$0\nu\beta\beta$ in Effective Field Theory

Wouter Dekens

with

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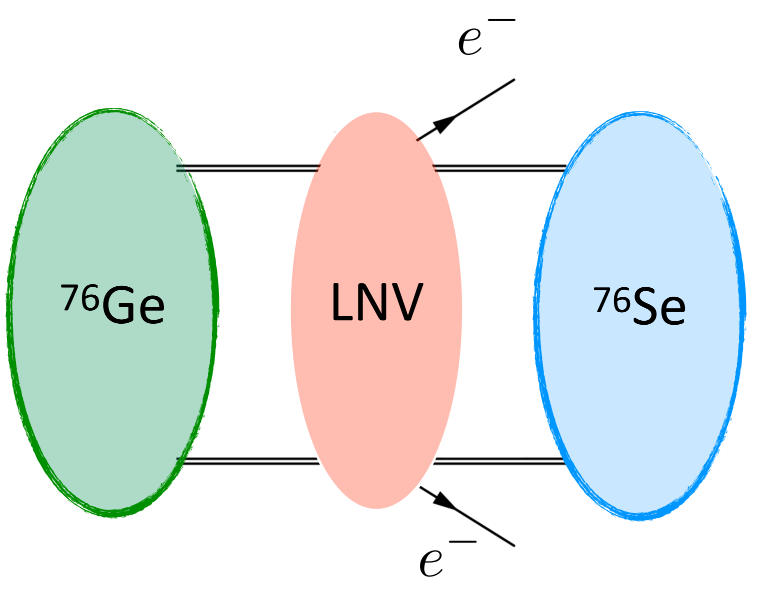
Introduction

0νββ

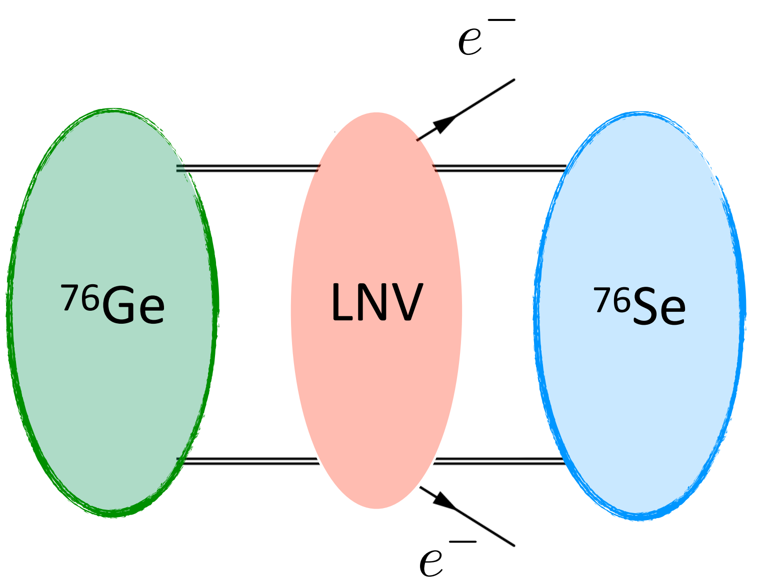


- Violates lepton number, ΔL=2

Schechter, Valle, `82;

Introduction

0νββ



- Violates lepton number, ΔL=2

- Stringently constrained experimentally
  - To be improved by 1-2 orders

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge})$ Gerda	$T^{0\nu}_{1/2}(^{130}\mathrm{Te})$ Cuore	$T^{0\nu}_{1/2}(^{136}\mathrm{Xe})$ KamLAND-zen
$> 9 \cdot 10^{25}\,\mathrm{yr}$	$> 3.2 \cdot 10^{25}\,\mathrm{yr}$	$> 2.3 \cdot 10^{26}\,\mathrm{yr}$

Future reach:
(LEGEND, nEXO, CUPID)

$$T^{0\nu}_{1/2} > 10^{28}\mathrm{yr}$$

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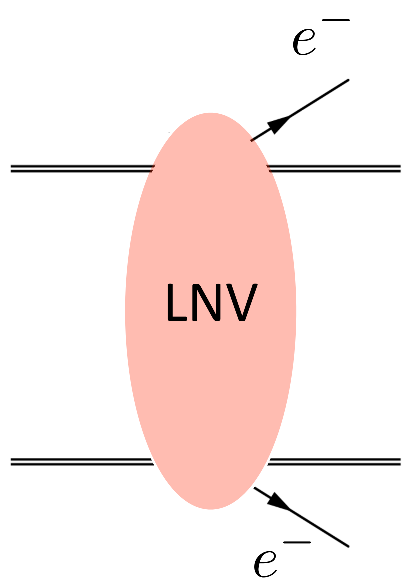

= **BSM physics**

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- Would imply
  - Neutrino's are Majorana particles
  - Physics beyond the SM
  - Connections to LHC, leptogenesis?

Future reach:
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Schechter, Valle, `82; Graesser et al '22; G. Li et al, '21,'22; Peng et al '15; Harz et al '22; Deppisch et al. '15, '17;

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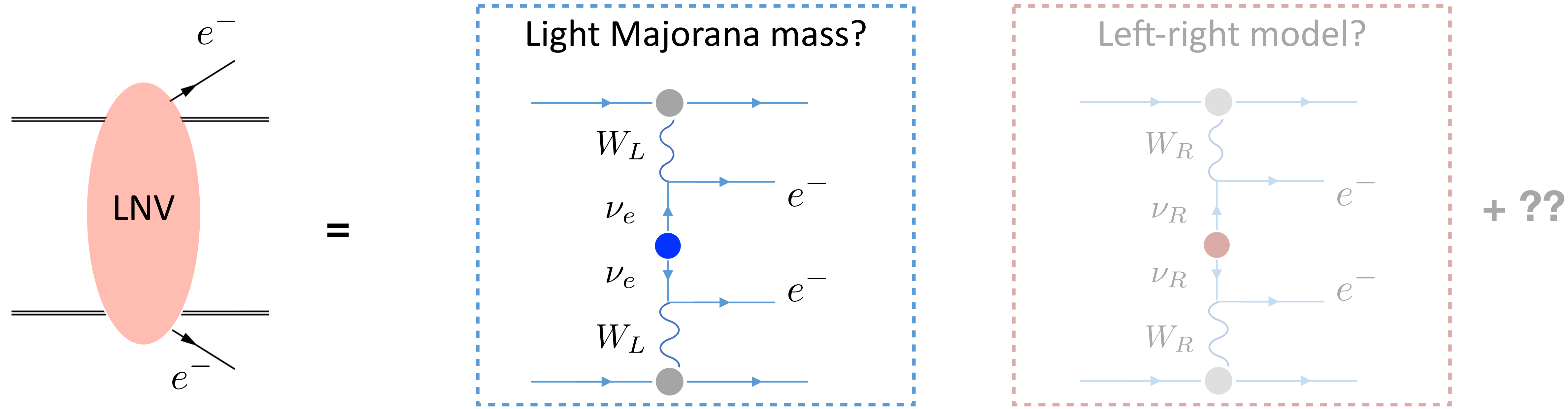
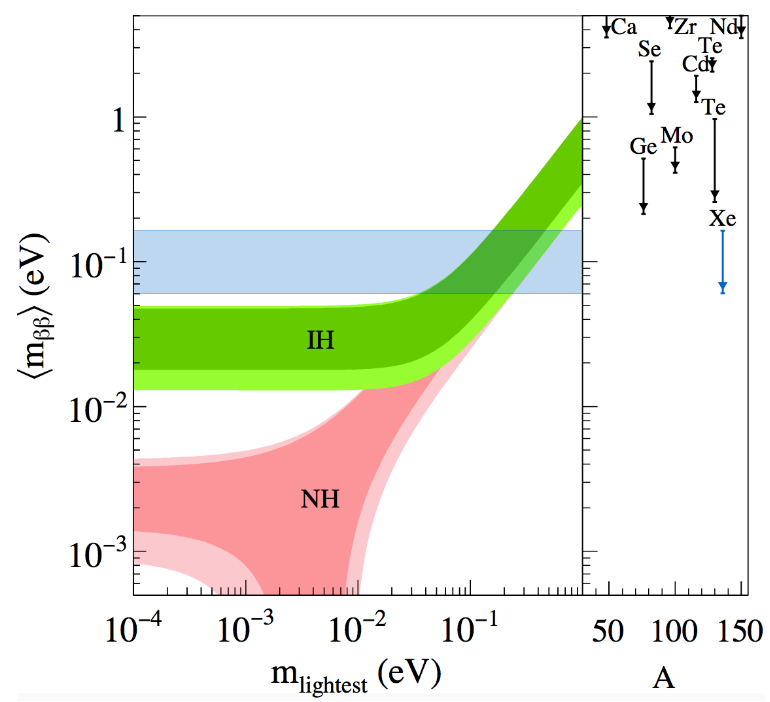


Well-known Majorana mass mechanism



- Implications for the mass hierarchy

Introduction

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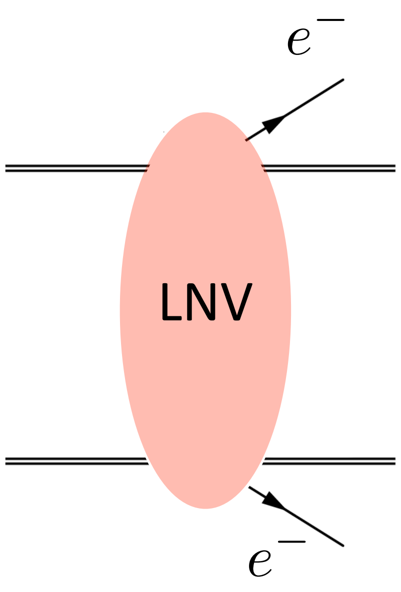

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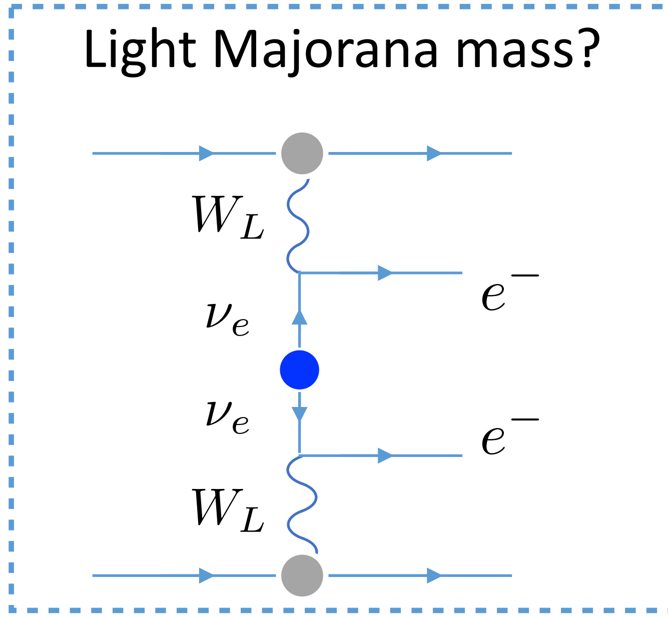

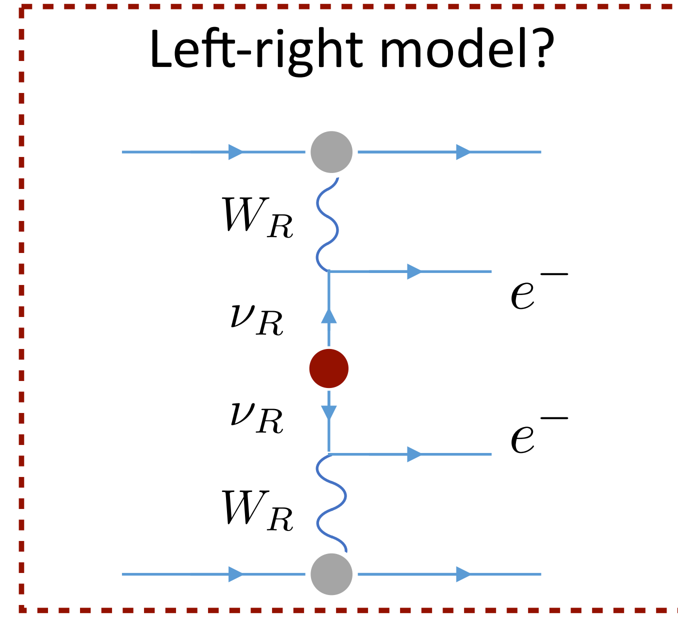

+ ??

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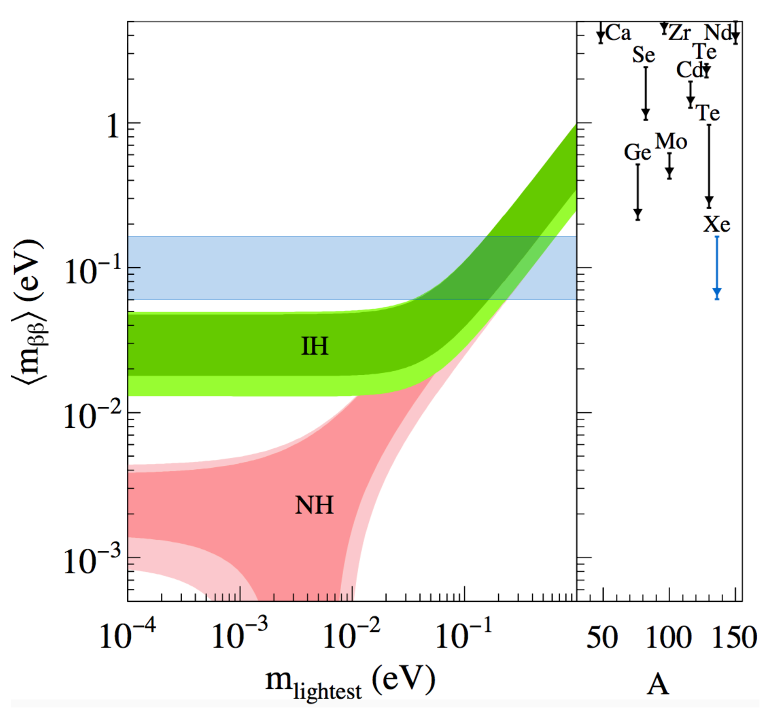

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BSM mechanisms

- Many possible scenarios
  - Sterile neutrinos
  - Left-right model
  - Leptoquarks…

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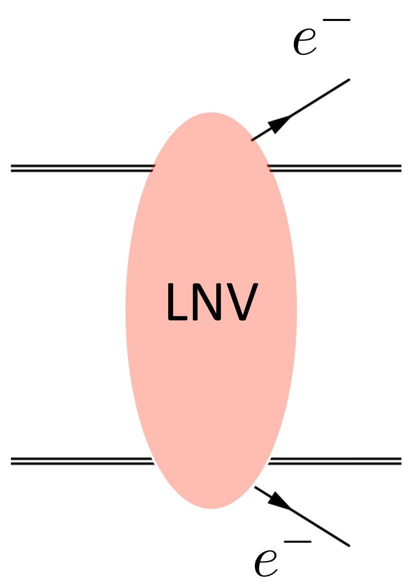

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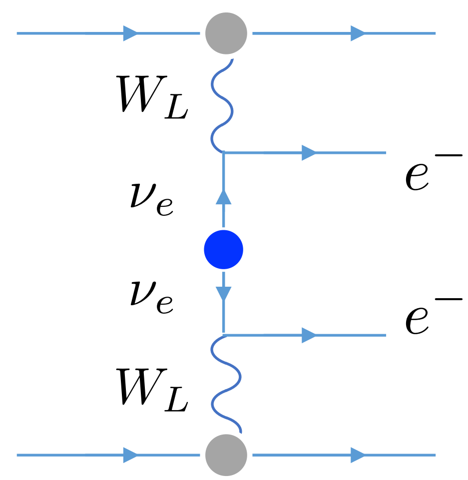
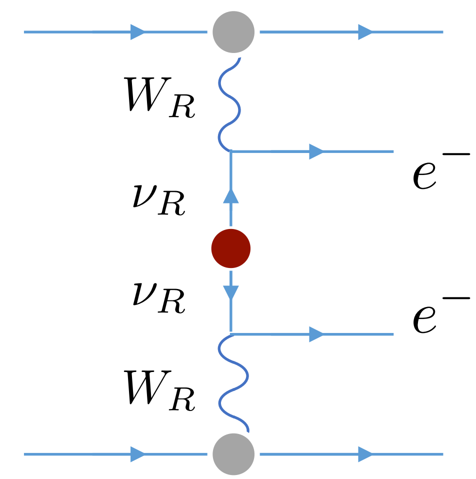
Light Majorana mass?



Left-right model?



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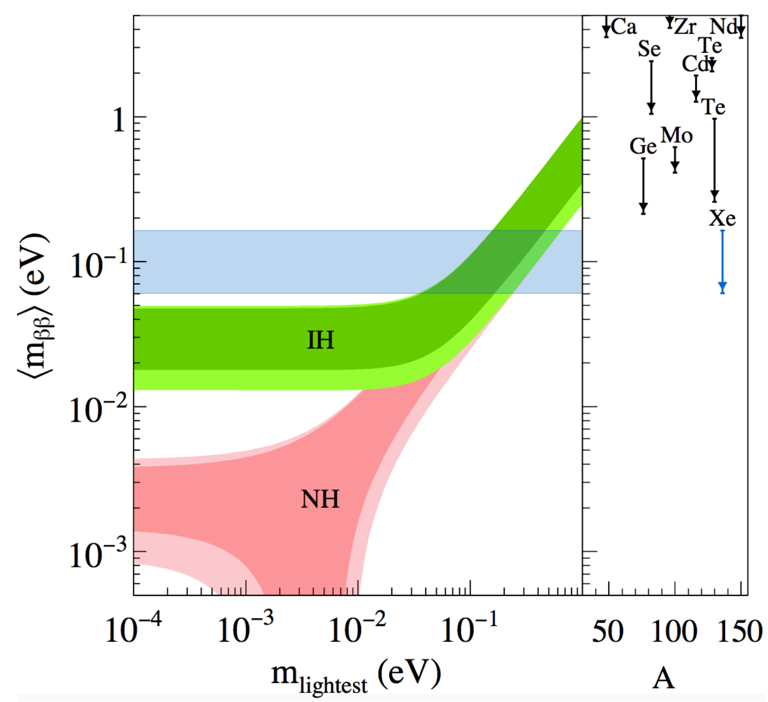

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- Many possible scenarios
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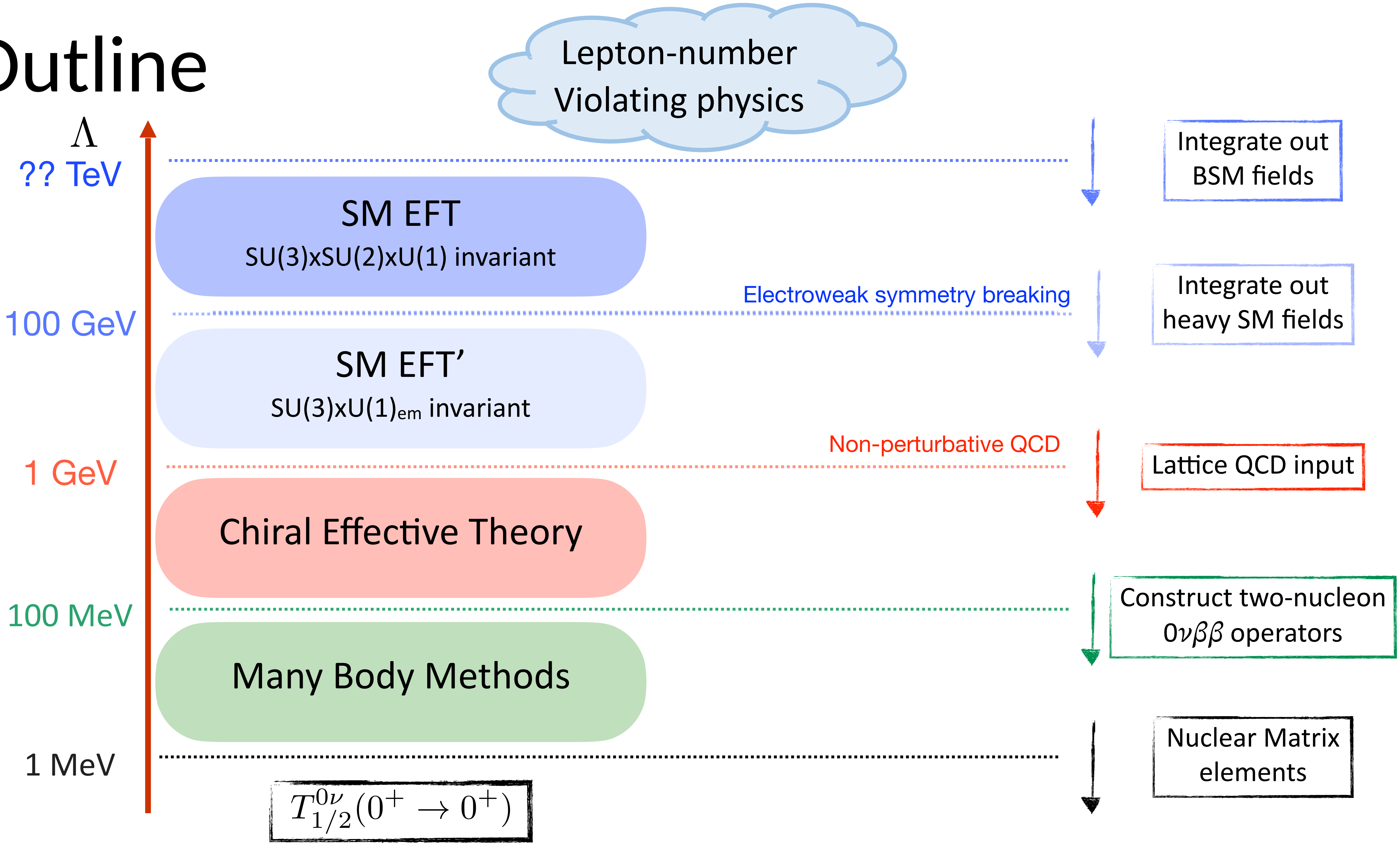
  - Left-right model
  - Leptoquarks…
- How to describe all LNV sources systematically?

Outline



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100 GeV
1 GeV
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SU(3)xSU(2)xU(1) invariant
Electroweak symmetry breaking
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SU(3)xU(1)em invariant
Non-perturbative QCD
Chiral Effective Theory
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$T^{0\nu}_{1/2}(0^+ \to 0^+)$
Integrate out BSM fields
Integrate out heavy SM fields
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Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

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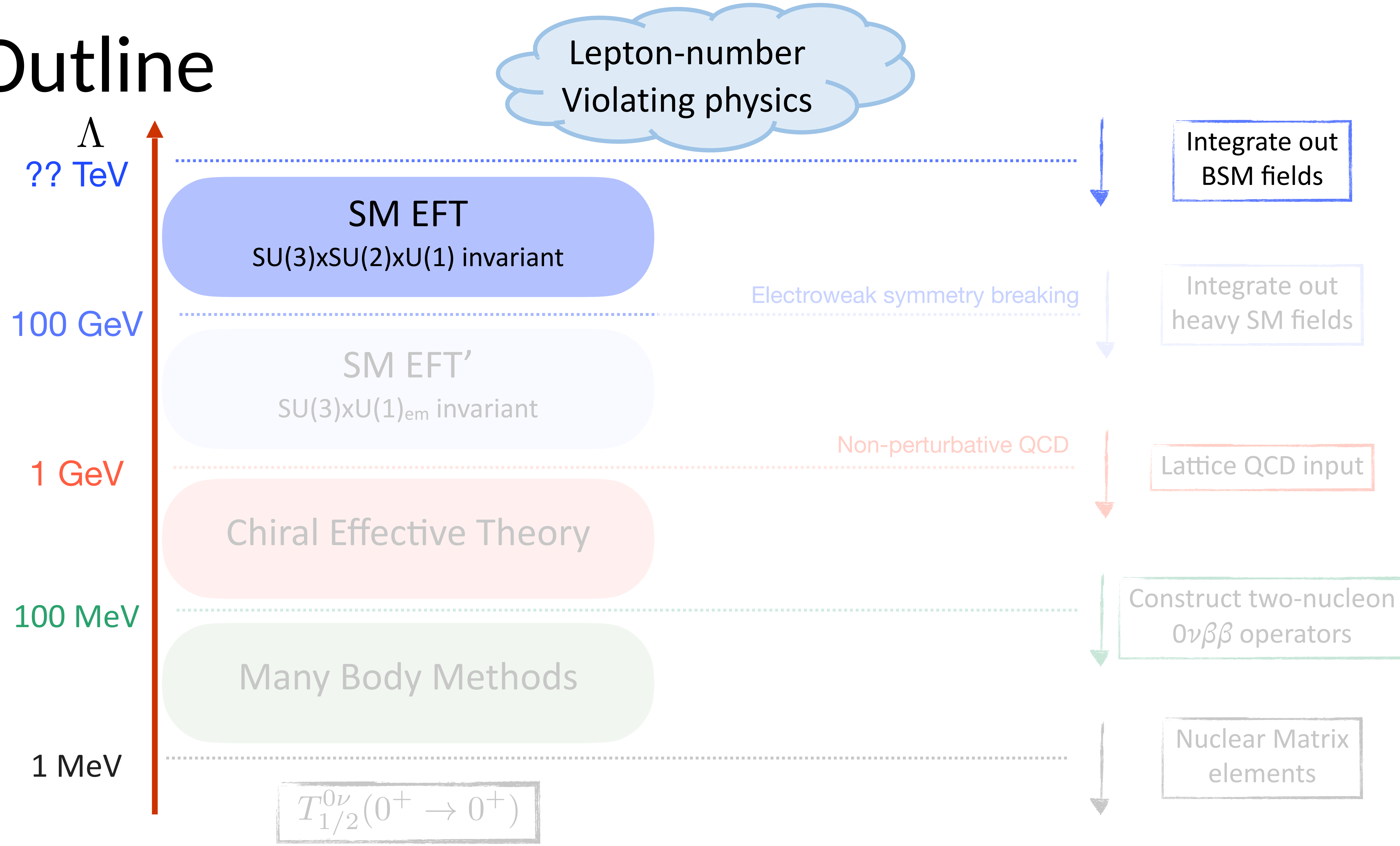

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Effective Field Theory

Heavy $\Delta L = 2$ physics

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \frac{c_i^{(7)}}{\Lambda^3} O_i^{(7)} + \frac{c_i^{(9)}}{\Lambda^5} O_i^{(9)} + \ldots$$

Dimension-five

$$\mathcal{L}_5 = \frac{c_5}{\Lambda} (L^T C \tilde{H})(\tilde{H}^T L)$$

Dimension-seven

- 12 ΔL=2 operators

$1: \psi^2 H^4 + \text{h.c.}$

$\mathcal{O}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(L^i C L^m) H^j H^n (H^\dagger H)$

$3: \psi^2 H^3 D + \text{h.c.}$

$\mathcal{O}_{LHDe}$	$\epsilon_{ij}\epsilon_{mn}\,(L^i C \gamma_\mu e)\, H^j H^m D^\mu H^n$

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$\mathcal{O}^{(1)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L^i C D^\mu L^j)$
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Dimension-nine

- Consider subset of operators

$$\begin{aligned}
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Liao and Ma '20; Li et al '20;

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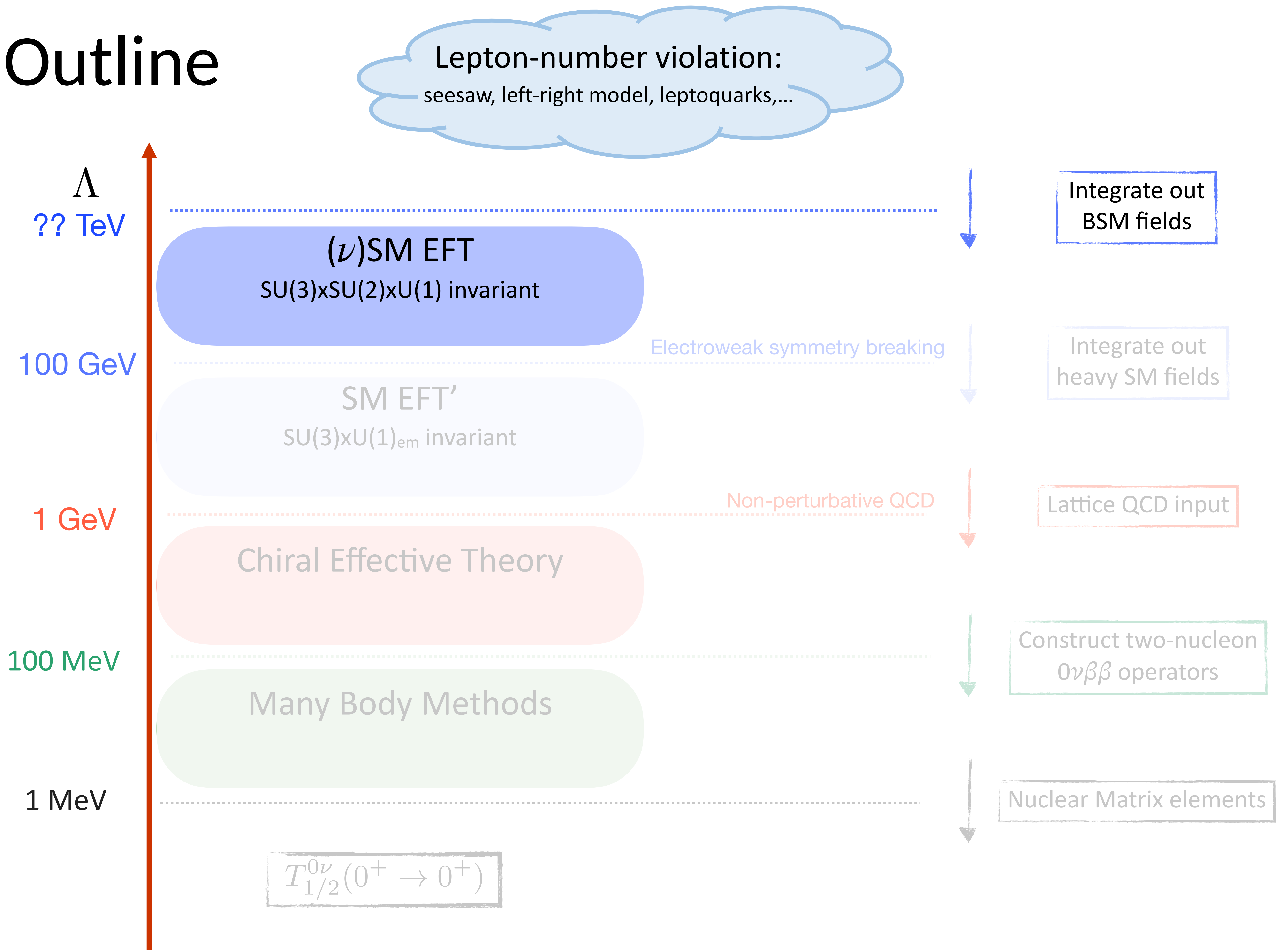

