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ν Mass & $0\nu\beta\beta$ in EFT Framework

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Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **JHY**, Yu-Hui Zheng, 2007.07899

Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **JHY**, Yu-Hui Zheng, 2012.09188

Hao-Lin Li, Zhe Ren, Ming-Lei Xiao, **JHY**, Yu-Hui Zheng, 2105.09329

Yong Du, Hao-Lin Li, Yu-Han Ni, Ming-Lei Xiao, **JHY**, in preparation

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May 22, 2021

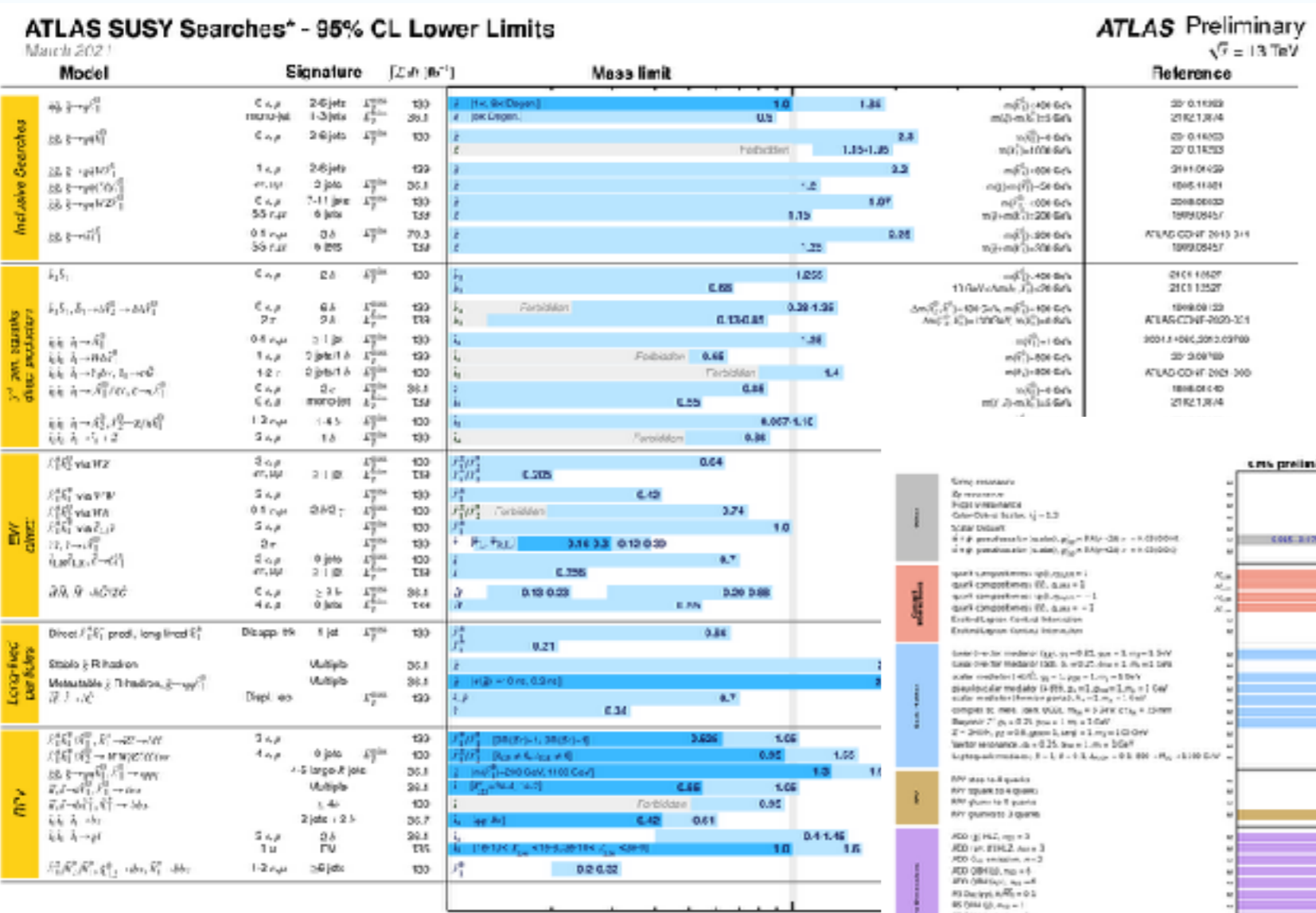
Outline

- Why $0\nu b\bar{b}$ in EFT approach?
- SMEFT: $0\nu b\bar{b}$ and $n\nu$ masses, UV physics
- LEFT: quark currents and weak sources
- ChiPT: short-range, pion-range, long-range
- Summary and outlook

Introduction

Why 0vbb in EFT approach?

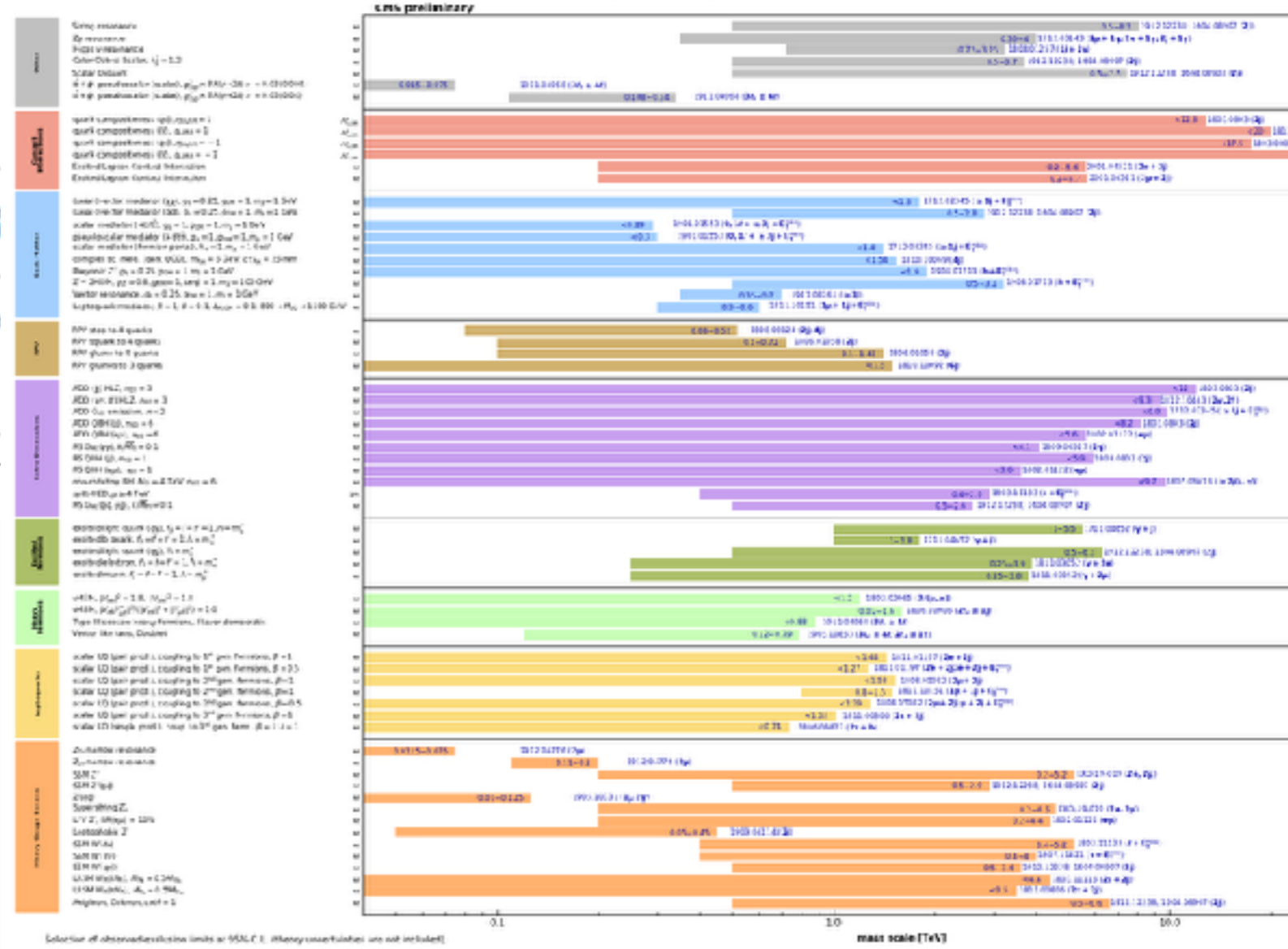
Search For New Physics



*Only a selection of the available mass limits on rows listed or parameters is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

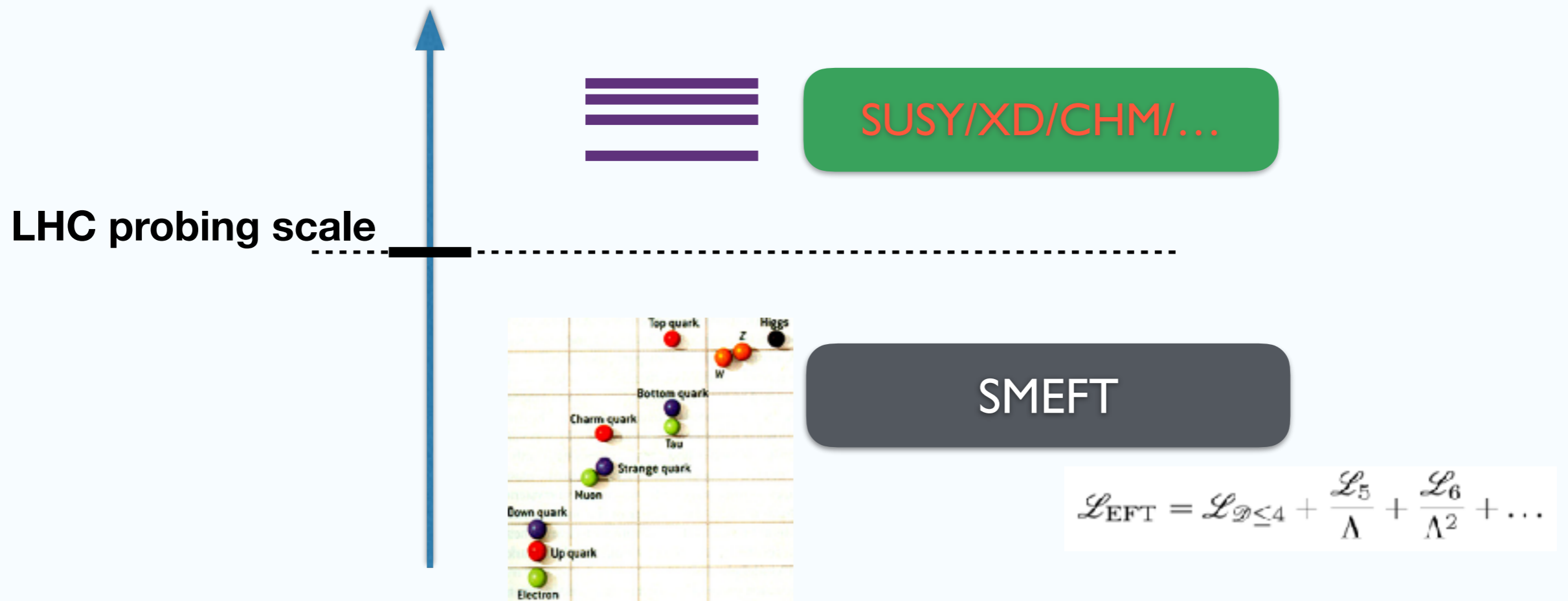


Overview of CMS EXO results



Exclusion of observed/expected limits at 95% CL (Many assumptions are not included)

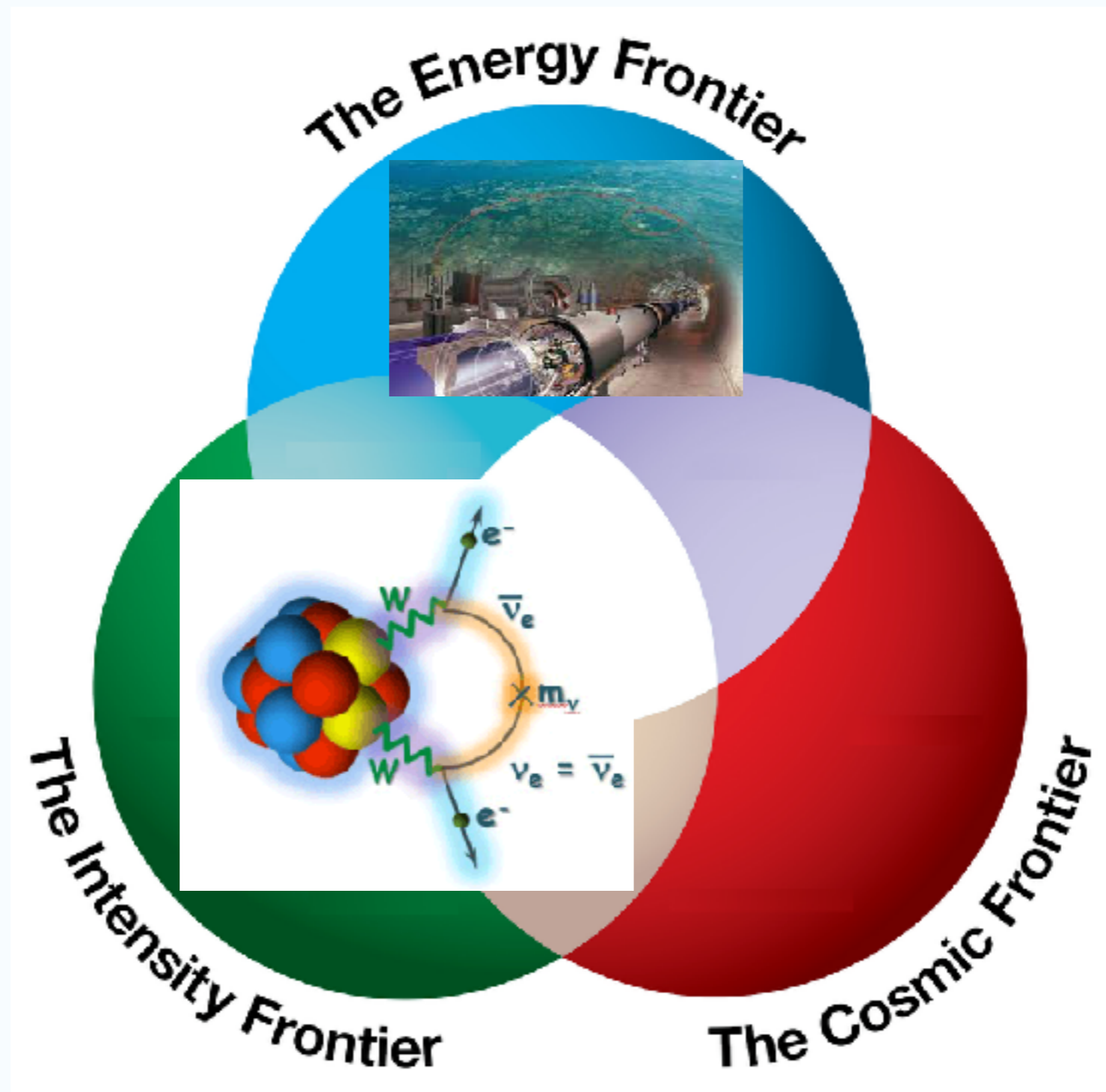
New Physics w/o New Particle



Top-down: Integrate out and matching/running

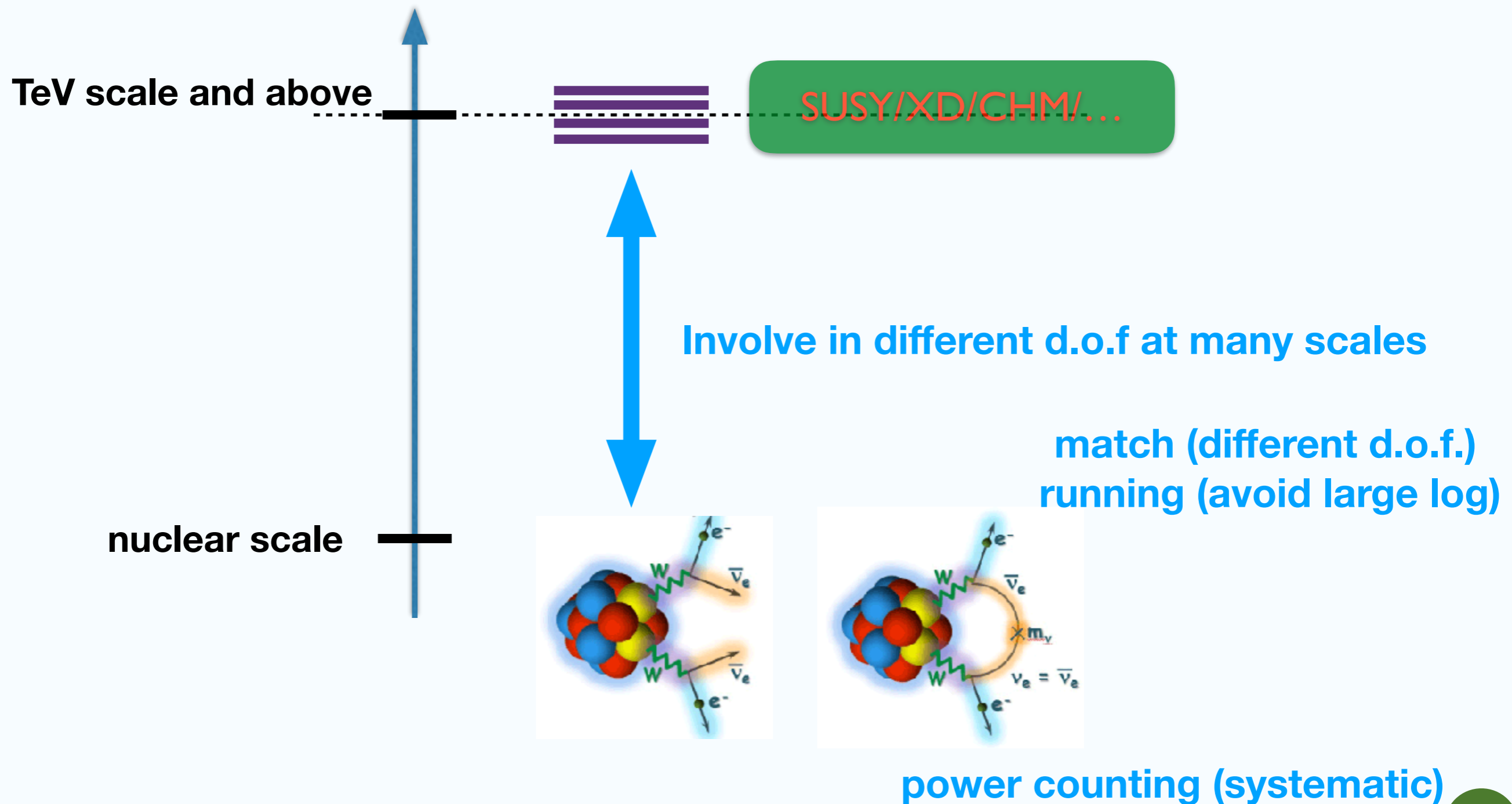
Bottom-up: field d.o.f and symmetry at IR scale

