



v Mass & Ovbb 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 0vbb in EFT approach?
- SMEFT: 0vbb and nv masses, UV physics
- LEFT: quark currents and weak sources
- ChiPT: short-range, pion-range, long-range
- Summary and outlook

Introduction

Why Ovbb in EFT approach?

Search For New Physics

ATLAS SUSY Searches^a - 95% CL Lower Limits

March 2021

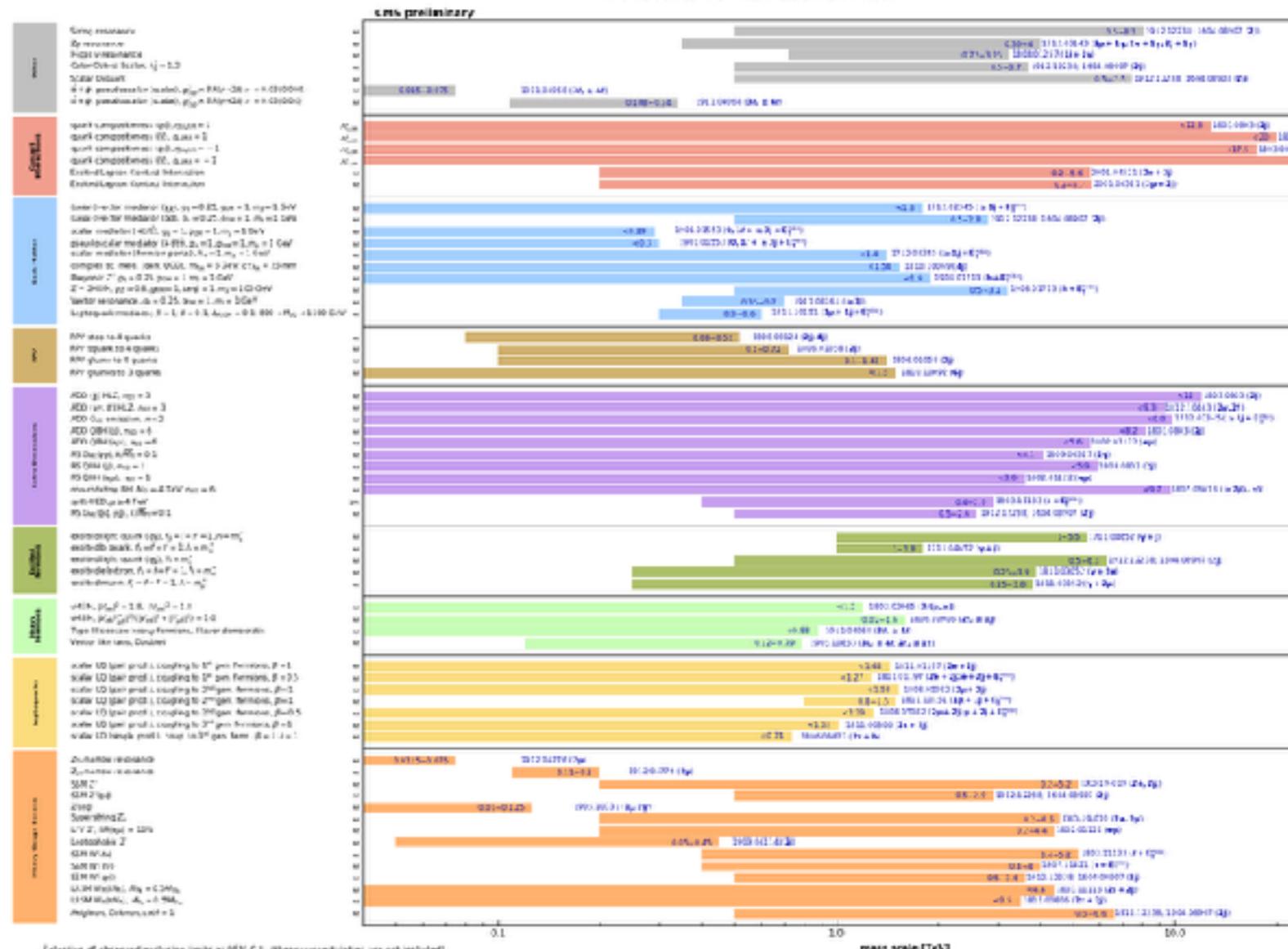
Only a selection of the available mesh links on new sites or platforms is shown. Many of the links are based on different protocols, e.g., [http://www.ncbi.nlm.nih.gov](#)

ATLAS Preliminary

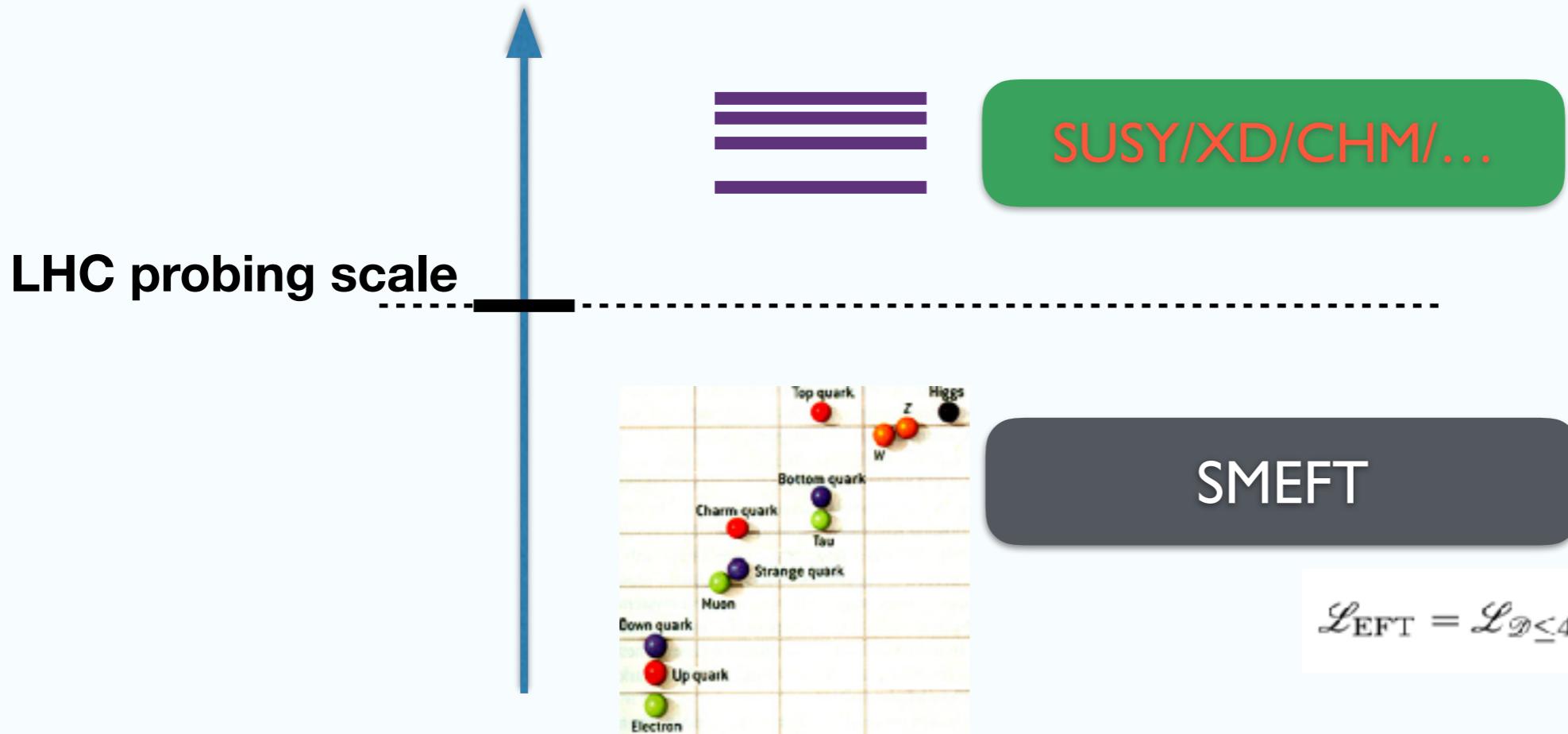
$$\sqrt{s} = 13 \text{ TeV}$$

Reference	
39	0.16893
21	R2.128/4
69	0.14693
20	0.18233
21	H1.01429
18	5.11081
20	0.06033
18	9.05451
ATLAS	CDF-AT-2013-3+4
	1899.05451
21	0.1627
21	C1.12527
1899.08.123	
ATLAS	CDF-AT-2020-3+1
2021.1.1865.205.203700	
39	0.06769
ATLAS	CDF-AT-2013-300
1898.01.440	
21	R2.128/4

Overview of CMS EXO results



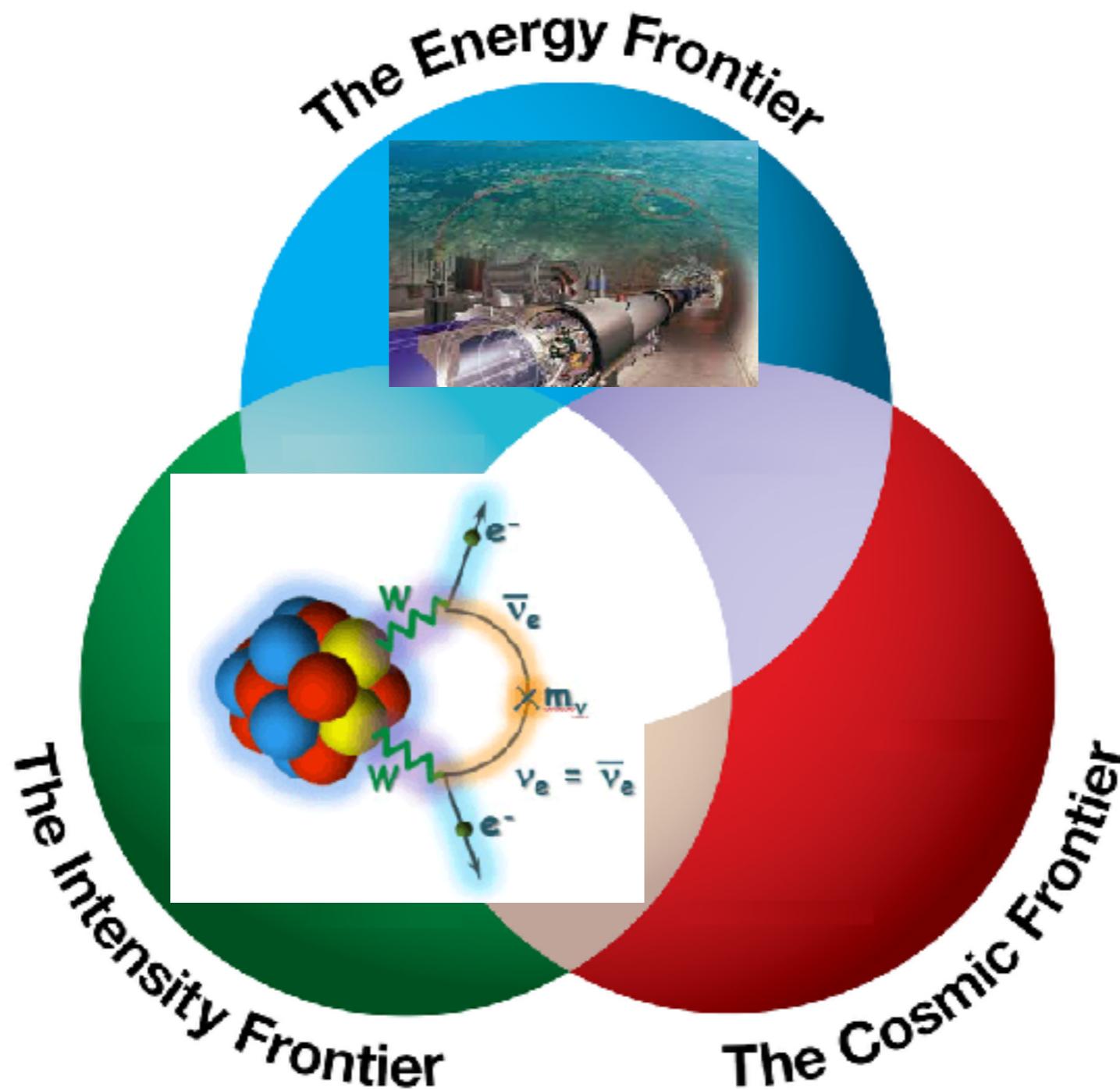
New Physics w/o New Particle



Top-down: Integrate out and matching/running

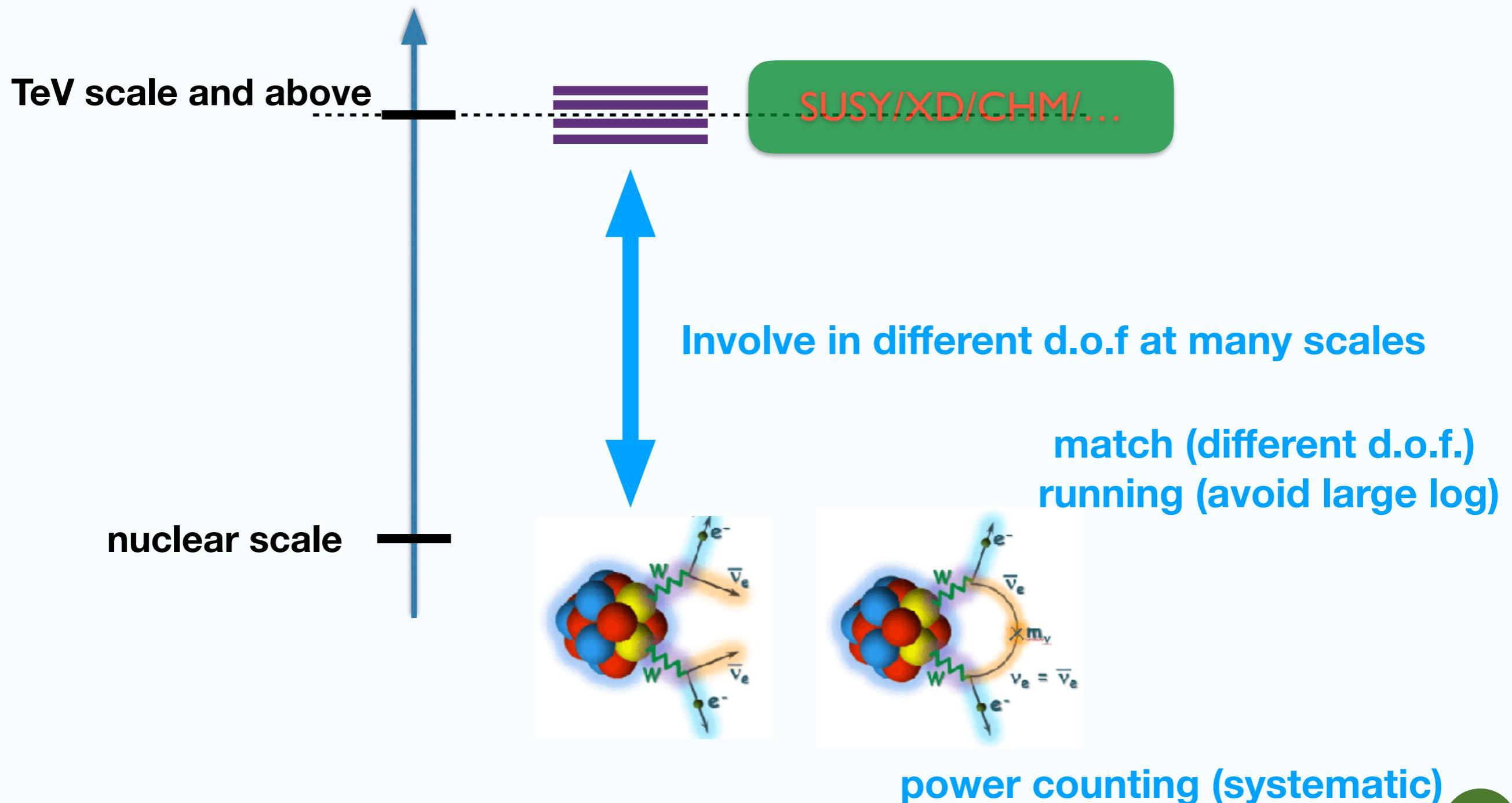
Bottom-up: field d.o.f and symmetry at IR scale

