Theory perspective on Large-scale xenon detectors

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with

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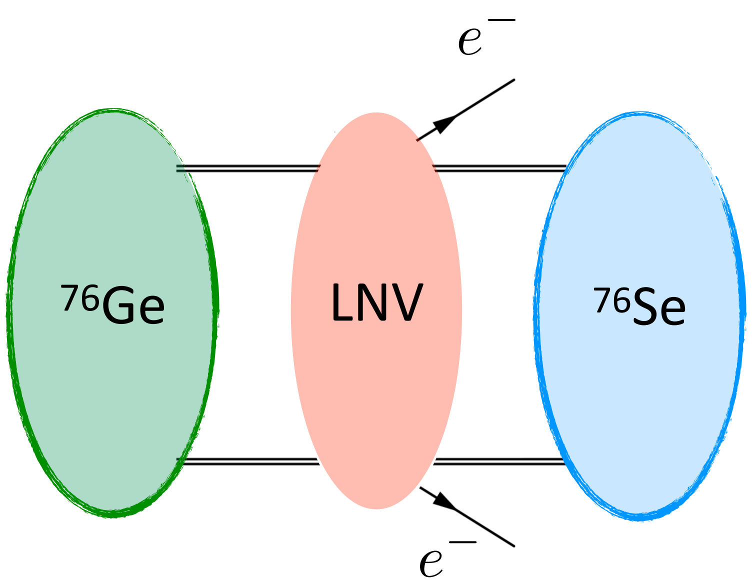
E. Mereghetti, M. Piarulli, S. Pastore,
U. van Kolck, A. Walker-Loud, R.B. Wiringa

UNIVERSITY of WASHINGTON

INSTITUTE for NUCLEAR THEORY

Introduction

0νββ



- Violates lepton number, ΔL=2
- Stringently constrained experimentally
  - Next generation to improve 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
$> 9 \cdot 10^{25}\,\mathrm{yr}$	$> 3.2 \cdot 10^{25}\,\mathrm{yr}$	$> 2.3 \cdot 10^{26}\,\mathrm{yr}$

- Would imply that
  - Neutrino's are Majorana particles
  - Physics beyond the SM

Schechter, Valle, `82

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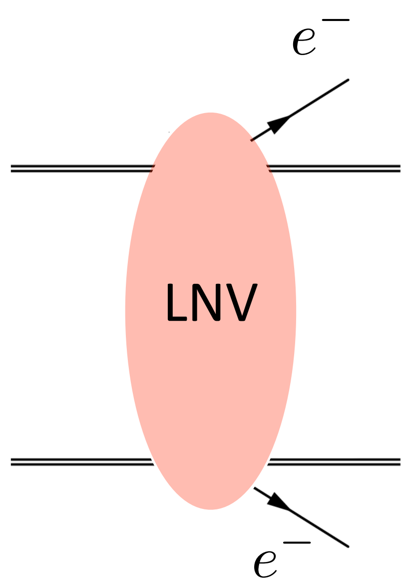

= **BSM physics**

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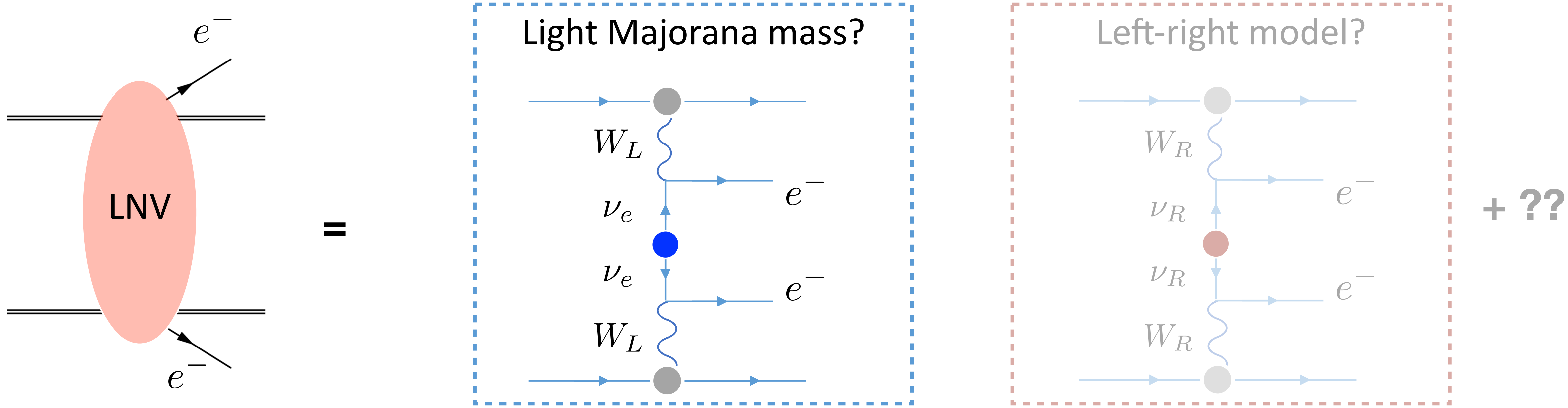
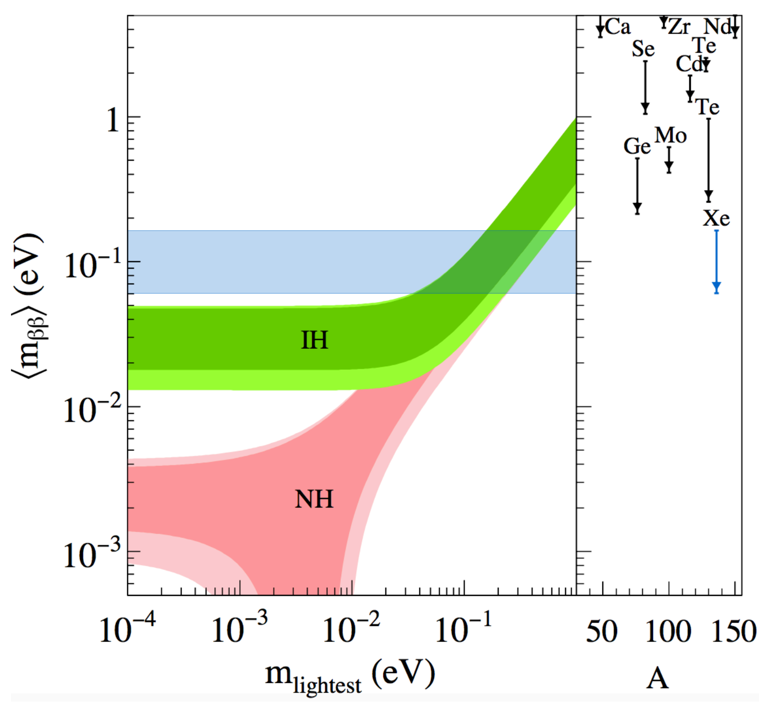


Well-known Majorana mass mechanism



- Implications for the mass hierarchy

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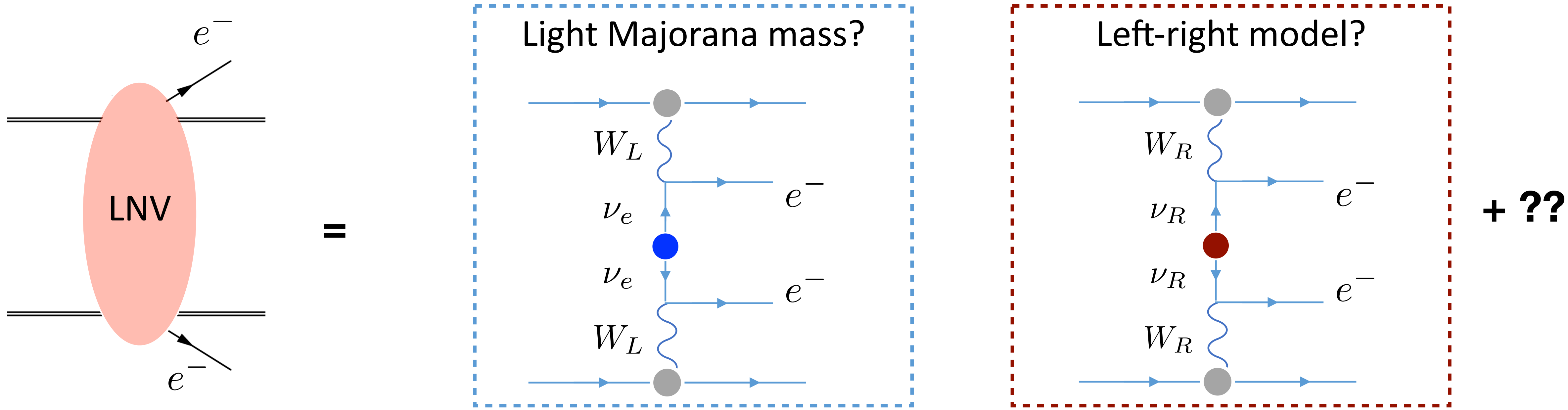

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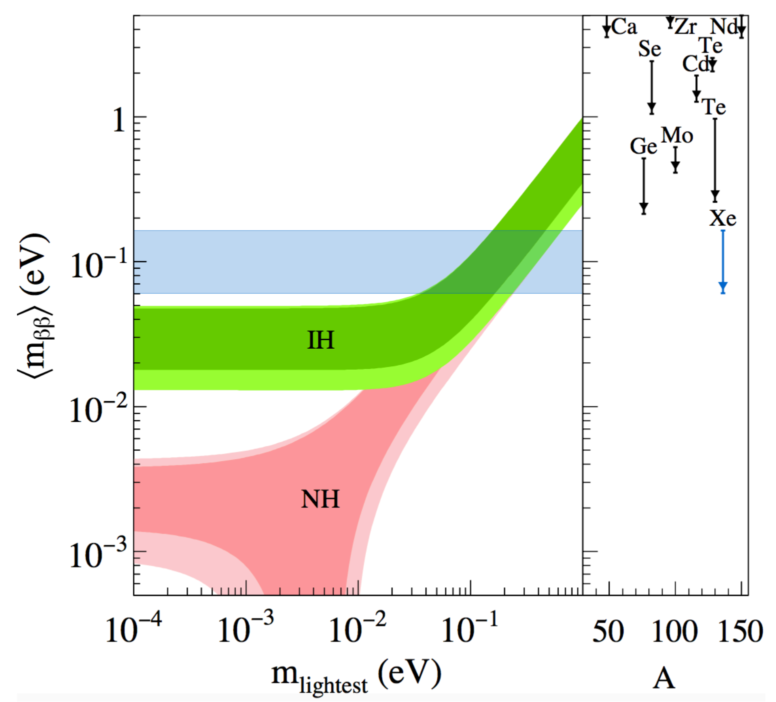

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Heavy BSM mechanisms

- Many possible scenarios
    - Left-right model,
    - R-parity violating SUSY
    - Leptoquarks…

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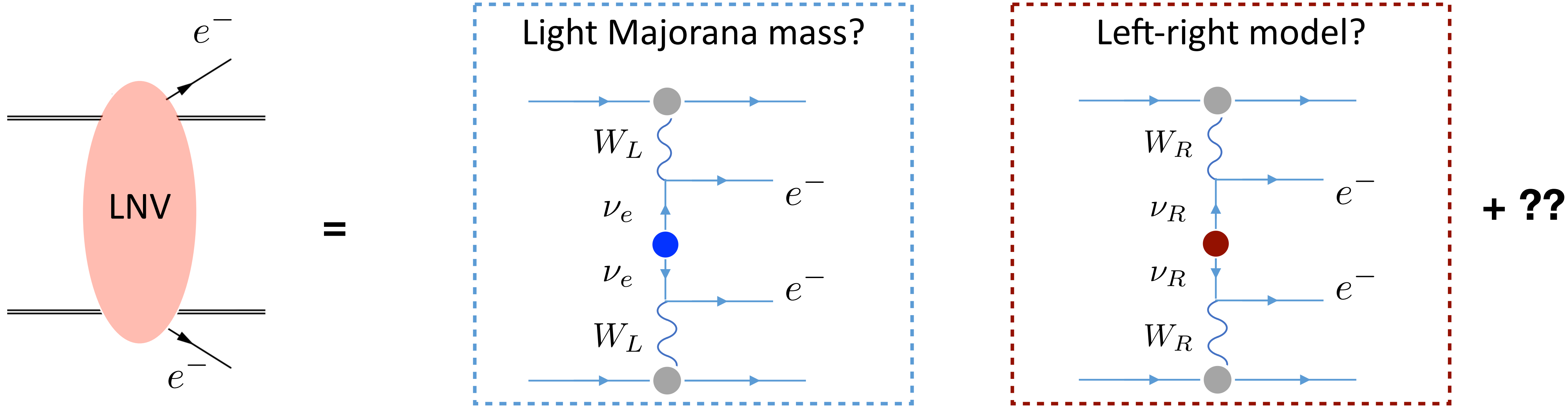

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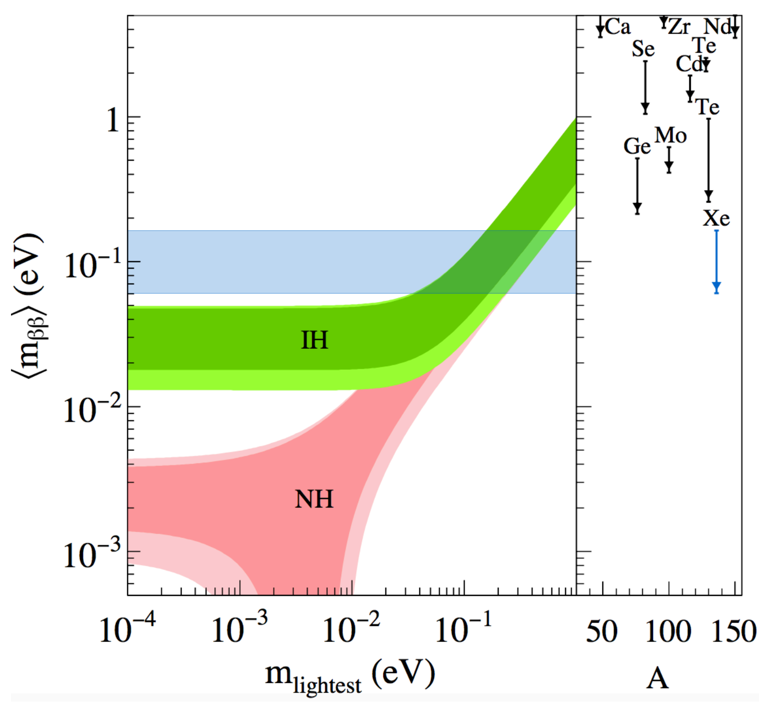

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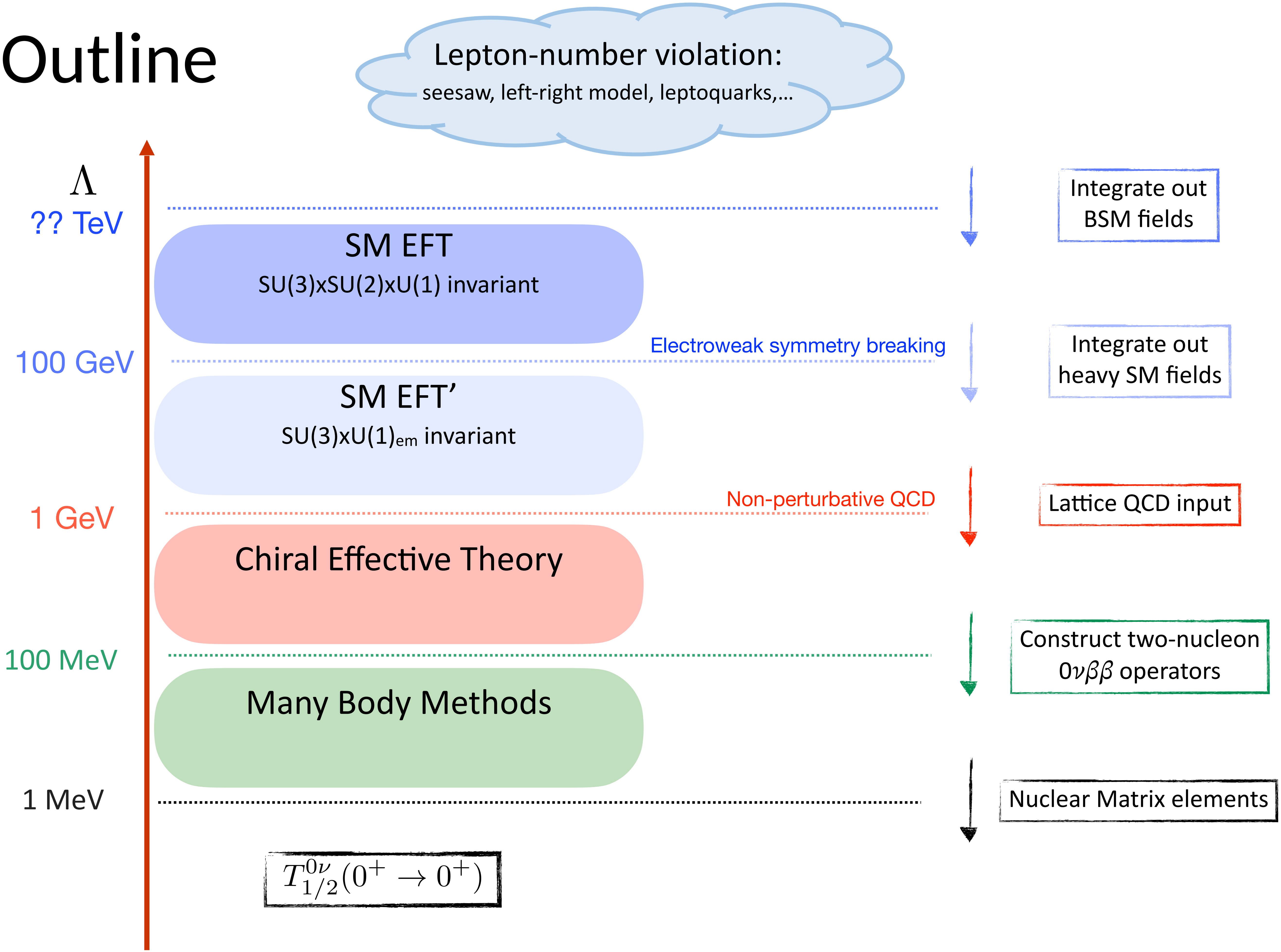
  - Leptoquarks…
- How to describe all LNV sources systematically?

Outline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seesaw, left-right model, leptoquarks,...
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SU(3)xSU(2)xU(1) invariant
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Electroweak symmetry breaking
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Chiral Effective Theory
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Many Body Methods
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Integrate out BSM fields
Integrate out heavy SM fields
Lattice QCD input
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

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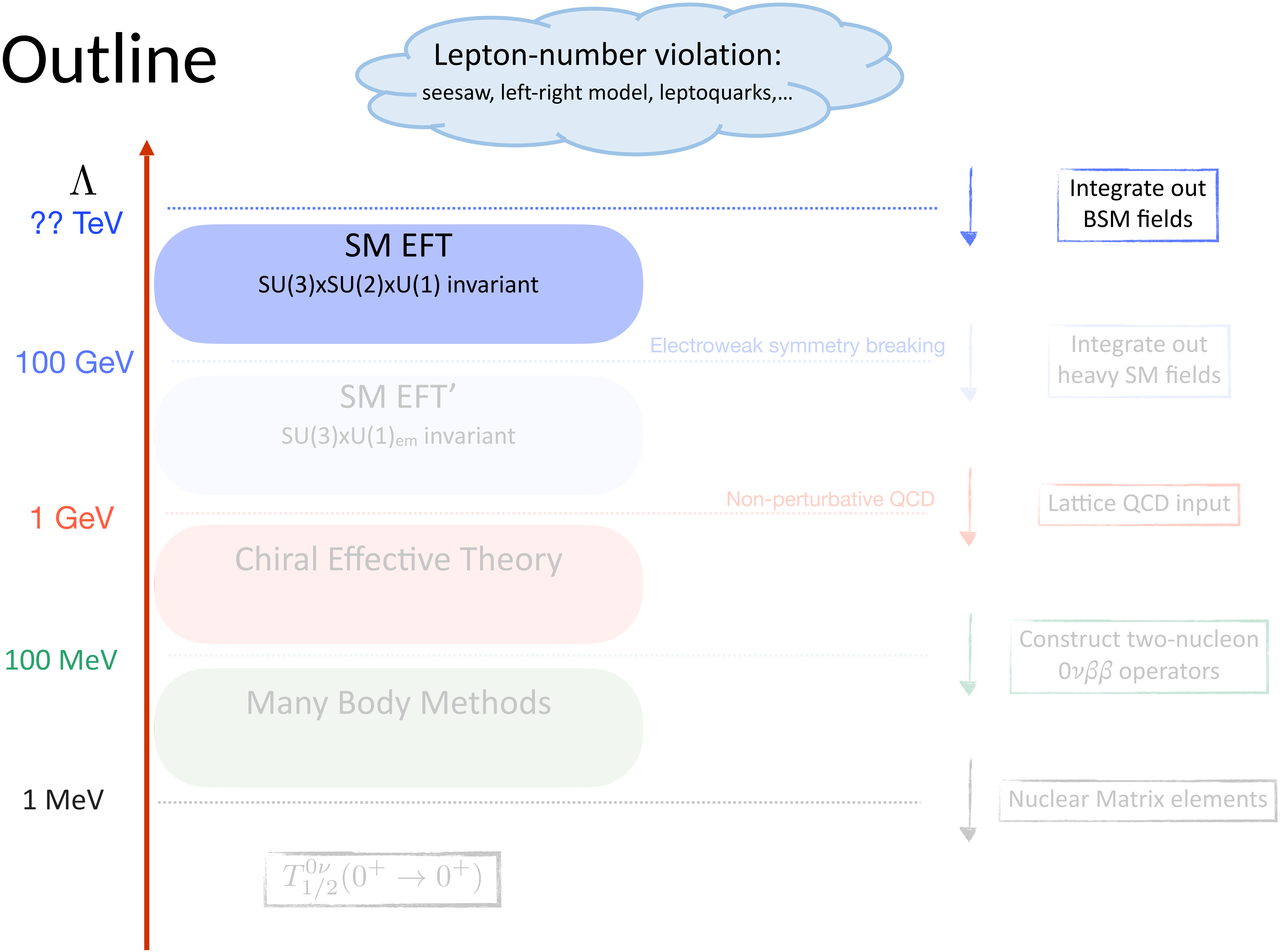

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From heavy $\Delta L = 2$ physics

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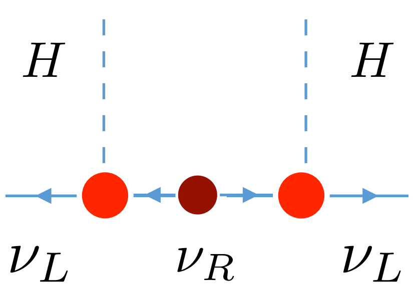
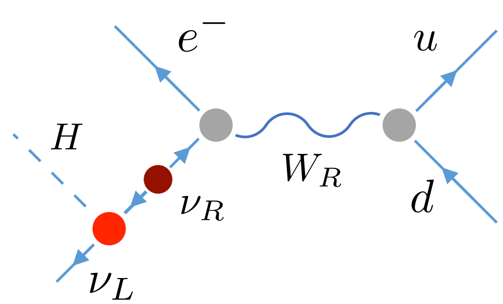
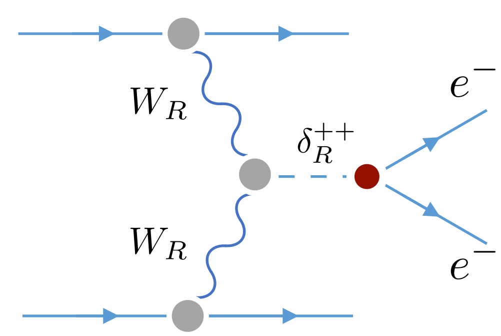
Example: Left-right model:







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- Majorana mass (L violating)

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

Interactions involving light ν_R

- Can be described in the same framework (νSMEFT):

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

- Majorana mass (L violating)
- Dirac mass (L conserving)

Zhou, Fuyuto, de Vries, Mereghetti, WD, '20; Blennow et al, '10; Barea et al, '15; Giunti et al, '15; Bolton et al, '19;

