_0^\mu \qquad L(\vec{\eta})=e^{i\vec{\eta}\cdot\vec{K}}$$

## Missing Goldstone

$$\left.\begin{array}{l}|v_0,0,\sigma\rangle\\ |v_0,\vec{k}\rangle\end{array}\right\}\longrightarrow|v_0,\vec{k},\sigma\rangle.$$

# NN and 3N operators

Nucleon-nucleon sector

3 nucleon sector

LO

[ Weinberg 1990 ] [ Weinberg 1991 ]

[ van Kolck, Ordonez, 1992 ]

NLO

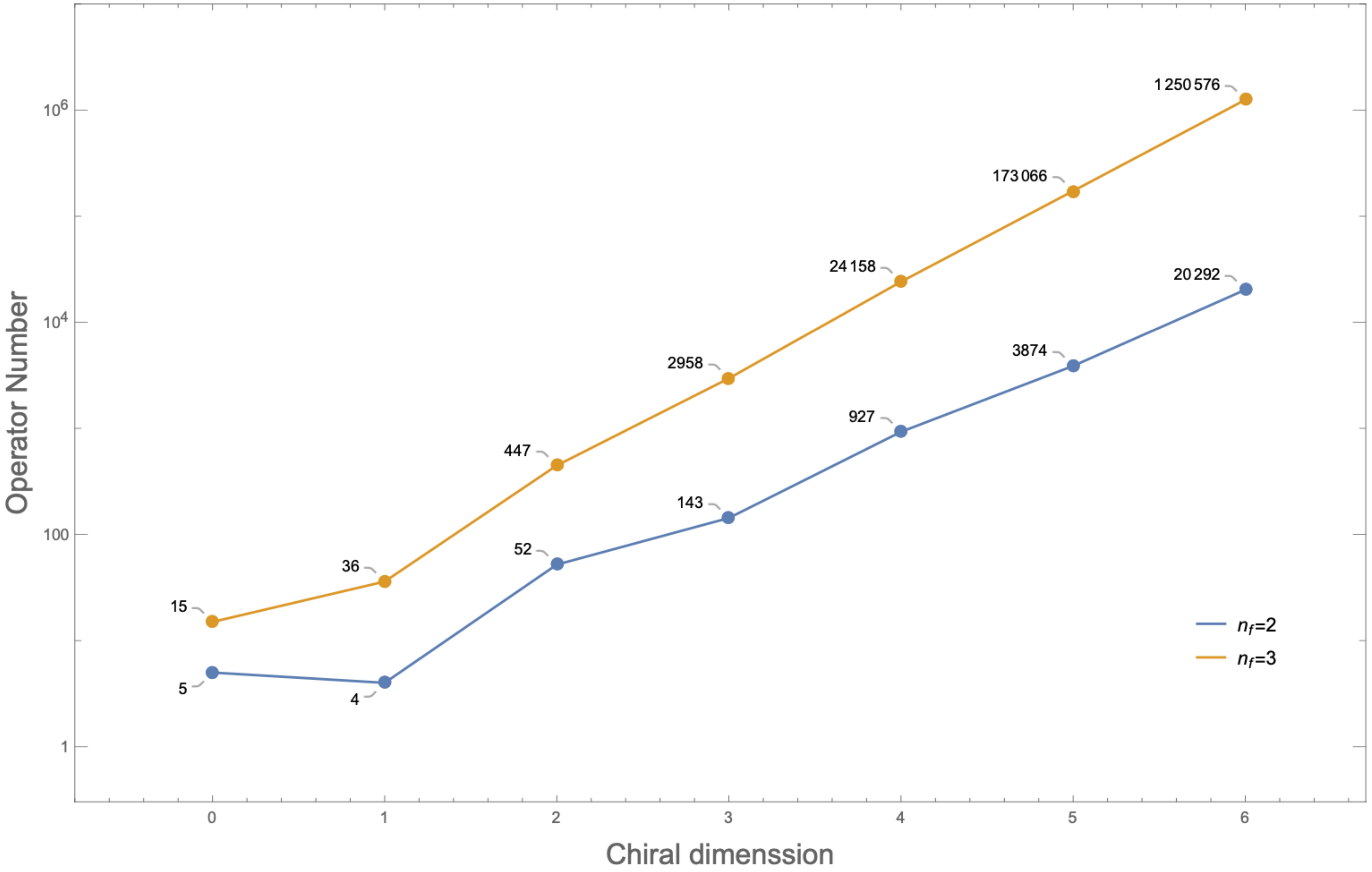
[ Girlanda, Pastore, Schiavilla, Viviani, 2010 ]

[ Petschauer, Kaiser, 2013 ] [ Xiao, Geng, Ren, 2019 ]

NNLO

[ Petschauer, Haidenbauer, Kaiser, Meisner, Weise, 2016 ]

[ Nasoni, Filandri, Girlanda, 2023 ]



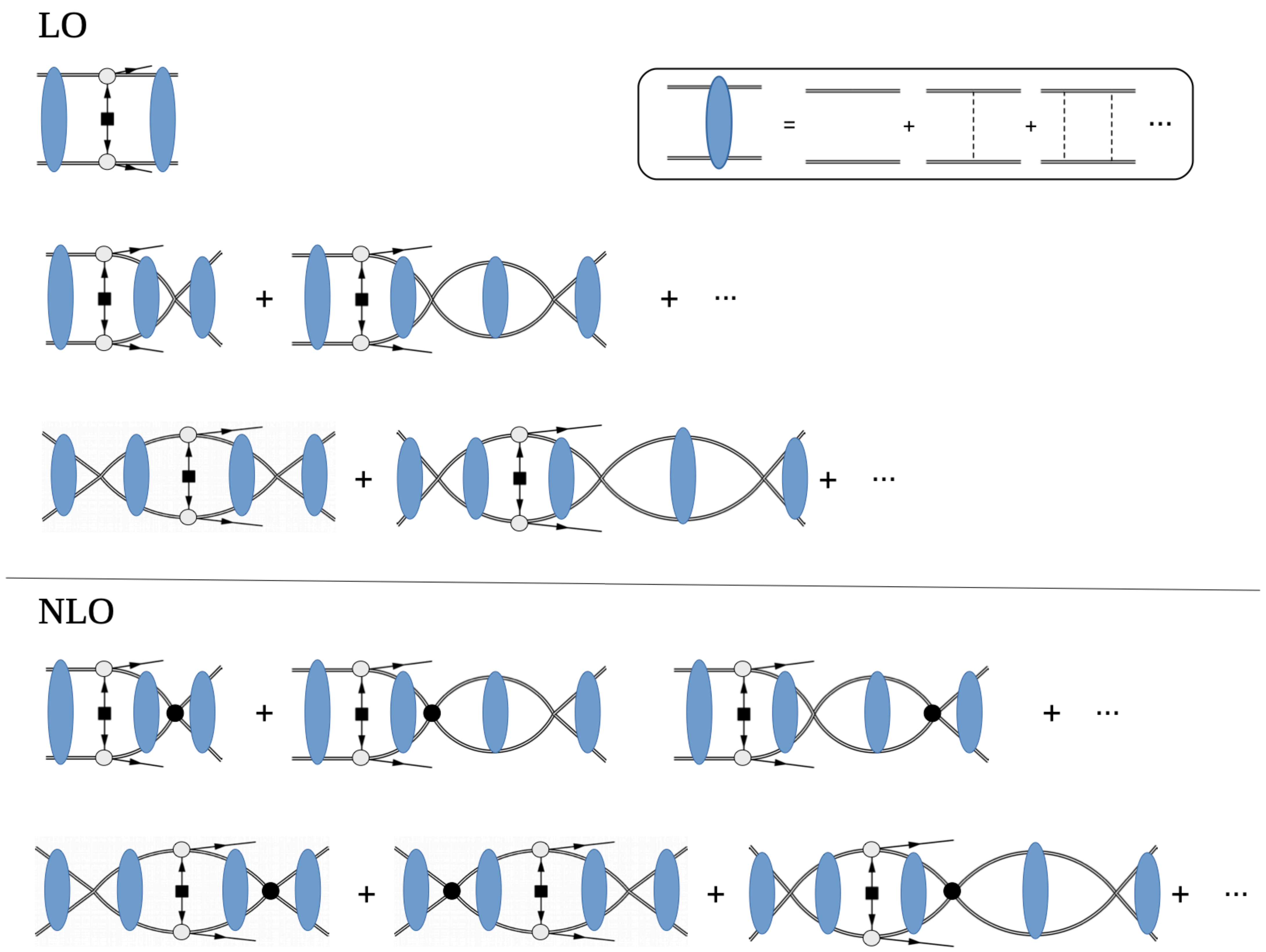

In order to obtain the most general contact Lagrangian in flavor SU(3), we follow the same procedure as used for the four-baryon contact terms in Ref. [47]. Generalizing these construction rules straightforwardly to six-baryon contact terms, we end up with a (largely) overcomplete set of terms for the leading covariant Lagrangian:

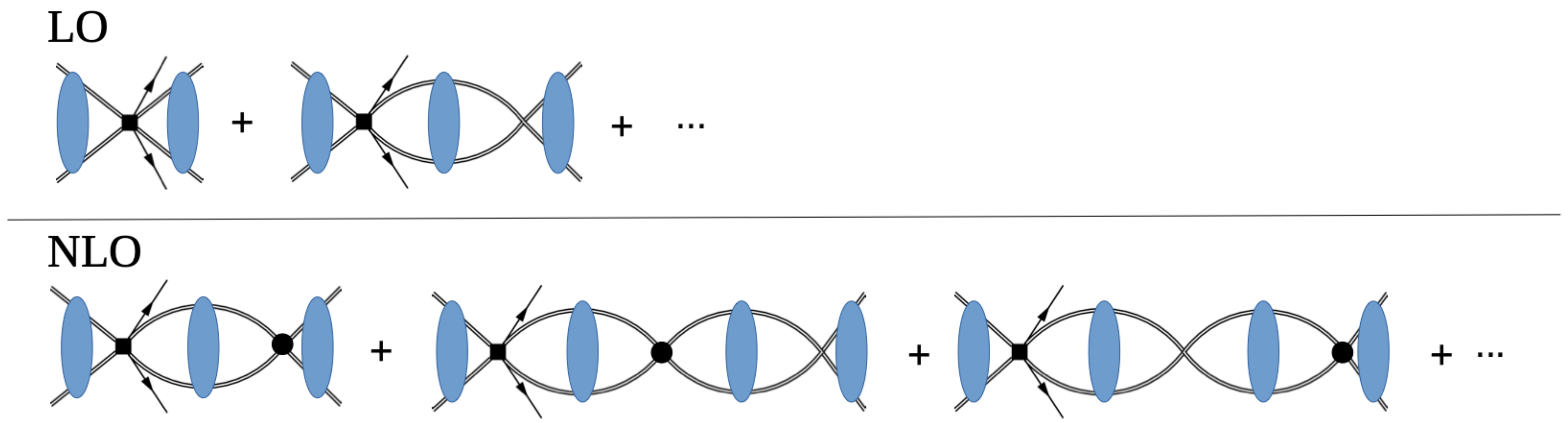
[ Hao Sun, Yi-Ning Wang, **J.H.Yu**, 2501.14018 ]

[ Yong-Kang Li, Yi-Ning Wang, **J.H.Yu**, in preparation ]

# Nuclear many body effects for 0vbb

Long-range and short-range weak currents



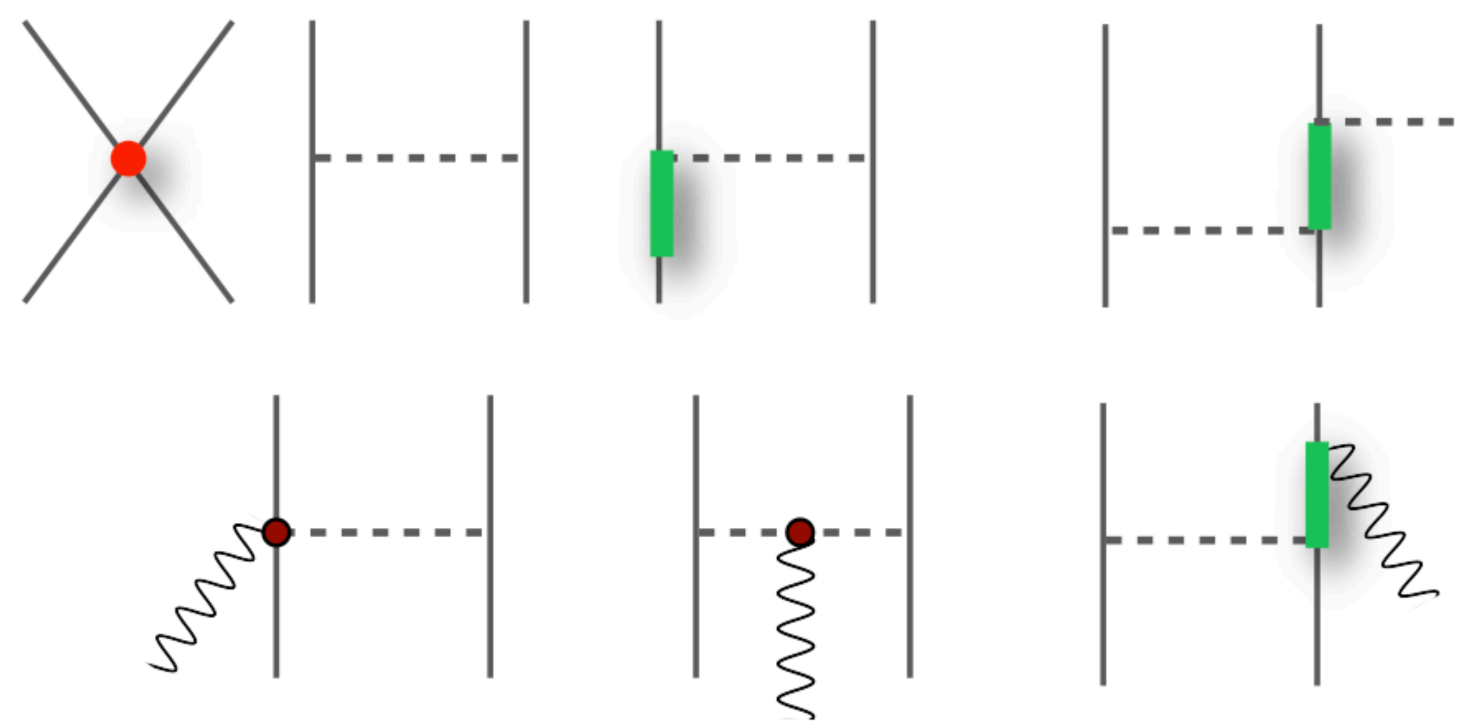




[ Cirigliano, Dekens, de Vries, Graesser, Mereghetti, 2019]