New Physics w/o New Particle



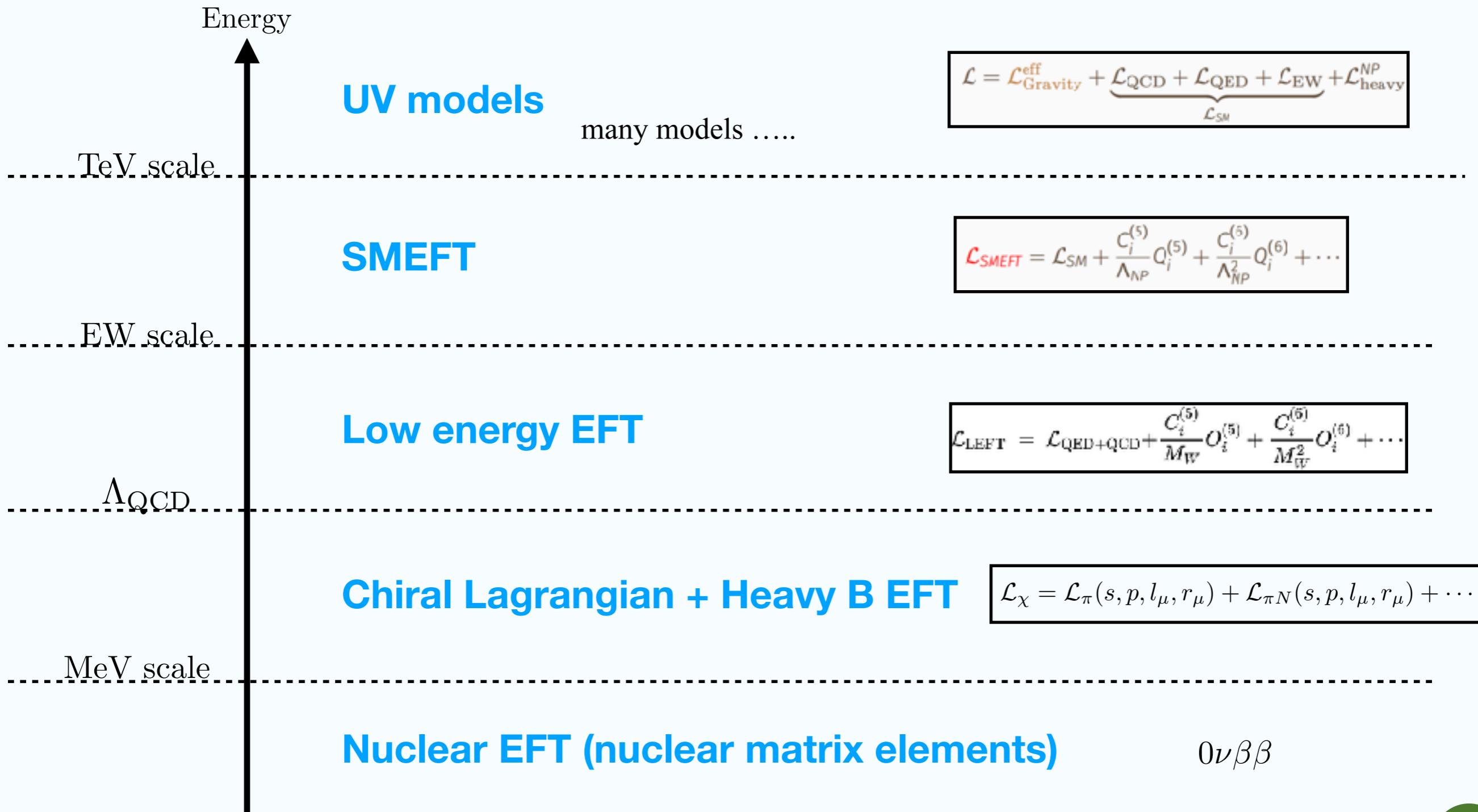
Low Energy Probe of HEP

Low energy probes of high energy physics

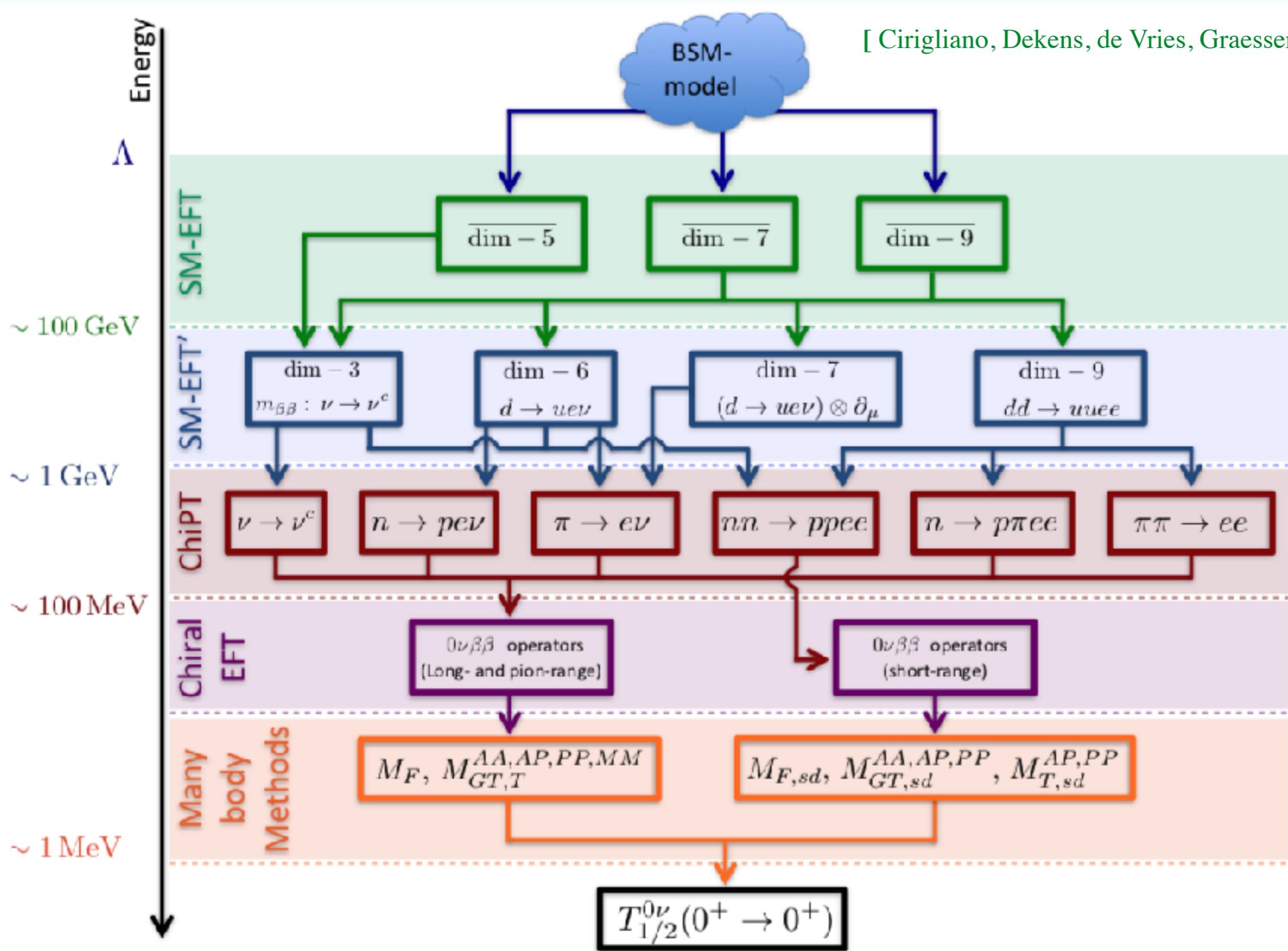


EFT Framework

Model independent systematical parametrization of new physics

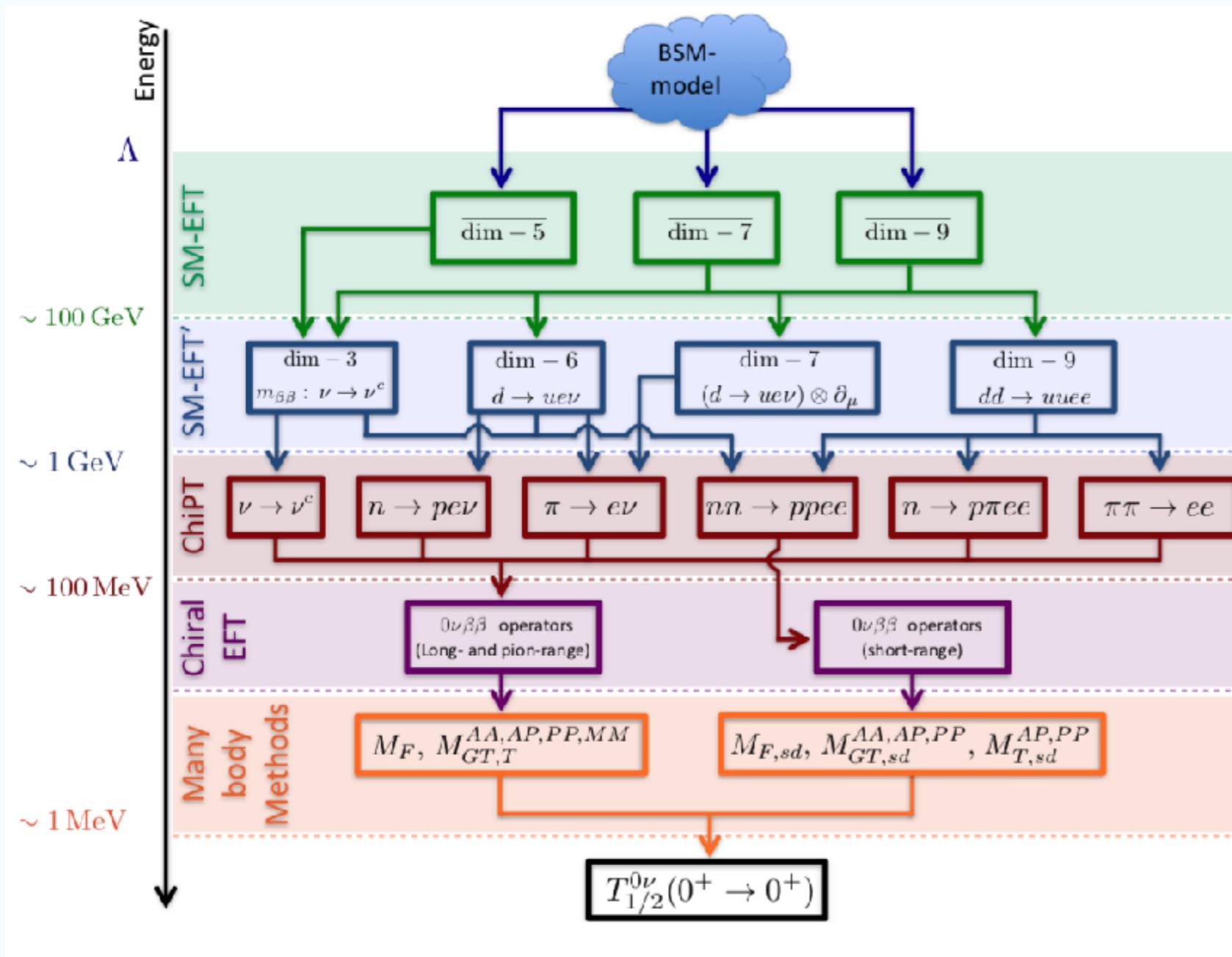


EFT for $0\nu\text{bb}$



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?

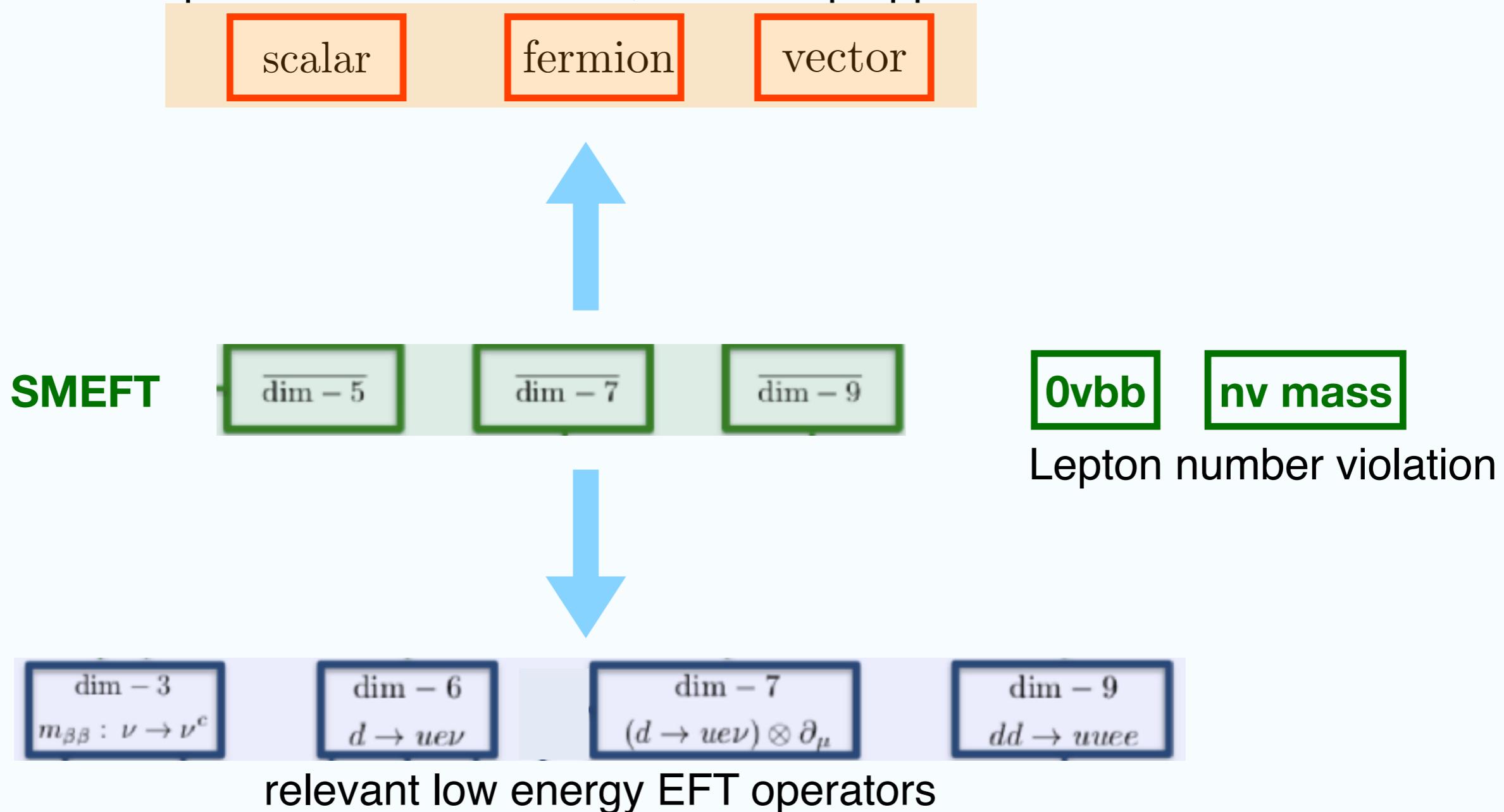
Still top-down: Integrate out and matching/running

SMEFT

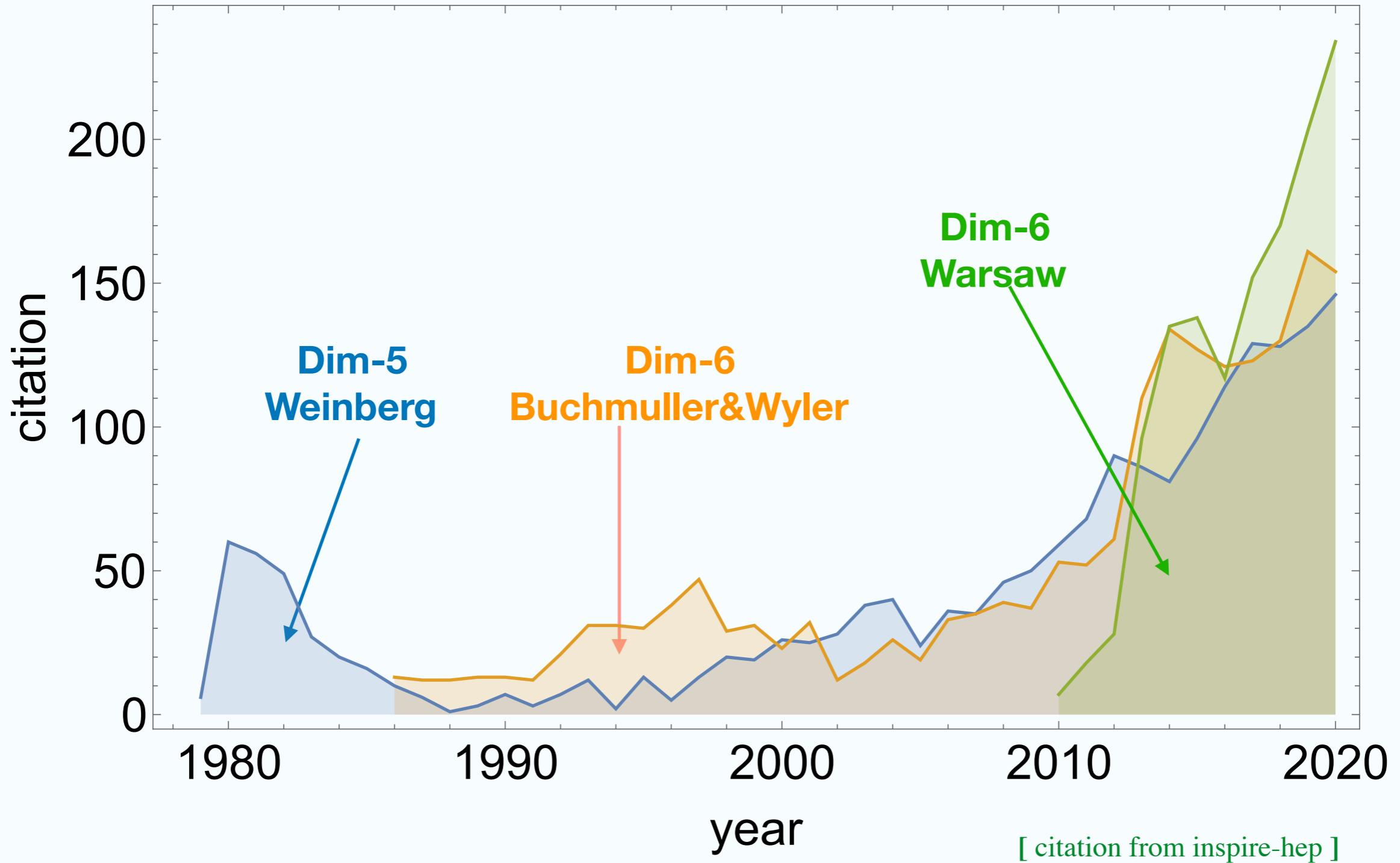
0vbb/nv operators and UV Resonances

SMEFT

Various possible UV realization, bottom-up approach

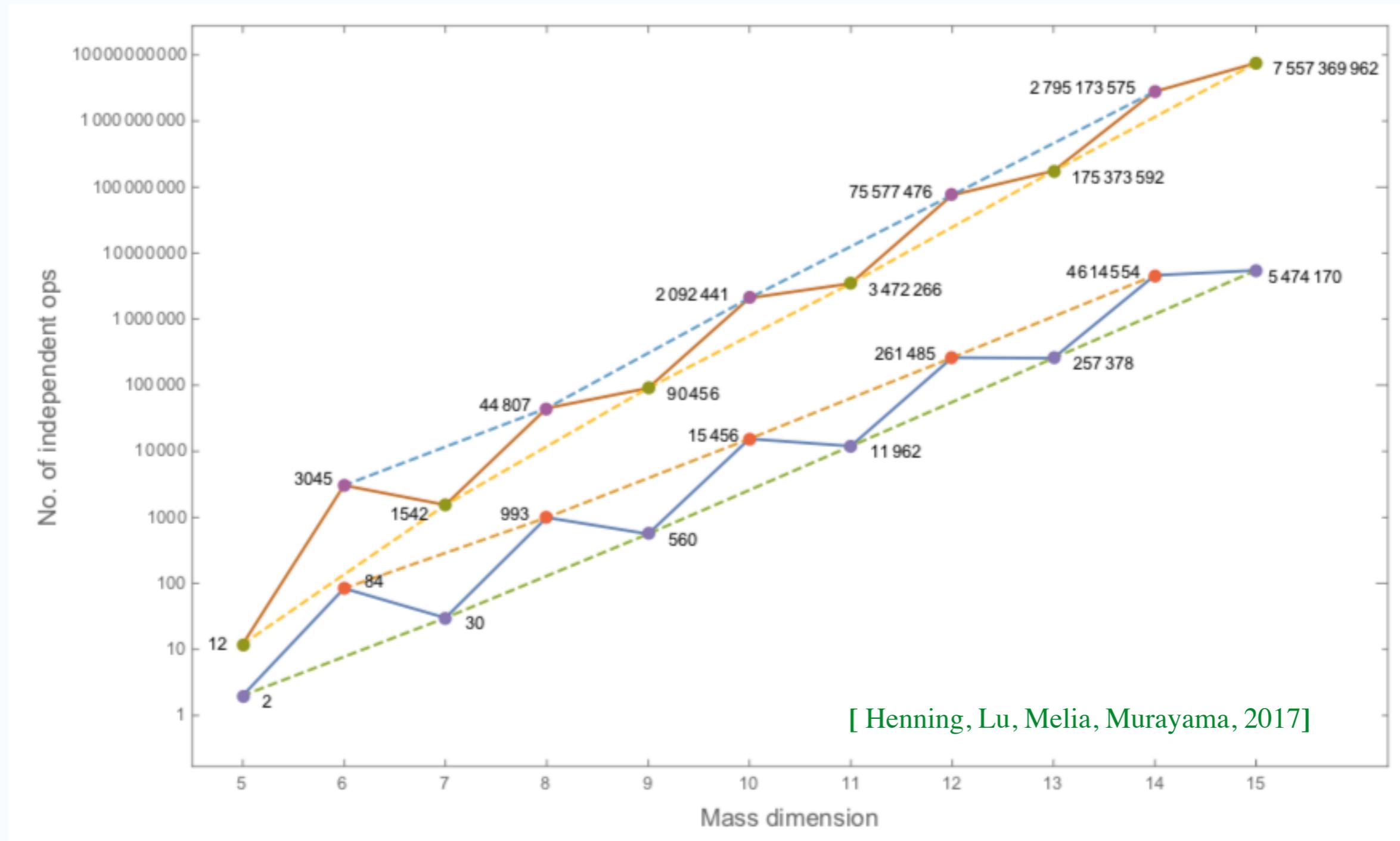


SMEFT Operators



Hilbert Series Counting

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



Higher Dim Operators!?

Given numbers of independent operators

does not mean we know explicit form of operators!

Derivatives

$$BWHH^\dagger D^2$$

2

Repeated fields

$$QQQL$$

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

Which 2 should be picked up?

What flavor relations should be imposed?

$$\begin{aligned}
 & \epsilon^{abc} \epsilon^{ik} \epsilon^{jl} (L_{pi} Q_{rak}) (Q_{sbk} Q_{tcl}) \\
 & \epsilon^{abc} \epsilon^{ik} \epsilon^{jl} (L_{pi} Q_{slk}) (Q_{raj} Q_{tcl}) \\
 & \epsilon^{abc} \epsilon^{ij} \epsilon^{kl} (L_{pi} Q_{sik}) (Q_{raj} Q_{tcl}) \\
 & \epsilon^{abc} \epsilon^{ij} \epsilon^{kl} (L_{pi} Q_{slk}) (Q_{raj} Q_{tcl})
 \end{aligned}$$

$p, r, s, t = 1, 2, 3$

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）

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

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

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

$$\partial \psi = \left(1, \frac{1}{2}\right) + \left(0, \frac{1}{2}\right) \quad (D\psi)_{\alpha\beta\dot{\alpha}} = -\frac{1}{2} \epsilon_{\alpha\beta} (\not{D}\psi)_{\dot{\alpha}} + \frac{1}{2} (D\psi)_{(\alpha\beta)\dot{\alpha}}$$

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

$$\square = [1^2]$$

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

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

SSYT

Operator Construction

$$BWHH^\dagger D^2$$

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

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

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

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highest weight representation

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

$$\begin{aligned} & (DH^\dagger)_{\alpha\beta}(DH)_{\beta\delta} B_{L[\gamma\delta]} W_{L[\zeta\eta]} e^{\alpha\beta} e^{\eta\delta} e^{\gamma\zeta} \\ & (DH^\dagger)_{\alpha\beta}(DH)_{\beta\delta} B_{L[\gamma\delta]} W_{L[\zeta\eta]} \frac{1}{2} e^{\alpha\beta} e^{\eta\delta} (e^{\alpha\zeta} e^{\gamma\eta} + e^{\beta\zeta} e^{\gamma\eta}) \\ & (DH^\dagger)_{\alpha\beta} H B_{L[\gamma\delta]} (DB_L)_{[\alpha\beta\zeta]\beta} W_{L[\zeta\eta]} e^{\alpha\beta} e^{\eta\delta} e^{\gamma\zeta} \\ & (DH^\dagger)_{\alpha\beta} H B_{L[\gamma\delta]} (DW_L)_{[\beta\eta\delta]\beta} e^{\alpha\beta} e^{\eta\delta} e^{\gamma\zeta} \\ & H^\dagger (DH)_{\alpha\beta} (DB_L)_{[\beta\gamma\delta]\beta} W_{L[\zeta\eta]} e^{\alpha\beta} e^{\eta\delta} e^{\gamma\zeta} \\ & H^\dagger (DH)_{\alpha\beta} B_{L[\gamma\delta]} (DW_L)_{[\beta\eta\delta]\beta} e^{\alpha\beta} e^{\eta\delta} e^{\gamma\zeta} \\ & H^\dagger H (DB_L)_{[\alpha\beta\gamma]\beta} (DW_L)_{[\eta\delta\gamma]\beta} e^{\alpha\beta} e^{\eta\delta} e^{\gamma\zeta} \end{aligned}$$