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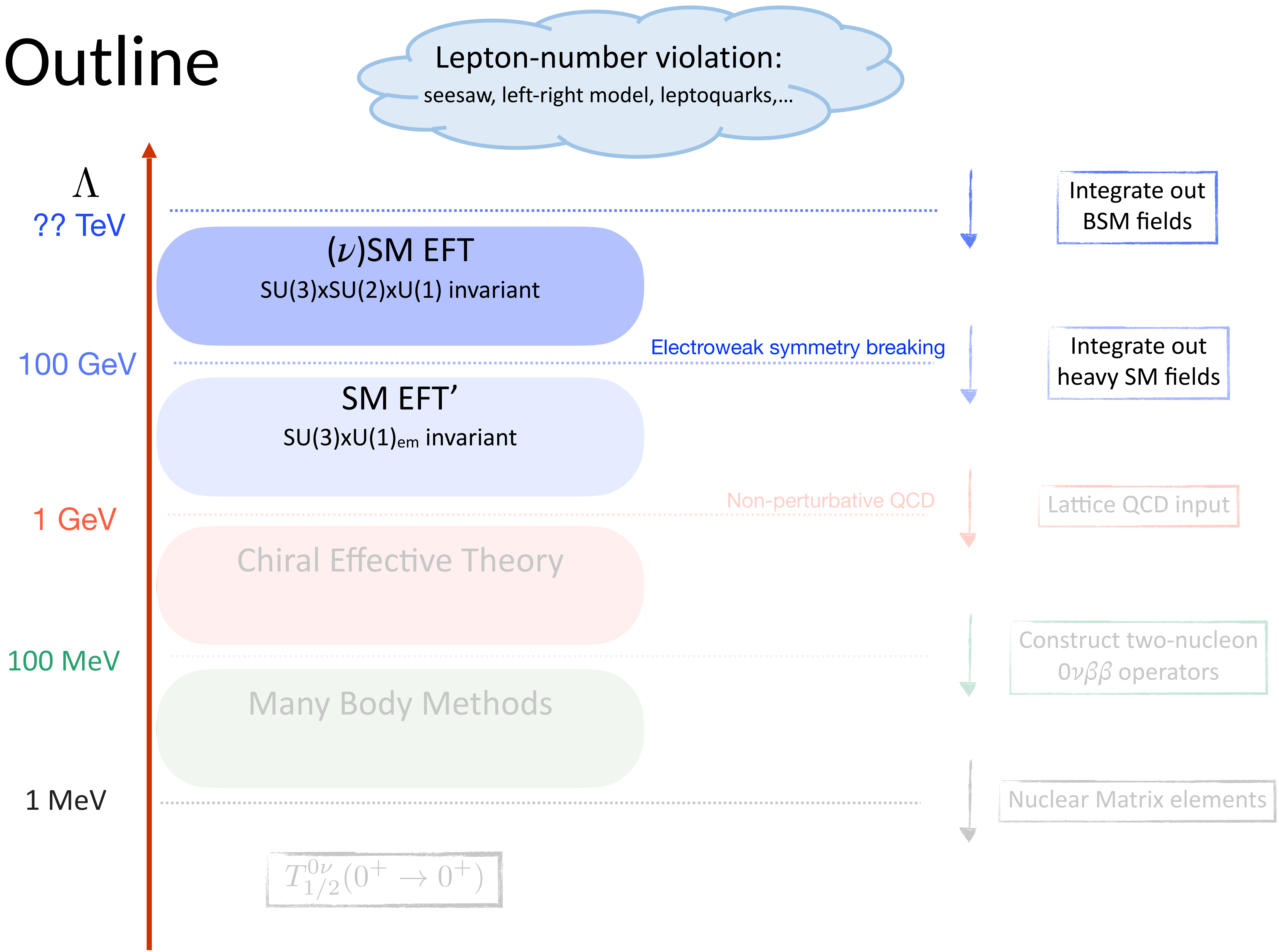

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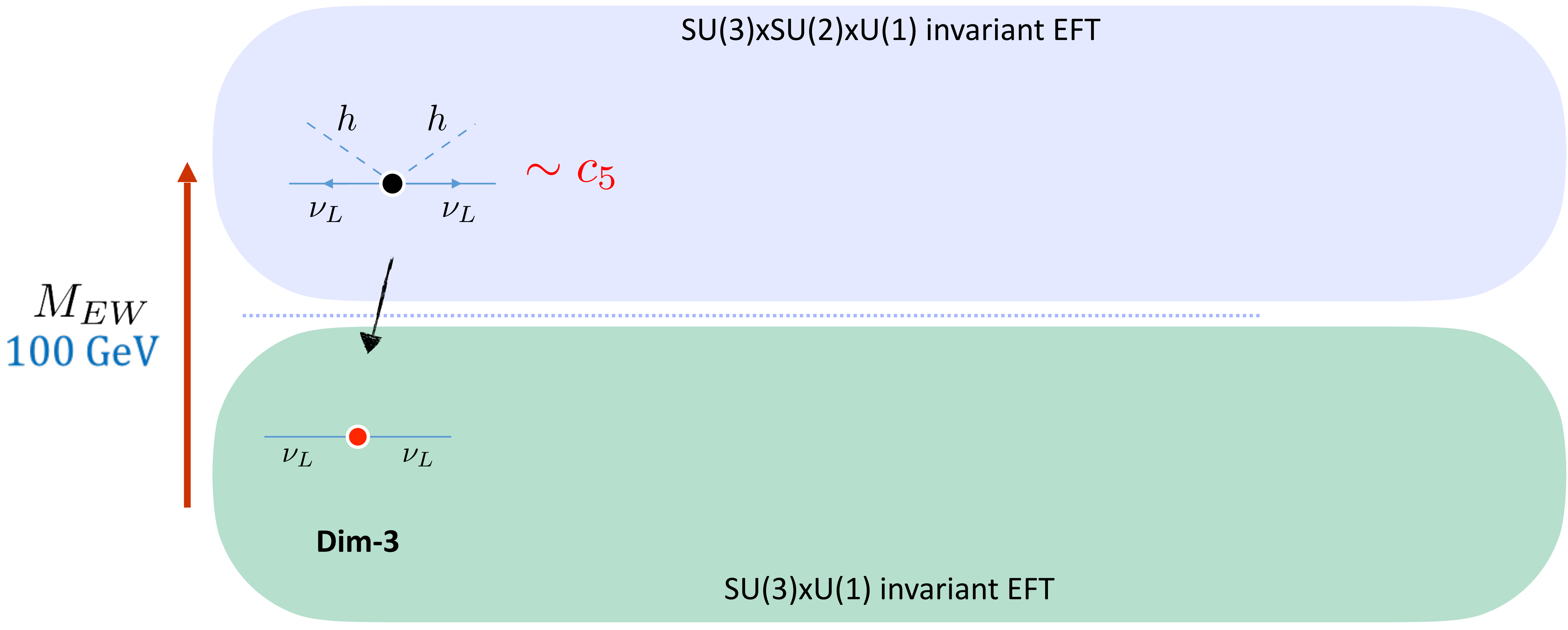
Low-energy operators

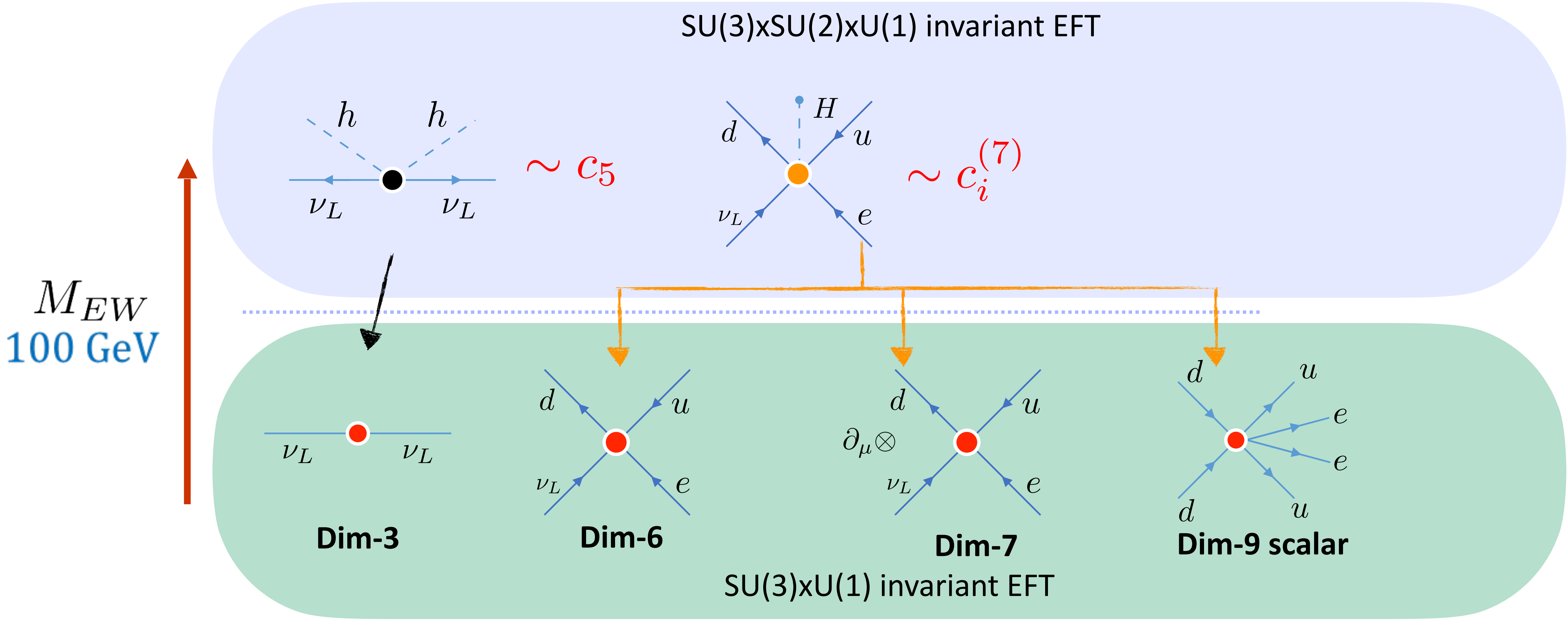
At/below the weak scale*



* very similar for operators involving ν_R

Low-energy operators

At/below the weak scale*



* very similar for operators involving ν_R

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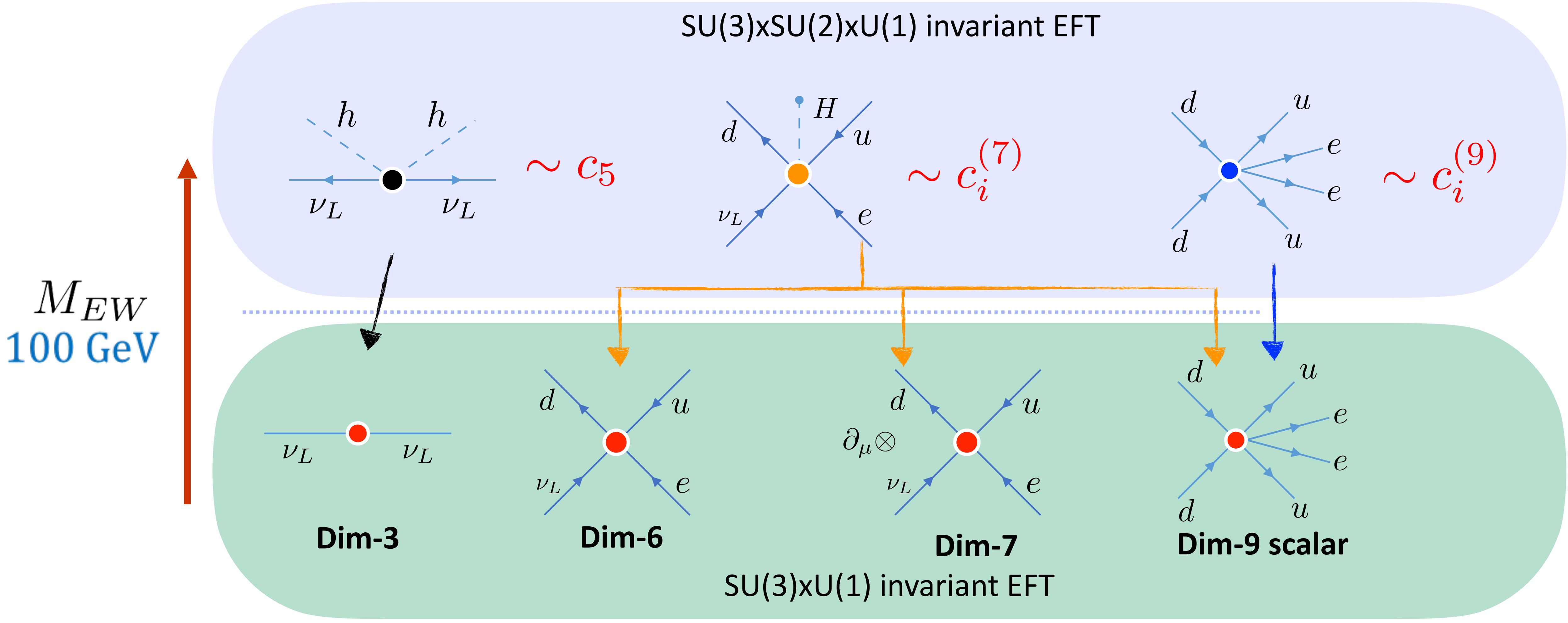

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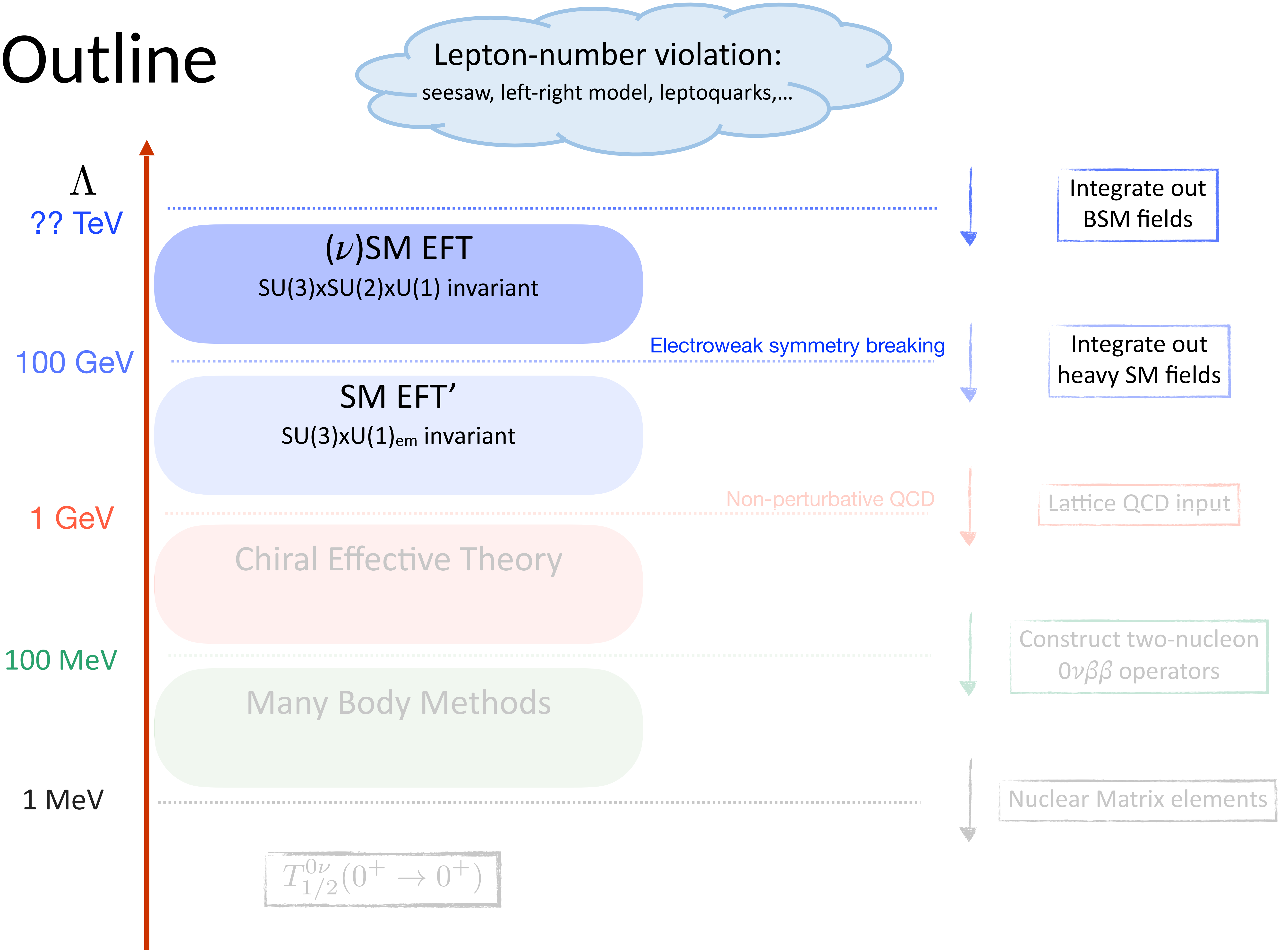
Outline



Lepton-number violation:
seesaw, left-right model, leptoquarks,...
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SU(3)xSU(2)xU(1) invariant
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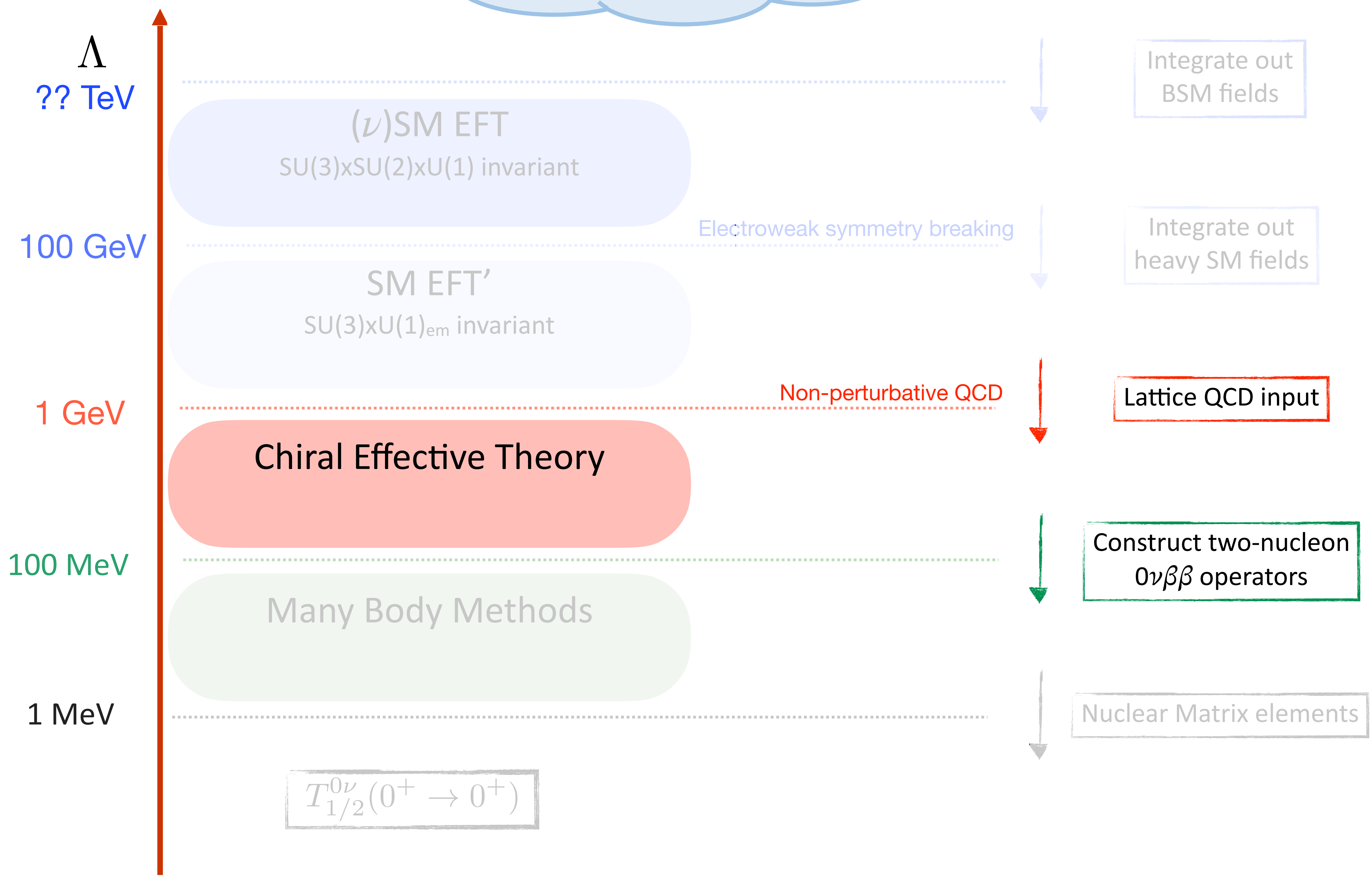
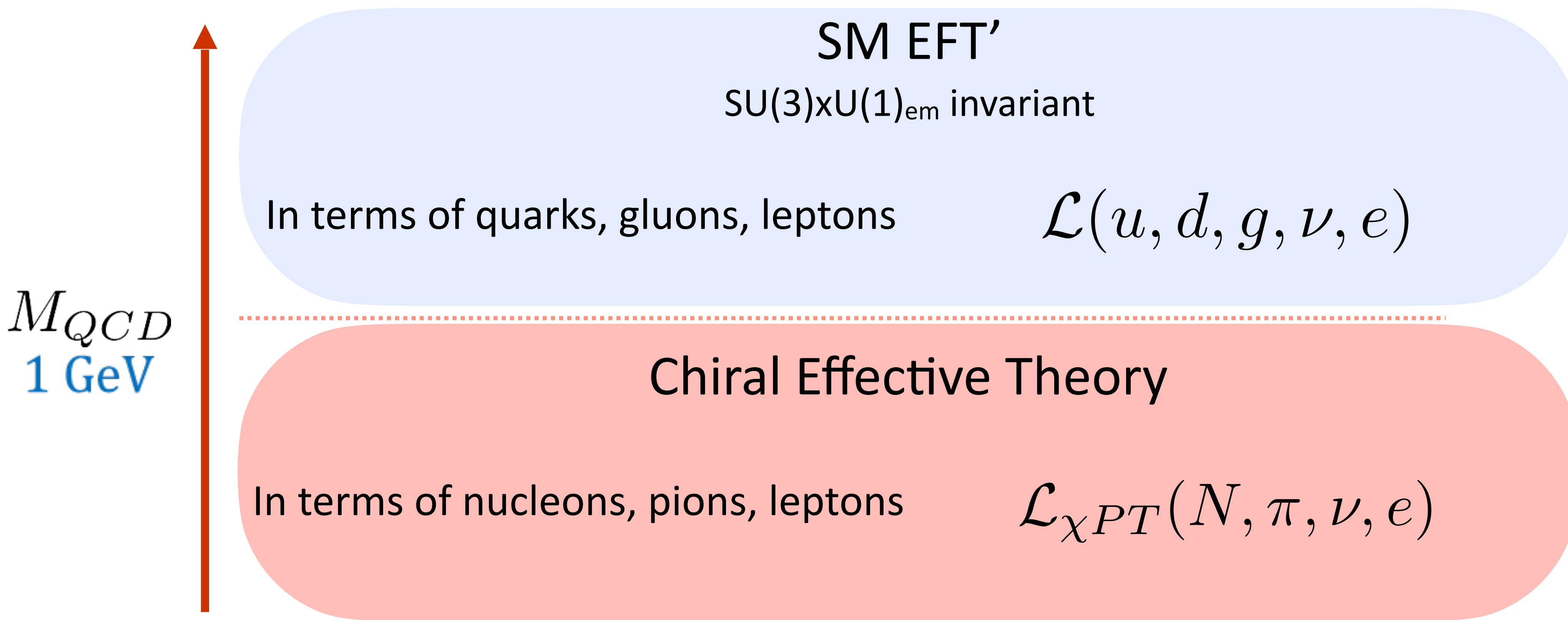


Matching to Chiral EFT



Form of operators determined by chiral symmetry

The operators come with unknown constants (LECs)

Need a power-counting scheme

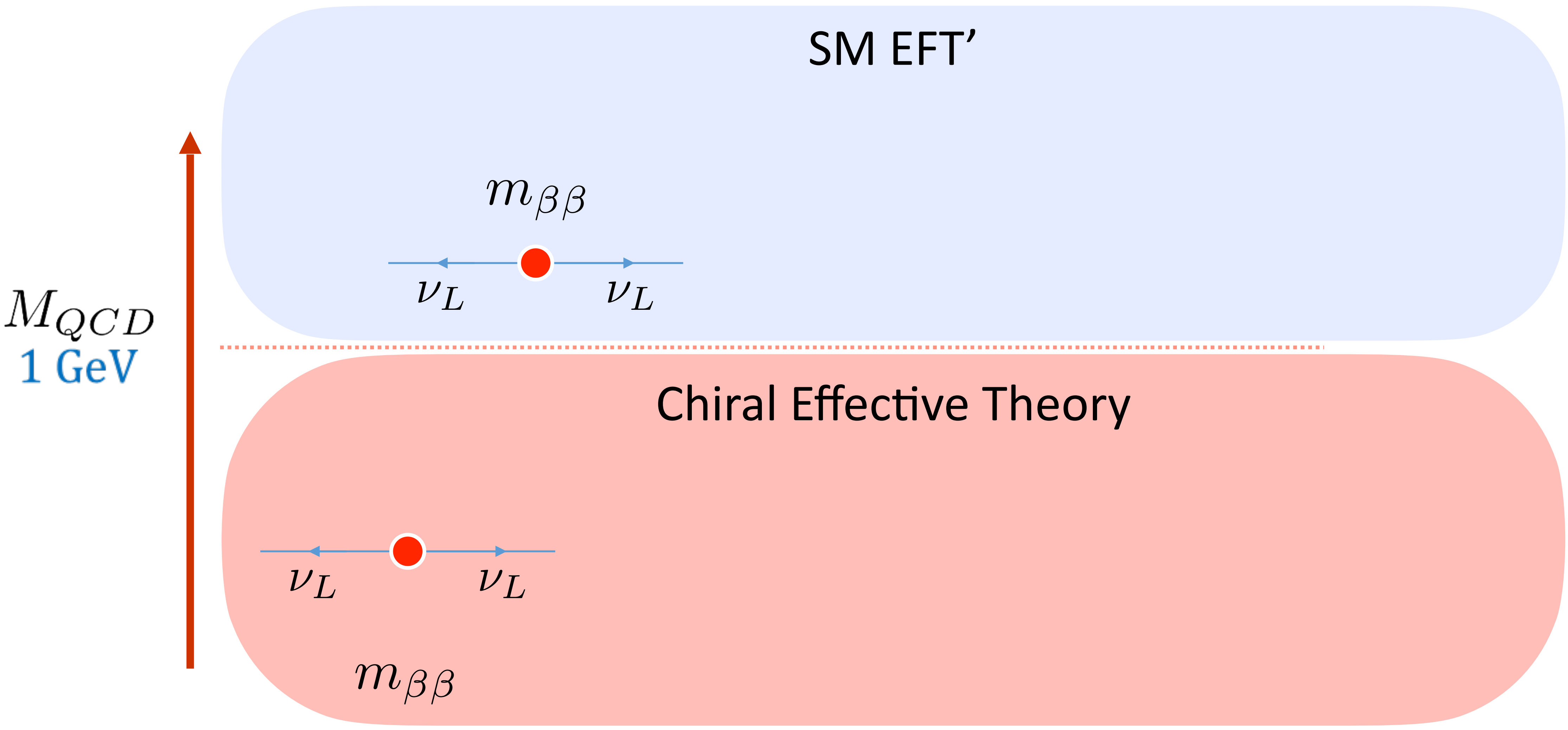
- Often used: Weinberg counting / Naive dimensional analysis (NDA)