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Liao & Ma, '17

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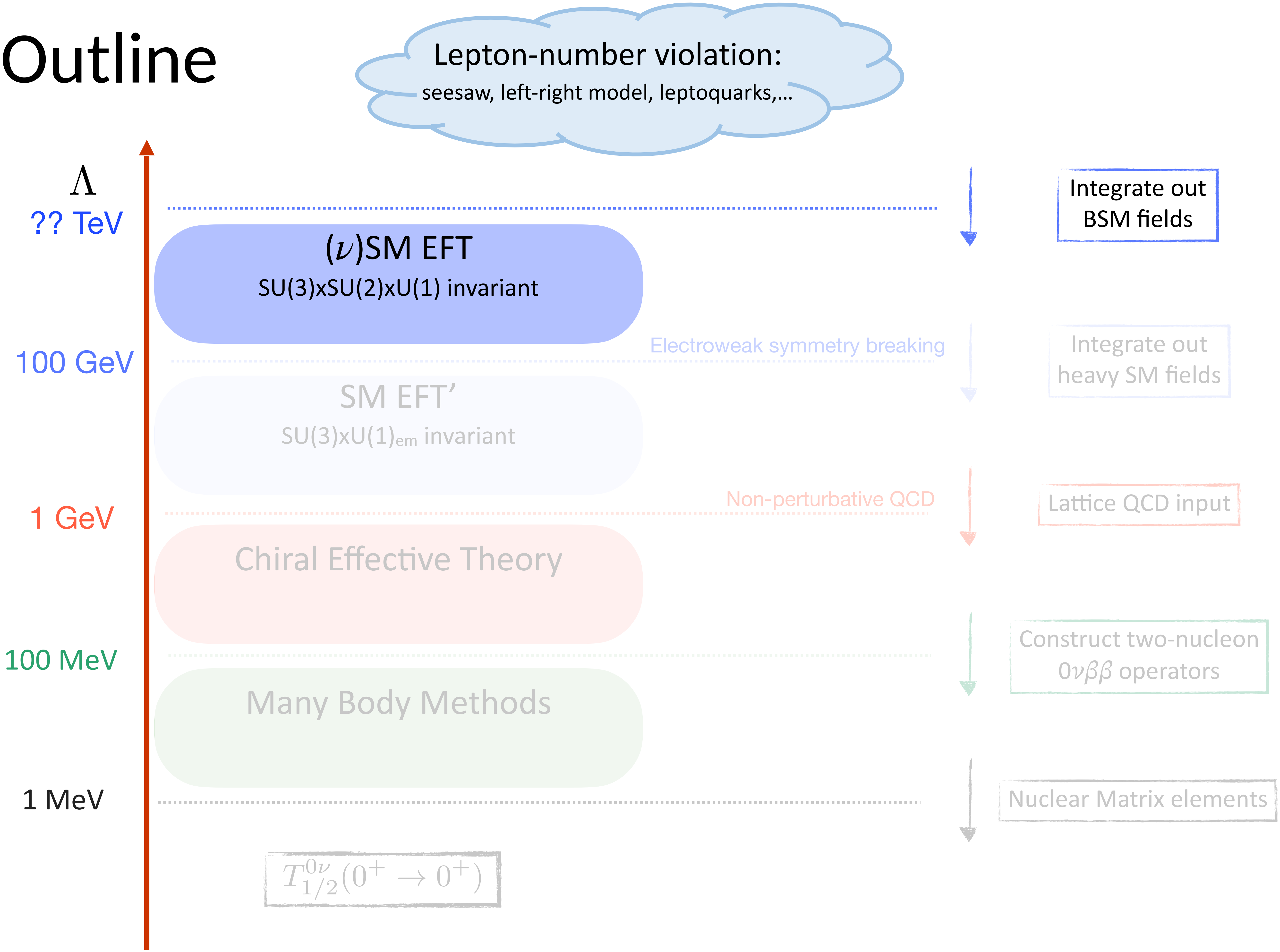
- Majorana mass (L violating)

- Dirac mass (L conserving)

- Dimension-6 (L-conserving)
- Dimension-7 operators (L-violating)
- Induced by heavy BSM physics

Zhou, Fuyuto, de Vries, Mereghetti, WD, '20; Blennow et al, '10; Barea et al, '15; Giunti et al, '15; Bolton et al, '19;

Outline



Lepton-number violation:
seesaw, left-right model, leptoquarks,...
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Construct two-nucleon $0\nu\beta\beta$ operators
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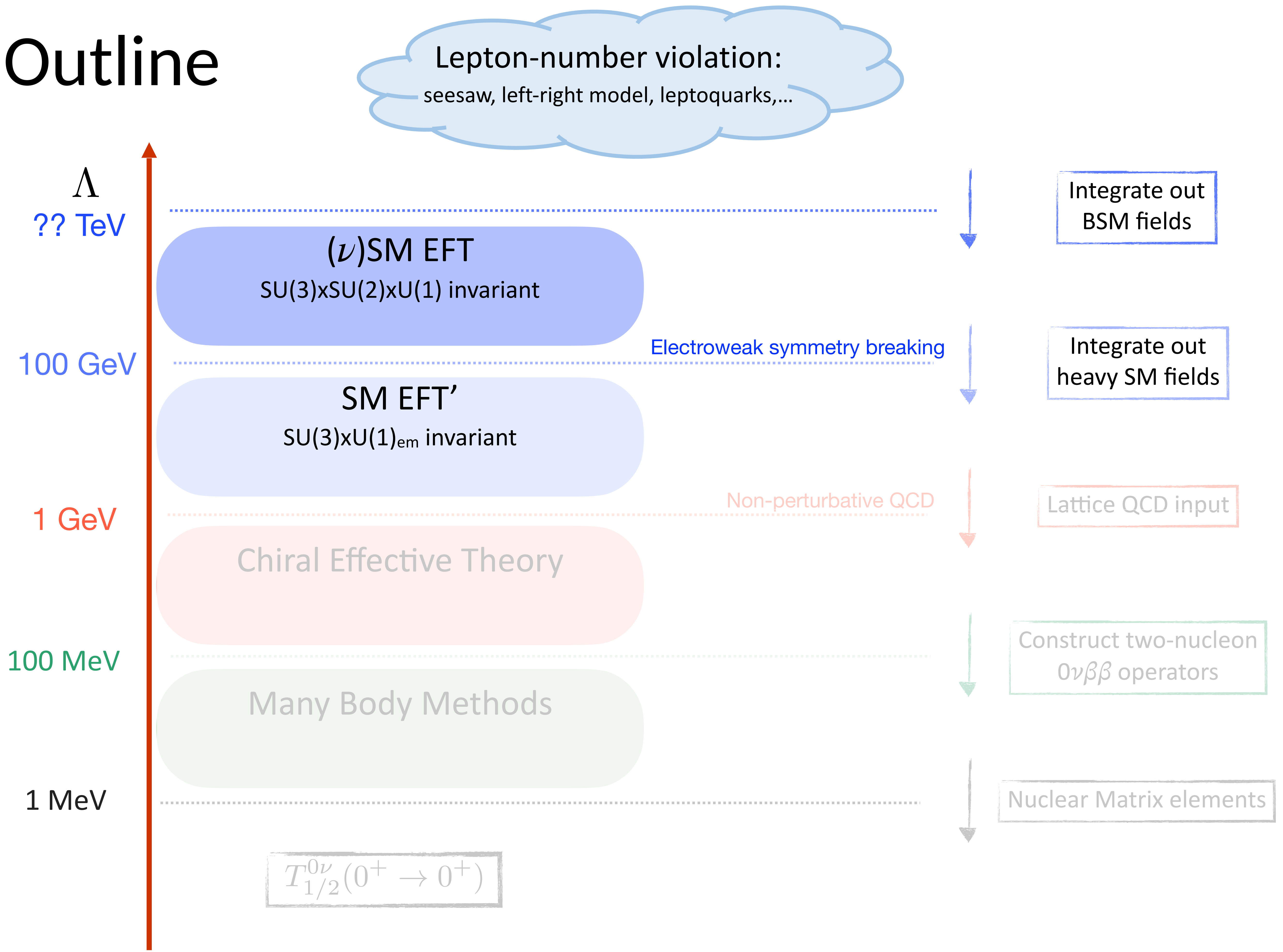

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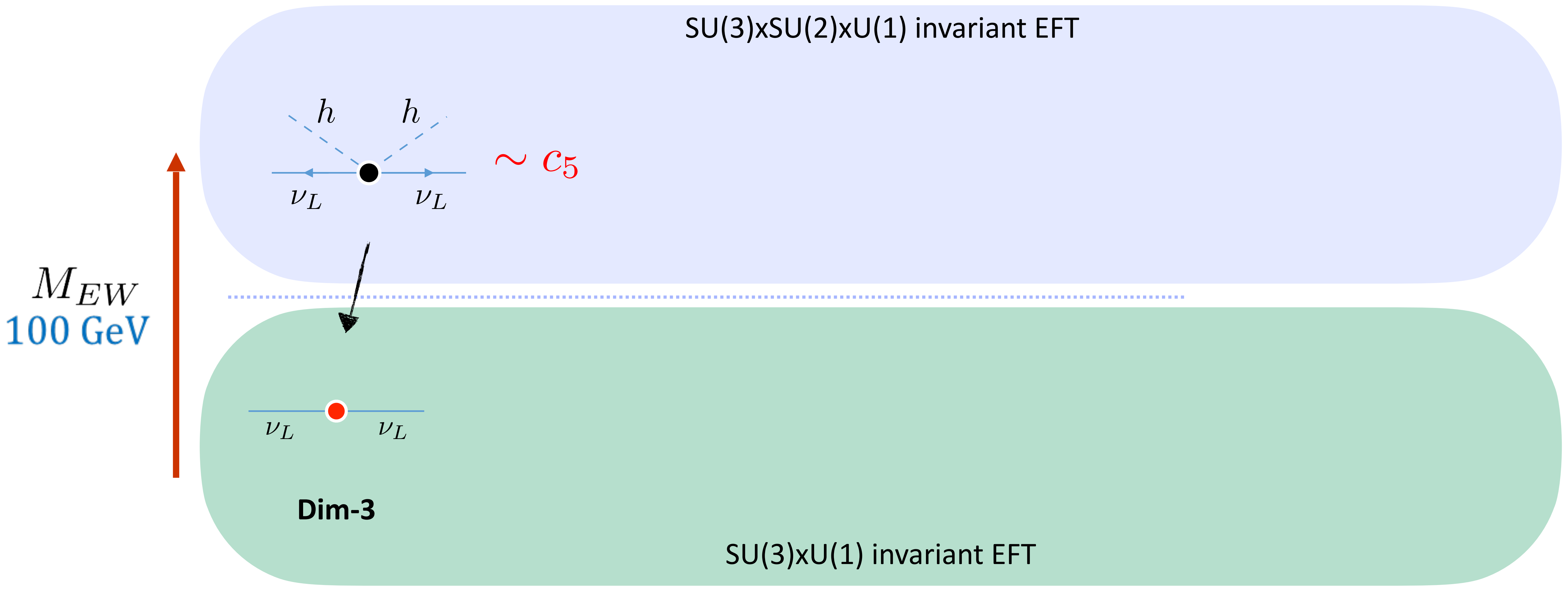
Low-energy operators

At/below the weak scale*



* very similar for operators involving ν_R

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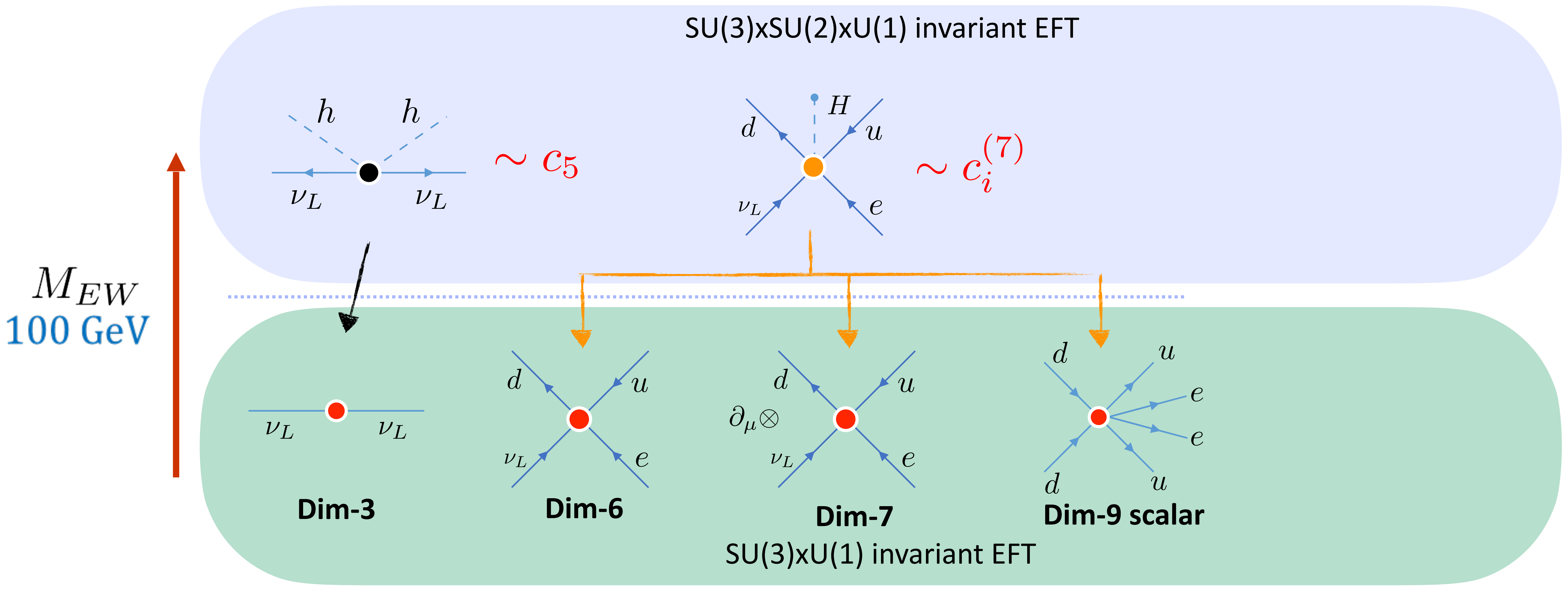

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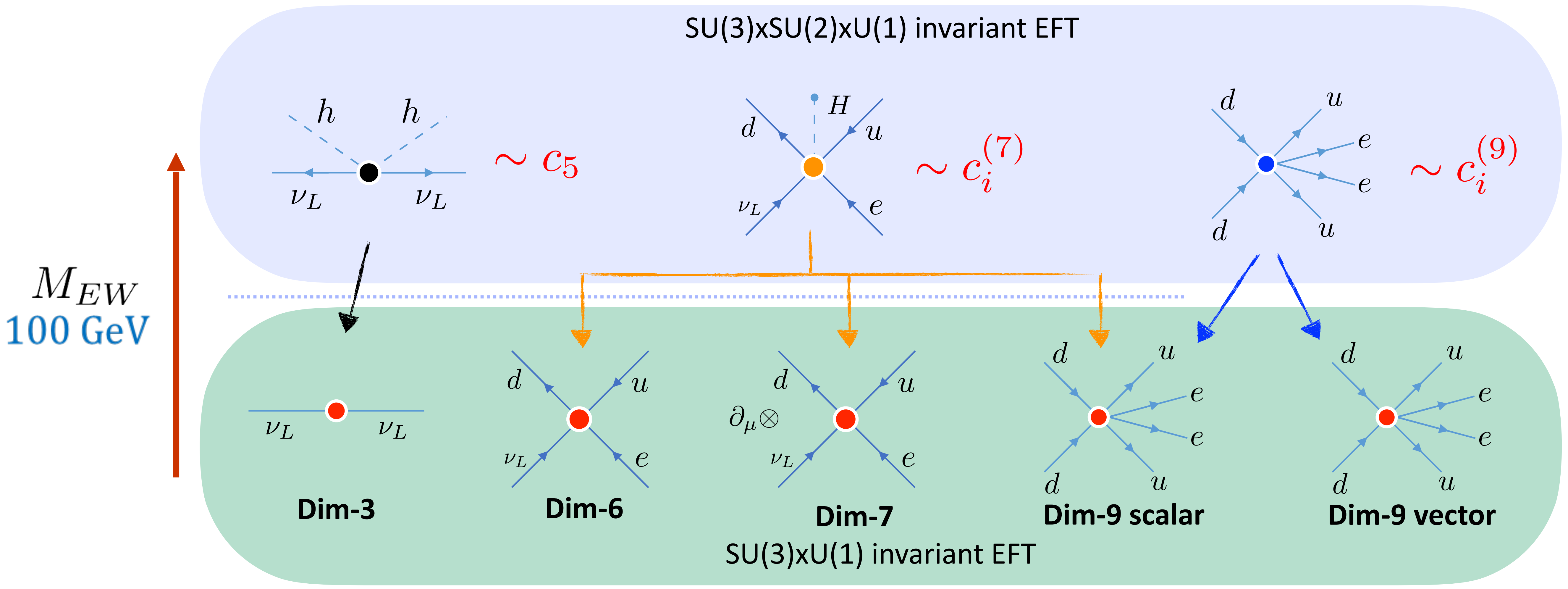

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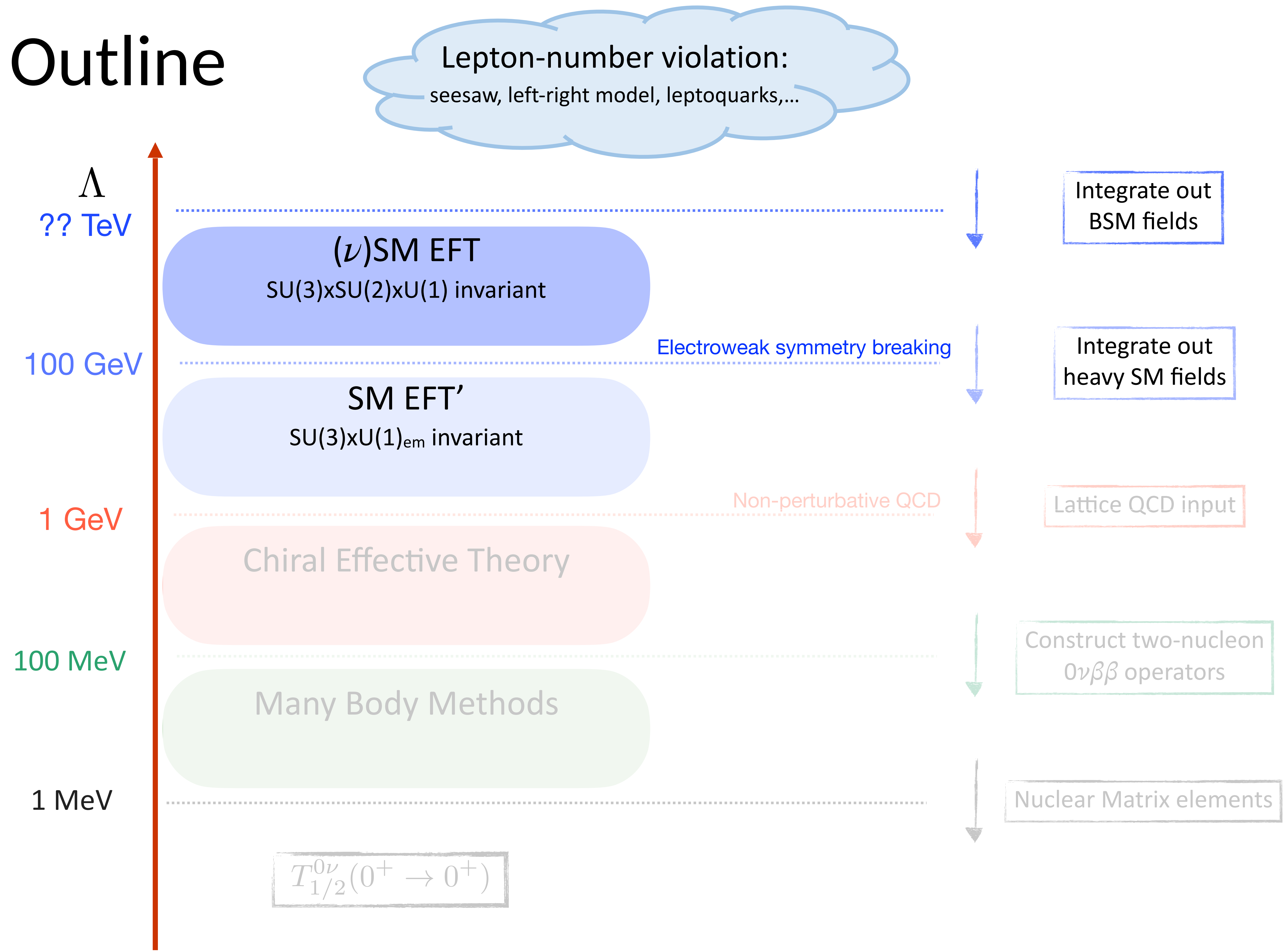

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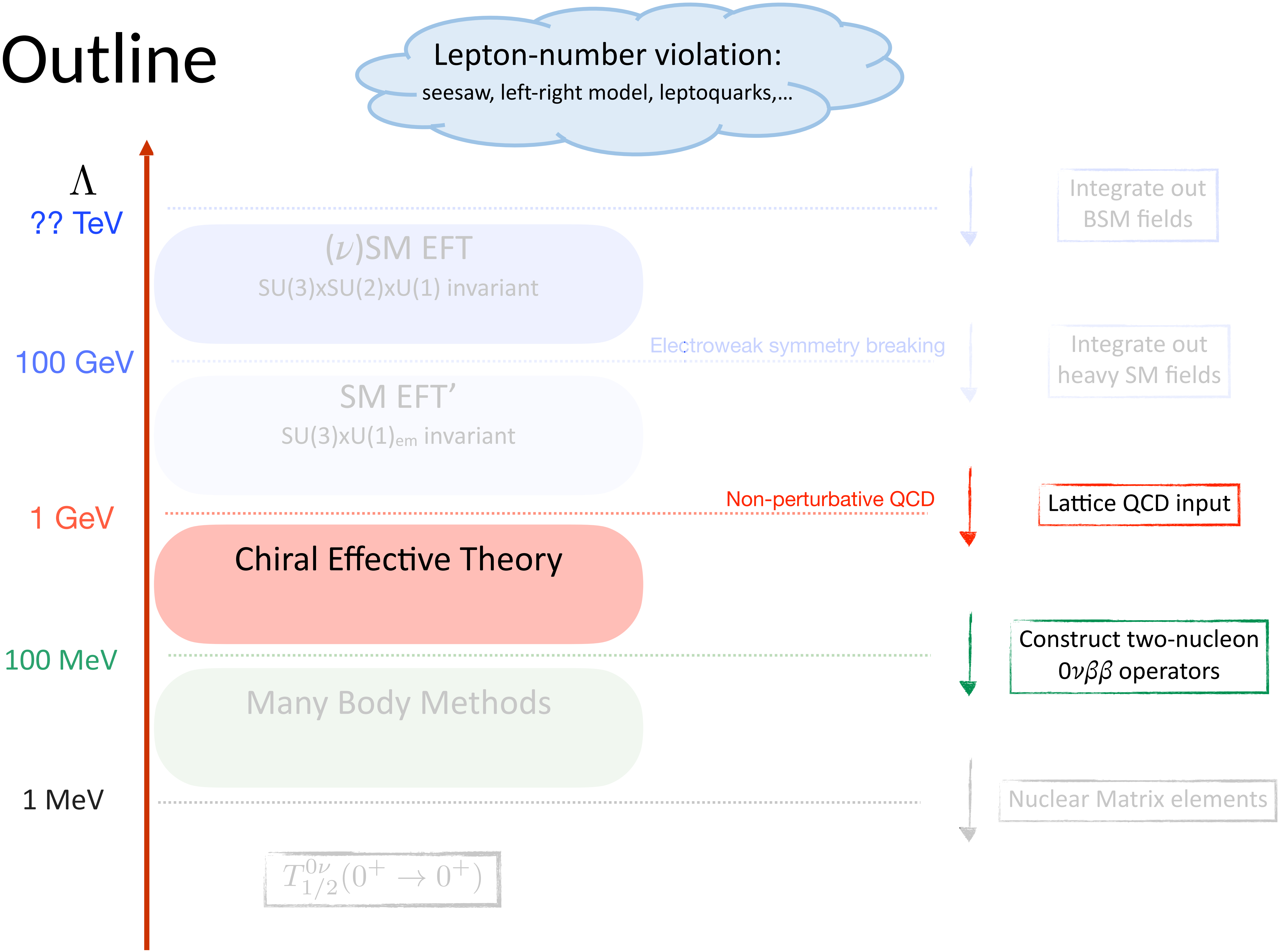

