Institute of Theoretical Physics
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ν Mass & 0νbb in EFT Framework

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

Gang Li, Hao Sun, **JHY** , in collaboration

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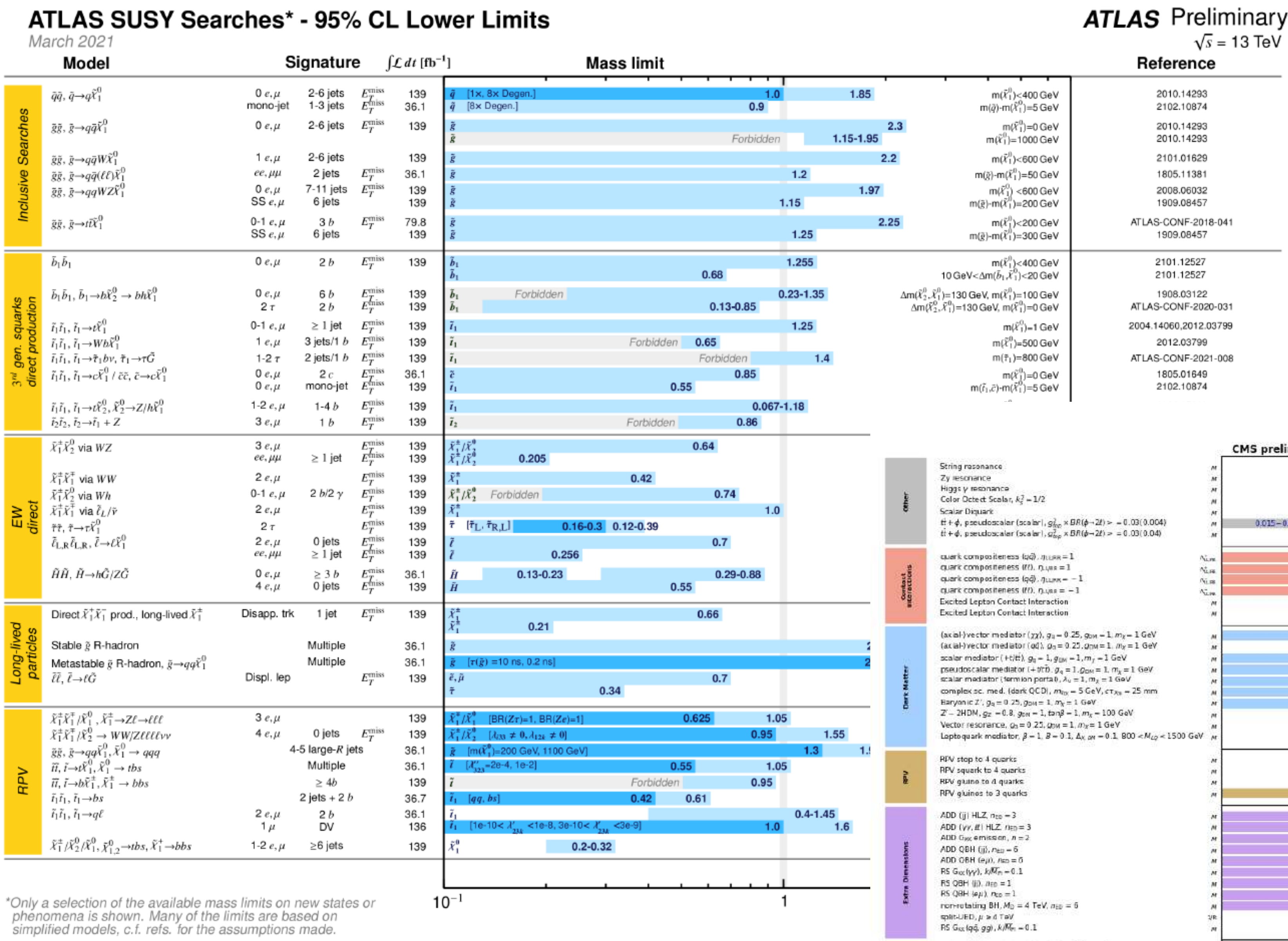
Outline

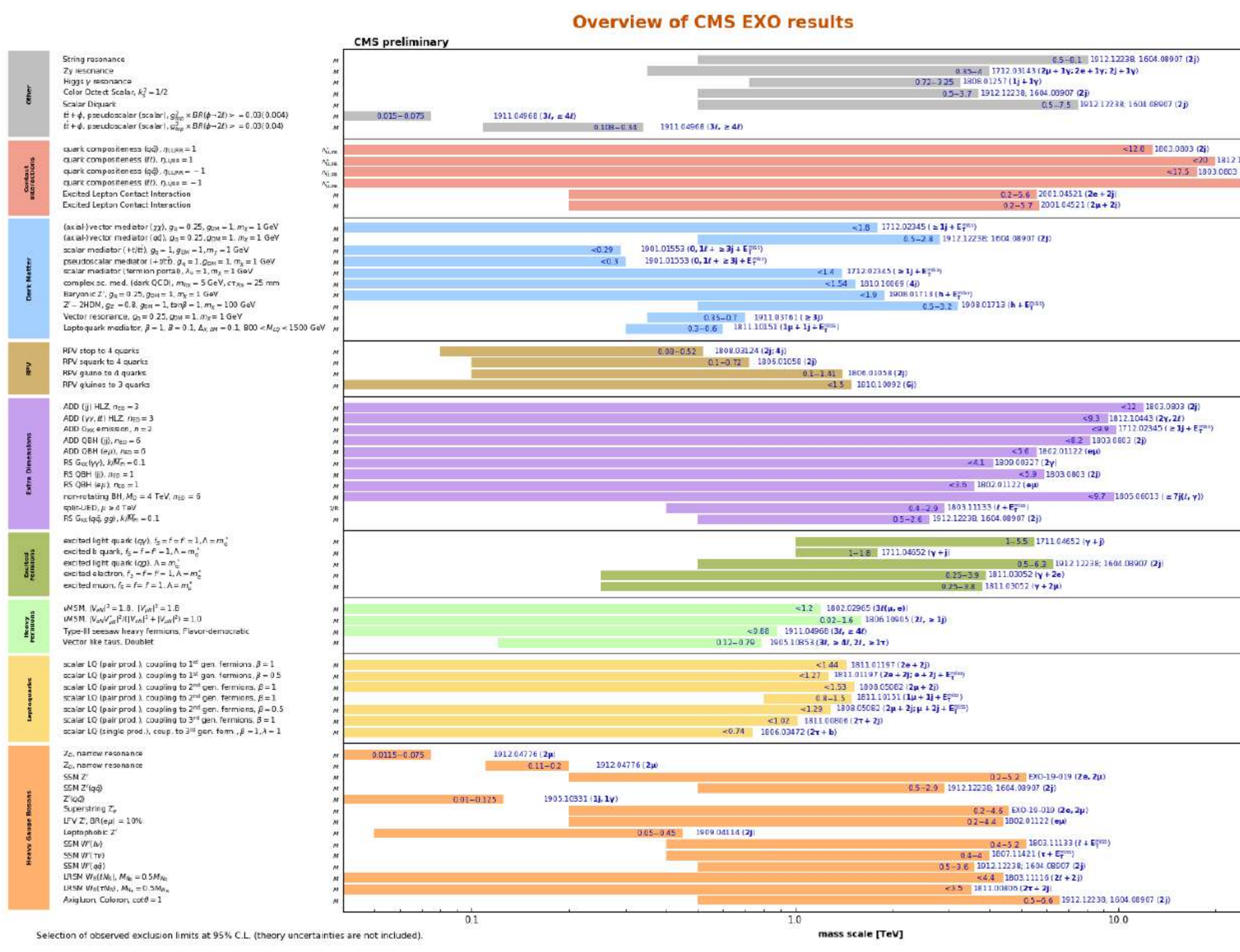
- Why 0vbb in EFT approach?
- SMEFT: 0vbb and nv masses, UV physics
- LEFT: quark currents and weak sources
- ChiPT: short-range, pion-range, long-range
- Summary and outlook

Introduction

Why 0vbb in EFT approach?

Search For New Physics

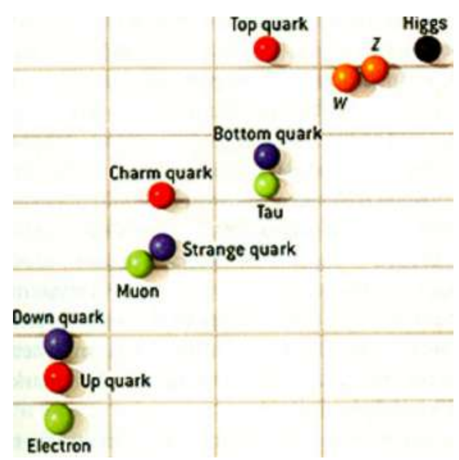




New Physics w/o New Particle

SUSY/XD/CHM/…

LHC probing scale



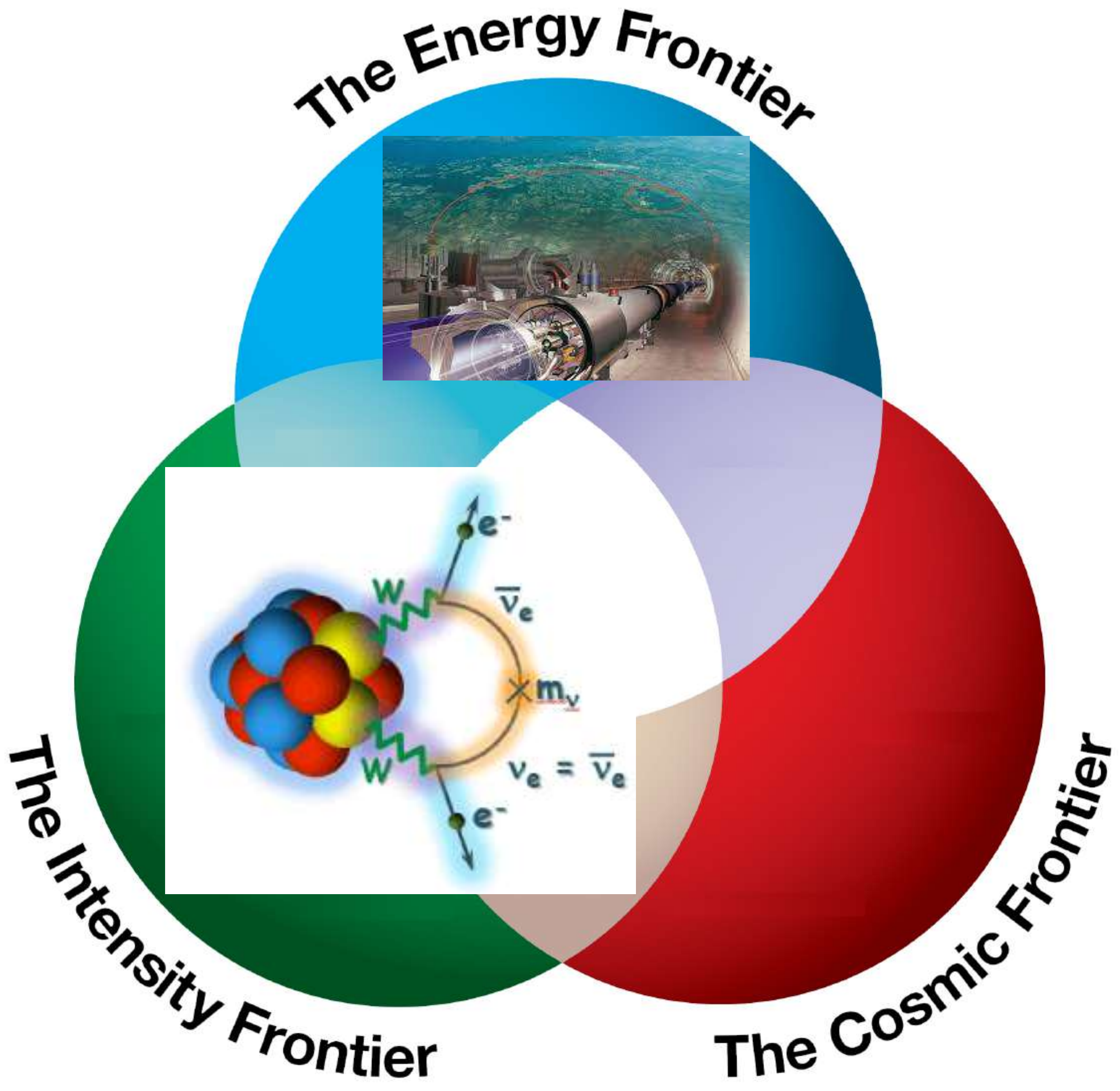
SMEFT

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

Top-down: Integrate out and matching/running

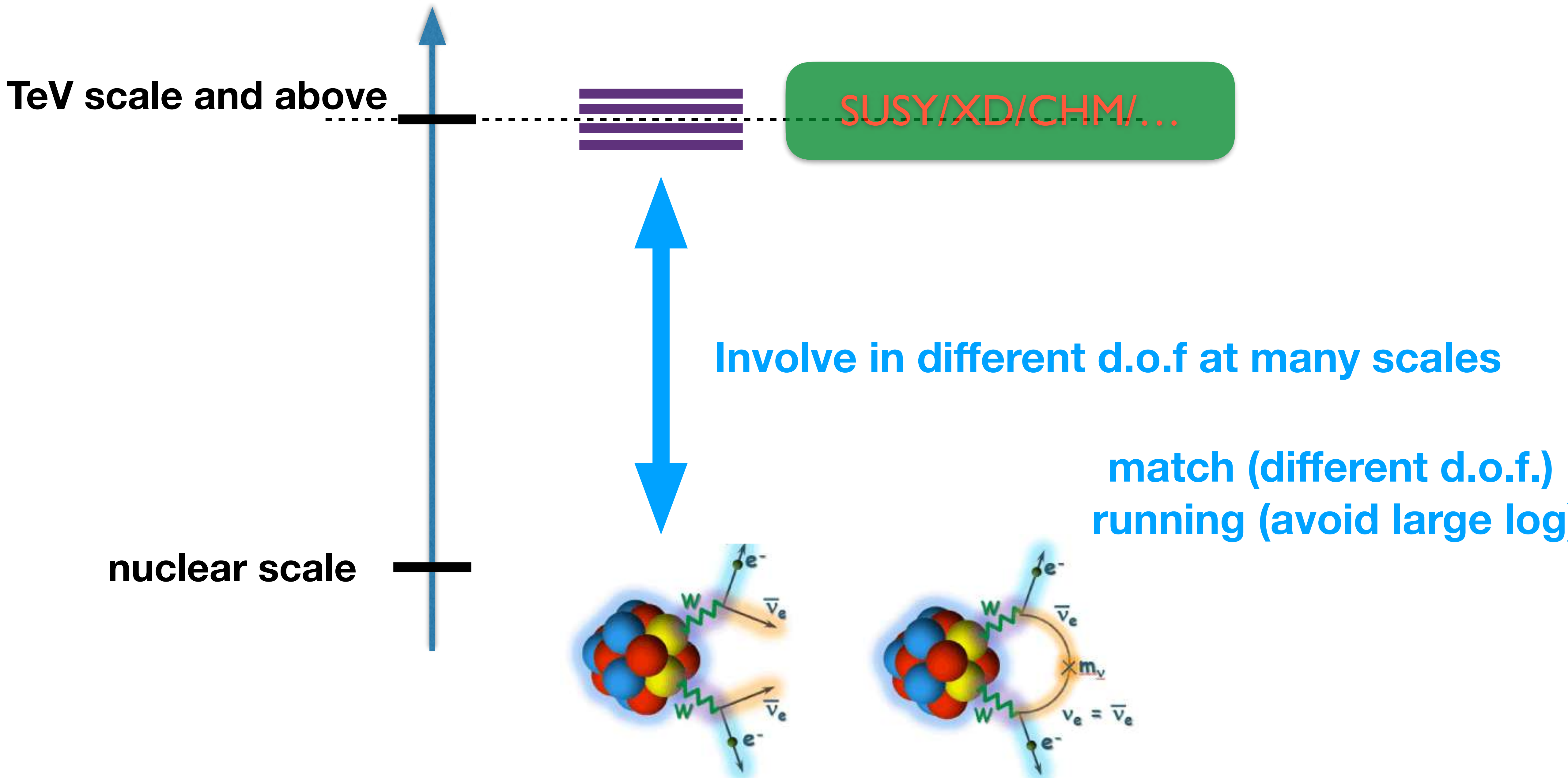
Bottom-up: field d.o.f and symmetry at IR scale

New Physics w/o New Particle



Low Energy Probe of HEP

Low energy probes of high energy physics



power counting (systematic)

EFT Framework

Model independent systematical parametrization of new physics

Energy

UV models many models …..

$$\mathcal{L} = \mathcal{L}^{\text{eff}}_{\text{Gravity}} + \underbrace{\mathcal{L}_{\text{QCD}} + \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{EW}}}_{\mathcal{L}_{SM}} + \mathcal{L}^{NP}_{\text{heavy}}$$

TeV scale

SMEFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{C_i^{(5)}}{\Lambda_{NP}} Q_i^{(5)} + \frac{C_i^{(6)}}{\Lambda_{NP}^2} Q_i^{(6)} + \cdots$$

EW scale

Low energy EFT

$$\mathcal{L}_{\text{LEFT}} = \mathcal{L}_{\text{QED+QCD}} + \frac{C_i^{(5)}}{M_W} O_i^{(5)} + \frac{C_i^{(6)}}{M_W^2} O_i^{(6)} + \cdots$$

Λ_{QCD}

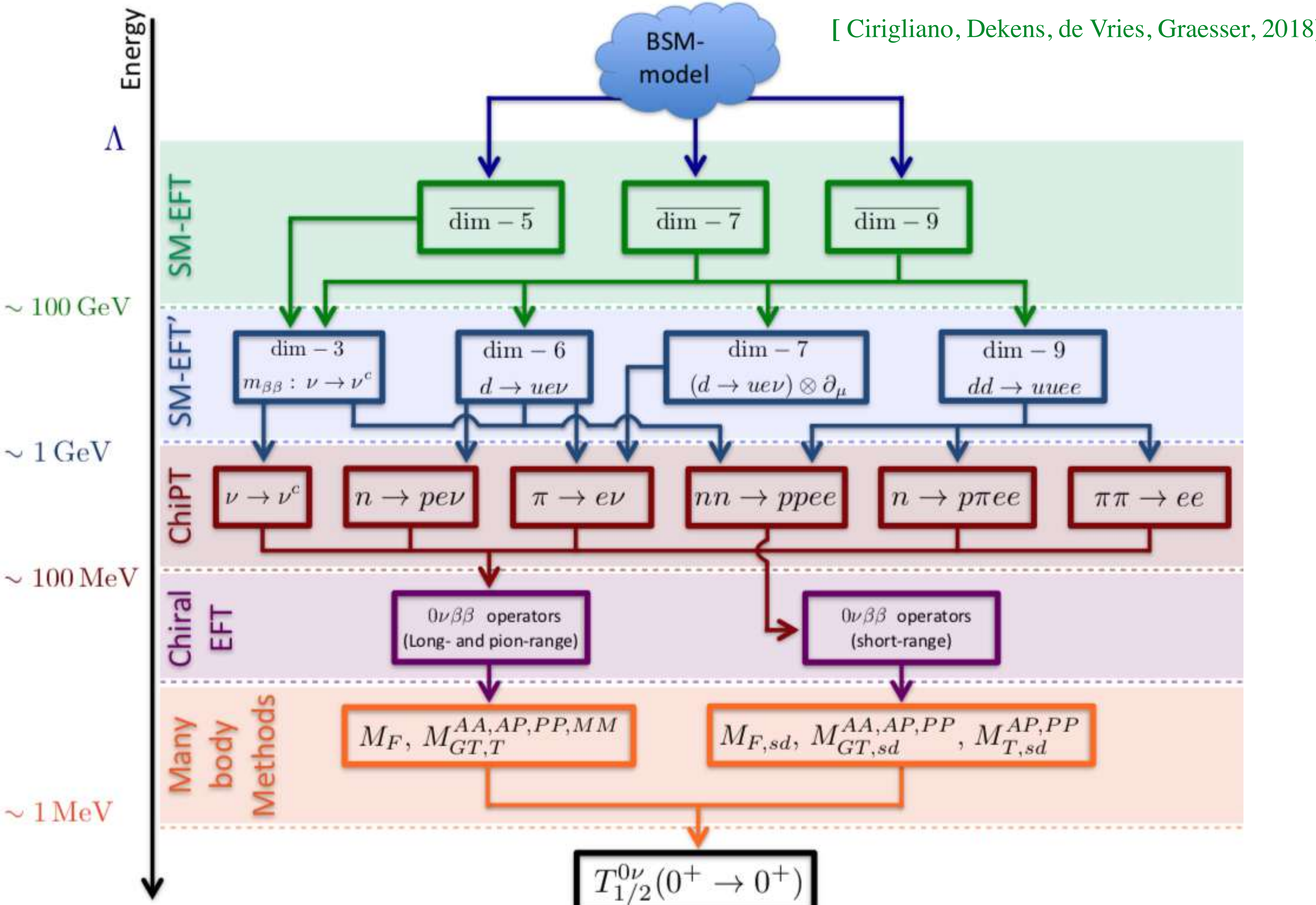
Chiral Lagrangian + Heavy B EFT

$$\mathcal{L}_{\chi} = \mathcal{L}_{\pi}(s, p, l_\mu, r_\mu) + \mathcal{L}_{\pi N}(s, p, l_\mu, r_\mu) + \cdots$$

