International School of Nuclear Physics
43rd Course
Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics
Erice, September 16-22, 2022

Neutrino-less double beta decay (theory)

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Institute for Nuclear Theory
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Outline

- Introduction: neutrino mass, Lepton Number, and 0νββ decay
- 'End-to-end' Effective Field Theory framework for LNV and 0νββ
    - 0νββ from high-scale see-saw (LNV @ dim 5)
    - 0νββ from (multi)TeV-scale dynamics (LNV @ dim 7, 9, …)
    - 0νββ and sterile neutrinos
- Conclusions & outlook

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

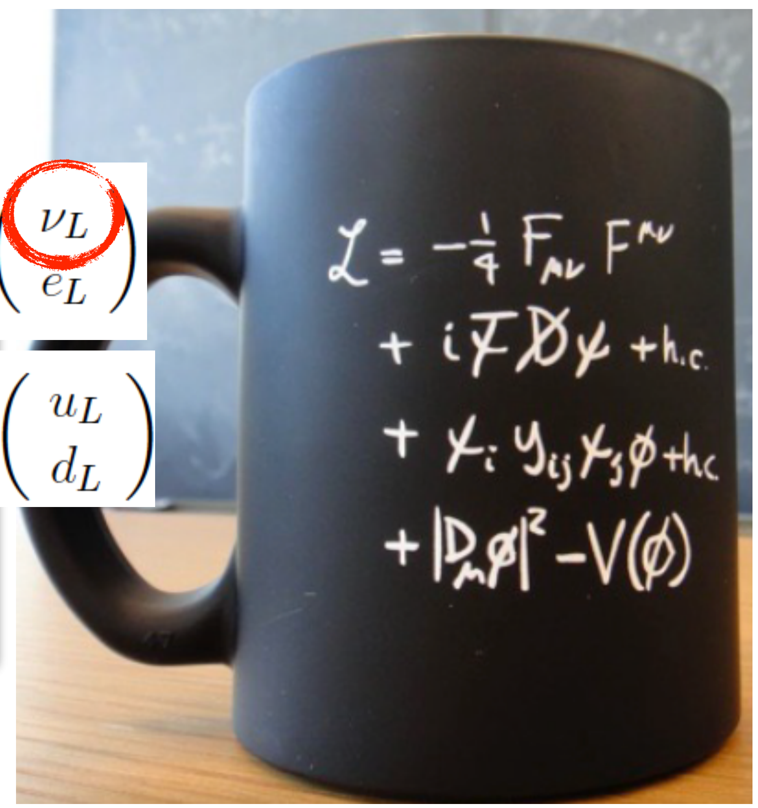
Neutrino mass and new physics

- Massive neutrinos provide concrete evidence of physics beyond the SM

The Standard Model

$$\psi_i = \begin{pmatrix} \ell_L \\ e_R \\ q_L \\ u_R \\ d_R \end{pmatrix}_i \qquad i = 1,2,3$$

$$\ell_L \rightarrow \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad q_L \rightarrow \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$



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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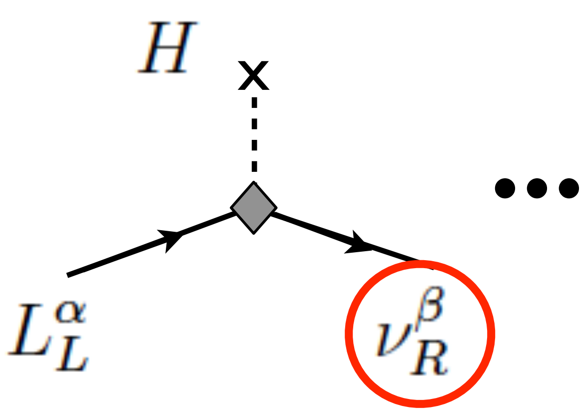

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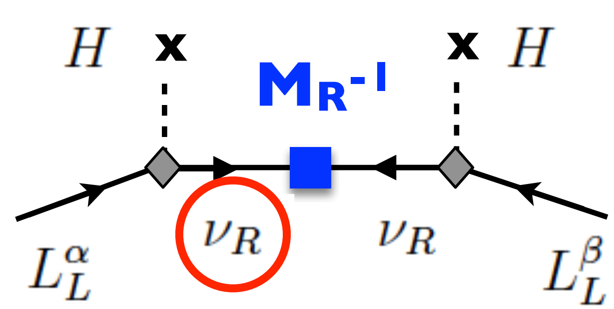

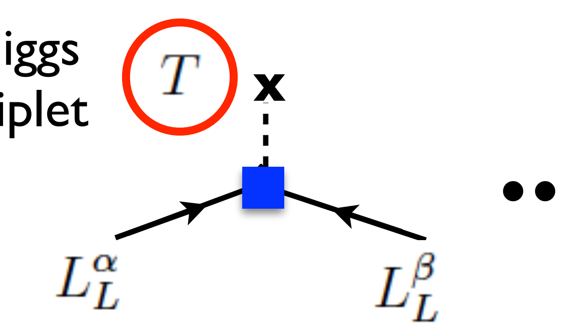

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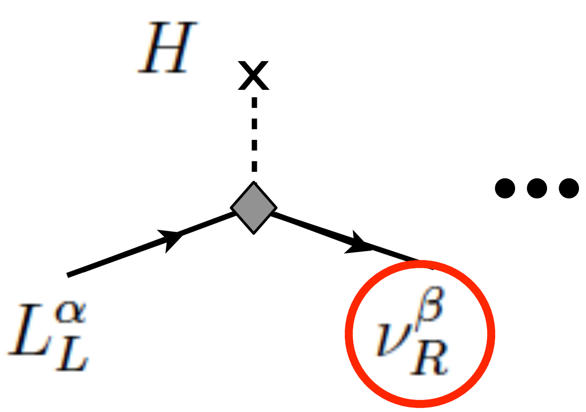

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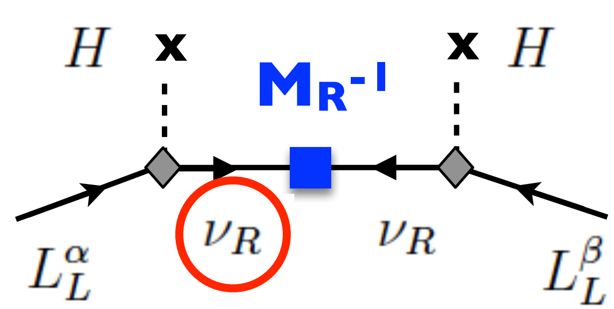
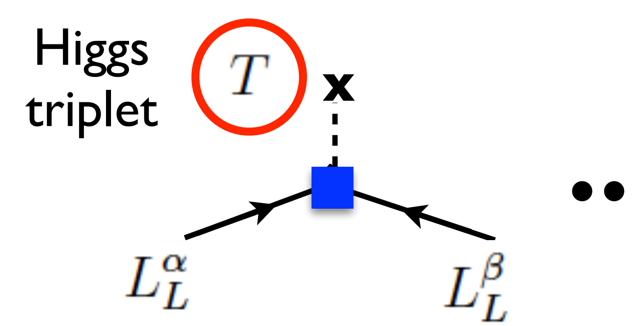
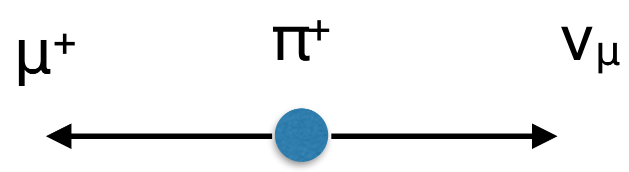


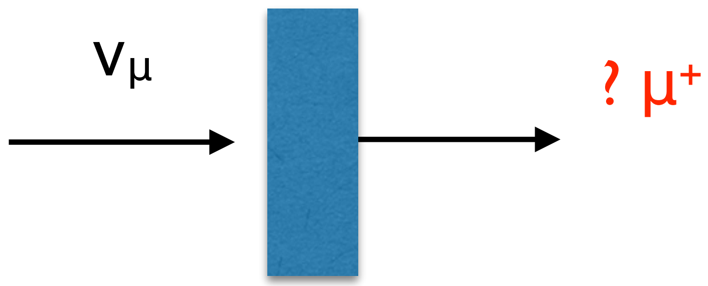


- Violates $L_{e,\mu,\tau}$, conserves L
- Violates $L_{e,\mu,\tau}$ and L ($\Delta L=2$)

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 $\pi^+ \rightarrow \mu^+ \nu_\mu$ is $\sim(m_\nu/E_\nu)^2 < 10^{-16}$!!

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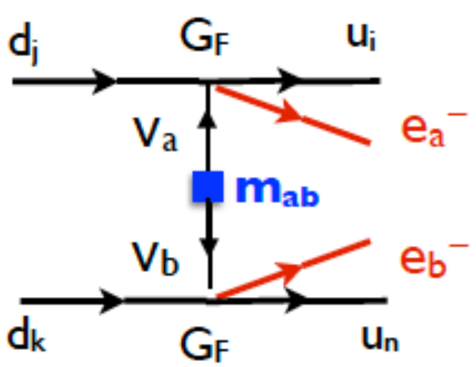


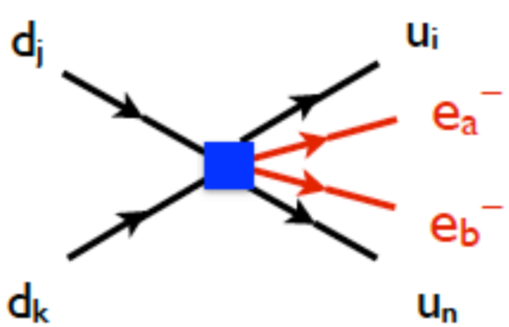
$$(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$$

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

$$\tau^- \rightarrow \ell^+ h_1^- h_2^-$$

$$\ldots$$

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

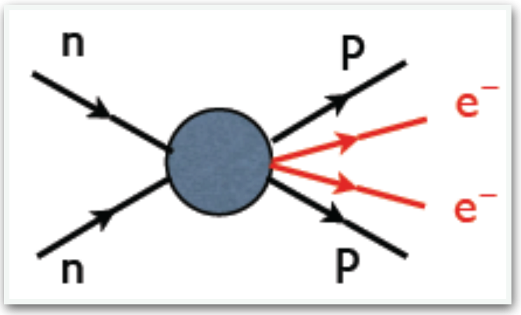


- 0νββ provides in many scenarios the strongest sensitivity to LNV couplings ("Avogadro's number wins", P. Vogel)
- Other processes can be very competitive in models with low-scale LNV