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Matching to Chiral EFT

SM EFT'

SU(3)xU(1)$_{em}$ invariant

In terms of quarks, gluons, leptons $\mathcal{L}(u, d, g, \nu, e)$

M_{QCD}

1 GeV

Chiral Effective Theory

In terms of nucleons, pions, leptons $\mathcal{L}_{\chi PT}(N, \pi, \nu, e)$

Form of operators determined by chiral symmetry

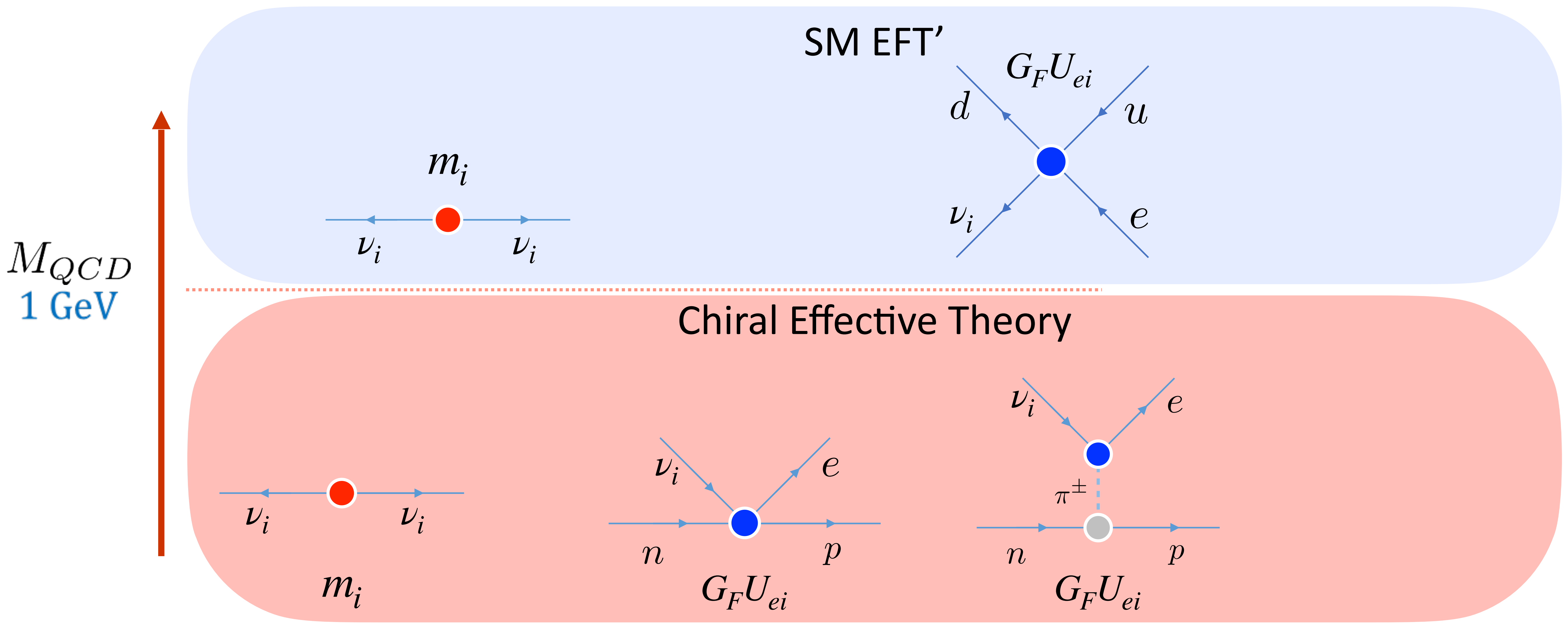
The operators come with unknown constants (LECs)

Need a power-counting scheme

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

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

Matching to Chiral EFT



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

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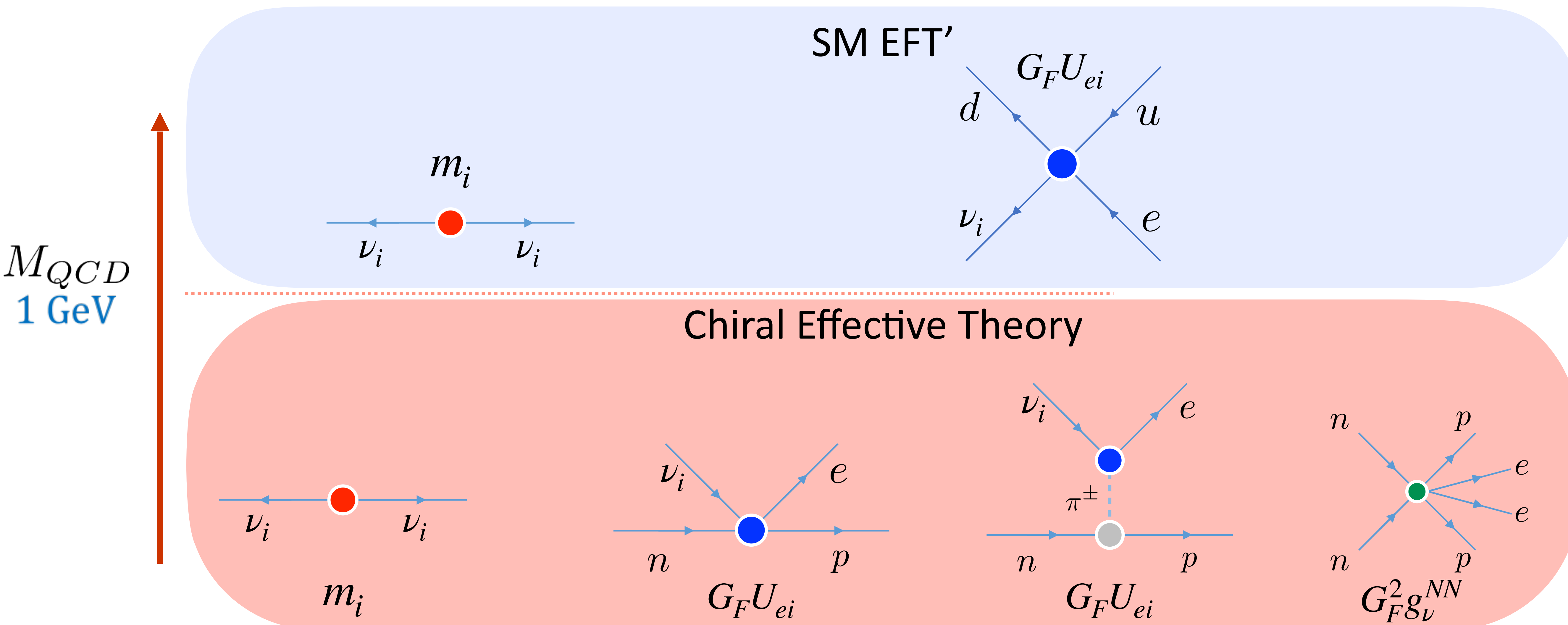


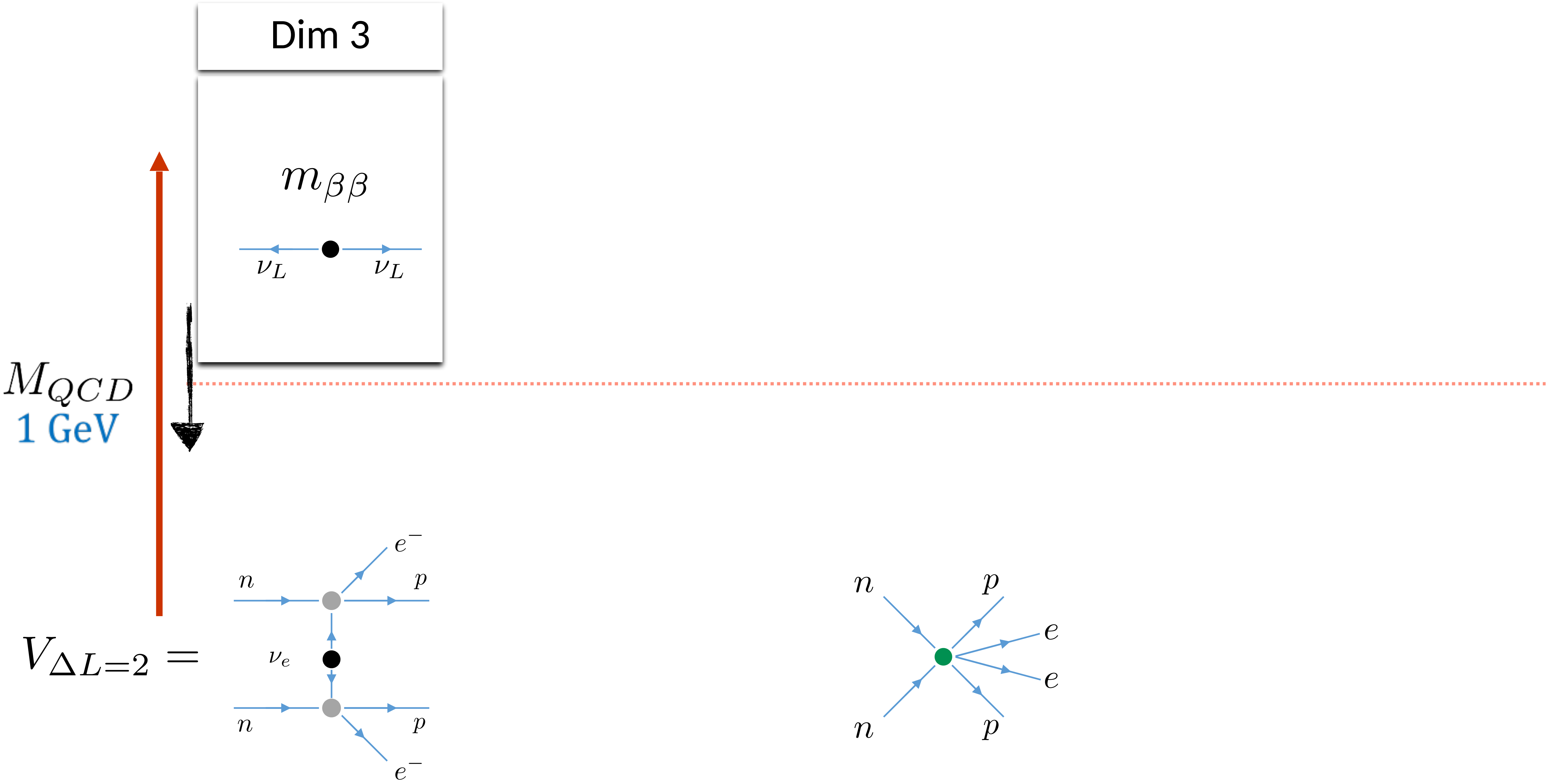
- At LO in Weinberg counting, only need the nucleon one-body currents
  - All needed low-energy constants are known

- Additional `non-NDA' contact interaction needed for renormalization
  - New LEC, g_ν^{NN}.
  - Currently only model estimates

Cirigliano et al '18,'19

Cirigliano et al '20,'21; Richardson et al '21

Chiral EFT



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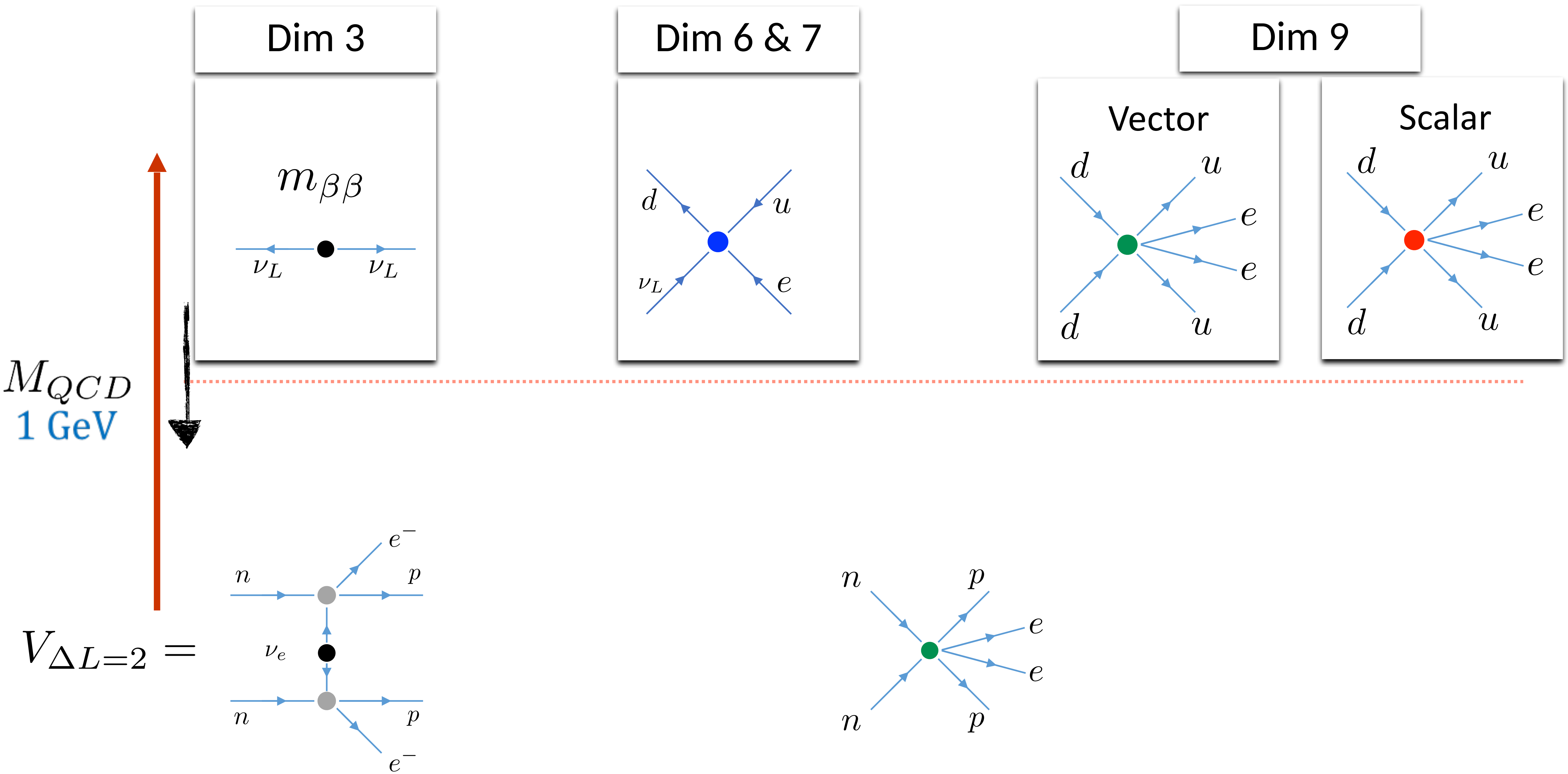

- Contributions of dimension-6,7,9 operators

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

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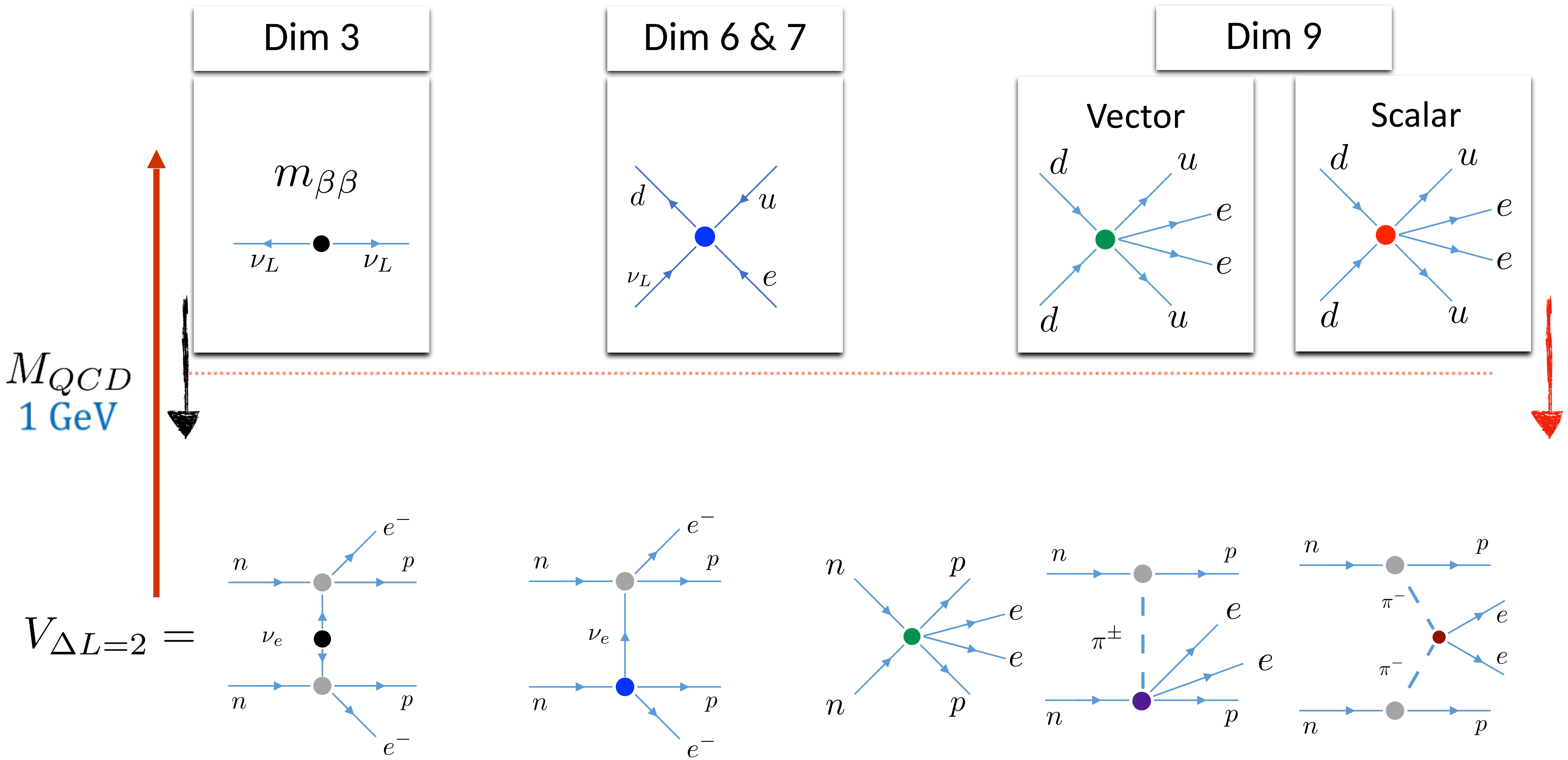

- Contributions of dimension-6,7,9 operators
  - Give additional interactions and LECs
  - LECs for the nucleon currents and $\pi\pi$ interactions are partially known

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

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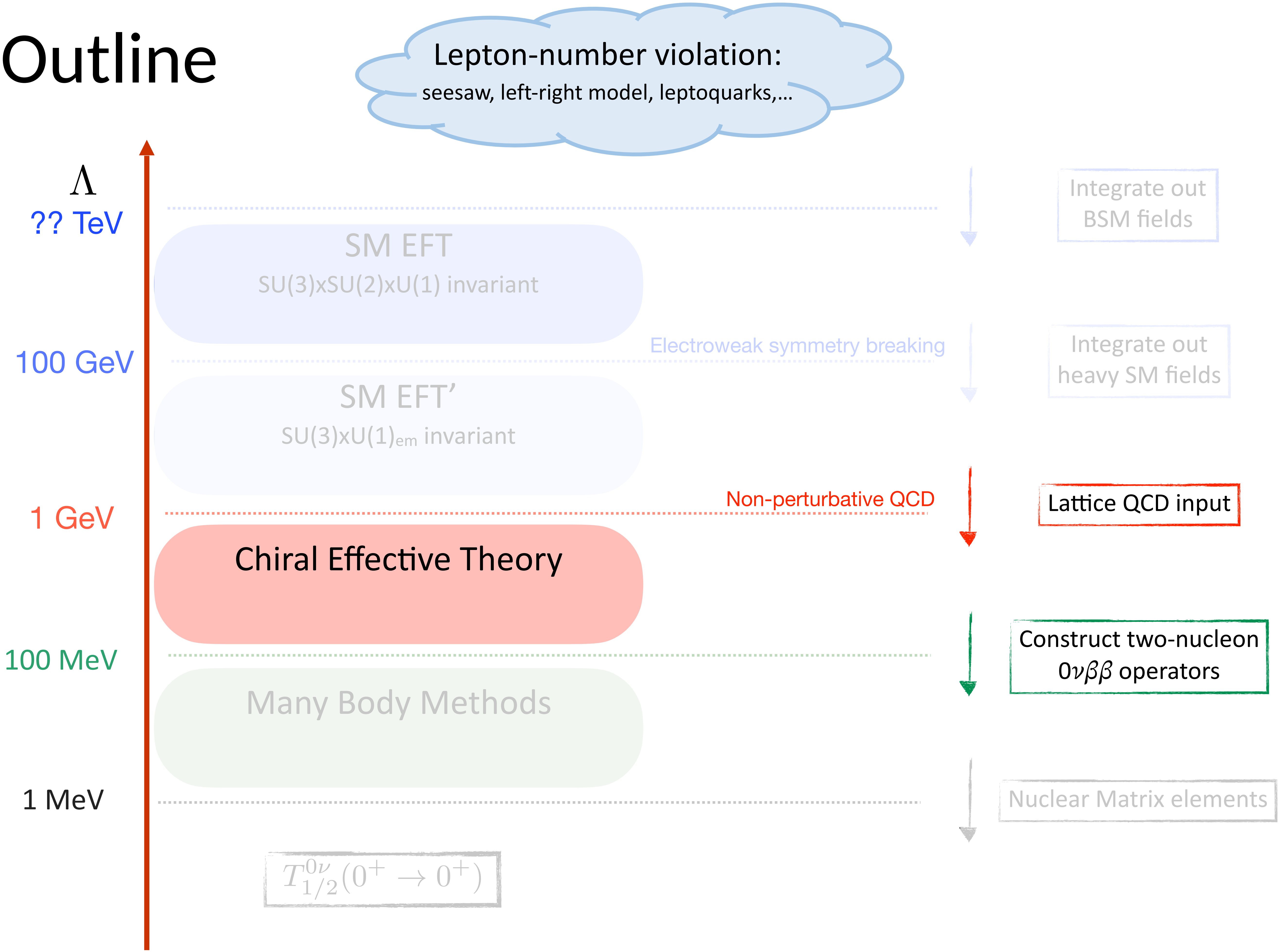