MeV scale

Nuclear EFT (nuclear matrix elements) $0\nu\beta\beta$

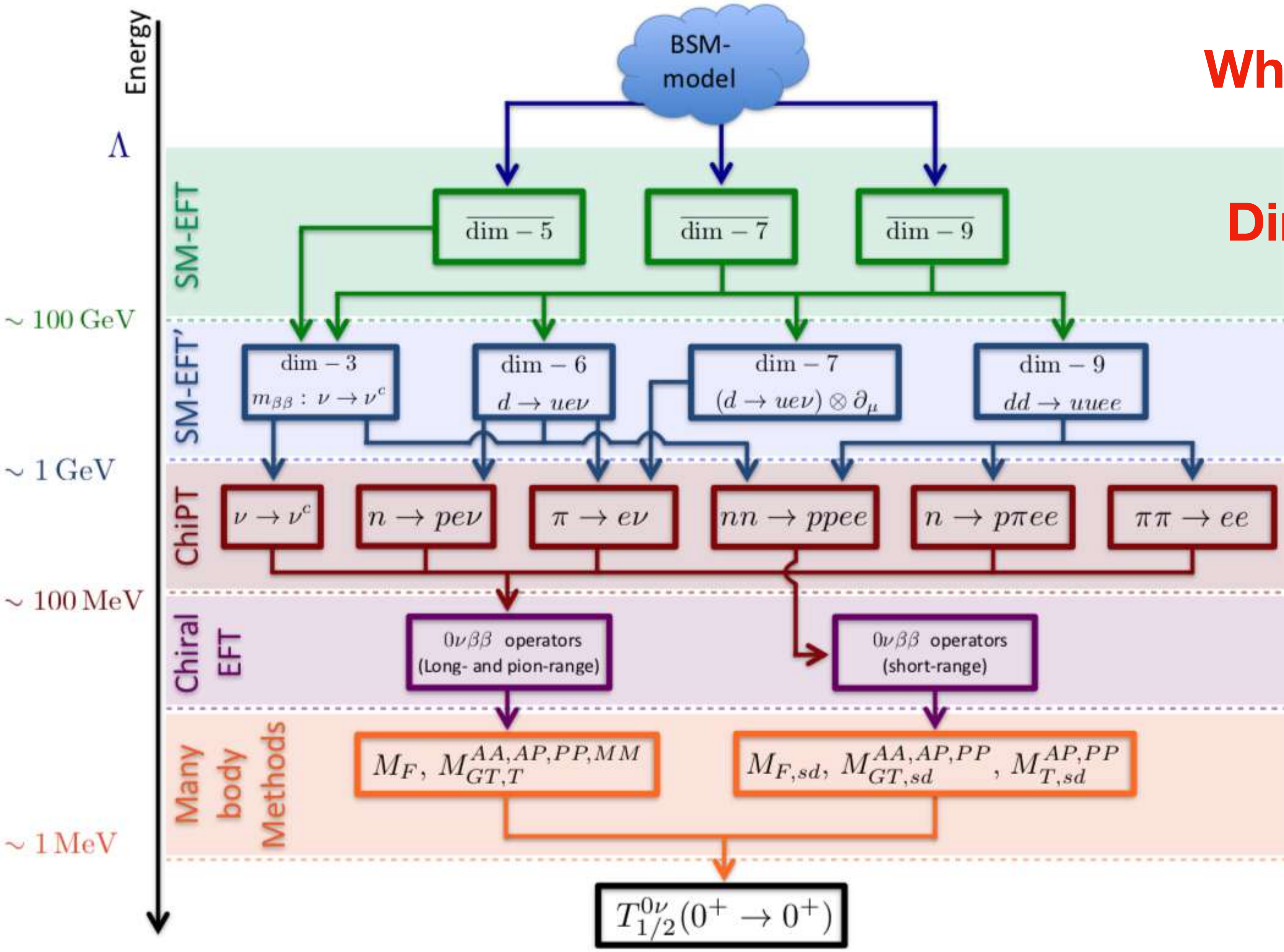
EFT for 0vbb



[Cirigliano, Dekens, de Vries, Graesser, 2018]
Energy
Λ
~ 100 GeV
~ 1 GeV
~ 100 MeV
~ 1 MeV
BSM-model
SM-EFT
$\overline{\dim - 5}$
$\overline{\dim - 7}$
$\overline{\dim - 9}$
SM-EFT'
$\dim - 3$
$m_{\beta\beta}: \nu \to \nu^c$
$\dim - 6$
$d \to ue\nu$
$\dim - 7$
$(d \to ue\nu) \otimes \partial_\mu$
$\dim - 9$
$dd \to uuee$
ChiPT
$\nu \to \nu^c$
$n \to pe\nu$
$\pi \to e\nu$
$nn \to ppee$
$n \to p\pi ee$
$\pi\pi \to ee$
Chiral EFT
$0\nu\beta\beta$ operators
(Long- and pion-range)
$0\nu\beta\beta$ operators
(short-range)
Many body Methods
$M_F,\ M_{GT,T}^{AA,AP,PP,MM}$
$M_{F,sd},\ M_{GT,sd}^{AA,AP,PP},\ M_{T,sd}^{AP,PP}$
$T_{1/2}^{0\nu}(0^+ \to 0^+)$

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

scalar | fermion | vector

SMEFT

$\overline{\text{dim}} - 5$ | $\overline{\text{dim}} - 7$ | $\overline{\text{dim}} - 9$

0vbb | **nv mass**

Lepton number violation

$\text{dim} - 3$: $m_{\beta\beta} : \nu \to \nu^c$

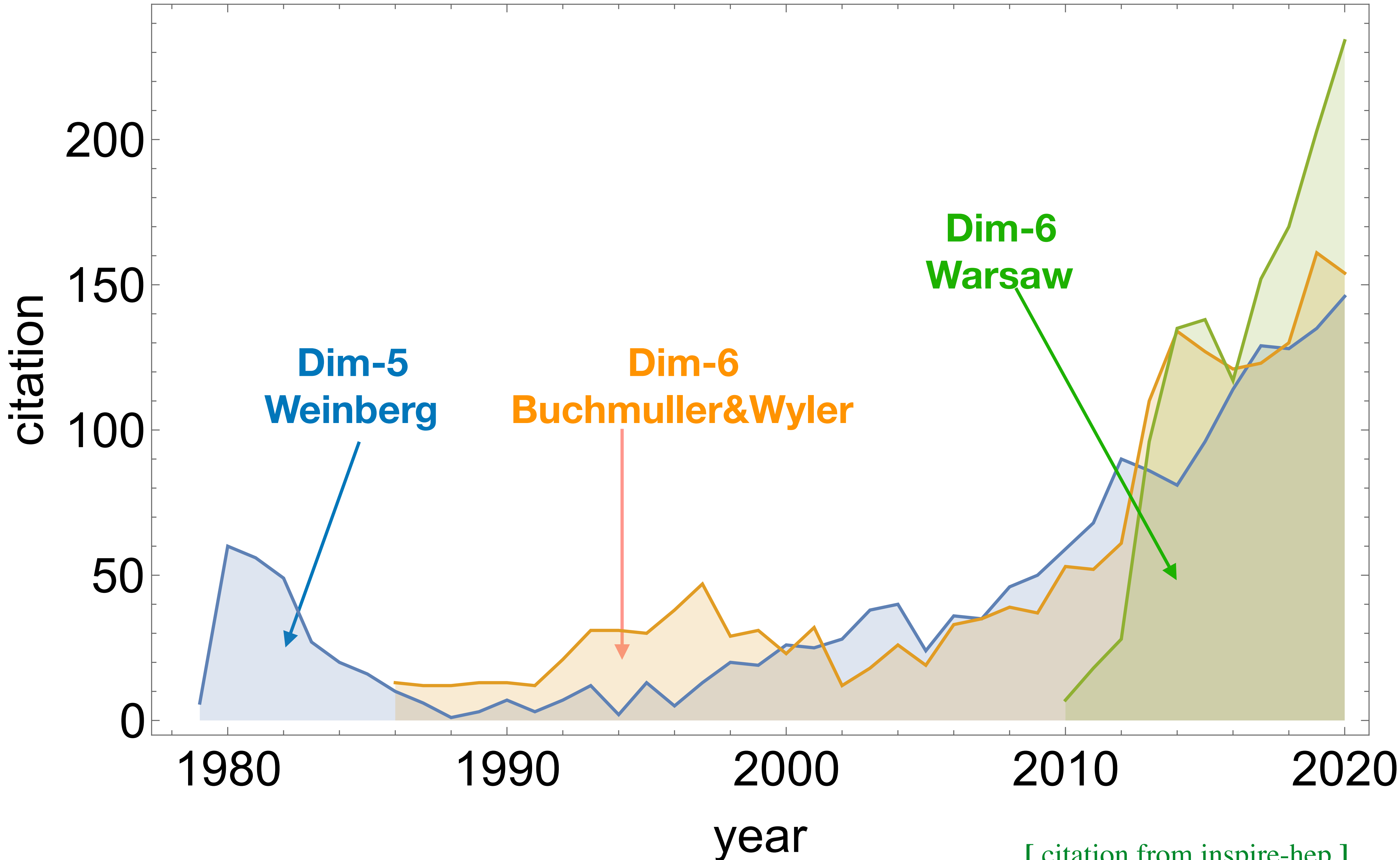
$\text{dim} - 6$: $d \to ue\nu$

$\text{dim} - 7$: $(d \to ue\nu) \otimes \partial_\mu$

$\text{dim} - 9$: $dd \to uuee$

relevant low energy EFT operators

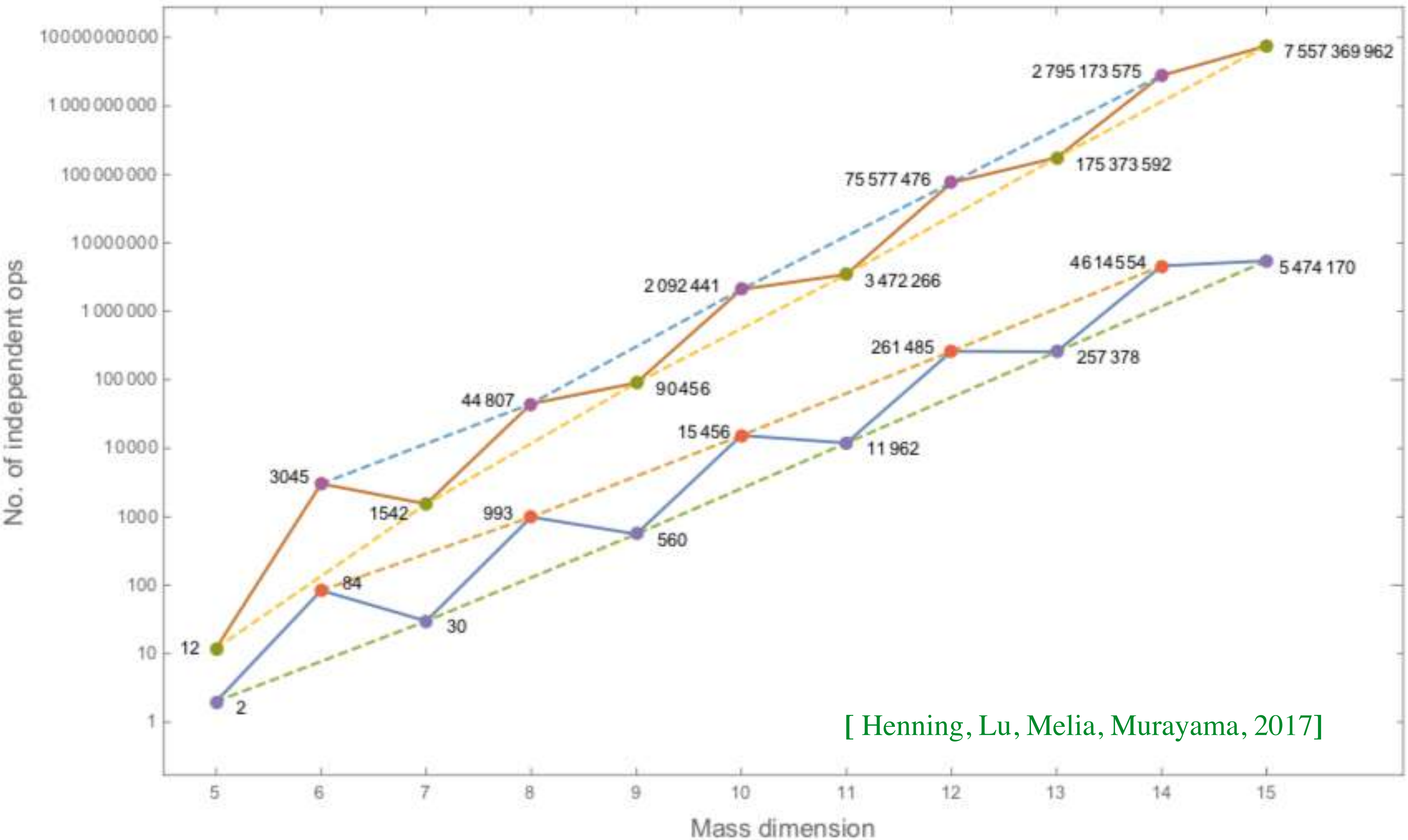
SMEFT Operators



[citation from inspire-hep]

Hilbert Series Counting

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



Higher Dim Operators!?

Given numbers of independent operators

does not mean we know explicit form of operators!

Derivatives

$BWHH^\dagger D^2$

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

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Which 2 should be picked up?

Repeated fields

$QQQL$

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$$Q^{qqq\ell}_{prst} = C^{prst} \begin{array}{l} \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}(L_{pi}Q_{raj})(Q_{sbk}Q_{tcl}) \\ \epsilon^{abc}\epsilon^{ik}\epsilon^{jl}(L_{pi}Q_{sbk})(Q_{raj}Q_{tcl}) \\ \epsilon^{abc}\epsilon^{ij}\epsilon^{kl}(L_{pi}Q_{sbk})(Q_{raj}Q_{tcl}) \\ \epsilon^{abc}\epsilon^{ij}\epsilon^{kl}(L_{pi}Q_{raj})(Q_{sbk}Q_{tcl}) \end{array} \qquad p,r,s,t = 1,2,3$$

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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）

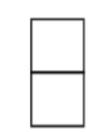
$$\boxed{H_i \in (0,0) \quad \psi_\alpha \in (1/2,0) \quad F_{\mathrm{L}\alpha\beta} = \frac{i}{2}F_{\mu\nu}\sigma^{\mu\nu}_{\alpha\beta} \in (1,0) \quad D_{\alpha\dot\alpha} = D_\mu \sigma^\mu_{\alpha\dot\alpha} \in (1/2,1/2).}$$

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

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

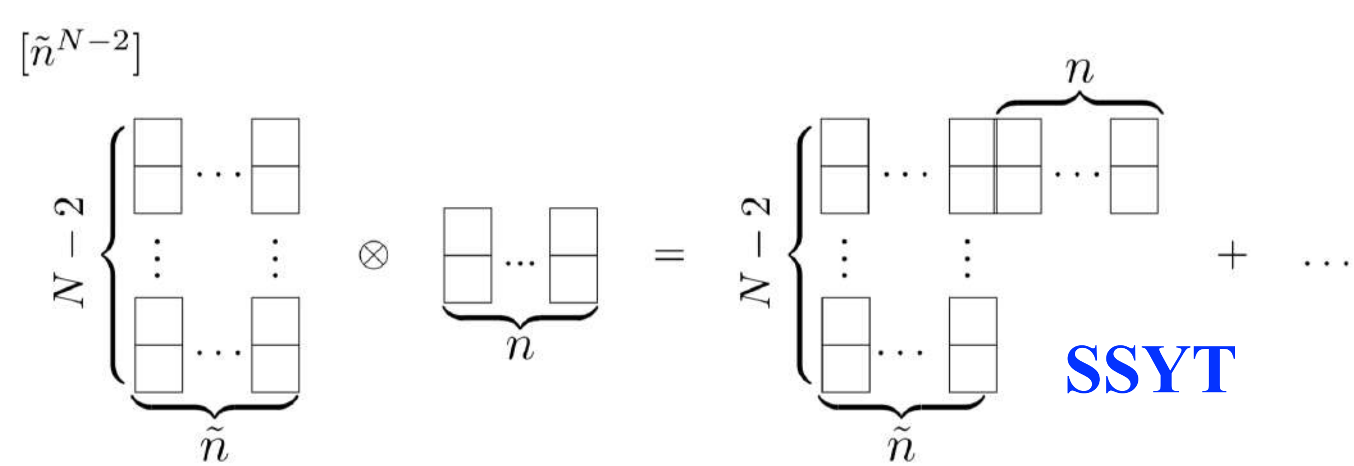
$$\partial\psi = \left(1,\frac{1}{2}\right)+\left(0,\frac{1}{2}\right) \qquad (D\psi)_{\alpha\beta\dot\alpha} = -\frac{1}{2}\epsilon_{\alpha\beta}(\not{D}\psi)_{\dot\alpha} + \frac{1}{2}(D\psi)_{(\alpha\beta)\dot\alpha}$$

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

 $= [1^2]$

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

$$\mathcal{M} = (\epsilon^{\alpha_i\alpha_j})^{\otimes n}(\tilde\epsilon_{\dot\alpha_i\dot\alpha_j})^{\otimes\tilde n}\prod_{i=1}^{N}(D^{r_i-|h_i|}\Phi_i)^{\dot\alpha_i^{r_i+h_i}}_{\alpha_i^{r_i-h_i}} =$$



Operator Construction

$$BWHH^\dagger D^2$$

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

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

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

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highest weight representation

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

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

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

$$\begin{array}{|c|c|c|c|}\hline 1&1&1&3\\\hline 2&2&2&4\\\hline\end{array} \qquad \begin{array}{|c|c|c|c|}\hline 1&1&1&2\\\hline 2&2&3&4\\\hline\end{array}$$

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

2

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

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

SMEFT

Dimension-5

$$\epsilon_{ij}\epsilon_{mn}(L^iCL^m)H^jH^n$$

[Weinberg, 1979]

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Dimension-6

Φ^6 and Φ^4D^2	$\psi^2\Phi^3$	X^3
$O_\Phi=(\Phi^\dagger\Phi)^3$	$O_{l\Phi}=(\Phi^\dagger\Phi)(\bar{L}_i\, l_j\Phi)$	$O_G=-f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$O_{\Phi\Box}=(\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$O_{u\Phi}=(\Phi^\dagger\Phi)(\bar{Q}_i\, u_j\Phi^c)$	$O_{\tilde{G}}=-f^{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$
$O_{\Phi D}=(\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$O_{d\Phi}=(\Phi^\dagger\Phi)(\bar{Q}_i\, d_j\Phi)$	$O_W=-\epsilon^{abc}W_\mu^{a\nu}W_\nu^{b\rho}W_\rho^{c\mu}$
		$O_{\tilde{W}}=-\epsilon^{abc}\tilde{W}_\mu^{a\nu}W_\nu^{b\rho}W_\rho^{c\mu}$

$X^2\Phi^2$	ψ^2X
$O_{\Phi G}=(\Phi^\dagger\Phi)G_{\mu\nu}^AG^{A\mu\nu}$	O_{uG}
$O_{\Phi\tilde{G}}=(\Phi^\dagger\Phi)\tilde{G}_{\mu\nu}^AG^{A\mu\nu}$	O_{dG}
$O_{\Phi W}=(\Phi^\dagger\Phi)W_{\mu\nu}^aW^{a\mu\nu}$	O_{lW}
$O_{\Phi\tilde{W}}=(\Phi^\dagger\Phi)\tilde{W}_{\mu\nu}^aW^{a\mu\nu}$	O_{uW}
$O_{\Phi B}=(\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu}$	O_{dW}
$O_{\Phi\tilde{B}}=(\Phi^\dagger\Phi)\tilde{B}_{\mu\nu}B^{\mu\nu}$	O_{lB}
$O_{\Phi WB}=-(\Phi^\dagger\tau^a\Phi)W_{\mu\nu}^aB^{\mu\nu}$	O_{uB}
$O_{\Phi\tilde{W}B}=-(\Phi^\dagger\tau^a\Phi)\tilde{W}_{\mu\nu}^aB^{\mu\nu}$	O_{dB}