[ See Pengwei Zhao's talk ]

# Ab initio nuclear structure

Effective Hamiltonians and consistent currents

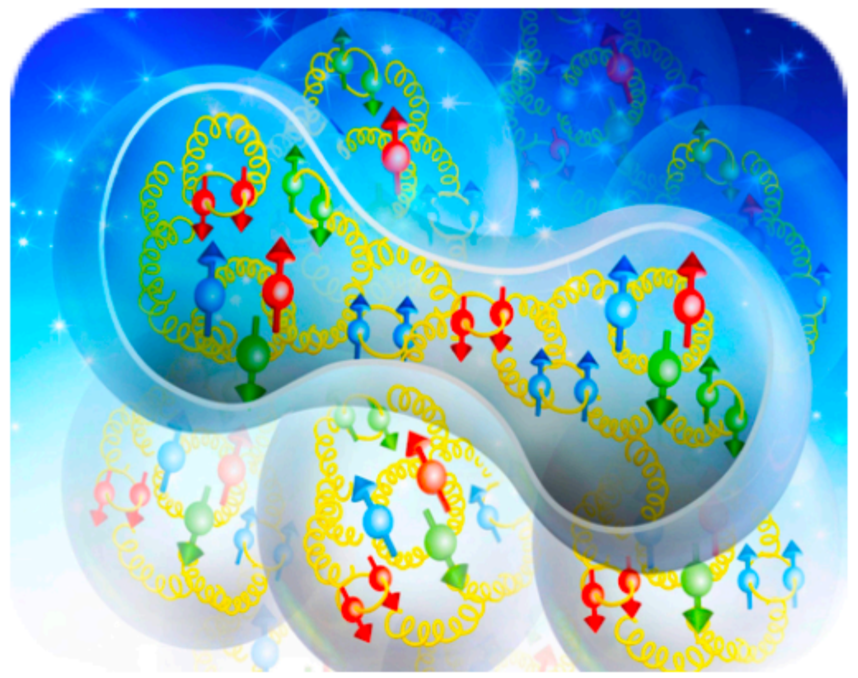


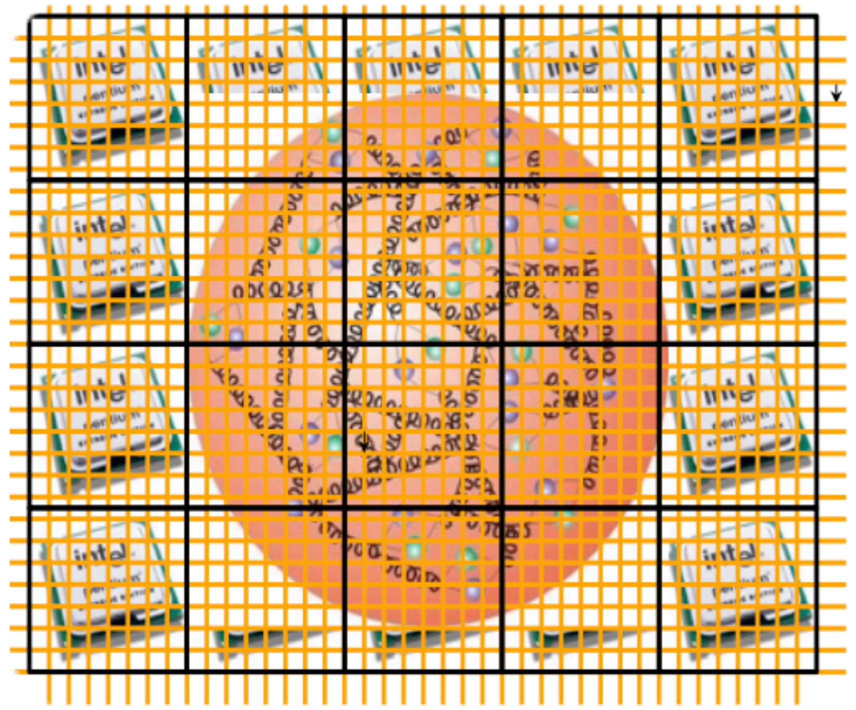
Accurate nuclear many-body methods


$$H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

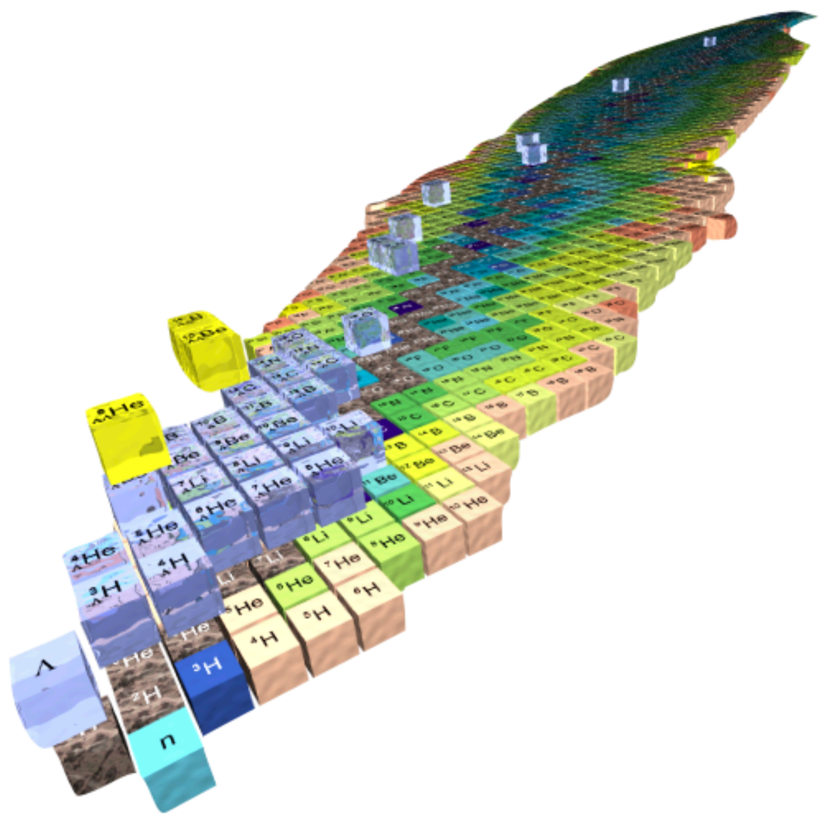
$$J_{mn} = \langle\Psi_m|J|\Psi_n\rangle$$

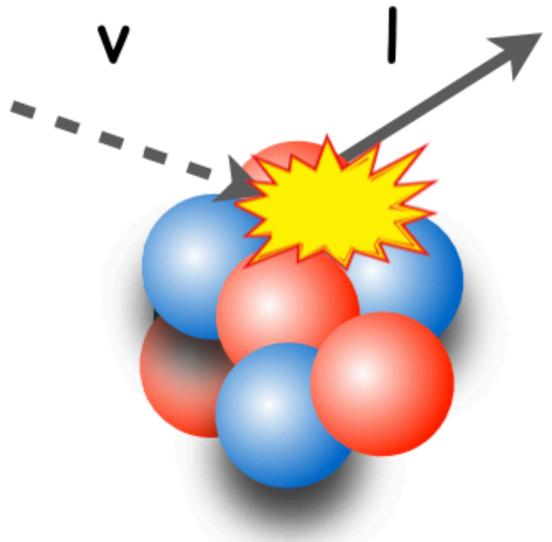
Quantum Chromodynamcs





Nuclei and electroweak interactions



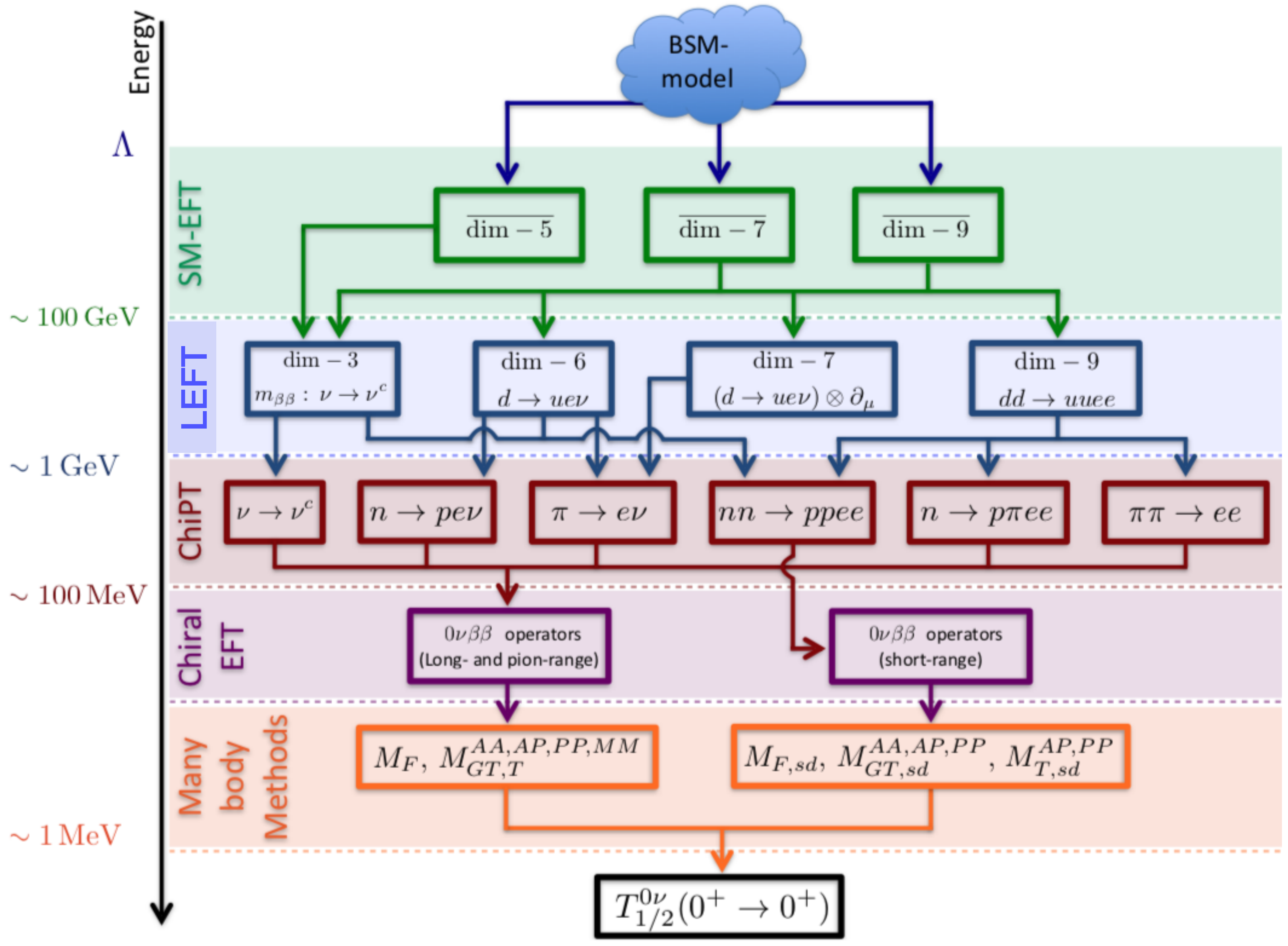



[ See Pengwei Zhao's talk ]

# Complete EFT Framework for 0vbb

Operator bases for different EFTs are necessarily needed to provide most general description

