Neutrinoless double beta decay in effective field theory

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with

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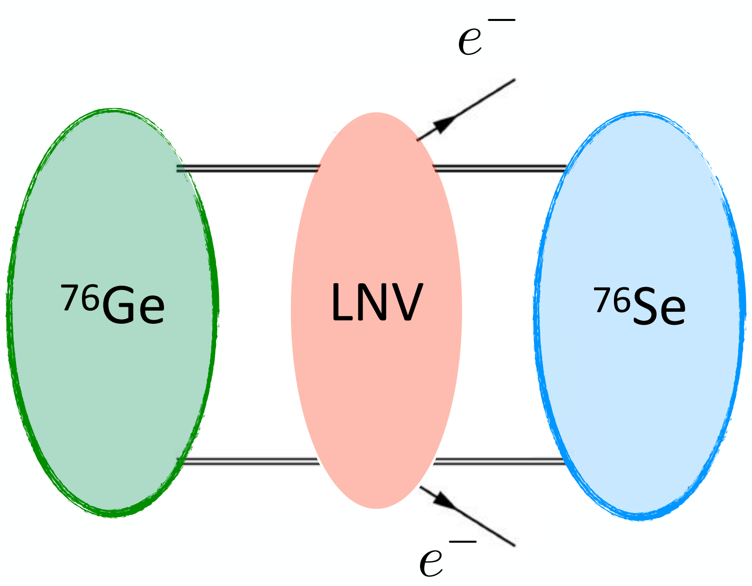
E. Mereghetti, M. Piarulli, S. Pastore,
U. van Kolck, A. Walker-Loud, R.B. Wiringa

UNIVERSITY of WASHINGTON

INSTITUTE for NUCLEAR THEORY

Introduction

0νββ



- Violates lepton number, ΔL=2

Schechter, Valle, `82

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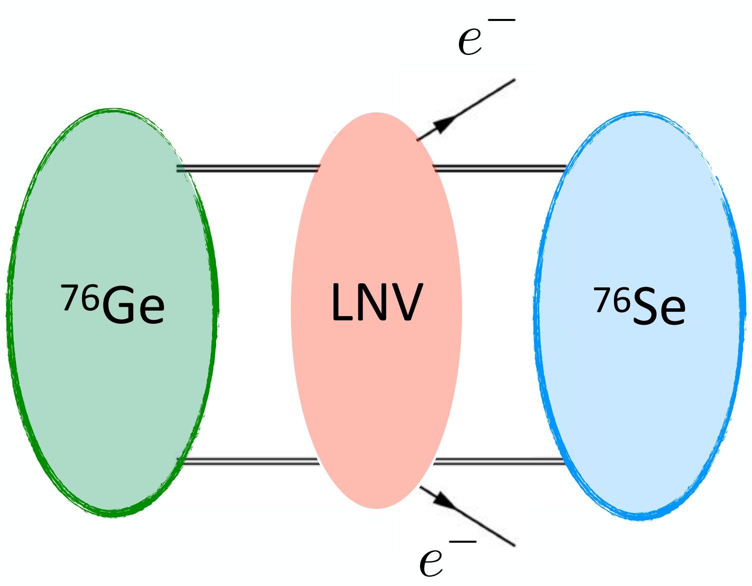

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- Stringently constrained experimentally
  - To be improved by 1-2 orders

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge})$ Gerda	$T^{0\nu}_{1/2}(^{130}\mathrm{Te})$ Cuore	$T^{0\nu}_{1/2}(^{136}\mathrm{Xe})$ KamLAND-zen
$> 9 \cdot 10^{25}\,\mathrm{yr}$	$> 3.2 \cdot 10^{25}\,\mathrm{yr}$	$> 1.1 \cdot 10^{26}\,\mathrm{yr}$

Future reach:
(LEGEND, nEXO, CUPID)

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

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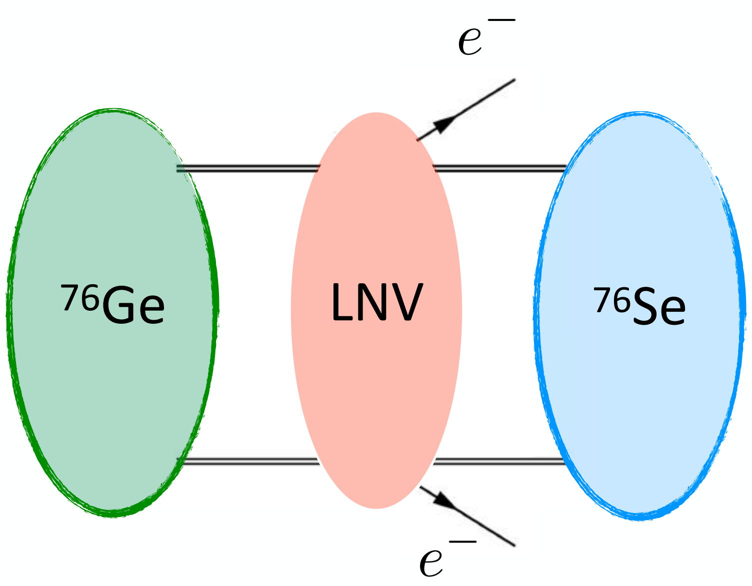

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- Would imply that
  - Neutrino's are Majorana particles
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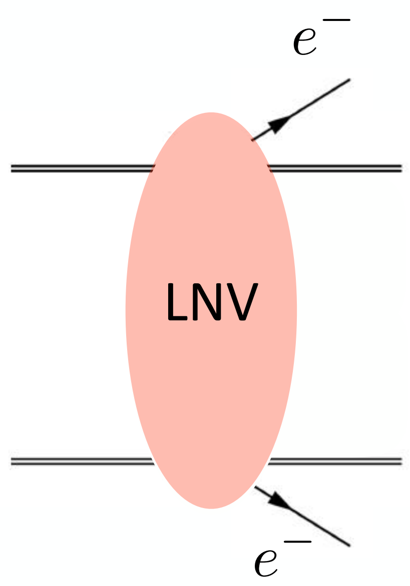

= **BSM physics**

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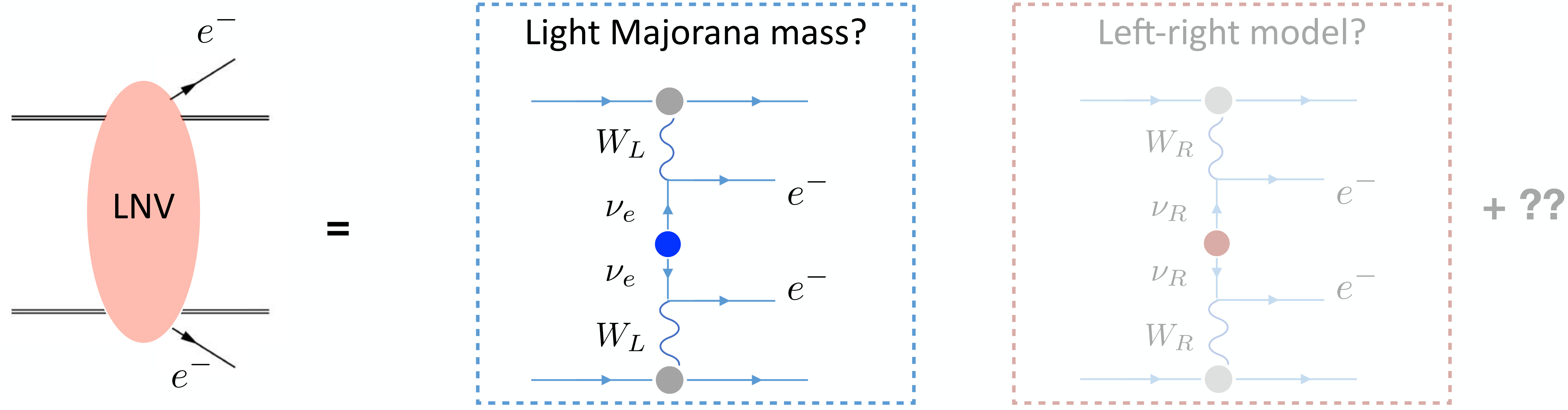
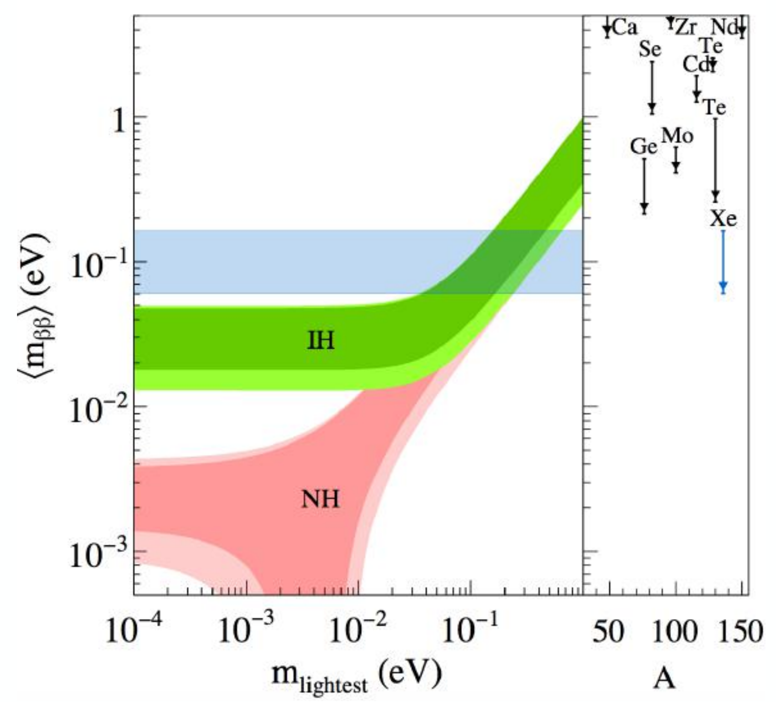


Well-known Majorana mass mechanism



- Implications for the mass hierarchy

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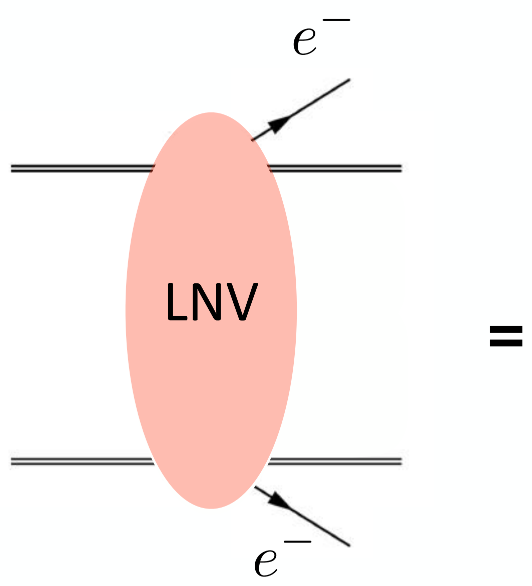

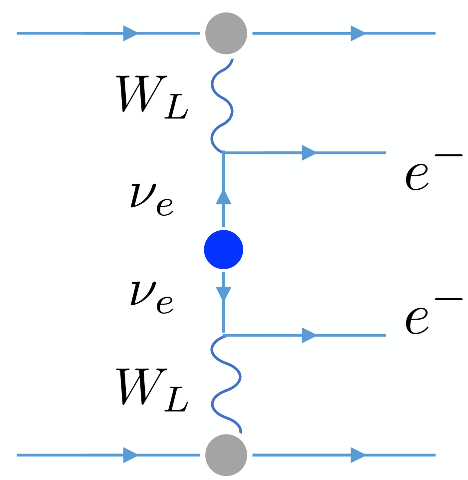

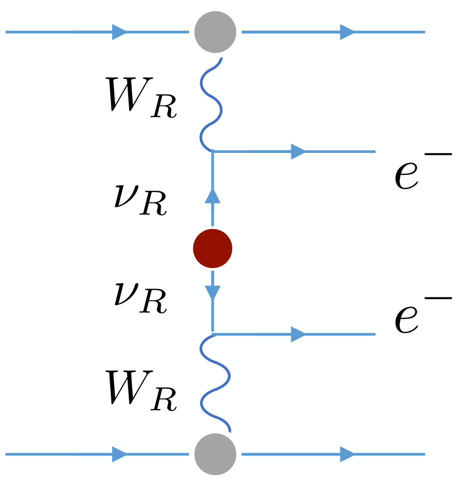

+ ??

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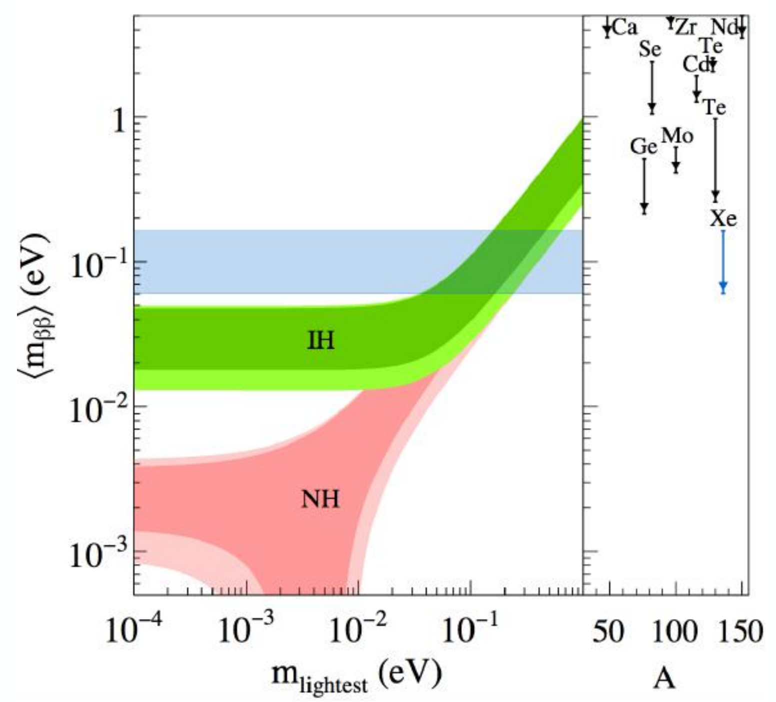

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Heavy BSM mechanisms

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

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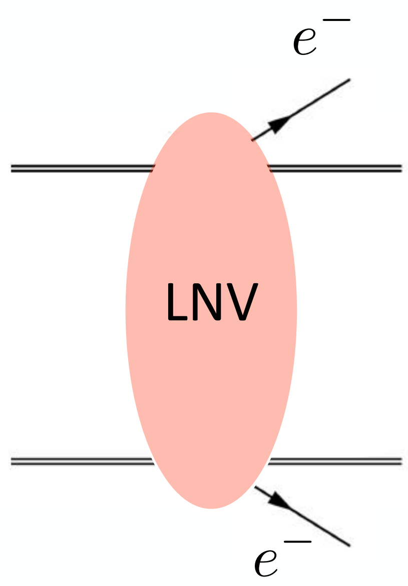

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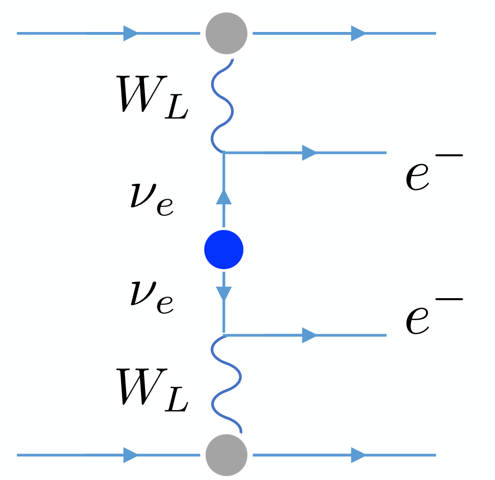
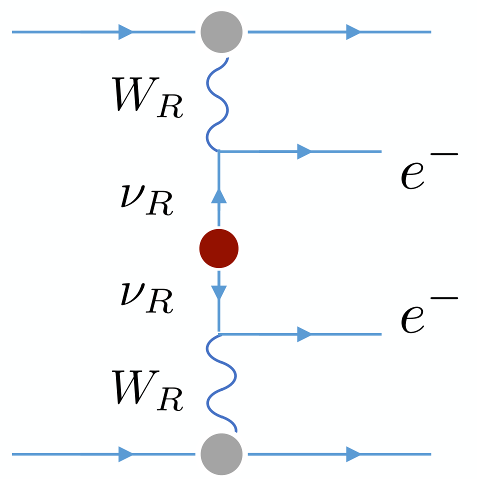
Light Majorana mass?



Left-right model?



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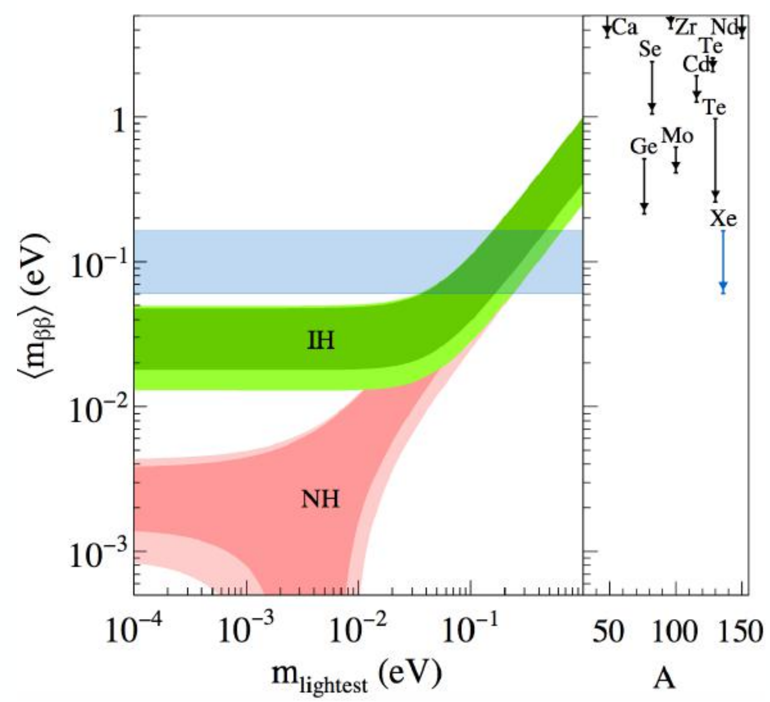

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  - Left-right model,
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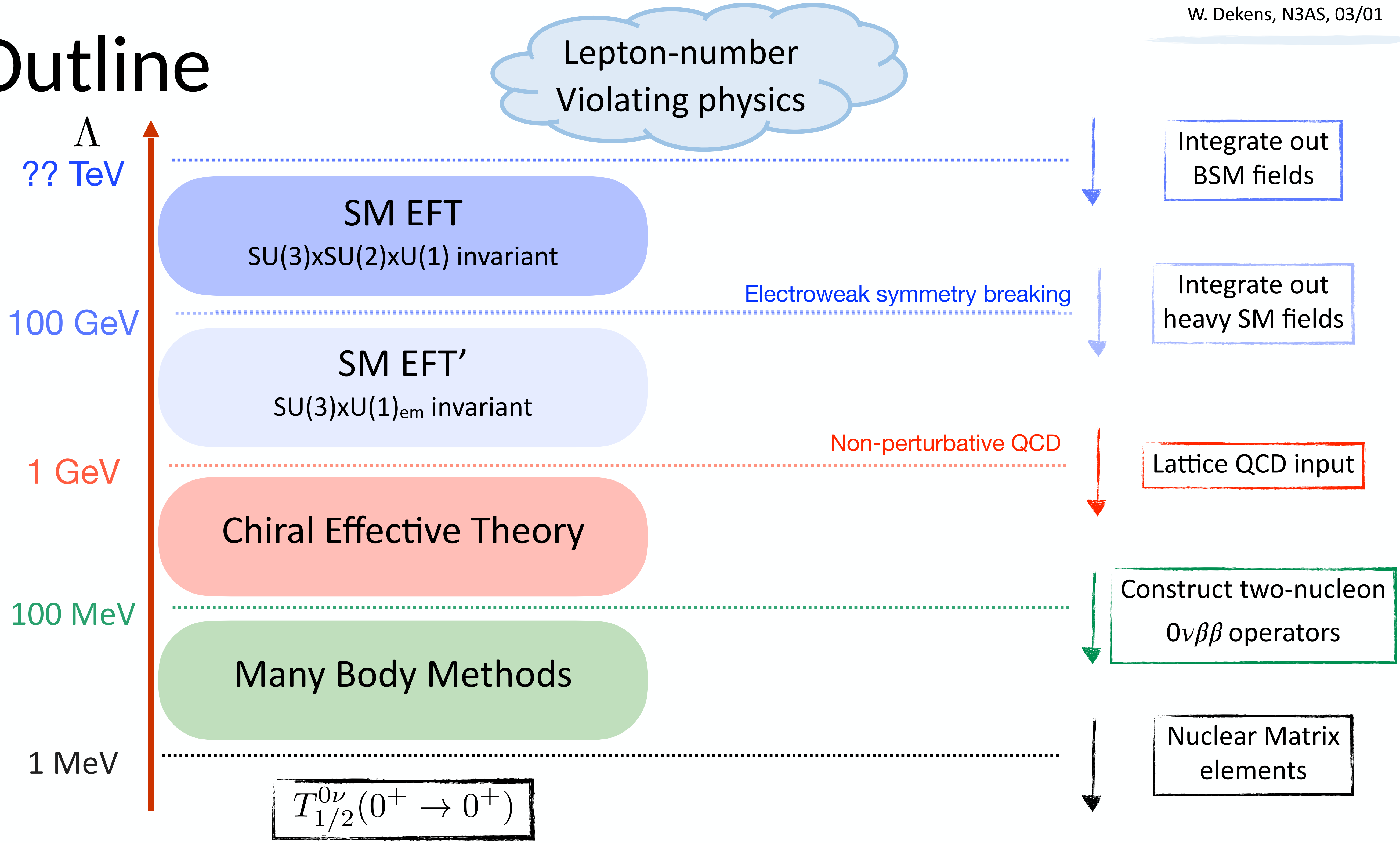
  - Leptoquarks…
- How to describe all LNV sources systematically?