Manohar, Georgi, \`84; Weinberg, \`90, \`91

Matching to Chiral EFT

Warning: Based on NDA

Example: dimension-3 LNV



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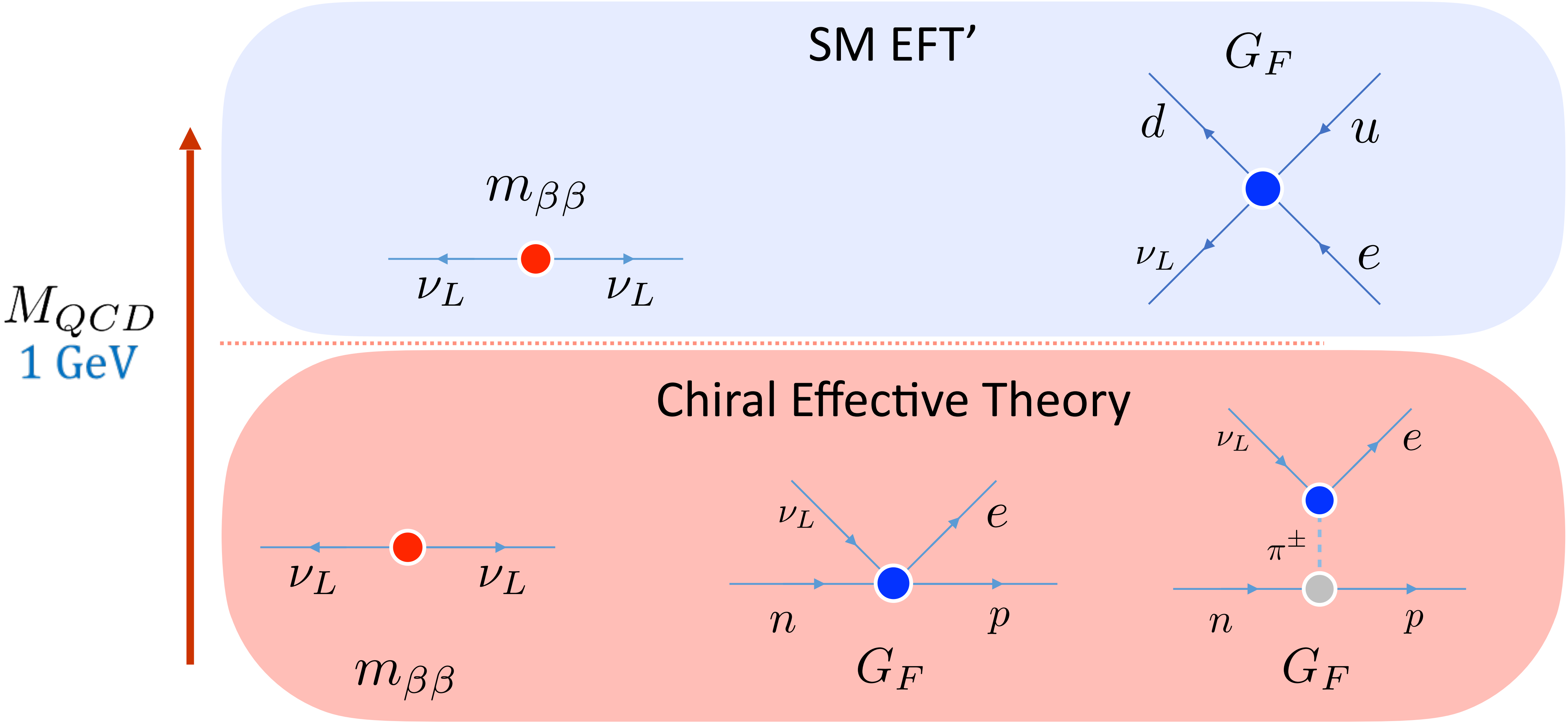
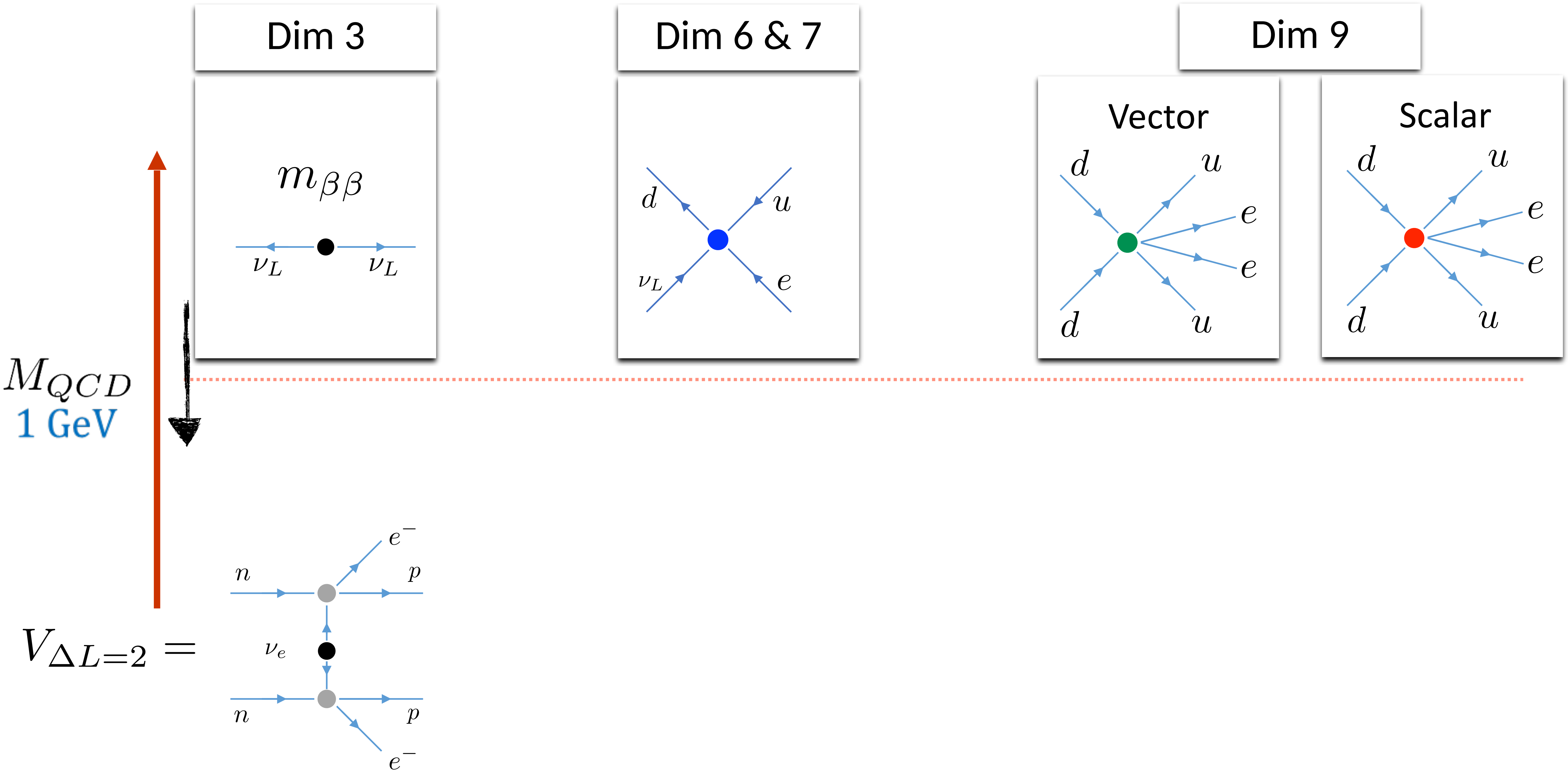


- At LO in Weinberg counting, only need the nucleon one-body currents
    - All needed low-energy constants are known

Chiral EFT

Ramsey-Musolf ’03; Cirigliano, (WD) et al. ‘17 ; Detmold et al, ’22; Nicholson et al.’18

Chiral EFT



- Contributions of dimension-6,7,9 operators

Ramsey-Musolf ’03; Cirigliano, (WD) et al. ‘17 ; Detmold et al, ’22; Nicholson et al.’18

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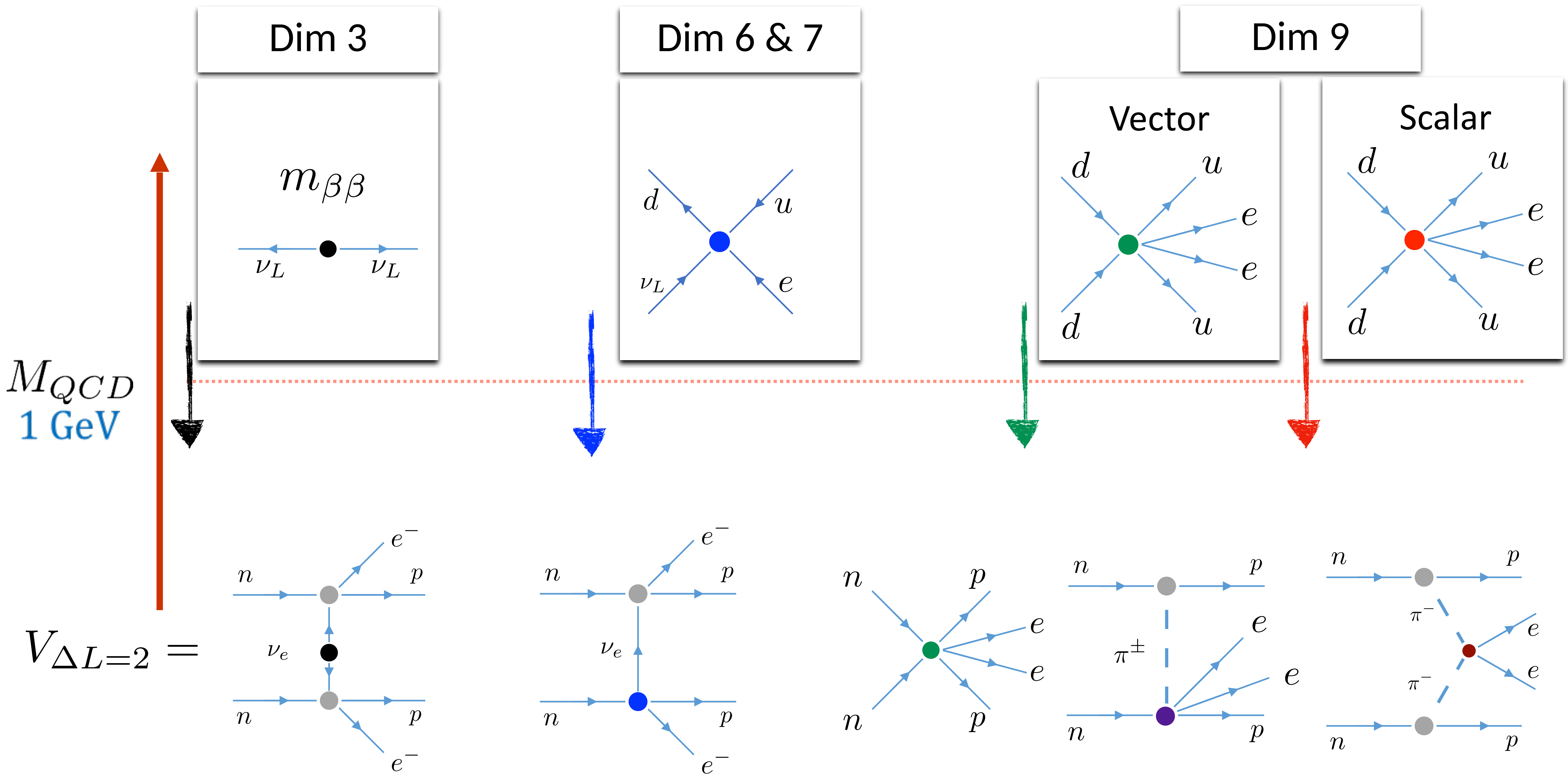

- Contributions of dimension-6,7,9 operators
  - Give additional interactions and LECs
  - LECs for the nucleon currents and $\pi\pi$ interactions are partially known

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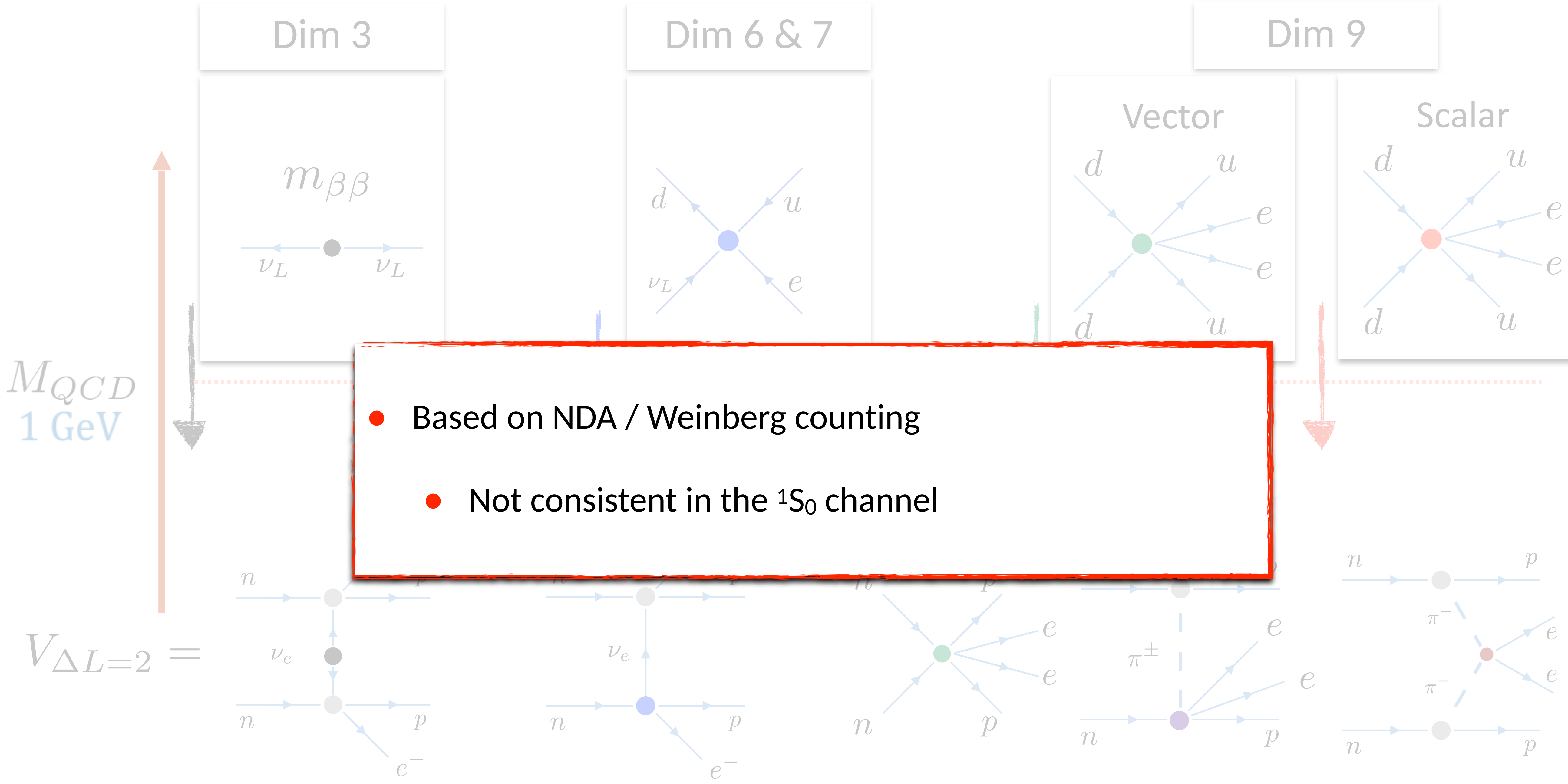

- Based on NDA / Weinberg counting
  - Not consistent in the $^1S_0$ channel

- Contributions of dimension-6,7,9 operators
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  - LECs for the nucleon currents and $\pi\pi$ interactions are partially known

Kaplan, Savage, Wise, ’96; Beane, Bedaque, Savage, van Kolck, ’03, Nogga, Timmermans, van Kolck, ’05, Long, Yang, ’12;

Checking the power counting

Dimension-3

Check that $\mathcal{A}(nn \to ppee)$ is finite

Checking the power counting

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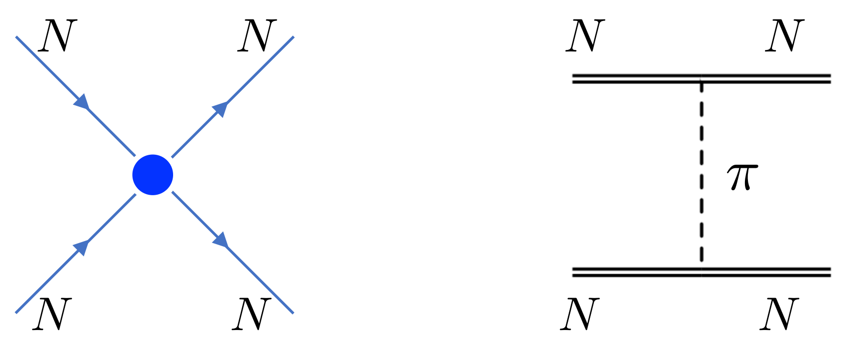
Check that $\mathcal{A}(nn \to ppee)$ is finite

- Requires inclusion of the strong interaction

$$\mathcal{L}_\chi = C\left(N^T P_{{}^1S_0} N\right)^\dagger N^T P_{{}^1S_0} N - \frac{g_A}{2F_\pi}\nabla\pi \cdot \bar{N}\tau\boldsymbol{\sigma}N$$



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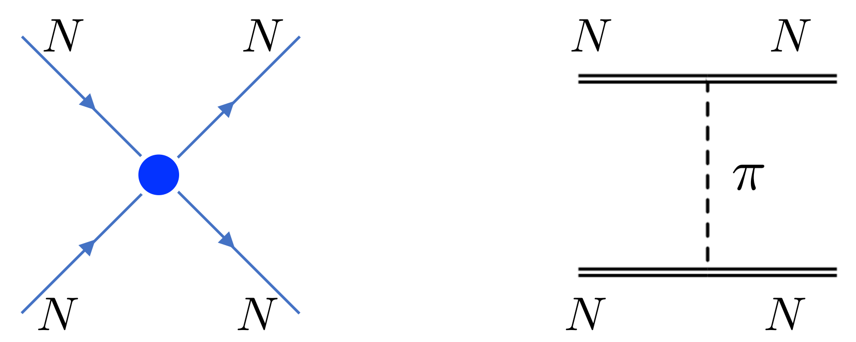
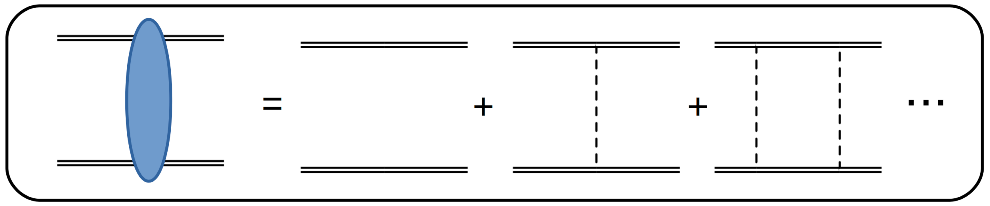
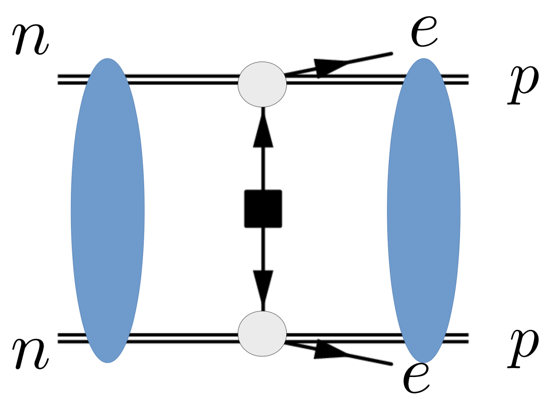


Dress the ΔL=2 potential with (renormalized) strong interactions:





✓ finite

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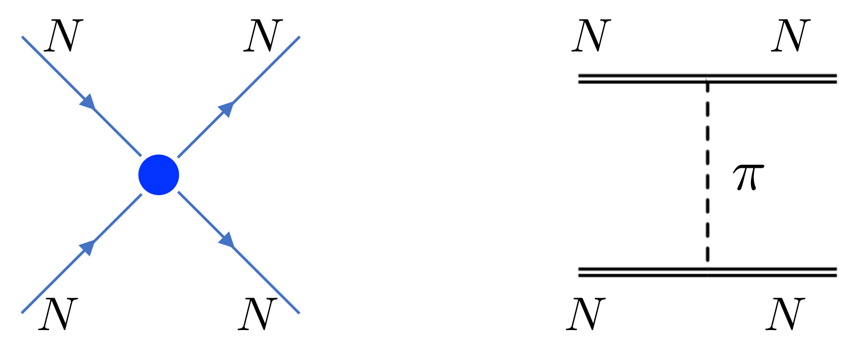

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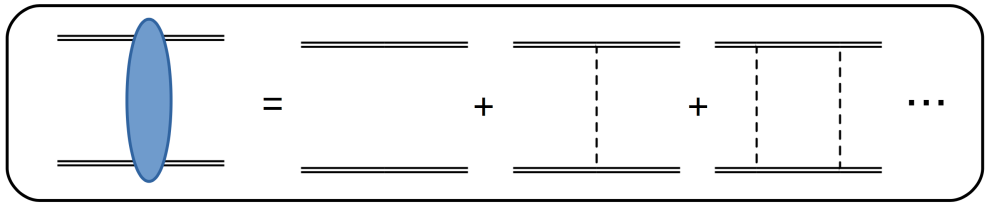

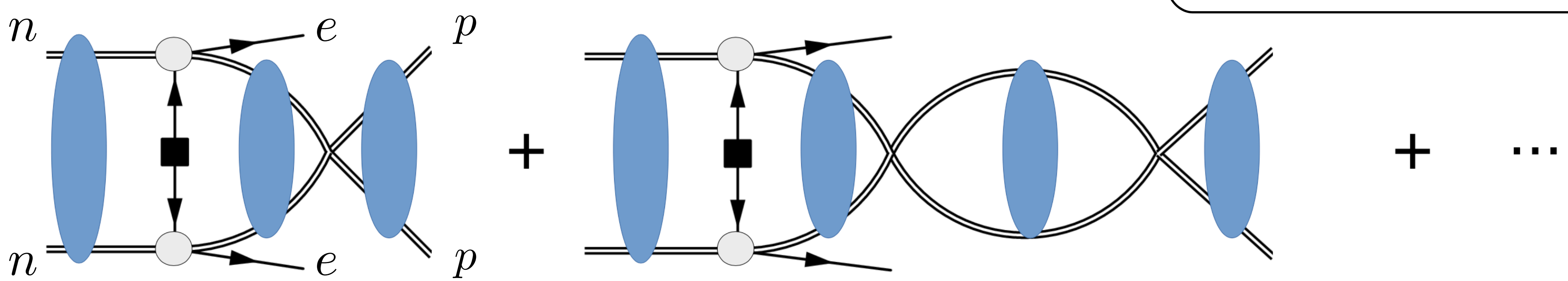

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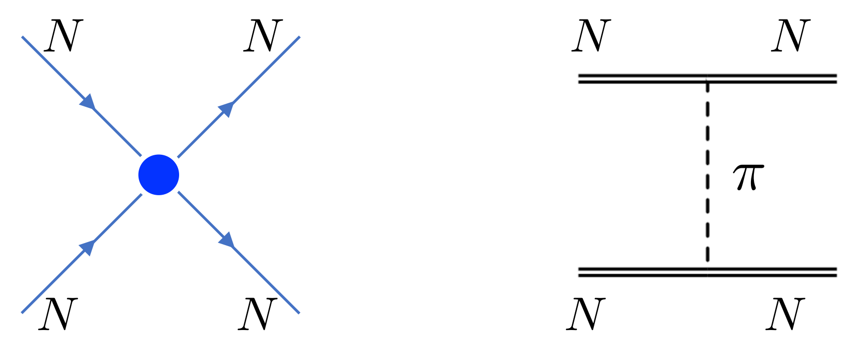

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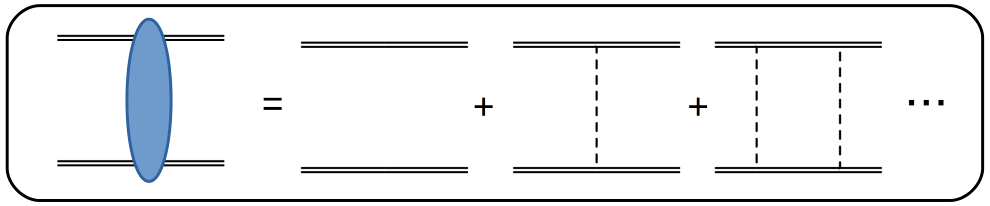

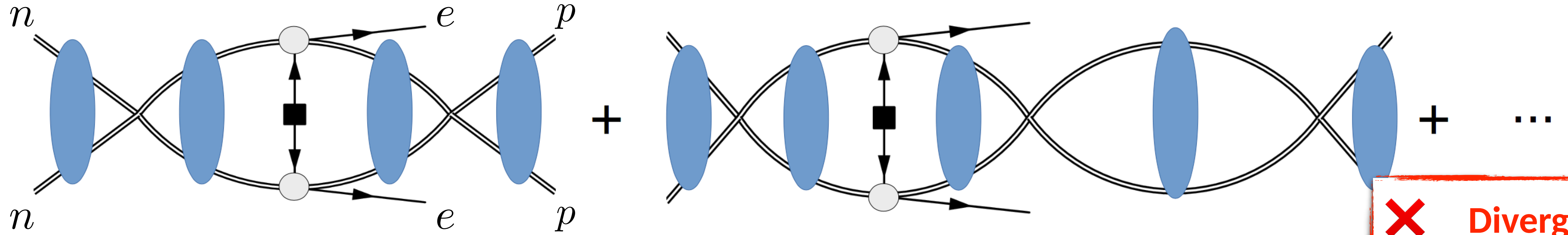

❌ Divergent

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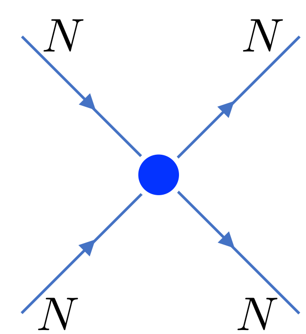
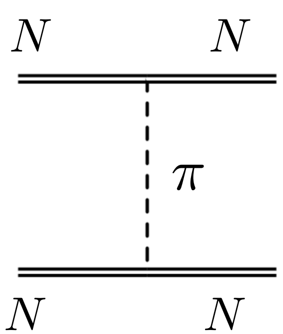
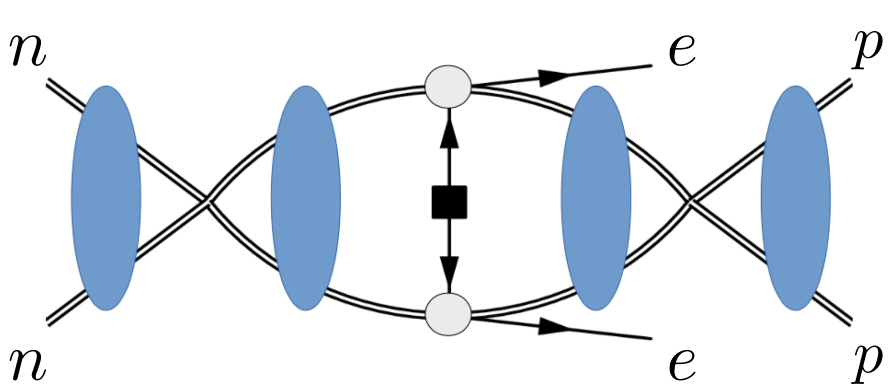




Dress the ΔL=2 potential with (renormalized) strong interactions:

In MS-bar:

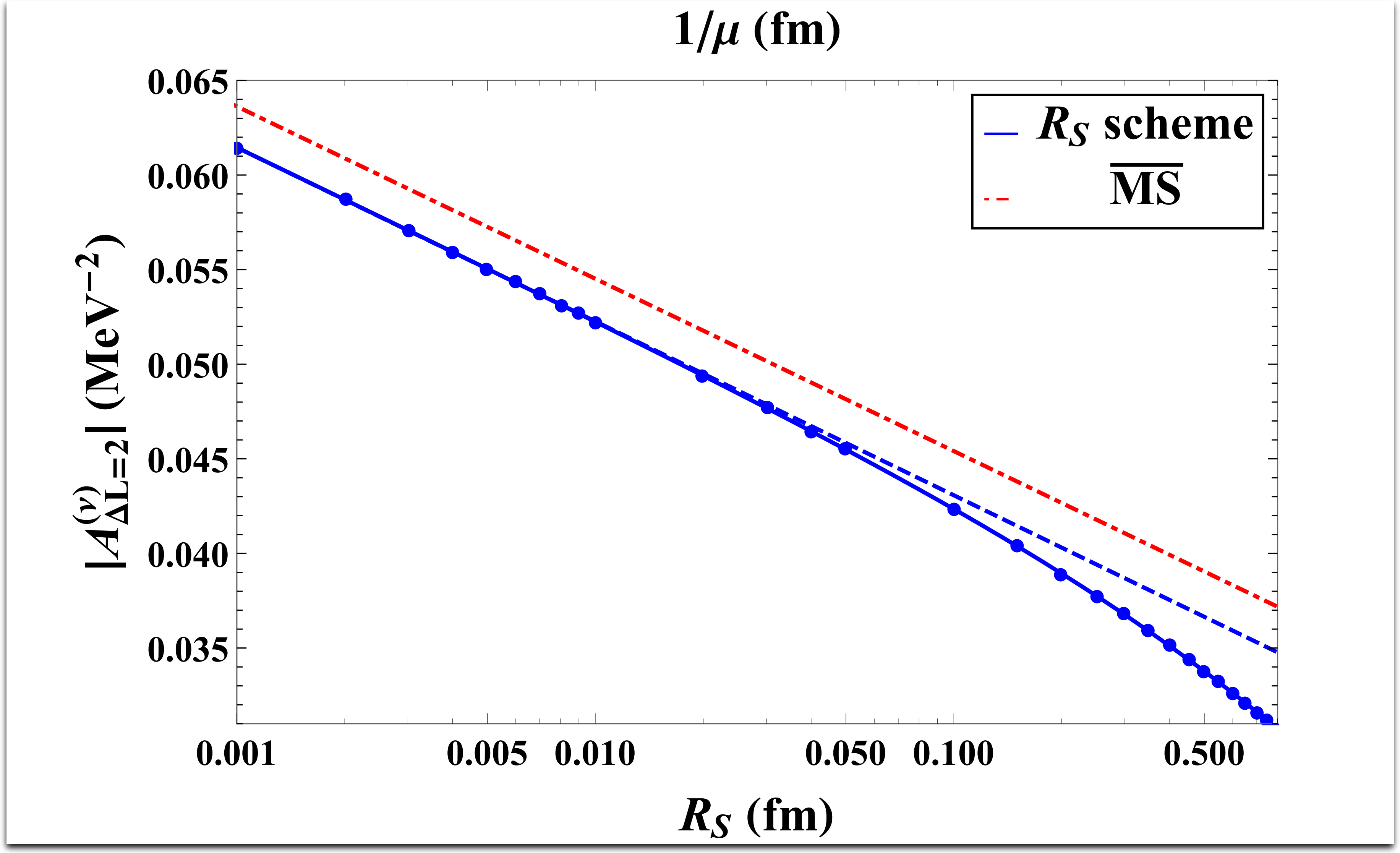


$$= -\left(\frac{m_N}{4\pi}\right)^2 (1 + 2g_A^2)\frac{1}{2}\left(\log\frac{\mu^2}{-(|\mathbf{p}| + |\mathbf{p}'|)^2 + i0^+} + 1\right)$$

$+\text{finite}$

Regulator dependent

Numerical results



- Amplitudes obtained using
  - MS-bar
  - Coordinate-space cut-off

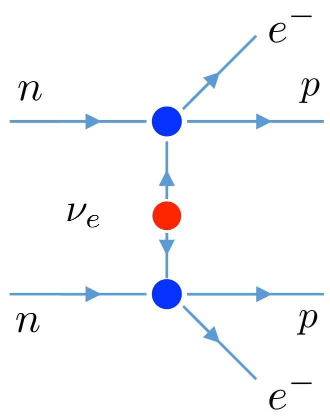
$$\tilde{C}\,\delta^{(3)}(\mathbf{r}) \to \frac{\tilde{C}(R_S)}{(\sqrt{\pi}R_S)^3}\exp\left(-\frac{r^2}{R_S^2}\right)$$

- Clear μ or R_S dependence

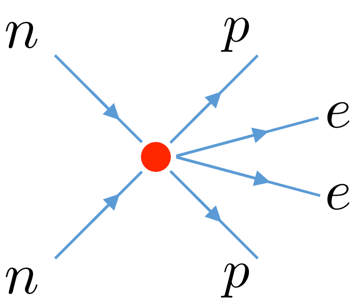
Need for a counter term

New interaction needed at leading order to get physical amplitudes:

$V_{\Delta L=2} =$



$+ \quad g_\nu^{NN}$



$$\mathscr{L} \sim g_\nu^{NN} G_F^2 m_{\beta\beta} (\bar{N}\tau^+ N)(\bar{N}\tau^+ N)\bar{e}_L e_L^c$$

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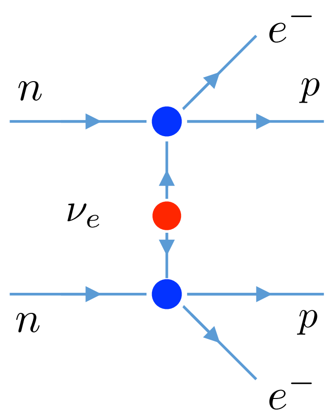

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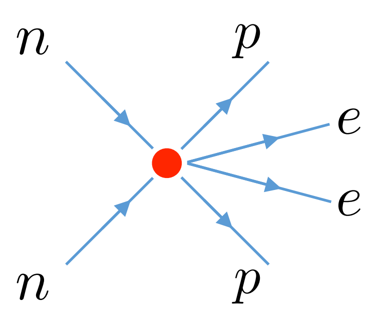