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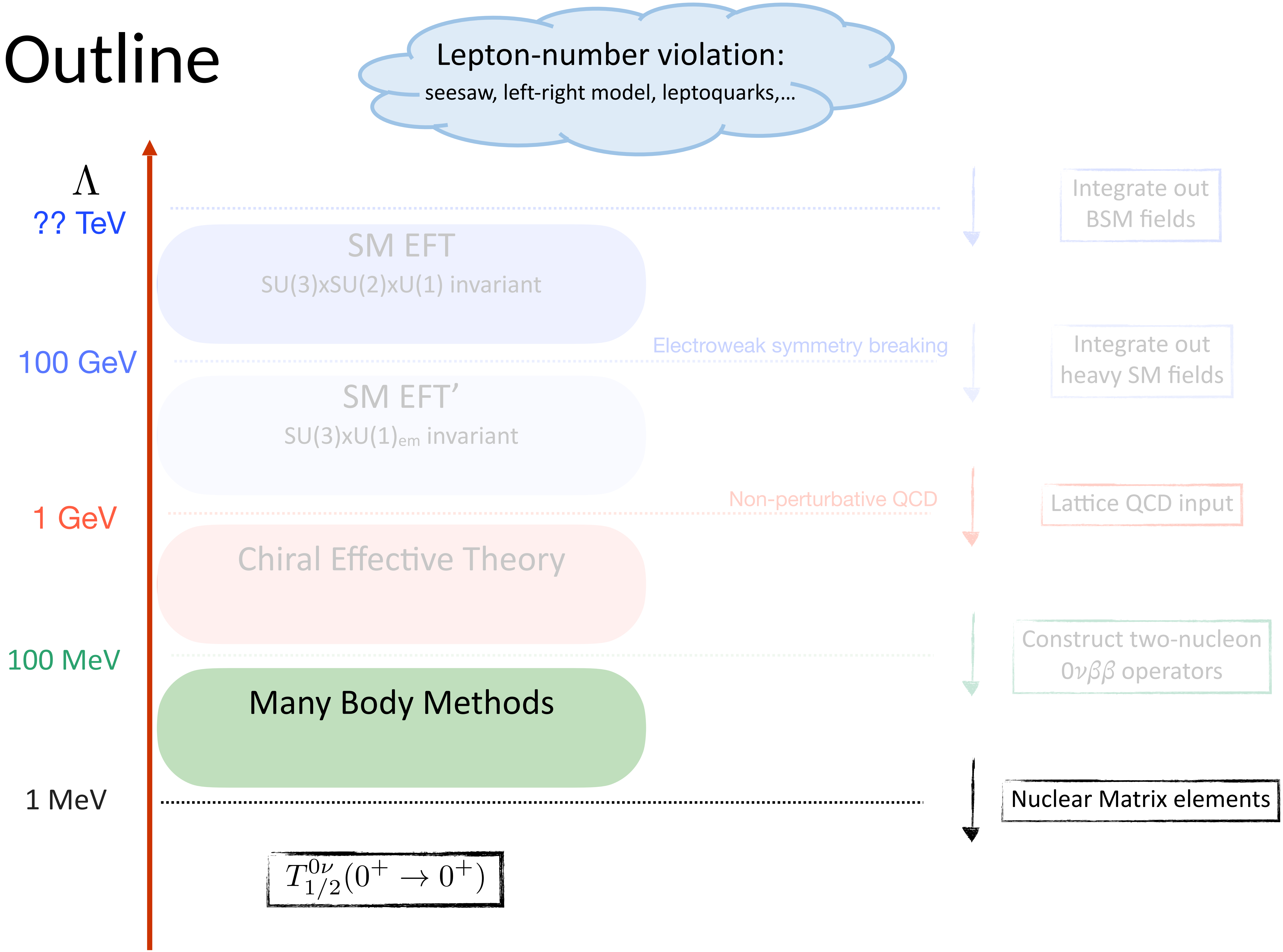

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Nuclear matrix elements

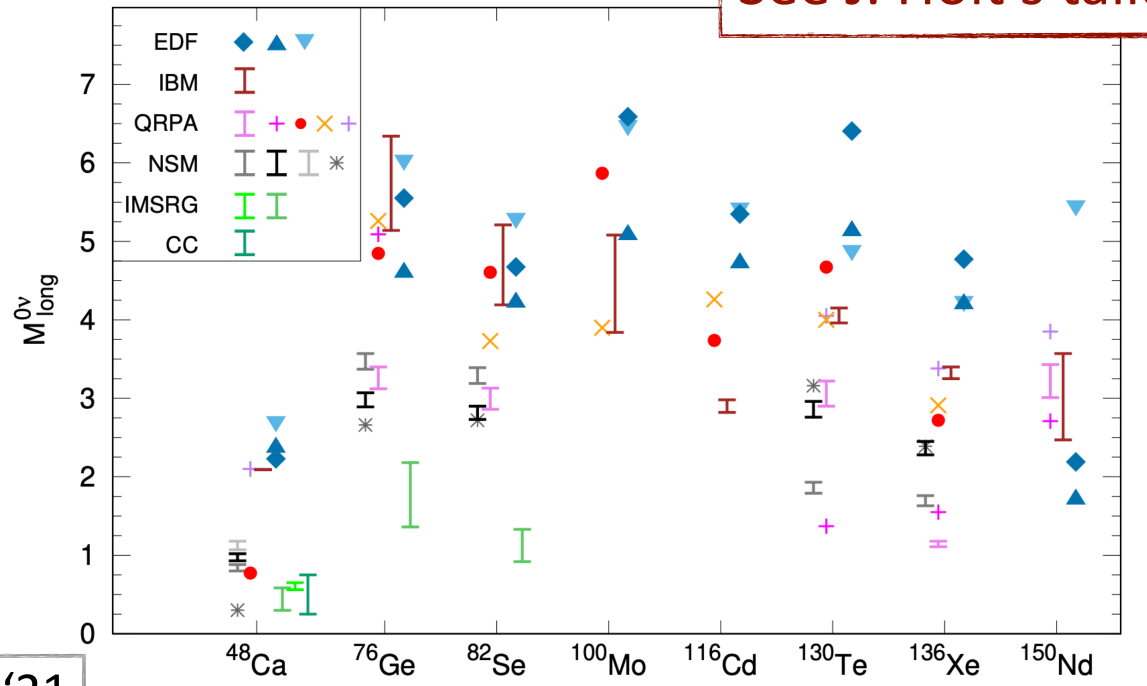
Light Majorana neutrino exchange

- NMEs can differ factor 2-3

- Recent *ab initio* NMEs for $A \geq 48$
  - Include estimates of g_ν^{NN} effect

Agostini et al, ’22; Belley et al ’23,’20; Yao et al ’20; Wirth, Yao, Hegert ‘21

See J. Holt’s talk



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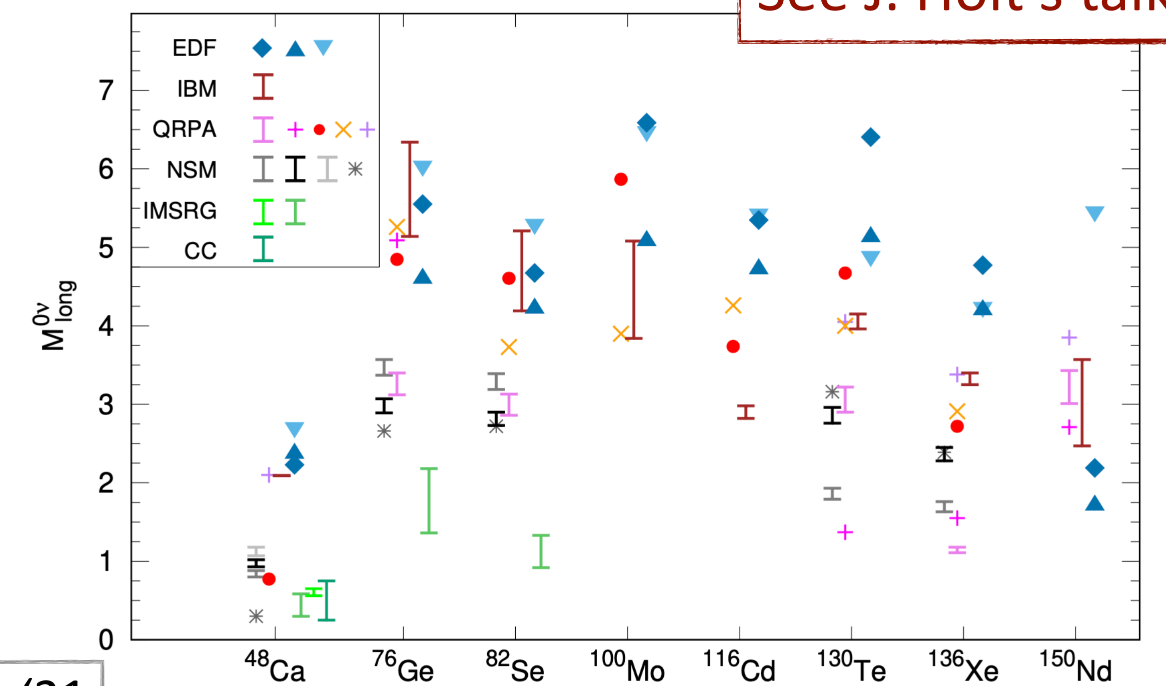

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Dimension 7 and 9 operators

- Need 15 NMEs for dimension-7, -9 contributions
  - Computed in the literature
- Similar status to Majorana-mass operator
  - Not well studied in *ab initio* or for arbitrary ν_R masses

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		
M_{GT}^{PP}	0.66	0.33		
M_{GT}^{MM}	0.51	0.25		
M_T^{AA}	–	–		
M_T^{AP}	-0.35	0.01		
M_T^{PP}	0.10	0.00		
M_T^{MM}	-0.04	0.00		

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

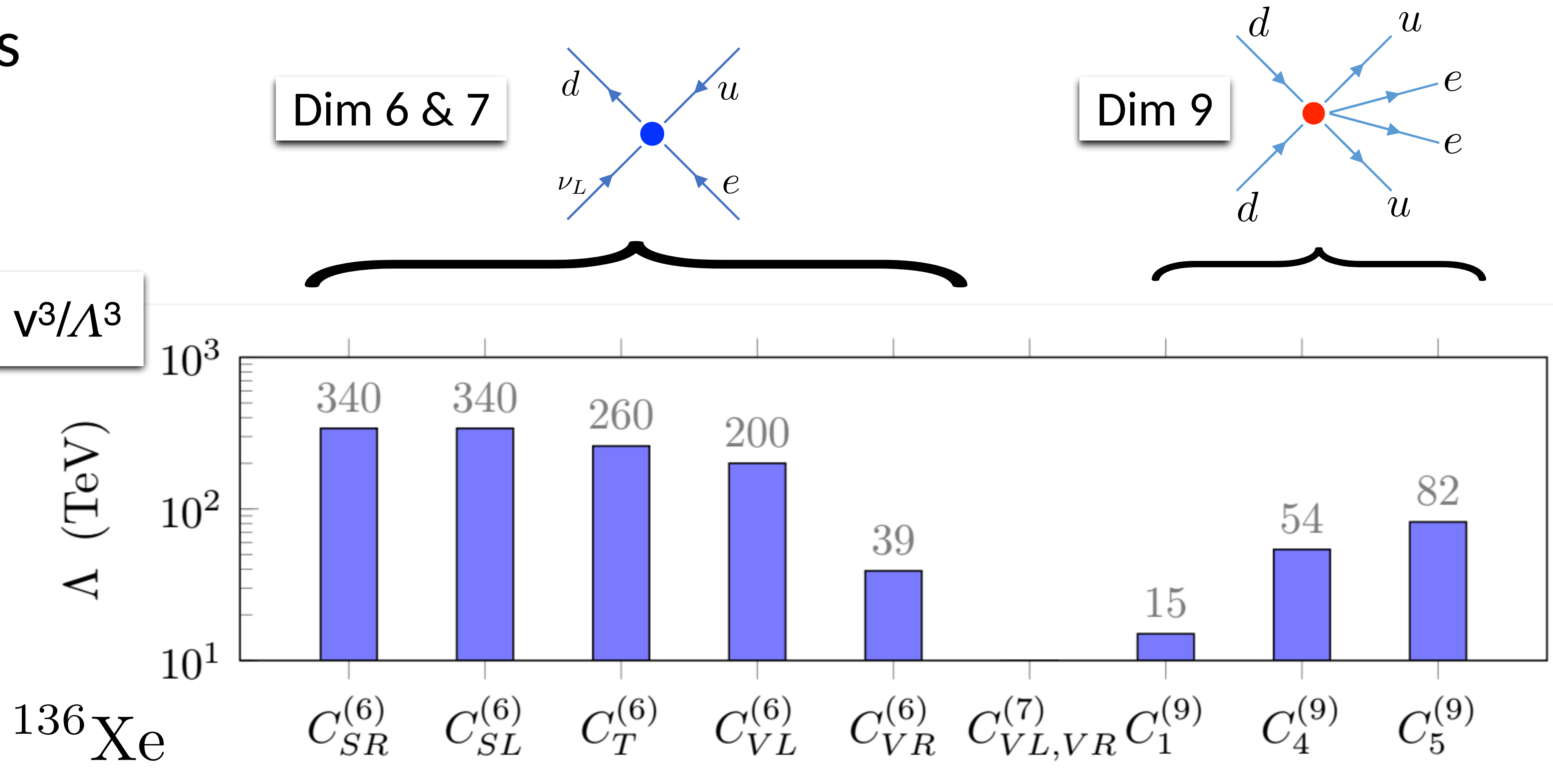
Phenomenology

Heavy LNV physics

Phenomenology

From heavy new physics

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

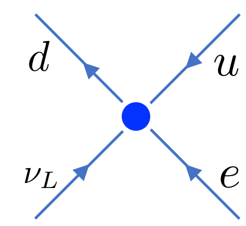


- O(1) uncertainties:
  - Unknown LECs
  - Nuclear Matrix elements

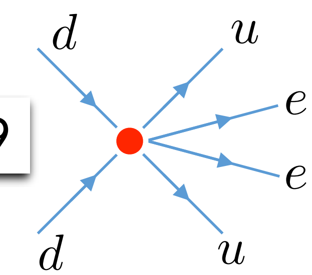
Phenomenology

From heavy new physics

Dim 6 & 7



Dim 9



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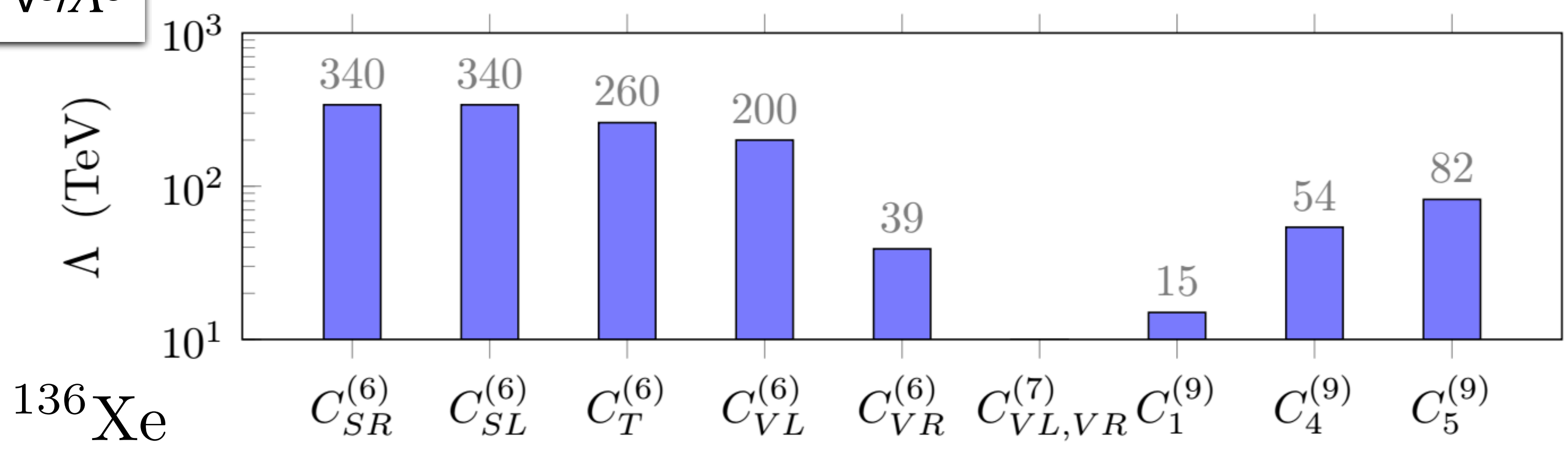
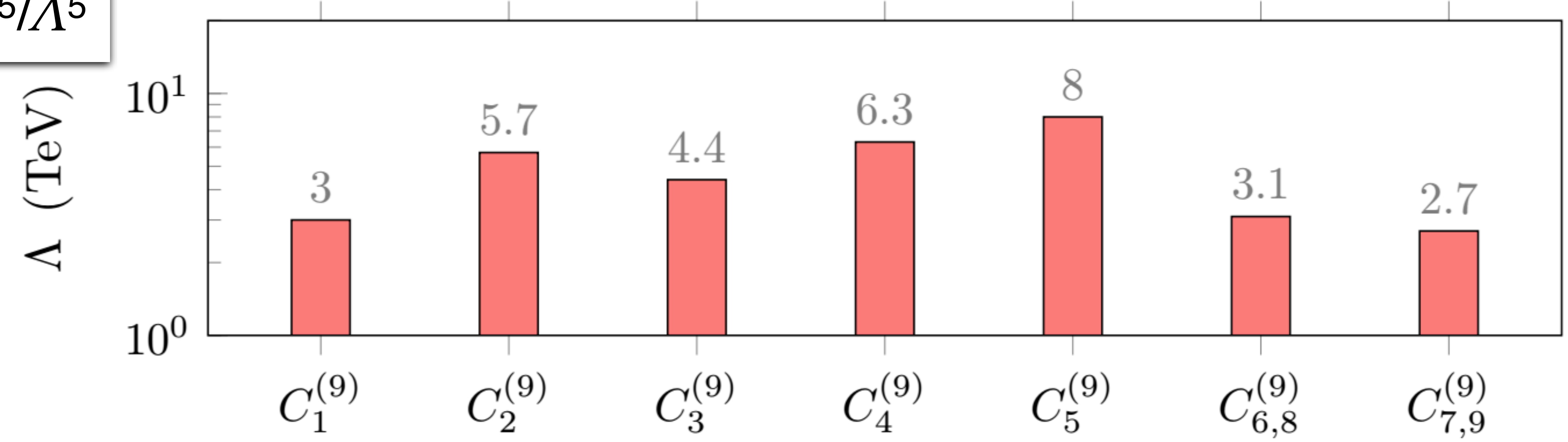


- Couplings with $C_i \sim v^5/\Lambda^5$



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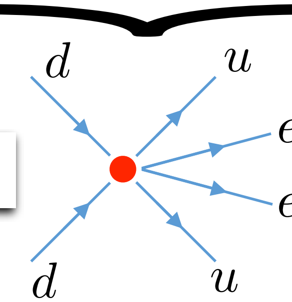

Phenomenology:

Light LNV: sterile neutrinos

Toy model: 1+1+1

- Involves 1 active, two sterile neutrinos
  - Assume steriles much heavier than the active neutrinos; $M_1, M_2 \gg m_\nu$

Bolton et al, 2020; Mohapatra et al, ’86; Nandi and Sarkar ’86;

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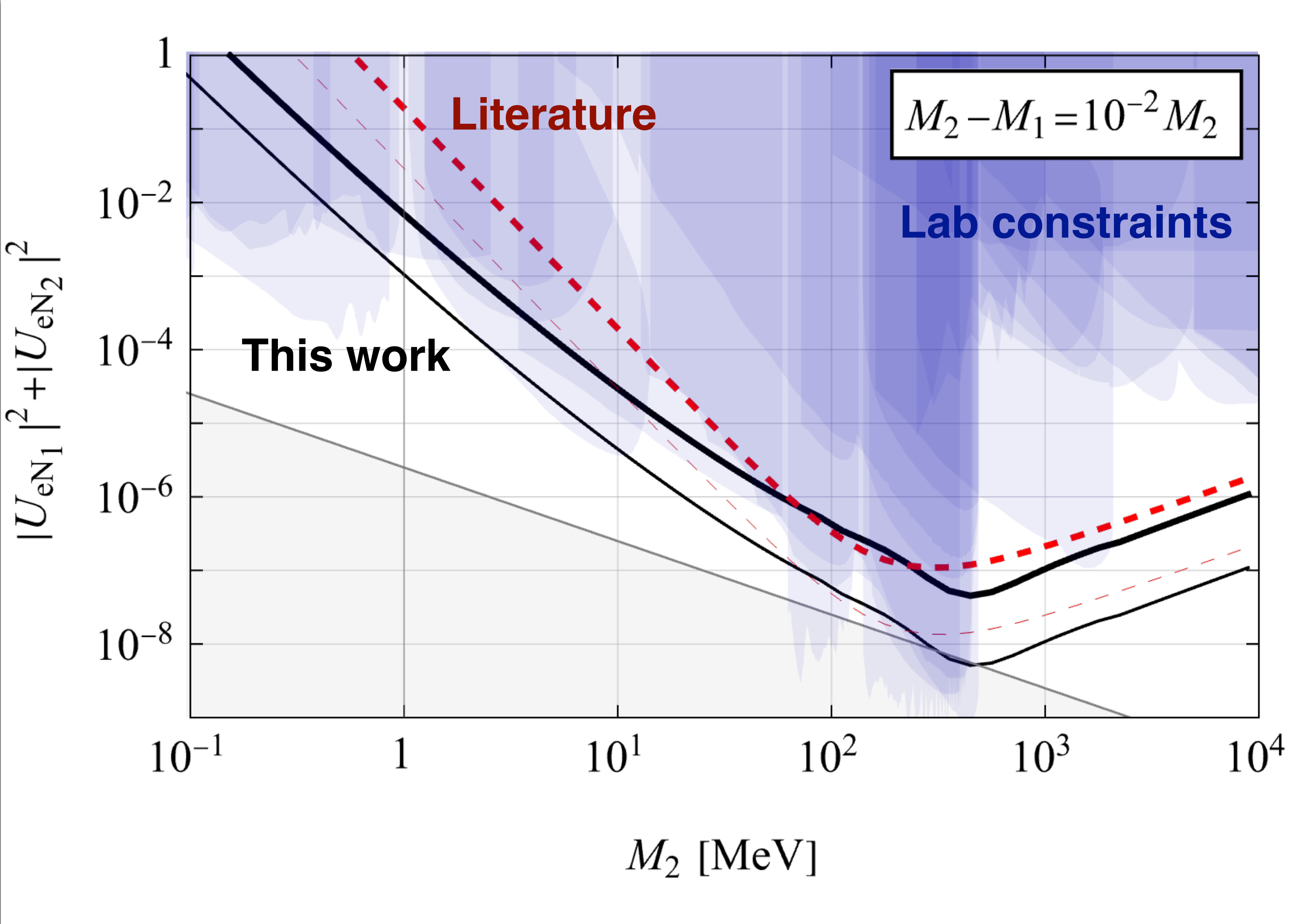
`Pseudo-Dirac' limit $M_2 - M_1 \ll M_{1,2}$