Outline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Many Body Methods
$T^{0\nu}_{1/2}(0^+ \to 0^+)$
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Integrate out heavy SM fields
Lattice QCD input
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

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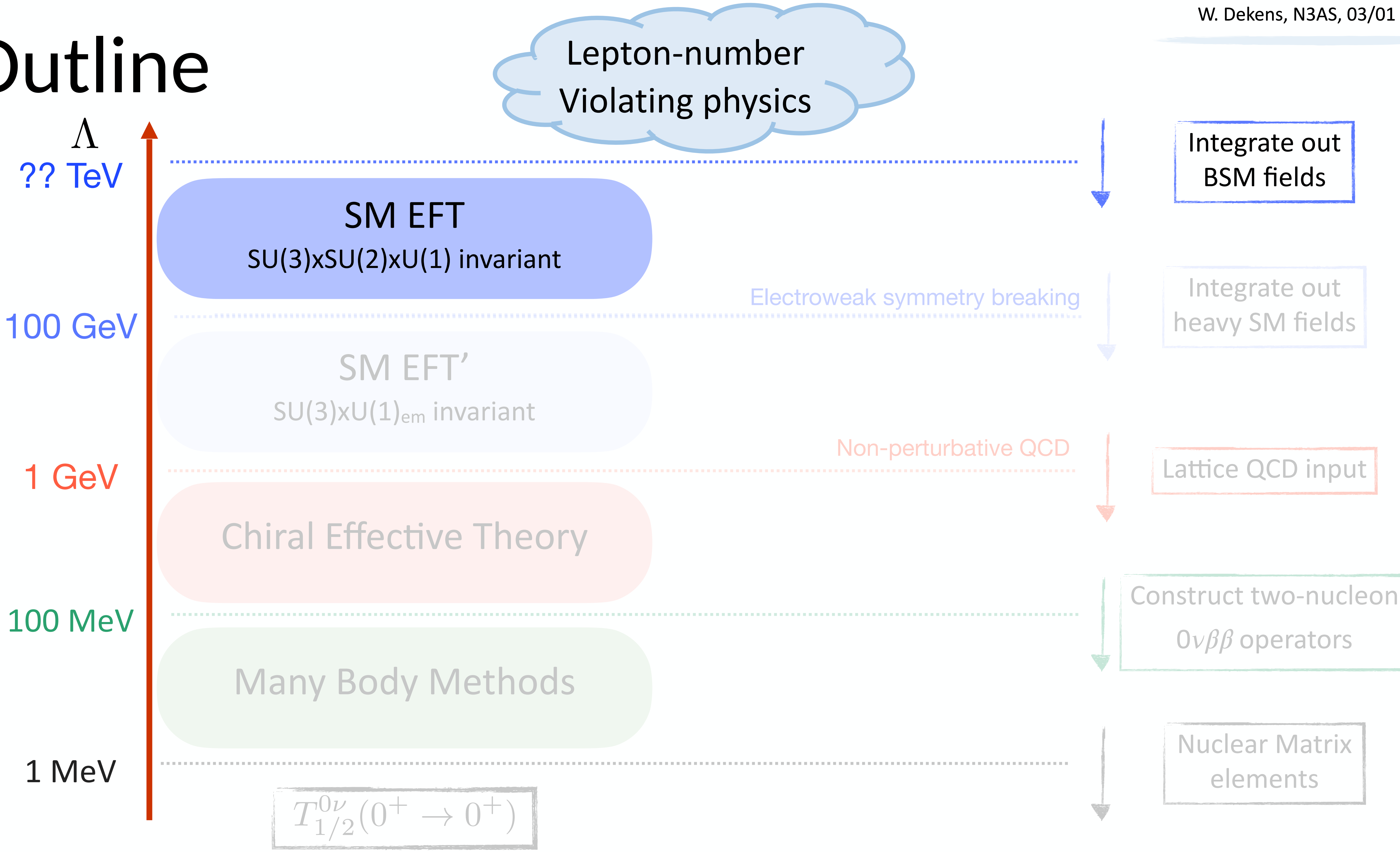
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Effective Field Theory

From heavy $\Delta L = 2$ physics

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

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

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Dimension-nine

- Consider subset of operators

$$\begin{aligned}
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Interactions involving light ν_R

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

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

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- Majorana mass (L violating)

WD et al, '20; Blennow et al, '10; Barea et al, '15; Giunti et al, '15; Bolton et al, '19;

Effective Field Theory

From heavy $\Delta L = 2$ physics

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

Interactions involving light ν_R

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

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Liao & Ma, '17

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

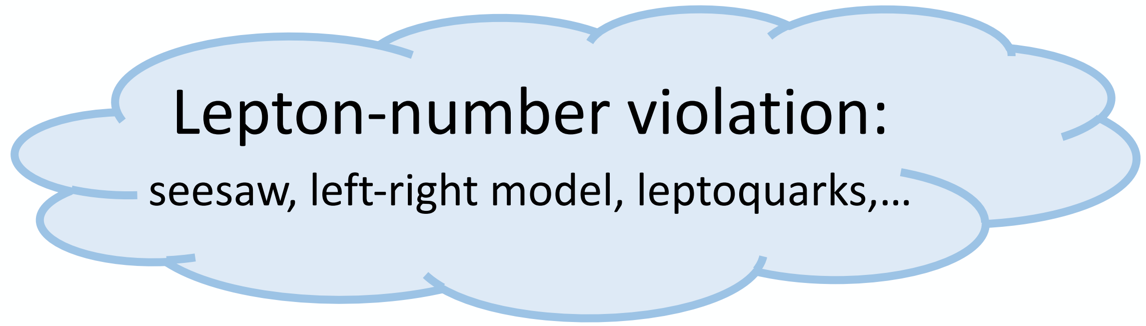
- Majorana mass (L violating)

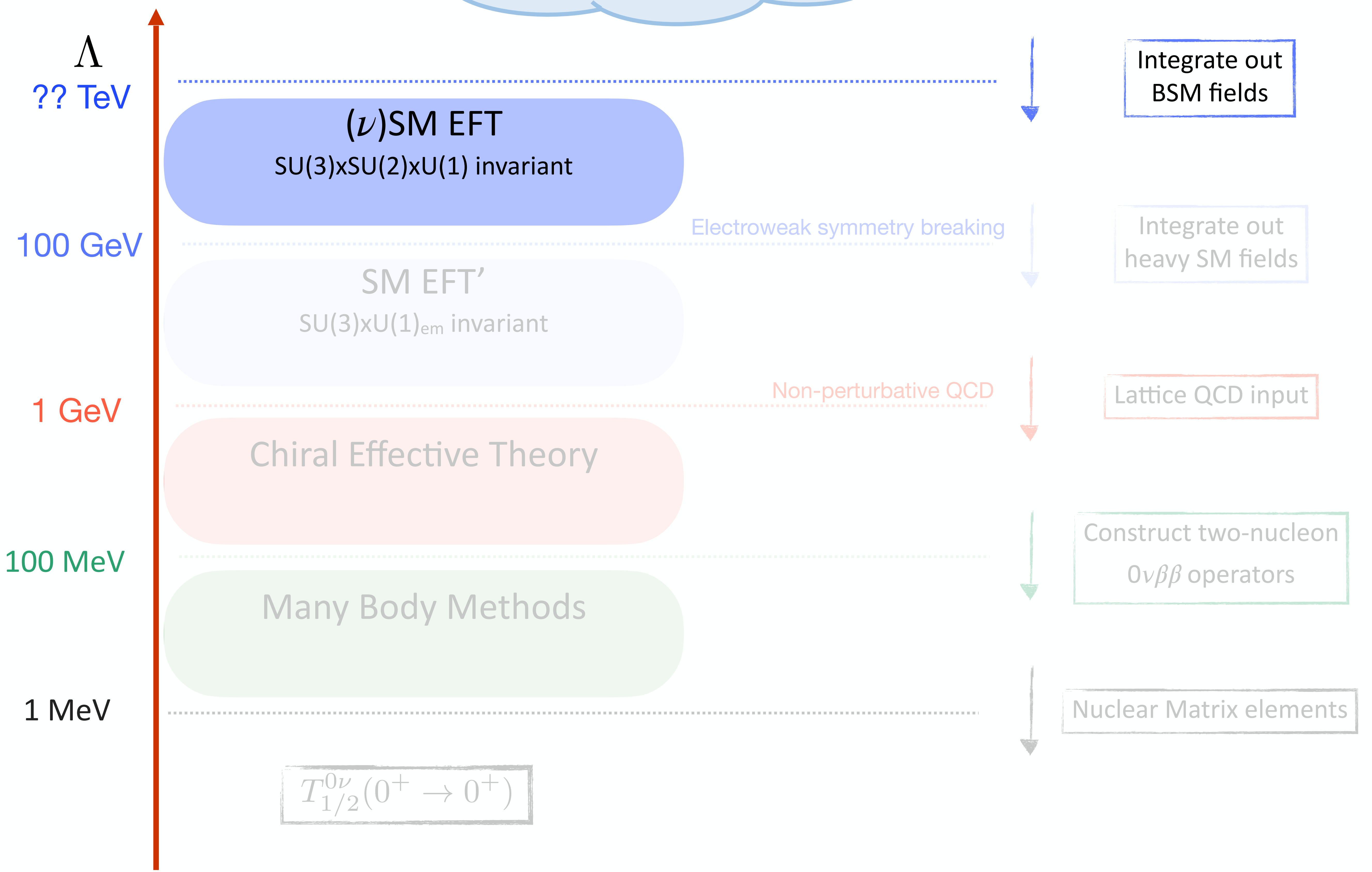
- Dirac mass (L conserving)

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

WD et al, '20; Blennow et al, '10; Barea et al, '15; Giunti et al, '15; Bolton et al, '19;

Outline


Lepton-number violation:
seesaw, left-right model, leptoquarks,...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?? TeV
100 GeV
1 GeV
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SU(3)xSU(2)xU(1) invariant
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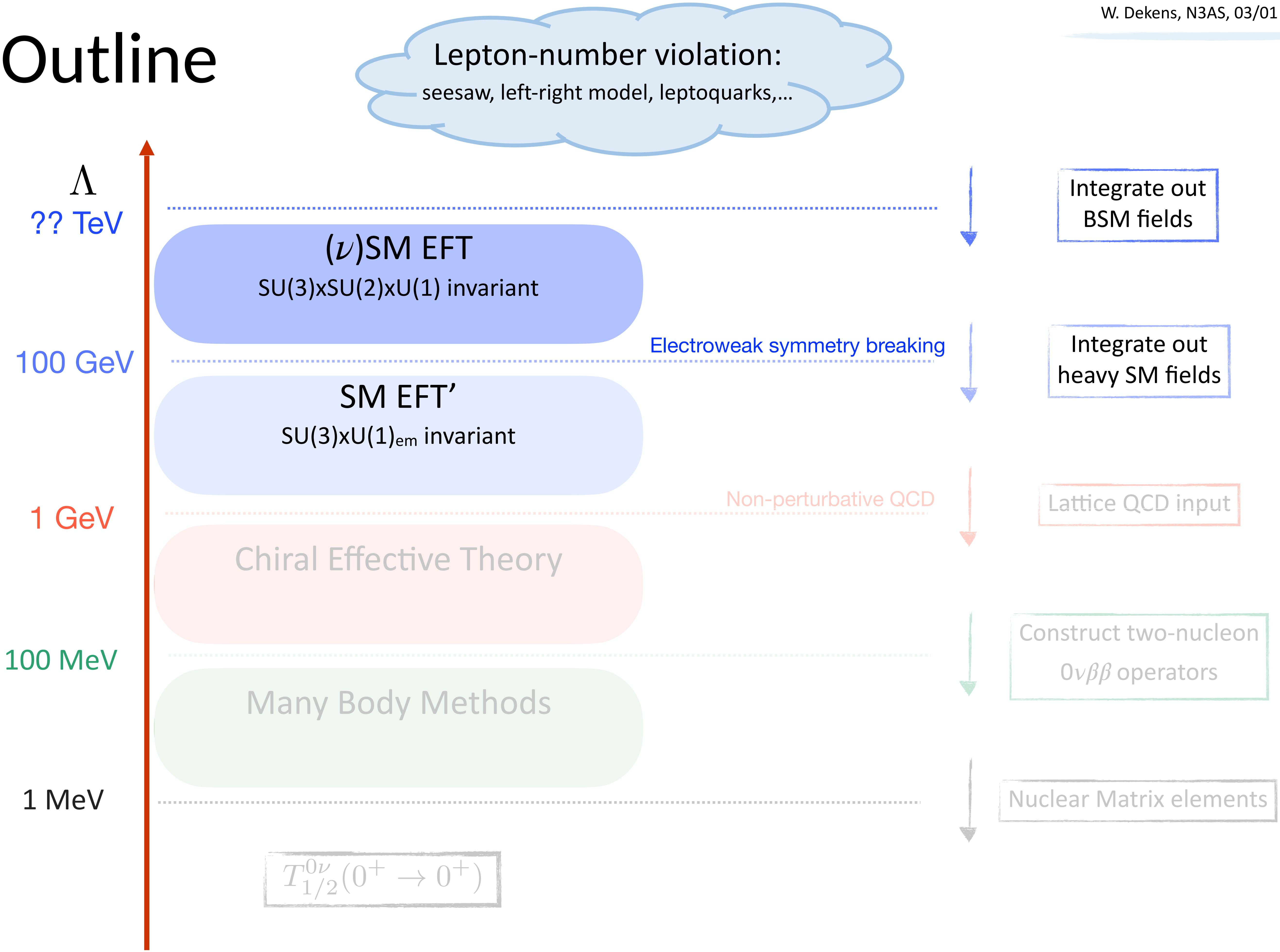
$T^{0\nu}_{1/2}(0^+ \to 0^+)$
Integrate out BSM fields
Integrate out heavy SM fields
Lattice QCD input
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

Outline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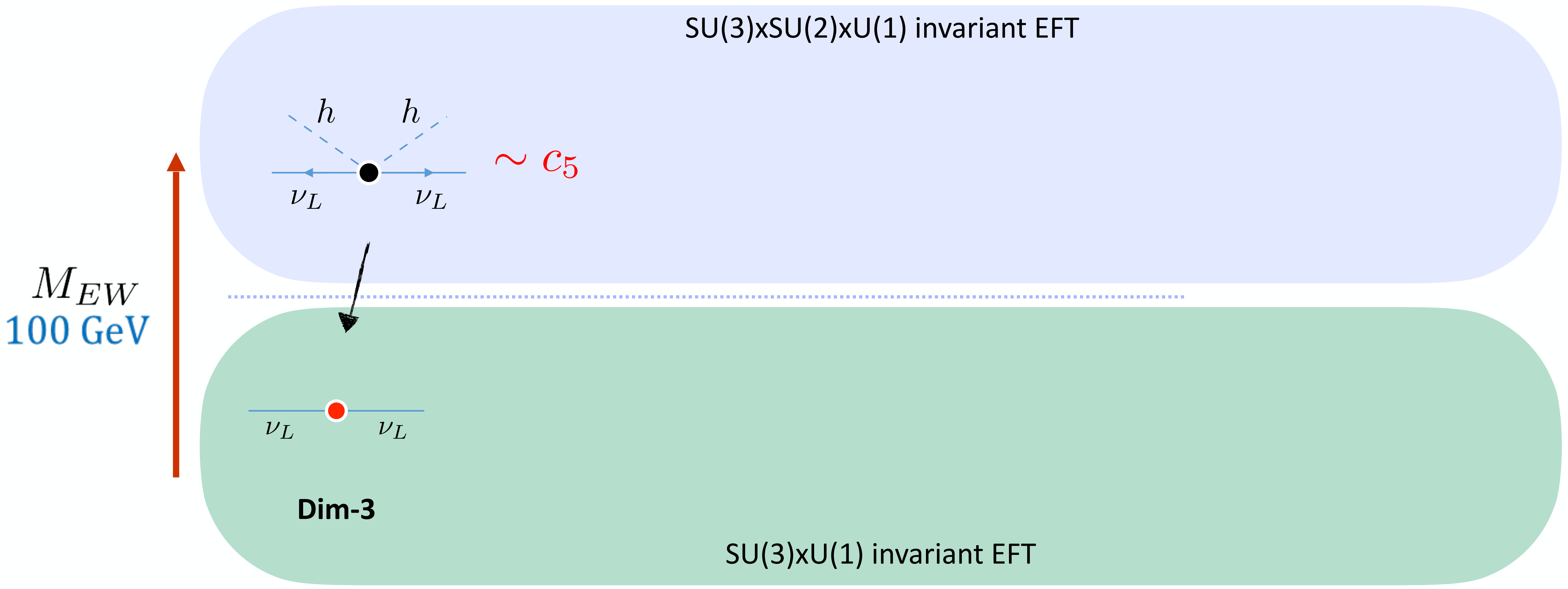
Low-energy operators

At/below the weak scale*



* very similar for operators involving ν_R

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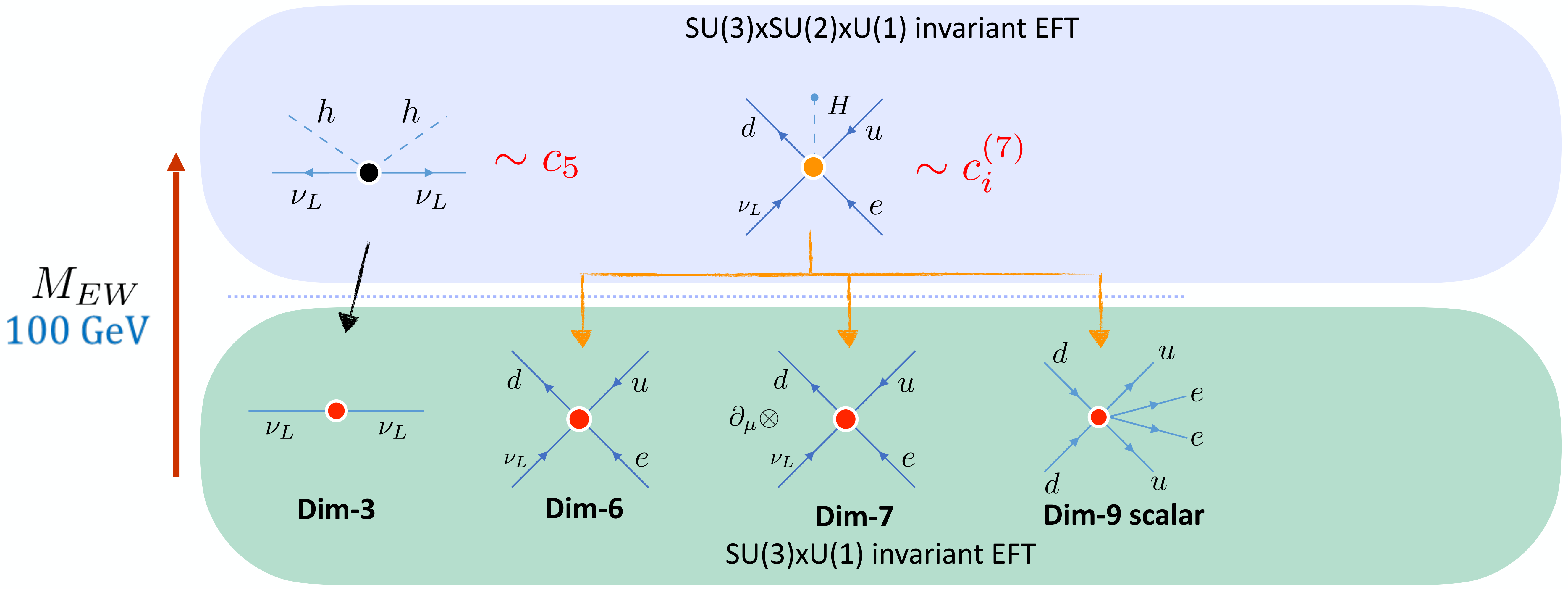

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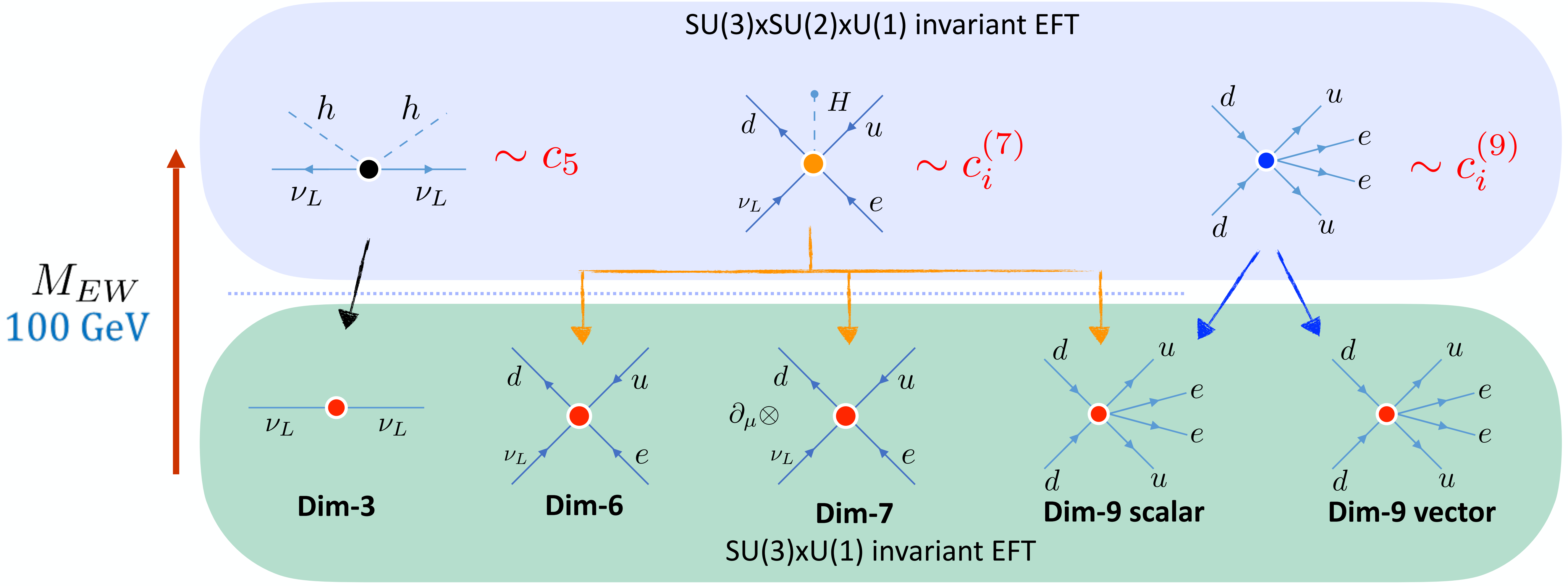

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Outline

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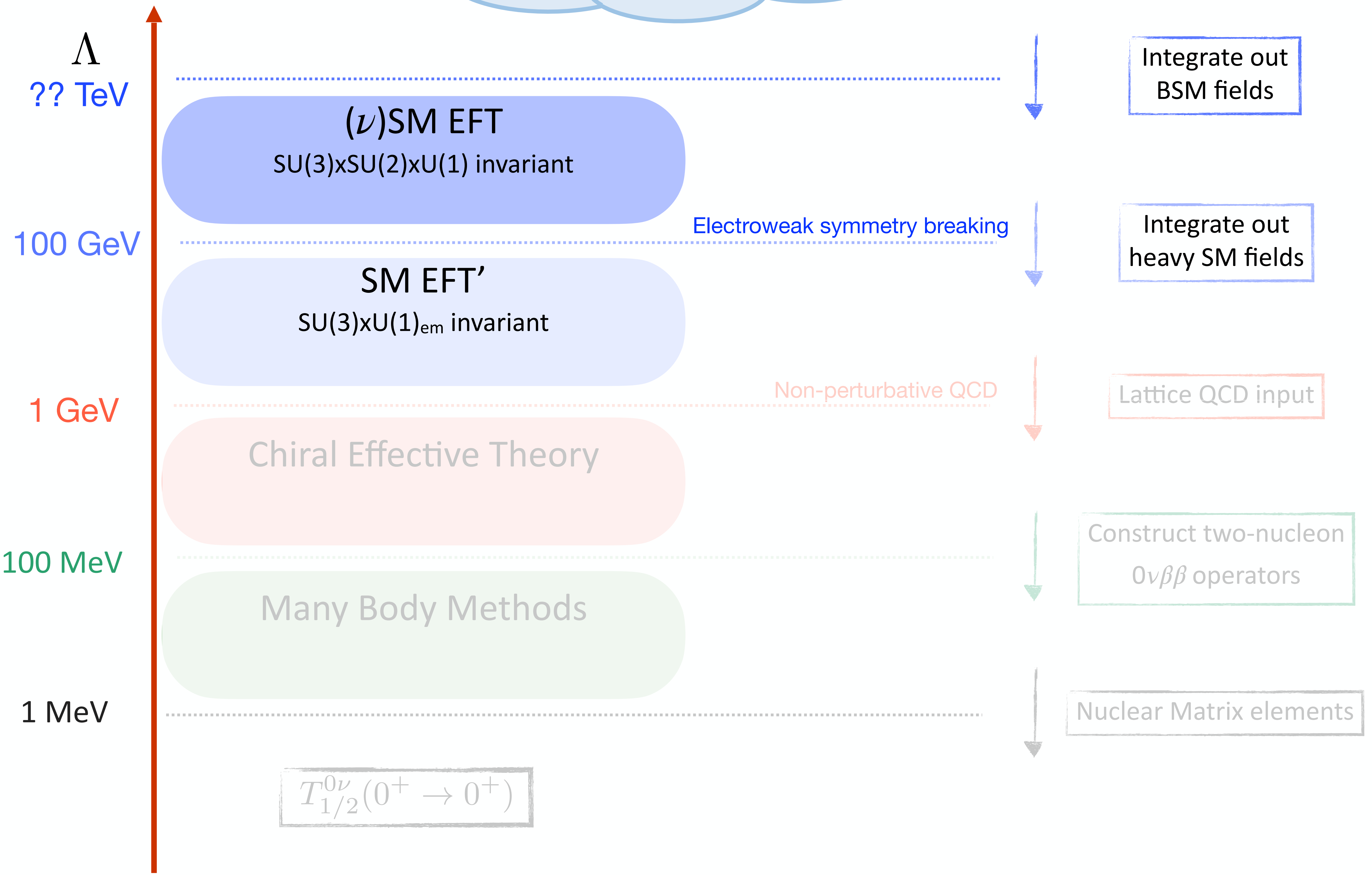
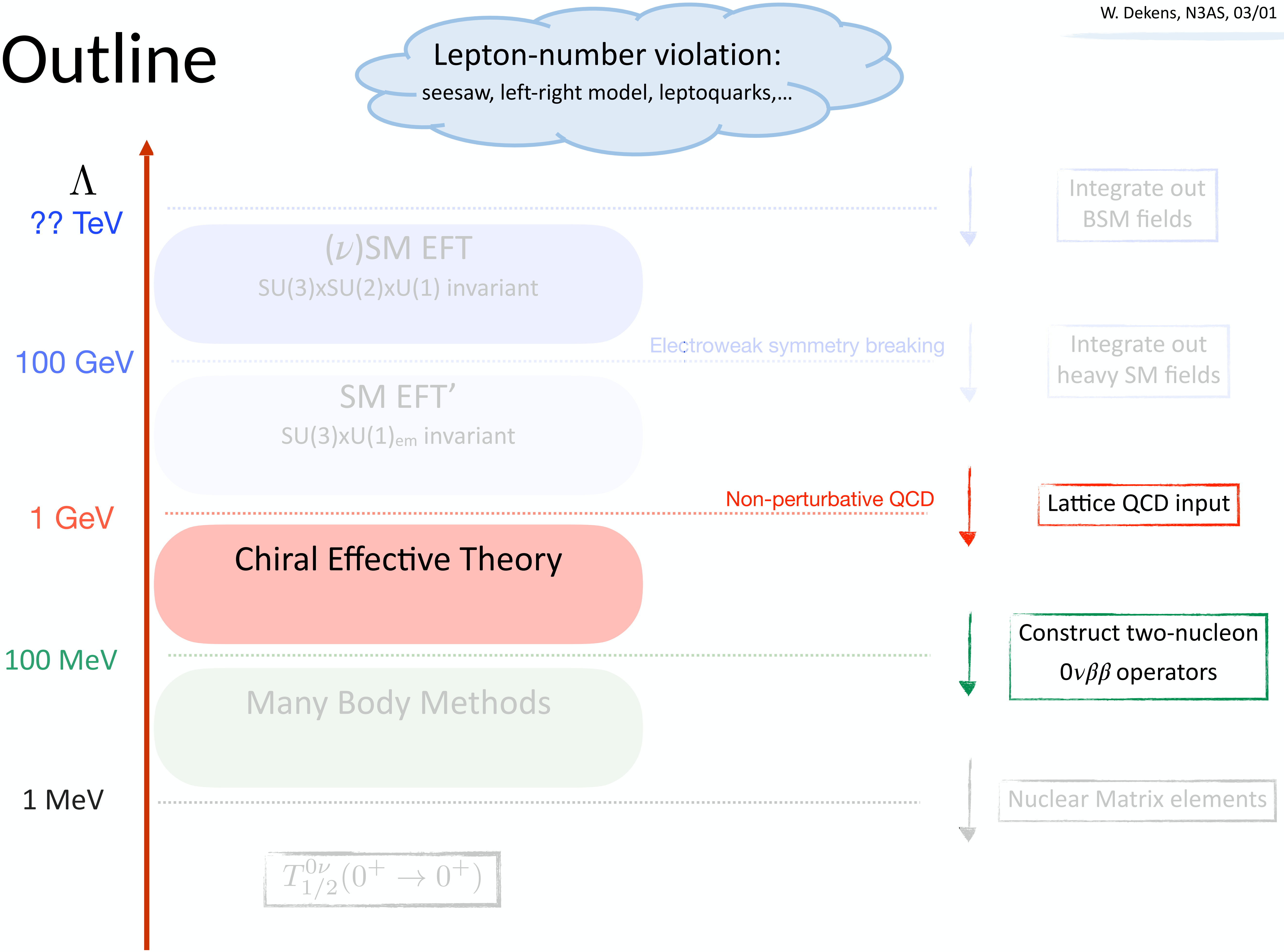