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




**UV models new particles**

↓

**Quark level operators**

↓

**Hadronic level operators**

↓

**Nuclear level operators**

**Setup a general framework**

**How to find complete UV?**

# UV Completion for nν mass and 0νbb

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

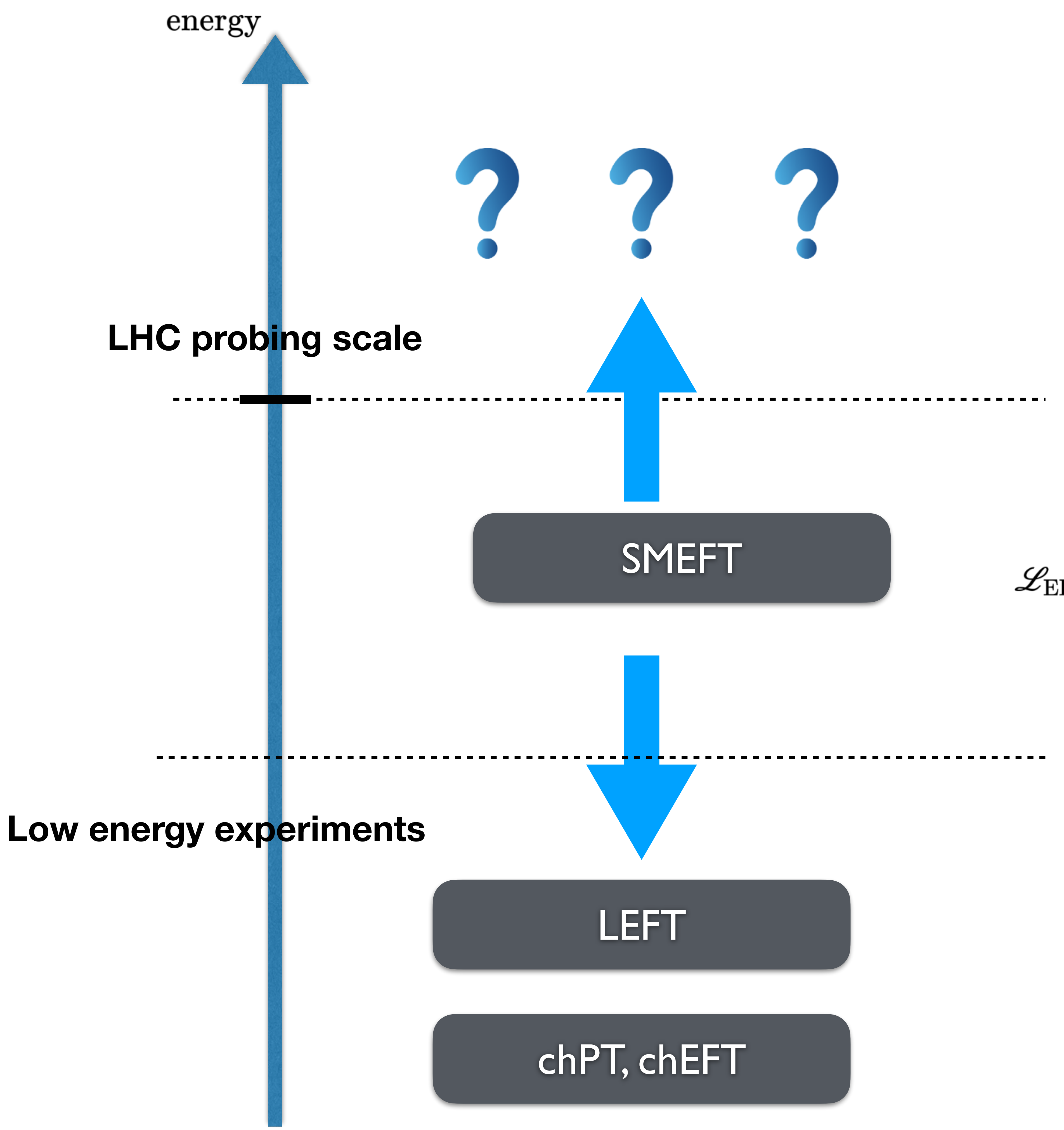
[ Xu-Xiang Li, Zhe Ren, **J.H.Yu,** 2307.10380 ]

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

[ Gang Li, **J.H.Yu,** Xiang Zhao, 2311.15422 ]

# SMEFT Inverse Problem

Given effective operators, how to find complete UV ?




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

# UV of Weinberg Operator

[ See Xiao-Gang He's talk ]

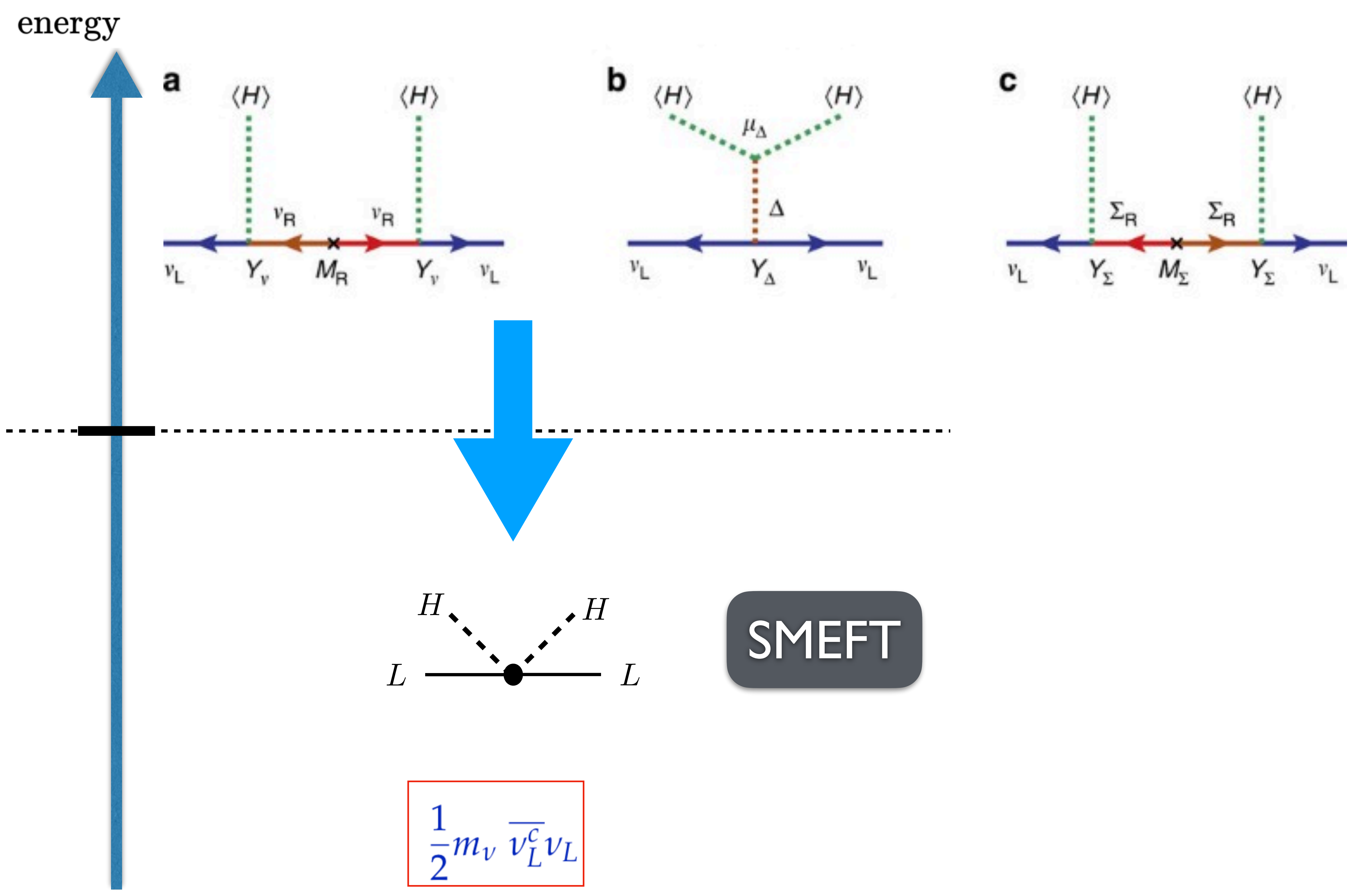
Top-down Approach

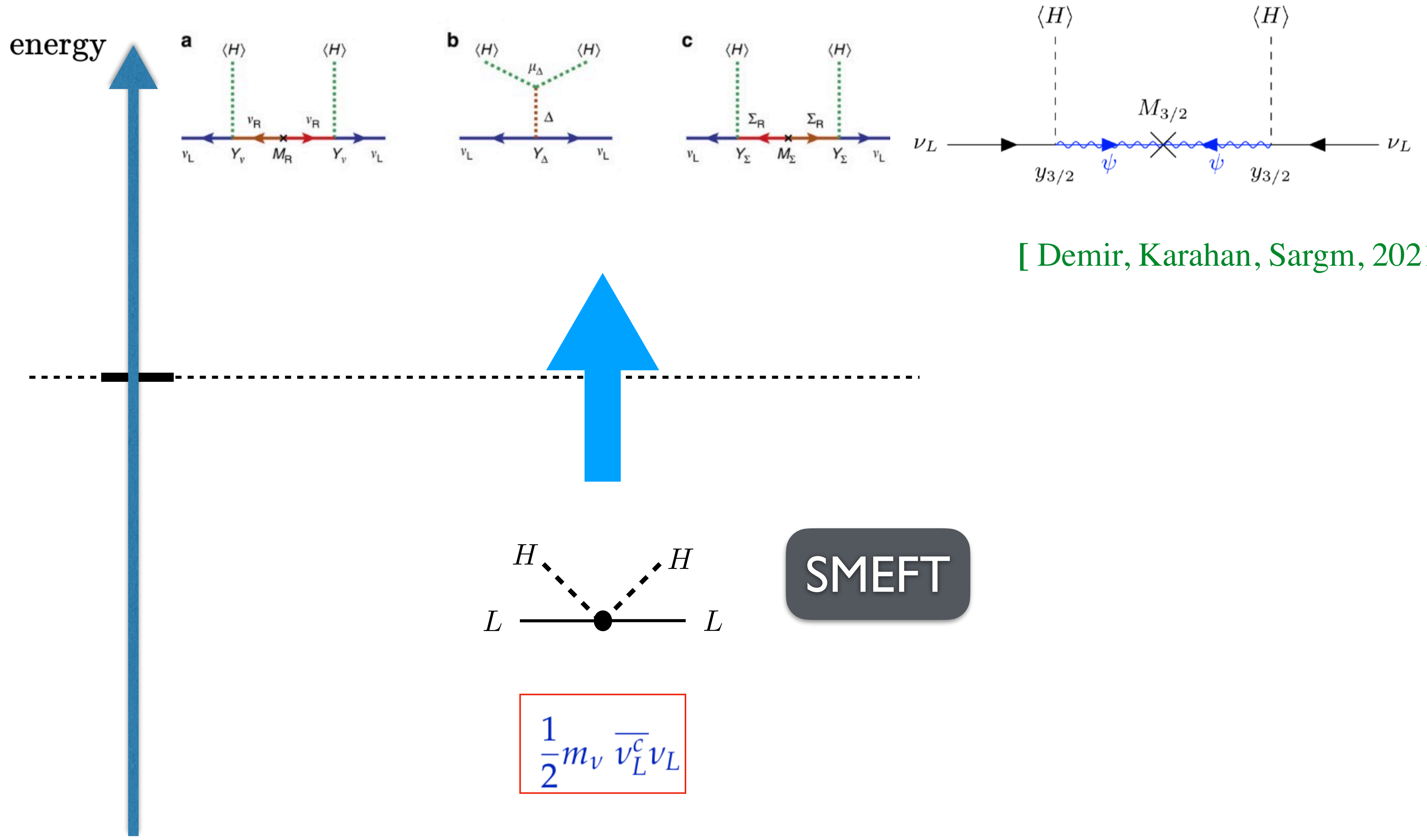
Bottom-up Approach

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

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

[ Foot, Lew, He, Joshi 1989 ]



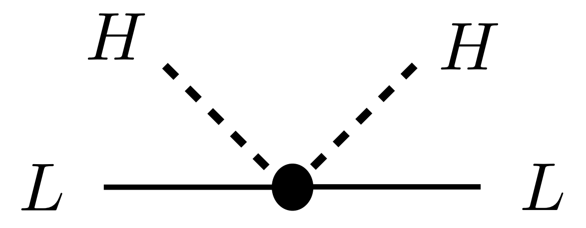

[ Demir, Karahan, Sargm, 2021 ]

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



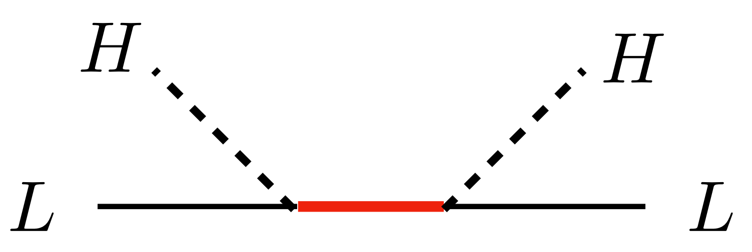

$\mathcal{O}^S = (HL)(HL)$

**Generalized partial wave analysis for Poincare/Gauge Casimir**

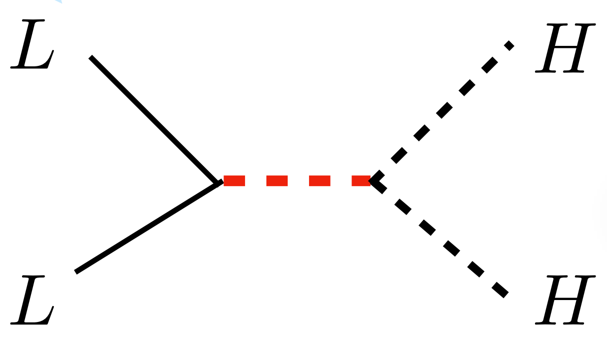
$$\mathbf{W}^2\mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$

