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Effective field theory approach to neutrino-less double beta decay

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Outline

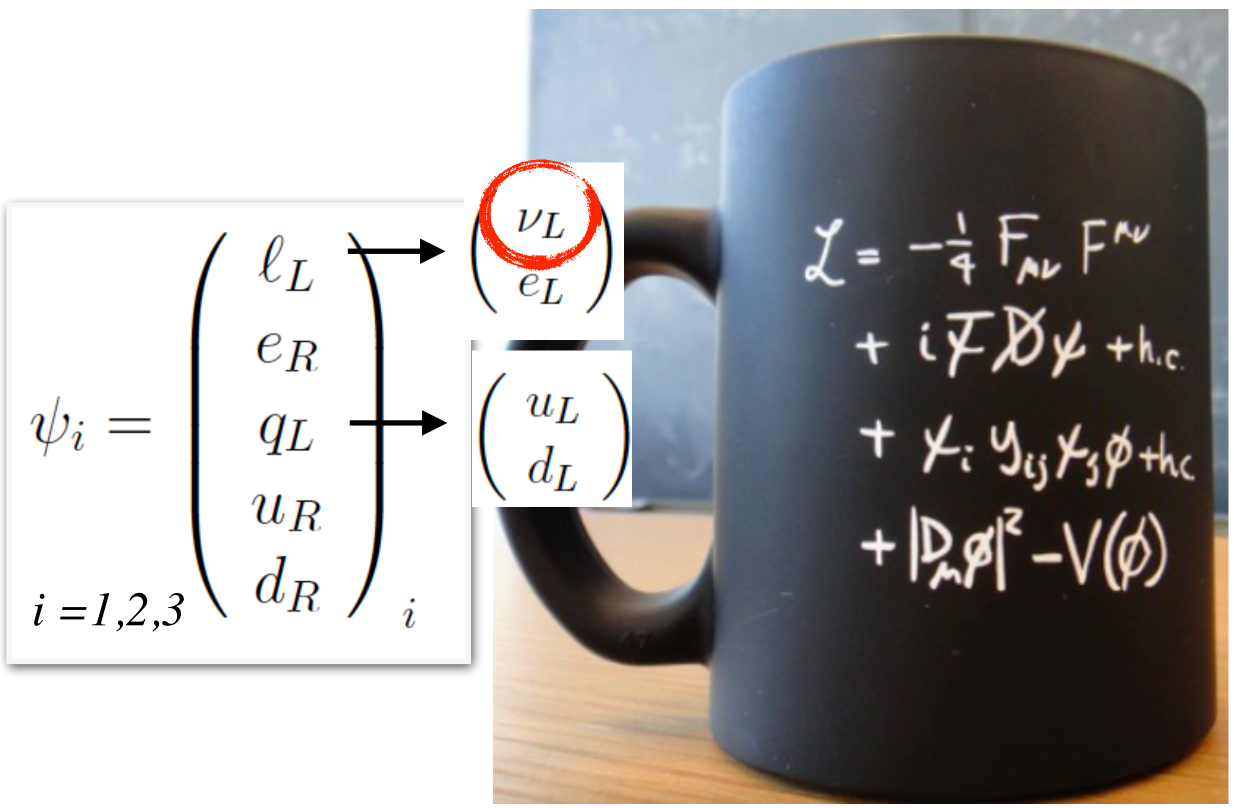
- Introduction: neutrino mass, Lepton Number, and $0\nu\beta\beta$ decay
- 'End-to-end' EFT framework for LNV and $0\nu\beta\beta$
    - $0\nu\beta\beta$ from high-scale dynamics (LNV @ dim 5)
    - $0\nu\beta\beta$ from (multi)TeV-scale dynamics (LNV @ dim 7, 9, …)
- Conclusions & outlook

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

Neutrino mass and new physics

- Massive neutrinos provide concrete evidence of physics beyond the SM

The Standard Model



No neutrino mass

Understanding origin and nature of neutrino mass is an open problem, with implications for baryogenesis, DM, structure formation, …

Neutrino mass and new physics

- Lorentz invariance ⇒ two options: Dirac or Majorana

Dirac mass:

$$m_D \, \overline{\psi_L} \, \psi_R \; + \; \text{h.c.}$$

Majorana mass:

$$m_M \, \psi_L^T \, C \psi_L \; + \; \text{h.c.}$$

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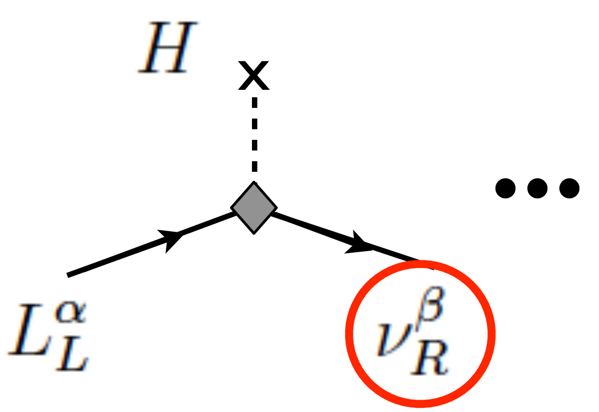

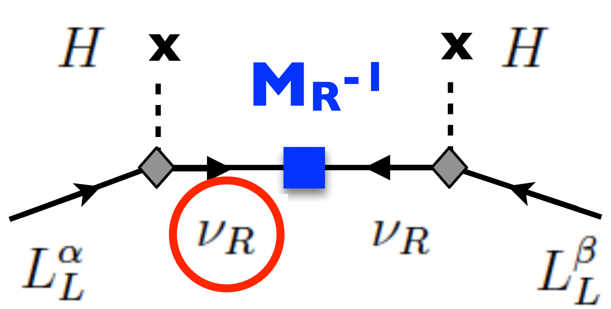

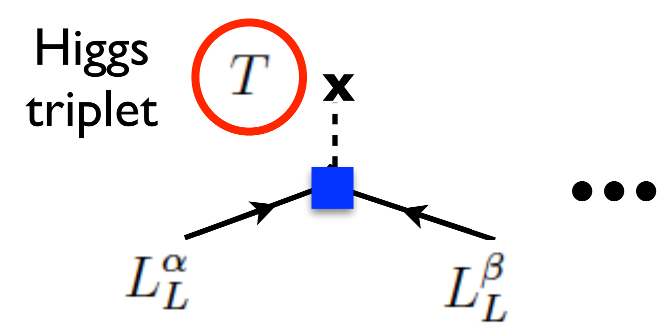

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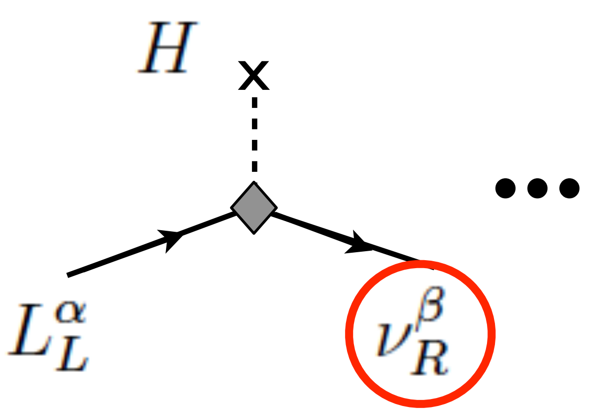

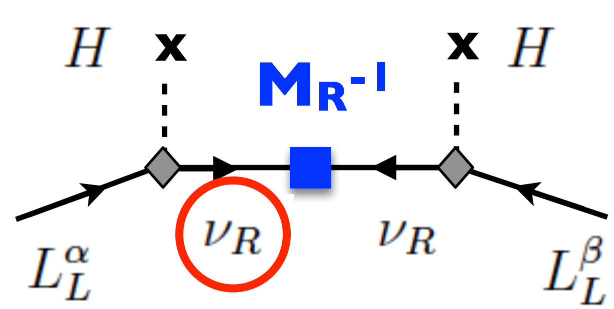

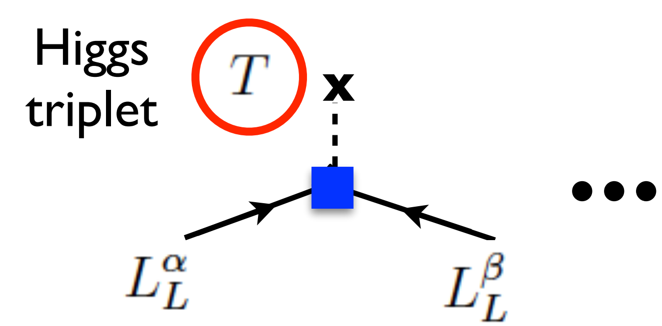

- Violates $L_{e,\mu,\tau}$, conserves L
- Violates $L_{e,\mu,\tau}$ and L ($\Delta L=2$)

Which option is realized in nature?

- Smallness of ν mass and chiral nature of the weak interactions implies that *neutrino-less* processes are the best probes of $\Delta L=2$ interactions

A Majorana neutrino with helicity=+1 (R-handed) will produce μ^+.
But fraction of R-helicity ν's produced in $\pi^+ \to \mu^+\nu_\mu$ is $\sim(m_\nu/E_\nu)^2 < 10^{-16}$!!

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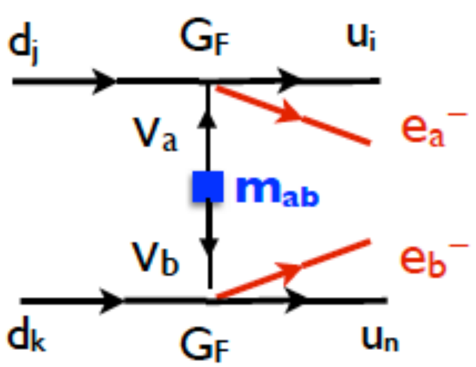
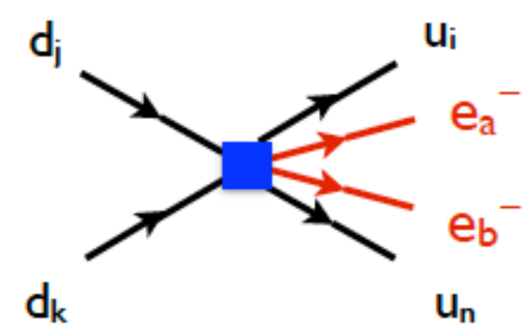


$$(N,Z) \to (N-2, Z+2) + e^- + e^-$$

$$K^+ \to \pi^- \ell_1^+ \ell_2^+ \qquad B^+ \to h^- \ell_1^+ \ell_2^+$$

$$\tau^- \to \ell^+ h_1^- h_2^- \qquad \ldots$$

$$pp \to \ell\ell + 2 \text{ jets}$$

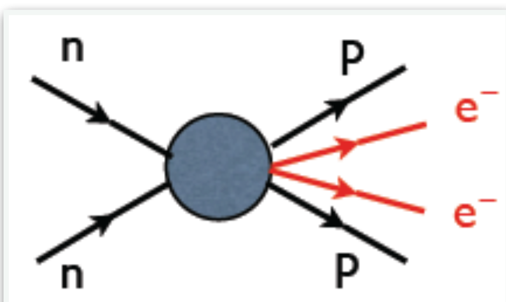


- 0νββ provides in many scenarios the strongest sensitivity to LNV couplings (“Avogadro’s number wins”, P. Vogel)
- Other processes can be very competitive in models with low-scale LNV

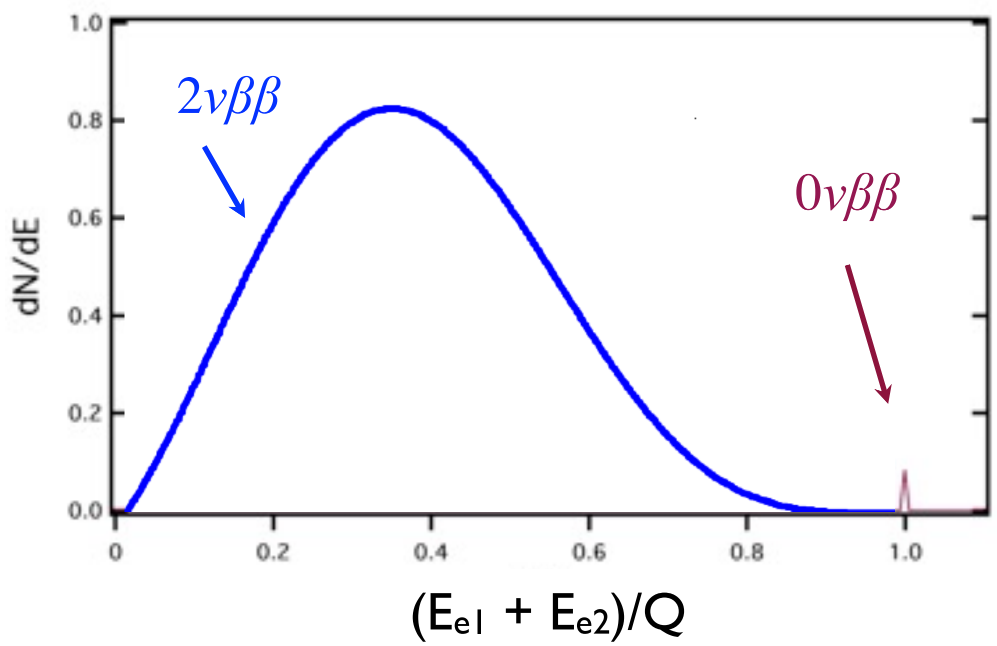
Neutrinoless double beta decay

$$(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$$

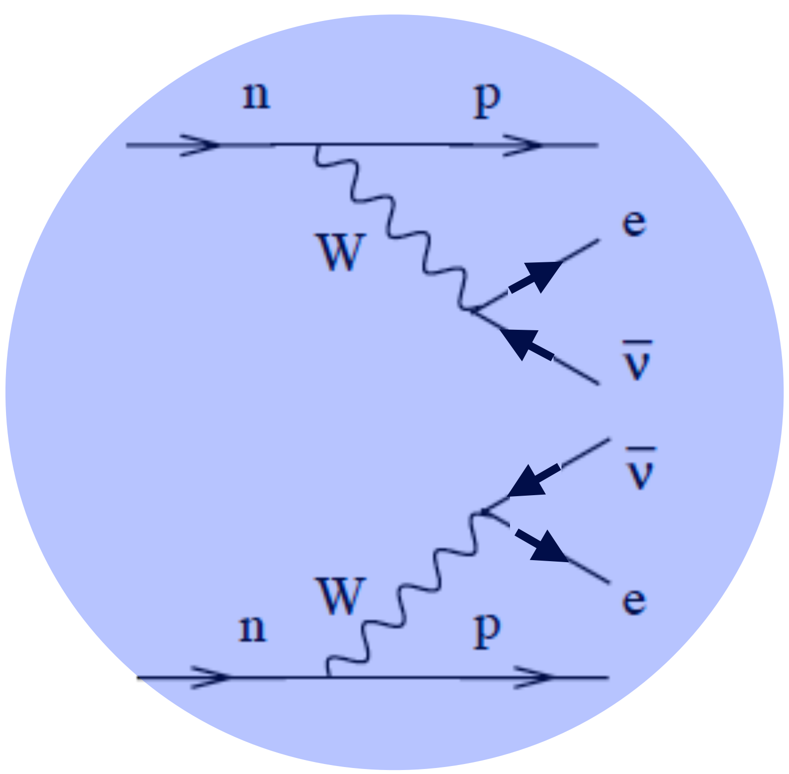
$$T_{1/2} > \# 10^{25} \text{yr}$$



ΔL=2



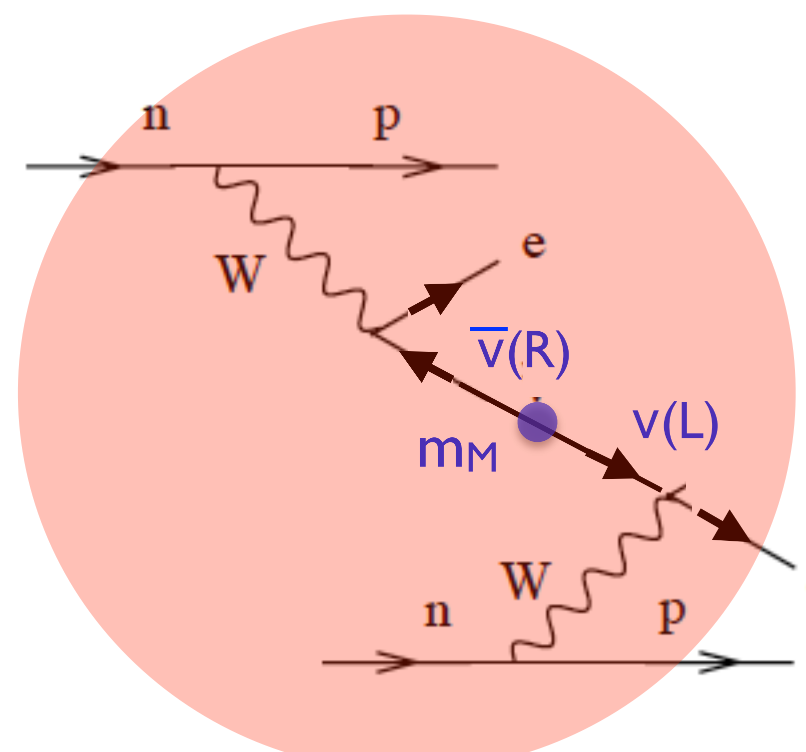
Potentially observable in certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …) for which single beta decay is energetically forbidden



Simplest mechanism:
Majorana mass term

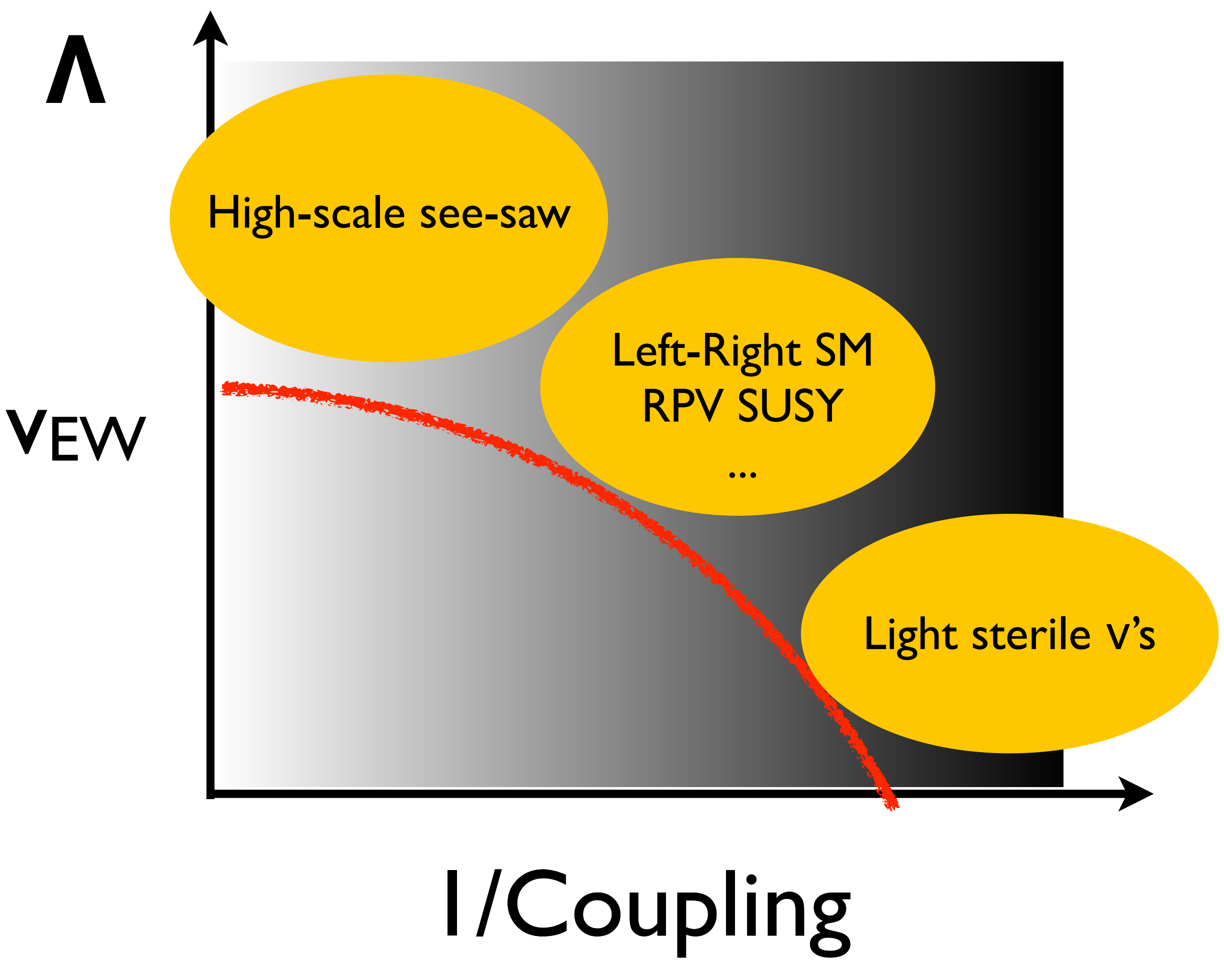
But not the only one!

