Sterile neutrinos in $0\nu\beta\beta$

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with
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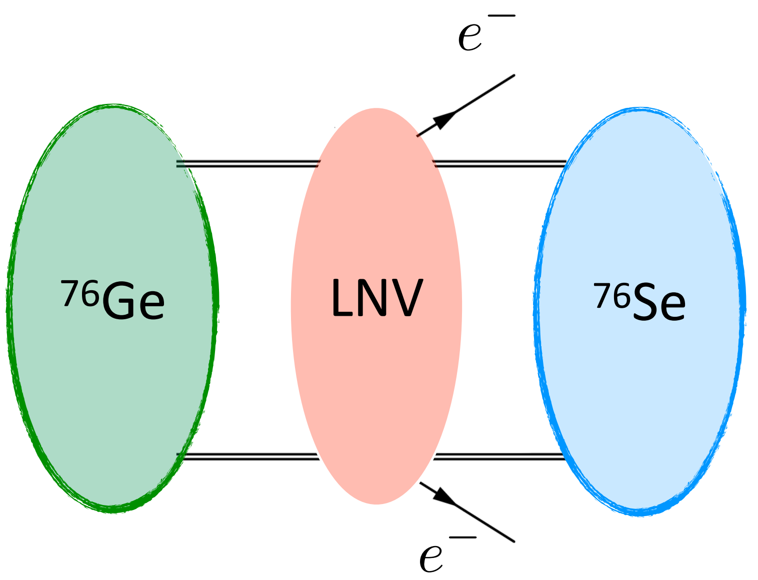
arXiv:2303.04168, 2002.07182

UNIVERSITY of WASHINGTON

INSTITUTE for NUCLEAR THEORY

$0\nu\beta\beta$

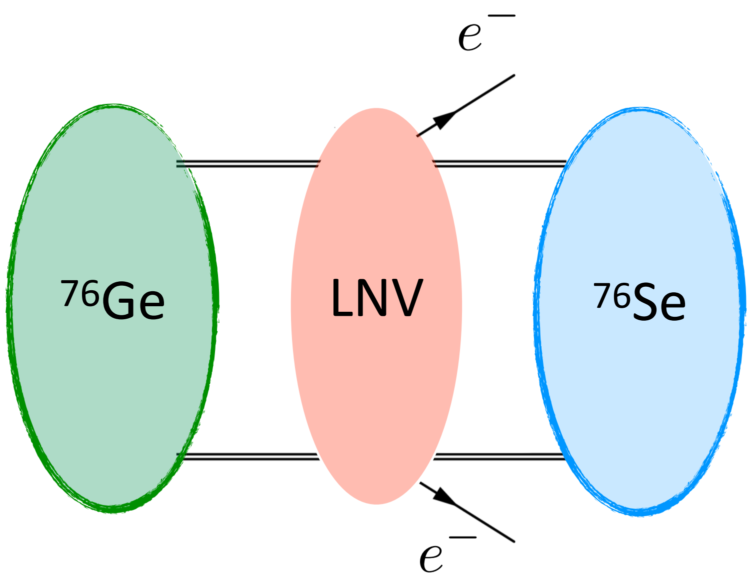


- Violates lepton number, $\Delta L=2$
- Stringently constrained experimentally
  - To be improved by 1-2 orders

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

Schechter, Valle, `82

$0\nu\beta\beta$



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

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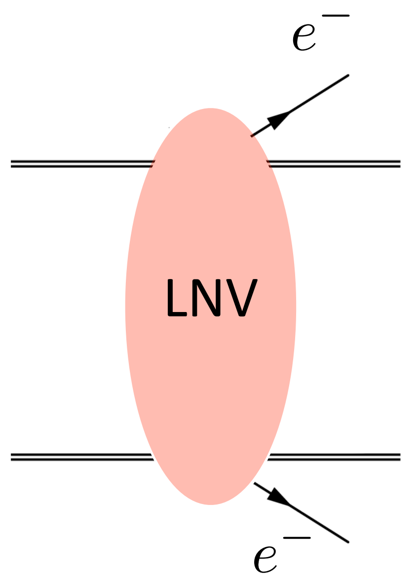

= **BSM physics**

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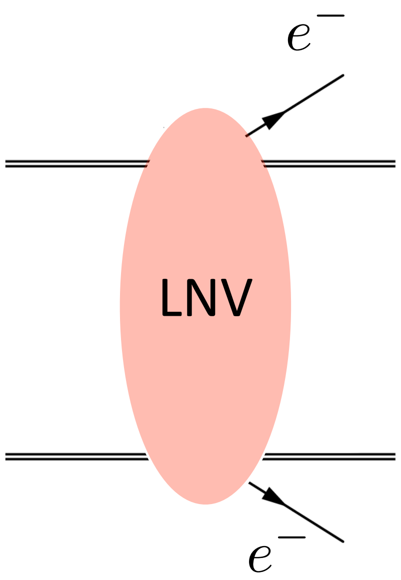

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This talk: Sterile Neutrinos

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Sterile neutrinos

- ν_R's could help solve several SM deficiencies:
  - Neutrino masses
  - Leptogenesis — Canetti et al. '13
  - Dark matter candidate — Boyarski et al. '19
- Appear in Left-Right/Leptoquarks/GUTs

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- Add n singlets, ν_R, to the SM(EFT):

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

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Majorana mass | Dirac mass | Heavy BSM physics

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This talk: minimal scenario

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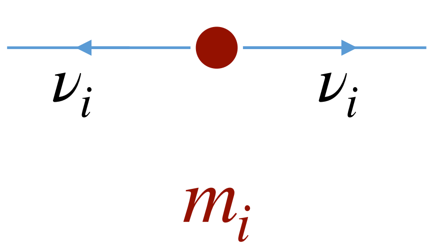

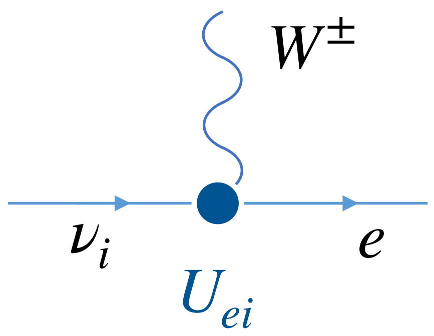

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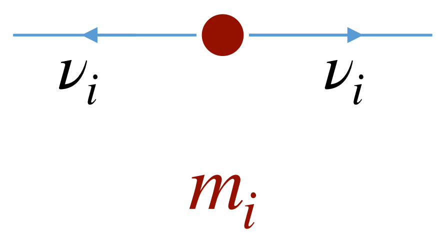
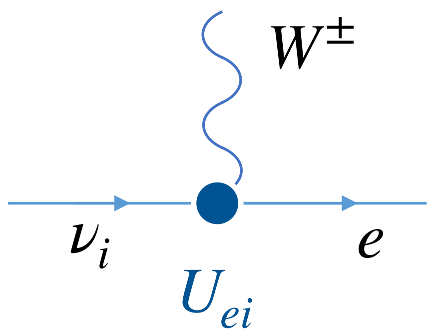
$$\Delta L = 2 \implies 0\nu\beta\beta$$





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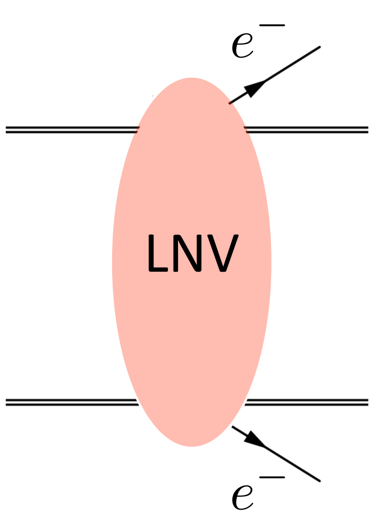

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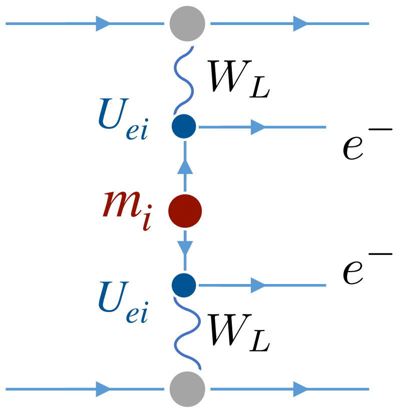

$$\propto \sum_{i=1}^{3+n} \frac{m_i}{q^2 - m_i^2} U_{ei}^2$$

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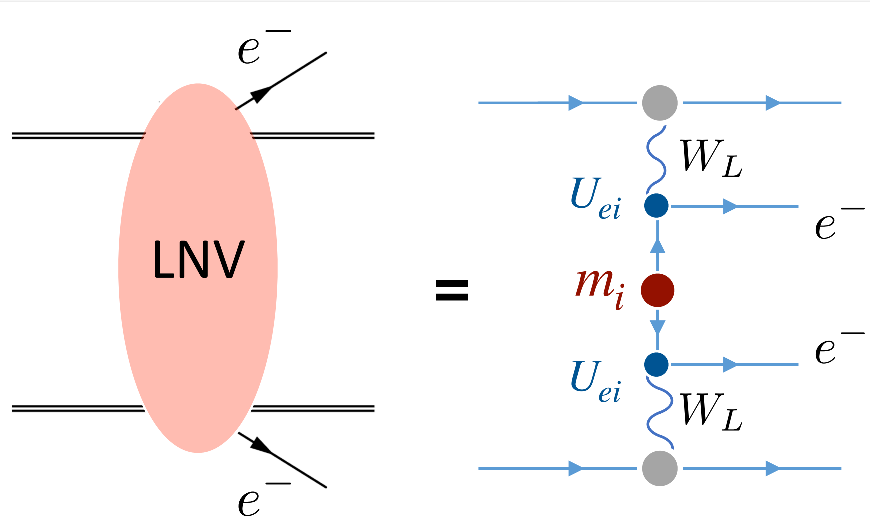

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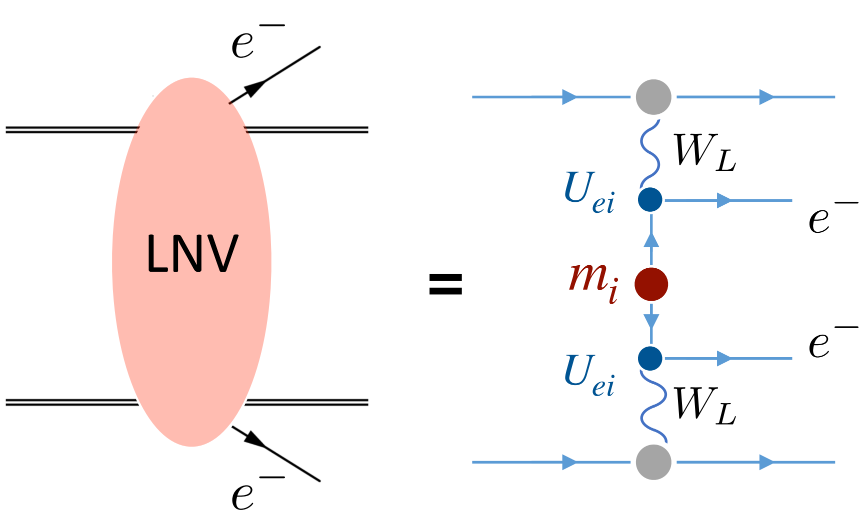

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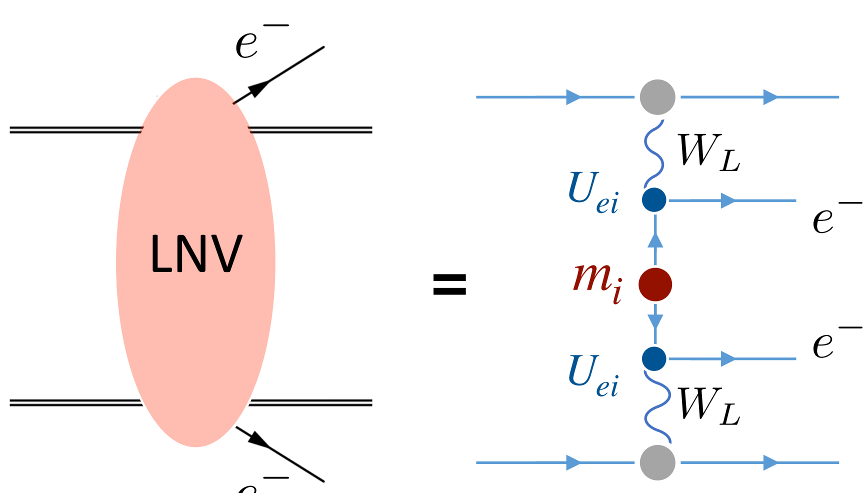

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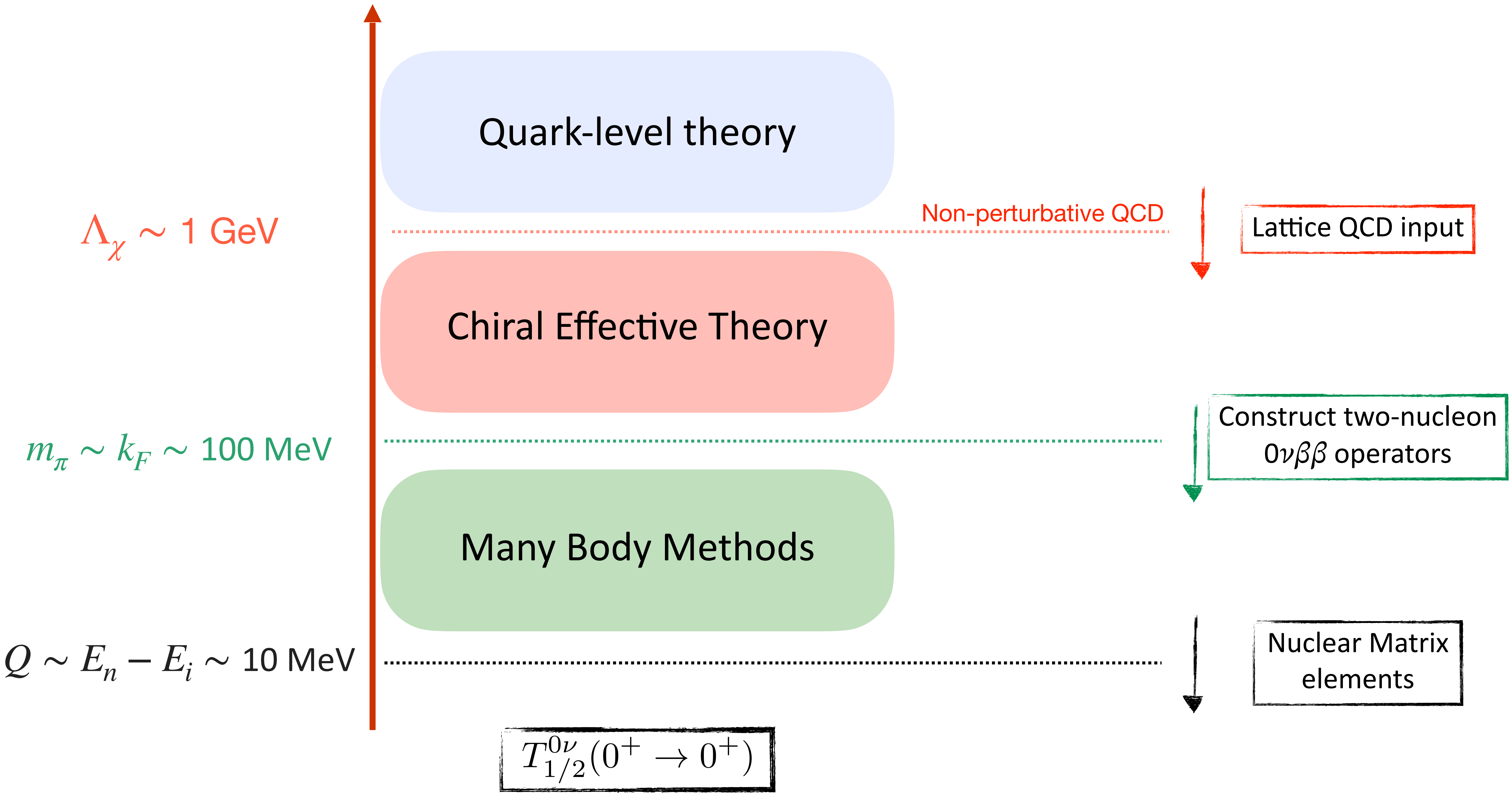
Need to keep track of m_i *dependence!*

EFT approach

One scale at a time



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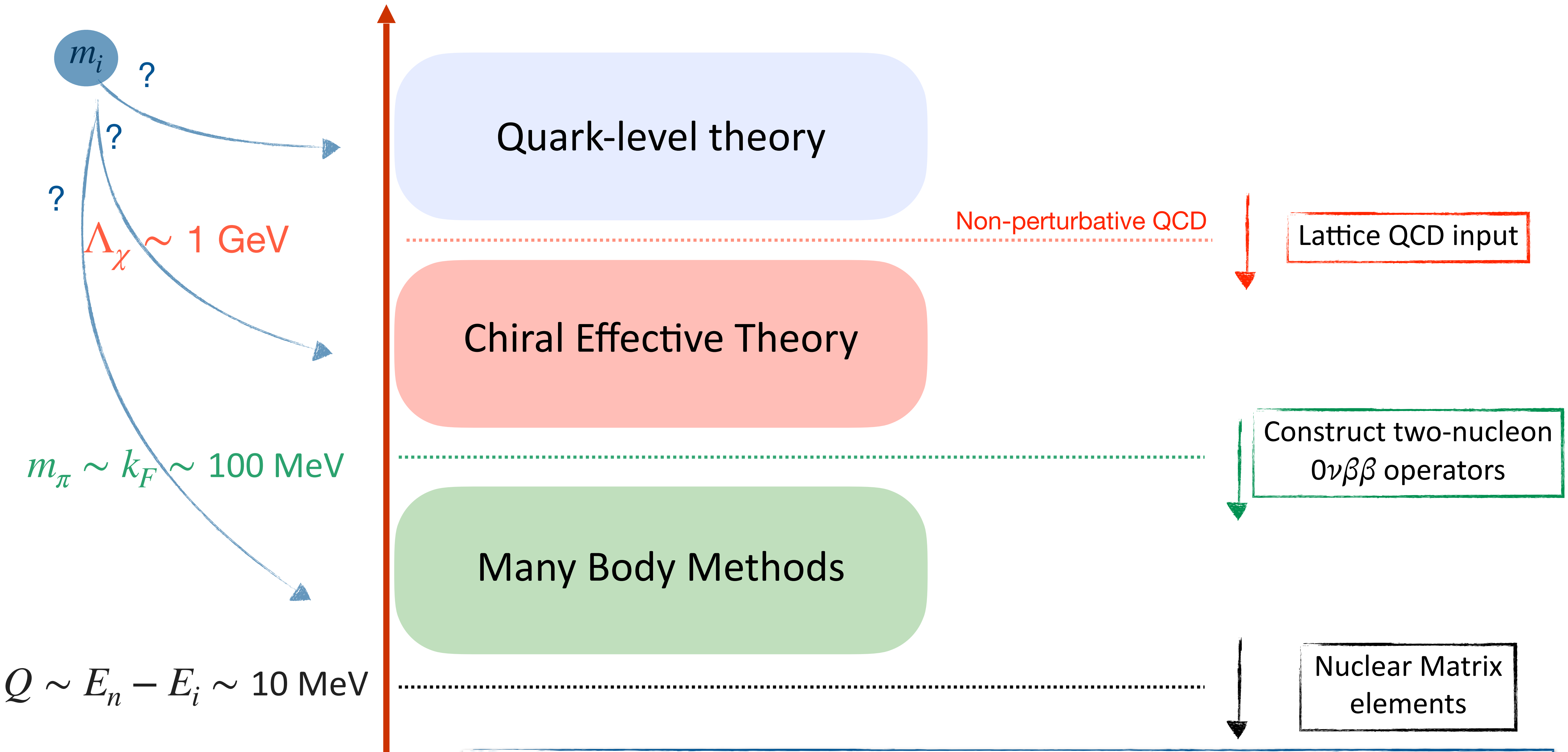

- How to include ν_i depends on its mass

EFT approach

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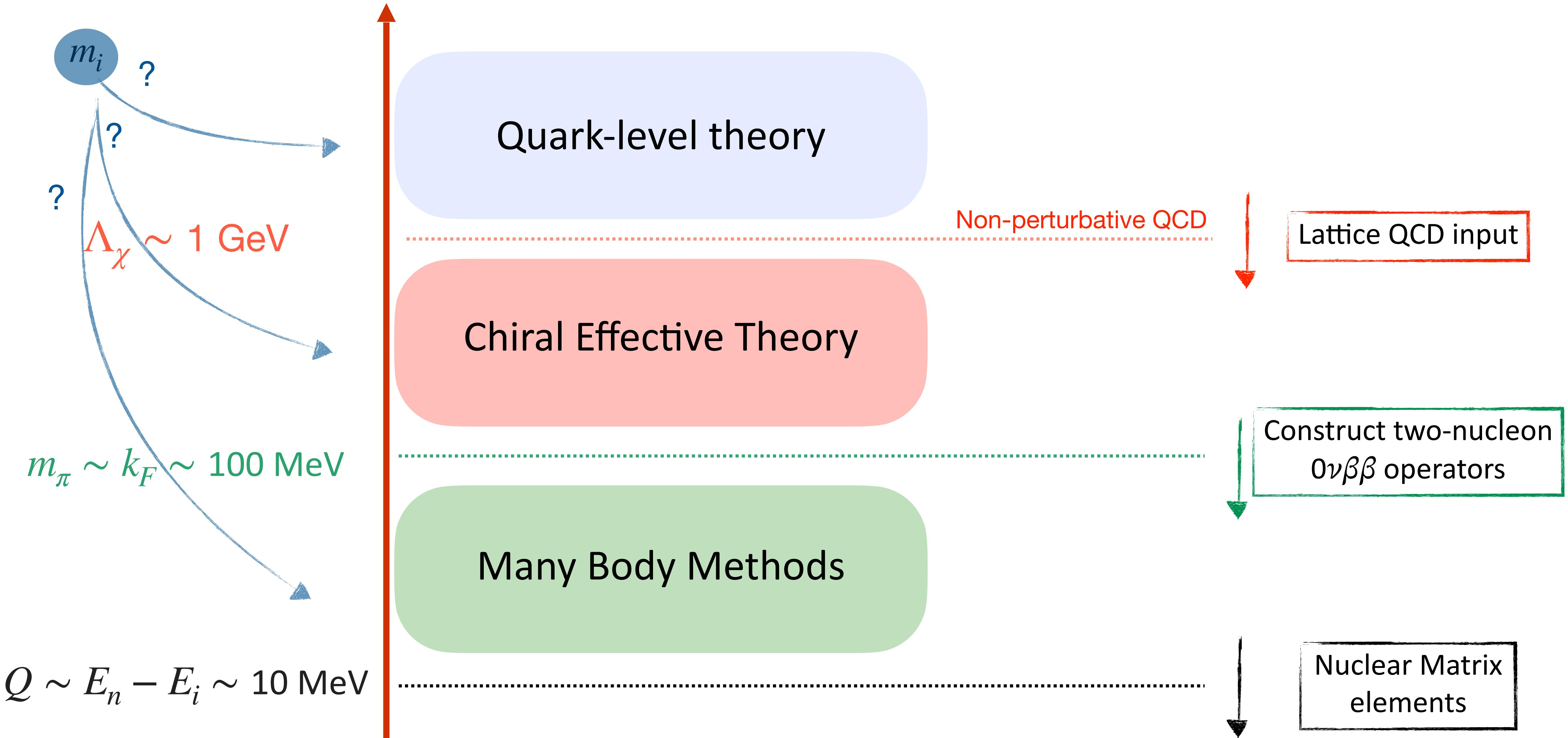
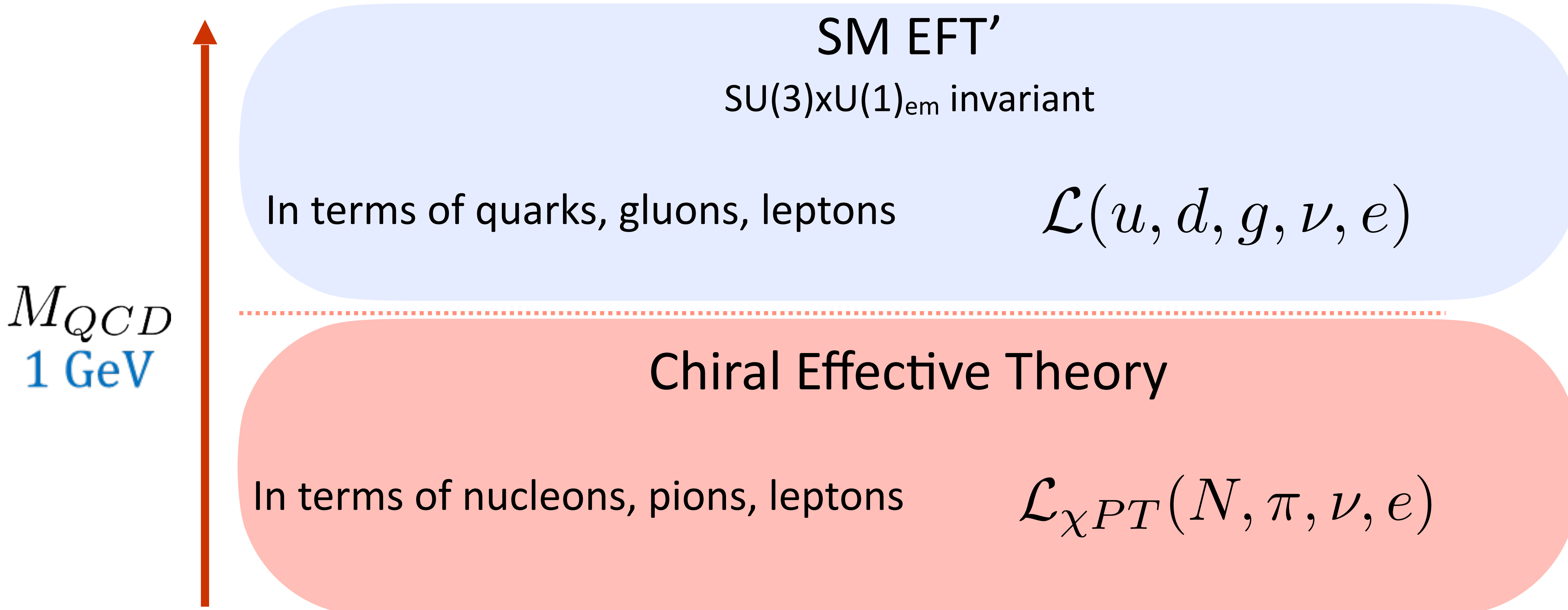