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

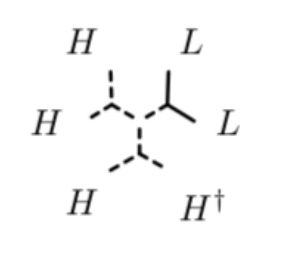
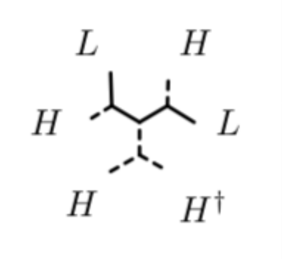
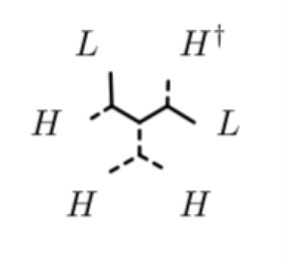
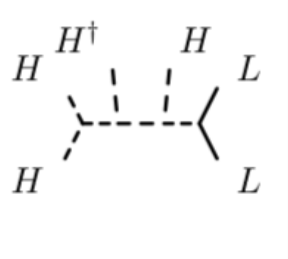
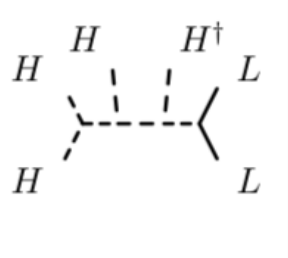
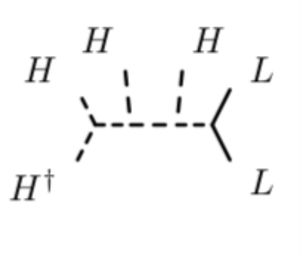
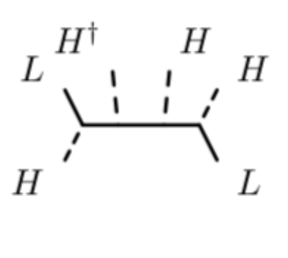
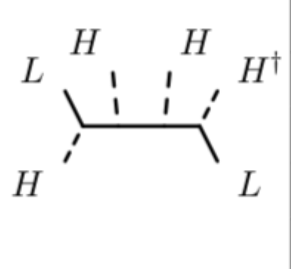
| j-basis | Model |
|---|---|
| $\mathcal{O}^{(1/2,\mathbf{1})}_{HL\to HL} = \mathcal{O}^S + \mathcal{O}^A$ | type I |
| $\mathcal{O}^{(1/2,\mathbf{3})}_{HL\to HL} = \mathcal{O}^S - 3\mathcal{O}^A$ | type III |

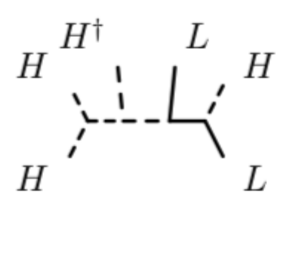
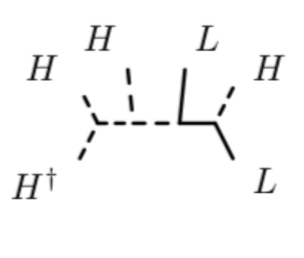
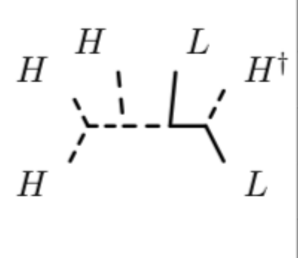
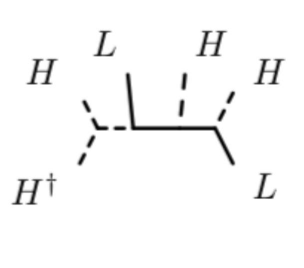
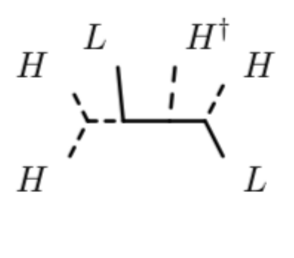
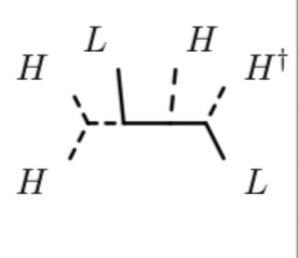
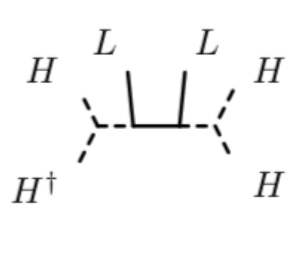
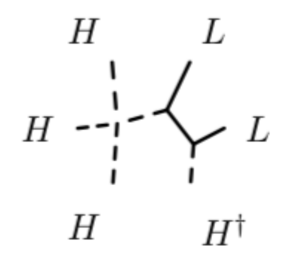
$\mathcal{O}^S = (HL)(HL), \quad \mathcal{O}^A = (HH)(LL)$

| 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 $\{J, \mathbf{R}, Y\}$ |
|---|---|---|
|  | $\mathcal{O}_{\{12\|34\|56\},1} = 2\mathcal{O}_1^p - 4\mathcal{O}_2^p$, | $\{0,3,-1\},\{0,3,1\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|34\|56\},2} = 2\mathcal{O}_2^p + 4\mathcal{O}_3^p$, | $\{0,3,-1\},\{0,1,1\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|34\|56\},3} = 12\mathcal{O}_4^p$, | $\{0,1,-1\},\{0,3,1\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|34\|56\},4} = 4\mathcal{O}_1^p + 4\mathcal{O}_2^p$, | $\{0,3,-1\},\{0,3,1\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{12\|34\|56\},5} = 2\mathcal{O}_4^p + 4\mathcal{O}_5^p$. | $\{0,1,-1\},\{0,1,1\},\{0,1,0\}$ |
|  | $\mathcal{O}_{\{13\|24\|56\},1} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|24\|56\},2} = -\mathcal{O}_1^p + 3\mathcal{O}_2^p + 2\mathcal{O}_3^p + 3\mathcal{O}_4^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},1,0\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|24\|56\},3} = -\mathcal{O}_1^p + \mathcal{O}_2^p - 2\mathcal{O}_3^p - 3\mathcal{O}_4^p$, | $\{\frac{1}{2},1,0\},\{\frac{1}{2},3,0\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|24\|56\},4} = -\mathcal{O}_1^p - \mathcal{O}_2^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},3,0\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{13\|24\|56\},5} = \mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p$. | $\{\frac{1}{2},1,0\},\{\frac{1}{2},1,0\},\{0,1,0\}$ |
|  | $\mathcal{O}_{\{16\|23\|45\},1} = 2\mathcal{O}_1^p - 2\mathcal{O}_2^p - 2\mathcal{O}_3^p + 6\mathcal{O}_4^p + 6\mathcal{O}_5^p$, | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|23\|45\},2} = -2\mathcal{O}_1^p - \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},1,0\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|23\|45\},3} = 3\mathcal{O}_2^p + 3\mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p$, | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},3,0\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|23\|45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_4^p + 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},3,0\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{16\|23\|45\},5} = \mathcal{O}_2^p - \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p$. | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},1,0\},\{0,1,1\}$ |
|  | $\mathcal{O}_{\{12\|125\|34\},1} = \mathcal{O}_1^p + 4\mathcal{O}_2^p$, | $\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|125\|34\},2} = -8\mathcal{O}_1^p + 4\mathcal{O}_2^p$, | $\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|125\|34\},3} = -12\mathcal{O}_4^p$, | $\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|125\|34\},4} = -2\mathcal{O}_2^p - 4\mathcal{O}_3^p$, | $\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{12\|125\|34\},5} = -2\mathcal{O}_4^p - 4\mathcal{O}_5^p$. | $\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$ |
|  | $\mathcal{O}_{\{12\|126\|34\},1} = 3\mathcal{O}_1^p$, | $\{0,3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|126\|34\},2} = 12\mathcal{O}_2^p$, | $\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|126\|34\},3} = -12\mathcal{O}_4^p$, | $\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{12\|126\|34\},4} = -2\mathcal{O}_2^p - 4\mathcal{O}_3^p$, | $\{0,3,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{12\|126\|34\},5} = -2\mathcal{O}_4^p - 4\mathcal{O}_5^p$. | $\{0,1,-1\},\{0,2,-\frac{3}{2}\},\{0,1,1\}$ |
|  | $\mathcal{O}_{\{12\|124\|36\},1} = -\mathcal{O}_1^p - 4\mathcal{O}_3^p$, | $\{0,3,-1\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|124\|36\},2} = 2\mathcal{O}_1^p + 6\mathcal{O}_2^p + 2\mathcal{O}_3^p$, | $\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|124\|36\},3} = -6\mathcal{O}_4^p - 6\mathcal{O}_5^p$, | $\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{12\|124\|36\},4} = -2\mathcal{O}_1^p + 2\mathcal{O}_2^p + 2\mathcal{O}_3^p$, | $\{0,3,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{12\|124\|36\},5} = -2\mathcal{O}_4^p + 2\mathcal{O}_5^p$. | $\{0,1,-1\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$ |
|  | $\mathcal{O}_{\{13\|135\|24\},1} = \mathcal{O}_1^p - 2\mathcal{O}_3^p - 6\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{13\|135\|24\},2} = -\mathcal{O}_1^p - 3\mathcal{O}_2^p - 4\mathcal{O}_3^p + 9\mathcal{O}_4^p + 6\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{13\|135\|24\},3} = \mathcal{O}_1^p - \mathcal{O}_2^p + 2\mathcal{O}_3^p + 3\mathcal{O}_4^p$, | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{13\|135\|24\},4} = \mathcal{O}_1^p - 3\mathcal{O}_2^p - 2\mathcal{O}_3^p - 3\mathcal{O}_4^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$ |
| | $\mathcal{O}_{\{13\|135\|24\},5} = \mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p$. | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{\frac{1}{2},1,0\}$ |
|  | $\mathcal{O}_{\{16\|146\|23\},1} = -2\mathcal{O}_1^p + 4\mathcal{O}_3^p - 12\mathcal{O}_5^p$, | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{16\|146\|23\},2} = 2\mathcal{O}_1^p - 3\mathcal{O}_2^p - \mathcal{O}_3^p + 9\mathcal{O}_4^p + 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{16\|146\|23\},3} = 3\mathcal{O}_2^p + 3\mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p$, | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},3,0\}$ |
| | $\mathcal{O}_{\{16\|146\|23\},4} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p - 3\mathcal{O}_4^p - 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$ |
| | $\mathcal{O}_{\{16\|146\|23\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p - \mathcal{O}_4^p + \mathcal{O}_5^p$, | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{\frac{1}{2},1,0\}$ |

| | | |
|---|---|---|
|  | $\mathcal{O}_{\{13\|123\|45\},1} = \mathcal{O}_1^p - 4\mathcal{O}_2^p - 4\mathcal{O}_3^p$, | $\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|123\|45\},2} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p - 9\mathcal{O}_4^p - 9\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|123\|45\},3} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p$, | $\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|123\|45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p - 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{13\|123\|45\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p$. | $\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,1\}$ |
|  | $\mathcal{O}_{\{13\|123\|46\},1} = \mathcal{O}_1^p - 4\mathcal{O}_2^p - 4\mathcal{O}_3^p$, | $\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|123\|46\},2} = \mathcal{O}_1^p + 2\mathcal{O}_2^p - \mathcal{O}_3^p - 9\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|123\|46\},3} = -\mathcal{O}_1^p - 2\mathcal{O}_2^p + \mathcal{O}_3^p - 3\mathcal{O}_5^p$, | $\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{13\|123\|46\},4} = -\mathcal{O}_1^p - \mathcal{O}_3^p + 6\mathcal{O}_4^p + 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{0,4,-\frac{1}{2}\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{13\|123\|46\},5} = -\mathcal{O}_1^p - \mathcal{O}_3^p - 2\mathcal{O}_4^p - \mathcal{O}_5^p$. | $\{\frac{1}{2},1,0\},\{0,2,-\frac{1}{2}\},\{0,1,0\}$ |
|  | $\mathcal{O}_{\{16\|126\|34\},1} = 6\mathcal{O}_1^p$, | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|126\|34\},2} = -3\mathcal{O}_2^p + 9\mathcal{O}_4^p$, | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|126\|34\},3} = -3\mathcal{O}_2^p - 3\mathcal{O}_4^p$, | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|126\|34\},4} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p$, | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|126\|34\},5} = \mathcal{O}_2^p + 2\mathcal{O}_3^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p$. | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\},\{0,3,1\}$ |
|  | $\mathcal{O}_{\{23\|235\|46\},1} = \mathcal{O}_1^p - 2\mathcal{O}_3^p + 6\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{23\|235\|46\},2} = \mathcal{O}_1^p - 6\mathcal{O}_2^p - 5\mathcal{O}_3^p - 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{23\|235\|46\},3} = \mathcal{O}_1^p + 2\mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_5^p$, | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{23\|235\|46\},4} = -\mathcal{O}_1^p - \mathcal{O}_3^p - 6\mathcal{O}_4^p - 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{23\|235\|46\},5} = -\mathcal{O}_1^p - \mathcal{O}_3^p + 2\mathcal{O}_4^p + \mathcal{O}_5^p$. | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$ |
|  | $\mathcal{O}_{\{13\|136\|45\},1} = \mathcal{O}_1^p + 2\mathcal{O}_2^p + 2\mathcal{O}_3^p - 6\mathcal{O}_4^p - 6\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|136\|45\},2} = 2\mathcal{O}_1^p - 5\mathcal{O}_2^p - 5\mathcal{O}_3^p - 3\mathcal{O}_4^p - 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|136\|45\},3} = 2\mathcal{O}_1^p + \mathcal{O}_2^p + \mathcal{O}_3^p + 3\mathcal{O}_4^p + 3\mathcal{O}_5^p$, | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{13\|136\|45\},4} = \mathcal{O}_2^p - \mathcal{O}_3^p + 3\mathcal{O}_4^p - 3\mathcal{O}_5^p$, | $\{\frac{1}{2},3,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{13\|136\|45\},5} = -\mathcal{O}_2^p + \mathcal{O}_3^p + \mathcal{O}_4^p - \mathcal{O}_5^p$. | $\{\frac{1}{2},1,0\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$ |
|  | $\mathcal{O}_{\{16\|156\|34\},1} = 2\mathcal{O}_1^p - 4\mathcal{O}_2^p + 12\mathcal{O}_4^p$, | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},4,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|156\|34\},2} = 4\mathcal{O}_1^p + \mathcal{O}_2^p - 3\mathcal{O}_4^p$, | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|156\|34\},3} = -3\mathcal{O}_2^p - 3\mathcal{O}_4^p$, | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,3,1\}$ |
| | $\mathcal{O}_{\{16\|156\|34\},4} = -\mathcal{O}_2^p - 2\mathcal{O}_3^p + 3\mathcal{O}_4^p + 6\mathcal{O}_5^p$, | $\{\frac{1}{2},3,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$ |
| | $\mathcal{O}_{\{16\|156\|34\},5} = \mathcal{O}_2^p + 2\mathcal{O}_3^p + \mathcal{O}_4^p + 2\mathcal{O}_5^p$. | $\{\frac{1}{2},1,-1\},\{\frac{1}{2},2,-\frac{1}{2}\},\{0,1,1\}$ |
|  | $\mathcal{O}_{\{34\|134\|56\},1} = -\mathcal{O}_1^p + 2\mathcal{O}_2^p + 6\mathcal{O}_4^p$, | $\{0,3,1\},\{\frac{1}{2},4,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{34\|134\|56\},2} = 4\mathcal{O}_1^p - 8\mathcal{O}_2^p + 12\mathcal{O}_4^p$, | $\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{34\|134\|56\},3} = 2\mathcal{O}_2^p + 4\mathcal{O}_3^p$, | $\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,3,0\}$ |
| | $\mathcal{O}_{\{34\|134\|56\},4} = -4\mathcal{O}_1^p - 4\mathcal{O}_2^p$, | $\{0,3,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$ |
| | $\mathcal{O}_{\{34\|134\|56\},5} = 2\mathcal{O}_4^p + 4\mathcal{O}_5^p$. | $\{0,1,1\},\{\frac{1}{2},2,\frac{1}{2}\},\{0,1,0\}$ |
|  | $\mathcal{O}_{\{16\|126\},1} = 6\mathcal{O}_1^p$, | $\{\frac{1}{2},3,-1\},\{0,4,-\frac{3}{2}\}$ |
| | $\mathcal{O}_{\{16\|126\},2,3} = \begin{pmatrix} \mathcal{O}_2^p - \mathcal{O}_3^p - 3\mathcal{O}_4^p + 3\mathcal{O}_5^p \\ -2\mathcal{O}_2^p - \mathcal{O}_3^p + 6\mathcal{O}_4^p + 3\mathcal{O}_5^p \end{pmatrix}$, | $\{\frac{1}{2},3,-1\},\{0,2,-\frac{3}{2}\}$ |
| | $\mathcal{O}_{\{16\|126\},4,5} = \begin{pmatrix} -\mathcal{O}_2^p - 2\mathcal{O}_3^p - \mathcal{O}_4^p - 2\mathcal{O}_5^p \\ -2\mathcal{O}_2^p - \mathcal{O}_3^p - 2\mathcal{O}_4^p - \mathcal{O}_5^p \end{pmatrix}$. | $\{\frac{1}{2},1,-1\},\{0,2,-\frac{3}{2}\}$ |