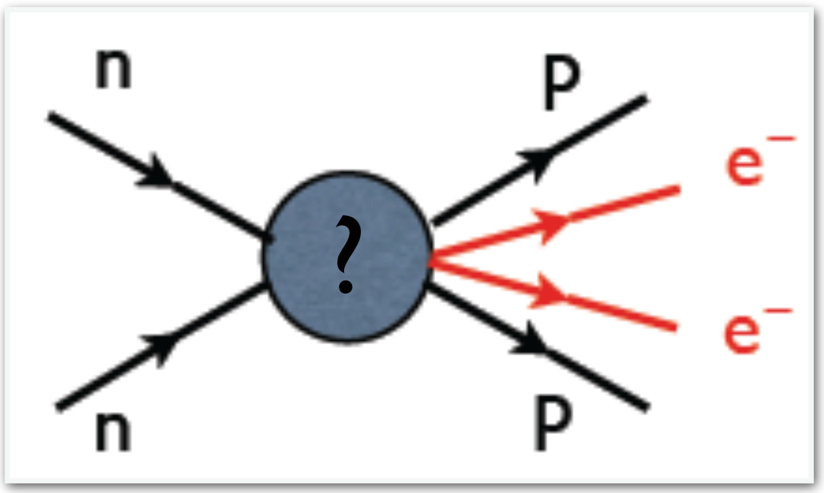
Furry 1939



0νββ physics reach

- Ton-scale 0νββ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) will probe LNV from a broad range of mechanisms





See VC-Dekens-deVries-Graesser-Mereghetti 1806.02780 and references therein

Snowmass white paper: 2203. 21169

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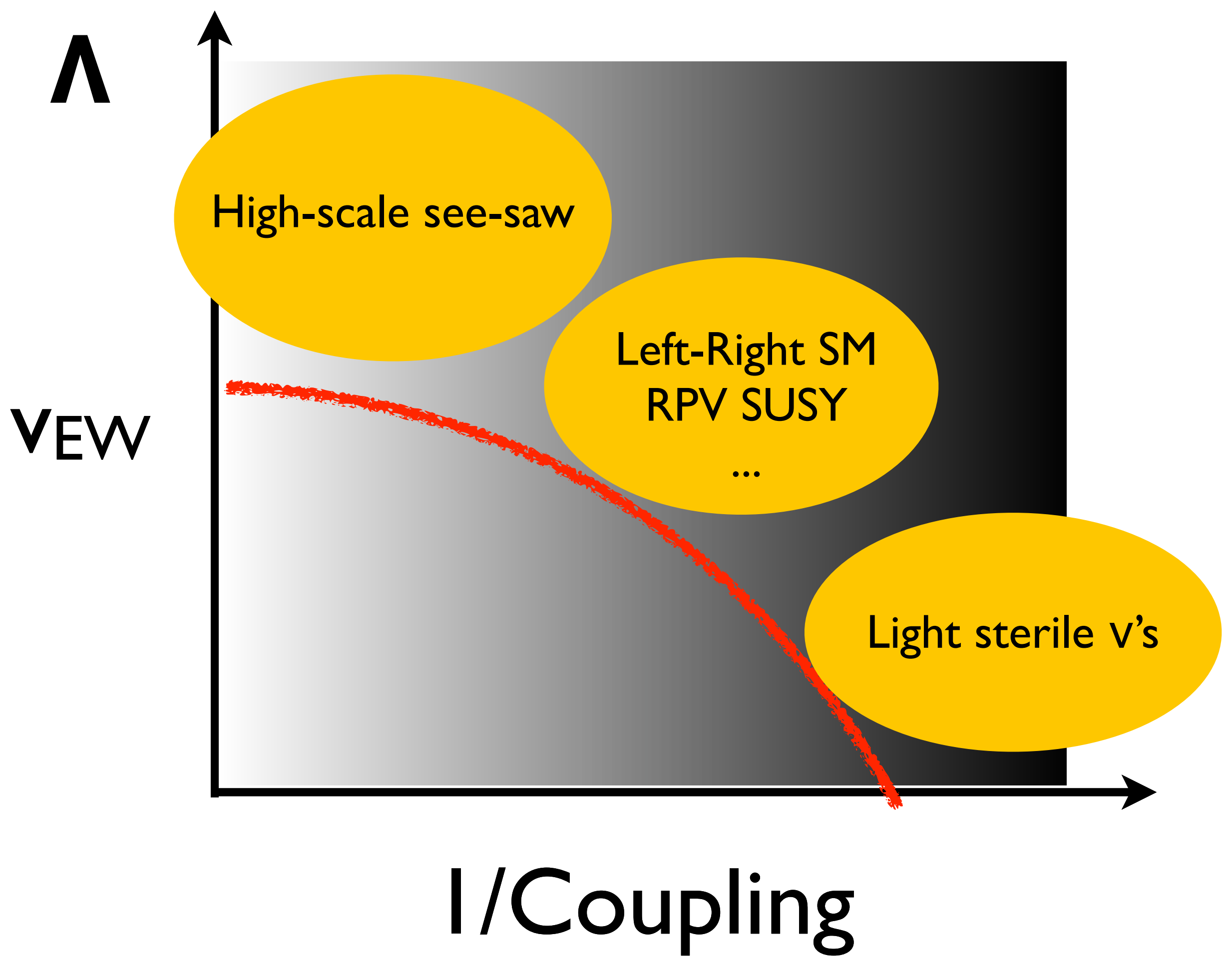

Impact of 0νββ searches and relation to other probes of LNV is best analyzed through a tower of EFTs that connect LNV scale Λ to nuclear scales, with controllable uncertainties

See VC-Dekens-deVries-Graesser-Mereghetti 1806.02780 and references therein

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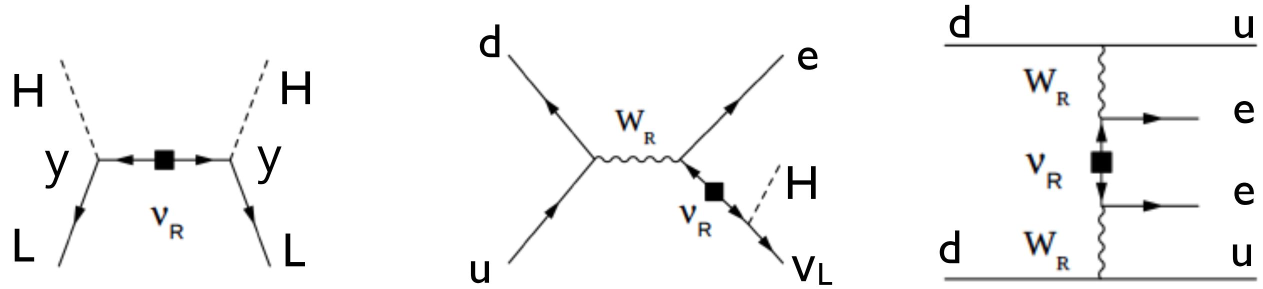
‘End-to-end’ EFT framework

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 Λ~ TeV

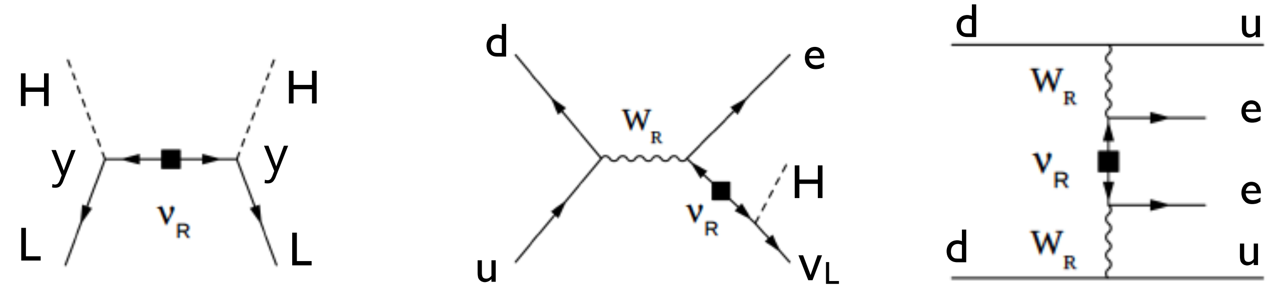
Λ_X
(~GeV)

For low-energy probes such as 0νββ, 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

E



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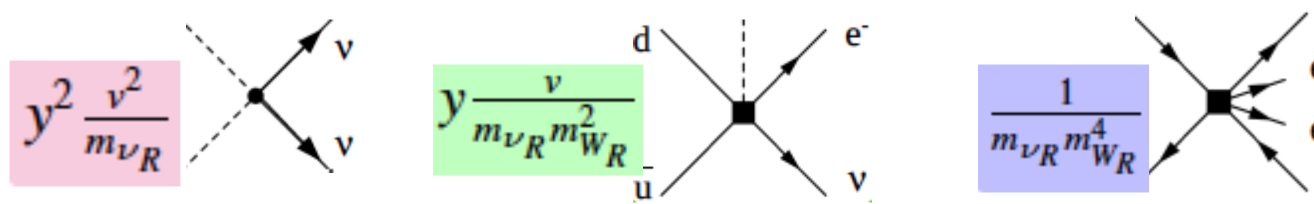


SM-EFT

dim5 — Weinberg'79

dim7 — Babu-Leung '01 ... Lehman 1410.4193

dim9 — Graesser 1606.04549, Liao and Ma 2007.08125

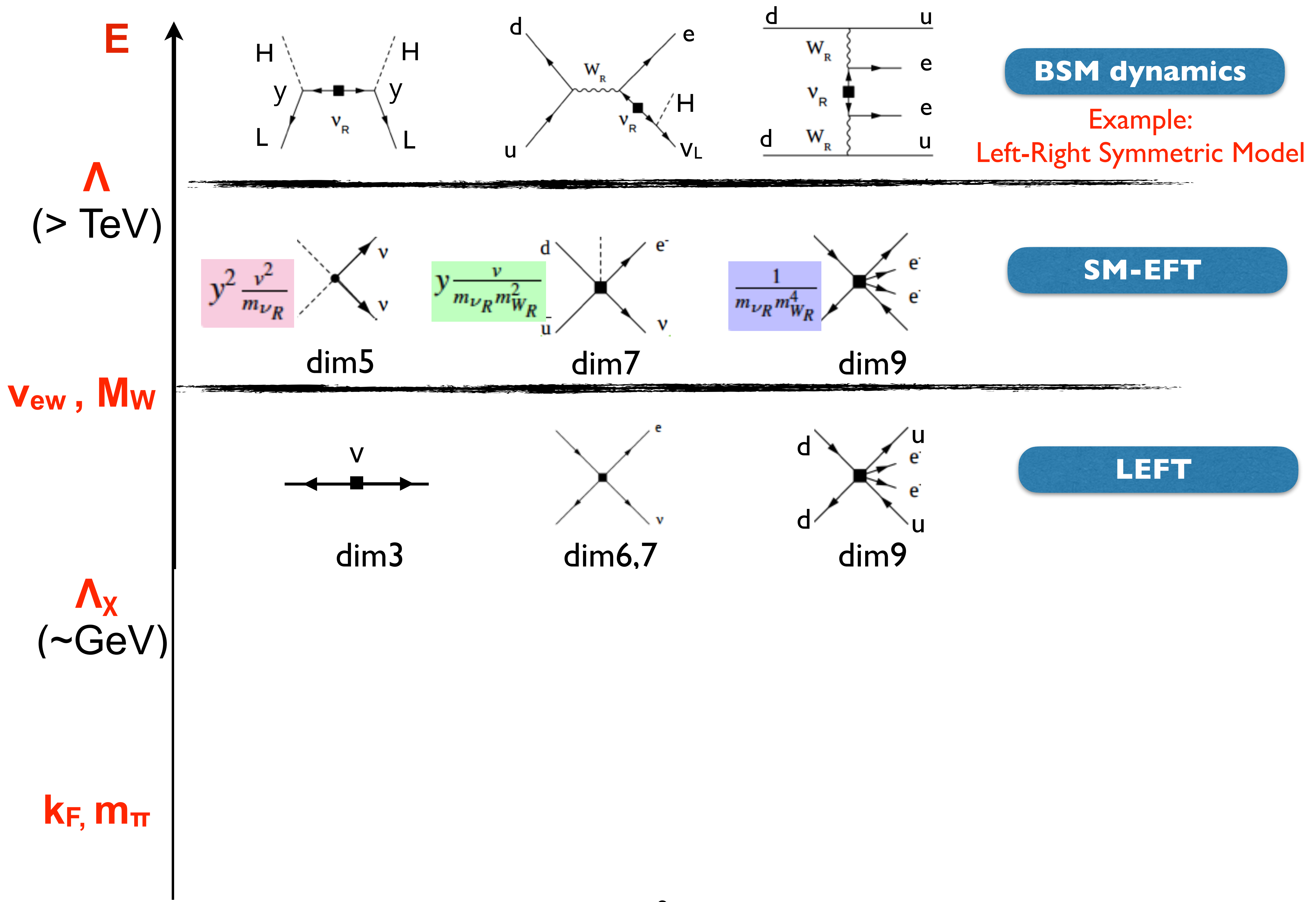
v_{ew} , M_W

Λ_χ
(~GeV)

- ΔL=2, ΔB=0 operators appear only at odd dimension — A. Kobach 1604.05726
- Insertions of small dimensionless (Yukawa) coupling can make dim=5,7,9 operators equally important for Λ~ TeV
- ν_R with mass < Λ can be included in the framework — Dekens et al. 2002.07182

k_F, m_π

‘End-to-end’ EFT framework



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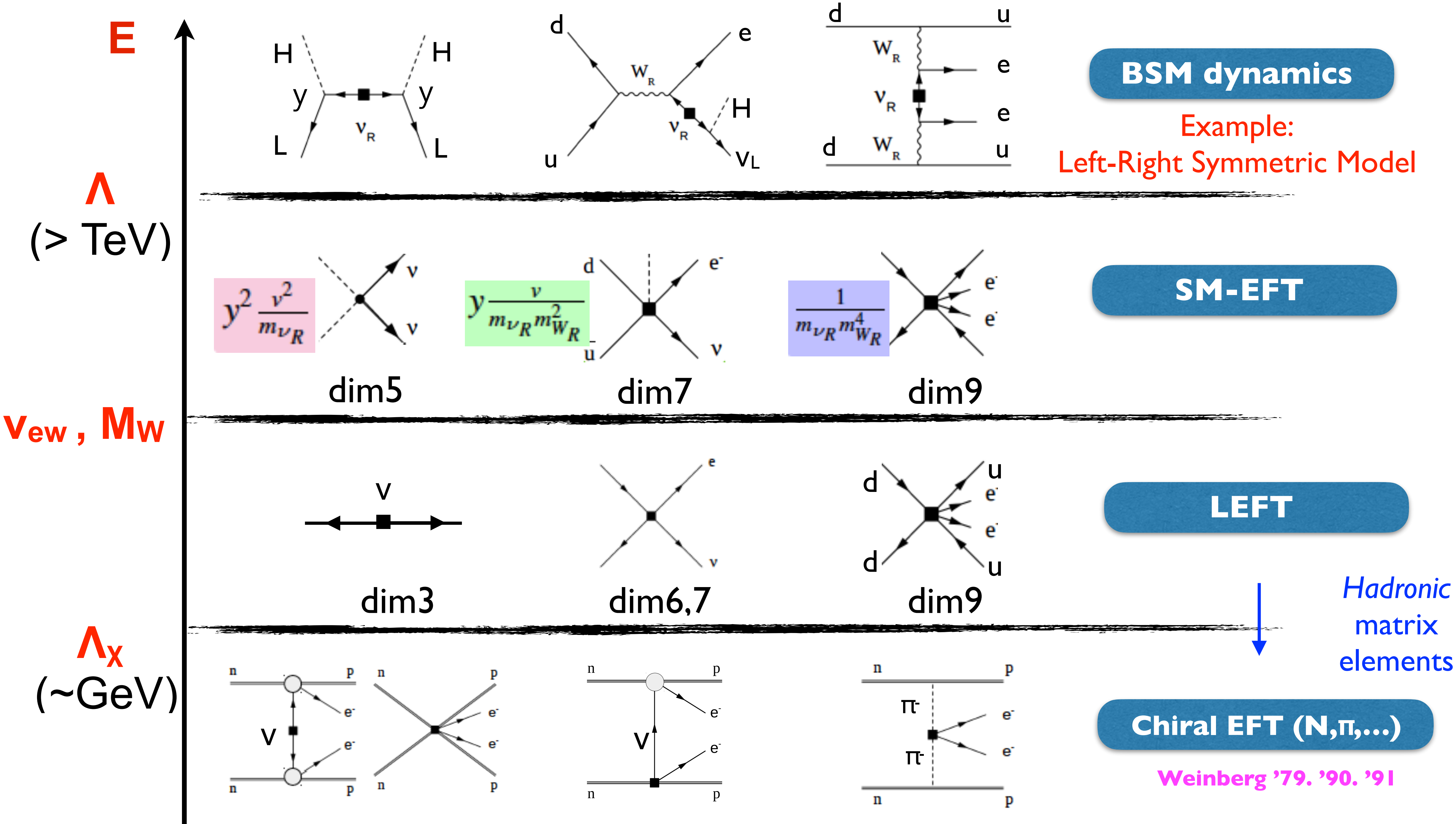
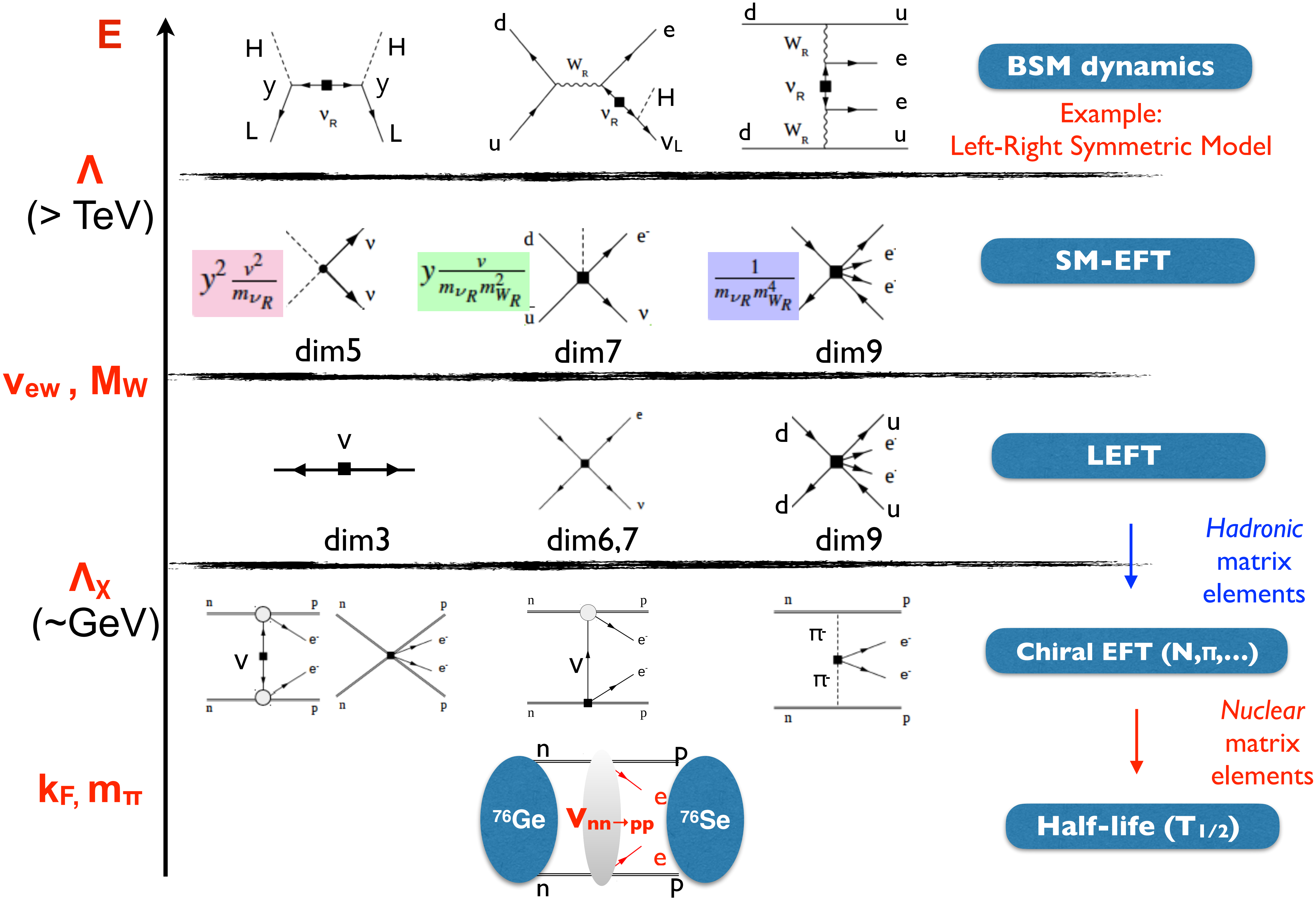


k_F, m_π

Map ΔL=2 interactions onto π, N operators, organized according to 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



