Effective theories for $0\nu\beta\beta$

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with

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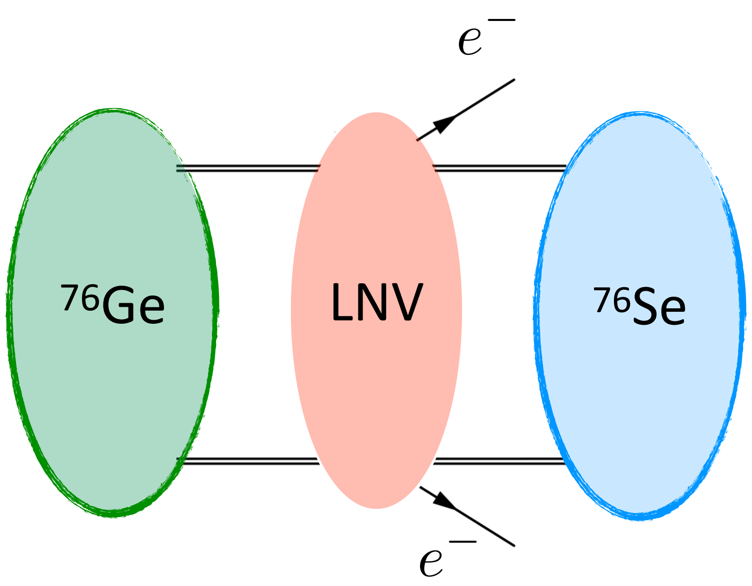
UNIVERSITY of WASHINGTON

INSTITUTE for NUCLEAR THEORY

Introduction

0νββ



- Violates lepton number, ΔL=2

Schechter, Valle, `82;

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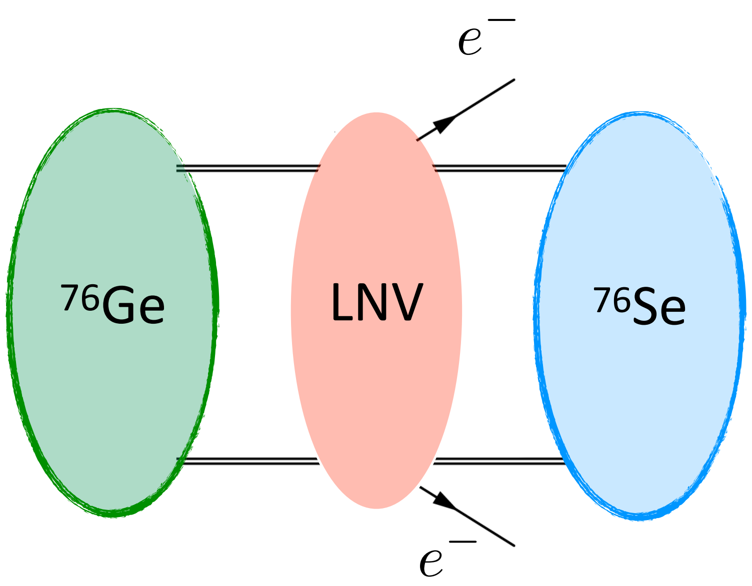
0νββ



- Violates lepton number, ΔL=2

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

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

Future reach:
(LEGEND, nEXO, CUPID)

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

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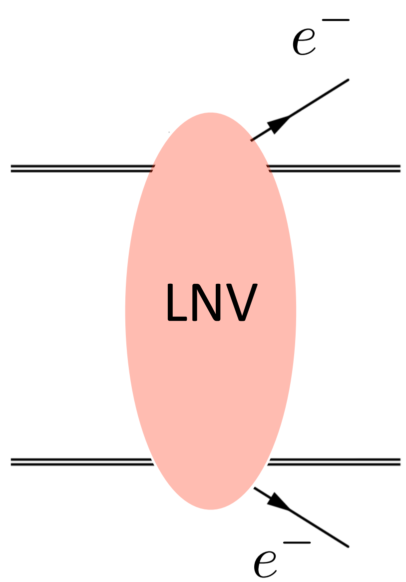

= **BSM physics**

- Violates lepton number, ΔL=2

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

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

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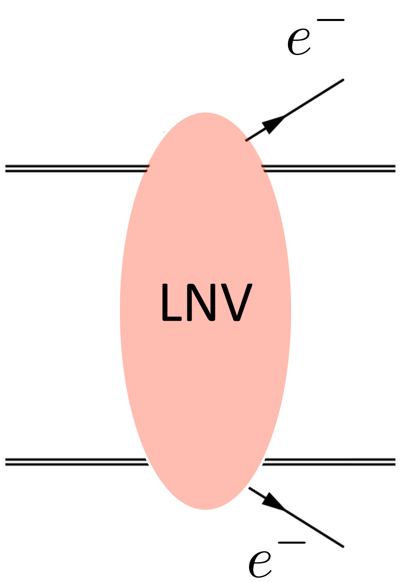

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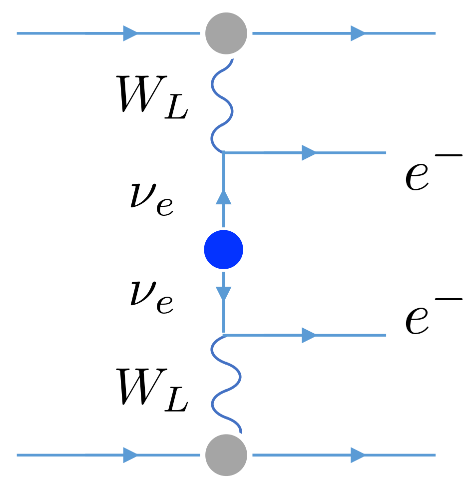
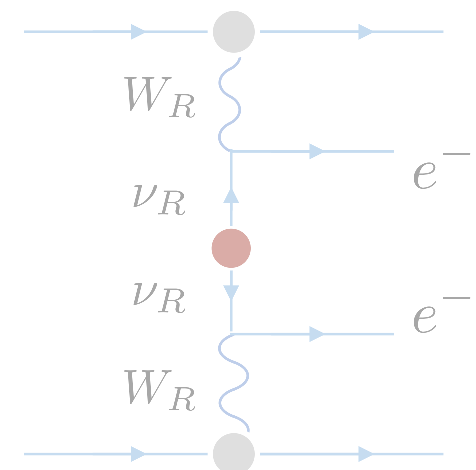
Light Majorana mass?

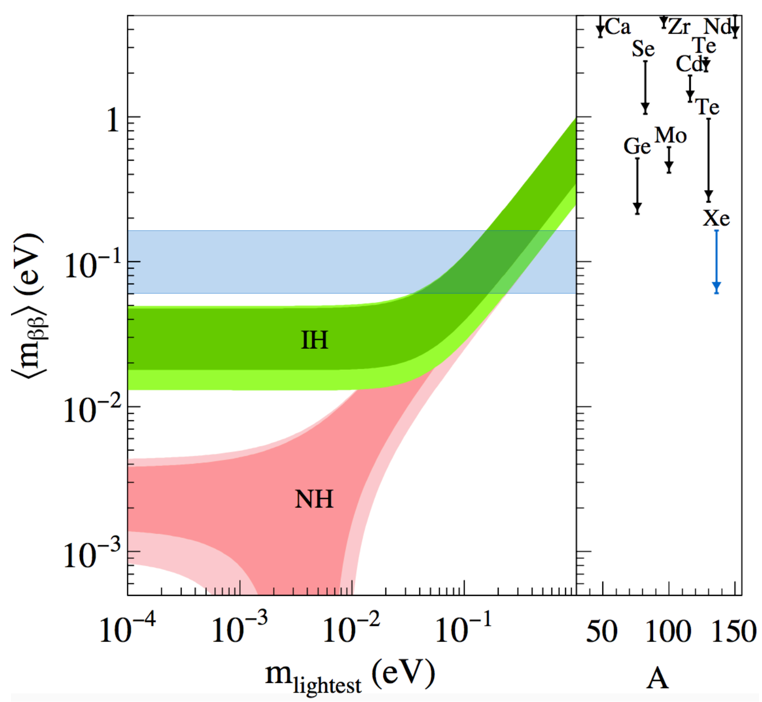


Left-right model?



+ ??

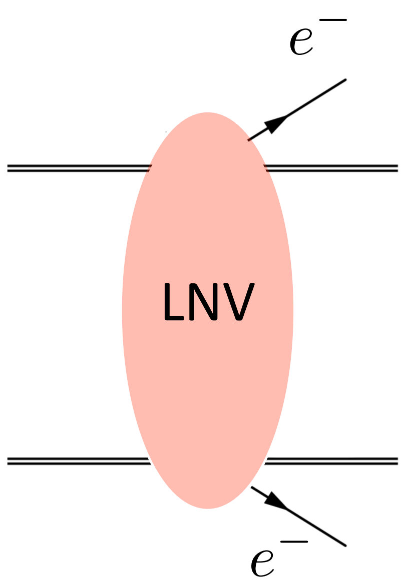
Well-known Majorana mass mechanism



- Implications for the mass hierarchy

Introduction

0νββ



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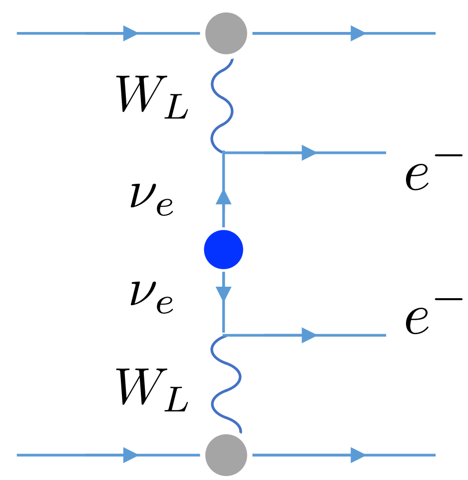

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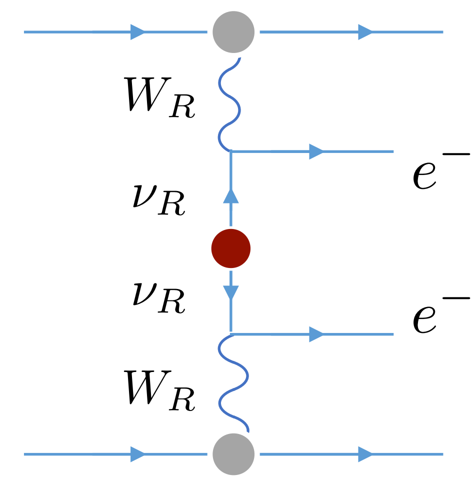

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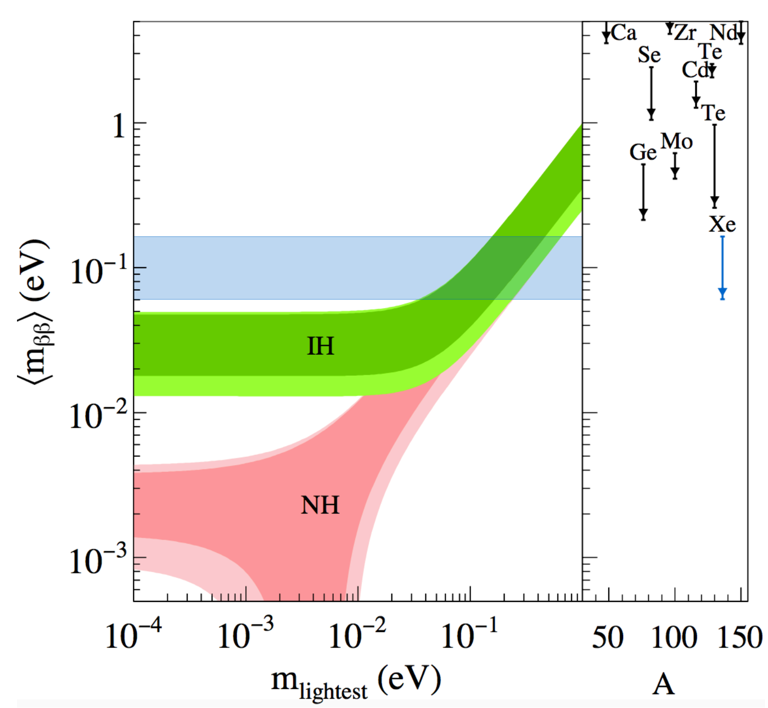

- Implications for the mass hierarchy

Heavy BSM mechanisms

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

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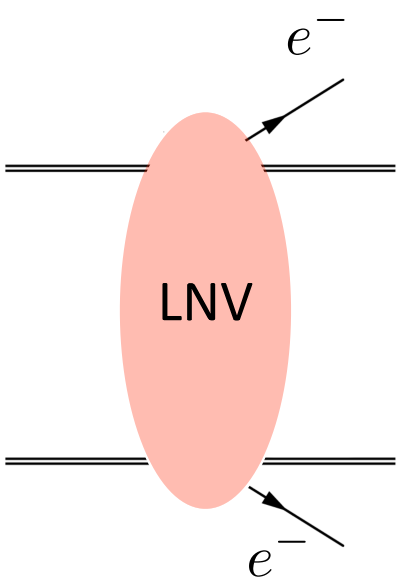

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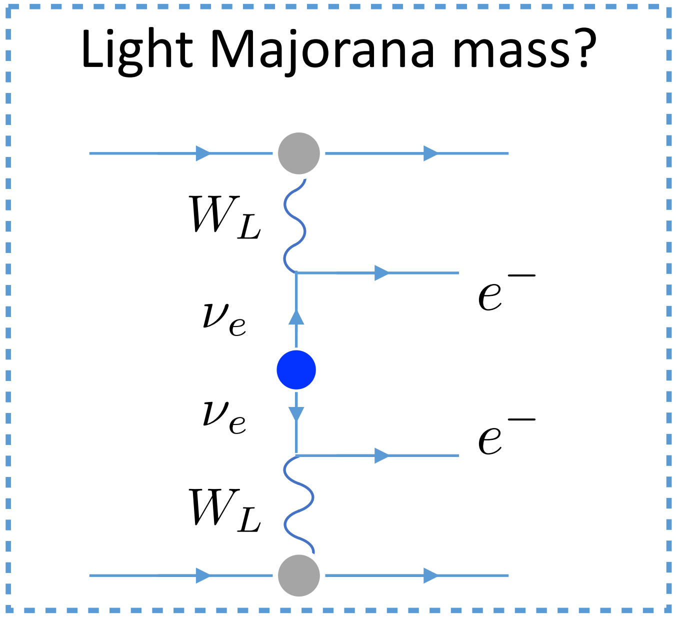

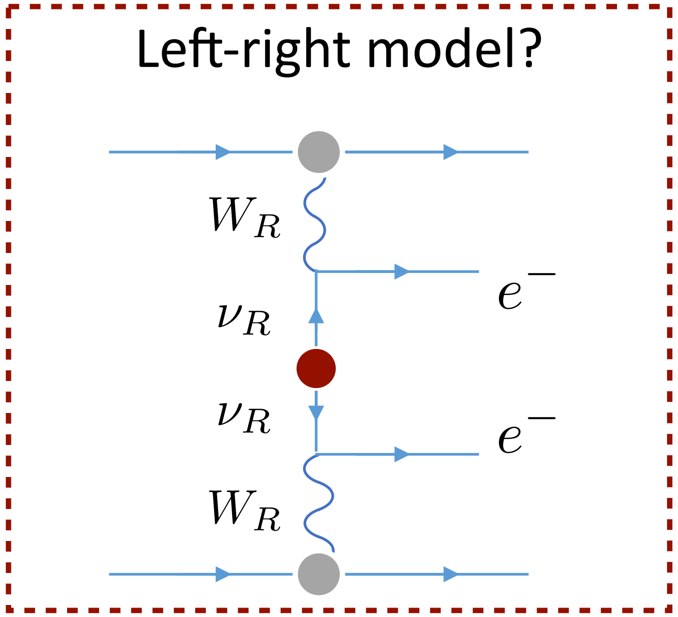

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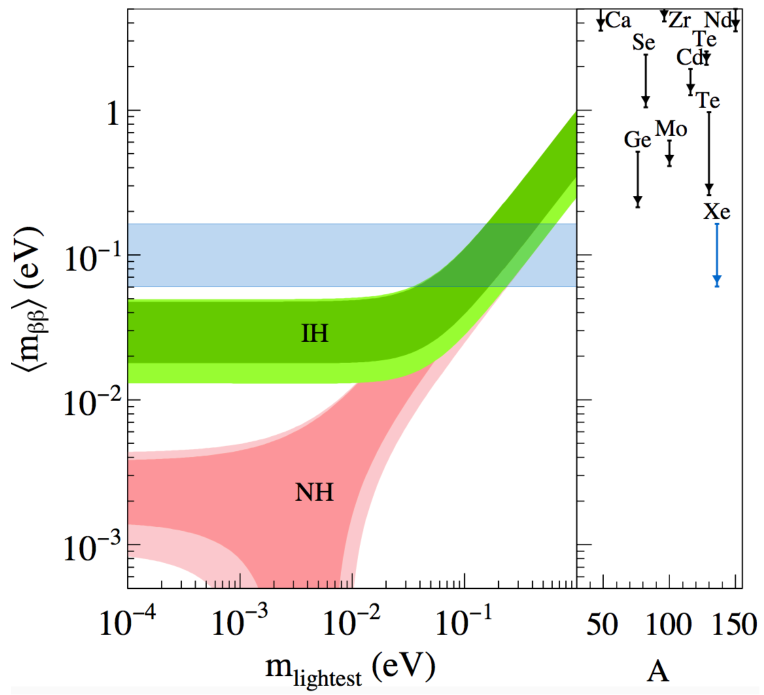
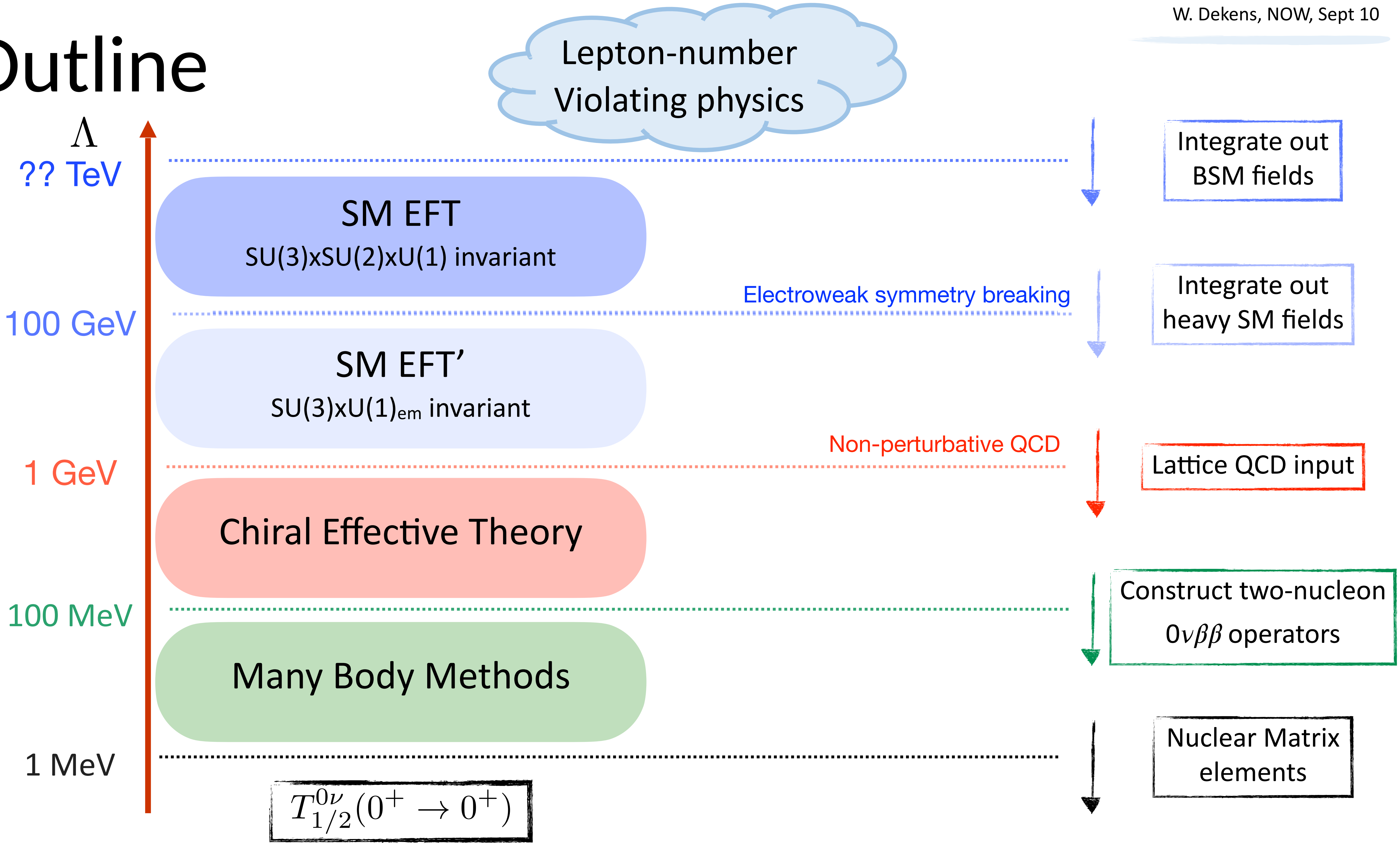


- Implications for the mass hierarchy

Heavy BSM mechanisms

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

Outline


Lepton-number Violating physics
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

Effective Field Theory

From heavy $\Delta L = 2$ physics

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

Dimension-five

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

Dimension-seven

- 12 ΔL=2 operators

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

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

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

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

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

- Consider subset of operators

$$\mathrm{LM1} = i\sigma^{(2)}_{ab}(\overline{Q}_a\gamma^\mu Q_c)(\overline{u}_R\gamma_\mu d_R)(\overline{\ell}_b\ell^C_c)$$
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- Recently complete basis

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Interactions involving light ν_R

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

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

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

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

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From heavy $\Delta L = 2$ physics

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

Interactions involving light ν_R

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

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)

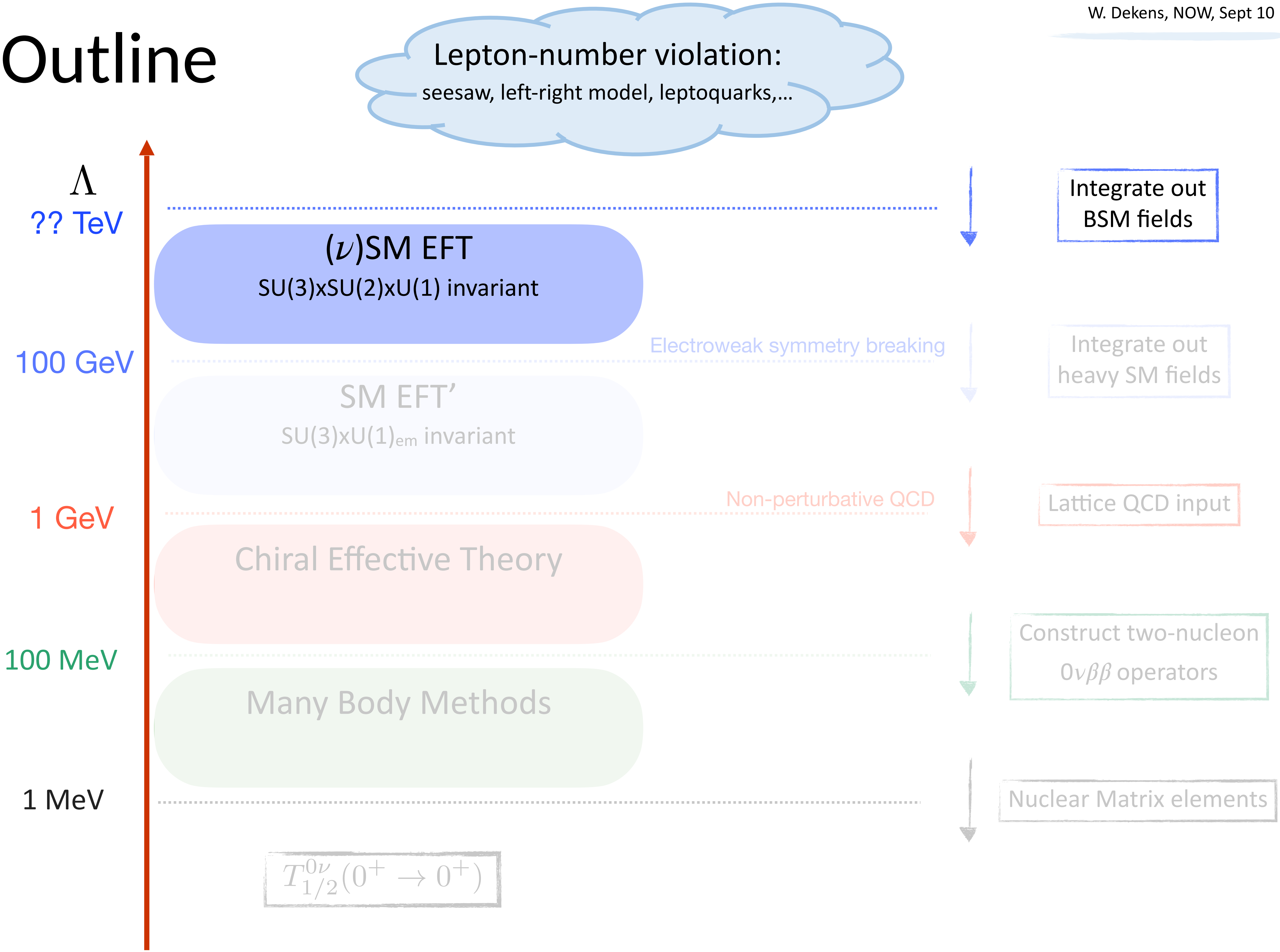
- Dirac mass (L conserving)