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

1	1	1	3
2	2	2	4

1	1	1	2
2	2	3	4

$$B_L{}^{\alpha\beta} W_{L\alpha\beta} (DH^\dagger)^\gamma{}_{\dot{\alpha}} (DH)_{\gamma}{}^{\dot{\alpha}}, \quad B_L{}^{\alpha\beta} W_{L\alpha}{}^\gamma (DH^\dagger)_{\beta\dot{\alpha}} (DH)_{\gamma}{}^{\dot{\alpha}} \quad 2$$

$$[i \boxed{j}] \times [k] \times \boxed{l} = \begin{array}{|c|c|} \hline i & j \\ \hline k & l \\ \hline \end{array}$$

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

SMEFT

Dimension-5

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

[Weinberg, 1979]

2

ψ^4 and $\phi^4 D^4$	$\psi^2 \bar{\psi}^2$	X^8
$O_3 = (\psi^4)^2$	$O_{\bar{3}} = (\bar{\psi}^4)^2$	$O_8 = -i^{16} C_i G_i^{\mu\nu} G_i^{\rho\sigma}$
$O_{451} = (\psi^4)^2 (\bar{\psi}^4) \psi^4 \bar{\psi}^4$	$O_{452} = (\bar{\psi}^4)^2 (\bar{\psi}^4) \bar{\psi}^4 \psi^4$	$O_9 = -i^{16} \bar{C}_i G_i^{\mu\nu} G_i^{\rho\sigma}$
$O_{450} = (\psi^4)^2 (\bar{\psi}^4) (\psi^4 \bar{\psi}^4)$	$O_{453} = (\bar{\psi}^4)^2 (\bar{\psi}^4) (\bar{\psi}^4 \psi^4)$	$O_{10} = -e^{i\omega} W_i^\mu W_i^\nu W_i^\rho W_i^\sigma$
		$O_{11} = -e^{-i\omega} \bar{W}_i^\mu \bar{W}_i^\nu \bar{W}_i^\rho \bar{W}_i^\sigma$

$\psi^4 D^2$	$\psi^2 \bar{\psi}^2$	$(LL)(RR)$	$(LR)(LR)$
$O_{42} = (\psi^4)^2 G_i^{\mu\nu} G_i^{\rho\sigma}$	$O_{\bar{42}} = (\bar{\psi}^4)^2 G_i^{\mu\nu} G_i^{\rho\sigma}$	$O_{43} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} L_\sigma)$	$O_{\bar{43}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} L_\sigma)$
$O_{421} = (\psi^4)^2 G_i^{\mu\nu} G_i^{\rho\sigma}$	$O_{\bar{421}} = (\bar{\psi}^4)^2 G_i^{\mu\nu} G_i^{\rho\sigma}$	$O_{44} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} L_\sigma)$	$O_{\bar{44}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} L_\sigma)$
$O_{420} = (\psi^4)^2 G_i^{\mu\nu} W_i^{\rho\sigma}$	$O_{\bar{420}} = (\bar{\psi}^4)^2 G_i^{\mu\nu} W_i^{\rho\sigma}$	$O_{45} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$	$O_{\bar{45}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$
$O_{420} = (\psi^4)^2 G_i^{\mu\nu} \bar{W}_i^{\rho\sigma}$	$O_{\bar{420}} = (\bar{\psi}^4)^2 G_i^{\mu\nu} \bar{W}_i^{\rho\sigma}$	$O_{46} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$	$O_{\bar{46}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$
$O_{421} = (\psi^4)^2 G_i^{\mu\nu} W_i^{\rho\sigma}$	$O_{\bar{421}} = (\bar{\psi}^4)^2 G_i^{\mu\nu} W_i^{\rho\sigma}$	$O_{47} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$	$O_{\bar{47}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$
$O_{420} = (\psi^4)^2 G_i^{\mu\nu} \bar{W}_i^{\rho\sigma}$	$O_{\bar{420}} = (\bar{\psi}^4)^2 G_i^{\mu\nu} \bar{W}_i^{\rho\sigma}$	$O_{48} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$	$O_{\bar{48}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$
$O_{421} = (\psi^4)^2 G_i^{\mu\nu} \bar{W}_i^{\rho\sigma}$	$O_{\bar{421}} = (\bar{\psi}^4)^2 G_i^{\mu\nu} \bar{W}_i^{\rho\sigma}$	$O_{49} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$	$O_{\bar{49}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$
$O_{420} = -(\psi^4)^2 \bar{G}_i^{\mu\nu} \bar{G}_i^{\rho\sigma}$	$O_{\bar{420}} = -(\bar{\psi}^4)^2 G_i^{\mu\nu} G_i^{\rho\sigma}$	$O_{50} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$	$O_{\bar{50}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$
$O_{421} = -(\psi^4)^2 \bar{G}_i^{\mu\nu} \bar{G}_i^{\rho\sigma}$	$O_{\bar{421}} = -(\bar{\psi}^4)^2 G_i^{\mu\nu} G_i^{\rho\sigma}$	$O_{51} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$	$O_{\bar{51}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$
$O_{420} = -(\psi^4)^2 \bar{G}_i^{\mu\nu} \bar{G}_i^{\rho\sigma}$	$O_{\bar{420}} = -(\bar{\psi}^4)^2 G_i^{\mu\nu} G_i^{\rho\sigma}$	$O_{52} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$	$O_{\bar{52}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Y^{\rho\sigma})$

$(LR)(R\bar{L})$ and $(LR)(L\bar{R})$		B -violating
$O_{453} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Q_i^{\mu\nu})$	$O_{\bar{453}} = (\bar{L}_{T_\mu} L_\nu) (\bar{L}_{T_\rho} Q_i^{\mu\nu})$	$O_{53} = e^{i\omega} \epsilon_{\mu\nu} [(Q_i^{\mu\nu})^2 C_i] / [(Q_i^{\mu\nu})^2 C_i]$
$O_{454}^{(1)} = (\bar{Q}_i^{\mu\nu})^2 C_i$	$O_{\bar{454}^{(1)}} = (\bar{Q}_i^{\mu\nu})^2 C_i$	$O_{54} = e^{i\omega} \epsilon_{\mu\nu} [(Q_i^{\mu\nu})^2 C_i] / [(Q_i^{\mu\nu})^2 C_i]$
$O_{455}^{(1)} = (\bar{Q}_i^{\mu\nu})^2 C_i$	$O_{\bar{455}^{(1)}} = (\bar{Q}_i^{\mu\nu})^2 C_i$	$O_{55} = e^{i\omega} \epsilon_{\mu\nu} [(Q_i^{\mu\nu})^2 C_i] / [(Q_i^{\mu\nu})^2 C_i]$
$O_{456}^{(1)} = (\bar{Q}_i^{\mu\nu})^2 C_i$	$O_{\bar{456}^{(1)}} = (\bar{Q}_i^{\mu\nu})^2 C_i$	$O_{56} = e^{i\omega} \epsilon_{\mu\nu} [(Q_i^{\mu\nu})^2 C_i] / [(Q_i^{\mu\nu})^2 C_i]$
$O_{457}^{(1)} = (\bar{Q}_i^{\mu\nu})^2 C_i$	$O_{\bar{457}^{(1)}} = (\bar{Q}_i^{\mu\nu})^2 C_i$	$O_{57} = e^{i\omega} \epsilon_{\mu\nu} [(Q_i^{\mu\nu})^2 C_i] / [(Q_i^{\mu\nu})^2 C_i]$

[Buchmuller, Wyler, 1986]

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

Dimension-8

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

[Murphy, 2020]

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(n, k)	Number	N_{typ}	N_{con}	N_{spur}	Equation
4 (1, 0)	$\lambda_0^4 + h.c.$	16	20	26	[4.10]
(3, 1)	$E_L^2 \psi^2 D + h.c.$	22	22	22n ₁ ²	[4.20]
	$\phi^4 D^4 + h.c.$	4-11	18-11	18n ₁ ² (n ₂ -1)	[4.75, 478, 4.88]
	$\psi_L^2 \psi_R^2 \phi^2 + h.c.$	16	32	32n ₁ ²	[4.40]
	$E_L^2 \phi^2 D^2 + h.c.$	8	12	12	[4.10]
(3, 2)	$\lambda_0^2 \lambda_1^2$	16	17	17	[4.18]
	$E_L^2 E_R \psi^2 D$	27	30	30n ₁ ²	[4.30, 4.43]
	$\psi_L^2 \psi_R^2 D^2$	17-11	34-18	n ₁ ² (3n ₁ + 11) (6n ₁)	[4.71, 420-4.81]
	$\psi_L^2 \psi_R^2 \phi^2 + h.c.$	16	16	16n ₁ ²	[4.40]
	$E_L^2 E_R \psi^2 D^2$	5	6	5	[4.14]
	$\psi_L^2 \psi^2 D^2$	7	16	16n ₁ ²	[4.31, 4.32]
	$\eta^2 D^8$	1	3	3	[4.8]
5 (1, 0)	$\lambda_0^5 + h.c.$	12-13	66-51	13n ₁ ² (2n ₁ - 1)	[4.98, 4.99, 4.99]
	$E_L^2 \psi^2 D + h.c.$	32	30	30n ₁ ²	[4.47, 4.48]
	$\psi_L^2 \psi^2 D + h.c.$	6	6	6	[4.11]
(3, 1)	$\lambda_0 \lambda_1 \lambda_2 \psi^2 D^2 + h.c.$	84-72	177-131	10n ₁ ² (5n ₁ ² - 12) (4n ₁ ²)	[4.85-4.95, 4.98-4.97]
	$E_L^2 \psi^2 D + h.c.$	32	30	30n ₁ ²	[4.47, 4.48]
	$\psi^2 \phi^2 \psi D + h.c.$	32-18	108-78	n ₁ ² (13n ₁ - 1) + n ₁ ² (29n ₁ + 3)	[4.64-4.65-4.75]
	$E_L^2 \psi^2 \phi^2 D + h.c.$	38	32	32n ₁ ²	[4.30, 4.40]
	$\psi^2 \phi^2 D^2 + h.c.$	4	36	36n ₁ ²	[4.28]
	$E_L^2 \phi^2 \phi^2 + h.c.$	4	8	8	[4.11]
(2, 0)	$\phi^6 D^4 + h.c.$	12-14	46-16	5 (3n ₁ + n ₂ ²) - 2 (3n ₁ ² + n ₂ ²)	[4.52, 4.59, 4.62, 4.58]
	$E_L^2 \phi^2 \phi^2 + h.c.$	16	22	22n ₁ ²	[4.28]
	$\phi_L^2 \phi^2 + h.c.$	8	10	10	[4.10]
(1, 1)	$\psi^2 \psi^2 \phi^2$	23-13	52-14	n ₁ ² (4n ₁ ² + n ₂ ²) + 2 (3n ₁ ² + 2n ₂ ²) - 1	[4.11, 4.15, 4.18, 4.21]
	$\psi^2 \phi^2 \phi^2 D$	7	13	13n ₁ ²	[4.28, 4.31]
	$\phi_L^2 D^2$	1	2	2	[4.8]
2 (1, 0)	$\phi^2 \phi^6 + h.c.$	8	8	8n ₁ ²	[4.20]
3 (0, 0)	ϕ^2	1	1	1	[4.3]
Total		48	177-421	187364-848	98 (2n ₁ - 1) - 18640 (n ₂ - 1)

Jiang-Hao Yu

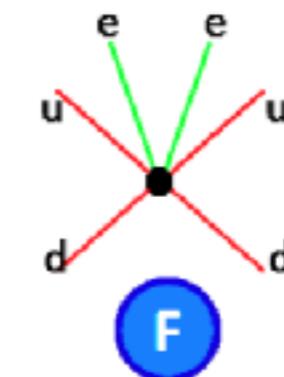
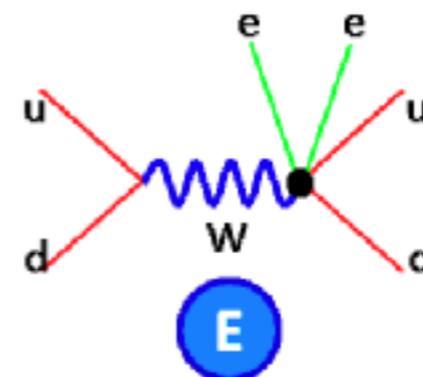
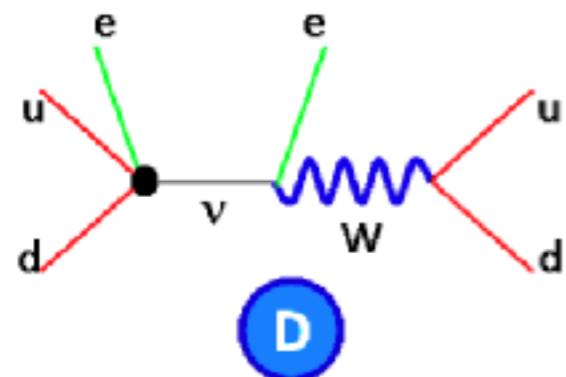
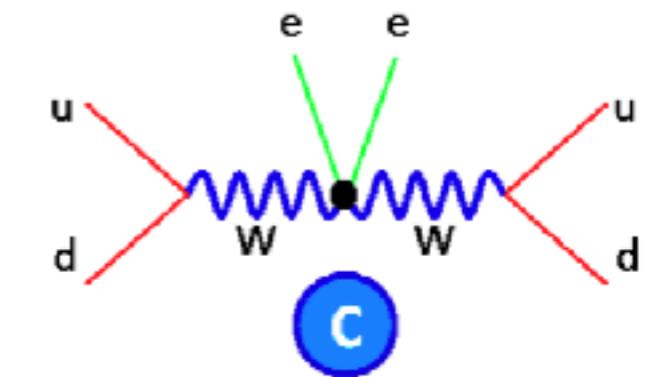
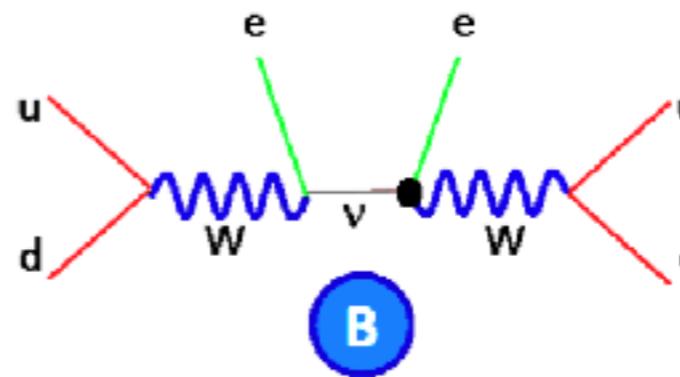
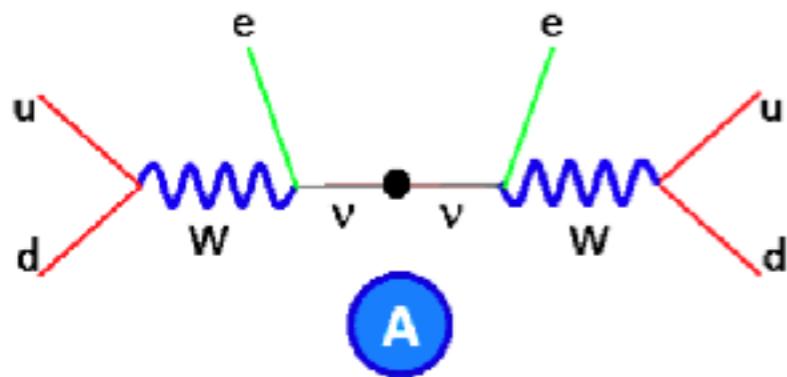
Dimension-6

Dimension-7

1 : $\psi^2 X H^2 + \text{h.c.}$		2 : $\psi^2 H^4 + \text{h.c.}$	
Q_{DWWH^2}	$e_{\alpha\beta\gamma} (\tau^I \epsilon_{jk}) (l_p^m C_i \phi^{\mu\nu} l_j^i) H^{\alpha} H^{\beta} W_{\mu\nu}^T$	Q_{DWH^4}	$e_{\alpha\beta\gamma} e_{jk} (l_p^m C_i) H^{\alpha} H^{\beta} H^4$
Q_{DHHH^2}	$e_{\alpha\beta\gamma} e_{jk} (l_p^m C_i \phi^{\mu\nu} l_j^i) H^{\alpha} H^{\beta} B_{\mu\nu}$		
3(B) : $\psi^4 H + \text{h.c.}$		3(B) : $\psi^4 H + \text{h.c.}$	
$Q_{D\psi\psi H}$	$e_{\mu\lambda} e_{\nu\rho} e_{jk} (l_p^m C_i) H^{\mu} H^{\nu} \bar{\psi}^{\rho} \bar{\psi}^{\lambda}$	$Q_{D\psi\psi M}$	$e_{\alpha\beta\gamma} (\bar{l}_p d_\nu^{\mu} \bar{\psi}^{\rho}) (l_p^m C_i) \bar{\psi}^{\lambda}$
$Q_{D\psi\psi H}$	$e_{\mu\lambda} e_{\nu\rho} e_{jk} (l_p^m C_i) H^{\mu} H^{\nu} \bar{\psi}^{\rho} \bar{\psi}^{\lambda}$	$Q_{D\psi\psi H}$	$e_{\alpha\beta\gamma} e_{jk} (\bar{l}_p d_\nu^{\mu} \bar{\psi}^{\rho}) (l_p^m C_i) \bar{\psi}^{\lambda}$
$Q_{D\psi\psi H}$	$e_{\mu\lambda} e_{\nu\rho} e_{jk} (l_p^m C_i) H^{\mu} H^{\nu} \bar{\psi}^{\rho} \bar{\psi}^{\lambda}$	$Q_{D\psi\psi H}$	$e_{\alpha\beta\gamma} (\bar{l}_p d_\nu^{\mu} \bar{\psi}^{\rho}) (l_p^m C_i) \bar{\psi}^{\lambda}$
4 : $\psi^2 H^2 D + \text{h.c.}$		5(B) : $\psi^4 D + \text{h.c.}$	
$Q_{D\psi H^2 D}$	$e_{\mu\lambda} e_{\nu\rho} e_{jk} (l_p^m C_i \psi^\mu l_j^i) H^{\alpha} H^{\beta} D_\mu H$		

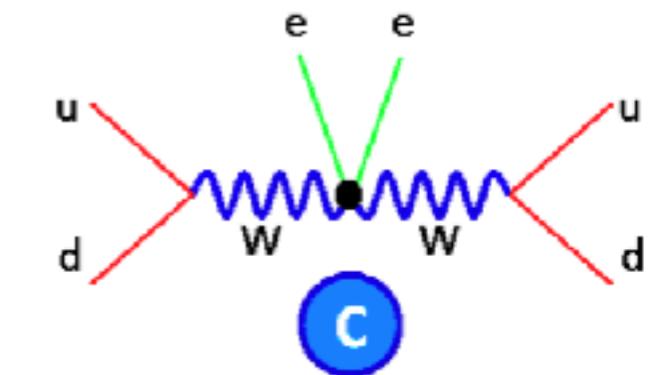
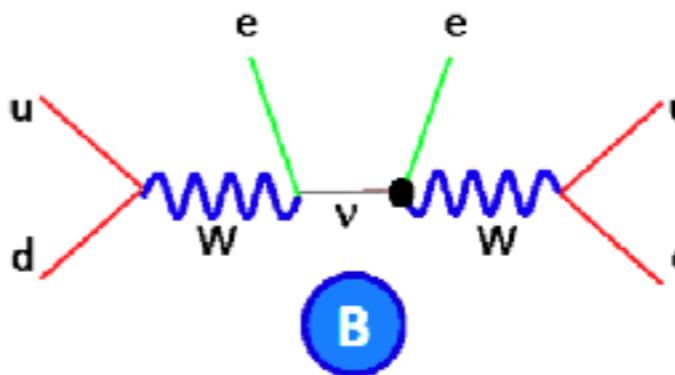
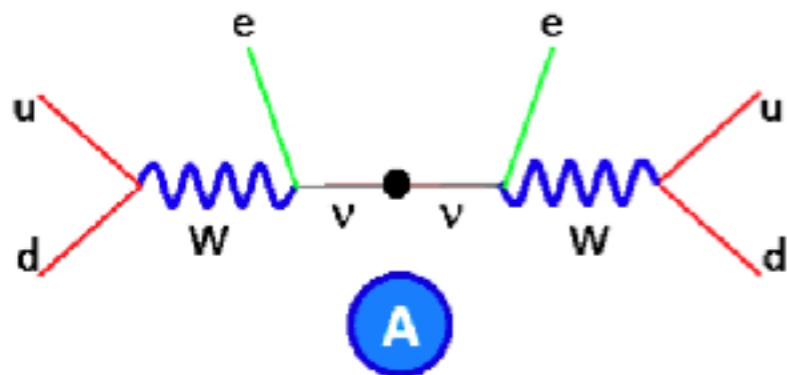
0vbb Related Operators

SMEFT broken phase:



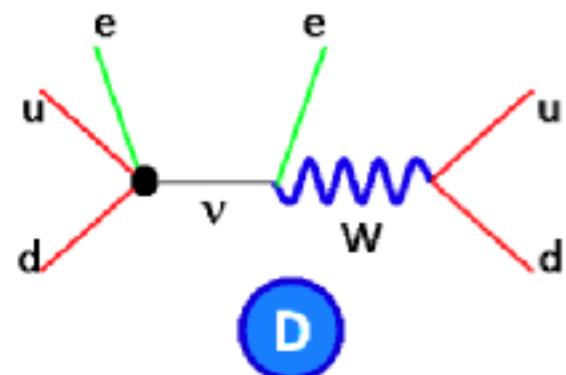
0vbb Related Operators

Relate to SMEFT unbroken operators:

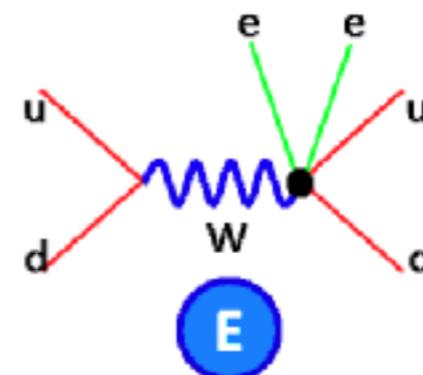


$$(\bar{\ell}_\alpha \phi) (\tilde{\phi}^\dagger \ell_\beta)$$

Dim-5



Dim-7, 9

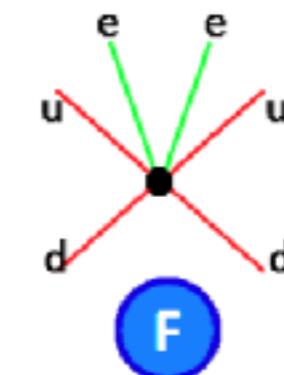


Dim-7, 9

$$(\phi^\dagger D_\mu \phi) (\phi^\dagger \overline{e}_{\alpha R} \gamma^\mu \tilde{\ell}_\beta)$$

$$\overline{e}_{\alpha R} e_{\beta R}^c (\phi^\dagger D \phi)^2$$

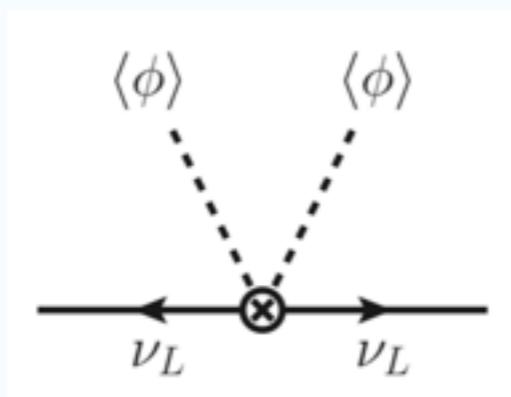
Dim-7, 9



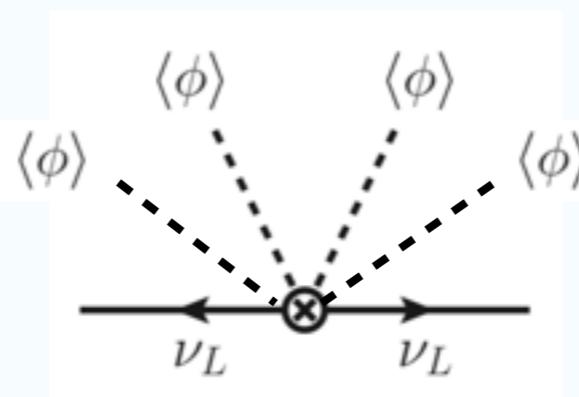
Dim-9

N_v Mass Related Operators

Higgs taking VEV:



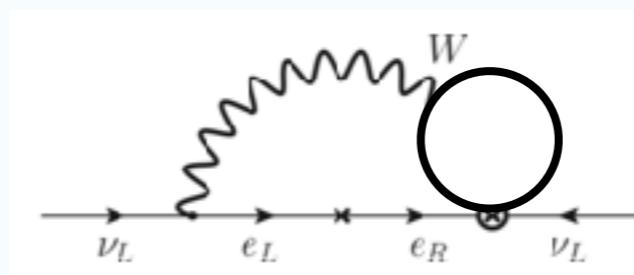
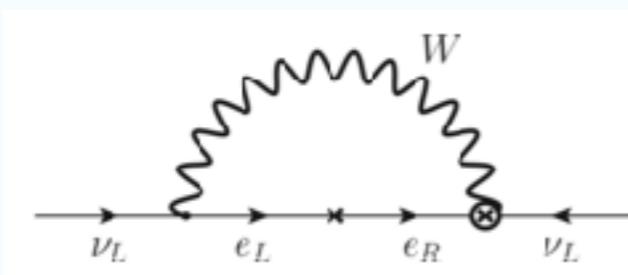
$LLHH$



$LLHHHH$

...

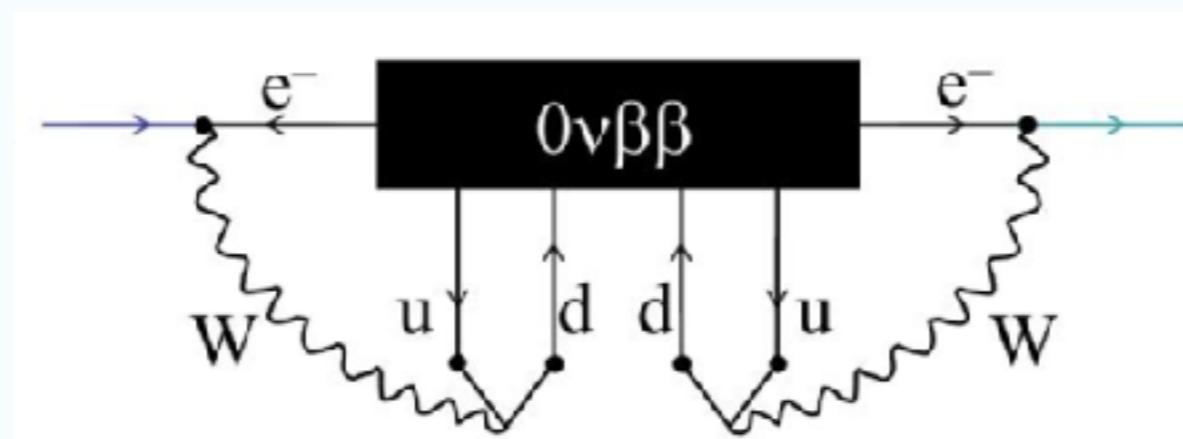
Could from other lepton number violation operators: anomalous RG



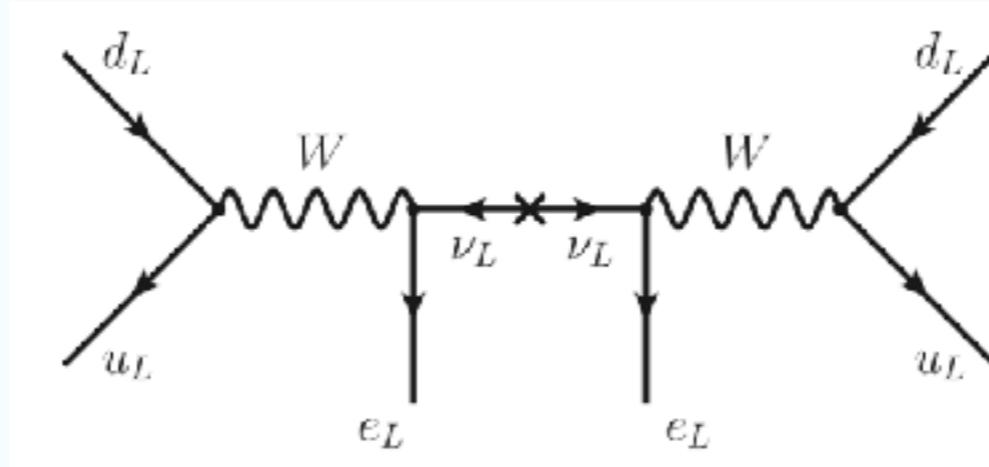
...

Neutrino Masses and 0vbb

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

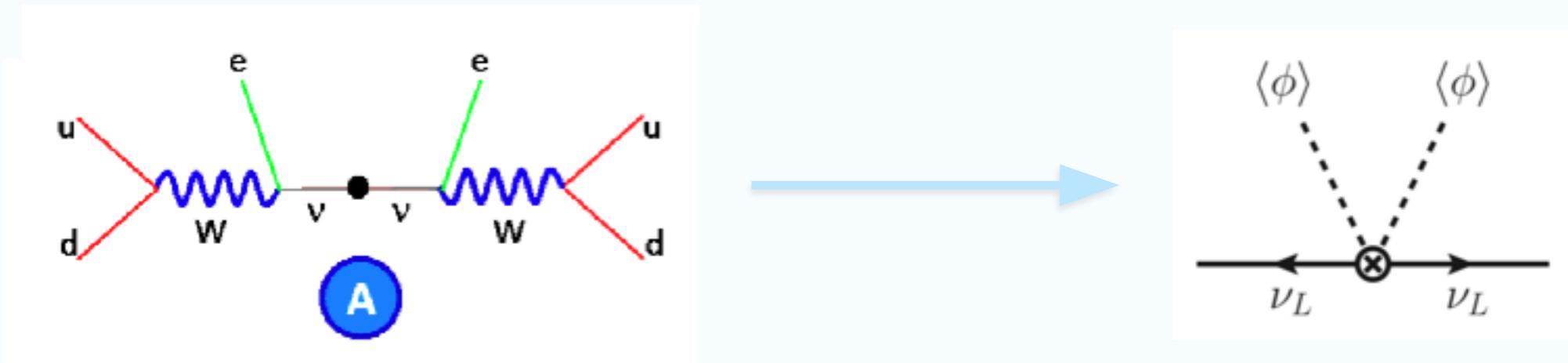


[Schechter-Valle, 1982]



Strong Correlation

Standard mechanism: origin of 0vbb = origin of neutrino masses

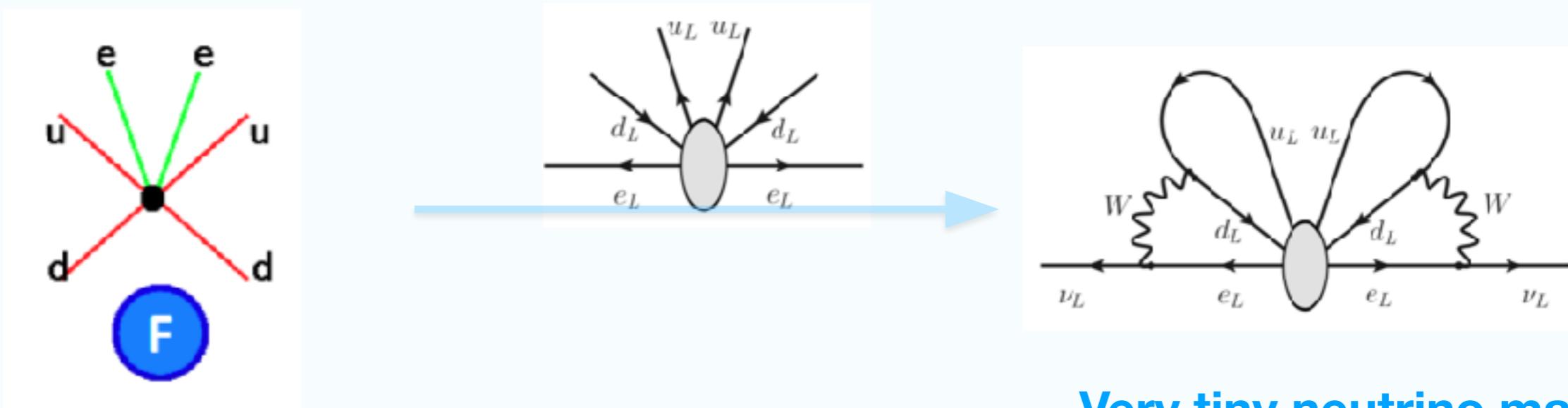


$$L^{\mu\nu} = - \int \int dx_2 dx_1 \sum_i \bar{e}(x_1) \gamma^\mu (1 - \gamma_5) U_{ei} \underbrace{\nu_{iL}(x_1) \bar{\nu}_{iL}^c(x_2)}_{\nu_L} \gamma_\nu (1 + \gamma_5) U_{ei} e_L^c(x_2)$$
$$m_{\beta\beta} = \sum_{i=1}^3 U_{ei}^2 m_{\nu_i}.$$

0vbb has direct connection to neutrino physics

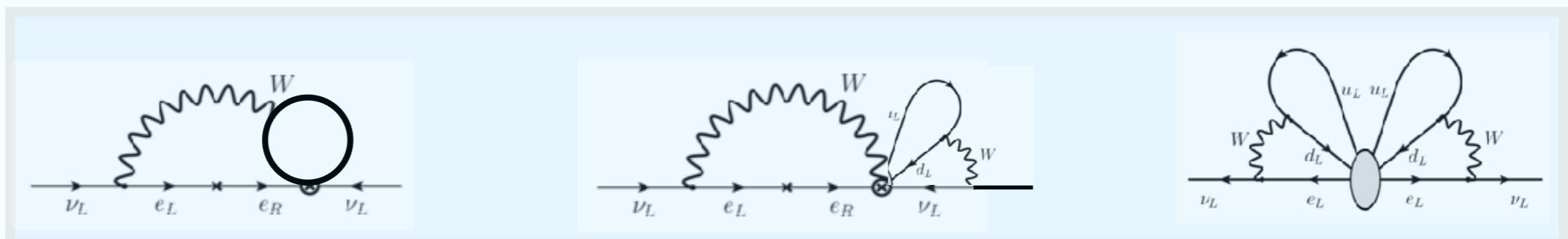
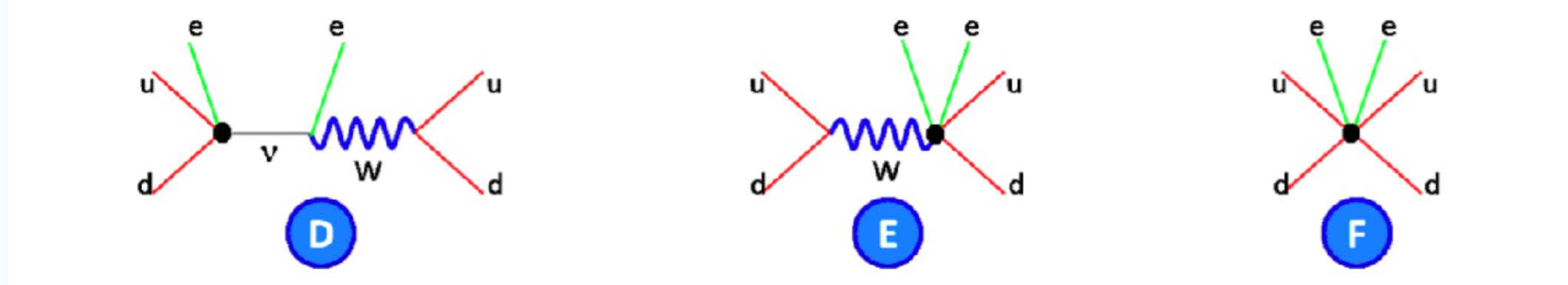
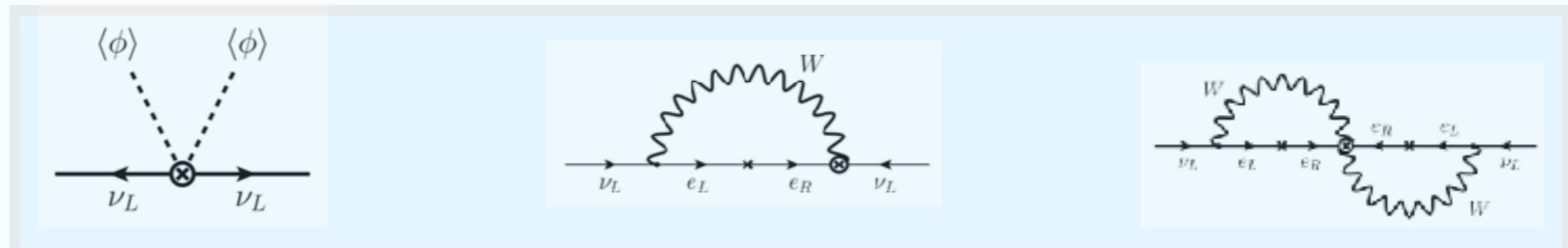
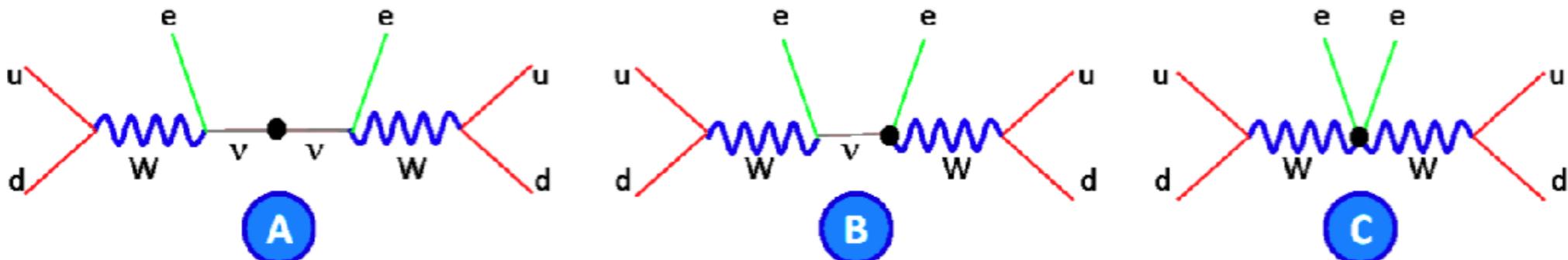
Strong Correlation???

Lepton number violation operator: origin of $0vbb$ = small part of nv mass



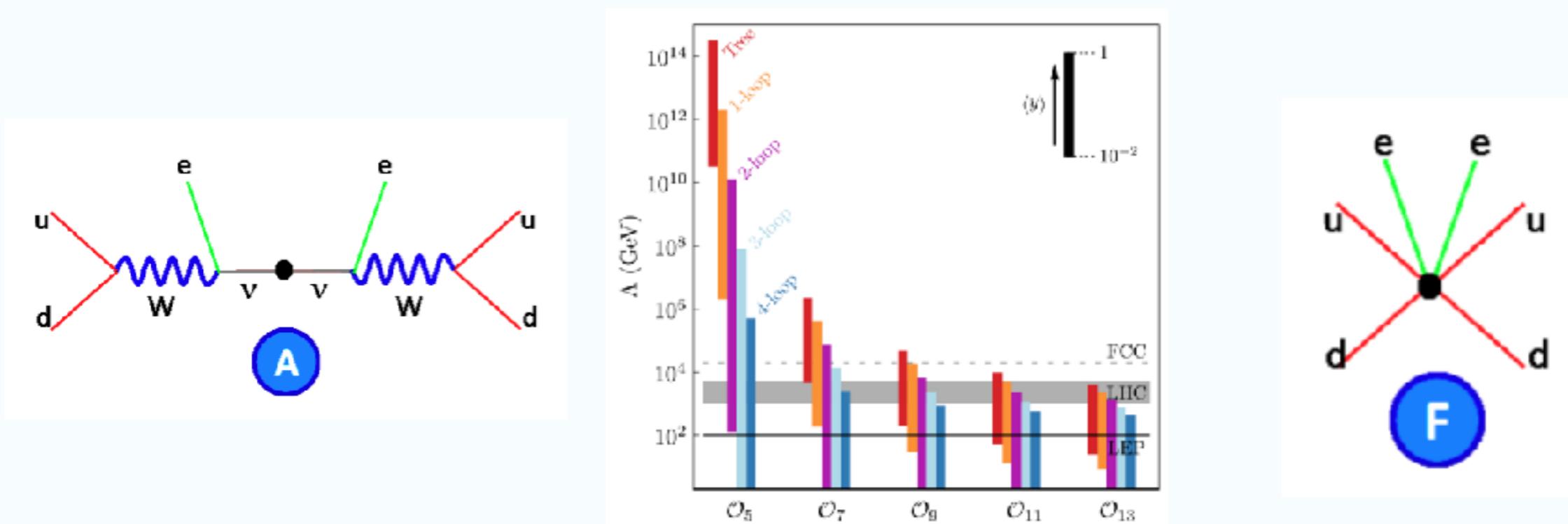
0vbb does not need to connect to current neutrino exp.

Neutrino Masses and 0vbb



Which One Dominate Ω_{vbb} ?