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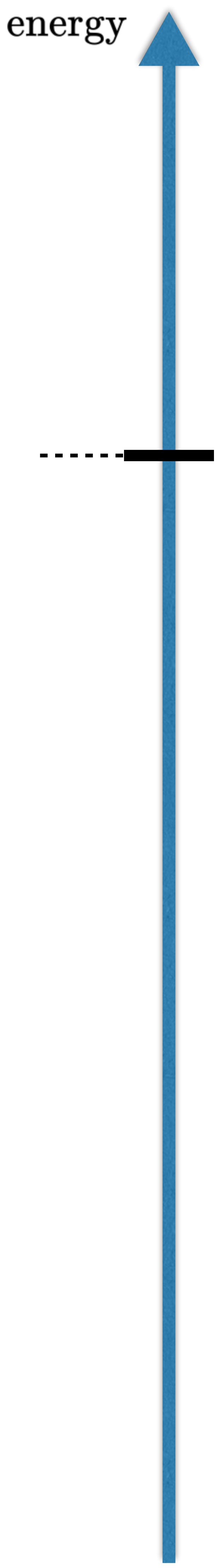
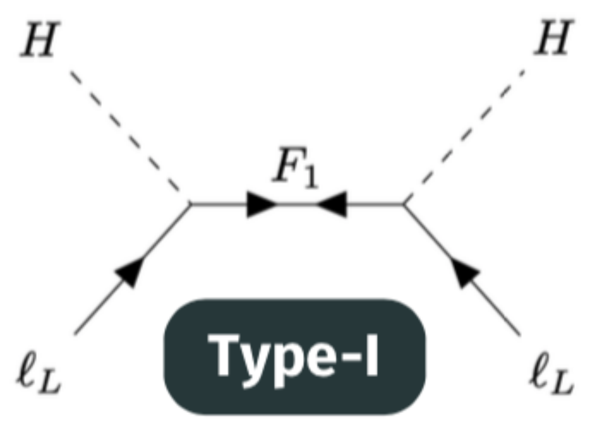
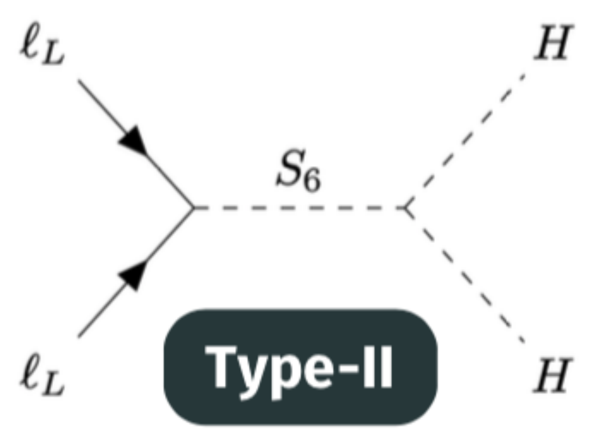
[ Bonnet, Hernandez, Ota, Winter, 2009]

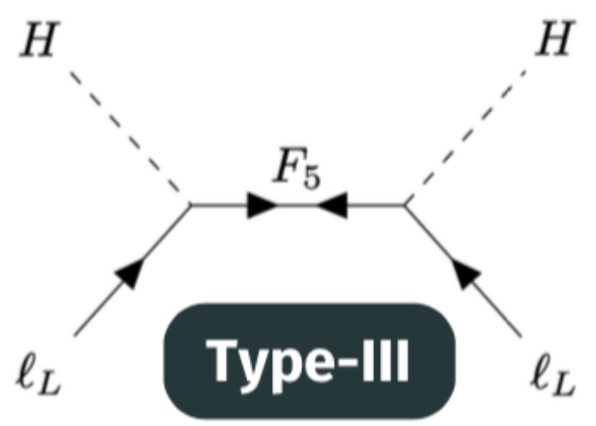
# Top-Down from Bottom-up

[ Xu-Xiang Li, Zhe Ren, **J.H.Yu,** 2307.10380 ]

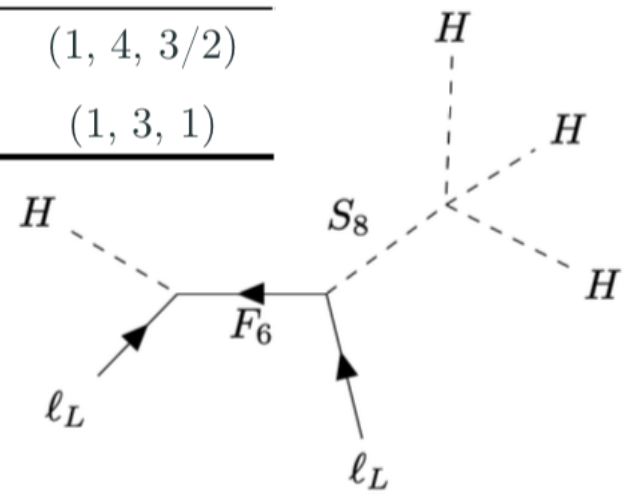



| Field | (C, W, Y) |
|---|---|
| $S_8$ | $(1,\ 4,\ 3/2)$ |
| $F_6$ | $(1,\ 3,\ 1)$ |




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

**One-loop CDE**

| Operators | Seesaw models | | | $Y_{\nu,\Sigma} \stackrel{?}{=} 0$ |
|---|---|---|---|---|
| | Type-I | Type-II | Type-III | |
| **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 |

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

[ Zhang, Zhou, 2107.12133 ]

[ Li, Zhang, Zhou, 2201.05082 ]

# Complete Dim-7 UV Resonances

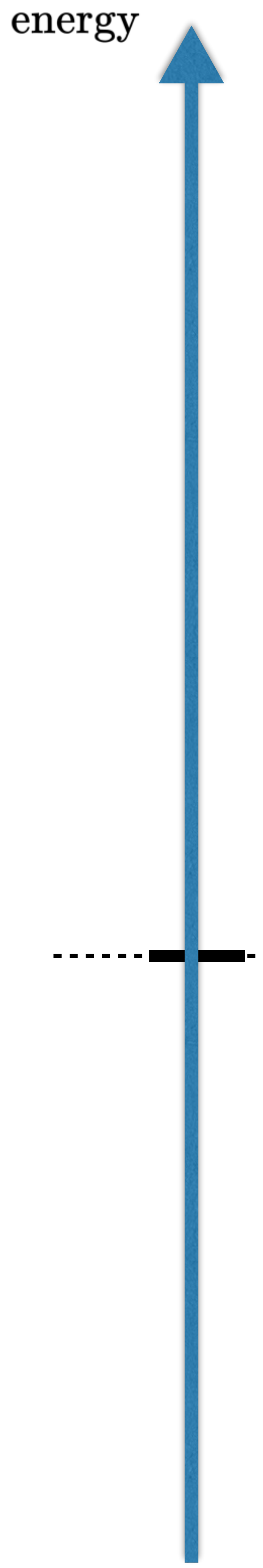
[ Li, Ni, Xiao, **Yu**, 2204.03660 ]

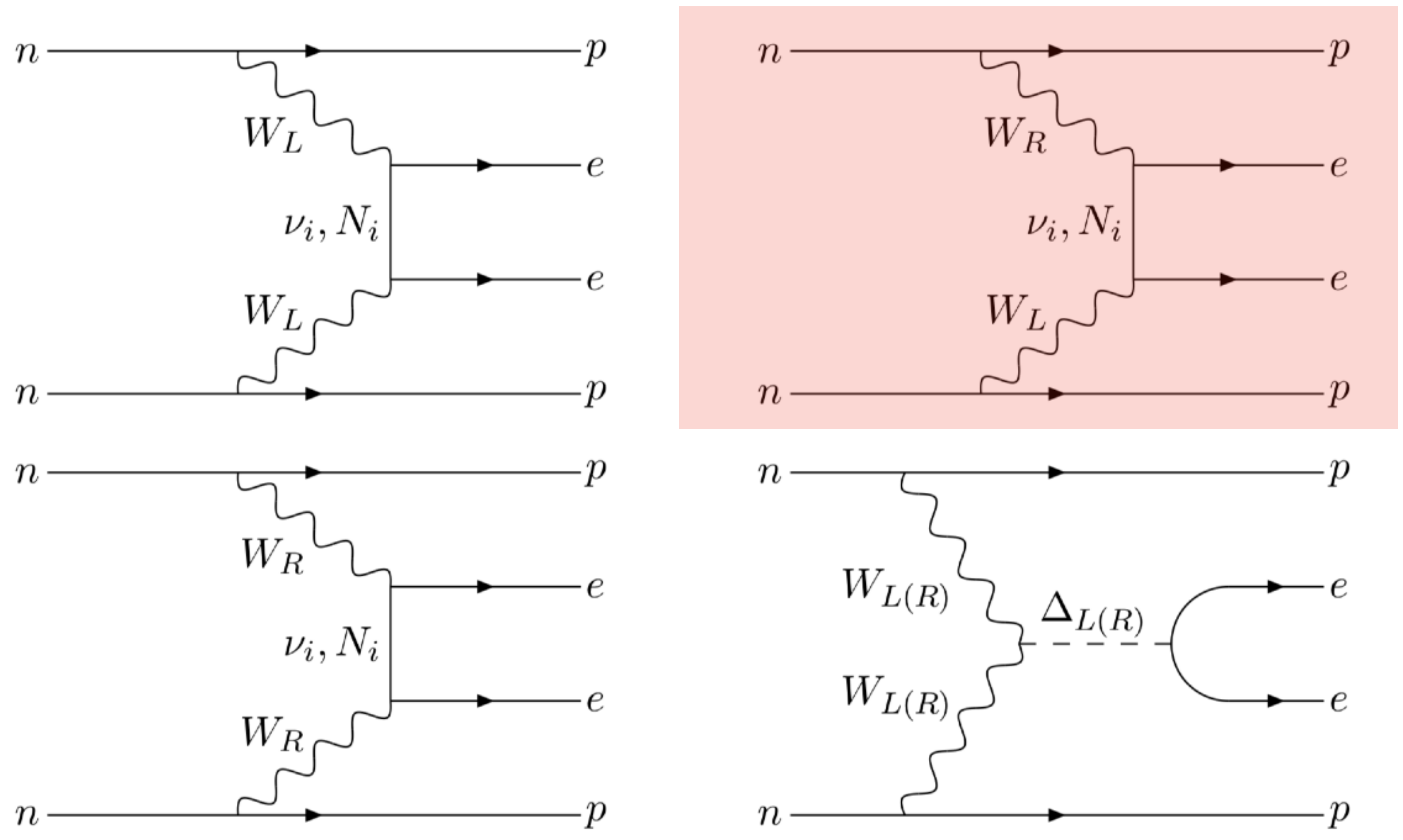
| $(\mathrm{SU}(3)_c, \mathrm{SU}(2)_2, \mathrm{U}(1)_y)$ | Scalar |
|---|---|
| $S1\ (\mathbf{1},\mathbf{1},0)$ | $H^3H^\dagger L^2[(S6),(F5),(F1),(S4,S6),(S4,F5),(S4,F1),(F3,F5),(F1,F3),(S6,F3)]$ |
| $S2\ (\mathbf{1},\mathbf{1},1)$ | $e_{\mathbb{C}}HL^3[(S4),(F4),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S4),(F10),(F9)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(F8),(F12)]$ $De_{\mathbb{C}}H^{\dagger3}L^\dagger[(F1),(F3),(V3)]$ |
| $S4\ (\mathbf{1},\mathbf{2},\frac{1}{2})$ | $e_{\mathbb{C}}HL^3[(S6),(S2),(F5),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S6),(S2),(F5),(F1)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(S2),(F5),(F1)]$ $H^3H^\dagger L^2[(S6),(F5),(F1),(S5,S6),(S1,S6),(S6,F5),(S6,F1),(S5,F5),(S5,F1),(S1,F5),(S1,F1)]$ |
| $S5\ (\mathbf{1},\mathbf{3},0)$ | $H^3H^\dagger L^2[(S6),(F1,F5),(S6,S7),(S4,S6),(S7,F5),(S4,F5),(S4,F1),(F5,F7),(F3,F5),(F1,F3),(S6,F7),(S6,F3)]$ |
| $S6\ (\mathbf{1},\mathbf{3},1)$ | $D^2H^2L^2$ $e_{\mathbb{C}}HL^3[(S4),(F4),(F5)]$ $d_{\mathbb{C}}HL^2Q[(S4),(F10),(F14)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(F13),(F12)]$ $De_{\mathbb{C}}H^{\dagger3}L^\dagger[(F5),(F3),(V3)]$ $H^2L^2W_L[(F7)]$ $H^3H^\dagger L^2[(S4),(S8),(S7),(S5),(S1),(F5,F6),(F1,F6),(S5,S7),(S4,S5),(S1,S4),(S7,F5),(S4,F5),(S4,F1),(F5,F7),(F3,F5),(F1,F3),(S8,F6),(F6,F7),(F3,F6),(S5,F7),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$ |
| $S7\ (\mathbf{1},\mathbf{4},\frac{1}{2})$ | $H^3H^\dagger L^2[(S6),(F5),(S5,S6),(S6,F5),(S5,F5)]$ |
| $S8\ (\mathbf{1},\mathbf{4},\frac{3}{2})$ | $H^3H^\dagger L^2[(S6),(F6),(S6,F6)]$ |
| $S10\ (\mathbf{3},\mathbf{1},-\frac{1}{3})$ | $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S12),(F10),(F1)]$ $d_{\mathbb{C}}HL^2Q[(S12),(F10),(F1)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S12),(F10),(F1)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S12),(F10),(F1)]$ |
| $S11\ (\mathbf{3},\mathbf{1},\frac{2}{3})$ | $d_{\mathbb{C}}{}^3H^\dagger L[(S12),(F11),(F2)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(F11),(S13),(F1)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(S13),(F3),(F8)]$ |
| $S12\ (\mathbf{3},\mathbf{2},\frac{1}{6})$ | $d_{\mathbb{C}}{}^3H^\dagger L[(S11),(F11)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(F11),(S10),(F10)]$ $d_{\mathbb{C}}HL^2Q[(S10),(S14),(F5),(F1),(F14),(F9)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(F3),(F12)]$ |
| $S13\ (\mathbf{3},\mathbf{2},\frac{7}{6})$ | $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S11),(F10)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(S11),(F10)]$ |
| $S14\ (\mathbf{3},\mathbf{3},-\frac{1}{3})$ | $d_{\mathbb{C}}HL^2Q[(S12),(F10),(F5)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S12),(F10),(F5)]$ |