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

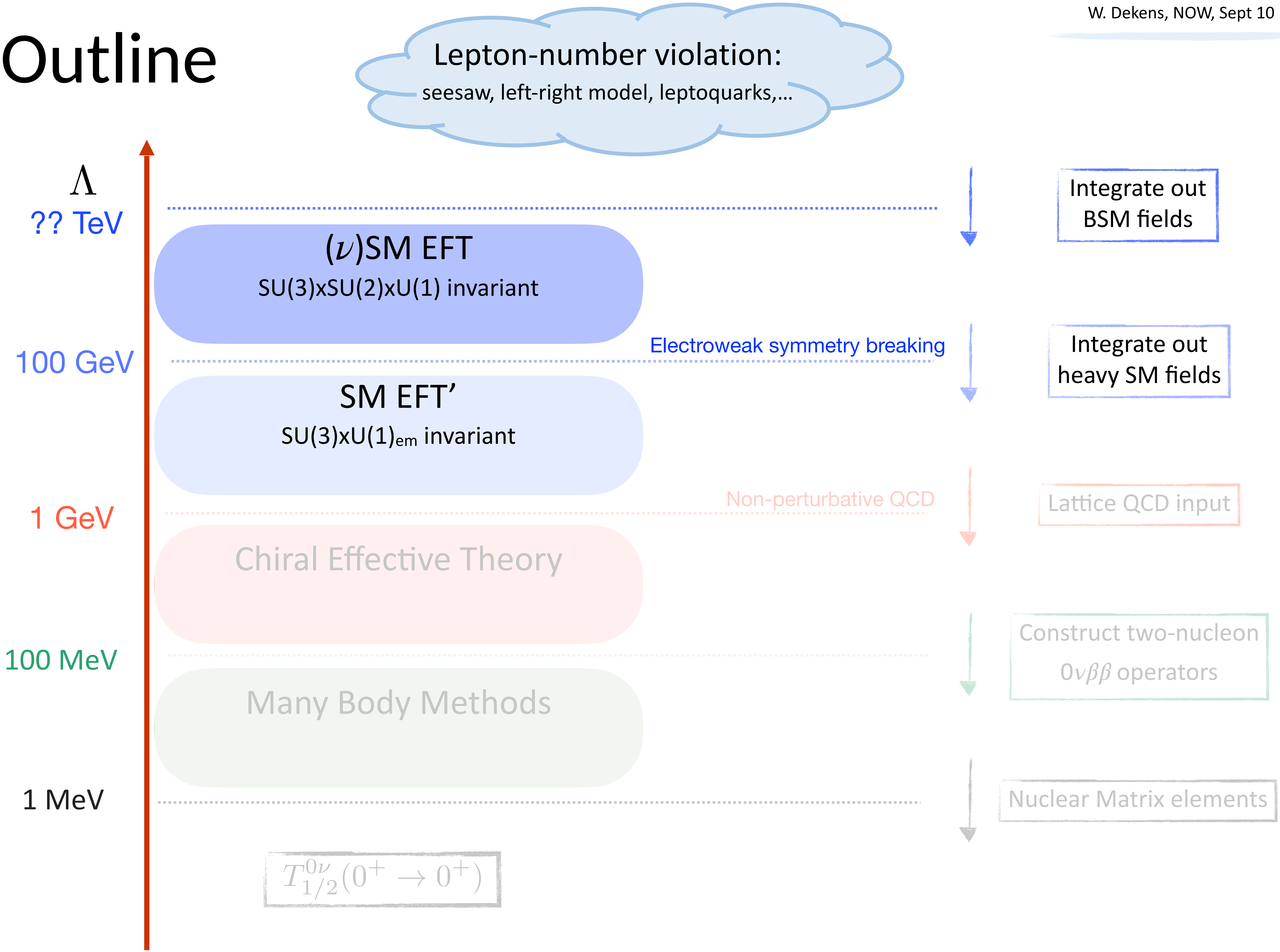
WD et al, '20; Blennow et al, '10; Barea et al, '15; Giunti et al, '15; Bolton et al, '19;

Outline

W. Dekens, NOW, Sept 10



Outline


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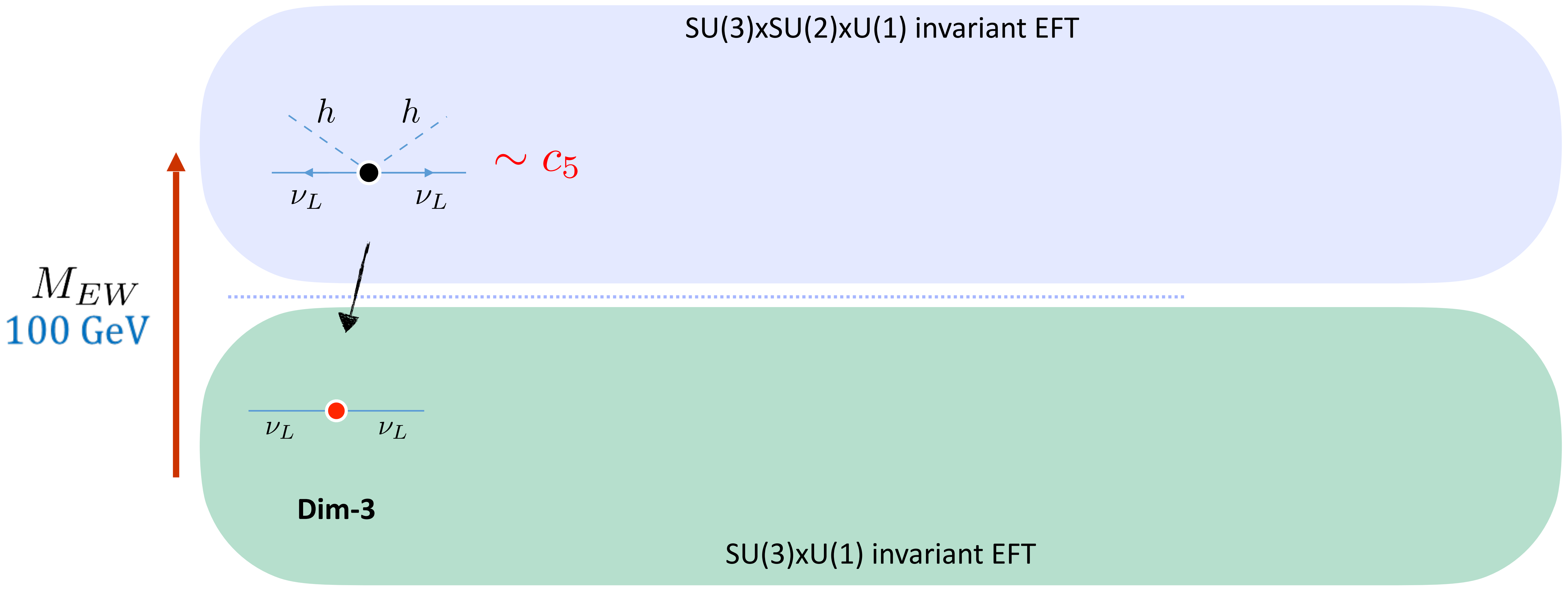
Construct two-nucleon $0\nu\beta\beta$ operators
Nuclear Matrix elements

Low-energy operators

At/below the weak scale*



* very similar for operators involving ν_R

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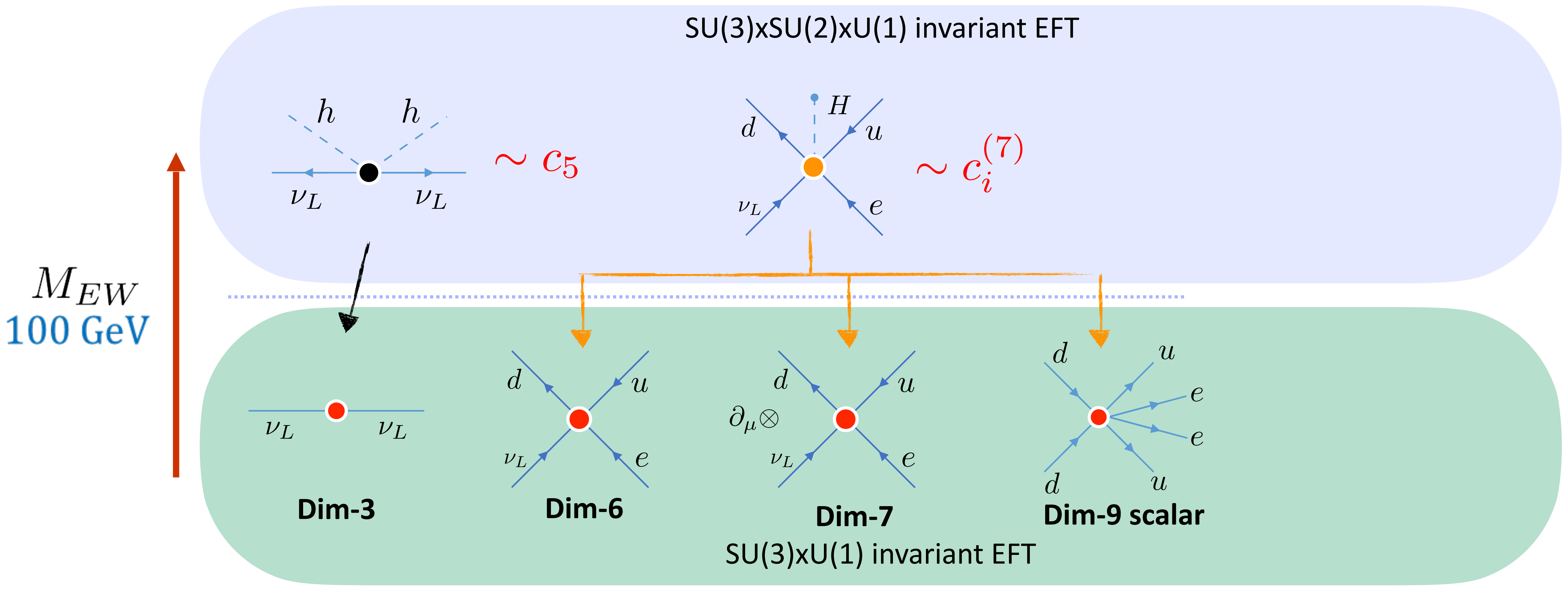

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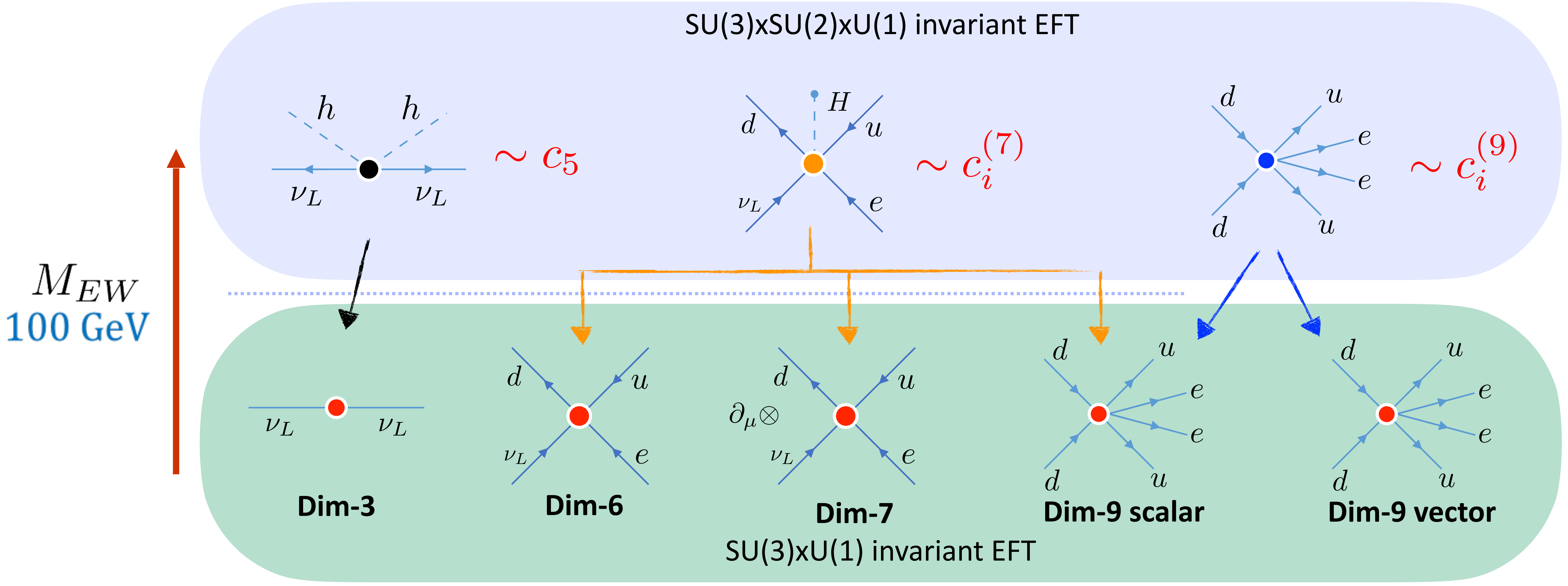

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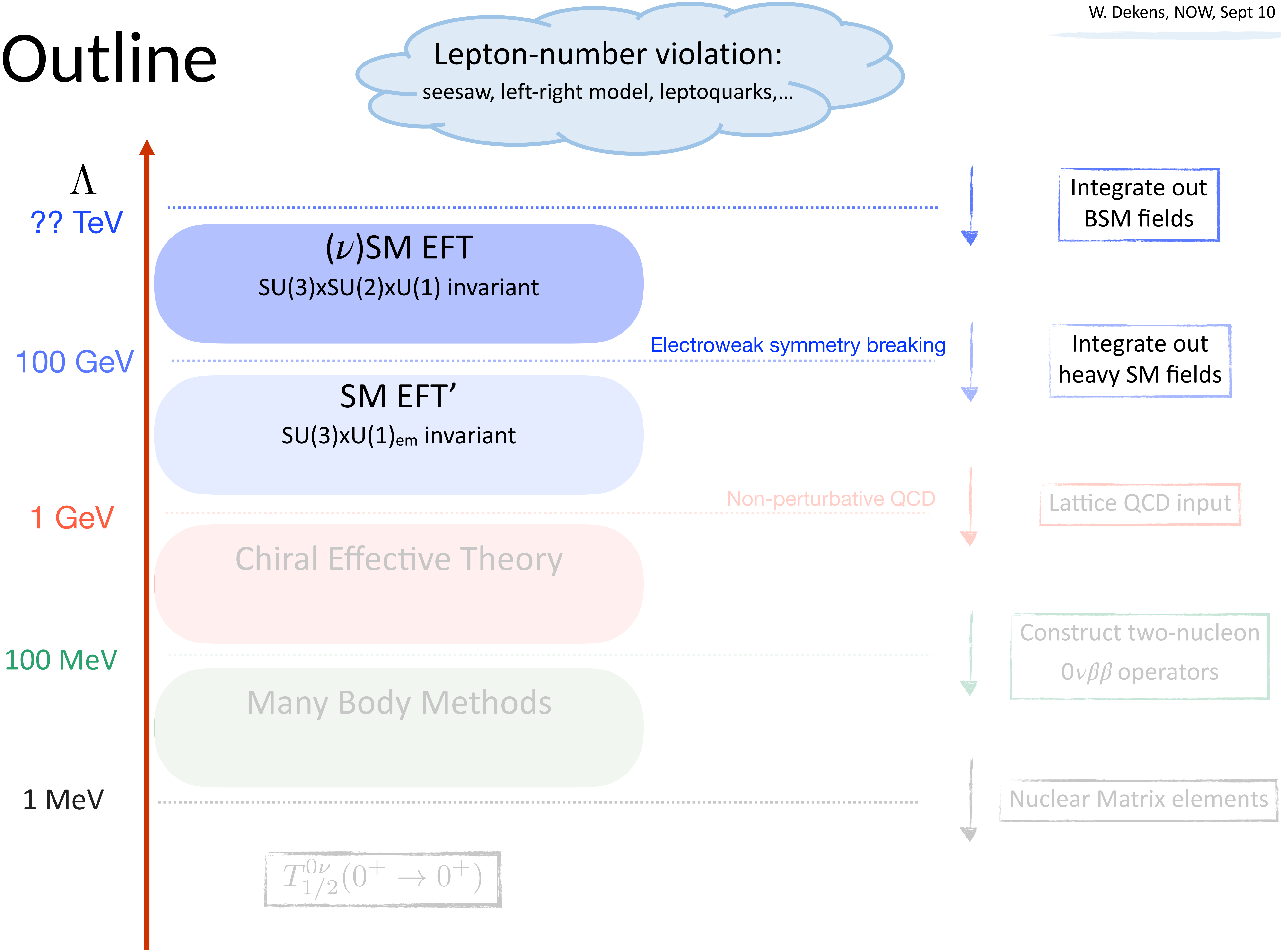
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100 MeV

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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)

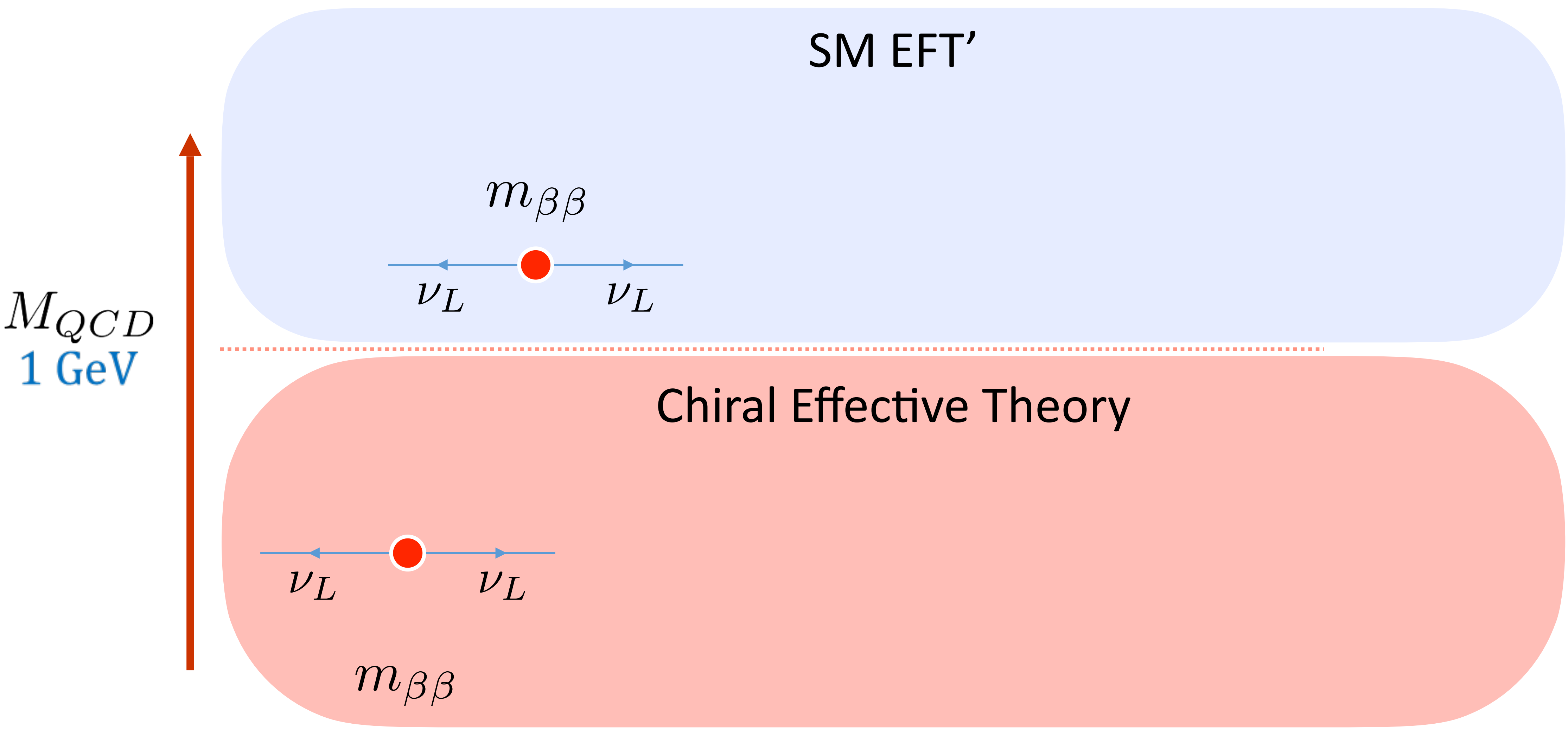
Need a power-counting scheme
- Start by assuming Naive dimensional analysis (NDA)
- Will come back to whether it breaks down

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

Matching to Chiral EFT

Dimension-3

Warning: Based on NDA



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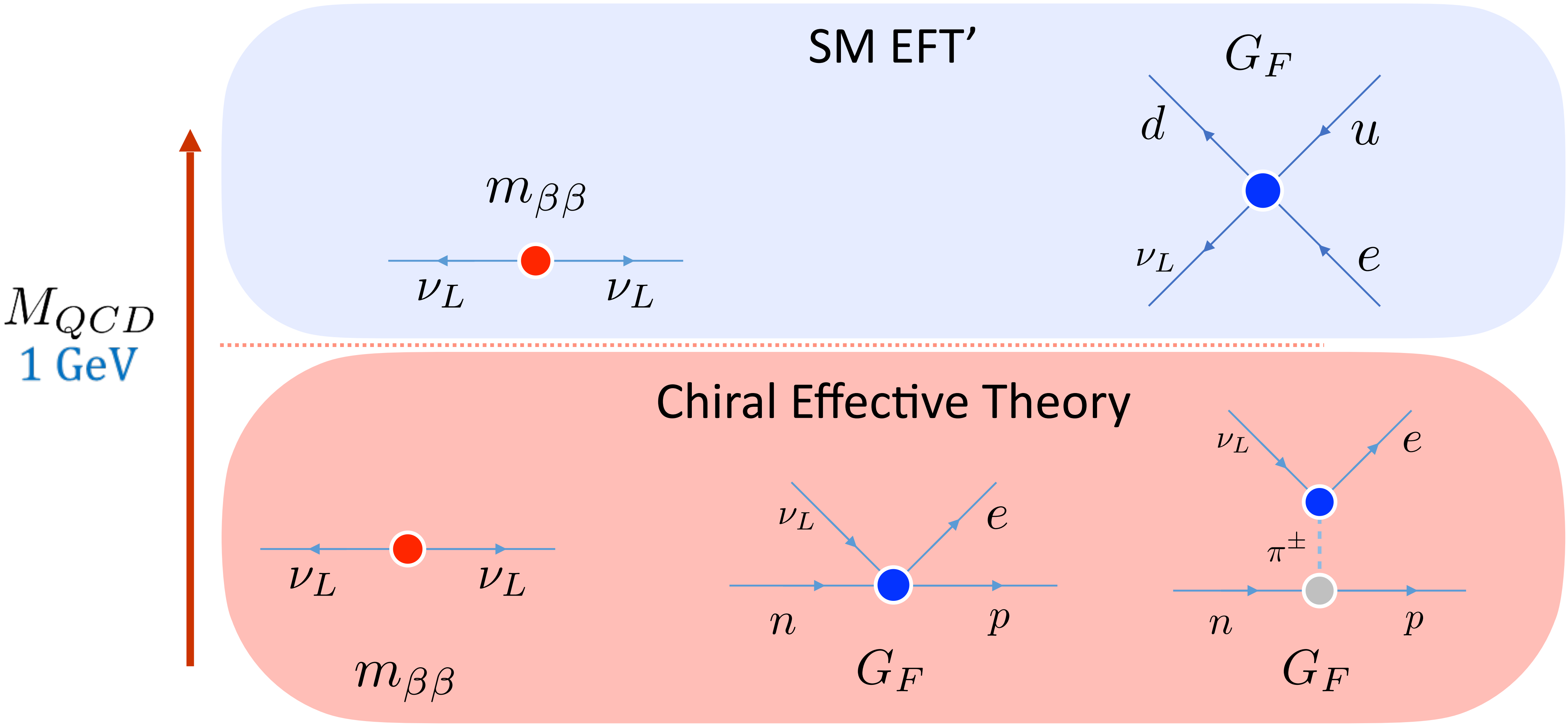

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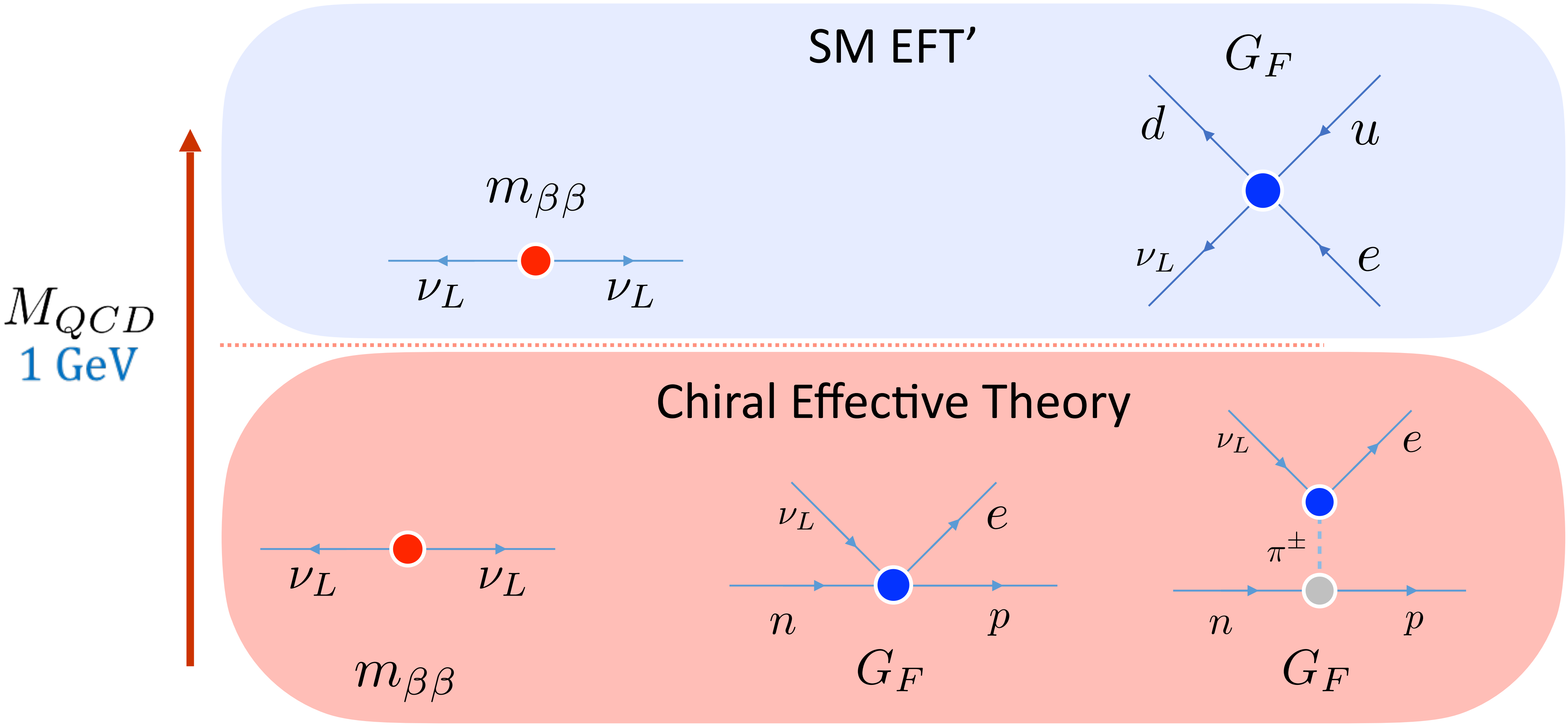

