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

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Office of Science

UNIVERSITY of WASHINGTON

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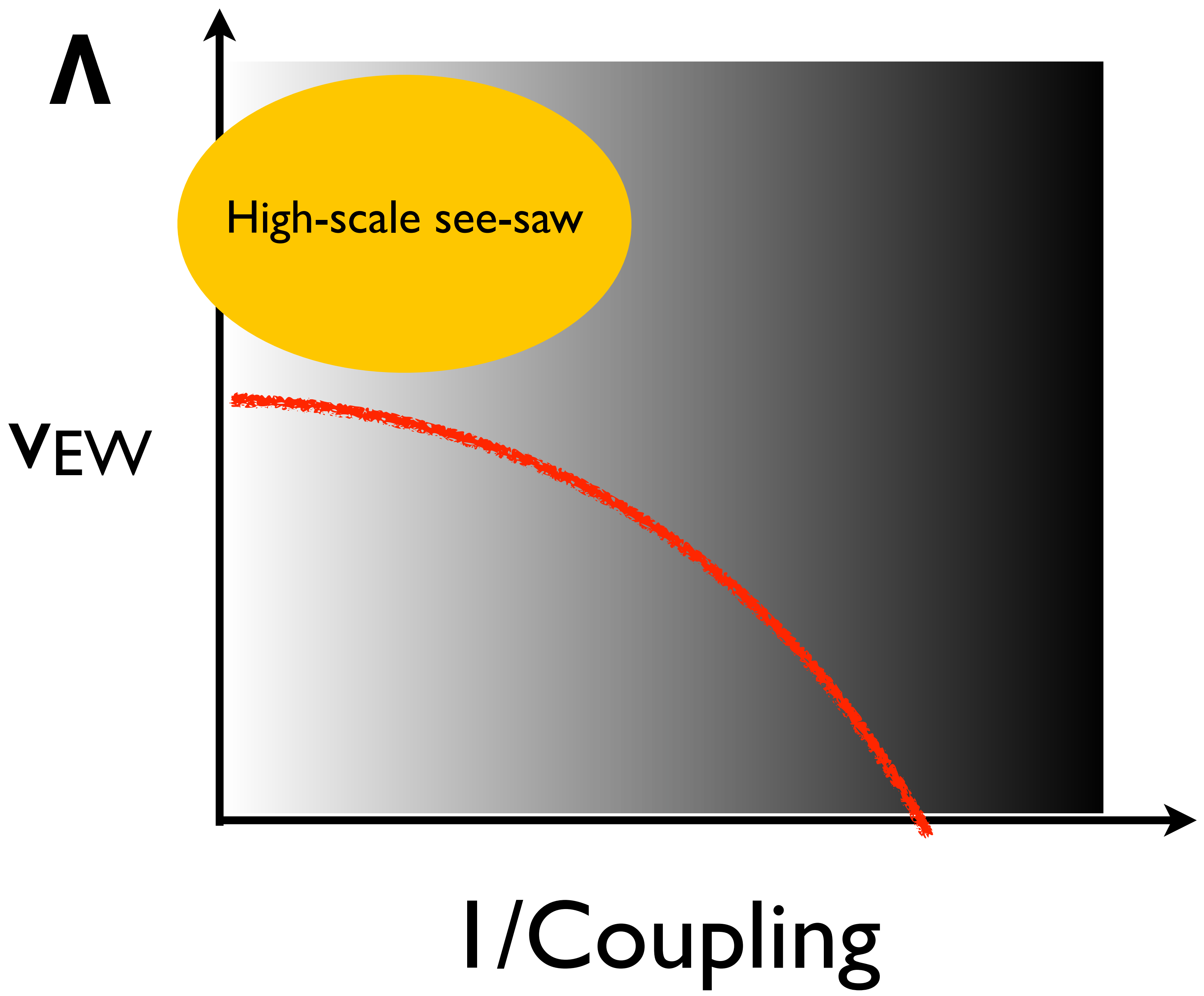
0νββ from high-scale LNV (dim-5 operator)

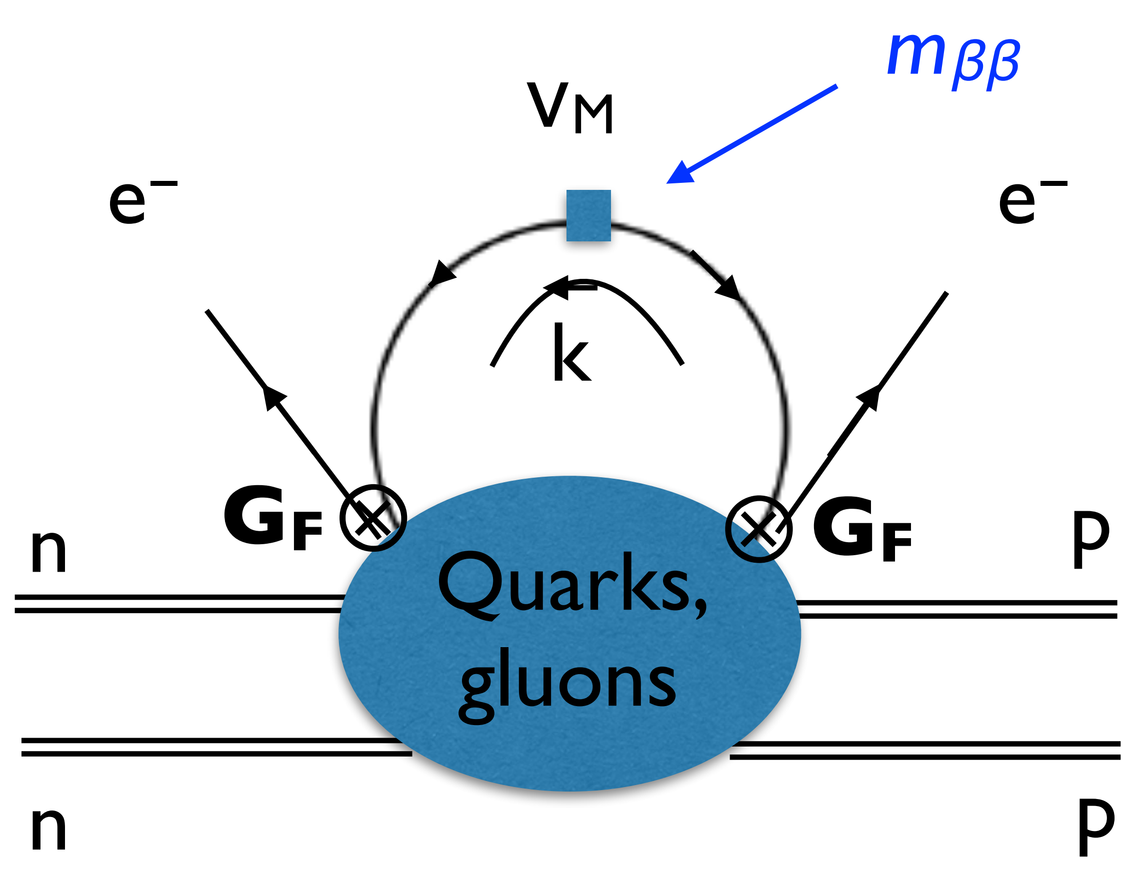


Hadronic ΔL=2 amplitudes in EFT

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

E < M_W

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



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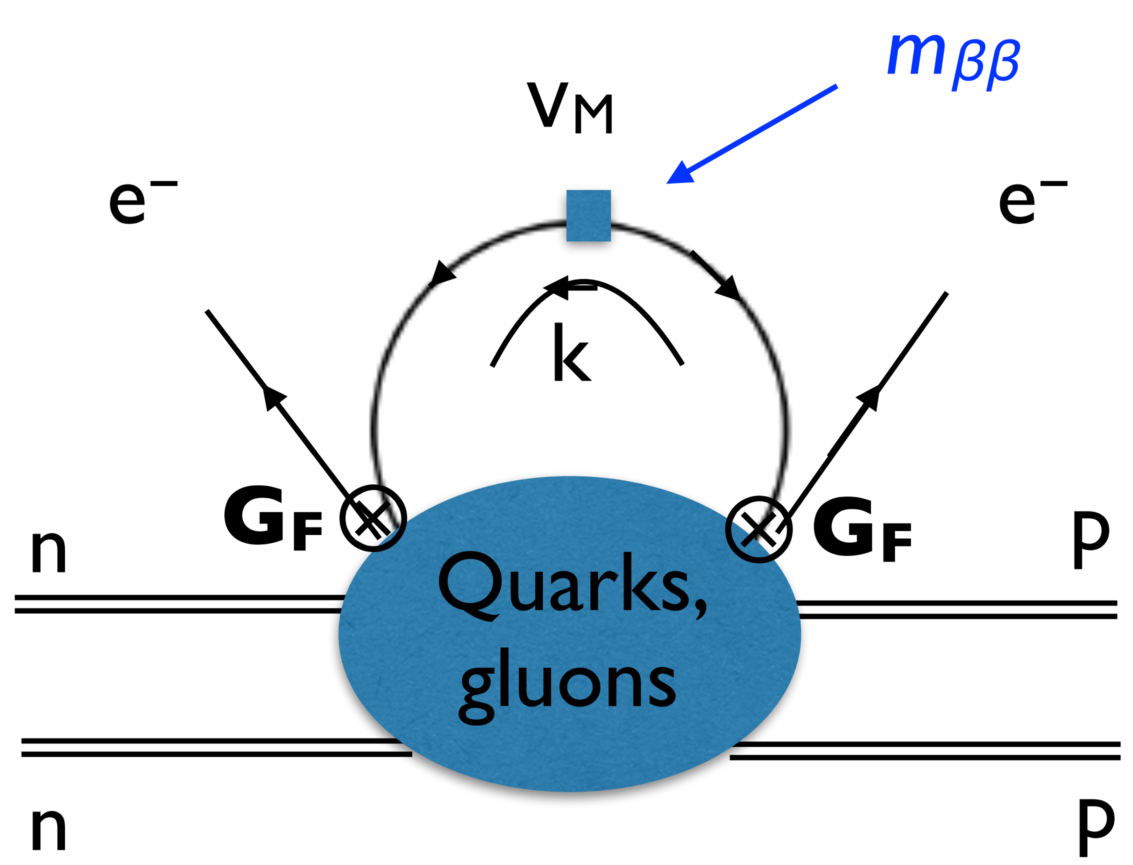
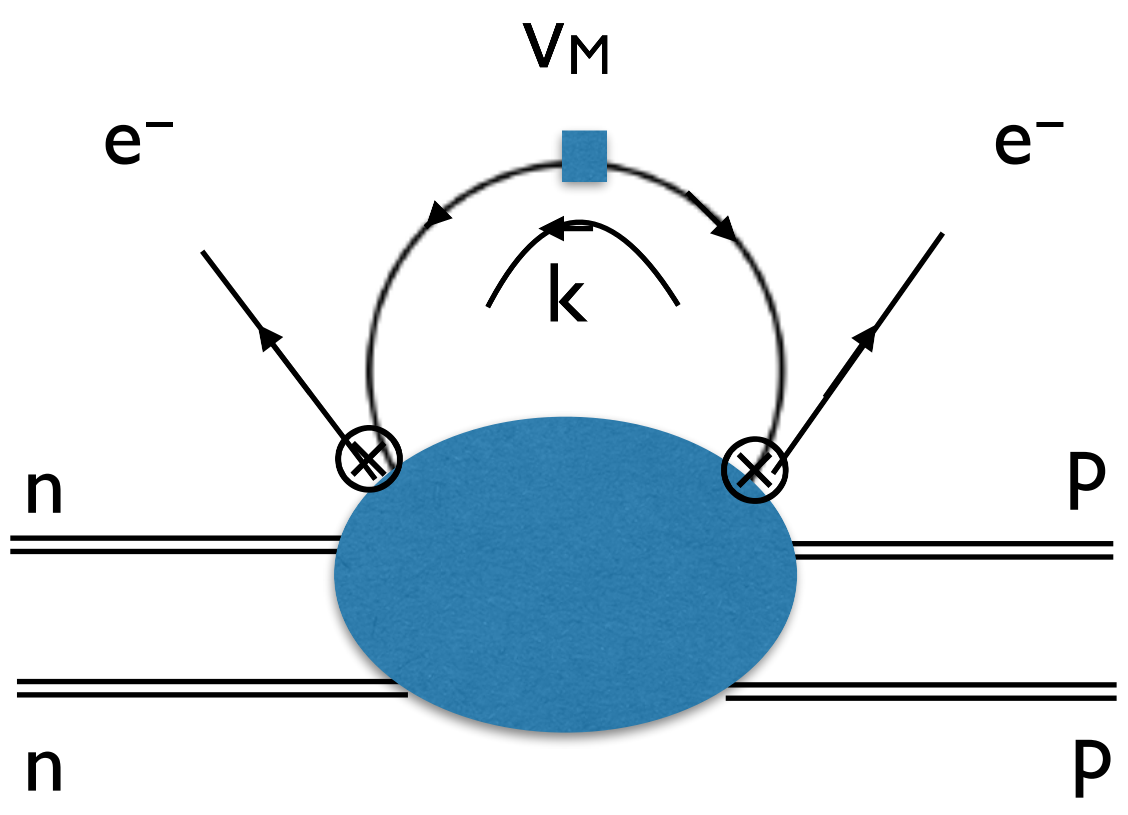
LNV hadronic amplitudes such as nn → ppee in principle receive contributions from neutrinos of all virtualities (k)



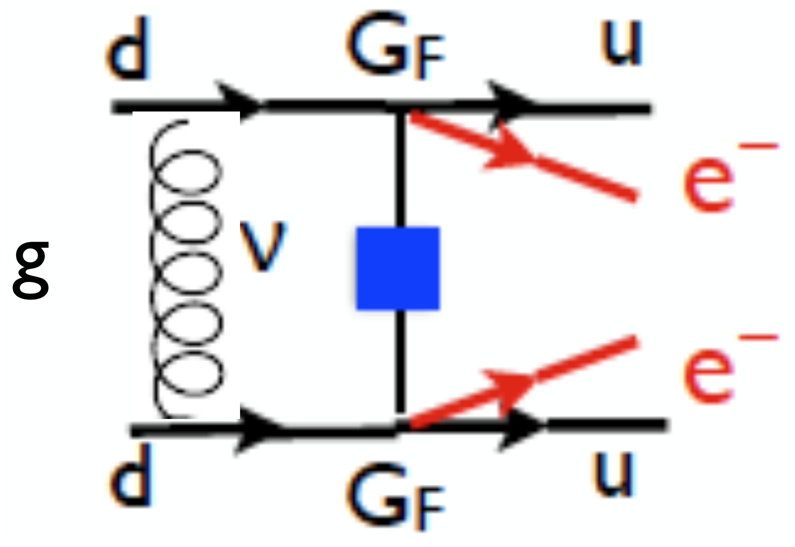
Chiral EFT captures contributions from all relevant momentum regions

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

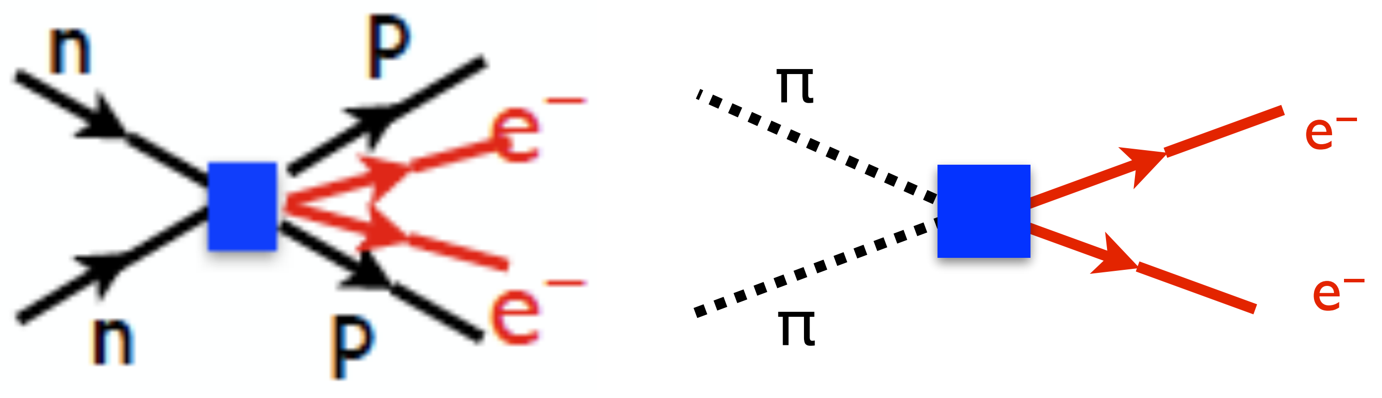
Classifying contributions



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



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



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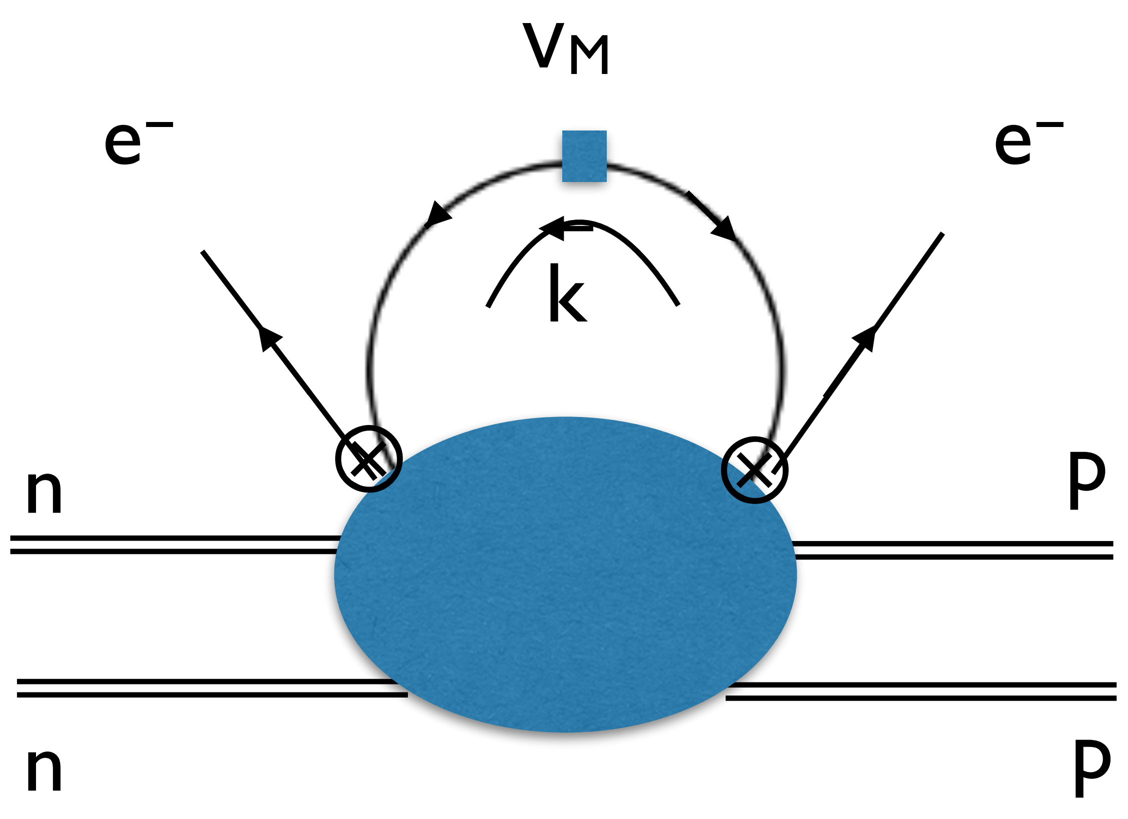

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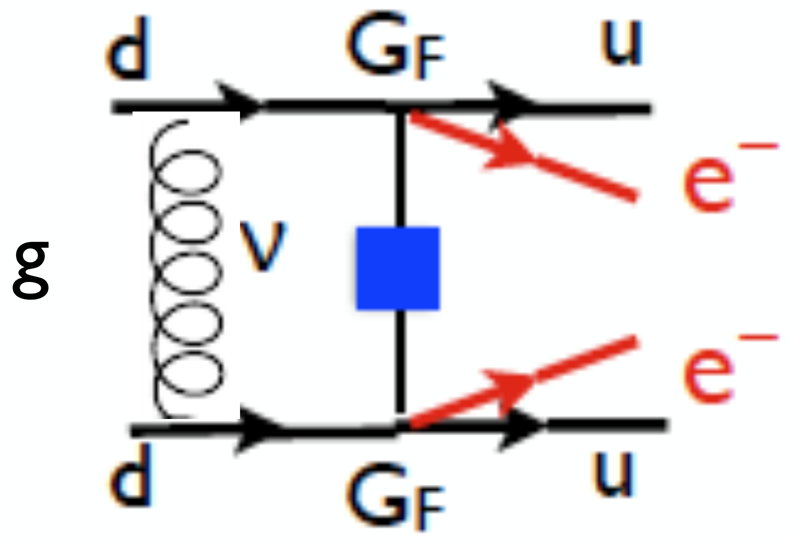

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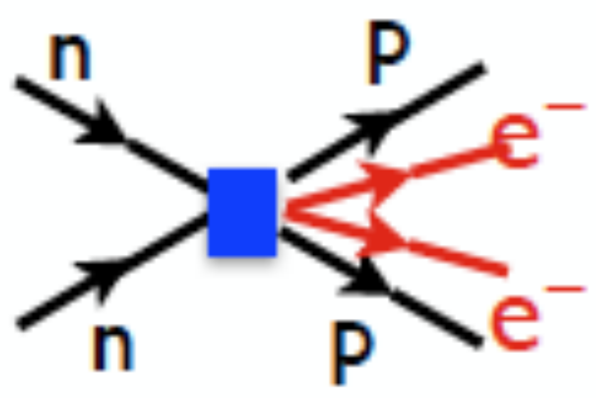
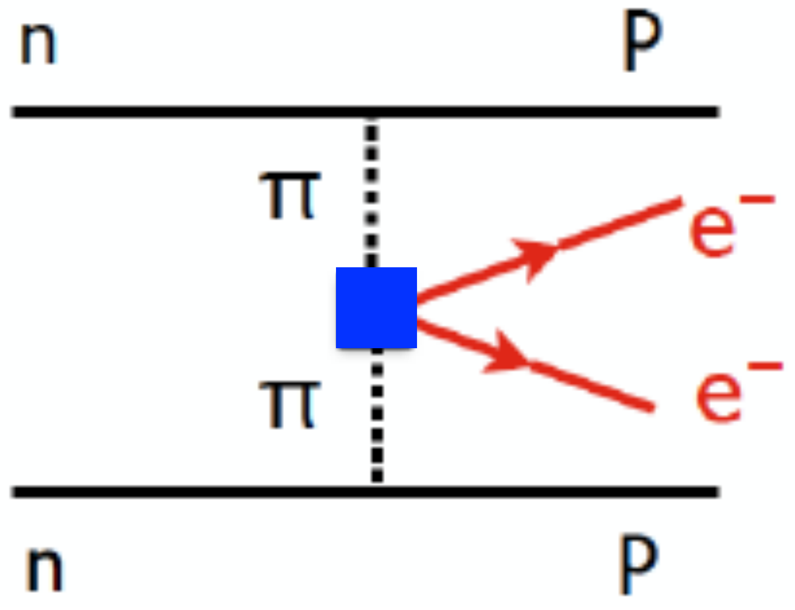
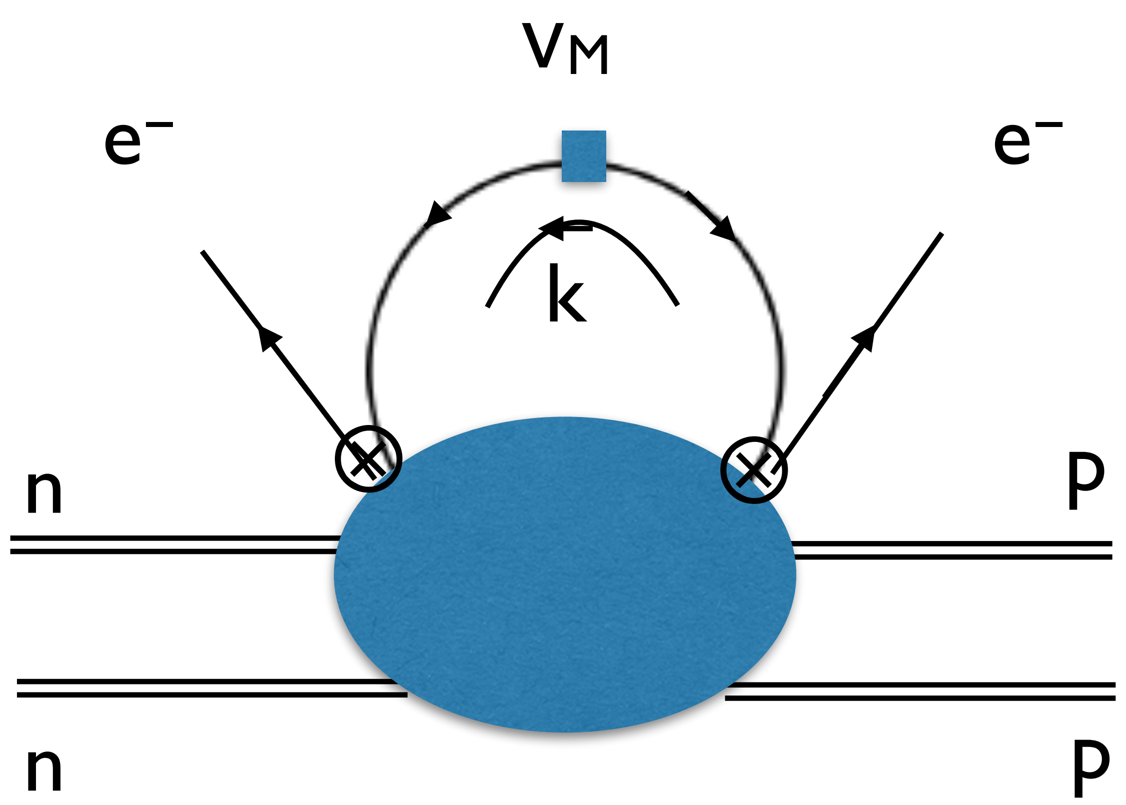




Short- and pion-range contributions to
"Neutrino potential" mediating nn→pp

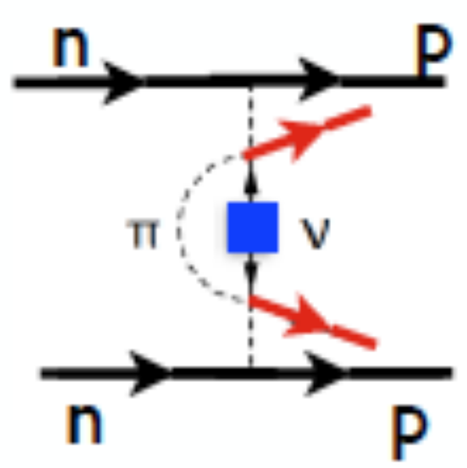
Classifying contributions

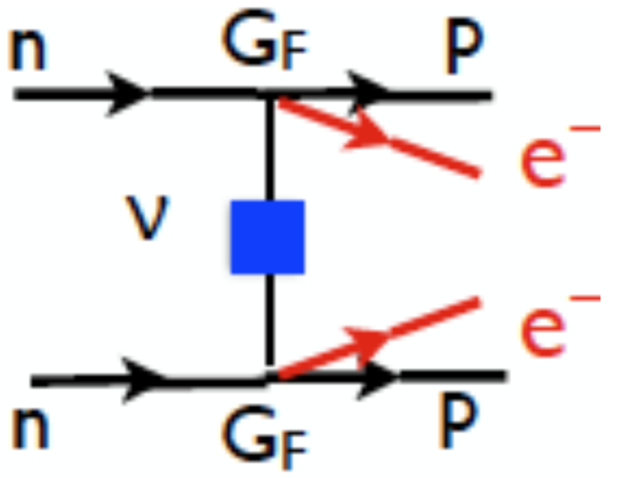


“Soft” & “Potential” neutrinos:

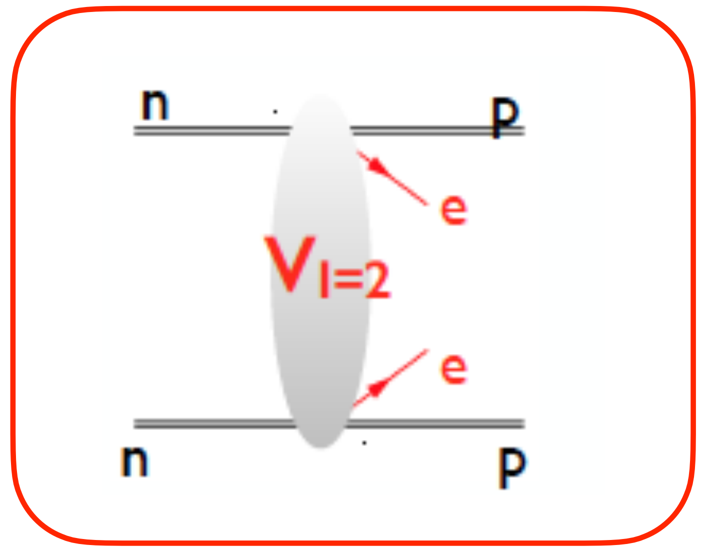
Soft: $(k^0, |\mathbf{k}|) \sim Q \sim k_F \sim m_\pi$

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



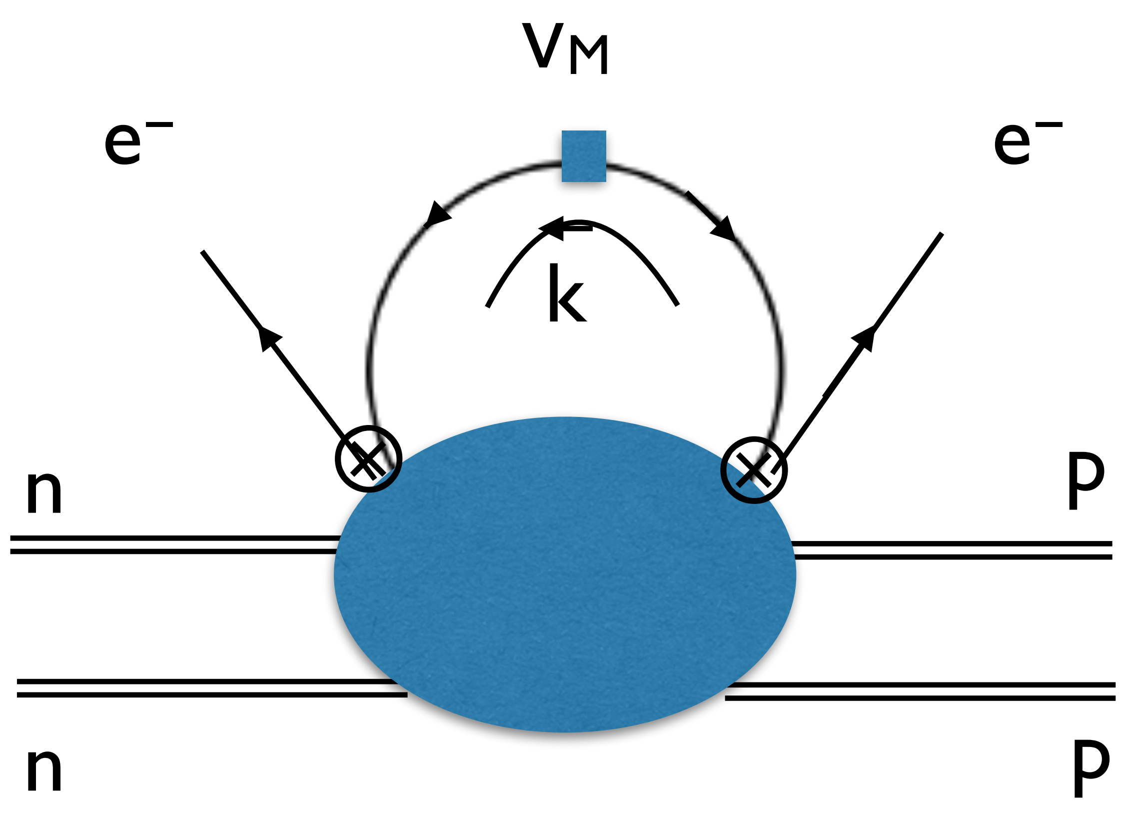


Calculable long- and pion-range contributions to the “Neutrino potential” mediating nn→pp



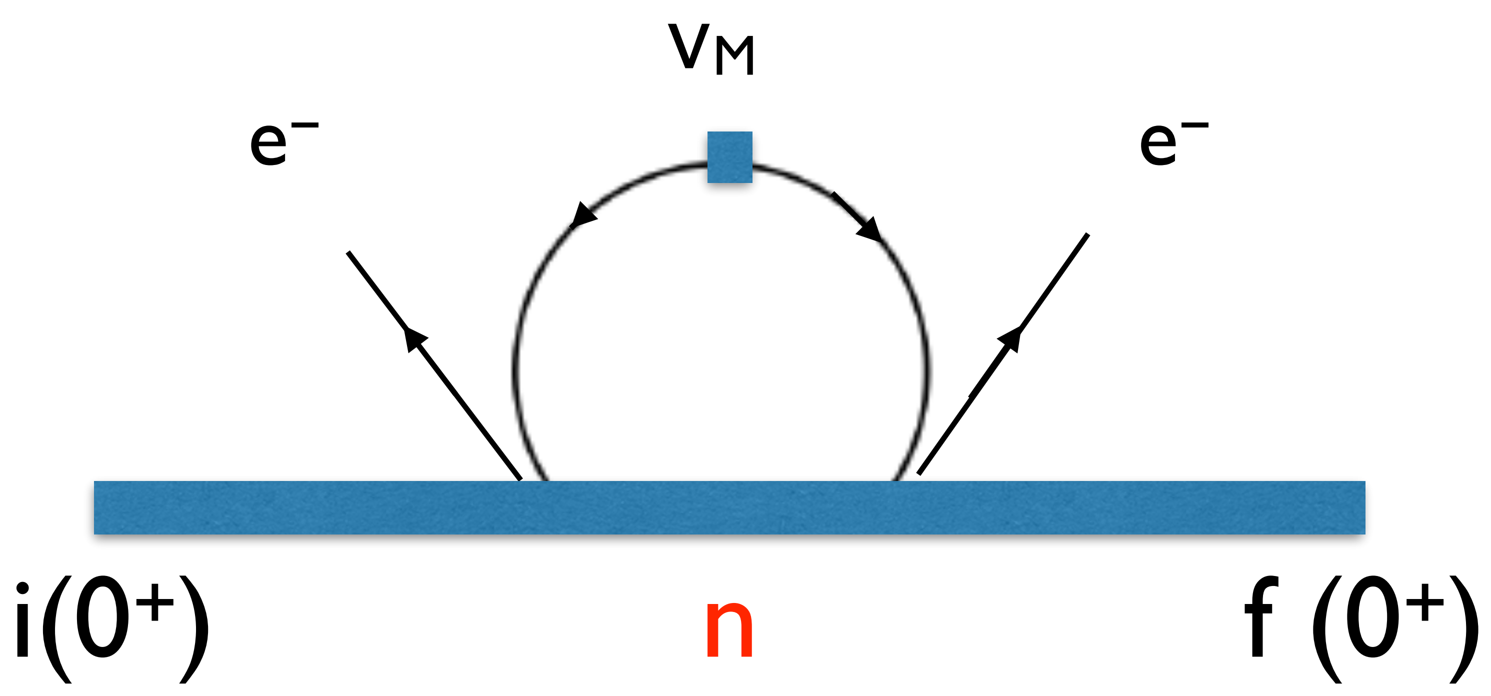
At the nuclear level, these operators mediate the transition between the initial (0^+) and final (0^+) nuclear states

Classifying contributions



"UltraSoft" neutrinos:

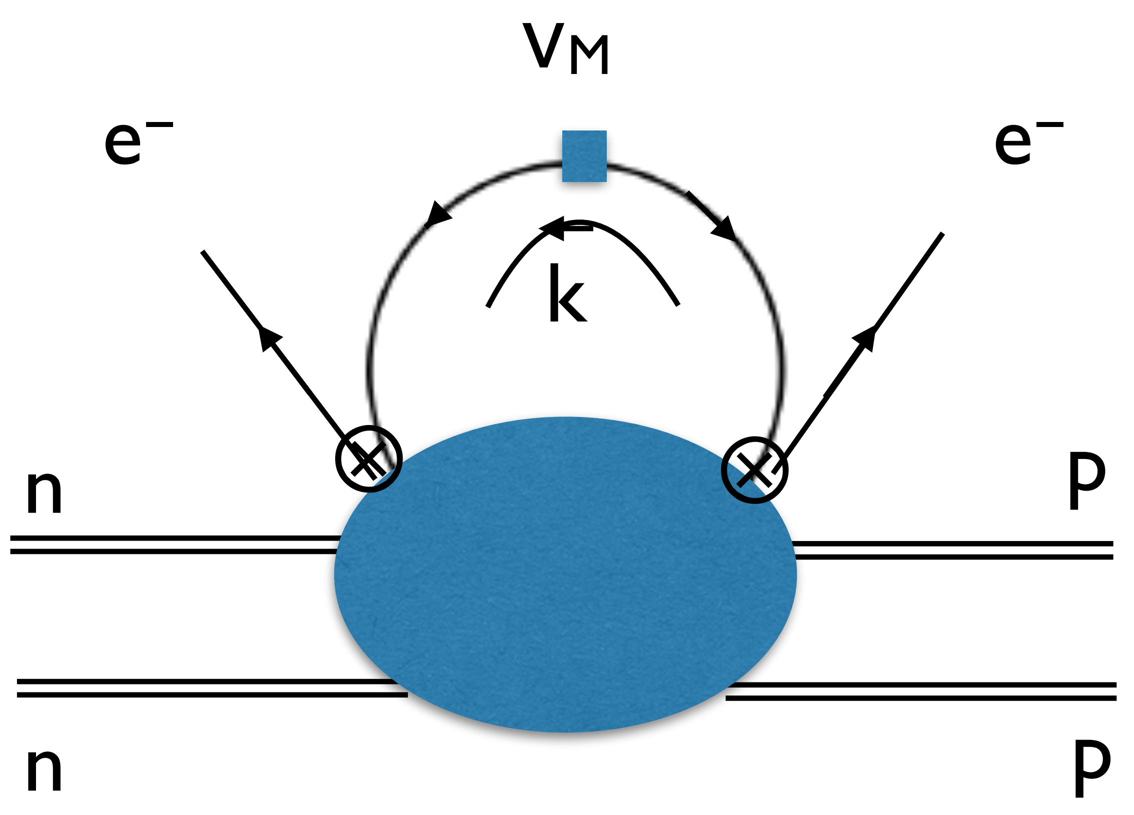
$(k^0, |\mathbf{k}|) \sim Q^2/m_N << k_F$



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

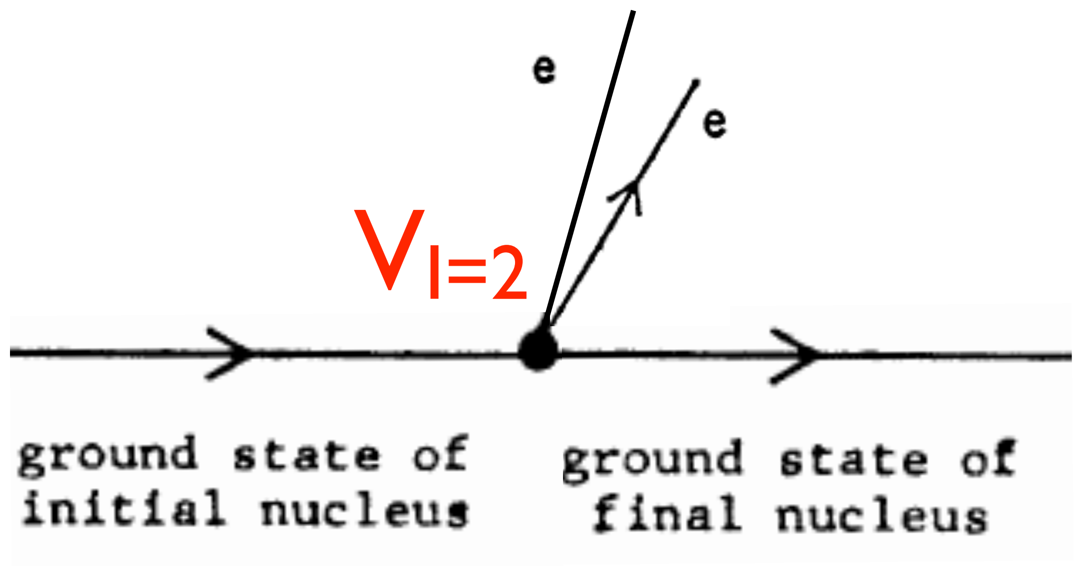
$$H_{\rm Nucl} = H_0 + \boxed{\sqrt{2} G_F V_{ud}\, \bar{N} \left(g_V \delta^{\mu 0} - g_A \delta^{\mu i} \sigma^i \right) \tau^+ N\, \bar{e}_L \gamma_\mu \nu_L} + 2 G_F^2 V_{ud}^2 m_{\beta\beta}\, \bar{e}_L e_L^c\, V_{I=2}$$

"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

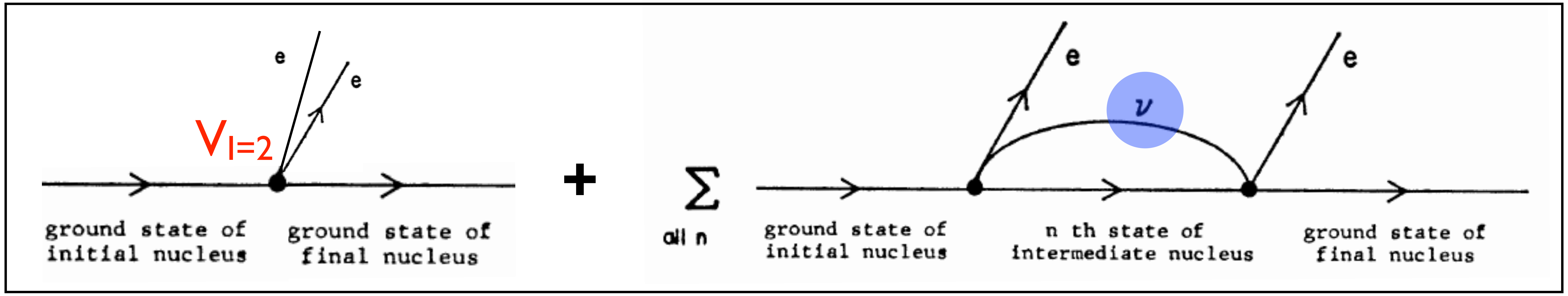
$$V_{I=2} = \sum_{a \neq b} \left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \dots \right)$$

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

LO N²LO

Anatomy of $0\nu\beta\beta$ amplitude in EFT

Figure adapted from Primakoff-Rosen 1969



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LO N²LO

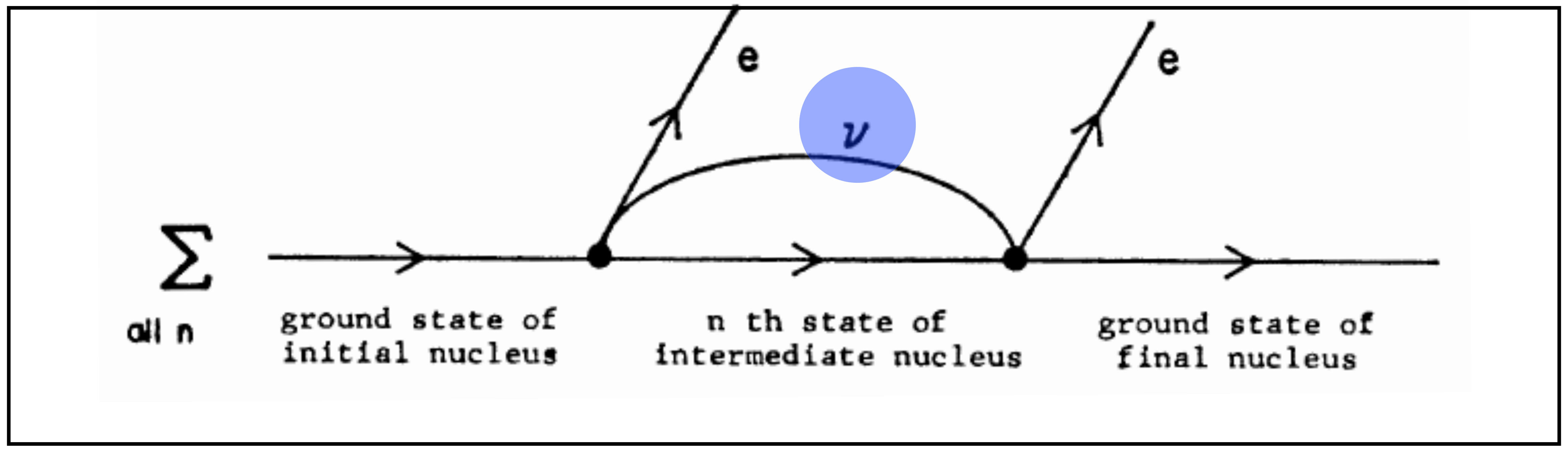
Ultrasoft ν

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 $2\nu\beta\beta$.

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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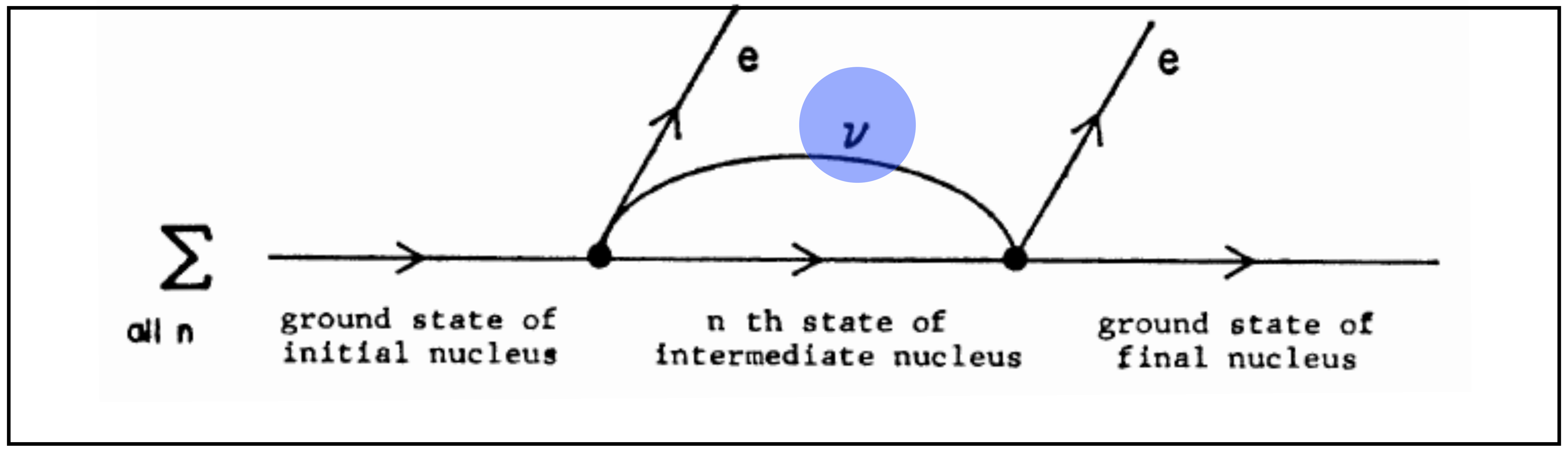

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Complete set of QCD states

Quark-level weak currents

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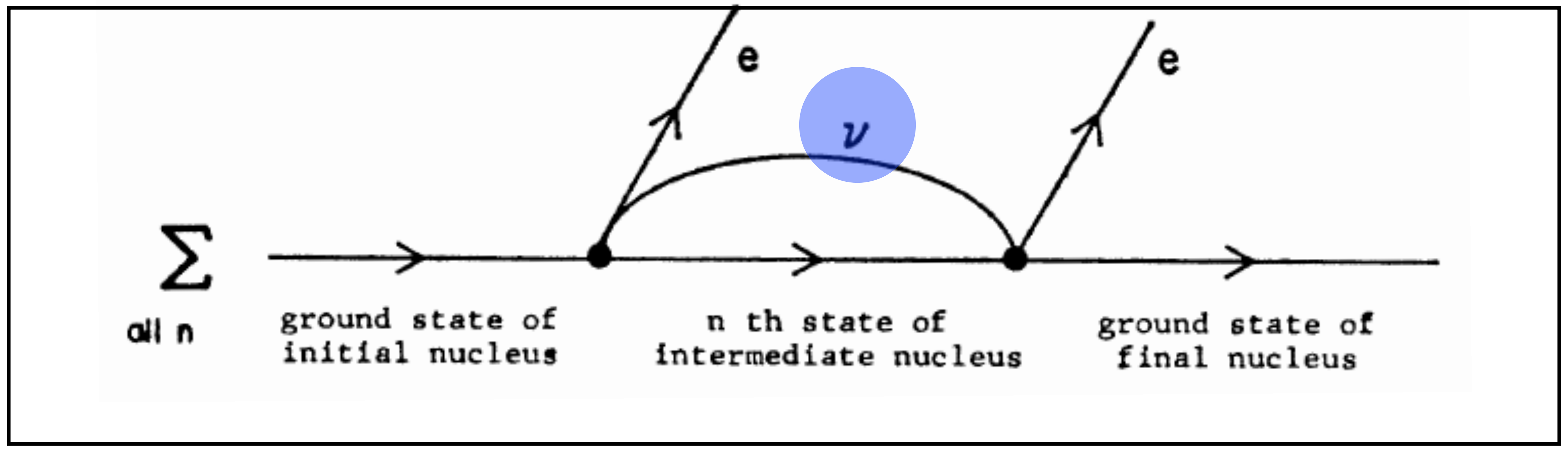
Figure adapted from Primakoff-Rosen 1969



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

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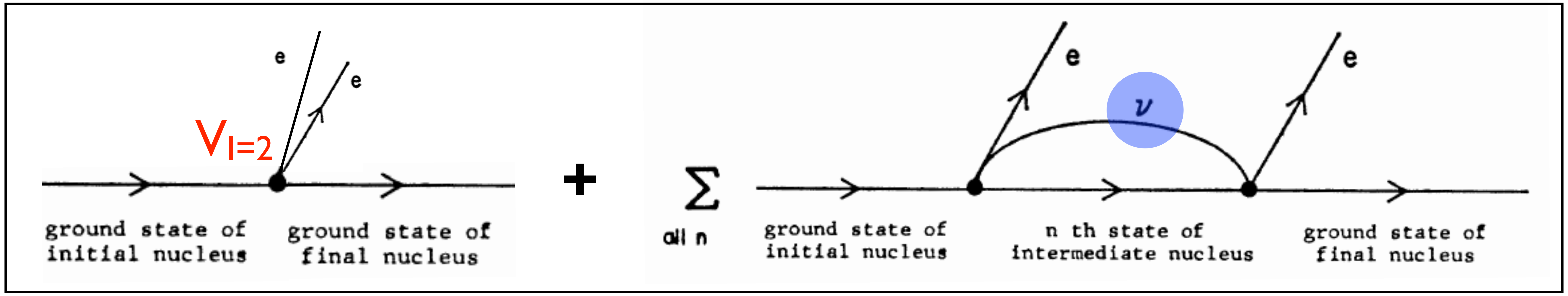
Complete set of nuclear states (built as bound states of nucleons)

Nucleon-level weak currents

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



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Contributes to the amplitude at N²LO

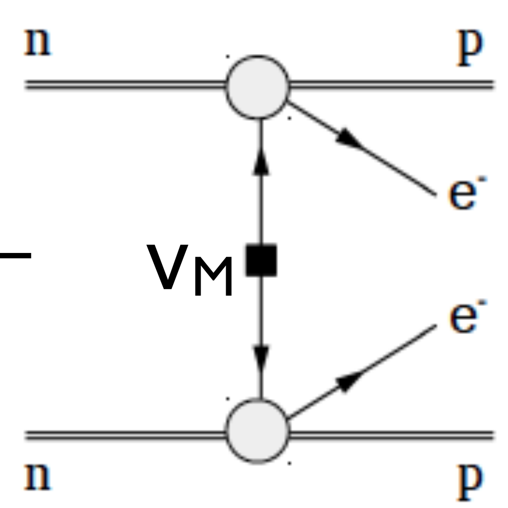
Key new insight from EFT

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

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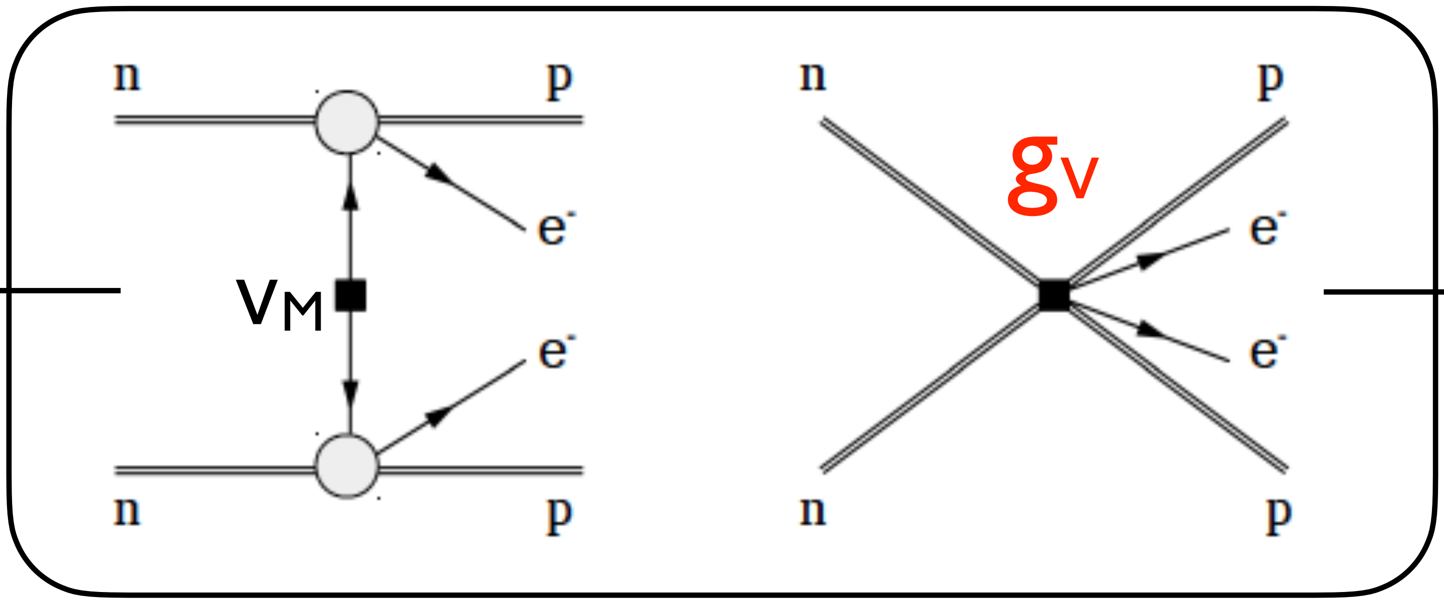
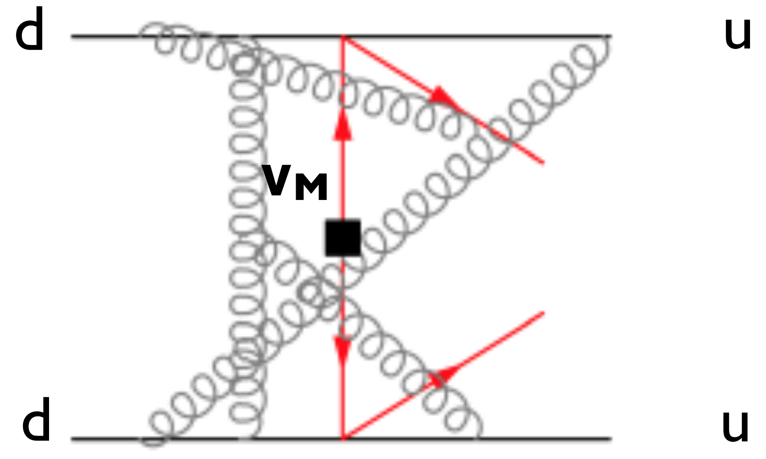


'New': short-range potential with coupling $g_\nu \sim 1/Q^2$



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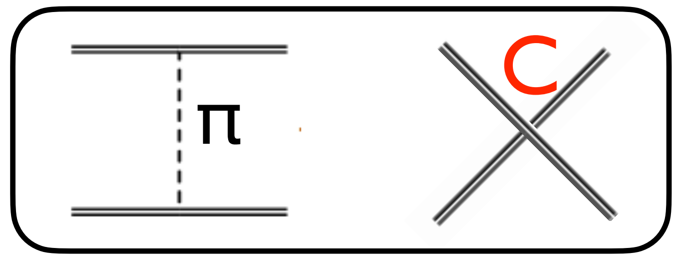
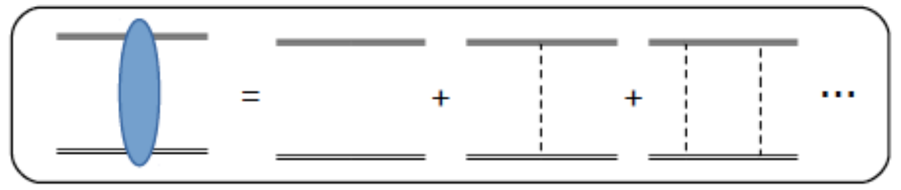
- To leading order (LO) in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV), the $nn \to pp$ transition operator has *two contributions:*

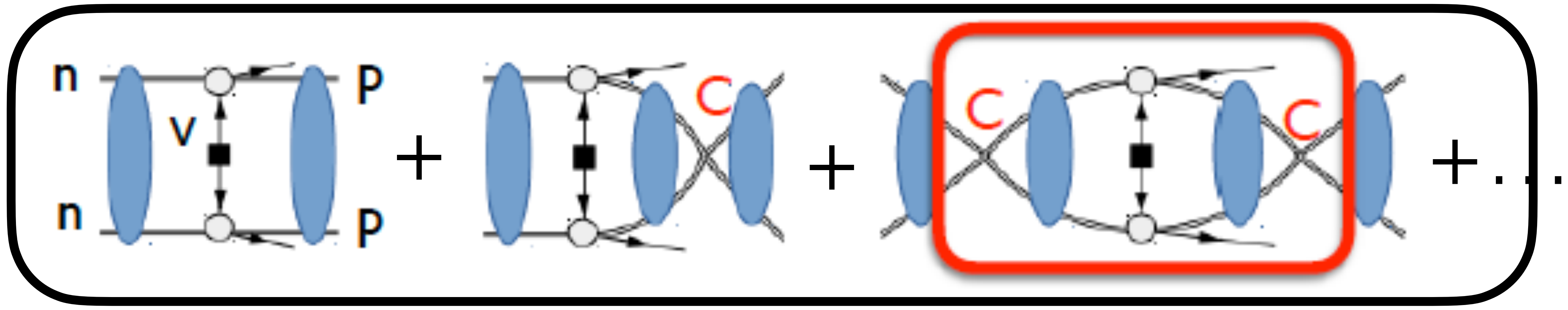
- LO contact term is required by renormalization of the ${}^1S_0$ $nn \to pp$ amplitude in presence of strong interactions

LO strong potential



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





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

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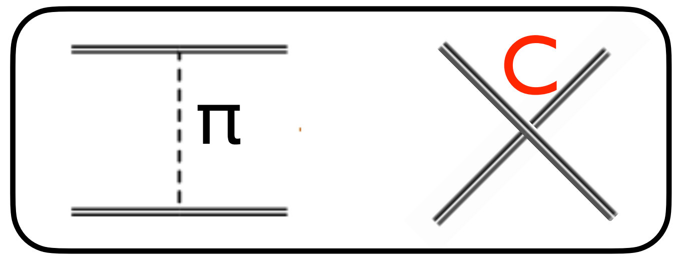

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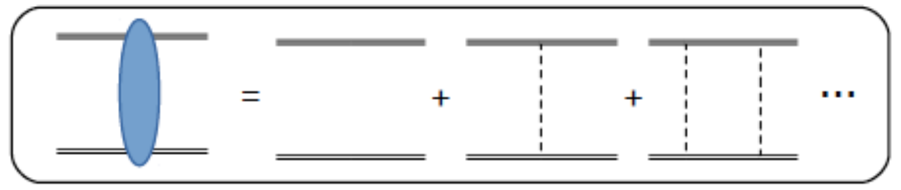
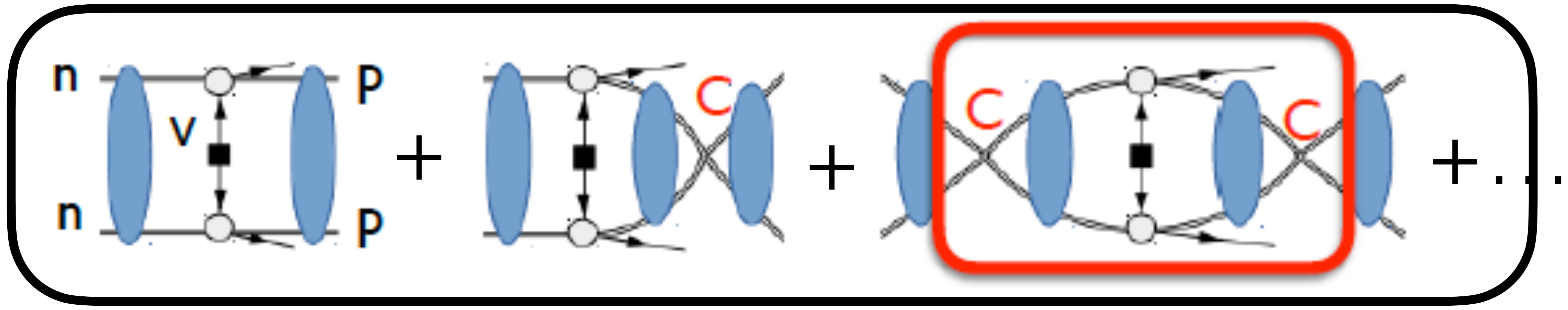
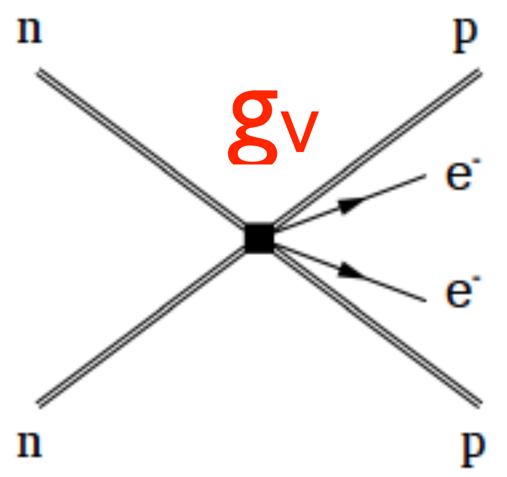




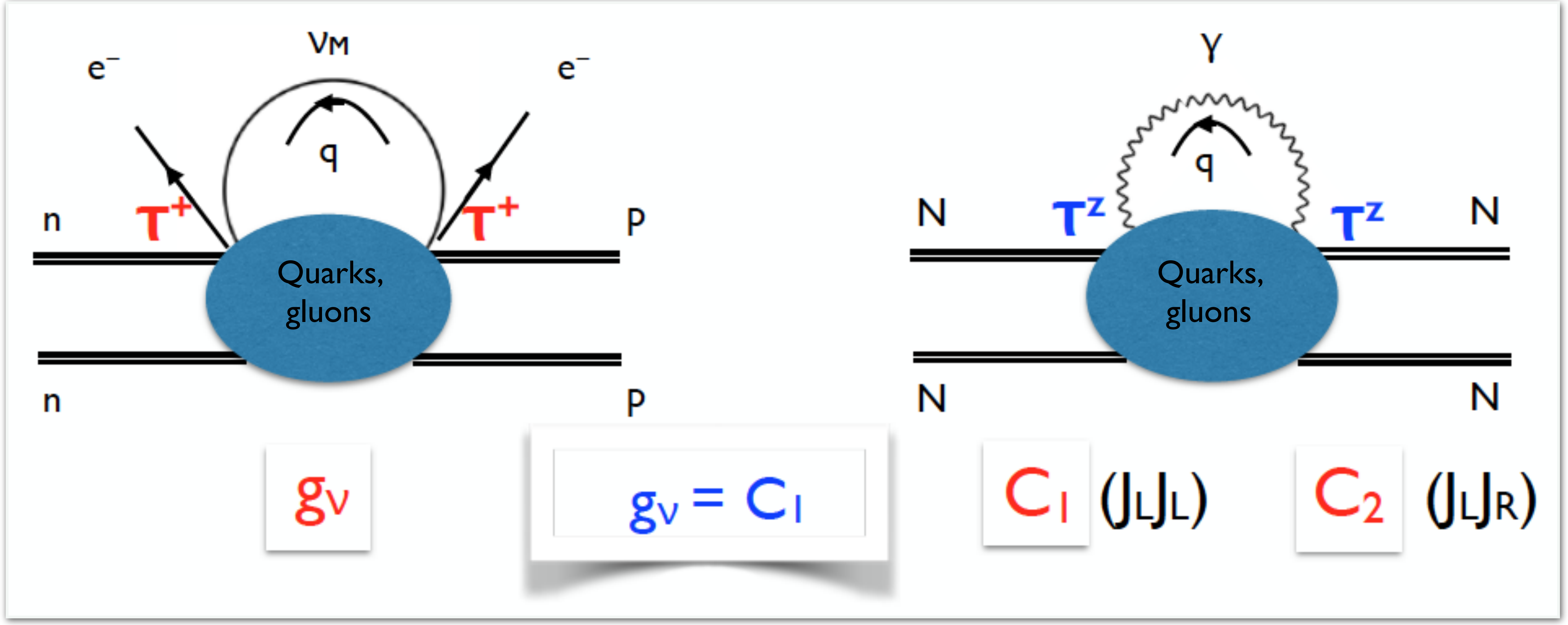


UV divergence $\propto$ $(m_N C/4\pi)^2 \sim 1/Q^2$

g_ν flows to
$1/Q^2 \gg 1/(4\pi F_\pi)^2$

Can we extract g_V from data?

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

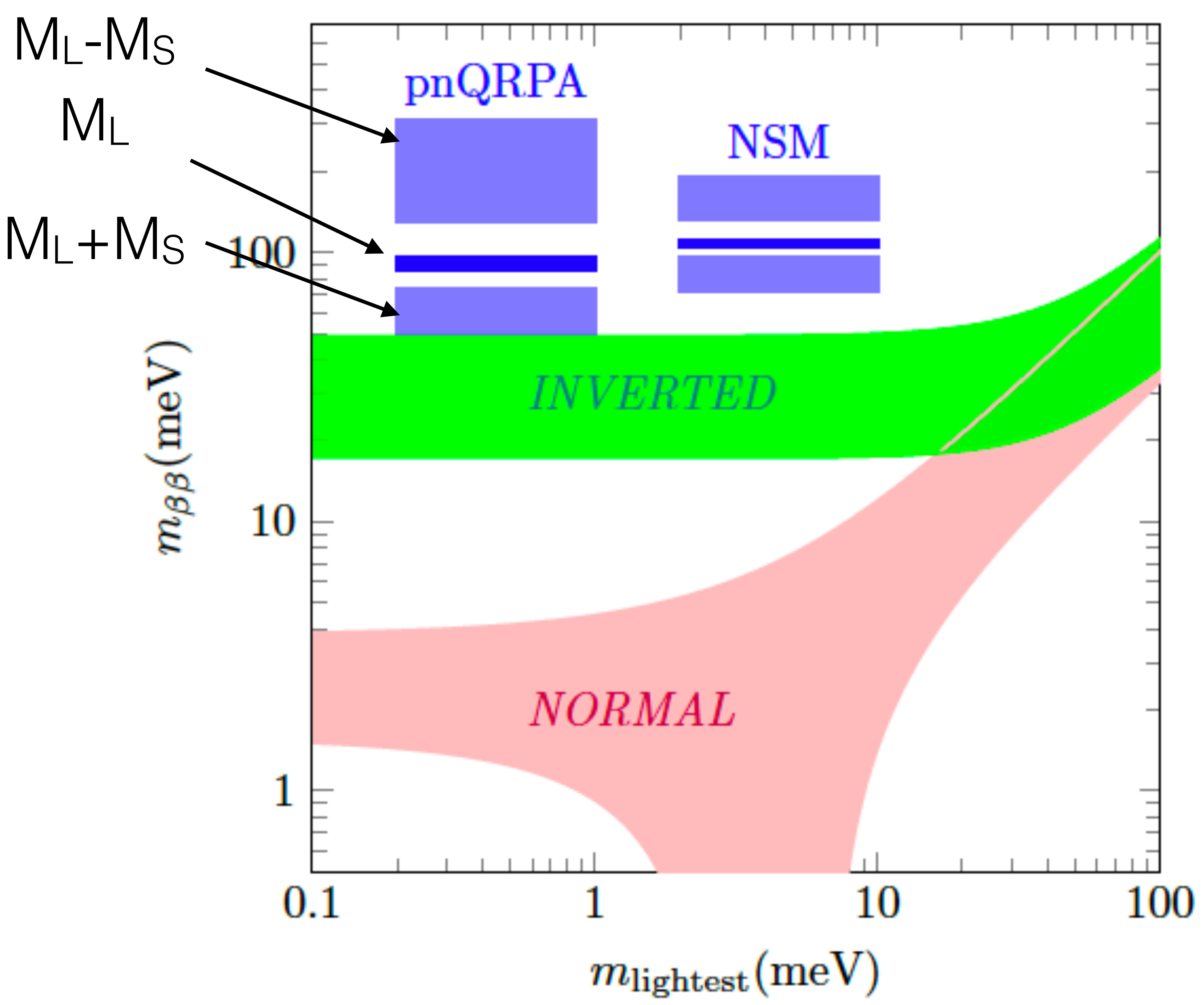


- NN scattering data at low energy ($a_{nn}+a_{pp}-2a_{np}$) determine C_1+C_2, confirming LO scaling!

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



Jokiniemi-Soriano-Menendez, 2107.13354

Key question:
is the interference
constructive or
destructive?