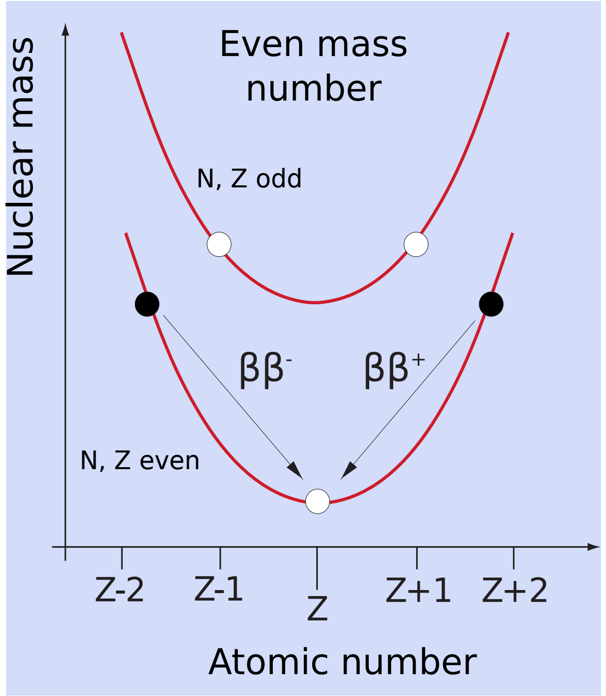
Neutrinoless double beta decay

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

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



ΔL=2



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

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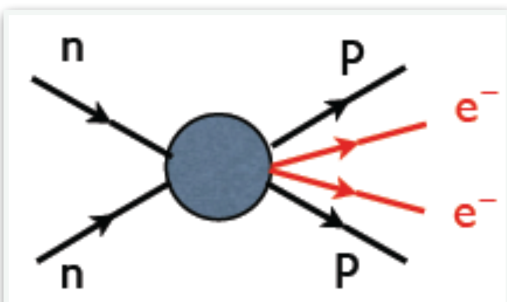

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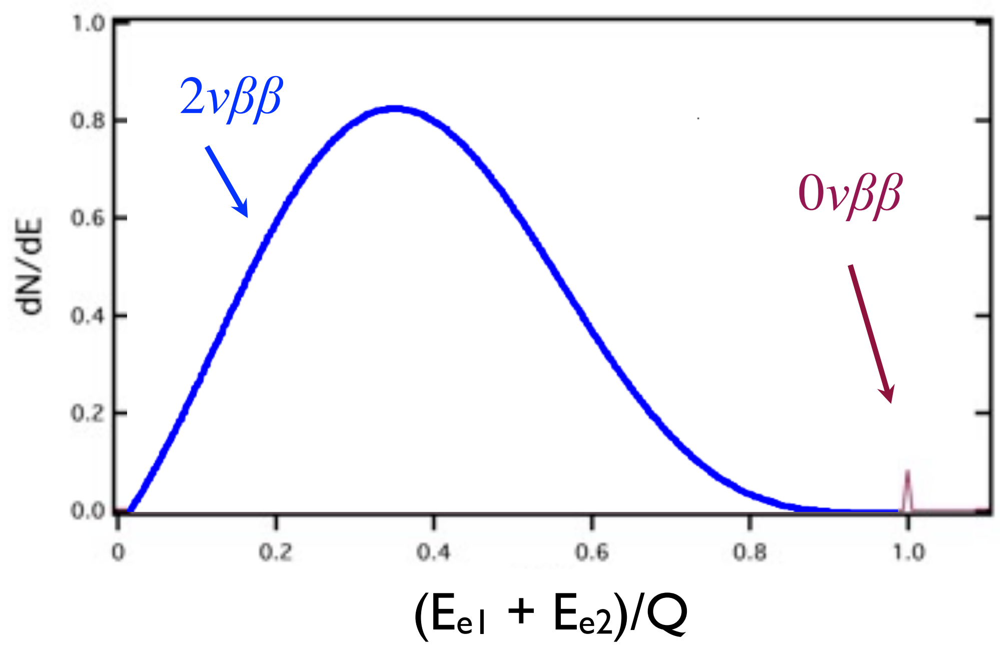

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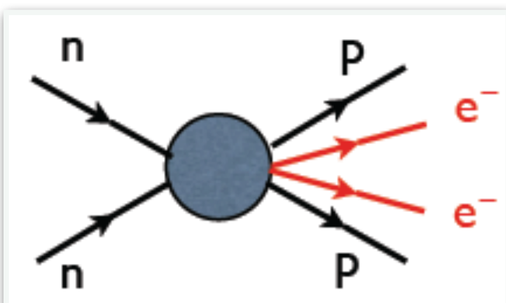

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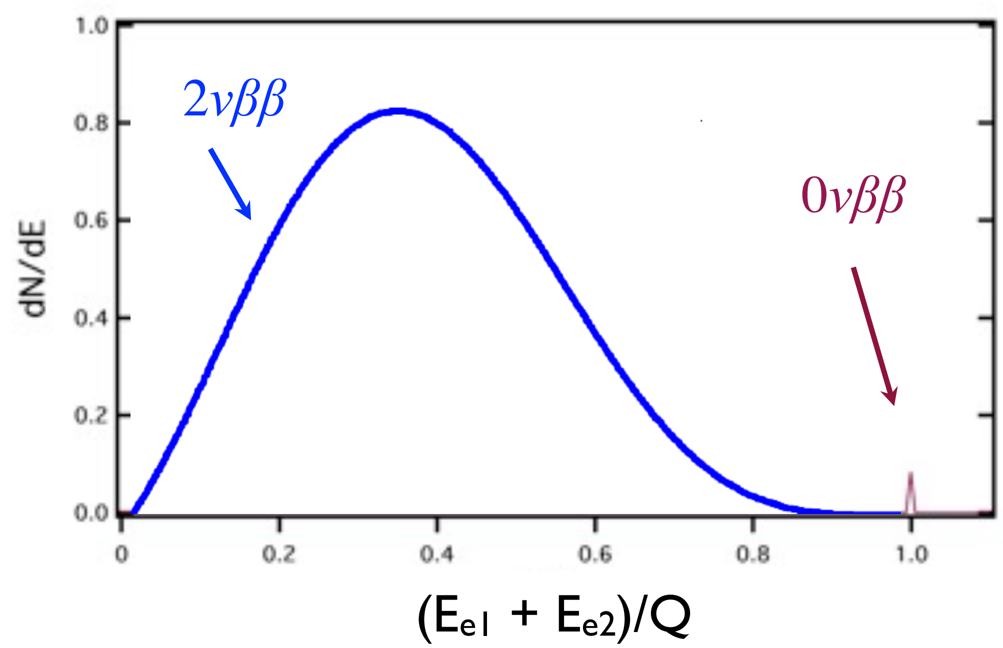

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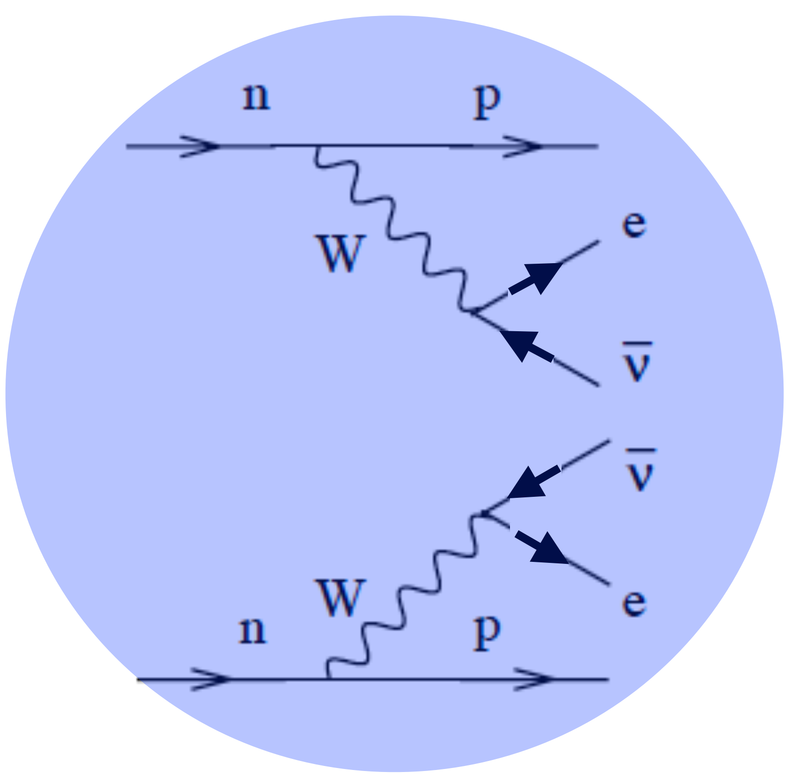
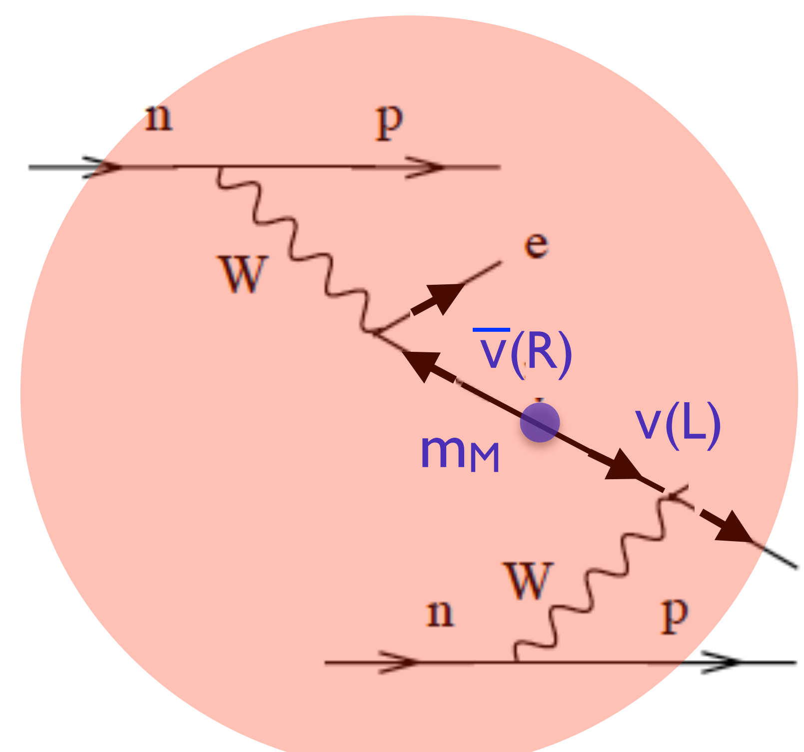