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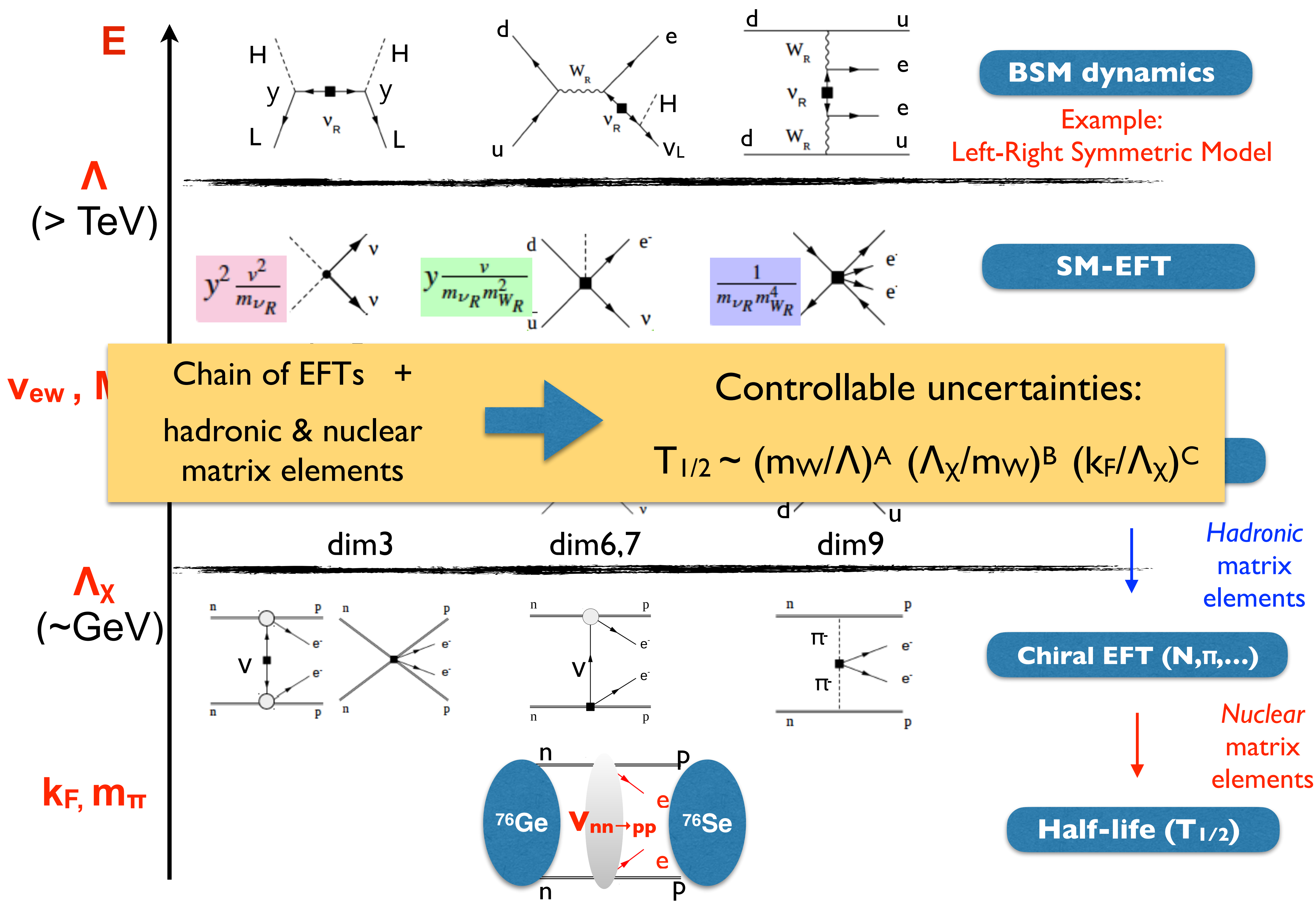
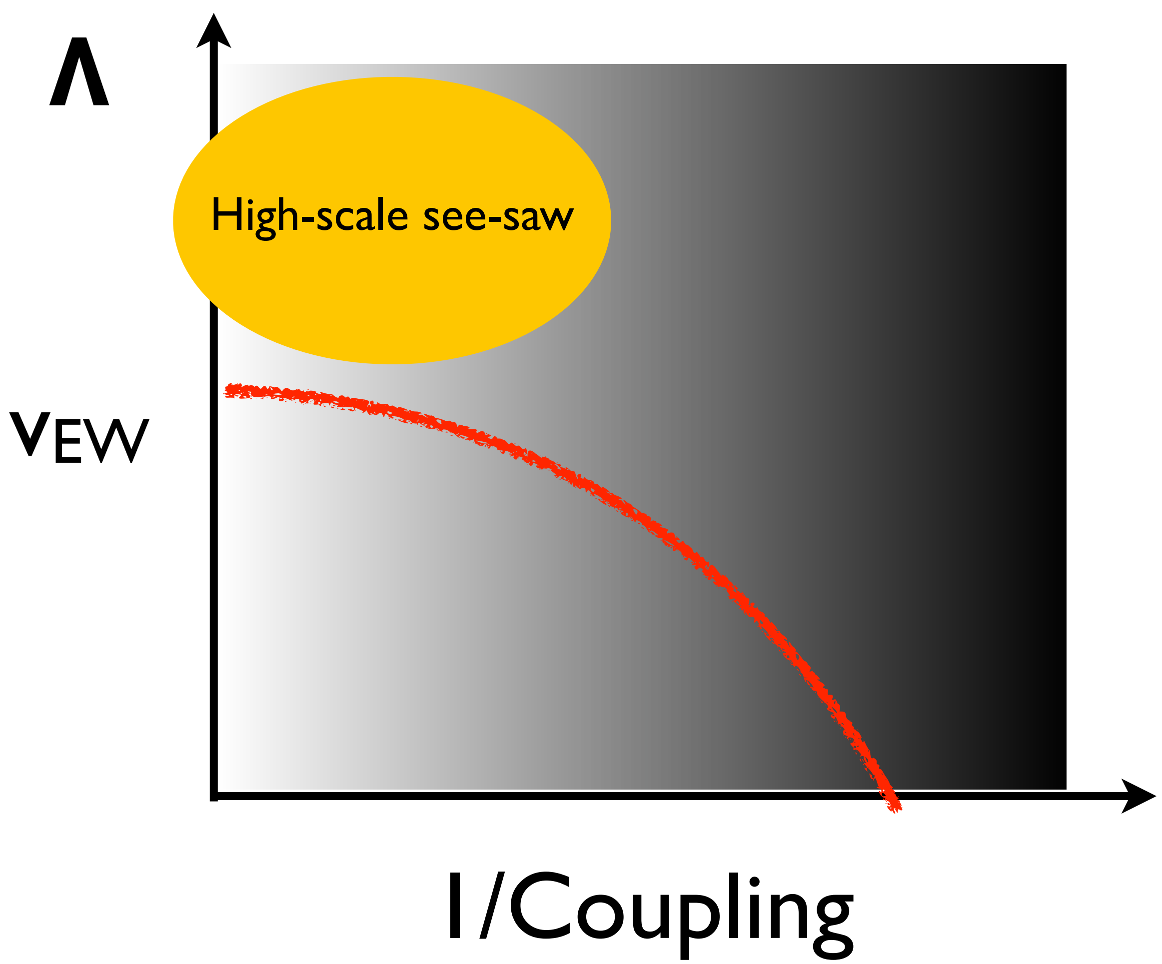
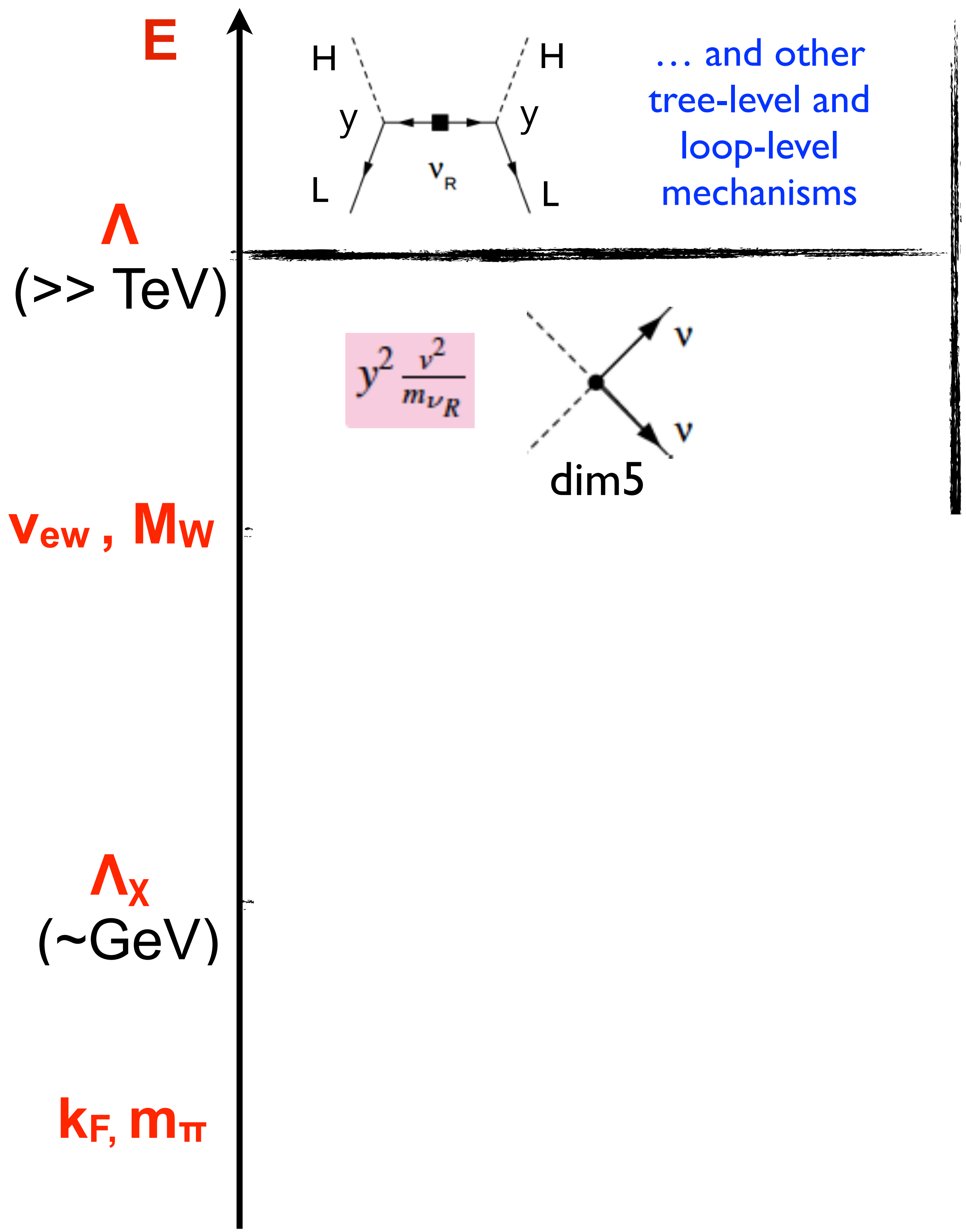


0νββ from high-scale LNV (dim-5 operator)



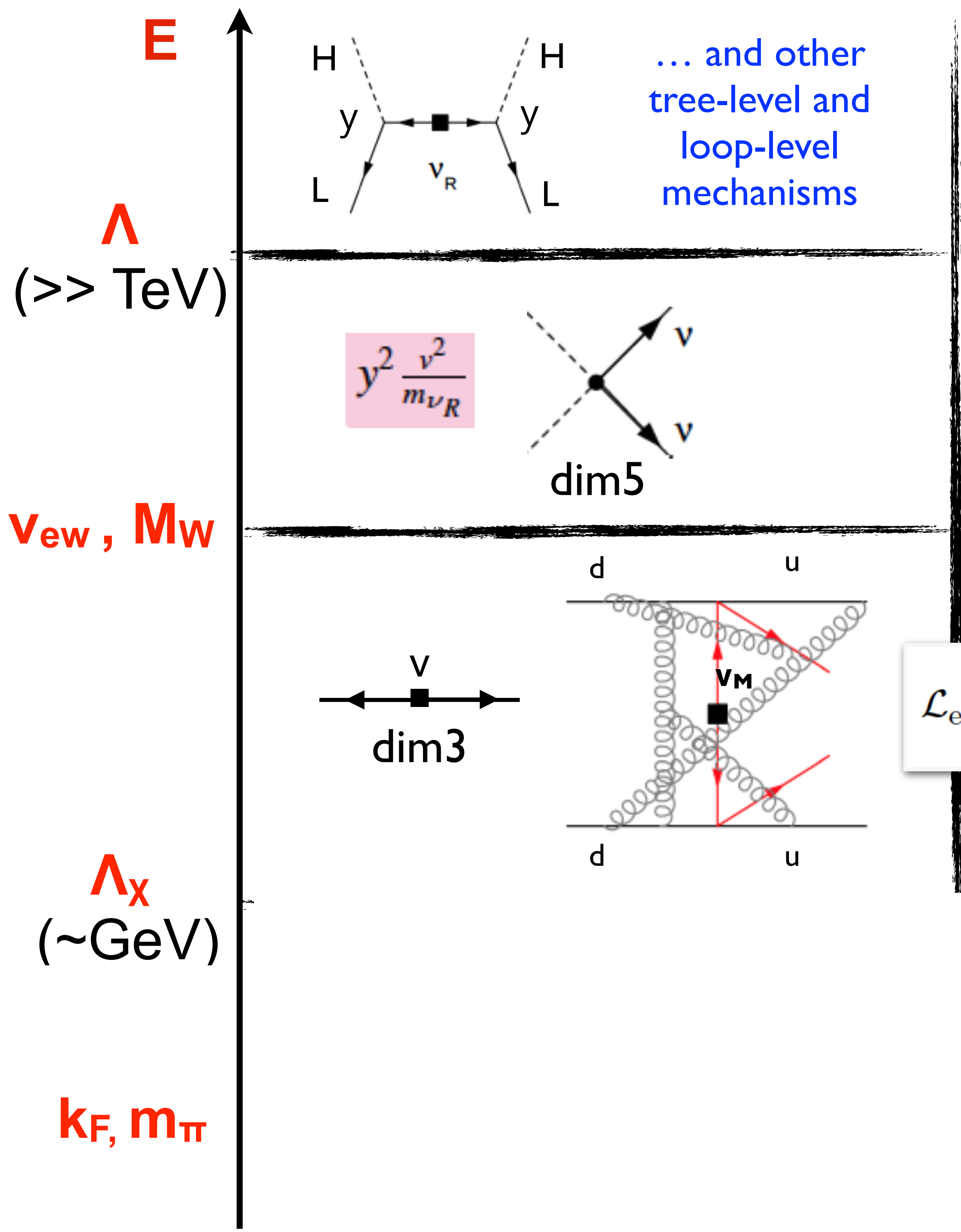
High scale LNV



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

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

High scale LNV



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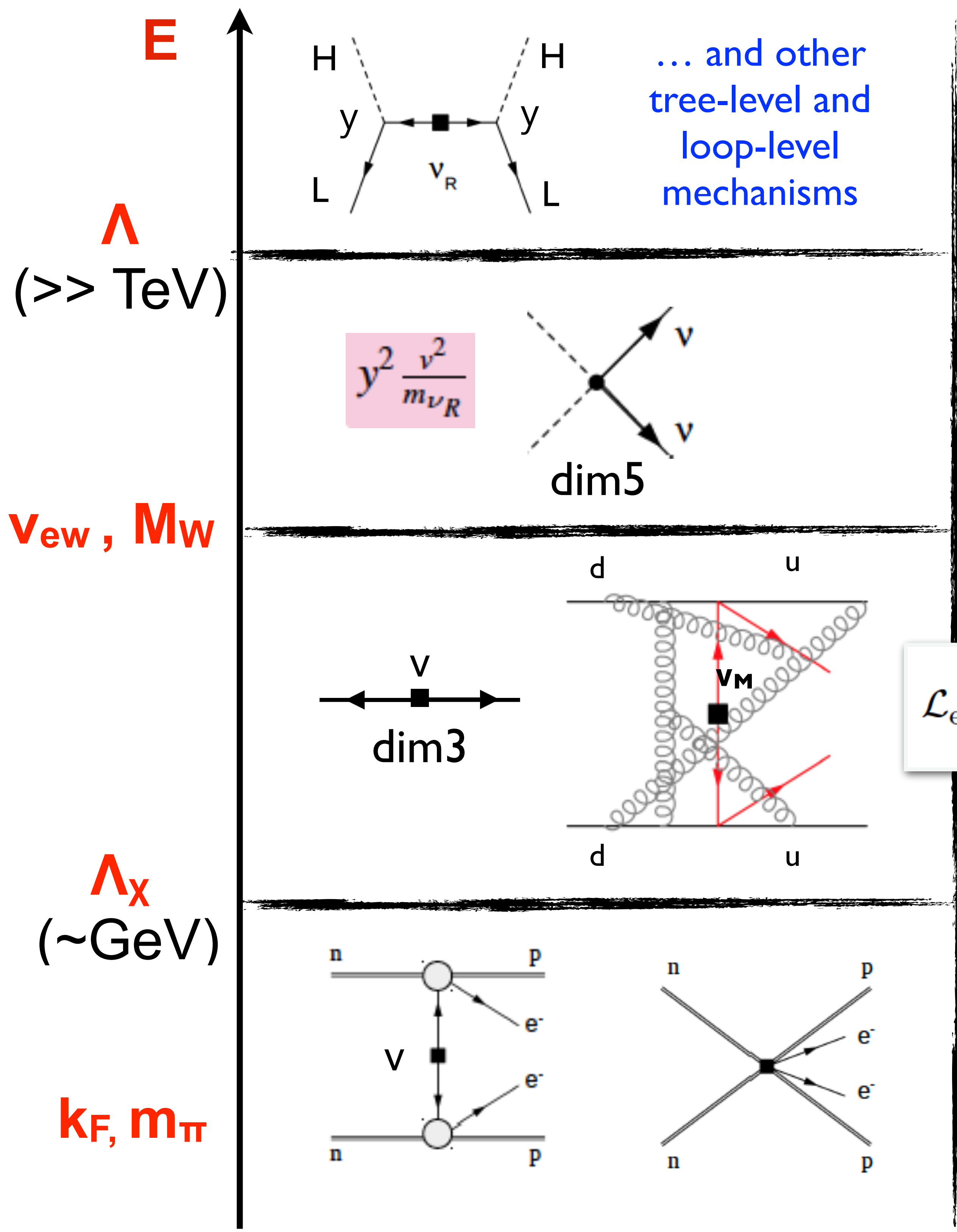
- Below the weak scale this is just the neutrino Majorana mass ($m_{\beta\beta} \sim w_{ee} \, v^2/\Lambda$)

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

High scale LNV



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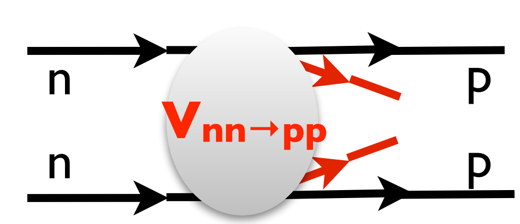
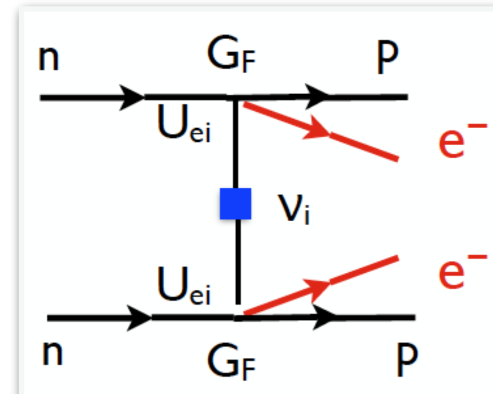
- $0\nu\beta\beta$ mediated by *active* ν_M with potential $V_{nn\to pp}$ with long- and short-range components proportional to $m_{\beta\beta}$



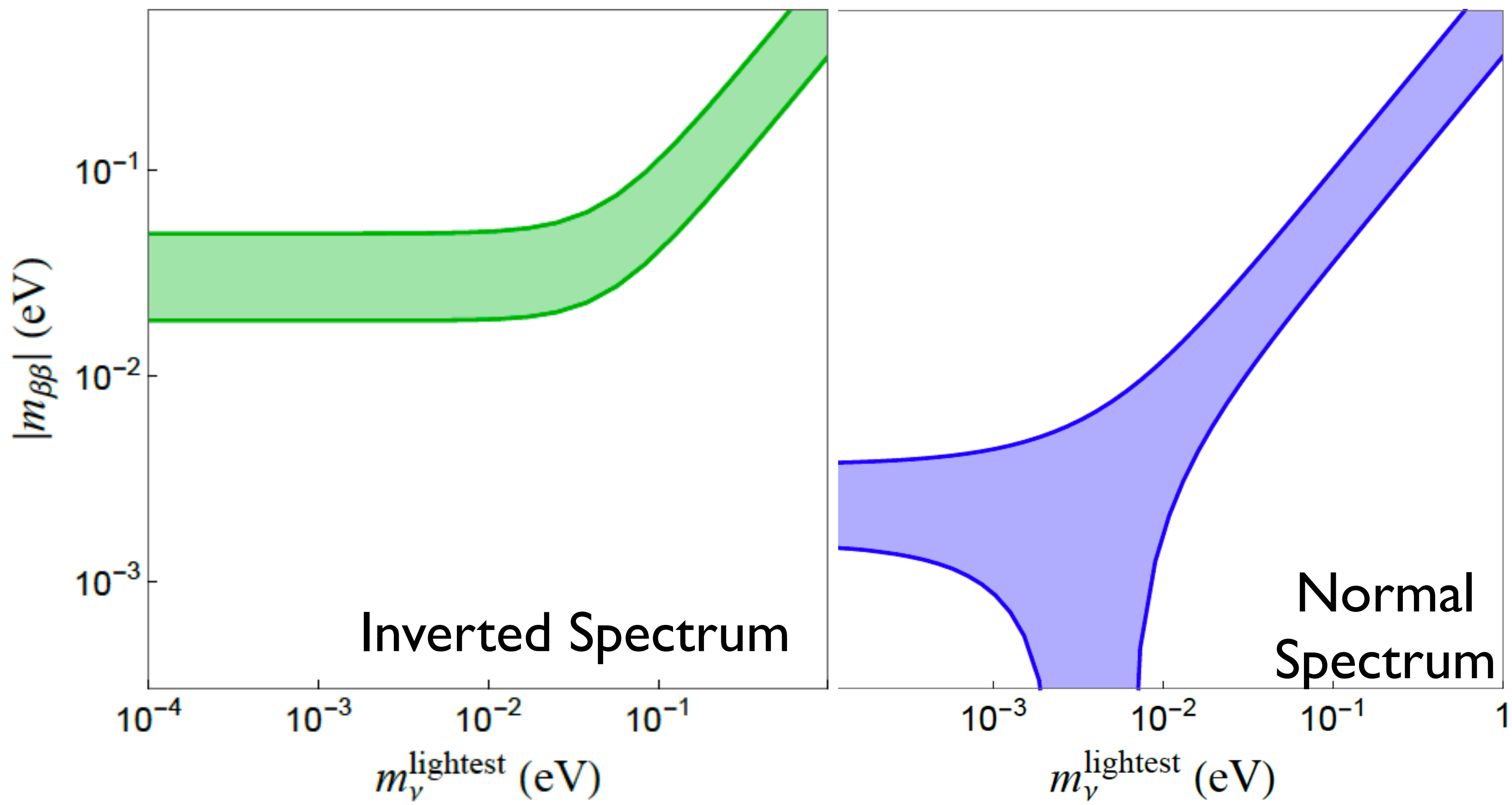
Discovery potential / target

- In this case $0\nu\beta\beta$ is a *direct* probe of ν Majorana mass: $\Gamma \propto |M_{0\nu}|^2 \, (m_{\beta\beta})^2$