Outline

W. Dekens, N3AS, 03/01



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)

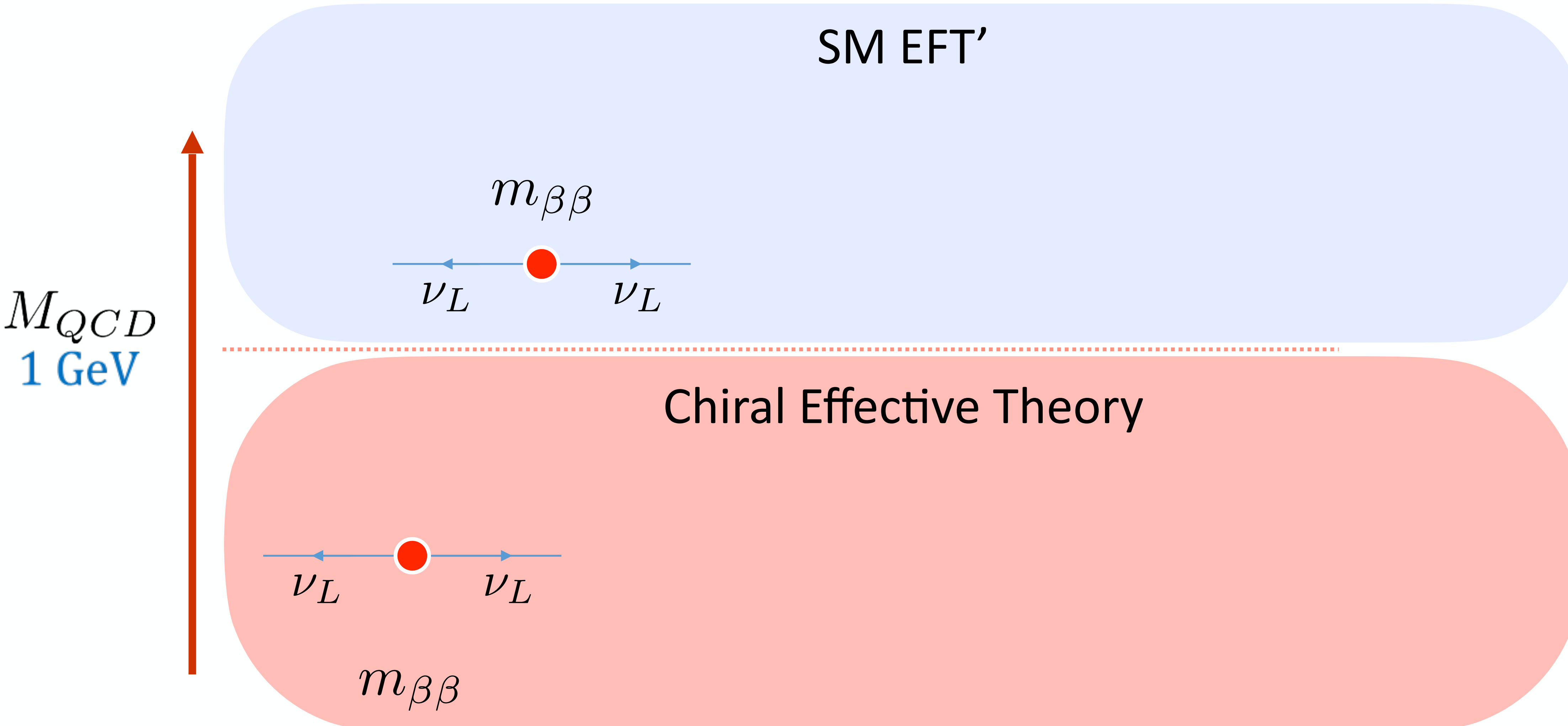
Need a power-counting scheme
- Start by assuming Naive dimensional analysis (NDA)
- Will come back to whether it breaks down

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

Matching to Chiral EFT

Dimension-3

Warning: Based on NDA



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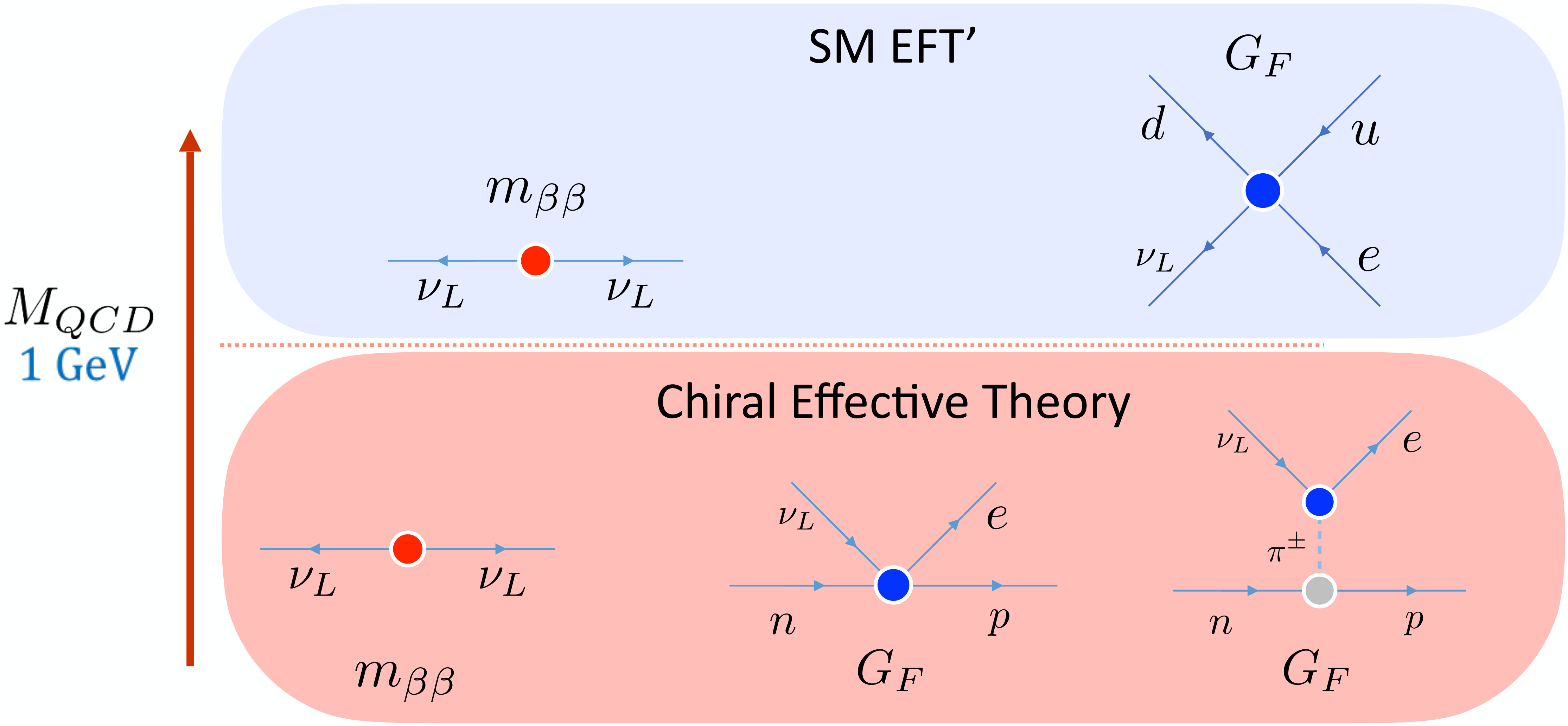

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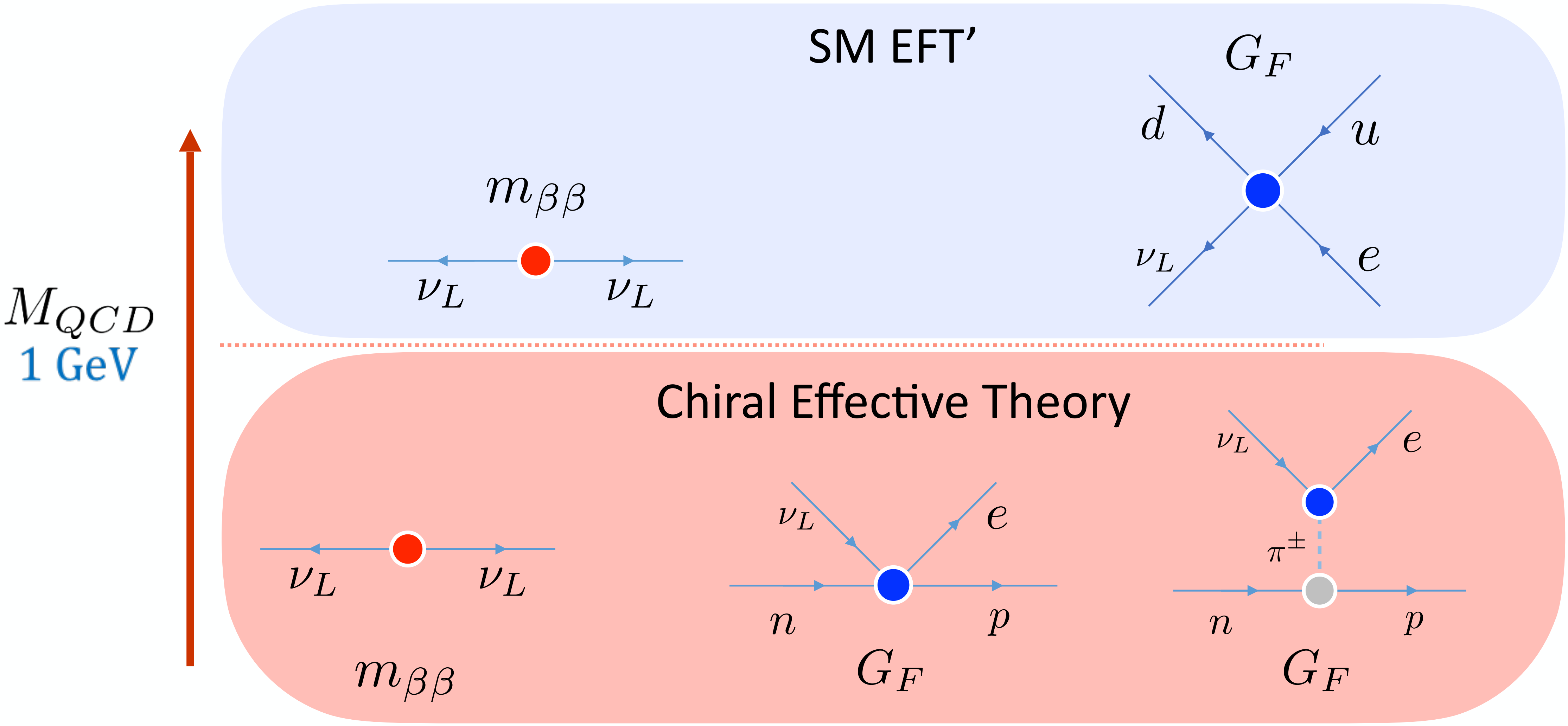
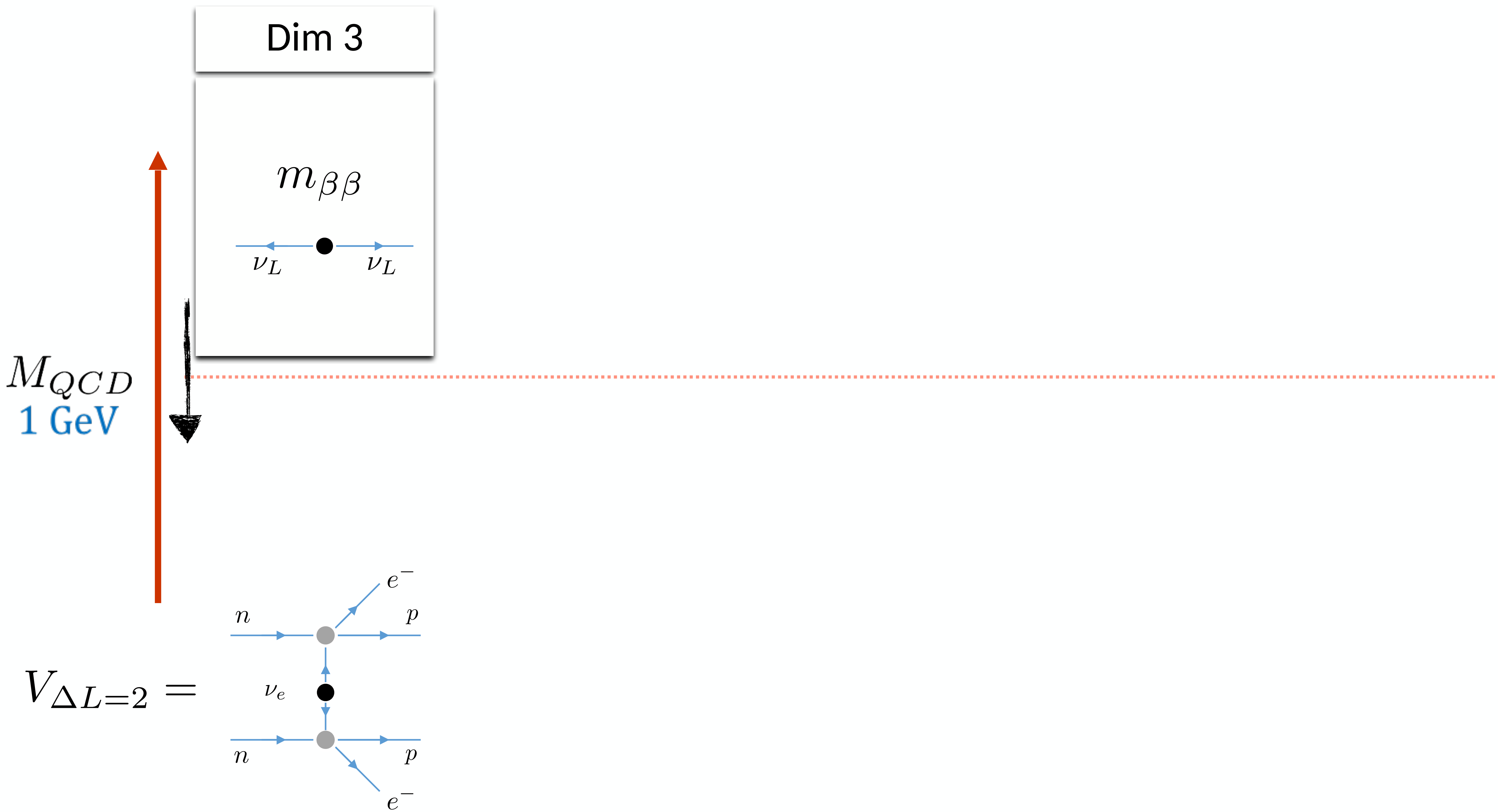


- At LO in Weinberg counting, only need the nucleon one-body currents
- All needed low-energy constants are known

Chiral EFT



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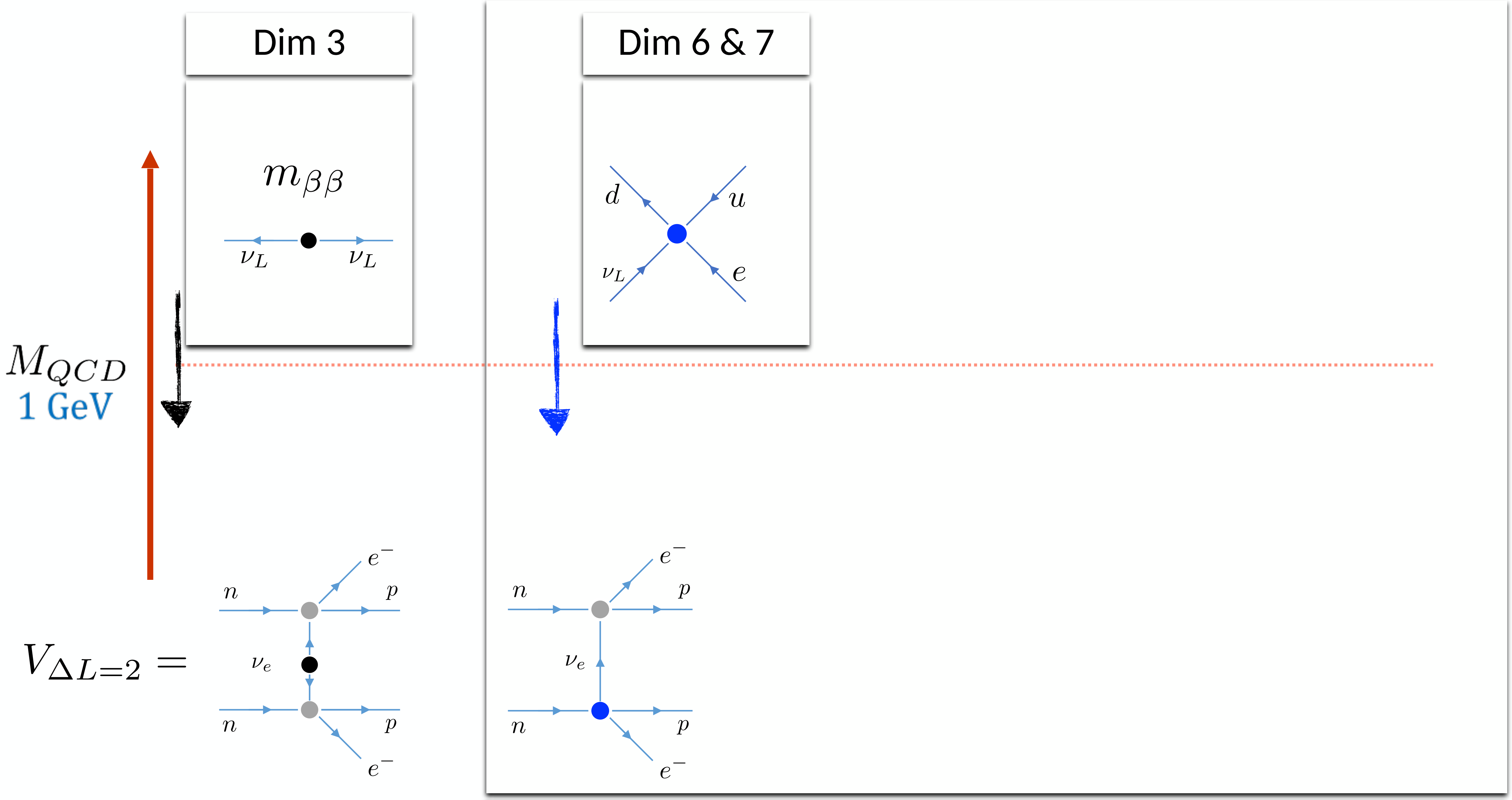
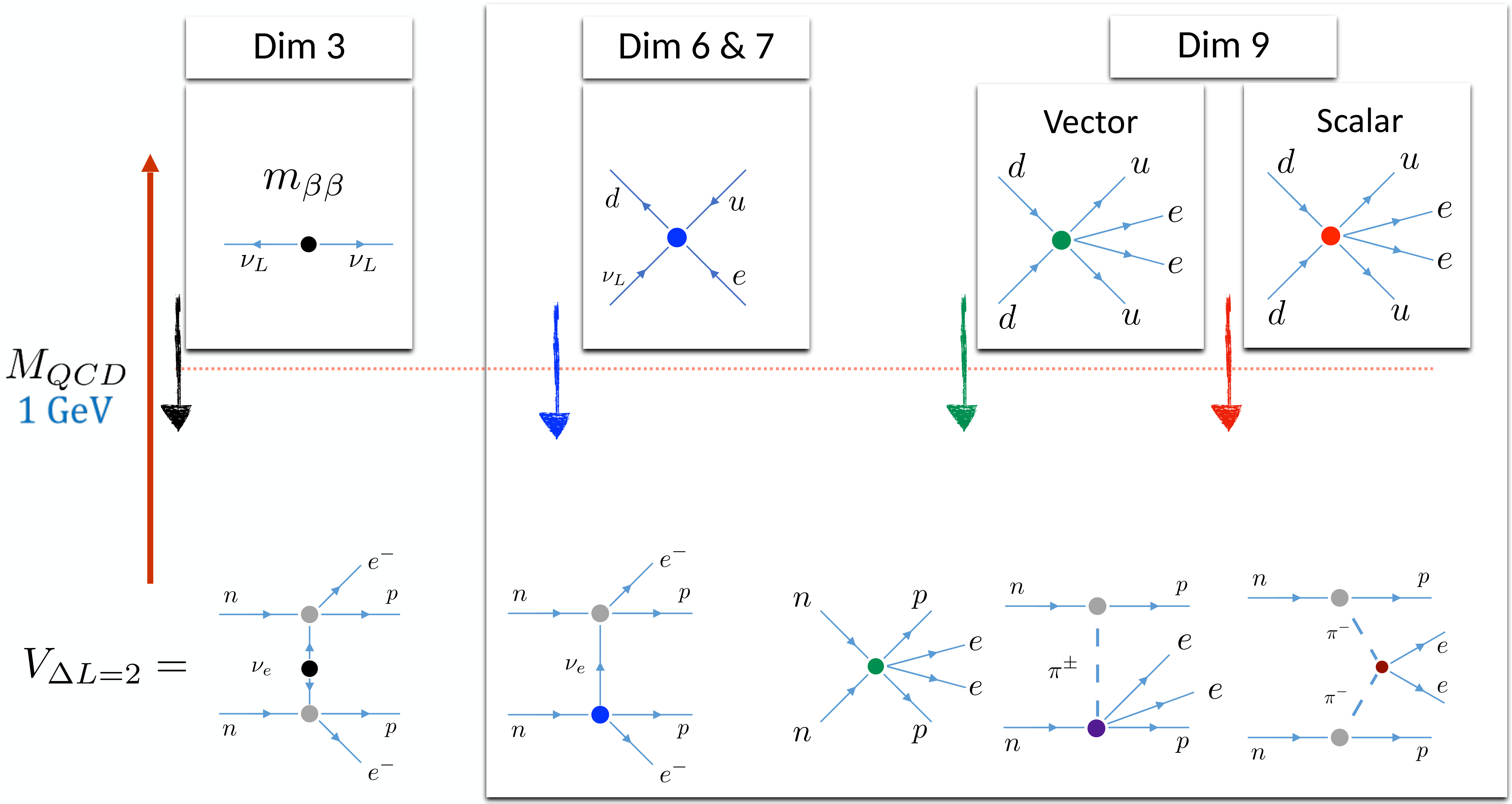