Impact on nuclear matrix elements

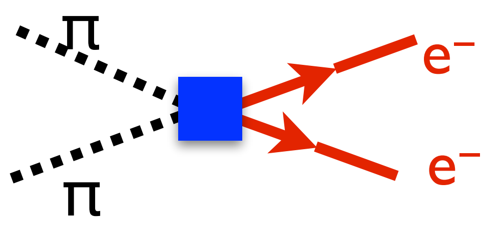
- *Assuming* $g_V \sim (C_1+C_2)/2$ $\rightarrow$ O(1) impact on m.e. and $m_{\beta\beta}$ extraction

- Several approaches to determine g_V

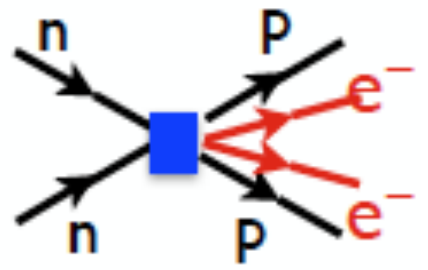
    - Large-N_C arguments point to $g_V \sim (C_1+C_2)/2$

      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)

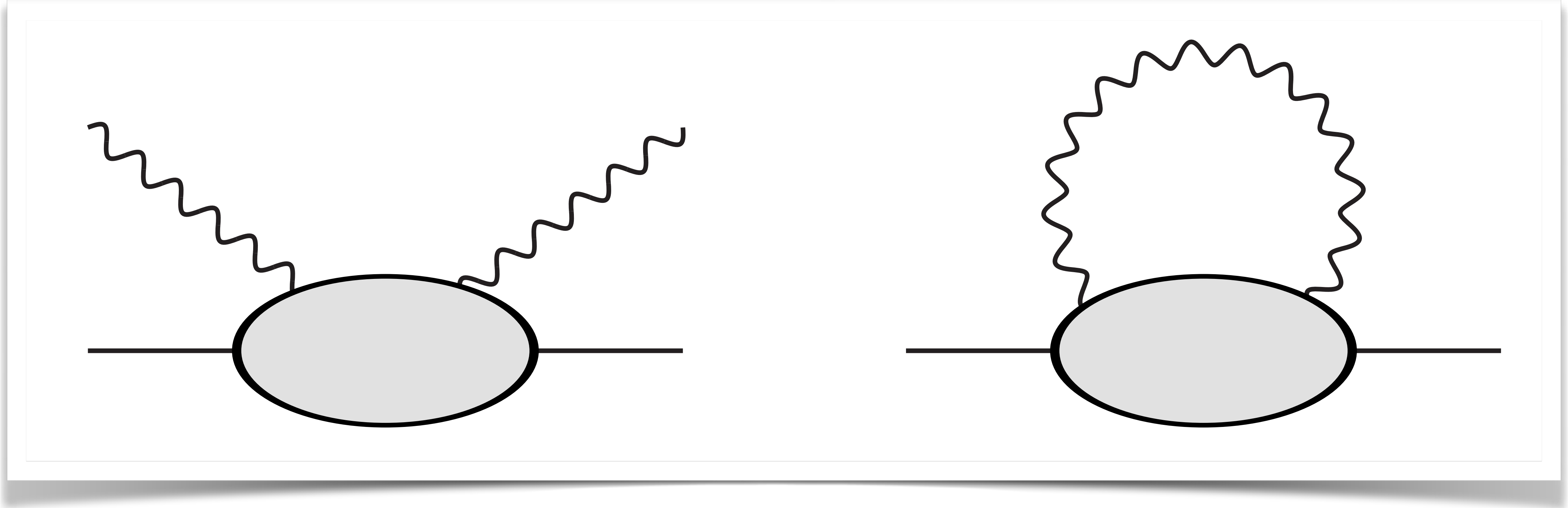
      VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Estimating the contact term

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

Forward Compton amplitude

Self-energy ~ mass

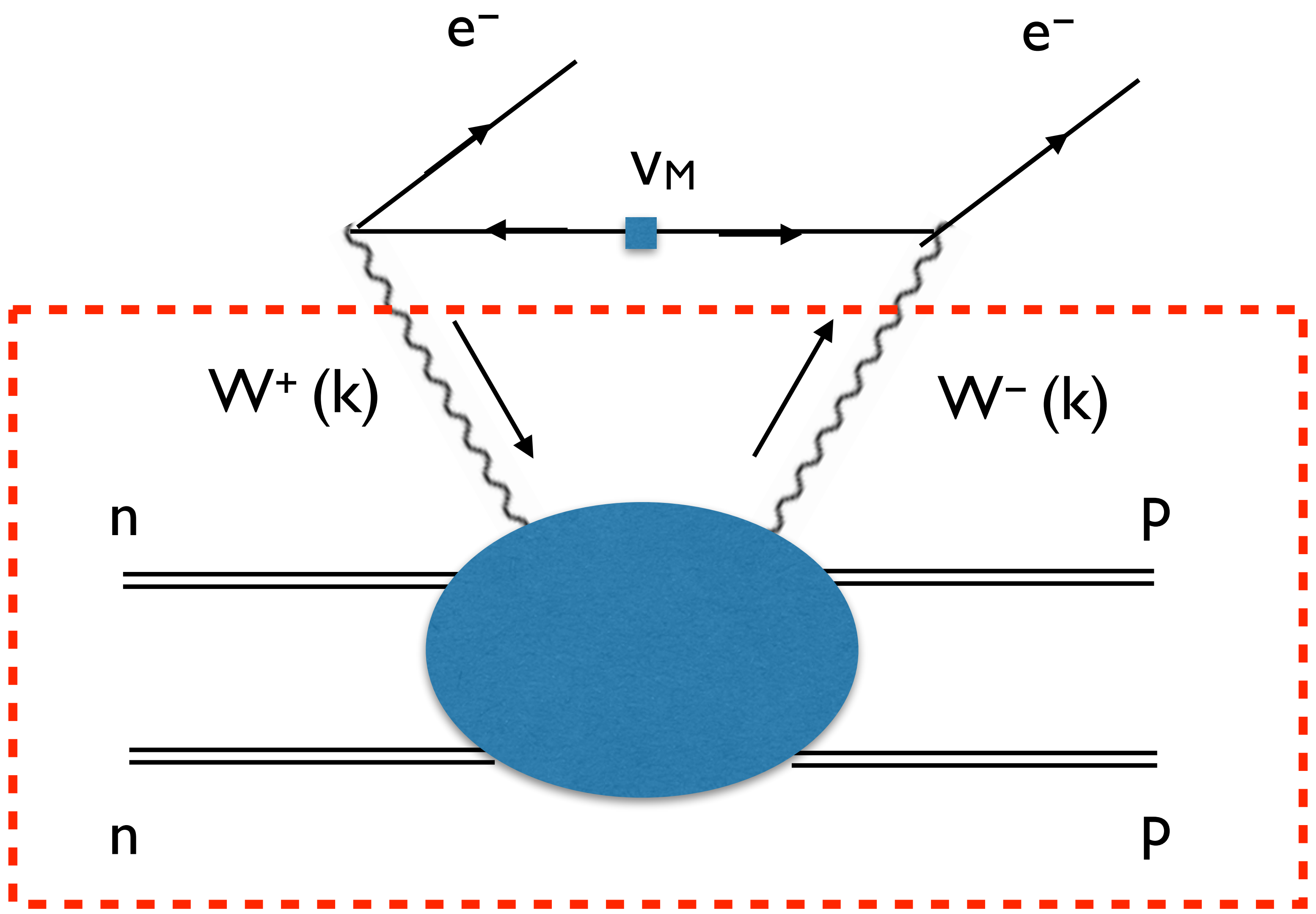


Cottingham (1963) approach to electromagnetic contributions to hadron masses

Estimating the contact term

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

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

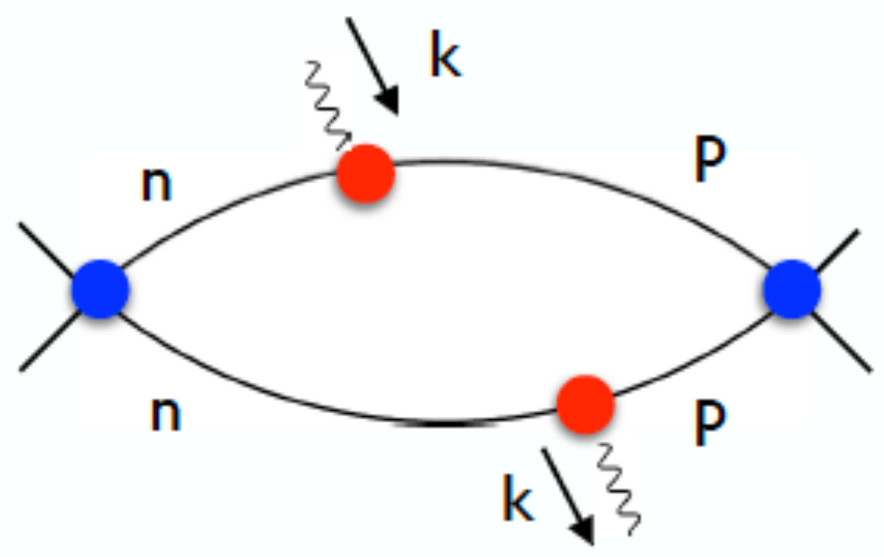


Estimating the contact term

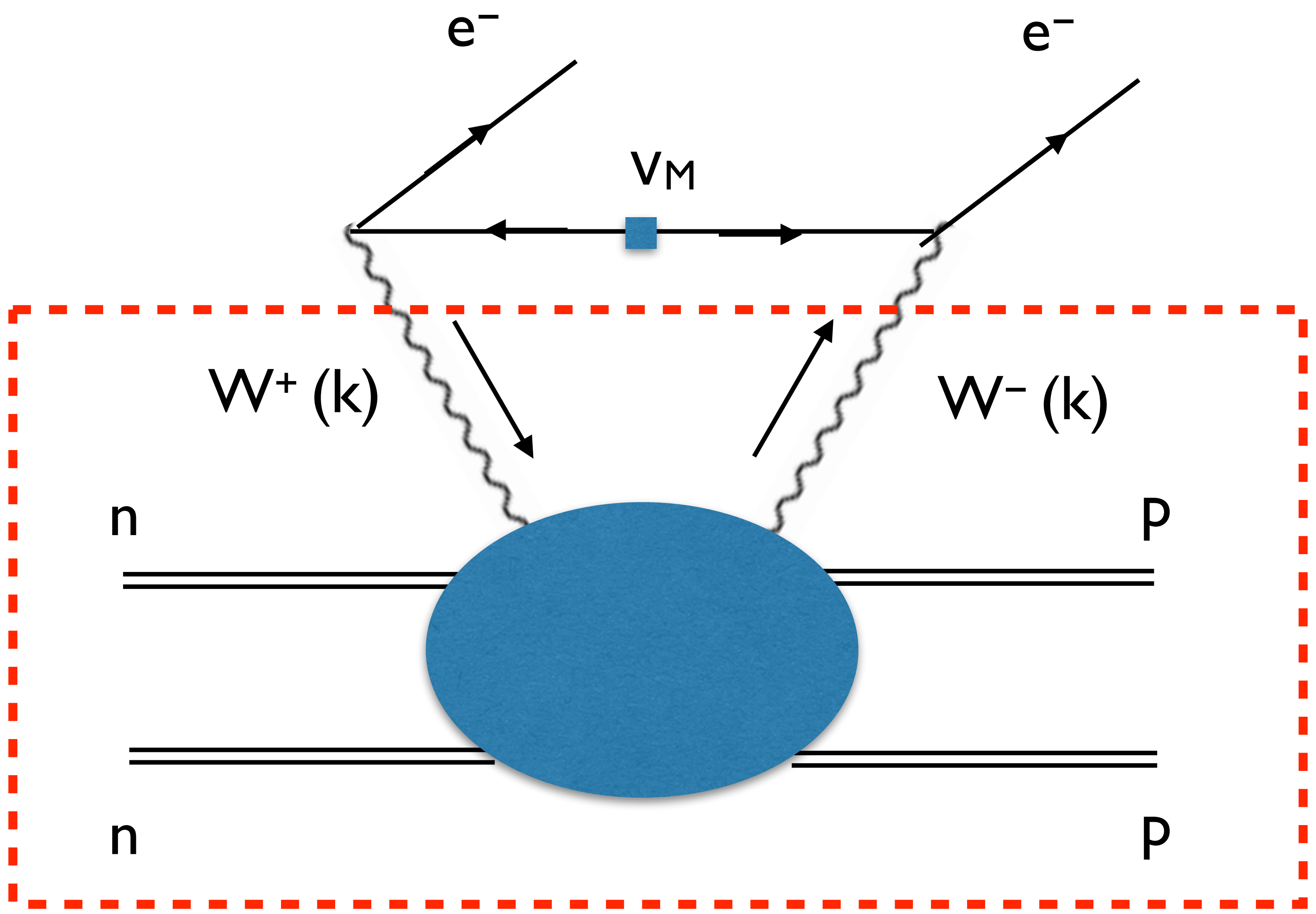
VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

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

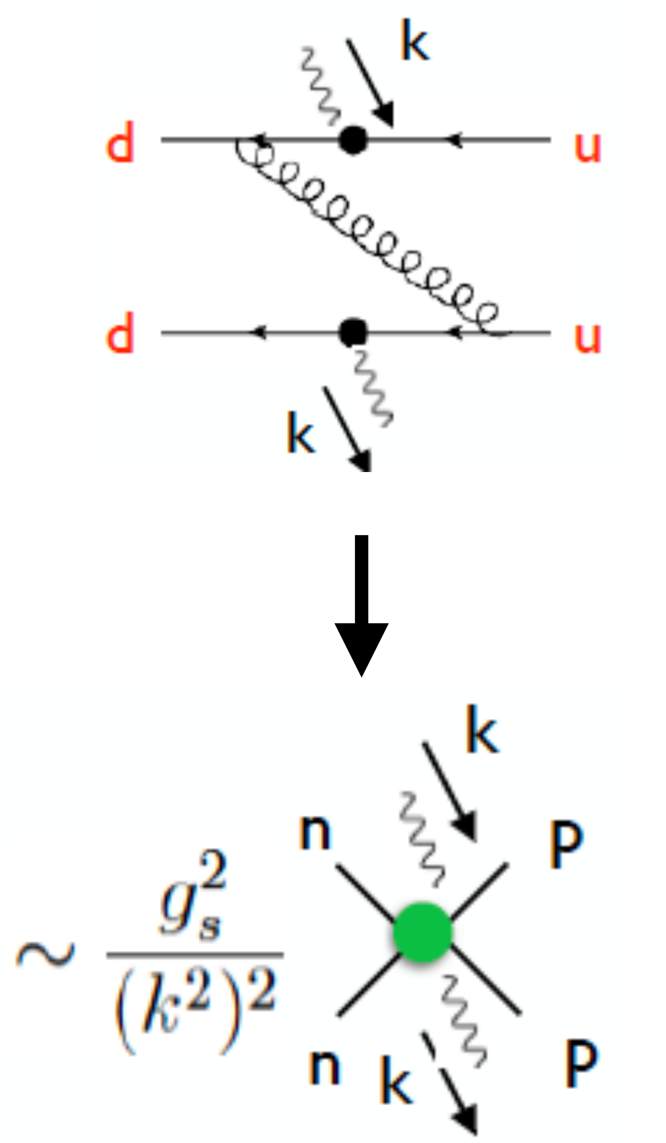
Low k: chiral EFT to NLO



Intermediate k: resonance contributions
in and ,
πNN intermediate state, …



High k: QCD OPE

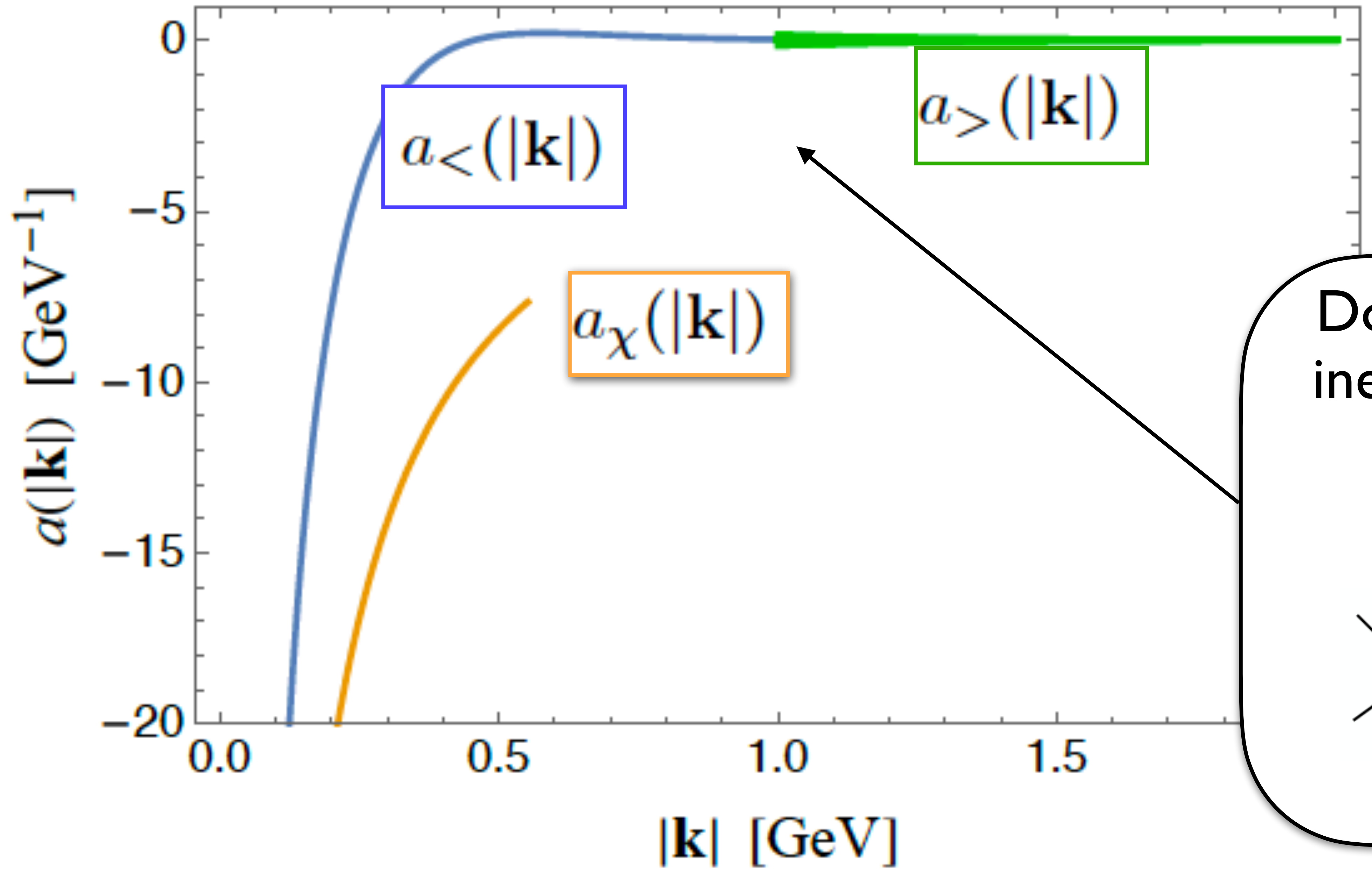


Estimating the contact term

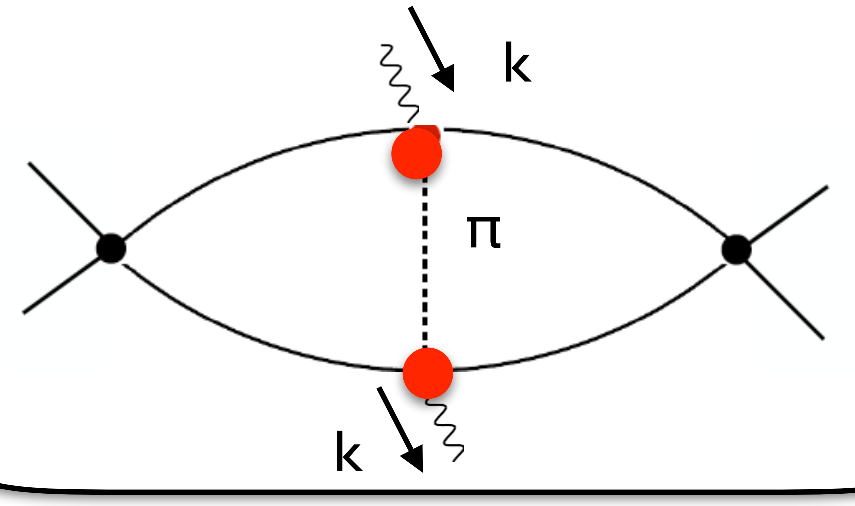
VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

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 intermediate states (NNπ, …):



Impact of the contact term

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

Determined g_ν with ~30% uncertainty (validated with $\Delta I=2$ NN electromagnetic coupling $C_1 + C_2$)

↓

We provided 'synthetic data' for the $nn \to pp$ amplitude to be used to fit g_ν 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]

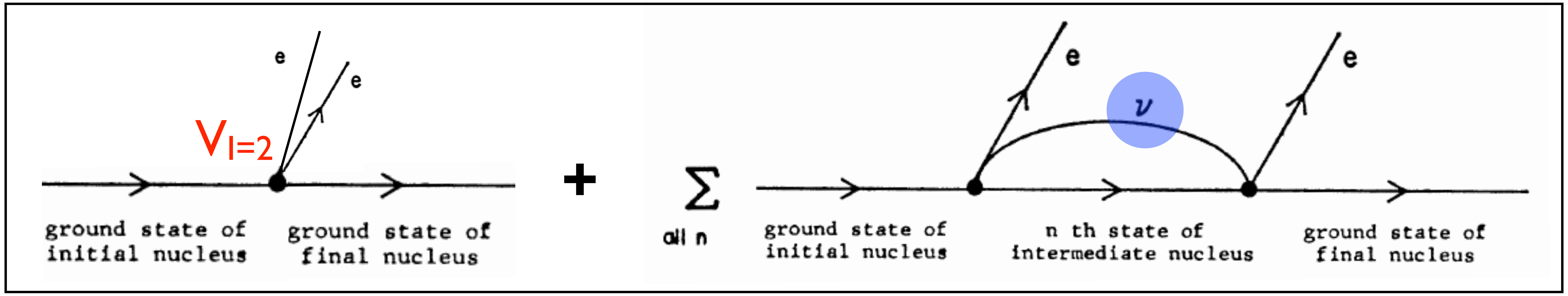
[2] Wirth, Yao, Hergert, 2105.05415 [3] Belley et al, 2307.15156 [4] Belley et al, 2308.15634

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

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

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

LO N²LO

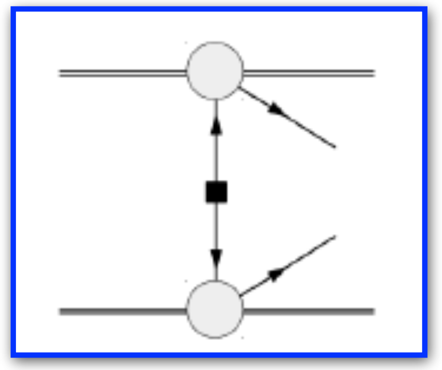
Ultrasoft ν

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.

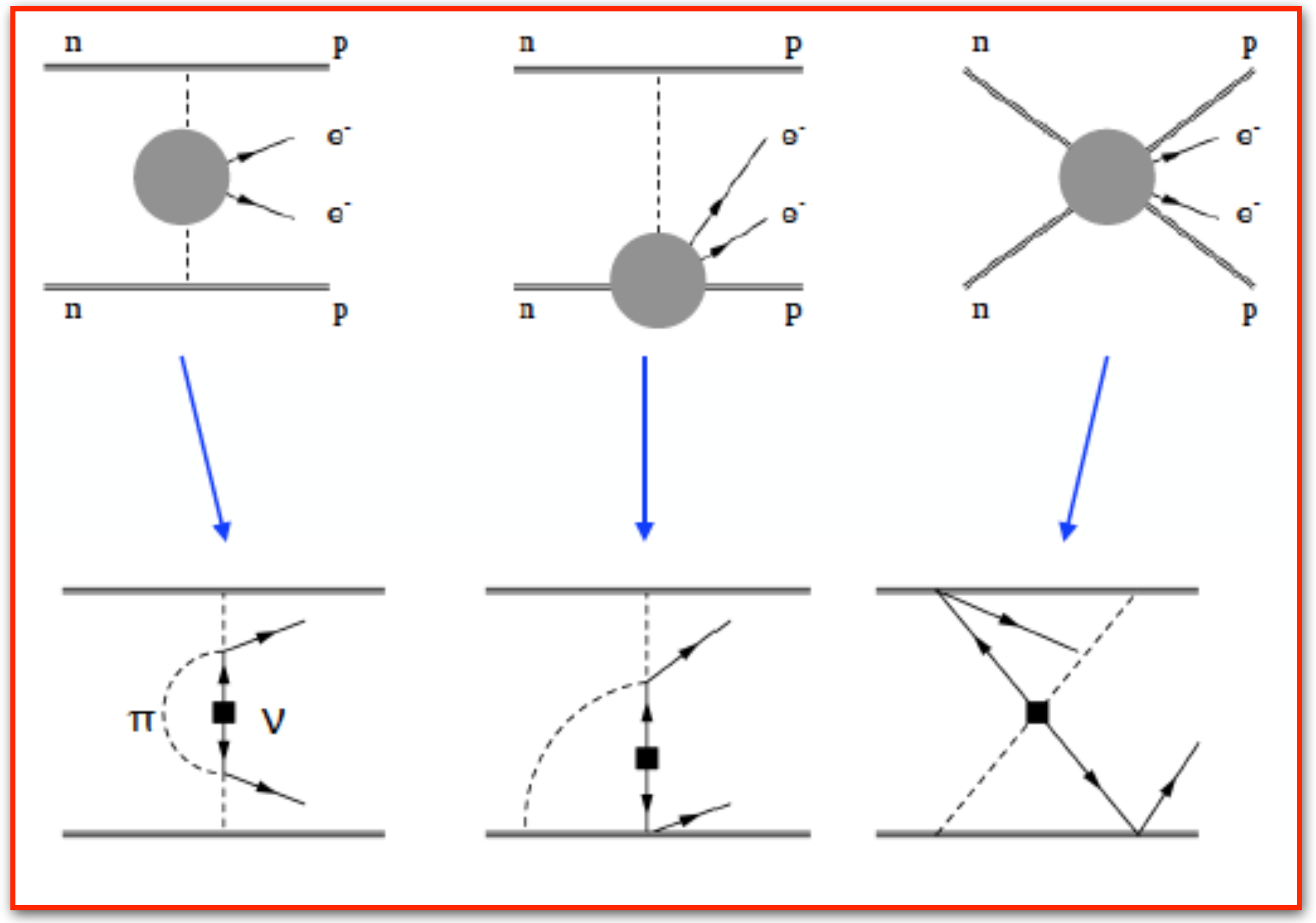
Contributes to the amplitude at N²LO

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

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

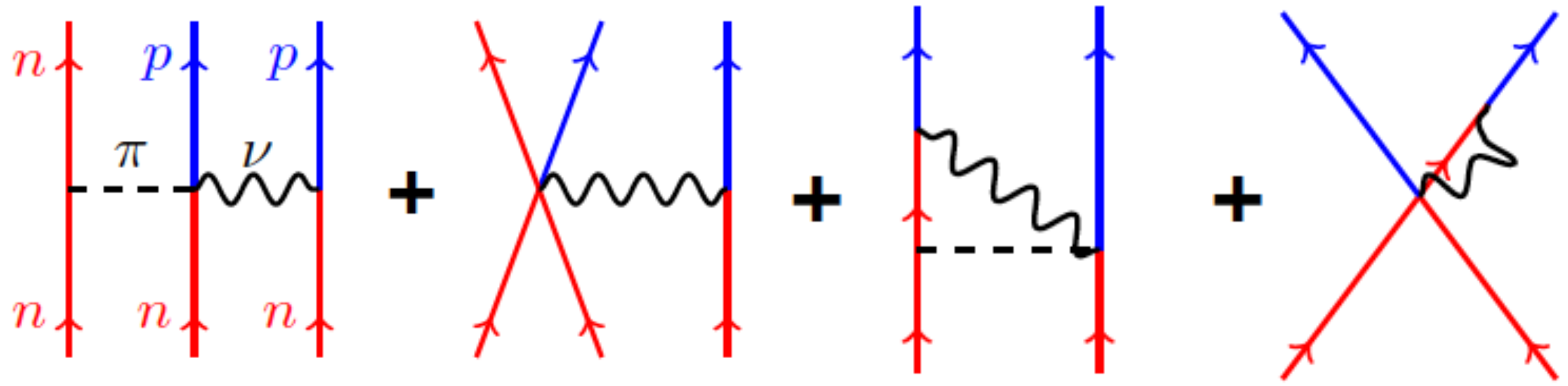


- Non-factorizable contributions to $V_{\nu,2} \sim V_{\nu,0}\,(k_F/4\pi F_\pi)^2$
[π-N loops and new contact terms]



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

N²LO 0νββ potential

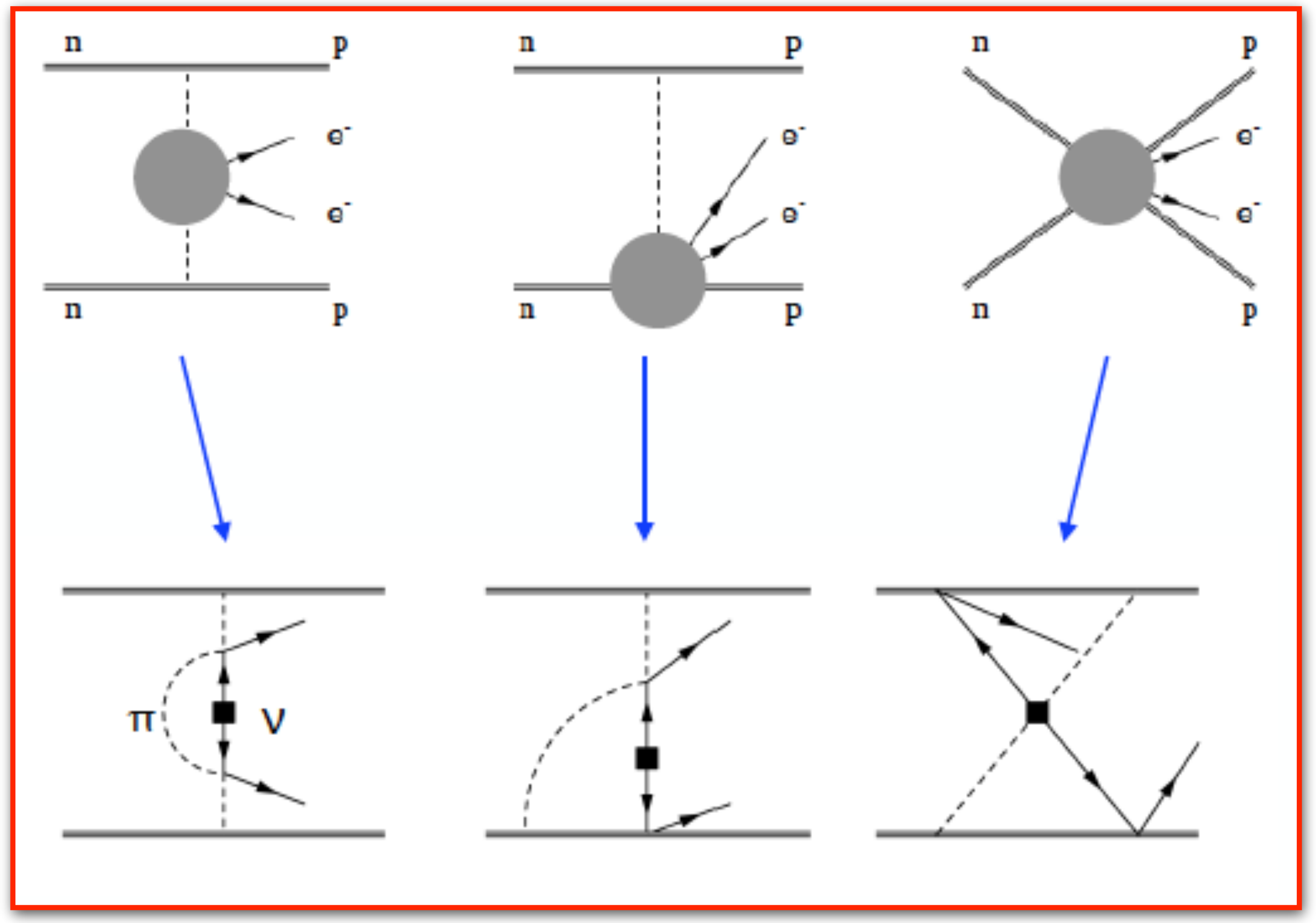
Calculations of these effects in light and heavy nuclei show O(10%) corrections

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

Castillo, Jokiniemi, Menendez, Soriano 2408.03373, Belley et al, 2308.15634

- 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

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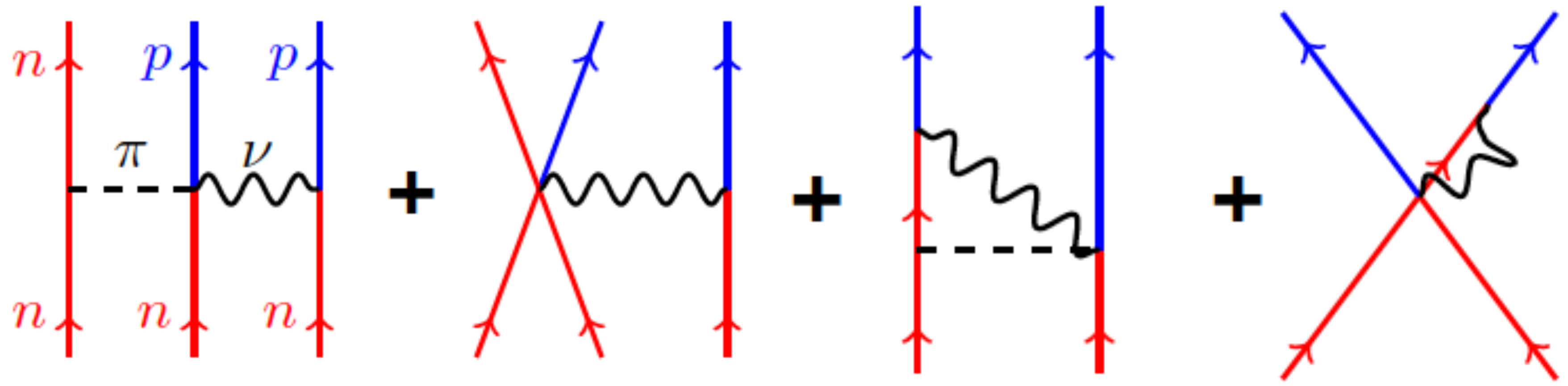
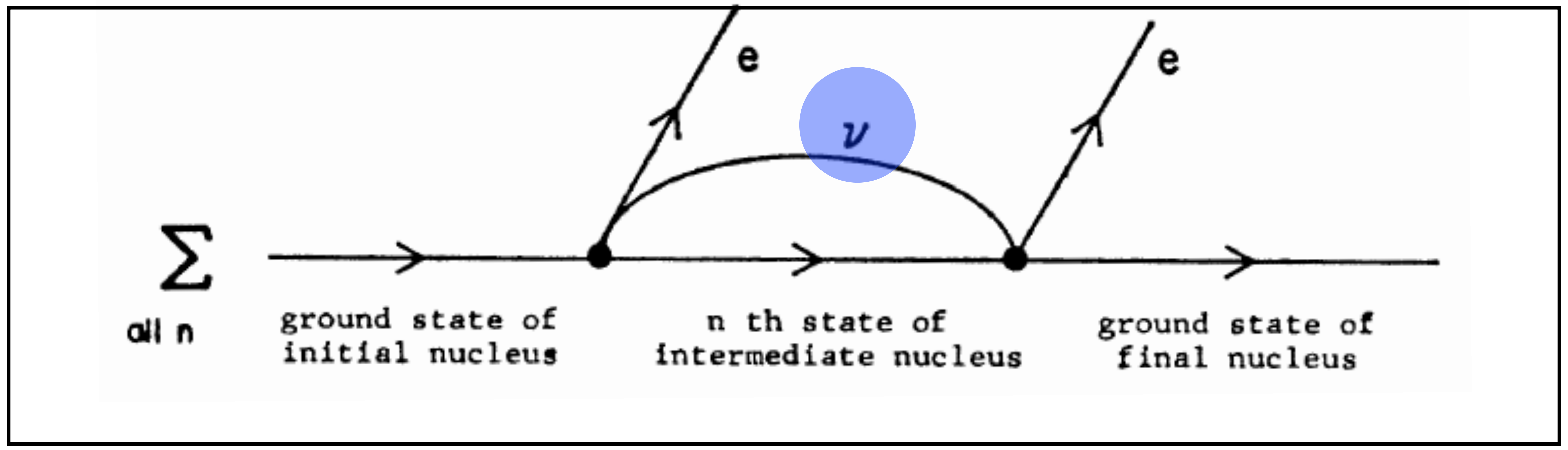


Wang-Engel-Yao 1805.10276

Ultrasoft neutrino contributions

Figure adapted from Primakoff-Rosen 1969



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

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 $(E_n - E_i)/(4\pi k_F) \sim (Q/\Lambda_\chi)^2$. → N2LO contribution.
  This scaling is consistent with previous studies of the closure approximation and recent calculations