New Physics w/o New Particle



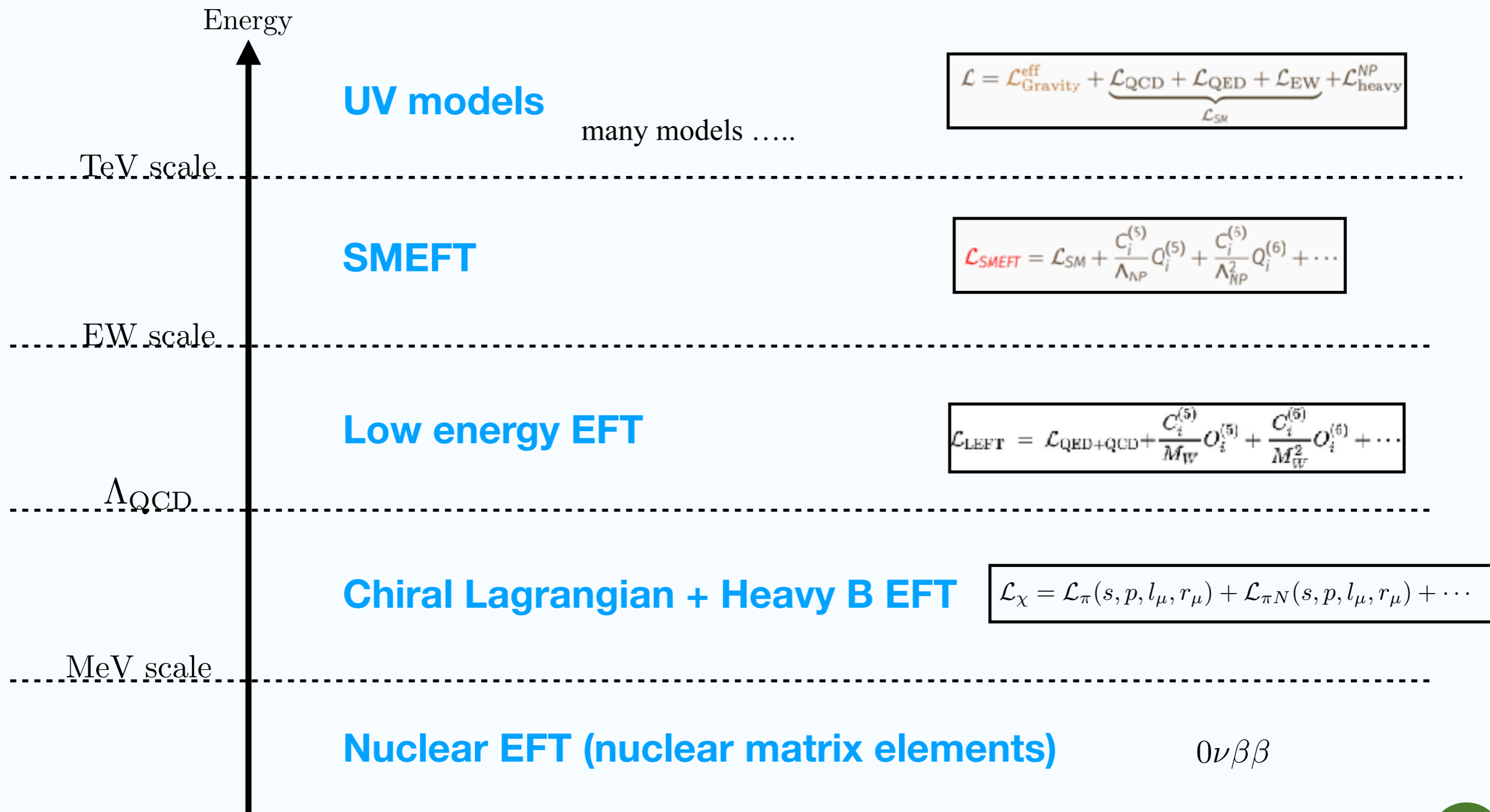
Low Energy Probe of HEP

Low energy probes of high energy physics



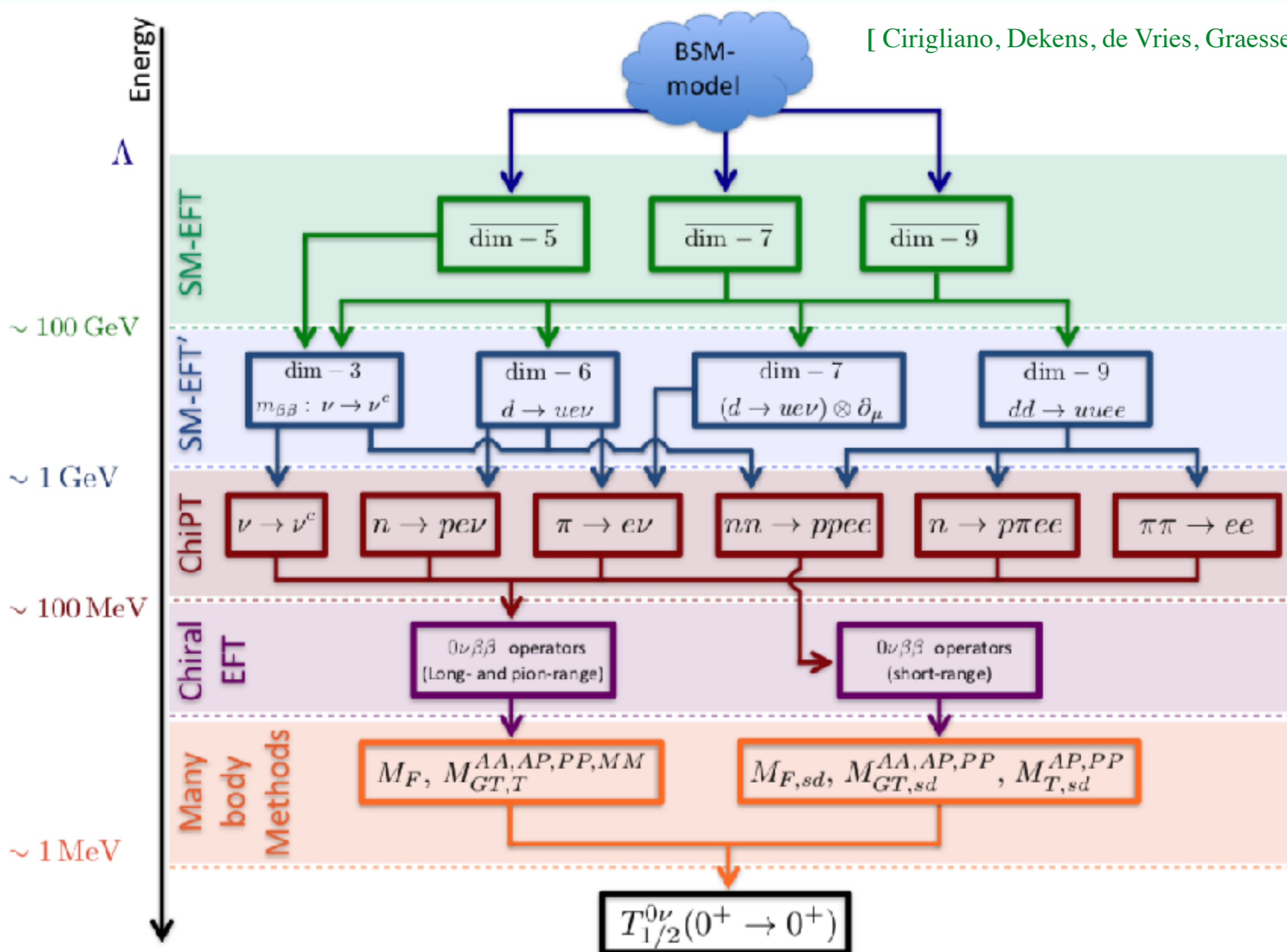
EFT Framework

Model independent systematical parametrization of new physics



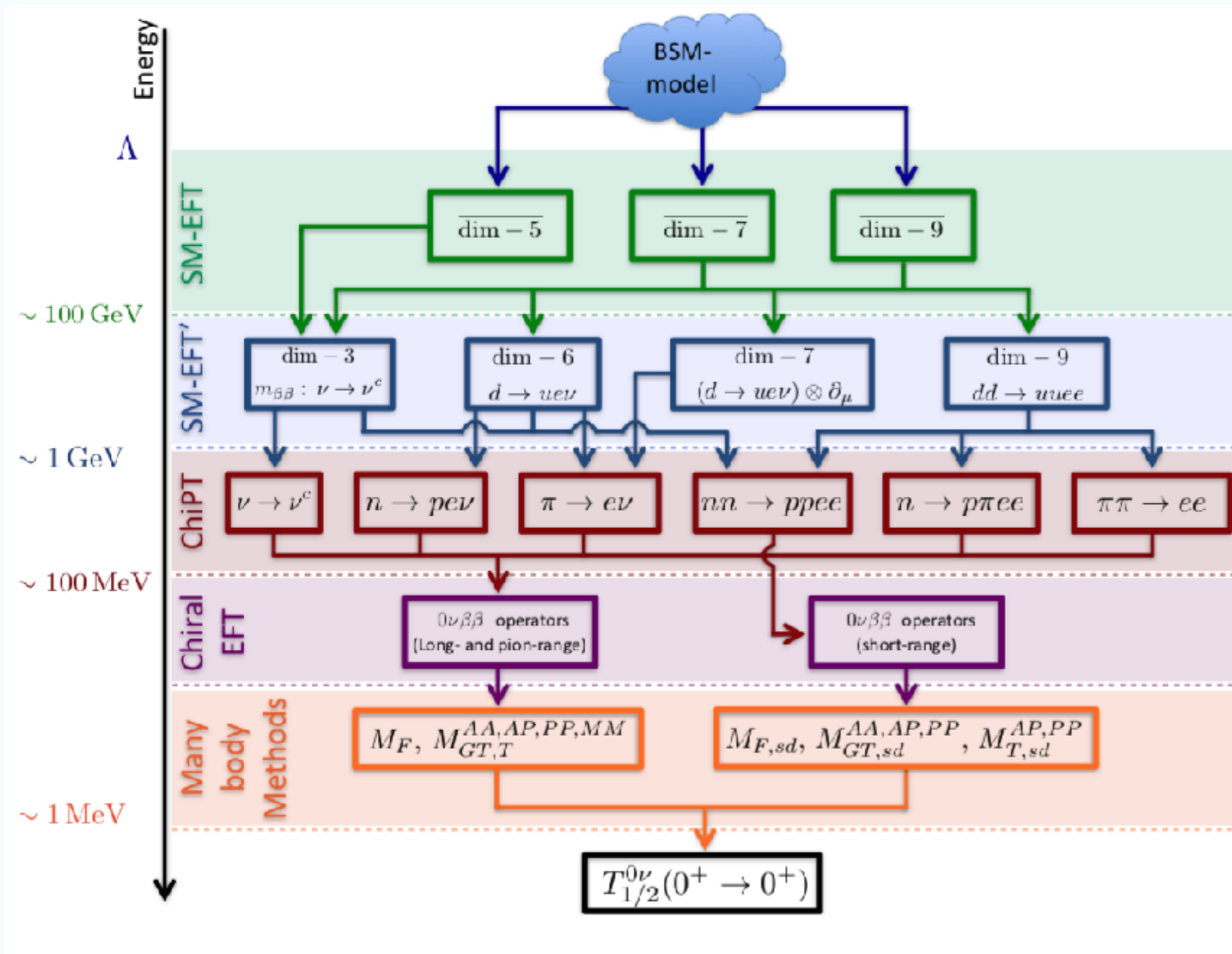
EFT for $0\nu\beta\beta$

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



Why Not Enough?

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



What is in the UV?

Dim-9 SMEFT not known!

Dim-8/9 LEFT?

More PiN ChiPT?

More Chiral EFT?

More nuclear ME?

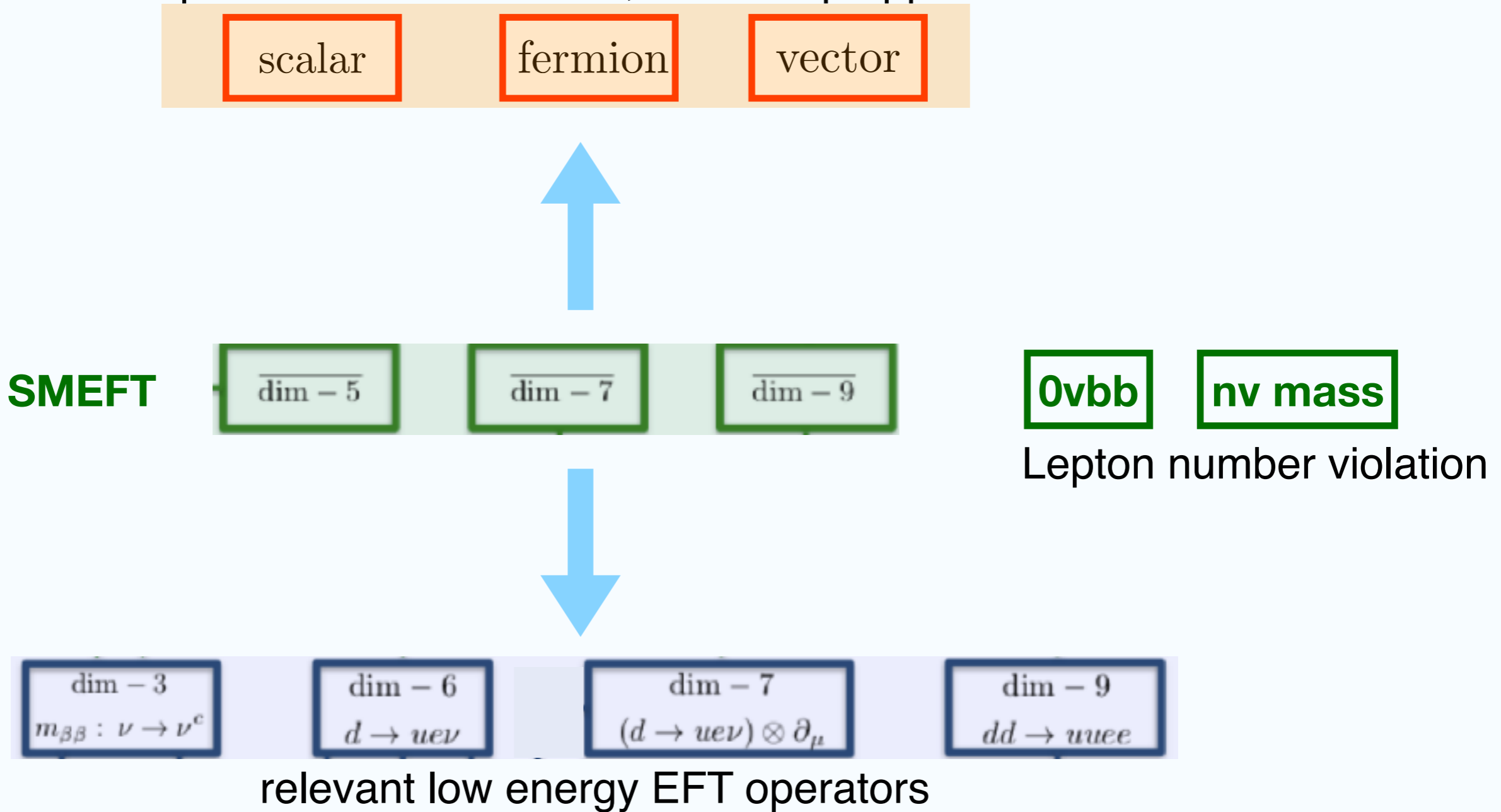
Still top-down: Integrate out and matching/running

SMEFT

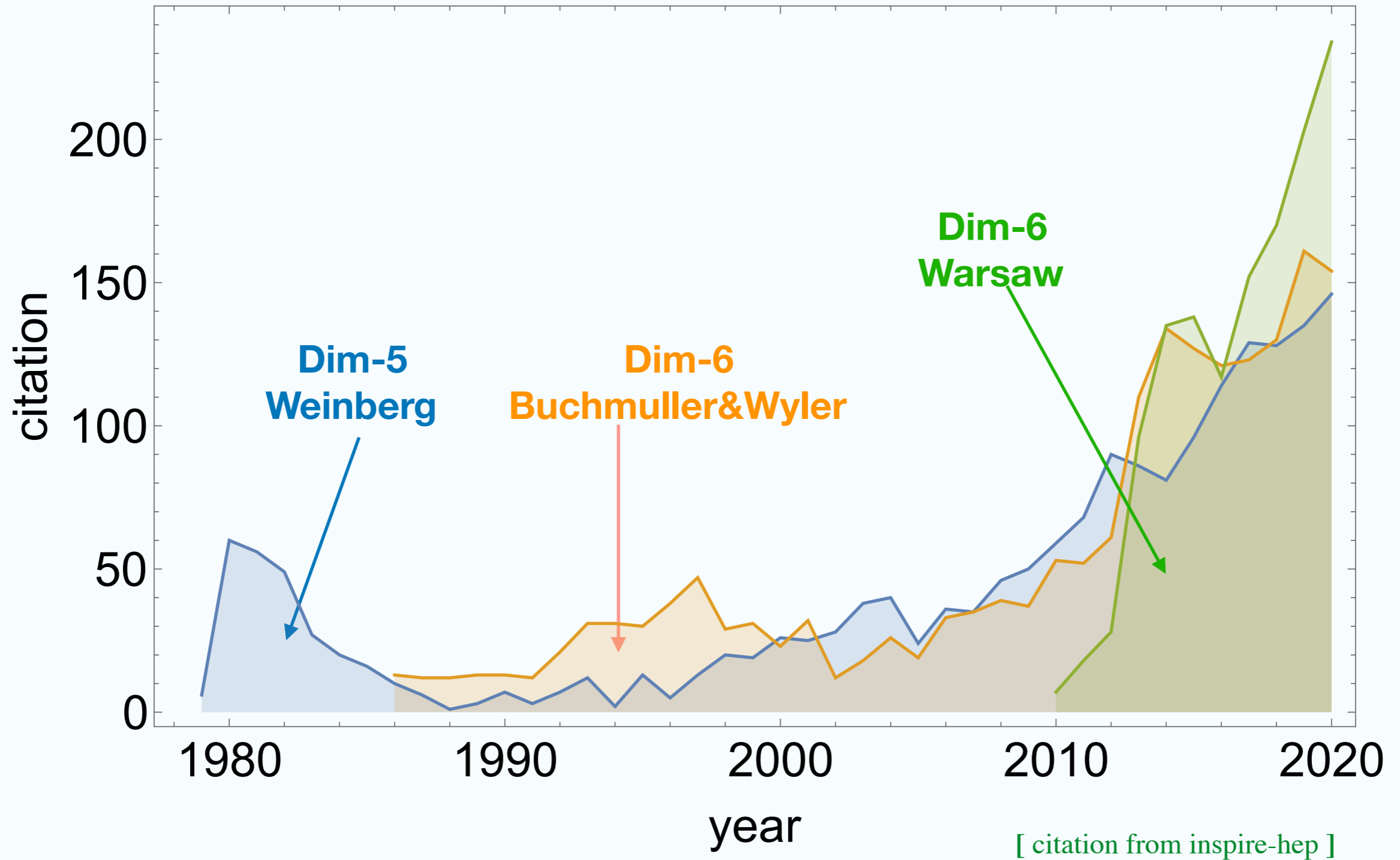
0vbb/nv operators and UV Resonances

SMEFT

Various possible UV realization, bottom-up approach

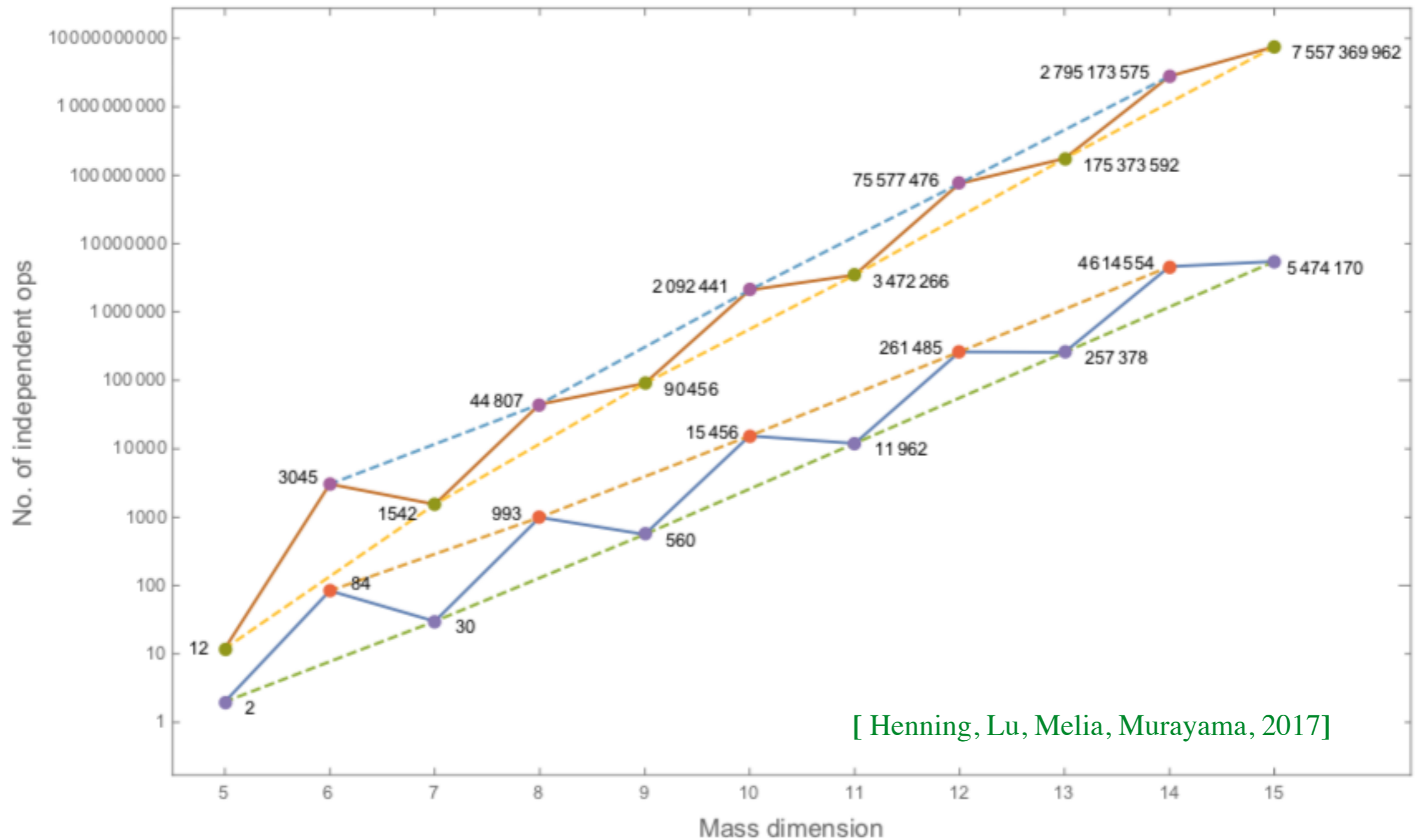


SMEFT Operators



Hilbert Series Counting

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \frac{1}{\Lambda^3} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \frac{1}{\Lambda^5} \mathcal{L}_9 + \dots,$$



[Henning, Lu, Melia, Murayama, 2017]

Higher Dim Operators!?

Given numbers of independent operators

does not mean we know explicit form of operators!

Derivatives

$BW H H^\dagger D^2$

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Repeated fields

$QQQL$

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$$\begin{aligned}
 & (D^2 H^\dagger) H B_{L_{\mu\nu}} W_L^{\mu\nu}, (D^\mu D_\nu H^\dagger) H B_{L_{\mu\nu}} W_L^{\mu\nu}, (D_\nu D^\mu H^\dagger) H B_{L_{\mu\nu}} W_L^{\mu\nu}, (D_\mu H^\dagger) (D^\mu H) B_{L_{\mu\nu}} W_L^{\mu\nu}, \\
 & (D_\mu H^\dagger) (D^\mu H) B_{L_{\mu\nu}} W_L^{\mu\nu}, (D^\nu H^\dagger) (D_\nu H) B_{L_{\mu\nu}} W_L^{\mu\nu}, (D_\mu H^\dagger) H (D^\mu B_{L_{\mu\nu}}) W_L^{\mu\nu}, (D_\mu H^\dagger) H (D^\nu B_{L_{\mu\nu}}) W_L^{\mu\nu}, \\
 & (D^\mu H^\dagger) H (D_\mu B_{L_{\mu\nu}}) W_L^{\mu\nu}, (D_\nu H^\dagger) H B_{L_{\mu\nu}} (D^\mu W_L^{\mu\nu}), (D_\nu H^\dagger) H B_{L_{\mu\nu}} (D^\mu W_L^{\nu\rho}), (D^\mu H^\dagger) H B_{L_{\mu\nu}} (D_\mu W_L^{\nu\rho}), \\
 & H^\dagger (D^2 H) B_{L_{\mu\nu}} W_L^{\mu\nu}, H^\dagger (D^\mu D_\nu H) B_{L_{\mu\nu}} W_L^{\mu\nu}, H^\dagger (D^\mu H) (D_\nu B_{L_{\mu\nu}}) W_L^{\mu\nu}, H^\dagger (D^\mu H) (D_\nu B_{L_{\mu\nu}}) W_L^{\nu\rho}, \\
 & H^\dagger (D^\mu H) (D_\nu B_{L_{\mu\nu}}) W_L^{\nu\rho}, H^\dagger (D_\mu H) (D^\nu B_{L_{\mu\nu}}) W_L^{\mu\nu}, H^\dagger (D^\mu H) B_{L_{\mu\nu}} (D_\mu W_L^{\nu\rho}), H^\dagger (D^\mu H) B_{L_{\mu\nu}} (D_\mu W_L^{\nu\rho}), \\
 & H^\dagger (D_\nu H) B_{L_{\mu\nu}} (D^\mu W_L^{\nu\rho}), H^\dagger H (D^2 B_{L_{\mu\nu}}) W_L^{\mu\nu}, H^\dagger H (D^\mu D_\nu B_{L_{\mu\nu}}) W_L^{\mu\nu}, H^\dagger H (D^\mu D_\nu B_{L_{\mu\nu}}) W_L^{\nu\rho}, \\
 & H^\dagger H (D^\mu B_{L_{\mu\nu}}) (D_\mu W_L^{\nu\rho}), H^\dagger H (D^\nu B_{L_{\mu\nu}}) (D_\mu W_L^{\nu\rho}), H^\dagger H (D_\mu B_{L_{\mu\nu}}) (D^\mu W_L^{\nu\rho}), H^\dagger H B_{L_{\mu\nu}} (D^2 W_L^{\mu\nu}), \\
 & H^\dagger H B_{L_{\mu\nu}} (D^\mu D_\nu W_L^{\mu\nu}), H^\dagger H B_{L_{\mu\nu}} (D_\mu D^\nu W_L^{\mu\nu})
 \end{aligned} \tag{14}$$

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$$Q_{prst}^{qqql} = C^{prst} \begin{aligned}
 & \epsilon^{abc} \epsilon^{ik} \epsilon^{jl} (L_{pi} Q_{raj}) (Q_{sbk} Q_{tcl}) \\
 & \epsilon^{abc} \epsilon^{ik} \epsilon^{jl} (L_{pi} Q_{sbk}) (Q_{raj} Q_{tcl}) \\
 & \epsilon^{abc} \epsilon^{ik} \epsilon^{jl} (L_{pi} Q_{sbk}) (Q_{raj} Q_{tcl}) \\
 & \epsilon^{abc} \epsilon^{ij} \epsilon^{kl} (L_{pi} Q_{raj}) (Q_{sbk} Q_{tcl})
 \end{aligned} \quad p, r, s, t = 1, 2, 3$$

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Which 2 should be picked up?

What flavor relations should be imposed?

