Neutrinoless double beta decay in effective field theory

with V. Cirigliano, J. de Vries, M.L. Graesser, E. Mereghetti, S. Pastore,
B. van Kolck, A. Walker-Loud

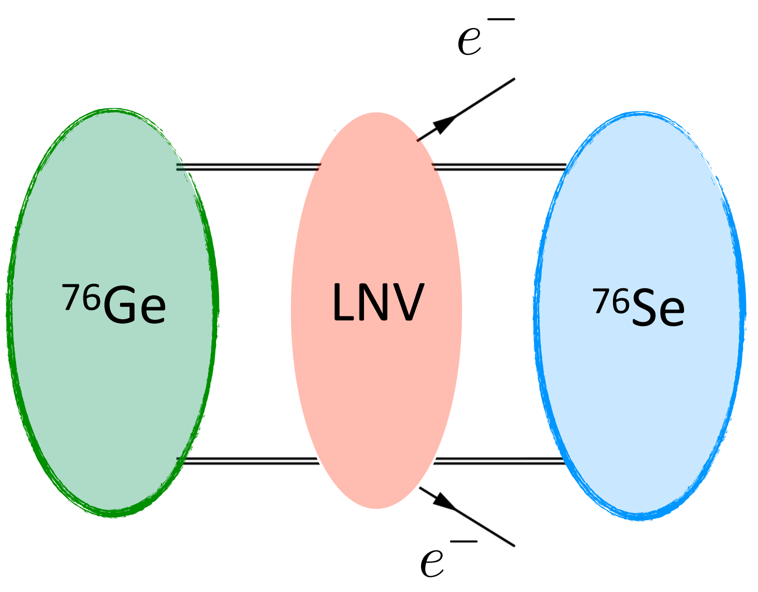
Based on:

arXiv:1806.02780, 1710.01729, 1802.10097,
1710.05026, 1708.09390

Los Alamos
NATIONAL LABORATORY
EST. 1943

Introduction

0νββ



- Violates lepton number, ΔL=2

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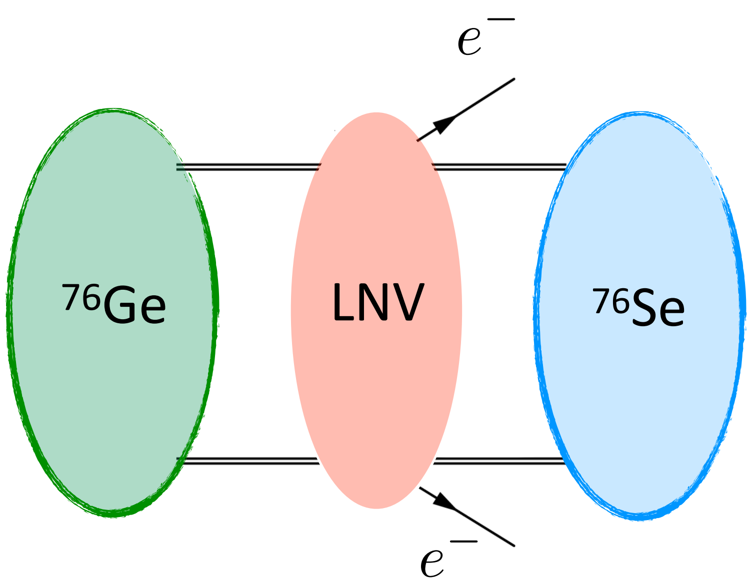

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- Stringently constrained experimentally
  - To be improved by 1-2 orders

	$^{76}\mathrm{Ge}$	$^{130}\mathrm{Te}$	$^{136}\mathrm{Xe}$
$T_{1/2}^{0\nu}$ >	$5.3 \cdot 10^{25}$ [61]	$4.0 \cdot 10^{24}$ [63]	$1.07 \cdot 10^{26}$ [64]

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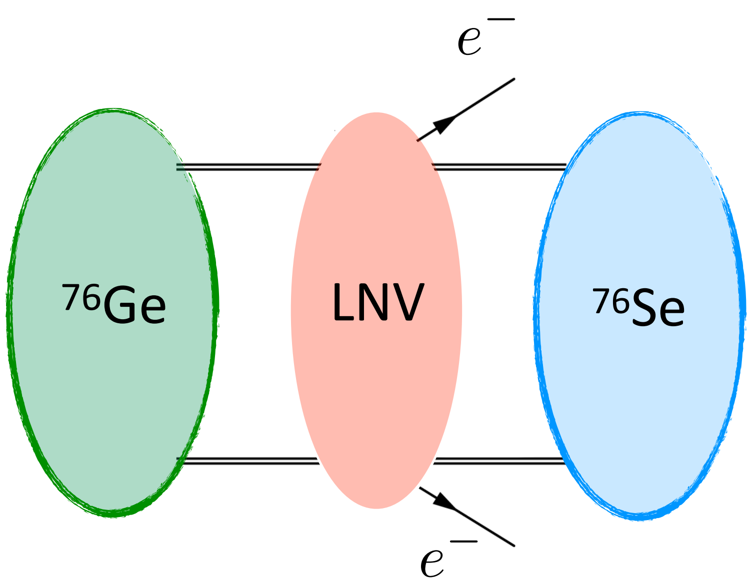

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  - •Neutrino's are Majorana particles
  - •Physics beyond the SM

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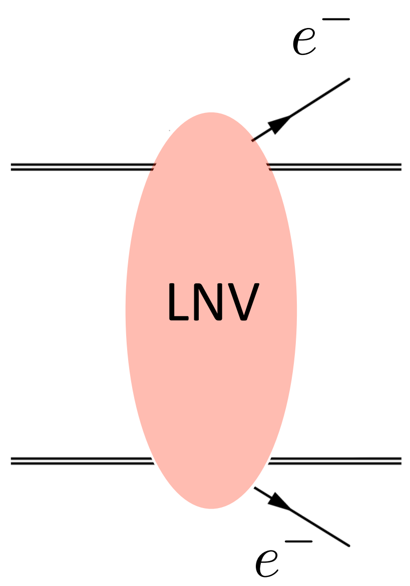

= **BSM physics**

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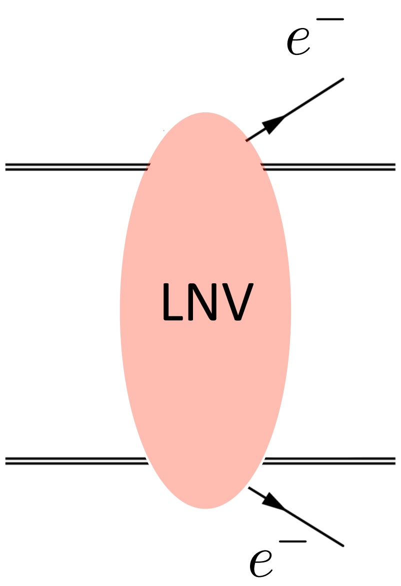

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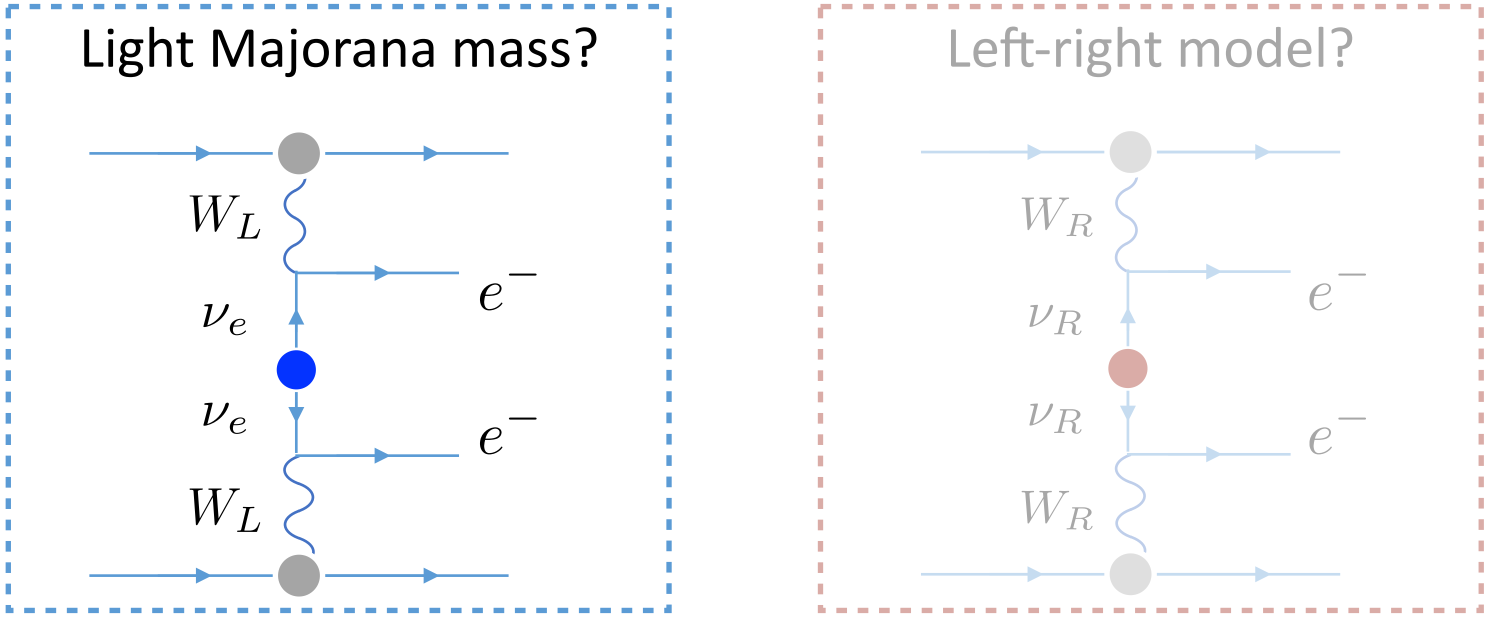
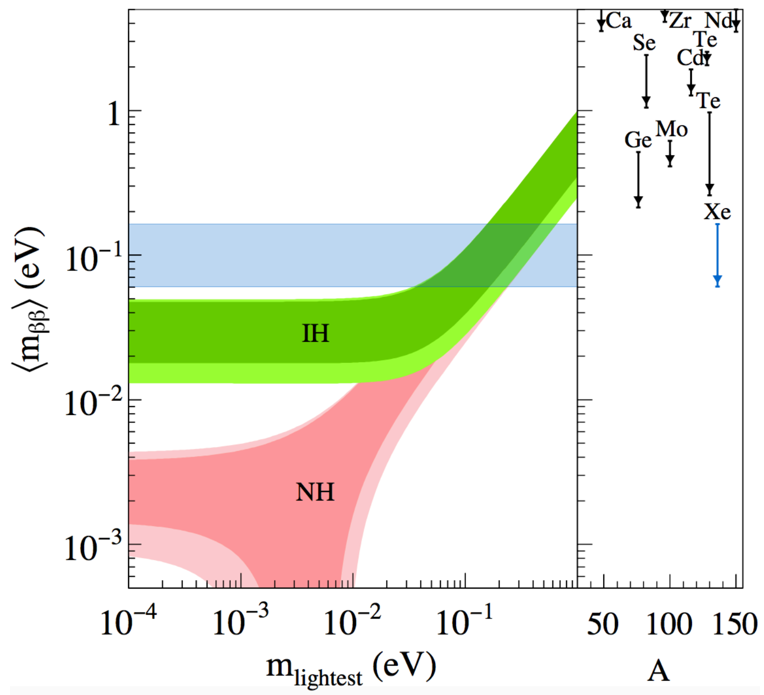


+ ??

Well-known Majorana mass mechanism



- Implications for the mass hierarchy

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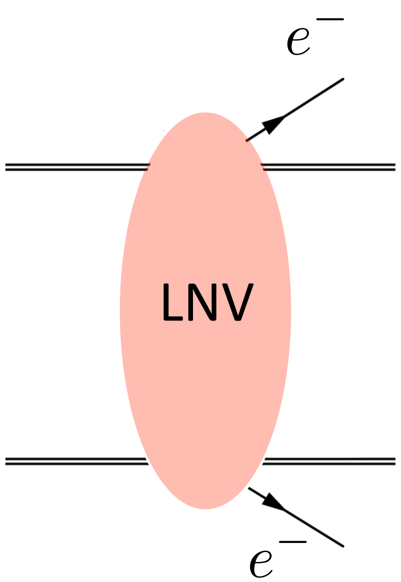

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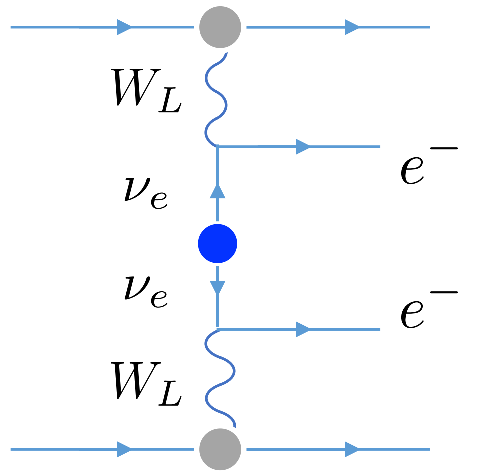

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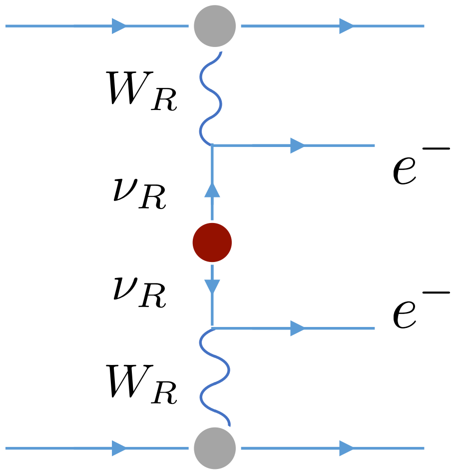

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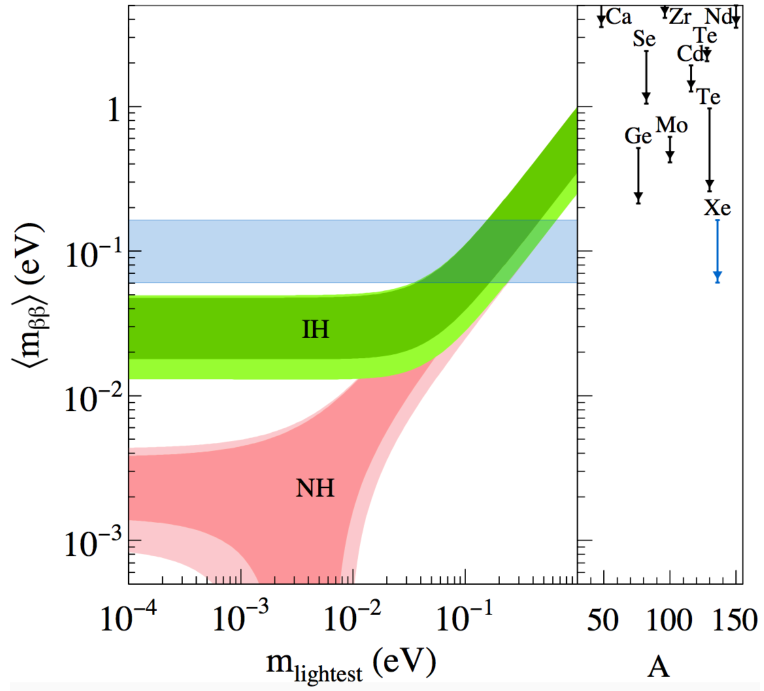

- Implications for the mass hierarchy

Heavy BSM mechanisms

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

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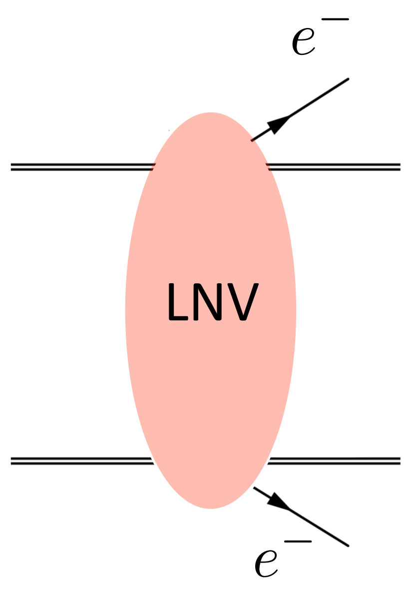

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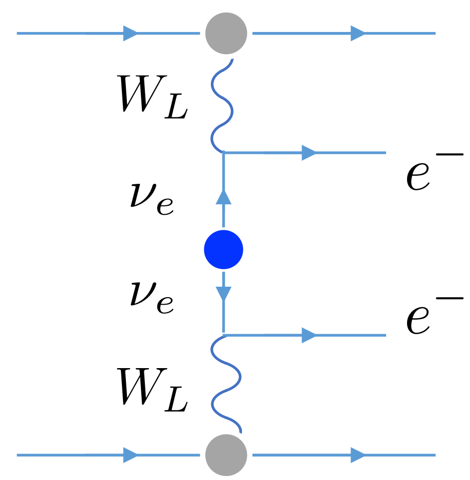

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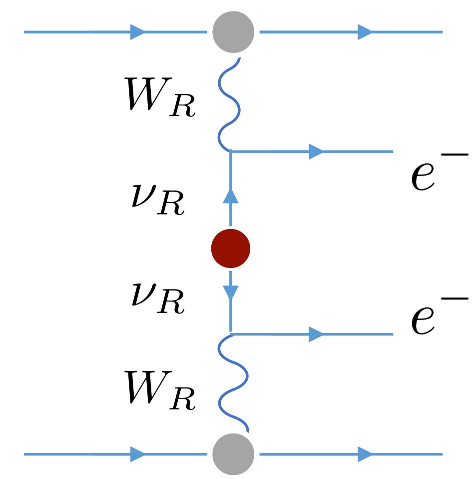

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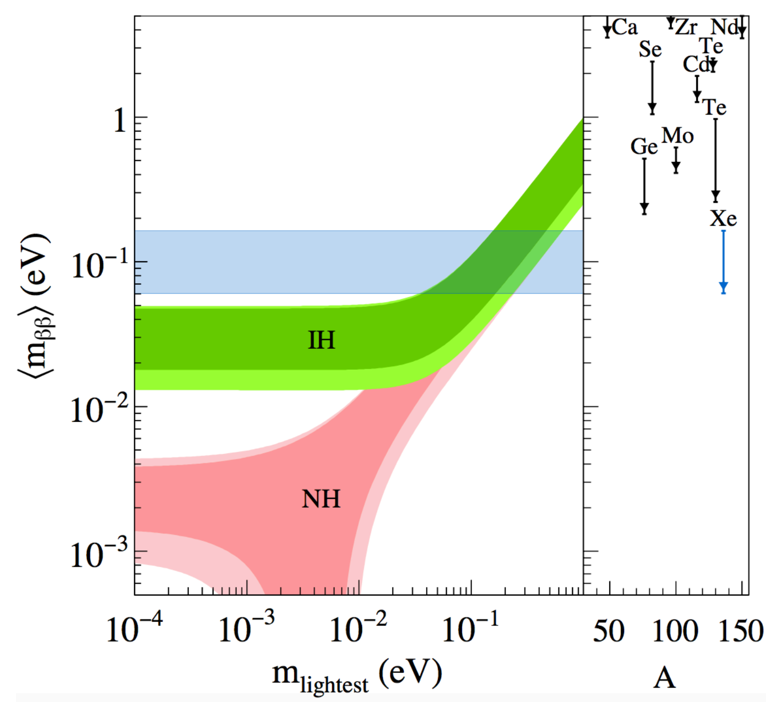

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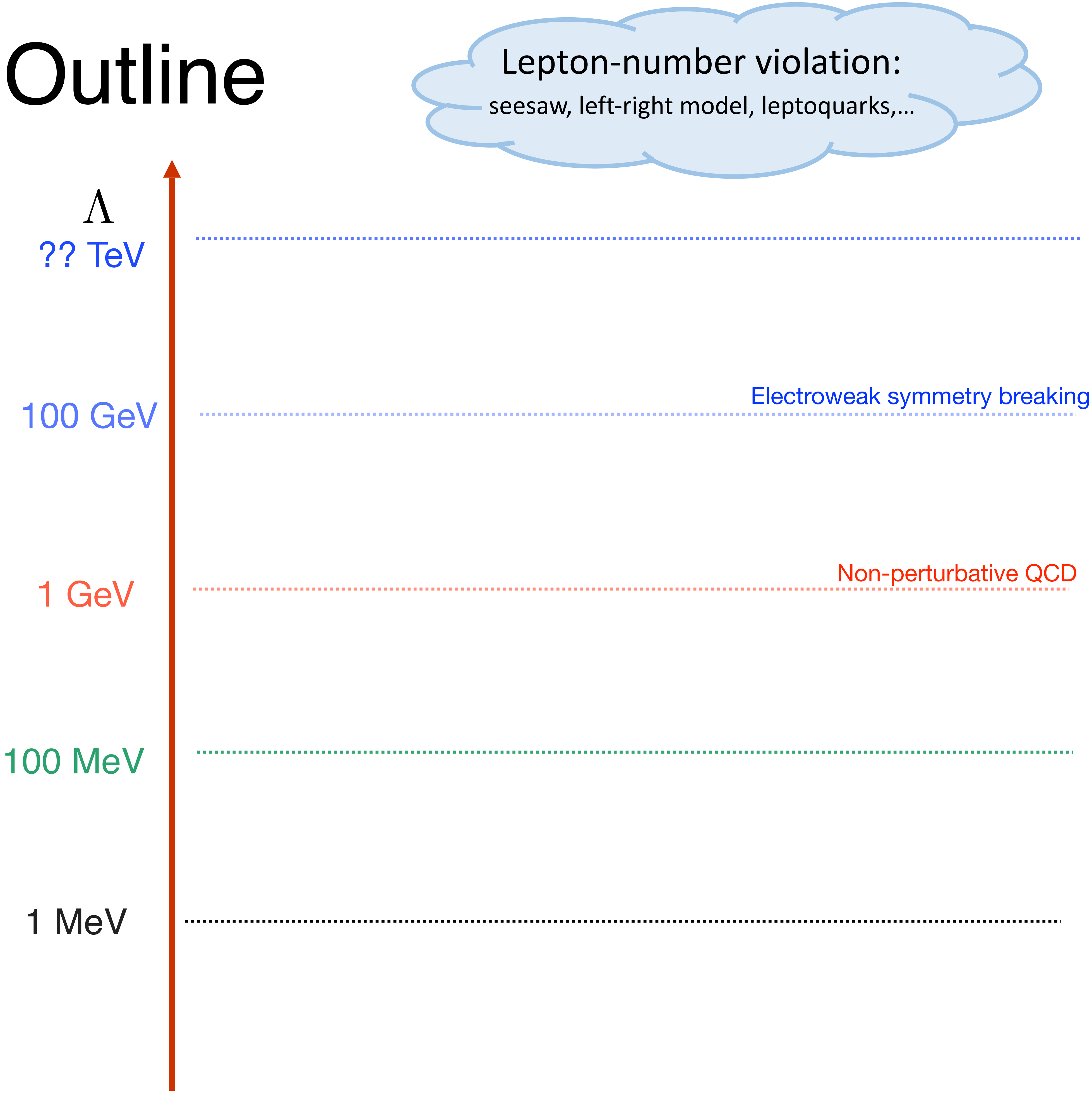
Heavy BSM mechanisms

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

Outline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seesaw, left-right model, leptoquarks,...
Λ
?? TeV
100 GeV
Electroweak symmetry breaking
1 GeV
Non-perturbative QCD
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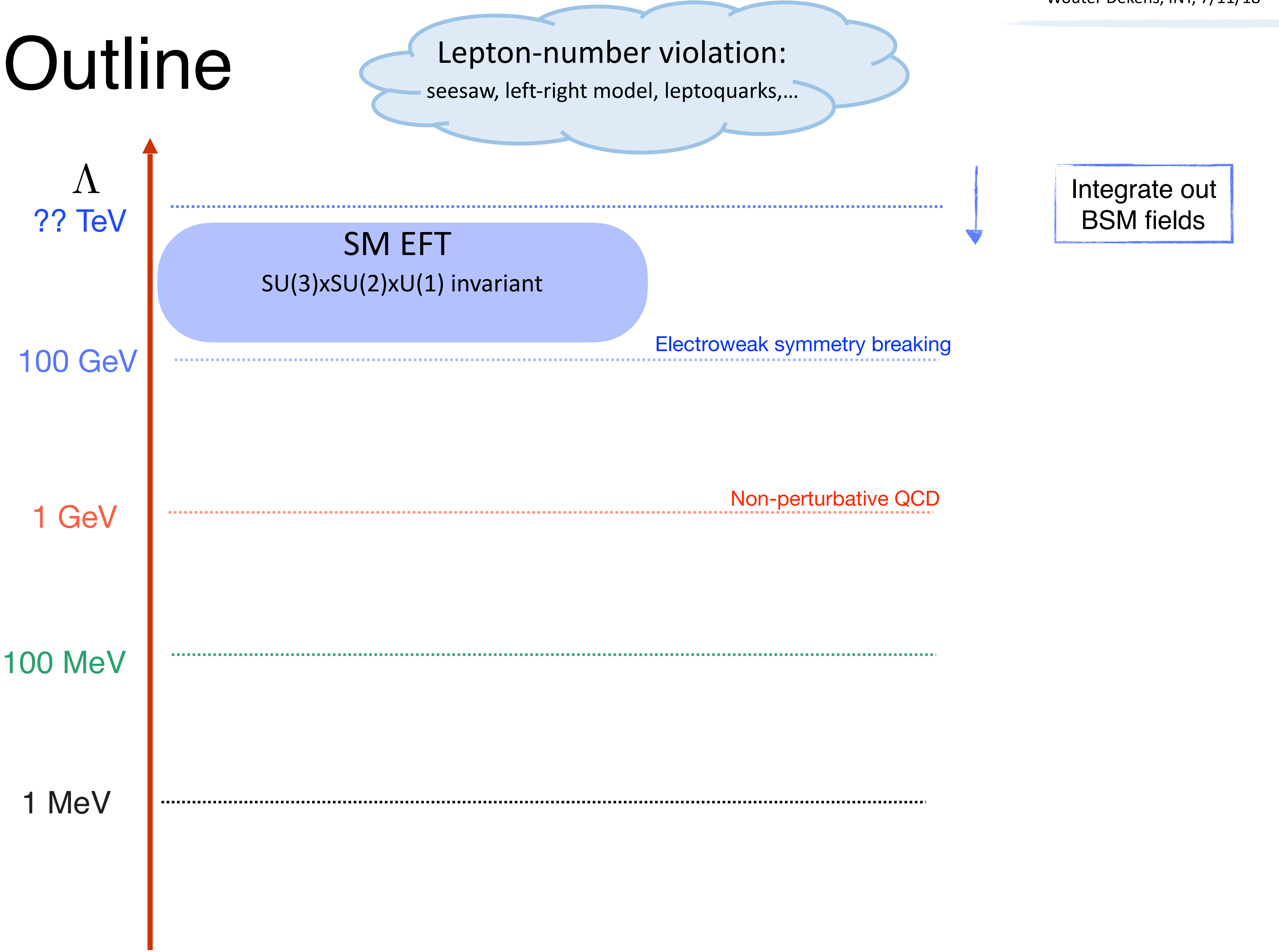
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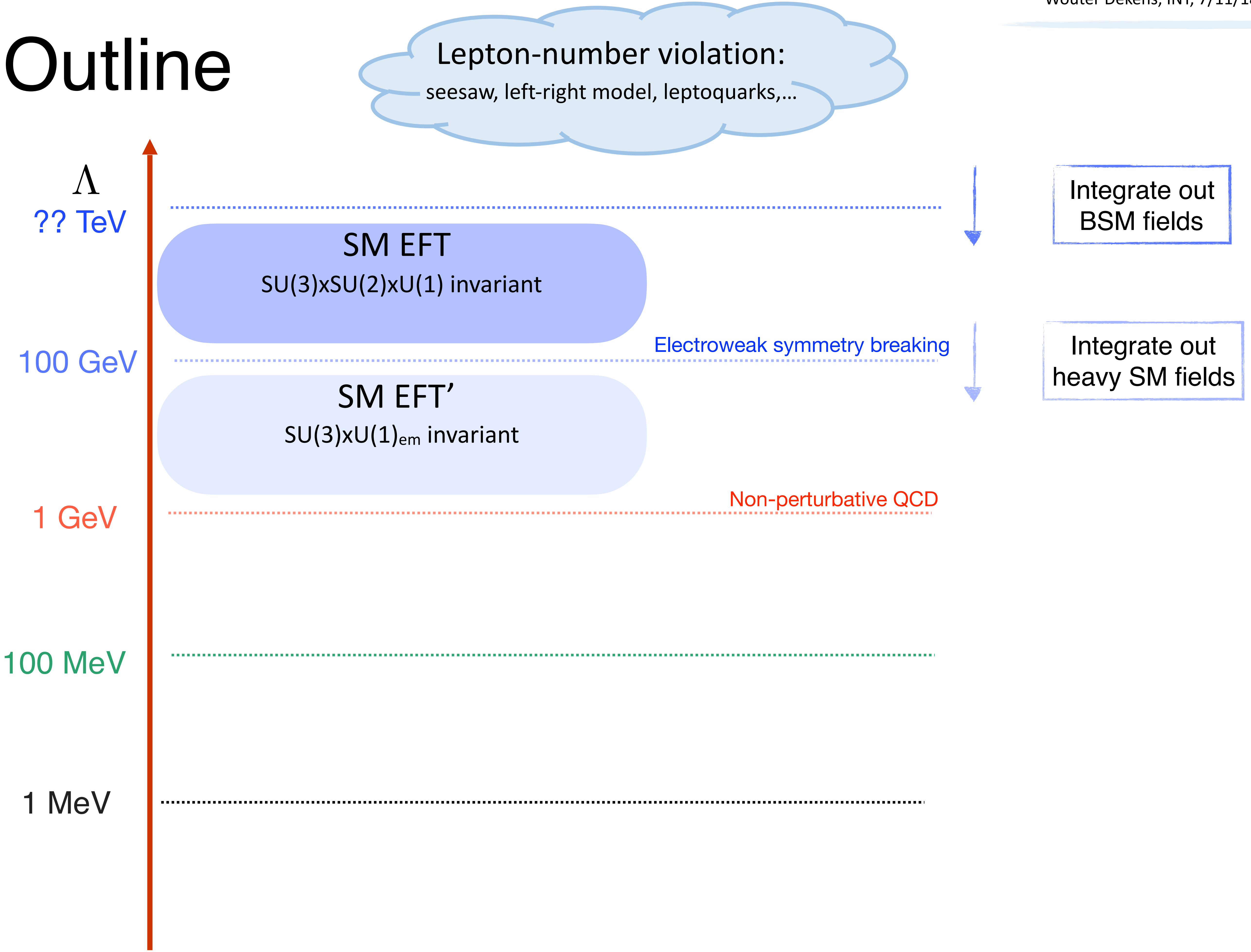
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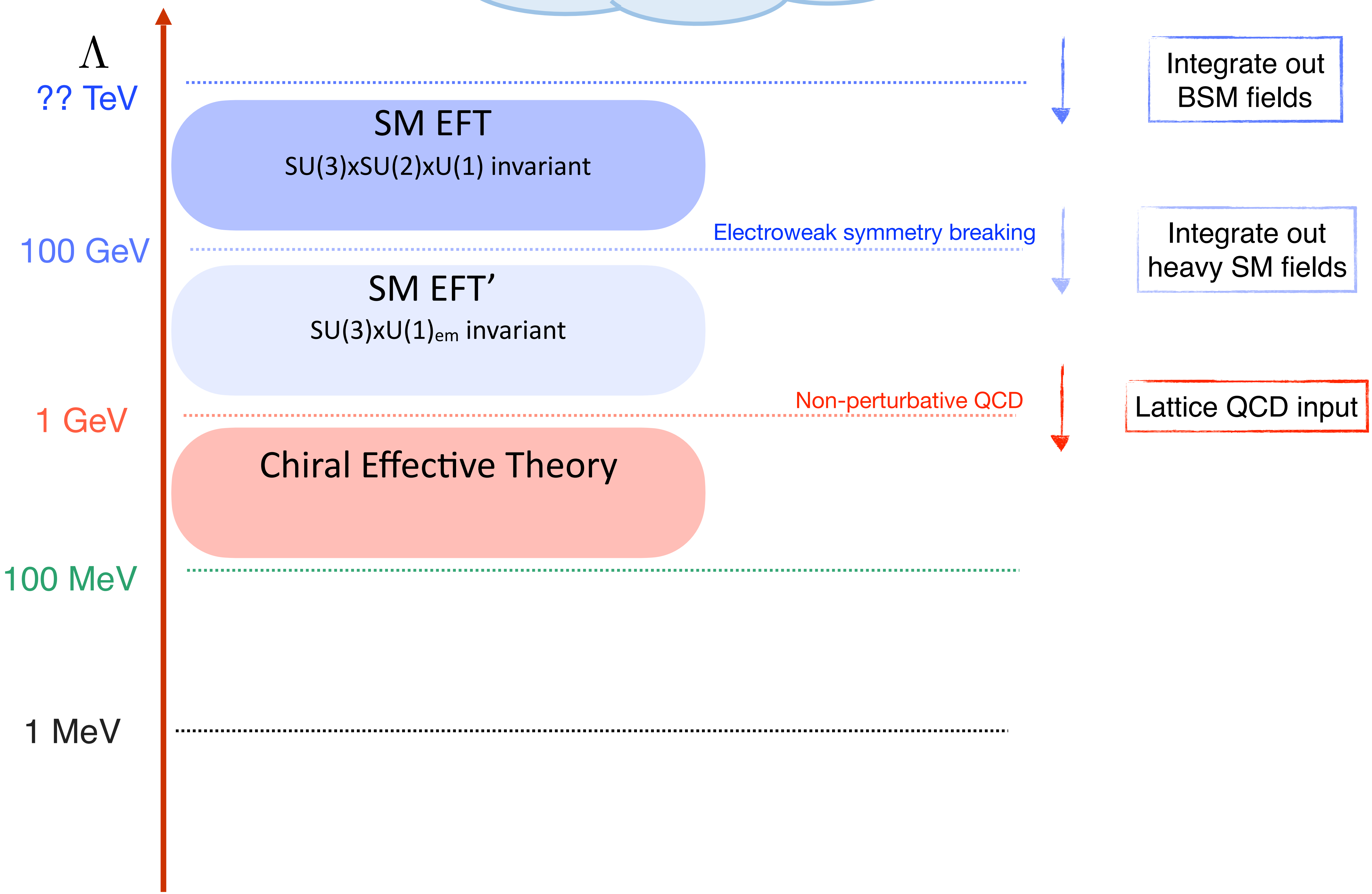

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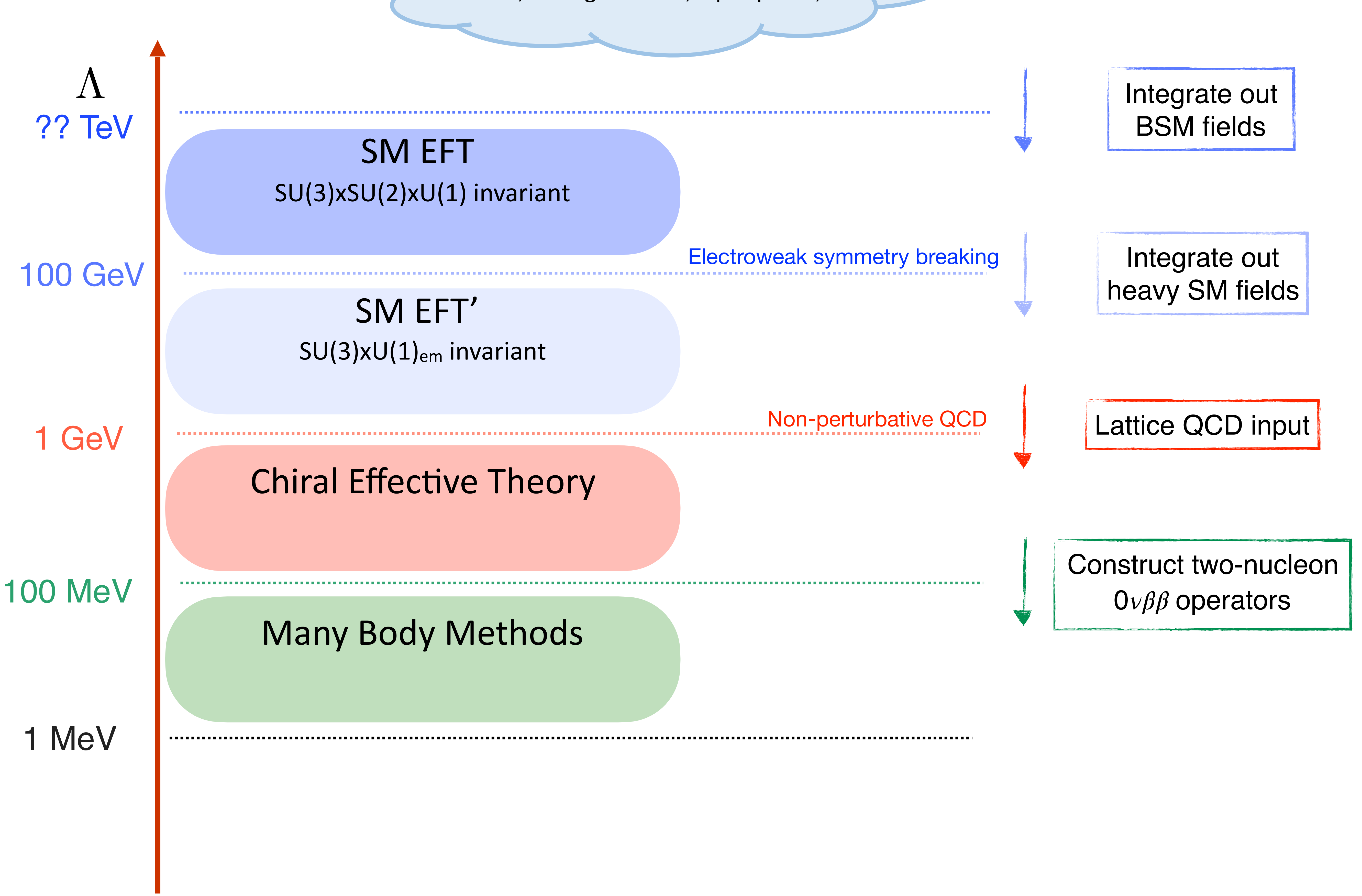