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

Castillo, Jokiniemi, Menendez, Soriano 2408.03373

Progress in controlling all uncertainties

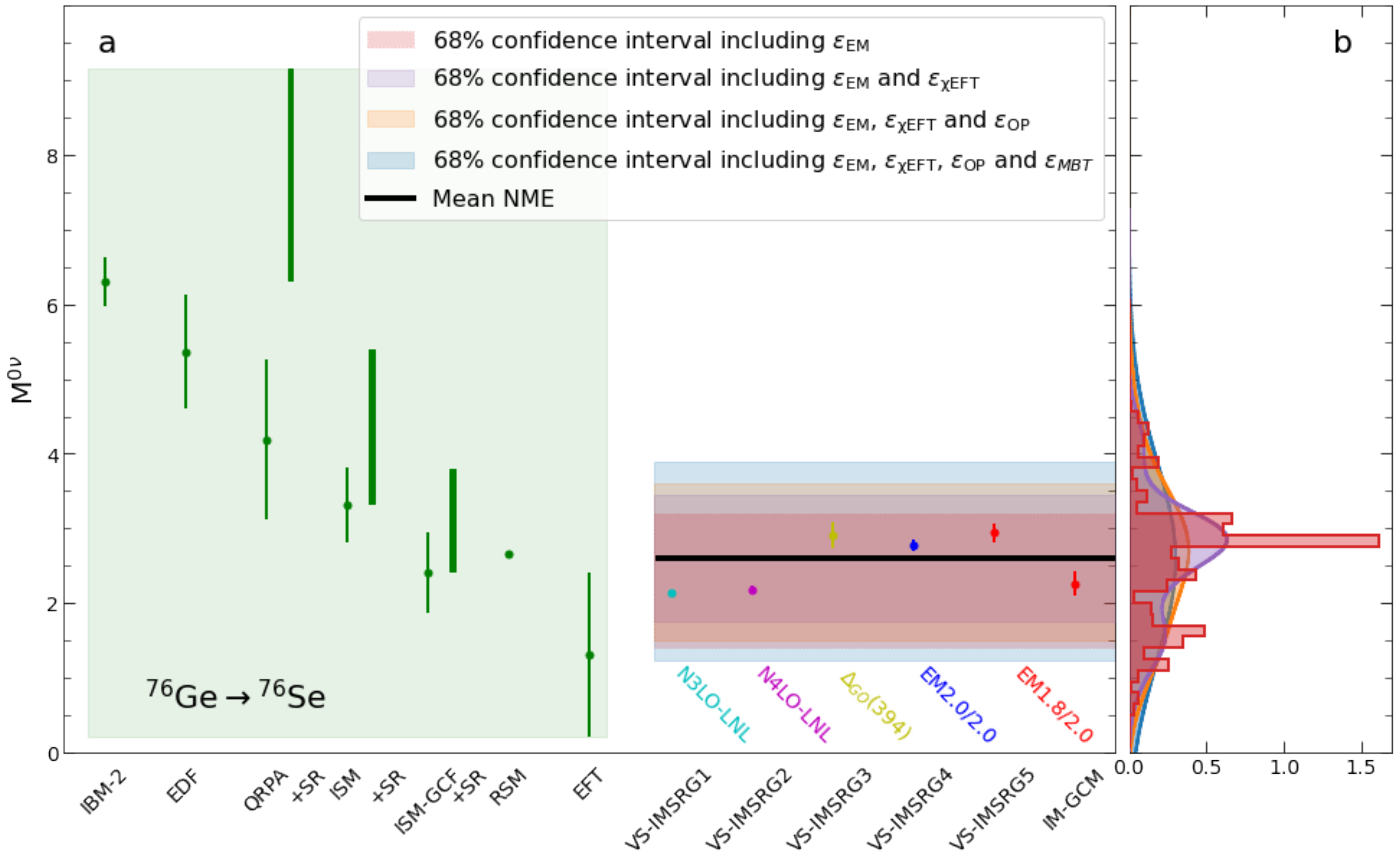
Belley et al, 2308.15634 and references therein

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

$M^{0\nu}$	ϵ_{LEC}	$\epsilon_{\chi\mathrm{EFT}}$	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: $\boxed{m_{\beta\beta} < 320\ \mathrm{meV}}$

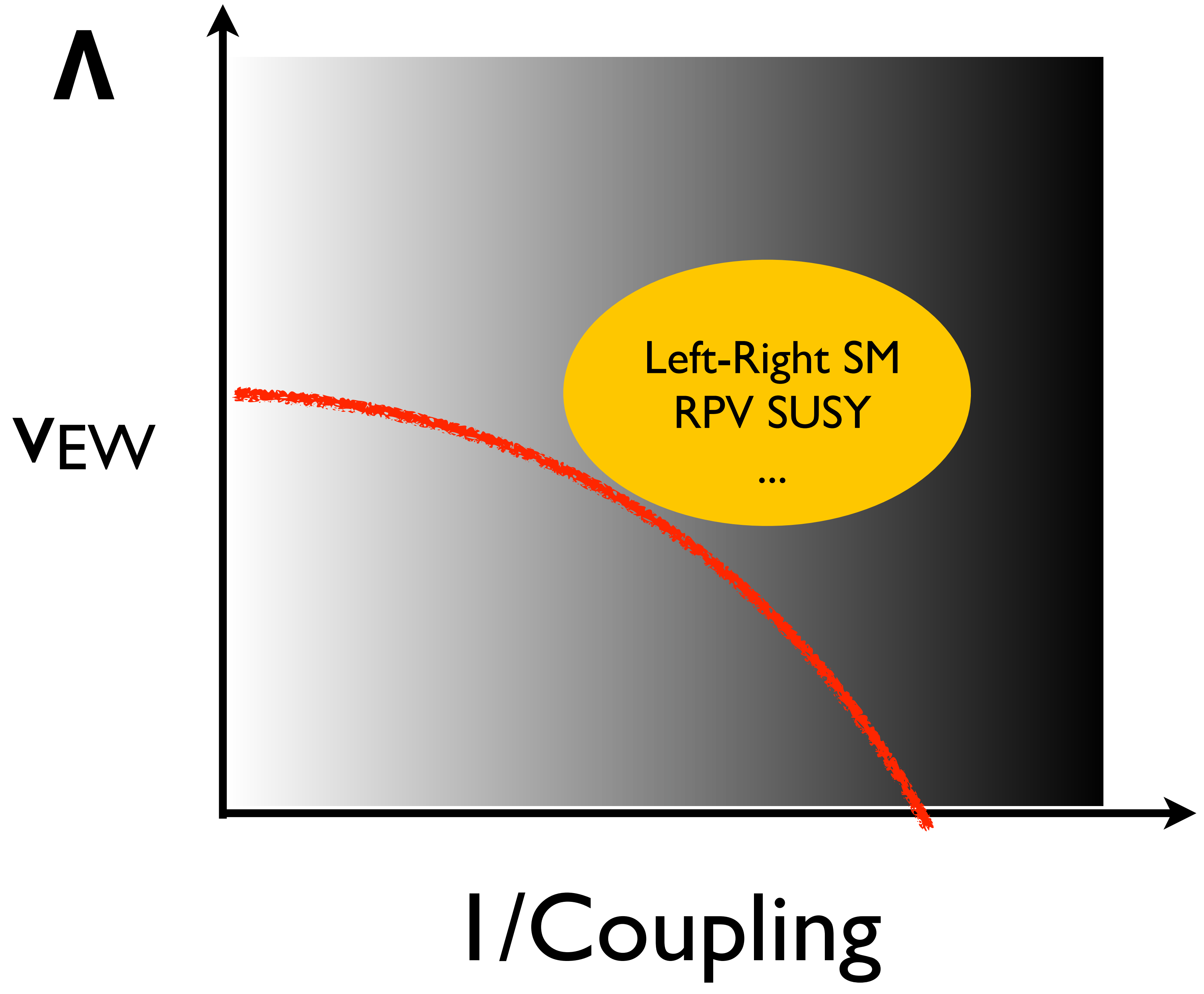
LEGEND-200: 2505.10440



Various nuclear models

'Ab initio' methods using different chiral interactions

0vββ from multi-TeV scale dynamics (dim-7, 9, …operators)



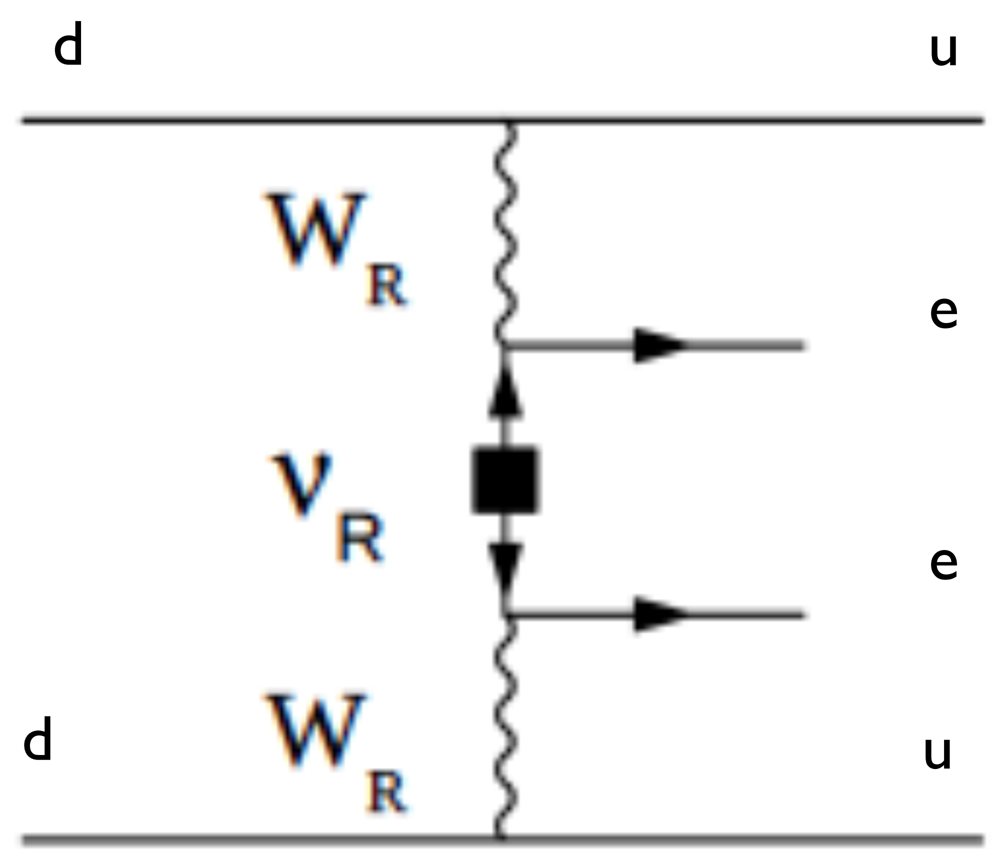
LNV @ multi-TeV-scale: key features

- Observable contributions to $0\nu\beta\beta$ *not directly related to the exchange of light neutrinos:*

$$m_{\beta\beta} G_F^2/Q^2 \sim 1/\Lambda^5$$

if $m_{\beta\beta} \sim 0.1$ eV and $\Lambda \sim$ TeV

(For example $\Lambda \sim M_{\nu R} \sim M_{WR}$)



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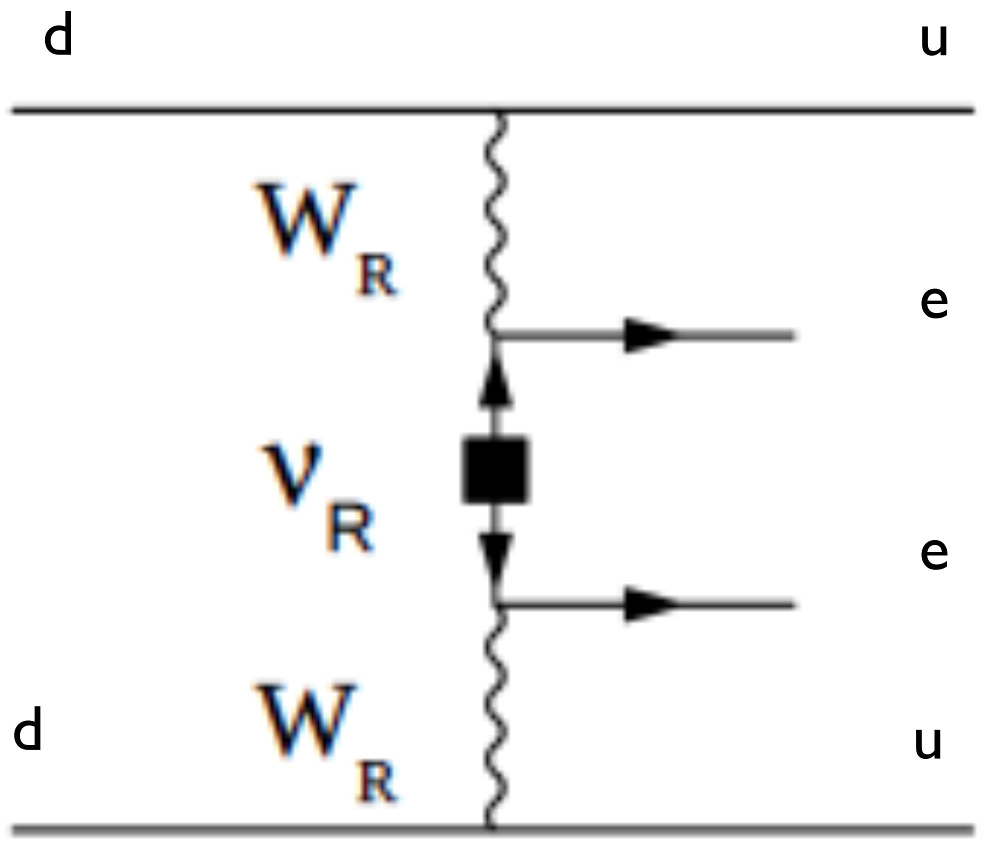
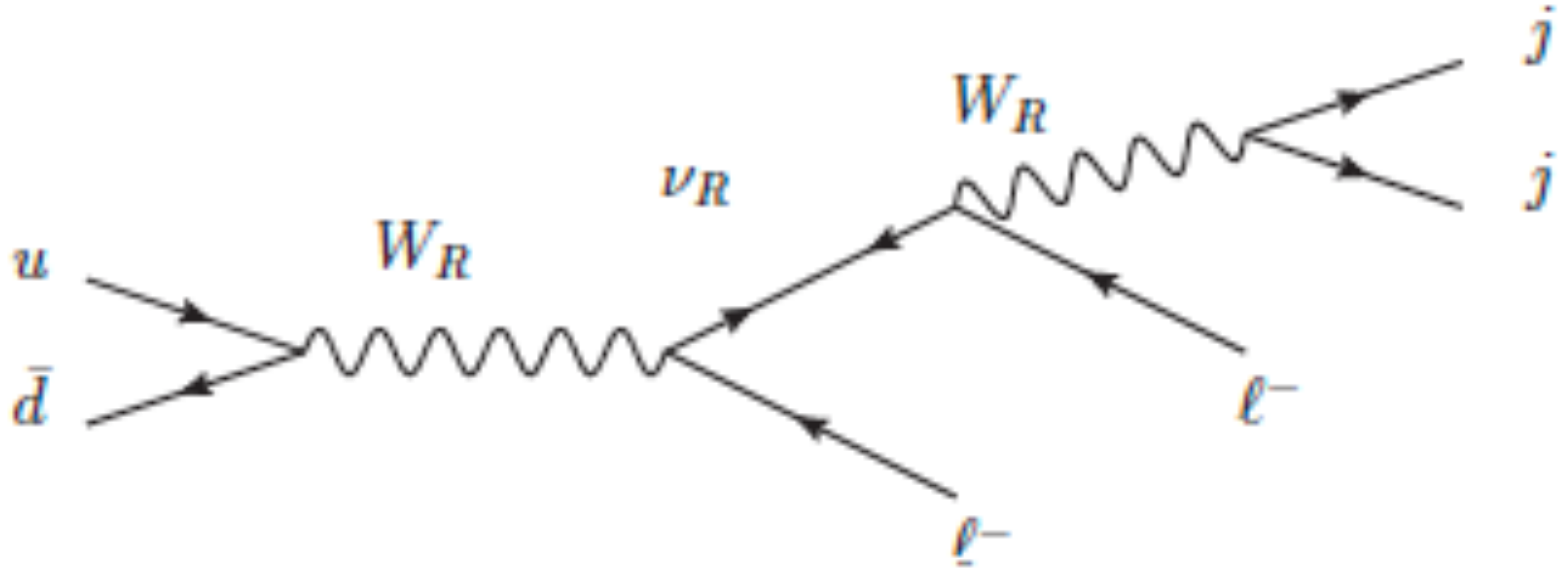


- Possible correlated signal at LHC: $pp \rightarrow ee\, jj$



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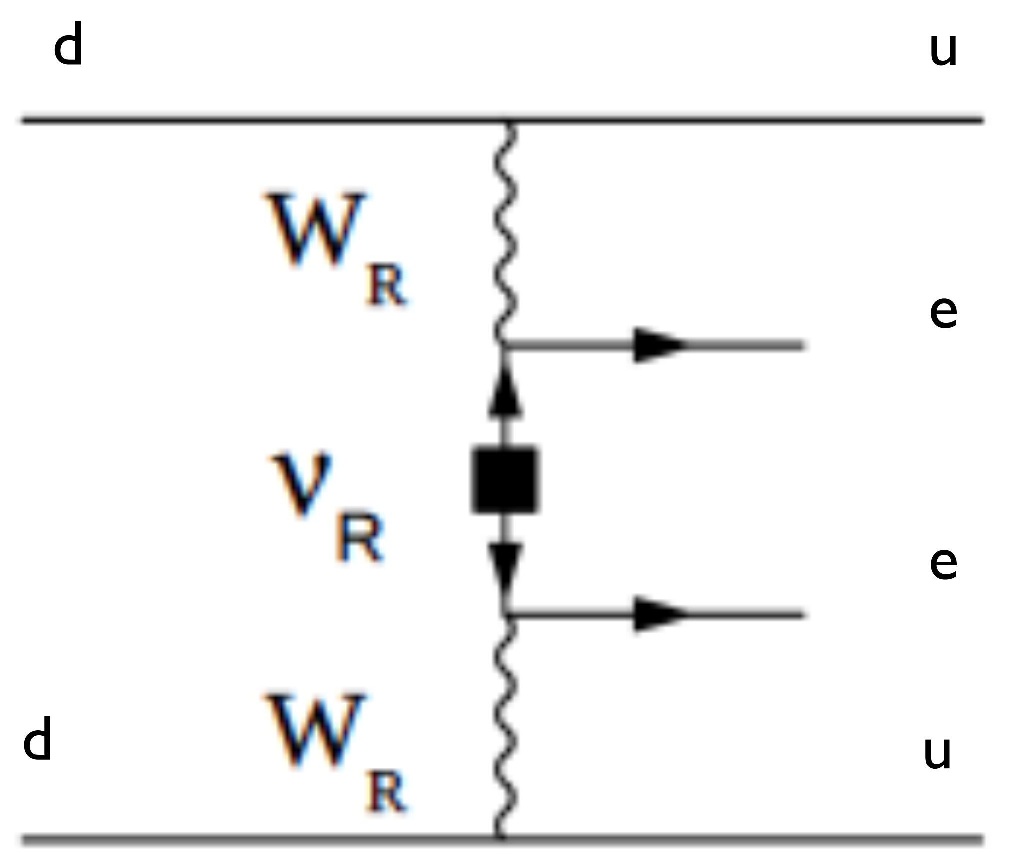

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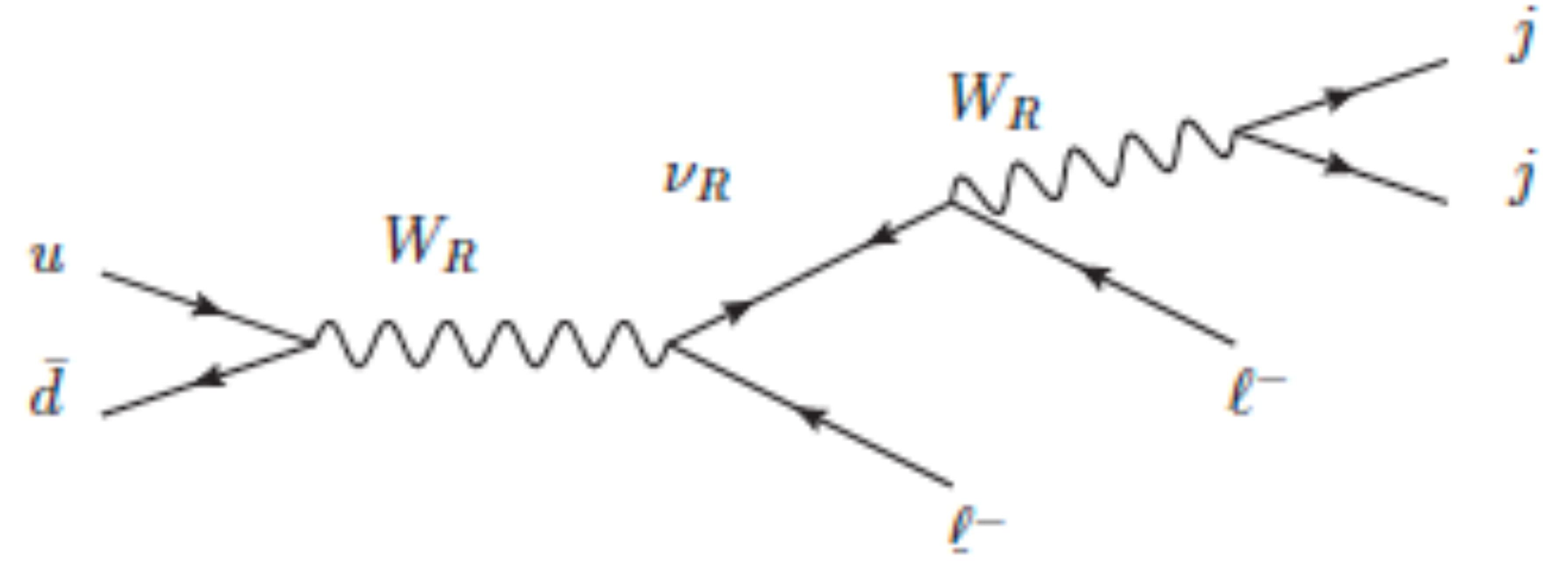
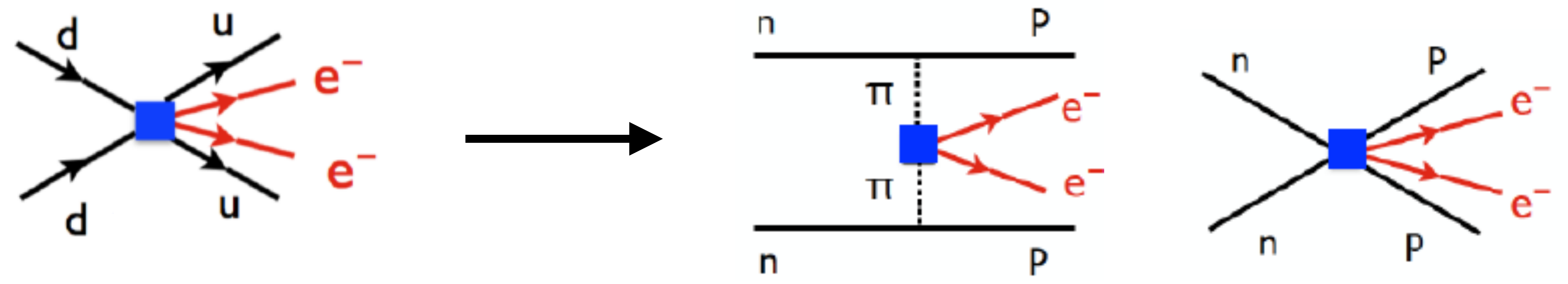
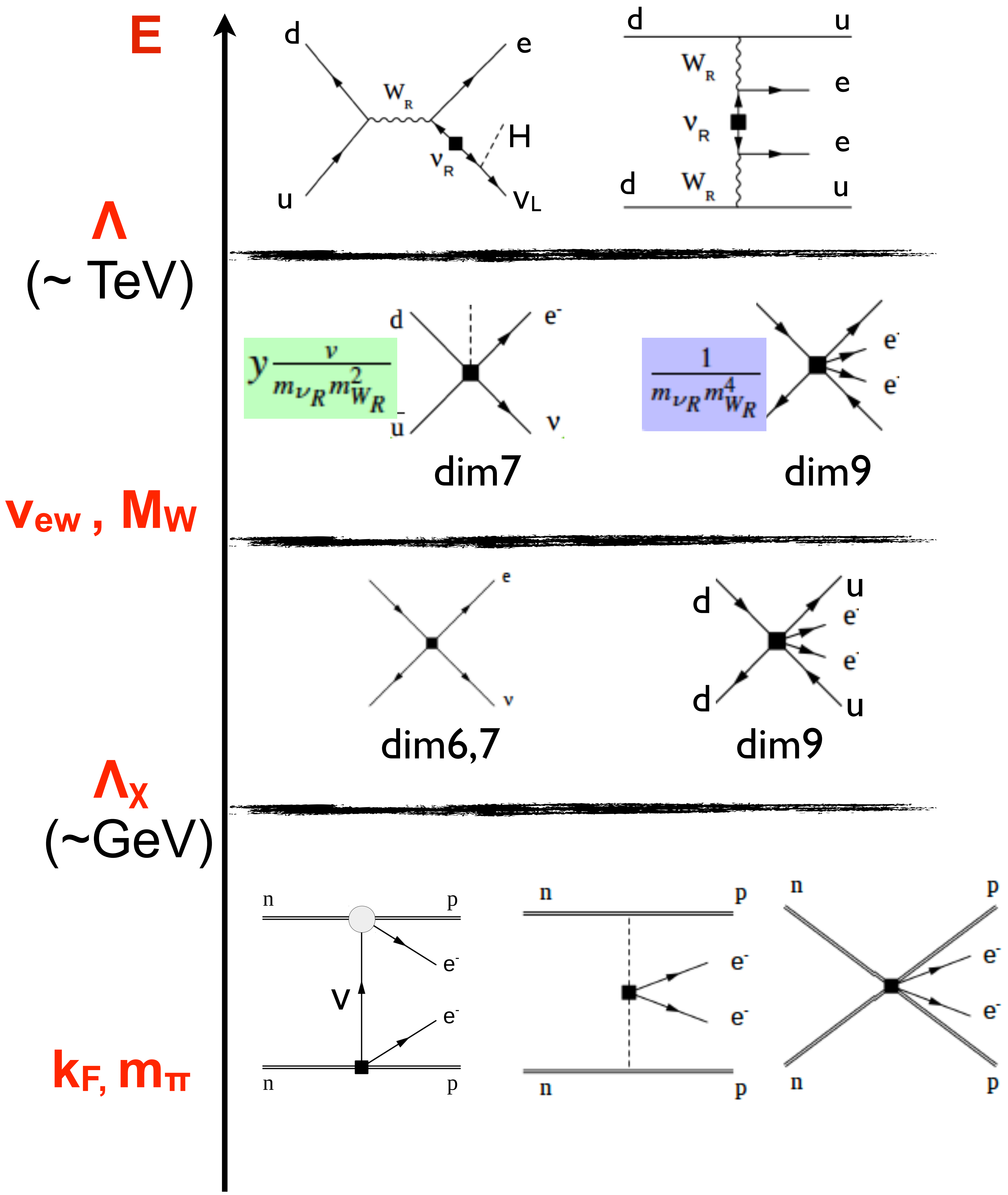


- Hadronic scale: new pion-range and short-range transition operators.



LNV @ multi-TeV-scale: EFT

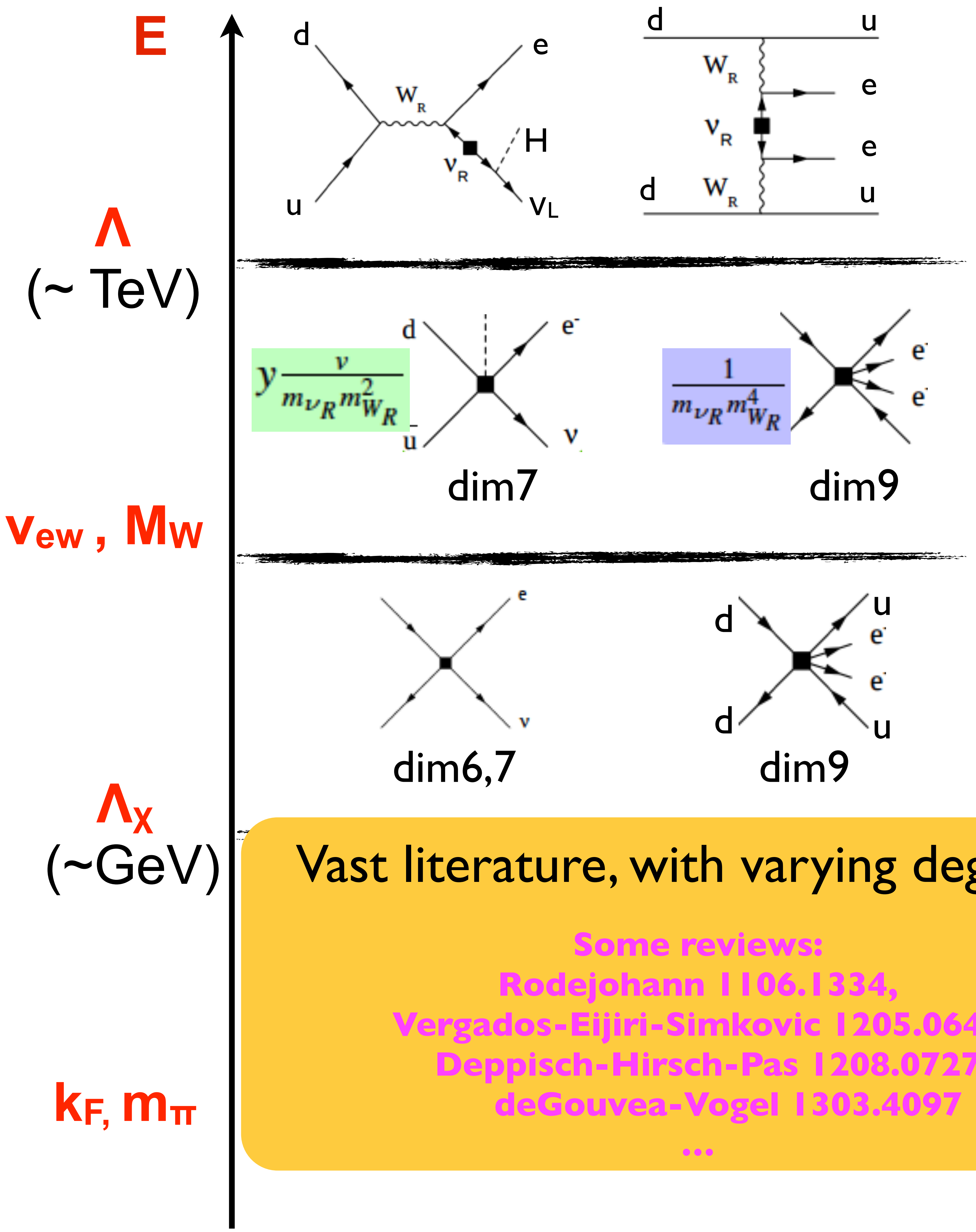


- Higher dim operators arise in well motivated models of neutrino mass. Can compete with Dim=5 operator if Λ~ O(1-10 TeV)

- 31 operators up to dimension 9

- New mechanisms at the hadronic scale: need appropriate chiral EFT treatment. Not including pion-range effects leads to factor ~ $(Q/Λ_χ)^2$ ~1/100 reduction in sensitivity to short-distance couplings!

LNV @ multi-TeV-scale: EFT



- Higher dim operators arise in well motivated models of neutrino mass. Can compete with Dim=5 operator if Λ~ O(1-10 TeV)

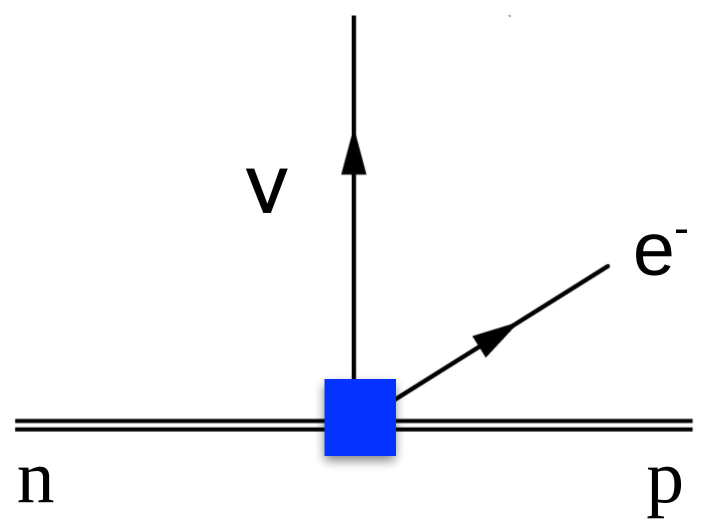
- 31 operators up to dimension 9

Vast literature, with varying degree of enthusiasm for EFT tools (SM-EFT, chiral EFT)

Some reviews:
Rodejohann 1106.1334,
Vergados-Eijiri-Simkovic 1205.0649
Deppisch-Hirsch-Pas 1208.0727
deGouvea-Vogel 1303.4097
...

Some recent papers:
VC-Dekens-deVries-Graesser-Mereghetti,1806.02780
Neacsu-Horoi 1801.04496.
Graf-Deppisch-Iachello-Kotila, 1806.06058
Graf, Lindner, Scholer 2204.10845
...

