MAYORANA International School
Modica
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Neutrinoless double beta decay and Lepton Number Violation - II

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Plan for the lectures

- Significance of neutrinoless double beta decay & connection to big questions
  - Origin and nature of neutrino mass
  - The baryon asymmetry of the universe
  - Discovery potential of $0\nu\beta\beta$ — overview

- *End-to-end* Effective Field Theory for Lepton Number Violation (LNV) and $0\nu\beta\beta$
  - $0\nu\beta\beta$ from high-scale see-saw (LNV @ dim 5) [the 3-Majorana ν's paradigm]
  - $0\nu\beta\beta$ from (multi)TeV-scale dynamics (LNV @ dim 7, 9, …)
  - $0\nu\beta\beta$ from sterile neutrinos

- Conclusions and outlook

1st lecture

2nd lecture

3rd lecture

Special thanks to collaborators on these topics:
W. Dekens, J. de Vries, M. Graesser, M. Hoferichter, E. Mereghetti, S. Pastore, M. Piarulli,
S. Urrutia-Quiroga, U. van Kolck, A. Walker-Loud, R. Wiringa

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$0\nu\beta\beta$ decay: summary of significance

The neutrino and its mysteries

Demonstrate Majorana nature of massive neutrinos (neutrino=antineutrino)

A cosmic mystery

Demonstrate that an excess of matter over antimatter can be created in an elementary process

Point to baryogengesis via leptogenesis

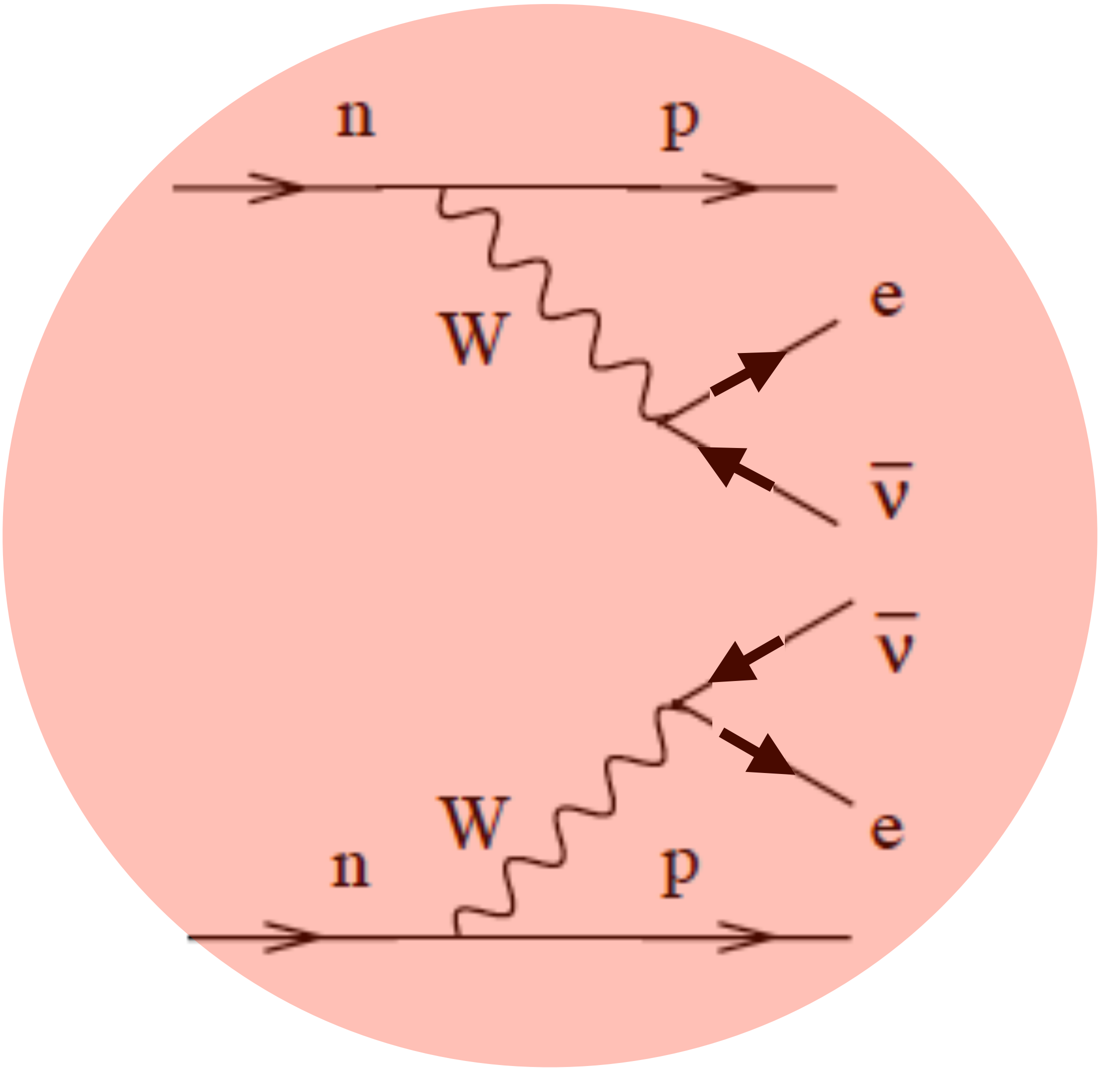
Nuclear $0\nu\beta\beta$ decay

A ‘matter-creating’ nuclear process whose observation would have far reaching implications

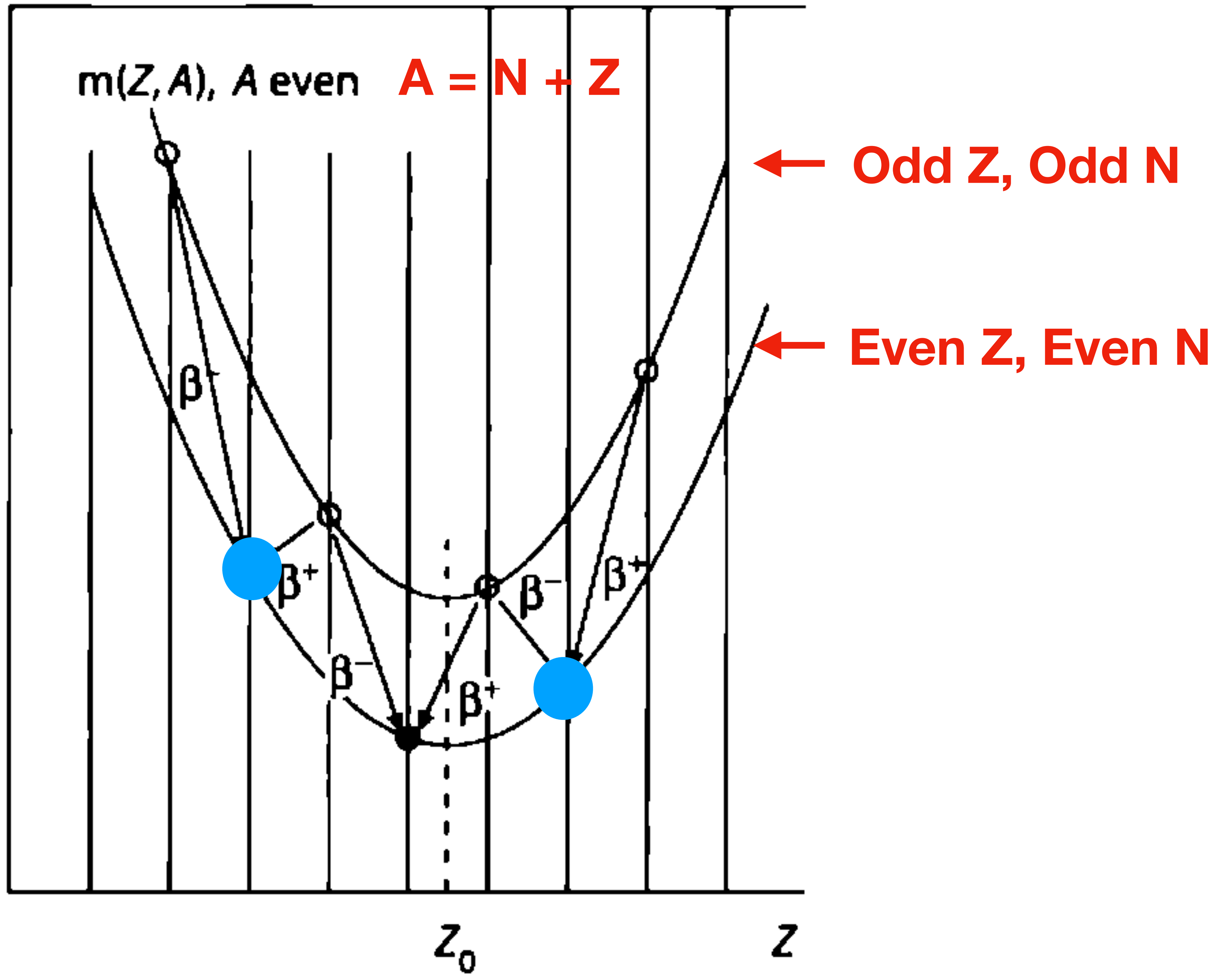
The quest is on…

- For certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …), single β decay is energetically forbidden → ββ decay
- 2νββ is the rarest process ever observed, with $T_{1/2} \sim 10^{21}$ years

M. Goppert Mayer, 1935



Credit: C. Bertulani's book



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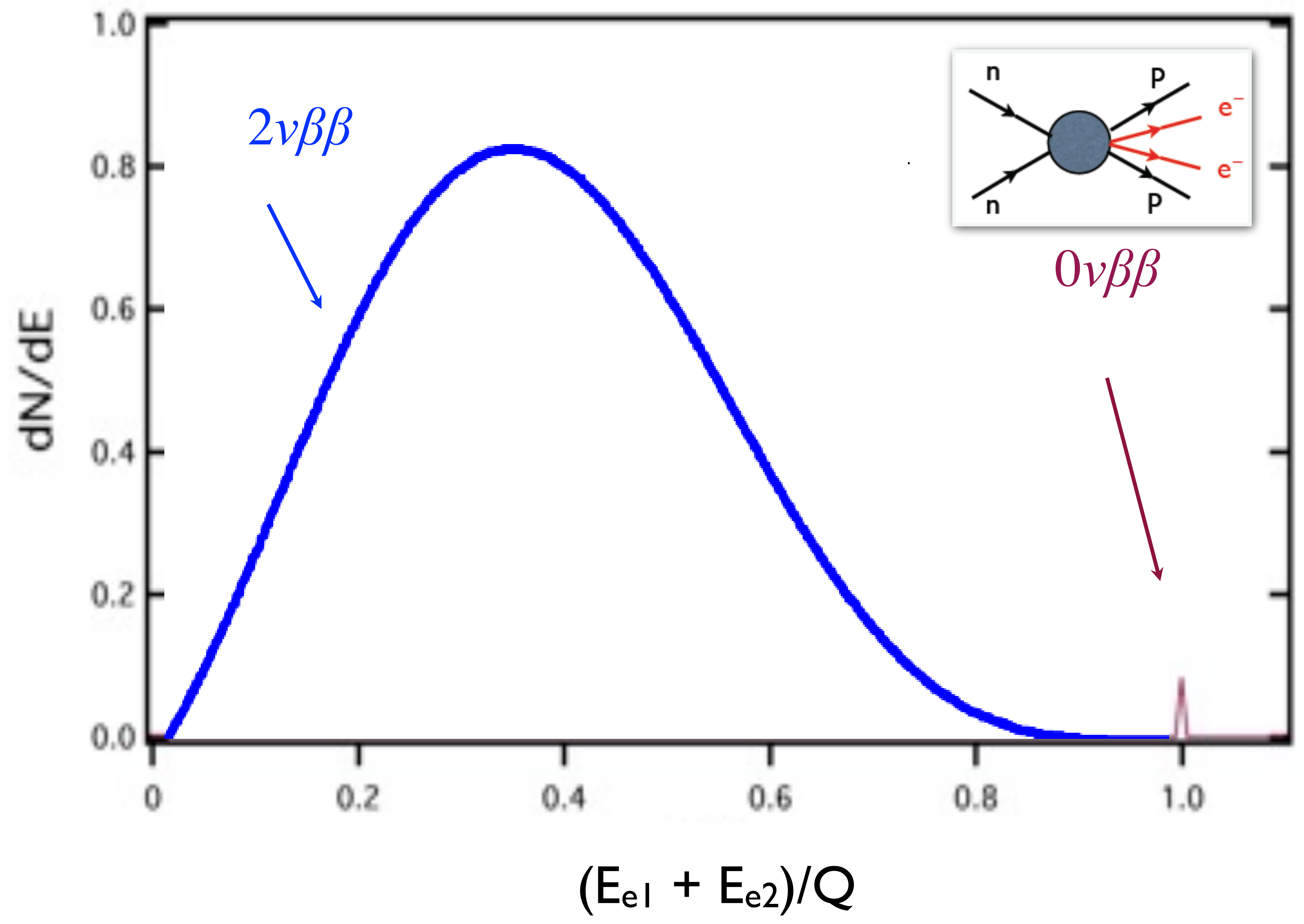
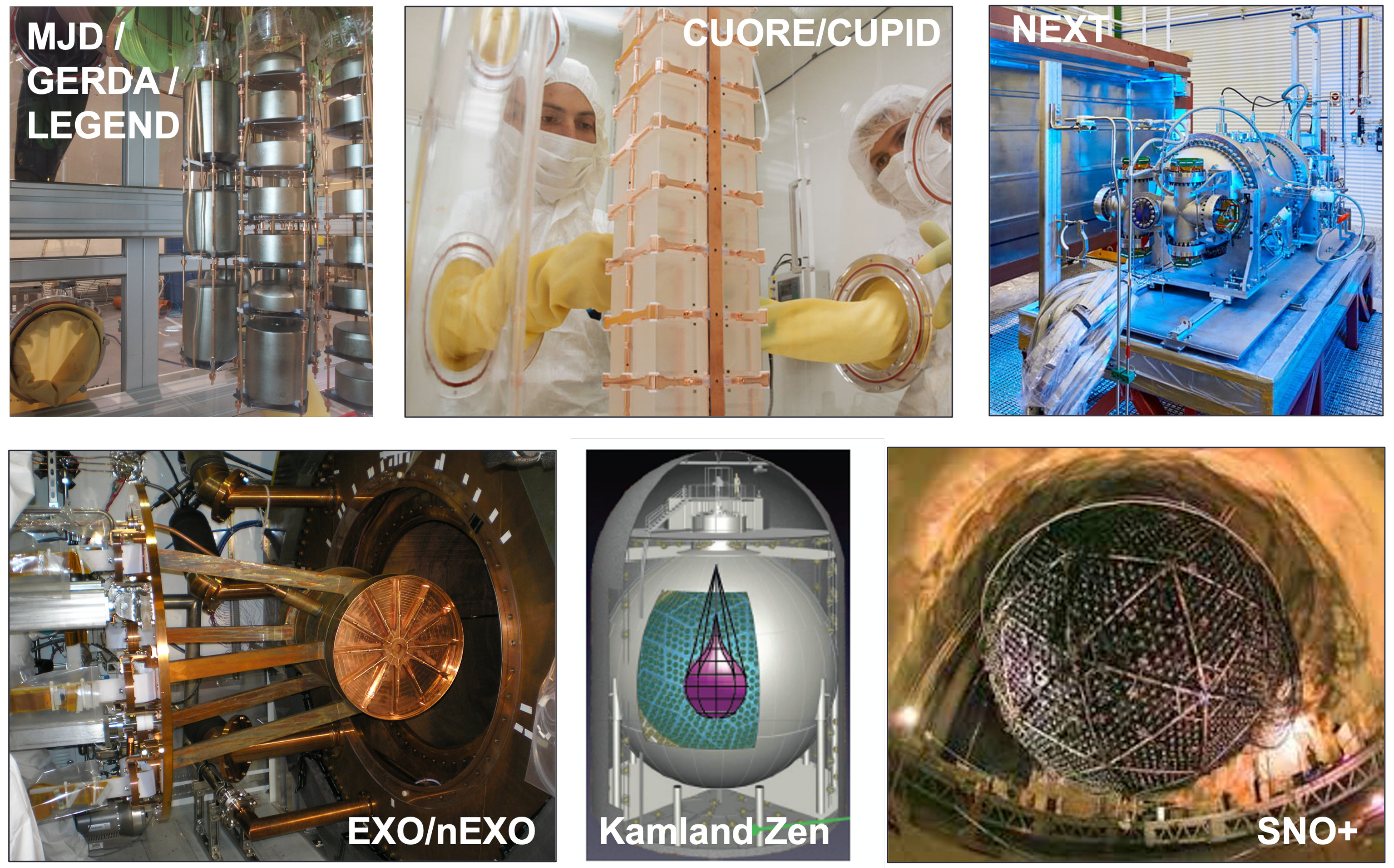
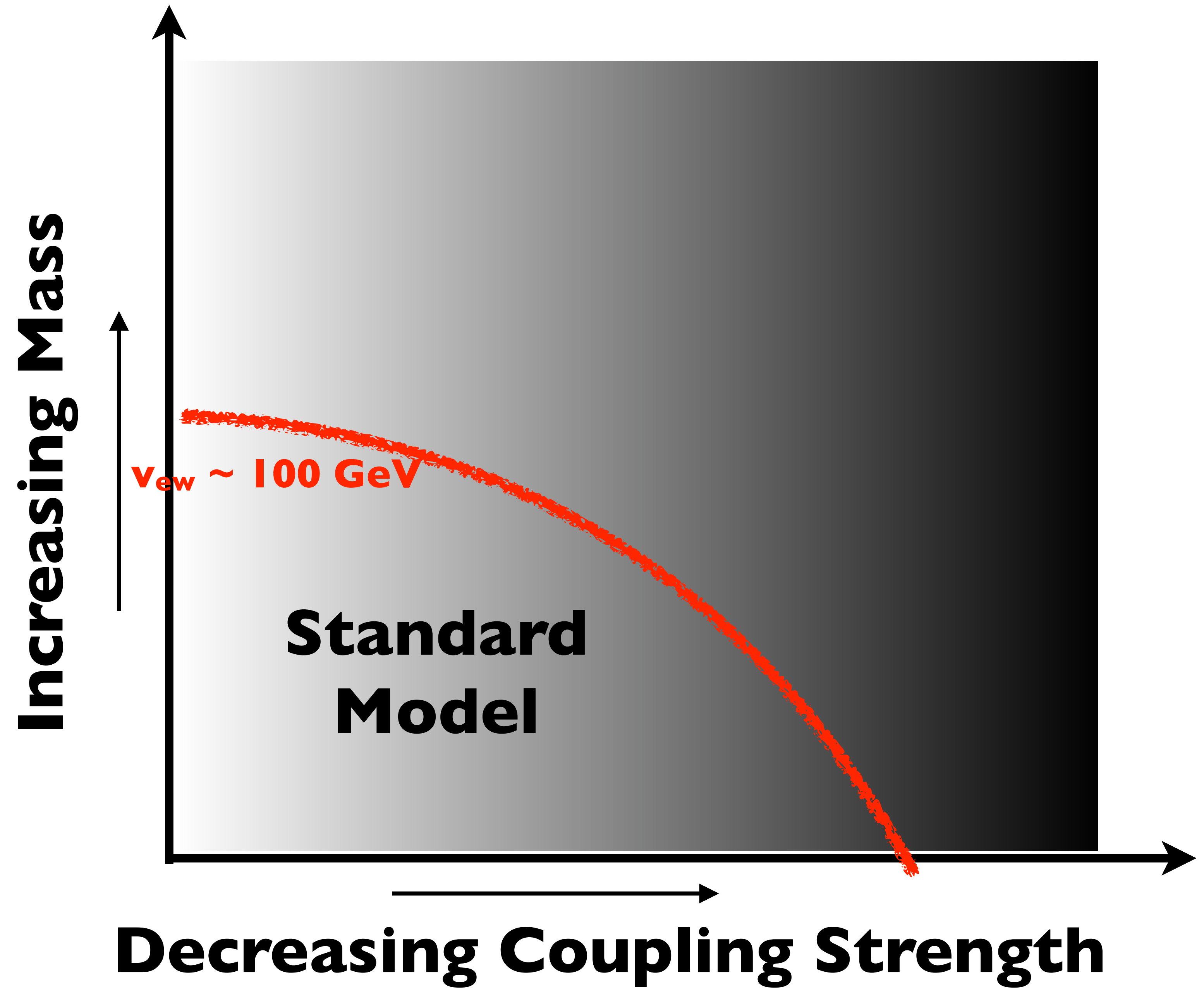
- 2νββ is the rarest process ever observed, with $T_{1/2} \sim 10^{21}$ years
- Several "ton-scale" experiments with different isotopes and technologies are searching for 0νββ, with sensitivity up to $T_{1/2} \sim 10^{28}$ yr, which is 10^{18} times the age of the universe!





$0\nu\beta\beta$ decay: broad discovery potential

- Ton-scale $0\nu\beta\beta$ searches can discover Lepton Number Violation from a broad variety of mechanisms that involve different mass scales and interaction strengths



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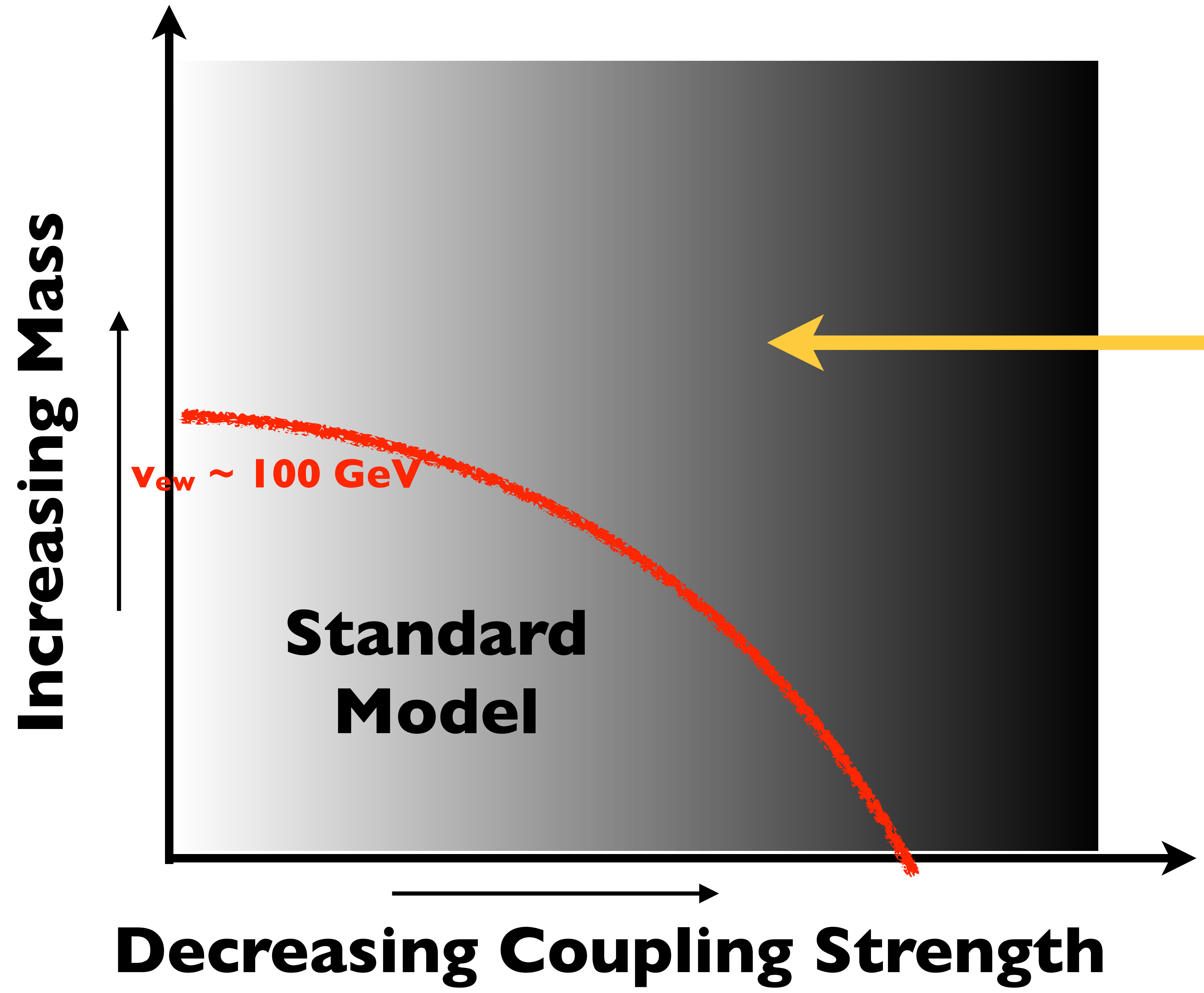
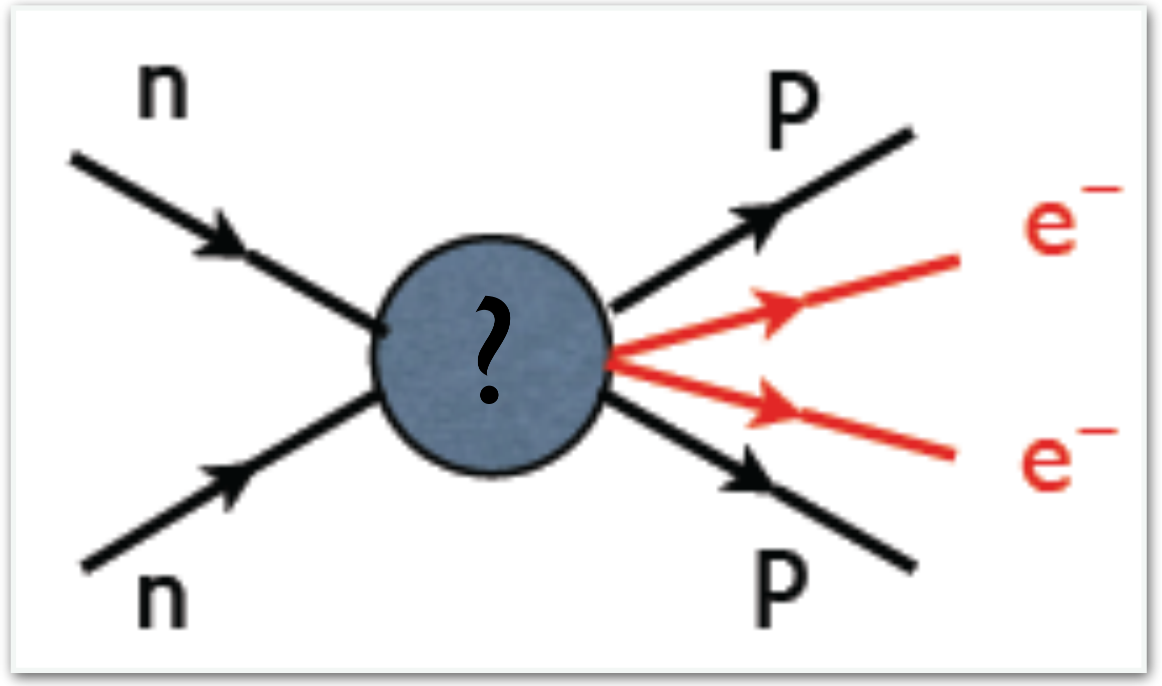


Somewhere out here there must be new physics responsible for neutrino masses

If Lepton Number is not conserved most of this uncharted territory can be explored only by 0νββ decay



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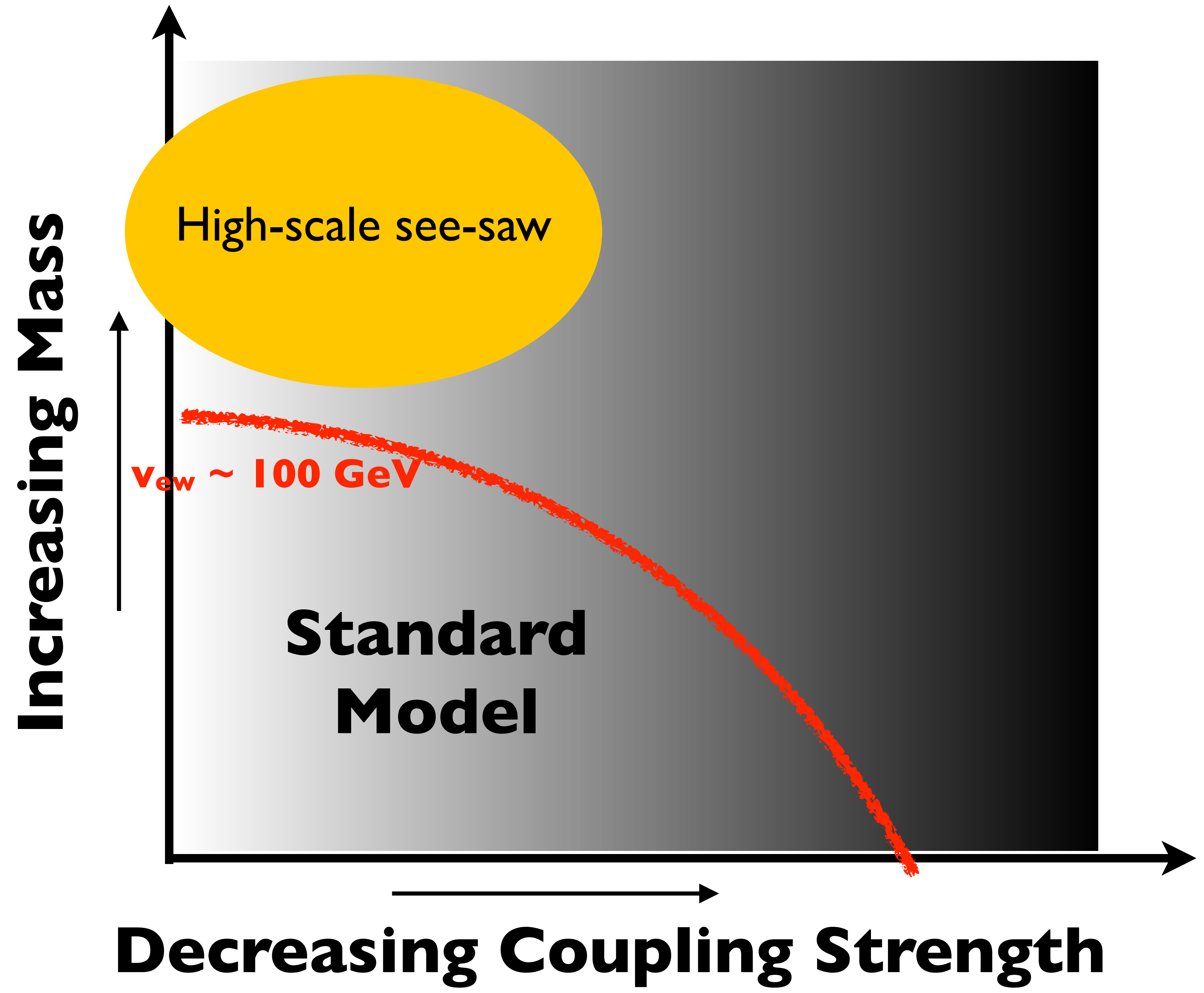

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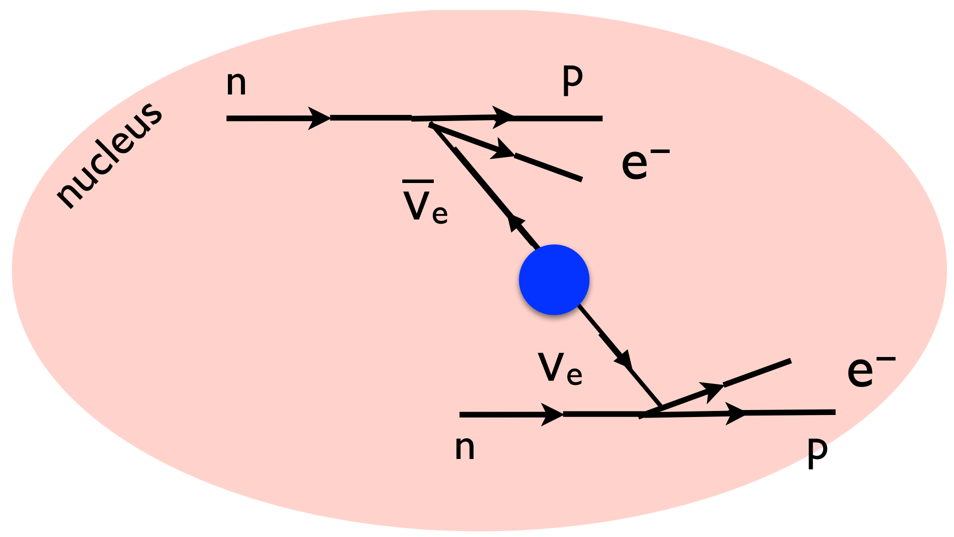

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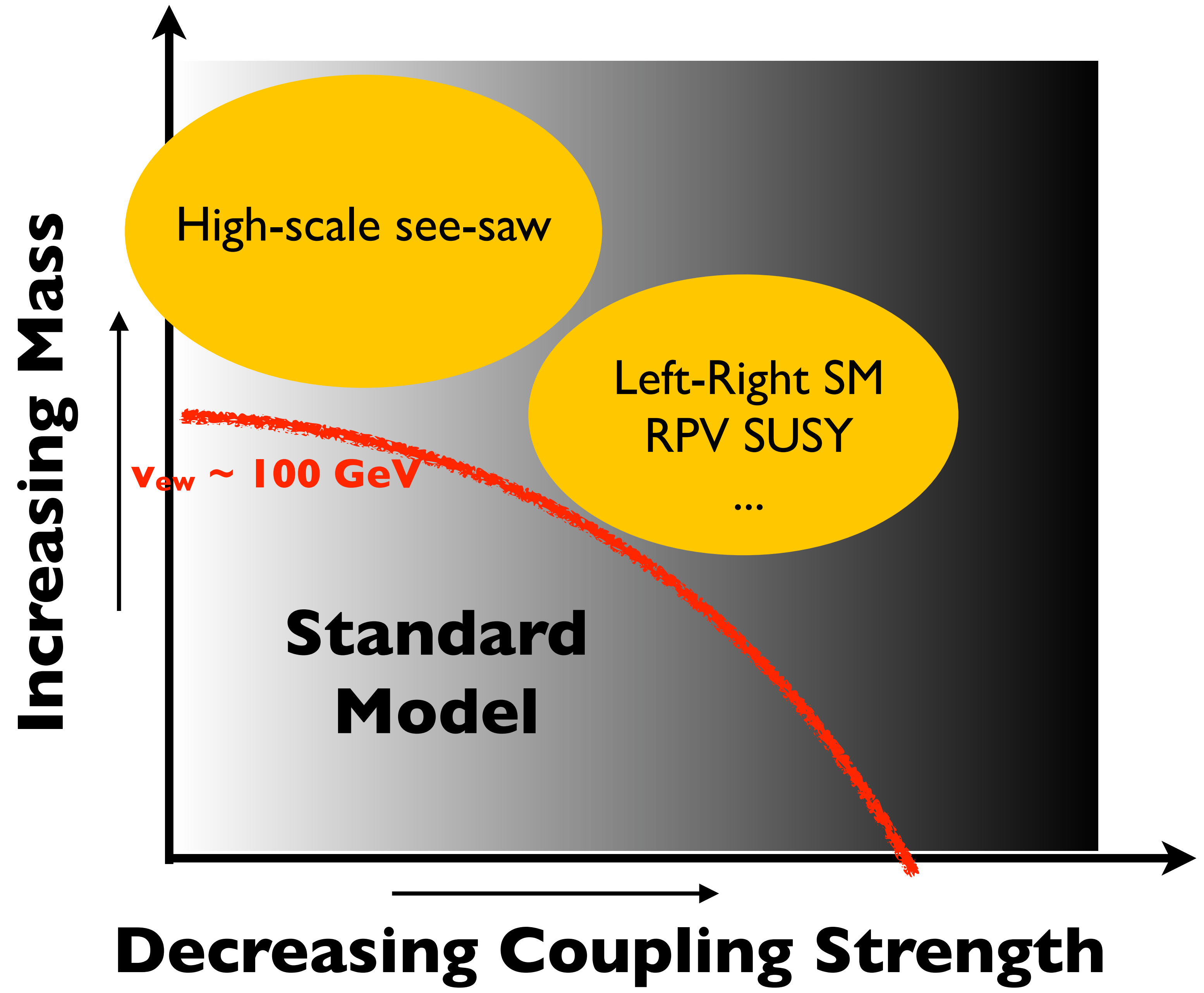