- How to include ν_i depends on its mass
- First: simpler case of $m_i \ll Q, k_F, \Lambda_\chi$ **[ignoring cancellations]**
  Similar to the `usual' mechanism

$$m_i \ll Q, k_F, \Lambda_\chi$$

Ignoring cancellations

Matching to Chiral EFT



Form of operators determined by chiral symmetry

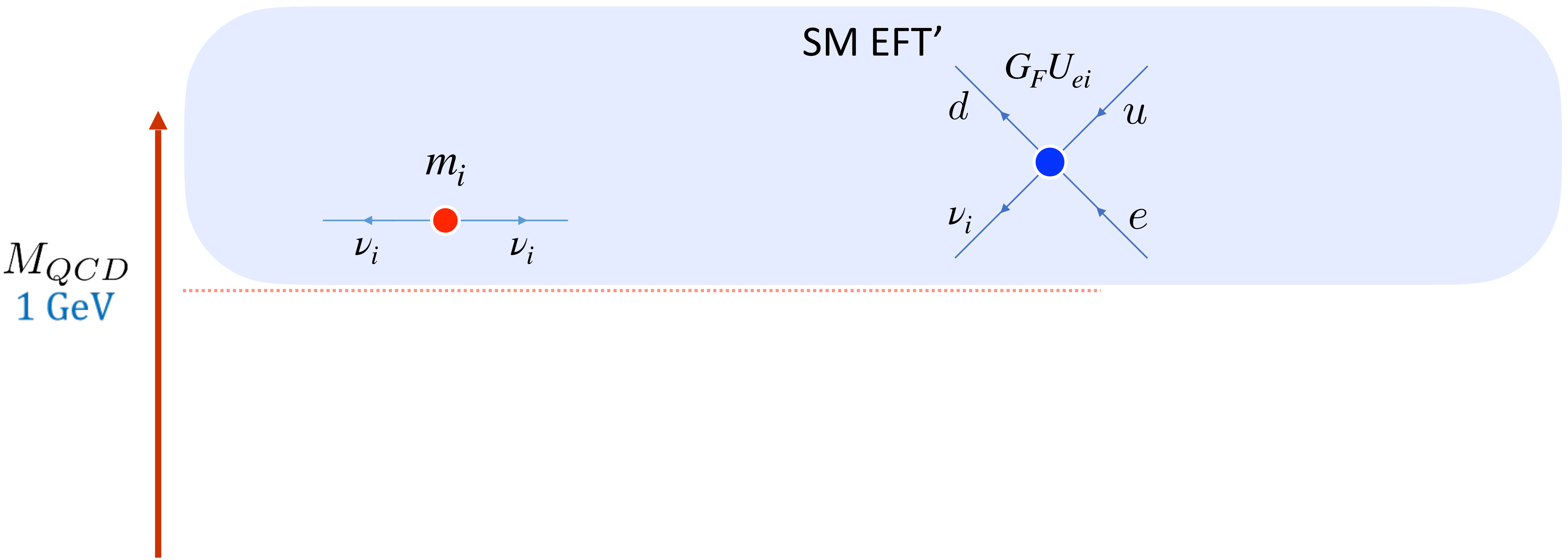
The operators come with unknown constants (LECs)

Need a power-counting scheme

- Often used: Weinberg counting / Naive dimensional analysis (NDA)

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

Matching to Chiral EFT



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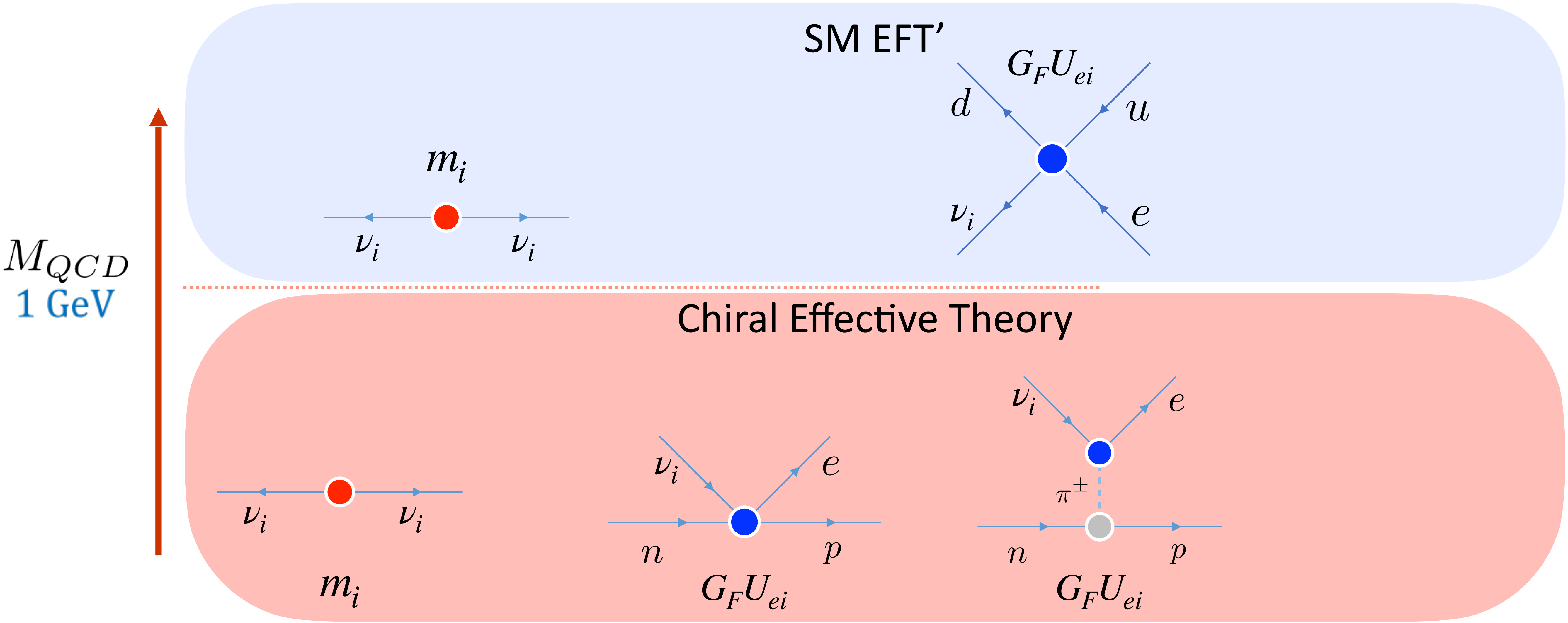
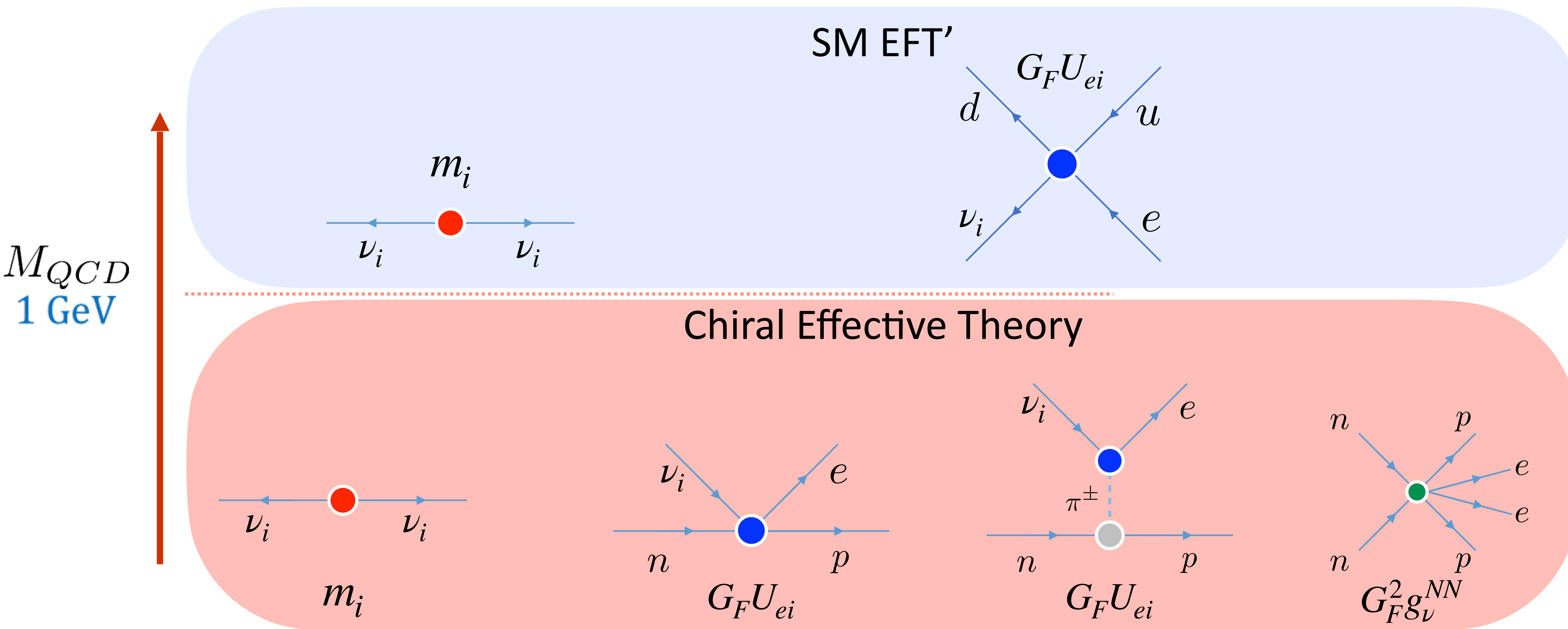


- At LO in Weinberg counting all needed low-energy constants are known

Matching to Chiral EFT



- At LO in Weinberg counting all needed low-energy constants are known

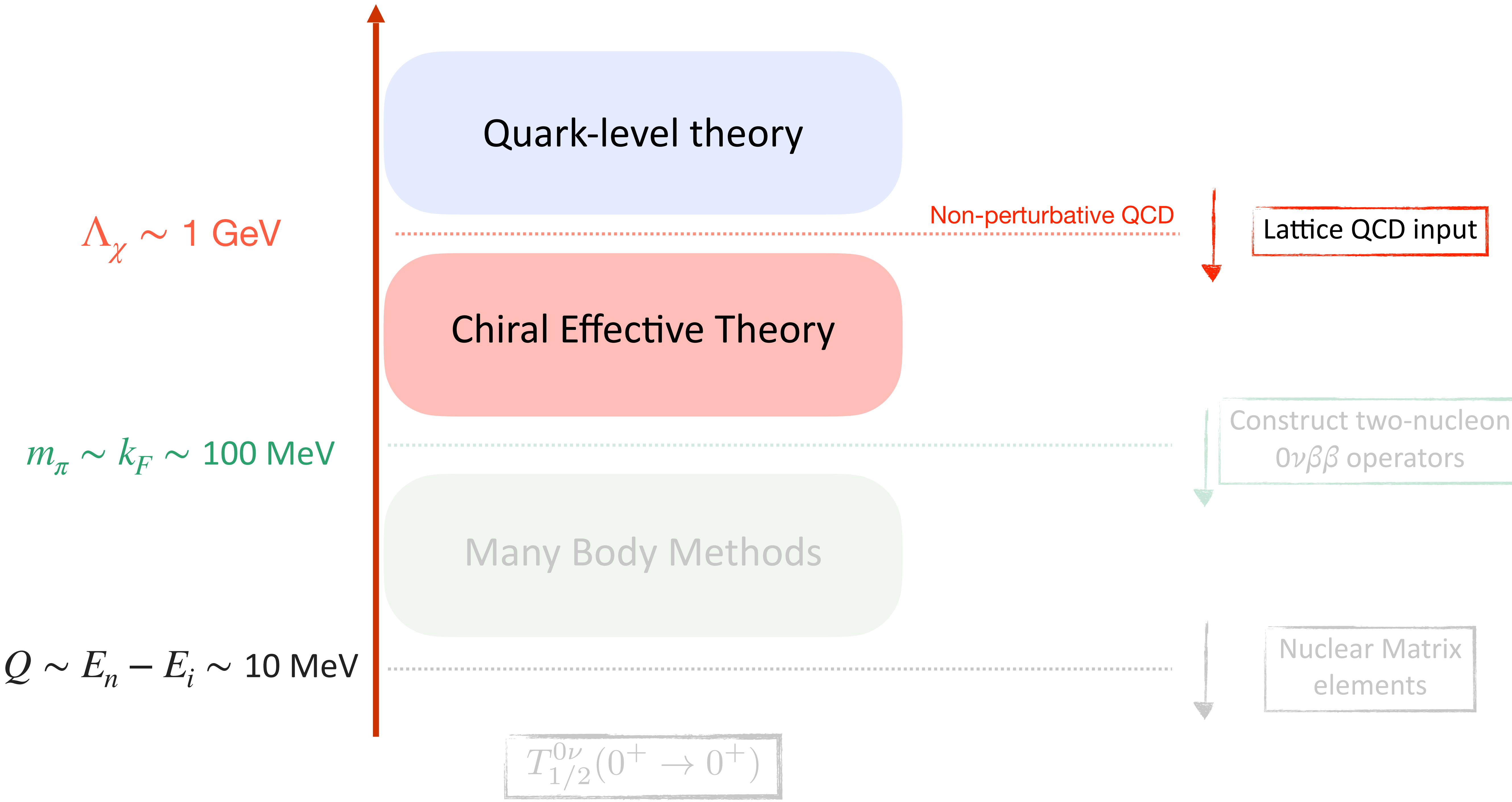
- Additional `non-NDA' contact interaction needed for renormalization
  - New LEC, g_ν^{NN}.
  - Currently unknown only model estimates

Cirigliano et al '18,'19

Cirigliano, et al, '21; Richardson et al, '21

EFT approach

One scale at a time



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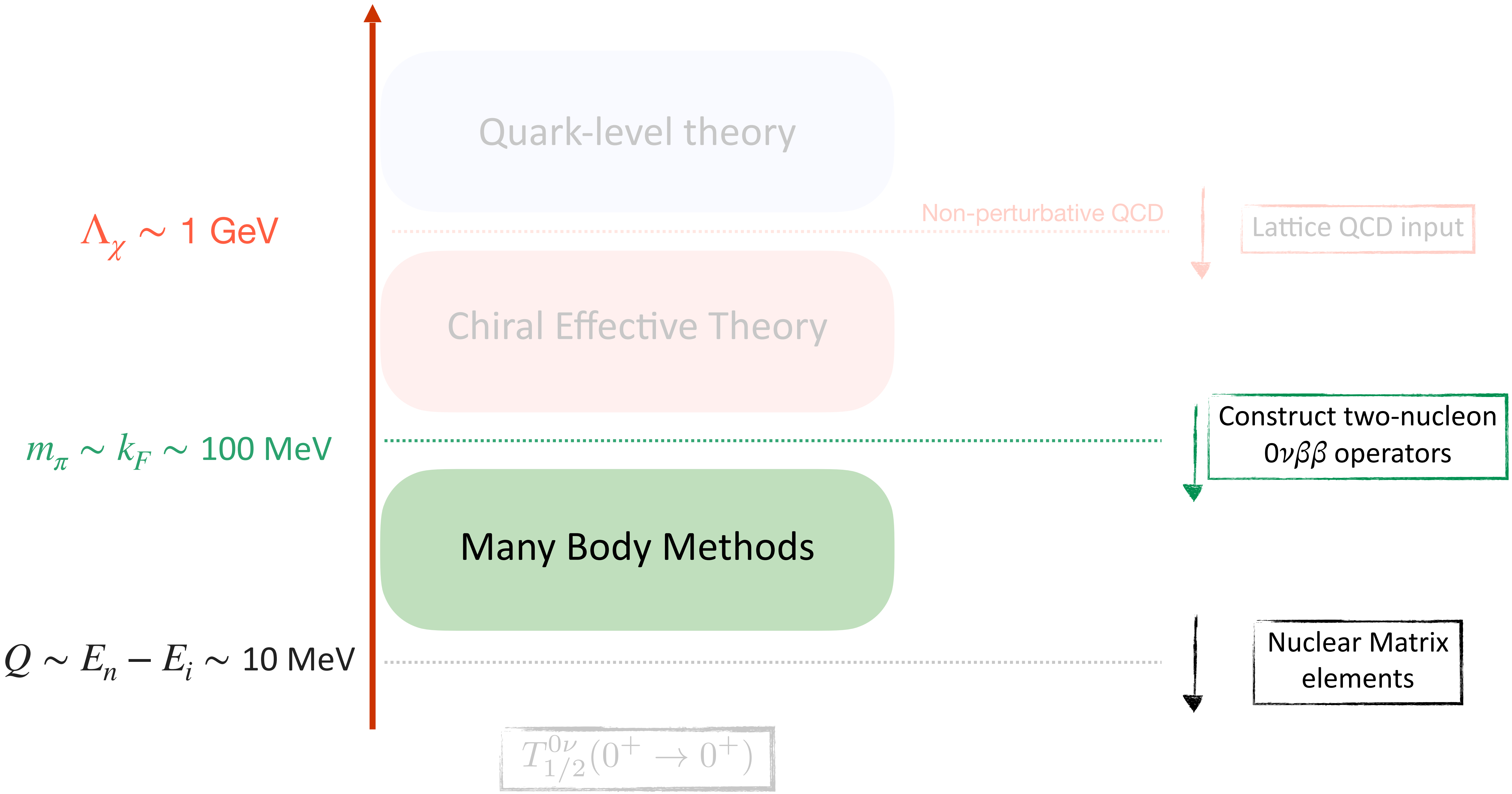
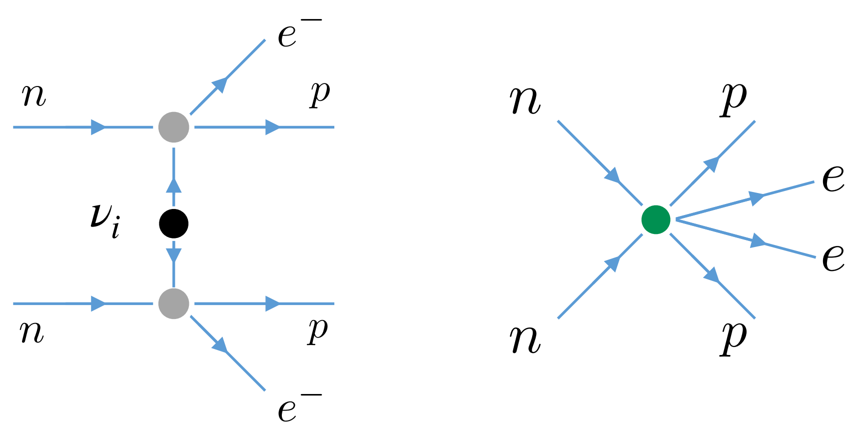


Chiral EFT

Active $\nu's$: leading order

Leading order

$$V_{\Delta L=2} =$$

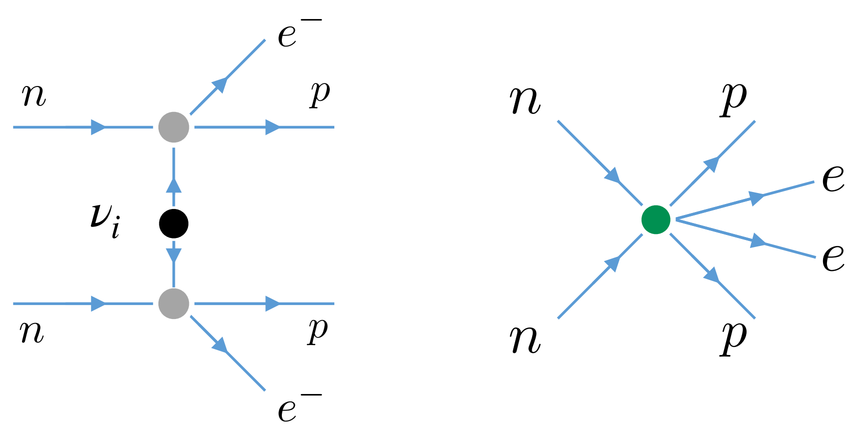


Need to evaluate $A_\nu = \langle {}^{136}\mathrm{Ba} \,|\, V \,|\, {}^{136}\mathrm{Xe} \rangle$

Chiral EFT

Active $\nu's$: leading order

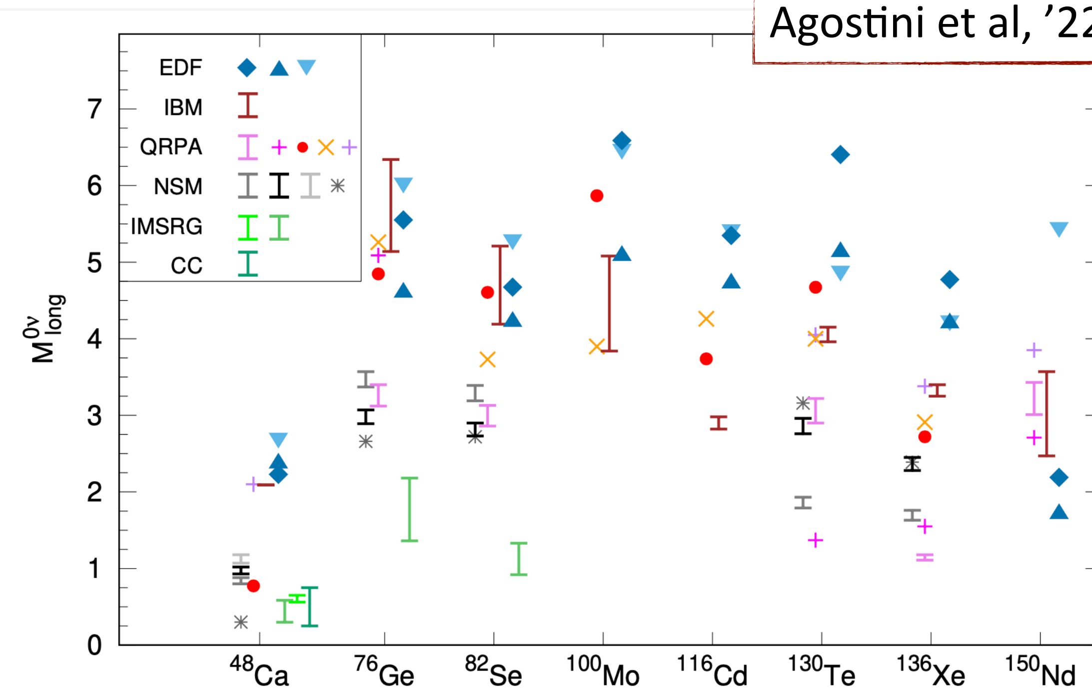
Leading order

$V_{\Delta L=2} =$ 

Need to evaluate $A_\nu = \langle {}^{136}\mathrm{Ba} | V | {}^{136}\mathrm{Xe} \rangle$

- Requires many-body methods
- Matrix elements differ factor 2-3 between methods
- *Ab initio* NMEs for $A \geq 48$ are starting to appear
- Including estimates of g_ν^{NN} effects

Agostini et al, ’22;

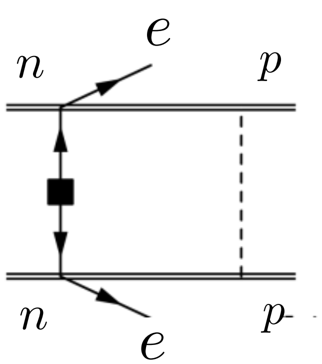


Agostini et al, ’22; Belley et al ’23,’20; Yao et al ’20; Wirth, Yao, Hegert ‘21

Chiral EFT

Active $\nu's$: N2LO

Loops and counterterms



- Leads to:
  - form factors
  - correction to the potential
  - Estimated to be $\lesssim \mathcal{O}(10\%)$ in light nuclei

Pastore et al ‘17

Cirigliano et al ‘17

Chiral EFT

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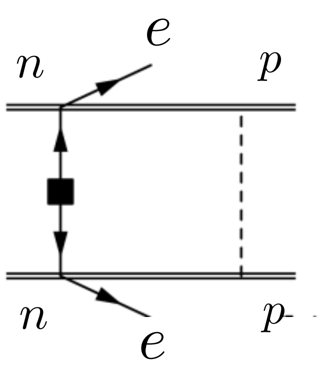

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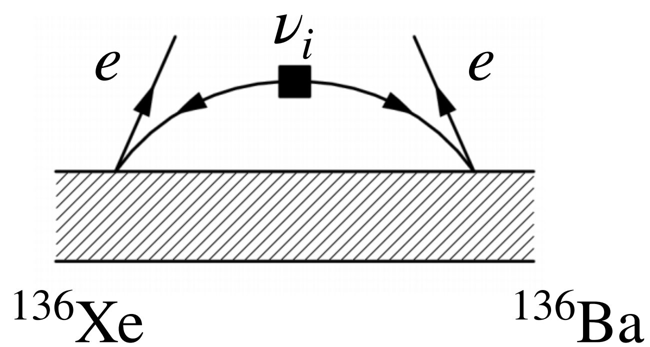
Pastore et al '17