- Additional N-currents NN, πN, $\pi\pi$ interactions and LECs
- LECs for the N-currents and $\pi\pi$ interactions are partially known

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

Chiral EFT



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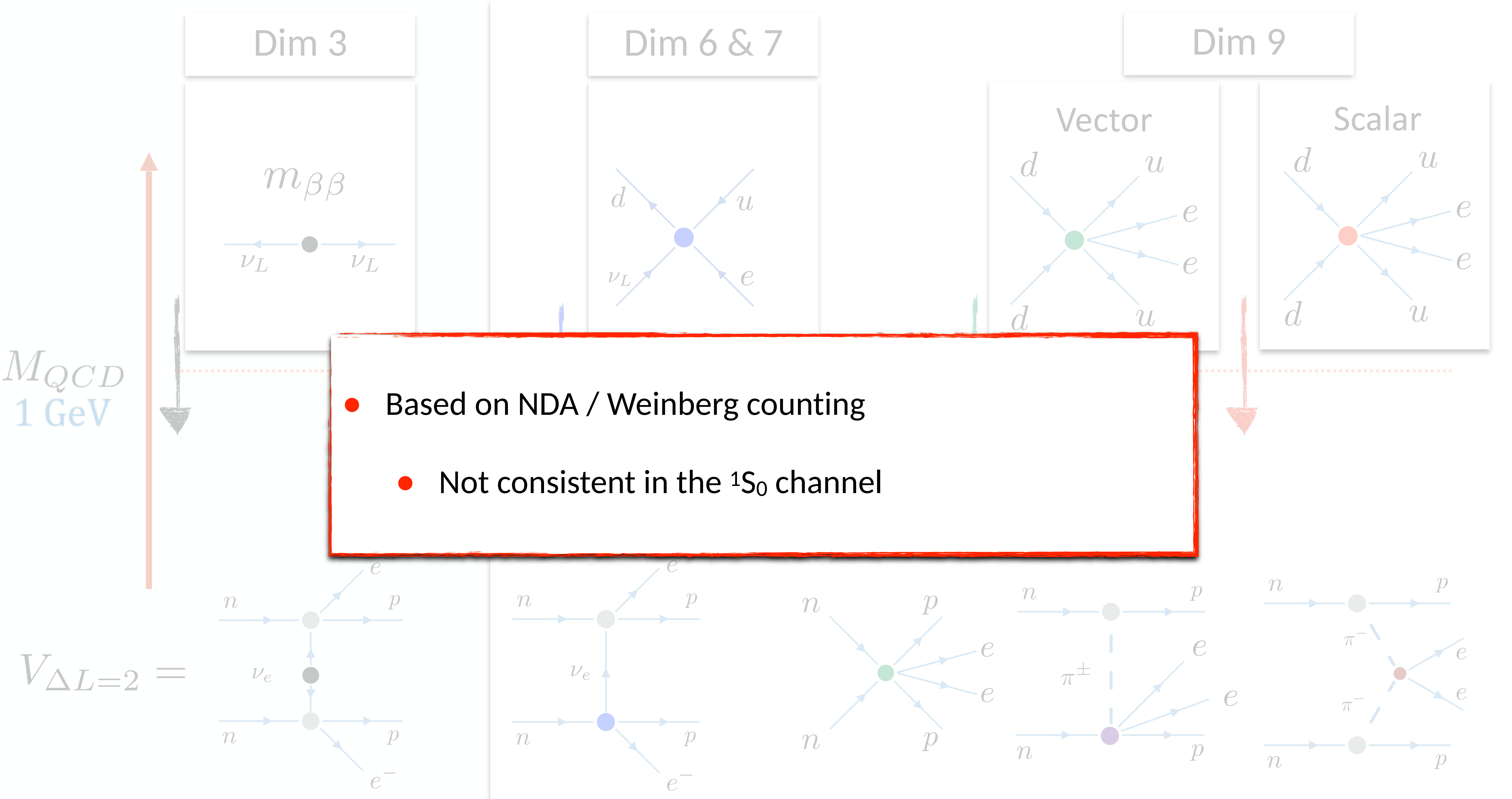


- Based on NDA / Weinberg counting
  - Not consistent in the $^1S_0$ channel

- Additional N-currents NN, πN, $\pi\pi$ interactions and LECs
- LECs for the N-currents and $\pi\pi$ interactions are partially known

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

Checking the power counting

Dimension-3

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

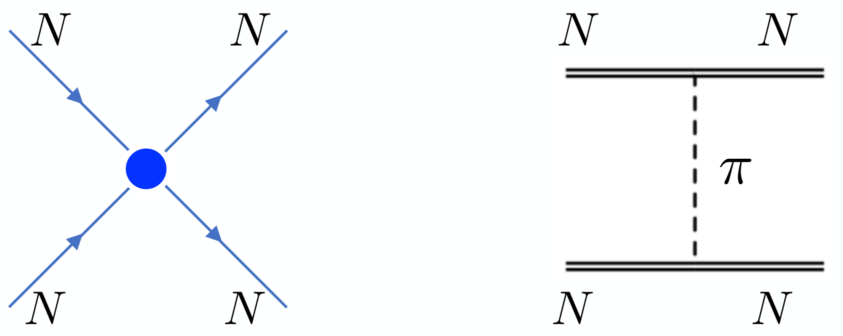
Checking the power counting

Dimension-3

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

- Requires inclusion of the strong interaction

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



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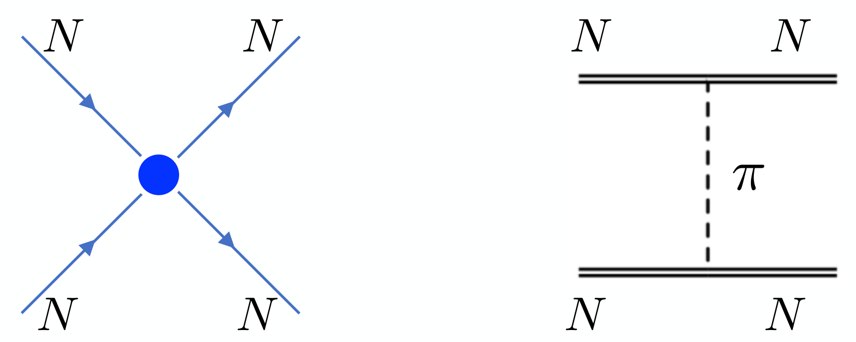
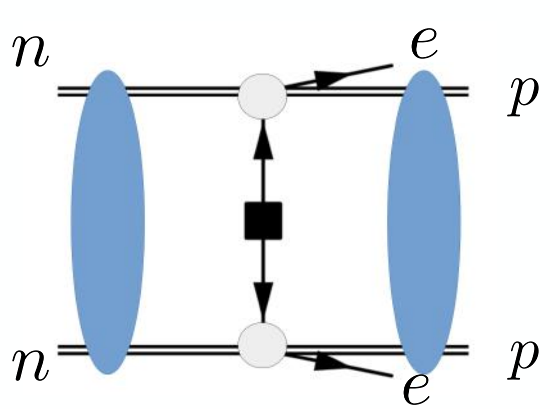
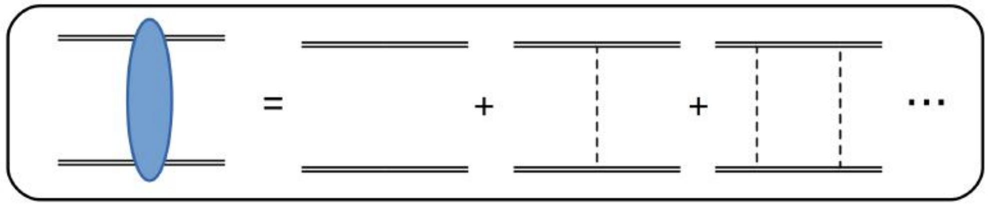


Dress the ΔL=2 potential with (renormalized) strong interactions:





✓ finite

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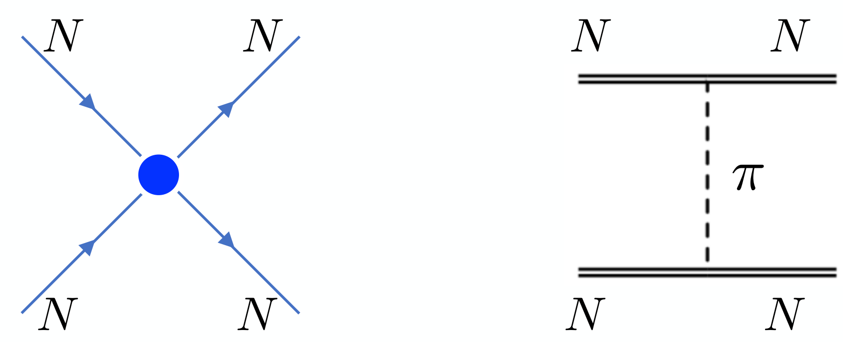

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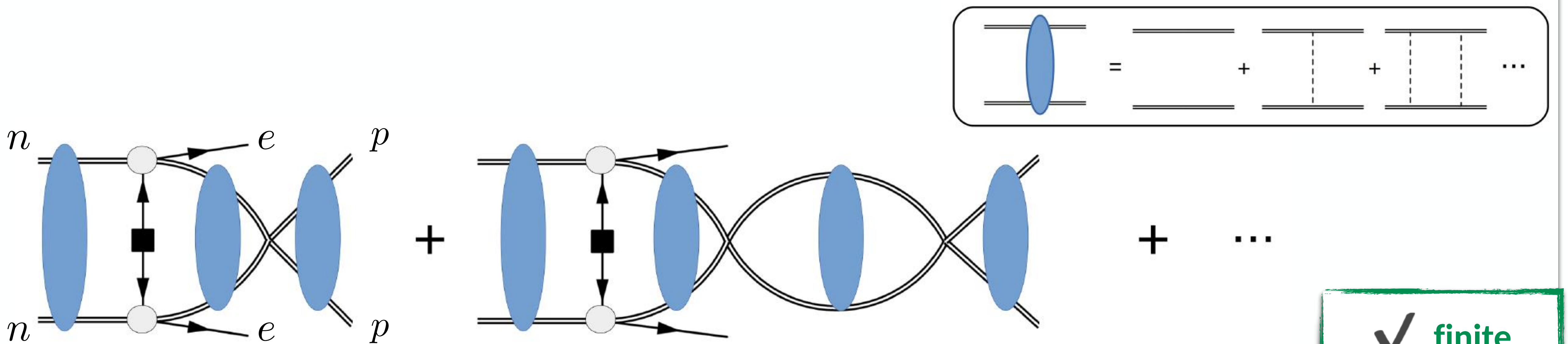

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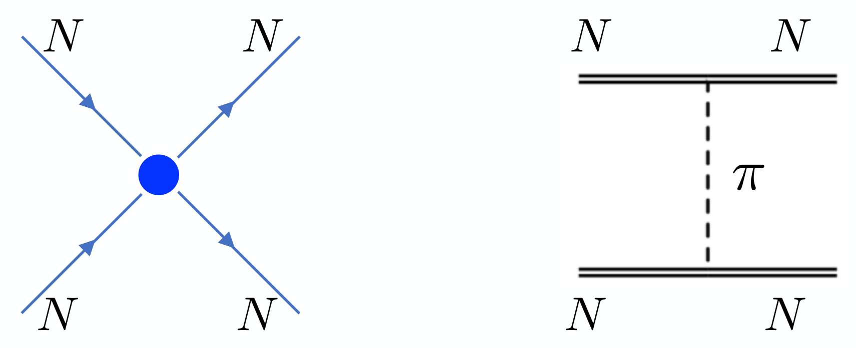

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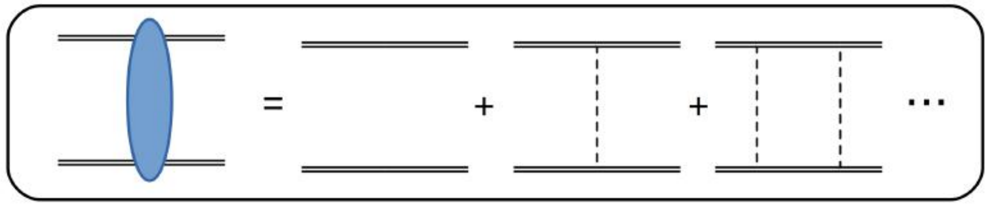

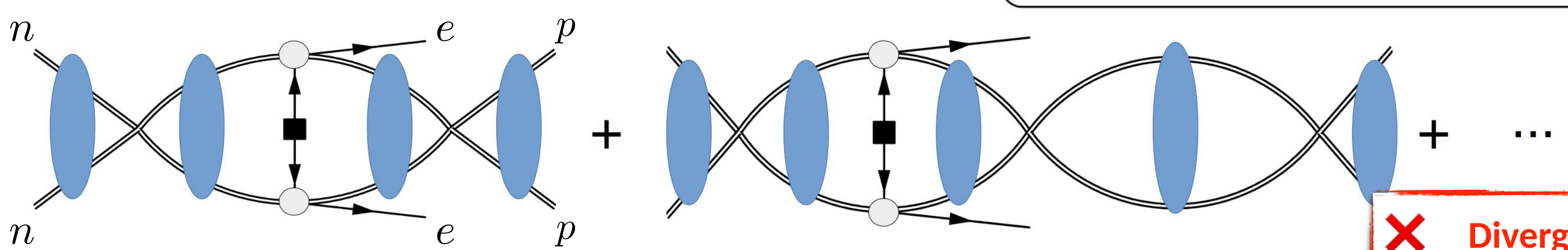

✗ Divergent

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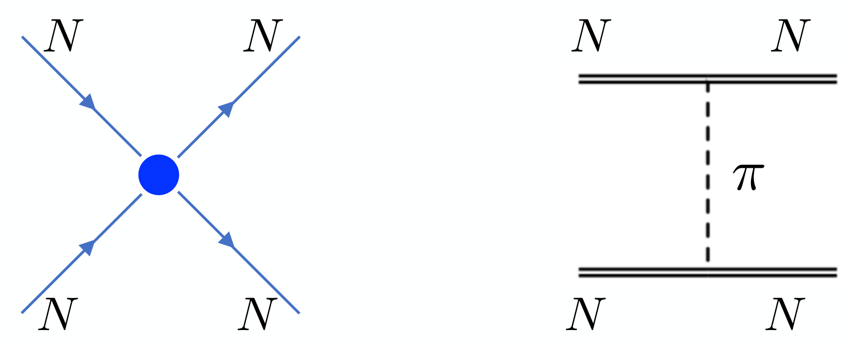
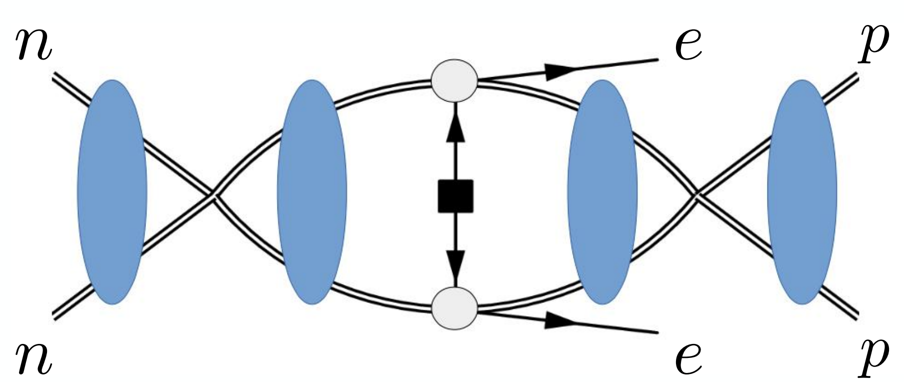


Dress the ΔL=2 potential with (renormalized) strong interactions:

In MS-bar:

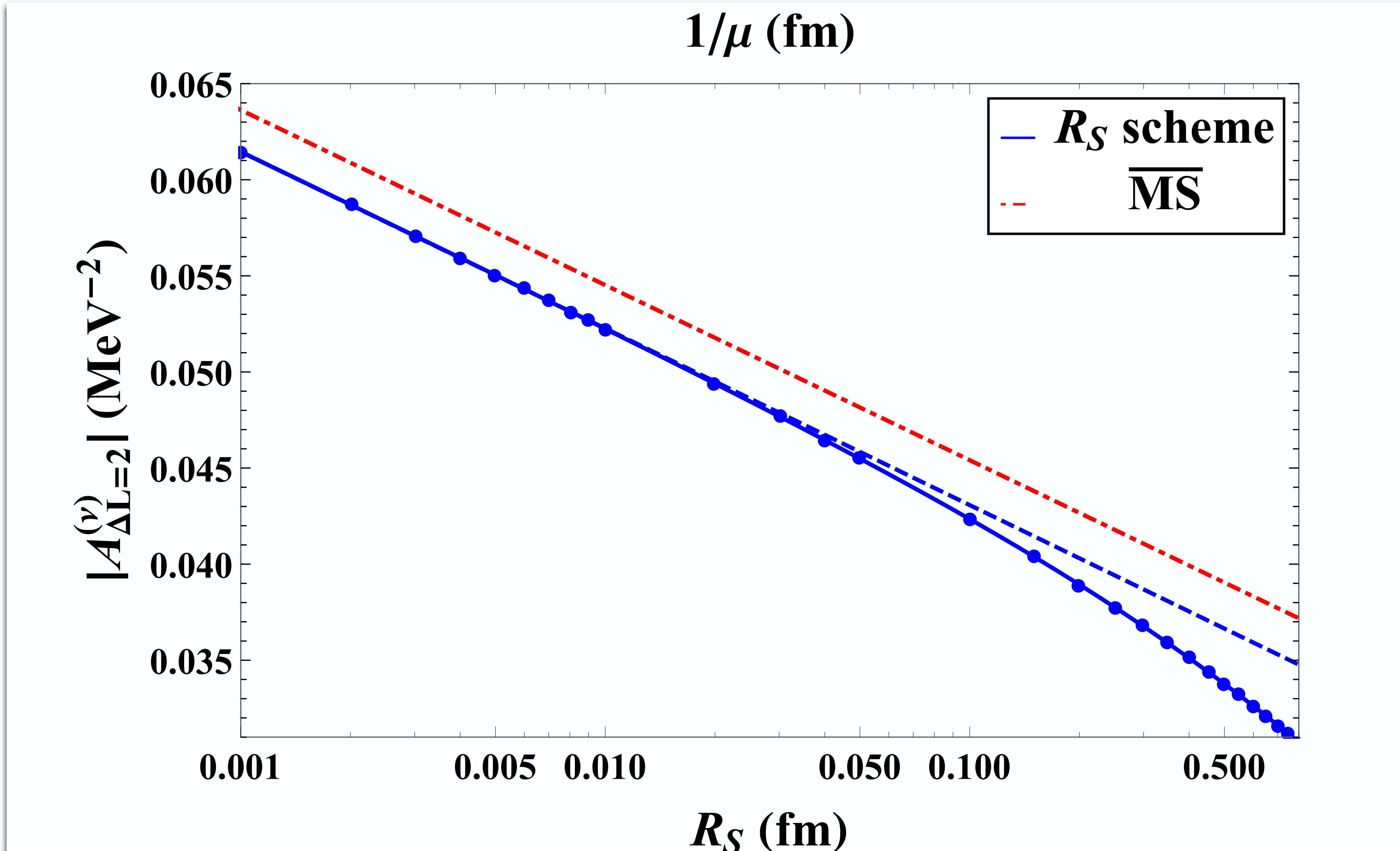


$$= -\left(\frac{m_N}{4\pi}\right)^2 (1+2g_A^2)\frac{1}{2}\left(\log\frac{\mu^2}{-(|\mathbf{p}|+|\mathbf{p}'|)^2+i0^+}+1\right)$$

$+\text{finite}$

Regulator dependent

Numerical results



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

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

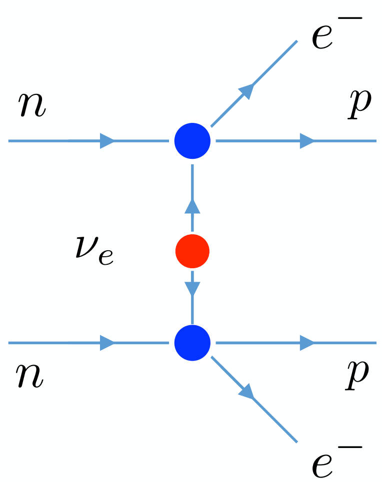
- Clear μ or R_S dependence

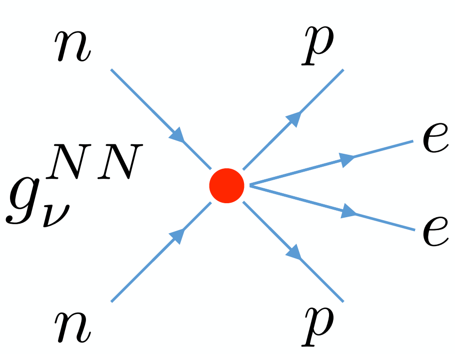
Need for a counter term

New interaction needed at leading order to get physical amplitudes:

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

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





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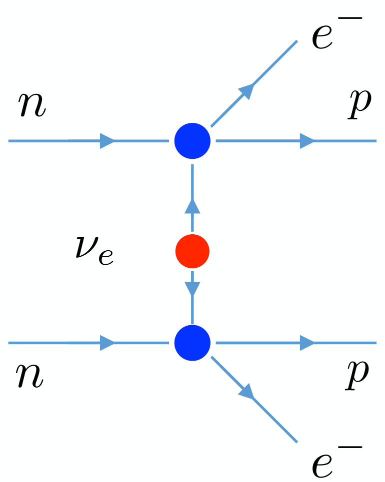

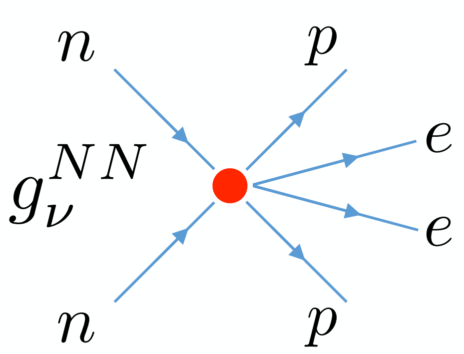

- g_ν^{NN} to be determined from a lattice calculation of $\mathcal{A}(nn \to ppe^- e^-)$
  - Area of active research

Davoudi and Kadam, '20, '21
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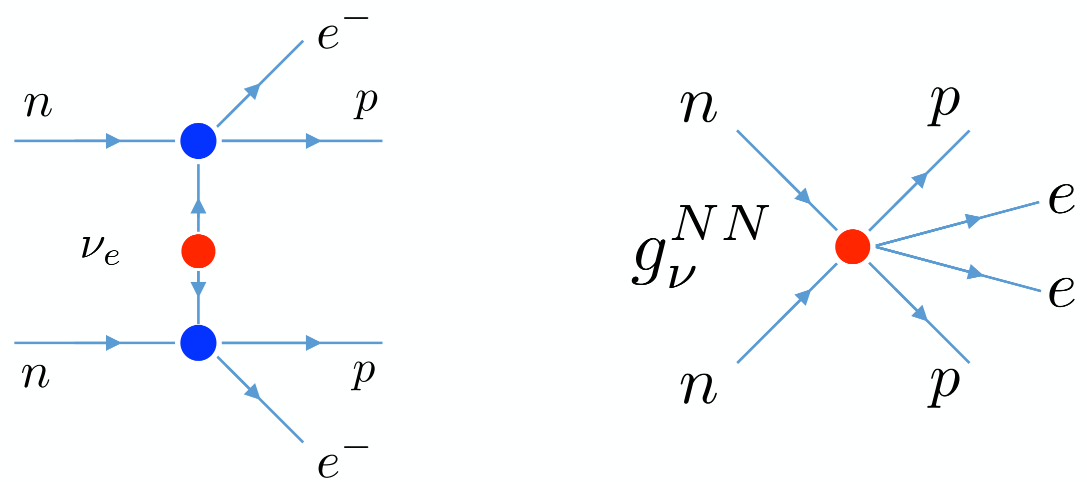