Operator as Young Tensor

算符的基元为Lorentz群的不可约表示：取最高权（无需运动方程）

$$H_i \in (0,0) \quad \psi_\alpha \in (1/2,0) \quad F_{L\alpha\beta} = \frac{i}{2} F_{\mu\nu} \sigma_{\alpha\beta}^{\mu\nu} \in (1,0) \quad D_{\alpha\dot{\alpha}} = D_\mu \sigma_{\alpha\dot{\alpha}}^\mu \in (1/2,1/2),$$

$$\partial^2 \phi = (0,0) + (0,1) + (1,0) + (1,1)$$

$$D_{\mu_1} D_{\mu_2} \phi = (D^2 \phi)_{\alpha\beta\dot{\alpha}\dot{\beta}} = \frac{1}{2} \epsilon_{\alpha\beta} \epsilon_{\dot{\alpha}\dot{\beta}} D^\mu D_\mu \phi - \frac{i}{4} \epsilon_{\dot{\alpha}\dot{\beta}} \sigma_{\alpha\beta}^{\mu\nu} [D_\mu, D_\nu] \phi - \frac{i}{4} \epsilon_{\alpha\beta} \bar{\sigma}_{\dot{\alpha}\dot{\beta}}^{\mu\nu} [D_\mu, D_\nu] \phi + \frac{1}{4} (D^2 \phi)_{(\alpha\beta)(\dot{\alpha}\dot{\beta})}$$

$$\partial \psi = \left(1, \frac{1}{2}\right) + \left(0, \frac{1}{2}\right) \quad (D\psi)_{\alpha\beta\dot{\alpha}} = -\frac{1}{2} \epsilon_{\alpha\beta} (D\psi)_{\dot{\alpha}} + \frac{1}{2} (D\psi)_{(\alpha\beta)\dot{\alpha}}$$

$$\partial F_L = \left(\frac{1}{2}, \frac{1}{2}\right) \oplus \left(\frac{3}{2}, \frac{1}{2}\right)$$

$$\begin{array}{|c|} \hline \square \\ \hline \square \\ \hline \end{array} = [1^2]$$

算符在总动量的小群变换下为：U(N)表示（无需动量积分） $\epsilon^{\alpha_i \alpha_j} \rightarrow \sum_{k,l} U_k^i U_l^j \epsilon^{\alpha_k \alpha_l}$

$$\mathcal{M} = (\epsilon^{\alpha_i \alpha_j})^{\otimes n} (\tilde{\epsilon}_{\alpha_i \alpha_j})^{\otimes \tilde{n}} \prod_{i=1}^N (D^{r_i - |h_i|} \Phi_i)_{\alpha_i}^{\alpha_i r_i + h_i} = \begin{array}{c} [\tilde{n}^{N-2}] \\ \underbrace{\left\{ \begin{array}{c} \square \cdots \square \\ \square \cdots \square \\ \vdots \\ \square \cdots \square \end{array} \right\}}_{\tilde{n}} \otimes \underbrace{\left\{ \begin{array}{c} \square \cdots \square \\ \square \cdots \square \end{array} \right\}}_n = \begin{array}{c} \underbrace{\left\{ \begin{array}{c} \square \cdots \square \cdots \square \\ \square \cdots \square \cdots \square \\ \vdots \\ \square \cdots \square \end{array} \right\}}_{\tilde{n}} + \dots \end{array}$$

SSYT

Operator Construction

Li, Ren, Shu, Xiao, **JHYu**, Zheng, arXiv: 2005.00008

Li, Ren, Xiao, **JHYu**, Zheng, arXiv: 2007.07899

$BW H H^\dagger D^2$

($D^2 H^\dagger$) $H B_{L\alpha\beta} W_L^{\alpha\beta}$, ($D^\alpha D_\alpha H^\dagger$) $H B_{L\alpha\beta} W_L^{\alpha\beta}$, ($D_\alpha D^\alpha H^\dagger$) $H B_{L\alpha\beta} W_L^{\alpha\beta}$, ($D_\alpha H^\dagger$)($D^\alpha H$) $B_{L\alpha\beta} W_L^{\alpha\beta}$,
 ($D_\alpha H^\dagger$)($D^\alpha H$) $B_{L\alpha\beta} W_L^{\alpha\beta}$, ($D^\alpha H^\dagger$)($D_\alpha H$) $B_{L\alpha\beta} W_L^{\alpha\beta}$, ($D^\alpha H^\dagger$) H ($D^\alpha B_{L\alpha\beta}$) $W_L^{\alpha\beta}$, ($D^\alpha H^\dagger$) H ($D^\alpha B_{L\alpha\beta}$) $W_L^{\alpha\beta}$,
 ($D^\alpha H^\dagger$) H ($D_\alpha B_{L\alpha\beta}$) $W_L^{\alpha\beta}$, ($D^\alpha H^\dagger$) $H B_{L\alpha\beta}$ ($D^\alpha W_L^{\alpha\beta}$), ($D^\alpha H^\dagger$) $H B_{L\alpha\beta}$ ($D^\alpha W_L^{\alpha\beta}$), ($D^\alpha H^\dagger$) $H B_{L\alpha\beta}$ ($D_\alpha W_L^{\alpha\beta}$),
 H^\dagger ($D^2 H$) $B_{L\alpha\beta} W_L^{\alpha\beta}$, H^\dagger ($D^\alpha D_\alpha H$) $B_{L\alpha\beta} W_L^{\alpha\beta}$, H^\dagger ($D_\alpha D^\alpha H$) $B_{L\alpha\beta} W_L^{\alpha\beta}$, H^\dagger ($D^\alpha H$)($D_\alpha B_{L\alpha\beta}$) $W_L^{\alpha\beta}$,
 H^\dagger ($D^\alpha H$)($D_\alpha B_{L\alpha\beta}$) $W_L^{\alpha\beta}$, H^\dagger ($D_\alpha H$)($D^\alpha B_{L\alpha\beta}$) $W_L^{\alpha\beta}$, H^\dagger ($D^\alpha H$) $B_{L\alpha\beta}$ ($D_\alpha W_L^{\alpha\beta}$), H^\dagger ($D^\alpha H$) $B_{L\alpha\beta}$ ($D_\alpha W_L^{\alpha\beta}$),
 H^\dagger ($D_\alpha H$) $B_{L\alpha\beta}$ ($D^\alpha W_L^{\alpha\beta}$), H^\dagger ($D_\alpha H$) $B_{L\alpha\beta}$ ($D^\alpha W_L^{\alpha\beta}$), H^\dagger ($D_\alpha H$) $B_{L\alpha\beta}$ ($D_\alpha W_L^{\alpha\beta}$), H^\dagger ($D_\alpha H$) $B_{L\alpha\beta}$ ($D_\alpha W_L^{\alpha\beta}$),
 $H^\dagger H$ ($D^\alpha B_{L\alpha\beta}$)($D_\alpha W_L^{\alpha\beta}$), $H^\dagger H$ ($D^\alpha B_{L\alpha\beta}$)($D_\alpha W_L^{\alpha\beta}$), $H^\dagger H$ ($D_\alpha B_{L\alpha\beta}$)($D^\alpha W_L^{\alpha\beta}$), $H^\dagger H$ ($D_\alpha B_{L\alpha\beta}$)($D^\alpha W_L^{\alpha\beta}$),
 $H^\dagger H B_{L\alpha\beta}$ ($D^\alpha D_\alpha W_L^{\alpha\beta}$), $H^\dagger H B_{L\alpha\beta}$ ($D_\alpha D^\alpha W_L^{\alpha\beta}$) (14)

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highest weight representation

$$(D^{r-|h|}\Phi)_{\alpha_1 \dots \alpha_{r-h}} \in \left(\frac{r-h}{2}, \frac{r+h}{2} \right)$$

(DH^\dagger) $_{\alpha\beta}$ (DH) $_{\beta\delta}$ $B_{L\alpha\gamma}$ $W_L(\zeta) e^{i\alpha_1 \tau} e^{i\alpha_2 \tau} e^{i\alpha_3 \tau}$
 (DH^\dagger) $_{\alpha\beta}$ (DH) $_{\beta\delta}$ $B_{L\alpha\gamma}$ $W_L(\zeta) \frac{1}{2} e^{i\alpha_1 \tau} e^{i\alpha_2 \tau} (e^{i\alpha_3 \tau} \tau + e^{i\alpha_3 \tau} \tau^\dagger)$
 (DH^\dagger) $_{\alpha\beta}$ H ($D B_{L\alpha\gamma}$) $_{\beta\delta}$ $W_L(\zeta) e^{i\alpha_1 \tau} e^{i\alpha_2 \tau} e^{i\alpha_3 \tau}$
 (DH^\dagger) $_{\alpha\beta}$ H $B_{L\alpha\gamma}$ ($D W_{L\delta}$) $_{\beta\delta}$ $W_L(\zeta) e^{i\alpha_1 \tau} e^{i\alpha_2 \tau} e^{i\alpha_3 \tau}$
 H^\dagger (DH) $_{\alpha\beta}$ ($D B_{L\alpha\gamma}$) $_{\beta\delta}$ $W_L(\zeta) e^{i\alpha_1 \tau} e^{i\alpha_2 \tau} e^{i\alpha_3 \tau}$
 H^\dagger (DH) $_{\alpha\beta}$ $B_{L\alpha\gamma}$ ($D W_{L\delta}$) $_{\beta\delta}$ $W_L(\zeta) e^{i\alpha_1 \tau} e^{i\alpha_2 \tau} e^{i\alpha_3 \tau}$
 $H^\dagger H$ ($D B_{L\alpha\gamma}$) $_{\beta\delta}$ ($D W_{L\delta}$) $_{\beta\delta}$ $W_L(\zeta) e^{i\alpha_1 \tau} e^{i\alpha_2 \tau} e^{i\alpha_3 \tau}$

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$$\mathcal{M} = (e^{\alpha_i \alpha_j})^{\otimes n} (\tilde{z}_{\alpha_i \alpha_j})^{\otimes \tilde{n}} \prod_{i=1}^N (D^{r_i - |h_i|} \Phi_i)_{\alpha_i}^{\alpha_i^{r_i+h_i}} \in [\mathcal{M}]_{N, n, \tilde{n}} = [\mathcal{A}]_{N, n, \tilde{n}} \oplus [\mathcal{B}]_{N, n, \tilde{n}}$$

1	1	1	3
2	2	2	4

1	1	1	2
2	2	3	4

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

2

$$\begin{bmatrix} i & j \end{bmatrix} \times \begin{bmatrix} k \end{bmatrix} \times \begin{bmatrix} l \end{bmatrix} = \begin{bmatrix} i & j \\ k & l \end{bmatrix}$$

$$e^{ik} e^{jl} B_L^{\alpha\beta} W_{L\alpha\beta ij} (DH^\dagger)_{\dot{\alpha}k}^\gamma (DH)_{\gamma}^{\dot{\alpha}l}, \quad e^{ik} e^{jl} B_L^{\alpha\beta} W_{L\alpha\gamma ij} (DH^\dagger)_{\beta\dot{\alpha}k} (DH)_{\gamma}^{\dot{\alpha}l}$$

SMEFT

Dimension-5

$$\epsilon_{ij} \epsilon_{mn} (L^i C L^m) H^j H^n$$

[Weinberg, 1979]

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Dimension-6

$\psi^2 \text{ and } \psi^2 D^2$	$\psi^2 \psi'$	X^2
$O_{\psi 3} = (H^\dagger \psi^i \psi^j)$	$O_{\psi 1} = (H^\dagger \psi^i \psi^j \bar{L}_k)$	$O_{\psi 6} = -\bar{\psi}^i \psi^j \psi^k \psi^l \psi^m \psi^n$
$O_{\psi 21} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 2} = (H^\dagger \psi^i \psi^j \bar{L}_k \psi^l)$	$O_{\psi 7} = -\bar{\psi}^i \psi^j \psi^k \psi^l \psi^m \psi^n \psi^o$
$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 3} = (H^\dagger \psi^i \psi^j \bar{L}_k \psi^l)$	$O_{\psi 8} = -\bar{\psi}^i \psi^j \psi^k \psi^l \psi^m \psi^n \psi^o$

$X^2 \psi^2$	$\psi^2 X^2$	$d(L \psi d)$	$d(\psi d)$	$d(L \psi d)$
$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$
$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$

$d(L \psi d)$ and $d(\psi d)$	B -invariant
$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$
$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$	$O_{\psi 22} = (H^\dagger \psi^i \psi^j \psi^k \psi^l)$

[Buchmuller, Wyler, 1986]

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

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[Murphy, 2020]

Dimension-7

1 : $\psi^2 X H^2 + \text{h.c.}$		2 : $\psi^2 H^4 + \text{h.c.}$	
$Q_{\psi W}$	$\epsilon_{mn} (T^a)_{jk} (L_m^i C \sigma^{\mu\nu} \bar{L}_l^j) H^k H^a W_{\mu\nu}^i$	$Q_{\psi H}$	$\epsilon_{mn} \epsilon_{kl} (L_m^i C \bar{L}_j) H^k H^l (H^a H^a)$
$\bar{Q}_{\psi W}$	$\epsilon_{mn} \epsilon_{kl} (L_m^i C \sigma^{\mu\nu} \bar{L}_l^j) H^k H^a W_{\mu\nu}^i$	$\bar{Q}_{\psi H}$	$\epsilon_{mn} \epsilon_{kl} (L_m^i C \bar{L}_j) H^k H^l (H^a H^a)$

3(B) : $\psi^4 H + \text{h.c.}$		3(B) : $\psi^4 H + \text{h.c.}$	
$Q_{\psi H}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j) (L_n^k C \bar{L}_l^m) H^i$	$Q_{\psi H}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j) (\psi^k C \bar{L}_l^m) H^i$
$\bar{Q}_{\psi H}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j) (L_n^k C \bar{L}_l^m) H^i$	$\bar{Q}_{\psi H}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j) (\psi^k C \bar{L}_l^m) H^i$

4 : $\psi^2 H^2 D + \text{h.c.}$		5(B) : $\psi^4 D + \text{h.c.}$	
$Q_{\psi W}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j C \gamma^\mu \psi^k) H^l D_\mu H^a$	$Q_{\psi H}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j \psi^k) (L_n^l C D_\mu \bar{L}_m)$
$\bar{Q}_{\psi W}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j C \gamma^\mu \psi^k) H^l D_\mu H^a$	$\bar{Q}_{\psi H}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j \psi^k) (L_n^l C D_\mu \bar{L}_m)$

6 : $\psi^2 H^2 D^2 + \text{h.c.}$		5(B) : $\psi^4 D + \text{h.c.}$	
$Q_{\psi W}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j C D^\mu \psi^k) H^l (D_\mu H^a)$	$Q_{\psi H}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j \psi^k) (L_n^l C D_\mu \bar{L}_m)$
$\bar{Q}_{\psi W}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j C D^\mu \psi^k) H^l (D_\mu H^a)$	$\bar{Q}_{\psi H}$	$\epsilon_{mnl} (\bar{L}_m^i \psi^j \psi^k) (L_n^l C D_\mu \bar{L}_m)$

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[Lehman, 2014]
[Liao, Ma, 2018]

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Dimension-8

[Li, Ren, Shu, Xiao, Yu, Zheng, 2020]

N (n, d)	Subclasses	N_{typ}	N_{non}	N_{total}	Equations
4 (2, 2)	$\psi^4 + \text{h.c.}$	15	20	35	(5.10)
	$\psi^2 \psi^2 + \text{h.c.}$	22	22	44	(5.20)
	$\psi^2 \psi^2 D + \text{h.c.}$	10	12	22	(5.30)
5 (3, 1)	$\psi^4 + \text{h.c.}$	18	17	35	(5.40)
	$\psi^2 \psi^2 + \text{h.c.}$	27	30	57	(5.50)
	$\psi^2 \psi^2 D + \text{h.c.}$	17	18	35	(5.60)
	$\psi^2 \psi^2 D^2 + \text{h.c.}$	10	10	20	(5.70)
	$\psi^2 \psi^2 D^3 + \text{h.c.}$	5	6	11	(5.80)
	$\psi^2 \psi^2 D^4 + \text{h.c.}$	2	3	5	(5.90)
	$\psi^2 \psi^2 D^5 + \text{h.c.}$	1	1	2	(5.10)
6 (3, 0)	$\psi^4 + \text{h.c.}$	12	13	25	(6.10)
	$\psi^2 \psi^2 + \text{h.c.}$	32	33	65	(6.20)
	$\psi^2 \psi^2 D + \text{h.c.}$	6	6	12	(6.30)
	$\psi^2 \psi^2 D^2 + \text{h.c.}$	10	11	21	(6.40)
	$\psi^2 \psi^2 D^3 + \text{h.c.}$	5	6	11	(6.50)
	$\psi^2 \psi^2 D^4 + \text{h.c.}$	2	3	5	(6.60)
7 (2, 1)	$\psi^4 + \text{h.c.}$	14	15	29	(7.10)
	$\psi^2 \psi^2 + \text{h.c.}$	32	33	65	(7.20)
	$\psi^2 \psi^2 D + \text{h.c.}$	10	11	21	(7.30)
	$\psi^2 \psi^2 D^2 + \text{h.c.}$	5	6	11	(7.40)
	$\psi^2 \psi^2 D^3 + \text{h.c.}$	2	3	5	(7.50)
8 (2, 0)	$\psi^4 + \text{h.c.}$	12	13	25	(8.10)
	$\psi^2 \psi^2 + \text{h.c.}$	10	11	21	(8.20)
	$\psi^2 \psi^2 D + \text{h.c.}$	3	4	7	(8.30)
	$\psi^2 \psi^2 D^2 + \text{h.c.}$	1	2	3	(8.40)
9 (1, 1)	$\psi^4 + \text{h.c.}$	10	11	21	(9.10)
	$\psi^2 \psi^2 + \text{h.c.}$	7	8	15	(9.20)
	$\psi^2 \psi^2 D + \text{h.c.}$	1	2	3	(9.30)
10 (1, 0)	$\psi^4 + \text{h.c.}$	8	8	16	(10.10)
11 (0, 0)	$\psi^4 + \text{h.c.}$	1	1	2	(11.10)
Total	42	57	104	161	161

Jiang-Hao Yu

Dimension-9

[Li, Ren, Xiao, Yu, Zheng, 2020]

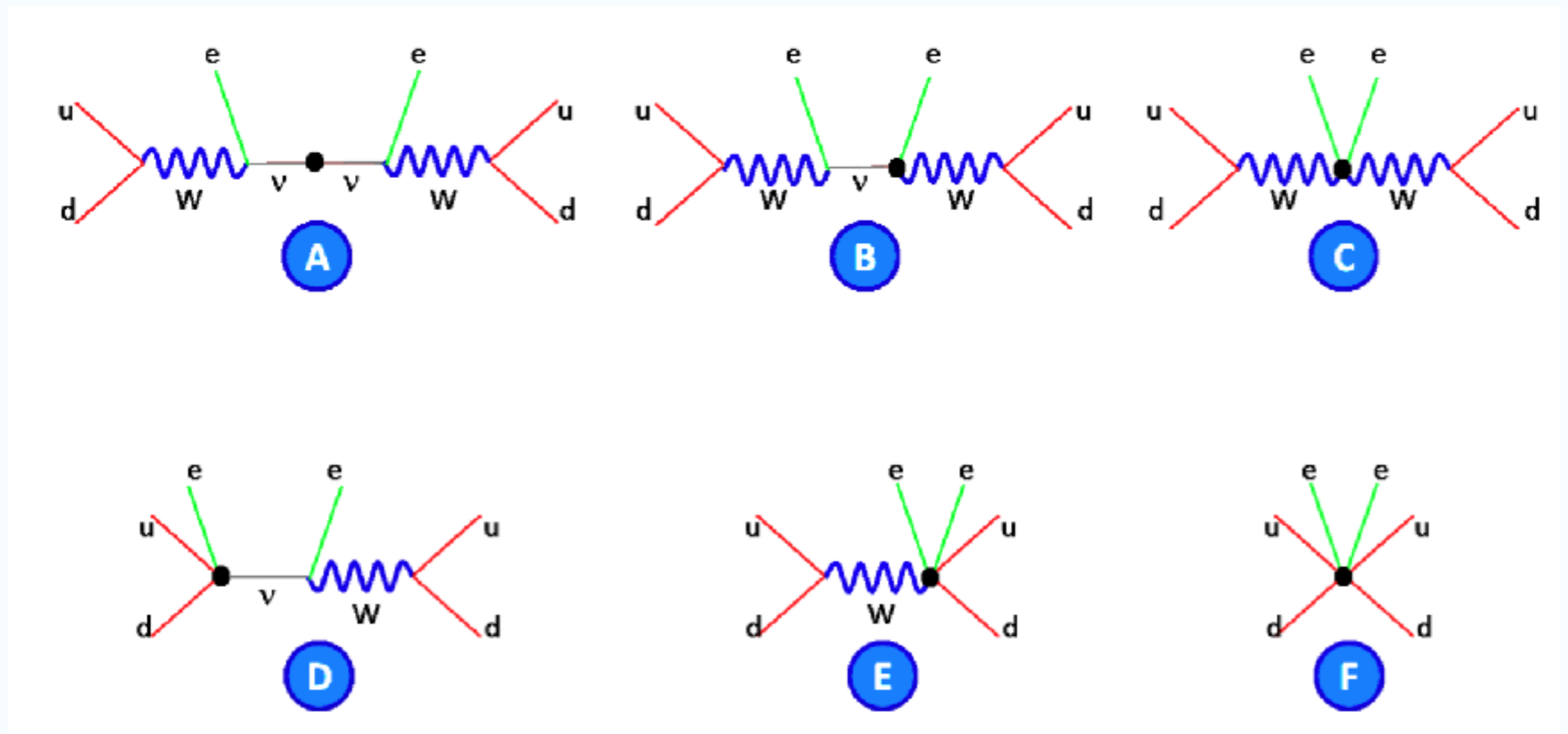
N (n, d)	Classes	N_{typ}	N_{non}	N_{total}	Equations
4 (3, 2)	$\psi^4 + \text{h.c.}$	0+1+2+0	3	3	(5.50)(7.50)
	$\psi^2 \psi^2 + \text{h.c.}$	0+0+2+0	5	5	(5.20)
5 (3, 1)	$\psi^4 + \text{h.c.}$	0+1+2+0	3	3	(5.50)(7.50)
	$\psi^2 \psi^2 + \text{h.c.}$	0+1+2+0	10	10	(5.45-5.48)
	$\psi^2 \psi^2 D + \text{h.c.}$	0+0+1+0	54	54	(5.26)(7.26)
	$\psi^2 \psi^2 D^2 + \text{h.c.}$	0+0+1+0	24	24	(5.26)(7.26)
6 (3, 0)	$\psi^4 + \text{h.c.}$	0+1+2+0	3	3	(5.50)(7.50)
	$\psi^2 \psi^2 + \text{h.c.}$	0+1+2+0	102	102	(5.54-5.56)
	$\psi^2 \psi^2 D + \text{h.c.}$	0+0+1+0	20	20	(5.26)
	$\psi^2 \psi^2 D^2 + \text{h.c.}$	0+0+1+0	6	6	(5.26)
7 (2, 1)	$\psi^4 + \text{h.c.}$	4+26+20+4	54	54	(5.53-5.59)
	$\psi^2 \psi^2 + \text{h.c.}$	0+1+2+0	15	15	(5.54-5.56)
	$\psi^2 \psi^2 D + \text{h.c.}$	0+0+1+0	15	15	(5.26)
	$\psi^2 \psi^2 D^2 + \text{h.c.}$	0+0+1+0	15	15	(5.26)
	$\psi^2 \psi^2 D^3 + \text{h.c.}$	0+0+1+0	15	15	(5.26)
	$\psi^2 \psi^2 D^4 + \text{h.c.}$	0+0+1+0	15	15	(5.26)
	$\psi^2 \psi^2 D^5 + \text{h.c.}$	0+0+1+0	15	15	(5.26)
7 (2, 0)	$\psi^4 + \text{h.c.}$	0+0+1+0	15	15	(5.35-5.37)
	$\psi^2 \psi^2 + \text{h.c.}$	0+0+1+0	8	8	(5.26)
8 (1, 1)	$\psi^4 + \text{h.c.}$	0+1+0+0	11	11	(5.35-5.37)
	$\psi^2 \psi^2 + \text{h.c.}$	0+0+1+0	2	2	(5.10)
8 (1, 0)	$\psi^4 + \text{h.c.}$	0+0+1+0	2	2	(5.9)
Total	42	6	122	134	134