Simplest mechanism:
Majorana mass term

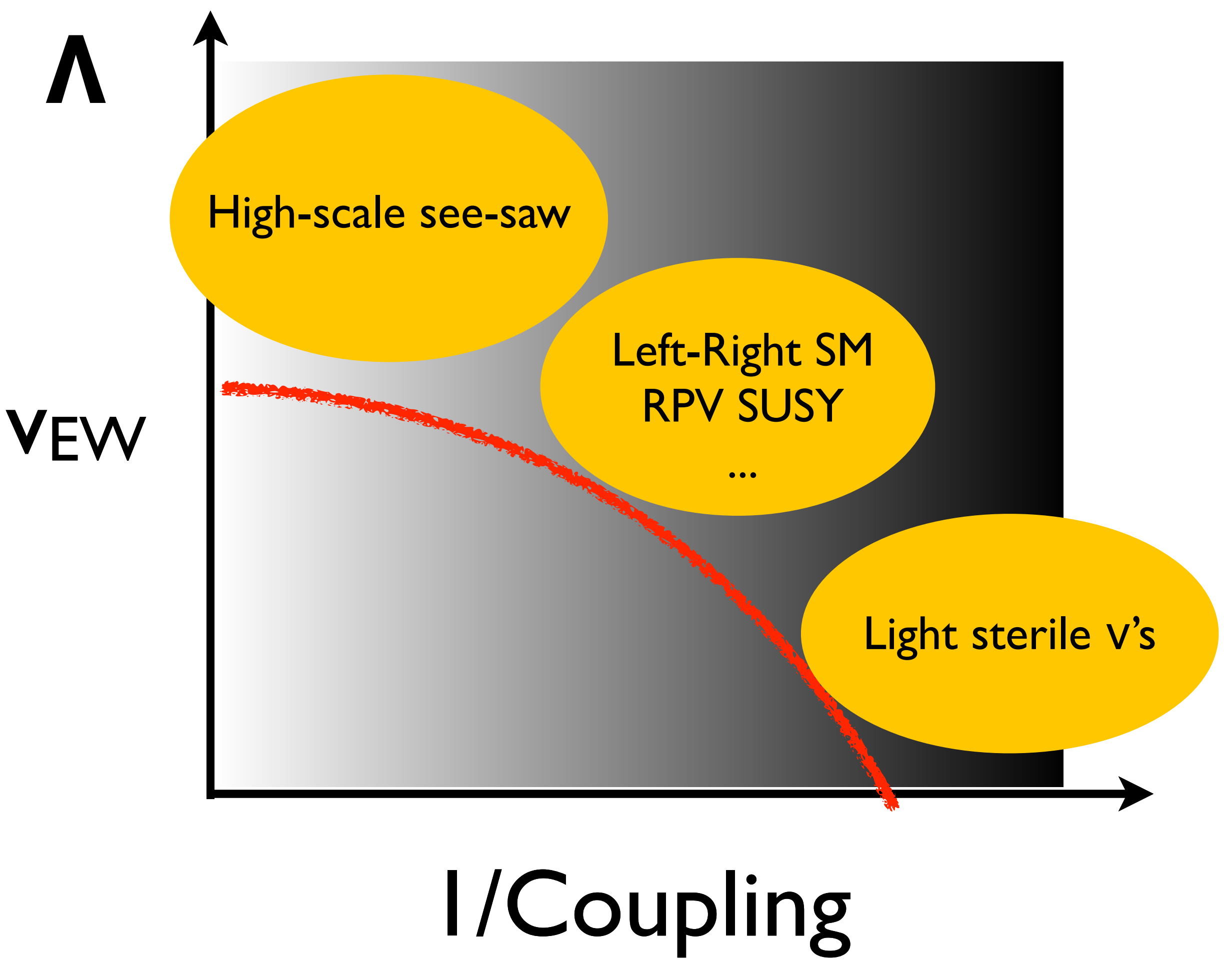
But not the only one!

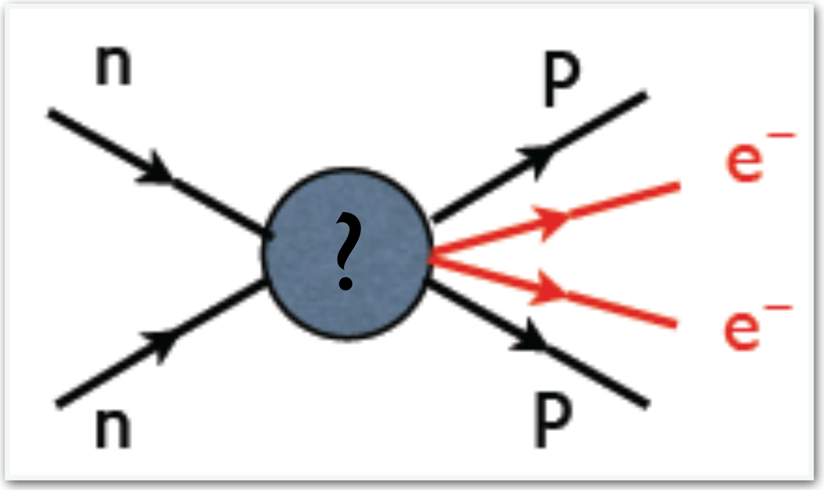
Furry 1939



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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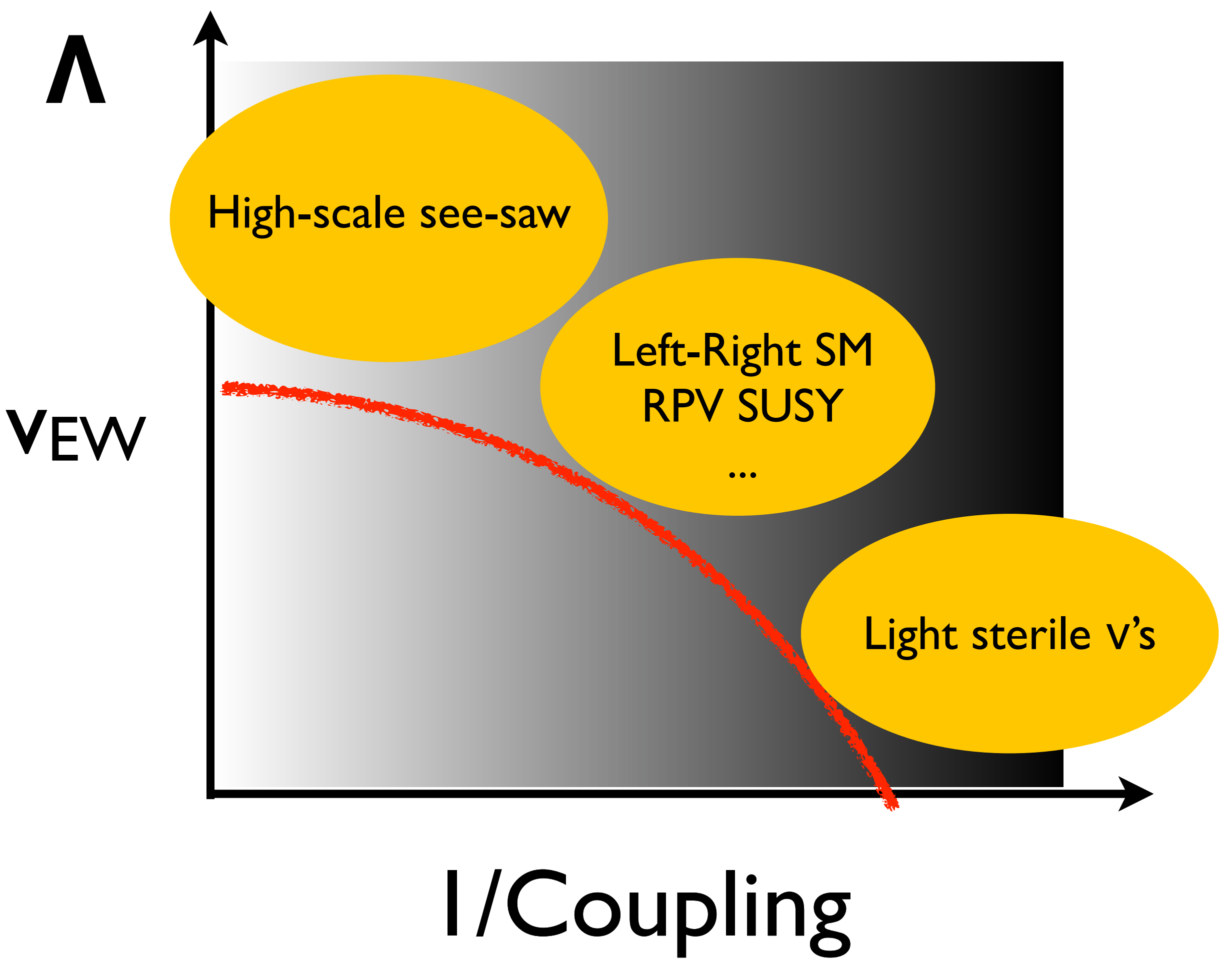

Impact of 0νββ searches and relation to other probes of LNV is best analyzed through a tower of EFTs that connect LNV scale Λ to nuclear scales, with controllable uncertainties

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

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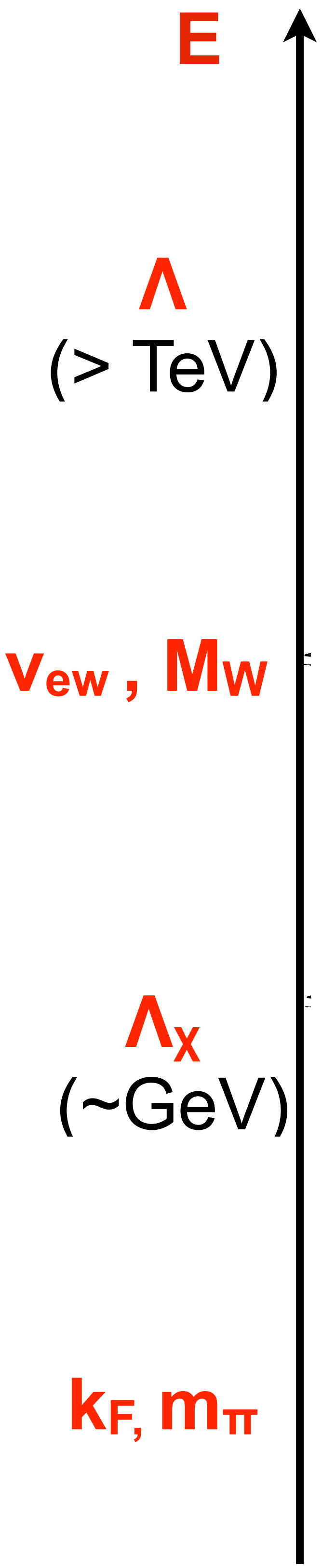
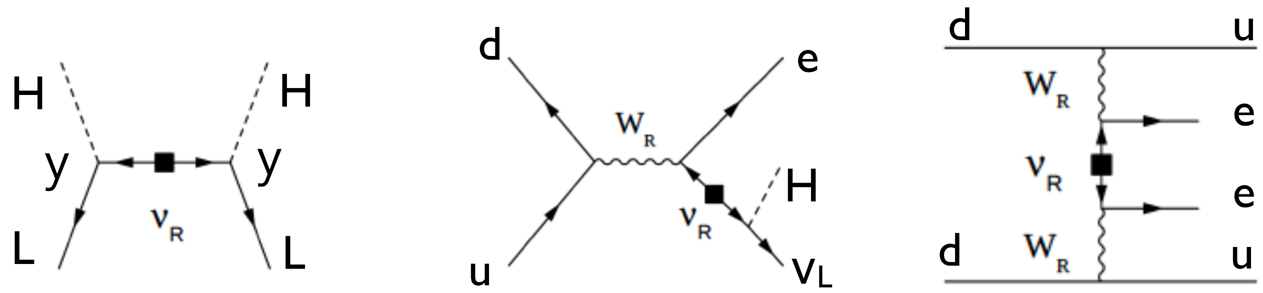
‘End-to-end’ EFT framework