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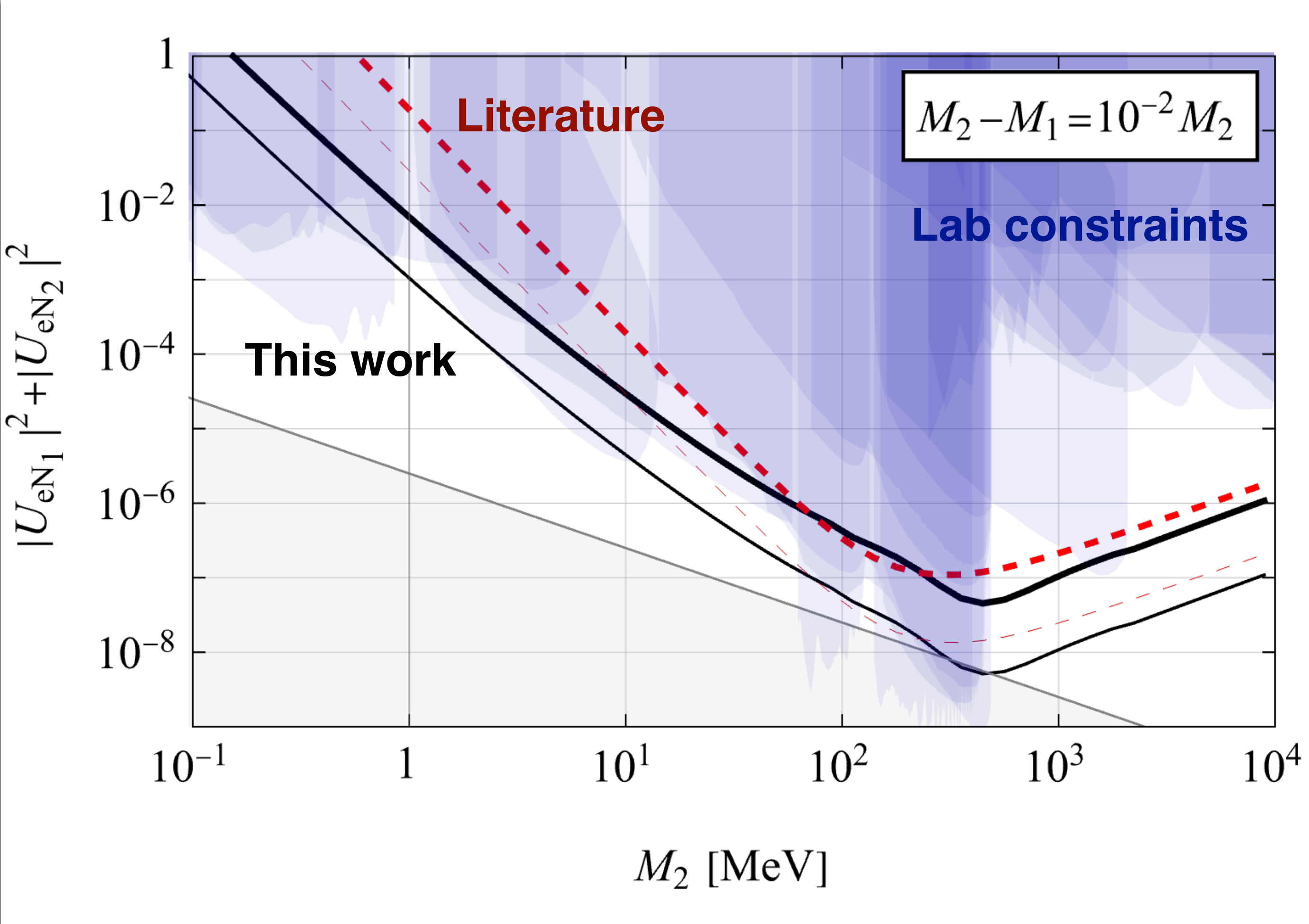
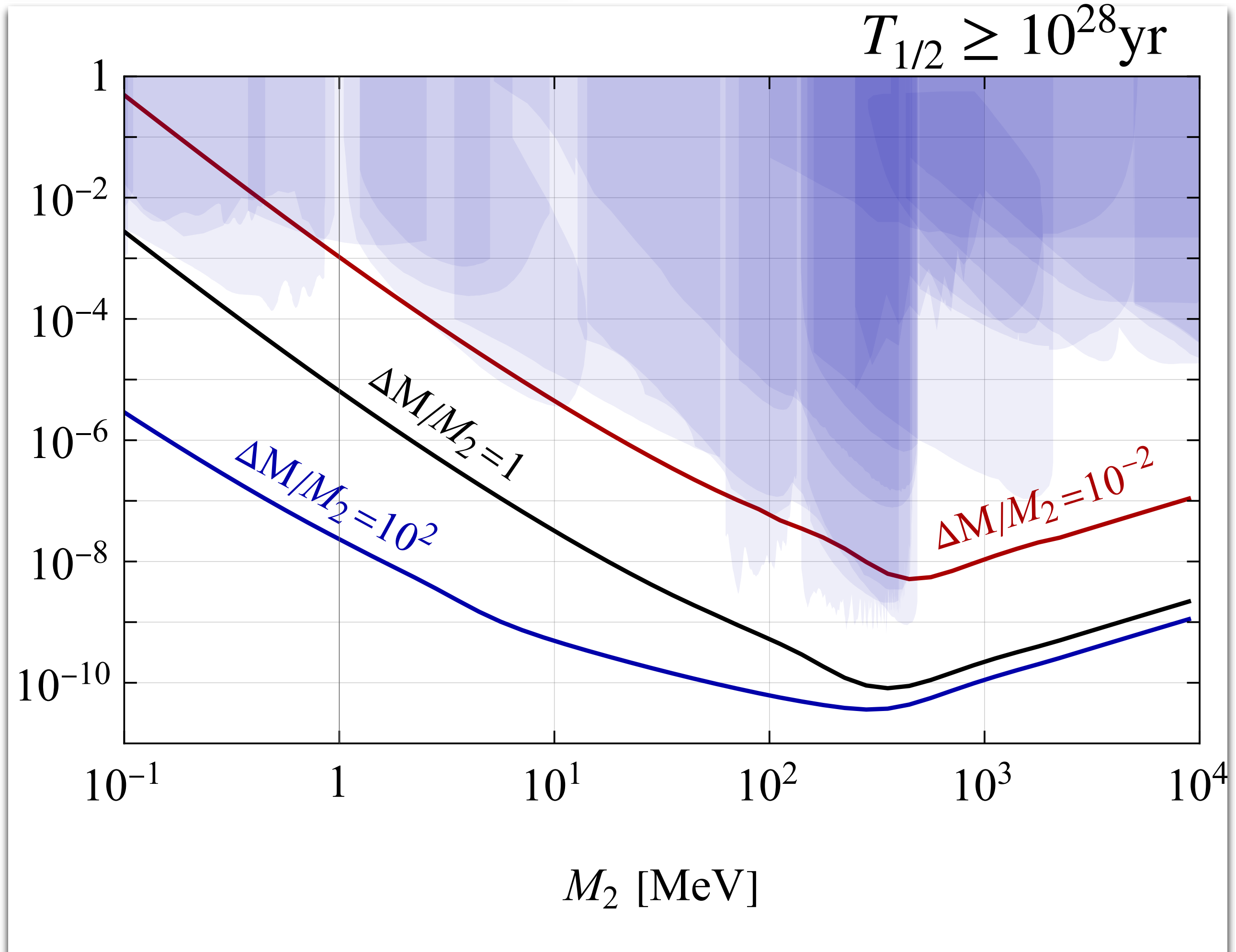


Larger mass splittings:



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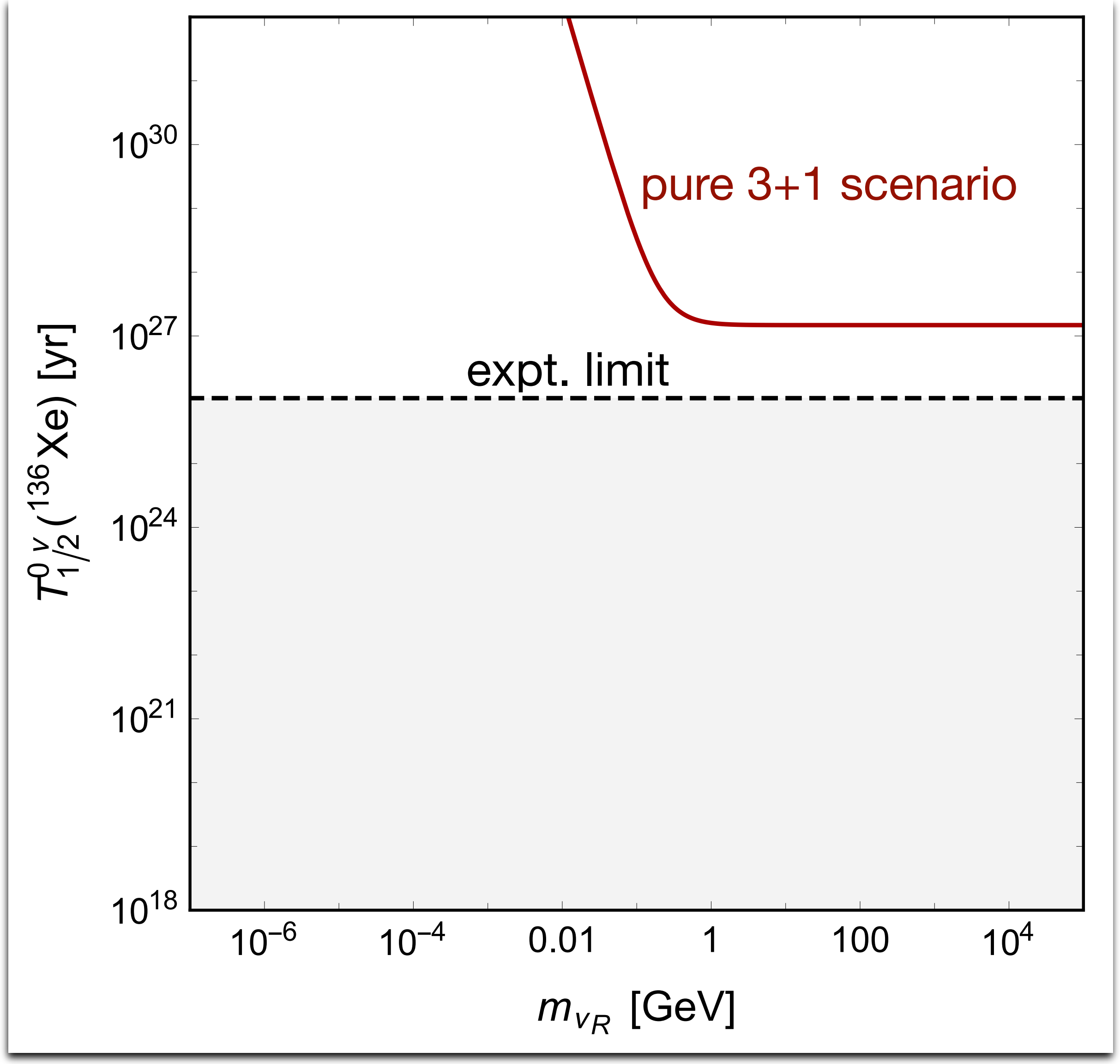
Phenomenology

From heavy new physics + light ν_R

Example with ν_R

- Toy Model
  - SM + 1 light ν_R



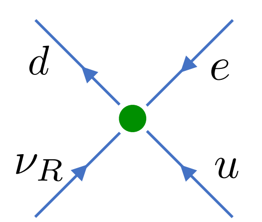
Phenomenology

From heavy new physics + light ν_R

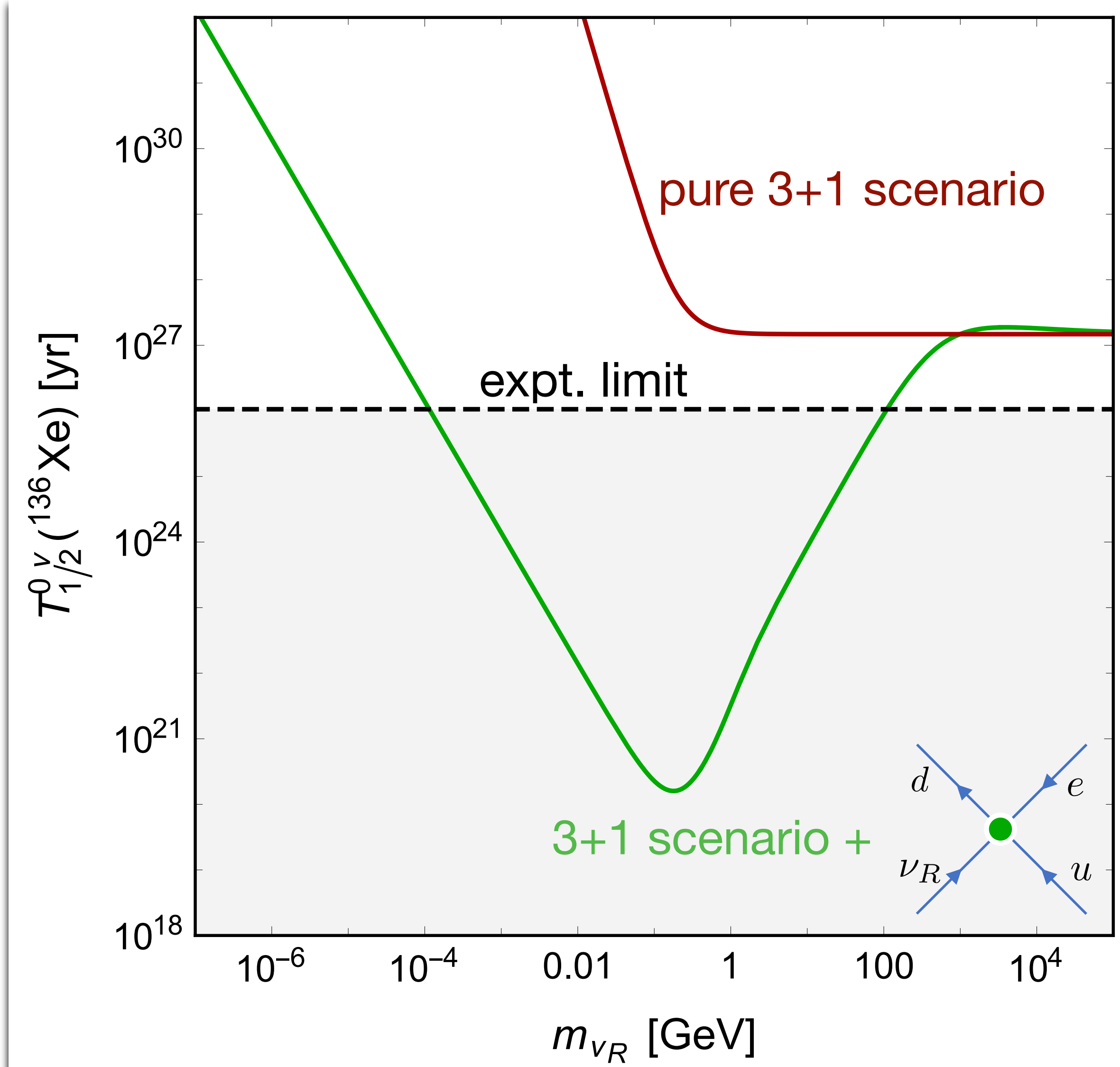
Example with ν_R

- Toy Model
  - SM + 1 light ν_R

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



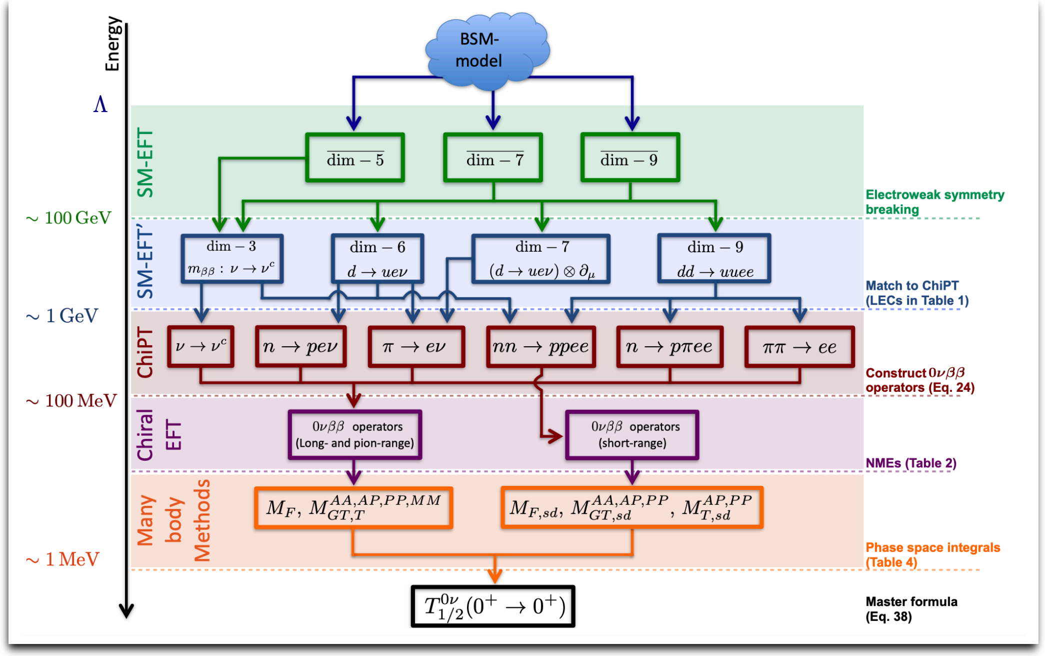
$\Lambda = 10\,\mathrm{TeV}$



- Higher dimensional ν_R terms can have a large impact!

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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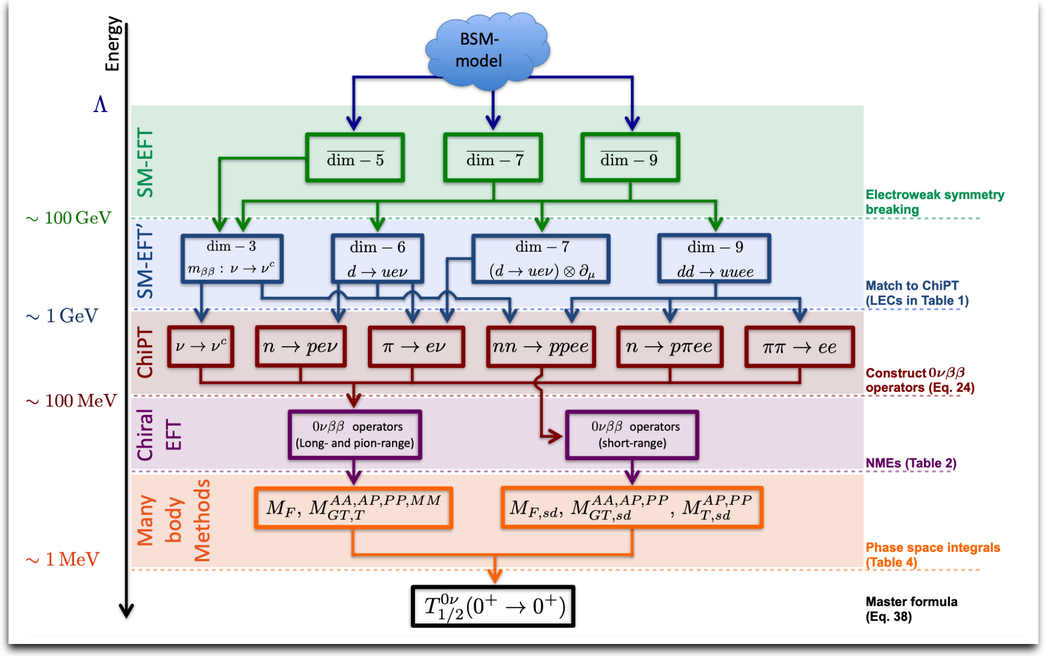
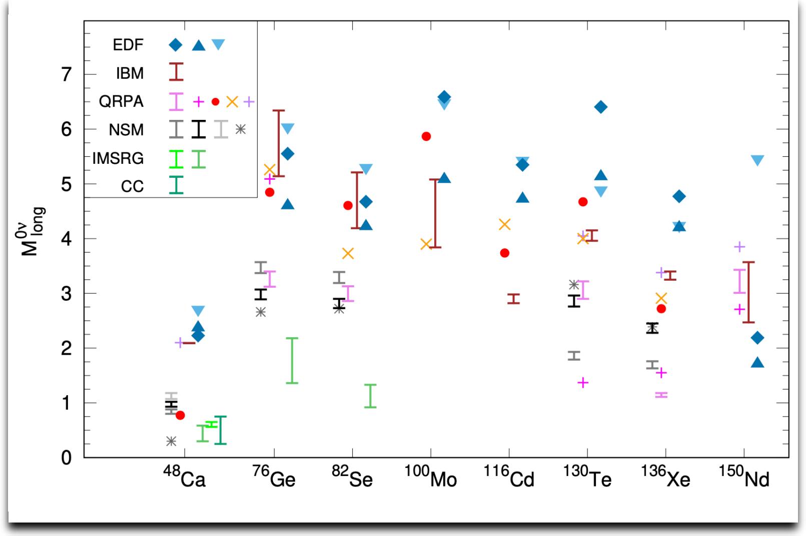


- Matching to chiral EFT involves unknown LECs
  - Renormalization requires terms beyond usual counting
- Needed Nuclear Matrix Elements determined in literature



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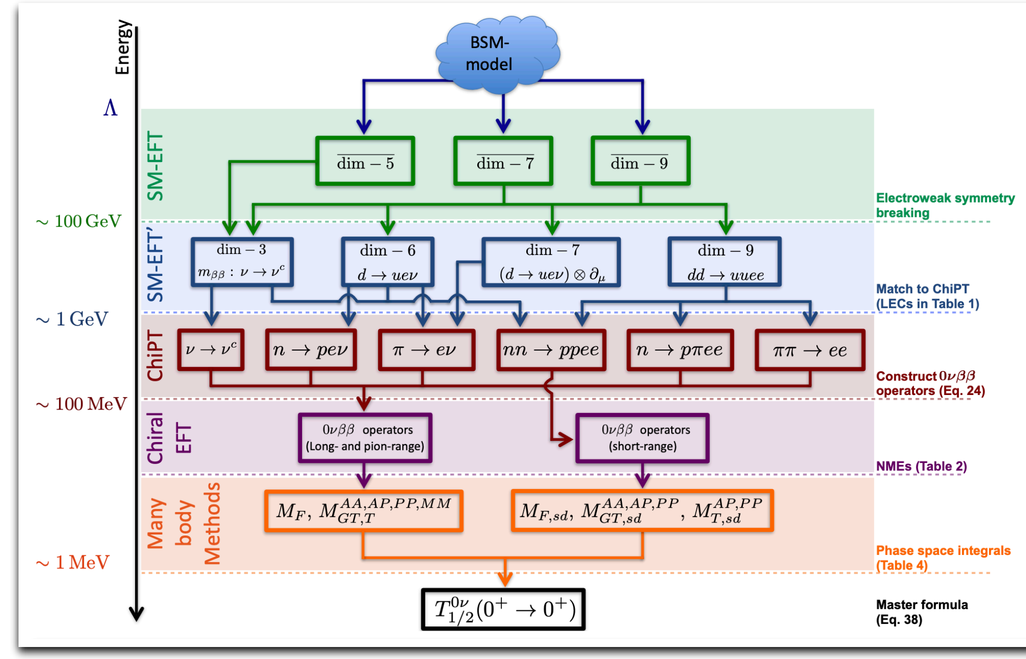

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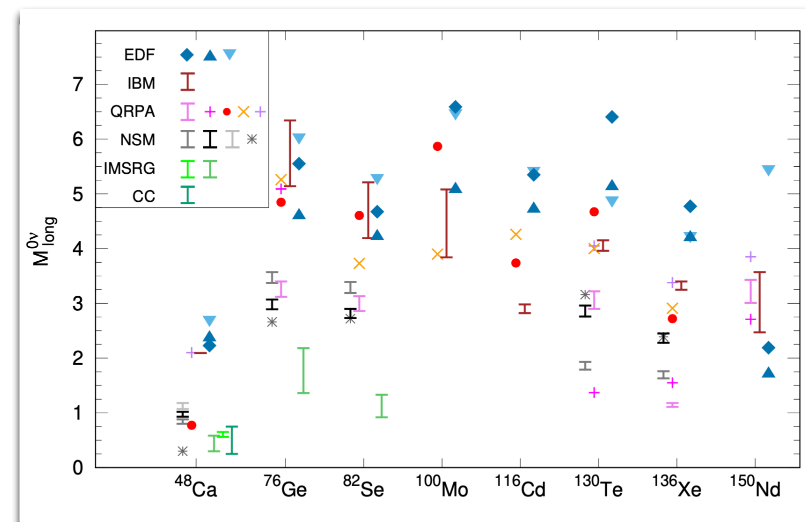
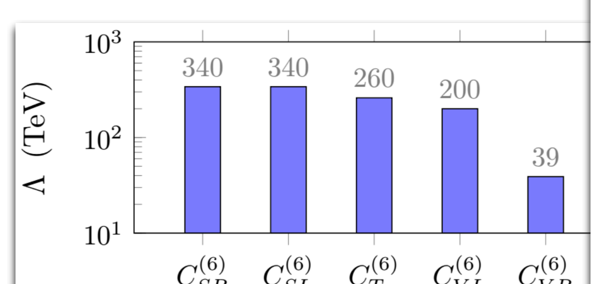
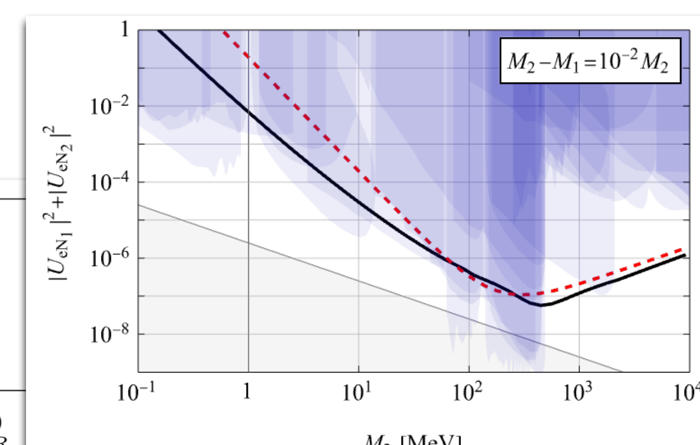