`Ultrasoft' neutrinos



$$A_\nu^{\rm usoft} \sim \sum_N \langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle \Delta E \left(\ln\frac{\mu}{2\Delta E}+1\right)$$

$$\Delta E = E_n - E_i + E_e$$

- Due to neutrinos with small momenta $q^0 \sim |\vec{q}| \sim k_F^2/m_N \sim \Delta E$
  - See the nucleus as a whole
- Dependence on intermediate state, `closure' correction

Cirigliano et al '17

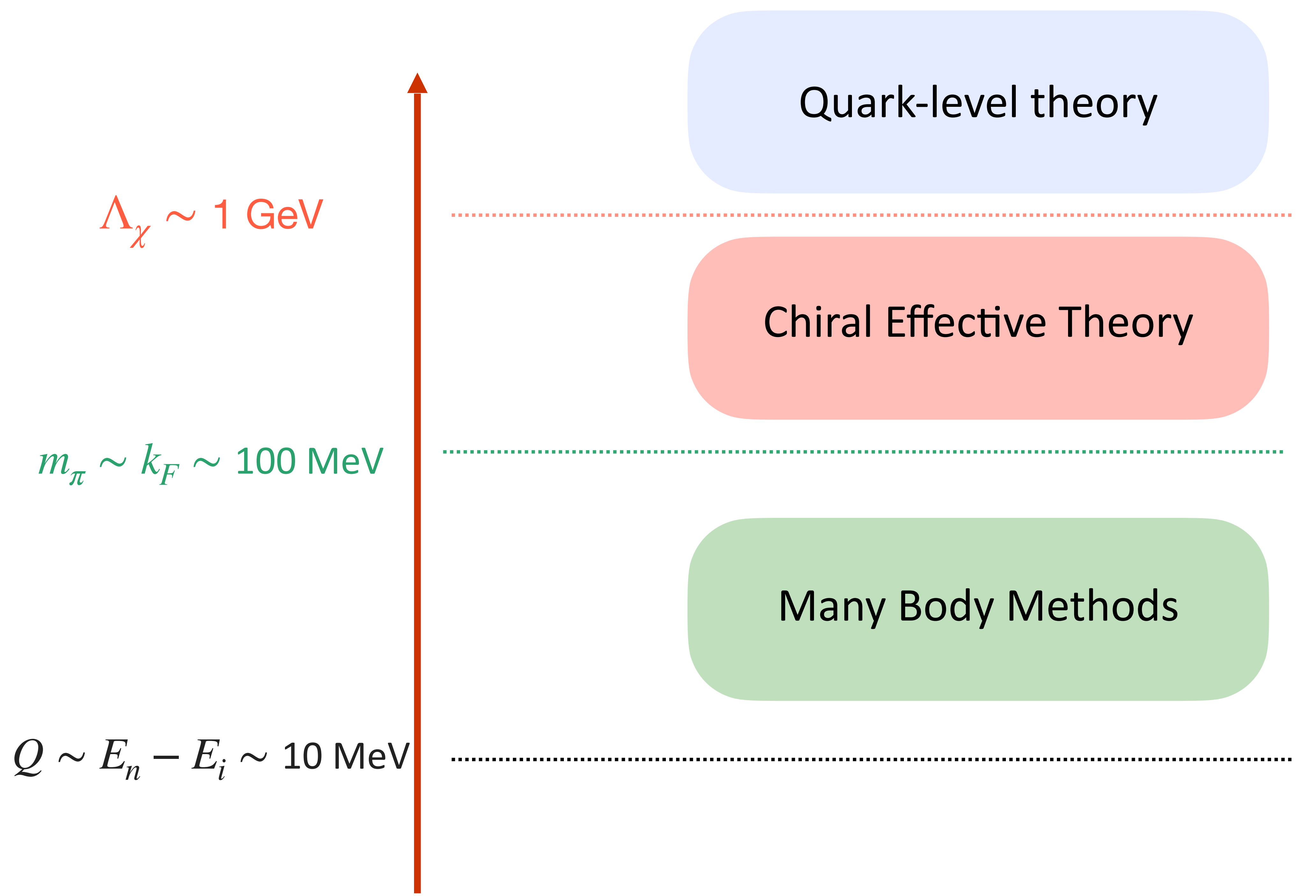
Minimal SM extension

Including cancellation mechanism

EFT approach

Non-negligible masses

- How to include ν_i depends on m_i



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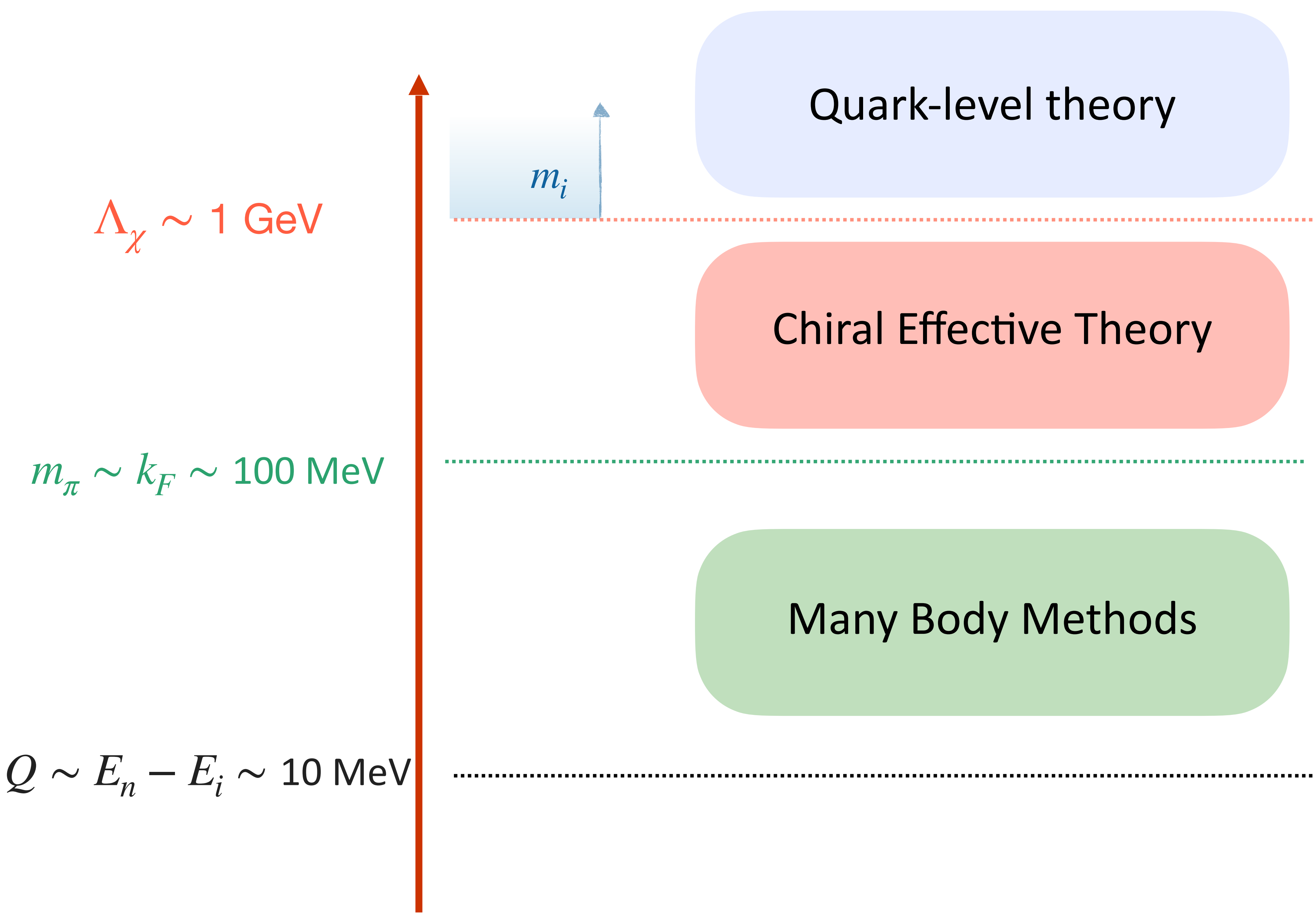
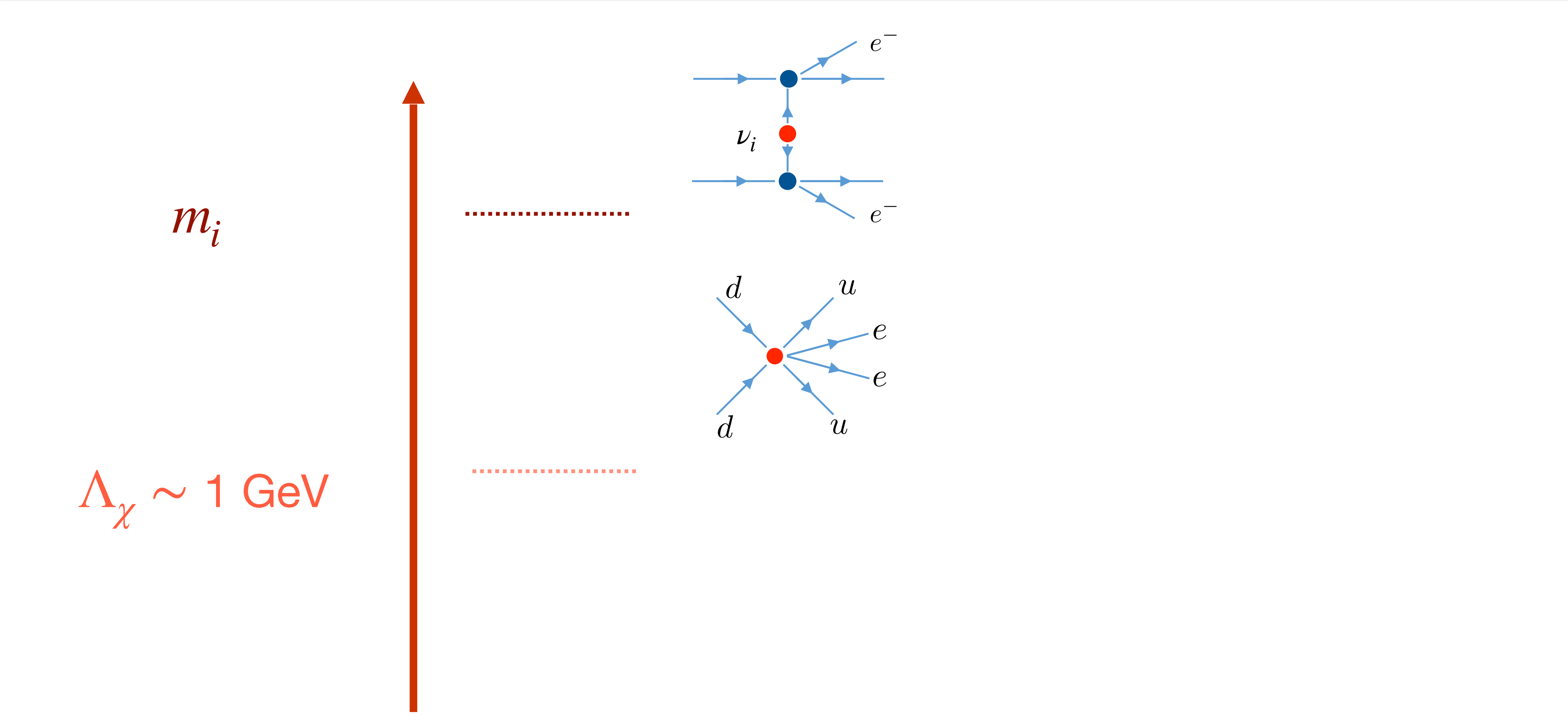
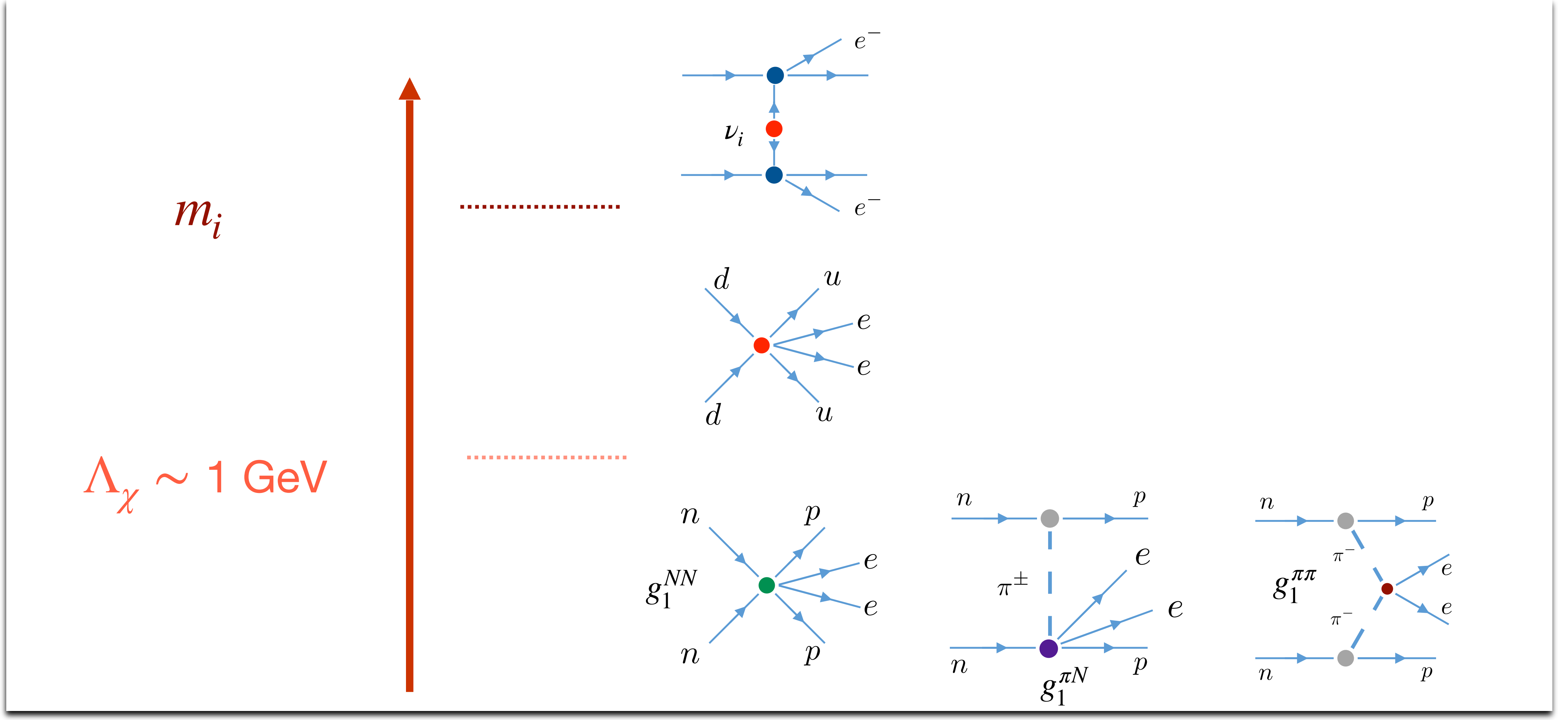


$m_i \gg \Lambda_\chi$



- ν_i can be integrated-out at quark level
  - Determines m_i dependence: $A_\nu(m_i) \sim U_{ei}^2/m_i^2$

$m_i \gg \Lambda_\chi$



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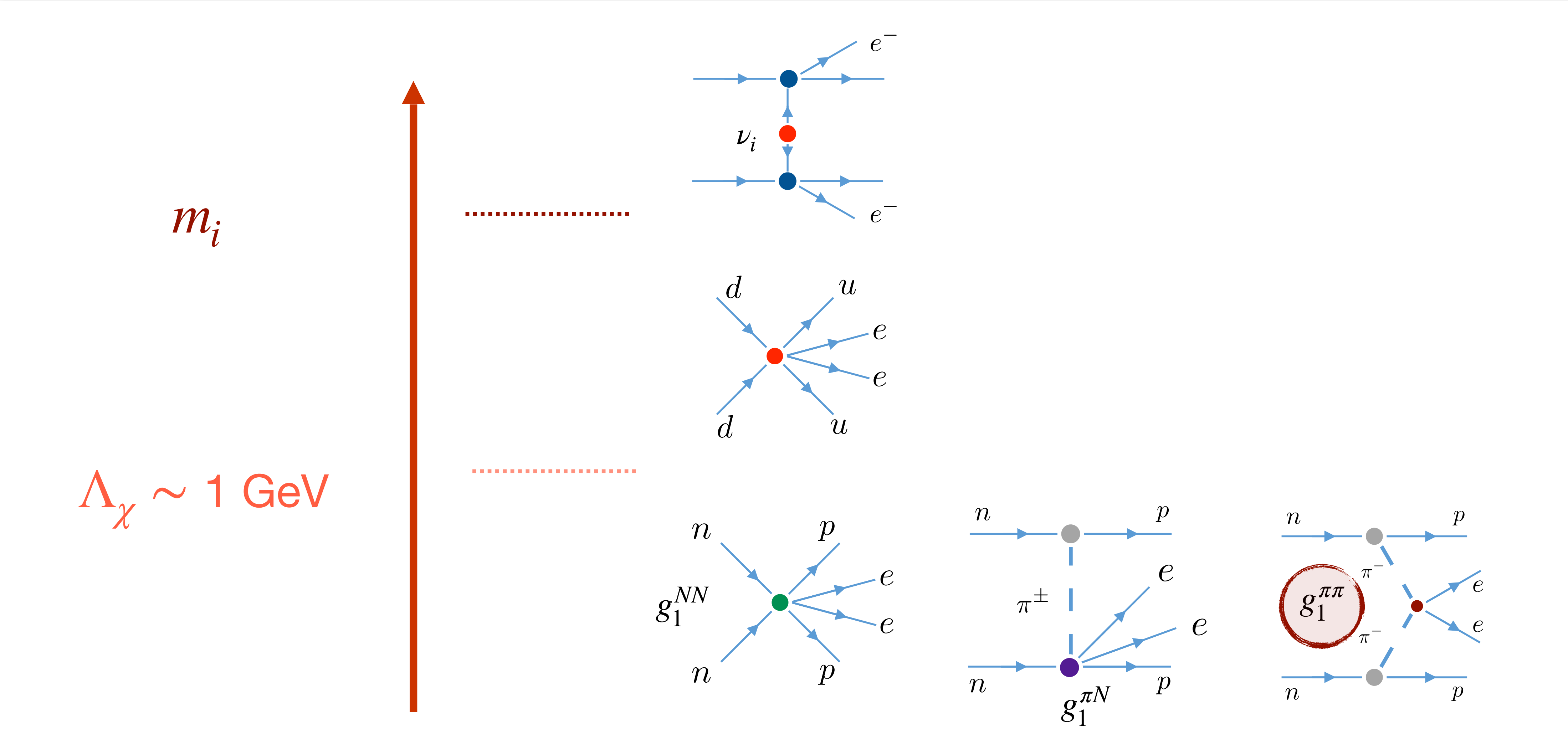
  - Determines m_i dependence: $A_\nu(m_i) \sim U_{ei}^2/m_i^2$

- Match to chiral EFT without ν_i
- Involves several LECs

$m_i \gg \Lambda_\chi$



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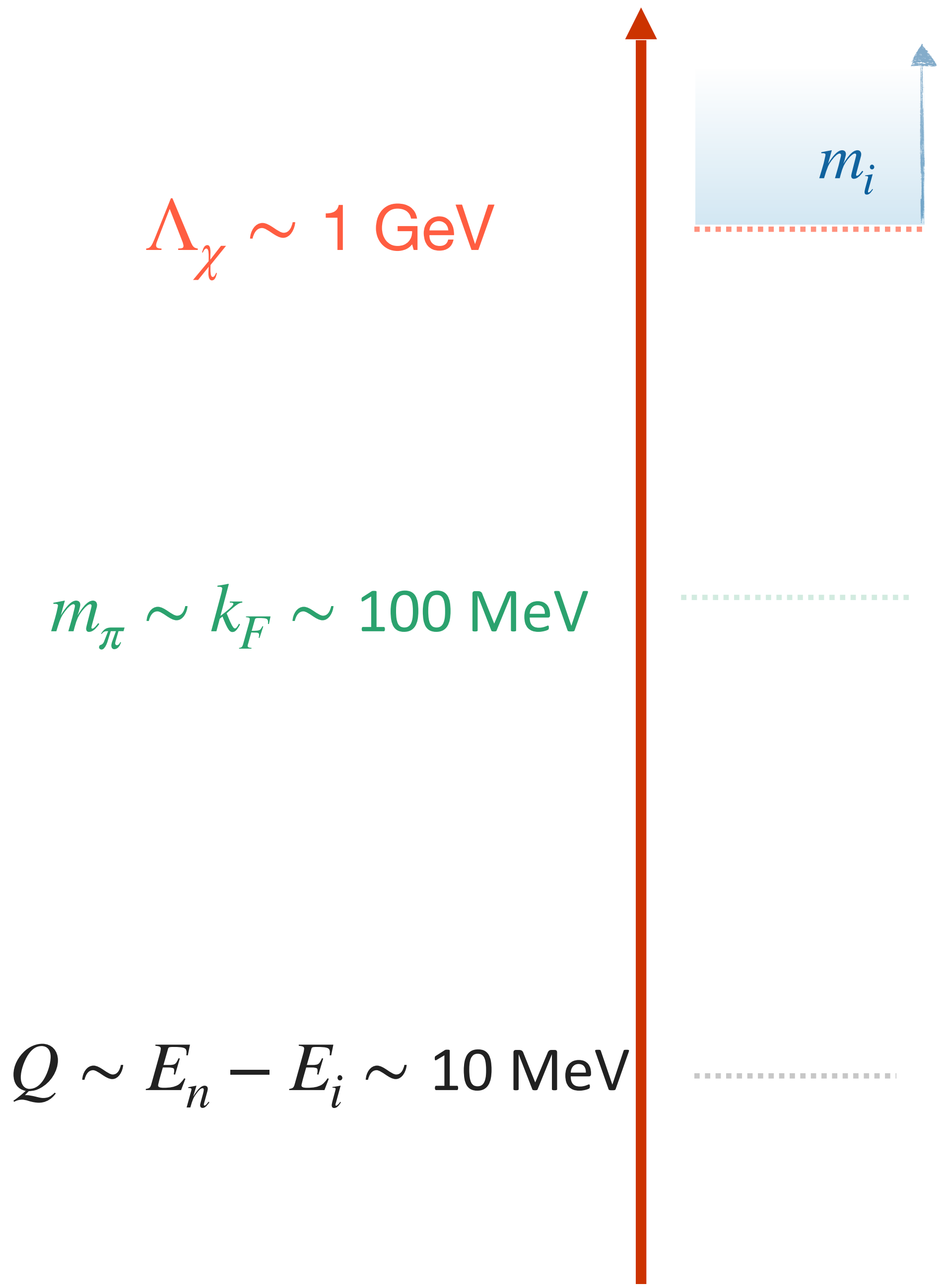
- Match to chiral EFT without ν_i
- Involves several LECs
  - Only $g_1^{\pi\pi}$ known

Nicholson et al '18; Detmold et al '22

EFT approach

One momentum scale at a time



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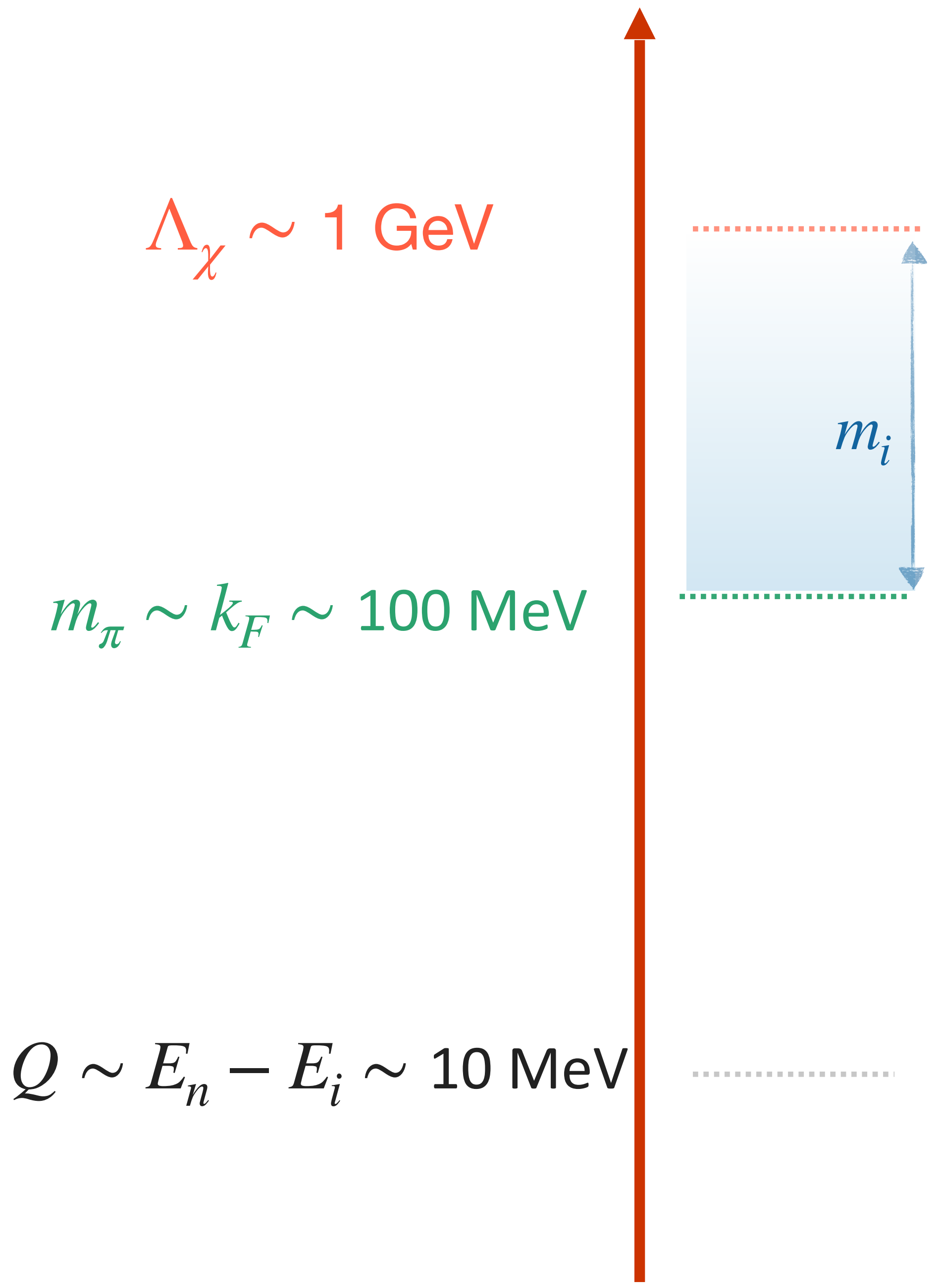
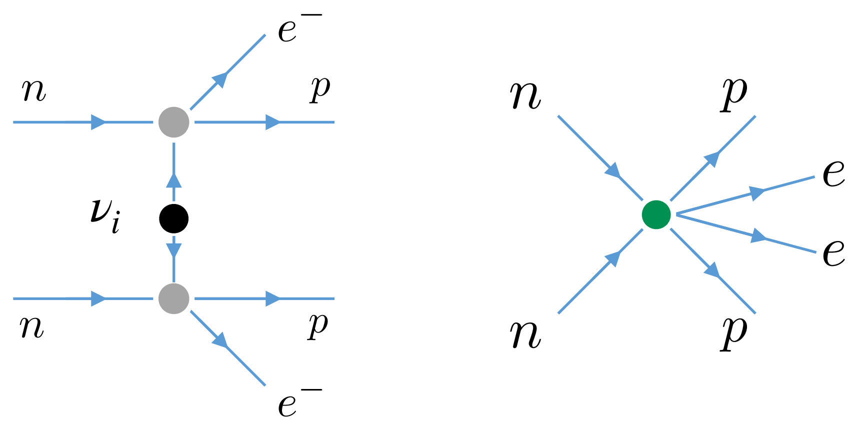


$$\Lambda_\chi \gtrsim m_i \gtrsim k_F$$

$V_{\Delta L=2} =$



- Have to keep ν_i in the chiral theory
- Again have `potential' + `hard' contributions
- m_i dependence in NMEs and g_ν^{NN}