$(\bar{L}L)(\bar{L}L)$	$(\bar{R}R)(\bar{R}R)$	$(\bar{L}L)(\bar{R}R)$
$O_{LL}=(\bar{L}_i\gamma_\mu L_j)(\bar{L}_k\gamma^\mu L_l)$	$O_{ll}=(\bar{l}_i\gamma_\mu l_j)(\bar{l}_k\gamma^\mu l_l)$	$O_{Ll}=(\bar{L}_i\gamma_\mu L_j)(\bar{l}_k\gamma^\mu l_l)$
$O_{QQ}^{(1)}=(\bar{Q}_i\gamma_\mu Q_j)(\bar{Q}_k\gamma^\mu Q_l)$	$O_{uu}=(\bar{u}_i\gamma_\mu u_j)(\bar{u}_k\gamma^\mu u_l)$	$O_{Lu}=(\bar{L}_i\gamma_\mu L_j)(\bar{u}_k\gamma^\mu u_l)$
$O_{QQ}^{(3)}=(\bar{Q}_i\gamma_\mu\tau^a Q_j)(\bar{Q}_k\gamma^\mu\tau^a Q_l)$	$O_{dd}=(\bar{d}_i\gamma_\mu d_j)(\bar{d}_k\gamma^\mu d_l)$	$O_{Ld}=(\bar{L}_i\gamma_\mu L_j)(\bar{d}_k\gamma^\mu d_l)$
$O_{LQ}^{(1)}=(\bar{L}_i\gamma_\mu L_j)(\bar{Q}_k\gamma^\mu Q_l)$	$O_{lu}=(\bar{l}_i\gamma_\mu l_j)(\bar{u}_k\gamma^\mu u_l)$	$O_{Ql}=(\bar{Q}_i\gamma_\mu Q_j)(\bar{l}_k\gamma^\mu l_l)$
$O_{LQ}^{(3)}=(\bar{L}_i\gamma_\mu\tau^a L_j)(\bar{Q}_k\gamma^\mu\tau^a Q_l)$	$O_{ld}=(\bar{l}_i\gamma_\mu l_j)(\bar{d}_k\gamma^\mu d_l)$	$O_{Qu}^{(1)}=(\bar{Q}_i\gamma_\mu Q_j)(\bar{u}_k\gamma^\mu u_l)$
	$O_{ud}^{(1)}=(\bar{u}_i\gamma_\mu u_j)(\bar{d}_k\gamma^\mu d_l)$	$O_{Qu}^{(8)}=\left(\bar{Q}_i\gamma_\mu\frac{\lambda^A}{2}Q_j\right)\left(\bar{u}_k\gamma^\mu\frac{\lambda^A}{2}u_l\right)$
	$O_{ud}^{(8)}=\left(\bar{u}_i\gamma_\mu\frac{\lambda^A}{2}u_j\right)\left(\bar{d}_k\gamma^\mu\frac{\lambda^A}{2}d_l\right)$	$O_{Qd}^{(1)}=(\bar{Q}_i\gamma_\mu Q_j)(\bar{d}_k\gamma^\mu d_l)$
		$O_{Qd}^{(8)}=\left(\bar{Q}_i\gamma_\mu\frac{\lambda^A}{2}Q_j\right)\left(\bar{d}_k\gamma^\mu\frac{\lambda^A}{2}d_l\right)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	B-violating
$O_{LdlQ}=(\bar{L}_i^\sigma l_j)(\bar{d}_kQ_l^\sigma)$	$O_{duQ}=\epsilon^{\alpha\beta\gamma}\epsilon_{\sigma\tau}\left[(d_i^\alpha)^TCu_j^\beta\right]\left[(Q_k^{\gamma\sigma})^TCL_l^\tau\right]$
$O_{QuQd}^{(1)}=(\bar{Q}_i^\sigma u_j)\epsilon_{\sigma\tau}(\bar{Q}_k^\tau d_l)$	$O_{QQu}=\epsilon^{\alpha\beta\gamma}\epsilon_{\sigma\tau}\left[(Q_i^{\alpha\sigma})^TCQ_j^{\beta\tau}\right]\left[(u_k^\gamma)^TCl_l\right]$
$O_{QuQd}^{(8)}=\left(\bar{Q}_i^\sigma\frac{\lambda^A}{2}u_j\right)\epsilon_{\sigma\tau}\left(\bar{Q}_k^\tau\frac{\lambda^A}{2}d_l\right)$	$O_{QQQ}=\epsilon^{\alpha\beta\gamma}\epsilon_{\sigma\tau}\epsilon_{\sigma'\tau'}\left[(Q_i^{\alpha\sigma})^TCQ_j^{\beta\tau}\right]\left[(Q_k^{\gamma\sigma'})^TCL_l^{\tau'}\right]$
$O_{LlQu}^{(1)}=(\bar{L}_i^\sigma l_j)\epsilon_{\sigma\tau}(\bar{Q}_k^\tau u_l)$	$O_{duu}=\epsilon^{\alpha\beta\gamma}\left[(d_i^\alpha)^TCu_j^\beta\right]\left[(u_k^\gamma)^TCl_l\right]$
$O_{LlQu}^{(3)}=(\bar{L}_i^\sigma\sigma_{\mu\nu}l_j)\epsilon_{\sigma\tau}(\bar{Q}_k^\tau\sigma^{\mu\nu}u_l)$	

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[Buchmuller, Wyler, 1986] [Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

Dimension-7

$1:\psi^2XH^2+\text{h.c.}$	
$Q_{l^2WH^2}$	$\epsilon_{mn}(\tau^I\epsilon)_{jk}(l_p^mCi\sigma^{\mu\nu}l_r^j)H^nH^kW_{\mu\nu}^I$
$Q_{l^2BH^2}$	$\epsilon_{mn}\epsilon_{jk}(l_p^mCi\sigma^{\mu\nu}l_r^j)H^nH^kB_{\mu\nu}$

$2:\psi^2H^4+\text{h.c.}$	
$Q_{l^2H^4}$	$\epsilon_{mn}\epsilon_{jk}(l_p^mCl_r^j)H^nH^k(H^\dagger H)$

$3(B):\psi^4H+\text{h.c.}$	
Q_{l^3eH}	$\epsilon_{jk}\epsilon_{mn}(\bar{e}_pl_r^j)(l_s^kCl_t^m)H^n$
Q_{leudH}	$\epsilon_{jk}(\bar{d}_pl_r^j)(u_sCe_t)H^k$
$Q_{l^2qdH}^{(1)}$	$\epsilon_{jk}\epsilon_{mn}(\bar{d}_pl_r^j)(q_s^kCl_t^m)H^n$
$Q_{l^2qdH}^{(2)}$	$\epsilon_{jm}\epsilon_{kn}(\bar{d}_pl_r^j)(q_s^kCl_t^m)H^n$
Q_{l^2quH}	$\epsilon_{jk}(\bar{q}_p^mu_r)(l_{sm}Cl_t^j)H^k$

$3(\cancel{B}):\psi^4H+\text{h.c.}$	
Q_{lud^2H}	$\epsilon_{\alpha\beta\gamma}(\bar{l}_pd_r^\alpha)(u_s^\beta Cd_t^\gamma)\tilde{H}$
Q_{lq^2dH}	$\epsilon_{\alpha\beta\gamma}\epsilon_{jk}(\bar{l}_p^md_r^\alpha)(q_{sm}^\beta Cq_t^{j\gamma})\tilde{H}^k$
Q_{ld^3H}	$\epsilon_{\alpha\beta\gamma}(\bar{l}_pd_r^\alpha)(d_s^\beta Cd_t^\gamma)H$
Q_{eqd^2H}	$\epsilon_{\alpha\beta\gamma}\epsilon_{jk}(\bar{e}_pq_r^{j\alpha})(d_s^\beta Cd_t^\gamma)\tilde{H}^k$

$4:\psi^2H^3D+\text{h.c.}$	
Q_{leH^3D}	$\epsilon_{mn}\epsilon_{jk}(l_p^mC\gamma^\mu e_r)H^nH^jiD_\mu H^k$

$5(B):\psi^4D+\text{h.c.}$	
Q_{l^2udD}	$\epsilon_{jk}(\bar{d}_p\gamma^\mu u_r)(l_s^jCiD_\mu l_t^k)$

$6:\psi^2H^2D^2+\text{h.c.}$	
$Q_{l^2H^2D^2}^{(1)}$	$\epsilon_{jk}\epsilon_{mn}(l_p^jCD^\mu l_r^k)H^m(D_\mu H^n)$
$Q_{l^2H^2D^2}^{(2)}$	$\epsilon_{jm}\epsilon_{kn}(l_p^jCD^\mu l_r^k)H^m(D_\mu H^n)$

$5(\cancel{B}):\psi^4D+\text{h.c.}$	
Q_{lqd^2D}	$\epsilon_{\alpha\beta\gamma}(\bar{l}_p\gamma^\mu q_r^\alpha)(d_s^\beta CiD_\mu d_t^\gamma)$
Q_{ed^3D}	$\epsilon_{\alpha\beta\gamma}(\bar{e}_p\gamma^\mu d_r^\alpha)(d_s^\beta CiD_\mu d_t^\gamma)$

30

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

Dimension-8

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

[Murphy, 2020]

N	$(n,\tilde{n})$	Subclasses	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$	$\mathcal{N}_{\text{operator}}$	Equations
4	(4,0)	$F_L^4+h.c.$	14	26	26	(4.19)
	(3,1)	$F_L^2\psi\psi^\dagger D+h.c.$	22	22	$22n_f^2$	(4.51)
		$\psi^4D^2+h.c.$	$4\underline{+4}$	$18\underline{+14}$	$12n_f^4\underline{+n_f^3(5n_f-1)}$	(4.75, 4.78, 4.80)
		$F_L\psi^2\phi D^2+h.c.$	16	32	$32n_f^2$	(4.44)
		$F_L^2\phi^2D^2+h.c.$	8	12	12	(4.14)
	(2,2)	$F_L^2F_R^2$	14	17	17	(4.19)
		$F_LF_R\psi\psi^\dagger D$	27	35	$35n_f^2$	(4.50, 4.51)
		$\psi^2\psi^{\dagger 2}D^2$	$17\underline{+4}$	$54\underline{+8}$	$\frac{1}{2}n_f^2(75n_f^2+11)\underline{+6n_f^4}$	(4.74, 4.79-4.81)
		$F_R\psi^2\phi D^2+h.c.$	16	16	$16n_f^2$	(4.44)
		$F_LF_R\phi^2D^2$	5	6	6	(4.14)
		$\psi\psi^\dagger\phi^2D^3$	7	16	$16n_f^2$	(4.31, 4.32)
		ϕ^4D^4	1	3	3	(4.8)
5	(3,0)	$F_L\psi^4+h.c.$	$12\underline{+10}$	$66\underline{+54}$	$42n_f^4\underline{+2n_f^3(9n_f+1)}$	(4.86, 4.88, 4.89, 4.91)
		$F_L^2\psi^2\phi+h.c.$	32	60	$60n_f^2$	(4.47, 4.48)
		$F_L^3\phi^2+h.c.$	6	6	6	(4.16)
	(2,1)	$F_L\psi^2\psi^{\dagger 2}+h.c.$	$84\underline{+24}$	$172\underline{+32}$	$2n_f^2(59n_f^2-2)\underline{+24n_f^4}$	(4.84-4.85), (4.88-4.92)
		$F_R^2\psi^2\phi+h.c.$	32	36	$36n_f^2$	(4.47, 4.48)
		$\psi^3\psi^\dagger\phi D+h.c.$	$32\underline{+14}$	$180\underline{+56}$	$n_f^3(135n_f-1)\underline{+n_f^3(29n_f+3)}$	(4.66, 4.69-4.72)
		$F_L\psi\psi^\dagger\phi^2D+h.c.$	38	92	$92n_f^2$	(4.39, 4.40)
		$\psi^2\phi^3D^2+h.c.$	6	36	$36n_f^2$	(4.28)
		$F_L\phi^4D^2+h.c.$	4	6	6	(4.10)
6	(2,0)	$\psi^4\phi^2+h.c.$	$12\underline{+4}$	$48\underline{+18}$	$5(5n_f^4+n_f^2)\underline{+\frac{2}{3}(8n_f^4+n_f^2)}$	(4.55, 4.59, 4.62, 4.64)
		$F_L\psi^2\phi^3+h.c.$	16	22	$22n_f^2$	(4.36)
		$F_L^2\phi^4+h.c.$	8	10	10	(4.12)
	(1,1)	$\psi^2\psi^{\dagger 2}\phi^2$	$23\underline{+10}$	$57\underline{+14}$	$n_f^2(42n_f^2+n_f+2)\underline{+3n_f^3(3n_f-1)}$	(4.54, 4.55, 4.59-4.63)
		$\psi\psi^\dagger\phi^4D$	7	13	$13n_f^2$	(4.24, 4.25)
		ϕ^6D^2	1	2	2	(4.8)
7	(1,0)	$\psi^2\phi^5+h.c.$	6	6	$6n_f^2$	(4.21)
8	(0,0)	ϕ^8	1	1	1	(4.8)
Total		48	$471\underline{+70}$	$1070\underline{+196}$	$993(n_f=1)$, $44807(n_f=3)$	

993

Dimension-9

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

[Liao, Ma, 2020]

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$	$\mathcal{N}_{\text{operator}}$	Equations
4	(3,2)	$\psi^3\psi^\dagger D^3+h.c.$	$0+4+2+0$	10	$\frac{2}{3}n_f^2(7n_f^2-1)$	(5.50)(5.51)
		$\psi^2\phi^2D^4+h.c.$	$0+0+2+0$	6	$3n_f(n_f+1)$	(5.21)
5	(3,1)	$F_L\psi^3\psi^\dagger D+h.c.$	$0+10+6+0$	72	$32n_f^4$	(5.59)(5.60)
		$\psi^4\phi D^2+h.c.$	$0+4+4+0$	100	$40n_f^4$	(5.45-5.48)
		$F_L\psi^2\phi^2D^2+h.c.$	$0+0+4+0$	34	$17n_f^2-n_f$	(5.28)(5.29)
	(2,2)	$F_R\psi^3\psi^\dagger D+h.c.$	$0+10+6+0$	54	$4n_f^3(6n_f+1)$	(5.59)(5.60)
		$\psi^2\psi^{\dagger 2}\phi D^2$	$0+4+4+0$	84	$n_f^3(49n_f+1)$	(5.45-5.48)
		$F_R\psi^2\phi^2D^2+h.c.$	$0+0+4+0$	20	$2n_f(5n_f-1)$	(5.28)(5.29)
		$\psi\psi^\dagger\phi^3D^3$	$0+0+2+0$	6	$6n_f^2$	(5.19)
6	(3,0)	$\psi^6+h.c.$	$2+4+6+0$	116	$\frac{1}{24}n_f^2(415n_f^4+53n_f^3+59n_f^2+139n_f+6)$	(5.63-5.70)
		$F_L\psi^4\phi+h.c.$	$0+12+10+0$	102	$2n_f^3(21n_f+1)$	(5.54-5.56)
		$F_L^2\psi^2\phi^2+h.c.$	$0+0+8+0$	20	$2n_f(5n_f+2)$	(5.32)
	(2,1)	$\psi^4\psi^{\dagger 2}+h.c.$	$4+26+20+4$	244	$\frac{1}{6}n_f^3(382n_f^3-9n_f^2+2n_f+21)$	(5.63-5.69)
		$F_L\psi^2\psi^{\dagger 2}\phi+h.c.$	$0+24+24+0$	92	$52n_f^4$	(5.54-5.56)
		$F_L^2\psi^{\dagger 2}\phi^2+h.c.$	$0+0+8+0$	12	$2n_f(3n_f+2)$	(5.32)
		$\psi^3\psi^\dagger\phi^2D+h.c.$	$0+12+18+0$	186	$\frac{2}{3}n_f^2(146n_f^2+1)$	(5.39-5.42)
		$F_L\psi\psi^\dagger\phi^3D+h.c.$	$0+0+8+0$	12	$12n_f^2$	(5.25)
		$\psi^2\phi^4D^2+h.c.$	$0+0+4+0$	24	$2n_f(6n_f+1)$	(5.17)
7	(2,0)	$\psi^4\phi^3+h.c.$	$0+6+6+0$	32	$\frac{4}{3}n_f^2(10n_f^2-1)$	(5.35-5.37)
		$F_L\psi^2\phi^4+h.c.$	$0+0+4+0$	8	$2n_f(2n_f-1)$	(5.23)
	(1,1)	$\psi^2\psi^{\dagger 2}\phi^3$	$0+6+10+0$	24	$14n_f^4$	(5.35-5.37)
		$\psi\psi^\dagger\phi^5D$	$0+0+2+0$	2	$2n_f^2$	(5.12)
8	(1,0)	$\psi^2\phi^6+h.c.$	$0+0+2+0$	2	$n_f^2+n_f$	(5.9)
Total		42	6+122+164+4	1262	$8+204+348+0\ (n_f=1)$ $2862+42234+44874+486\ (n_f=3)$	

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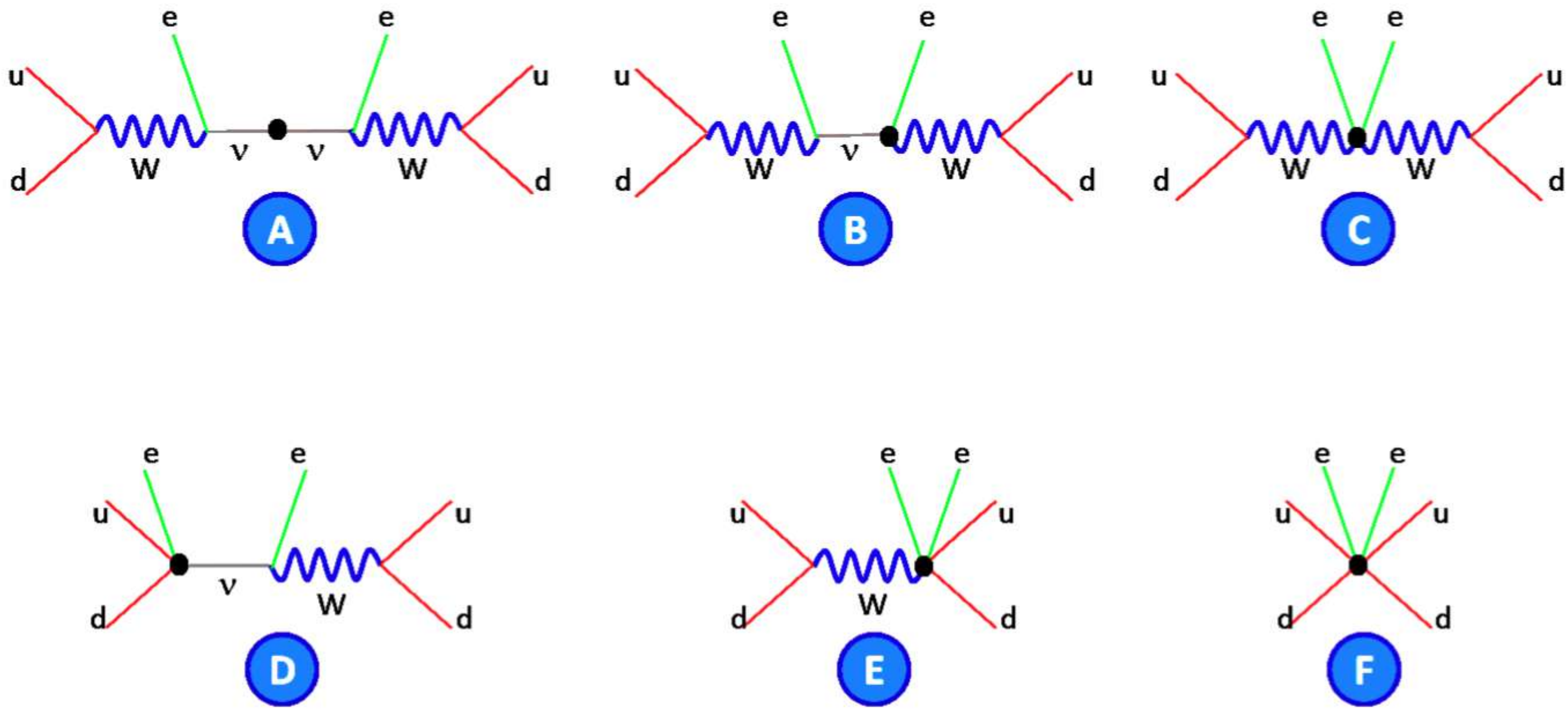
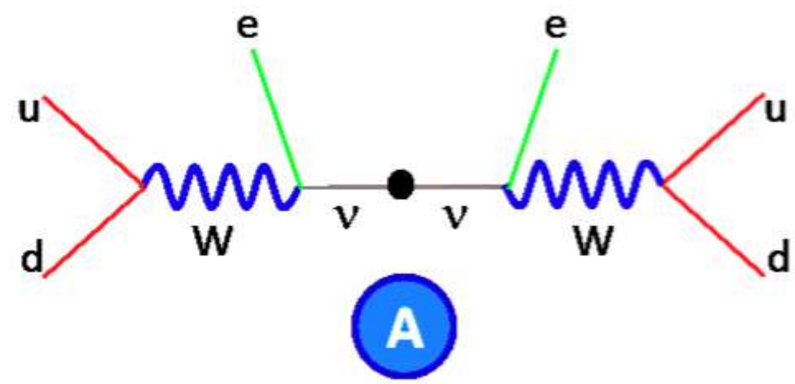
0vbb Related Operators

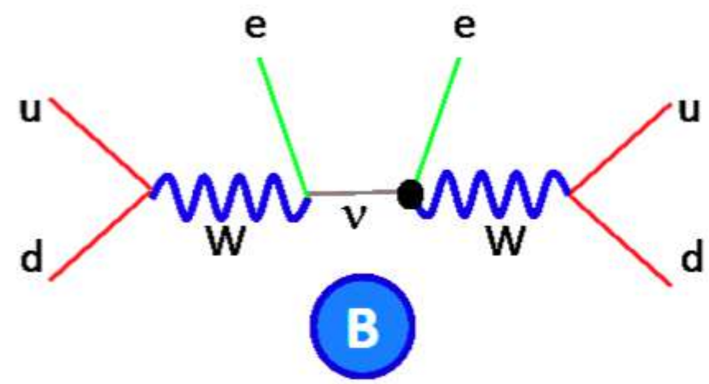
SMEFT broken phase:

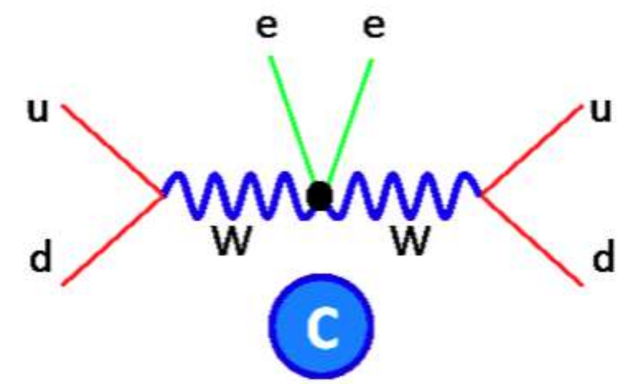


0vbb Related Operators

Relate to SMEFT unbroken operators:







$\left(\overline{\tilde{\ell}_\alpha}\phi\right)\left(\tilde{\phi}^\dagger \ell_\beta\right)$

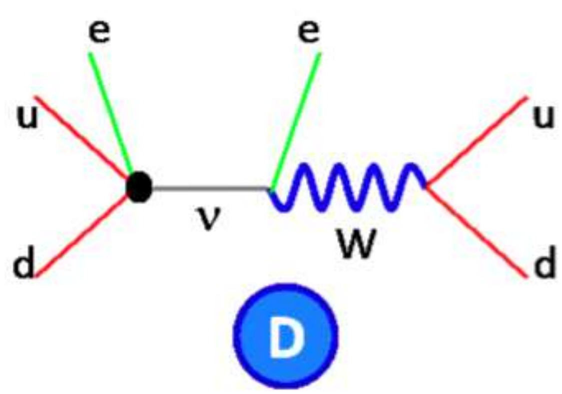
Dim-5

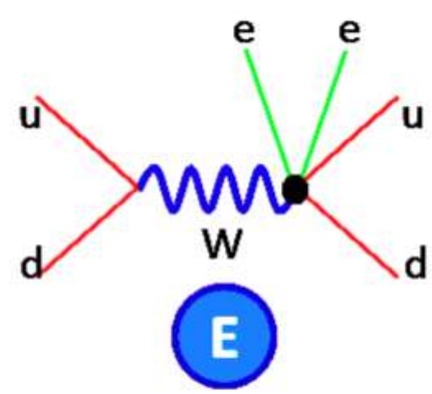
$\left(\phi^\dagger D_\mu \tilde{\phi}\right)\left(\phi^\dagger \overline{e_{\alpha \mathrm{R}}}\gamma^\mu \tilde{\ell}_\beta\right)$

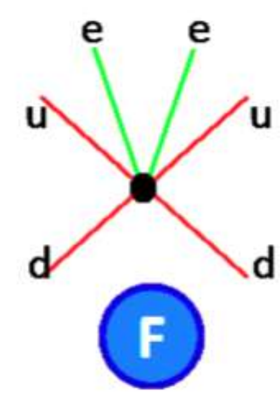
Dim-7, 9

$\overline{e_{\alpha \mathrm{R}}} e^c_{\beta \mathrm{R}} \left(\phi^\dagger D \tilde{\phi}\right)^2$

Dim-7, 9







Dim-7, 9

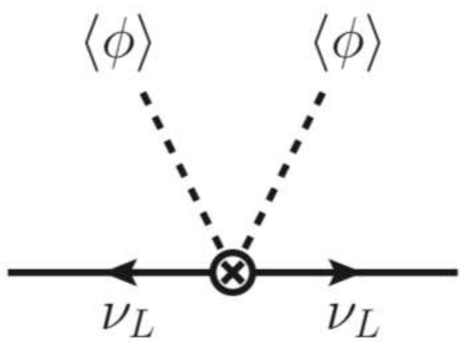
Dim-9

Dim-9

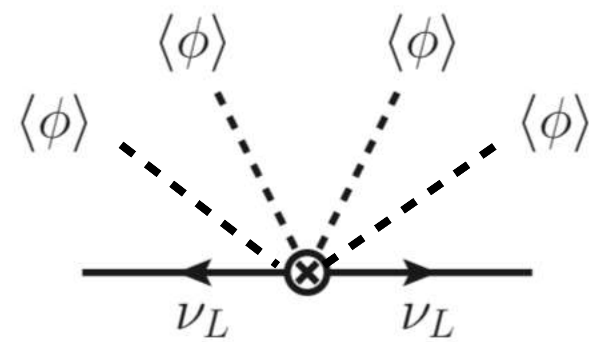
Not complete

Nv Mass Related Operators

Higgs taking VEV:



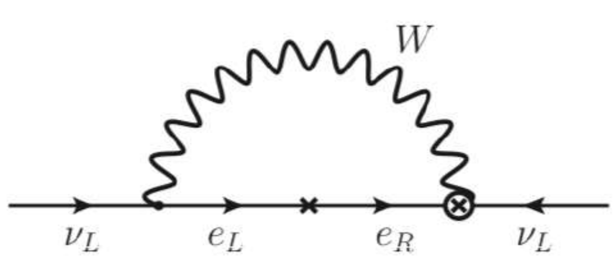
$LLHH$

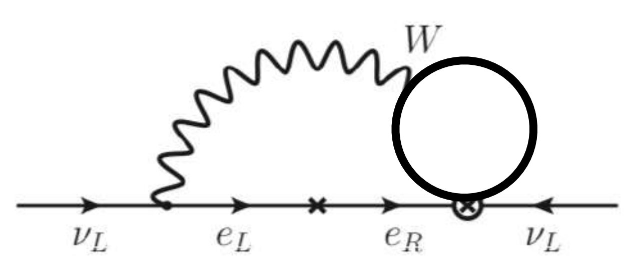


$LLHHHH$

…

Could from other lepton number violation operators: anomalous RG

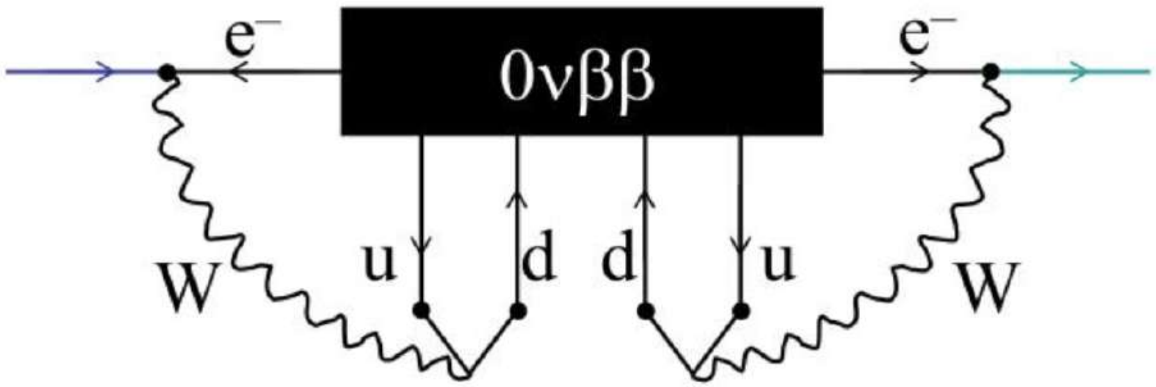




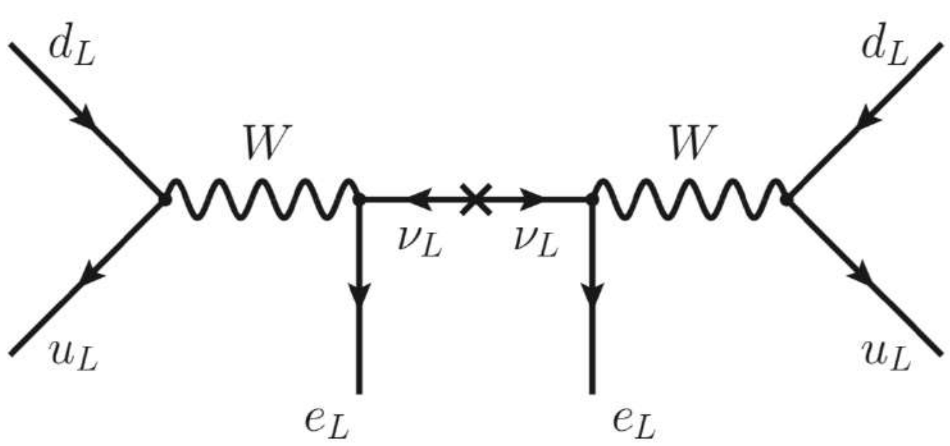
…

Neutrino Masses and 0vbb

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

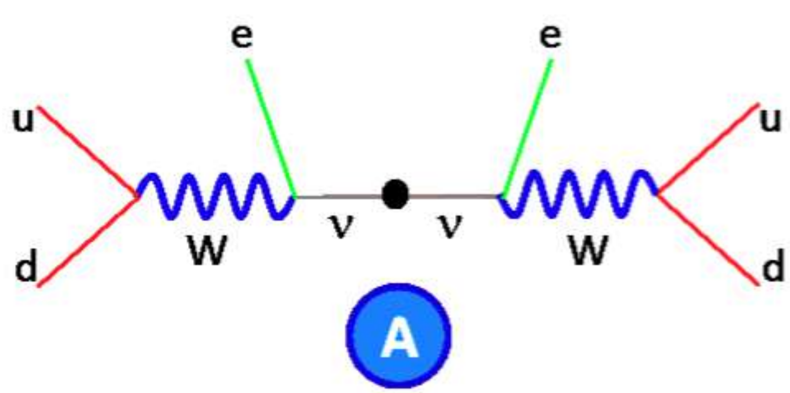


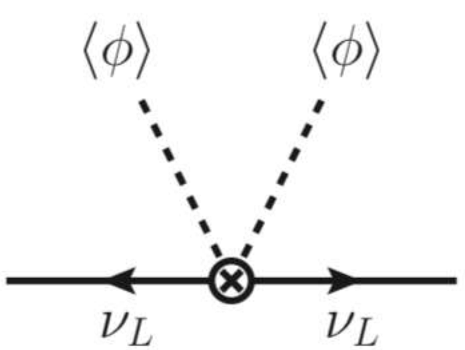
[Schechter-Valle, 1982]



Strong Correlation

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



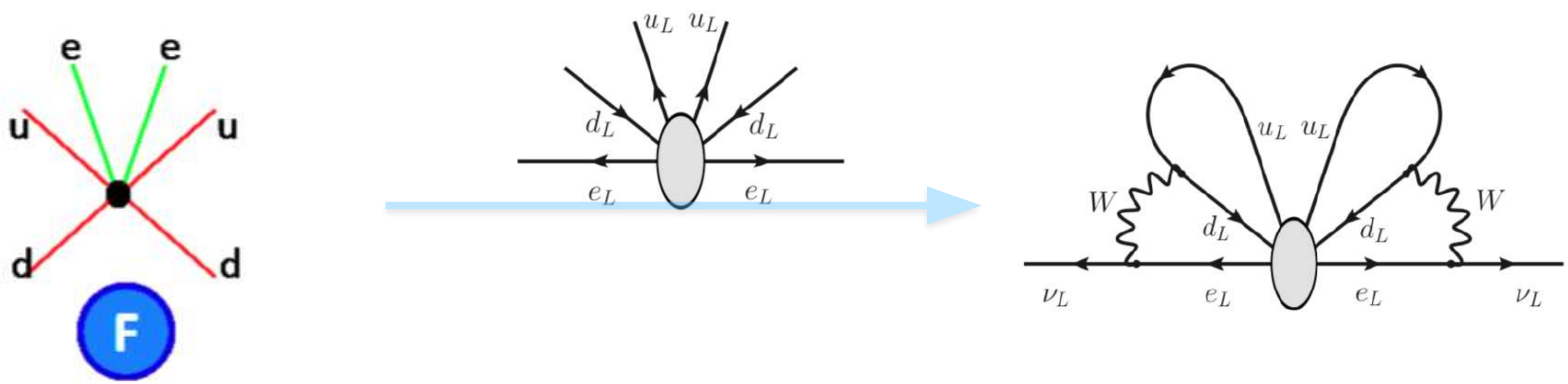


$$L^{\mu\nu} = -\int\int dx_2 dx_1 \sum_i \bar{e}(x_1)\gamma^\mu(1-\gamma_5)U_{ei}\,\underbrace{\nu_{iL}(x_1)\bar{\nu}^c_{iL}}(x_2)\gamma_\nu(1+\gamma_5)U_{ei}e^C_L(x_2) \qquad m_{\beta\beta} = \sum_{i=1}^{3} U^2_{ei} m_{\nu_i}.$$

0vbb has direct connection to neutrino physics

Strong Correlation???

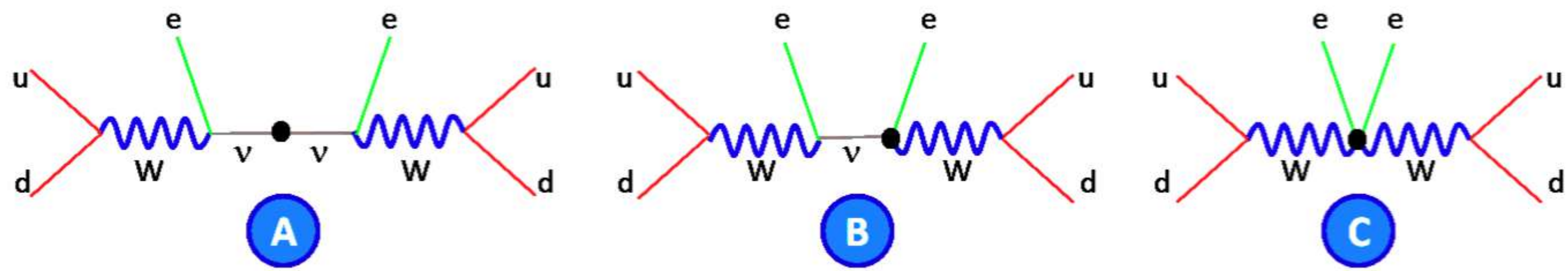
Lepton number violation operator: origin of 0vbb = small part of nv mass

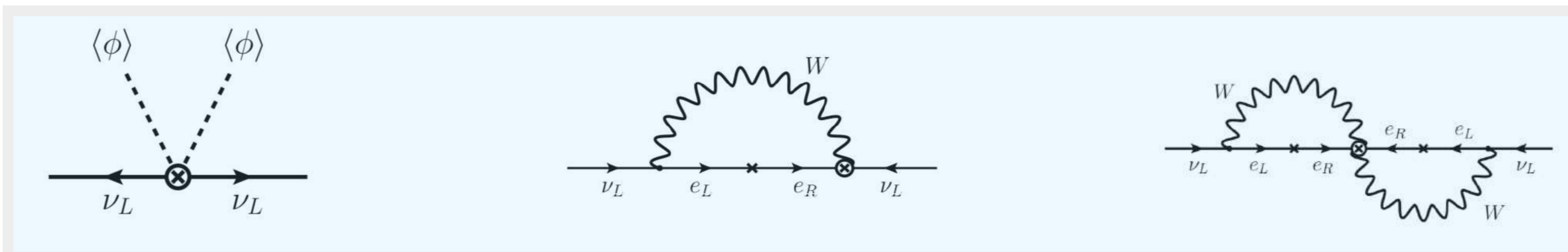


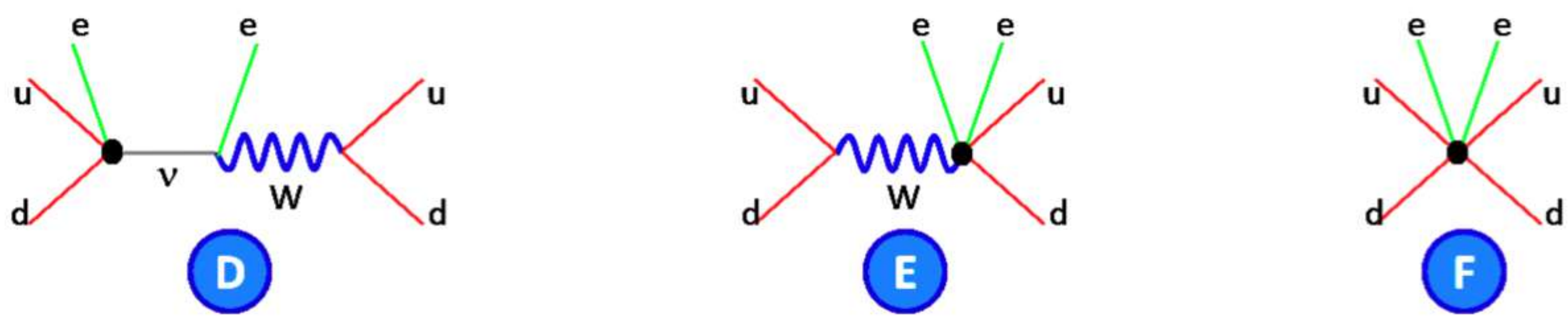
Very tiny neutrino mass

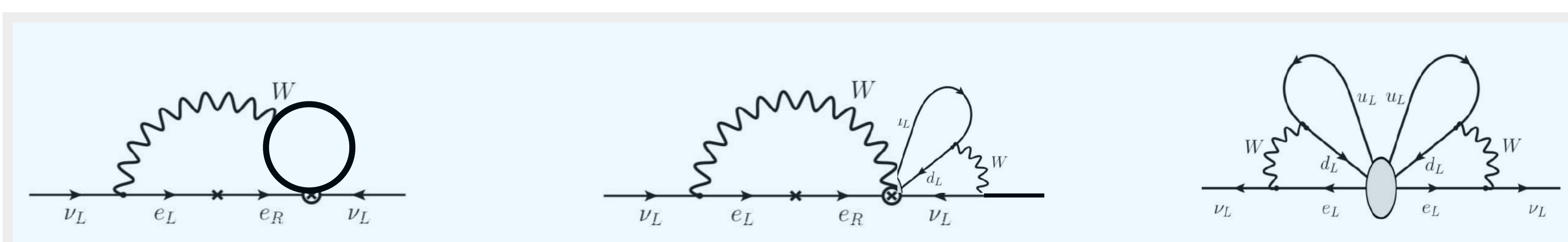
0vbb does not need to connect to current neutrino exp.

Neutrino Masses and 0vbb



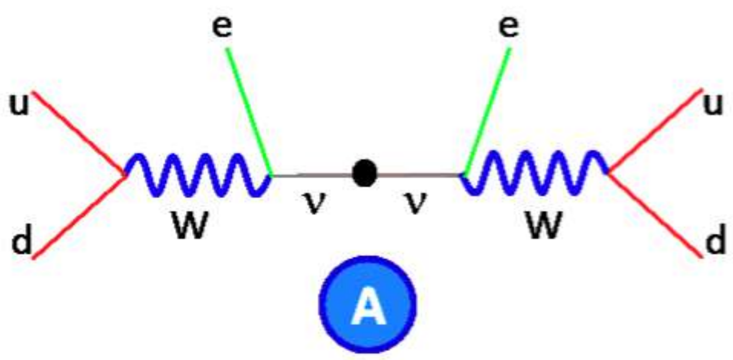


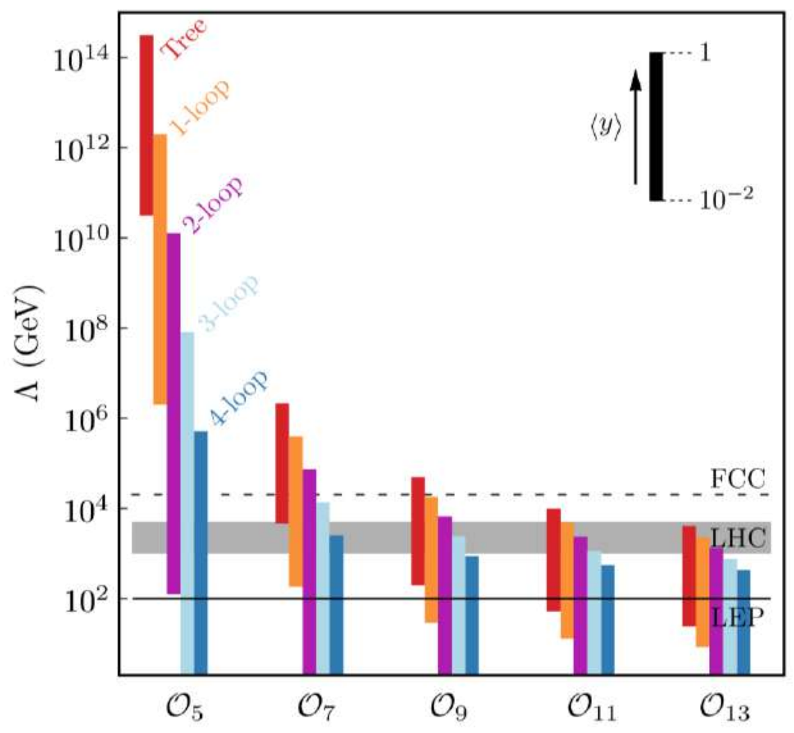


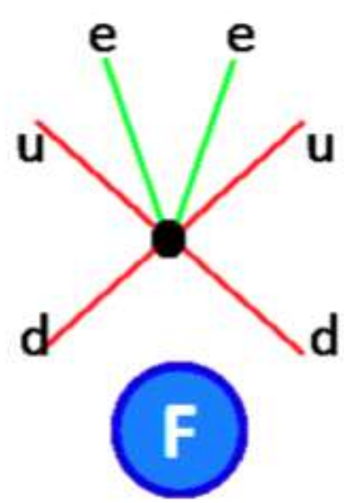


Which One Dominate 0vbb?