- $0\nu\beta\beta$ probes
  - Heavy LNV to $O(100)$ TeV scales
  - Light sterile ν_R interactions to $\Lambda \sim 10$ TeV





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:

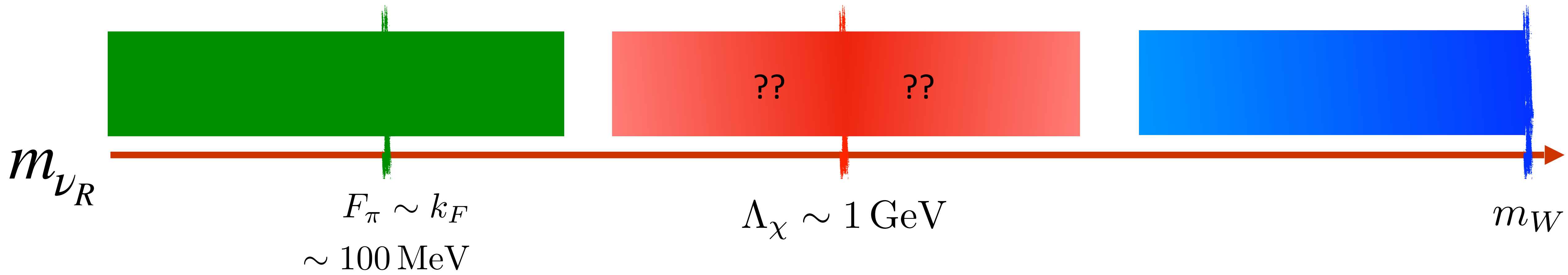
- $c_5 \ll O(1), \qquad \Lambda = \mathcal{O}(1-100)\mathrm{TeV}$
  - Relative enhancement of higher-dimensional terms due to $c_{7,9}/c_5 \gg 1$
- Happens, for example, in the left-right model

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

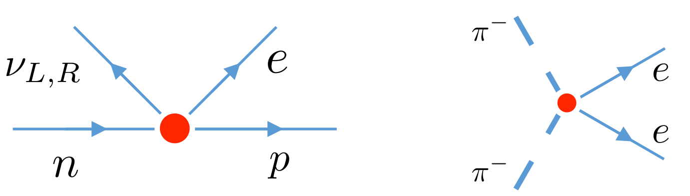
Sterile neutrinos

Sterile neutrinos

Complication: m_{ν_R} dependence

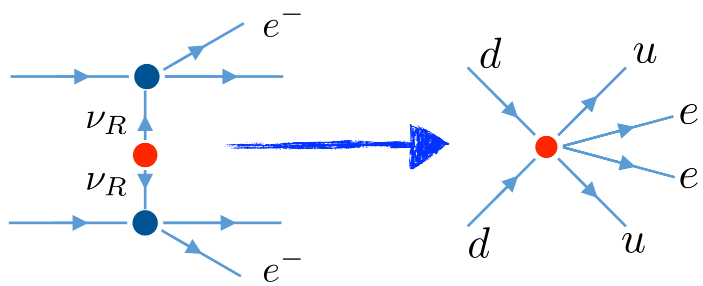


- Chiral EFT involving ν_R



- Neither EFT works well here
  - Missing operators ~ Λ_χ / m_{ν_R}
  - Loop corrections ~ m_{ν_R} / Λ_χ

- Integrate out ν_R



$\rightarrow$ Chiral EFT without ν_R

$A \propto m_{\nu_R}$

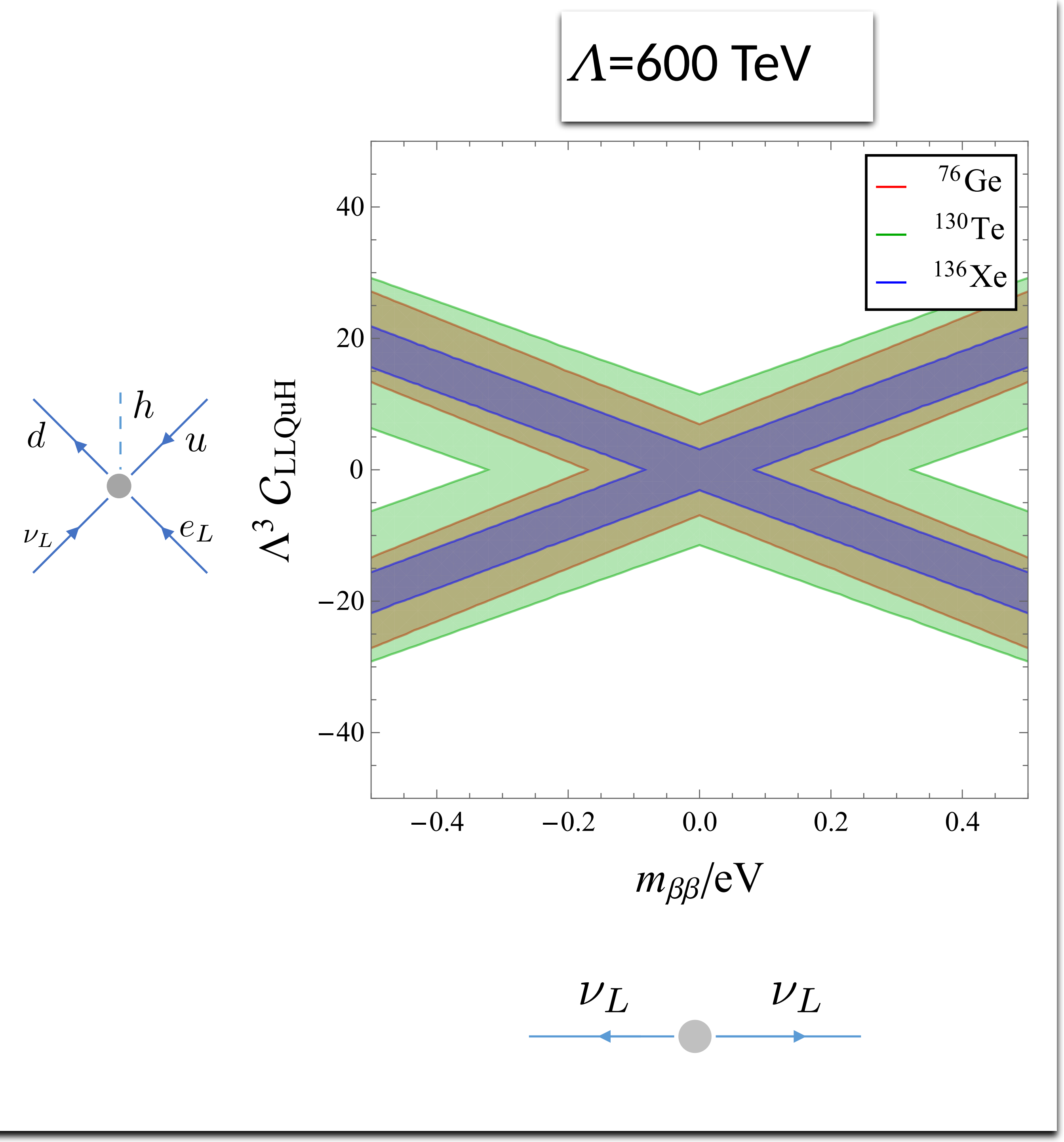
Interpolate

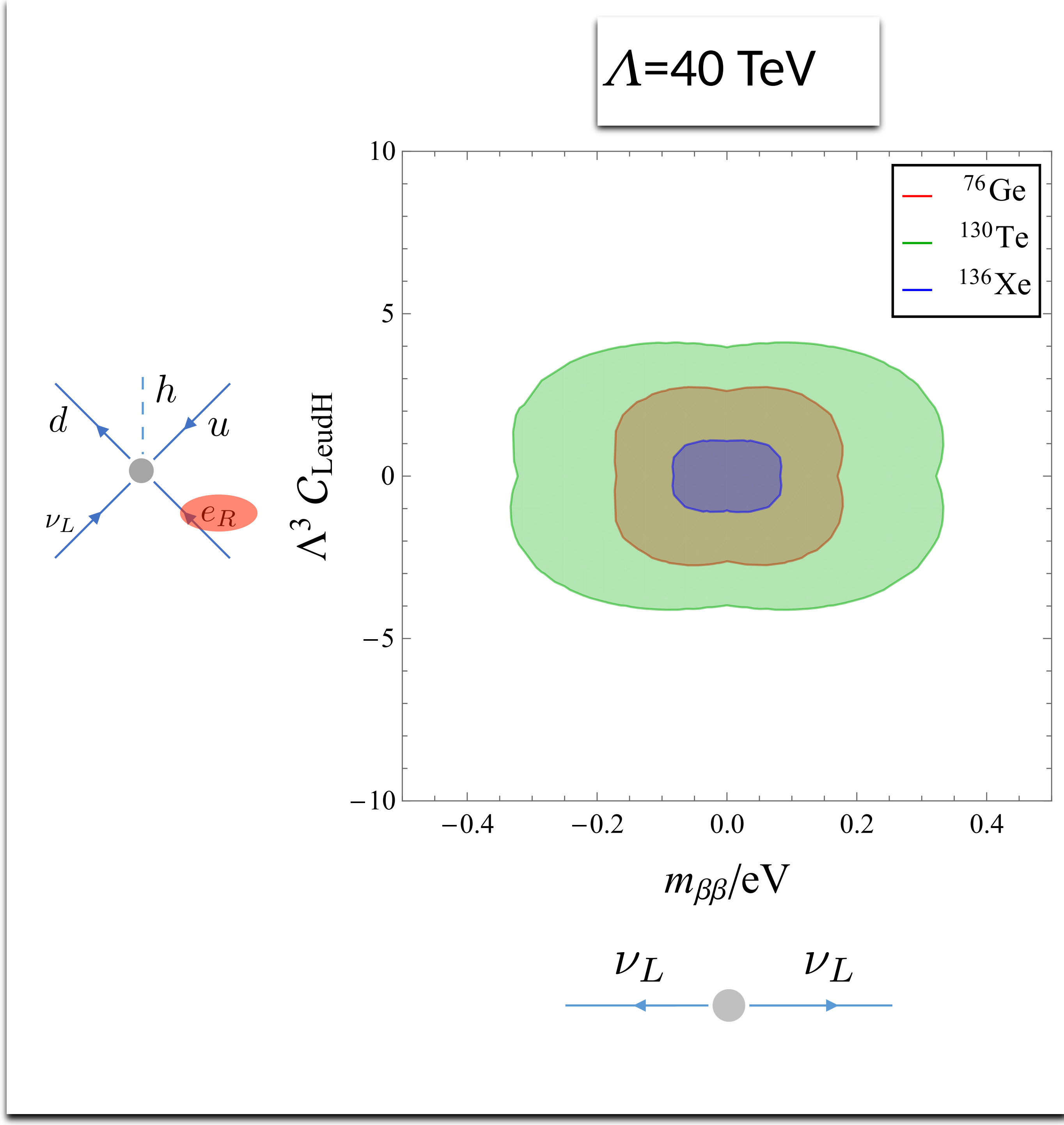
$A \propto m_{\nu_R}^{-1}$

Disentangling operators

Phenomenology

From heavy new physics

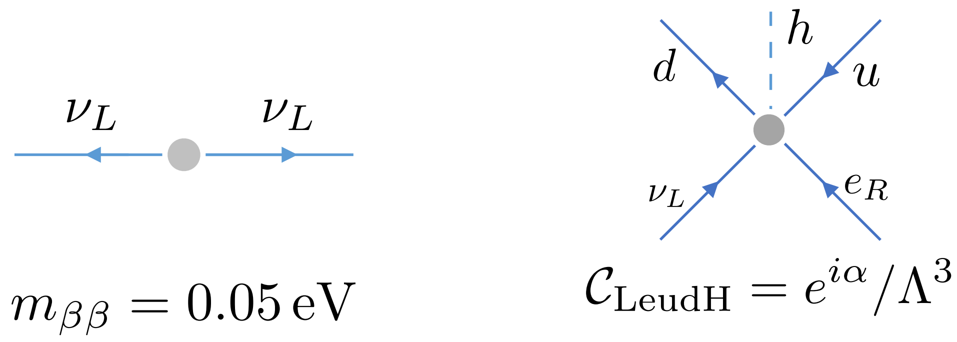




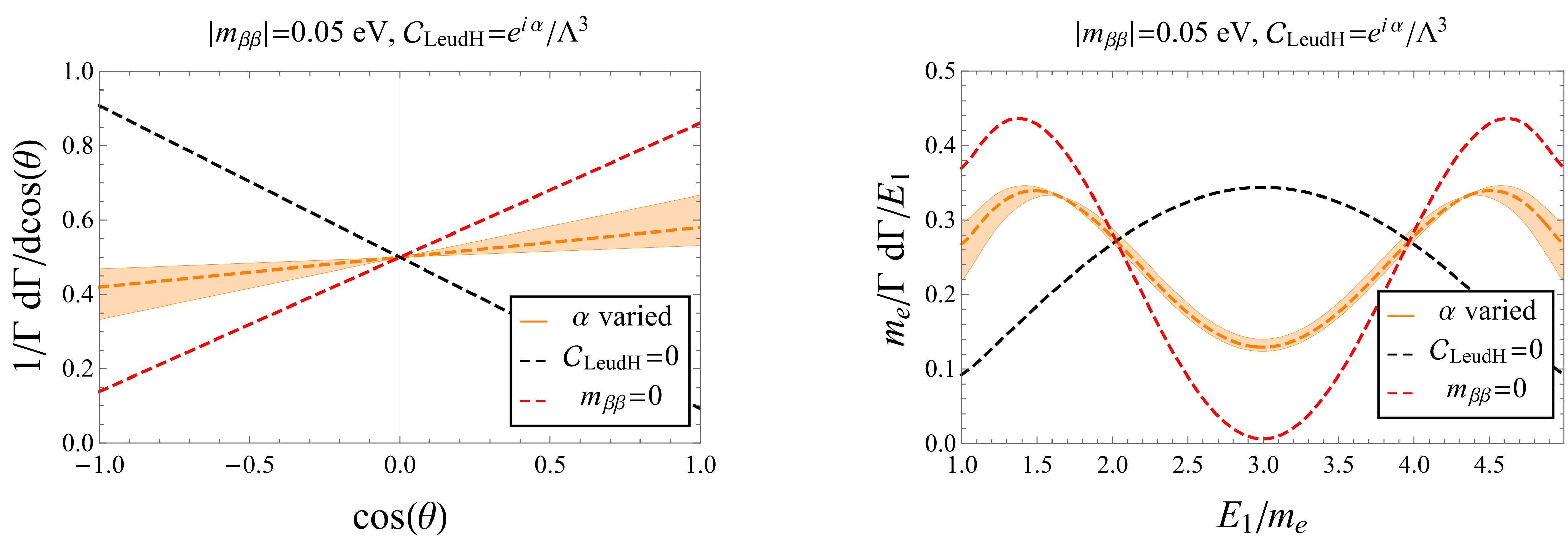
Disentangling operators

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

- Picking the allowed values



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



Example:
The left-right model

An example: LR model

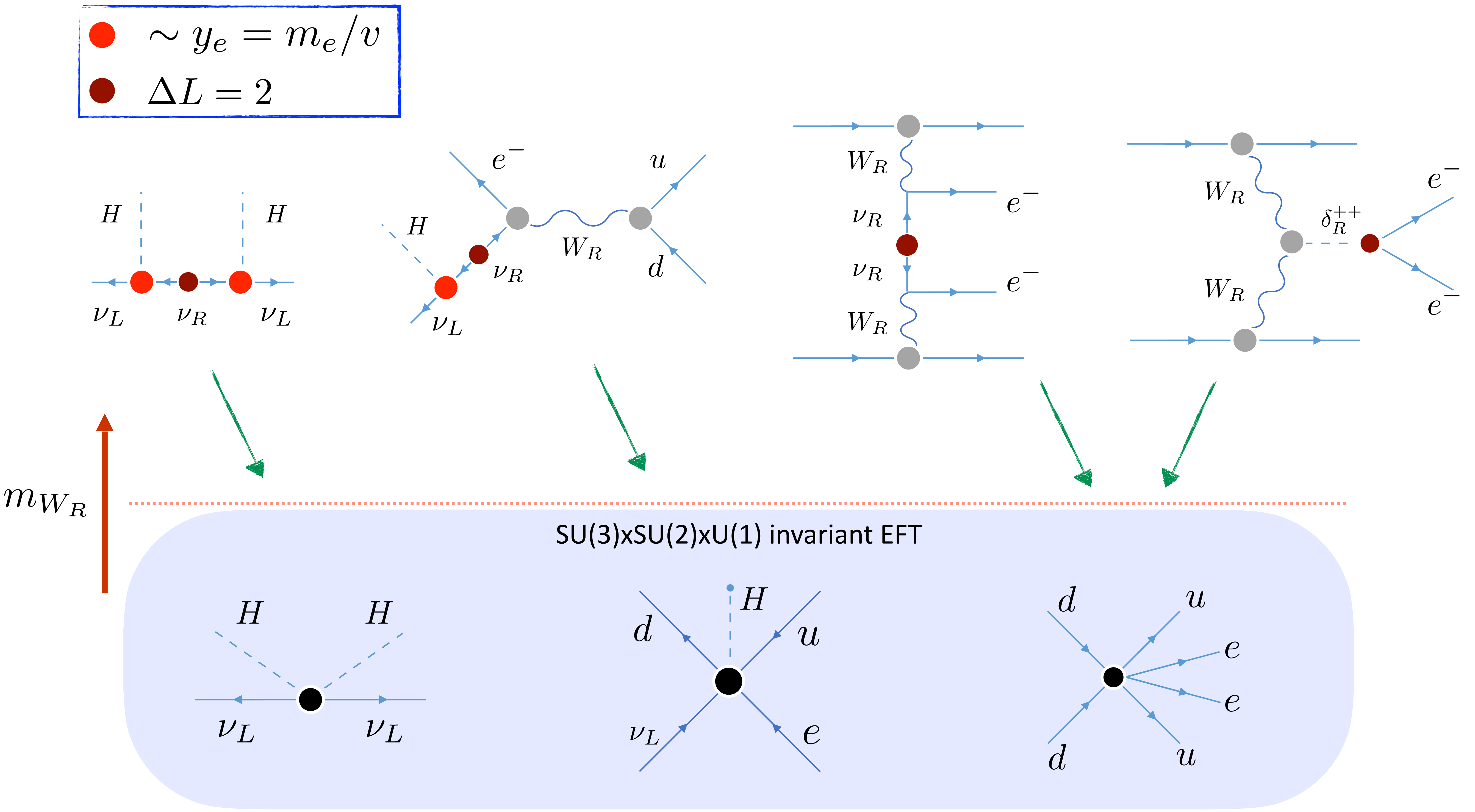
In Left-Right models:

- SM gauge symmetry is extended to $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$
- Allows for parity or charge-conjugation to be restored at high energies
- Explains neutrino masses through the see-saw mechanism (Type-I & Type-II)

Violates lepton number

- New Fields:
  - Right-handed bosons $W_R,\ Z_R$
  - Right-handed neutrinos ν_R
  - Heavy new scalars δ_R^{++}

An example: LR model

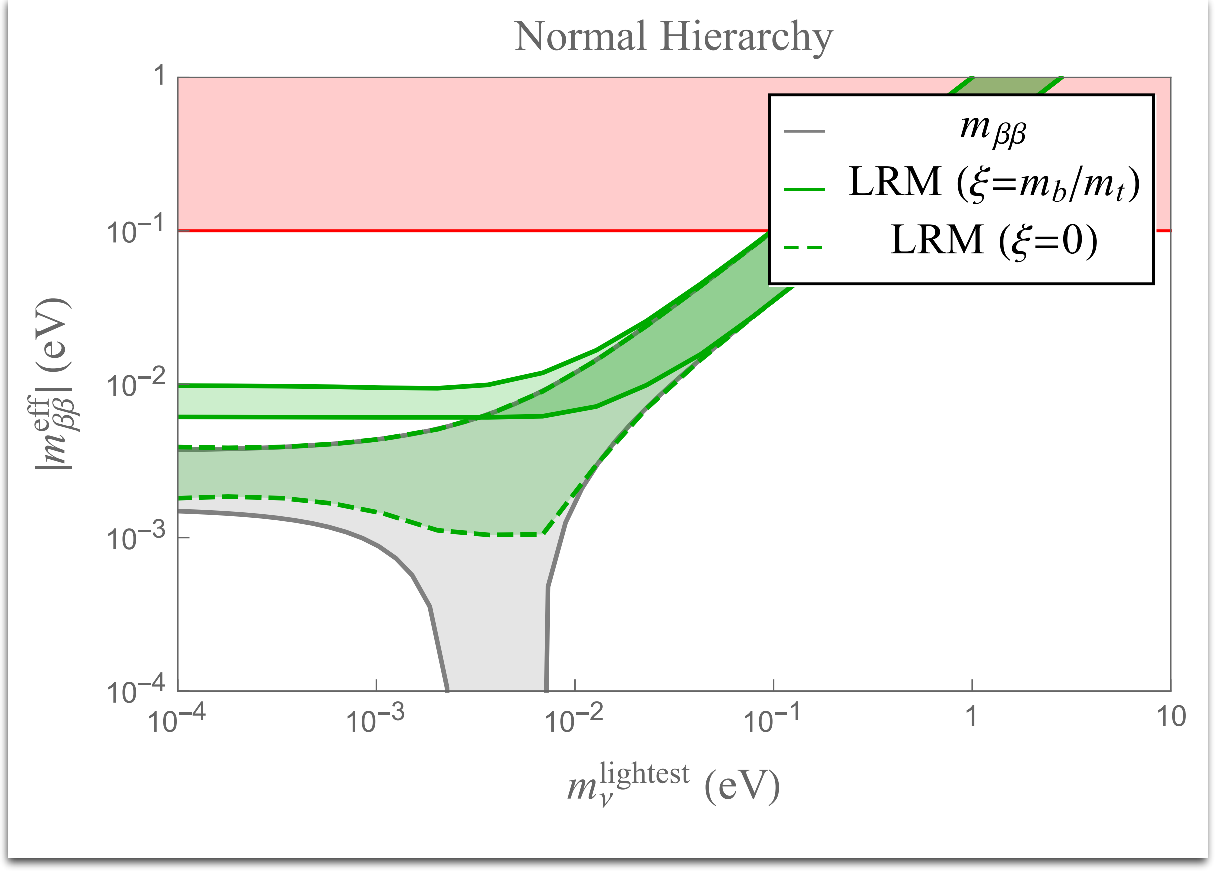


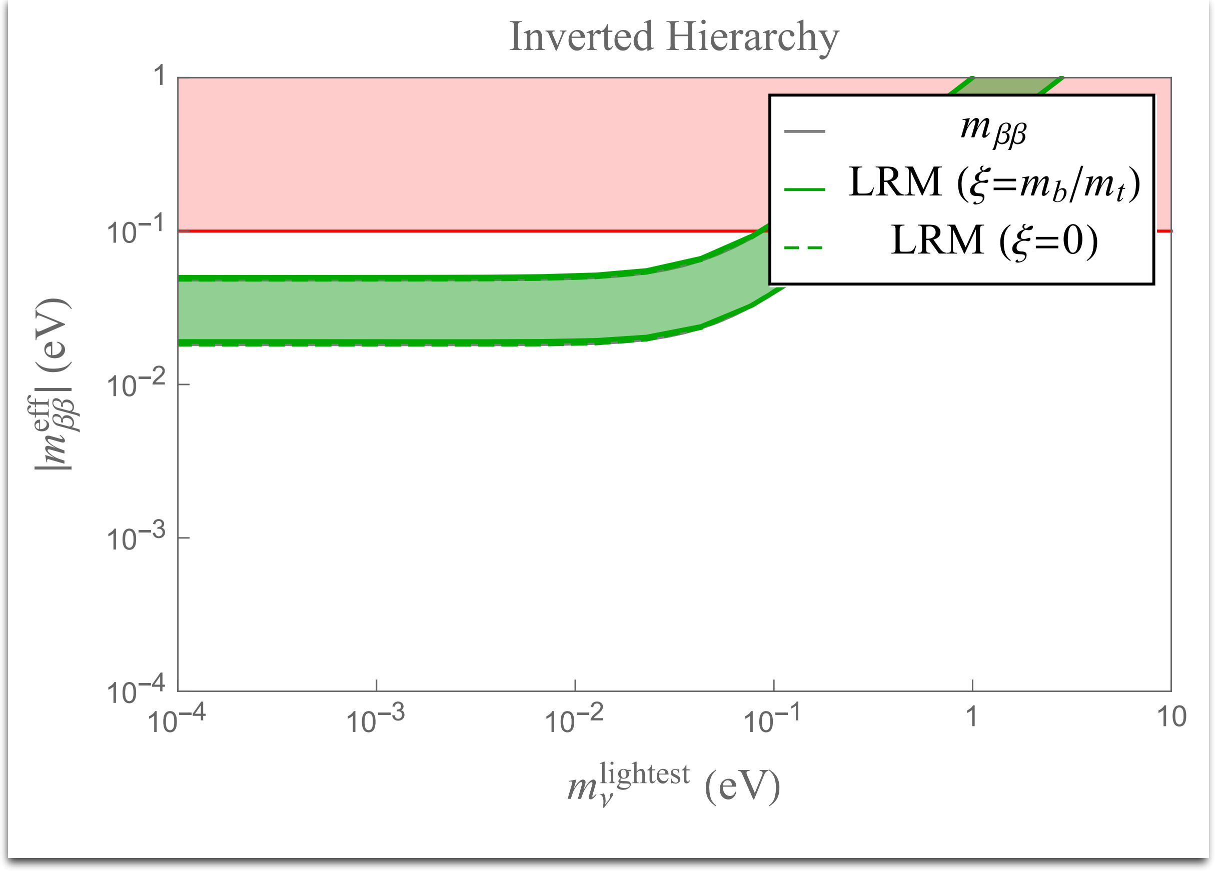
dim-5 $\sim y_e^2 \left(\frac{v}{\Lambda}\right)$ dim-7 $\sim y_e \left(\frac{v}{\Lambda}\right)^3$ Dim-9 $\sim \left(\frac{v}{\Lambda}\right)^5$