BSM dynamics

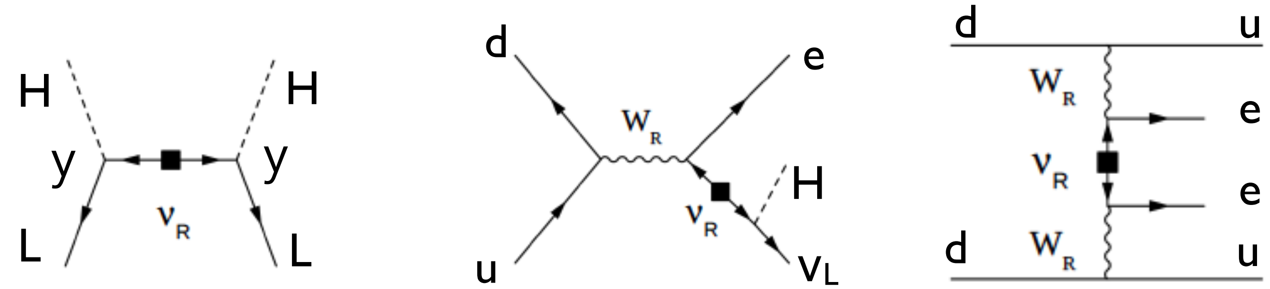
Example:
Left-Right Symmetric Model

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

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

‘End-to-end’ EFT framework

E



BSM dynamics

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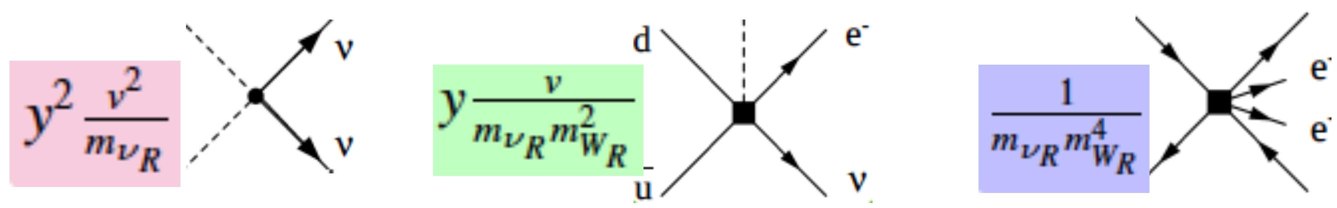
Λ (> TeV)



SM-EFT

dim5	dim7	dim9
Weinberg’79	Babu-Leung ’01 … Lehman 1410.4193	Graesser 1606.04549 Liao and Ma 2007.08125

v_{ew} , M_W

Λ_X (~GeV)

k_F, m_π

- 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

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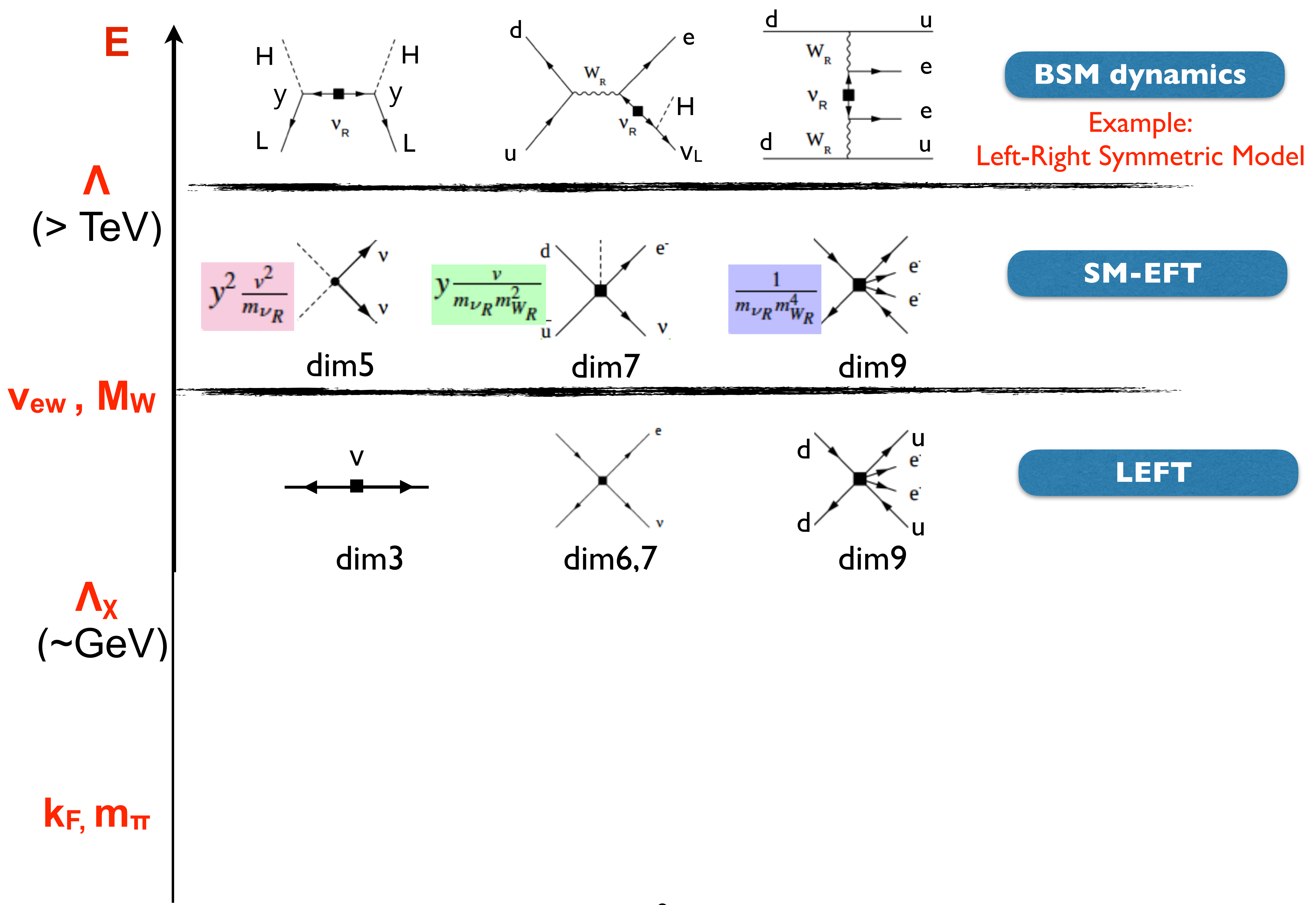

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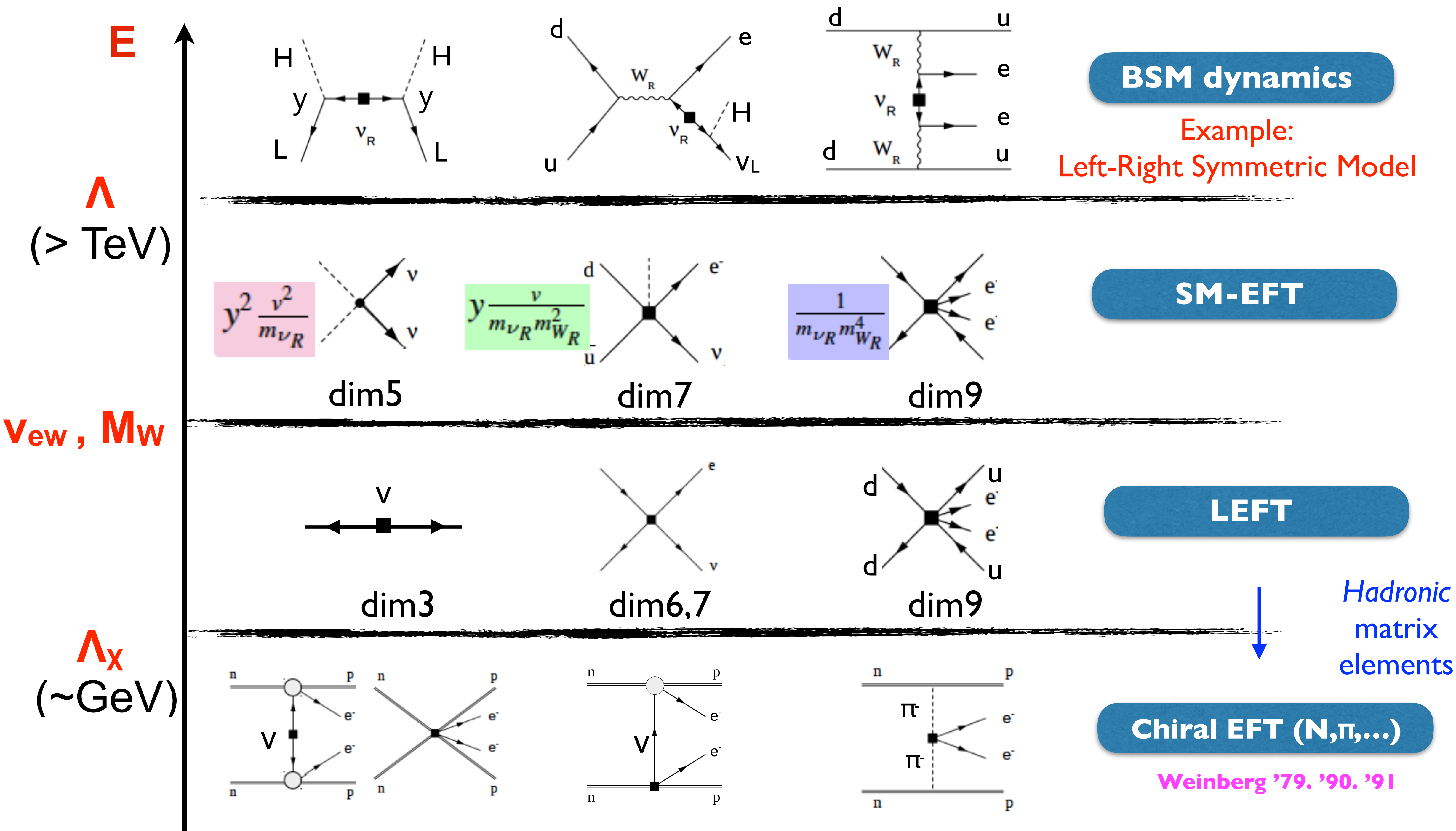
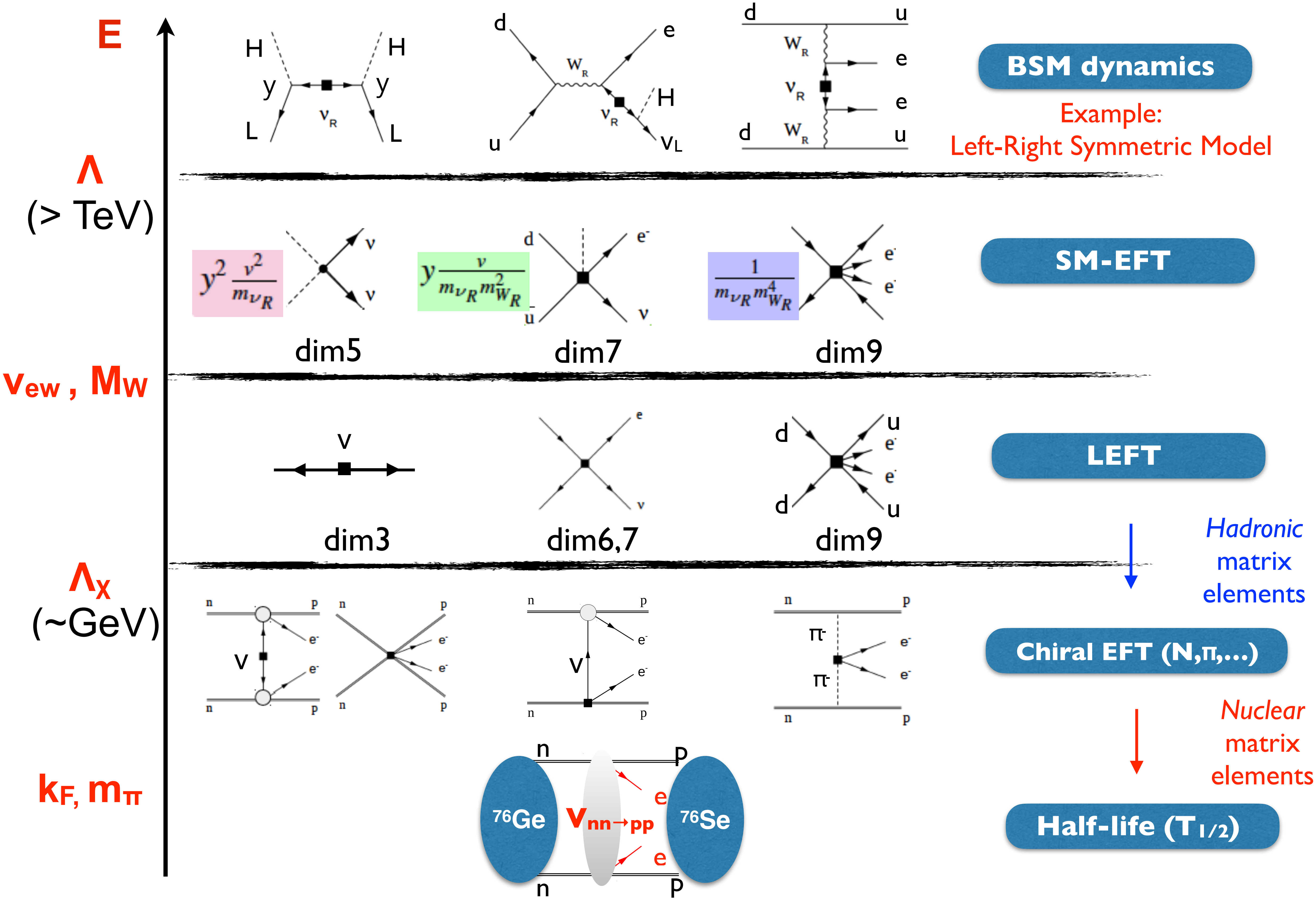