Dimension 6 and 7 operators



(In the LEFT, between EW and GeV scale)

$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big(C^{(6)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{R,i}\,\gamma_\mu\,C\bar{\nu}^T_{L,j}$$
$$+ C^{(6)}_{\mathrm{SR},ij}\,\bar{u}_L d_R\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{SL},ij}\,\bar{u}_R d_L\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{T},ij}\,\bar{u}_L\sigma^{\mu\nu} d_R\,\bar{e}_{L,i}\sigma_{\mu\nu}\,C\bar{\nu}^T_{L,j}\Big) + \mathrm{h.c.}$$

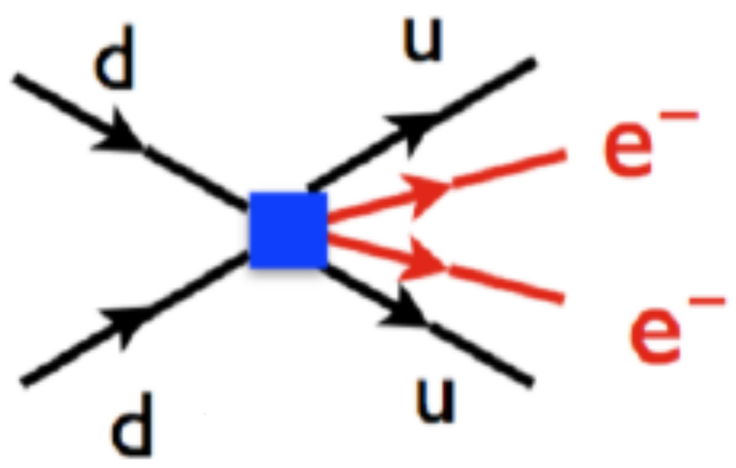
Dim 7 in SM-EFT

C ~$(v_{ew}/\Lambda)^3$

$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v}\Big(C^{(7)}_{\mathrm{VL},ij}\,\bar{u}_L\gamma^\mu d_L\,\bar{e}_{L,i}\,C\,i\overleftrightarrow{\partial}_\mu\bar{\nu}^T_{L,j} + C^{(7)}_{\mathrm{VR},ij}\,\bar{u}_R\gamma^\mu d_R\,\bar{e}_{L,i}\,Ci\overleftrightarrow{\partial}_\mu\bar{\nu}^T_{L,j}\Big) + \mathrm{h.c.}$$

Dimension 9 operators

(In the LEFT, between EW and GeV scale)



$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \left[\left(C^{(9)}_{i\mathrm{R}}\, \bar{e}_R C \bar{e}^T_R + C^{(9)}_{i\mathrm{L}}\, \bar{e}_L C \bar{e}^T_L \right) O_i + C^{(9)}_i\, \bar{e}\gamma_\mu\gamma_5 C\bar{e}^T\, O^\mu_i \right]$$

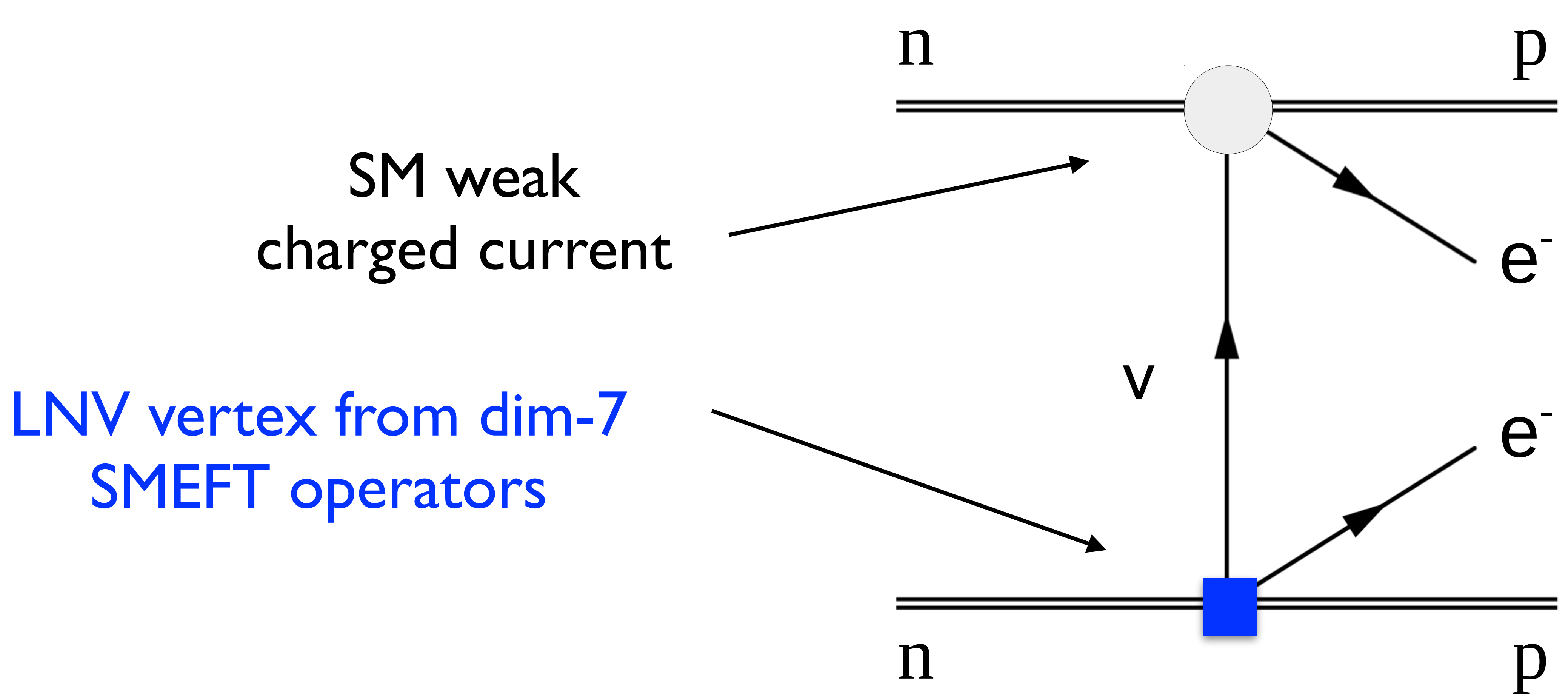
Dim 9 in SM-EFT

$C \sim (v_{ew}/\Lambda)^5$

$$\begin{aligned}
O_1 &= \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\alpha_L\, \bar{q}^\beta_L \gamma^\mu \tau^+ q^\beta_L\,, & O_1' &= \bar{q}^\alpha_R \gamma_\mu \tau^+ q^\alpha_R\, \bar{q}^\beta_R \gamma^\mu \tau^+ q^\beta_R\\
O_2 &= \bar{q}^\alpha_R \tau^+ q^\alpha_L\, \bar{q}^\beta_R \tau^+ q^\beta_L\,, & O_2' &= \bar{q}^\alpha_L \tau^+ q^\alpha_R\, \bar{q}^\beta_L \tau^+ q^\beta_R\,,\\
O_3 &= \bar{q}^\alpha_R \tau^+ q^\beta_L\, \bar{q}^\beta_R \tau^+ q^\alpha_L\,, & O_3' &= \bar{q}^\alpha_L \tau^+ q^\beta_R\, \bar{q}^\beta_L \tau^+ q^\alpha_R\,,\\
O_4 &= \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\alpha_L\, \bar{q}^\beta_R \gamma^\mu \tau^+ q^\beta_R\,, & &\\
O_5 &= \bar{q}^\alpha_L \gamma_\mu \tau^+ q^\beta_L\, \bar{q}^\beta_R \gamma^\mu \tau^+ q^\alpha_R\,, & &
\end{aligned}$$

$$\begin{aligned}
O^\mu_6 &= (\bar{q}_L \tau^+ \gamma^\mu q_L)\,(\bar{q}_L \tau^+ q_R)\ , & O^{\mu\prime}_6 &= (\bar{q}_R \tau^+ \gamma^\mu q_R)\,(\bar{q}_R \tau^+ q_L)\ ,\\
O^\mu_7 &= (\bar{q}_L t^a \tau^+ \gamma^\mu q_L)\,(\bar{q}_L t^a \tau^+ q_R)\ , & O^{\mu\prime}_7 &= (\bar{q}_R t^a \tau^+ \gamma^\mu q_R)\,(\bar{q}_R t^a \tau^+ q_L)\ ,\\
O^\mu_8 &= (\bar{q}_L \tau^+ \gamma^\mu q_L)\,(\bar{q}_R \tau^+ q_L)\ , & O^{\mu\prime}_8 &= (\bar{q}_R \tau^+ \gamma^\mu q_R)\,(\bar{q}_L \tau^+ q_R)\ ,\\
O^\mu_9 &= (\bar{q}_L t^a \tau^+ \gamma^\mu q_L)\,(\bar{q}_R t^a \tau^+ q_L)\ , & O^{\mu\prime}_9 &= (\bar{q}_R t^a \tau^+ \gamma^\mu q_R)\,(\bar{q}_L t^a \tau^+ q_R)\ ,
\end{aligned}$$

Hadronic realization of dim-7 operators



V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

Doi, Kotani, Takasugi 1985

Pas, Hirsch, Klapdor-Kleingrothaus, Kovalenko 1999

- Long range neutrino exchange without mass insertion
- Hadronic input in good shape: isovector nucleon charges V, A, S, P, T
- Nuclear m.e.: same as the ones needed for light ν_M exchange

Horoi and Neacsu, 1706.05391 and refs therein

Hadronic realization of dim-9 operators

VC, W. Dekens, M. Graesser, E. Mereghetti, J. de Vries 1806.02780

- Example: scalar operators (arising in most models)

$$\begin{aligned} \mathcal{O}_1 &= \bar{u}_L \gamma^\mu d_L \, \bar{u}_L \gamma_\mu d_L \\ \mathcal{O}_2 &= \bar{u}_L d_R \, \bar{u}_L \, d_R, \qquad \mathcal{O}_3 = \bar{u}_L^\alpha d_R^\beta \, \bar{u}_L^\beta \, d_R^\alpha \\ \mathcal{O}_4 &= \bar{u}_L \gamma^\mu d_L \, \bar{u}_R \gamma_\mu d_R, \qquad \mathcal{O}_5 = \bar{u}_L^\alpha \gamma^\mu d_L^\beta \, \bar{u}_R^\beta \, \gamma_\mu d_R^\alpha \end{aligned}$$

Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205
M. Graesser 1606.04549

- Hadronic realization depends on O_i's chiral properties

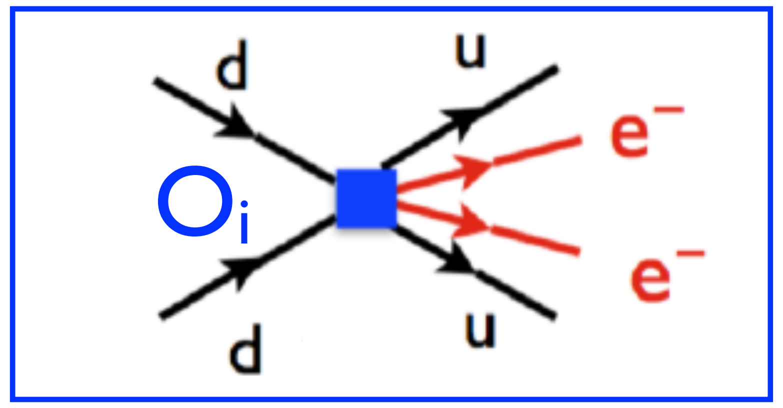
$$\mathcal{L}_{NN}^{\text{scalar}} = \left(g_1^{NN} C_{1\text{L}}^{(9)} + g_2^{NN} C_{2\text{L}}^{(9)} + g_3^{NN} C_{3\text{L}}^{(9)} + g_4^{NN} C_{4\text{L}}^{(9)} + g_5^{NN} C_{5\text{L}}^{(9)} \right) (\bar{p}n)\,(\bar{p}n)\, \frac{\bar{e}_L C \bar{e}_L^T}{v^5}$$

$$\mathcal{L}_{\pi N}^{\text{scalar}} = \sqrt{2} g_A g_1^{\pi N} C_{1\text{L}}^{(9)} F_0 \left[\bar{p}\, S \cdot (\partial \pi^-) n \right] \frac{\bar{e}_L C \bar{e}_L^T}{v^5} + (L \leftrightarrow R) + \dots$$

$$\mathcal{L}_{\pi}^{\text{scalar}} = \frac{F_0^2}{2} \left[\frac{5}{3} g_1^{\pi\pi} C_{1\text{L}}^{(9)} \partial_\mu \pi^- \partial^\mu \pi^- + \left(g_4^{\pi\pi} C_{4\text{L}}^{(9)} + g_5^{\pi\pi} C_{5\text{L}}^{(9)} - g_2^{\pi\pi} C_{2\text{L}}^{(9)} - g_3^{\pi\pi} C_{3\text{L}}^{(9)} \right) \pi^- \pi^- \right] \frac{\bar{e}_L C \bar{e}_L^T}{v^5} + (L \leftrightarrow R) + \dots$$

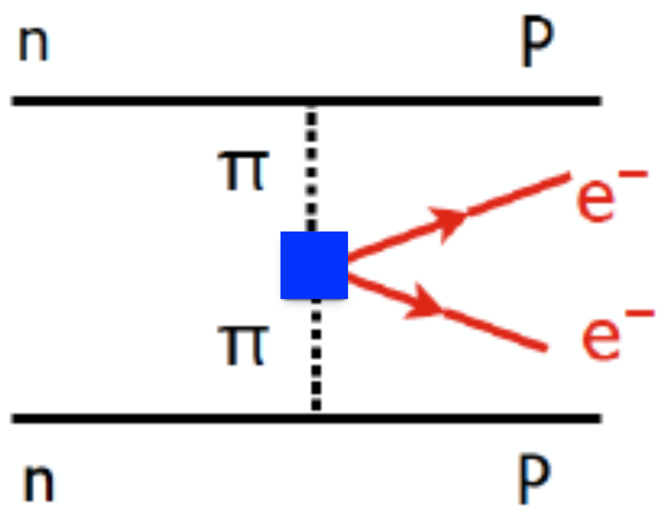
$$g_1^{\pi\pi} \sim \mathcal{O}(1), \qquad g_{2,3,4,5}^{\pi\pi} \sim \mathcal{O}(\Lambda_\chi^2) \qquad\qquad g_1^{NN} \sim \mathcal{O}(1), \qquad g_{2,3,4,5}^{NN} \sim \mathcal{O}\left(\frac{\Lambda_\chi^2}{F_\pi^2} \right)$$

Hadronic realization of dim-9 operators

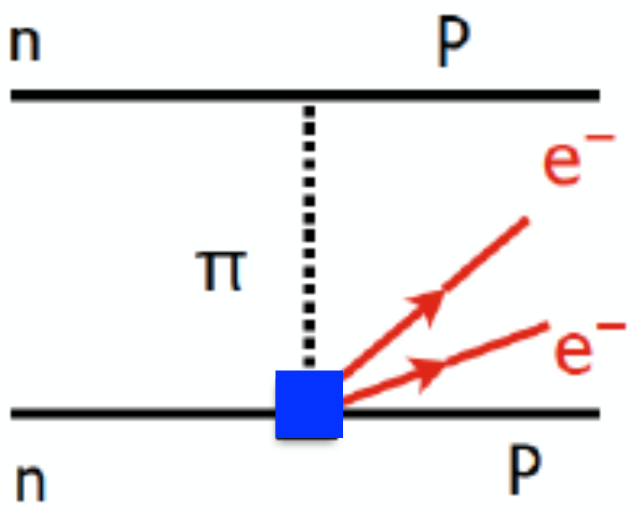


Pion-range effects

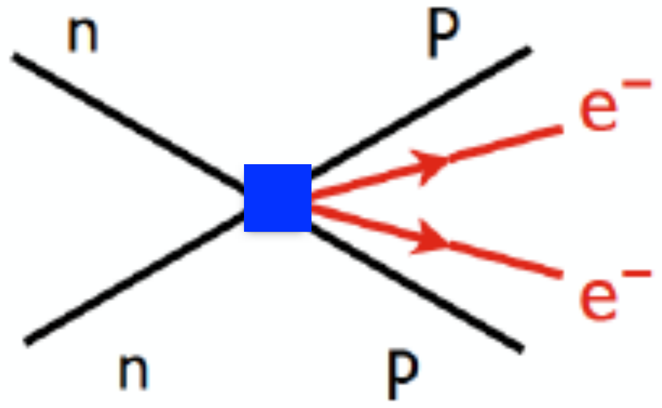
Short-range effects



Q^{-2}



Q^{0}

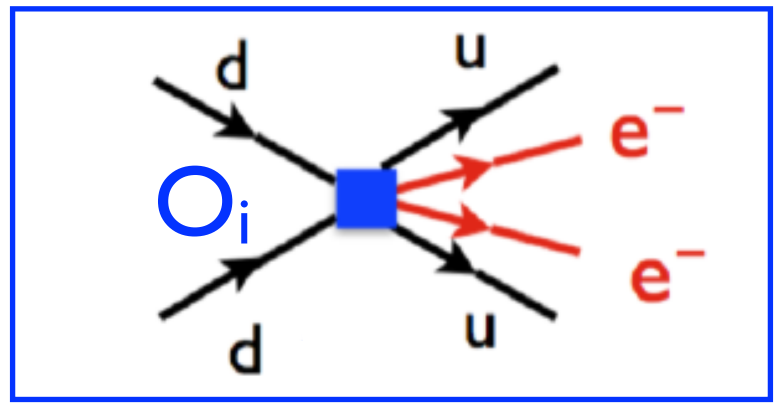


Q^{0}

Naive dimensional analysis $\rightarrow$ $V_{\pi\pi}$ dominates (except for O_1)

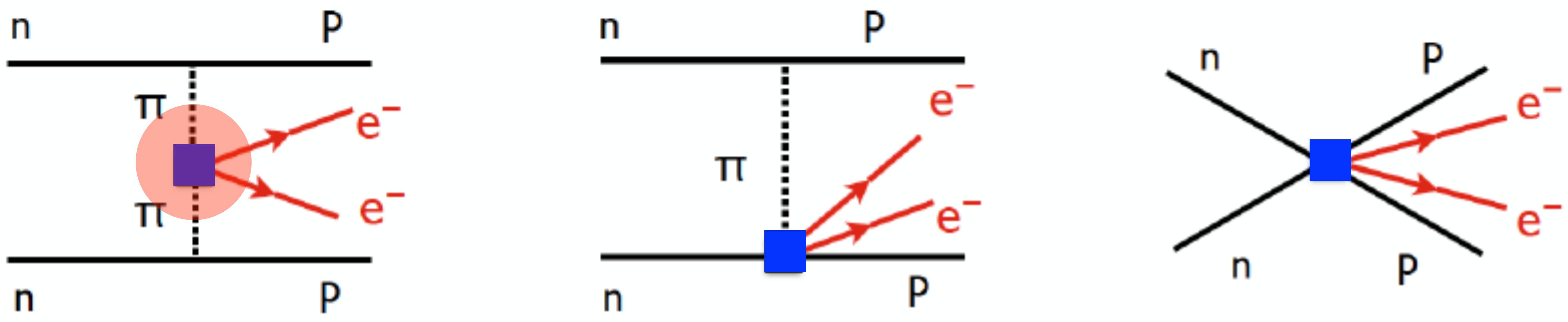
Vergados 1982, Faessler, Kovalenko, Simkovic, Schweiger 1996
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

Hadronic realization of dim-9 operators



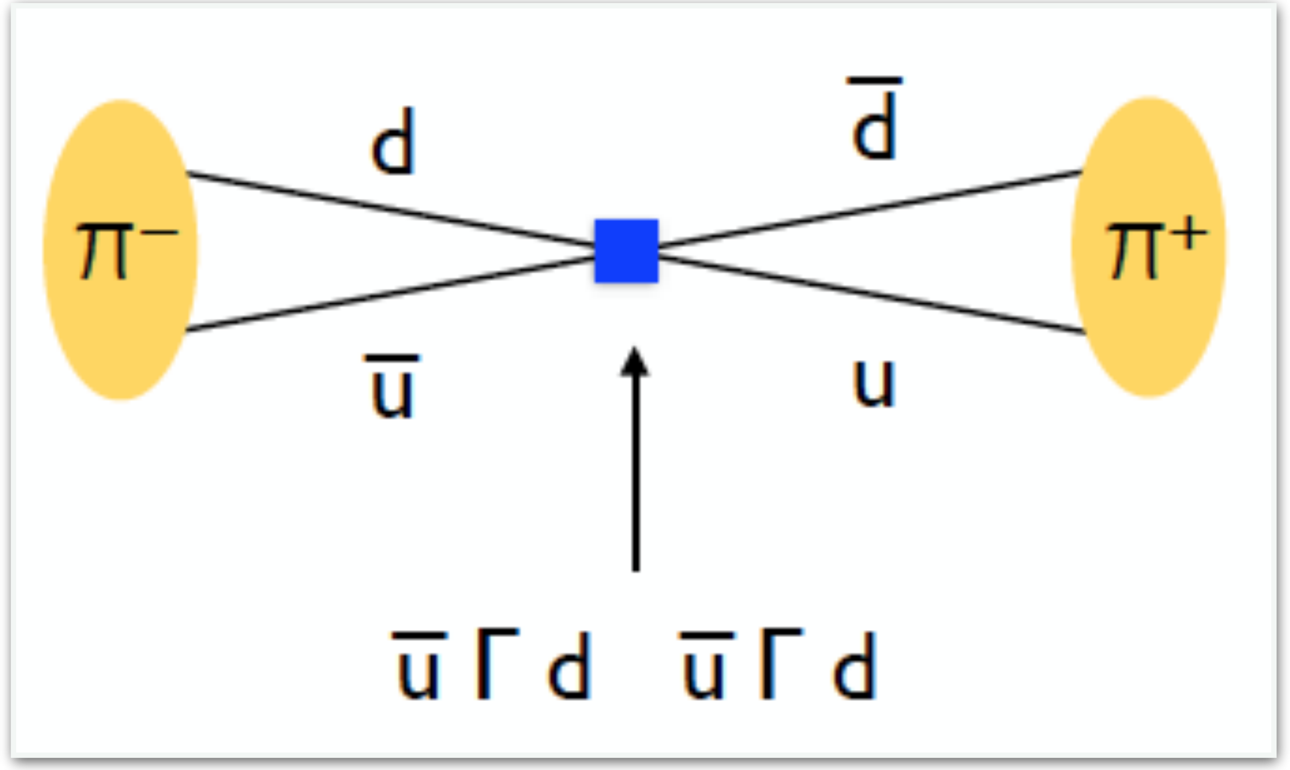
Pion-range effects

Short-range effects



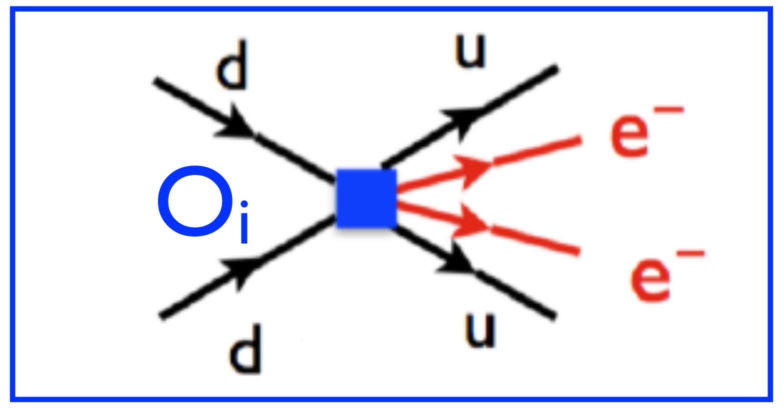
- Developments:

  1. ππ matrix elements now precisely calculated in lattice QCD



Nicholson et al (CalLat), 1805.02634
Detmold et al, 2208.05322

Hadronic realization of dim-9 operators



Pion-range effects

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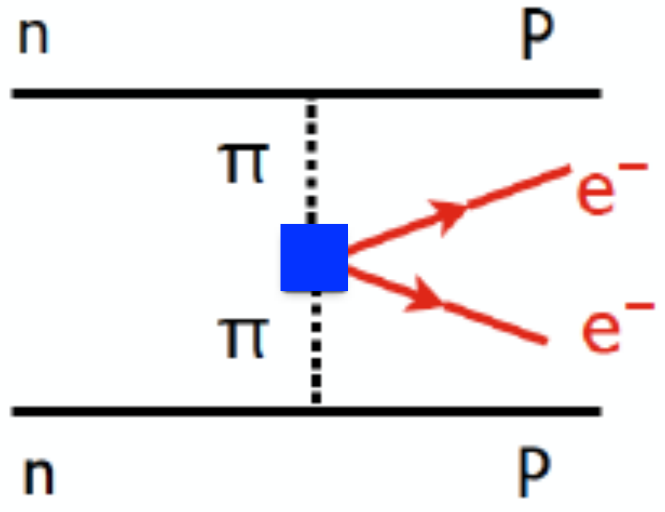
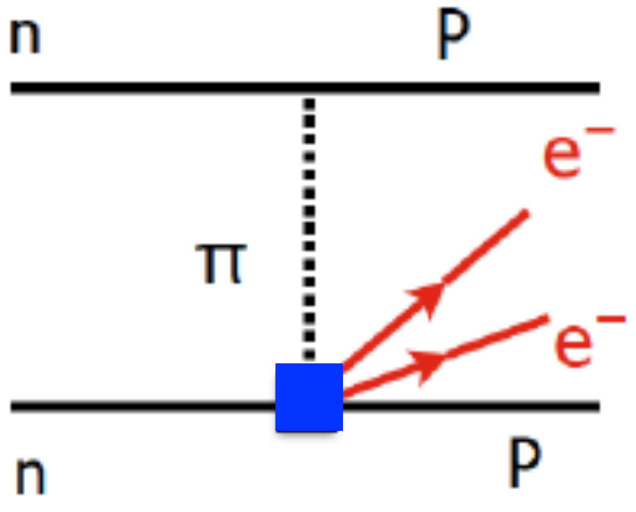
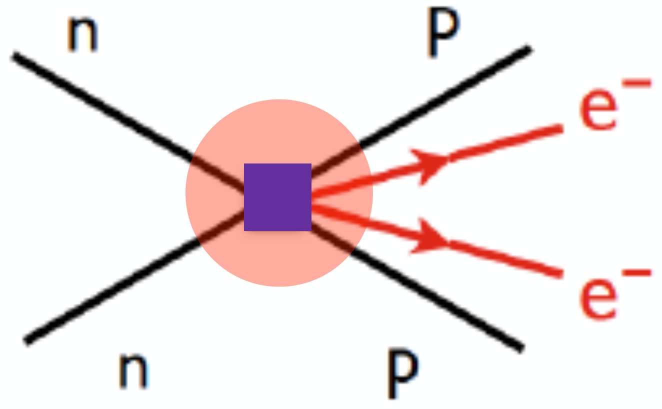
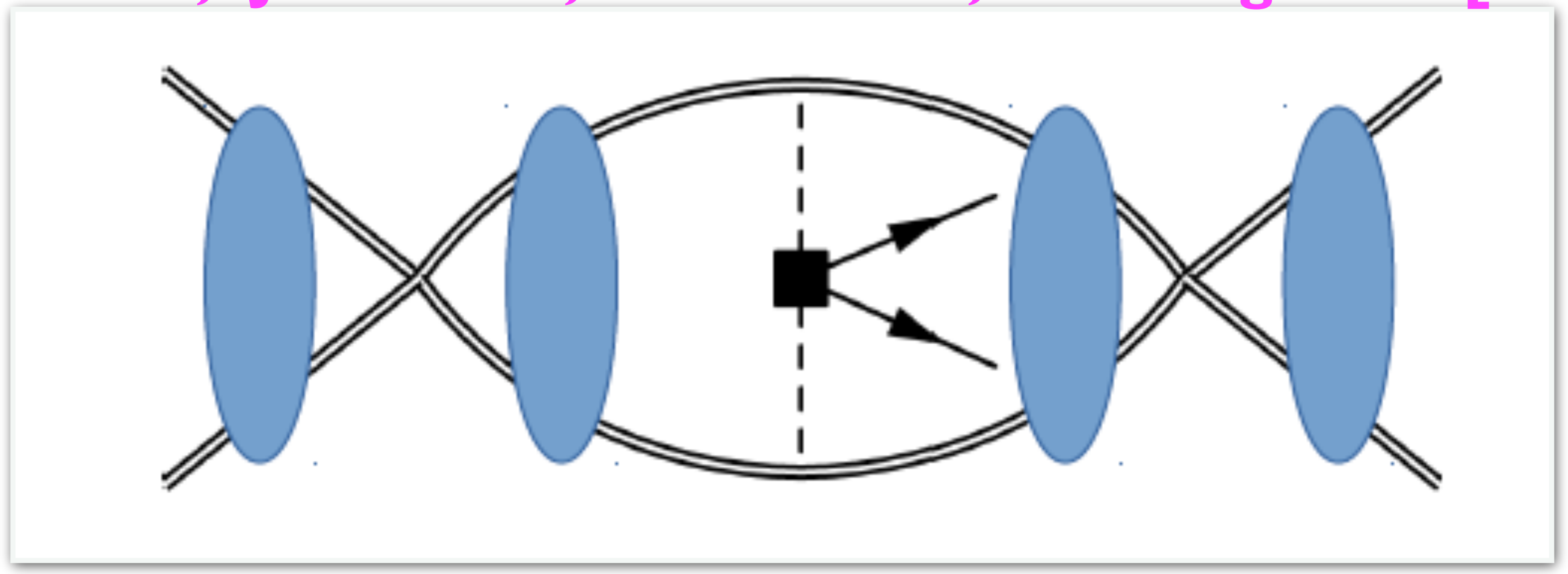






- Developments:

V.C, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti [1806.02780]



2. Renormalization → $V_{\pi\pi}$ and V_{NN} are both leading order

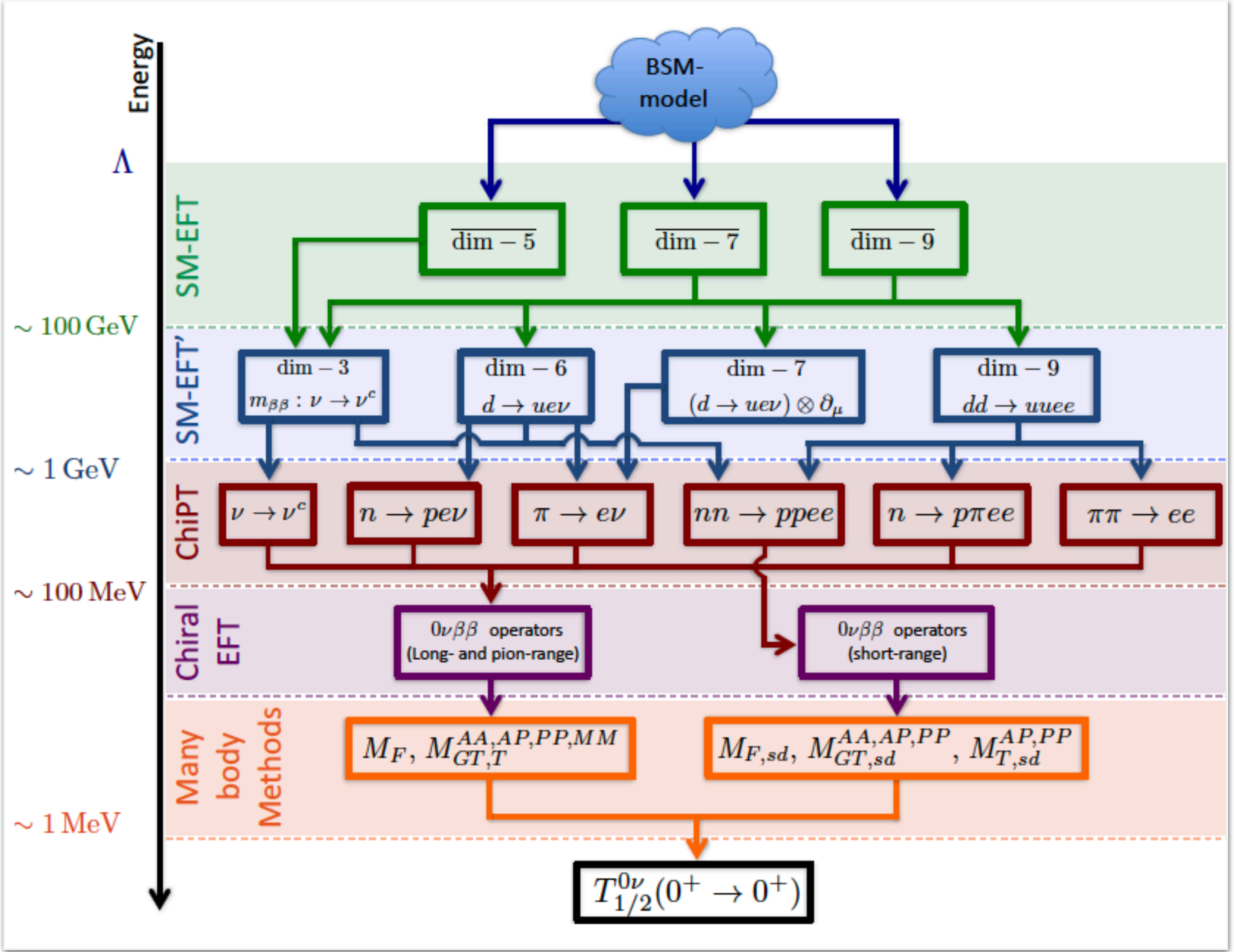
(Similar to light neutrino exchange!)

Several unknown LO NN contact couplings! Opportunity for LQCD

EFT-based master formula for half-life

V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

- Put everything together: master formula for half-life
- Framework to interpret 0νββ searches in terms of any high-scale model and possibly unravel the underlying mechanism in case of discovery



vDoBe Python tool:
Scholer-deVries-Graf, 2304.05415

EFT-based master formula for half-life

V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

$$\left(T^{0\nu}_{1/2}\right)^{-1} = \frac{1}{8\ln 2}\frac{1}{(2\pi)^5}\int \frac{d^3k_1}{2E_1}\frac{d^3k_2}{2E_2}|\mathcal{A}|^2 F(Z,E_1)F(Z,E_2)\delta(E_1+E_2+E_f-M_i)$$

$$\begin{aligned}\mathcal{A} \;=\; & \frac{g_A^2 G_F^2 m_e}{\pi R_A}\Big[\mathcal{A}_\nu\,\bar u(k_1)P_R C\bar u^T(k_2) + \mathcal{A}_R\,\bar u(k_1)P_L C\bar u^T(k_2) \\ & + \mathcal{A}_E\,\bar u(k_1)\gamma_0 C\bar u^T(k_2)\frac{E_1-E_2}{m_e} + \mathcal{A}_{m_e}\,\bar u(k_1)C\bar u^T(k_2) + \mathcal{A}_M\,\bar u(k_1)\gamma_0\gamma_5 C\bar u^T(k_2)\Big]\end{aligned}$$

Nuclear amplitudes depend on 32 effective LNV couplings and corresponding nuclear matrix elements

$$\begin{aligned}
\mathcal{A}_\nu =& \frac{m_{\beta\beta}}{m_e}\mathcal{M}_\nu^{(3)} + \frac{m_N}{m_e}\mathcal{M}_\nu^{(6)}\left(C^{(6)}_{\rm SL}, C^{(6)}_{\rm SR}, C^{(6)}_{\rm T}, C^{(7)}_{\rm VL}, C^{(7)}_{\rm VR}\right) \\
& + \frac{m_N^2}{m_e v}\mathcal{M}_\nu^{(9)}\left(C^{(9)}_{\rm 1L}, C^{(9)\prime}_{\rm 1L}, C^{(9)}_{\rm 2L}, C^{(9)\prime}_{\rm 2L}, C^{(9)}_{\rm 3L}, C^{(9)\prime}_{\rm 3L}, C^{(9)}_{\rm 4L}, C^{(9)}_{\rm 5L}\right), \\
\mathcal{A}_R =& \frac{m_N^2}{m_e v}\mathcal{M}_R^{(9)}\left(C^{(9)}_{\rm 1R}, C^{(9)\prime}_{\rm 1R}, C^{(9)}_{\rm 2R}, C^{(9)\prime}_{\rm 2R}, C^{(9)}_{\rm 3R}, C^{(9)\prime}_{\rm 3R}, C^{(9)}_{\rm 4R}, C^{(9)}_{\rm 5R}\right), \\
\mathcal{A}_E =& \mathcal{M}^{(6)}_{E,L}\left(C^{(6)}_{\rm VL}\right) + \mathcal{M}^{(6)}_{E,R}\left(C^{(6)}_{\rm VR}\right), \\
\mathcal{A}_{m_e} =& \mathcal{M}^{(6)}_{m_e,L}\left(C^{(6)}_{\rm VL}\right) + \mathcal{M}^{(6)}_{m_e,R}\left(C^{(6)}_{\rm VR}\right), \\
\mathcal{A}_M =& \frac{m_N}{m_e}\mathcal{M}_M^{(6)}\left(C^{(6)}_{\rm VL}\right) + \frac{m_N^2}{m_e v}\mathcal{M}_M^{(9)}\left(C^{(9)}_6, C^{(9)\prime}_6, C^{(9)}_7, C^{(9)\prime}_7, C^{(9)}_8, C^{(9)\prime}_8, C^{(9)}_9, C^{(9)\prime}_9\right)
\end{aligned}$$

EFT-based master formula for half-life

V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

$$\left(T^{0\nu}_{1/2}\right)^{-1} = \frac{1}{8\ln 2}\frac{1}{(2\pi)^5}\int \frac{d^3k_1}{2E_1}\frac{d^3k_2}{2E_2}|\mathcal{A}|^2 F(Z,E_1)F(Z,E_2)\delta(E_1+E_2+E_f-M_i)$$

$$\begin{aligned}\mathcal{A} \;=\; & \frac{g_A^2 G_F^2 m_e}{\pi R_A}\Big[\mathcal{A}_\nu\, \bar{u}(k_1)P_R C\bar{u}^T(k_2) + \mathcal{A}_R\, \bar{u}(k_1)P_L C\bar{u}^T(k_2) \\ & + \mathcal{A}_E\, \bar{u}(k_1)\gamma_0 C\bar{u}^T(k_2)\frac{E_1-E_2}{m_e} + \mathcal{A}_{m_e}\, \bar{u}(k_1)C\bar{u}^T(k_2) + \mathcal{A}_M\, \bar{u}(k_1)\gamma_0\gamma_5 C\bar{u}^T(k_2)\Big]\end{aligned}$$

Different leptonic structure lead to different phase space weights

$$G_{0k} = \frac{1}{\ln 2}\frac{G_F^4 m_e^2}{64\pi^5 R_A^2}\int dE_1 dE_2 |\mathbf{k}_1||\mathbf{k}_2| d\cos\theta\, b_{0k}\, F(Z,E_1)F(Z,E_2)\delta(E_1+E_2+E_f-M_i)$$

$$\begin{aligned} b_{01} &= E_1E_2 - \mathbf{k}_1\cdot\mathbf{k}_2\,, \quad b_{02} = \left(\frac{E_1-E_2}{m_e}\right)^2 \frac{E_1E_2+\mathbf{k}_1\cdot\mathbf{k}_2 - m_e^2}{2}\,, \quad b_{03} = (E_1-E_2)^2\,, \\ b_{04} &= \left(E_1E_2 - \mathbf{k}_1\cdot\mathbf{k}_2 - m_e^2\right)\,, \quad b_{06} = 2m_e\left(E_1+E_2\right)\,, \quad b_{09} = 2\left(E_1E_2+\mathbf{k}_1\cdot\mathbf{k}_2+m_e^2\right)\end{aligned}$$