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  - All low-energy constants are known

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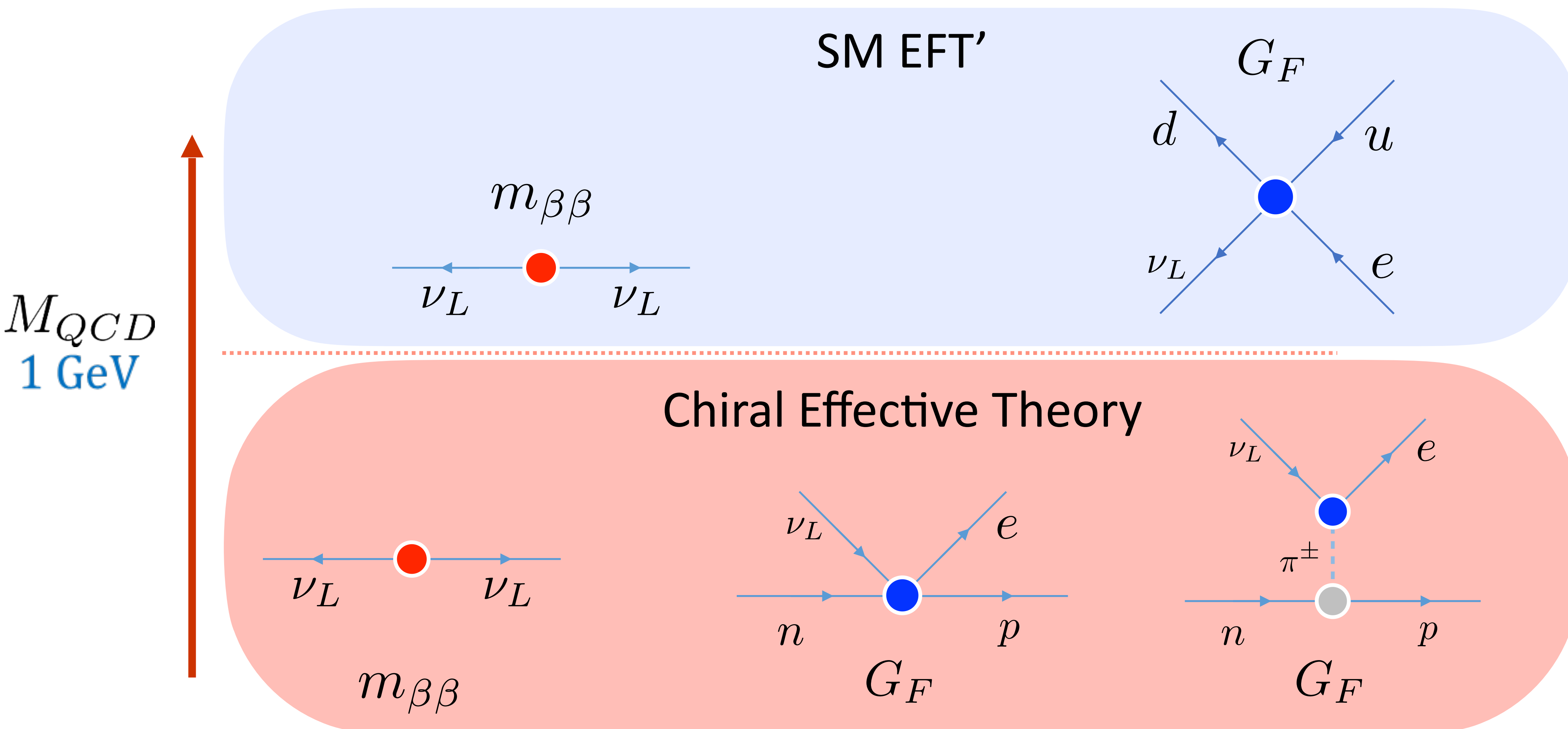
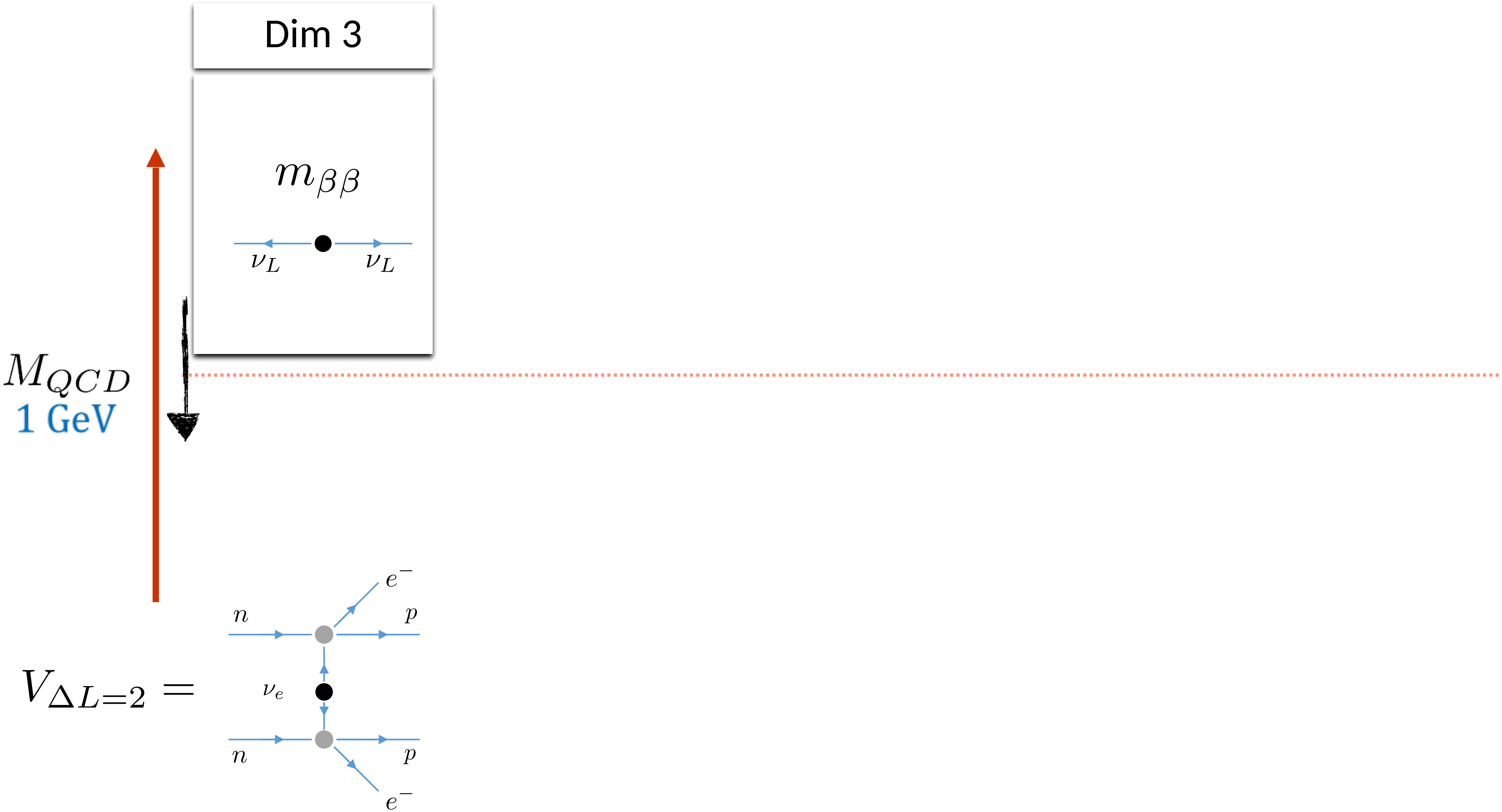


- At LO: only need the nucleon one-body currents
  - All low-energy constants are known
- At N2LO
  - Contributions from loops, counterterms, ultrasoft $\nu' s$

[see backup]

Cirigliano, (WD) et al, '18; Pastore, (WD) et al, '18;

Chiral EFT



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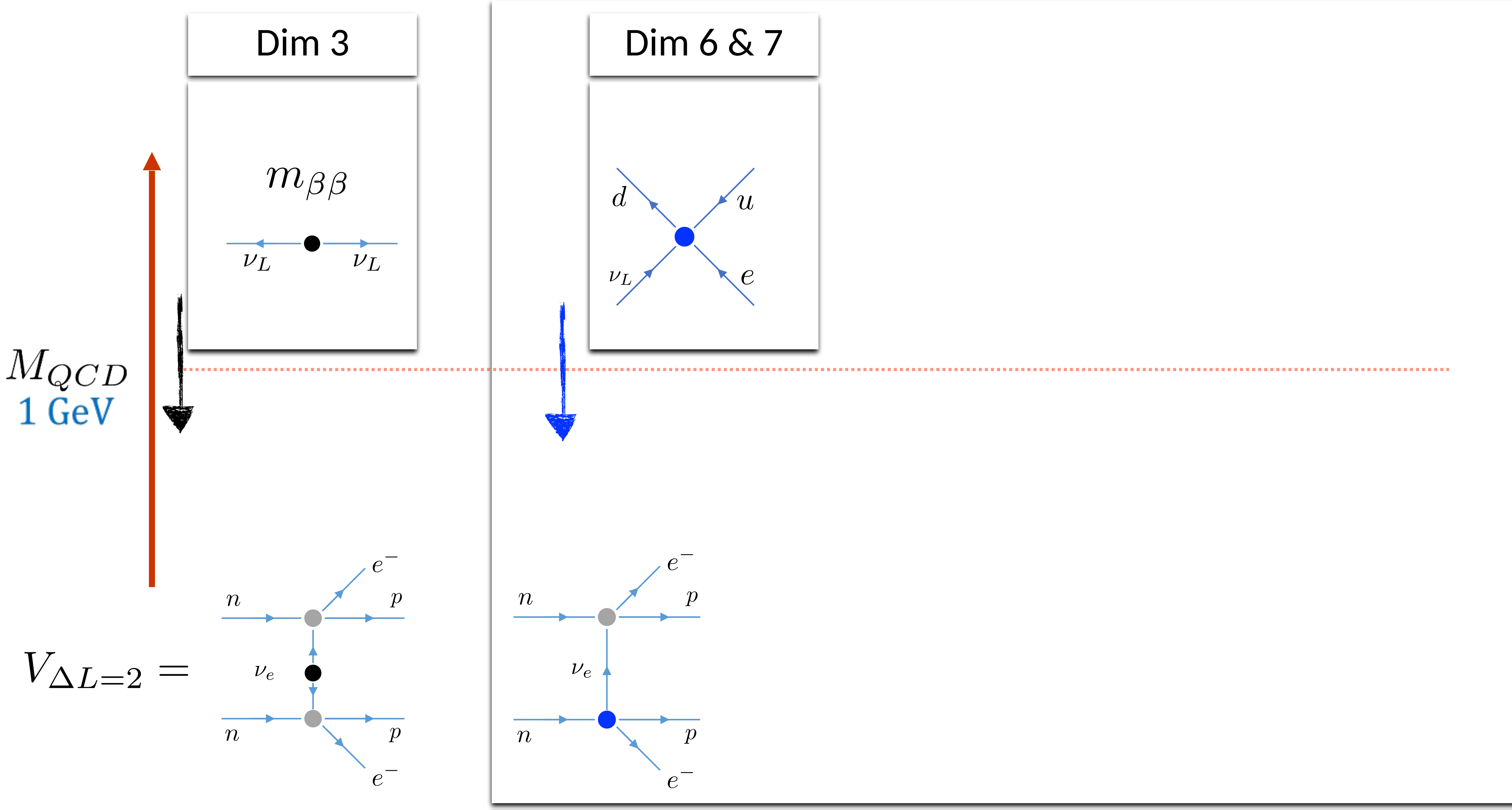

- Additional N-currents NN, πN, $\pi\pi$ interactions and LECs
- LECs for the N-currents and $\pi\pi$ interactions are partially known

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

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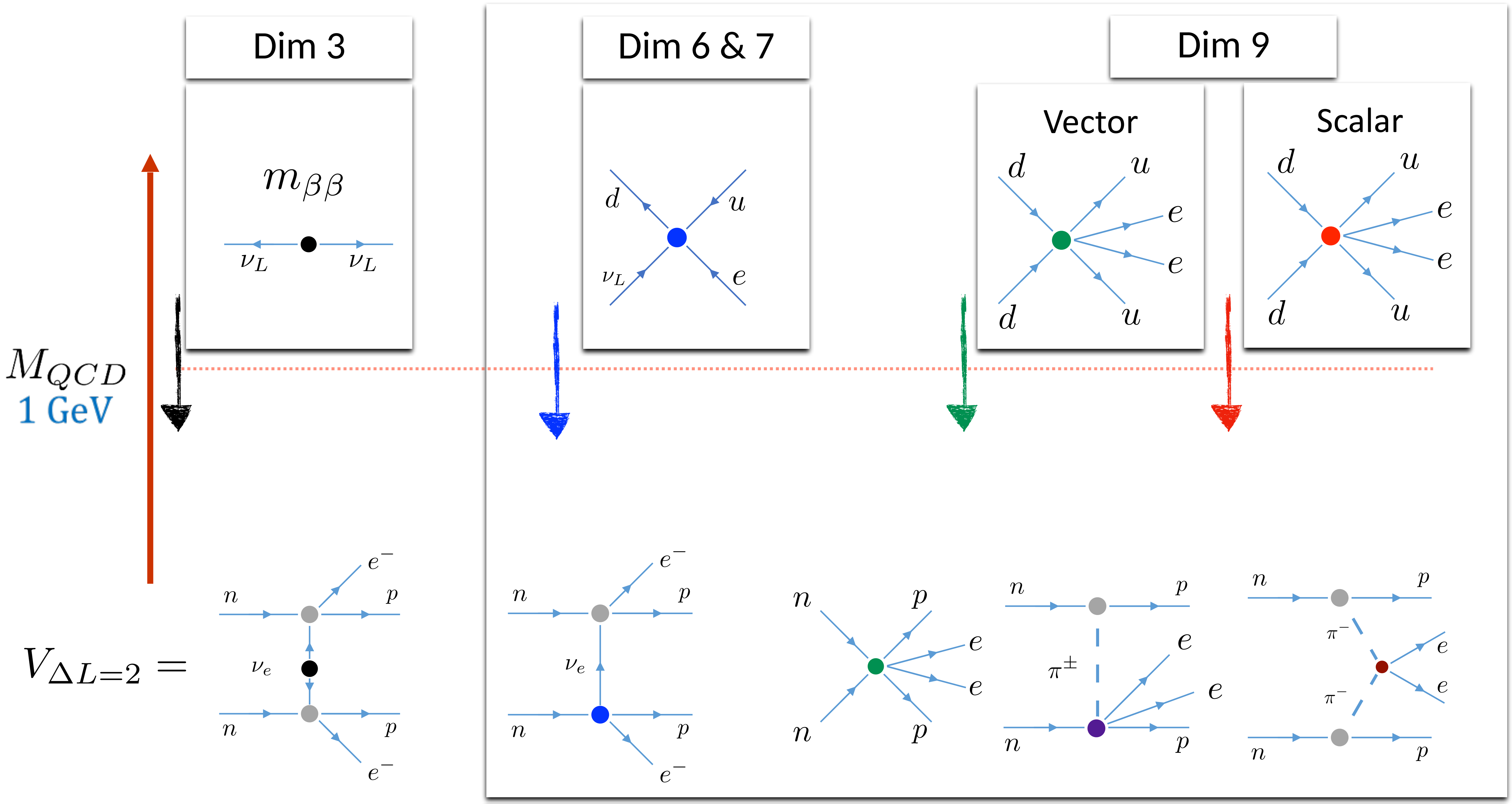

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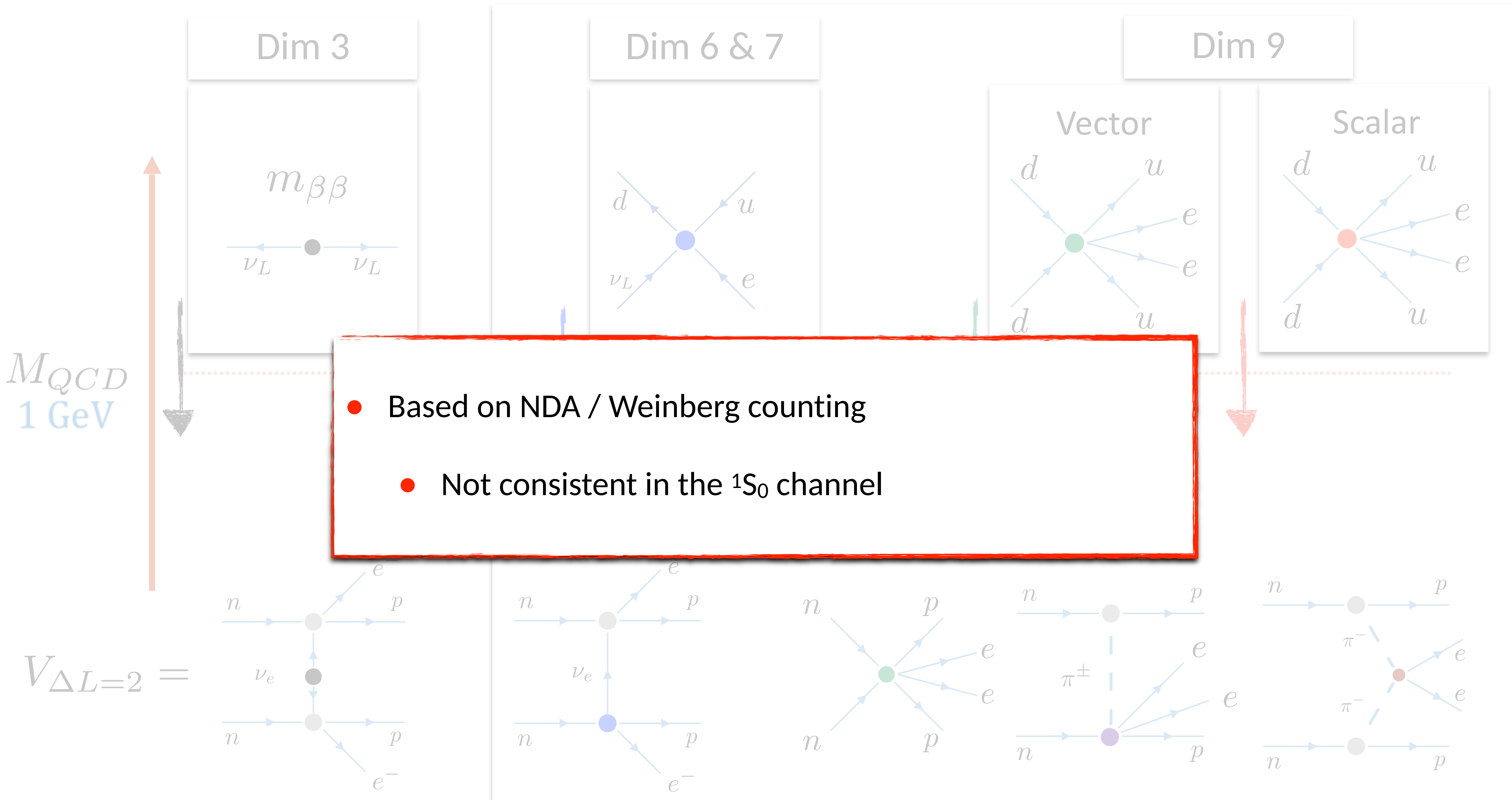

- Based on NDA / Weinberg counting
  - Not consistent in the $^1S_0$ channel

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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

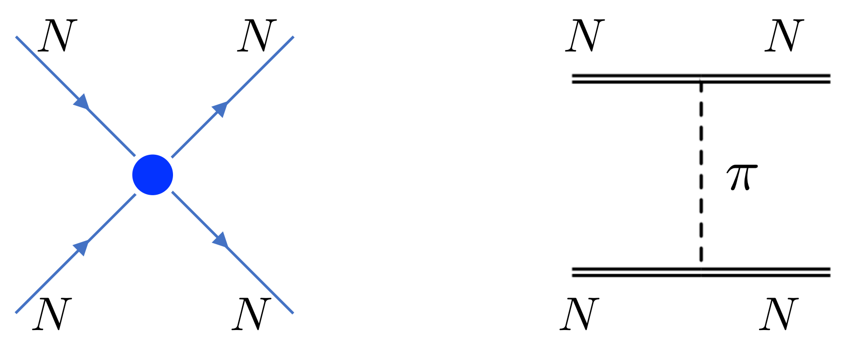
Checking the power counting

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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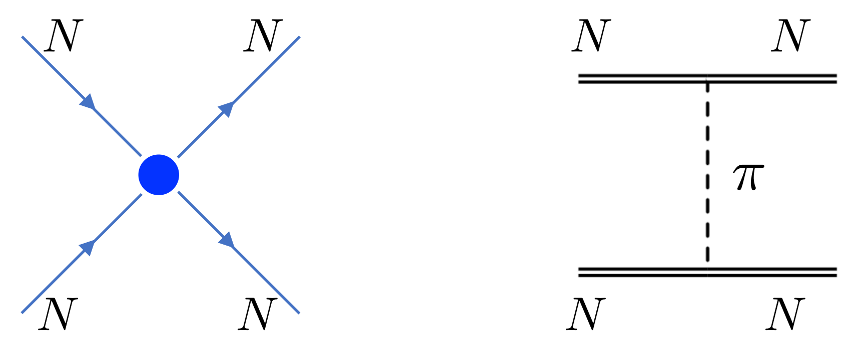
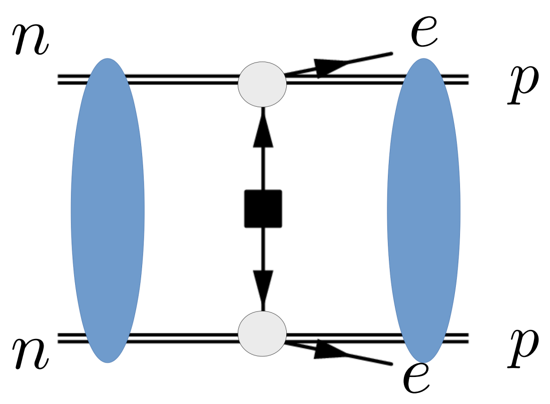
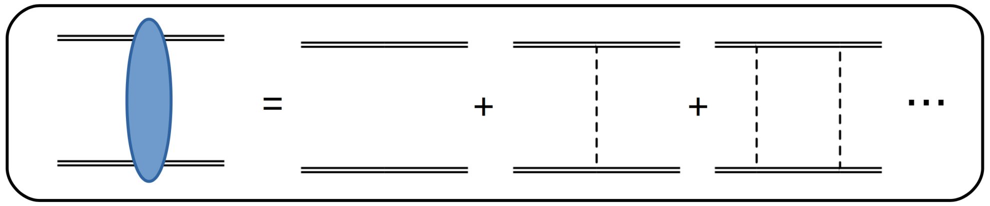


Dress the ΔL=2 potential with (renormalized) strong interactions:





✓ finite

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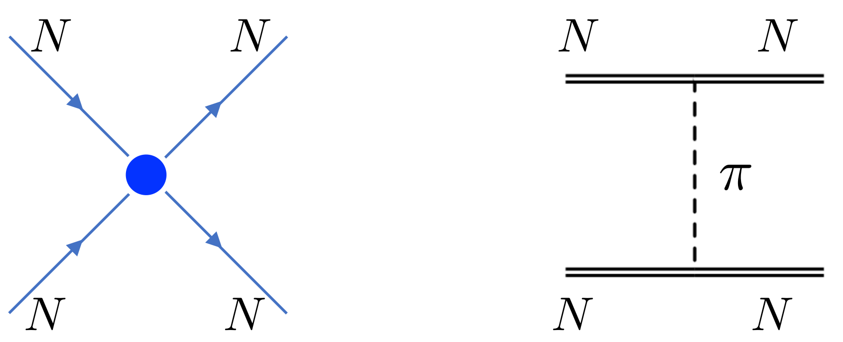