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  - Controlled errors
  - Active area of research

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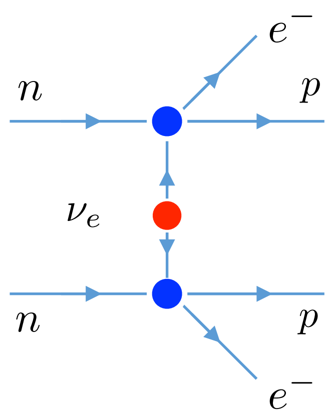

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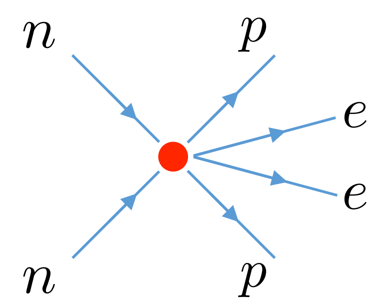

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See backup

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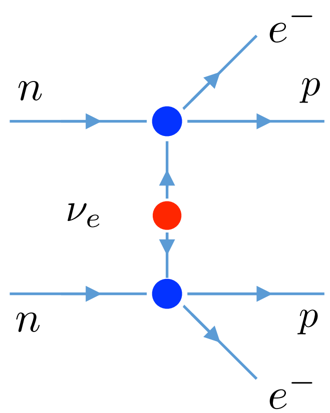

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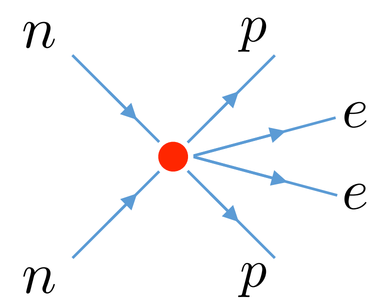

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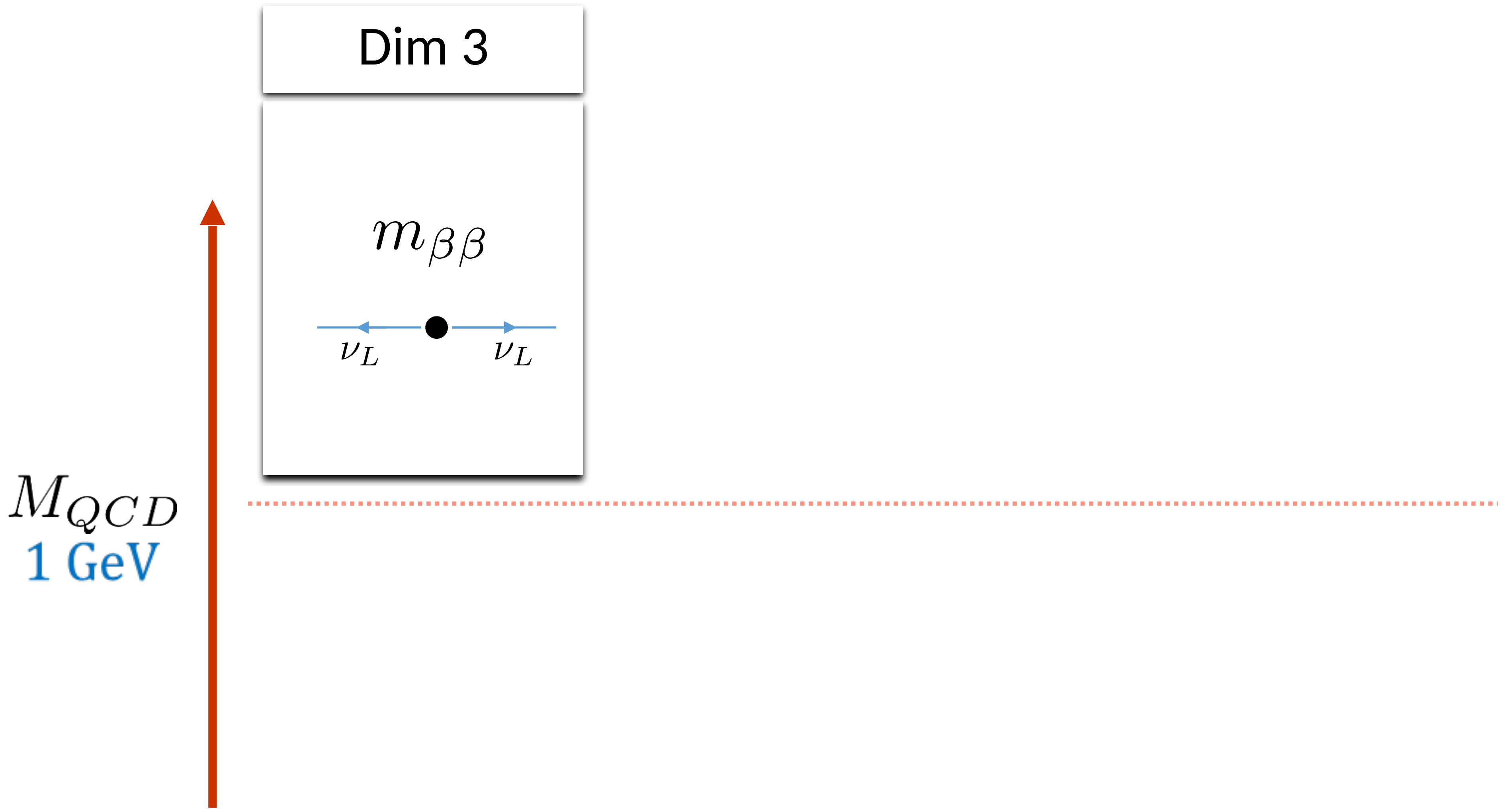
All give

$\tilde{g}_\nu^{NN} = \mathcal{O}(1)$

Chiral EFT

'Non-Weinberg' counting



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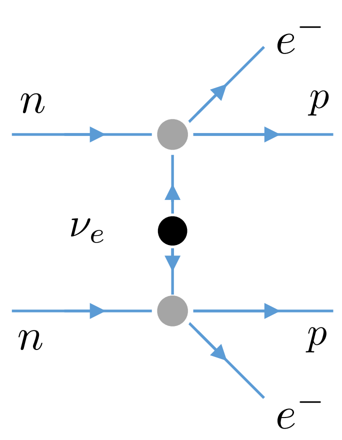

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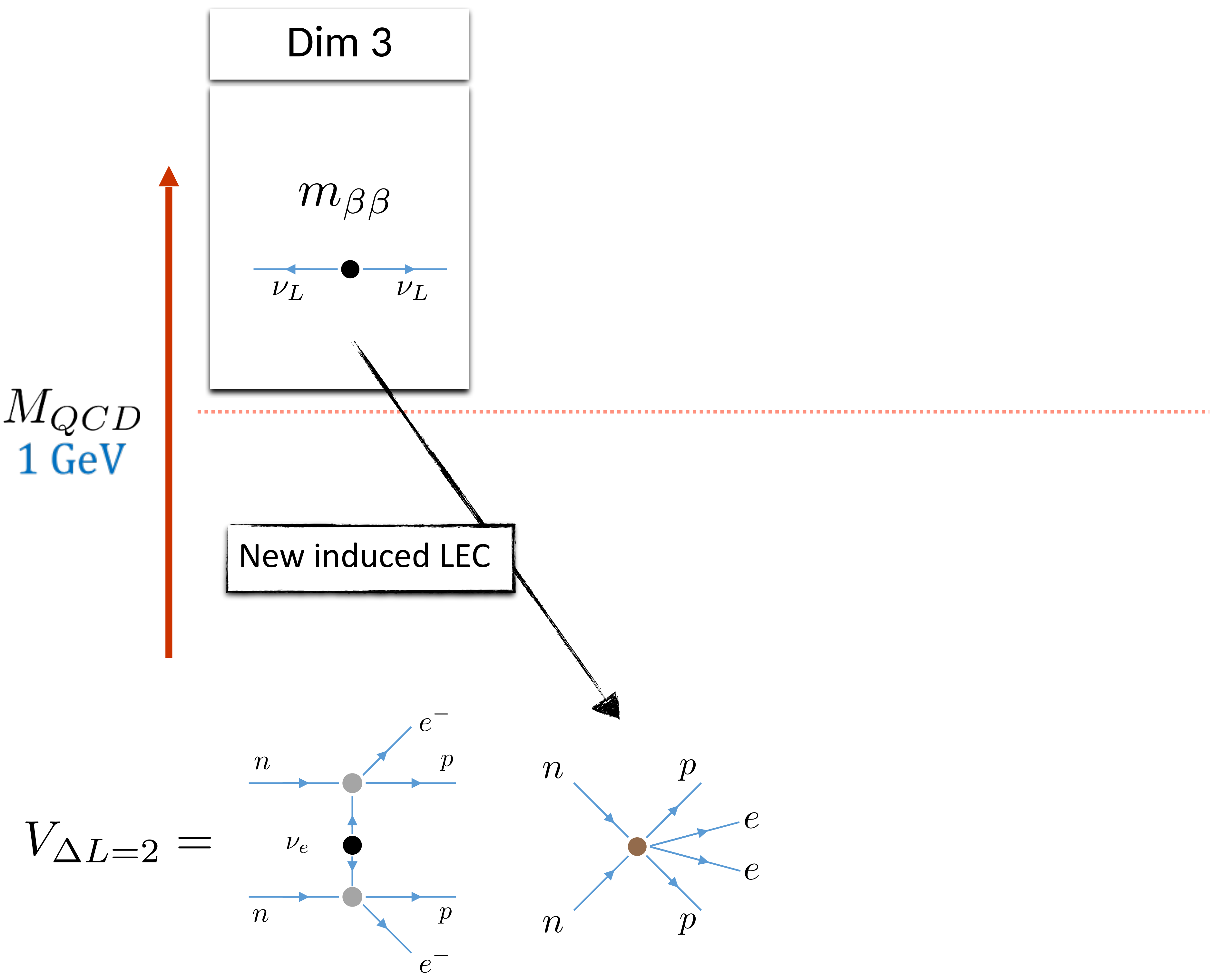
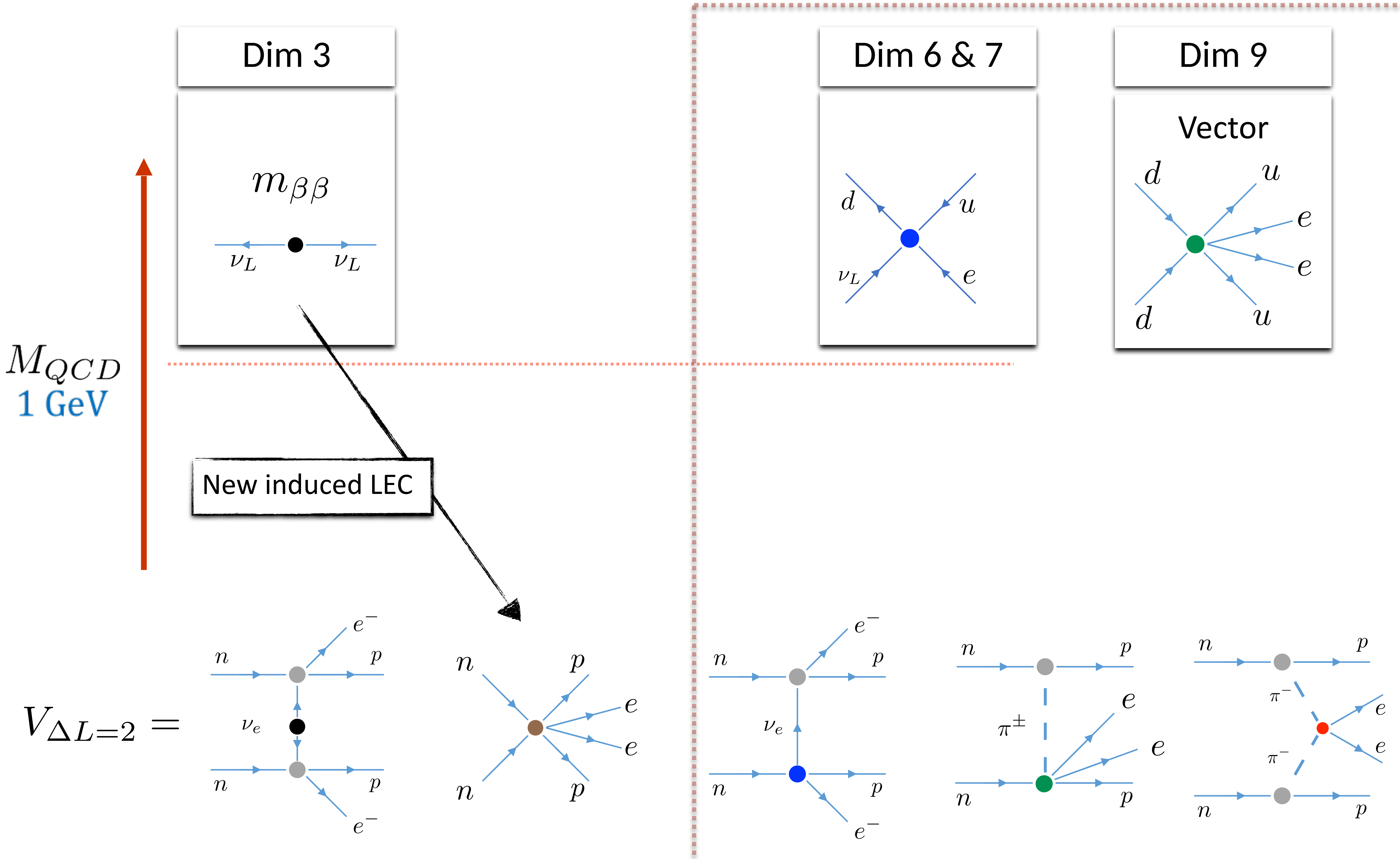


Chiral EFT

'Non-Weinberg' counting affects higher dimensional interactions as well



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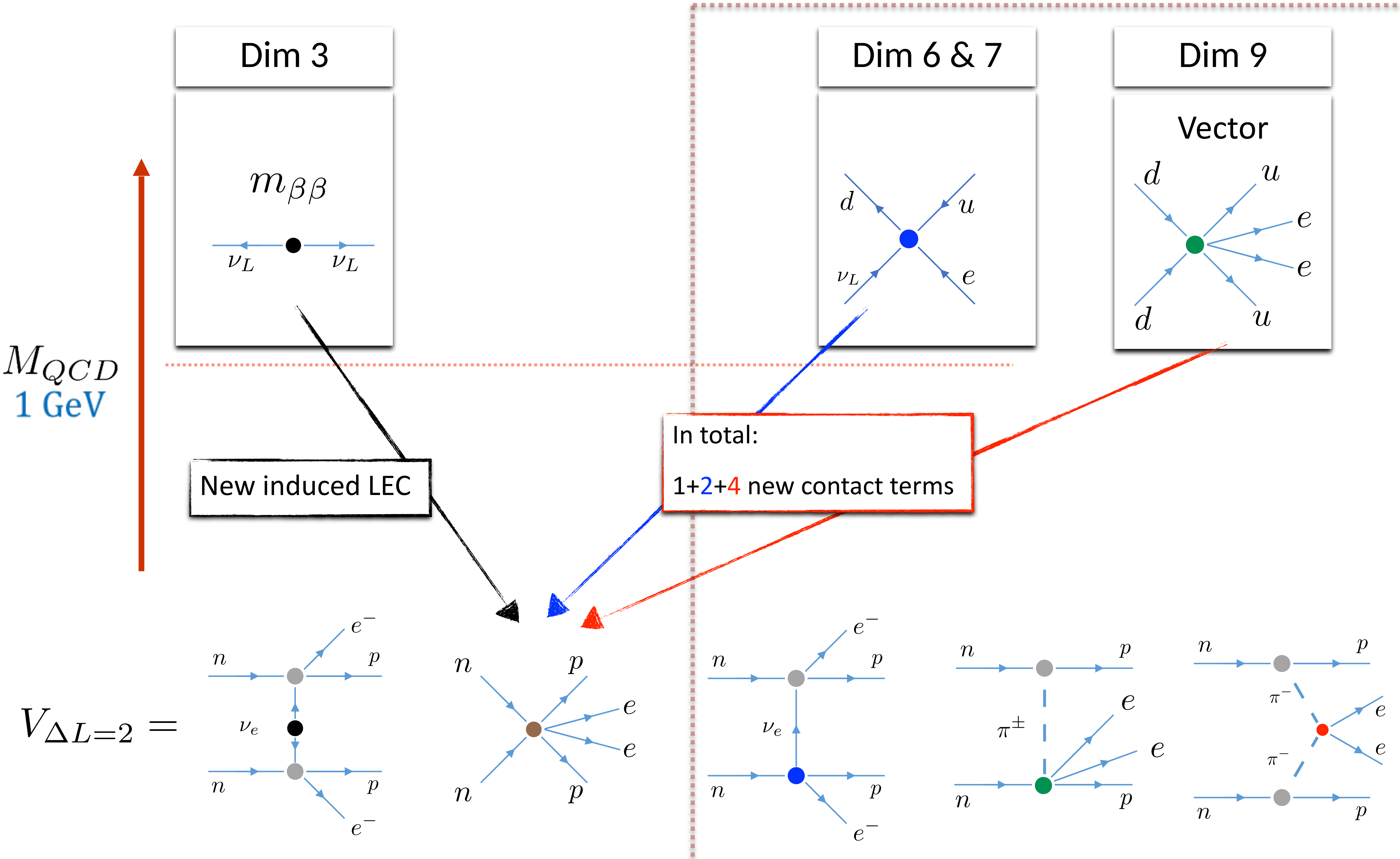

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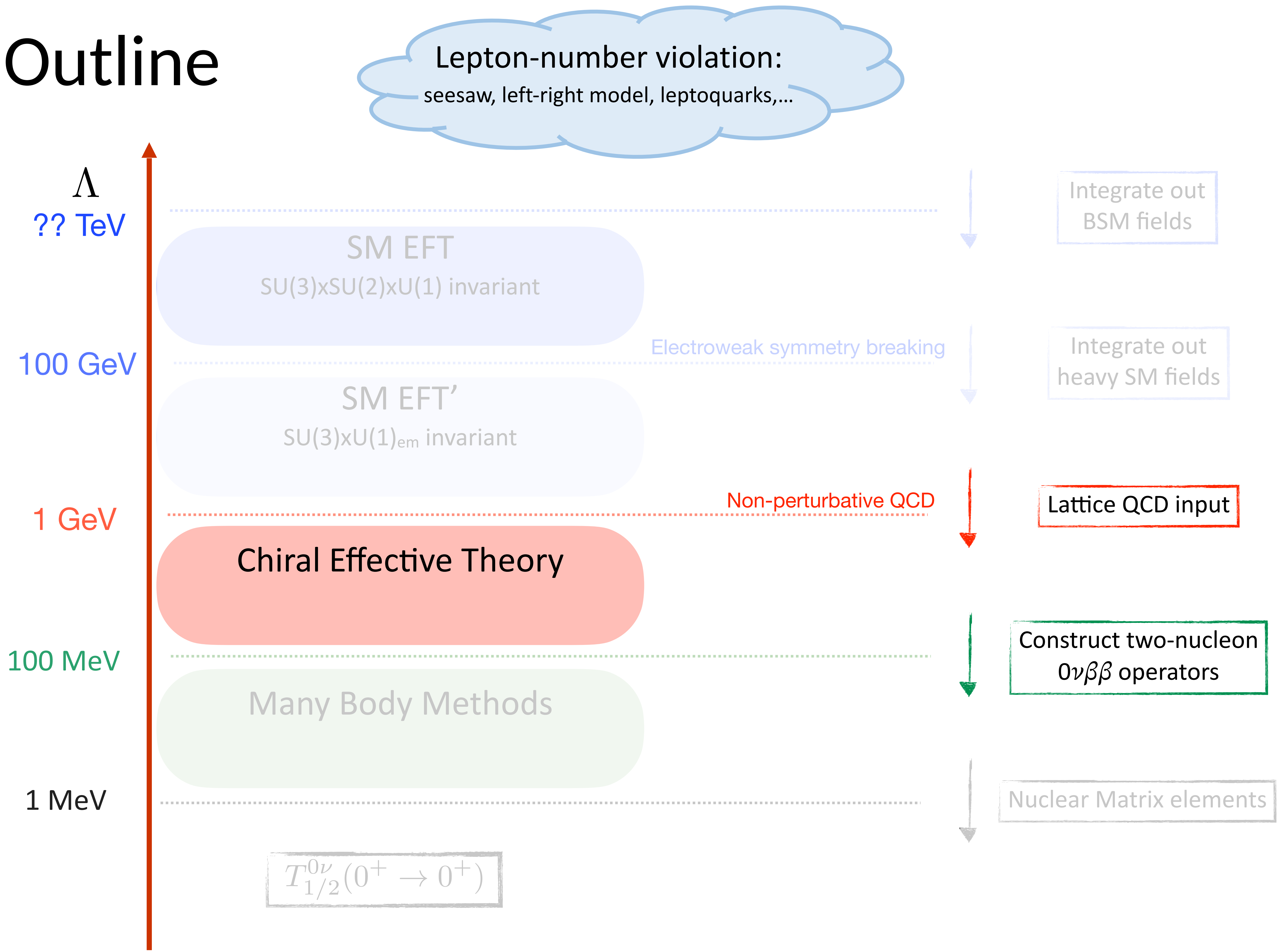

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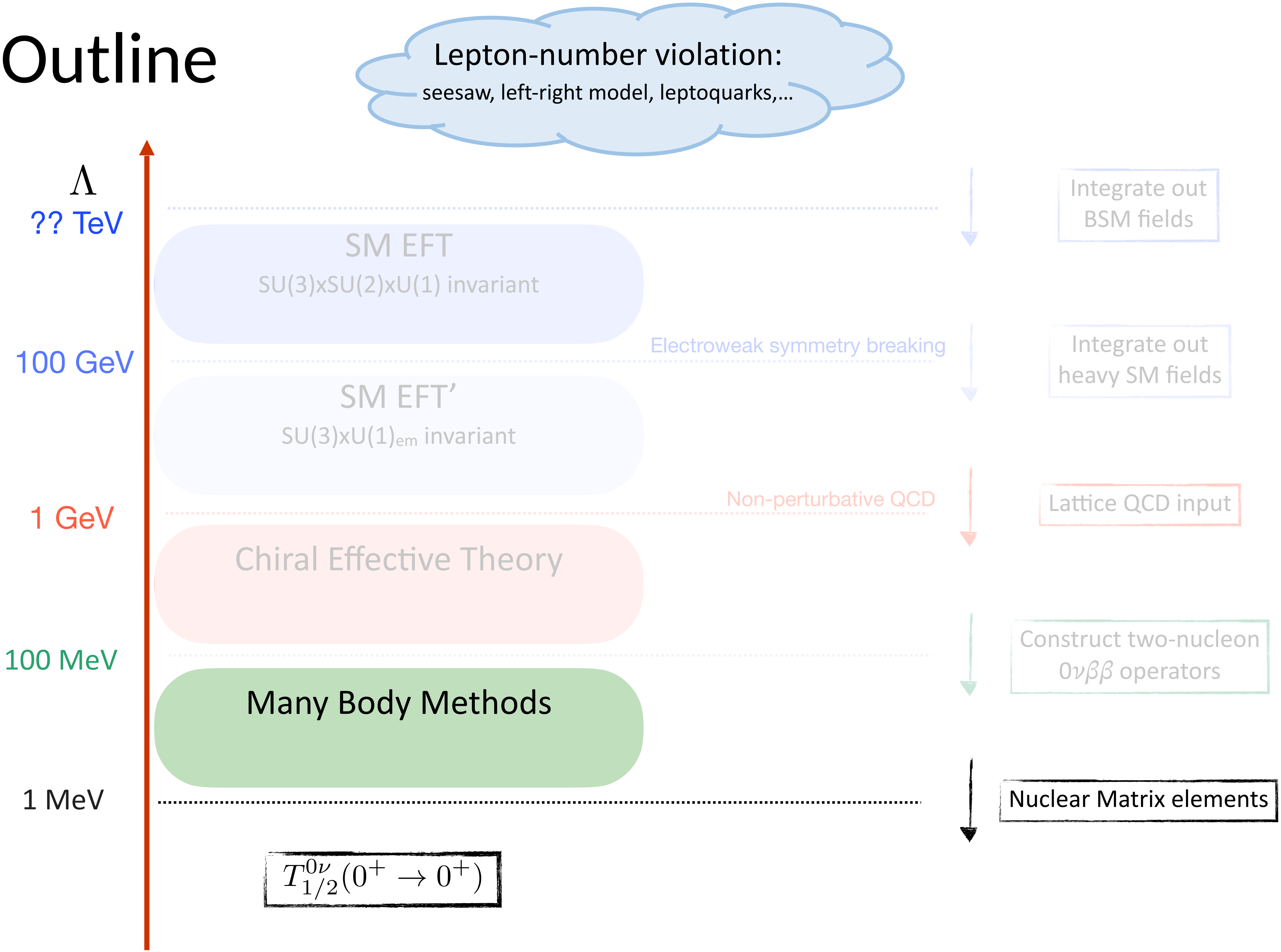

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Nuclear matrix elements

- All NMEs can be obtained from literature*
  - 9 long-distance & 6 short-distance
- Follow LO ChiPT relations fairly well

NMEs	^{76}Ge			
	[74]	[31]	[81]	[82, 83]
M_F	-1.74	-0.67	-0.59	-0.68
M_{GT}^{AA}	5.48	3.50	3.15	5.06
M_{GT}^{AP}	-2.02	-0.25	[illegible]	[illegible]
M_{GT}^{PP}	0.66	0.33	[illegible]	[illegible]
M_{GT}^{MM}	0.51	0.25	[illegible]	[illegible]
M_T^{AA}	–	–	[illegible]	[illegible]
M_T^{AP}	-0.35	0.01	[illegible]	[illegible]
M_T^{PP}	0.10	0.00	[illegible]	[illegible]
M_T^{MM}	-0.04	0.00	[illegible]	[illegible]

NMEs	^{76}Ge			
$M_{F,\,sd}$	-3.46	-1.55	-1.46	-1.1
$M_{GT,\,sd}^{AA}$	11.1	4.03	4.87	3.62
$M_{GT,\,sd}^{AP}$	-5.35	-2.37	-2.26	-1.37
$M_{GT,\,sd}^{PP}$	1.99	0.85	0.82	0.42
$M_{T,\,sd}^{AP}$	-0.85	0.01	-0.05	-0.97
$M_{T,\,sd}^{PP}$	0.32	0.00	0.02	0.38

Barea et al. ’15; Hyvarinen et al, ’15; Horoi et al. ’17, Menendez et al, ’18; Agostini et al. `22

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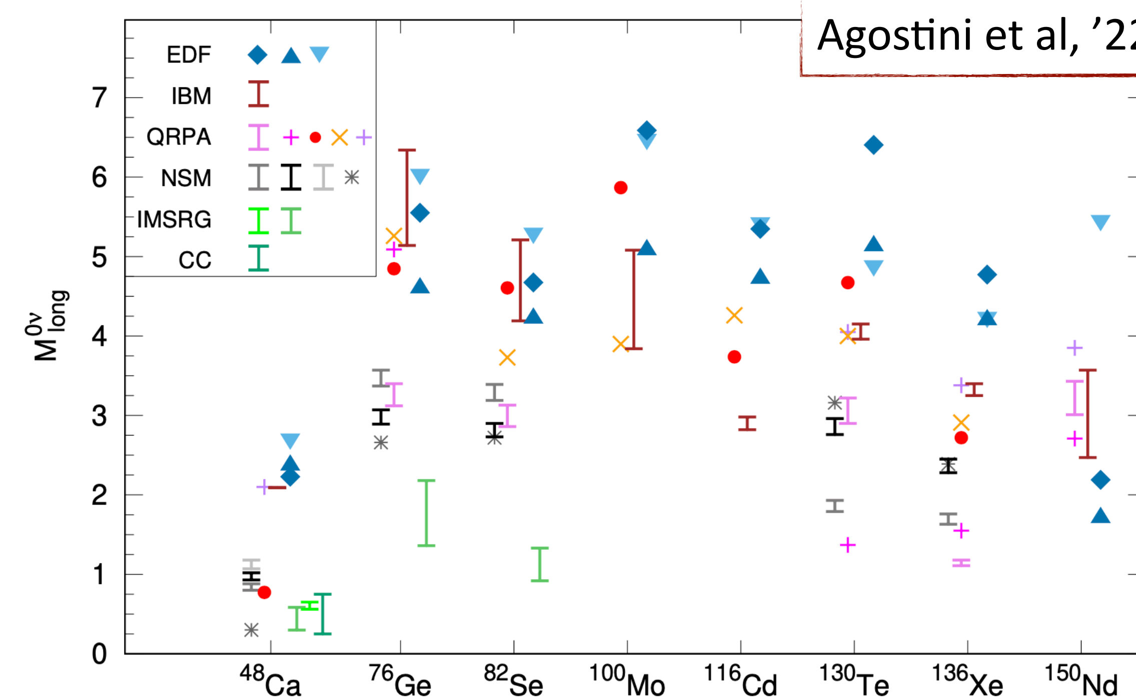
- The NMEs differ by a factor 2-3 between methods
- *Ab initio* NMEs for $A \geq 48$ are starting to appear

