Neutrinoless double beta decay in effective field theory

with
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B. van Kolck, A. Walker-Loud, B. Wiringa

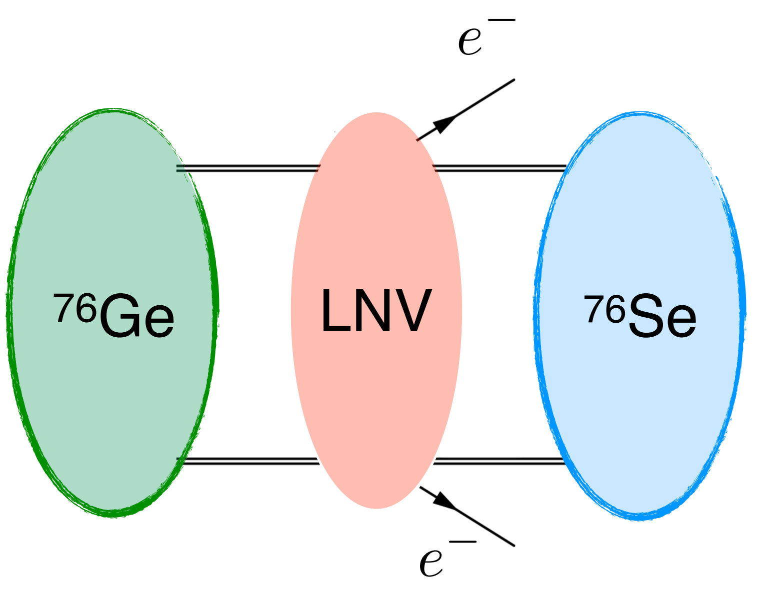
Based on:

arXiv:1907.11254 ,1806.02780, 1710.01729,
1802.10097, 1710.05026, 1708.09390

UC San Diego

Introduction

0νββ



- Violates lepton number, ΔL=2

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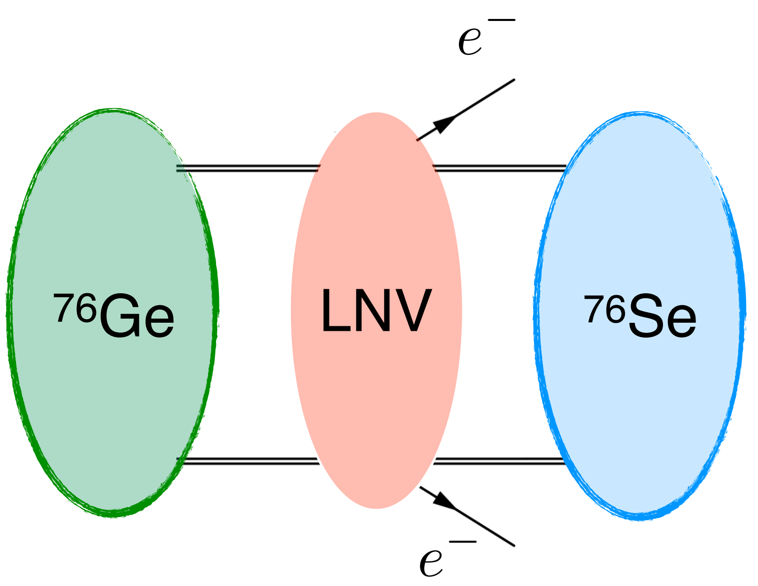

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- Stringently constrained experimentally
  - To be improved by 1-2 orders

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge})$ Gerda	$T^{0\nu}_{1/2}(^{130}\mathrm{Te})$ Cuore	$T^{0\nu}_{1/2}(^{136}\mathrm{Xe})$ KamLAND-zen
$> 8 \cdot 10^{25}\,\mathrm{yr}$	$> 1.5 \cdot 10^{25}\,\mathrm{yr}$	$> 1.1 \cdot 10^{26}\,\mathrm{yr}$

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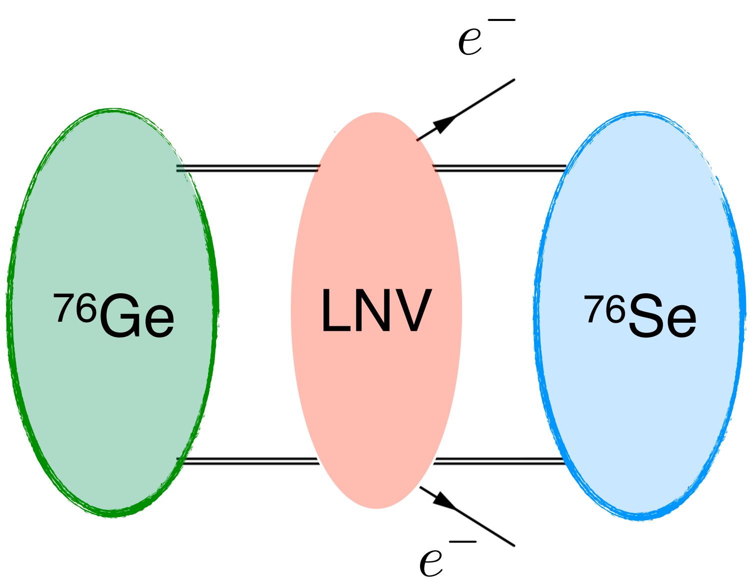

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- Would imply that
  - Neutrino's are Majorana particles
  - Physics beyond the SM

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Schechter, Valle, `82

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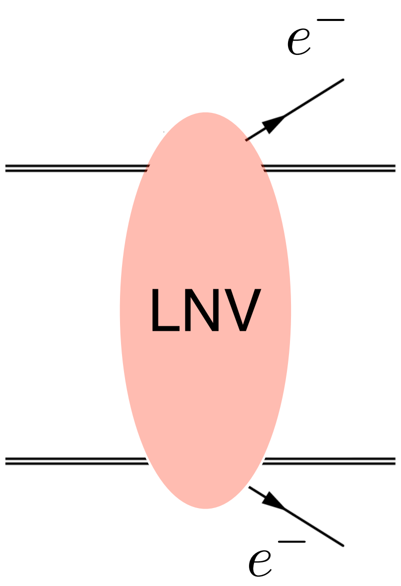

= **BSM physics**

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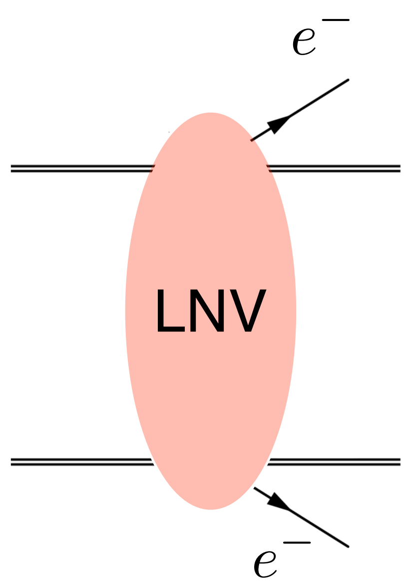

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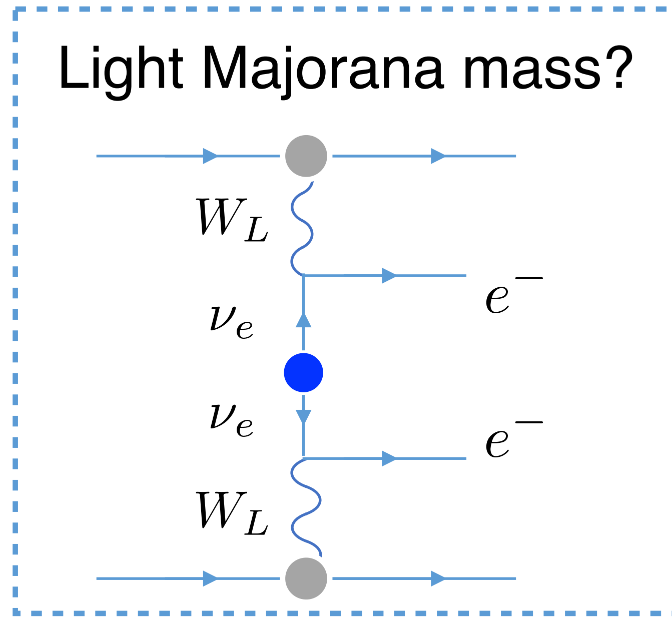
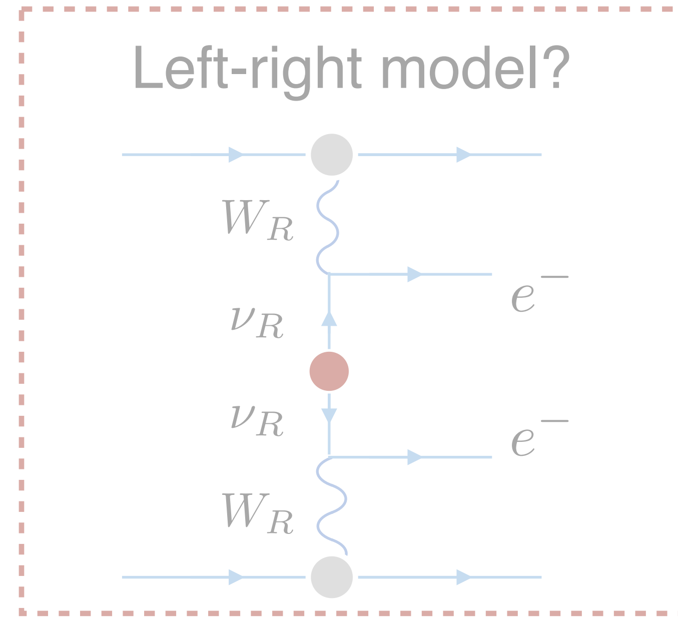
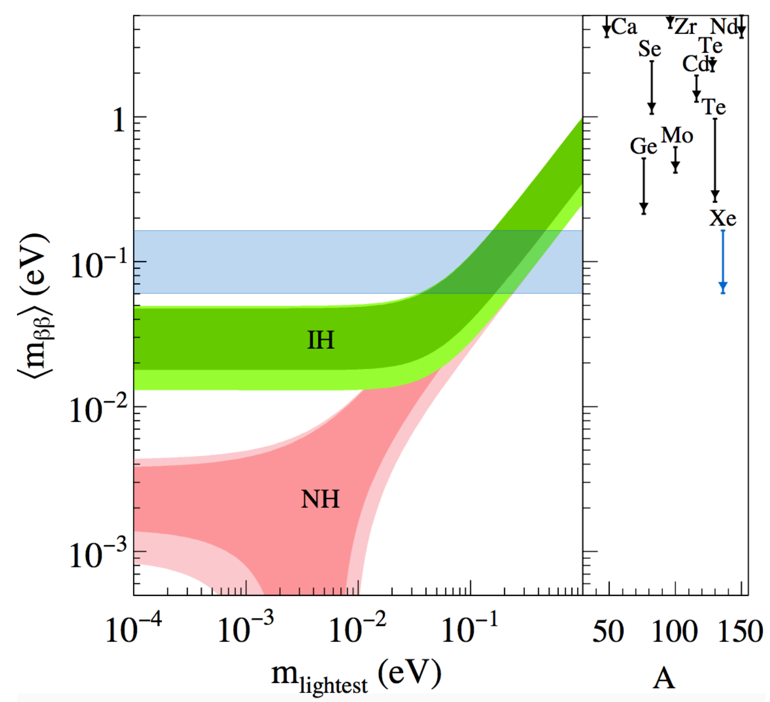




+ ??

Well-known Majorana mass mechanism



- Implications for the mass hierarchy

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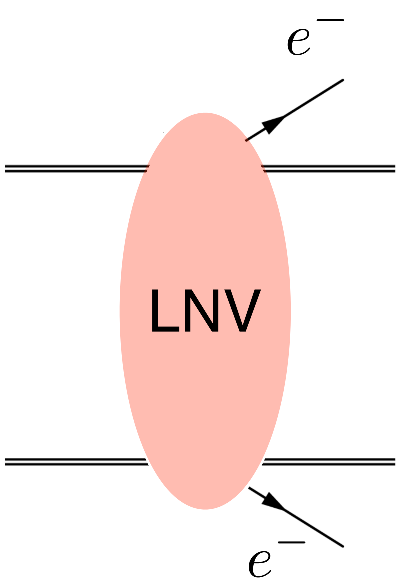
0νββ



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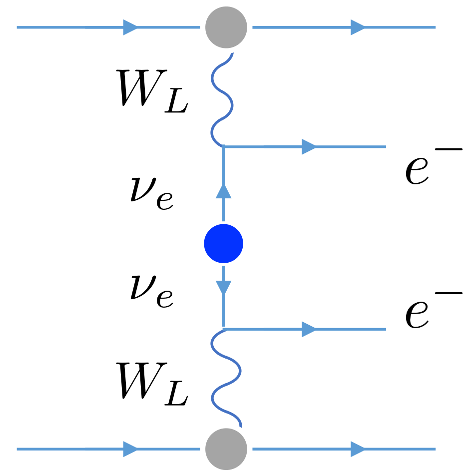
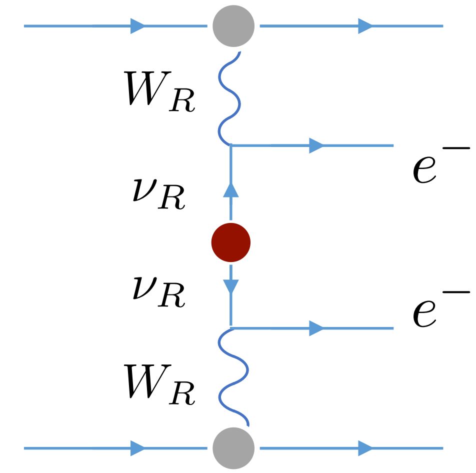


Left-right model?



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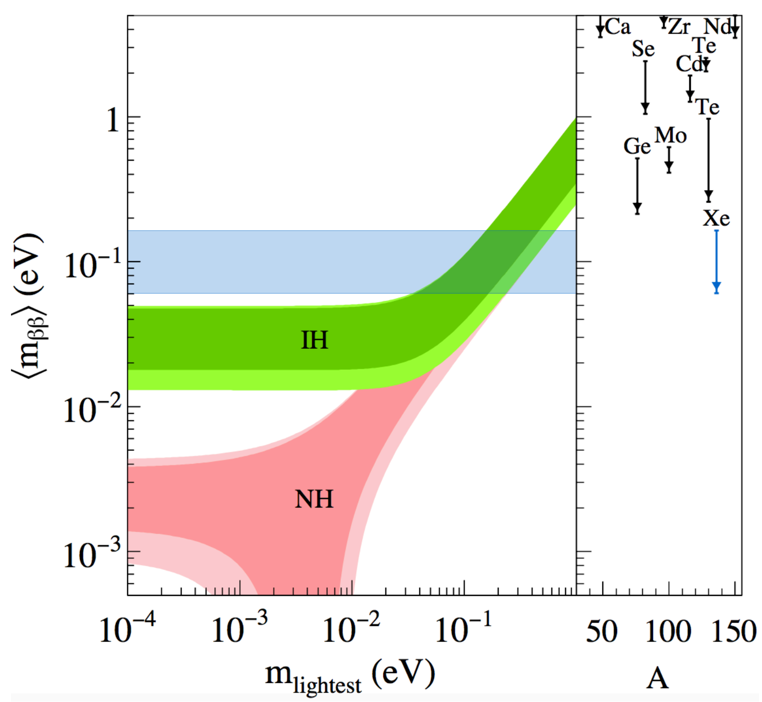

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Heavy BSM mechanisms

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

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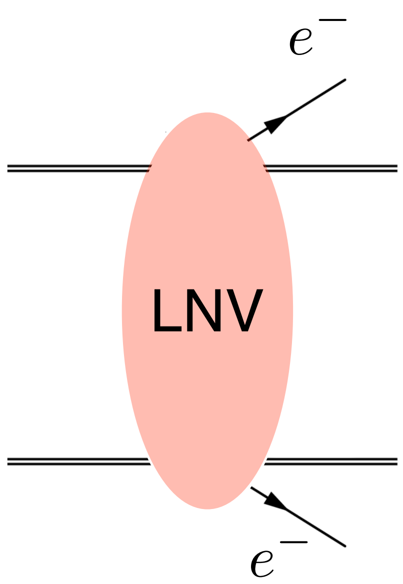

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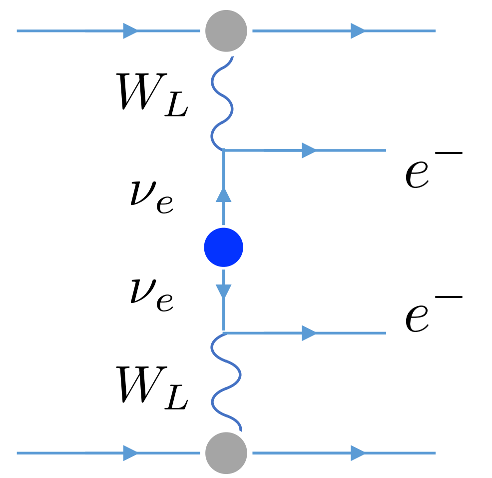

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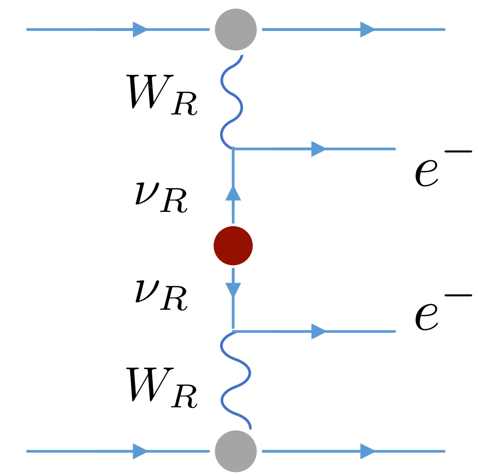

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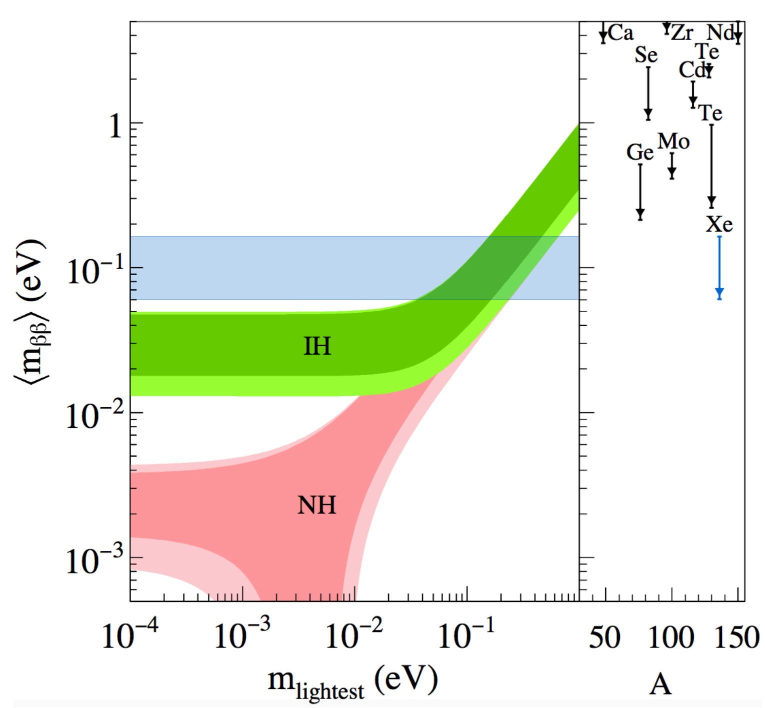

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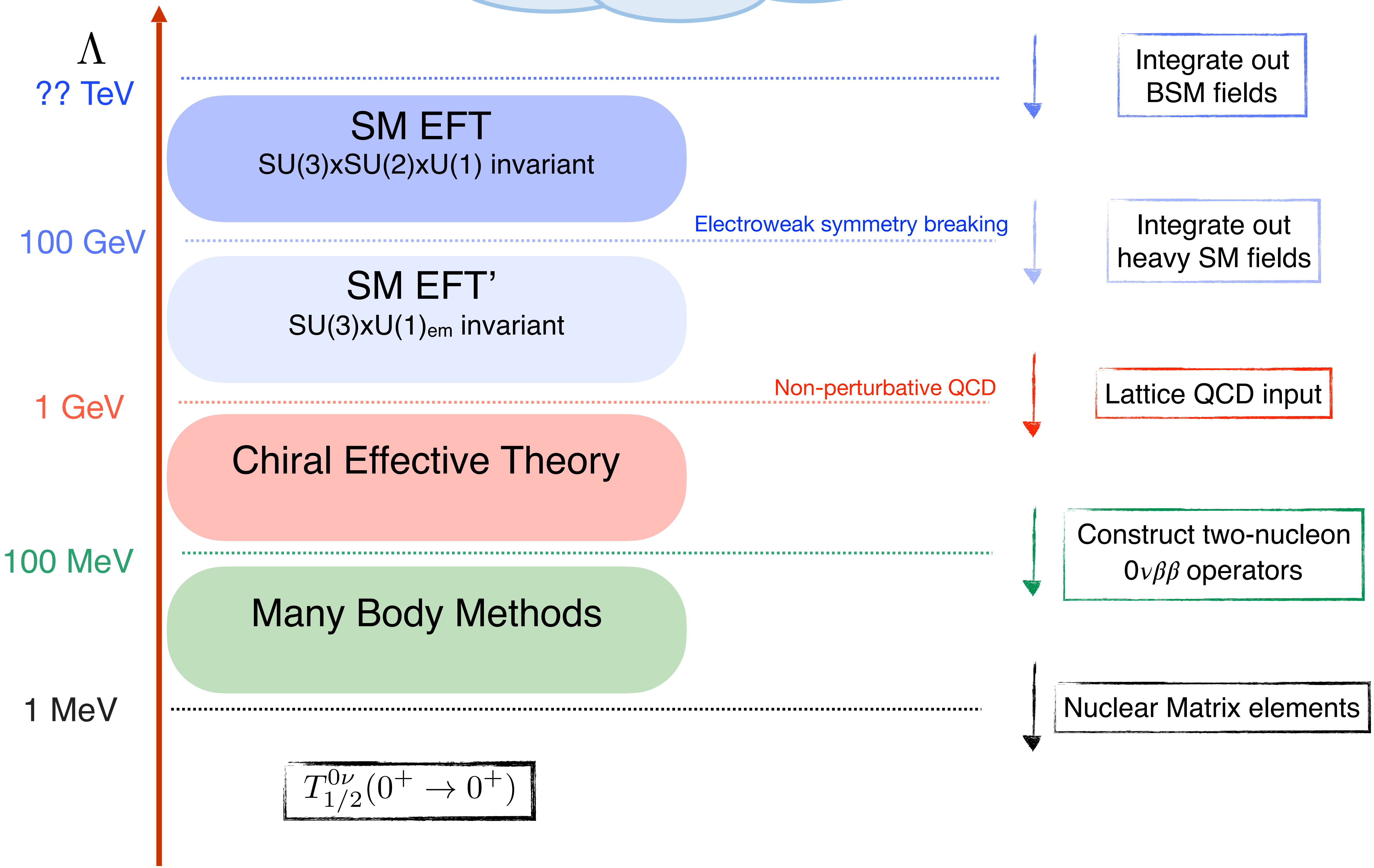
Heavy BSM mechanisms

- Many possible scenarios
  - Left-right model,
  - R-parity violating SUSY
  - Leptoquarks…
- How to describe all LNV sources systematically?

Outline

Lepton-number violation:
seesaw, left-right model, leptoquarks, …



Outline

Lepton-number violation:
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Λ

?? TeV

Integrate out BSM fields

SM EFT
SU(3)xSU(2)xU(1) invariant

Electroweak symmetry breaking

100 GeV

Integrate out heavy SM fields

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

Non-perturbative QCD

1 GeV

Lattice QCD input

Chiral Effective Theory

100 MeV

Construct two-nucleon $0\nu\beta\beta$ operators

Many Body Methods

1 MeV

Nuclear Matrix elements

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

Effective Field Theory

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

Dimension-five

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

Dimension-seven

- 12 ΔL=2 operators

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

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

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

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Dimension-nine

- Subset of operators constructed

$$\begin{aligned}
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\end{aligned}$$

- But no complete basis

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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?

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

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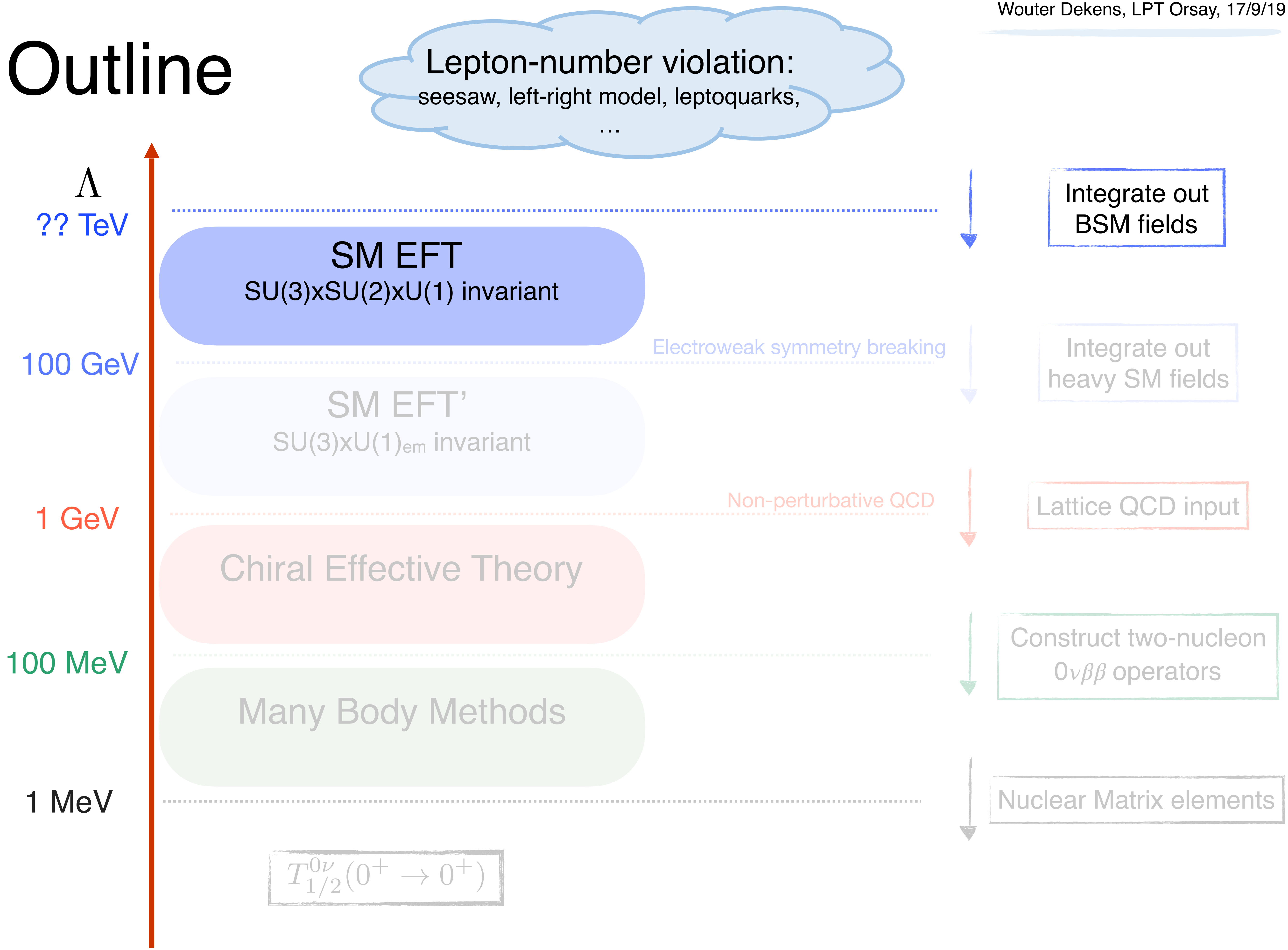
- However, if $c_5 = \mathcal{O}(1), \qquad \Lambda = 10^{15}\,\mathrm{GeV}$ dimension-7, -9 irrelevant in this case


Wouter Dekens, LPT Orsay, 17/9/19
Outline
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seesaw, left-right model, leptoquarks,
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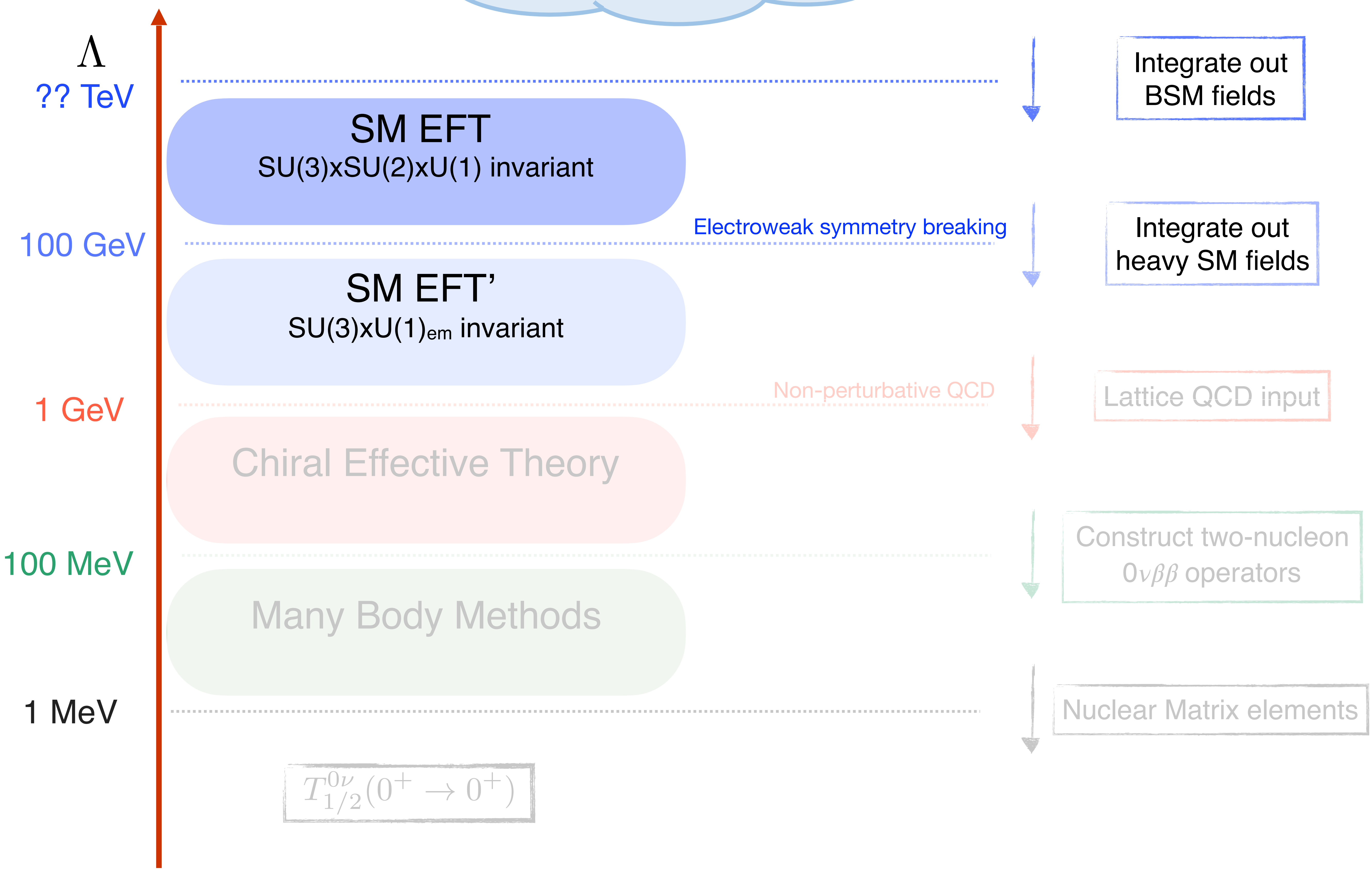
1 MeV
SM EFT
SU(3)xSU(2)xU(1) invariant
Electroweak symmetry breaking
SM EFT'
SU(3)xU(1)em invariant
Non-perturbative QCD
Chiral Effective Theory
Many Body Methods
$T^{0\nu}_{1/2}(0^+ \to 0^+)$
Integrate out BSM fields
Integrate out heavy SM fields
Lattice QCD input
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

Outline

Lepton-number violation:
seesaw, left-right model, leptoquarks, …



Running/matching at the weak scale

SM EFT

SU(3)xSU(2)xU(1) invariant

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

M_{EW}
100 GeV

Electroweak symmetry breaking

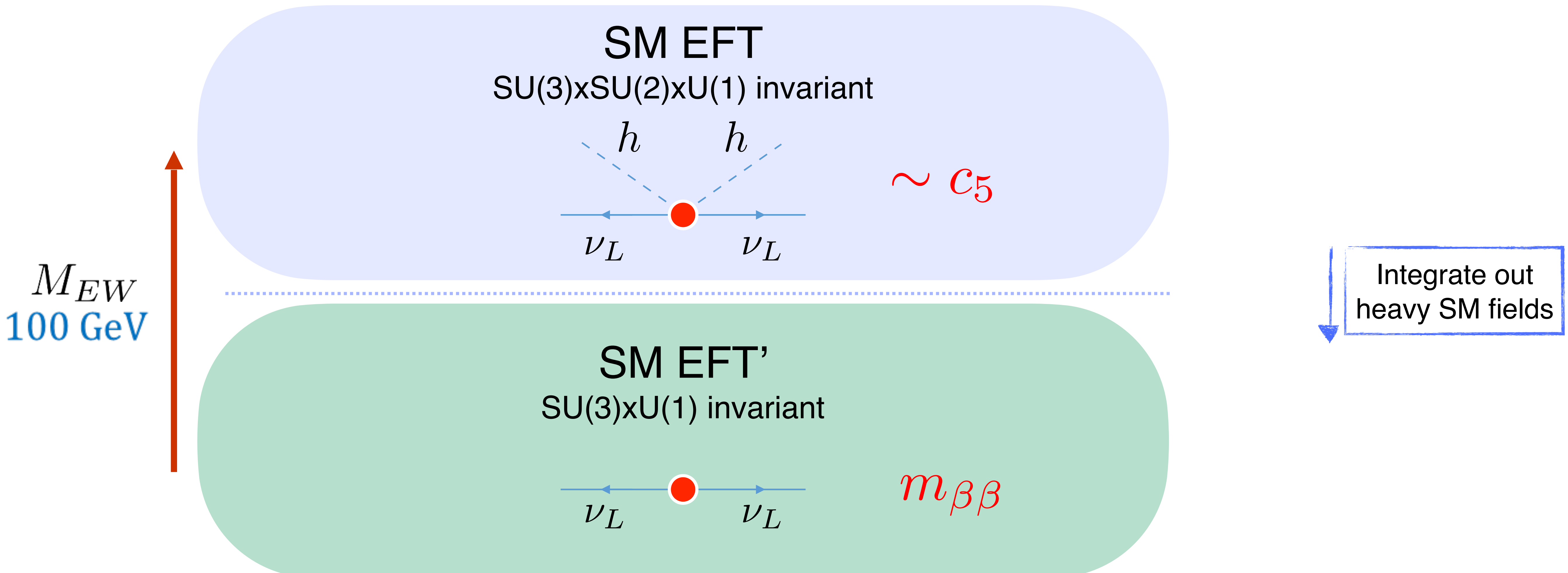
SM EFT’

SU(3)xU(1) invariant

$$\mathcal{L} = \frac{c_i^{(3)}}{\Lambda} O_i^{(3)} + \frac{c_i^{(6)}}{\Lambda^3} O_i^{(6)} + \frac{c_i^{(7)}}{\Lambda^3} O_i^{(7)} + \frac{c_i^{(9)}}{\Lambda^5} O_i^{(9)}$$

- Mismatch in dimensions due to insertions of the Higgs vacuum expectation value

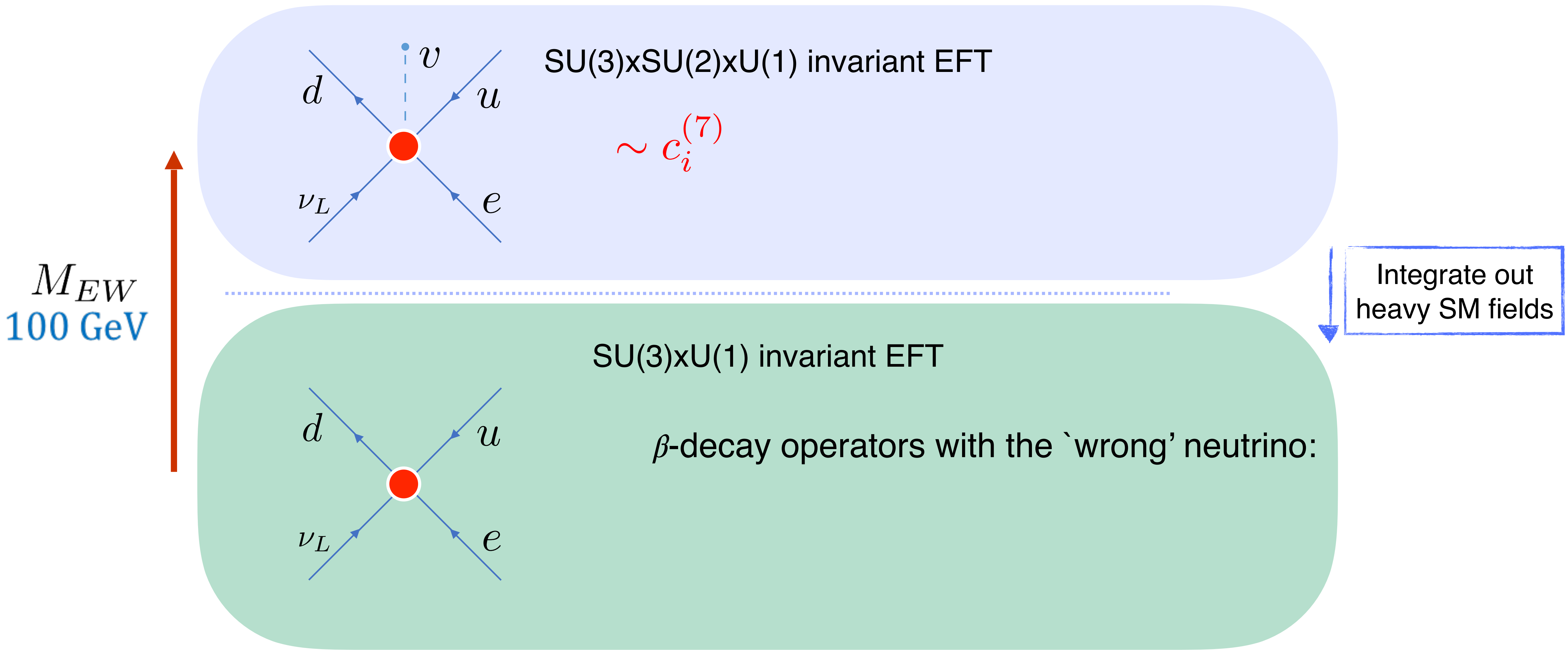
Low-energy operators
Dimension-3



Induced by dimension-5 SU(2)-invariant operator

$$m_{\beta\beta} \sim v^2/\Lambda$$

Low-energy operators
Dimension-6

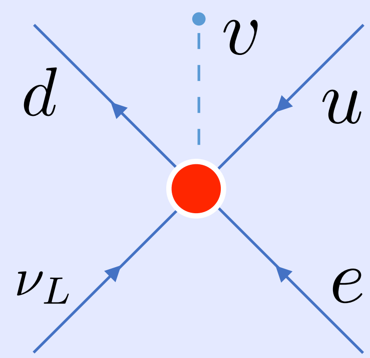


$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big\{ C^{(6)}_{\mathrm{VL},ij}\, \bar{u}_L\gamma^\mu d_L\, \bar{e}_{R,i}\,\gamma_\mu\, C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{VR},ij}\, \bar{u}_R\gamma^\mu d_R\, \bar{e}_{R,i}\,\gamma_\mu\, C\bar{\nu}^T_{L,j}$$

$$+C^{(6)}_{\mathrm{SR},ij}\, \bar{u}_L d_R\, \bar{e}_{L,i}\, C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{SL},ij}\, \bar{u}_R d_L\, \bar{e}_{L,i}\, C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{T},ij}\, \bar{u}_L\sigma^{\mu\nu} d_R\, \bar{e}_{L,i}\sigma_{\mu\nu}\, C\bar{\nu}^T_{L,j}\Big\}$$