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



Bands: unknown Majorana phases



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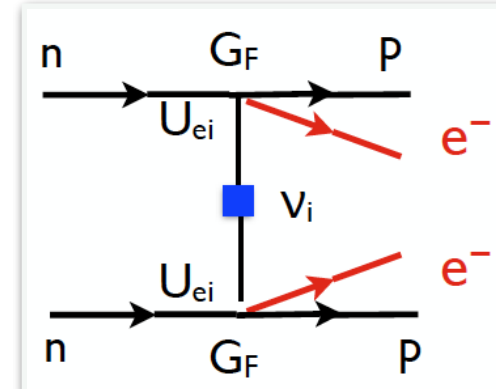

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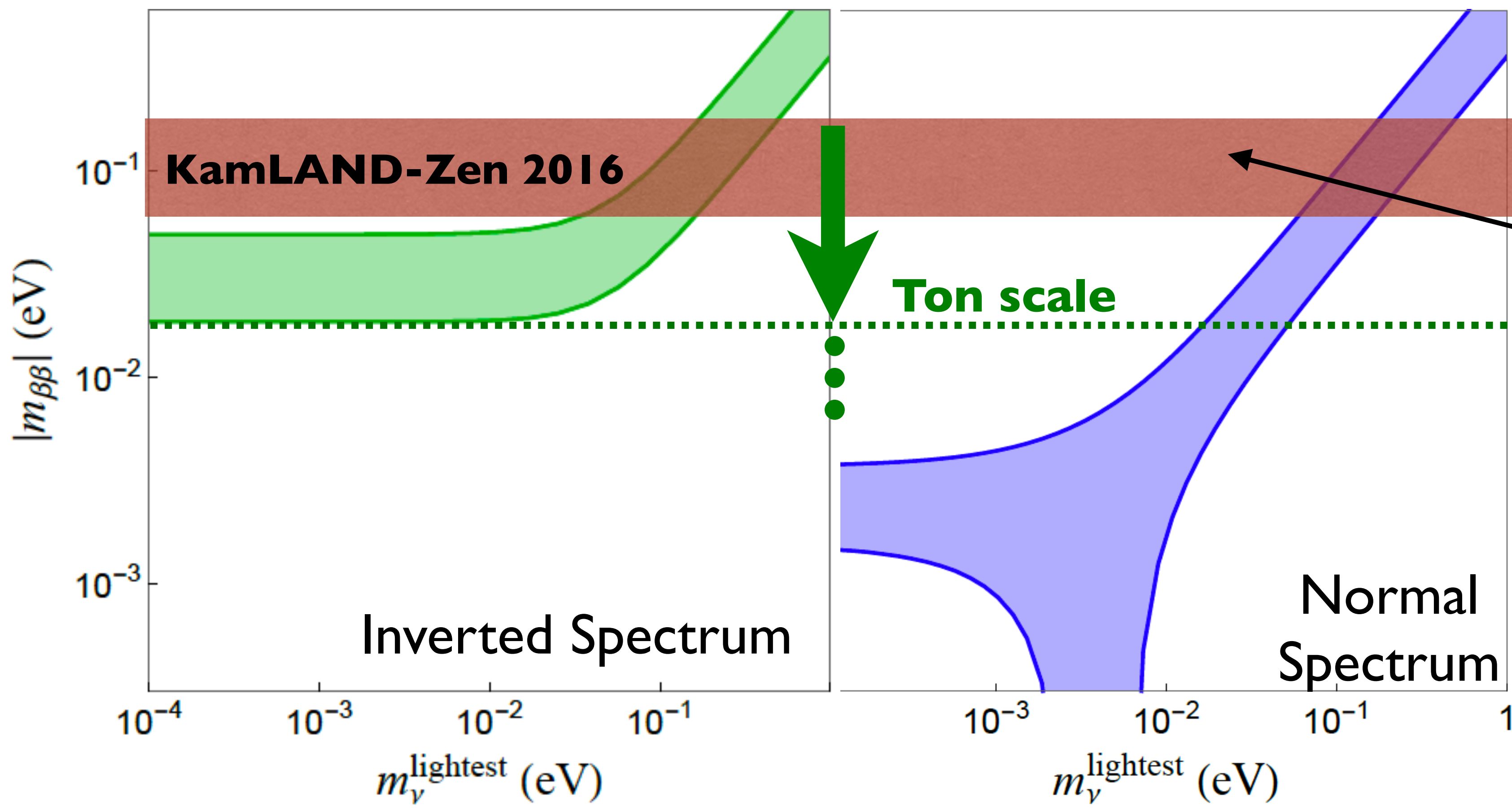


Assume range for nuclear matrix elements from different nuclear calculations

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

Diagnosing power

- High scale seesaw implies falsifiable correlation with other ν mass probes. Future data can unravel new LNV sources or physics beyond "ΛCDM + m_ν"

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

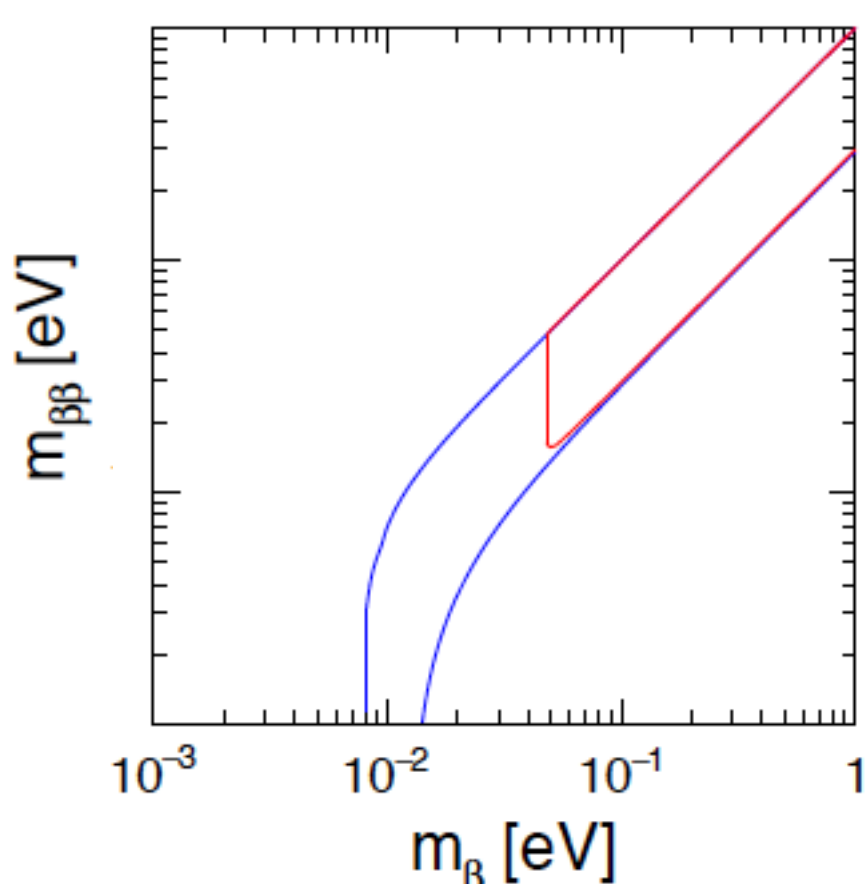
0νββ decay

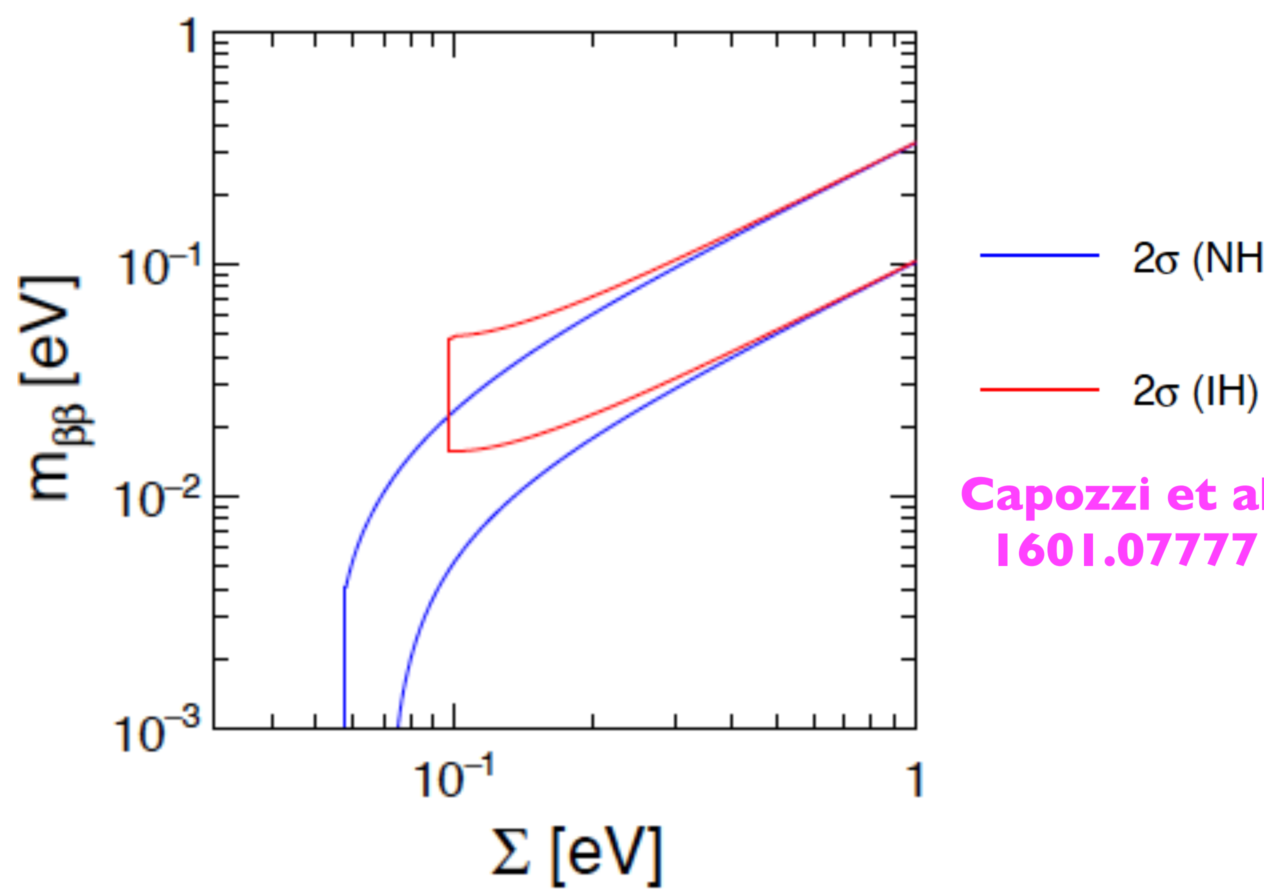
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





Capozzi et al, 1601.07777

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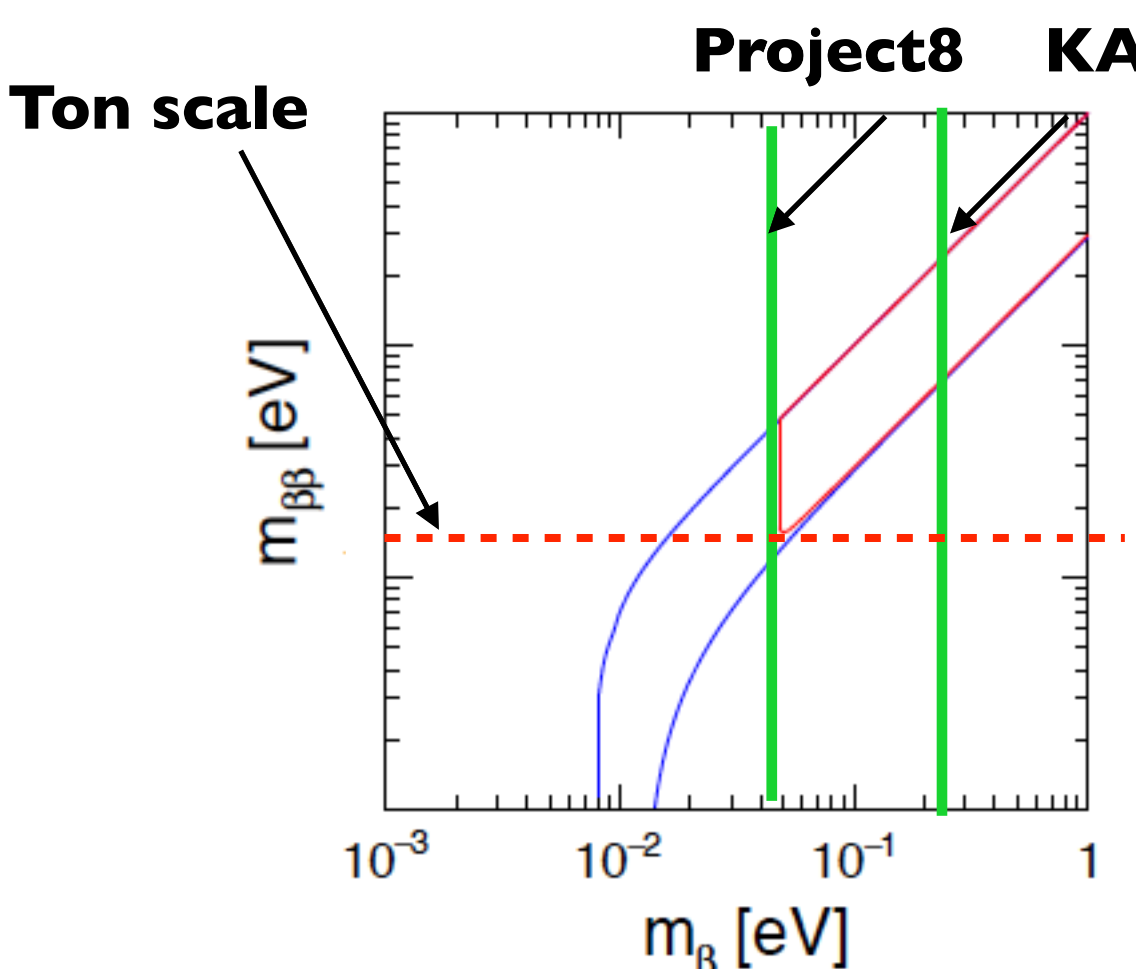

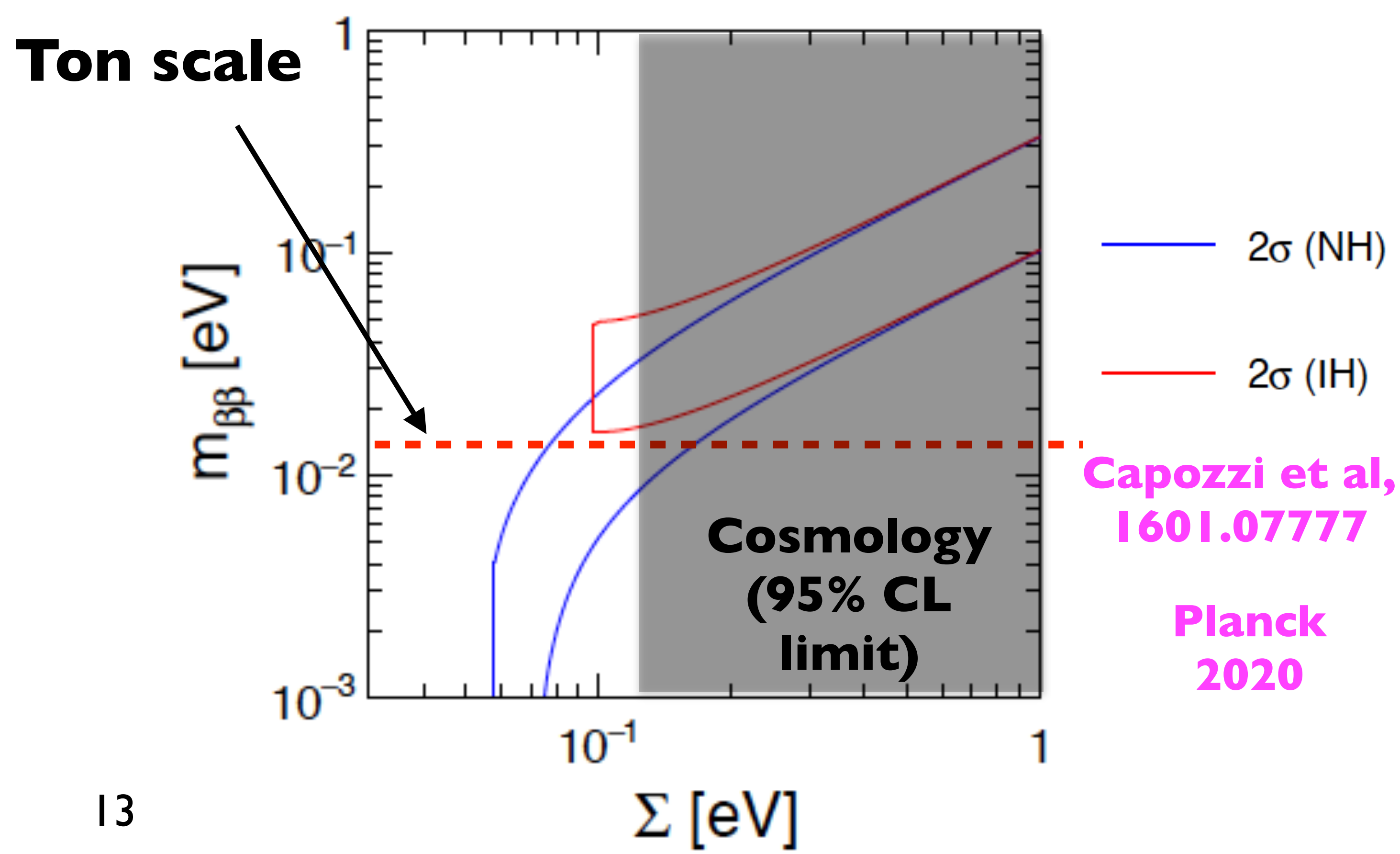

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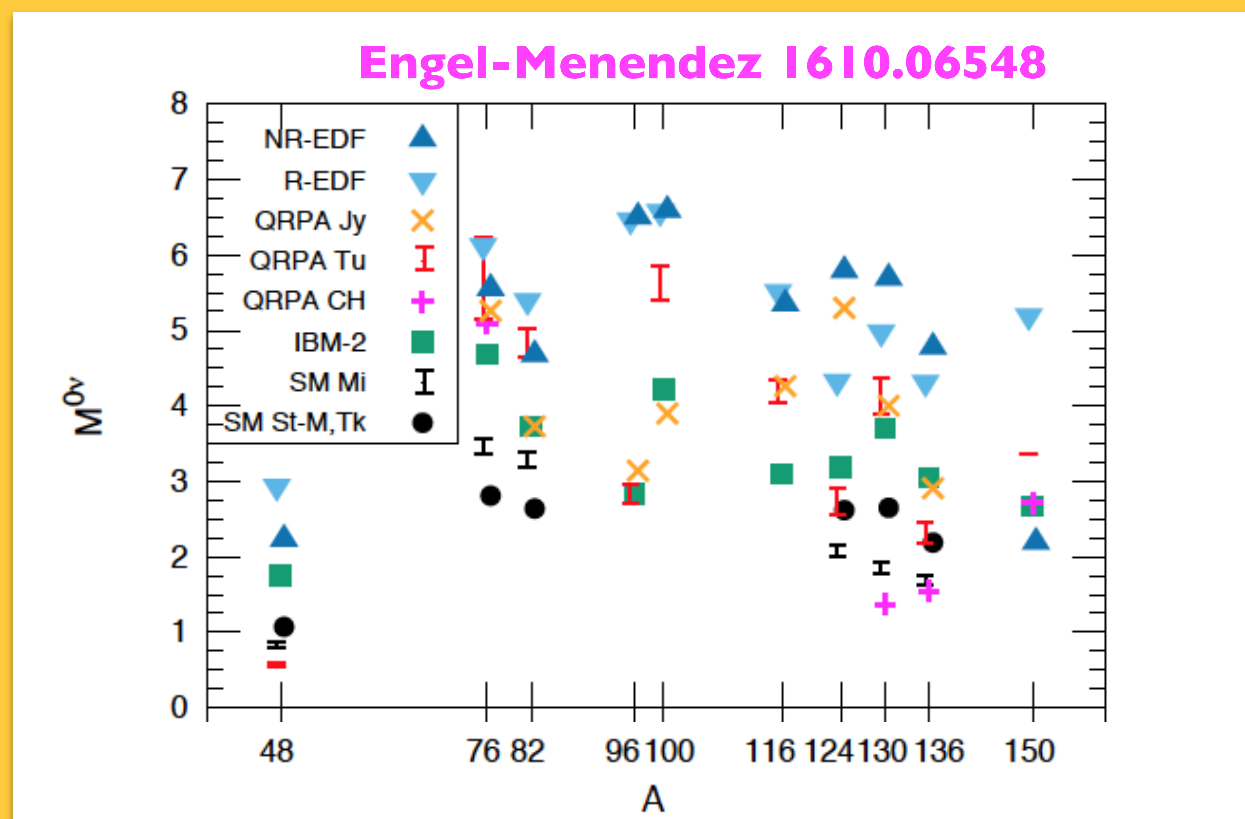
Cosmology

To

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



H)

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7

m_β [eV]

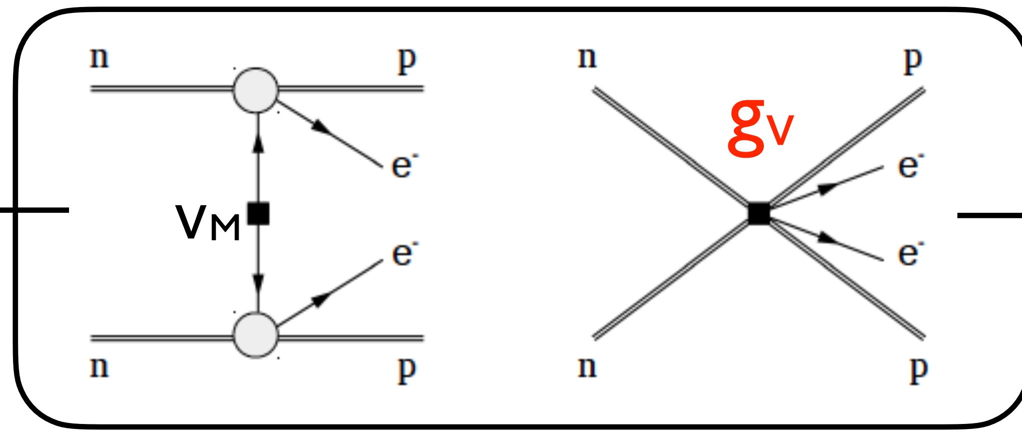
Σ [eV]