An example: LR model

$$m_{W_R} = 4.5\,\mathrm{TeV}, \qquad m_{\nu_R} = 10\,\mathrm{TeV}, \qquad m_{\delta_R^{++}} = 4\,\mathrm{TeV}$$

- Assume right-handed neutrino mixing follows the PMNS matrix





- Mild effect on NH (due to dim-9)

- Negligible effect in IH case, dim-5 terms dominate
  - Due to chiral suppression of the induced dim-6,7,9 operators

An example: LR model

Not excluded by collider searches

$$m_{W_R} = 4.5\,\mathrm{TeV}, \qquad m_{\nu_R} = 10\,\mathrm{GeV}, \qquad m_{\delta_R^{++}} = 4\,\mathrm{TeV}$$

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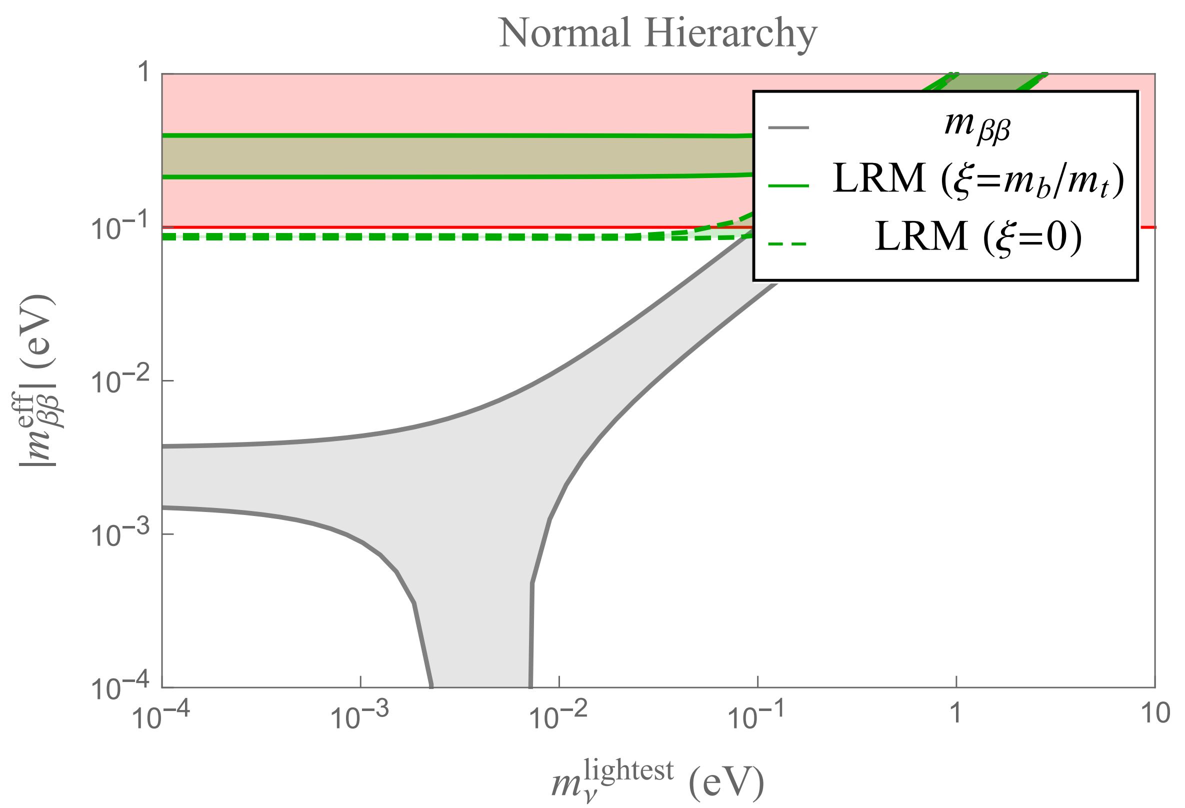
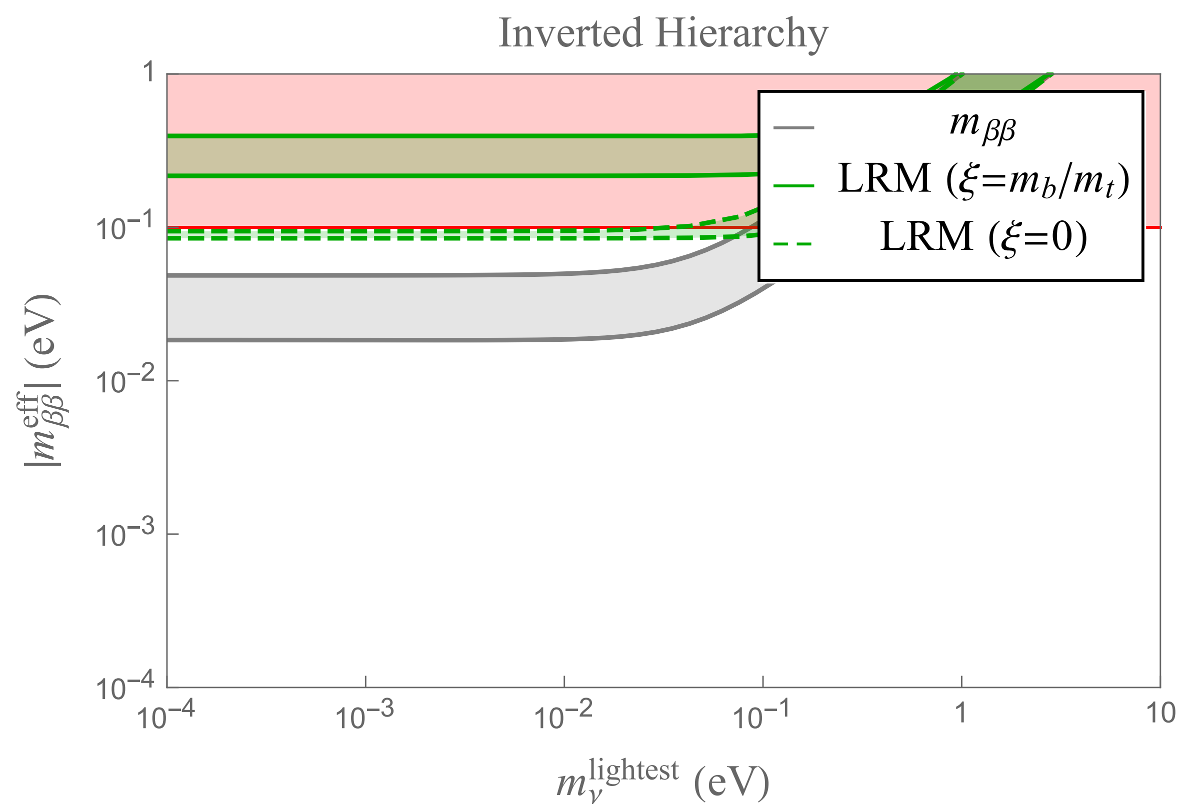




Subject to NME / LEC uncertainties

- Large effect in both NH & IH
- Now dominated by dim-9 terms

Checking the power counting

Checking the power counting

Dimension-3

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

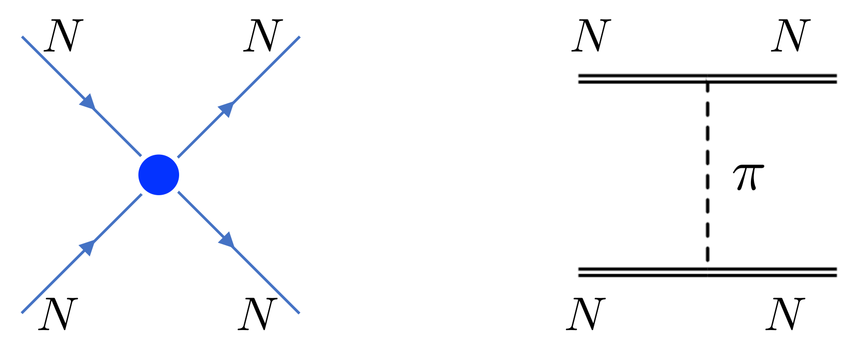
Checking the power counting

Dimension-3

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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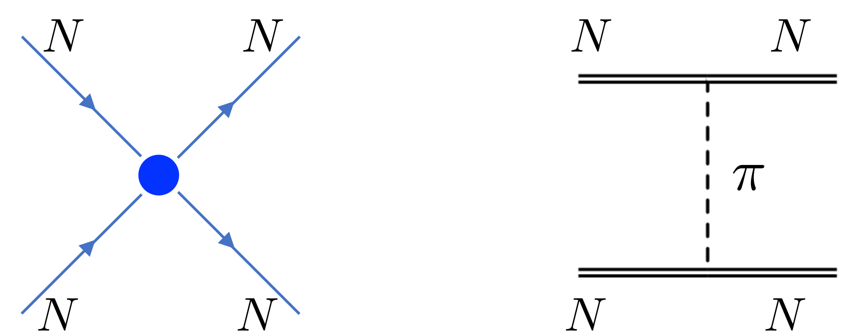
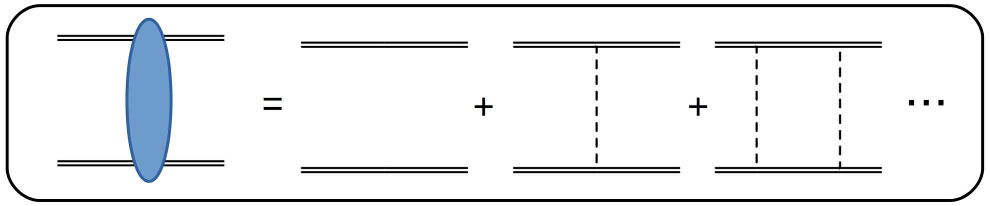
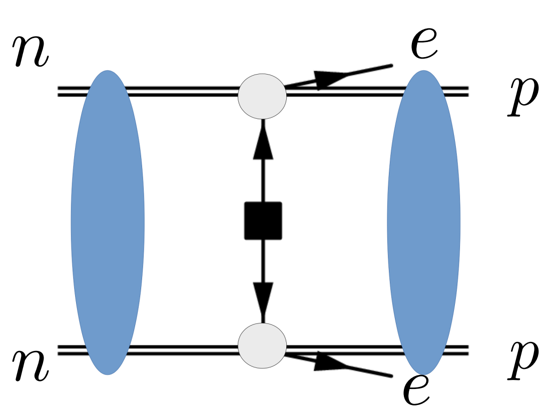


Dress the ΔL=2 potential with (renormalized) strong interactions:





✓ finite

Checking the power counting

Dimension-3

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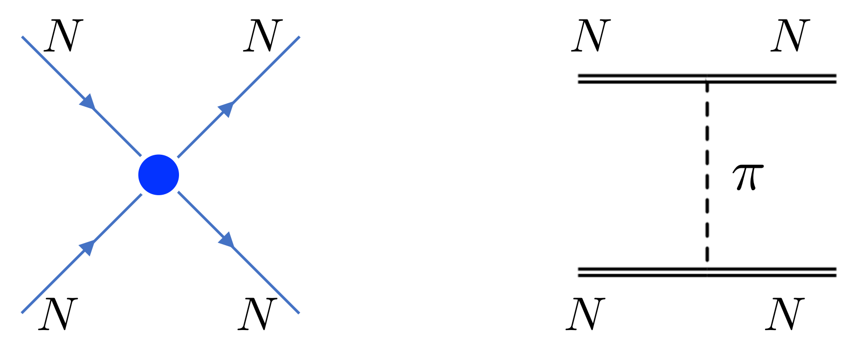

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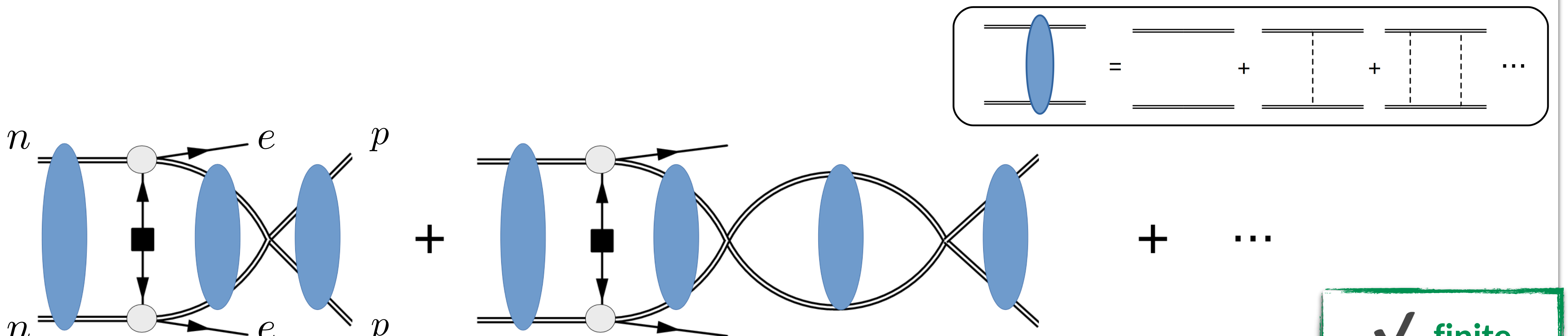

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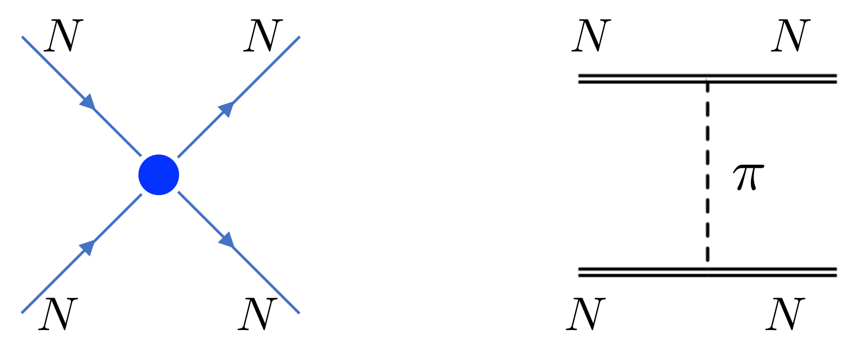

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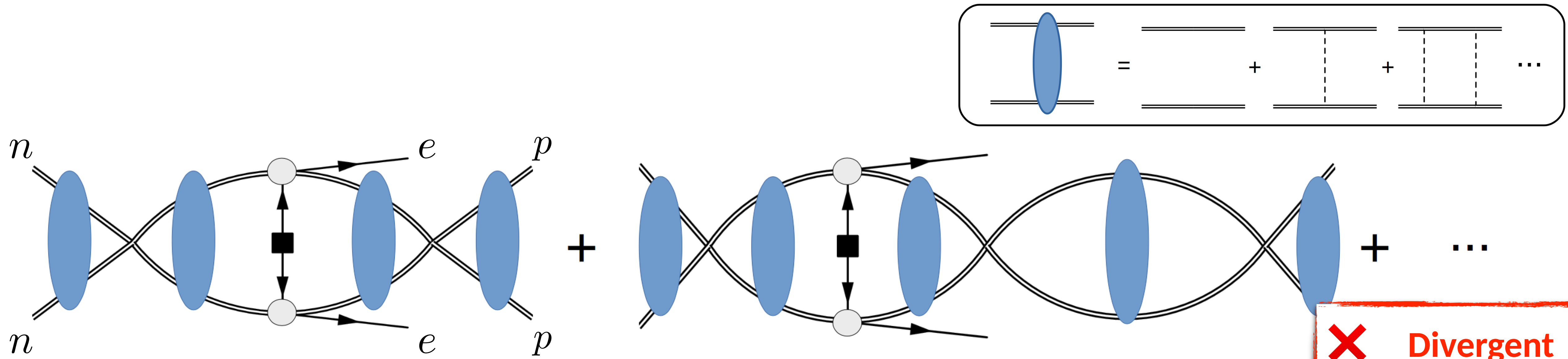

❌ Divergent

Checking the power counting

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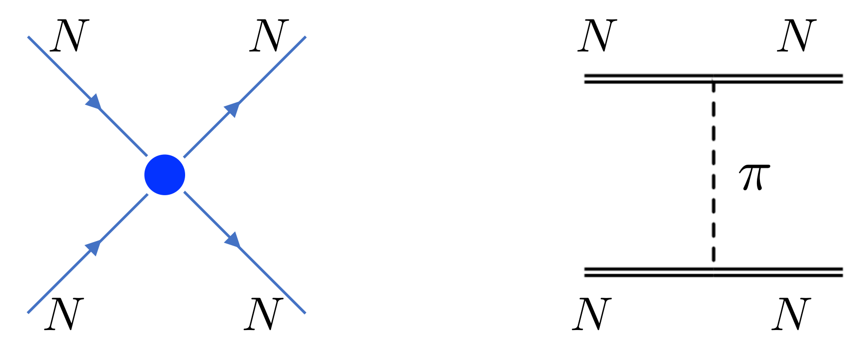
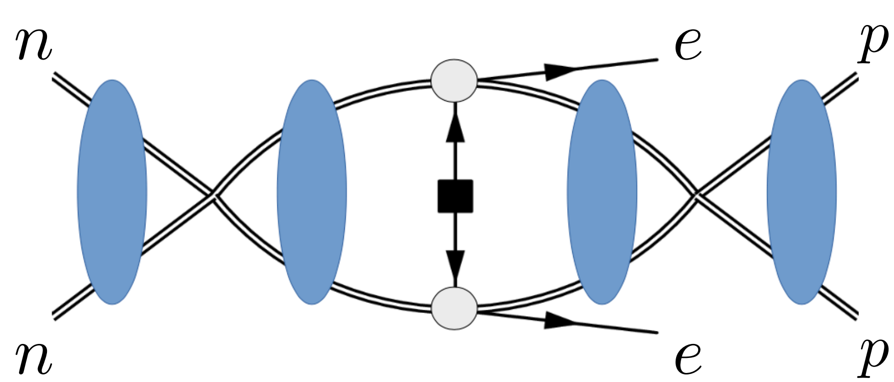


Dress the ΔL=2 potential with (renormalized) strong interactions:

In MS-bar:

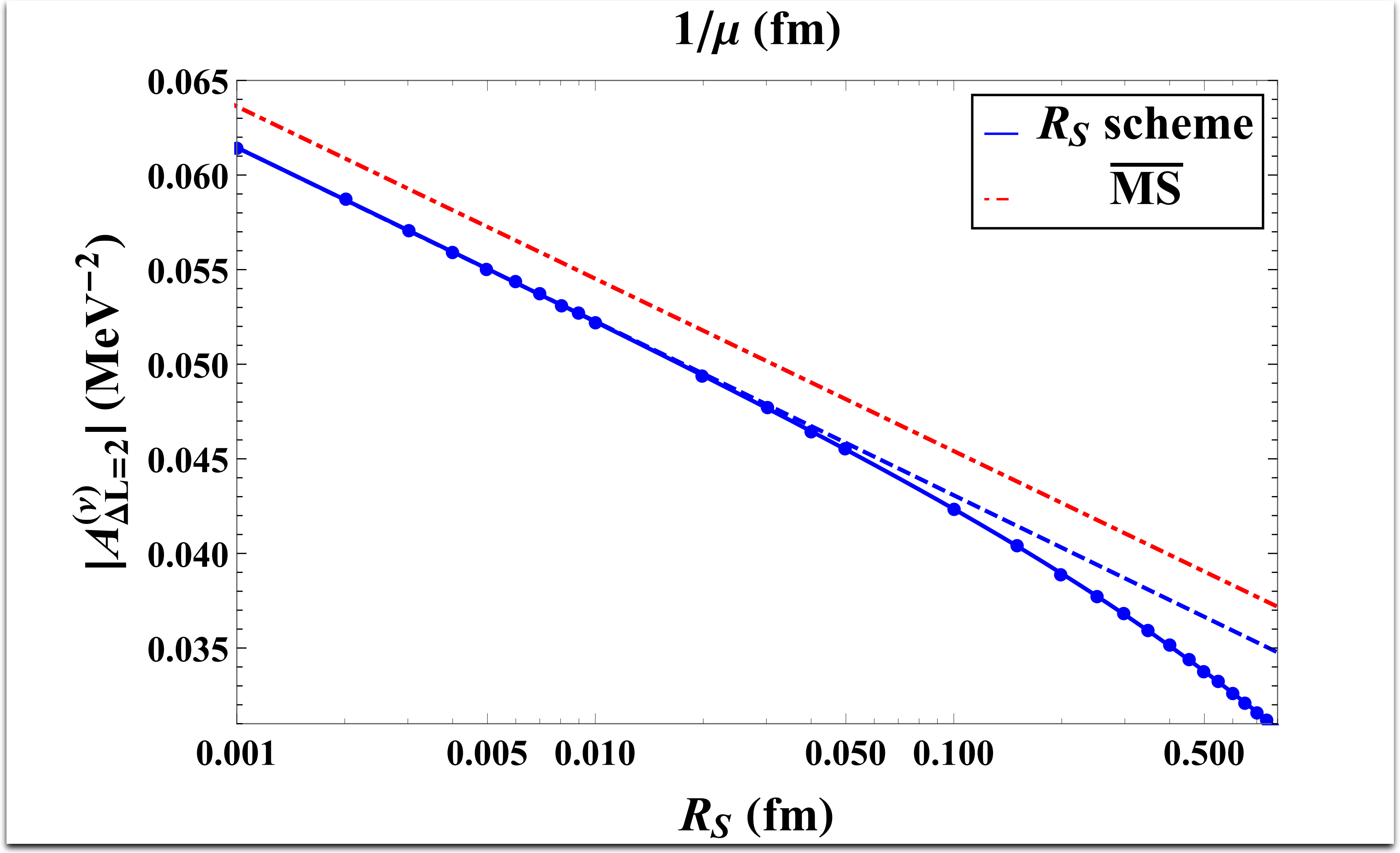


$$= -\left(\frac{m_N}{4\pi}\right)^2 (1+2g_A^2)\frac{1}{2}\left(\log\frac{\mu^2}{-(|\mathbf{p}|+|\mathbf{p}'|)^2+i0^+}+1\right)$$

$+\text{finite}$

Regulator dependent

Numerical results



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

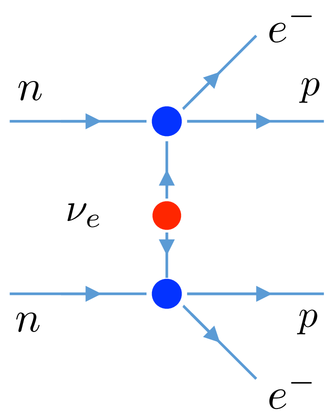
$$\tilde{C}\,\delta^{(3)}(\mathbf{r}) \to \frac{\tilde{C}(R_S)}{(\sqrt{\pi}R_S)^3}\exp\left(-\frac{r^2}{R_S^2}\right)$$