k_F, m_π

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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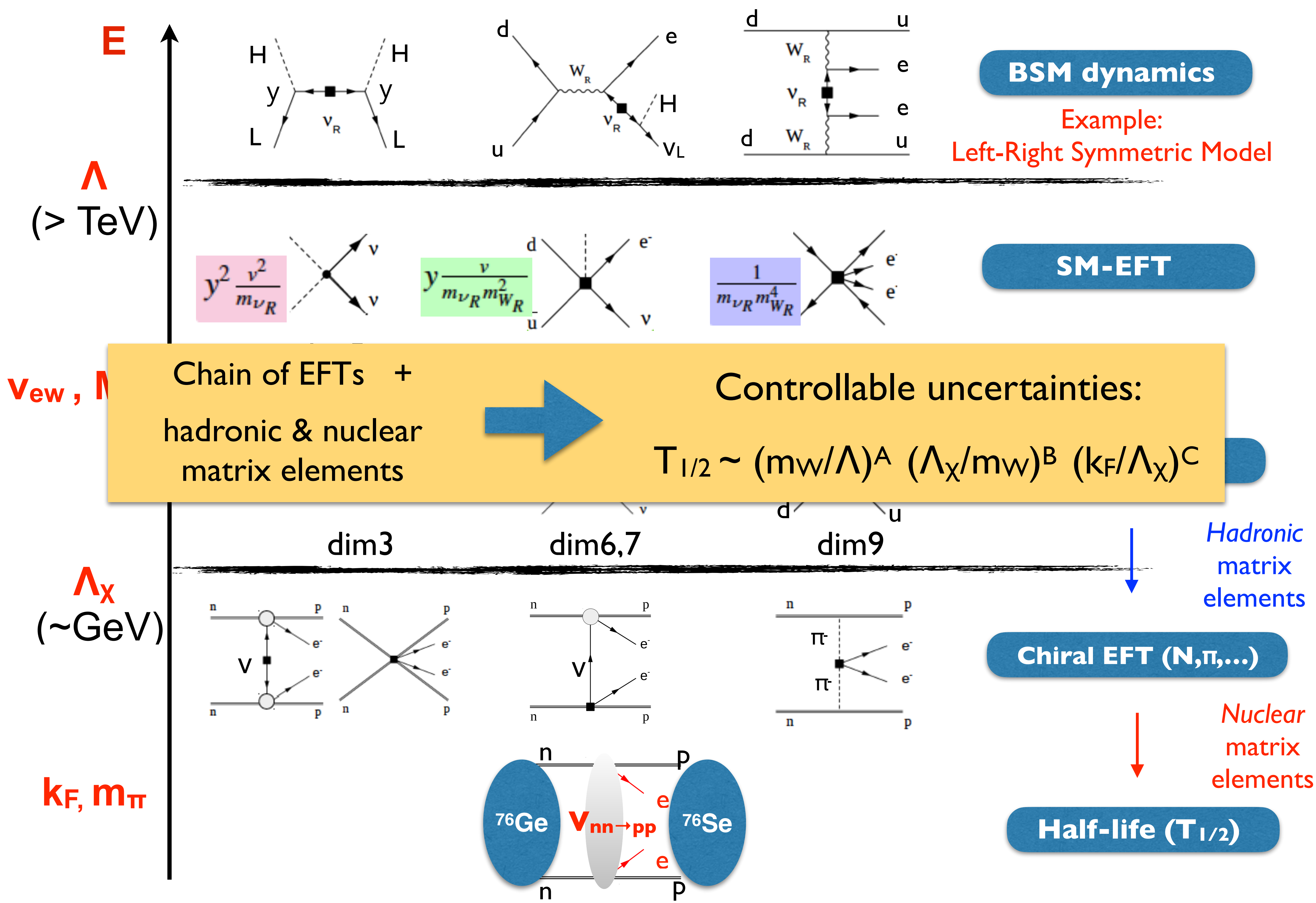
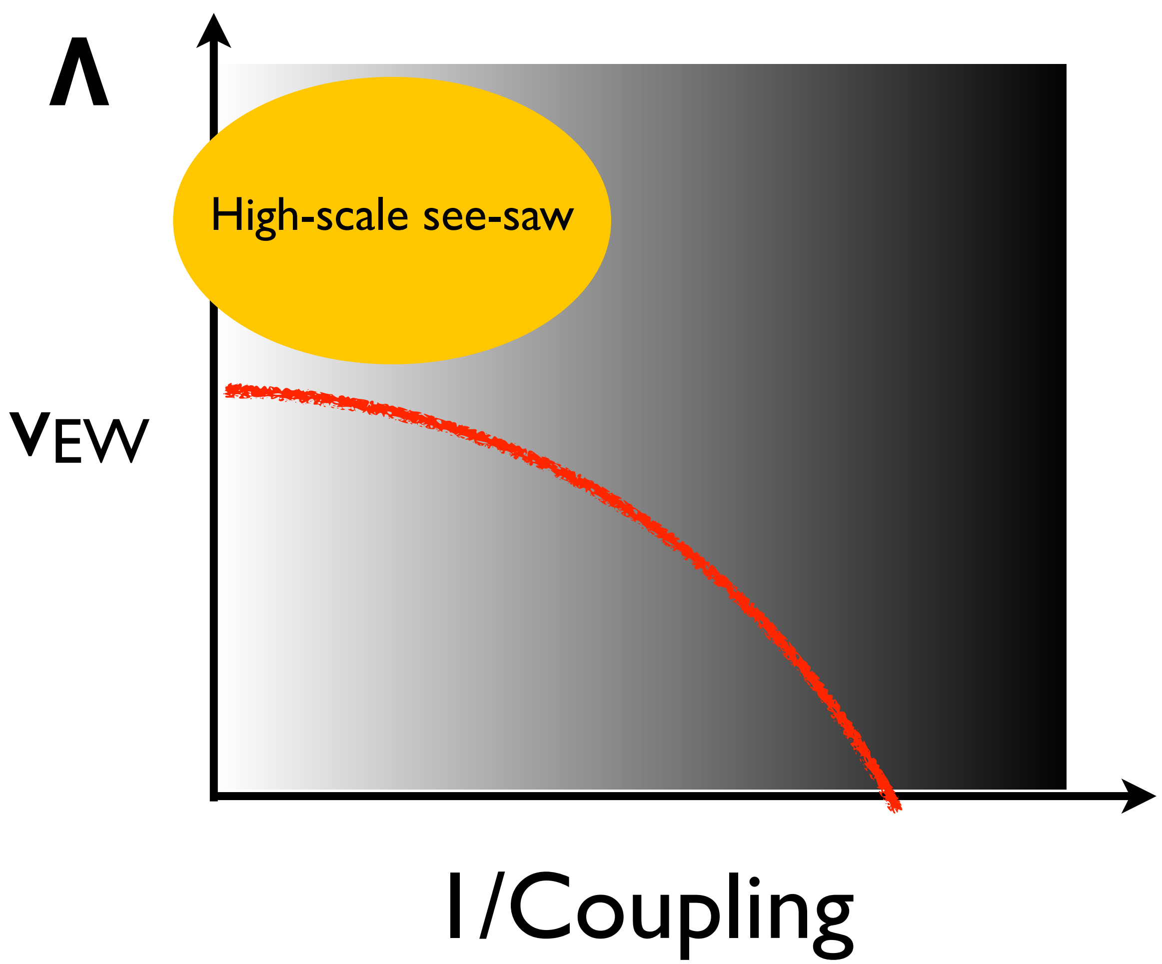
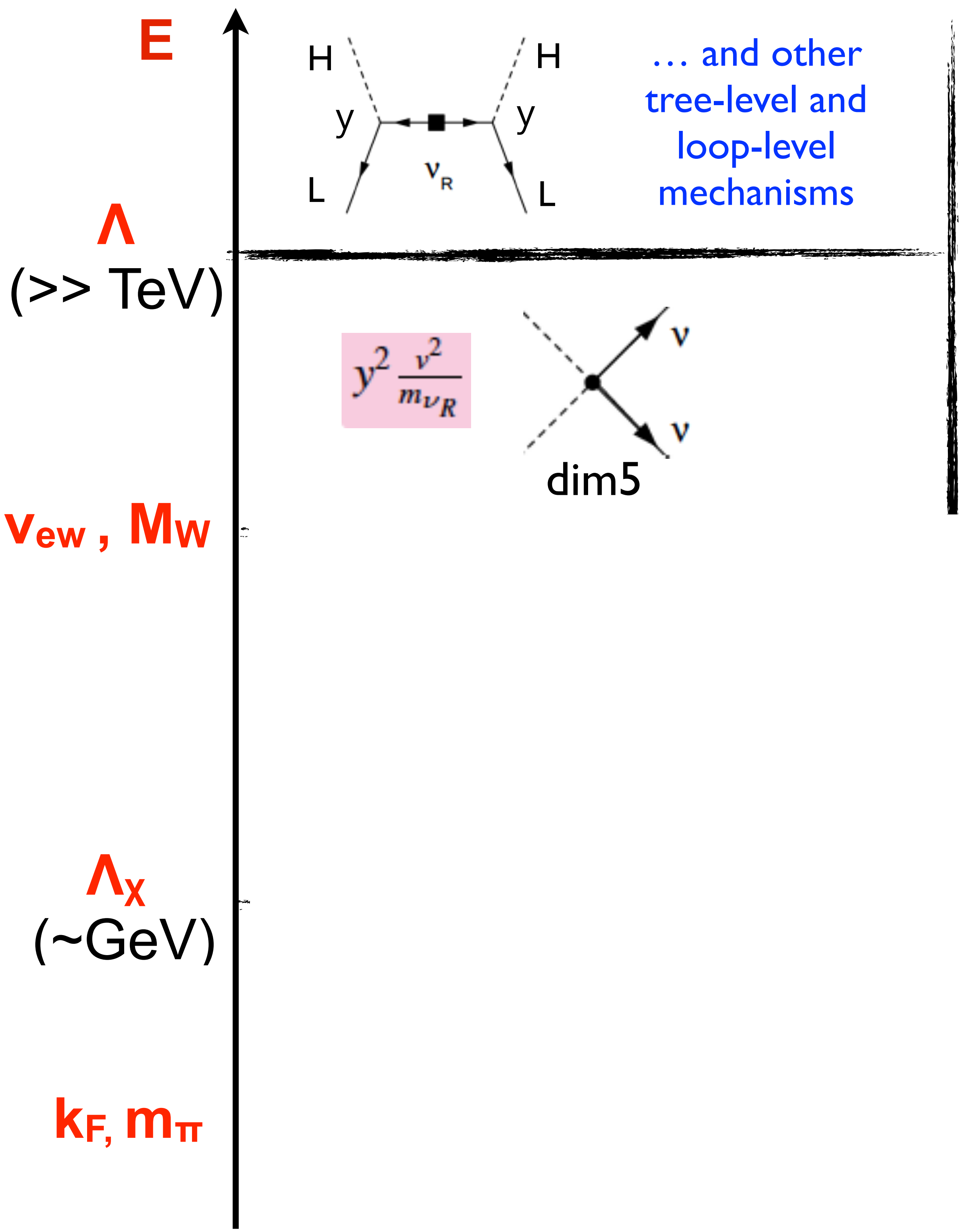