The higher dim operator, the lower cutoff scale



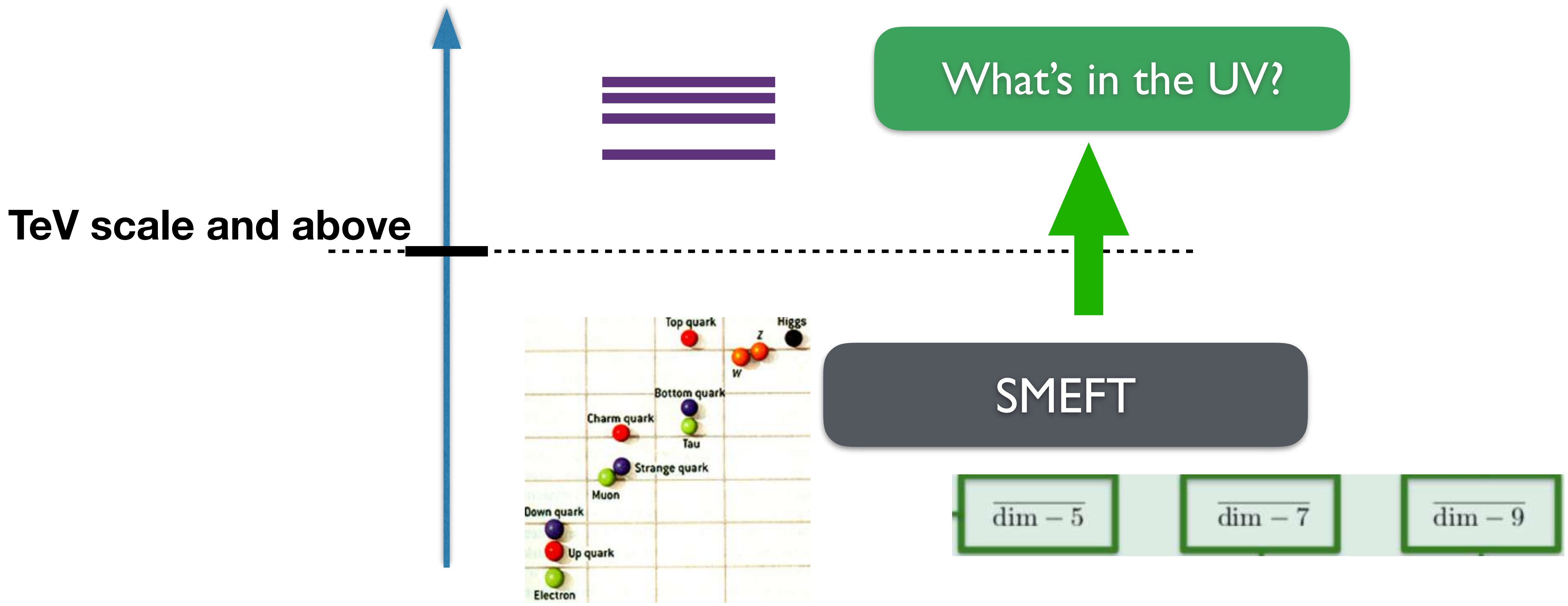




Could be comparable!

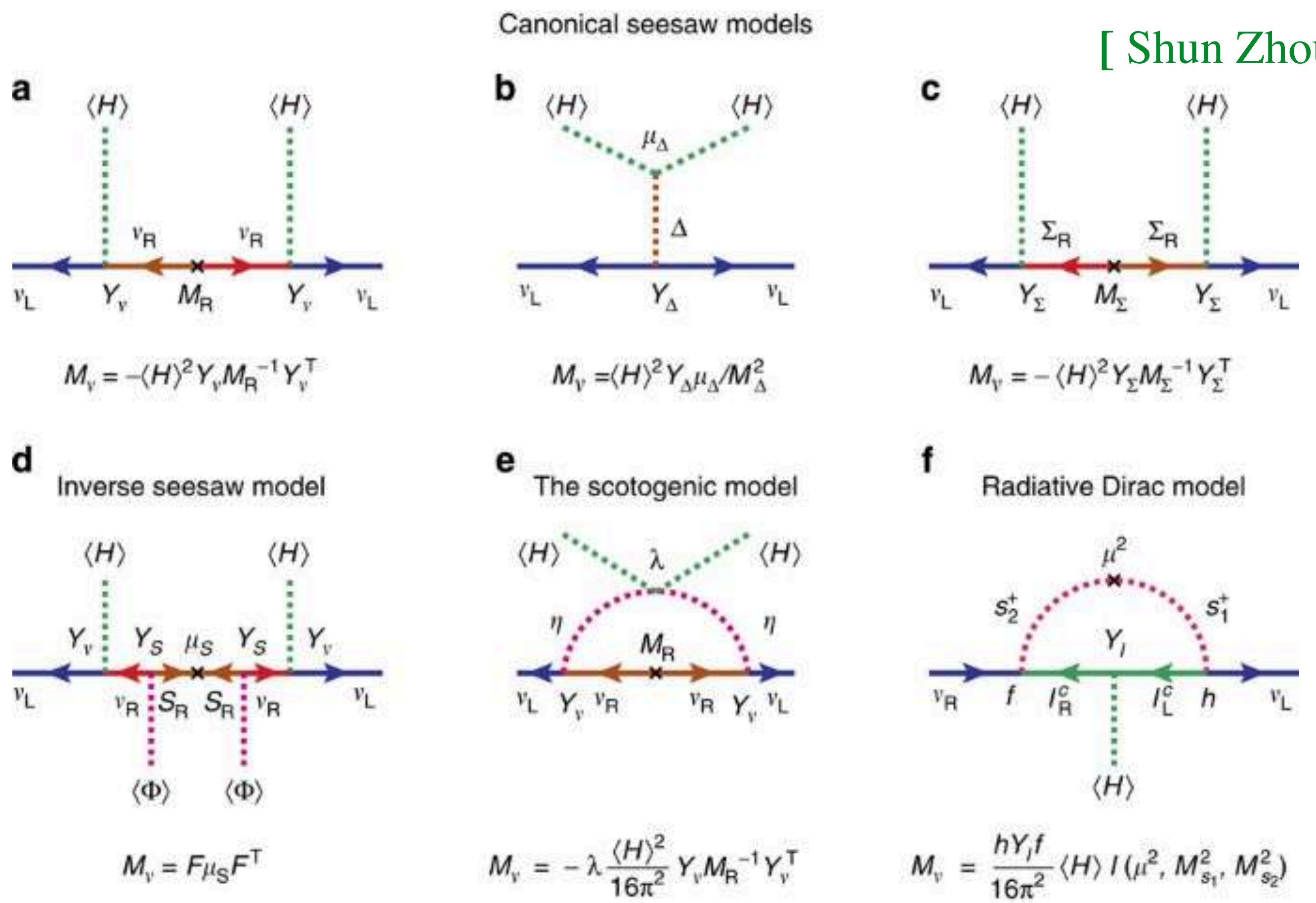
Not necessarily related to neutrino physics

What is in the UV?



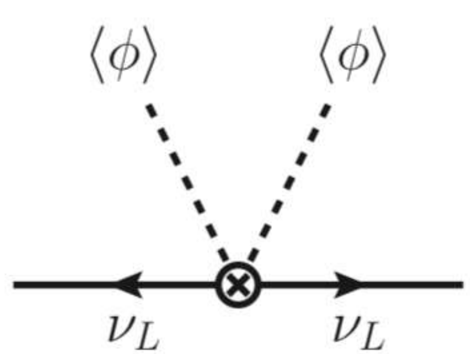
UV Realization of Nv Masses

[Shun Zhou, 2016]



Integrate out heavy particles

Top-down approach



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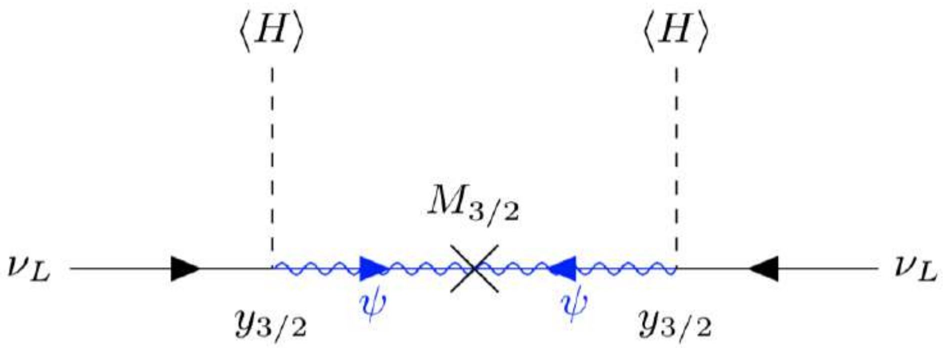
More UV realization?



Type-3/2 Seesaw Mechanism

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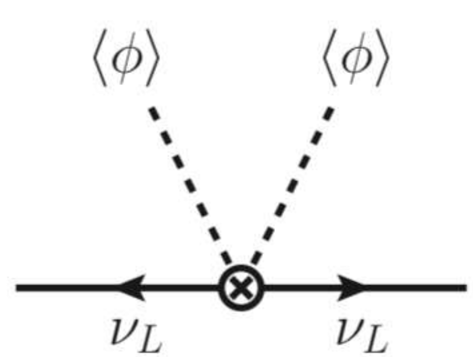
(Dated: May 17, 2021)

Bottom-up Approach



J-Basis Operator: Partial Wave

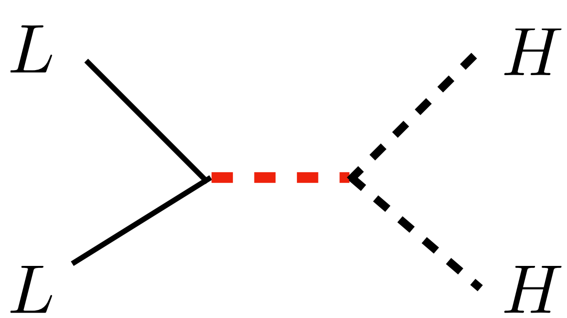
$$\mathcal{Y}\left[\boxed{p}\boxed{r}\right] \epsilon_{ik}\epsilon_{jl}\epsilon_{\alpha\beta} L_p^{\alpha i} L_r^{\beta j} H^k H^l$$

Partial wave expansion on operator

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

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

$LL \to HH$ channel

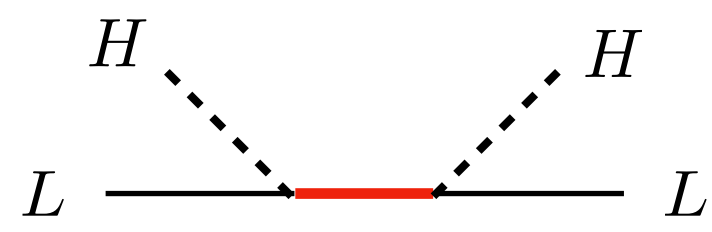


$J = 0$

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

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

$LH \to LH$ channel



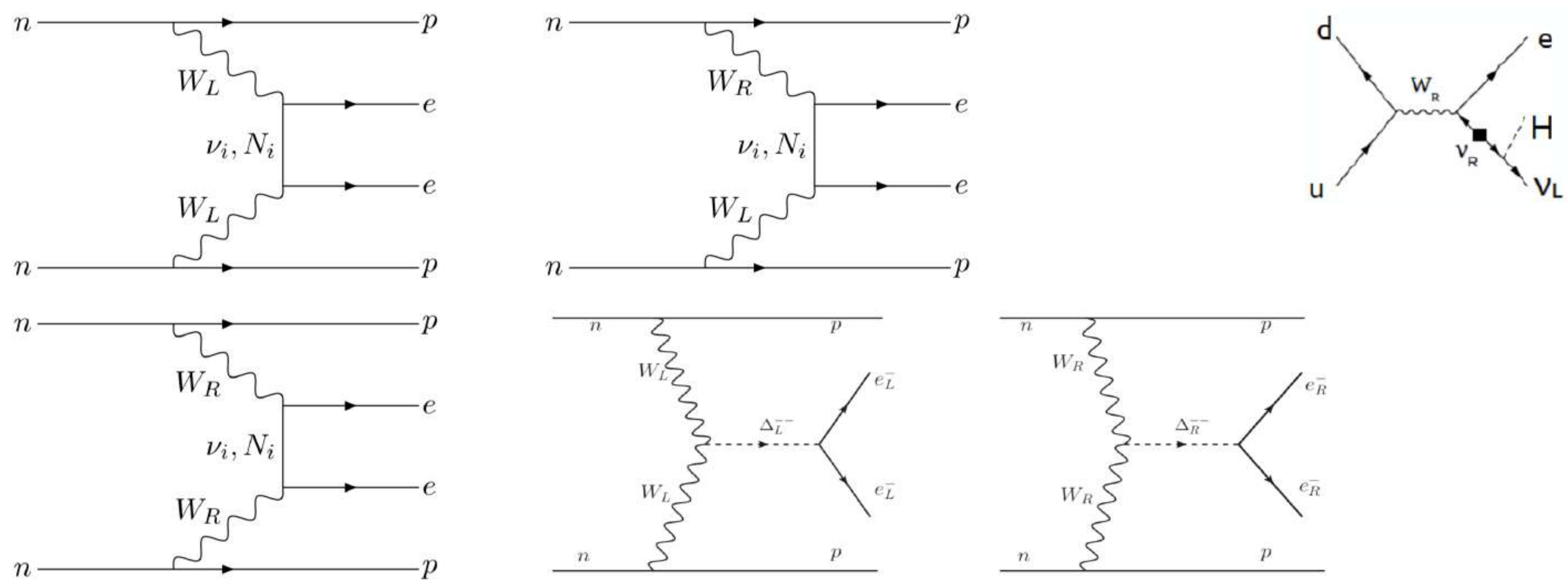
$J = \frac{1}{2}$

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

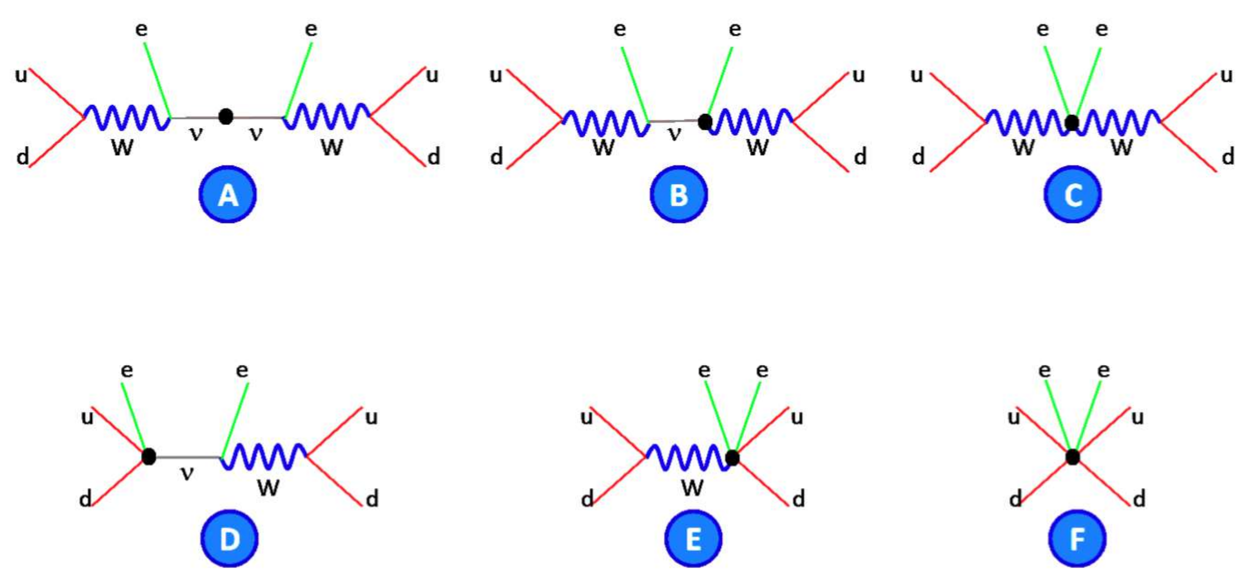
j-basis	Model
$\mathcal{O}_{HL\to HL}^{(1/2,\mathbf{1})} = \mathcal{O}^S + \mathcal{O}^A$	type I
$\mathcal{O}_{HL\to HL}^{(1/2,\mathbf{3})} = \mathcal{O}^S - 3\mathcal{O}^A$	type III

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

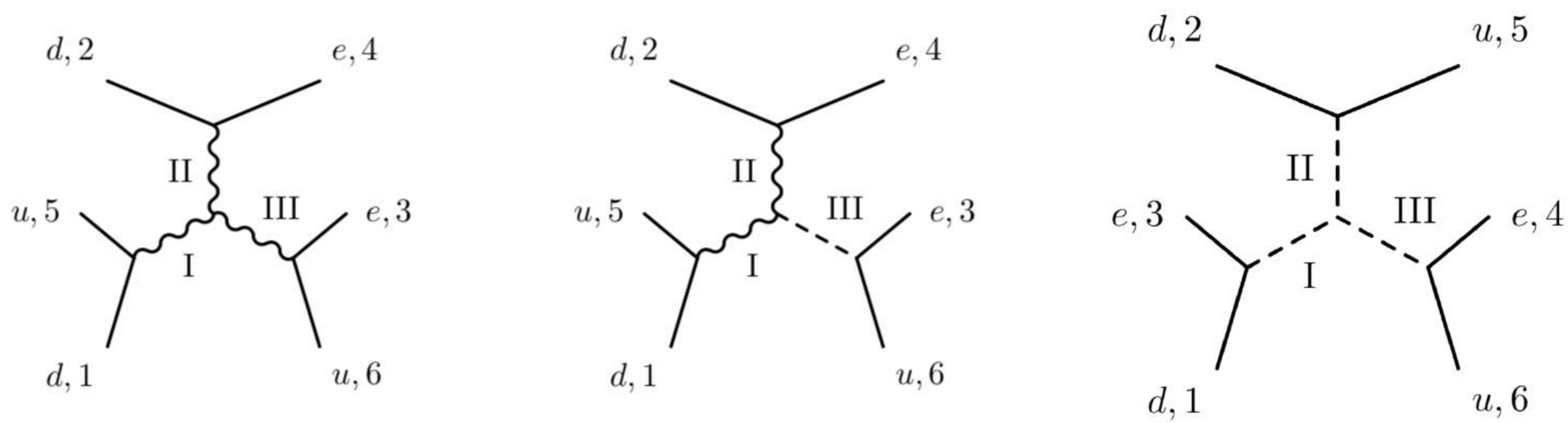
UV Realization of 0vbb



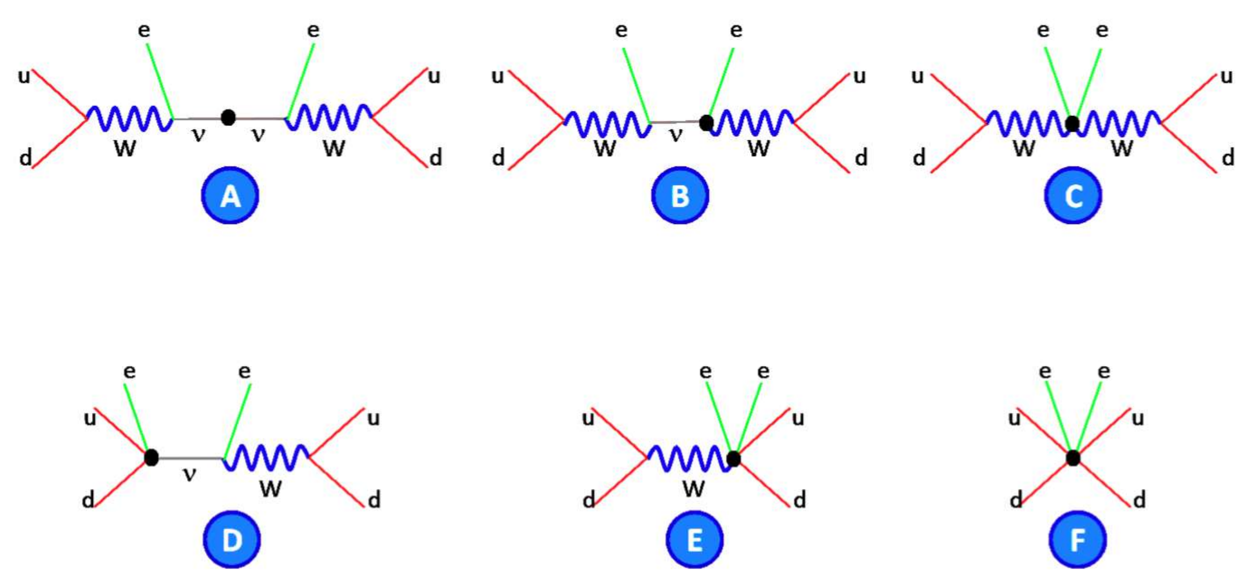
Integrate out heavy particles



More UV Realizations

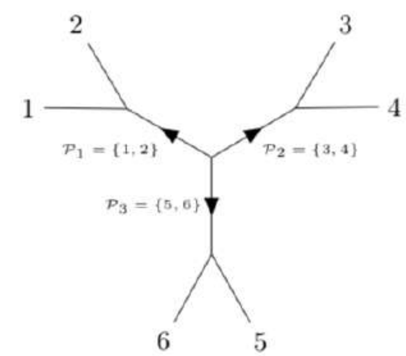


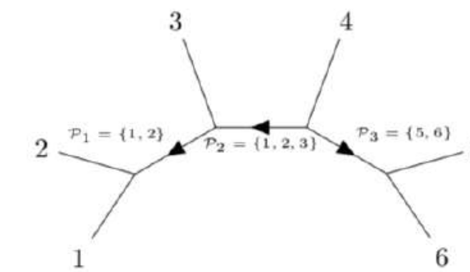
$$\mathbf{W}^2\mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$