Low-energy operators
Dimension-6

M_{EW}
100 GeV

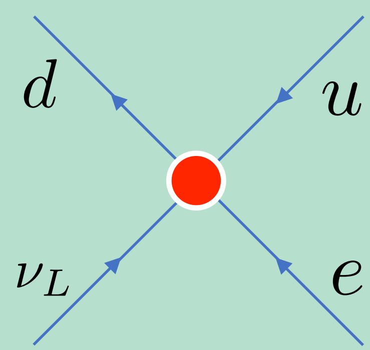


SU(3)xSU(2)xU(1) invariant EFT

$\sim c_i^{(7)}$

Integrate out heavy SM fields

SU(3)xU(1) invariant EFT

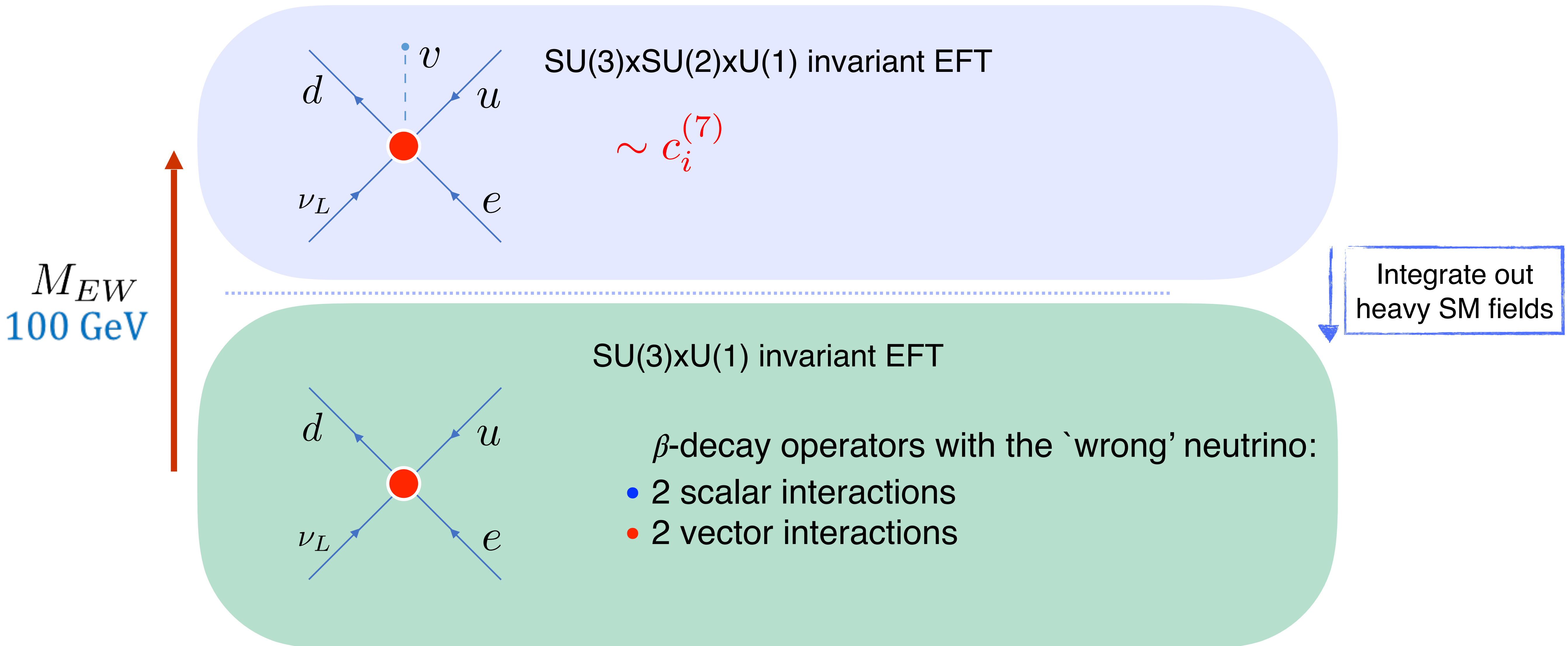


β-decay operators with the `wrong' neutrino:
- 2 scalar interactions

$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big\{ C^{(6)}_{\mathrm{VL},ij}\,\bar u_L\gamma^\mu d_L\,\bar e_{R,i}\,\gamma_\mu\, C\bar\nu^T_{L,j} + C^{(6)}_{\mathrm{VR},ij}\,\bar u_R\gamma^\mu d_R\,\bar e_{R,i}\,\gamma_\mu\, C\bar\nu^T_{L,j}$$
$$+ C^{(6)}_{\mathrm{SR},ij}\,\bar u_L d_R\,\bar e_{L,i}\, C\bar\nu^T_{L,j} + C^{(6)}_{\mathrm{SL},ij}\,\bar u_R d_L\,\bar e_{L,i}\, C\bar\nu^T_{L,j} + C^{(6)}_{\mathrm{T},ij}\,\bar u_L\sigma^{\mu\nu} d_R\,\bar e_{L,i}\sigma_{\mu\nu}\, C\bar\nu^T_{L,j}\Big\}$$

Low-energy operators

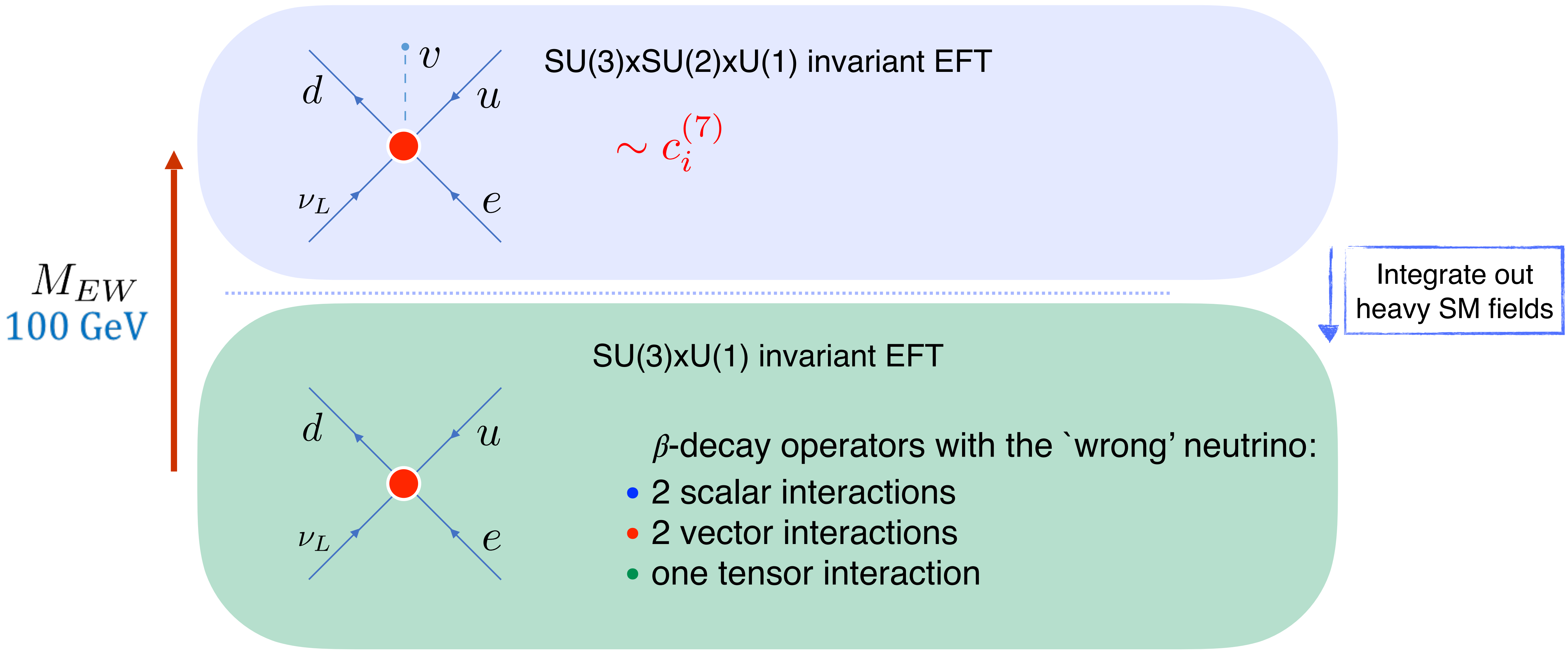
Dimension-6



$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big\{ C^{(6)}_{\mathrm{VL},ij}\,\bar u_L\gamma^\mu d_L\,\bar e_{R,i}\,\gamma_\mu\, C\bar\nu^T_{L,j} + C^{(6)}_{\mathrm{VR},ij}\,\bar u_R\gamma^\mu d_R\,\bar e_{R,i}\,\gamma_\mu\, C\bar\nu^T_{L,j}$$

$$+ C^{(6)}_{\mathrm{SR},ij}\,\bar u_L d_R\,\bar e_{L,i}\, C\bar\nu^T_{L,j} + C^{(6)}_{\mathrm{SL},ij}\,\bar u_R d_L\,\bar e_{L,i}\, C\bar\nu^T_{L,j} + C^{(6)}_{\mathrm{T},ij}\,\bar u_L\sigma^{\mu\nu} d_R\,\bar e_{L,i}\sigma_{\mu\nu}\, C\bar\nu^T_{L,j}\Big\}$$

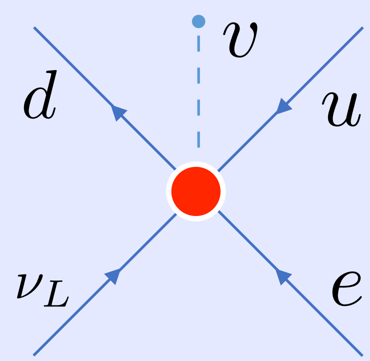
Low-energy operators
Dimension-6



$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big\{ C^{(6)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j}$$
$$+ C^{(6)}_{\mathrm{SR},ij}\,\bar{u}_L d_R\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{SL},ij}\,\bar{u}_R d_L\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{T},ij}\,\bar{u}_L\sigma^{\mu\nu} d_R\,\bar{e}_{L,i}\sigma_{\mu\nu}\,C\bar{\nu}^T_{L,j}\Big\}$$

Low-energy operators
Dimension-6

M_{EW}
100 GeV

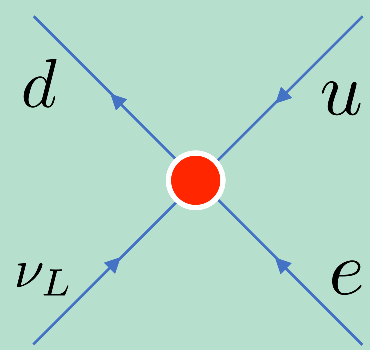


SU(3)xSU(2)xU(1) invariant EFT

$\sim c_i^{(7)}$

Integrate out heavy SM fields

SU(3)xU(1) invariant EFT



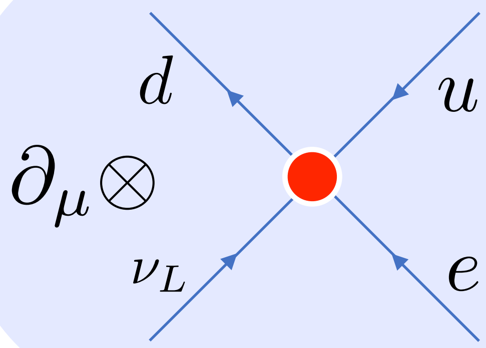
β-decay operators with the `wrong' neutrino:

- 2 scalar interactions
- 2 vector interactions
- one tensor interaction

Induced by dimension-7 SU(2)-invariant operators

$$C_i^{(6)} \sim v^3/\Lambda^3$$

Low-energy operators
Dimension-7



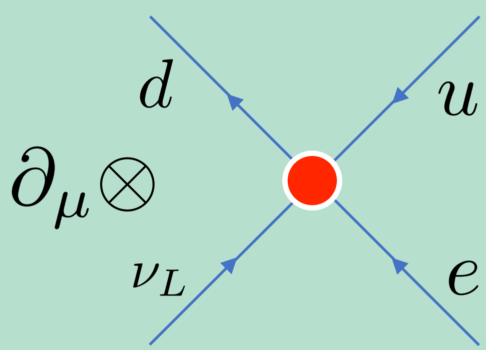
SU(3)xSU(2)xU(1) invariant EFT

$\sim c_i^{(7)}$

M_{EW}
100 GeV

Integrate out heavy SM fields

SU(3)xU(1) invariant EFT



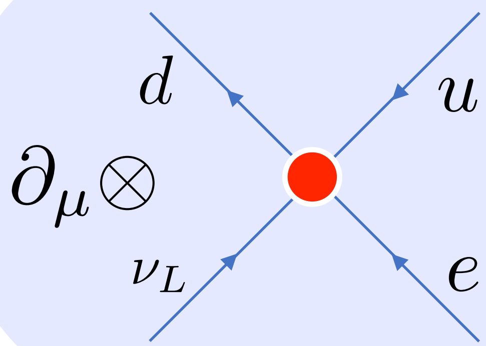
β-decay operators with the `wrong' neutrino and a derivative

- Two vector-like operators

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

Low-energy operators
Dimension-7

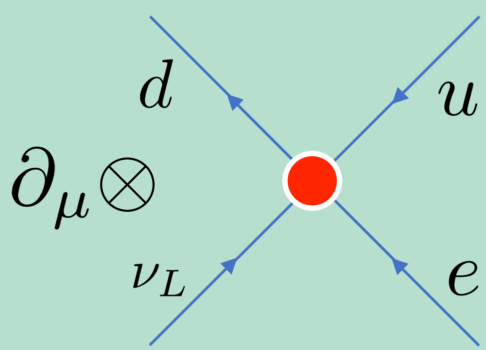
M_{EW}
100 GeV



SU(3)xSU(2)xU(1) invariant EFT

$\sim c_i^{(7)}$

Integrate out heavy SM fields



SU(3)xU(1) invariant EFT

β-decay operators with the `wrong' neutrino and a derivative

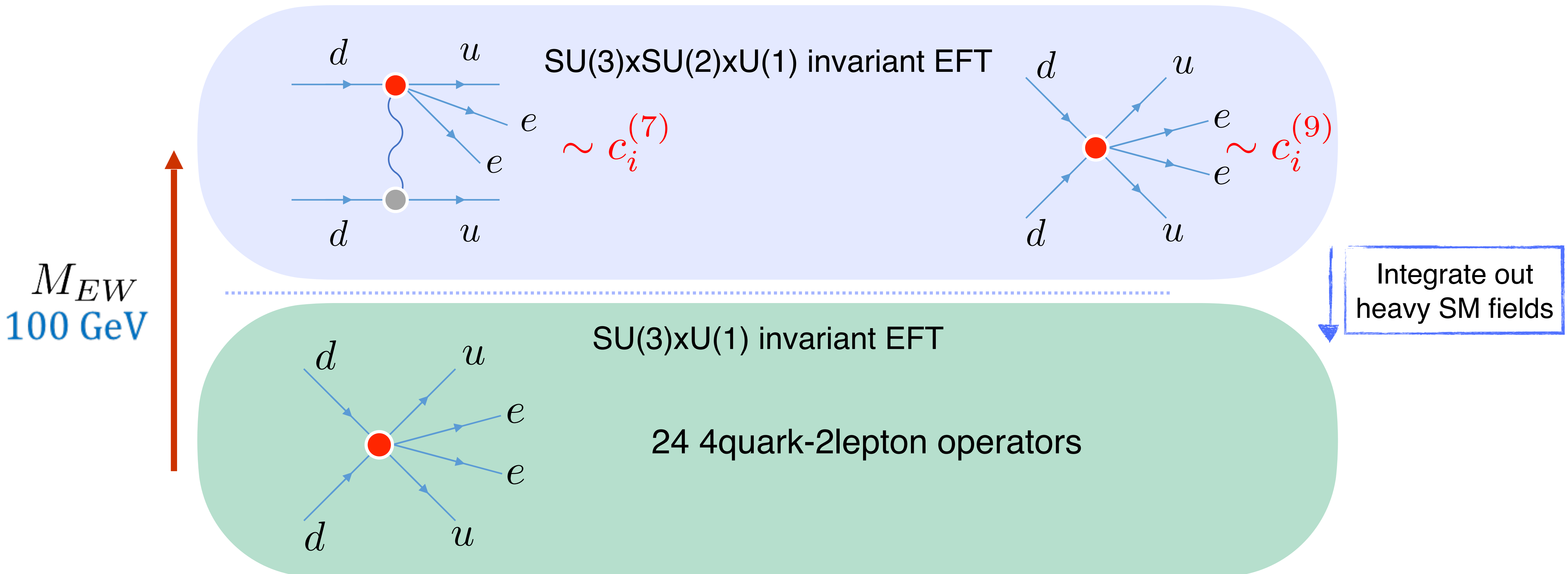
- Two vector-like operators

$\mathcal{L}^{(7)}_{\Delta L=2} =$ … $\overleftrightarrow{\partial}_\mu \bar{\nu}^T_{L,j} \Big\} + \text{h.c.}$

Induced by dimension-7 SU(2)-invariant operators

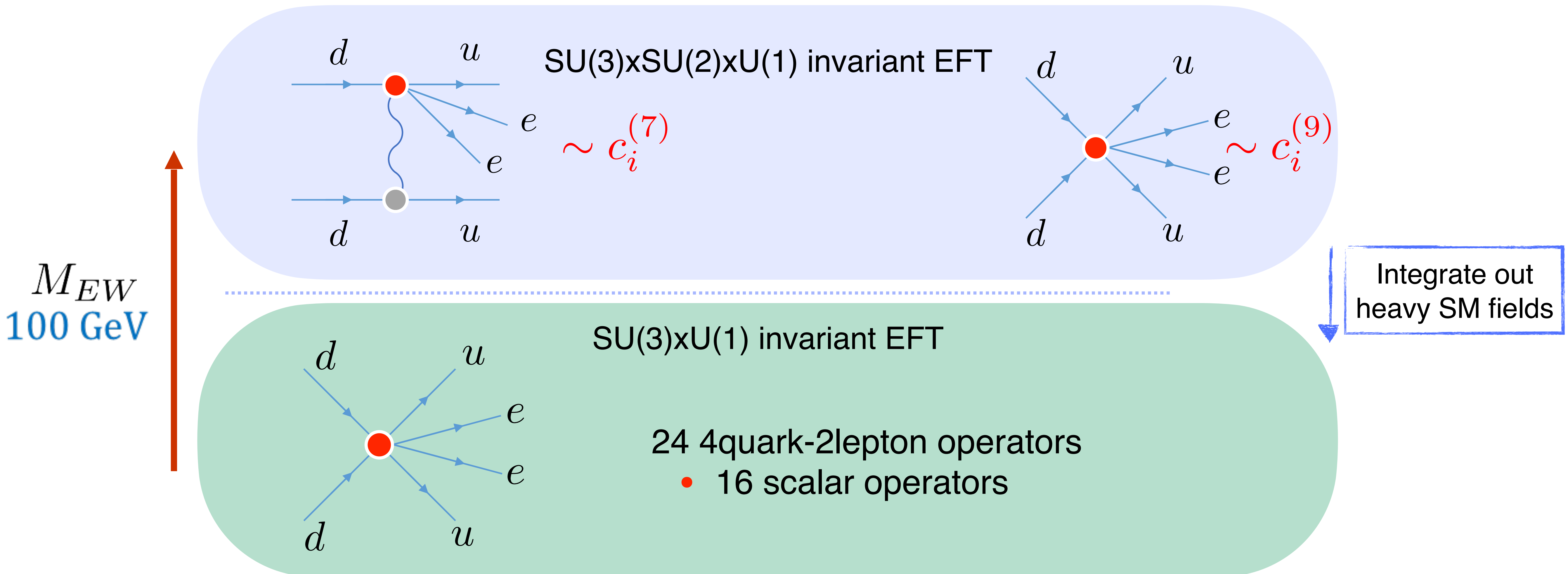
$$C_i^{(7)} \sim v^3/\Lambda^3$$

Low-energy operators
Dimension-9



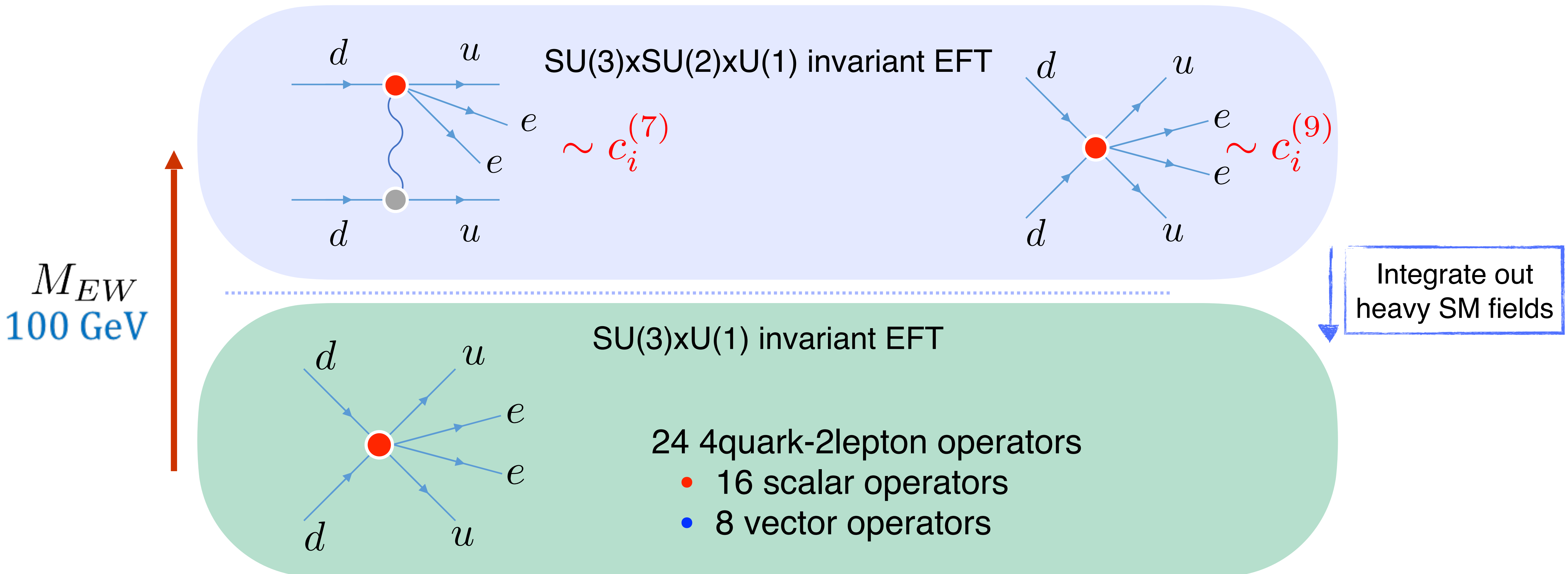
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \left[\left(C^{(9)}_{i\,\mathrm{R}}\,\bar e_R C\bar e_R^T + C^{(9)}_{i\,\mathrm{L}}\,\bar e_L C \bar e_L^T\right) O_i + C^{(9)}_i \bar e\gamma_\mu\gamma_5 C\bar e^T O_i^\mu\right],$$

Low-energy operators
Dimension-9



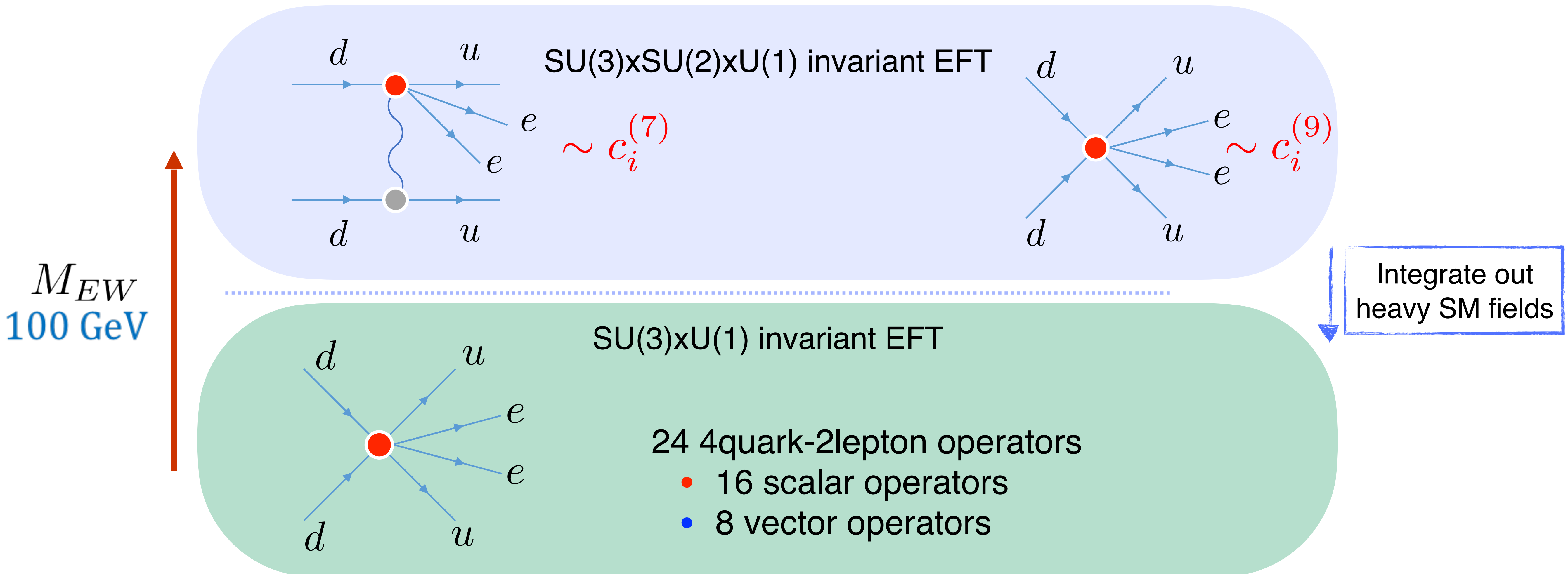
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \left[\left(C^{(9)}_{i\,\mathrm{R}}\, \bar e_R C \bar e_R^T + C^{(9)}_{i\,\mathrm{L}}\, \bar e_L C \bar e_L^T \right) O_i + C^{(9)}_i \bar e \gamma_\mu \gamma_5 C \bar e^T\, O_i^\mu \right],$$

Low-energy operators
Dimension-9



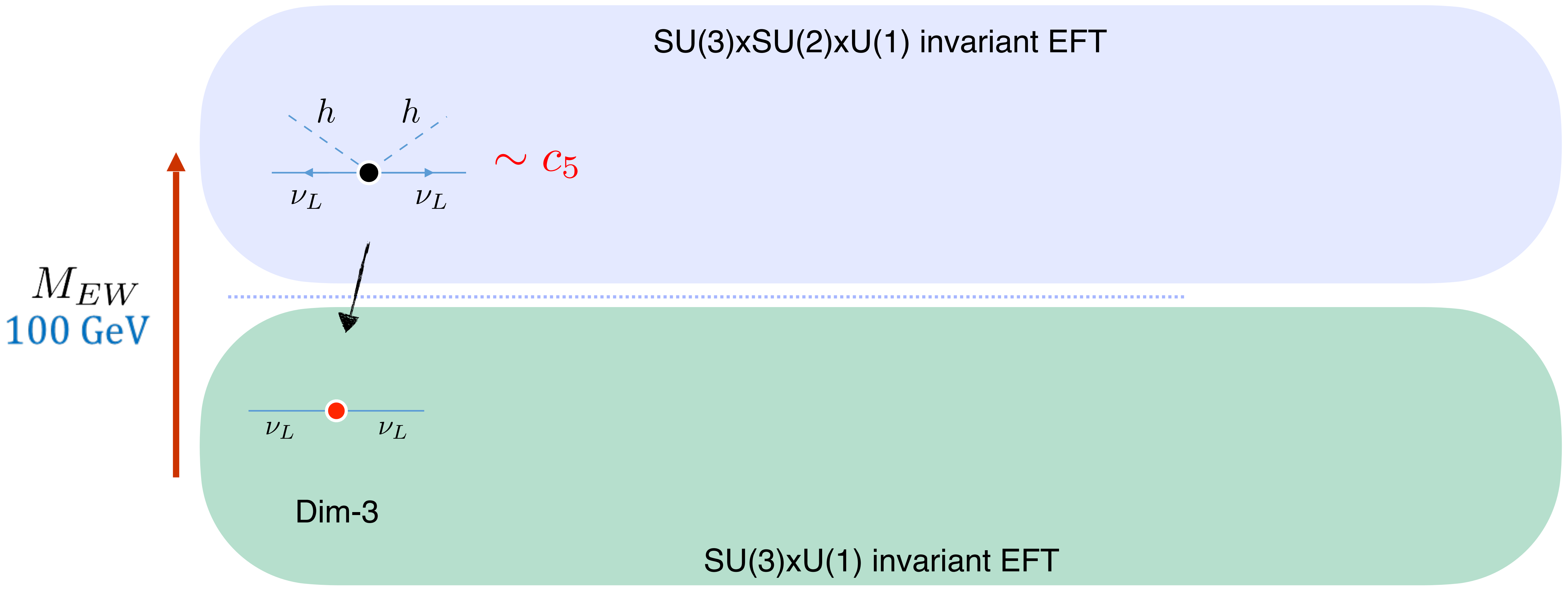
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \Big[\Big(C^{(9)}_{i\,\mathrm{R}}\, \bar e_R C \bar e_R^T + C^{(9)}_{i\,\mathrm{L}}\, \bar e_L C \bar e_L^T \Big) O_i + C^{(9)}_i\, \bar e \gamma_\mu \gamma_5 C \bar e^T O_i^\mu \Big],$$

Low-energy operators
Dimension-9

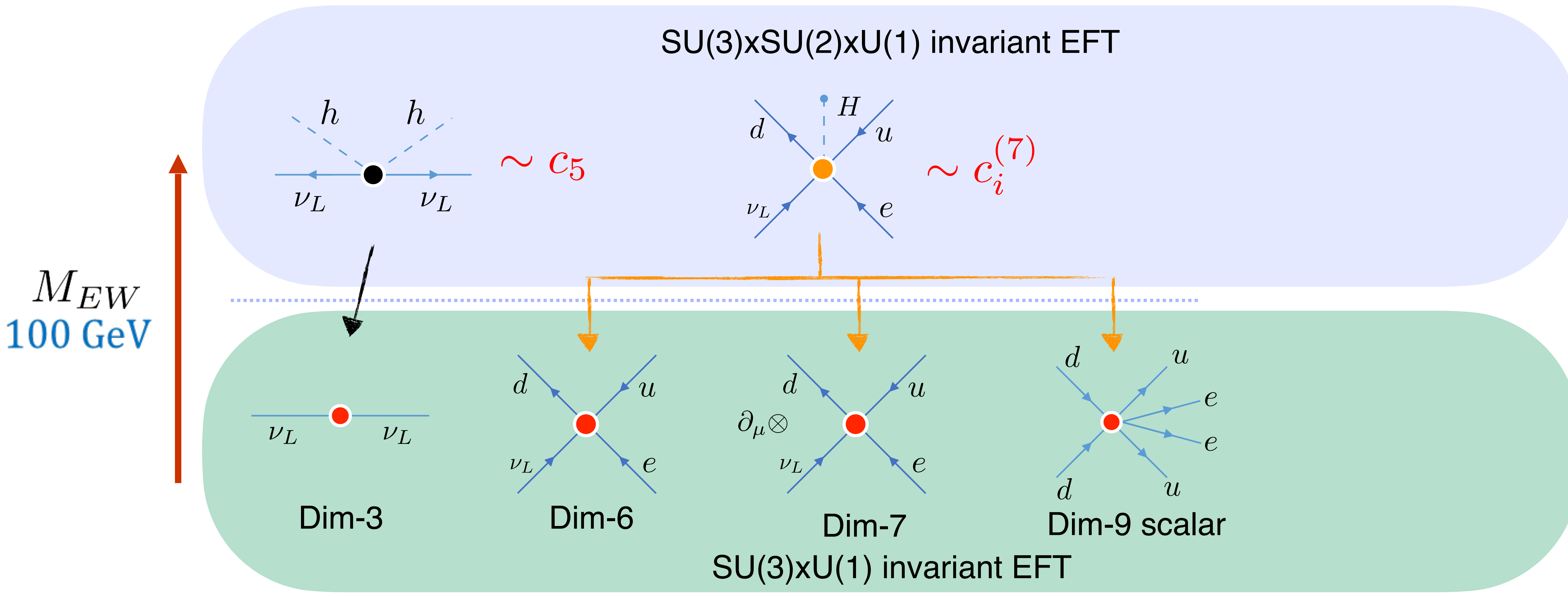


- 3 can be induced by dimension-7 operators $C_i^{(9)} \sim v^3/\Lambda^3$
- 19 can be induced by dimension-9 operators $C_i^{(9)} \sim v^5/\Lambda^5$