0νββ from high-scale LNV (dim-5 operator)



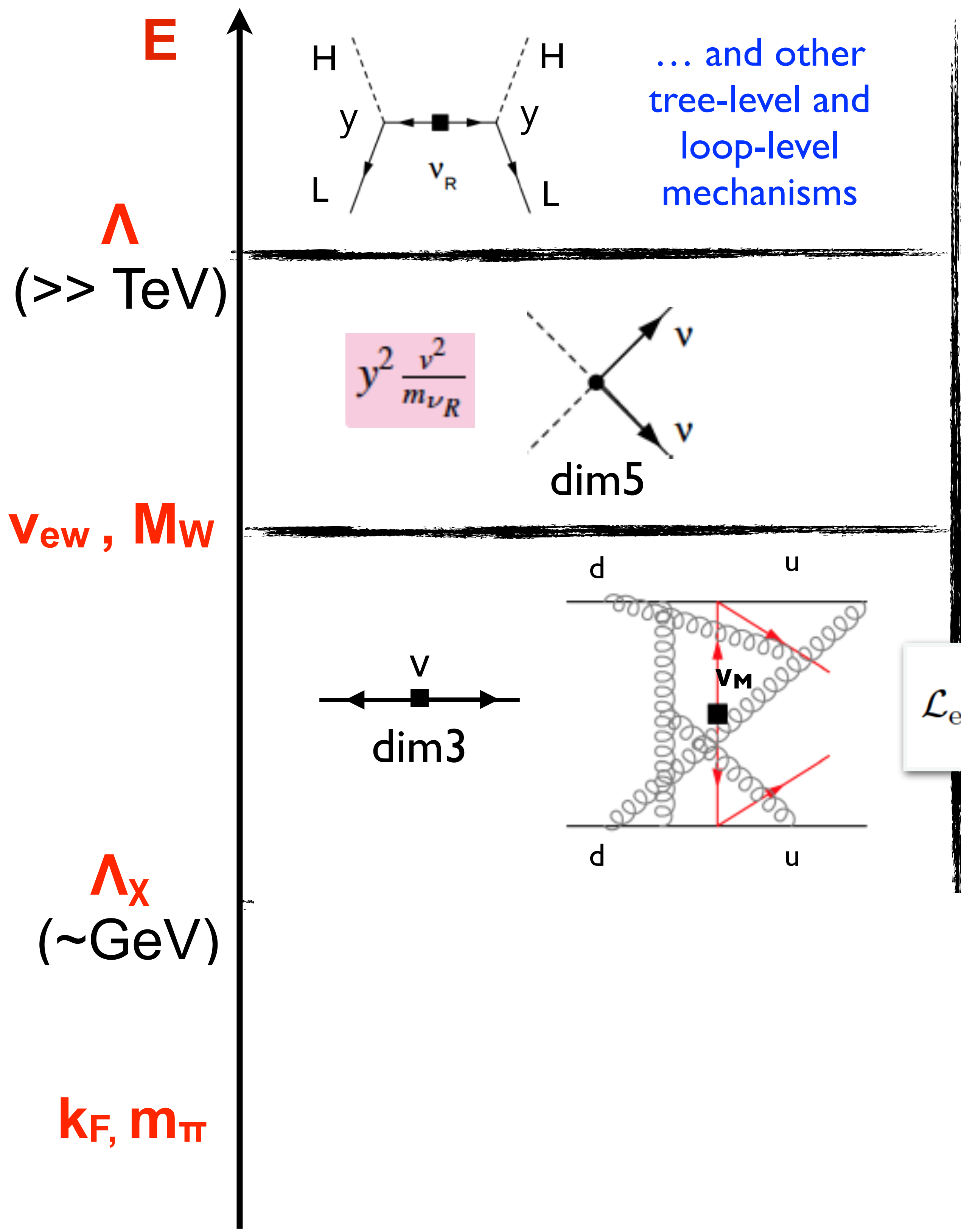
High scale LNV



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

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

High scale LNV



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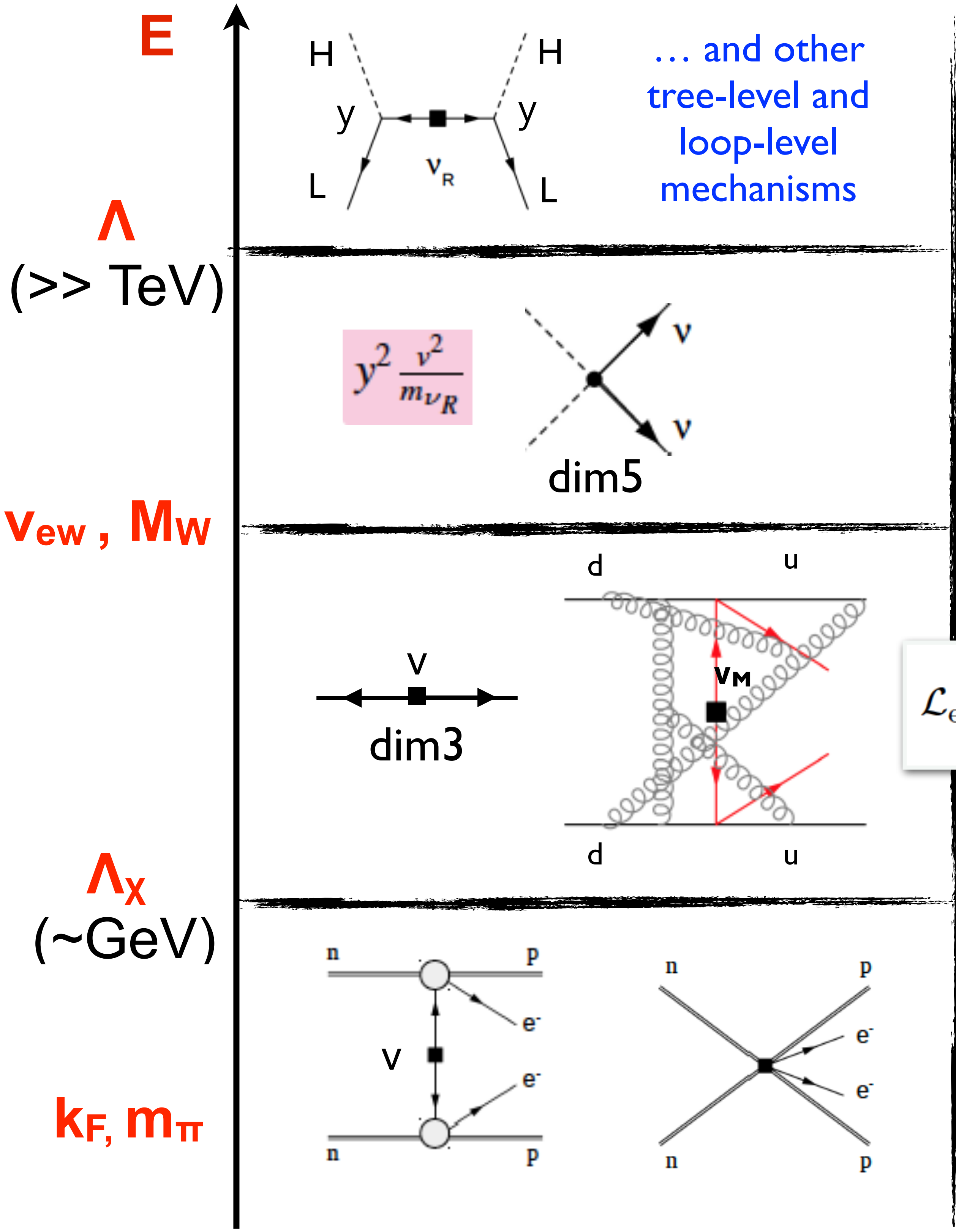
- Below the weak scale this is just the neutrino Majorana mass ($m_{\beta\beta} \sim w_{ee} \, v^2/\Lambda$)

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

High scale LNV



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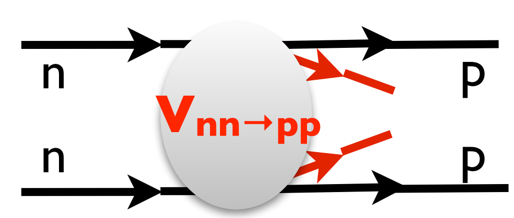
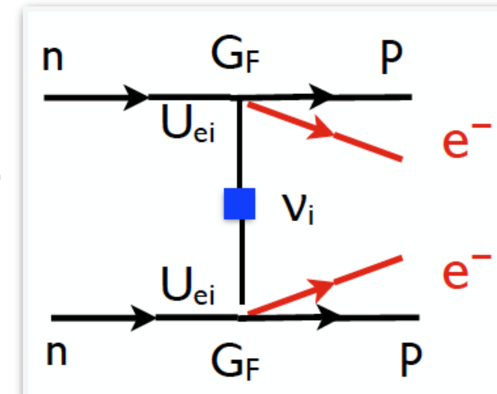
- $0\nu\beta\beta$ mediated by *active* ν_M with potential $V_{nn\to pp}$ with long- and short-range components proportional to $m_{\beta\beta}$