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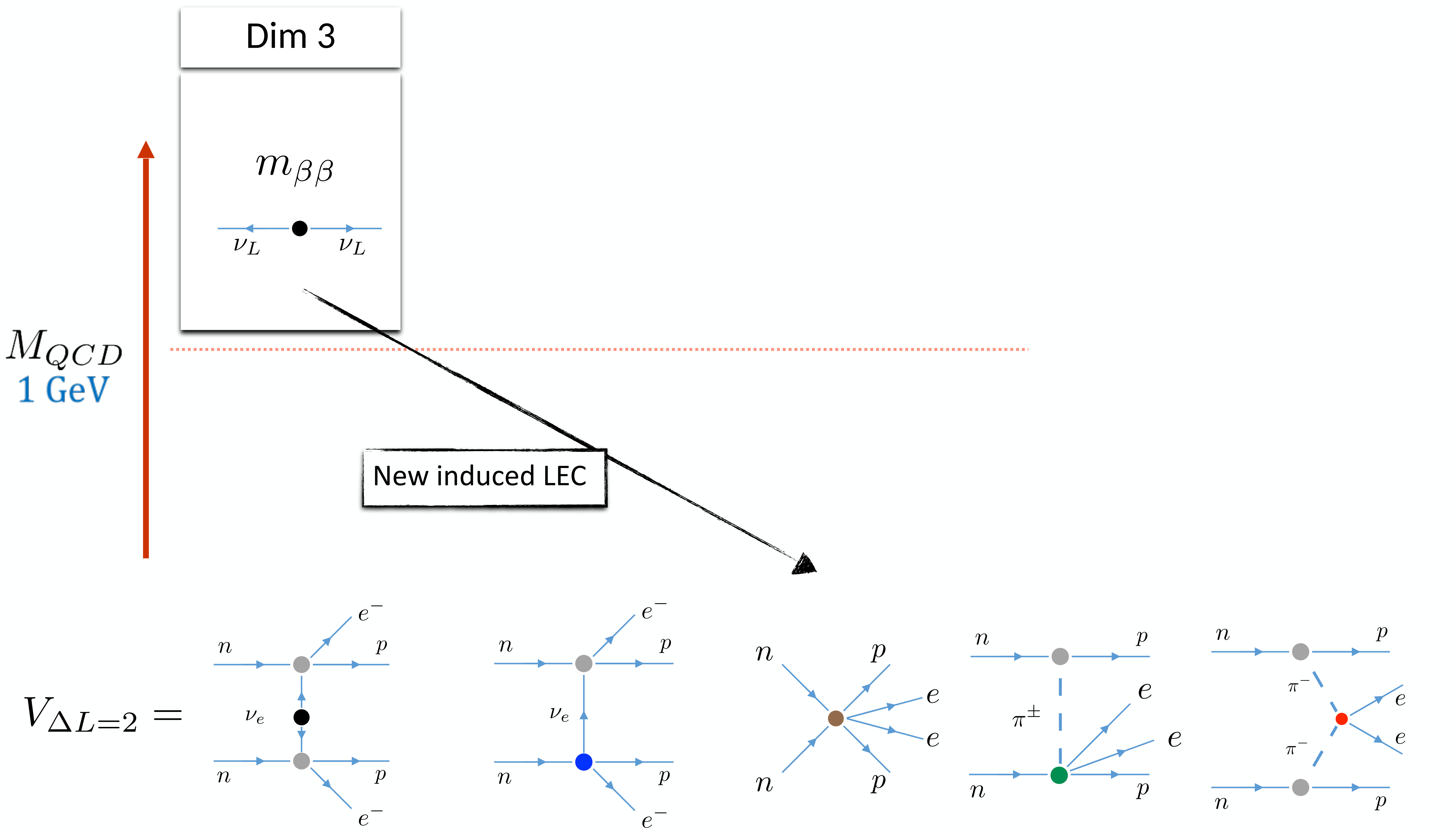
- Several estimates give $\tilde{g}_\nu^{NN} = \mathcal{O}(1)$
  - Comparison with isospin-breaking observables
  - Model (Cottingham) estimate — Cirigliano, et al, '19,'20, '21
  - Large-Nc estimate — Richardson et al, '21

See backup

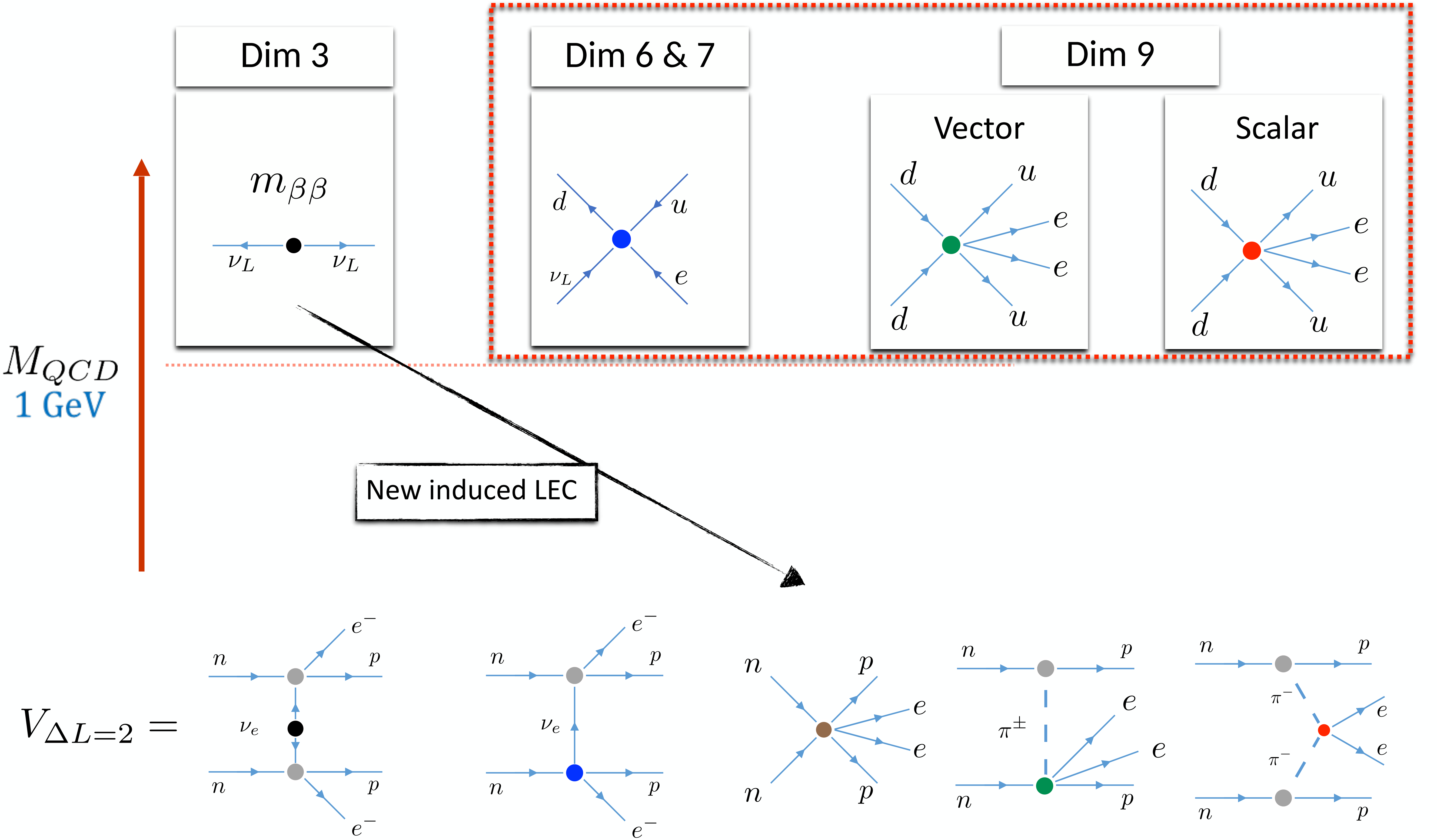
Chiral EFT

Non-Weinberg counting



Chiral EFT

Non-Weinberg counting affects higher dimensional interactions as well



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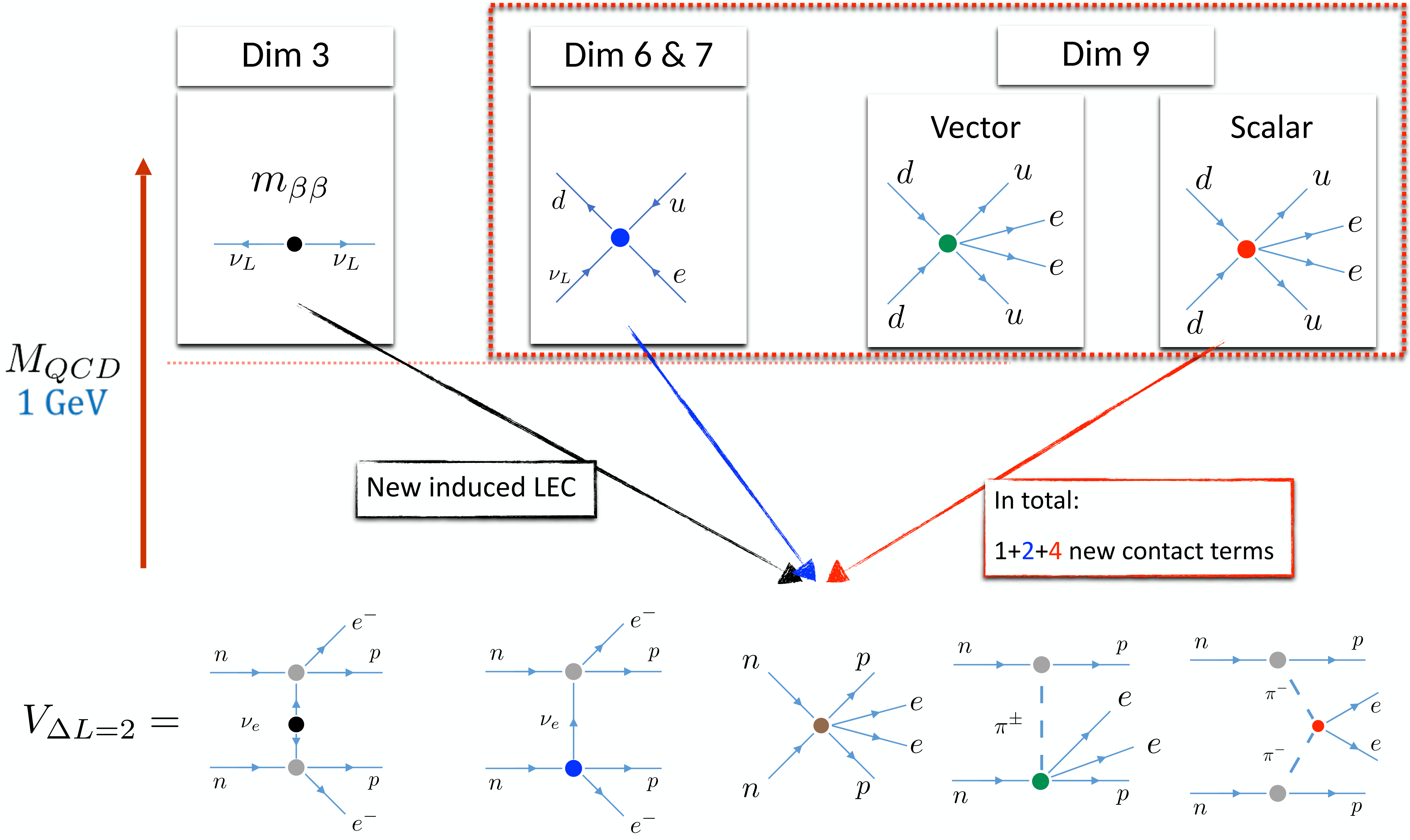
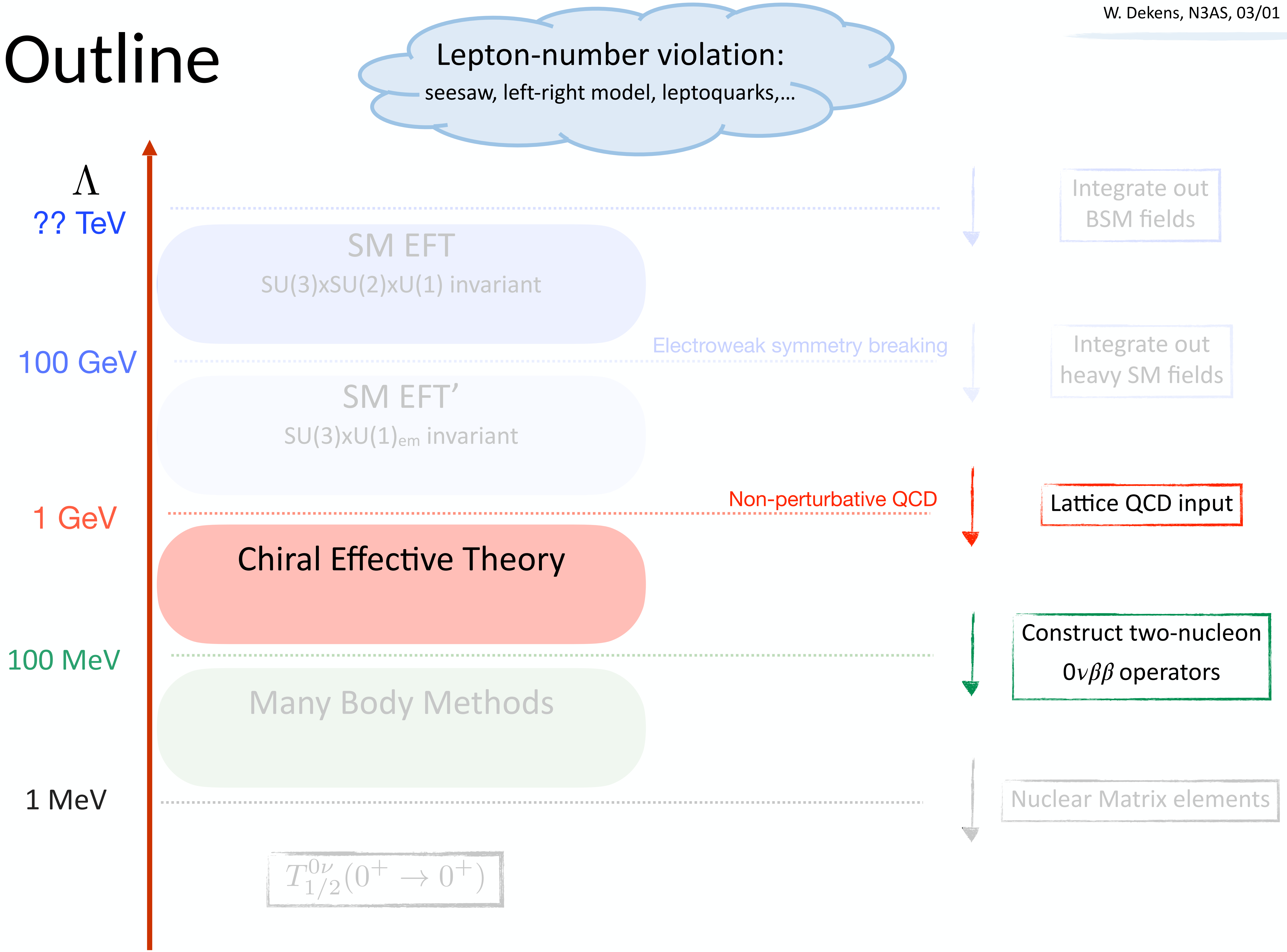


W. Dekens, N3AS, 03/01

Outline



Outline

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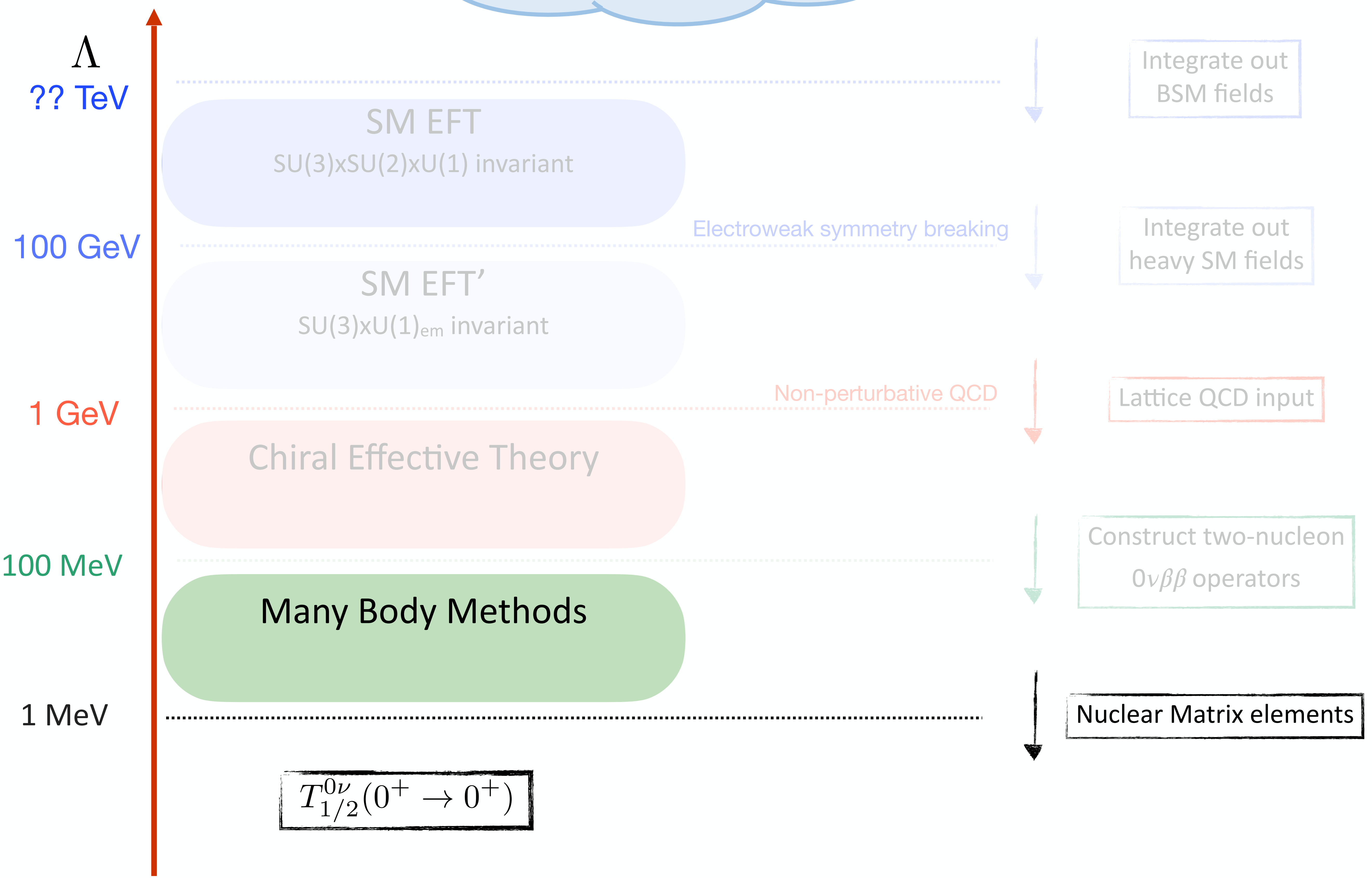

Nuclear matrix elements

*More complicated for NME with ν_R

- All NMEs can be obtained from literature*
  - 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) and

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

$$M_{GT,sd}^{AP} = -\frac{2}{3}M_{GT,sd}^{AA} - M_{GT}^{AP}\,, \qquad M_{GT}^{MM} = \frac{g_M^2 m_\pi^2}{6 g_A^2 m_N^2} M_{GT,sd}^{AA}\,,$$

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

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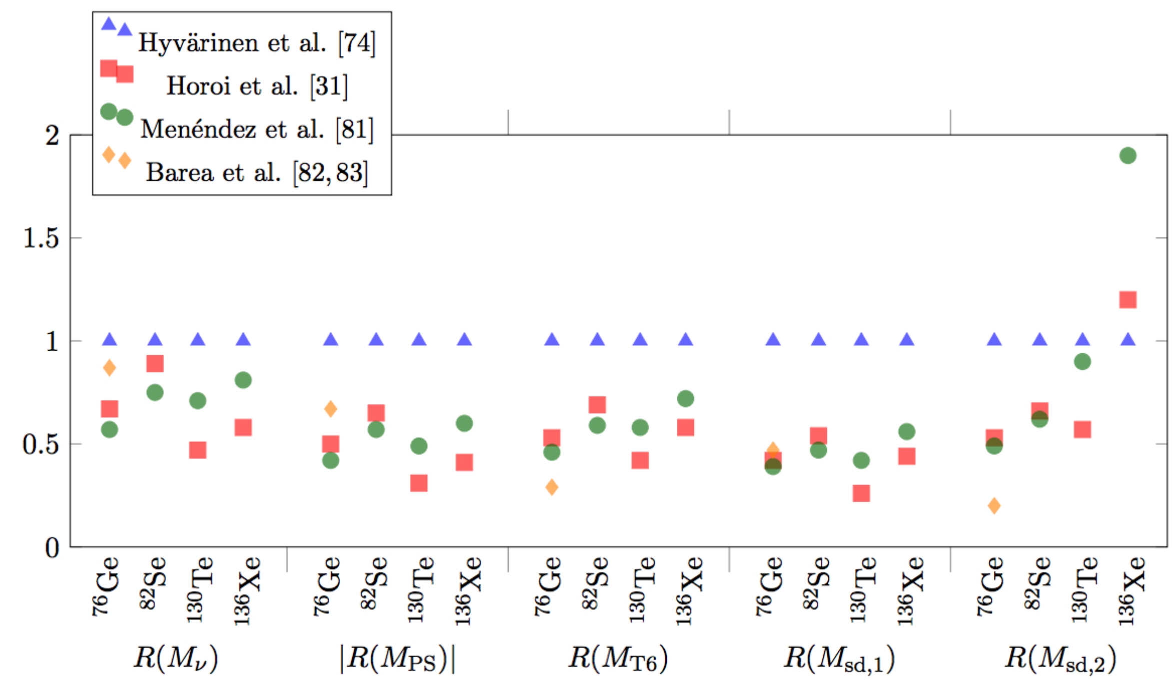
$M_{T,sd}^{PP}$	0.32	0.00	0.02	0.38

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

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

$$M_{GT,sd}^{AP} = -\frac{2}{3}M_{GT,sd}^{AA} - M_{GT}^{AP}\,, \qquad M_{GT}^{MM} = \frac{g_M^2 m_\pi^2}{6g_A^2\, m_N^2}M_{GT,sd}^{AA}\,,$$

- The NMEs differ by a factor 2-3 between methods

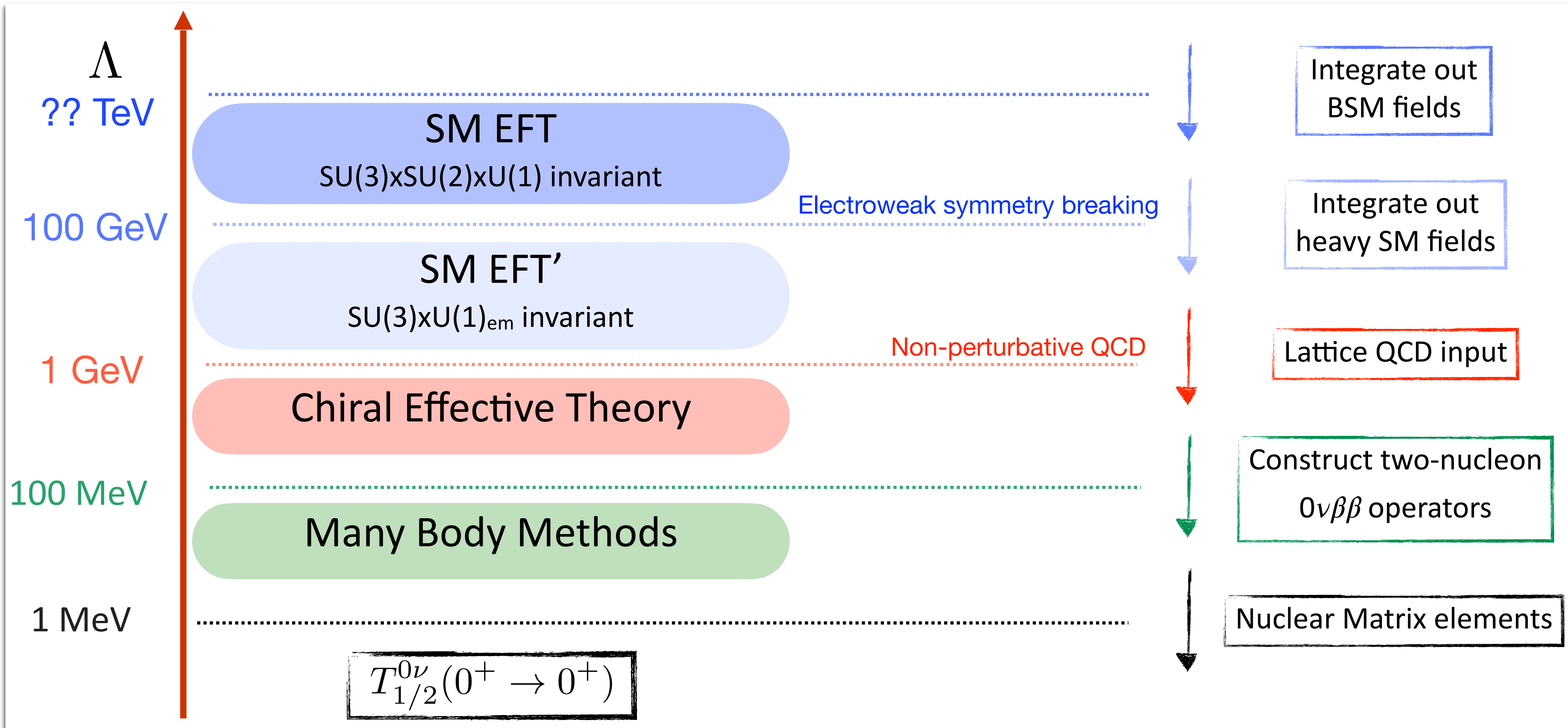


- *Ab initio* NMEs for $A \geq 48$ are starting to appear
  - e.g. Belley et al '20; Yao et al '20; Wirth, Yao, Hegert '21

