Institute of Theoretical Physics
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v Mass & 0vbb 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
Gang Li, Hao Sun, **JHY** , in collaboration

Zhuhai, Zhong-Shan Univ
May 22, 2021

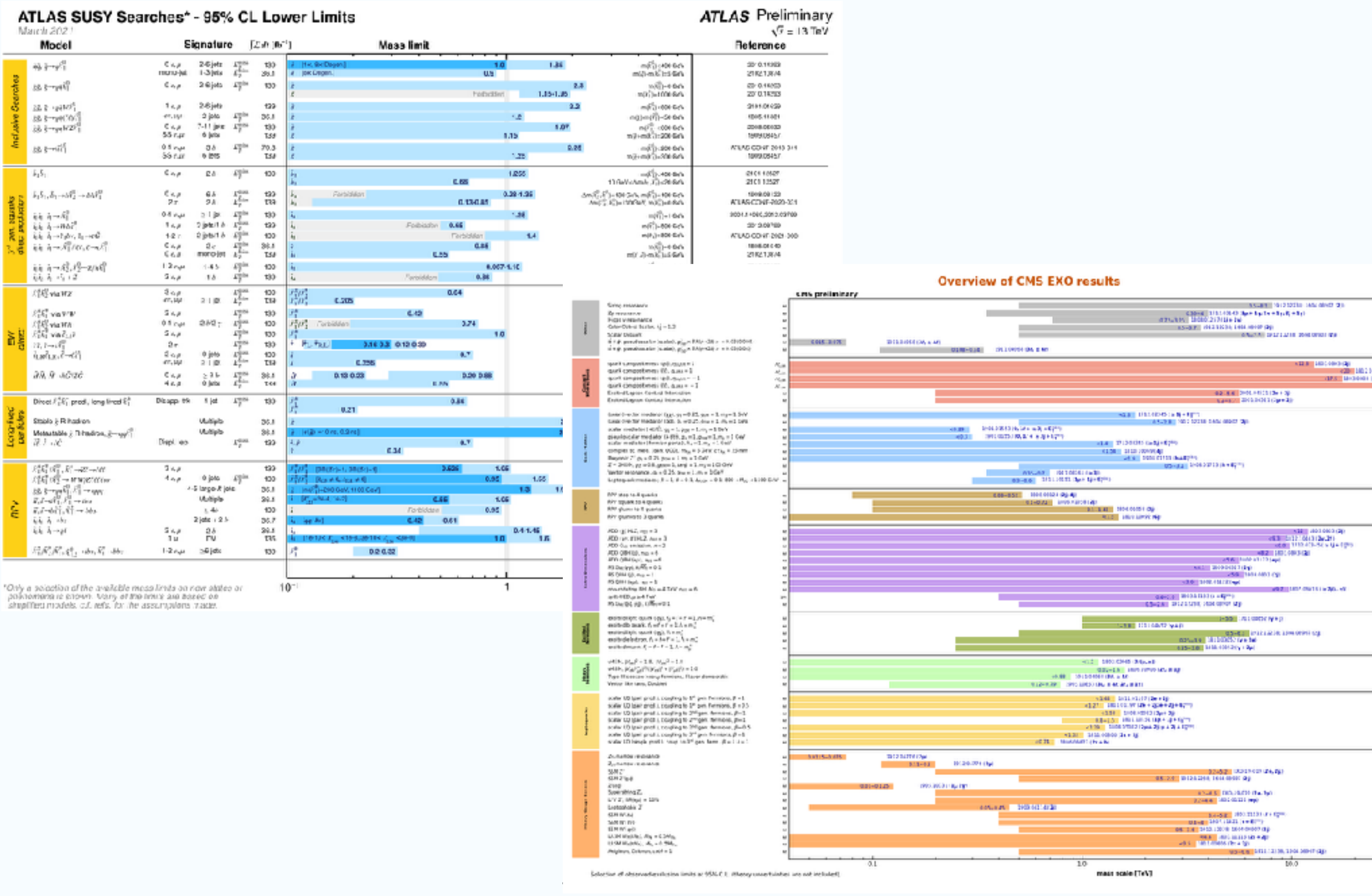
Outline

- 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

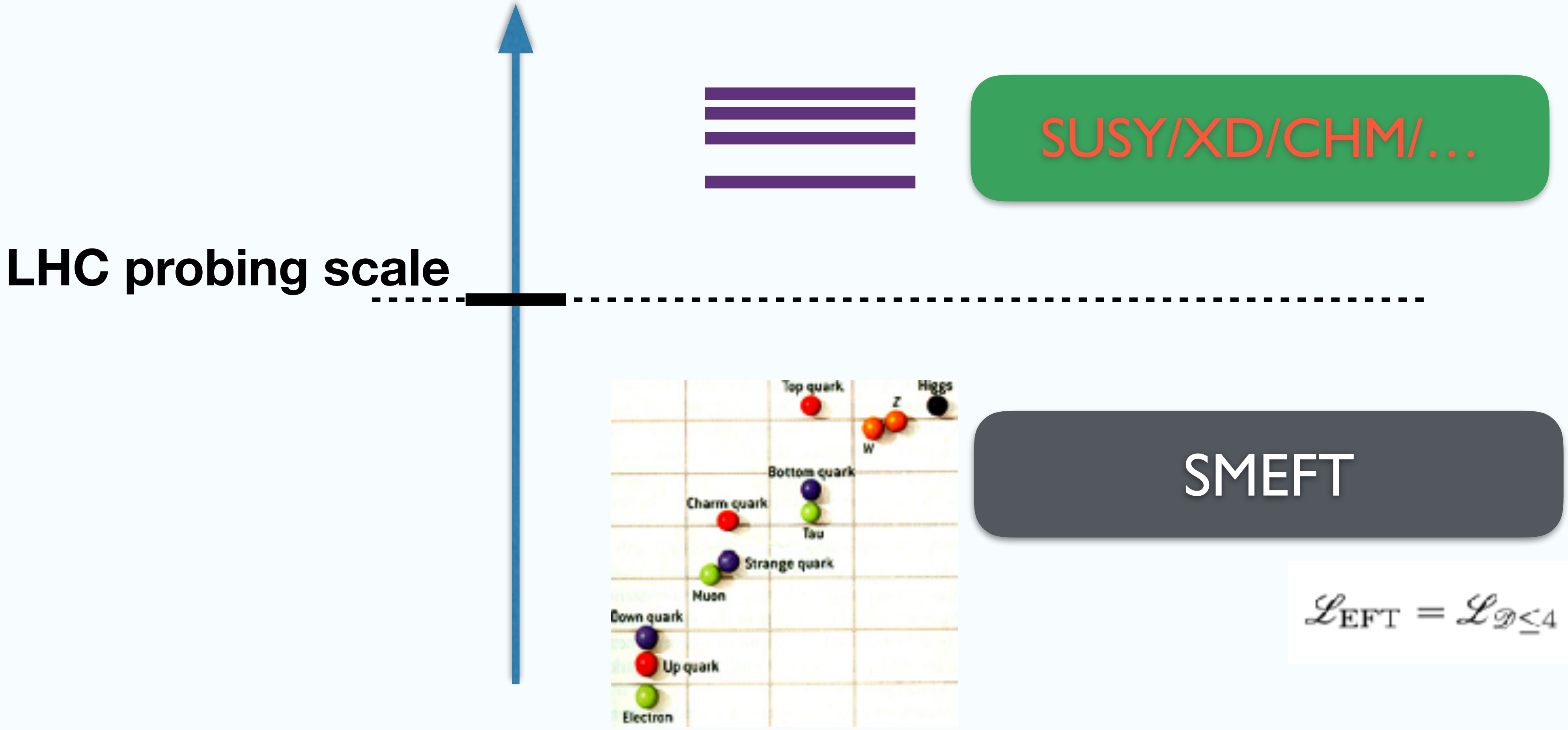
Introduction

Why 0vbb in EFT approach?

Search For New Physics



New Physics w/o New Particle



SUSY/XD/CHM/…

LHC probing scale

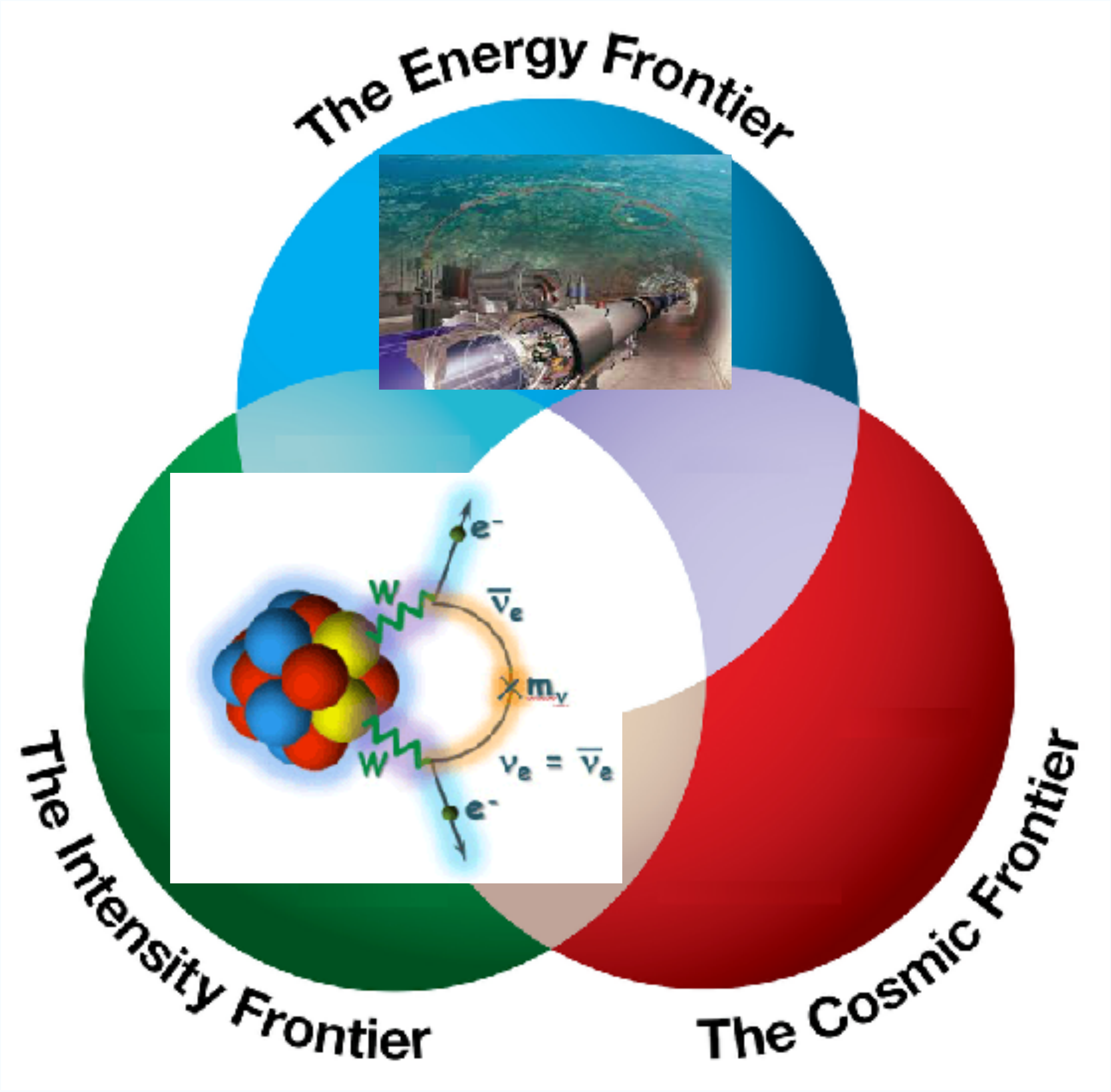
SMEFT

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

Top-down: Integrate out and matching/running

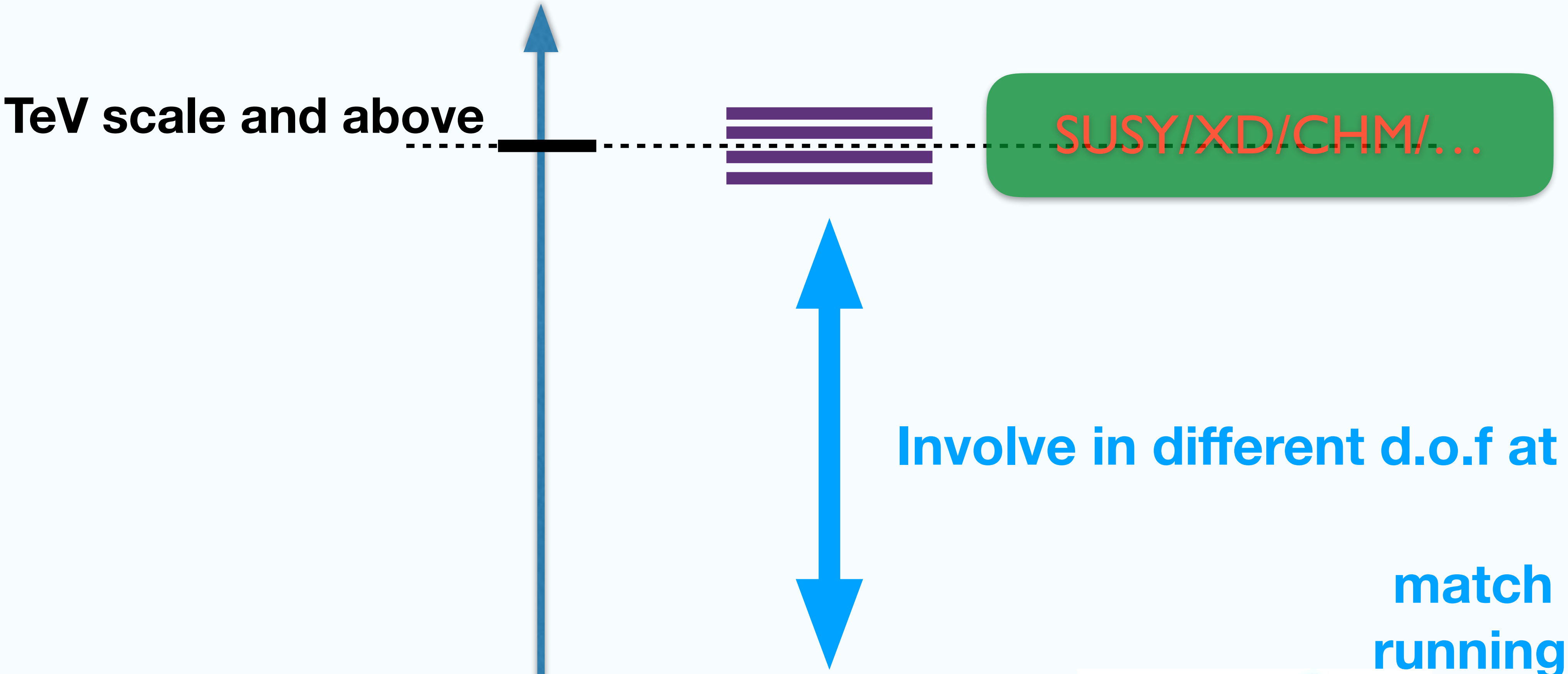
Bottom-up: field d.o.f and symmetry at IR scale

New Physics w/o New Particle



Low Energy Probe of HEP

Low energy probes of high energy physics



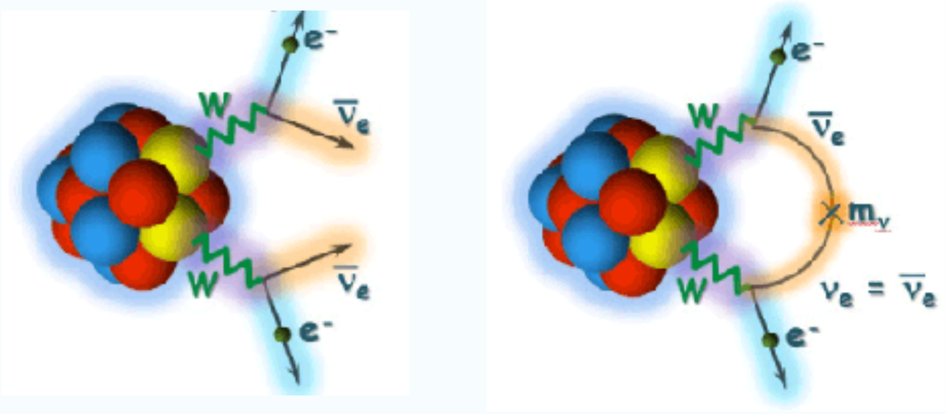
TeV scale and above

SUSY/XD/CHM/…

Involve in different d.o.f at many scales

match (different d.o.f.)
running (avoid large log)

nuclear scale



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

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

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

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

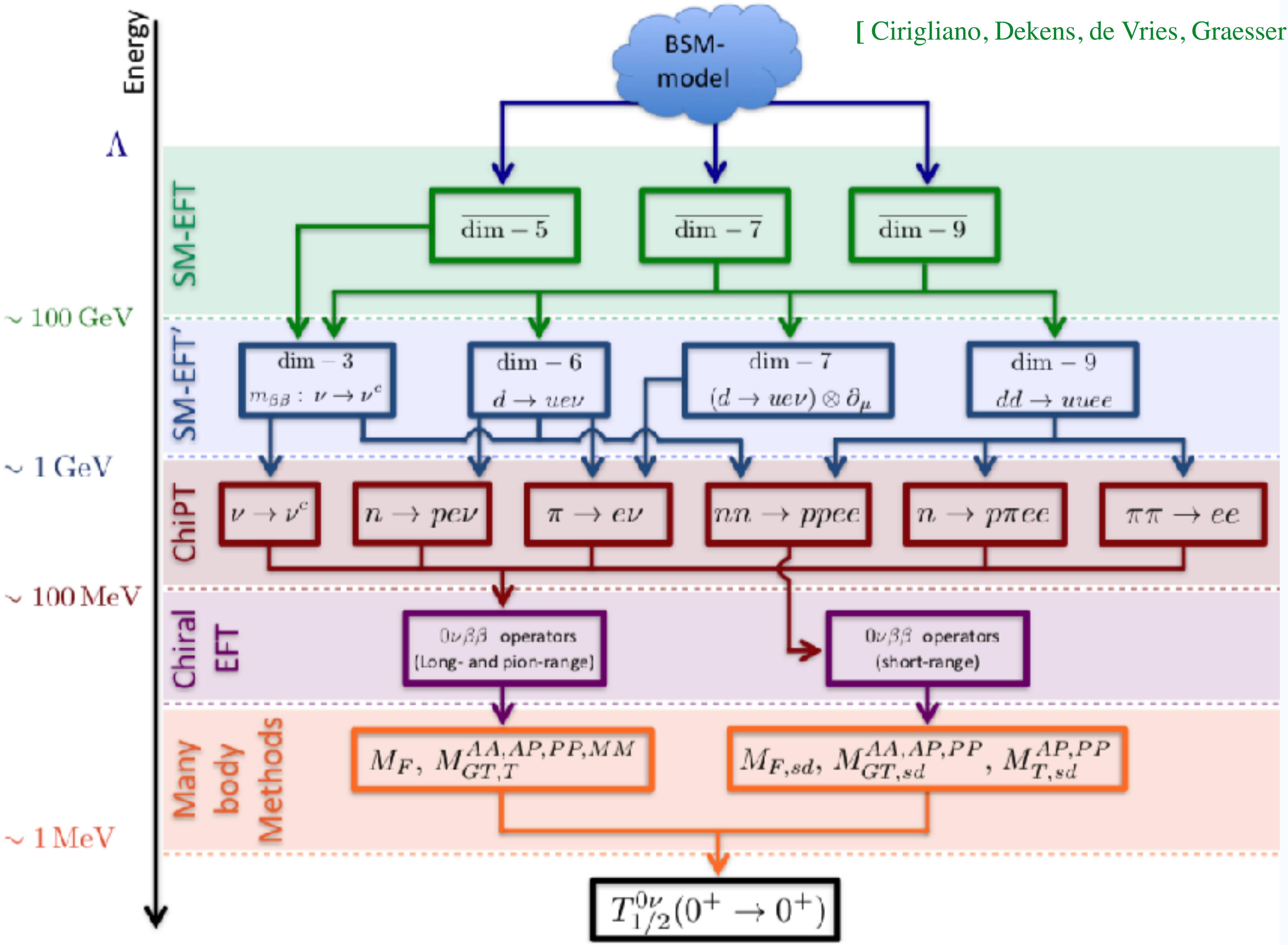
MeV scale

Nuclear EFT (nuclear matrix elements)

$0\nu\beta\beta$

EFT for 0vbb

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



Energy

Λ

BSM-model

SM-EFT

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

~ 100 GeV

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 $dd \to uuee$

~ 1 GeV

ChiPT

$\nu \to \nu^c$ $n \to pe\nu$ $\pi \to e\nu$ $nn \to ppee$ $n \to p\pi ee$ $\pi\pi \to ee$