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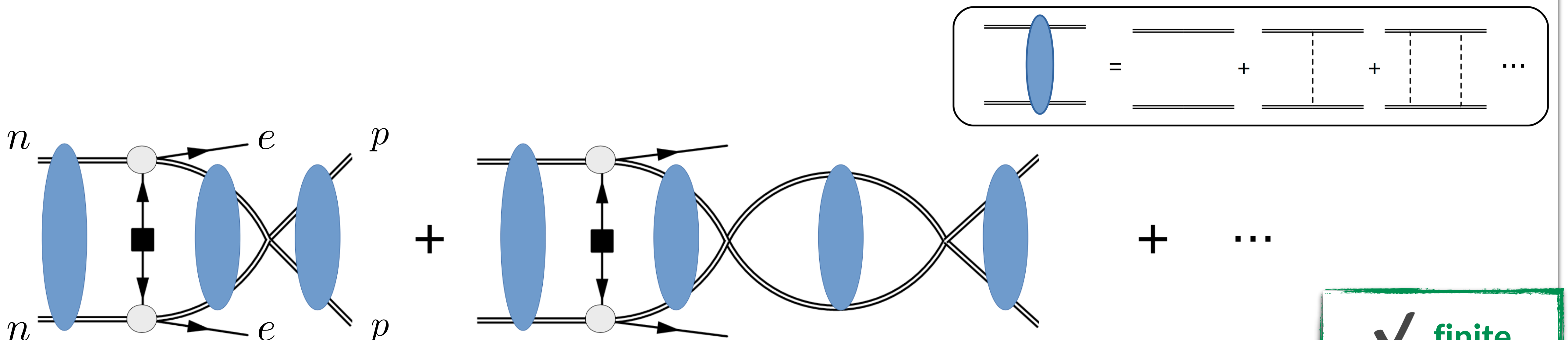

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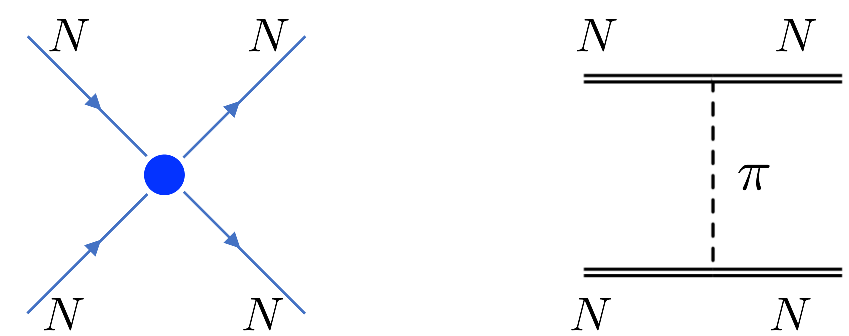

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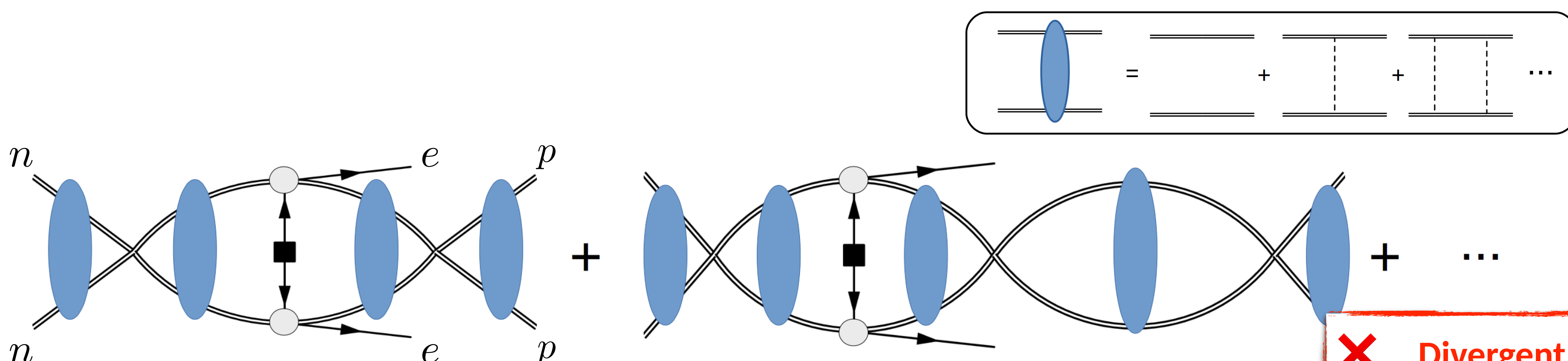

❌ Divergent

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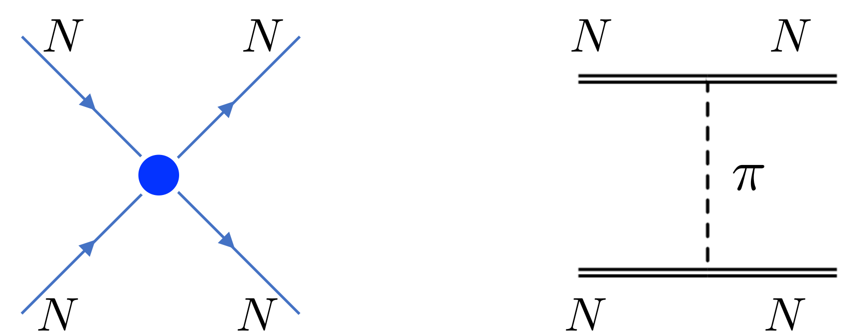
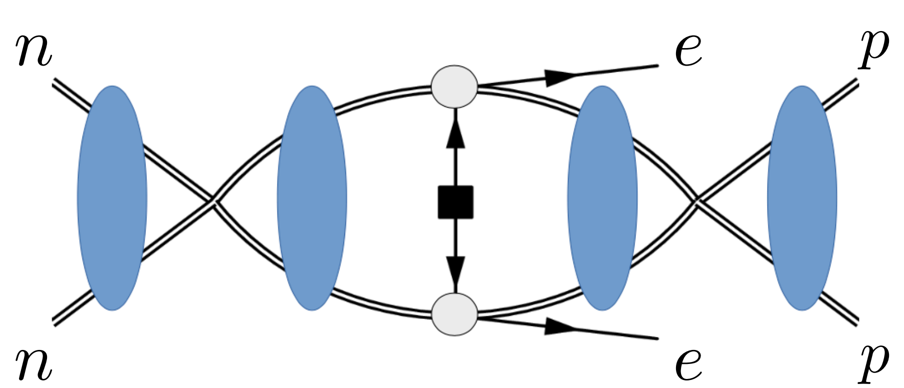


Dress the ΔL=2 potential with (renormalized) strong interactions:

In MS-bar:

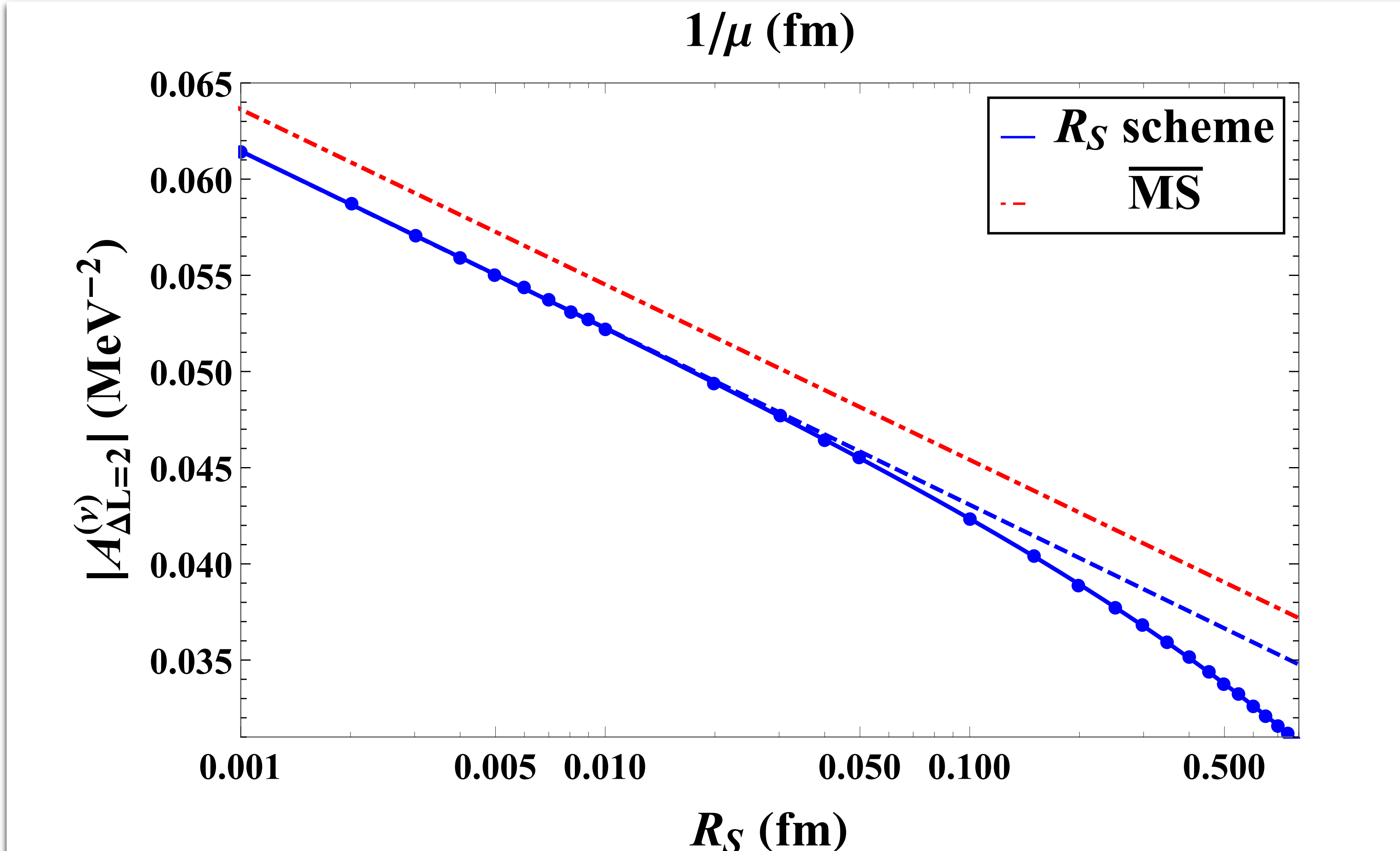


$$= -\left(\frac{m_N}{4\pi}\right)^2 (1+2g_A^2)\frac{1}{2}\left(\log\frac{\mu^2}{-(|\mathbf{p}|+|\mathbf{p}'|)^2+i0^+}+1\right)$$

$+\text{finite}$

Regulator dependent

Numerical results



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

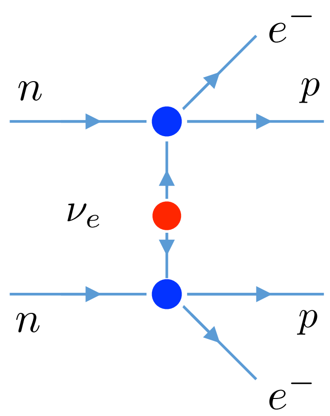
$$\tilde{C}\,\delta^{(3)}(\mathbf{r}) \rightarrow \frac{\tilde{C}(R_S)}{(\sqrt{\pi}R_S)^3}\exp\left(-\frac{r^2}{R_S^2}\right)$$

- Clear μ or R_S dependence

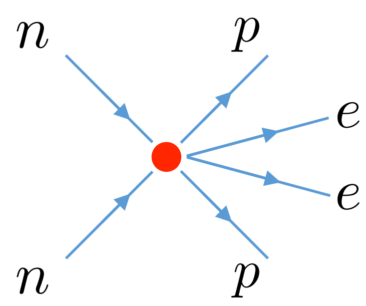
Need for a counter term

New interaction needed at leading order to get physical amplitudes:

$V_{\Delta L=2} =$



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



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

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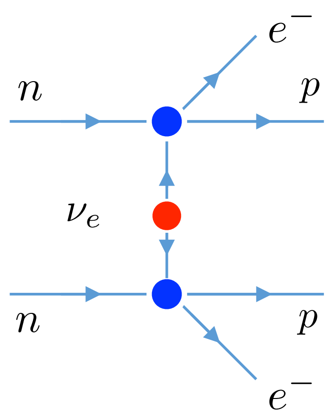

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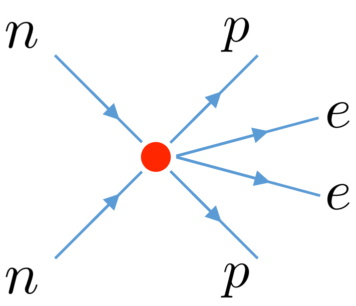

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- Lattice calculation of $\mathcal{A}(nn \to ppe^-e^-)$
  - Controlled errors
  - Hard, active area of research

Davoudi & Kadam, ’20, ’21
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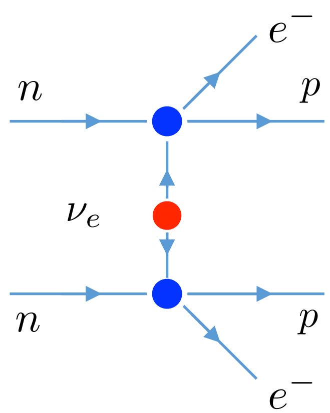

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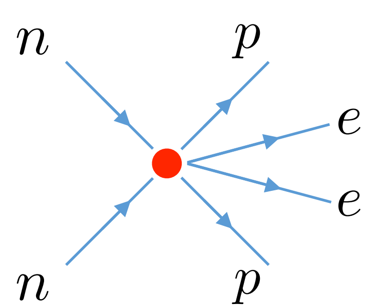

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- Phenomenological (model) estimates:

See backup

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

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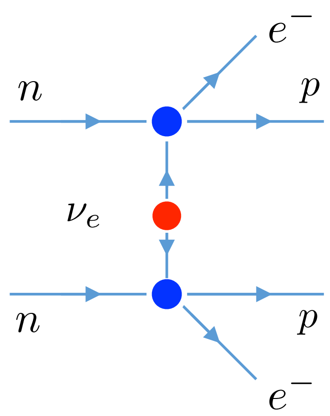

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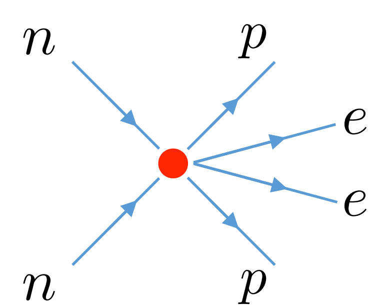

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See backup

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

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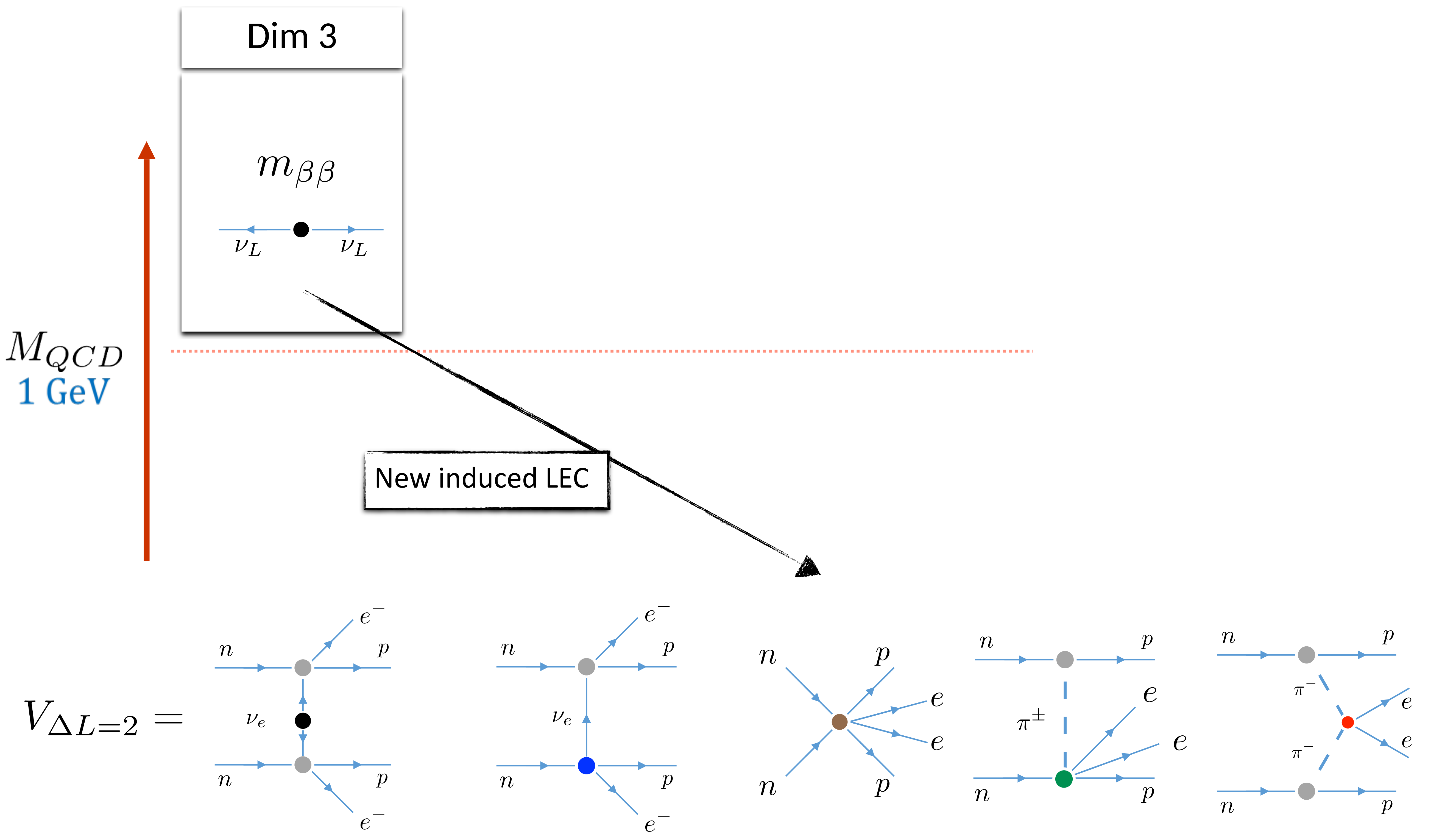
All give

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

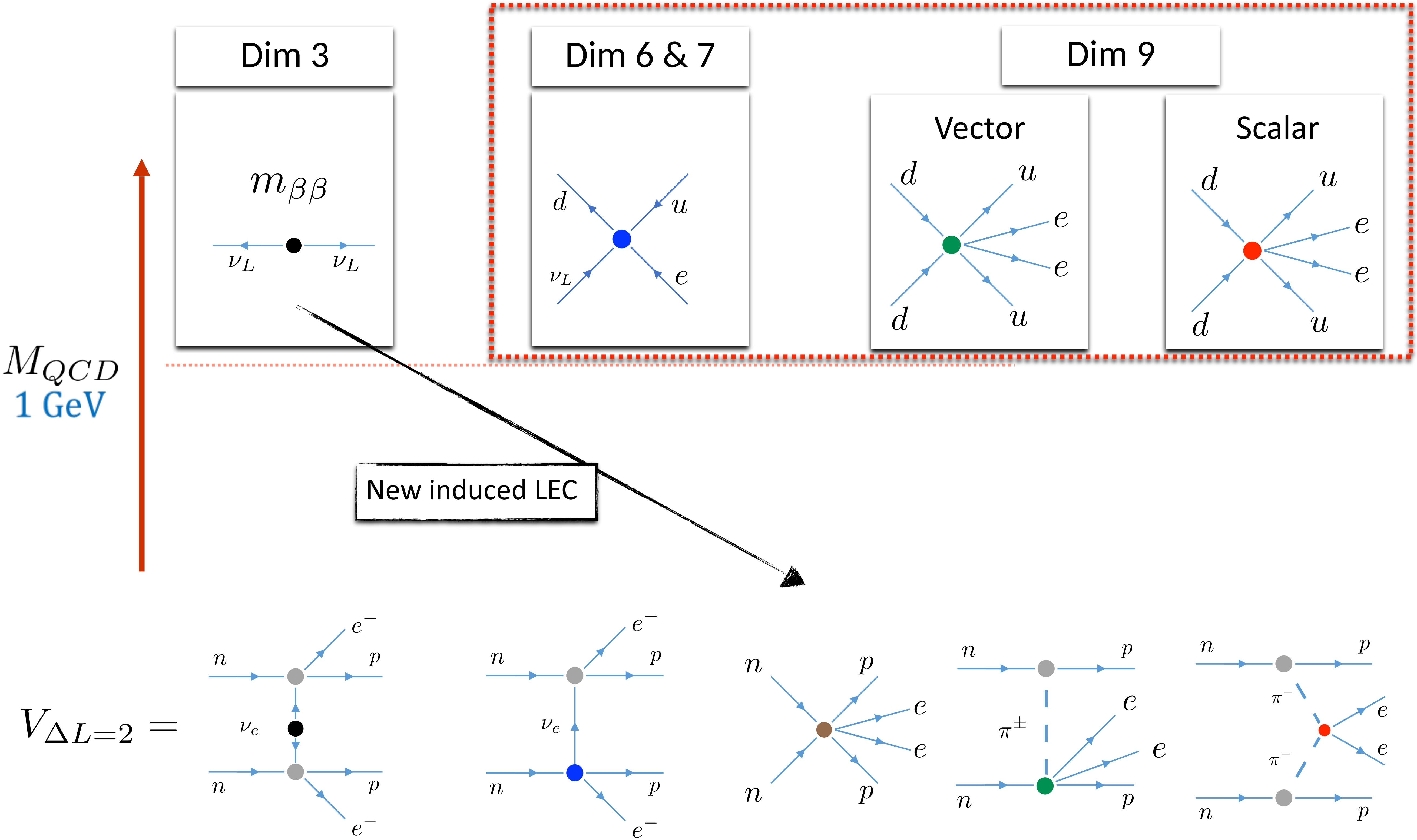
Chiral EFT

Non-Weinberg counting



Chiral EFT

Non-Weinberg counting affects higher dimensional interactions as well



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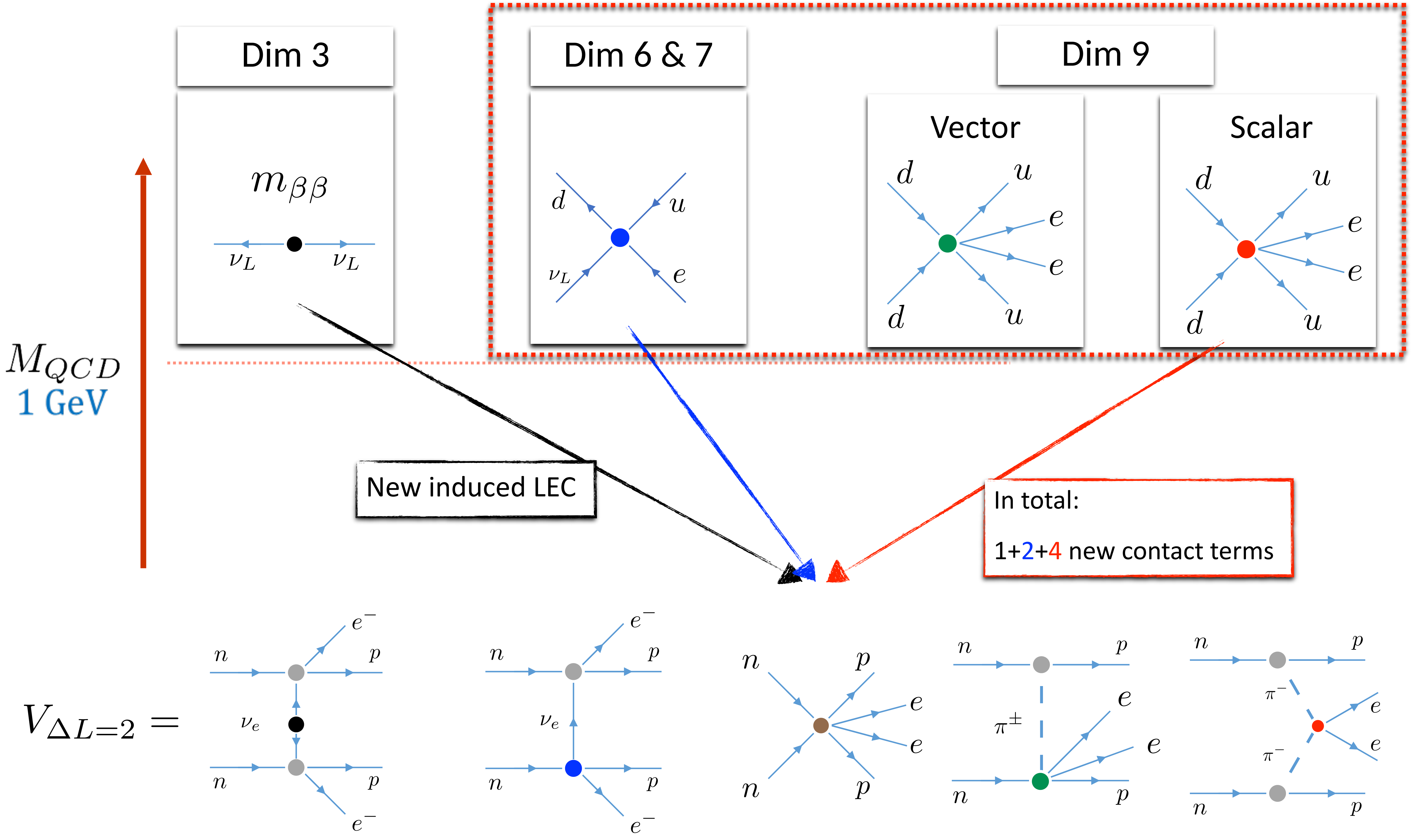