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

Sterile neutrinos

Can now go through the same steps as before:



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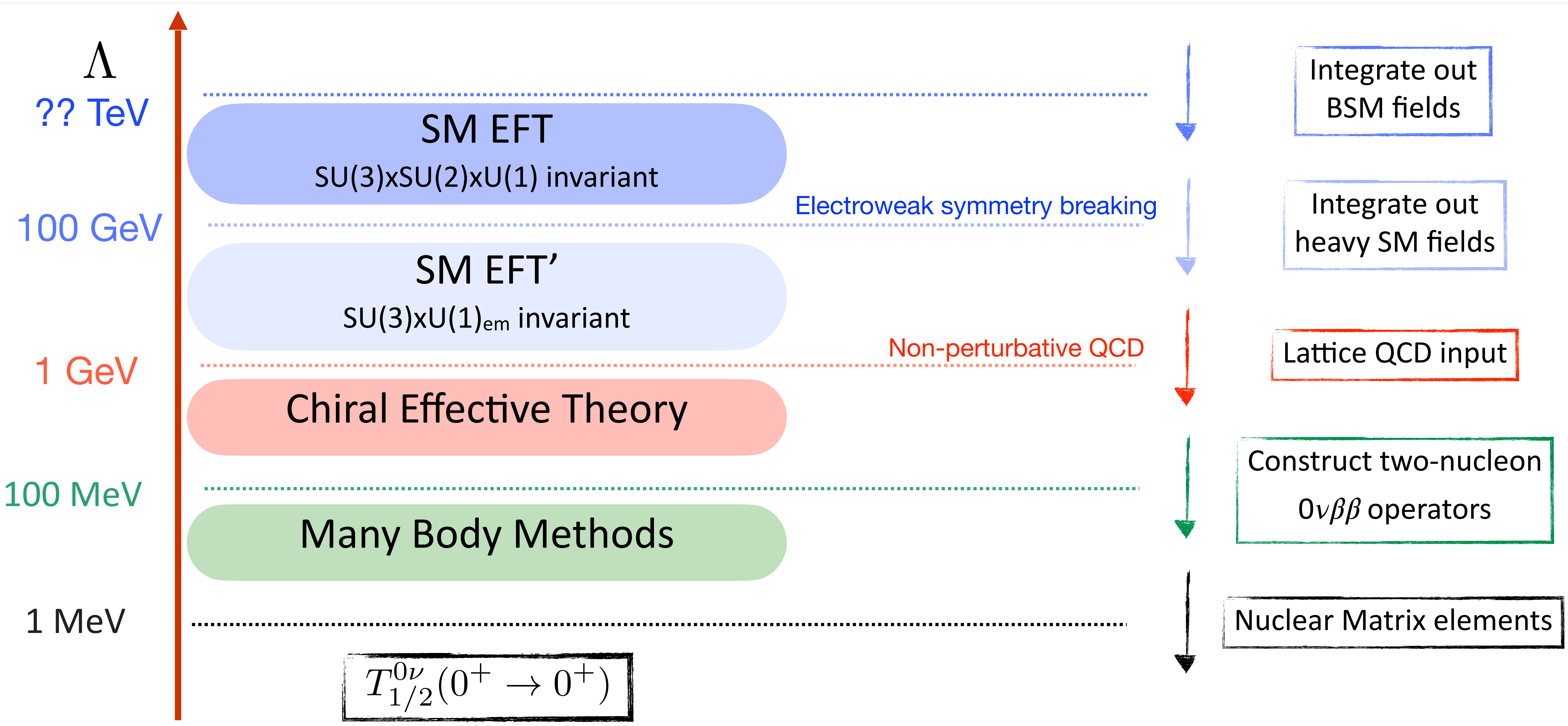


- EFT now includes ν_R as explicit degrees of freedom
- When/if ν_R can be integrated out depends on m_{ν_R}
- LECs and NMEs now depend on m_{ν_R}

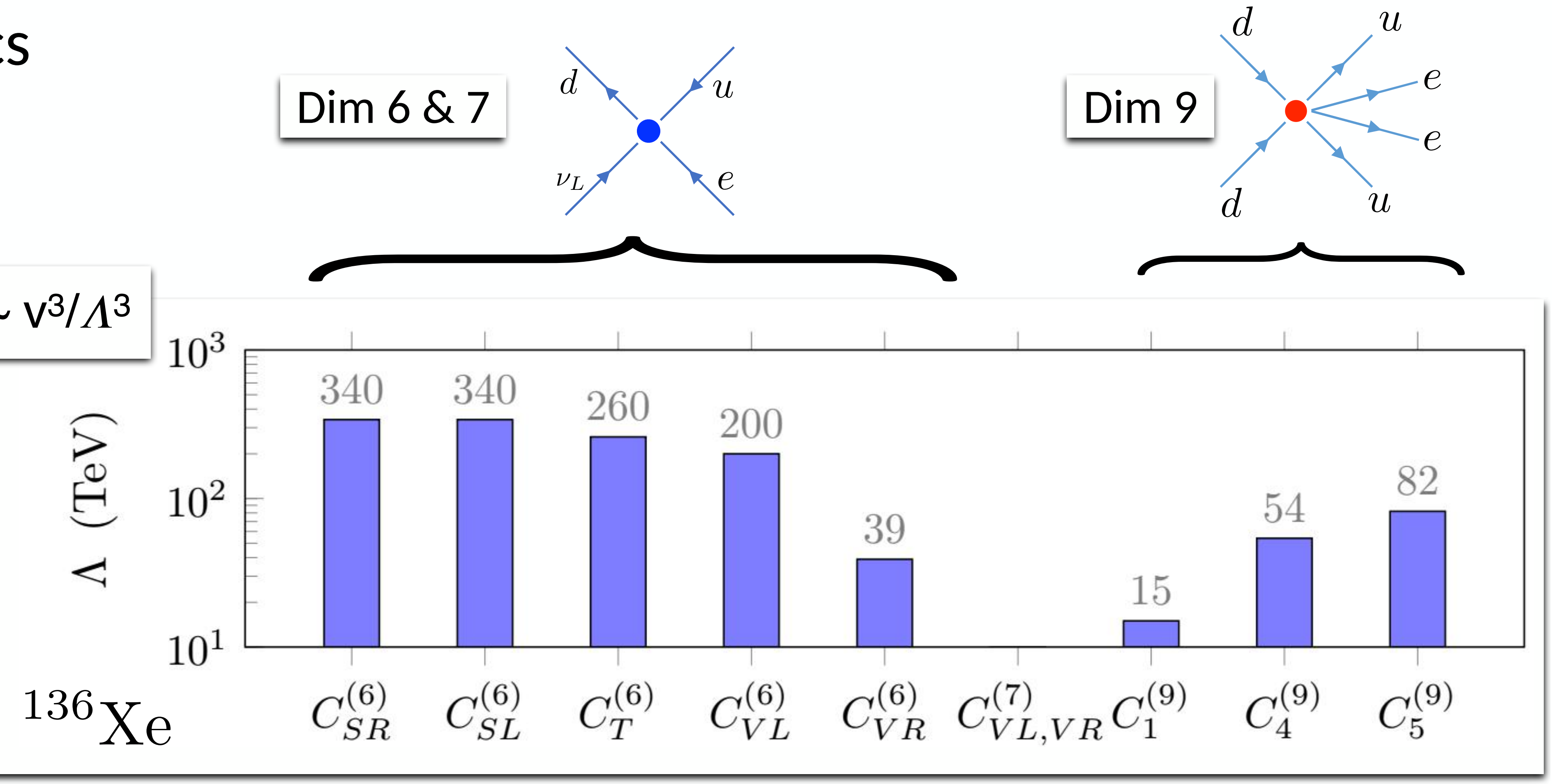
See backup

Phenomenology

Phenomenology

From heavy new physics

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

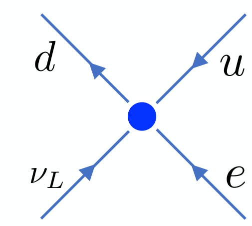


- O(1) uncertainties:
  - Unknown LECs
  - Nuclear Matrix elements

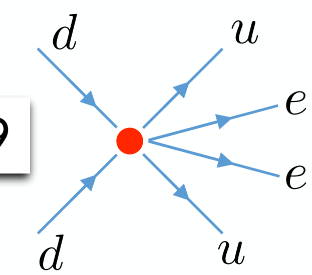
Phenomenology

From heavy new physics

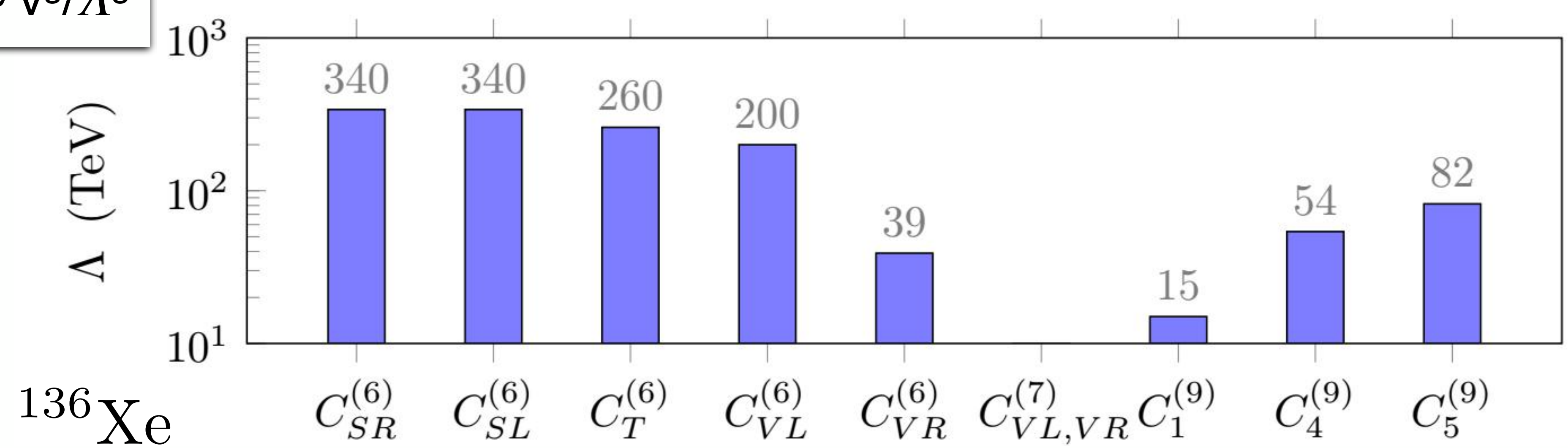
Dim 6 & 7



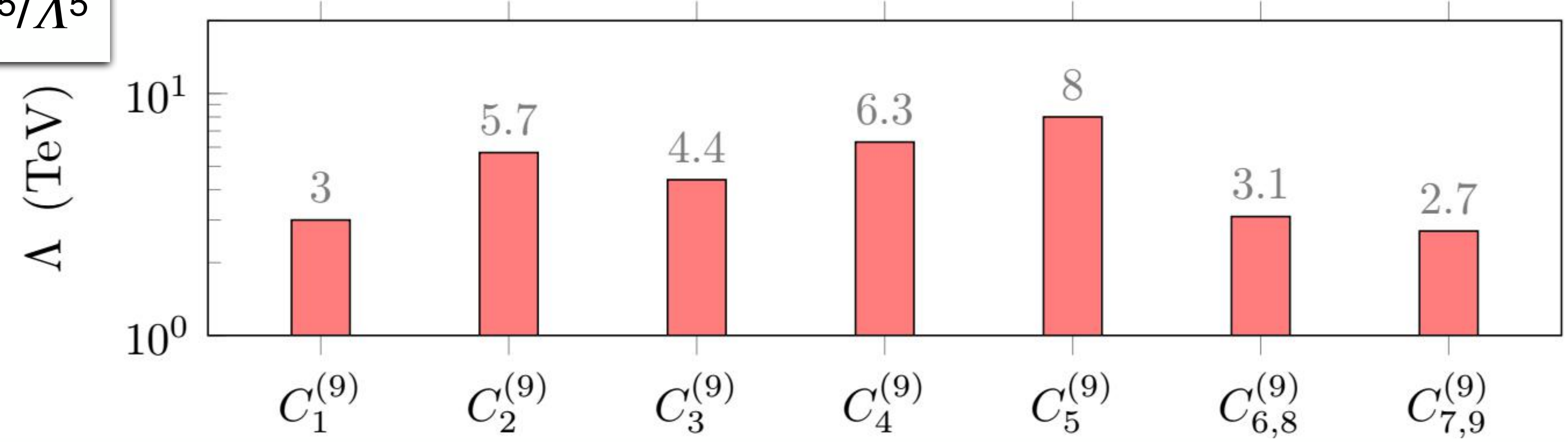
Dim 9



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



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



- O(1) uncertainties:
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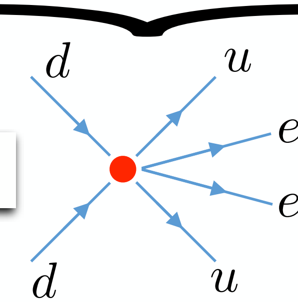
Dim 9



Phenomenology with sterile neutrinos

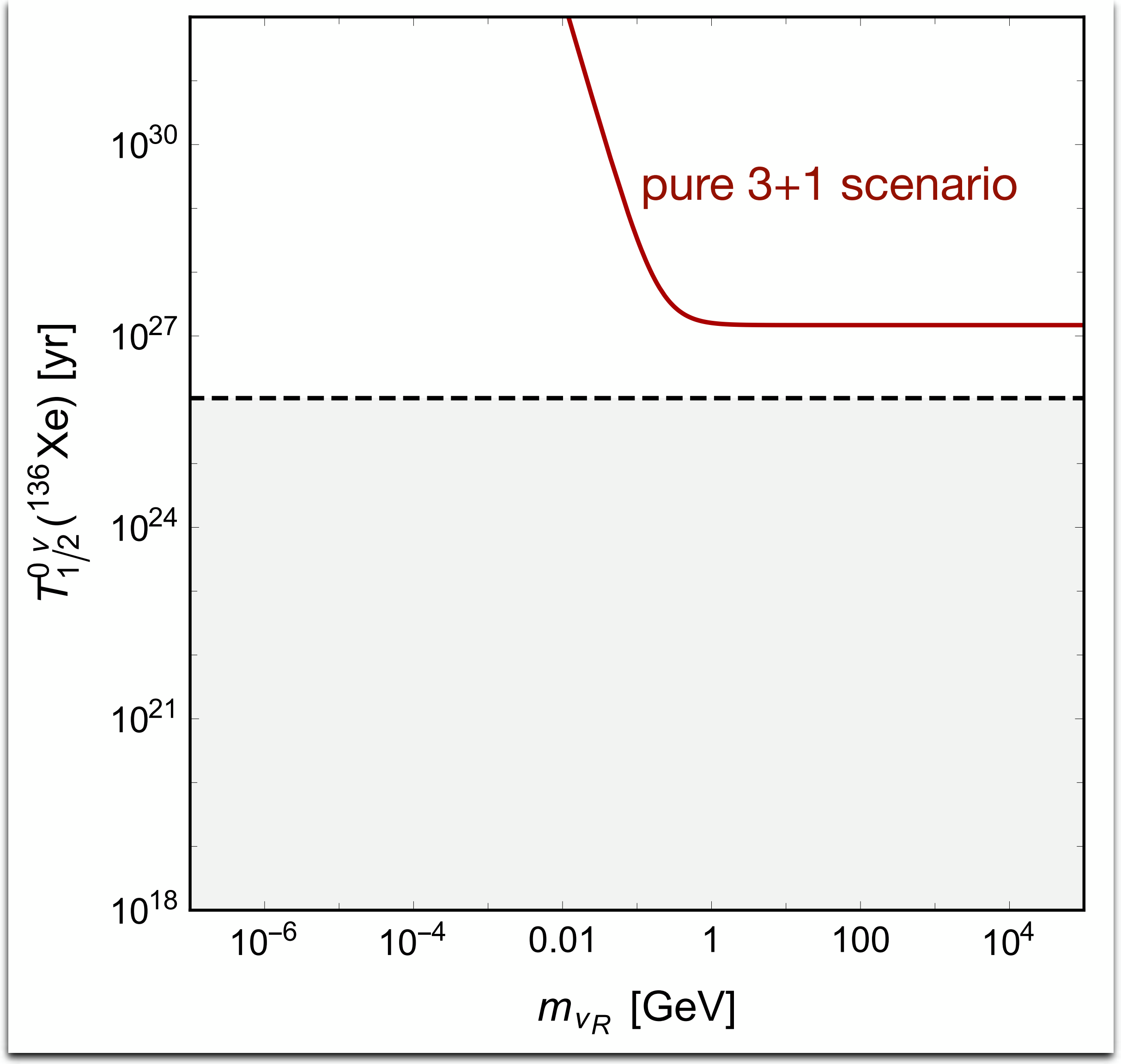
Phenomenology

From heavy new physics + light ν_R

Example with ν_R

O(100%) uncertainties not shown

- Toy Model
  - SM + 1 light ν_R



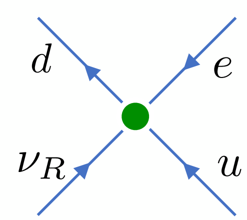
Phenomenology

From heavy new physics + light ν_R

Example with ν_R

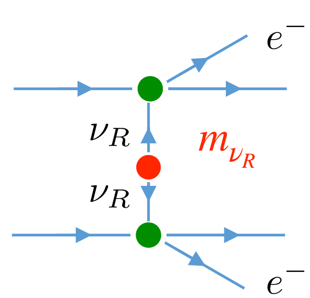
O(100%) uncertainties not shown

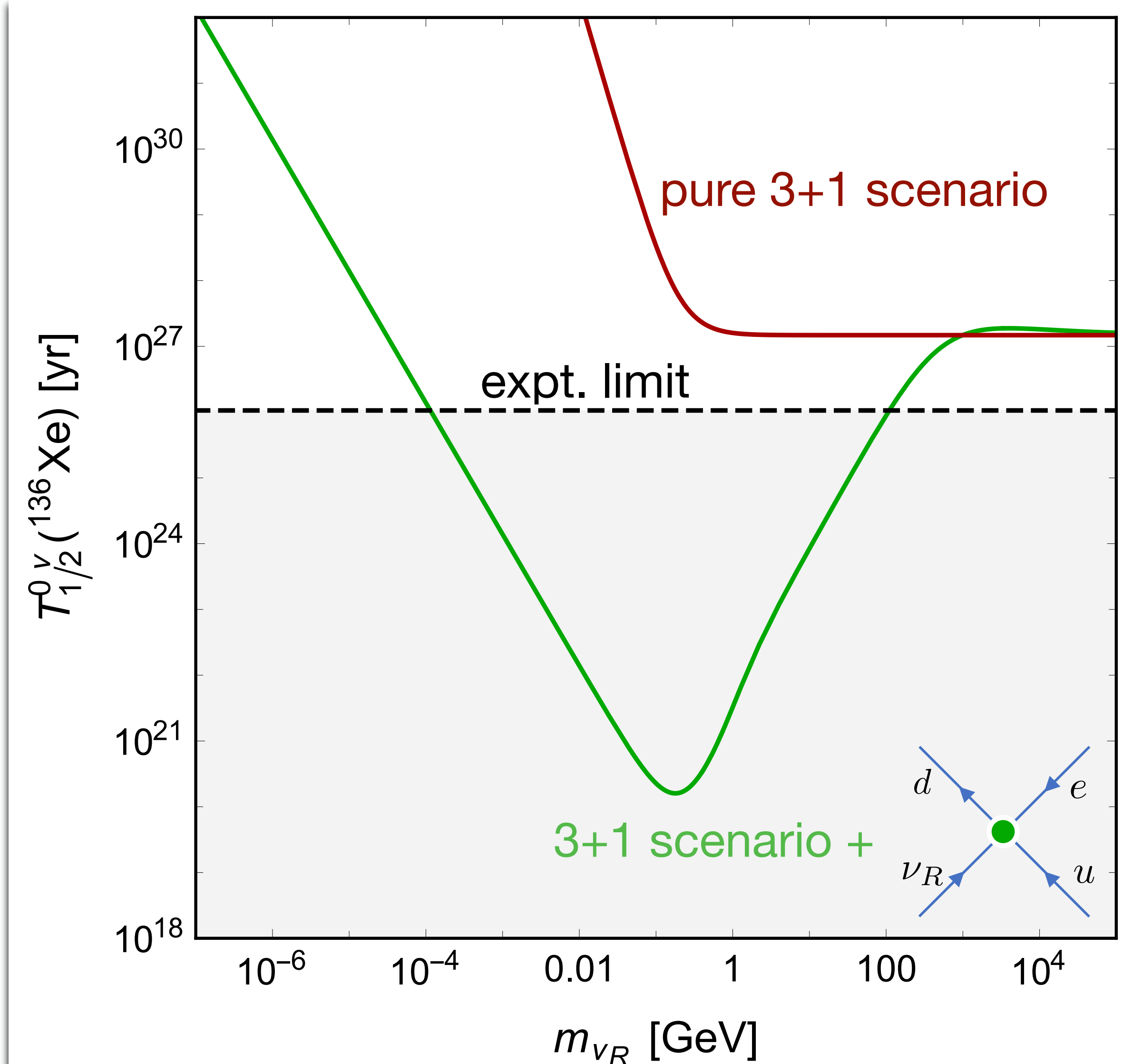
- Toy Model
  - SM + 1 light ν_R
- Add dimension-six interaction
  - SM + 1 light ν_R +



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

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



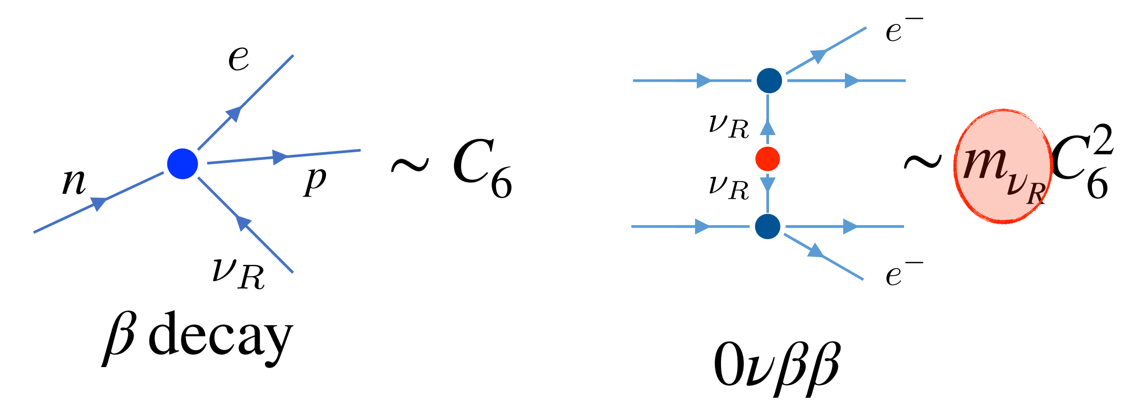


- Higher dimensional ν_R terms can have a large impact!

Phenomenology

From heavy new physics + light ν_R

- Complementarity with neutron & nuclear β decays
- What can $0\nu\beta\beta$ say if these probes find a signal?