~ 100 MeV

Chiral EFT

$0\nu\beta\beta$ operators (Long- and pion-range)

$0\nu\beta\beta$ operators (short-range)

Many body Methods

$M_F,\ M_{GT,T}^{AA,AP,PP,MM}$

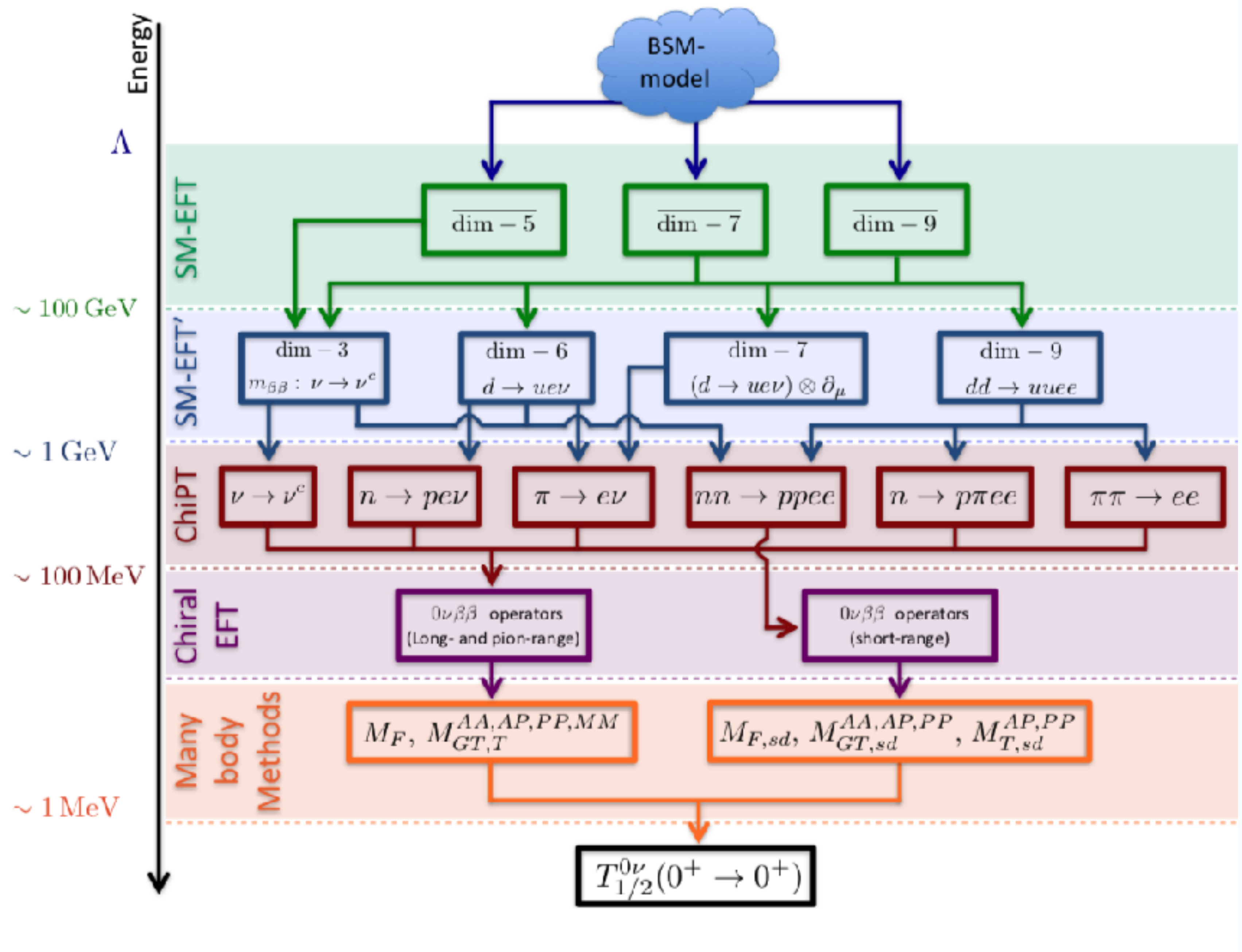
$M_{F,sd},\ M_{GT,sd}^{AA,AP,PP},\ M_{T,sd}^{AP,PP}$

~ 1 MeV

$T_{1/2}^{0\nu}(0^+ \to 0^+)$

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?

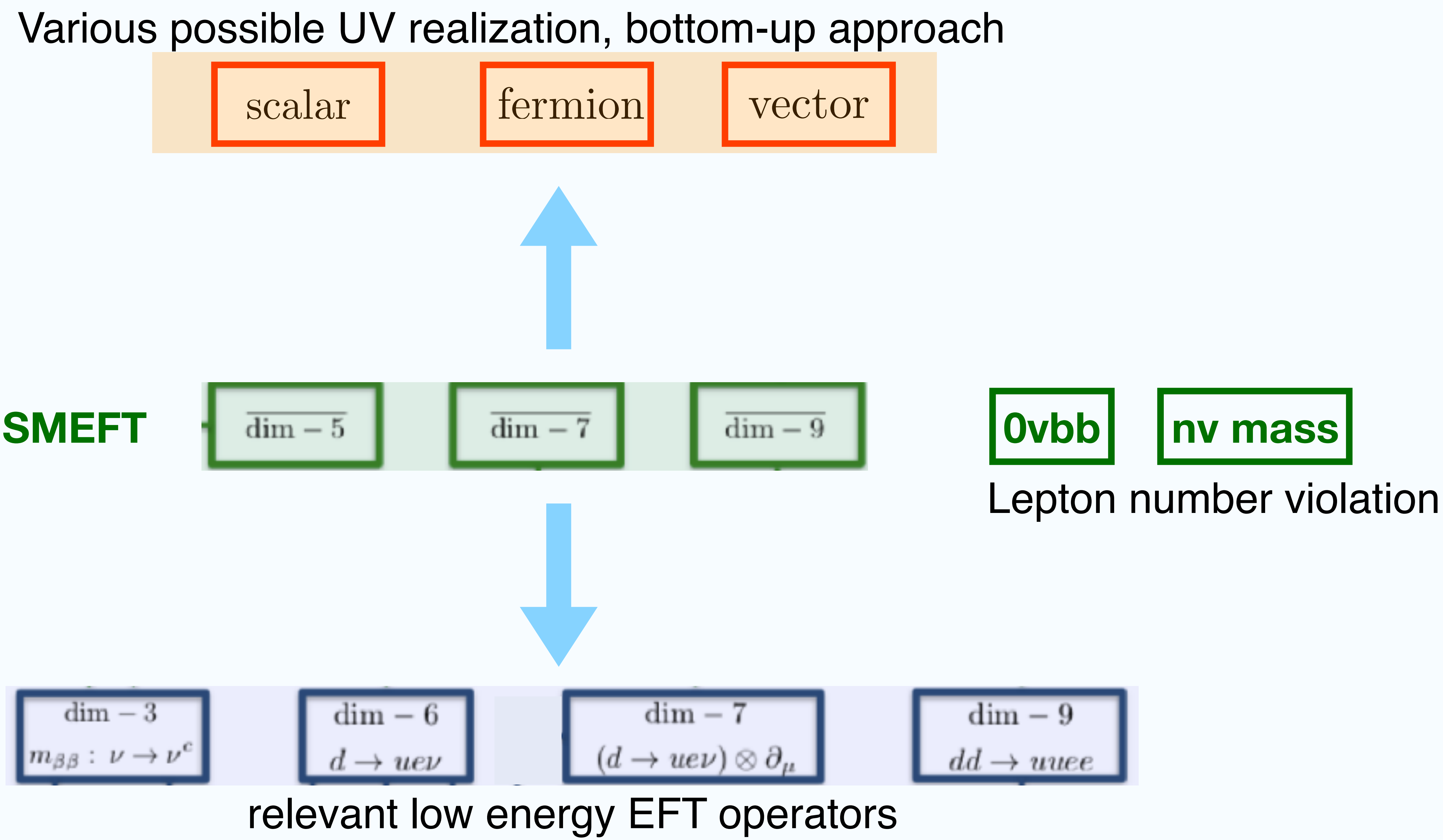
More nuclear ME?

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

dim − 5

dim − 7

dim − 9

0vbb

nv mass

Lepton number violation

dim − 3

$m_{\beta\beta} : \nu \to \nu^c$

dim − 6

$d \to u e \nu$

dim − 7

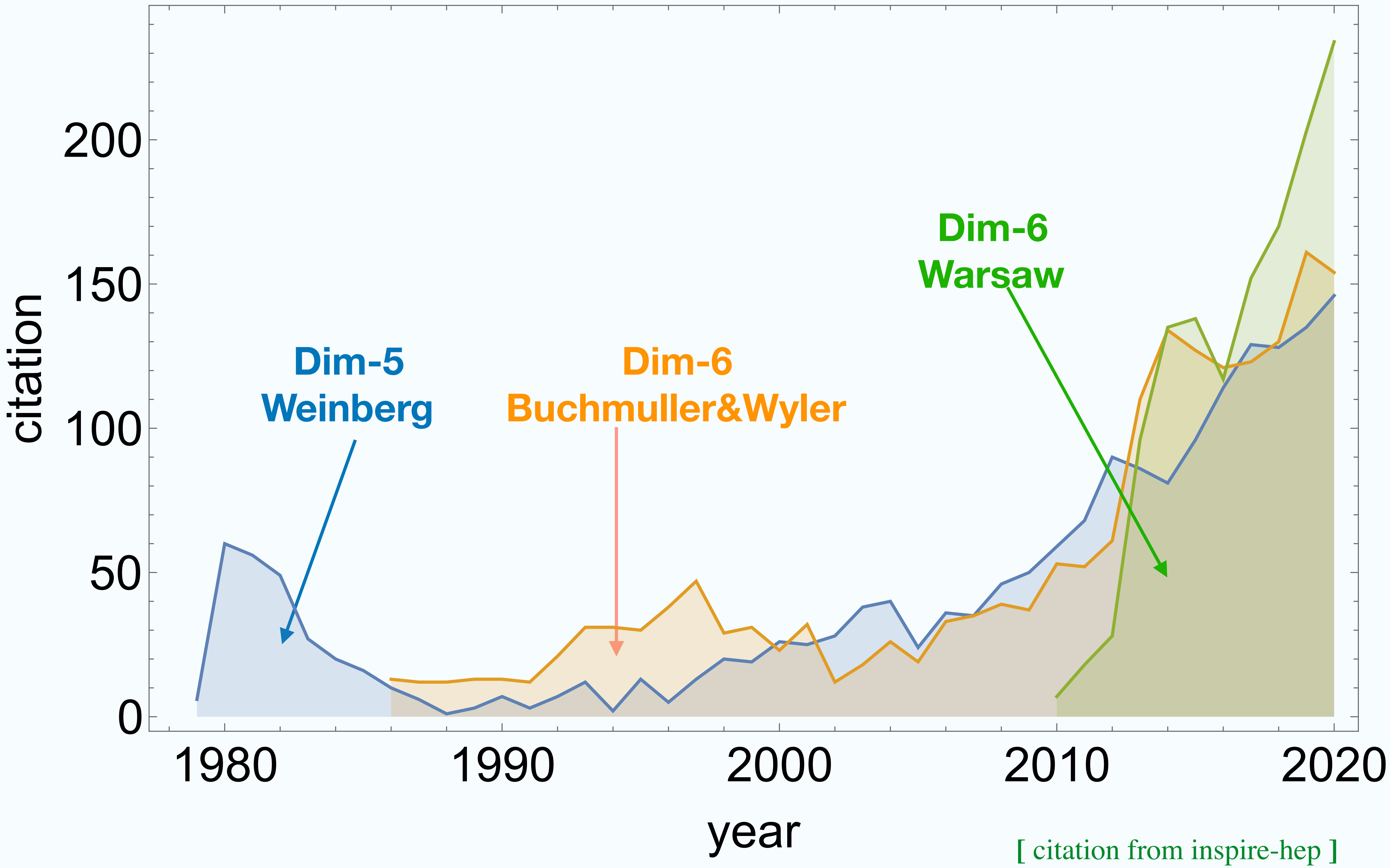
$(d \to u e \nu) \otimes \partial_\mu$

dim − 9

$dd \to uuee$

relevant low energy EFT operators

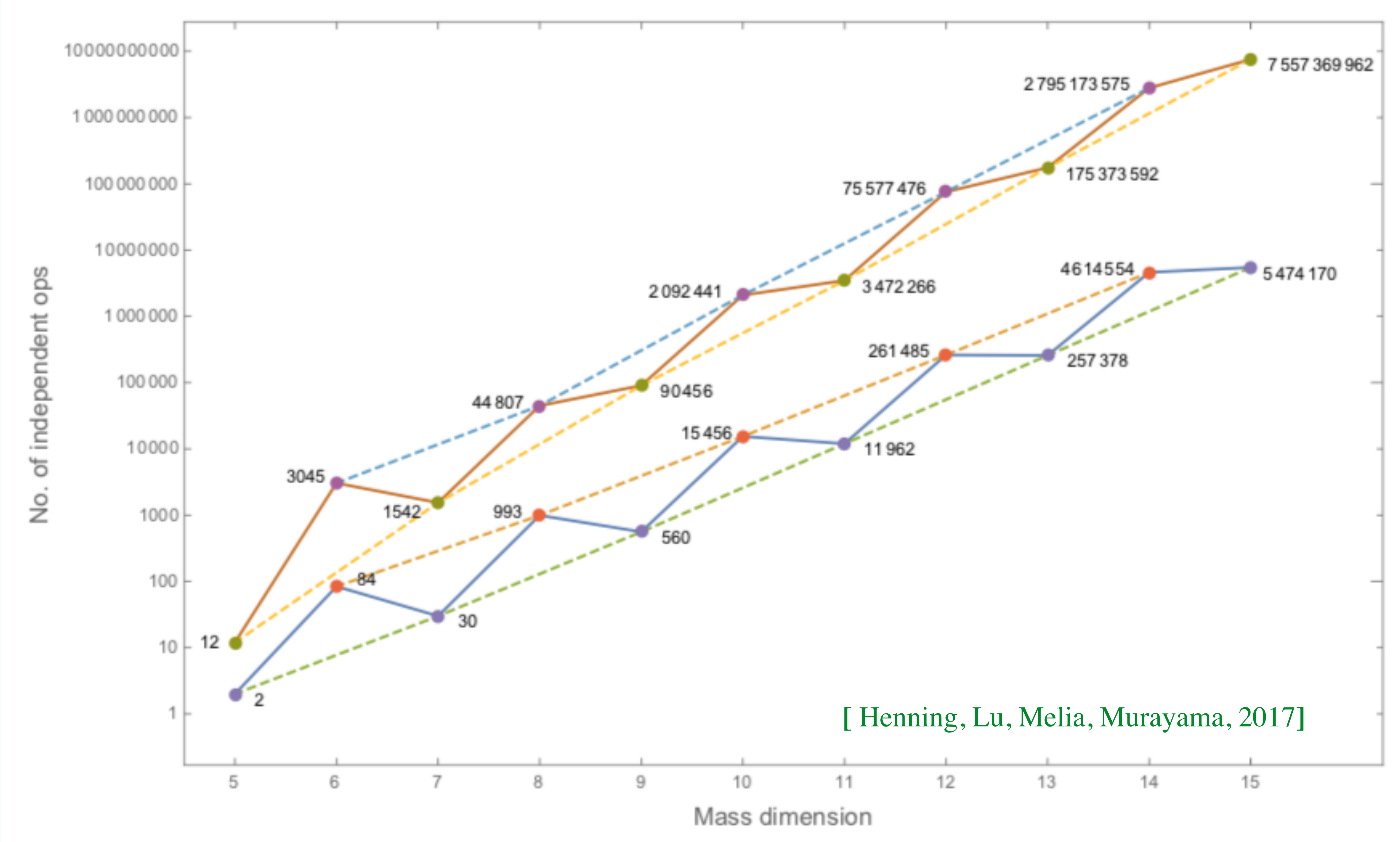
SMEFT Operators



[citation from inspire-hep]

Hilbert Series Counting

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



[Henning, Lu, Melia, Murayama, 2017]

Higher Dim Operators!?

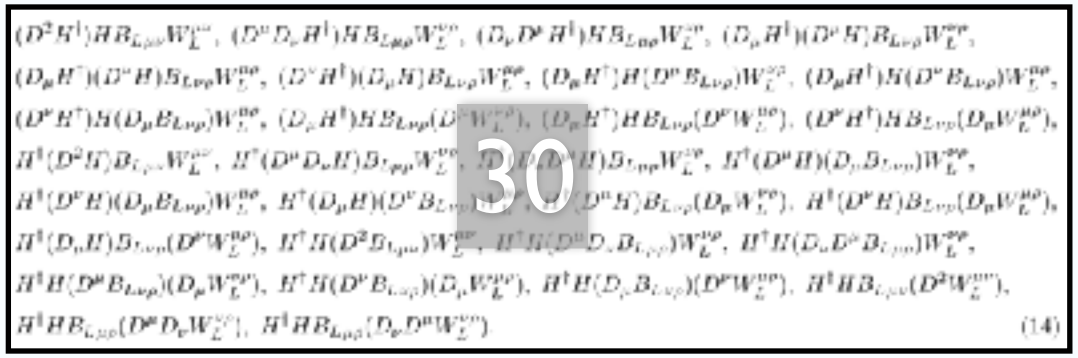
Given numbers of independent operators

does not mean we know explicit form of operators!

Derivatives

$BWHH^\dagger D^2$

2



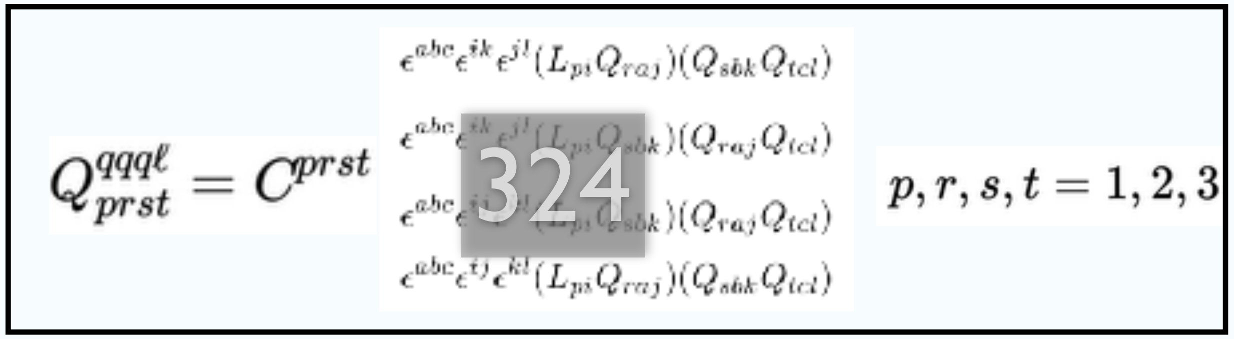
(14)

Which 2 should be picked up?