Belley et al ’23,’20; Yao et al ’20; Wirth, Yao, Hergert ‘21

Estimate effect of g_ν^{NN} to be $\sim 40-90\,\%$



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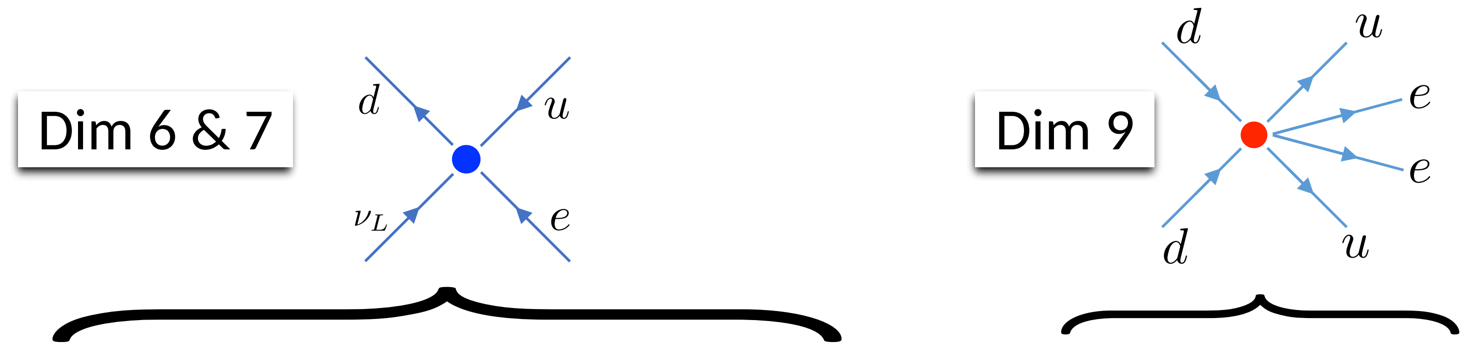
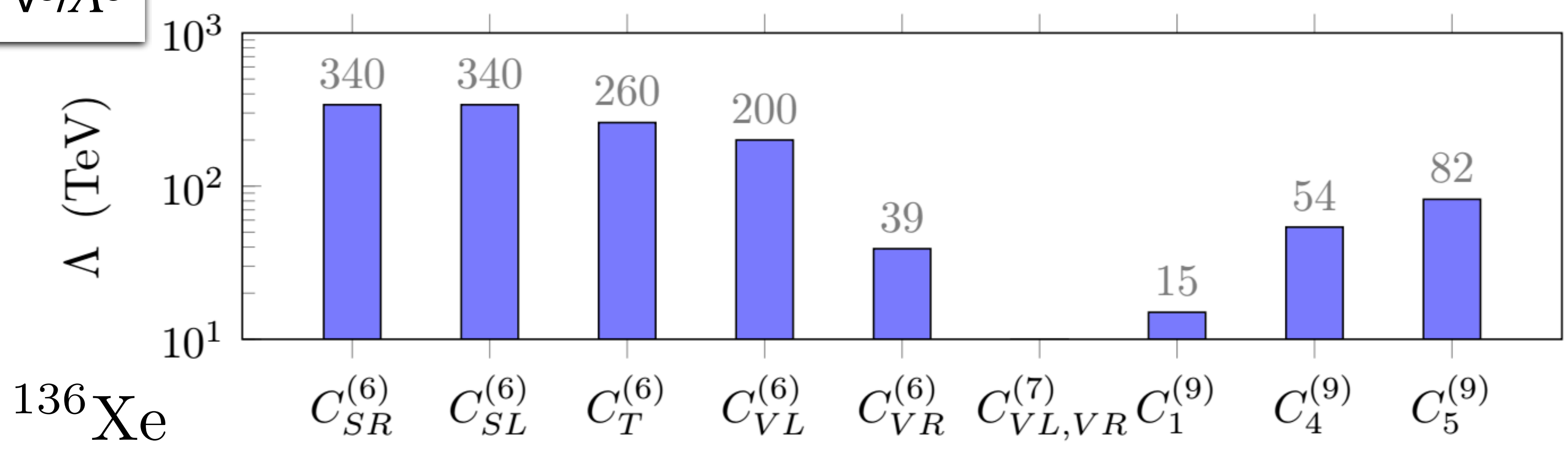
Phenomenology

Phenomenology

From heavy new physics



- Couplings with $C_i \sim v^3/\Lambda^3$



- O(1) uncertainties:
  - Unknown LECs
  - Nuclear Matrix elements

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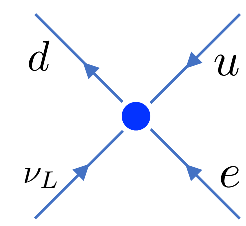
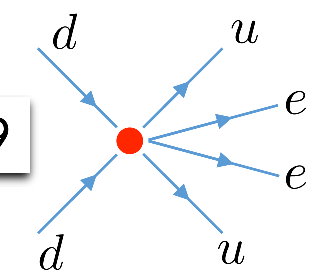
Dim 6 & 7



Dim 9



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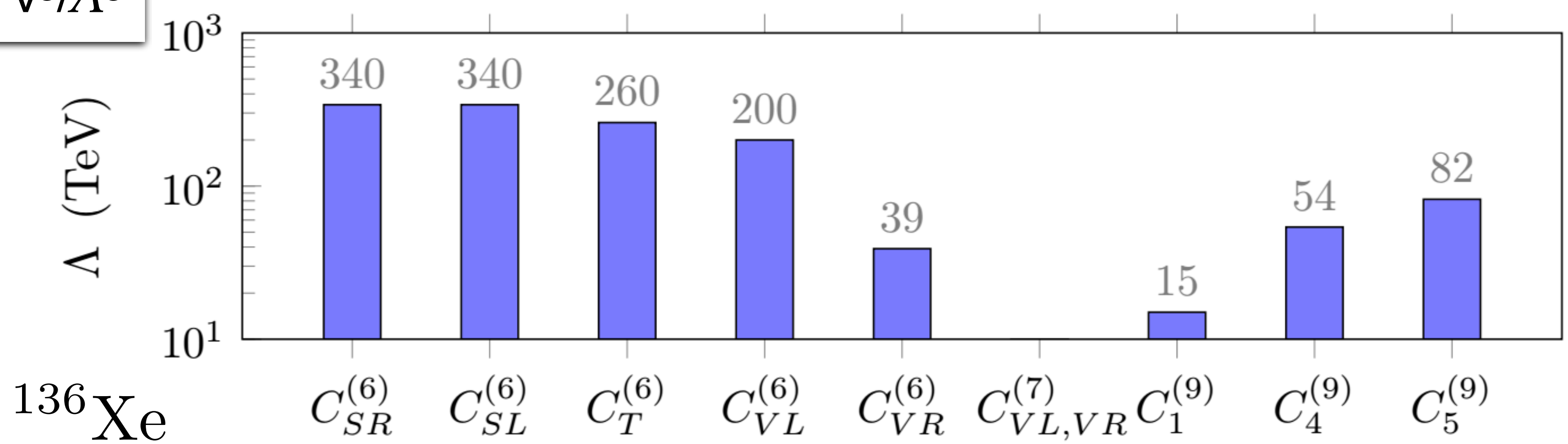
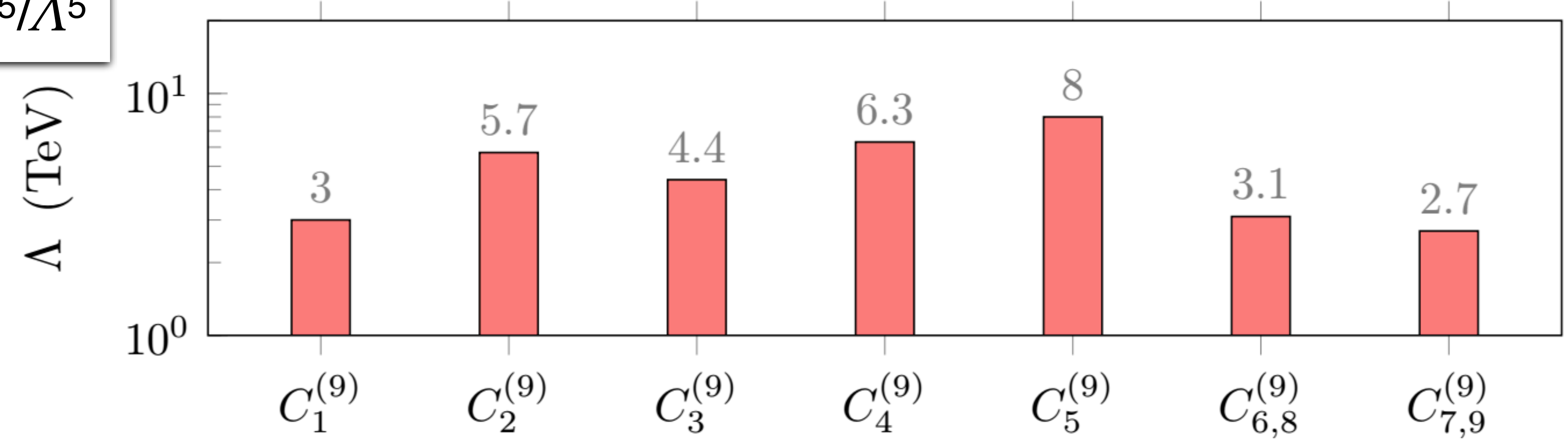


- Couplings with $C_i \sim v^5/\Lambda^5$



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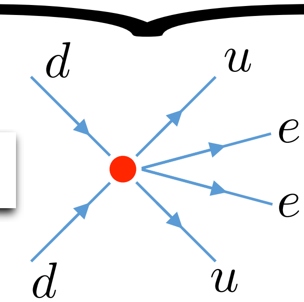

Light lepton-number violation: ν_R

Including sterile neutrinos

- ν_R's can help solve several SM deficiencies:
  - Neutrino masses
  - Leptogenesis
  - Dark matter candidate
- Appear in numerous BSM models: Left-Right/Leptoquarks/GUTs..

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$$\mathcal{L}_{\nu_R} = i\bar{\nu}_R \partial\!\!\!/ \nu_R - \frac{1}{2}\bar{\nu}^c_R M_R \nu_R - \bar{L}\tilde{H} Y_D \nu_R + \mathcal{L}^{(6)}_{\nu_R} + \mathcal{L}^{(7)}_{\nu_R}$$

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- Majorana mass (L violating)

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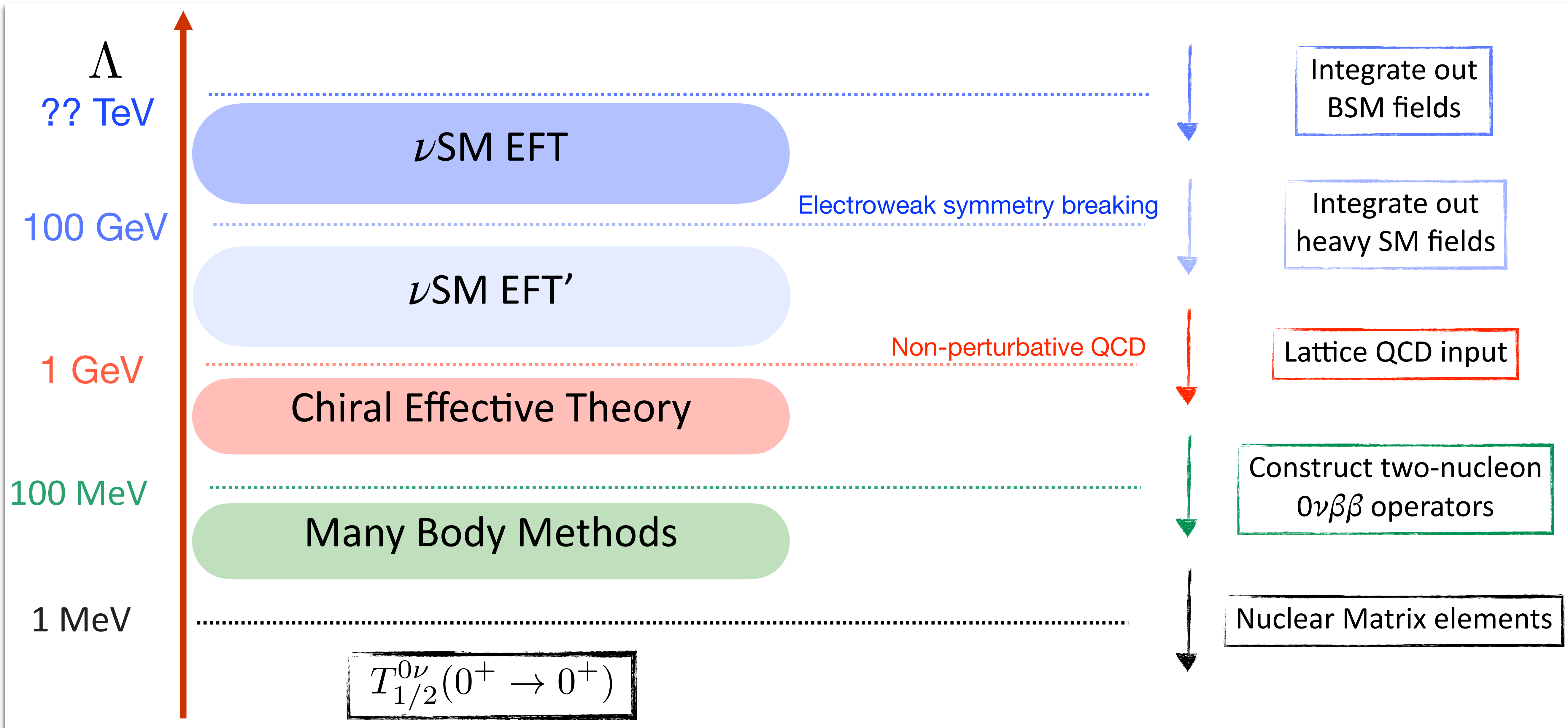
- Higher-dimensional operators
  - Induced by heavy BSM physics

Sterile neutrinos

Can now go through the same steps as before:



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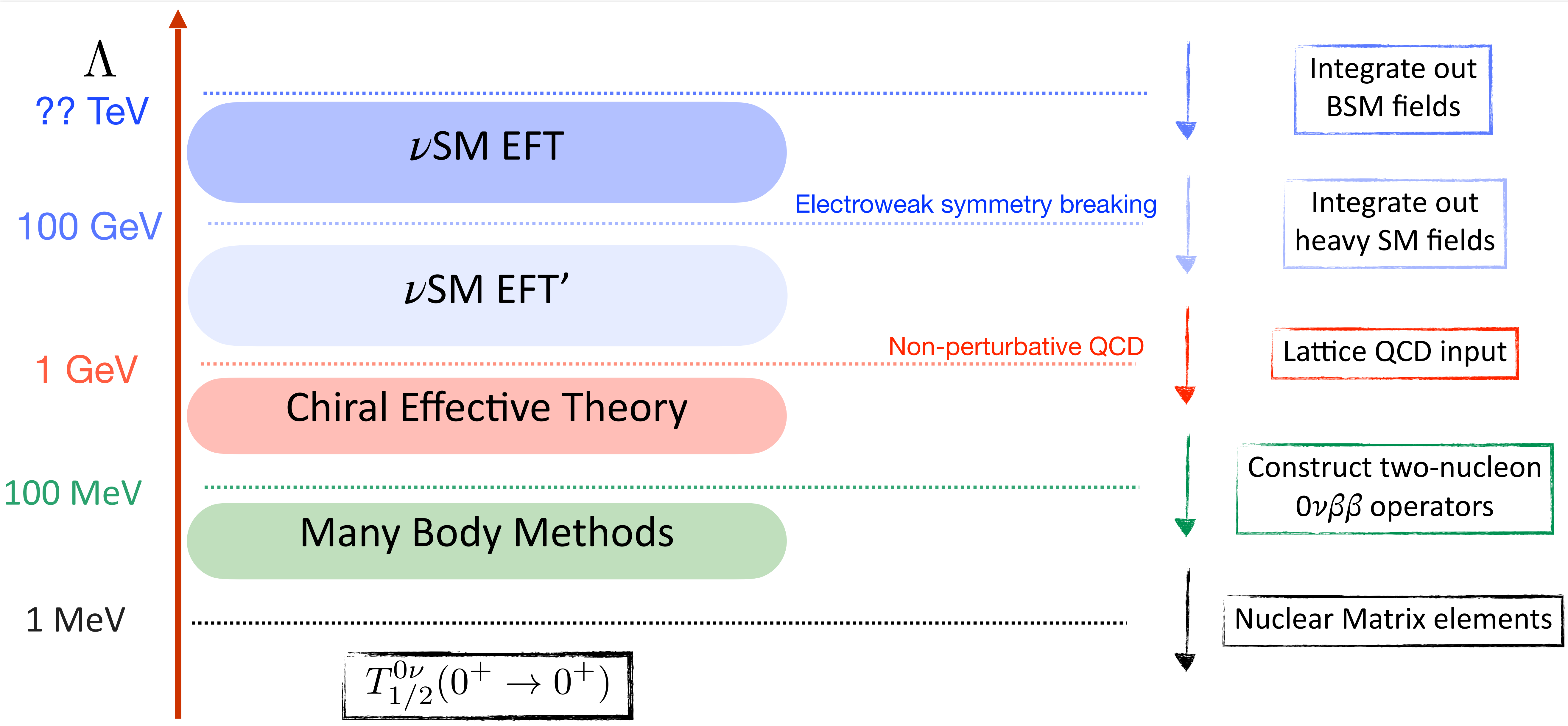

- When/if ν_R can be integrated out depends on m_{ν_R}
- LECs and NMEs now depend on m_{ν_R}

Example:
minimal ν_R scenario

Minimal ν_R scenario

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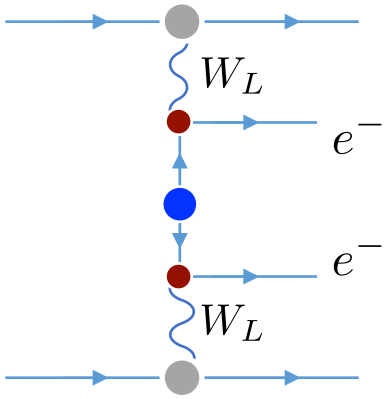

$$\propto \sum_{i=1}^{3+n} \frac{m_i}{q^2 - m_i^2} U_{ei}^2$$

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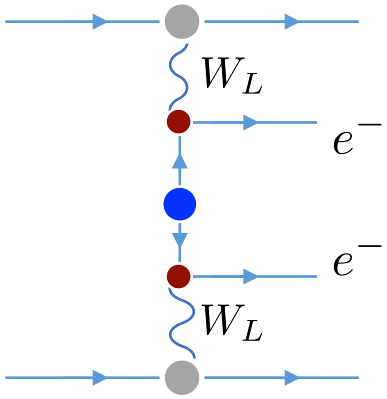

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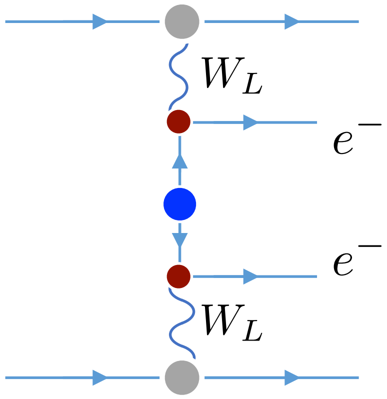

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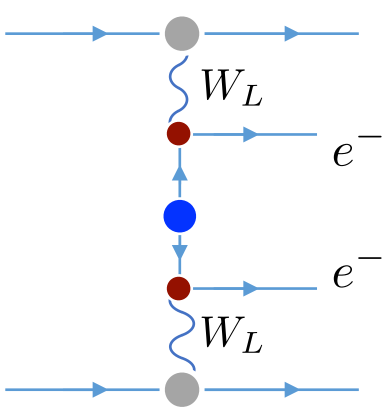

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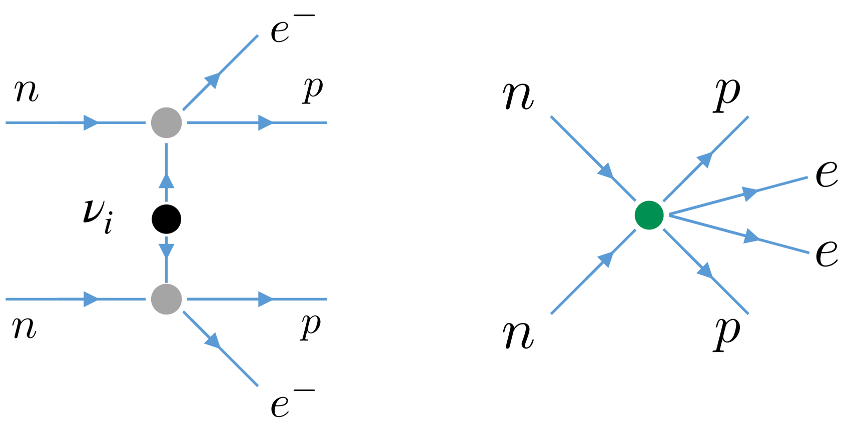
Need to keep track of m_i *dependence!*

ν_i contributions

`Usual' contributions:

- Similar to $m_{\beta\beta}$ case:
  - NMEs and LECs now m_i dependent

$$V_{\Delta L=2} =$$



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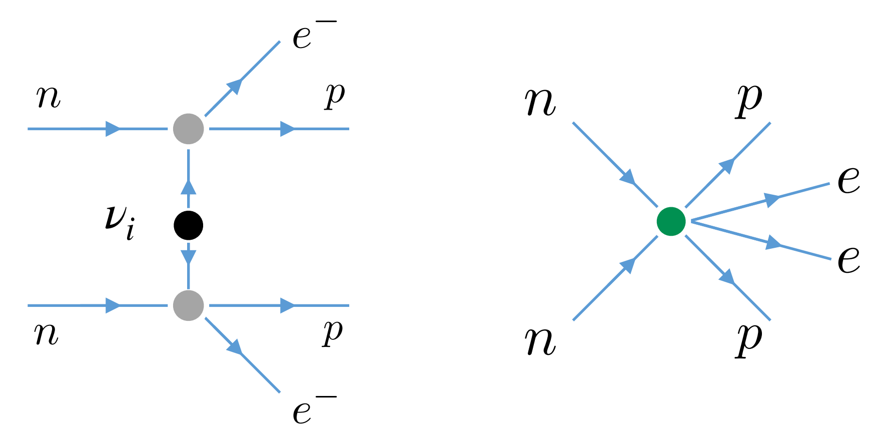

New: 'Ultrasoft' neutrinos

G. Zhou, J. de Vries, E. Mereghetti, J. Menéndez, P. Soriano, WD '23

- Neutrinos with momenta $q^0 \sim \vec{q} \sim k_F^2/m_N$
  - See to the nucleus as a whole
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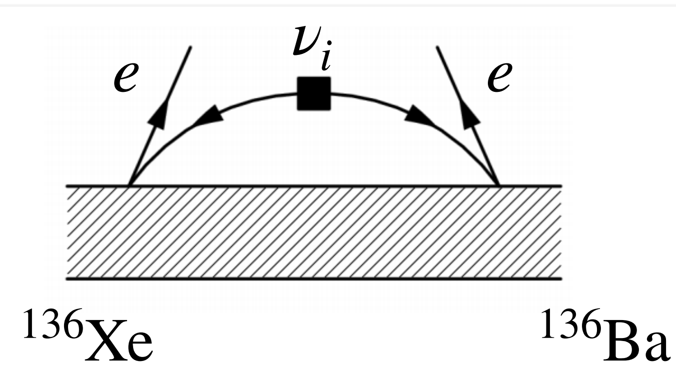
Cirigliano et al, '17



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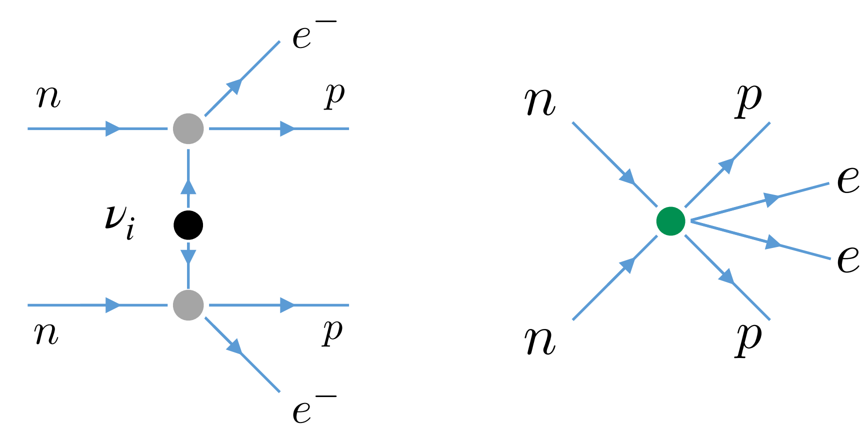

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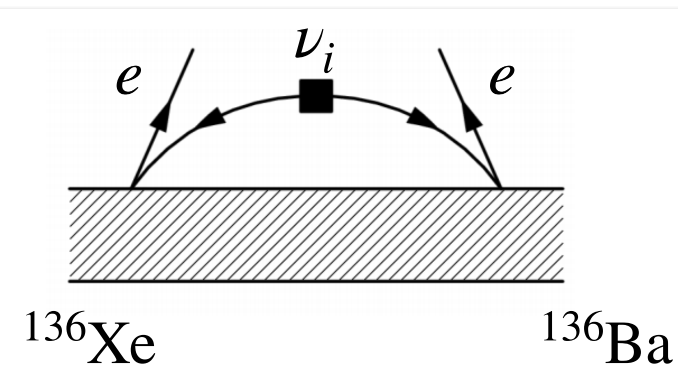

$$A_\nu^{\rm usoft} \sim \sum_n \langle f | J_\mu | n \rangle \langle n | J^\mu | i \rangle \times \begin{cases} \dfrac{m_i}{k_F}, & \Delta E \lesssim m_i \lesssim k_F \\ \dfrac{m_i^2}{4\pi k_F \Delta E} \ln \dfrac{m_i}{\Delta E}, & m_i \lesssim \Delta E \end{cases}$$

- Depends on intermediate state energies, $\Delta E \equiv E_n + E_e - E_i$
- Overlap integrals

Phenomenology:
A toy model

Toy model: 1+1+1 pseudo-Dirac

- Involves 1 active, two sterile neutrinos
  - Assume steriles much heavier than the active neutrinos; $M_1 \simeq M_2 \gg m_\nu$
  - Two heavier ν's, form a pseudo-Dirac pair
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Bolton et al, 2020; Mohapatra et al, '86; Nandi and Sarkar '86;

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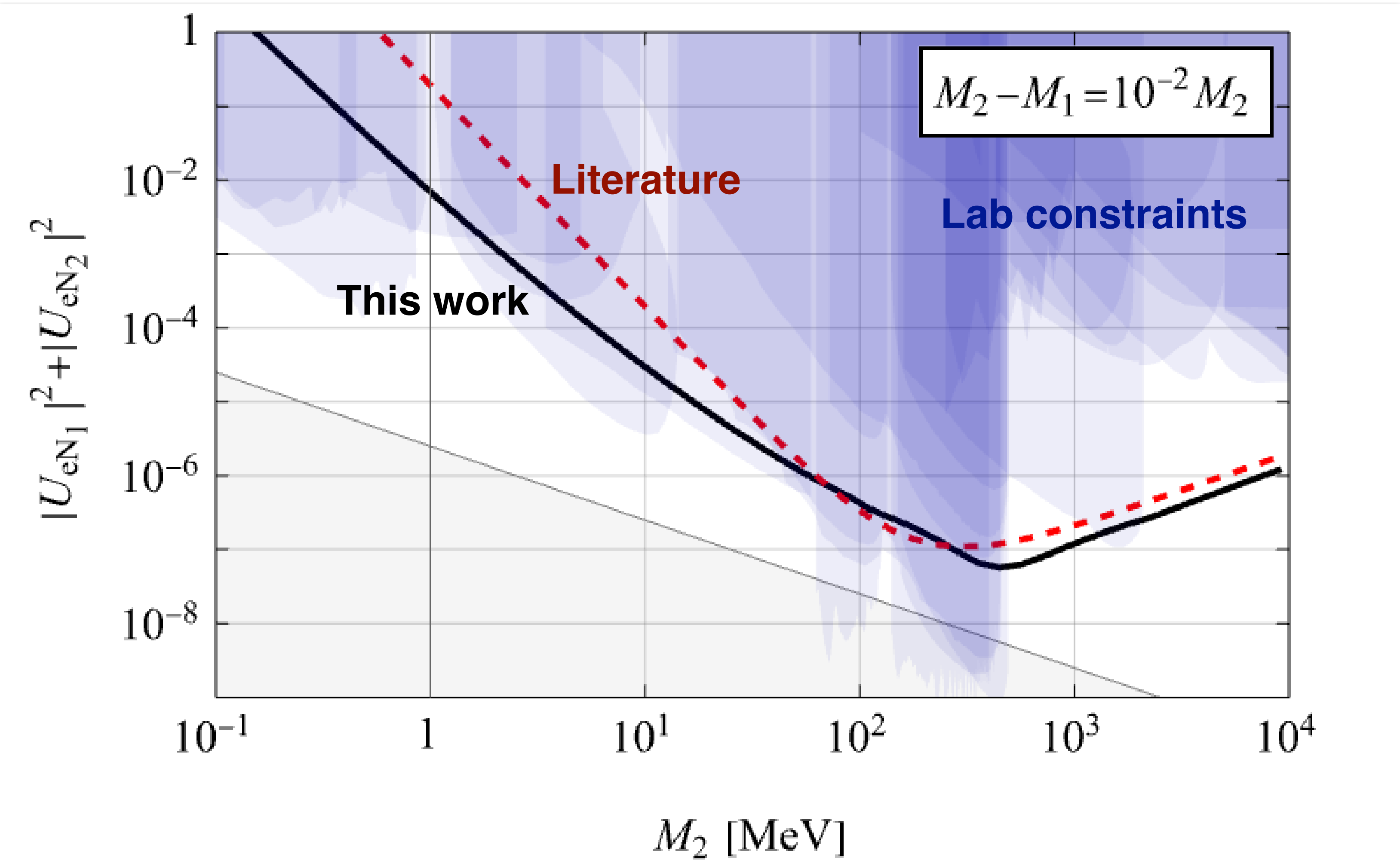

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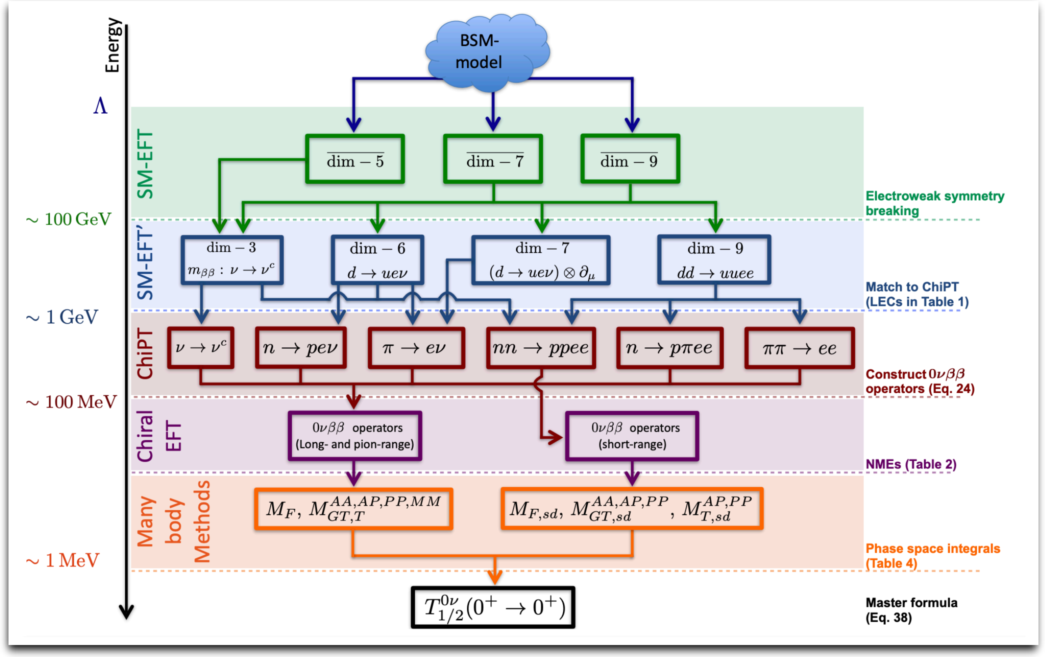
Summary

- EFTs allow one to systematically describe ΔL=2 sources
  - Standard mechanism (dim-5)
  - Dimension-7 & -9 sources
  - Effects from ν_R