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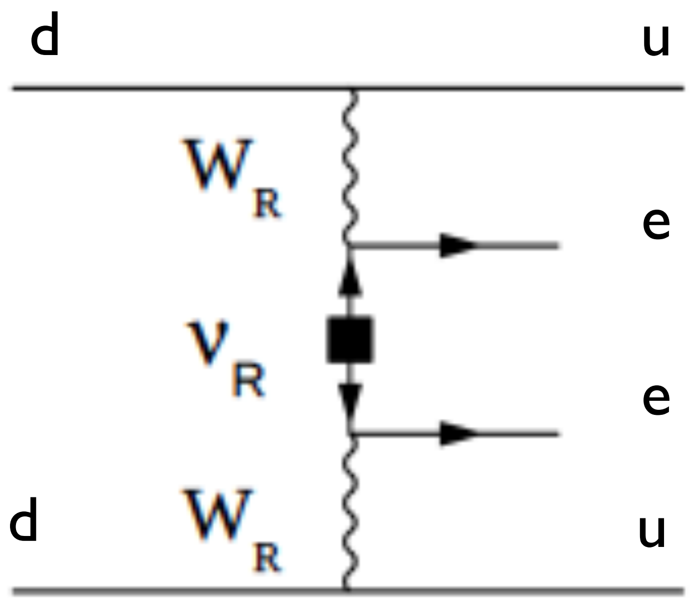

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0νββ decay: broad discovery potential

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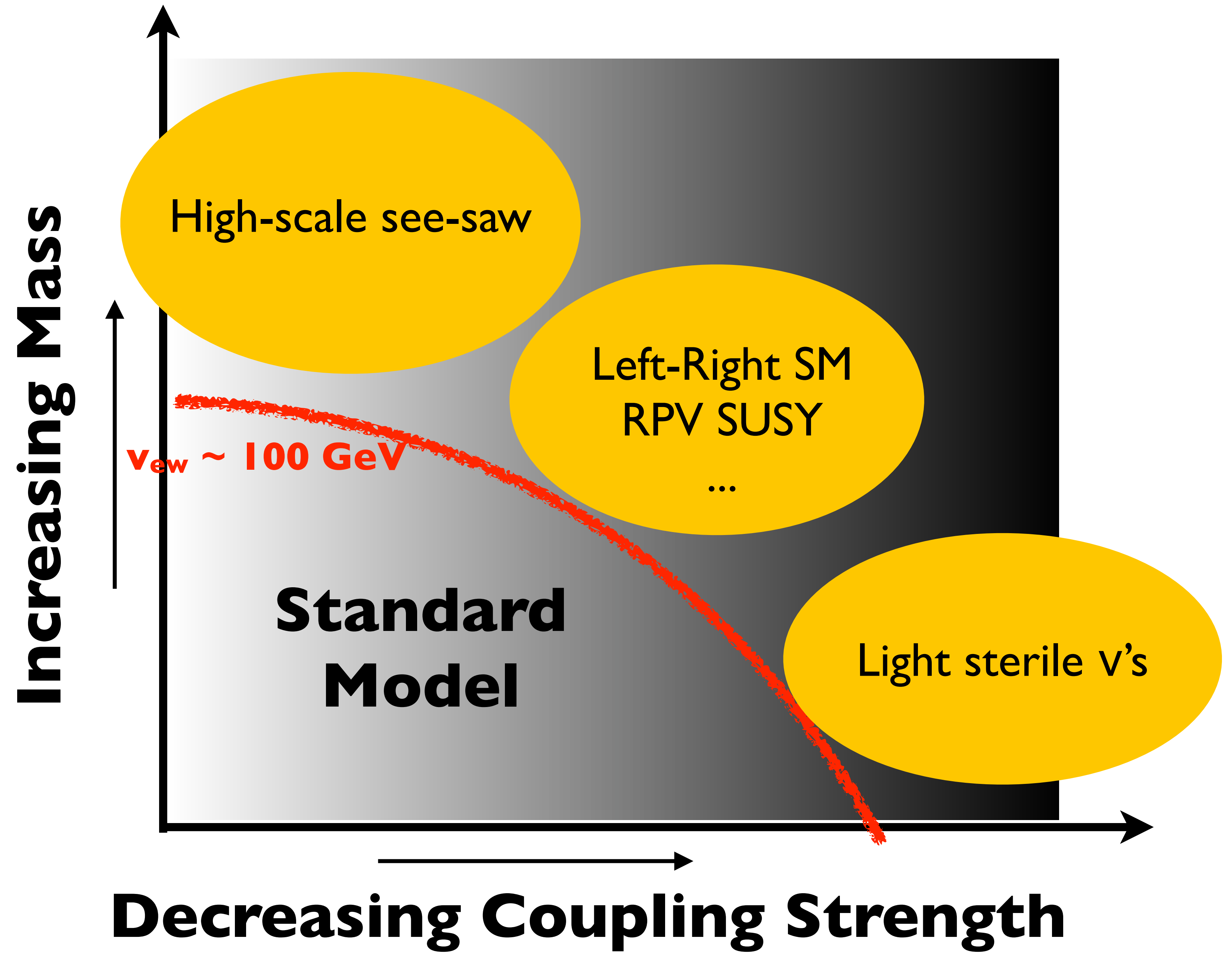

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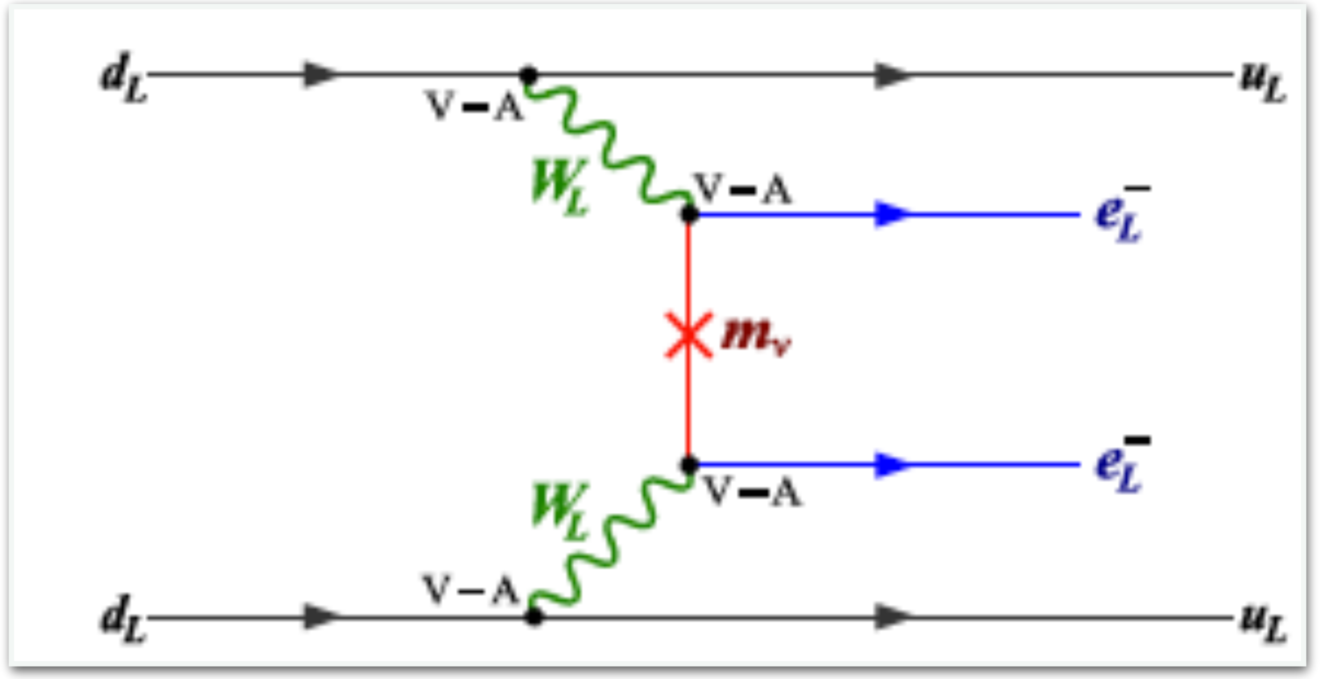
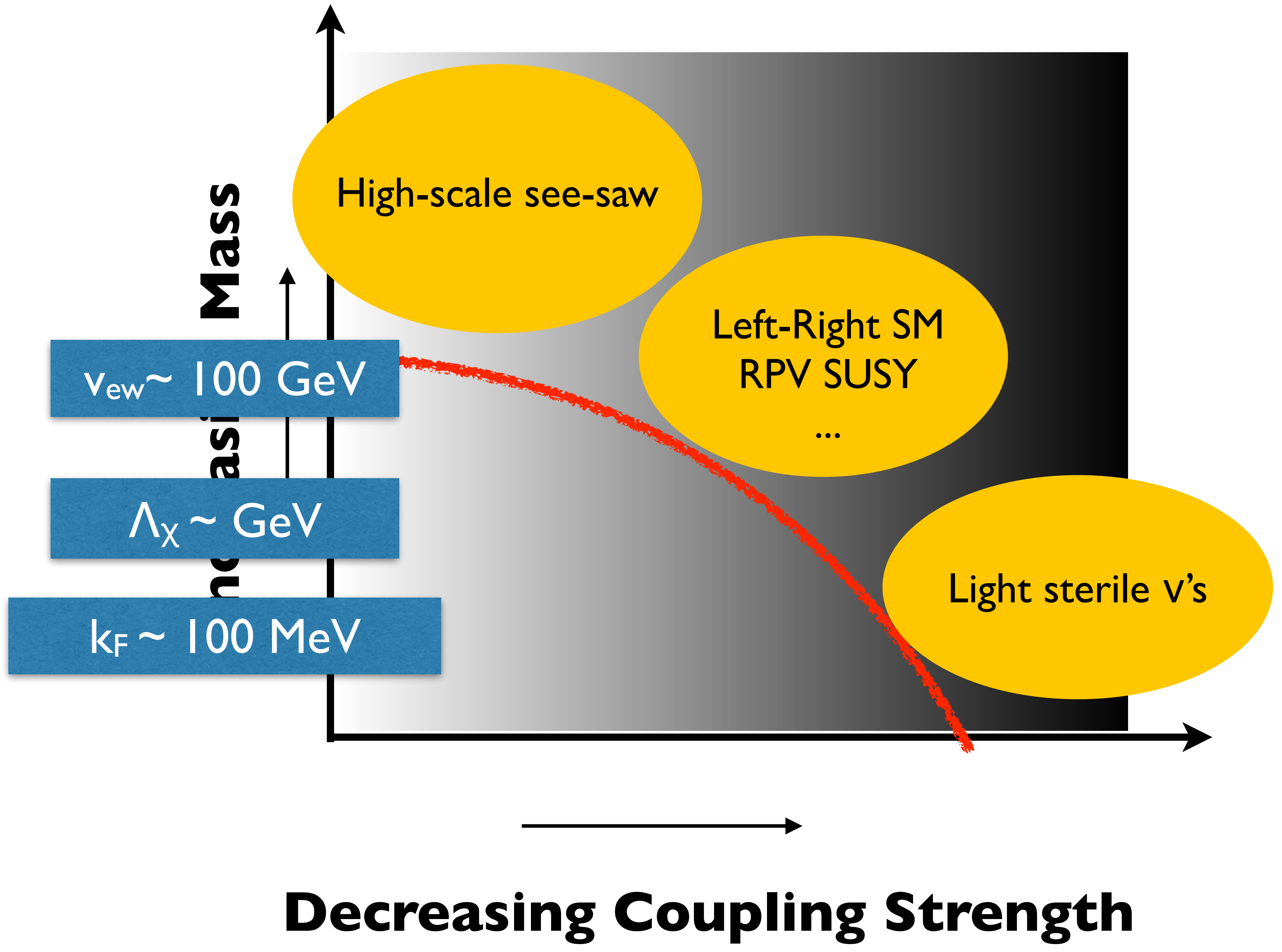


0νββ decay: theoretical challenges

- Connecting sources of LNV to nuclei is a multi-scale problem. Best tackled through a tower of EFTs** coupled to lattice QCD and ab-initio nuclear many-body calculations to achieve controlled uncertainty



** Effective Field Theory:
exploit separation of scales & use appropriate degrees of freedom at each scale

LNV parameter	SMEFT	LEFT	Chiral EFT

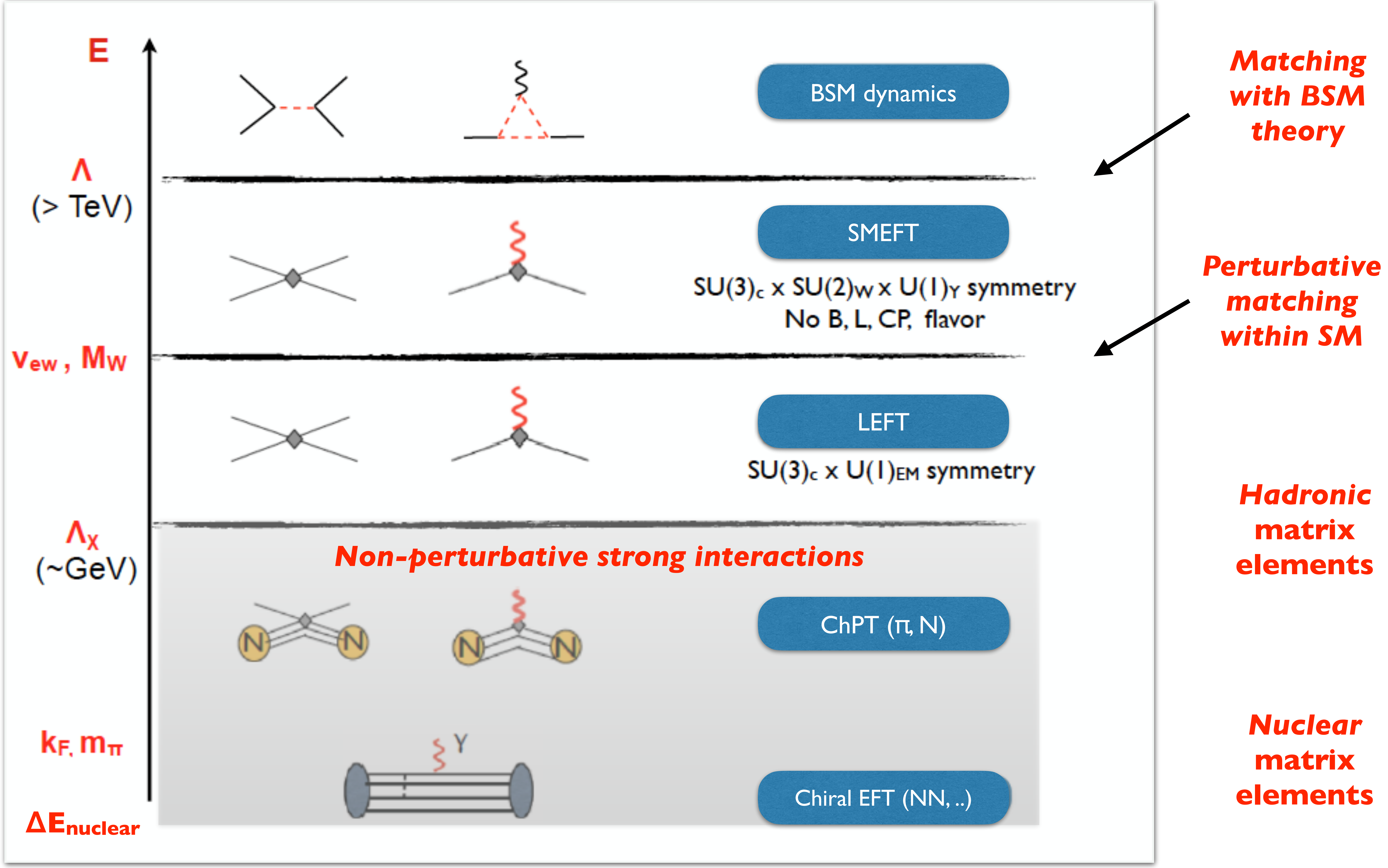
$$(T_{1/2})^{-1} \propto (g_{LNV})^2 \, (m_W/\Lambda_{LNV})^A \, (\Lambda_\chi/m_W)^B \, (k_F/\Lambda_\chi)^C$$

White papers 2203. 21169 & 2207.01085 and refs therein

Connecting scales

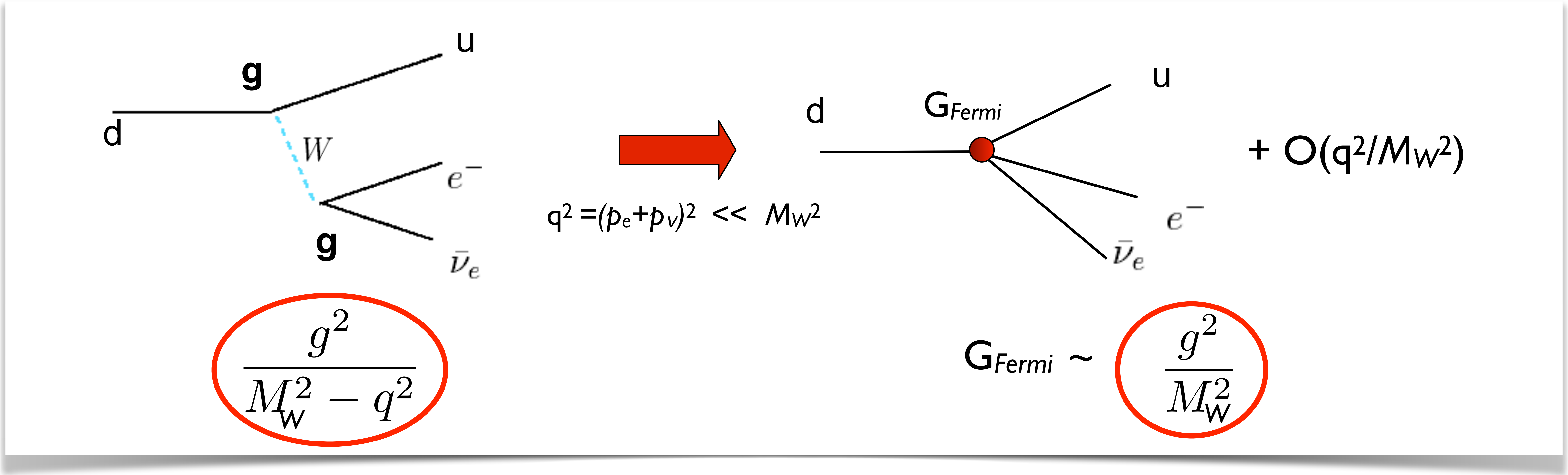
To connect UV physics to nuclei, use a tower of EFTs

- Use appropriate degrees of freedom in each range of energies
- Write down all interactions consistent with the given symmetries
- At each threshold, need appropriate perturbative and non-perturbative matching conditions: $A_{hi} = A_{low}$
- Expand amplitudes to a given order in m_{low}/m_{hi}



Classic example

Fermi's theory of beta decay as the low-energy EFT of the Standard Model weak interactions



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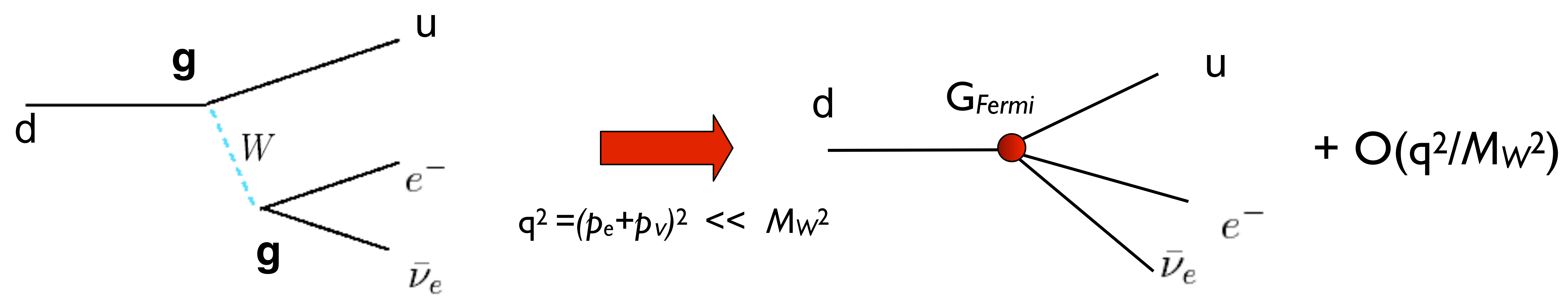


$$\frac{g^2}{M_W^2 - q^2}$$

$$G_{Fermi} \sim \frac{g^2}{M_W^2}$$

More generally: how do heavy particles affect physics at E << M?

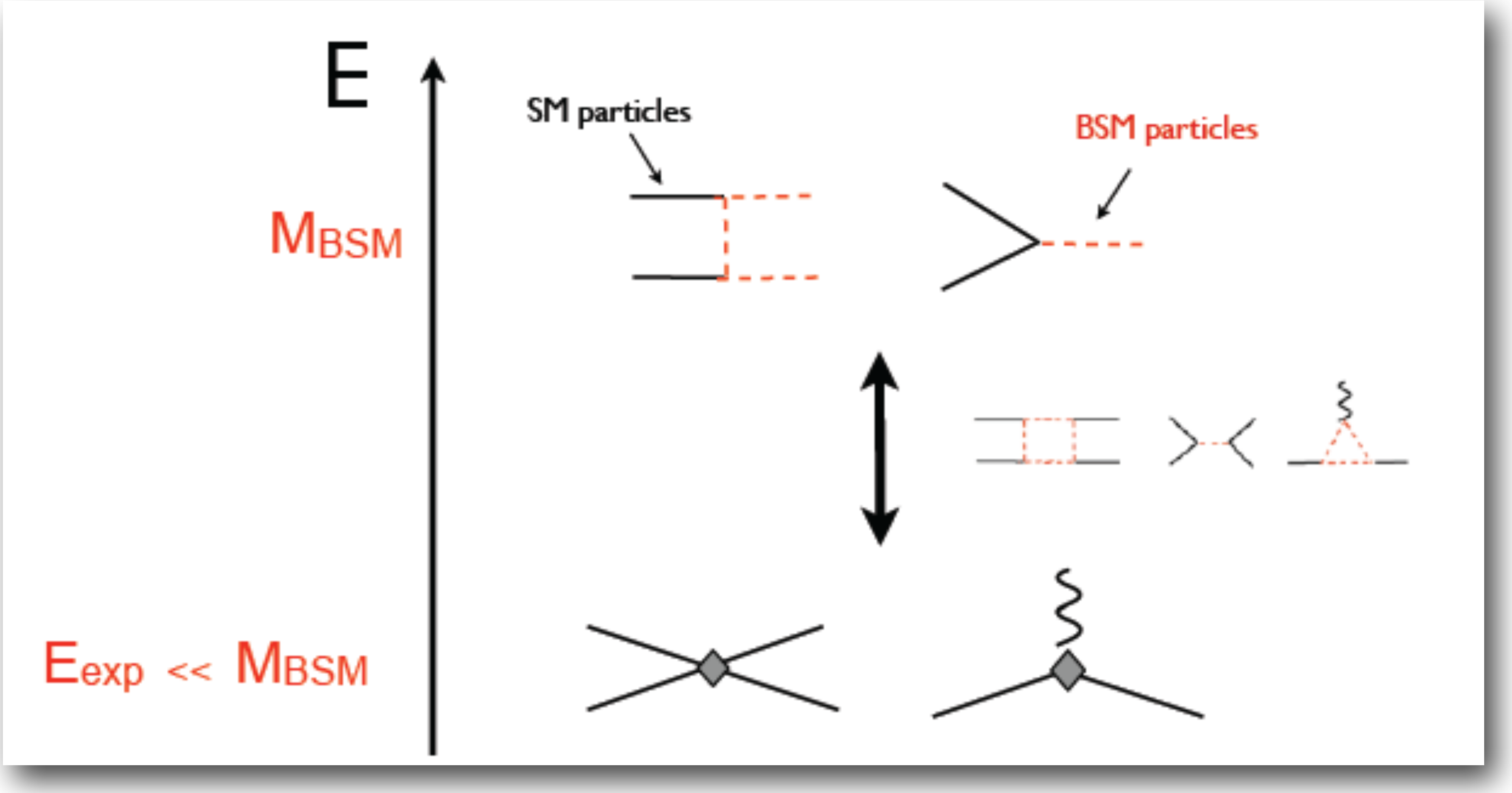
Exchange of heavy particles generates a series of local interactions of increasing mass dimension (multiplied by inverse power of the new physics mass scale) consistent with the underlying symmetries (Lorentz, gauge, …)

Homework

- Work out mass dimension of fields:
  - Spin 1/2: $[\Psi]=3/2$
  - Spin 0 and 1: $[\phi] = [V_\mu] = 1$

Standard Model EFT (SMEFT)

- In a model-independent way, describe effects of new physics originating at $\Lambda >> v_{ew}$ through local operators



[$\Lambda \leftrightarrow M_{BSM}$] $\quad C_i\ [g_{\rm BSM},\ M_a/M_b]$

$$\boxed{\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots}$$

- "Standard Model EFT" (SMEFT):
  - ★ Build operators out of SM fields
  - ★ Impose Lorentz + SM gauge symmetry, but no other symmetry (B, L, CP, flavor)**
  - ★ Organize operators according to mass dimension: power counting in E/Λ, M_W/Λ.
    At a given order the EFT is renormalizable and predictive

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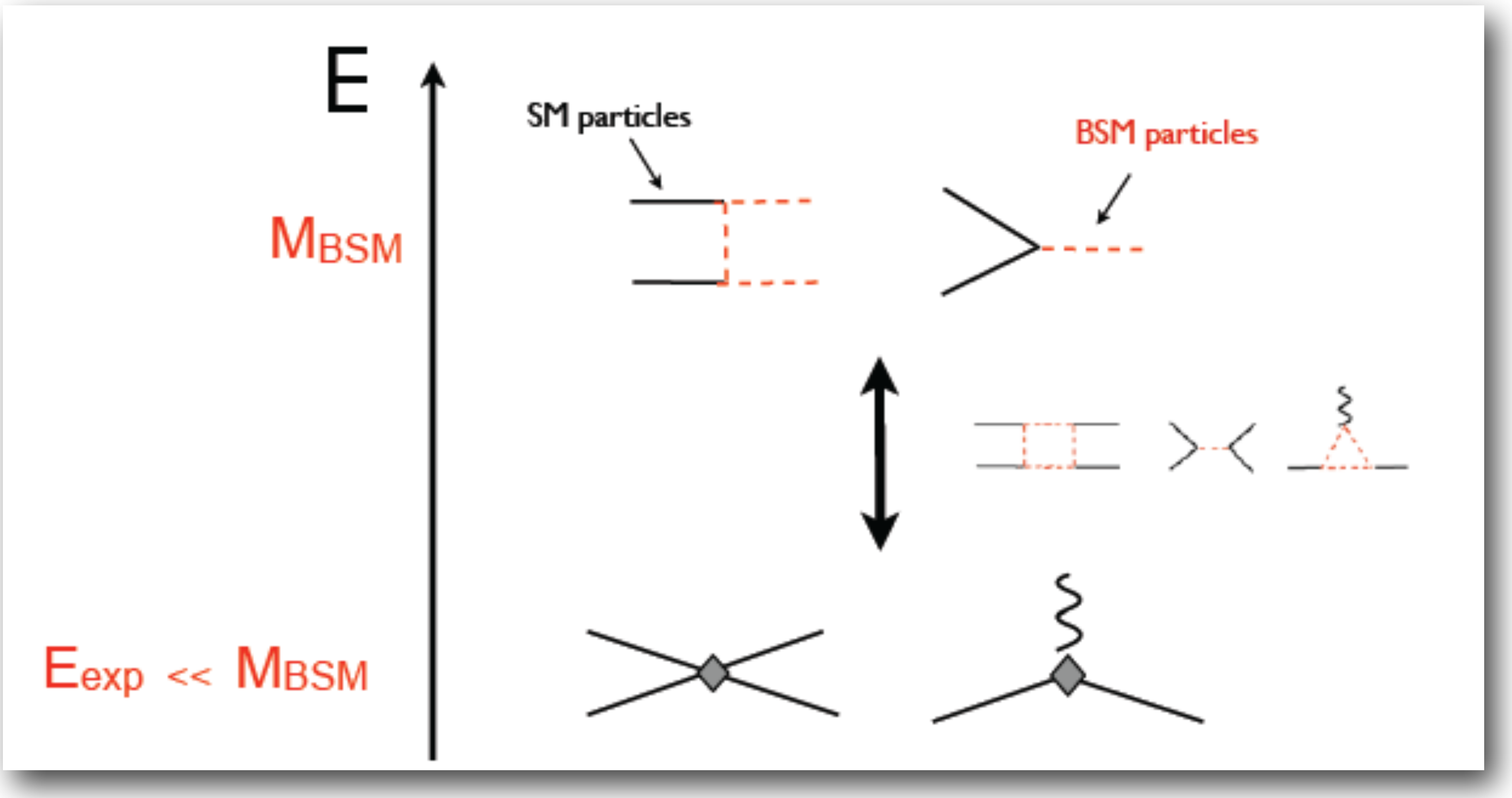

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$\Delta L=2 \qquad \Delta B=1$, CPV, FCNC, …

- Comment on symmetries in the SM-EFT:

  - B, L, $L_{e,\mu,\tau}$ not enforced: per Weinberg's definition, they are ``accidental" in the SM, i.e. consequence of keeping operators of dimension ≤ 4 built out of SM fields

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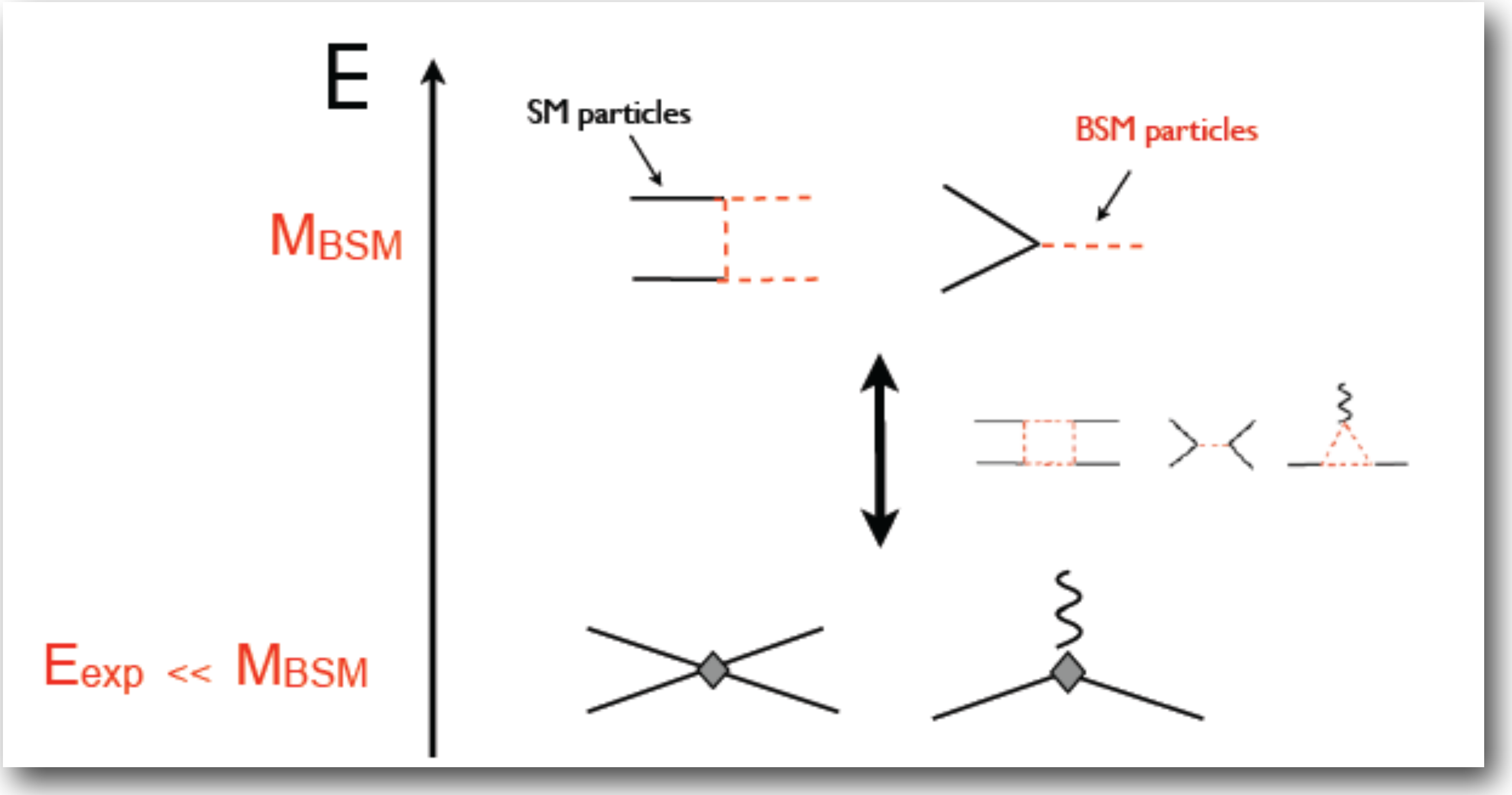