The higher dim operator, the lower cutoff scale

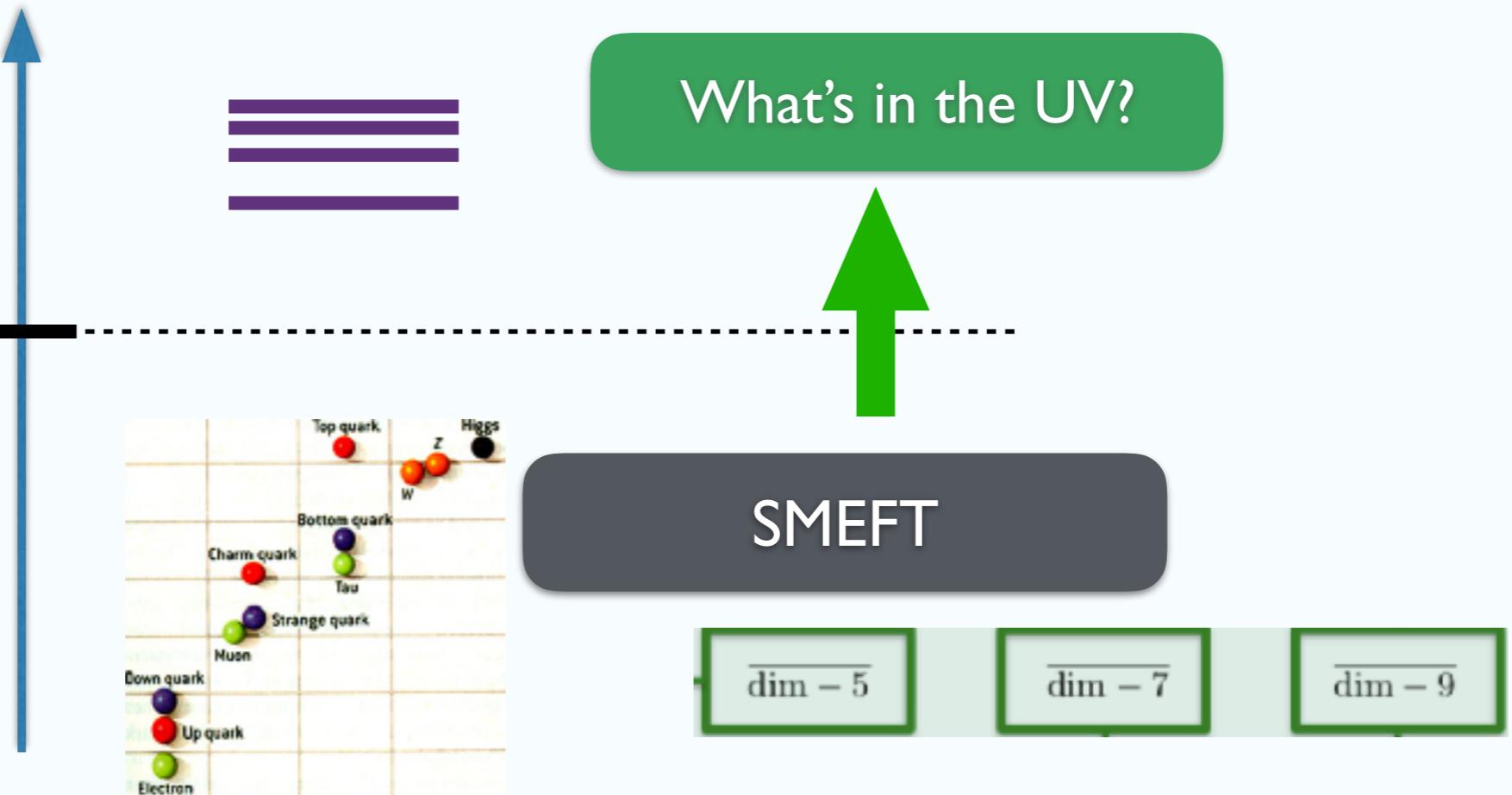


Could be comparable!

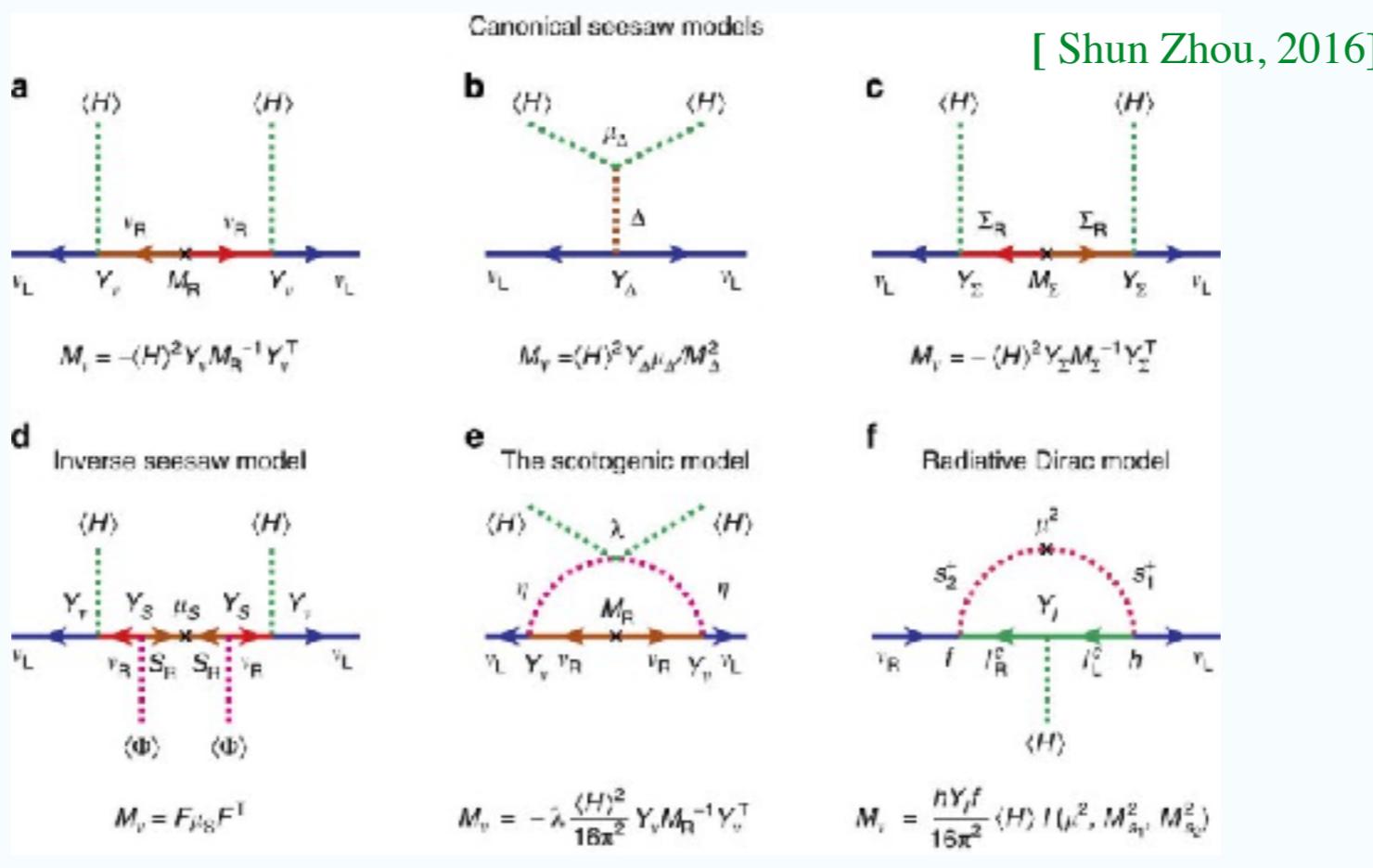
Not necessarily related to neutrino physics

What is in the UV?

TeV scale and above

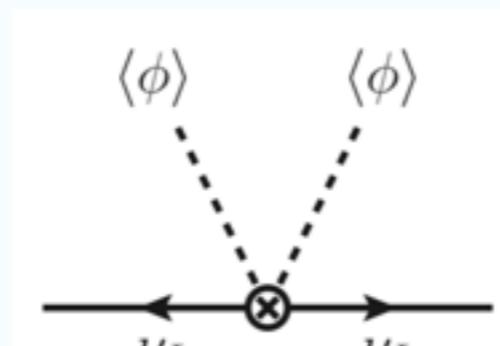


UV Realization of N_v Masses

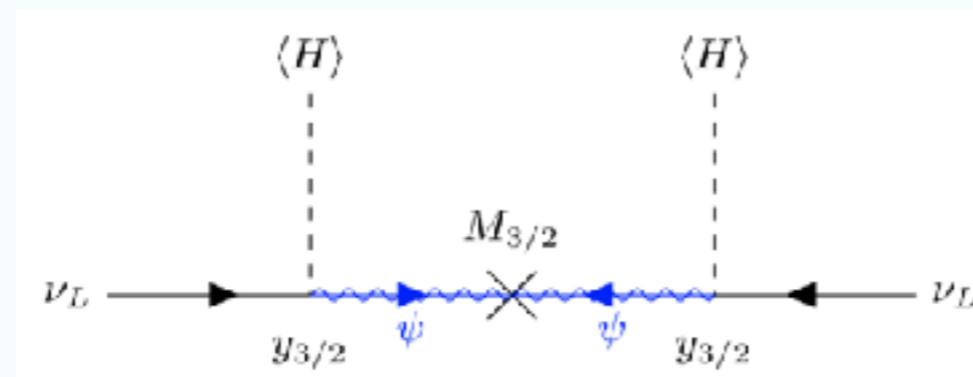


Integrate out heavy particles

Top-down approach



More UV realization?



Type-3/2 Seesaw Mechanism

Durmuş Demir,¹ Canan Karahan,² and Ozan Sargin³

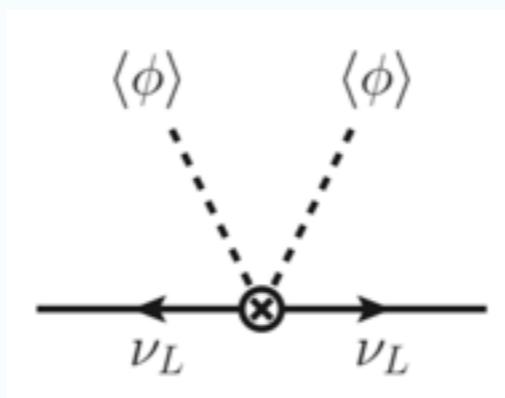
¹Sabancı University, Faculty of Engineering and Natural Sciences, 34956 Tuzla İstanbul, Turkey

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

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

(Dated: May 17, 2021)

Bottom-up Approach



Jiang-Hao Yu

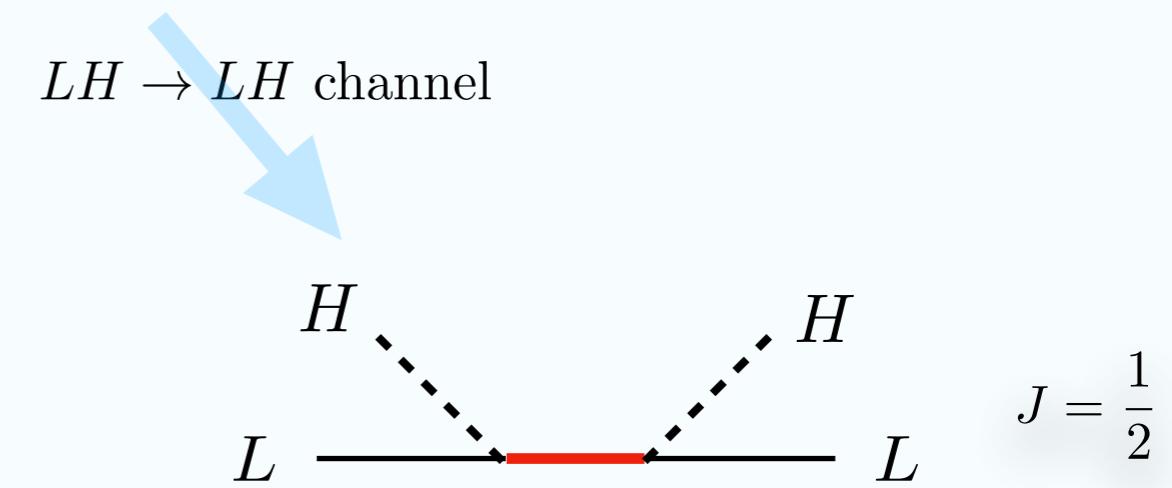
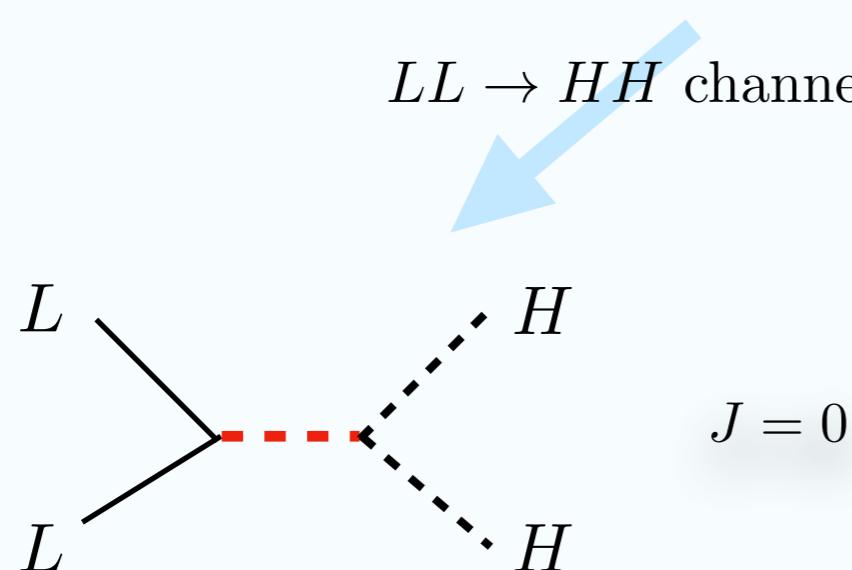
J-Basis Operator: Partial Wave

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

Partial wave expansion on operator

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

$$\mathbf{w}^2 = \frac{s}{8} \sum_{i,j=1}^N (\langle i, \partial_j \rangle \langle j, \partial_i \rangle + |i, \partial_j| |j, \partial_i|) - \frac{1}{4} \sum_{i,j,k,l} |i, j\rangle \langle j, \partial_k \rangle \langle k, l| \langle l, \partial_i|$$



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

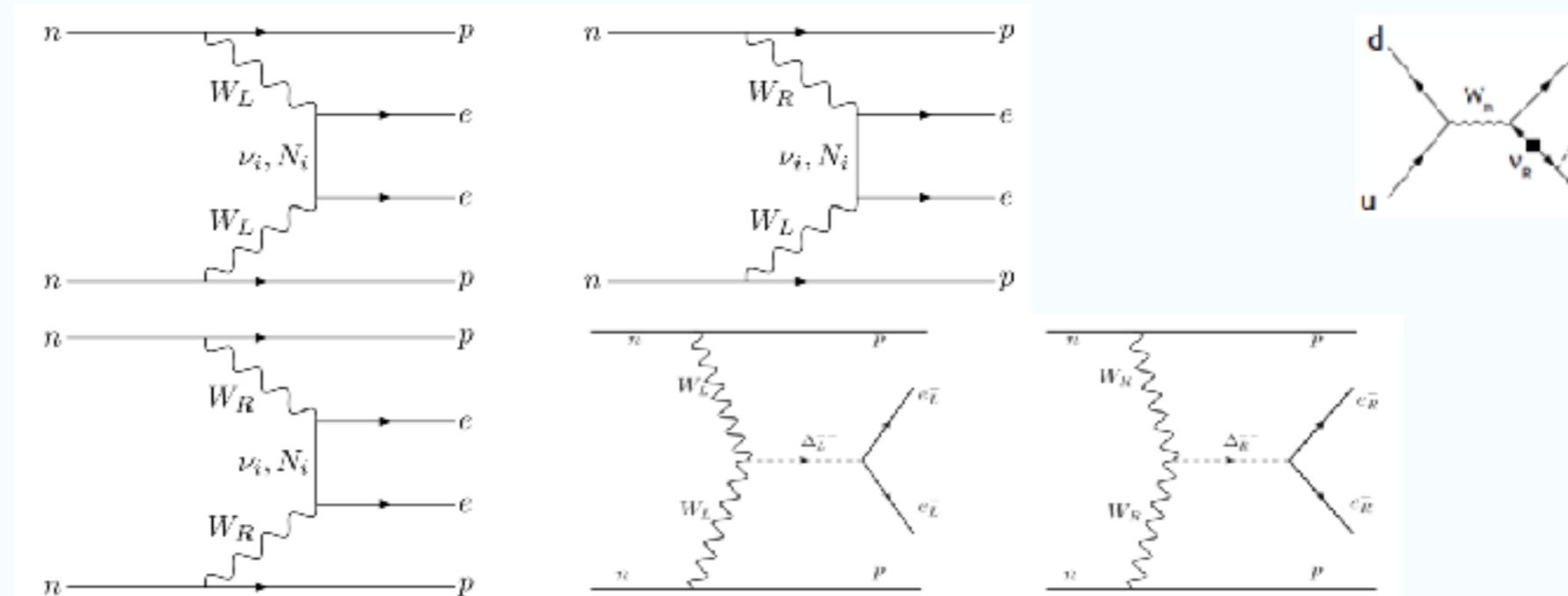
Type-I and III: SU(2) single and triplet

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

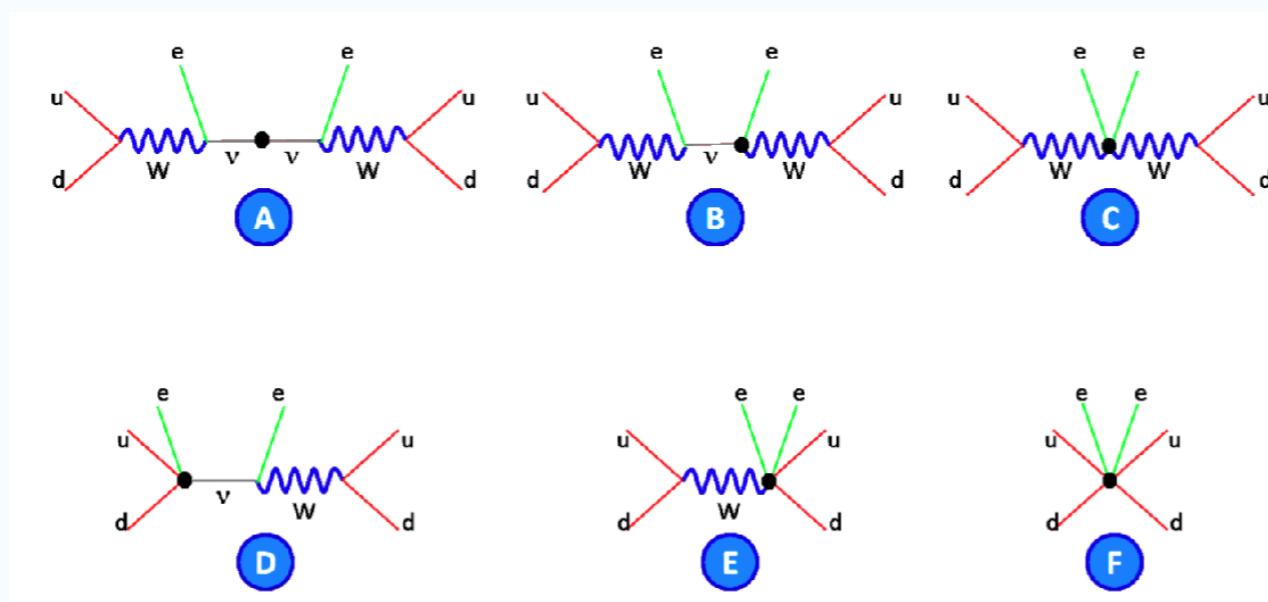
j-basis	Model
$\mathcal{O}_{HL \rightarrow HL}^{(1/2,1)} = \mathcal{O}^S + \mathcal{O}^A$	type I
$\mathcal{O}_{HL \rightarrow HL}^{(1/2,3)} = \mathcal{O}^S - 3\mathcal{O}^A$	type III