New insights from EFT

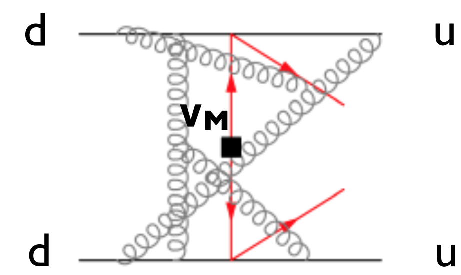
VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729
VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

- Transition operator to leading order in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV)

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



'New': short-range
coupling $g_V \sim 1/Q^2$



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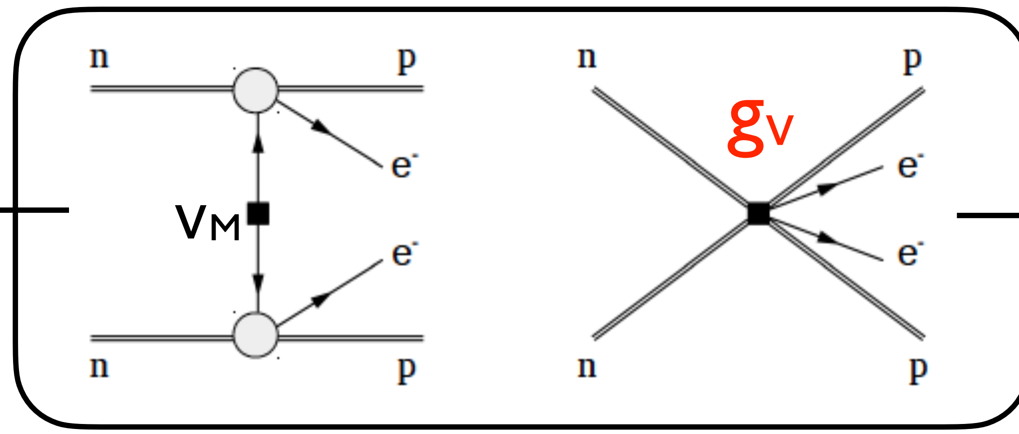

'New': short-range
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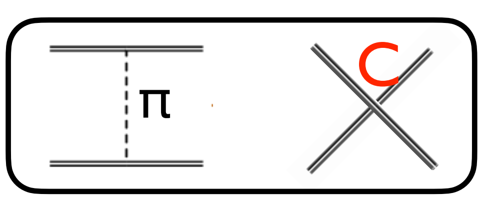
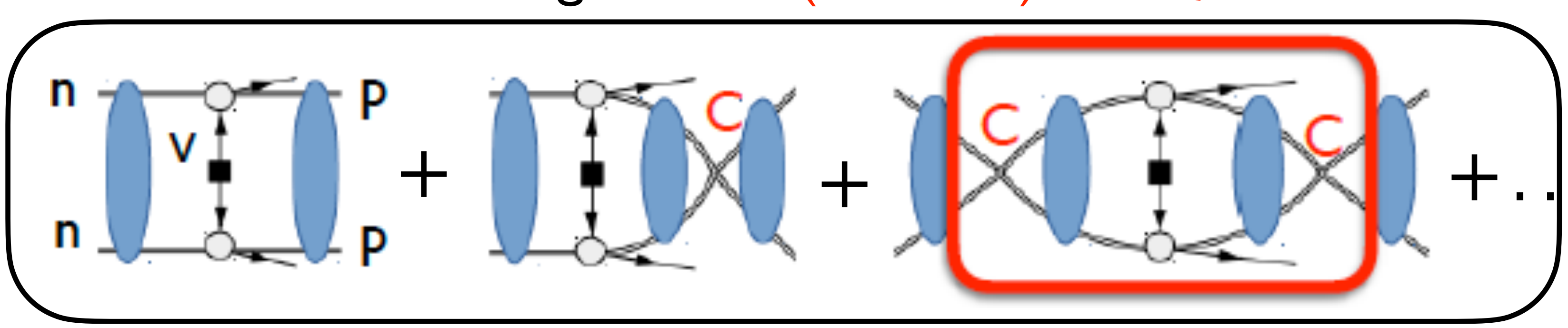
- Required by renormalization of $nn \to pp$ amplitude in presence of strong interactions

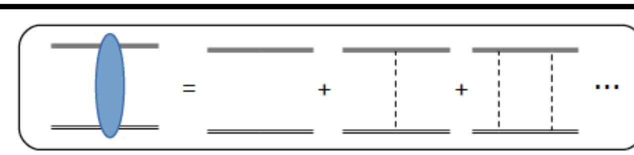
UV divergence $\propto$ $(m_N C/4\pi)^2 \sim 1/Q^2$

LO strong potential



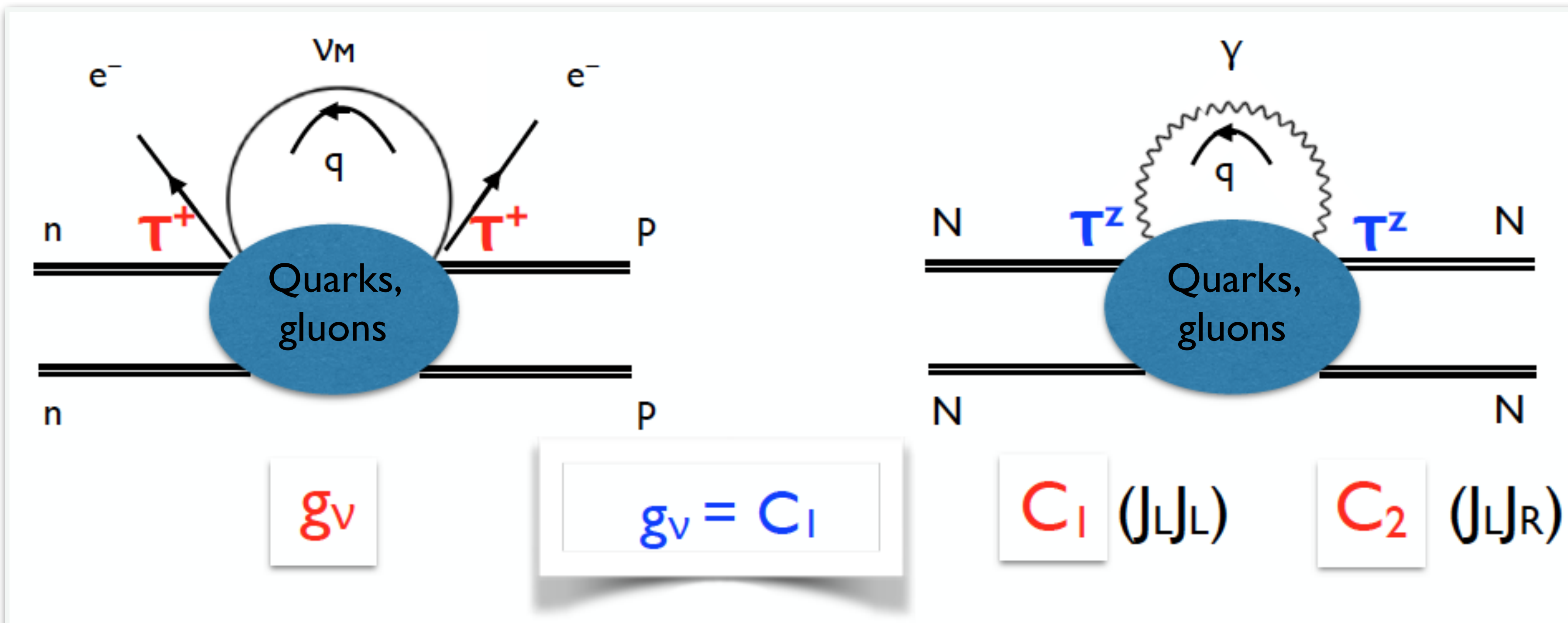
$C \sim 4\pi/(m_N Q)$





Connection with data?

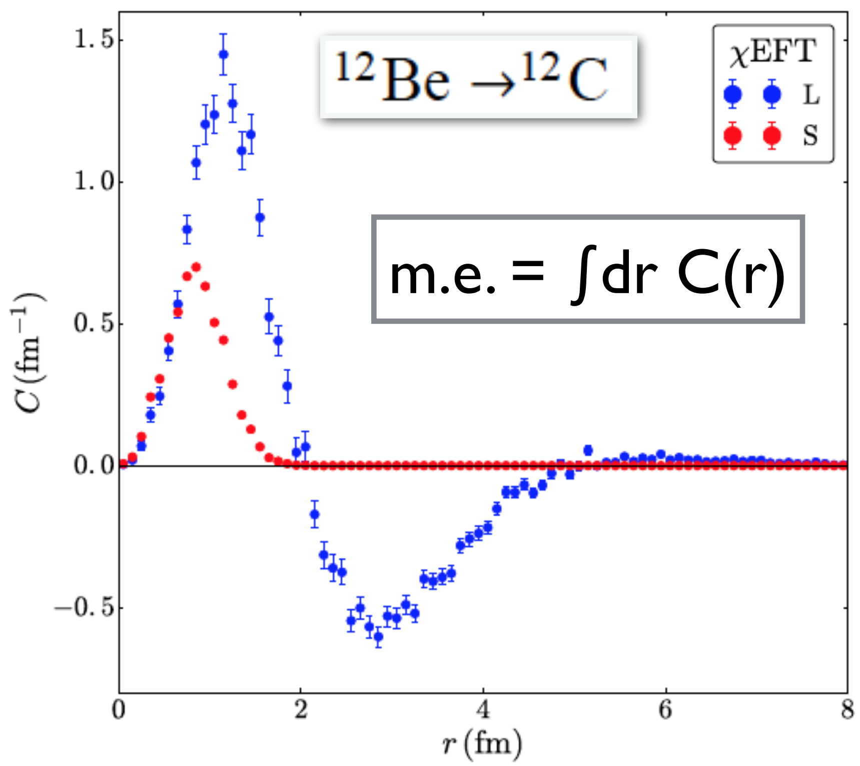
- Isospin symmetry relates g_V to one of two I=2 e.m. couplings (hard γ's & ν's)



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

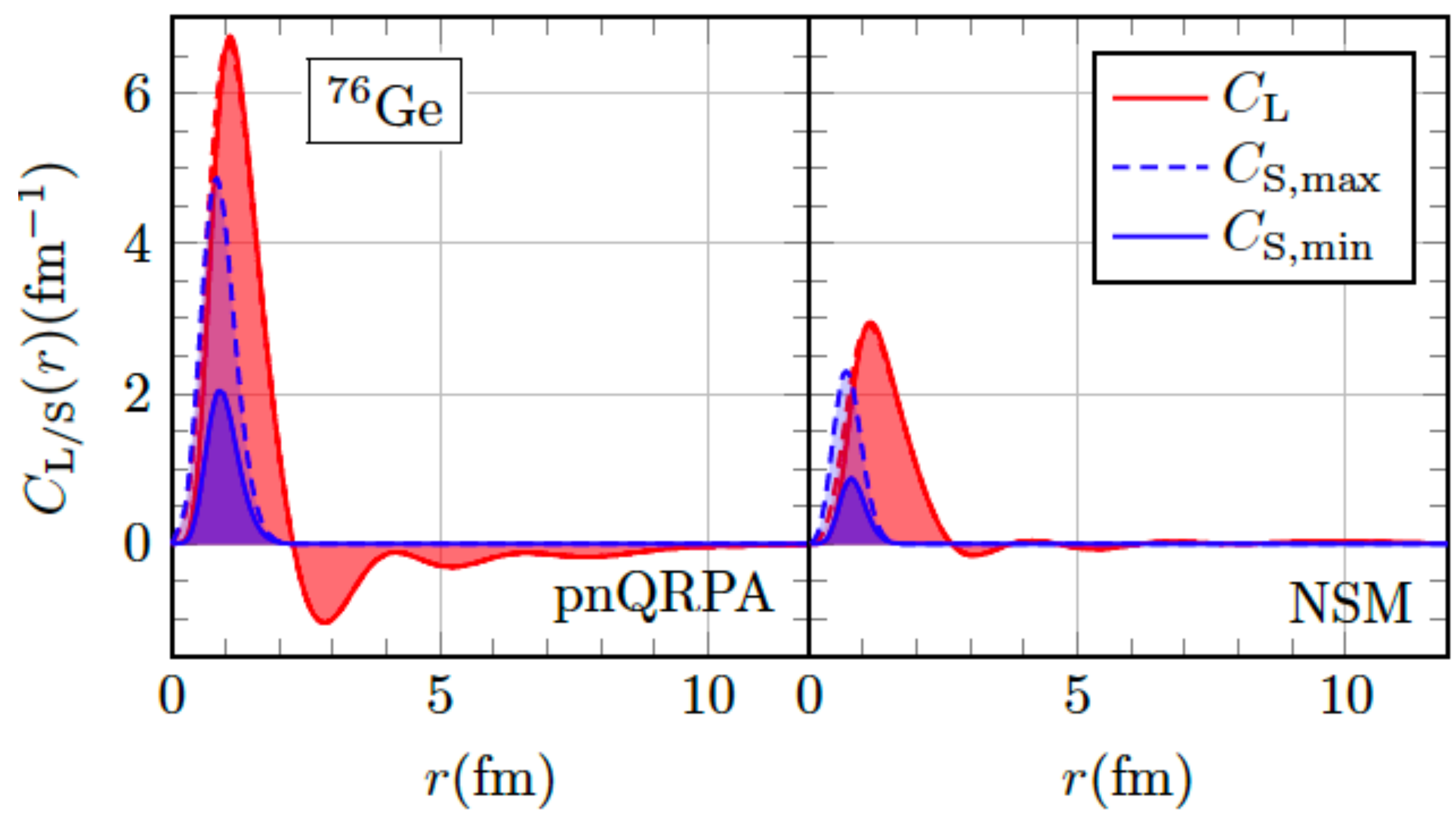
Impact on nuclear matrix elements

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



70% effect in ^{12}Be transition, using Variational Monte Carlo methods + Norfolk chiral potential [1606.06335]

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa, 1907.11254



30-70% effect in QRPA and 15-45% in NSM. Similar or larger in other isotopes

Jokiniemi-Soriano-Menendez, 2107.13354

Impact on nuclear matrix elements

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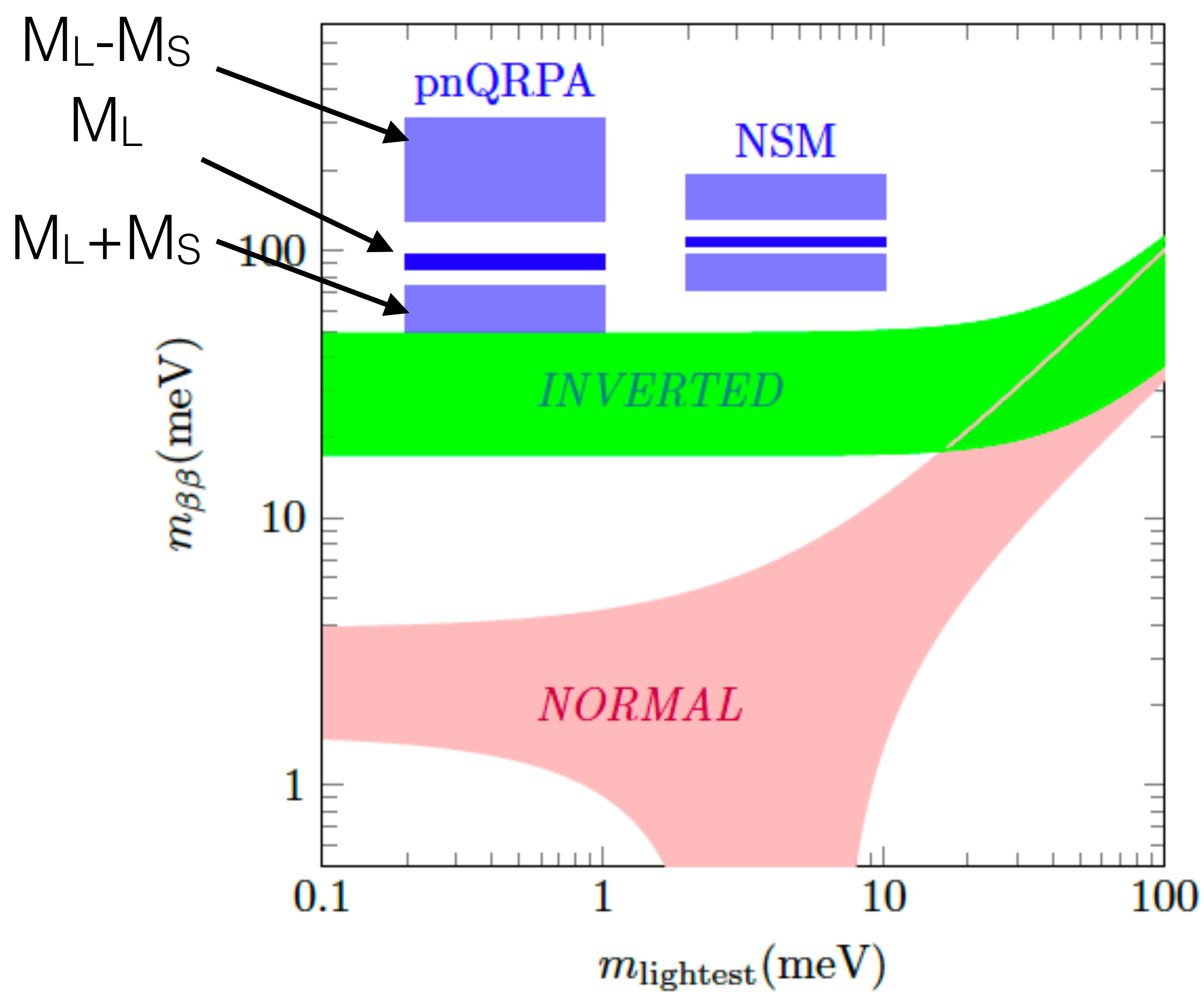


Key question:
is the interference constructive or destructive?

Jokiniemi-Soriano-Menendez, 2107.13354

Towards determining of g_V

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

Richardson, Shindler, Pastore, Springer, 2102.02814

- Lattice QCD
  - $\pi^- \to \pi^+ e^- e^-$ precisely known
  - Formalism for NN developed

Tuo et al. 1909.13525;
Detmold, Murphy 2004.07404

Davoudi, Kadam, 2012.02083

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

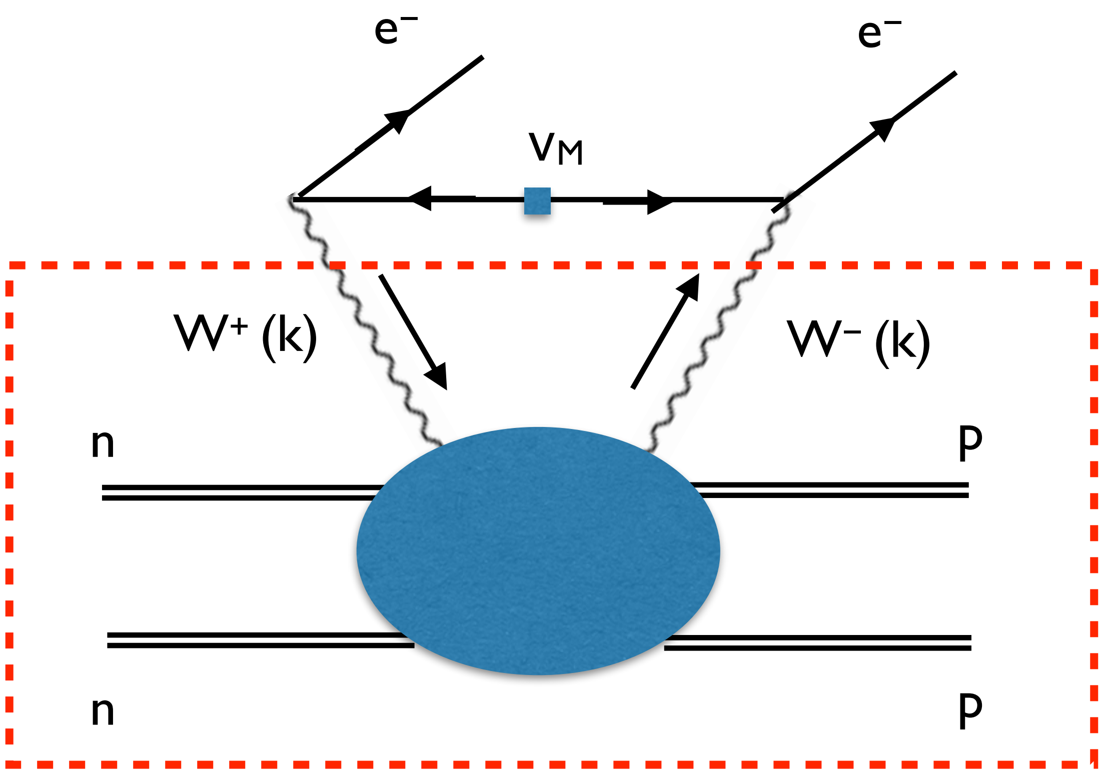
VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Estimating the contact term (1)

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

- Useful representation of the amplitude

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



Forward "Compton" amplitude

Estimating the contact term (I)

