

Neutrinoless double beta decay in effective field theory

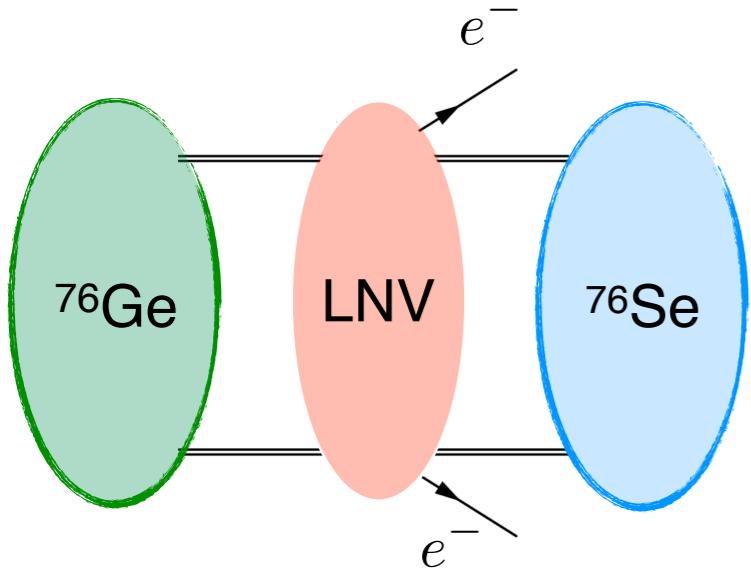
with M. Piarulli, B. Wiringa, S. Pastore, V. Cirigliano,
J. de Vries, M.L. Graesser, E. Mereghetti,
B. van Kolck, A. Walker-Loud

Based on:

arXiv:1806.02780, 1710.01729, 1802.10097,
1710.05026, 1708.09390

Introduction

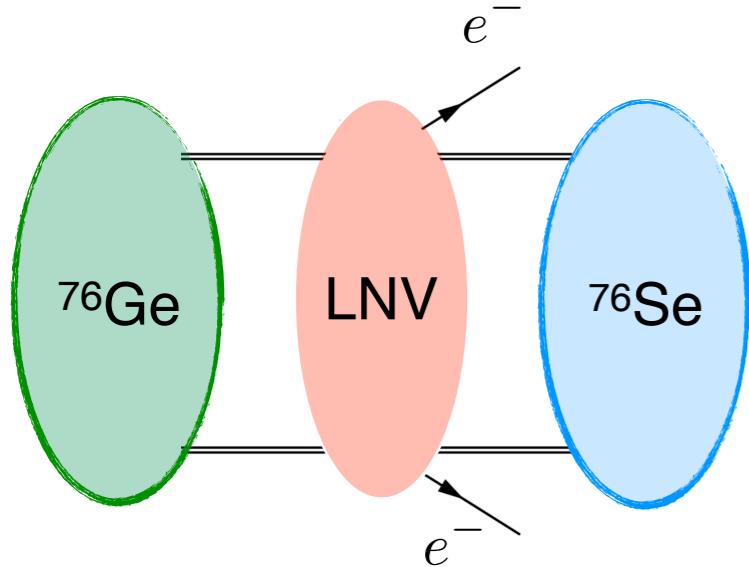
$0\nu\beta\beta$



- Violates lepton number, $\Delta L=2$

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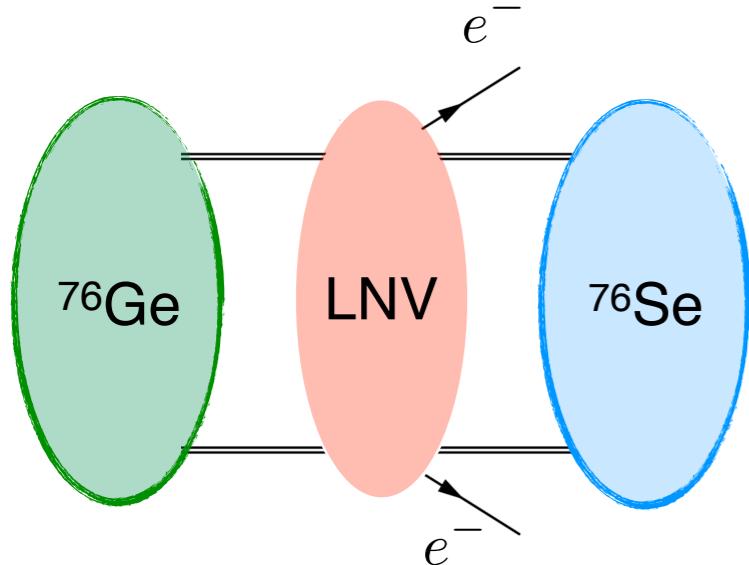


- Violates lepton number, $\Delta L=2$
- Stringently constrained experimentally
 - To be improved by 1-2 orders

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

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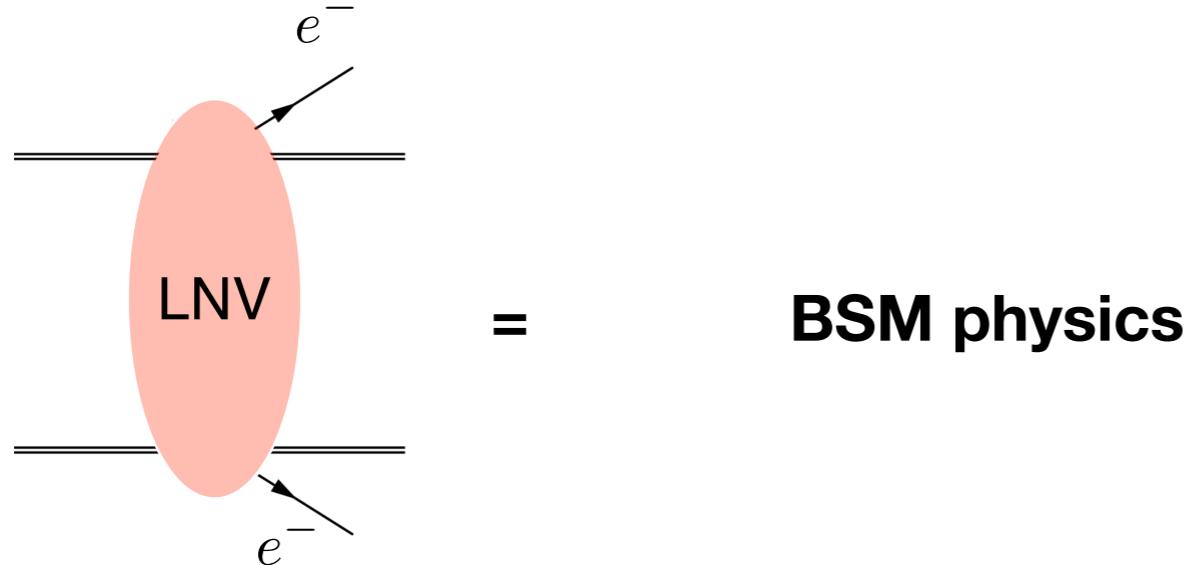


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- Would imply that
 - Neutrino's are Majorana particles
 - Physics beyond the SM

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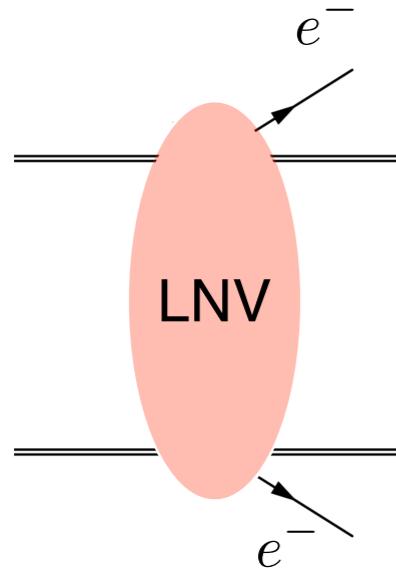


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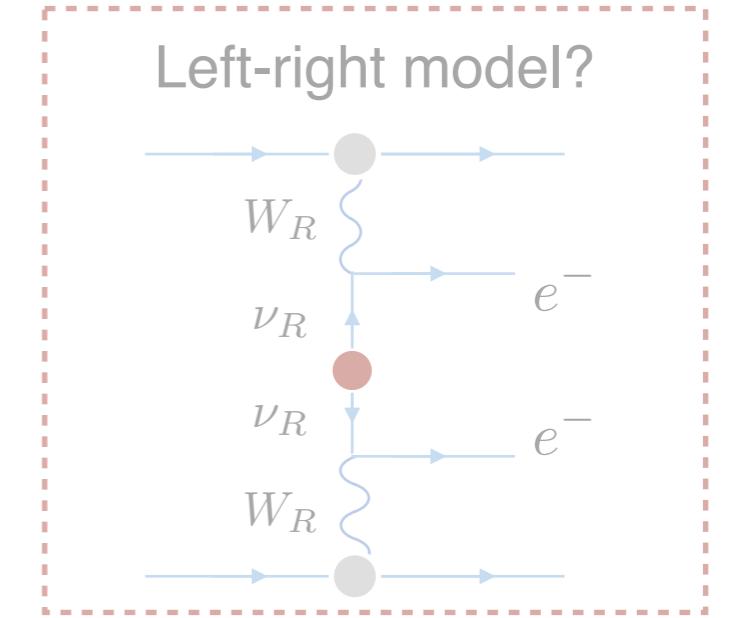
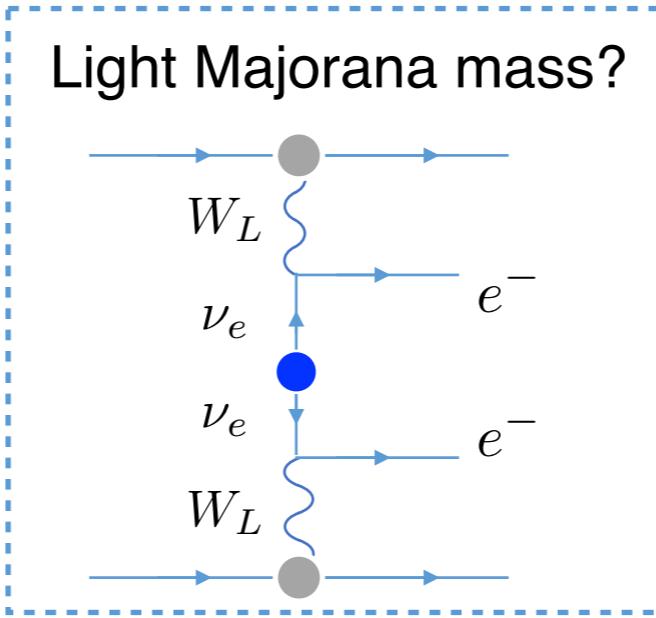
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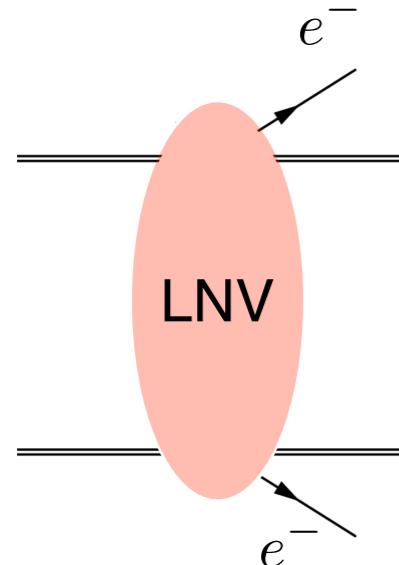


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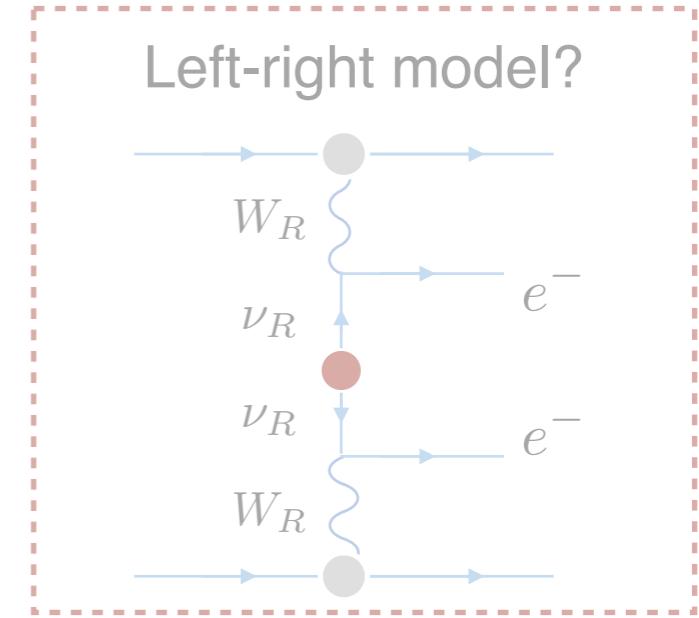
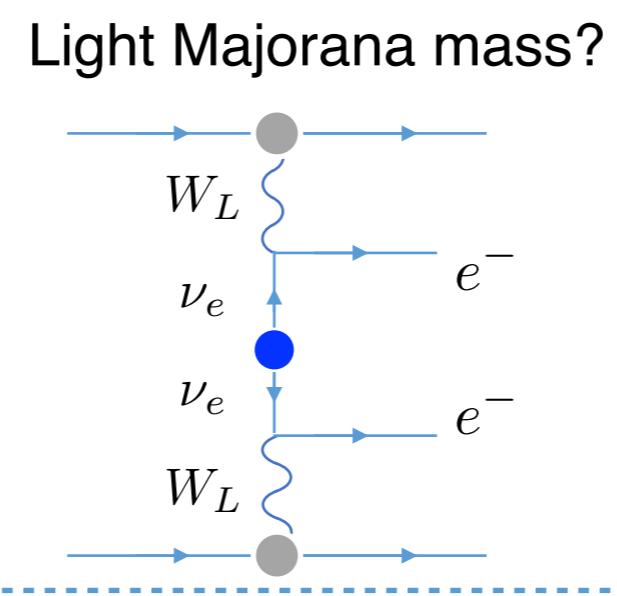


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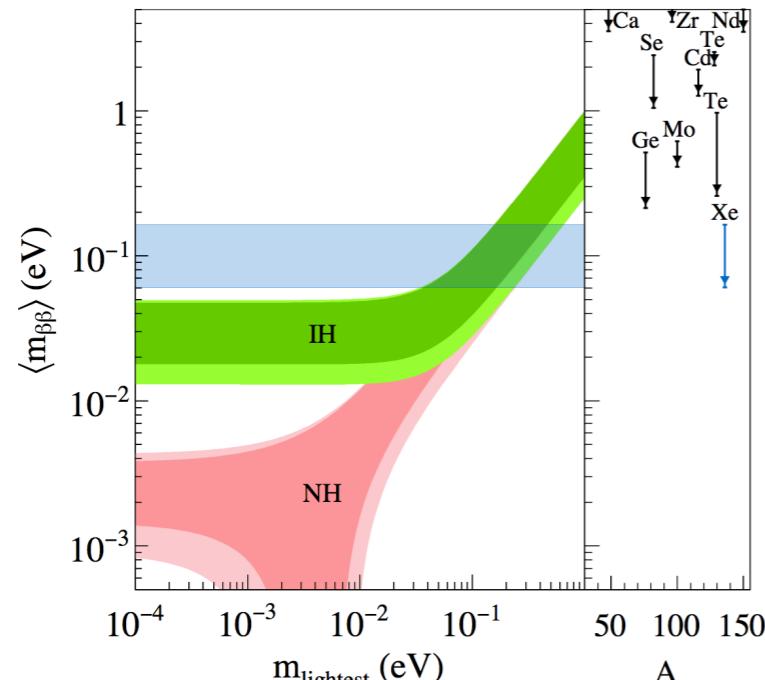


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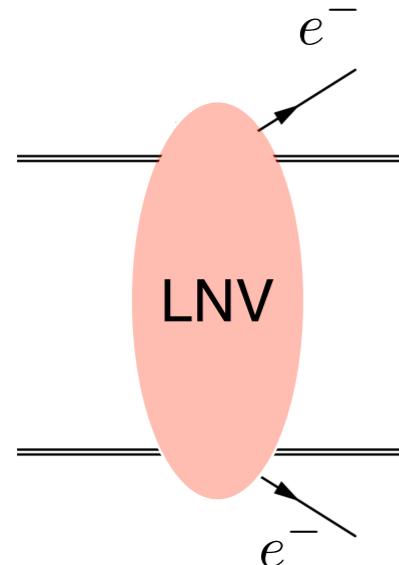
Well-known Majorana mass mechanism



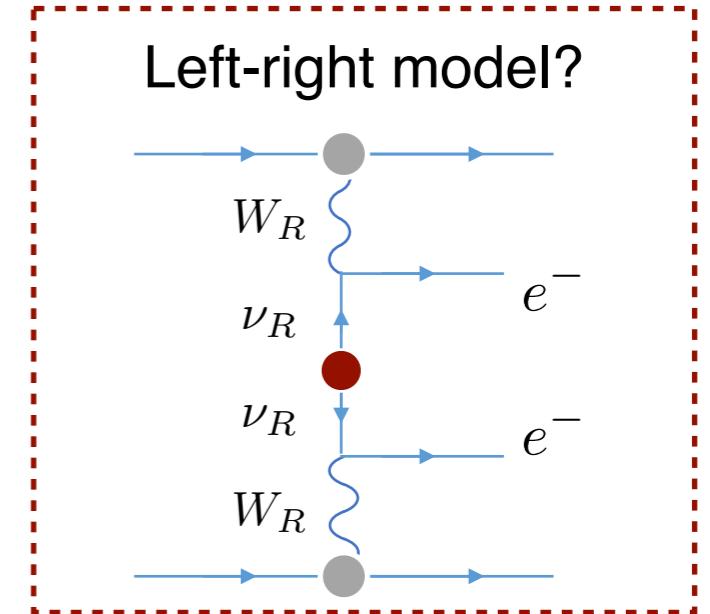
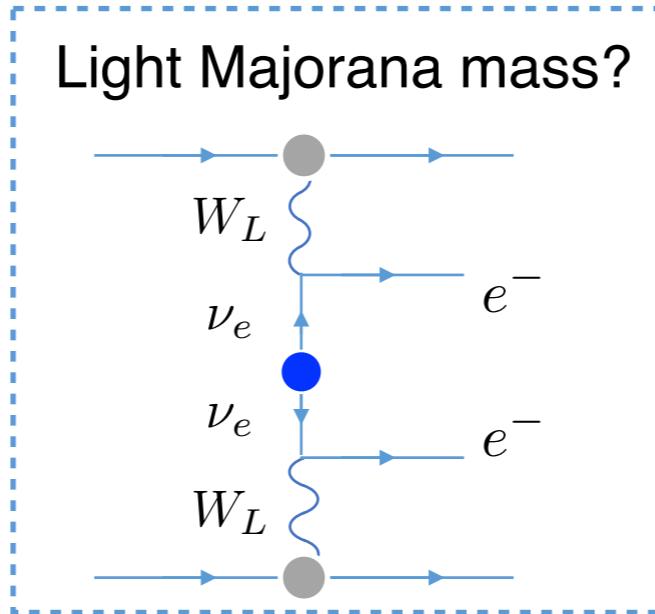
- Implications for the mass hierarchy

Introduction

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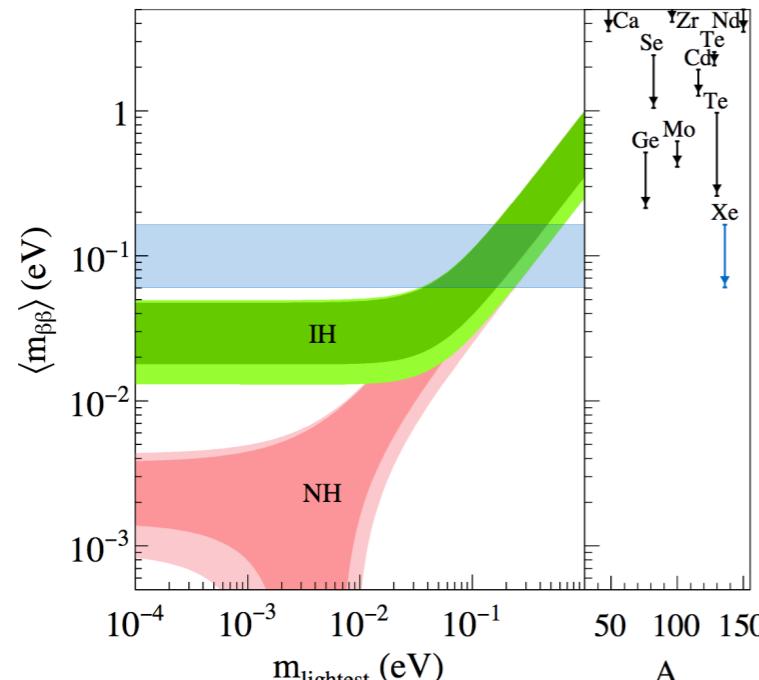


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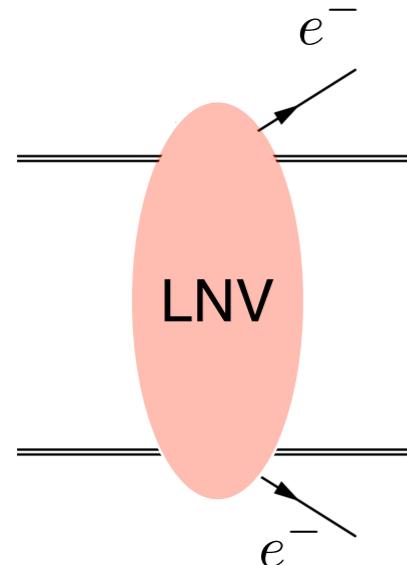
- Many possible scenarios
 - Left-right model,
 - R-parity violating SUSY
 - Leptoquarks...