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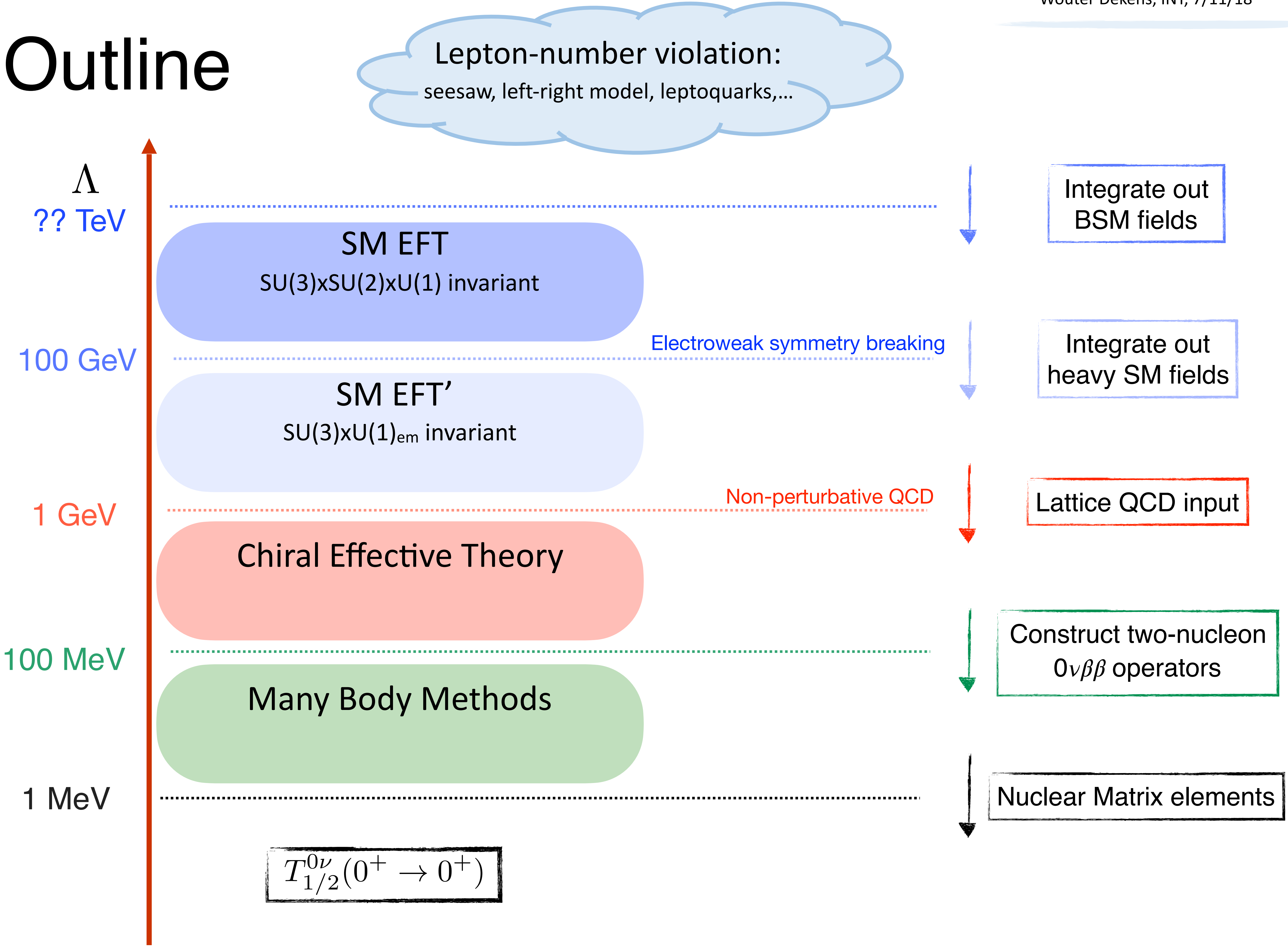

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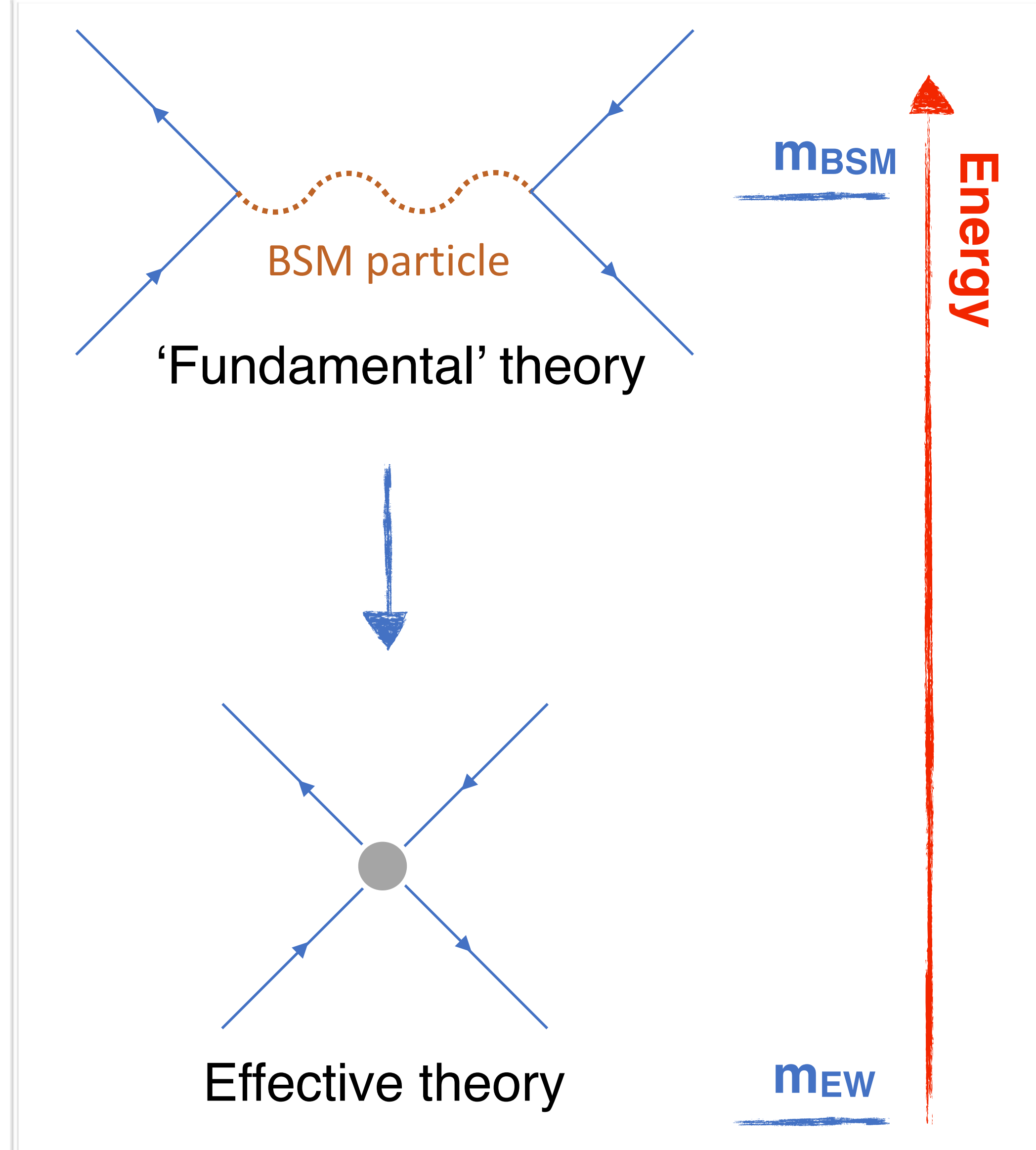
Effective Field Theory

$$\mathcal{L} = ??$$

Assumptions

- No new light degrees of freedom
- BSM physics appears above the electroweak scale, $m_{EW} << m_{BSM}$
- SM gauge group SU(3)xSU(2)xU(1) is linearly realized (elementary scalar SU(2) doublet)



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

Effective Field Theory

ΔL=2 operators only appear at odd dimensions, 5, 7, 9…

Dimension-five

- Just one operator
- Induces Majorana mass

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

Kobach ’16; Weinberg ’79; Lehman ’14

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Dimension-seven

- All operators have been derived
- 12 ΔL=2 operators

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

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

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

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

$5 : \psi^4 D + \text{h.c.}$

$\mathcal{O}^{(1)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L^i C D^\mu L^j)$
$\mathcal{O}^{(2)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L^i C \sigma^{\mu\nu} D_\nu L^j)$
$\mathcal{O}^{(1)}_{\bar{L}QddD}$	$(QC\gamma_\mu d)(\bar{L}D^\mu d)$
$\mathcal{O}^{(2)}_{\bar{L}QddD}$	$(\bar{L}\gamma_\mu Q)(dCD^\mu d)$
$\mathcal{O}_{ddd\bar{e}D}$	$(\bar{e}\gamma_\mu d)(dCD^\mu d)$

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Dimension-nine

- Subset of operators constructed

$$\text{LM1} = i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu Q_c)(\overline{u}_R\gamma_\mu d_R)(\bar{\ell}_b\ell^C_c)$$
$$\text{LM2} = i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu\lambda^A Q_c)(\overline{u}_R\gamma_\mu\lambda^A d_R)(\bar{\ell}_b\ell^C_c)$$
$$\text{LM3} = (\overline{u}_R Q_a)(\overline{u}_R Q_b)(\bar{\ell}_a\ell^C_b)$$
$$\text{LM4} = (\overline{u}_R\lambda^A Q_a)(\overline{u}_R\lambda^A Q_b)(\bar{\ell}_a\ell^C_b)$$
$$\text{LM5} = i\sigma^{(2)}_{ab}\, i\sigma^{(2)}_{cd}(\overline{Q}_a d_R)(\overline{Q}_c d_R)(\bar{\ell}_b\ell^C_d)$$
$$\text{LM6} = i\sigma^{(2)}_{ab}\, i\sigma^{(2)}_{cd}(\overline{Q}_a\lambda^A d_R)(\overline{Q}_c\lambda^A d_R)(\bar{\ell}_b\ell^C_d)$$
$$\text{LM7} = (\overline{u}_R\gamma^\mu d_R)(\overline{u}_R\gamma_\mu d_R)(\overline{e}_R e^C_R)$$
$$\text{LM8} = (\overline{u}_R\gamma^\mu d_R)\, i\sigma^{(2)}_{ab}(\overline{Q}_a d_R)(\bar{\ell}_b\gamma_\mu e^C_R)$$
$$\text{LM9} = (\overline{u}_R\gamma^\mu\lambda^A d_R)\, i\sigma^{(2)}_{ab}(\overline{Q}_a\lambda^A d_R)(\bar{\ell}_b\gamma_\mu e^C_R)$$
$$\text{LM10} = (\overline{u}_R\gamma^\mu d_R)(\overline{u}_R Q_a)(\bar{\ell}_a\gamma_\mu e^C_R)$$
$$\text{LM11} = (\overline{u}_R\gamma^\mu\lambda^A d_R)(\overline{u}_R\lambda^A Q_a)(\bar{\ell}_a\gamma_\mu e^C_R)$$

- But no complete basis

Kobach '16; Weinberg '79; Lehman '14; Prezeau and Ramsey-Musolf '03; Graesser '16

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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$m_\nu \sim c_5 v^2/\Lambda$ implies two possible extremes:

- $c_5 = \mathcal{O}(1)$, $\Lambda = 10^{15}\,\mathrm{GeV}$ dimension-7, -9 irrelevant in this case (no signal at colliders)

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- $c_5 \ll O(1)$, $\Lambda = \mathcal{O}(1-100)\mathrm{TeV}$ dimension-7, -9 relevant when $c_{7,9}/c_5 \gg 1$

- This happens in well-known BSM models
  - For example the Left right model gives

$$c_9 = \mathcal{O}(1), \qquad c_7 = \mathcal{O}(y_e), \qquad c_5 = \mathcal{O}(y_e^2)$$
$$y_e = m_e/v \sim 10^{-6}$$

  - The dimension-5, -7 and -9 operators can all be relevant for $\Lambda = \mathcal{O}(1-100)\mathrm{TeV}$

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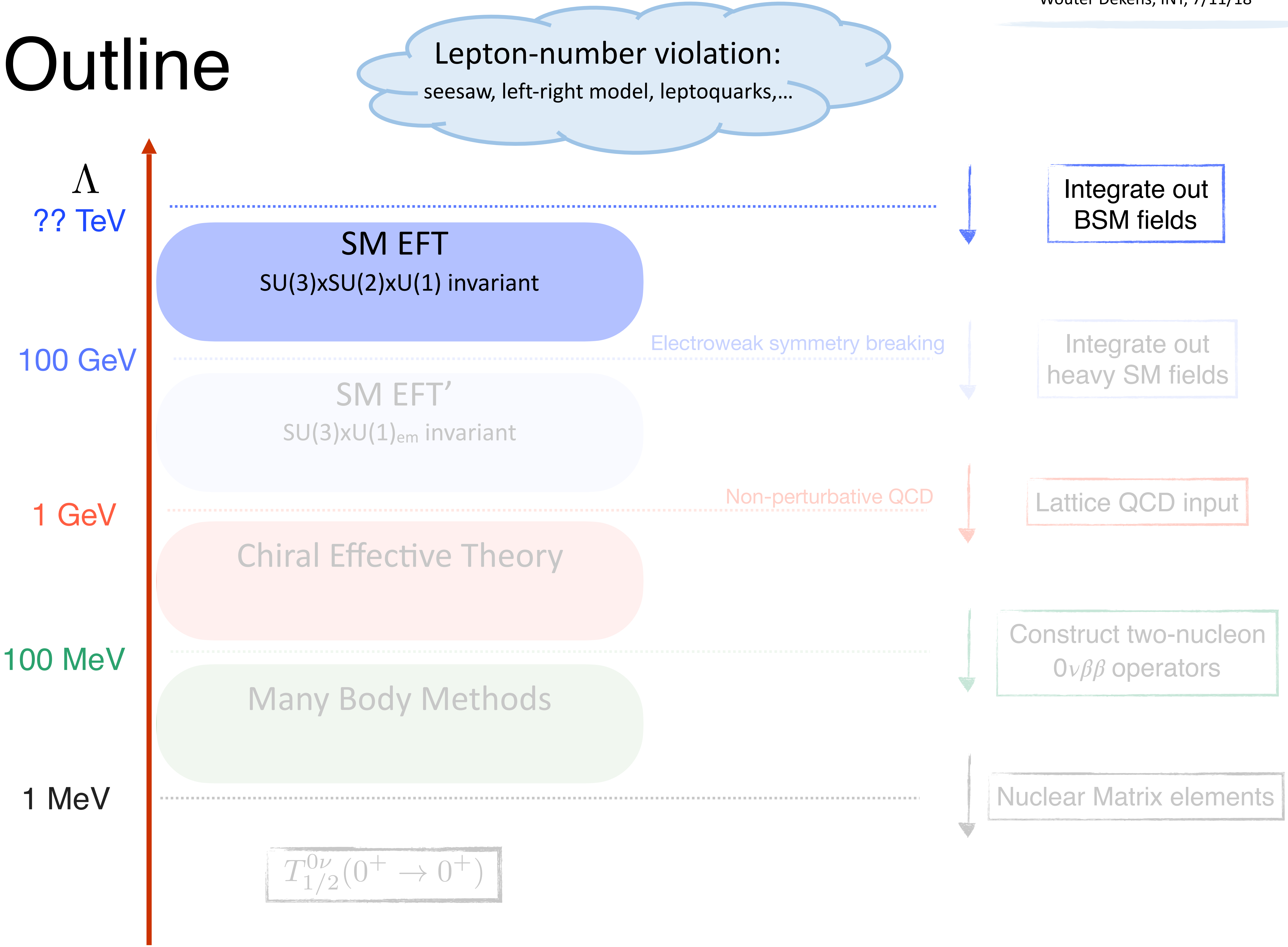
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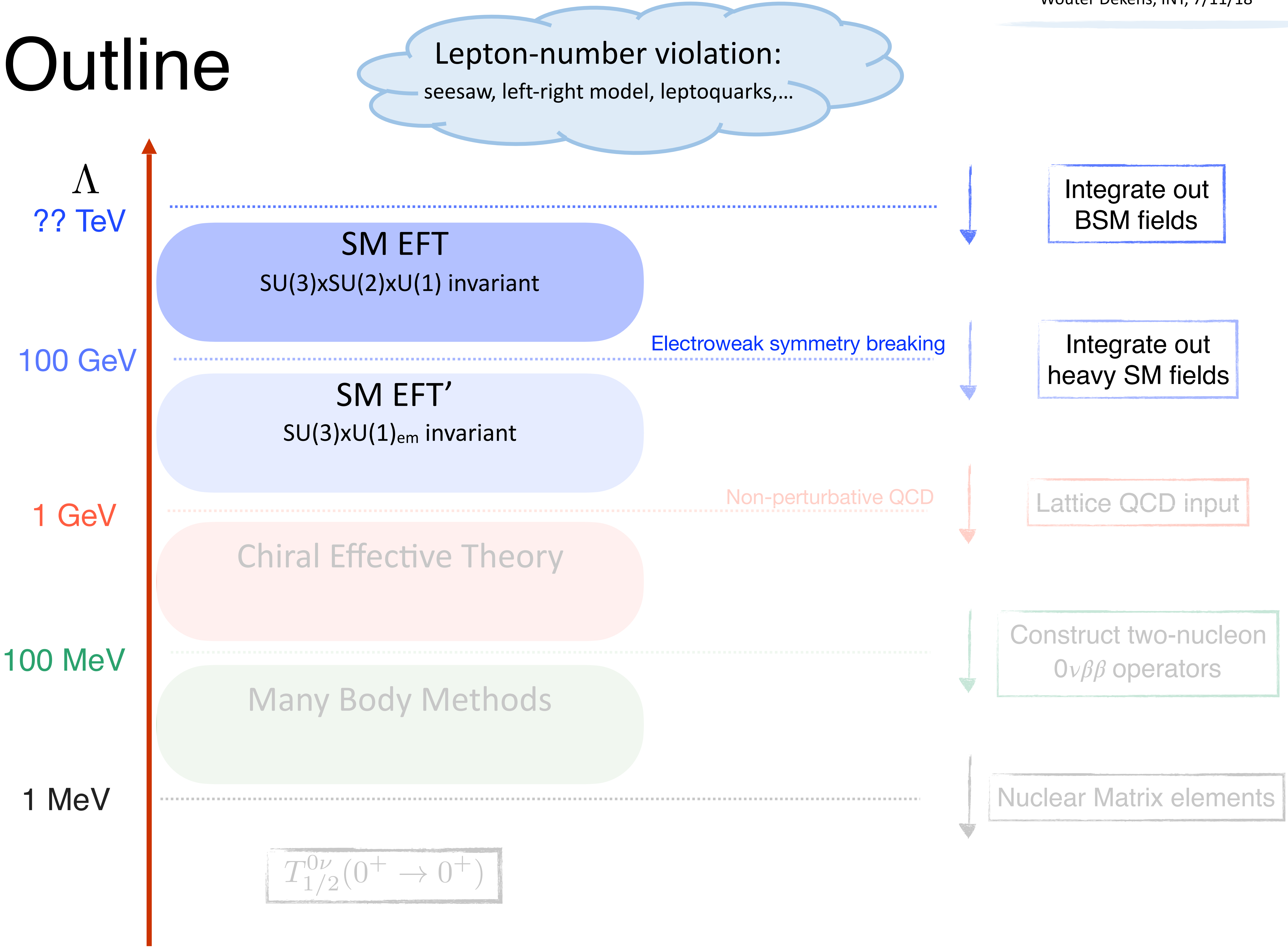

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Matching at the electroweak scale

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

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

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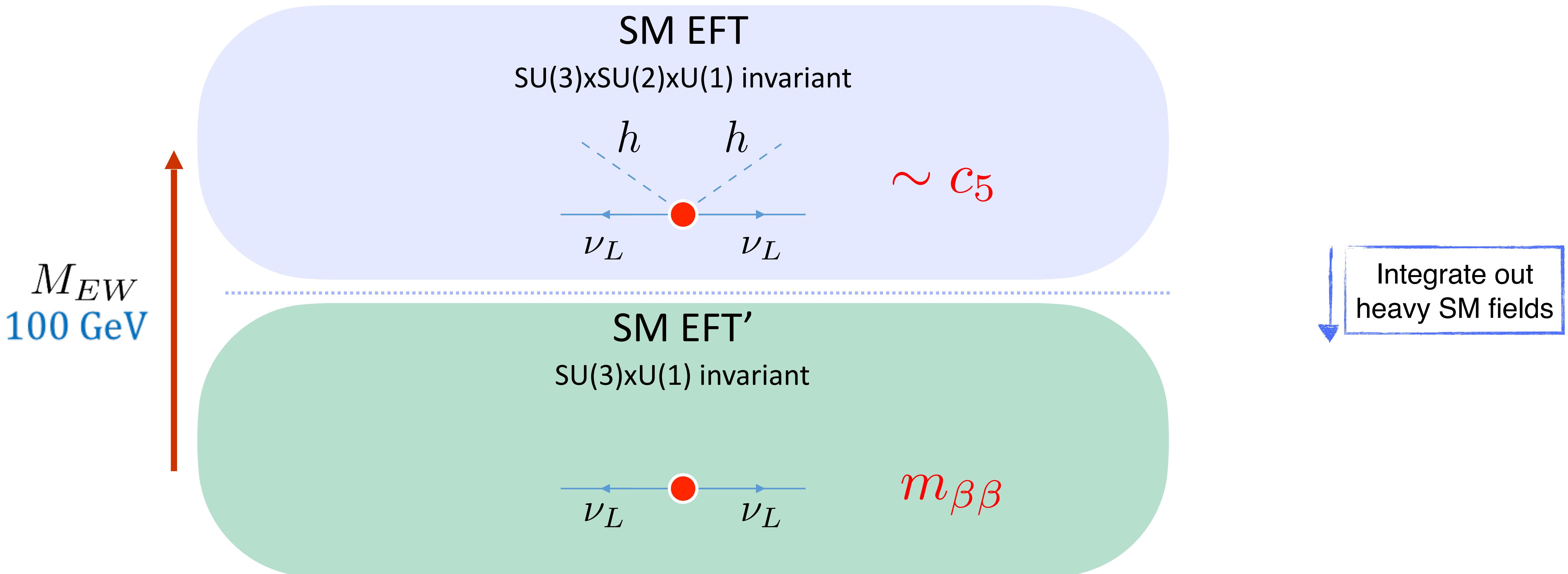
- Mismatch in dimensions due to insertions of the Higgs vacuum expectation value

- Complete basis unknown
- Take into account the known dimension-9 terms

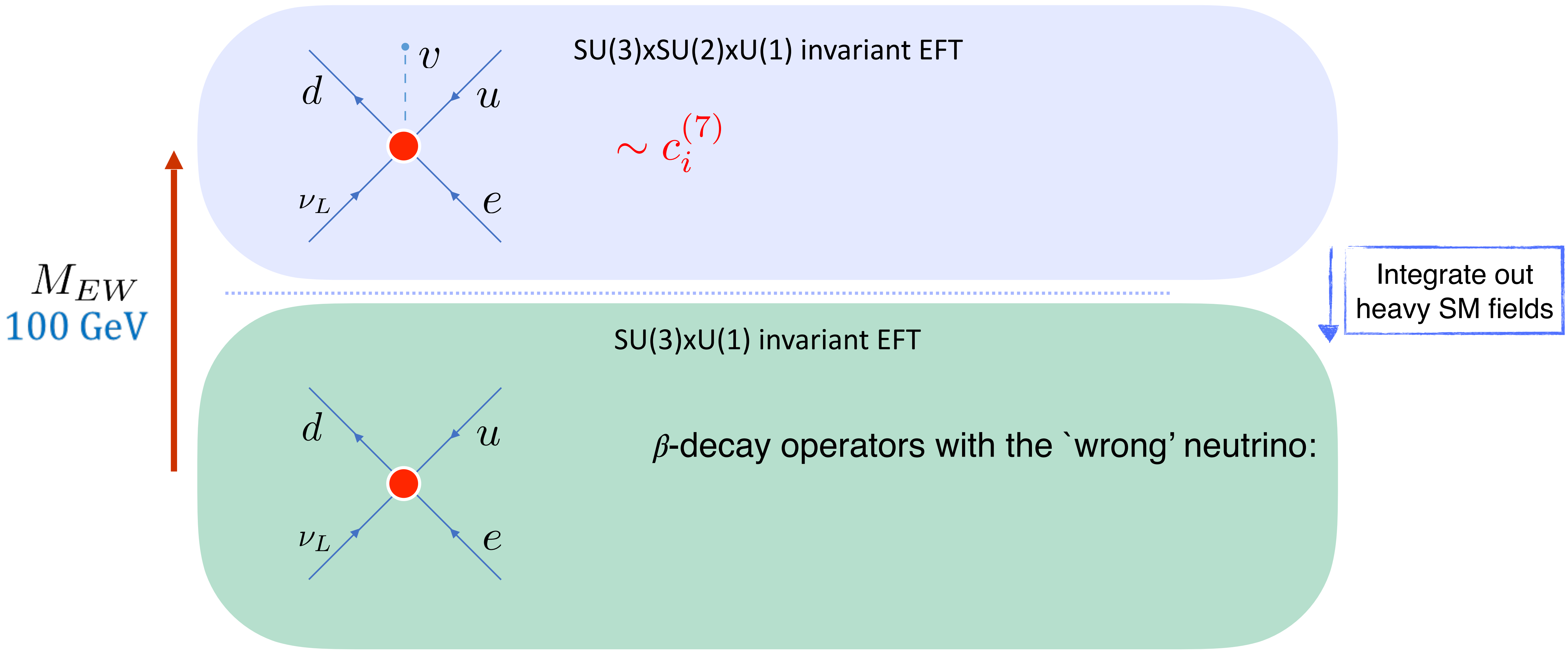
Low-energy operators
Dimension-3



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

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

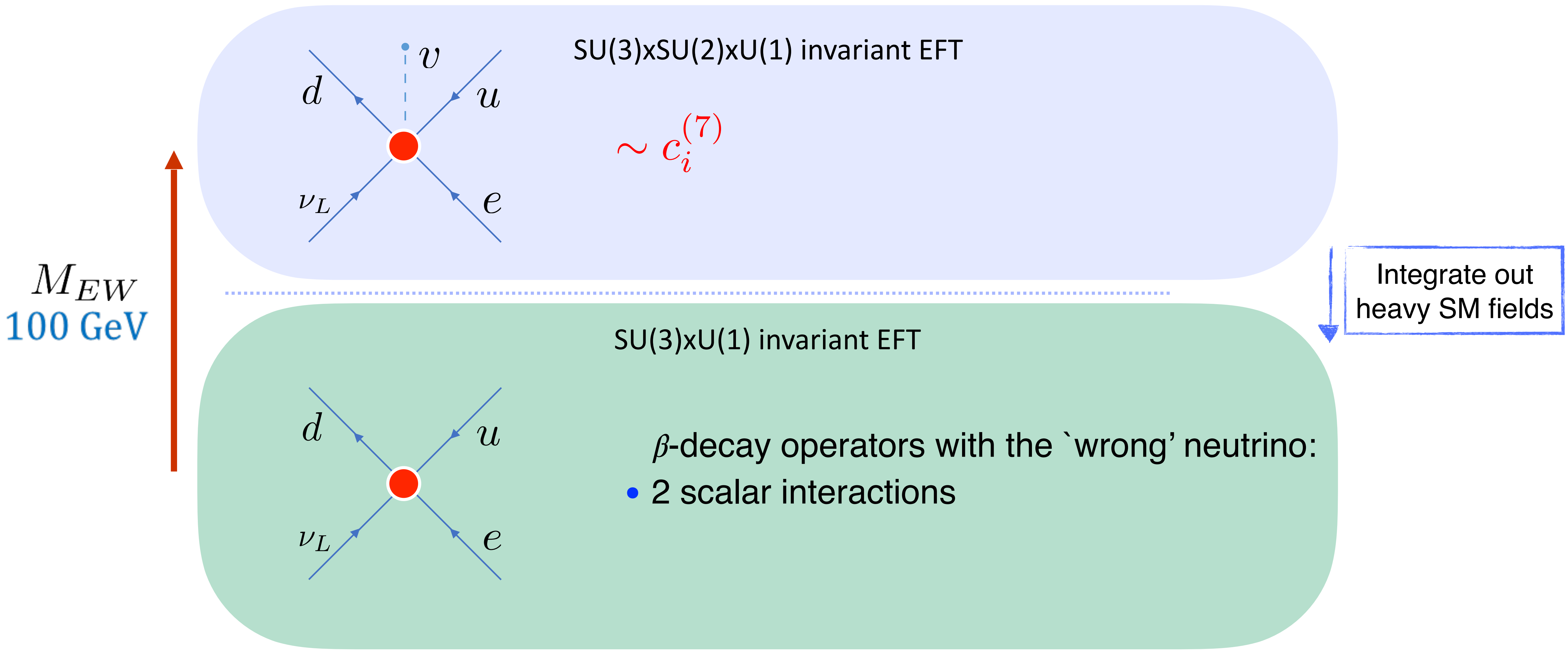
Low-energy operators
Dimension-6



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

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

Low-energy operators
Dimension-6

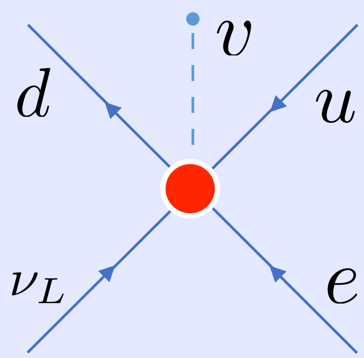


$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big\{ C^{(6)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j}$$

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

Low-energy operators
Dimension-6

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

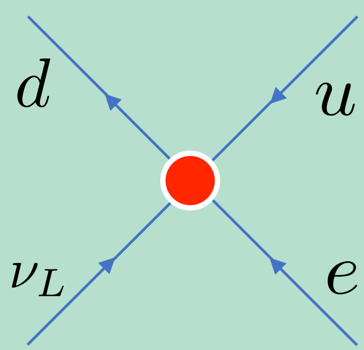


$\sim c_i^{(7)}$

M_{EW}
100 GeV

Integrate out heavy SM fields

SU(3)xU(1) invariant EFT

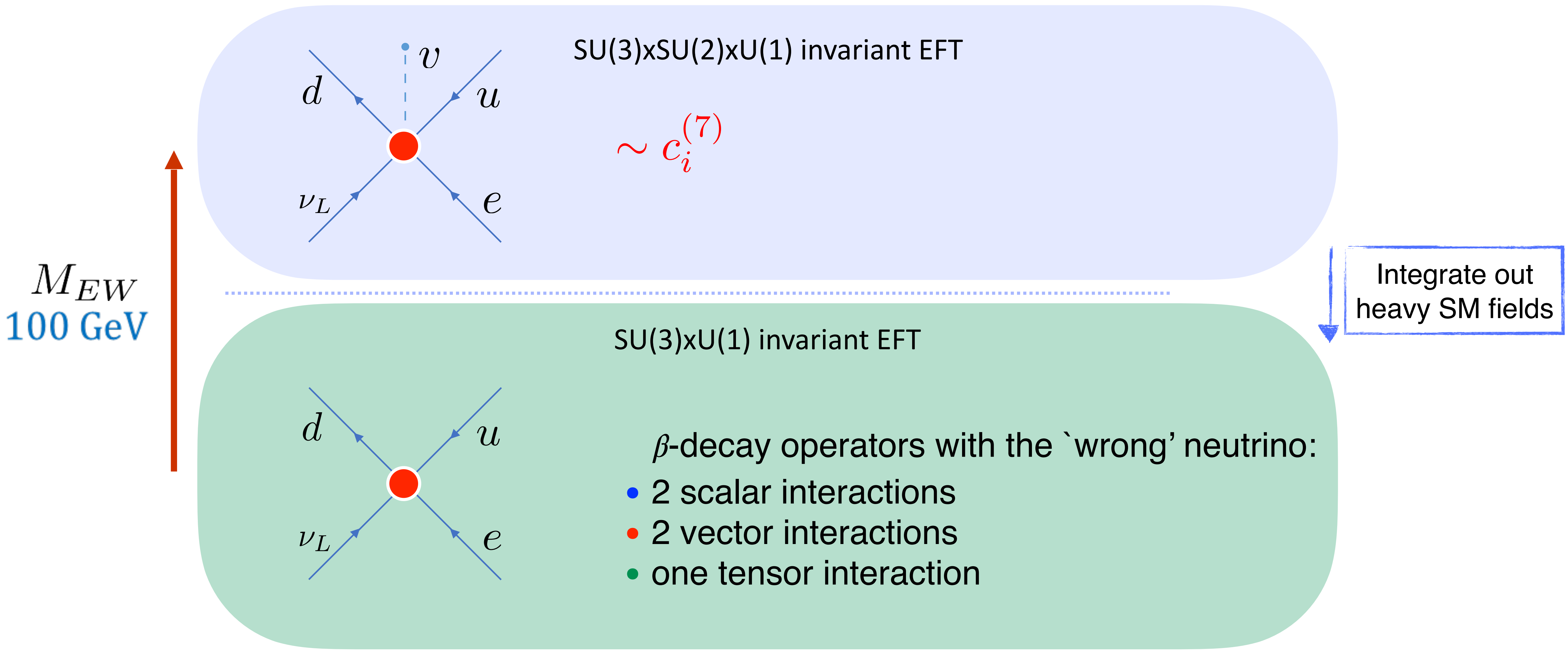


β-decay operators with the `wrong' neutrino:

- 2 scalar interactions
- 2 vector interactions

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

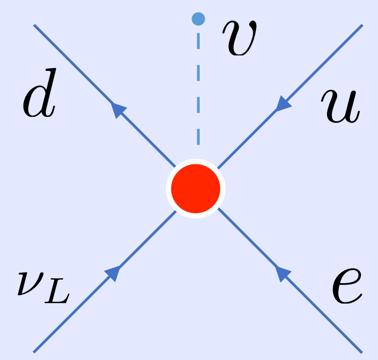
Low-energy operators
Dimension-6



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

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

Low-energy operators
Dimension-6



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

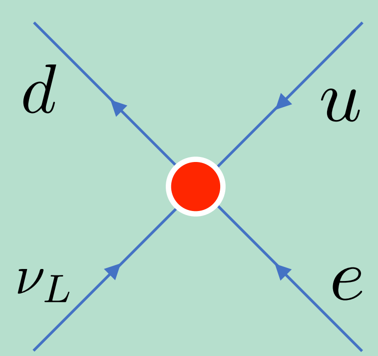
$\sim c_i^{(7)}$

M_{EW}

100 GeV

Integrate out heavy SM fields

SU(3)xU(1) invariant EFT



β-decay operators with the `wrong' neutrino:

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

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

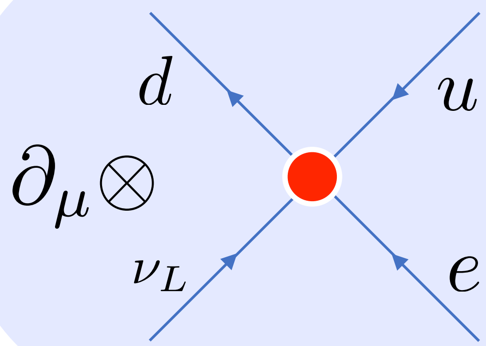
$$C_i^{(6)} \sim v^3/\Lambda^3$$

Low-energy operators
Dimension-7

M_{EW}

100 GeV

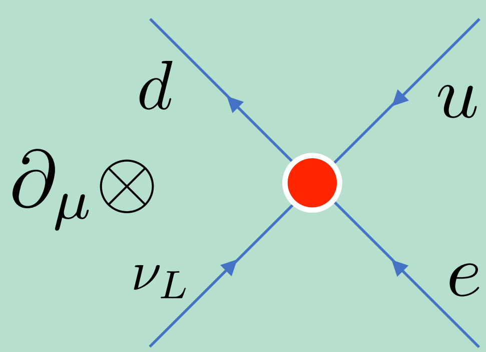
SU(3)xSU(2)xU(1) invariant EFT



$\sim c_i^{(7)}$

Integrate out heavy SM fields

SU(3)xU(1) invariant EFT



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

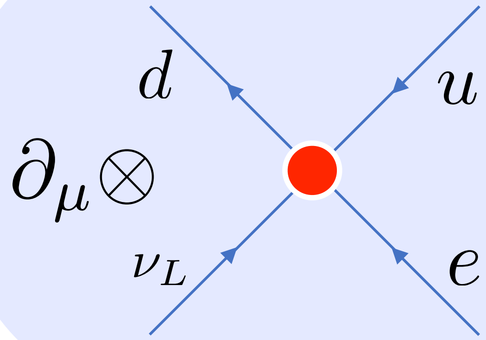
- Two vector-like operators

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

Low-energy operators
Dimension-7

M_{EW}
100 GeV

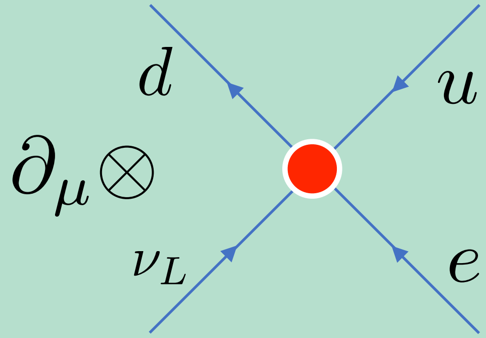
SU(3)xSU(2)xU(1) invariant EFT



$\sim c_i^{(7)}$

Integrate out heavy SM fields

SU(3)xU(1) invariant EFT



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

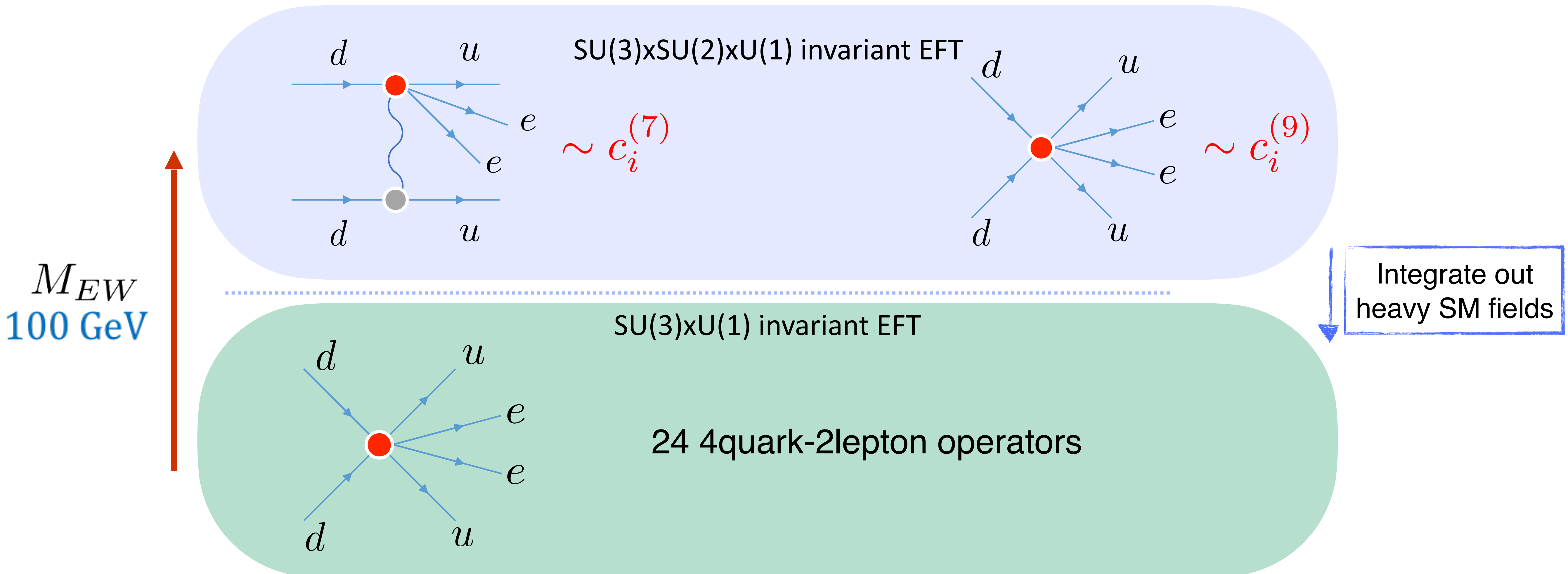
- Two vector-like operators

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

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

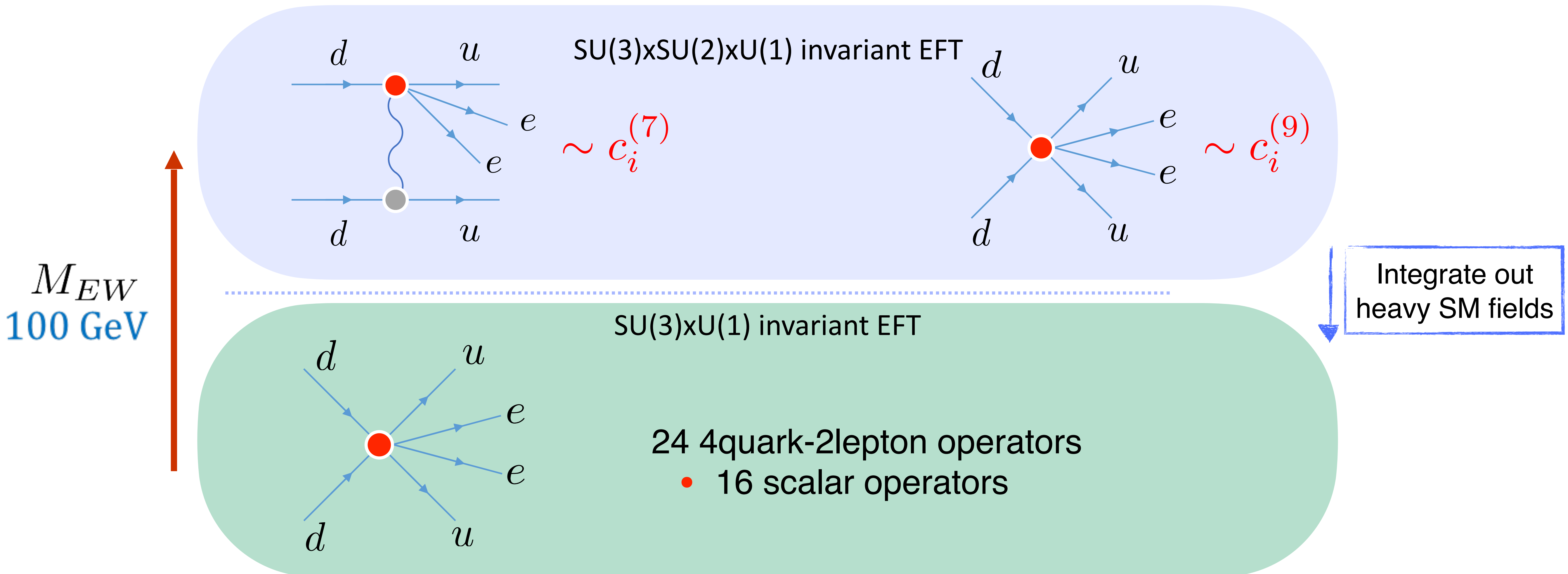
$$C_i^{(7)} \sim v^3/\Lambda^3$$

Low-energy operators
Dimension-9



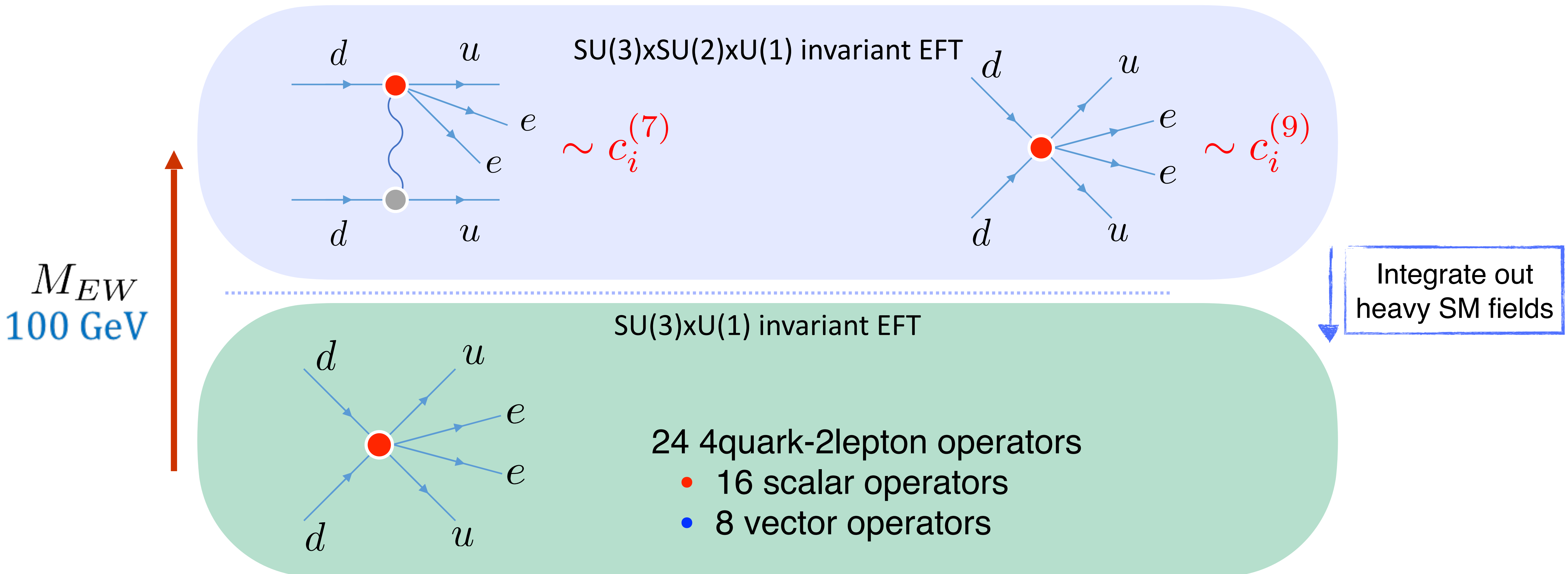
$$\mathcal{L}_{\Delta L=2}^{(9)} = \frac{1}{v^5} \sum_i \left[\left(C_{i\,\mathrm{R}}^{(9)} \, \bar{e}_R C \bar{e}_R^T + C_{i\,\mathrm{L}}^{(9)} \, \bar{e}_L C \bar{e}_L^T \right) O_i + C_i^{(9)} \bar{e} \gamma_\mu \gamma_5 C \bar{e}^T \, O_i^\mu \right],$$

Low-energy operators
Dimension-9



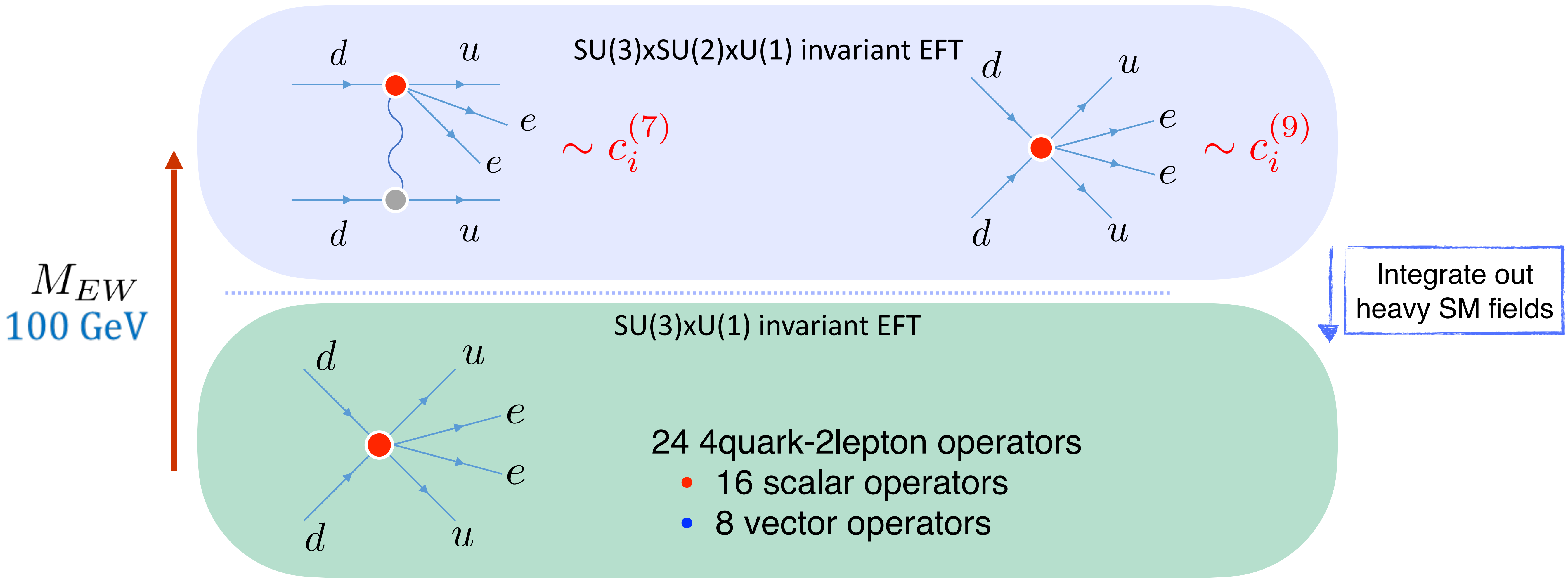
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \left[\left(C^{(9)}_{i\,\mathrm{R}}\, \bar{e}_R C \bar{e}_R^T + C^{(9)}_{i\,\mathrm{L}}\, \bar{e}_L C \bar{e}_L^T \right) O_i + C_i^{(9)}\, \bar{e}\gamma_\mu\gamma_5 C \bar{e}^T\, O_i^\mu \right],$$

Low-energy operators
Dimension-9



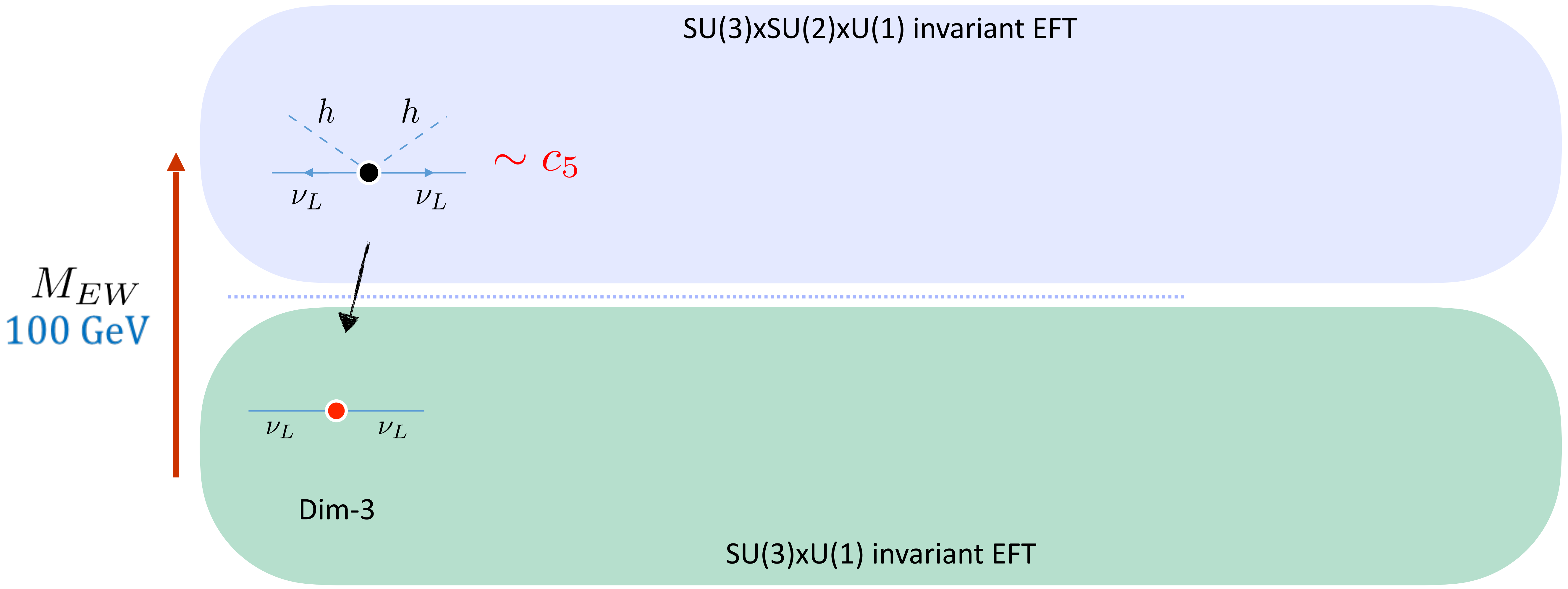
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \left[\left(C^{(9)}_{i\,\mathrm{R}}\, \bar{e}_R C \bar{e}_R^T + C^{(9)}_{i\,\mathrm{L}}\, \bar{e}_L C \bar{e}_L^T \right) O_i + C^{(9)}_i \bar{e}\gamma_\mu\gamma_5 C \bar{e}^T O_i^\mu \right],$$

Low-energy operators
Dimension-9

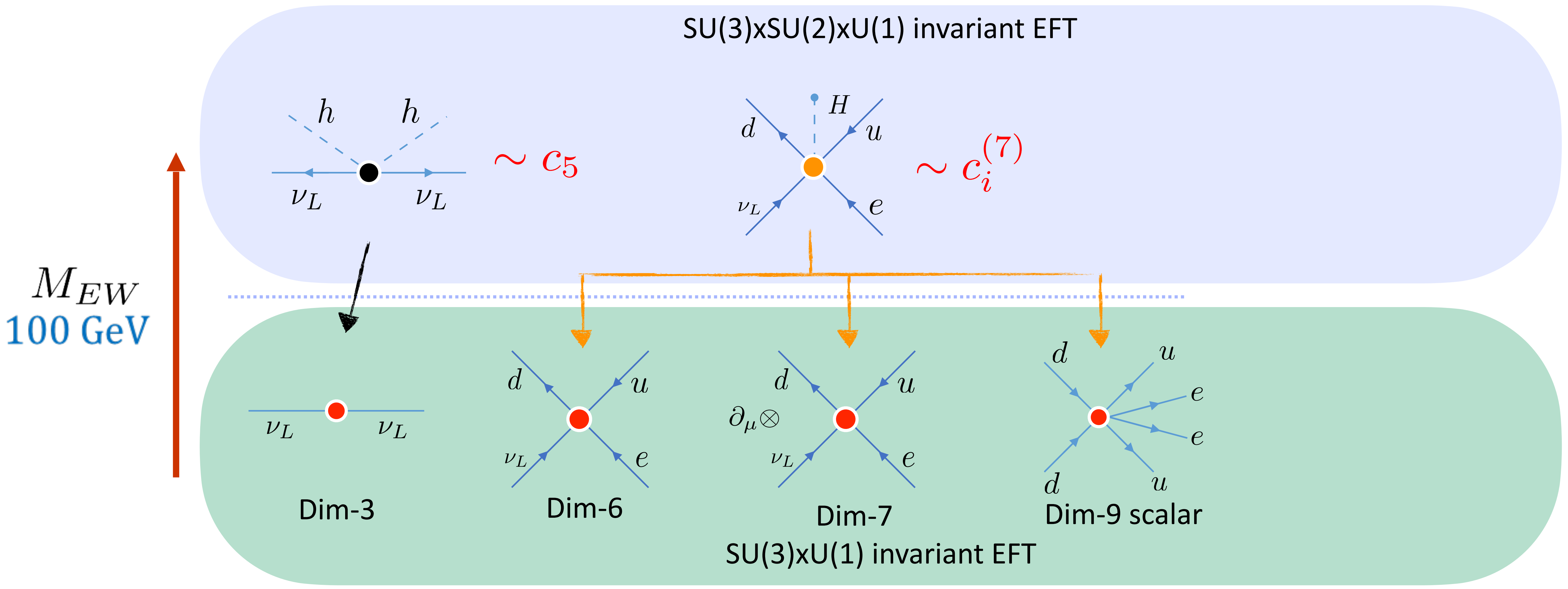


- 3 can be induced by dimension-7 operators $C_i^{(9)} \sim v^3/\Lambda^3$
- 19 can be induced by dimension-9 operators $C_i^{(9)} \sim v^5/\Lambda^5$

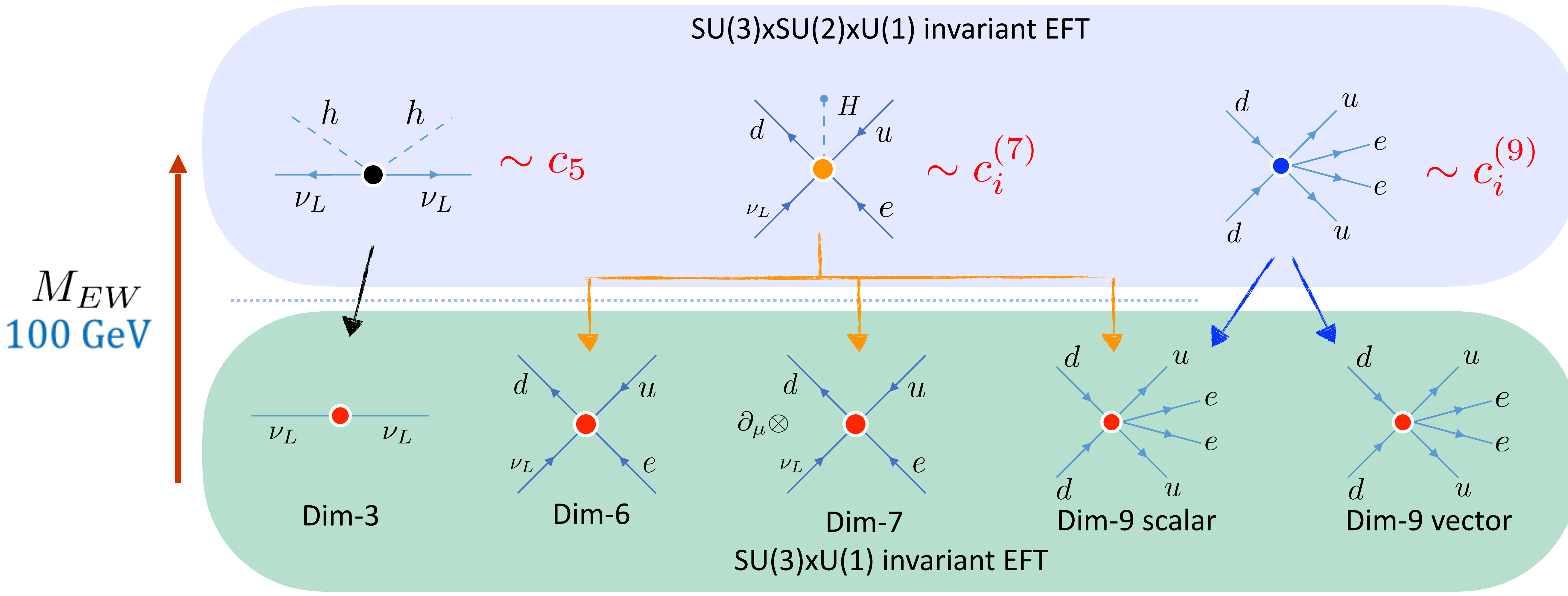
Low-energy operators
Summary



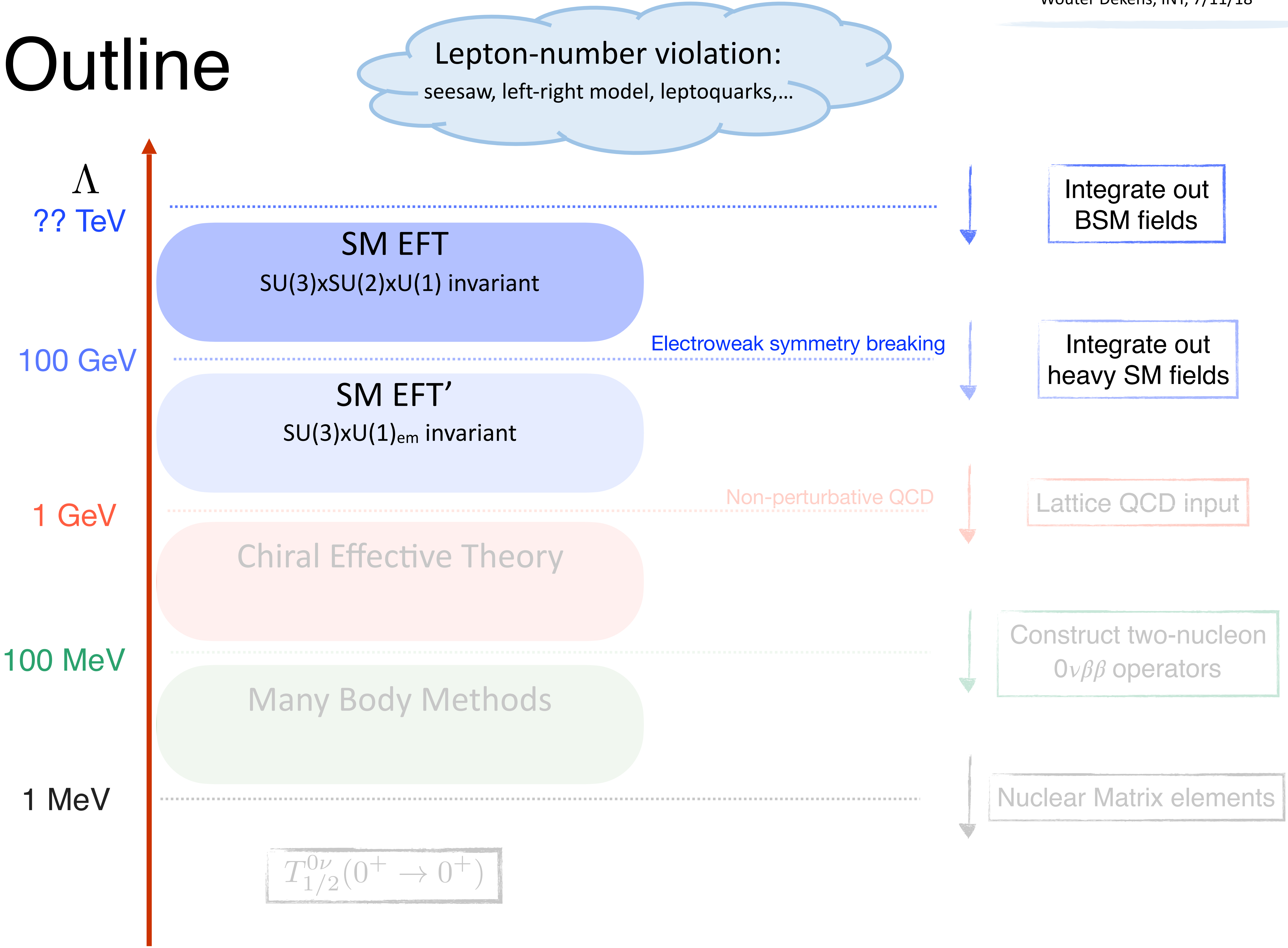
Low-energy operators
Summary



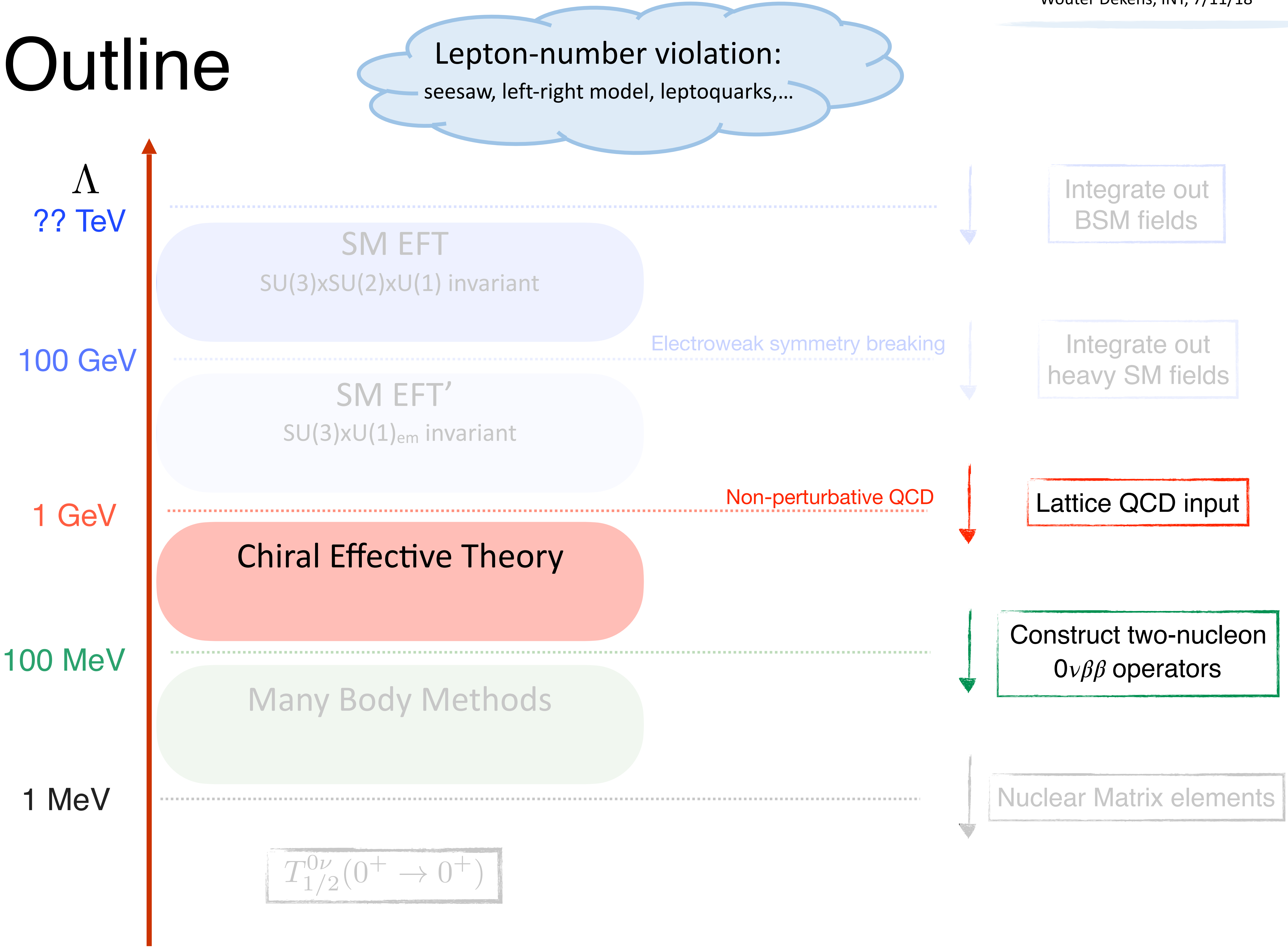
Low-energy operators
Summary



Outline


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

Outline



Lepton-number violation:
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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

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

Unknown constants (LECs) require non-perturbative input

- Lattice calculations / Experiment
- Naive dimensional analysis

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

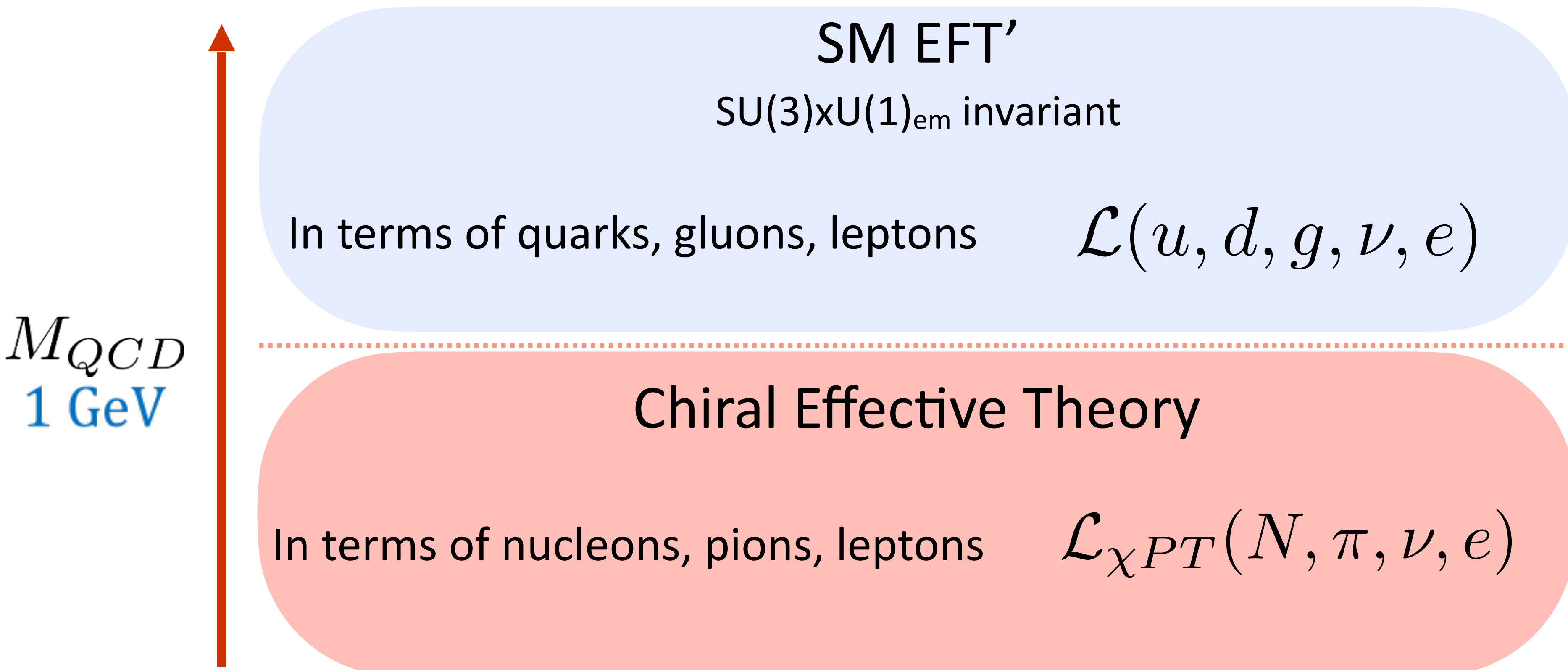
In terms of nucleons, pions, leptons $\mathcal{L}_{\chi PT}(N, \pi, \nu, e)$

Form of operators determined by chiral symmetry

Unknown constants (LECs) require non-perturbative input

- Lattice calculations / Experiment
- Naive dimensional analysis
- Arguments based on renormalization

Matching to Chiral EFT



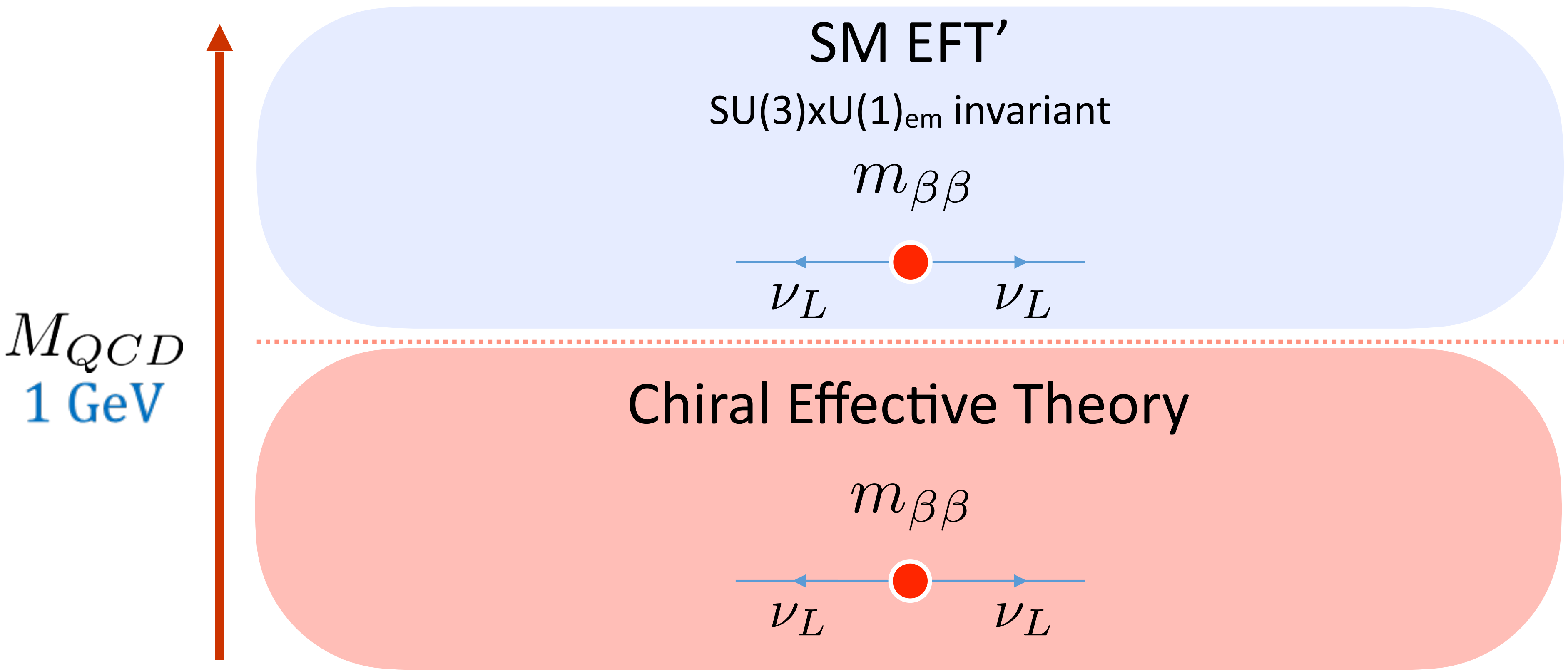
Form of operators determined by chiral symmetry

Unknown constants (LECs) require non-perturbative input
- Lattice calculations / Experiment
- Naive dimensional analysis
- Arguments based on renormalization

Matching to Chiral EFT

Majorana mass (dimension-3)