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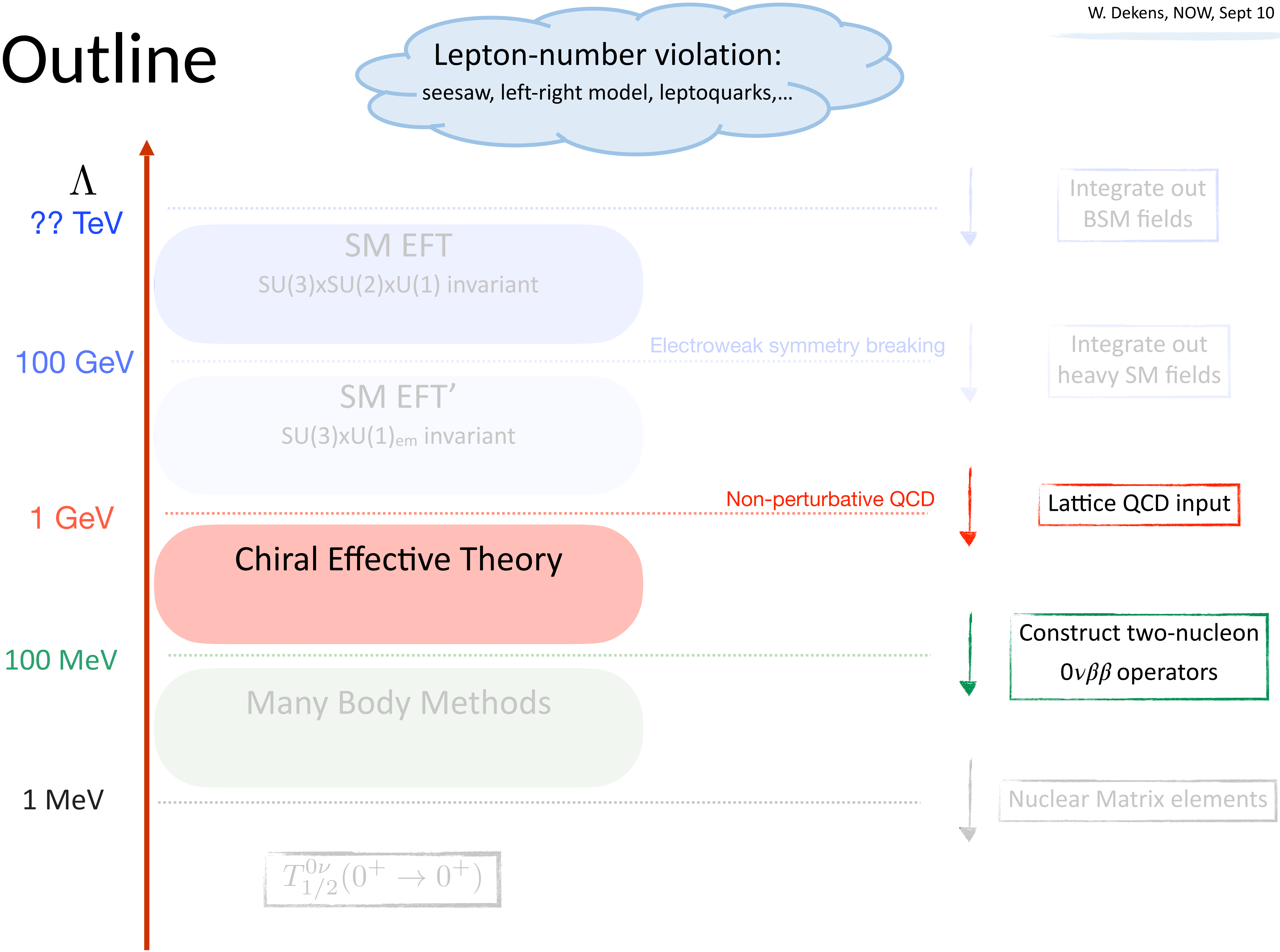
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1 MeV

Nuclear Matrix elements

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

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; Agostini et al. `22

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	

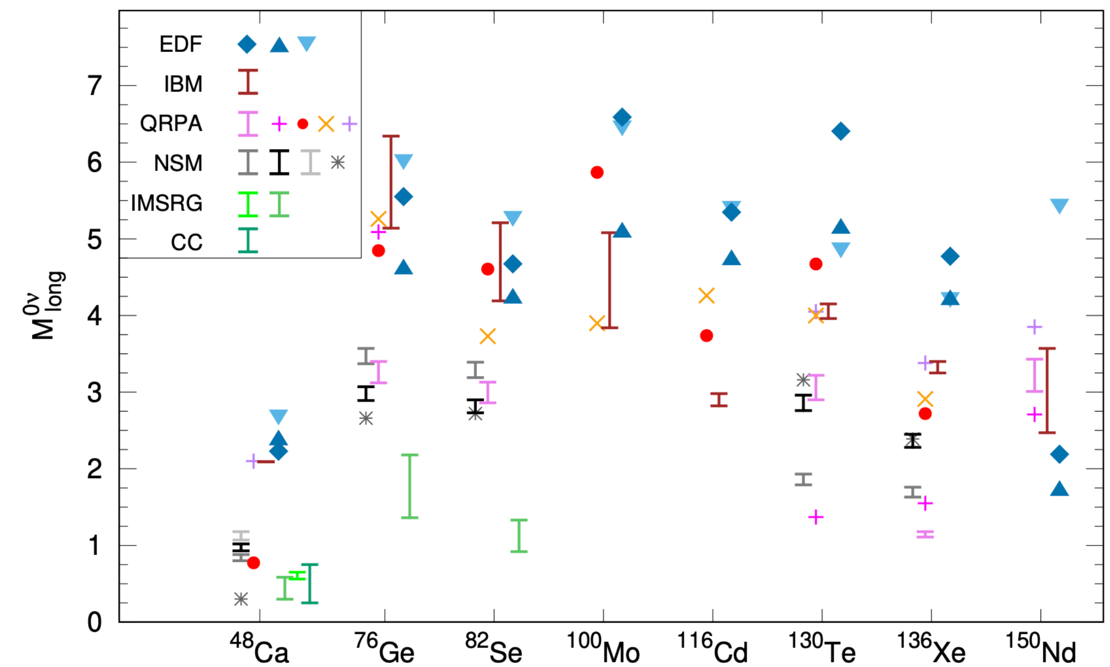
NMEs	^{76}Ge			
$M_{F,\,sd}$	-3.46	-1.55	-1.46	-1.1
$M_{GT,\,sd}^{AA}$	11.1	4.03	4.87	3.62
$M_{GT,\,sd}^{AP}$	-5.35	-2.37	-2.26	-1.37
$M_{GT,\,sd}^{PP}$	1.99	0.85	0.82	0.42
$M_{T,\,sd}^{AP}$	-0.85	0.01	-0.05	-0.97
$M_{T,\,sd}^{PP}$	0.32	0.00	0.02	0.38

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

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

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

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



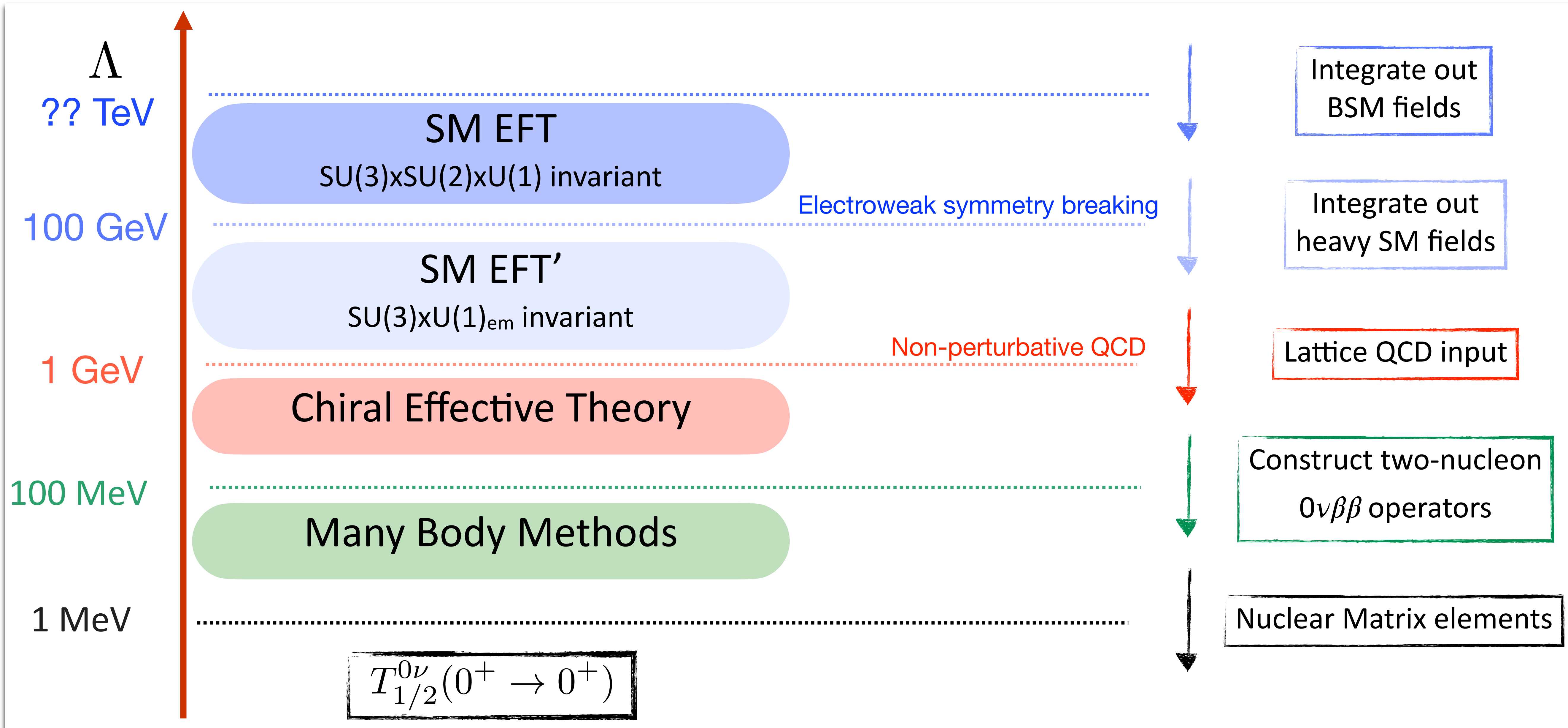
- *Ab initio* NMEs for $A \geq 48$ are starting to appear

  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; Agostini et al. `22

Sterile neutrinos

Can now go through the same steps as before:



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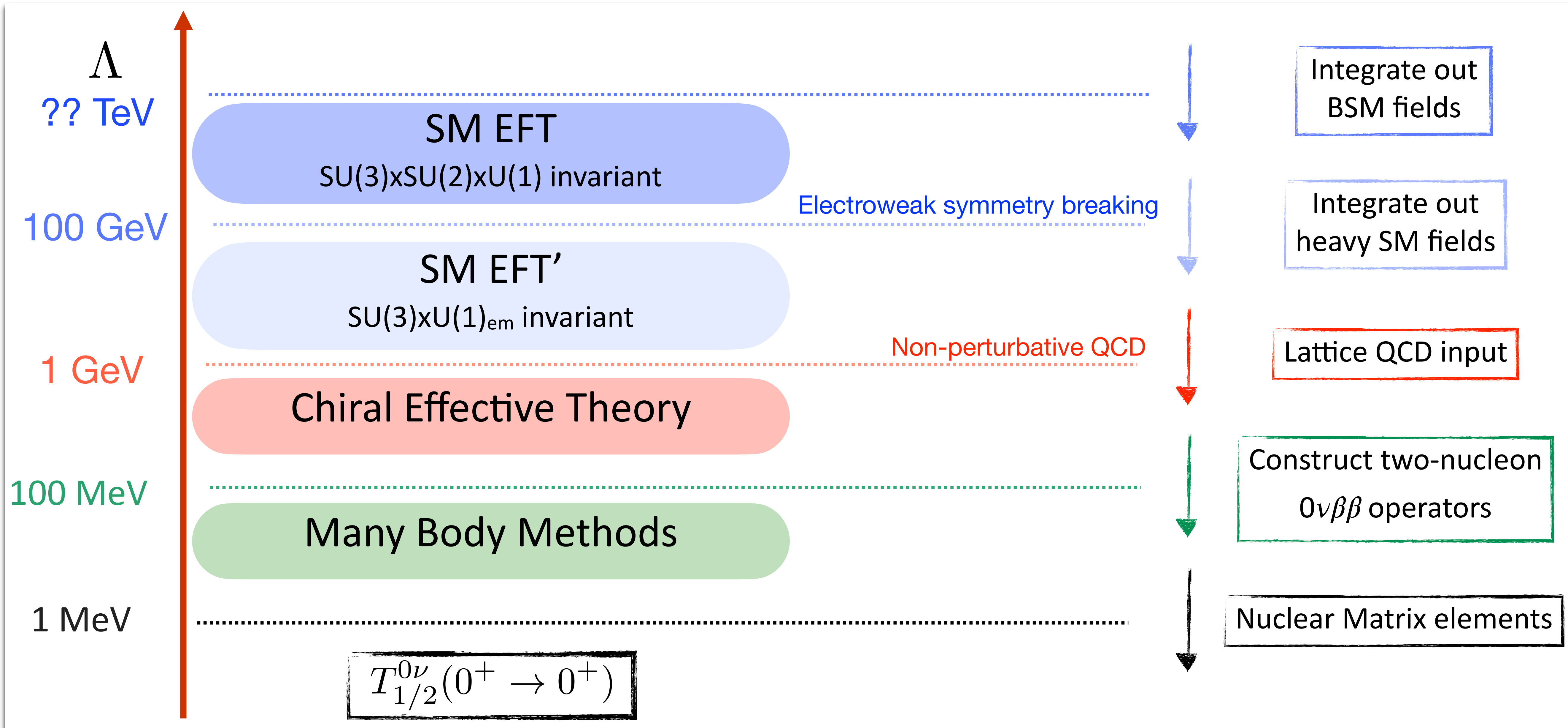


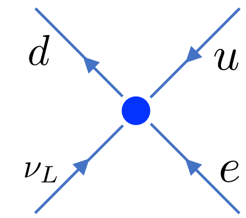
- EFT now includes ν_R as explicit degrees of freedom
- When/if ν_R can be integrated out depends on m_{ν_R}
- LECs and NMEs now depend on m_{ν_R}

Phenomenology

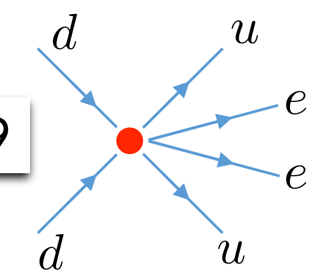
Phenomenology

From heavy new physics

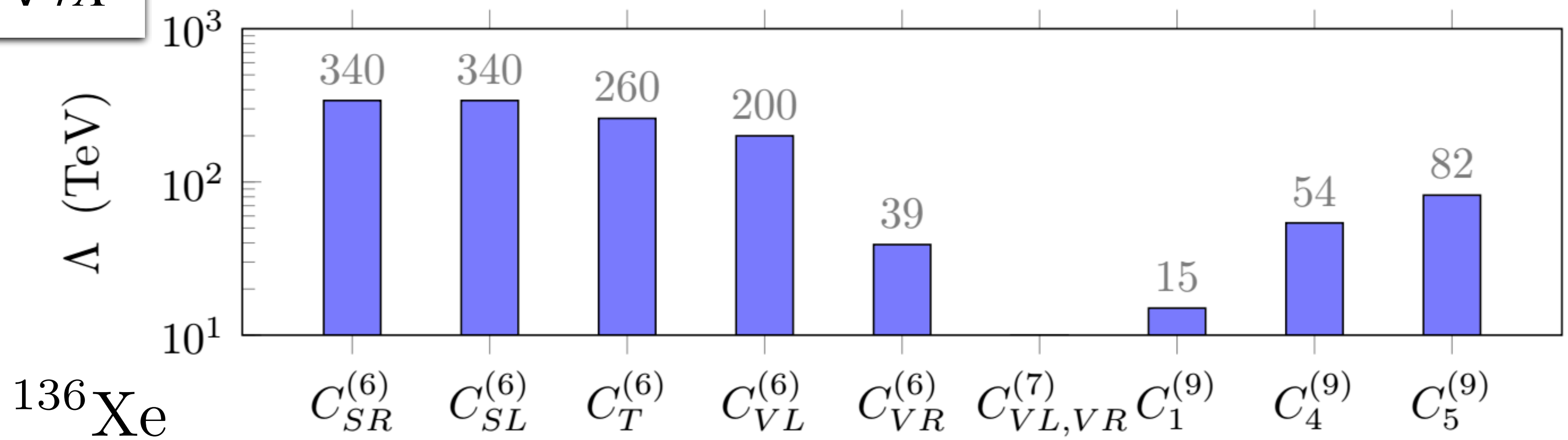
Dim 6 & 7



Dim 9



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

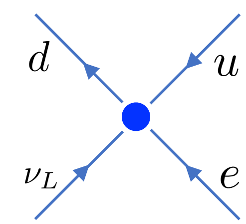


- O(1) uncertainties:
  - Unknown LECs
  - Nuclear Matrix elements

Phenomenology

From heavy new physics

Dim 6 & 7



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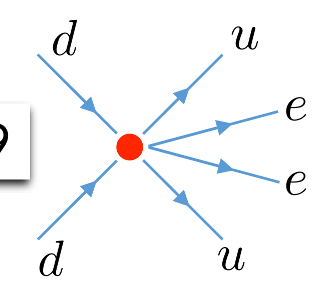

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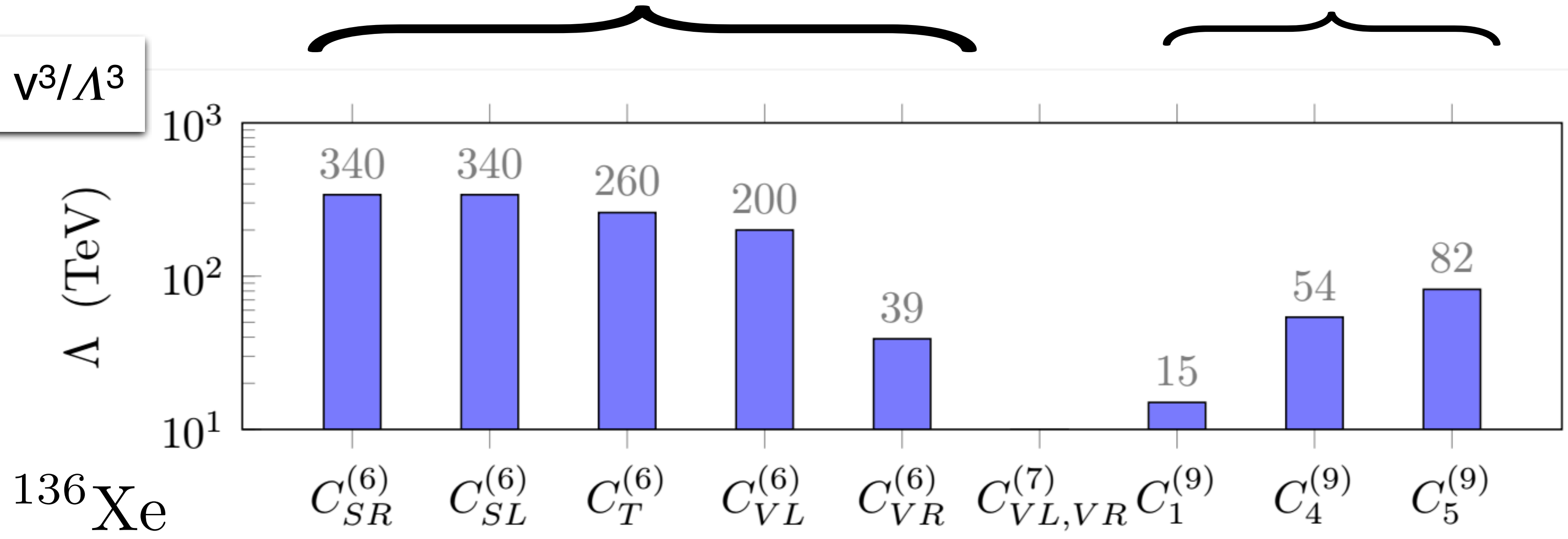
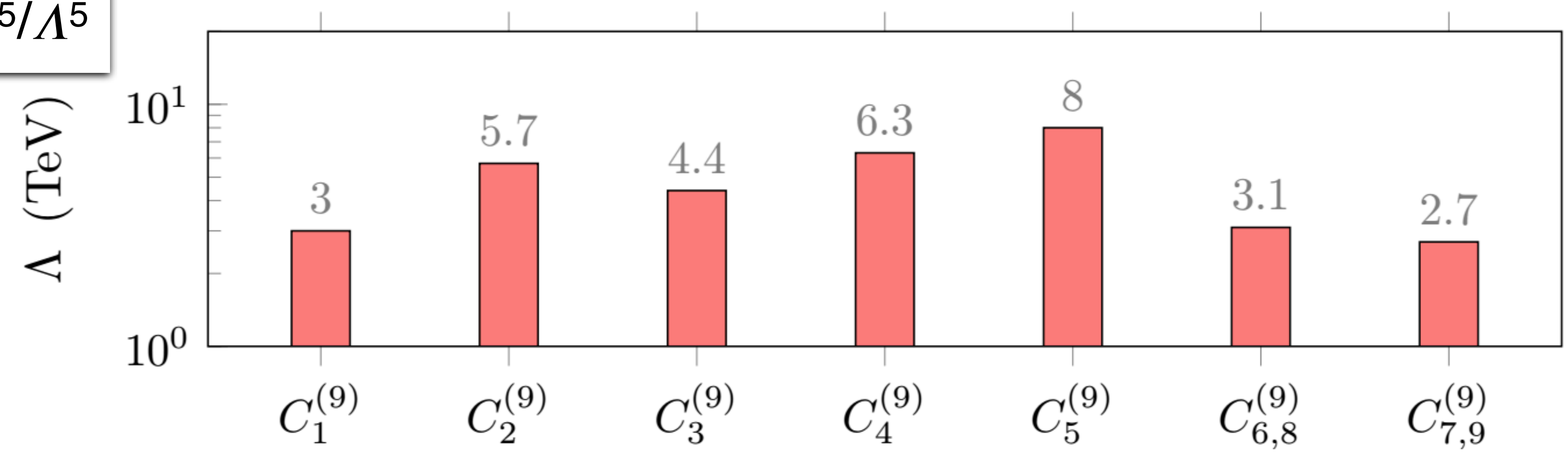


- Couplings with $C_i \sim v^5/\Lambda^5$



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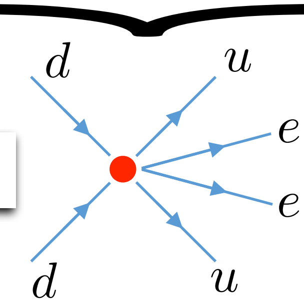


Phenomenology with sterile neutrinos

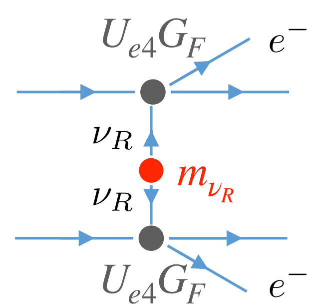
Phenomenology

From heavy new physics + light ν_R

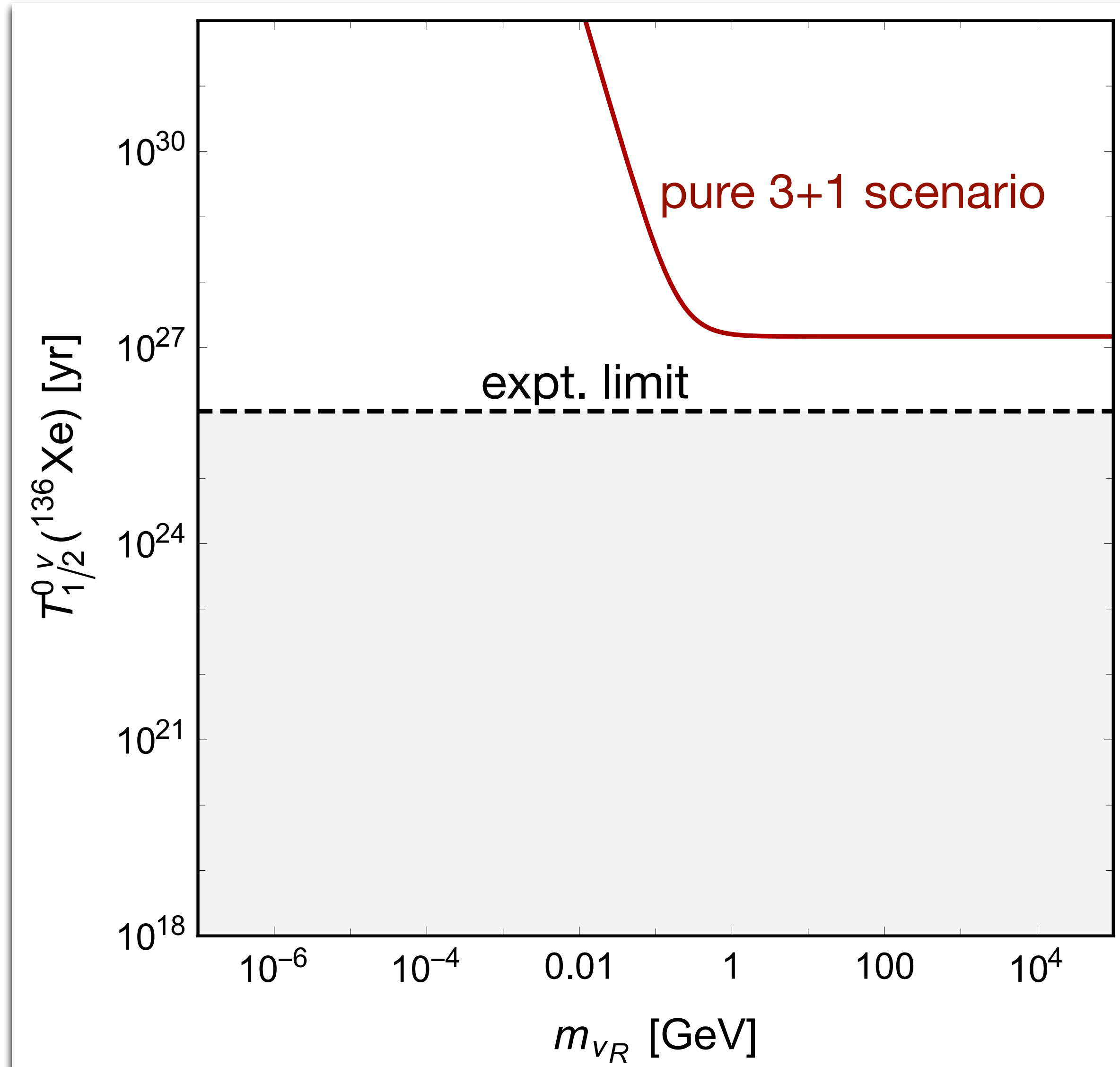
Example with ν_R

- Toy Model
  - SM + 1 light ν_R

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



O(100%) uncertainties not shown



Phenomenology

From heavy new physics + light ν_R

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- Toy Model
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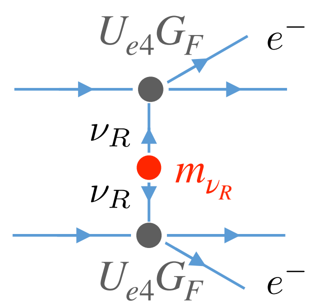
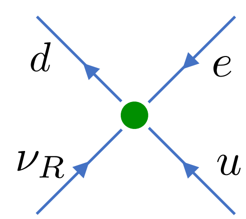
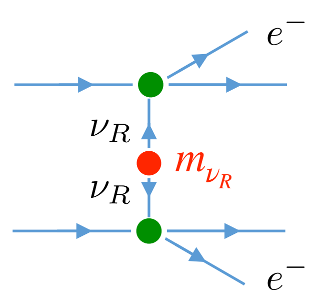