| $(\mathrm{SU}(3)_c, \mathrm{SU}(2)_2, \mathrm{U}(1)_y)$ | Fermion |
|---|---|
| $F1\ (\mathbf{1},\mathbf{1},0)$ | $D^2H^2L^2$ $e_{\mathbb{C}}HL^3[(S4),(S2)]$ $d_{\mathbb{C}}HL^2Q[(S4),(S10),(S12)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(V5),(V8)]$ $De_{\mathbb{C}}H^{\dagger3}L^\dagger[(F3),(V2)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S11),(S10)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(V5)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S10),(V8)]$ $H^2L^2W_L[(F5)]$ $H^3H^\dagger L^2[(S4),(S5,F5),(S1),(S6,F6),(F3,F5),(F3),(F3,F6),(S4,S6),(S6,F3),(S4,S5),(S1,S4),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$ |
| $F2\ (\mathbf{1},\mathbf{1},1)$ | $d_{\mathbb{C}}{}^3H^\dagger L[(S11)]$ |
| $F3\ (\mathbf{1},\mathbf{2},\frac{1}{2})$ | $De_{\mathbb{C}}H^{\dagger3}L^\dagger[(F5),(F1),(S6),(V2)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S12),(V8)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(V8),(S11)]$ $H^3H^\dagger L^2[(F5),(F1,F5),(F1),(F5,F6),(F1,F6),(S6,F5),(S6,F1),(S5,F5),(S5,F1),(S1,F5),(S1,F1),(S6,F6),(S5,S6),(S1,S6)]$ |
| $F4\ (\mathbf{1},\mathbf{2},\frac{3}{2})$ | $e_{\mathbb{C}}HL^3[(S6),(S2)]$ |
| $F5\ (\mathbf{1},\mathbf{3},0)$ | $e_{\mathbb{C}}HL^3[(S4),(S6)]$ $d_{\mathbb{C}}HL^2Q[(S4),(S12),(S14)]$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S4),(V9),(V8)]$ $D^2H^2L^2$ $De_{\mathbb{C}}H^{\dagger3}L^\dagger[(S6),(F3),(V5)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S14),(V8)]$ $H^2L^2W_L[(F7),(F1)]$ $H^3H^\dagger L^2[(S4),(S7),(S5,F1),(S1),(S6,F6),(F7),(F3),(F1,F3),(F6,F7),(F3,F6),(S6,S7),(S4,S6),(S6,F7),(S6,F3),(S5,S7),(S4,S5),(S1,S4),(S5,F7),(S5,F3),(S1,F3)]$ $H^2L^2W_L$ $B_LH^2L^2$ $e_{\mathbb{C}}HL^3$ $HL^2Q^\dagger u_{\mathbb{C}}^\dagger$ $d_{\mathbb{C}}HL^2Q$ $De_{\mathbb{C}}^\dagger H^3L$ |
| $F6\ (\mathbf{1},\mathbf{3},1)$ | $H^3H^\dagger L^2[(S8),(S6,F5),(S6,F1),(F5,F7),(F3,F5),(F1,F3),(S6,S8),(S6,F7),(S6,F3)]$ |
| $F7\ (\mathbf{1},\mathbf{4},\frac{1}{2})$ | $H^2L^2W_L[(F5),(S6)]$ $H^3H^\dagger L^2[(F5),(S6,F5),(F5,F6),(S6,F6),(S5,F5),(S5,S6)]$ |
| $F8\ (\mathbf{3},\mathbf{1},-\frac{1}{3})$ | $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S2),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(V8),(S12),(V5)]$ $d_{\mathbb{C}}{}^2e_{\mathbb{C}}^\dagger HQ^\dagger[(V5),(S11)]$ |
| $F9\ (\mathbf{3},\mathbf{1},\frac{2}{3})$ | $d_{\mathbb{C}}HL^2Q[(S12),(S2)]$ |
| $F10\ (\mathbf{3},\mathbf{2},-\frac{5}{6})$ | $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S12),(S10),(S13)]$ $d_{\mathbb{C}}HL^2Q[(S10),(S6),(S2),(S14)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(S10),(V3),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(S10),(S14),(V9),(V5)]$ |
| $F11\ (\mathbf{3},\mathbf{2},\frac{1}{6})$ | $d_{\mathbb{C}}{}^3H^\dagger L[(S11),(S12)]$ $d_{\mathbb{C}}{}^2HLu_{\mathbb{C}}[(S11),(S12)]$ |
| $F12\ (\mathbf{3},\mathbf{2},\frac{7}{6})$ | $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(S2),(V9),(V5)]$ $d_{\mathbb{C}}e_{\mathbb{C}}^\dagger HLu_{\mathbb{C}}^\dagger[(V5),(S12),(V3)]$ |
| $F13\ (\mathbf{3},\mathbf{3},-\frac{1}{3})$ | $HL^2Q^\dagger u_{\mathbb{C}}^\dagger[(S6),(V8)]$ $d_{\mathbb{C}}HLQ^{\dagger2}[(V8),(S12),(V9)]$ |
| $F14\ (\mathbf{3},\mathbf{3},\frac{2}{3})$ | $d_{\mathbb{C}}HL^2Q[(S12),(S6)]$ |

# Complete Dim-7 UV for 0vbb

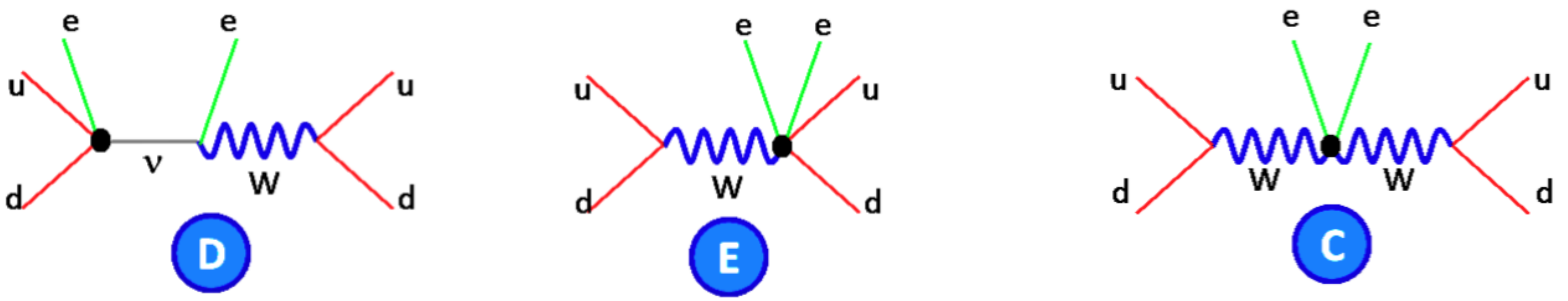
[ Xu-Xiang Li, Zhe Ren, **J.H.Yu,** 2307.10380 ]




| **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)**

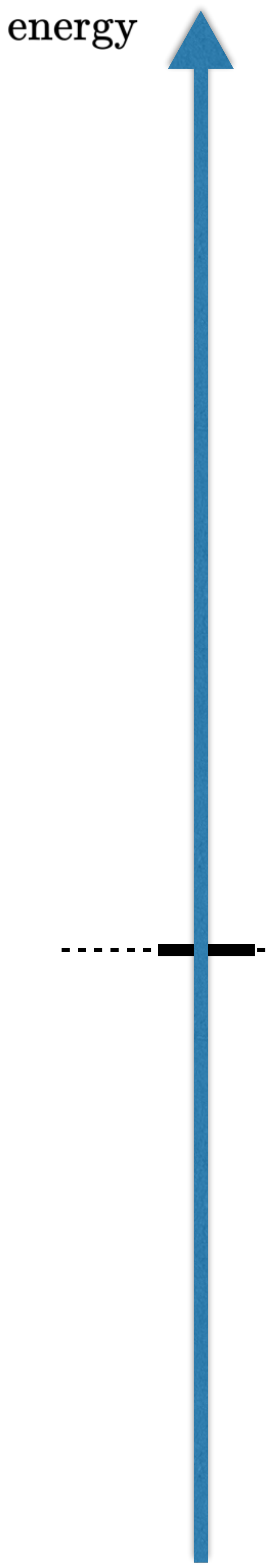


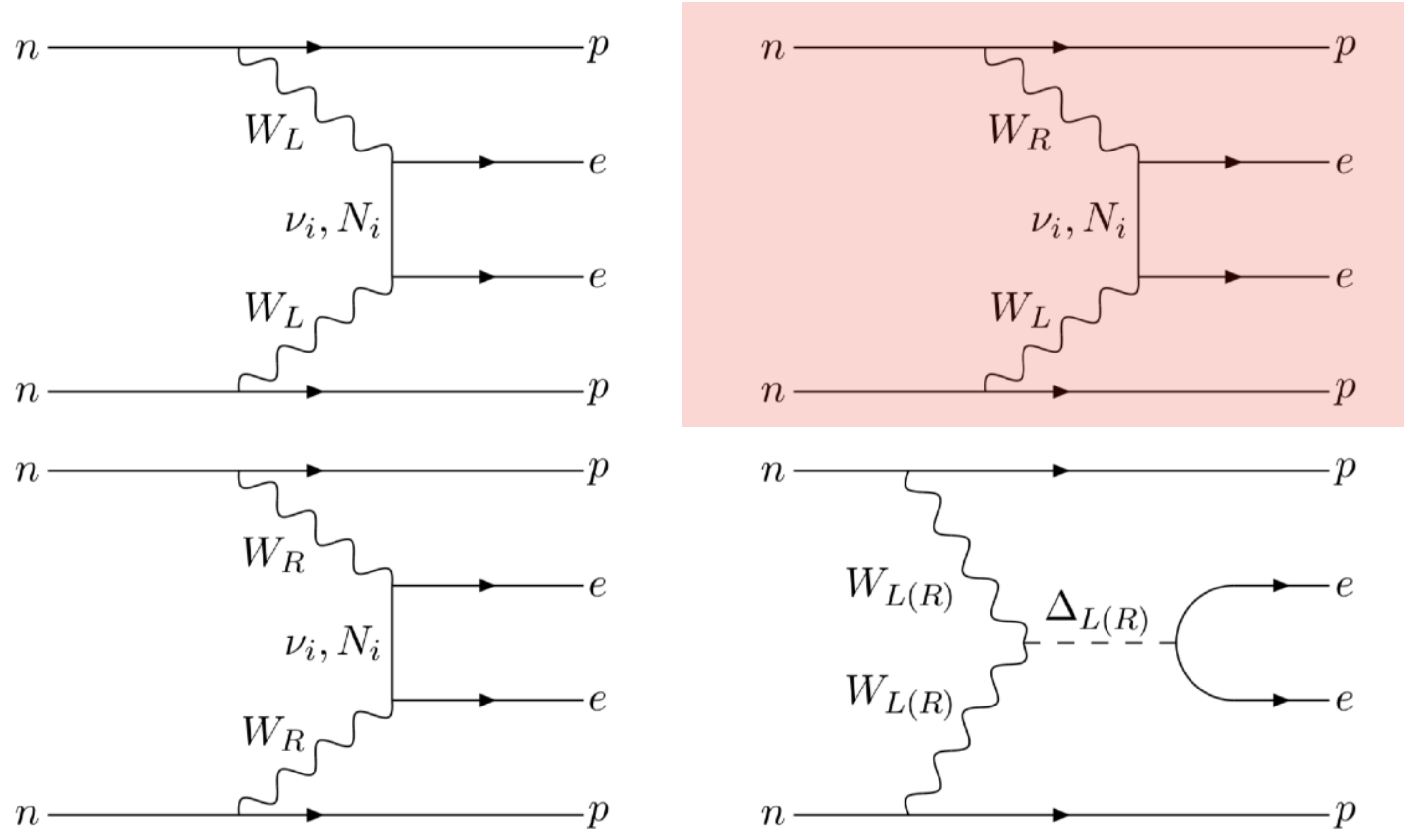



Jiang-Hao Yu (ITP-CAS)