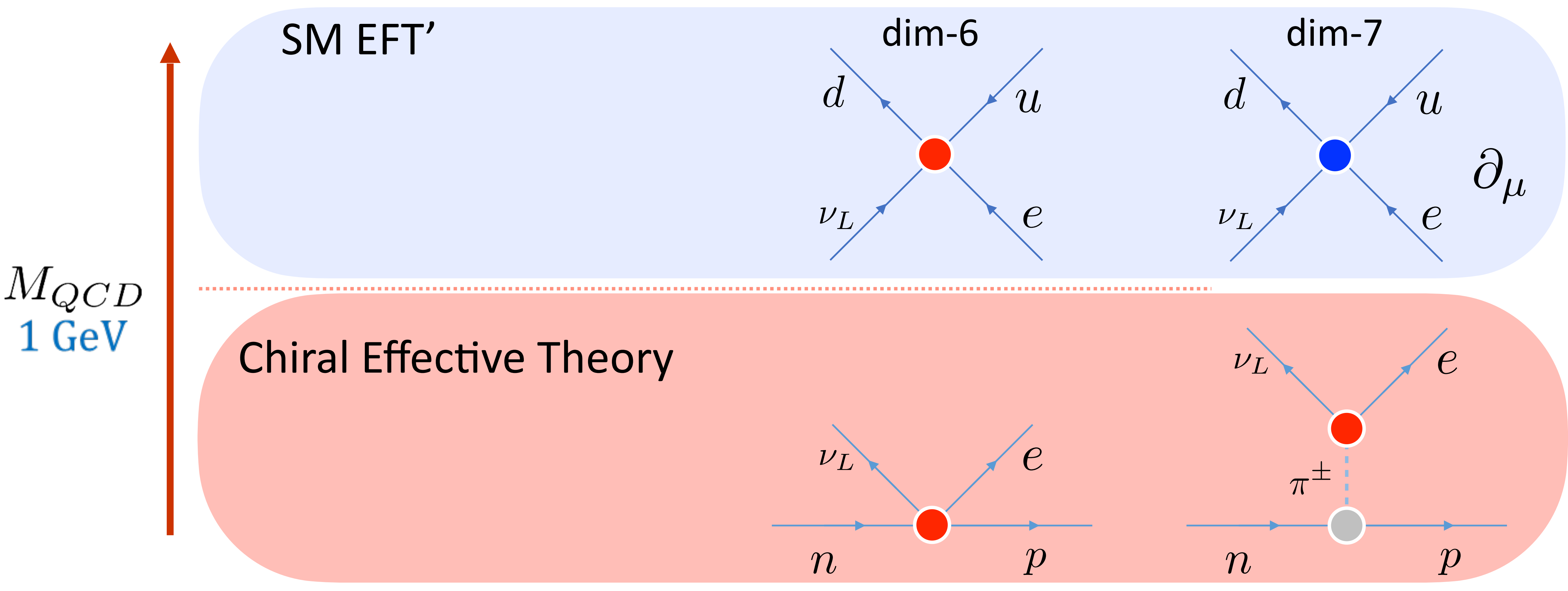
Warning: Based on NDA



Matching to Chiral EFT

Dimension-6 and -7

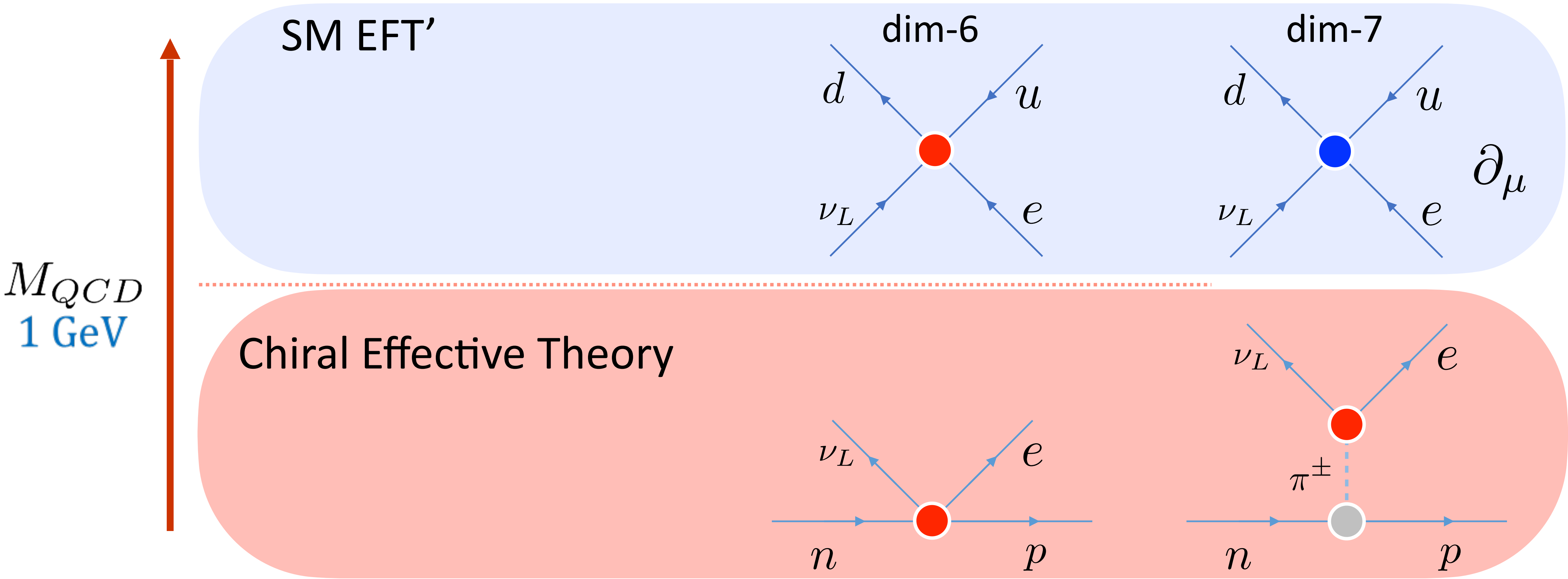
Warning: Based on NDA



Matching to Chiral EFT

Dimension-6 and -7

Warning: Based on NDA

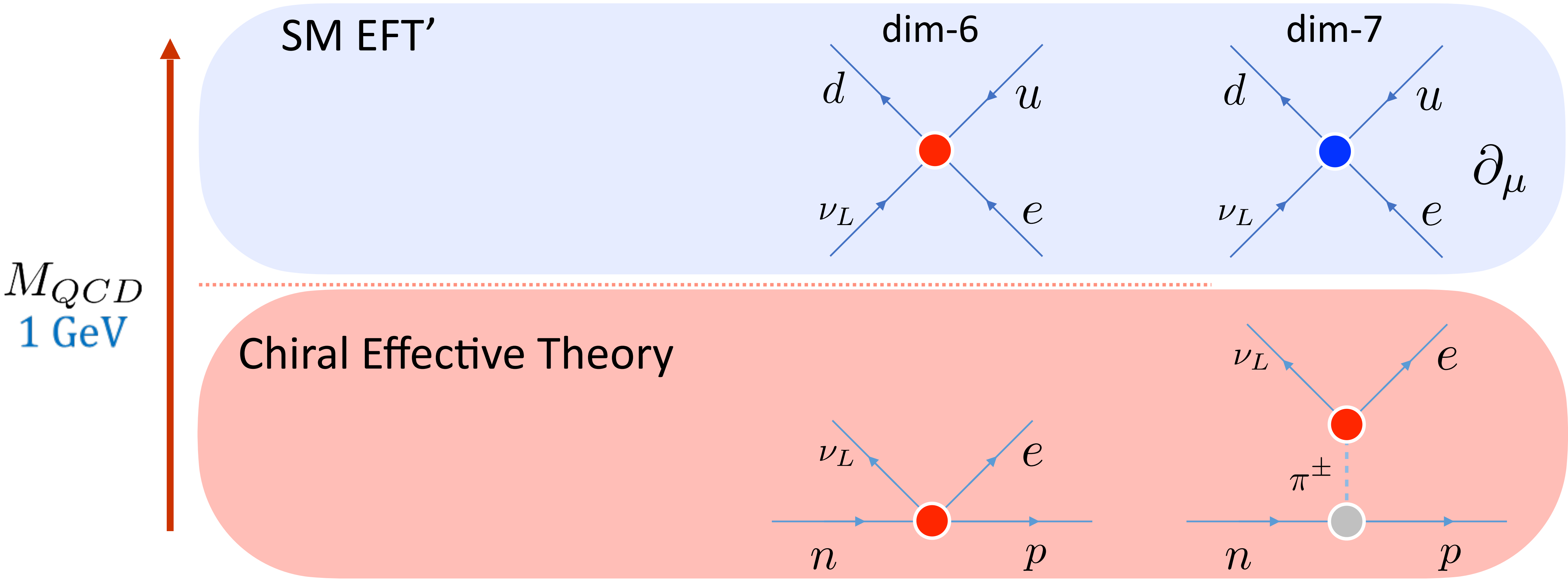


- Needed low-energy constants are the (scalar, vector, tensor) nucleon charges
  - g_V, g_A, g_S, g_M, g_T, g'_T

Matching to Chiral EFT

Dimension-6 and -7

Warning: Based on NDA



- Needed low-energy constants are the (scalar, vector, tensor) nucleon charges
  - g_V, g_A, g_S, g_M, g_T, g'_T

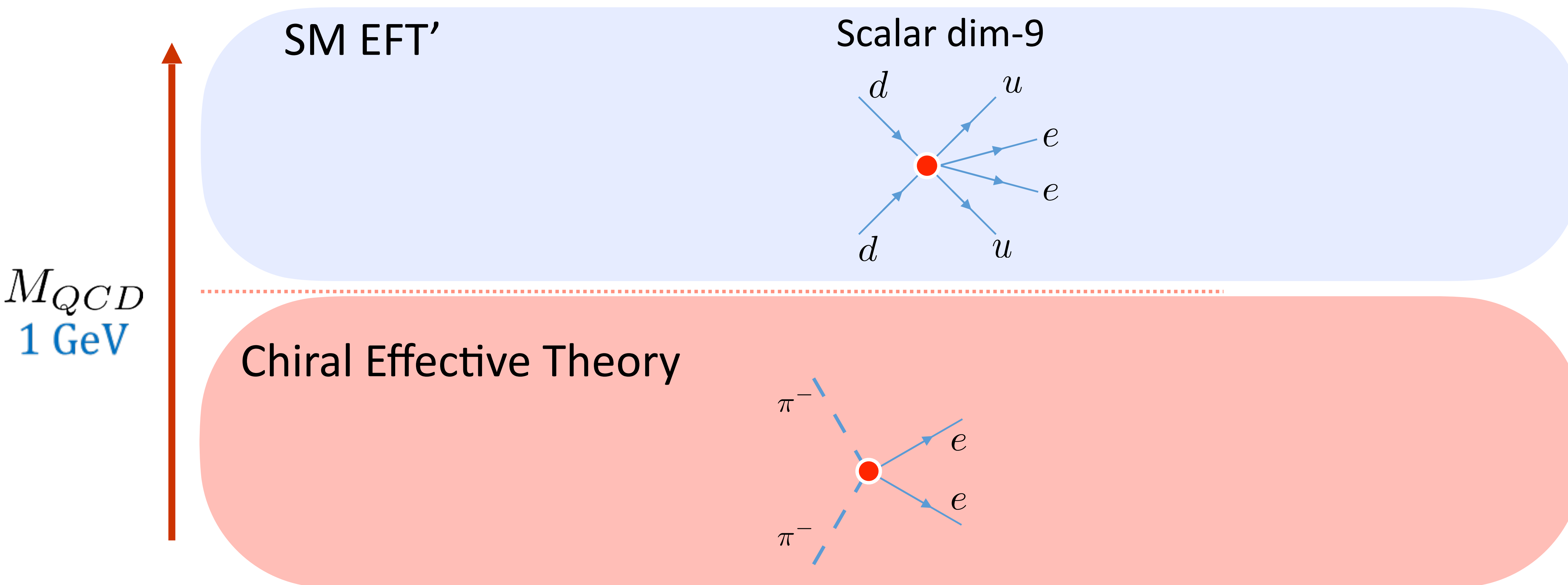
- Known from experiment and/or Lattice QCD
- Only estimates available, O(1) by NDA

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

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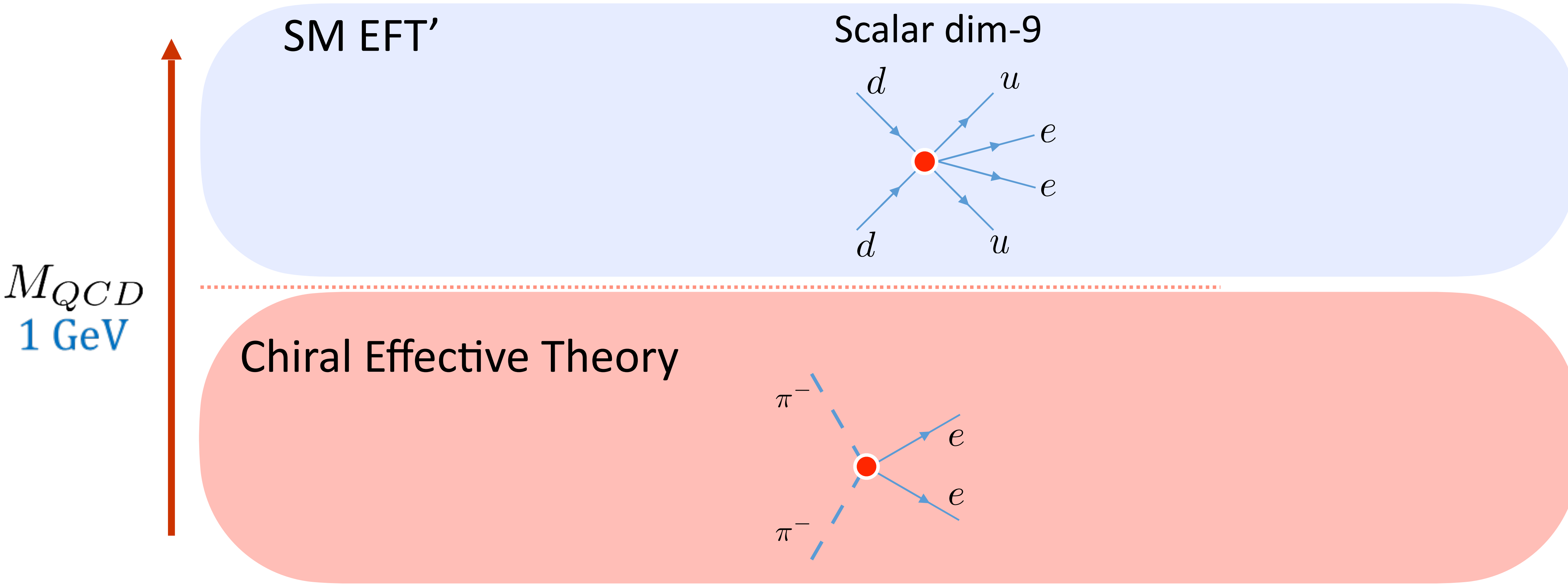
$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \left[\left(C^{(9)}_{i\,\mathrm{R}}\,\bar e_R C \bar e_R^T + C^{(9)}_{i\,\mathrm{L}}\,\bar e_L C\bar e_L^T\right) O_i + C_i^{(9)} \bar e\gamma_\mu\gamma_5 C\bar e^T O_i^\mu\right],$$

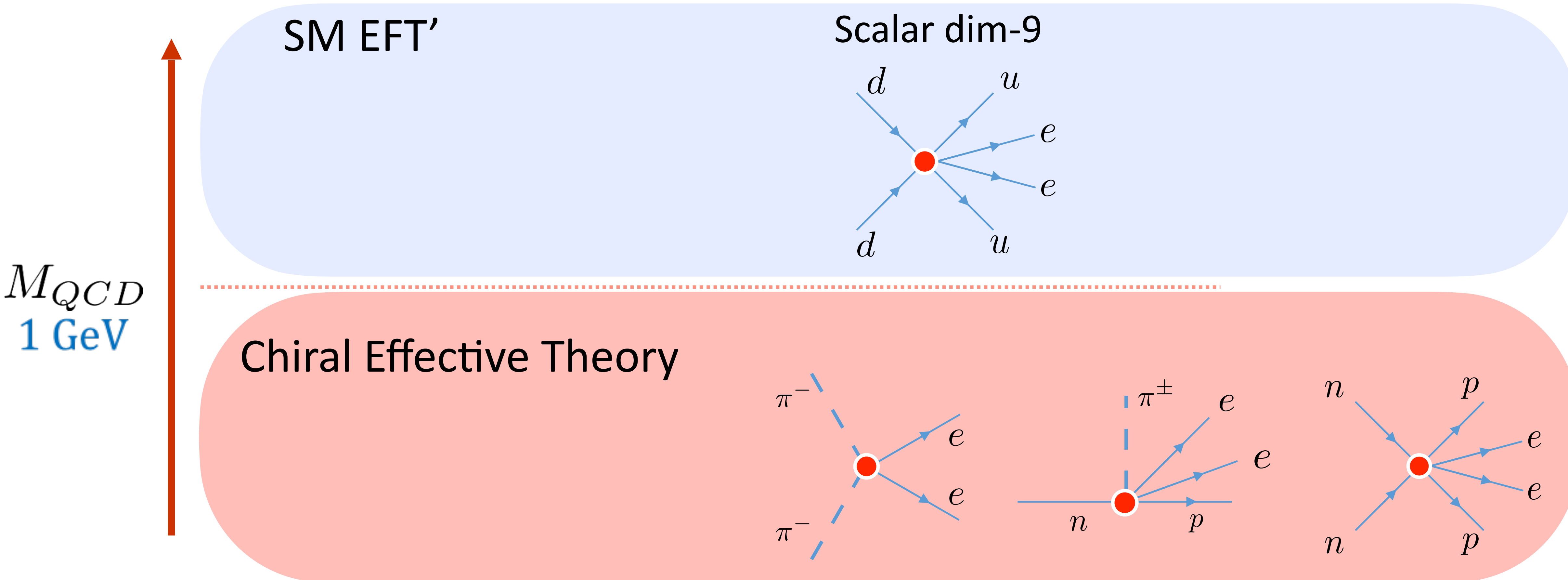


- Most scalar operators only induce $\pi\pi$ interactions

Matching to Chiral EFT
Dimension-9

Warning: Based on NDA

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

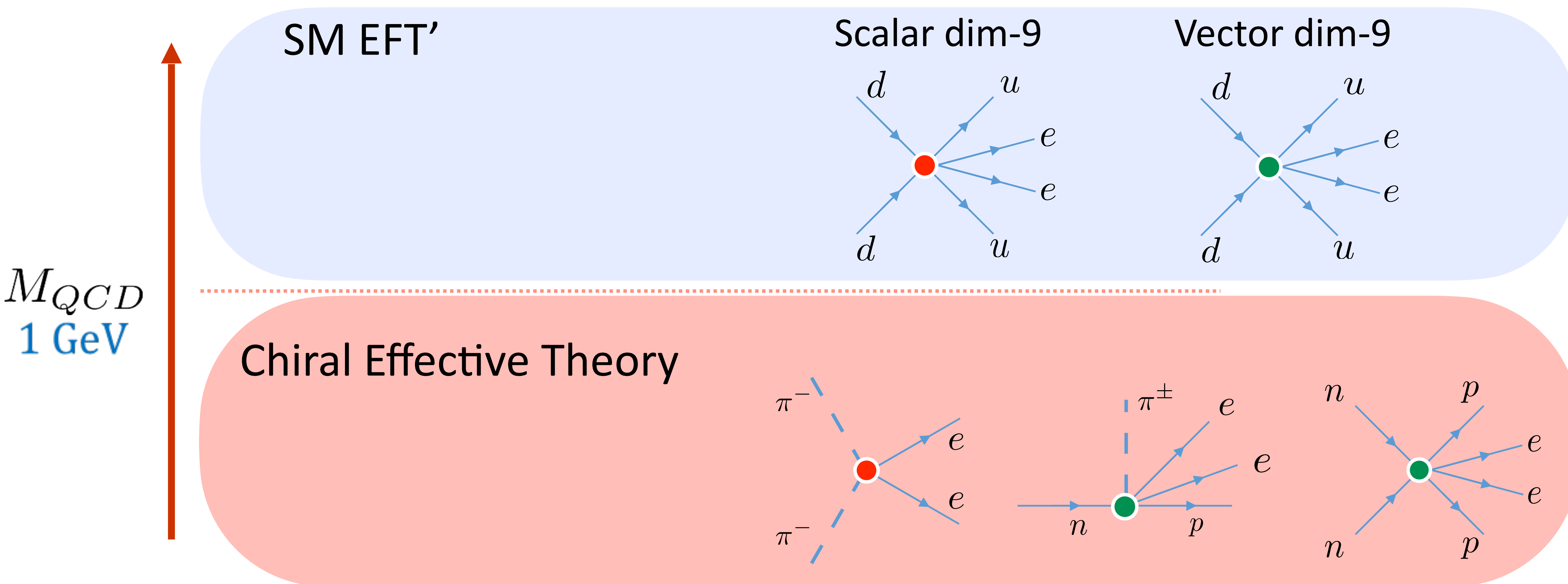


- Most scalar operators only induce $\pi\pi$ interactions
  - One hadronic structure for which πN & NN terms are important

Matching to Chiral EFT
Dimension-9

Warning: Based on NDA

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



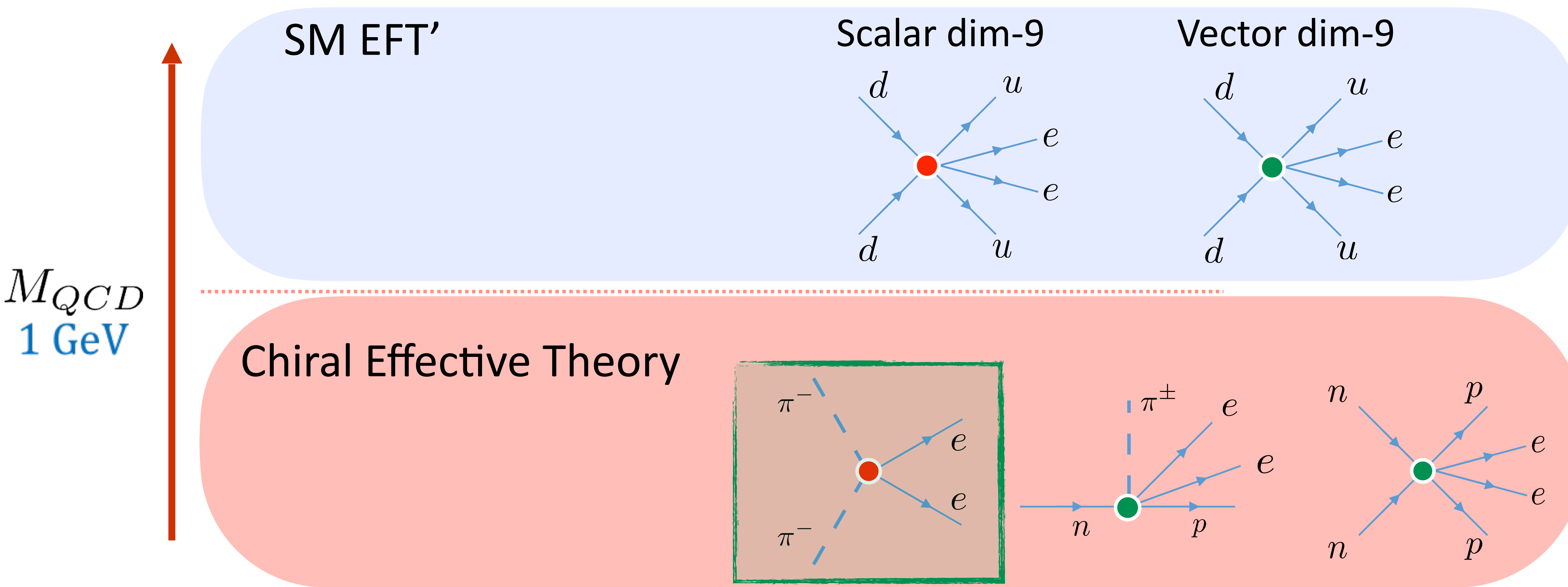
- Most scalar operators only induce $\pi\pi$ interactions
  - One hadronic structure for which πN & NN terms are important
- Vector operators induce πN & NN interactions

Matching to Chiral EFT

Dimension-9

Warning: Based on NDA

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



- The LECs for the $\pi\pi$ terms are known
  - Direct lattice calculation
  - K-Kbar mixing + SU(3) chiral symmetry

- Vector operators induce πN & NN interactions

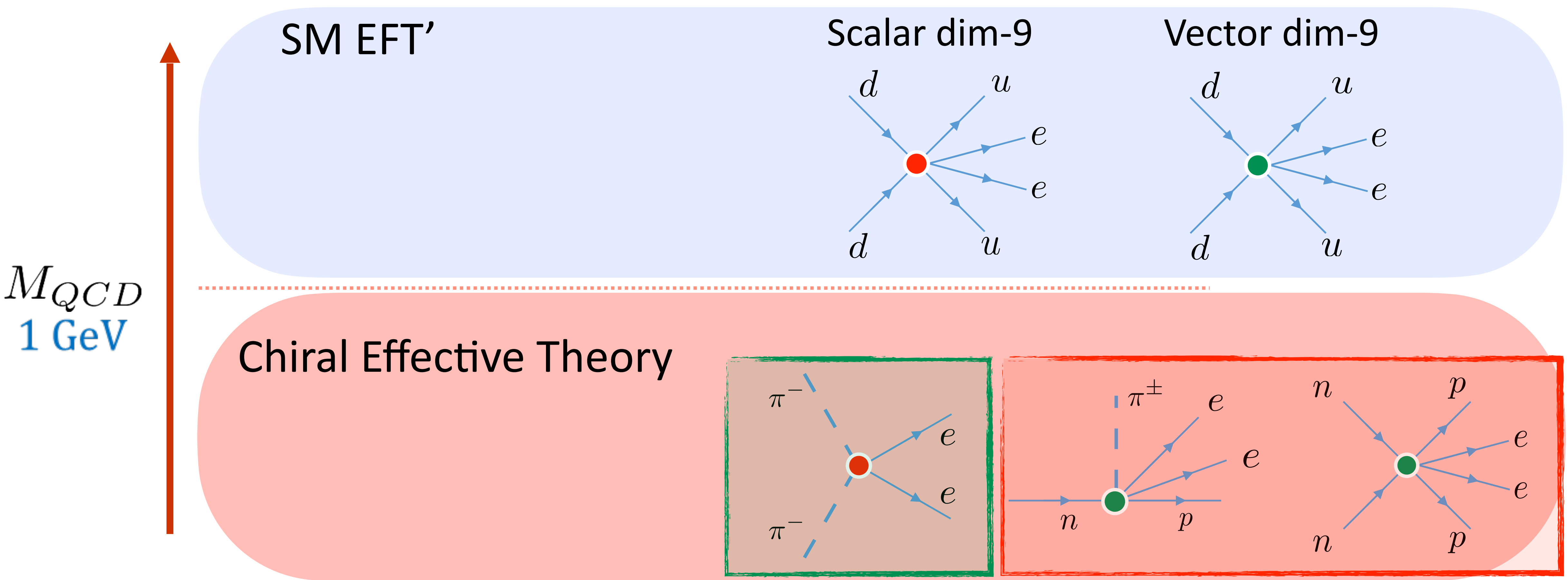
Nicholson et al.'18, Cirigliano et al. '17

Matching to Chiral EFT

Dimension-9

Warning: Based on NDA

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



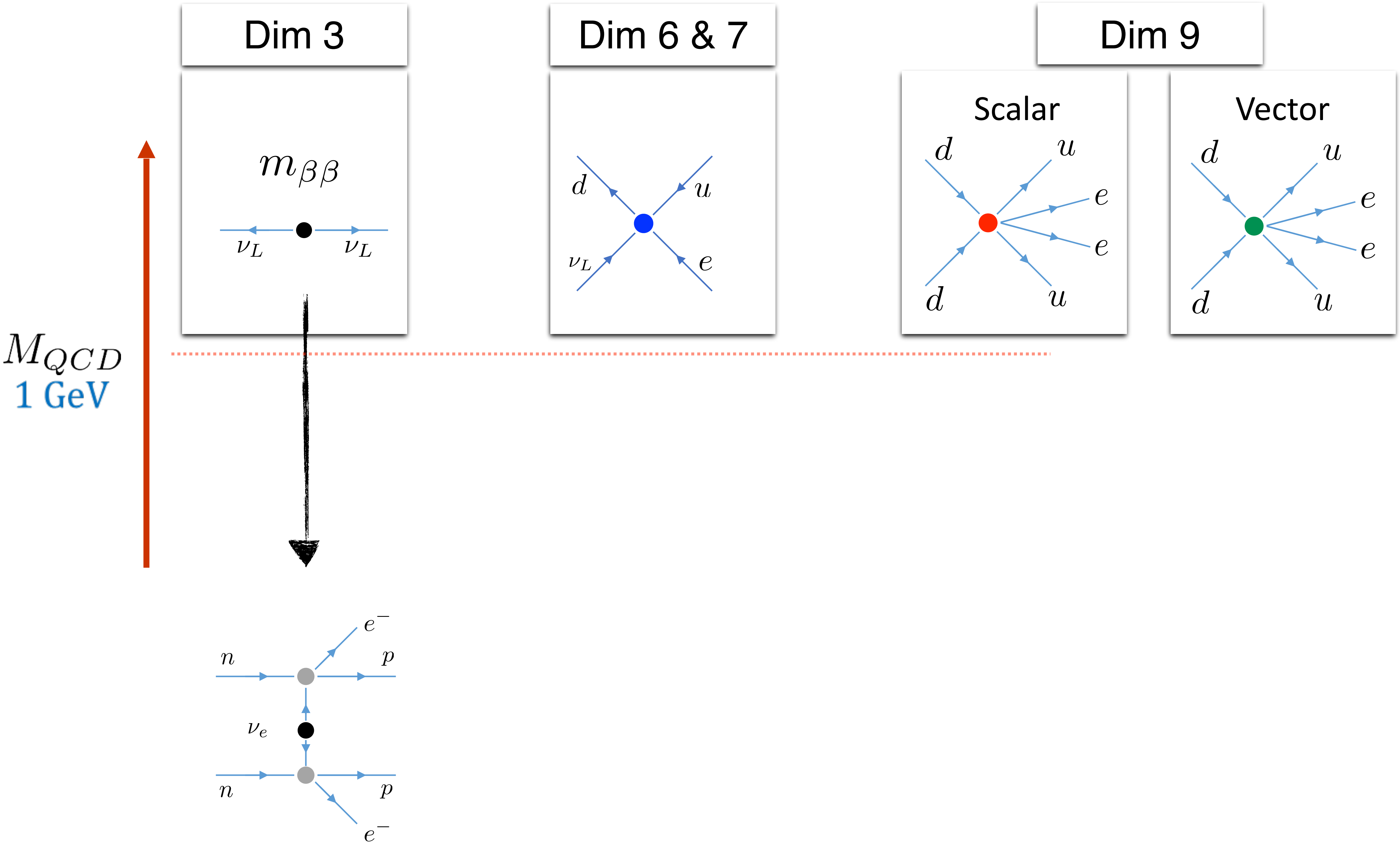
- The LECs for the $\pi\pi$ terms are known
  - Direct lattice calculation
  - K-Kbar mixing + SU(3) chiral symmetry

- The low-energy constants for the πN and NN interactions are unknown

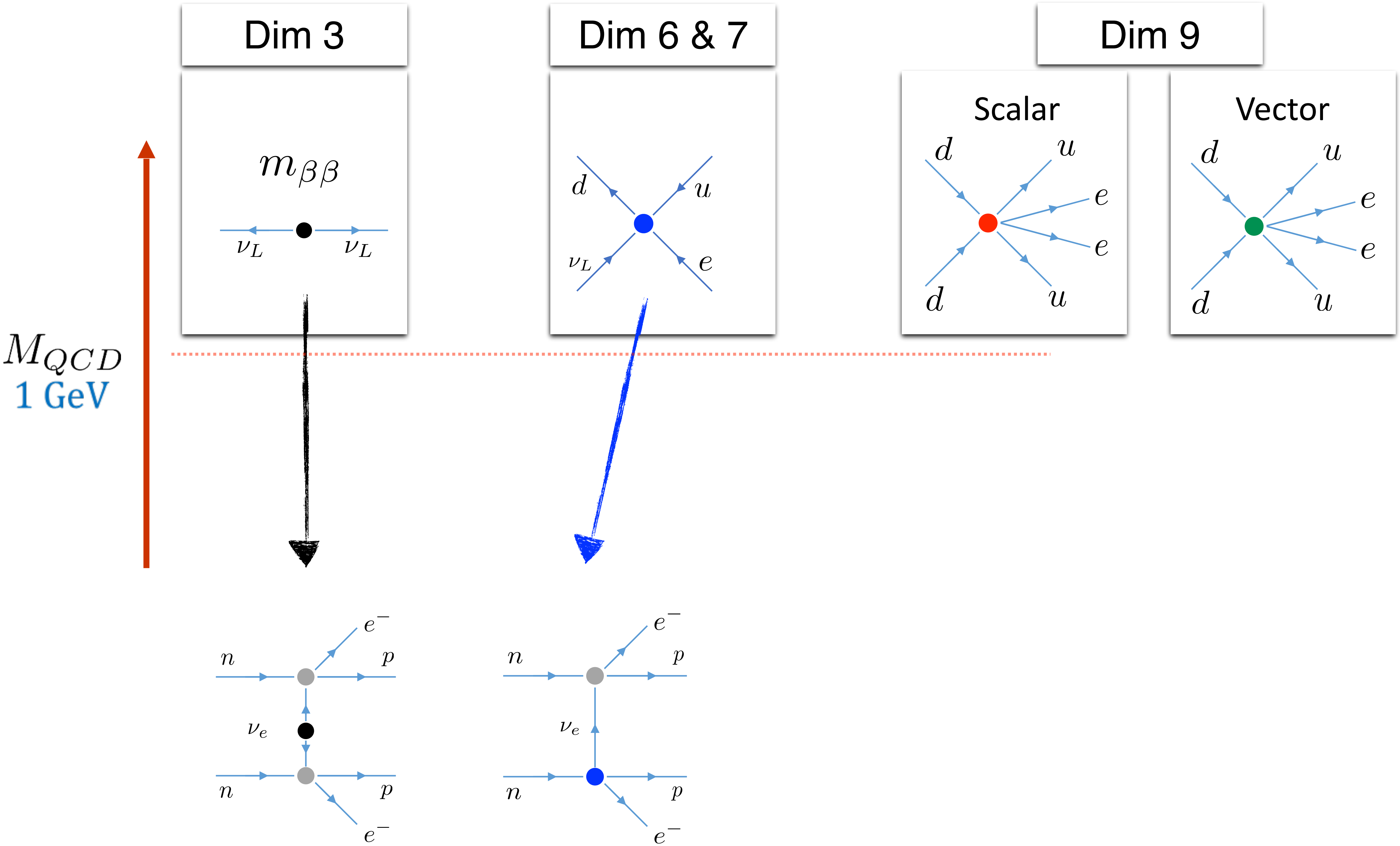
Nicholson et al.'18, Cirigliano et al. '17