560

18

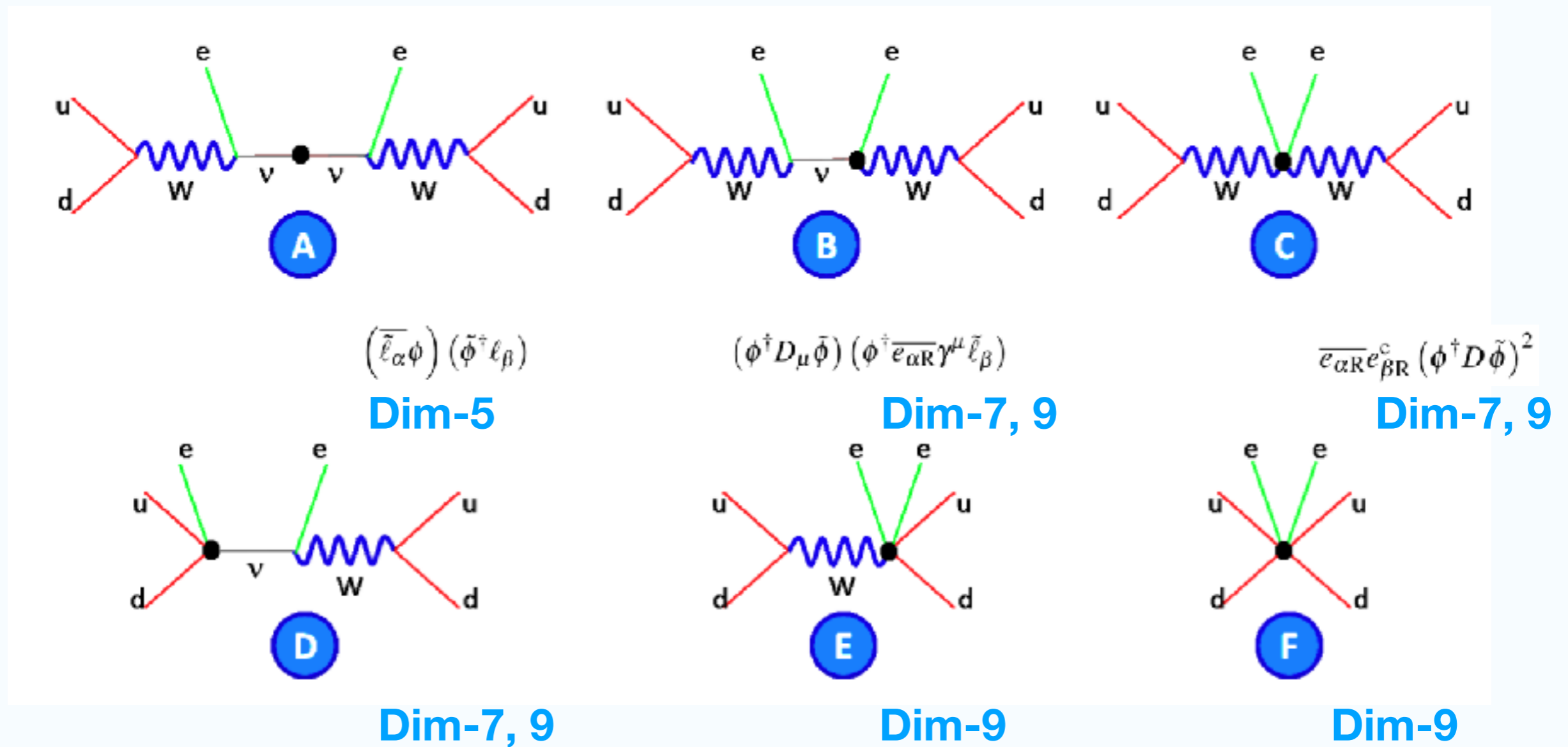
0vbb Related Operators

SMEFT broken phase:



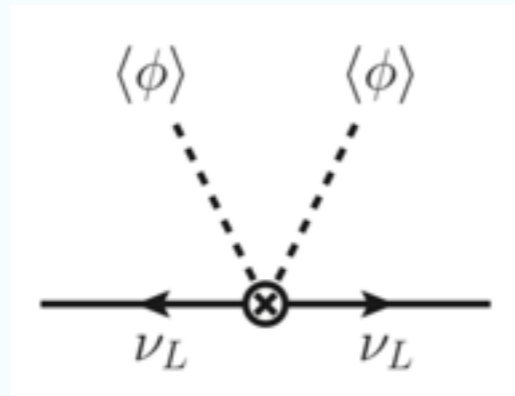
Ovbb Related Operators

Relate to SMEFT unbroken operators:

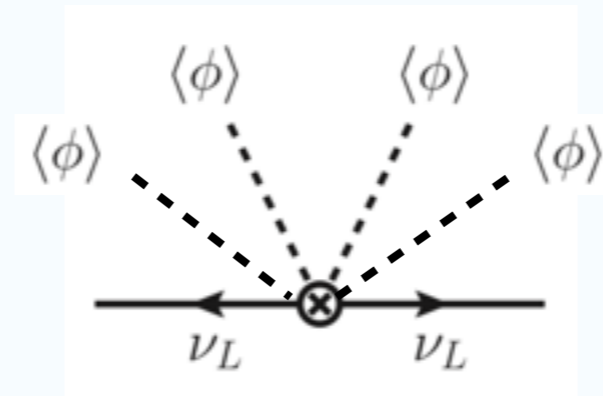


Nv Mass Related Operators

Higgs taking VEV:



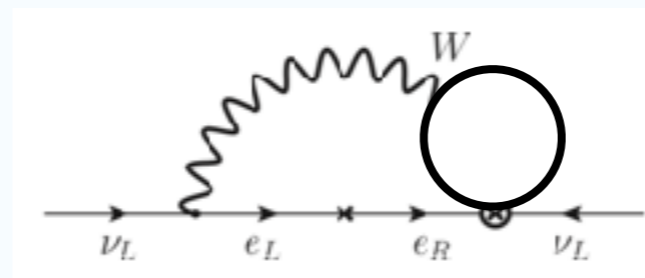
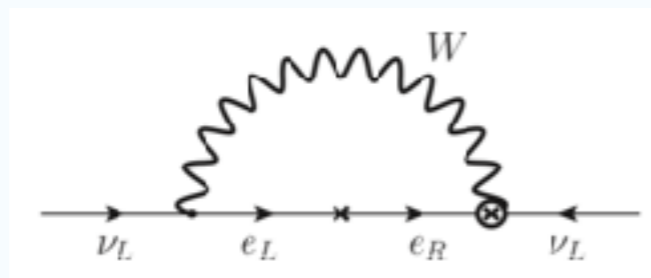
LLHH



LLHHHH

...

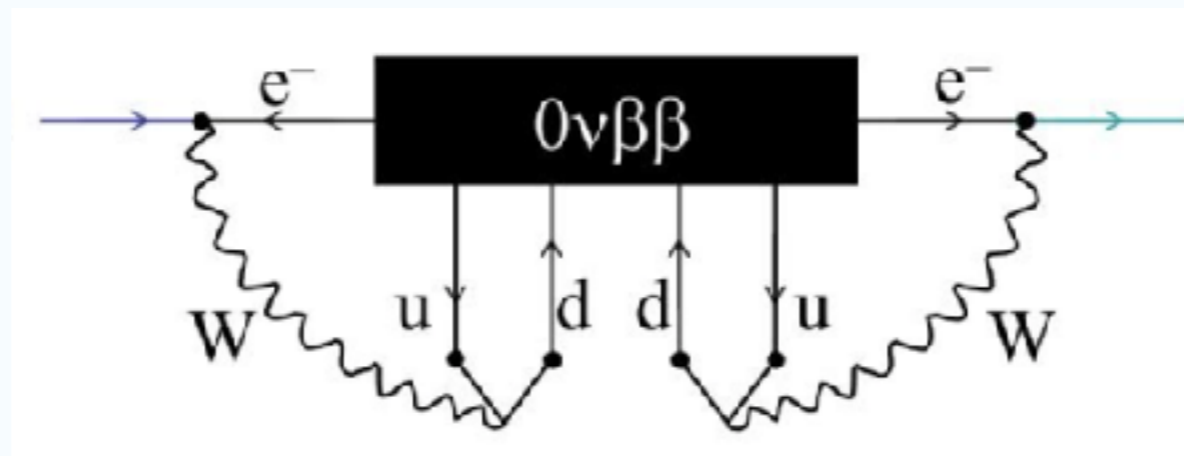
Could from other lepton number violation operators: anomalous RG



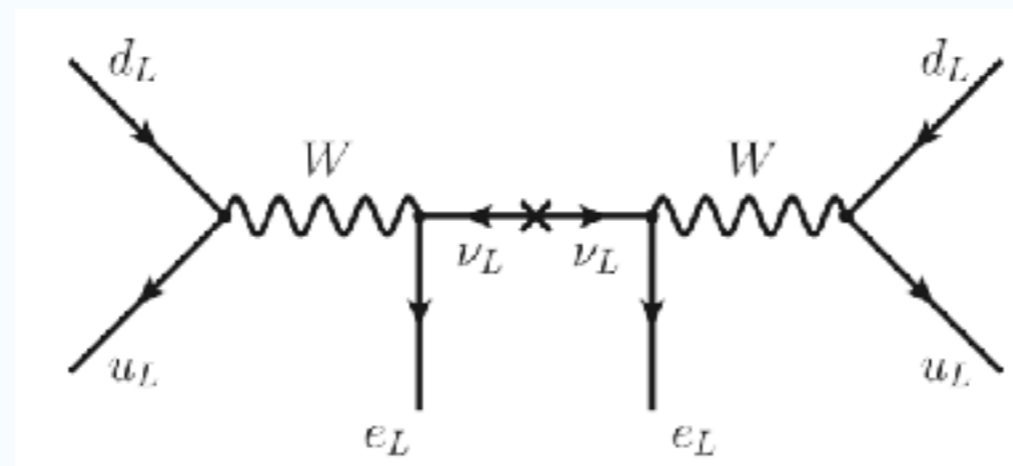
...

Neutrino Masses and $0\nu\beta\beta$

Schechter-Valle Theorem: whatever processes cause $0\nu\beta\beta$, its observation would imply existence of Majorana mass term

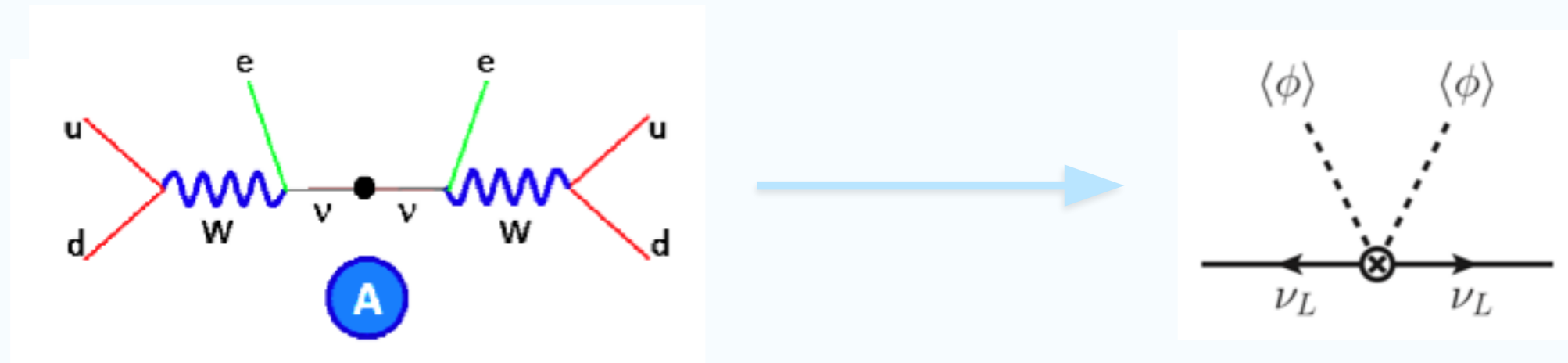


[Schechter-Valle, 1982]



Strong Correlation

Standard mechanism: origin of $0\nu\beta\beta$ = origin of neutrino masses



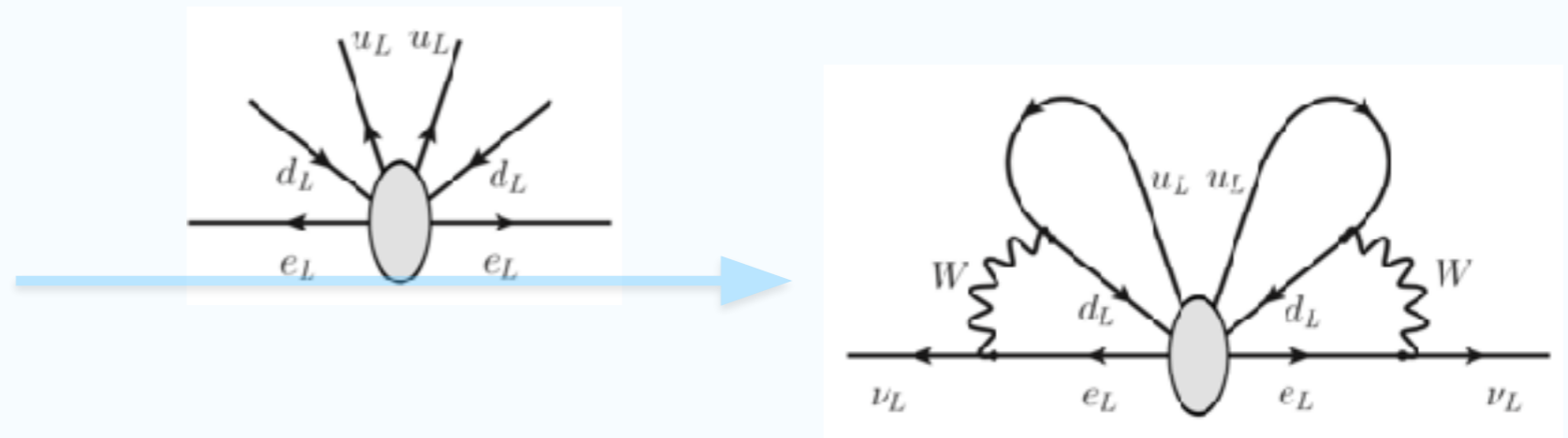
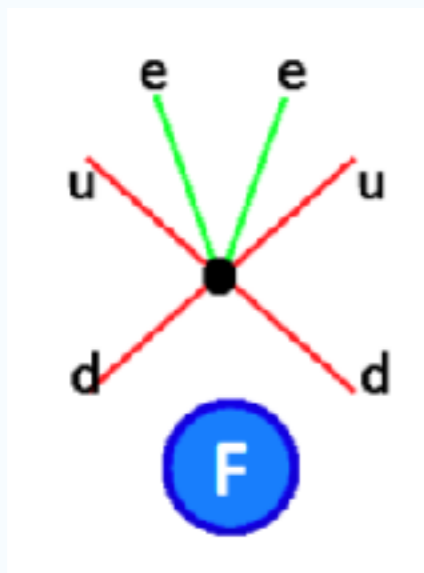
$$L^{\mu\nu} = - \int \int dx_2 dx_1 \sum_i \bar{e}(x_1) \gamma^\mu (1 - \gamma_5) U_{ei} \underbrace{\nu_{iL}(x_1) \bar{\nu}_{iL}^c(x_2)} \gamma^\nu (1 + \gamma_5) U_{ei} e_L^c(x_2)$$

$$m_{\beta\beta} = \sum_{i=1}^3 U_{ei}^2 m_{\nu_i}$$

$0\nu\beta\beta$ has direct connection to neutrino physics

Strong Correlation???

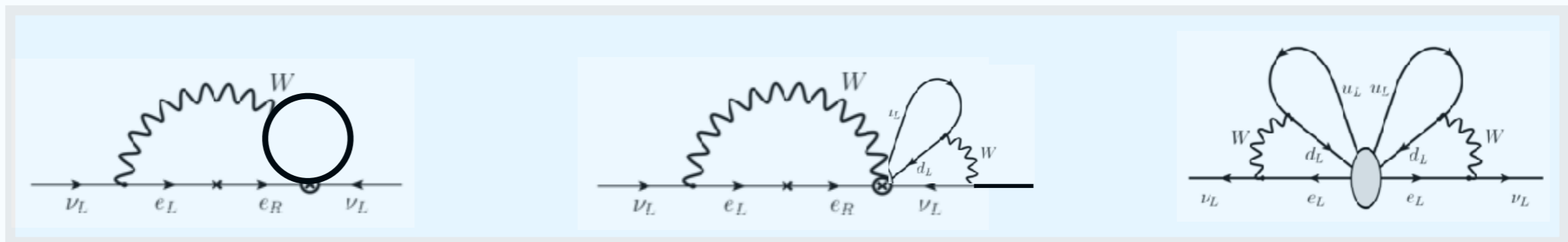
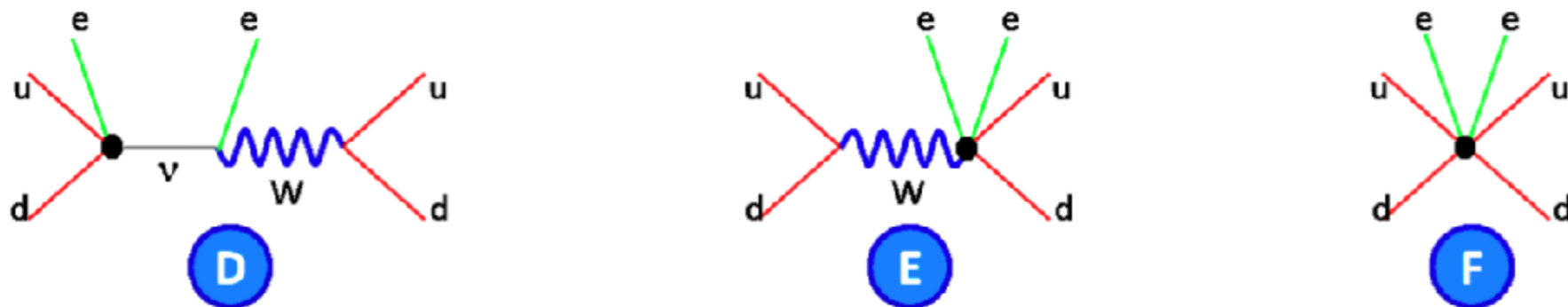
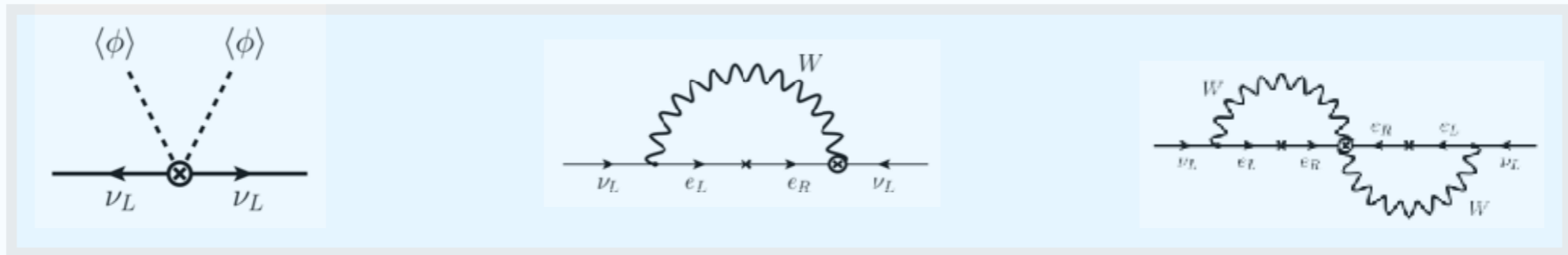
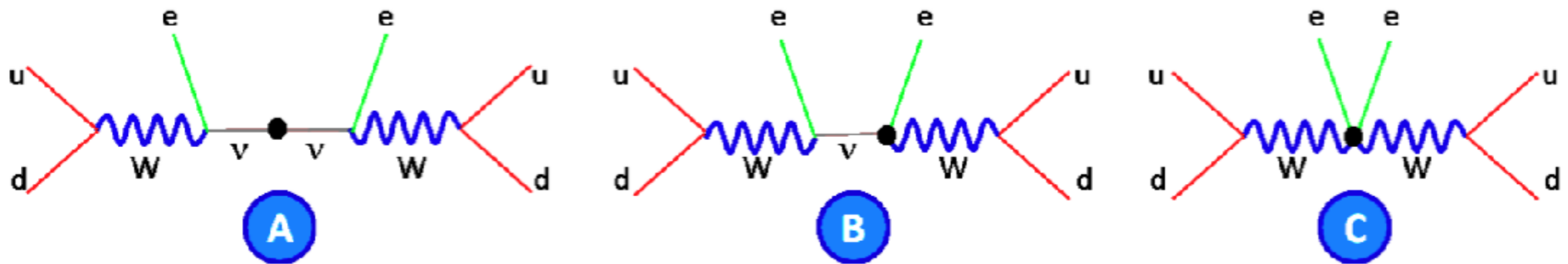
Lepton number violation operator: origin of $0\nu\beta\beta$ = small part of ν mass



Very tiny neutrino mass

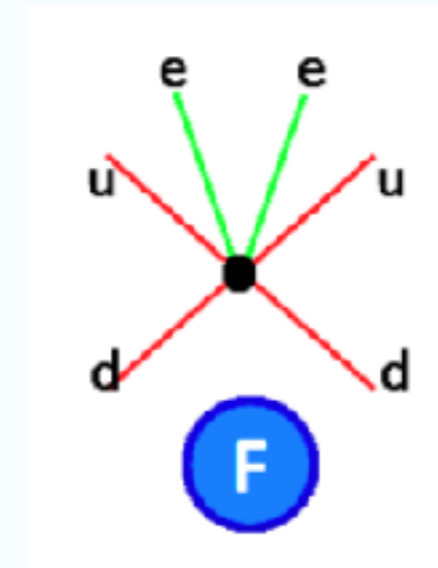
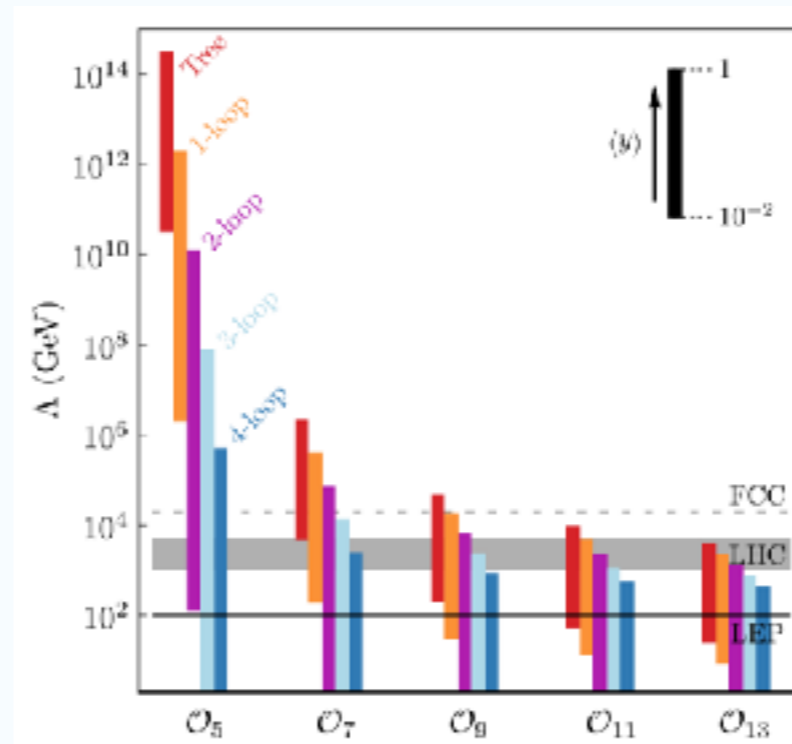
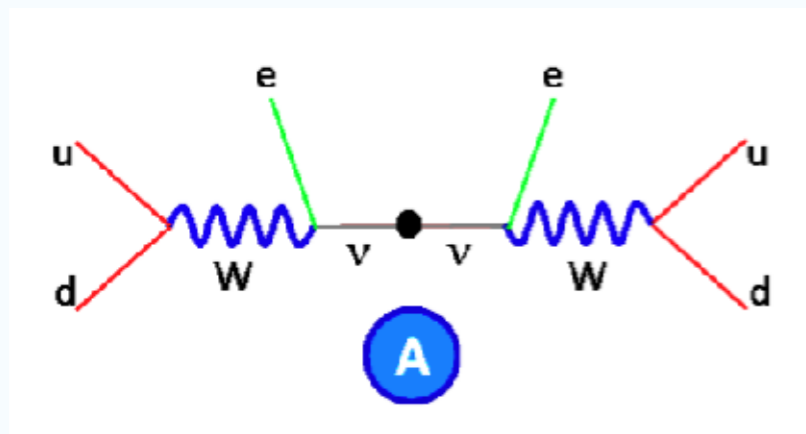
$0\nu\beta\beta$ does not need to connect to current neutrino exp.