- Implications for the mass hierarchy

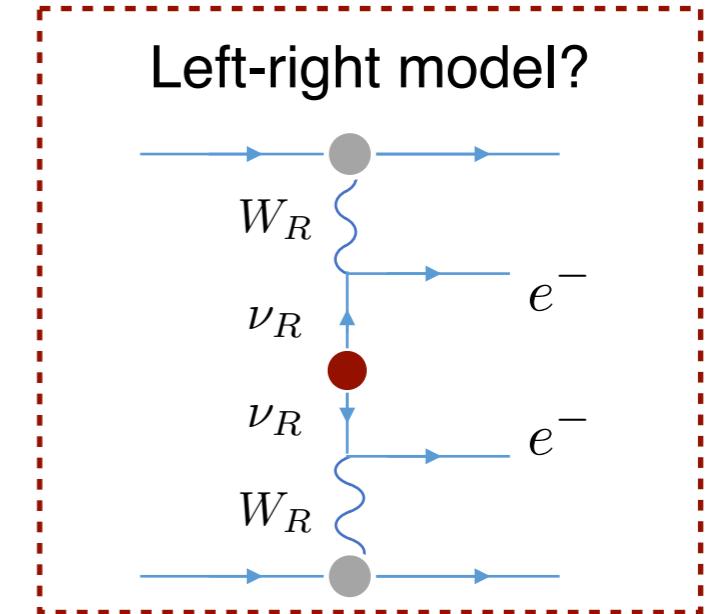
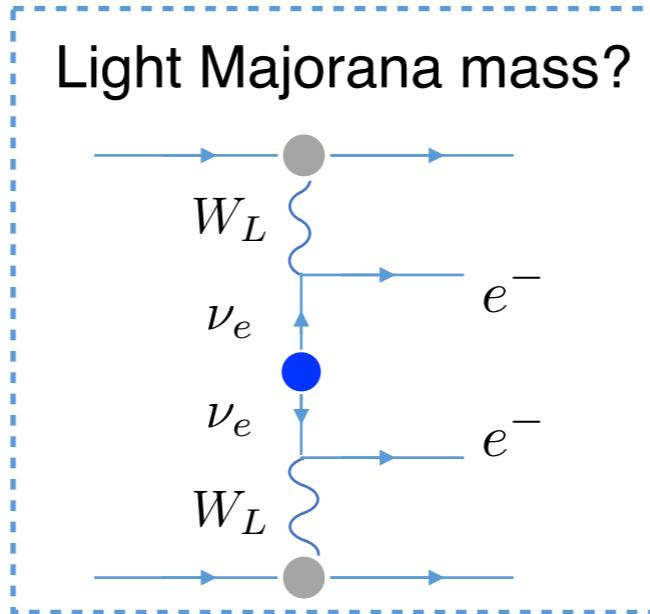
Heavy BSM mechanisms

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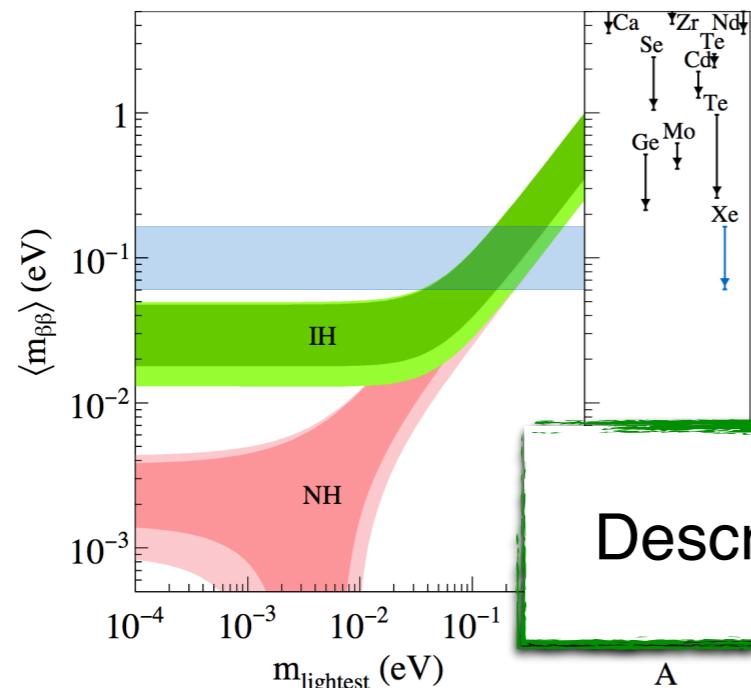


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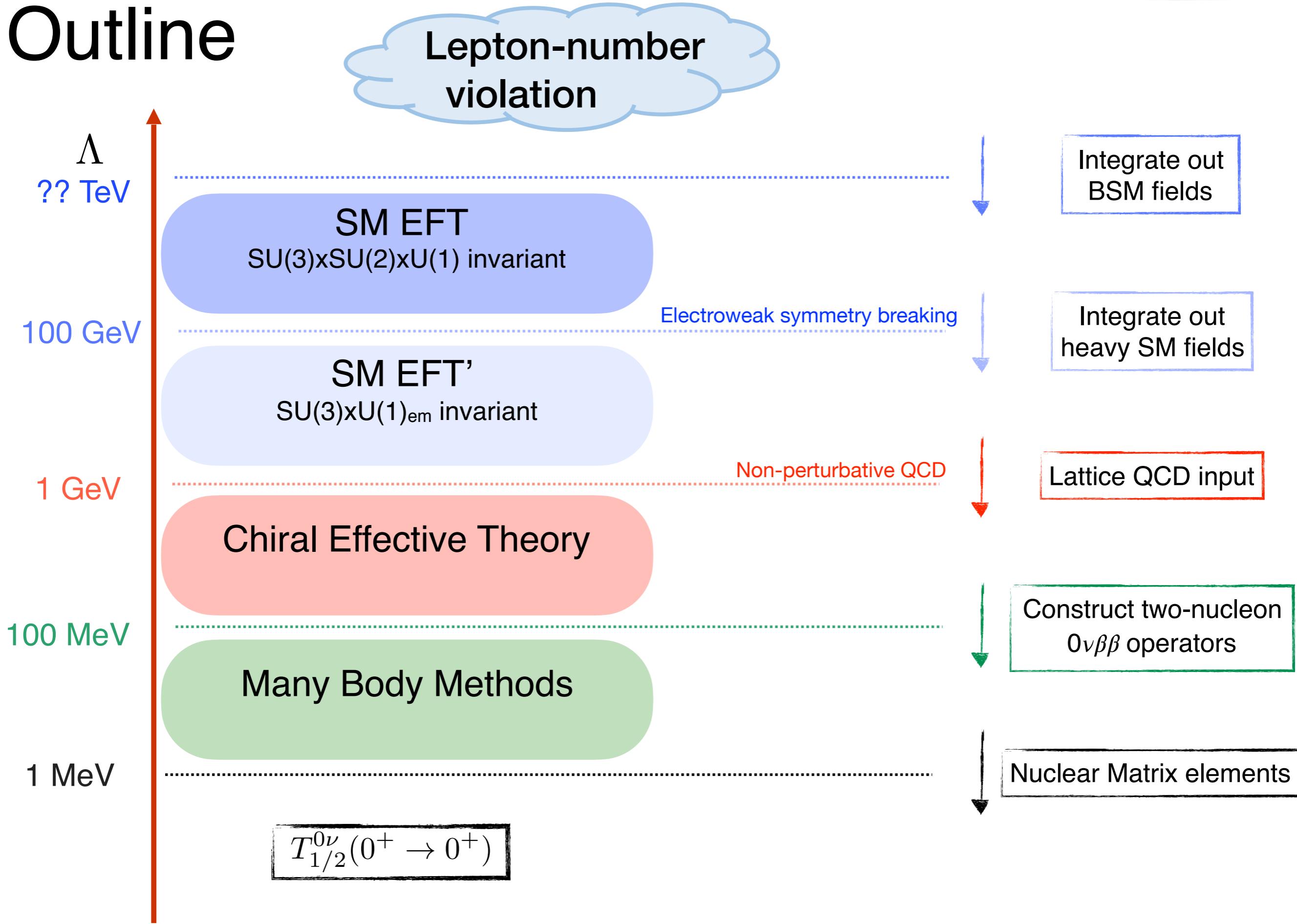
Heavy BSM mechanisms

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 - Left-right model,
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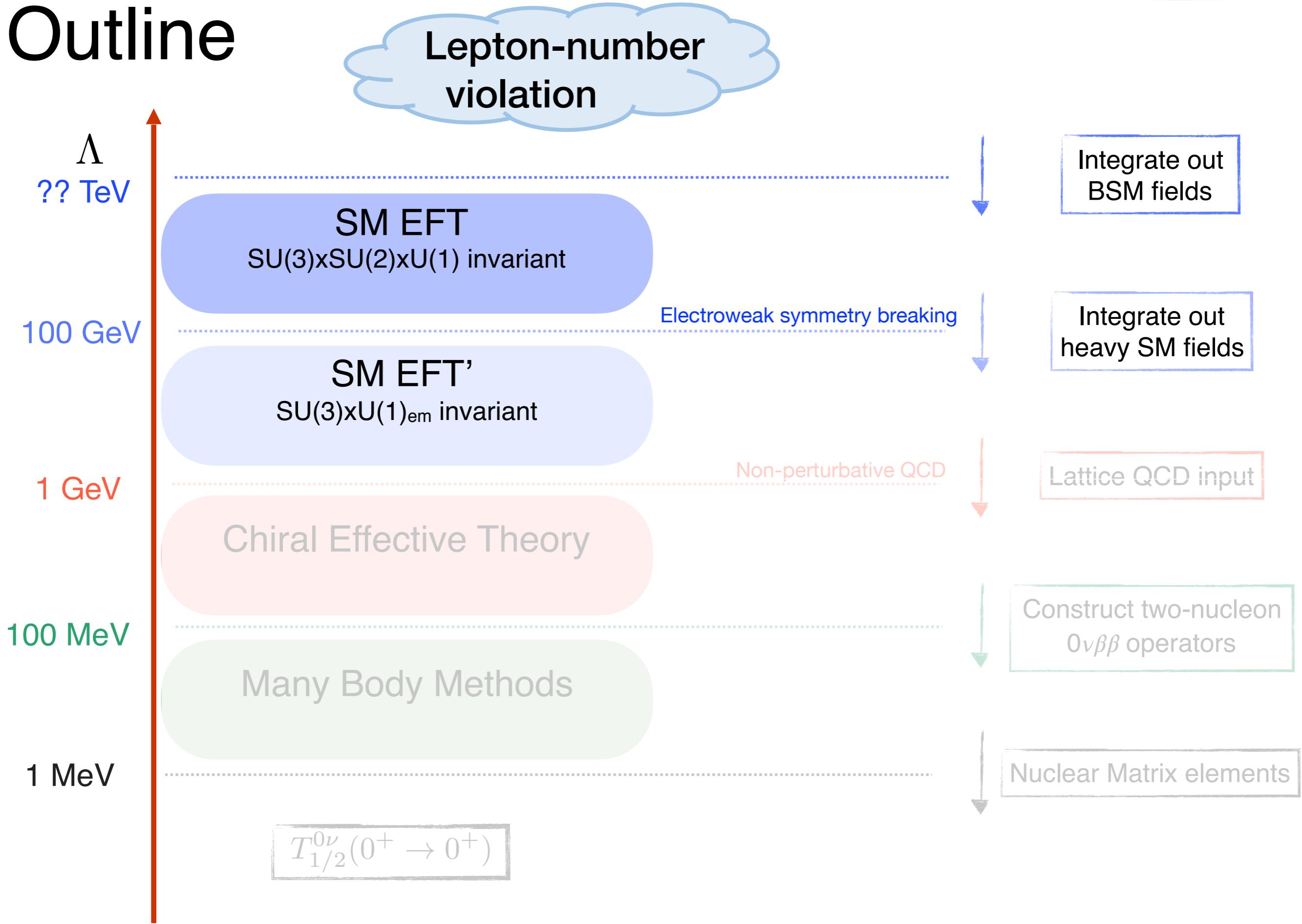
Describe both in an EFT framework

- Implications for the mass hierarchy

Outline



Outline



Effective Field Theory

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

Dimension-five

Dimension-seven

Dimension-nine

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

1 : $\psi^2 H^4 + \text{h.c.}$	
\mathcal{O}_{LH}	$\epsilon_{ij}\epsilon_{mn}(L^i CL^m)H^j H^n(H^\dagger H)$
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$\mathcal{O}_{\bar{L}QddD}^{(1)}$	$(QC\gamma_\mu d)(\bar{L}D^\mu d)$
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- LM1 = $i\sigma_{ab}^{(2)}(\bar{Q}_a \gamma^\mu Q_c)(\bar{u}_R \gamma_\mu d_R)(\bar{\ell}_b \ell_c^C)$
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Effective Field Theory

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

Dimension-five

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

Dimension-seven

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Dimension-nine

$$\begin{aligned}
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Effective Field Theory

Most of
this talk

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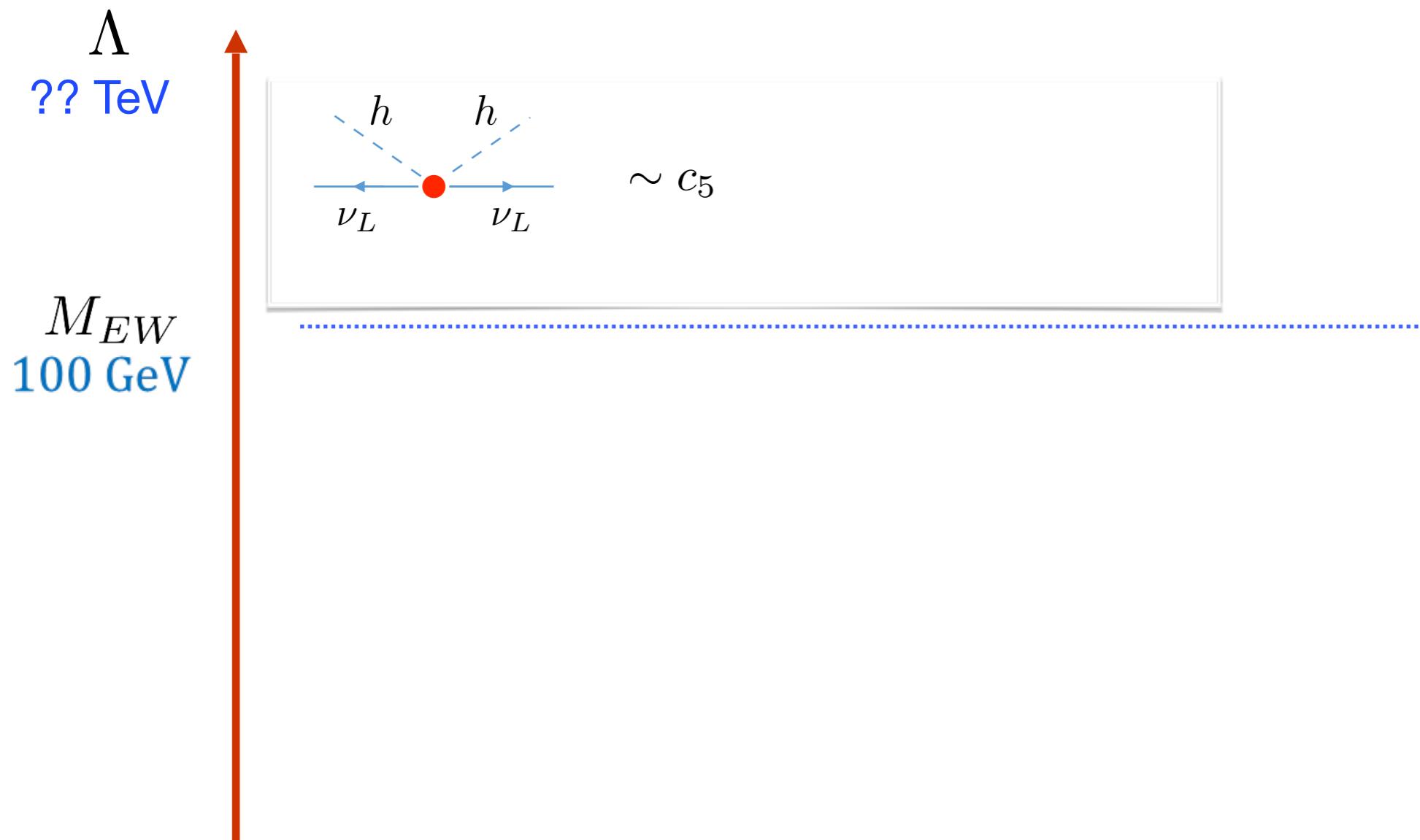
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$\mathcal{O}_{\bar{L}QddD}^{(1)}$	$(Q C \gamma_\mu d)(\bar{L} D^\mu d)$
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 LM8 &= (\bar{u}_R \gamma^\mu d_R) i\sigma_{ab}^{(2)} (\bar{Q}_a d_R)(\bar{\ell}_b \gamma_\mu e_R^C) \\
 LM9 &= (\bar{u}_R \gamma^\mu \lambda^A d_R) i\sigma_{ab}^{(2)} (\bar{Q}_a \lambda^A d_R)(\bar{\ell}_b \gamma_\mu e_R^C) \\
 LM10 &= (\bar{u}_R \gamma^\mu d_R)(\bar{u}_R Q_a)(\bar{\ell}_a \gamma_\mu e_R^C) \\
 LM11 &= (\bar{u}_R \gamma^\mu \lambda^A d_R)(\bar{u}_R \lambda^A Q_a)(\bar{\ell}_a \gamma_\mu e_R^C)
 \end{aligned}$$

Effective Field Theory

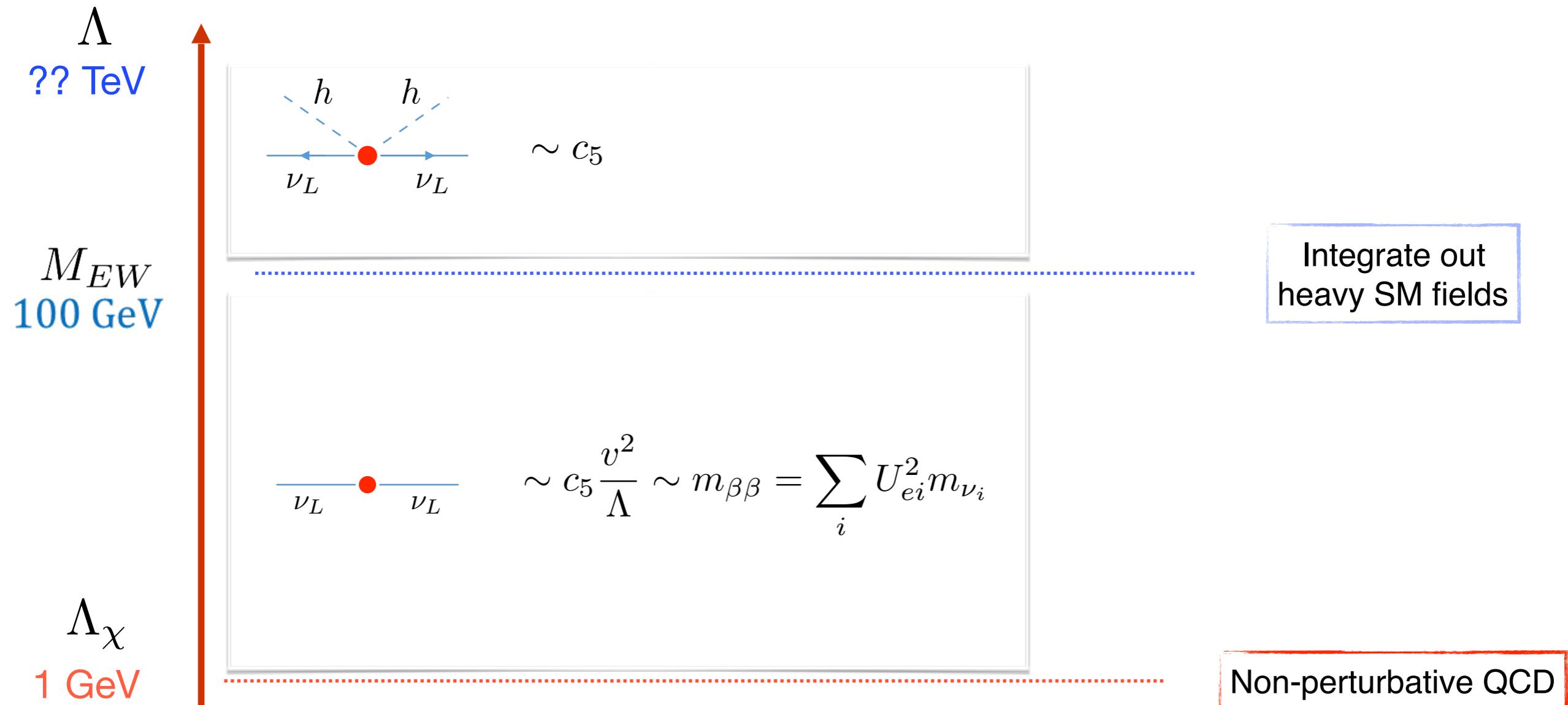
$$\mathcal{L}_5 = \frac{c_5}{\Lambda} (L^T C \tilde{H})(\tilde{H}^T L)$$