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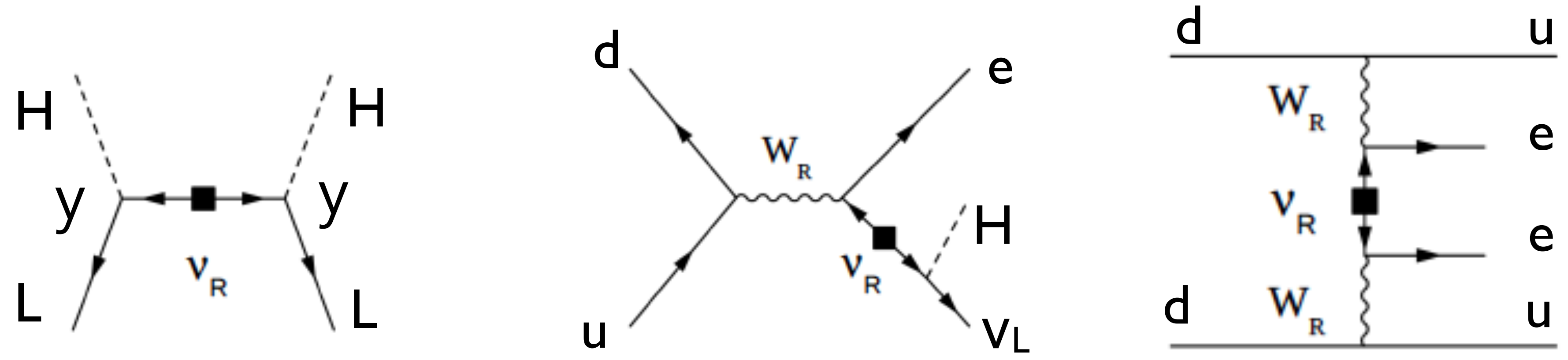
$\Delta L=2$ $\Delta B=1$, CPV, FCNC, …

- Other EFTs differ in particle content and/or symmetry realization:
  - νSMEFT: SMEFT + ν_R
  - …

‘End-to-end’ EFT framework for LNV

E



BSM dynamics

Example:
Left-Right Symmetric Model

Λ
(> TeV)

v_{ew} , M_W

Full or simplified model is needed to study the cosmological implications of LNV and the collider signatures, if $\Lambda \sim$ TeV

Λ_χ
(~GeV)

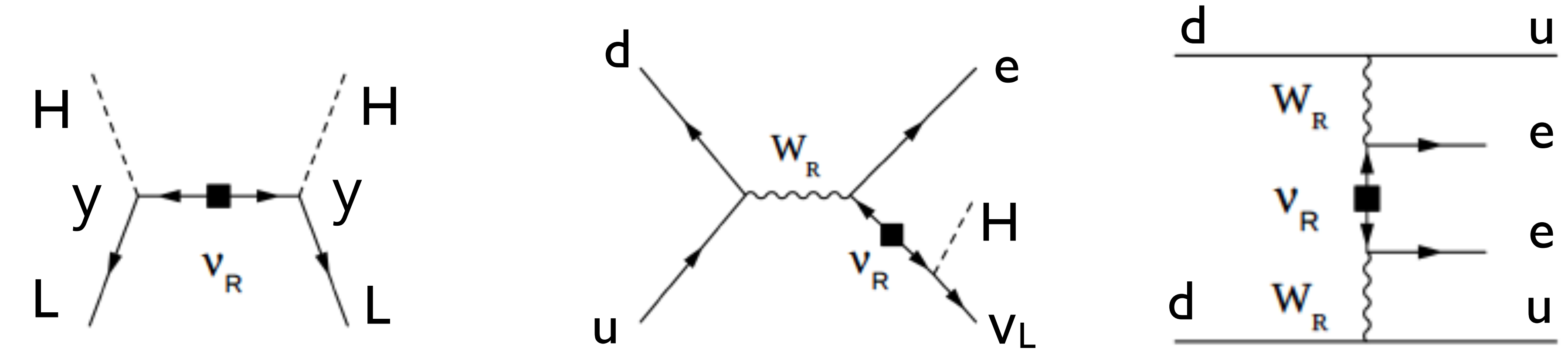
For low-energy probes such as $0\nu\beta\beta$, it’s much more convenient to match to EFT and do the analysis ‘once and for all’

k_F, m_π

‘End-to-end’ EFT framework for LNV

E

Λ
(> TeV)



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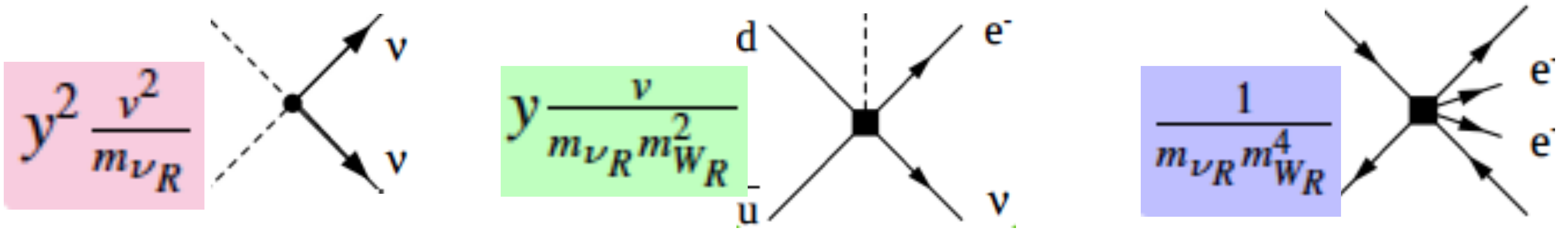


SM-EFT

dim5 | dim7 | dim9

v_{ew} , M_W

Weinberg’79

Babu-Leung ’01
...
Lehman 1410.4193

Graesser 1606.04549
Liao and Ma 2007.08125

Λ_χ
(~GeV)

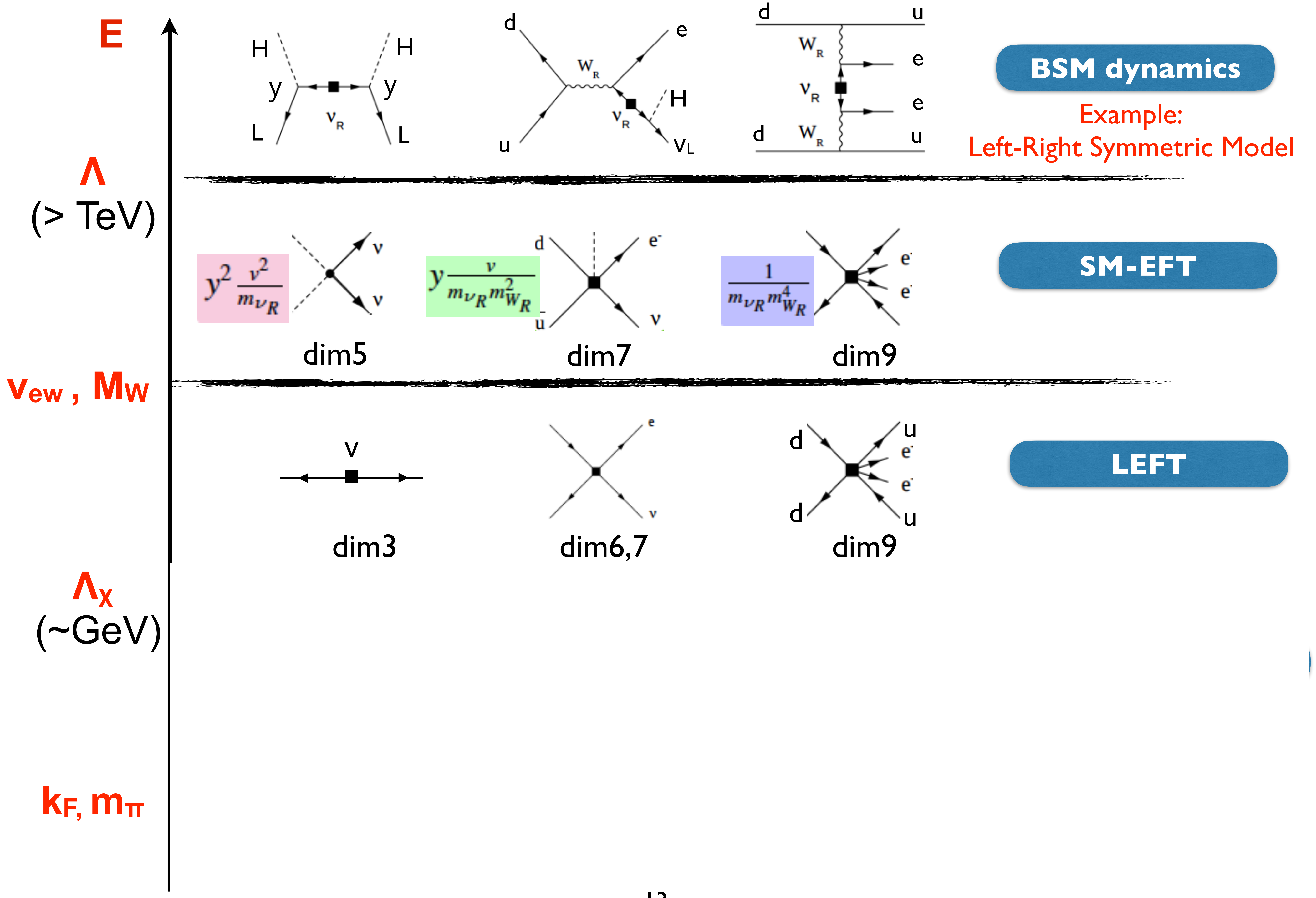
- $\Delta L=2$, $\Delta B=0$ operators appear only at odd dimension
- Insertions of small dimensionless (Yukawa) coupling can make dim=5,7,9 operators equally important for $\Lambda \sim$ TeV
- ν_R with mass $< \Lambda$ can be included in the framework

A. Kobach 1604.05726

Dekens et al. 2002.07182

k_F, m_π

‘End-to-end’ EFT framework for LNV



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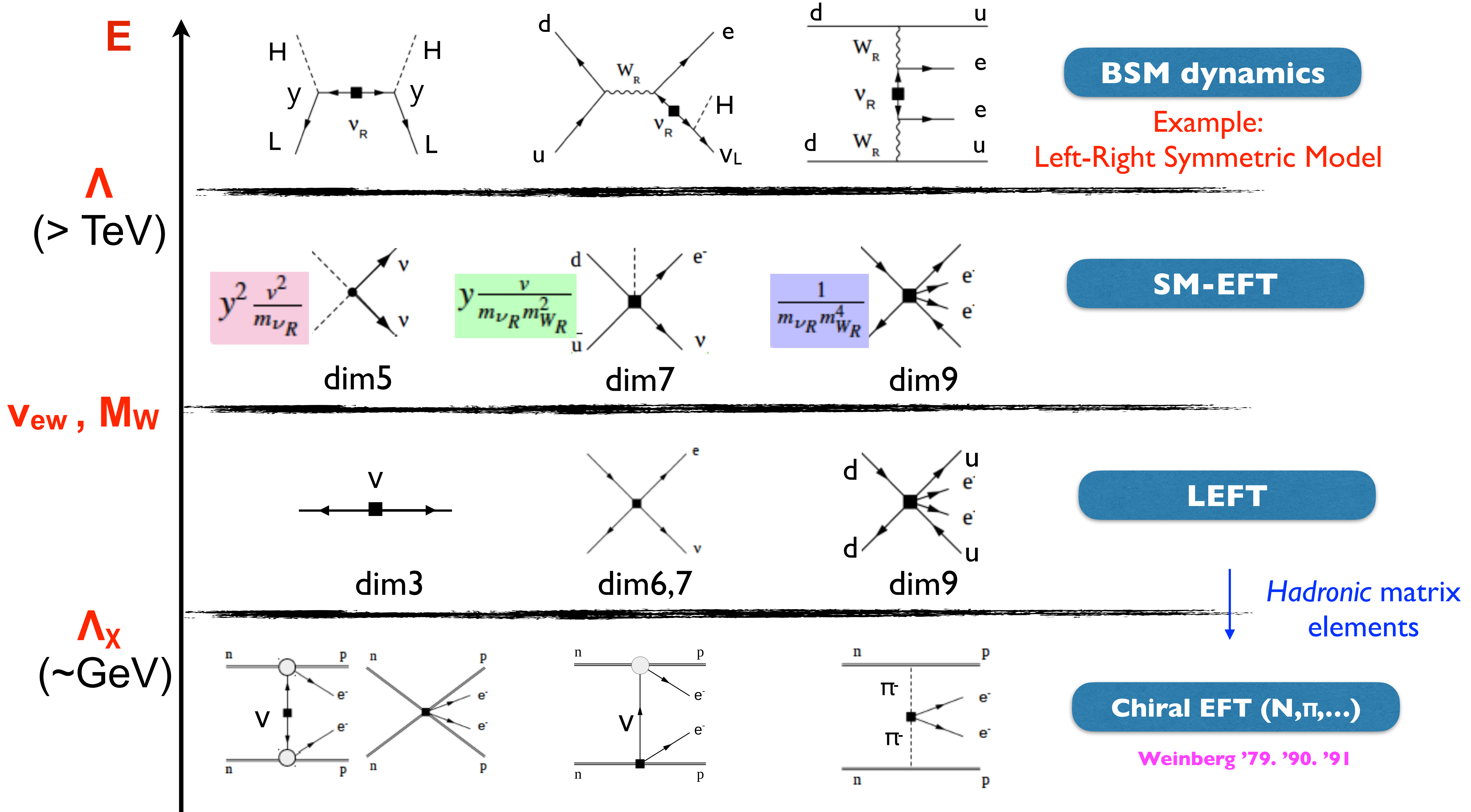
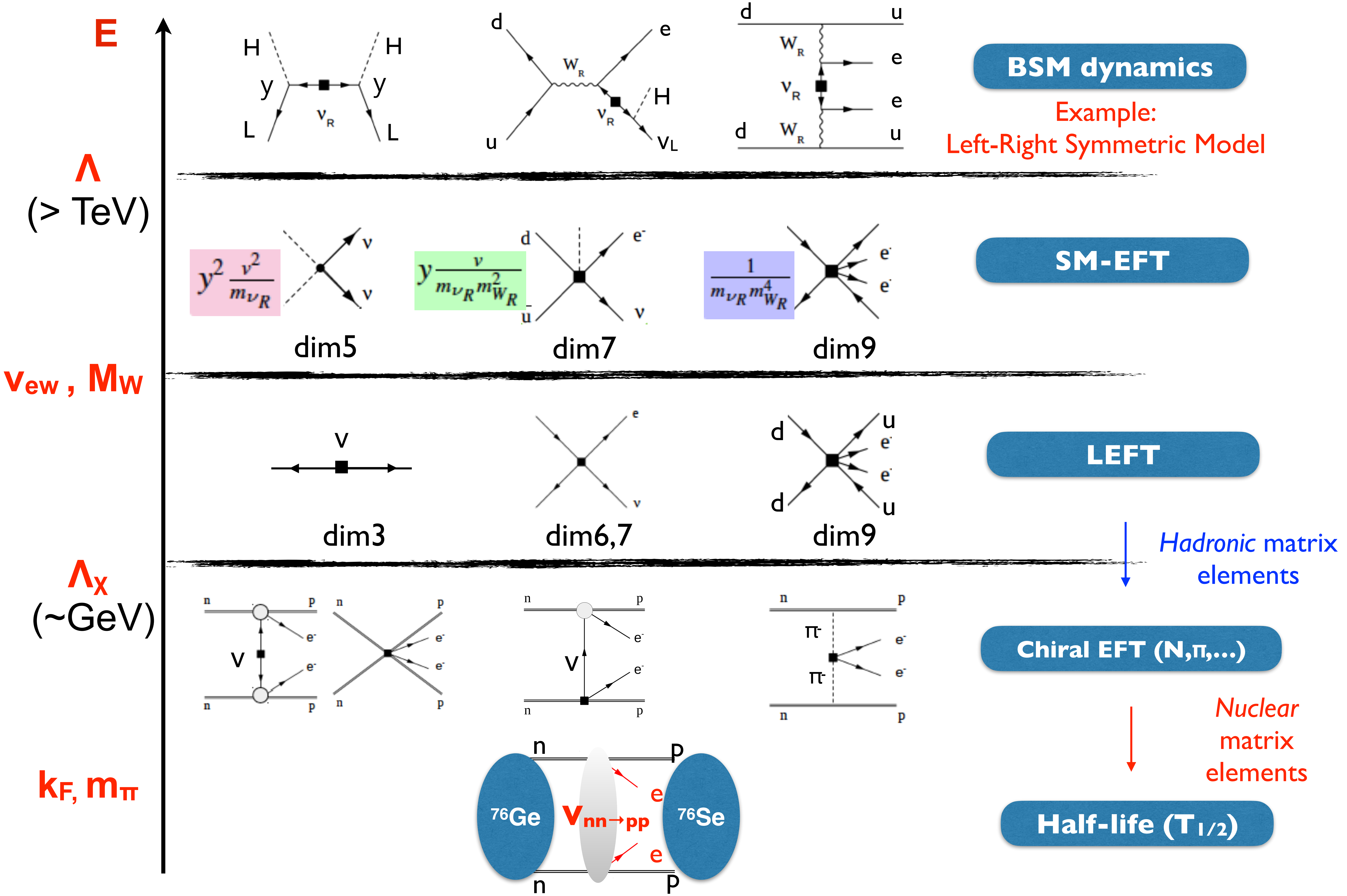


k_F, m_π

Map ΔL=2 interactions onto π, N operators, organized according to QCD symmetries and power-counting in Q/Λ_χ ($Q \sim k_F \sim m_\pi$) → NN transition operators $V_{nn \to pp}$

'End-to-end' EFT framework for LNV



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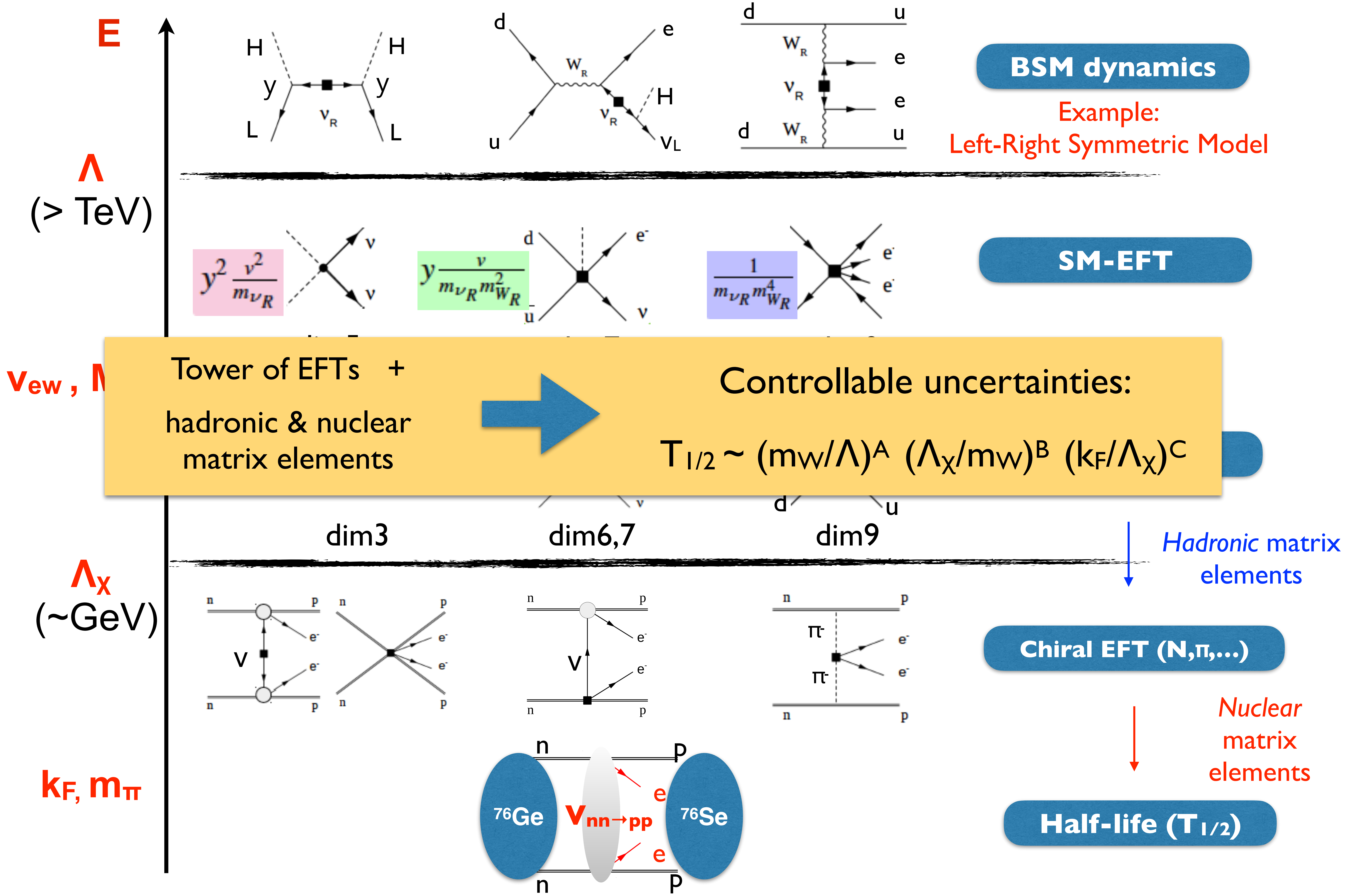
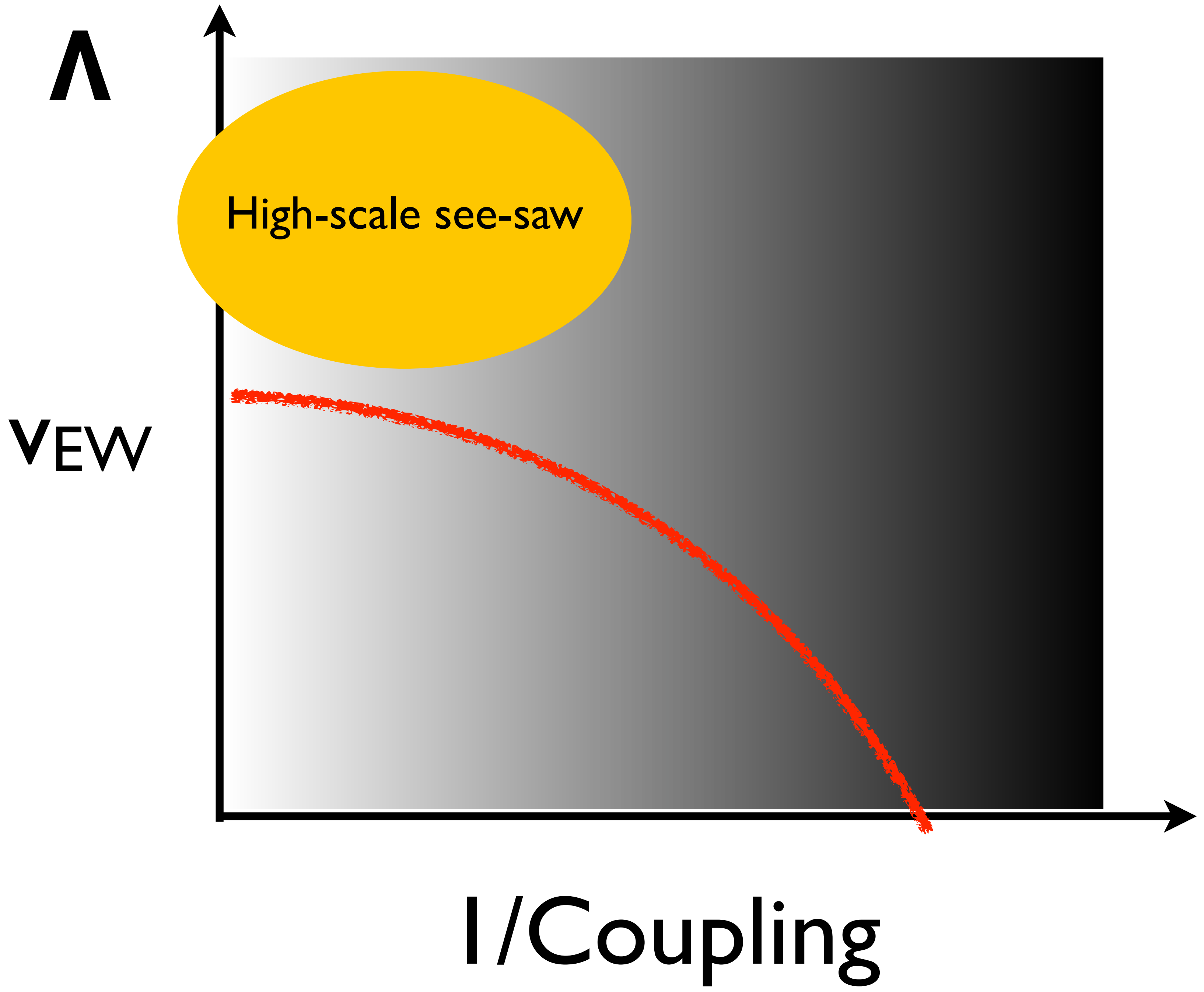
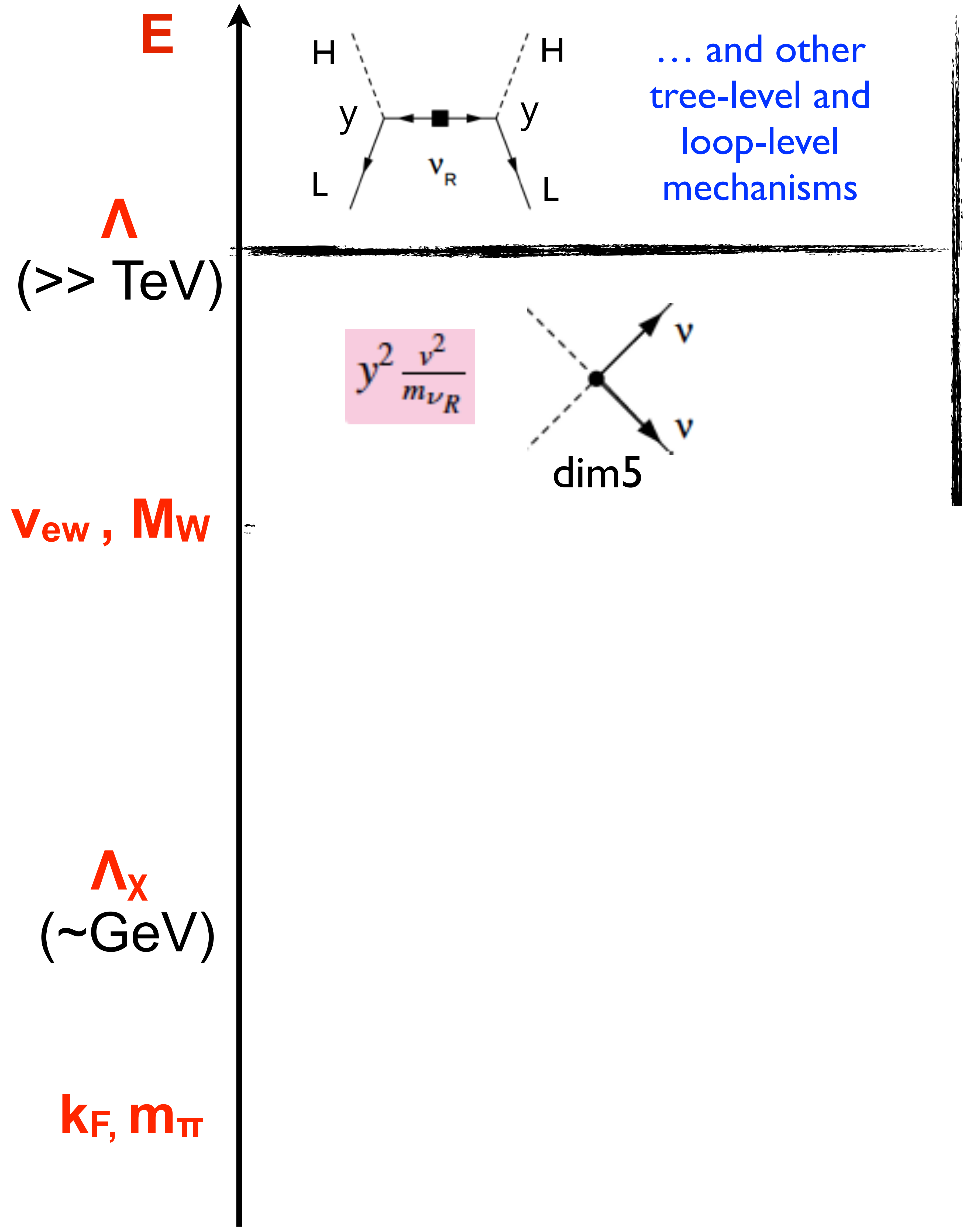


0νββ from high-scale LNV (dim-5 operator)



High scale LNV



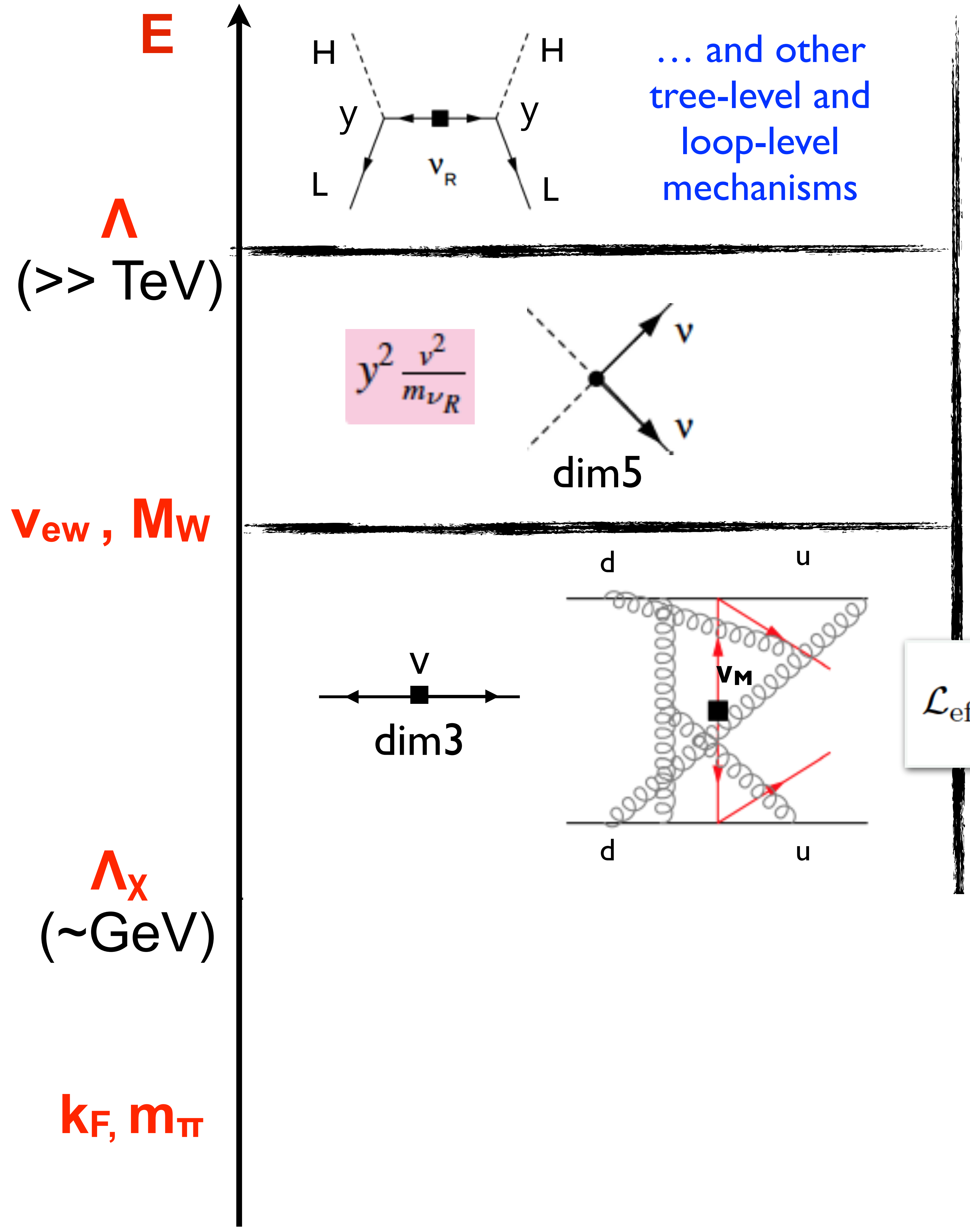
- LNV originates at very high scale ($\Lambda >> v$) → dominant low-energy remnant is Weinberg's dim-5 operator:

$$\mathcal{L}_5 = \frac{w_{\alpha\alpha'}}{\Lambda} L_\alpha^T C \epsilon H \, H^T \epsilon L_{\alpha'}$$

$$H = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \qquad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$w_{ee}/\Lambda \sim y^T m_R^{-1} y$$