Neutrino Masses and $0\nu\beta\beta$



Which One Dominate $0\nu\beta\beta$?

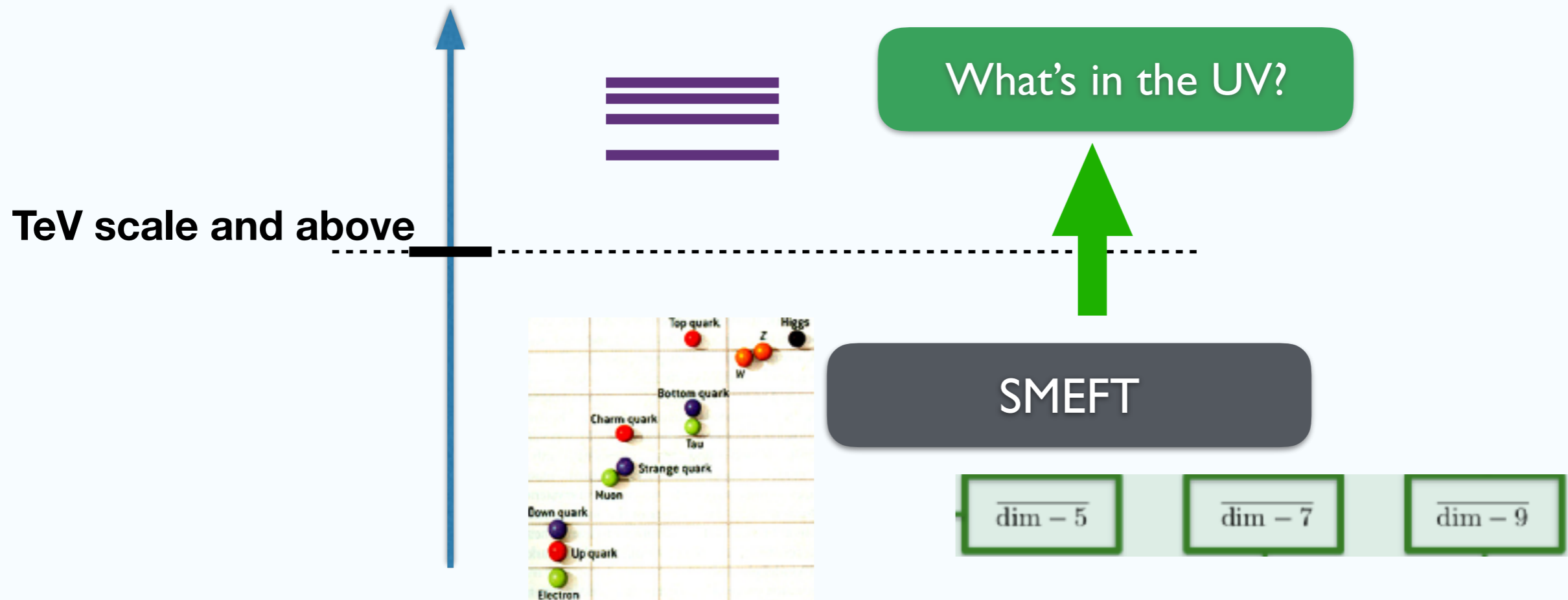
The higher dim operator, the lower cutoff scale



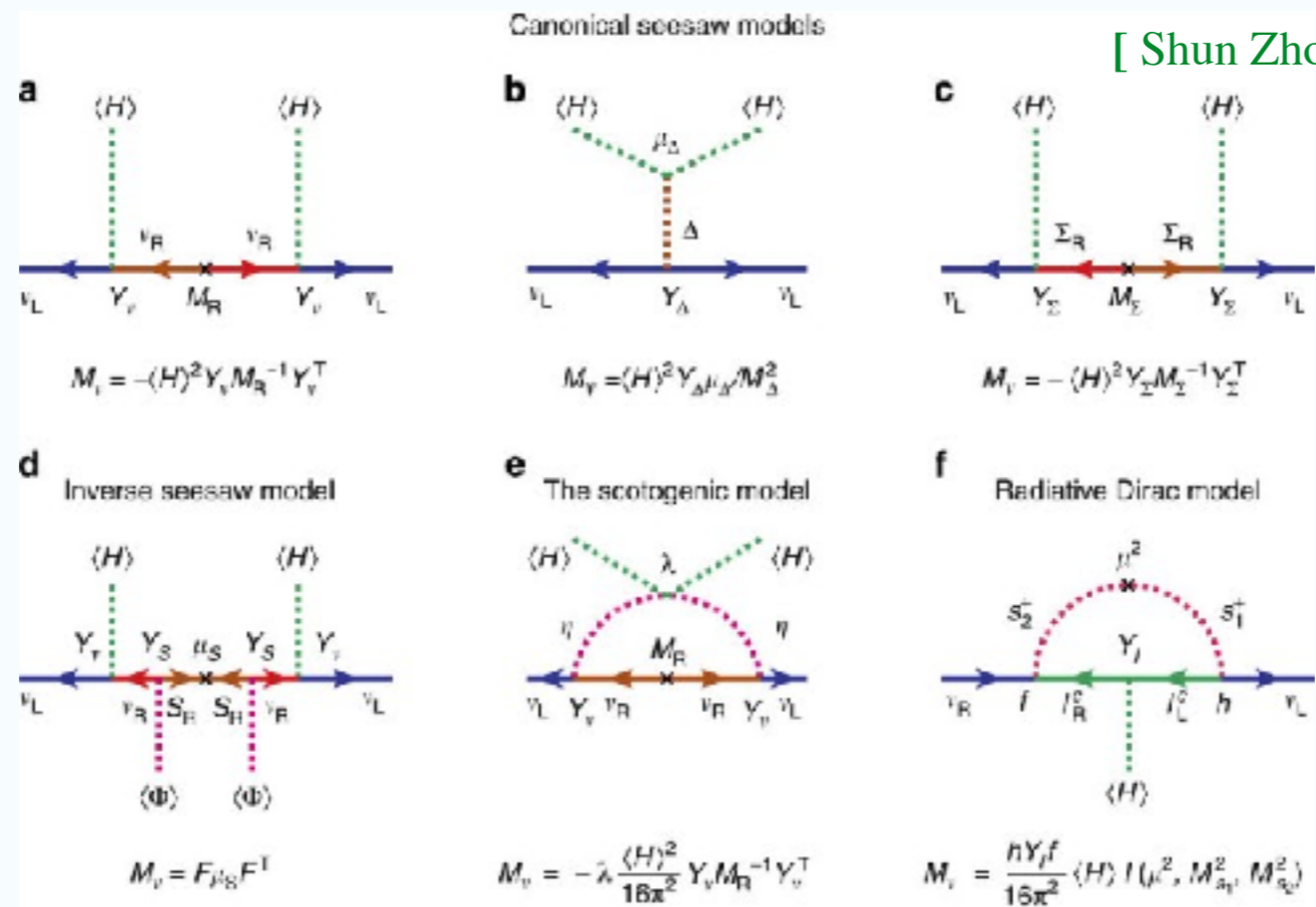
Could be comparable!

Not necessarily related to neutrino physics

What is in the UV?

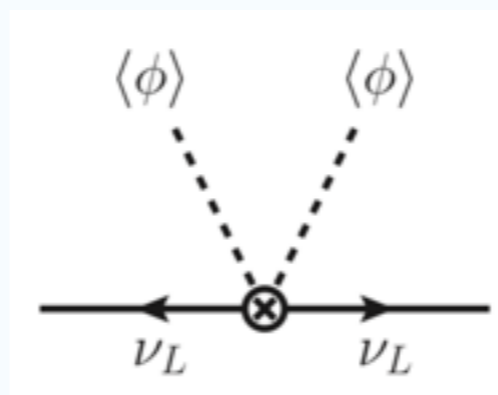


UV Realization of N_ν Masses

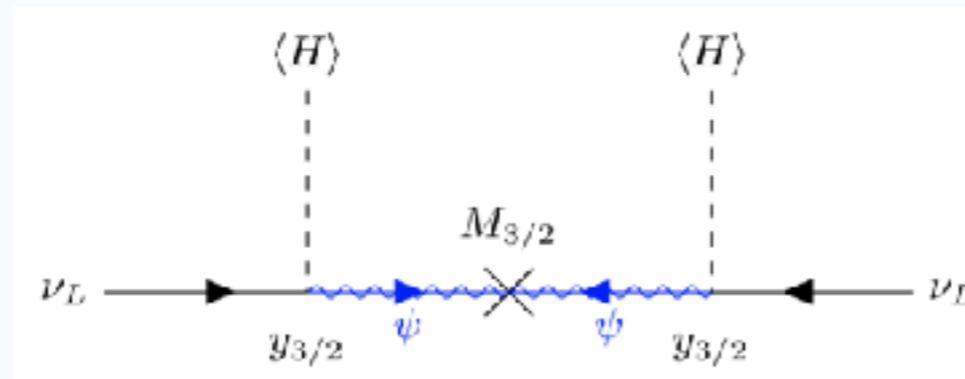


Integrate out heavy particles

Top-down approach



More UV realization?



Type-3/2 Seesaw Mechanism

Durmuş Demir,¹ Canan Karahan,²  and Ozan Sargin³

¹Sabanci University, Faculty of Engineering and Natural Sciences, 34956 Tuzla Istanbul, Turkey

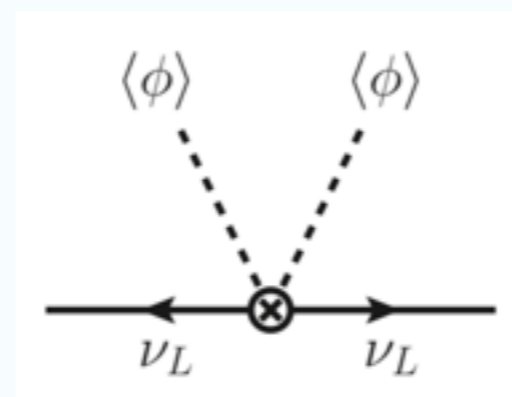
²Physics Engineering Department, Istanbul Technical University, 34469 Maslak Istanbul, Turkey

³Izmir Institute of Technology, Department of Physics, 35430, Izmir, Turkey

(Dated: May 17, 2021)



Bottom-up Approach



Jiang-Hao Yu

J-Basis Operator: Partial Wave

$$\mathcal{Y}[\overline{pr}] \epsilon_{ik} \epsilon_{jl} \epsilon_{\alpha\beta} L_p^{\alpha i} L_r^{\beta j} H^k H^l$$

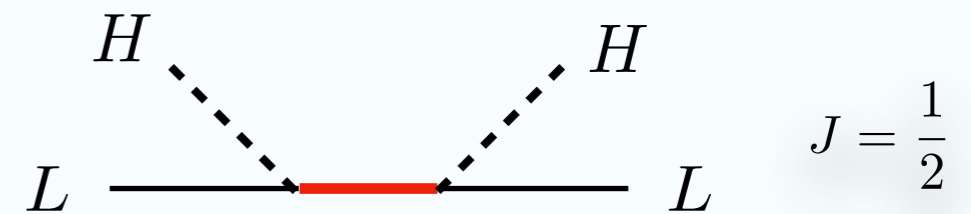
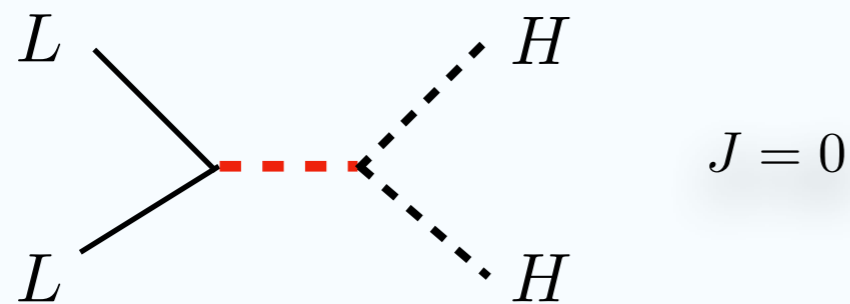
Partial wave expansion on operator

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

$$\mathbf{w}^2 = \frac{s}{8} \sum_{i,j=1}^N (i, \theta_i)(j, \theta_j) + |i, \theta_i||j, \theta_j| - \frac{1}{4} \sum_{i,j,k,l} |i, \theta_i||j, \theta_j|(k, \theta_k)(l, \theta_l)$$

$LL \rightarrow HH$ channel

$LH \rightarrow LH$ channel



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

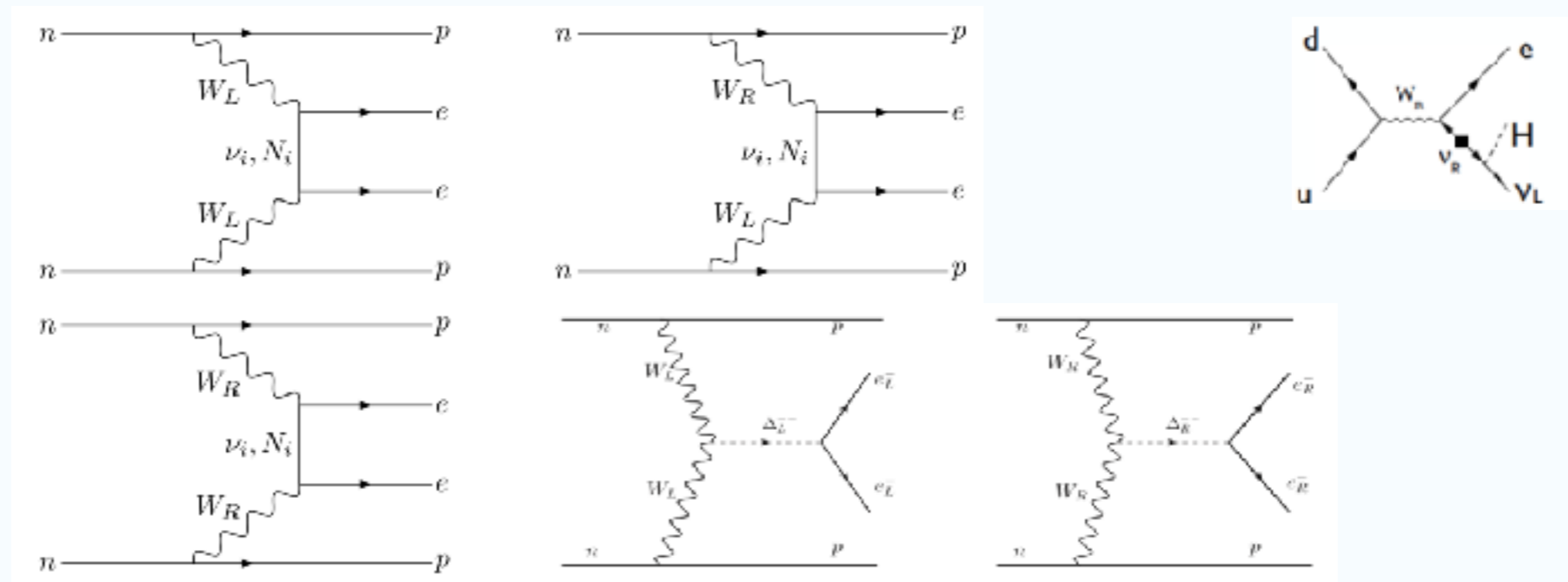
Type-I and III: **SU(2) single and triplet**

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

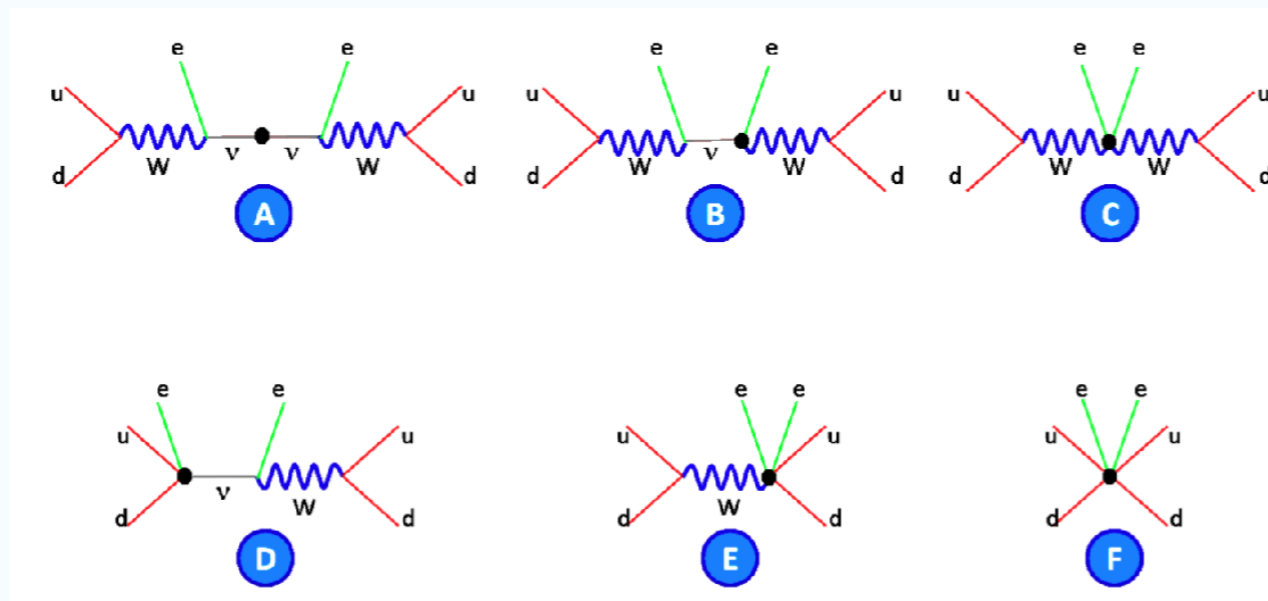
j-basis	Model
$\mathcal{O}_{HL \rightarrow HL}^{(1/2,1)} = \mathcal{O}^S + \mathcal{O}^A$	type I
$\mathcal{O}_{HL \rightarrow HL}^{(1/2,3)} = \mathcal{O}^S - 3\mathcal{O}^A$	type III

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

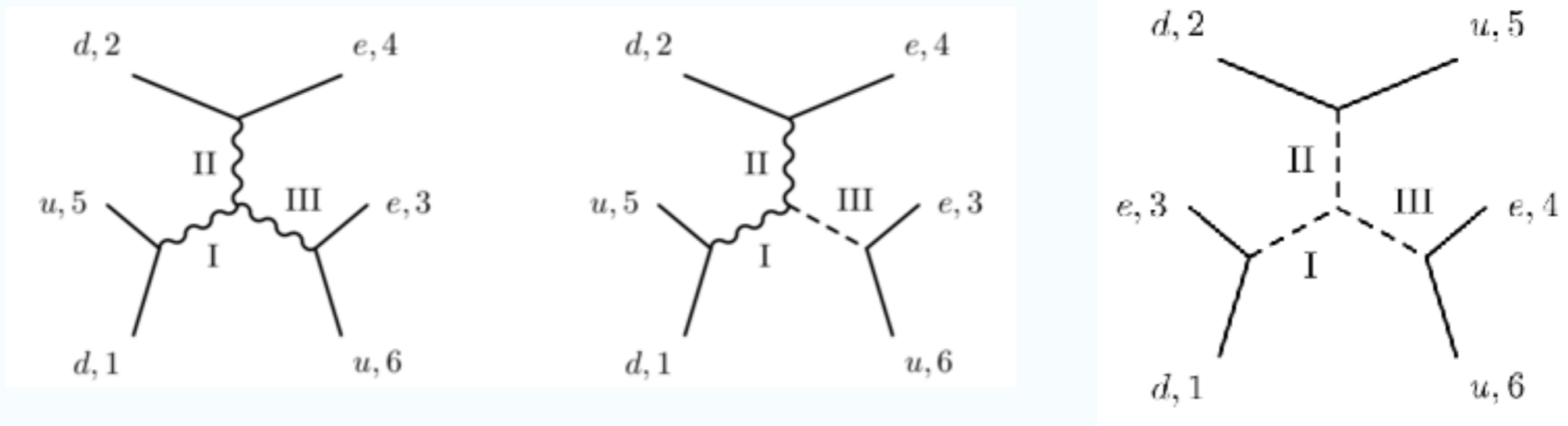
UV Realization of $0\nu\beta\beta$



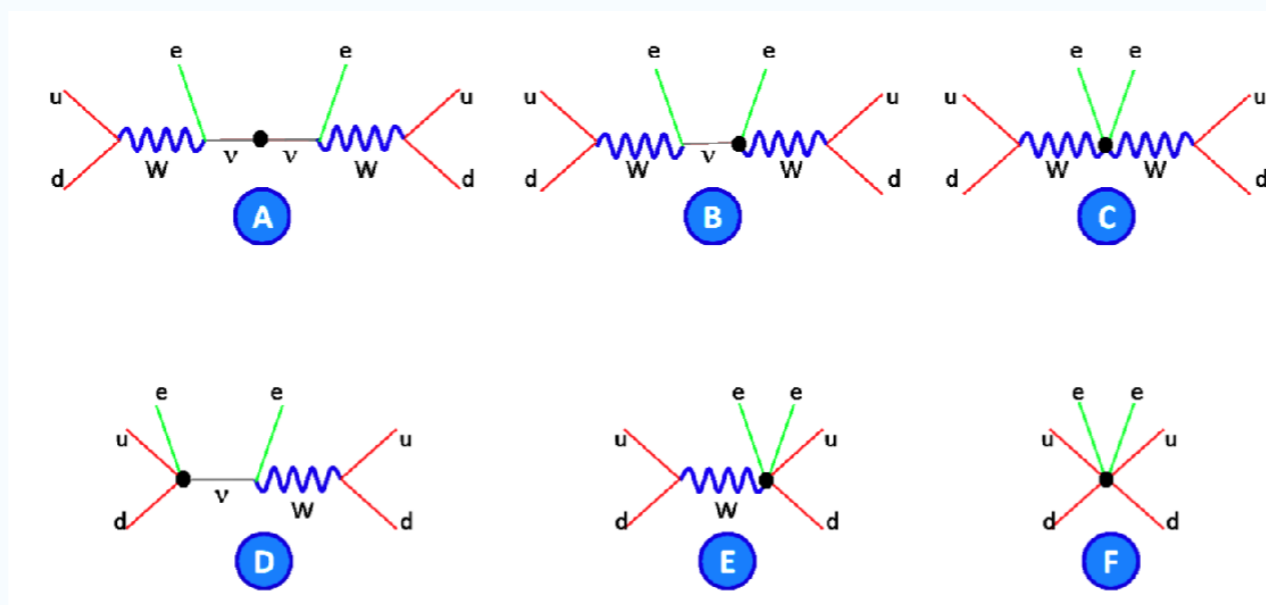
Integrate out heavy particles



More UV Realizations



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

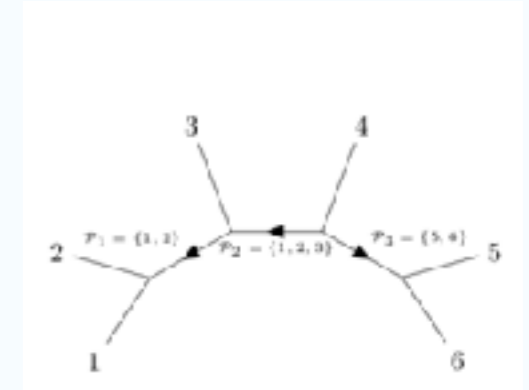
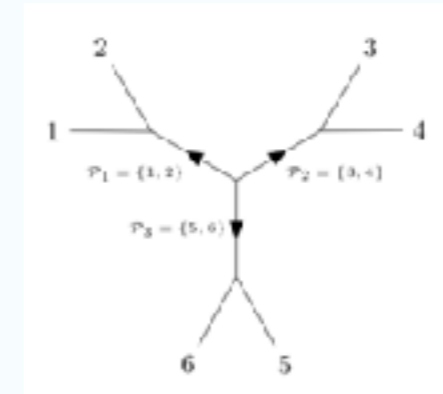