Repeated fields

$QQQL$

57



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

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）

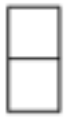
$$\boxed{H_i \in (0,0) \quad \psi_\alpha \in (1/2,0) \quad F_{\mathrm{L}\alpha\beta} = \frac{i}{2}F_{\mu\nu}\sigma^{\mu\nu}_{\alpha\beta} \in (1,0) \quad D_{\alpha\dot\alpha} = D_\mu\sigma^\mu_{\alpha\dot\alpha} \in (1/2,1/2),}$$

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

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

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

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

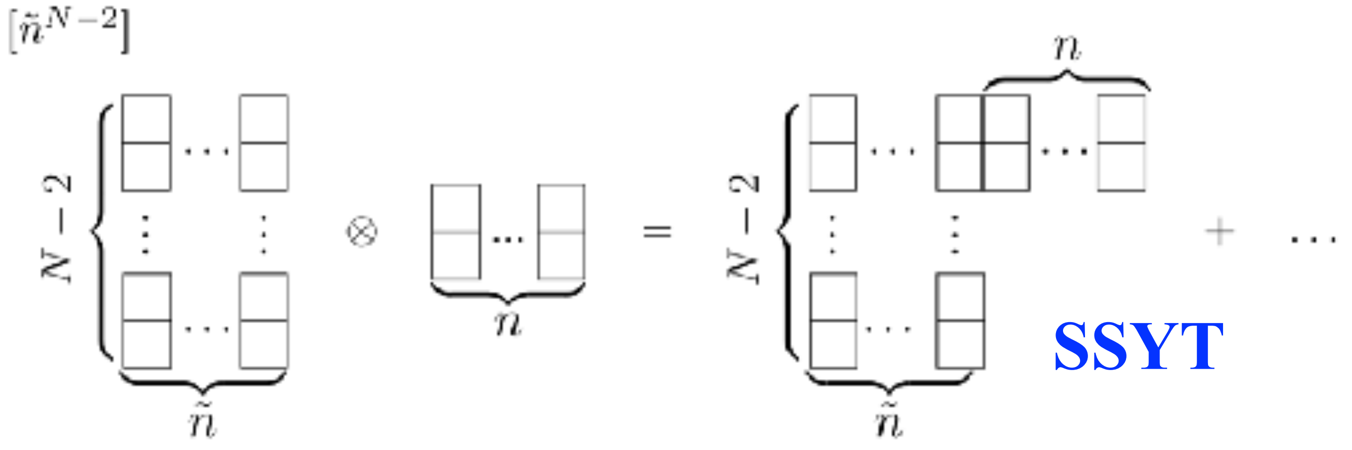


$= [1^2]$

算符在总动量的小群变换下为：U(N)表示（无需动量积分）

$$\epsilon^{\alpha_i\alpha_j} \to \sum_{k,l}\mathcal{U}^i_k\mathcal{U}^j_l\epsilon^{\alpha_k\alpha_l}$$

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



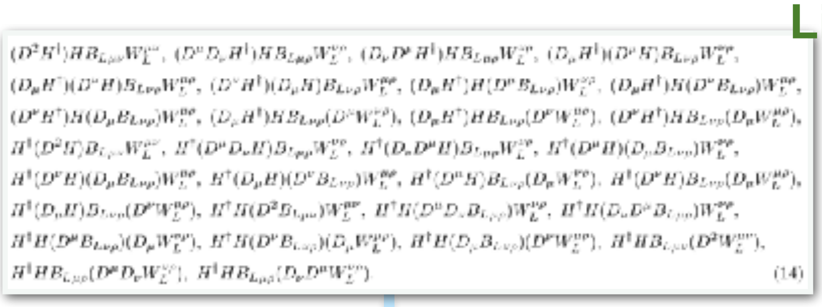
SSYT

Operator Construction

$BWHH^\dagger D^2$

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

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

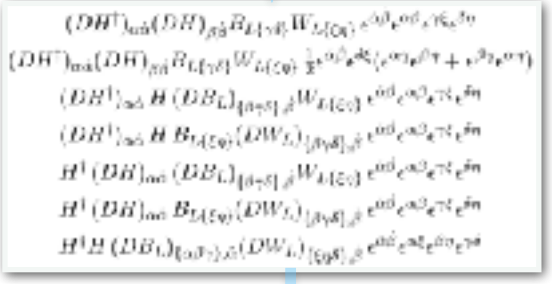


$$(D^2H^\dagger)HB_{L\mu\nu}W_L^{\mu\nu},\ (D^\mu D_\nu H^\dagger)HB_{L\mu\rho}W_L^{\nu\rho},\ (D_\nu D^\mu H^\dagger)HB_{L\mu\rho}W_L^{\nu\rho},\ (D_\mu H^\dagger)(D^\nu H)B_{L\nu\rho}W_L^{\mu\rho},$$
$$(D_\mu H^\dagger)(D^\nu H)B_{L\nu\rho}W_L^{\rho\mu},\ (D^\nu H^\dagger)(D_\mu H)B_{L\nu\rho}W_L^{\mu\rho},\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

30

highest weight representation

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



7

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

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

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

2

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

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

SMEFT

Dimension-5

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

[Weinberg, 1979]

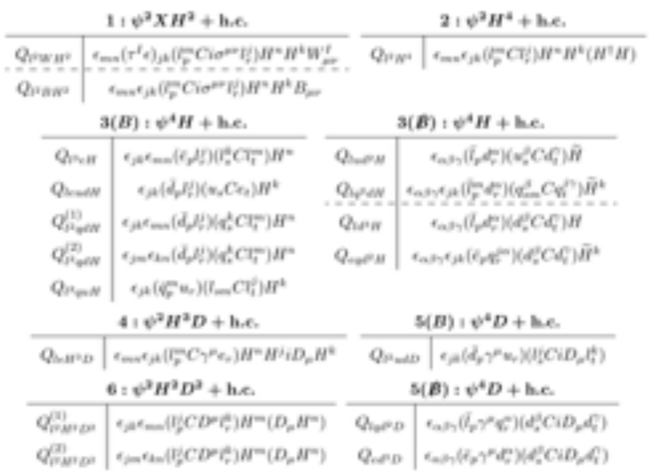
2

Dimension-6

84

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

Dimension-7



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

Dimension-8

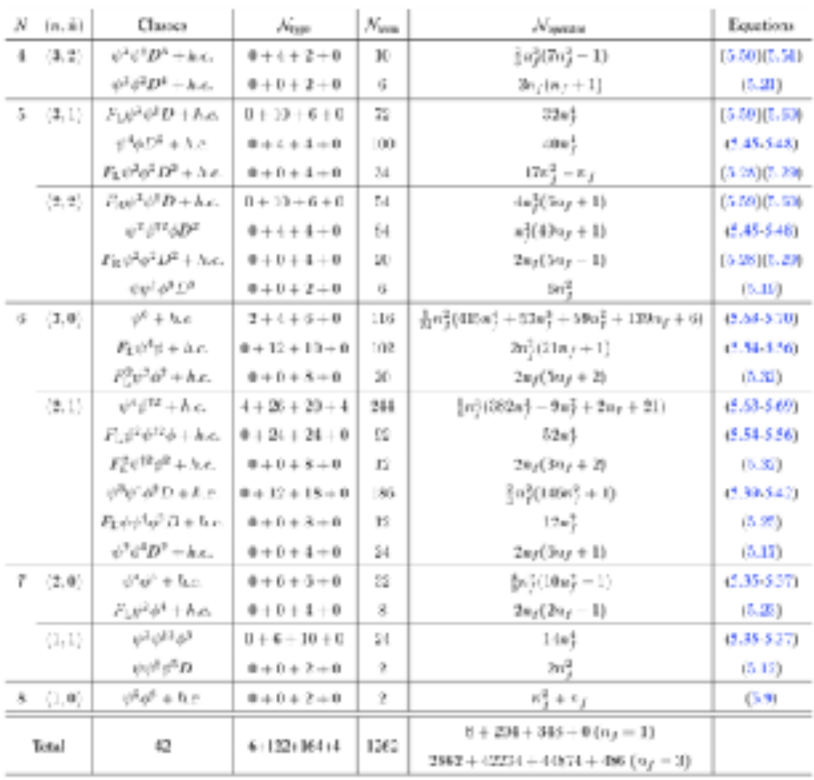
[Li, Ren, Shu, Xiao, **Yu**, Zheng, **2020**]

[Murphy, 2020]

993

Dimension-9

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

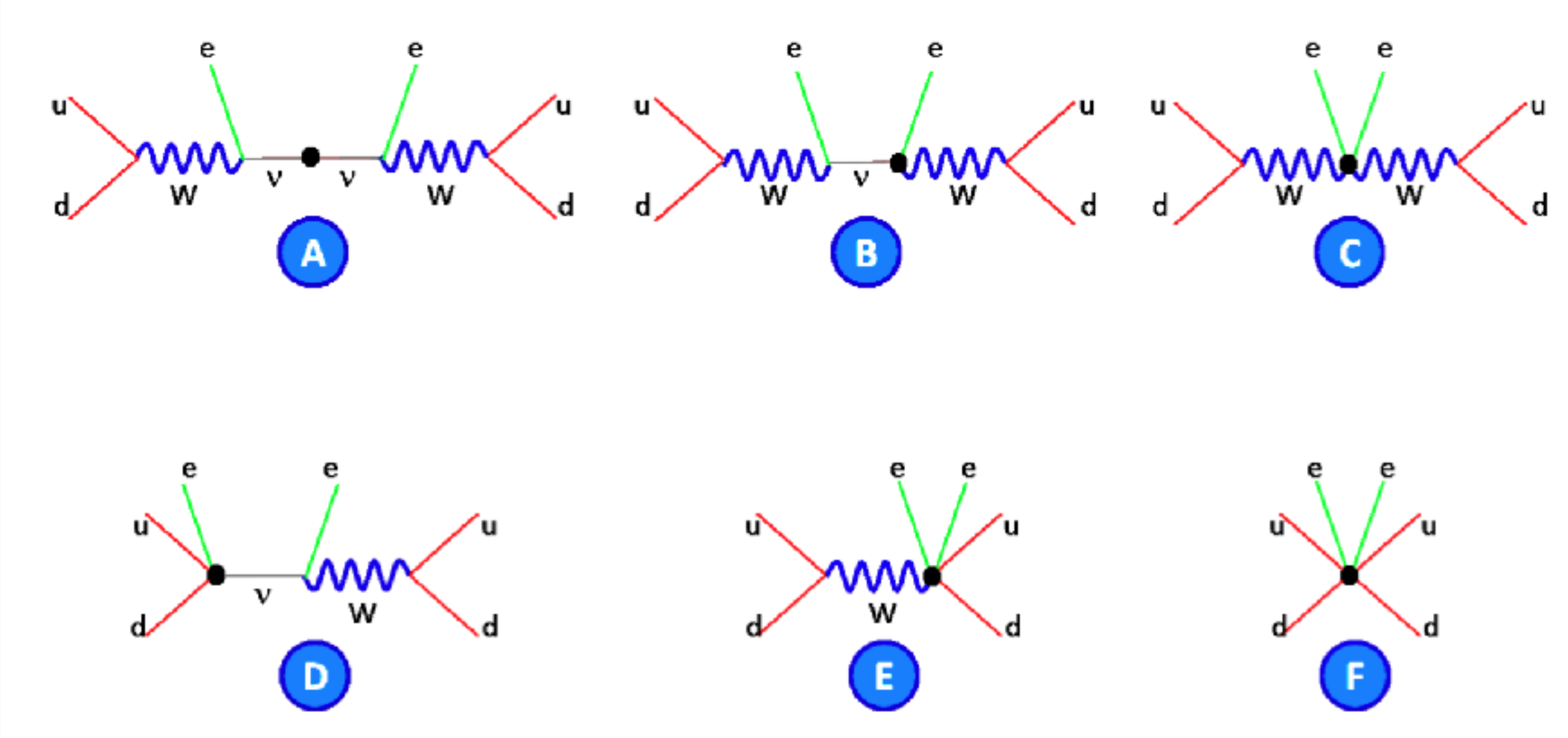


[Liao, Ma, 2020]

560

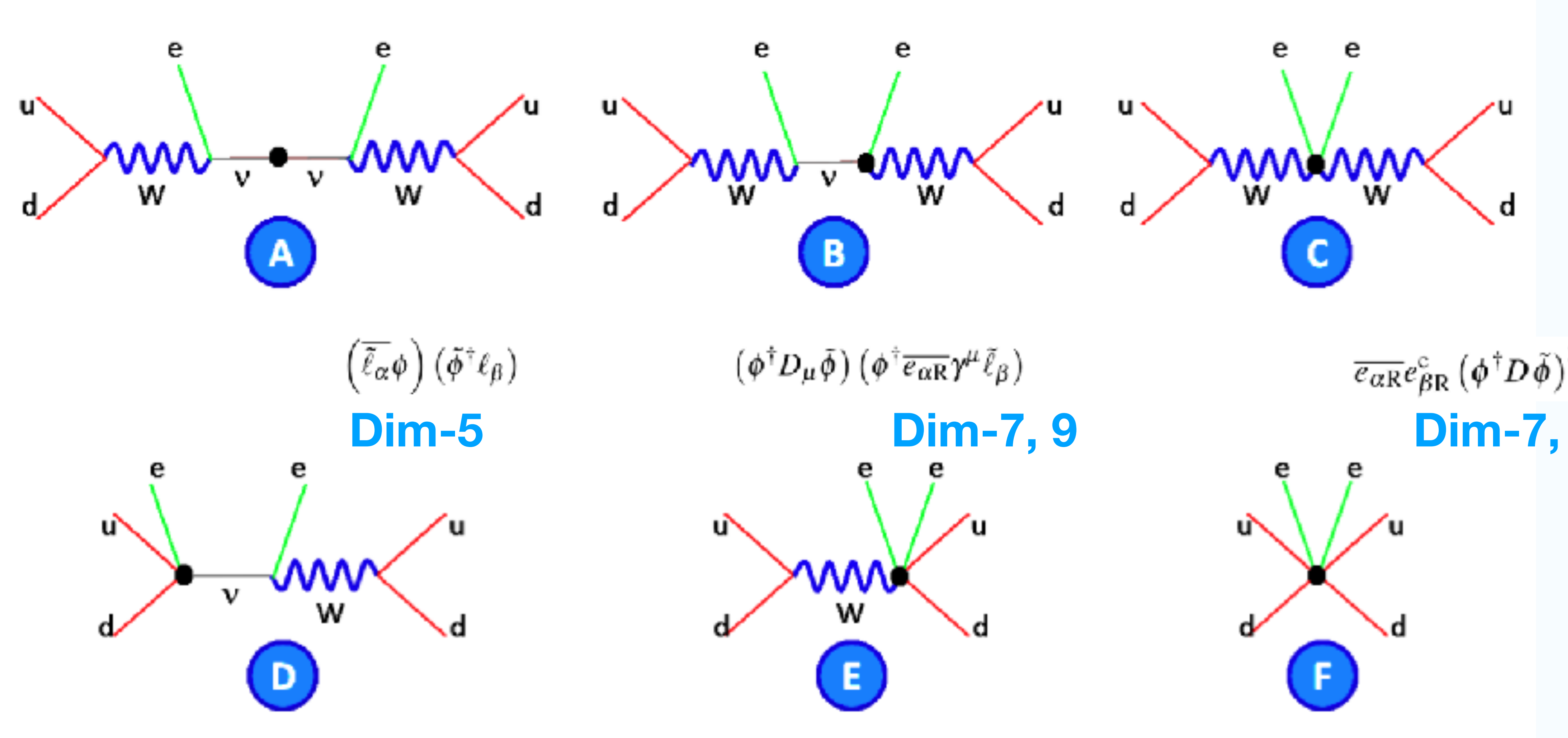
0vbb Related Operators

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

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

Dim-7, 9

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

Dim-7, 9

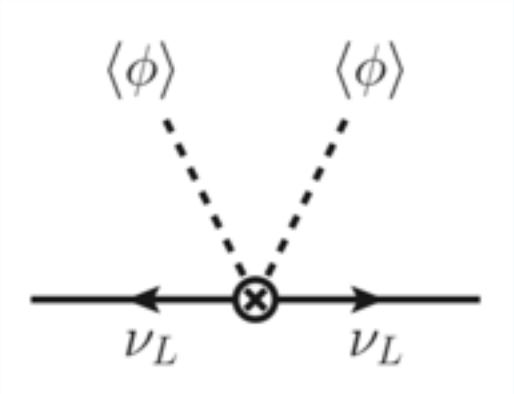
Dim-7, 9

Dim-9

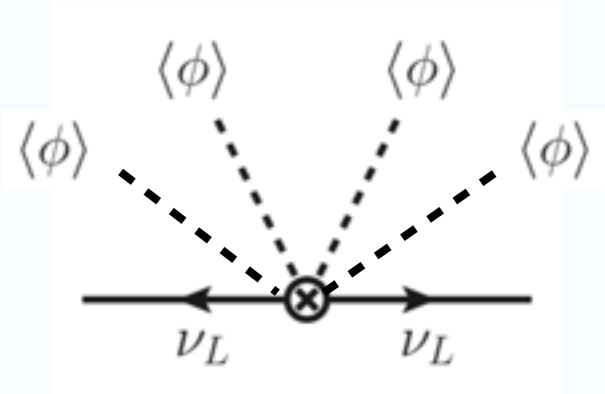
Dim-9

Nν Mass Related Operators

Higgs taking VEV:



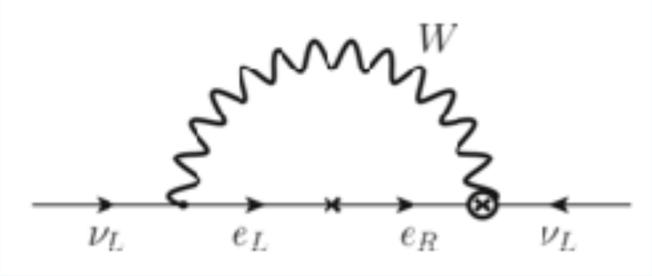
$LLHH$

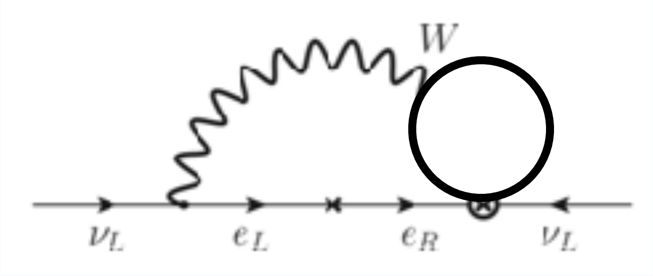


$LLHHHH$

…

Could from other lepton number violation operators: anomalous RG

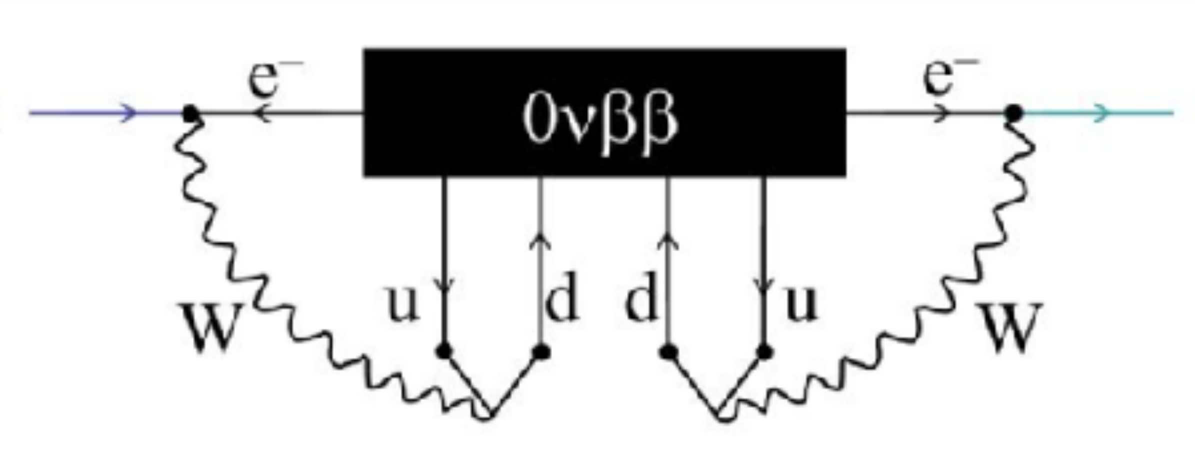




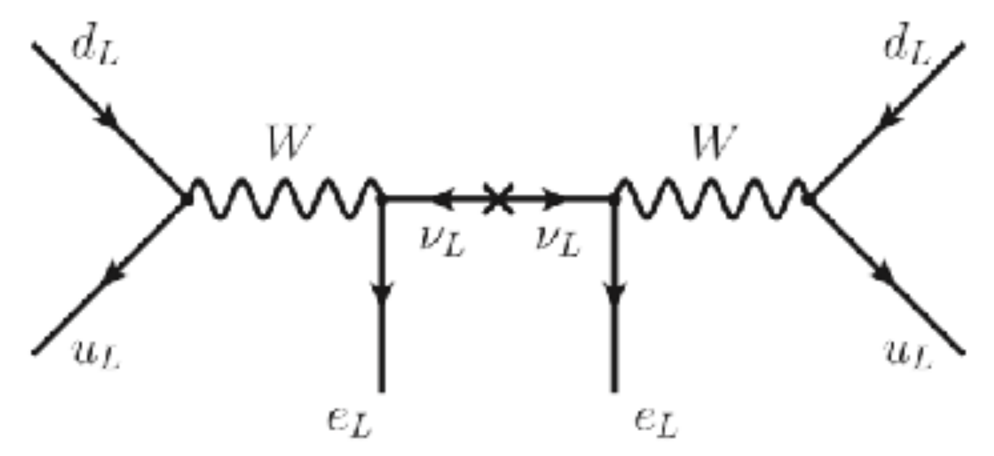
…

Neutrino Masses and 0vbb

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

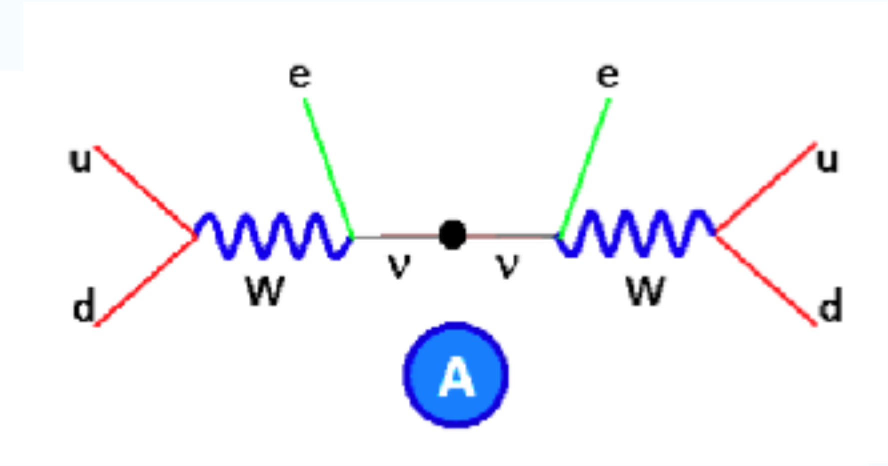


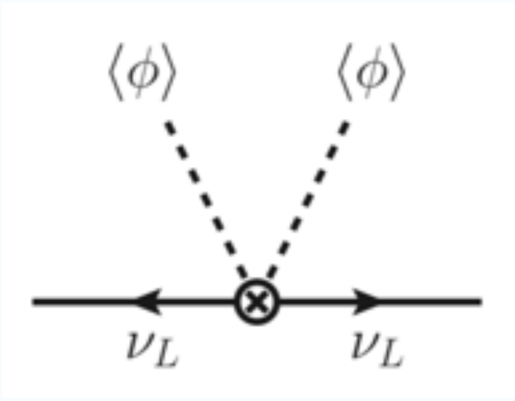
[Schechter-Valle, 1982]