# Complete Dim-7 UV for 0vbb

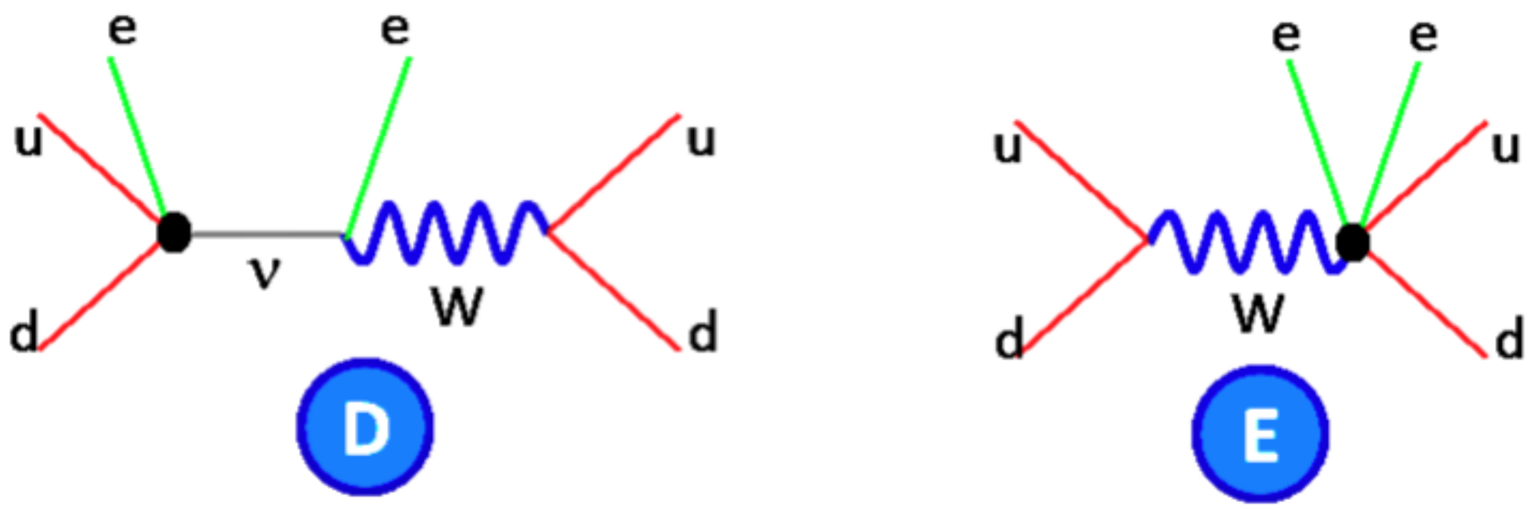
[ Xu-Xiang Li, Zhe Ren, **J.H.Yu,** 2307.10380 ]




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

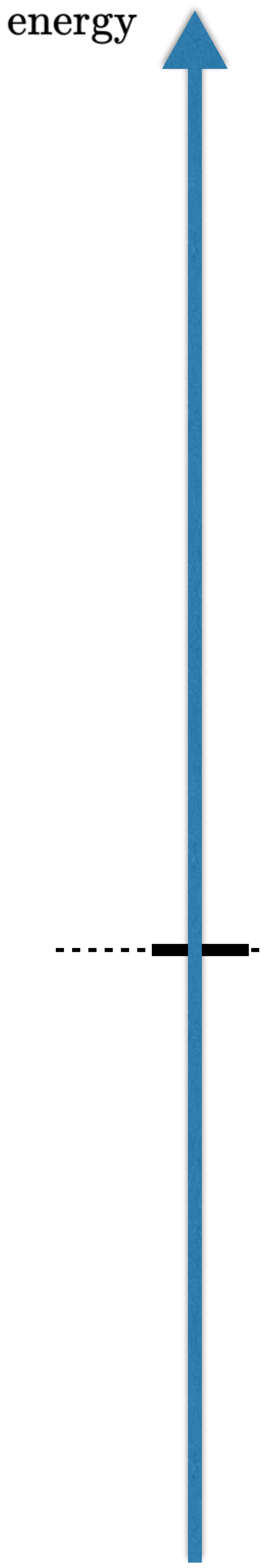
| | $\mathcal{O}_{LeHD}$ | $\mathcal{O}_{eLLLH}$ | $\mathcal{O}_{dLQLH1}$ | $\mathcal{O}_{dLQLH2}$ | $\mathcal{O}_{dLueH}$ | $\mathcal{O}_{QuLLH}$ |
|---|---|---|---|---|---|---|
| $S_2$ | | $S_4/F_1/F_4$ | | $S_4/F_9/F_{10}$ | | $S_4/F_8/F_{12}$ |
| $S_4$ | | $S_2/S_6/F_5$ | $S_6/F_1/F_5$ | $S_2/S_6/F_1/F_5$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

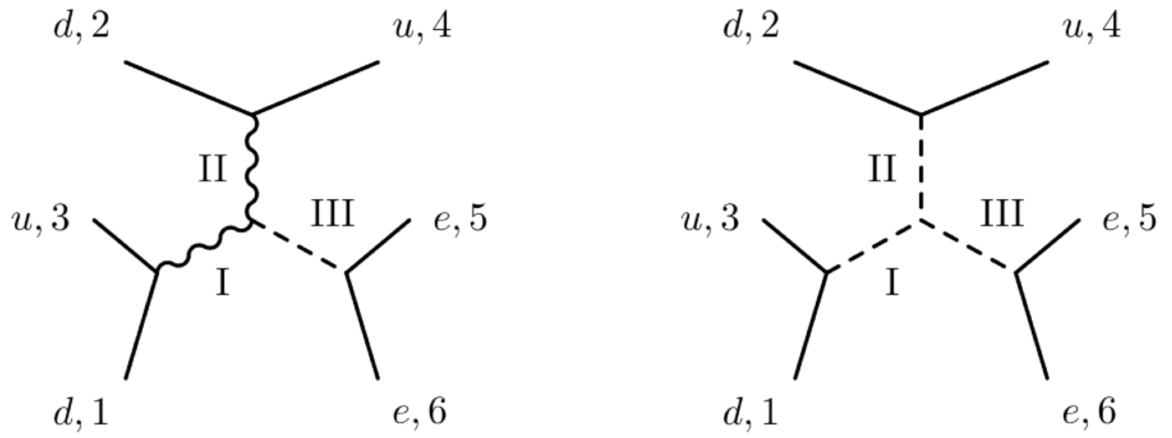


# Complete Dim-9 UV for 0vbb

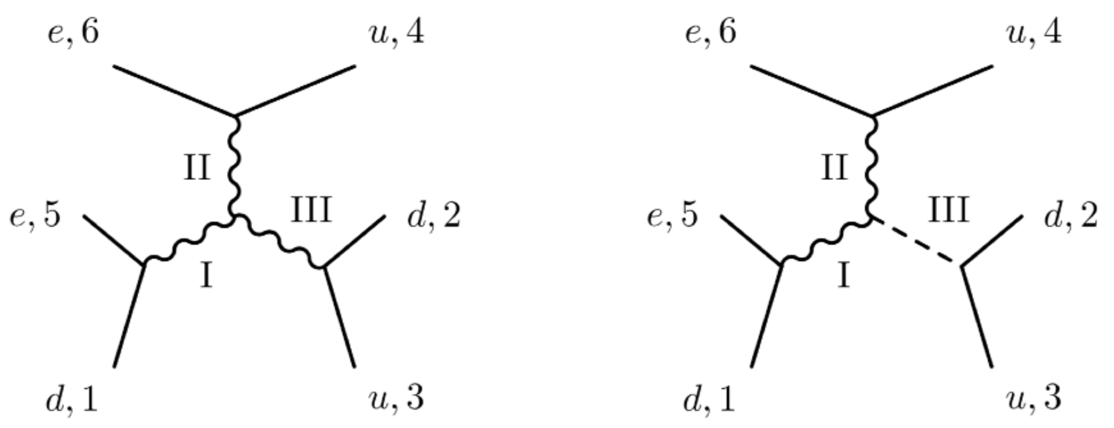
[ Li, Ni, Xiao, **Yu**, in preparation ]

[ Li, **Yu**, Zhao, 2311.15422 ]

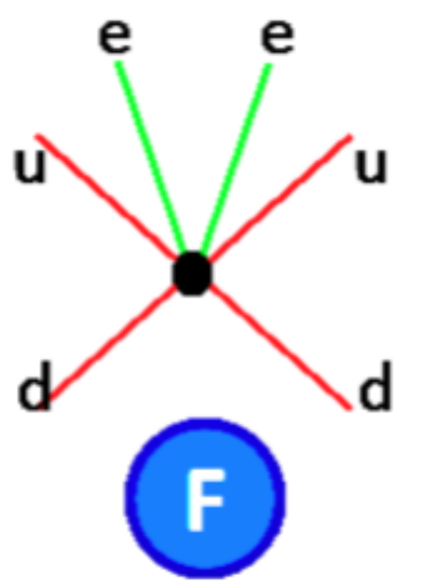



| $(\mathbf{r}_i, J_i)$ | $(1,1,0)$ | $(0,0,0)$ |
|---|---|---|
| $(\mathbf{8}_2, \mathbf{8}_2, \mathbf{1}_3)$ | $\frac{4}{3}\mathcal{O}_1 + 2\mathcal{O}_2$ | $-\frac{2}{3}\mathcal{O}_2$ |
| $(\mathbf{8}_2, \mathbf{8}_2, \mathbf{1}_1)$ | $-2\mathcal{O}_2$ | $\frac{4}{3}\mathcal{O}_1 + \frac{2}{3}\mathcal{O}_2$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




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



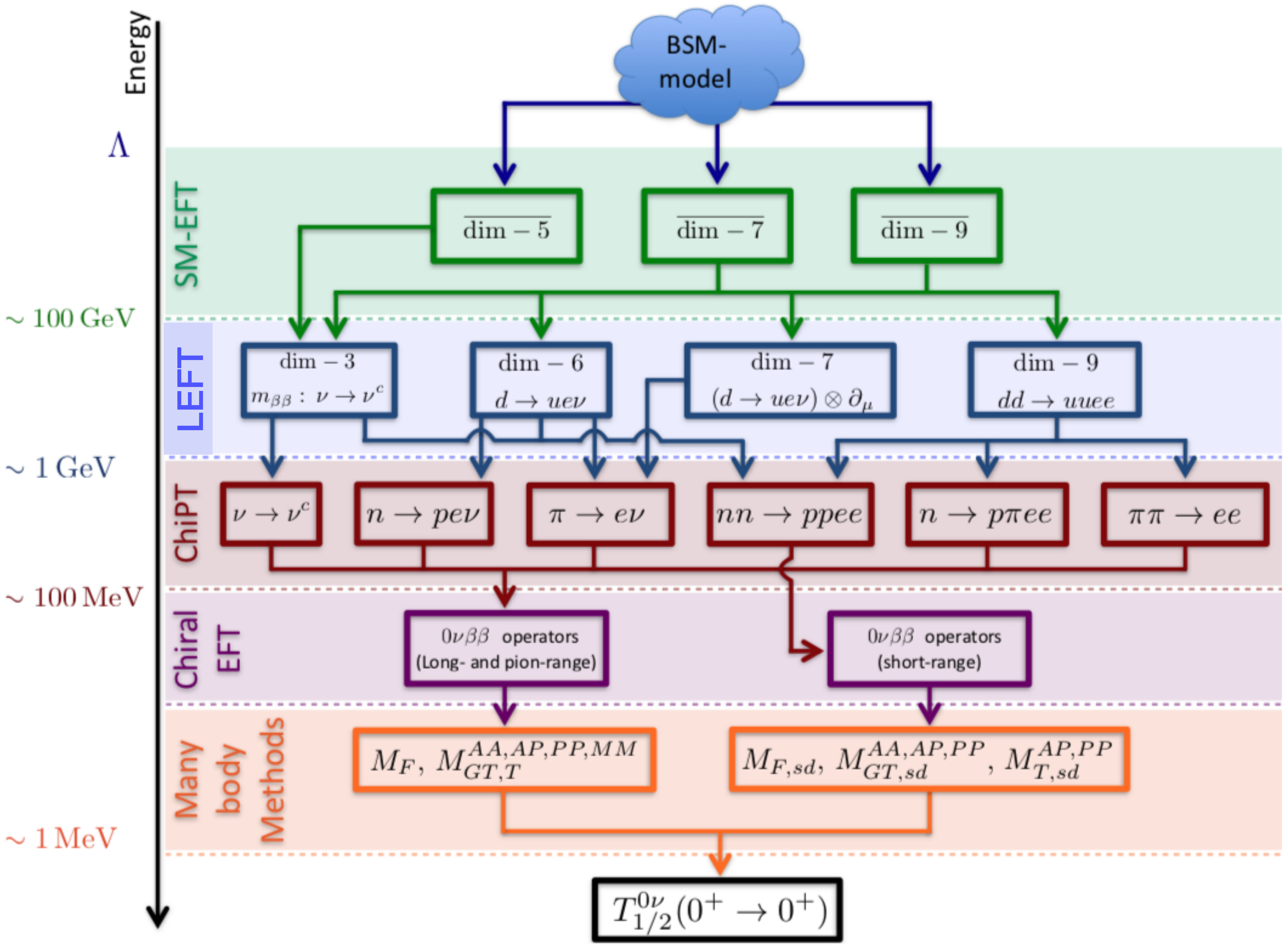

$$\mathcal{O}_1 = \frac{1}{4}(L^{\dagger}{}_u{}^j L^{\dagger}{}_v{}^i)(Q_{pai}Q_{rbj})(u_{cs}{}^b u_{ct}{}^a)$$