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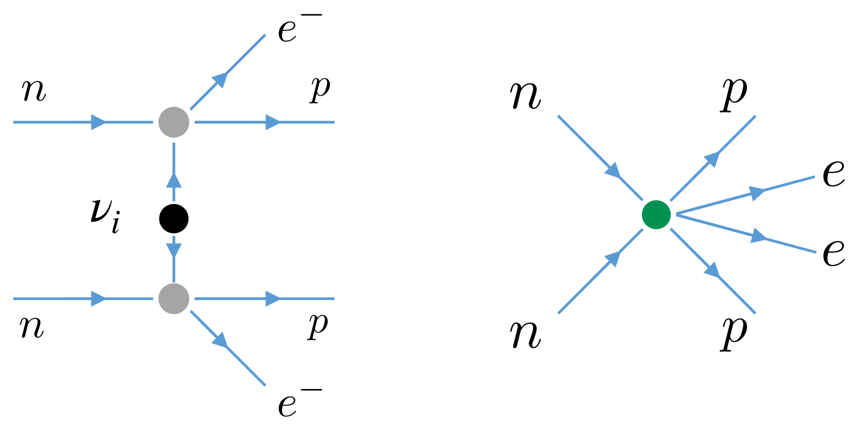
$V_{\Delta L=2} =$ 

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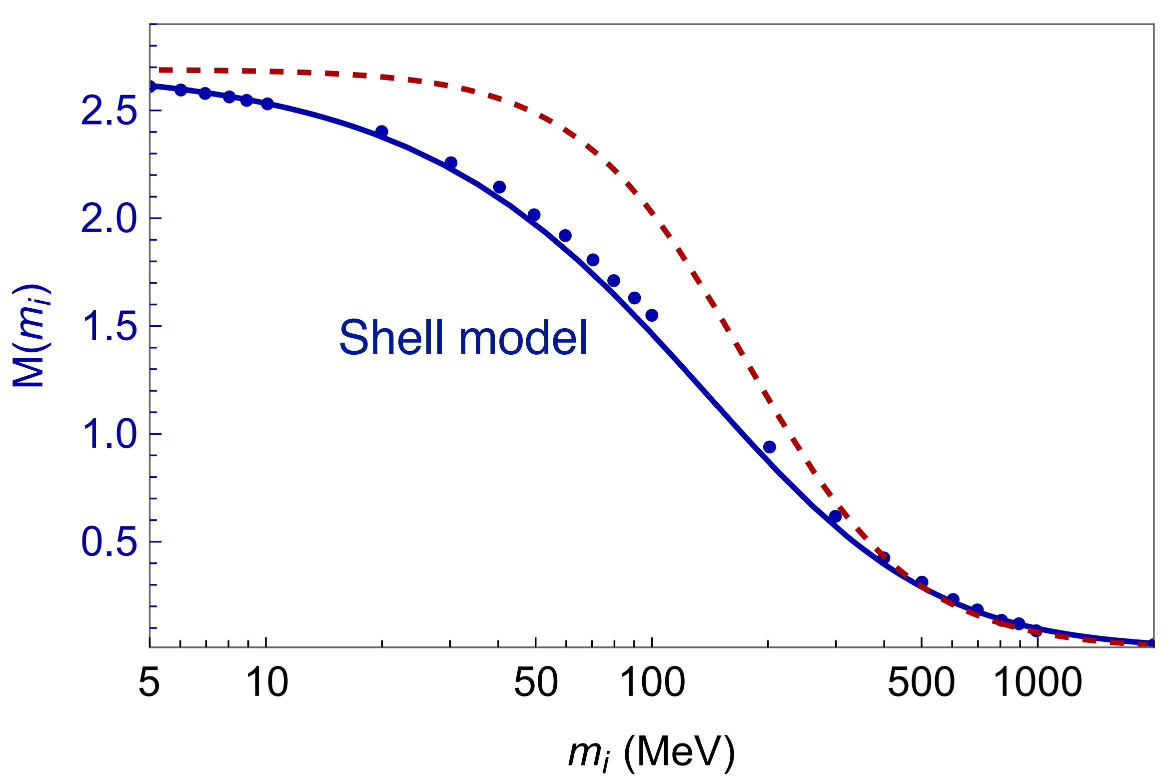

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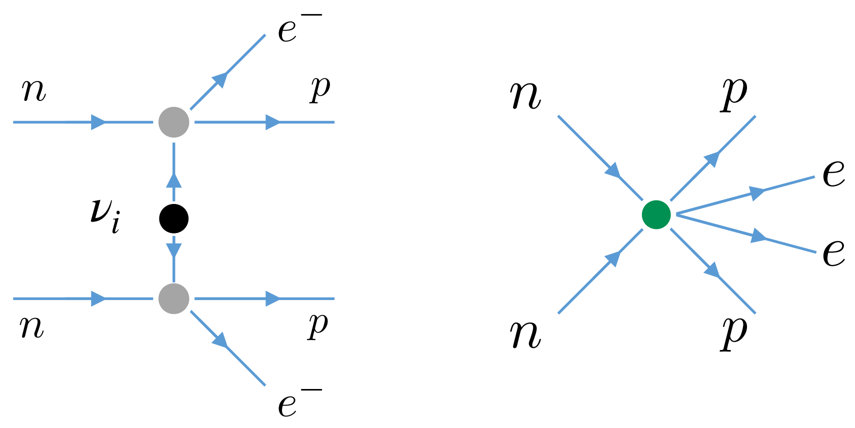
$V_{\Delta L=2} =$ 

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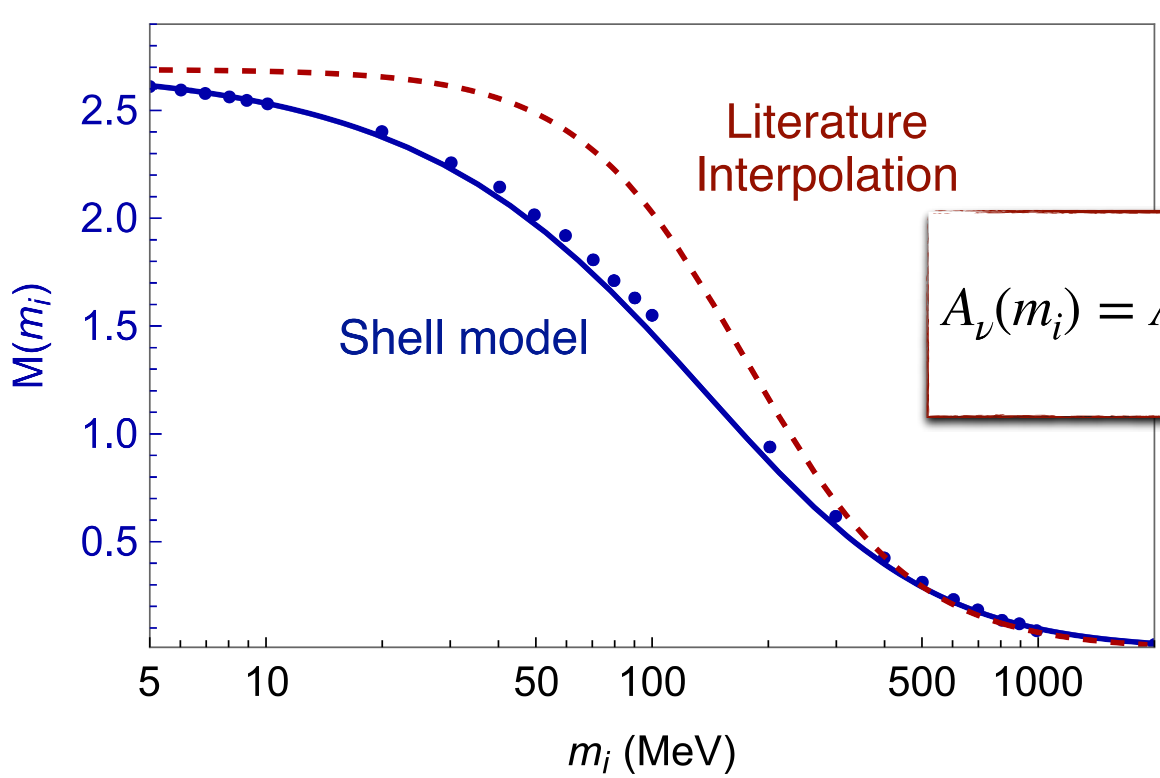

$$A_\nu(m_i) = A_\nu(0)\frac{\langle p^2\rangle}{\langle p^2\rangle + m_i^2}$$

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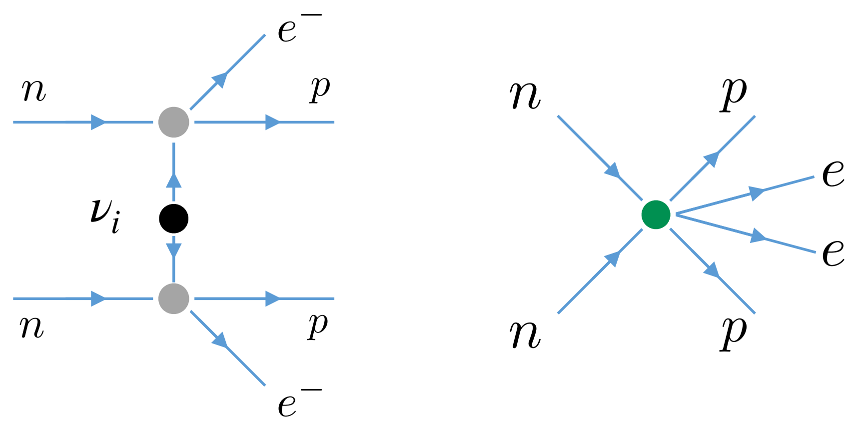
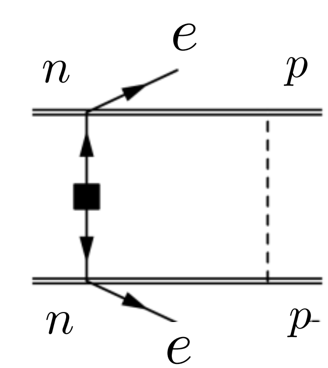
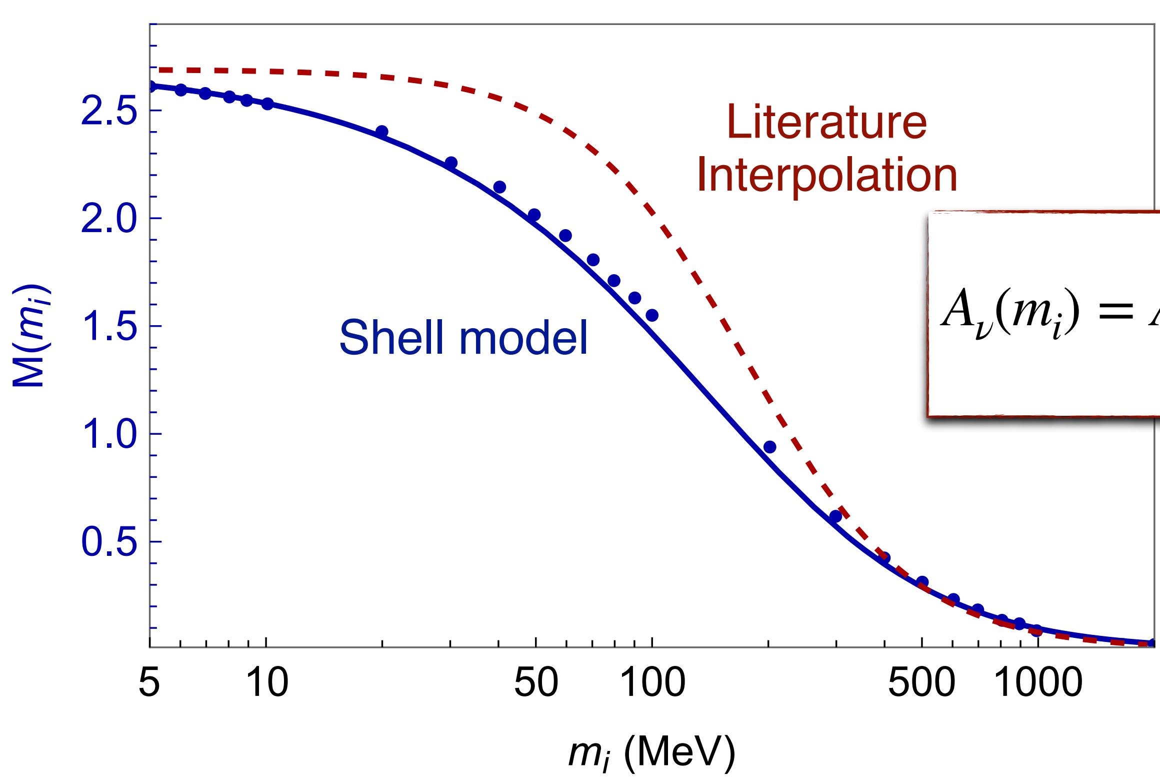


Soft contributions $\mathcal{O}\left(\frac{m_i^2}{\Lambda_\chi^2}\right)$



- Have to keep ν_i in the chiral theory
- Again have `potential' + `hard' contributions
- m_i dependence in NMEs and g_ν^{NN}

- `soft' contributions can be significant



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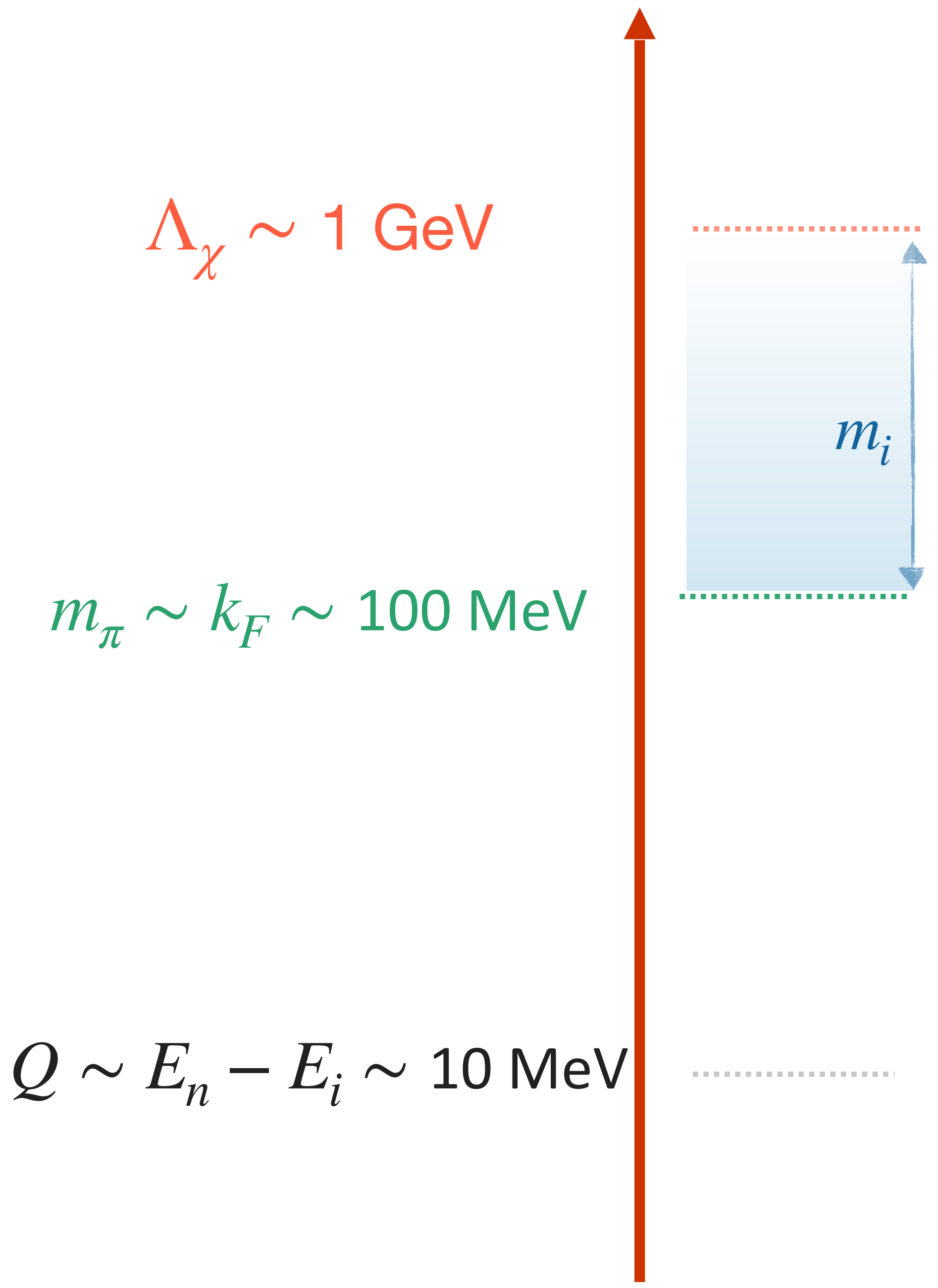
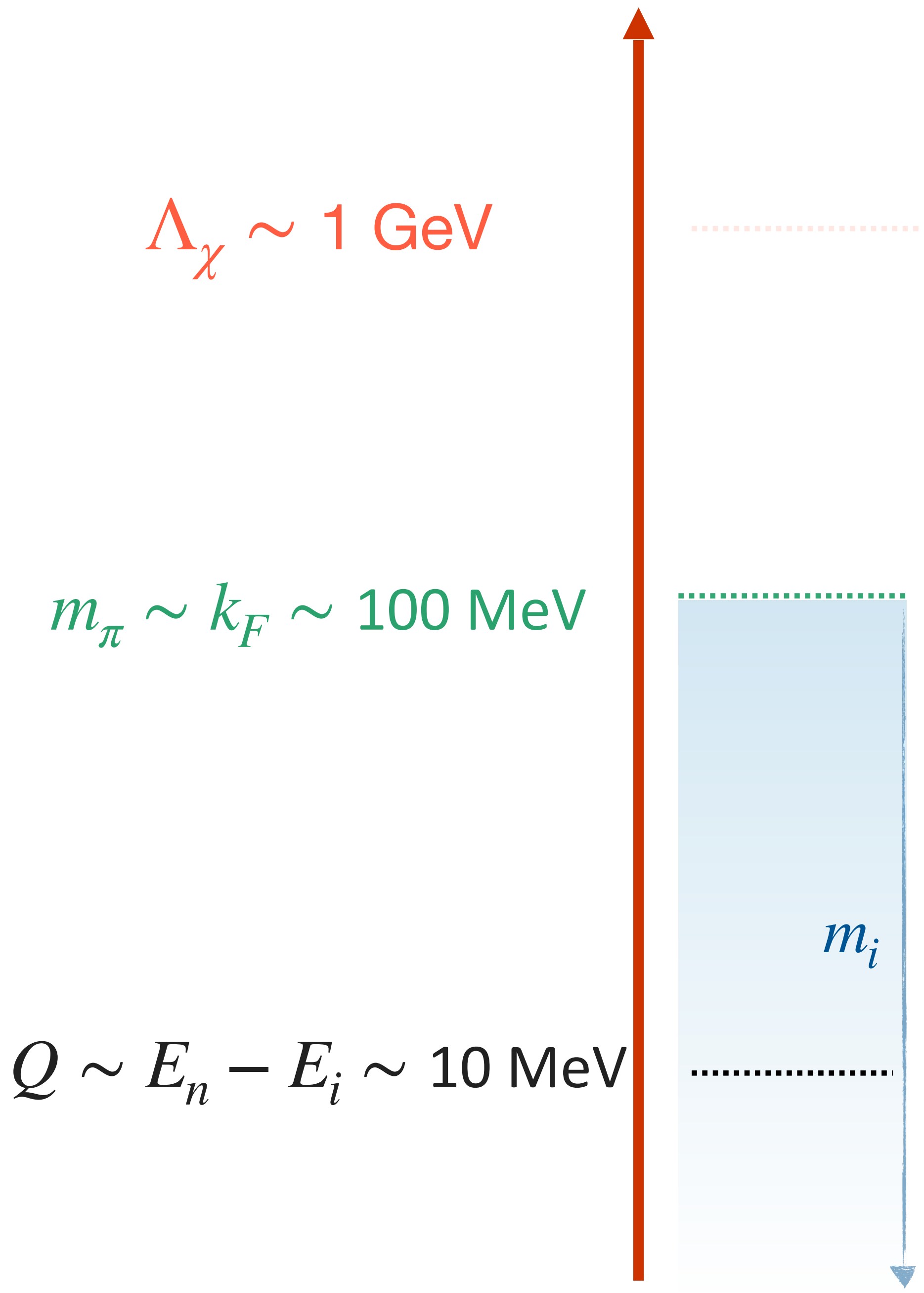
EFT approach

One momentum scale at a time



EFT approach

One momentum scale at a time



$$k_F \gtrsim m_i$$

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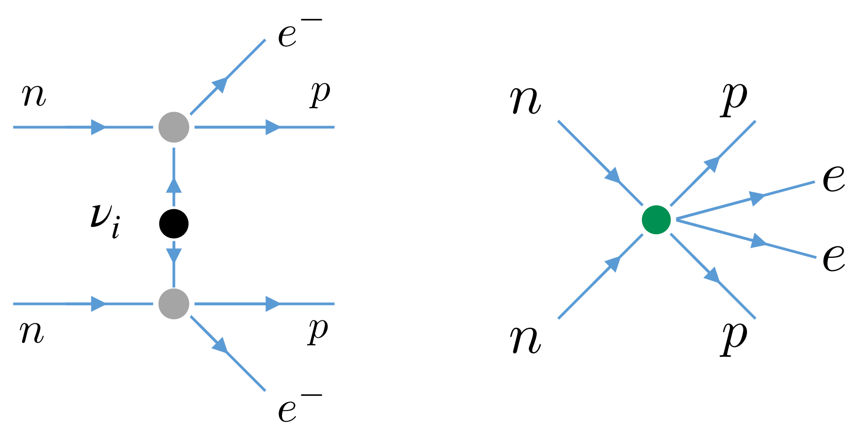

- Similar to previous case:
  - Contributions from potential + hard regions
  - Soft loop contributions are now negligible

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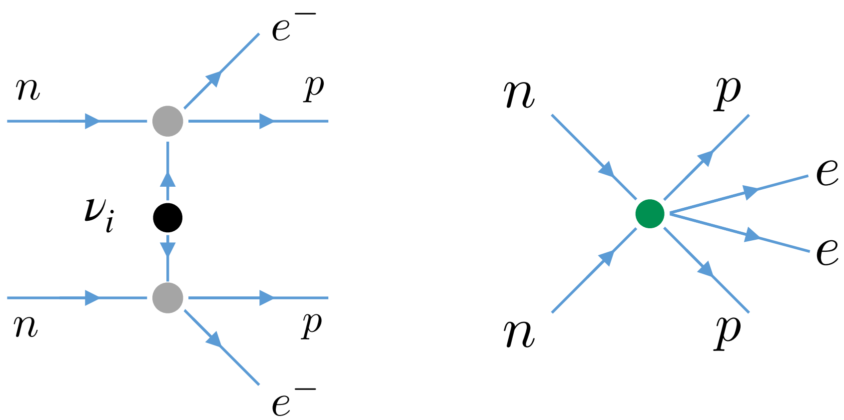
$V_{\Delta L=2} =$ 