Example

Dim-9 operators:





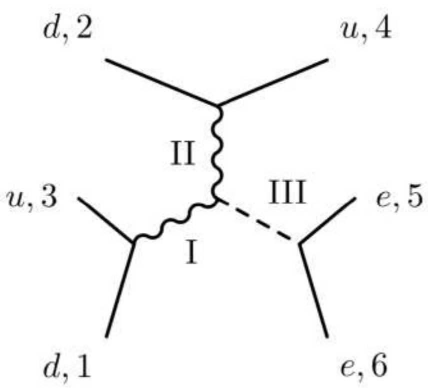
$$T^{abcdef}_{SU(3)}\psi^{\dagger 6} \qquad T^{ijkl}_{SU(2)}\psi^4\psi^{\dagger 2}$$

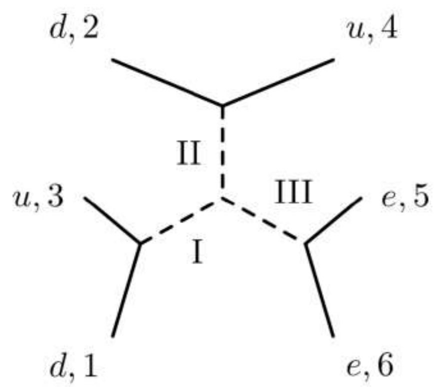
Lorentz	y-basis
ψ^6	$\mathcal{B}_1 = \langle 12\rangle\langle 34\rangle\langle 56\rangle$ $\mathcal{B}_2 = \langle 12\rangle\langle 35\rangle\langle 46\rangle$ $\mathcal{B}_3 = \langle 13\rangle\langle 24\rangle\langle 56\rangle$ $\mathcal{B}_4 = \langle 13\rangle\langle 25\rangle\langle 46\rangle$ $\mathcal{B}_5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

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

type	$\bigoplus_{[\lambda]} \mathfrak{n}_{[\lambda]}\{[\lambda_1],[\lambda_2],\dots\}$
$d_c^{\dagger 4}u_c^{\dagger 2}$	$2\{\ydiagram{2}_u,\ydiagram{4}_d\} \oplus \{\ydiagram{2}_u,\ydiagram{3,1}_d\} \oplus$ $2\{\ydiagram{2}_u,\ydiagram{2,2}_d\} \oplus 2\{\ydiagram{1,1}_u,\ydiagram{3,1}_d\} \oplus$ $\{\ydiagram{2}_u,\ydiagram{2,1,1}_d\} \oplus 2\{\ydiagram{1,1}_u,\ydiagram{2,1,1}_d\} \oplus \{\ydiagram{2}_u,\ydiagram{1,1,1,1}_d\}$
$Q^4 d_c^{\dagger 2}$	$\{\ydiagram{4}_Q,\ydiagram{2}_{d^\dagger}\} \oplus 3\{\ydiagram{2,2}_Q,\ydiagram{2}_{d^\dagger}\} \oplus$ $2\{\ydiagram{3,1}_Q,\ydiagram{1,1}_{d^\dagger}\} \oplus 2\{\ydiagram{2,1,1}_Q,\ydiagram{1,1}_{d^\dagger}\} \oplus \{\ydiagram{1,1,1,1}_Q,\ydiagram{2}_{d^\dagger}\}$
$Q^2 d_c^{\dagger 3}u_c^{\dagger}$	$\{\ydiagram{2}_Q,\ydiagram{3}_{d^\dagger}\} \oplus 2\{\ydiagram{2}_Q,\ydiagram{2,1}_{d^\dagger}\} \oplus$ $\{\ydiagram{1,1}_Q,\ydiagram{3}_{d^\dagger}\} \oplus \{\ydiagram{1,1}_Q,\ydiagram{2,1}_{d^\dagger}\} \oplus$ $\{\ydiagram{2}_Q,\ydiagram{1,1,1}_{d^\dagger}\} \oplus \{\ydiagram{1,1}_Q,\ydiagram{1,1,1}_{d^\dagger}\}$

Example

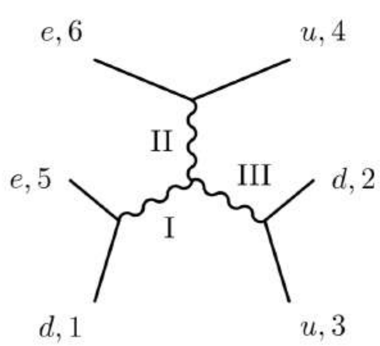


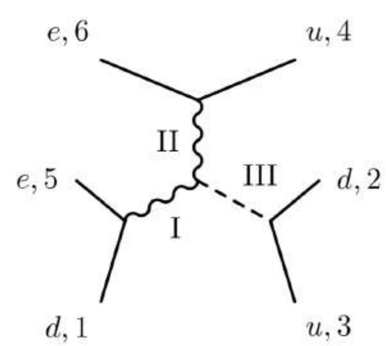


$$\mathcal{O}_1 = \frac{1}{4}(L^{\dagger}{}_u{}^j L^{\dagger}{}_v{}^i)(Q_{pai} Q_{rbj})(u_{cs}{}^b u_{ct}{}^a)$$

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

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



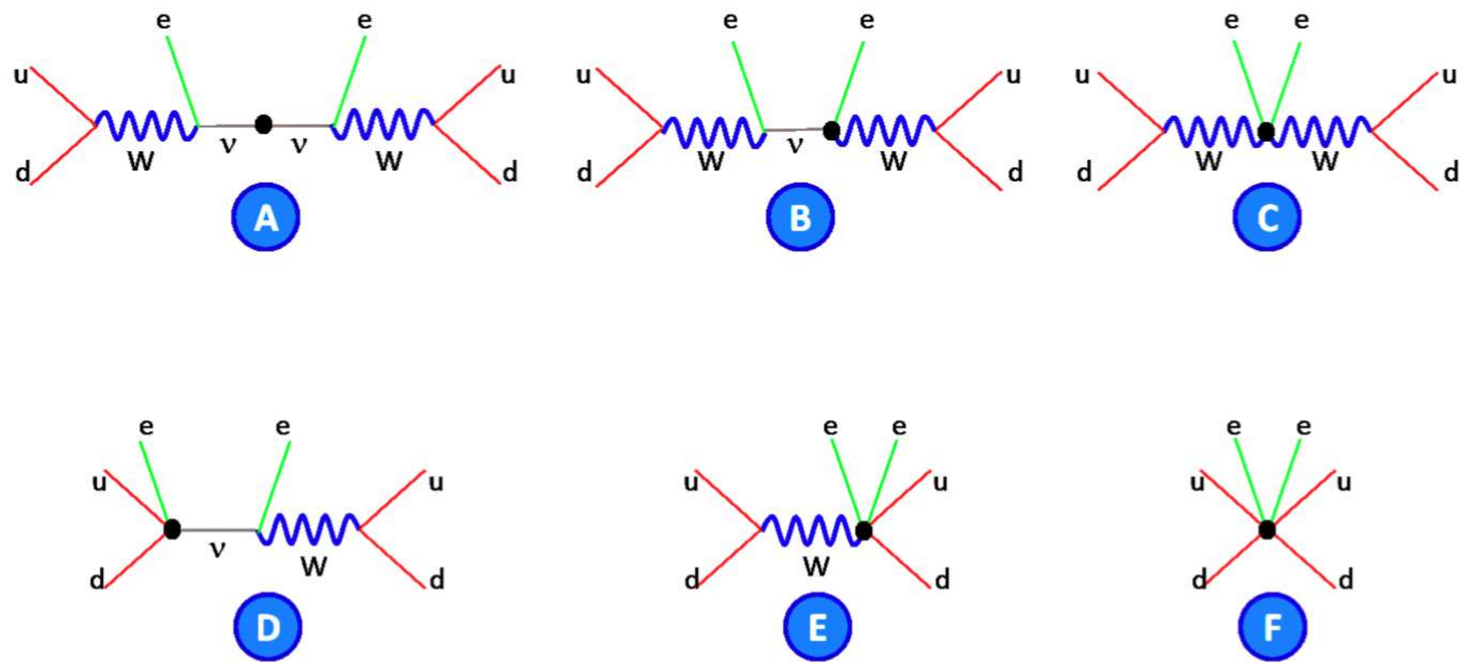


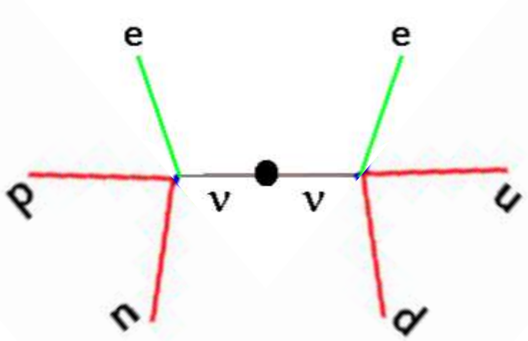
$(\mathbf{r}_i, J_i)$	$(1,1,1)$	$(1,1,0)$
$(\mathbf{3}_3, \mathbf{8}_2, \bar{\mathbf{3}}_2)$	$-\frac{8}{3}\mathcal{O}_1$	$\frac{4}{3}\mathcal{O}_1 + \frac{8}{3}\mathcal{O}_2$
$(\mathbf{3}_1, \mathbf{8}_2, \bar{\mathbf{3}}_2)$	$-\frac{8}{3}\mathcal{O}_1$	0
$(\mathbf{3}_3, \mathbf{1}_2, \bar{\mathbf{3}}_2)$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

LEFT

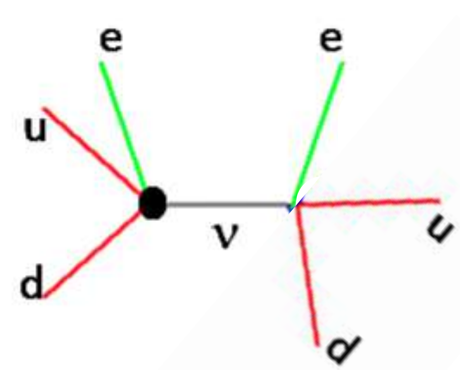
Nucleon currents and weak sources

LEFT Related Operators

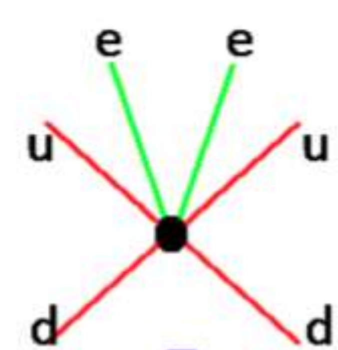




Dim-3, 5

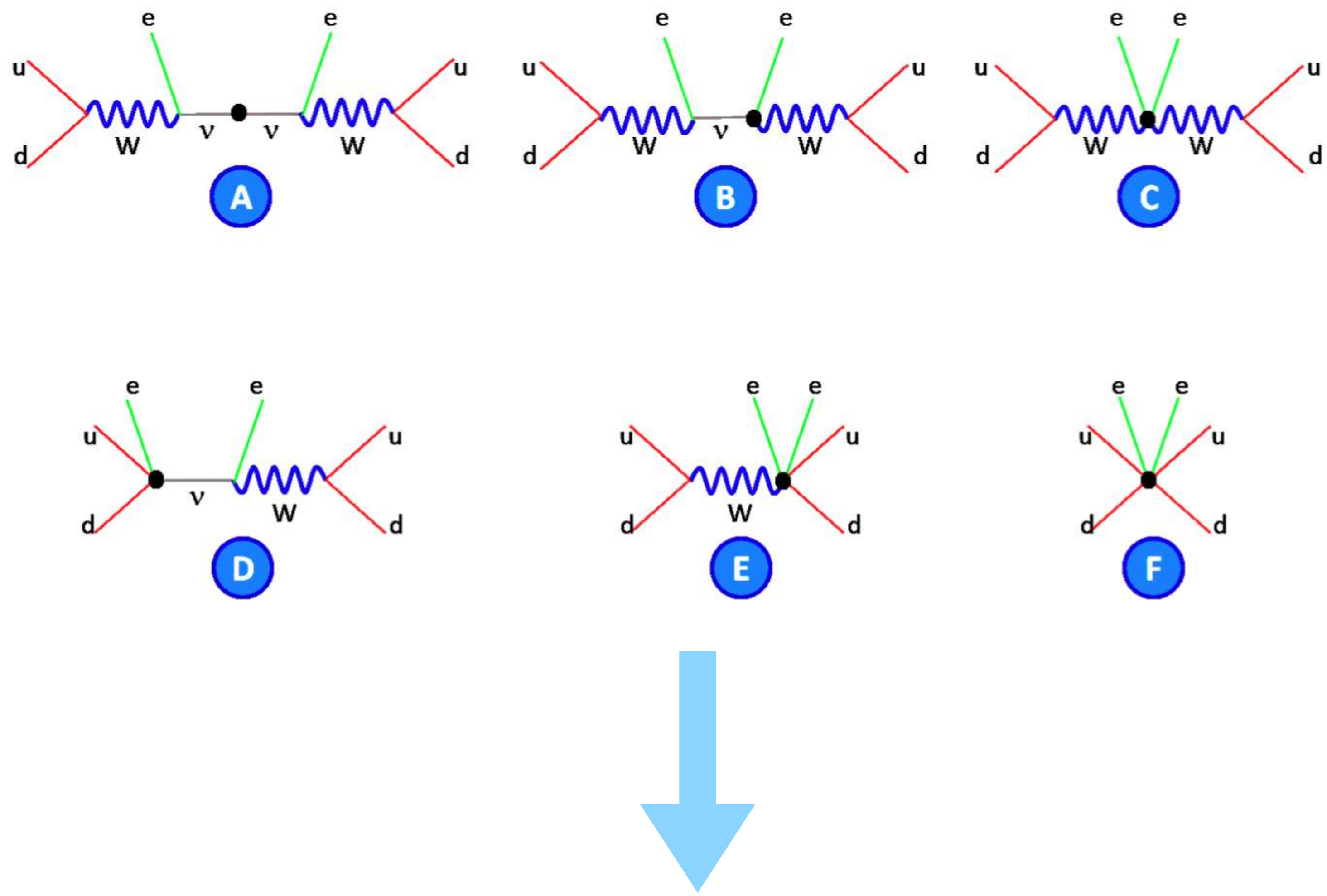


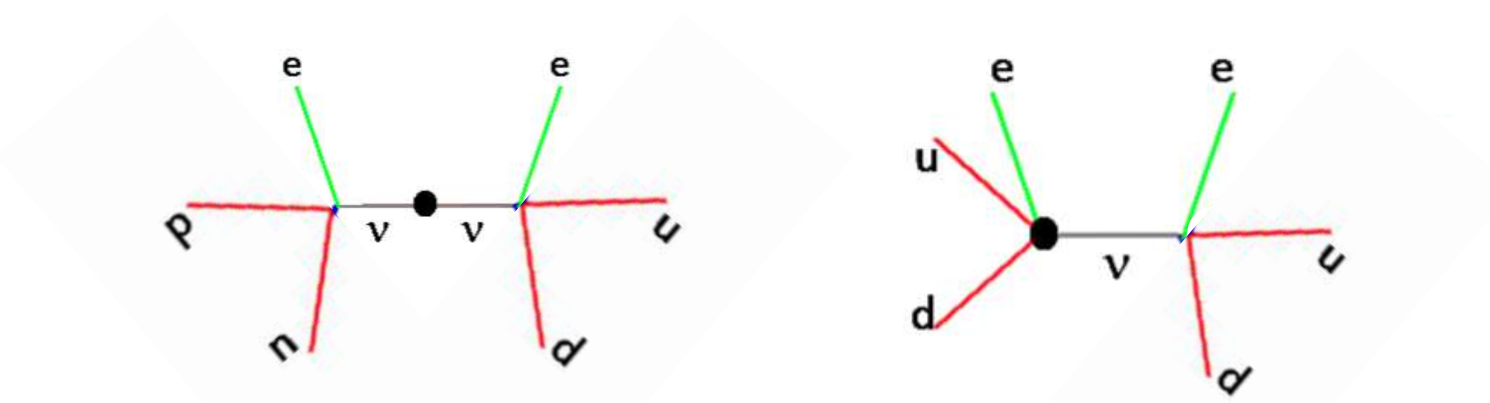
Dim-6, 7, 8, 9



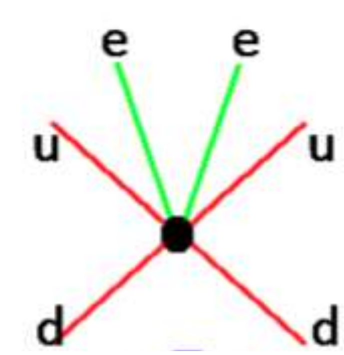
Dim-9, 11

LEFT Related Operators





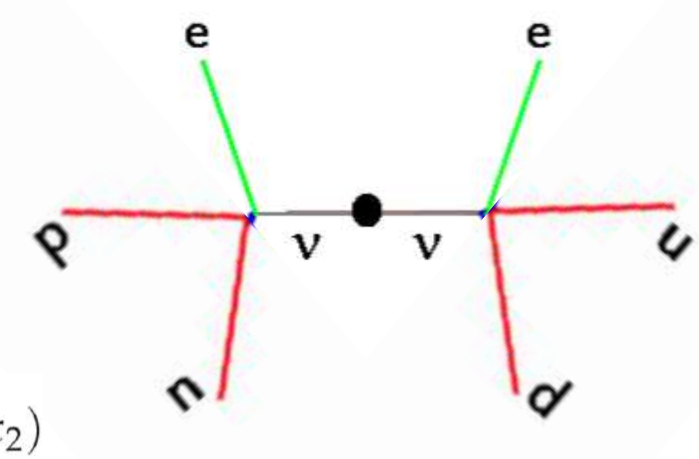
Long-range interaction



Short-range interaction

Long-Range Interaction

Standard mechanism: long-range neutrino potential



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

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

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

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

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

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

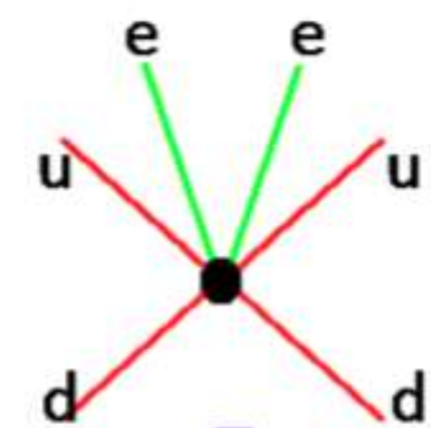
completeness relation

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

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

Short-Range Interaction

General quark currents = dim-9 LEFT operators



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

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

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

$\mathcal{O}_1^{RRR}$	$[\bar{u}^i(1+\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$\mathcal{O}_1^{RRL}$	$[\bar{u}^i(1+\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$\mathcal{O}_1^{LRR} \equiv \mathcal{O}_1^{RLR}$	$[\bar{u}^i(1-\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$\mathcal{O}_1^{LRL} \equiv \mathcal{O}_1^{RLL}$	$[\bar{u}^i(1-\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$\mathcal{O}_1^{LLR}$	$[\bar{u}^i(1-\gamma_5)d_i]\,[\bar{u}^j(1-\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$\mathcal{O}_1^{LLL}$	$[\bar{u}^i(1-\gamma_5)d_i]\,[\bar{u}^j(1-\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$\mathcal{O}_2^{RRR}$	$[\bar{u}^i\sigma^{\mu\nu}(1+\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$\mathcal{O}_2^{RRL}$	$[\bar{u}^i\sigma^{\mu\nu}(1+\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$\mathcal{O}_2^{LLR}$	$[\bar{u}^i\sigma^{\mu\nu}(1-\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1-\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$\mathcal{O}_2^{LLL}$	$[\bar{u}^i\sigma^{\mu\nu}(1-\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1-\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$\mathcal{O}_3^{RRR}$	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$\mathcal{O}_3^{RRL}$	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$\mathcal{O}_3^{LRR} \equiv \mathcal{O}_3^{RLR}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$\mathcal{O}_3^{LRL} \equiv \mathcal{O}_3^{RLL}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$\mathcal{O}_3^{LLR}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1-\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$\mathcal{O}_3^{LLL}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1-\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$\mathcal{O}_4^{RR}$	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1+\gamma_5)d_j]\,[\bar{e}\gamma^{\nu}\gamma_5 e^c]$
$\mathcal{O}_4^{RL}$	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1-\gamma_5)d_j]\,[\bar{e}\gamma^{\nu}\gamma_5 e^c]$
$\mathcal{O}_4^{LR}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1+\gamma_5)d_j]\,[\bar{e}\gamma^{\nu}\gamma_5 e^c]$
$\mathcal{O}_4^{LL}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1-\gamma_5)d_j]\,[\bar{e}\gamma^{\nu}\gamma_5 e^c]$
$\mathcal{O}_5^{RR}$	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}\gamma_{\mu}\gamma_5 e^c]$
$\mathcal{O}_5^{RL}$	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j(1-\gamma_5)d_j]\,[\bar{e}\gamma_{\mu}\gamma_5 e^c]$
$\mathcal{O}_5^{LR}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}\gamma_{\mu}\gamma_5 e^c]$
$\mathcal{O}_5^{LL}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j(1-\gamma_5)d_j]\,[\bar{e}\gamma_{\mu}\gamma_5 e^c]$