High scale LNV



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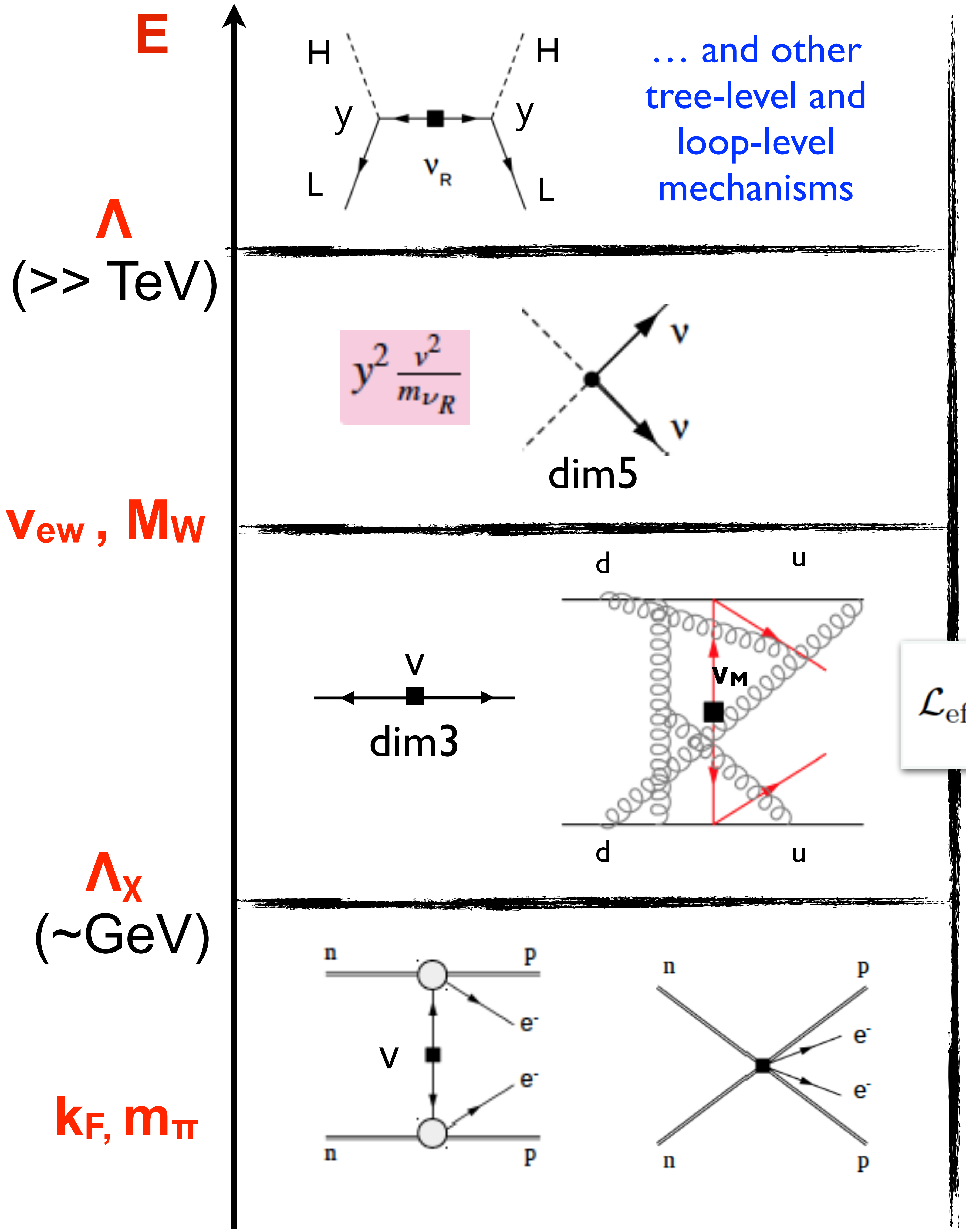
- Below the weak scale this is just the neutrino Majorana mass ($m_{\beta\beta} \sim w_{ee} \, v^2/\Lambda$)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}} - \frac{4G_F}{\sqrt{2}} V_{ud} \, \bar{u}_L \gamma^\mu d_L \, \bar{e}_L \gamma_\mu \nu_{eL} - \frac{m_{\beta\beta}}{2} \nu_{eL}^T C \nu_{eL} + \text{H.c.}$$

High scale LNV



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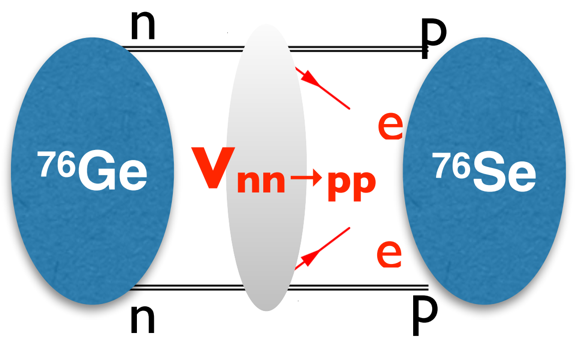
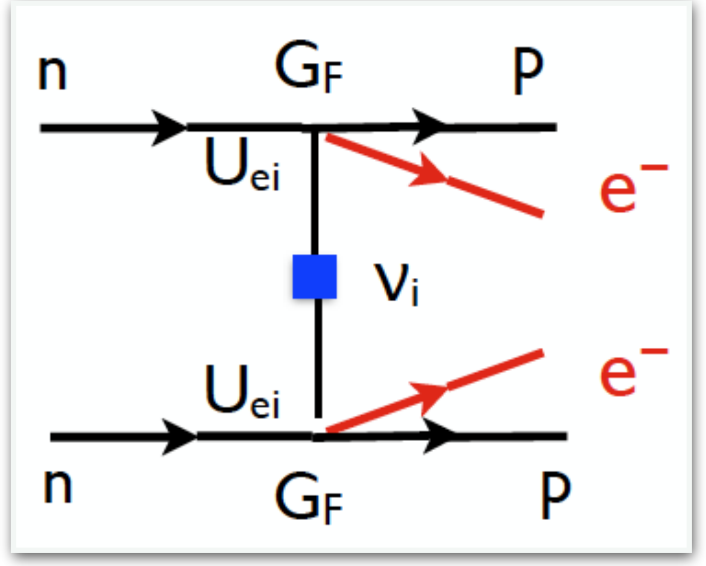
- 0νββ mediated by *active* ν_M with potential $V_{nn\rightarrow pp}$ with long- and short-range components proportional to $m_{\beta\beta}$

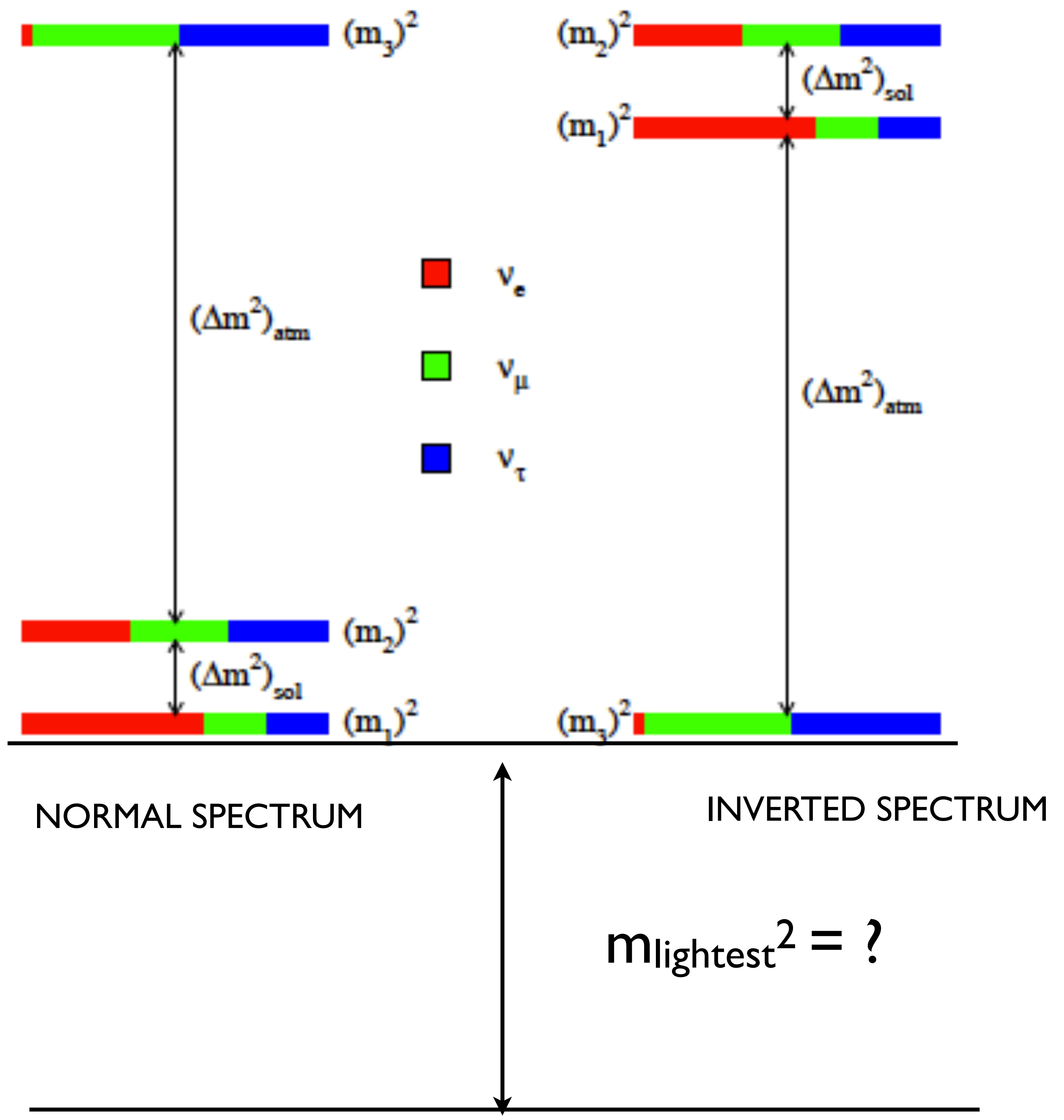


Discovery potential / target

- Within the high-scale seesaw, $0\nu\beta\beta$ can be *predicted* in terms of ν mass parameters: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$





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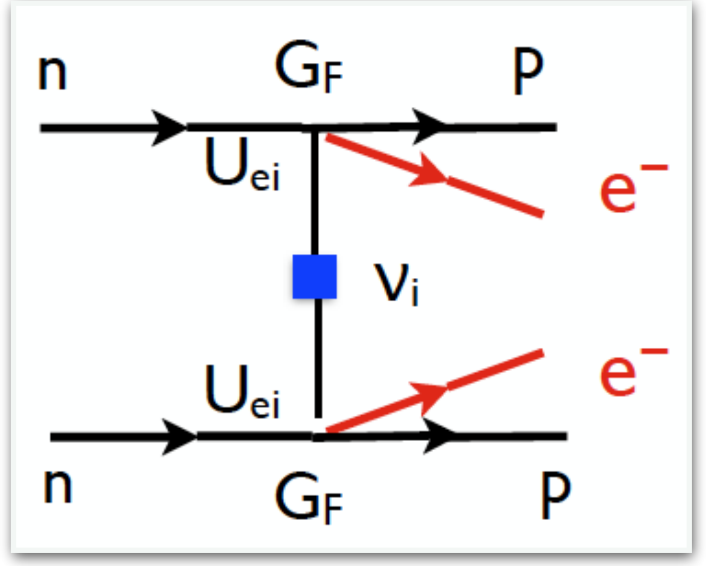
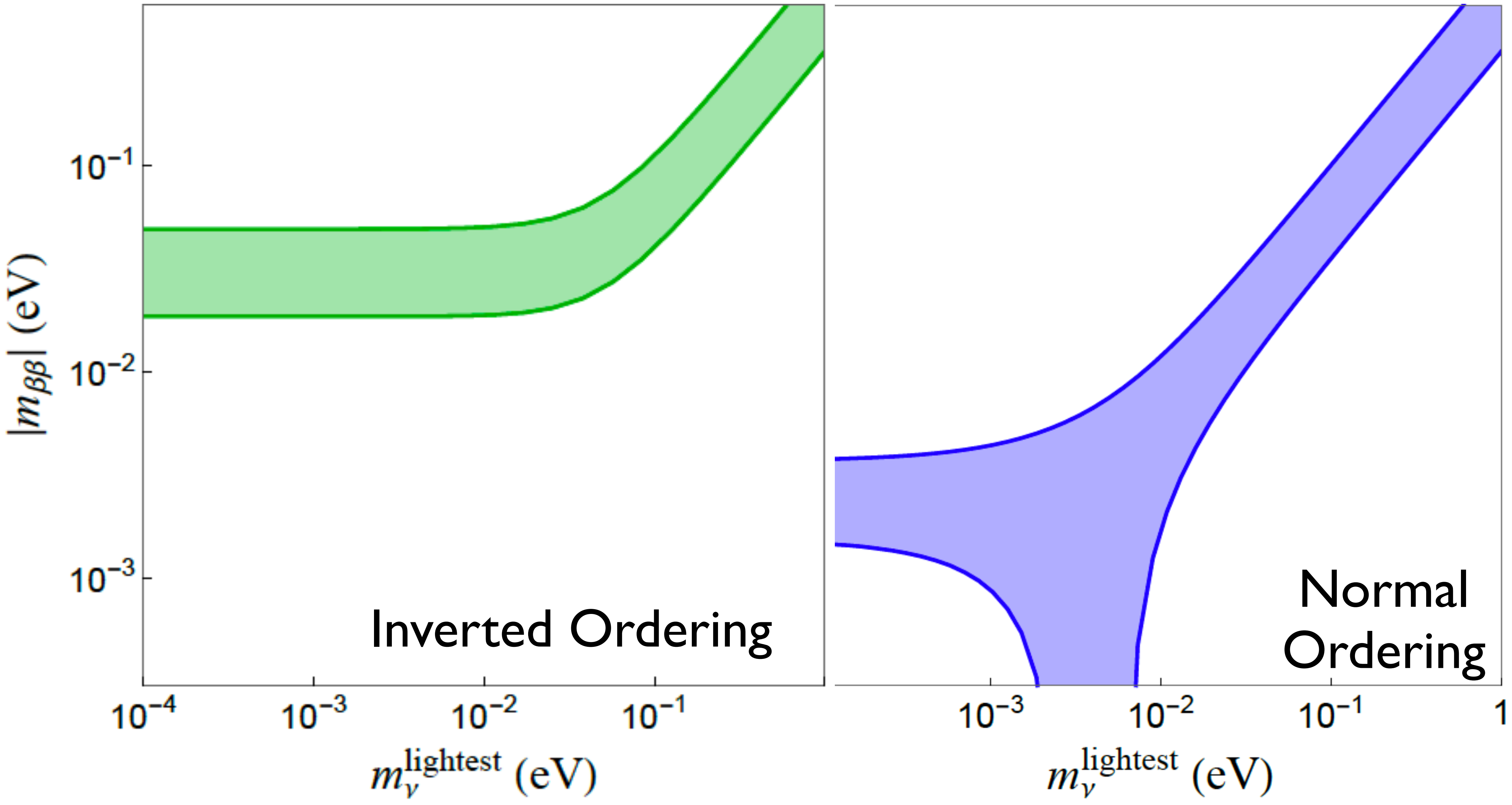


Bands: unknown Majorana phases



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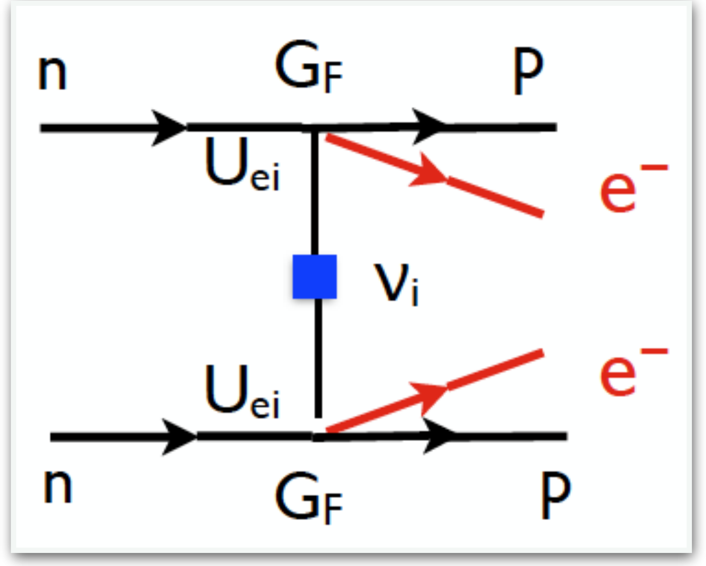

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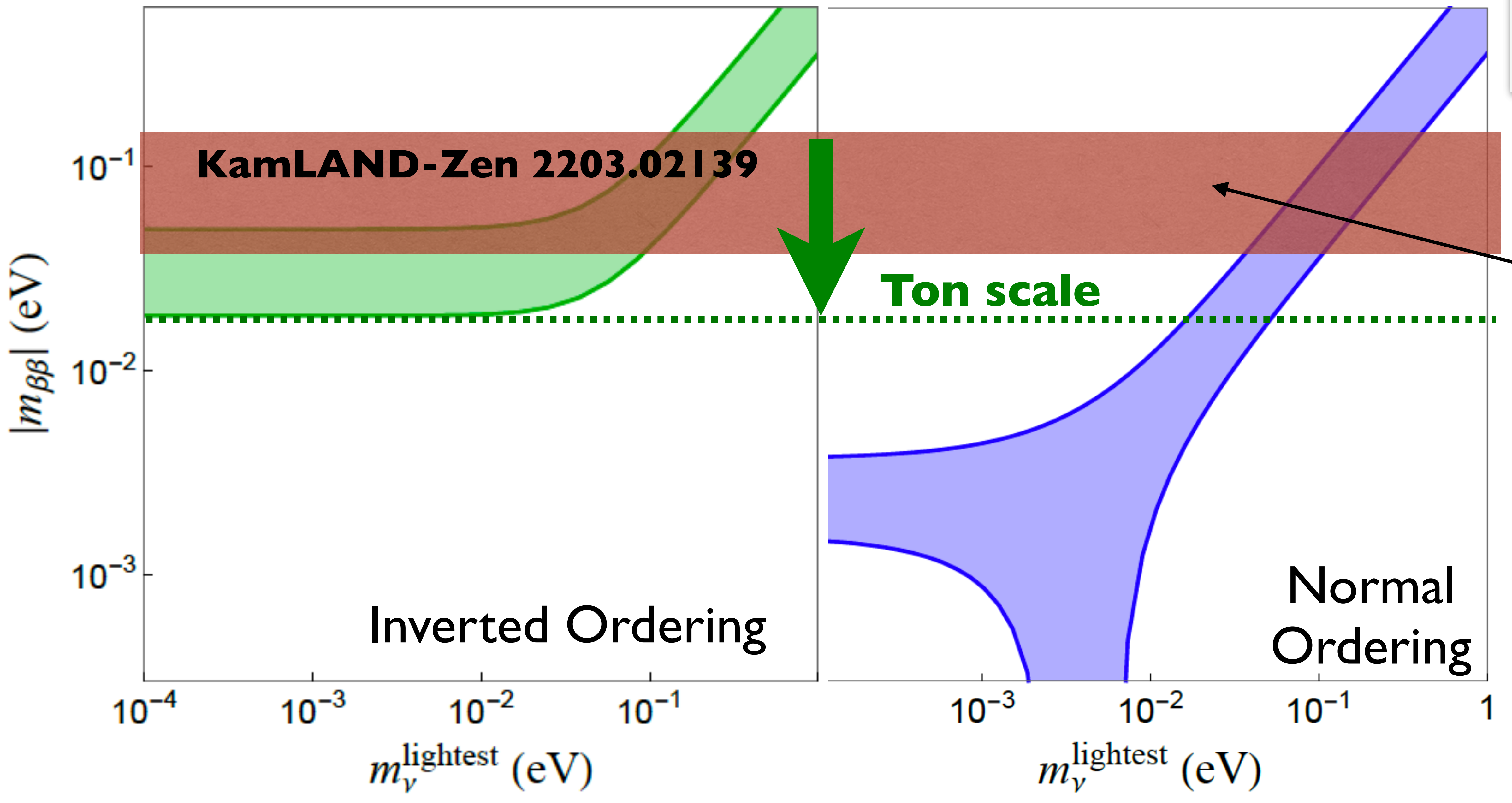

Assume range for nuclear matrix elements from different nuclear calculations

Assuming current range for matrix elements, discovery @ ton-scale *possible* for inverted spectrum or $m_{lightest}$ > 50 meV

Discovery potential / target

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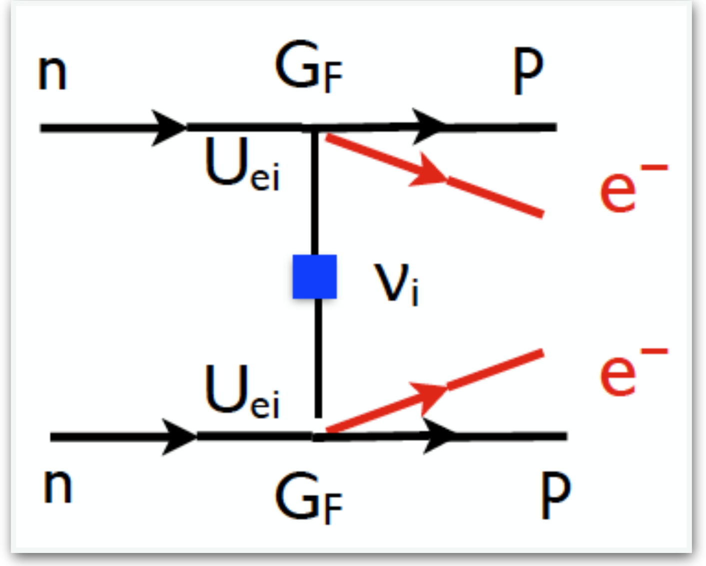

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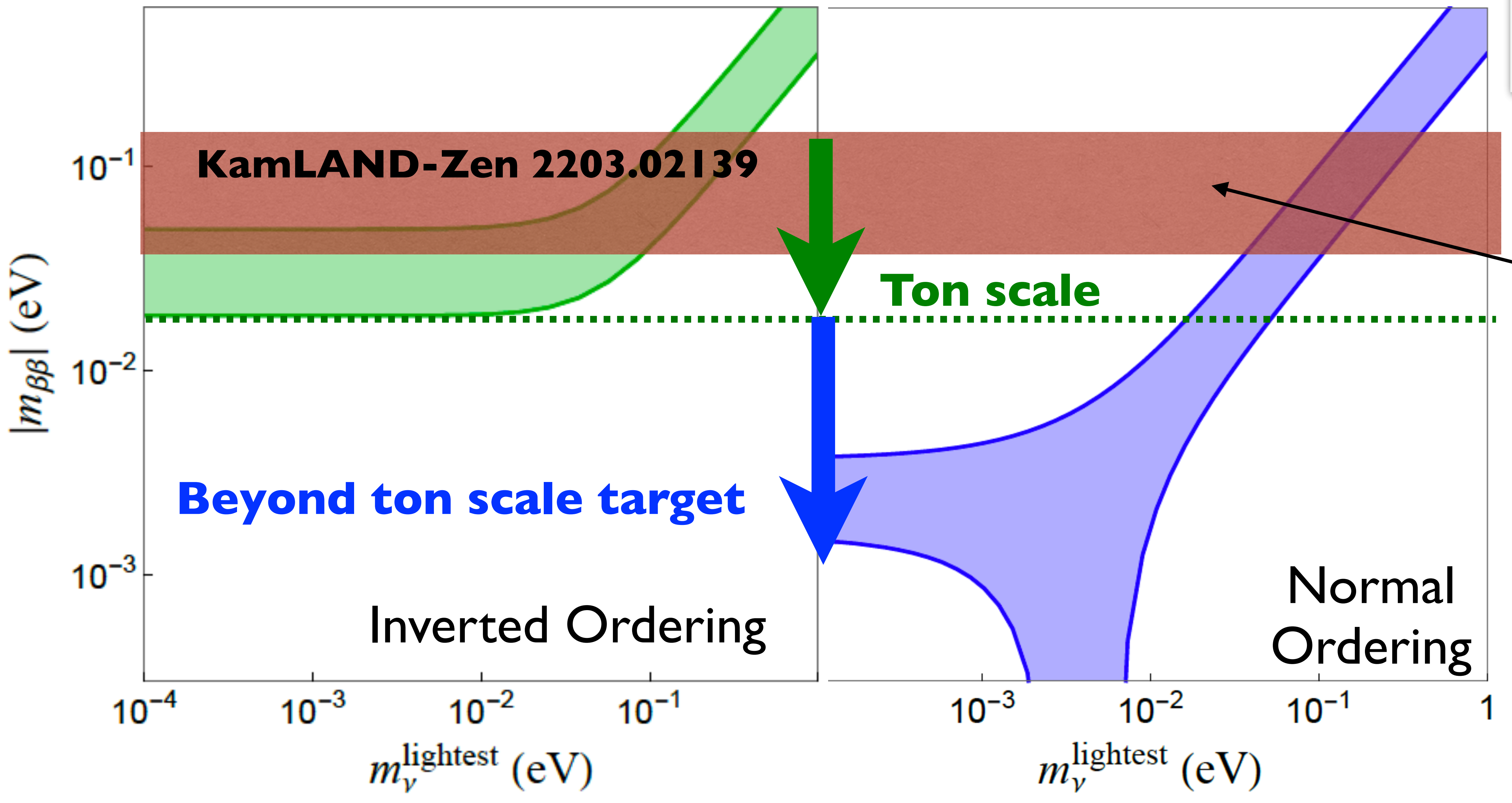


Assume range for nuclear matrix elements from different nuclear calculations

Natural (but challenging!) beyond ton-scale target is $m_{\beta\beta} \sim$ meV

Diagnosing power

- High scale seesaw implies falsifiable correlation with other ν mass probes

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \, m_i \right|$$

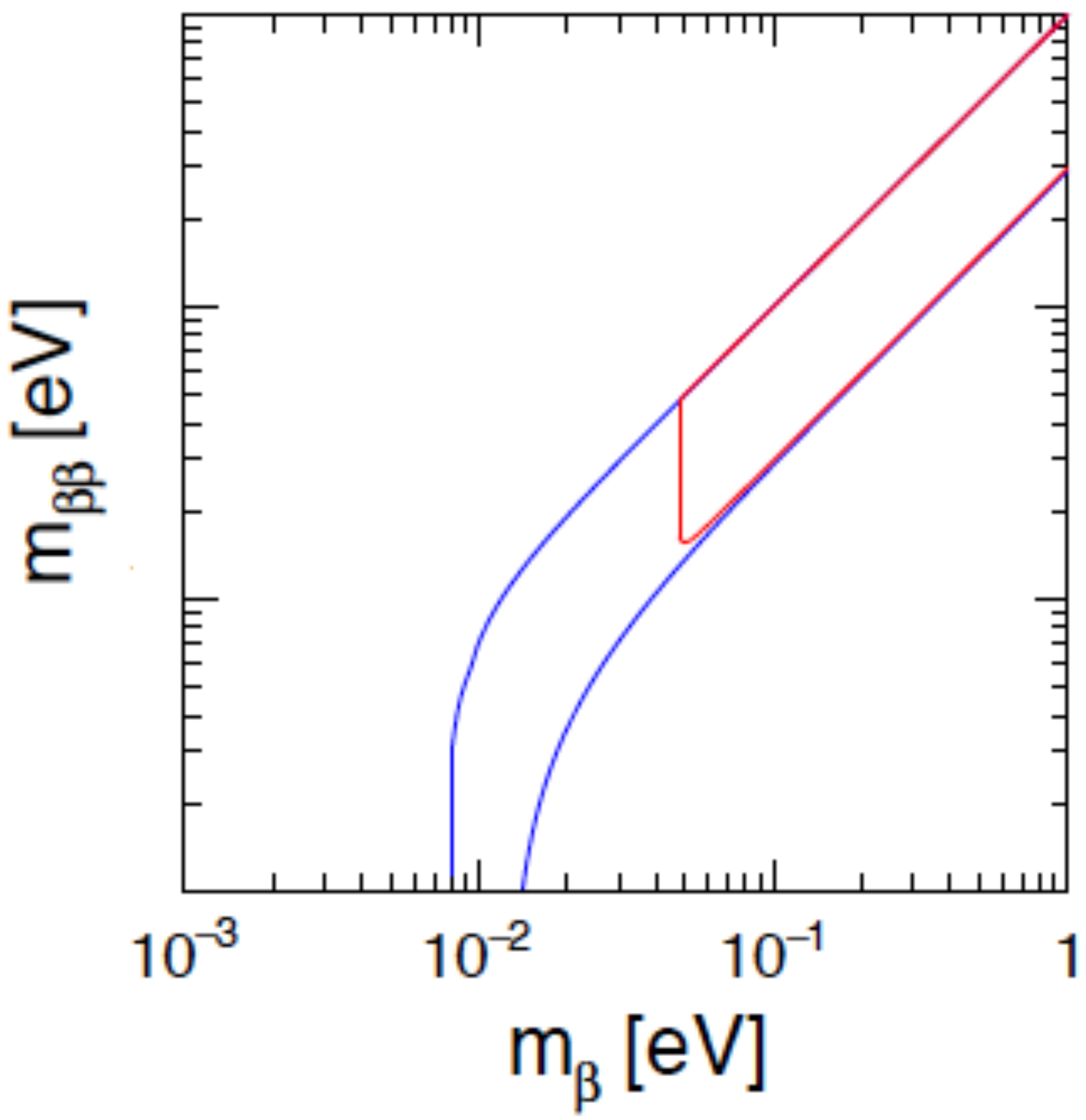
0νββ decay

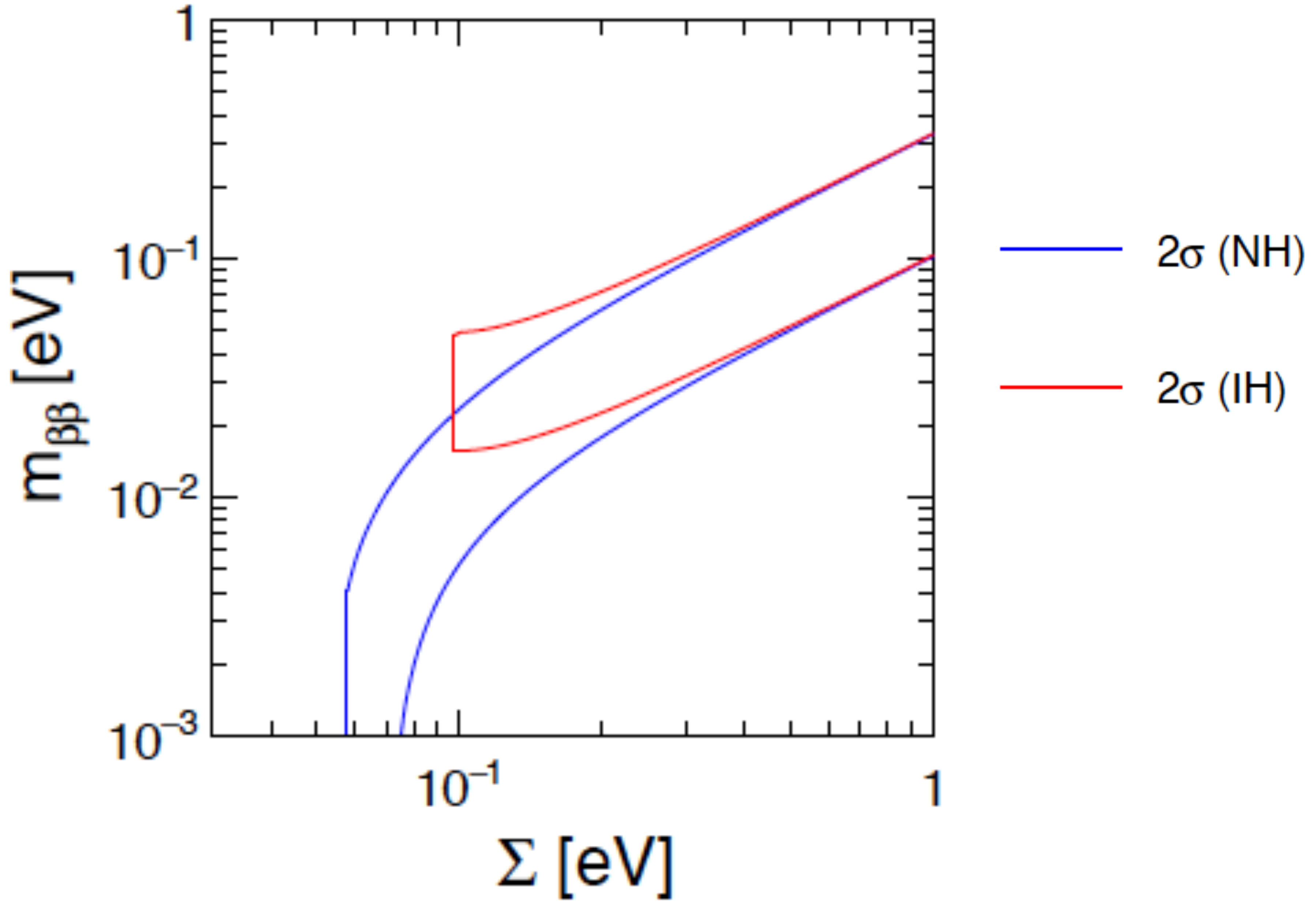
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





Diagnosing power

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- Future data coupled with improved theory can challenge the 3-neutrino paradigm and reveal new sources of LNV or physics beyond "ΛCDM + m_ν"

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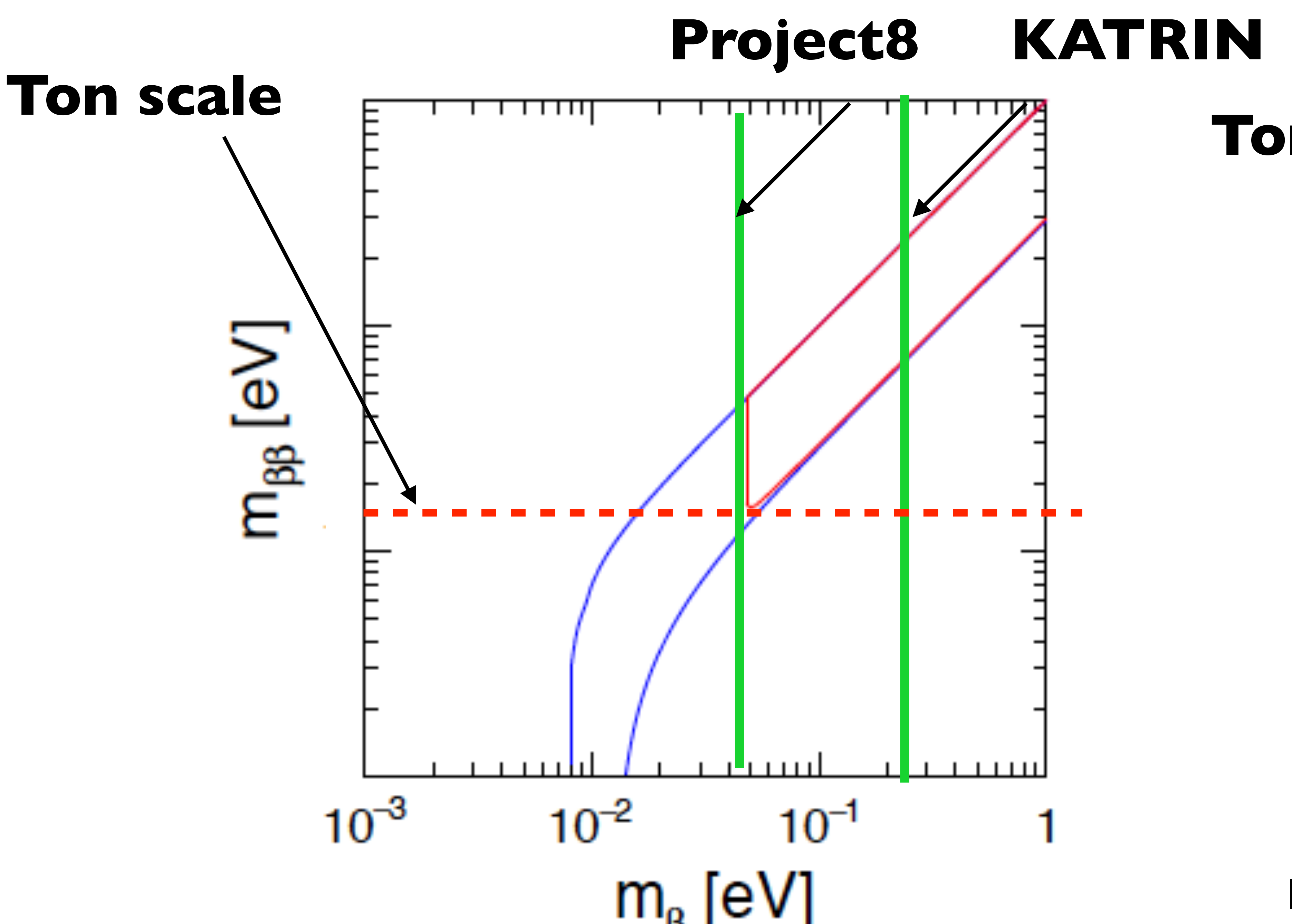