Strong Correlation

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





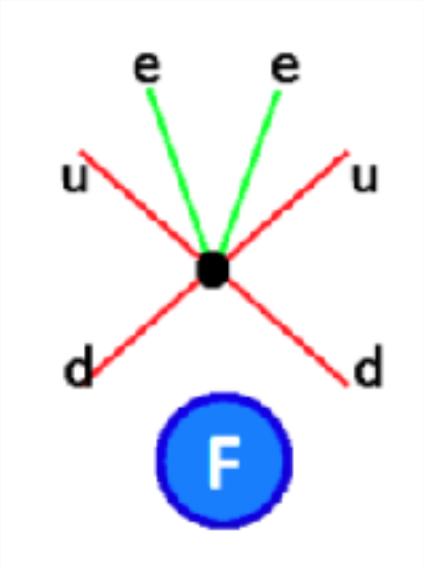
$$L^{\mu\nu} = -\int\int dx_2 dx_1 \sum_i \bar{e}(x_1)\gamma^\mu(1-\gamma_5)U_{ei}\,\underbrace{\nu_{iL}(x_1)\bar{\nu}^c_{iL}(x_2)}\gamma_\nu(1+\gamma_5)U_{ei}e^C_L(x_2)$$

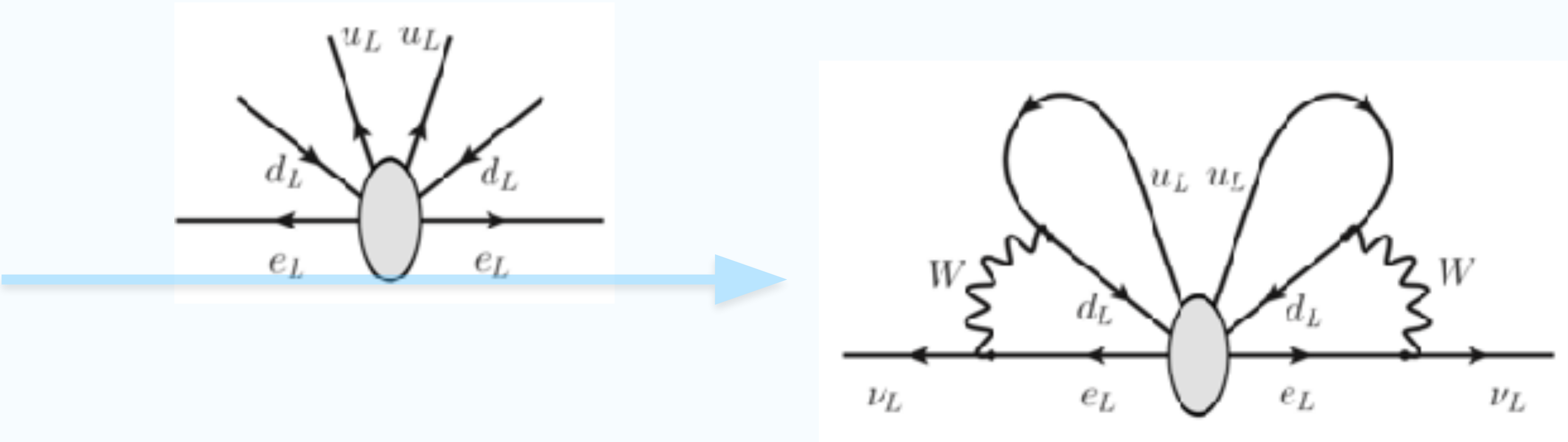
$$m_{\beta\beta} = \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i}.$$

0vbb has direct connection to neutrino physics

Strong Correlation???

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

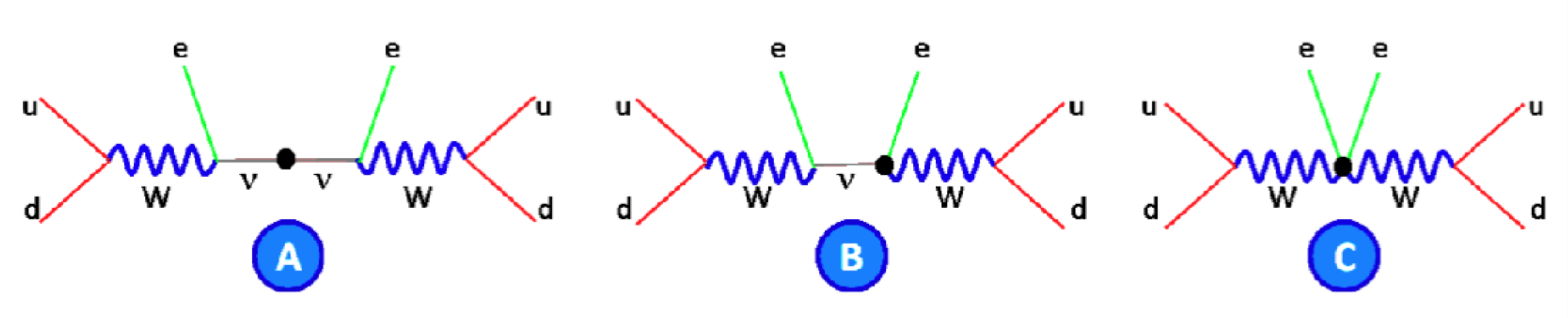


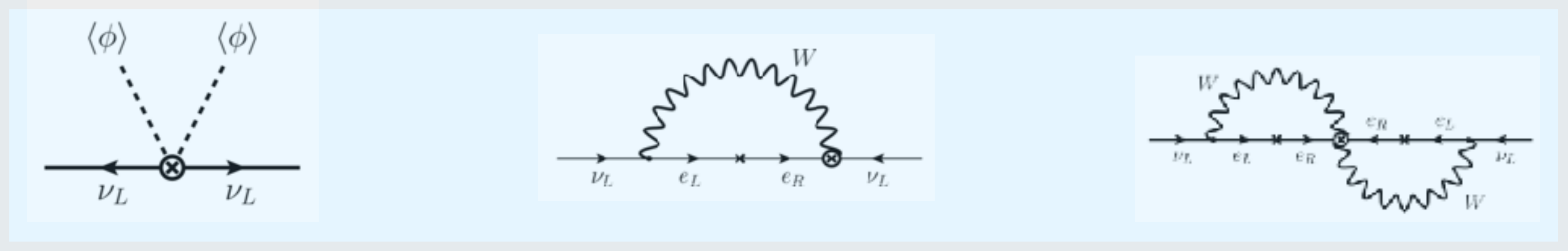


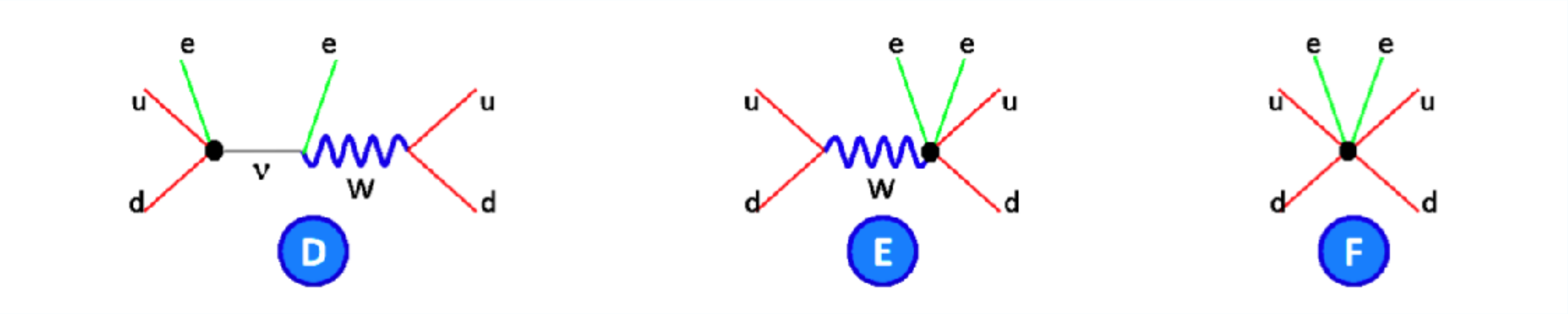
Very tiny neutrino mass

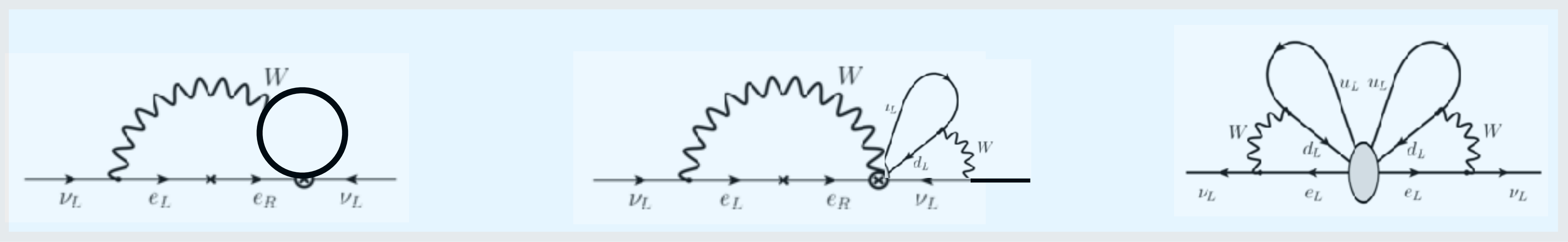
0vbb does not need to connect to current neutrino exp.

Neutrino Masses and 0vbb



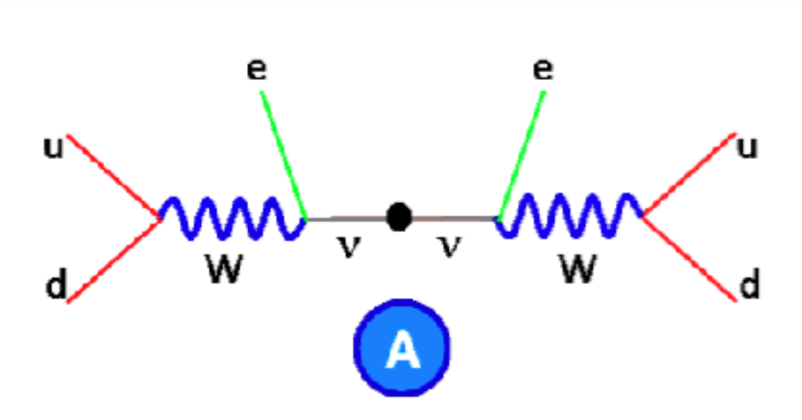


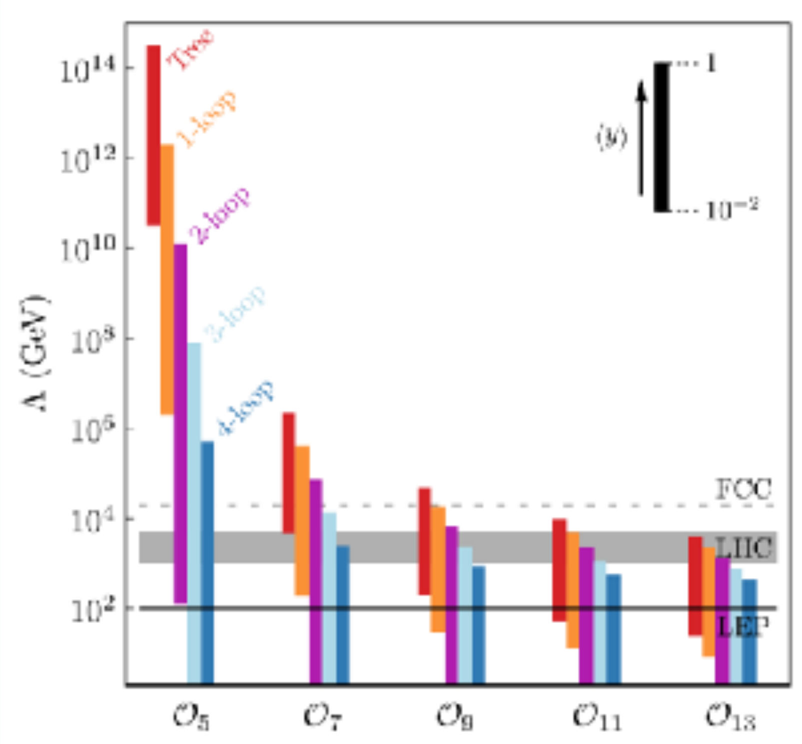


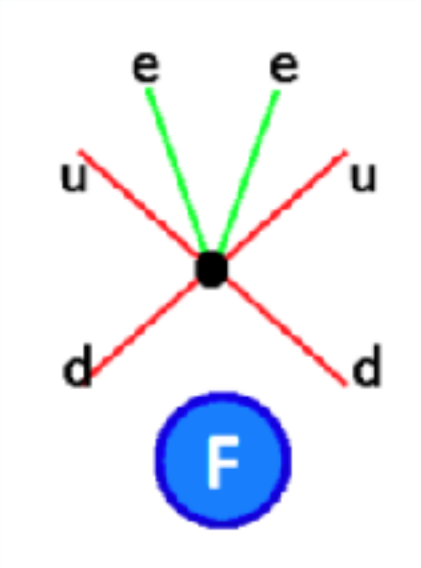


Which One Dominate 0vbb?

The higher dim operator, the lower cutoff scale



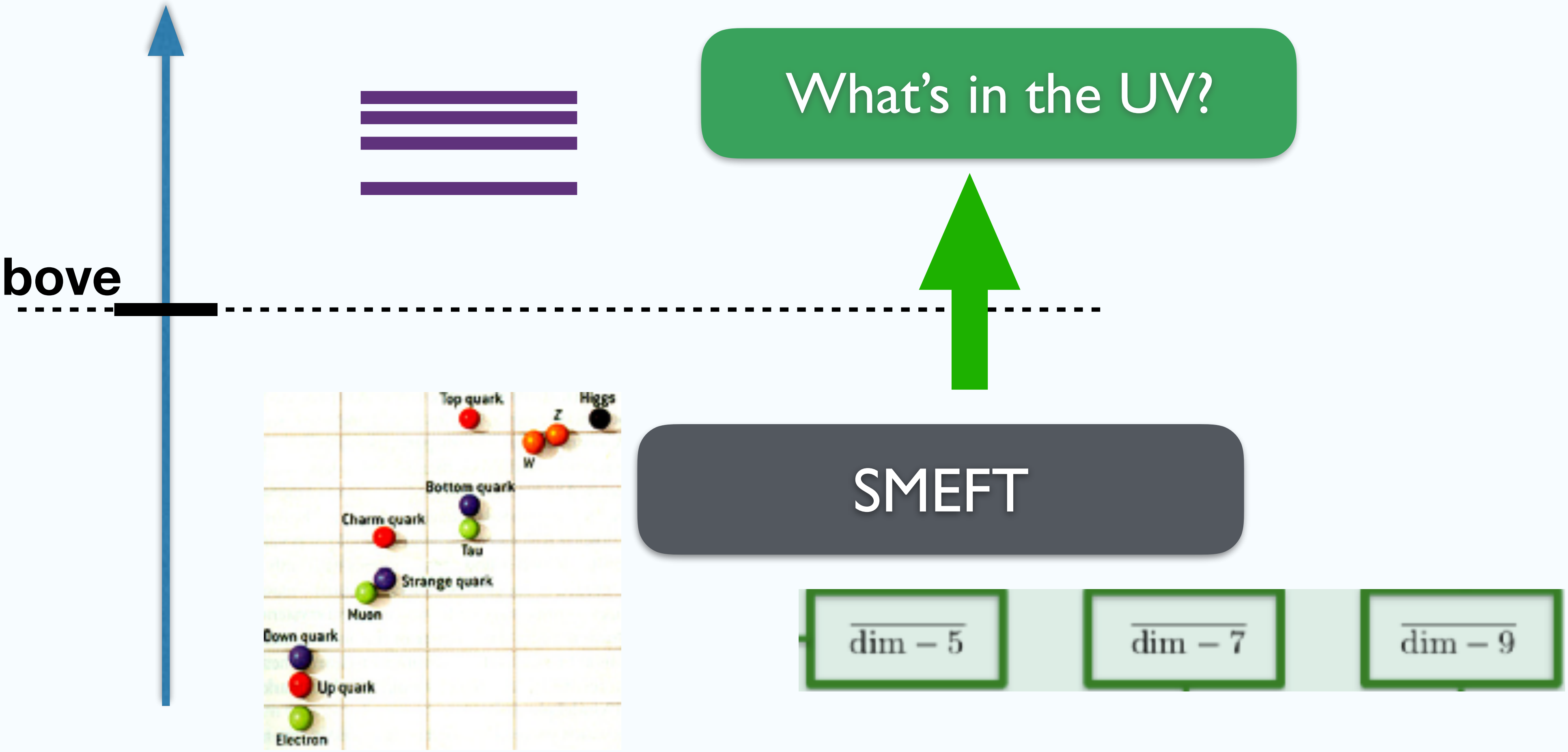




Could be comparable!

Not necessarily related to neutrino physics

What is in the UV?



TeV scale and above

What’s in the UV?