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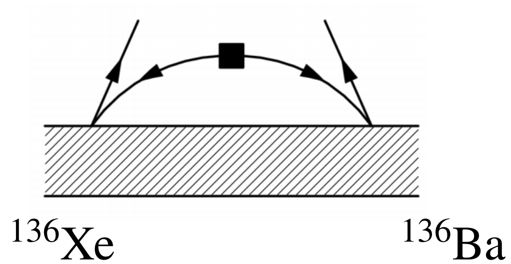
Ultrasoft contributions



- Usually N2LO effect, now leading
- Depend on:
  - Overlap integrals
  - Intermediate state energies, $\Delta E \equiv E_n + E_e - E_i$

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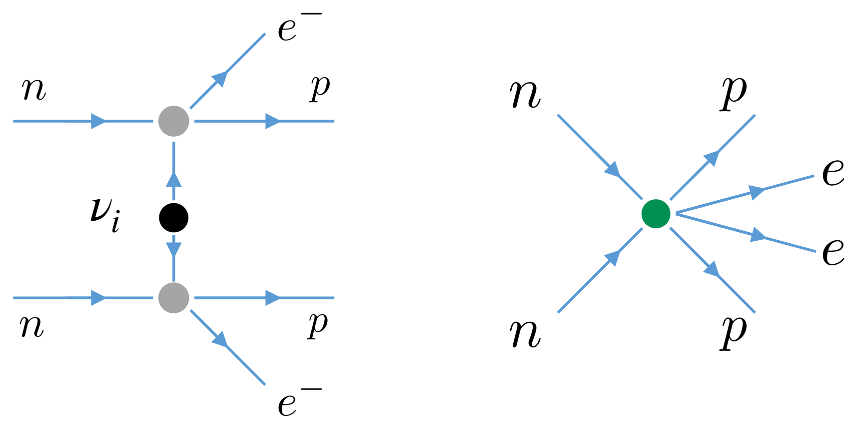

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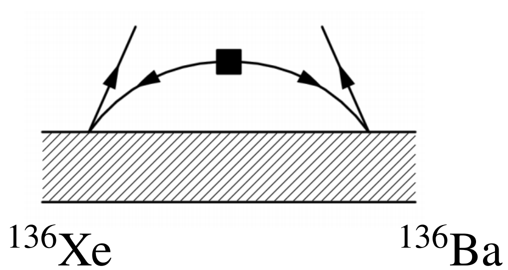

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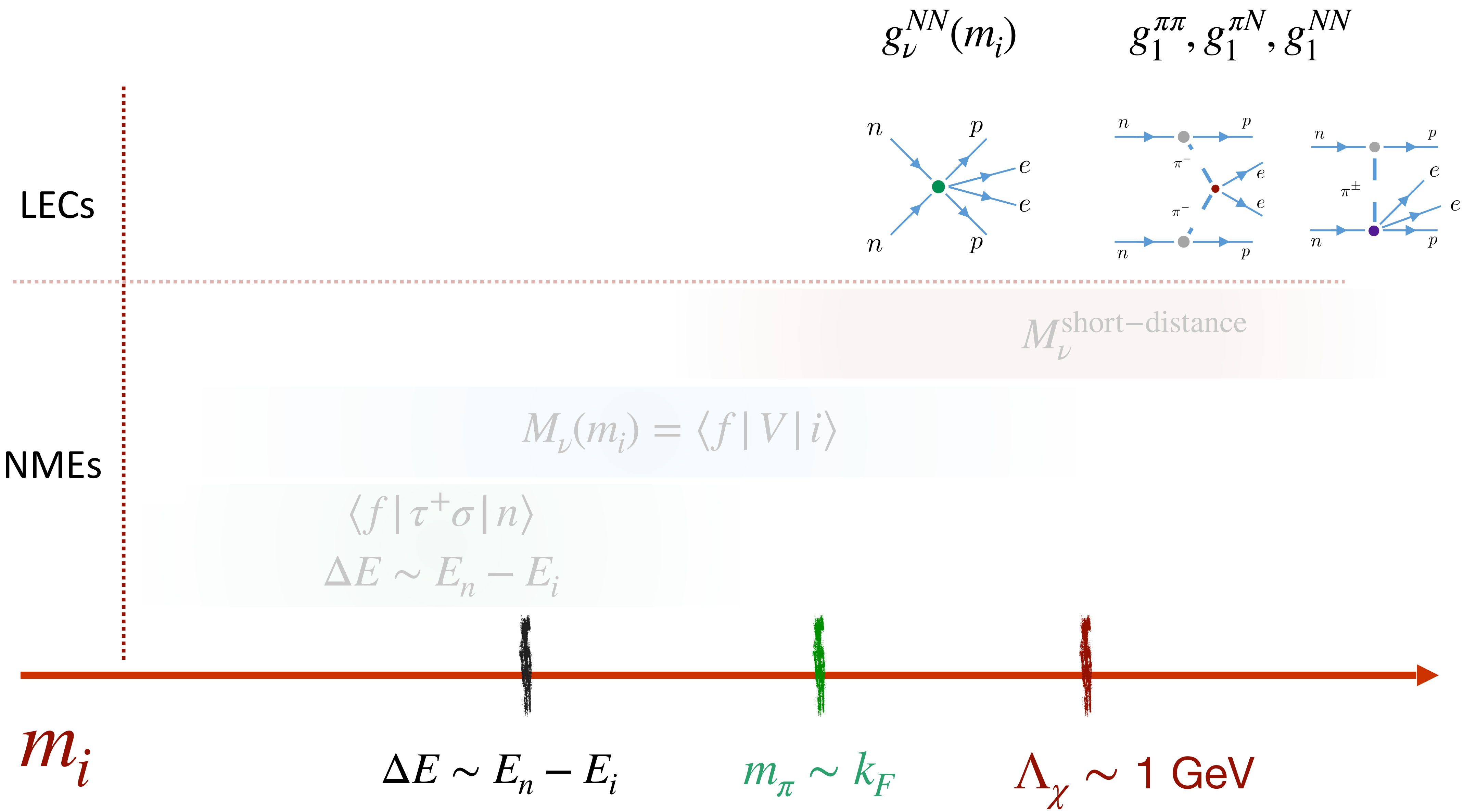
$$A_\nu^{\text{usoft}} \sim \sum_n \langle f | J_\mu | n \rangle \langle n | J^\mu | i \rangle \times \begin{cases} \dfrac{m_i}{k_F}, & \Delta E \lesssim m_i \lesssim k_F \\ \dfrac{m_i^2}{4\pi k_F \Delta E} \ln \dfrac{m_i}{\Delta E}, & m_i \lesssim \Delta E \end{cases}$$

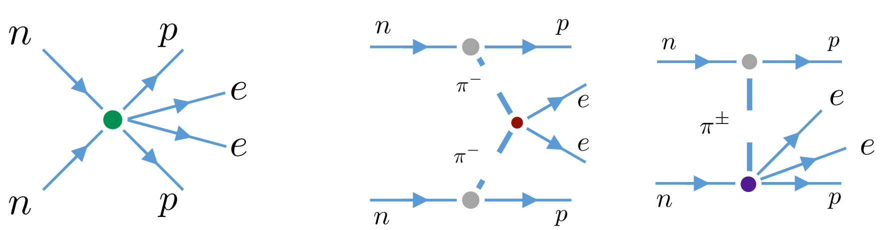
Hadronic/nuclear input



Hadronic/nuclear input

Known from LQCD

$g_\nu^{NN}(m_i)$ $\quad$ $g_1^{\pi\pi}, g_1^{\pi N}, g_1^{NN}$



LECs

$M_\nu^{\text{short-distance}}$

NMEs

$M_\nu(m_i) = \langle f | V | i \rangle$

$\langle f | \tau^+ \sigma | n \rangle$

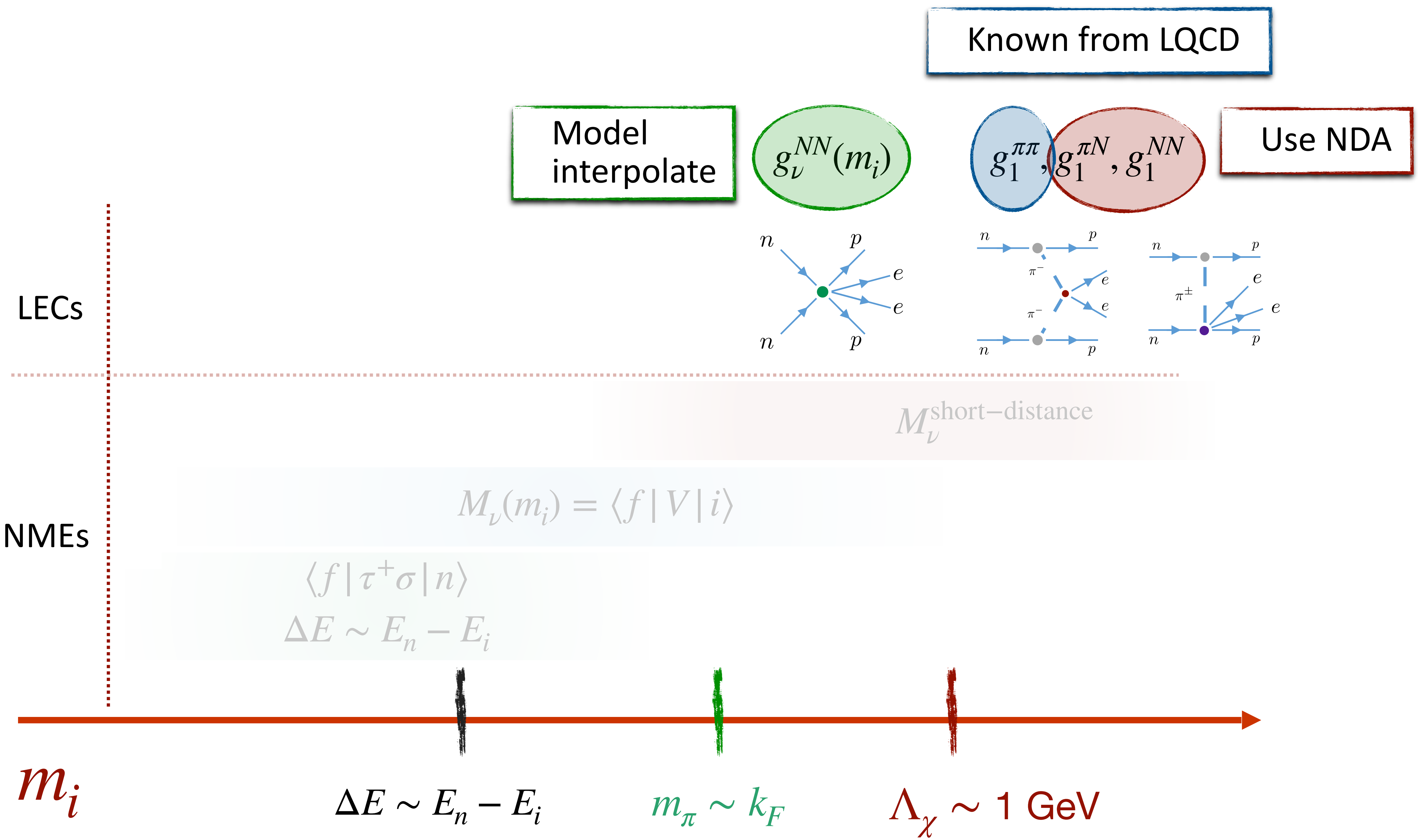
$\Delta E \sim E_n - E_i$

m_i

$\Delta E \sim E_n - E_i$ $\quad$ $m_\pi \sim k_F$ $\quad$ $\Lambda_\chi \sim$ 1 GeV

Nicholson et al ’18; Detmold et al ‘22

Hadronic/nuclear input



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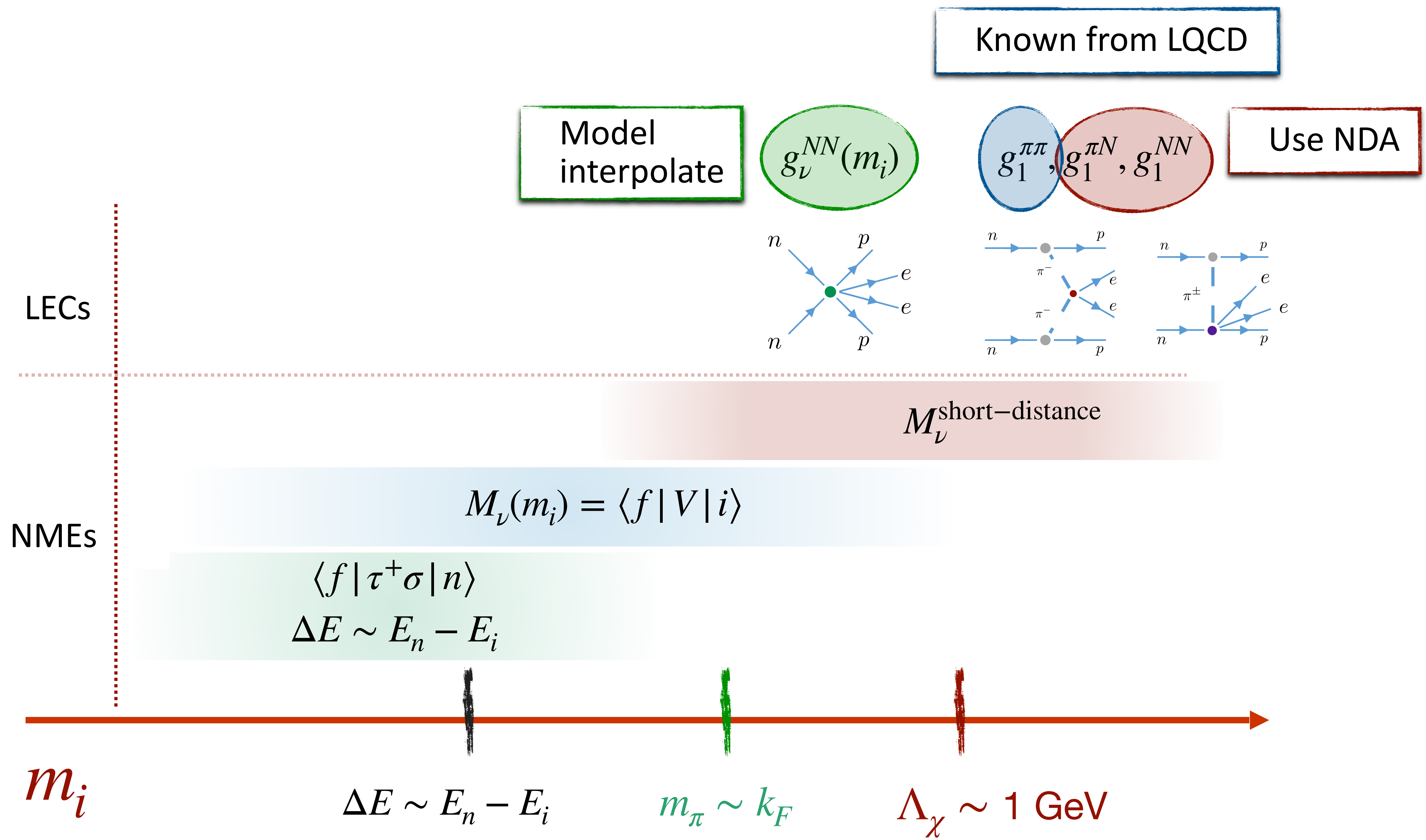

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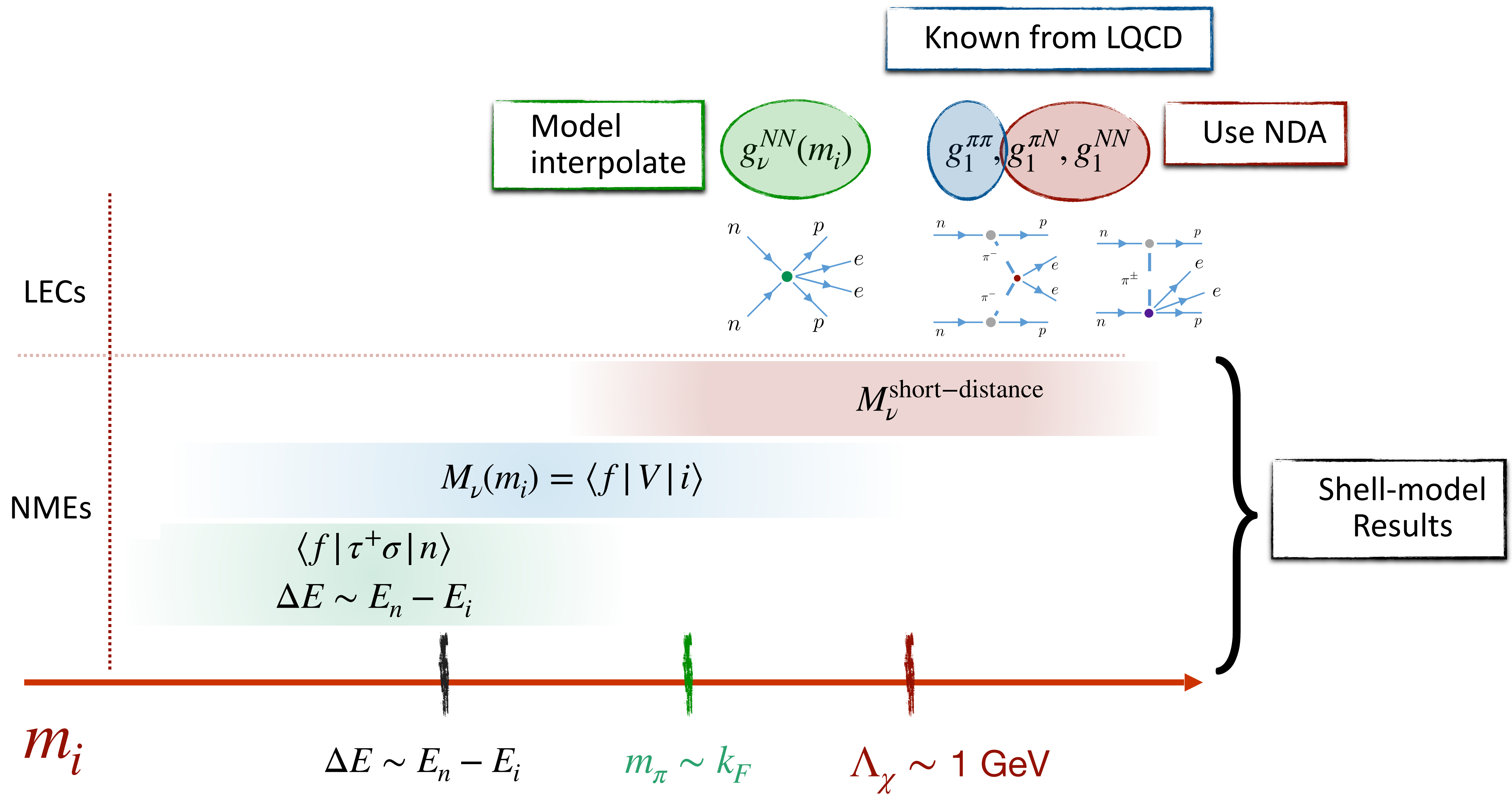

Nicholson et al ’18; Detmold et al ‘22

Phenomenology

Toy model: 1+1+1 pseudo-Dirac

- Involves 1 active, two sterile neutrinos
  - Assume steriles much heavier than the active neutrinos; $M_1 \simeq M_2 \gg m_\nu$
  - Two heavier ν's, form a pseudo-Dirac pair
  - Light neutrino mass proportional to LNV parameter (opposite to seesaw)

Bolton et al, 2020; Mohapatra et al, '86; Nandi and Sarkar '86;

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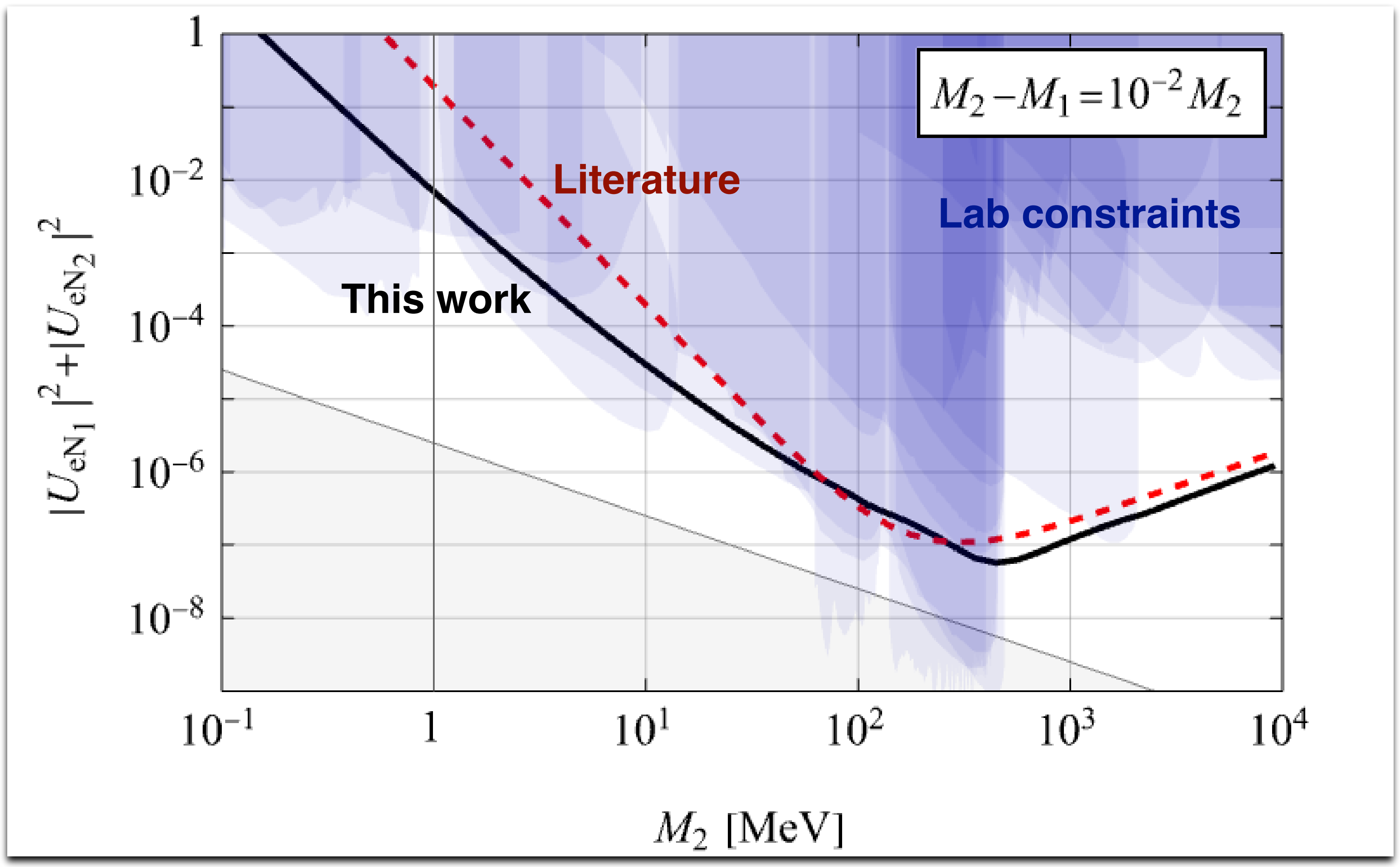

Bolton et al, 2020; Mohapatra et al, '86; Nandi and Sarkar '86;

Summary

- Sterile neutrinos are motivated by
  - Neutrino masses
  - Leptogenesis
  - Dark matter candidate

- Generally induce $0\nu\beta\beta$
  - Minimal extension of the SM leads to a cancellation: $$\sum_{i=1}^{3+n} m_i U_{ei}^2 = 0$$

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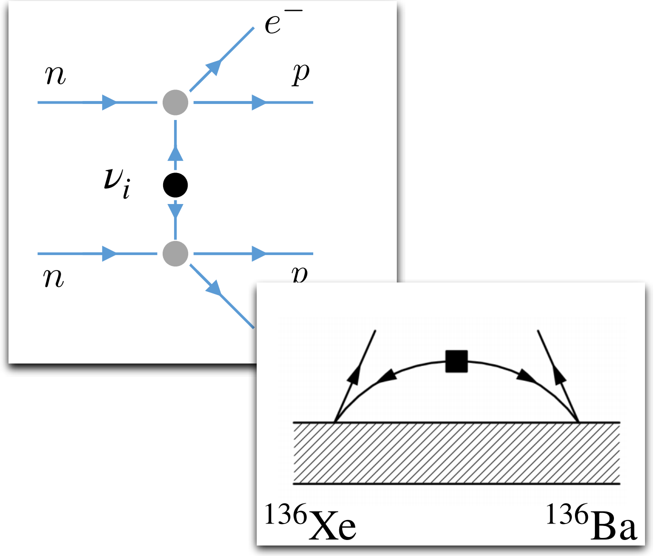
- Requires usually subleading m_i dependence
  - Can be captured in EFT approach



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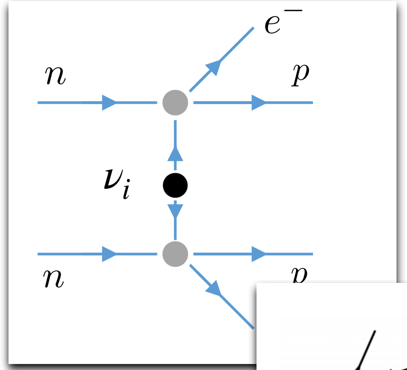
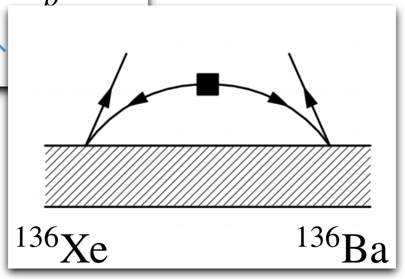
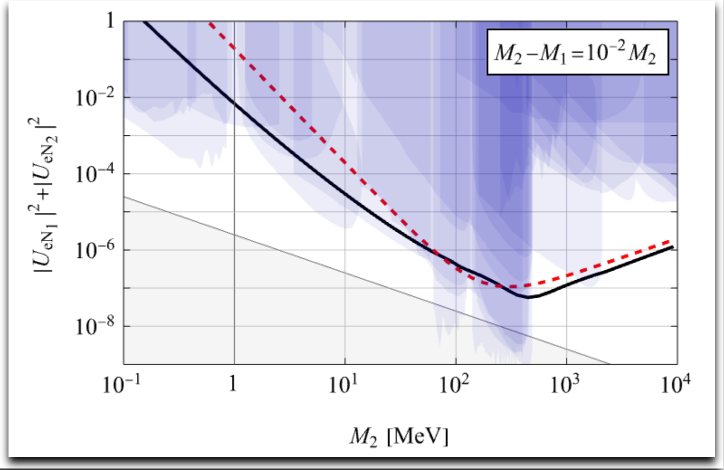