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

# Summary

# Summary

Operator bases for different EFTs are necessarily needed to provide most general description




**UV models new particles**

**Repeat for each model**

**Quark level operators**

**Operator correlation**

**How to do matching**

**Hadronic level operators**

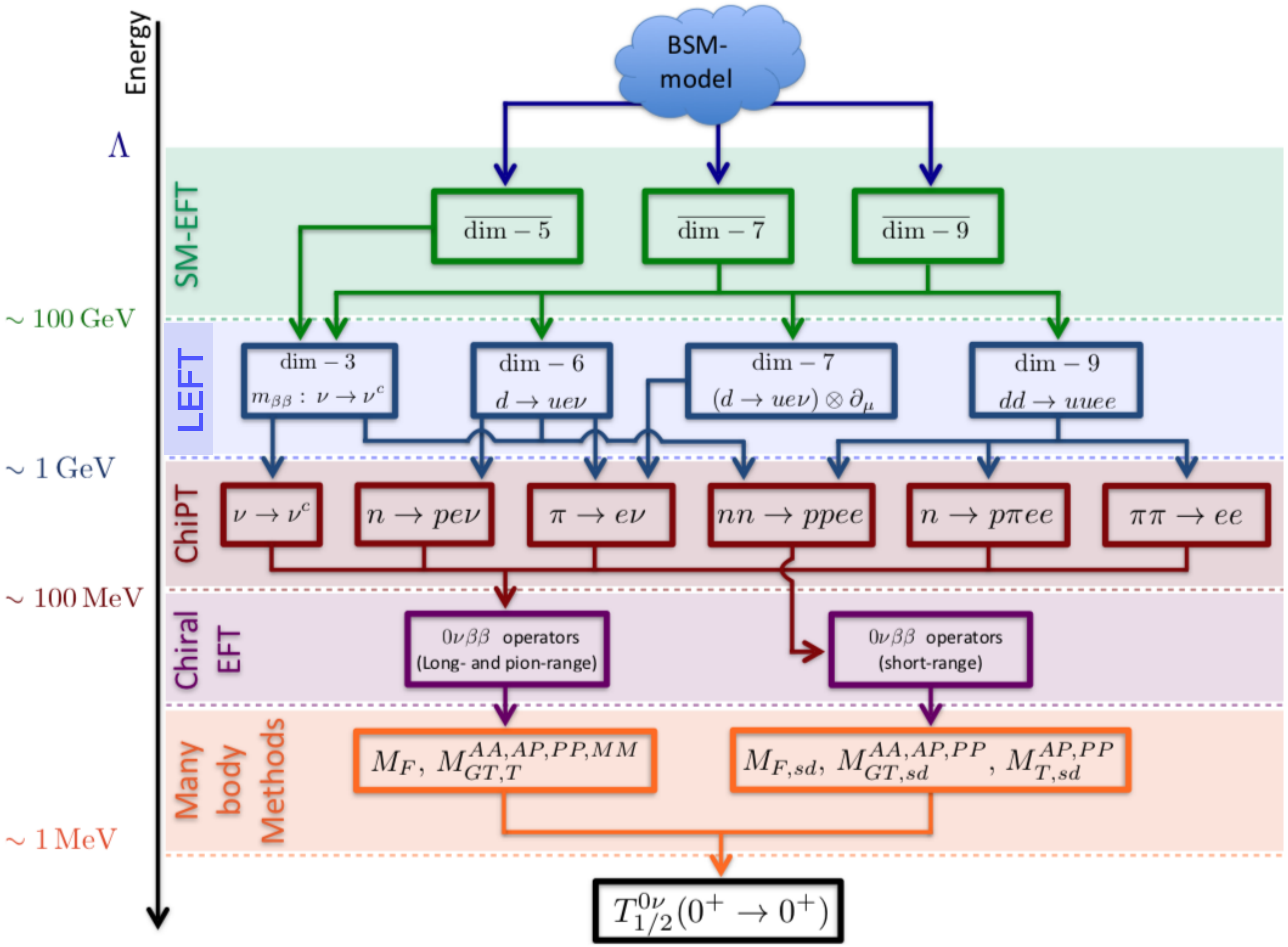
**External source not enough**

**Nuclear level operators**

**Nucleon matrix element incomplete**

# Summary

Operator bases for different EFTs are necessarily needed to provide most general description




**UV models new particles**

↓

**Quark level operators**

↓

**Hadronic level operators**

↓

**Nuclear level operators**

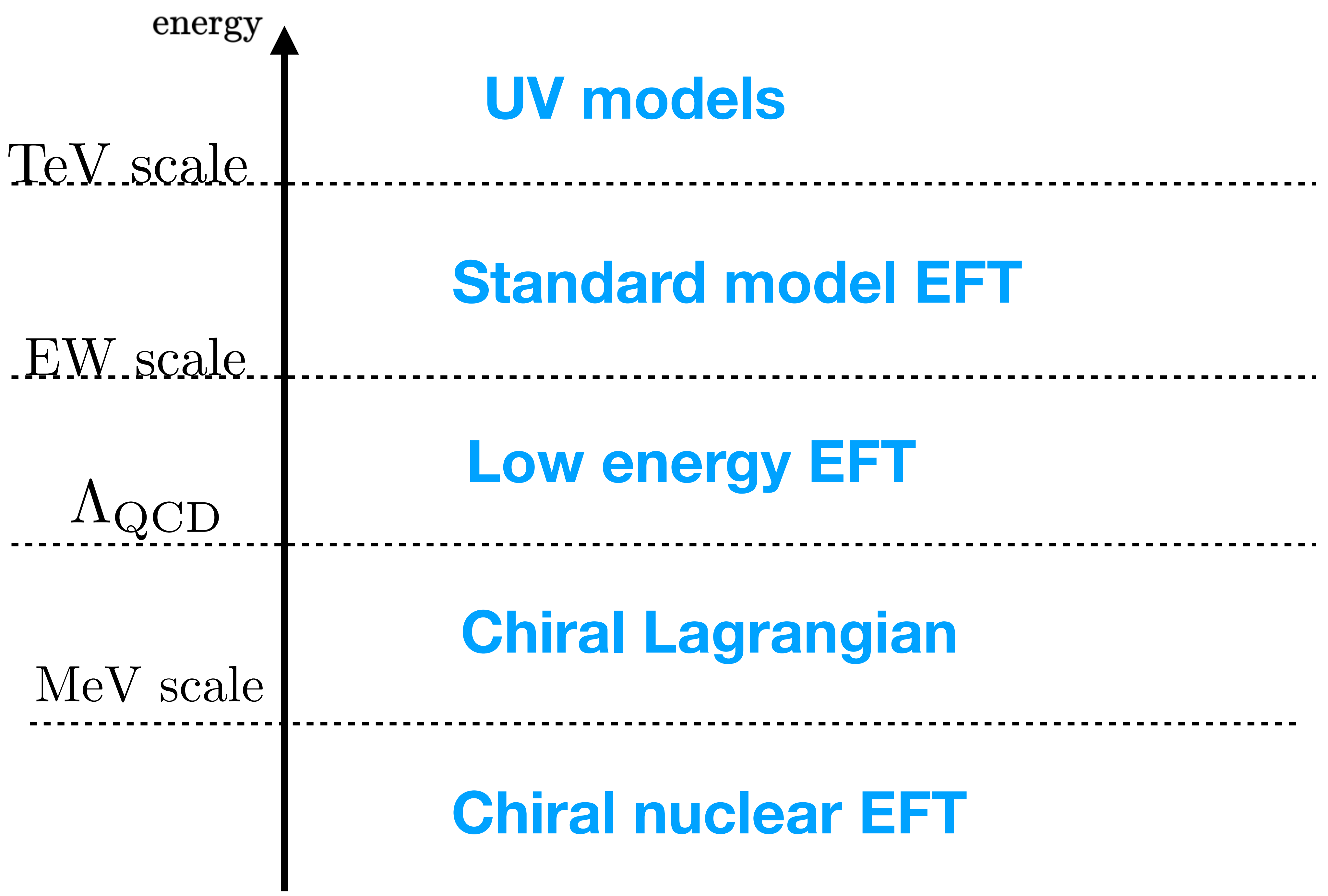
**Setup a general framework**

**Need complete operators at each level**

# 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



Jiang-Hao Yu (ITP-CAS)

# Thanks for your attention!

# Matching: external source vs spurion

$$\mathcal{L} = \mathcal{L}^0_{\rm QCD} + \bar{q}\gamma^\mu[\nu_\mu + \gamma_5 a_\mu]q - \bar{q}[s - i\gamma_5 p]q$$

$$\nu^\mu \to \bar{e}\gamma^\mu e\,, \quad a^\mu \to \bar{e}\gamma^5\gamma^\mu e\,, \quad s \to \bar{e}e\,, \quad p \to \bar{e}\gamma^5 e$$

$\Lambda_{\rm QCD}$

$$\langle u_\mu u^\mu\rangle\langle\Sigma_+\rangle \qquad \langle f_+{}^{\mu\nu}[u_\mu, u_\nu]\rangle \qquad \langle u^\mu[D_\mu f_{+\nu\lambda}, f_-{}^{\nu\lambda}]\rangle \qquad \langle D_\mu f_+{}^{\mu\nu}[u_\nu, \Sigma_-]\rangle$$

[ Gang Li, Chuan-Qiang Song, **J.H.Yu**, 2507.02538 ]

[ Chuan-Qiang Song, Hao Sun, **J.H.Yu**, 2501.09787 ]

**Find same lepton structure, and same T spurion, and matching**

$$(\bar{q}\overleftrightarrow{\partial}^\mu \mathbf{T} q)(\bar{e}_L\gamma_\mu e_L)\,,$$
$$(\bar{q}\overleftrightarrow{\partial}^\mu \mathbf{T} q)(\bar{e}_R\gamma_\mu e_R)\,,$$
$$(\bar{q}\gamma^5\overleftrightarrow{\partial}^\mu \mathbf{T} q)(\bar{e}_L\gamma_\mu e_L)\,,$$
$$(\bar{q}\gamma^5\overleftrightarrow{\partial}^\mu \mathbf{T} q)(\bar{e}_R\gamma_\mu e_R)\,.$$

$$\frac{\Lambda^4_{\rm EW}}{16\pi^2}\left[\frac{\Lambda_\chi}{\Lambda_{\rm EW}}\right]^{N_p+2N_F+\frac{3}{2}N_\psi}\left[\frac{\partial}{\Lambda_\chi}\right]^{N_p}\left[\frac{F}{\Lambda_\chi^2}\right]^{N_F}\left[\frac{\psi}{\sqrt{\Lambda_\chi}f}\right]^{N_\psi}$$

$\Lambda_{\rm QCD}$

$$\left[\frac{\Lambda_\chi}{\Lambda_{\rm EW}}\right]^{\mathcal{D}}\left(f^2\Lambda_\chi^2\left[\frac{\partial}{\Lambda_\chi}\right]^{N_p}\left[\frac{F}{\Lambda_\chi^2}\right]^{N_F}\left[\frac{\psi}{\sqrt{\Lambda_\chi}f}\right]^{N_\psi}\right)$$

$$\langle\Sigma_+[u_\nu, D^\nu u_\mu]\rangle(\bar{e}_L\gamma^\mu e_L)\,, \quad \langle[\Sigma_-, u_\mu]u^\nu u_\nu\rangle(\bar{e}_L\gamma^\mu e_L)$$

$$\langle\bar{B}\gamma^\mu\Sigma_+ B\rangle(\bar{e}_L\gamma_\mu e_L)\,, \quad \langle\bar{B}\gamma^\mu B\Sigma_+\rangle(\bar{e}_L\gamma_\mu e_L)\,, \quad \langle\bar{B}\gamma^\mu B\rangle\langle\Sigma_+\rangle(\bar{e}_L\gamma_\mu e_L)\,.$$

**Reformulate using SU(3) x SU(3)**

$$\bar{q}_L \to \xi^\dagger\,, q_L \to \xi\,, \bar{q}_R \to \xi\,, q_R \to \xi^\dagger\,, \xi = \exp\left(\frac{i\Pi}{\sqrt{2}f}\right)\,,$$
$$\bar{q}_L \to D^\mu\xi^\dagger\,, q_L \to D^\mu\xi\,, \bar{q}_R \to D^\mu\xi\,, q_R \to D^\mu\xi^\dagger\,,$$

# Electroweak processes at nuclear scale

Many body nuclear effects in nuclear physics and particle physics community