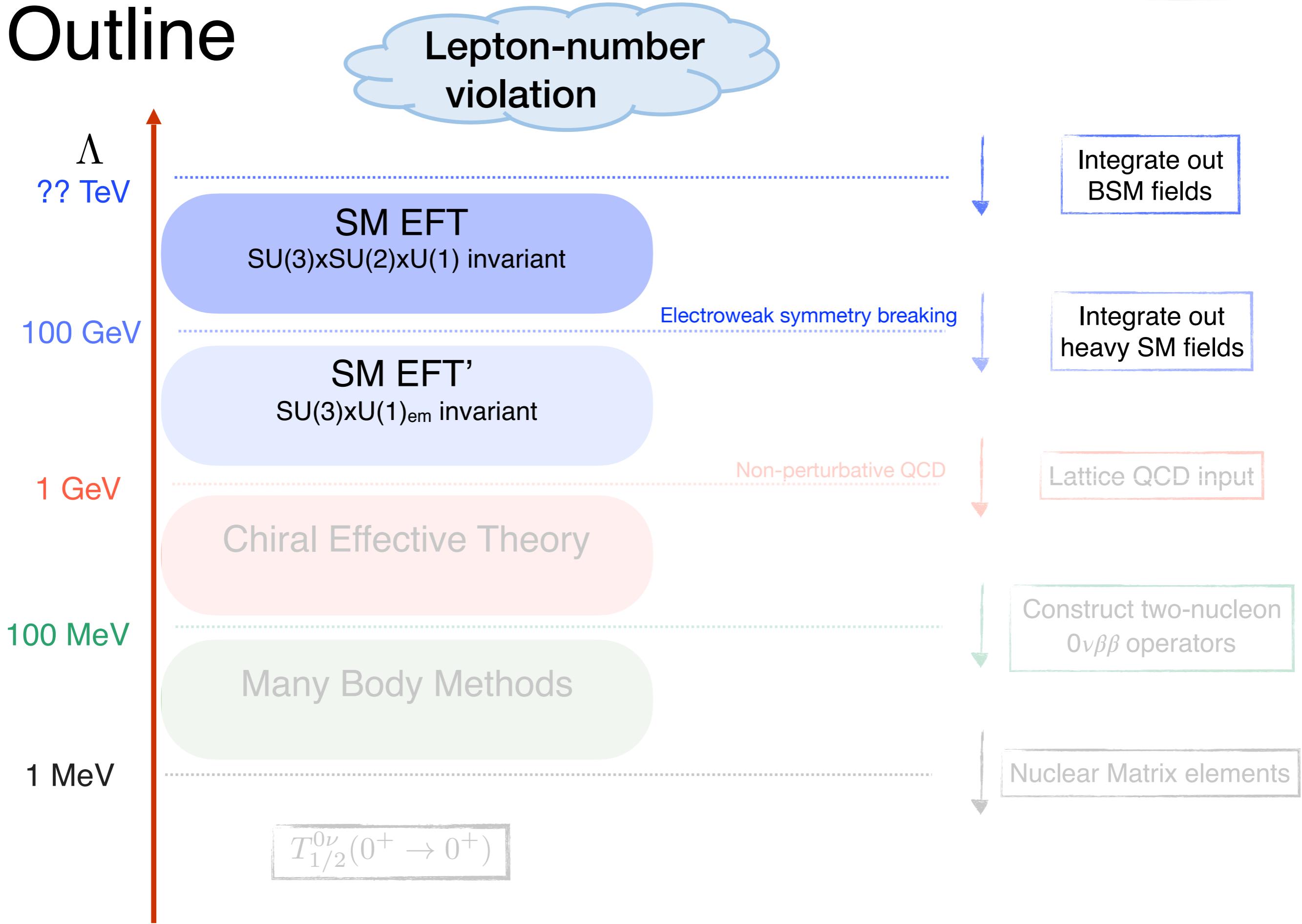
Integrate out
heavy SM fields

Effective Field Theory

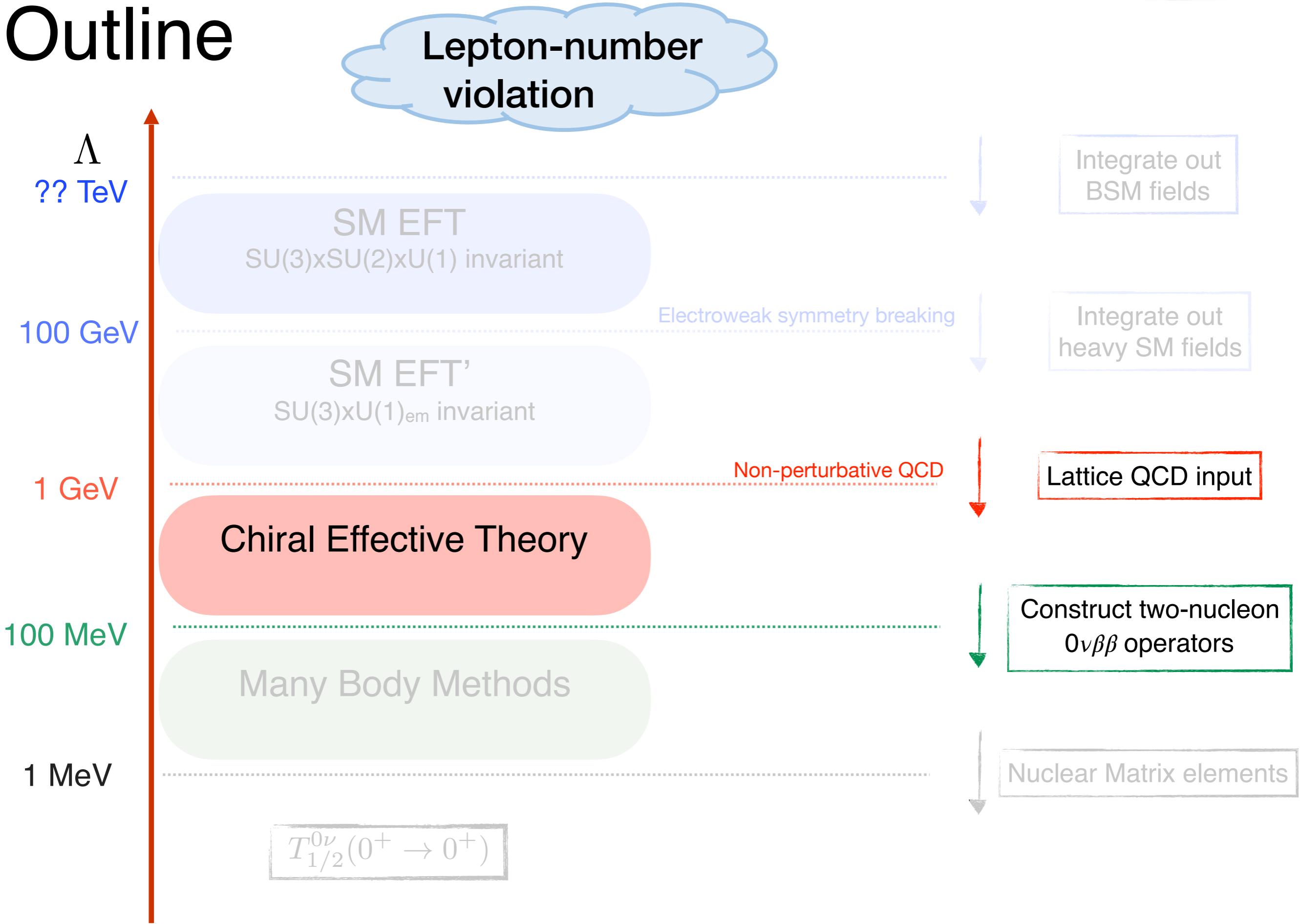
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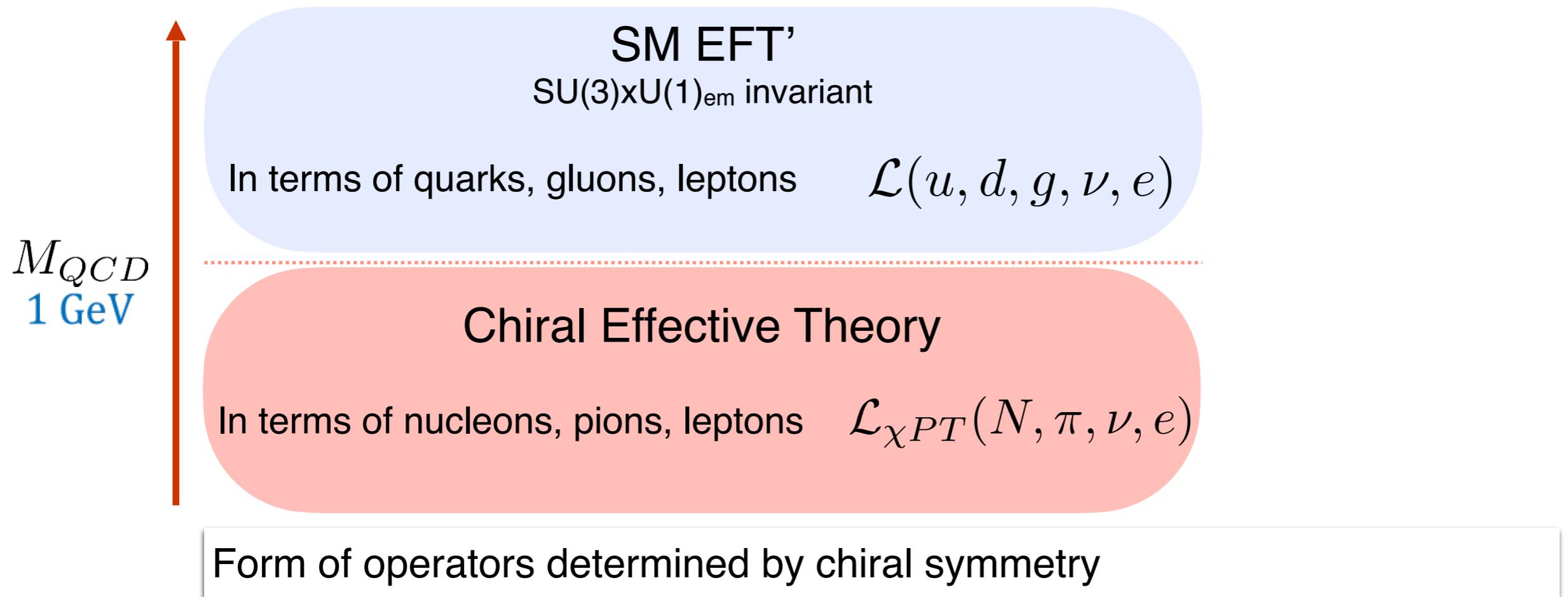
Outline



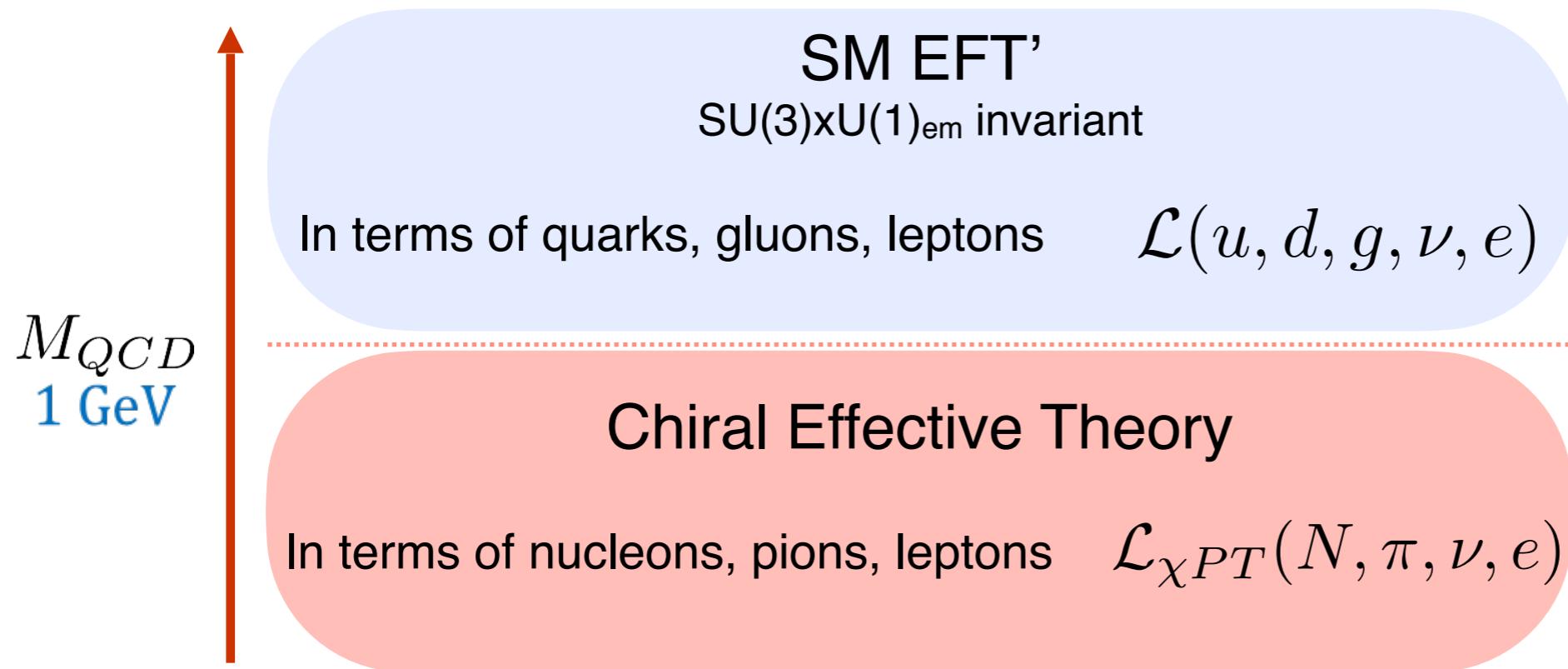
Outline



Matching to Chiral EFT



Matching to Chiral EFT

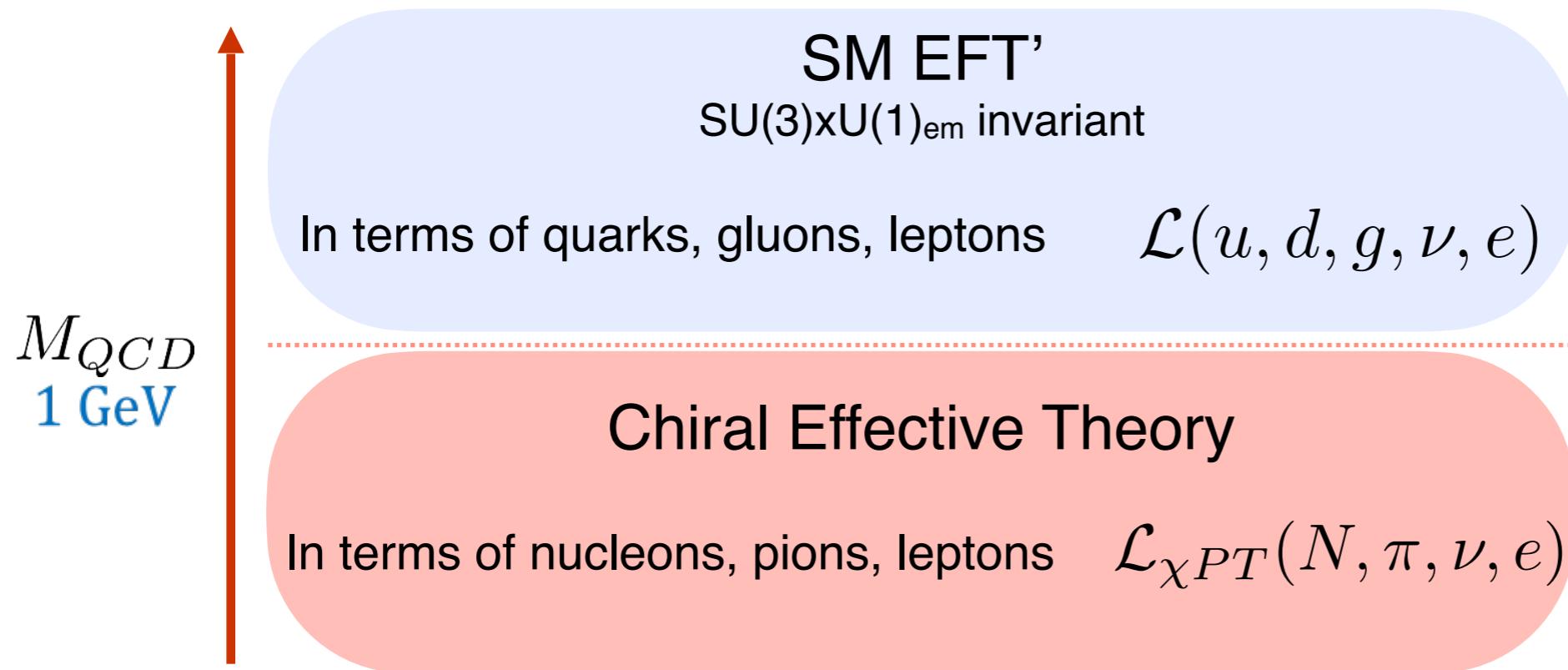


Form of operators determined by chiral symmetry

The operators come with unknown constants (LECs)

- Parametrize non-perturbative physics

Matching to Chiral EFT



Form of operators determined by chiral symmetry

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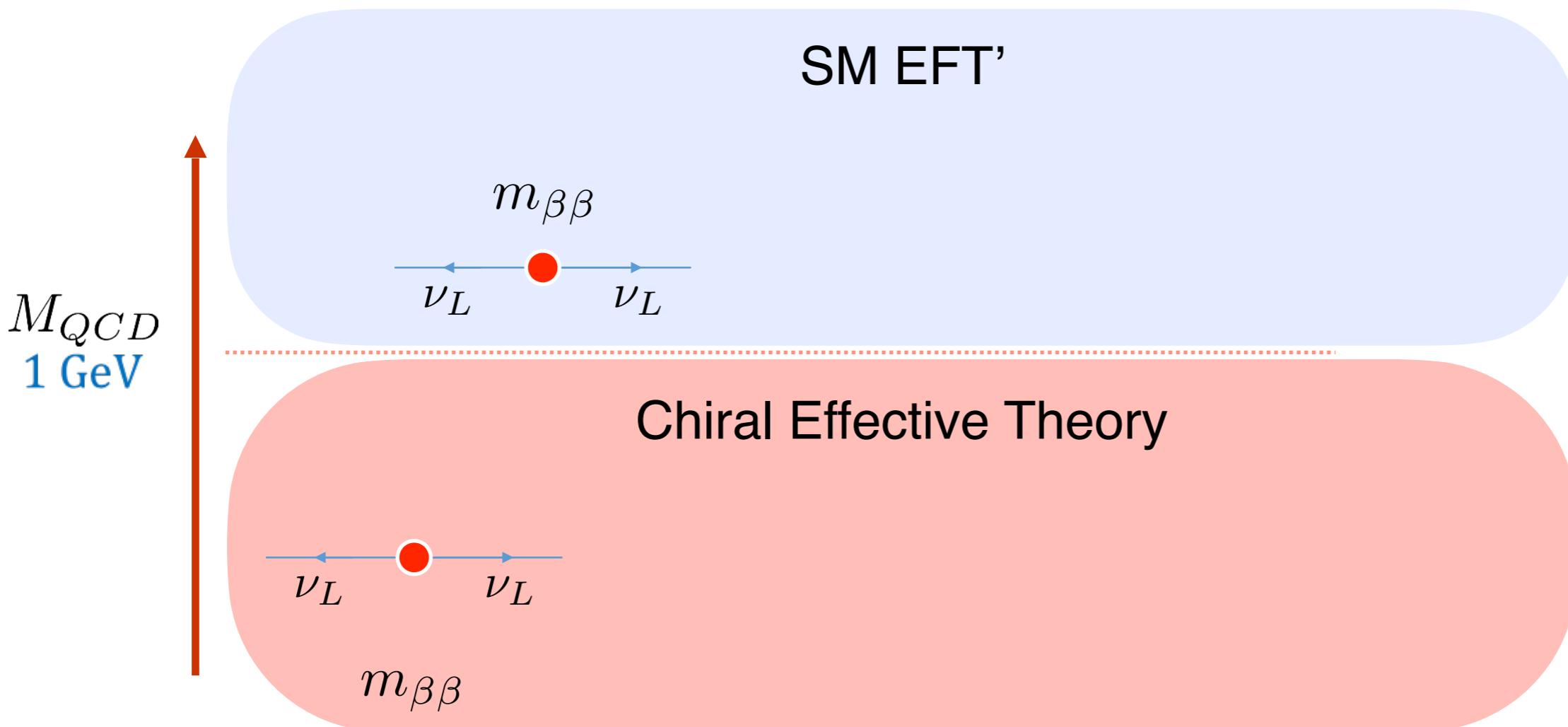
- Parametrize non-perturbative physics

Need a power-counting scheme

- Usually Weinberg's power counting (based on NDA)

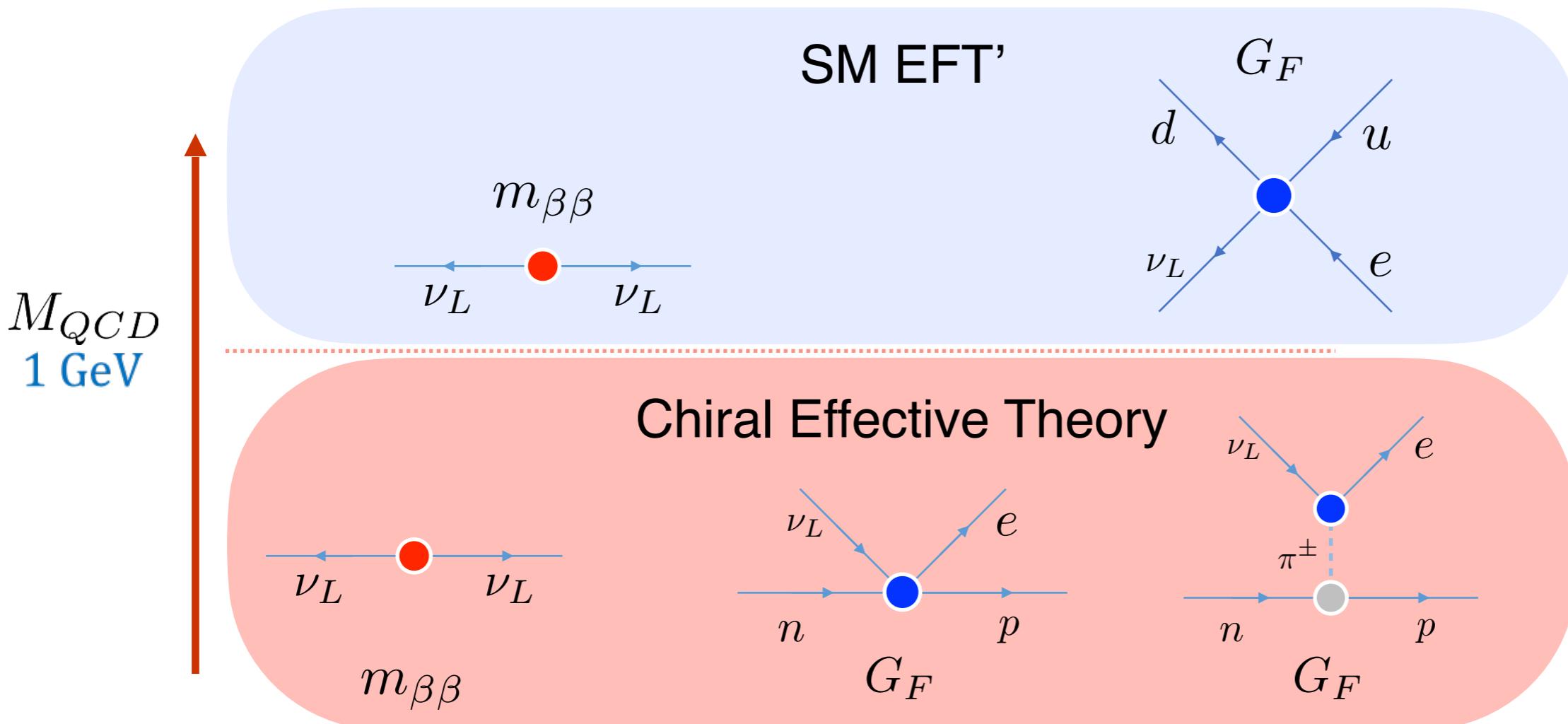
Matching to Chiral EFT

Warning: Based on NDA



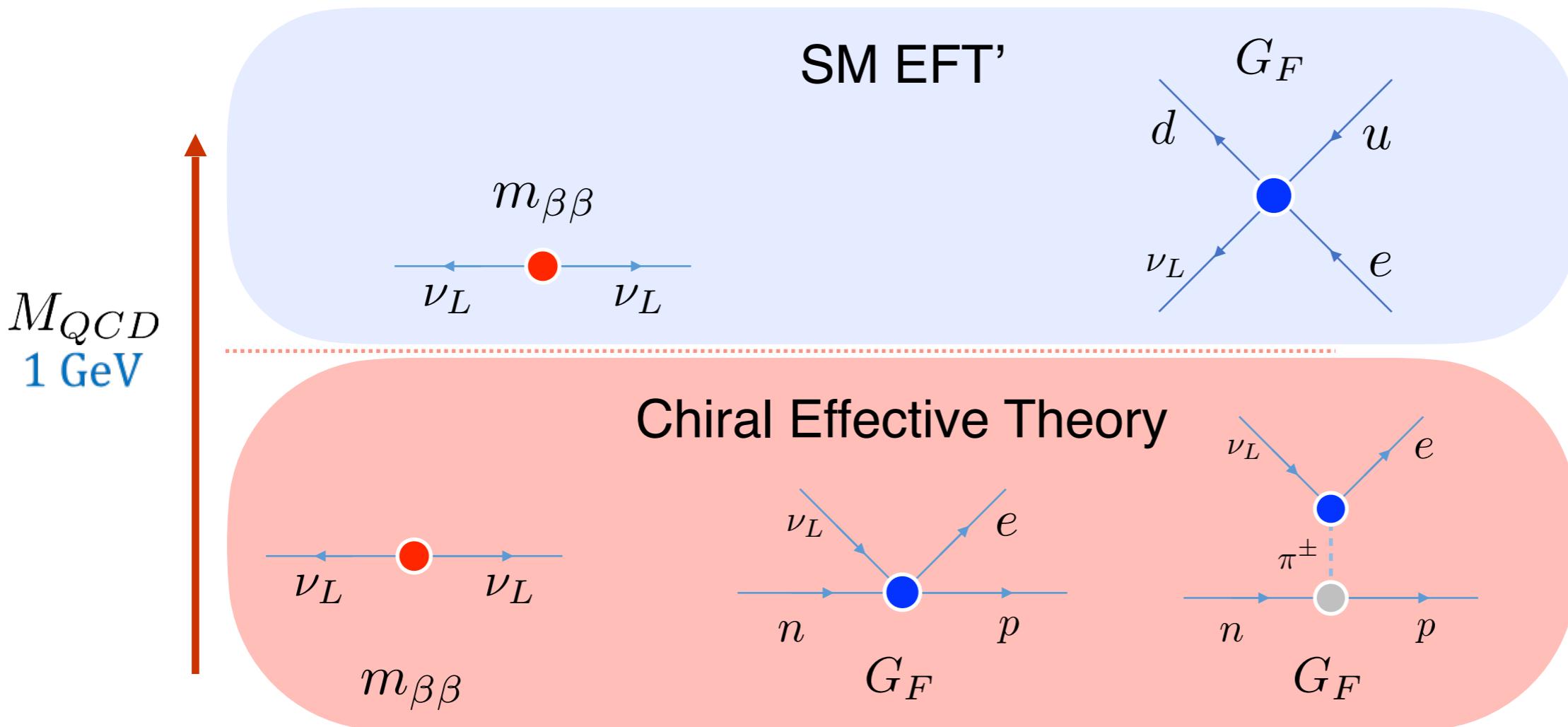
Matching to Chiral EFT

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Matching to Chiral EFT

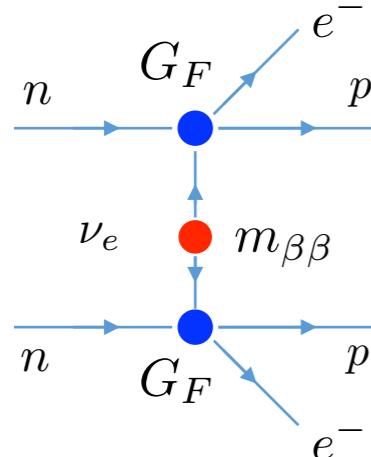
Warning: Based on NDA



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

$\Delta L=2$ potential

Warning: Based on NDA

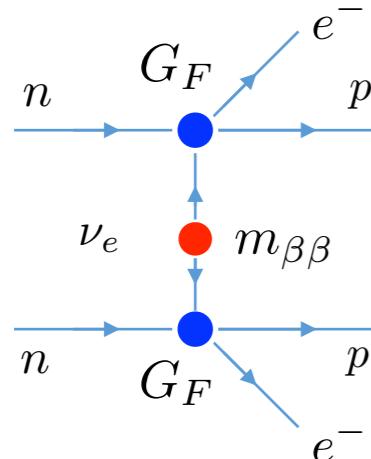


$$V_{\nu,0}^{(a,b)} = \tau^{(a)+} \tau^{(b)+} \frac{1}{\mathbf{q}^2} \left\{ 1 - g_A^2 \left[\boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} - \boldsymbol{\sigma}^{(a)} \cdot \mathbf{q} \boldsymbol{\sigma}^{(b)} \cdot \mathbf{q} \frac{2m_\pi^2 + \mathbf{q}^2}{(\mathbf{q}^2 + m_\pi^2)^2} \right] \right\}$$