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

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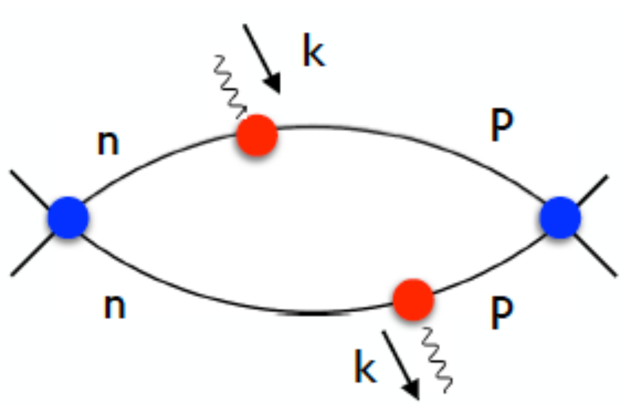
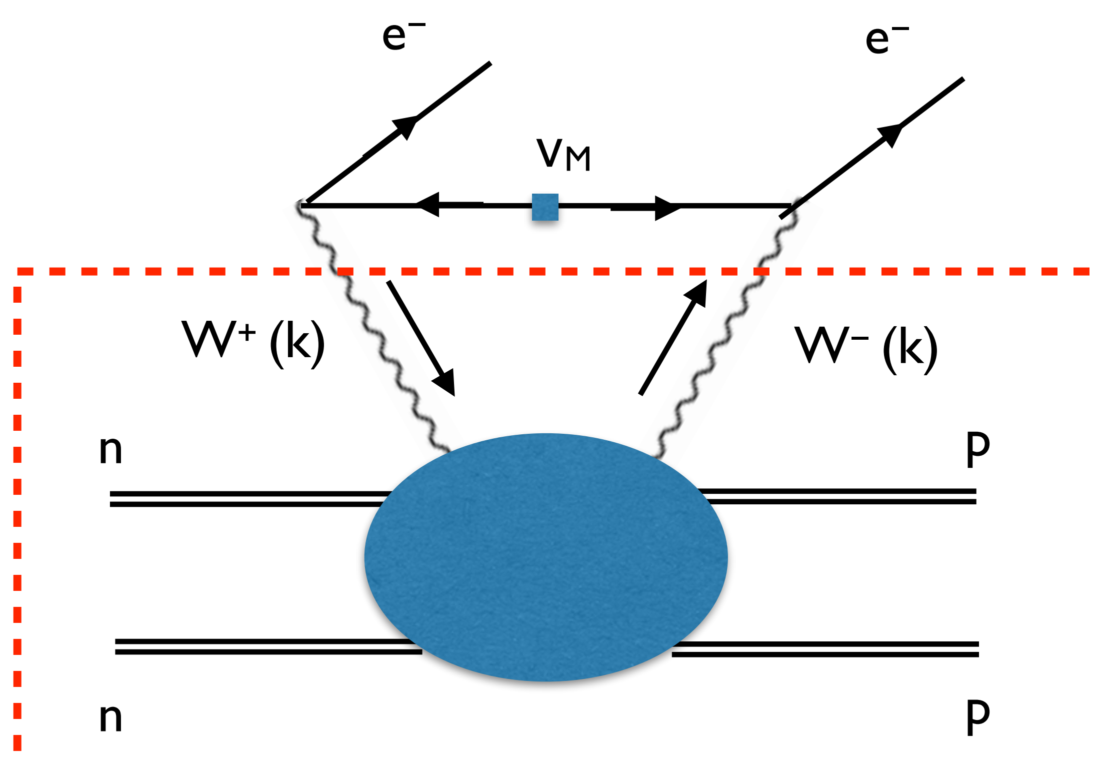
Low k: chiral EFT to NLO

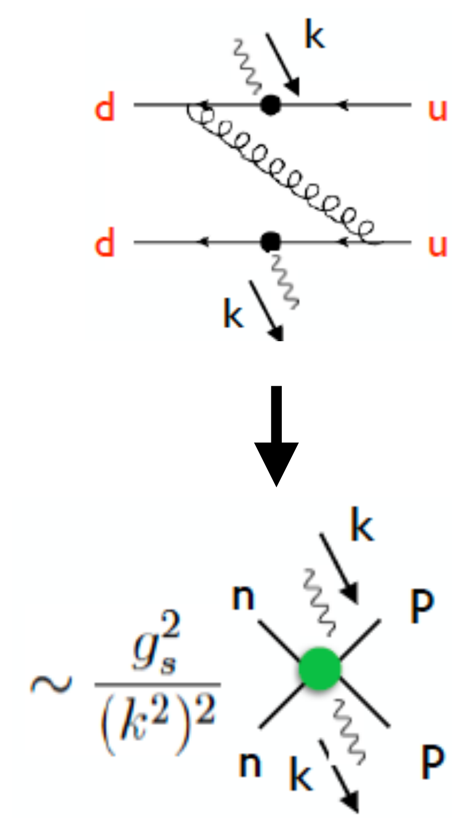


Intermediate k: resonance contributions in [blue dot] and [red dot], πNN intermediate state, …



Forward "Compton" amplitude

High k: QCD OPE

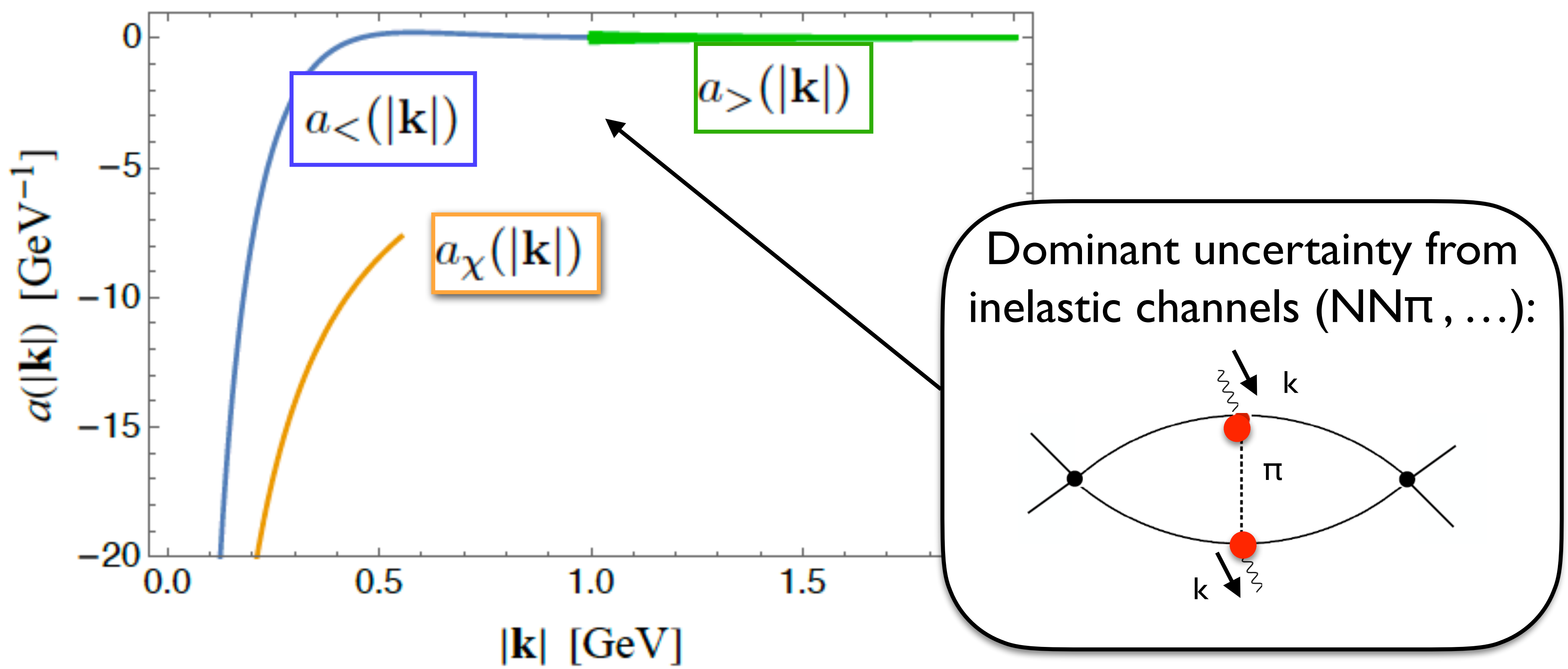


Estimating the contact term (2)

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

- Determine $C_{1,2}$ with ~ 30% uncertainty (dominated by intermediate k)

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



Estimating the contact term (2)

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

- Determine $C_{1,2}$ with ~ 30% uncertainty (dominated by intermediate k)
- Validation: $C_1+C_2 \Rightarrow (a_{nn}+a_{pp})/2 - a_{np}$ = 15.5(4.5) fm versus 10.4(2) fm (exp)
- Provided 'synthetic data' for the nn→pp amplitude at threshold
- First calculation of $^{48}Ca \rightarrow {}^{48}Ti$ with contact fitted to synthetic data ⇒ contact term enhances nuclear matrix element by (43±7)%

Wirth, Yao, Hergert, 2105.05415

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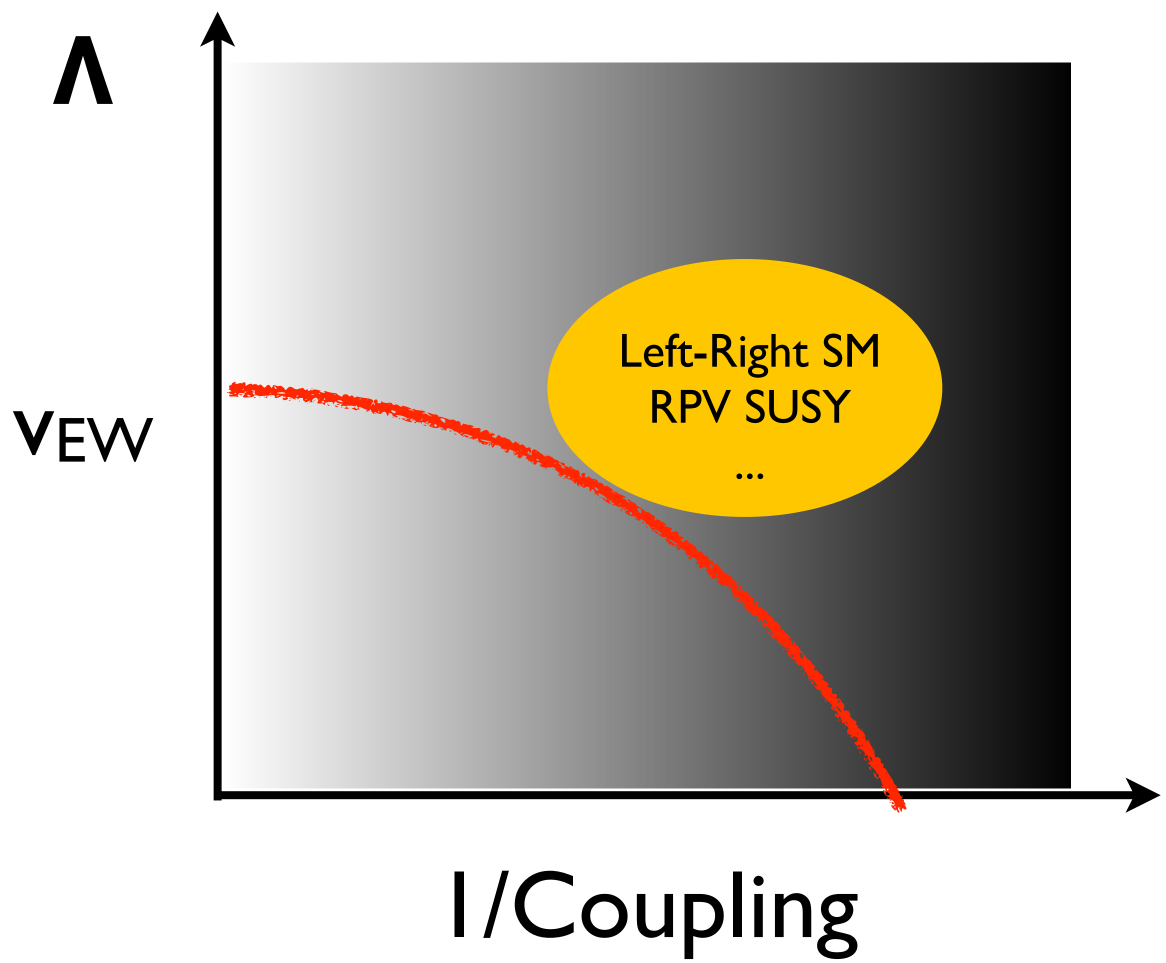
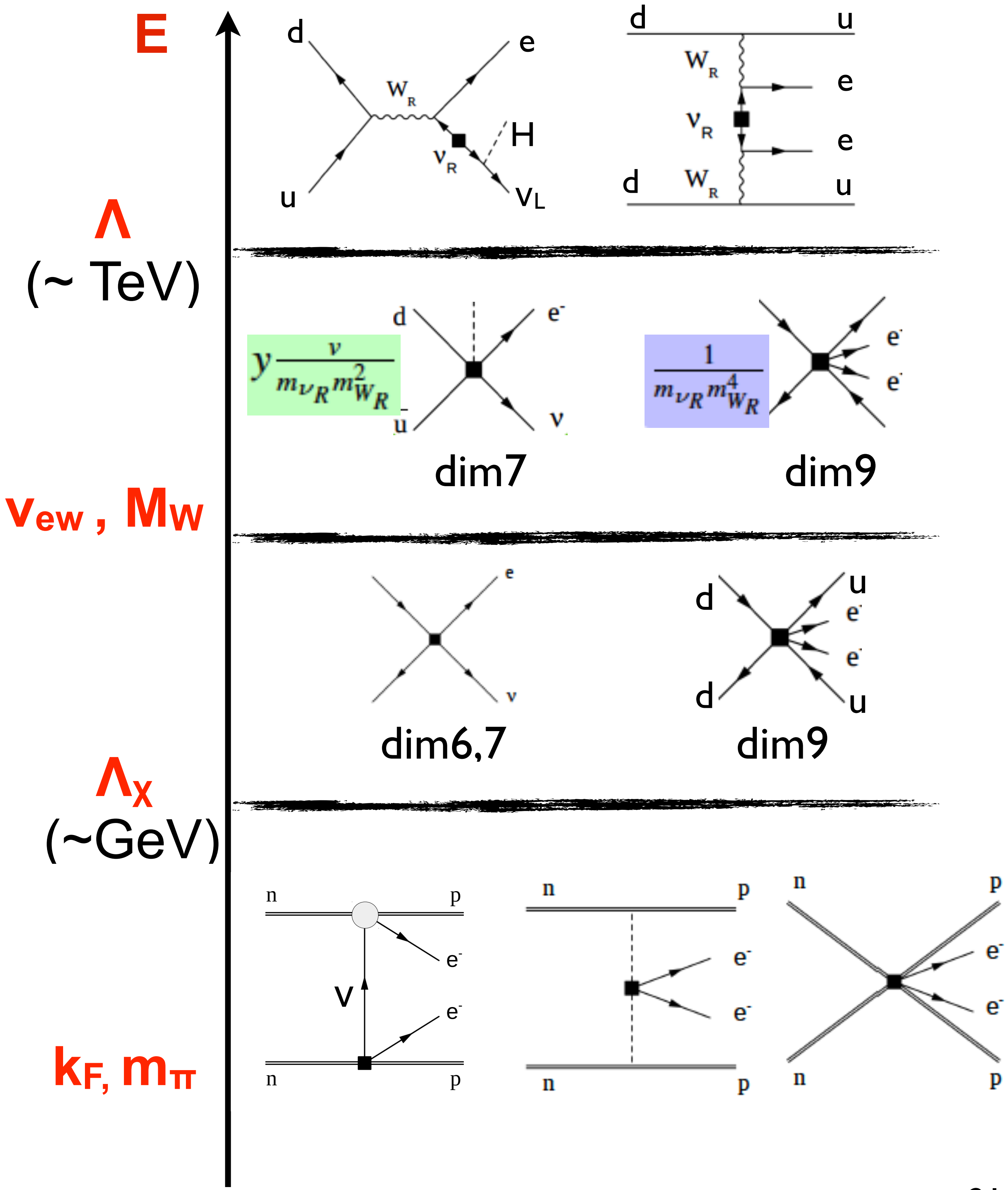
Wirth, Yao, Hergert, 2105.05415

Good news, while we wait for lattice results

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



~TeV-scale LNV



- Higher dim operators arise in well motivated models

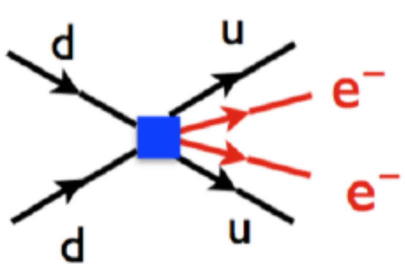
  See talks by Babu, Fileviez Perez., …

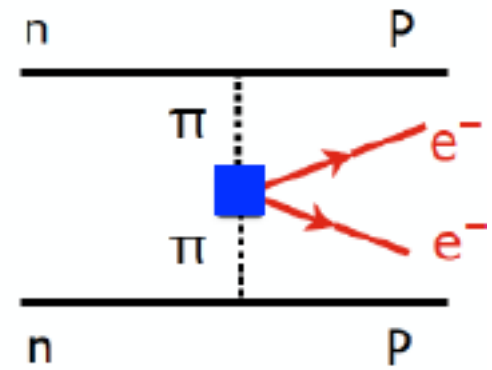
- 31 operators up to dimension 9

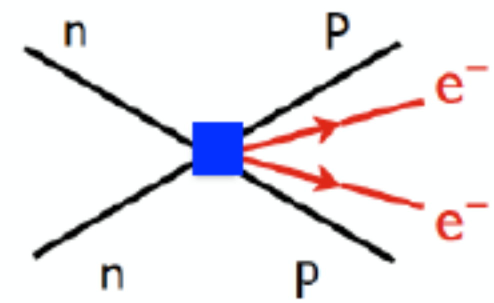
- New mechanisms at the hadronic scale: need appropriate chiral EFT treatment. Not including pion range effects leads to factor ~ $(Q/\Lambda_\chi)^2$ ~1/100 reduction in sensitivity to short-distance couplings!

Hadronic theory developments

- Leading order hadronic realization of dim-9 operators:







In Weinberg's counting, pion-exchange contribution dominates

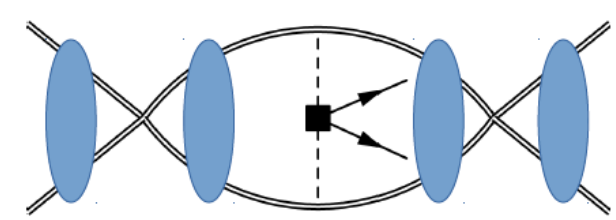
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

Vergados 1982, Faessler, Kovalenko, Simkovic, Schweiger 1996

ππ matrix element known from Lattice QCD at <10%

Nicholson et al (CalLat), 1805.02634

Renromalization requires a contact at the same order!



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

- Several unknown LO NN contact couplings! Opportunity for LQCD

Phenomenological interest

- TeV-scale LNV induces contributions to $0\nu\beta\beta$ *not directly related to the exchange of light neutrinos,* within reach of current experiments

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

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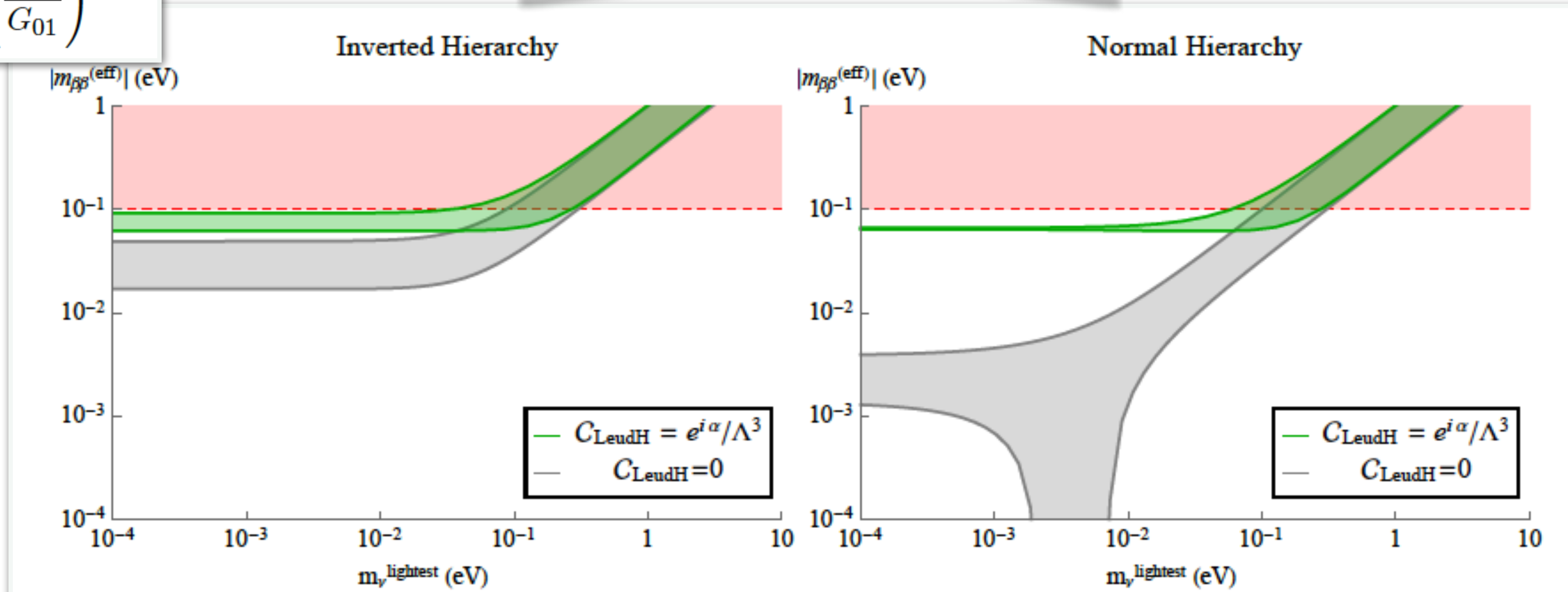
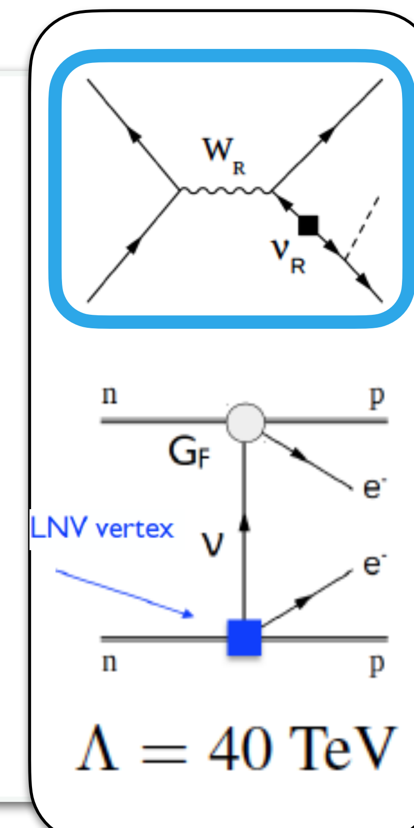
$$C_{LeudH}\, \epsilon_{ij}\, (\bar{d}\gamma^{\mu} u)\, (L_m^T C \gamma_{\mu} e)\, H_j$$