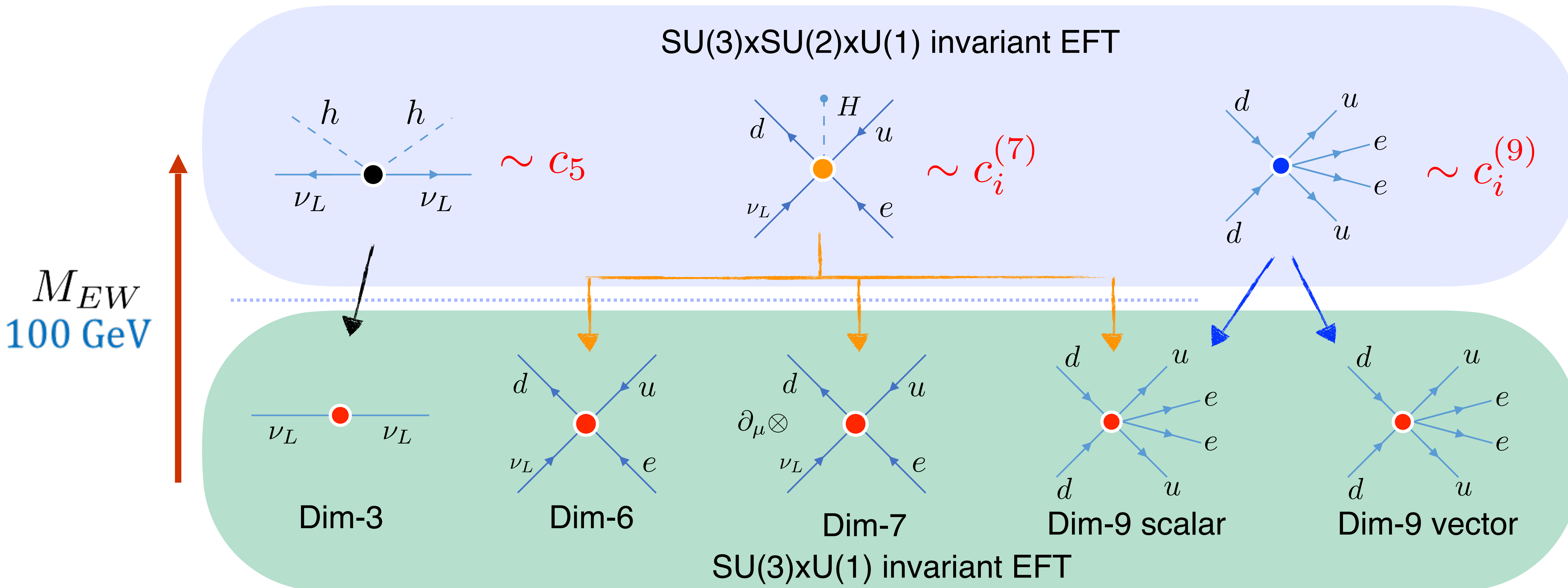
Low-energy operators
Summary



Low-energy operators
Summary

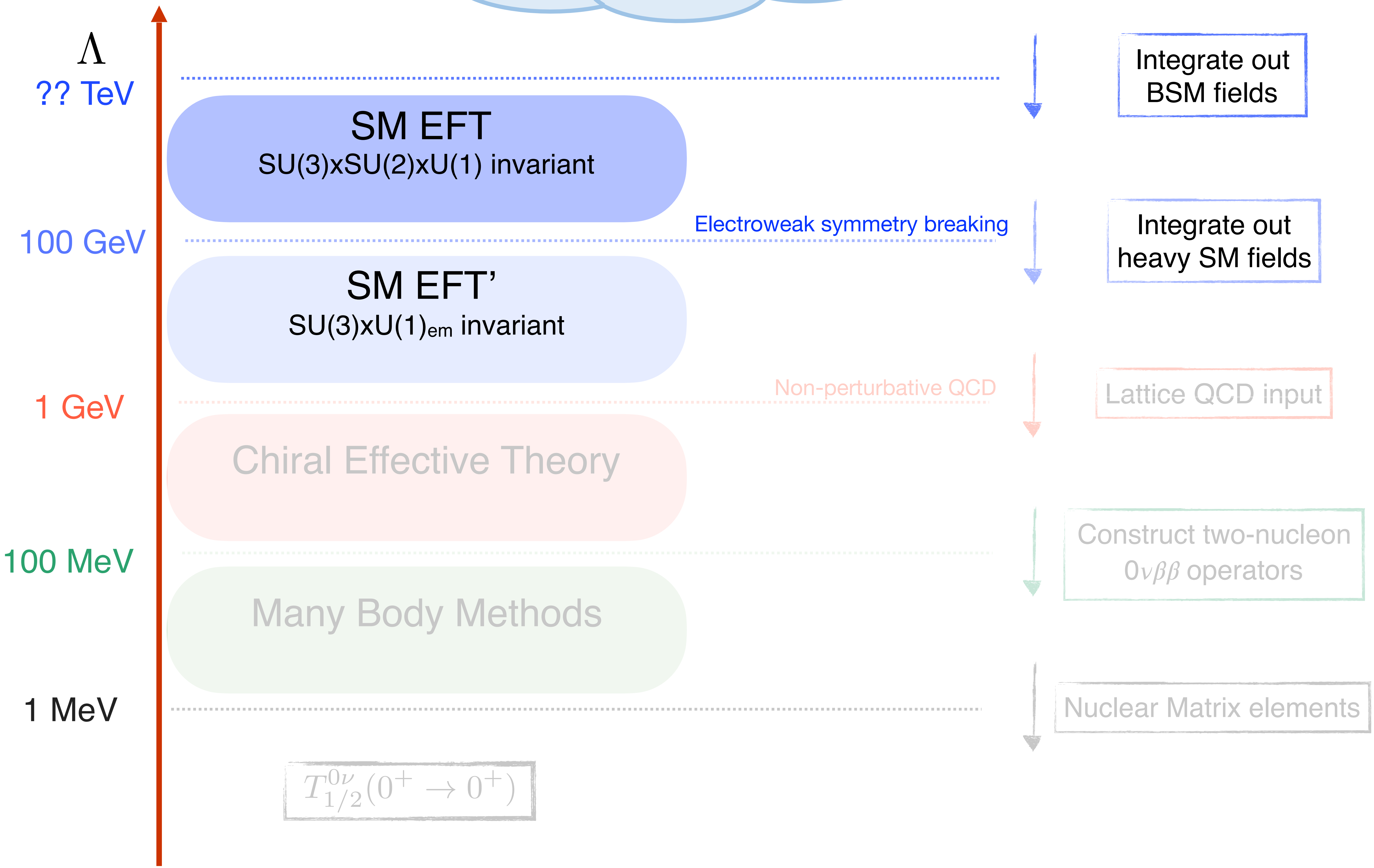


Low-energy operators
Summary

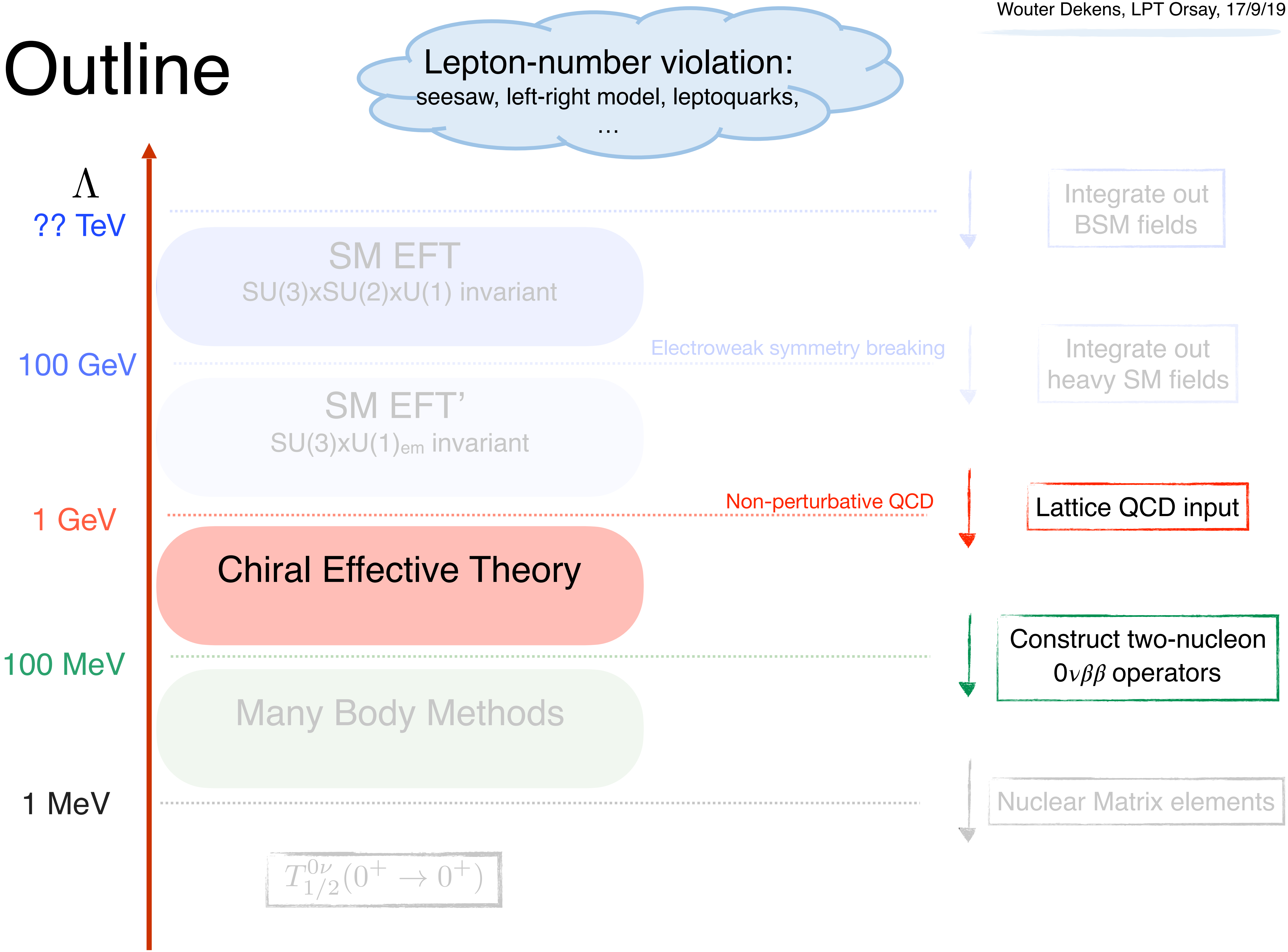


Outline

Lepton-number violation:
seesaw, left-right model, leptoquarks, …



Outline



Lepton-number violation:
seesaw, left-right model, leptoquarks, …
Λ
?? TeV
100 GeV
1 GeV
100 MeV
1 MeV
SM EFT
SU(3)xSU(2)xU(1) invariant
Electroweak symmetry breaking
SM EFT'
SU(3)xU(1)$_{em}$ invariant
Non-perturbative QCD
Chiral Effective Theory
Many Body Methods
$T^{0\nu}_{1/2}(0^+ \to 0^+)$
Integrate out BSM fields
Integrate out heavy SM fields
Lattice QCD input
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

Matching to Chiral EFT

M_{QCD}
1 GeV

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

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

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)

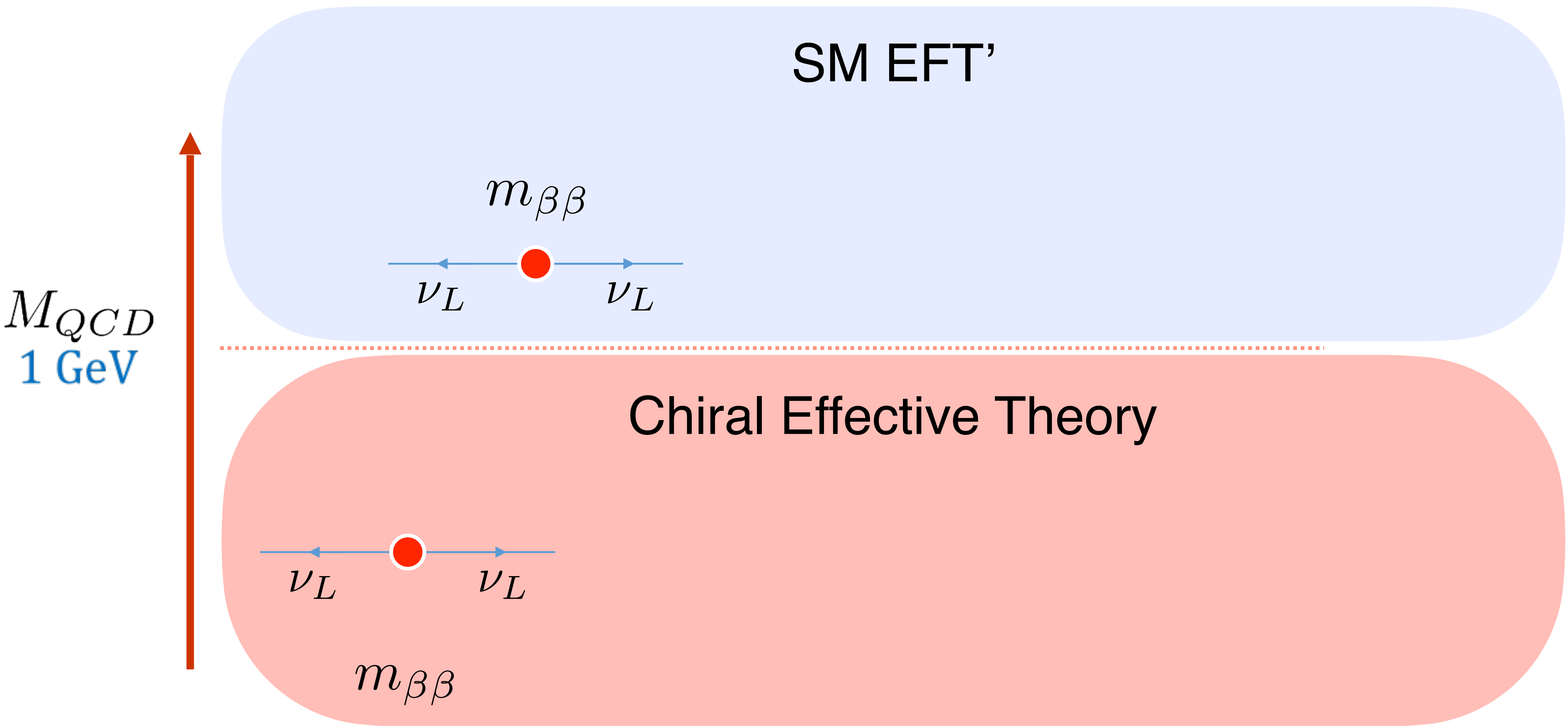
Need a power-counting scheme
- Start by assuming Naive dimensional analysis (NDA)
- Will come back to whether it breaks down

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

Matching to Chiral EFT

Dimension-3

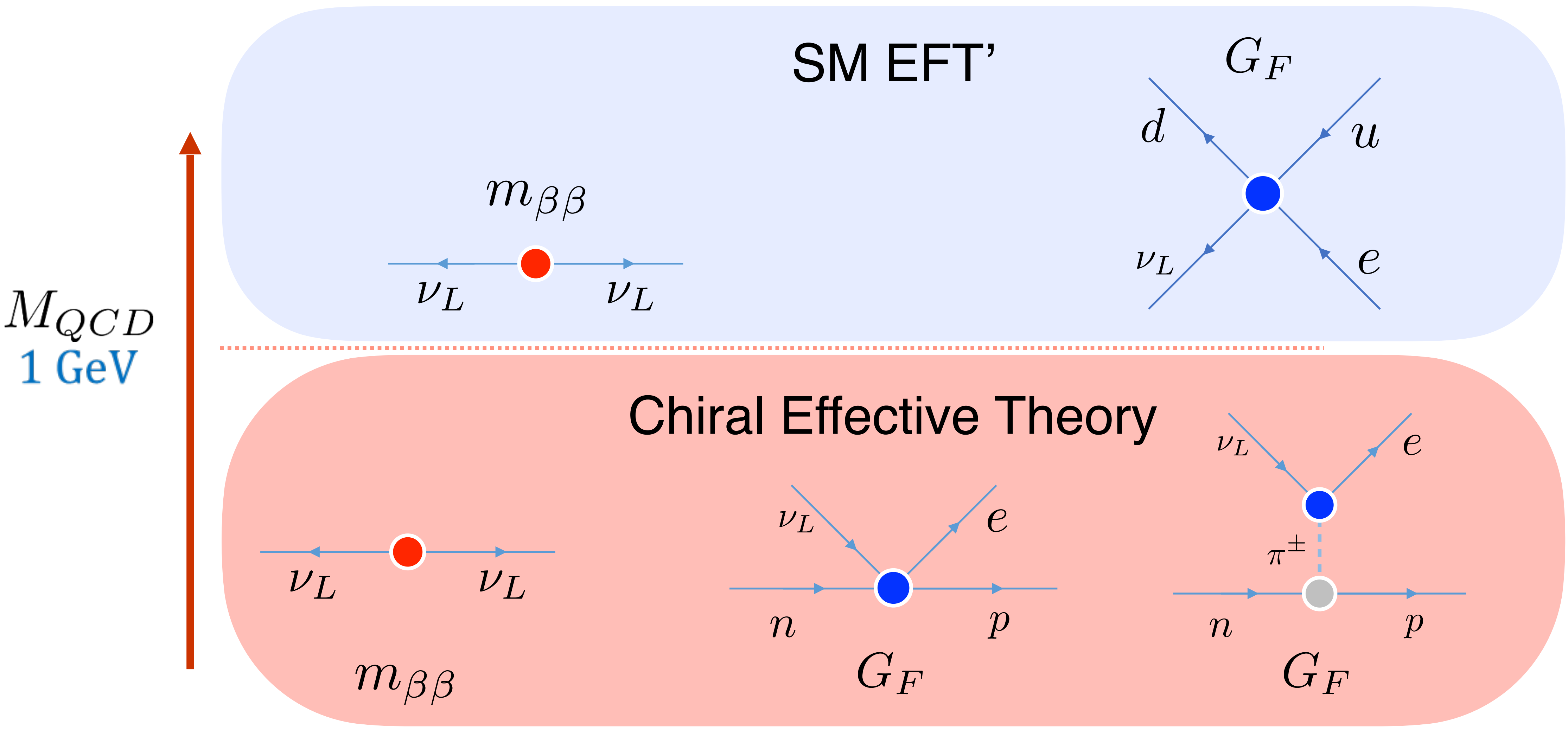
Warning: Based on NDA



Matching to Chiral EFT

Dimension-3

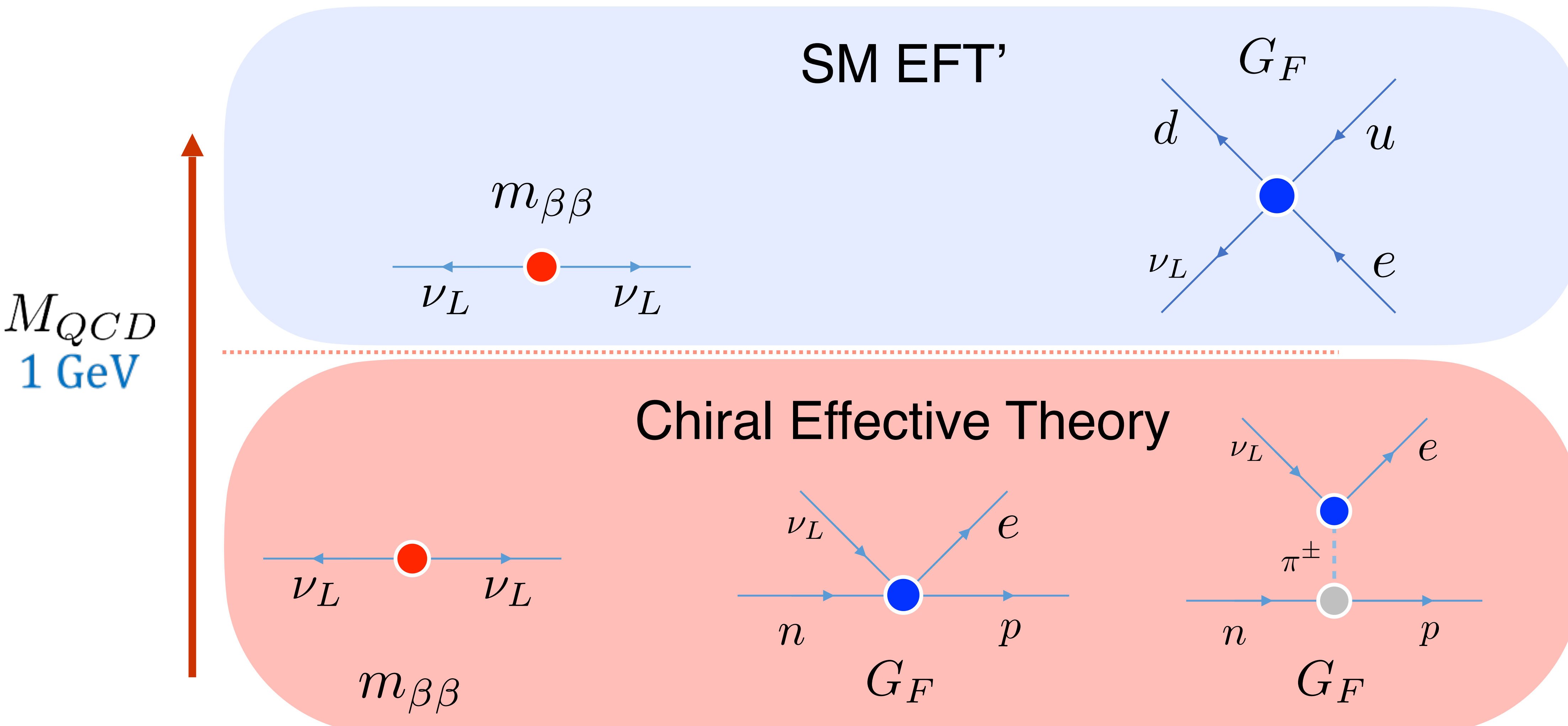
Warning: Based on NDA



Matching to Chiral EFT

Dimension-3

Warning: Based on NDA

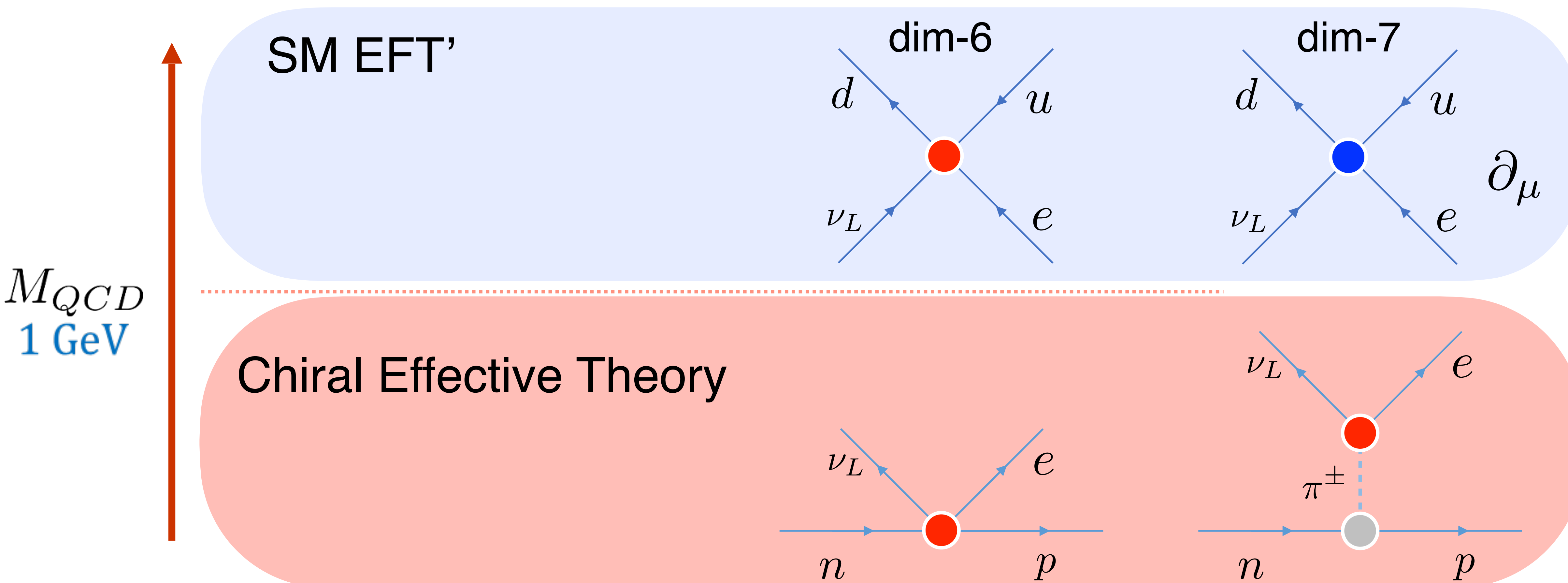


- At LO in Weinberg counting, only need the nucleon one-body currents
  - The needed low-energy constants are the nucleon charges g_V, g_A
  - Known from experiment / Lattice QCD

Matching to Chiral EFT

Dimension-6 and -7: vector & scalar

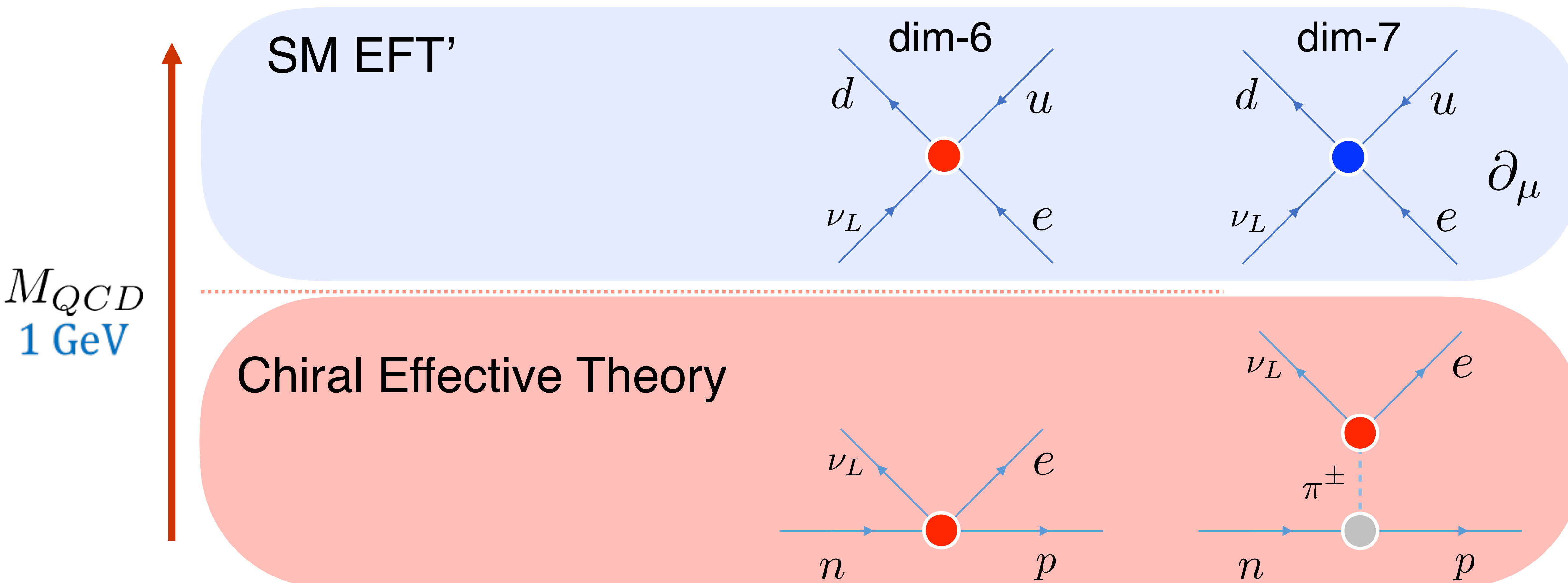
Warning: Based on NDA



Matching to Chiral EFT

Dimension-6 and -7: vector & scalar

Warning: Based on NDA

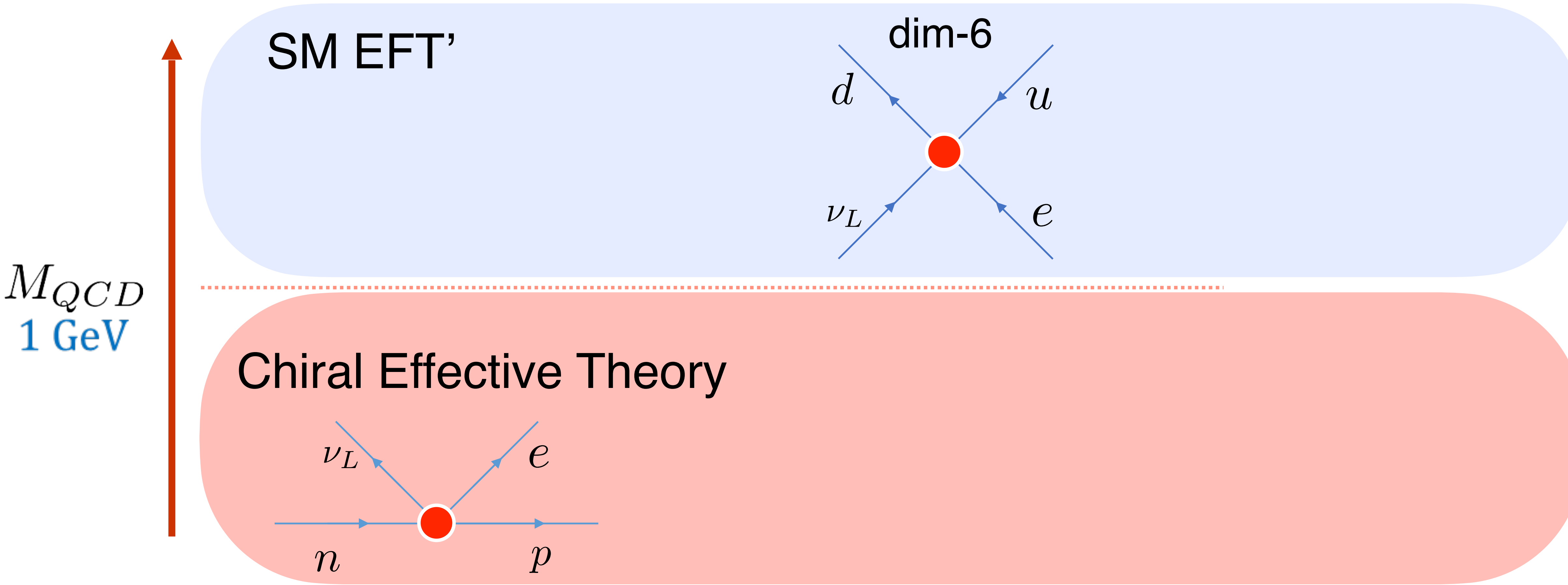


- Needed low-energy constants are the (scalar, vector) nucleon charges
  - gV, gA, gS, gM
  - Known from experiment and/or Lattice QCD

Matching to Chiral EFT

Dimension-6: tensor, left-handed vector

Warning: Based on NDA

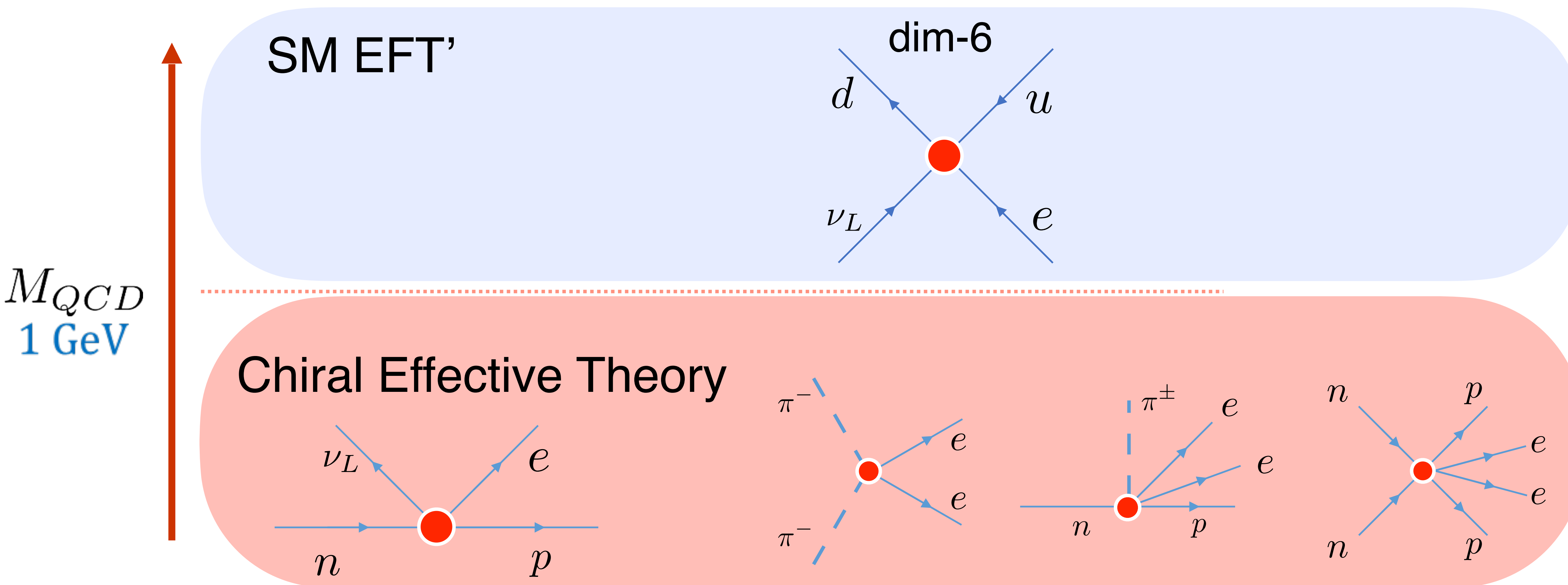


- Generate beta-decay like operators

Matching to Chiral EFT

Dimension-6: tensor, left-handed vector

Warning: Based on NDA



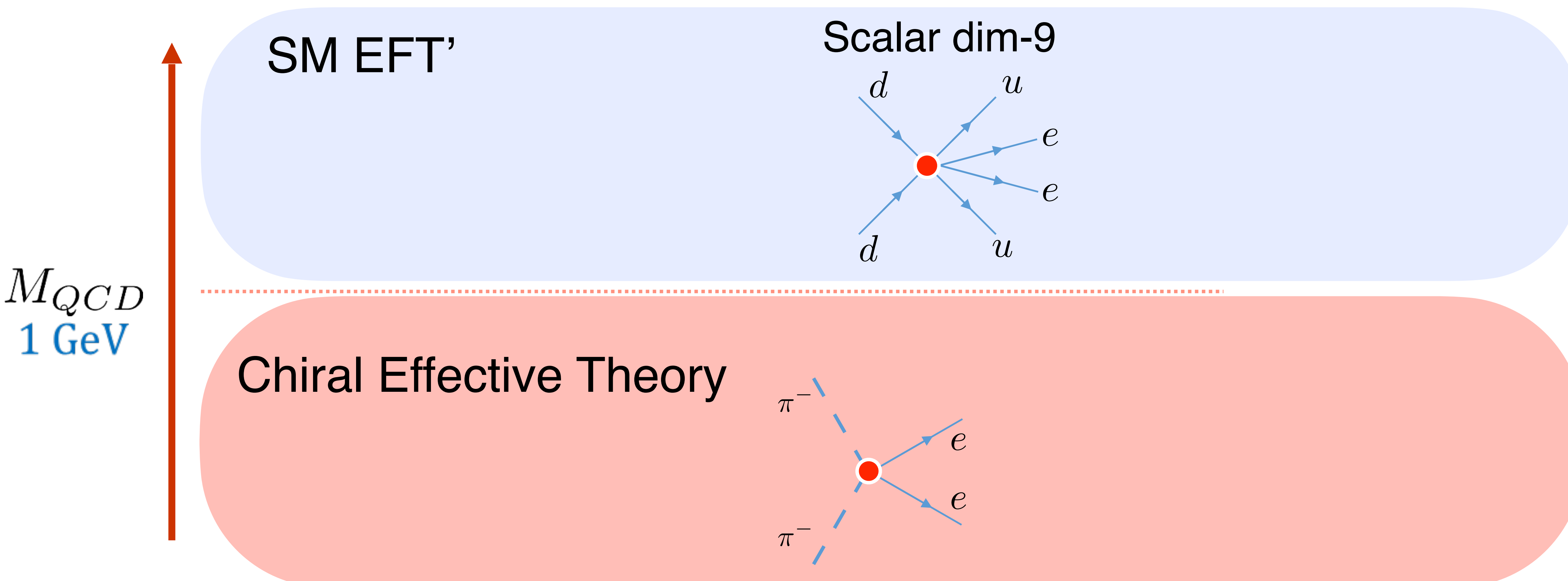
- Generate beta-decay like operators
- Also induce $\pi\pi$, πN, and NN interactions
  - Come with unknown LECs

Matching to Chiral EFT

Dimension-9

Warning: Based on NDA

$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \left[\left(C^{(9)}_{i\,\mathrm{R}}\, \bar{e}_R C \bar{e}_R^T + C^{(9)}_{i\,\mathrm{L}}\, \bar{e}_L C \bar{e}_L^T \right) O_i + C^{(9)}_i \bar{e}\gamma_\mu\gamma_5 C \bar{e}^T\, O_i^\mu \right],$$

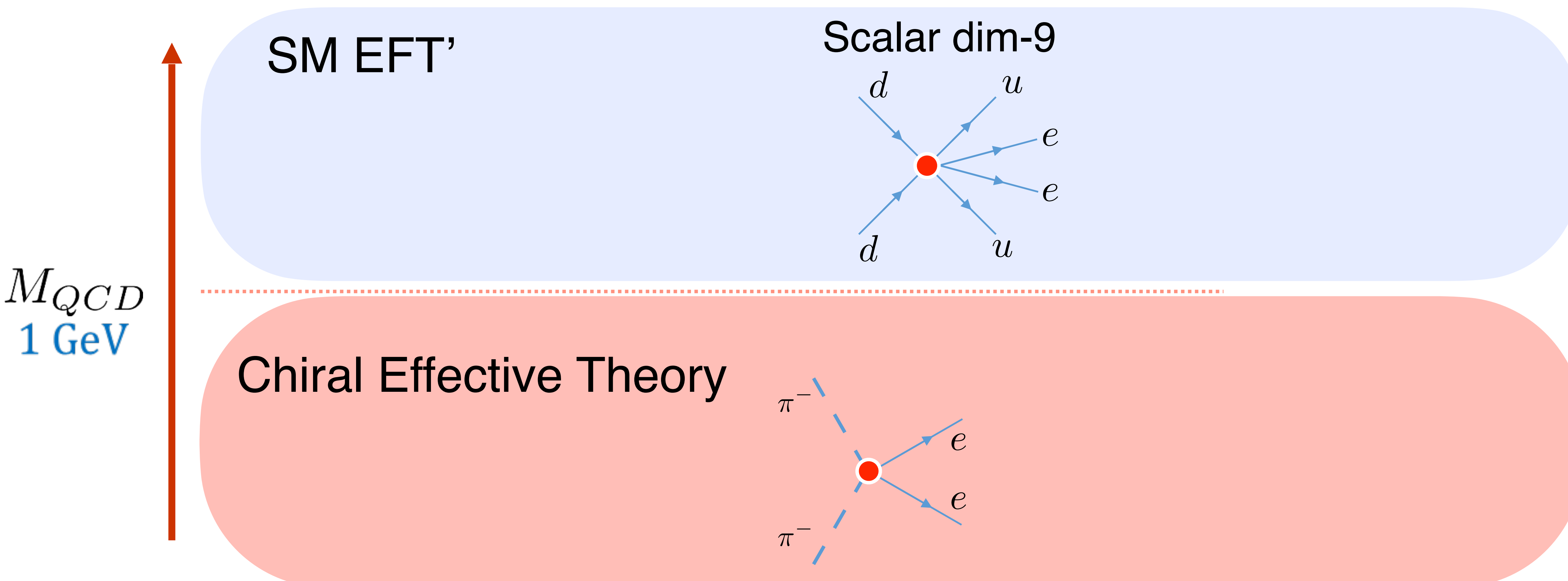


Matching to Chiral EFT

Dimension-9

Warning: Based on NDA

$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \left[\left(C^{(9)}_{i\,\mathrm{R}}\, \bar e_R C \bar e_R^T + C^{(9)}_{i\,\mathrm{L}}\, \bar e_L C \bar e_L^T \right) O_i + C^{(9)}_i \bar e \gamma_\mu \gamma_5 C \bar e^T O_i^\mu \right],$$



- Most scalar operators only induce $\pi\pi$ interactions
  - Known from Lattice QCD / SU(3) chiral symmetry

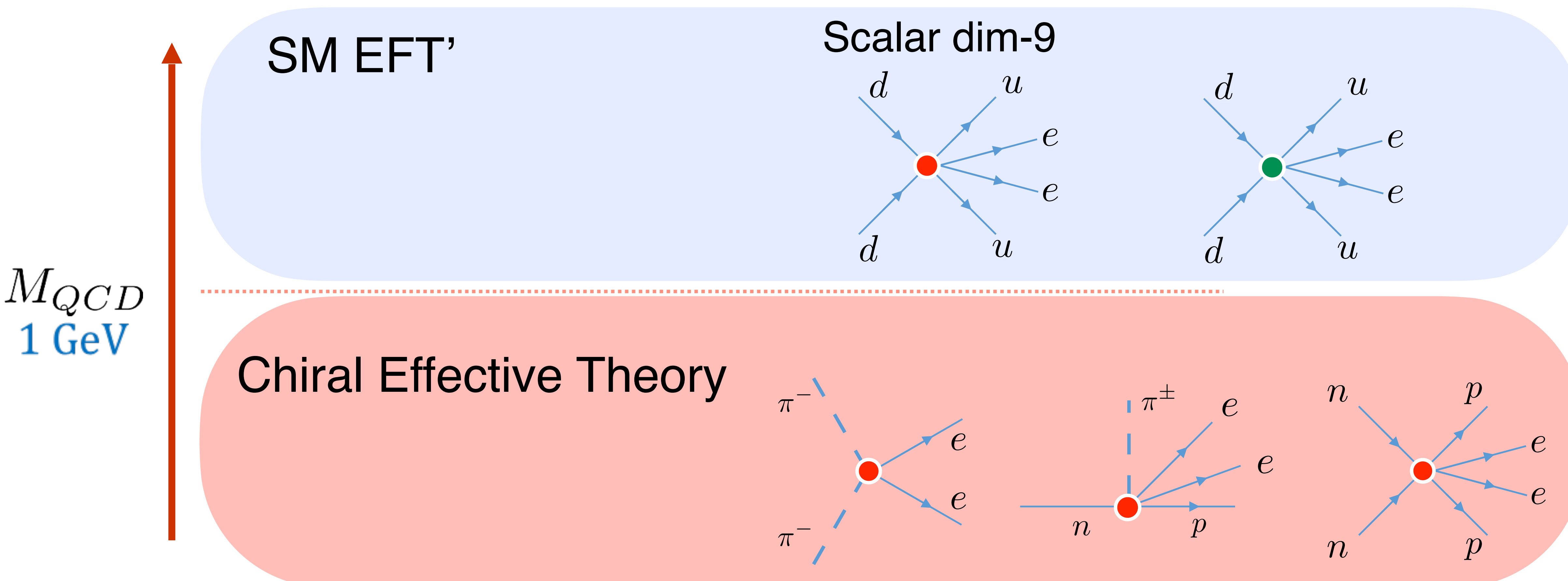
Nicholson et al.'18; Cirigliano et al. '17

Matching to Chiral EFT

Dimension-9

Warning: Based on NDA

$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \left[\left(C^{(9)}_{i\,\mathrm{R}}\, \bar{e}_R C \bar{e}_R^T + C^{(9)}_{i\,\mathrm{L}}\, \bar{e}_L C \bar{e}_L^T \right) O_i + C^{(9)}_i \bar{e}\gamma_\mu\gamma_5 C \bar{e}^T O^\mu_i \right],$$