- Chiral result agrees with the usual derivation at LO

$\Delta L=2$ potential

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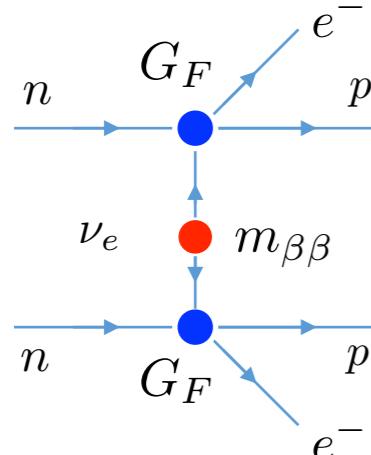
- Chiral result agrees with the usual derivation at LO

- Combining with wave functions gives the decay rate

$$\Gamma^{0\nu}(0^+ \rightarrow 0^+) \sim \left| \langle 0^+ | \sum_{\text{nucleons}} \int \frac{d^3 \mathbf{q}}{(2\pi)^3} e^{i\mathbf{q} \cdot \mathbf{r}} V(\mathbf{q}^2) | 0^+ \rangle \right|^2$$

$\Delta L=2$ potential

Warning: Based on NDA



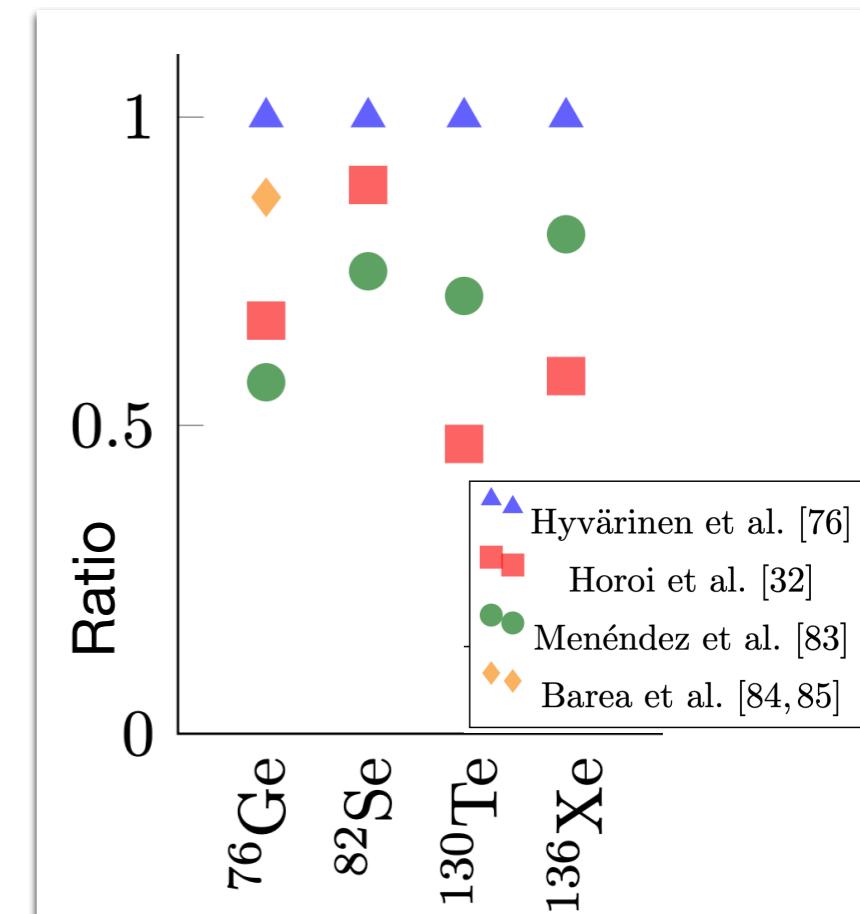
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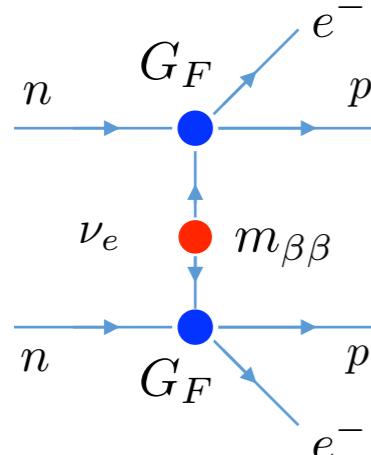
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- Requires nuclear matrix elements
 - Many-body methods disagree by factor $\sim 2-3$
 - Similar for higher-dimensional operators



$\Delta L=2$ potential

Warning: Based on NDA



$$V_{\nu,0}^{(a,b)} = \tau^{(a)} + \tau^{(b)} + \frac{1}{\mathbf{q}^2} \left\{ 1 - g_A^2 \left[\boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} - \boldsymbol{\sigma}^{(a)} \cdot \mathbf{q} \boldsymbol{\sigma}^{(b)} \cdot \mathbf{q} \frac{2m_\pi^2 + \mathbf{q}^2}{(\mathbf{q}^2 + m_\pi^2)^2} \right] \right\}$$

- Chiral result agrees with the usual derivation at LO

- Combining with wave functions gives the decay rate

The potential is based on Weinberg power counting

- Known to fail in the strong interaction (NN scattering)
- Does it hold for $0\nu\beta\beta$?

- Requires nuclear inputs
 - Many-body methods disagree by factor ~2-3
 - Similar for higher-dimensional operators

76Ge
82Se
130Te
136Xe

Hyvärinen et al. [76]
Horoi et al. [32]
Menéndez et al. [83]
Barea et al. [84, 85]

Checking the power counting

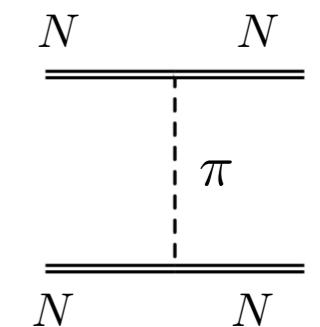
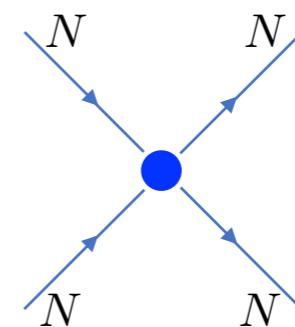
Check that $\mathcal{A}(nn \rightarrow ppee)$ is finite

Checking the power counting

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

- Requires inclusion of the strong interaction

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

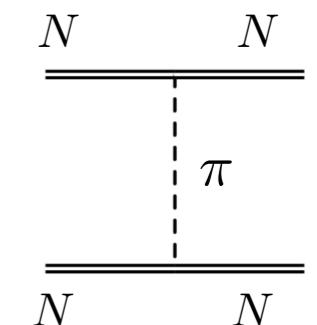
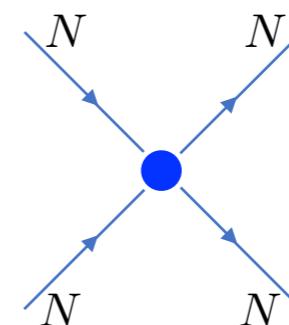


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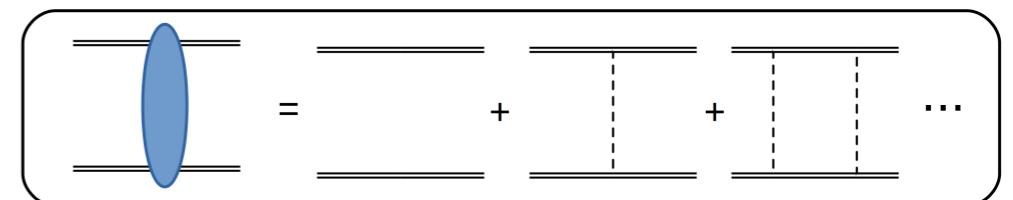
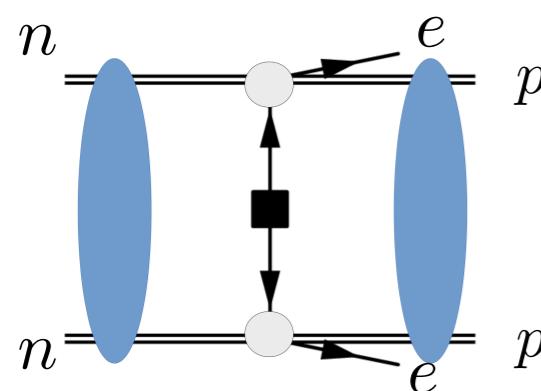
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Dress the $\Delta L=2$ potential with (renormalized) strong interactions:



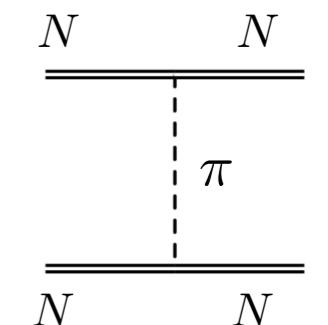
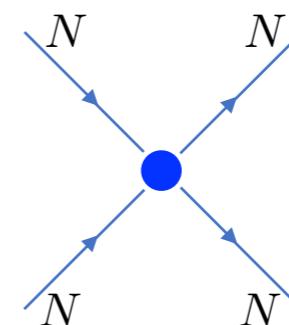
✓ finite

Checking the power counting

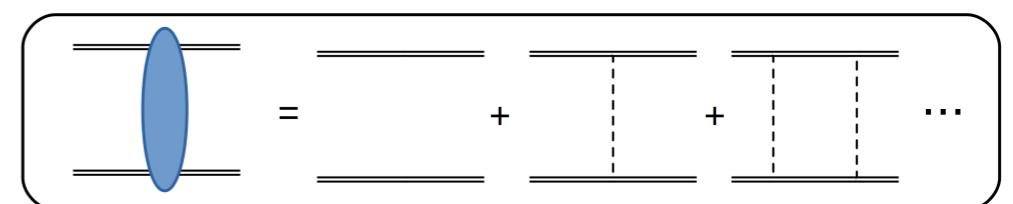
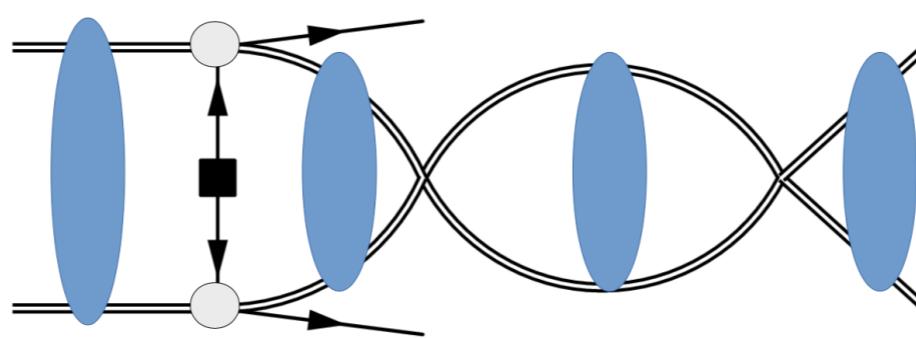
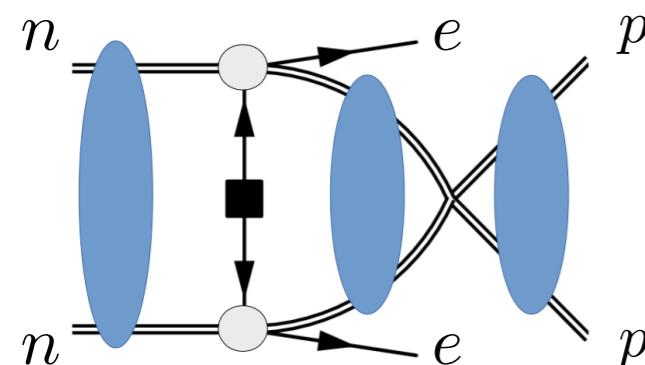
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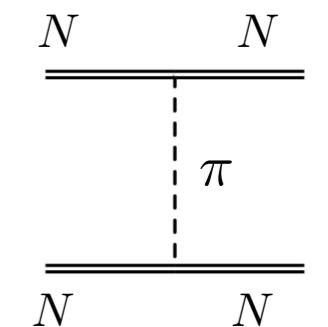
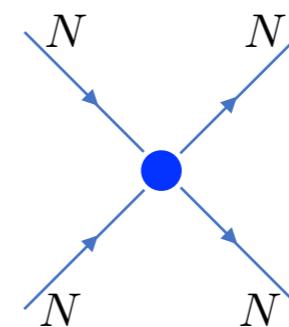
+ finite

Checking the power counting

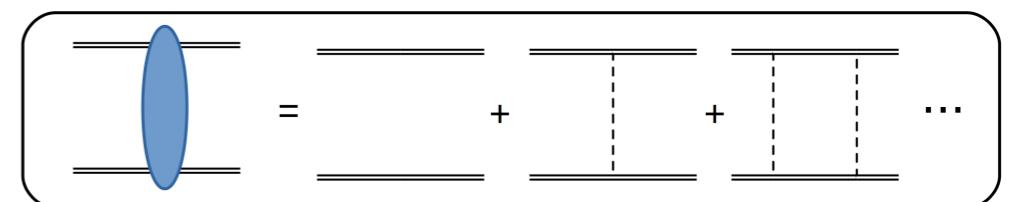
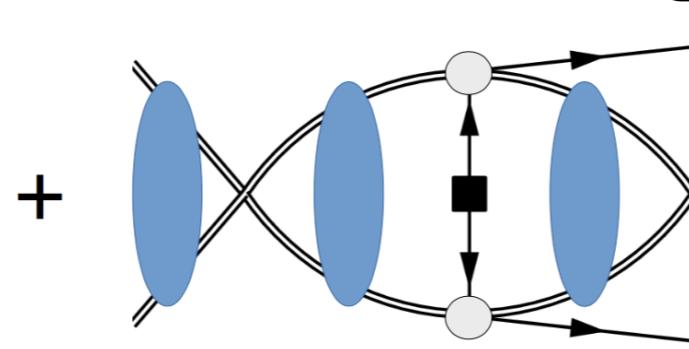
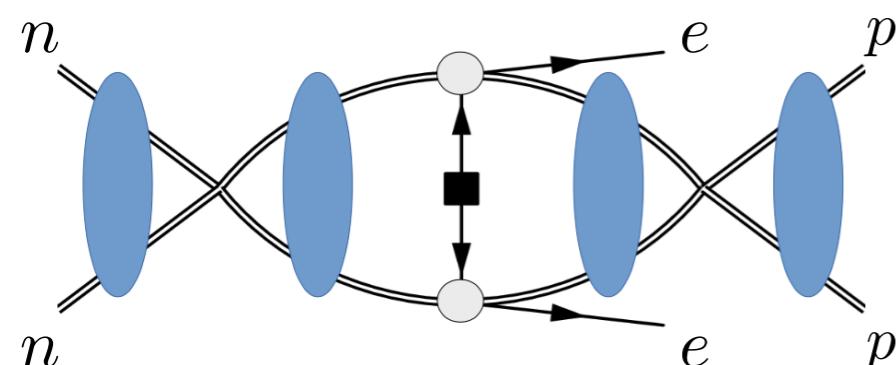
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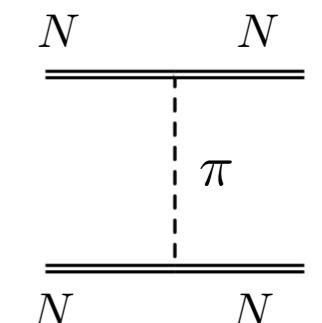
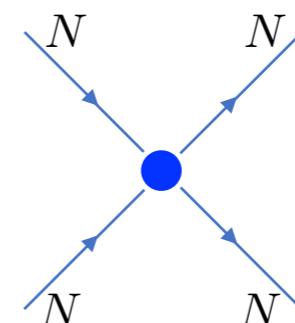
Divergent

Checking the power counting

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

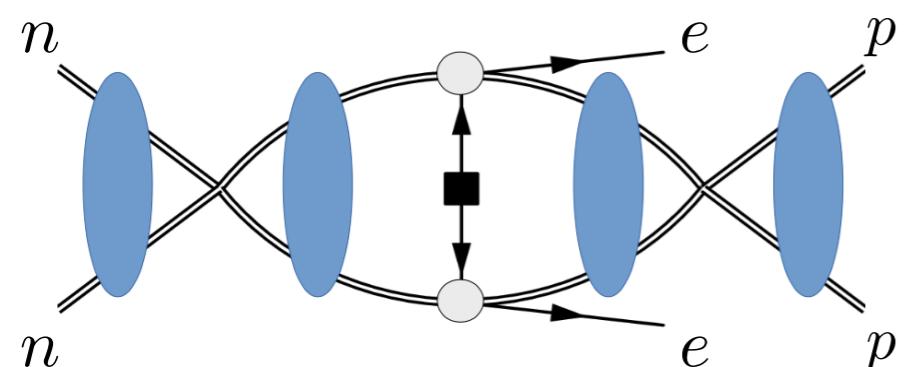
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Dress the $\Delta L=2$ potential with (renormalized) strong interactions:

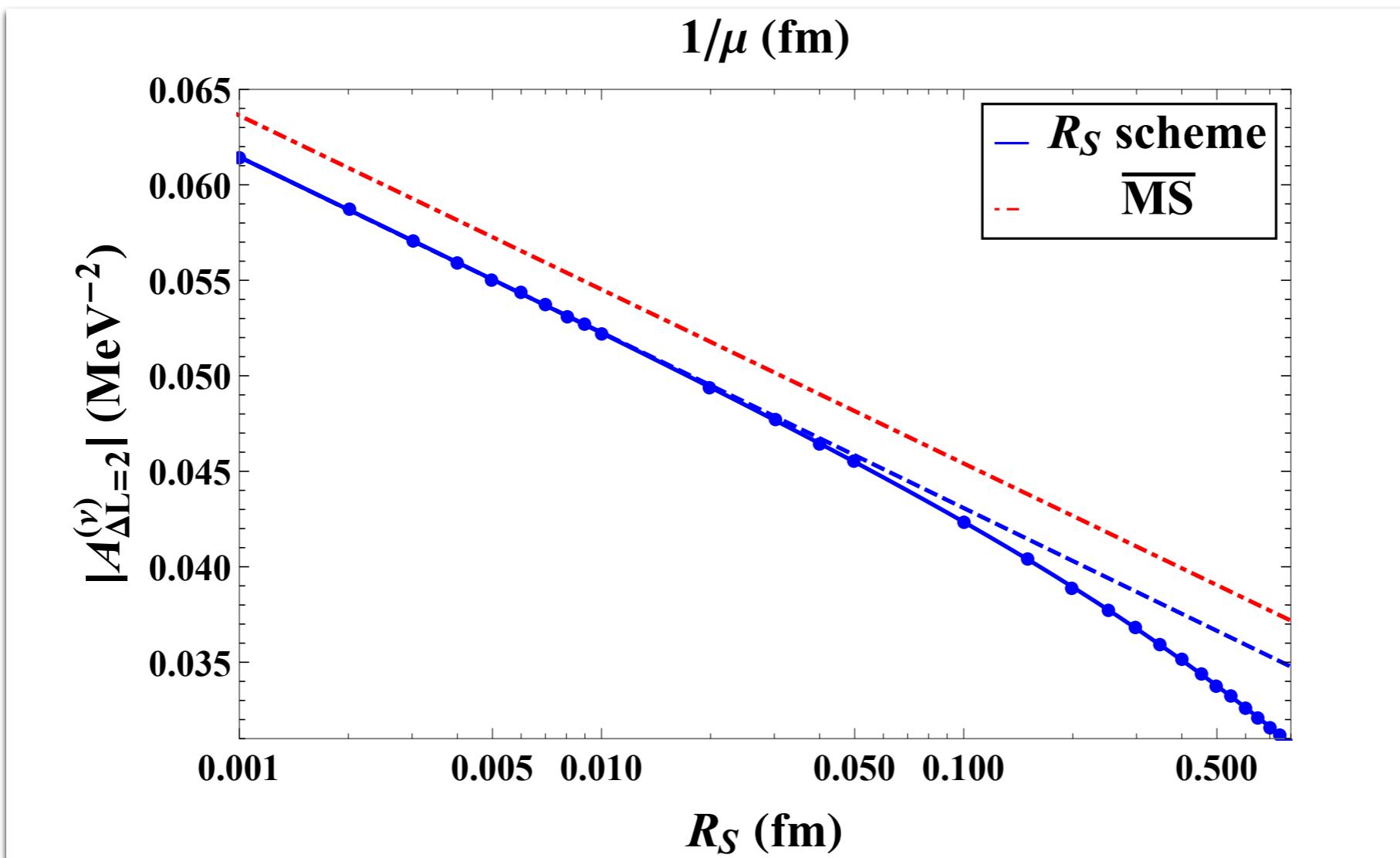
In MS-bar:



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

Regulator dependent

Numerical results



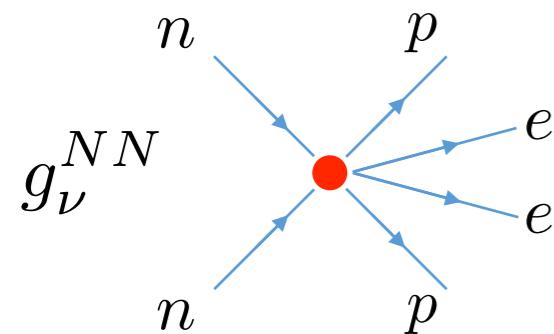
- Amplitudes obtained using
 - MS-bar
 - Coordinate-space cut-off

- Clear μ or R_S dependence

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

Need for a new counter term

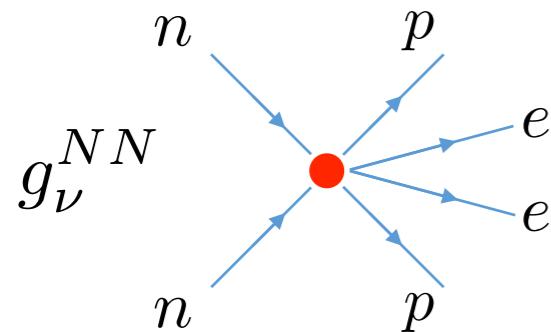
Need a counter term to absorb the divergence/regulator dependence