- Add dimension-six interaction
  - SM + 1 light ν_R +



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

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



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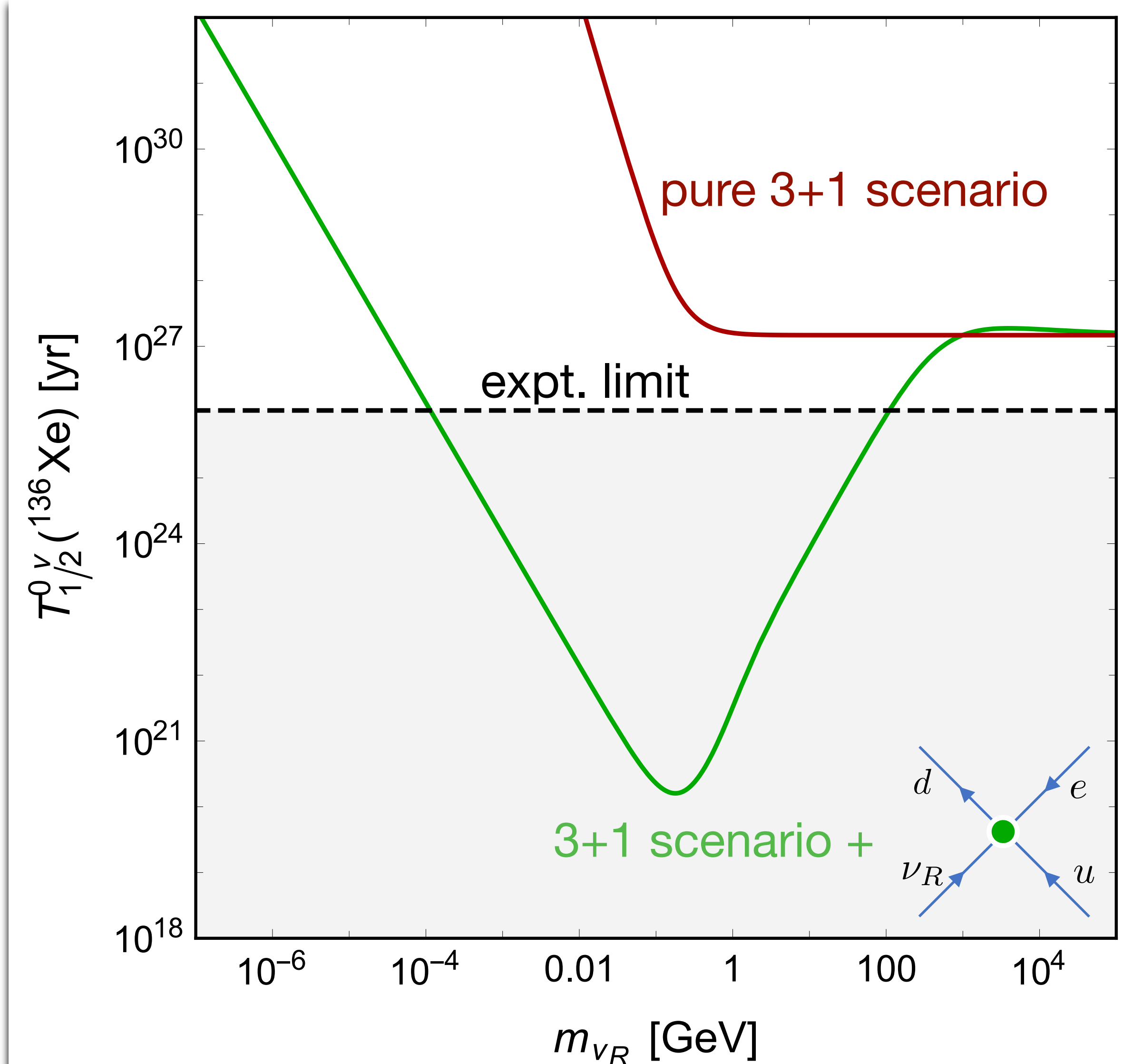
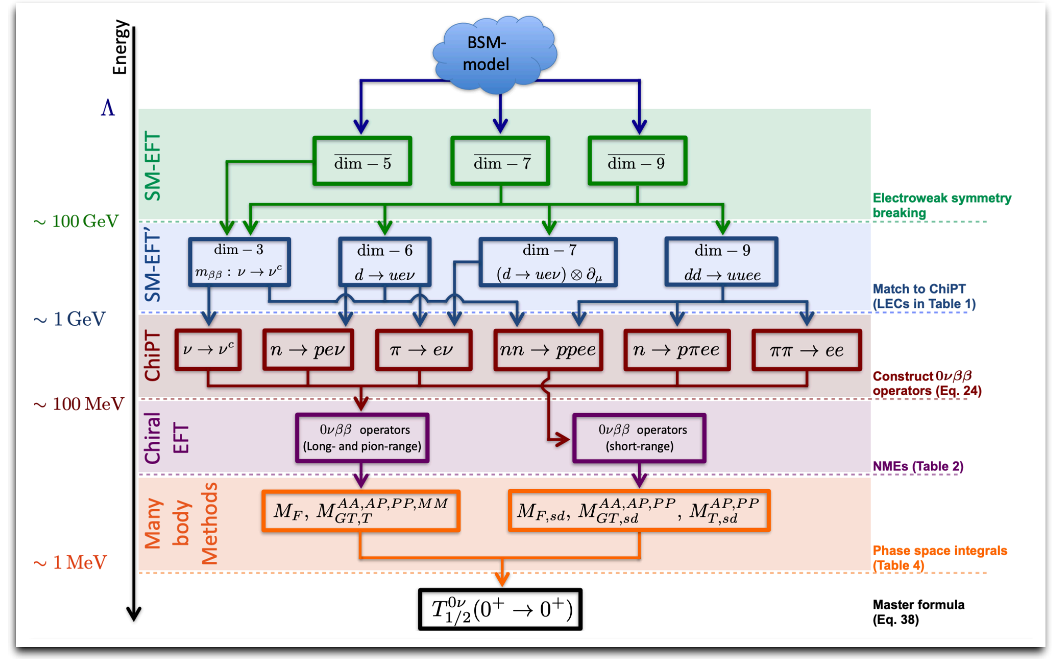


- Higher dimensional ν_R terms can have a large impact!

Summary

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



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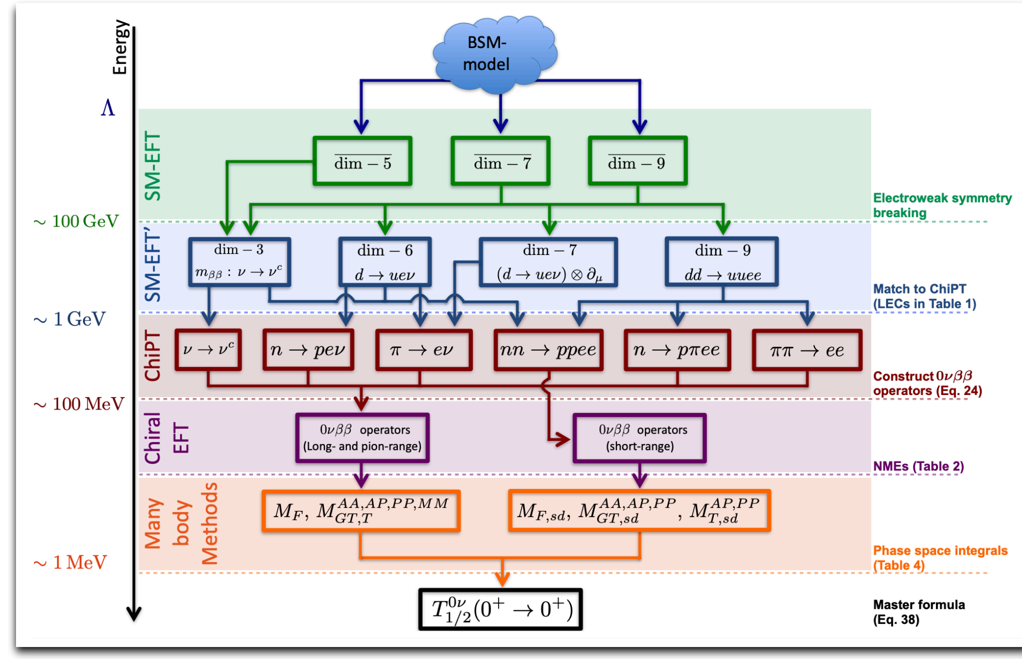
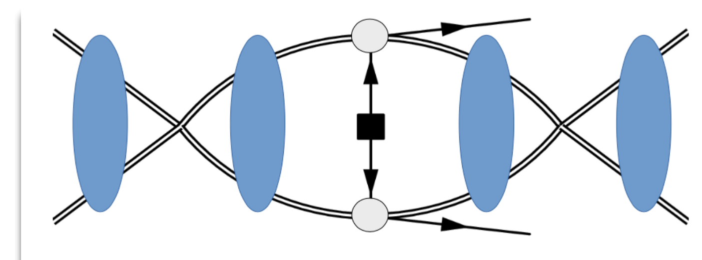
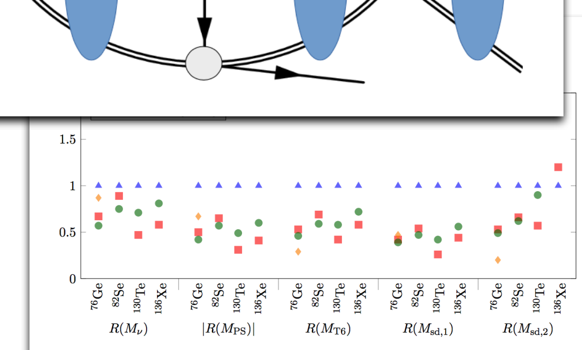


- Matching to chiral EFT involves unknown LECs
  - Renormalization requires terms beyond Weinberg counting
    - Can in principle be determined from LQCD
- Needed Nuclear Matrix Elements determined in literature





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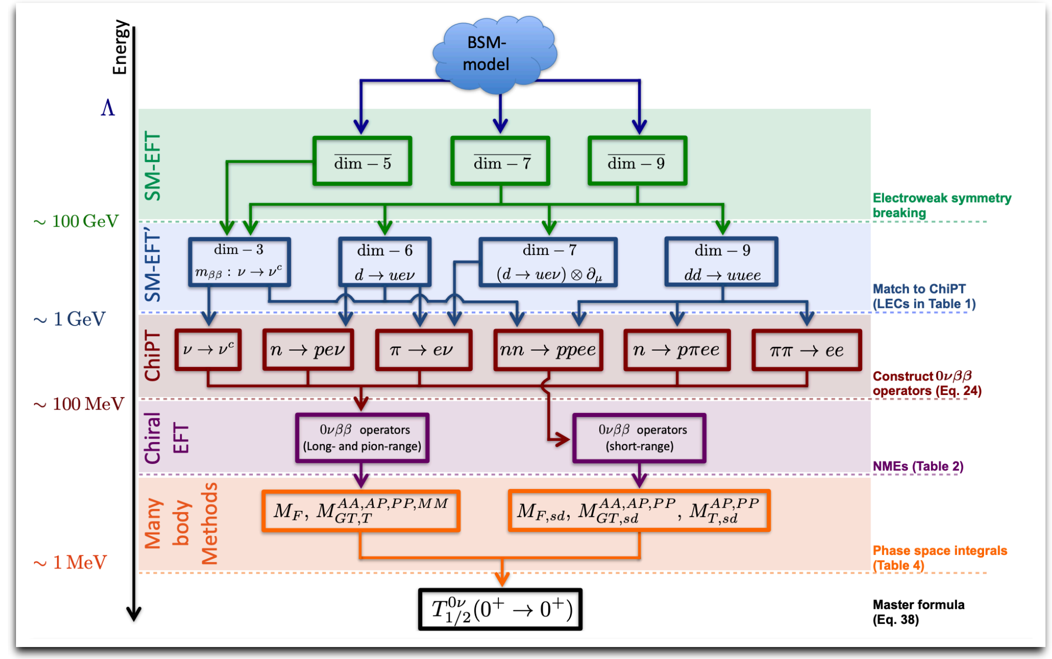

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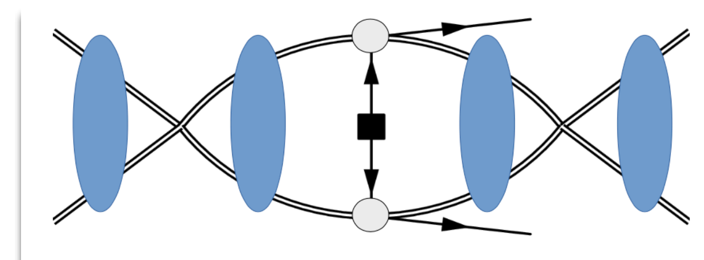
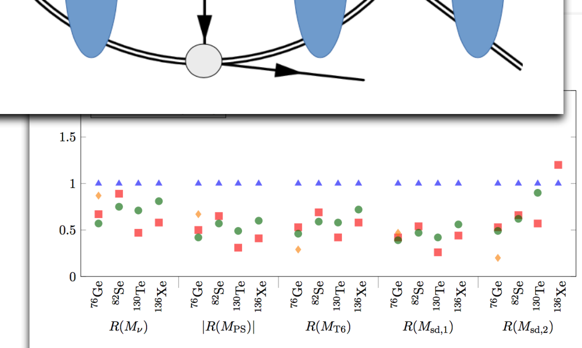
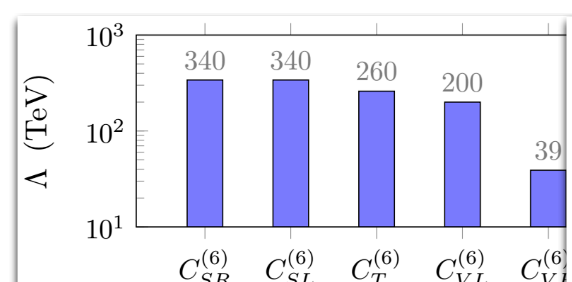
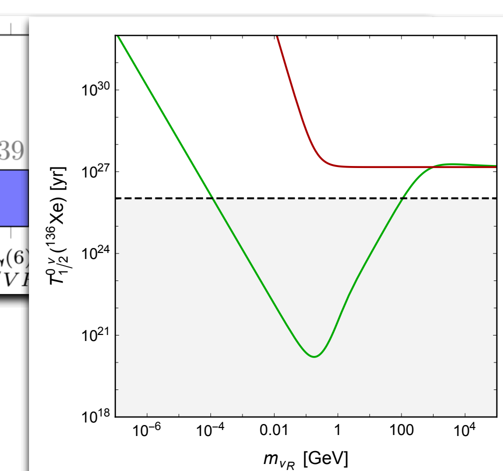




- $0\nu\beta\beta$ can probe
  - O(1-10) TeV scales for dim-9
  - O(100) TeV scales for dim-7
  - O(10) TeV scales for ν_R interactions
- Interplay with other observables (e.g. β decay)





Thank you for your attention!

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?

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$m_\nu \sim c_5 v^2/\Lambda$ 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

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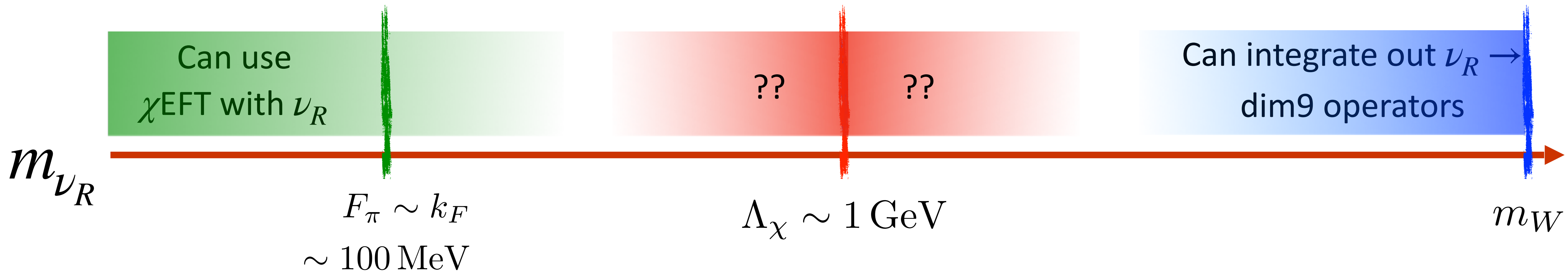
- Happens, for example, in the left-right model

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

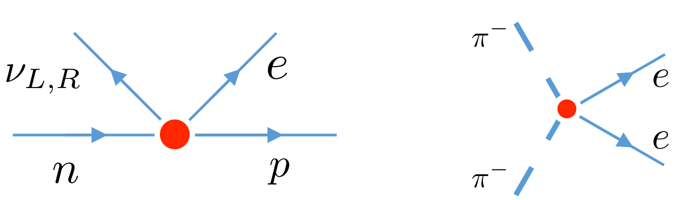
Sterile neutrinos

Sterile neutrinos

Complication: m_{ν_R} dependence

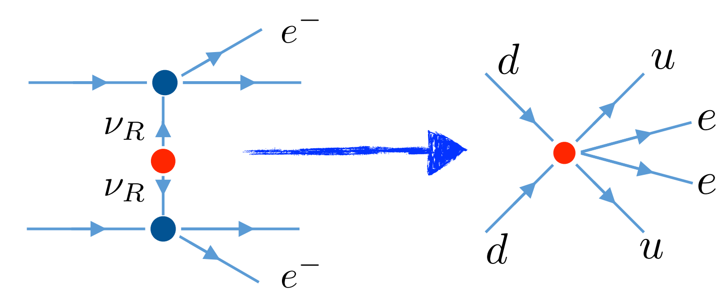


- Chiral EFT involving ν_R



- 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

$A \propto m_{\nu_R}$

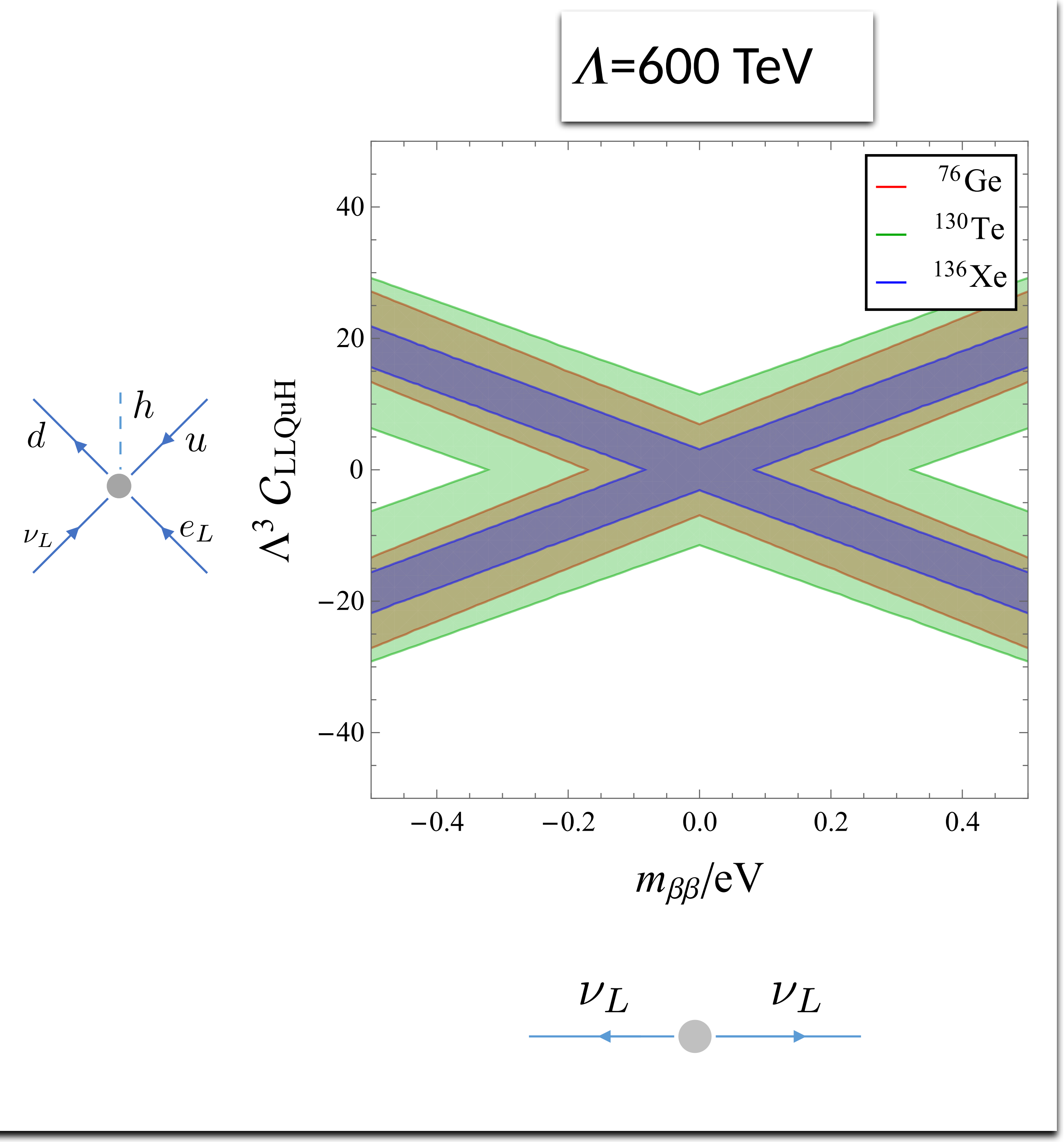
Interpolate

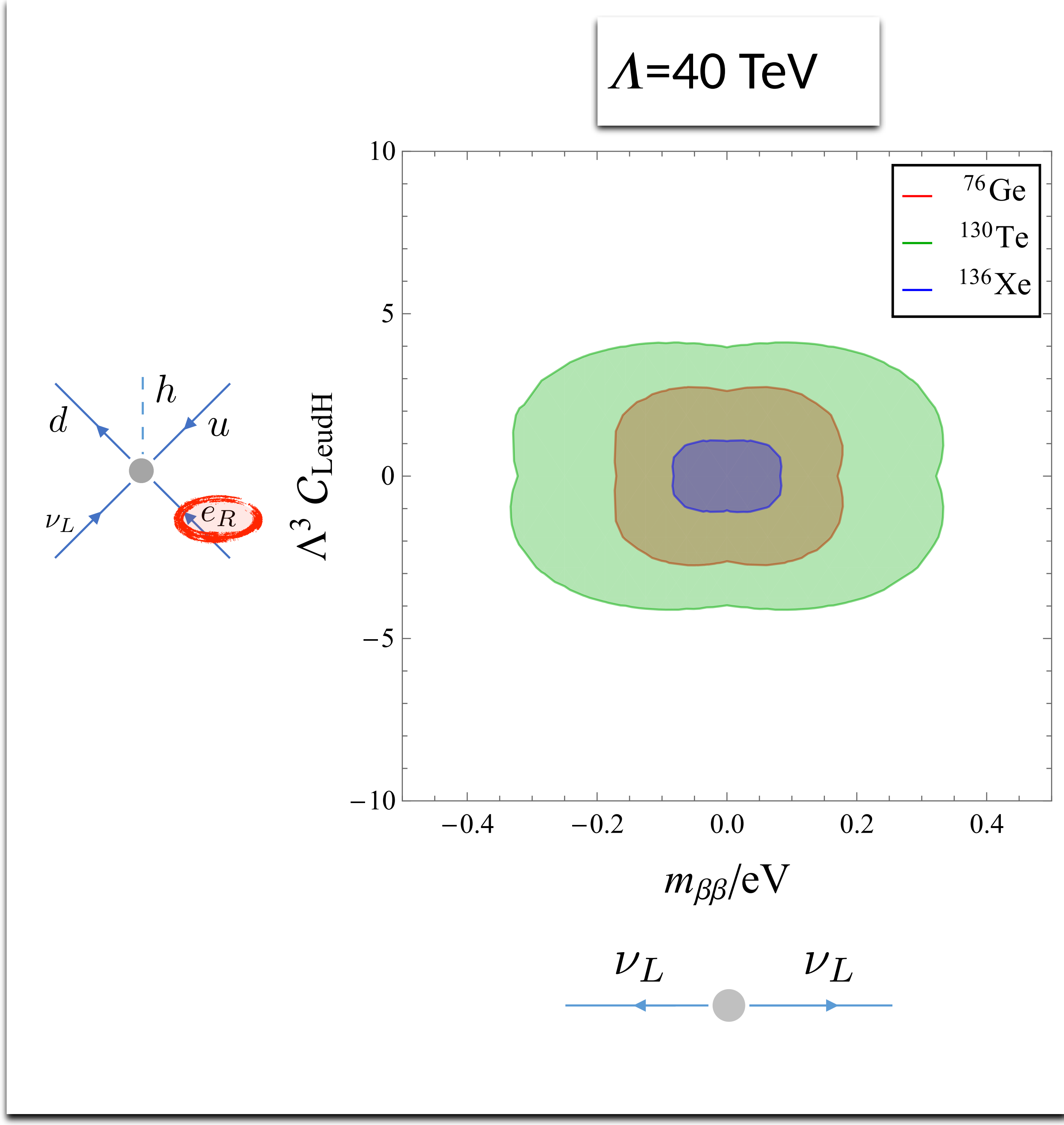
$A \propto m_{\nu_R}^{-1}$

Disentangling operators

Phenomenology

From heavy new physics





Disentangling operators

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

- Measurement in a single isotope could be due to any operator

- Could measure the rate in several nuclei, however
  - Different isotopes have similar sensitivity to LNV operators
  - Made worse by the nuclear uncertainties