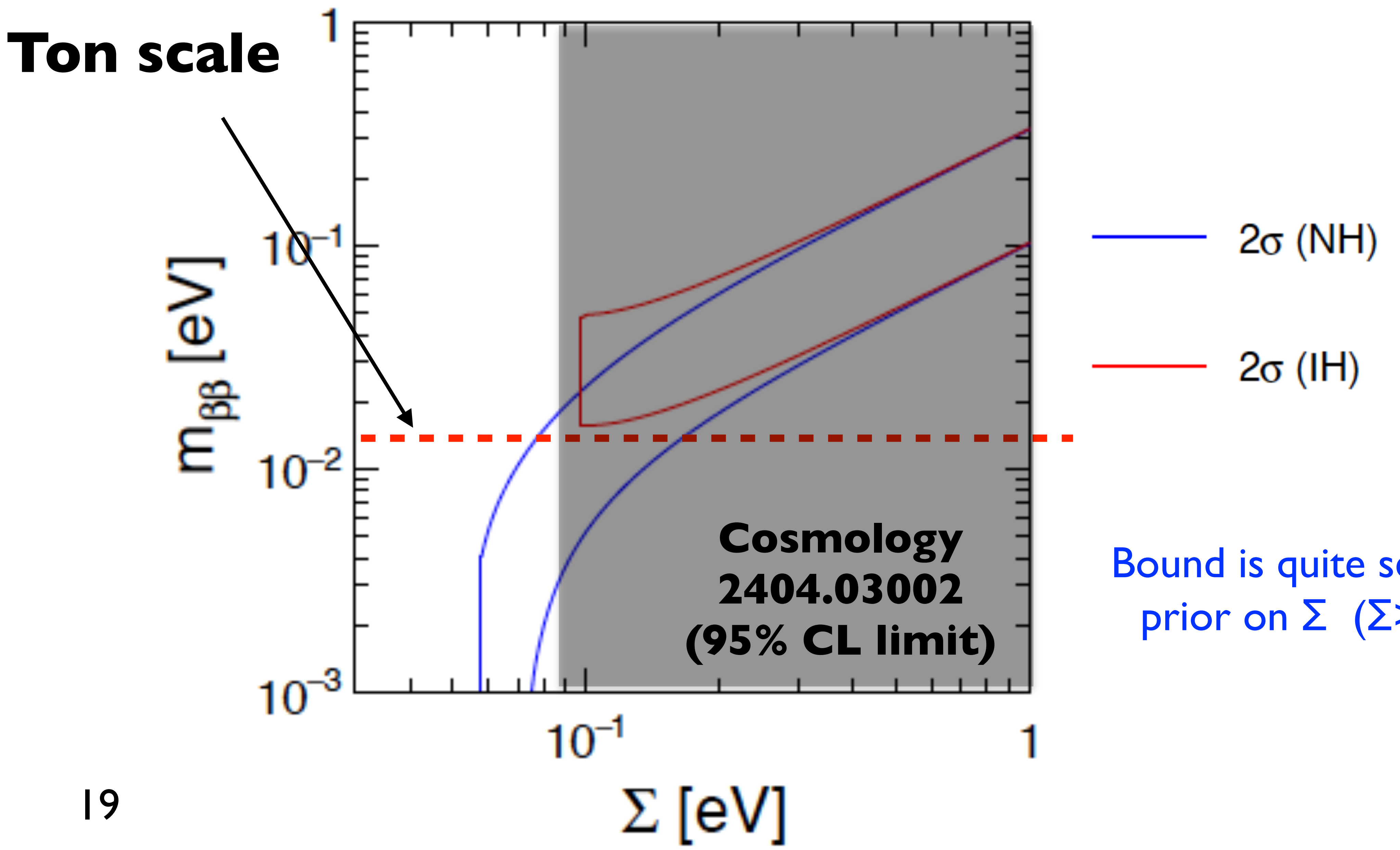

Bound is quite sensitive to prior on Σ (Σ>0 used)

Diagnosing power

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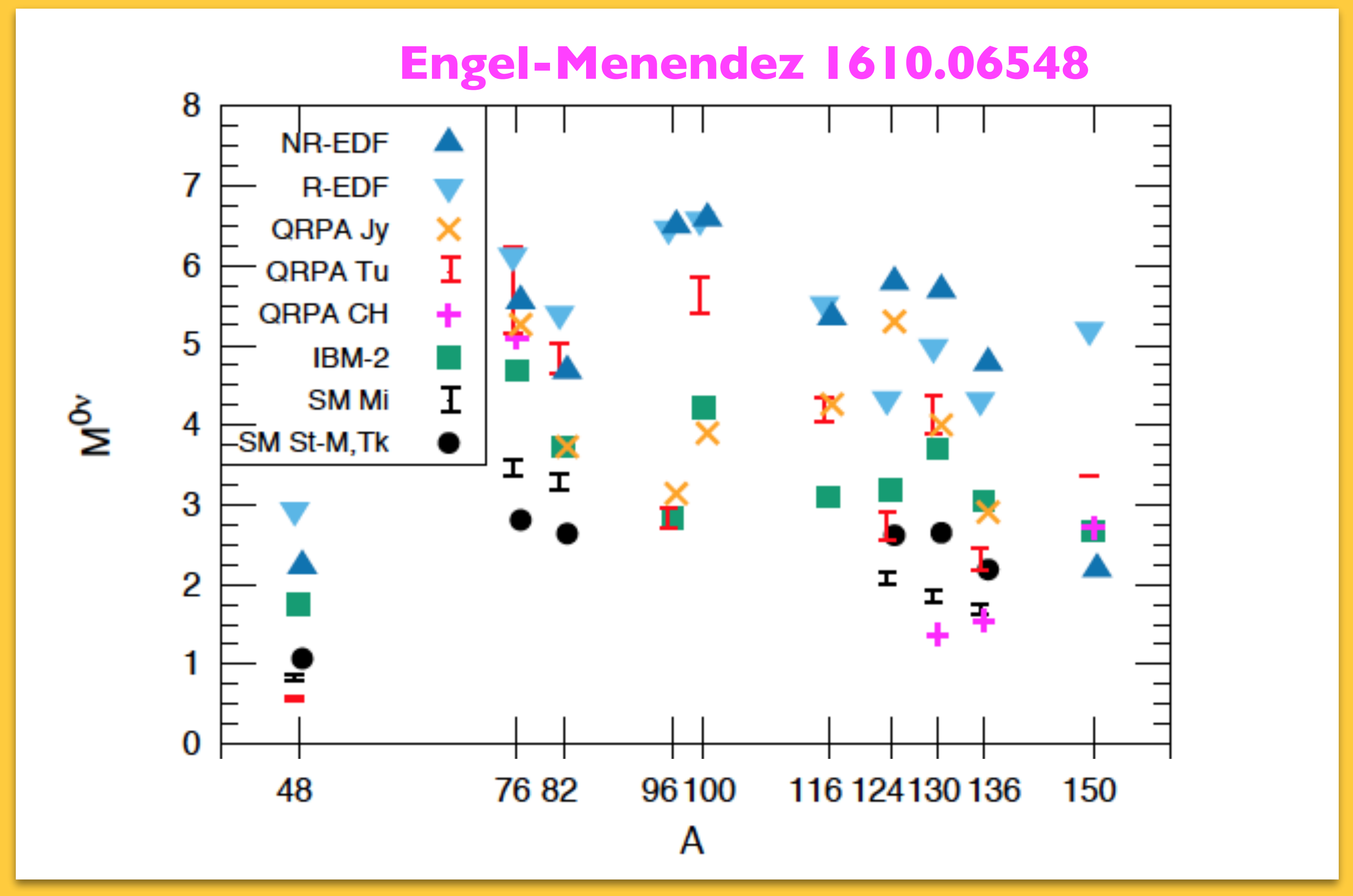
Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology

These important *quantitative* connections require knowing nuclear matrix elements and their uncertainties!

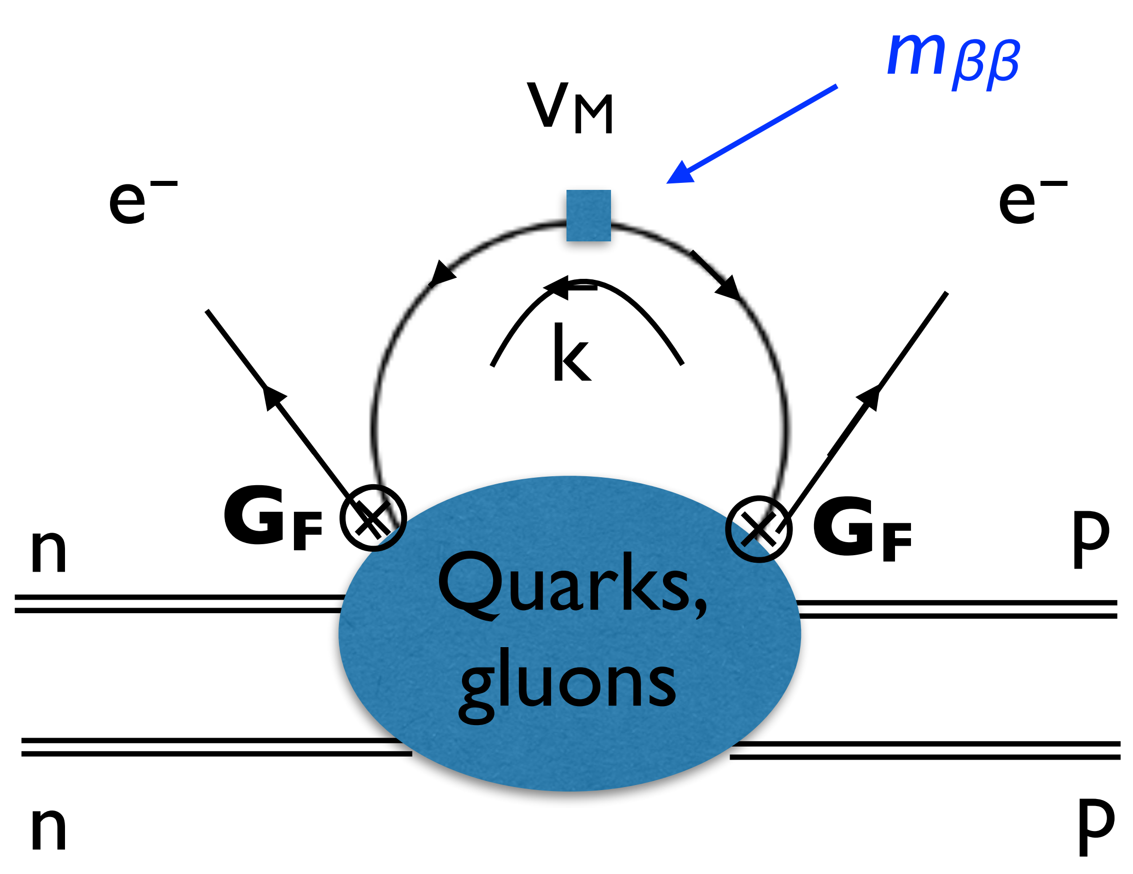


te sensitive to (Σ>0 used)

Hadronic ΔL=2 amplitudes in EFT

V. C., W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} - \frac{4G_F}{\sqrt{2}} V_{ud}\, \bar{u}_L \gamma^\mu d_L\, \bar{e}_L \gamma_\mu \nu_{eL} - \frac{m_{\beta\beta}}{2}\, \nu_{eL}^T C \nu_{eL} + \text{H.c.}$$



Hadronic ΔL=2 amplitudes in EFT

V. C., W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

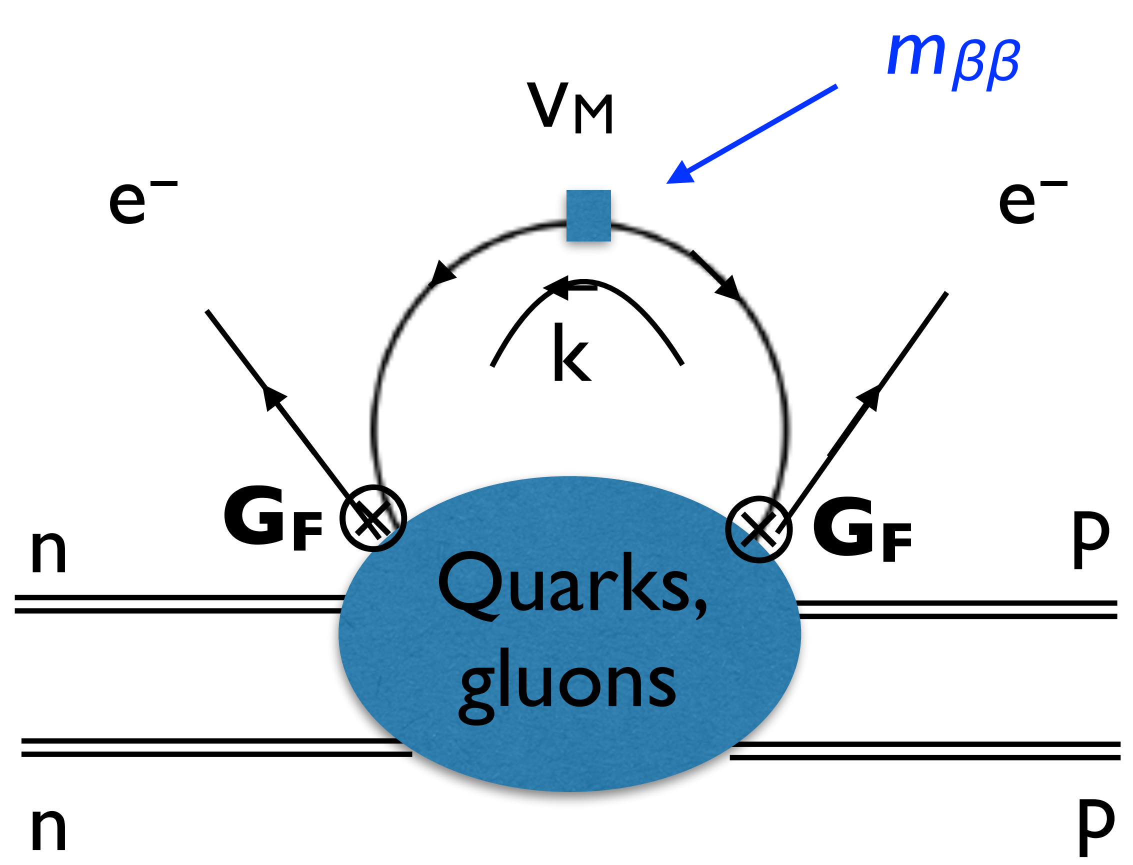
- ΔL=2 amplitudes determined by neutrino-less non-local effective action

$$S_{\rm eff}^{\Delta L=2} = \frac{8G_F^2 V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x d^4y \; S(x-y) \times \bar{e}_L(x)\gamma^\mu\gamma^\nu e_L^c(y) \times T\Big(\bar{u}_L\gamma_\mu d_L(x)\; \bar{u}_L\gamma_\nu d_L(y)\Big)$$

Scalar massless propagator

$|p_1 - p_2|/k_F \ll 1.$

$$g^{\mu\nu}\, \bar{e}_L(x) e_L^c(x) + \dots$$



Hadronic ΔL=2 amplitudes in EFT

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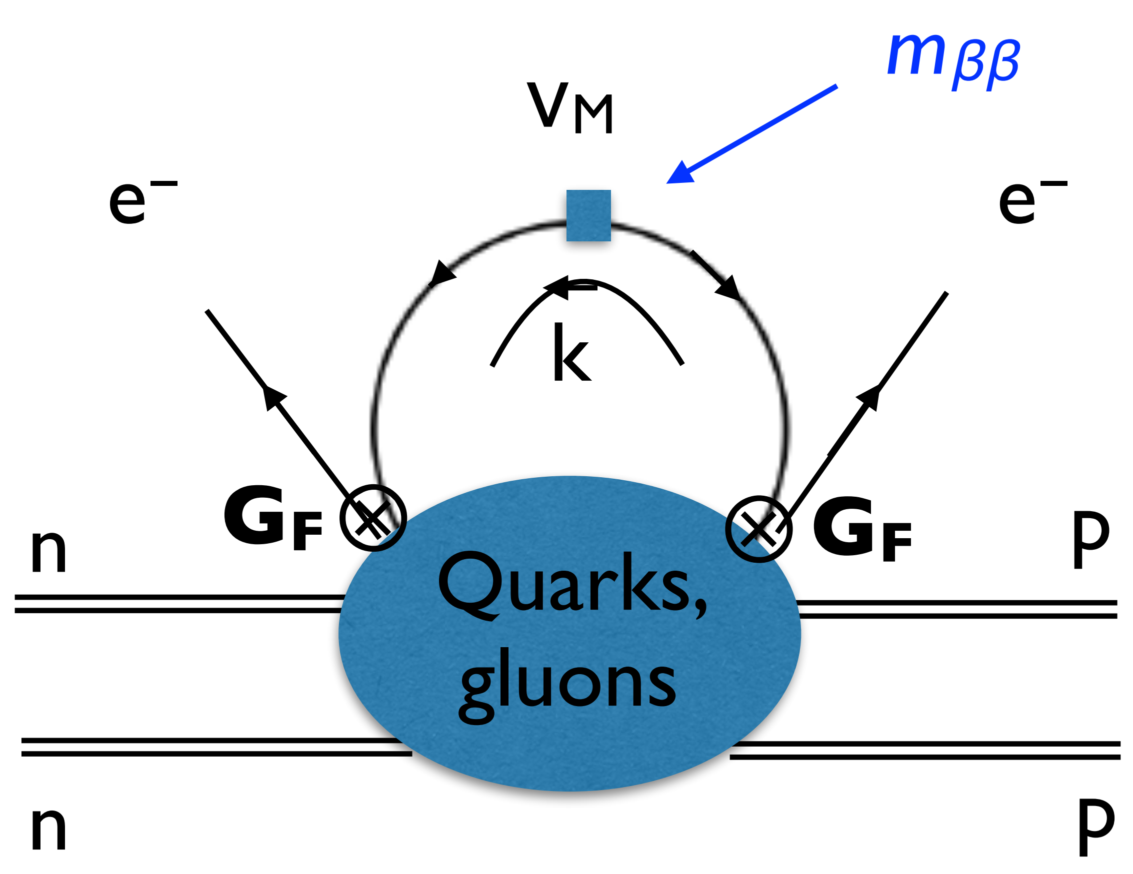
$$\hat{\Pi}_{\mu\nu}^{++}(k,x) = \int d^4r \, e^{ik\cdot r} \, \langle h_f | T\Big(\bar{u}_L \gamma_\mu d_L(x + r/2) \, \bar{u}_L \gamma_\nu d_L(x - r/2) \Big) | h_i \rangle \, .$$

Momentum space representation

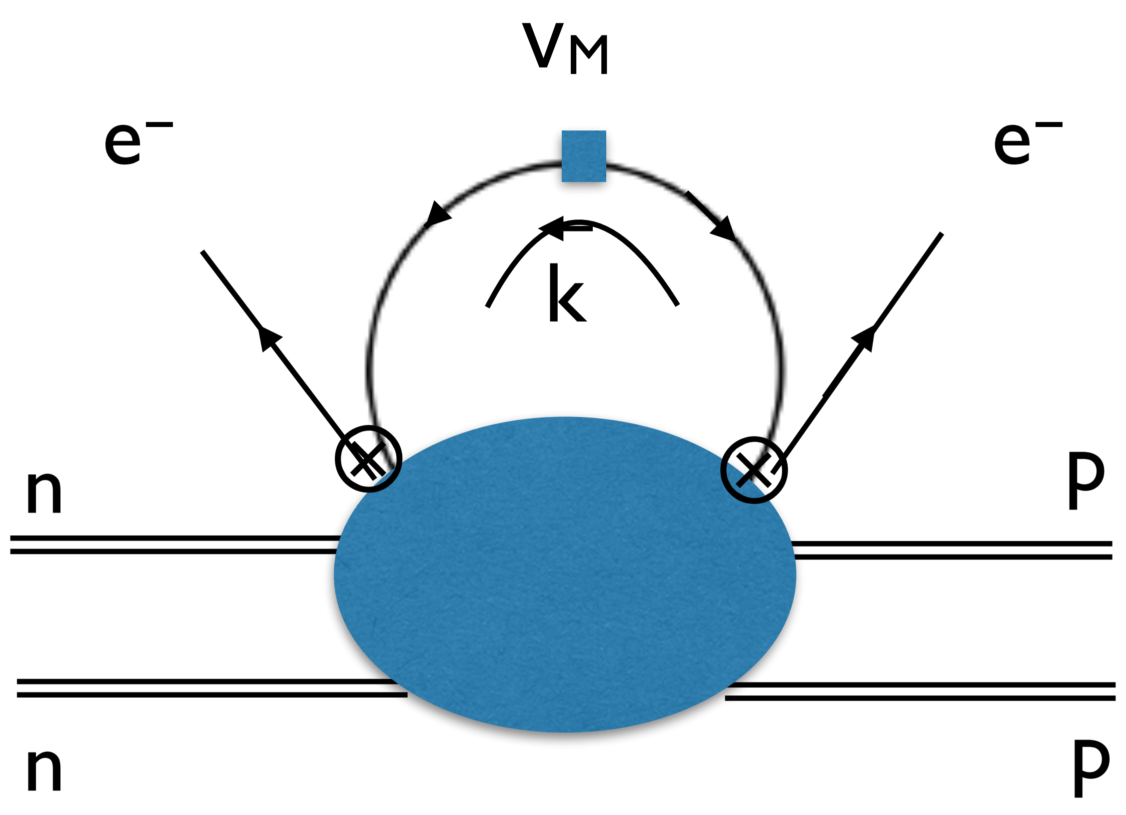
LNV hadronic amplitudes such as nn → ppee in principle receive contributions from neutrinos of all virtualities (k)



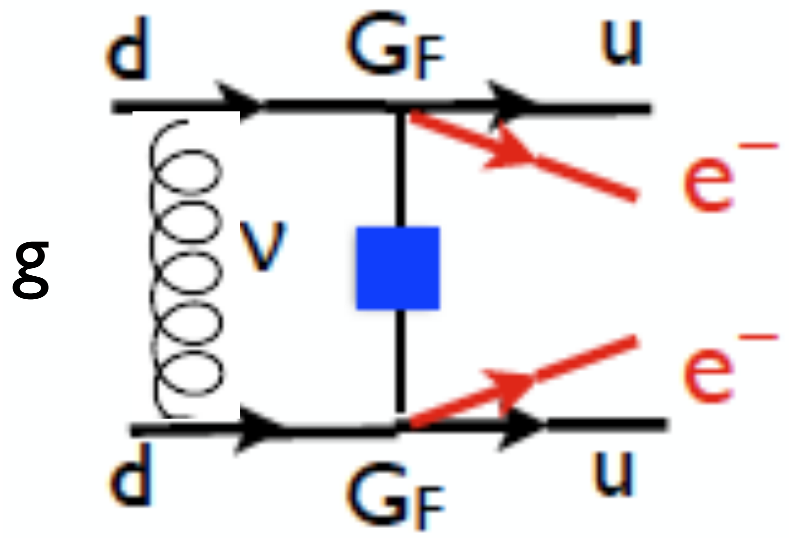
Chiral EFT captures contributions from all relevant momentum regions

$k^\mu = (k^0, \mathbf{k})$

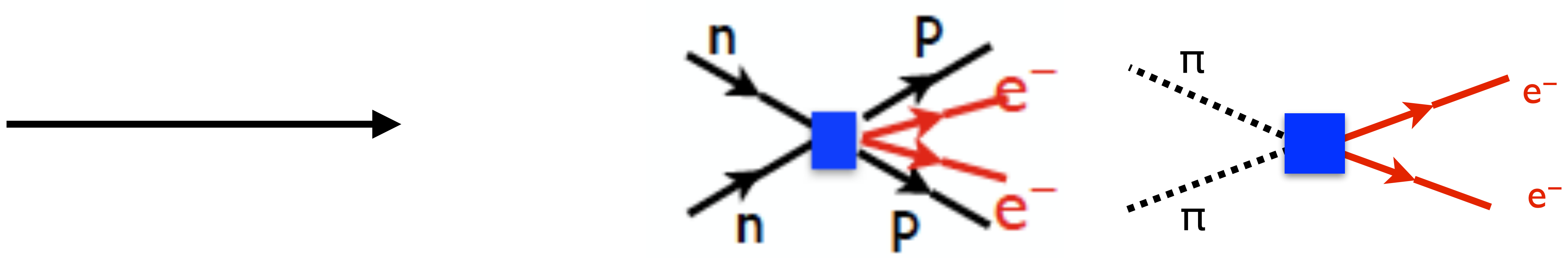
Classifying contributions



"Hard neutrinos":
$k^0, |\mathbf{k}| > \Lambda_\chi \sim m_N \sim \text{GeV}$



Short-range ΔL=2 operators at the hadronic level,
still proportional to $m_{\beta\beta}$



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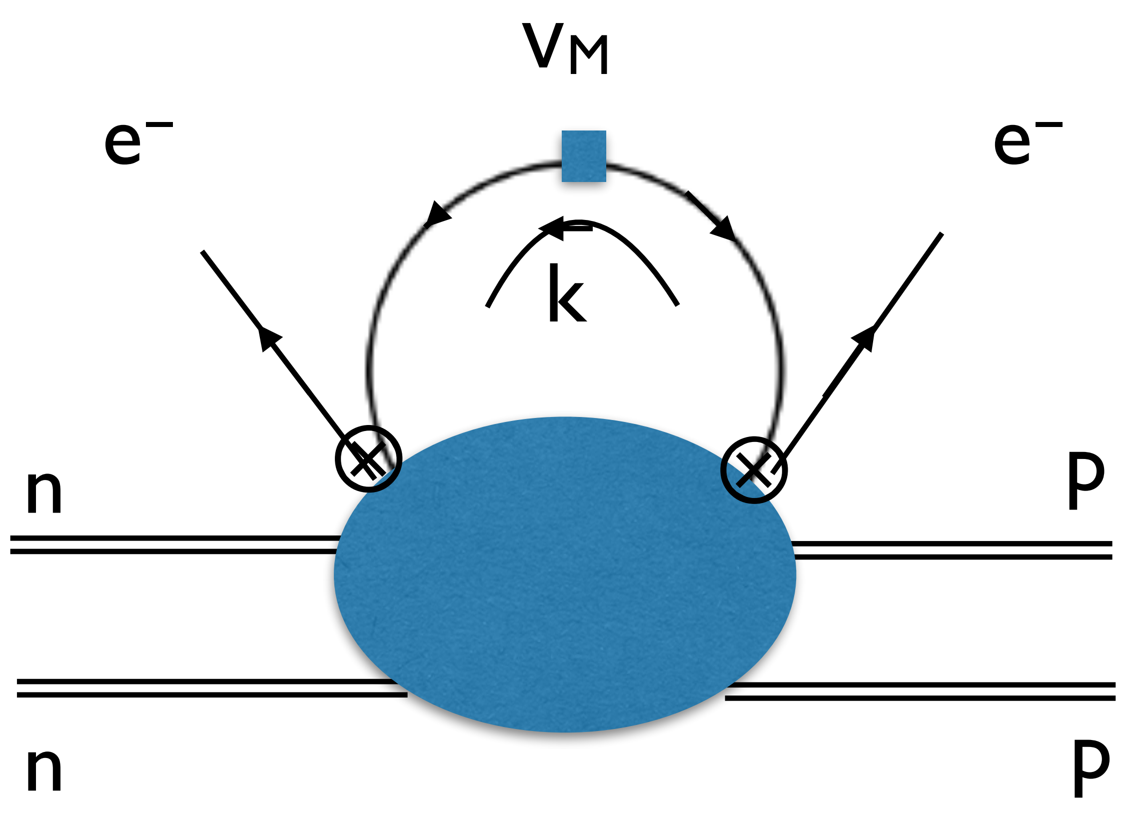

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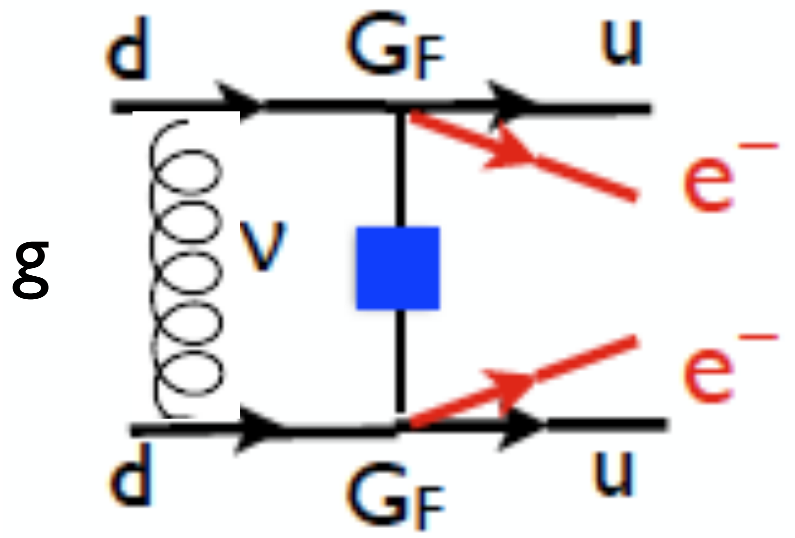

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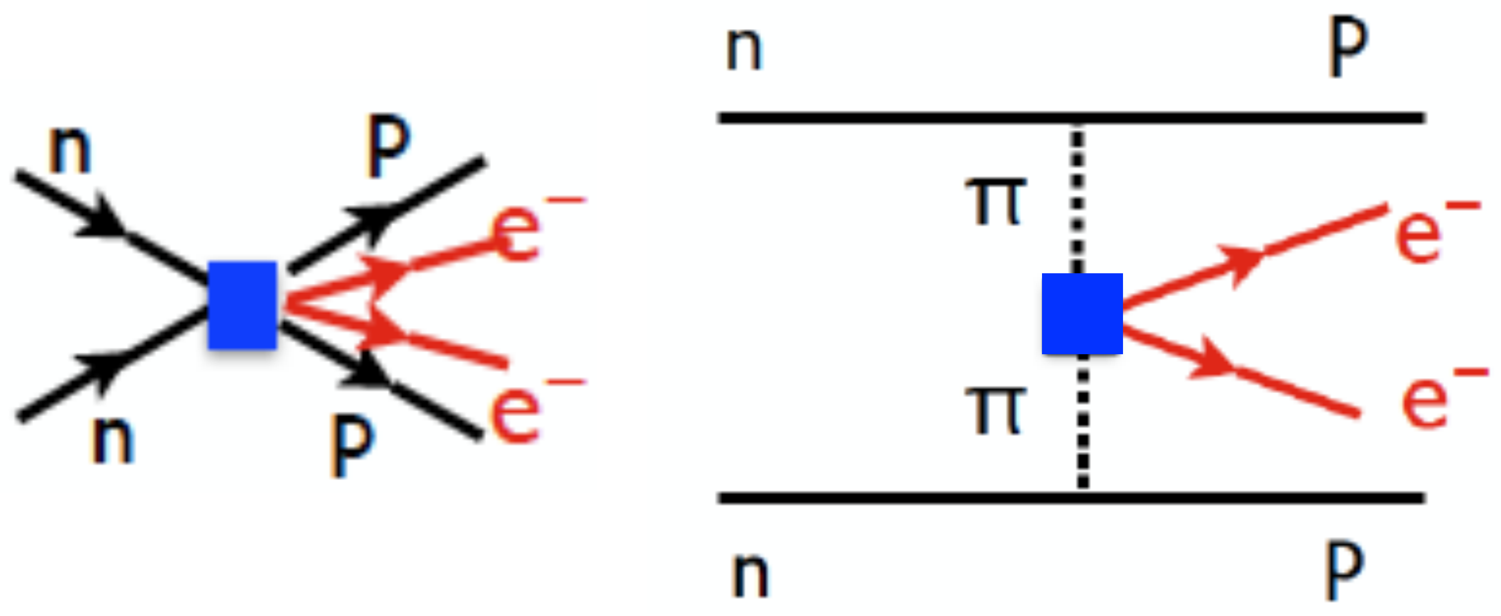
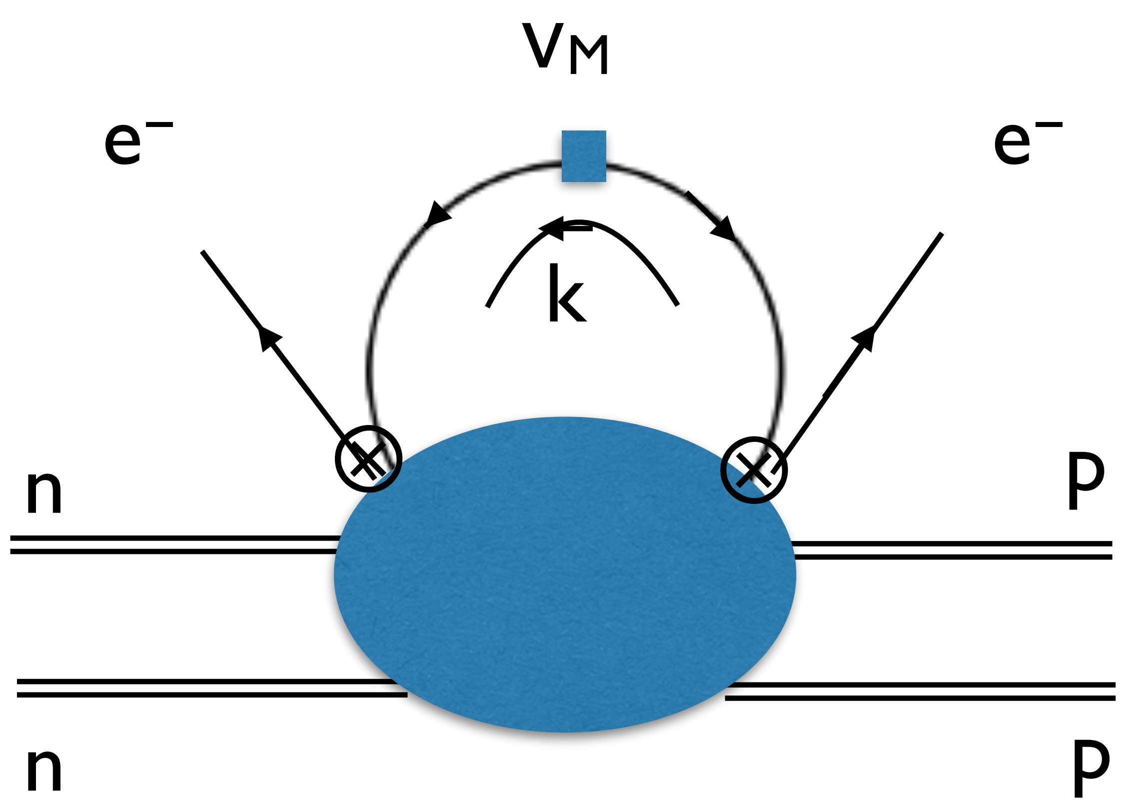