Chiral EFT

Summary

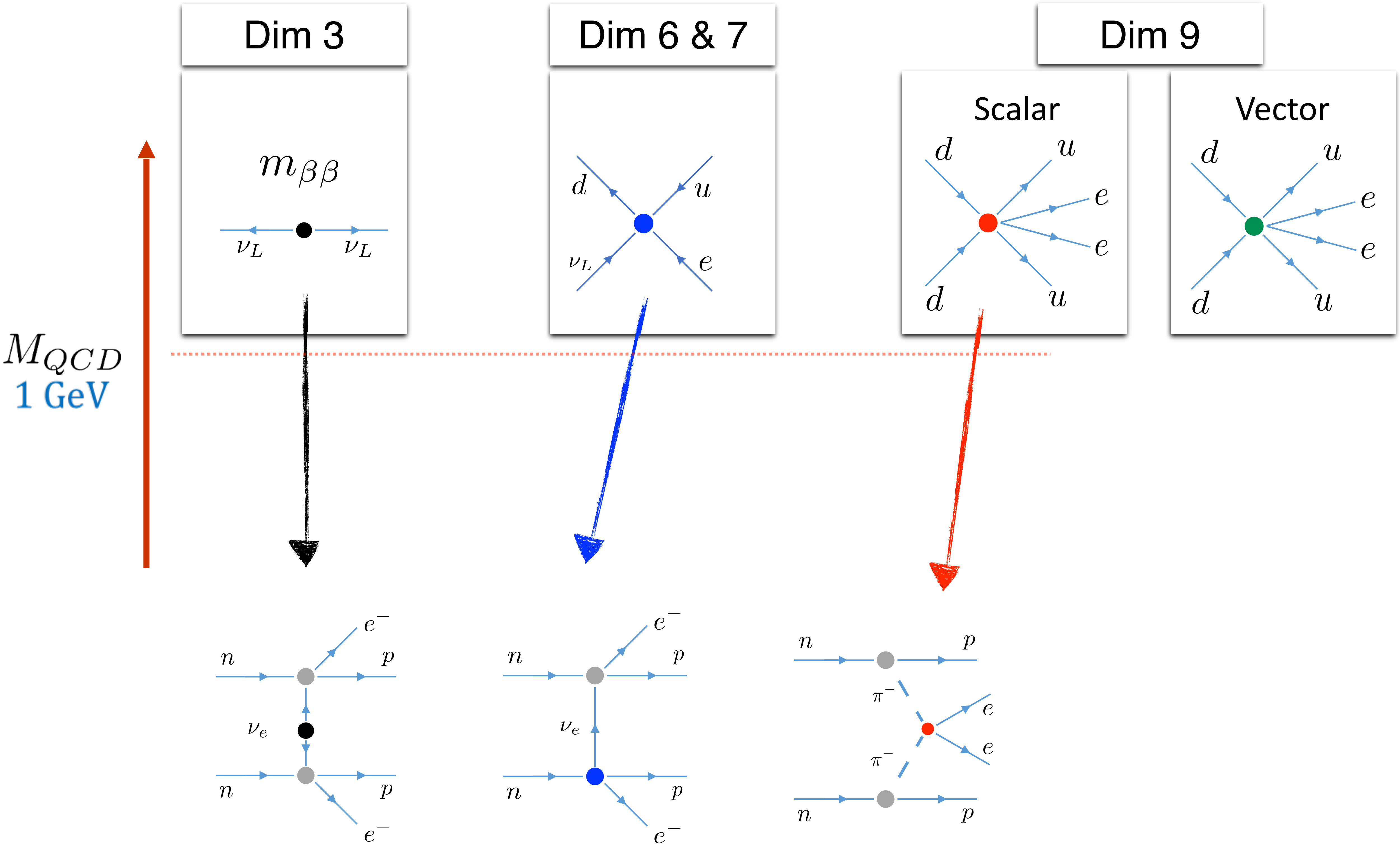


Chiral EFT
Summary



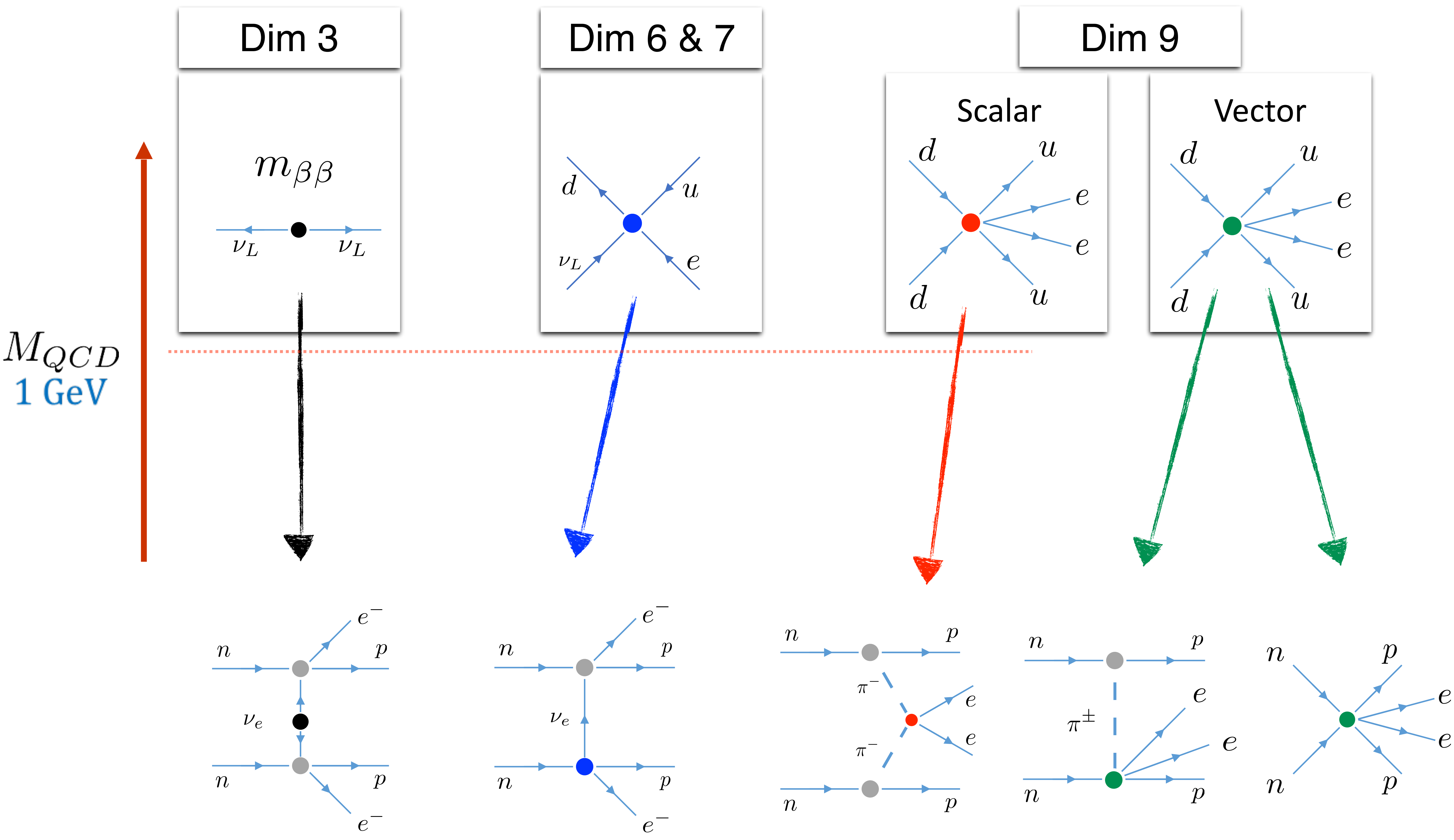
Chiral EFT

Summary



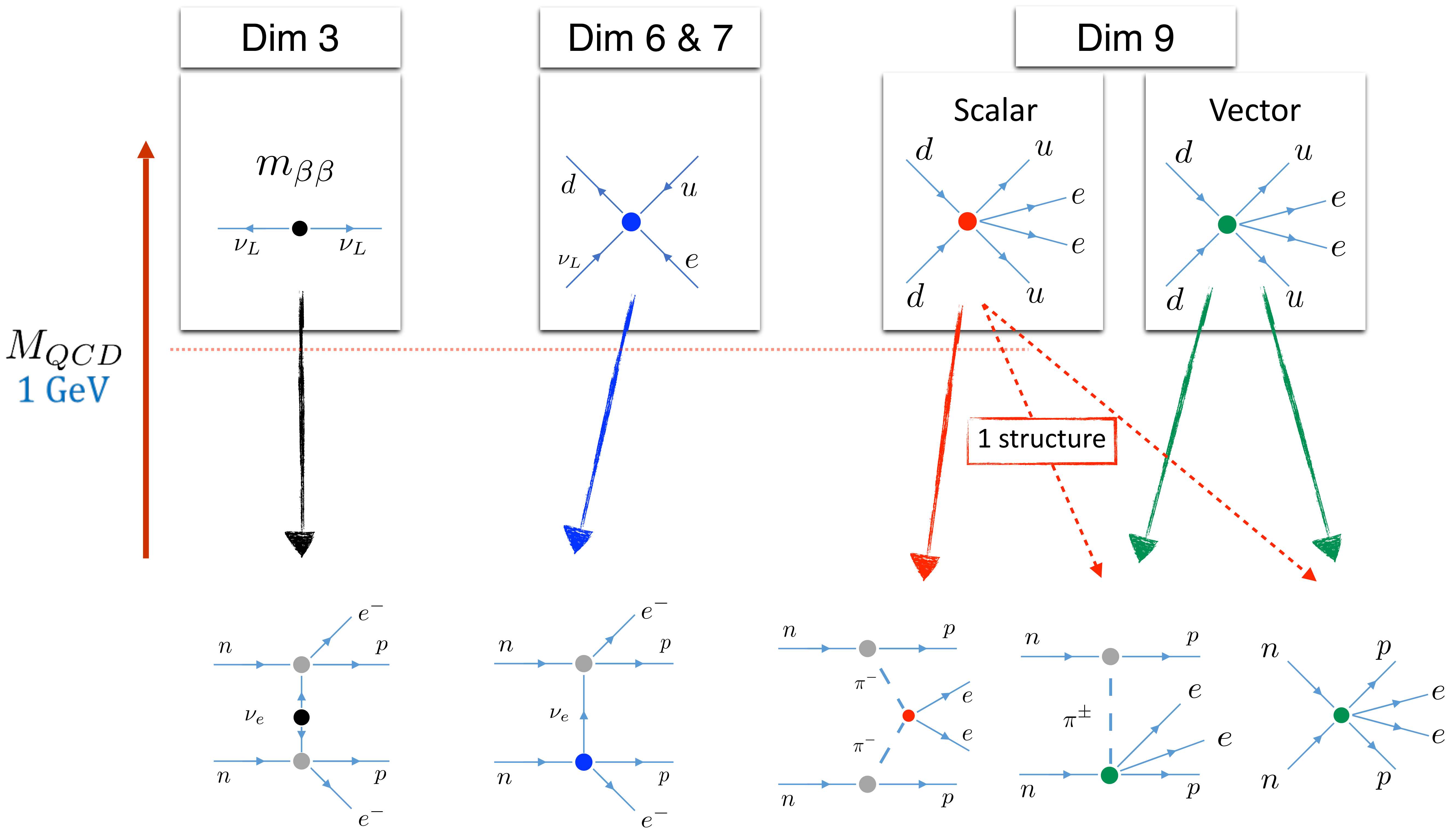
Chiral EFT

Summary



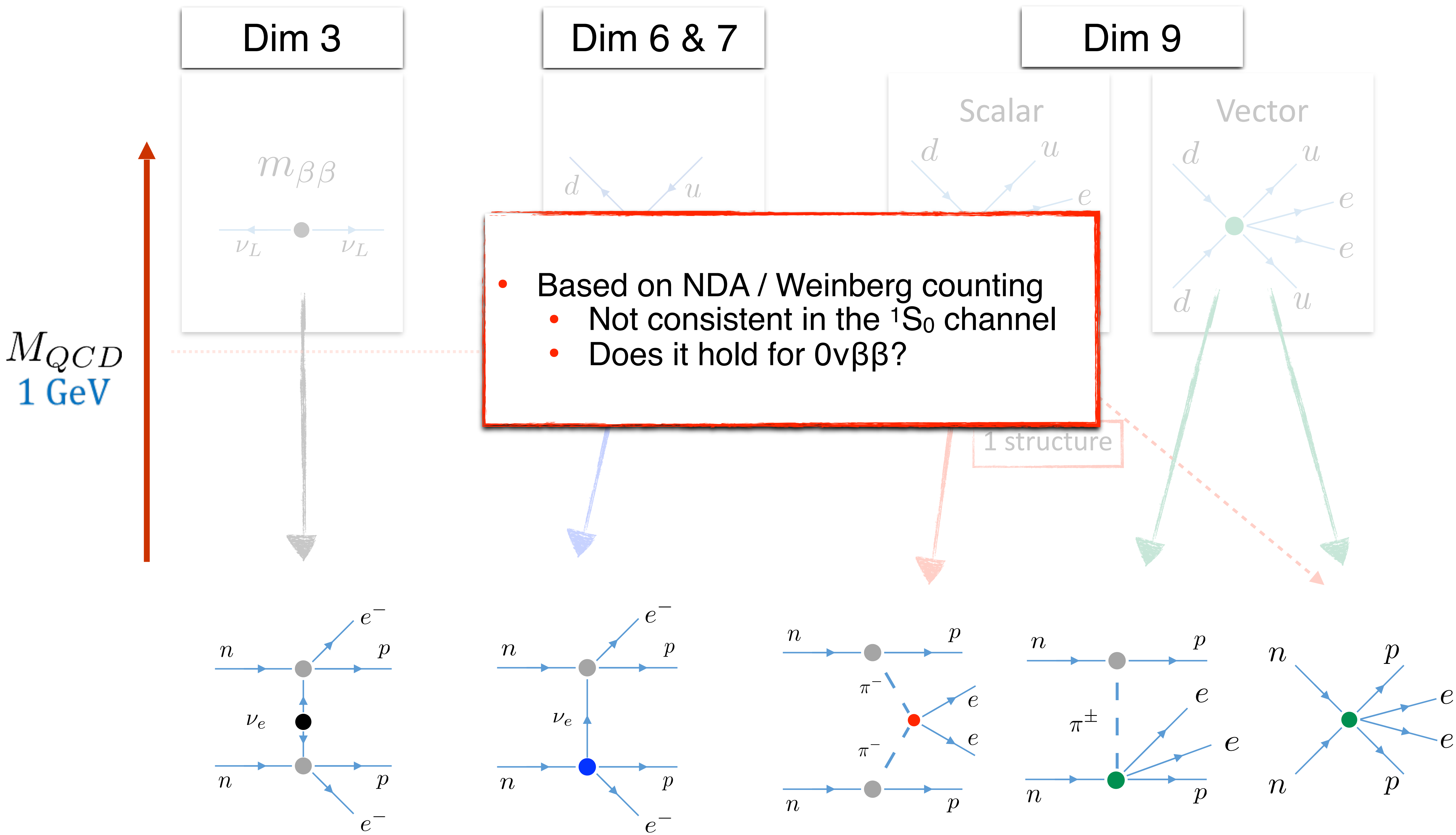
Chiral EFT

Summary



Chiral EFT

Summary



- 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 Weinberg counting

Majorana mass (dim 3)

- Use LO strong potential

$$V_0(\mathbf{q}) = \tilde{C} - \frac{g_A^2}{4F_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$

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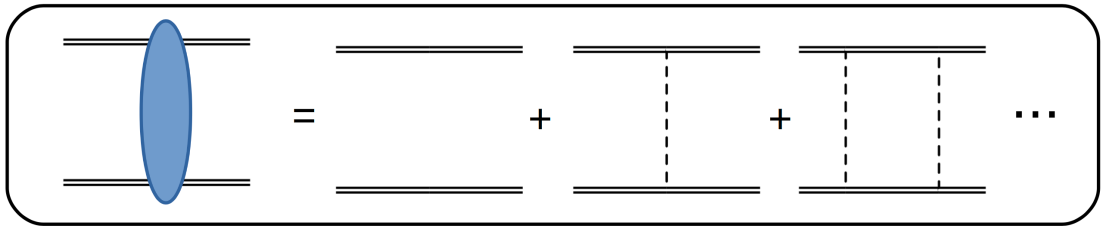
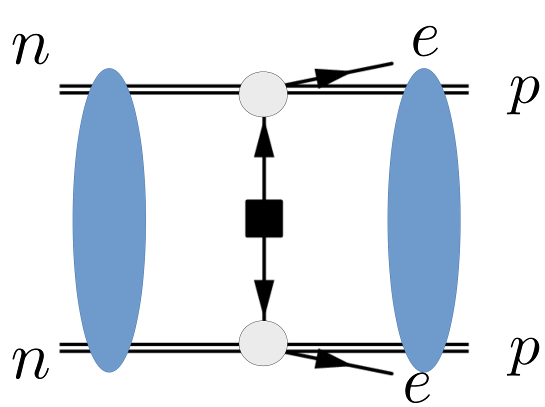
Check if LO $\mathcal{A}(nn \to ppee)$ is finite

Dress the ΔL=2 potential with strong interactions:





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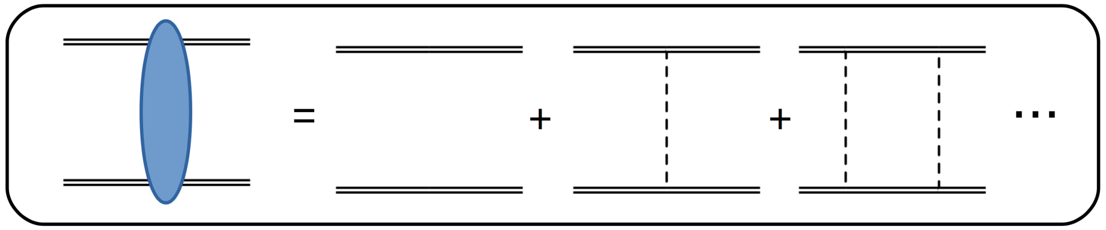

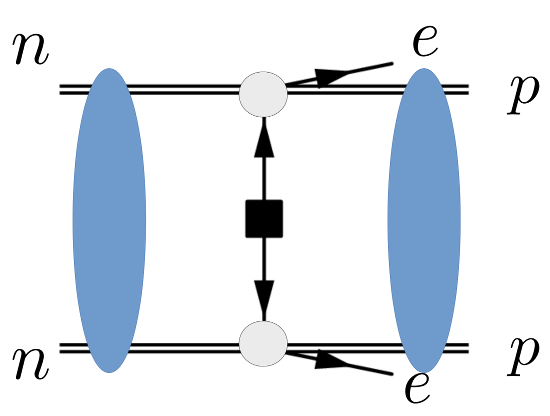

✓ finite

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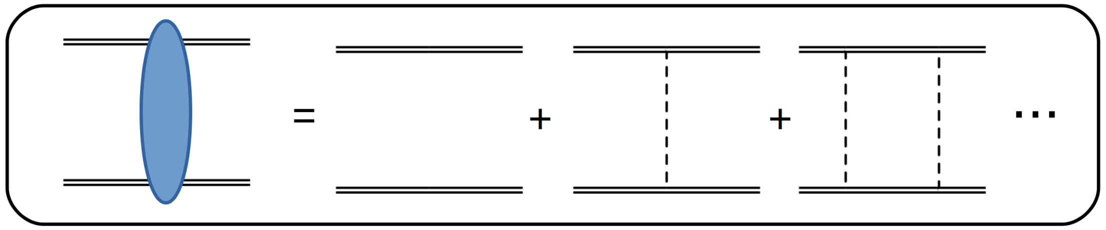

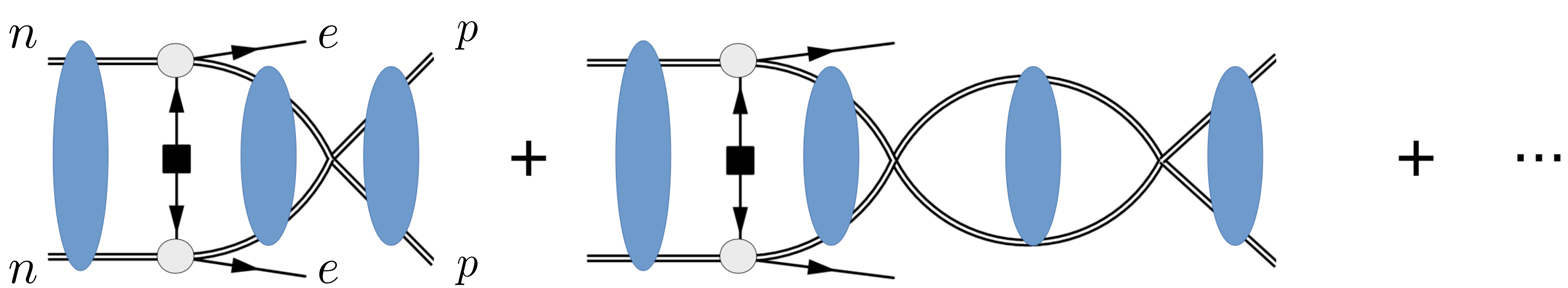

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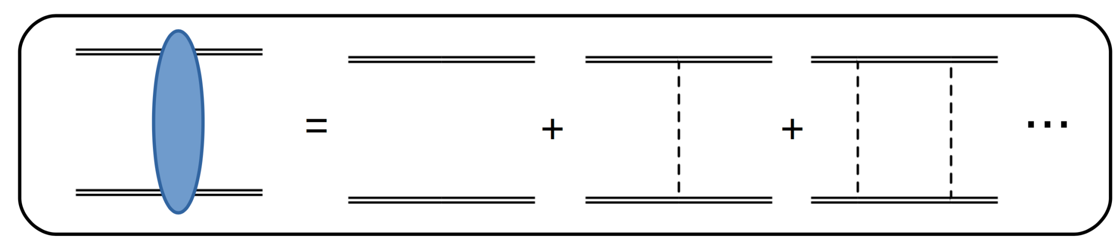

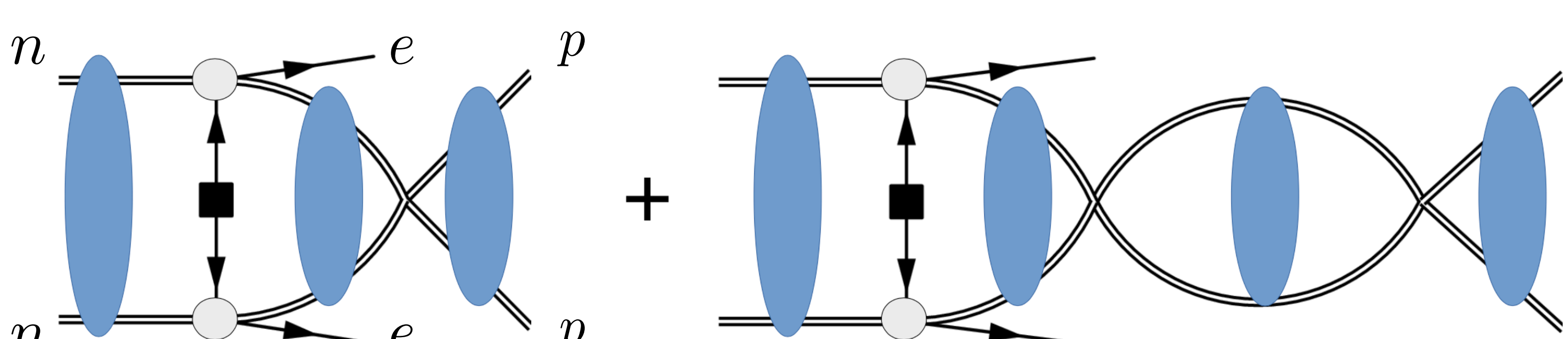

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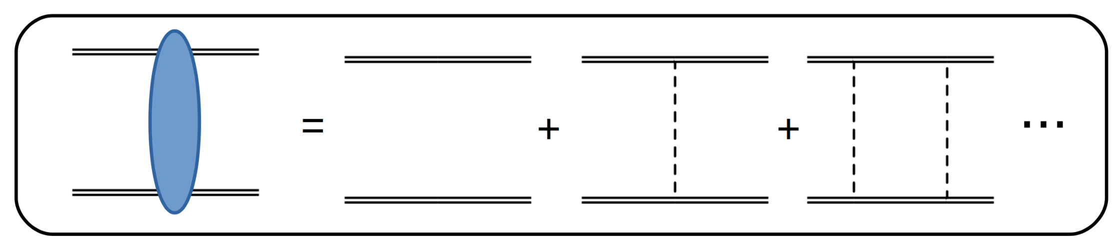

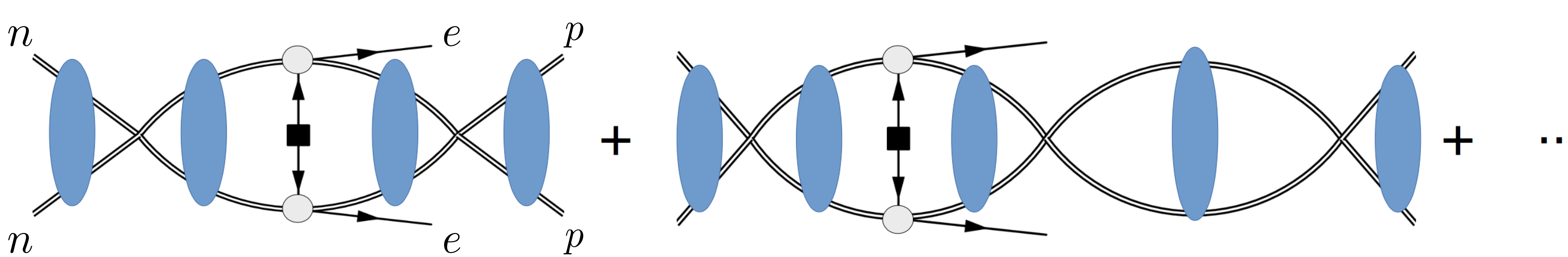

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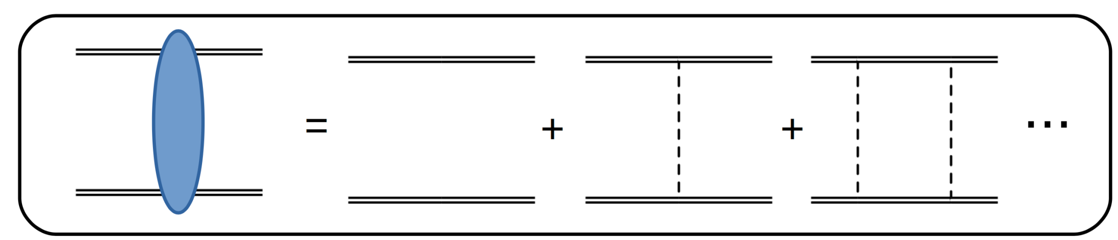

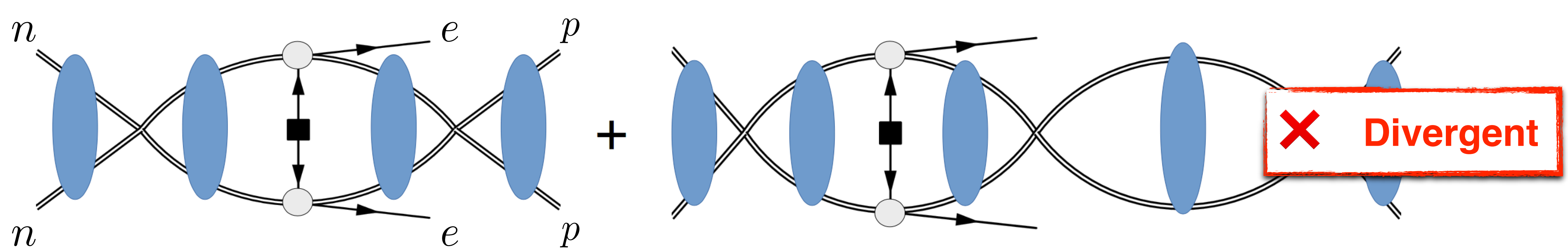

Checking the Weinberg counting

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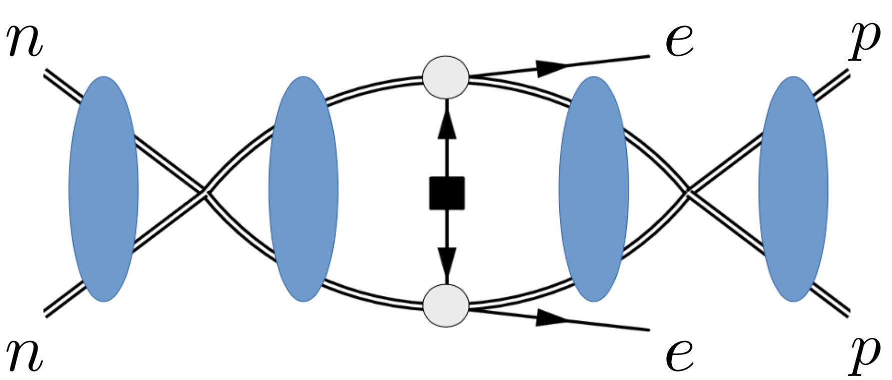

$$\sim m_N^2 \int d^3q d^3k \frac{1}{m_N E - \vec{q}^2} \frac{1}{(\vec{q}-\vec{k})^2} \frac{1}{m_N E' - \vec{k}^2}$$

$$+\text{finite}$$

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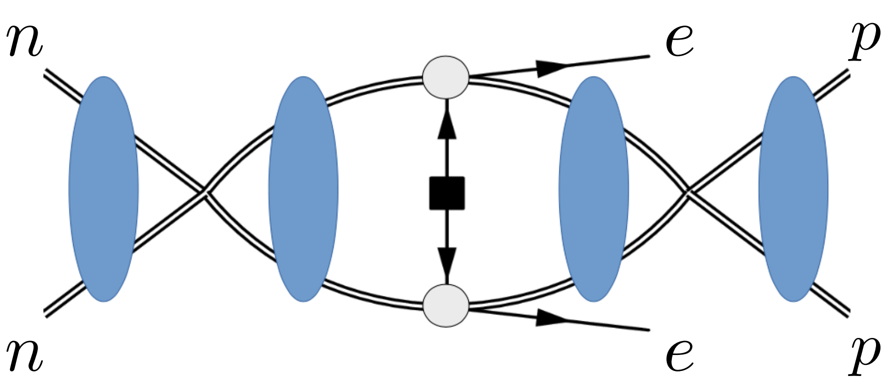

$$= -\left(\frac{m_N}{4\pi}\right)^2 (1+2g_A^2)\frac{1}{2}\left(\log\frac{\mu^2}{-(|\mathbf{p}|+|\mathbf{p}'|)^2+i0^+}+1\right)$$

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Regulator dependent

Checking the Weinberg counting

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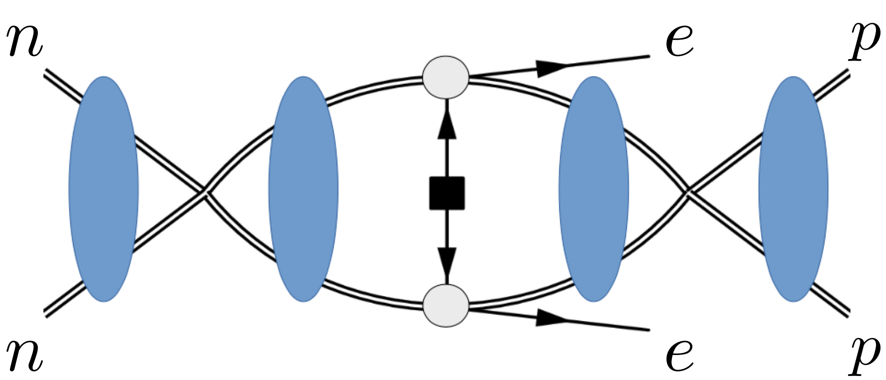

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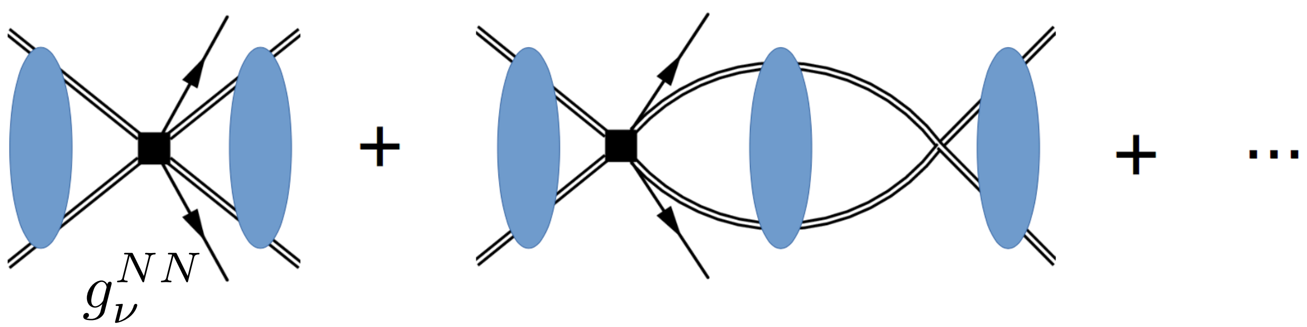
Regulator dependent

Regulator dependence can be absorbed by a counterterm



$$H_{\text{eff}} = 2G_F^2V_{ud}^2\, m_{\beta\beta}\, \bar{e}_L C\bar{e}_L^T\, V_\nu$$

$$V_{\nu,CT} = -2g_\nu^{NN}\, \tau^{(1)+}\tau^{(2)+}$$

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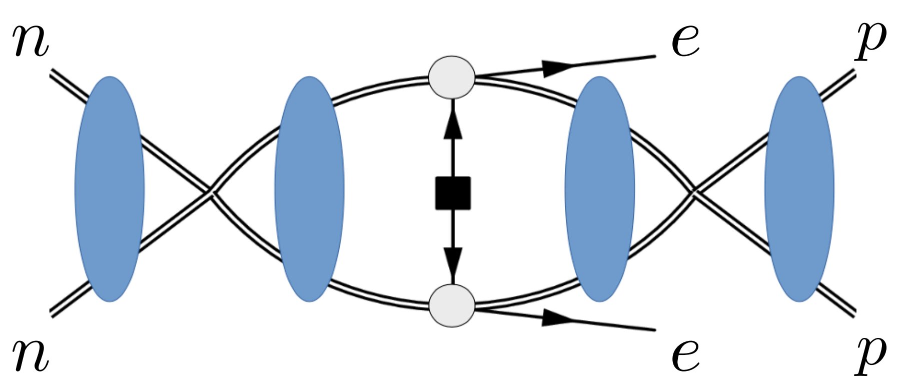

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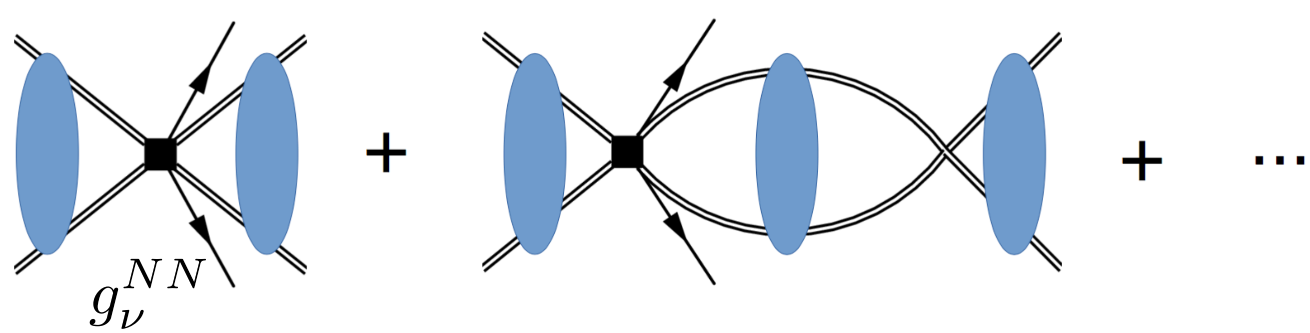

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$$\frac{d}{d\ln\mu}\frac{g_\nu^{NN}}{(m_N\tilde{C}/4\pi)^2} = \frac{1}{2}+g_A^2 \qquad\qquad g_\nu^{NN} = \mathcal{O}(1/F_\pi^2)$$

Checking the Weinberg counting
Majorana mass (dim 3)

Similar for r-space regulator:

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

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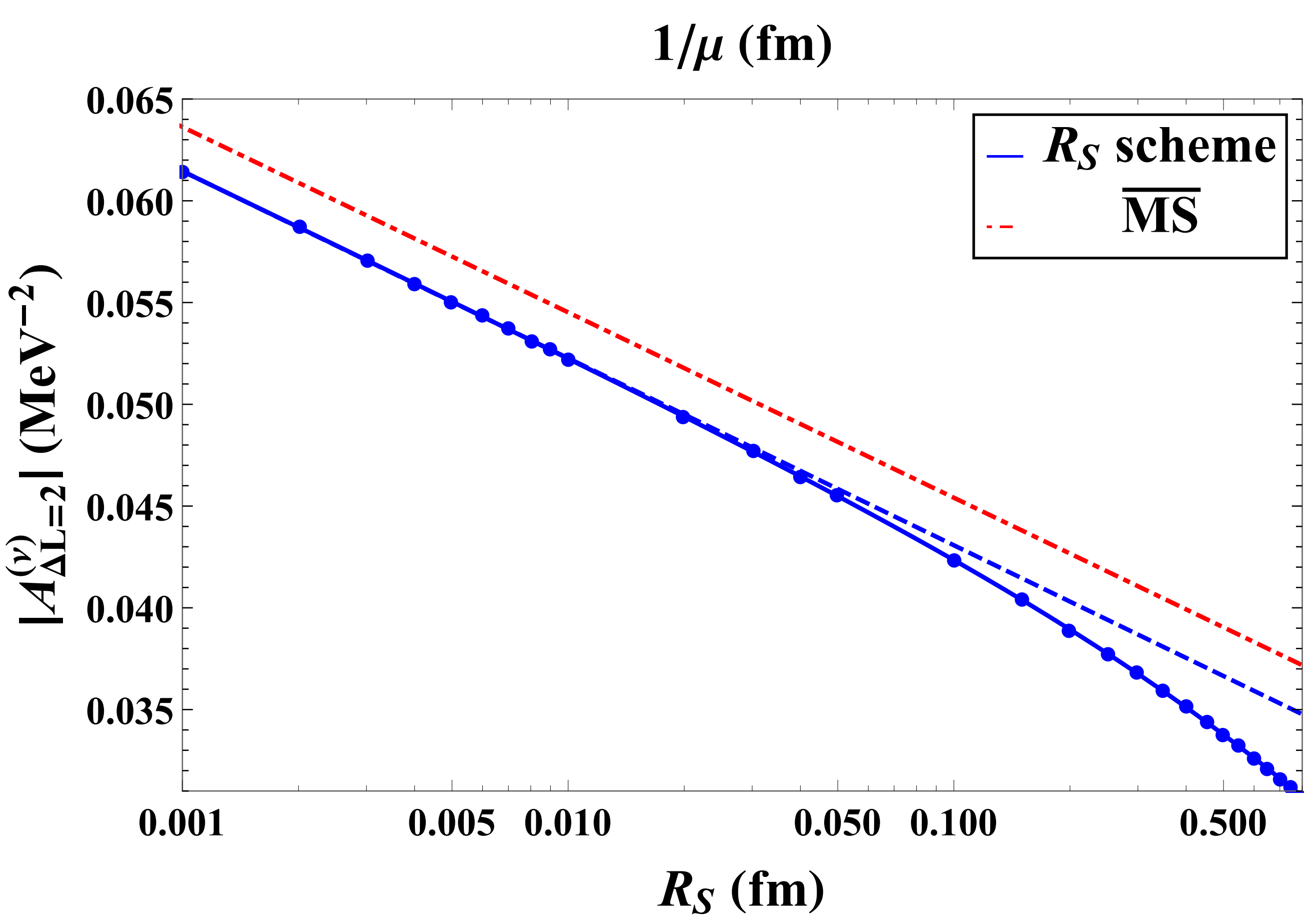
Majorana mass (dim 3)

- Amplitudes obtained using
  - MSbar
  - Coordinate-space cut-off



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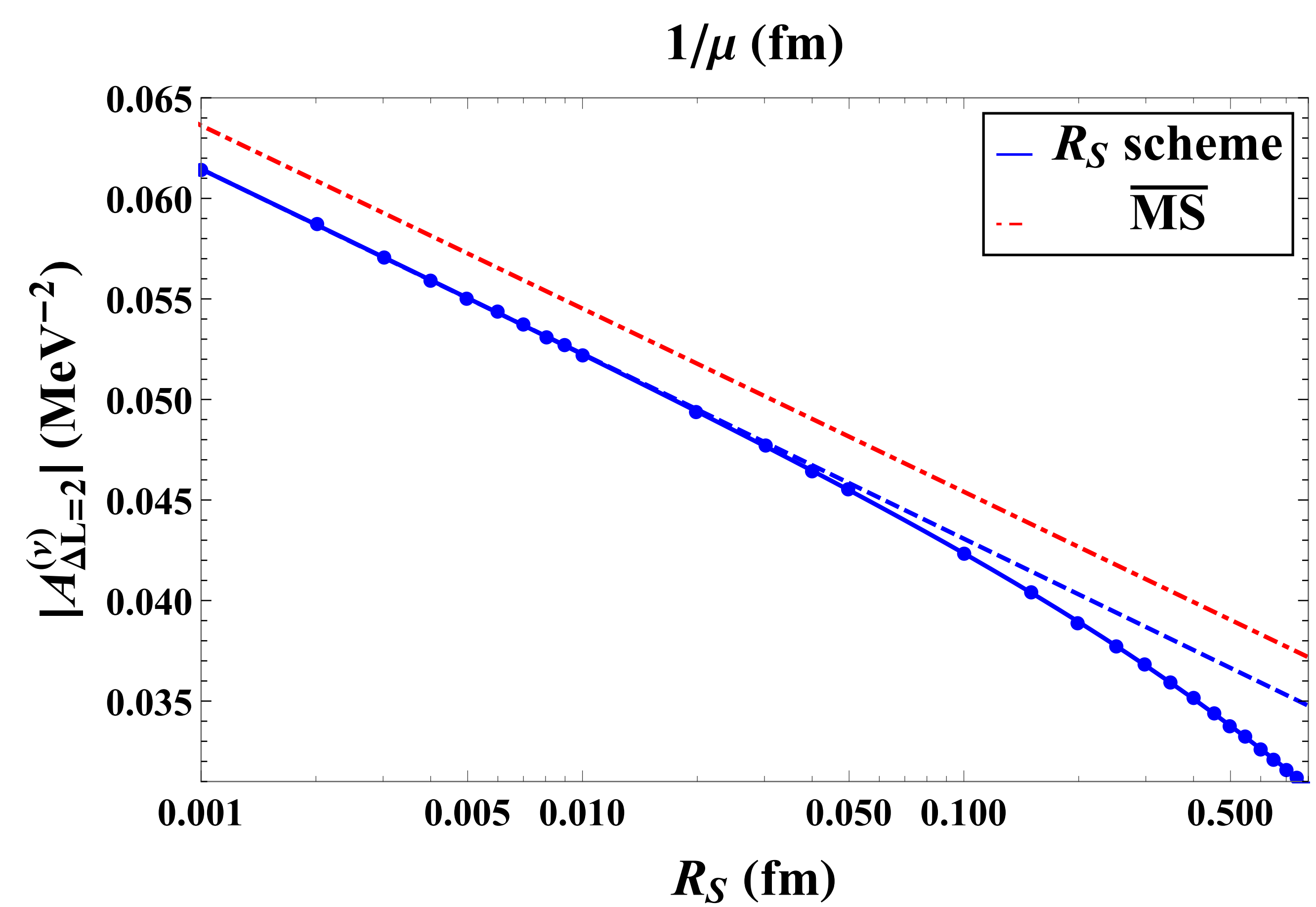
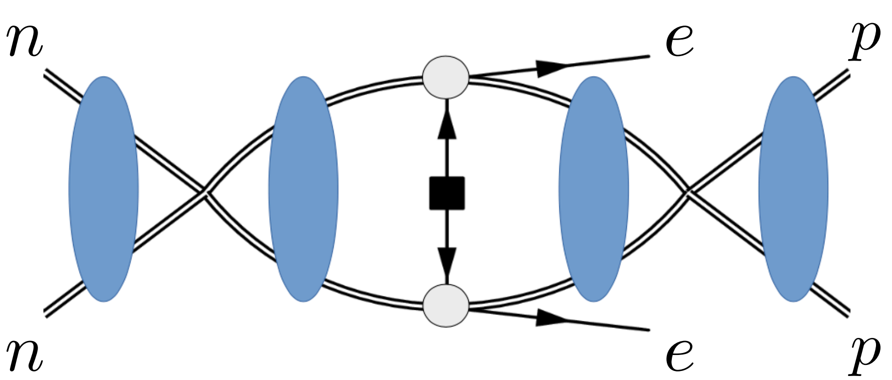