Disentangling operators

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

- Measurement in a single isotope could be due to any operator

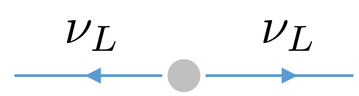
- Could measure the rate in several nuclei, however
  - Different isotopes have similar sensitivity to LNV operators
  - Made worse by the nuclear uncertainties

- Instead look at angular & energy distributions of the leptons

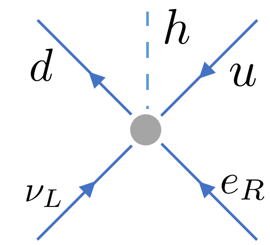
Disentangling operators

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

- Picking the allowed values

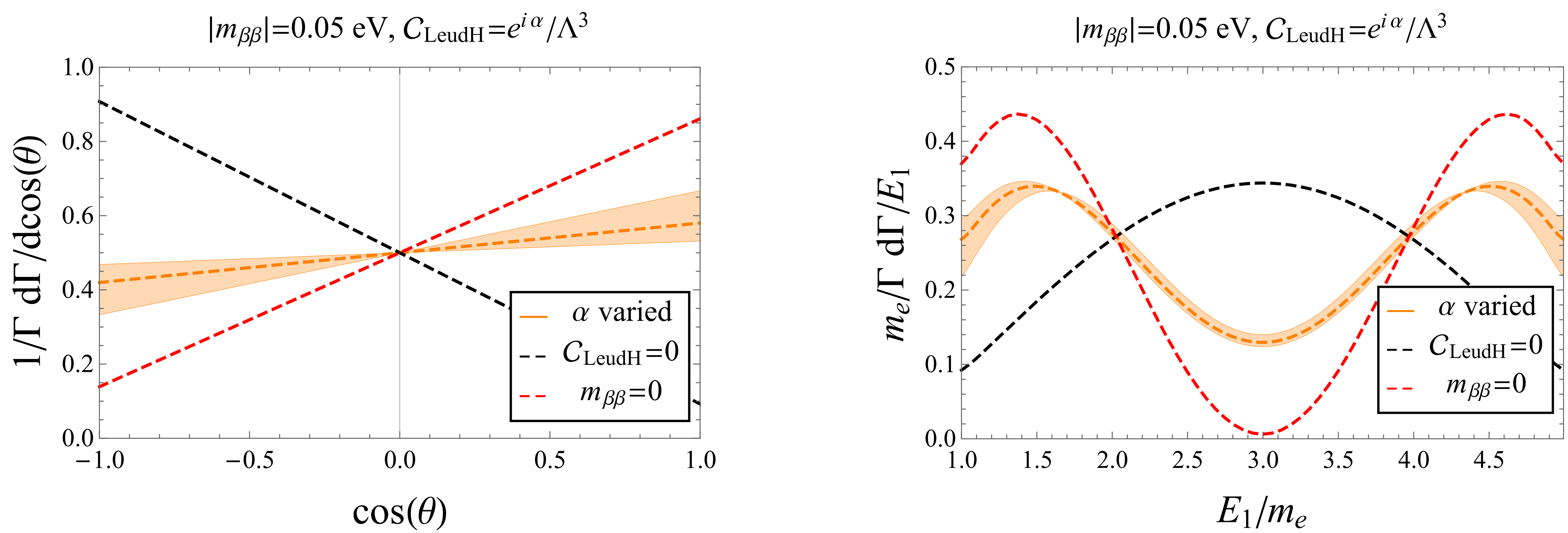


$m_{\beta\beta} = 0.05\,\mathrm{eV}$



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

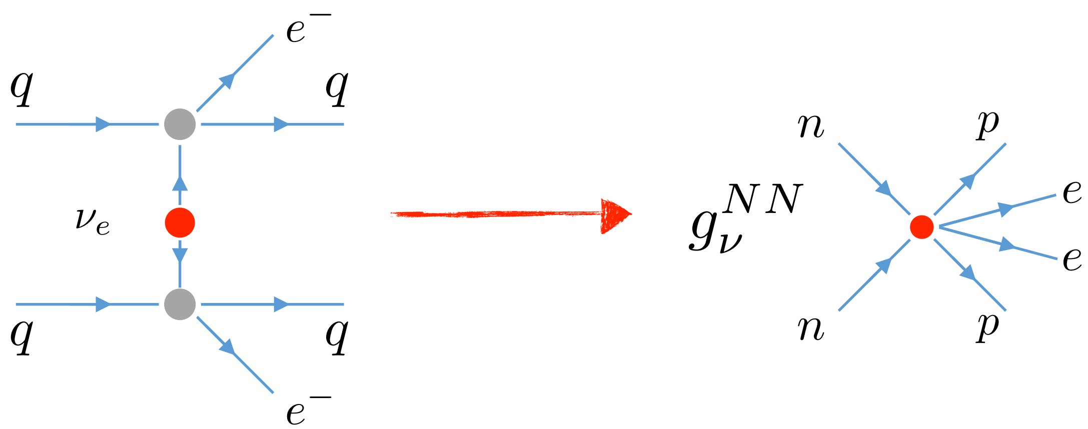
$\Lambda = 40\,\mathrm{TeV}$



Relation to electromagnetism

Relation to electromagnetism

LNV contact term



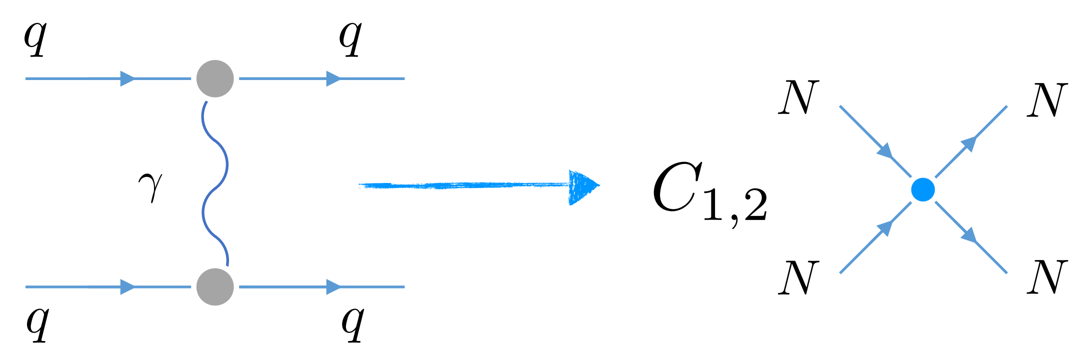
g_ν^{NN}

- 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



$C_{1,2}$

- Hard part of two EM currents

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

- Non-hadronic part is the photon propagator

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

Relation to electromagnetism

- Only two ΔI=2 operators can be induced

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

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

with spurions

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

EM

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

LNV

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

Chiral symmetry

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

Relation to electromagnetism

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

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

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

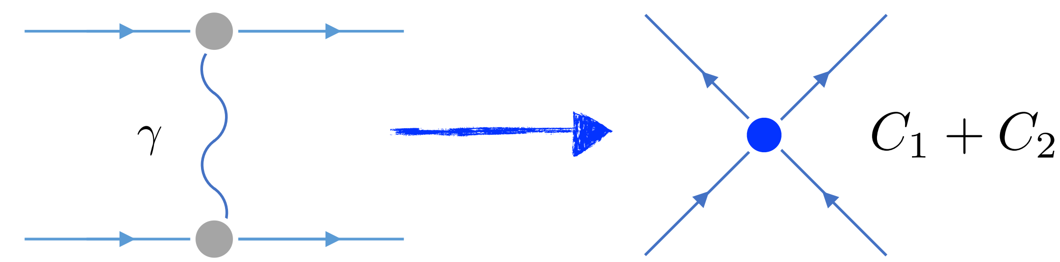
Chiral symmetry

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

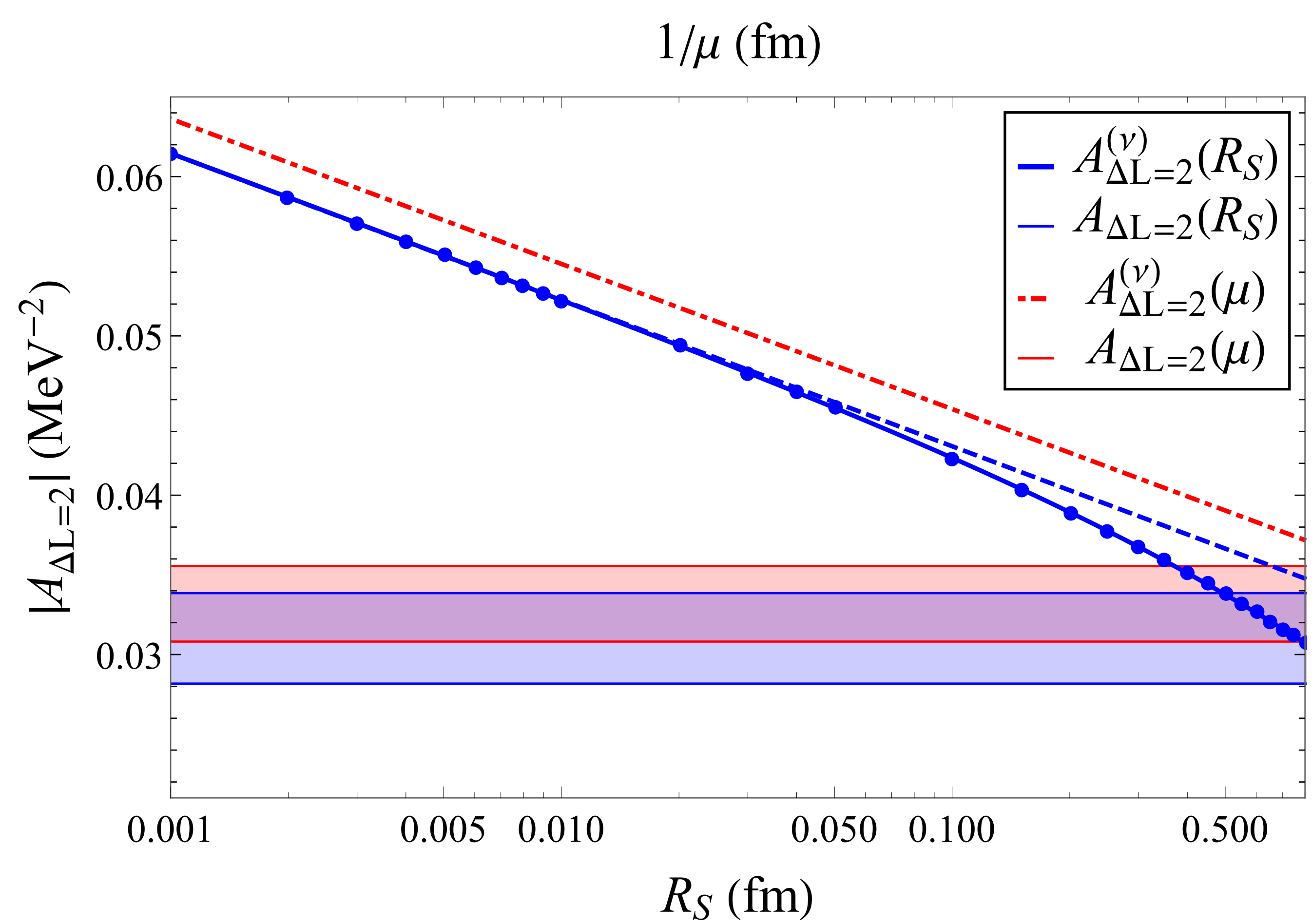
Relation to electromagnetism

- 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

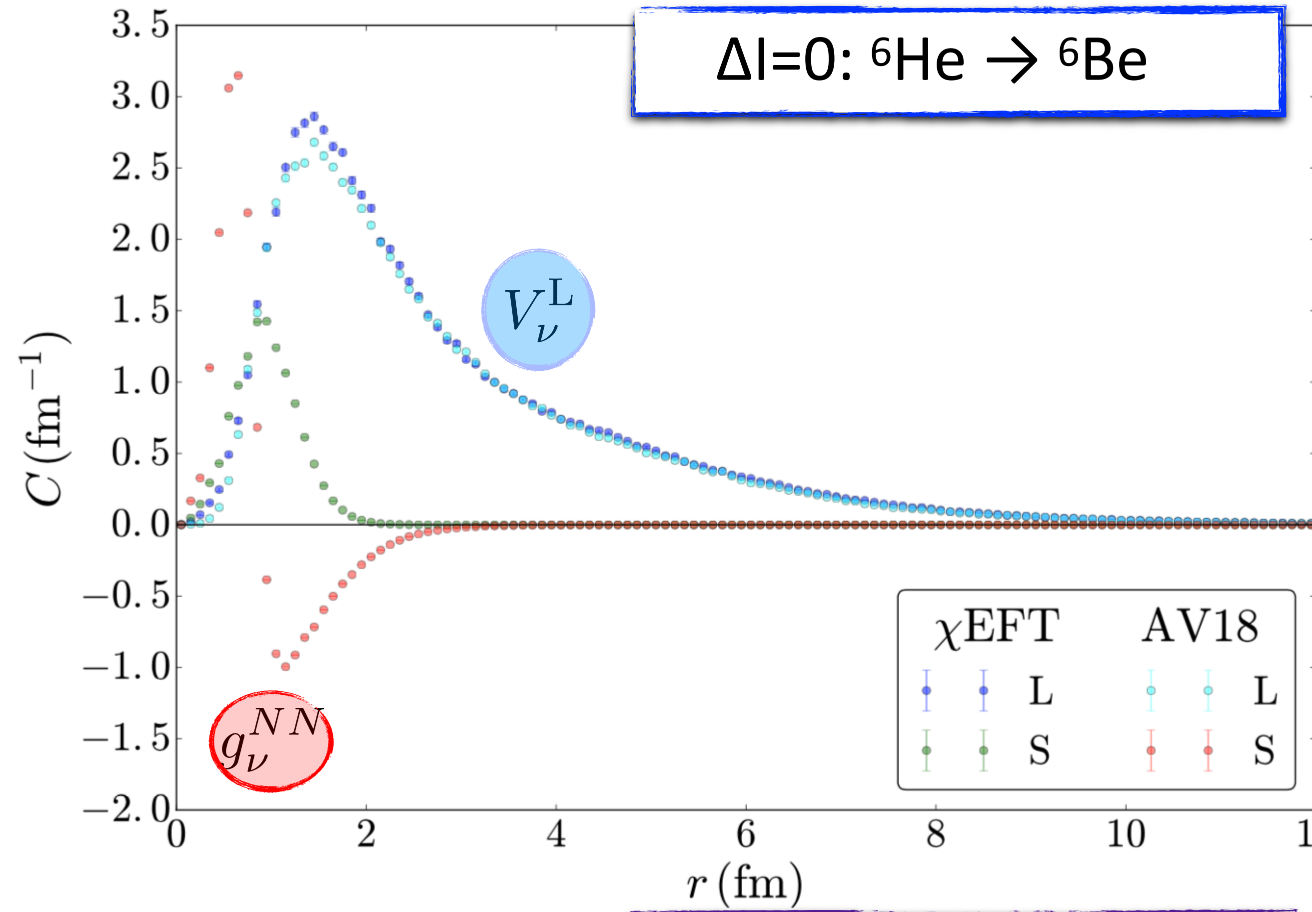
Estimate of impact

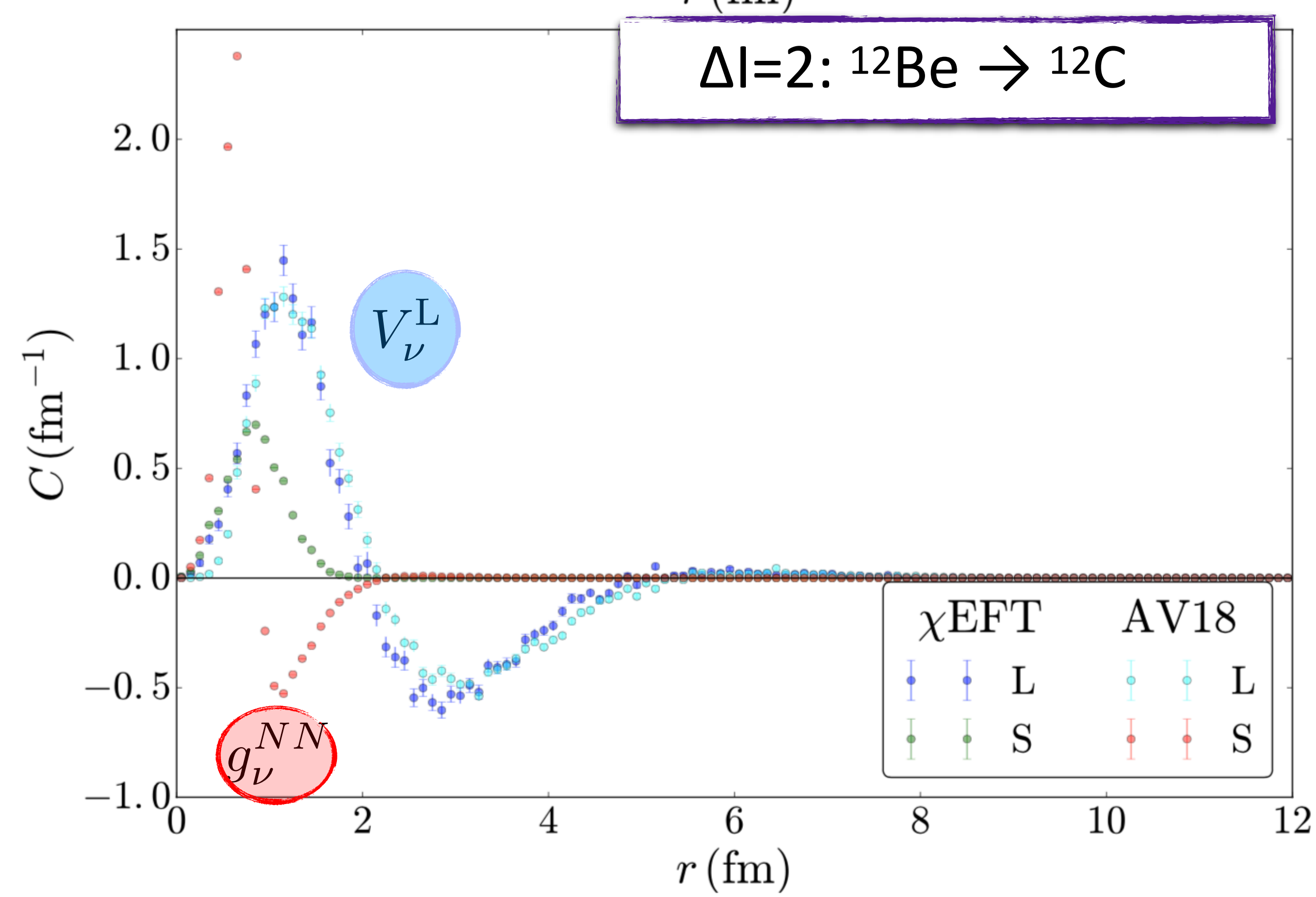
Light nuclei

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





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

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

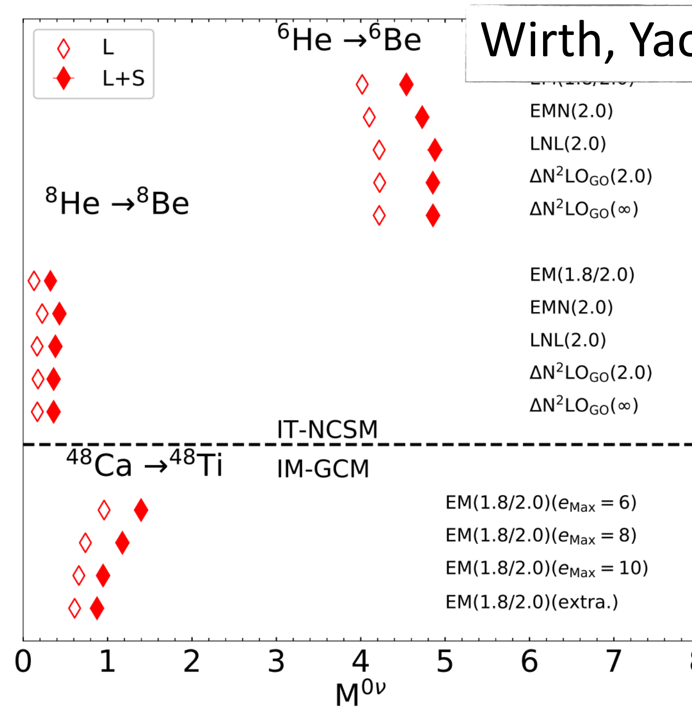
$$M_{GT,sd}^{AP} = -\frac{2}{3}M_{GT,sd}^{AA} - M_{GT}^{AP}\,, \qquad M_{GT}^{MM} = \frac{g_M^2 m_\pi^2}{6 g_A^2 m_N^2}M_{GT,sd}^{AA}\,,$$

- 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

  - Can include effect of g_ν^{NN}
    - ~50% effect in ^{48}Ca, assuming *Cottingham* estimate g_ν^{NN}

Wirth, Yao, Hegert '21



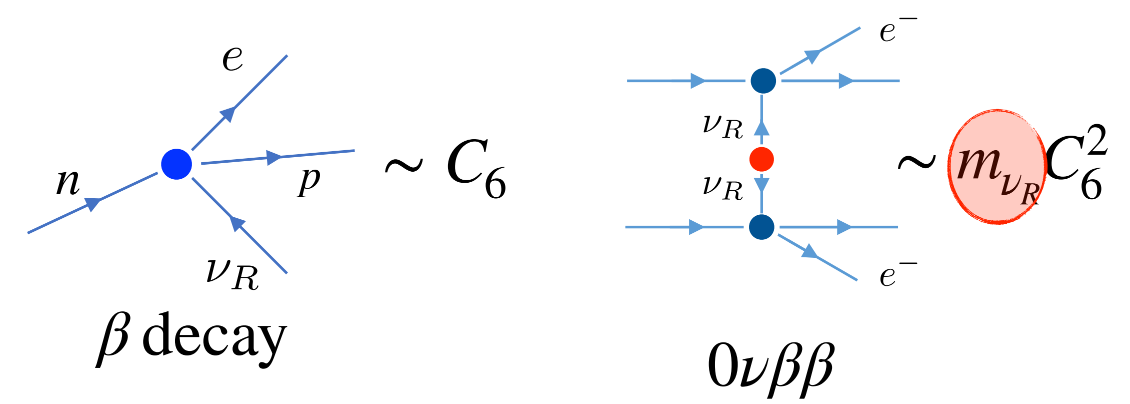
Barea et al. '15; Hyvarinen et al, '15; Horoi et al. '17, Menendez et al, '18; Agostini et al. `22

Sterile neutrinos

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?