EFT-based master formula for half-life

V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, JHEP 1812 (2018) 097 [1806.02780]

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \frac{1}{8\ln 2}\frac{1}{(2\pi)^5}\int \frac{d^3k_1}{2E_1}\frac{d^3k_2}{2E_2}|\mathcal{A}|^2 F(Z,E_1)F(Z,E_2)\delta(E_1+E_2+E_f-M_i)$$

$$\begin{aligned}\mathcal{A} \;=\; & \frac{g_A^2 G_F^2 m_e}{\pi R_A}\Big[\mathcal{A}_\nu\, \bar{u}(k_1)P_R C\bar{u}^T(k_2) + \mathcal{A}_R\, \bar{u}(k_1)P_L C\bar{u}^T(k_2) \\ & + \mathcal{A}_E\, \bar{u}(k_1)\gamma_0 C\bar{u}^T(k_2)\frac{E_1-E_2}{m_e} + \mathcal{A}_{m_e}\, \bar{u}(k_1)C\bar{u}^T(k_2) + \mathcal{A}_M\, \bar{u}(k_1)\gamma_0\gamma_5 C\bar{u}^T(k_2)\Big]\end{aligned}$$

$$\begin{aligned}\left(T_{1/2}^{0\nu}\right)^{-1} \;=\; & g_A^4\Big\{ G_{01}\left(|\mathcal{A}_\nu|^2+|\mathcal{A}_R|^2\right) - 2(G_{01}-G_{04})\mathrm{Re}\mathcal{A}_\nu^*\mathcal{A}_R + 4G_{02}\,|\mathcal{A}_E|^2 \\ & + 2G_{04}\left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re}\left(\mathcal{A}_{m_e}^*(\mathcal{A}_\nu+\mathcal{A}_R)\right)\right] - 2G_{03}\,\mathrm{Re}\left[(\mathcal{A}_\nu+\mathcal{A}_R)\mathcal{A}_E^* + 2\mathcal{A}_{m_e}\mathcal{A}_E^*\right] \\ & + G_{09}\,|\mathcal{A}_M|^2 + G_{06}\,\mathrm{Re}\left[(\mathcal{A}_\nu-\mathcal{A}_R)\mathcal{A}_M^*\right]\Big\}\end{aligned}$$

G_{ik} = phase space factors

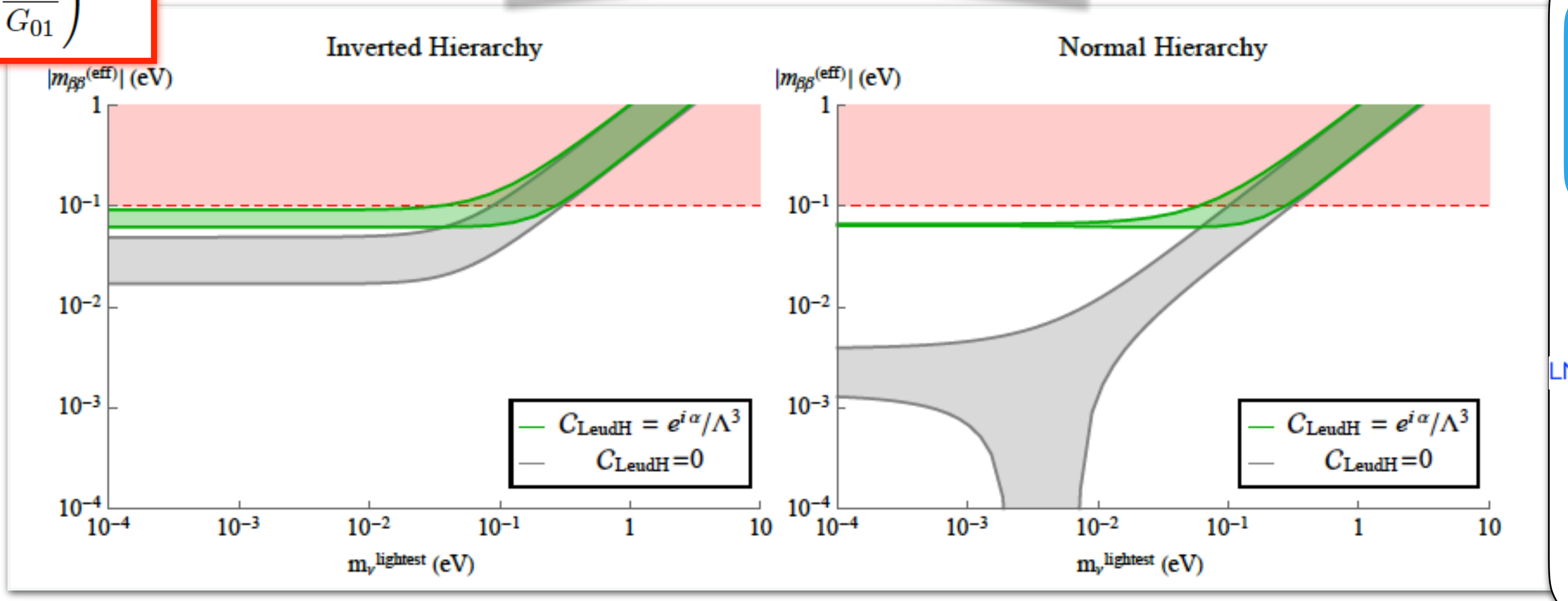
Kotila-Iachello 1209.5722

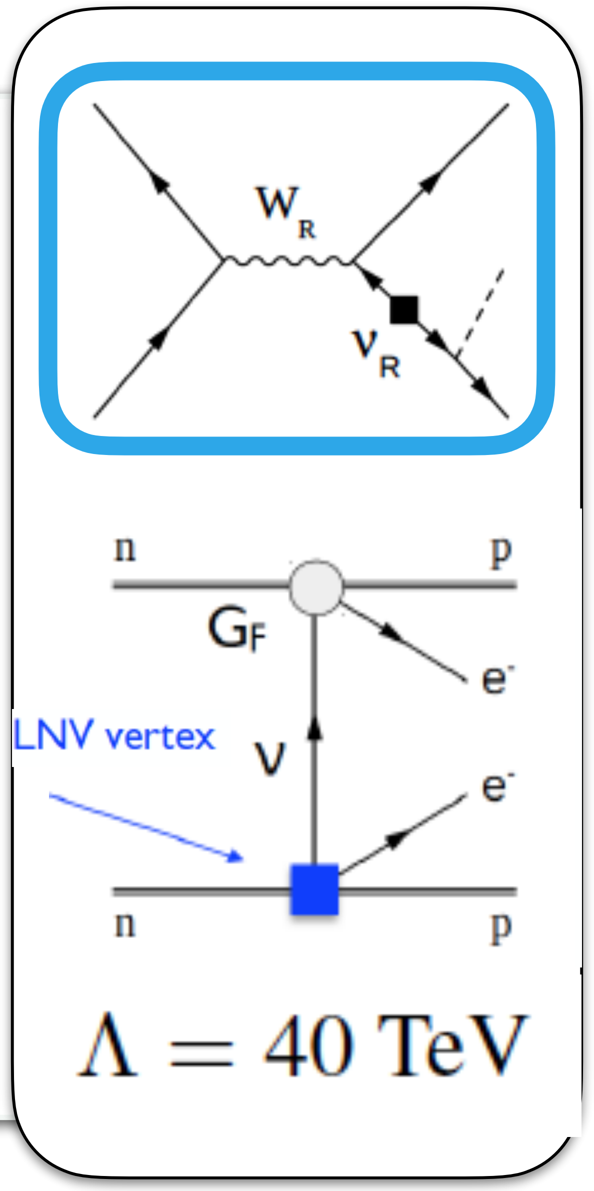
$0\nu\beta\beta$ from multiple operators

New contributions can add incoherently *or interfere with $m_{\beta\beta}$*, significantly affecting the interpretation of experimental results

$$C_{LeudH}\,\epsilon_{ij}\,(\bar{d}\gamma^{\mu}u)\,(L_m^T C\gamma_{\mu}e)\,H_j$$

$$m_{\beta\beta}^{(\mathrm{eff})} = \frac{m_e}{g_A^2 M_\nu}\left(\frac{T_{1/2}^{0\nu}}{G_{01}}\right)^{-1/2}$$





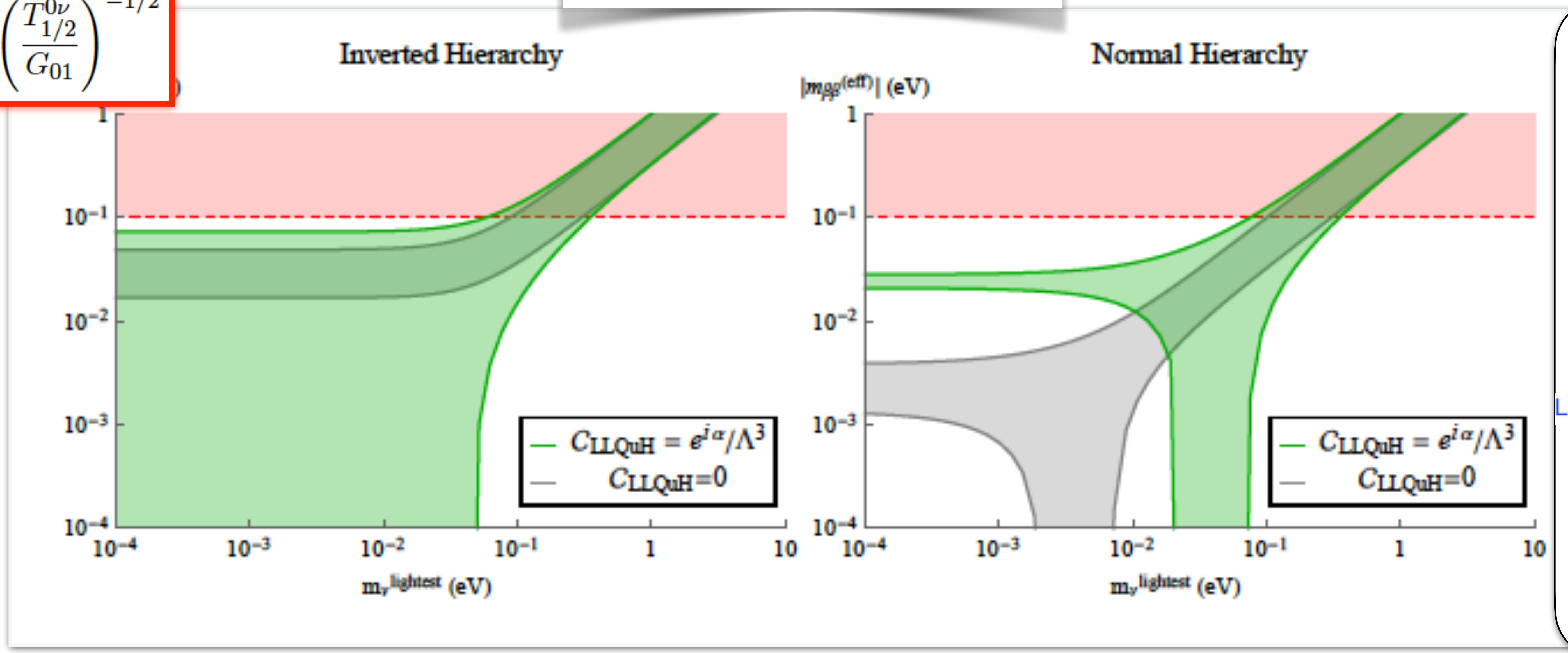
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

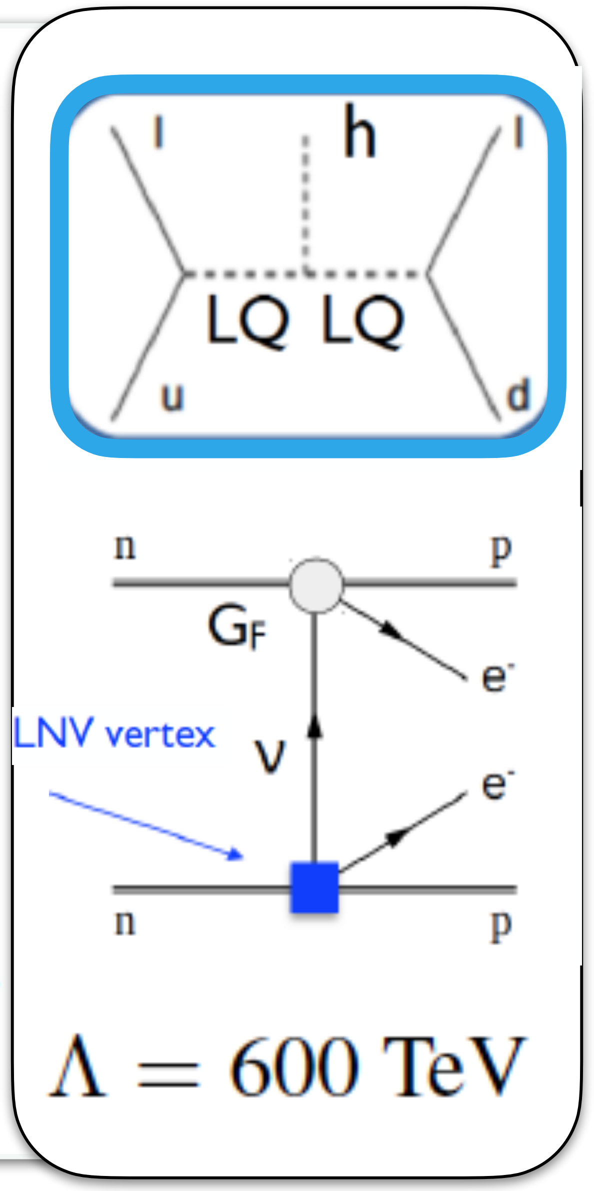
0νββ from multiple operators

New contributions can add incoherently *or interfere with $m_{\beta\beta}$*, significantly affecting the interpretation of experimental results

$$m_{\beta\beta}^{(\mathrm{eff})} = \frac{m_e}{g_A^2 M_\nu}\left(\frac{T_{1/2}^{0\nu}}{G_{01}}\right)^{-1/2}$$

$$C_{LL\bar{Q}uH}\, \epsilon_{ij}\, (\bar{Q}_m u)\, (L_m^T C L_i)\, H_j$$





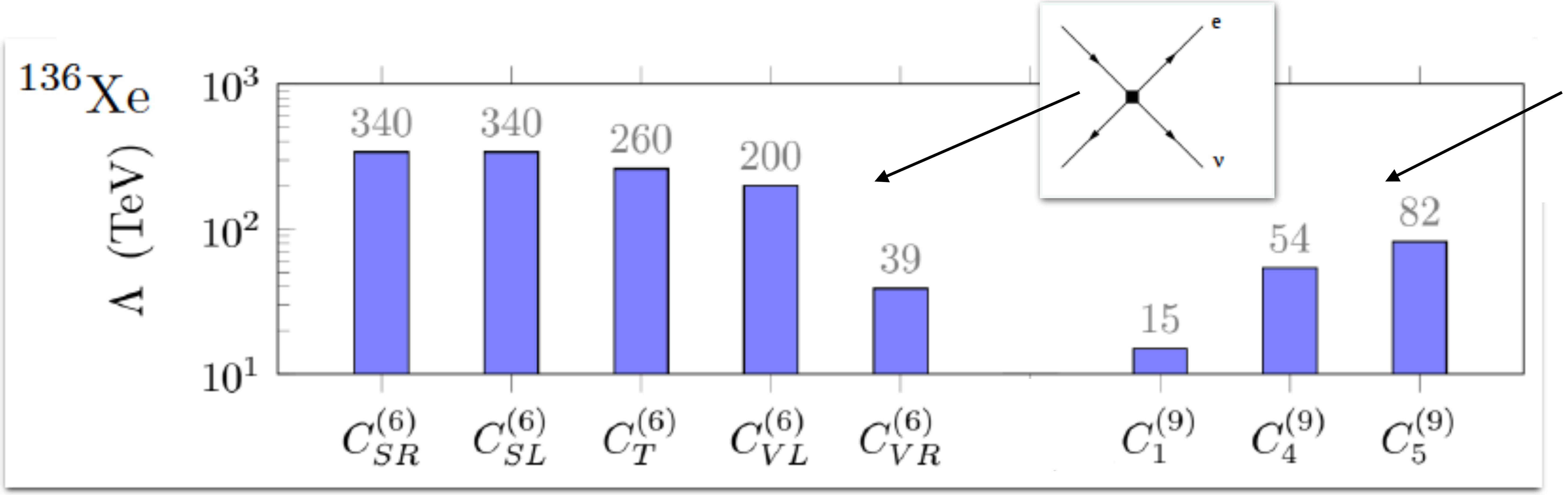
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

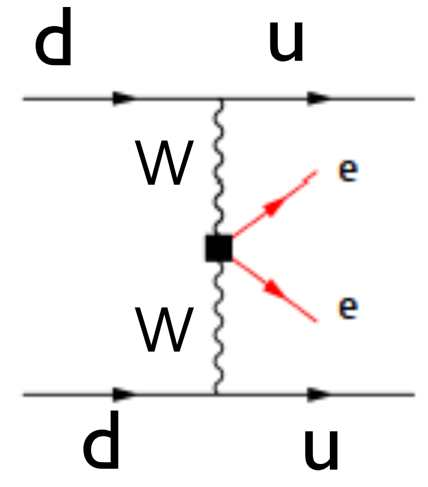
What scales are we probing?

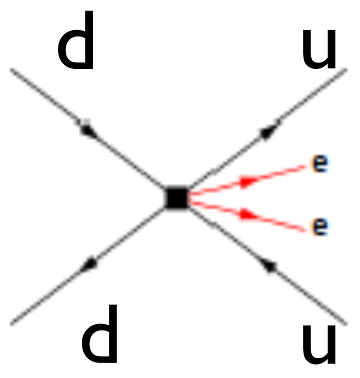
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1806.02780

Dim 7 in SM-EFT

$(v_{ew}/\Lambda)^3$

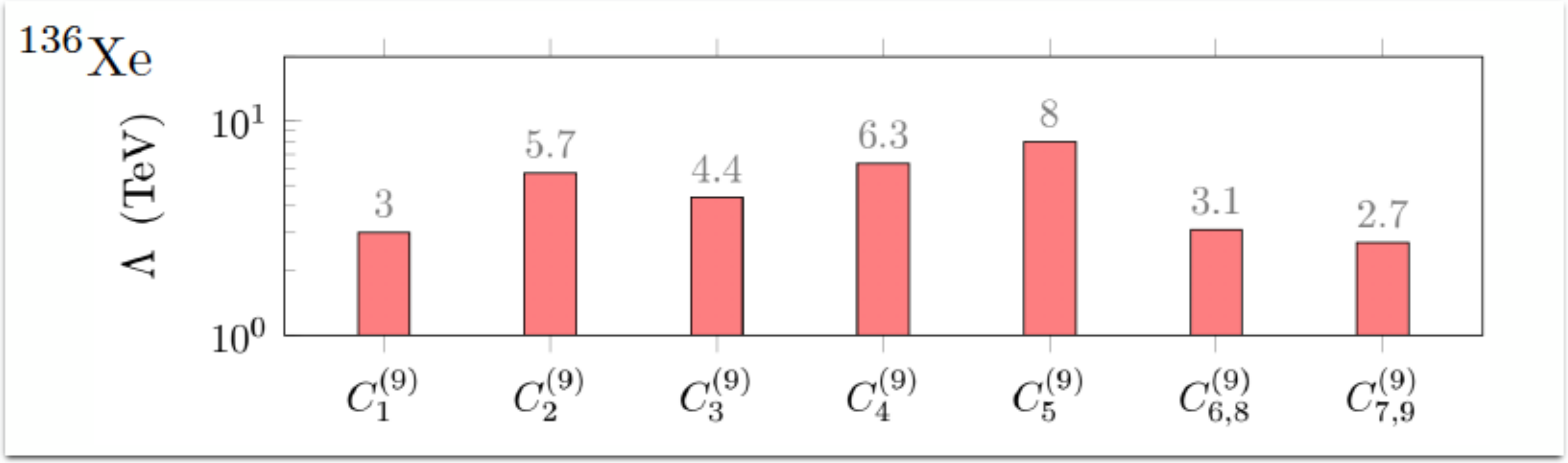






Dim 9 in SM-EFT

$(v_{ew}/\Lambda)^5$



Sensitivities reflect dependence on Λ_χ/Λ and Q/Λ_χ

What scales are we probing?

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1806.02780

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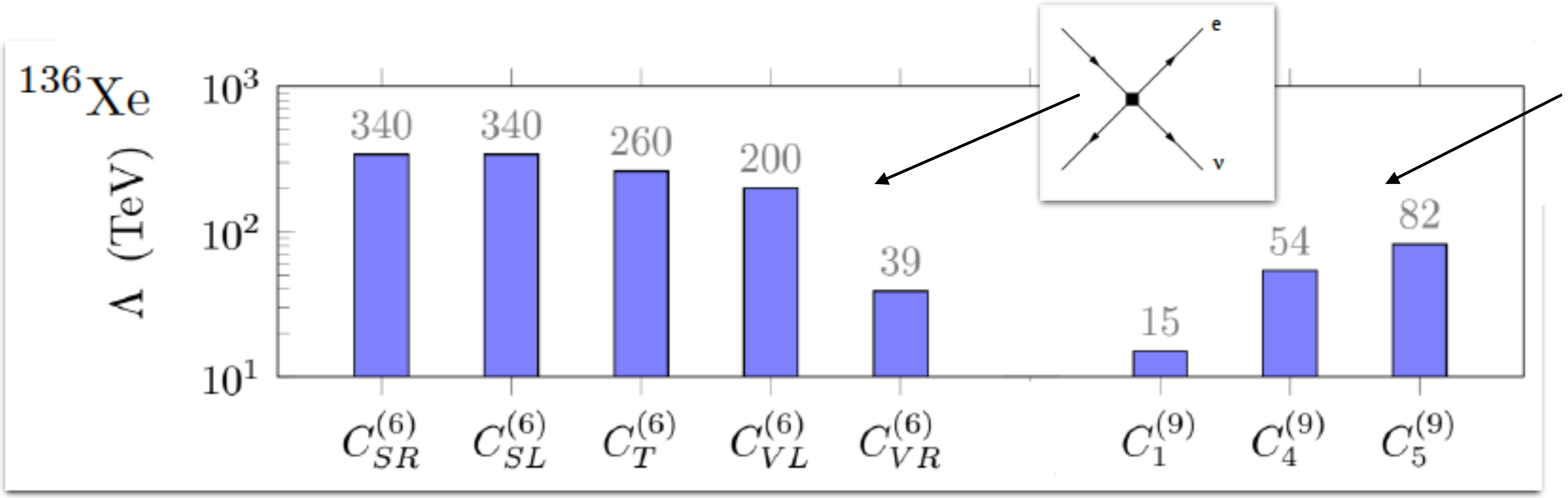

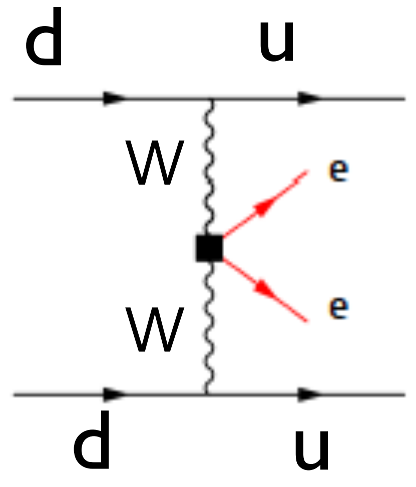

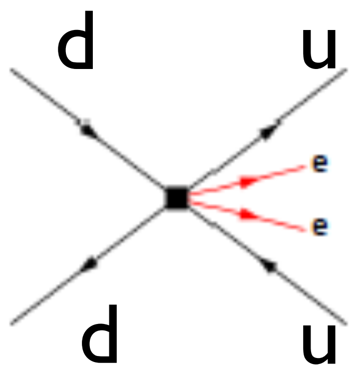

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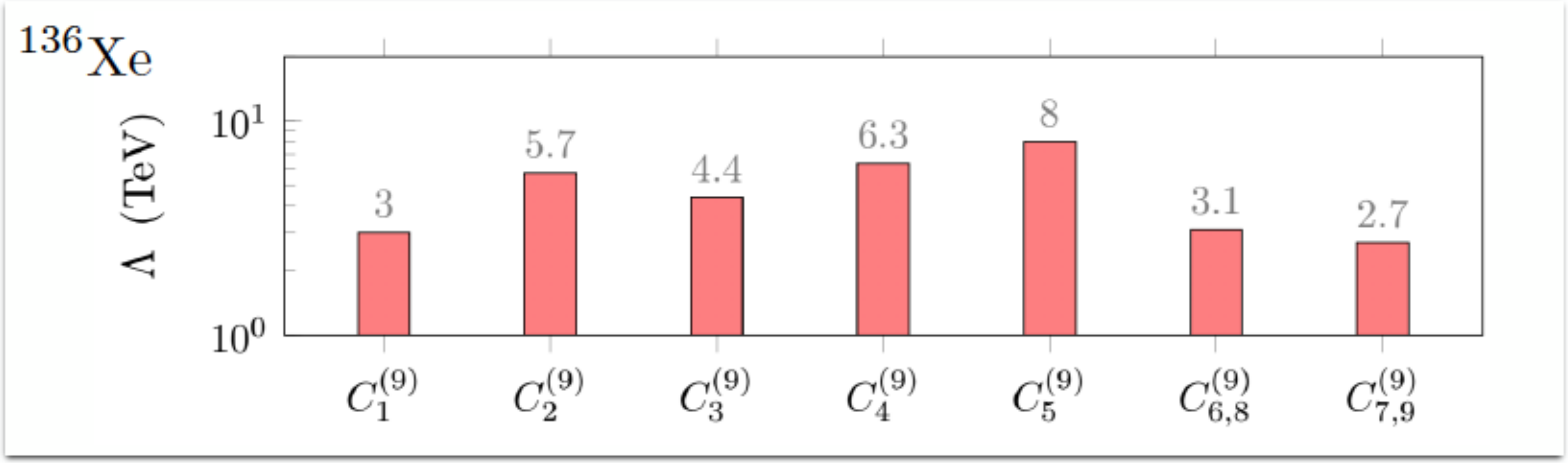


For some mechanisms, there is a possibility of simultaneous detection in $0\nu\beta\beta$ and at the LHC

Sensitivities reflect dependence on Λ_χ/Λ and Q/Λ_χ

Connection to collider physics

- May lead to correlated (or precursor!) signal at LHC: pp $\to$ee jj

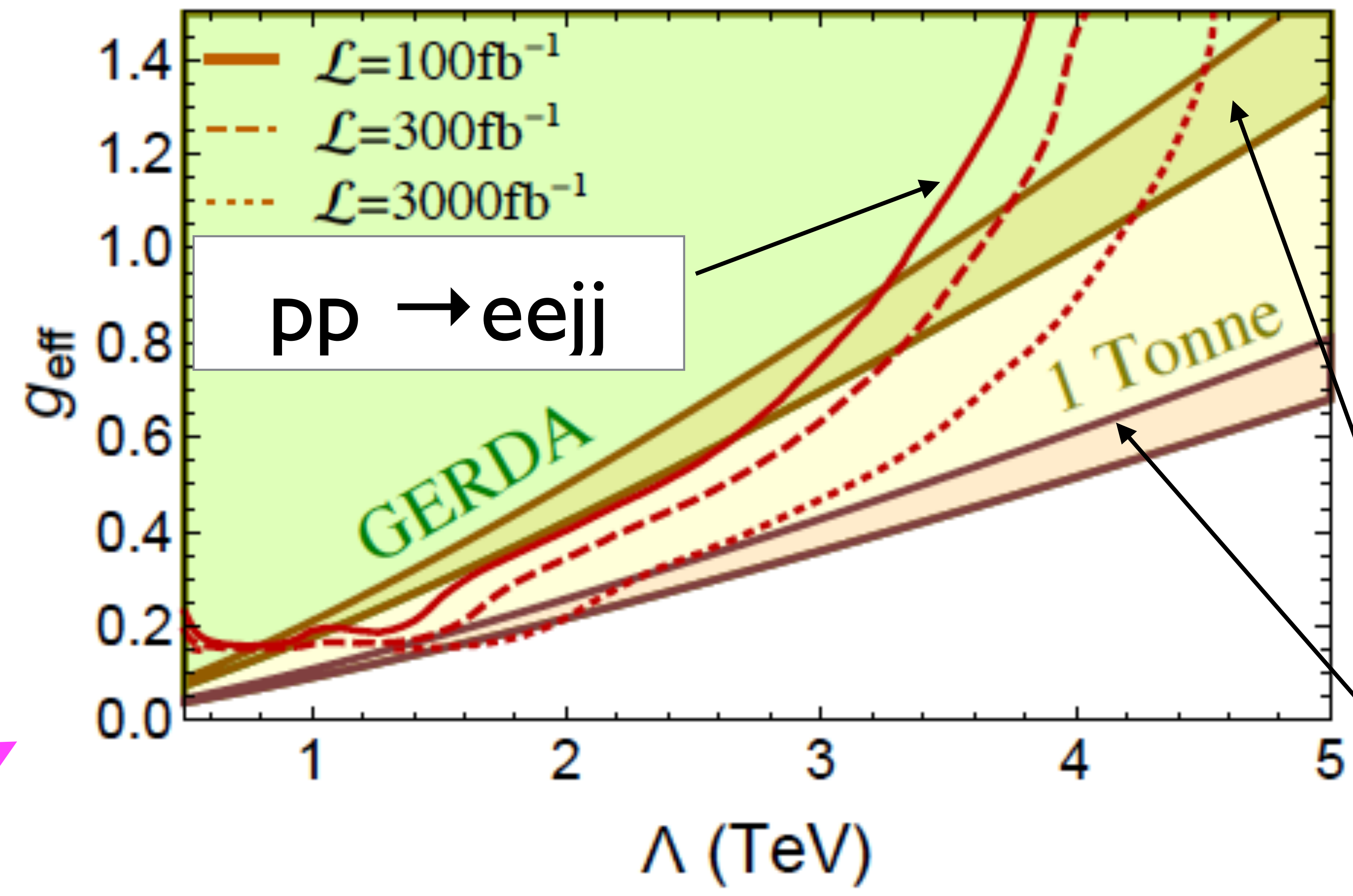
Keung-Senjanovic '83

Maiezza-Nemevesek-Nesti- Senjanovic 1005.5160

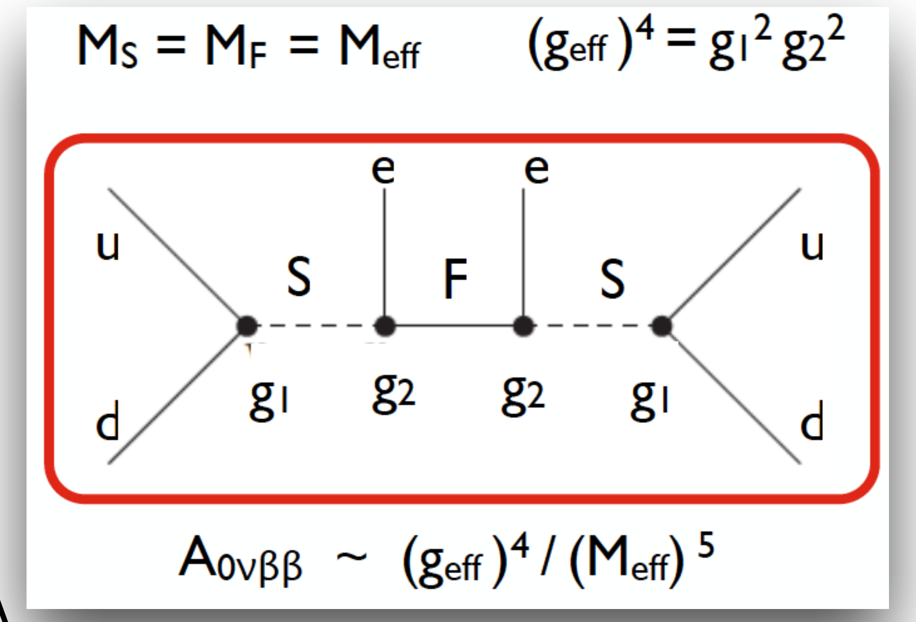
Helo-Kovalenko-Hirsch-Pas 1303.0899, 1307.4849

Cai, Han, Li, Ruiz 1711.02180

Peng, Ramsey-Musolf, Winslow, 1508.0444 …



Simplified model



Hadronic / nuclear uncertainty

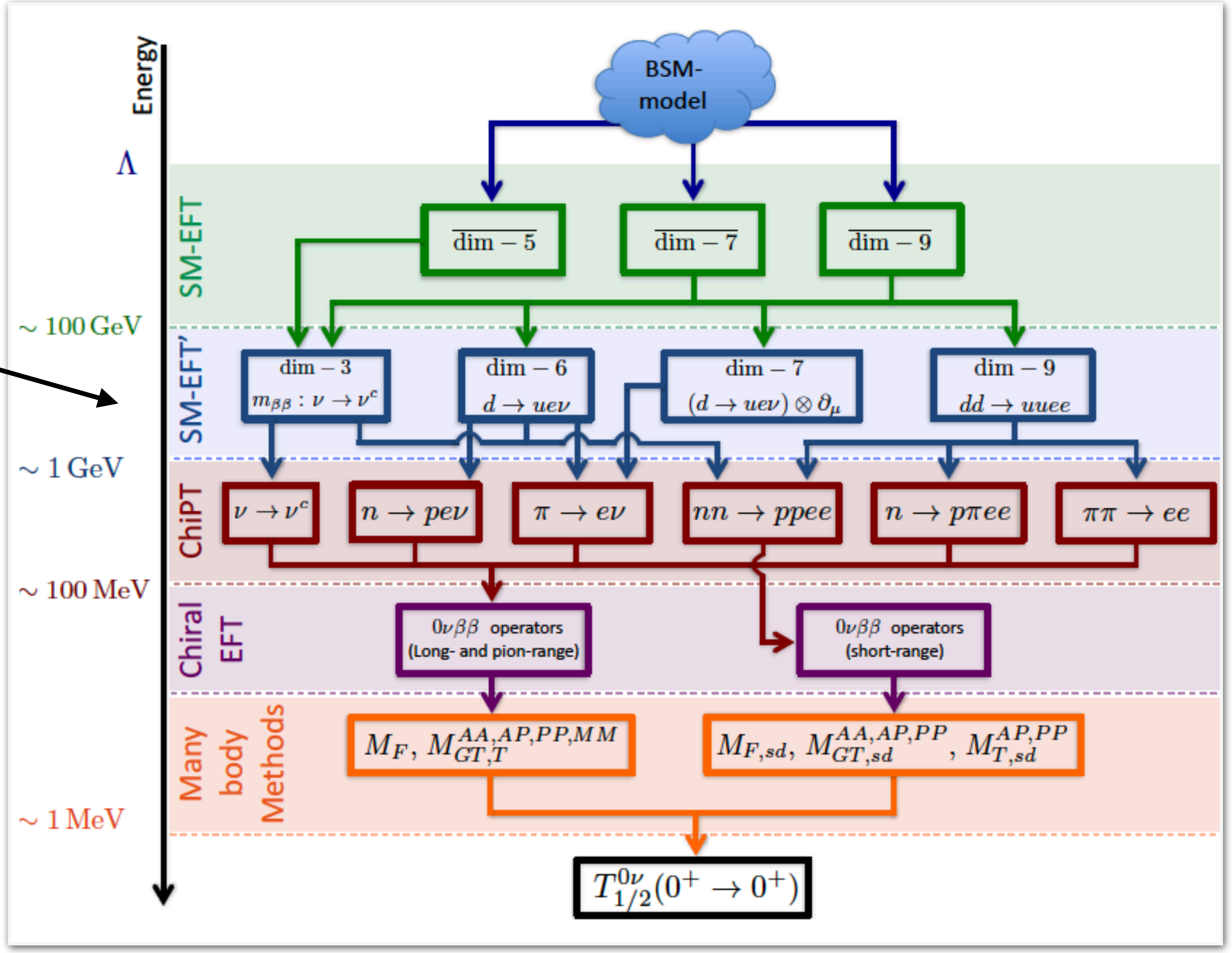
- LHC searches important to unravel origin of LNV and implications for letpogenesis

Deppisch-Harz-Hirsch 1312.4447, Deppisch-Graf-Harz-Huang 1711.10432, Harz, Ramsey-Musolf, Shen, Urrutia-Quiroga 2106.10838 , …

Unraveling 0νββ mechanisms?