Complete dim-9 LEFT 6-fermion operator basis

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

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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 $(n,\tilde{n})$	Classes	$\mathcal{N}_{\rm type}$
3 $(2,0)$	$F_{\rm L}\psi_{\rm L}{}^2+h.c.$	$10+0+2+0$

10

Dimension-6

Dim-6 operators

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\rm type}$	$\mathcal{N}_{\rm term}$
3	$(3,0)$	$F_{\rm L}^3+h.c.$	$2+0+0+0$	2
4	$(2,0)$	$\psi_{\rm L}^4+h.c.$	$14+12+8+2$	78
	$(1,1)$	$\psi_{\rm L}^2\psi_{\rm R}^2$	$40+20+12+0$	84
Total		5	$56+32+20+2$	164

[Jenkins, Manohar, Stoffer, 2017]

Dimension-7

Dim-7 operators

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\rm type}$	$\mathcal{N}_{\rm term}$
4	$(3,0)$	$F_{\rm L}^2\psi_{\rm L}^2+h.c.$	$16+0+4+0$	32
	$(2,1)$	$F_{\rm L}^2\psi_{\rm R}^2+h.c.$	$16+0+4+0$	24
		$\psi_{\rm L}^3\psi_{\rm R}D+h.c.$	$50+32+22+$	
Total		6	$82+32+30+$	

120

166

[Liao, Ma, Wang, 2020]

Dimension-8

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

[Murphy, 2020]

N	$(n,\tilde{n})$	Subclasses	$\mathcal{N}_{\rm type}$	$\mathcal{N}_{\rm term}$	$\mathcal{N}_{\rm operator}$	Equations
4	$(4,0)$	$F_{\rm L}^4+h.c.$	14	26	26	(4.19)
	$(3,1)$	$F_{\rm L}^2\psi\psi^\dagger D+h.c.$	22	22	$22n_f^2$	(4.51)
		$\psi^4D^2+h.c.$	$4+\underline{4}$	$18+\underline{14}$	$12n_f^4+\underline{n_f^3(5n_f-1)}$	(4.75, 4.78, 4.80)
		$F_{\rm L}\psi^2\phi D^2+h.c.$	16	32	$32n_f^2$	(4.44)
		$F_{\rm L}^2\phi^2D^2+h.c.$	8	12	12	(4.14)
	$(2,2)$	$F_{\rm L}^2F_{\rm R}^2$	14	17	17	(4.19)
		$F_{\rm L}F_{\rm R}\psi\psi^\dagger D$	27	35	$35n_f^2$	(4.50, 4.51)
		$\psi^2\psi^{\dagger2}D^2$	$17+\underline{4}$	$54+\underline{8}$	$\frac{1}{2}n_f^2(75n_f^2+11)+\underline{6n_f^4}$	(4.74, 4.79-4.81)
		$F_{\rm R}\psi^2\phi D^2+h.c.$	16	16	$16n_f^2$	(4.44)
		$F_{\rm L}F_{\rm R}\phi^2D^2$	5	6	6	(4.14)
		$\psi\psi^\dagger\phi^2D^3$	7	16	$16n_f^2$	(4.31, 4.32)
		ϕ^4D^4	1	3	3	(4.8)
5	$(3,0)$	$F_{\rm L}\psi^4+h.c.$	$12+\underline{10}$	$66+\underline{54}$	$42n_f^4+\underline{2n_f^3(9n_f+1)}$	(4.86, 4.88, 4.89, 4.91)
		$F_{\rm L}^2\psi^2\phi+h.c.$	32	60	$60n_f^2$	(4.47, 4.48)
		$F_{\rm L}^3\phi^2+h.c.$	6	6	6	(4.16)
	$(2,1)$	$F_{\rm L}\psi^2\psi^{\dagger2}+h.c.$	$84+\underline{24}$	$172+\underline{32}$	$2n_f^2(59n_f^2-2)+\underline{24n_f^4}$	(4.84-4.85), (4.88-4.92)
		$F_{\rm R}^2\psi^2\phi+h.c.$	32	36	$36n_f^2$	(4.47, 4.48)
		$\psi^3\psi^\dagger\phi D+h.c.$	$32+\underline{14}$	$180+\underline{56}$	$n_f^3(135n_f-1)+\underline{n_f^3(29n_f+3)}$	(4.66, 4.69-4.72)
		$F_{\rm L}\psi\psi^\dagger\phi^2D+h.c.$	38	92	$92n_f^2$	(4.39, 4.40)
		$\psi^2\phi^3D^2+h.c.$	6	36	$36n_f^2$	(4.28)
		$F_{\rm L}\phi^4D^2+h.c.$	4	6	6	(4.10)
6	$(2,0)$	$\psi^4\phi^2+h.c.$	$12+\underline{4}$	$48+\underline{18}$	$5(5n_f^4+n_f^2)+\underline{\frac{2}{3}(8n_f^4+n_f^2)}$	(4.55, 4.59, 4.62, 4.64)
		$F_{\rm L}\psi^2\phi^3+h.c.$	16	22	$22n_f^2$	(4.36)
		$F_{\rm L}^2\phi^4+h.c.$	8	10	10	(4.12)
	$(1,1)$	$\psi^2\psi^{\dagger2}\phi^2$	$23+\underline{10}$	$57+\underline{14}$	$n_f^2(42n_f^2+n_f+2)+\underline{3n_f^3(3n_f-1)}$	(4.54, 4.55, 4.59-4.63)
		$\psi\psi^\dagger\phi^4D$	7	13	$13n_f^2$	(4.24, 4.25)
		ϕ^6D^2	1	2	2	(4.8)
7	$(1,0)$	$\psi^2\phi^5+h.c.$	6	6	$6n_f^2$	(4.21)
8	$(0,0)$	ϕ^8	1	1	1	(4.8)
Total		48	$471+\underline{70}$	$1070+\underline{196}$	$993(n_f=1)$, $44807(n_f=3)$	

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Dimension-9

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

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\rm type}$	$\mathcal{N}_{\rm term}$	$\mathcal{N}_{\rm operator}$	Equations
4	$(3,2)$	$\psi^3\psi^\dagger D^3+h.c.$	$0+4+2+0$	10	$\frac{2}{3}n_f^2(7n_f^2-1)$	(5.50)(5.51)
		$\psi^2\phi^2D^4+h.c.$	$0+0+2+0$	6	$3n_f(n_f+1)$	(5.21)
5	$(3,1)$	$F_{\rm L}\psi^3\psi^\dagger D+h.c.$	$0+10+6+0$	72	$32n_f^4$	(5.59)(5.60)
		$\psi^4\phi D^2+h.c.$	$0+4+4+0$	100	$40n_f^4$	(5.45-5.48)
		$F_{\rm L}\psi^2\phi^2D^2+h.c.$	$0+0+4+0$	34	$17n_f^2-n_f$	(5.28)(5.29)
	$(2,2)$	$F_{\rm R}\psi^3\psi^\dagger D+h.c.$	$0+10+6+0$	54	$4n_f^3(6n_f+1)$	(5.59)(5.60)
		$\psi^2\psi^{\dagger2}\phi D^2$	$0+4+4+0$	84	$n_f^3(49n_f+1)$	(5.45-5.48)
		$F_{\rm R}\psi^2\phi^2D^2+h.c.$	$0+0+4+0$	20	$2n_f(5n_f-1)$	(5.28)(5.29)
		$\psi\psi^\dagger\phi^3D^3$	$0+0+2+0$	6	$6n_f^2$	(5.19)
6	$(3,0)$	$\psi^6+h.c.$	$2+4+6+0$	116	$\frac{1}{24}n_f^2(415n_f^4+53n_f^3+59n_f^2+139n_f+6)$	(5.63-5.70)
		$F_{\rm L}\psi^4\phi+h.c.$	$0+12+10+0$	102	$2n_f^3(21n_f+1)$	(5.54-5.56)
		$F_{\rm L}^2\psi^2\phi^2+h.c.$	$0+0+8+0$	20	$2n_f(5n_f+2)$	(5.32)
	$(2,1)$	$\psi^4\psi^{\dagger2}+h.c.$	$4+26+20+4$	244	$\frac{1}{6}n_f^3(382n_f^3-9n_f^2+2n_f+21)$	(5.63-5.69)
		$F_{\rm L}\psi^2\psi^{\dagger2}\phi+h.c.$	$0+24+24+0$	92	$52n_f^4$	(5.54-5.56)
		$F_{\rm L}^2\psi^{\dagger2}\phi^2+h.c.$	$0+0+8+0$	12	$2n_f(3n_f+2)$	(5.32)
		$\psi^3\psi^\dagger\phi^2D+h.c.$	$0+12+18+0$	186	$\frac{2}{3}n_f^2(146n_f^2+1)$	(5.39-5.42)
		$F_{\rm L}\psi\psi^\dagger\phi^3D+h.c.$	$0+0+8+0$	12	$12n_f^2$	(5.25)
		$\psi^2\phi^4D^2+h.c.$	$0+0+4+0$	24	$2n_f(6n_f+1)$	(5.17)
7	$(2,0)$	$\psi^4\phi^3+h.c.$	$0+6+6+0$	32	$\frac{4}{3}n_f^2(10n_f^2-1)$	(5.35-5.37)
		$F_{\rm L}\psi^2\phi^4+h.c.$	$0+0+4+0$	8	$2n_f(2n_f-1)$	(5.23)
	$(1,1)$	$\psi^2\psi^{\dagger2}\phi^3$	$0+6+10+0$	24	$14n_f^4$	(5.35-5.37)
		$\psi\psi^\dagger\phi^5D$	$0+0+2+0$	2	$2n_f^2$	(5.12)
8	$(1,0)$	$\psi^2\phi^6+h.c.$	$0+0+2+0$	2	$n_f^2+n_f$	(5.9)
Total		42	6+122+164+4	1262	$8+204+348+0\ (n_f=1)$ $2862+42234+44874+486\ (n_f=3)$	

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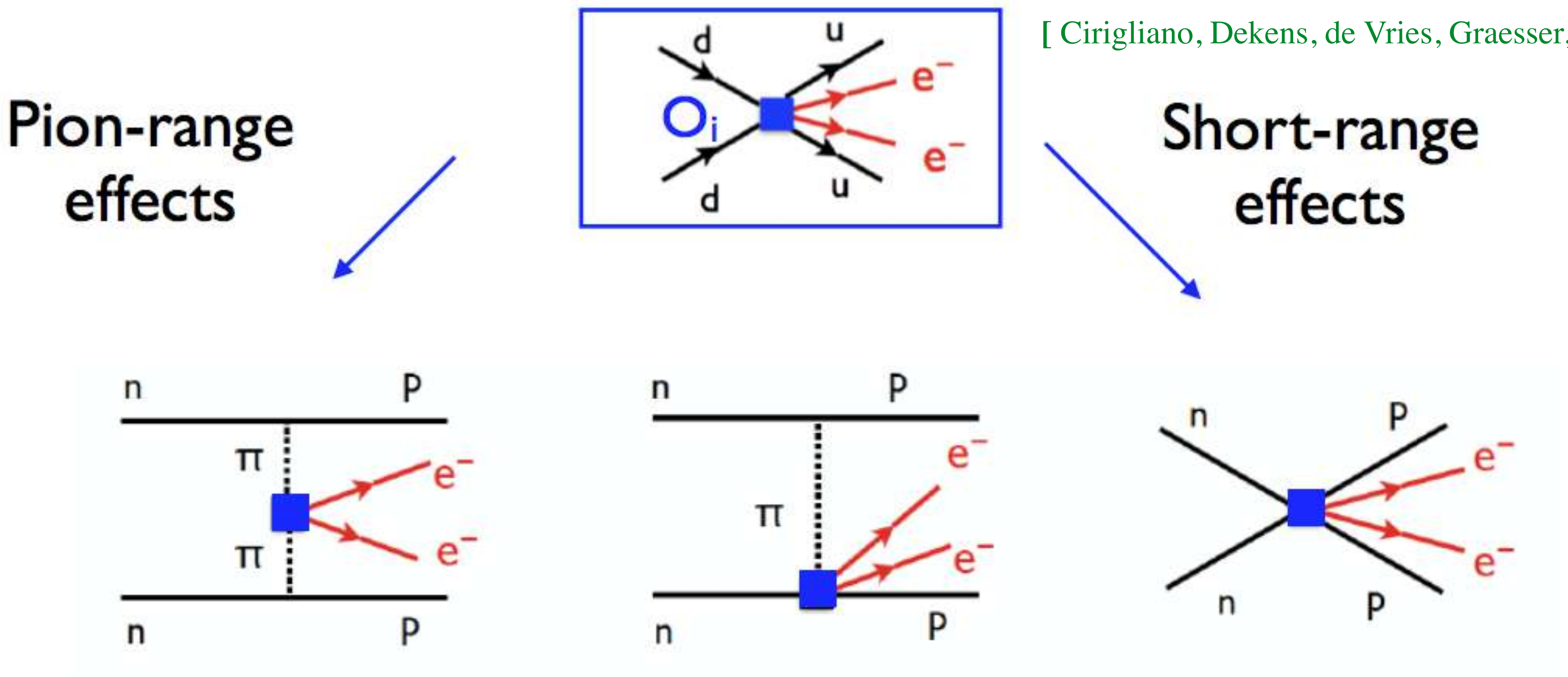
ChiPT: Quark to Nucleon

Chiral perturbation theory + Heavy baryon EFT + LNV external source

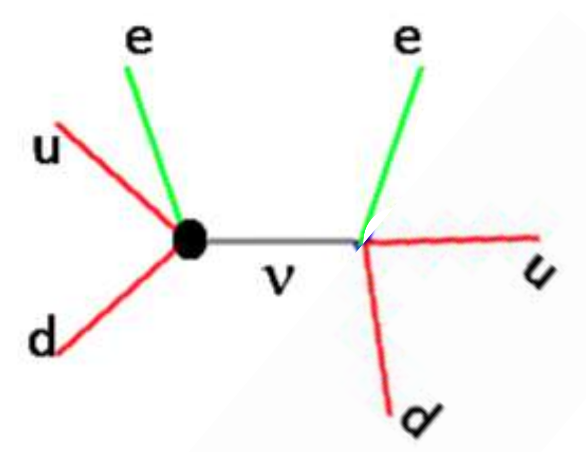
[Cirigliano, Dekens, de Vries, Graesser, 2018]



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

Long-Range from LNV Operators

Long-range neutrino potential: no nv mass dependence



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

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

Complete dim-6 LEFT 4-fermion operator basis

$$\begin{aligned} \mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big\{ & C^{(6)}_{\text{VL},ij}\,\bar u_L\gamma^{\mu} d_L\,\bar e_{R,i}\gamma_{\mu}\,C\bar\nu^T_{L,j} + C^{(6)}_{\text{VR},ij}\,\bar u_R\gamma^{\mu} d_R\,\bar e_{R,i}\gamma_{\mu}\,C\bar\nu^T_{L,j} \qquad (7) \\ & + C^{(6)}_{\text{SR},ij}\,\bar u_L d_R\,\bar e_{L,i}\,C\bar\nu^T_{L,j} + C^{(6)}_{\text{SL},ij}\,\bar u_R d_L\,\bar e_{L,i}\,C\bar\nu^T_{L,j} + C^{(6)}_{\text{T},ij}\,\bar u_L\sigma^{\mu\nu} d_R\,\bar e_{L,i}\sigma_{\mu\nu}\,C\bar\nu^T_{L,j}\Big\} + \text{h.c.} \end{aligned}$$

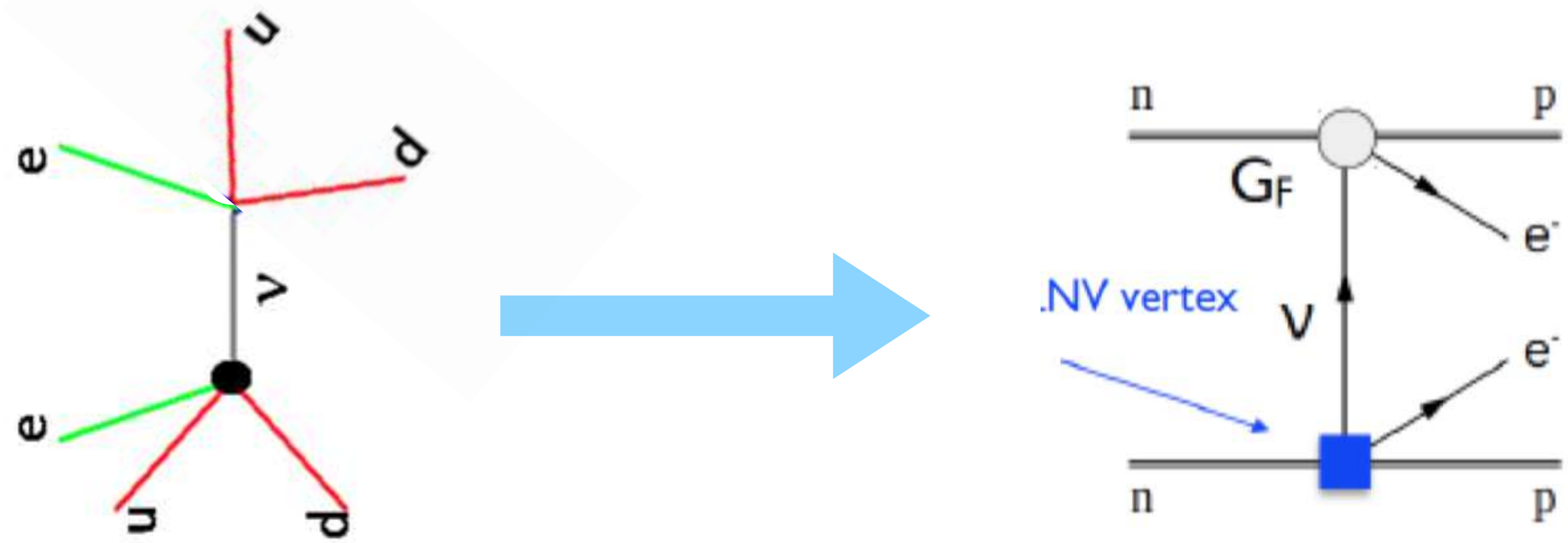
$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v}\Big\{ C^{(7)}_{\text{VL},ij}\,\bar u_L\gamma^{\mu} d_L\,\bar e_{L,i}\,C\,i\overleftrightarrow{\partial}_{\mu}\bar\nu^T_{L,j} + C^{(7)}_{\text{VR},ij}\,\bar u_R\gamma^{\mu} d_R\,\bar e_{L,i}\,C i\overleftrightarrow{\partial}_{\mu}\bar\nu^T_{L,j}\Big\} + \text{h.c.} \qquad (8)$$

dim-7/8/9 LEFT 4-fermion operator?

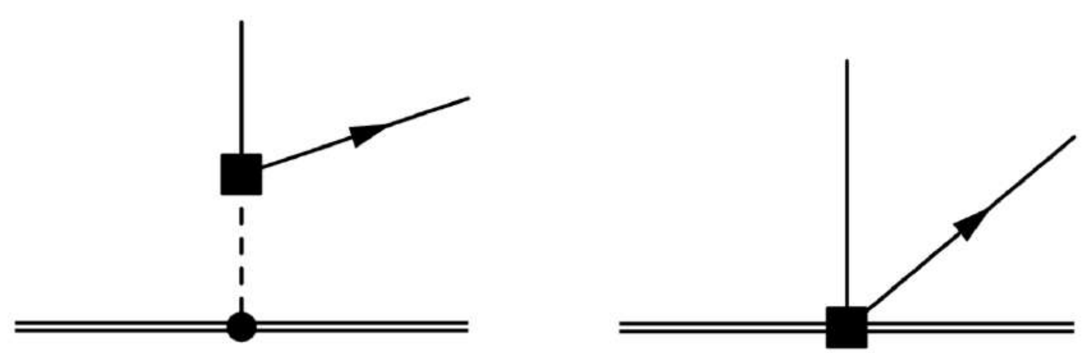
No dim-9 SMEFT 4-fermion operator!