- Need a LO contact interaction to cancel this dependence, g_ν^{NN}
  - At present unknown, unable to reliably estimate the impact
  - Could be determined from lattice calculation of nn->ppee
  - Estimate from relation to EM suggests a 25-60% contribution (backup slides)
    - Assumptions with uncontrolled error

Checking the Weinberg counting

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



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- In the Majorana-mass case, the divergence is due to the LNV potential at large q (small r)
  - Behaves like $V_{\Delta L=2} \sim 1/\vec{q}^2$

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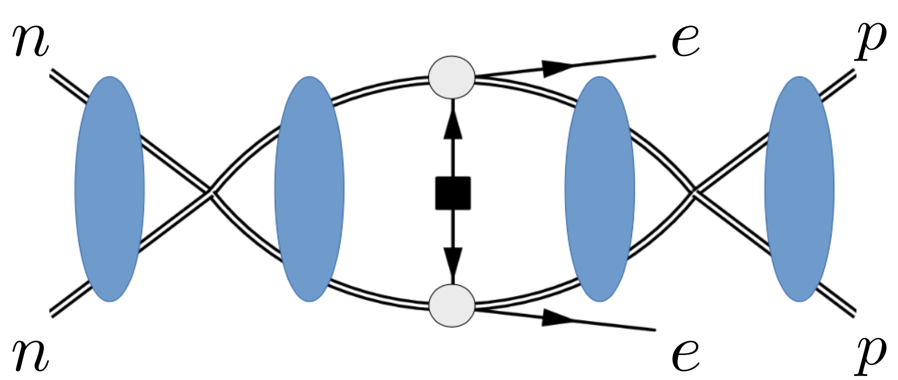

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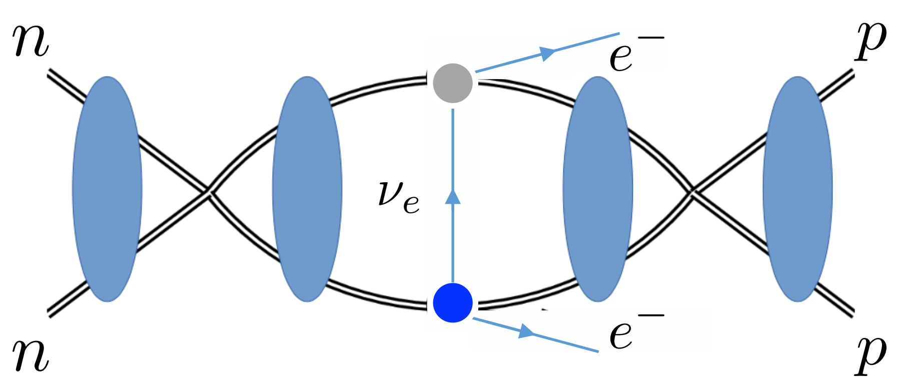

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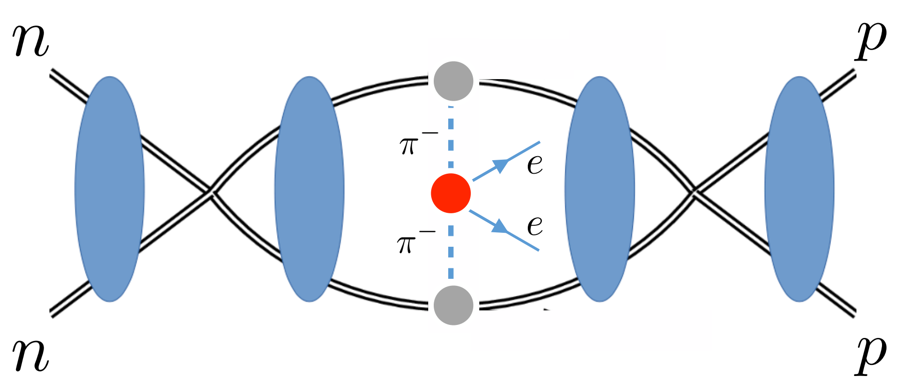

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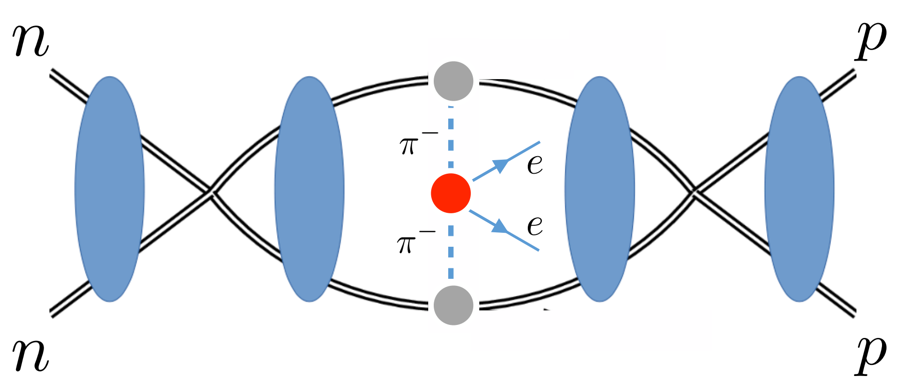

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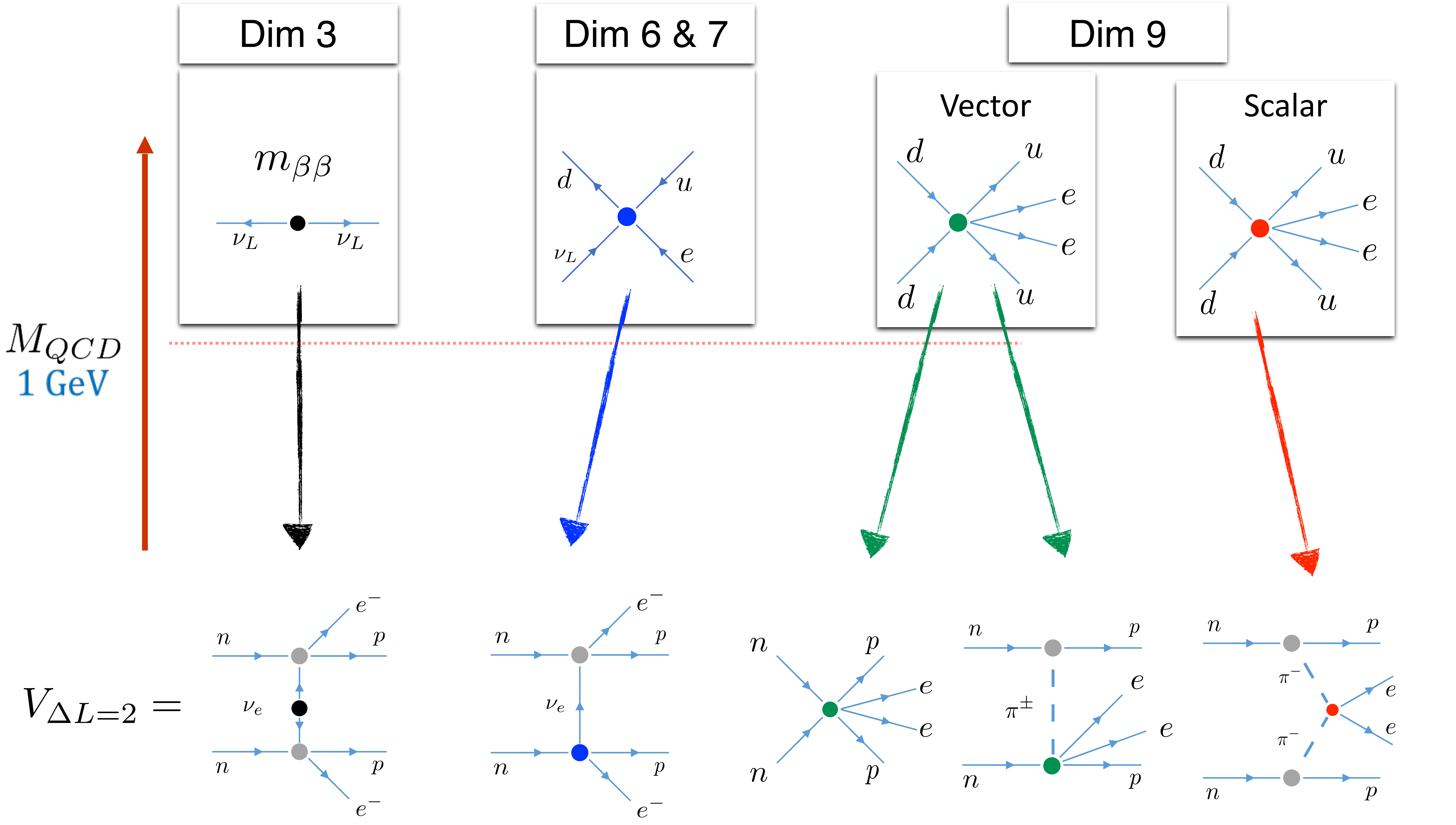
- Need to include contact interactions at LO in these cases
  - Often disagrees with the Weinberg / NDA counting

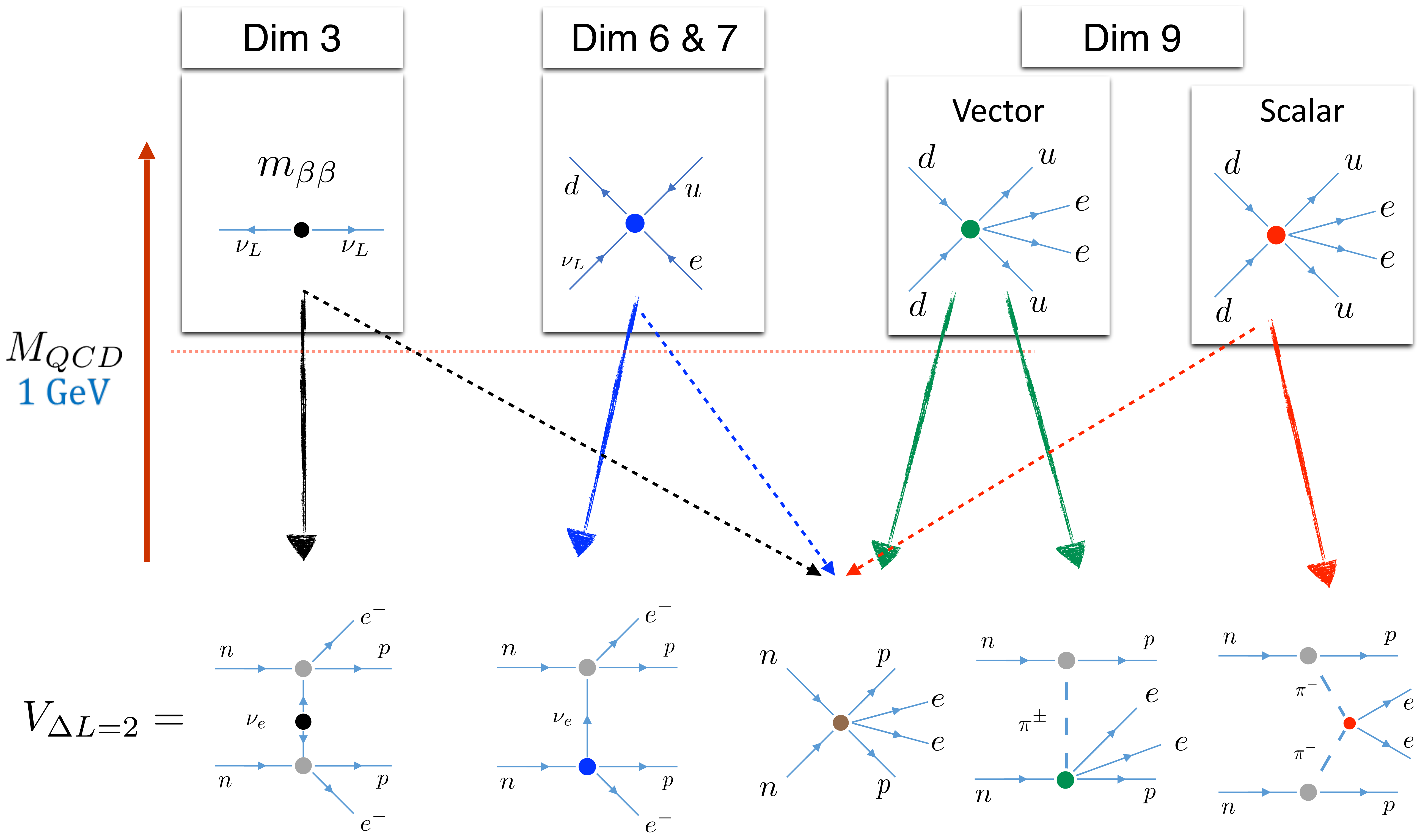
Chiral EFT

NDA / Weinberg



Chiral EFT

Beyond NDA / Weinberg



Chiral EFT

Power counting

Contributions to the amplitude scale as

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

$$\Lambda_\chi = 1\,\mathrm{GeV}, \qquad \epsilon_\chi = m_\pi/\Lambda_\chi$$

Chiral EFT
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- The dimension-seven and -nine operators are suppressed by Λ_χ/v

Chiral EFT

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- The dimension-seven and -nine operators are suppressed by Λ_χ/v
- Most operators are suppressed by two or three powers of $\epsilon_\chi = m_\pi/\Lambda_\chi$

Chiral EFT

Power counting

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	$d{=}3$	$C^{(6)}_{\rm SL,\,SR}$	$C^{(6)}_{\rm T}$	$C^{(6)}_{\rm VL}$	$C^{(6)}_{\rm VR}$	$C^{(7)}_{\rm VL,\,VR}$	$C^{(9)\,(\prime)}_{\rm 1R}$	$C^{(9)(\prime)}_{\rm 1L}$	$C^{(9)(\prime)}_{\rm 2R-5R}$	$C^{(9)(\prime)}_{\rm 2L-5L}$	$C^{(9)}_{\rm vector}$
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- The dimension-seven and -nine operators are suppressed by Λ_χ/v

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

- Should be combined with the scaling of the Wilson coefficients to see which are important
  - To be determined in explicit models of new physics

Outline

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

Λ

?? TeV

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

Integrate out BSM fields

100 GeV

Electroweak symmetry breaking

SM EFT’
SU(3)xU(1)$_{em}$ invariant

Integrate out heavy SM fields

1 GeV

Non-perturbative QCD

Lattice QCD input

Chiral Effective Theory

100 MeV

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

Many Body Methods

1 MeV

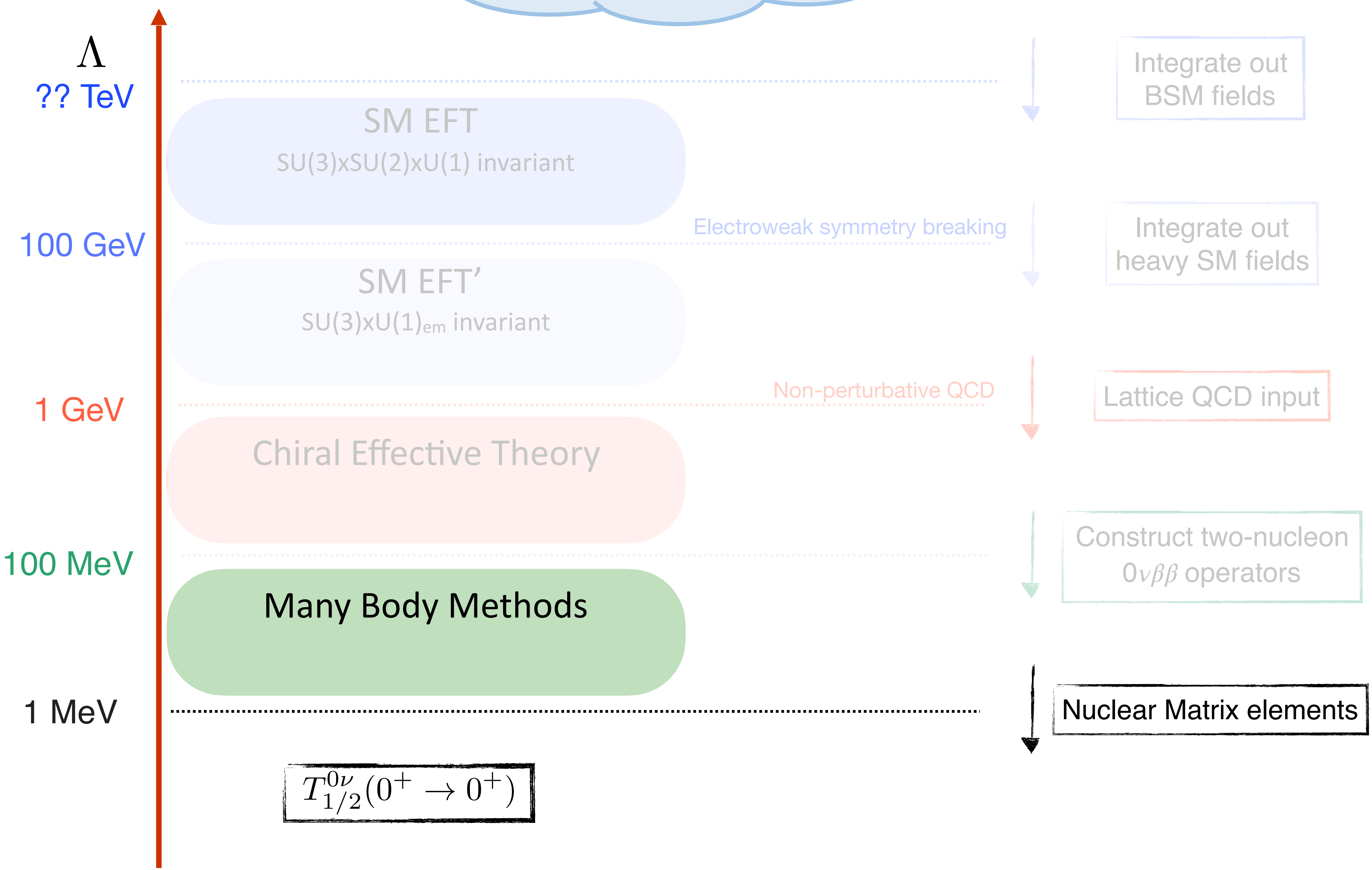
Nuclear Matrix elements

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

Outline

Lepton-number violation:

seesaw, left-right model, leptoquarks,...



The $0\nu\beta\beta$ half-life

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

- Combinations of Wilson coefficients
  - Perturbative, determined by BSM physics

The $0\nu\beta\beta$ half-life

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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	

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

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

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

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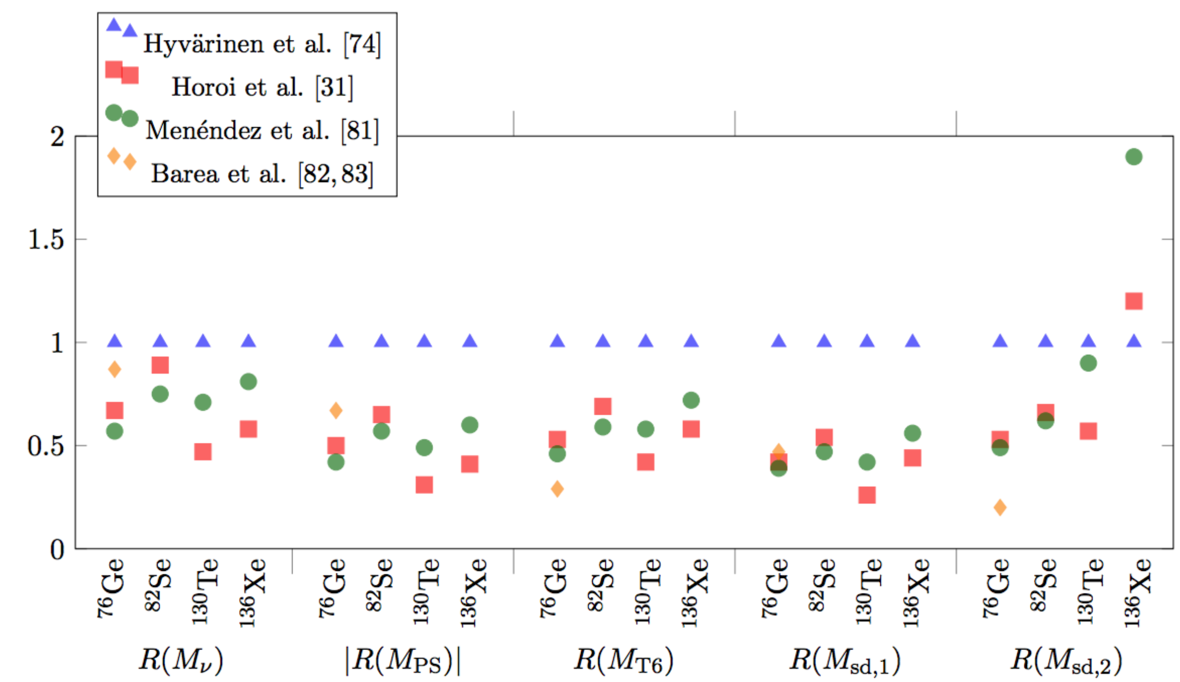
- The NMEs differ by a factor 2-3 between methods
  - For Majorana-mass term & other LNV sources



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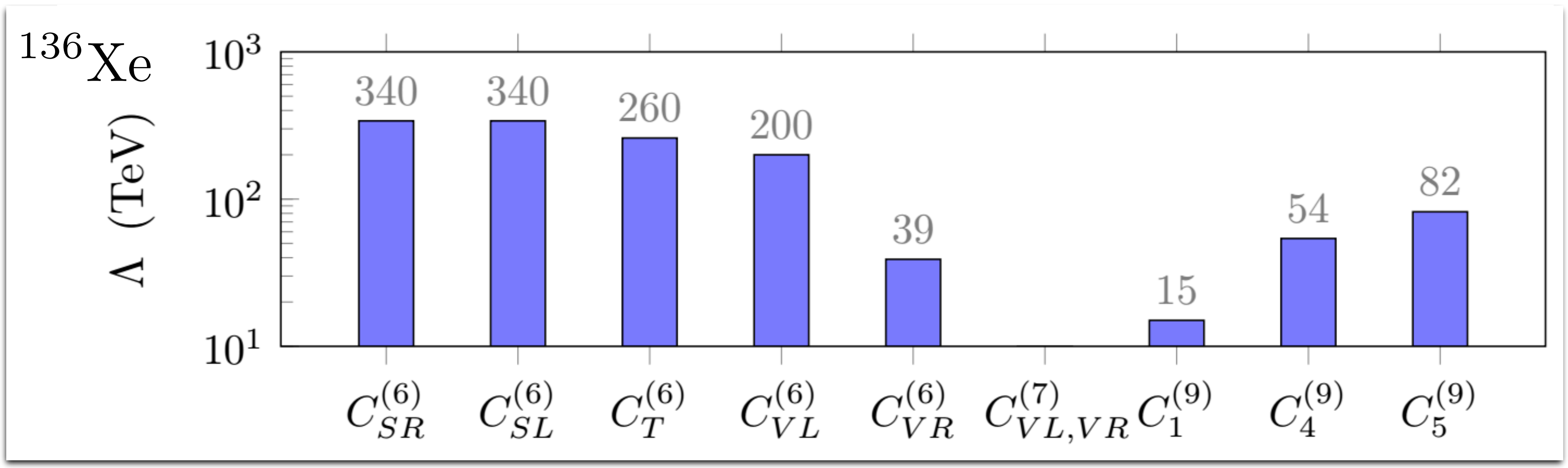
Current limits

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



- Uncertainties:
  - Unknown LECs
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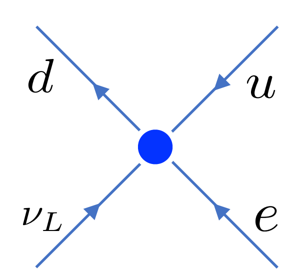
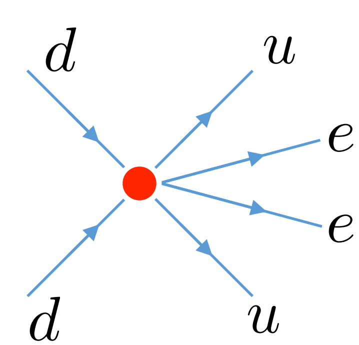


Dim 6 & 7



Dim 9

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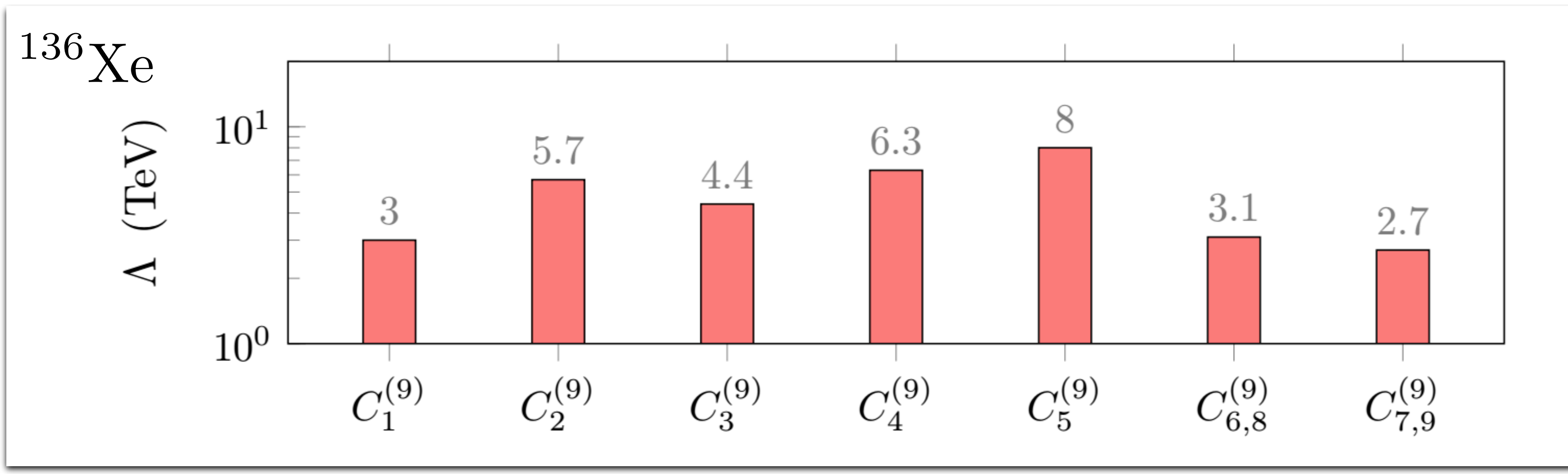

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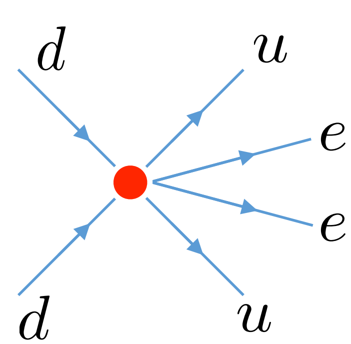
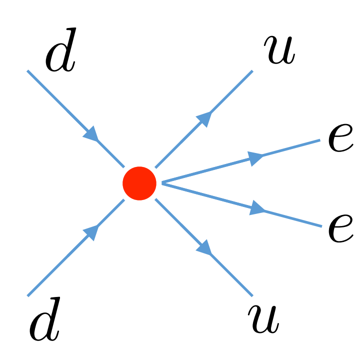


Dim 9
Scalar



Dim 9
Vector

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)

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Violates lepton number

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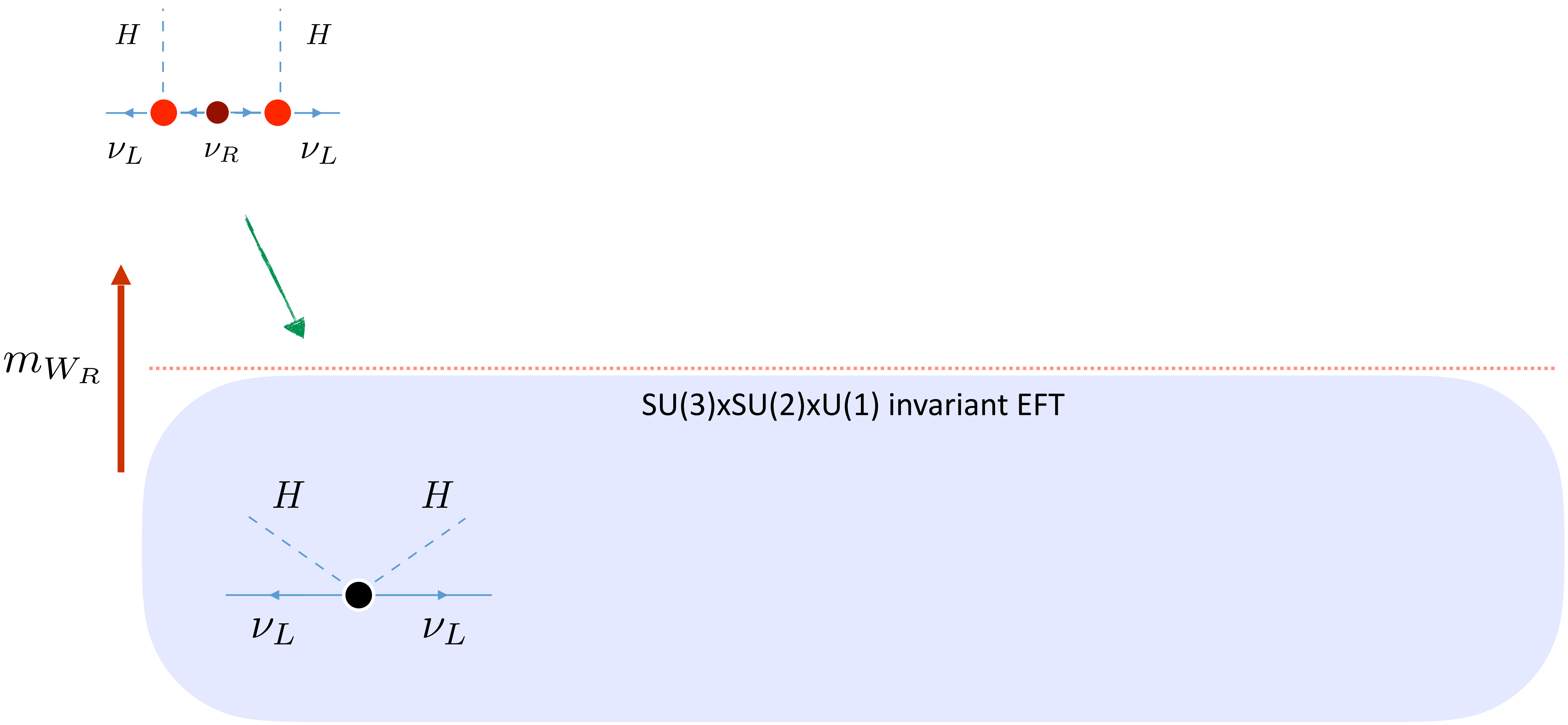
An example: LR model

- $\sim y_e = m_e/v$
- $\Delta L = 2$



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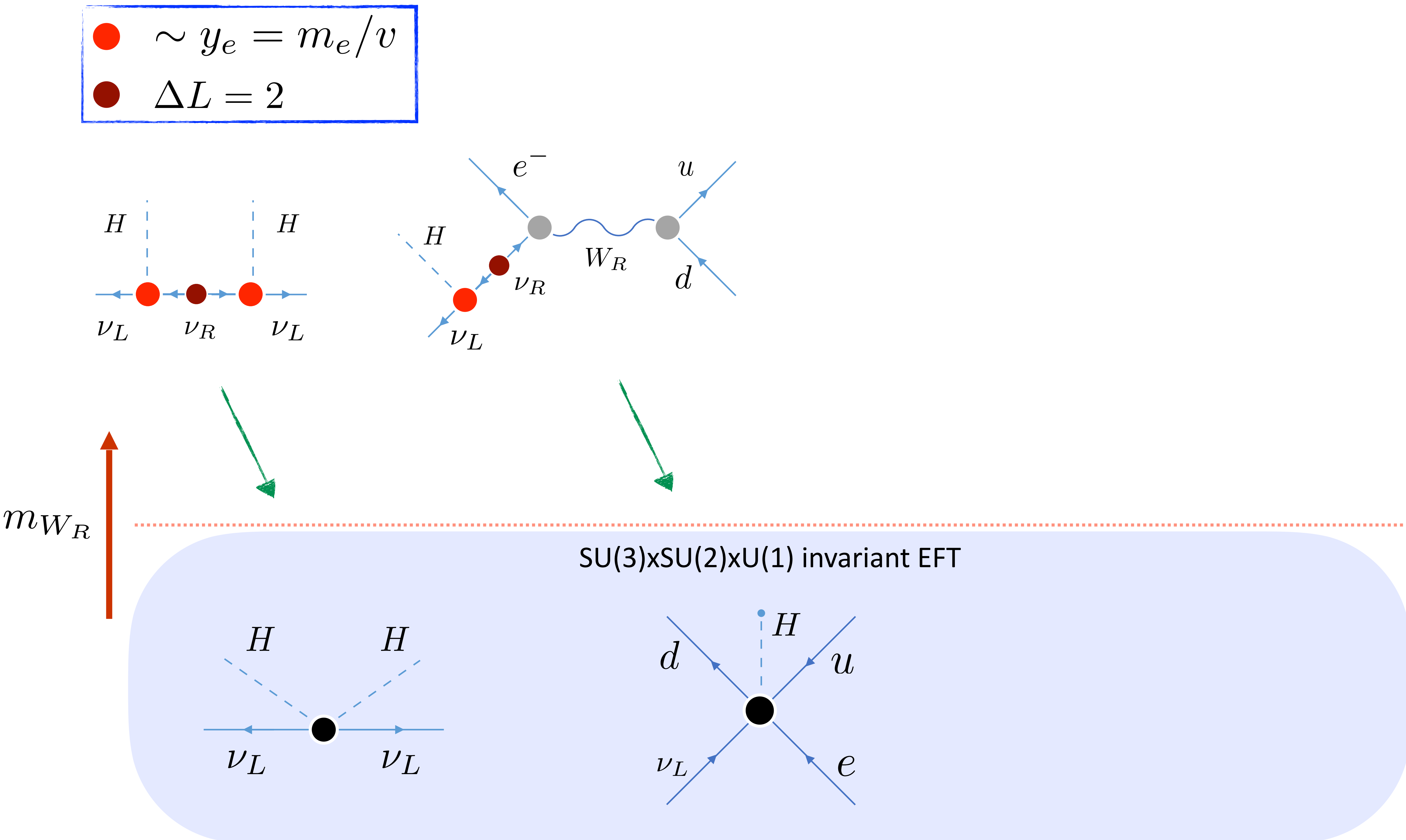
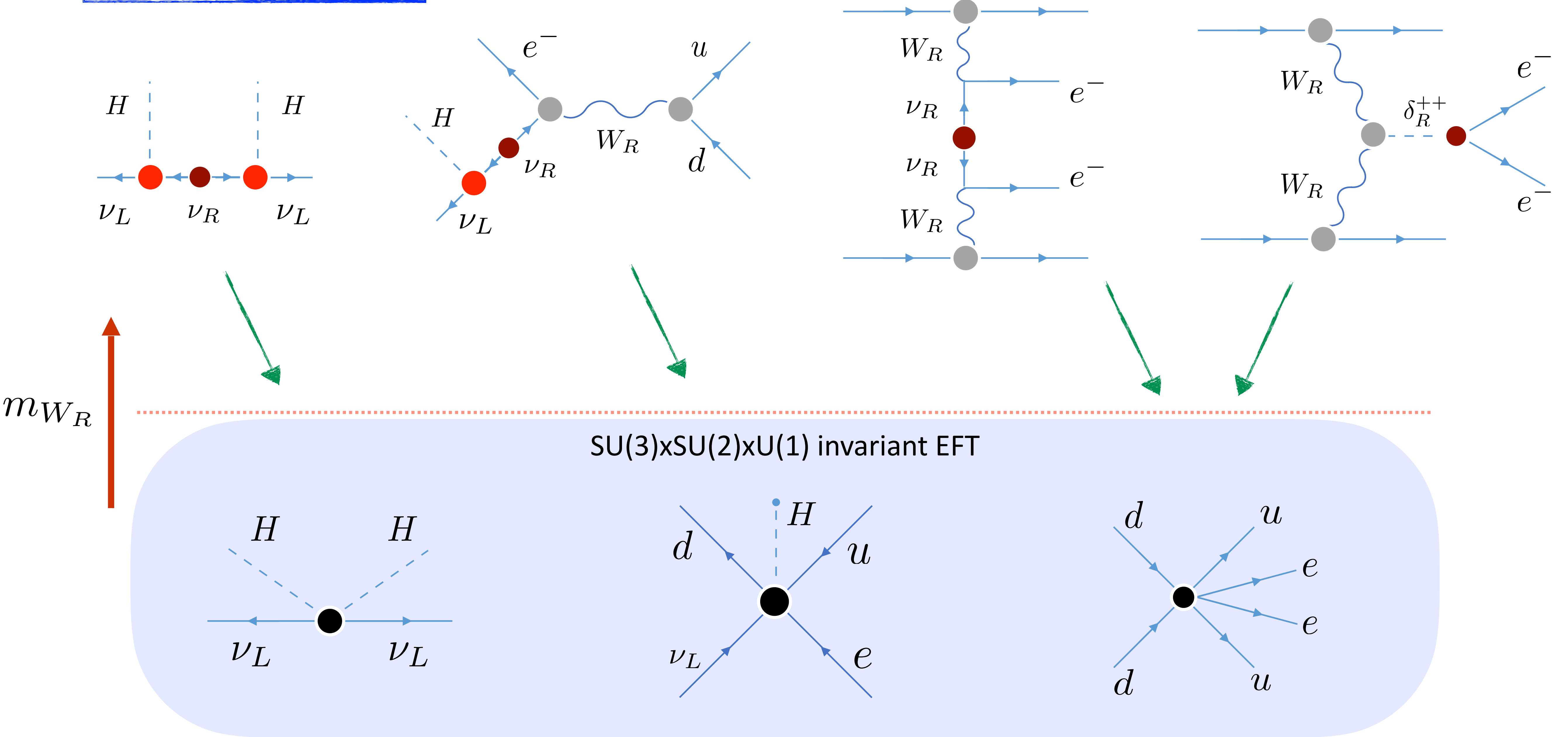