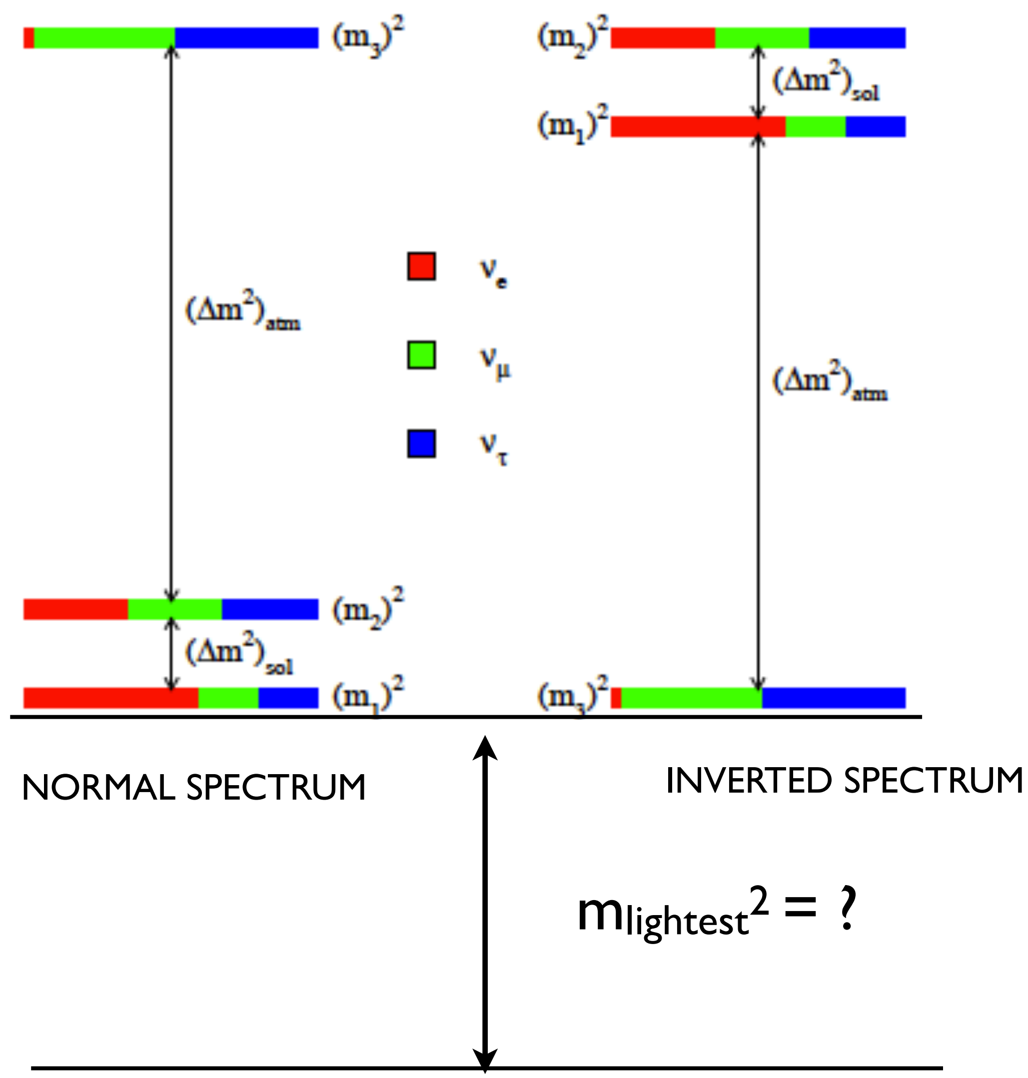


Discovery potential / target

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

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





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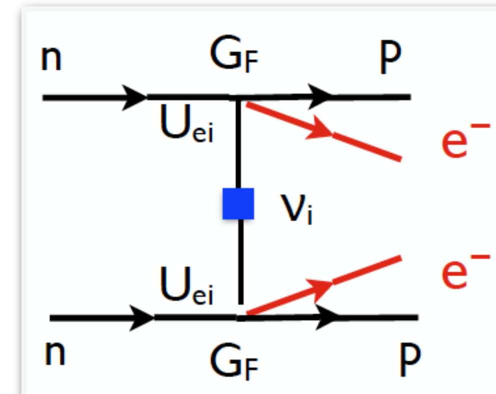
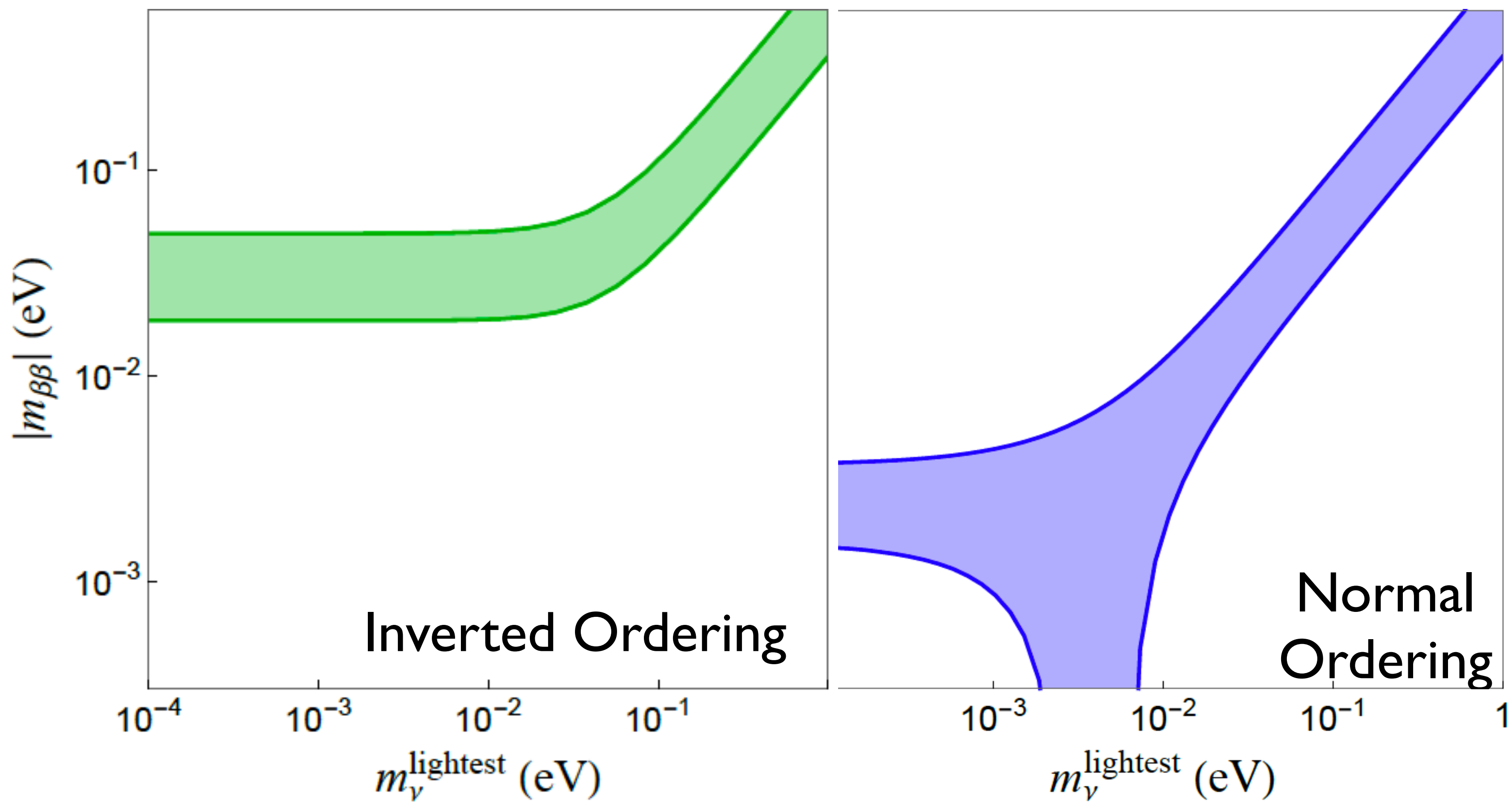


Bands: unknown Majorana phases



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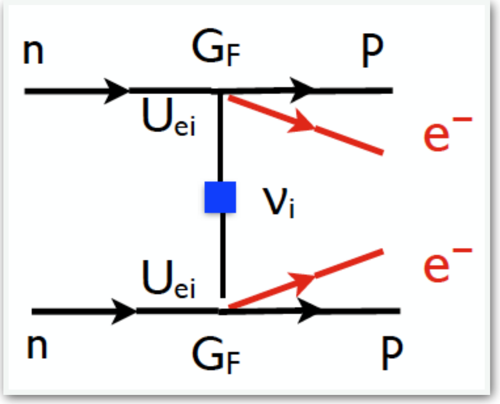

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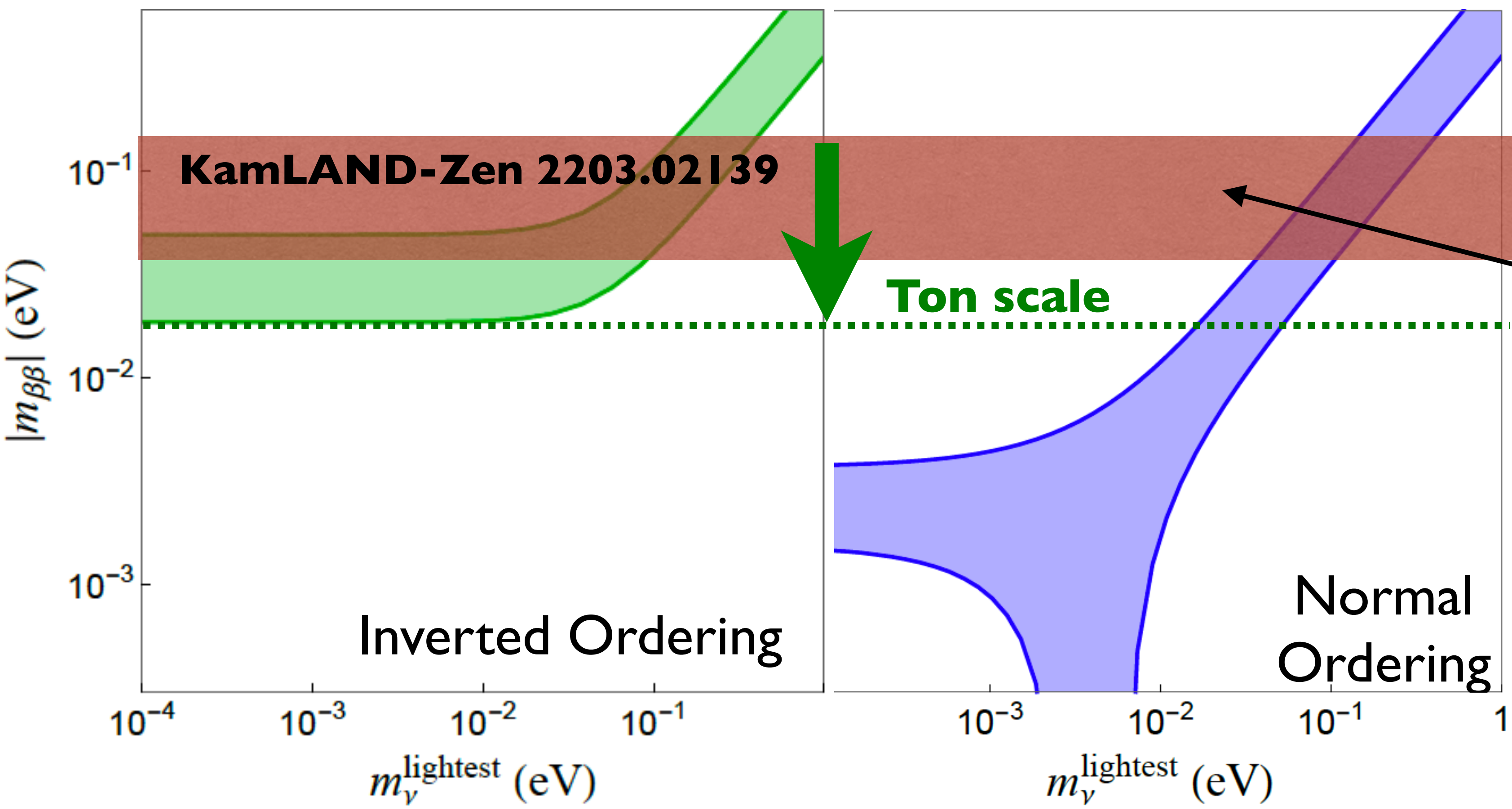