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

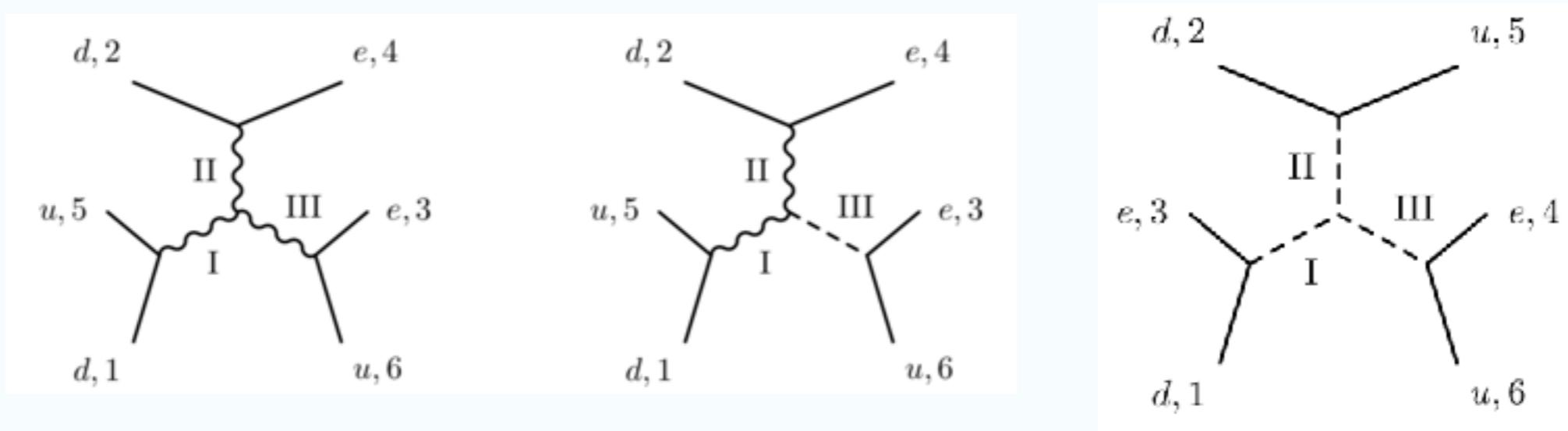
UV Realization of 0vbb



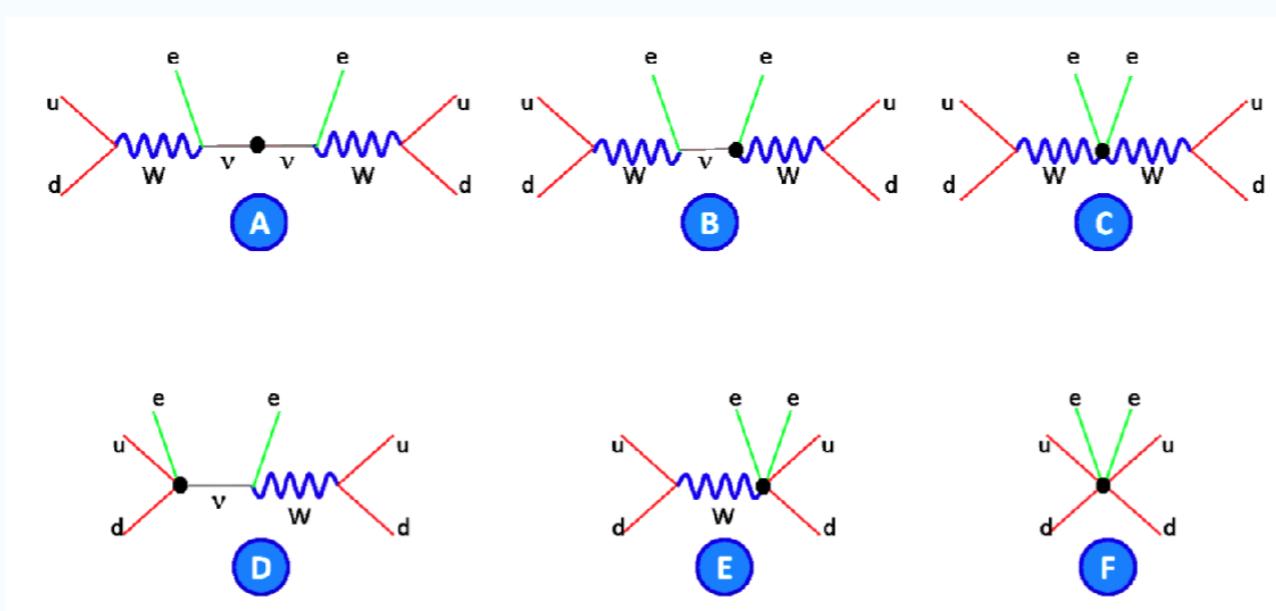
Integrate out heavy particles



More UV Realizations



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

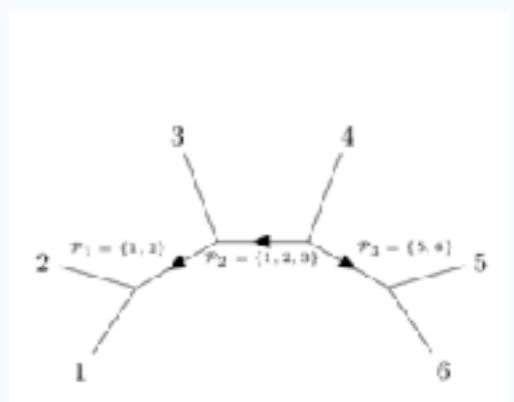
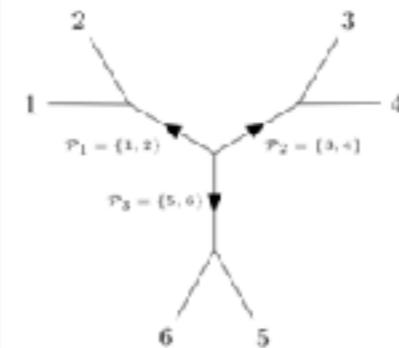


Example

Dim-9 operators:

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

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



Lorentz	y-basis
ψ^6	$B_1 = \langle 12 \rangle \langle 34 \rangle \langle 56 \rangle \quad B_2 = \langle 12 \rangle \langle 35 \rangle \langle 46 \rangle$ $B_3 = \langle 13 \rangle \langle 24 \rangle \langle 56 \rangle \quad B_4 = \langle 13 \rangle \langle 25 \rangle \langle 46 \rangle$ $B_5 = \langle 14 \rangle \langle 25 \rangle \langle 36 \rangle$
$\psi^4 \psi^{\dagger 2}$	$B_1 = \langle 12 \rangle \langle 34 \rangle [56] \quad B_2 = \langle 13 \rangle \langle 24 \rangle [56]$

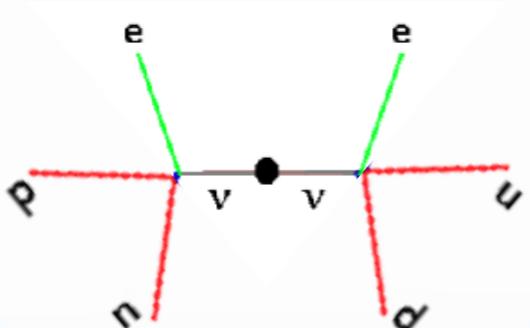
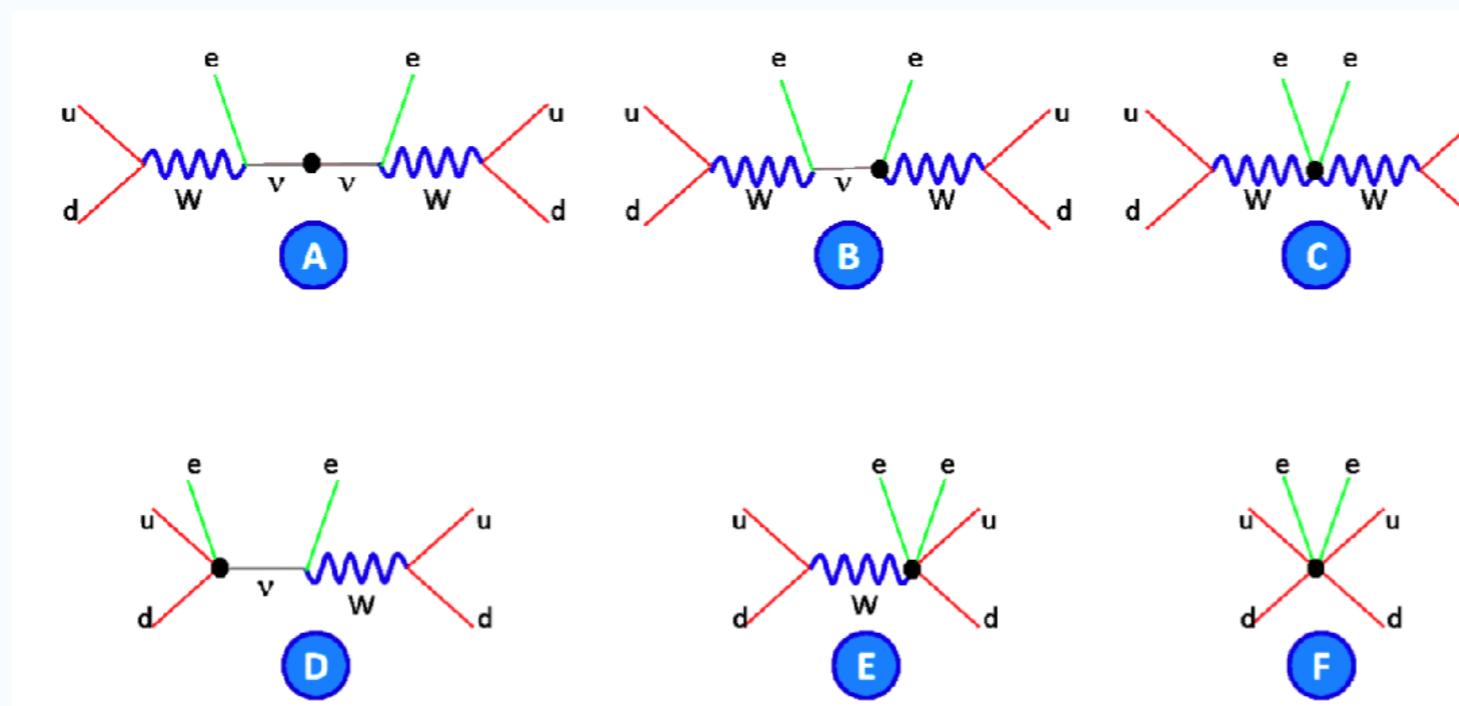
gauge classes	y-basis
$T_{SU(3)}^{abcdef}$	$T_1 = \epsilon^{ace} \epsilon^{bdf} \quad T_2 = \epsilon^{acd} \epsilon^{bef}$ $T_3 = \epsilon^{abc} \epsilon^{cdf} \quad T_4 = \epsilon^{abd} \epsilon^{cef}$ $T_5 = \epsilon^{abc} \epsilon^{def}$
$T_{SU(2)}^{ijkl}$	$T'_1 = \epsilon^{ij} \epsilon^{kl} \quad T'_2 = \epsilon^{ik} \epsilon^{jl}$
$T_{SU(2)}^{ij}$	$T'_1 = \epsilon^{ij}$

type	$\bigoplus_{[\lambda]} n_{[\lambda]} \{ [\lambda_1], [\lambda_2], \dots \}$
$d_c^{\dagger 4} u_c^{\dagger 2}$	$2\{\square\square_u, \square\square\square_d\} \oplus \{\square\square_u, \square\square_d\} \oplus$ $2\{\square\square_u, \square\square_d\} \oplus 2\{\square_u, \square\square_d\} \oplus$ $(\square\square_u, \square_d) \oplus 2(\square_u, \square_d) \oplus \{\square\square_u, \square_d\}$
$Q^4 d_c^{\dagger 2}$	$(\square\square\square_Q, \square_d) \oplus 3\{\square_Q, \square_d\} \oplus$ $2\{\square_Q, \square_d\} \oplus 2\{\square_Q, \square_d\} \oplus \{\square_Q, \square_d\}$
$Q^2 d_c^{\dagger 3} u_c^{\dagger}$	$(\square_Q, \square\square_d) \oplus 2\{\square_Q, \square_d\} \oplus$ $\{\square_Q, \square\square_d\} \oplus \{\square_Q, \square_d\} \oplus \{\square_Q, \square_d\}$

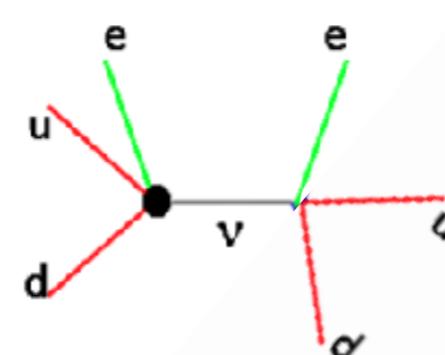
LEFT

Nucleon currents and weak sources

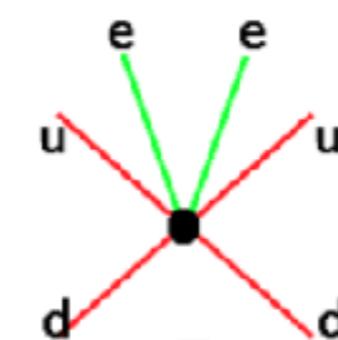
LEFT Related Operators



Dim-3

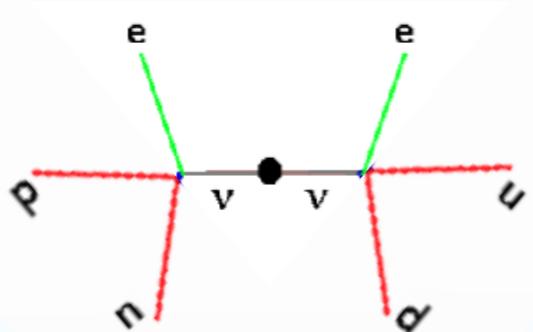
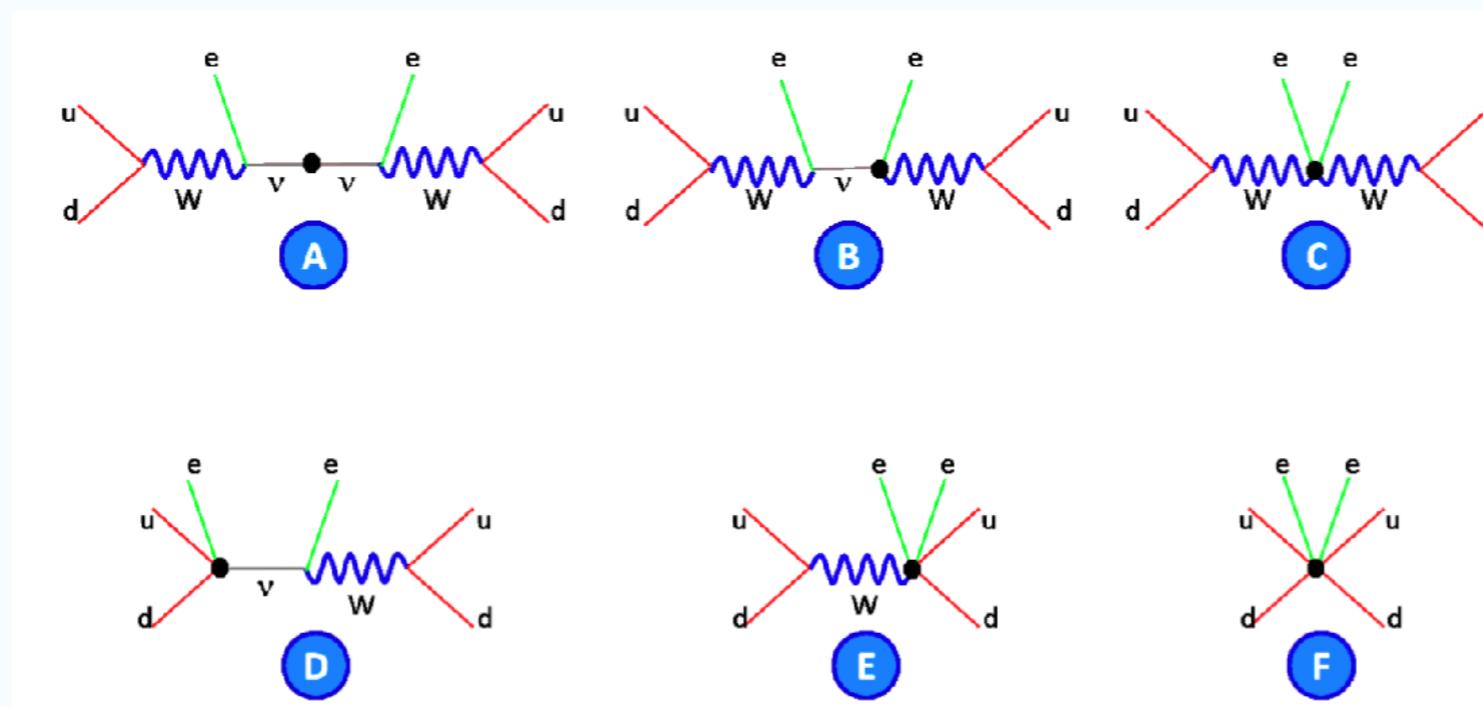


Dim-6, 7

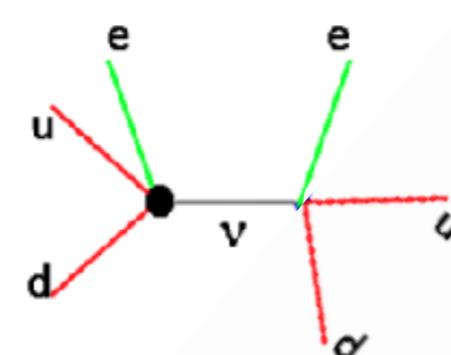


Dim-9

LEFT Related Operators



Long-range interaction

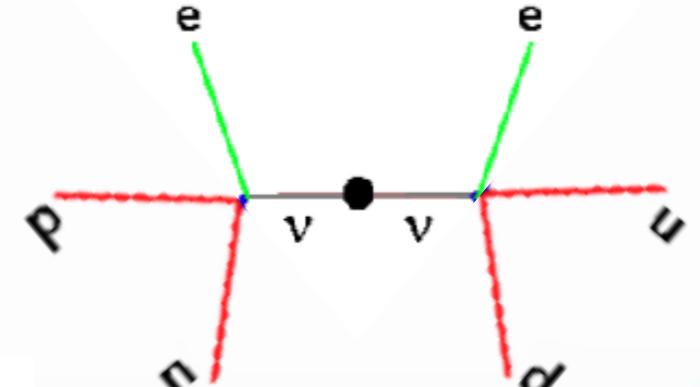


Short-range interaction

Long-Range Interaction

Standard mechanism: long-range neutrino potential

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



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

$$\begin{aligned} \frac{m_i}{q^2 - m_i^2} &\propto \frac{m_i}{q^2} \quad \text{if } m_i^2 \ll q^2 \\ &\propto -\frac{1}{m_i} \quad \text{if } m_i^2 \gg q^2. \end{aligned}$$

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

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

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

completeness relation

$$\begin{aligned} J_{0L}(\vec{x}) &\simeq \sum_i \delta(\vec{x} - \vec{x}_i) f_1(0) \tau_i^+ \\ \vec{J}_L(\vec{x}) &\simeq \sum_i \delta(\vec{x} - \vec{x}_i) g_1(0) \vec{\sigma}_i \tau_i^+ \end{aligned}$$

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

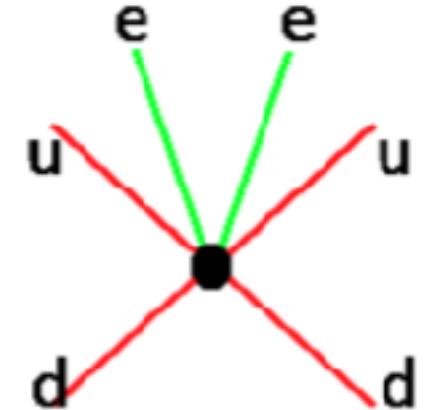
Short-Range Interaction

General quark currents = dim-9 LEFT operators

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

$$J_{R,L} = \bar{u}_a(1 \pm \gamma_5)d_a, \quad J_{R,L}^\mu = \bar{u}_a \gamma^\mu (1 \pm \gamma_5)d_a, \quad J_{R,L}^{\mu\nu} = \bar{u}_a \sigma_{\mu\nu} (1 \pm \gamma_5)d_a,$$

$$j_{R,L} = \bar{e}(1 \mp \gamma_5)e^c, \quad j^\mu = \bar{e} \gamma^\mu \gamma_5 e^c.$$



Complete dim-9 LEFT 6-fermion operator basis

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



Regular Article - Theoretical Physics | Open Access | Published: 14 December 2018