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

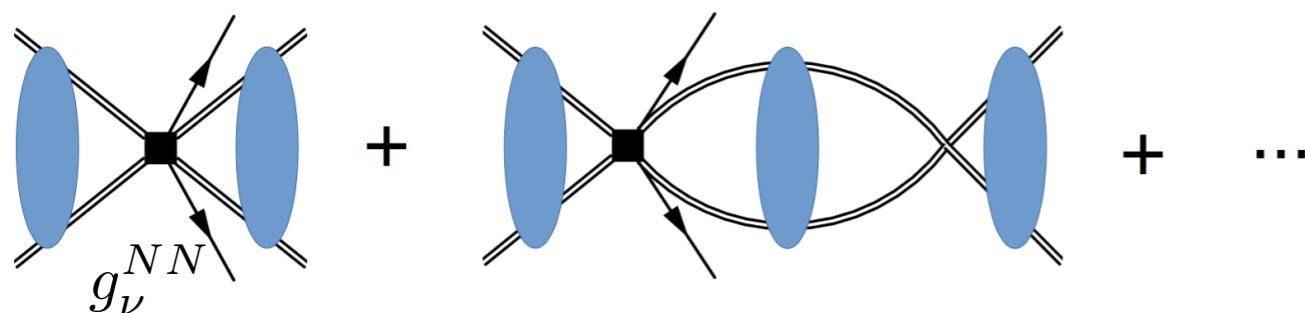
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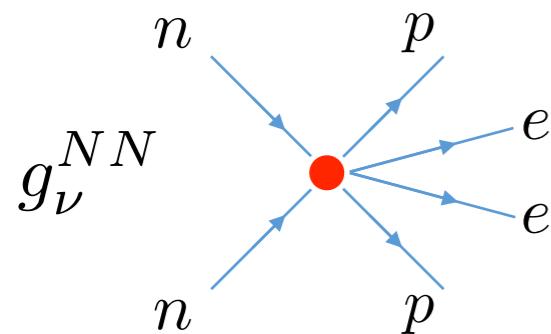
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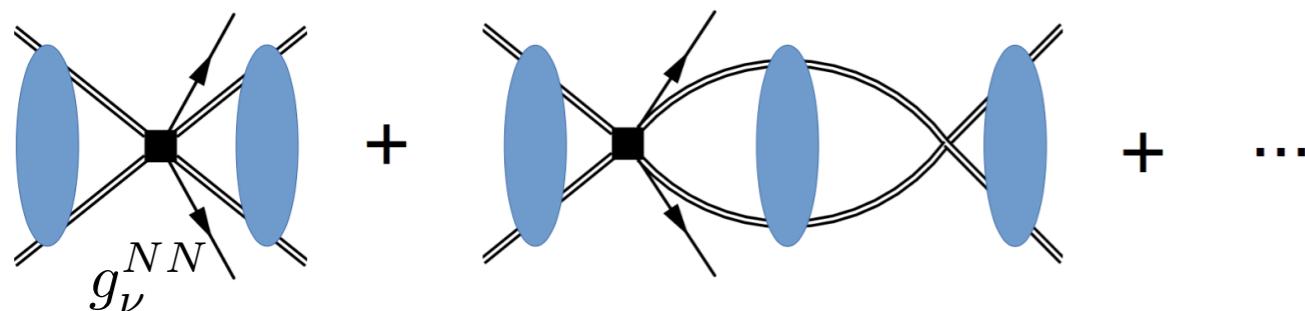
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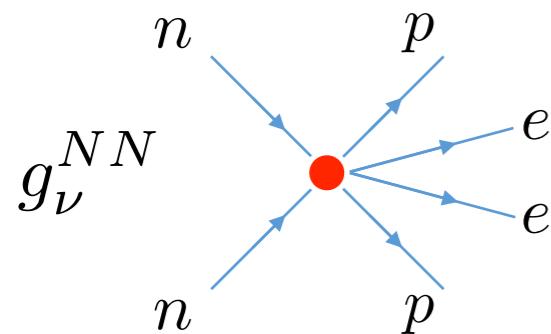
Dressing with strong interactions:



Can absorb the divergence

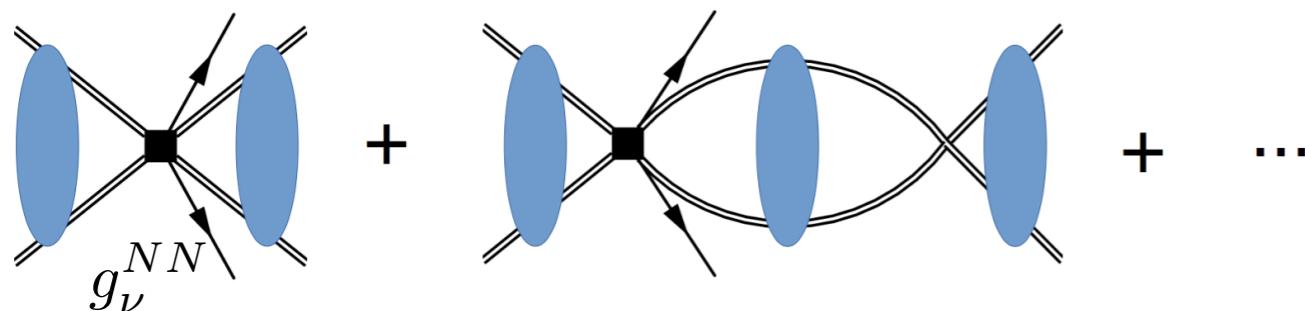
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Dressing with strong interactions:



Can absorb the divergence

- The renormalization group suggests this counter term is leading order

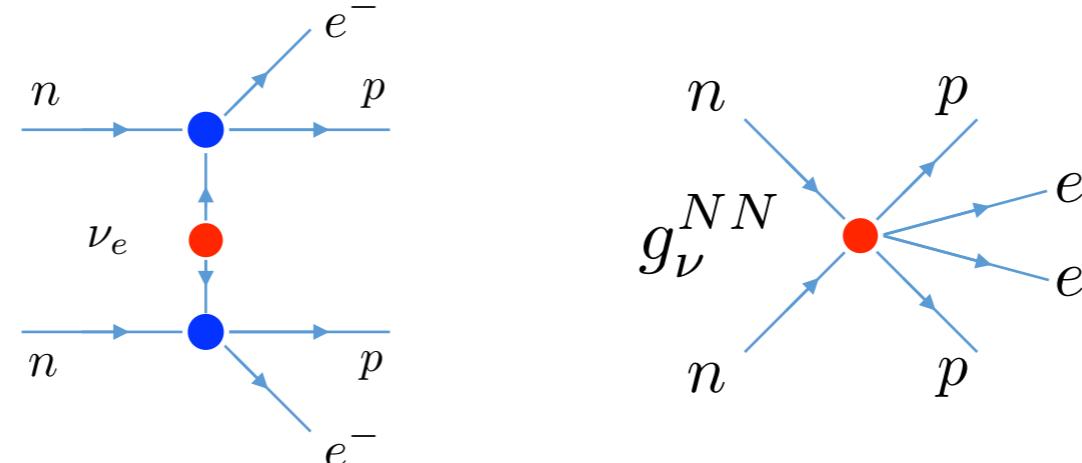
$$\frac{d}{d \ln \mu} \frac{g_\nu^{NN}}{(m_N \tilde{C}/4\pi)^2} = \frac{1}{2} + g_A^2 \quad g_\nu^{NN} = \mathcal{O}(1/F_\pi^2)$$

- Same conclusion in a cut-off scheme

Impact of the counter term

- To obtain a physical amplitude we have to include g_ν^{NN} in the potential

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

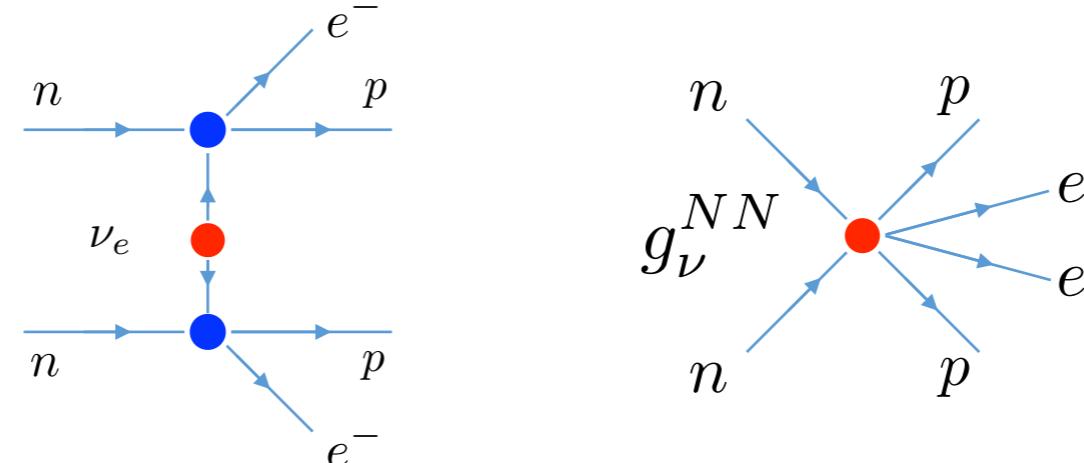


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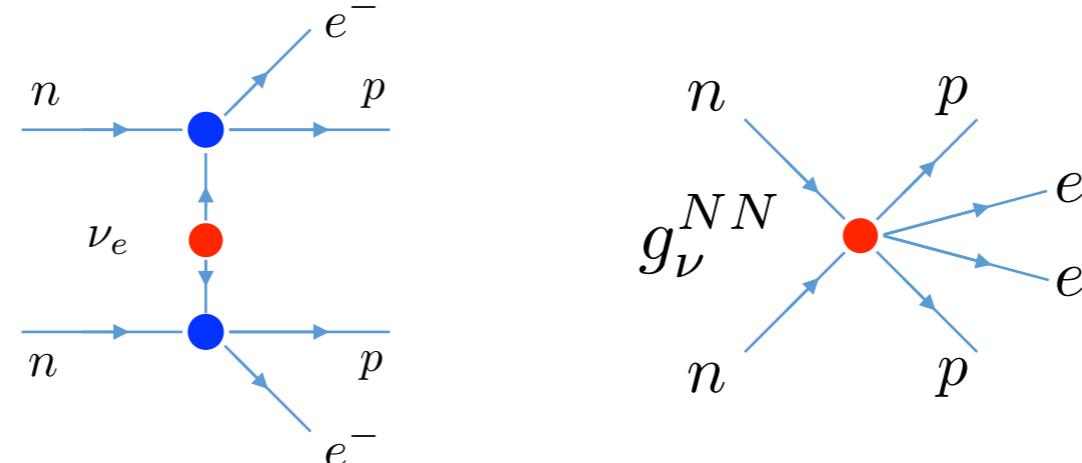
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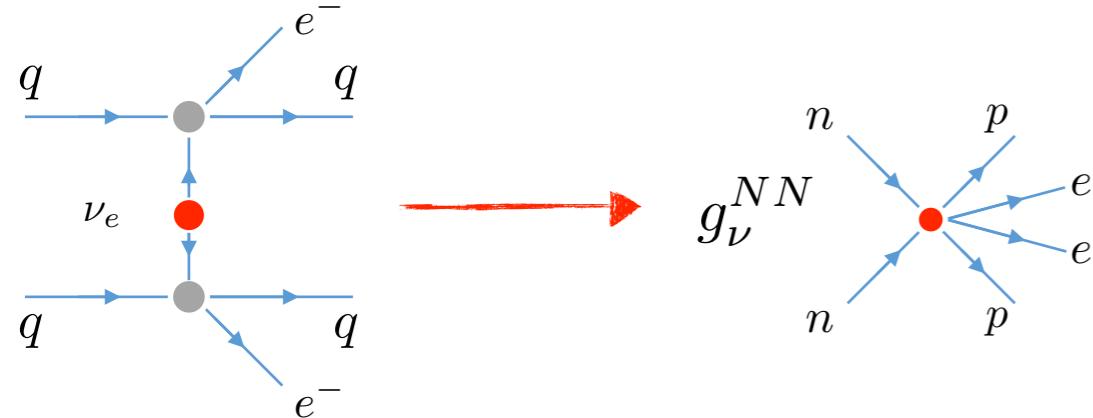
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- Estimate from relation to EM

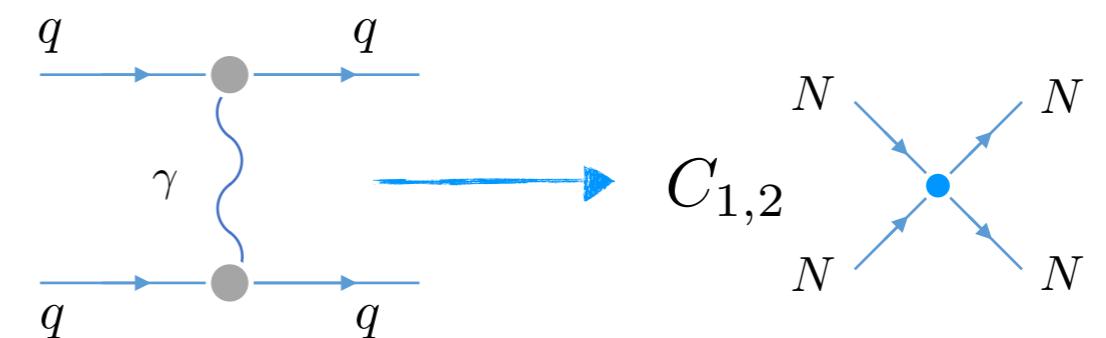
Relation to electromagnetism

Relation to electromagnetism

LNV contact term

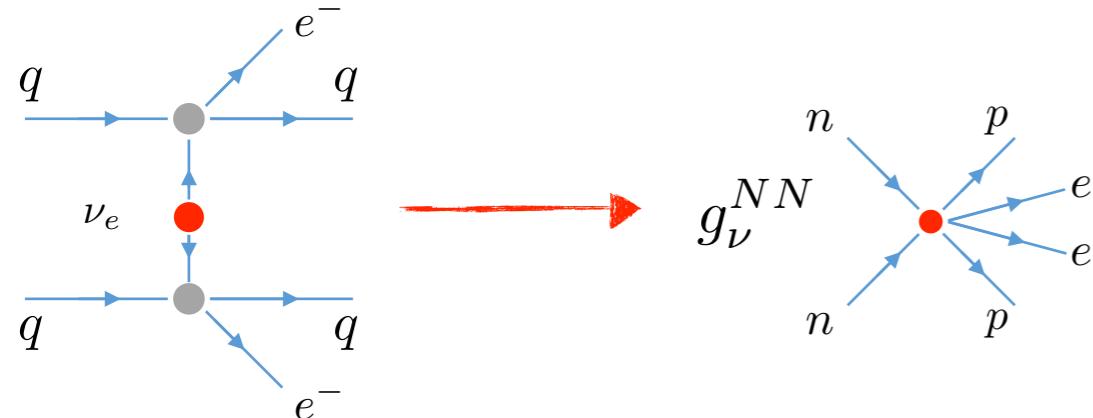


EM contact term

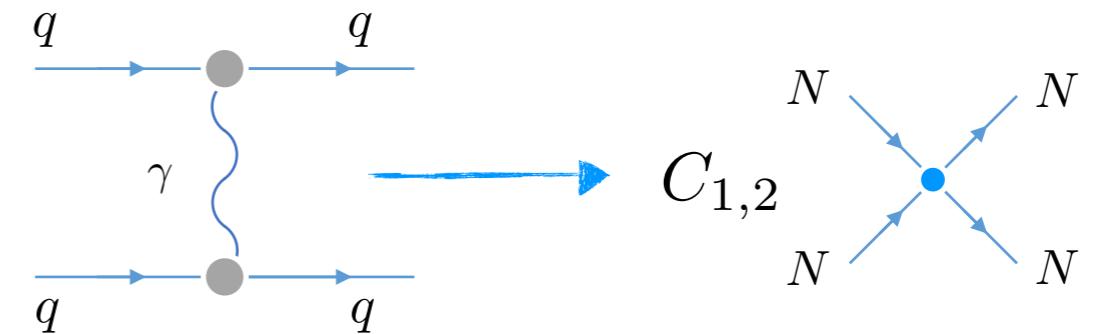


Relation to electromagnetism

LNV contact term



EM contact term



- Hard part of two Weak currents

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

- Leptonic part combines to boson propagator

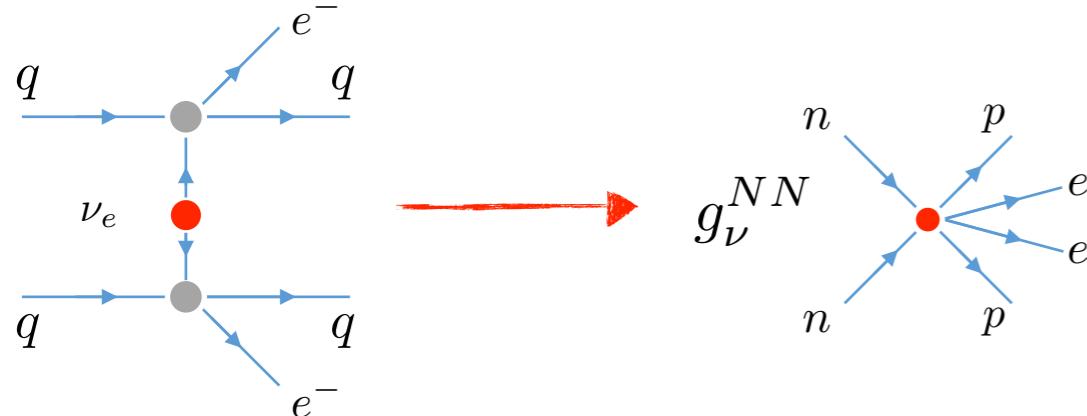
- Hard part of two EM currents

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

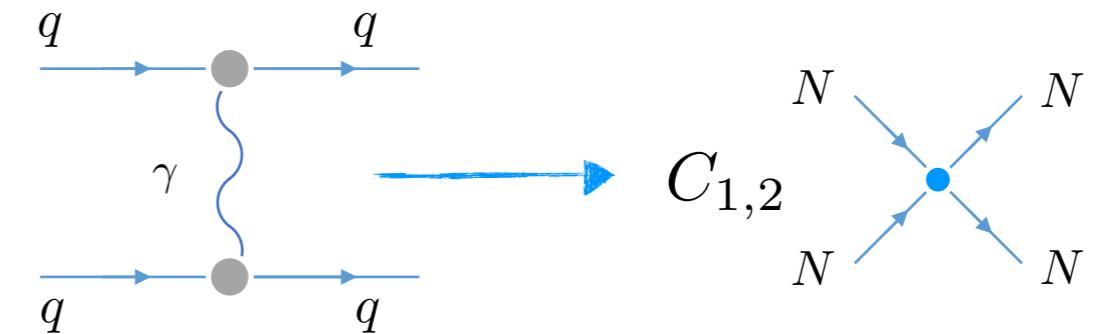
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Relation to electromagnetism

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- Non-hadronic part is the photon propagator

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

Relation to electromagnetism

- Only two $\Delta l=2$ operators can be induced

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with spurions

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LNV

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

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Chiral symmetry

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

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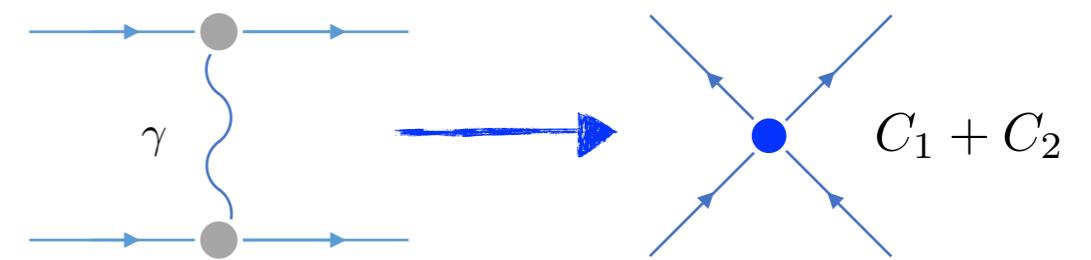
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- EM induces an extra term
 - Equivalent up to 2 pions
 - Hard to disentangle

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

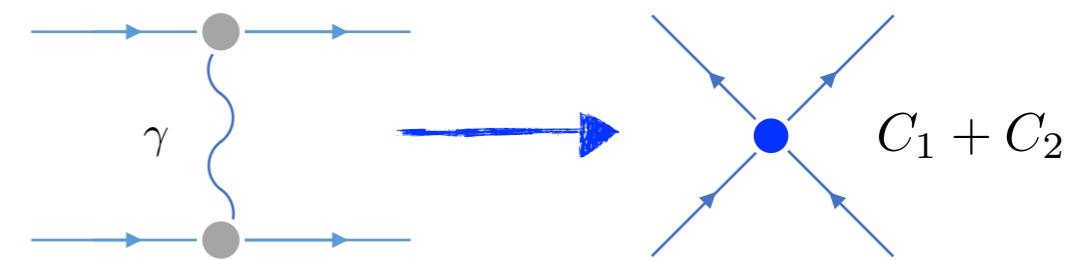
Relation to electromagnetism

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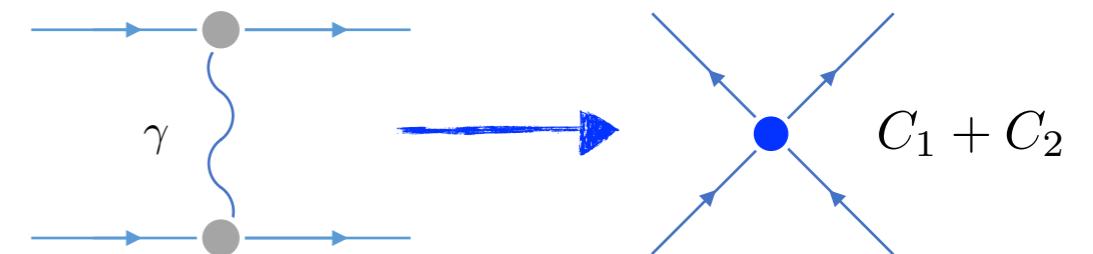
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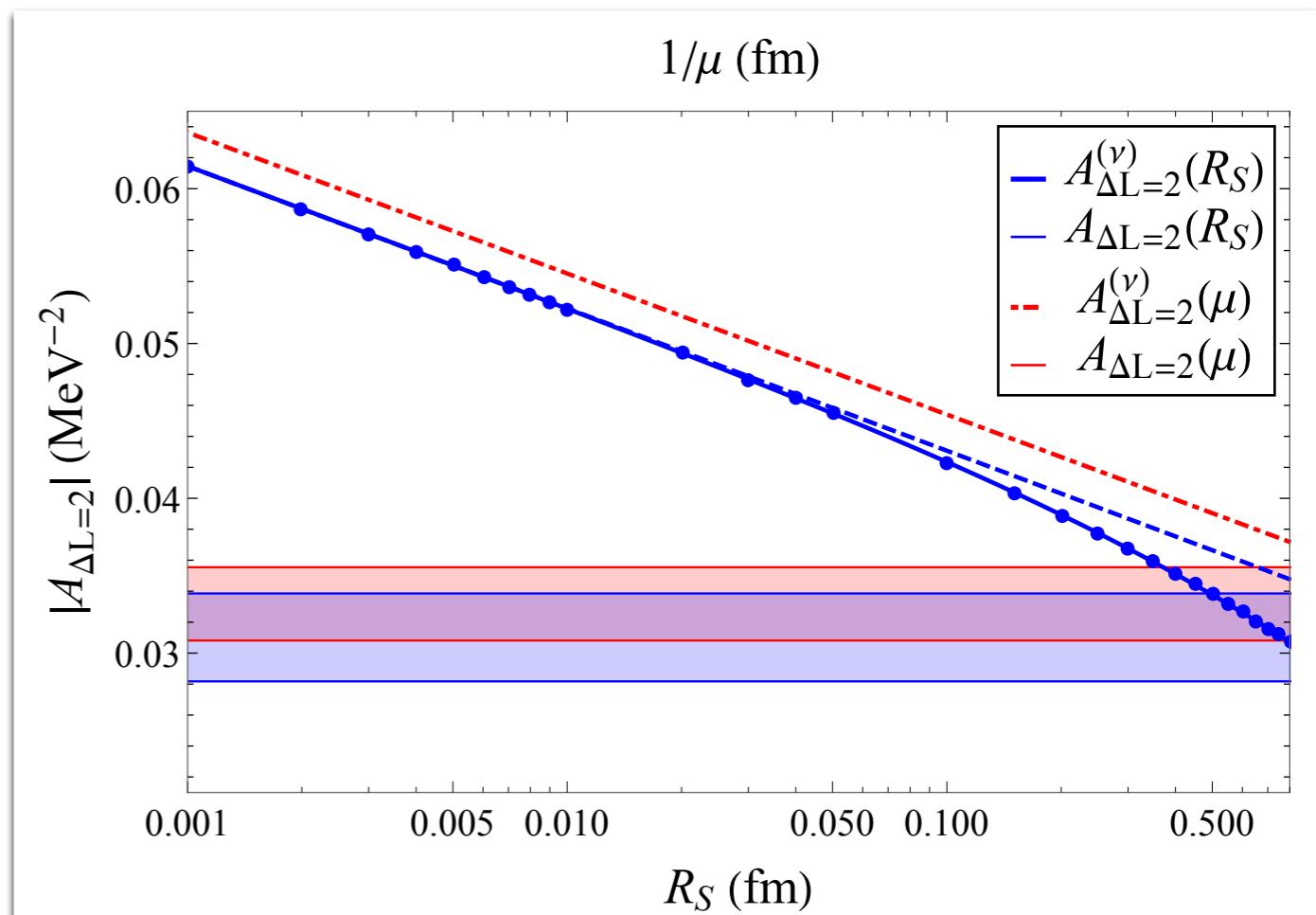
- Allows an estimate of g_ν^{NN}
 - Extract $C_1 + C_2$ from CIB
 - Assume $g_\nu^{NN}(\mu) = \frac{C_1(\mu) + C_2(\mu)}{2}$
 - Roughly 10% effect for $R_s = 0.6$ fm
 - Uncontrolled error