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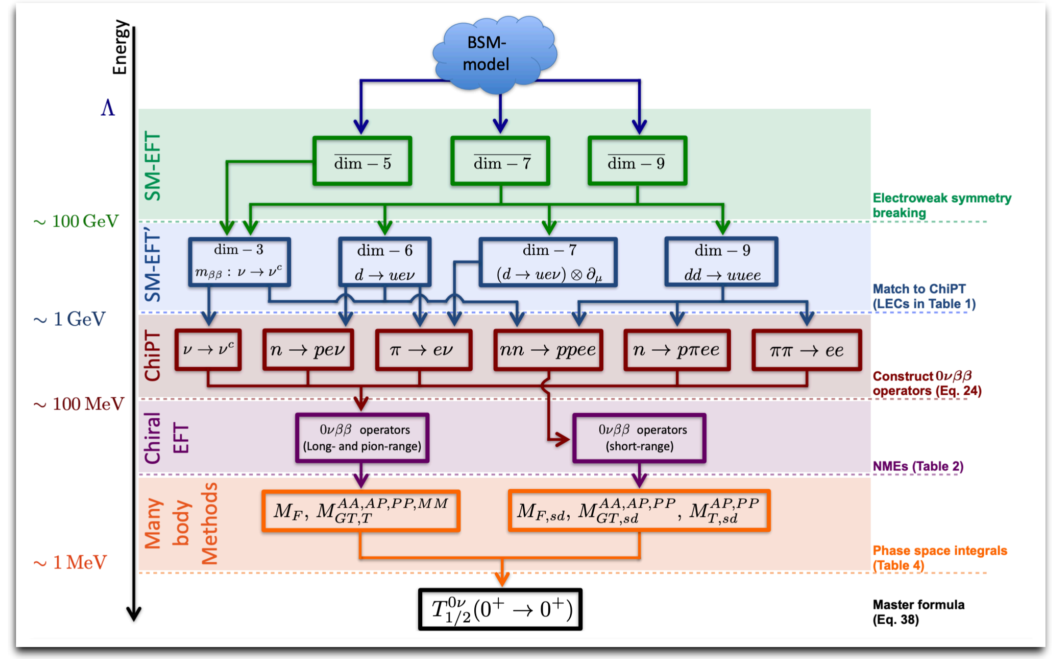
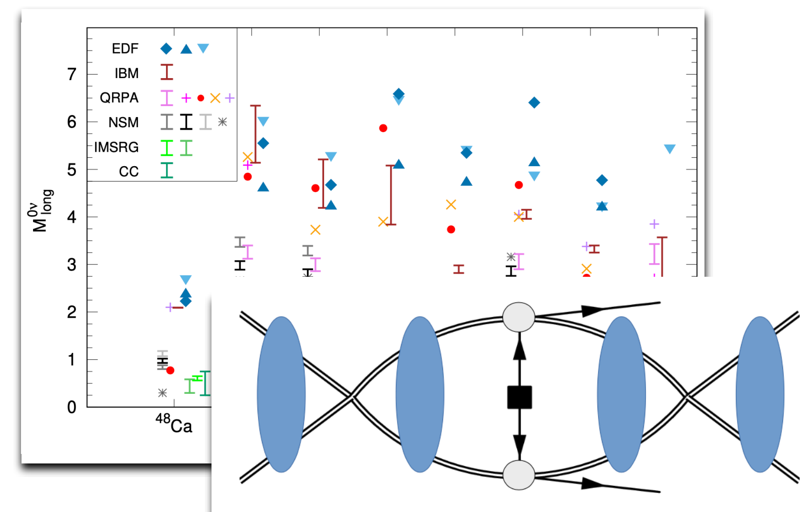


- Matching to chiral EFT involves unknown LECs
  - Renormalization requires terms beyond usual counting
- Needed Nuclear Matrix Elements determined in literature



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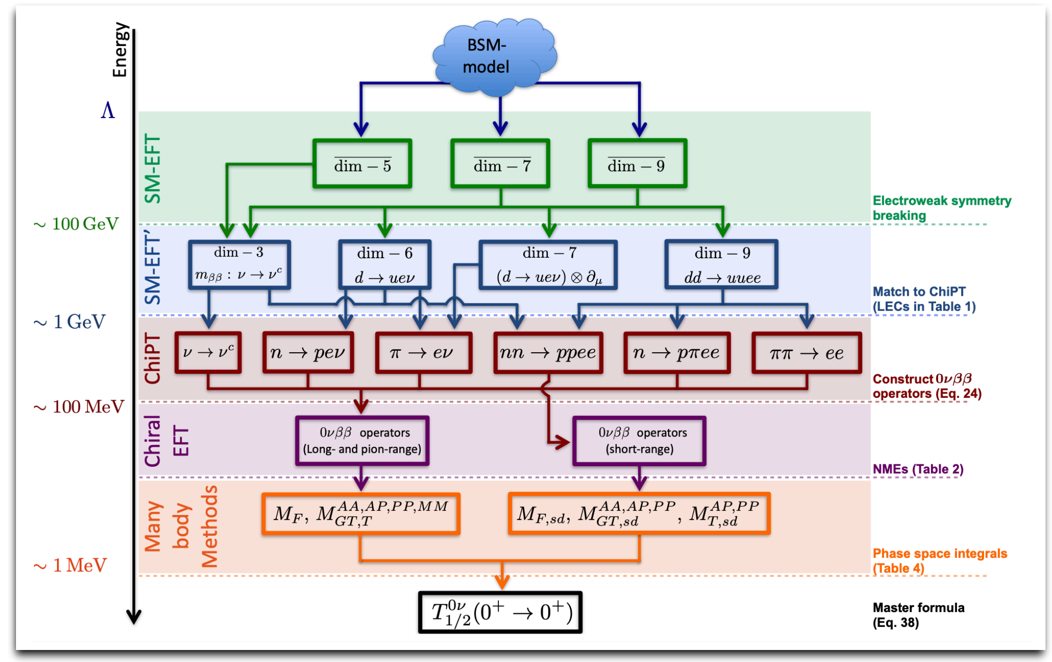

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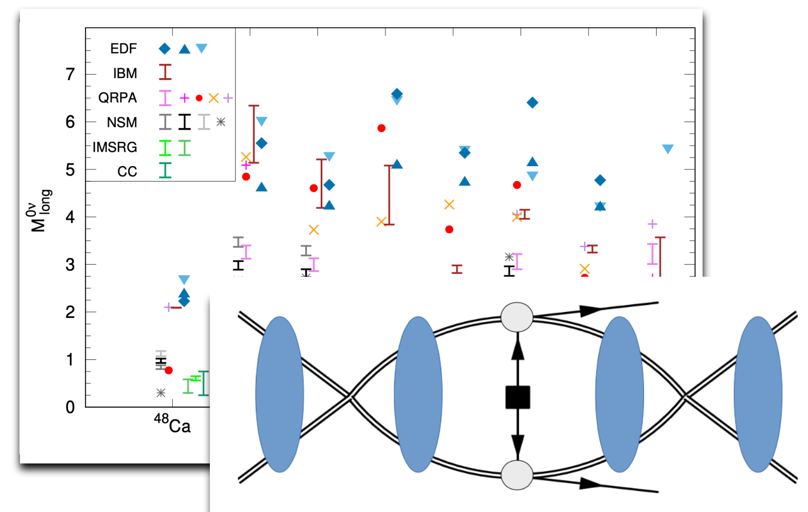
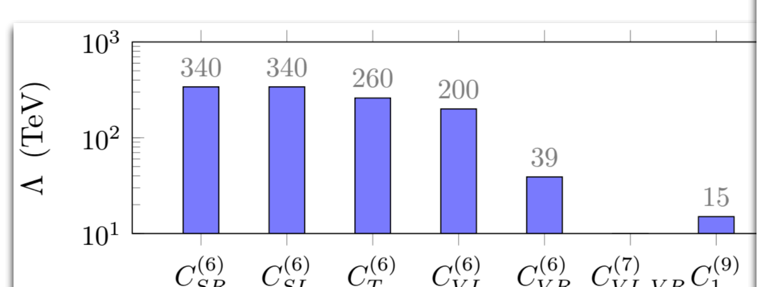
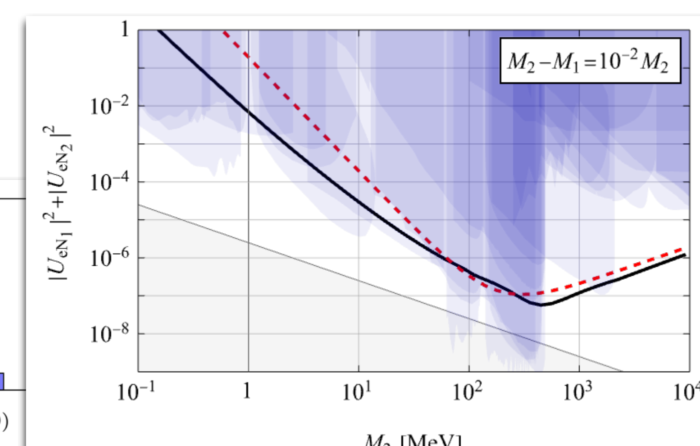


- $0\nu\beta\beta$ probes
  - Up to O(100) TeV scales heavy BSM
  - Light sterile ν_R interactions





Back up slides

Why dim 7, 9?

Effective Field Theory

Naive scaling of Dimension 5, 7, 9 operators

$$\mathcal{A}_{0\nu\beta\beta} \sim \frac{c_5}{\Lambda}\left[1 + \left(\frac{v}{\Lambda}\right)^2 \frac{c_7}{c_5} + \left(\frac{v}{\Lambda}\right)^4 \frac{c_9}{c_5}\right]$$

- $v/\Lambda \ll 1$ So why keep dimension 7 & 9?

$m_\nu \sim c_5 v^2/\Lambda$ Allows for relative enhancement:

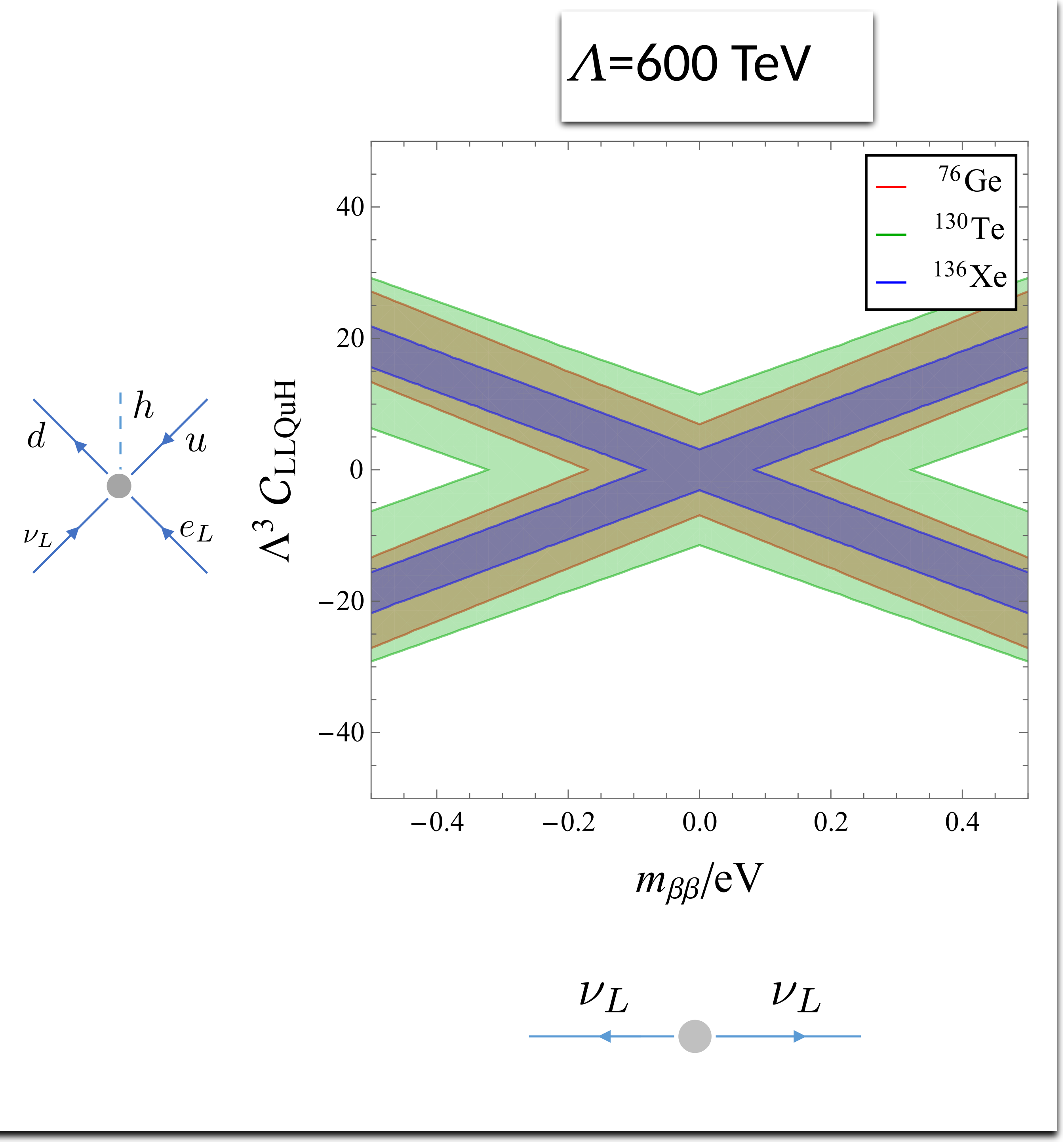
- $c_5 \ll O(1), \qquad \Lambda = \mathcal{O}(1-100)\text{TeV}$
  - Relative enhancement of higher-dimensional terms due to $c_{7,9}/c_5 \gg 1$
- Happens, for example, in the left-right model

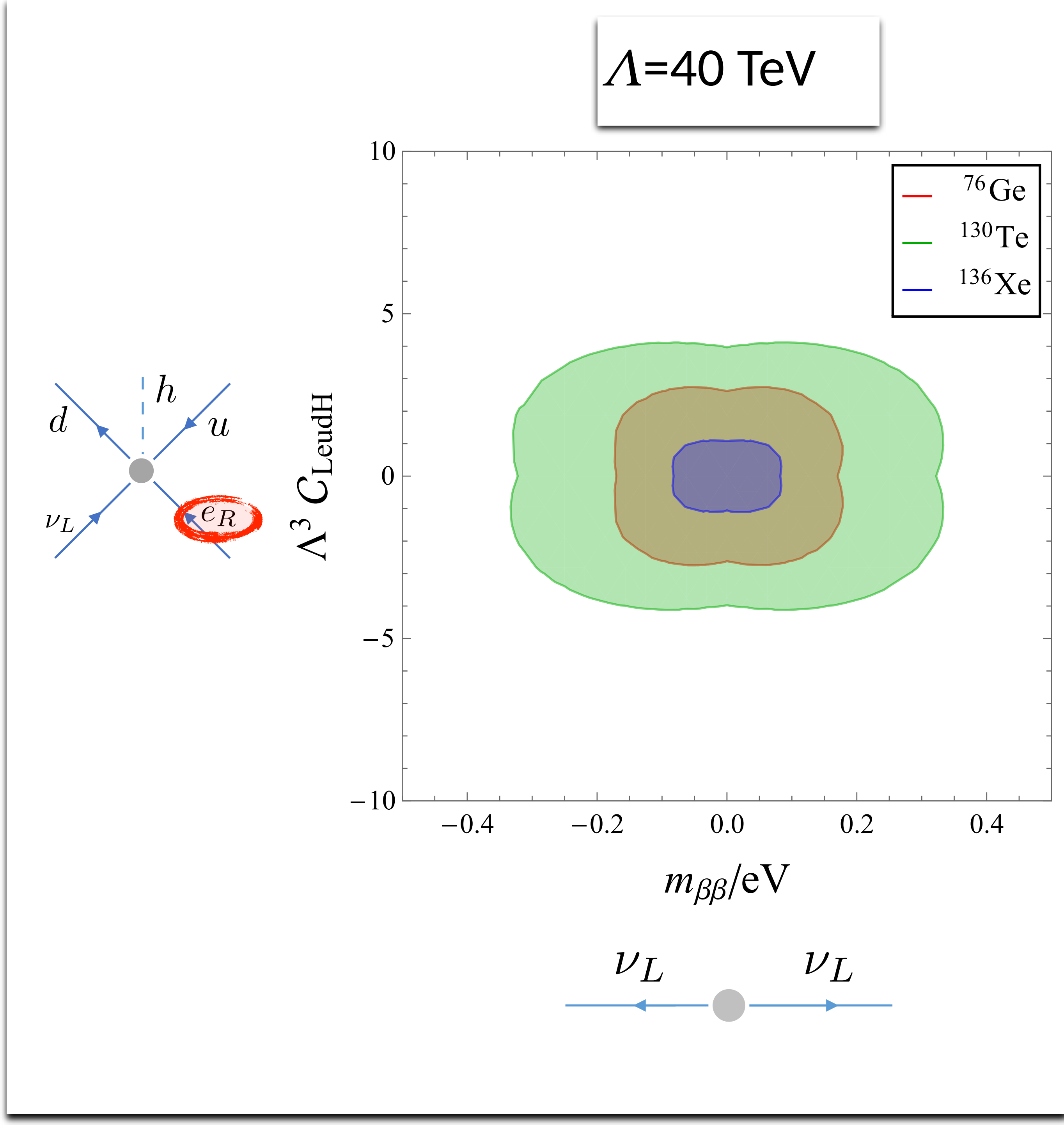
- However, if $c_5 = \mathcal{O}(1), \qquad \Lambda = 10^{15}\ \text{GeV}$
  - dimension-7, -9 irrelevant in this case

Disentangling operators

Phenomenology

From heavy new physics

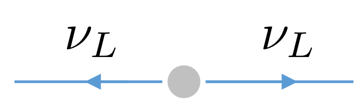




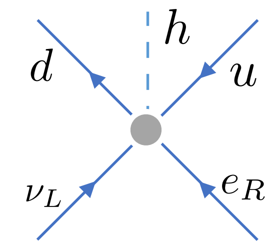
Disentangling operators

What if a $0\nu\beta\beta$ signal is measured?

- Picking the allowed values

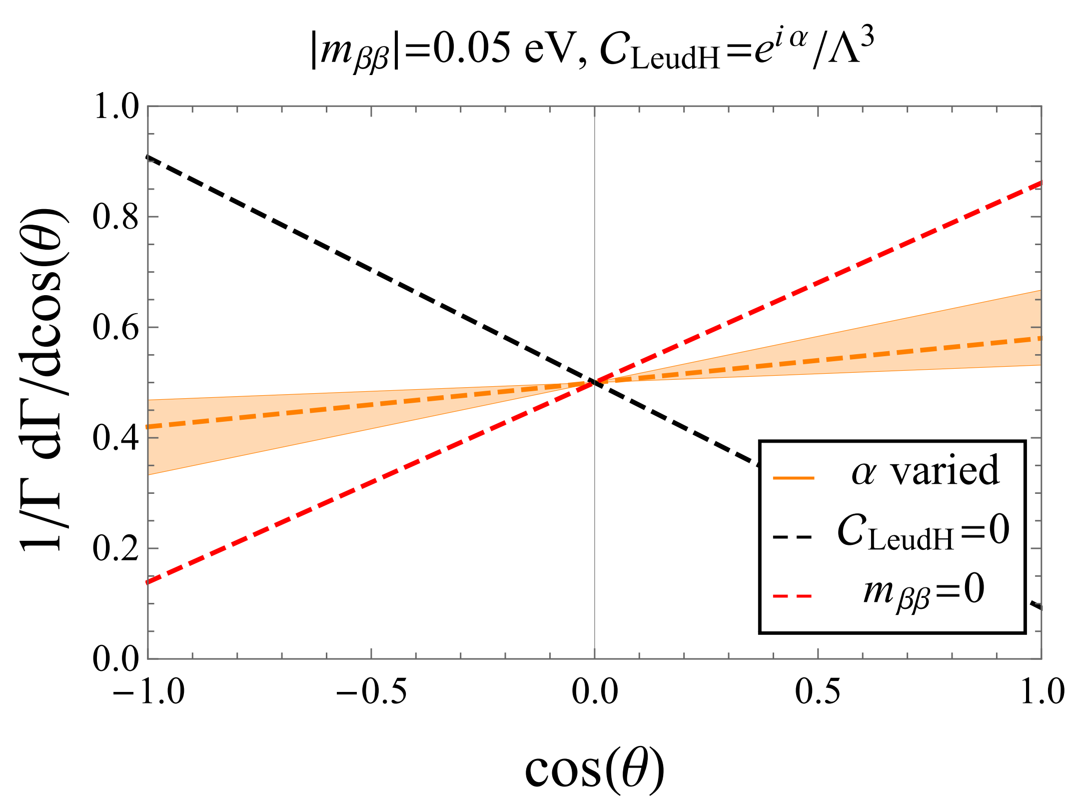


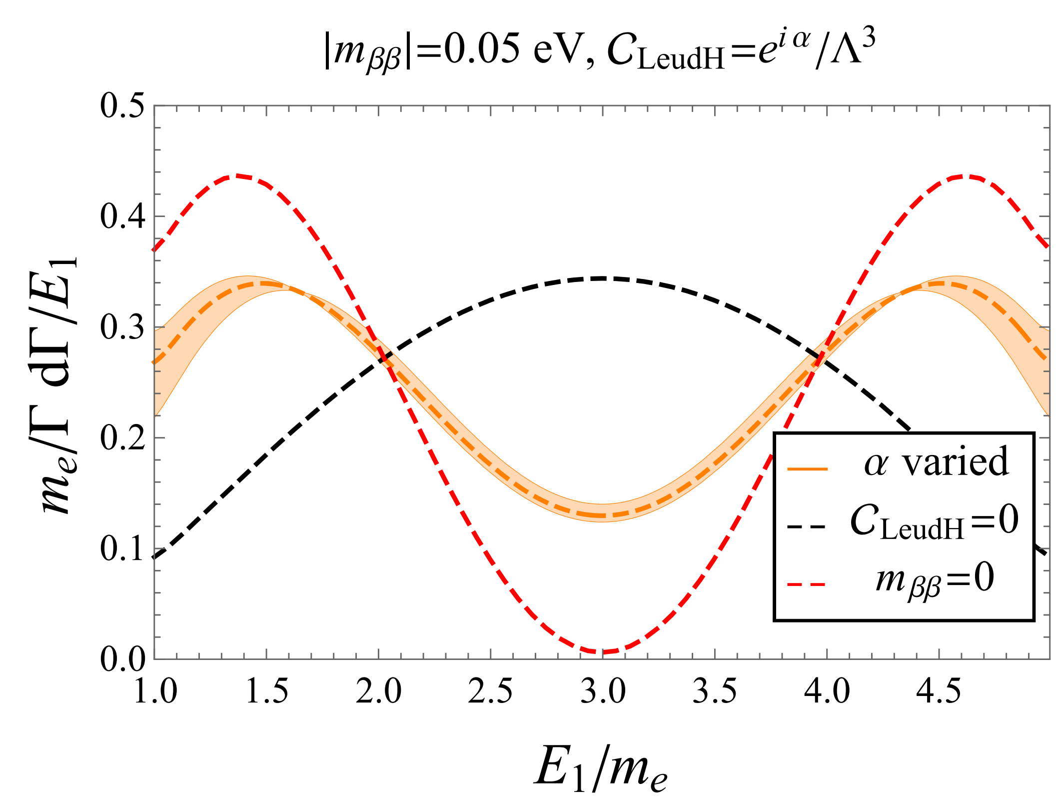
$m_{\beta\beta} = 0.05\,\text{eV}$



$\mathcal{C}_{\text{LeudH}} = e^{i\alpha}/\Lambda^3$

$\Lambda = 40\,\text{TeV}$

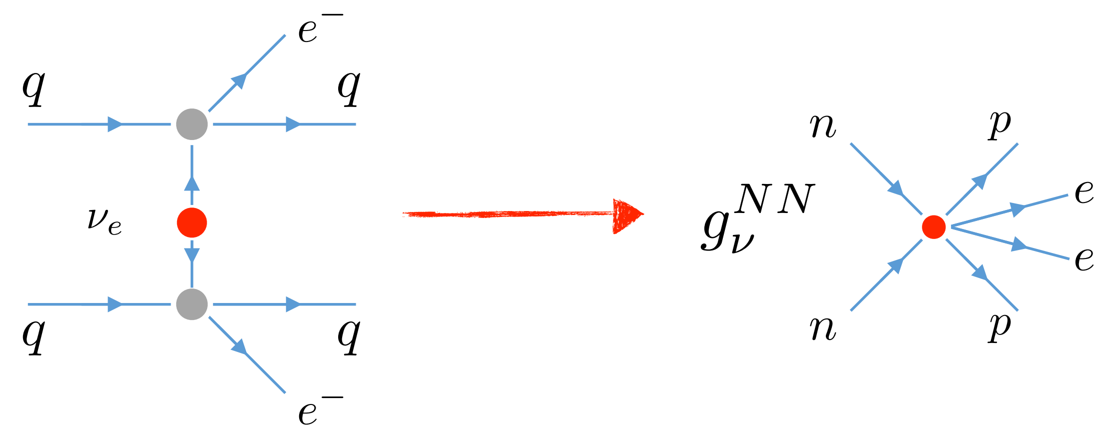




g_ν^{NN}: Relation to electromagnetism

Relation to electromagnetism

LNV contact term

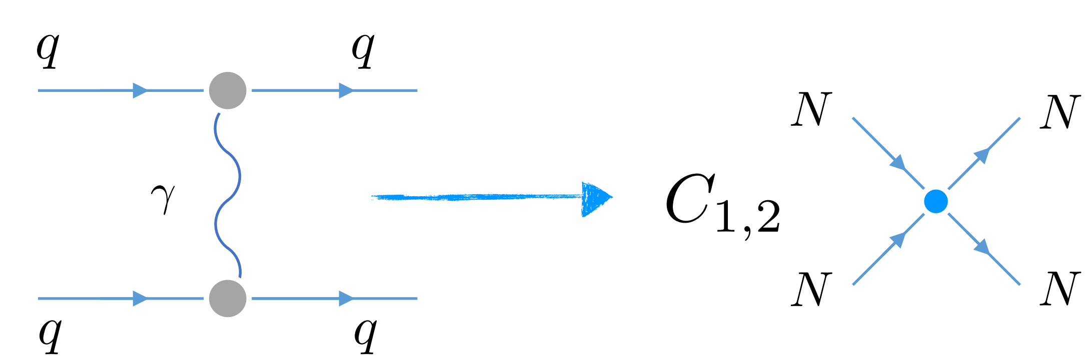


- Hard part of two Weak currents

$$\sim G_F^2 m_{\beta\beta}\langle NN|J_L^\mu(x)J_{L\,\mu}(y)|NN\rangle$$
$$\times \int \frac{d^4q}{(2\pi)^4}\frac{e^{iq\cdot(x-y)}}{q^2}$$

- Leptonic part combines to boson propagator

EM contact term



- Hard part of two EM currents

$$\sim e^2\langle NN|J_{\mathrm{EM}}^\mu(x)J_{\mathrm{EM}\,\mu}(y)|NN\rangle$$
$$\times \int \frac{d^4q}{(2\pi)^4}\frac{e^{iq\cdot(x-y)}}{q^2}$$

- Non-hadronic part is the photon propagator

The appearance of the photon propagator allows one to relate the two!