An example: LR model

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



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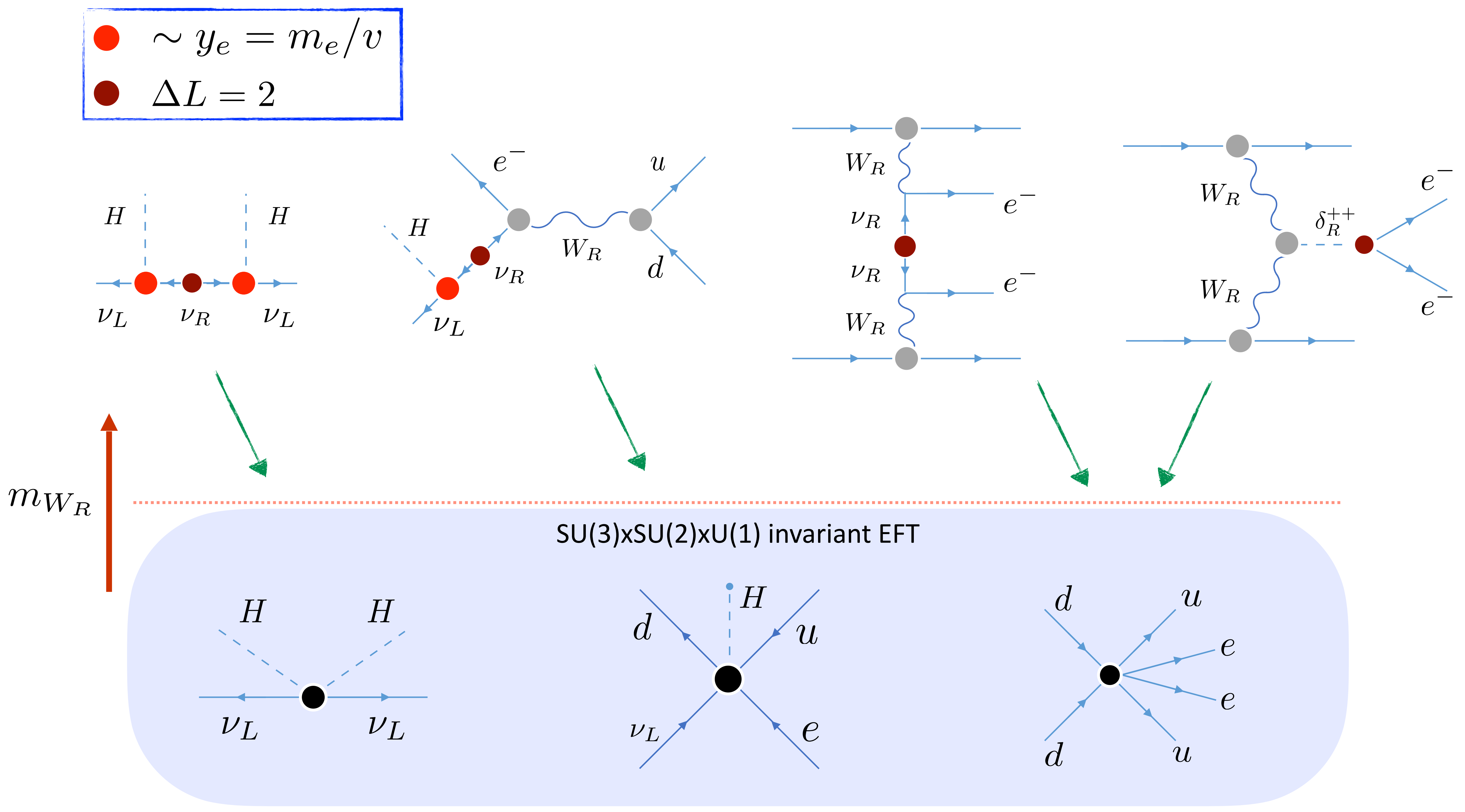

dim-5 $\sim y_e^2 \left(\frac{v}{\Lambda}\right)$

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

Dim-9 $\sim \left(\frac{v}{\Lambda}\right)^5$

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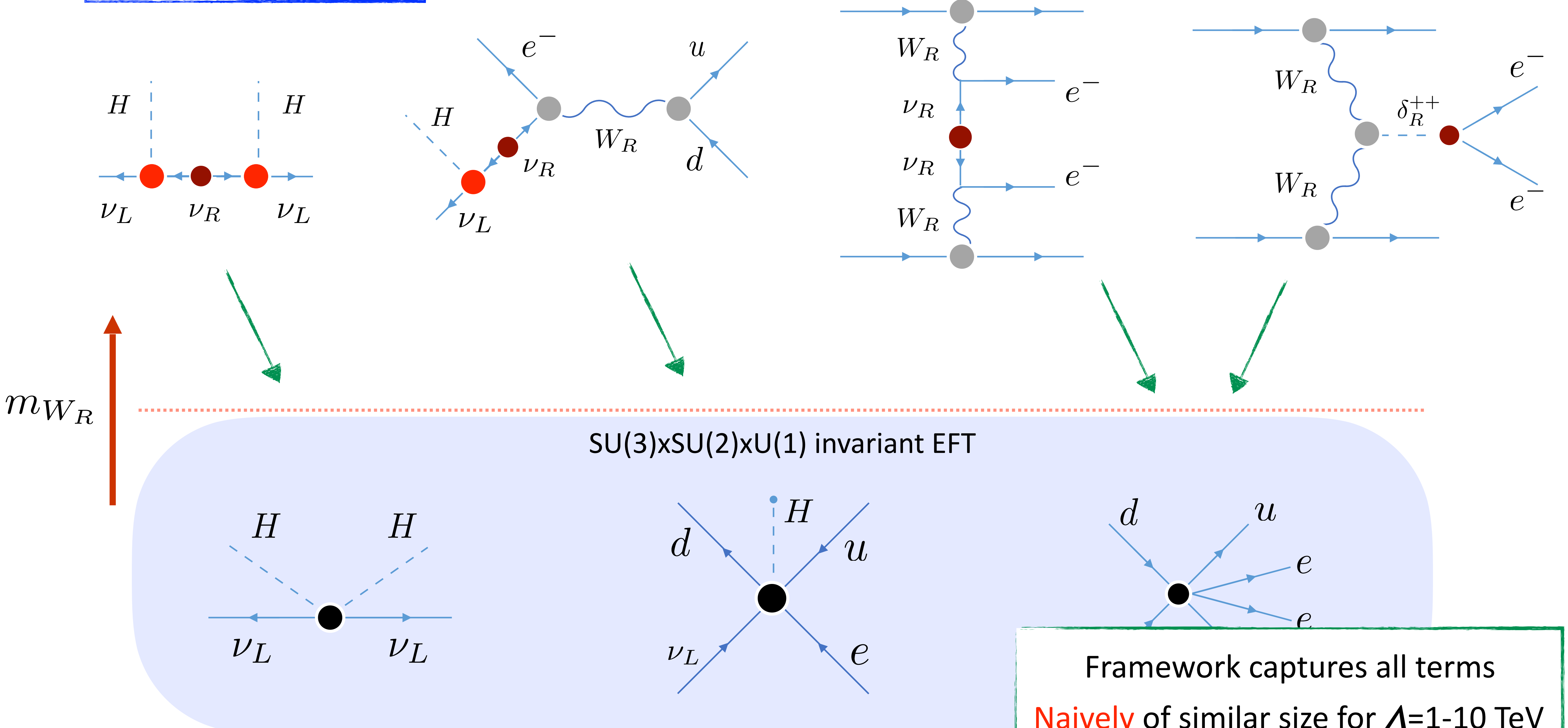


Framework captures all terms

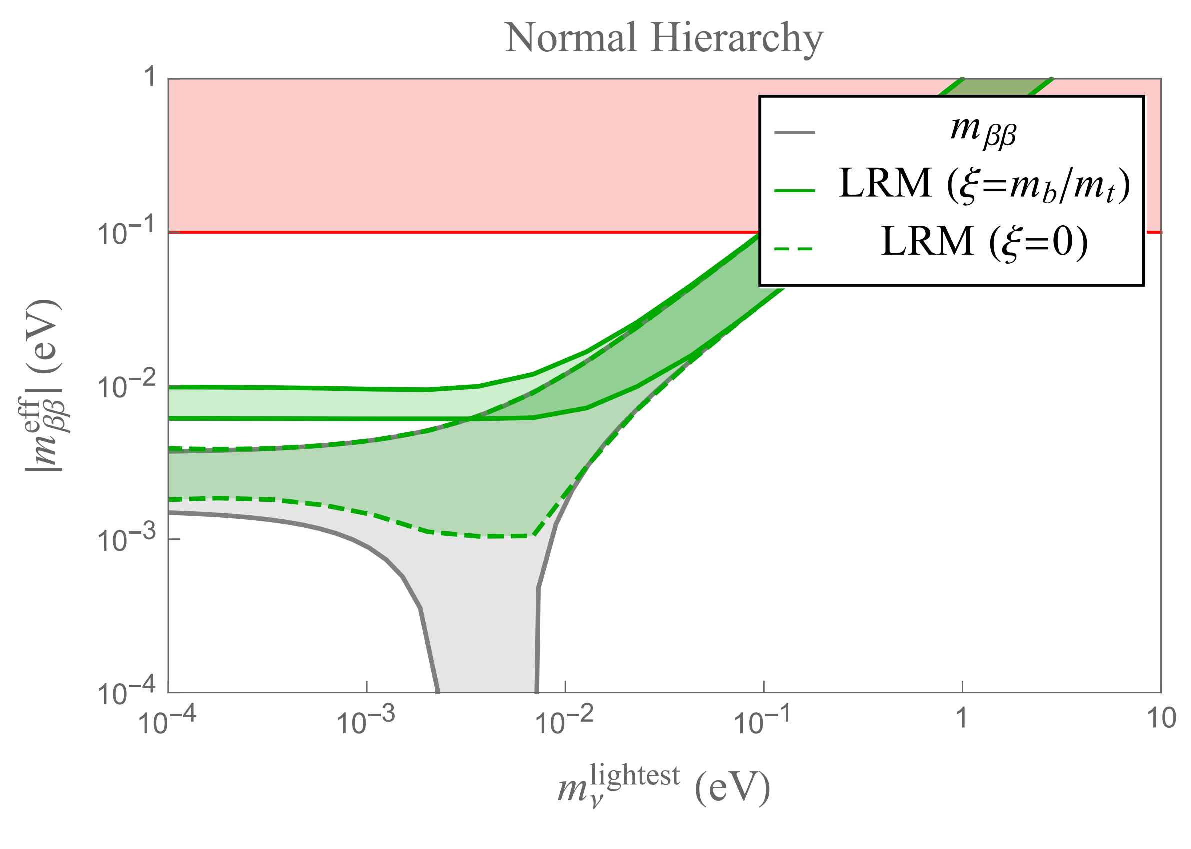
Naively of similar size for Λ=1-10 TeV

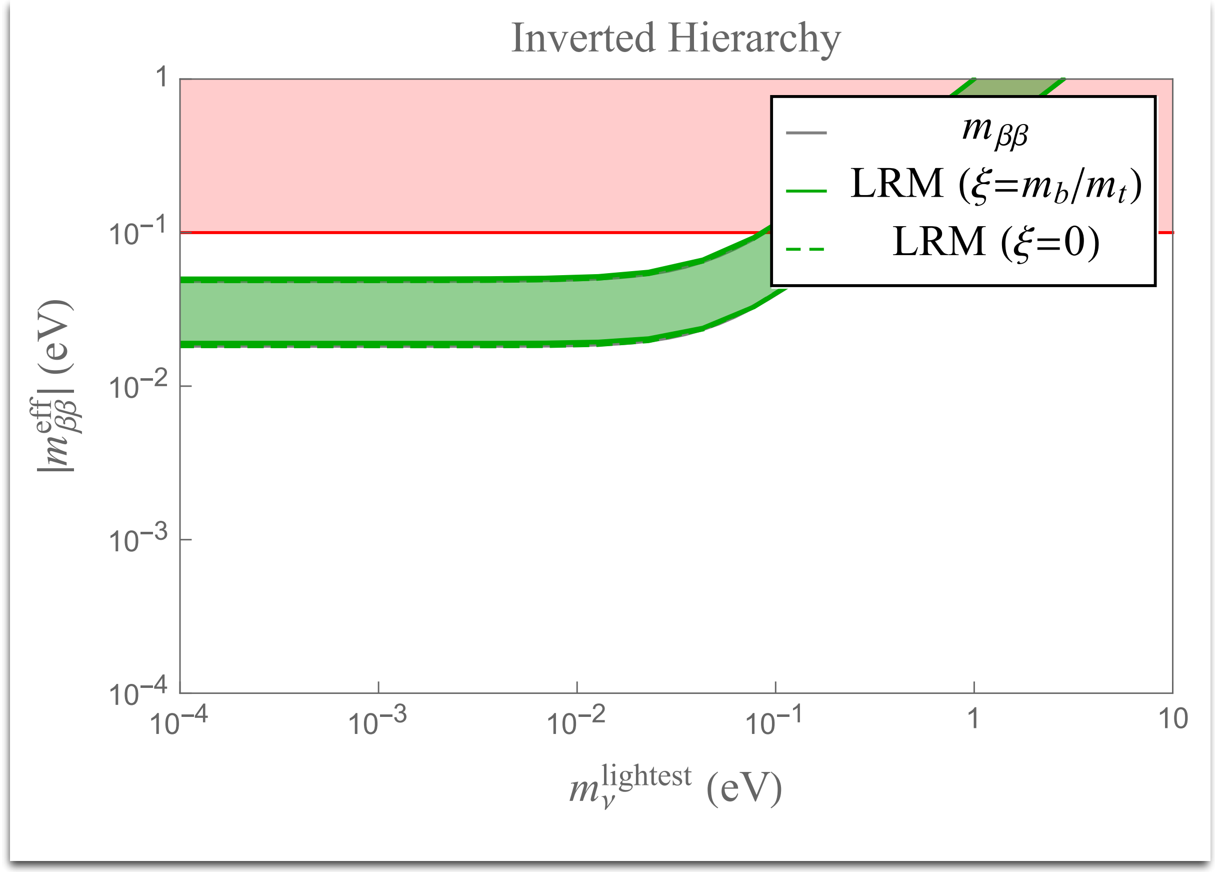
dim-5 $\sim y_e^2 \left(\frac{v}{\Lambda}\right)$ dim-7 $\sim y_e \left(\frac{v}{\Lambda}\right)^3$ Dim-9 $\sim \left(\frac{v}{\Lambda}\right)^5$

An example: LR model

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

- 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 searches

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

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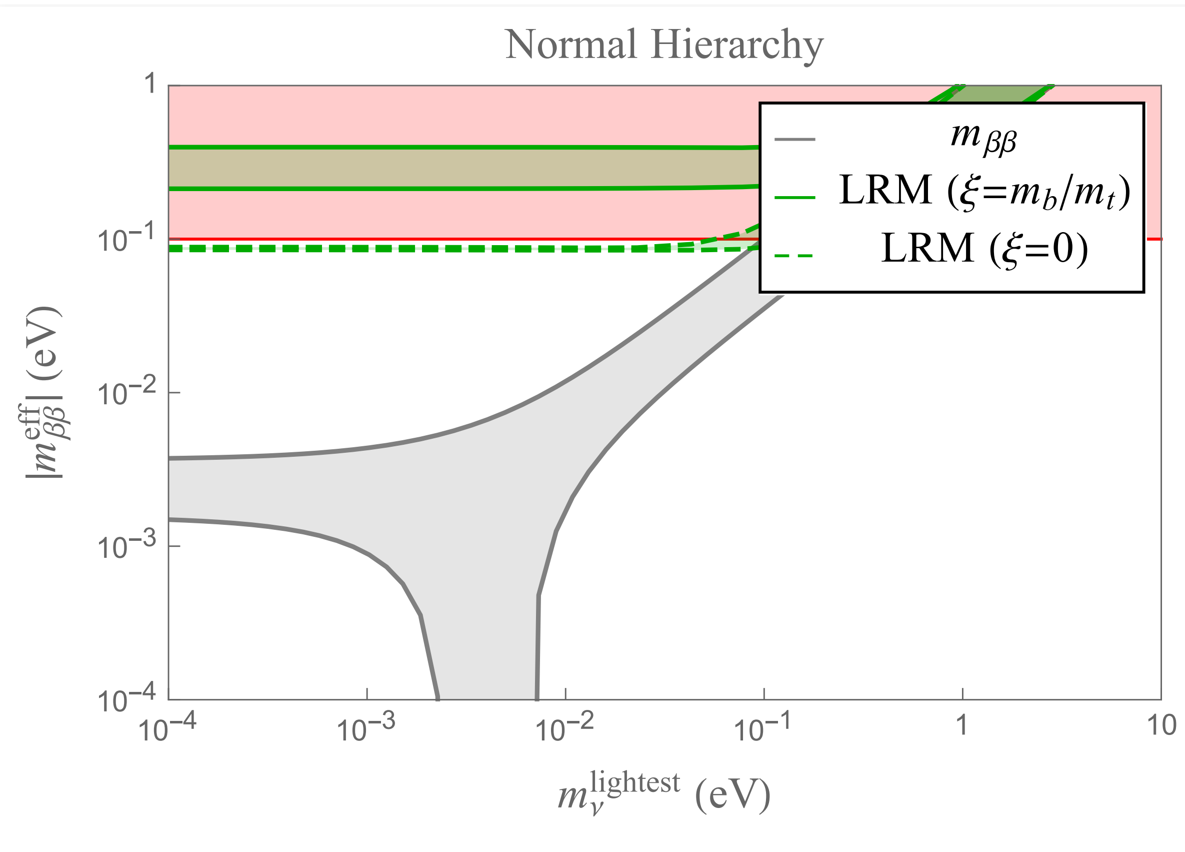
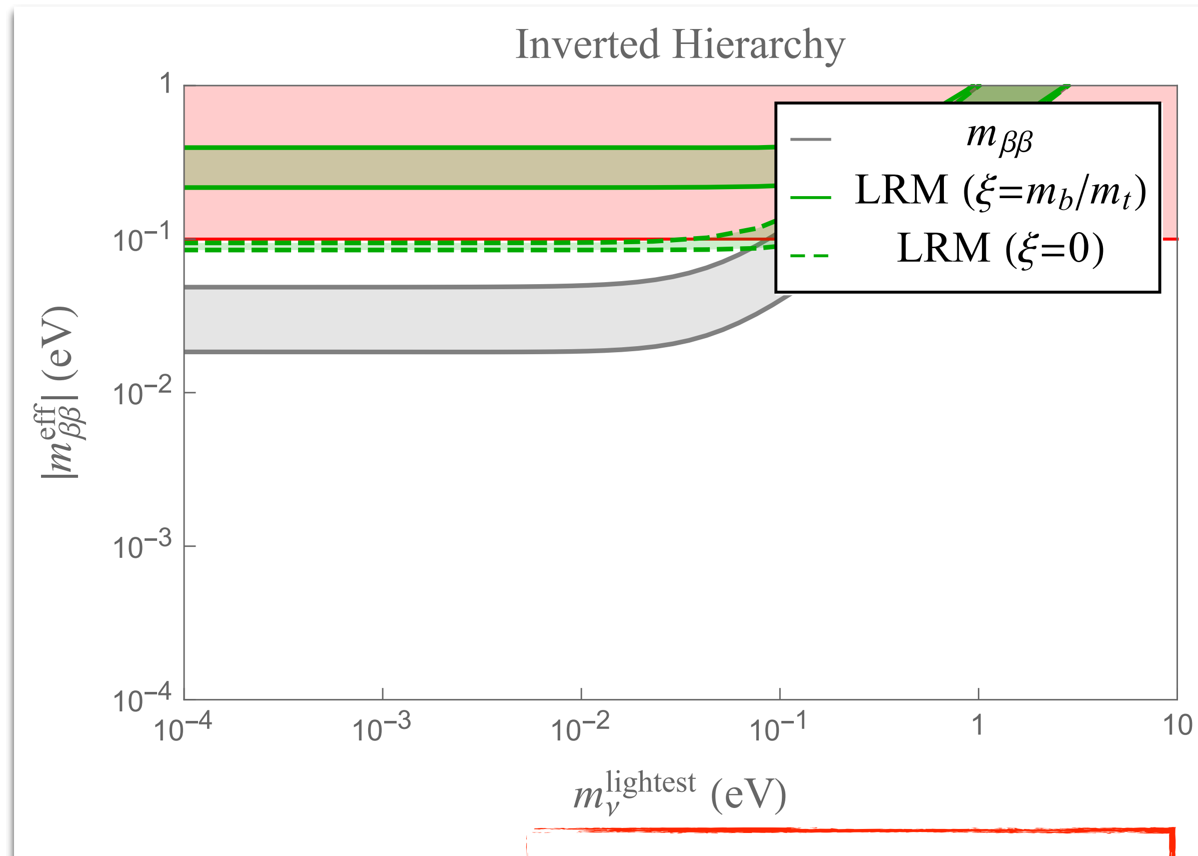


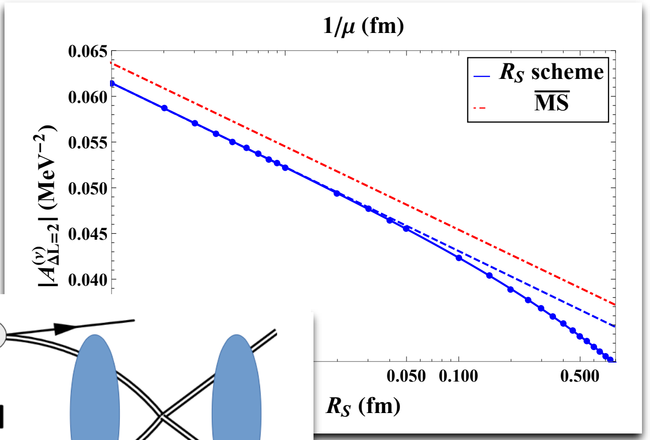


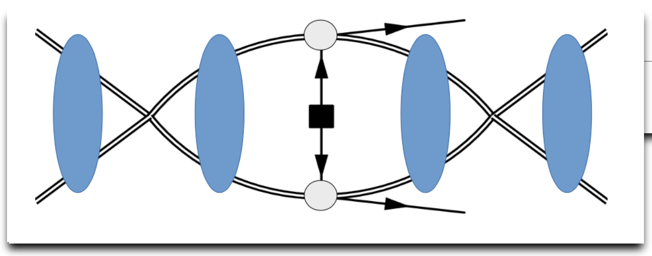
Subject to
NME / LEC uncertainties

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

Summary

- EFTs allow a model-independent description of ΔL=2 scenarios
- Renormalization requires counterterms beyond NDA





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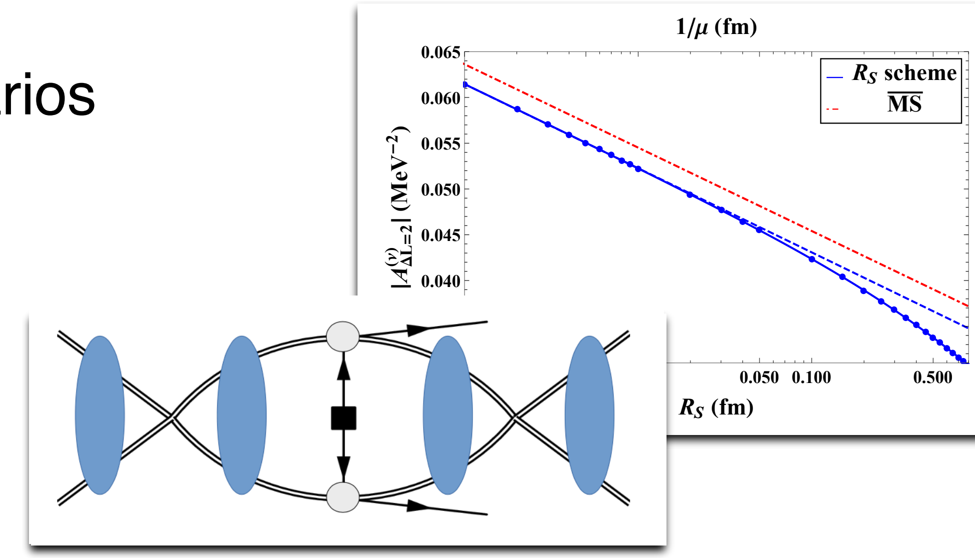
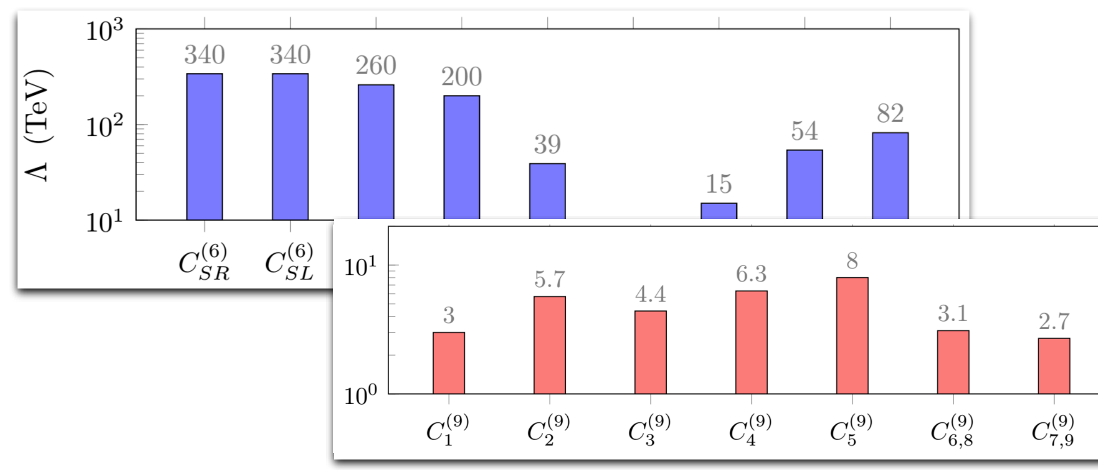


- Limits on higher-dimensional operators probe
  - O(1-10) TeV scales for dim-9
  - O(100) TeV scales for dim-7
- Order 1 uncertainties
  - Unknown LECs + NMEs



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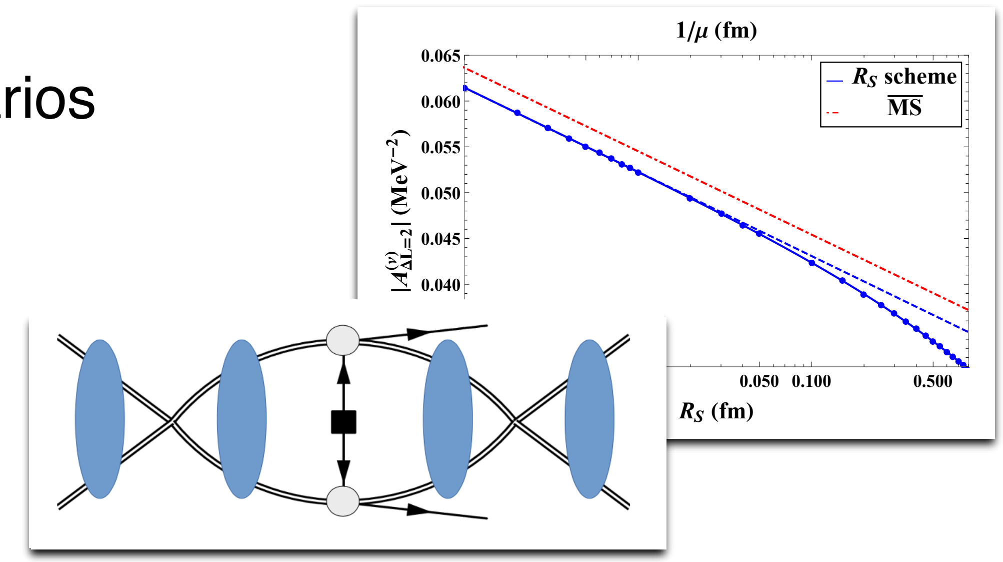

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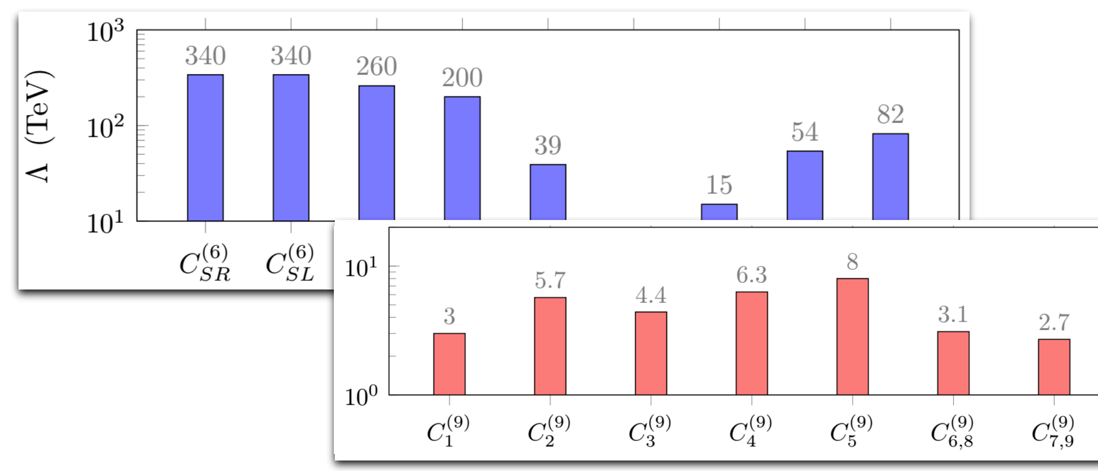
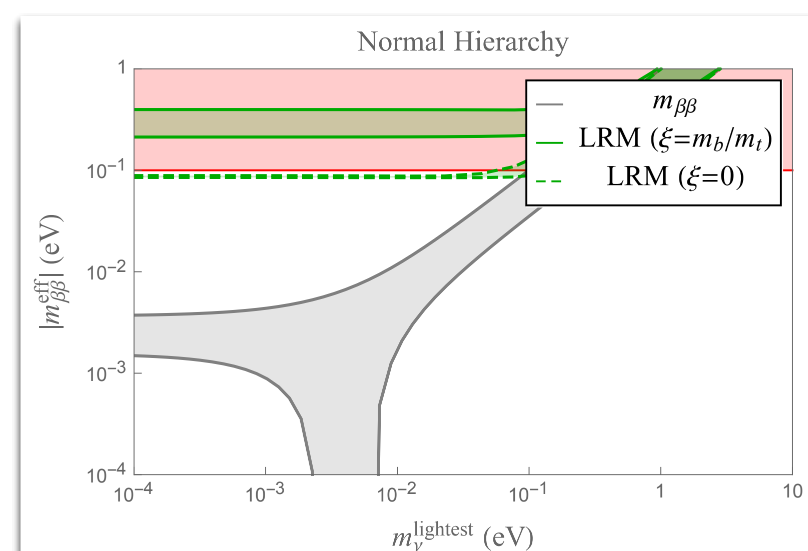


- Explicit example: Left-right model
- Dimension-5, -7, and -9 induced
  - Captured by the EFT
  - Higer-dim. Operators can be important



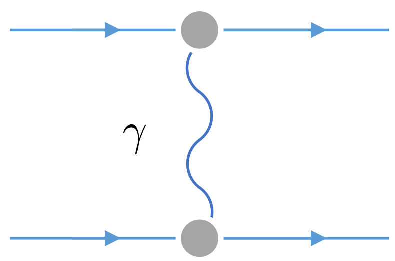
Back up slides

Relation to electromagnetism

Relation to electromagnetism

Majorana mass

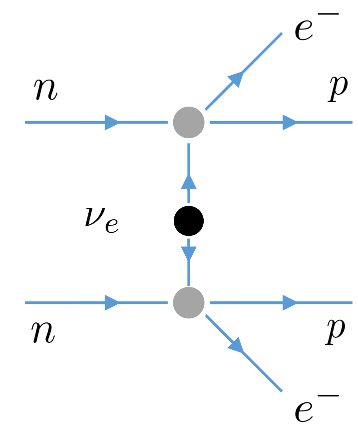
EM



$\sim e^2/q^2$

?

LNV



$\sim G_F^2 m_{\beta\beta}/q^2$

- Relation to Coulomb exchange?
  - ΔI=2 piece of EM has similar chiral properties
  - Leptonic LNV part combines to a photon propagator

Relation to electromagnetism
Majorana mass

- 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

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

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LNV

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EM

$$\mathcal{L}_{em} = e^2/4\,(C_1 O_1 + C_2 O_2)$$
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- EM induces an extra term
  - Equivalent up to 2 pions
  - Hard to disentangle

LNV

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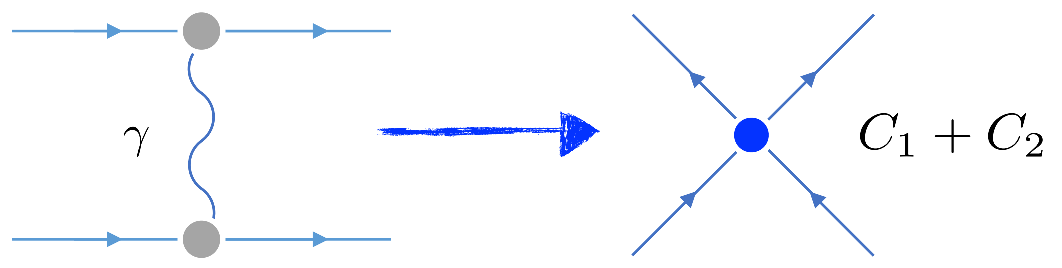
Relation to electromagnetism
Majorana mass

- 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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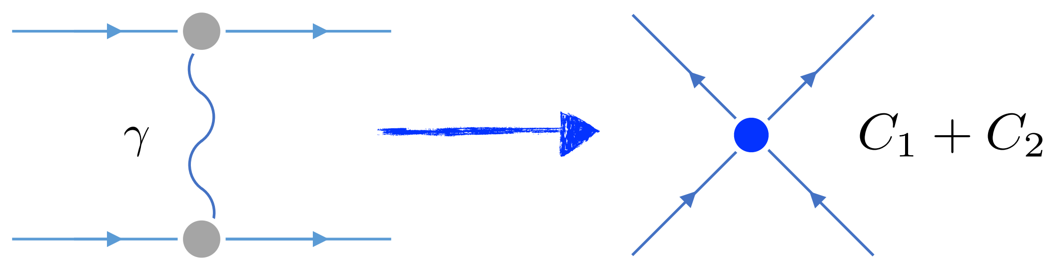

- Allows an estimate of g_ν^{NN}
  - Extract $C_1 + C_2$ from CIB
  - Assume $g_\nu^{NN}(\mu) = \frac{C_1(\mu) + C_2(\mu)}{2}$
  - Roughly 10% effect for Rs = 0.6 fm
  - Uncontrolled error

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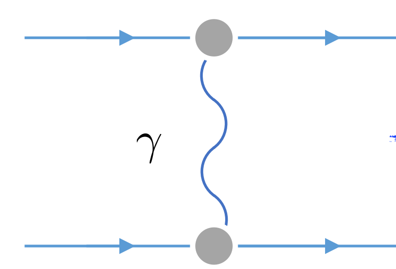

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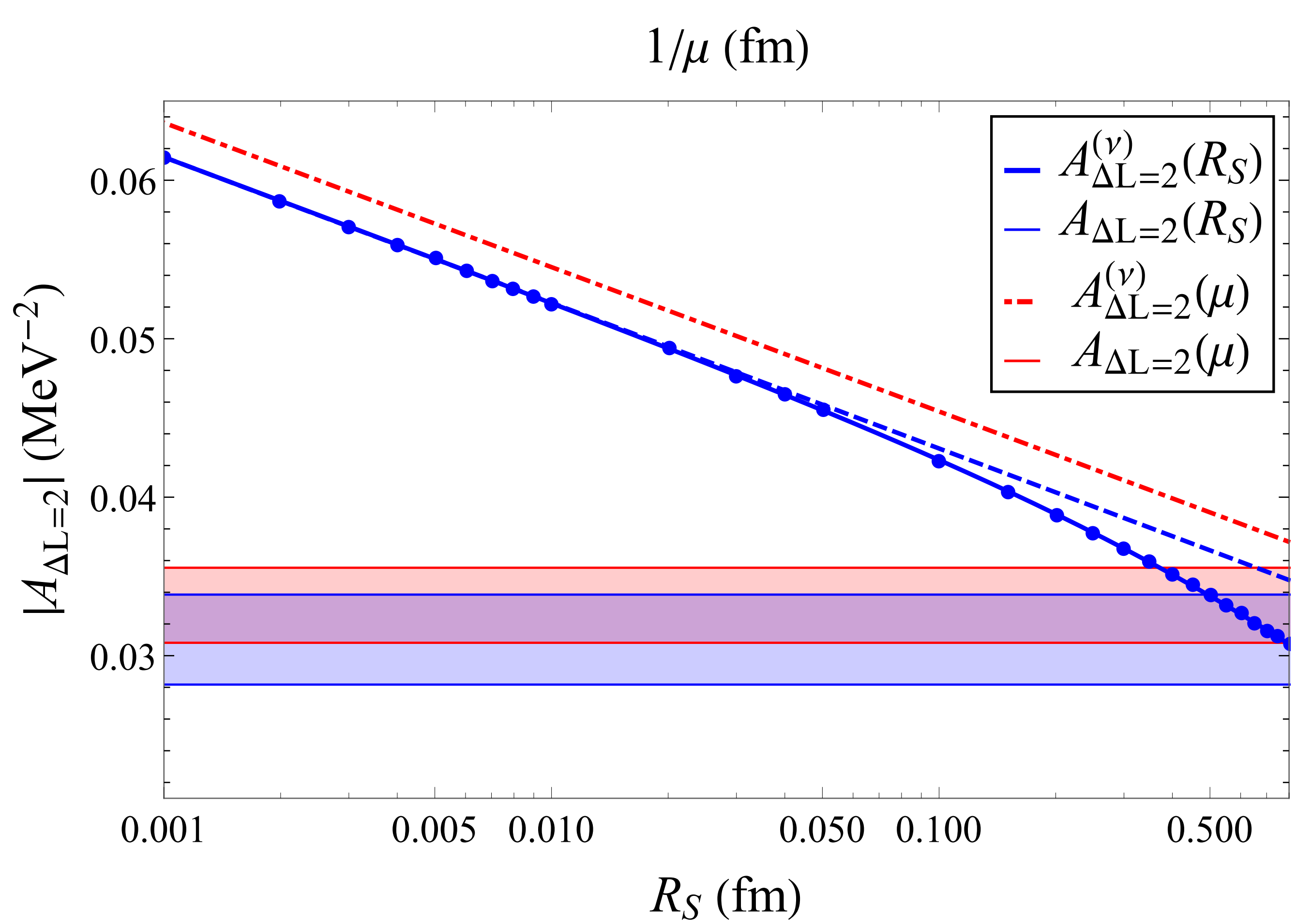
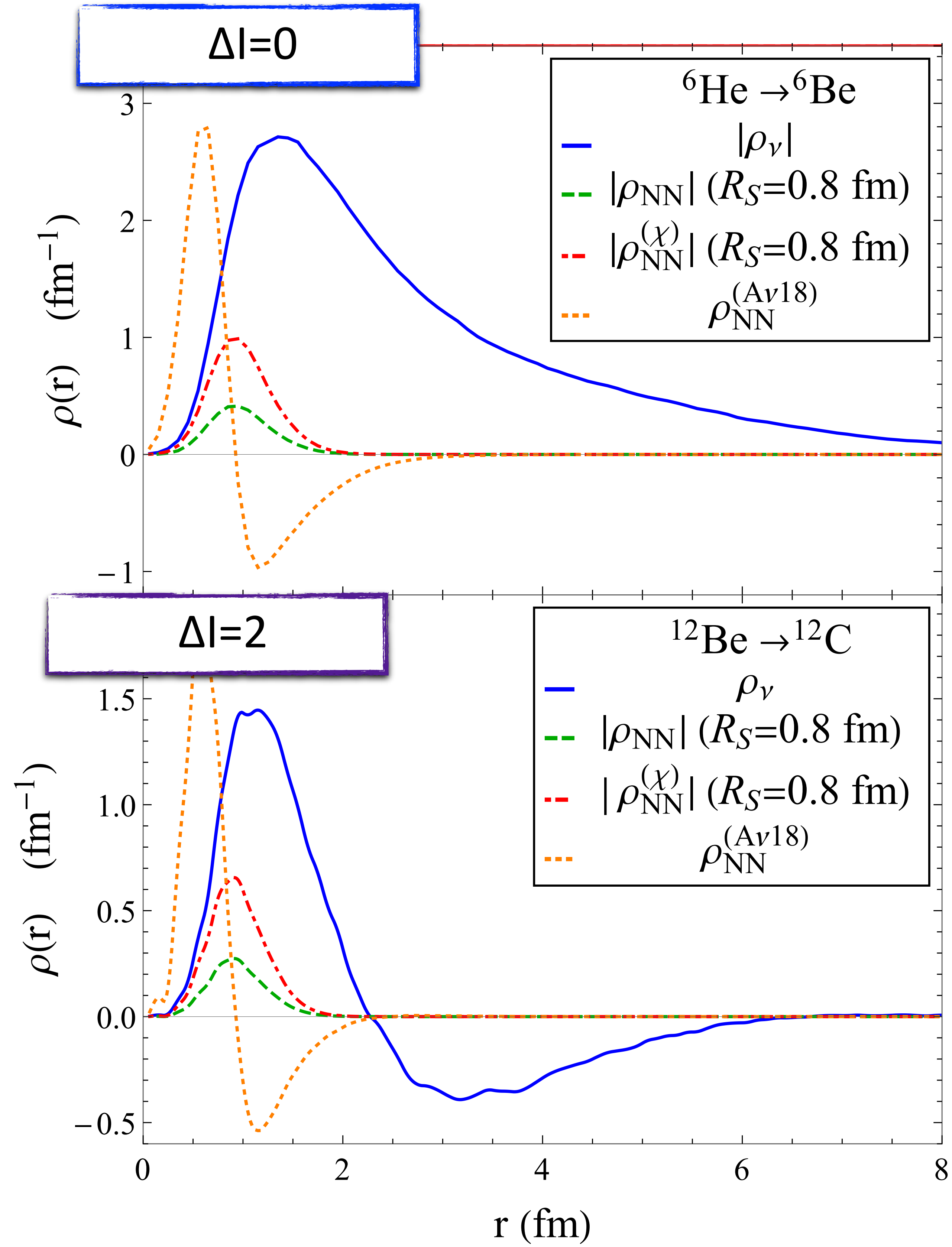
  - Uncontrolled error