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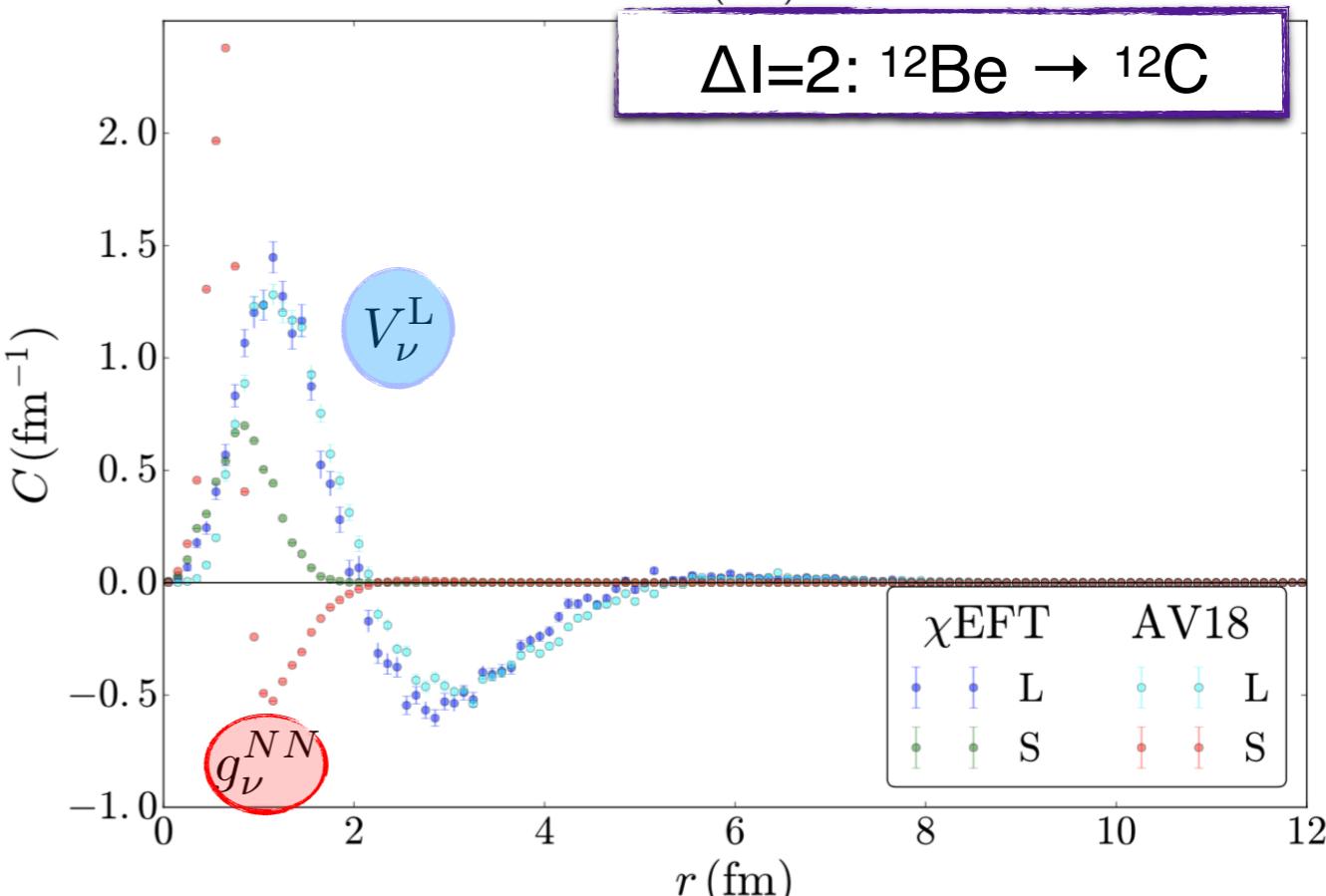
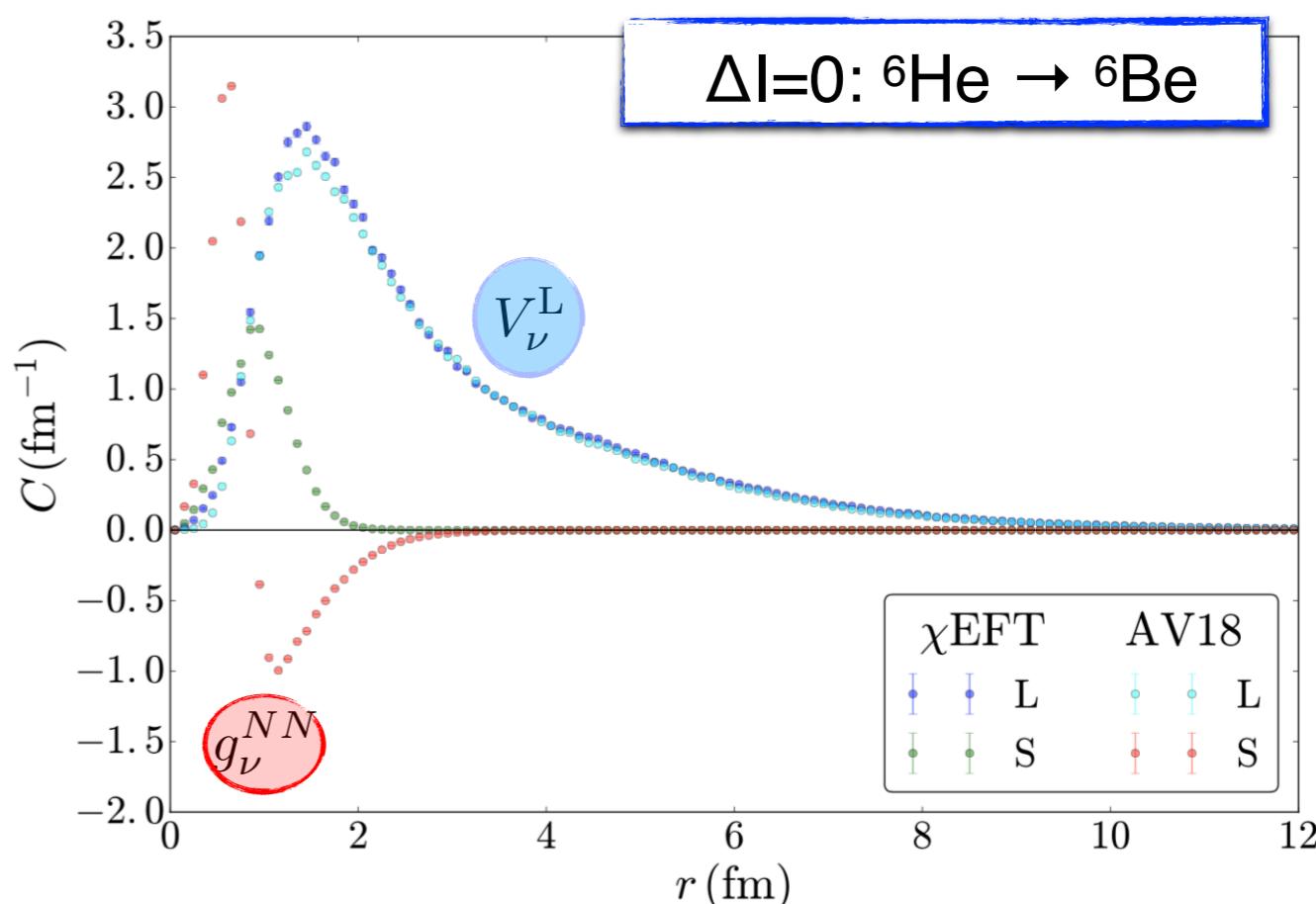
Estimate of impact in light nuclei

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
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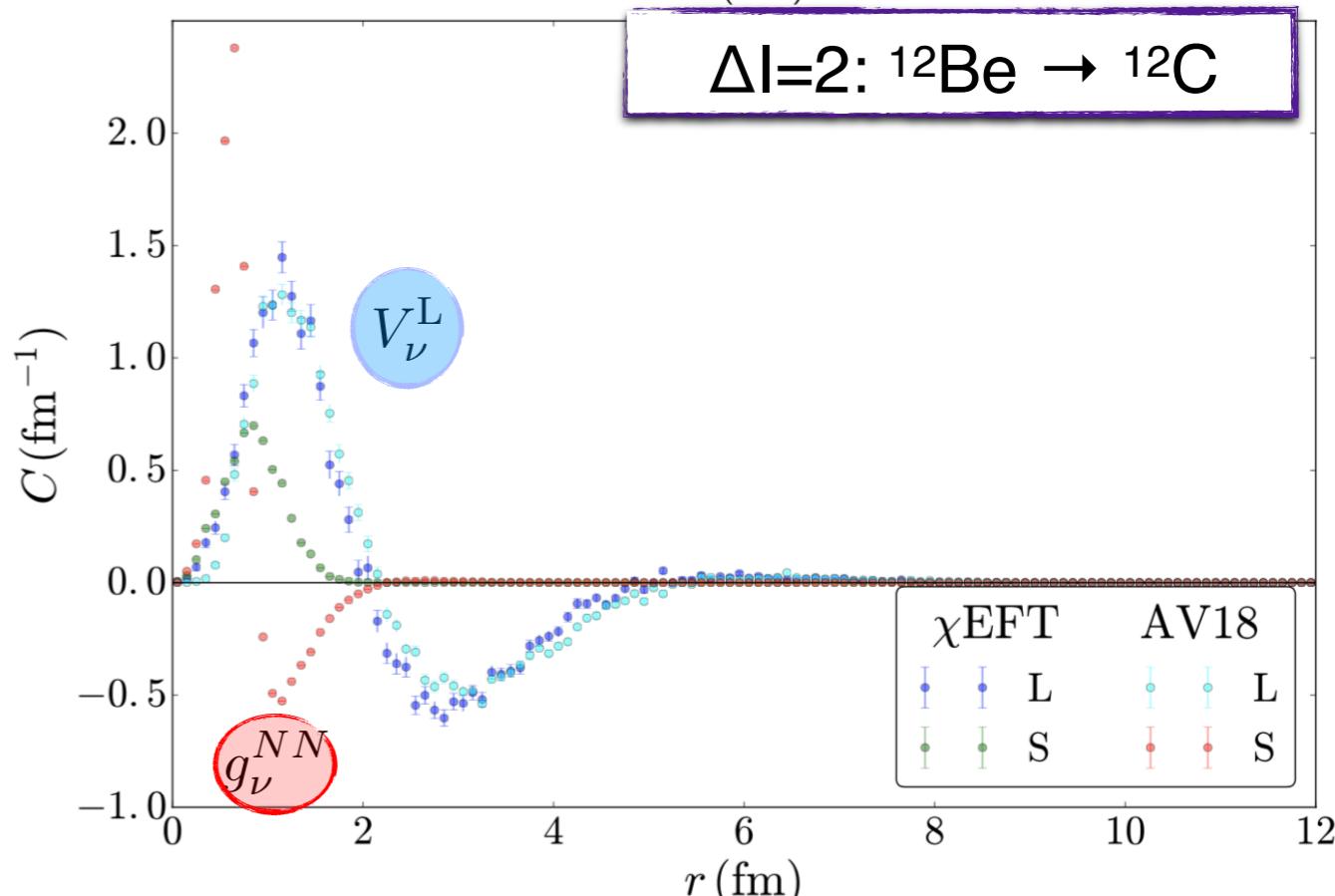
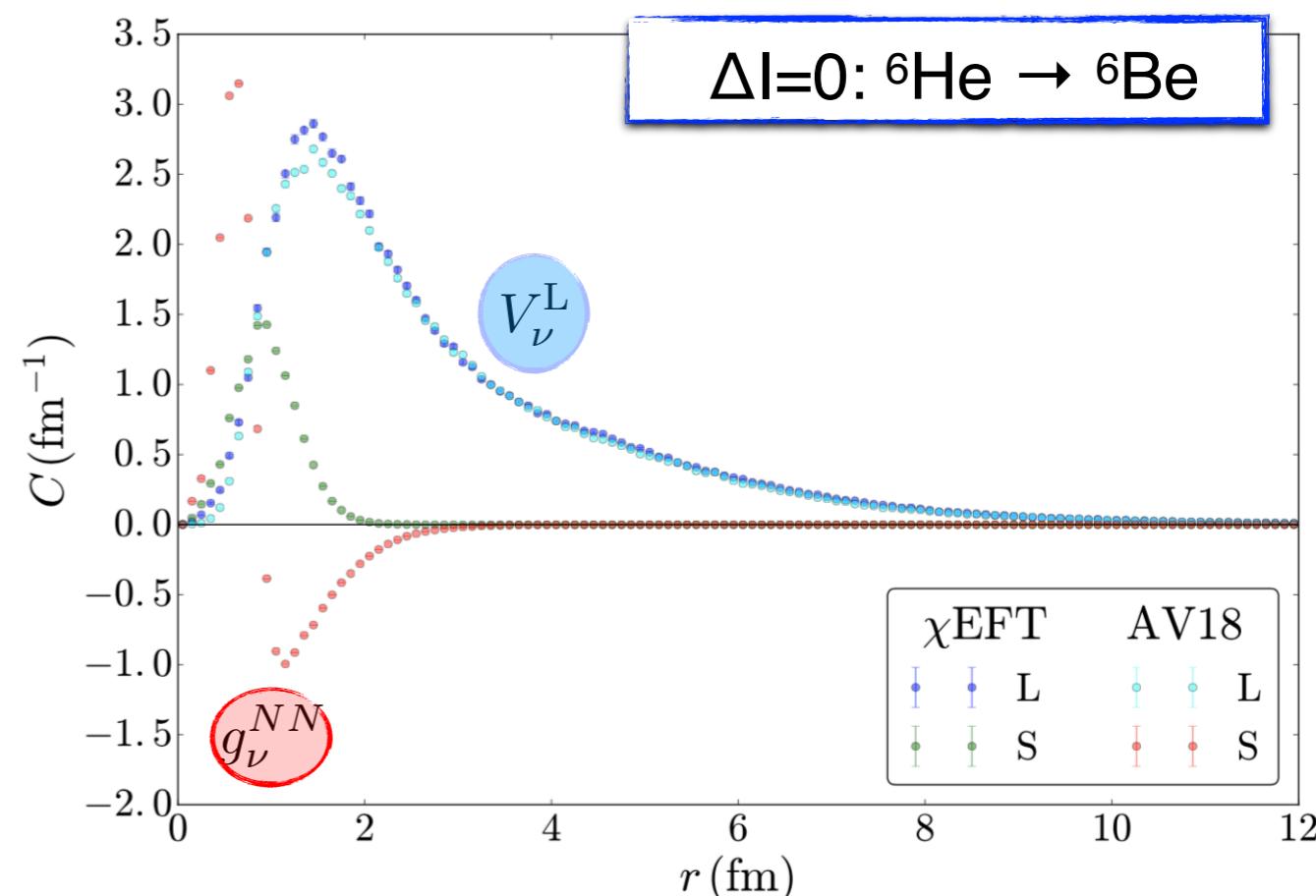
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 - Feature in realistic $0\nu\beta\beta$ candidates