Relation to electromagnetism

- Only two ΔI=2 operators can be induced

$$O_1 = \bar{N}\mathcal{Q}_L N\,\bar{N}\mathcal{Q}_L N - \frac{\mathrm{Tr}\,\mathcal{Q}_L^2}{6}\bar{N}\vec{\tau}N\,\bar{N}\vec{\tau}N + (L \to R)$$

$$O_2 = \bar{N}\mathcal{Q}_L N\,\bar{N}\mathcal{Q}_R N - \frac{\mathrm{Tr}\,\mathcal{Q}_L\mathcal{Q}_R}{6}\bar{N}\vec{\tau}N\,\bar{N}\vec{\tau}N + (L \leftrightarrow R)$$

with spurions

$$\mathcal{Q}_L = u^\dagger Q_L u, \quad \mathcal{Q}_R = u Q_R u^\dagger,$$

$$u = \exp\left(i\pi \cdot \tau/2F_\pi\right)$$

EM

$$\mathcal{L}_{em} = e^2/4\,(C_1 O_1 + C_2 O_2)$$

$$Q_L = Q_R = \tau^3/2$$

LNV

$$\mathcal{L}_{LNV} = g_\nu^{NN} G_F^2 m_{\beta\beta} O_1\,\bar{e}e^c$$

$$Q_L = \tau^+, \qquad Q_R = 0$$

Chiral symmetry

$$g_\nu^{NN} = C_1$$

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$$Q_L = Q_R = \tau^3/2$$

LNV

$$\mathcal{L}_{LNV} = g_\nu^{NN} G_F^2 m_{\beta\beta} O_1\,\bar{e}e^c$$

$$Q_L = \tau^+, \qquad Q_R = 0$$

- EM induces an extra term
  - Equivalent up to 2 pions
  - Hard to disentangle

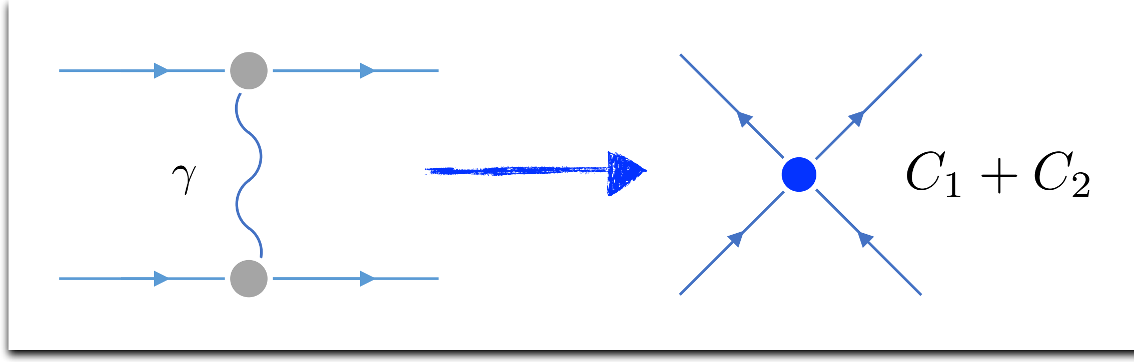
Chiral symmetry

$$g_\nu^{NN} = C_1$$

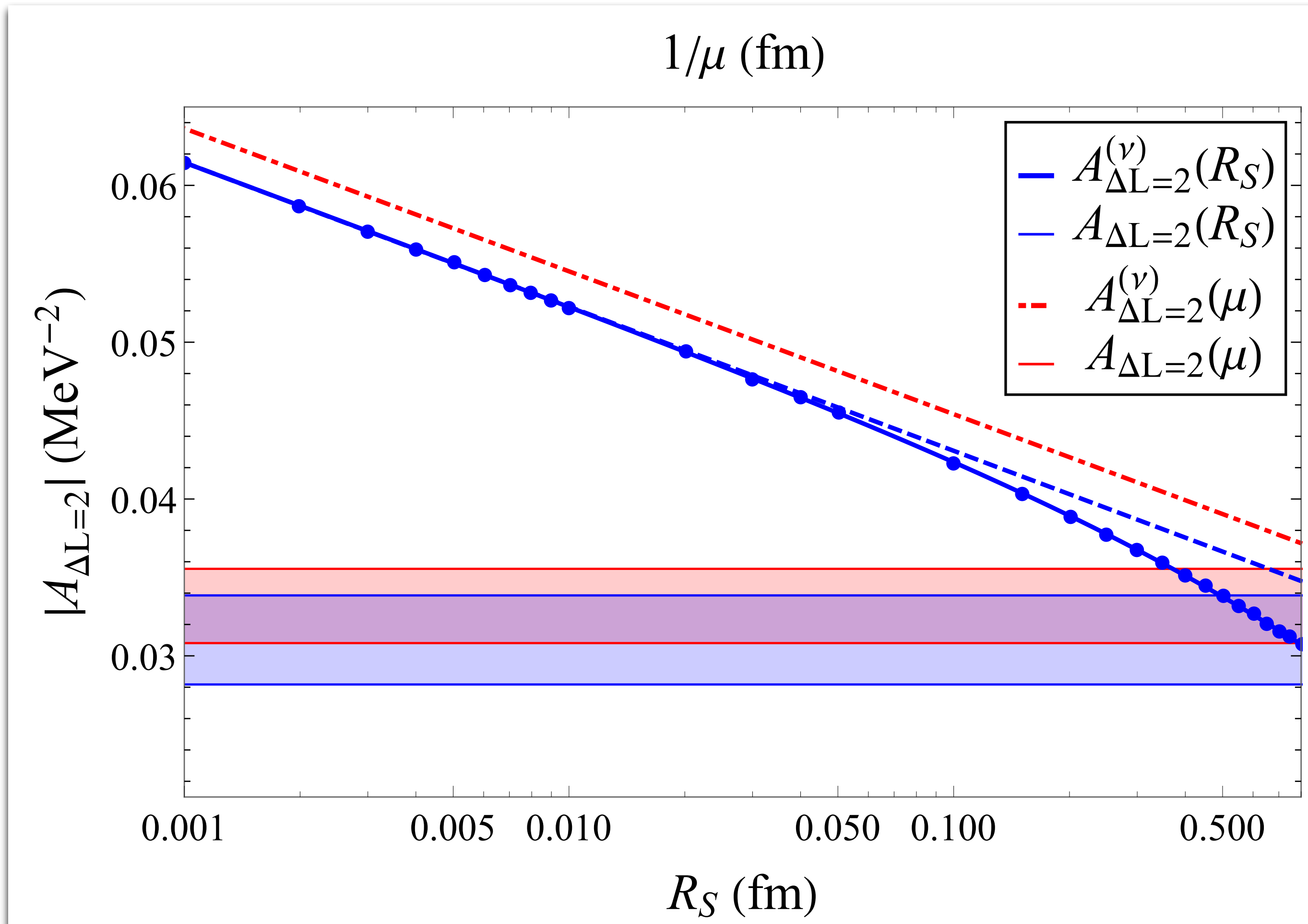
Relation to electromagnetism

- ΔI=2 in NN scattering

- Charge-independence breaking $(a_{nn} + a_{pp})/2 - a_{np}$
  - From photon exchange & the pion mass difference
  - $C_1 + C_2$ (needed at LO in isospin breaking)



- Allows an estimate of g_ν^{NN}
  - Extract $C_1 + C_2$ from CIB
  - Assume $g_\nu^{NN}(\mu) = \dfrac{C_1(\mu) + C_2(\mu)}{2}$
  - Roughly 10% effect for Rs = 0.6 fm
  - Uncontrolled error



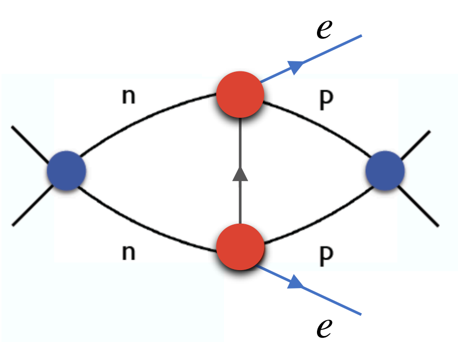
g_ν^{NN}: Estimate from Cottingham approach

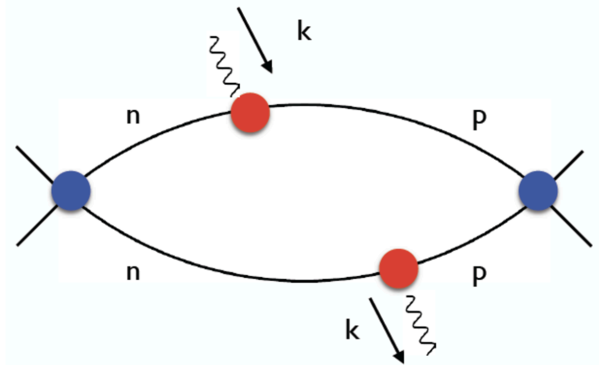
Determination of the counterterm

Cirigliano, (WD) et al, '20, '21

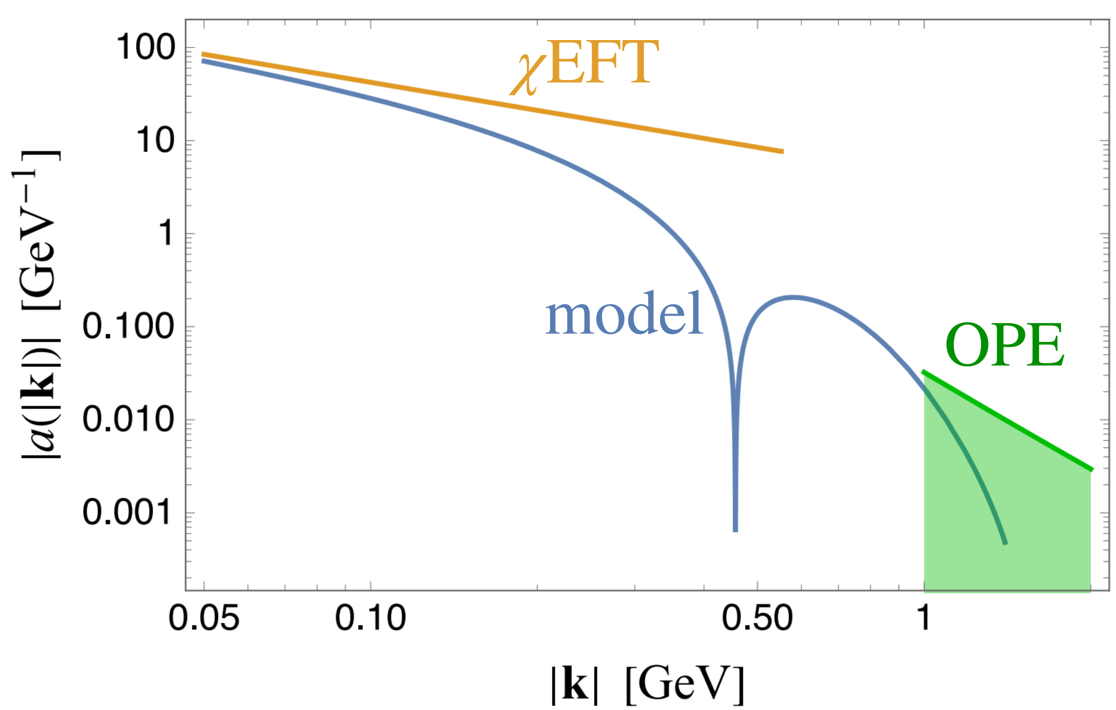
- Analogy to the Cottingham approach for pion/nucleon mass differences

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\mu\nu}}{k^2+i\epsilon} \int d^4x\, e^{ik\cdot x} \langle pp|T\{j_{\rm w}^\mu(x) j_{\rm w}^\nu(0)\}|nn\rangle$$

$\mathcal{A}_\nu =$ 

$\propto \int dk\, a(k) = \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2+i\epsilon}$ 

- Estimate the A_ν by constraining the integrand
  - $k \ll \Lambda_\chi$ region determined by χEFT
  - $k \gg$ GeV region determined by OPE
  - Model intermediate region using:
    - Form factors
    - Off-shell effects from NN intermediate states



W. Cottingham '63; H. Harari, '66

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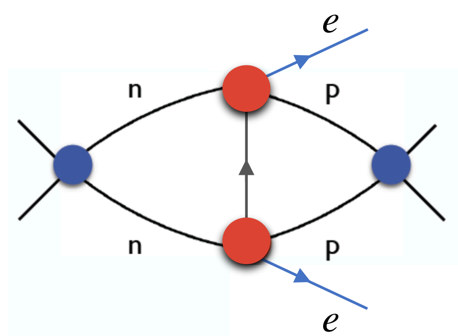
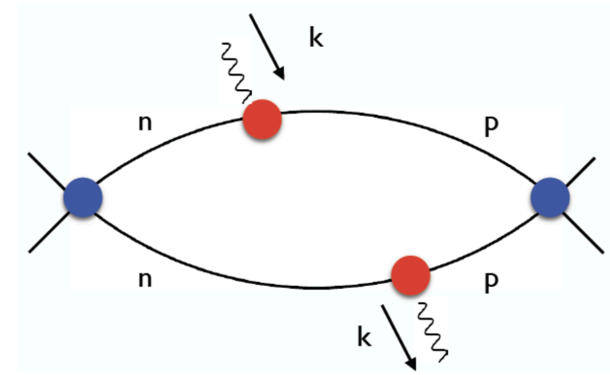
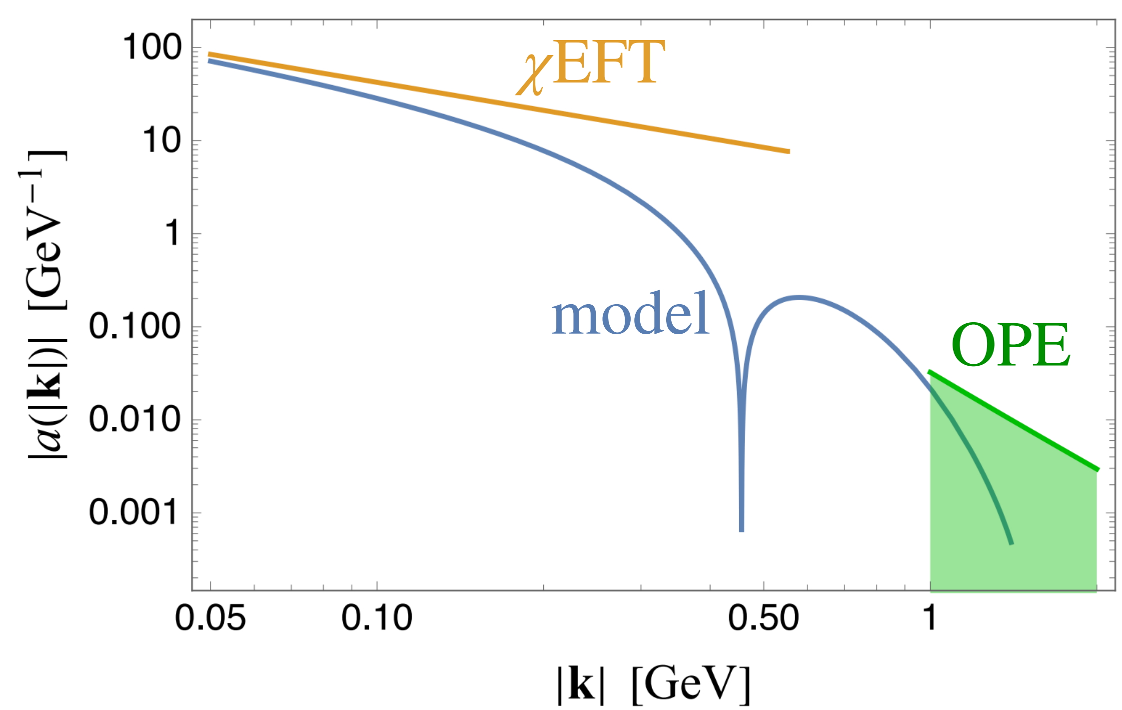
$\mathcal{A}_\nu =$ 

$$\propto \int dk\, a(k) = \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 + i\epsilon}$$



- Gives $\tilde{g}_\nu^{NN}(\mu = m_\pi) = 1.3(6)$ in $\overline{\rm MS}$
  - Estimated 30% uncertainty
  - Validated in isospin-breaking observables
  - Consistent with large-Nc estimate

Richardson et al, ‘21



W. Cottingham ’63; H. Harari, ‘66

g_ν^{NN}: Impact in nuclei

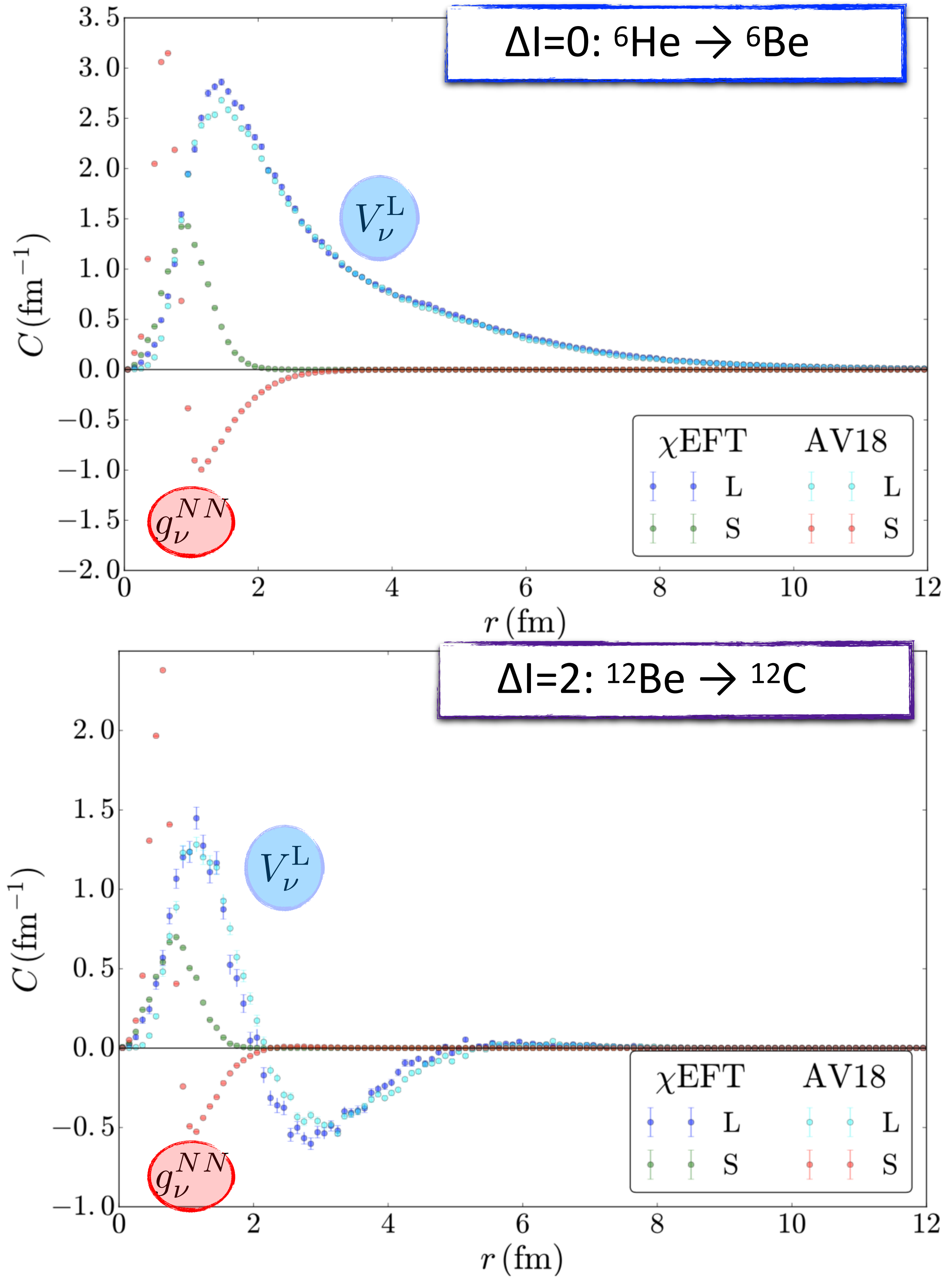
Estimate of impact

Light nuclei

M. Piarulli, R. Wiringa, S. Pastore

- Using $g_\nu = (C_1 + C_2)/2$
- With:
  - Chiral potential — M. Piarulli et. al. '16
  - AV18 potential — R. Wiringa, Stoks, Schiavilla, '95

- ~10% effect in $^6He \to {}^6Be$
- ~60% effect in $^{12}Be \to {}^{12}C$
  - Due to presence of a node
  - Feature in realistic 0νββ candidates



Estimate of impact

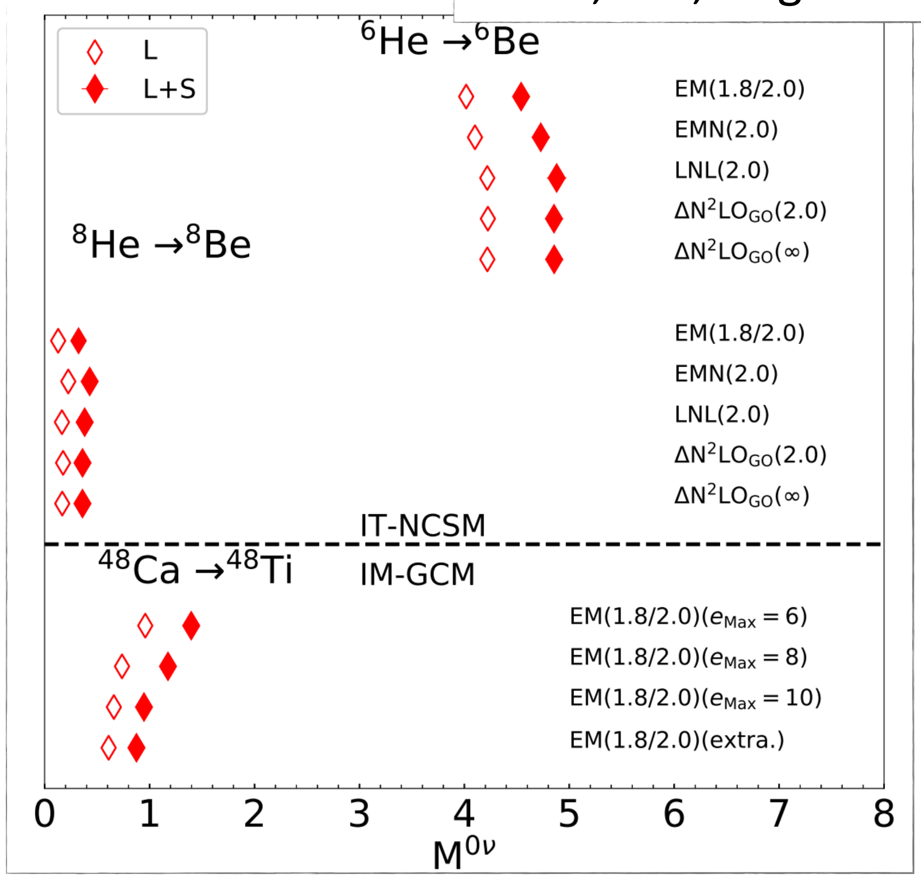
Heavy nuclei

- *Ab initio* NMEs for $A \geq 48$ are starting to appear

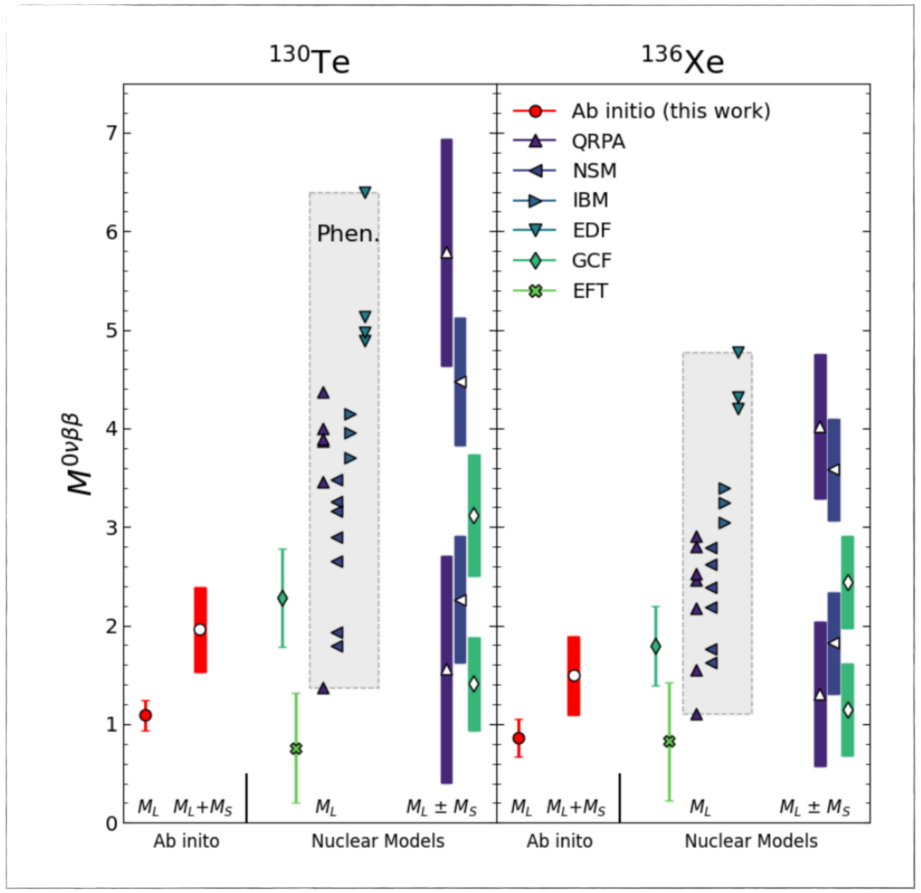
Belley et al '23,'20; Yao et al '20; Wirth, Yao, Hergert '21

- Can estimate effect of g_ν^{NN} :
  - ~40% effect in ^{48}Ca, assuming *Cottingham* estimate g_ν^{NN}
  - ~60-90% in Te, Xe

Wirth, Yao, Hegert '21



Belley, Miyagi, Stroberg, Holt, '23

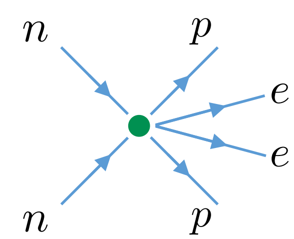


Sterile neutrinos

Momentum scales

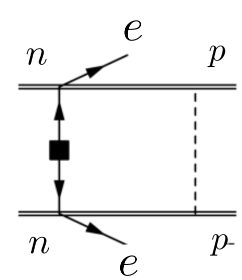
Active + sterile $\nu's$

$\Lambda_\chi \sim 1$ GeV

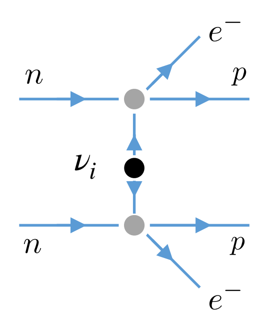


\`hard $\nu's$':
$q_0 \sim \vec{q} \sim \Lambda_\chi$

$m_\pi \sim k_F \sim 100$ MeV



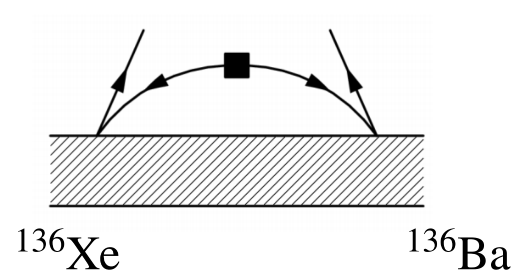
\`soft $\nu's$':
$q_0 \sim \vec{q} \sim m_\pi$



\`potential $\nu's$':
$\vec{q} \sim k_F \gg q_0 \sim k_F^2/m_N$

$V_{\Delta L=2}$

$Q \sim E_n - E_i \sim 10$ MeV

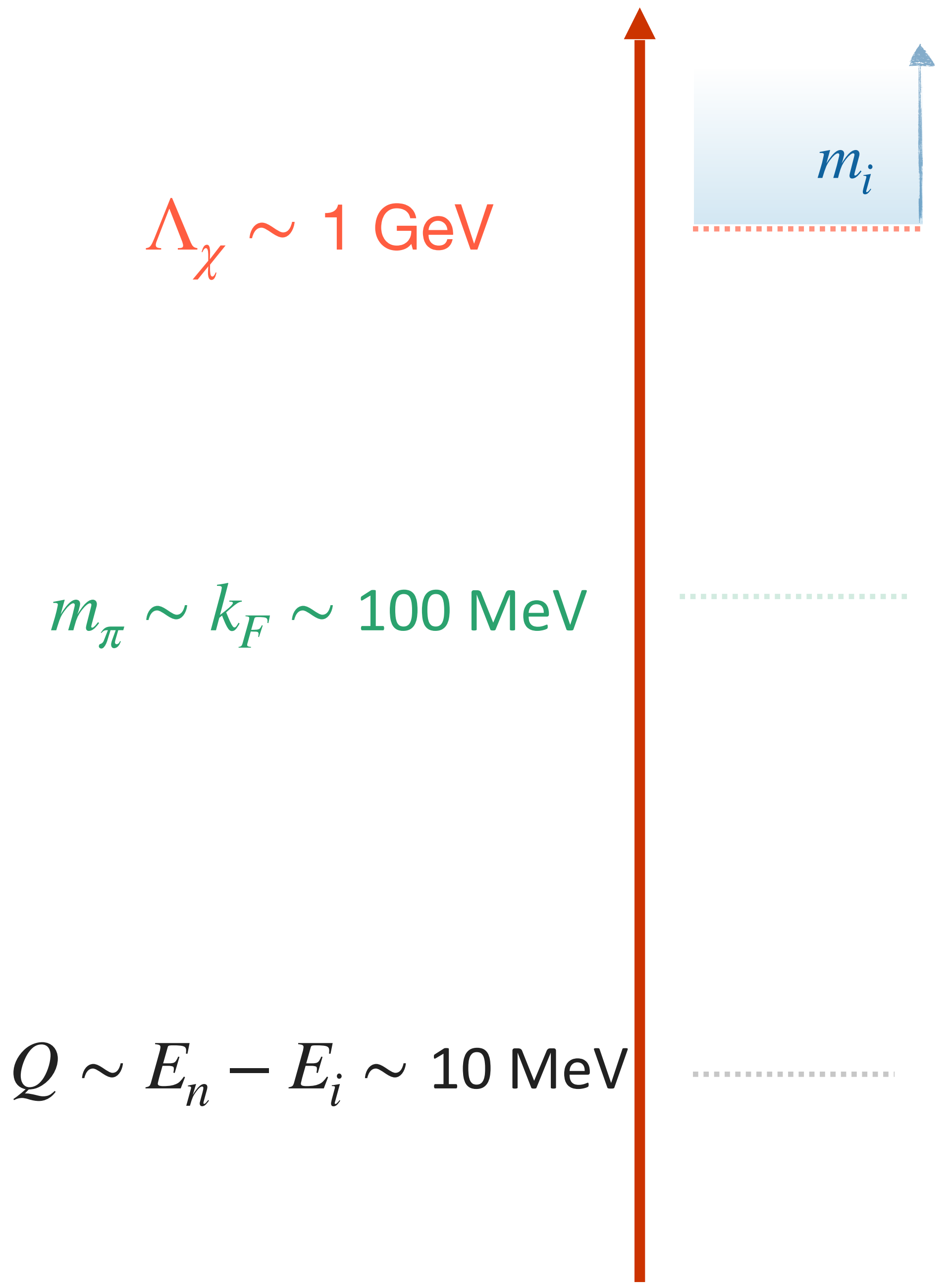


\`ultrasoft $\nu's$':
$q_0 \sim \vec{q} \sim E_n - E_i$

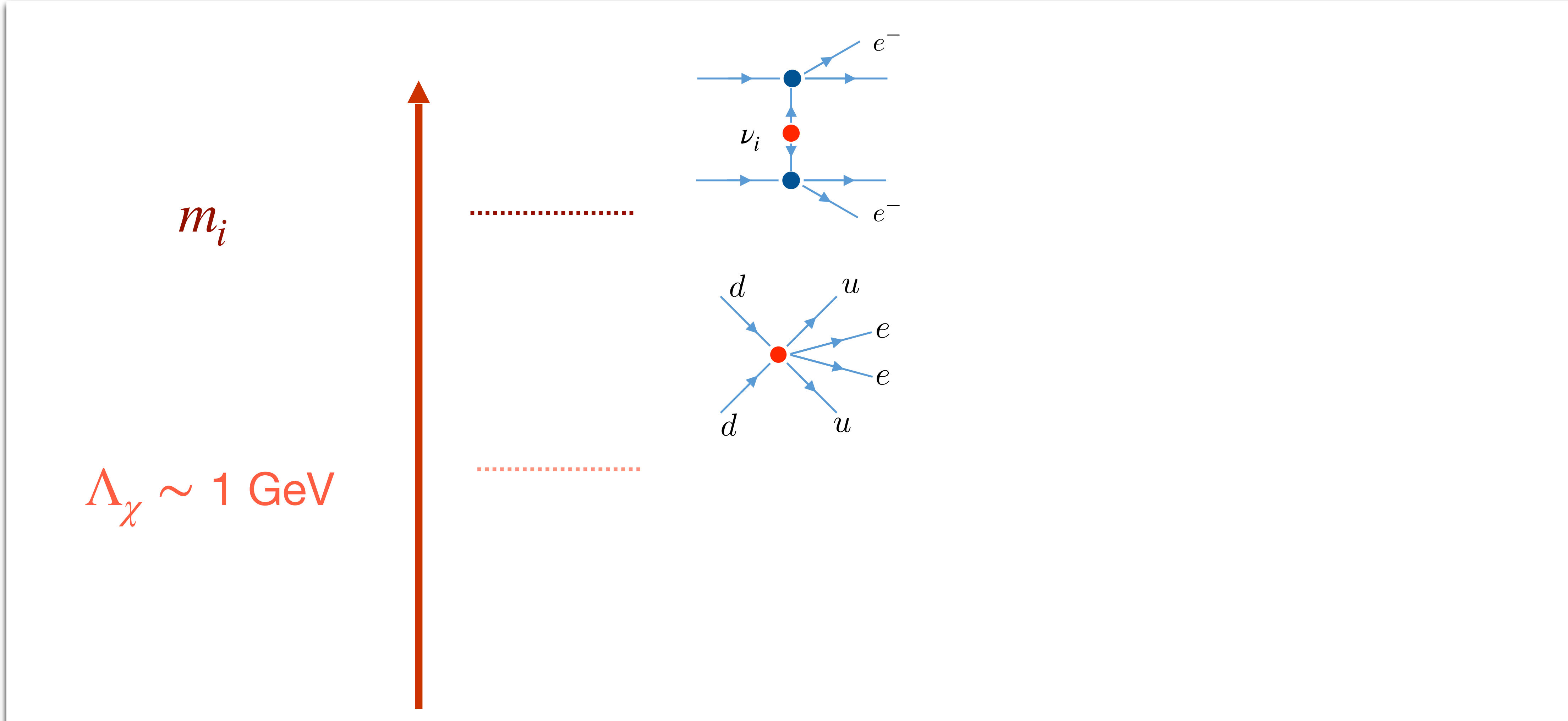
$$A_\nu = \langle {}^{136}\mathrm{Ba} \,|\, V_{\Delta L=2} \,|\, {}^{136}\mathrm{Xe} \rangle \quad + \quad A_\nu^{\mathrm{usoft}}$$