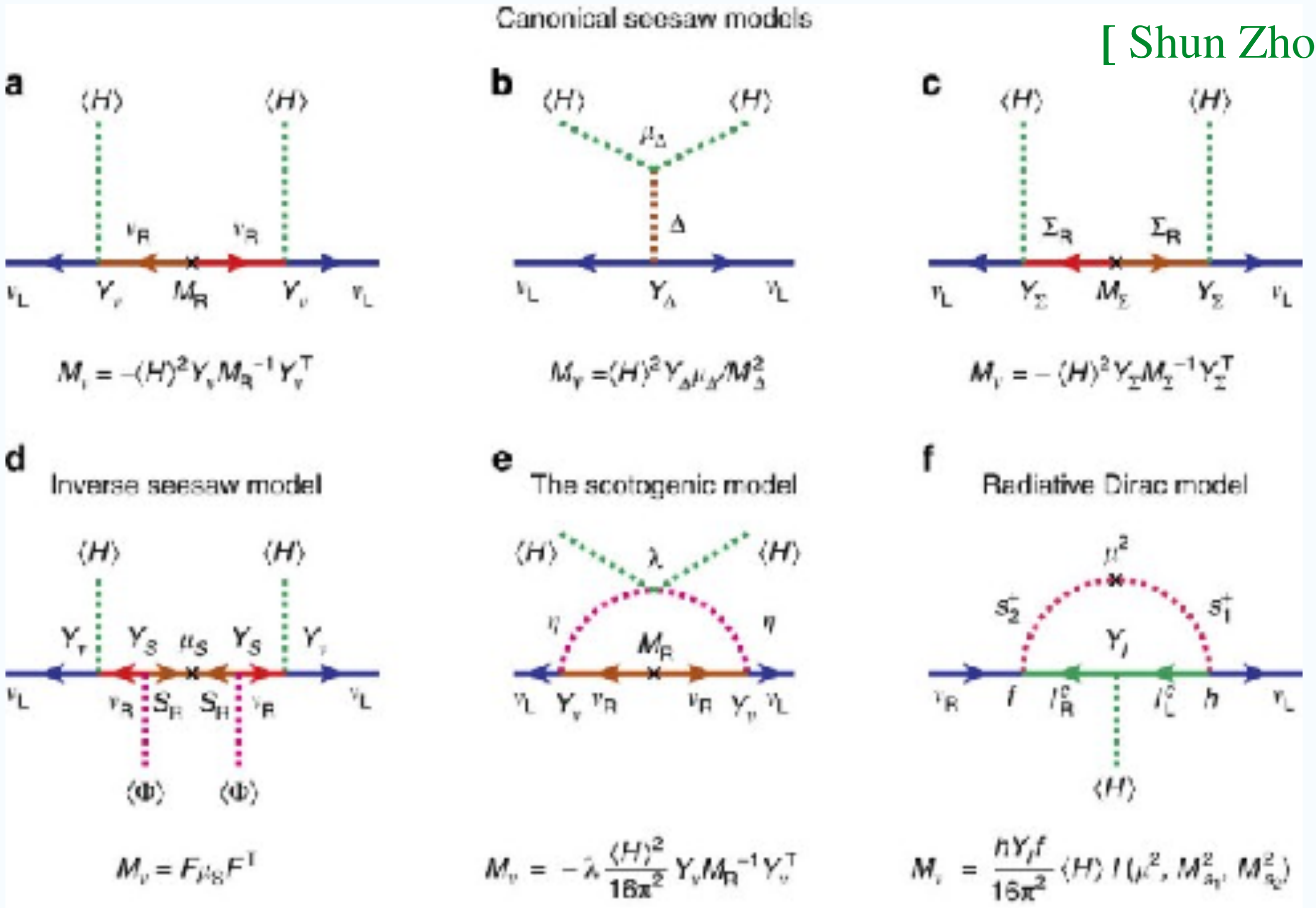
SMEFT

dim − 5

dim − 7

dim − 9

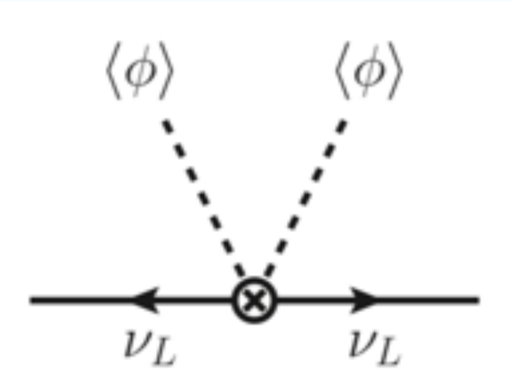
UV Realization of Nv Masses



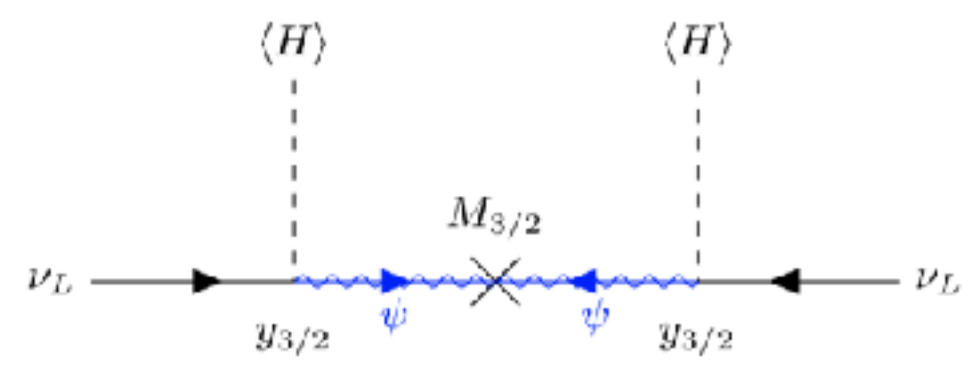
[Shun Zhou, 2016]

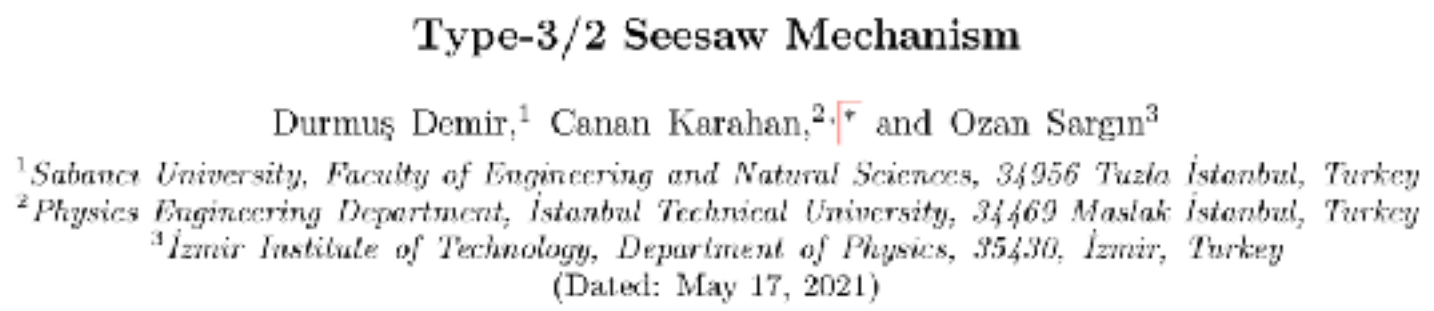
Integrate out heavy particles

Top-down approach



More UV realization?



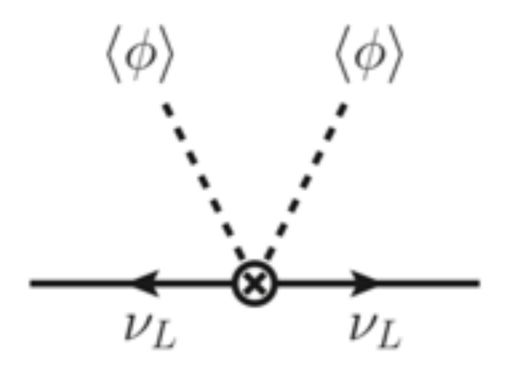


Type-3/2 Seesaw Mechanism

Durmuş Demir,[1] Canan Karahan,[2,*] and Ozan Sargın[3]

[1] *Sabancı University, Faculty of Engineering and Natural Sciences, 34956 Tuzla İstanbul, Turkey*
[2] *Physics Engineering Department, İstanbul Technical University, 34469 Maslak İstanbul, Turkey*
[3] *İzmir Institute of Technology, Department of Physics, 35430, İzmir, Turkey*

(Dated: May 17, 2021)



Bottom-up Approach

J-Basis Operator: Partial Wave

$$\mathcal{Y}\left[\young(pr)\right]\epsilon_{ik}\epsilon_{jl}\epsilon_{\alpha\beta}L_p^{\alpha i}L_r^{\beta j}H^kH^l$$

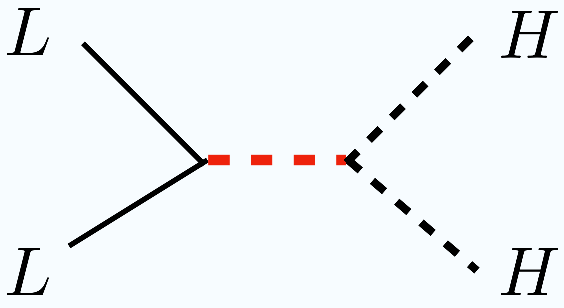
Partial wave expansion on operator

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

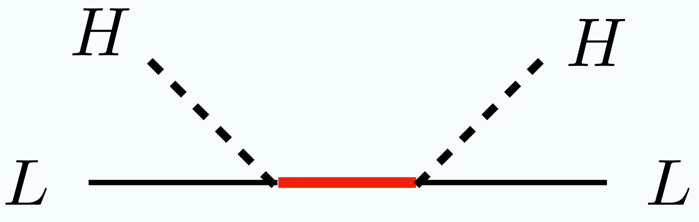
$$\mathbf{W}^2 = \frac{s}{8}\sum_{i,j=1}^{N}\left(\langle i,\partial_j\rangle\langle j,\partial_i\rangle + [i,\partial_j][j,\partial_i]\right) - \frac{1}{4}\sum_{i,j,k,l}[i,j]\langle j,\partial_k\rangle\langle k,l\rangle[l,\partial_i]$$

$LL \to HH$ channel

$LH \to LH$ channel



$J = 0$



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

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

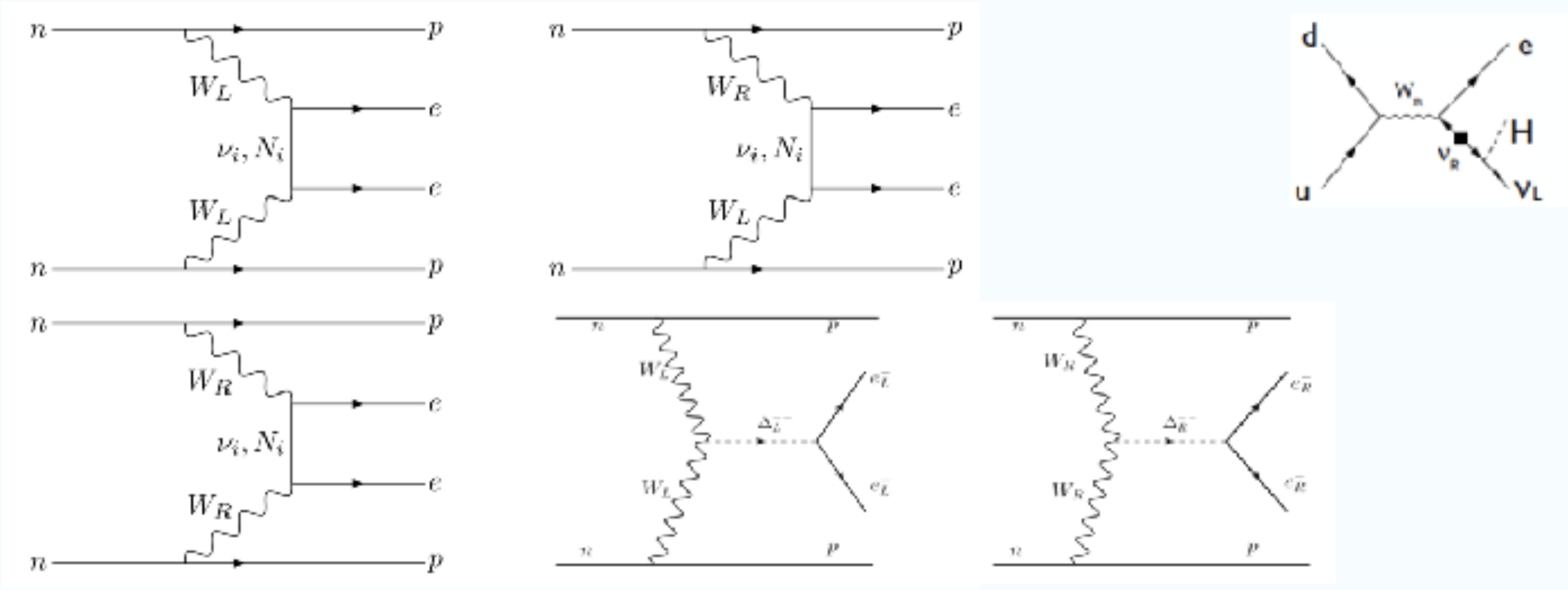
Type-I and III: SU(2) **single** and **triplet**

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

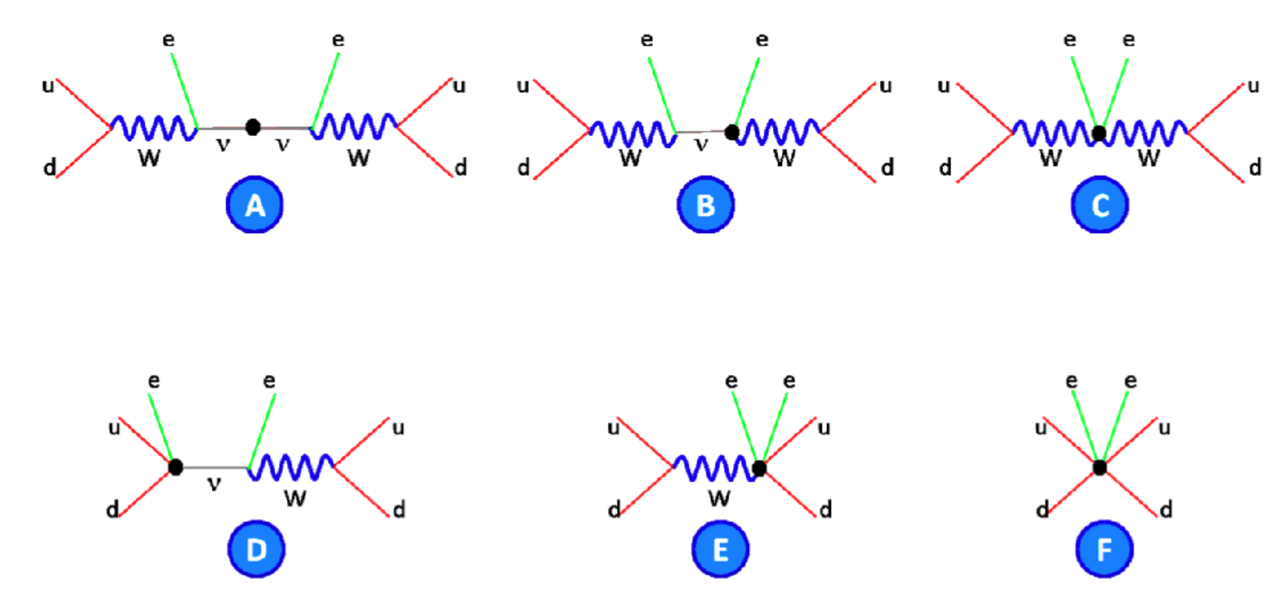
j-basis	Model
$\mathcal{O}^{(1/2,\mathbf{1})}_{HL\to HL} = \mathcal{O}^S + \mathcal{O}^A$	type I
$\mathcal{O}^{(1/2,\mathbf{3})}_{HL\to HL} = \mathcal{O}^S - 3\mathcal{O}^A$	type III

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

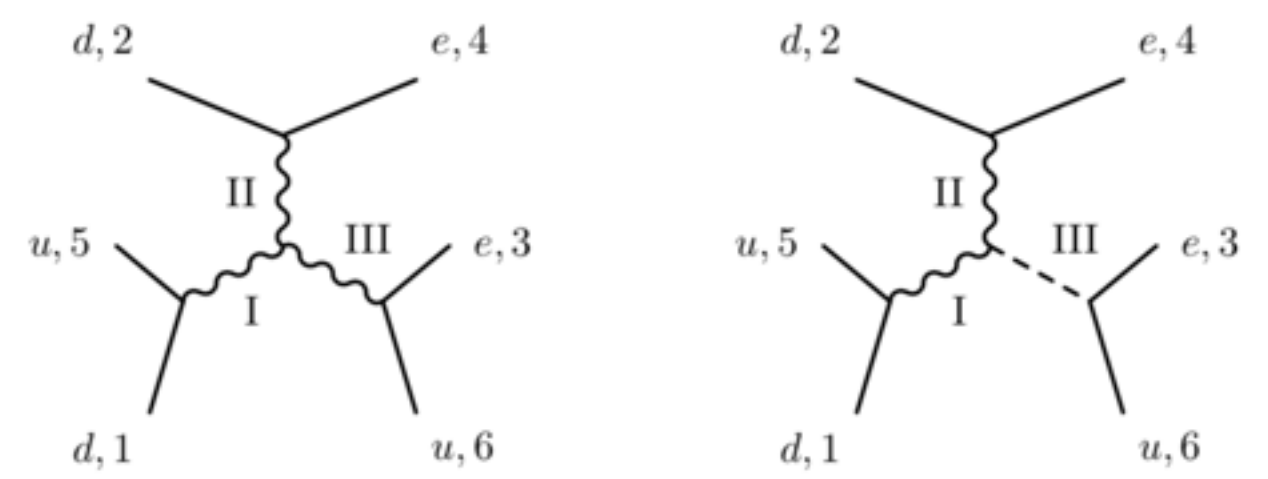
UV Realization of 0vbb

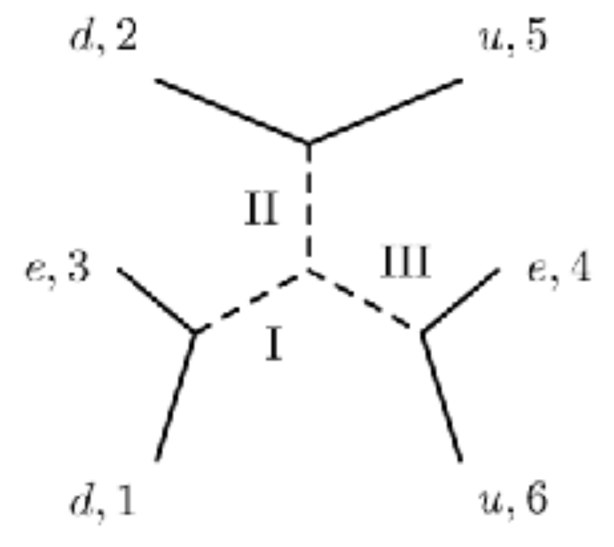


Integrate out heavy particles

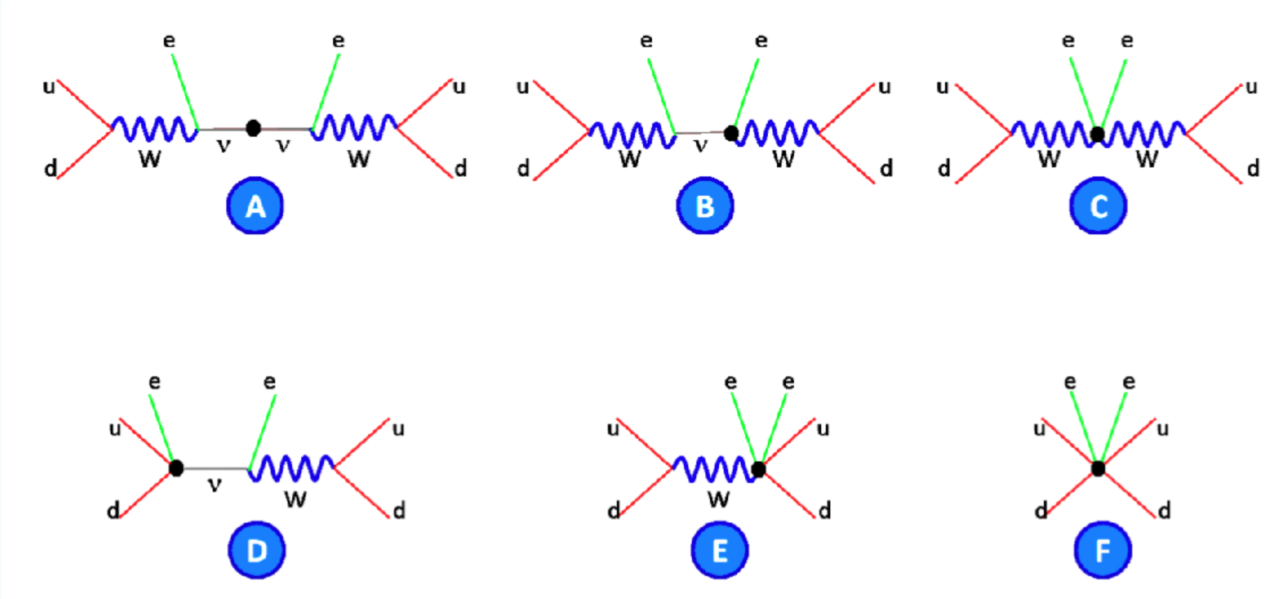


More UV Realizations





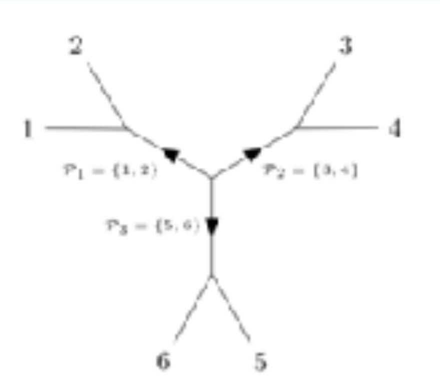
$$\mathbf{W}^2\mathcal{B}^J = -sJ(J+1)\mathcal{B}^J$$