Short- and pion-range contributions to
"Neutrino potential" mediating nn→pp

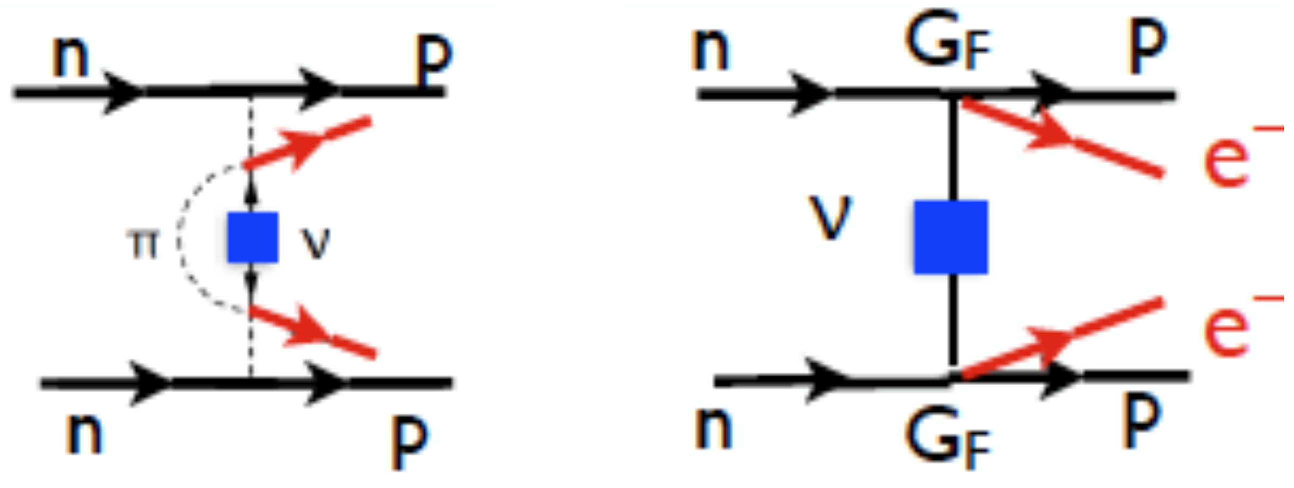
Classifying contributions



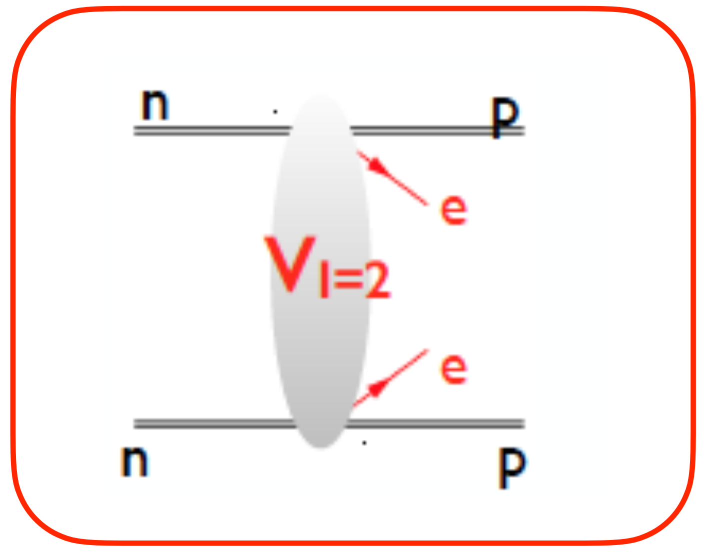
"Soft" & "Potential" neutrinos:

Soft: $(k^0, |\mathbf{k}|) \sim Q \sim k_F \sim m_\pi$

Potential: $(k^0, |\mathbf{k}|) \sim (Q^2/m_N,\ Q)$

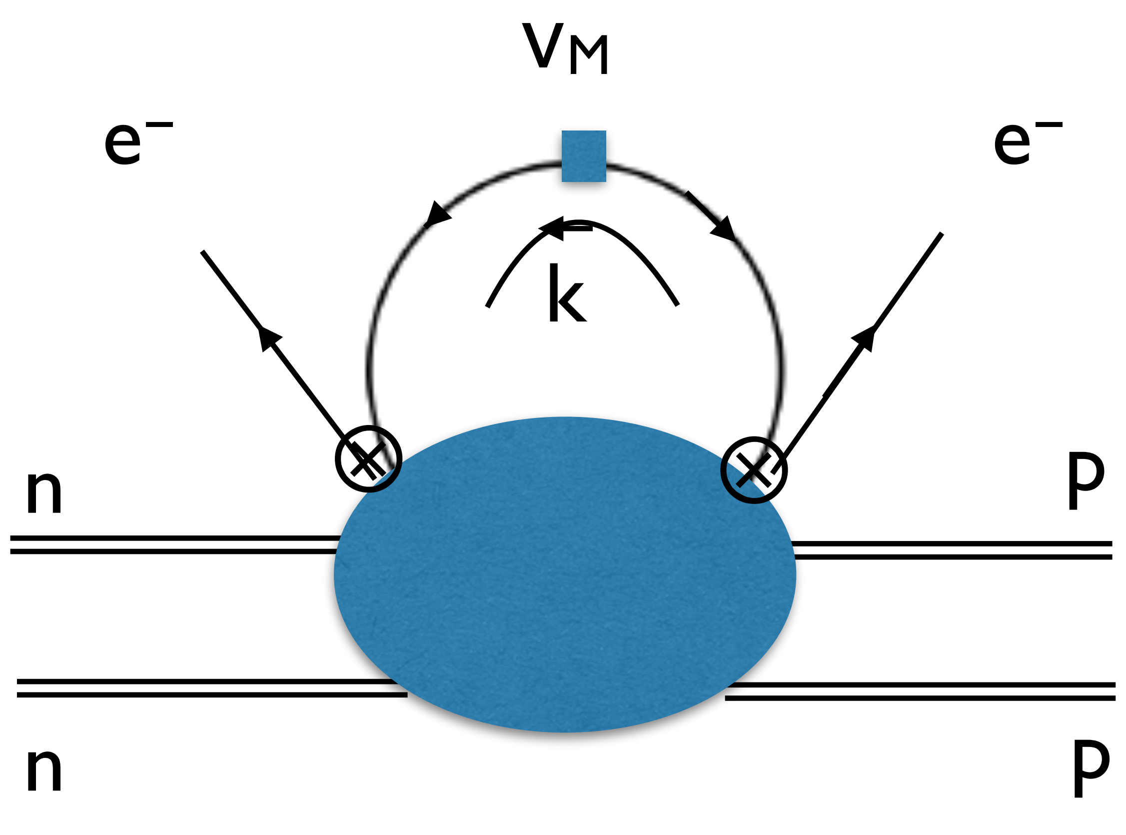


Calculable long- and pion-range contributions to the "Neutrino potential" mediating $nn \to pp$



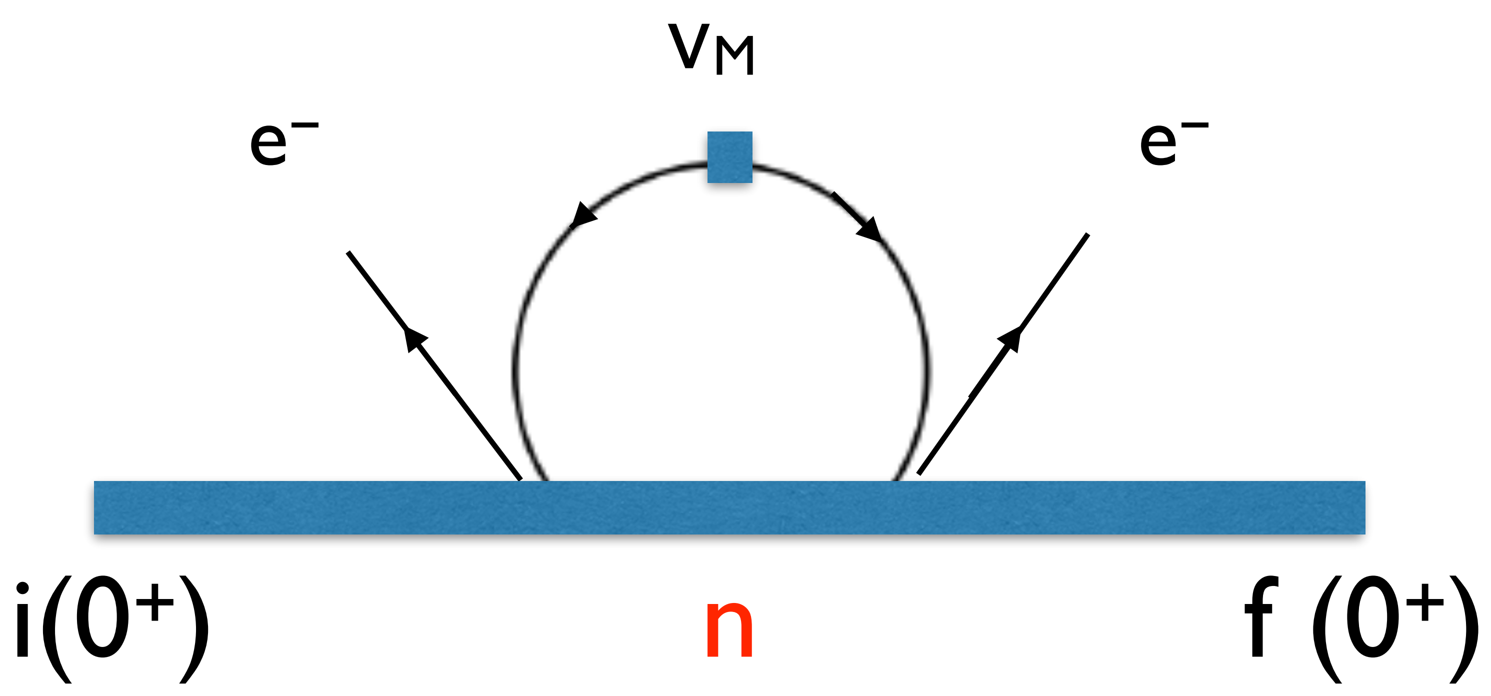
At the nuclear level, these operators mediate the transition between the initial (0^+) and final (0^+) nuclear states

Classifying contributions



"UltraSoft" neutrinos:

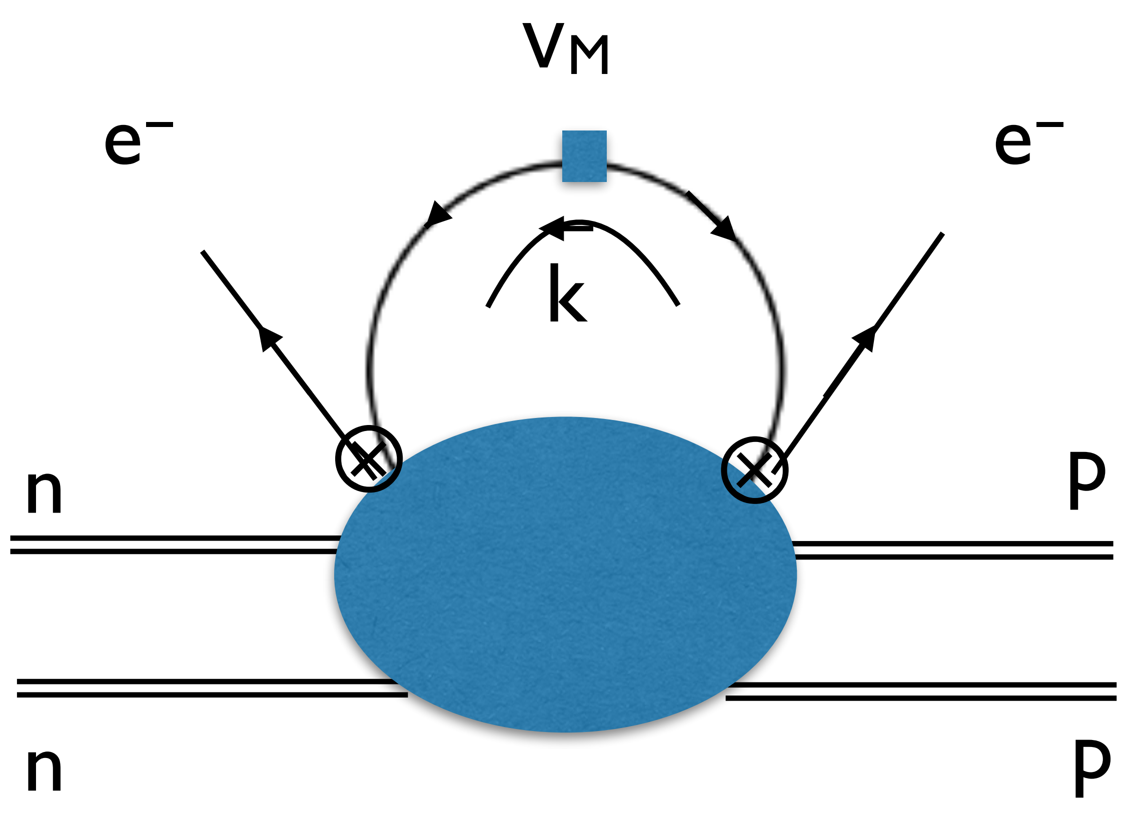
$(k^0, |\mathbf{k}|) \sim Q^2/m_N$ **<<** k_F



Sum over intermediate nuclear states

Double insertions of the weak current
at the hadronic / nuclear level

Nuclear scale effective Hamiltonian



Kinetic energy and *strong* NN potential

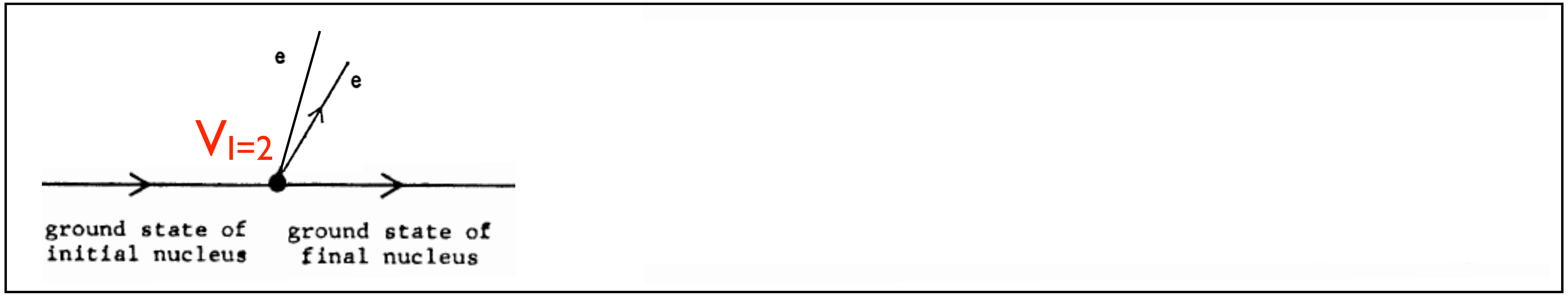
$$H_{\text{Nucl}} = H_0 + \boxed{\sqrt{2}G_F V_{ud}\,\bar{N}\left(g_V\delta^{\mu 0} - g_A\delta^{\mu i}\sigma^i\right)\tau^+ N\,\bar{e}_L\gamma_\mu\nu_L} + 2G_F^2 V_{ud}^2 m_{\beta\beta}\,\bar{e}_L e_L^c\,V_{I=2}$$

"Ultra-soft" (e, ν) with (E,|**p**|) << k_F
cannot be integrated out

"Isotensor" 0νββ potential mediates nn→pp.
It can be identified to a given order in Q/Λ_χ by computing 2-nucleon amplitudes

Anatomy of 0vββ amplitude in EFT

Figure adapted from Primakoff-Rosen 1969



Hard, soft, and potential ν

$$V_{I=2} = \sum_{a \neq b} \left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \ldots \right)$$

$V_\nu \sim 1/Q^2\ ,\ \ 1/(\Lambda_\chi)^2, \ldots$

↑ LO ↑ N^2LO

Anatomy of 0νββ amplitude in EFT

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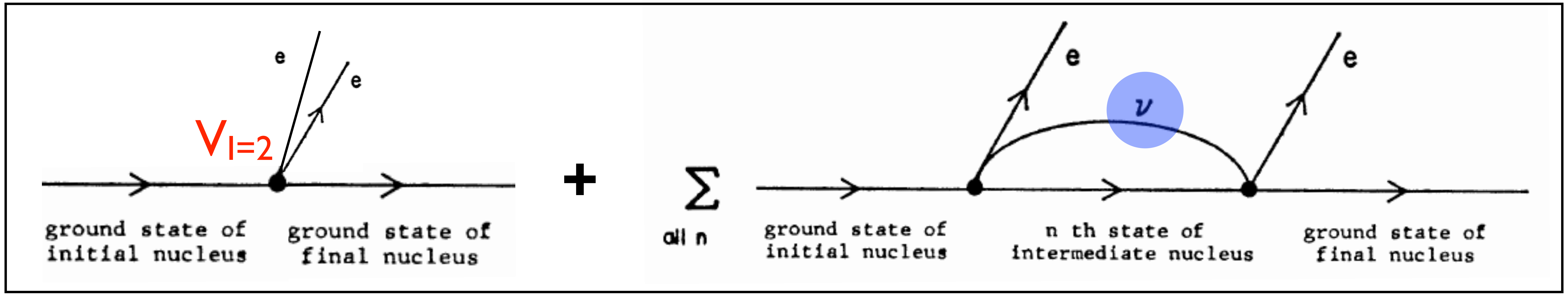

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LO N²LO

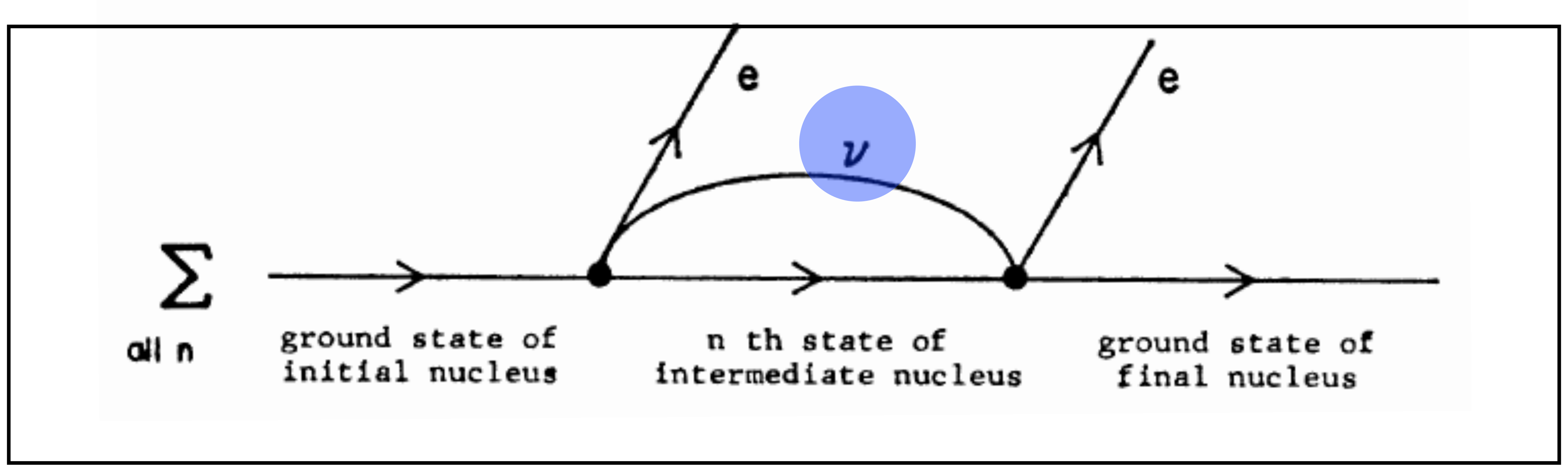
Ultrasoft ν

Loop calculable in terms of $E_n - E_i$ and $\langle f\,|J_\mu|n\rangle\langle n|J^\mu|i\rangle$, that also control 2νββ.

Contributes to the amplitude at N²LO

Connection with non-EFT approach

Figure adapted from Primakoff-Rosen 1969



- EFT result corresponds to the full amplitude expanded according to chiral power counting (by design):

$$\mathcal{A}_\nu \propto \sum_n \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{1}{|\mathbf{k}|} \left[\frac{\langle f|J^L_\mu(\mathbf{k})|n\rangle\langle n|J^{L\mu}(-\mathbf{k})|i\rangle}{|\mathbf{k}| + (E_n - E_i + E_{e2})} + \frac{\langle f|J^L_\mu(\mathbf{k})|n\rangle\langle n|J^{L\mu}(-\mathbf{k})|i\rangle}{|\mathbf{k}| + (E_n - E_i + E_{e1})} \right]$$

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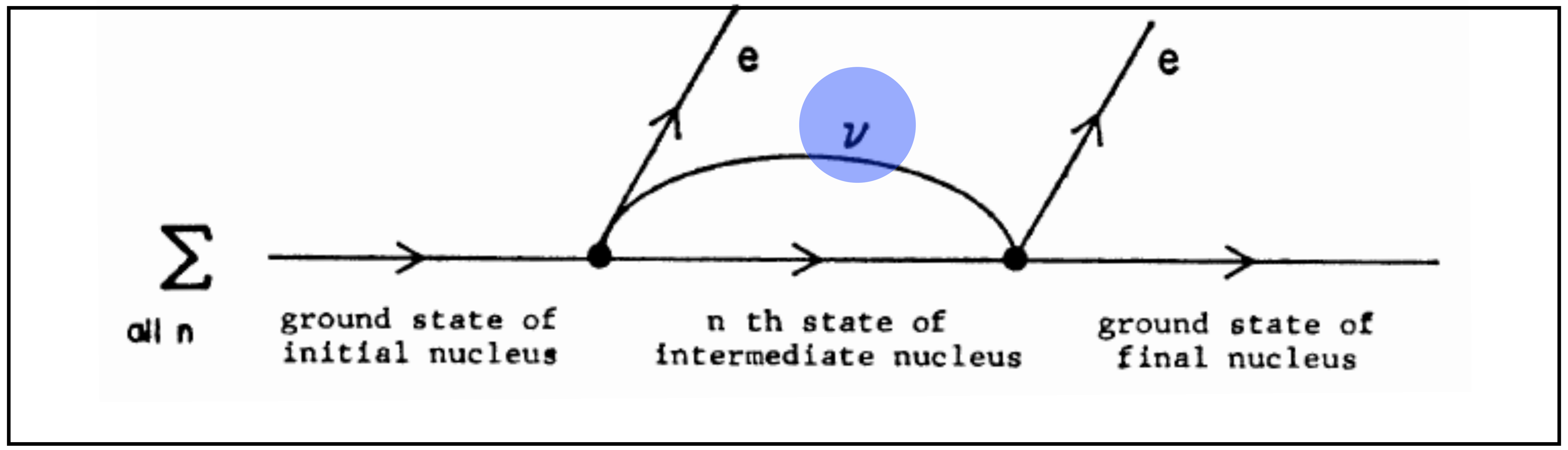

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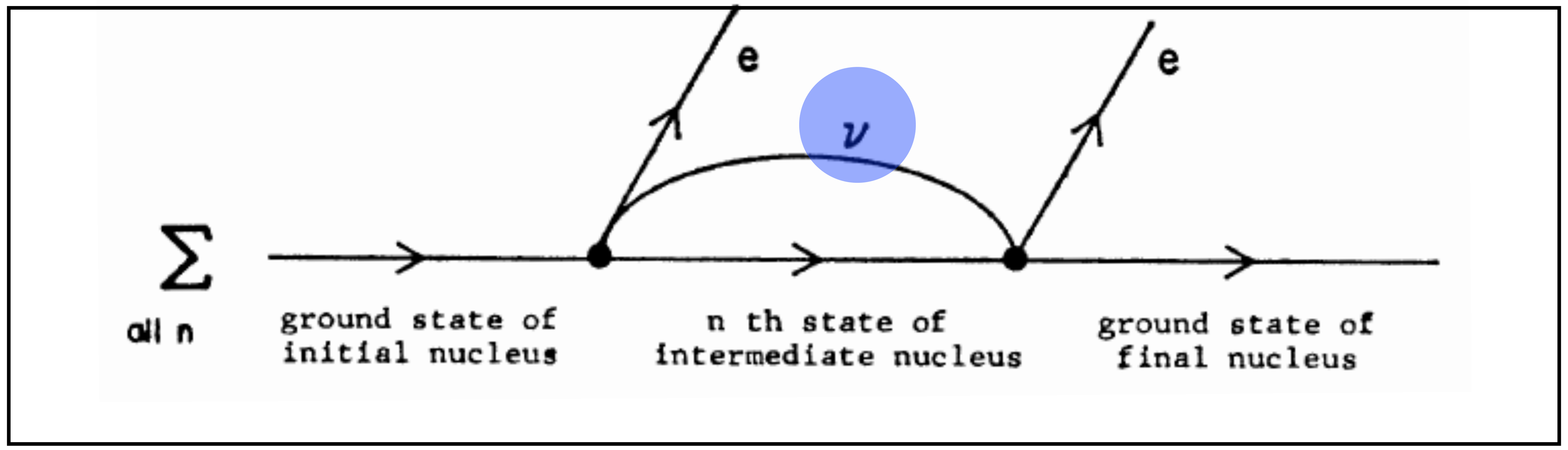
Complete set of QCD states

Quark-level weak currents

Connection with non-EFT approach

Figure adapted from Primakoff-Rosen 1969



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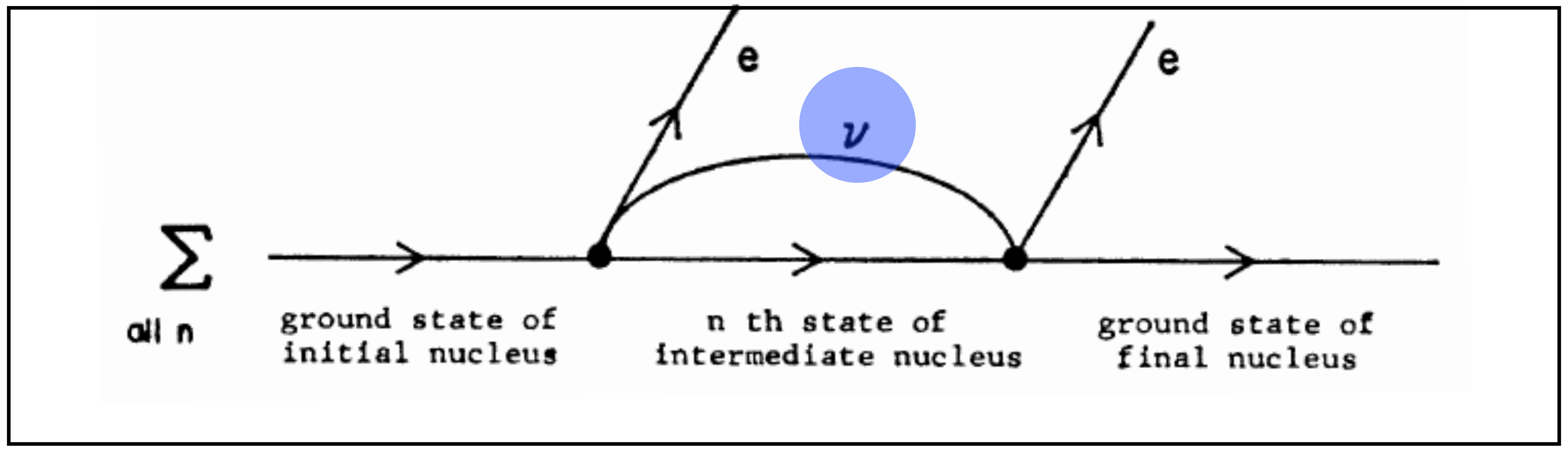
Complete set of QCD states

Quark-level weak currents

- Note: for hard, soft, and potential modes the 'closure approximation' is justified ($|\mathbf{k}| >> E_n - E_i + E_{ej}$)

Connection with non-EFT approach

Figure adapted from Primakoff-Rosen 1969



- Traditional approach uses this form *at the nucleon level*

$$\mathcal{A}_\nu \propto \sum_n \int \frac{d^3\mathbf{k}}{(2\pi)^3} \frac{1}{|\mathbf{k}|} \left[\frac{\langle f | J^L_\mu(\mathbf{k}) | n\rangle\langle n | J^{L\mu}(-\mathbf{k}) | i\rangle}{|\mathbf{k}| + (E_n - E_i + E_{e2})} + \frac{\langle f | J^L_\mu(\mathbf{k}) | n\rangle\langle n | J^{L\mu}(-\mathbf{k}) | i\rangle}{|\mathbf{k}| + (E_n - E_i + E_{e1})} \right]$$

Complete set of nuclear states

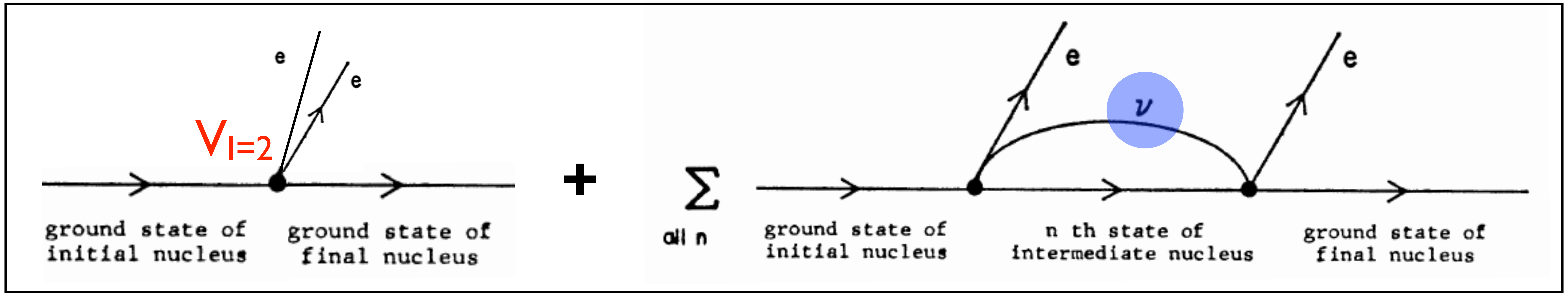
(Built as bound states of nucleons)

Nucleon-level weak currents

- Note: the sum over nuclear states cannot reproduce effect of hard modes, that probe different degrees of freedom!

Back to EFT

Figure adapted from Primakoff-Rosen 1969



Hard, soft, and potential ν

Ultrasoft ν

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$V_\nu \sim 1/Q^2$, $1/(\Lambda_\chi)^2$, …

LO N²LO

Loop calculable in terms of $E_n - E_i$ and $\langle f\,|J_\mu|n\rangle\langle n|J^\mu|i\rangle$, that also control 2νββ.