- Significant changes compared to usual approach
  - Can already be seen in simple toy models



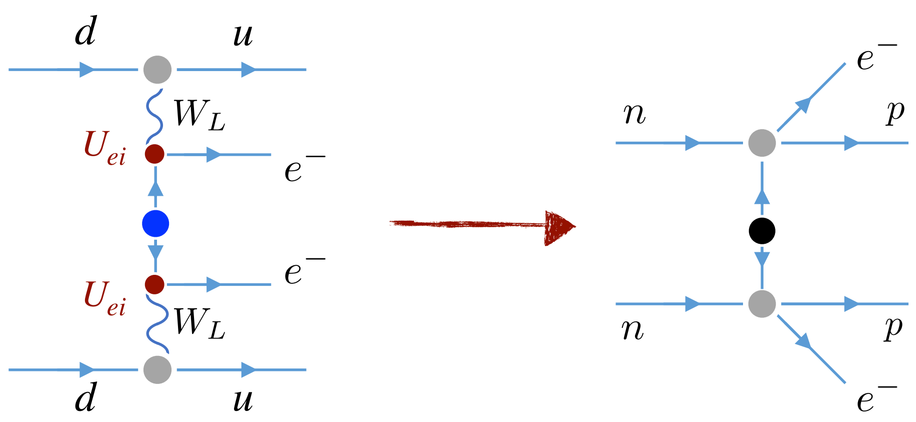
Back up slides

Literature approach

$0\nu\beta\beta$

Commonly used approach:

- Assume quark currents factorize:



$= V(q)$

$$A_\nu(m_i) \sim \langle {}^{136}\mathrm{Ba} \,|\, V(q) \,|\, {}^{136}\mathrm{Xe} \rangle$$

- Approximate amplitude by

$$A_\nu(m_i) = A_\nu(0) \frac{\langle p^2 \rangle}{\langle p^2 \rangle + m_i^2} \qquad \langle p^2 \rangle \simeq k_F^2$$

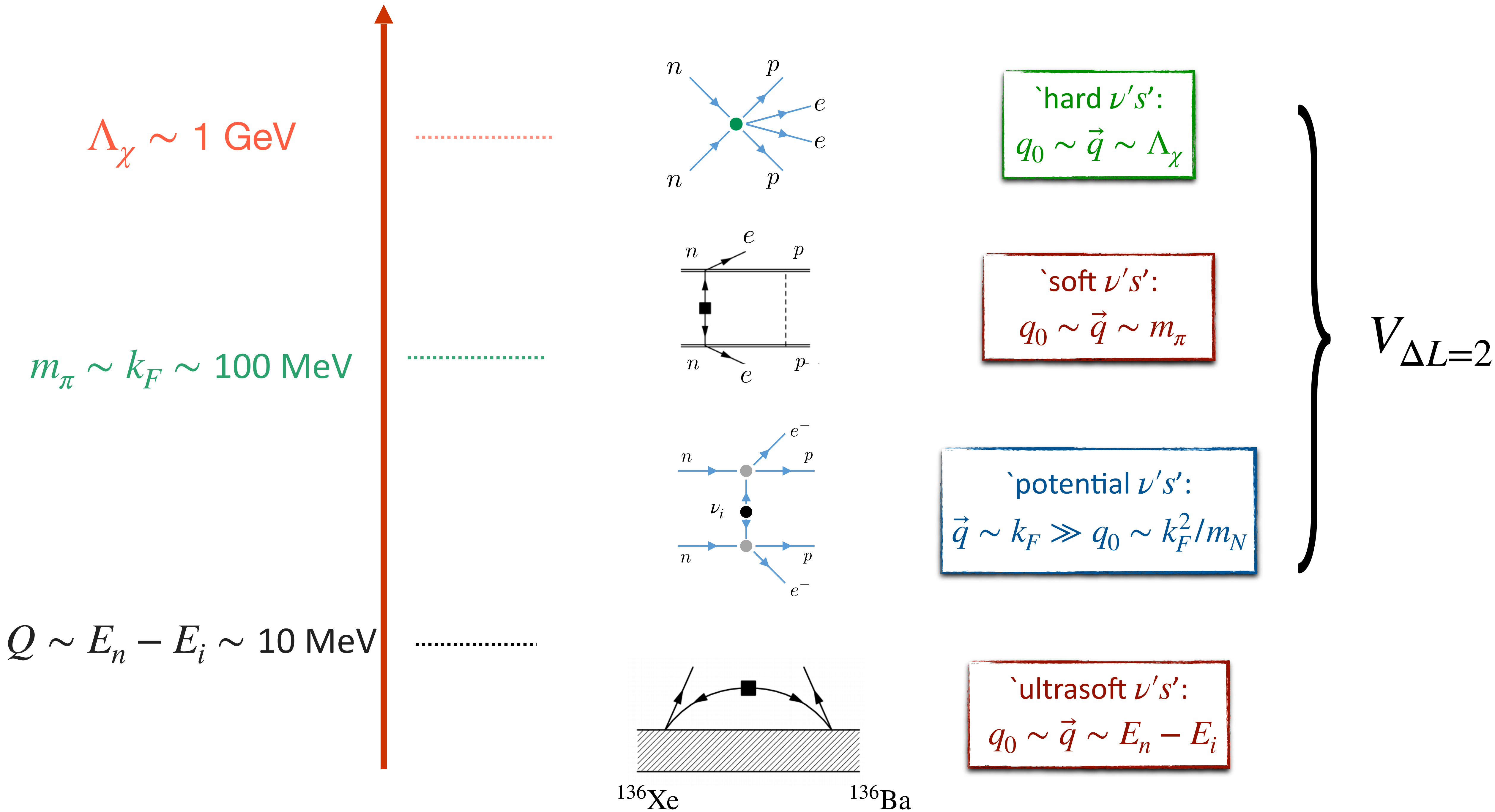
- m_i dependence seems reasonable, however,
  - Does not have the right QCD behavior for $m_i \gg \Lambda_\chi \sim \mathrm{GeV}$
  - Misses several effects for $m_i \leq \Lambda_\chi$

Faessler et al, '14; Asaka et al '16; Bolton et al '20,'22; Fang et al, '22;

Overview of Contributions

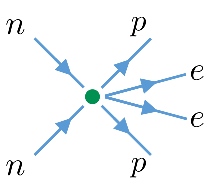
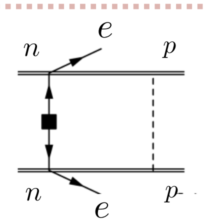
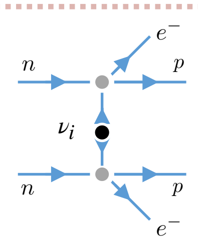
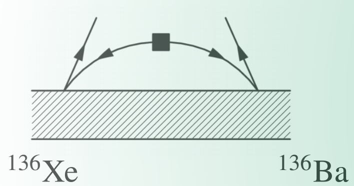
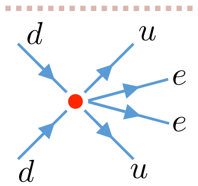
Momentum scales

$m_i = 0$



$$A_\nu = \langle {}^{136}\mathrm{Ba} \,|\, V_{\Delta L=2} \,|\, {}^{136}\mathrm{Xe} \rangle \quad + \quad A_\nu^{\mathrm{usoft}}$$

Overview

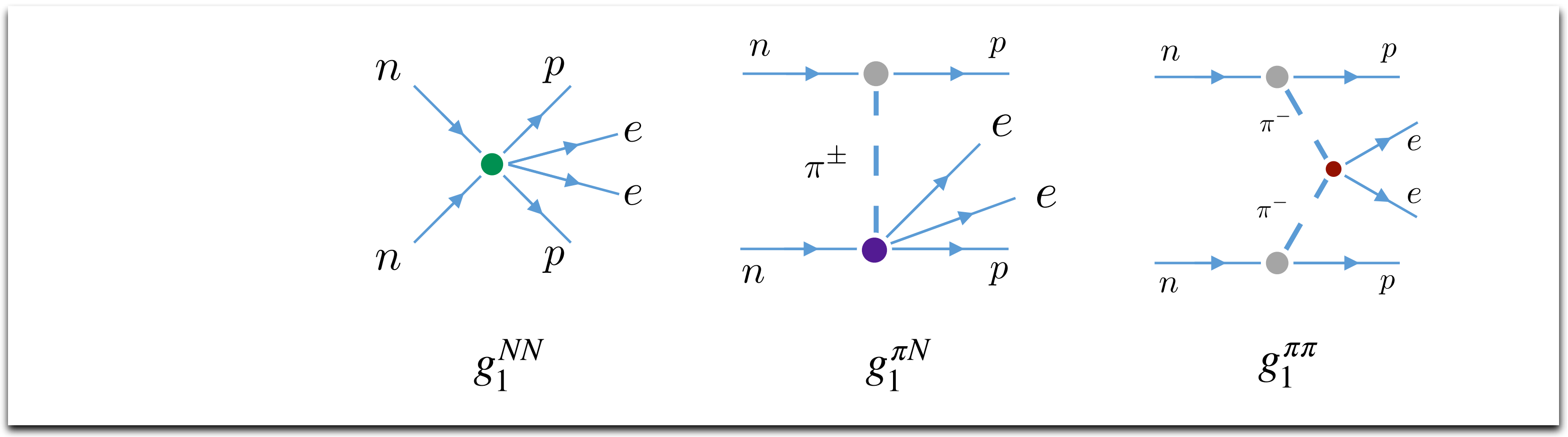
Leading m_i dependence		$m_i \ll \Delta E$	$\Delta E \ll m_i \ll k_F$	$k_F \ll m_i \ll \Lambda_\chi$	$\Lambda_\chi \ll m_i$
	Hard			$\frac{k_F^2}{m_i^2}$	
	Soft			$\frac{m_i^2}{\Lambda_\chi^2}$	
	Potential	$\frac{m_i^2}{k_F^2}$		$\frac{k_F^2}{m_i^2}$	
	Ultrasoft	$\frac{m_i^2}{4\pi \Delta E k_F} \ln \frac{m_i}{\Delta E}$	$\frac{m_i}{k_F}$		
	Perturbative				$\frac{k_F^2}{m_i^2}$

Ultrasoft dominant for small masses

Hadronic matrix elements

Required LECs

$m_i \gg \Lambda_\chi$



NDA	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(1)$
Used value	$\frac{1+3g_A^2}{4}$	0	0.36

LQCD: Nicholson et al '18

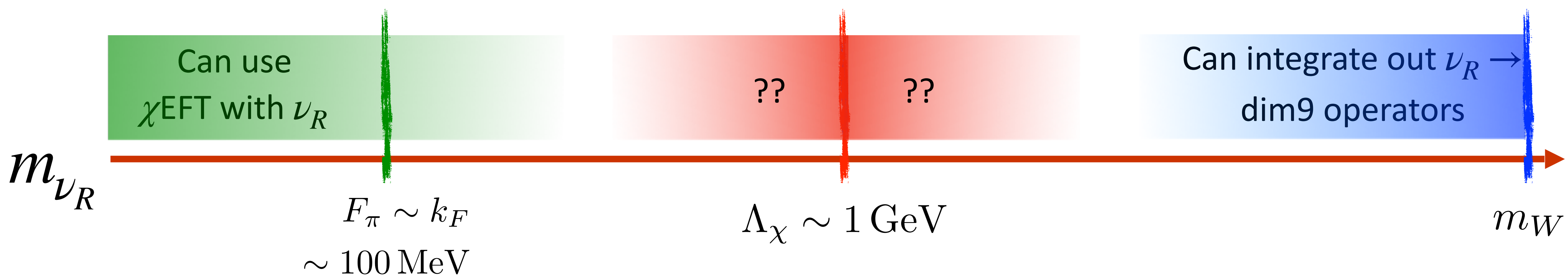
Required LECs

$m_i \lesssim \Lambda_\chi$

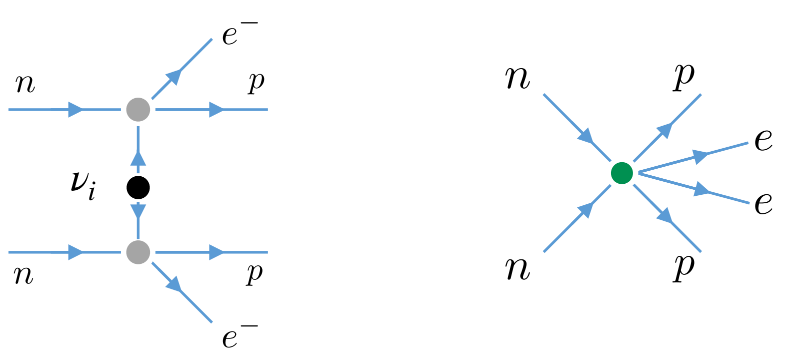
Interpolation

$$g_\nu^{NN}(m_i) = g_\nu^{NN}(0)\frac{1+(m_i/m_c)^2}{1+(m_i/m_c)^2(m_i/m_d)^2}\,,$$

- NDA gives $m_c \sim 1\,\mathrm{GeV}^2$
- Model esteems imply $g_\nu^{NN}(0) \sim -\,\mathrm{fm}^2$

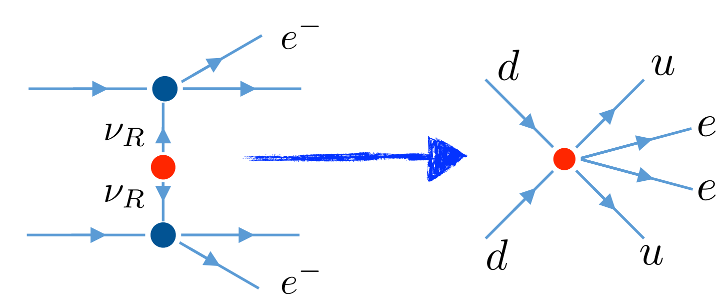


- Chiral EFT involving ν_R



Match for $m_i \sim 2$ GeV
$\Longrightarrow\ m_d$

- Integrate out ν_R

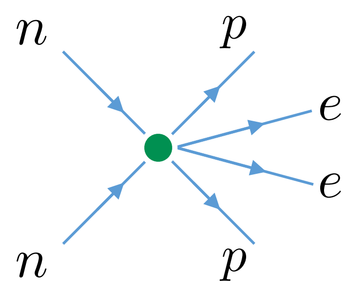


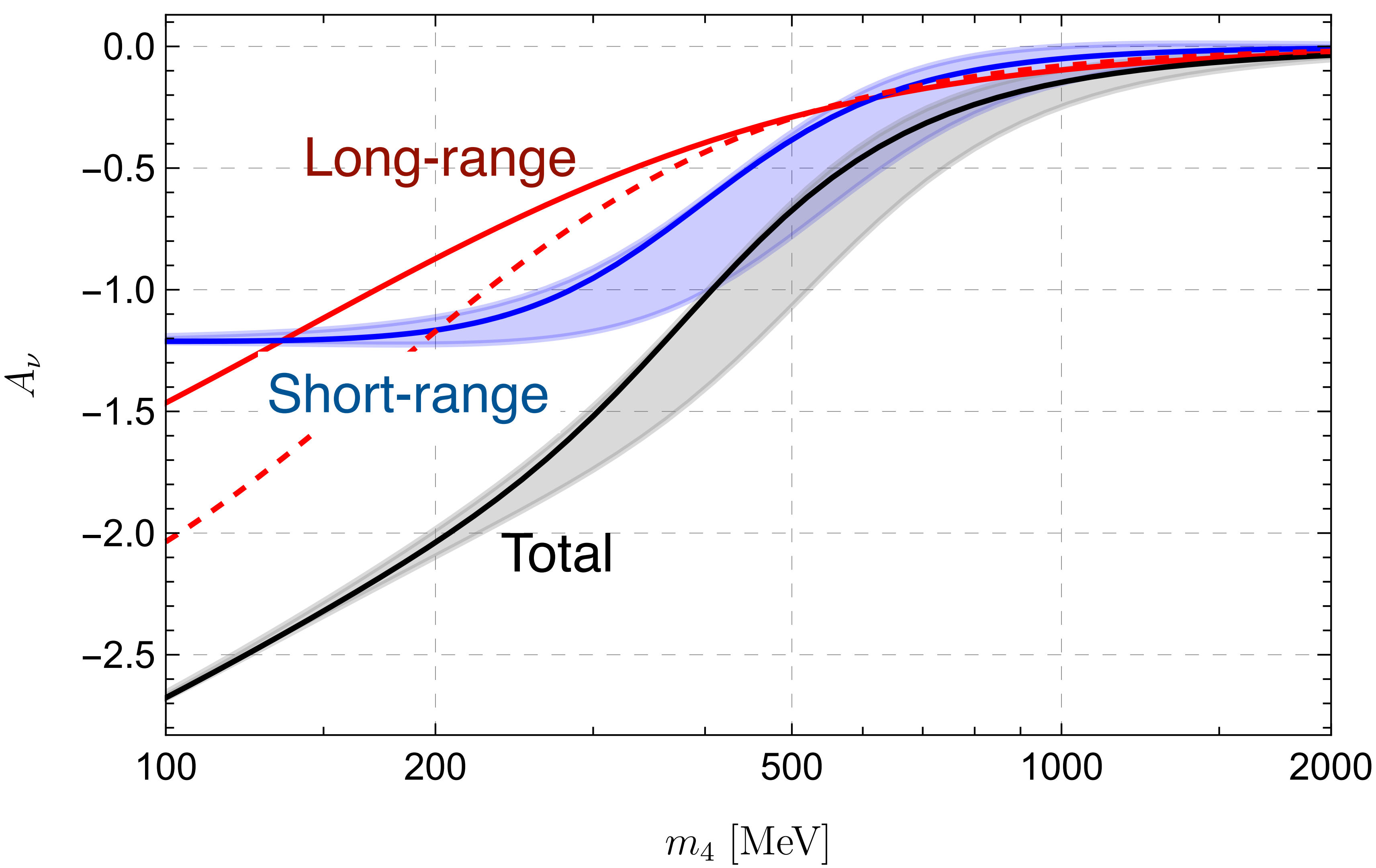
$\to$ Chiral EFT without ν_R

Uncertainties

LEC uncertainties

Varying g_1^{NN}



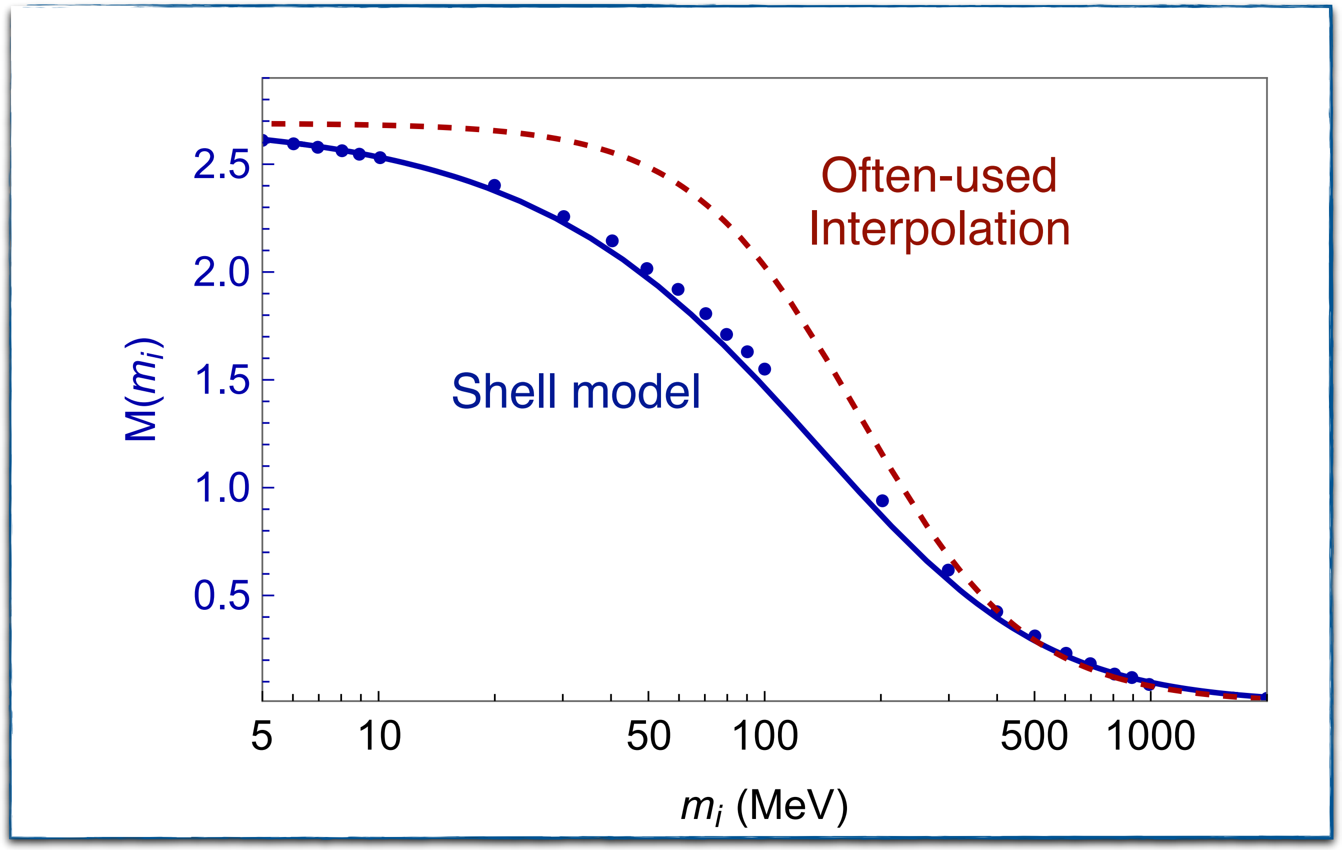


Nuclear matrix elements

Required NMEs

Potential contribution

$$A_\nu = \langle {}^{136}\mathrm{Ba} \,|\, V(m_i) \,|\, {}^{136}\mathrm{Xe} \rangle$$



Required NMEs

Ultrasoft contribution

$\frac{E_n-E_i}{\text{MeV}}$	$\langle n\vert\boldsymbol{\sigma}\tau^+\vert 0_i^+\rangle$	$\langle 0_f^+\vert\boldsymbol{\sigma}\tau^+\vert n\rangle$
0.17	1.0	0.13
0.63	-0.19	-0.0063
0.89	-0.25	-0.016
1.02	0.30	0.036
1.05	0.23	0.025
1.1	-0.13	-0.00076
1.2	0.12	-0.0052
1.3	0.16	-0.0028
1.4	-0.23	-0.0098
1.5	0.20	-0.012
1.6	-0.36	0.0084
1.7	-0.24	0.00058
1.9	0.22	0.011
2.0	0.34	0.0070
2.2	0.35	0.0060
2.3	-0.49	-0.0086
2.6	0.62	0.021
2.7	-0.91	-0.024
2.9	0.37	0.0064
3.1	0.30	0.0013

$\frac{E_n-E_i}{\text{MeV}}$	$\langle n\vert\boldsymbol{\sigma}\tau^+\vert 0_i^+\rangle$	$\langle 0_f^+\vert\boldsymbol{\sigma}\tau^+\vert n\rangle$
3.3	0.39	-0.0013
3.6	0.39	0.0021
3.8	0.45	-0.013
4.0	-0.44	-0.0032
4.3	-0.35	-0.0038
4.6	-0.36	-0.0067
4.8	0.44	0.0083
5.1	0.44	0.0066
5.4	-0.55	-0.0093
5.7	0.63	0.012
6.1	0.85	0.013
6.3	-1.2	-0.016
6.7	-1.3	-0.014
7.0	-1.9	-0.016
7.3	3.1	0.023
7.5	-4.0	-0.028
7.7	2.6	0.017
8.1	1.4	0.0091
8.4	-1.0	-0.0057
8.8	-0.93	-0.0064

$\frac{E_n-E_i}{\text{MeV}}$	$\langle n\vert\boldsymbol{\sigma}\tau^+\vert 0_i^+\rangle$	$\langle 0_f^+\vert\boldsymbol{\sigma}\tau^+\vert n\rangle$
9.1	0.80	0.0038
9.4	0.59	0.0014
9.8	-0.50	0.0027
10.1	0.35	-0.0027
10.5	0.26	-0.00053
10.9	-0.22	-0.00021
11.3	0.17	-0.00037
11.7	-0.16	-0.00054
12.0	-0.16	-0.0010
12.4	0.14	0.00092
12.8	0.12	-0.00014
13.1	0.092	-0.00040
13.5	-0.079	-0.00019
13.9	0.071	-0.00026
14.2	-0.070	0.000031
14.6	-0.035	0.00021
15.1	-0.051	-0.00015
16.2	-0.039	0.00011
17.3	-0.043	-0.000091
17.7	0.11	-0.000029

$$A_\nu^{(\text{usoft})} = -\frac{R_A}{2\pi}\sum_n \langle 0^+|\tau^+\boldsymbol{\sigma}|n\rangle\langle n|\tau^+\boldsymbol{\sigma}|0^+\rangle \times [f(m_i,\Delta E_1)+f(m_i,\Delta E_2)]\ ,$$

$$f(m,E) = -2\left[E\left(1+\ln\frac{\mu_{us}}{m}\right)+\sqrt{m^2-E^2}\times\left(\frac{\pi}{2}-\tan^{-1}\frac{E}{\sqrt{m^2-E^2}}\right)\right],\qquad k_F \gtrsim m_i \gtrsim k_F^2/m_N$$

$$f(m,E) = -2\left[E\left(1+\ln\frac{\mu_{us}}{m}\right) -\sqrt{E^2-m^2}\ln\frac{E+\sqrt{E^2-m^2}}{m}\right].\qquad m_i \lesssim \Delta E$$