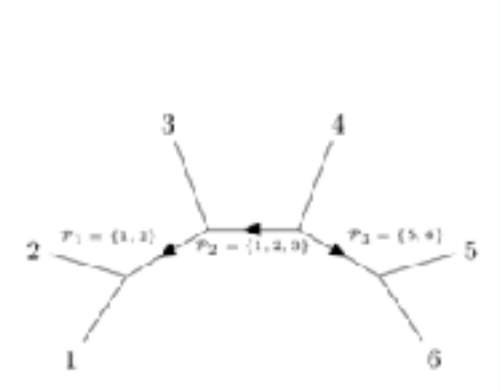


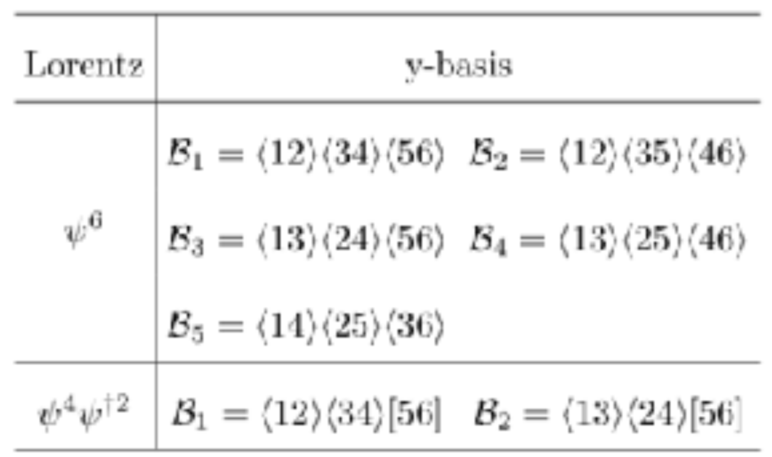
Example

Dim-9 operators:

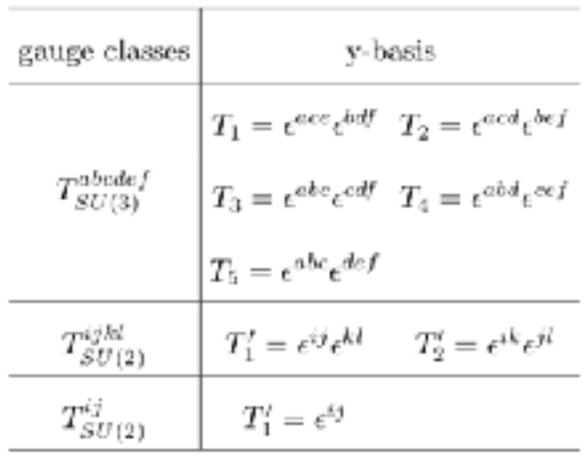
$T^{abcdef}_{SU(3)}\psi^{\dagger 6}$ $T^{ijkl}_{SU(2)}\psi^4\psi^{\dagger 2}$



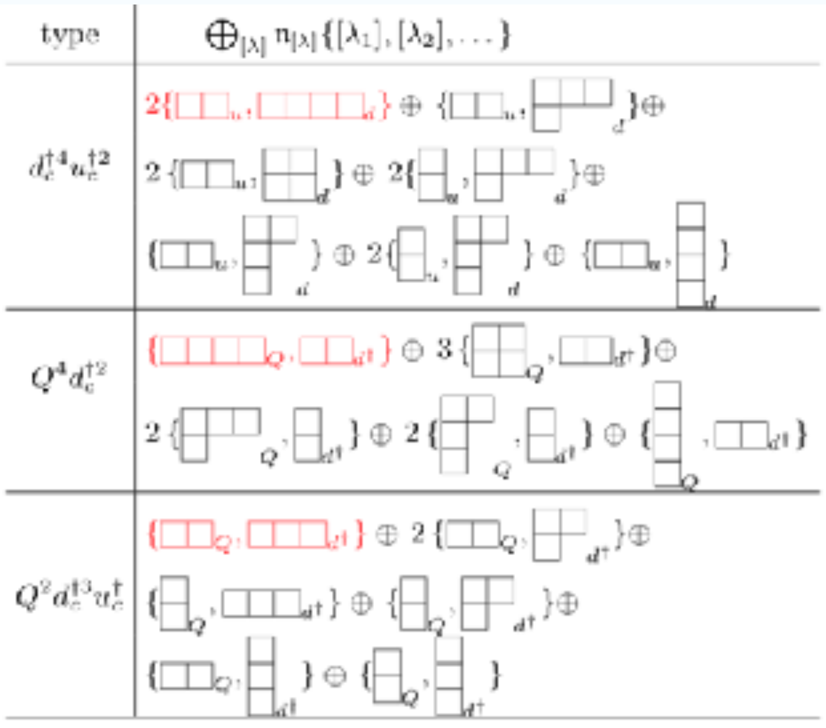




Lorentz	y-basis
ψ^6	$\mathcal{B}_1=\langle12\rangle\langle34\rangle\langle56\rangle$ $\mathcal{B}_2=\langle12\rangle\langle35\rangle\langle46\rangle$ $\mathcal{B}_3=\langle13\rangle\langle24\rangle\langle56\rangle$ $\mathcal{B}_4=\langle13\rangle\langle25\rangle\langle46\rangle$ $\mathcal{B}_5=\langle14\rangle\langle25\rangle\langle36\rangle$
$\psi^4\psi^{\dagger 2}$	$\mathcal{B}_1=\langle12\rangle\langle34\rangle[56]$ $\mathcal{B}_2=\langle13\rangle\langle24\rangle[56]$



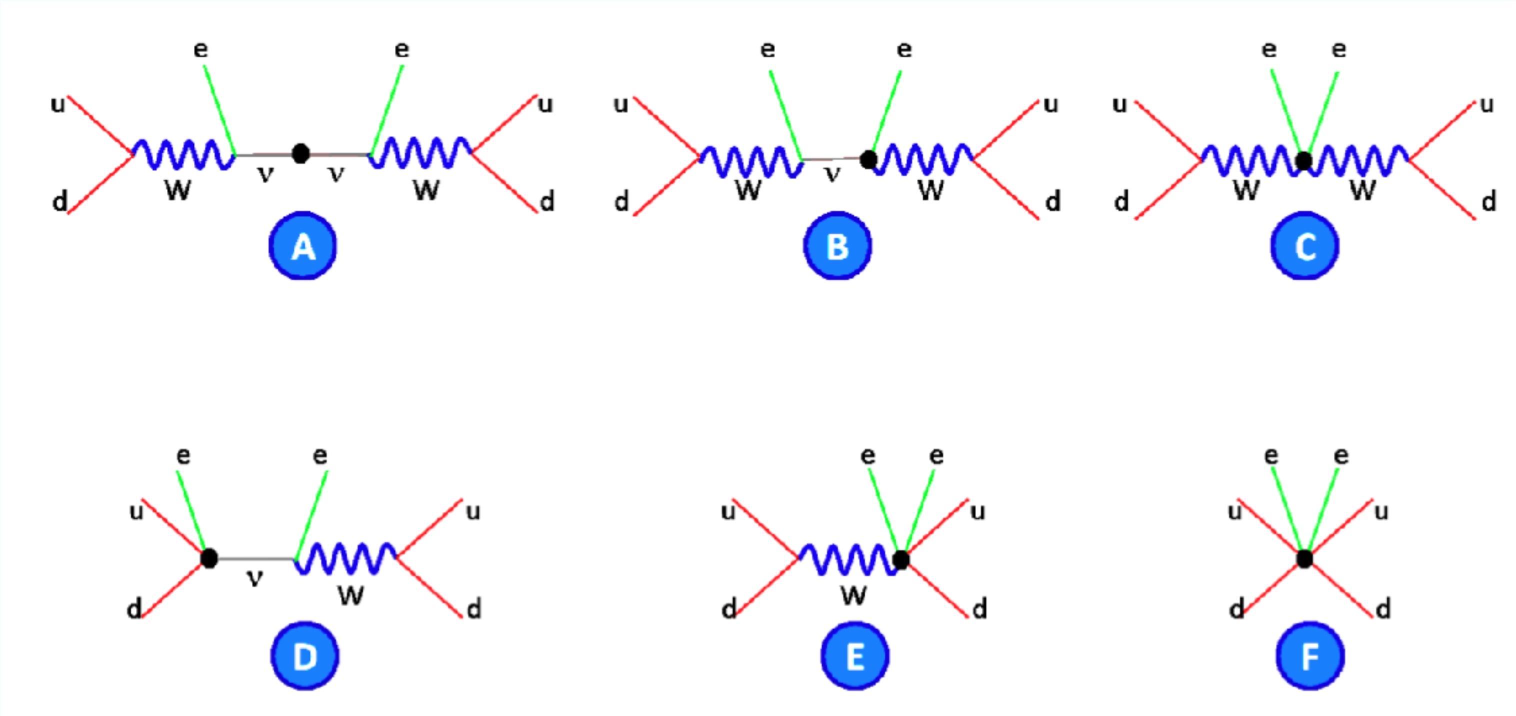
gauge classes	y-basis
$T^{abcdef}_{SU(3)}$	$T_1=\epsilon^{ace}\epsilon^{bdf}$ $T_2=\epsilon^{acd}\epsilon^{bef}$ $T_3=\epsilon^{abe}\epsilon^{cdf}$ $T_4=\epsilon^{abd}\epsilon^{cef}$ $T_5=\epsilon^{abc}\epsilon^{def}$
$T^{ijkl}_{SU(2)}$	$T'_1=\epsilon^{ij}\epsilon^{kl}$ $T'_2=\epsilon^{ik}\epsilon^{jl}$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

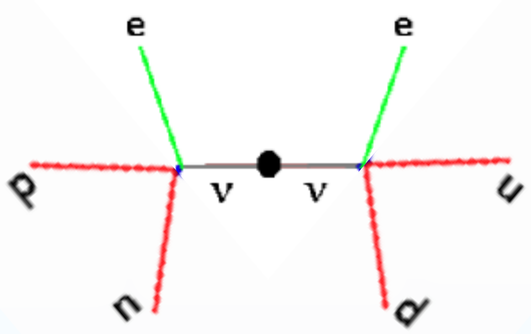


LEFT

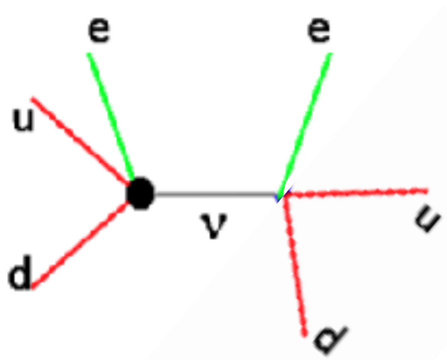
Nucleon currents and weak sources

LEFT Related Operators

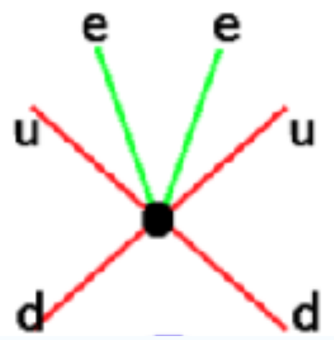




Dim-3

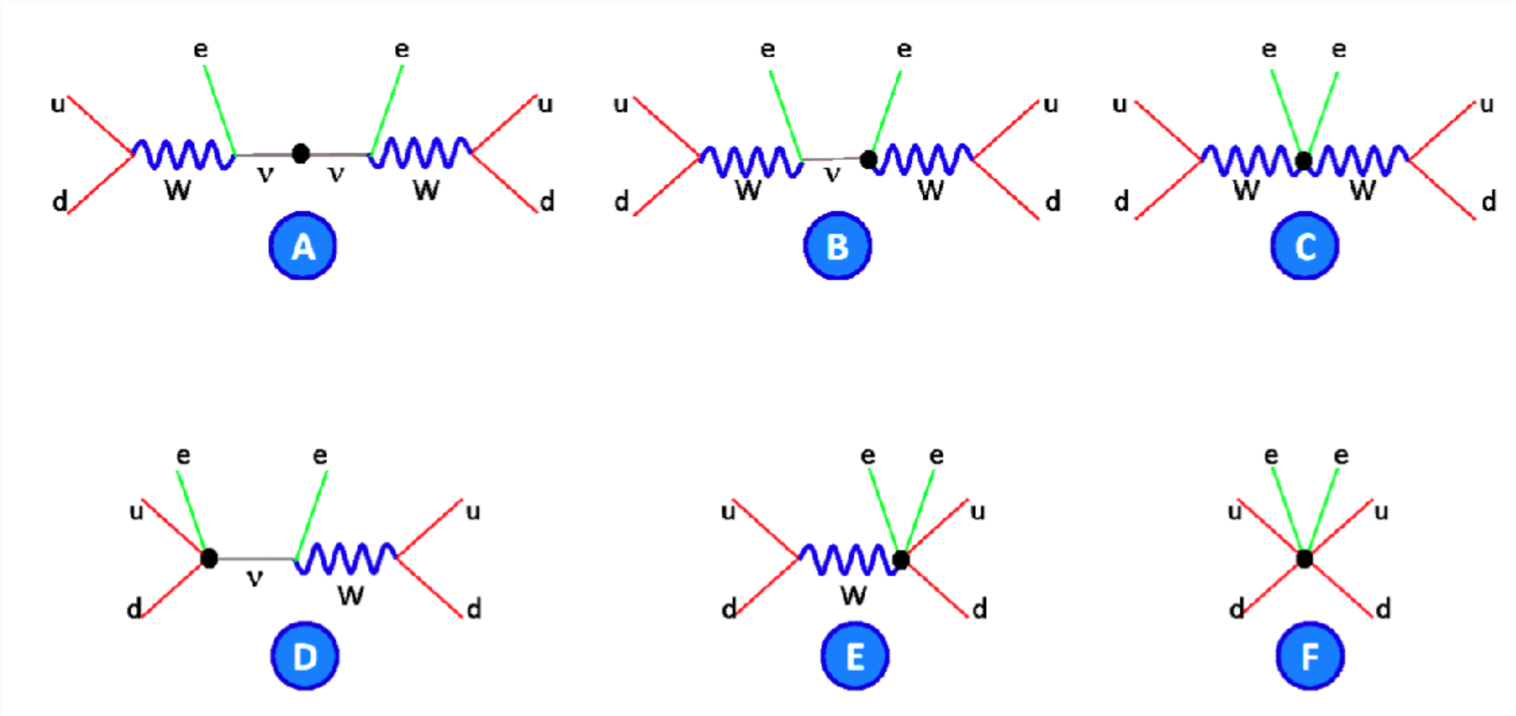


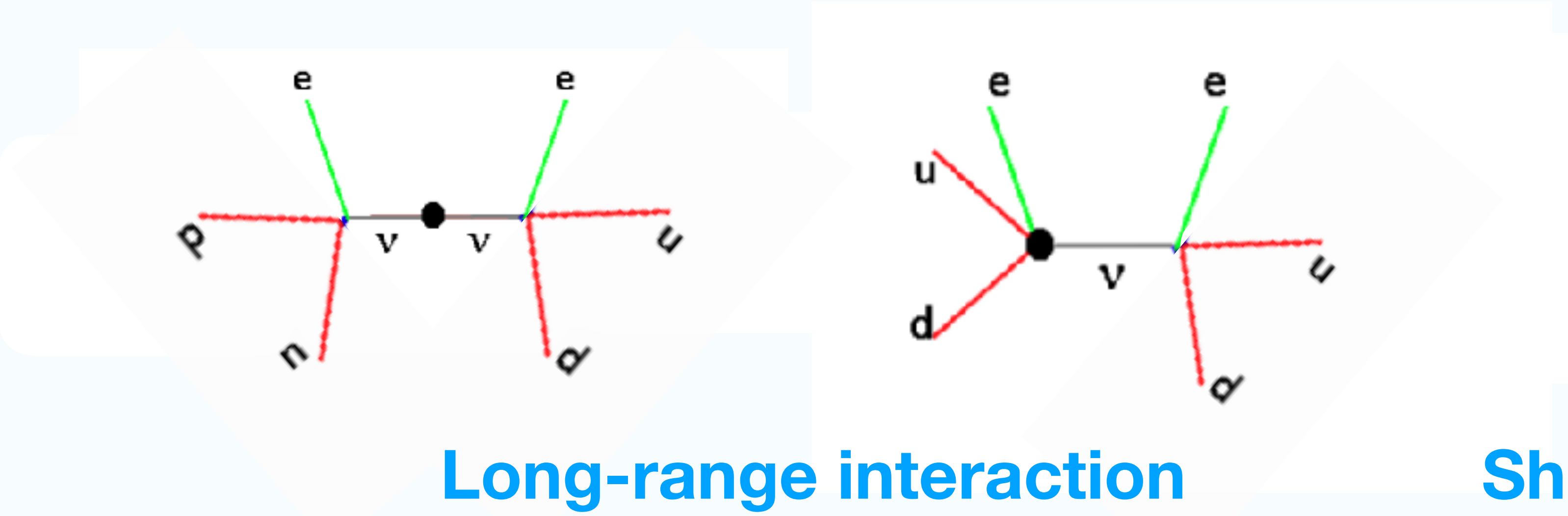
Dim-6, 7

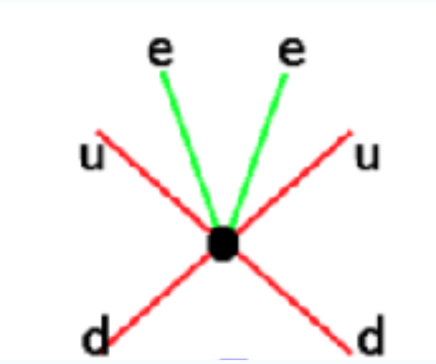


Dim-9

LEFT Related Operators







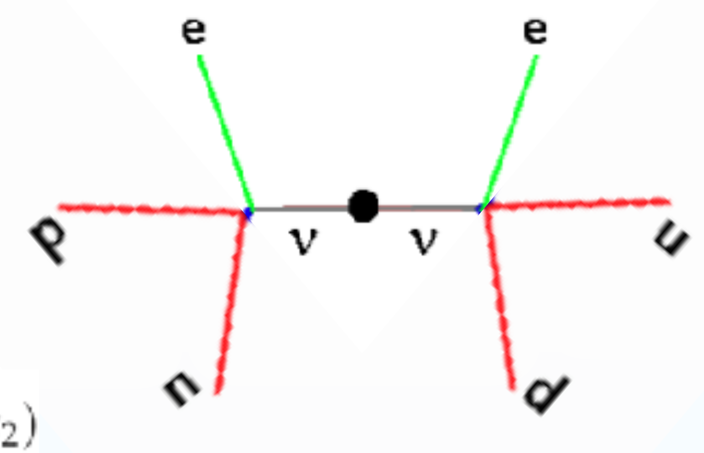
Long-range interaction

Short-range interaction

Jiang-Hao Yu

Long-Range Interaction

Standard mechanism: long-range neutrino potential



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

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

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

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

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

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

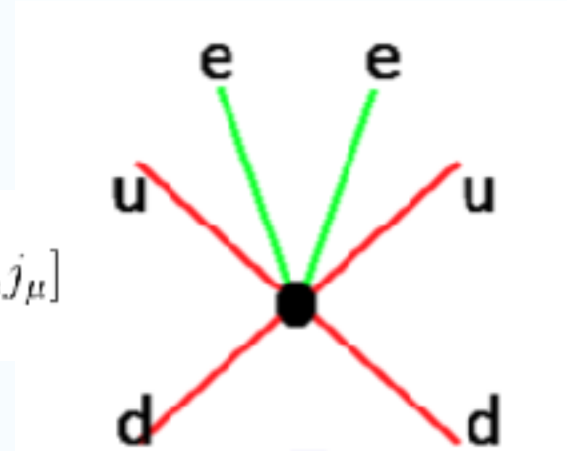
completeness relation

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

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

Short-Range Interaction

General quark currents = dim-9 LEFT operators

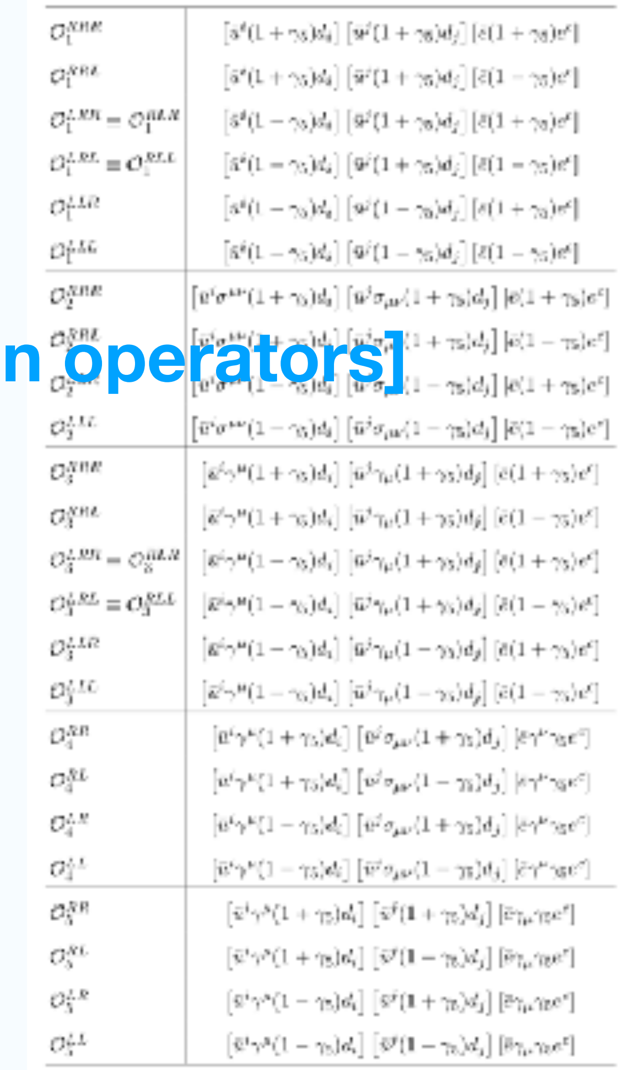


$$\mathcal{L}_{\rm SR} = \frac{G_F^2}{2m_p} \sum_{\rm chiralities} \left[\epsilon_1^{\bullet} J_{\circ} J_{\circ} j_{\circ} + \epsilon_2^{\bullet} J_{\circ}^{\mu\nu} J_{\circ\mu\nu} j_{\circ} + \epsilon_3^{\bullet} J_{\circ}^{\mu} J_{\circ\mu} j_{\circ} + \epsilon_4^{\bullet} J_{\circ}^{\mu} J_{\circ\mu\nu}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