Graf, Lindner, Scholer 2204.10845

- 32 operators below weak scale @ dim=3, 6, 7, 9 contribute to 0νββ



- Can they be distinguished by

1. Isotope-dependence of the decay rates?

3. Phase space observables? (single electron spectra, relative angle of outgoing electrons)

Useful diagnosing tools 'within' 0νββ — can falsify specific models

Phase space observables

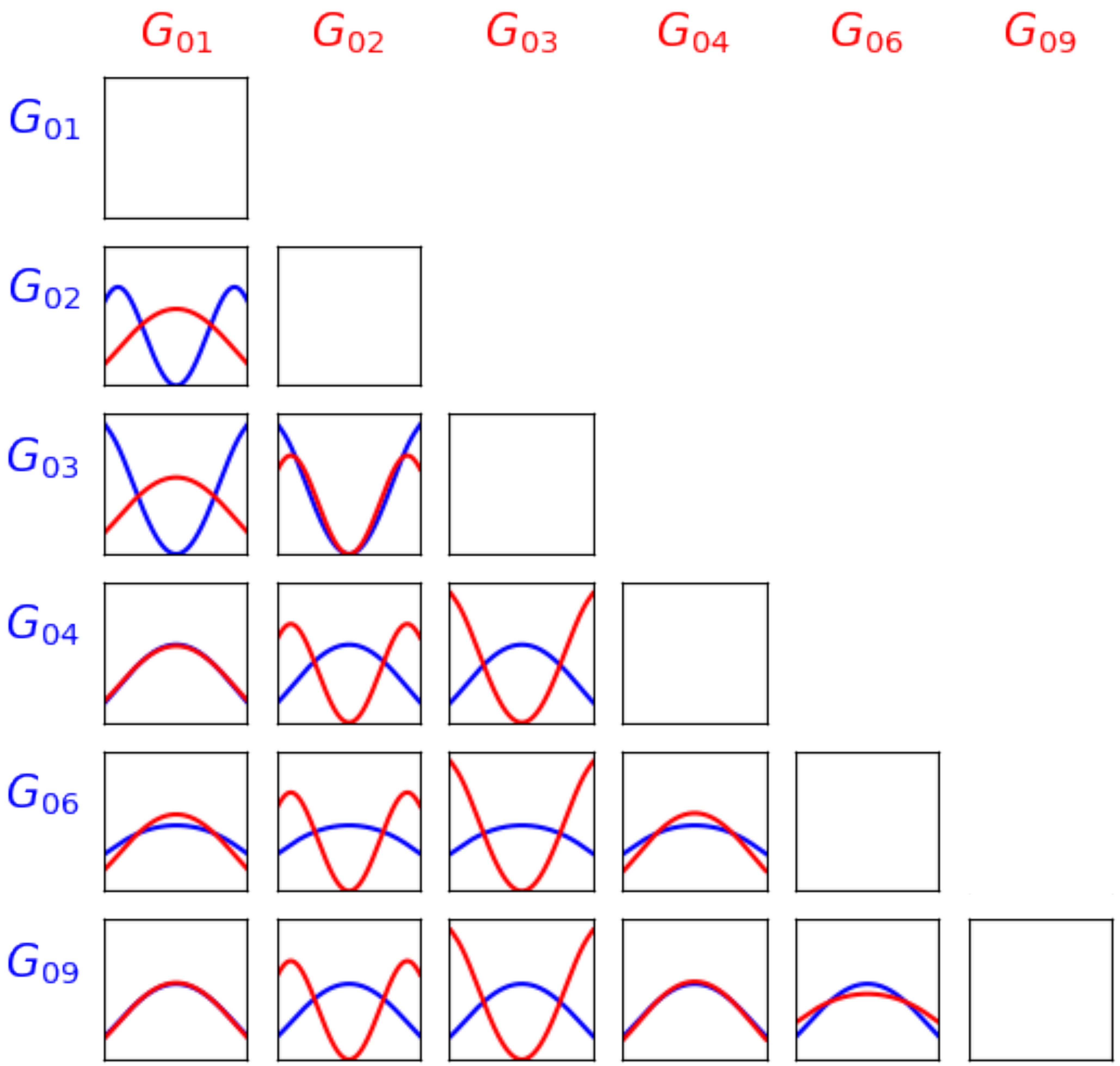
Graf, Lindner, Scholer 2204.10845

- Six phase space structures G_{0k}, after including interference terms

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta\,\mathrm{d}\tilde{\epsilon}_1} = a_0\left(1 + \frac{a_1}{a_0}\cos\theta\right)$$

$$\tilde{\epsilon}_i = \frac{\epsilon_i - m_e}{Q_{\beta\beta}} \in [0,1]$$

$\propto a_0(\tilde{\varepsilon}_1) \longrightarrow$



Phase space observables

Graf, Lindner, Scholer 2204.10845

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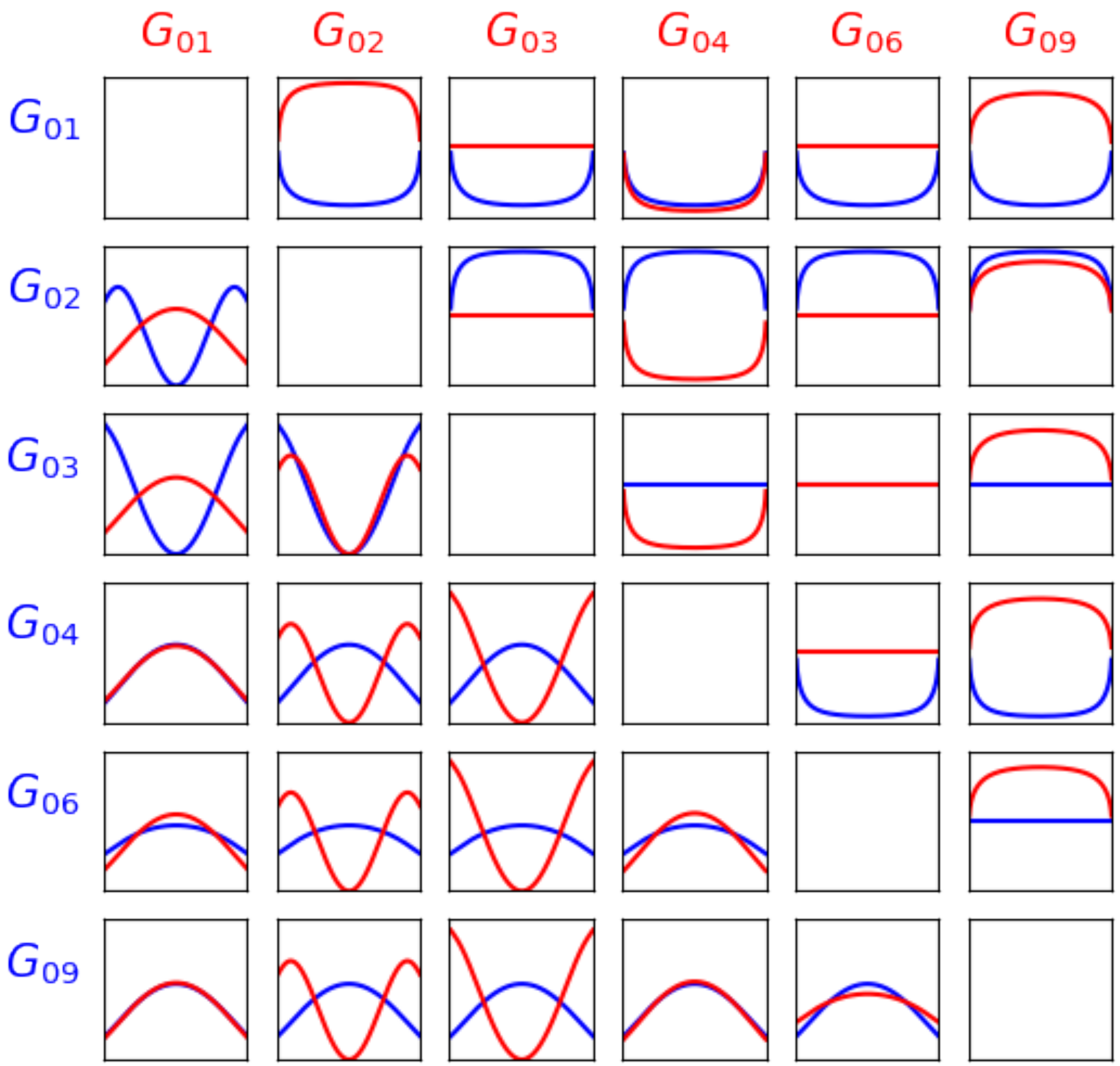


$\longleftarrow \propto a_1(\tilde{\varepsilon}_1)$

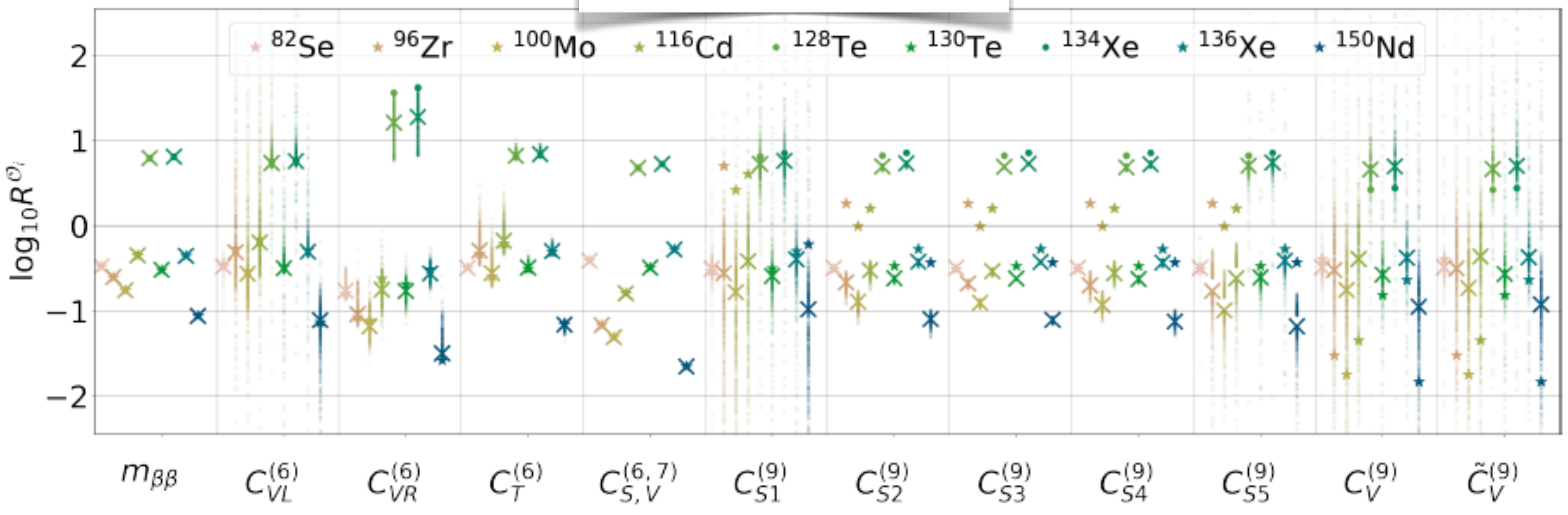
In practice, only 4 groups of operators can be distinguished

Isotope dependence

Graf, Lindner, Scholer 2204.10845

- 12 groups of operators can be distinguished by taking ratios of decay rates
- Quite sensitive to LECs (varied around reference values denoted by larger markers)
- Distinguishing classes of operators will require combined theoretical uncertainty of ~10% , due to LEC + NME (here only IBM used)

$$R^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})}$$



Isotope dependence

Graf, Lindner, Scholer 2204.10845

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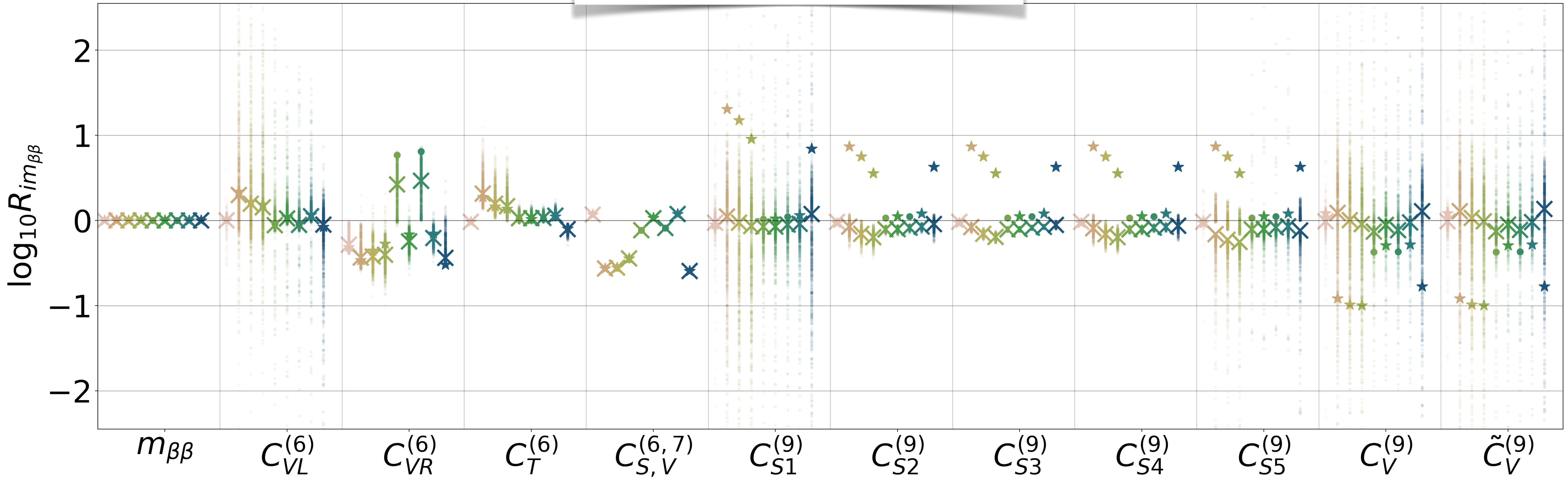
$$R_{ij}(^AX) = \frac{R^{\mathcal{O}_i}(^AX)}{R^{\mathcal{O}_j}(^AX)}$$



Isotope dependence

Graf, Lindner, Scholer 2204.10845

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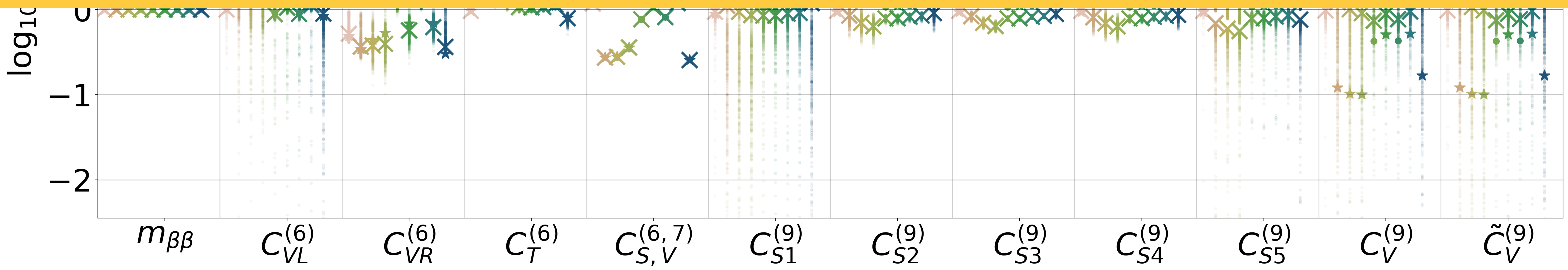
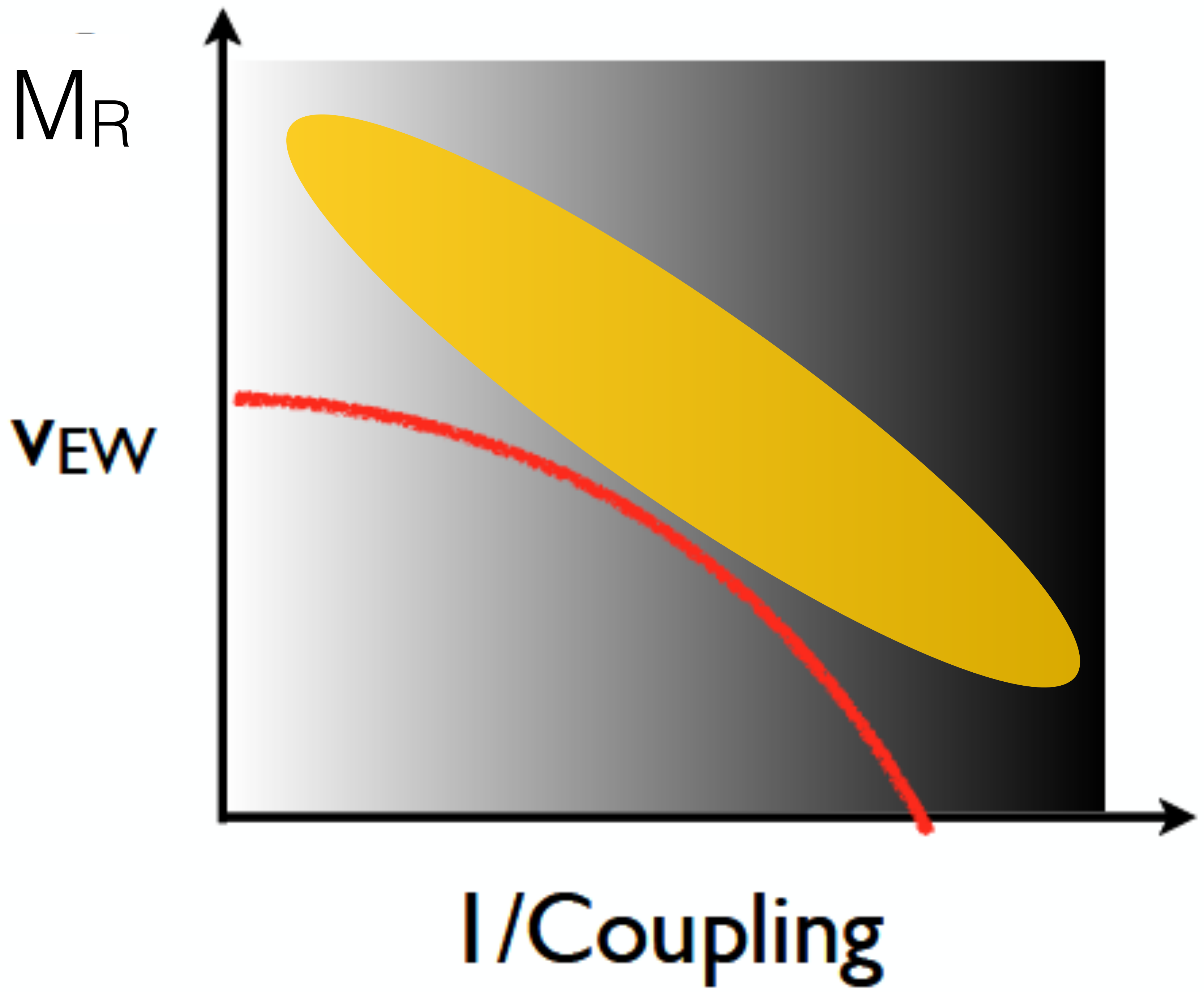
- Distinguishing classes of operators will require combined theoretical uncertainty of ~10% , due to LEC + NME (here only IBM used)

- Despite degeneracies, useful diagnosing tools 'within' 0νββ
- This analysis reiterates two important points:
  - Need improved hadronic and nuclear input, with O(10%) uncertainty. With these in hand, specific mechanisms can be falsified by isotope dependence
  - Unraveling the mechanism of LNV will also require other probes (collider, cosmology, …)



0νββ and sterile neutrinos



Thanks to Wouter Dekens and Sebastian Urrutia-Quiroga
for material presented in the following slides

Minimal and non-minimal scenarios

- Add n ν_R singlets and include operators of dimension 4 and higher: νSMEFT

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

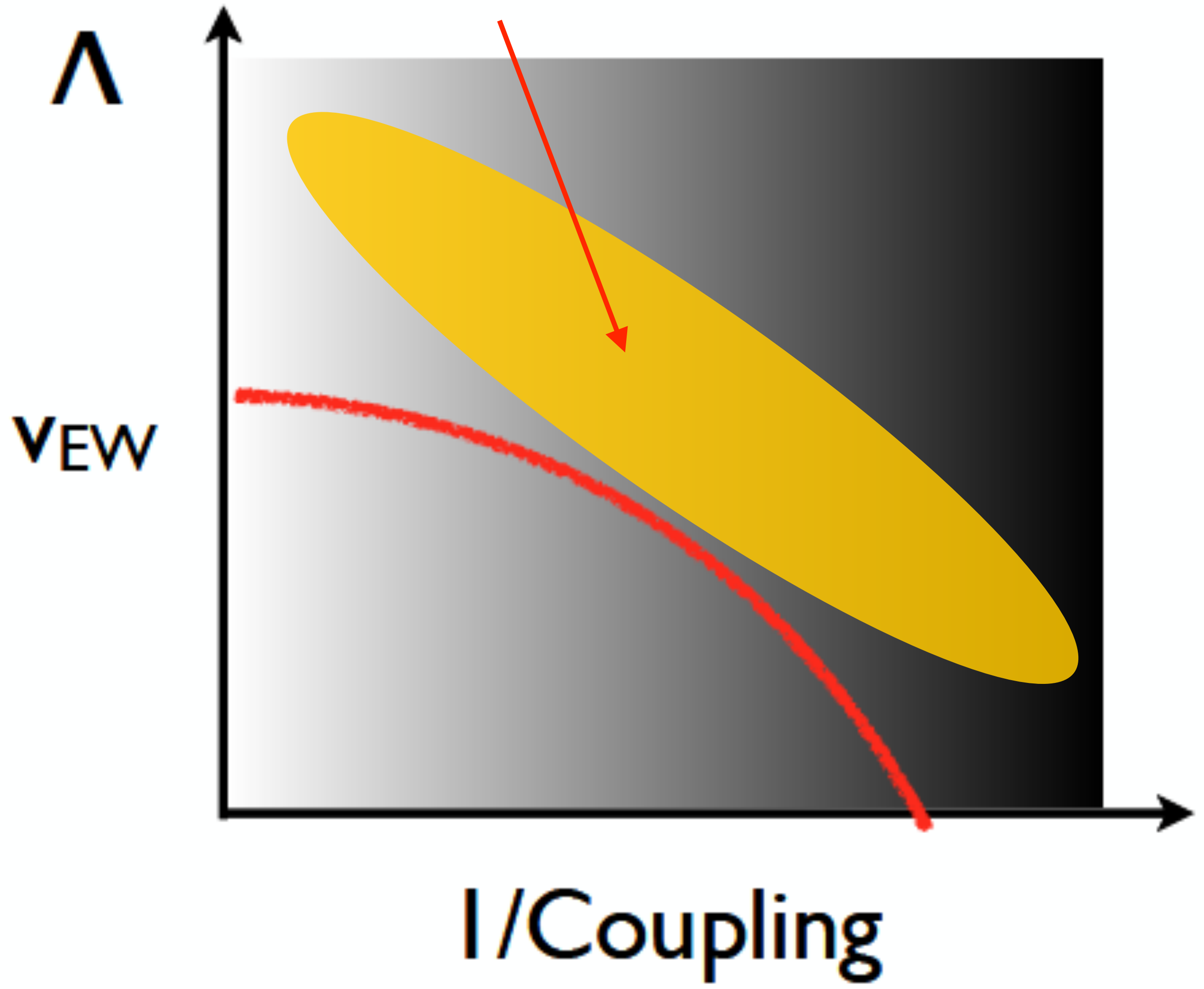
Minimal and non-minimal scenarios

- Add n ν_R singlets and include operators of dimension 4 and higher: νSMEFT

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

$$\mathscr{L}_{\text{mass}} = \frac{1}{2}\bar{N}^c M_\nu N \qquad N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \qquad M_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}}Y_D \\ \frac{v}{\sqrt{2}}Y_D & M_R^\dagger \end{pmatrix} \qquad \nu_{\text{mass}} = UN_{\text{flavor}}$$

Arbitrary scale $M_R \leftrightarrow \Lambda$

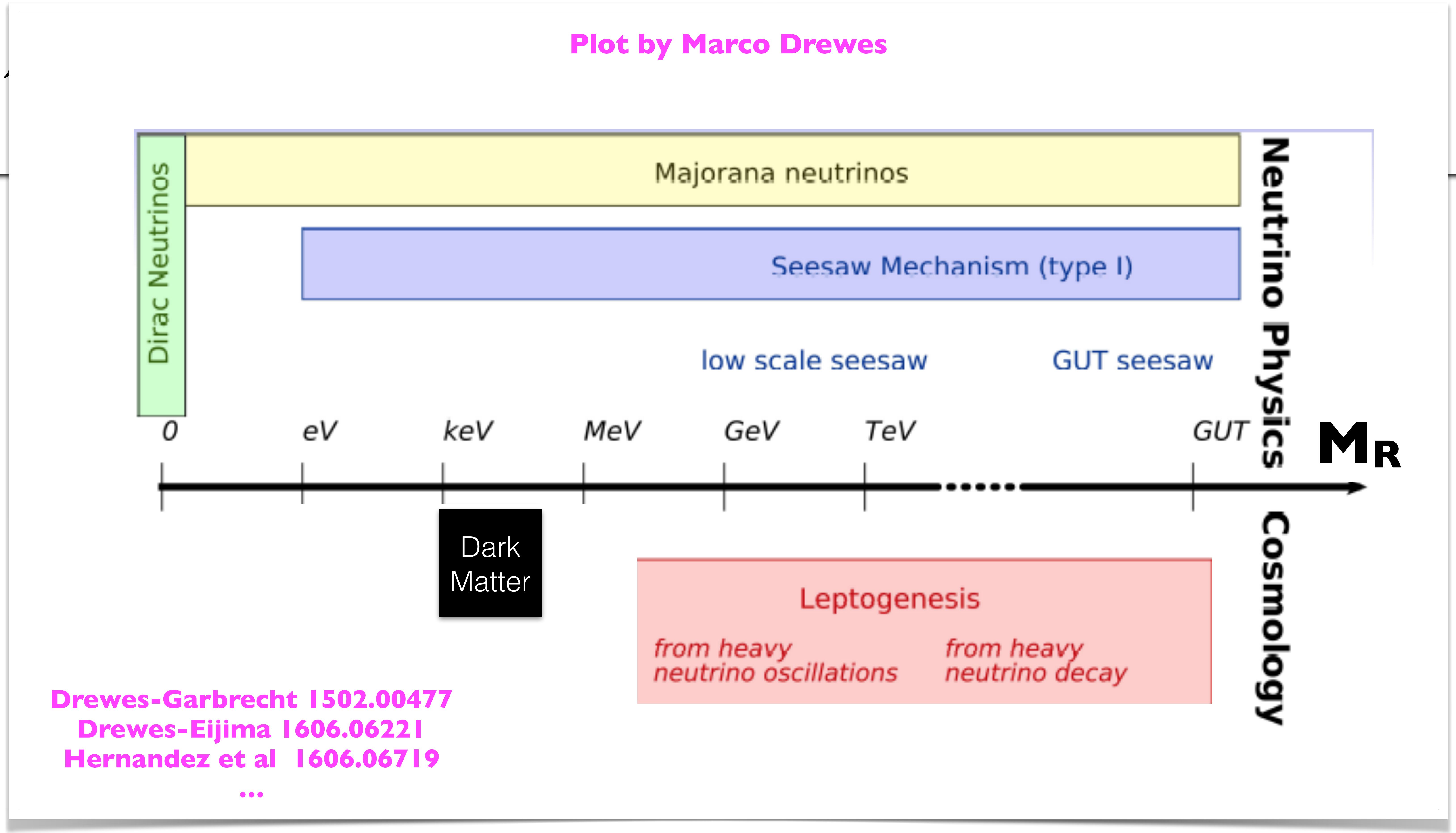


- 3+n seesaw by itself an attractive class of "minimal" models
  - ν_R can give rise to light neutrino masses
  - ν_R can provide a dark matter candidate
  - ν_R can generate the baryon asymmetry through leptogenesis

Akhmedov. Rubakov, Smirnov hep-ph/9803255
Canetti, Drewes, Shaposhnikov 1204.3902
...

Minimal and non-minimal scenarios

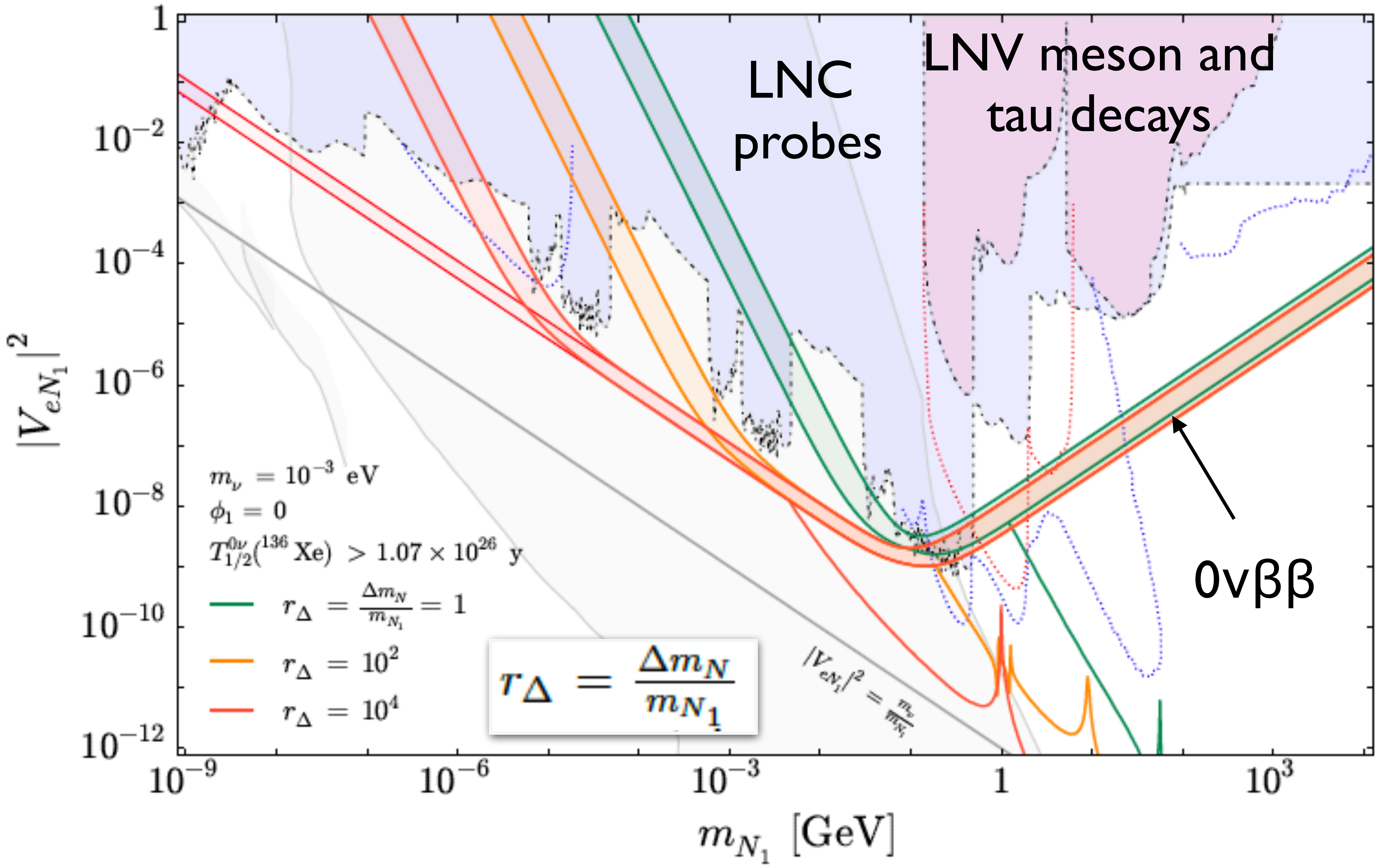
- Add n ν_R singlets and include operators of dimension 4 and higher: νSMEFT



3+n model phenomenology

- Can be probed at colliders, beam dump, semileptonic decays, EWPO, …

…
Mitra-Senjanovic-Vissani 1108.0004
Abada et al. 1712.03984
Bolton, Deppisch, Dev 1912.03058
…



- $0\nu\beta\beta$ provides strong constraints on sterile ν_R's in various mass ranges

- Flip side: plenty of "discovery potential" for $0\nu\beta\beta$ within this class of models

$$K^+ \to \pi^- \ell_1^+ \ell_2^+ \qquad \ell_{1,2} = e, \mu \qquad \boxed{\mathrm{BRs} < \#10^{-10}}$$

$$B^+ \to h^- \ell_1^+ \ell_2^+ \qquad h = \pi, K \quad \ell_{1,2} = e, \mu \qquad \boxed{\mathrm{BR}\ (\pi^- \mu^+ \mu^+) < \#10^{-9}}$$

$$\mu^- q \to e^+ q'$$

$$\tau^- \to \ell^+ h_1^- h_2^- \qquad \ell = e, \mu \quad h_{1,2} = \pi, K \qquad \boxed{\mathrm{BRs} < \#10^{-8}}$$

($\mu^- \to e^+$ conversion BR at 10^{-12} level)

Theory developments and challenges

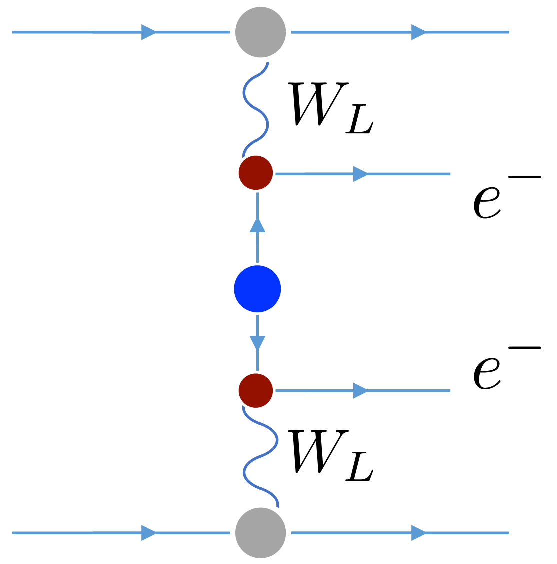
Dekens et al. 2002.07182, 2402.07993

- νSMEFT + chiral EFT analysis

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

$$\mathscr{L}_{\text{mass}} = \frac{1}{2}\bar{N}^c M_\nu N \qquad N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \qquad M_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y_D \\ \frac{v}{\sqrt{2}} Y_D & M_R^\dagger \end{pmatrix} \qquad \nu_{\text{mass}} = U N_{\text{flavor}}$$

- If new states are heavier than GeV: integrate them out, induce dim-9 operators
- If new states are lighter than GeV: contributions similar to the ones of active neutrinos, except that
  - The 'potential' and contact terms depend on m_i
  - For $m_i < k_F$, the leading term cancels and the ultra-soft contributions become leading



$$\propto \sum_{i=1}^{3+n} \frac{m_i}{q^2 - \underbrace{m_i^2}_{\simeq 0}} U_{ei}^2 \simeq \frac{1}{q^2} \left(M_\nu\right)^*_{ee} = 0$$

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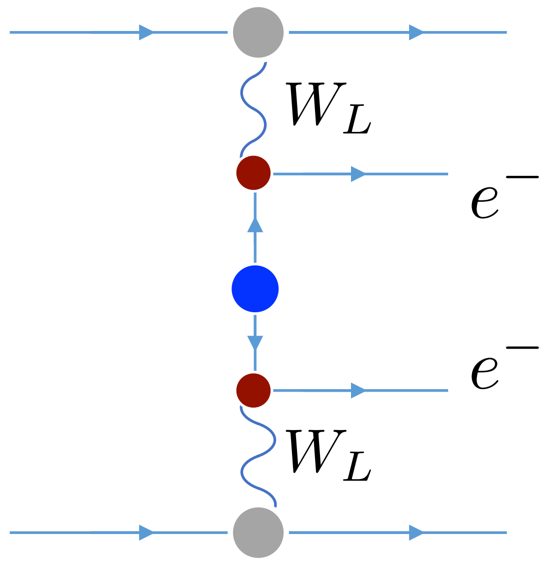