A neutrinoless double beta decay master formula from effective field theory

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

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

\mathcal{O}_1^{RRR}	$[\bar{u}^i(1 + \gamma_5)d_i] [\bar{u}^j(1 + \gamma_5)d_j] [\bar{e}(1 + \gamma_5)e^c]$
\mathcal{O}_1^{RRL}	$[\bar{u}^i(1 + \gamma_5)d_i] [\bar{u}^j(1 + \gamma_5)d_j] [\bar{e}(1 - \gamma_5)e^c]$
\mathcal{O}_1^{LLR} = \mathcal{O}_1^{RLR}	$[\bar{u}^i(1 - \gamma_5)d_i] [\bar{u}^j(1 + \gamma_5)d_j] [\bar{e}(1 + \gamma_5)e^c]$
\mathcal{O}_1^{LLR} = \mathcal{O}_1^{RLR}	$[\bar{u}^i(1 - \gamma_5)d_i] [\bar{u}^j(1 + \gamma_5)d_j] [\bar{e}(1 - \gamma_5)e^c]$
\mathcal{O}_1^{LLR}	$[\bar{u}^i(1 - \gamma_5)d_i] [\bar{u}^j(1 - \gamma_5)d_j] [\bar{e}(1 + \gamma_5)e^c]$
\mathcal{O}_1^{LLR}	$[\bar{u}^i(1 - \gamma_5)d_i] [\bar{u}^j(1 - \gamma_5)d_j] [\bar{e}(1 - \gamma_5)e^c]$
\mathcal{O}_2^{RRR}	$[\bar{u}^i \sigma^{\mu\nu}(1 + \gamma_5)d_i] [\bar{u}^j \sigma_{\mu\nu}(1 + \gamma_5)d_j] [\bar{e}(1 + \gamma_5)e^c]$
\mathcal{O}_2^{RRL}	$[\bar{u}^i \sigma^{\mu\nu}(1 + \gamma_5)d_i] [\bar{u}^j \gamma_\mu(1 + \gamma_5)d_j] [\bar{e}(1 - \gamma_5)e^c]$
\mathcal{O}_2^{LLR}	$[\bar{u}^i \sigma^{\mu\nu}(1 - \gamma_5)d_i] [\bar{u}^j \sigma_{\mu\nu}(1 - \gamma_5)d_j] [\bar{e}(1 + \gamma_5)e^c]$
\mathcal{O}_2^{LLR}	$[\bar{u}^i \sigma^{\mu\nu}(1 - \gamma_5)d_i] [\bar{u}^j \sigma_{\mu\nu}(1 - \gamma_5)d_j] [\bar{e}(1 - \gamma_5)e^c]$
\mathcal{O}_2^{LLR}	$[\bar{u}^i \sigma^{\mu\nu}(1 - \gamma_5)d_i] [\bar{u}^j \gamma_\mu(1 - \gamma_5)d_j] [\bar{e}(1 - \gamma_5)e^c]$
\mathcal{O}_3^{RRR}	$[\bar{u}^i \gamma^\mu(1 + \gamma_5)d_i] [\bar{u}^j \gamma_\mu(1 + \gamma_5)d_j] [\bar{e}(1 + \gamma_5)e^c]$
\mathcal{O}_3^{RRL}	$[\bar{u}^i \gamma^\mu(1 + \gamma_5)d_i] [\bar{u}^j \gamma_\mu(1 + \gamma_5)d_j] [\bar{e}(1 - \gamma_5)e^c]$
\mathcal{O}_3^{LLR} = \mathcal{O}_3^{RLR}	$[\bar{u}^i \gamma^\mu(1 - \gamma_5)d_i] [\bar{u}^j \gamma_\mu(1 + \gamma_5)d_j] [\bar{e}(1 + \gamma_5)e^c]$
\mathcal{O}_3^{LLR} = \mathcal{O}_3^{RLR}	$[\bar{u}^i \gamma^\mu(1 - \gamma_5)d_i] [\bar{u}^j \gamma_\mu(1 + \gamma_5)d_j] [\bar{e}(1 - \gamma_5)e^c]$
\mathcal{O}_3^{LLR}	$[\bar{u}^i \gamma^\mu(1 - \gamma_5)d_i] [\bar{u}^j \gamma_\mu(1 - \gamma_5)d_j] [\bar{e}(1 + \gamma_5)e^c]$
\mathcal{O}_3^{LLR}	$[\bar{u}^i \gamma^\mu(1 - \gamma_5)d_i] [\bar{u}^j \gamma_\mu(1 - \gamma_5)d_j] [\bar{e}(1 - \gamma_5)e^c]$
\mathcal{O}_4^{RRR}	$[\bar{u}^i \gamma^\mu(1 + \gamma_5)d_i] [\bar{u}^j \sigma_{\mu\nu}(1 + \gamma_5)d_j] [\bar{e} \gamma^\nu \gamma_5 e^c]$
\mathcal{O}_4^{RLR}	$[\bar{u}^i \gamma^\mu(1 + \gamma_5)d_i] [\bar{u}^j \sigma_{\mu\nu}(1 - \gamma_5)d_j] [\bar{e} \gamma^\nu \gamma_5 e^c]$
\mathcal{O}_4^{LLR}	$[\bar{u}^i \gamma^\mu(1 - \gamma_5)d_i] [\bar{u}^j \sigma_{\mu\nu}(1 + \gamma_5)d_j] [\bar{e} \gamma^\nu \gamma_5 e^c]$
\mathcal{O}_4^{LLR}	$[\bar{u}^i \gamma^\mu(1 - \gamma_5)d_i] [\bar{u}^j \sigma_{\mu\nu}(1 - \gamma_5)d_j] [\bar{e} \gamma^\nu \gamma_5 e^c]$
\mathcal{O}_4^{LLR}	$[\bar{u}^i \gamma^\mu(1 - \gamma_5)d_i] [\bar{u}^j \gamma_\nu(1 - \gamma_5)d_j] [\bar{e} \gamma^\nu \gamma_5 e^c]$
\mathcal{O}_5^{RRR}	$[\bar{u}^i \gamma^\mu(1 + \gamma_5)d_i] [\bar{u}^j \gamma^\nu(1 + \gamma_5)d_j] [\bar{e} \gamma_\nu \gamma_5 e^c]$
\mathcal{O}_5^{RLR}	$[\bar{u}^i \gamma^\mu(1 + \gamma_5)d_i] [\bar{u}^j \gamma^\nu(1 - \gamma_5)d_j] [\bar{e} \gamma_\nu \gamma_5 e^c]$
\mathcal{O}_5^{LLR}	$[\bar{u}^i \gamma^\mu(1 - \gamma_5)d_i] [\bar{u}^j \gamma^\nu(1 + \gamma_5)d_j] [\bar{e} \gamma_\nu \gamma_5 e^c]$
\mathcal{O}_5^{LLR}	$[\bar{u}^i \gamma^\mu(1 - \gamma_5)d_i] [\bar{u}^j \gamma^\nu(1 - \gamma_5)d_j] [\bar{e} \gamma_\nu \gamma_5 e^c]$

Low Energy EFT

Dimension-5

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

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[Jenkins, Manohar, Stoffer, 2017]

Dim-6 operators				
N	(n, \bar{n})	Classes	N_{typo}	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	164
			$56+32+20+2$	

56 + 32 + 20 + 2 = 164

Dimension-7

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

[Liao, Ma, Wang, 2020]

Dimension-8

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

N	(n, \bar{n})	Subclasses	N_{typo}	N_{term}	N_{operator}	Equation
4	(1,0)	$F_L^4 + h.c.$	14	25	26	(4.16)
	(3,1)	$F_L^2 \psi_L^2 D + h.c.$ $\psi_L^4 D^2 + h.c.$ $\psi_L^2 \psi_R^2 D^2 + h.c.$ $F_L^2 \psi_L^2 D^2 + h.c.$	22 18 16 8	22 18+12 32 12	226 $12n_f^3 + 12(n_f - 1)$ $3n_f^2$ 12	(4.21) (4.22), (4.23) (4.24) (4.25)
	(2,2)	$F_L^2 F_R^2$ $F_L F_R \psi_L^2 D$ $\psi_L^2 \psi_R^2 D^2$ $F_R \psi_L^2 \psi_R^2 D + h.c.$ $F_L F_R \psi_L^2 D^2$ $\psi_L^2 \psi_R^2 D^2$ $\psi_L^4 D^4$	14 27 17+8 16 5 7 1	17 35 $\lfloor n_f \rfloor (2n_f^2 + 10) + 6n_f^2$ 16n_f 4 16n_f 4	17 35 $\lfloor n_f \rfloor (2n_f^2 + 10) + 6n_f^2$ 16n_f 4 16n_f 4	(4.26), (4.27), (4.28) (4.29) (4.30) (4.31), (4.32) (4.33), (4.34)
5	(1,0)	$E_L \psi_L^2 + h.c.$ $F_L^2 \psi_L^2 \phi + h.c.$ $F_L^2 \phi^2 + h.c.$	12+18 32 4	10 53 4	42n_f^2 + 2n_f^2(3n_f + 11) $3n_f^2$ 4	(4.35), (4.36), (4.37), (4.38)
	(2,1)	$F_L \psi_L^2 \psi_L^2 D + h.c.$ $\psi_L^2 \psi_L^2 \phi + h.c.$ $\psi_L^2 \psi_R^2 D + h.c.$ $F_L \psi_L^2 \psi_R^2 D + h.c.$ $\psi_L^2 \psi_L^2 D^2 + h.c.$ $F_L \psi_L^2 D^2 + h.c.$	8+24 24 24 32+14 38 4	172+32 32 32 $n_f^2 (13n_f - 1) + n_f^2 (29n_f + 3)$ 32 32	$2n_f^2 (29n_f^2 - 2) + 24n_f^2$ $3n_f^2$ $n_f^2 (13n_f - 1) + n_f^2 (29n_f + 3)$ $3n_f^2$ $3n_f^2$ 4	(4.39), (4.40), (4.41), (4.42), (4.43), (4.44)
	(3,0)	$\psi_L^2 \psi_L^2 \phi + h.c.$ $F_L \psi_L^2 \phi^2 + h.c.$ $F_L^2 \phi^2 + h.c.$	18+18 16 8	18+18 22 10	$n_f^2 (2n_f^2 + n_f + 2) + 2n_f^2 (3n_f - 1)$ $2n_f^2$ 10	(4.45), (4.46), (4.47)
	(1,1)	$\psi_L^2 \psi_L^2 \phi^2$ $\psi_L^2 \psi_L^2 D$ $\psi_L^2 \psi_L^2$	25+14 7 1	25+14 15 7	$n_f^2 (2n_f^2 + n_f + 2) + 2n_f^2 (3n_f - 1)$ $15n_f$ 7	(4.48), (4.49), (4.50)
7	(1,0)	$\psi_L^2 \psi_L^2 + h.c.$	4	6	$6n_f^2$	(4.51)
8	(1,0)	ψ_L^8	1	1	1	(4.52)
Total			48	120	$1270 + 1376 + 1361$ $600(n_f - 1) + 4800(n_f - 2)$	

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[Murphy, 2020]

Dimension-9

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

N	(n, \bar{n})	Subclasses	N_{typo}	N_{term}	N_{operator}	Equation
4	(3,2)	$\psi^4 \psi^2 D^4 + h.c.$ $\psi^4 \phi^2 D^4 + h.c.$	0+4+2+0	10	$\frac{1}{2} n_f^2 (2n_f^2 - 1)$	(5.50), (5.51)
	(2,1)	$F_L \psi^2 \phi^2 D^4 + h.c.$	0+0+2+0	6	$3n_f (n_f + 1)$	(5.52)
5	(3,1)	$F_L \psi^2 \phi^2 D^4 + h.c.$ $\psi^4 \phi^2 + h.c.$ $F_L \psi^2 \phi^2 D^2 + h.c.$	0+12+6+0	72	$32n_f^4$	(5.53)
	(2,2)	$F_L \psi^2 \phi^2 D^4 + h.c.$ $\psi^2 \psi^2 \phi^2 D^2 + h.c.$ $F_L \psi^2 \phi^2 D^2 + h.c.$	0+4+4+0	24	$17n_f^2 - n_f$	(5.54), (5.55)
	(3,0)	$F_L \psi^2 \phi^2 D^4 + h.c.$ $\psi^2 \psi^2 \phi^2 D^2 + h.c.$ $F_L \psi^2 \phi^2 D^2 + h.c.$	0+12+6+0	72	$4n_f^2 (5n_f + 1)$	(5.56), (5.57)
	(1,1)	$\psi^2 \psi^2 \phi^2 D^2 + h.c.$	0+4+4+0	24	$n_f^2 (5n_f + 1)$	(5.58), (5.59)
	(2,0)	$\psi^2 \psi^2 \phi^2 D^2 + h.c.$ $F_L \psi^2 \phi^2 + h.c.$ $F_L^2 \psi^2 \phi^2 + h.c.$	0+0+8+0	20	$2n_f (5n_f - 1)$	(5.60), (5.61)
	(1,1)	$\psi^2 \psi^2 \phi^2 D^2 + h.c.$	0+0+2+0	6	$8n_f^2$	(5.62)
6	(3,0)	$\psi^6 + h.c.$ $F_L \psi^4 + h.c.$ $F_L^2 \psi^2 + h.c.$	2+4+5+0	116	$\frac{1}{2} n_f^2 (115n_f^4 + 53n_f^2 - 58n_f^2 + 129n_f + 6)$	(5.63), (5.64)
	(2,1)	$F_L \psi^4 + h.c.$ $F_L^2 \psi^2 + h.c.$	0+12+13+0	102	$2n_f^2 (21n_f + 1)$	(5.65), (5.66)
	(1,1)	$F_L \psi^4 + h.c.$	0+0+8+0	20	$2n_f (2n_f + 2)$	(5.67)
	(1,0)	$\psi^6 + h.c.$	4+26+29+4	248	$\{n_f\} (382n_f^2 - 9n_f^2 + 2n_f + 21)$	(5.68), (5.69)
	(0,1)	$F_L \psi^4 + h.c.$	0+21+24+0	12	$52n_f^2$	(5.70), (5.71)
	(0,0)	$F_L^2 \psi^2 + h.c.$	0+0+8+0	12	$28n_f (3n_f + 2)$	(5.72)
		$\psi^2 \psi^2 \phi^2 D + h.c.$	0+12+18+0	86	$\frac{1}{2} n_f^2 (14n_f^2 + 1)$	(5.73), (5.74)
		$F_L \psi^4 \psi^2 D + h.c.$	0+0+8+0	15	$12n_f^2$	(5.75)
		$\psi^2 \psi^2 D^2 + h.c.$	0+0+4+0	24	$2n_f (5n_f + 1)$	(5.76)
7	(2,0)	$\psi^4 \psi^4 + h.c.$	0+0+3+0	22	$\frac{1}{2} n_f^2 (10n_f^2 - 1)$	(5.77), (5.78)
	(1,1)	$F_L \psi^2 \phi^4 + h.c.$	0+0+4+0	8	$2n_f (2n_f - 1)$	(5.79)
	(1,0)	$\psi^2 \psi^2 \phi^4$	0+6+10+0	54	$14n_f^2$	(5.80), (5.81)
		$\psi^2 \psi^2 \phi^2 D$	0+0+2+0	2	$2n_f^2$	(5.82)
8	(1,0)	$\psi^2 \phi^6 + h.c.$	0+0+2+0	2	$n_f^2 + c_f$	(5.83)
Total			42	6+122+164+4	1262	$8 + 234 + 345 - 8(n_f - 1)$ $2942 + 42254 - 4(874 + 486(n_f - 3))$

3774

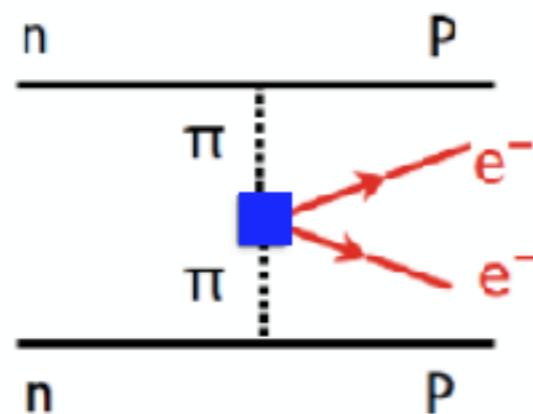
Jiang-Hao Yu

39

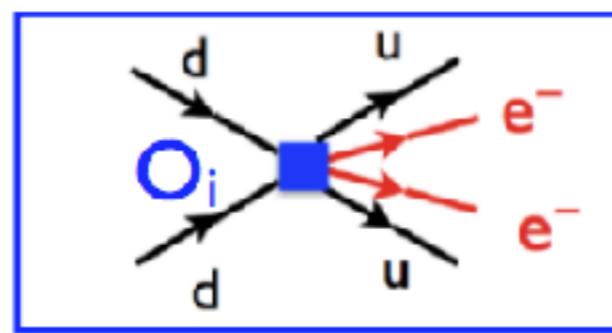
ChiPT: Quark to Nucleon

Chiral perturbation theory + Heavy baryon EFT + LNV external source

Pion-range
effects



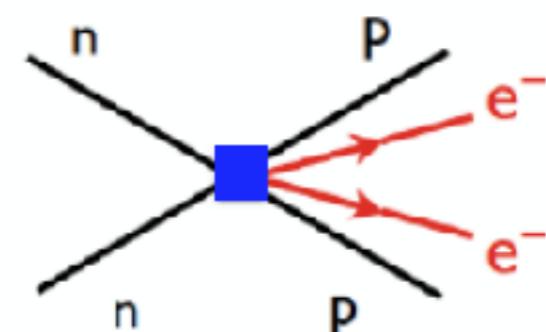
$$\mathcal{L}_{\pi\pi}$$



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

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

Short-range
effects



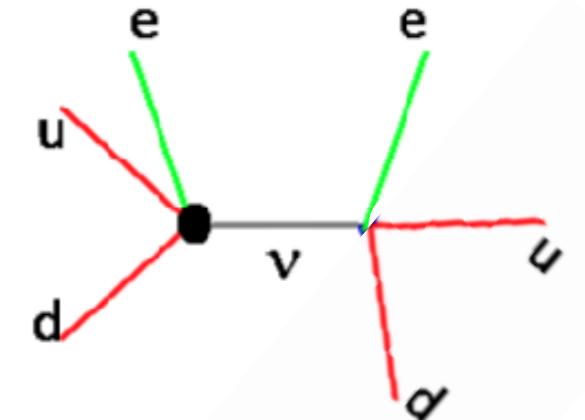
$$\mathcal{L}_{NN}$$

Long-Range from LNV Operators

Long-range neutrino potential: no nv mass dependence

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

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



Complete dim-6 LEFT 4-fermion operator basis

$$\mathcal{L}_{\Delta L=2}^{(6)} = \frac{2G_F}{\sqrt{2}} \left\{ C_{\text{VL},ij}^{(6)} \bar{u}_L \gamma^\mu d_L \bar{\epsilon}_{R,i} \gamma_\mu C \bar{\nu}_{L,j}^T + C_{\text{VR},ij}^{(6)} \bar{v}_R \gamma^\mu d_R \bar{\epsilon}_{R,i} \gamma_\mu C \bar{\nu}_{L,j}^T \right. \quad (7)$$

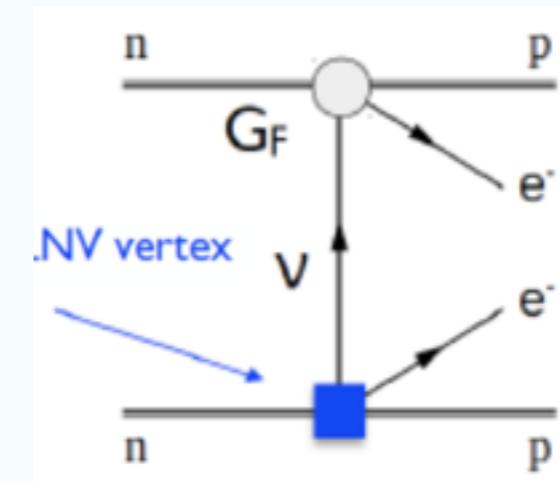
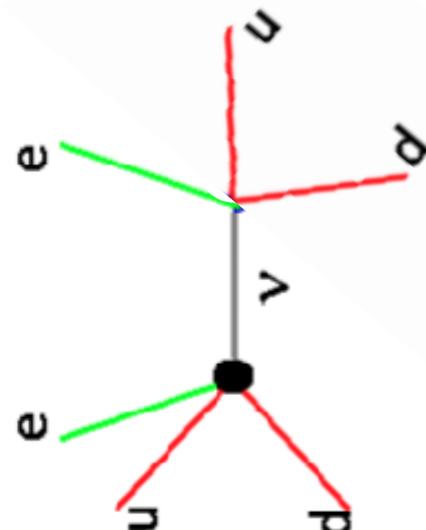
$$\left. + C_{\text{SR},ij}^{(6)} \bar{v}_L d_R \bar{\epsilon}_{L,i} C \bar{\nu}_{L,j}^T + C_{\text{SL},ij}^{(6)} \bar{v}_R d_L \bar{\epsilon}_{L,i} C \bar{\nu}_{L,j}^T + C_{\text{T},ij}^{(6)} \bar{u}_L \sigma^{\mu\nu} d_R \bar{\epsilon}_{L,i} \sigma_{\mu\nu} C \bar{\nu}_{L,j}^T \right\} + \text{h.c.}$$

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

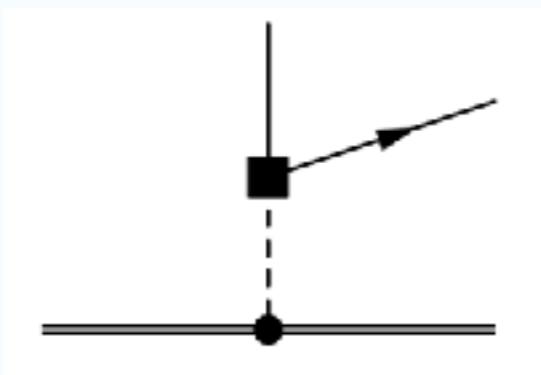
No dim-9 SMEFT 4-fermion operator!