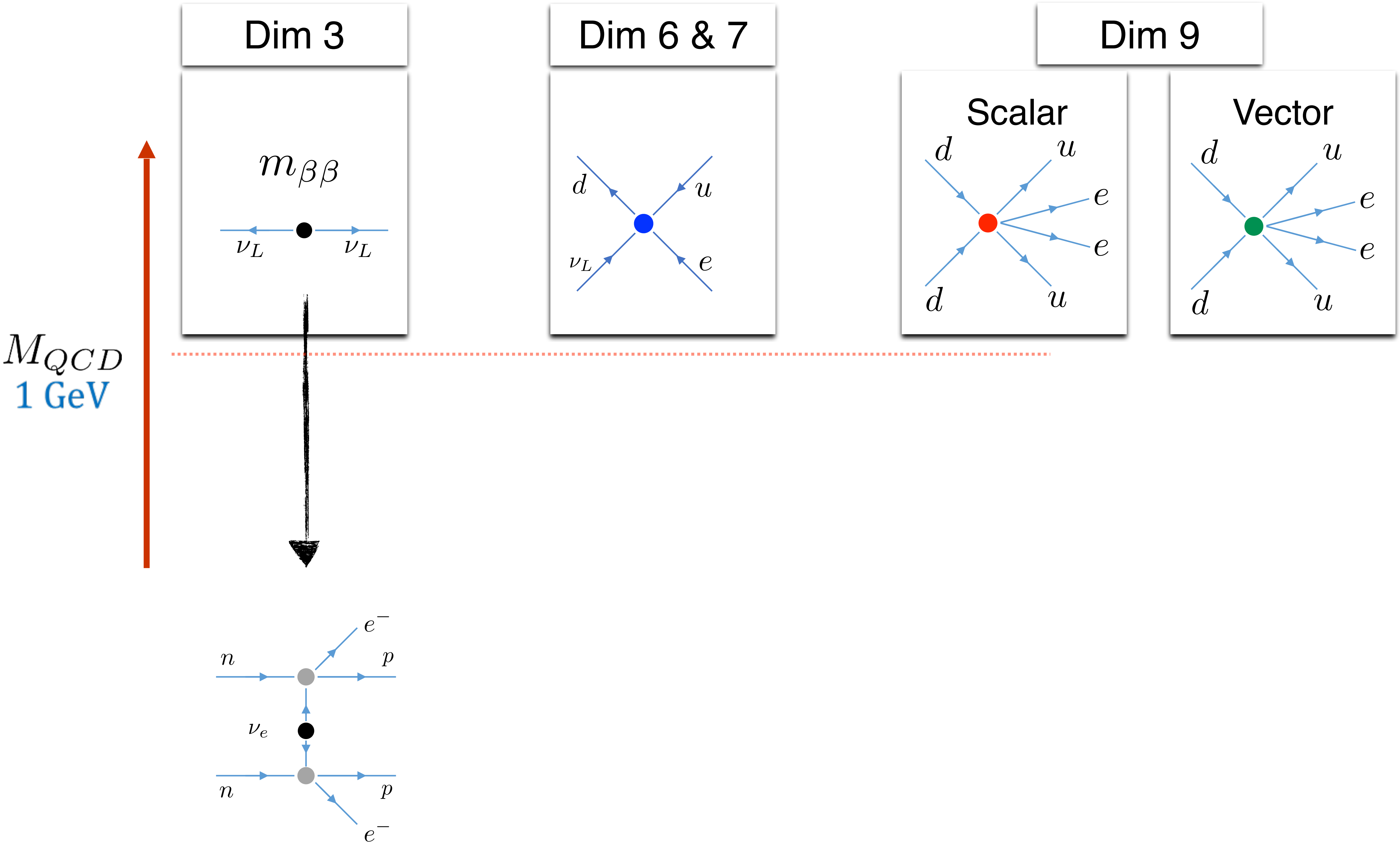
- Most scalar operators only induce $\pi\pi$ interactions
  - Known from Lattice QCD / SU(3) chiral symmetry

- One scalar structure + vector operators induce πN & NN terms
  - The low-energy constants for the πN and NN interactions are unknown

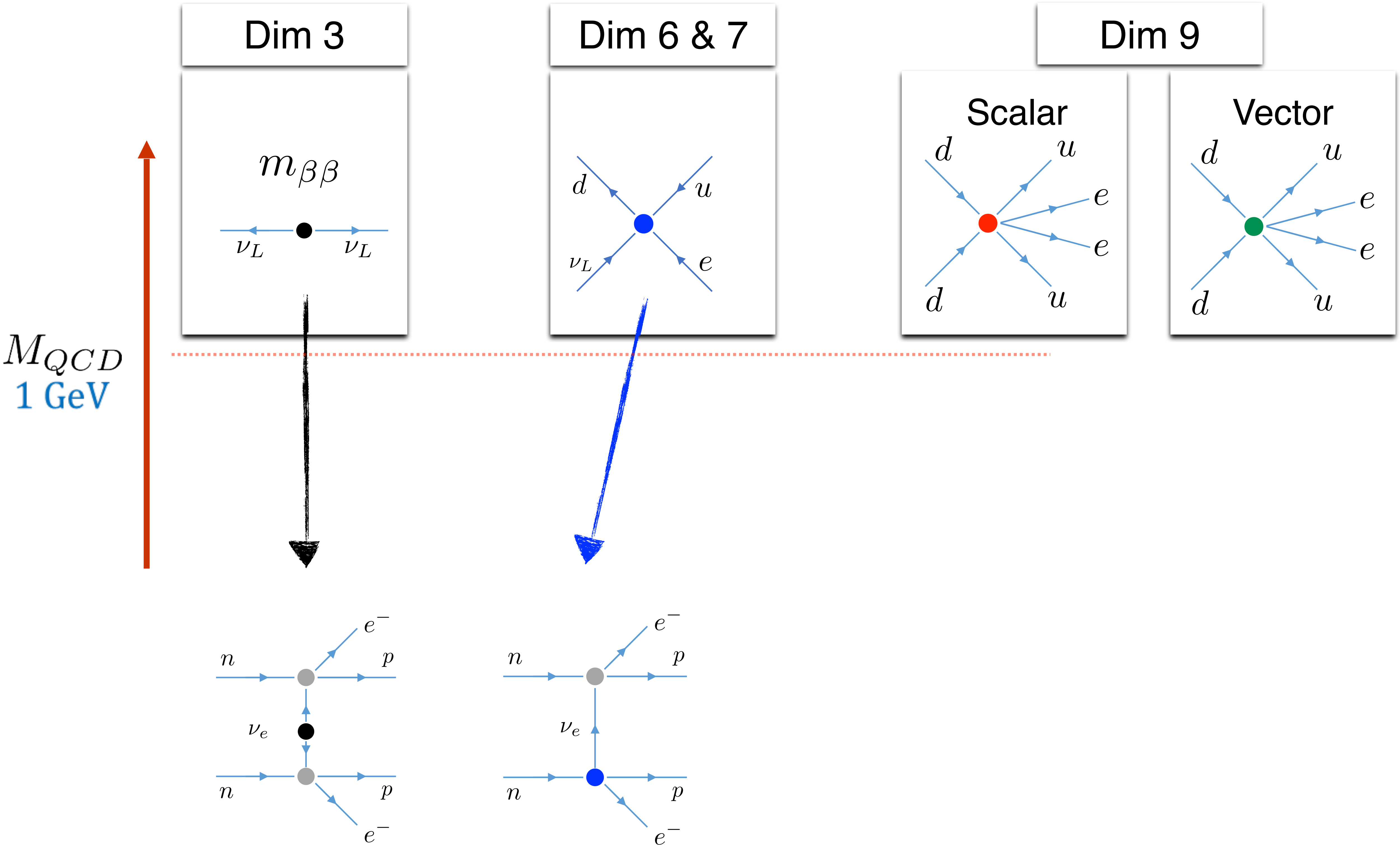
Nicholson et al.'18; Cirigliano et al. '17

Chiral EFT

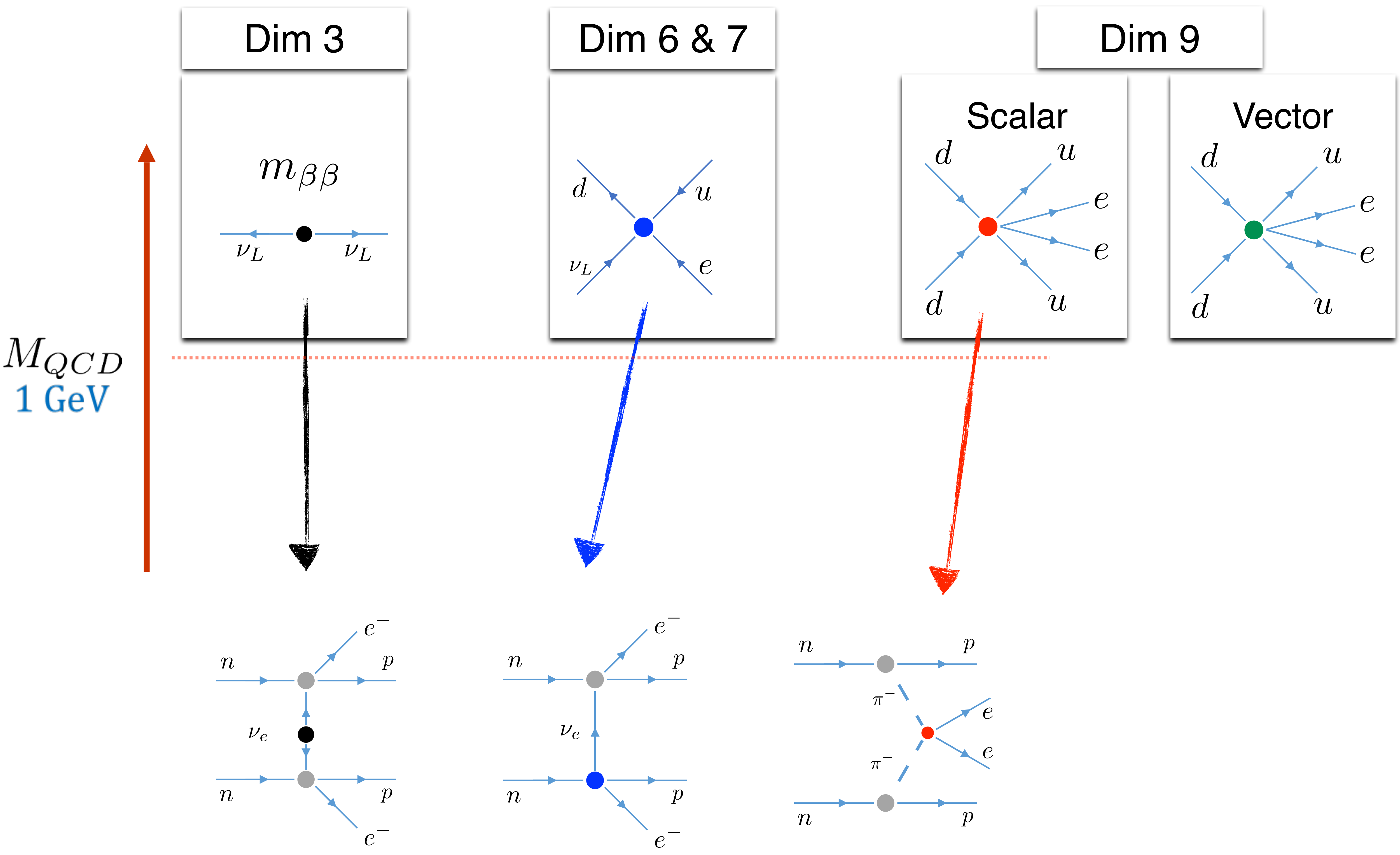
Summary



Chiral EFT
Summary

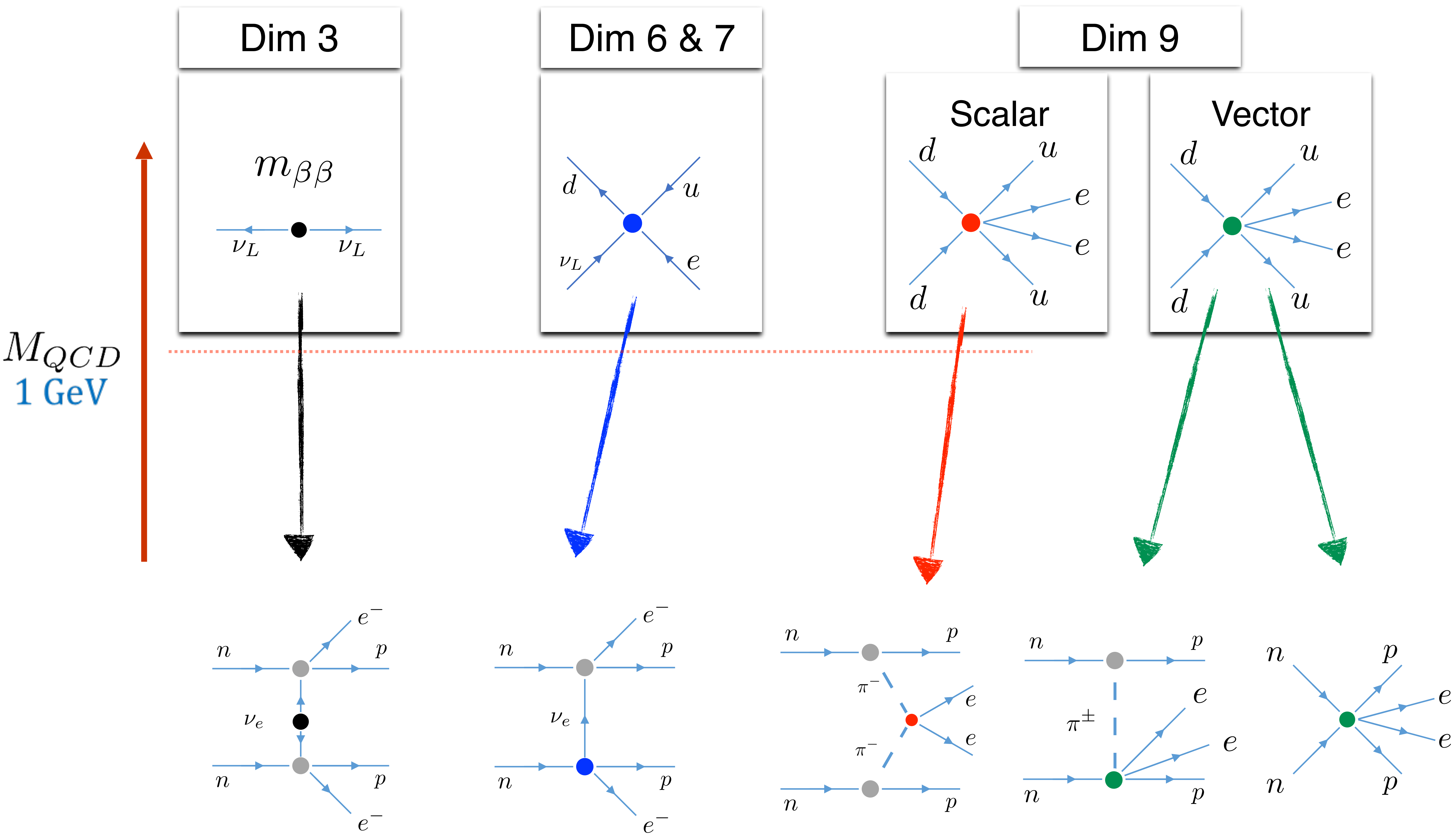


Chiral EFT
Summary



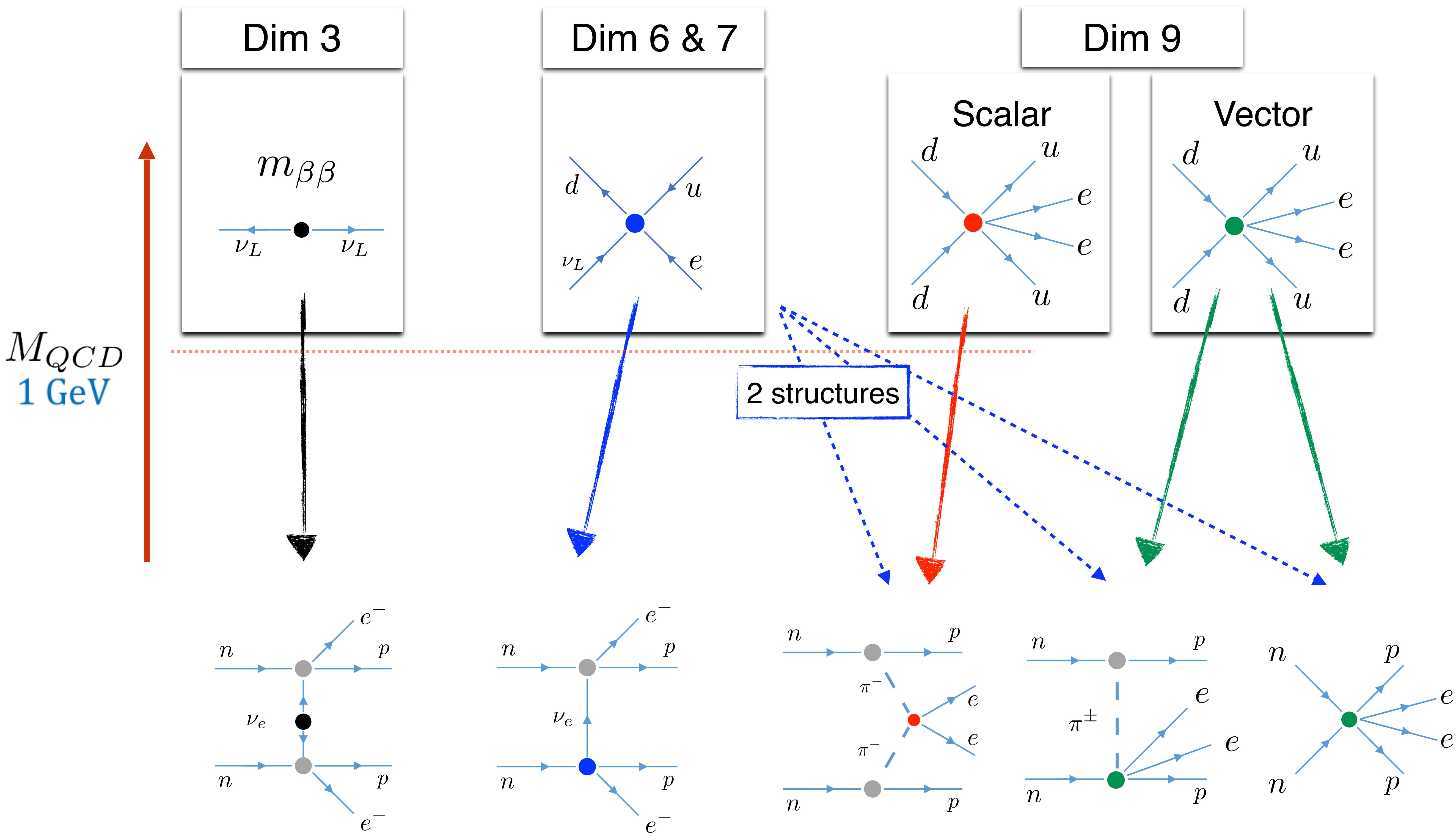
Chiral EFT

Summary



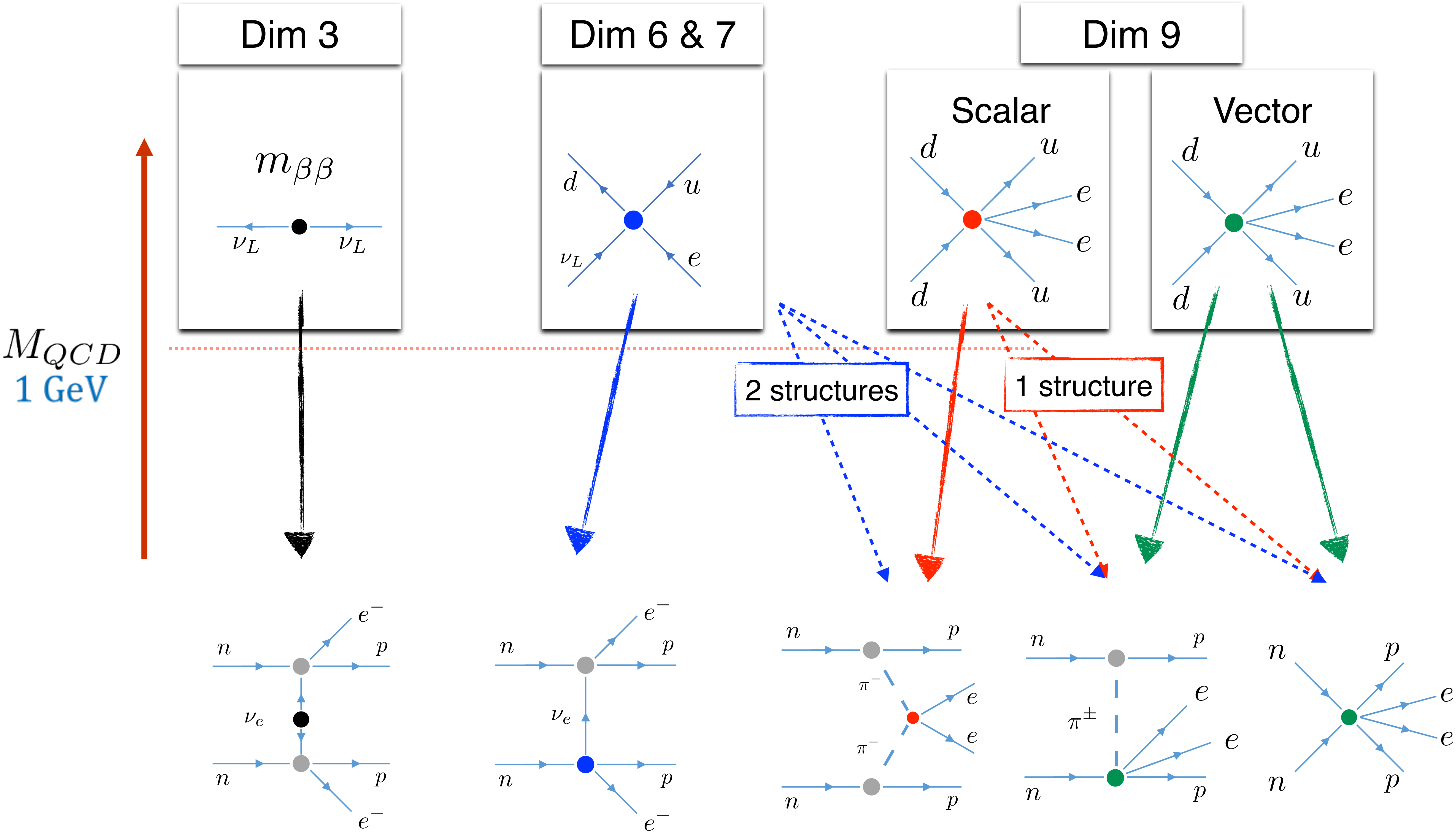
Chiral EFT

Summary



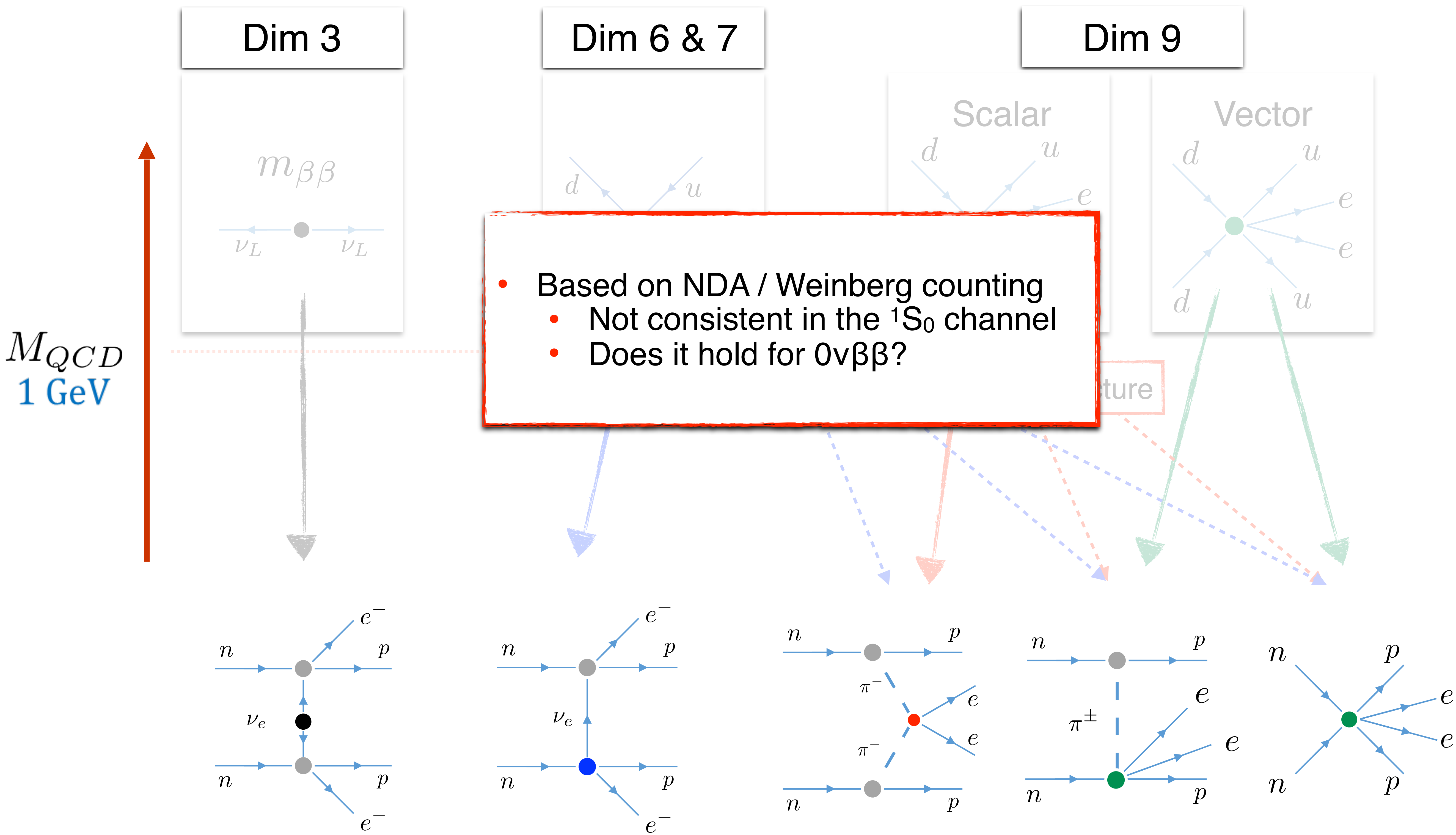
Chiral EFT

Summary



Chiral EFT

Summary



- Based on NDA / Weinberg counting
  - Not consistent in the $^1S_0$ channel
  - Does it hold for 0νββ?

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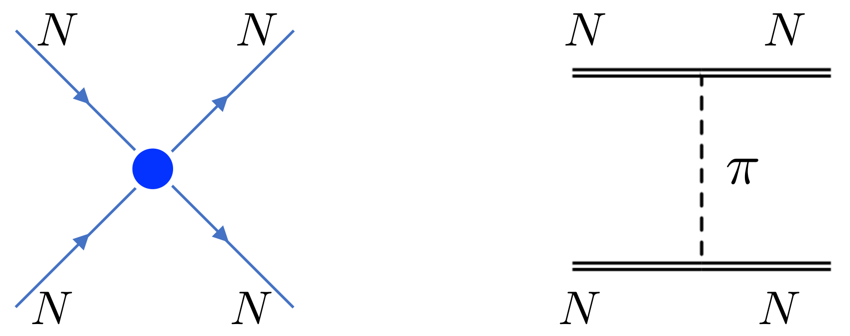
Check that $\mathcal{A}(nn \to ppee)$ is finite

- 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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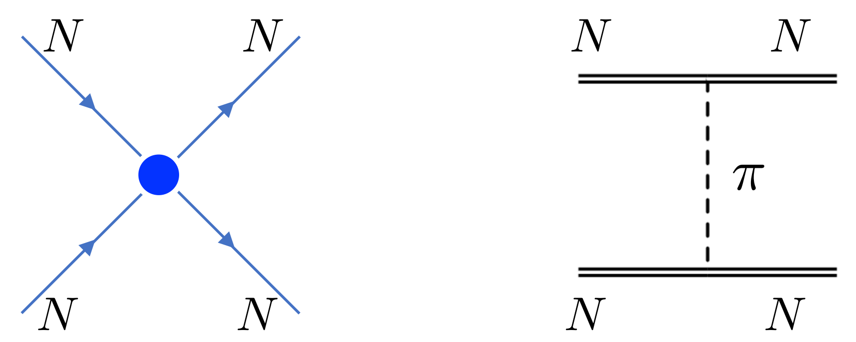
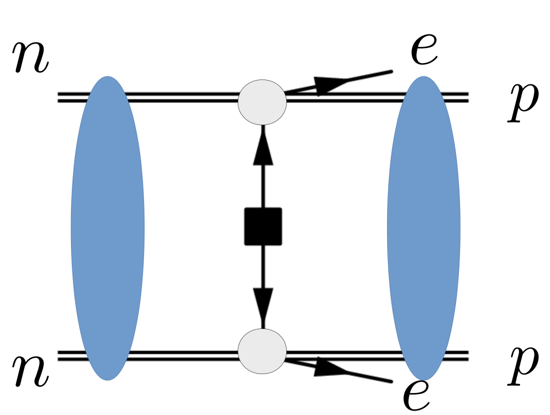
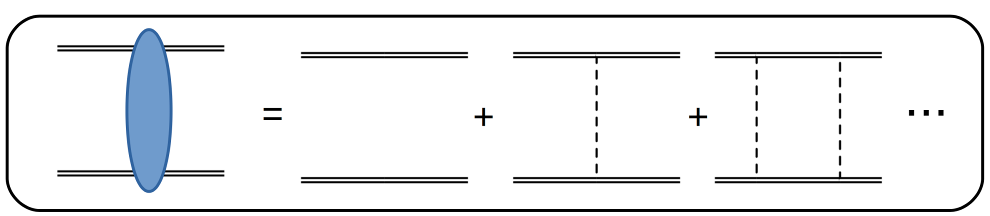


Dress the ΔL=2 potential with (renormalized) strong interactions:





✓ finite

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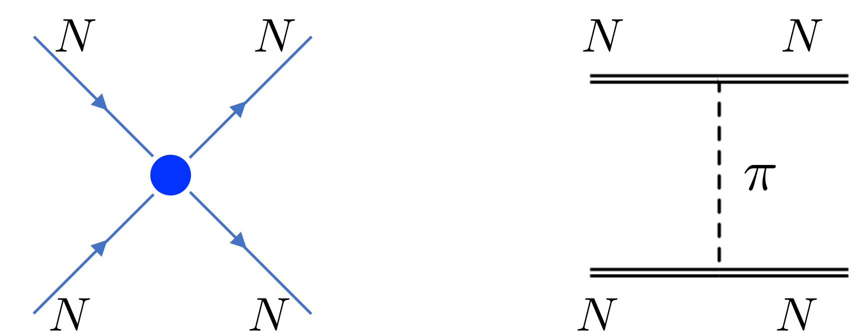

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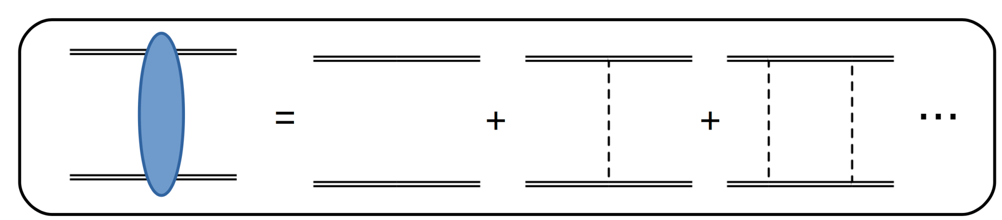

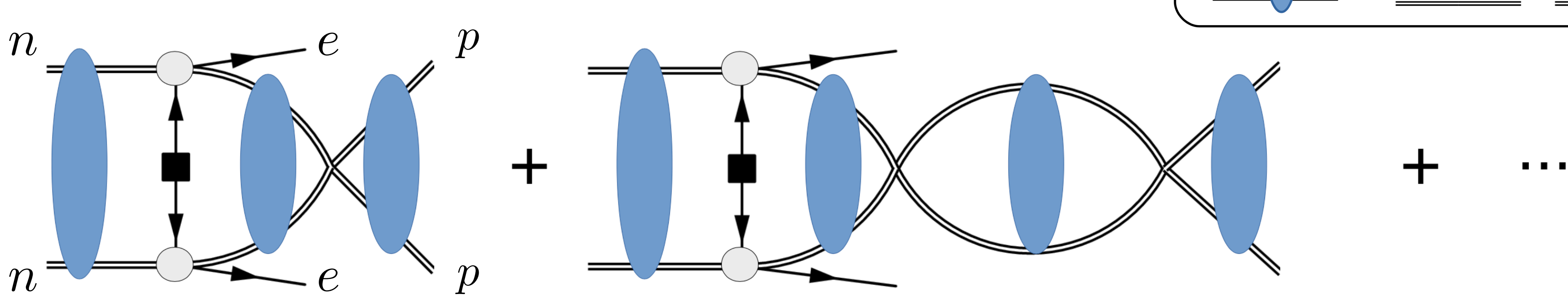

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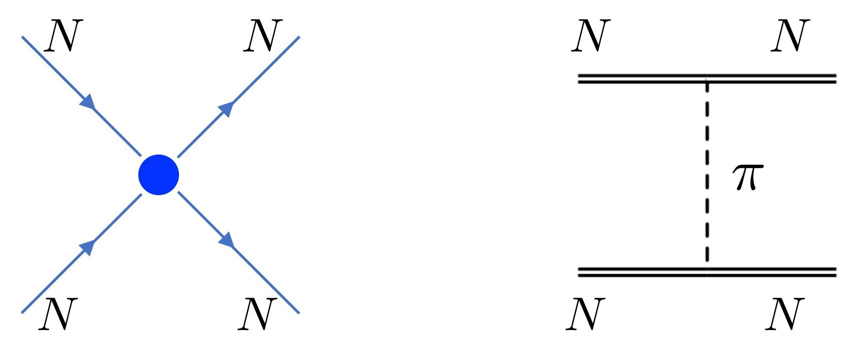

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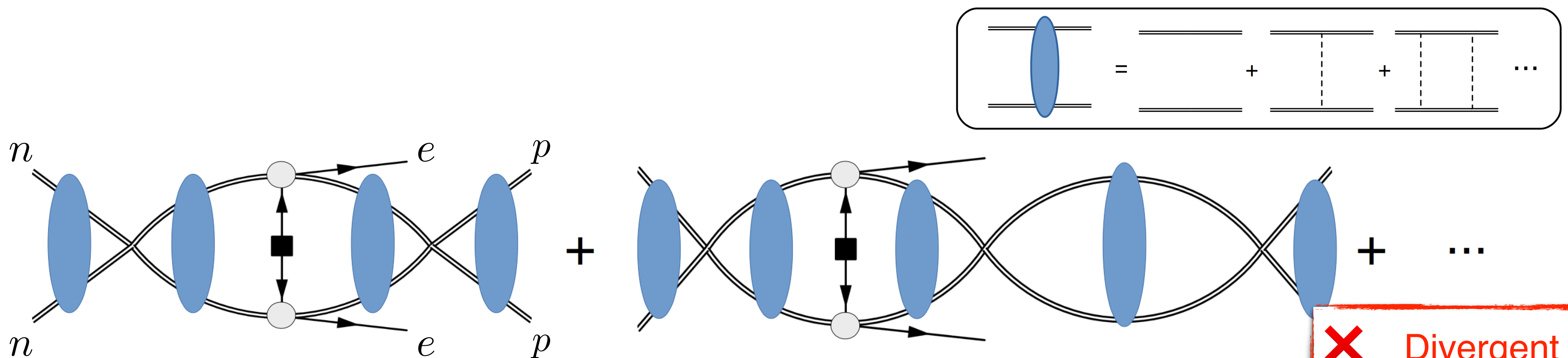

❌ Divergent

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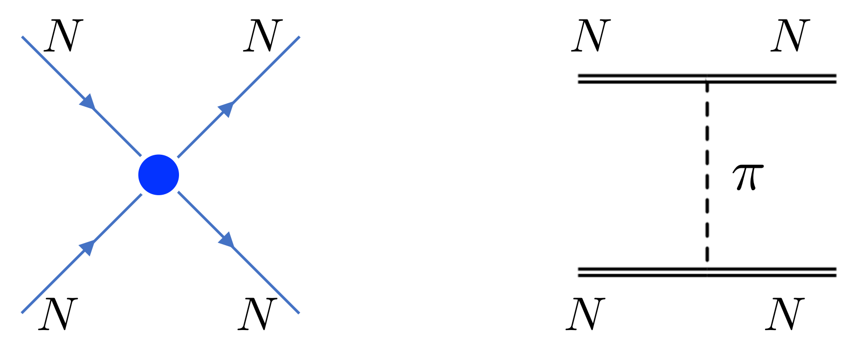
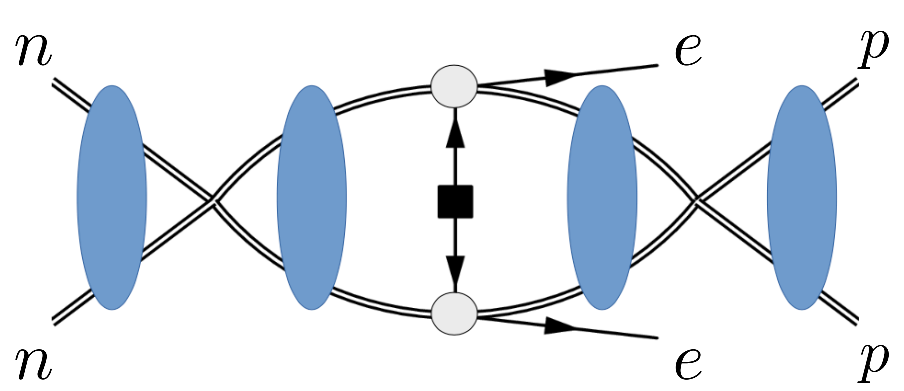


Dress the ΔL=2 potential with (renormalized) strong interactions:

In MS-bar:

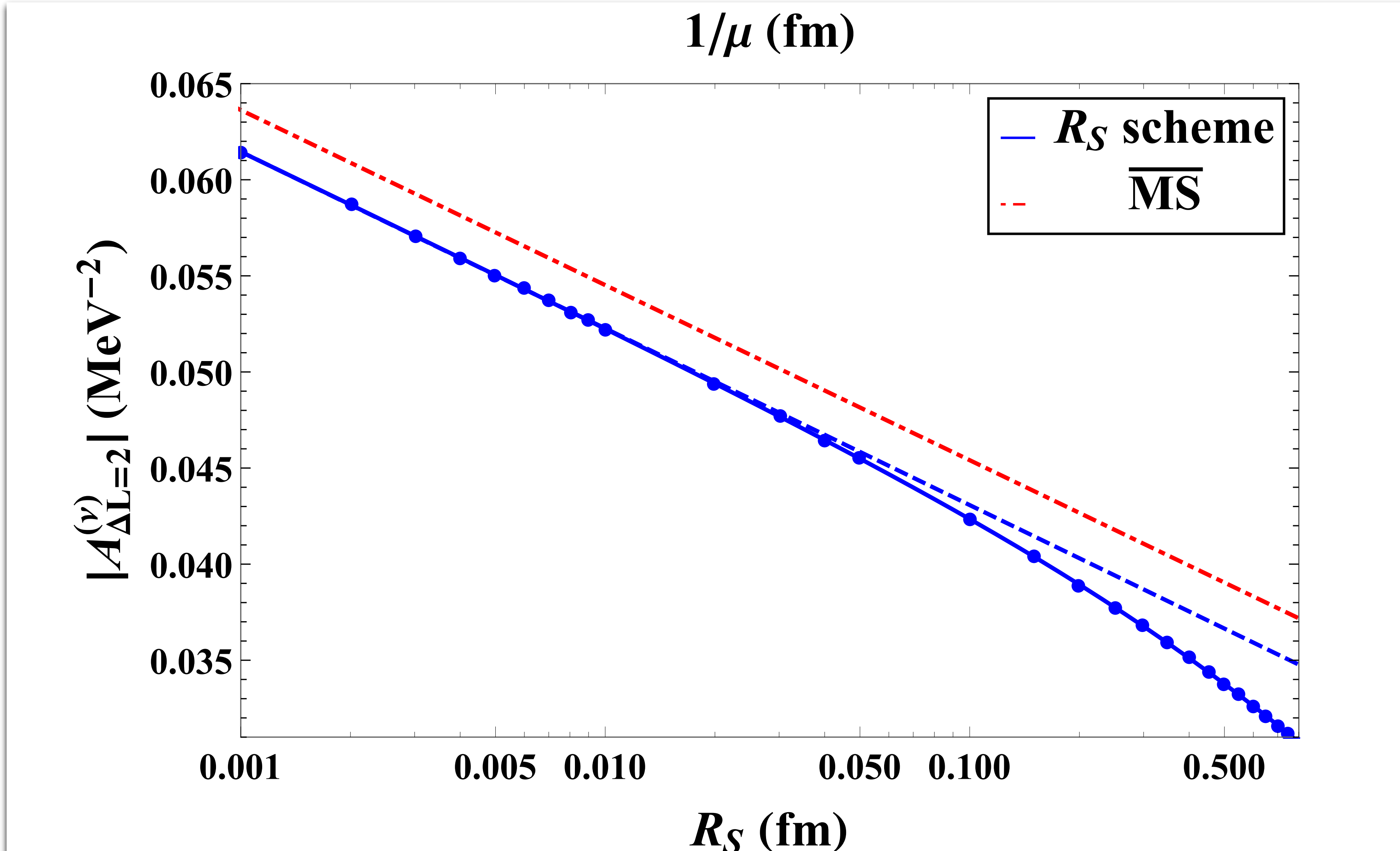


$$= -\left(\frac{m_N}{4\pi}\right)^2 (1+2g_A^2)\frac{1}{2}\left(\log\frac{\mu^2}{-(|\mathbf{p}|+|\mathbf{p}'|)^2+i0^+}+1\right)$$

$+\text{finite}$

Regulator dependent

Numerical results



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

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

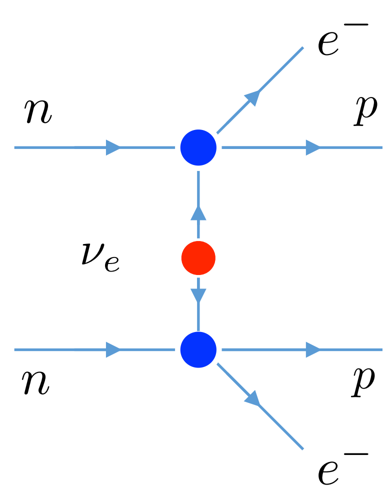
- Clear μ or R_S dependence

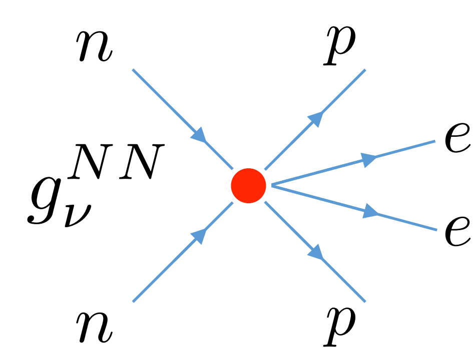
Need for a counter term

- Need a new contact interaction at leading order to get physical amplitudes:

$$\mathcal{L}_{CT} = 2G_F^2 V_{ud}^2 m_{\beta\beta}\, g_\nu^{NN}\, \bar{p}n\, \bar{p}n\, \bar{e}_L C \bar{e}_L^T$$

$$V_{\Delta L=2} = V_\nu + V_{\nu,CT} =$$





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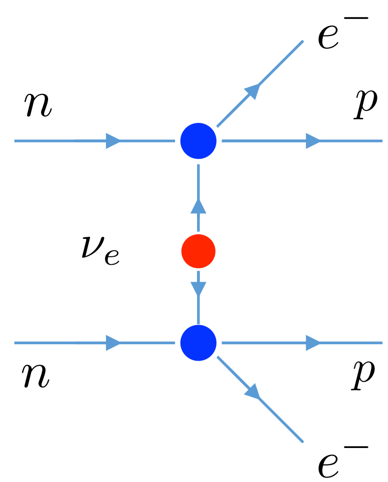
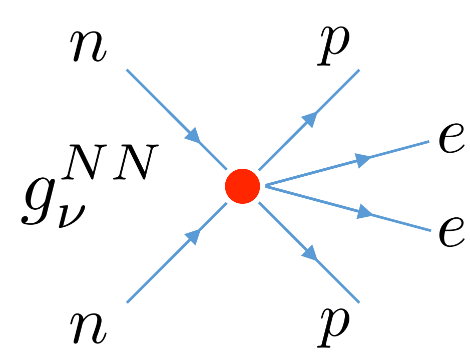




- Finite part of g_ν^{NN} is currently unknown, hard to estimate its impact

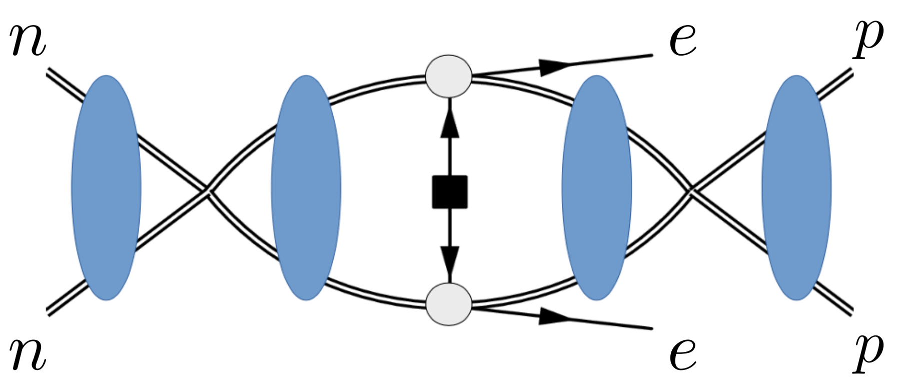
- Could be determined from a lattice calculation of $\mathcal{A}(nn \to ppe^-e^-)$

- Estimate from relation to EM (back-up slides)
  - ~10-30% contribution in $\mathcal{A}(nn \to ppe^-e^-)$
  - ~60% in light nuclei, $^{12}Be \to {}^{12}C e^- e^-$

Checking the Weinberg counting

Any effect for the dim-6,7,9 terms?

- In the Majorana-mass case, the LNV potential leads to a divergence
  - Due to the potential at large momenta $V_{\Delta L=2} \sim 1/\vec{q}^2$



$$\sim m_N^2 \int d^3q d^3k \frac{1}{m_N E - \vec{q}^2} \frac{1}{(\vec{q}-\vec{k})^2} \frac{1}{m_N E' - \vec{k}^2}$$

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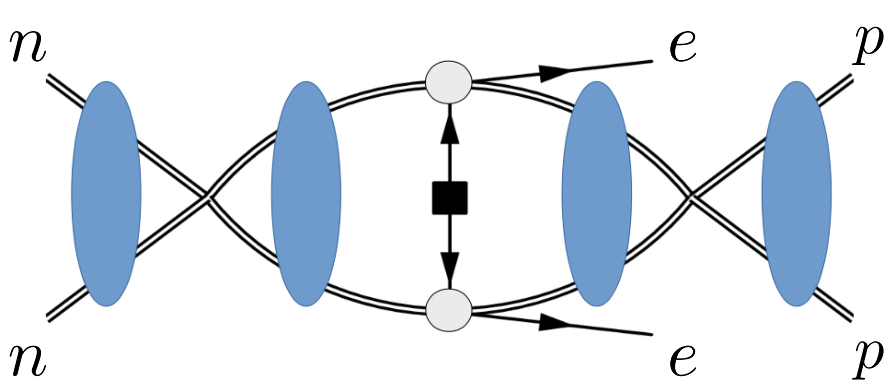

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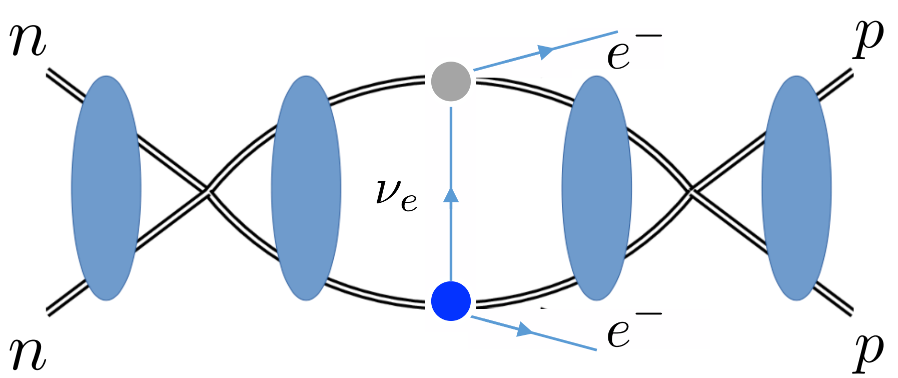

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Dimension-6,7,9

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  - The case for the vector operators

$$C^{(6)}_{VL,VR}: \quad V_{\Delta L=2} \sim 1/\vec{q}^2$$

$$C^{(9)}_{1-9}: \quad V_{\Delta L=2} \sim \frac{1}{\vec{q}^2 + m_\pi^2}$$

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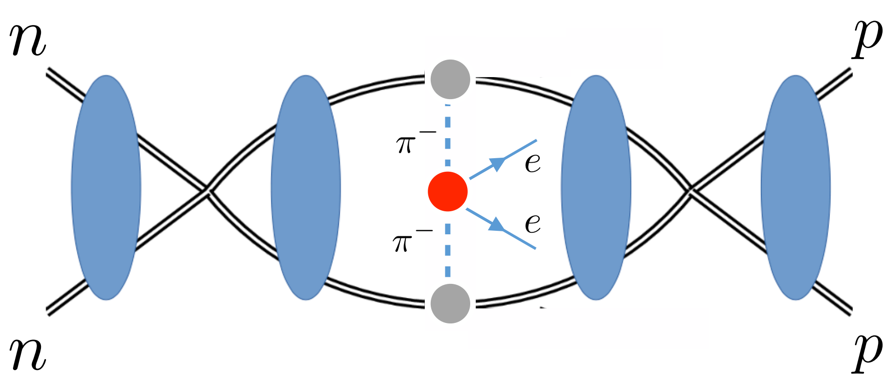

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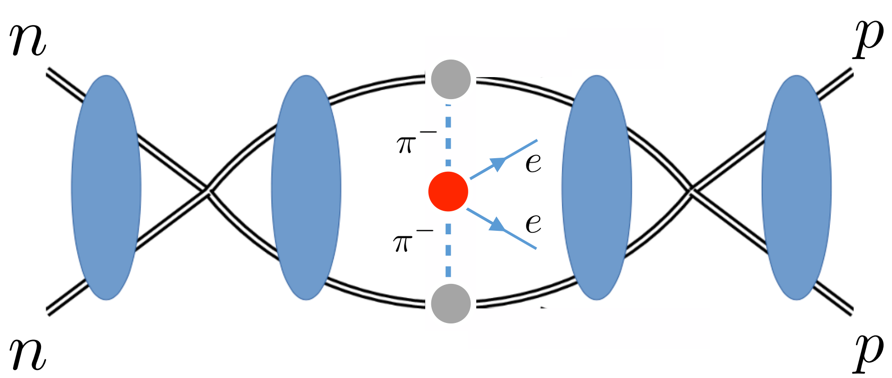

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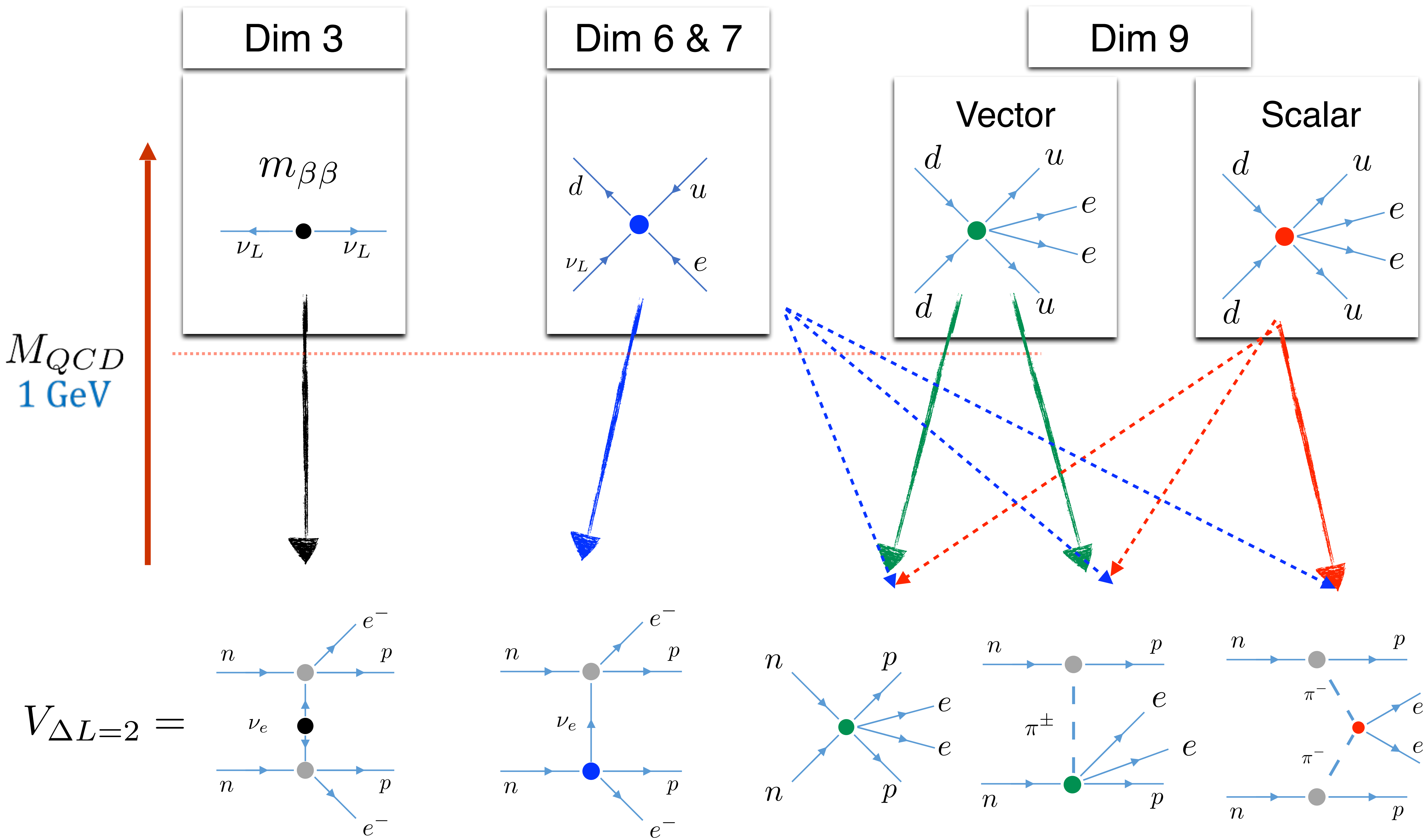
- Need to include contact interactions at LO in these cases
  - Often disagrees with the Weinberg / NDA counting

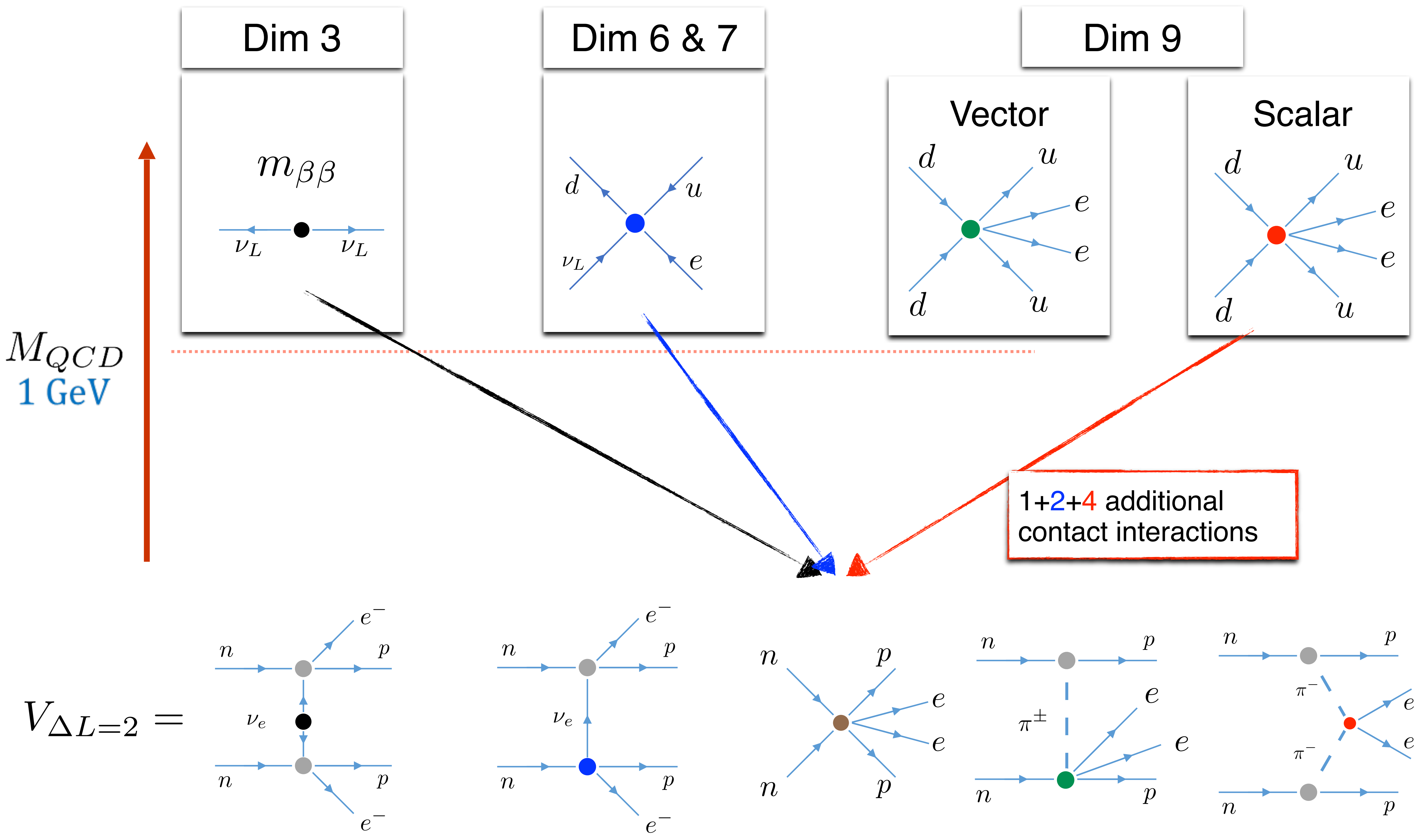
Chiral EFT

NDA / Weinberg

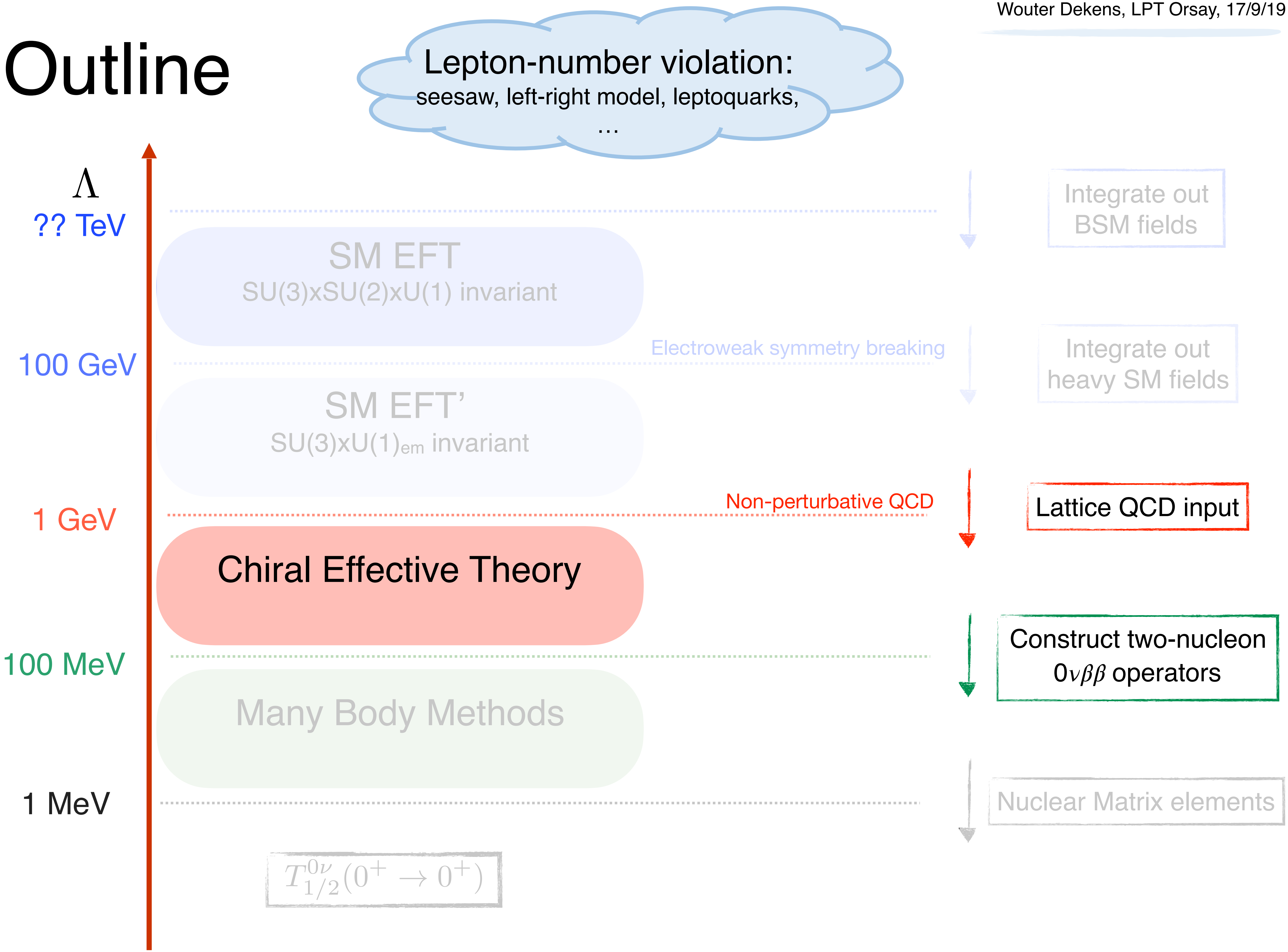


Chiral EFT

Beyond NDA / Weinberg



Outline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seesaw, left-right model, leptoquarks,
…
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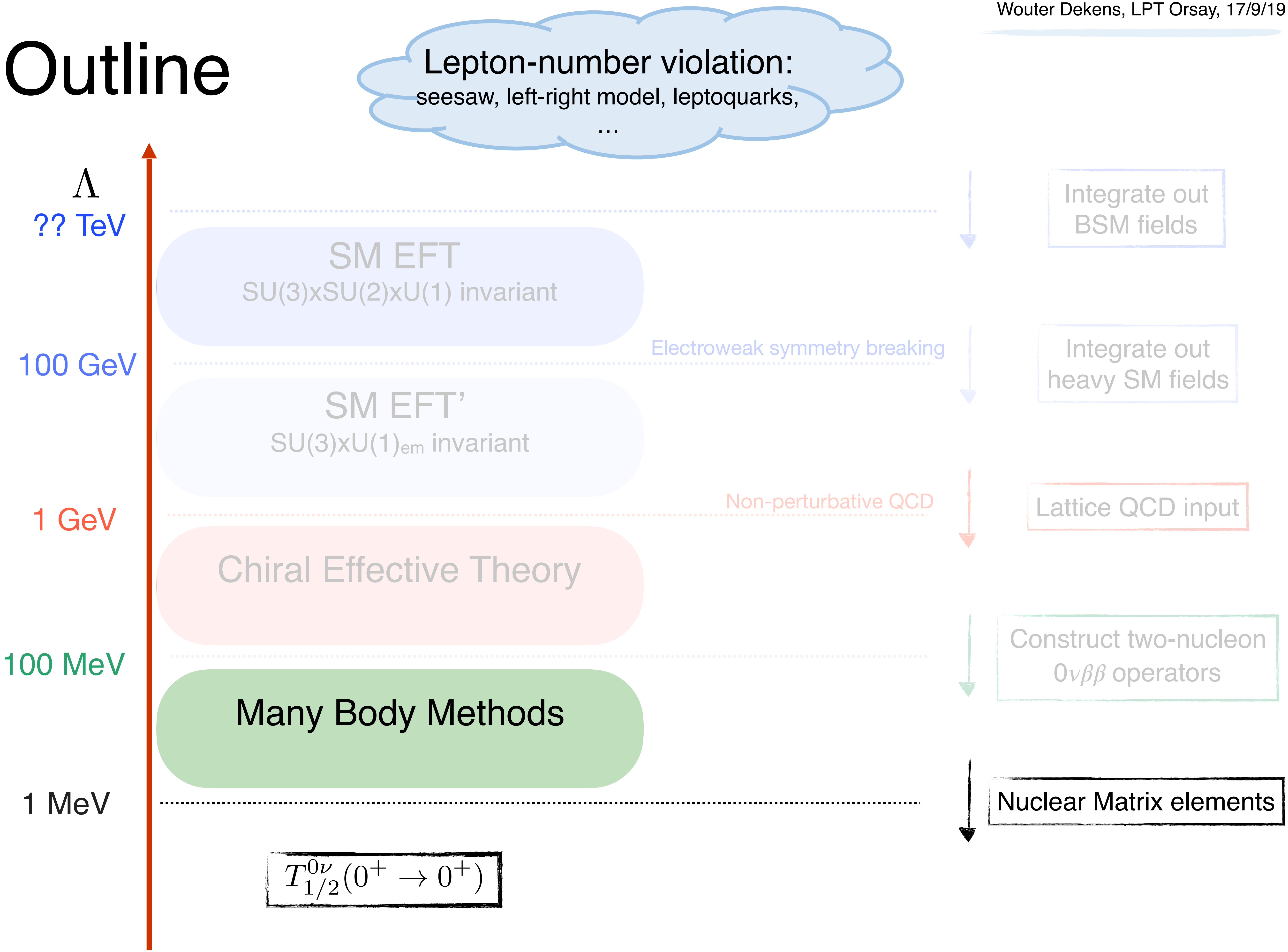
Chiral Effective Theory
Many Body Methods
$T^{0\nu}_{1/2}(0^+ \to 0^+)$
Integrate out BSM fields
Integrate out heavy SM fields
Lattice QCD input
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

Outline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$$\Gamma^{0\nu}(0^+ \to 0^+) \sim \left| \langle 0^+ | \sum_{\text{nucleons}} \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\, V(\boldsymbol{q}^2)\, |0^+\rangle \right|^2 = \sum_{i,j} G_{i,j} M_i M_j g_i g_j C_i C_j^*$$

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Nuclear matrix elements

- All NMEs can be obtained from those of light/heavy neutrino exchange
  - 9 long-distance & 6 short-distance
  - Have been determined in literature

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	-0.94	
M_{GT}^{PP}	0.66	0.33	0.30	
M_{GT}^{MM}	0.51	0.25	0.22	
M_T^{AA}	–	–	–	
M_T^{AP}	-0.35	0.01	-0.01	
M_T^{PP}	0.10	0.00	0.00	
M_T^{MM}	-0.04	0.00	0.00	

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$M_{F,\,sd}$	-3.46	-1.55	-1.46	-1.1
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$M_{T,\,sd}^{AP}$	-0.85	0.01	-0.05	-0.97
$M_{T,\,sd}^{PP}$	0.32	0.00	0.02	0.38

- Follow ChiPT expectations fairly well
  - E.g. all $O(1)$ and

$$M_{GT,sd}^{PP} = -\frac{1}{2}M_{GT,sd}^{AP} - M_{GT}^{PP}\,, \qquad M_{T,sd}^{PP} = -\frac{1}{2}M_{T,sd}^{AP} - M_T^{PP}\,,$$

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Barea et al. '15; Hyvarinen et al, '15; Horoi et al. '17, Menendez et al, '18

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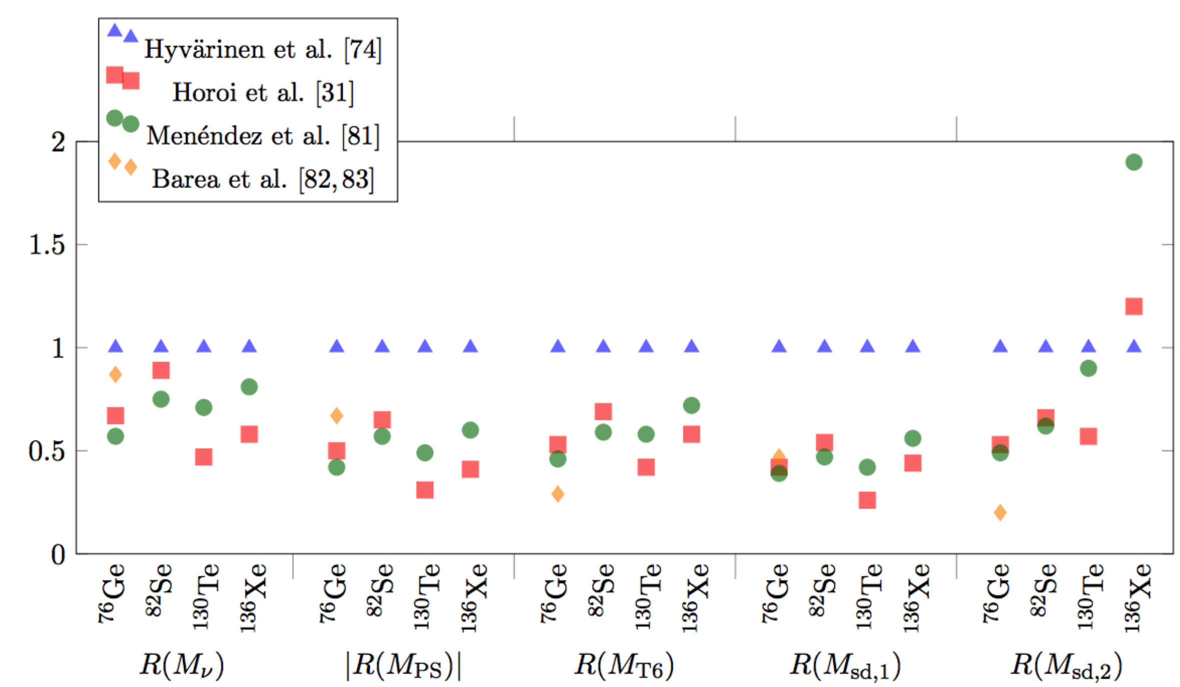
- The NMEs differ by a factor 2-3 between methods
  - For Majorana-mass term & other LNV sources



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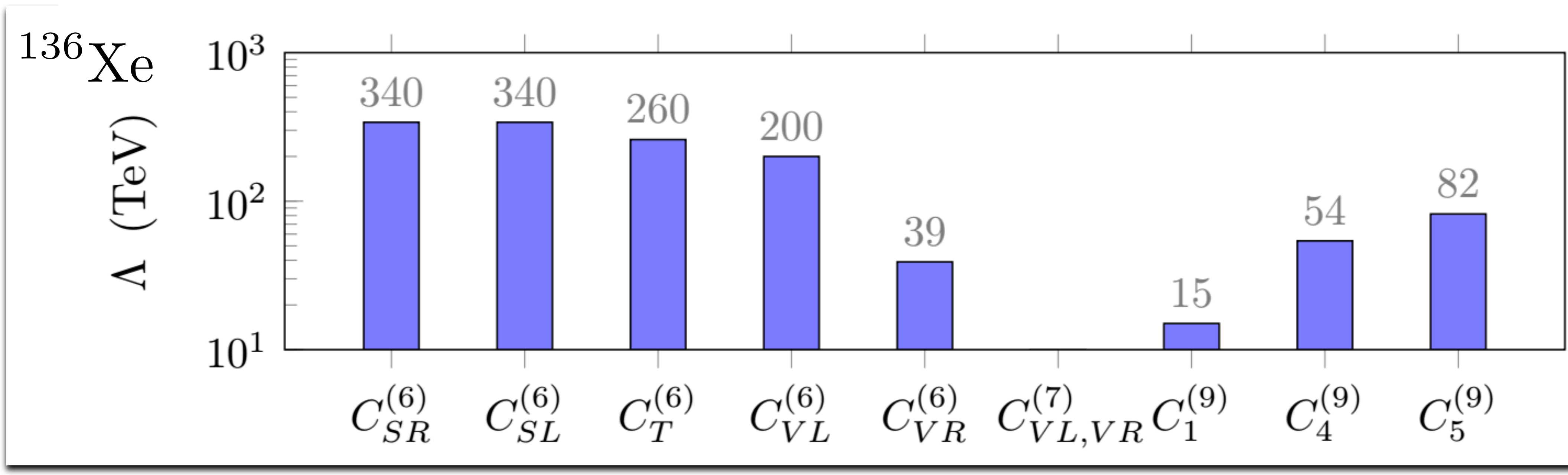
Phenomenology

Current limits

- Assumes $C_i = v^3/\Lambda^3$



- Uncertainties:
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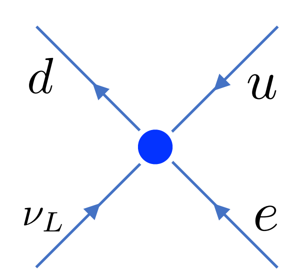
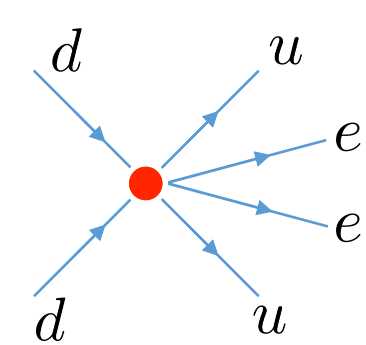
  - Nuclear Matrix elements



Dim 6 & 7



Dim 9

Current limits

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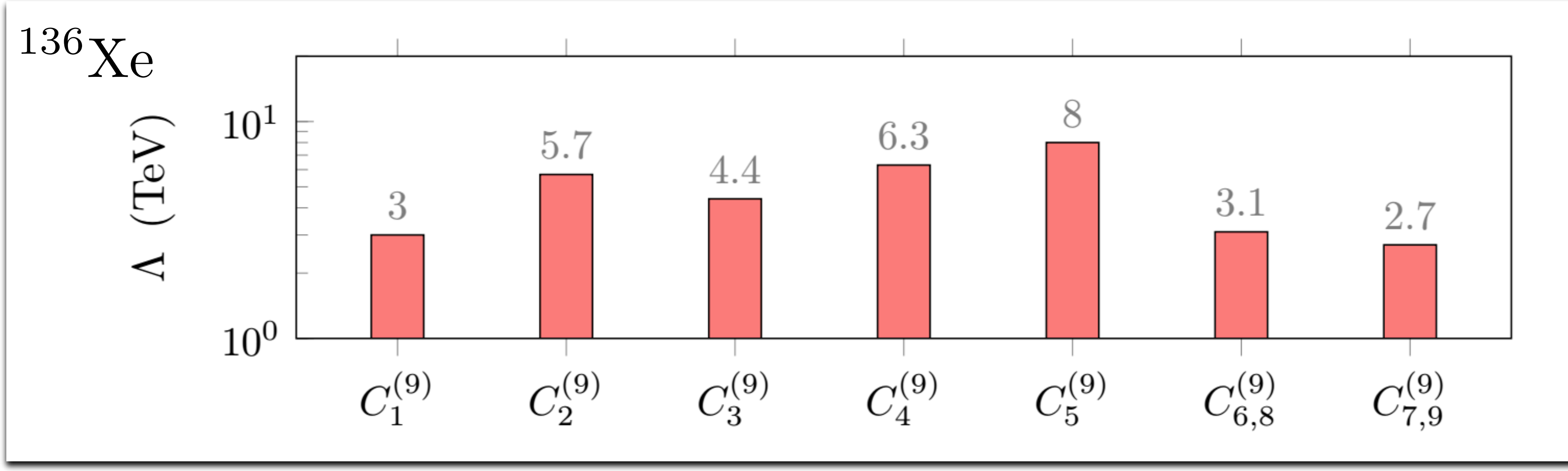

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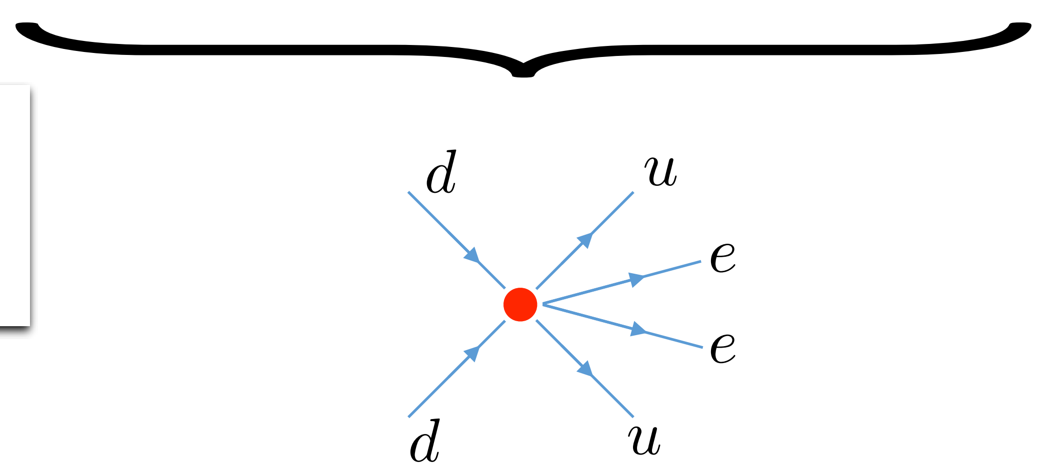
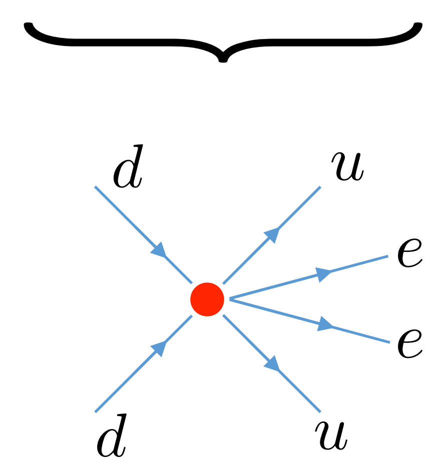