Example

Dim-9 operators:

$$T_{SU(3)}^{abcdef} \psi^{\dagger 6}$$

$$T_{SU(2)}^{ijkl} \psi^4 \psi^{\dagger 2}$$



Lorentz	y-basis
ψ^6	$\mathcal{B}_1 = \langle 12 \rangle \langle 34 \rangle \langle 56 \rangle$ $\mathcal{B}_2 = \langle 12 \rangle \langle 35 \rangle \langle 46 \rangle$ $\mathcal{B}_3 = \langle 13 \rangle \langle 24 \rangle \langle 56 \rangle$ $\mathcal{B}_4 = \langle 13 \rangle \langle 25 \rangle \langle 46 \rangle$ $\mathcal{B}_5 = \langle 14 \rangle \langle 25 \rangle \langle 36 \rangle$
$\psi^4 \psi^{\dagger 2}$	$\mathcal{B}_1 = \langle 12 \rangle \langle 34 \rangle [56]$ $\mathcal{B}_2 = \langle 13 \rangle \langle 24 \rangle [56]$

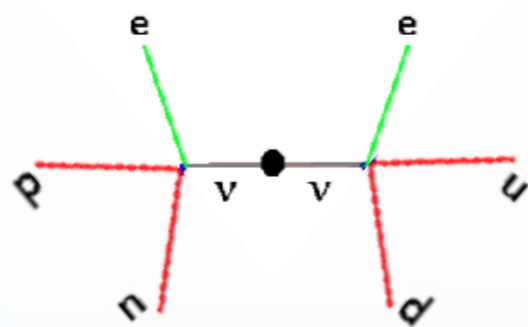
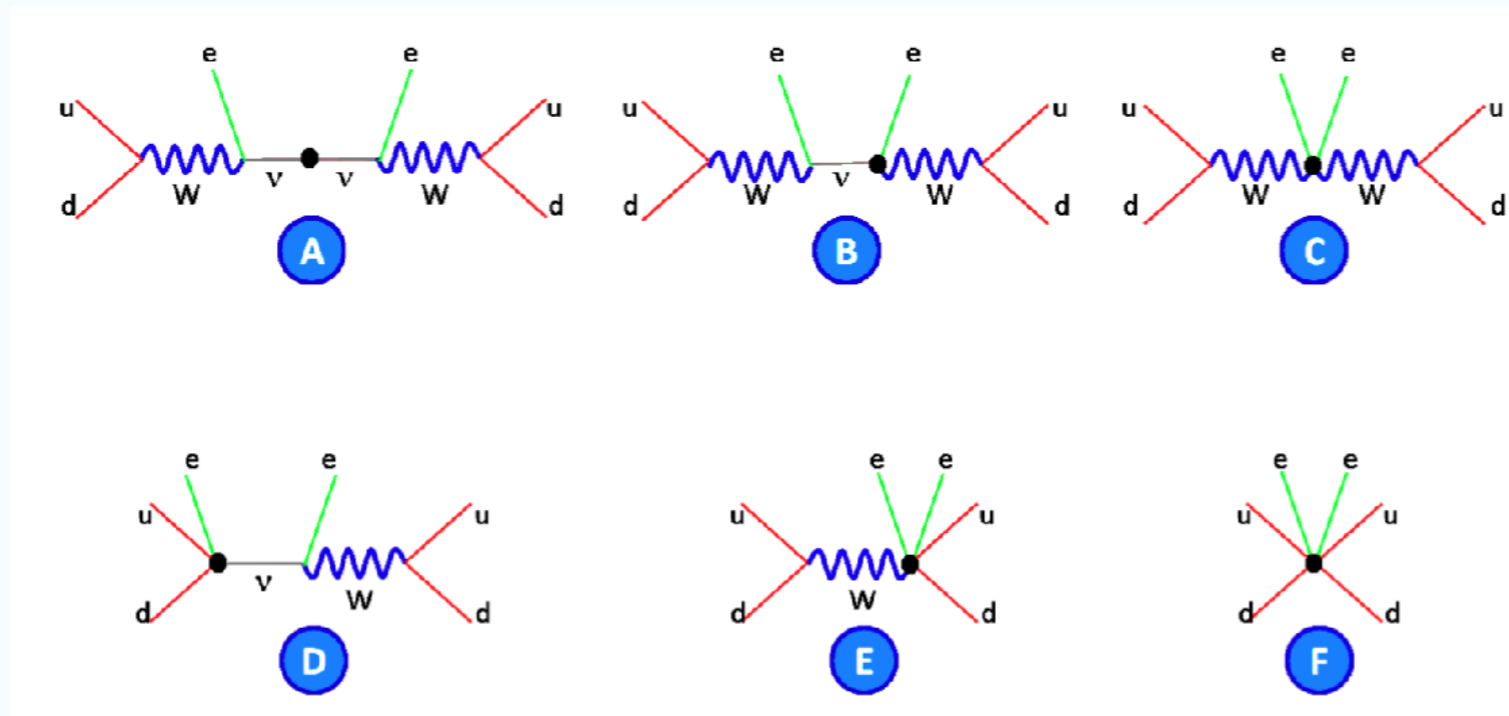
gauge classes	y-basis
$T_{SU(3)}^{abcdef}$	$T_1 = \epsilon^{acc} \epsilon^{bdf}$ $T_2 = \epsilon^{acd} \epsilon^{bef}$ $T_3 = \epsilon^{abc} \epsilon^{cdf}$ $T_4 = \epsilon^{abd} \epsilon^{cef}$ $T_5 = \epsilon^{abc} \epsilon^{def}$
$T_{SU(2)}^{ijkl}$	$T_1' = \epsilon^{ij} \epsilon^{kl}$ $T_2' = \epsilon^{ik} \epsilon^{jl}$
$T_{SU(2)}^{ij}$	$T_1' = \epsilon^{ij}$

type	$\bigoplus_{ \lambda } n_{ \lambda } \{[\lambda_1], [\lambda_2], \dots\}$
$d_c^{\dagger 4} u_c^{\dagger 2}$	$2\{[\square, \square], [\square, \square, \square]\} \oplus \{[\square, \square], [\square, \square]_d\} \oplus$ $2\{[\square, \square], [\square]_d\} \oplus 2\{[\square], [\square, \square]_d\} \oplus$ $\{[\square, \square], [\square]_d\} \oplus 2\{[\square], [\square]_d\} \oplus \{[\square, \square], [\square]_d\}$
$Q^4 d_c^{\dagger 2}$	$\{[\square, \square]_Q, [\square, \square]_{dt}\} \oplus 3\{[\square]_Q, [\square]_{dt}\} \oplus$ $2\{[\square, \square]_Q, [\square]_{dt}\} \oplus 2\{[\square]_Q, [\square]_{dt}\} \oplus \{[\square]_Q, [\square]_{dt}\}$
$Q^2 d_c^{\dagger 3} u_c^{\dagger}$	$\{[\square]_Q, [\square, \square]_{dt}\} \oplus 2\{[\square]_Q, [\square]_{dt}\} \oplus$ $\{[\square]_Q, [\square, \square]_{dt}\} \oplus \{[\square]_Q, [\square]_{dt}\} \oplus$ $\{[\square]_Q, [\square]_{dt}\} \oplus \{[\square]_Q, [\square]_{dt}\}$

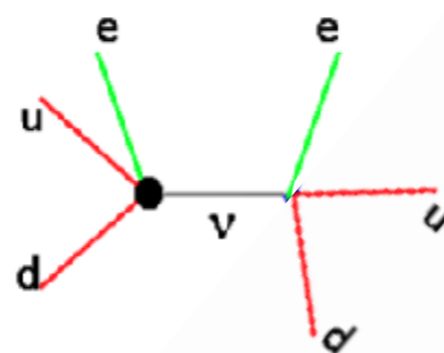
LEFT

Nucleon currents and weak sources

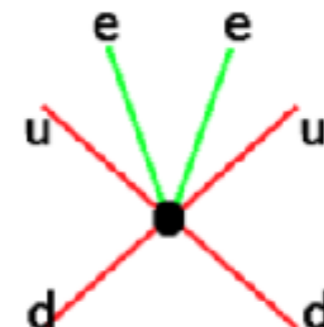
LEFT Related Operators



Dim-3

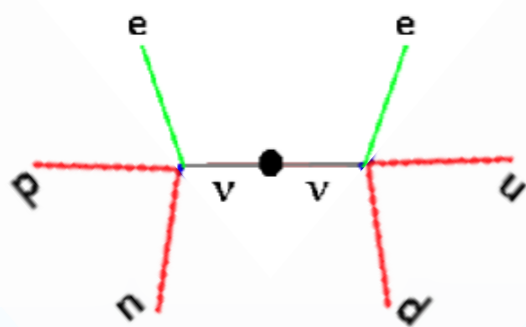
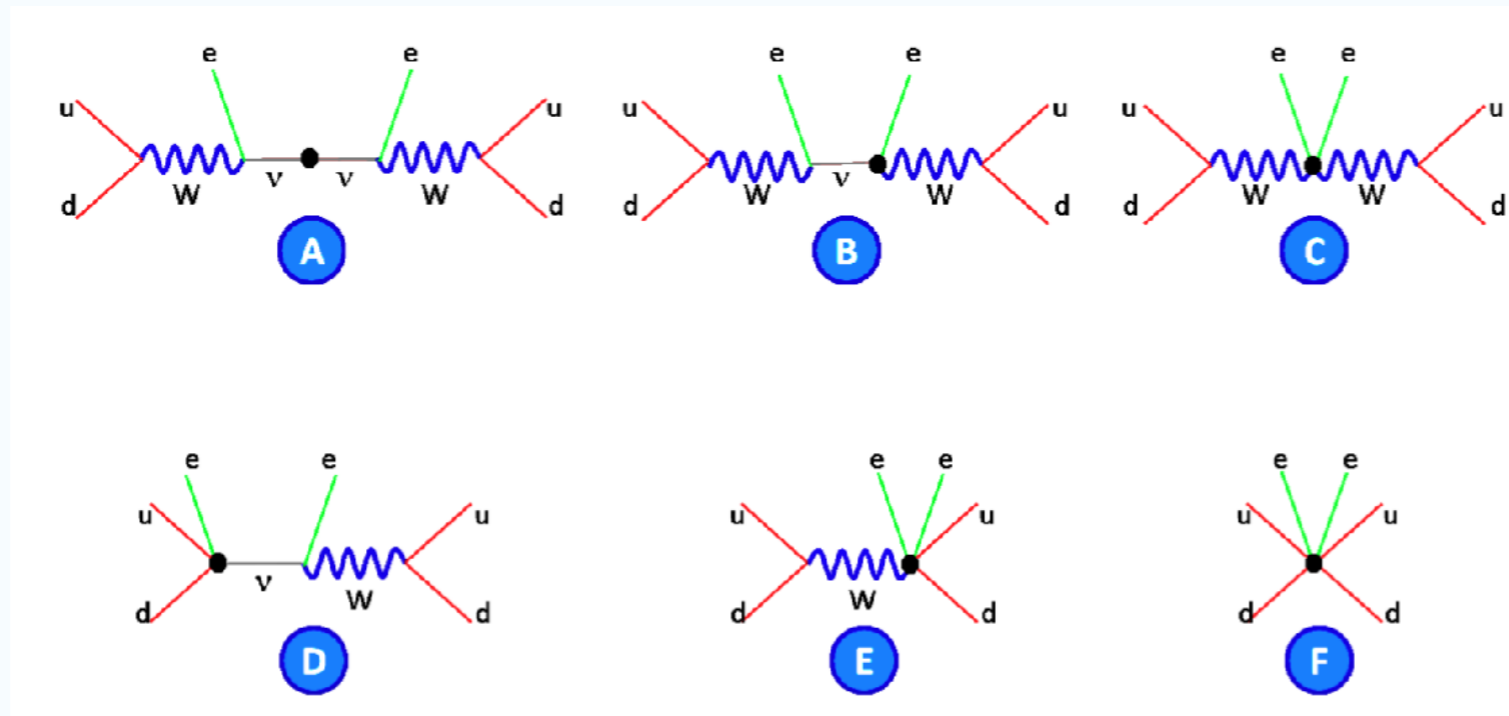


Dim-6, 7

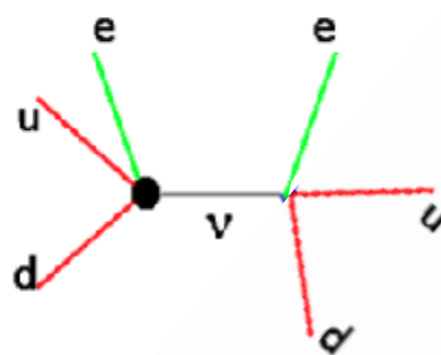


Dim-9

LEFT Related Operators



Long-range interaction

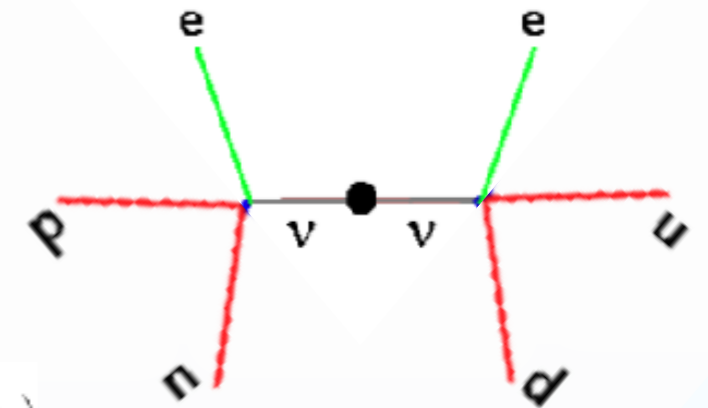


Short-range interaction

Long-Range Interaction

Standard mechanism: long-range neutrino potential

$$\mathcal{L} = \frac{G_F \cos \theta_C}{\sqrt{2}} [\bar{u}\gamma^\mu(1 - \gamma_5)d] \sum_{i=1}^3 U_{ei} [\bar{e}\gamma^\mu(1 - \gamma_5)\nu_i] + \text{h.c.}$$



$$L^{\mu\nu} = - \int \int dx_2 dx_1 \sum_i \bar{e}(x_1) \gamma^\mu (1 - \gamma_5) U_{ei} \underbrace{\nu_{iL}(x_1) \bar{\nu}_{iL}^c(x_2)} \gamma_\nu (1 + \gamma_5) U_{ei} e_L^c(x_2)$$

$$\frac{m_i}{q^2 - m_i^2} \propto \frac{m_i}{q^2} \quad \text{if } m_i^2 \ll q^2$$

$$\propto -\frac{1}{m_i} \quad \text{if } m_i^2 \gg q^2.$$

$$m_{\beta\beta} = \sum_{i=1}^3 U_{ei}^2 m_{\nu_i}$$

$$m_{\beta\beta} \rightarrow m_{\beta\beta} + \sum_{i=1}^{n_N} V_{eN_i}^2 m_{N_i}, \quad (m_{N_i} \ll 100 \text{ MeV}).$$

$$J_{\mu\nu}^{fi} = \sum_n \langle f | J_{\mu L}(\vec{x}_1) | n \rangle \langle n | J_{\nu L}(\vec{x}_2) | i \rangle e^{-i(E_n - E_f)x_{10}} e^{-i(E_n - E_i)x_{20}} + (\mu \rightarrow \nu, x_{10} \rightarrow x_{20}).$$

completeness relation

$$J_{0L}(\vec{x}) \simeq \sum_i \delta(\vec{x} - \vec{x}_i) f_1(0) \tau_i^+$$

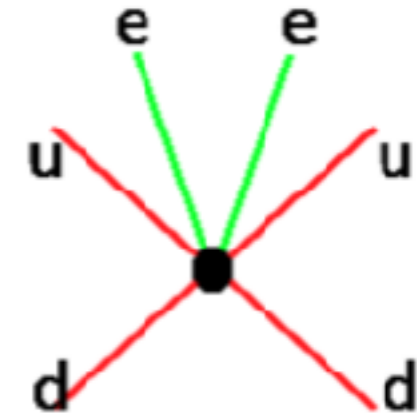
$$\vec{J}_L(\vec{x}) \simeq \sum_i \delta(\vec{x} - \vec{x}_i) g_1(0) \vec{\sigma}_i \tau_i^+$$

$$J_{\mu L}(\vec{x}_1) J_{\nu L}(\vec{x}_2) = \sum_{i,j} \tau_i^+ \tau_j^+ \delta(\vec{x}_1 - \vec{x}_i) \delta(\vec{x}_2 - \vec{x}_j) [f_1^2(0) - g_1^2(0) \vec{\sigma}_i \cdot \vec{\sigma}_j].$$

Short-Range Interaction

General quark currents = dim-9 LEFT operators

$$\mathcal{L}_{\text{SR}} = \frac{G_F^2}{2m_p} \sum_{\text{chiralities}} [\epsilon_1^\bullet J_\square J_\square j_\square + \epsilon_2^\bullet J_\square^{\mu\nu} J_{\square\mu\nu} j_\square + \epsilon_3^\bullet J_\square^\mu J_{\square\mu} j_\square + \epsilon_4^\bullet J_\square^\mu J_{\square\mu\nu} j^\nu + \epsilon_5^\bullet J_\square^\mu J_\square j_\mu]$$



$$J_{R,L} = \bar{u}_a(1 \pm \gamma_5)d_a, \quad J_{R,L}^\mu = \bar{u}_a\gamma^\mu(1 \pm \gamma_5)d_a, \quad J_{R,L}^{\mu\nu} = \bar{u}_a\sigma_{\mu\nu}(1 \pm \gamma_5)d_a, \\ j_{R,L} = \bar{e}(1 \mp \gamma_5)e^c, \quad j^\mu = \bar{e}\gamma^\mu\gamma_5e^c.$$

Complete dim-9 LEFT 6-fermion operator basis

[No need to know dim-9 SMEFT 6-fermion operators]

\mathcal{O}_1^{XXXX}	$[\bar{u}^a(1+\gamma_5)d_a][\bar{e}^b(1+\gamma_5)e^c][\bar{e}(1+\gamma_5)e^f]$
\mathcal{O}_1^{XXLL}	$[\bar{u}^a(1+\gamma_5)d_a][\bar{e}^b(1+\gamma_5)e^c][\bar{e}(1-\gamma_5)e^f]$
$\mathcal{O}_1^{LLXX} = \mathcal{O}_1^{LLLL}$	$[\bar{u}^a(1-\gamma_5)d_a][\bar{e}^b(1+\gamma_5)e^c][\bar{e}(1+\gamma_5)e^f]$
$\mathcal{O}_1^{LLXX} = \mathcal{O}_1^{LLLL}$	$[\bar{u}^a(1-\gamma_5)d_a][\bar{e}^b(1+\gamma_5)e^c][\bar{e}(1-\gamma_5)e^f]$
\mathcal{O}_1^{LLXX}	$[\bar{u}^a(1-\gamma_5)d_a][\bar{e}^b(1-\gamma_5)e^c][\bar{e}(1+\gamma_5)e^f]$
\mathcal{O}_1^{LLXX}	$[\bar{u}^a(1-\gamma_5)d_a][\bar{e}^b(1-\gamma_5)e^c][\bar{e}(1-\gamma_5)e^f]$
\mathcal{O}_2^{XXXX}	$[\bar{u}^a\sigma^{\mu\nu}(1+\gamma_5)d_a][\bar{e}^b\sigma_{\mu\nu}(1+\gamma_5)e^c][\bar{e}(1+\gamma_5)e^f]$
\mathcal{O}_2^{XXLL}	$[\bar{u}^a\sigma^{\mu\nu}(1+\gamma_5)d_a][\bar{e}^b\sigma_{\mu\nu}(1+\gamma_5)e^c][\bar{e}(1-\gamma_5)e^f]$
\mathcal{O}_2^{LLXX}	$[\bar{u}^a\sigma^{\mu\nu}(1-\gamma_5)d_a][\bar{e}^b\sigma_{\mu\nu}(1-\gamma_5)e^c][\bar{e}(1+\gamma_5)e^f]$
\mathcal{O}_2^{LLXX}	$[\bar{u}^a\sigma^{\mu\nu}(1-\gamma_5)d_a][\bar{e}^b\sigma_{\mu\nu}(1-\gamma_5)e^c][\bar{e}(1-\gamma_5)e^f]$
\mathcal{O}_3^{XXXX}	$[\bar{u}^a\gamma^\mu(1+\gamma_5)d_a][\bar{e}^b\gamma_\mu(1+\gamma_5)e^c][\bar{e}(1+\gamma_5)e^f]$
\mathcal{O}_3^{XXLL}	$[\bar{u}^a\gamma^\mu(1+\gamma_5)d_a][\bar{e}^b\gamma_\mu(1+\gamma_5)e^c][\bar{e}(1-\gamma_5)e^f]$
$\mathcal{O}_3^{LLXX} = \mathcal{O}_3^{LLLL}$	$[\bar{u}^a\gamma^\mu(1-\gamma_5)d_a][\bar{e}^b\gamma_\mu(1+\gamma_5)e^c][\bar{e}(1+\gamma_5)e^f]$
$\mathcal{O}_3^{LLXX} = \mathcal{O}_3^{LLLL}$	$[\bar{u}^a\gamma^\mu(1-\gamma_5)d_a][\bar{e}^b\gamma_\mu(1+\gamma_5)e^c][\bar{e}(1-\gamma_5)e^f]$
\mathcal{O}_3^{LLXX}	$[\bar{u}^a\gamma^\mu(1-\gamma_5)d_a][\bar{e}^b\gamma_\mu(1-\gamma_5)e^c][\bar{e}(1+\gamma_5)e^f]$
\mathcal{O}_3^{LLXX}	$[\bar{u}^a\gamma^\mu(1-\gamma_5)d_a][\bar{e}^b\gamma_\mu(1-\gamma_5)e^c][\bar{e}(1-\gamma_5)e^f]$
\mathcal{O}_4^{XXLL}	$[\bar{u}^a\gamma^\mu(1+\gamma_5)d_a][\bar{e}^b\sigma_{\mu\nu}(1+\gamma_5)e^c][\bar{e}^c\gamma^\nu e^f]$
\mathcal{O}_4^{LLXX}	$[\bar{u}^a\gamma^\mu(1+\gamma_5)d_a][\bar{e}^b\sigma_{\mu\nu}(1-\gamma_5)e^c][\bar{e}^c\gamma^\nu e^f]$
\mathcal{O}_4^{LLXX}	$[\bar{u}^a\gamma^\mu(1-\gamma_5)d_a][\bar{e}^b\sigma_{\mu\nu}(1+\gamma_5)e^c][\bar{e}^c\gamma^\nu e^f]$
\mathcal{O}_4^{LLXX}	$[\bar{u}^a\gamma^\mu(1-\gamma_5)d_a][\bar{e}^b\sigma_{\mu\nu}(1-\gamma_5)e^c][\bar{e}^c\gamma^\nu e^f]$
\mathcal{O}_5^{XXLL}	$[\bar{u}^a\gamma^\mu(1+\gamma_5)d_a][\bar{e}^b(1+\gamma_5)e^c][\bar{e}^c\gamma^\mu e^f]$
\mathcal{O}_5^{XXLL}	$[\bar{u}^a\gamma^\mu(1+\gamma_5)d_a][\bar{e}^b(1-\gamma_5)e^c][\bar{e}^c\gamma^\mu e^f]$
\mathcal{O}_5^{LLXX}	$[\bar{u}^a\gamma^\mu(1-\gamma_5)d_a][\bar{e}^b(1+\gamma_5)e^c][\bar{e}^c\gamma^\mu e^f]$
\mathcal{O}_5^{LLXX}	$[\bar{u}^a\gamma^\mu(1-\gamma_5)d_a][\bar{e}^b(1-\gamma_5)e^c][\bar{e}^c\gamma^\mu e^f]$