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





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

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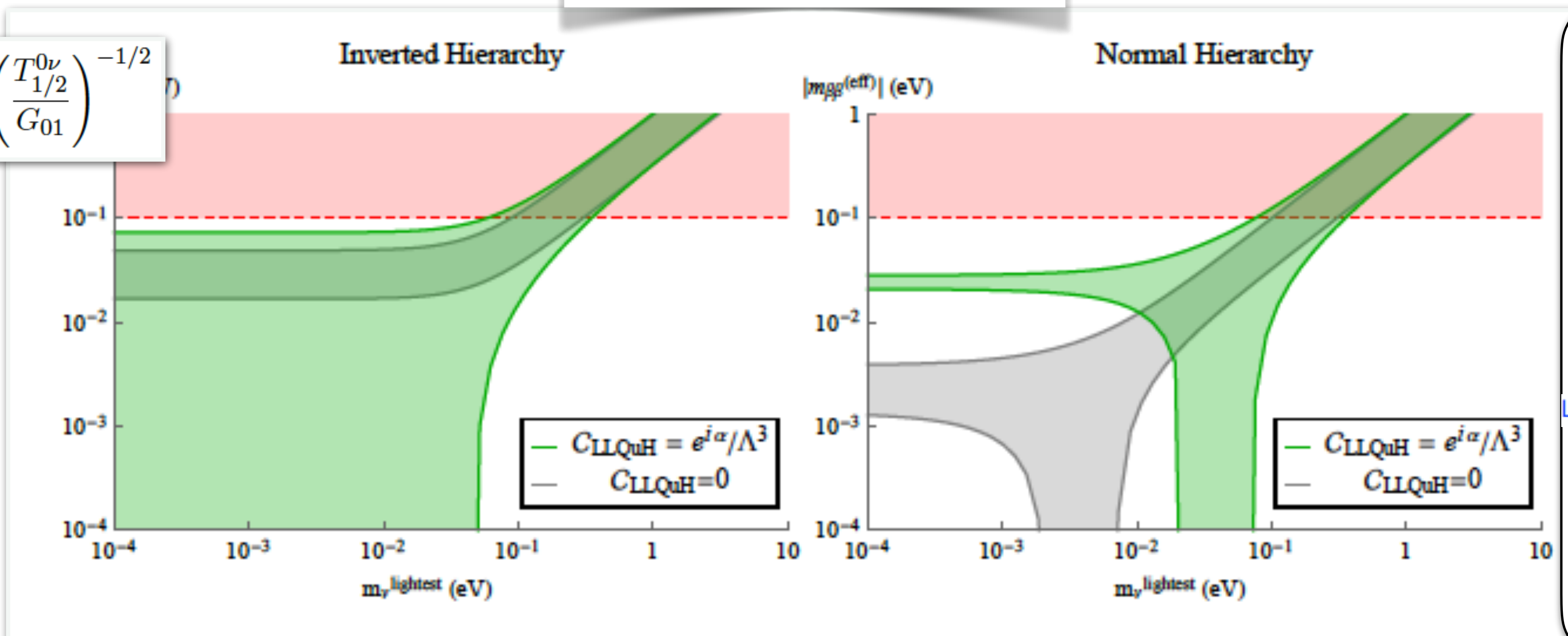

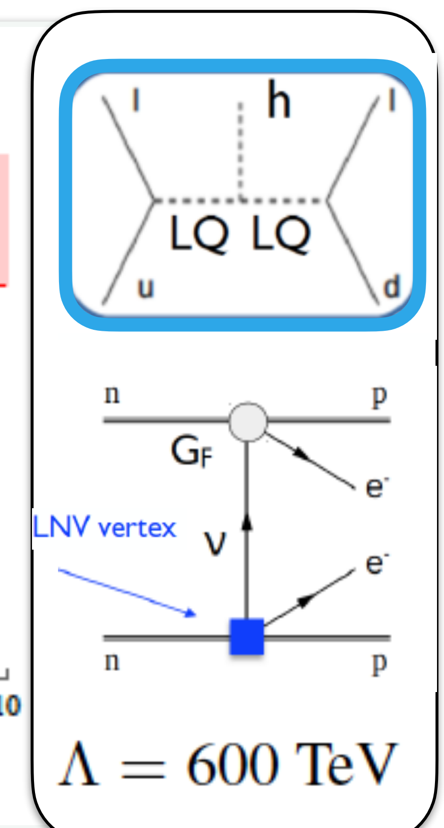

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

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

Keung-Senjanovic '83

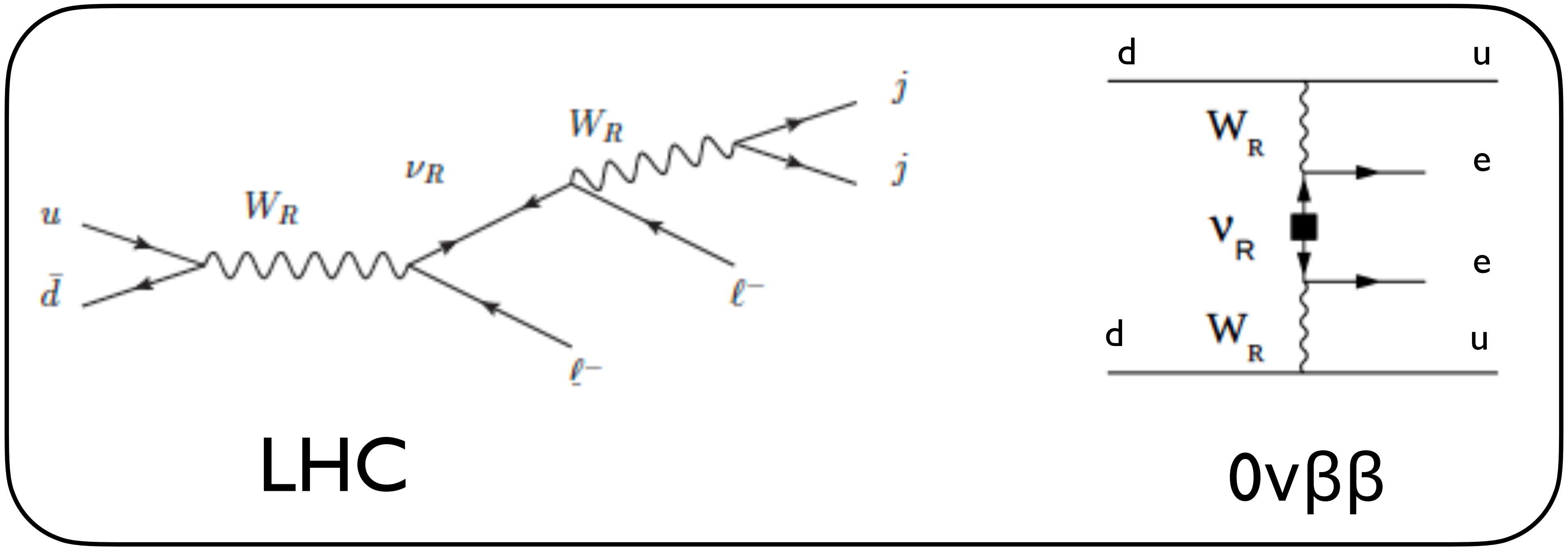
Maiezza-Nemevesek-Nesti- Senjanovic 1005.5160

Helo-Kovalenko-Hirsch-Pas 1303.0899, 1307.4849

Cai, Han, Li, Ruiz 1711.02180

...

Classic LRSM example



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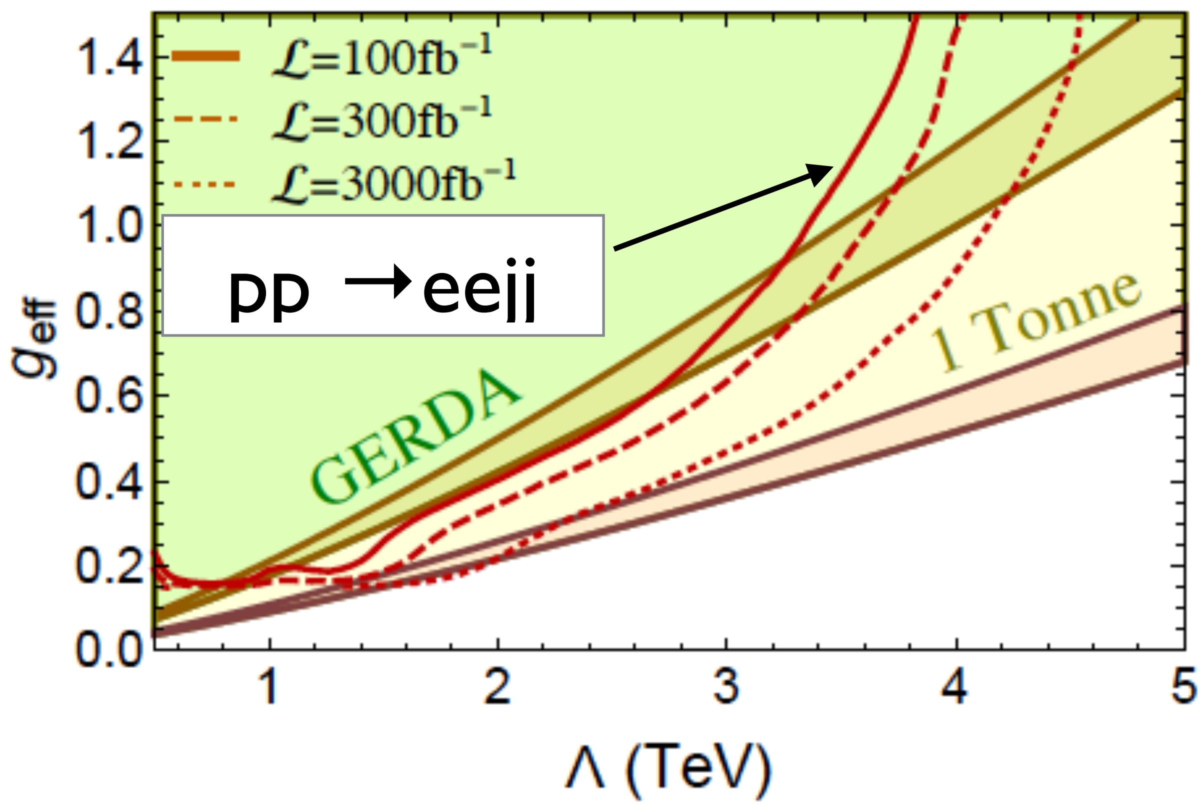
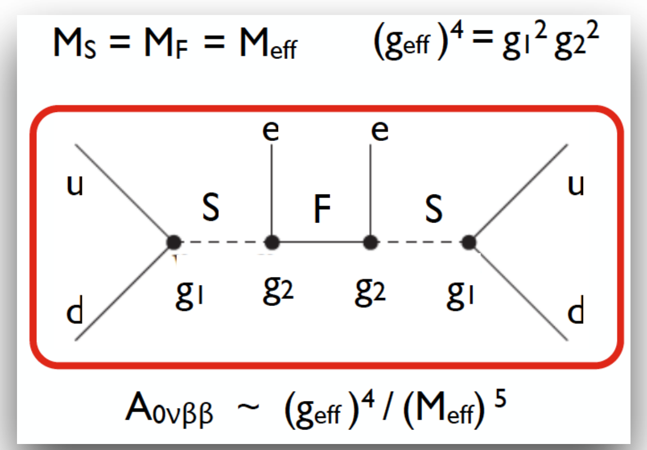
Cai, Han, Li, Ruiz 1711.02180

Peng, Ramsey-Musolf, Winslow, 1508.0444

...

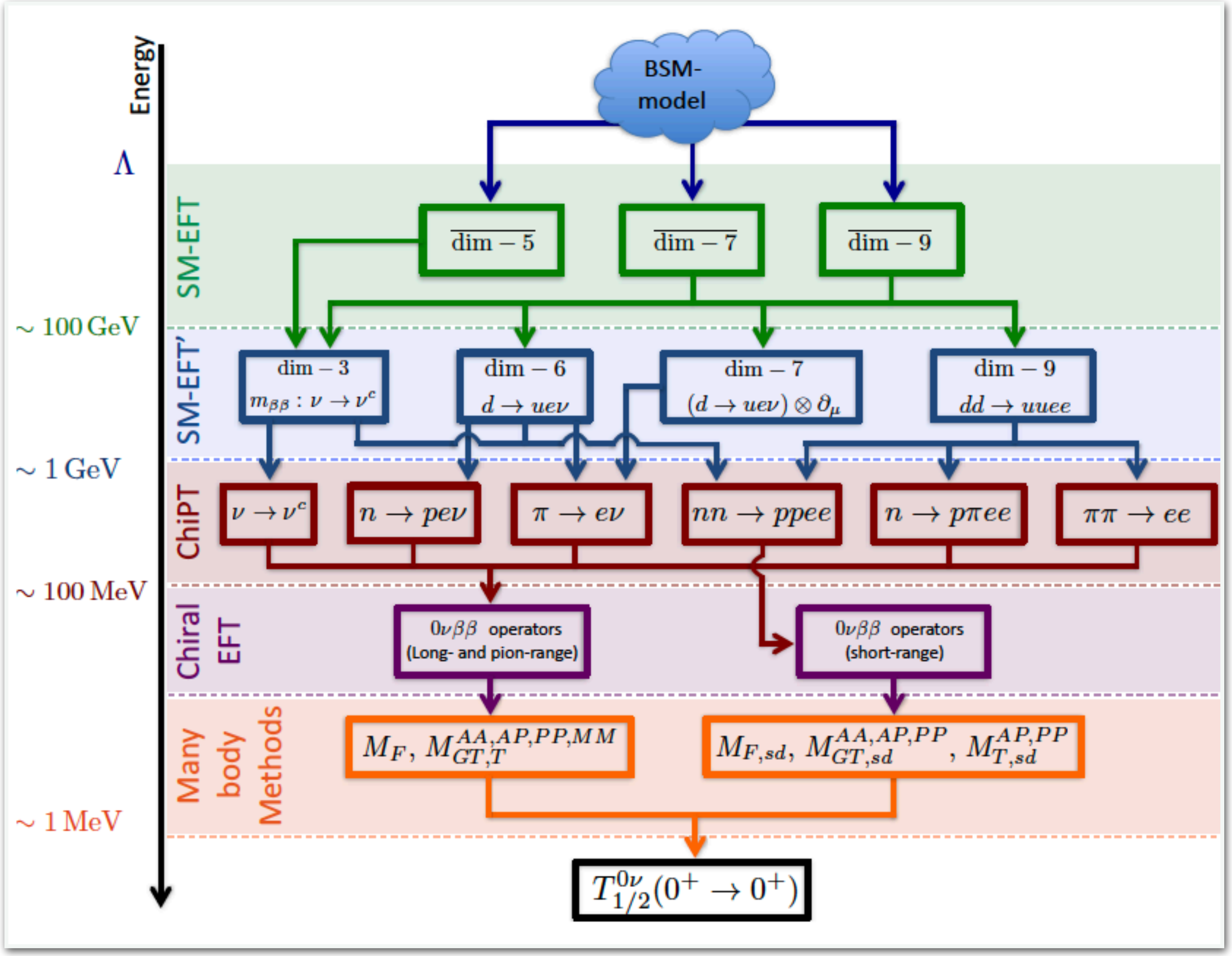


Simplified model



Summary: EFT-based master formula

- Framework to interpret 0νββ searches in terms of any high-scale model and possibly unravel the underlying mechanism in case of discovery



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

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

- EFT approach provides a general framework to:
  1. Relate $0\nu\beta\beta$ to underlying LNV dynamics (and collider & cosmology)
     - Master formula for $0\nu\beta\beta$ up dim-9 operators
  2. Organize contributions to hadronic and nuclear matrix elements
     - Identified new leading order short-range contributions

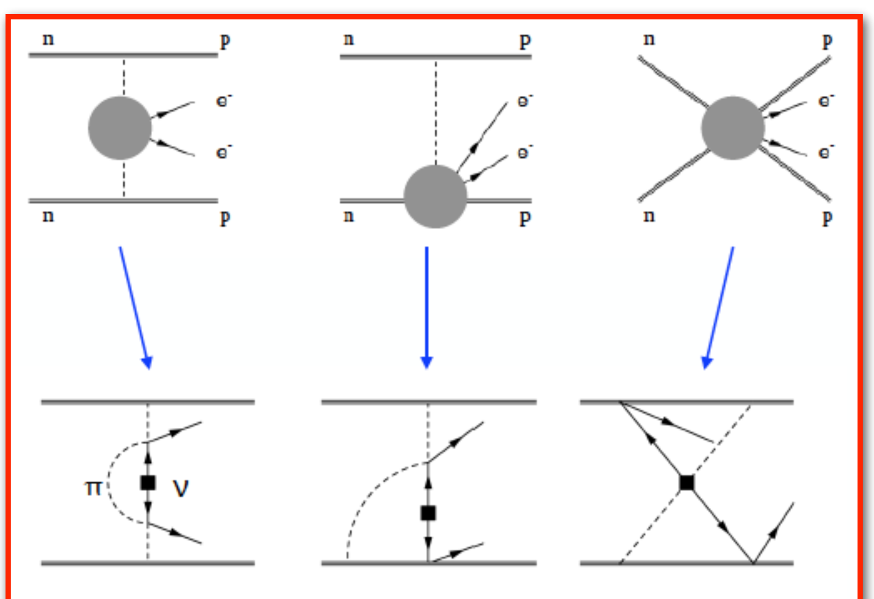
Improving the theory uncertainty is challenging, but there are exciting prospects thanks to advances in EFT, lattice QCD, and nuclear structure

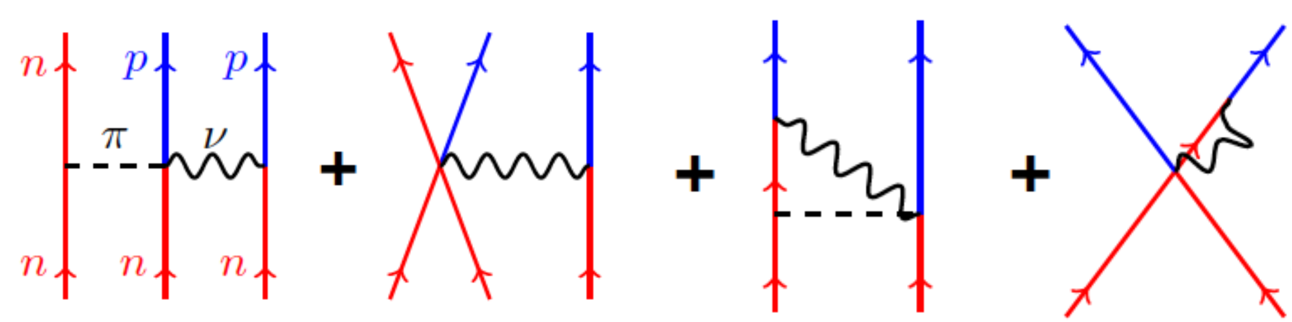
Backup

LNV@dim5: What about higher orders?

- N2LO
  - πN loops + new contact — VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729
  - 2-body **x** 1-body current (and a new contact) — Wang-Engel-Yao 1805.10276
  - Neglecting contact terms, calculations in light and heavy nuclei find O(10%) corrections: encouraging!