ChiPT: Quark to Nucleon

Chiral perturbation theory + Heavy baryon EFT + LNV external source

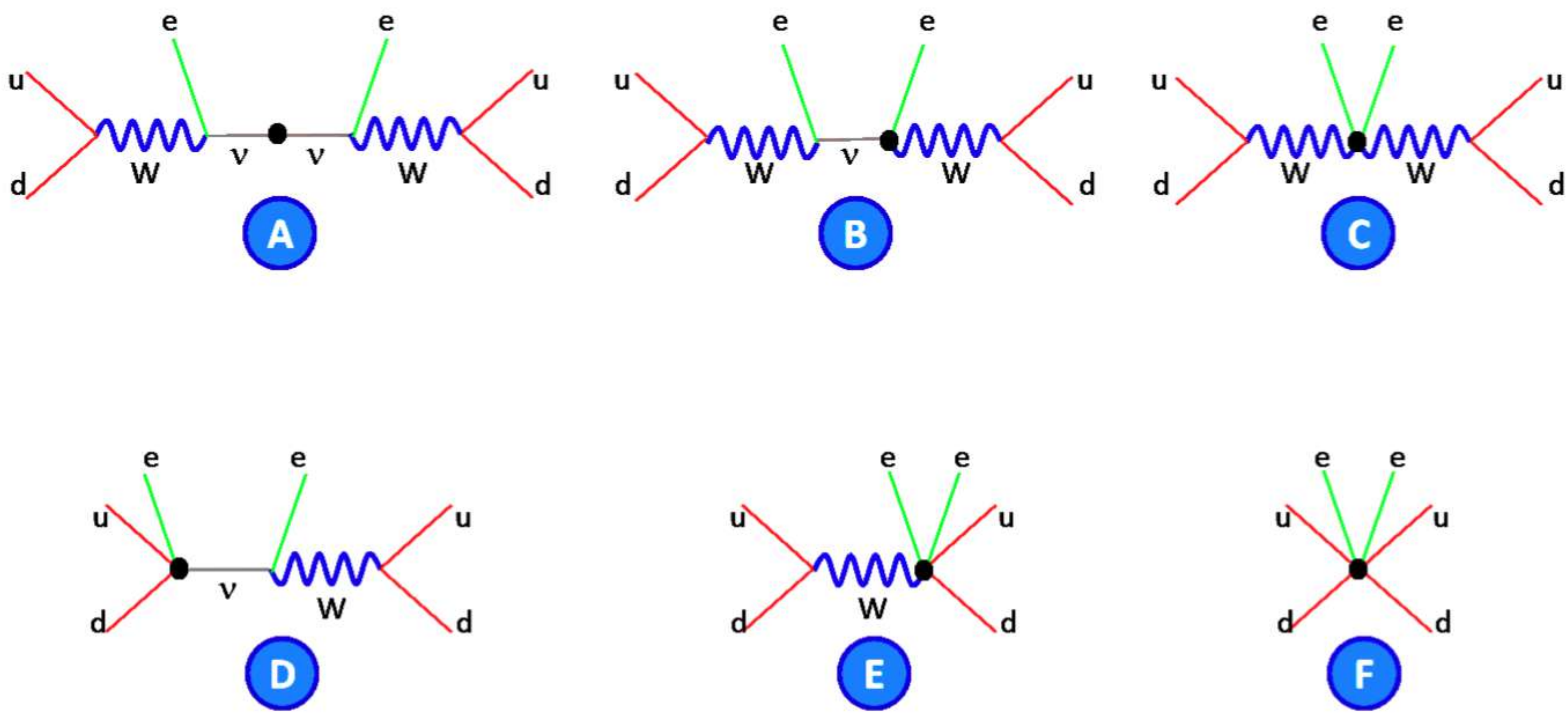


[Cirigliano, Dekens, de Vries, Graesser, 2018]

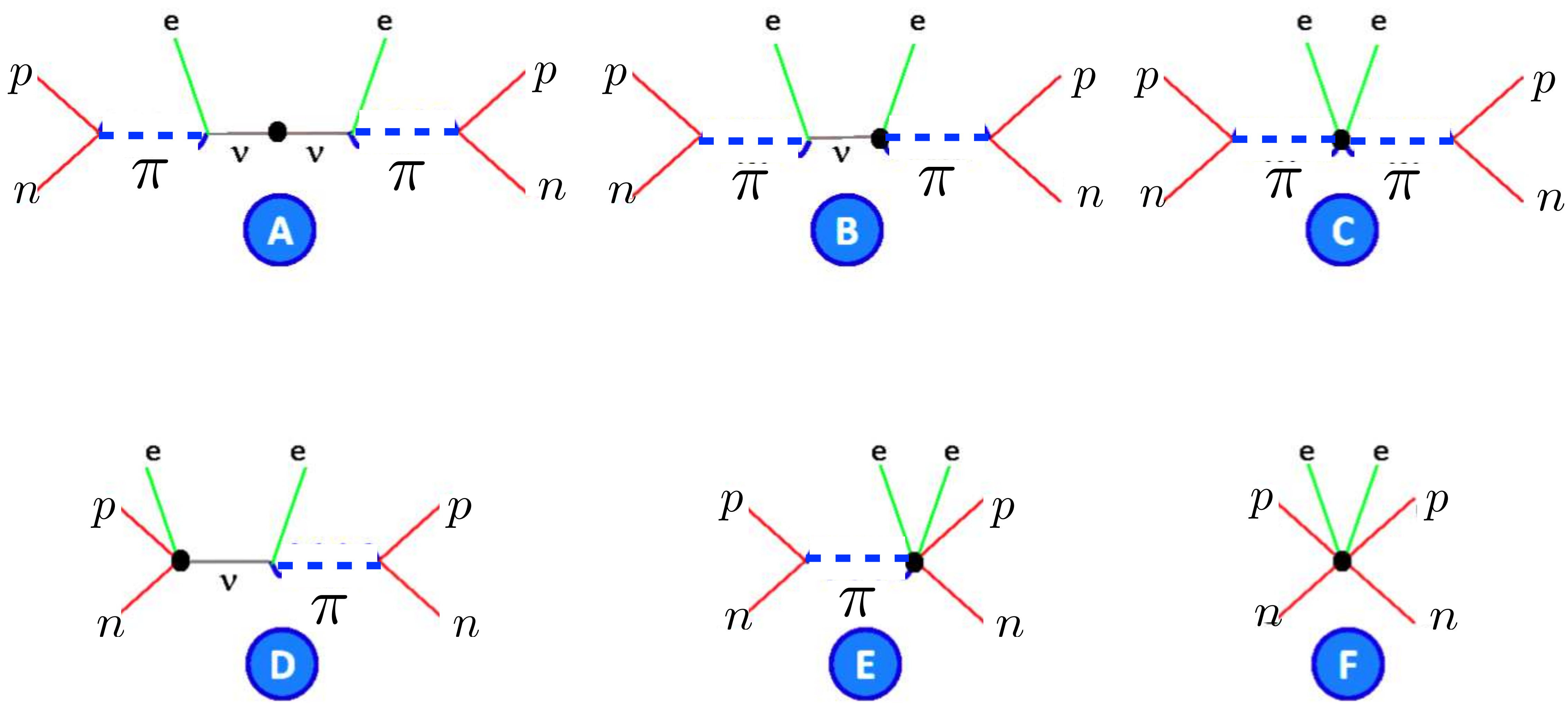


$\mathcal{L}_{\pi N}$ $\mathcal{L}_{\pi N}$

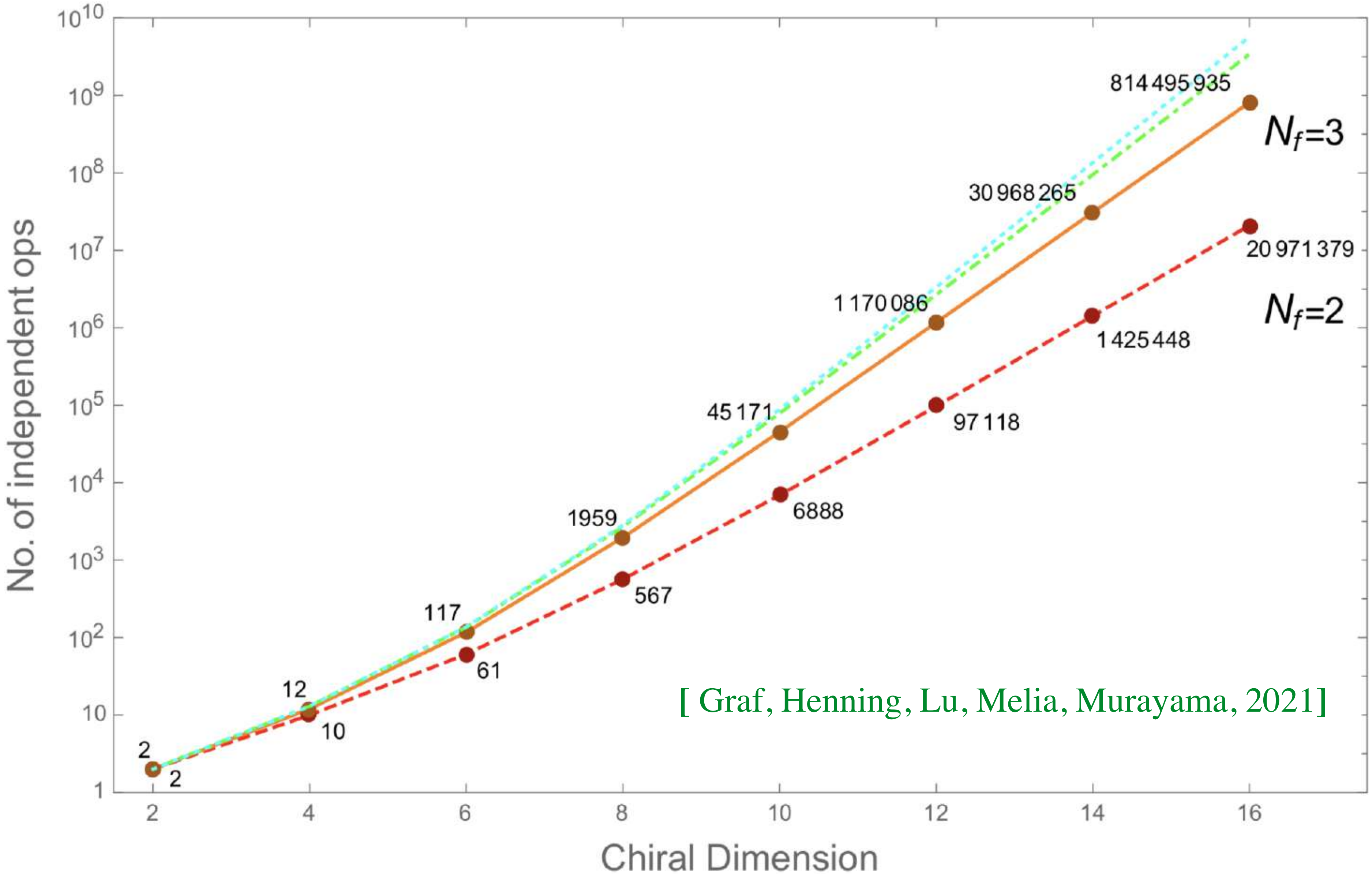
0vbb at SMEFT



0vbb at ChiPT



ChiPT Lagrangian



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

Fettes, Meisner, Mojzis, Steininger, 2000

Girlanda, Pastore, Schiavilla, Viviani, 2010

Nν Potential Master Formula

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

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

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

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

More matrix element?

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

Sterile Neutrino EFT

Dimension-5

Dim-5 operato

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
3	$(2,0)$	$F_{\rm L}\psi^2+h.c.$	$0+0+2+0$	2
4	$(1,0)$	$\psi^2\phi^2+h.c.$	$0+0+2+0$	2
Total		4	$0+0+4+0$	4

2

Dimension-6

Dim-6 operato

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	$(2,0)$	$\psi^4+h.c.$	$4+2+0+2$	14
		$F_{\rm L}\psi^2\phi+h.c.$	$4+0+0+0$	4
	$(1,1)$	$\psi^2\psi^{\dagger 2}$	$10+2+0+0$	12
		$\psi\psi^\dagger\phi^2 D$	$3+0+0+0$	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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[Aguila, Bar-Shalom, Soni, Wudka, 2009]

Dimension-7

Dim-7 operato

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	$(3,0)$	$F_{\rm L}^2\psi^2+h.c.$	$0+0+6+0$	6
	$(2,1)$	$F_{\rm L}^2\psi^{\dagger 2}+h.c.$	$0+0+6+0$	6
		$\psi^3\psi^\dagger D+h.c.$	$0+4+20+0$	24
		$F_{\rm L}\psi\psi^\dagger\phi D+h.c.$	$0+0+8+0$	8
		$\psi^2\phi^2 D^2+h.c.$	$0+0+4+0$	6
5	$(2,0)$	$\psi^4\phi+h.c.$	$0+2+10+0$	24
		$F_{\rm L}\psi^2\phi^2+h.c.$	$0+0+6+0$	6
	$(1,1)$	$\psi^2\psi^{\dagger 2}\phi$	$0+4+22+0$	30
		$\psi\psi^\dagger\phi^3 D$	$0+0+2+0$	4
6	$(1,0)$	$\psi^2\phi^4+h.c.$	$0+0+2+0$	2
Total		18	$0+10+86+0$	116

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[Bhattacharya, Wudka, 2016]

[Liao, Ma, 2017]

Dimension-8

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

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	$(3,1)$	$\psi^4 D^2+h.c.$	$4+0+2+2$	22
		$F_{\rm L}\psi^2\phi D^2+h.c.$	$4+0+0+0$	8
	$(2,2)$	$F_{\rm L}F_{\rm R}\psi\psi^\dagger D$	$3+0+0+0$	3
		$\psi^2\psi^{\dagger 2}D^2$	$10+2+0+0$	24
		$F_{\rm R}\psi^2\phi D^2+h.c.$	$4+0+0+0$	4
		$\psi\psi^\dagger\phi^2 D^3$	$3+0+0+0$	4
5	$(3,0)$	$F_{\rm L}\psi^4+h.c.$	$10+4+0+2$	50
		$F_{\rm L}{}^2\psi^2\phi+h.c.$	$8+0+0+0$	12
	$(2,1)$	$F_{\rm L}\psi^2\psi^{\dagger 2}+h.c.$	$42+12+0+0$	58
		$F_{\rm L}{}^2\psi^{\dagger 2}\phi+h.c.$	$8+0+0+0$	8
		$\psi^3\psi^\dagger\phi D+h.c.$	$24+6+0+2$	108
		$F_{\rm L}\psi\psi^\dagger\phi^2 D+h.c.$	$12+0+0+0$	16
		$\psi^2\phi^3 D^2+h.c.$	$2+0+0+0$	12
6	$(2,0)$	$\psi^4\phi^2+h.c.$	$8+2+0+2$	30
		$F_{\rm L}\psi^2\phi^3+h.c.$	$4+0+0+0$	6
	$(1,1)$	$\psi^2\psi^{\dagger 2}\phi^2$	$16+4+0+2$	28
		$\psi\psi^\dagger\phi^4 D$	$3+0+0+0$	3
7	$(1,0)$	$\psi^2\phi^5+h.c.$	$2+0+0+0$	2
Total		31	$167+30+2+10$	398

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Dimension-9

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

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	$(4,1)$	$F_{\rm L}{}^2\psi^2 D^2+h.c.$	$0+6+0+0$	12
	$(3,2)$	$F_{\rm L}F_{\rm R}\psi^2 D^2+h.c.$	$0+6+0+0$	6
		$F_{\rm L}{}^2\psi^{\dagger 2}D^2+h.c.$	$0+6+0+0$	6
		$\psi^3\psi^\dagger D^3+h.c.$	$4+20+0+0$	46
		$F_{\rm L}\psi\psi^\dagger\phi D^3+h.c.$	$0+8+0+0$	16
		$\psi^2\phi^2 D^4+h.c.$	$0+4+0+0$	8
5	$(4,0)$	$F_{\rm L}{}^3\psi^2+h.c.$	$0+10+0+0$	16
	$(3,1)$	$F_{\rm L}{}^3\psi^{\dagger 2}+h.c.$	$0+4+0+0$	4
		$F_{\rm L}\psi^3\psi^\dagger D+h.c.$	$10+42+0+0$	222
		$F_{\rm L}{}^2\psi\psi^\dagger\phi D+h.c.$	$0+16+0+0$	32
		$\psi^4\phi D^2+h.c.$	$2+10+0+0$	120
		$F_{\rm L}\psi^2\phi^2 D^2+h.c.$	$0+8+0+0$	42
	$(2,2)$	$F_{\rm L}F_{\rm R}{}^2\psi^2+h.c.$	$0+12+0+0$	12
		$F_{\rm R}\psi^3\psi^\dagger D+h.c.$	$10+42+0+0$	166
		$F_{\rm L}F_{\rm R}\psi\psi^\dagger\phi D$	$0+10+0+0$	24
		$\psi^2\psi^{\dagger 2}\phi D^2$	$4+22+0+0$	210
		$F_{\rm R}\psi^2\phi^2 D^2+h.c.$	$0+8+0+0$	24
		$\psi\psi^\dagger\phi^3 D^3$	$0+2+0+0$	20
6	$(3,0)$	$\psi^6+h.c.$	$6+10+6+2$	130
		$F_{\rm L}\psi^4\phi+h.c.$	$6+26+0+0$	110
		$F_{\rm L}{}^2\psi^2\phi^2+h.c.$	$0+12+0+0$	18
	$(2,1)$	$\psi^4\psi^{\dagger 2}+h.c.$	$40+106+14+0$	474
		$F_{\rm L}\psi^2\psi^{\dagger 2}\phi+h.c.$	$24+116+0+0$	176
		$F_{\rm L}{}^2\psi^{\dagger 2}\phi^2+h.c.$	$0+10+0+0$	10
		$\psi^3\psi^\dagger\phi^2 D+h.c.$	$10+44+0+0$	268
		$F_{\rm L}\psi\psi^\dagger\phi^3 D+h.c.$	$0+8+0+0$	32
		$\psi^2\phi^4 D^2+h.c.$	$0+4+0+0$	20
7	$(2,0)$	$\psi^4\phi^3+h.c.$	$2+12+0+0$	28
		$F_{\rm L}\psi^2\phi^4+h.c.$	$0+6+0+0$	6
	$(1,1)$	$\psi^2\psi^{\dagger 2}\phi^3$	$4+22+0+0$	34
		$\psi\psi^\dagger\phi^5 D$	$0+2+0+0$	4

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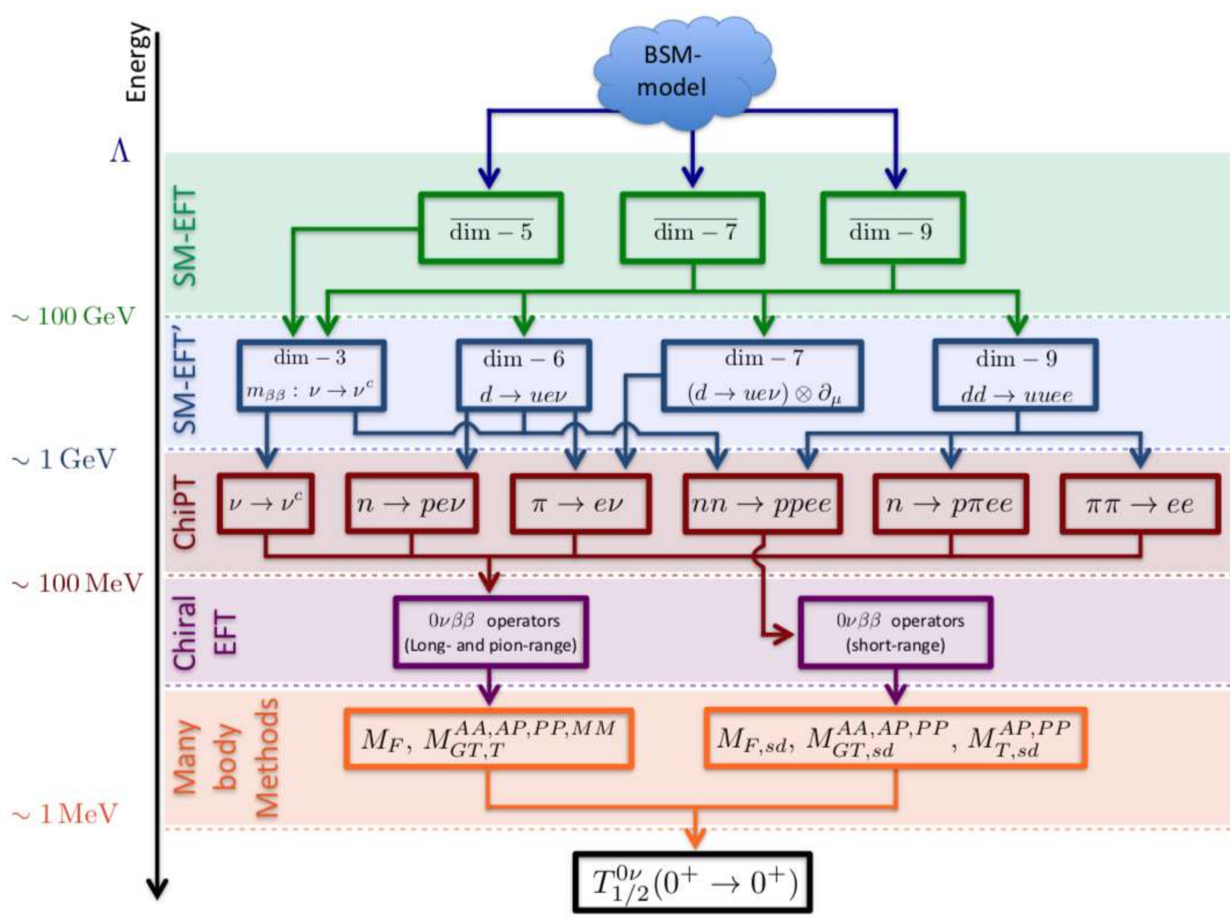
Summary

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!