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A neutrinoless double beta decay master formula from effective field theory

V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser & E. Mereghetti

Journal of High Energy Physics 2018, Article number: 97 (2018) | Cite this article

Low Energy EFT

Dimension-5

Dim-5 operators		
N	(n, \bar{n})	Classes
3	(2,0)	$F_L \psi_L^2 + h.c.$

10

Dimension-6

Dim-6 operators				
N	(n, \bar{n})	Classes	N_{types}	N_{term}
3	(3,0)	$F_L^3 + h.c.$	2 + 0 + 0 + 0	2
4	(2,0)	$\psi_L^4 + h.c.$	14 + 12 + 8 + 2	78
	(1,1)	$\psi_L^2 \psi_R^2$	40 + 20 + 12 + 0	84
Total		5	56 + 32 + 20 + 2	164

[Jenkins, Manohar, Stoffer, 2017]

Dimension-7

Dim-7 operators				
N	(n, \bar{n})	Classes	N_{types}	N_{term}
4	(3,0)	$F_L^2 \psi_L^2 + h.c.$	16 + 0 + 4 + 0	32
		$F_L^2 \psi_R^2 + h.c.$	16 + 0 + 4 + 0	24
	(2,1)	$\psi_L^3 \psi_R D + h.c.$	50 + 32 + 22 +	
Total		6	82 + 32 + 30 +	166

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[Liao, Ma, Wang, 2020]

Dimension-8

[Li, Ren, Xiao, Yu, Zheng, 2020]

N	(n, \bar{n})	Subclasses	N_{type}	N_{term}	N_{max}	Equations
4	(3,0)	$F_L^3 + h.c.$	14	25	25	(4.15)
		$F_L^2 \psi_L^2 + h.c.$	22	22	$22n_f^2$	(4.2)
		$F_L \psi_L^4 + h.c.$	10	32	$10(n_f^2 + 1)(2n_f - 1)$	(4.7), (4.8), (4.9)
	(2,1)	$F_L^2 \psi_R^2 + h.c.$	8	12	12	(4.1)
		$F_L F_R$	14	17	17	(4.15)
		$F_L F_R \psi_L^2 D$	27	35	$35n_f$	(4.6), (4.7)
		$\psi_L^2 \psi_R^2$	17	34	$17(n_f^2 + 1) + 6n_f$	(4.7), (4.79-4.81)
		$F_L \psi_L^2 \psi_R^2 + h.c.$	10	15	15	(4.4)
		$F_L F_R \psi_L^2 D^2$	5	6	6	(4.1)
		$\psi_L^2 \psi_R^2 D^2$	7	15	$15n_f$	(4.3), (4.2)
5	(3,0)	$F_L^3 + h.c.$	14	25	$14n_f^2 + 20n_f + 11$	(4.8), (4.9), (4.9), (4.4)
5	(3,1)	$F_L^2 \psi_L^2 + h.c.$	22	33	$33n_f$	(4.2), (4.8)
		$F_L^2 \psi_R^2 + h.c.$	6	6	6	(4.1)
		$F_L^2 \psi_L^2 \psi_R^2 + h.c.$	6	6	6	(4.1)
	(2,1)	$F_L^2 \psi_R^2 + h.c.$	8	12	$2n_f(22n_f - 2) + 21n_f^2$	(4.54-4.57), (4.78-4.81)
		$F_L \psi_L^3 + h.c.$	32	34	$34n_f$	(4.1), (4.9)
		$\psi_L^3 \psi_R^2 + h.c.$	32	34	$n_f^2(33n_f - 1) + n_f^2(29n_f + 3)$	(4.6), (4.6)-4.72)
		$F_L \psi_L^2 \psi_R^2 + h.c.$	38	39	$39n_f$	(4.5), (4.6)
		$\psi_L^2 \psi_R^3 + h.c.$	4	39	$39n_f$	(4.5)
		$F_L \psi_L^2 \psi_R^2 + h.c.$	4	6	6	(4.1)
		6	(3,0)	$F_L^3 + h.c.$	14	25
6	(3,1)	$F_L^2 \psi_L^2 + h.c.$	10	22	$22n_f$	(4.2)
		$F_L^2 \psi_R^2 + h.c.$	8	10	10	(4.1)
		$\psi_L^3 \psi_R^2 + h.c.$	20	18	$n_f^2(46n_f^2 + n_f + 2) + 2n_f^2(36n_f - 1)$	(4.5), (4.5), (4.5)-4.6)
	(1,1)	$\psi_L^3 \psi_R^2$	7	15	$15n_f$	(4.2), (4.2)
		$\psi_L^3 \psi_R^2$	1	1	1	(4.8)
7	(3,0)	$F_L^3 + h.c.$	4	6	$6n_f^2$	(4.2)
8	(3,0)	ψ_L^4	1	1	1	(4.8)
Total		48	471 (20)	1376 (135)	$600(n_f - 1) - 480(n_f - 2)$	

[Murphy, 2020]

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Jiang-Hao Yu

Dimension-9

[Li, Ren, Xiao, Yu, Zheng, 2020]

N	(n, \bar{n})	Classes	N_{type}	N_{term}	N_{max}	Equations
4	(3,2)	$\psi_L^4 \psi_R^2 + h.c.$	0 + 1 + 2 + 0	30	$\frac{1}{2}n_f^2(2n_f^2 - 1)$	(5.50)(5.54)
		$\psi_L^3 \psi_R^3 + h.c.$	0 + 0 + 2 + 0	6	$3n_f(2n_f + 1)$	(5.21)
		$F_L \psi_L^3 \psi_R^2 + h.c.$	0 + 20 + 6 + 0	26	$32n_f$	(5.50)(5.53)
5	(3,1)	$\psi_L^5 \psi_R^2 + h.c.$	0 + 1 + 4 + 0	100	$100n_f$	(5.45-5.48)
		$F_L \psi_L^4 \psi_R^2 + h.c.$	0 + 0 + 4 + 0	24	$17n_f^2 - n_f$	(5.28)(5.29)
		$F_L \psi_L^3 \psi_R^3 + h.c.$	0 + 13 + 6 + 0	19	$4n_f^2(3n_f + 1)$	(5.50)(5.53)
	(2,2)	$\psi_L^4 \psi_R^3 + h.c.$	0 + 1 + 4 + 0	64	$n_f^2(43n_f + 1)$	(5.45-5.48)
		$F_L \psi_L^4 \psi_R^2 + h.c.$	0 + 0 + 4 + 0	20	$2n_f(3n_f - 1)$	(5.28)(5.29)
		$\psi_L^5 \psi_R^2 + h.c.$	0 + 0 + 2 + 0	6	$6n_f^2$	(5.1)
6	(3,0)	$\psi_L^5 + h.c.$	2 + 1 + 5 + 0	116	$\frac{1}{2}n_f^2(42n_f^2 + 32n_f^2 + 58n_f^2 + 139n_f + 6)$	(5.54-5.57)
		$F_L^2 \psi_L^3 + h.c.$	0 + 12 + 13 + 0	102	$2n_f^2(21n_f + 1)$	(5.54-5.56)
		$F_L^2 \psi_R^3 + h.c.$	0 + 0 + 8 + 0	26	$2n_f(3n_f + 2)$	(5.2)
	(2,1)	$\psi_L^5 \psi_R^2 + h.c.$	4 + 26 + 20 + 4	244	$n_f^2(182n_f^2 - 9n_f^2 + 2n_f + 21)$	(5.53-5.59)
		$F_L \psi_L^4 \psi_R^2 + h.c.$	0 + 21 + 24 + 0	45	$52n_f$	(5.54-5.56)
		$F_L^2 \psi_L^2 \psi_R^3 + h.c.$	0 + 0 + 8 + 0	15	$2n_f(3n_f + 2)$	(5.2)
		$\psi_L^6 \psi_R^2 + h.c.$	0 + 12 + 18 + 0	30	$\frac{1}{2}n_f^2(18n_f^2 + 4)$	(5.58-5.62)
		$F_L \psi_L^4 \psi_R^2 + h.c.$	0 + 0 + 8 + 0	15	$15n_f$	(5.2)
		$\psi_L^5 \psi_R^3 + h.c.$	0 + 0 + 4 + 0	24	$2n_f(3n_f + 1)$	(5.1)
		7	(2,0)	$\psi_L^6 + h.c.$	0 + 6 + 3 + 0	33
7	(3,1)	$F_L \psi_L^4 \psi_R^2 + h.c.$	0 + 0 + 1 + 0	8	$2n_f(2n_f - 1)$	(5.2)
		$\psi_L^6 \psi_R^2$	0 + 6 + 10 + 0	16	$16n_f$	(5.35-5.37)
		$\psi_L^6 \psi_R^2 D$	0 + 0 + 2 + 0	2	$2n_f^2$	(5.1)
8	(3,0)	$\psi_L^6 + h.c.$	0 + 0 + 2 + 0	2	$n_f^2 + n_f$	(5.9)
Total		42	6 + 132 + 164 + 4	1262	$n + 234 + 345 - 6(n_f - 1) - 234n_f + 1222n_f^2 - 4187n_f^3 + 486(n_f - 2)$	

3774

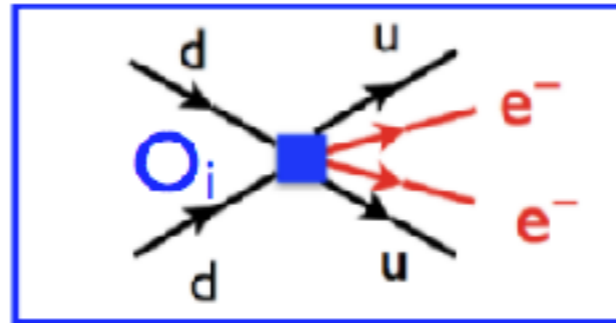
39

ChiPT: Quark to Nucleon

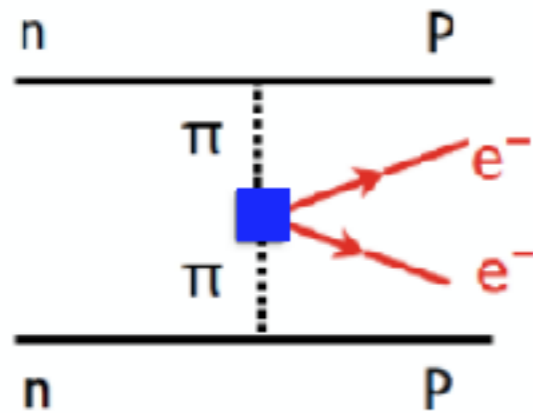
Chiral perturbation theory + Heavy baryon EFT + LNV external source

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

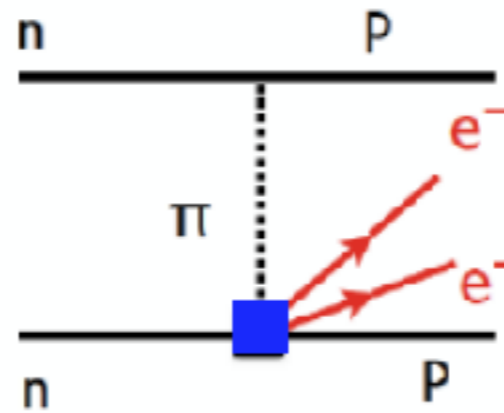
Pion-range effects



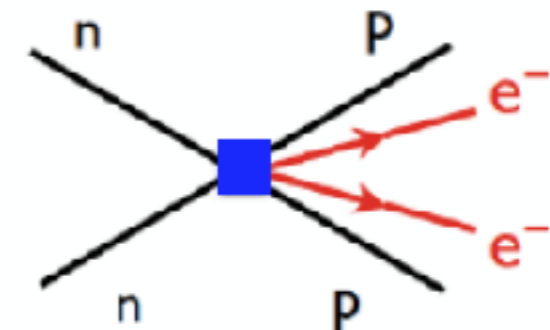
Short-range effects



$\mathcal{L}_{\pi\pi}$



$\mathcal{L}_{\pi N}$



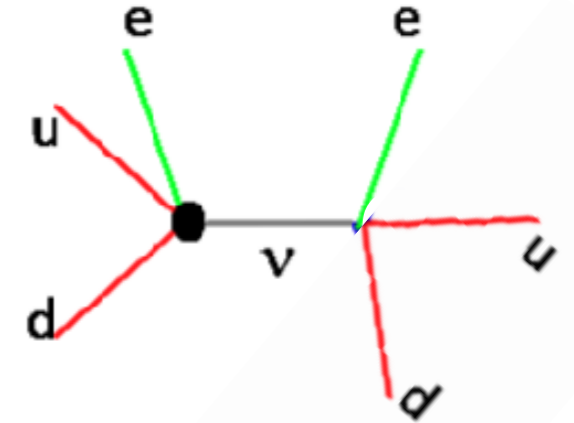
\mathcal{L}_{NN}

Long-Range from LNV Operators

Long-range neutrino potential: no ν mass dependence

$$\mathcal{L}^{4\text{-Fermi}} = \mathcal{L}^{\text{SM}} + \mathcal{L}^{\text{LNV}} = \frac{G_F}{\sqrt{2}} \left[j_{V-A}^\mu J_{V-A,\mu} + \sum_{\alpha, \beta \neq V-A} \epsilon_\alpha^\beta j_\beta J_\alpha \right]$$

$$\begin{aligned} J_{V\pm A}^\mu &= (J_{R/L})^\mu \equiv \bar{u}\gamma^\mu(1 \pm \gamma_5)d, & j_{V\pm A}^\mu &\equiv \bar{e}\gamma^\mu(1 \pm \gamma_5)\nu, \\ J_{S\pm P} &= J_{R/L} \equiv \bar{u}(1 \pm \gamma_5)d, & j_{S\pm P} &\equiv \bar{e}(1 \pm \gamma_5)\nu, \\ J_{T_{R/L}}^{\mu\nu} &= (J_{R/L})^{\mu\nu} \equiv \bar{u}\gamma^{\mu\nu}(1 \pm \gamma_5)d, & j_{T_{R/L}}^{\mu\nu} &\equiv \bar{e}\gamma^{\mu\nu}(1 \pm \gamma_5)\nu, \end{aligned}$$



Complete dim-6 LEFT 4-fermion operator basis

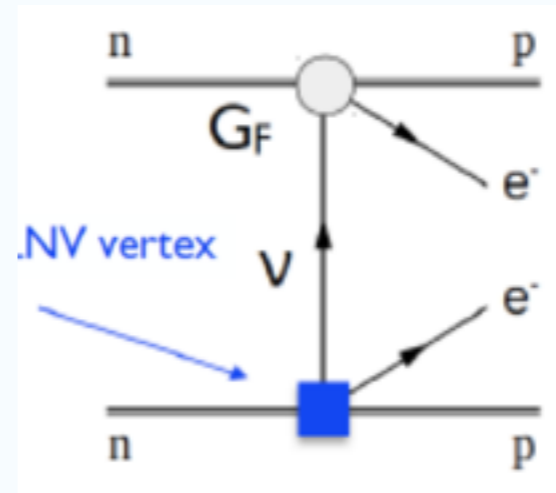
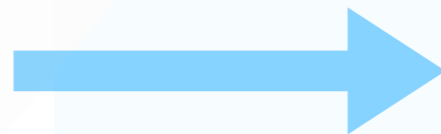
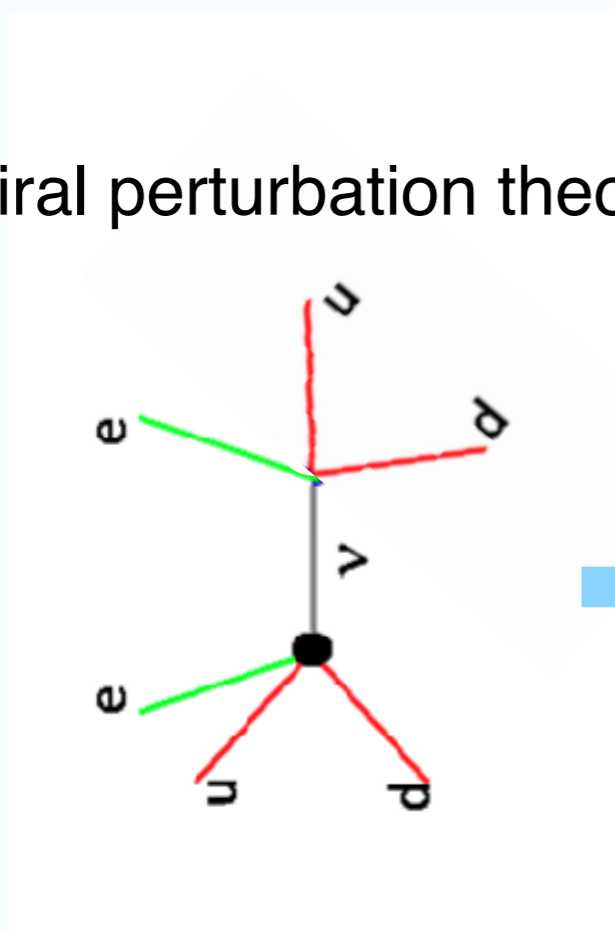
$$\begin{aligned} \mathcal{L}_{\Delta L=2}^{(6)} &= \frac{2G_F}{\sqrt{2}} \left\{ C_{\text{VL},ij}^{(6)} \bar{u}_L \gamma^\mu d_L \bar{e}_{R,i} \gamma_\mu C \bar{\nu}_{L,j}^T + C_{\text{VR},ij}^{(6)} \bar{u}_R \gamma^\mu d_R \bar{e}_{R,i} \gamma_\mu C \bar{\nu}_{L,j}^T \right. \\ &\quad \left. + C_{\text{SR},ij}^{(6)} \bar{u}_L d_R \bar{e}_{L,i} C \bar{\nu}_{L,j}^T + C_{\text{SL},ij}^{(6)} \bar{u}_R d_L \bar{e}_{L,i} C \bar{\nu}_{L,j}^T + C_{\text{T},ij}^{(6)} \bar{u}_L \sigma^{\mu\nu} d_R \bar{e}_{L,i} \sigma_{\mu\nu} C \bar{\nu}_{L,j}^T \right\} + \text{h.c.} \end{aligned} \quad (7)$$

$$\mathcal{L}_{\Delta L=2}^{(7)} = \frac{2G_F}{\sqrt{2}v} \left\{ C_{\text{VL},ij}^{(7)} \bar{u}_L \gamma^\mu d_L \bar{e}_{L,i} C i \overleftrightarrow{\partial}_\mu \bar{\nu}_{L,j}^T + C_{\text{VR},ij}^{(7)} \bar{u}_R \gamma^\mu d_R \bar{e}_{L,i} C i \overleftrightarrow{\partial}_\mu \bar{\nu}_{L,j}^T \right\} + \text{h.c.} \quad (8)$$

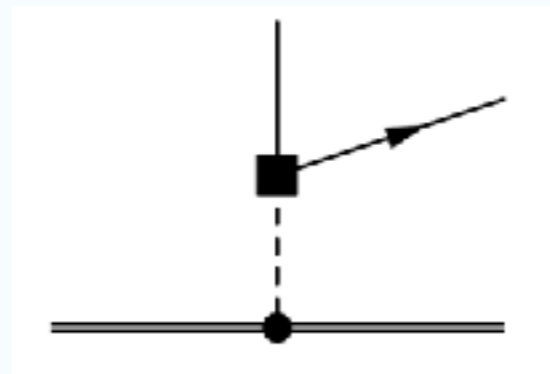
No dim-9 SMEFT 4-fermion operator!