- Clear μ or R_S dependence

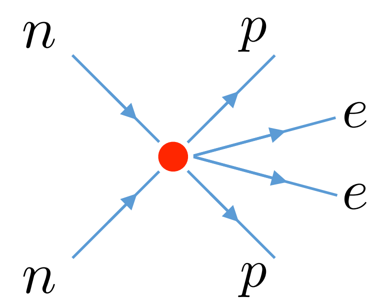
Need for a counter term

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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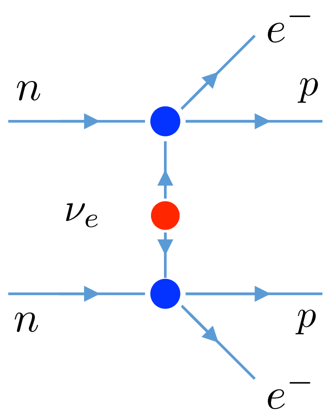

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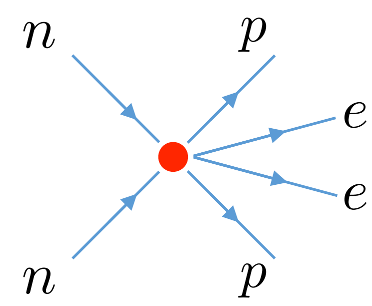

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How to determine g_ν^{NN}

- Could get g_ν^{NN} from a Lattice calculation
  - Controlled errors
  - Active area of research

Davoudi & Kadam, '20, '21
Feng et al, '19; Detmold & Murphy, '20

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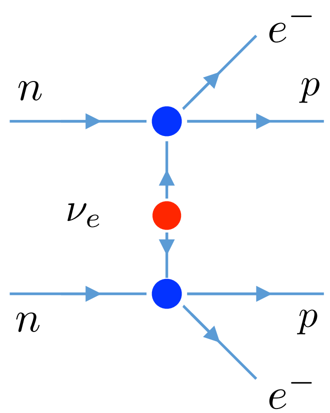
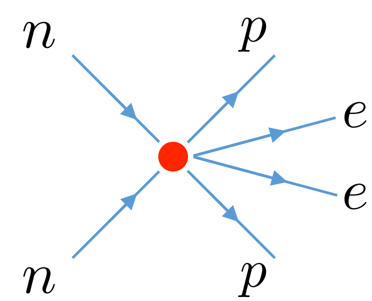
$V_{\Delta L=2} =$  $+ \; g_\nu^{NN}$ 

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  - Comparison with isospin-breaking observables
  - Cottingham approach
  - Large-Nc

See backup

Cirigliano, et al, '19,'20, '21

Richardson et al, '21

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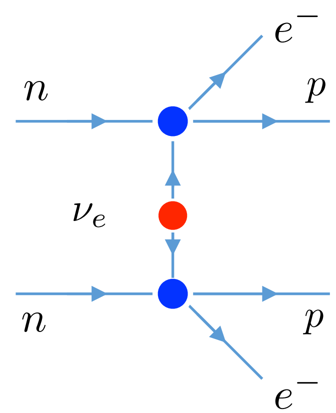

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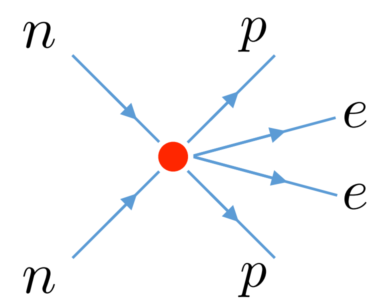

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Cirigliano, et al, '19,'20, '21

Richardson et al, '21

All give

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

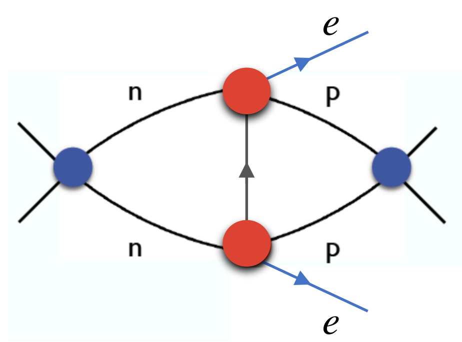
g_ν^{NN} :
Cottingham estimate

Determination of the counterterm

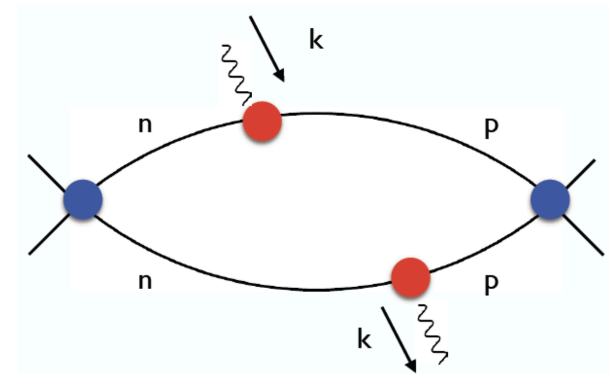
- Analogy to the Cottingham approach for pion/nucleon mass differences

Cirigliano et al, ’20, ‘21

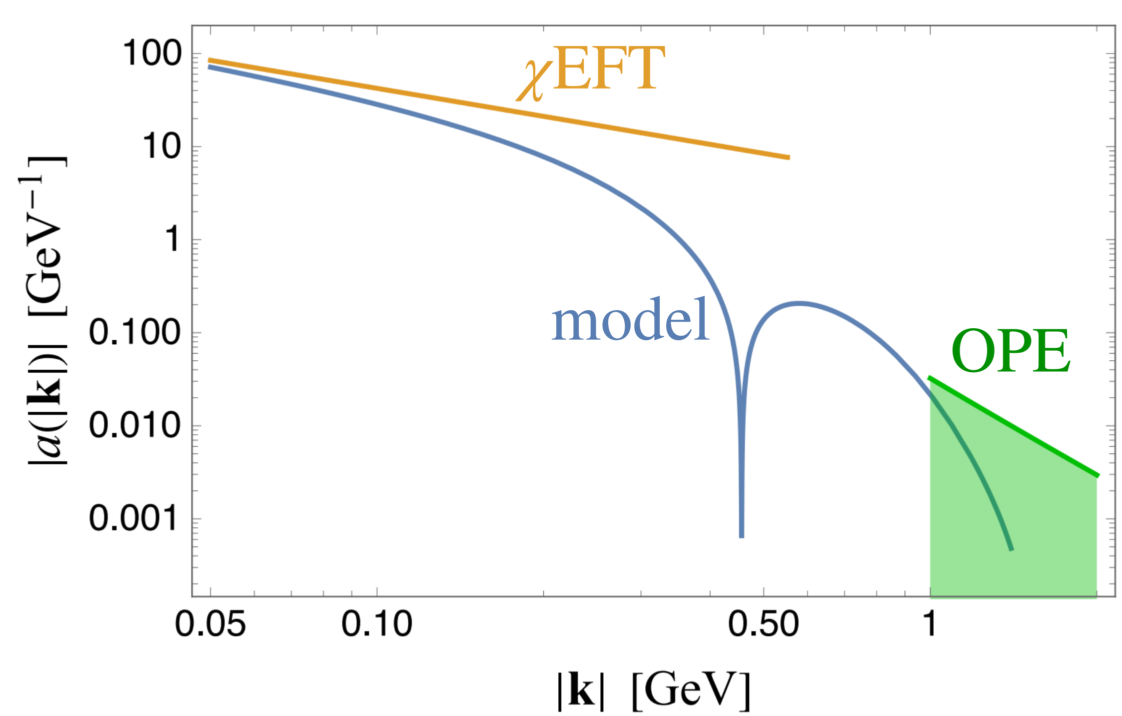
$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\mu\nu}}{k^2 + i\epsilon} \int d^4x\, e^{ik\cdot x} \langle pp | T\{ j_{\rm w}^\mu(x) j_{\rm w}^\nu(0)\} | nn \rangle$$

$\mathcal{A}_\nu =$ 

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



- Estimate the A_ν by constraining the integrand
  - $k \ll \Lambda_\chi$ region determined by χEFT
  - $k \gg \mathrm{GeV}$ 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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Cirigliano et al, ’20, ‘21

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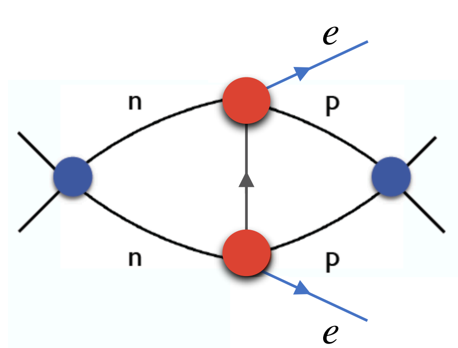

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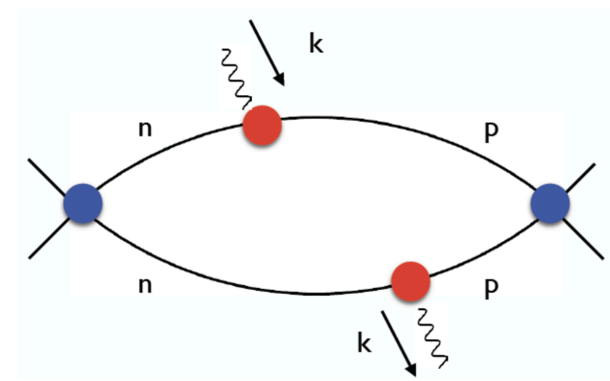
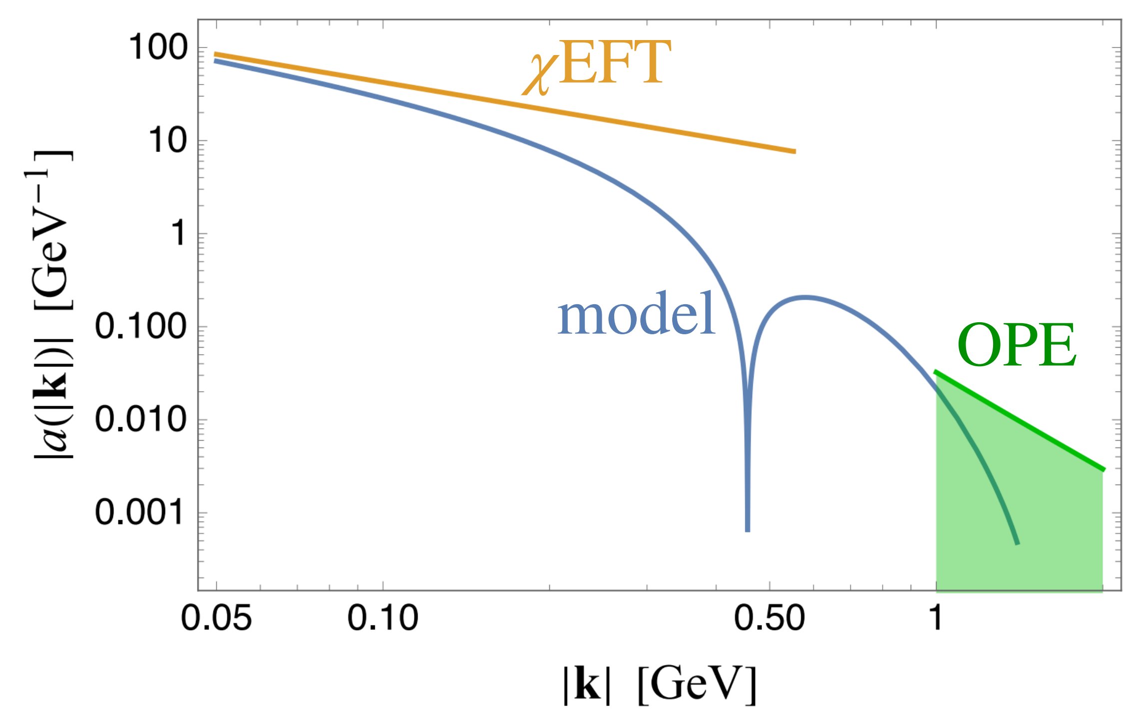


- Gives $\tilde{g}_\nu^{NN}(\mu = m_\pi) = 1.3(6)$ in $\overline{\rm MS}$
  - Estimated 30% uncertainty
  - Validated in isospin-breaking observables
  - Consistent with large-Nc estimate

Richardson et al, ‘21



W. Cottingham ’63; H. Harari, ‘66

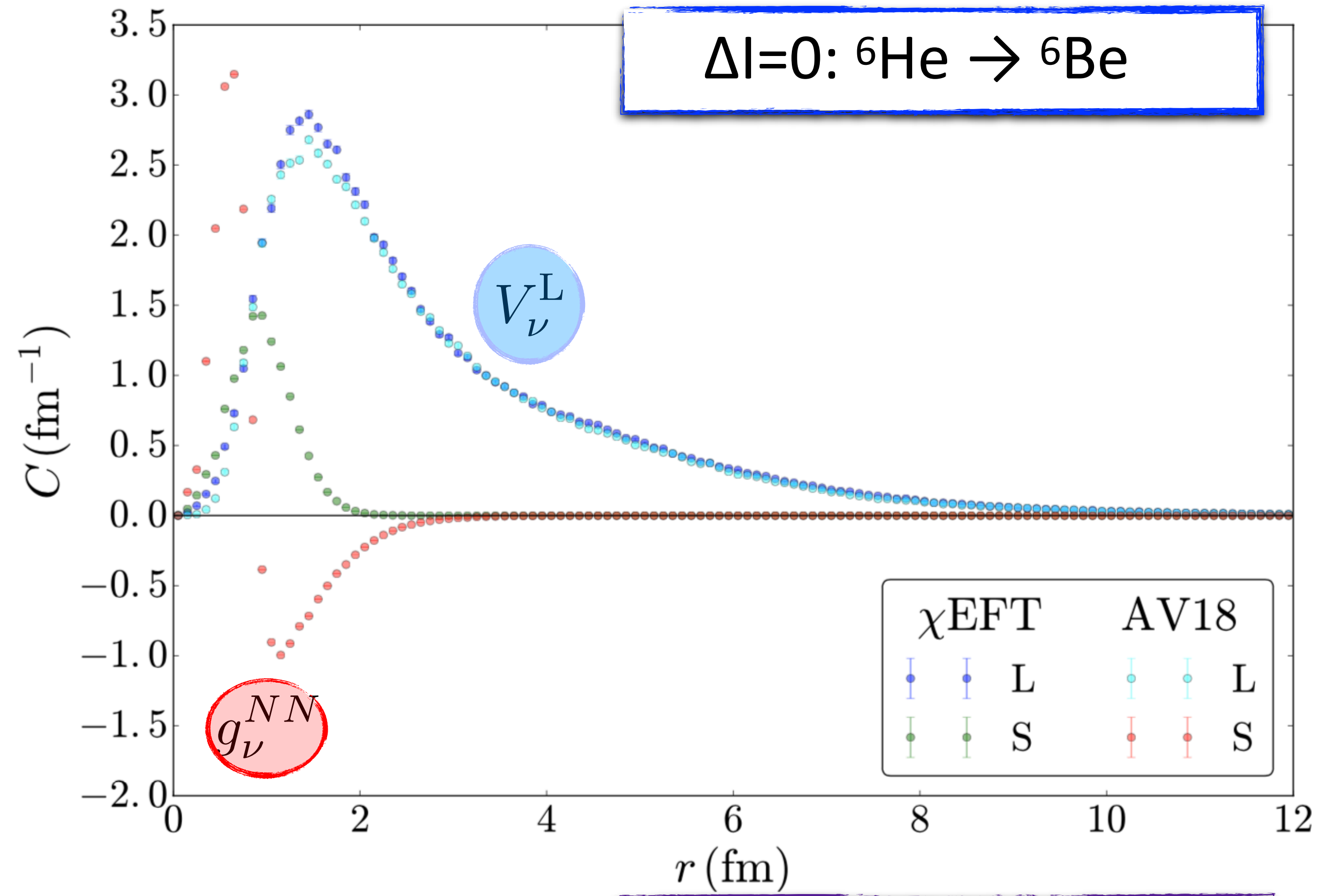
Estimate of impact in light nuclei

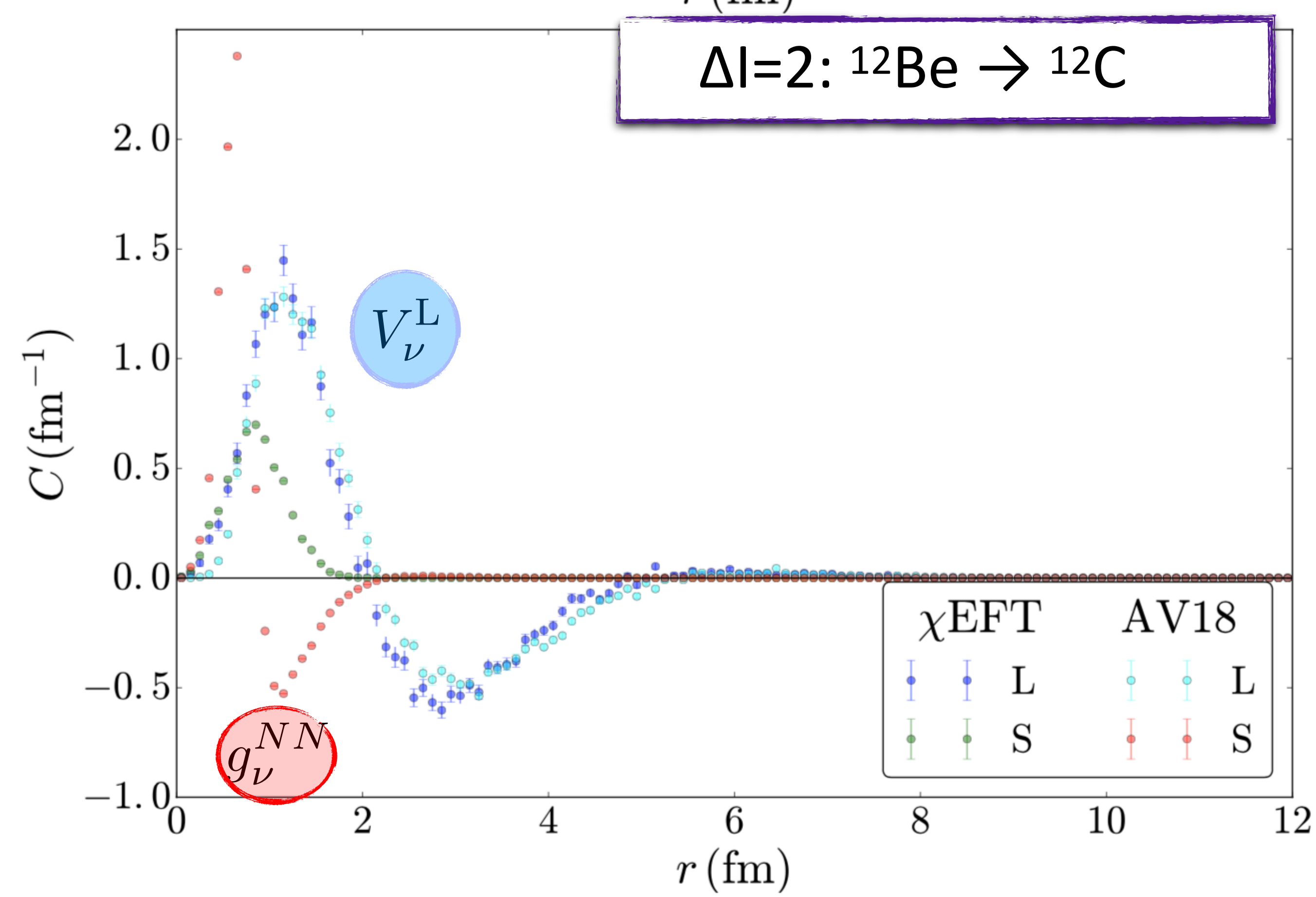
Estimate of impact

Light nuclei

M. Piarulli, R. Wiringa, S. Pastore

- Combine estimate $g_\nu = (C_1 + C_2)/2$
- With wavefunctions:
  - From Chiral potential
    M. Piarulli et. al. '16
  - Obtained from AV18 potential
    R. Wiringa, Stoks, Schiavilla, '95





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

Estimate of impact

Light nuclei

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- Combine estimate $g_\nu = (C_1 + C_2)/2$

  Uncontrolled error

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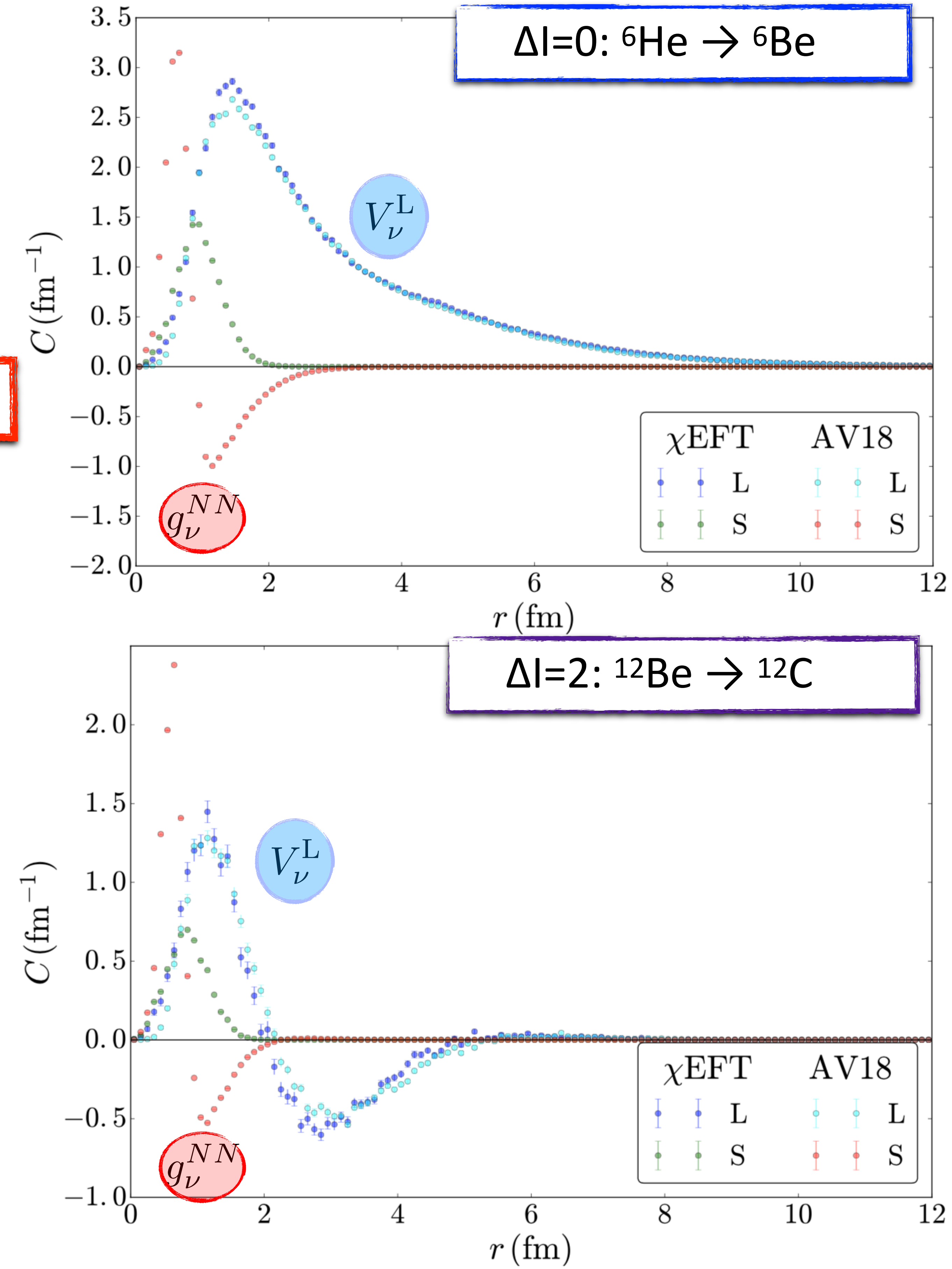

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