Required NMEs

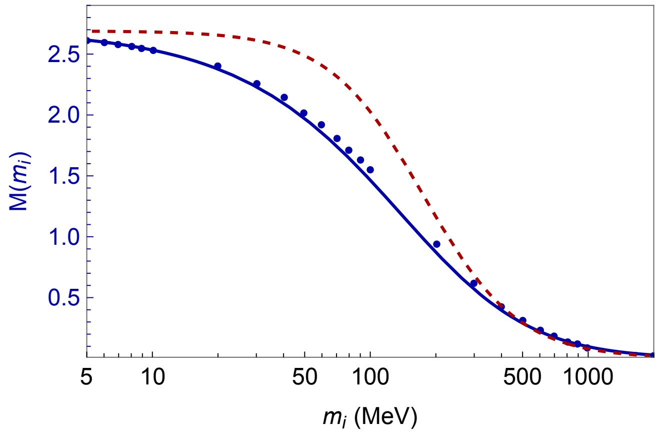
Ultrasoft/potential contributions

- Part of the ultrasoft and potential contributions are related:
  - For $m_\pi \gtrsim m_i \gtrsim \Delta E$

$$A_\nu^{\rm usoft} \simeq \frac{R_A}{2\pi} m_i \sum_n \langle 0^+ | \tau^+ \sigma | n \rangle \langle n | \tau^+ \sigma | 0^+ \rangle$$

- This linear term is also present in

$$A_\nu^{\rm pot} = \langle {}^{136}{\rm Ba} | V(m_i) | {}^{136}{\rm Xe} \rangle$$



- Have to make sure not to double count
  - In practice we remove the linear term from the potential contributions

- Allows for a cross check of the form

$$A_\nu^{\rm usoft} \simeq m_i \frac{d}{dm_i} A_\nu^{\rm pot}$$

  - Numerically works to $\sim 20\,\%$

Renormalization arguments

Checking the power counting

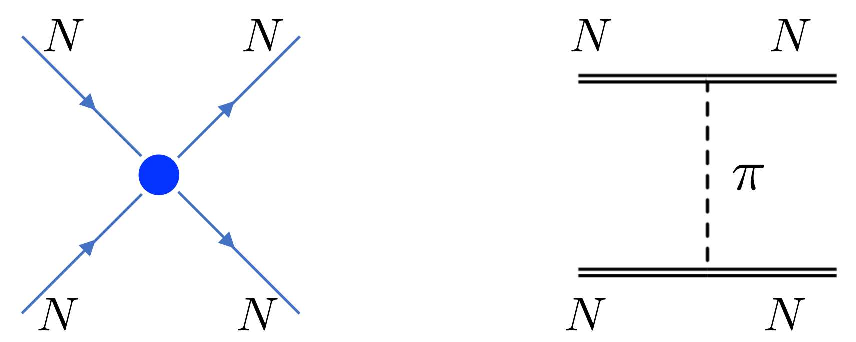
Check that $\mathcal{A}(nn \to ppee)$ is finite

Checking the power counting

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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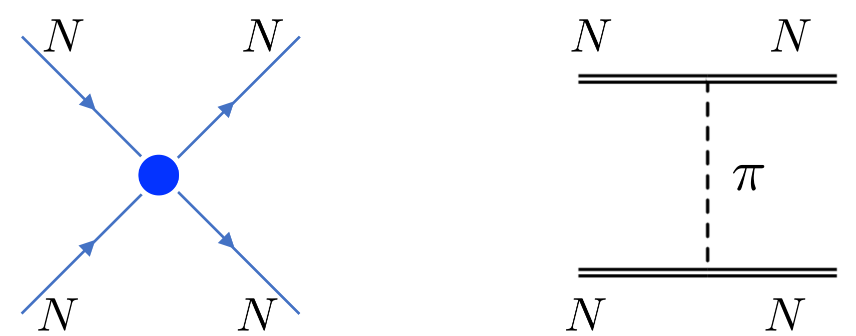
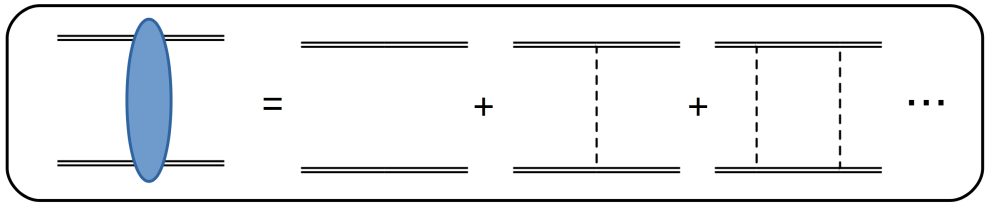
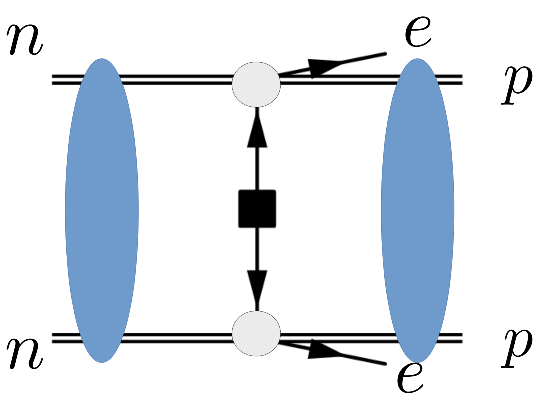


Dress the ΔL=2 potential with (renormalized) strong interactions:





✓ finite

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

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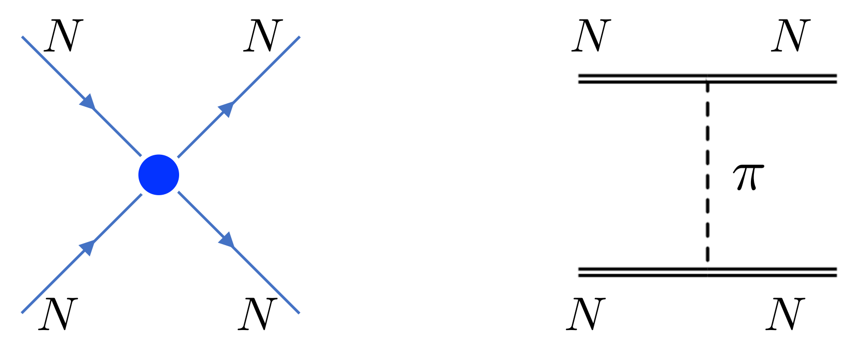
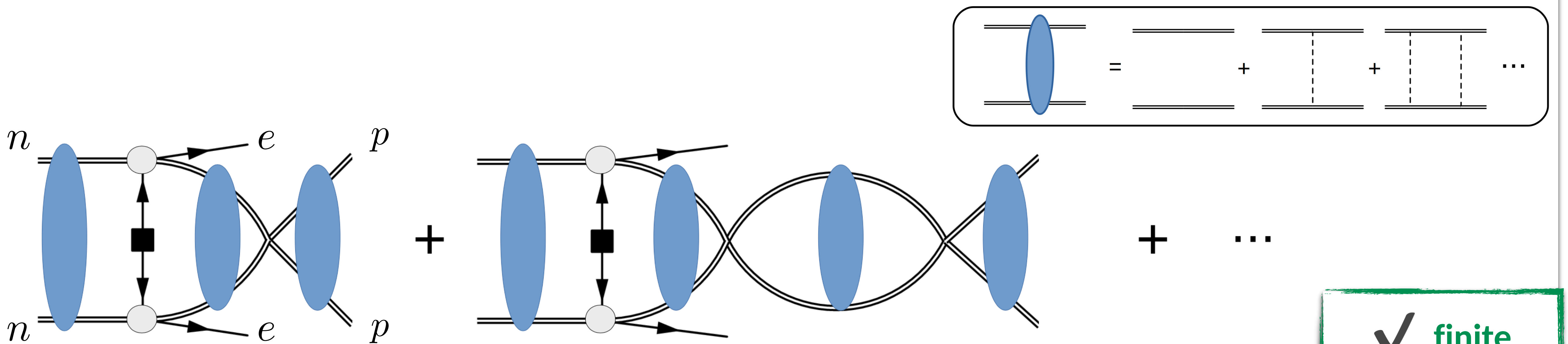


Dress the ΔL=2 potential with (renormalized) strong interactions:



✓ finite

Checking the power counting

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

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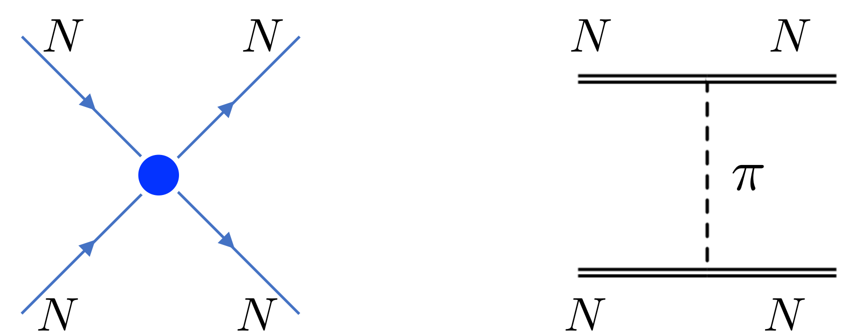

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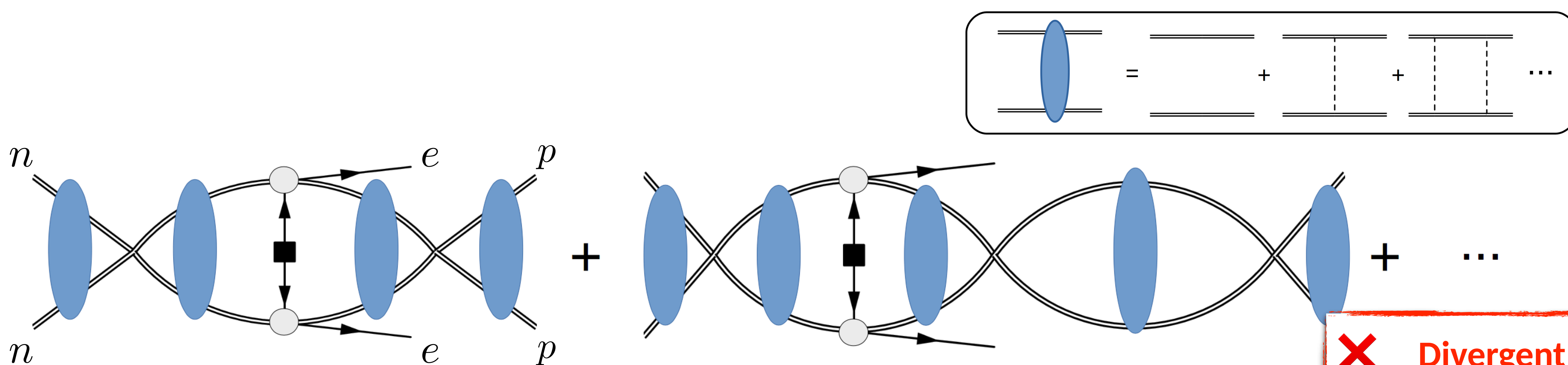


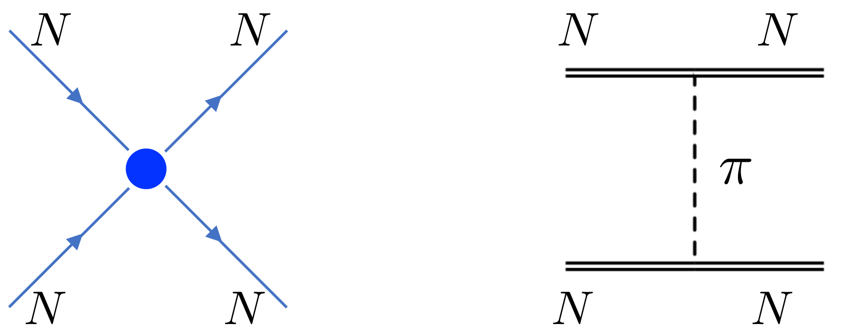
❌ Divergent

Checking the power counting

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

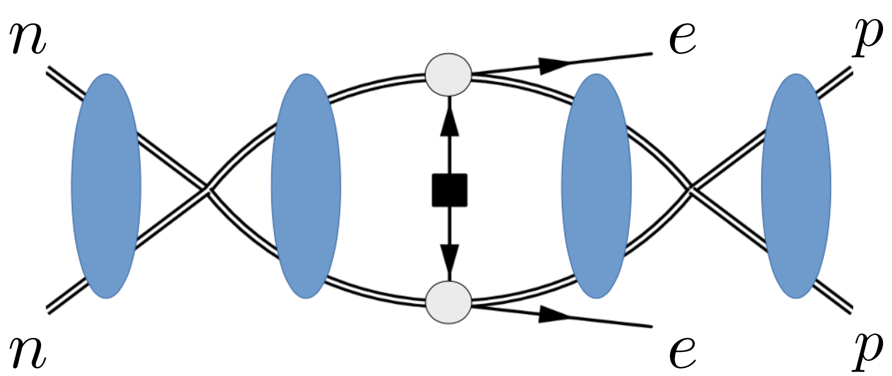
- Requires inclusion of the strong interaction

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



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

In MS-bar:

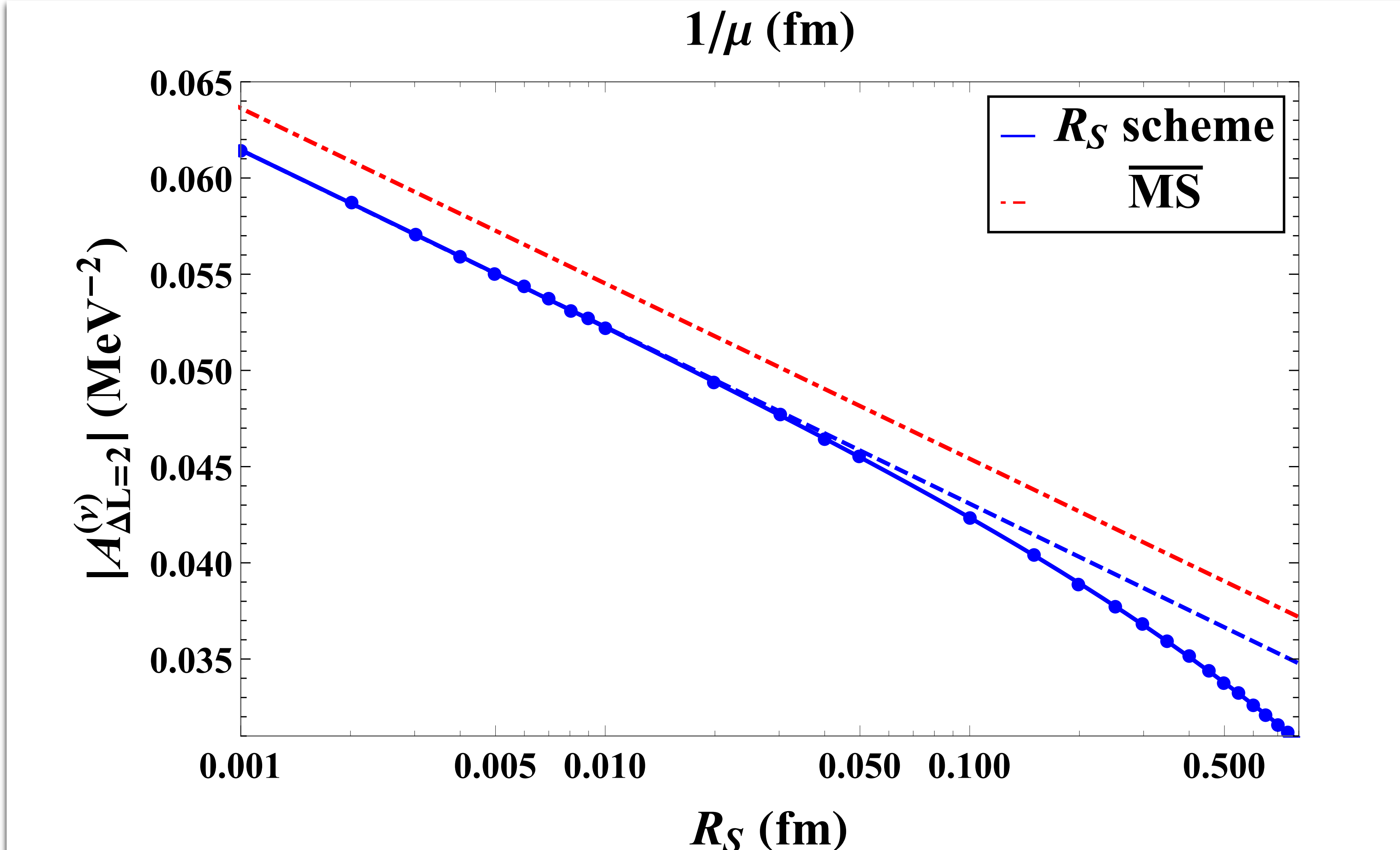


$$= -\left(\frac{m_N}{4\pi}\right)^2 (1+2g_A^2)\frac{1}{2}\left(\log\frac{\mu^2}{-(|\mathbf{p}|+|\mathbf{p}'|)^2+i0^+}+1\right)$$

$+\text{finite}$

Regulator dependent

Numerical results



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

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

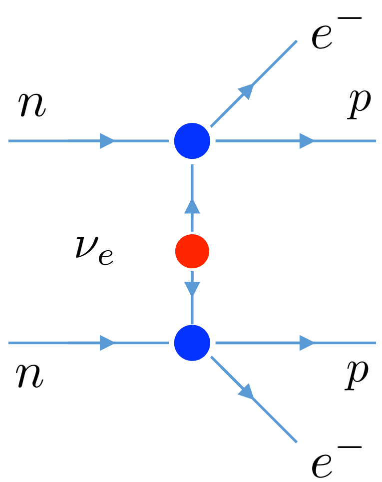
- Clear μ or R_S dependence

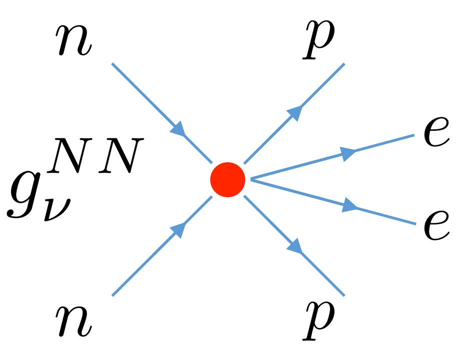
Need for a counter term

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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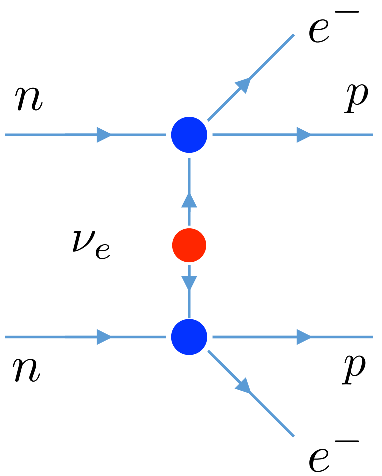

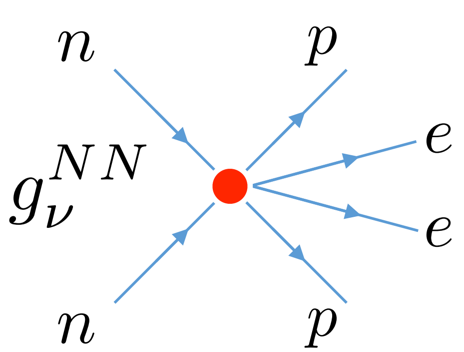

- g_ν^{NN} to be determined from a lattice calculation of $\mathcal{A}(nn \to ppe^- e^-)$
  - Area of active research

Davoudi and Kadam, ’20, ’21
Feng et al, ‘20

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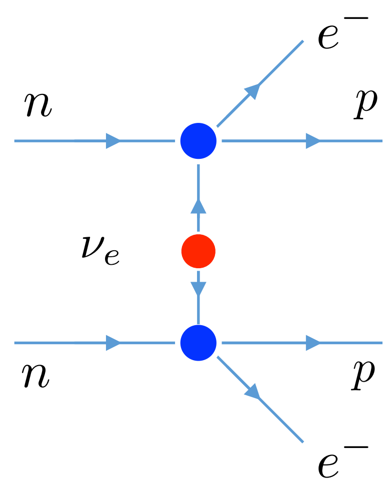

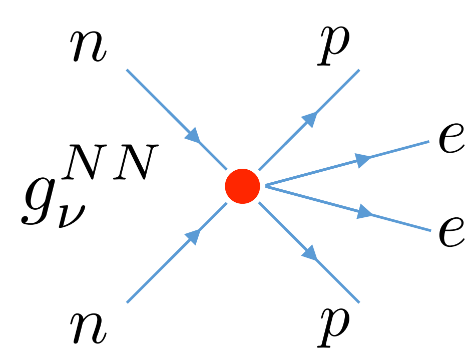

- g_ν^{NN} to be determined from a lattice calculation of $\mathcal{A}(nn \to ppe^-e^-)$
  - Area of active research

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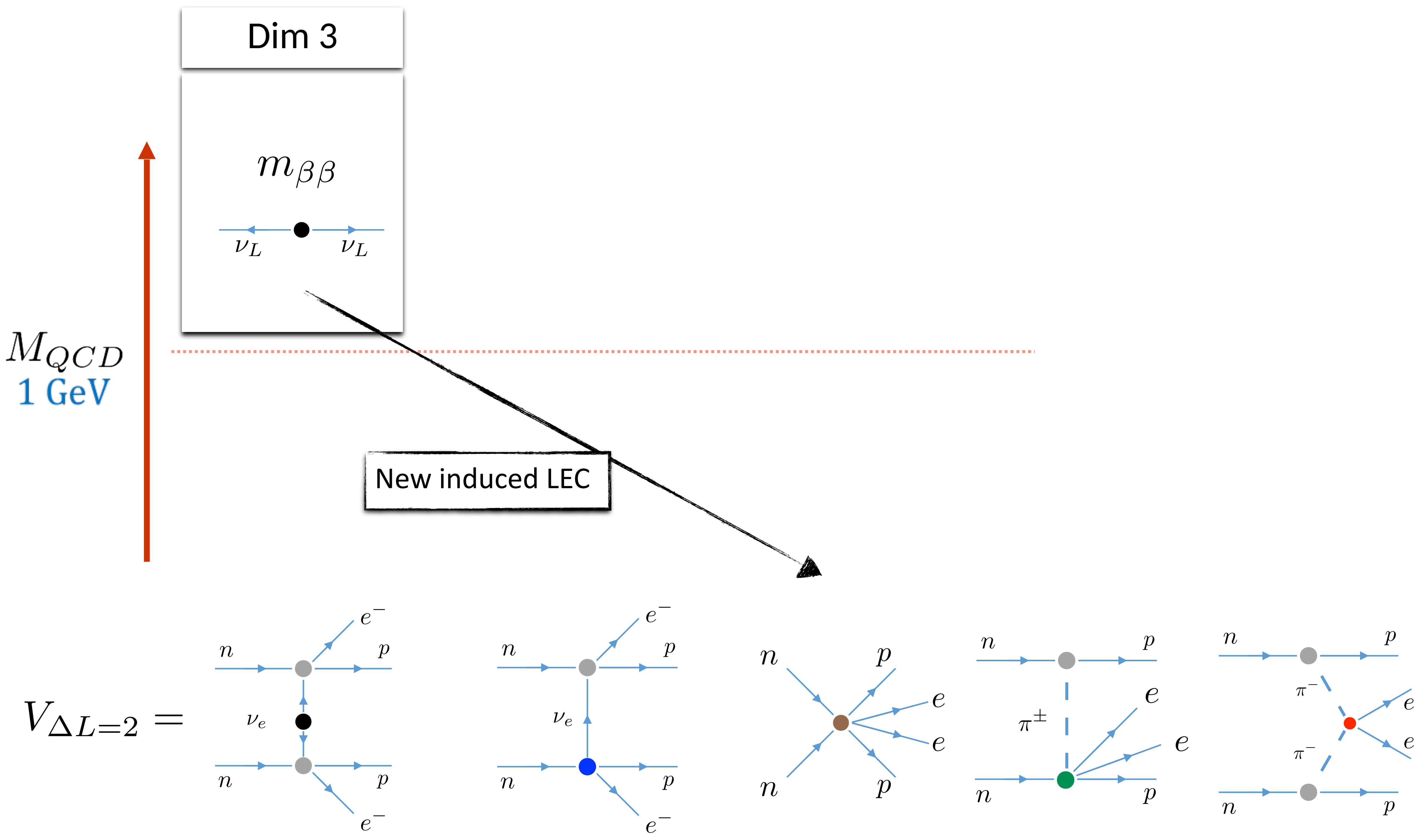
- Several estimates give $\tilde{g}_\nu^{NN} = \mathcal{O}(1)$
  - Comparison with isospin-breaking observables
  - Model (Cottingham) estimate — Cirigliano, et al, '19,'20, '21
  - Large-Nc estimate — Richardson et al, '21