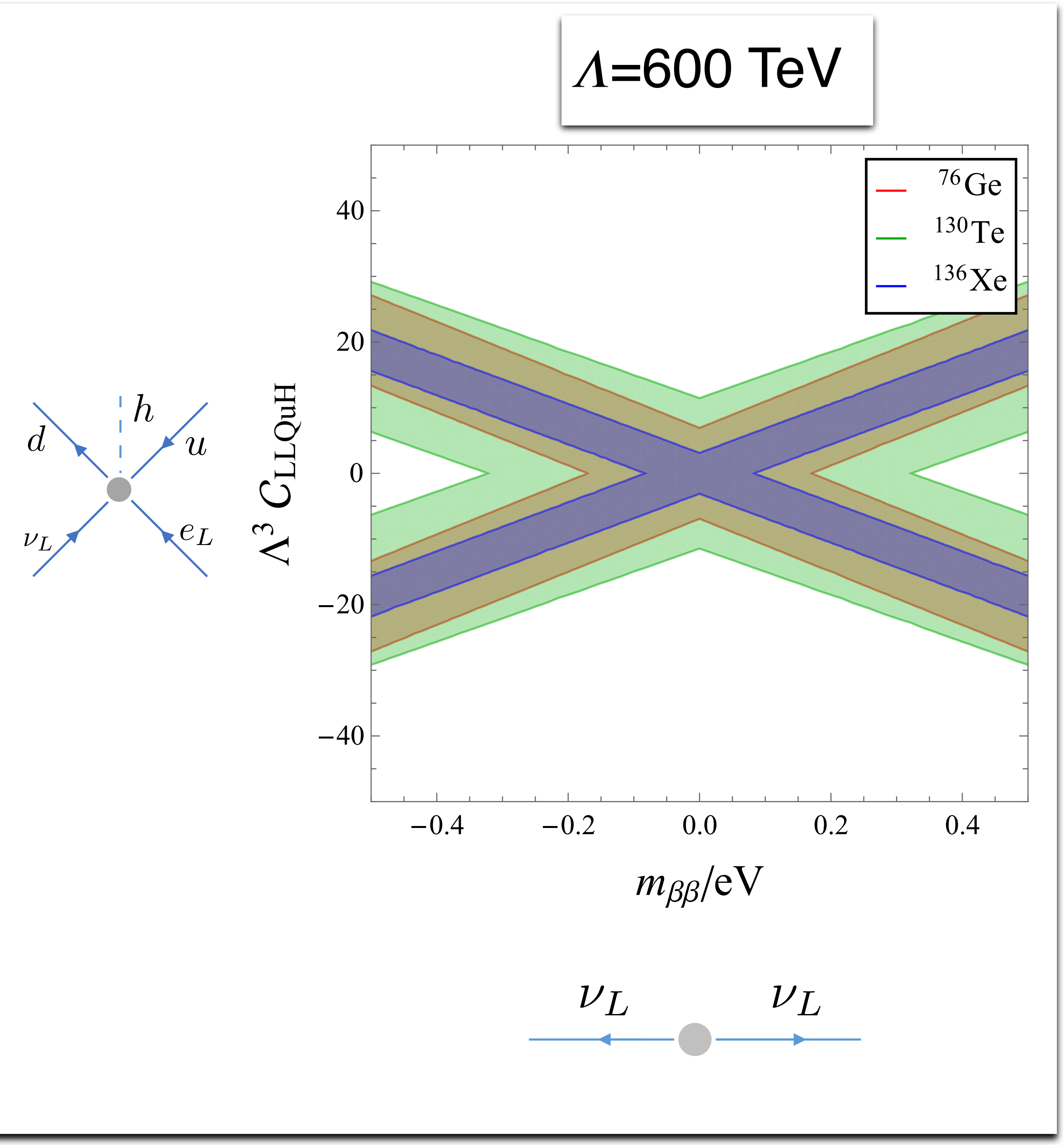
Dim 9 Scalar

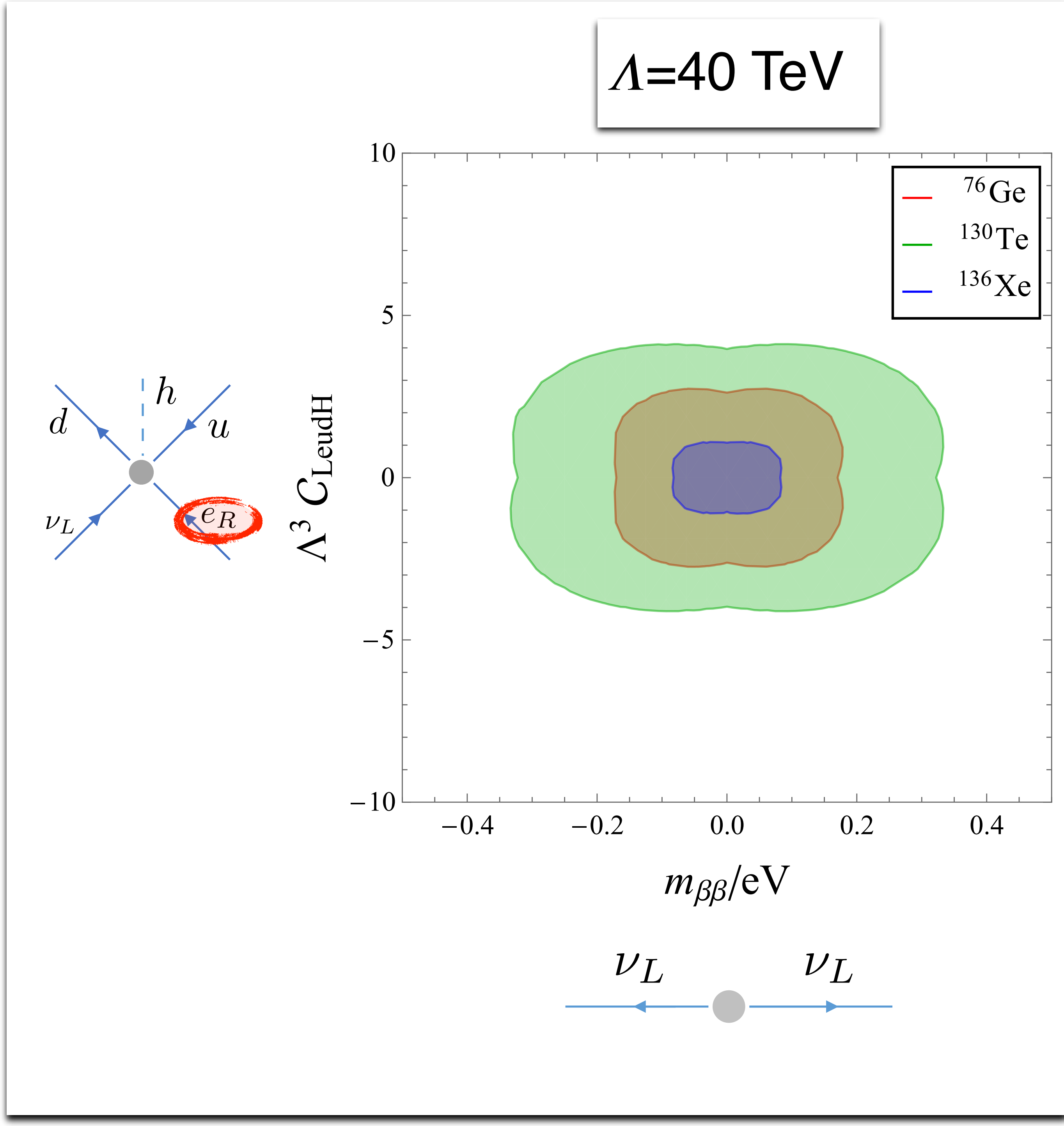


Dim 9 Vector

Current limits

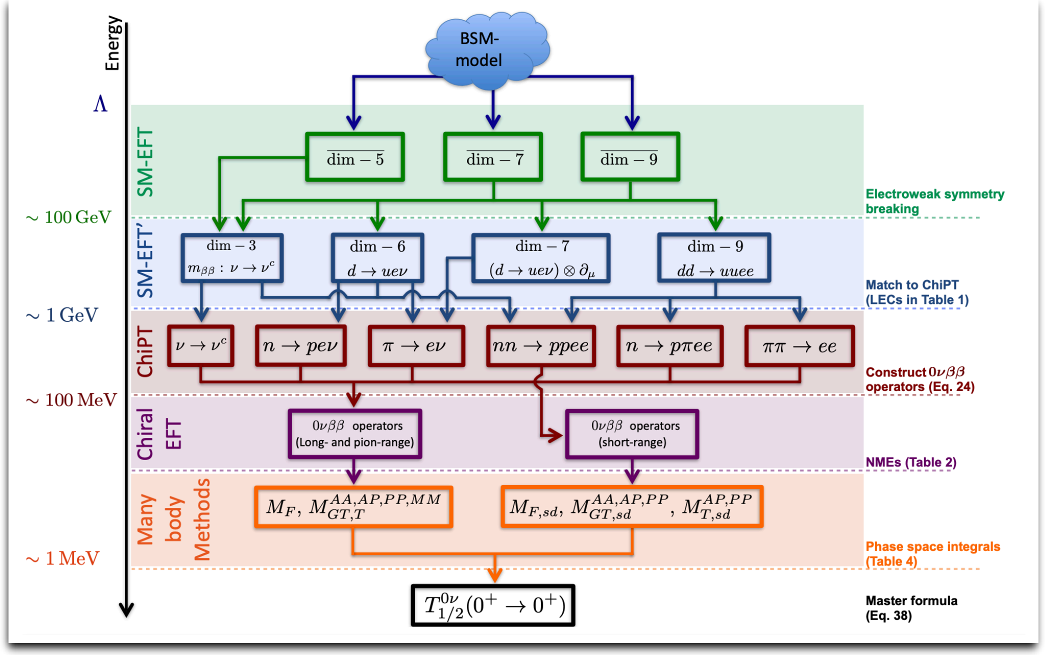
Two-coupling analysis





Summary

- EFTs allow one to systematically describe ΔL=2 sources



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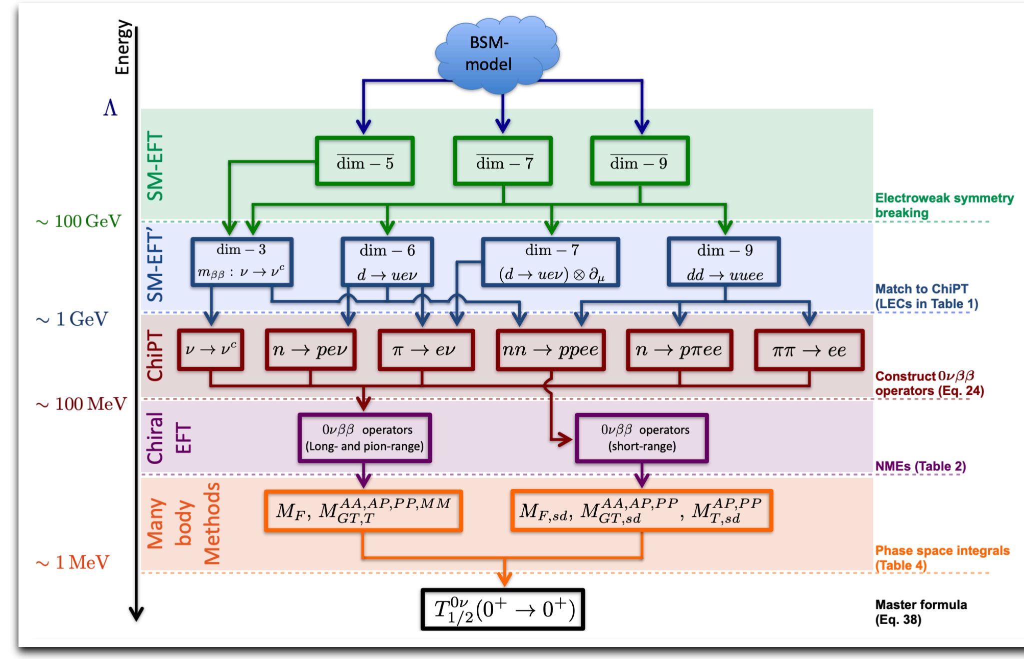
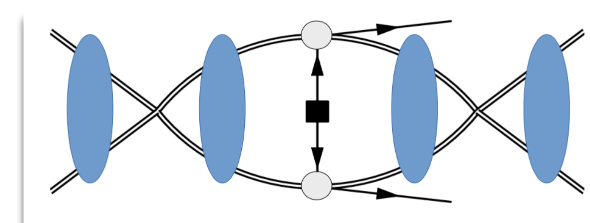
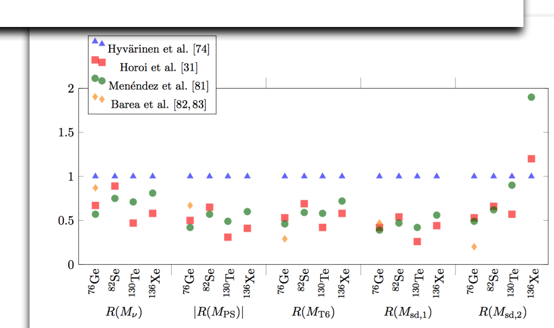


- Matching to chiral EFT involves unknown LECs
  - Several more required by renormalization
  - Can in principle be determined from LQCD
- Needed Nuclear Matrix Elements determined in literature





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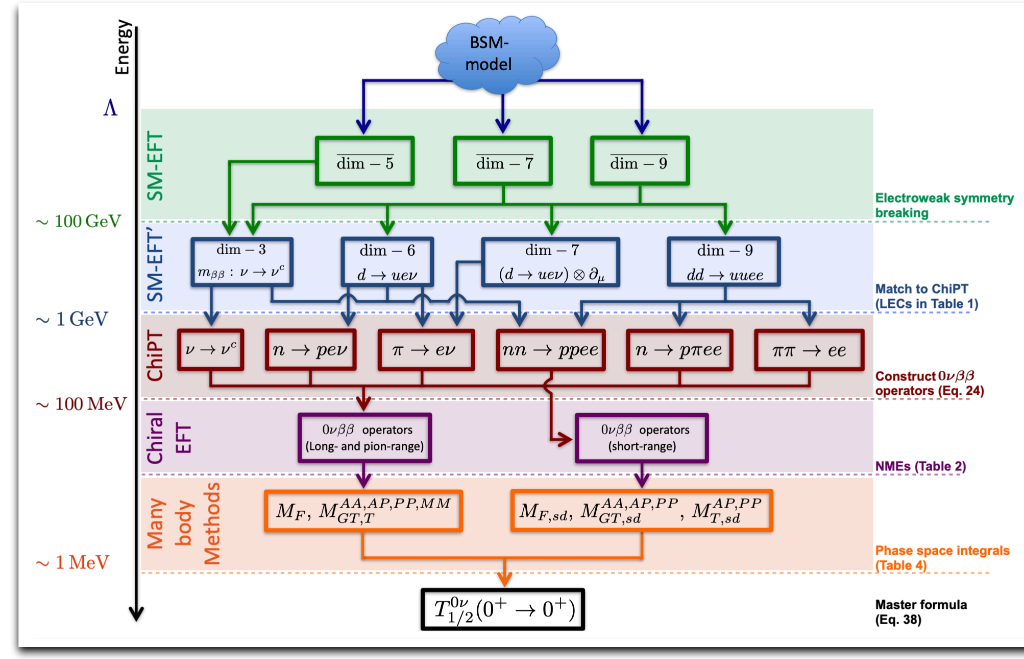

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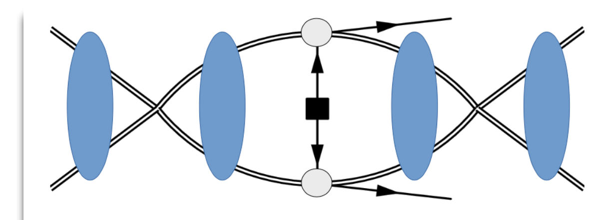

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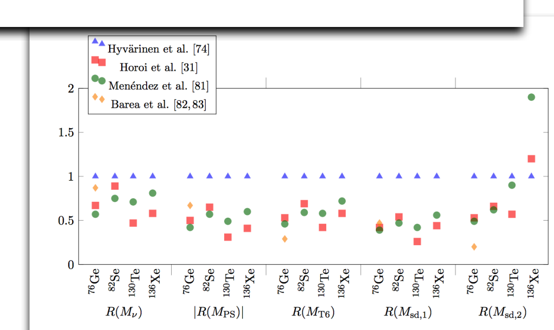
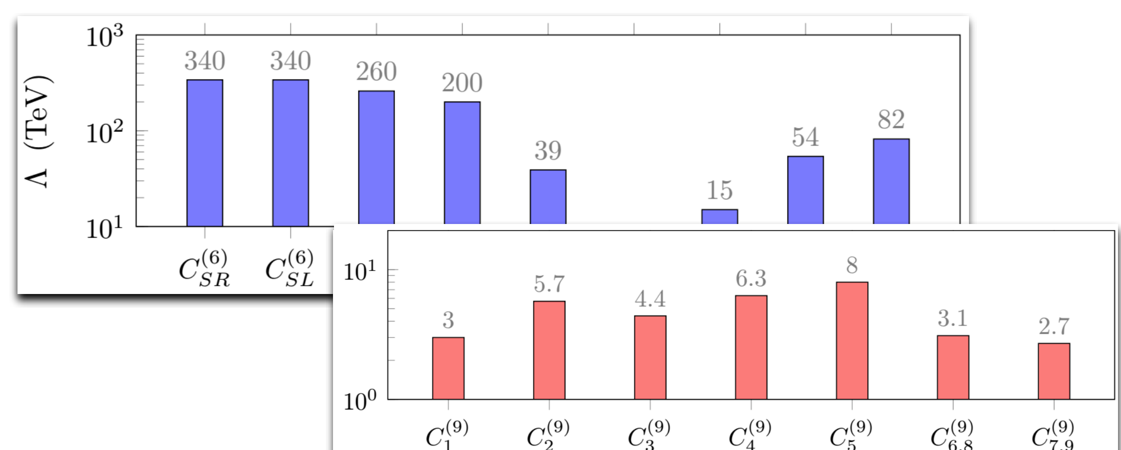


- Limits on higher-dimensional operators probe
  - O(1-10) TeV scales for dim-9
  - O(100) TeV scales for dim-7
- Order 1 uncertainties
  - Unknown LECs + NMEs

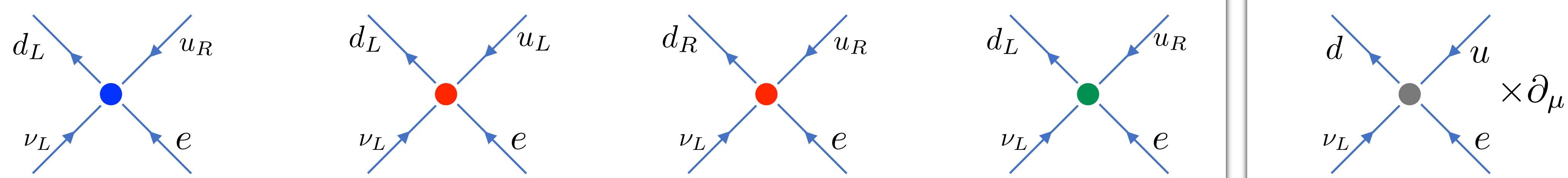


Back up slides

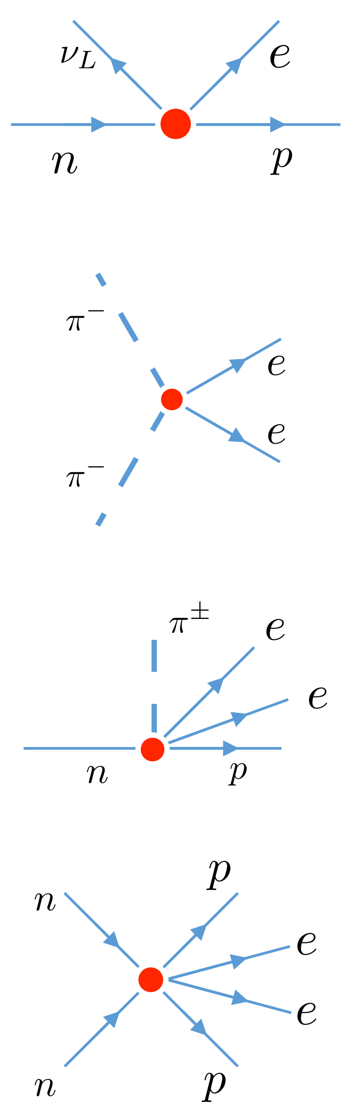
Low energy constants

LECs

Dimension 6				Dimension 7
$C^{(6)}_{SL,SR}$	$C^{(6)}_{VL}$	$C^{(6)}_{VR}$	$C^{(6)}_{T}$	$C^{(7)}_{VL,VR}$



Low energy constants



Quark condensate	Nucleon charges	Nucleon charges	Tensor charge NLO LEC	Quark condensate
			x1	
	x1		x1	
	x1	x2	x1	

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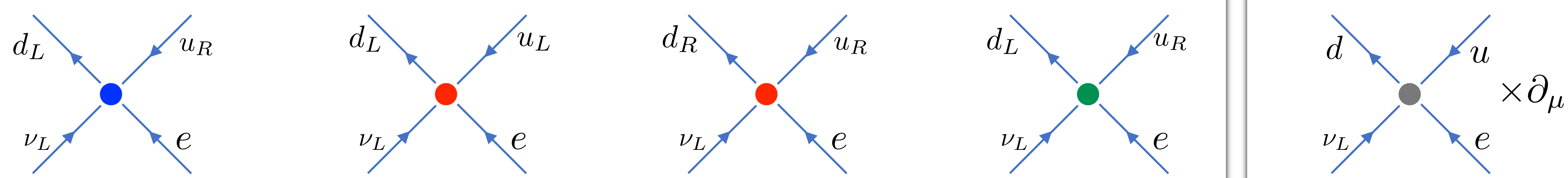
LECs

	Dimension 6				Dimension 7
	$C^{(6)}_{SL,SR}$	$C^{(6)}_{VL}$	$C^{(6)}_{VR}$	$C^{(6)}_{T}$	$C^{(7)}_{VL,VR}$



Low energy constants

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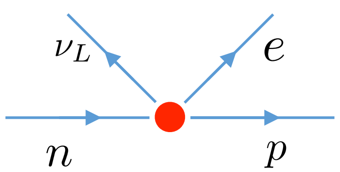
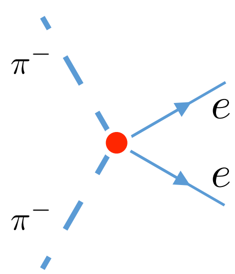
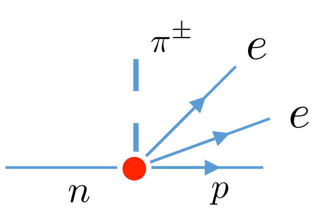
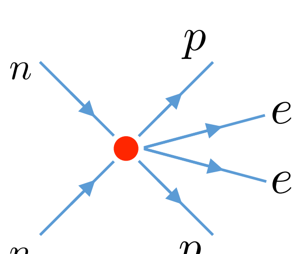
	Quark condensate ✓ LQCD	Nucleon charges ✓ expt	Nucleon charges ✓ expt	Tensor charge ✓ LQCD NLO LEC	Quark condensate ✓ LQCD
				x1	
		x1		x1	
		x1	x2	x1	

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LECs

Dimension 6				Dimension 7
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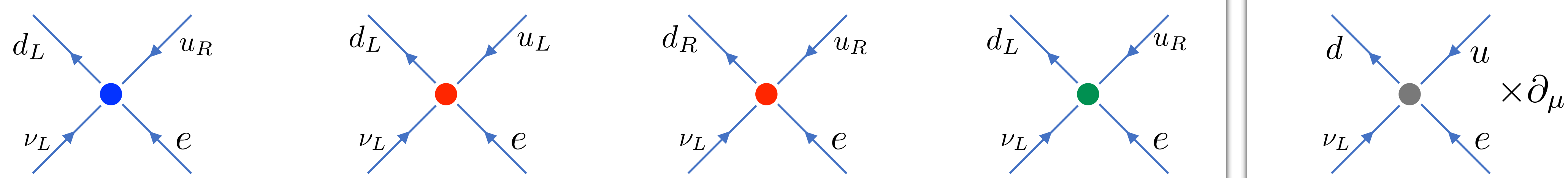

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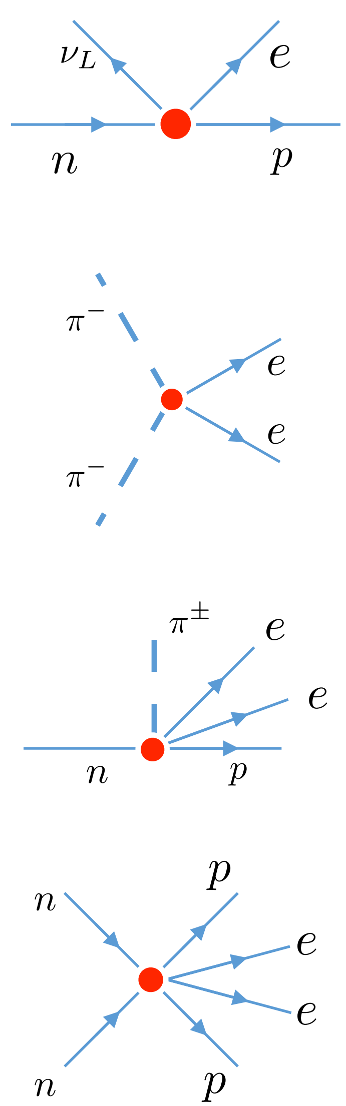

Low energy constants	$C^{(6)}_{SL,SR}$	$C^{(6)}_{VL}$	$C^{(6)}_{VR}$	$C^{(6)}_{T}$	$C^{(7)}_{VL,VR}$
$n \to p\, e\, \nu_L$	Quark condensate ✔ LQCD	Nucleon charges ✔ expt	Nucleon charges ✔ expt	Tensor charge ✔ LQCD; NLO LEC ✗	Quark condensate ✔ LQCD
$\pi^- \pi^- \to e\, e$				x1 ✗	
$n \to p\, \pi^\pm\, e\, e$		x1 ✗		x1 ✗	
$n\, n \to p\, p\, e\, e$		x1 ✗	x2 ✗	x1 ✗	

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LECs

	Dimension 6				Dimension 7
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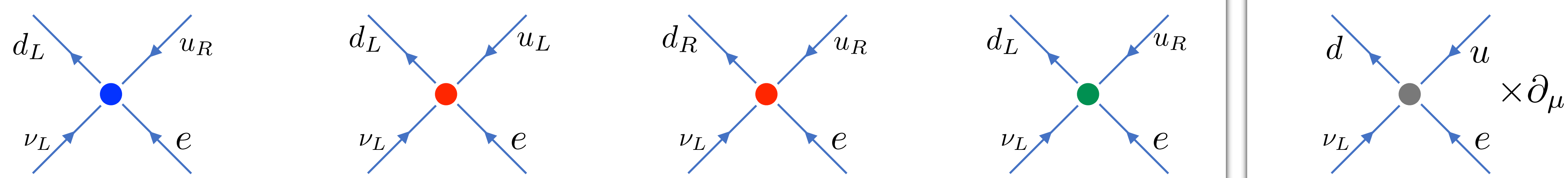
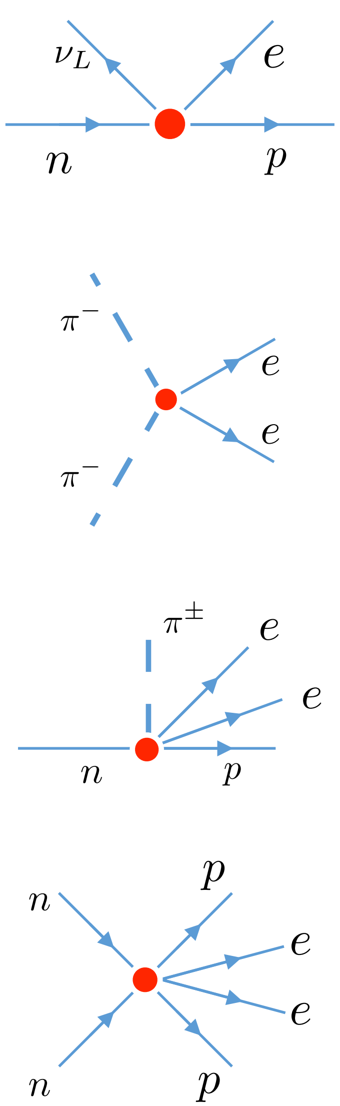


Low energy constants



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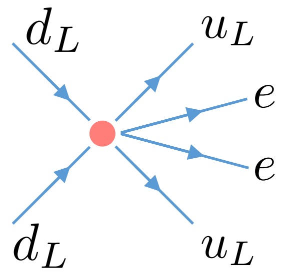
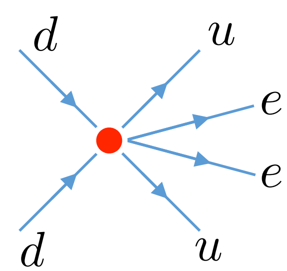
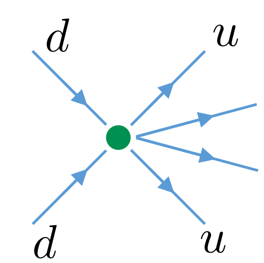
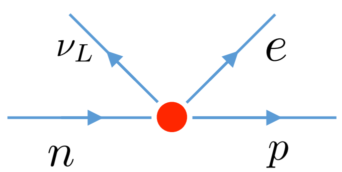
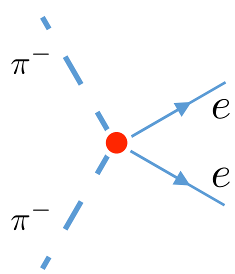
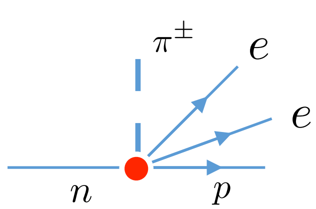
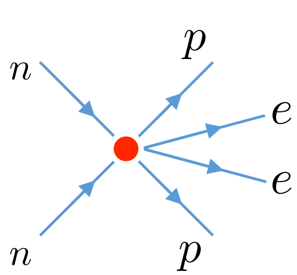
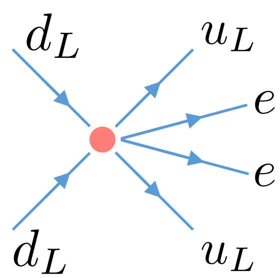
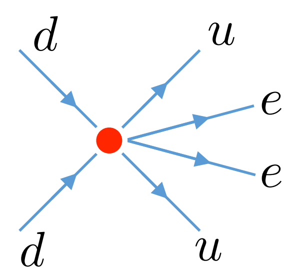
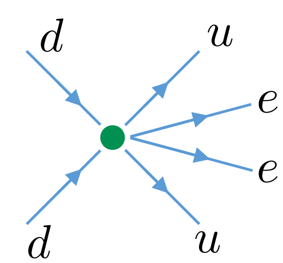
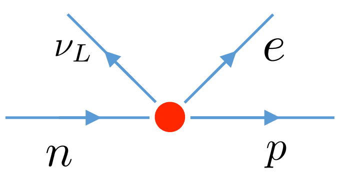
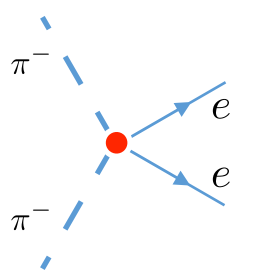
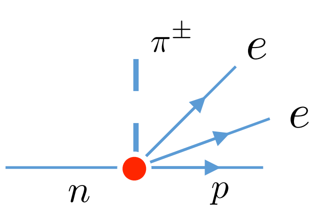
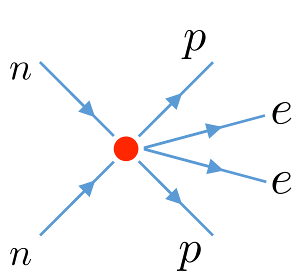
$\pi^- \pi^- e\, e$				x1 ✗	
$\pi^\pm n\, p\, e\, e$		x1 ✗		x1 ✗	
$n\, n\, p\, p\, e\, e$		x1 ✗	Non-NDA x2 ✗	x1 ✗	

LECs

Low energy constants	Dimension 9 - scalar: $C^{(9)}_{1L,1R}$	Dimension 9 - scalar: $C^{(9)}_{2,3,4,5}$	Dimension 9 - vector: $C^{(9)}_{6,7,8,9}$
			
			
	x1	x4	
	x1		x2
	x1	x4	x2

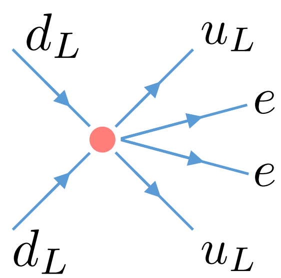
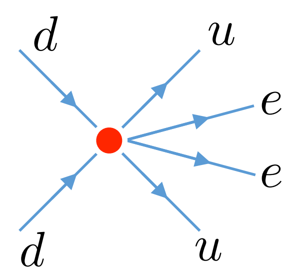
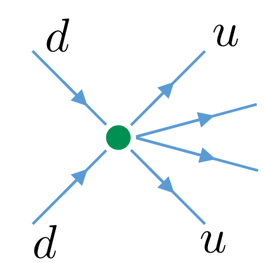
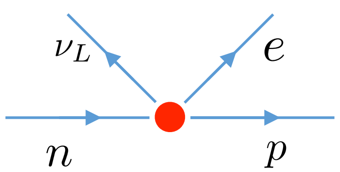
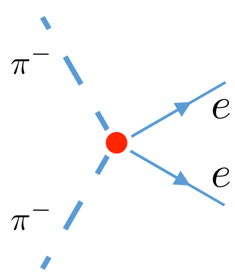
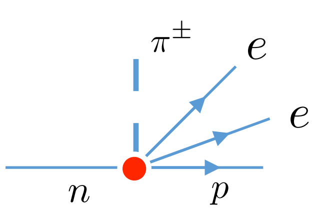
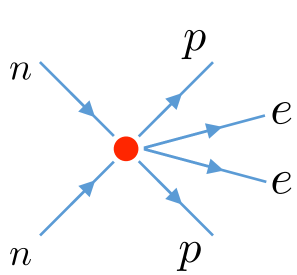
LECs

Low energy constants	Dimension 9 - scalar: $C^{(9)}_{1L,1R}$ 	Dimension 9 - scalar: $C^{(9)}_{2,3,4,5}$ 	Dimension 9 - vector: $C^{(9)}_{6,7,8,9}$ 
			
	x1 ✔ LQCD	x4 ✔ LQCD	
	x1		x2
	x1	x4	x2

Nicholson et al.'18

Wouter Dekens, LPT Orsay, 17/9/19

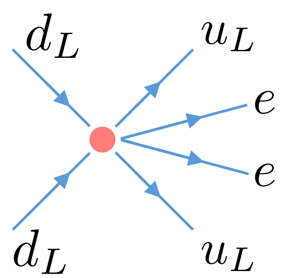
LECs

<table>
<tr><th>Low energy constants</th><th colspan="2">Dimension 9 - scalar</th><th>Dimension 9 - vector</th></tr>
<tr><td></td><td>$C^{(9)}_{1L,1R}$
</td><td>$C^{(9)}_{2,3,4,5}$
</td><td>$C^{(9)}_{6,7,8,9}$
</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>x1 ✓ LQCD</td><td>x4 ✓ LQCD</td><td></td></tr>
<tr><td></td><td>x1 ✗</td><td></td><td>x2 ✗</td></tr>
<tr><td></td><td>x1 ✗</td><td>x4 ✗</td><td>x2 ✗</td></tr>
</table>

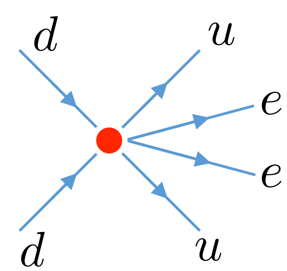
LECs

Dimension 9 - scalar

$C^{(9)}_{1L,1R}$



$C^{(9)}_{2,3,4,5}$



Dimension 9 - vector

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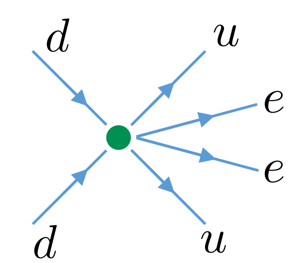
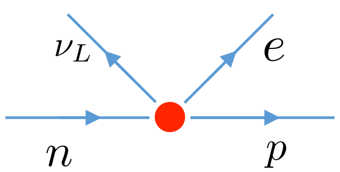
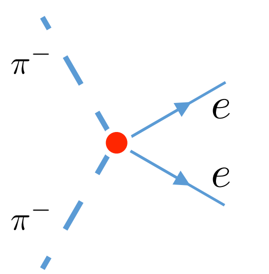
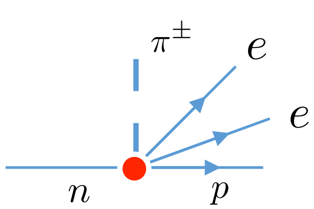
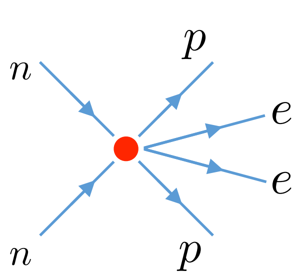


Low energy constants









Low energy constants	$C^{(9)}_{1L,1R}$ (scalar)	$C^{(9)}_{2,3,4,5}$ (scalar)	$C^{(9)}_{6,7,8,9}$ (vector)
$n \to p\, e\, \nu_L$			
$\pi^- \pi^- \to e\, e$	x1 ✓ LQCD	x4 ✓ LQCD	
$\pi^\pm\, n \to p\, e\, e$	x1 ✗		x2 ✗
$n\, n \to p\, p\, e\, e$	x1 ✗	x4 ✗ (Non-NDA)	x2 ✗

Disentangling operators

Disentangling operators

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

- Measurement in a single isotope could be due to any operator
- Could measure the rate in several nuclei, however
  - Different isotopes have similar sensitivity to LNV

Disentangling operators

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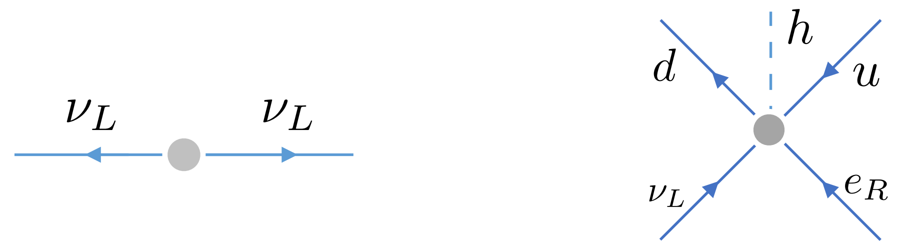
- Instead look at angular & energy distributions of the