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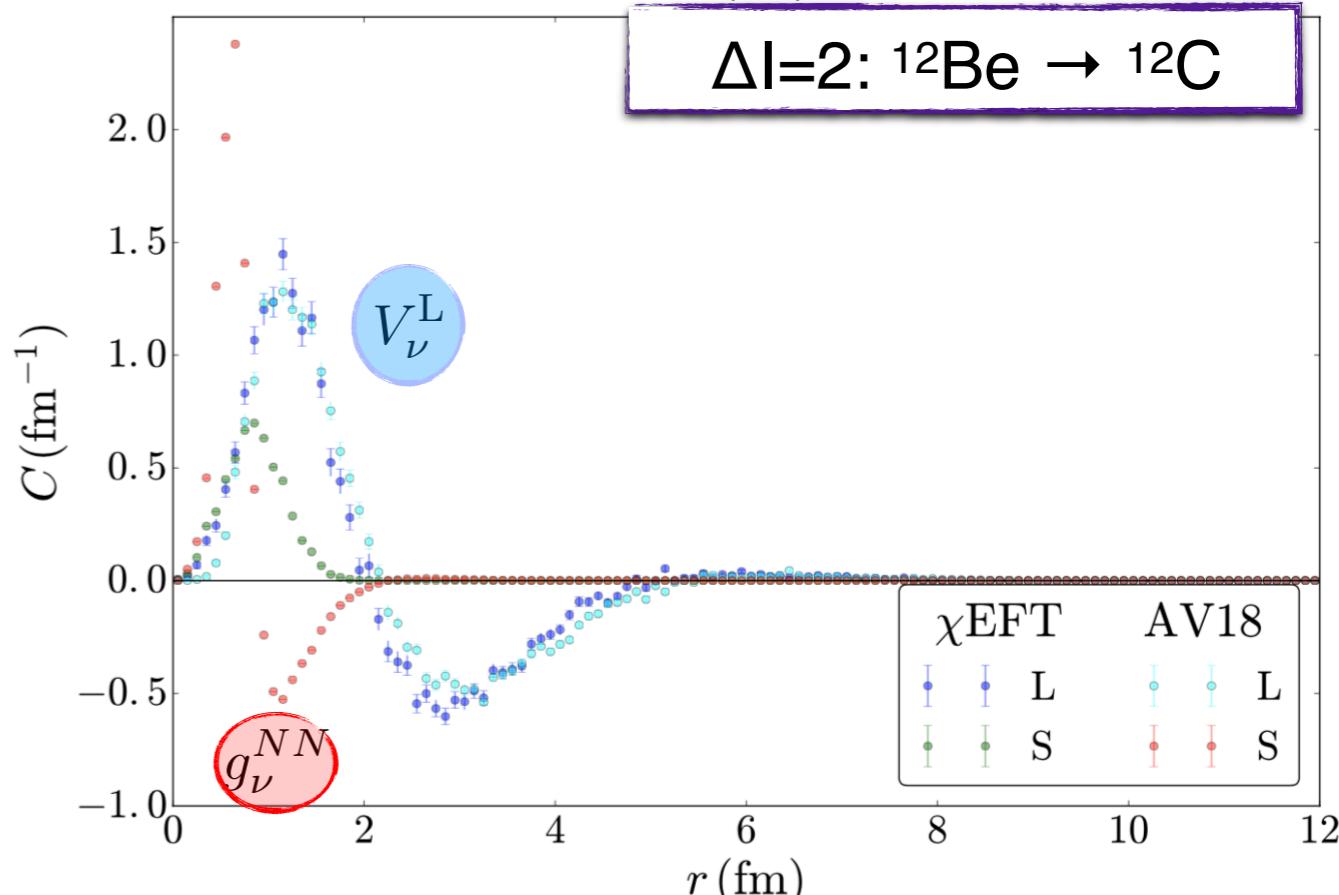
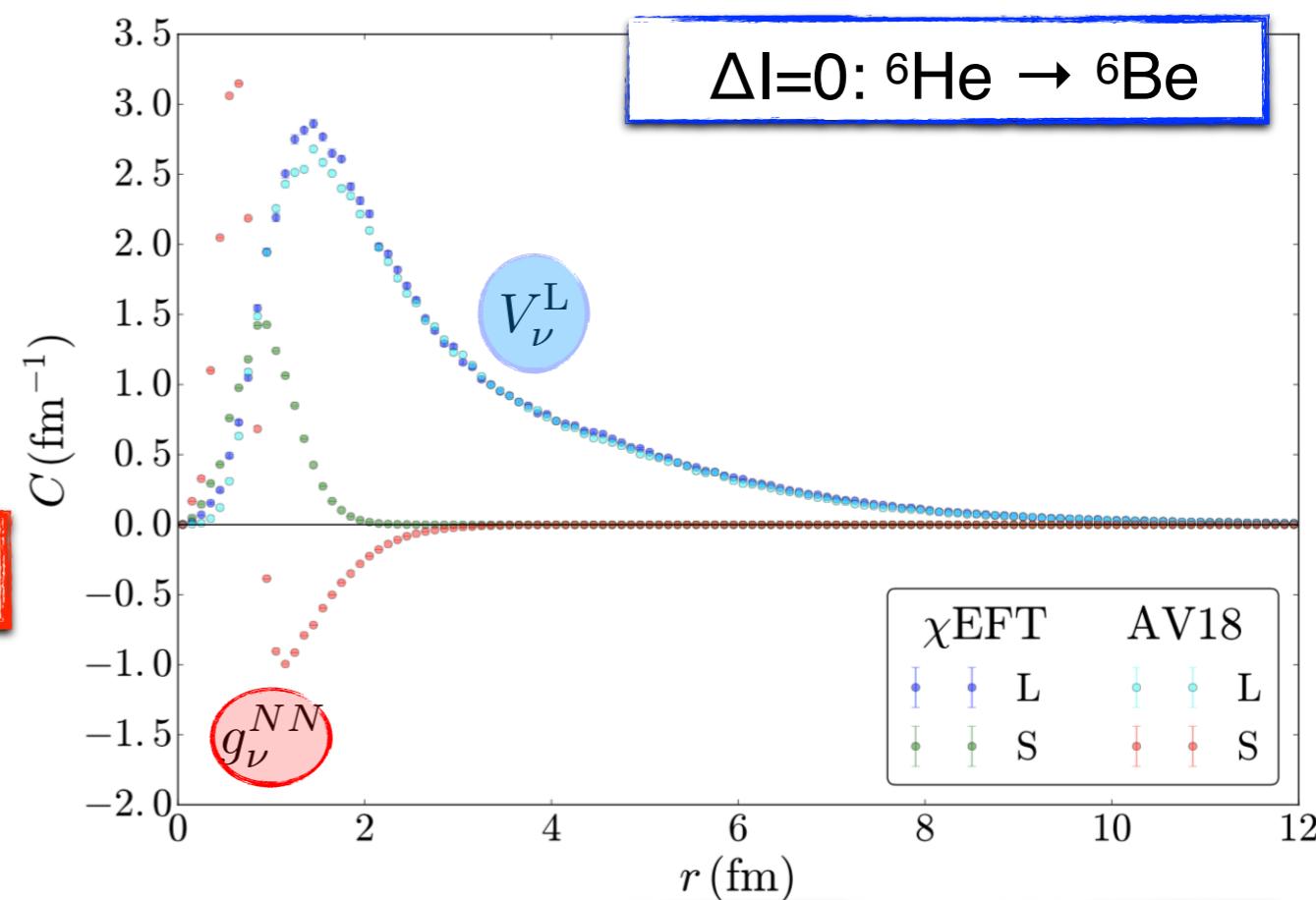
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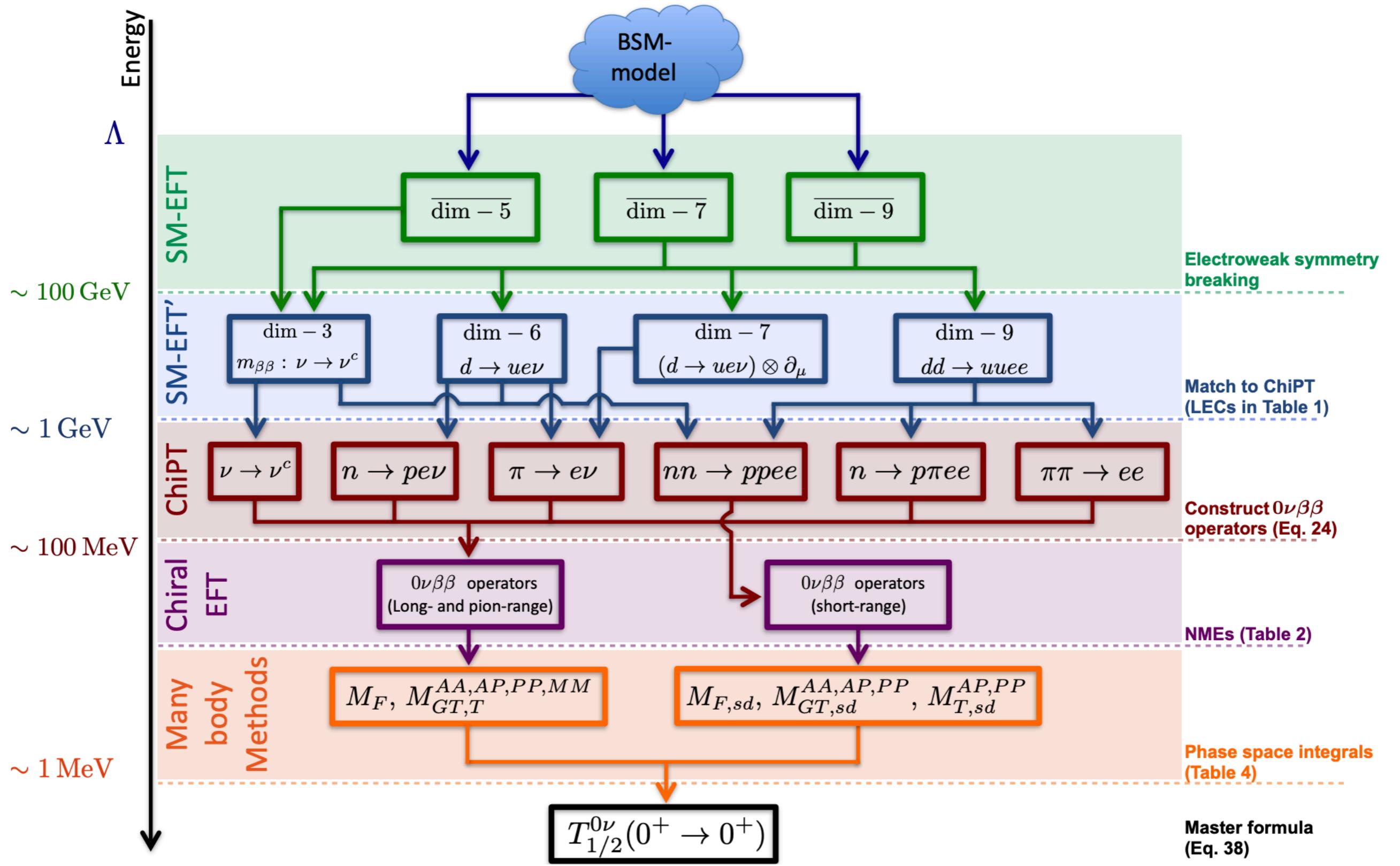
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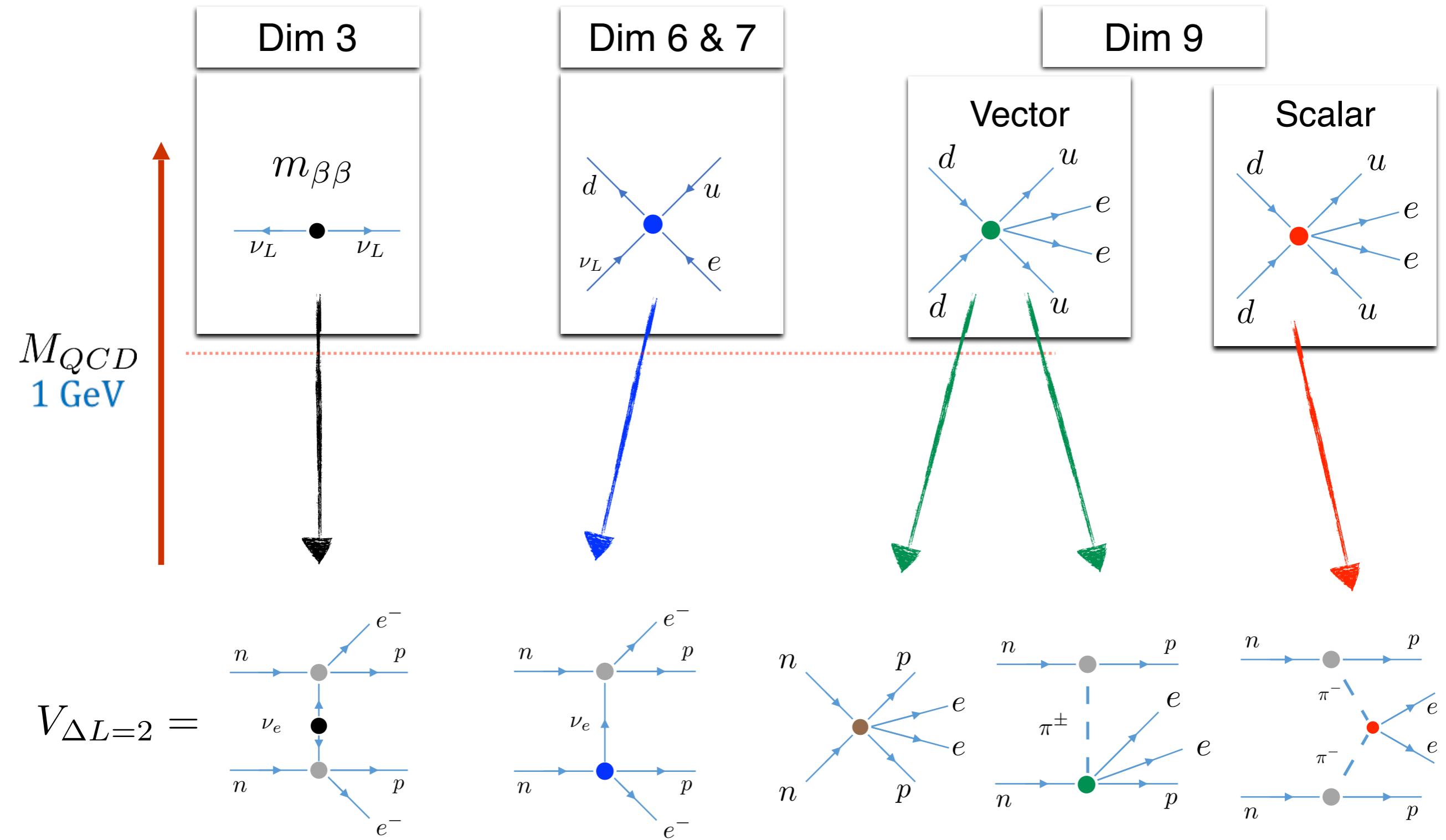
Higher-dimensional operators

Other mechanisms



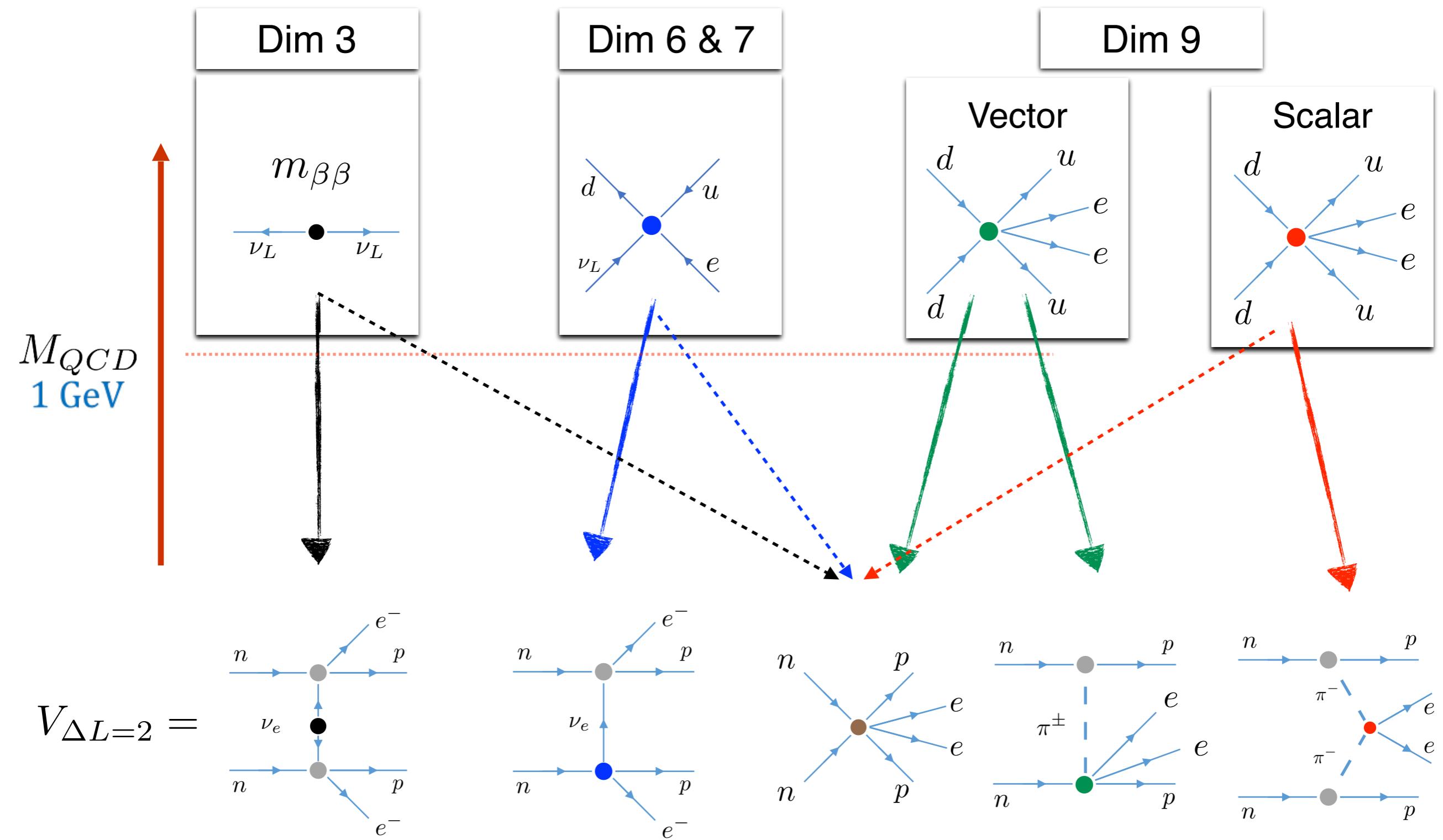
Matching to Chiral EFT

Weinberg power counting



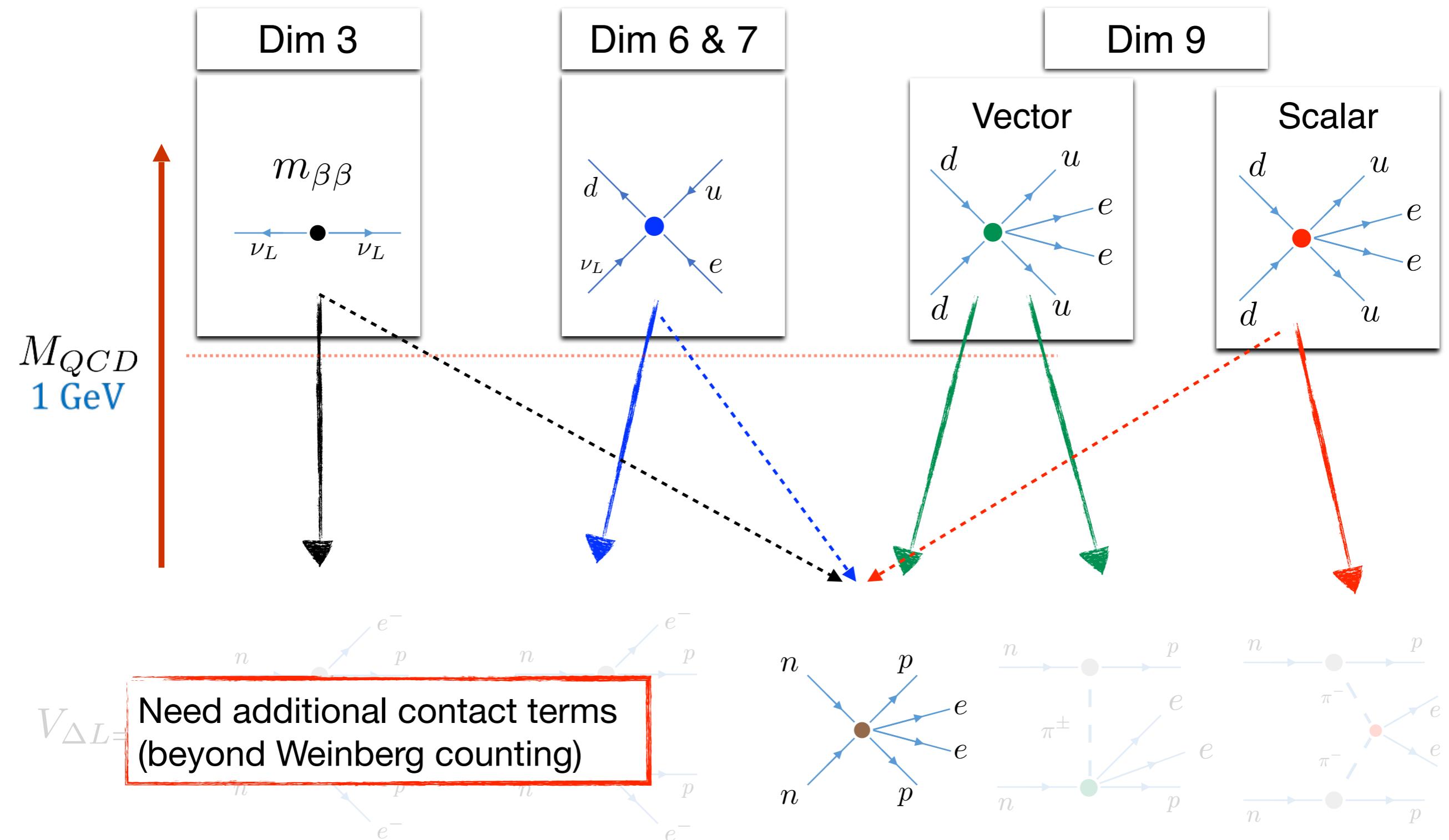
Matching to Chiral EFT

Beyond NDA / Weinberg



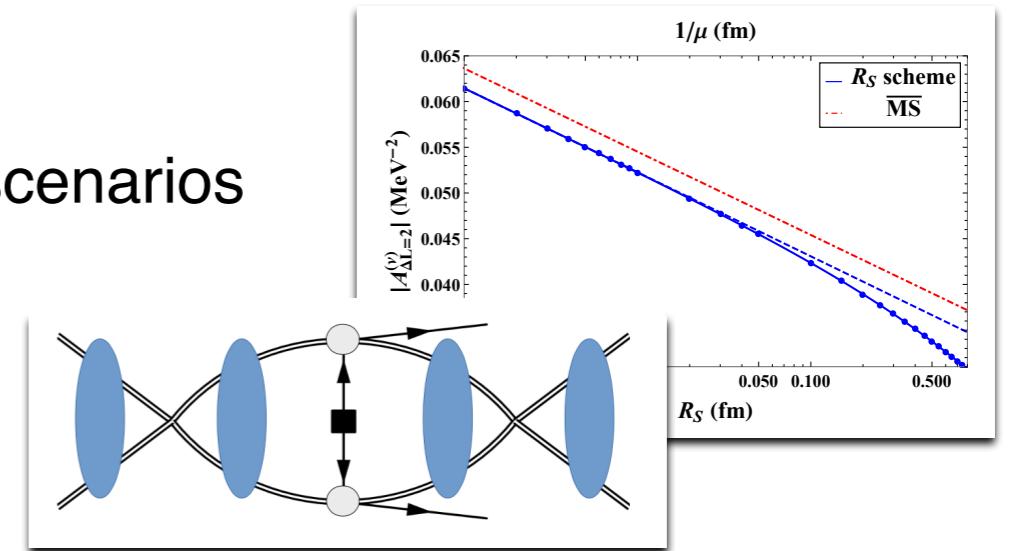
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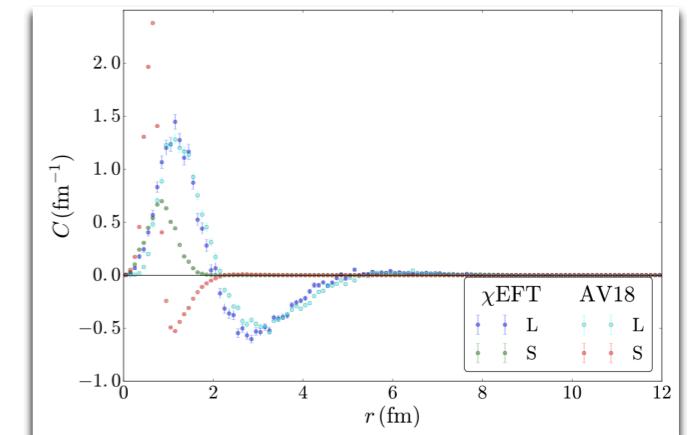


Summary

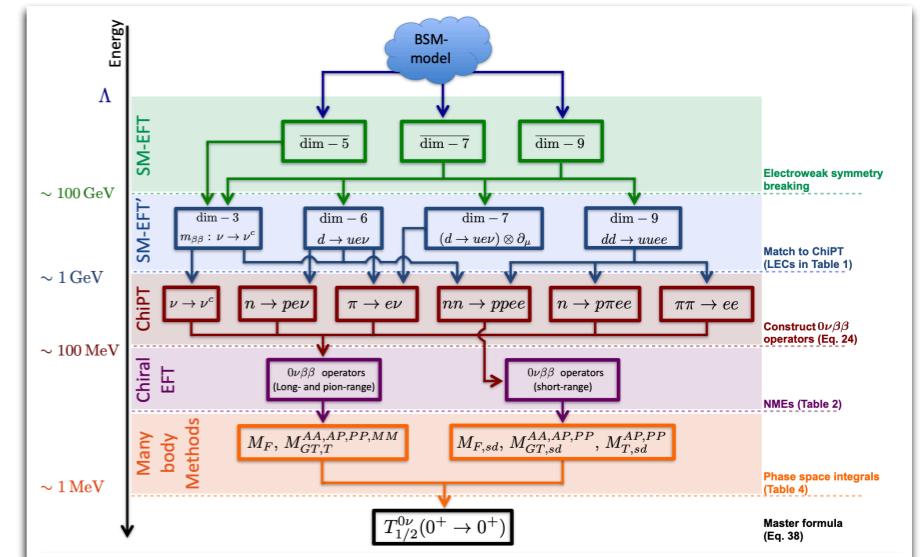
- EFTs allow a model-independent description of $\Delta L=2$ scenarios
- Renormalization requires counterterms beyond NDA



- The additional contact interaction appears at leading order
- Estimates suggest an $O(1)$ impact on the amplitude
 - Based on assumptions with uncontrolled errors



- Same framework applies to dimension-7,-9 operators
- Issues with NDA power counting appear here too