See backup

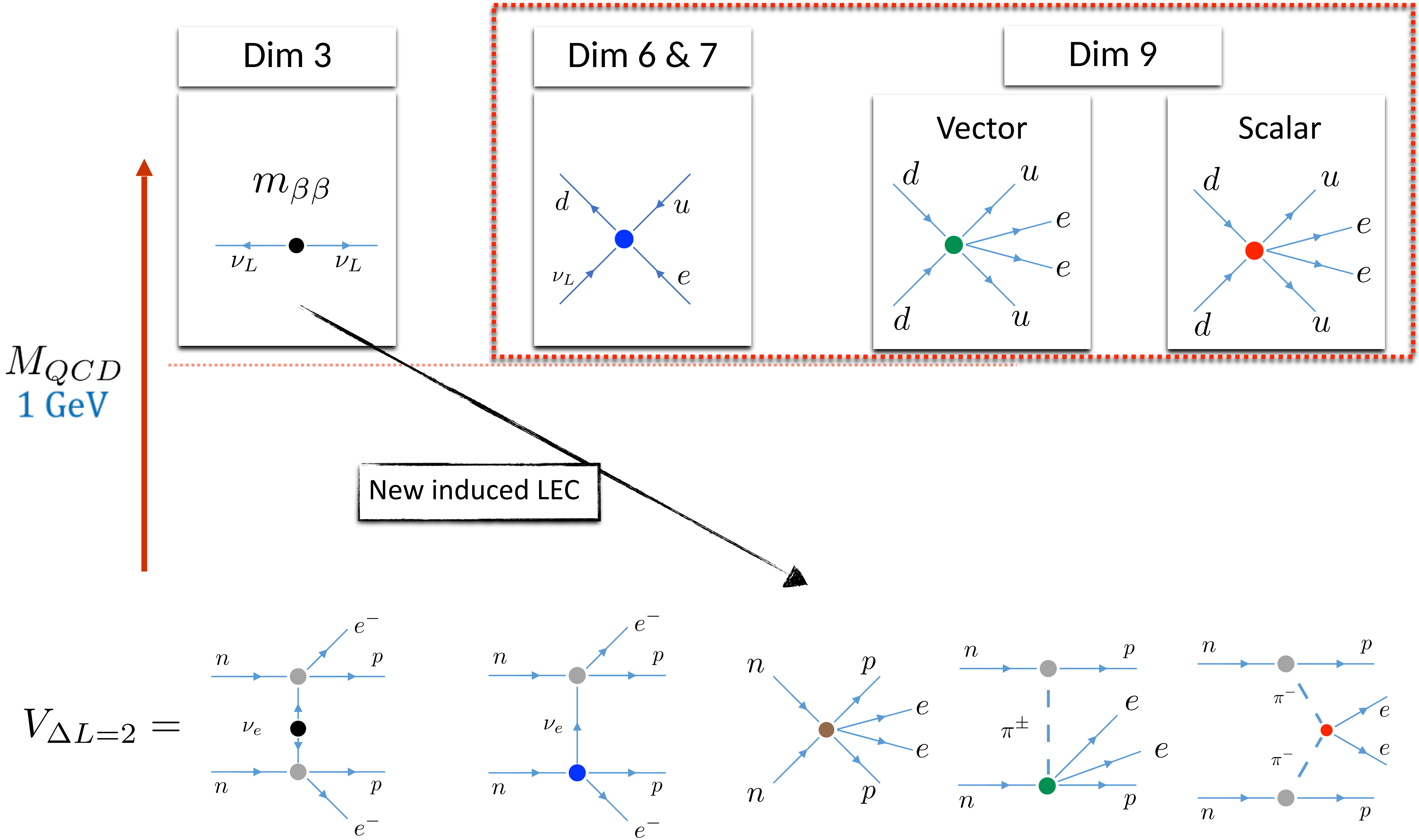
Chiral EFT

Non-Weinberg counting



Chiral EFT

Non-Weinberg counting affects higher dimensional interactions as well



Chiral EFT

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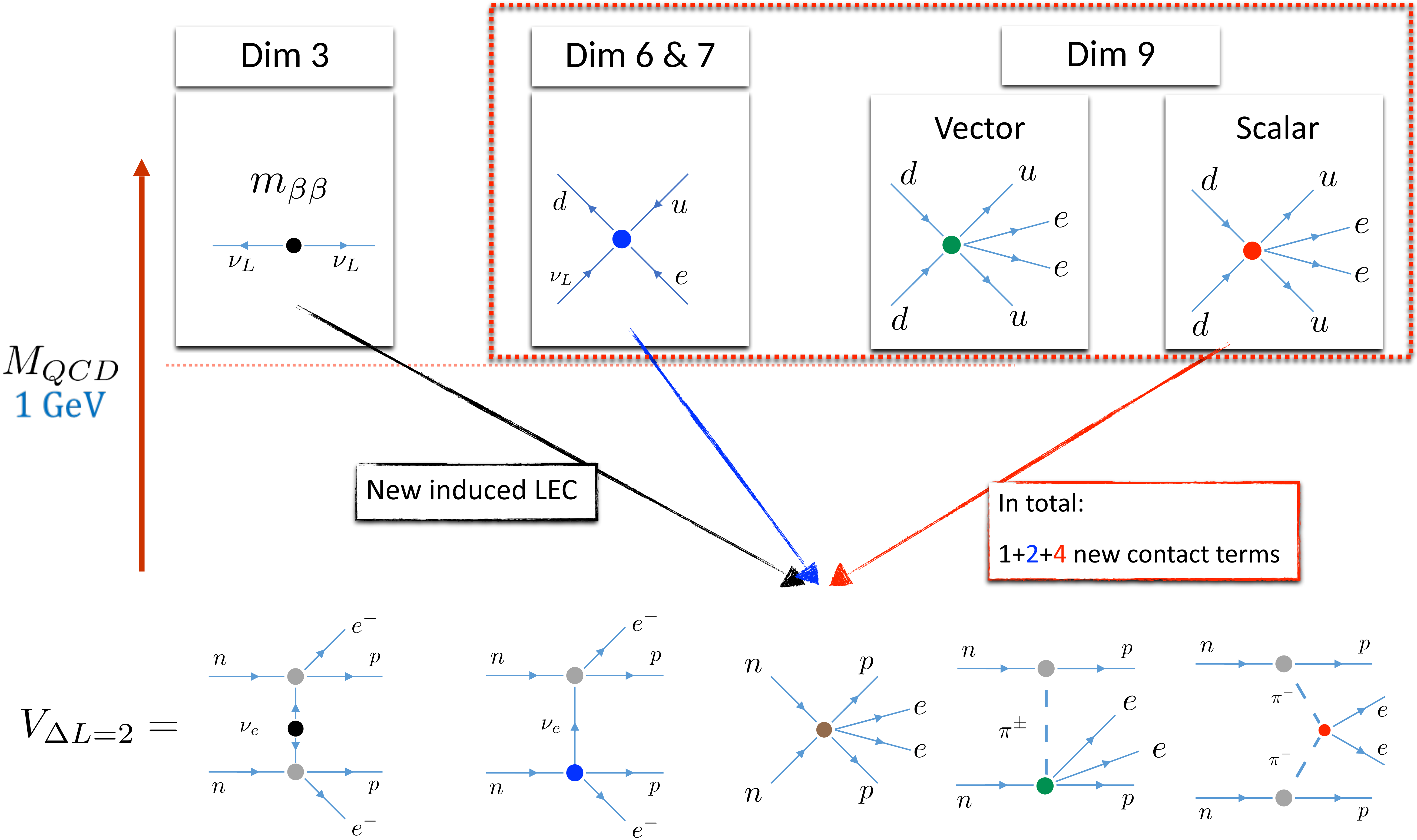


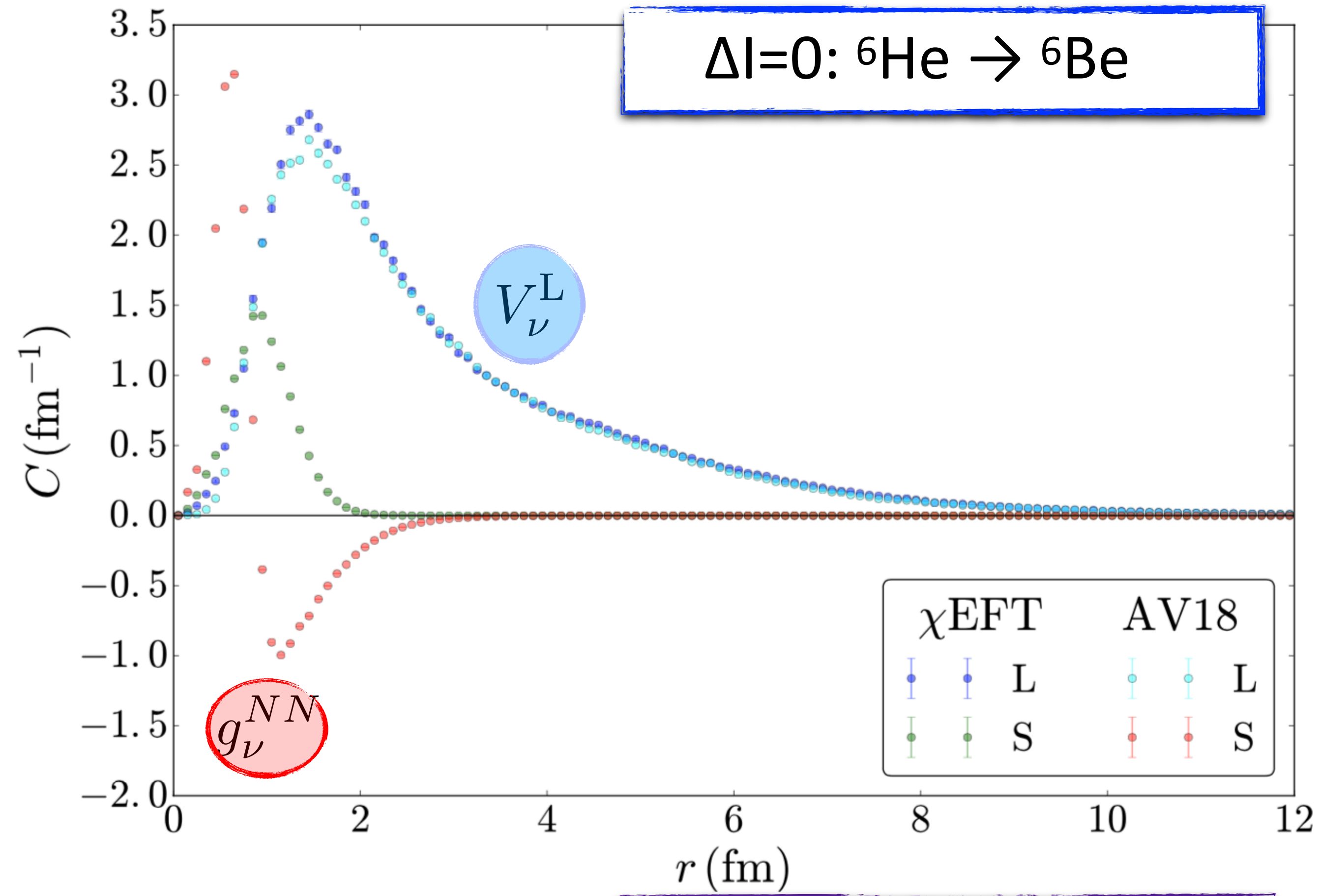
Estimate of impact in light nuclei

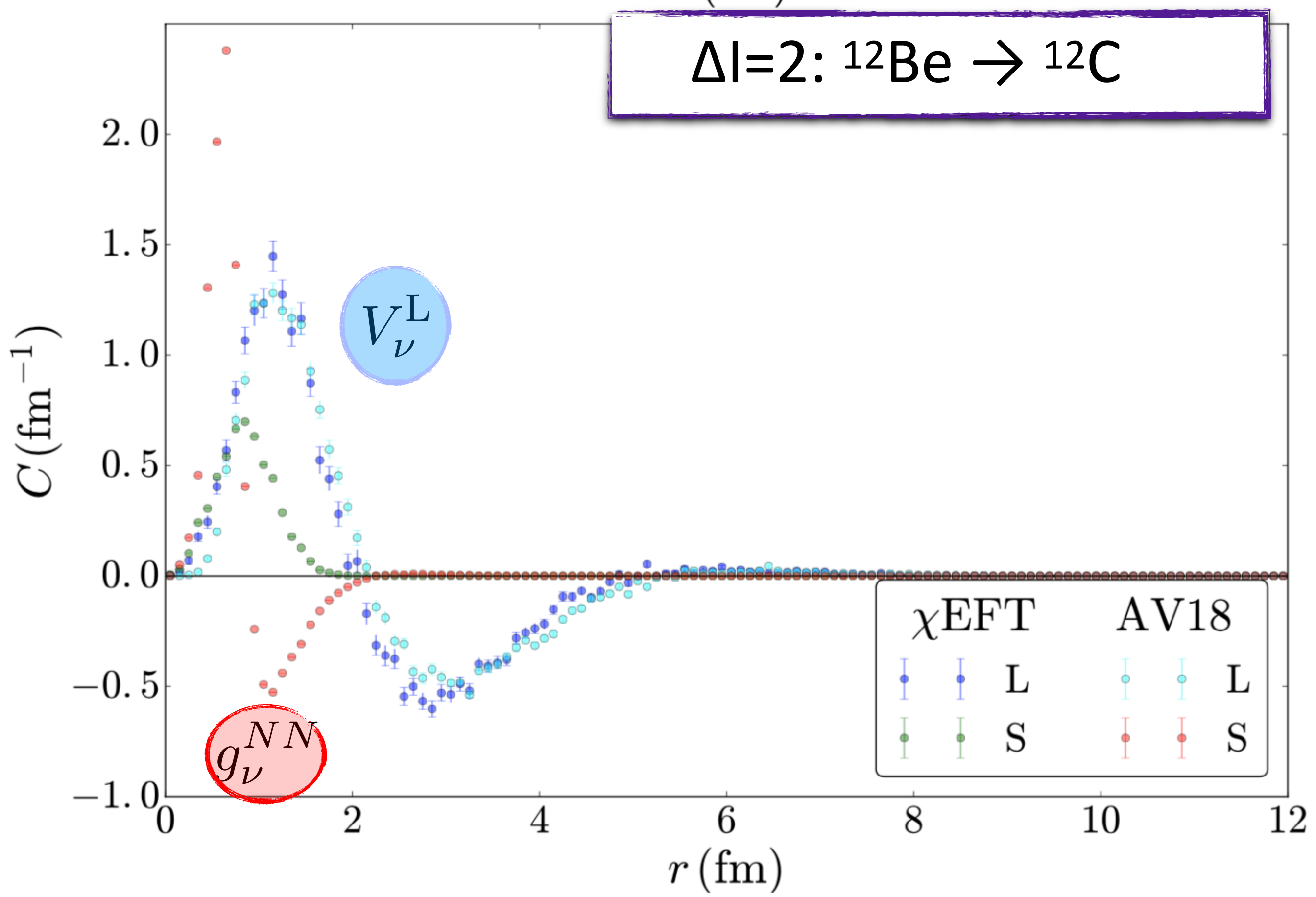
Estimate of impact

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
    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

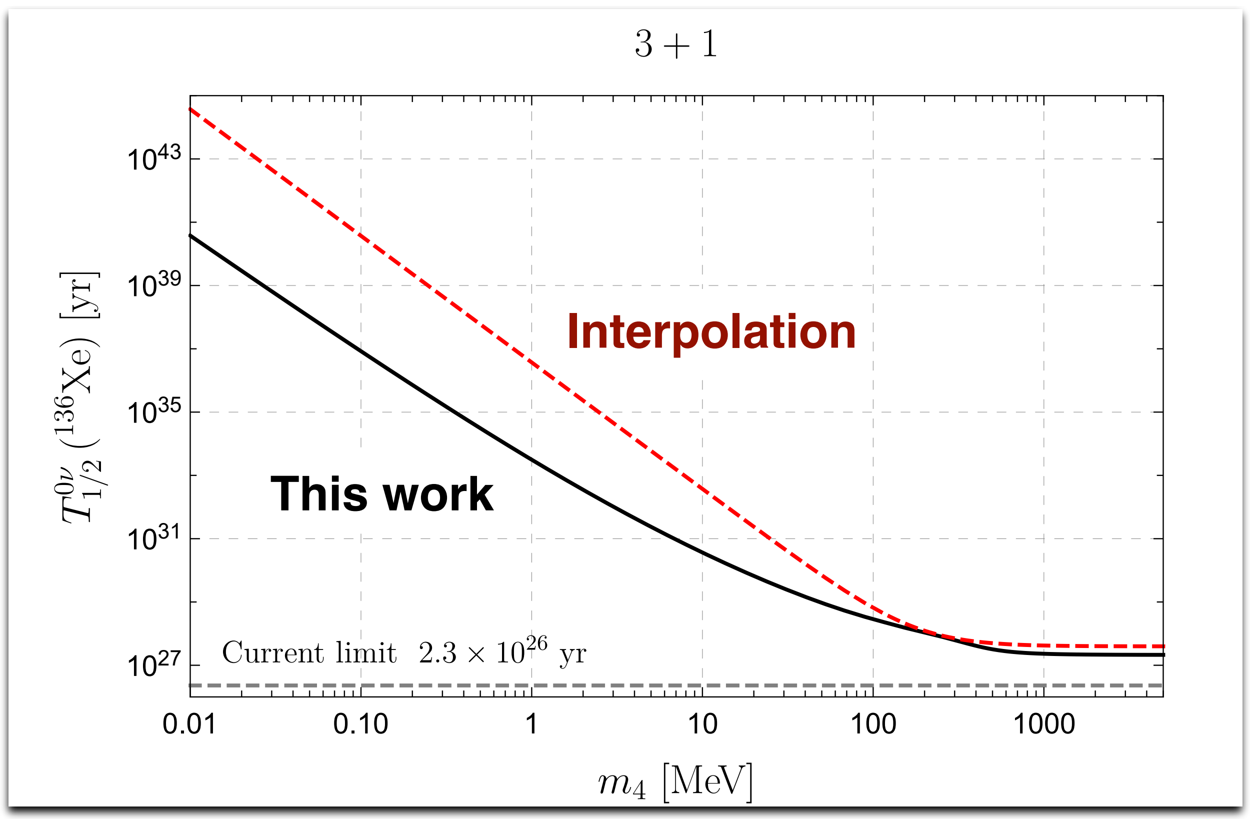
More simple models

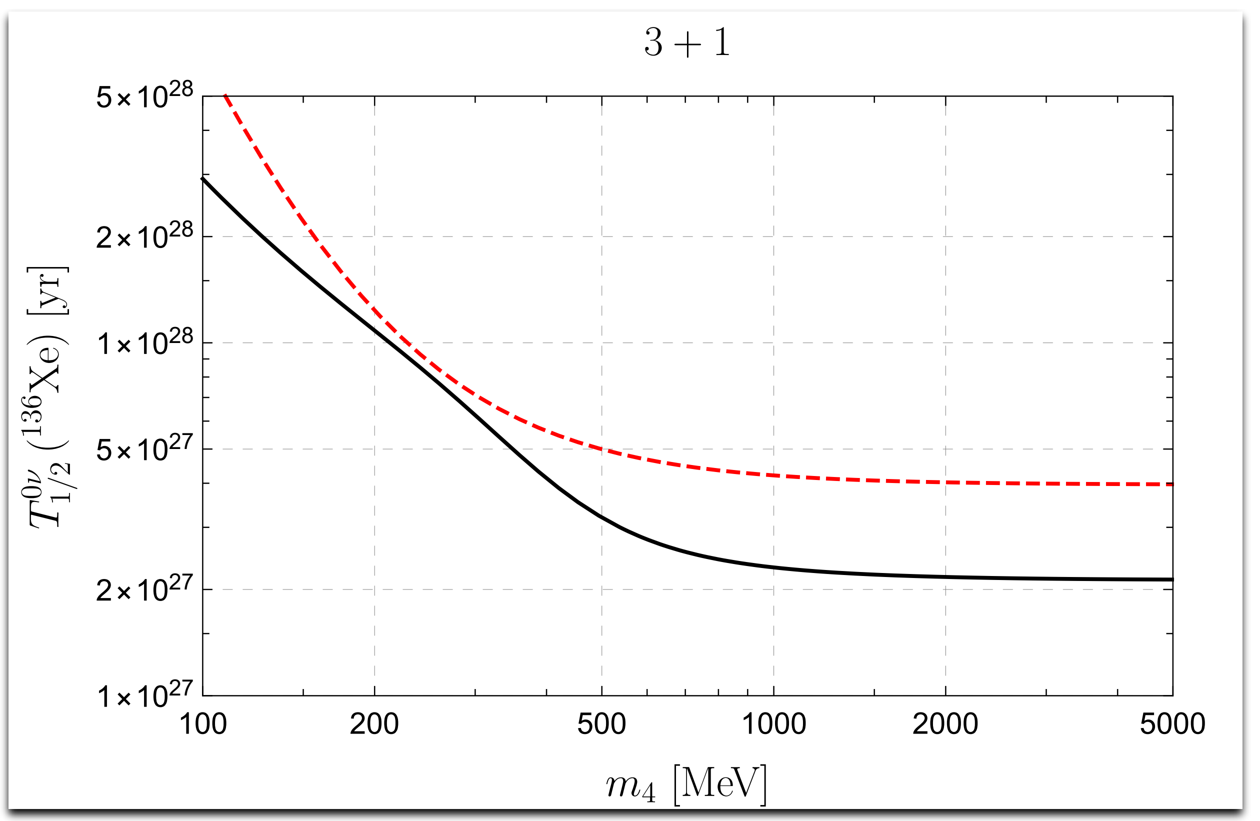
Toy model: 3+1

- Add just one sterile neutrino to the SM
  - Assume mass matrix of the form

$$M_\nu = \begin{pmatrix} 0 & 0 & 0 & M_D \\ 0 & 0 & 0 & M_D \\ 0 & 0 & 0 & M_D \\ M_D & M_D & M_D & M_R \end{pmatrix}$$

- Not realistic:
  - Only two nonzero ν masses
  - Does not reproduce mixing angles
- Simplest case to test differences with usual approach

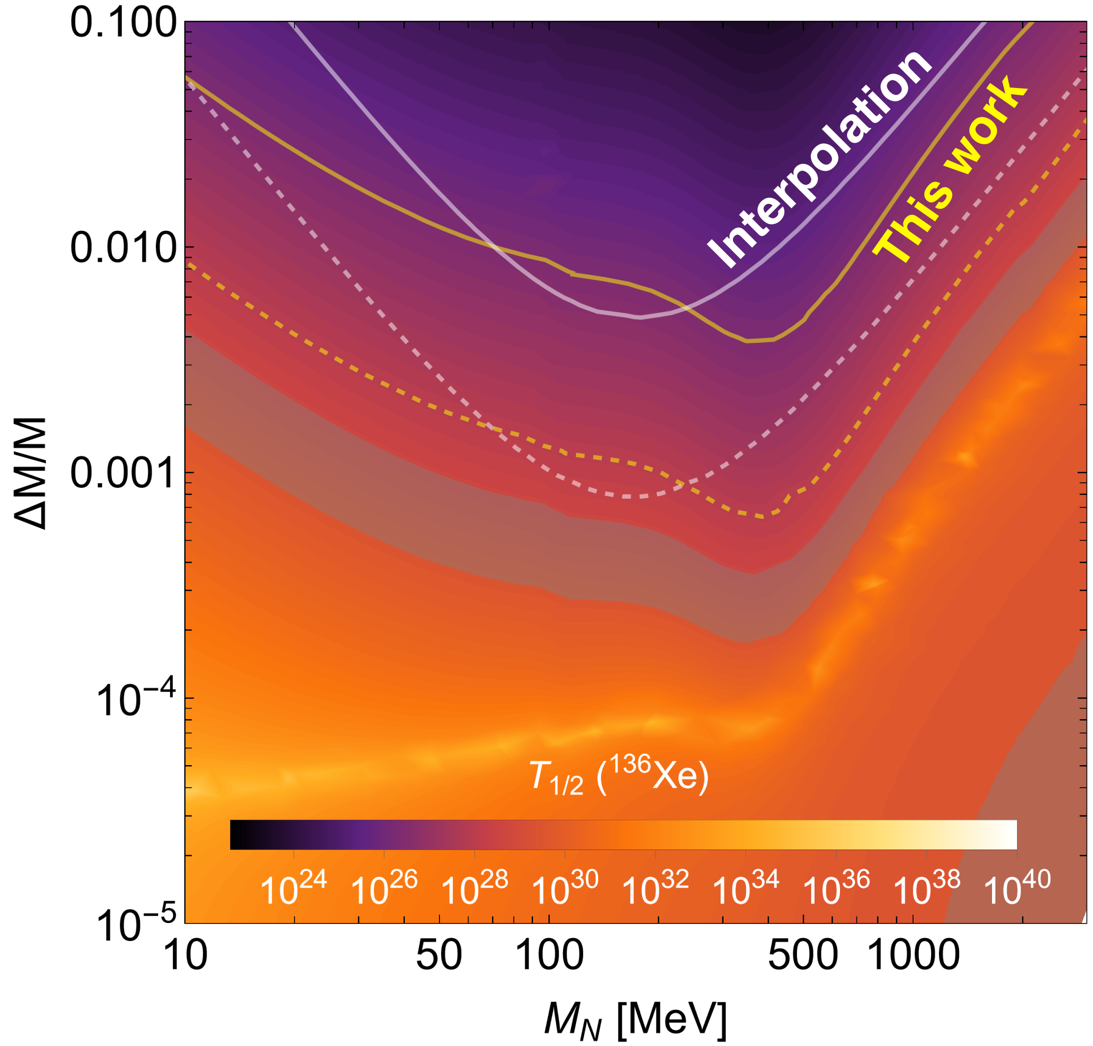




3+2 scenario

- Add 2 sterile neutrinos to the SM
  - Can now fit the oscillation data
  - Involves more parameters, for some choice can derive bounds:

- Normal hierarchy



- Inverted hierarchy