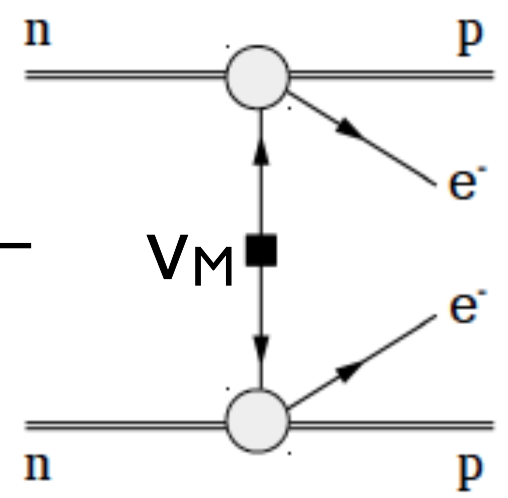
Contributes to the amplitude at N²LO

Key new insight from EFT

VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

- To leading order (LO) in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV), the nn → pp transition operator has *two contributions:*

'Usual' ν_M exchange $\sim 1/k_F^2 \sim 1/Q^2$
Coulomb-like long-range potential



Potential neutrino exchange

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

Hadronic input: g_A

Key new insight from EFT

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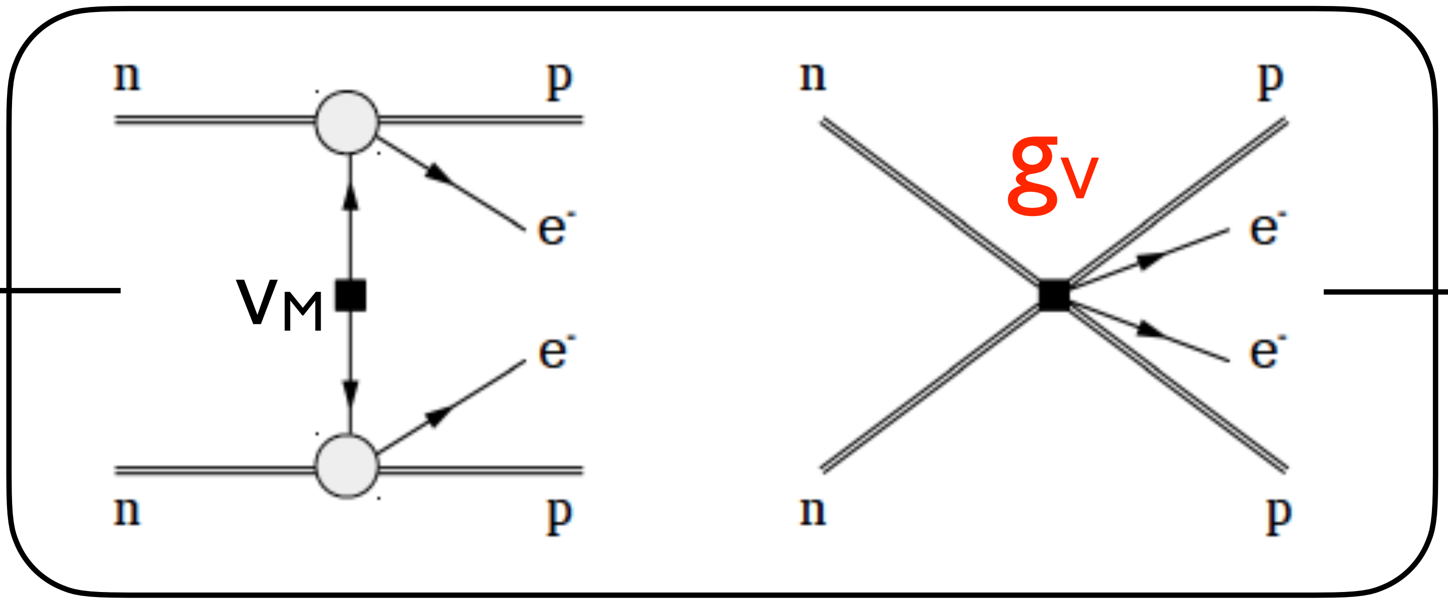
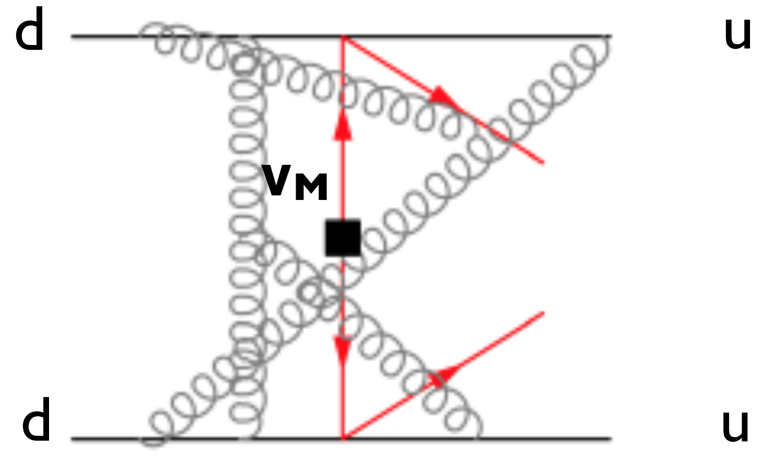


'New': short-range potential with coupling $g_\nu \sim 1/Q^2$



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Hadronic input: g_A

Hard neutrino exchange

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

$g_\nu \sim 1/Q^2 \gg 1/\Lambda_\chi^2 \sim 1/(4\pi F_\pi)^2$
(Much larger than estimate from Naive Dimensional Analysis)

Key new insight from EFT

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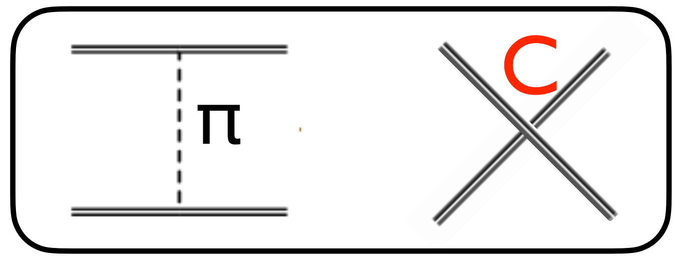
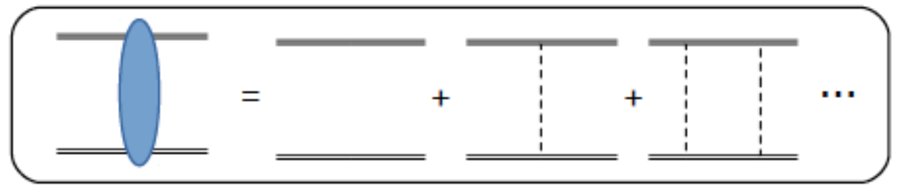
- To leading order (LO) in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV), the nn → pp transition operator has *two contributions:*

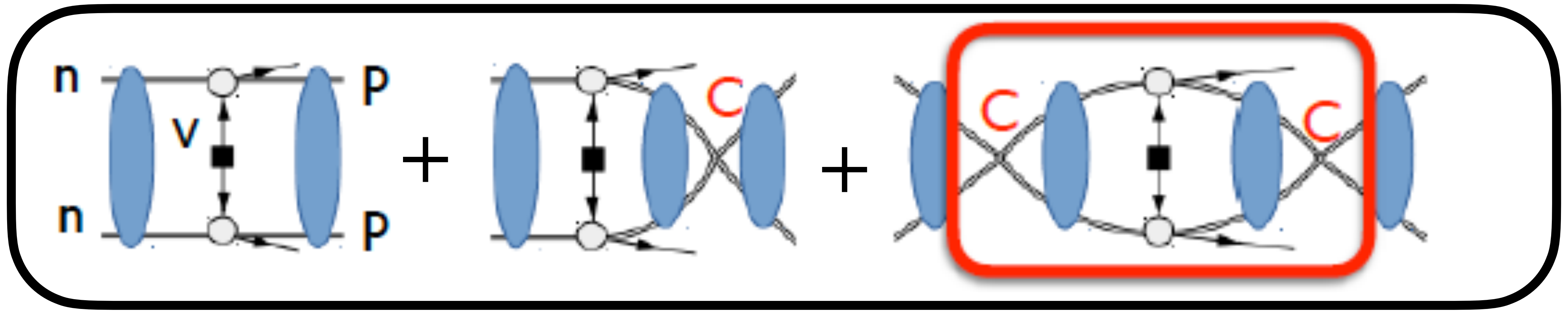
- LO contact term is required by renormalization of the $^1S_0$ nn→pp amplitude in presence of strong interactions

LO strong potential



$C \sim 4\pi/(m_N Q)$





$+\ldots$

UV divergence $\propto$ $(m_N C/4\pi)^2 \sim 1/Q^2$

Key new insight from EFT

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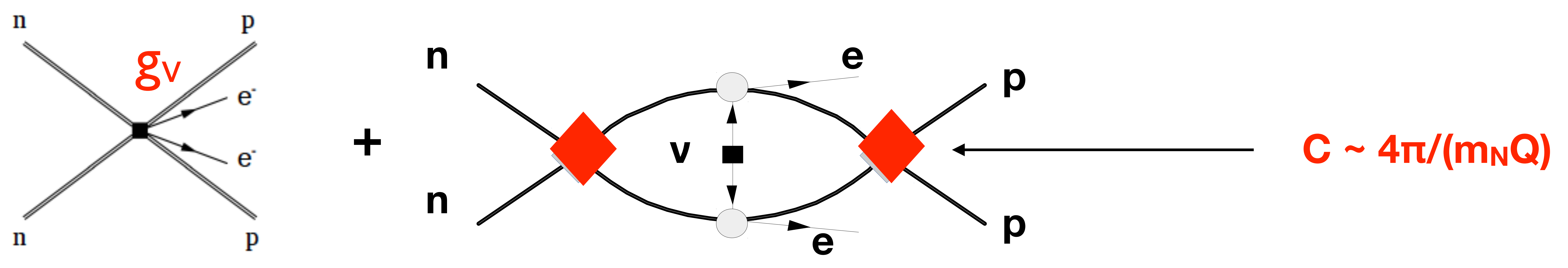
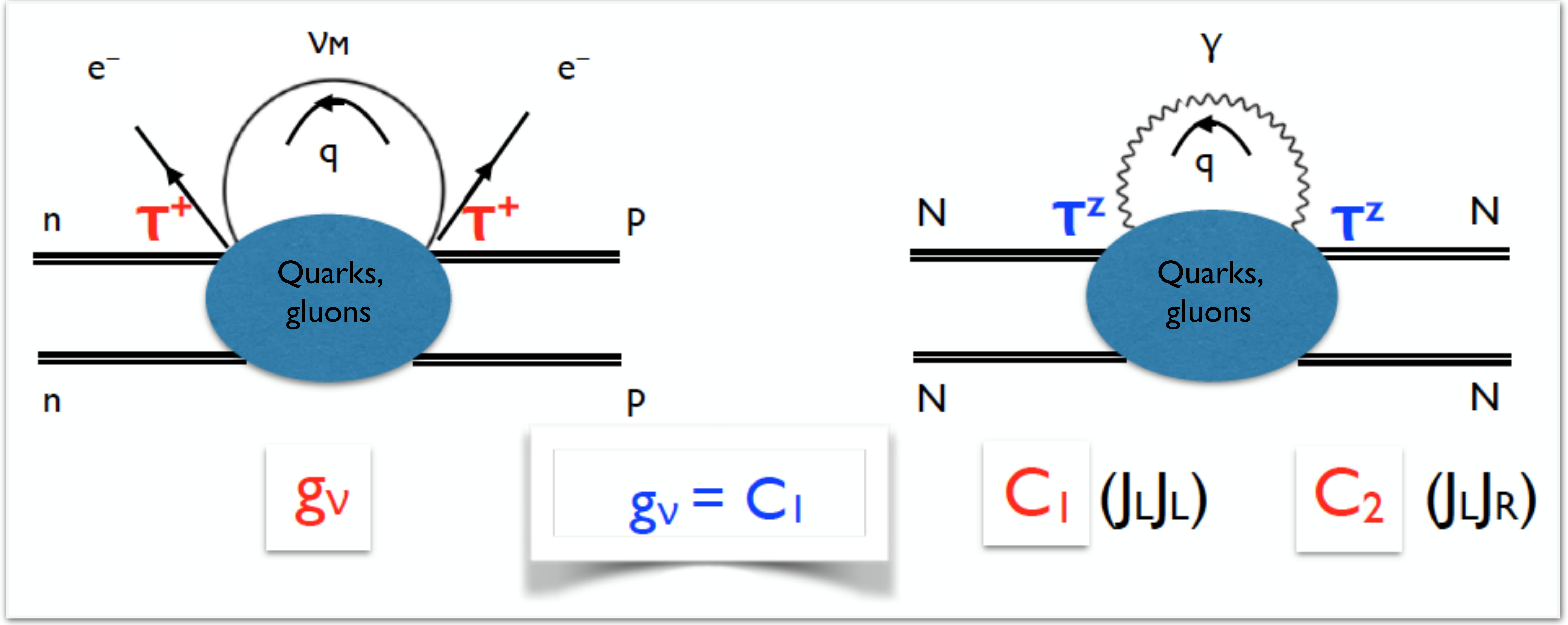
- Renormalization group running induced by short-range nuclear interaction in $^1S_0$ channel implies that the coupling flows to $g_V \sim 1/Q^2 \;>>\; 1/(4\pi F_\pi)^2$



Connection with data?

- Isospin symmetry relates g_V to one of two I=2 e.m. couplings (hard γ's versus hard ν's)

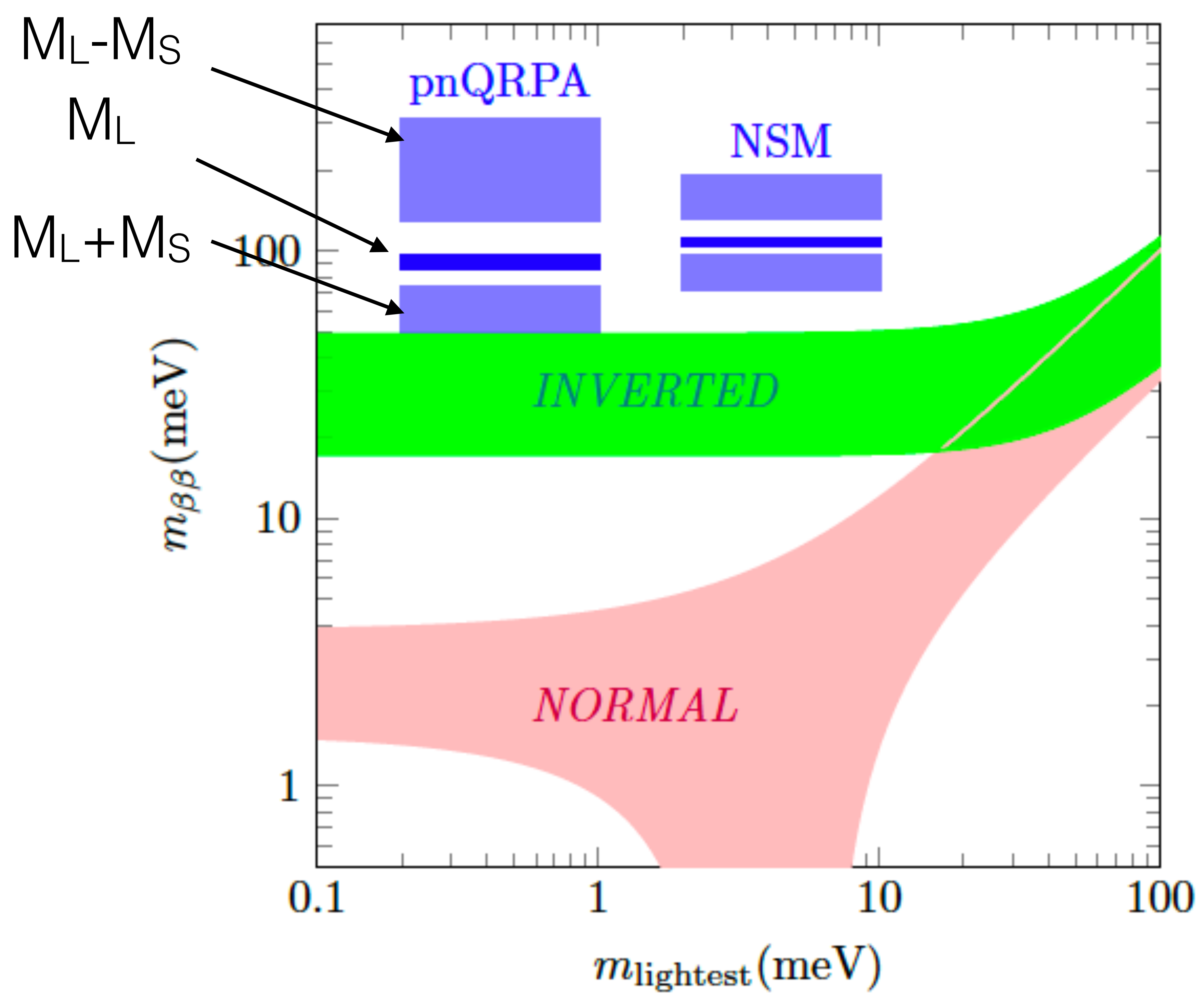


- NN scattering data at low energy ($a_{nn}+a_{pp}-2a_{np}$) determine C_1+C_2, confirming LO scaling!

Impact on nuclear matrix elements

- *Assuming* $g_V \sim (C_1+C_2)/2$ → O(1) impact on m.e. and $m_{\beta\beta}$ extraction

For ^{76}Ge:
30-70% effect in QRPA
and 15-45% in NSM.
Similar or large in other isotopes



Key question:
is the interference
constructive or
destructive?

Jokiniemi-Soriano-Menendez, 2107.13354

Impact on nuclear matrix elements

- *Assuming* $g_V \sim (C_1+C_2)/2$ $\rightarrow$ O(1) impact on m.e. and $m_{\beta\beta}$ extraction

- Several approaches to determine g_V

    - Large-N_C arguments point to $g_V \sim (C_1+C_2)/2$

      Richardson, Shindler, Pastore, Springer, 2102.02814

    - Lattice QCD — gearing up

      Tuo et al. 1909.13525; Detmold, Murphy 2004.07404

      Davoudi, Kadam, 2012.02083

    - Dispersive approach inspired by Cottingham formula for $\delta m_{p,n}$ (EM)

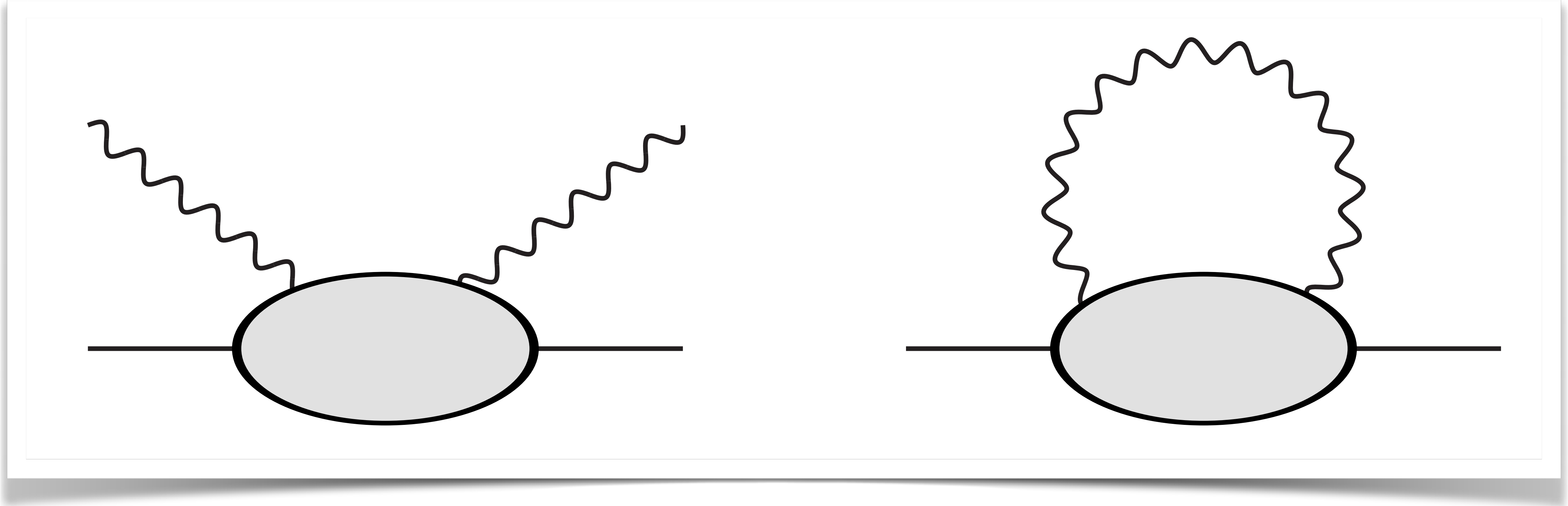
      VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Estimating the contact term

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Forward Compton amplitude

Self-energy ~ mass

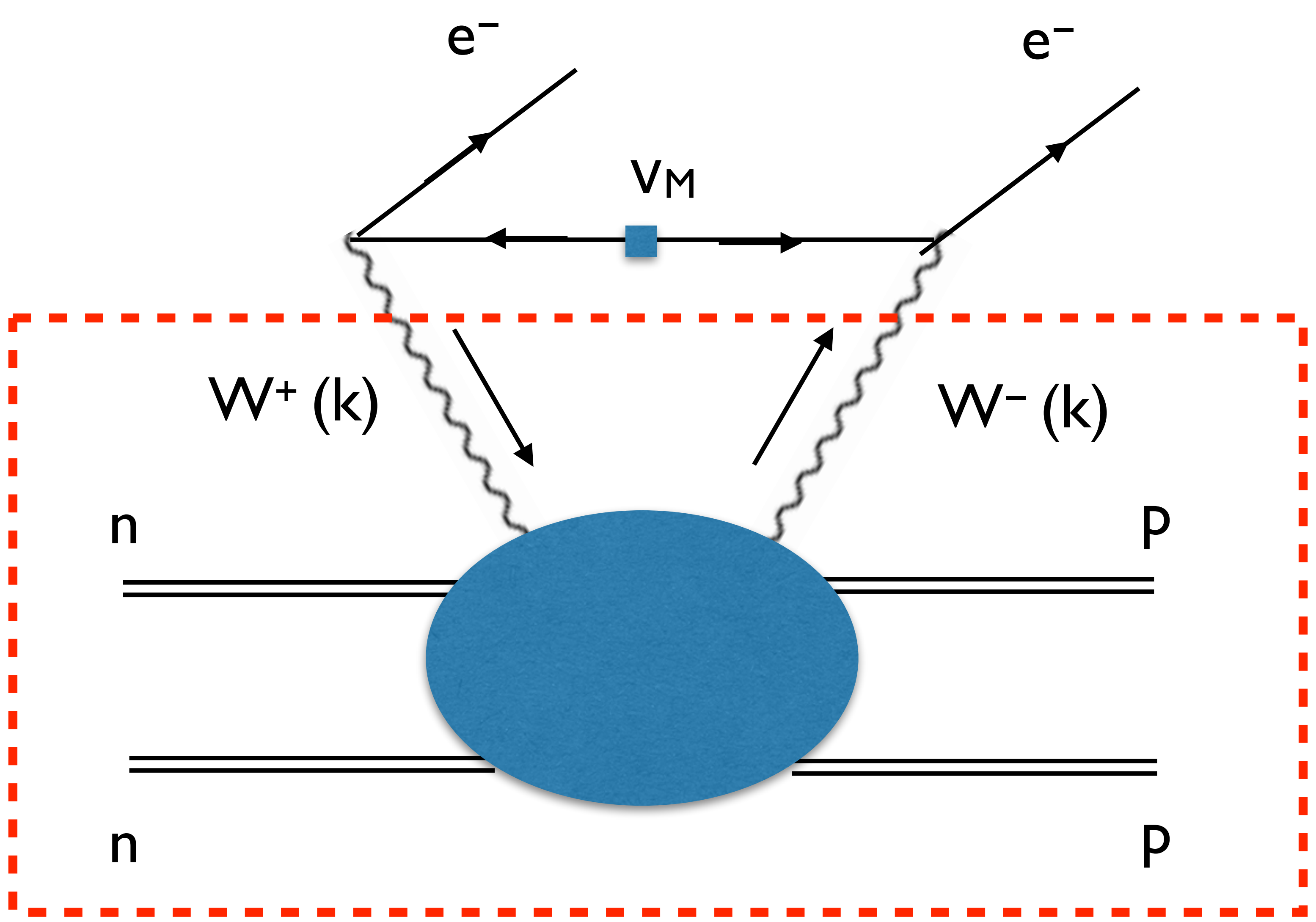


Cottingham (1963) approach to electromagnetic contributions to hadron masses

Estimating the contact term

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

nn → pp amplitude controlled by a forward "Compton" amplitude

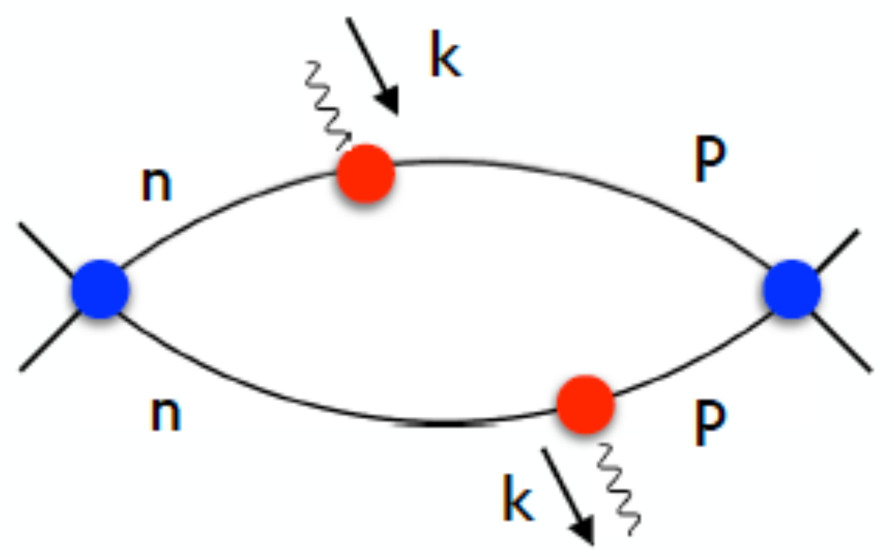


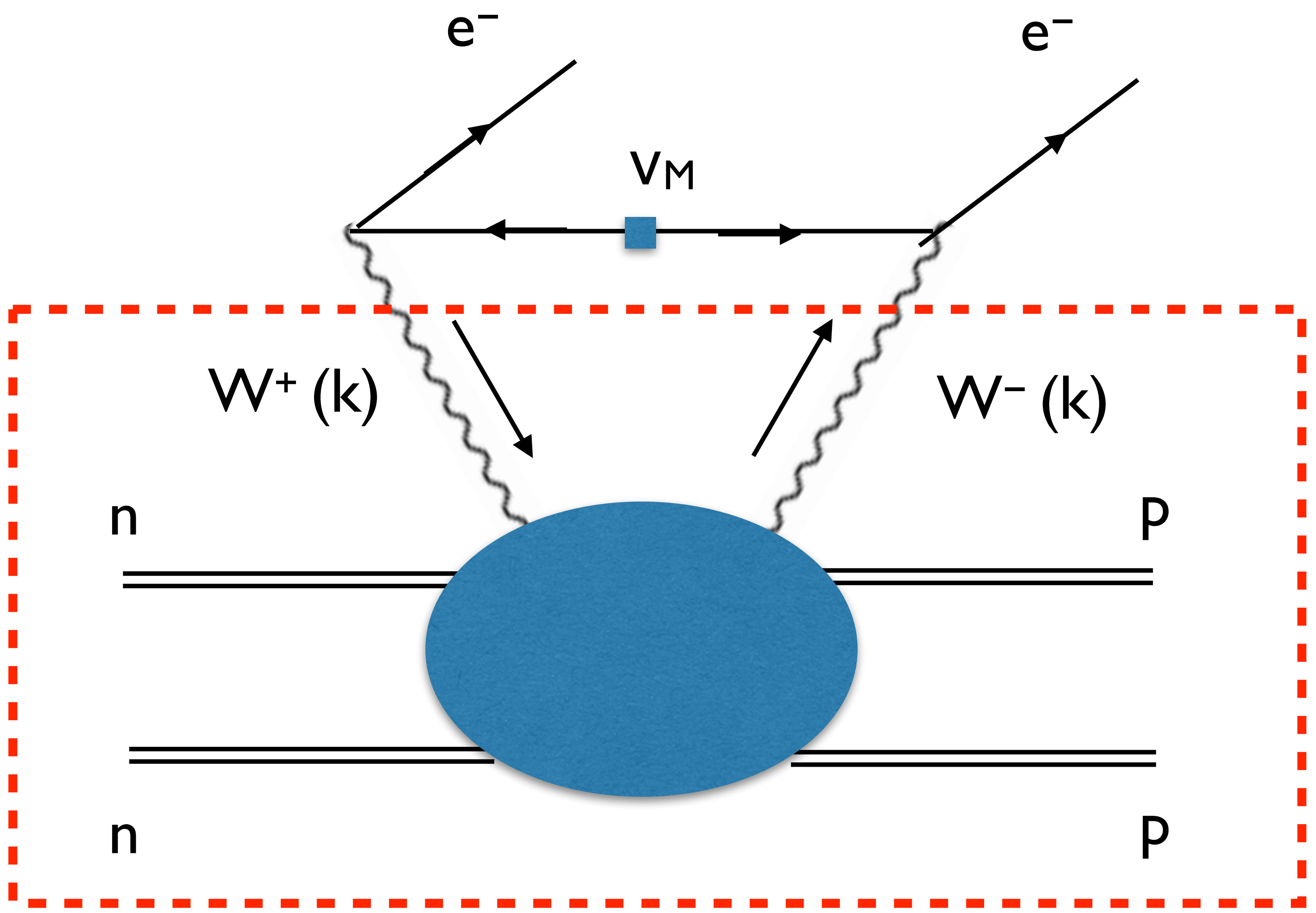
Estimating the contact term

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

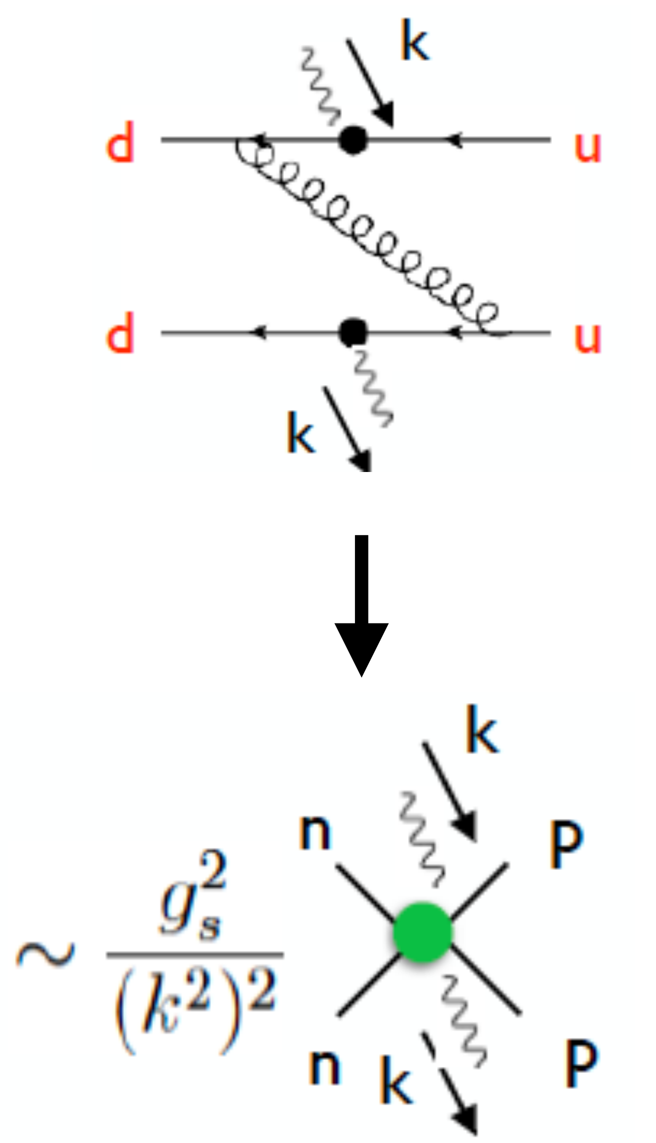
nn → pp amplitude controlled by a forward "Compton" amplitude

Low k: chiral EFT to NLO





High k: QCD OPE



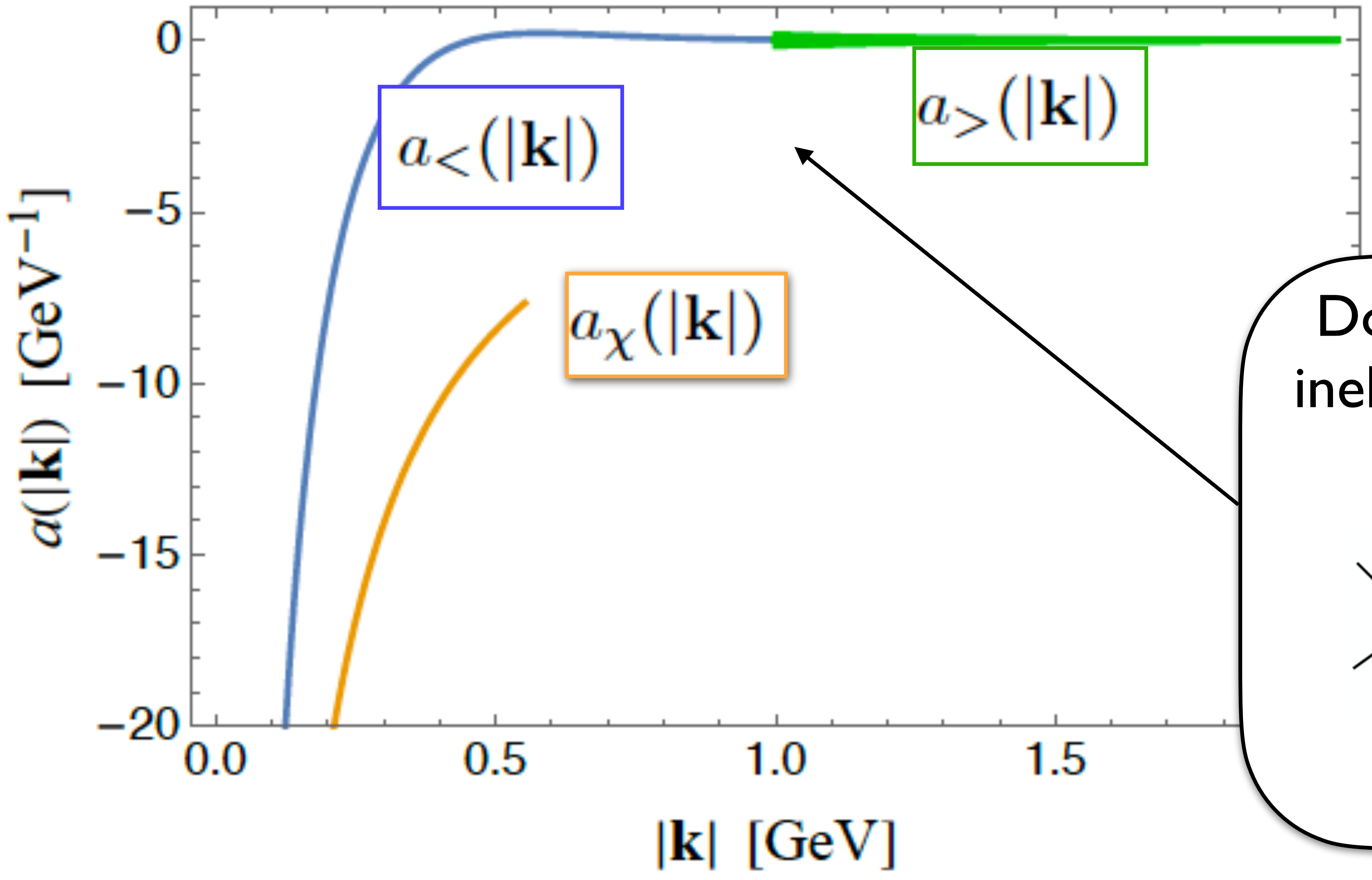
Intermediate k: resonance contributions in (blue) and (red),
πNN intermediate state, …

Estimating the contact term

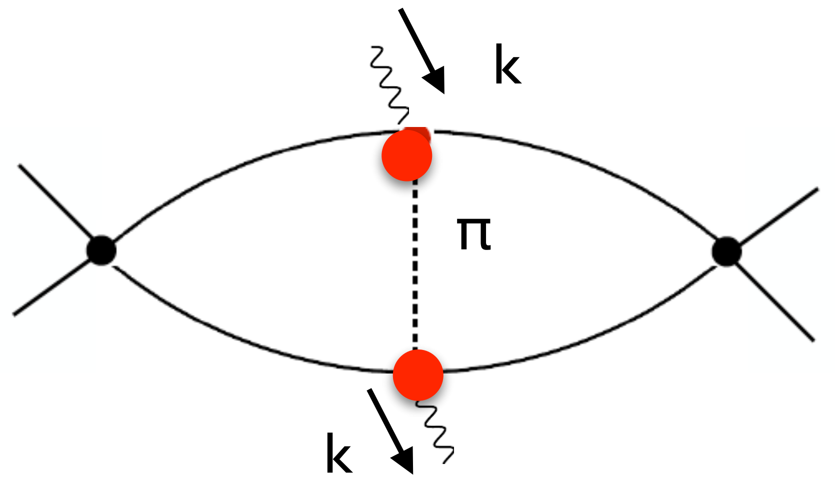
VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Determined g_V with ~30% uncertainty (validated with ΔI=2 NN electromagnetic coupling $C_1 + C_2$)

$$\mathcal{A}_\nu \propto \int_0^\Lambda d|\mathbf{k}|\ a_<(|\mathbf{k}|) + \int_\Lambda^\infty d|\mathbf{k}|\ a_>(|\mathbf{k}|)$$



Dominant uncertainty from inelastic channels (NNπ , …):



Impact of the contact term

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Determined g_V with ~30% uncertainty (validated with $\Delta I=2$ NN electromagnetic coupling)

↓

We provided 'synthetic data' for the $nn \to pp$ amplitude to be used to fit g_V in nuclear calculations

↓

Contact term fit to synthetic data and used in ab-initio calculations for

^{48}Ca [1], ^{130}Te [2], ^{136}Xe, [2], ^{76}Ge [3]

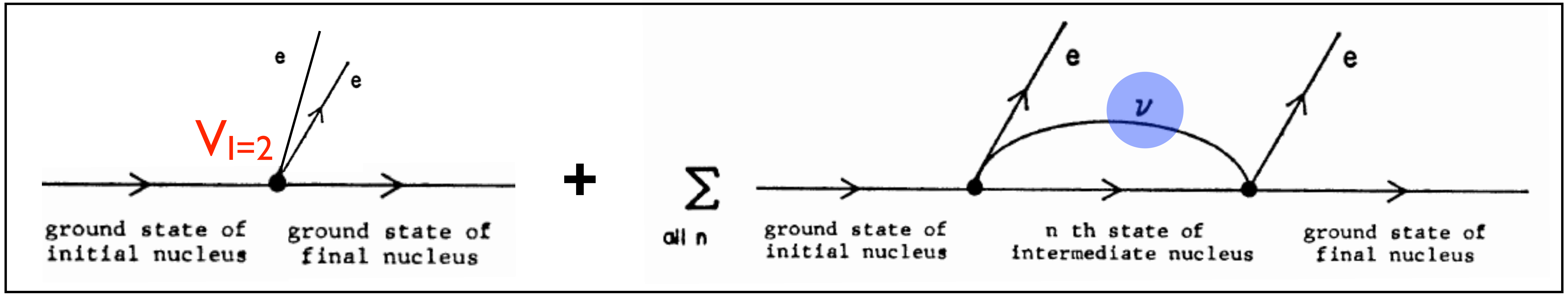
[2] Wirth, Yao, Hergert, 2105.05415 [3] Belley et al, 2307.15156 [4] Belley et al, 2308.15634

Enhances matrix elements by ~40% [Ca, Ge] and >50% [Te, Xe] —

good news for phenomenology, while we wait for Lattice QCD results

What about higher orders?