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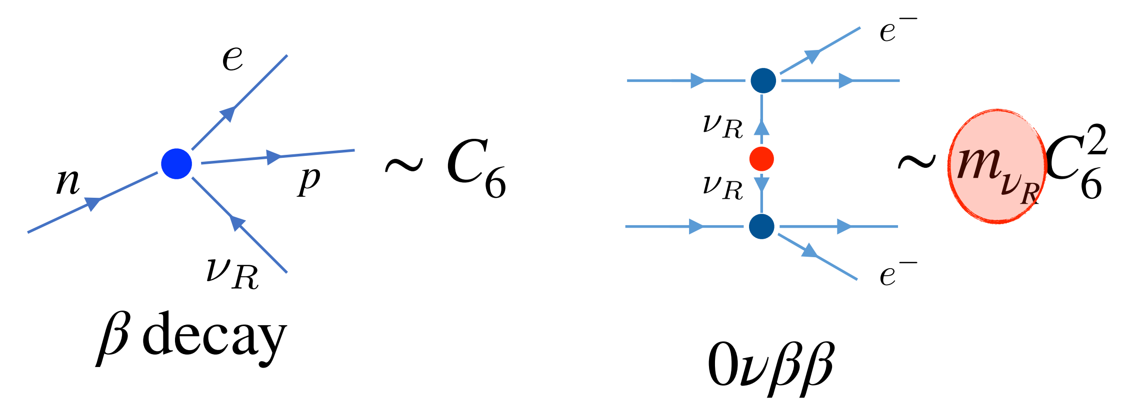


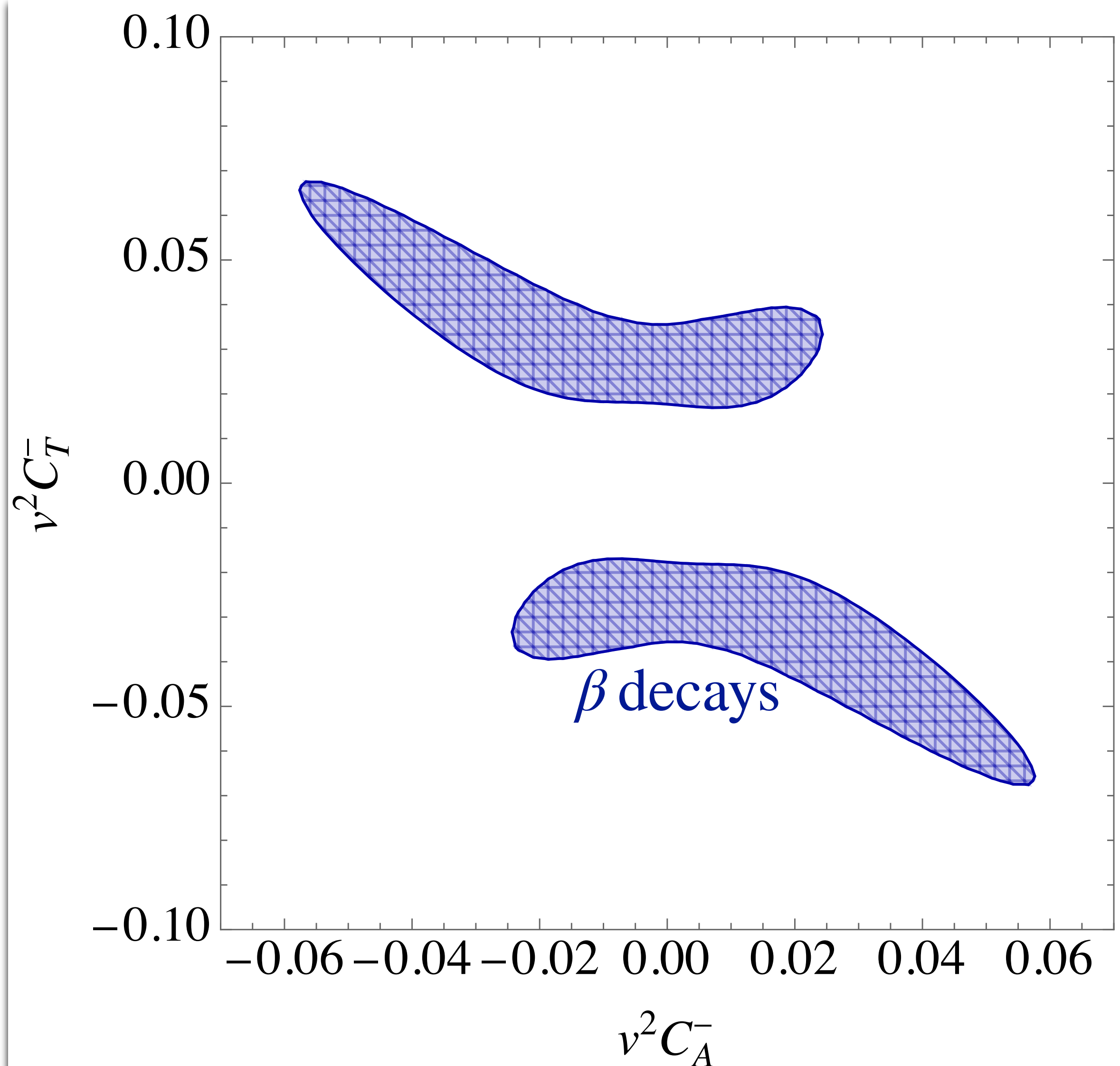
- β-decay fit has preference for BSM interactions

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

  - Driven by one experiment

    aSPECT, '19

  - Unclear if LHC can be satisfied in UV models



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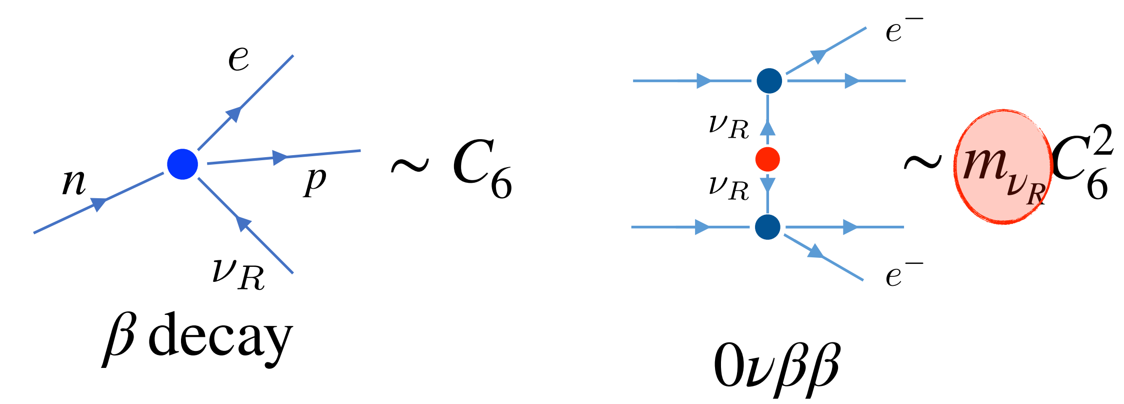

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  - Driven by one experiment — aSPECT, '19
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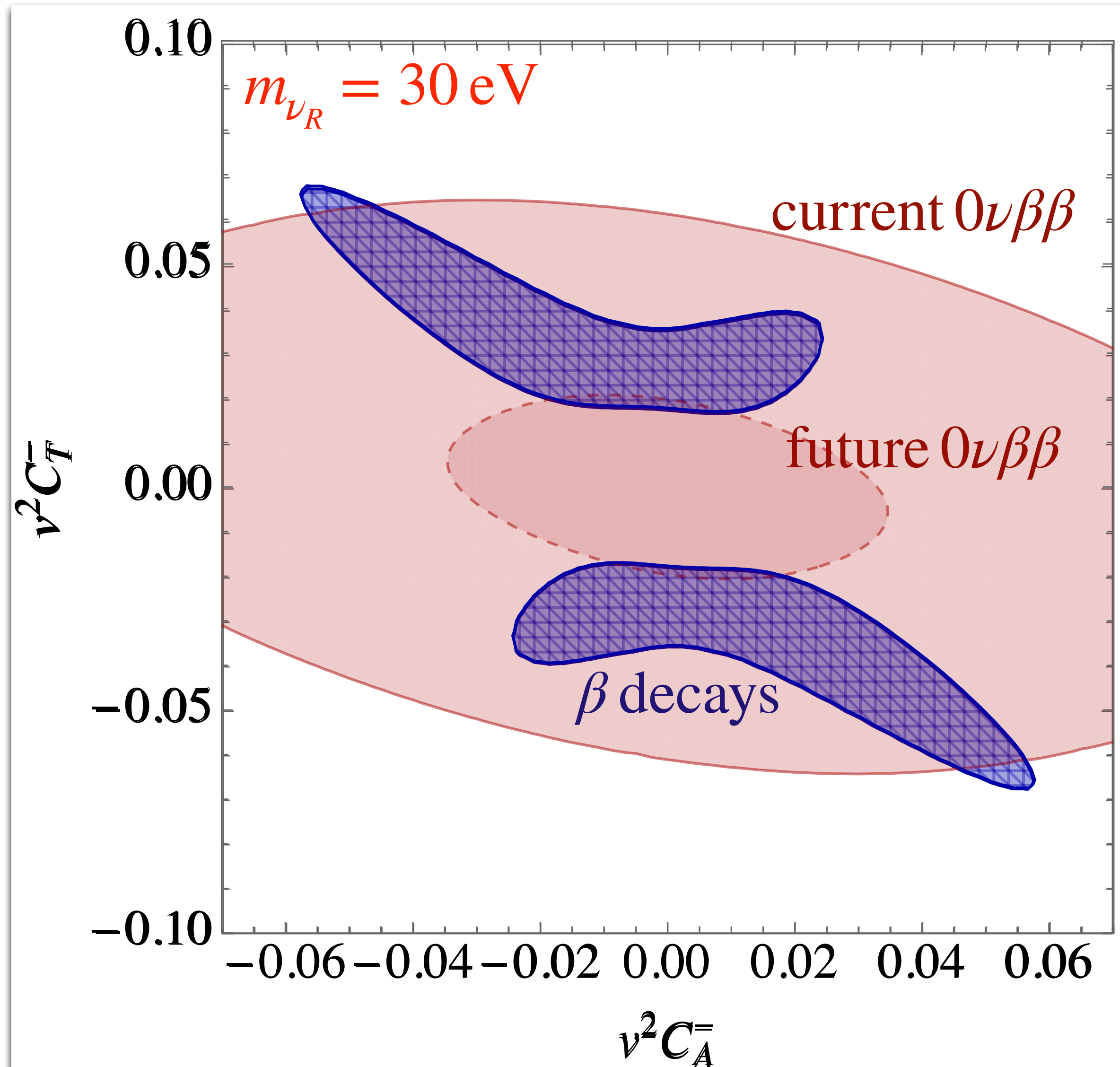
- If a β-decay signal is confirmed:
  - $0\nu\beta\beta$ gives upper limit on m_{ν_R}
  - (assuming Majorana ν_R)



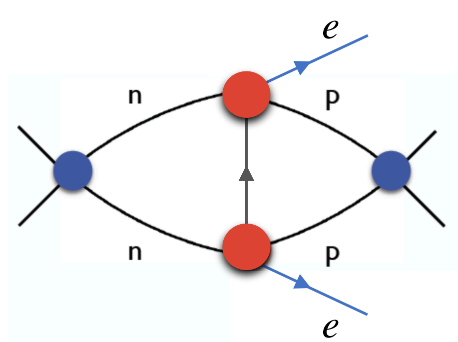
Estimating the counterterm

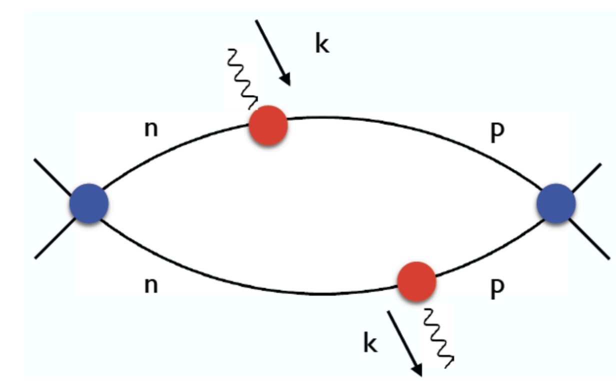
Determination of the counterterm

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

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

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

$\mathcal{A}_\nu =$ 

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

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

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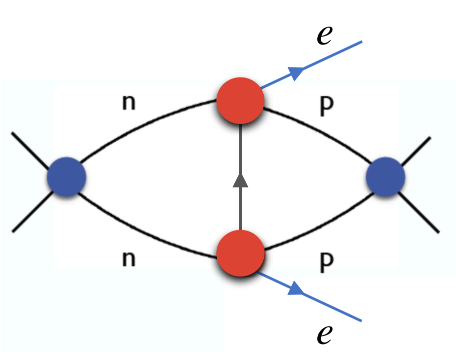
$\mathcal{A}_\nu =$ 

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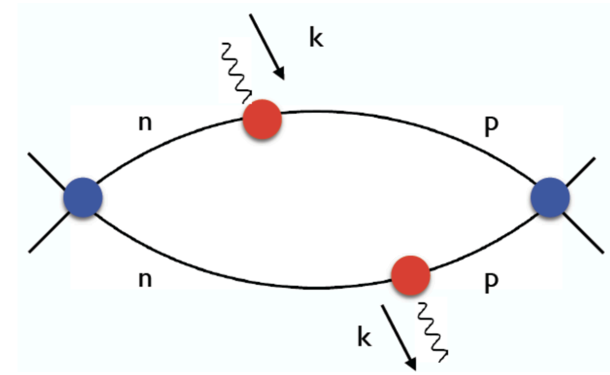
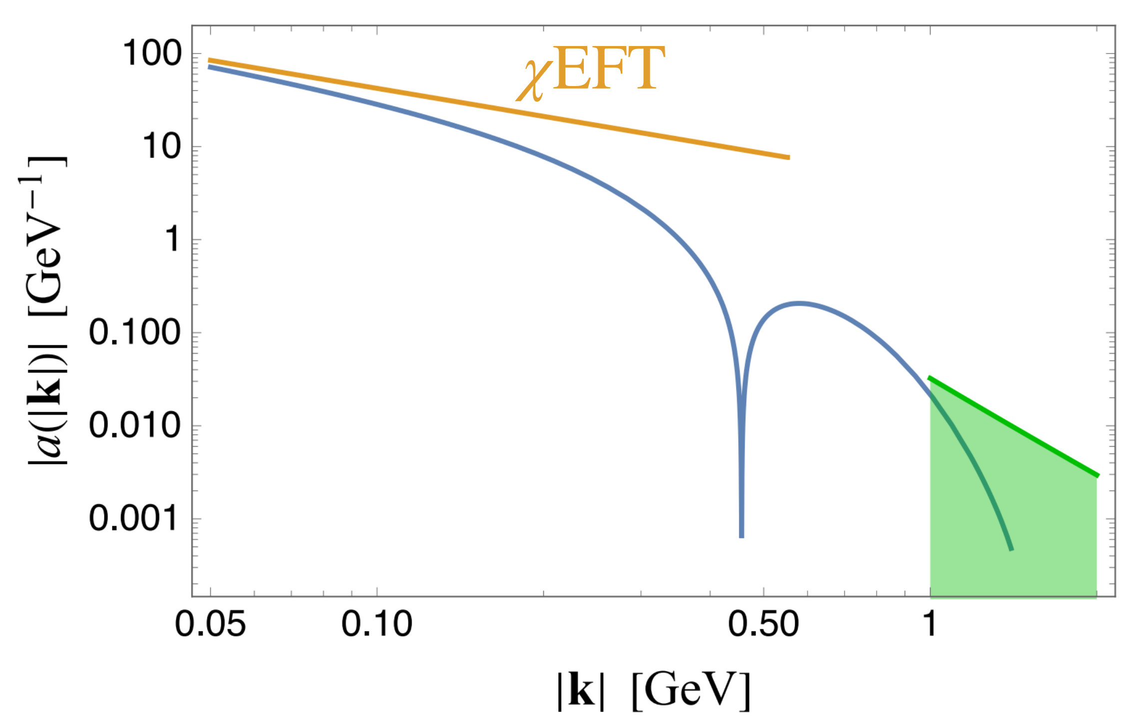


- Estimate the A_ν by constraining the integrand
  - $k \ll \Lambda_\chi$ region determined by χEFT



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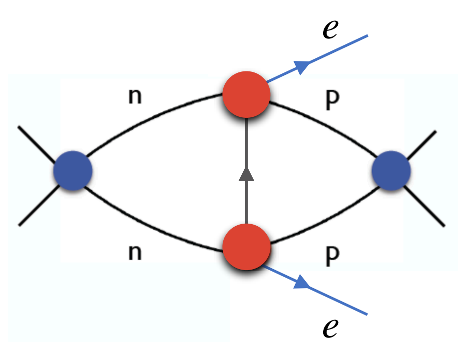

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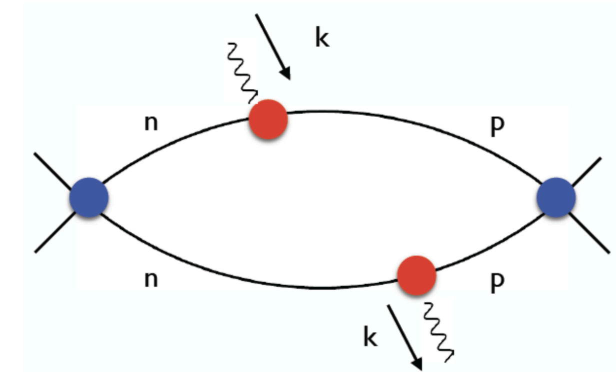

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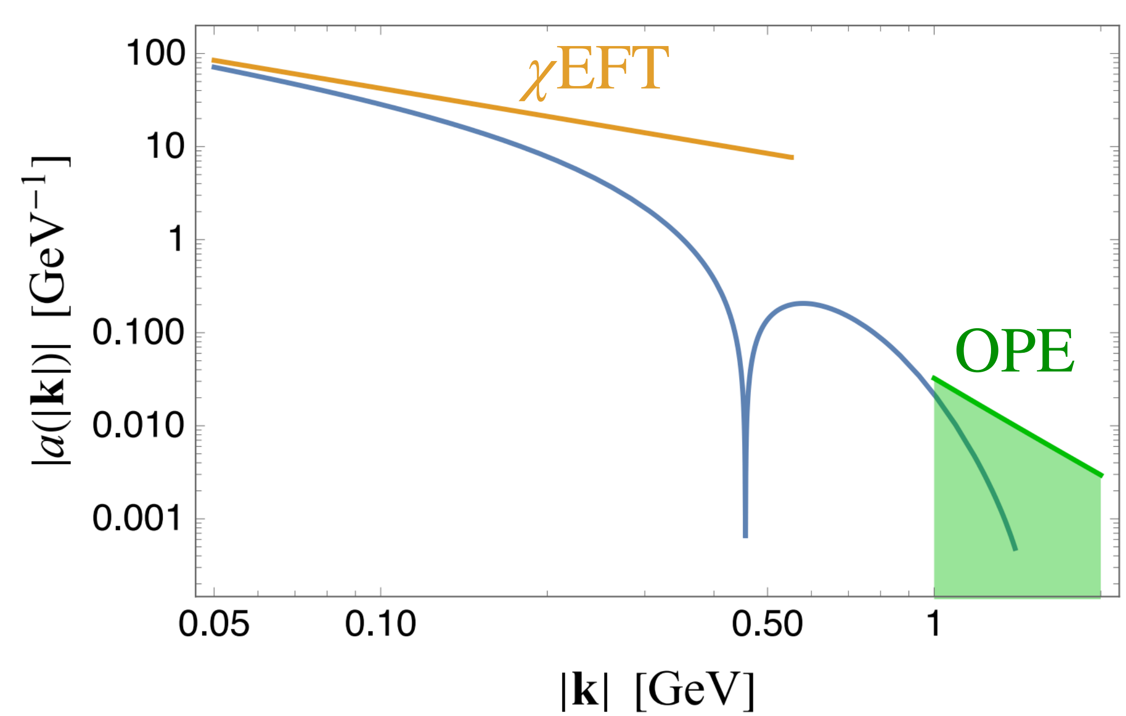
  - $k \gg \mathrm{GeV}$ region determined by OPE



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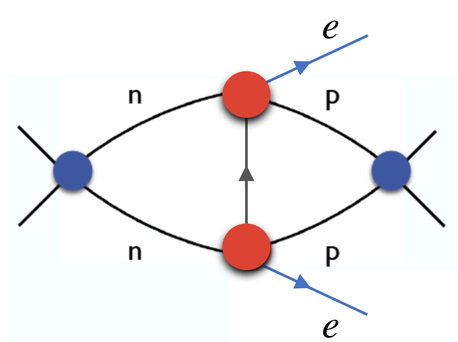

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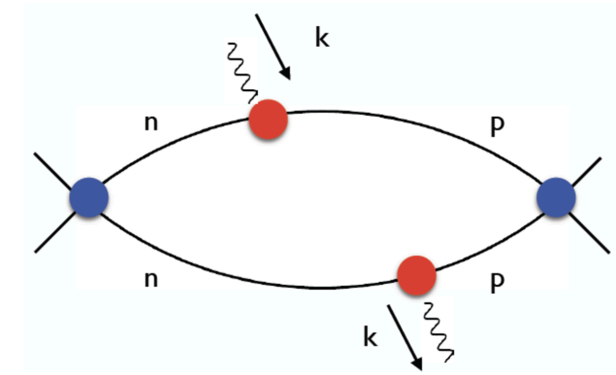
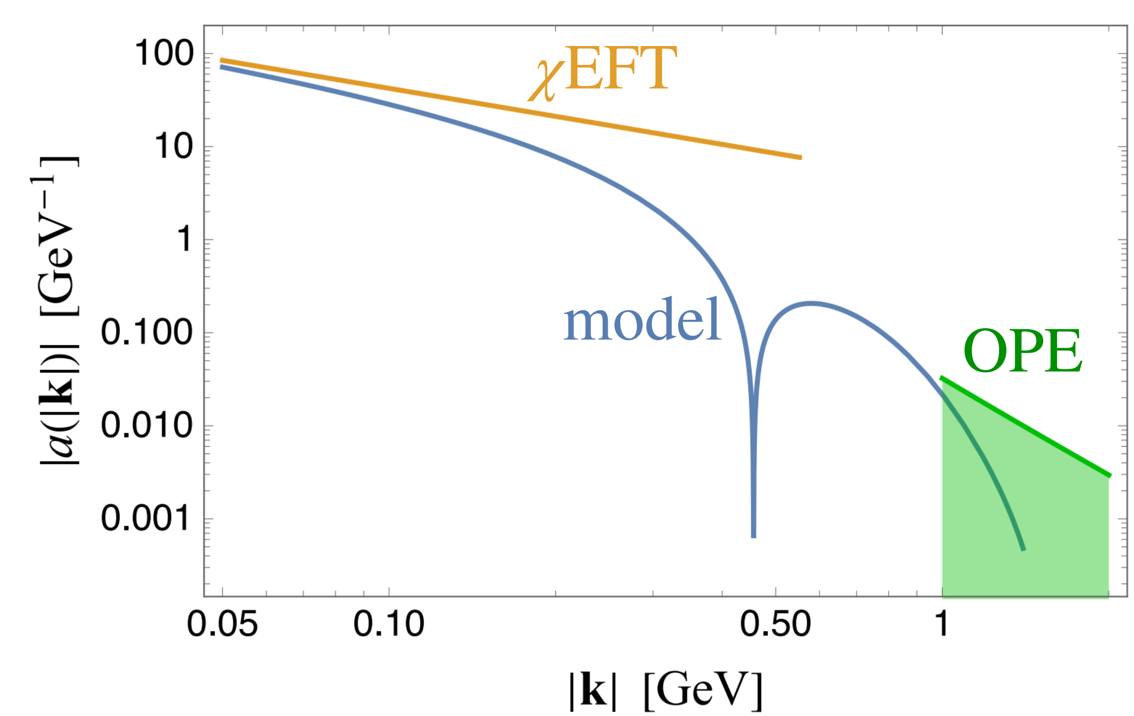


- Estimate the A_ν by constraining the integrand
  - $k \ll \Lambda_\chi$ region determined by χEFT
  - $k \gg$ GeV region determined by OPE
- Model intermediate region using:
  - Form factors
  - Off-shell effects from NN intermediate states



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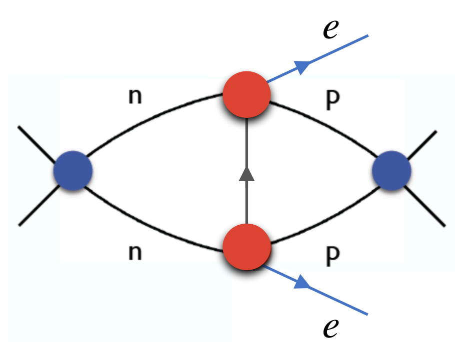

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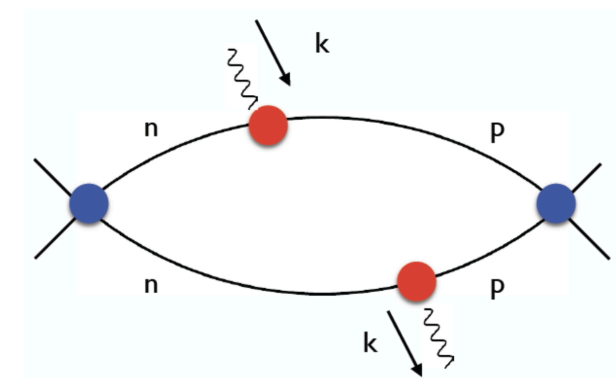
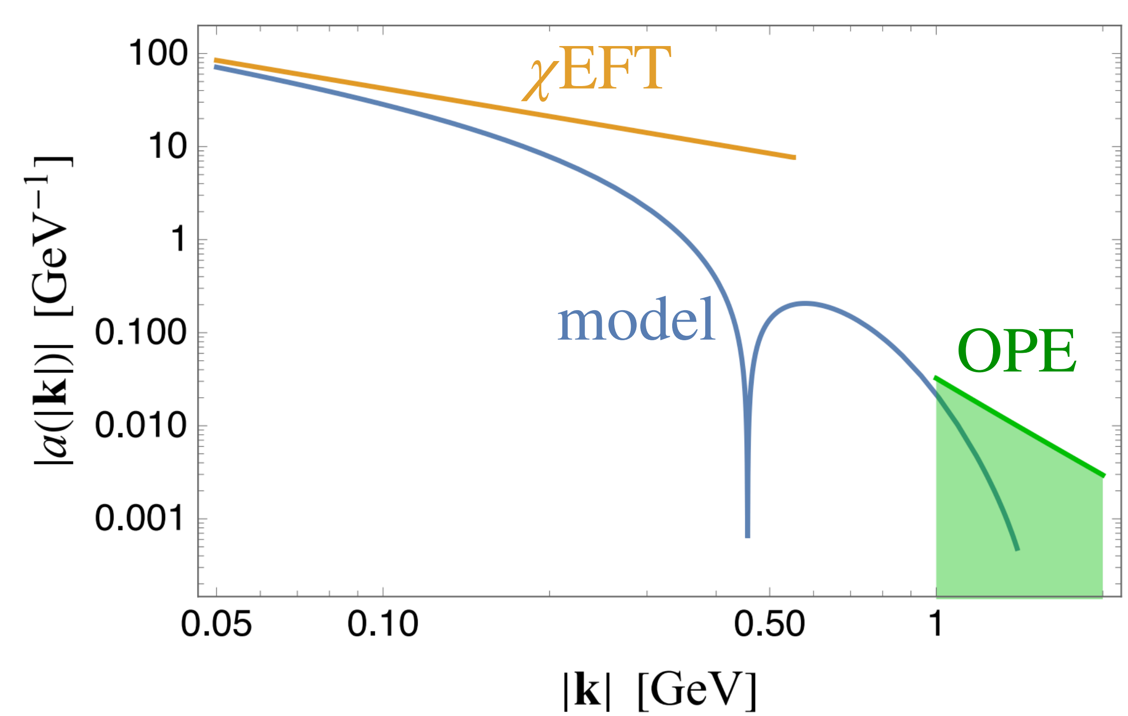


- Gives $\tilde{g}_\nu^{NN}(\mu = m_\pi) = 1.3(6)$ in $\overline{\rm MS}$

  - Estimated 30% uncertainty
  - Validated in isospin-breaking observables
  - Consistent with large-Nc estimate

Richardson et al, '21



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