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$m_i^2 \to \simeq 0$

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

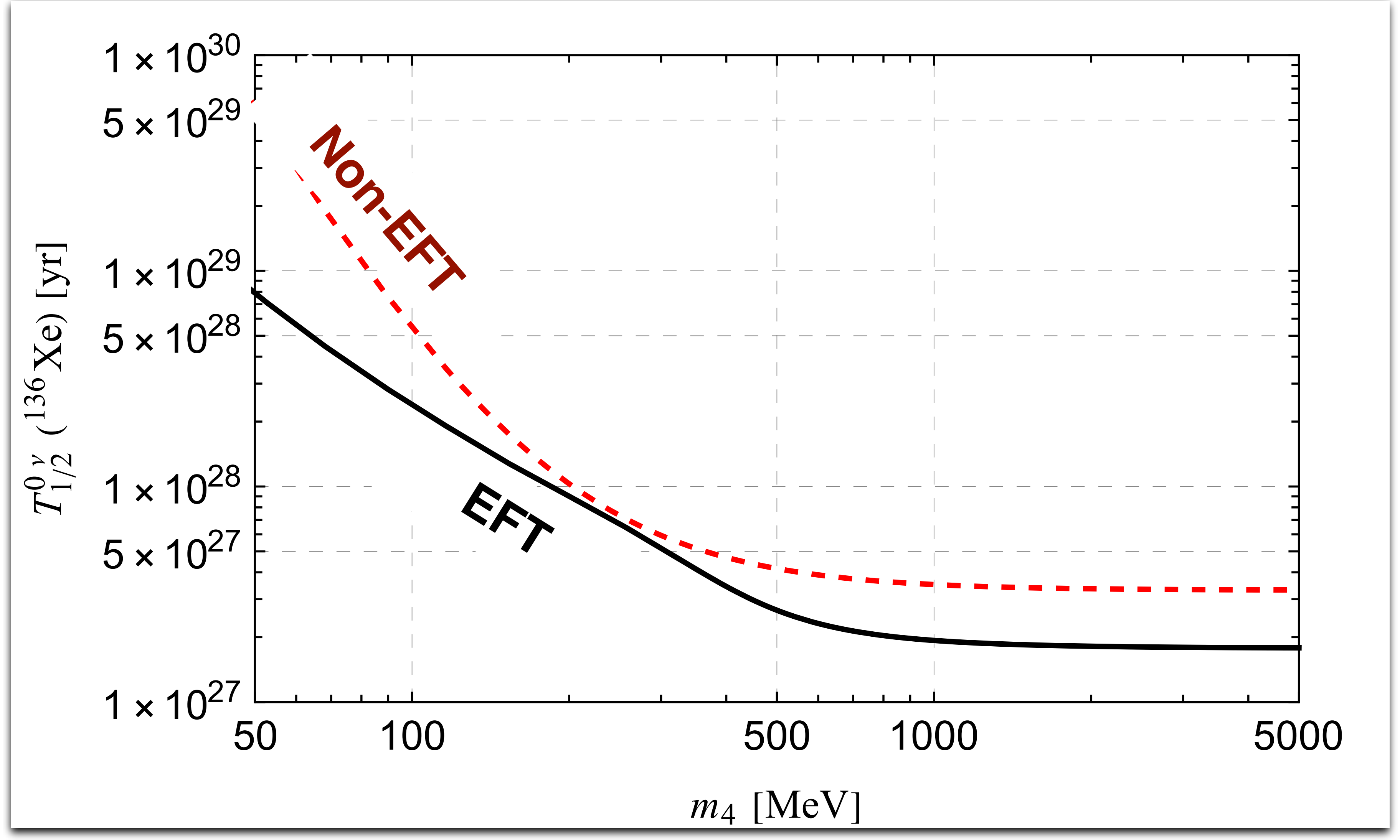
$$\Delta E \equiv E_n + E_e - E_i$$

This effect was missed in the previous literature

Simple illustration: 3+1toy model

Dekens et al. 2002.07182, 2402.07993

- Unrealistic neutrino mass spectrum but illustrates the main features



- Largest differences:
  - Ultrasoft neutrinos for $m_4 \ll m_\pi$

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Dekens et al. 2002.07182, 2402.07993

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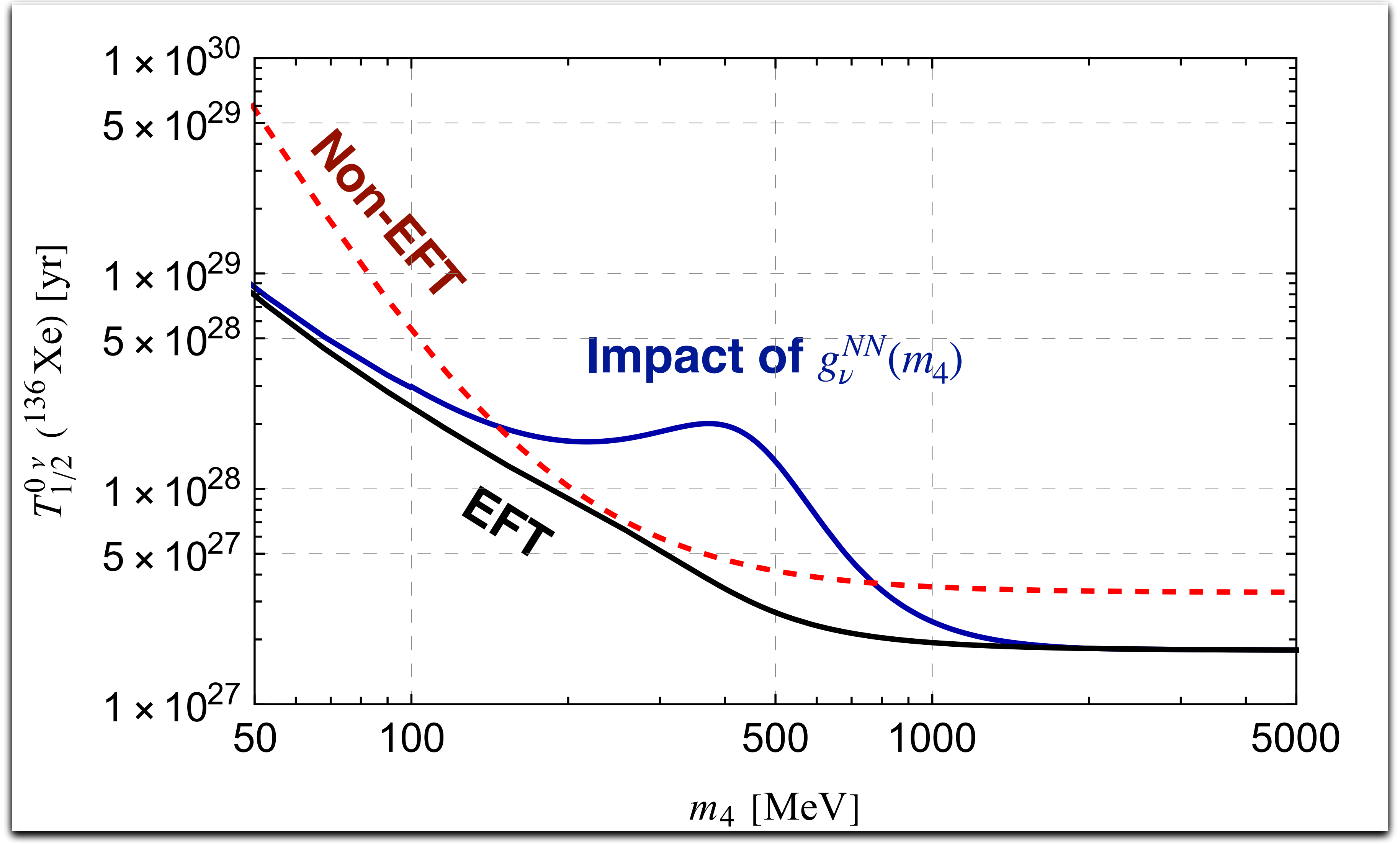


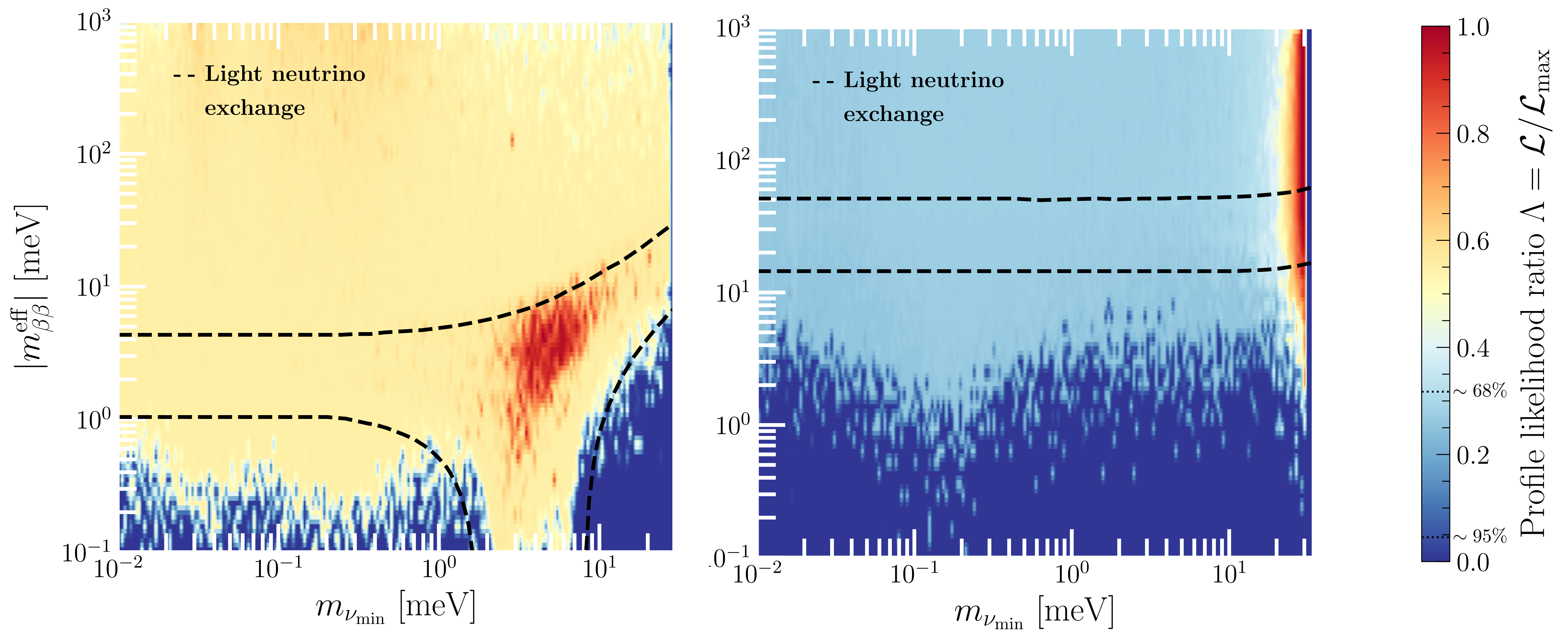
VC, W. Dekens, S. Urrutia-Quiroga, 2412.10497

- Largest differences:
  - Ultrasoft neutrinos for $m_4 \ll m_\pi$

- 'Cottingham' estimate of m_ν dependence of g_ν^{NN}
  - Significant impact for $m_4 \gtrsim m_\pi$

3+3 model: expectations for 0νββ

- Use up to date constraints (semileptonic decays, precision electroweak, …) to get likelihood function in 18-dimensional parameter spac
- Profile likelihood shows that 95% C.L. intervals extend beyond the ones for light neutrino exchange for both normal (NH) and inverted (IH) spectrum of light neutrinos ⇒ broad discovery potential



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VC, W. Dekens, S. Urrutia-Quiroga, 2505.09679

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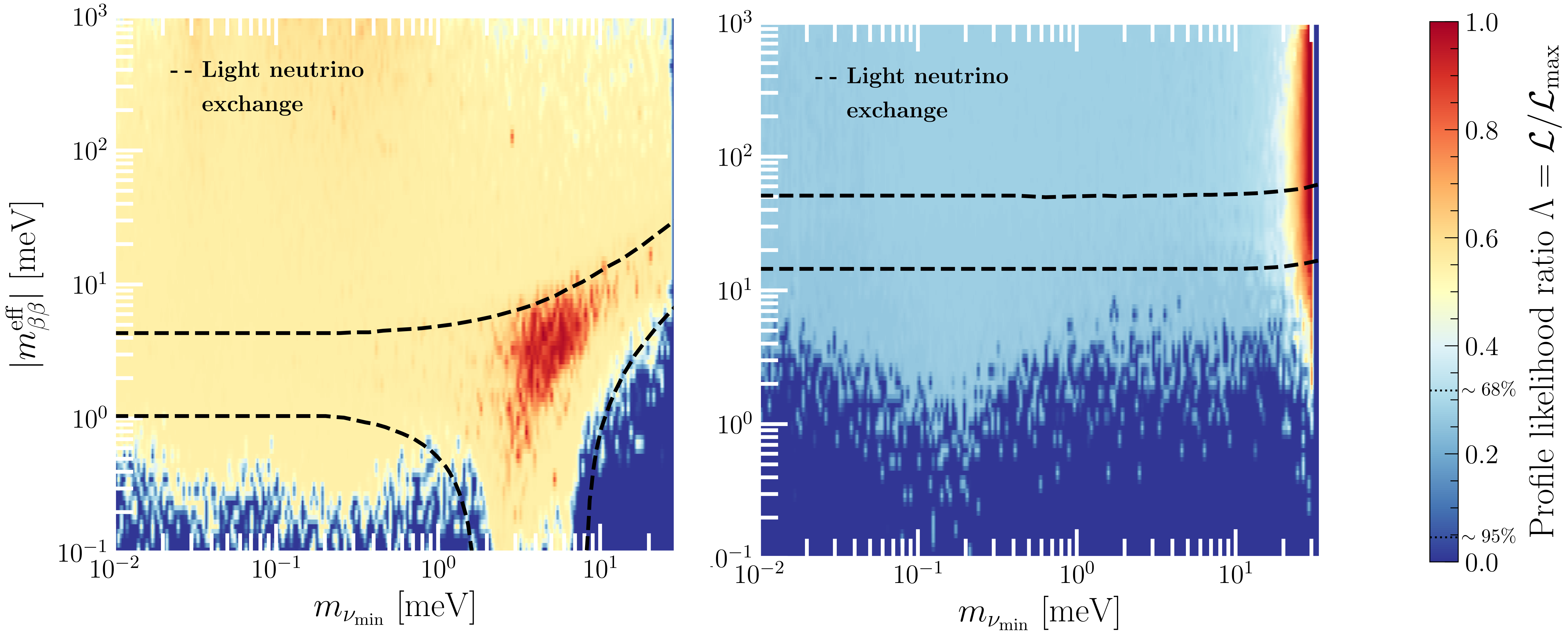
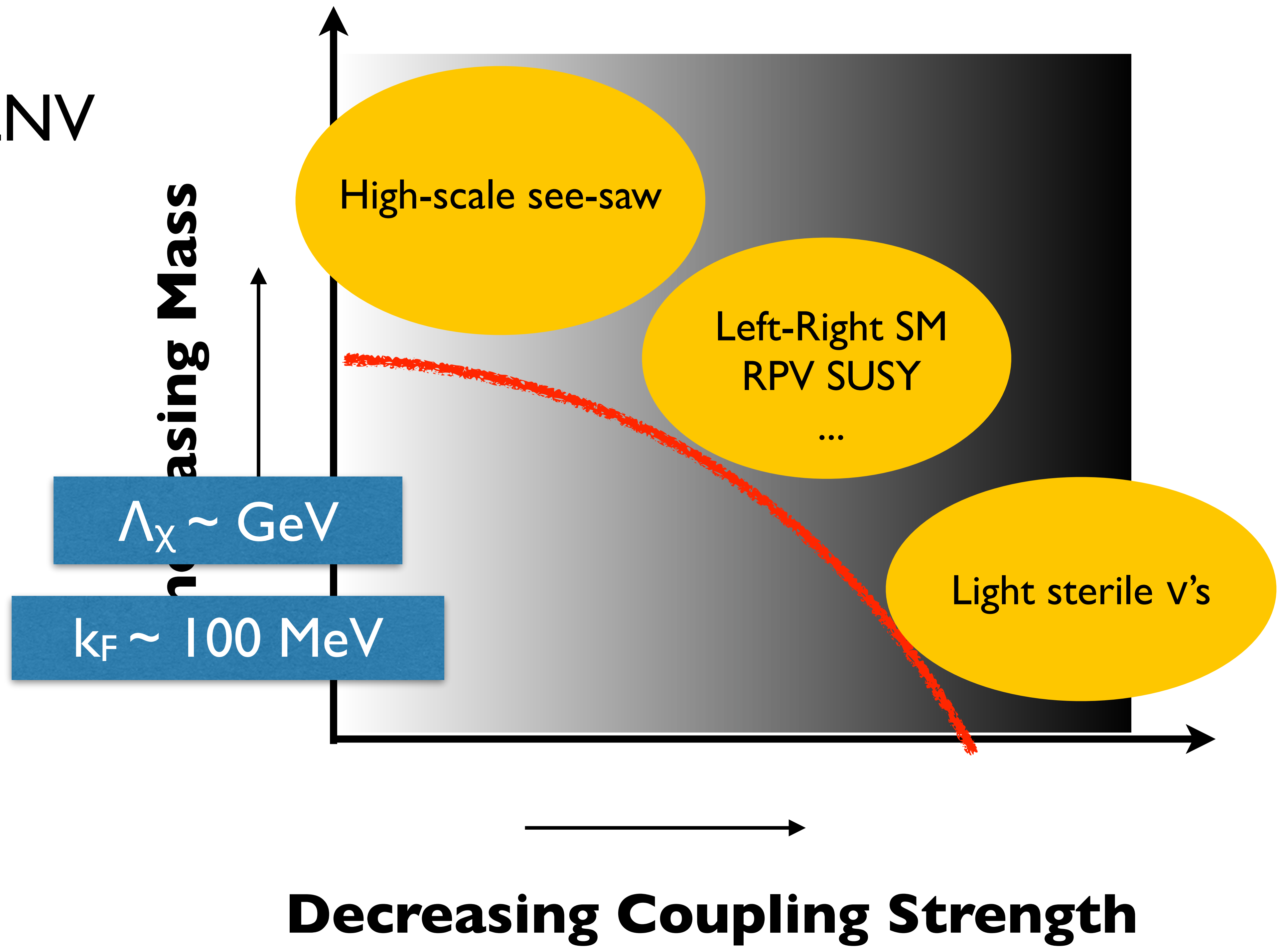


Conclusions & Outlook

- Ton-scale $0\nu\beta\beta$ searches have significant discovery potential — we simply don't know the origin of m_ν and the scale Λ associated with LNV

- Exciting prospects with multiple ton-scale experiments ready to start construction

- Theory is essential to get at the underlying physics. EFT approach provides a general framework to



1. Relate $0\nu\beta\beta$ to underlying LNV dynamics
2. Organize contributions to hadronic and nuclear matrix elements

Improving the theory uncertainty is challenging, but there are exciting prospects thanks to advances in EFT, lattice QCD, and nuclear structure

Backup

Contact term: results & validation

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

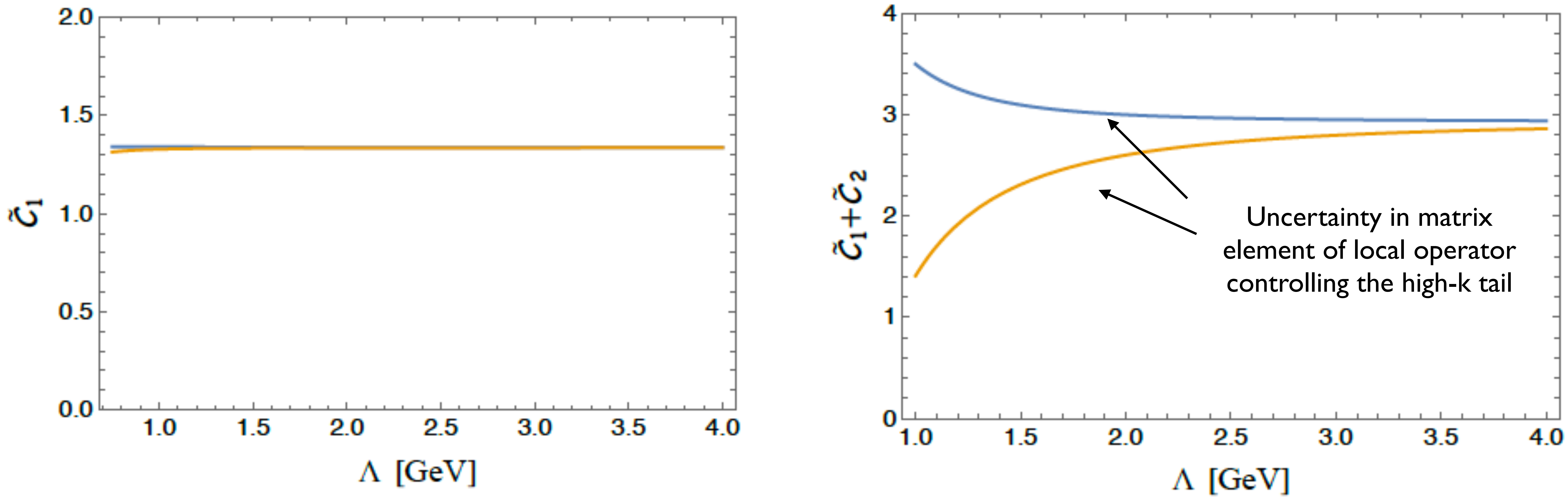
- LECs in dim. reg. with modified minimal subtraction

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

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

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

$$g_\nu = C_1$$



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$$g_\nu = C_1$$

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

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

Fairly good agreement.

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

Uncertainty estimate is realistic

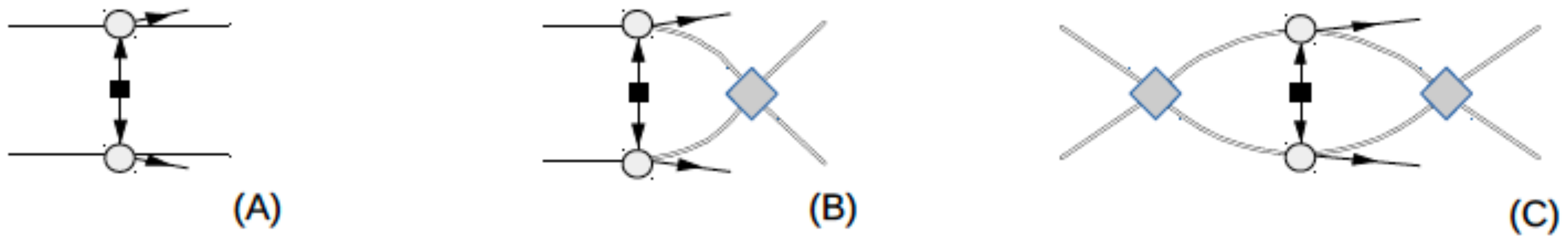
Connecting to nuclear structure

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

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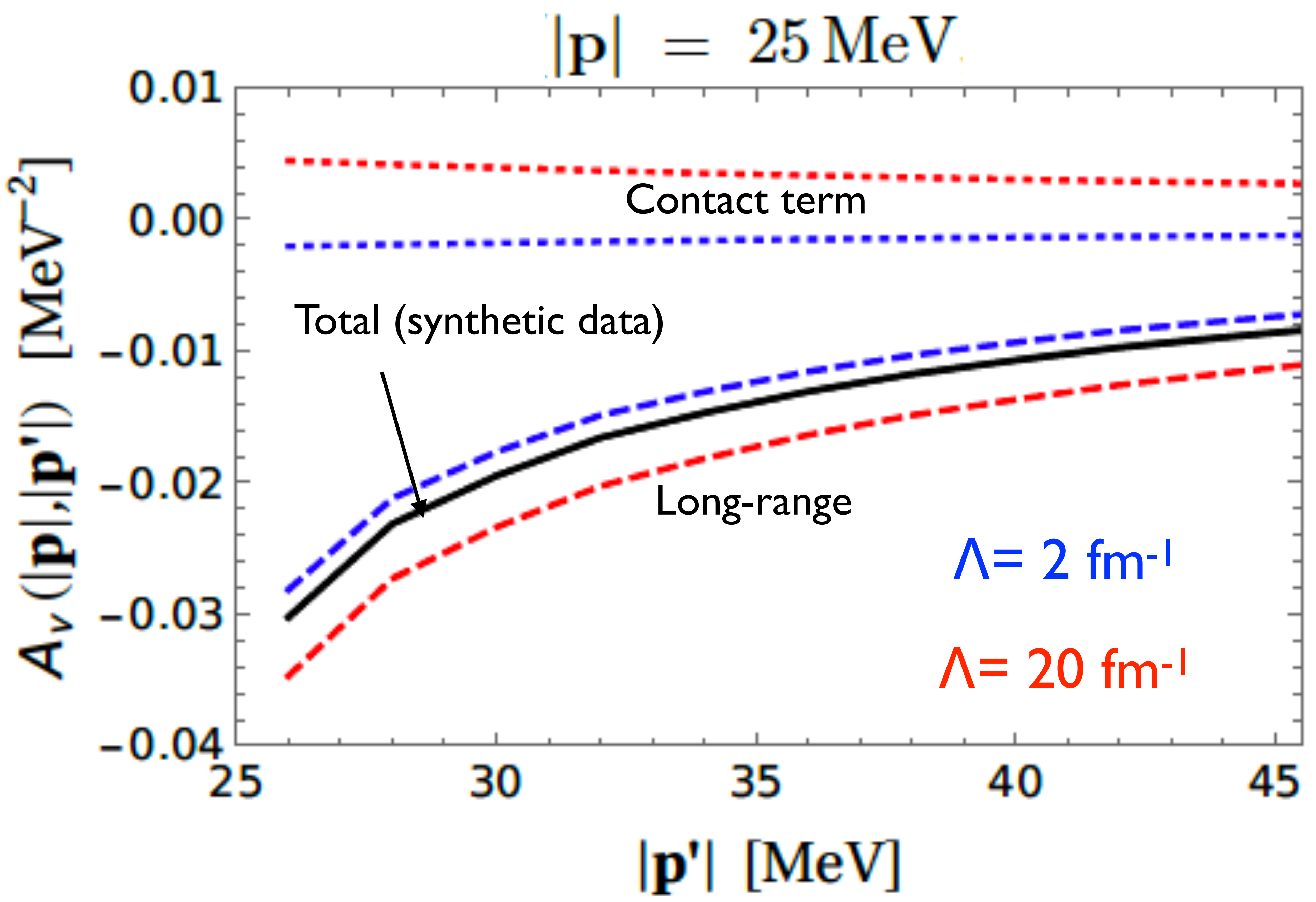
- Illustrated fitting procedure with various cutoffs

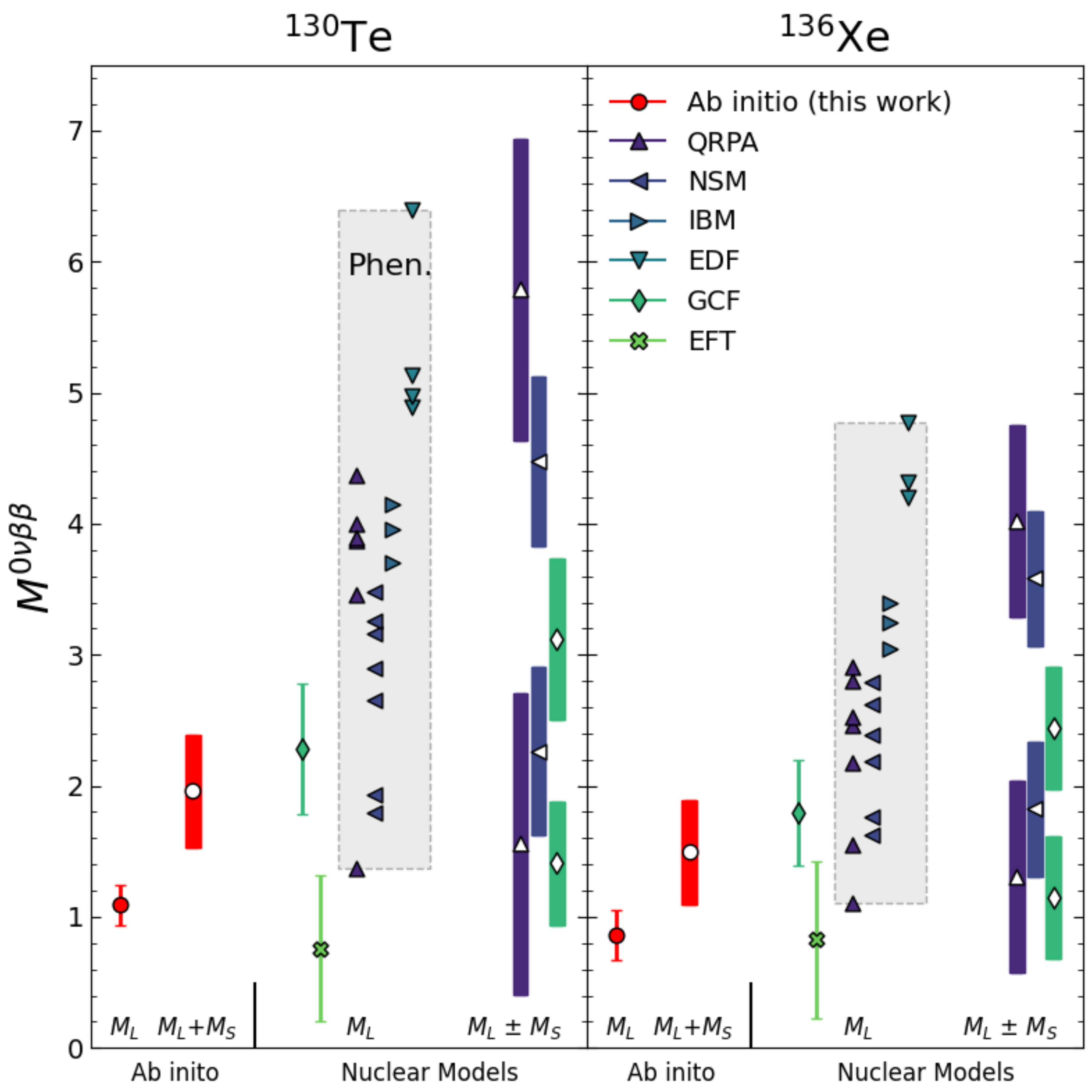
- Constructive or destructive? The sign of the interference is regulator dependent!

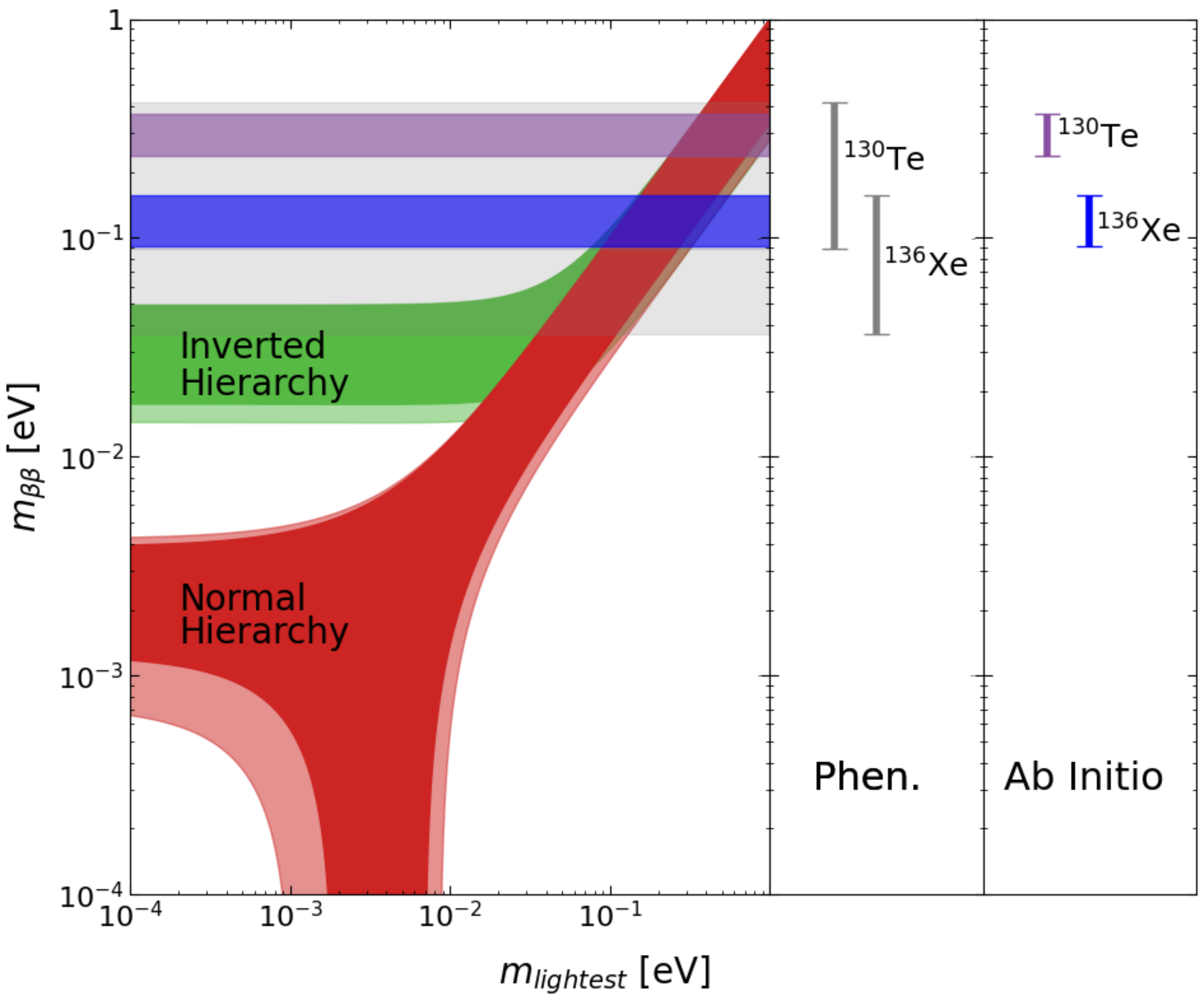


Matrix elements for ^{130}Te and ^{136}Xe

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 $m_{\beta\beta}$





Differential decay rate

$$\frac{d\Gamma}{dy\, d\cos\theta} = g_A^4 \Big\{ g_{01} \left(|\mathcal{A}_\nu|^2 + |\mathcal{A}_R|^2 \right) - 2(g_{01} - g_{04}) \mathrm{Re} \mathcal{A}_\nu^* \mathcal{A}_R + 4 g_{02} \, |\mathcal{A}_E|^2$$
$$+ 2 g_{04} \left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re} \left(\mathcal{A}_{m_e}^* (\mathcal{A}_\nu + \mathcal{A}_R) \right) \right] - 2 g_{03} \, \mathrm{Re} \left((\mathcal{A}_\nu + \mathcal{A}_R) \mathcal{A}_E^* + 2 \mathcal{A}_{m_e} \mathcal{A}_E^* \right)$$
$$+ g_{09} \, |\mathcal{A}_M|^2 + g_{06} \, \mathrm{Re} \left((\mathcal{A}_\nu - \mathcal{A}_R) \mathcal{A}_M^* \right) \Big\} ,$$

$$g_{0k} = \frac{1}{\ln 2} \frac{G_F^4 m_e^2}{64 \pi^5 R_A^2} \left(\frac{Q}{2} \right)^5 \sqrt{1 - y^2} \sqrt{\left(1 + y + \frac{4 m_e}{Q} \right) \left(1 - y + \frac{4 m_e}{Q} \right)}$$
$$\tilde{b}_{0k}(y, \cos\theta) \, F\left(Z, E_1\right) F\left(Z, E_2\right) \, .$$

$$y = (E_1 - E_2)/Q \in [-1, 1]$$