EFT approach

One momentum scale at a time

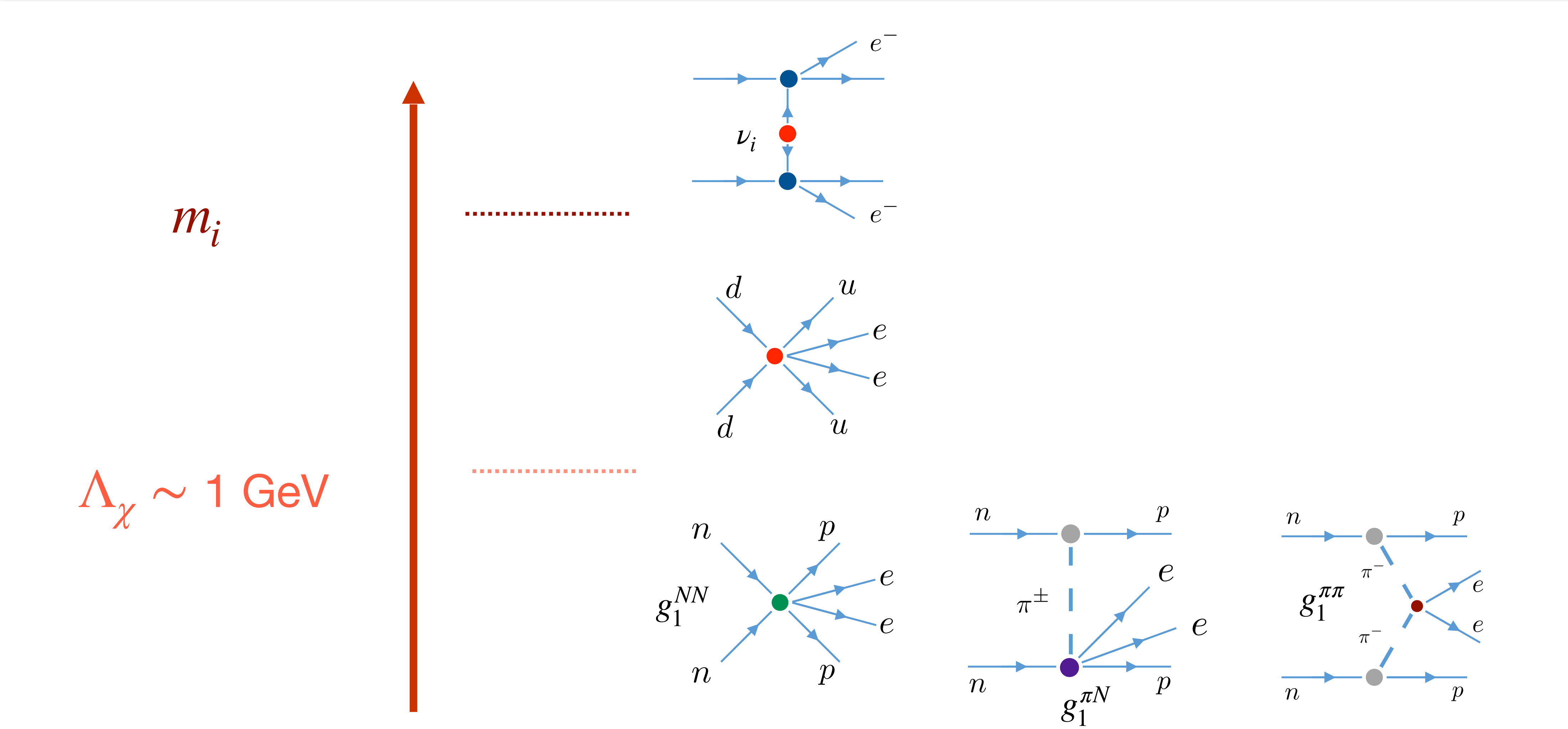


$m_i \gg \Lambda_\chi$



- ν_i can be integrated-out at quark level
  - Determines m_i dependence: $A_\nu(m_i) \sim U_{ei}^2/m_i^2$

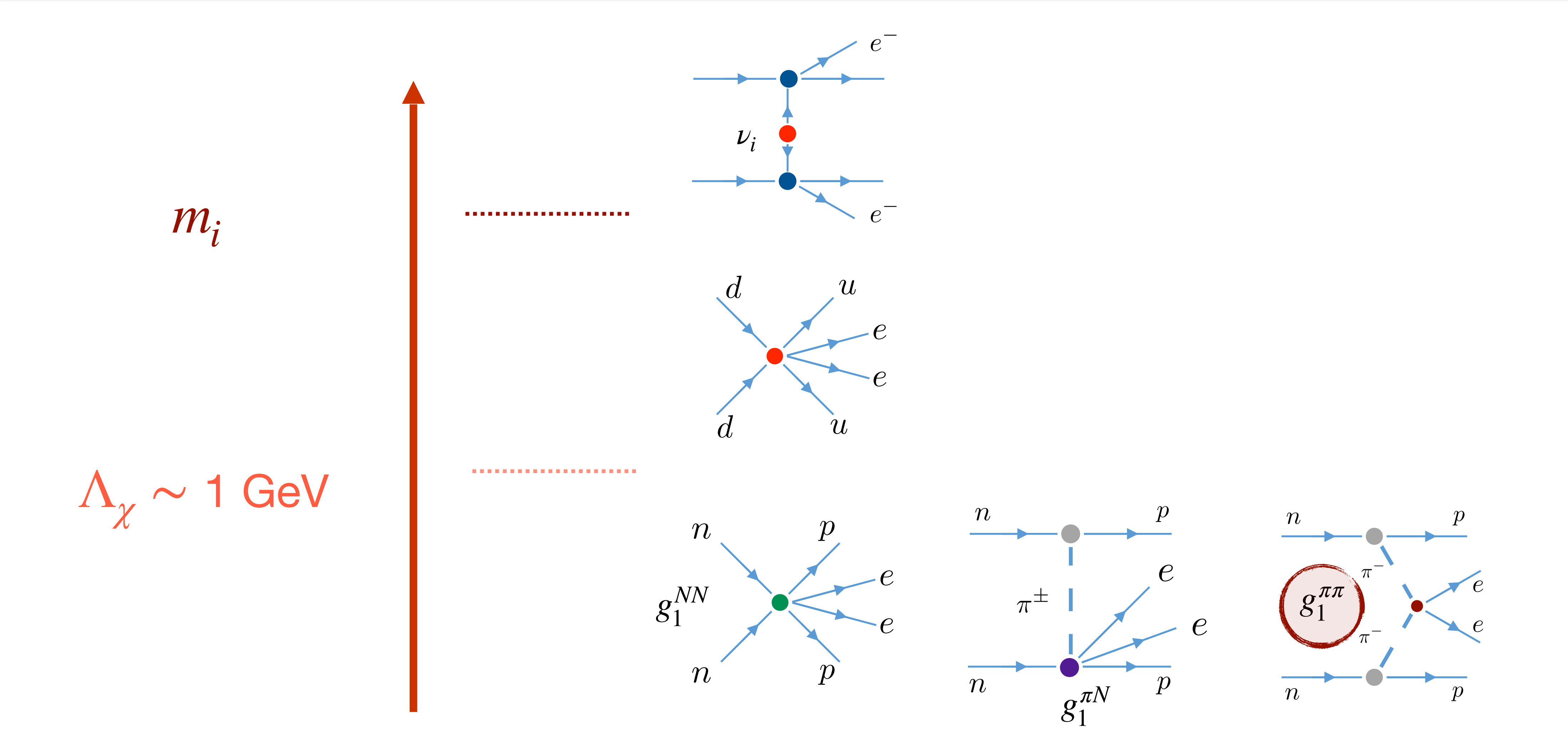
$m_i \gg \Lambda_\chi$



- ν_i can be integrated-out at quark level
  - Determines m_i dependence: $A_\nu(m_i) \sim U_{ei}^2/m_i^2$

- Match to chiral EFT without ν_i
- Involves several LECs

$m_i \gg \Lambda_\chi$



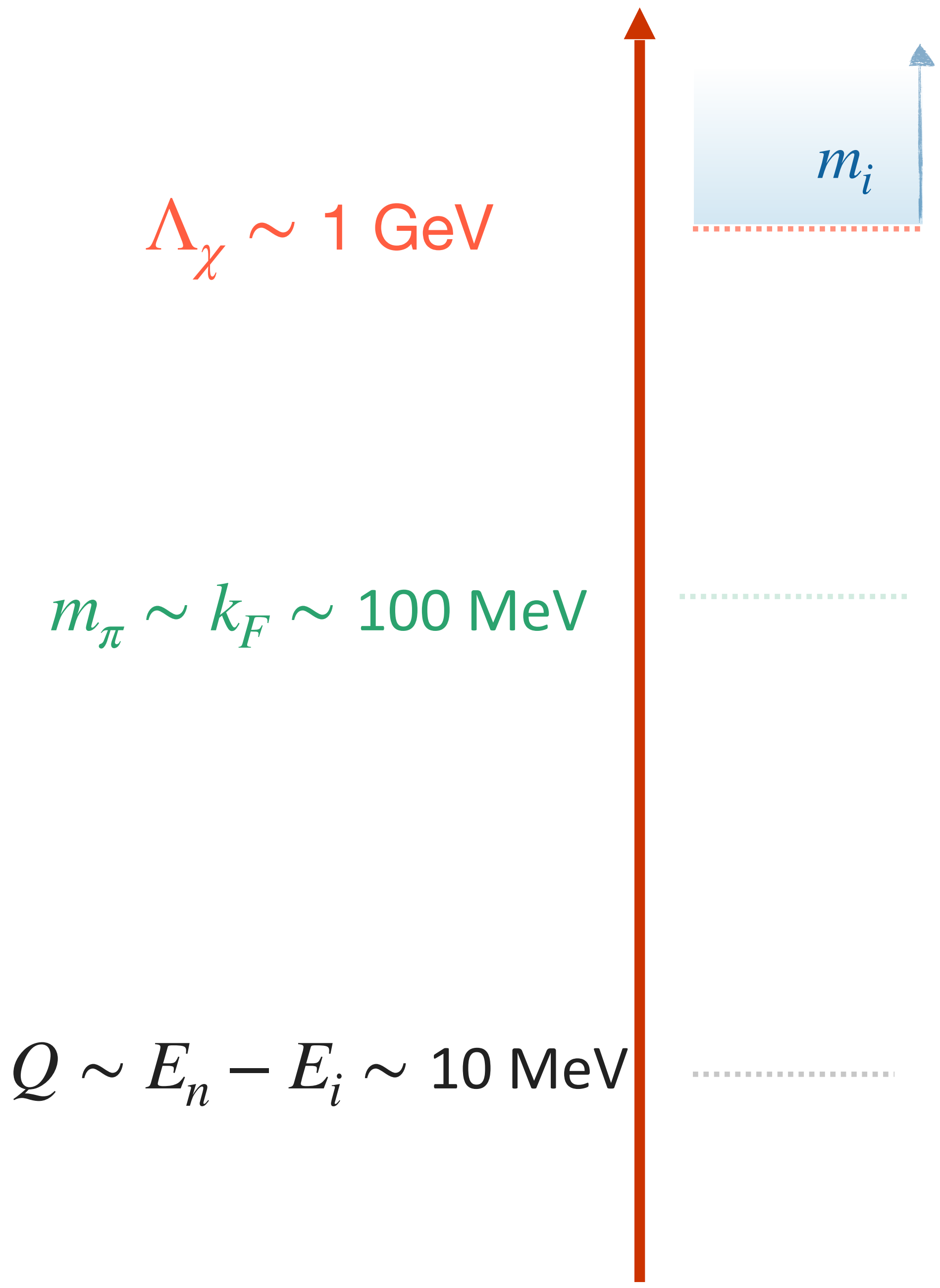
- ν_i can be integrated-out at quark level
  - Determines m_i dependence: $A_\nu(m_i) \sim U_{ei}^2/m_i^2$

- Match to chiral EFT without ν_i
- Involves several LECs
  - Only $g_1^{\pi\pi}$ known

Nicholson et al '18; Detmold et al '22

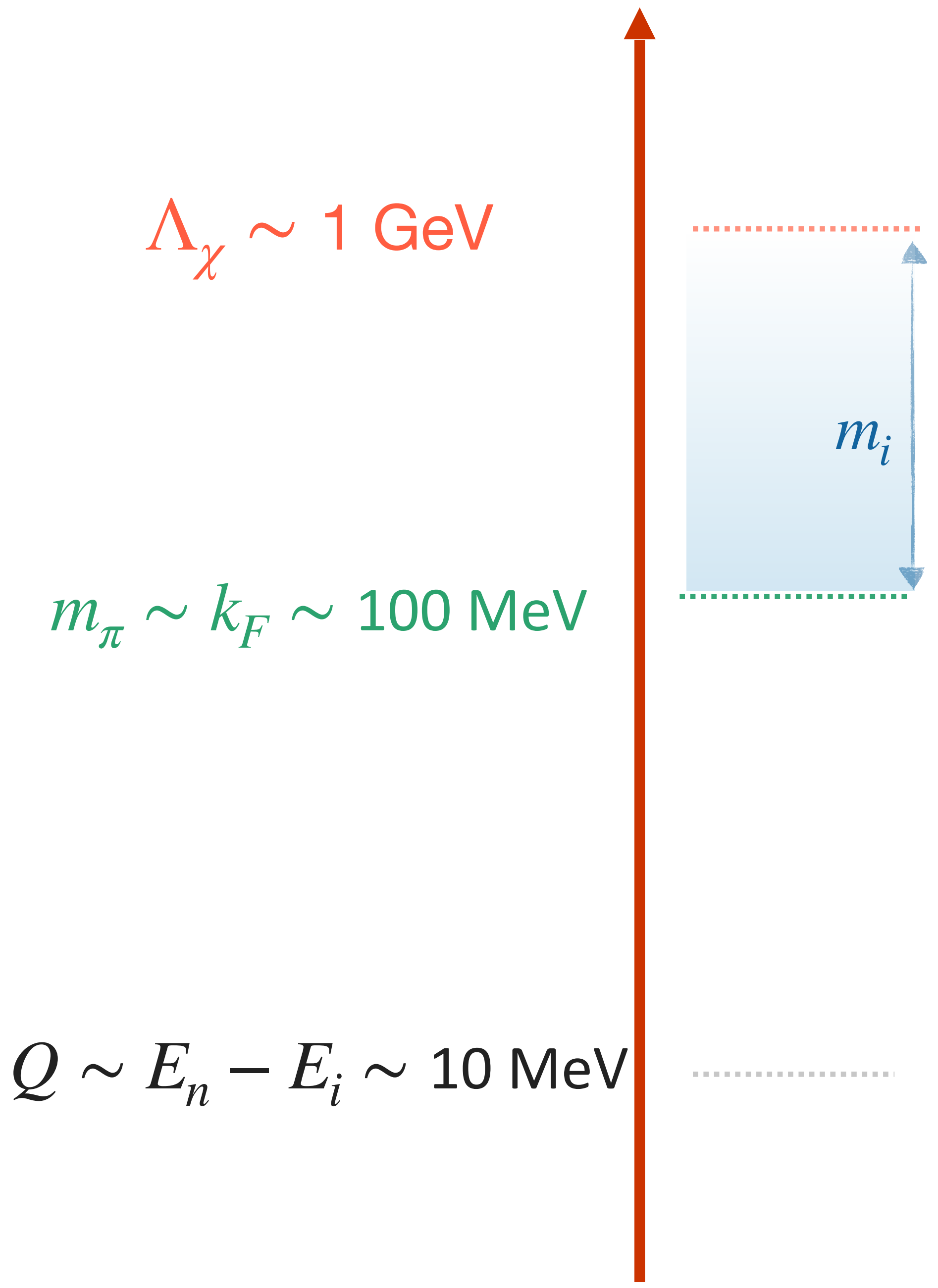
EFT approach

One momentum scale at a time



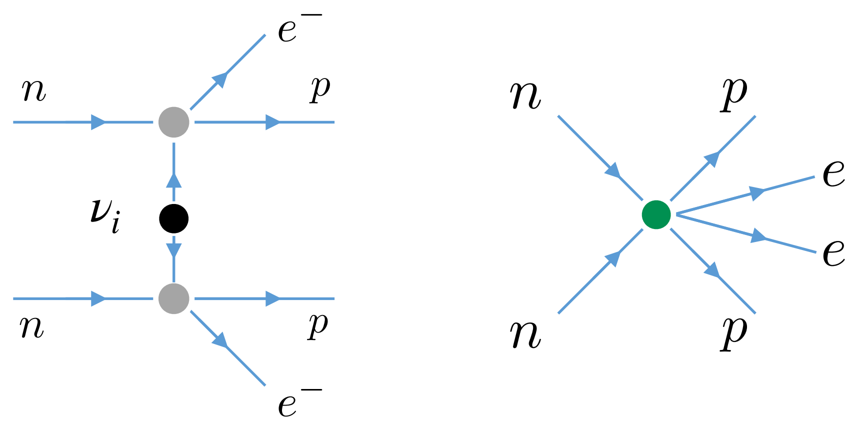
EFT approach

One momentum scale at a time



$\Lambda_\chi \gtrsim m_i \gtrsim k_F$

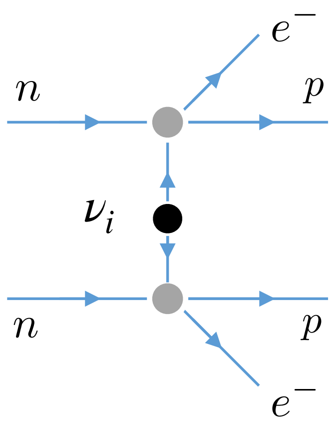
$V_{\Delta L=2} =$

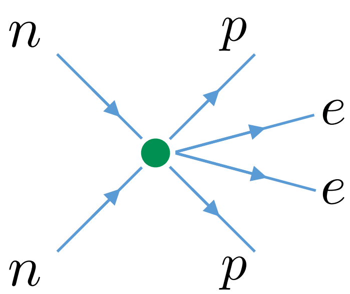


- Have to keep ν_i in the chiral theory
- Again have `potential' + `hard' contributions
- m_i dependence in NMEs and g_ν^{NN}

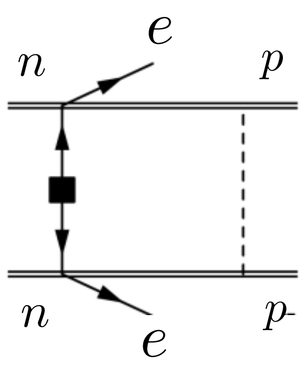
$\Lambda_\chi \gtrsim m_i \gtrsim k_F$

$V_{\Delta L=2} =$





Soft contributions $\mathcal{O}\left(\frac{m_i^2}{\Lambda_\chi^2}\right)$

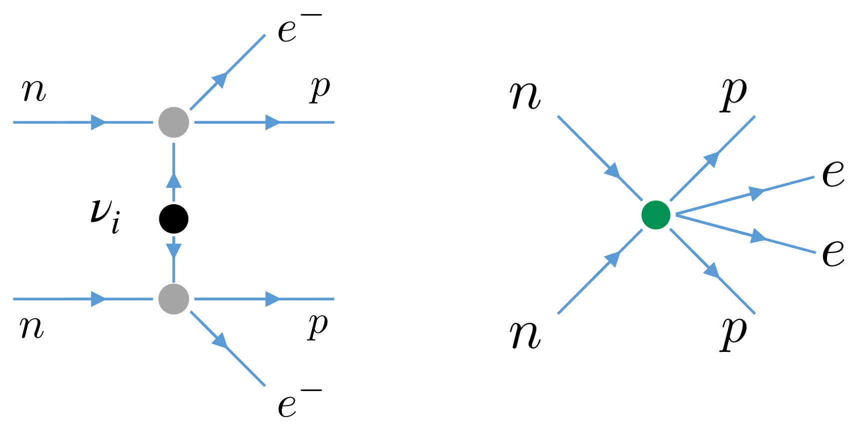


- Have to keep ν_i in the chiral theory
- Again have `potential' + `hard' contributions
- m_i dependence in NMEs and g_ν^{NN}

- `soft' contributions can be significant

$\Lambda_\chi \gtrsim m_i \gtrsim k_F$

$V_{\Delta L=2} =$

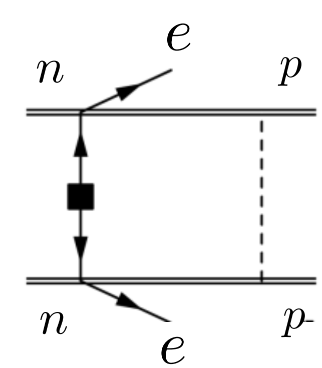


- Have to keep ν_i in the chiral theory
- Again have `potential' + `hard' contributions
- m_i dependence in NMEs and g_ν^{NN}

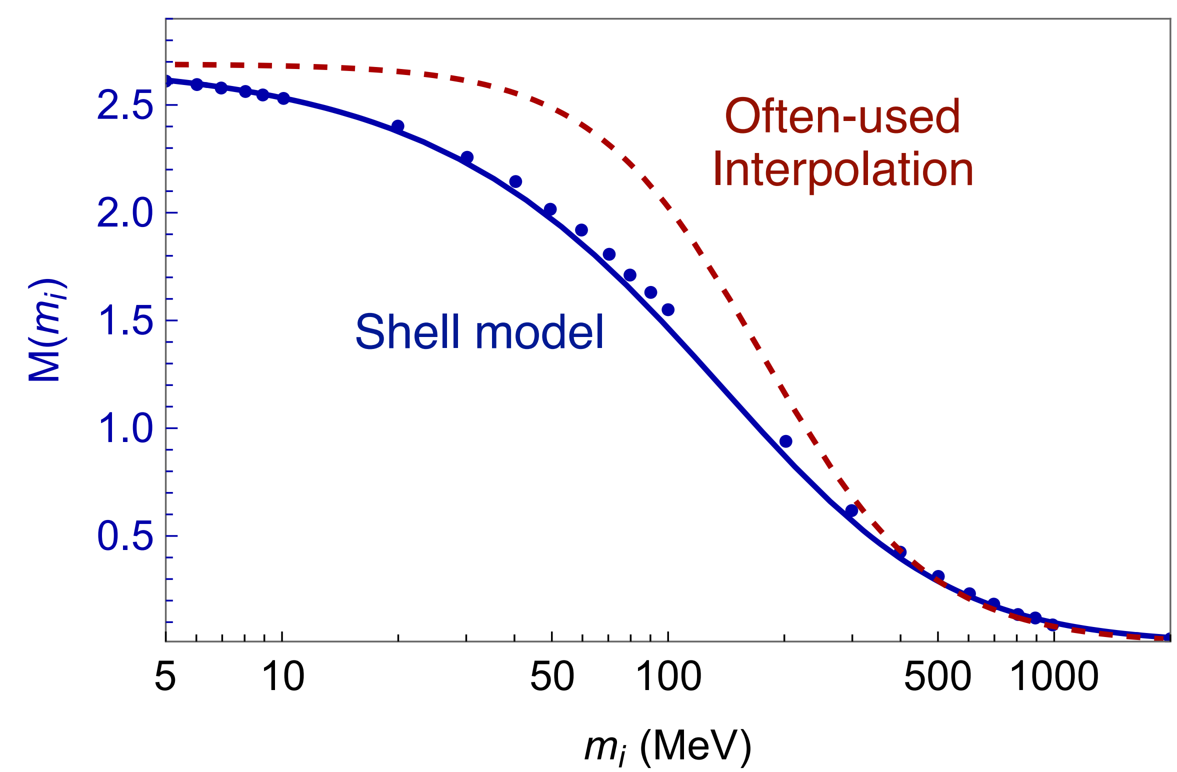
Present in usual approach

$$A_\nu(m_i) = A_\nu(0)\frac{\langle p^2 \rangle}{\langle p^2 \rangle + m_i^2}$$

Soft contributions $\mathcal{O}\left(\frac{m_i^2}{\Lambda_\chi^2}\right)$

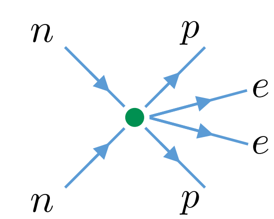
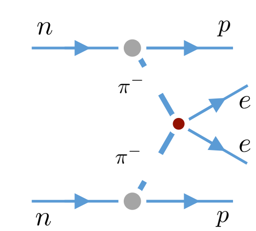
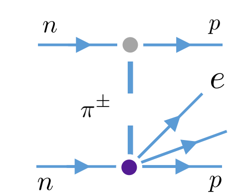


- `soft' contributions can be significant



Required NMEs/LECs

Overview

Required input	$m_i \ll \Delta E$	$\Delta E \ll m_i \ll k_F$	$k_F \ll m_i \ll \Lambda_\chi$	$\Lambda_\chi \ll m_i$
Low-energy constants			$g_\nu^{NN}(m_i)$ 	$g_1^{\pi\pi}, g_1^{\pi N}, g_1^{NN}$  

Nuclear matrix elements

$M_\nu^{\mathrm{short-distance}}$

$M_\nu(m_i) = \langle f | V | i \rangle$

$\langle f | \tau^+ \sigma | n \rangle$

$\Delta E \sim E_n - E_i$

- Known from LQCD
- Use NDA for $g_1^{\pi N}, g_1^{NN}$
- Interpolate g_ν^{NN} between $m_i = 0$ and $m_i \gg \Lambda_\chi$ regions

- Shell model calculations for the NMEs

Phenomenology with sterile neutrinos

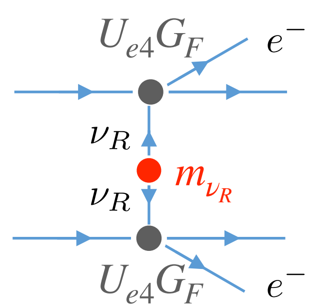
Phenomenology

From heavy new physics + light ν_R

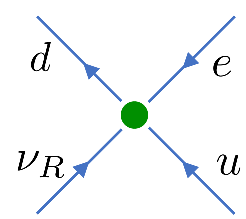
Example with ν_R

O(100%) uncertainties not shown

- Toy Model
  - SM + 1 light ν_R $\quad \Gamma_{0\nu\beta\beta} \sim$

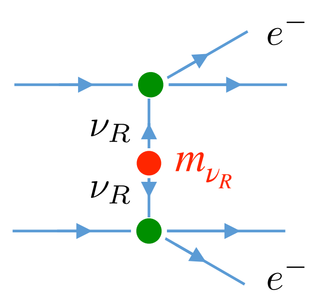


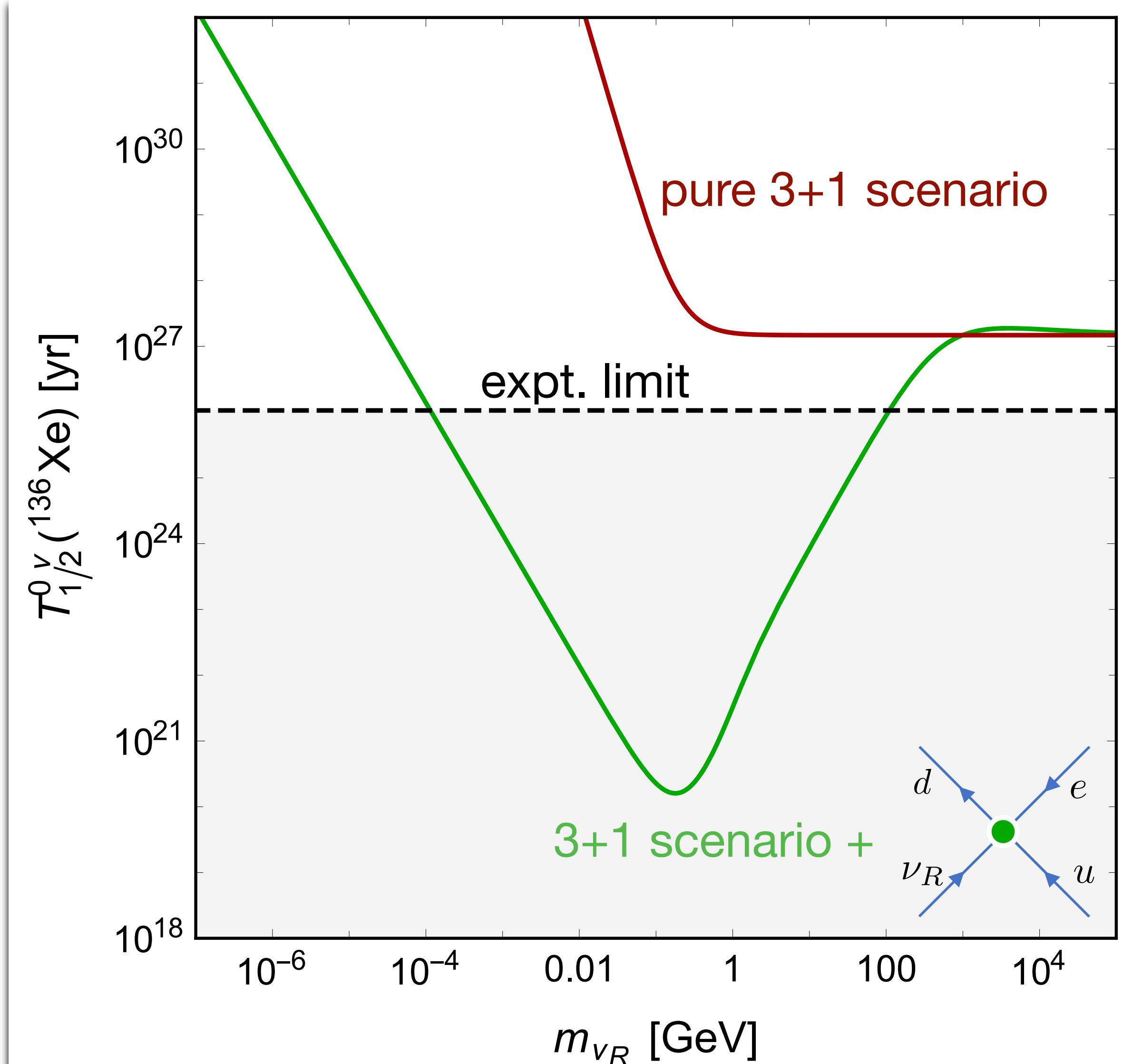
- Add dimension-six interaction
  - SM + 1 light ν_R +



$\Lambda = 10\,\mathrm{TeV}$

$\Gamma_{0\nu\beta\beta} \sim$





- Higher dimensional ν_R terms can have a large impact!