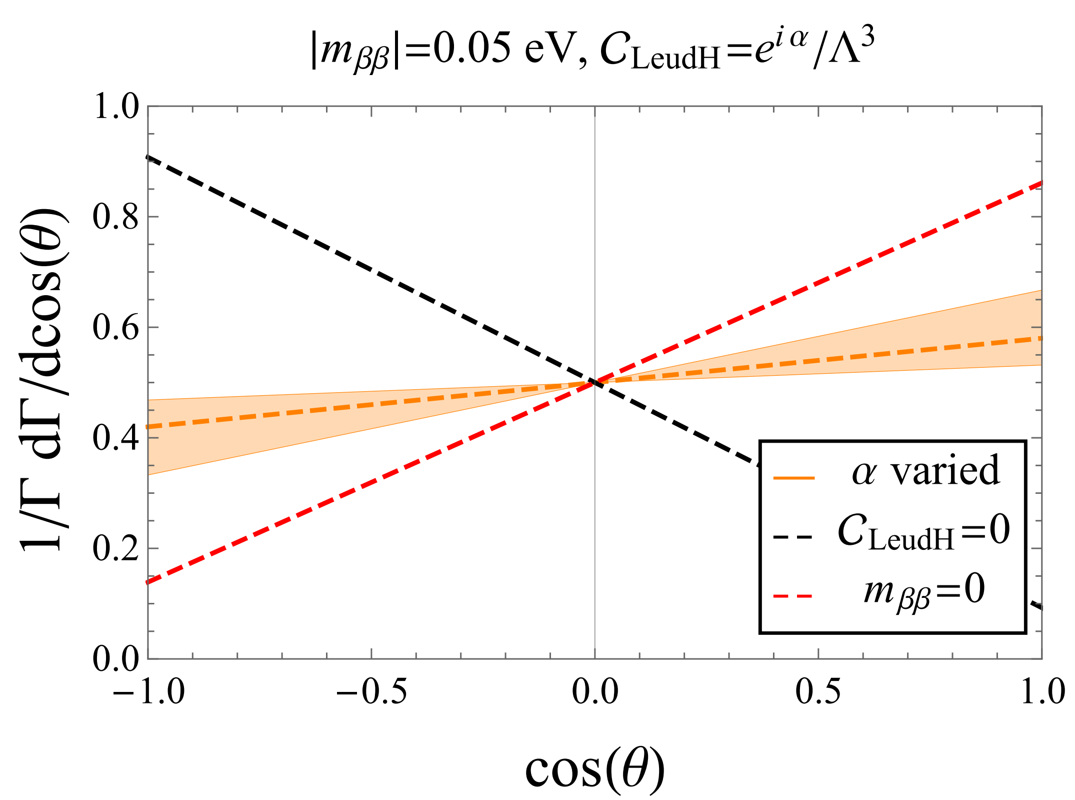
Disentangling operators

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

- Picking the allowed values



$m_{\beta\beta} = 0.05\,\text{eV}$ $\quad \mathcal{C}_{\text{LeudH}} = e^{i\alpha}/\Lambda^3 \quad \Lambda = 40\,\text{TeV}$



Disentangling operators

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

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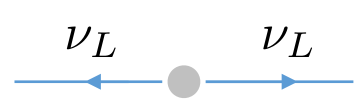

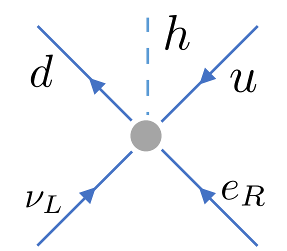

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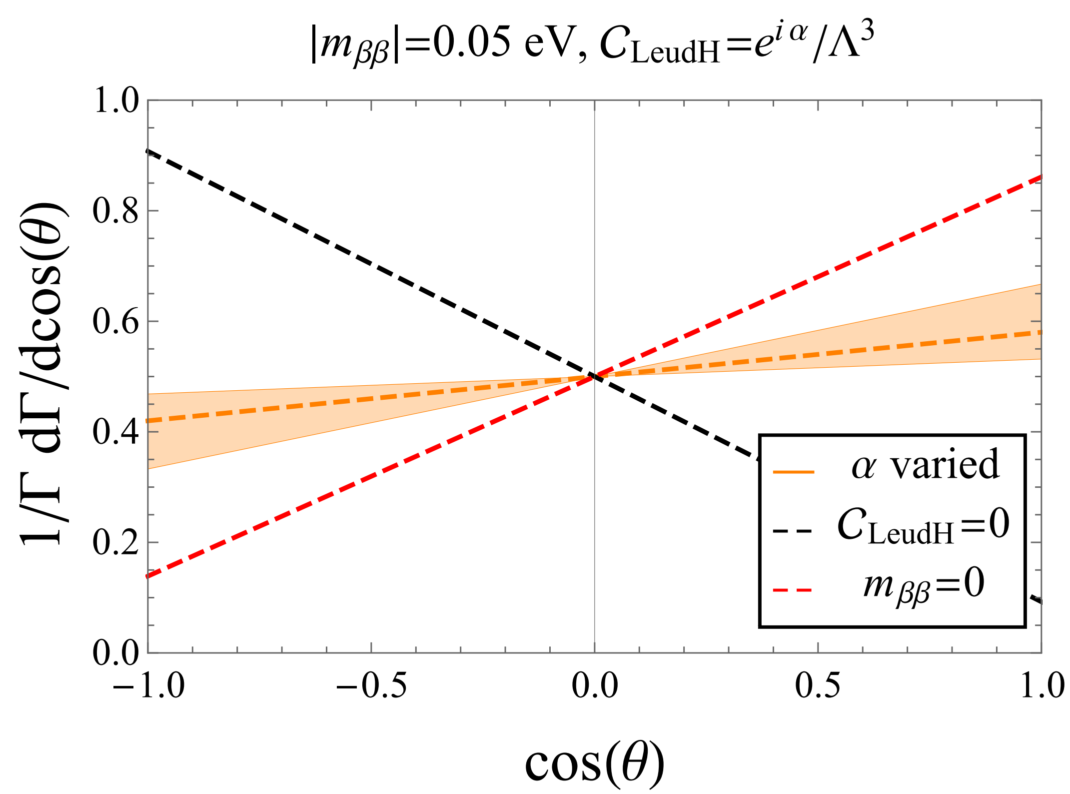

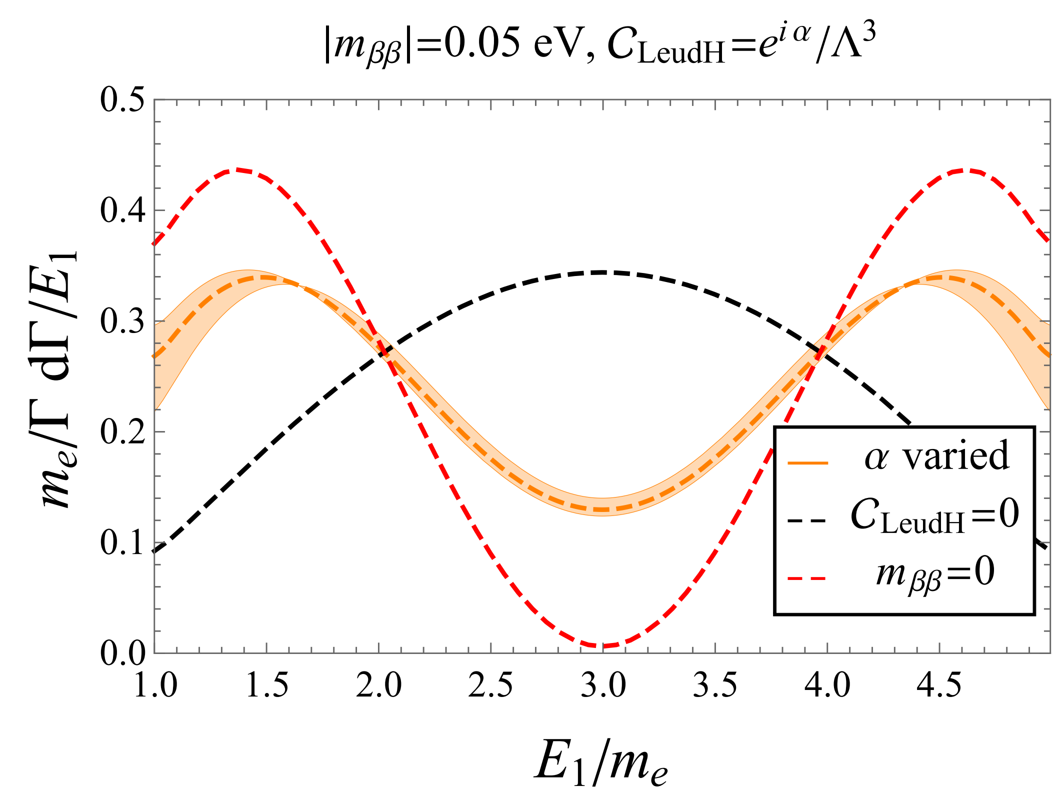

Why keep Dimension 7 and 9?

Effective Field Theory

Naive scaling of Dimension 5, 7, 9 operators

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

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

Chiral scalings

Chiral EFT

The potential

Can finally derive the potential and amplitude

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

The contributions scale as

	d=3	$C^{(6)}_{\mathrm{SL,\,SR}}$	$C^{(6)}_{\mathrm{T}}$	$C^{(6)}_{\mathrm{VL}}$	$C^{(6)}_{\mathrm{VR}}$	$C^{(7)}_{\mathrm{VL,\,VR}}$	$C^{(9)\,(\prime)}_{\mathrm{1R}}$	$C^{(9)(\prime)}_{\mathrm{1L}}$	$C^{(9)(\prime)}_{\mathrm{2R-5R}}$	$C^{(9)(\prime)}_{\mathrm{2L-5L}}$	$C^{(9)}_{\mathrm{vector}}$
$m_e\mathcal{A}$	$m_{\beta\beta}$	Λ_χ	$\Lambda_\chi\epsilon_\chi^2$	$\Lambda_\chi\epsilon_\chi^2$	$\Lambda_\chi\epsilon_\chi^3$	$\frac{\Lambda_\chi^2}{v}\,\epsilon_\chi^2$	$\frac{\Lambda_\chi^2}{v}\,\epsilon_\chi^2$	$\frac{\Lambda_\chi^2}{v}\,\epsilon_\chi^2$	$\frac{\Lambda_\chi^2}{v}$	$\frac{\Lambda_\chi^2}{v}$	$\frac{\Lambda_\chi^2}{v}\,\epsilon_\chi^2$

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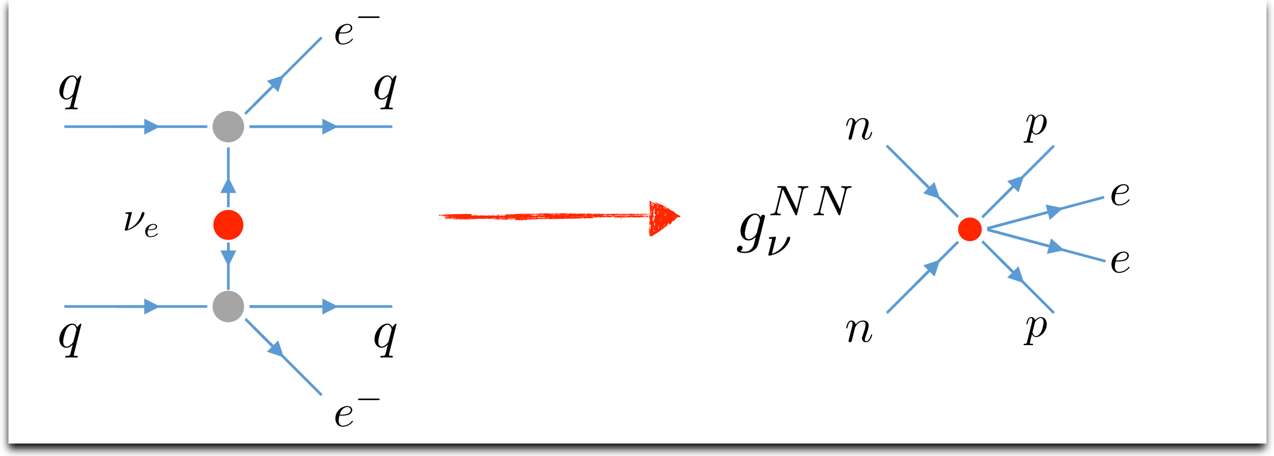
- Several operators are suppressed by two or three powers of $\epsilon_\chi = m_\pi/\Lambda_\chi$

- Scaling of Wilson coefficients needed to see which are important
  - To be determined in explicit models of new physics

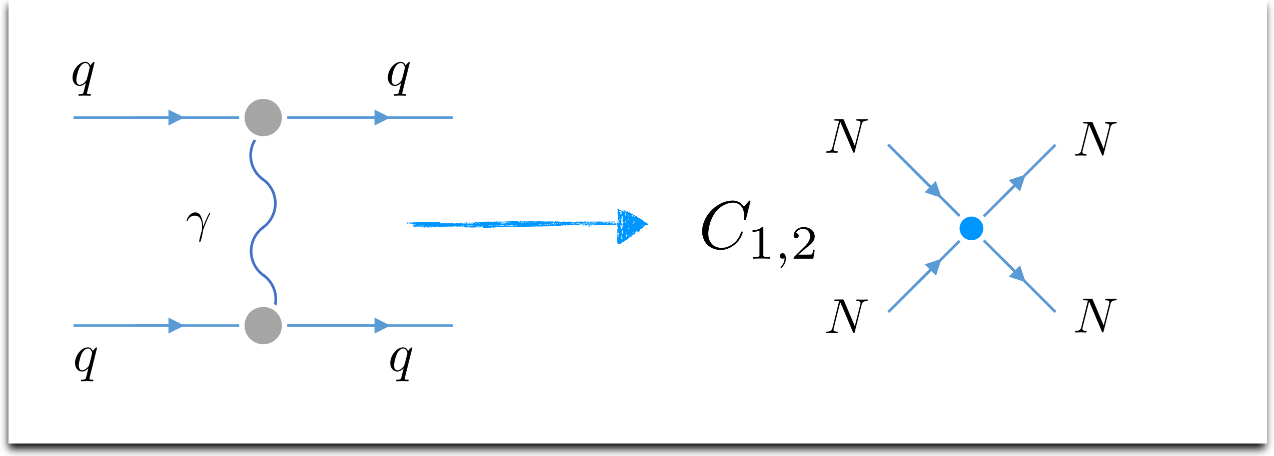
Relation to electromagnetism

Relation to electromagnetism

LNV contact term



EM contact term



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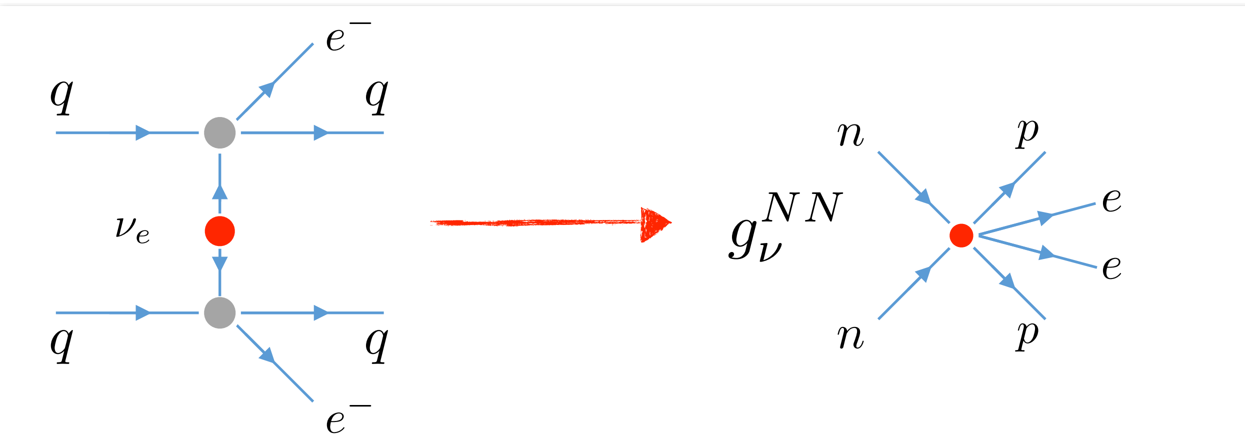

- Hard part of two Weak currents

$$\sim G_F^2 m_{\beta\beta} \langle NN | J_L^\mu(x) J_{L\,\mu}(y) | NN \rangle$$
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- Leptonic part combines to boson propagator

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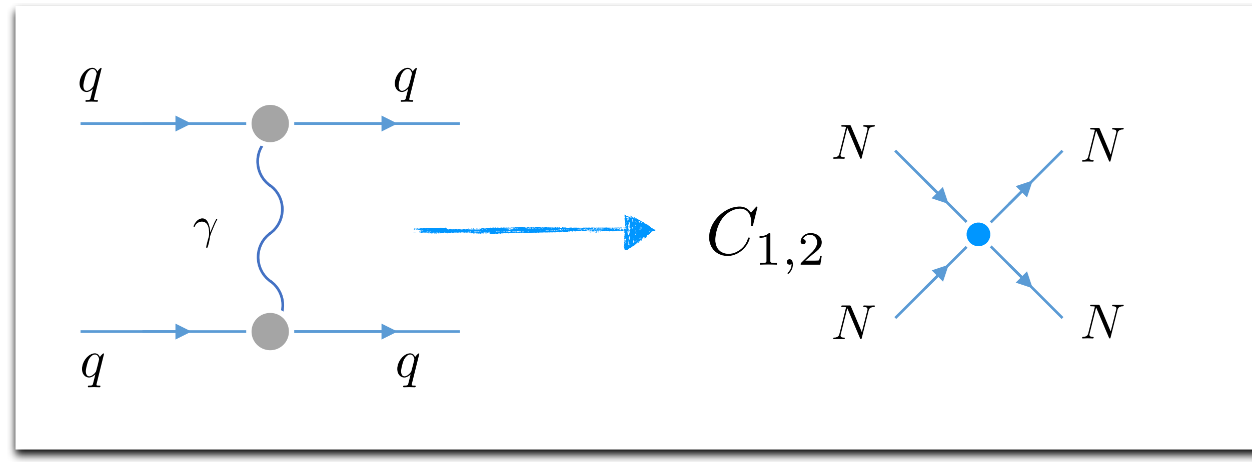

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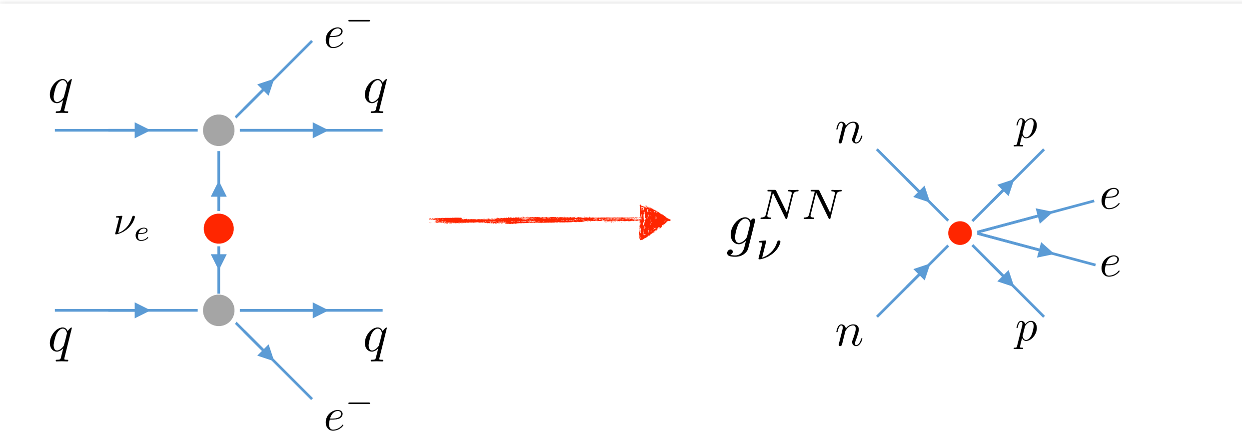

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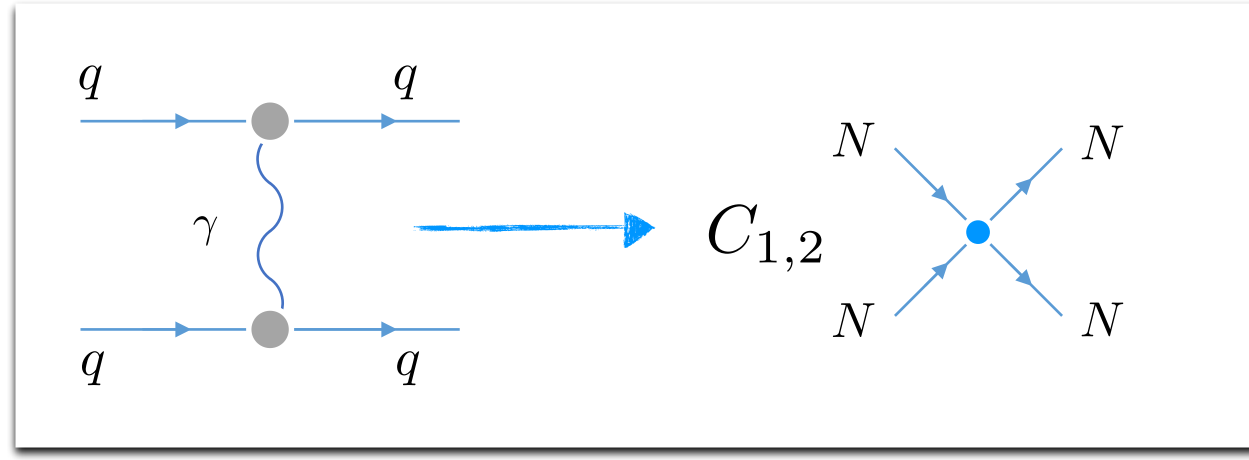

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- Non-hadronic part is the photon propagator

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

Relation to electromagnetism

- Only two ΔI=2 operators can be induced

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

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with spurions

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

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

LNV

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

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

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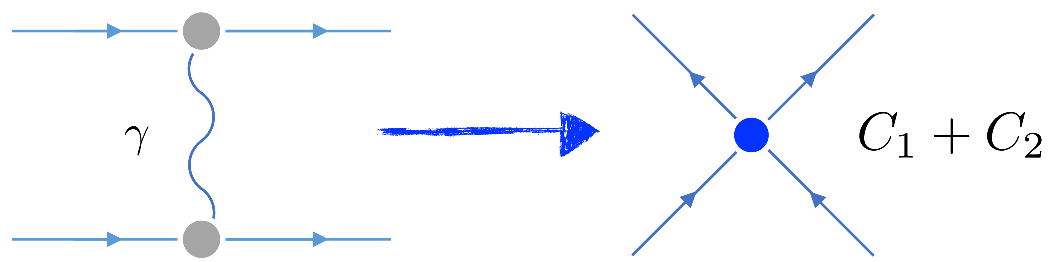
Relation to electromagnetism

- 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)



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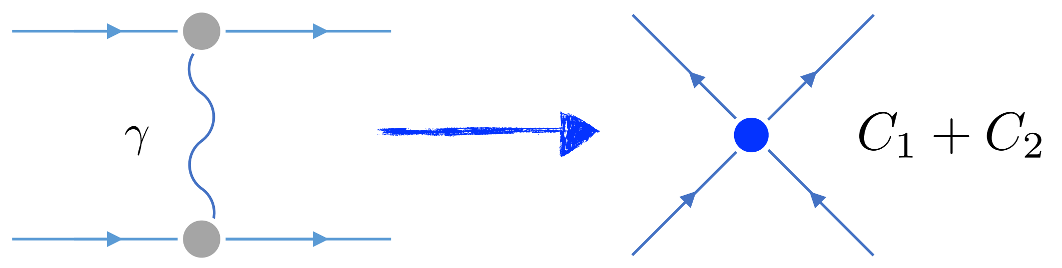

- Allows an estimate of g_ν^{NN}
  - Extract $C_1 + C_2$ from CIB
  - Assume $g_\nu^{NN}(\mu) = \frac{C_1(\mu) + C_2(\mu)}{2}$
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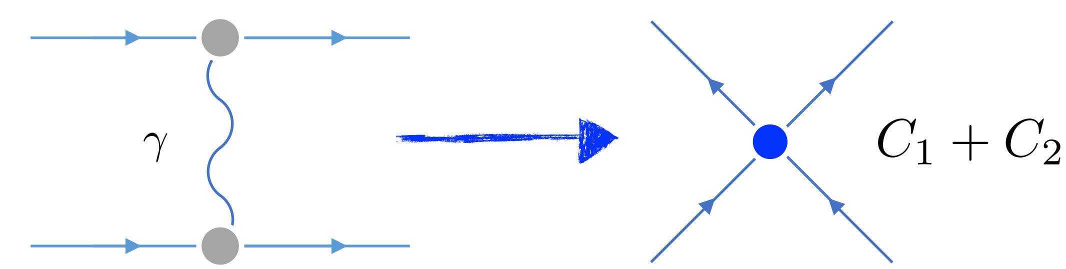

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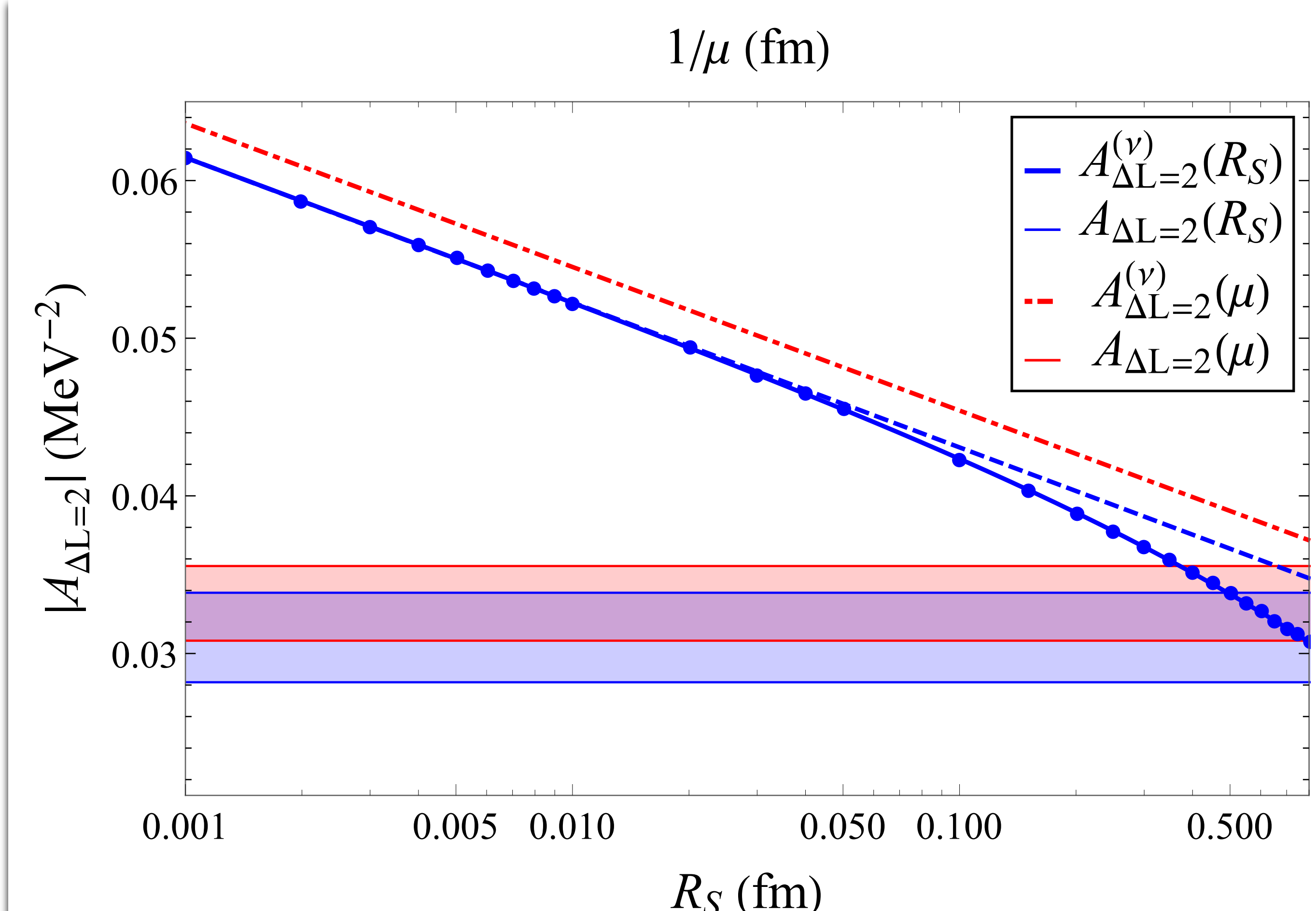

Estimate of impact in light nuclei

Estimate of impact
Light nuclei

M. Piarulli, R. Wiringa, S. Pastore

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- With wavefunctions:
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    M. Piarulli et. al. '16
  - Obtained from AV18 potential
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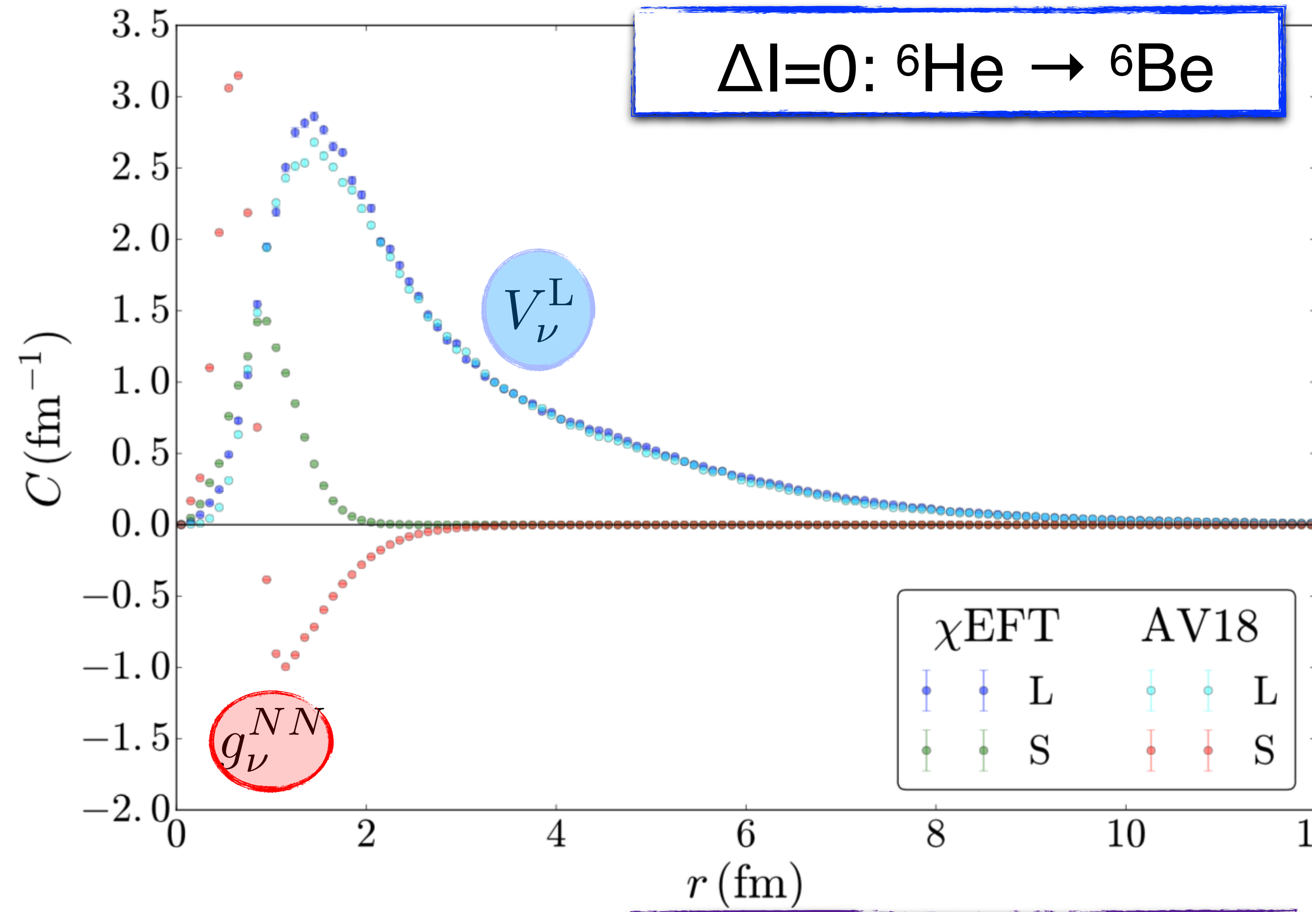

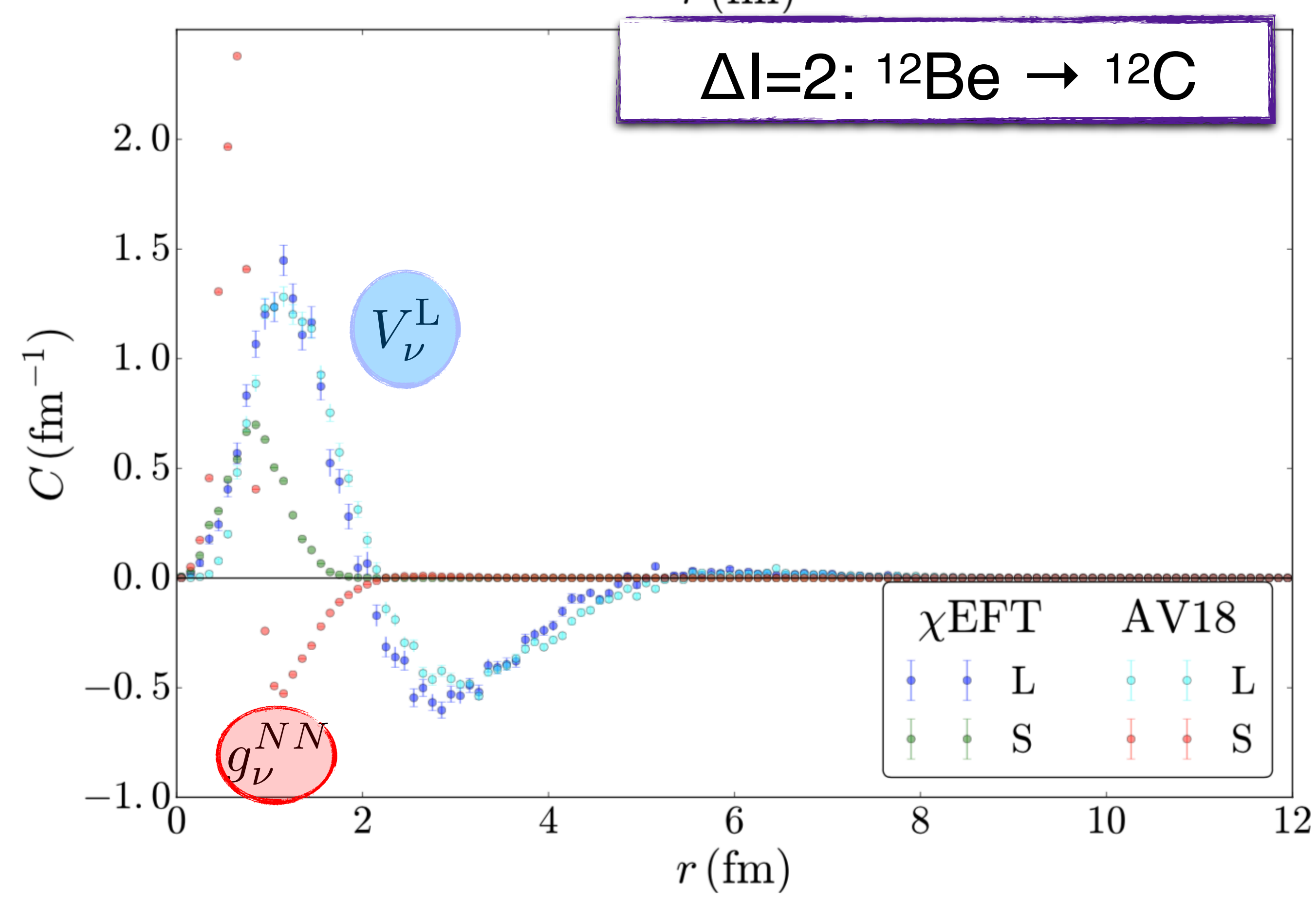

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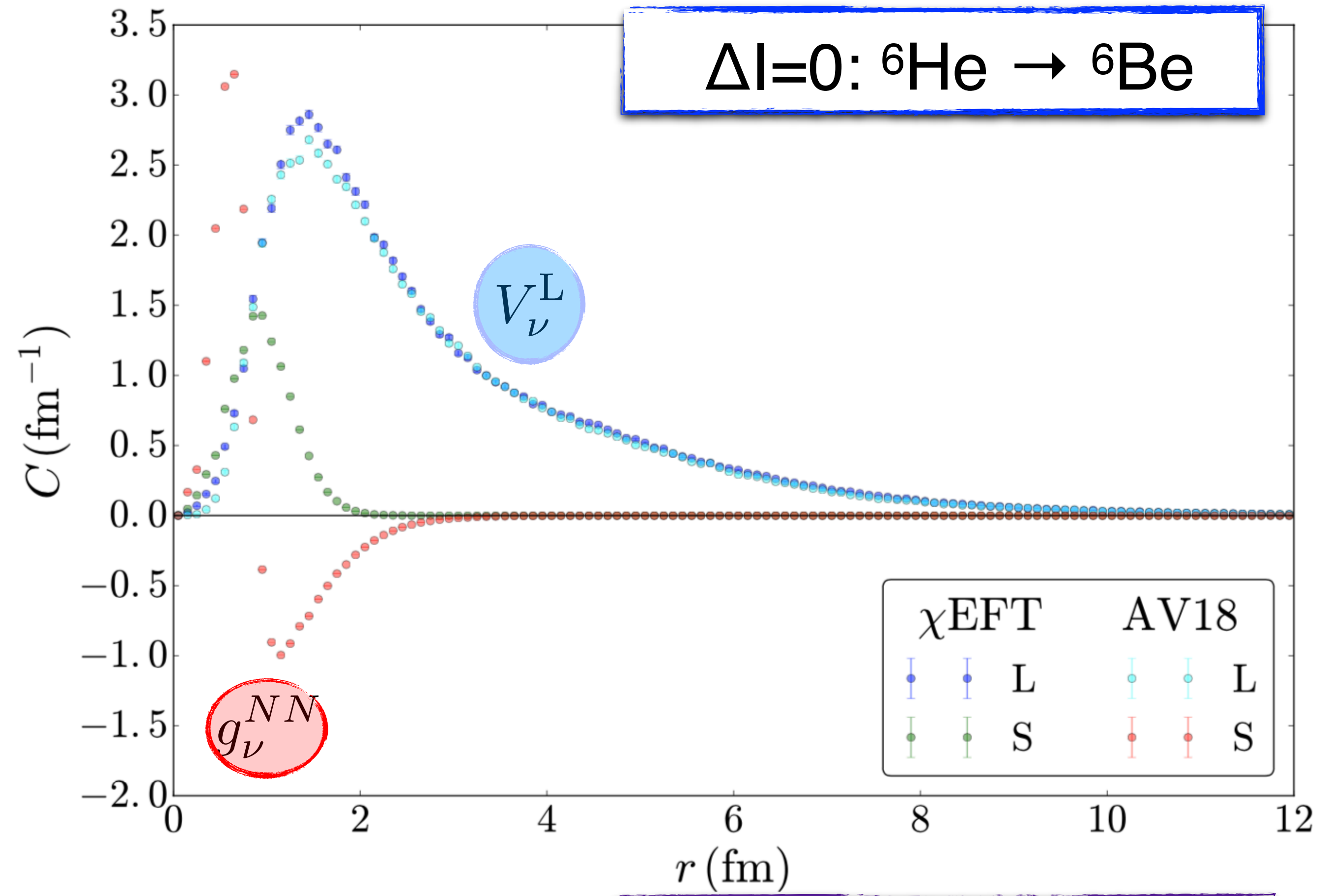