Estimate of impact
Light nuclei

- Use ab initio wavefunctions
  R. Wiringa, S. Pastore et. al.
- Estimate of $g_\nu^{NN}(R_S) = \frac{C_1(R_S) + C_2(R_S)}{2}$
  - Extract $C_1 + C_2$ from CIB in NN
  - From Chiral potential
    M. Piarulli et. al. '16
  - Use short-distance ΔI=2 AV18 potential
    R. Wiringa, Stoks, Schiavilla, '95



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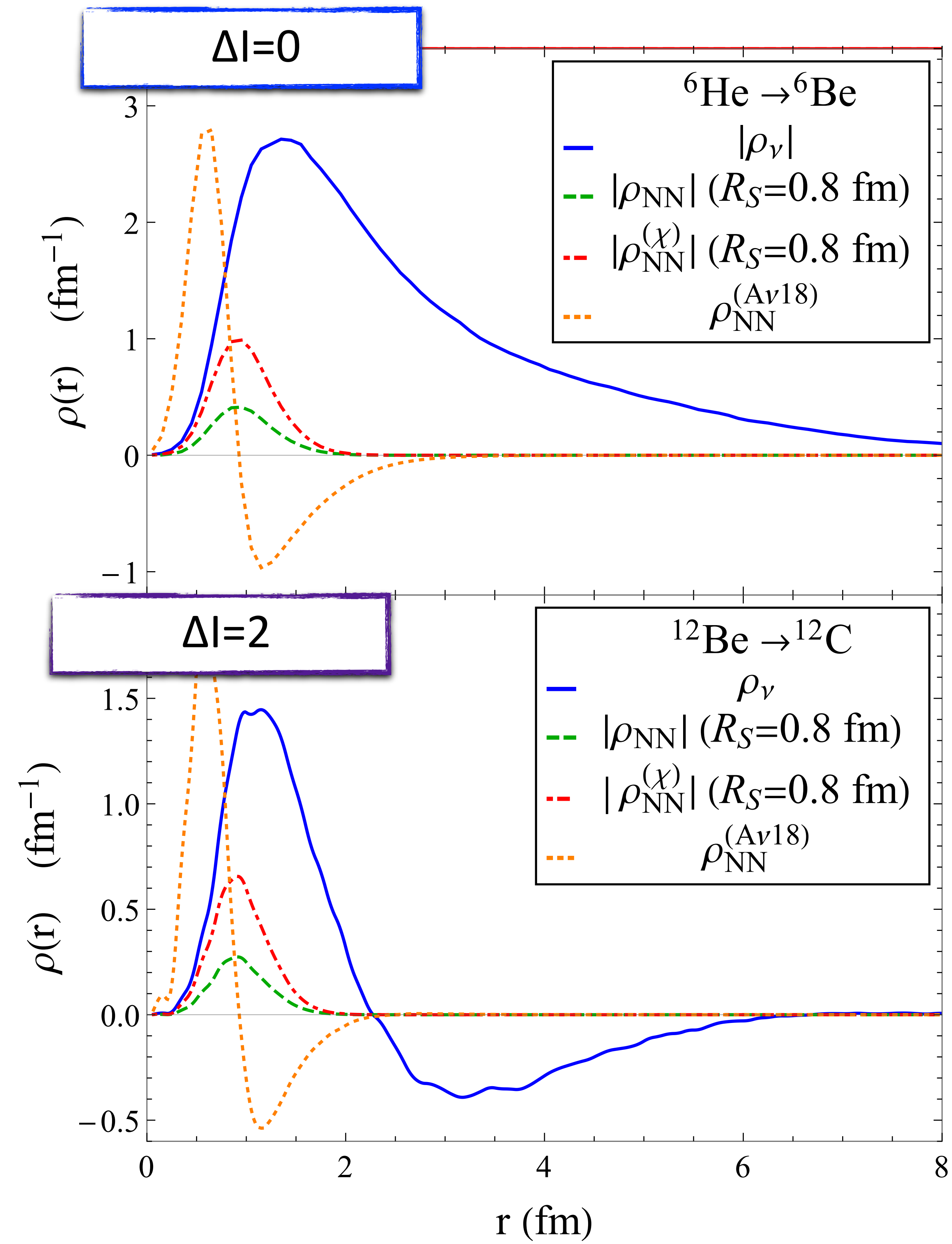
- 10% effect in ^{6}He → ^{6}Be
- 25-60% effect in ^{12}Be → ^{12}C
  - Due to presence of a node
  - Feature in realistic 0νββ candidates



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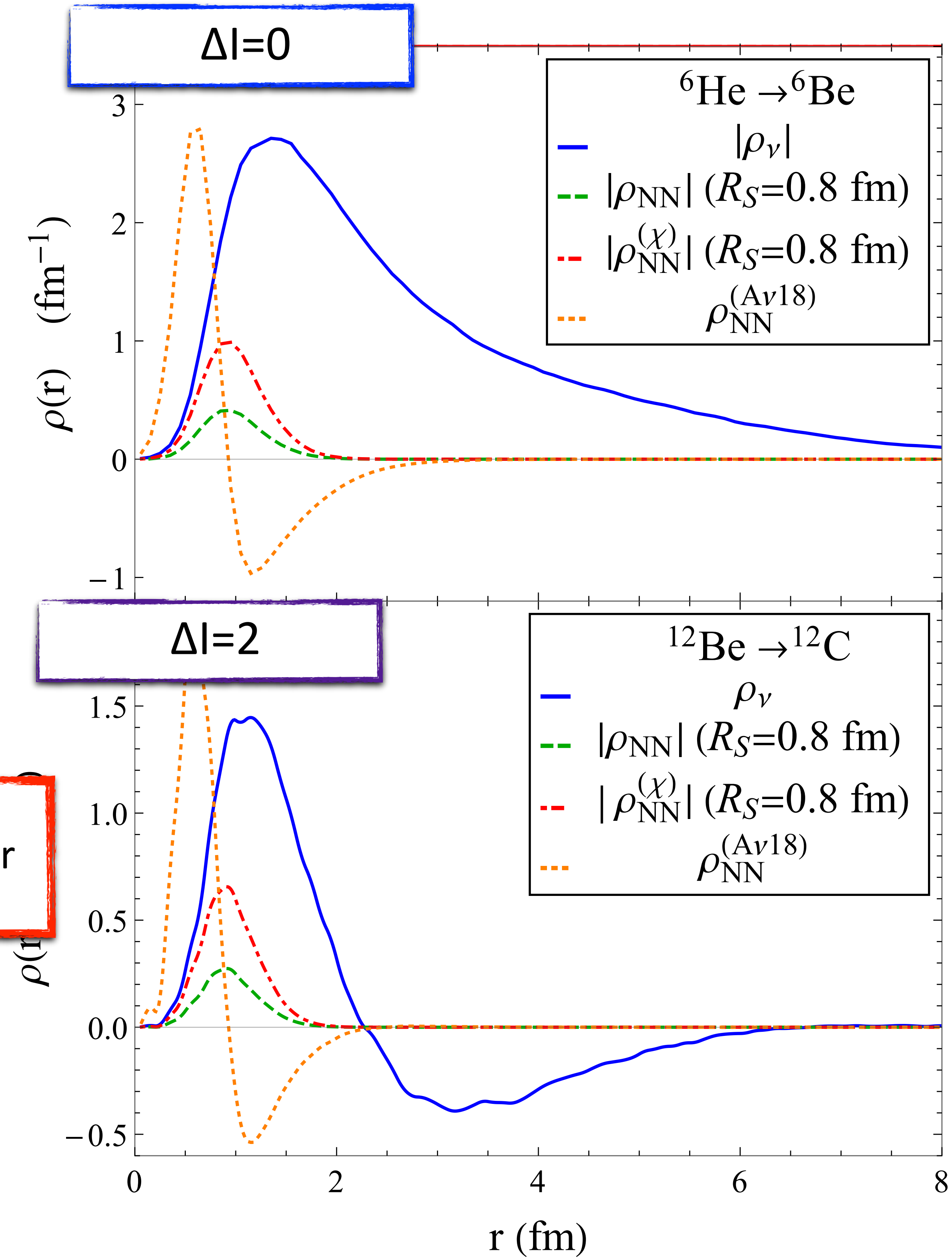
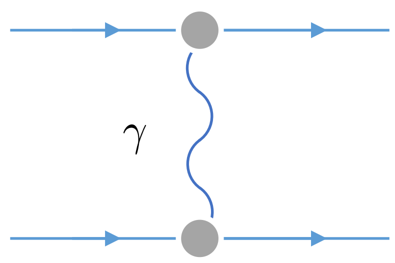


Relation to electromagnetism

For non-standard cases?

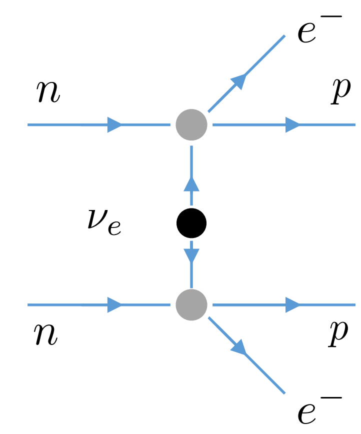
EM



$$\sim e^2/q^2$$

?

LNV



$$\sim G_F^2 m_{\beta\beta}/q^2$$

- Relation to Coulomb exchange relies on:
  - ΔI=2 piece of EM having similar chiral properties
  - Leptonic LNV part combines to a photon propagator

Relation to electromagnetism
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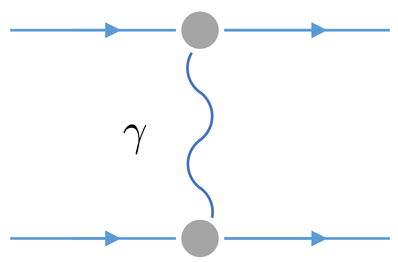

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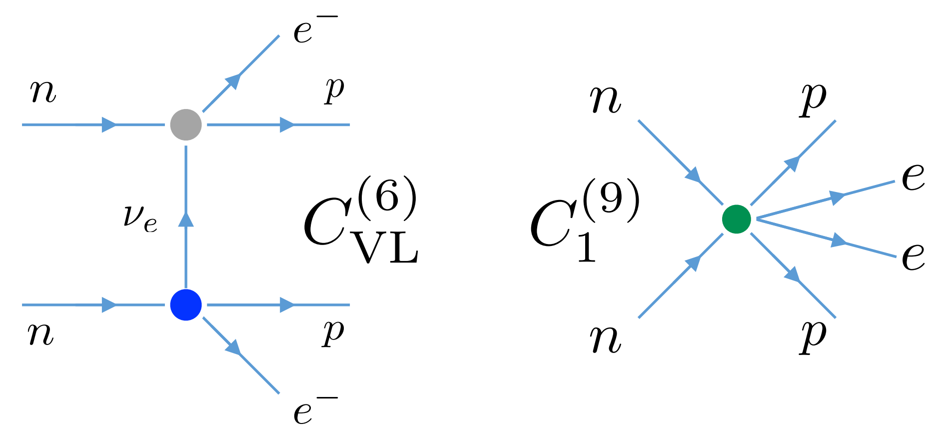

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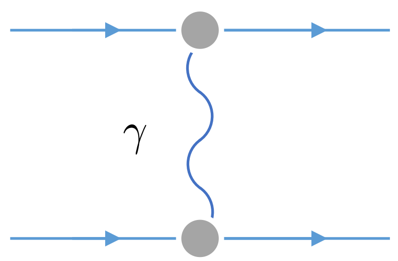

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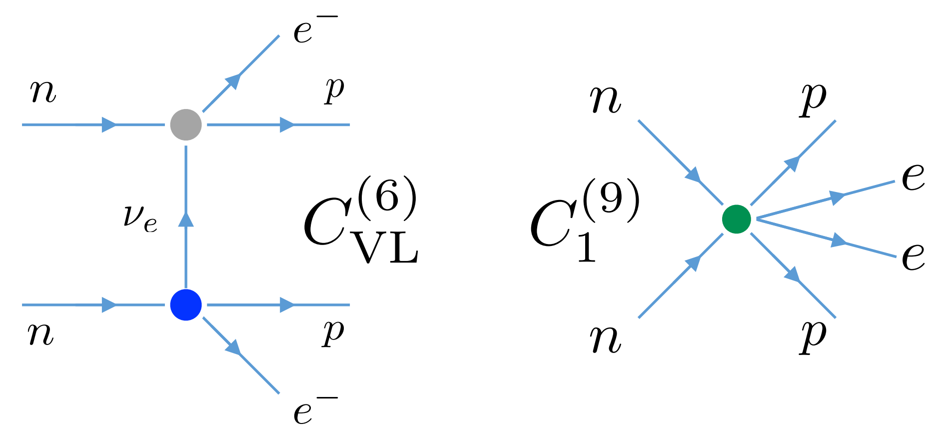

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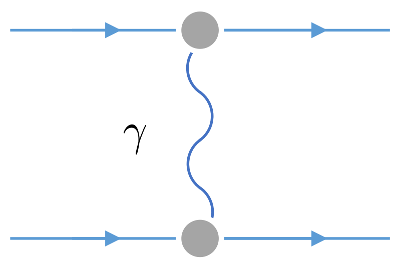

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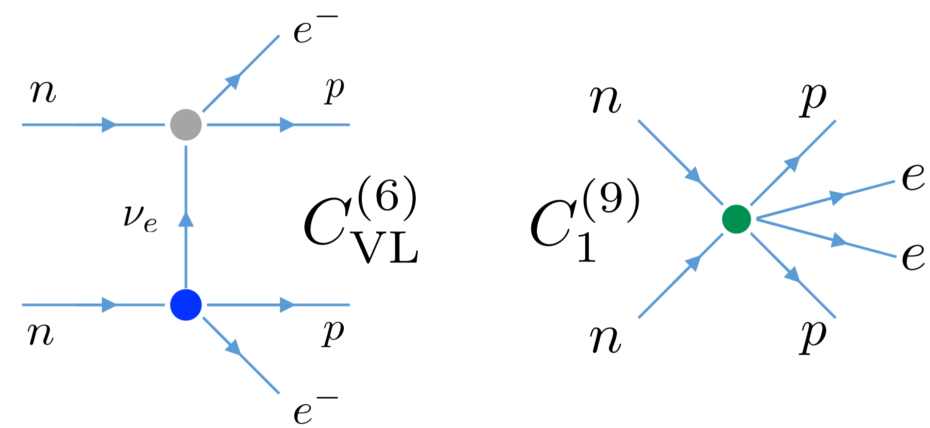
LNV



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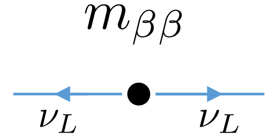
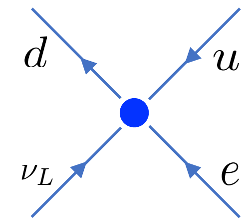
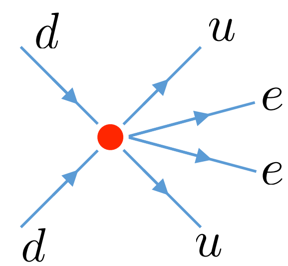
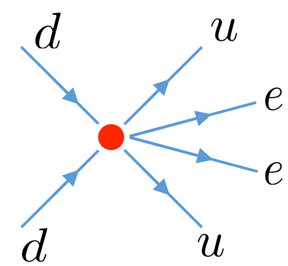
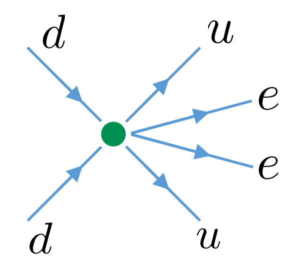
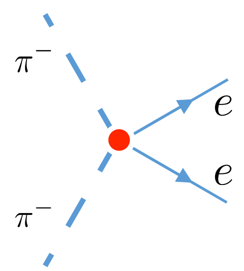
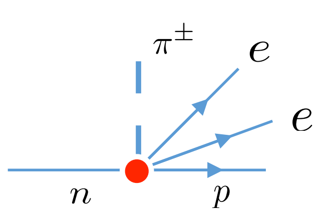
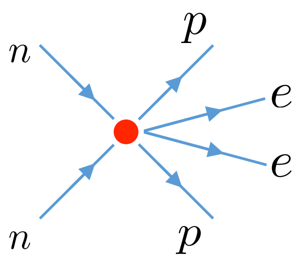
Short-distance Counterterms

Chiral EFT

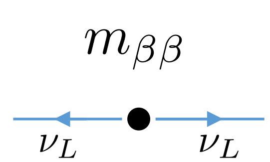
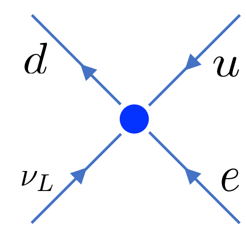
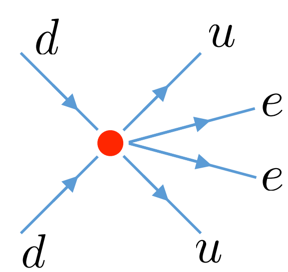
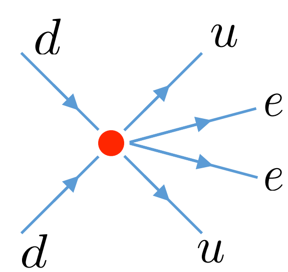
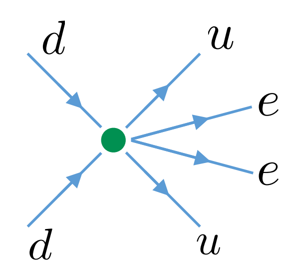
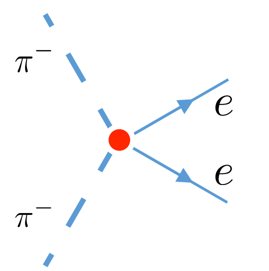
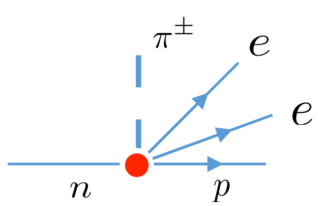
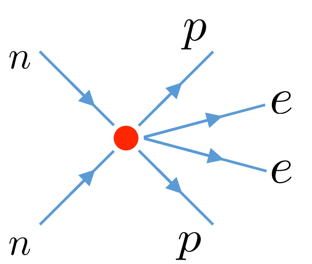
Short-range LECs

	Dim 3	Dim 6	Dim 9		
	$m_{\beta\beta}$ 	$C^{(6)}_{VL,VR}$ 	Scalar 	Scalar' 	Vector 
	-	-	✓ (green)	✓ (green)	-
	-	✓	-	✓	✓
	-	✓	-	✓	✓

✓ (green) = Lattice calculation

Chiral EFT

Short-range LECs

	Dim 3	Dim 6	Dim 9		
		$C^{(6)}_{VL,VR}$	Scalar	Scalar'	Vector
					
	-	-	✓ (green)	✓ (green)	-
	-	✓	-	✓	✓
	✓ (red)	✓ ✓ (red)	✓ (red)	✓	✓

✓ (green) = Lattice calculation

✓ (red) = Non-NDA

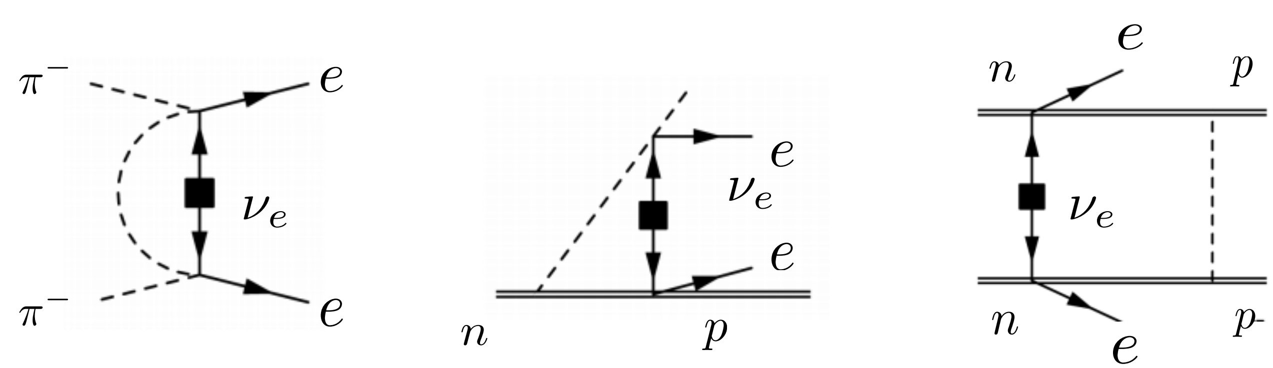
Ultrasoft contributions

$0\nu\beta\beta$ operators

Majorana-neutrino mass: N2LO

- N2LO Potential results from integrating out the ‘soft’ and `potential’

Full ChiPT
Degrees of freedom:
- Potential ν & π: $q^0 \ll k_F$, $\mathbf{q} \sim k_F$
- Soft ν & π: $q^0 \sim \mathbf{q} \sim k_F$
- Ultrasoft ν: $q^0 \sim \mathbf{q} \ll k_F$



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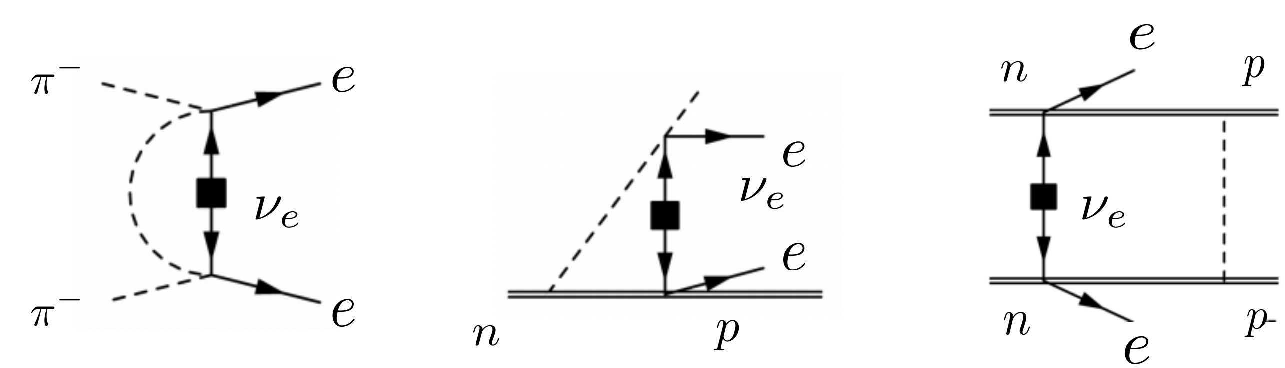
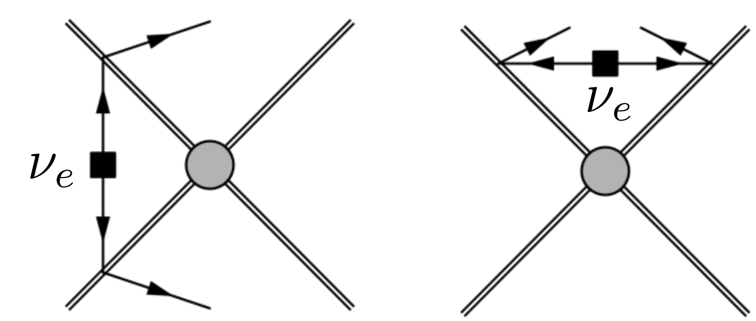


Low-energy EFT
Degrees of freedom:
Ultrasoft ν: $q^0 \sim \mathbf{q} \ll k_F$



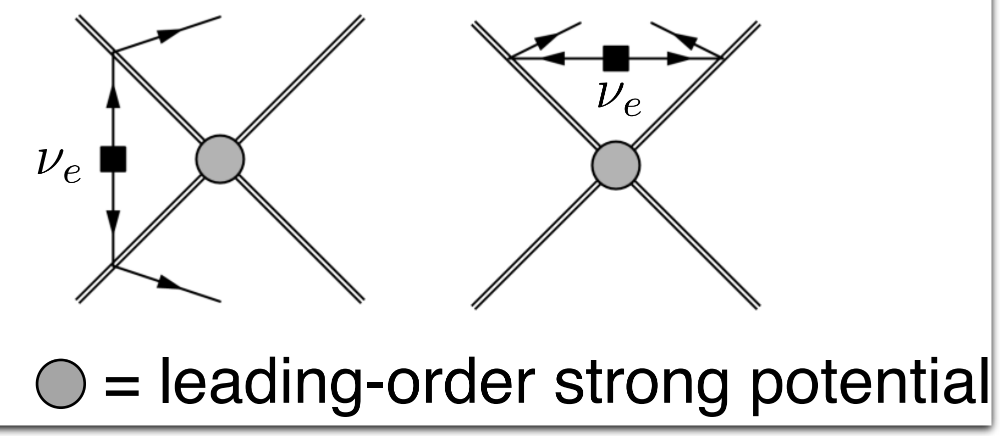
● = leading-order strong potential

$0\nu\beta\beta$ operators

Majorana-neutrino mass: N2LO

$$V_{\nu,2}^{(a,b)} = \tau^{(a)+}\tau^{(b)+}\left(\mathcal{V}_{VV}^{(a,b)} + \mathcal{V}_{AA}^{(a,b)} + \tilde{\mathcal{V}}_{AA}^{(a,b)} \log\frac{m_\pi^2}{\mu_{\rm us}^2} + \mathcal{V}_{CT}^{(a,b)}\right)$$

- Piece that depends on the renormalization scale
  - Arises from loops with ultrasoft neutrinos
  - What cancels this $\mu_{\rm us}$ dependence?



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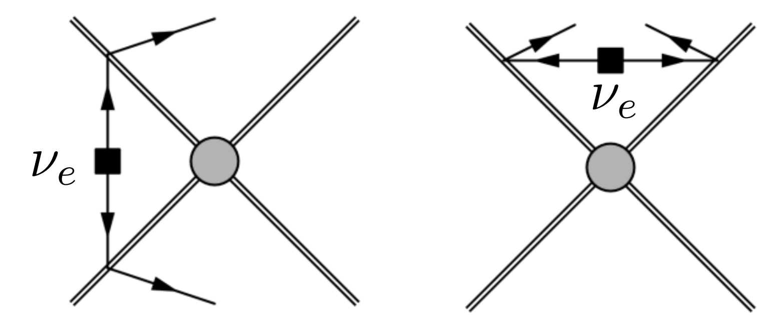

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- Still have propagating ultrasoft neutrinos
- Have to add their contributions to the amplitude!

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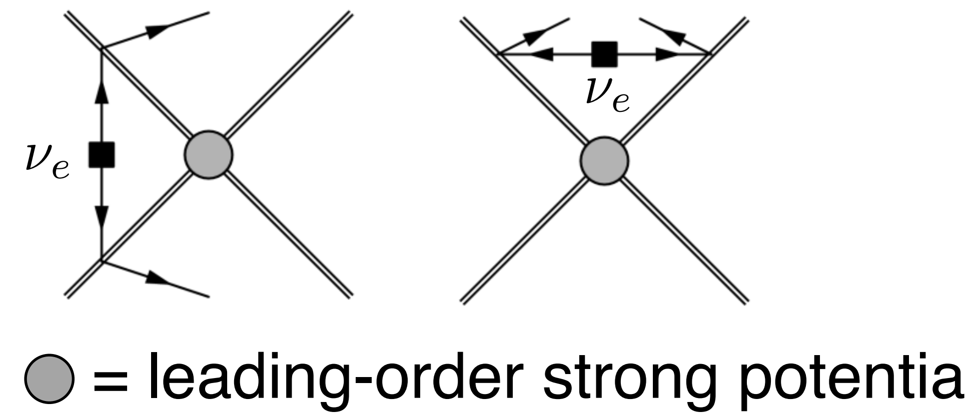

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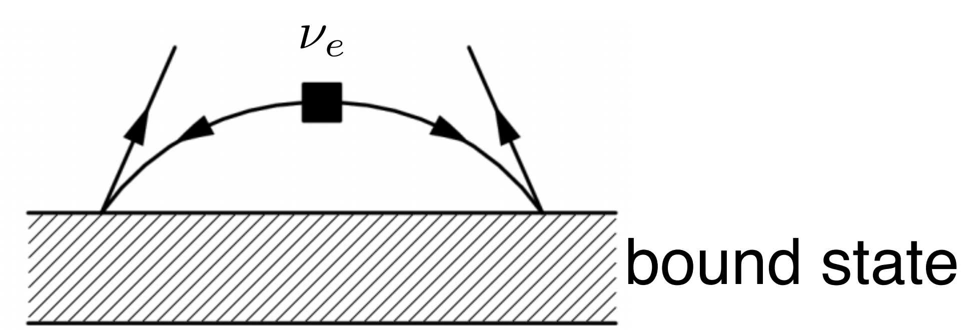

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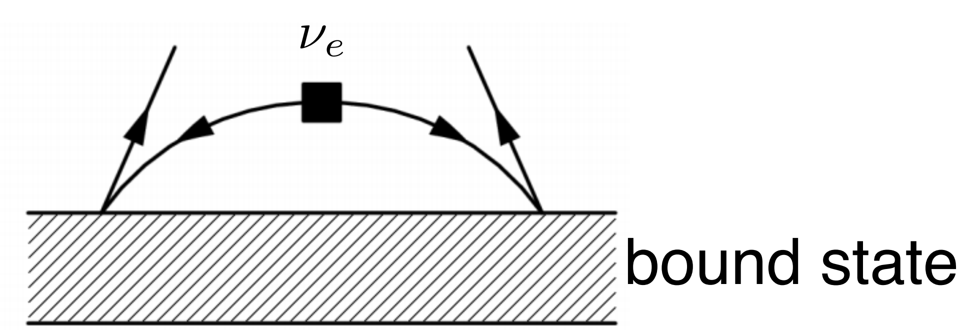
- Piece that depends on the renormalization scale

$$T'_{\rm usoft} = \frac{1}{8\pi^2} \sum_n \langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle \left\{ (E_2 + E_n - E_i)\left(\log \frac{\mu_{\rm us}}{2(E_2+E_n-E_i)} + 1 \right) + (1 \leftrightarrow 2) \right\}$$

= leading-order strong potential

- Still have propagating ultrasoft neutrinos
- Have to add their contributions to the amplitude!
  - Cancels the $\mu_{\rm us}$ dependence of the potential
  - Sensitive to the intermediate states
  - Same matrix elements as in $2\nu\beta\beta$



$0\nu\beta\beta$ operators

Majorana-neutrino mass: N2LO

- Standard approach

- At leading order
  - Use second order perturbation theory

$$\sum_n \frac{\langle f|J_L^\mu(\boldsymbol{q})|n\rangle\langle n|J_L^\nu(-\boldsymbol{q})|i\rangle}{|\boldsymbol{q}|(E_n+|\boldsymbol{q}|+E_{e2}-E_i)}$$

  - 'Closure approximation': $E_n - E_i \ll |\boldsymbol{q}|$

$$\frac{\langle f|J^\mu(\boldsymbol{q})J_\mu(-\boldsymbol{q})|i\rangle}{|\boldsymbol{q}|(|\boldsymbol{q}|+\bar{E}-(E_i+E_f)/2)}$$

e.g. Engel and Menendez, '16

$0\nu\beta\beta$ operators

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- At N^{2}LO:
  - Form factors
  - Ultrasoft contribution
  - Loops & Counterterms

e.g. Engel and Menendez, '16

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
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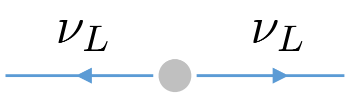
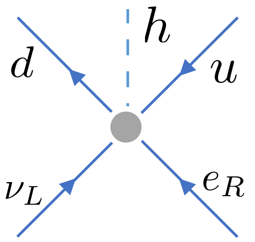
Disentangling operators

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

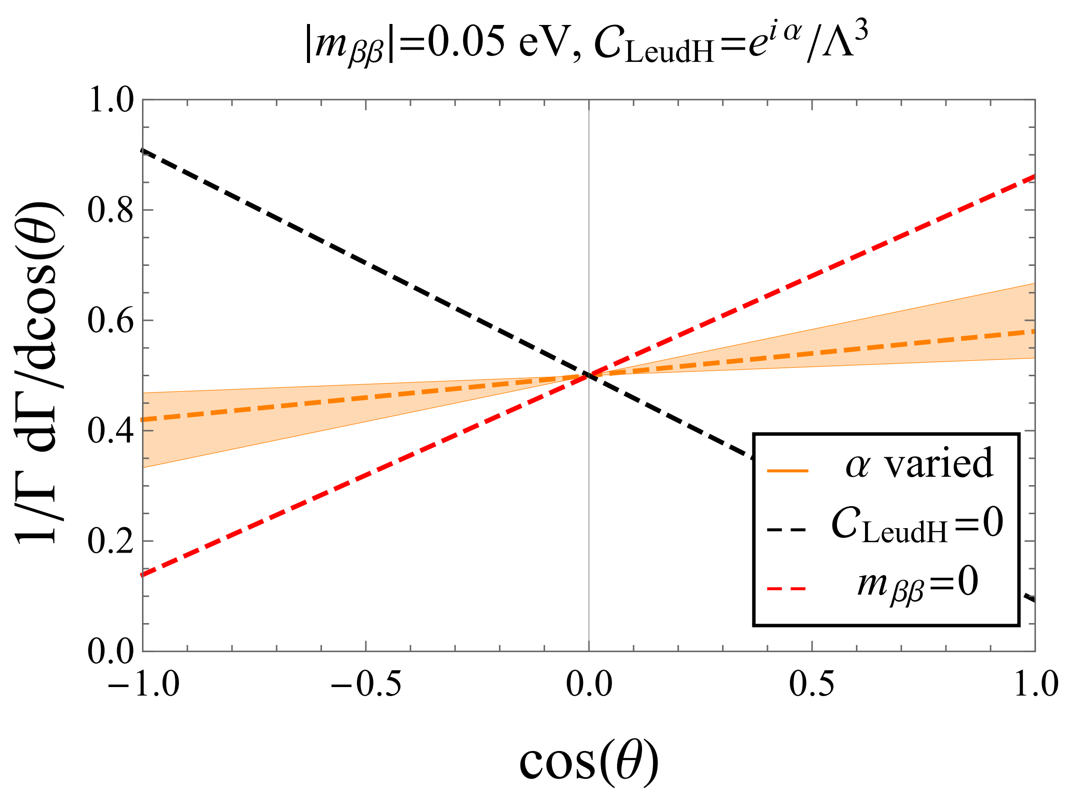
- Picking the allowed values



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



$\mathcal{C}_{\mathrm{LeudH}} = e^{i\alpha}/\Lambda^3$ $\quad \Lambda = 40\,\mathrm{TeV}$



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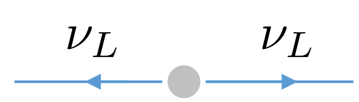

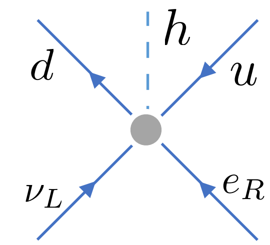

$m_{\beta\beta} = 0.05\,\mathrm{eV}$ $\quad$ $\mathcal{C}_{\mathrm{LeudH}} = e^{i\alpha}/\Lambda^3$ $\quad$ $\Lambda = 40\,\mathrm{TeV}$