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





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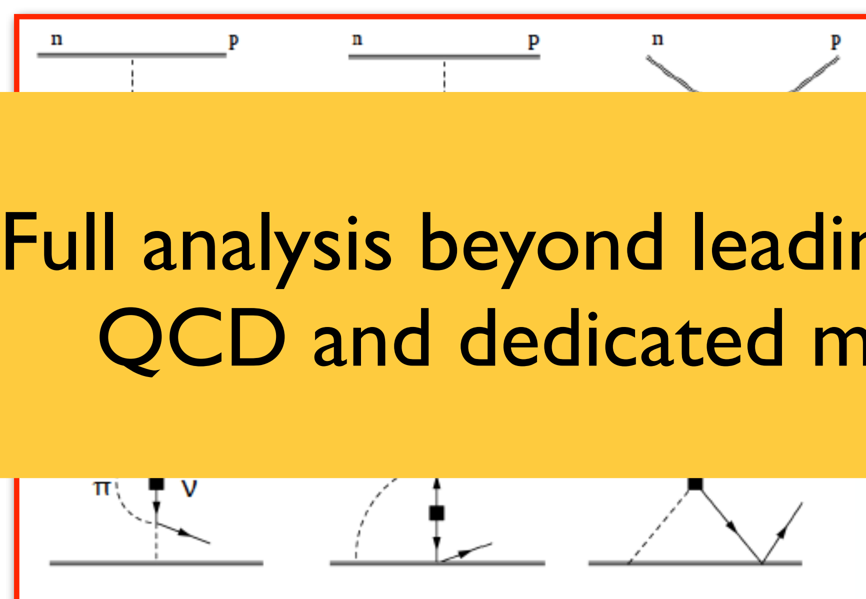
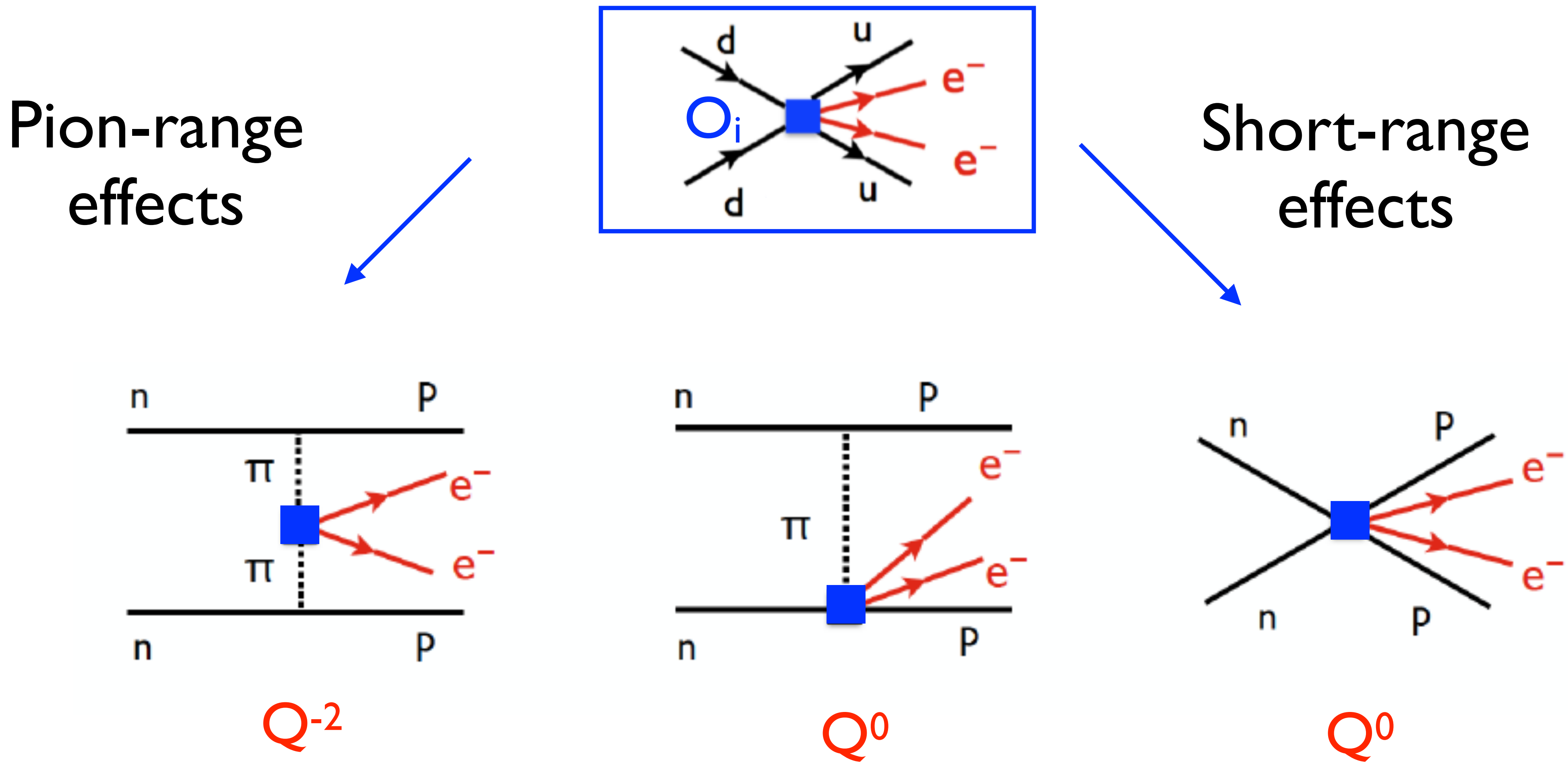


Full analysis beyond leading order requires again matching to Lattice QCD and dedicated many body calculations — long term goal

TeV-scale LNV: hadronic theory developments

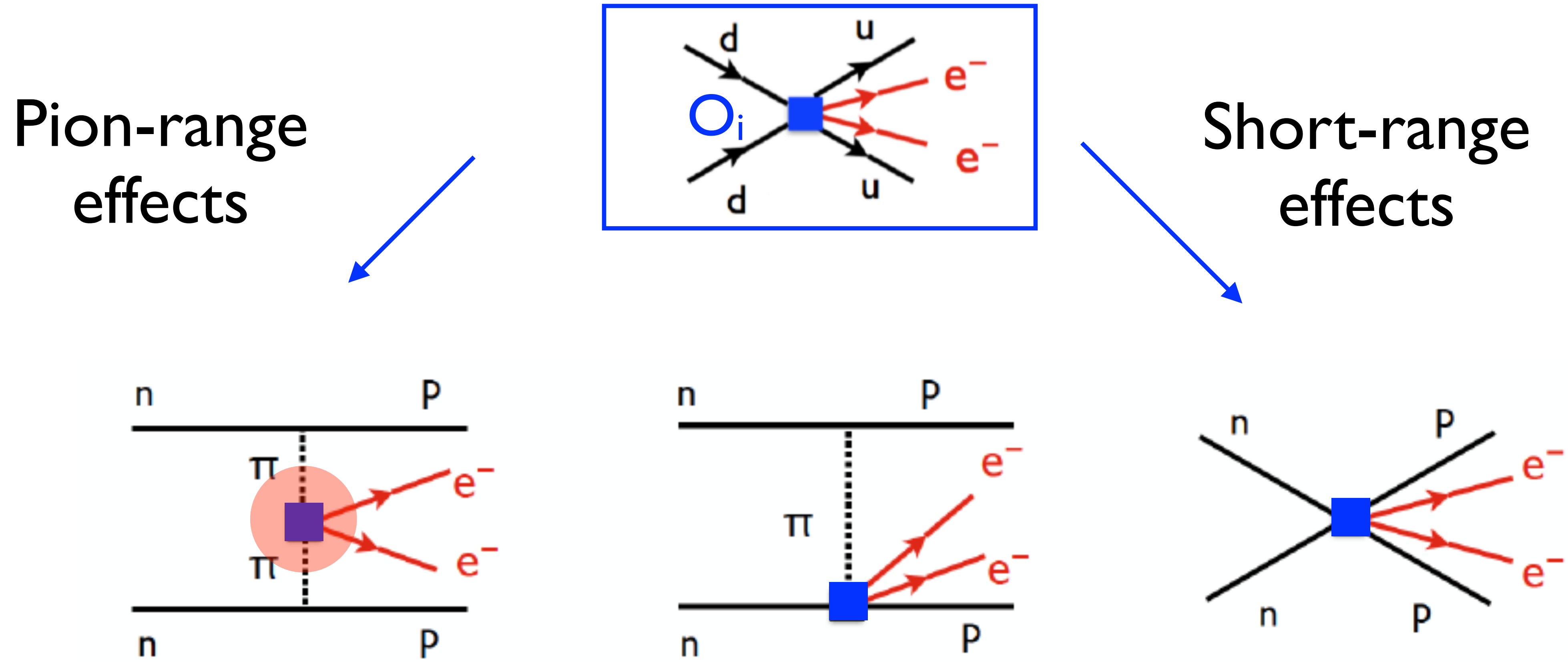


Hadronic realization of dim-9 operators in chiral EFT

Weinberg's counting (NDA for NN contact) → $V_{\pi\pi}$ dominates

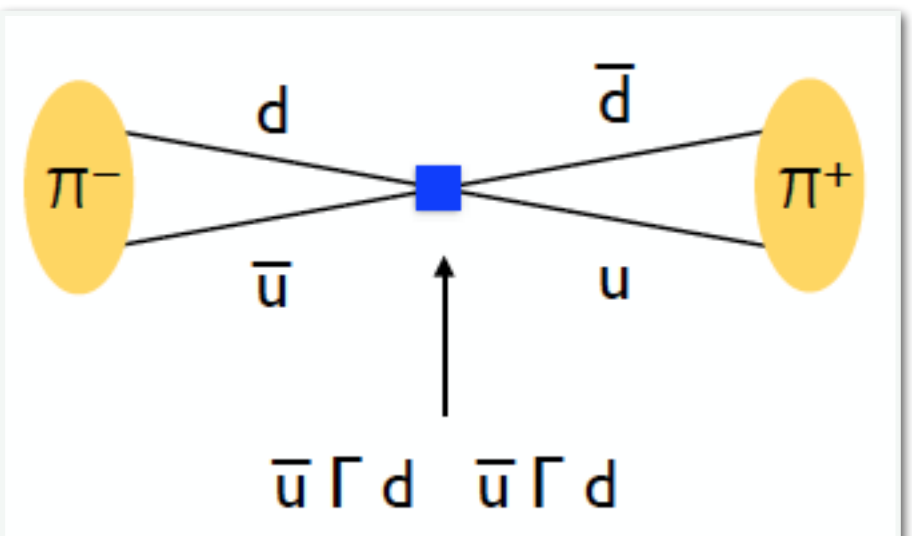
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

TeV-scale LNV: hadronic theory developments



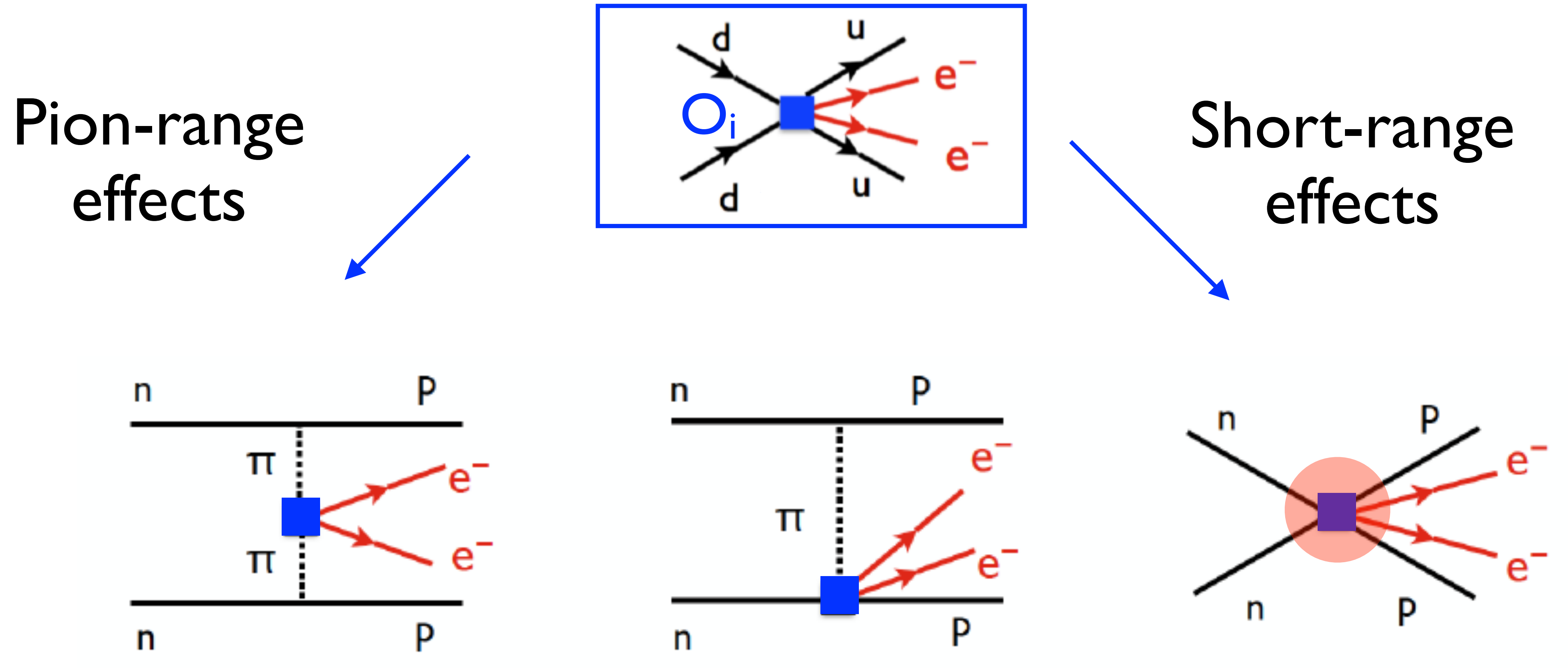
- Two recent developments:

  1. ππ matrix elements now precisely calculated in lattice QCD (~10% or better)



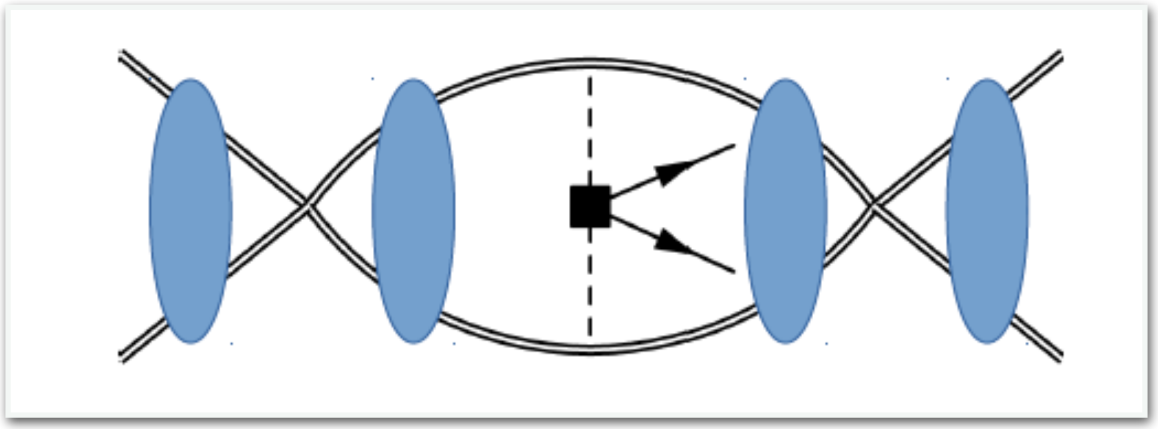
Nicholson et al (CalLat), 1805.02634, PRL

TeV-scale LNV: hadronic theory developments



- Two recent developments:

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



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

Dimension 6 and 7 operators

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

$$+ C^{(6)}_{\mathrm{SR},ij}\,\bar{u}_L d_R\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{SL},ij}\,\bar{u}_R d_L\,\bar{e}_{L,i}\,C\bar{\nu}^T_{L,j} + C^{(6)}_{\mathrm{T},ij}\,\bar{u}_L\sigma^{\mu\nu} d_R\,\bar{e}_{L,i}\sigma_{\mu\nu}\,C\bar{\nu}^T_{L,j}\Big) + \mathrm{h.c.}$$

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

Dimension 9 operators

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

$$\begin{aligned}
O_1 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha\, \bar{q}_L^\beta \gamma^\mu \tau^+ q_L^\beta\,, & O_1' &= \bar{q}_R^\alpha \gamma_\mu \tau^+ q_R^\alpha\, \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta \\
O_2 &= \bar{q}_R^\alpha \tau^+ q_L^\alpha\, \bar{q}_R^\beta \tau^+ q_L^\beta\,, & O_2' &= \bar{q}_L^\alpha \tau^+ q_R^\alpha\, \bar{q}_L^\beta \tau^+ q_R^\beta\,, \\
O_3 &= \bar{q}_R^\alpha \tau^+ q_L^\beta\, \bar{q}_R^\beta \tau^+ q_L^\alpha\,, & O_3' &= \bar{q}_L^\alpha \tau^+ q_R^\beta\, \bar{q}_L^\beta \tau^+ q_R^\alpha\,, \\
O_4 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha\, \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\beta\,, \\
O_5 &= \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta\, \bar{q}_R^\beta \gamma^\mu \tau^+ q_R^\alpha\,,
\end{aligned}$$

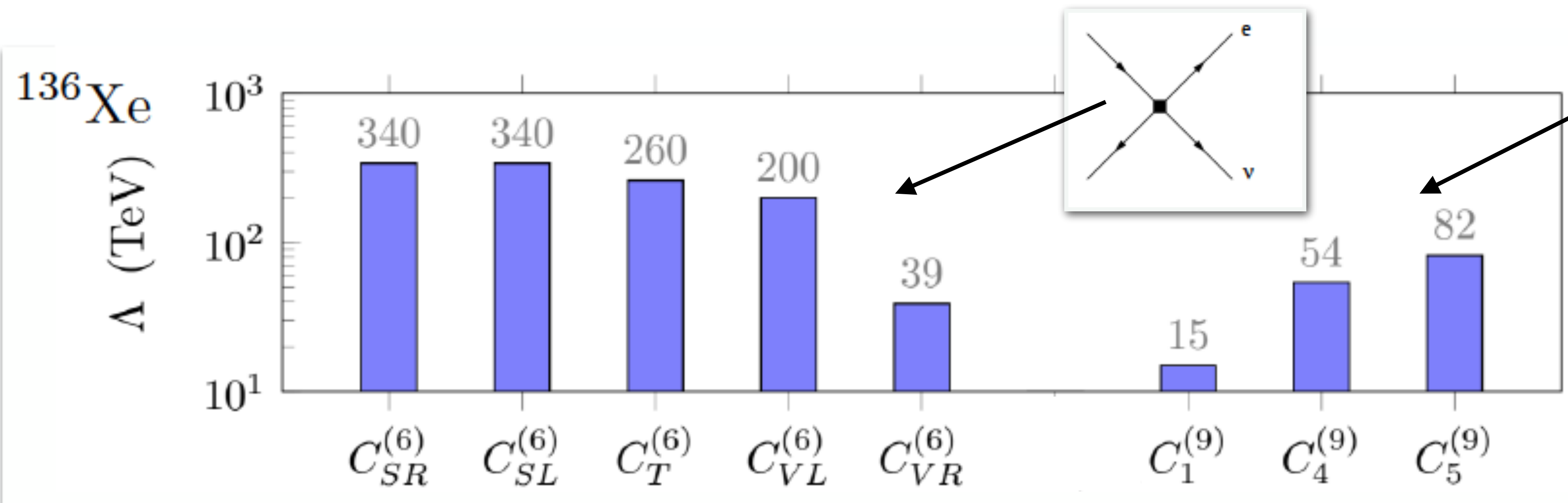
$$\begin{aligned}
O_6^\mu &= (\bar{q}_L \tau^+ \gamma^\mu q_L)\,(\bar{q}_L \tau^+ q_R)\,, & O_6^{\mu\,\prime} &= (\bar{q}_R \tau^+ \gamma^\mu q_R)\,(\bar{q}_R \tau^+ q_L)\,, \\
O_7^\mu &= (\bar{q}_L t^a \tau^+ \gamma^\mu q_L)\,(\bar{q}_L t^a \tau^+ q_R)\,, & O_7^{\mu\,\prime} &= (\bar{q}_R t^a \tau^+ \gamma^\mu q_R)\,(\bar{q}_R t^a \tau^+ q_L)\,, \\
O_8^\mu &= (\bar{q}_L \tau^+ \gamma^\mu q_L)\,(\bar{q}_R \tau^+ q_L)\,, & O_8^{\mu\,\prime} &= (\bar{q}_R \tau^+ \gamma^\mu q_R)\,(\bar{q}_L \tau^+ q_R)\,, \\
O_9^\mu &= (\bar{q}_L t^a \tau^+ \gamma^\mu q_L)\,(\bar{q}_R t^a \tau^+ q_L)\,, & O_9^{\mu\,\prime} &= (\bar{q}_R t^a \tau^+ \gamma^\mu q_R)\,(\bar{q}_L t^a \tau^+ q_R)\,,
\end{aligned}$$

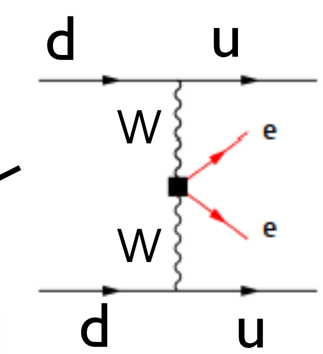
What scales are we probing?

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

Dim 7 in SM-EFT

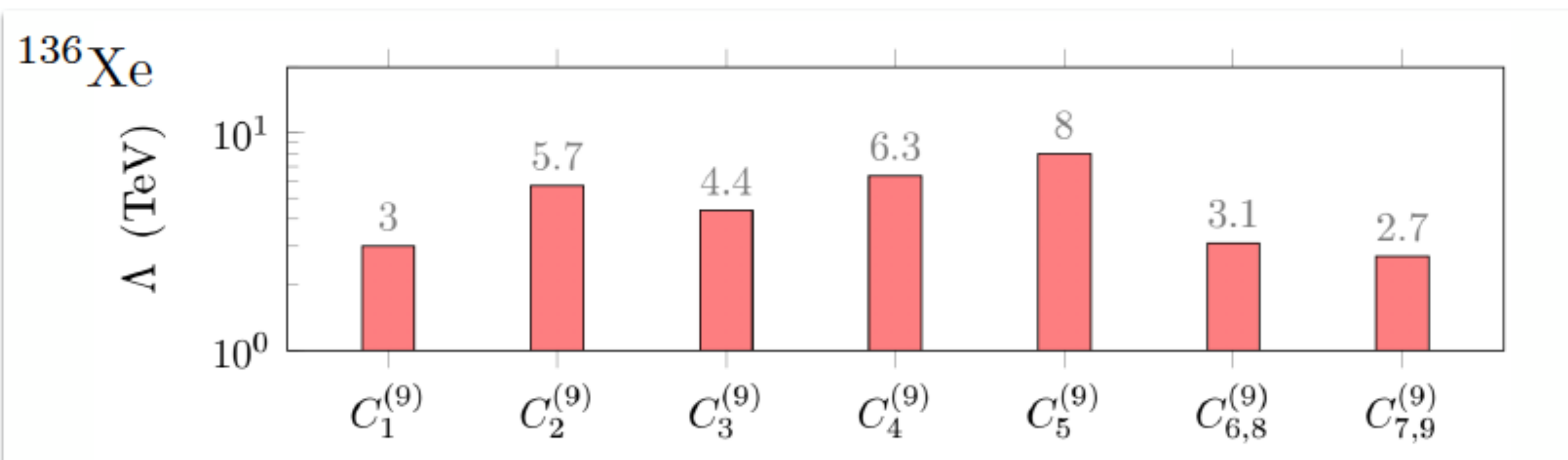
$(v/\Lambda)^3$

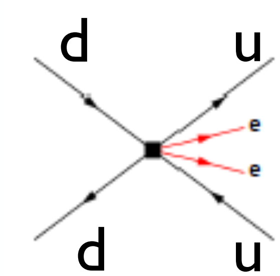




Dim 9 in SM-EFT

$(v/\Lambda)^5$





Bounds reflect dependence on Λ_χ / Λ and Q/Λ_χ