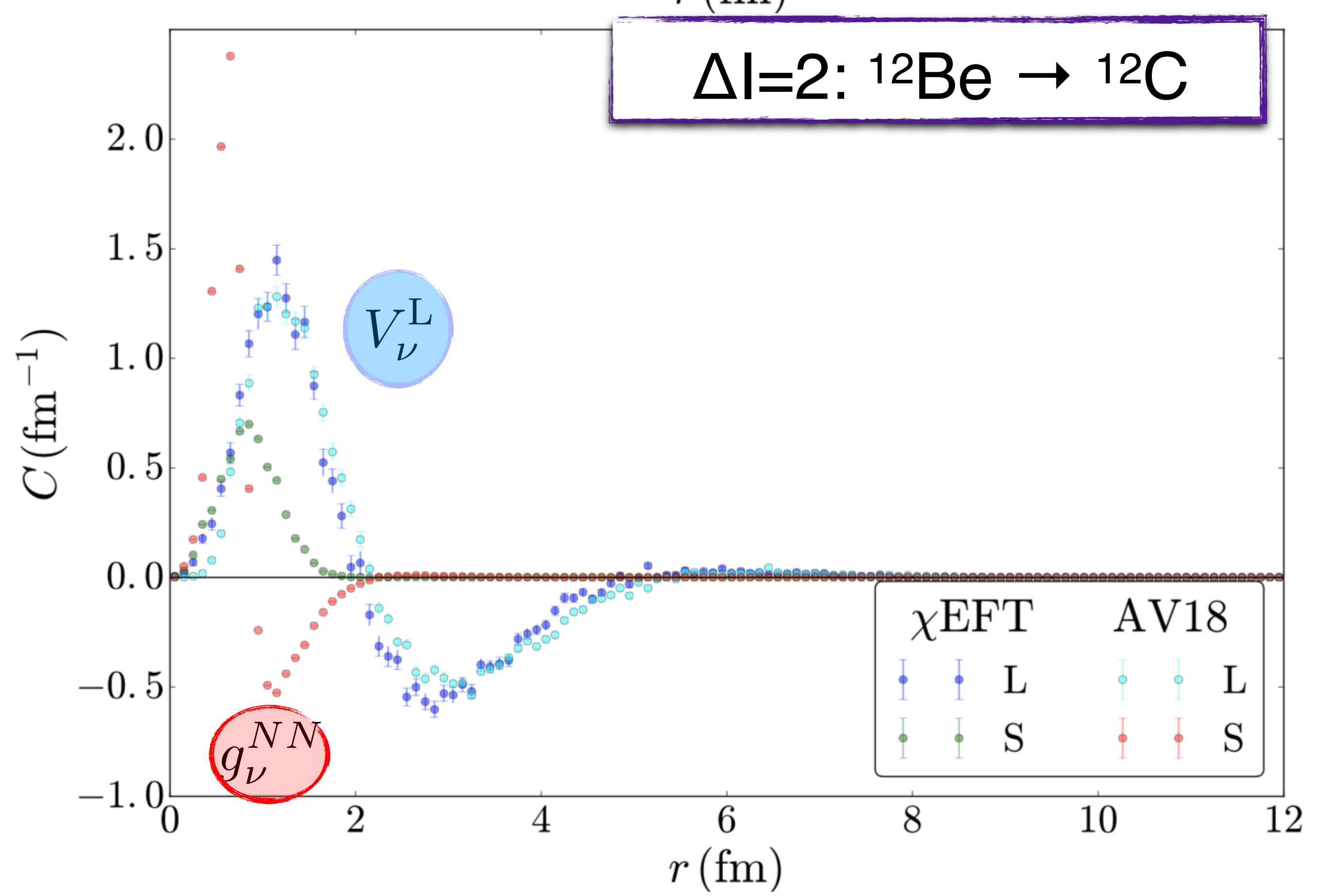

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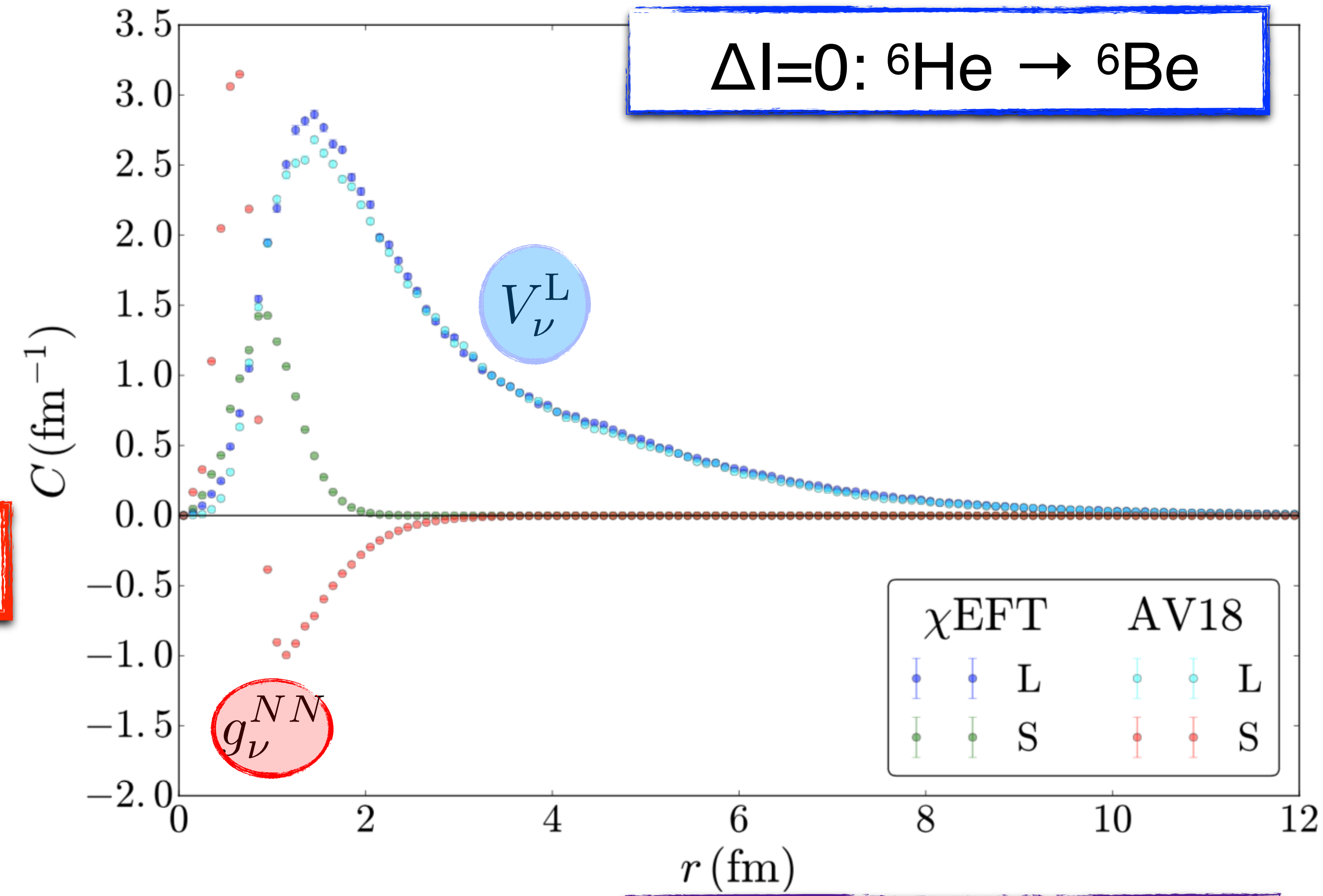

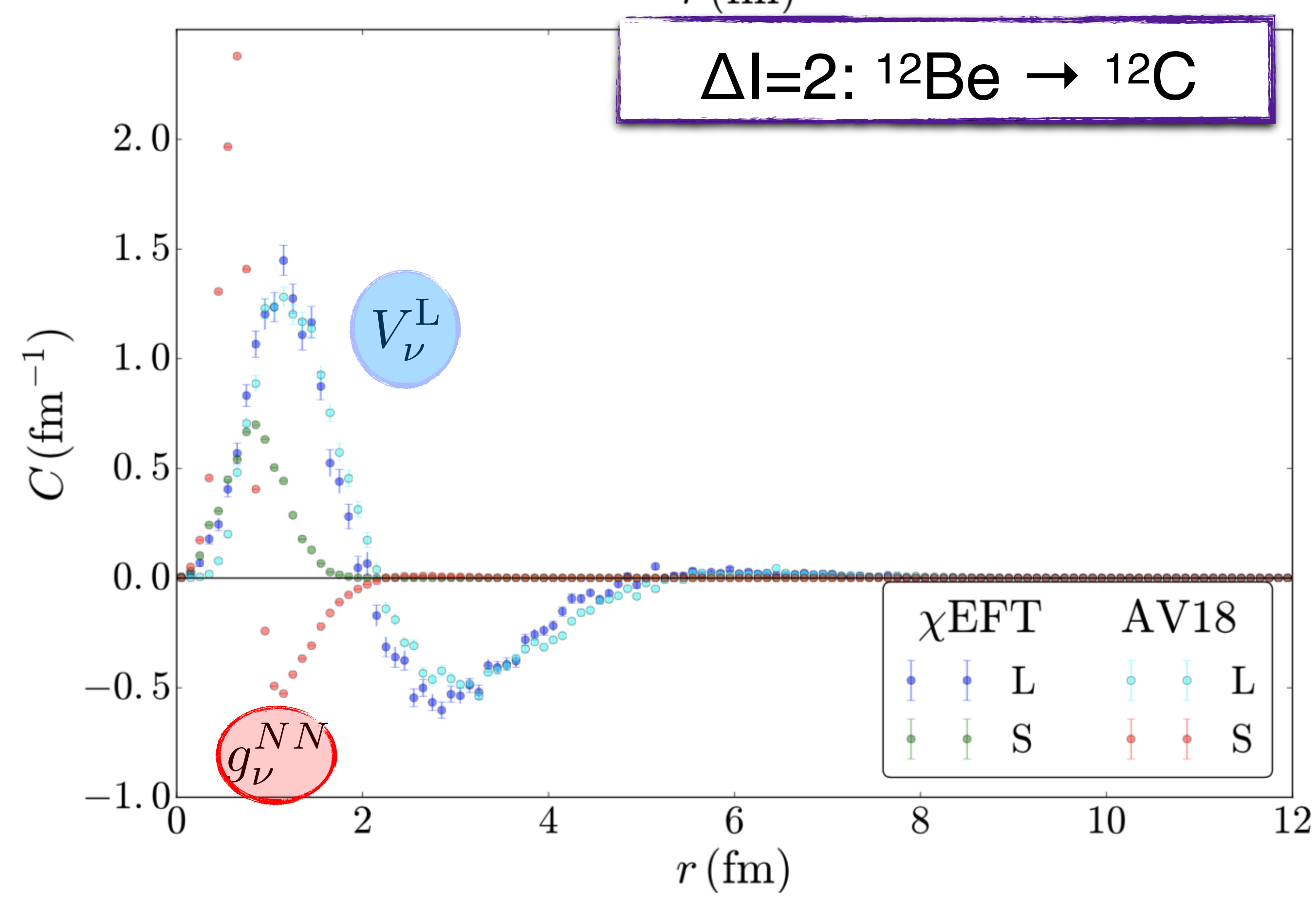

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Example:
The left-right model

An example: LR model

In Left-Right models:

- SM gauge symmetry is extended to $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$
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Violates lepton number

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  - Right-handed bosons $W_R,\ Z_R$
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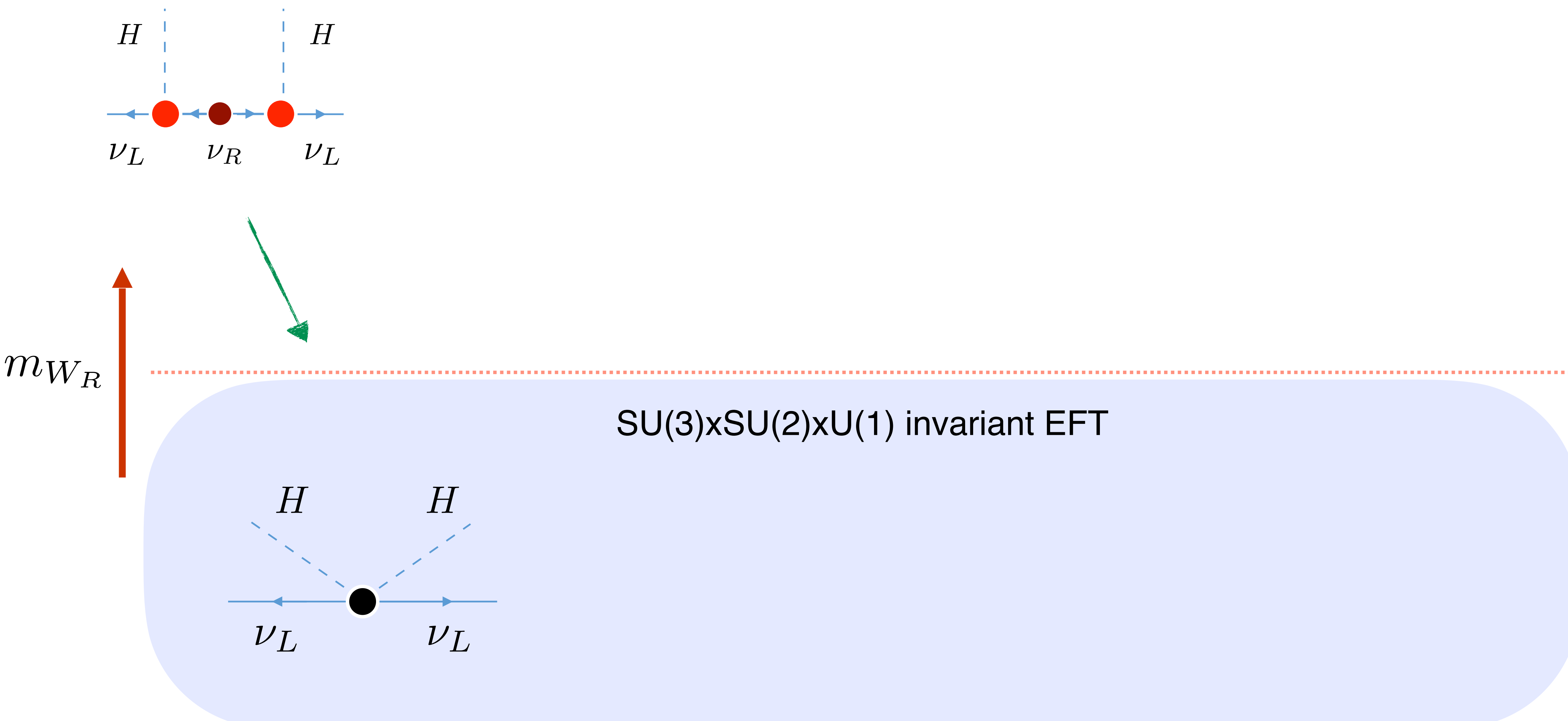
An example: LR model

- (red dot) $\sim y_e = m_e/v$
- (dark red dot) $\Delta L = 2$



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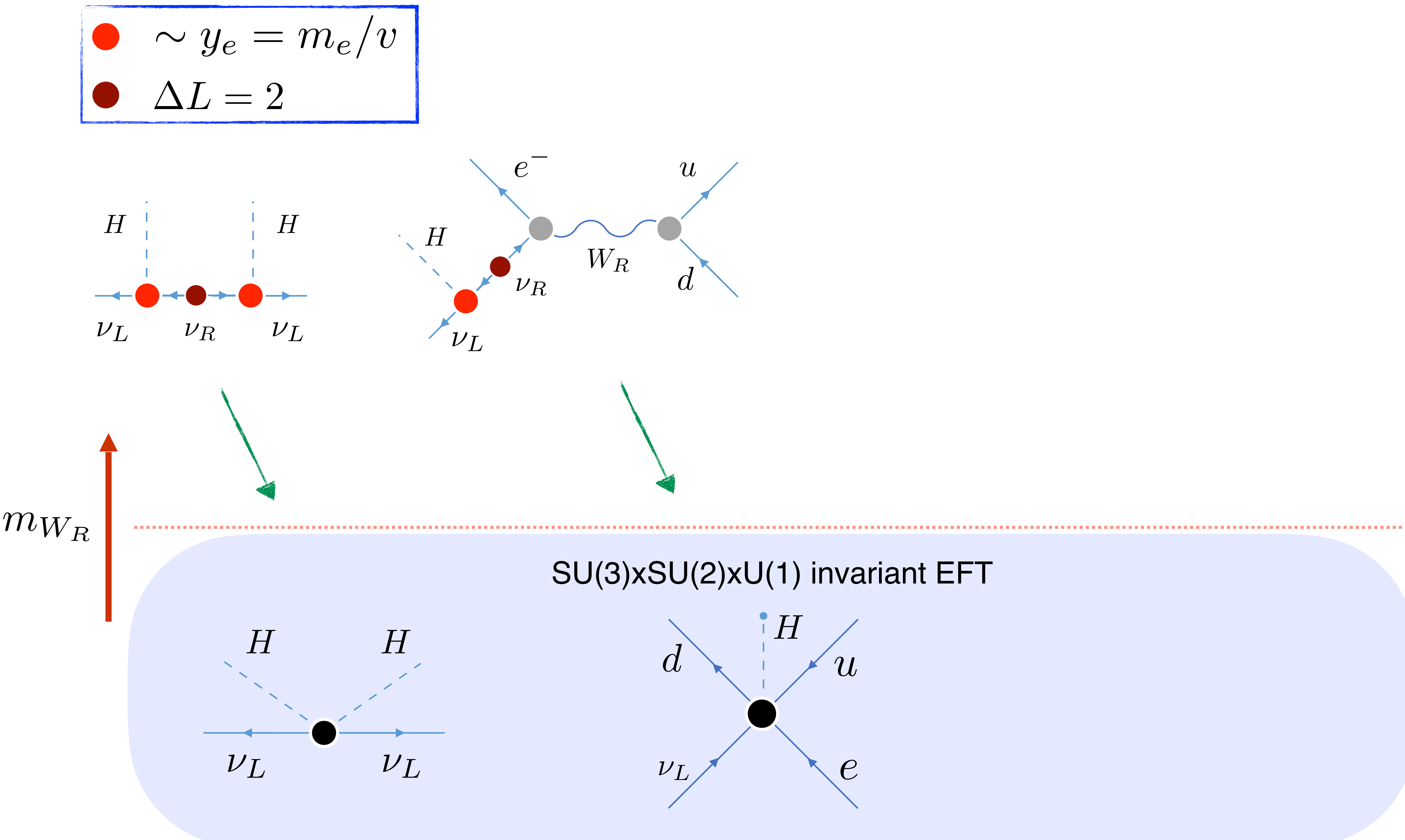

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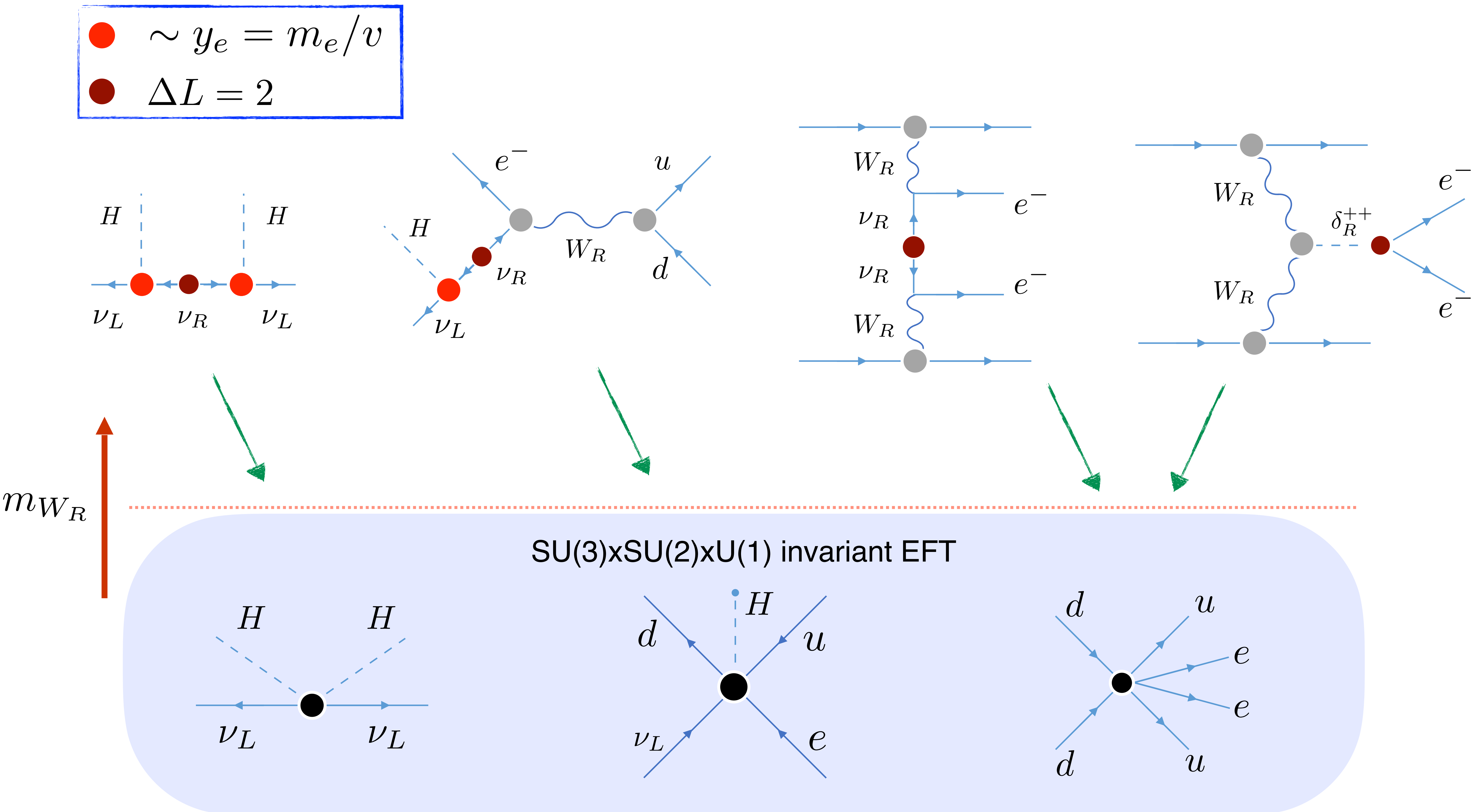

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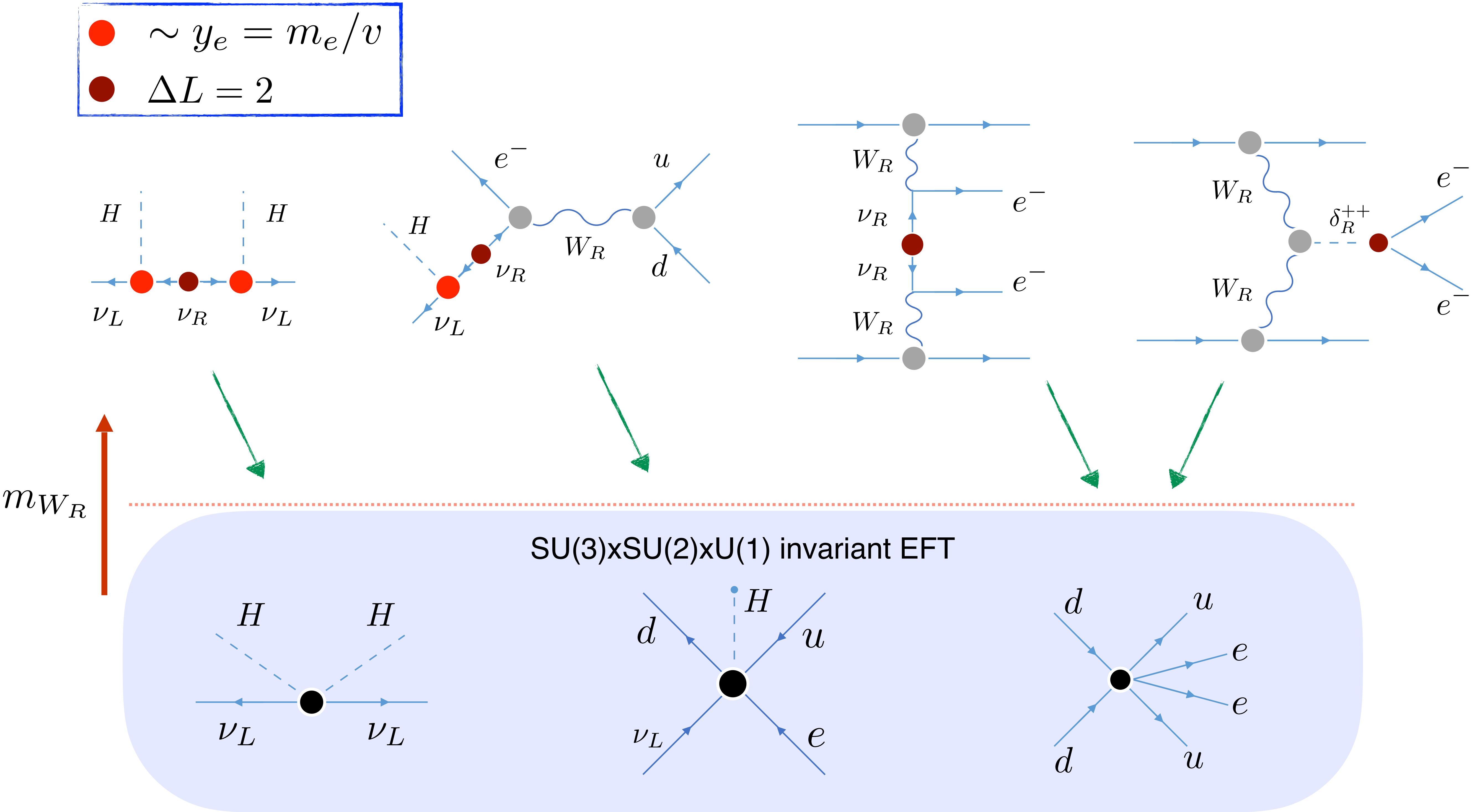

dim-5 $\sim y_e^2 \left(\frac{v}{\Lambda}\right)$ dim-7 $\sim y_e \left(\frac{v}{\Lambda}\right)^3$ Dim-9 $\sim \left(\frac{v}{\Lambda}\right)^5$

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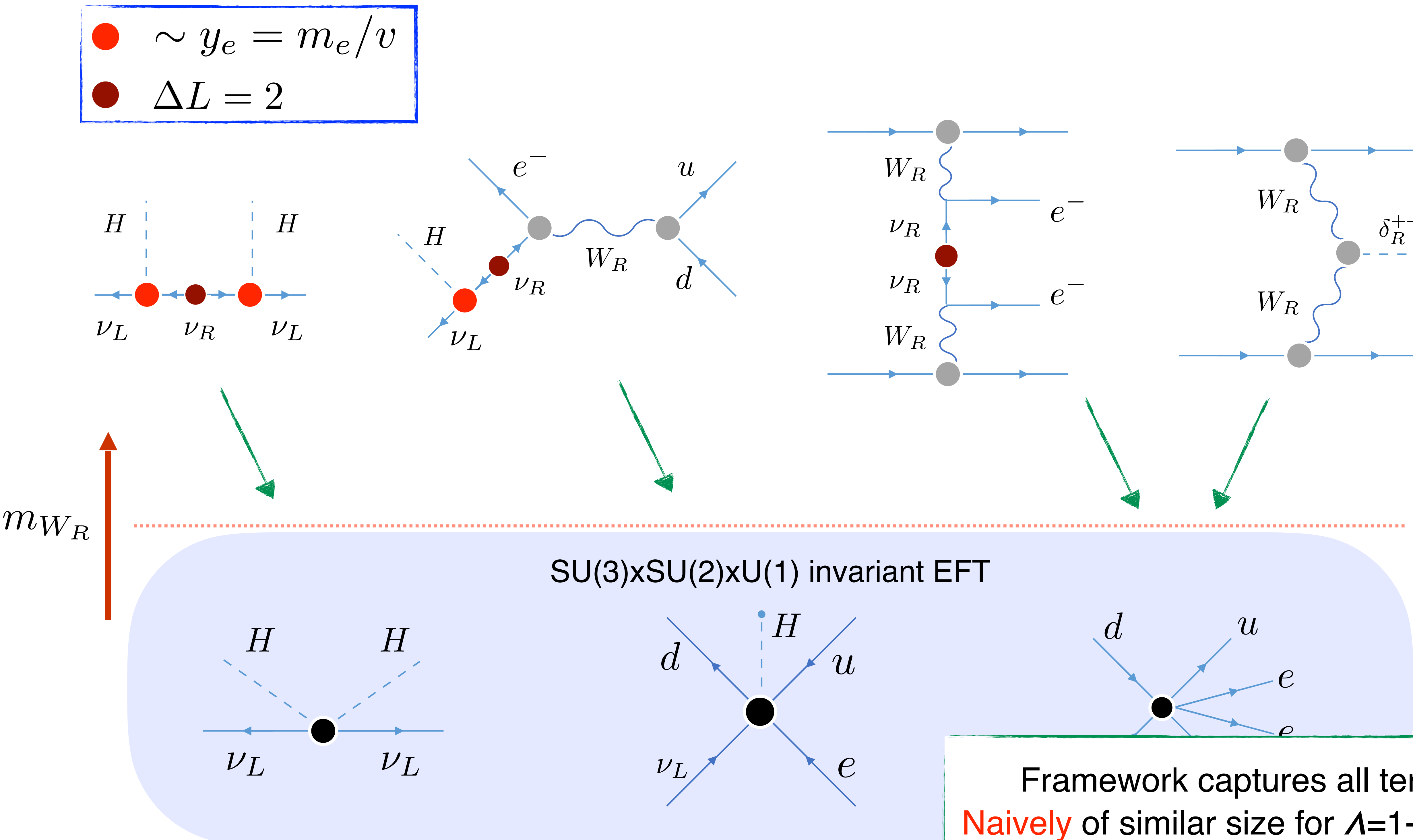

Framework captures all terms

Naively of similar size for Λ=1-10 TeV

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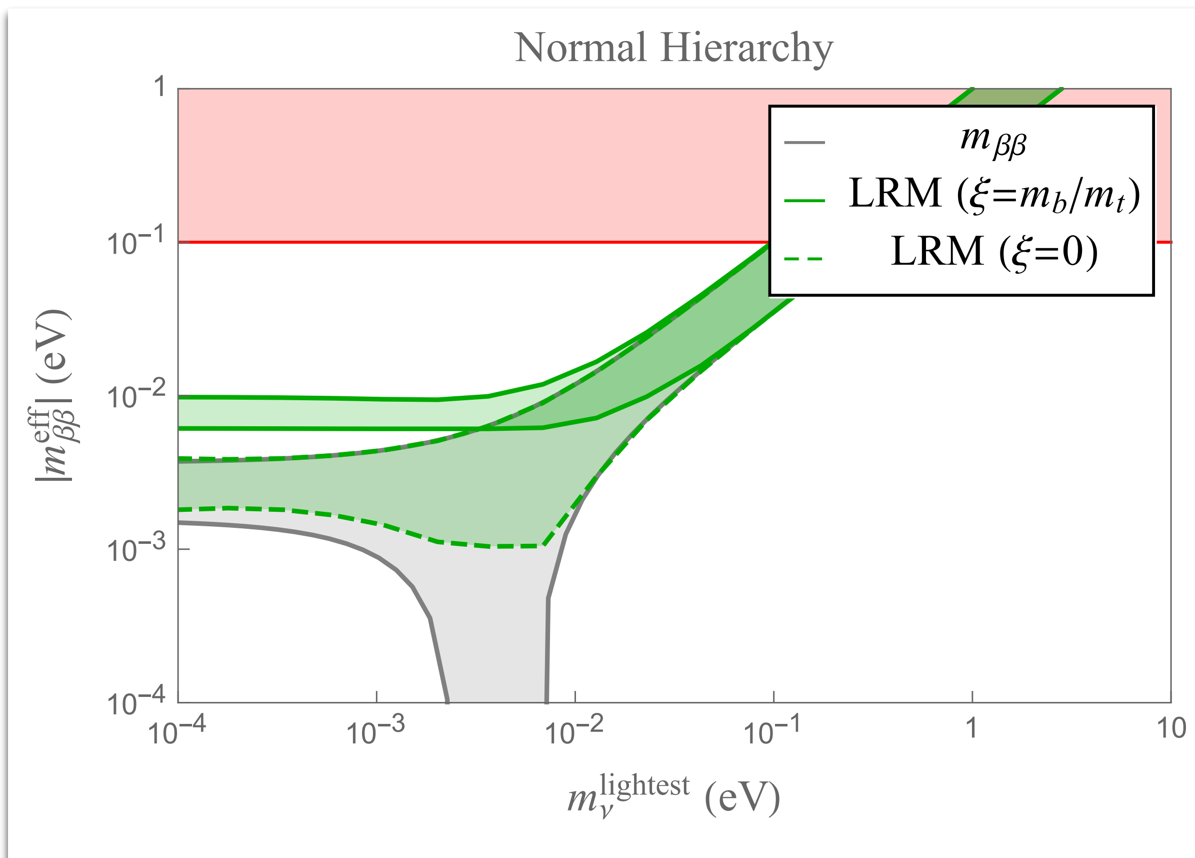
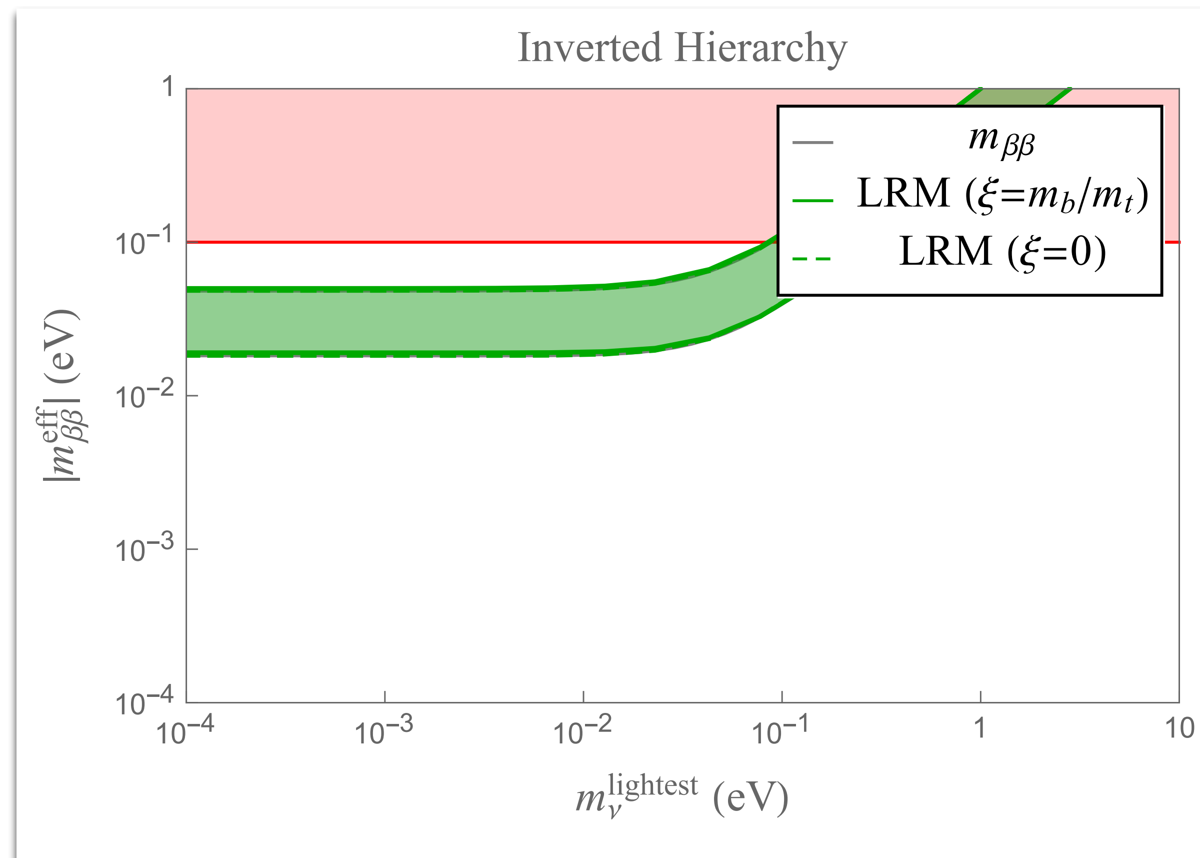
An example: LR model

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

- Assume right-handed neutrino mixing follows the PMNS matrix





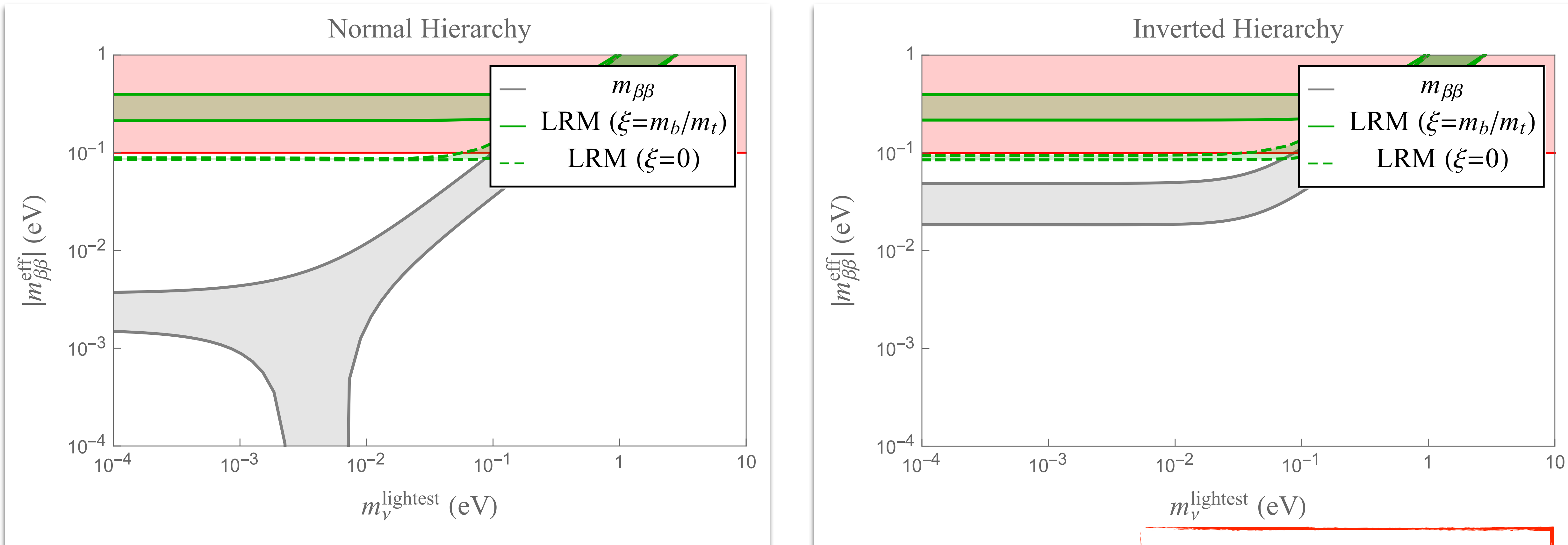
- Mild effect on NH (due to dim-9)
- Negligible effect in IH case, dim-5 terms dominate
  - Due to chiral suppression of the induced dim-6,7,9 operators

An example: LR model

Not excluded by collider

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

- Assume right-handed neutrino mixing follows the PMNS matrix



Subject to NME / LEC uncertainties

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