ChiPT: Quark to Nucleon

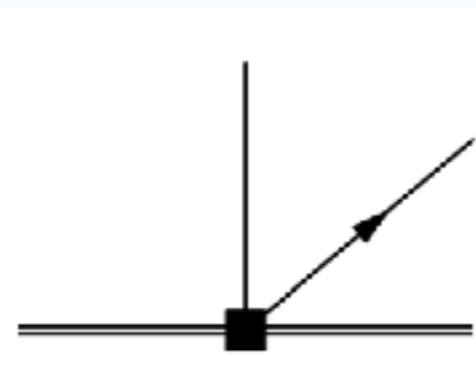
Chiral perturbation theory + Heavy baryon EFT + LNV external source



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

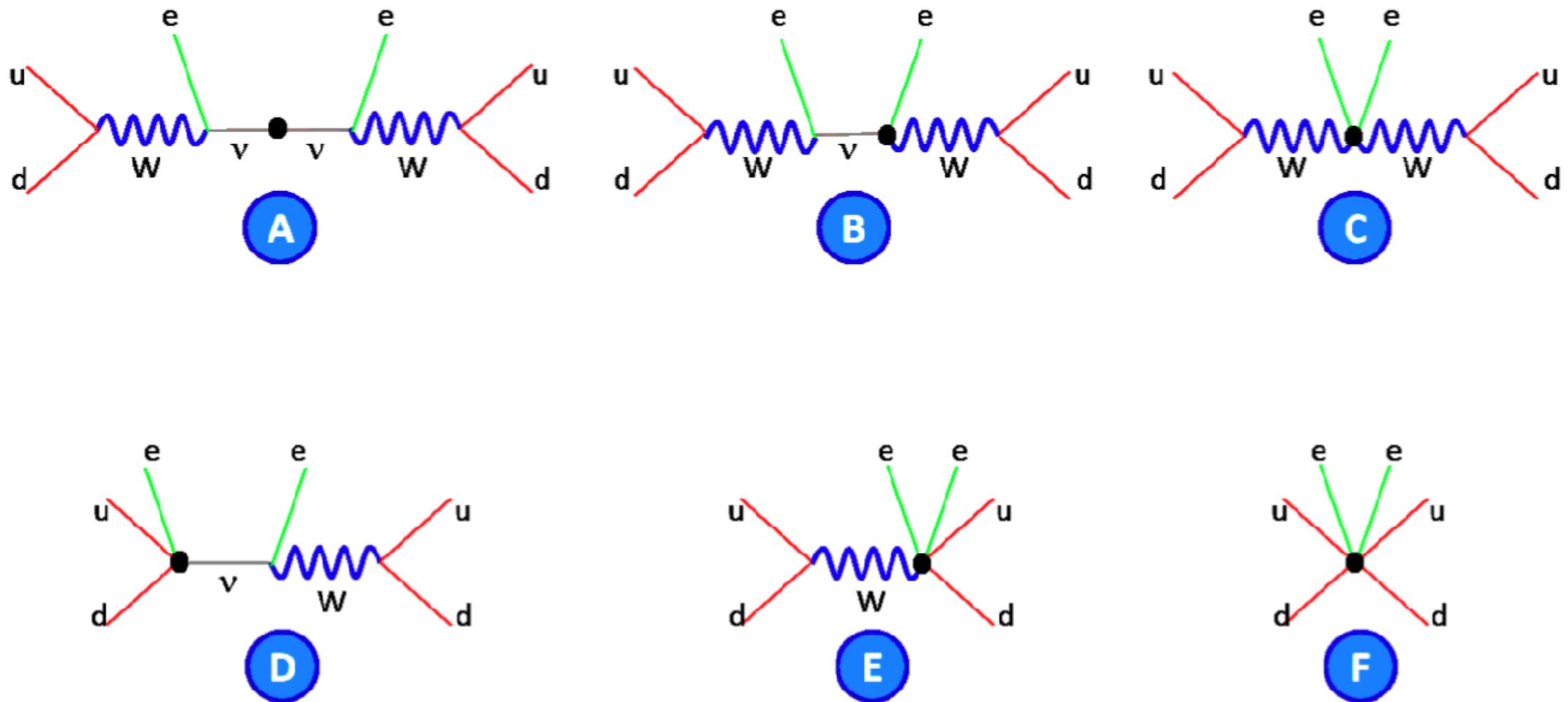


$$\mathcal{L}_{\pi N}$$

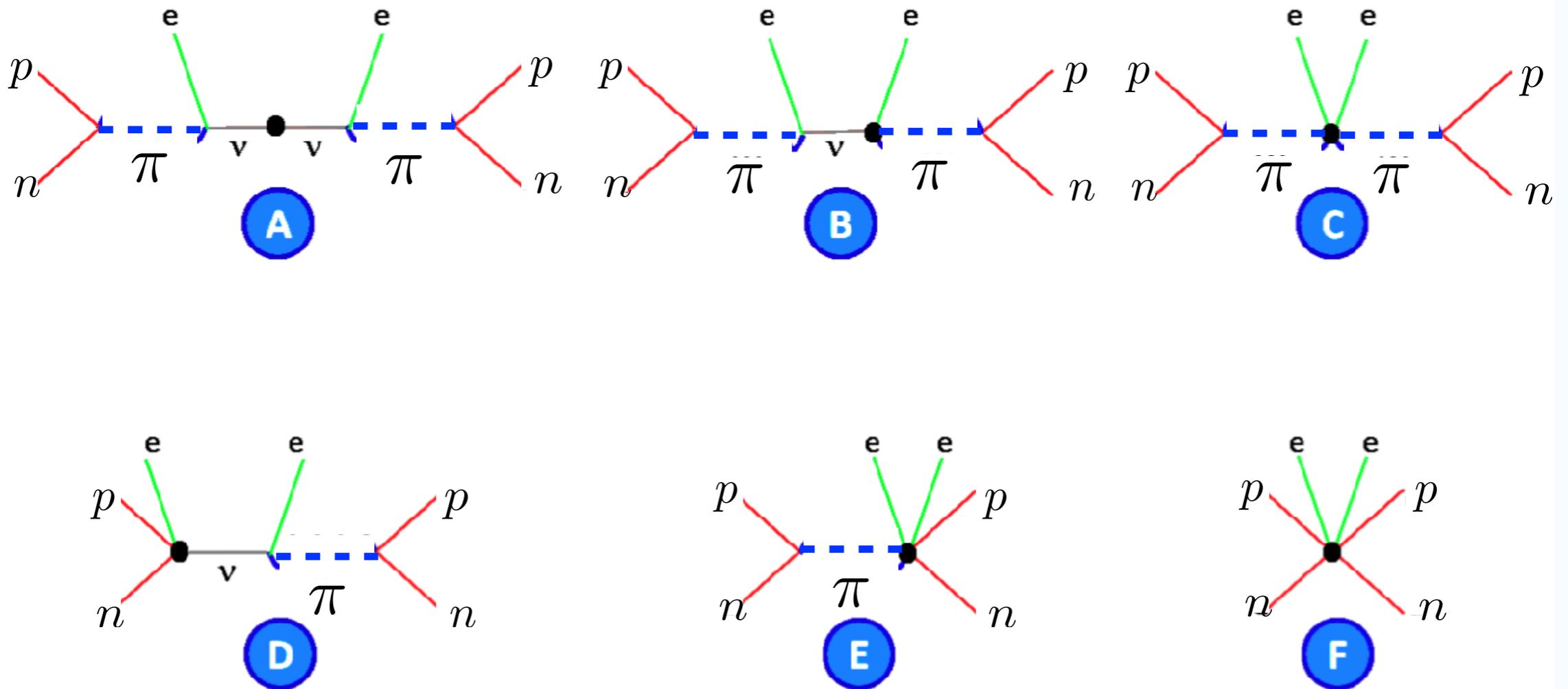


$$\mathcal{L}_{\pi N}$$

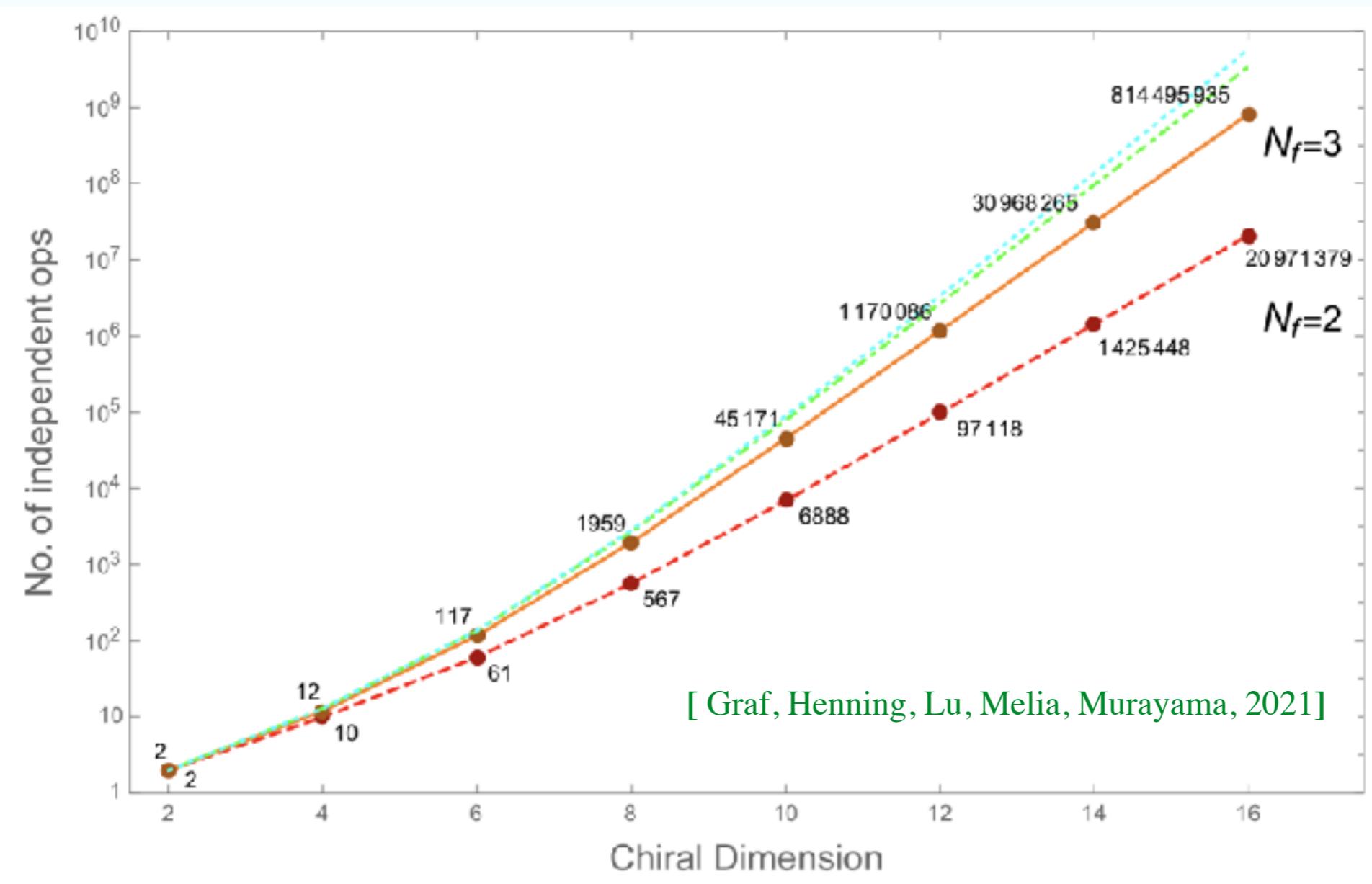
0vbb at SMEFT



0vbb at ChiPT



ChiPT Lagrangian



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

Fettes, Meisner, Mojzis, Steininger, 2000

Girlanda, Pastore, Schiavilla, Viviani, 2010

Nv Potential Master Formula

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

$$V(\mathbf{q}^2) = V_3(\mathbf{q}^2) + V_6(\mathbf{q}^2) + V_7(\mathbf{q}^2) + V_9(\mathbf{q}^2).$$

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

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

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

More matrix element?

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

Sterile Neutrino EFT

Dimension-5

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

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Dimension-6

Dim-6 operator			
N	(n, \bar{n})	Classes	N_{type}
			N_{new}
4	(2, 0)	$\psi^4 + \text{h.c.}$	4 + 2 + 0 + 2
		$F_L \psi^2 \phi + \text{h.c.}$	4 + 0 + 0 + 0
5	(1, 1)	$\psi^2 \psi^{12}$	10 + 2 + 0 + 0
		$\psi \psi^\dagger \psi^2 D$	3 + 0 + 0 + 0
5	(1, 0)	$\psi^2 \phi^3 + \text{h.c.}$	2 + 0 + 0 + 0
		Total	23 + 4 + 0 + 2
			35

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

Dimension-8

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

N	(n, \bar{n})	Classes	N_{type}	N_{new}
4	(3, 1)	$\psi^4 D^2 + \text{h.c.}$	4 + 0 + 2 + 2	22
		$F_L \psi^2 \phi D^2 + \text{h.c.}$	4 + 0 + 0 + 0	8
	(2, 2)	$F_L F_R \psi^\dagger D$	3 + 0 + 0 + 0	3
		$\psi^2 \psi^{12} D^2$	10 + 2 + 0 + 0	24
		$F_R \psi^2 \phi D^2 + \text{h.c.}$	4 + 0 + 0 + 0	4
	(3, 0)	$\psi \psi^\dagger \phi^2 D^2$	3 + 0 + 0 + 0	4
		$F_L \psi^4 + \text{h.c.}$	10 + 4 + 0 + 2	50
		$F_L \psi^2 \phi + \text{h.c.}$	8 + 0 + 0 + 0	12
		$F_L \psi^2 \psi^{12} + \text{h.c.}$	42 + 12 + 0 + 0	58
		$F_L \psi^2 \phi^{12} + \text{h.c.}$	8 + 0 + 0 + 0	8
5	(2, 1)	$\psi^3 \psi^* \phi D + \text{h.c.}$	24 + 6 + 0 + 2	108
		$F_L \psi \psi^\dagger \phi^2 D + \text{h.c.}$	12 + 0 + 0 + 0	16
		$\psi^2 \phi^3 D^2 + \text{h.c.}$	2 + 0 + 0 + 0	12
		$\psi^4 \phi^2 + \text{h.c.}$	8 + 2 + 0 + 2	30
		$F_L \psi^2 \phi^3 + \text{h.c.}$	4 + 0 + 0 + 0	6
	(1, 1)	$\psi^2 \psi^{12} \phi^2$	16 + 4 + 0 + 2	28
		$\psi \psi^\dagger \phi^4 D$	3 + 0 + 0 + 0	3
		$\psi^2 \phi^3 + \text{h.c.}$	2 + 0 + 0 + 0	2
	Total	31	167 + 30 + 2 + 10	398

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Jiang-Hao Yu

Dimension-7

N	(n, \bar{n})	Classes	N_{type}	N_{new}
4	(3, 0)	$F_L^2 \psi^2 + \text{h.c.}$	0 + 0 + 5 + 0	6
		$F_L^2 \psi^{12} + \text{h.c.}$	0 + 5 + 5 + 0	6
	(2, 1)	$\psi^2 \psi^2 D + \text{h.c.}$	0 + 4 + 20 + 0	24
		$F_L \psi \psi^\dagger \phi D + \text{h.c.}$	0 + 0 + 5 + 0	8
		$\psi^2 \phi^2 D^2 + \text{h.c.}$	0 + 0 + 4 + 0	6
	(1, 1)	$\psi^4 \psi + \text{h.c.}$	0 + 2 + 10 + 0	24
		$F_L \psi^2 \phi^2 + \text{h.c.}$	0 + 0 + 6 + 0	6
		$\psi^2 \psi^{12} \phi$	0 + 4 + 22 + 0	30
		$\psi \psi^\dagger \psi^2 D$	0 + 0 + 2 + 0	4
		$\psi^2 \phi^4 + \text{h.c.}$	0 + 0 + 2 + 0	2
	Total	18	0 + 10 + 56 + 0	116

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[Bhattacharya, Wudka, 2016]

[Liao, Ma, 2017]

Dimension-9

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

N	(n, \bar{n})	Classes	N_{type}	N_{new}
4	(4, 0)	$F_L^2 \psi^2 + \text{h.c.}$	0 + 6 + 0 + 0	12
		$F_L^2 F_R \psi^2 D^2 + \text{h.c.}$	0 + 6 + 0 + 0	6
		$F_L^2 \psi^{12} D^2 + \text{h.c.}$	0 + 6 + 0 + 0	6
		$\psi^2 \psi^{12} D^3 + \text{h.c.}$	4 + 20 + 0 + 0	48
		$F_L \psi \psi^\dagger \phi D^2 + \text{h.c.}$	0 + 8 + 0 + 0	16
	(3, 1)	$\psi^2 \psi^2 D^2 + \text{h.c.}$	0 + 1 + 0 + 0	8
		$F_L^2 \psi^2 + \text{h.c.}$	0 + 10 + 0 + 0	10
		$F_L^2 \psi^{12} + \text{h.c.}$	0 + 4 + 0 + 0	4
		$F_L^2 \psi^2 D + \text{h.c.}$	10 + 42 + 0 + 0	222
		$F_L^2 \psi \psi^\dagger \phi D + \text{h.c.}$	0 + 10 + 0 + 0	20
5	(4, 1)	$\psi^2 \psi^2 D + \text{h.c.}$	9 + 10 + 0 + 1	190
		$F_L^2 \psi^2 D^2 + \text{h.c.}$	0 + 8 + 0 + 0	40
		$F_L \psi^2 \psi^2 + \text{h.c.}$	0 + 12 + 0 + 0	12
		$F_L \psi^2 \psi^{12} D + \text{h.c.}$	10 + 12 + 0 + 0	166
		$F_L \psi \psi^\dagger \psi^2 D + \text{h.c.}$	0 + 10 + 0 + 0	20
	(3, 2)	$F_L^2 \psi \psi^\dagger \phi D + \text{h.c.}$	4 + 22 + 0 + 0	210
		$F_L \psi^2 \psi^2 D^2 + \text{h.c.}$	0 + 8 + 0 + 0	24
		$\psi \psi^\dagger \psi^2 D^2 + \text{h.c.}$	0 + 8 + 0 + 0	20
		$\psi \psi^\dagger \phi^2 D^2 + \text{h.c.}$	0 + 2 + 0 + 0	20
		$\psi^4 \phi^2 + \text{h.c.}$	0 + 10 + 0 + 2	100
6	(3, 0)	$F_L \psi^2 \phi^2 + \text{h.c.}$	6 + 26 + 0 + 3	110
		$F_L \psi^2 \phi^4 + \text{h.c.}$	0 + 12 + 0 + 3	12
		$F_L^2 \psi^2 \phi^2 + \text{h.c.}$	0 + 12 + 0 + 3	12
		$\psi^4 \phi^2 D + \text{h.c.}$	0 + 10 + 0 + 0	474
		$F_L \psi^2 \psi^{12} \phi + \text{h.c.}$	24 + 116 + 0 + 0	140
	(2, 1)	$F_L^2 \psi^2 \psi^{12} \phi + \text{h.c.}$	0 + 10 + 0 + 0	10
		$\psi^2 \psi^2 \psi^2 D + \text{h.c.}$	10 + 14 + 0 + 0	268
		$F_L \psi^2 \psi^2 \psi^2 D + \text{h.c.}$	0 + 8 + 0 + 0	32
		$\psi^2 \psi^4 D^2 + \text{h.c.}$	0 + 4 + 0 + 0	20
		$\psi^4 \phi^2 + \text{h.c.}$	2 + 12 + 0 + 3	28
7	(2, 0)	$F_L \psi^2 \phi^4 + \text{h.c.}$	0 + 6 + 0 + 0	6
		$\psi^2 \psi^2 \phi^2 \phi^2 + \text{h.c.}$	0 + 6 + 0 + 0	6
	(1, 1)	$\psi^2 \psi^2 \psi^2 \phi^2 + \text{h.c.}$	0 + 2 + 0 + 0	2
		$\psi^2 \psi^2 \psi^2 \phi^2 D + \text{h.c.}$	0 + 2 + 0 + 0	2

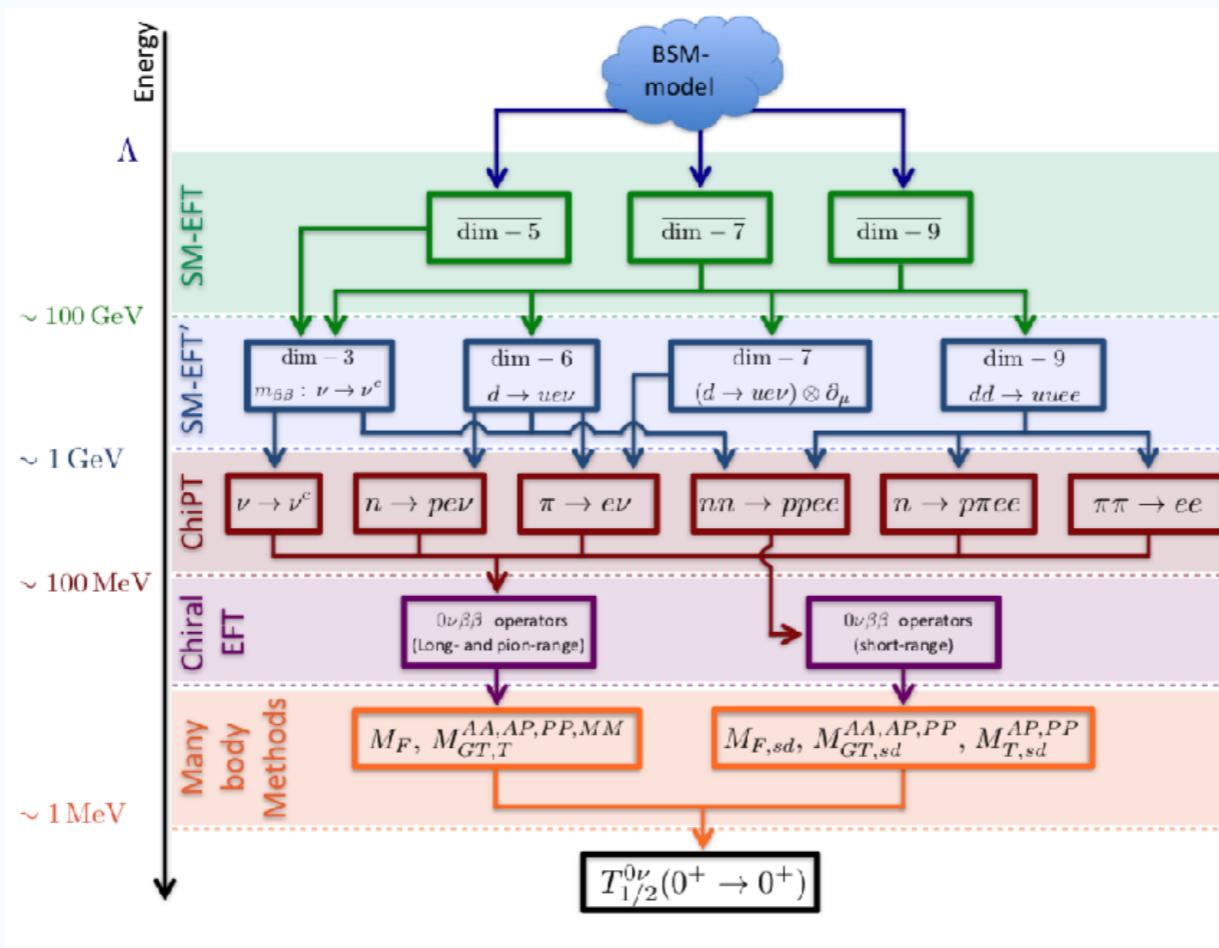
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Summary

Summary

- 0vbb 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!