ChiPT: Quark to Nucleon

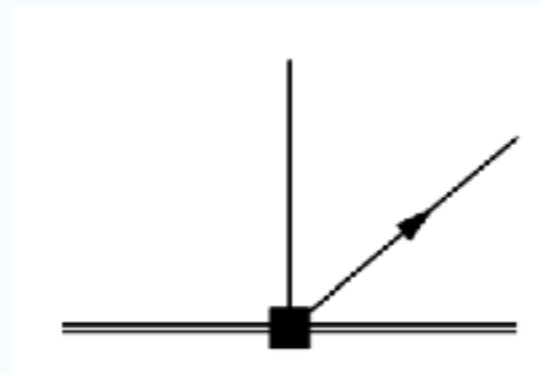
Chiral perturbation theory + Heavy baryon EFT + LNV external source



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

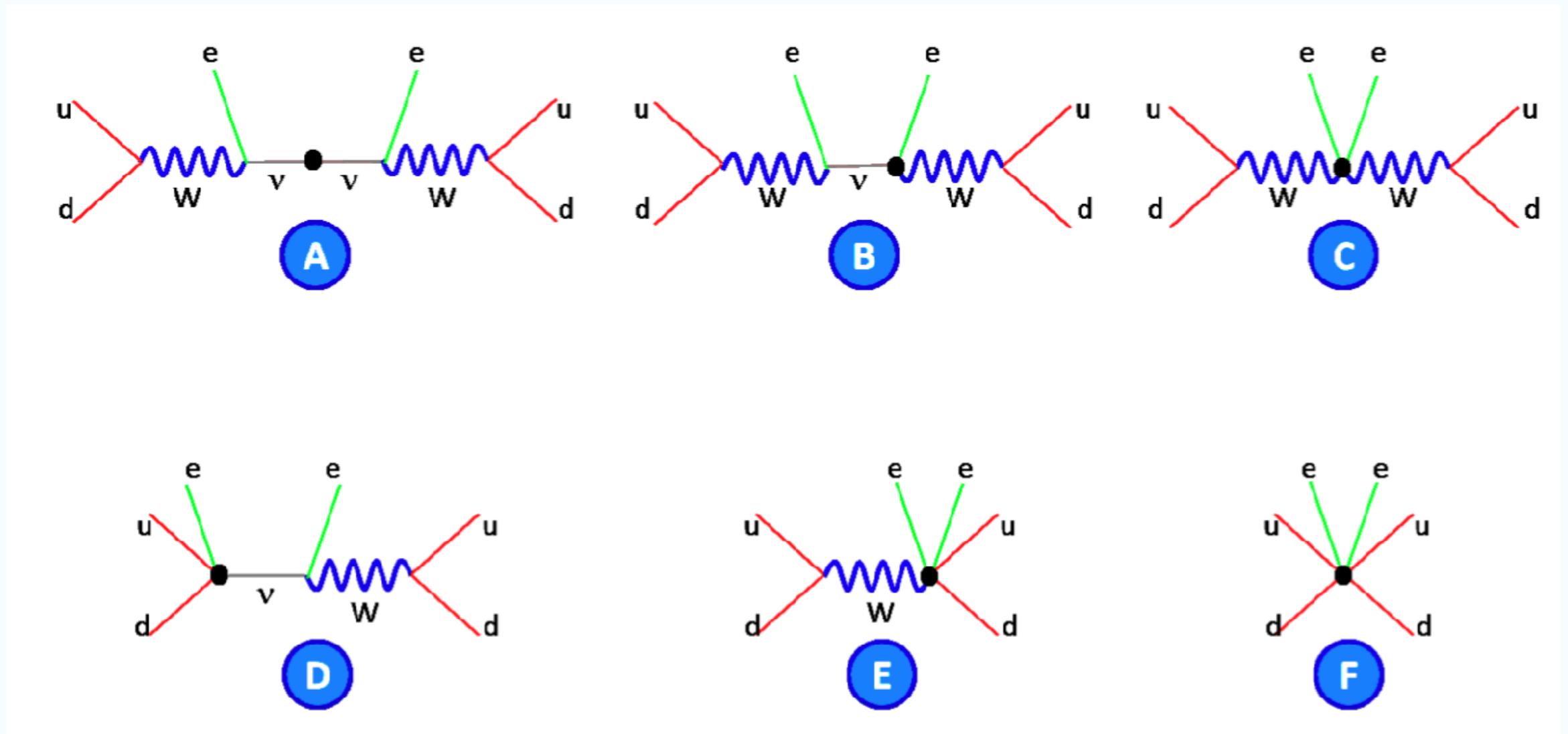


$\mathcal{L}_{\pi N}$

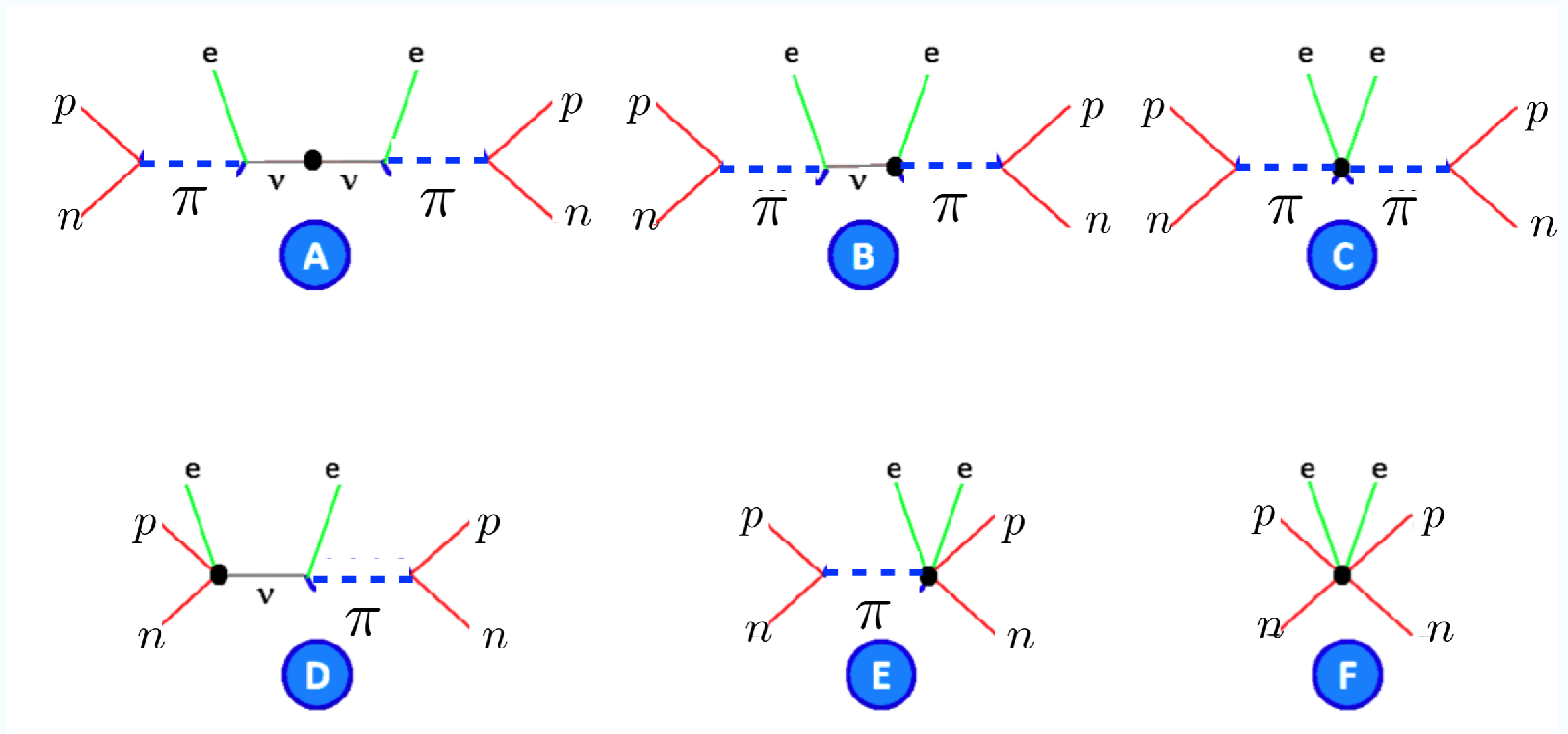


$\mathcal{L}_{\pi N}$

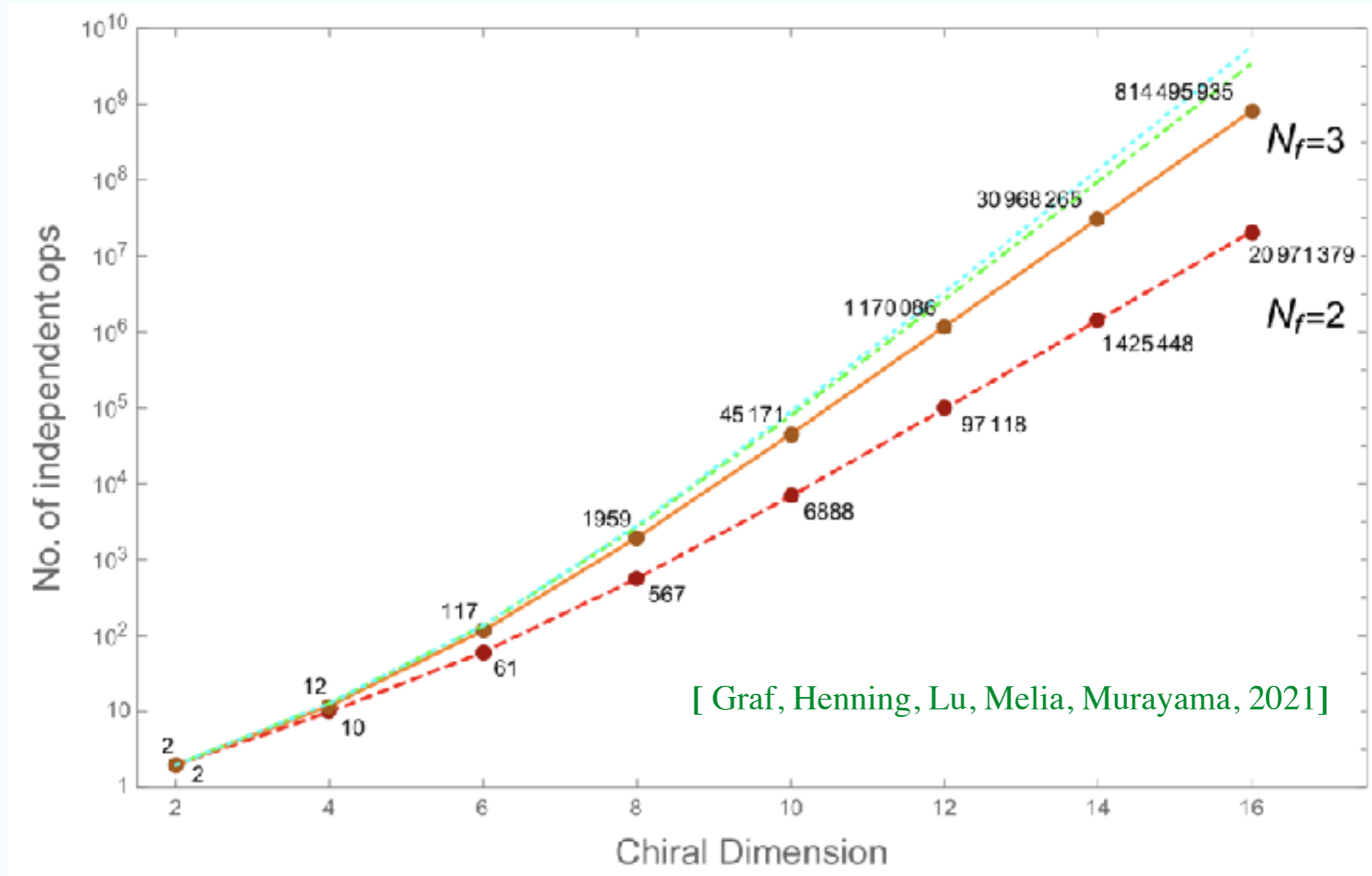
0vbb at SMEFT



0vbb at ChiPT



ChiPT Lagrangian



J. Bijnens, N. Hermansson-Truedsson, and S. Wang, 2019

Fettes, Meisner, Mojzis, Steininger, 2000

Girlanda, Pastore, Schiavilla, Viviani, 2010

Jiang-Hao Yu

Nv Potential Master Formula

$$\mathcal{A} = \langle 0^+ | \sum_{m,n} \int \frac{d^3 \mathbf{q}}{(2\pi)^3} e^{i\mathbf{q}\cdot\mathbf{r}} V(\mathbf{q}^2) | 0^+ \rangle \quad V(\mathbf{q}^2) = V_3(\mathbf{q}^2) + V_6(\mathbf{q}^2) + V_7(\mathbf{q}^2) + V_9(\mathbf{q}^2).$$

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

$$V_3(\mathbf{q}^2) = -(\tau^{(1)+}\tau^{(2)+})(4g_A^2 G_F^2 V_{ud}^2) m_{\beta\beta} \bar{u}(k_1) P_R C \bar{u}^T(k_2) \left\{ \frac{1}{\mathbf{q}^2} \left(-\frac{1}{g_A^2} h_F(\mathbf{q}^2) + \boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} h_{GT}(\mathbf{q}^2) + S^{(12)} h_T(\mathbf{q}^2) \right) + \frac{2g_V^{NN}}{g_A^2} h_F(\mathbf{q}^2) \right\}$$

$$V_6(\mathbf{q}^2) = \tau^{(1)+}\tau^{(2)+} 4g_A^2 G_F^2 V_{ud} \left(B \left(C_{SL}^{(6)} - C_{SR}^{(6)} \right) + \frac{m_\pi^2}{v} \left(C_{VL}^{(7)} - C_{VR}^{(7)} \right) \right) \frac{1}{\mathbf{q}^2} \bar{u}(k_1) P_R C \bar{u}^T(k_2) \left\{ \boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} \left(\frac{1}{2} h_{GT}^{AP}(\mathbf{q}^2) + h_{GT}^{PP}(\mathbf{q}^2) \right) + S^{(12)} \left(\frac{1}{2} h_T^{AP}(\mathbf{q}^2) + h_T^{PP}(\mathbf{q}^2) \right) \right\}. \quad (83)$$

More matrix element?

$$V_9(\mathbf{q}^2) = -(\tau^{(1)+}\tau^{(2)+}) g_A^2 \frac{4G_F^2}{v} \bar{u}(k_1) P_R C \bar{u}^T(k_2) \times \left[- \left(\boldsymbol{\sigma}^{(1)} \cdot \boldsymbol{\sigma}^{(2)} - S^{(12)} \right) \left(\frac{C_{\pi\pi L}^{(9)}}{6} \frac{\mathbf{q}^2}{(\mathbf{q}^2 + m_\pi^2)^2} - \frac{C_{\pi NL}^{(9)}}{3} \frac{\mathbf{q}^2}{\mathbf{q}^2 + m_\pi^2} \right) + \frac{2}{g_A^2} C_{NNL}^{(9)} \right]$$

Sterile Neutrino EFT

Dimension-5

Dim-5 operators			
N (n, \bar{n})	Classes	$\mathcal{N}_{\text{type}}$	\mathcal{N}_{num}
3 (2, 0)	$F_L \bar{\psi}^2 + h.c.$	$0+0+2+0$	2
4 (1, 0)	$\psi^2 \phi^2 + h.c.$	$0+0+2+0$	2
Total	4	$0+0+4+0$	4

2

[Aguila, Bar-Shalom, Soni, Wudka, 2009]

Dimension-6

Dim-6 operators			
N (n, \bar{n})	Classes	$\mathcal{N}_{\text{type}}$	\mathcal{N}_{num}
4 (2, 0)	$\psi^4 + h.c.$	$4+2+0+2$	14
	$F_L \psi^2 \phi + h.c.$	$4+0+0+0$	4
(1, 1)	$\psi^2 \psi^2$	$10+2+0+0$	12
	$\psi \psi^2 \phi^2 D$	$3+0+0+0$	3
5 (1, 0)	$\psi^2 \phi^3 + h.c.$	$2+0+0+0$	2
Total	8	$23+4+0+2$	35

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Dimension-7

Dim-7 operators			
N (n, \bar{n})	Classes	$\mathcal{N}_{\text{type}}$	\mathcal{N}_{num}
4 (3, 0)	$F_L^2 \psi^2 + h.c.$	$0+0+6+0$	6
	$F_L^2 \psi^2 + h.c.$	$0+0+6+0$	6
	$\psi^3 \psi^2 D + h.c.$	$0+4+20+0$	24
	$F_L \psi \psi^3 \phi D + h.c.$	$0+0+8+0$	8
(2, 1)	$\psi^2 \phi^2 D^2 + h.c.$	$0+0+4+0$	6
	$\psi^2 \phi^2 D^2 + h.c.$	$0+0+4+0$	6
5 (2, 0)	$\psi^4 + h.c.$	$0+2+10+0$	12
	$F_L \psi^2 \phi^2 + h.c.$	$0+0+6+0$	6
(1, 1)	$\psi^2 \psi^2 \phi$	$0+4+22+0$	26
	$\psi \psi^3 \phi^2 D$	$0+0+2+0$	2
6 (1, 0)	$\psi^2 \phi^3 + h.c.$	$0+0+2+0$	2
Total	18	$0+10+56+0$	116

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[Bhattacharya, Wudka, 2016]

[Liao, Ma, 2017]

Dimension-8

[Li, Ren, Xiao, Yu, Zheng, 2021]

N (n, \bar{n})	Classes	$\mathcal{N}_{\text{type}}$	\mathcal{N}_{num}	
4 (3, 1)	$\psi^4 D^2 + h.c.$	$4+0+2+2$	22	
	$F_L \psi^2 \phi D^2 + h.c.$	$4+0+0+0$	8	
	(2, 2)	$F_L F_R \psi \phi^2 D$	$3+0+0+0$	3
		$\psi^3 \psi^2 D^2$	$10+2+0+0$	12
5 (2, 0)	$F_R \psi^2 \phi D^2 + h.c.$	$4+0+0+0$	4	
	$\psi \psi^3 \phi^2 D^2$	$3+0+0+0$	3	
5 (3, 0)	$F_L \psi^4 + h.c.$	$10+4+0+2$	16	
	$F_L^2 \psi^2 \phi + h.c.$	$8+0+0+0$	8	
(2, 1)	$F_L \psi^2 \psi^2 + h.c.$	$42+12+0+0$	54	
	$F_L^2 \psi^2 \phi + h.c.$	$8+0+0+0$	8	
	$\psi^3 \psi^2 \phi D + h.c.$	$24+6+0+2$	30	
	$F_L \psi \psi^3 \phi^2 D + h.c.$	$12+0+0+0$	12	
	$\psi^2 \phi^3 D^2 + h.c.$	$2+0+0+0$	2	
	$\psi^2 \phi^3 D^2 + h.c.$	$2+0+0+0$	2	
6 (3, 0)	$\psi^4 \phi^2 + h.c.$	$8+2+0+2$	12	
	$F_L \psi^2 \phi^3 + h.c.$	$4+0+0+0$	4	
(1, 1)	$\psi^2 \psi^2 \phi^2$	$16+4+0+2$	22	
	$\psi \psi^3 \phi^2 D$	$3+0+0+0$	3	
7 (1, 0)	$\psi^2 \phi^3 + h.c.$	$2+0+0+0$	2	
Total	31	$167+30+2+10$	209	

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Jiang-Hao Yu

Dimension-9

[Li, Ren, Xiao, Yu, Zheng, 2021]

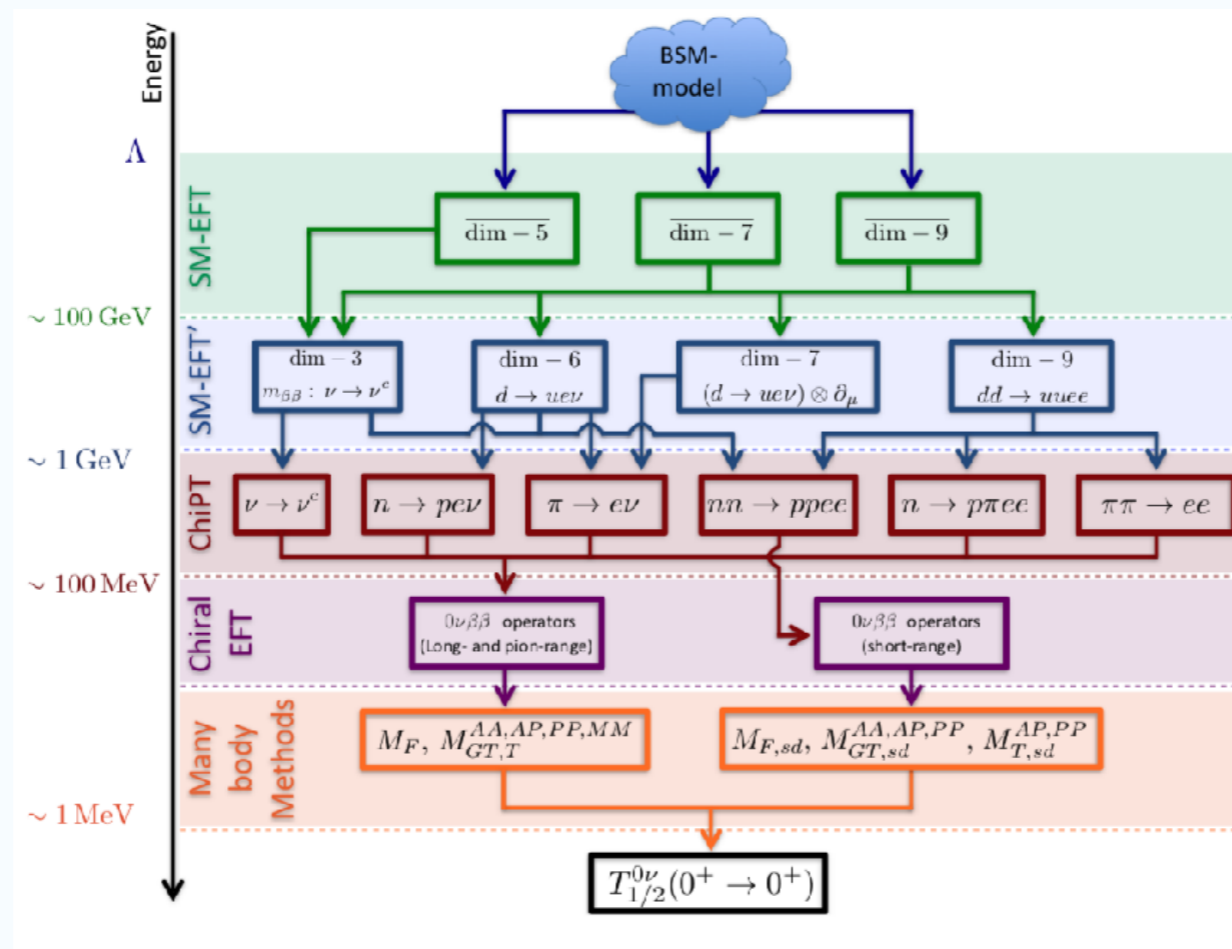
N (n, \bar{n})	Classes	$\mathcal{N}_{\text{type}}$	\mathcal{N}_{num}	
4 (4, 1)	$F_L^2 \psi^2 \phi^2 + h.c.$	$0+0+0+0$	0	
	$F_L F_R \psi^2 D^2 + h.c.$	$0+0+0+0$	0	
	$F_L^2 \psi^2 \phi^2 + h.c.$	$0+0+0+0$	0	
	$\psi^4 \phi^2 D^2 + h.c.$	$4+20+0+2$	26	
	$F_L \psi \psi^3 \phi^2 D + h.c.$	$0+0+0+0$	0	
5 (4, 0)	$F_L^2 \psi^2 + h.c.$	$0+10+0+3$	13	
	(3, 1)	$F_L \psi^3 + h.c.$	$0+1+0+0$	1
6 (3, 1)	$F_L \psi^3 \phi D + h.c.$	$10+12+0+0$	22	
	$F_L^2 \psi \psi^2 \phi D + h.c.$	$0+10+0+2$	12	
	$\psi^4 \phi^2 + h.c.$	$9+10+0+3$	22	
	$F_L \psi^2 \phi^2 D^2 + h.c.$	$0+0+0+0$	0	
	(2, 2)	$F_L F_R \psi^2 + h.c.$	$0+10+0+3$	13
	$F_L \psi^2 \phi^2 D + h.c.$	$10+12+0+0$	22	
7 (3, 0)	$F_L F_R \psi \phi^2 D$	$0+10+0+3$	13	
	$\psi^3 \psi^2 \phi D + h.c.$	$0+10+0+3$	13	
	$\psi^2 \phi^3 D^2 + h.c.$	$4+22+0+3$	29	
	$F_L \psi^2 \phi^2 D^2 + h.c.$	$0+1+0+0$	1	
	$\psi \psi^4 \phi^2 D^2 + h.c.$	$0+2+0+0$	2	
	$\psi^2 \phi^3 D^2 + h.c.$	$0+1+0+0$	1	
8 (3, 0)	$\psi^4 + h.c.$	$0+10+0+2$	12	
	$F_L \psi^2 \phi + h.c.$	$6+26+0+3$	35	
9 (2, 1)	$F_L^2 \psi^2 \phi^2 + h.c.$	$0+12+0+3$	15	
	(1, 1)	$\psi^4 \phi^2 + h.c.$	$0+100+14+0$	114
10 (2, 0)	$F_L \psi^2 \phi^2 \phi + h.c.$	$24+10+0+0$	34	
	$F_L^2 \psi^2 \phi^2 + h.c.$	$0+10+0+3$	13	
	$\psi^2 \phi^3 \phi D + h.c.$	$10+14+0+0$	24	
	$F_L \psi \psi^3 \phi^2 D + h.c.$	$0+0+0+0$	0	
	$\psi^2 \phi^3 D^2 + h.c.$	$0+1+0+0$	1	
	$\psi^2 \phi^3 D^2 + h.c.$	$0+1+0+0$	1	
11 (2, 0)	$\psi^4 \phi^2 + h.c.$	$2+12+0+2$	16	
	$F_L \psi^2 \phi^3 + h.c.$	$0+0+0+0$	0	
(1, 1)	$\psi^2 \psi^2 \phi^2$	$4+22+0+2$	28	
	$\psi \psi^3 \phi^2 D$	$0+1+0+0$	1	

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Summary

Summary

- $0\nu\beta\beta$ involves in many scales: SMEFT, LEFT, ChiEFT
- The complete bases just written down recently 2020 - 2021
- The formalism needs to be extended in each EFT levels



Thanks very much!