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

Complete dim-9 LEFT 6-fermion operator basis

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



O_1^{RRR}	$[\bar{u}^i(1+\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
O_1^{RRL}	$[\bar{u}^i(1+\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$O_1^{LRR} = O_1^{RLR}$	$[\bar{u}^i(1-\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$O_1^{LRL} = O_1^{RLL}$	$[\bar{u}^i(1-\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
O_1^{LLR}	$[\bar{u}^i(1-\gamma_5)d_i]\,[\bar{u}^j(1-\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
O_1^{LLL}	$[\bar{u}^i(1-\gamma_5)d_i]\,[\bar{u}^j(1-\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
O_2^{RRR}	$[\bar{u}^i\sigma^{\mu\nu}(1+\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
O_2^{RRL}	$[\bar{u}^i\sigma^{\mu\nu}(1+\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
O_2^{LLR}	$[\bar{u}^i\sigma^{\mu\nu}(1-\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1-\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
O_2^{LLL}	$[\bar{u}^i\sigma^{\mu\nu}(1-\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1-\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
O_3^{RRR}	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
O_3^{RRL}	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
$O_3^{LRR} = O_3^{RLR}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1+\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
$O_3^{LRL} = O_3^{RLL}$	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1+\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
O_3^{LLR}	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1-\gamma_5)d_j]\,[\bar{e}(1+\gamma_5)e^c]$
O_3^{LLL}	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\gamma_{\mu}(1-\gamma_5)d_j]\,[\bar{e}(1-\gamma_5)e^c]$
O_4^{RR}	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1+\gamma_5)d_j]\,[\bar{e}\gamma^{\nu}\gamma_5 e^c]$
O_4^{RL}	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1-\gamma_5)d_j]\,[\bar{e}\gamma^{\nu}\gamma_5 e^c]$
O_4^{LR}	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1+\gamma_5)d_j]\,[\bar{e}\gamma^{\nu}\gamma_5 e^c]$
O_4^{LL}	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j\sigma_{\mu\nu}(1-\gamma_5)d_j]\,[\bar{e}\gamma^{\nu}\gamma_5 e^c]$
O_5^{RR}	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}\gamma_{\mu}\gamma_5 e^c]$
O_5^{RL}	$[\bar{u}^i\gamma^{\mu}(1+\gamma_5)d_i]\,[\bar{u}^j(1-\gamma_5)d_j]\,[\bar{e}\gamma_{\mu}\gamma_5 e^c]$
O_5^{LR}	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j(1+\gamma_5)d_j]\,[\bar{e}\gamma_{\mu}\gamma_5 e^c]$
O_5^{LL}	$[\bar{u}^i\gamma^{\mu}(1-\gamma_5)d_i]\,[\bar{u}^j(1-\gamma_5)d_j]\,[\bar{e}\gamma_{\mu}\gamma_5 e^c]$

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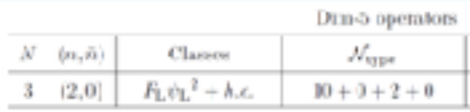
A neutrinoless double beta decay master formula from effective field theory

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

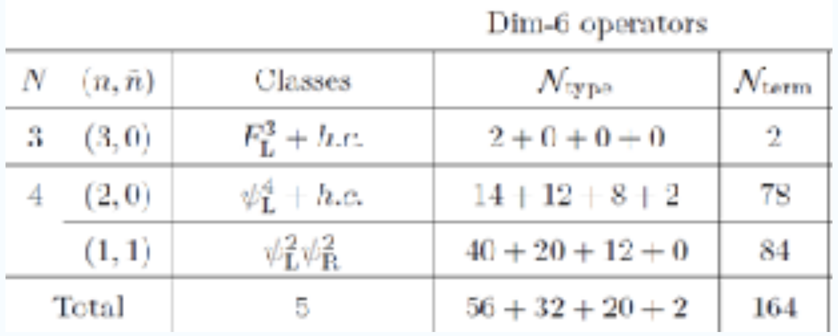


Dim-5 operators

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



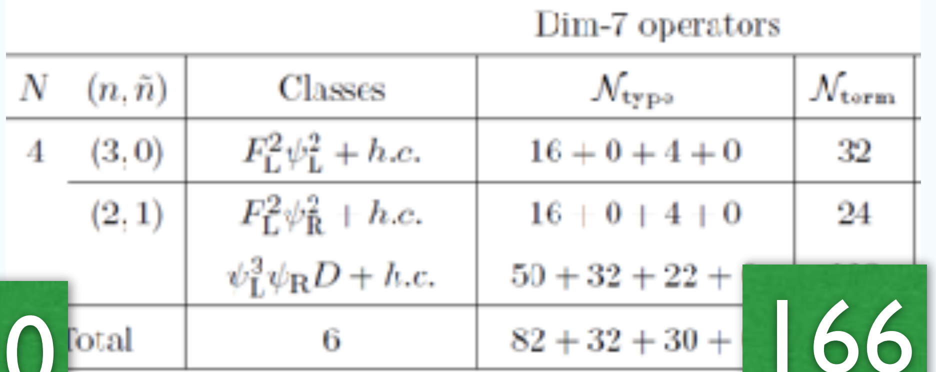
Dim-6 operators

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]

120

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	$82+32+30+$	

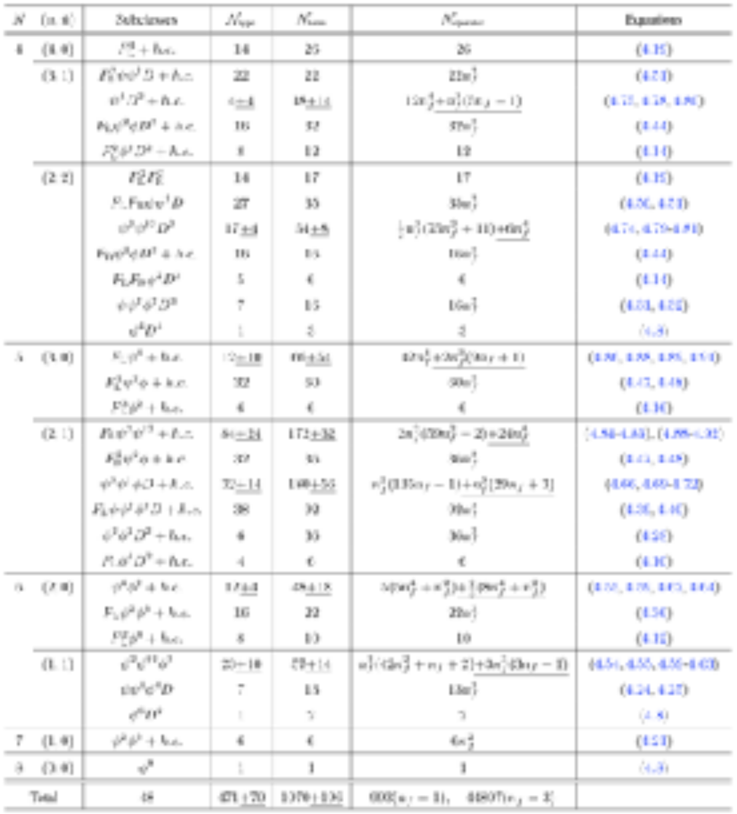
166

[Liao, Ma, Wang, 2020]

Dimension-8

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

[Murphy, 2020]



783

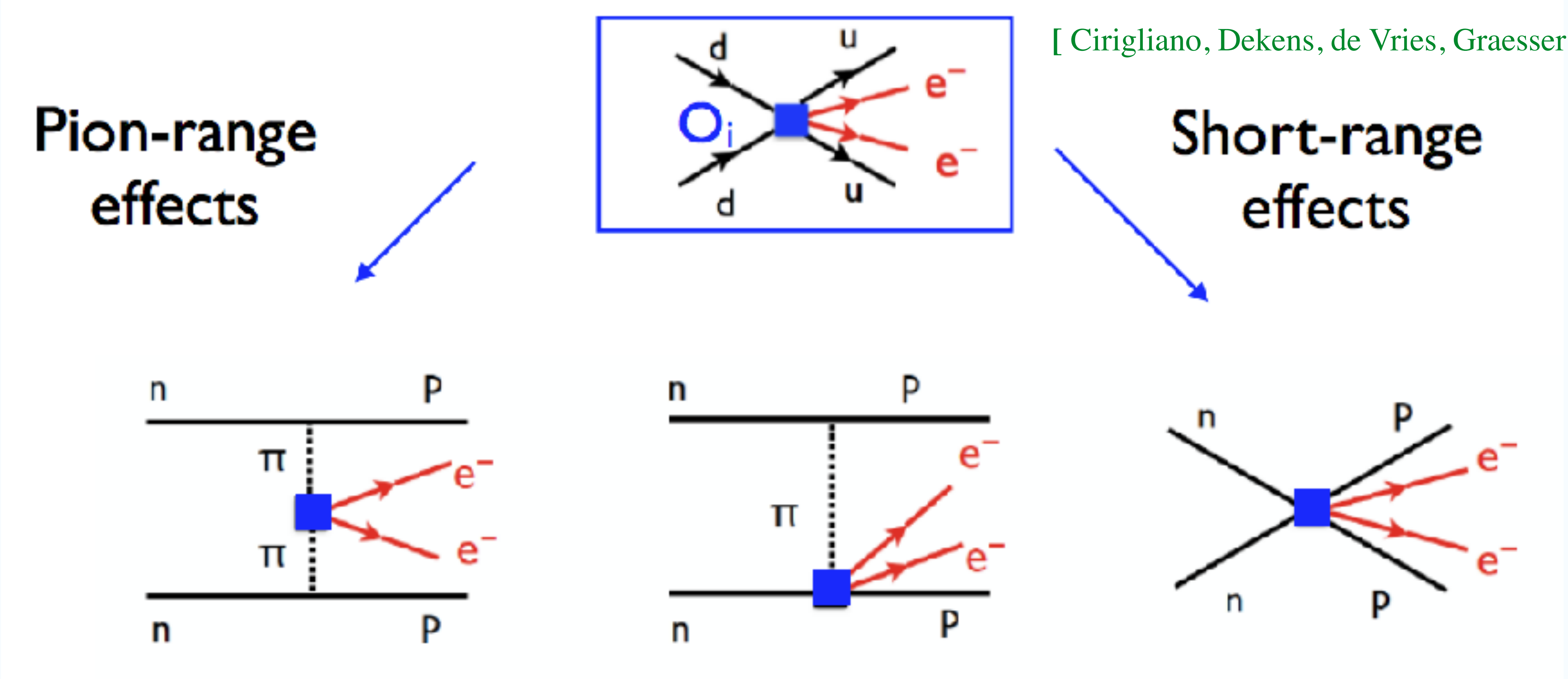
Dimension-9

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

3774

ChiPT: Quark to Nucleon

Chiral perturbation theory + Heavy baryon EFT + LNV external source



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

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

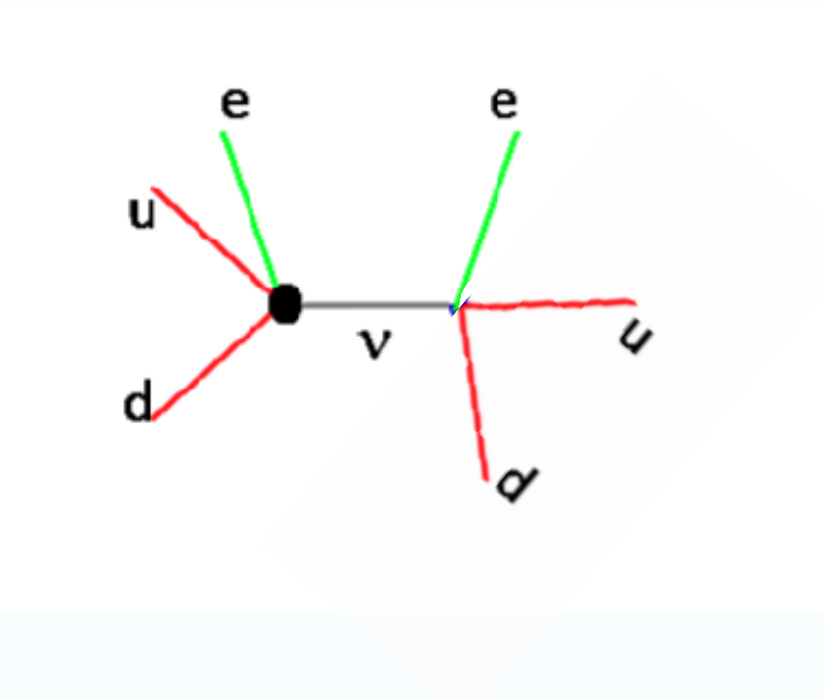
Jiang-Hao Yu

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

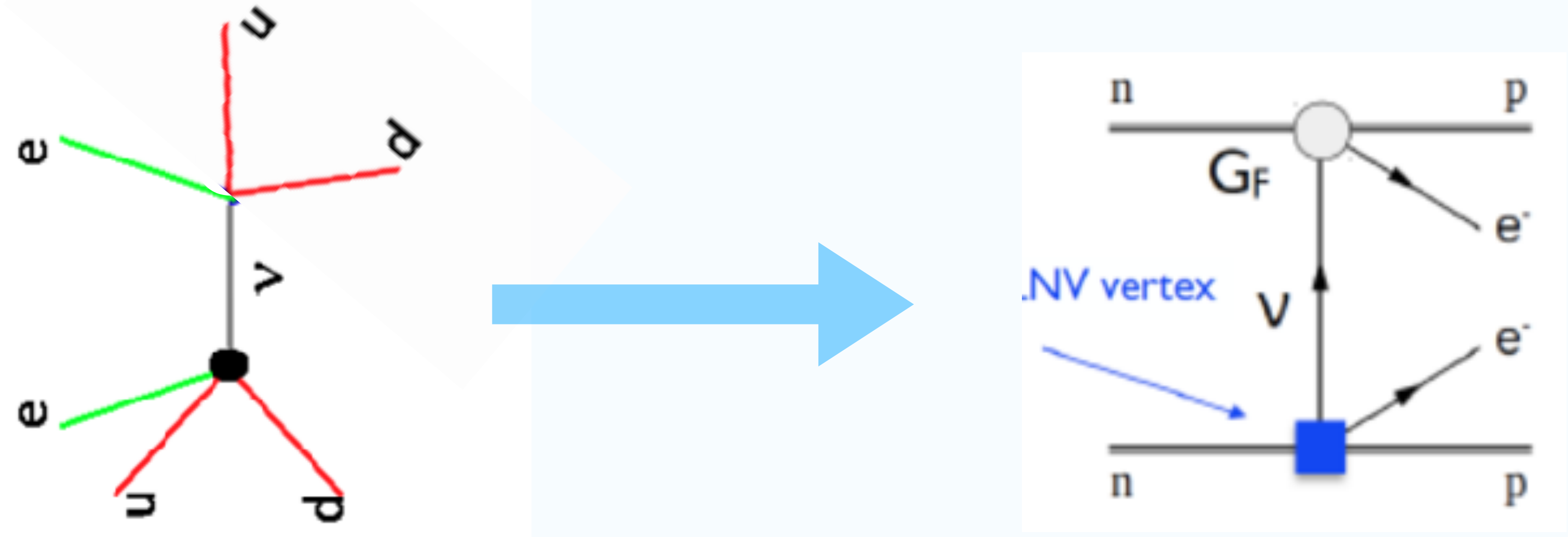
$$\begin{aligned} \mathcal{L}^{(6)}_{\Delta L=2} &= \frac{2G_F}{\sqrt{2}}\Big\{ C^{(6)}_{\text{VL},ij}\, \bar{u}_L\gamma^{\mu}d_L\, \bar{e}_{R,i}\,\gamma_{\mu}\, C\bar{\nu}^T_{L,j} + C^{(6)}_{\text{VR},ij}\, \bar{u}_R\gamma^{\mu}d_R\, \bar{e}_{R,i}\,\gamma_{\mu}\, C\bar{\nu}^T_{L,j} \qquad (7) \\ &\quad + C^{(6)}_{\text{SR},ij}\, \bar{u}_L d_R\, \bar{e}_{L,i}\, C\bar{\nu}^T_{L,j} + C^{(6)}_{\text{SL},ij}\, \bar{u}_R d_L\, \bar{e}_{L,i}\, C\bar{\nu}^T_{L,j} + C^{(6)}_{\text{T},ij}\, \bar{u}_L\sigma^{\mu\nu}d_R\, \bar{e}_{L,i}\sigma_{\mu\nu}\, C\bar{\nu}^T_{L,j} \Big\} + \text{h.c.} \\ \mathcal{L}^{(7)}_{\Delta L=2} &= \frac{2G_F}{\sqrt{2}v}\Big\{ C^{(7)}_{\text{VL},ij}\, \bar{u}_L\gamma^{\mu}d_L\, \bar{e}_{L,i}\, C\, i\overleftrightarrow{\partial}_{\mu}\bar{\nu}^T_{L,j} + C^{(7)}_{\text{VR},ij}\, \bar{u}_R\gamma^{\mu}d_R\, \bar{e}_{L,i}\, C i\overleftrightarrow{\partial}_{\mu}\bar{\nu}^T_{L,j} \Big\} + \text{h.c.} \qquad (8) \end{aligned}$$

No dim-9 SMEFT 4-fermion operator!