Phenomenology

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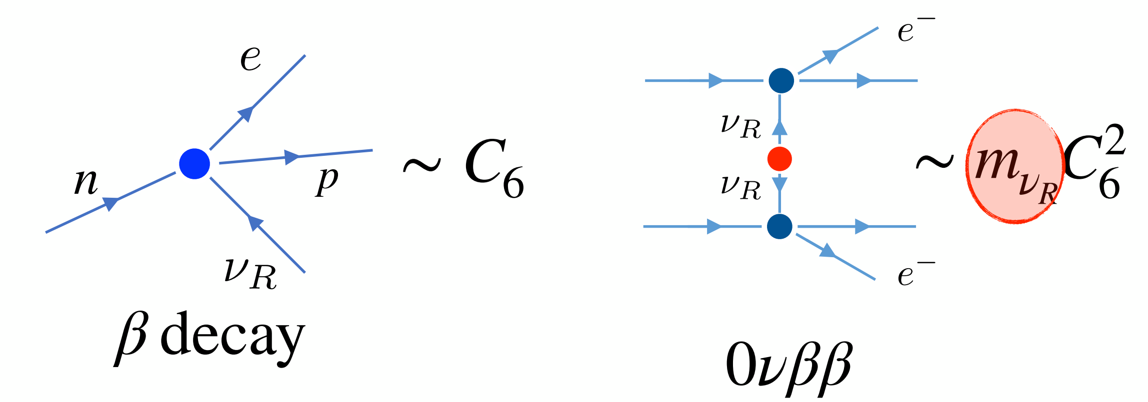


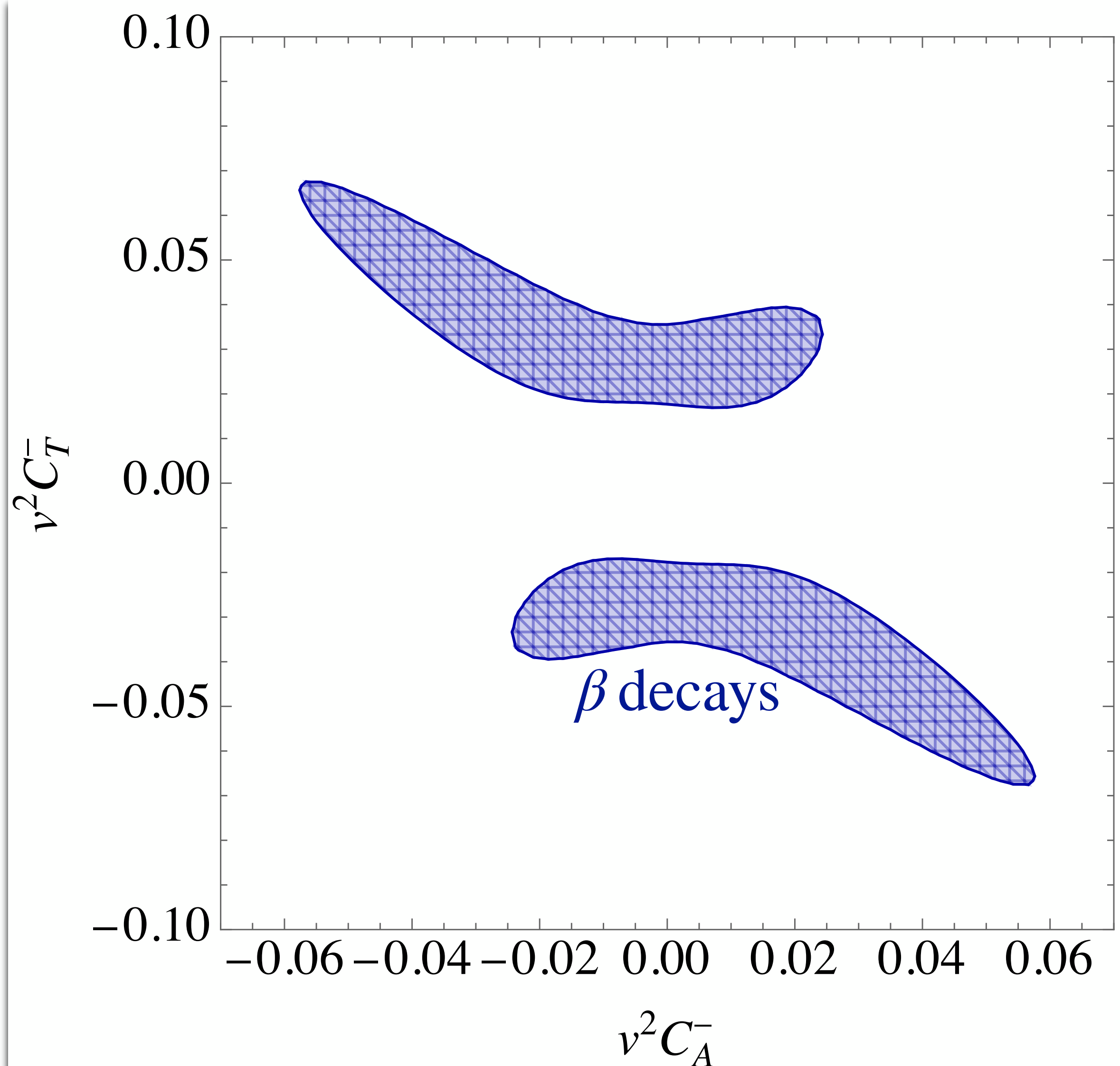
- β-decay fit has preference for BSM interactions

Falkowski, González-Alonso, Naviliat-Cuncic, '20

  - Driven by one experiment

aSPECT, '19

  - Unclear if LHC can be satisfied in UV models



Phenomenology

From heavy new physics + light ν_R

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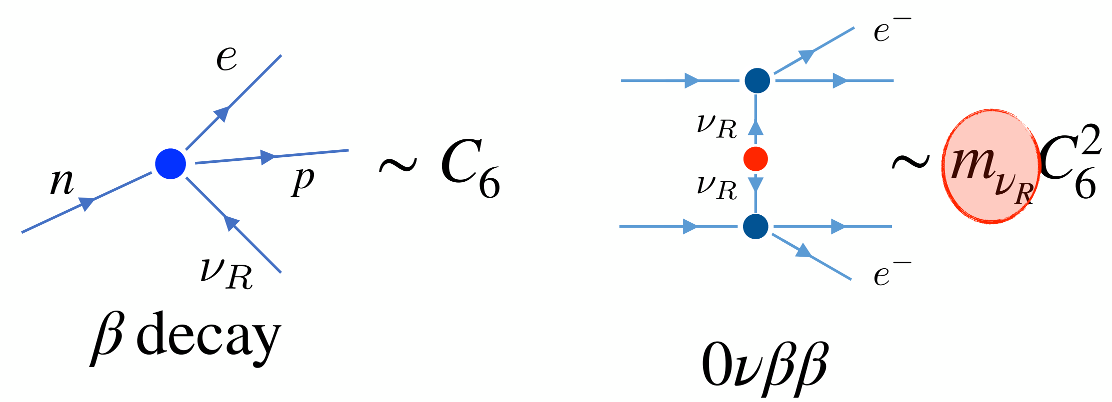
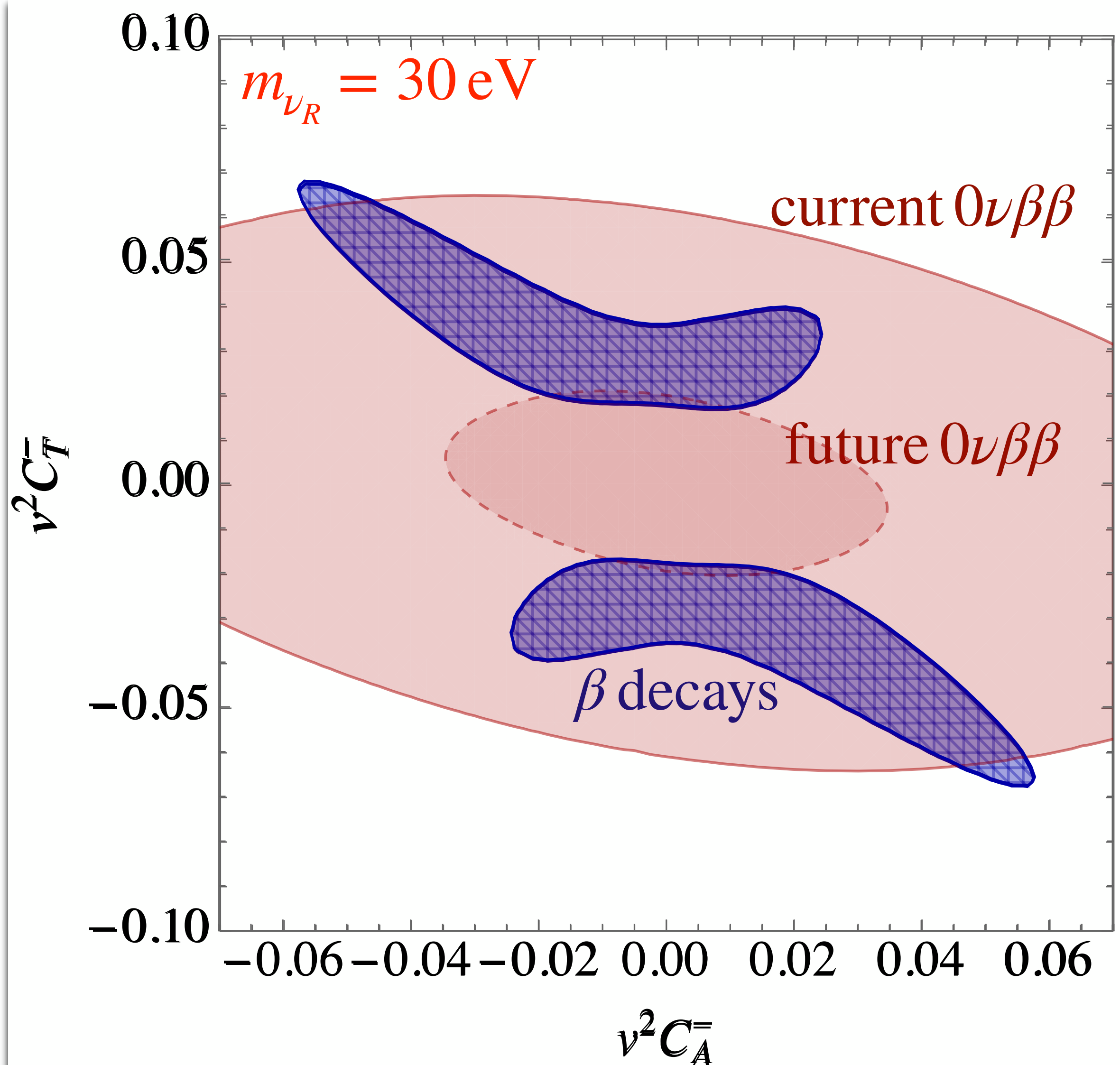


- β-decay fit has preference for BSM interactions

  Falkowski, González-Alonso, Naviliat-Cuncic, '20

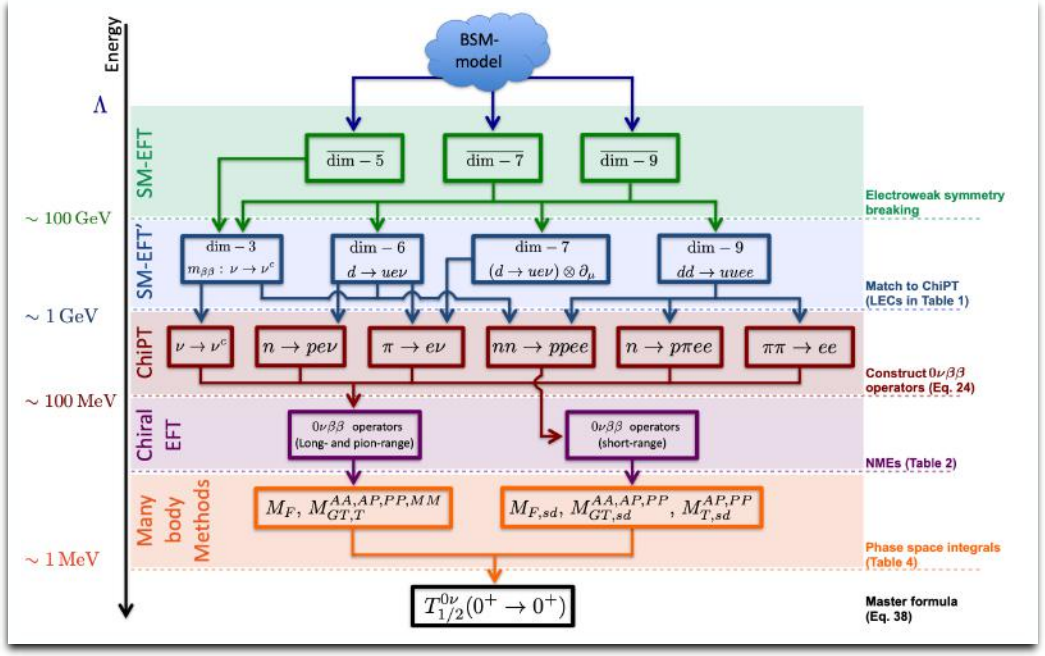
  - Driven by one experiment — aSPECT, '19
  - Unclear if LHC can be satisfied in UV models

- If a β-decay signal is confirmed:
  - $0\nu\beta\beta$ gives upper limit on m_{ν_R}
  - (assuming Majorana ν_R)



Summary

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



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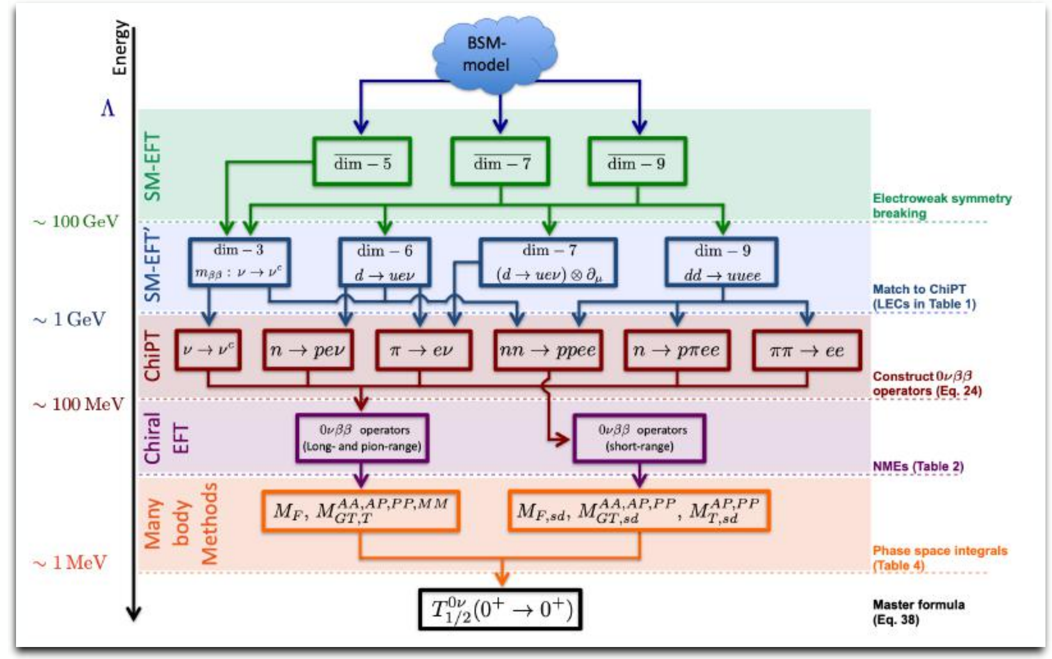
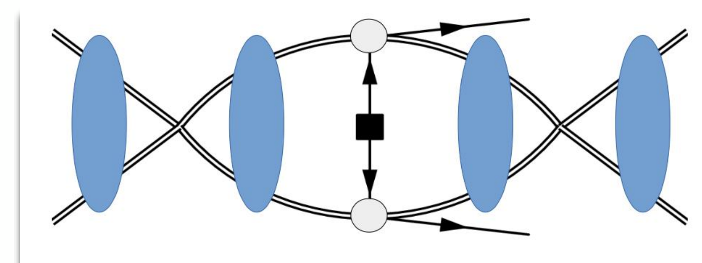
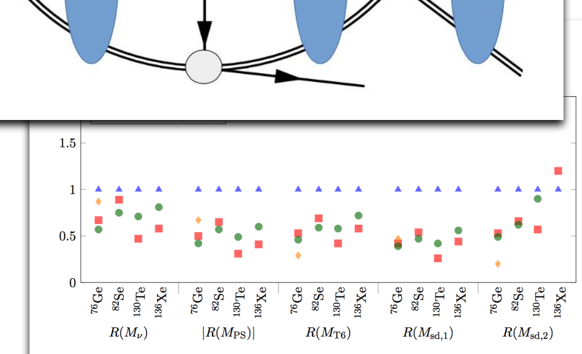


- Matching to chiral EFT involves unknown LECs
  - Renormalization requires terms beyond Weinberg counting
    - Can in principle be determined from LQCD
- Needed Nuclear Matrix Elements determined in literature





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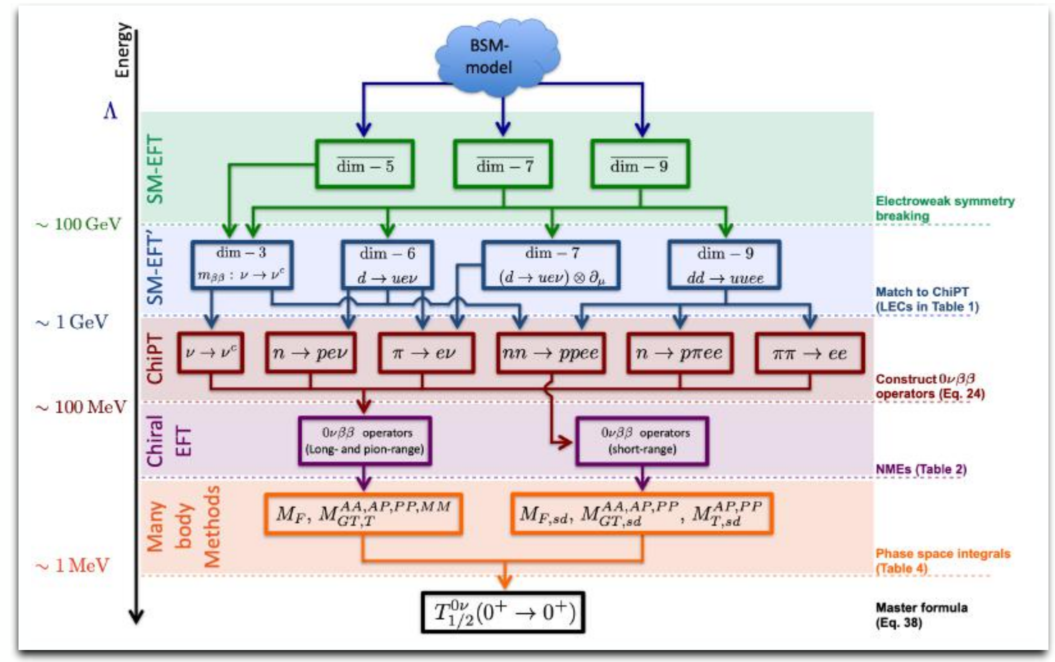

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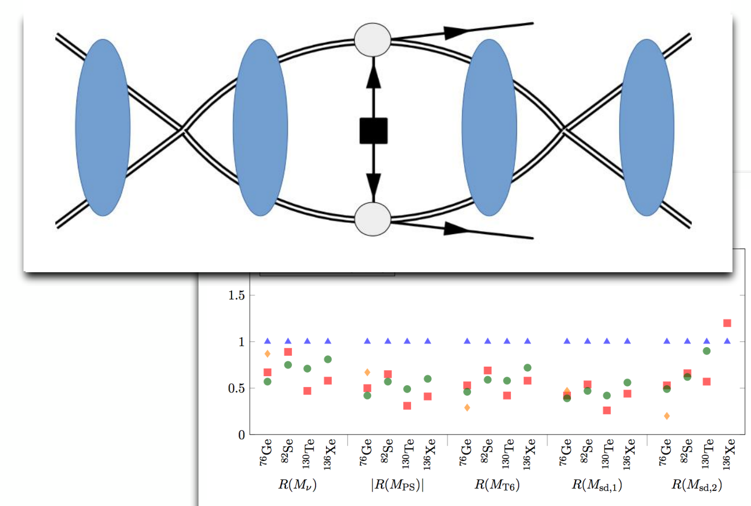
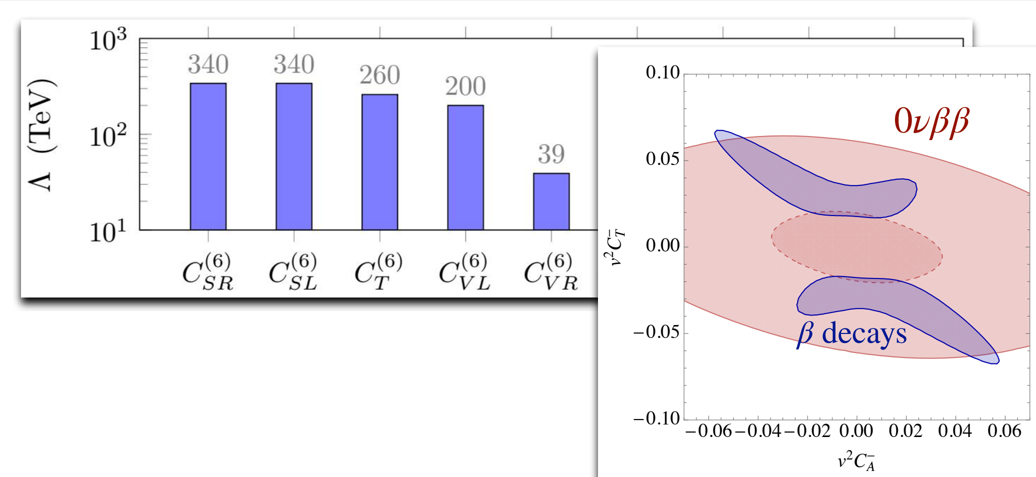


- $0\nu\beta\beta$ can probe
  - O(1-10) TeV scales for dim-9
  - O(100) TeV scales for dim-7
  - O(10) TeV scales for ν_R interactions
- Interplay with other observables (e.g. β decay)



Back up slides

Why dim 7, 9?