Back up slides

Dimension-7,-9 operators

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

$$c_9 = \mathcal{O}(1), \quad c_7 = \mathcal{O}(y_e), \quad c_5 = \mathcal{O}(y_e^2)$$

$$y_e = m_e/v \sim 10^{-6}$$

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

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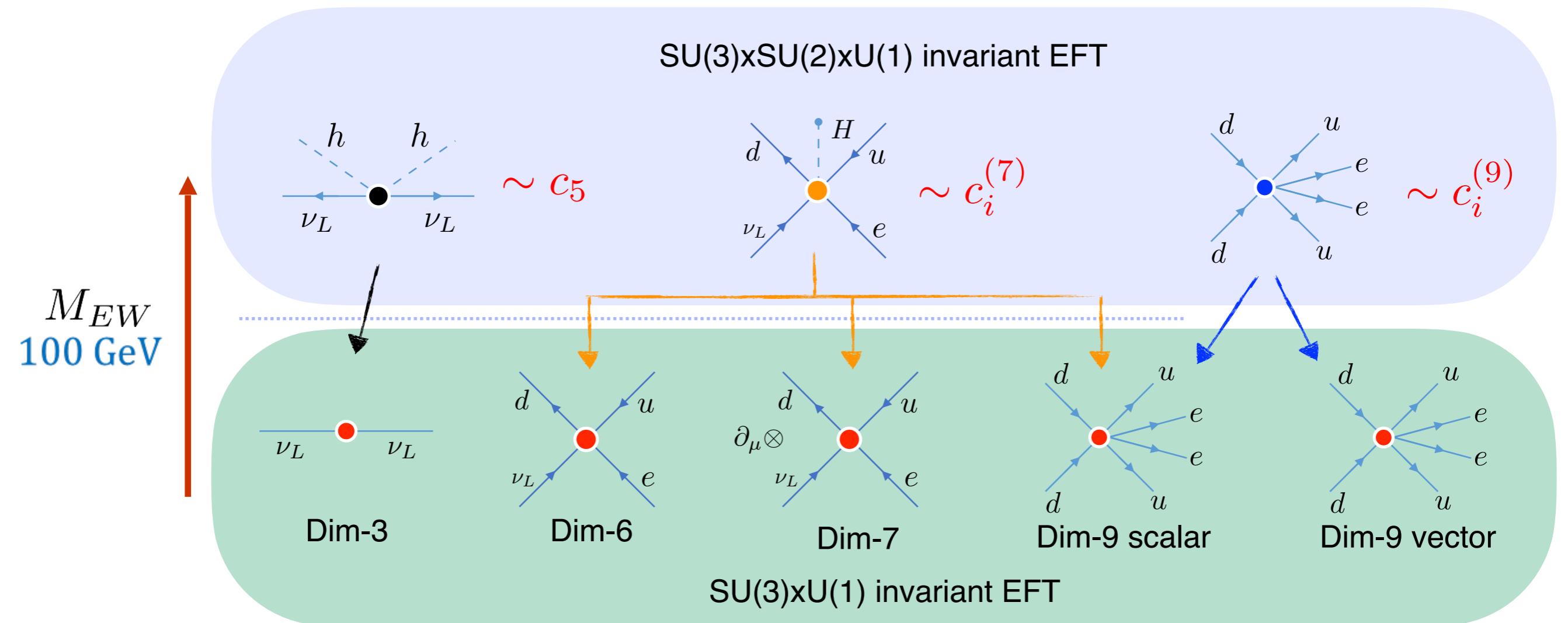
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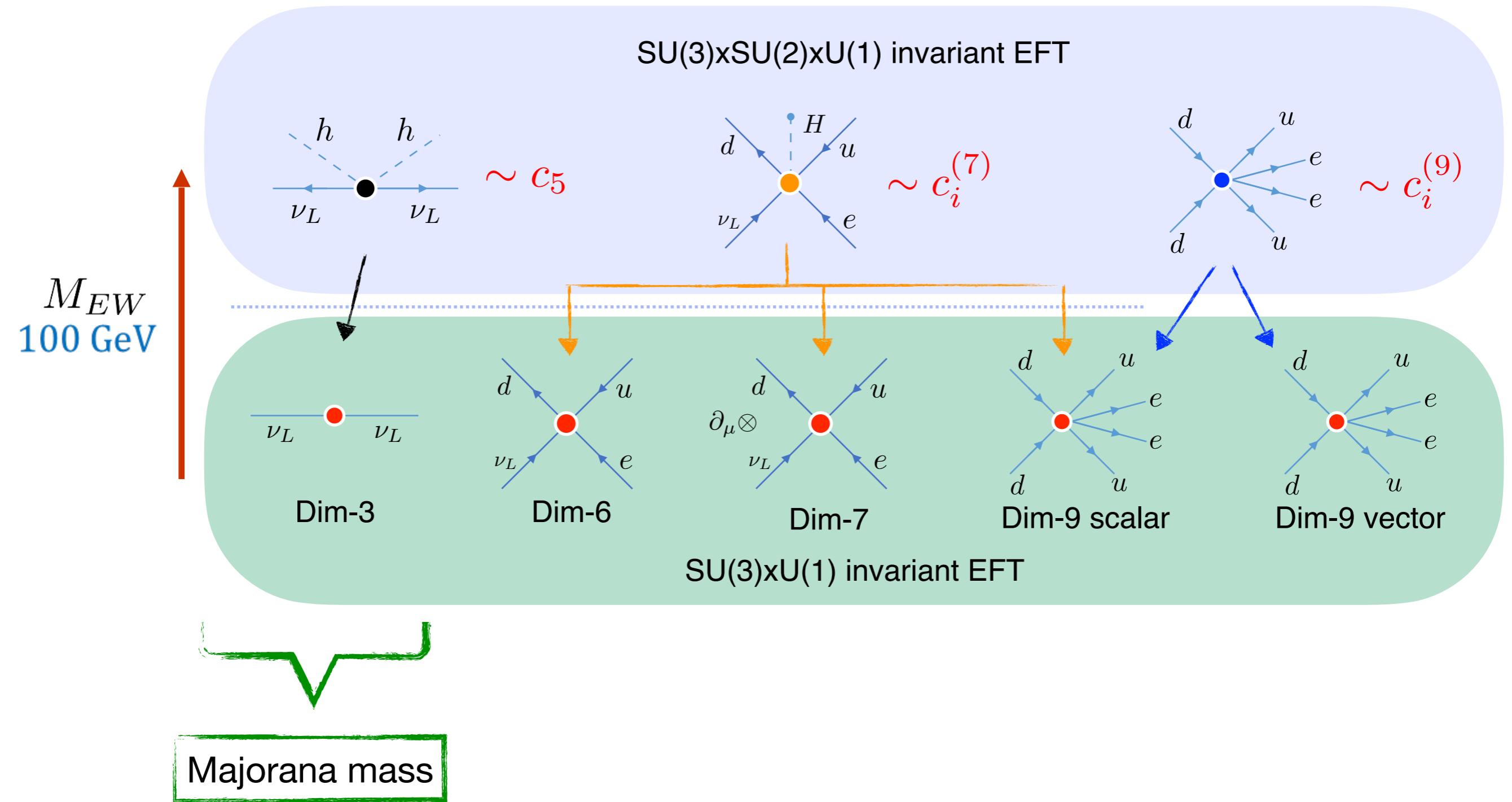
Low-energy operators

Matching



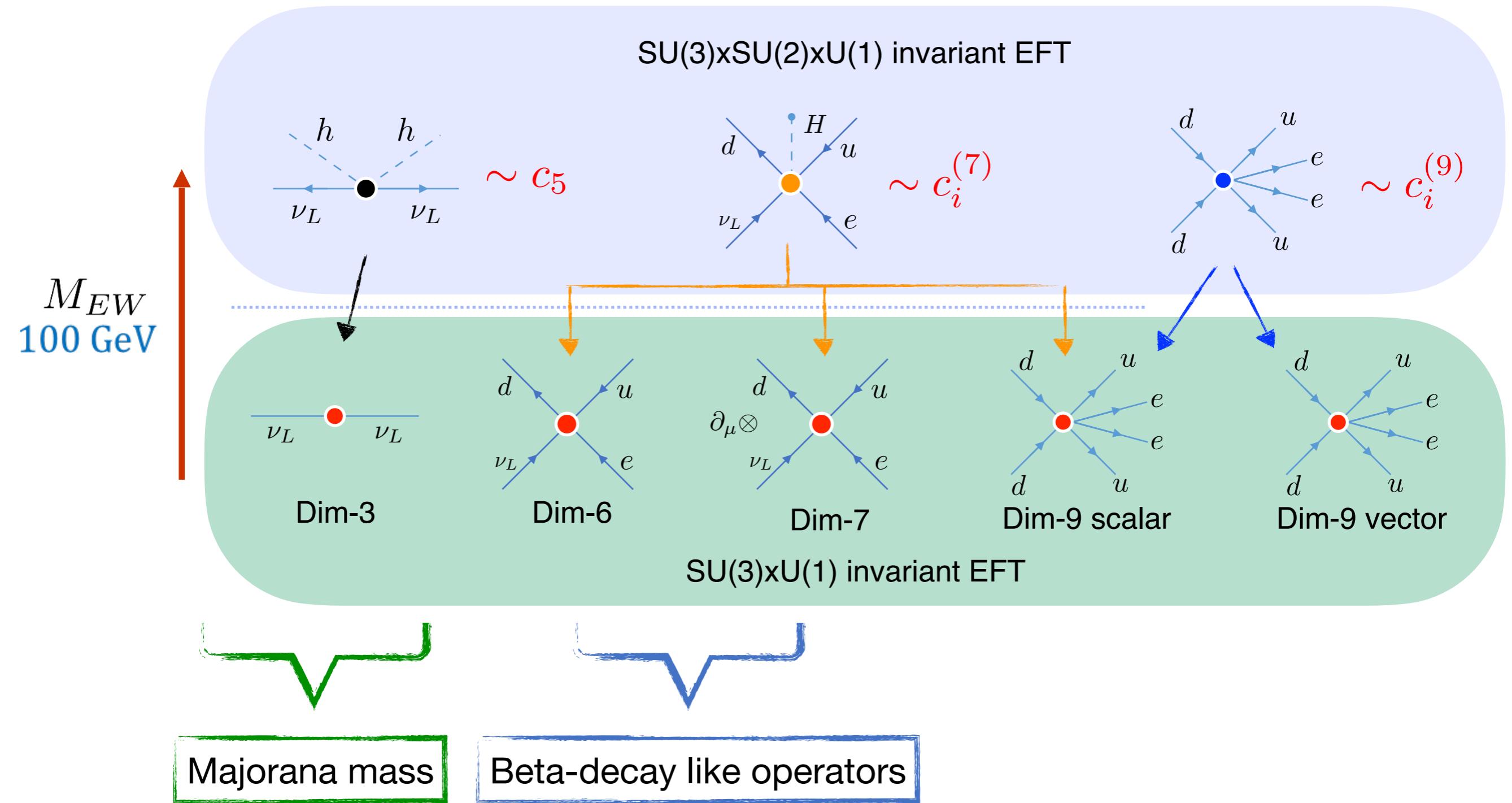
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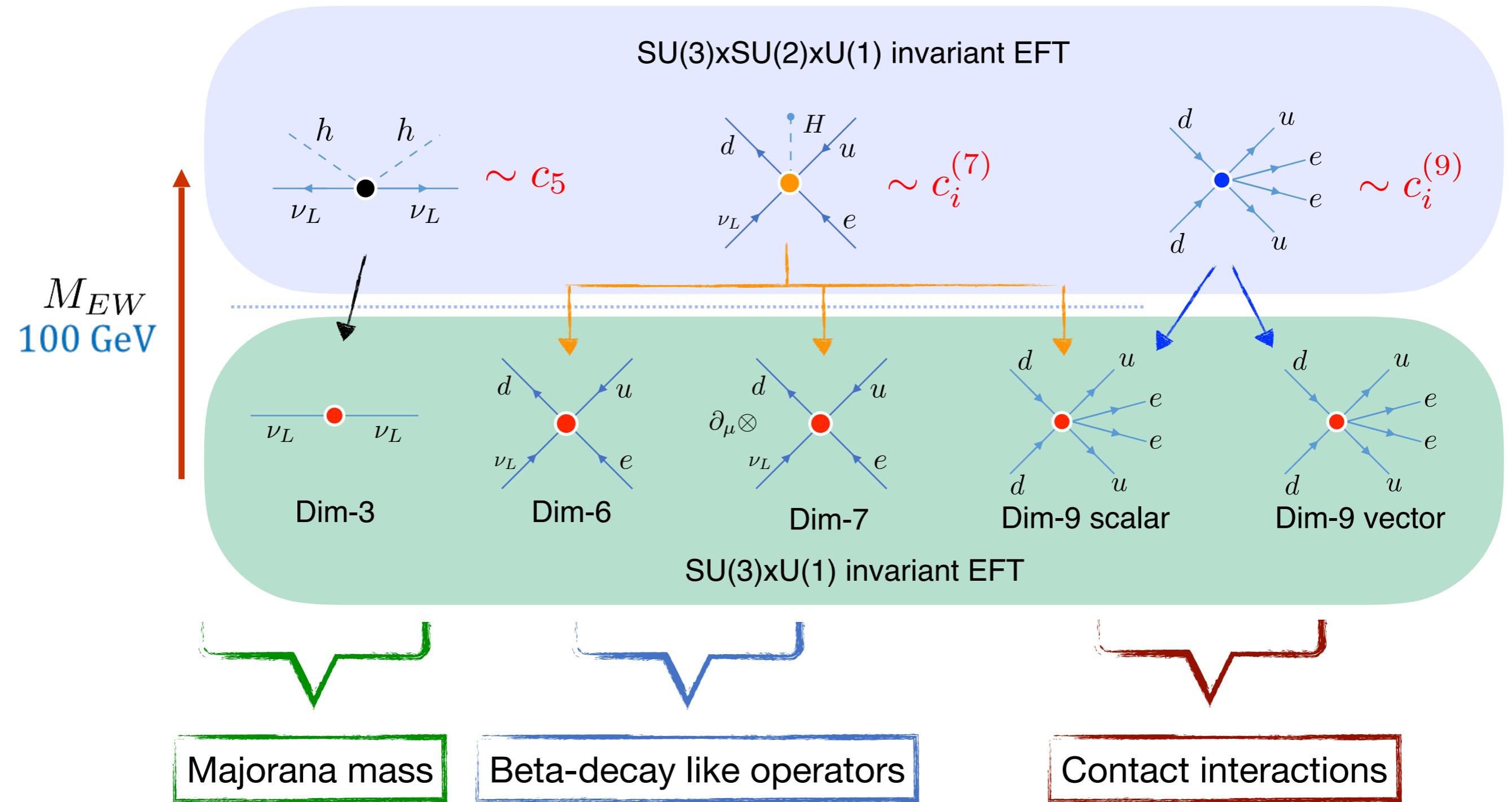
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Nuclear matrix elements

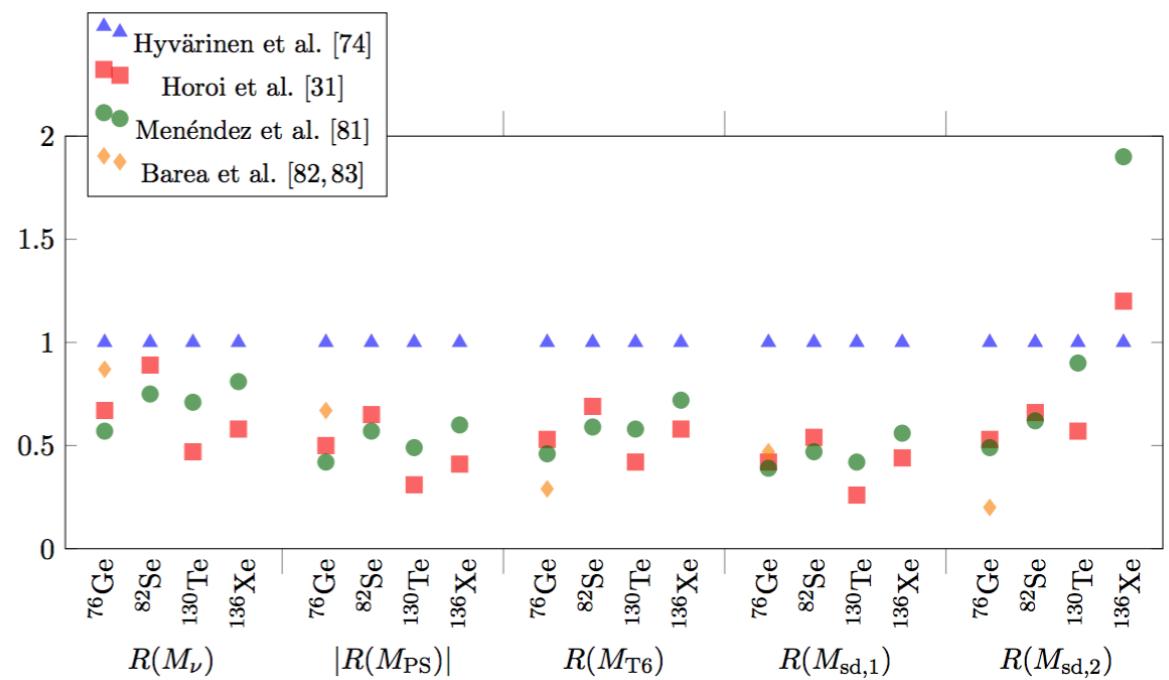
- All NMEs can be obtained from those of light/heavy neutrino exchange
 - 9 long-distance & 6 short-distance
 - Have been determined in literature

NMEs	${}^{76}\text{Ge}$			
	[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	${}^{76}\text{Ge}$			
	$M_{F, sd}$	$M_{GT, sd}^{AA}$	$M_{GT, sd}^{AP}$	$M_{GT, sd}^{PP}$
$M_{F, sd}$	-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

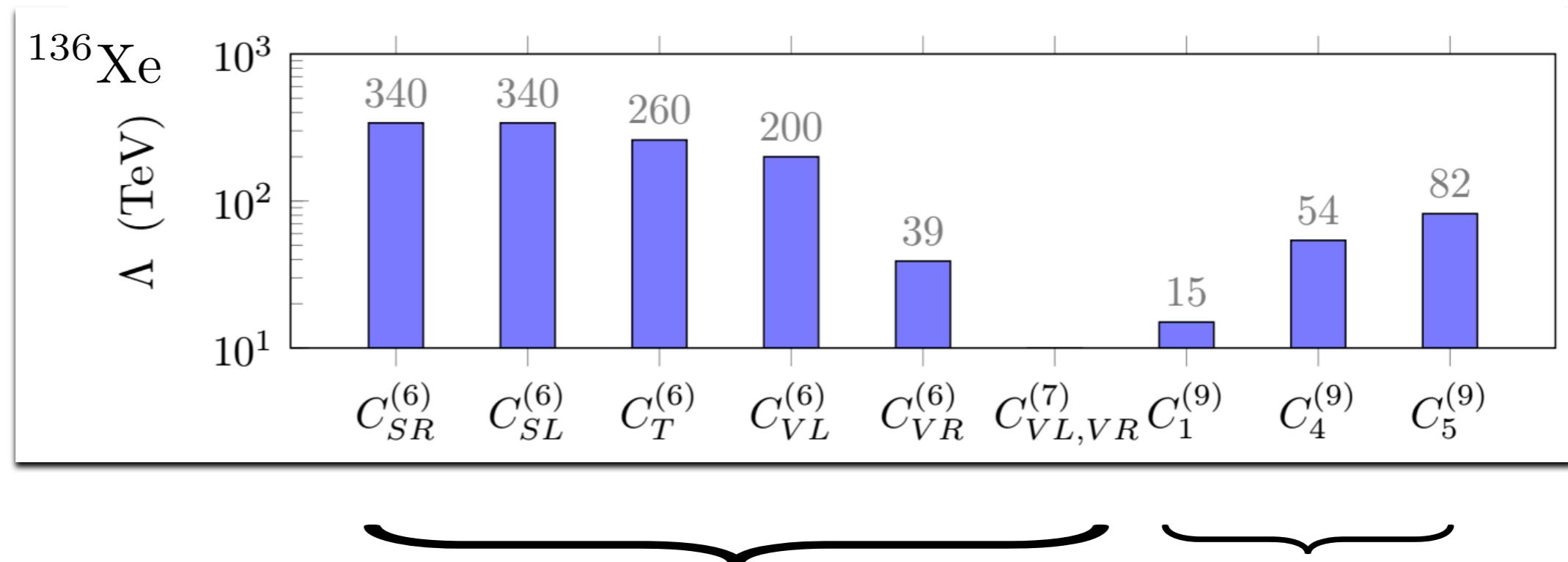
- Follow ChPT expectations fairly well
 - E.g. all $O(1)$

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

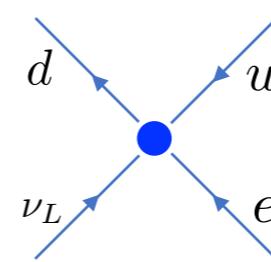


Current limits

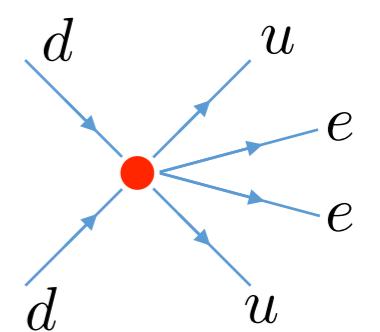
- Assumes $C_i = v^3/\Lambda^3$



- Uncertainties:
 - Unknown LECs
 - Nuclear Matrix elements



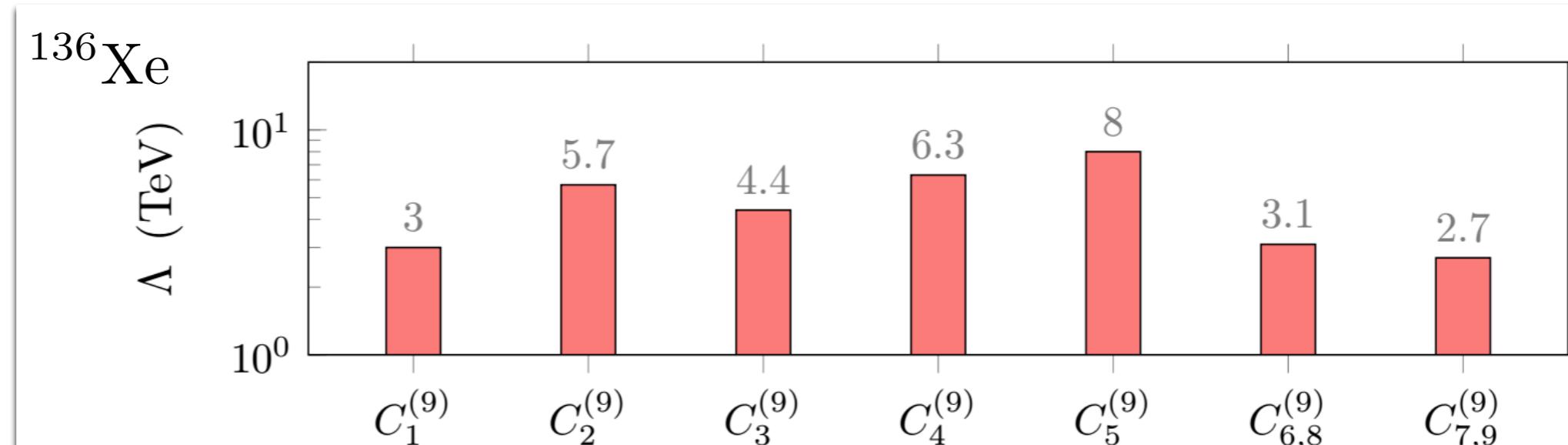
Dim 6 & 7



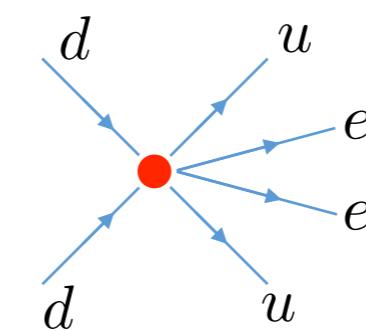
Dim 9

Current limits

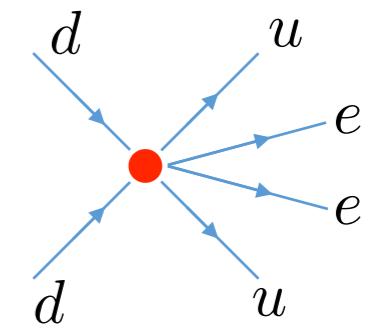
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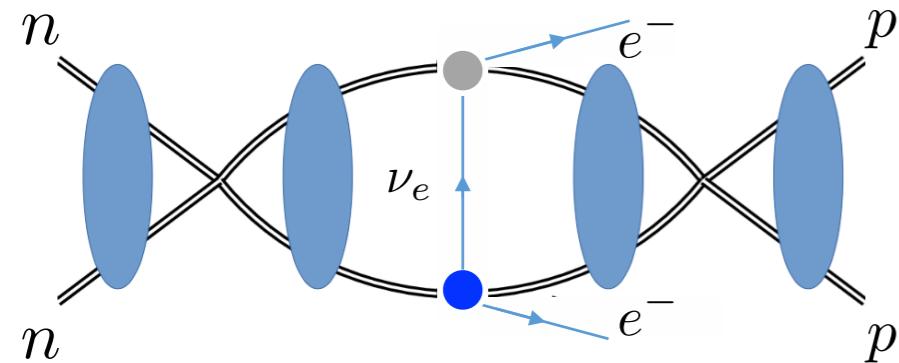
Dim 9
Scalar



Dim 9
Vector

Matching to Chiral EFT

Checking Weinberg power counting



$$\sim m_N^2 \int d^3 q d^3 k \frac{1}{m_N E - \vec{q}^2} V_{\Delta L=2} \frac{1}{m_N E' - \vec{k}^2}$$

Dimension-6,7,9

- Several potentials have the same behavior
 - The case for the vector operators $C_{VL,VB}^{(6)}$: $V_{\Delta L=2} \sim 1/\vec{q}^2$

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$$C_{1-9}^{(9)} : V_{\Delta L=2} \sim \frac{1}{\bar{q}^2 + m_\pi^2}$$

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