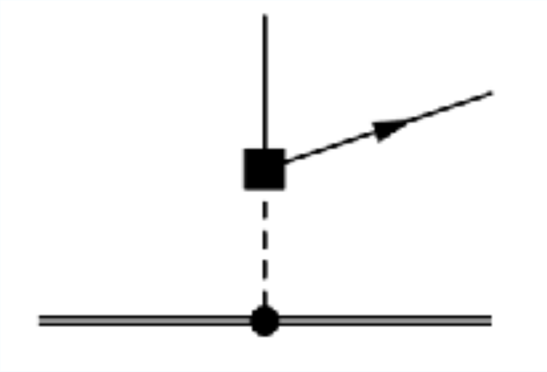
Jiang-Hao Yu

ChiPT: Quark to Nucleon

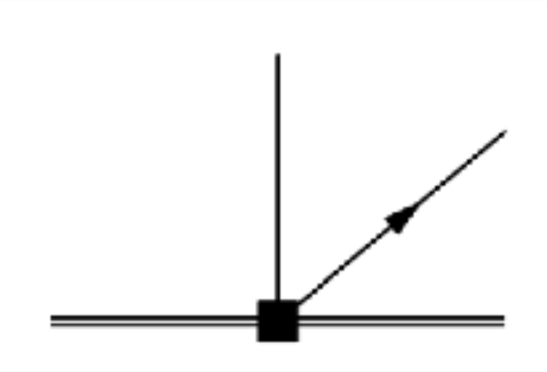
Chiral perturbation theory + Heavy baryon EFT + LNV external source



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

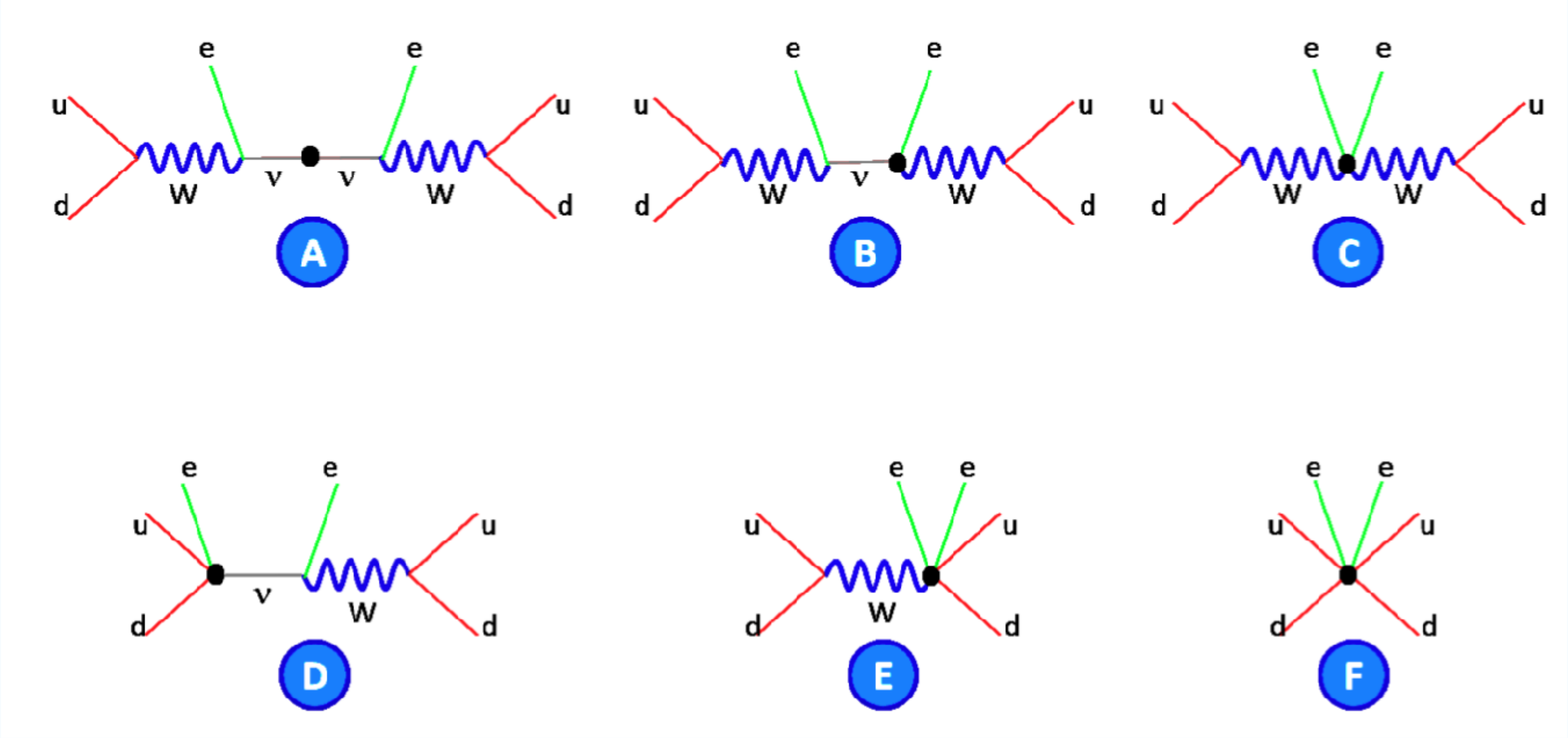


$\mathcal{L}_{\pi N}$

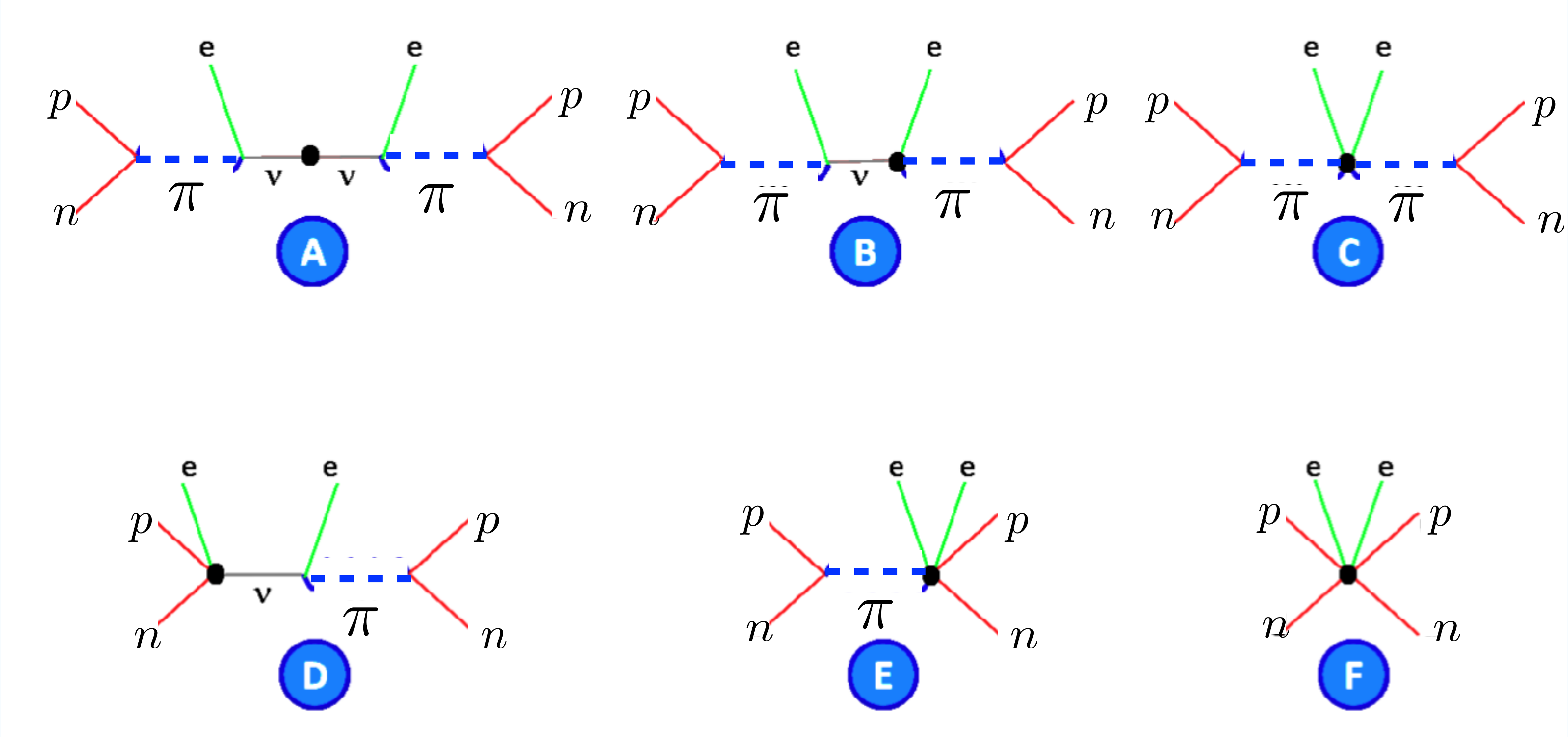


$\mathcal{L}_{\pi N}$

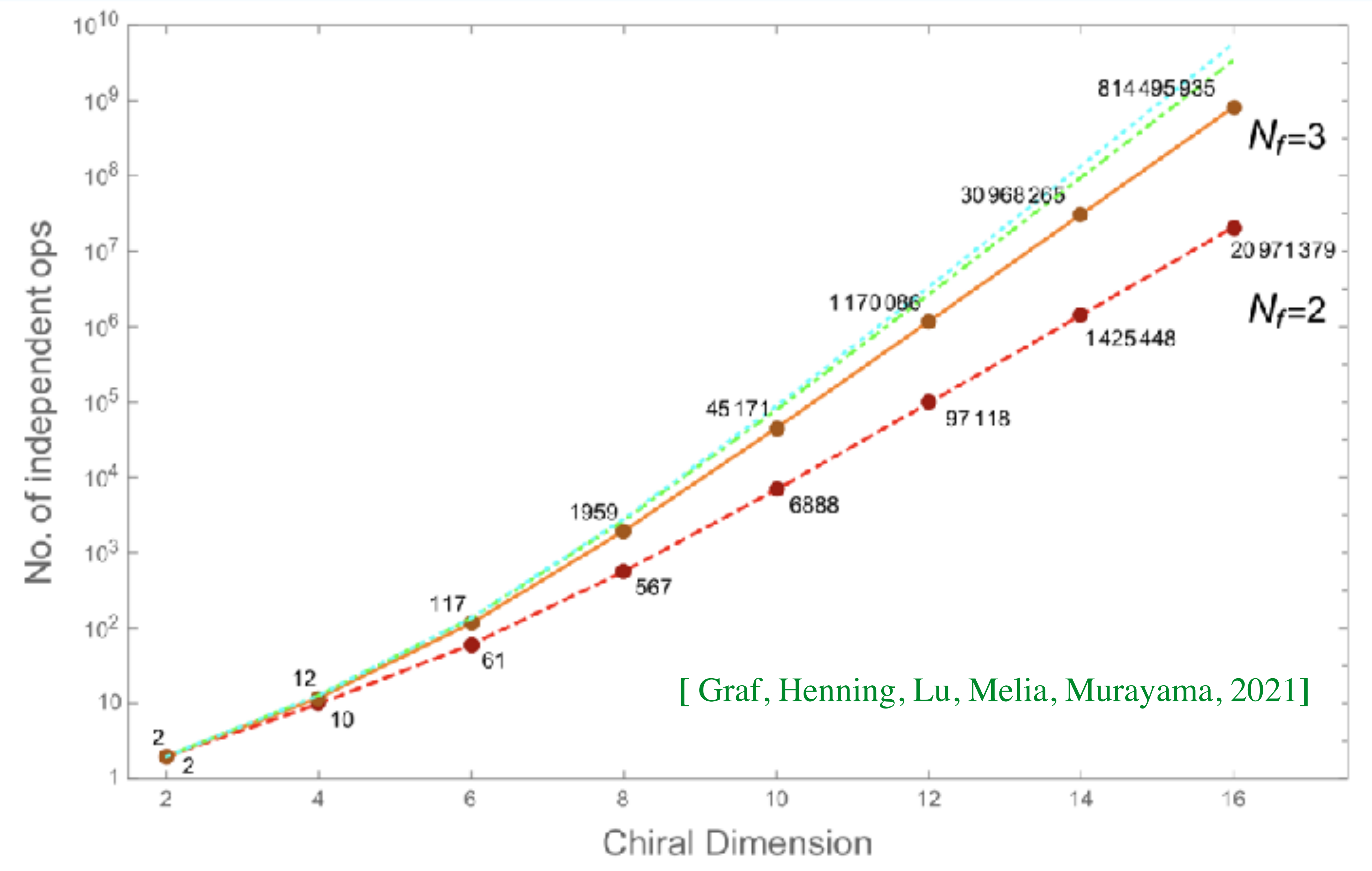
0vbb at SMEFT



0vbb at ChiPT



ChiPT Lagrangian



[Graf, Henning, Lu, Melia, Murayama, 2021]

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

Fettes, Meisner, Mojzis, Steininger, 2000

Girlanda, Pastore, Schiavilla, Viviani, 2010

Nν Potential Master Formula

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

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

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

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

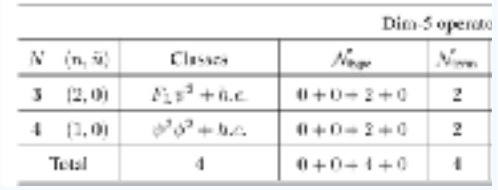
$$\begin{aligned} V_6(\mathbf{q}^2) = \quad & \tau^{(1)+}\tau^{(2)+}\; 4 g_A^2 G_F^2 V_{ud} \left(B \left(C_{\rm SL}^{(6)} - C_{\rm SR}^{(6)} \right) + \frac{m_\pi^2}{v} \left(C_{\rm VL}^{(7)} - C_{\rm VR}^{(7)} \right) \right) \frac{1}{\mathbf{q}^2}\, \bar{u}(k_1) P_R C \bar{u}^T(k_2) \\ & \left\{ \boldsymbol{\sigma}^{(1)}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

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

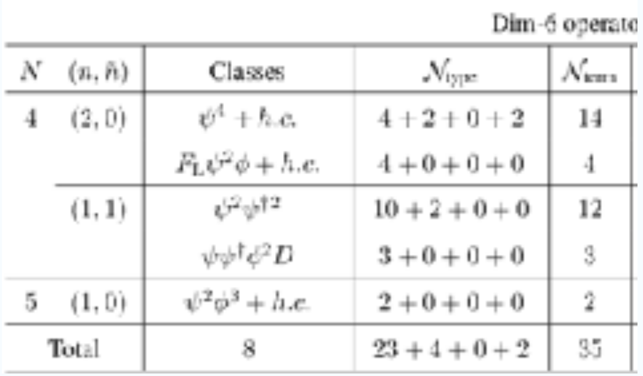


Dim-5 operato

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
3	(2,0)	$F_L\psi^2+h.c.$	$0+0+2+0$	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
		$F_L\psi^2\phi+h.c.$	$4+0+0+0$	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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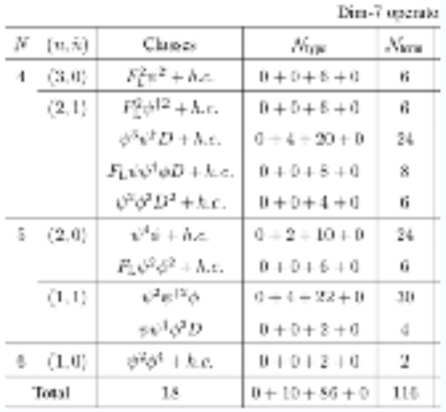
[Aguila, Bar-Shalom, Soni, Wudka, 2009]

Dimension-7



Dim-7 operato

N	$(n,\tilde{n})$	Classes	$\mathcal{N}_{\text{type}}$	$\mathcal{N}_{\text{term}}$
4	(3,0)	$F_L^2\psi^2+h.c.$	$0+0+6+0$	6
	(2,1)	$F_L^2\psi^{\dagger 2}+h.c.$	$0+0+6+0$	6
		$\psi^3\psi^\dagger D+h.c.$	$0+4+20+0$	24
		$F_L\psi\psi^\dagger\phi D+h.c.$	$0+0+8+0$	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
		$F_L\psi^2\phi^2+h.c.$	$0+0+6+0$	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	$0+10+56+0$	116

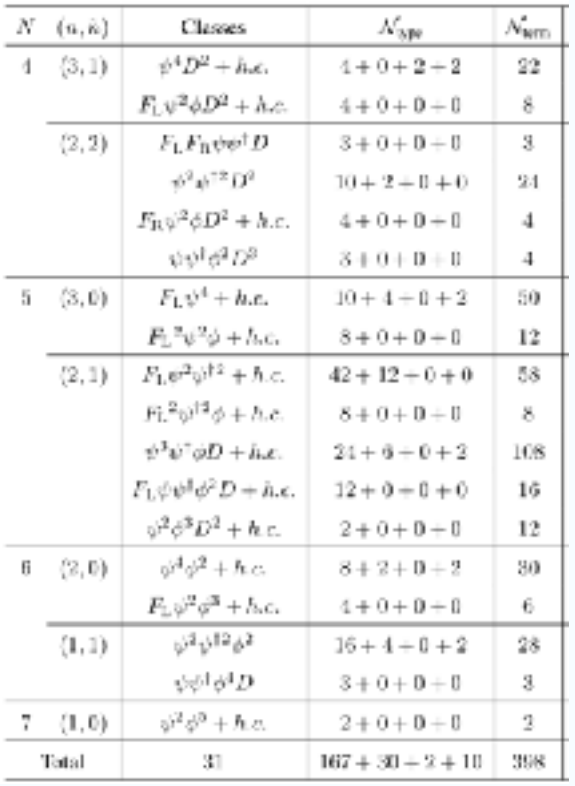
80

[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
		$F_L\psi^2\phi D^2+h.c.$	$4+0+0+0$	8
	(2,2)	$F_L F_R\psi\psi^\dagger D$	$3+0+0+0$	3
		$\psi^2\psi^{\dagger 2}D^2$	$10+2+0+0$	24
		$F_R\psi^2\phi D^2+h.c.$	$4+0+0+0$	4
		$\psi\psi^\dagger\phi^2 D^3$	$3+0+0+0$	4
5	(3,0)	$F_L\psi^4+h.c.$	$10+4+0+2$	50
		$F_L^2\psi^2\phi+h.c.$	$8+0+0+0$	12
	(2,1)	$F_L\psi^2\psi^{\dagger 2}+h.c.$	$42+12+0+0$	58
		$F_L^2\psi^{\dagger 2}\phi+h.c.$	$8+0+0+0$	8
		$\psi^3\psi^\dagger\phi D+h.c.$	$24+6+0+2$	108
		$F_L\psi\psi^\dagger\phi^2 D+h.c.$	$12+0+0+0$	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
		$F_L\psi^2\phi^3+h.c.$	$4+0+0+0$	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

323

Dimension-9

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

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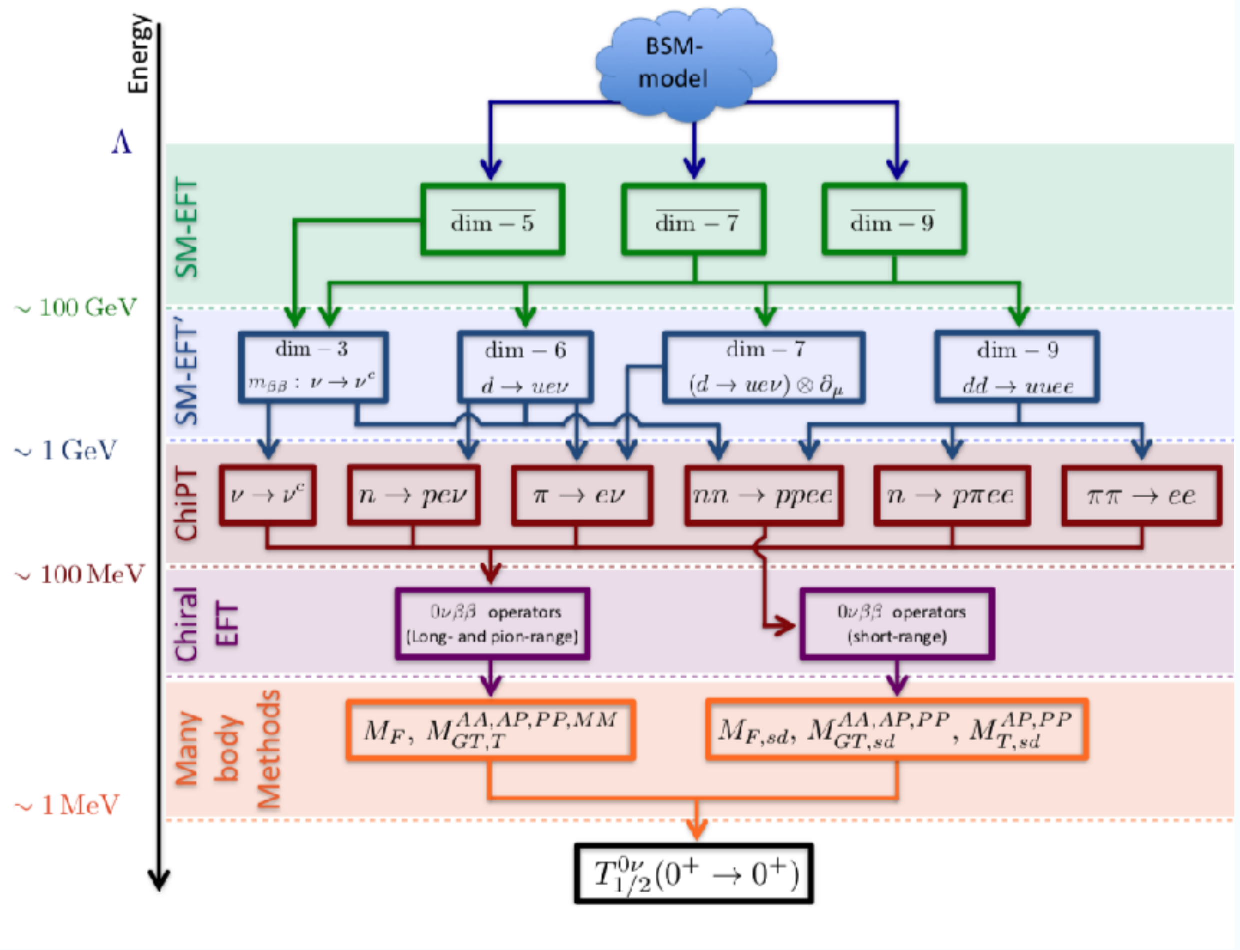
Jiang-Hao Yu

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!