Effective Field Theory

Naive scaling of Dimension 5, 7, 9 operators

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

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

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

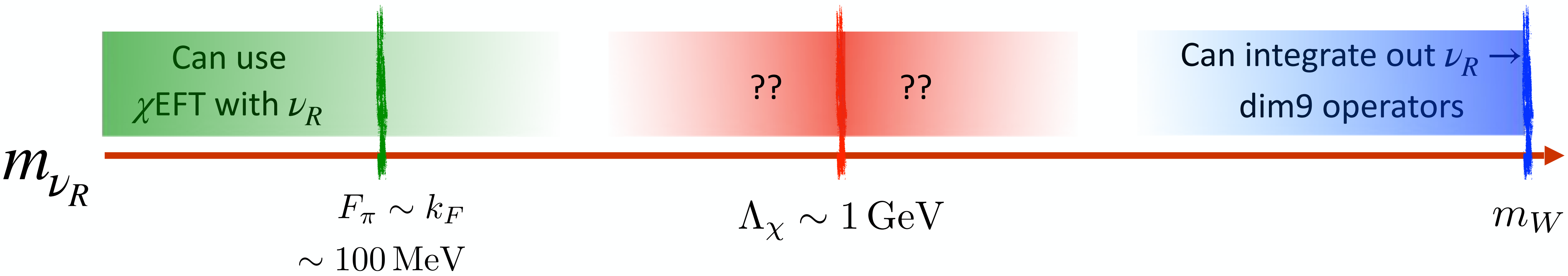
- $c_5 \ll O(1), \qquad \Lambda = \mathcal{O}(1-100)\mathrm{TeV}$
  - Relative enhancement of higher-dimensional terms due to $c_{7,9}/c_5 \gg 1$
- Happens, for example, in the left-right model

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

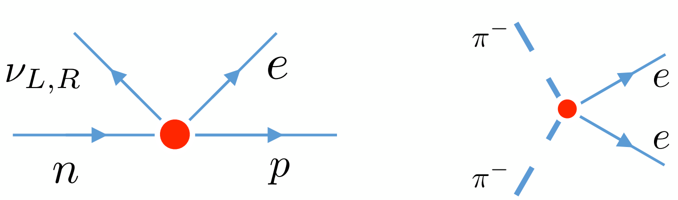
Sterile neutrinos

Sterile neutrinos

Complication: m_{ν_R} dependence

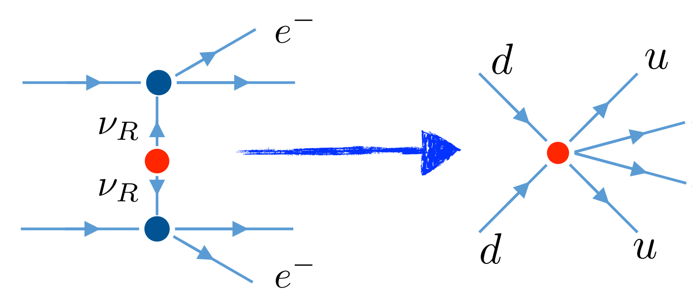


- Chiral EFT involving ν_R



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

- Integrate out ν_R



→ Chiral EFT without ν_R

$A \propto m_{\nu_R}$

Interpolate

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

Estimating the contact interaction

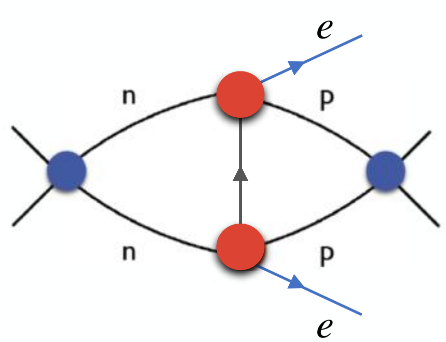
Determination of the counterterm

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

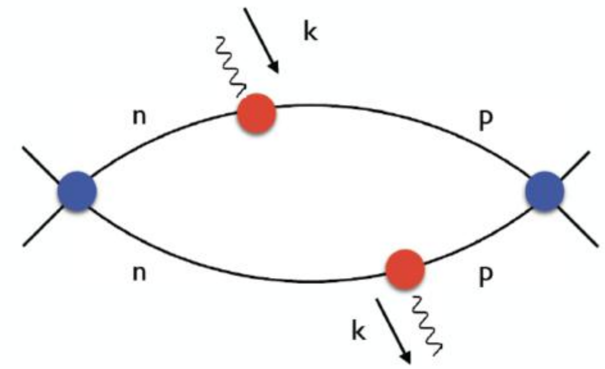
- Analogy to the Cottingham approach for pion/nucleon mass differences

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

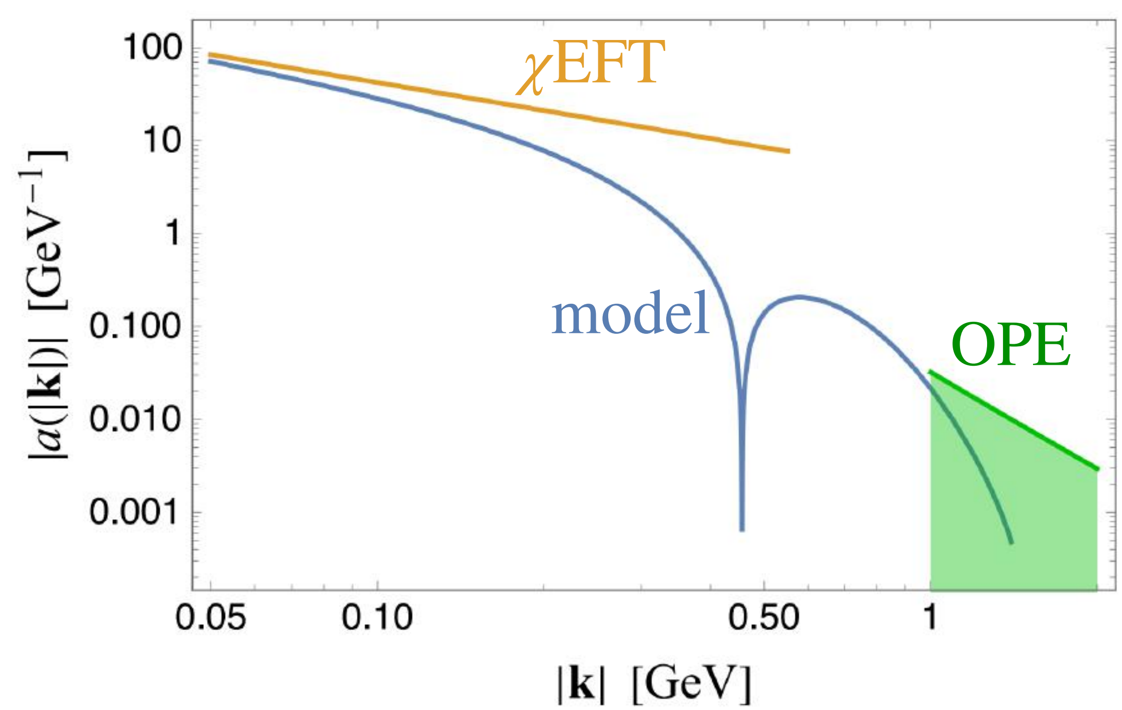
$\mathcal{A}_\nu =$



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



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



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

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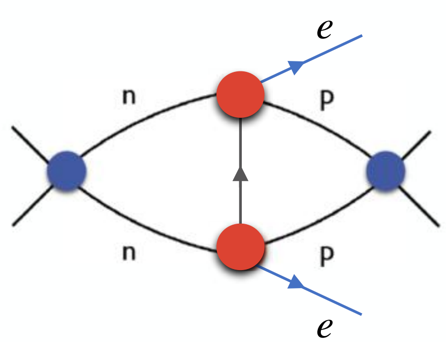
$\mathcal{A}_\nu =$ 

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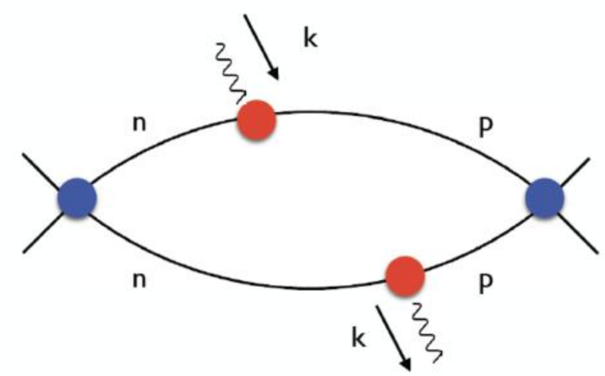
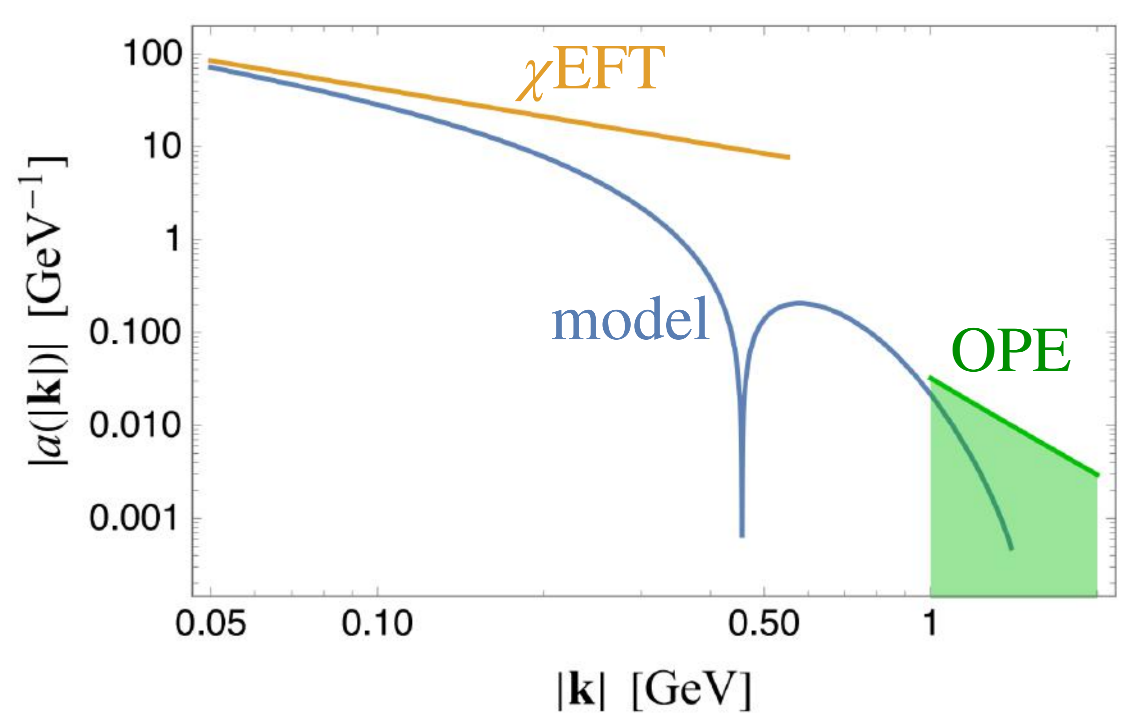


- Gives $\tilde{g}_\nu^{NN}(\mu = m_\pi) = 1.3(6)$ in $\overline{\rm MS}$
  - Estimated 30% uncertainty
  - Validated in isospin-breaking observables
  - Consistent with large-Nc estimate

Richardson et al, '21

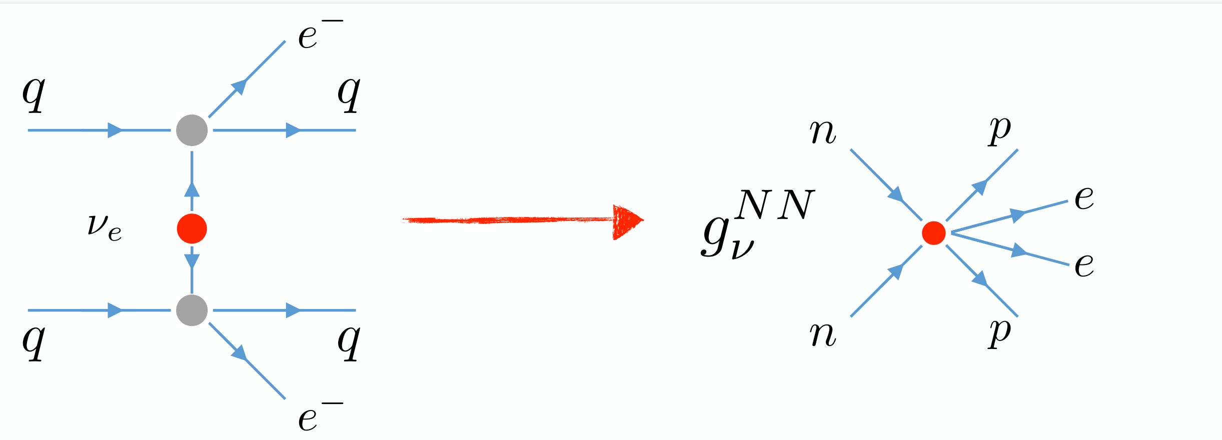


W. Cottingham '63; H. Harari, '66

Relation to electromagnetism

Relation to electromagnetism

LNV contact term

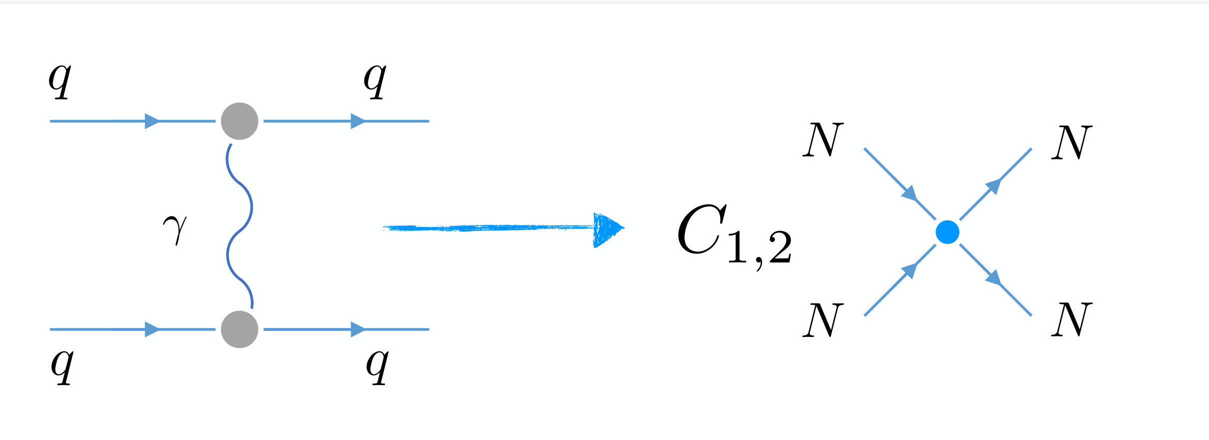


- Hard part of two Weak currents

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

- Leptonic part combines to boson propagator

EM contact term



- Hard part of two EM currents

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

- Non-hadronic part is the photon propagator

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

Relation to electromagnetism

- Only two ΔI=2 operators can be induced

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

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

with spurions

$$\mathcal{Q}_L = u^\dagger Q_L u, \quad \mathcal{Q}_R = u Q_R u^\dagger,$$
$$u = \exp\left(i\pi\cdot\tau/2F_\pi\right)$$

EM

$$\mathcal{L}_{em} = e^2/4\,(C_1 O_1 + C_2 O_2)$$
$$Q_L = Q_R = \tau^3/2$$

LNV

$$\mathcal{L}_{LNV} = g_\nu^{NN} G_F^2 m_{\beta\beta} O_1\,\bar{e}e^c$$
$$Q_L = \tau^+, \qquad Q_R = 0$$

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

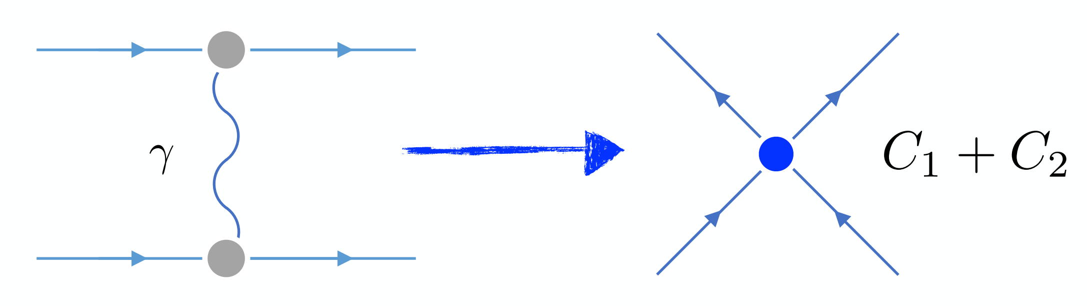
Chiral symmetry

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

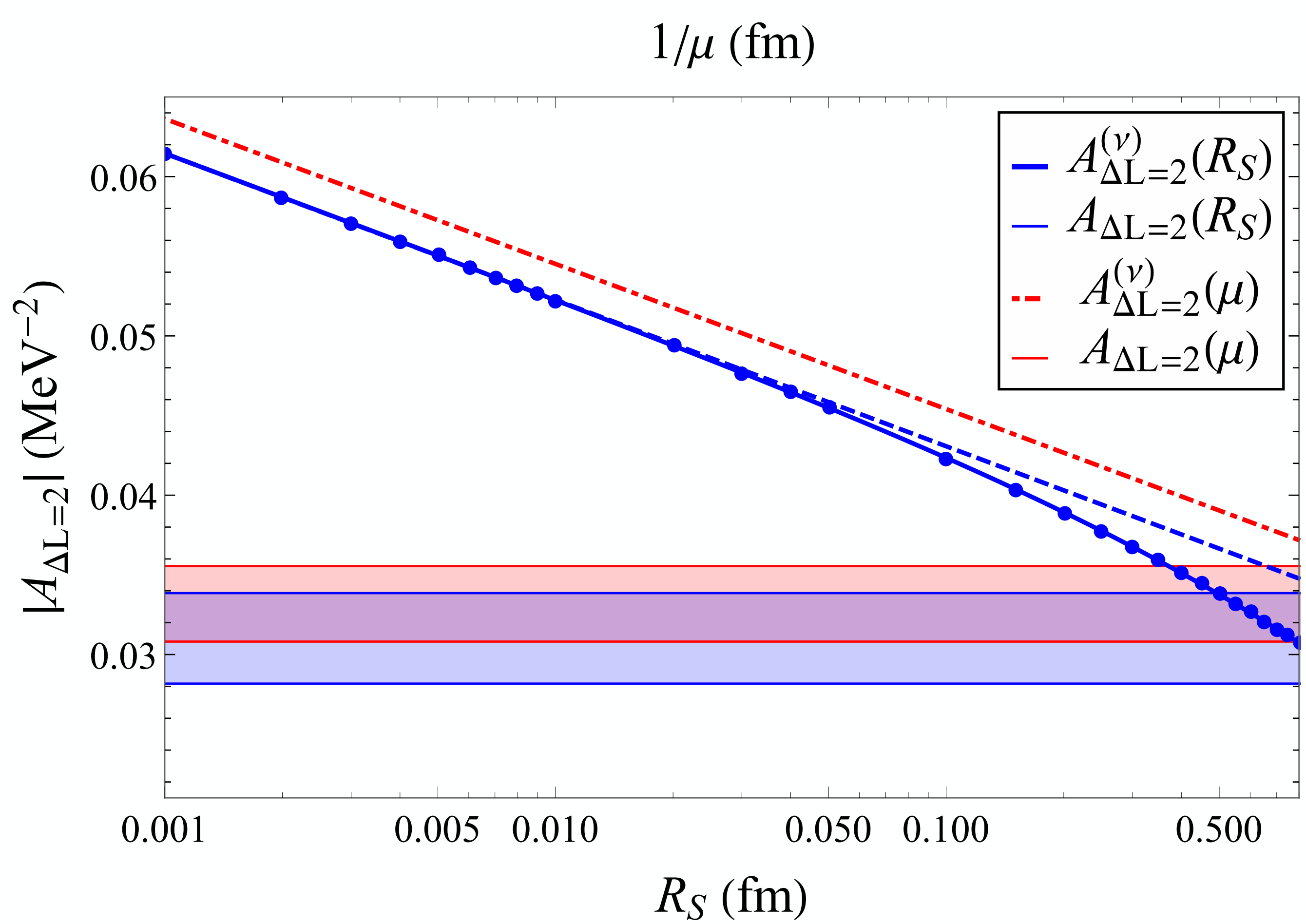
Relation to electromagnetism

- ΔI=2 in NN scattering

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



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



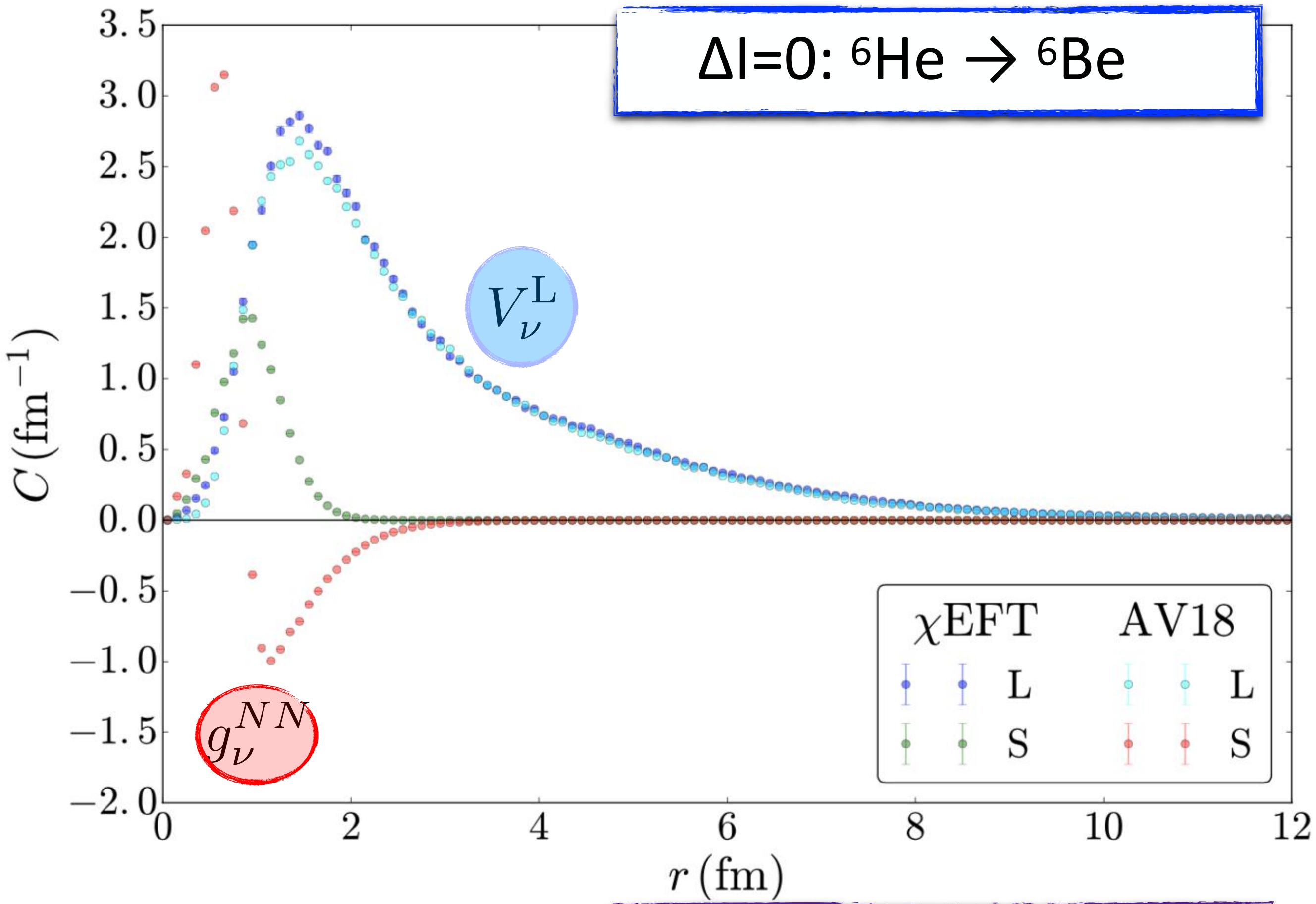
Estimate of impact in light nuclei

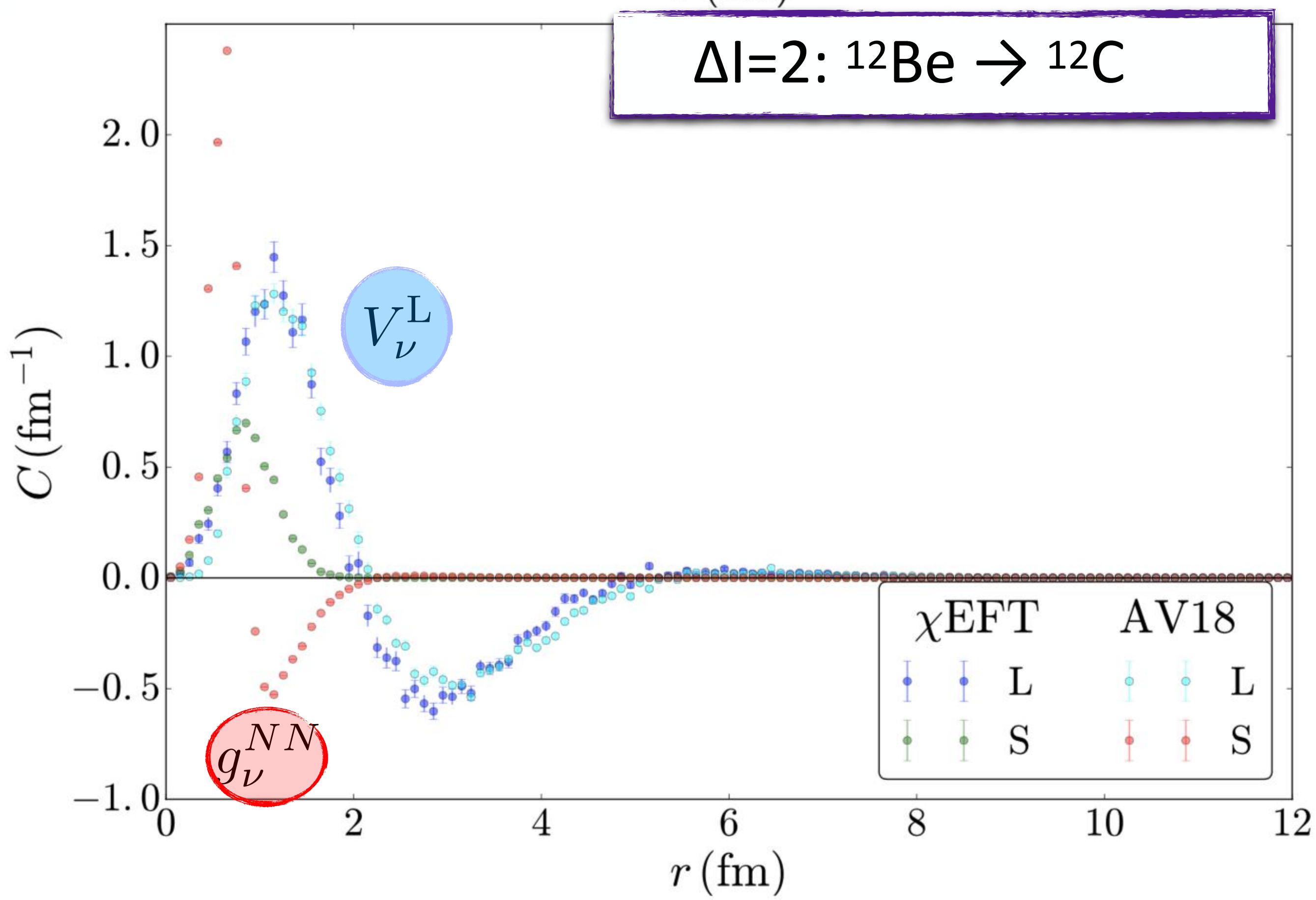
Estimate of impact

Light nuclei

M. Piarulli, R. Wiringa, S. Pastore

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





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