Figure adapted from Primakoff-Rosen 1969



Hard, soft, and potential ν

$$V_{I=2} = \sum_{a\neq b}\left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \dots\right)$$

$V_\nu \sim 1/Q^2$, $1/(\Lambda_\chi)^2, \dots$

LO N²LO

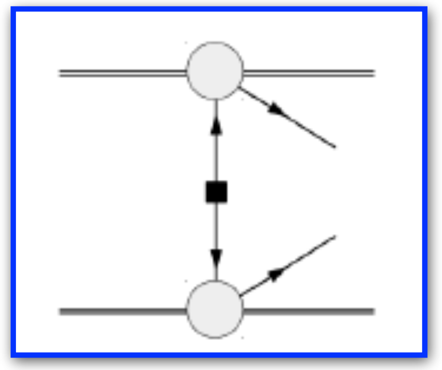
Ultrasoft ν

Loop calculable in terms of $E_n - E_i$ and $\langle f\, |J_\mu| n\rangle\langle n | J^\mu | i\rangle$, that also control 2νββ.

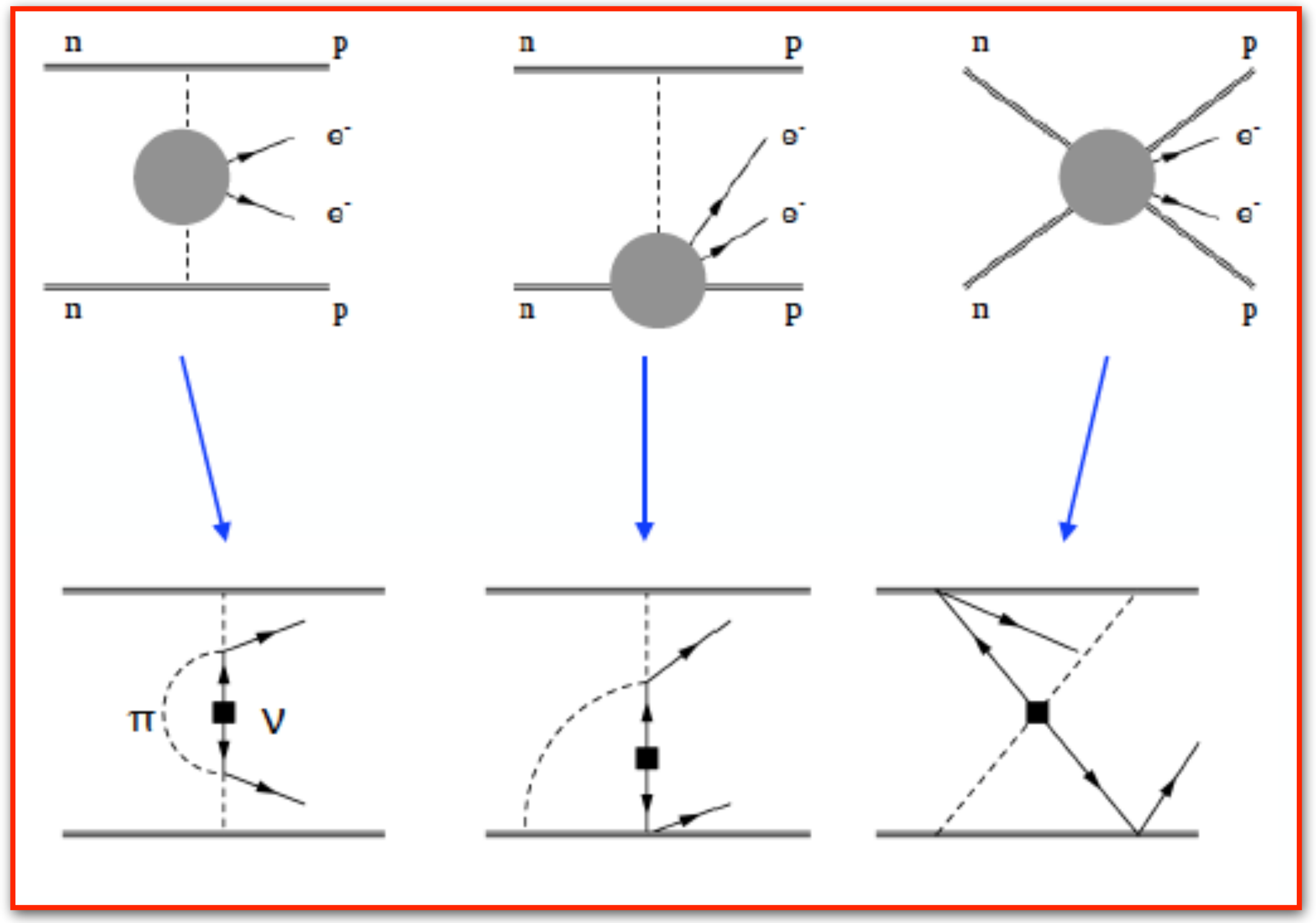
Contributes to the amplitude at N²LO

N^2LO $0\nu\beta\beta$ potential

- Known factorizable corrections to 1-body currents (radii, …)

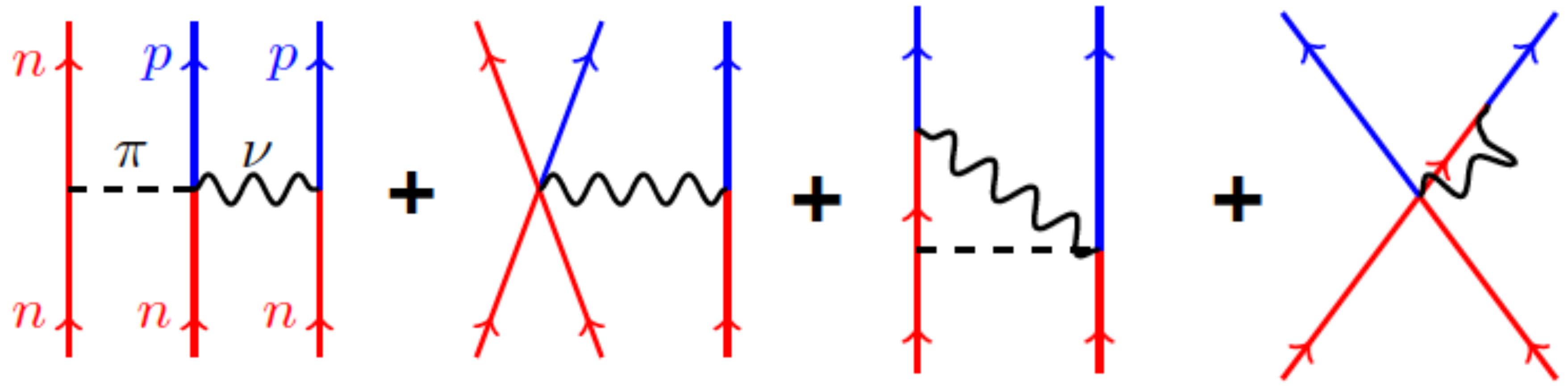


- Non-factorizable contributions to $V_{\nu,2} \sim V_{\nu,0}\,(k_F/4\pi F_\pi)^2$
  [π-N loops and new contact terms]



V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

- 2-body x 1-body current (and another contact…)



Wang-Engel-Yao 1805.10276

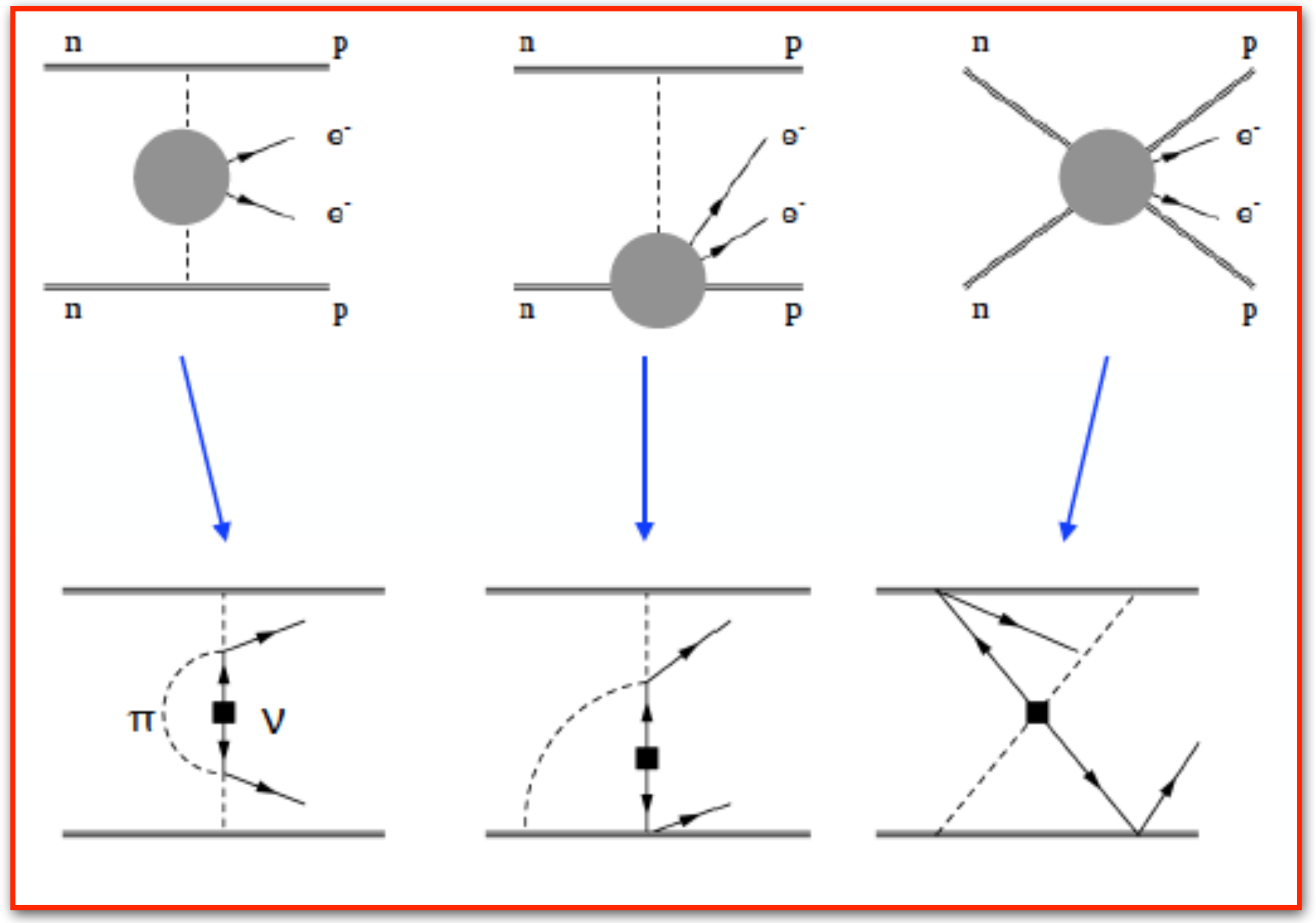
N^2LO $0\nu\beta\beta$ potential

Calculations of these effects in light and heavy nuclei show O(10%) corrections

S. Pastore, J. Carlson, V.C., W. Dekens, E. Mereghetti, R. Wiringa 1710.05026

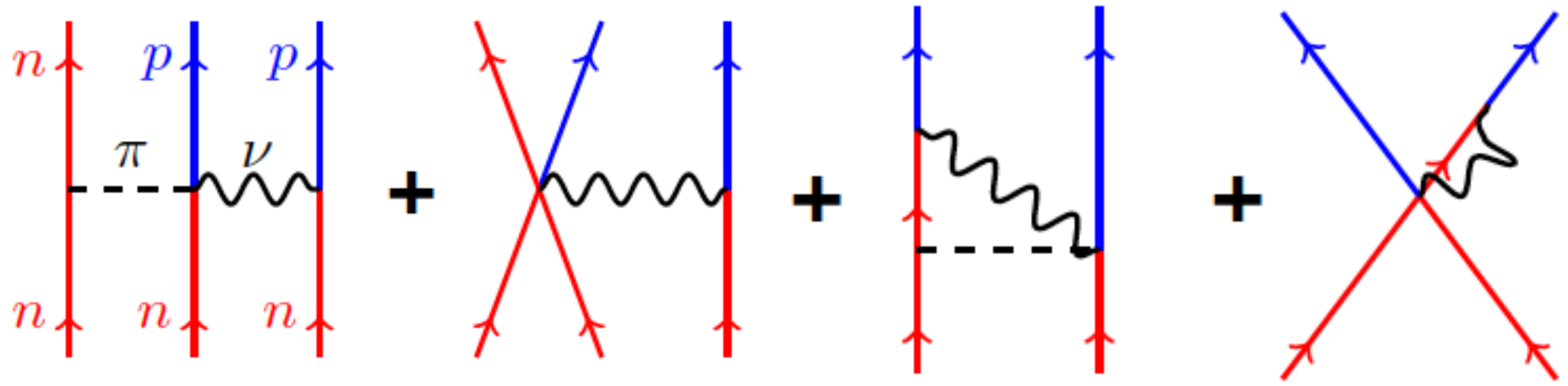
- Known fac

- Non-factorizable contributions to $V_{\nu,2} \sim V_{\nu,0}\,(k_F/4\pi F_\pi)^2$
  [π-N loops and new contact terms]



V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

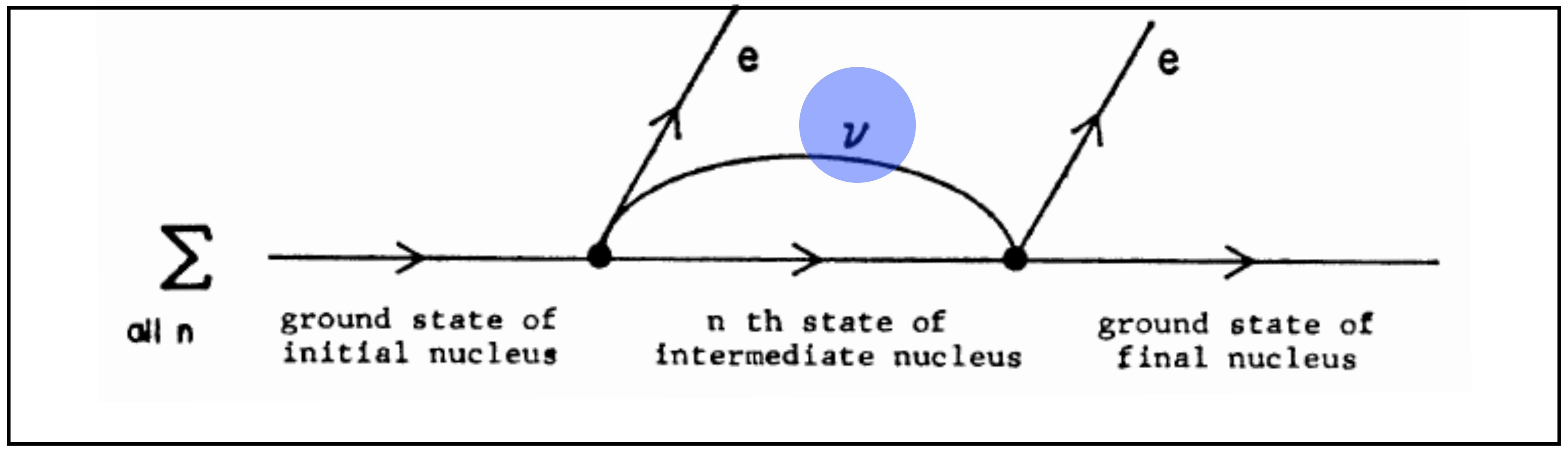
- 2-body **x** 1-body current (and another contact…)



Wang-Engel-Yao 1805.10276

Ultrasoft neutrino contributions

Figure adapted from Primakoff-Rosen 1969



$$T_{\mathrm{usoft}}(\mu_{\mathrm{us}}) = \frac{T_{\mathrm{lept}}}{8\pi^2} \sum_n \langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle \left\{ (E_2+E_n-E_i)\left(\log\frac{\mu_{\mathrm{us}}}{2(E_2+E_n-E_i)}+1\right)+1 \leftrightarrow 2\right\}$$

V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

- Ultrasoft ν's couple to *nuclear* states: sensitivity to $E_n - E_i$ and $\langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle$ (see also 2νββ amplitude)
- Ultrasoft ν loop suppressed by $(E_n - E_i)/(4\pi k_F) \sim (Q/\Lambda_\chi)^2 \rightarrow$ N2LO contribution. This scaling is consistent with previous studies of the closure approximation

Sen'kov-Horoi 1310.3254 , Wang-Zhao-Meng 2105.02649

- μ_{us} dependence cancels with $V_{\nu,2}$: consistency check

Progress in controlling all uncertainties

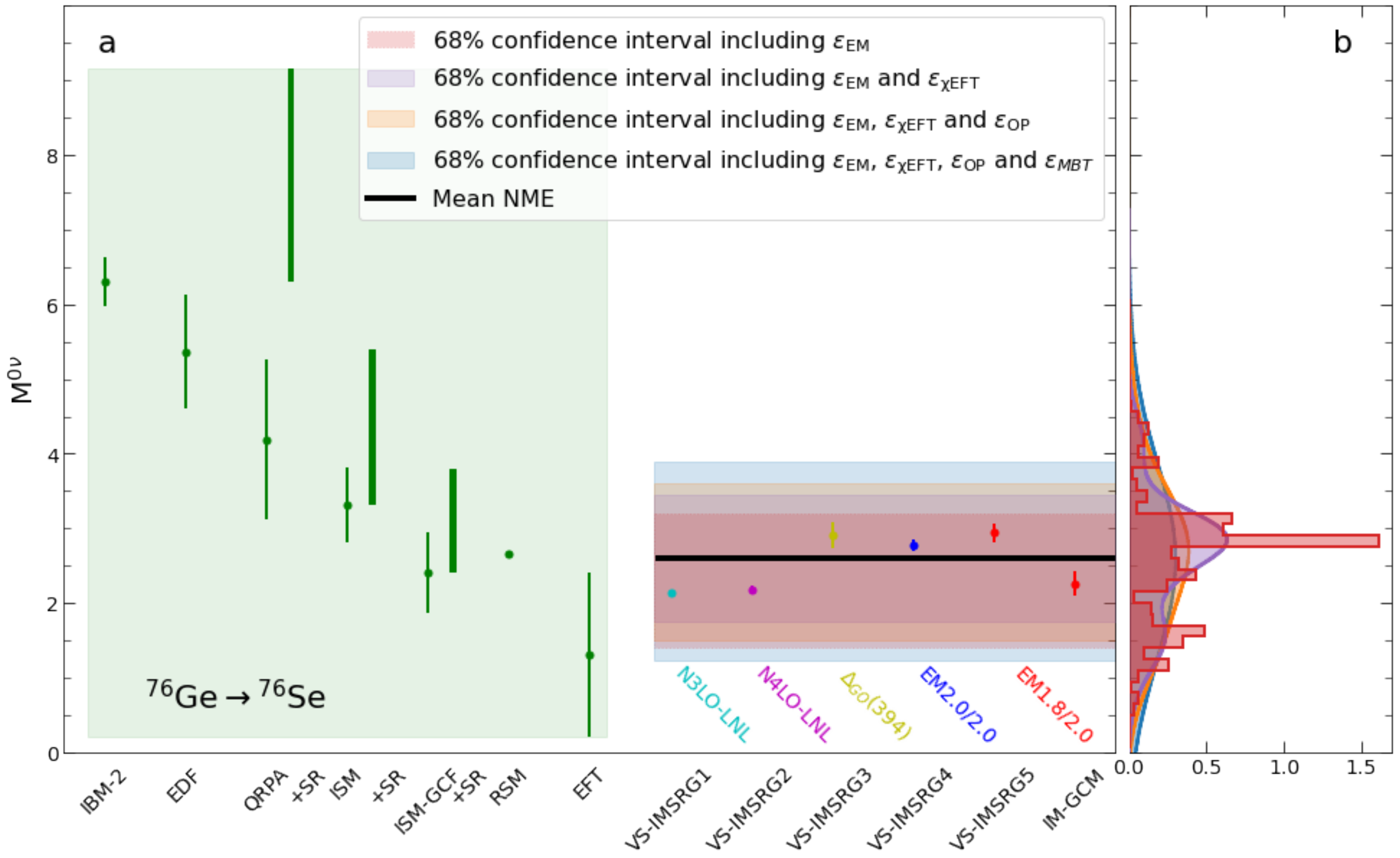
- Several first-principles many-body methods are being used for the calculation of matrix elements
- Sources of quantifiable uncertainty:
    - EFT for nuclear force (effective couplings, convergence, …)
    - Transition operator (contact term, closure approximation, …)
    - Truncations in many-body methods

$M^{0\nu}$	ϵ_{LEC}	$\epsilon_{\chi\text{EFT}}$	ϵ_{MBT}	ϵ_{OP}
$2.60^{+1.28}_{-1.36}$	0.75	0.3	0.88	0.47

- Overall uncertainty still sizable but improvable
- Smaller results compared to nuclear models.
- This input + LEGEND-200 result: $\boxed{m_{\beta\beta} < 320 \text{ meV}}$

LEGEND-200: 2505.10440

Belley et al, 2308.15634 and references therein



Various nuclear models

'Ab initio' methods using different chiral interactions

Backup

Contact term: results & validation

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

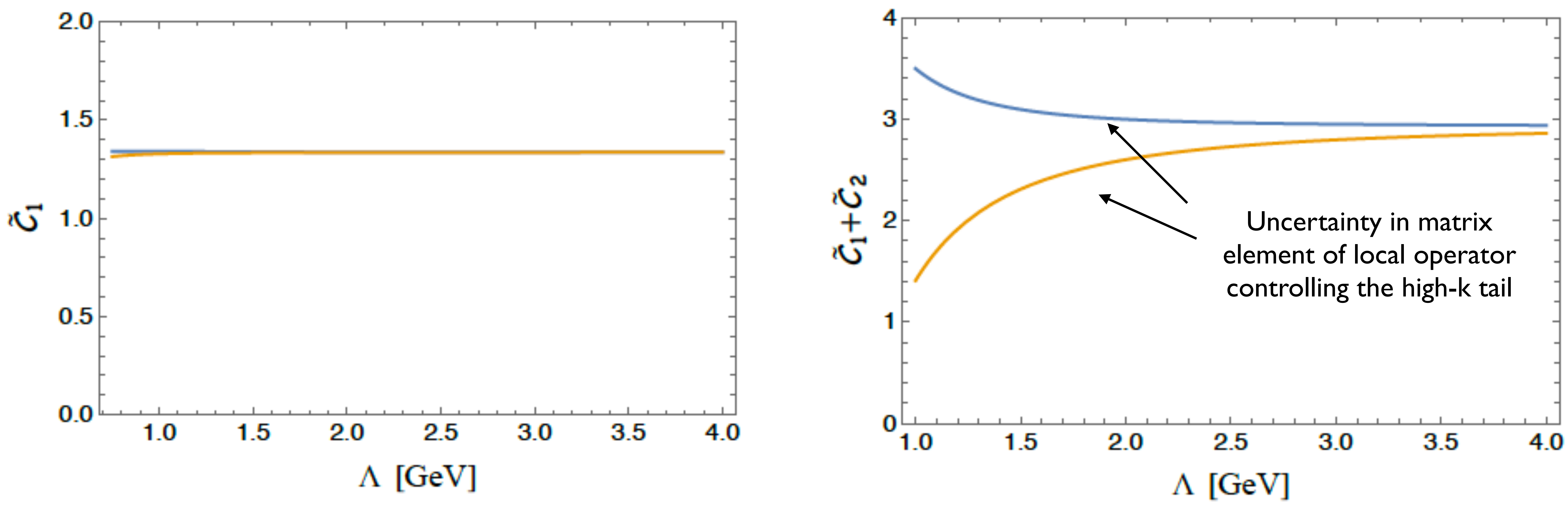
- LECs in dim. reg. with modified minimal subtraction

$$\tilde{\mathcal{C}}_1(\mu_\chi = M_\pi) = 1.3(6)$$

$$(\tilde{\mathcal{C}}_1 + \tilde{\mathcal{C}}_2)(\mu_\chi = M_\pi) = 2.9(1.2)$$

$$C_{1,2} = \left(\frac{m_N C_{^1S_0}}{4\pi}\right)^2 \tilde{\mathcal{C}}_{1,2}$$

$$g_\nu = C_1$$



Contact term: results & validation

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

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$$C_{1,2} = \left(\frac{m_N C_{^1S_0}}{4\pi}\right)^2 \tilde{\mathcal{C}}_{1,2}$$

$$g_\nu = C_1$$

- Validation: use C_1+C_2 to predict CIB scattering lengths to LO in χEFT

$$a_{\rm CIB} = \frac{a_{nn} + a_{pp}^C}{2} - a_{np} = 15.5^{+4.5}_{-4.0}\ \text{fm}$$ vs $10.4(2)$ fm, from data

Fairly good agreement.

Note: $(C_1+C_2)(M_\pi)=0$ → $a_{\rm CIB}$ ~ 30 fm: contact term pushes result in the right direction.

Uncertainty estimate is realistic

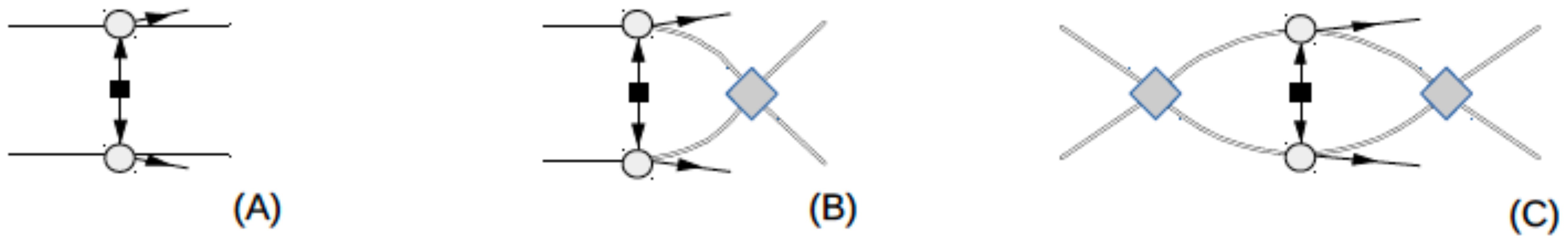
Connecting to nuclear structure

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Provided 'synthetic data' for the nn→pp amplitude to be used to fit g_V with regulators suitable for many-body nuclear calculations

$$|\mathbf{p}| = 25\,\mathrm{MeV} \qquad |\mathbf{p}'| = 30\,\mathrm{MeV}$$

$$\boxed{\mathcal{A}_\nu(|\mathbf{p}|, |\mathbf{p}'|)e^{-i(\delta_{{}^1S_0}(|\mathbf{p}|)+\delta_{{}^1S_0}(|\mathbf{p}'|))} = -0.0195(5)\,\mathrm{MeV}^{-2}}$$



Uncertainty dominated by topology C (fractional error of ~30-40%),
but A and B give large contribution to the amplitude at this kinematic point

Connecting to nuclear structure

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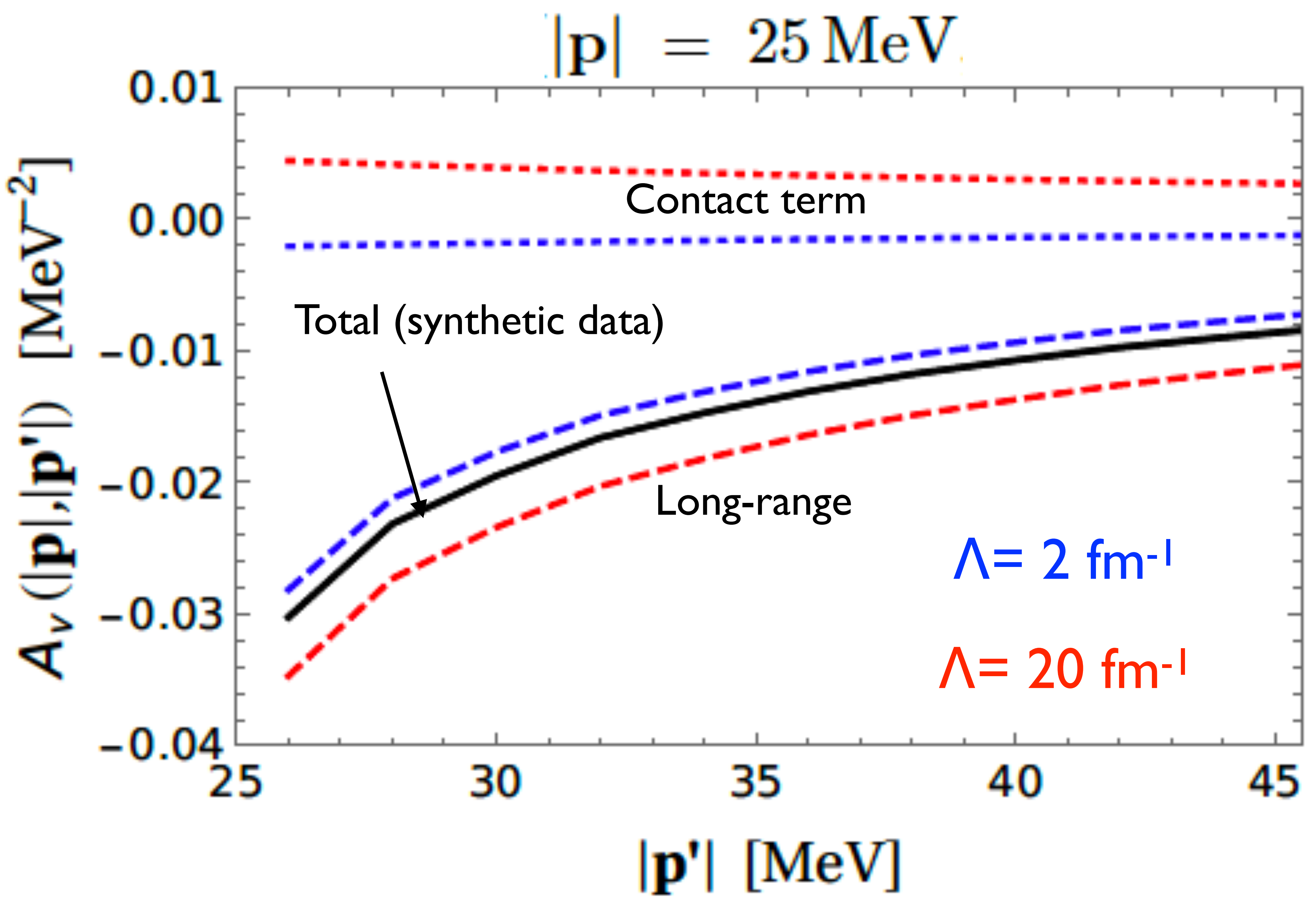
- Illustrated fitting procedure with various cutoffs

- Constructive or destructive? The sign of the interference is regulator dependent!



Matrix elements for ^{130}Te and ^{136}Xe

Belley, Miyagi, Stroberg, Holt., 2307.15156

- 'Ab-initio' results (VS-IMSRG) tend to be systematically lower than phenomenological nuclear models, with signifiant impact on the interpretation of current and future experiments in terms of $m_{\beta\beta}$