Assume range for nuclear matrix elements from different nuclear calculations

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

Discovery potential / target

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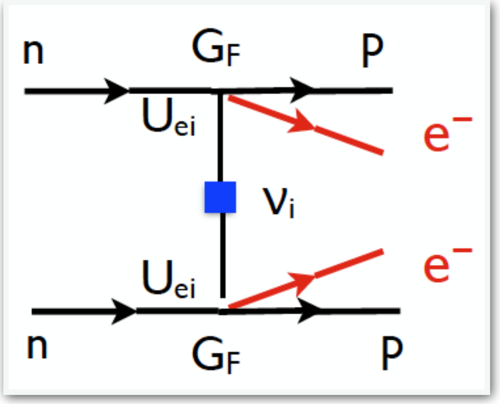

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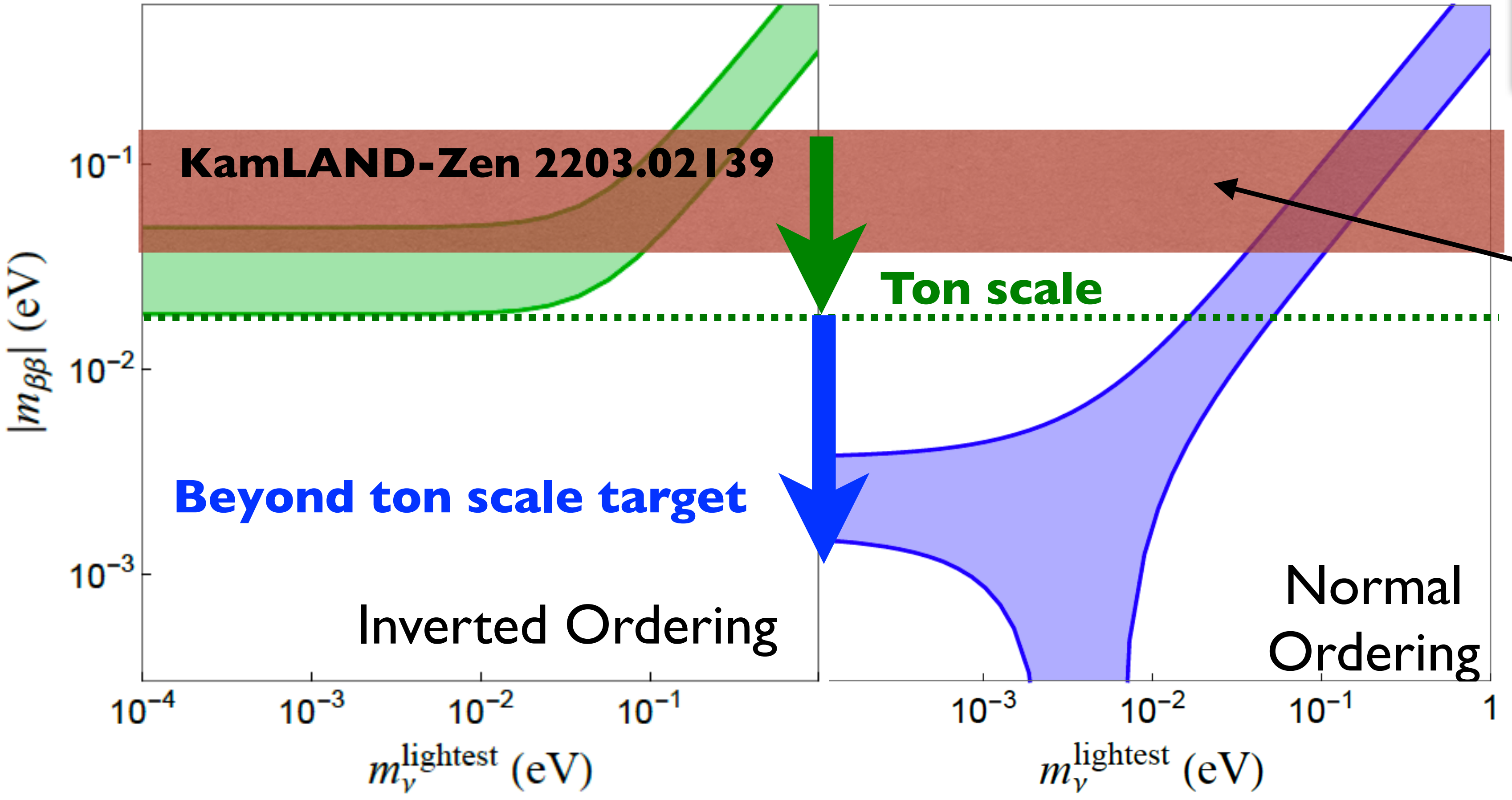


Assume range for nuclear matrix elements from different nuclear calculations

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

Diagnosing power

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

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

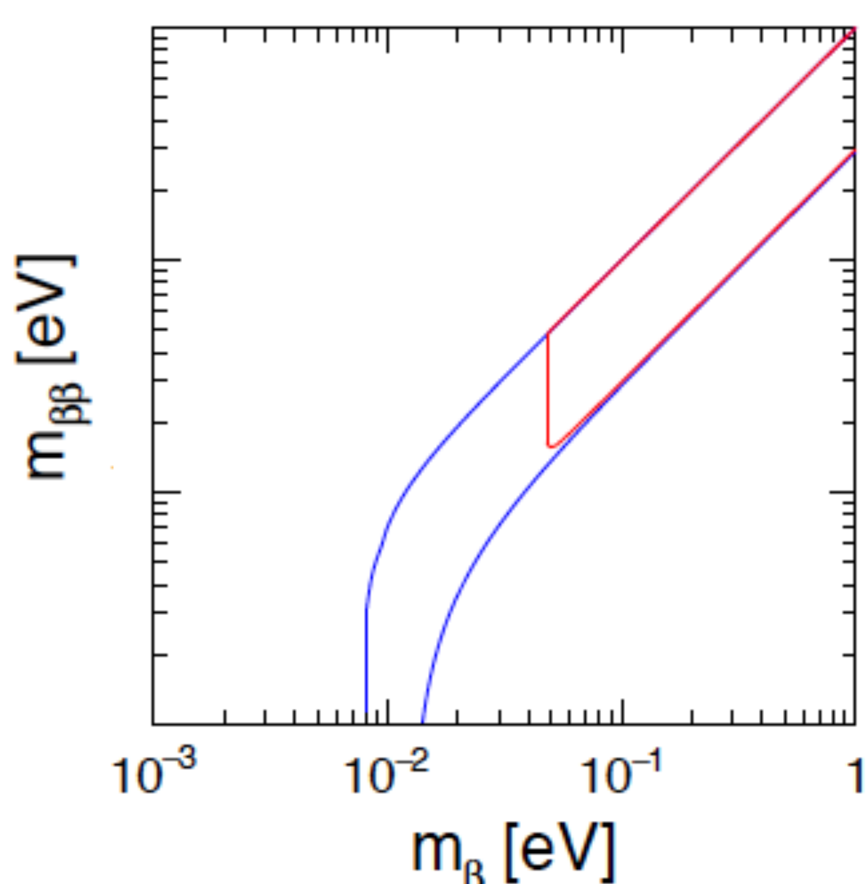
0νββ decay

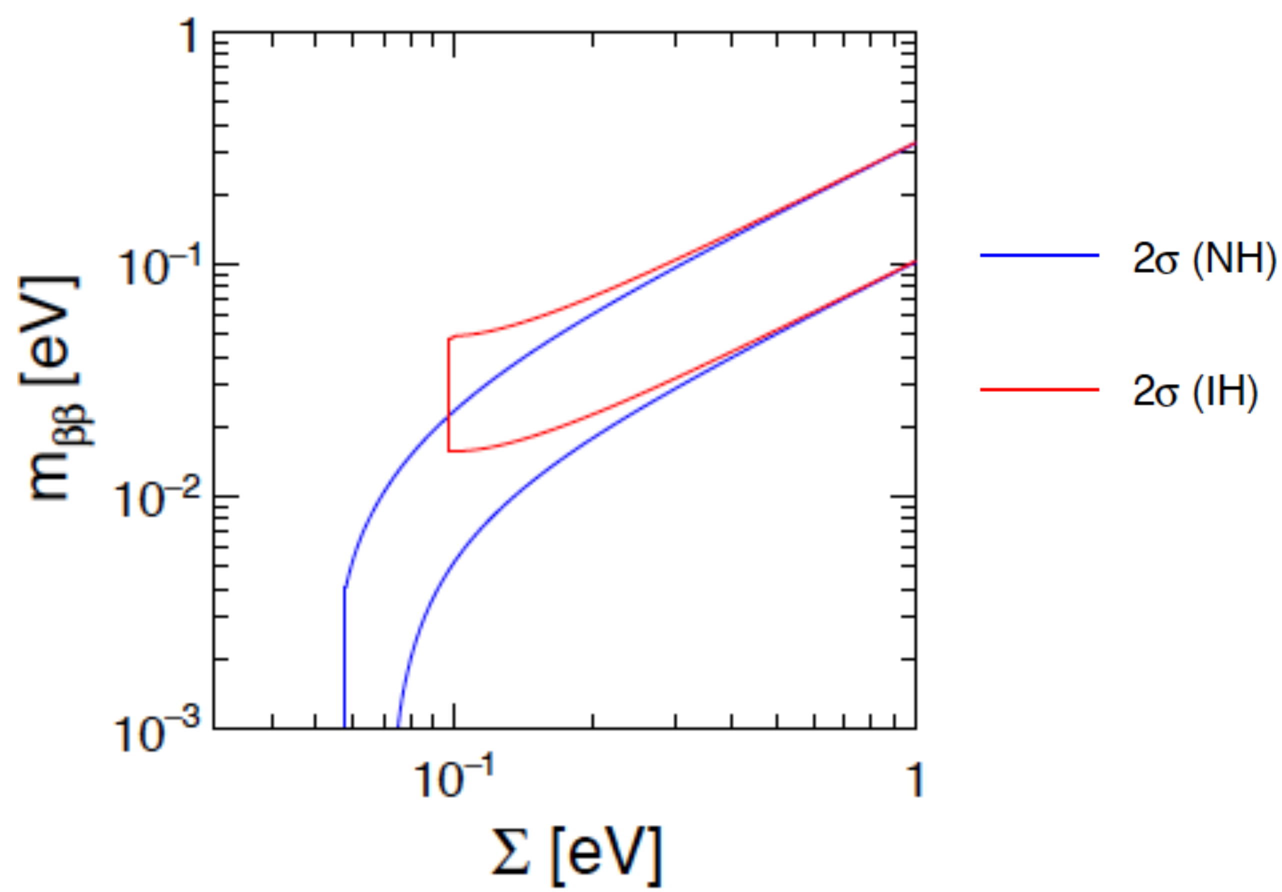
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





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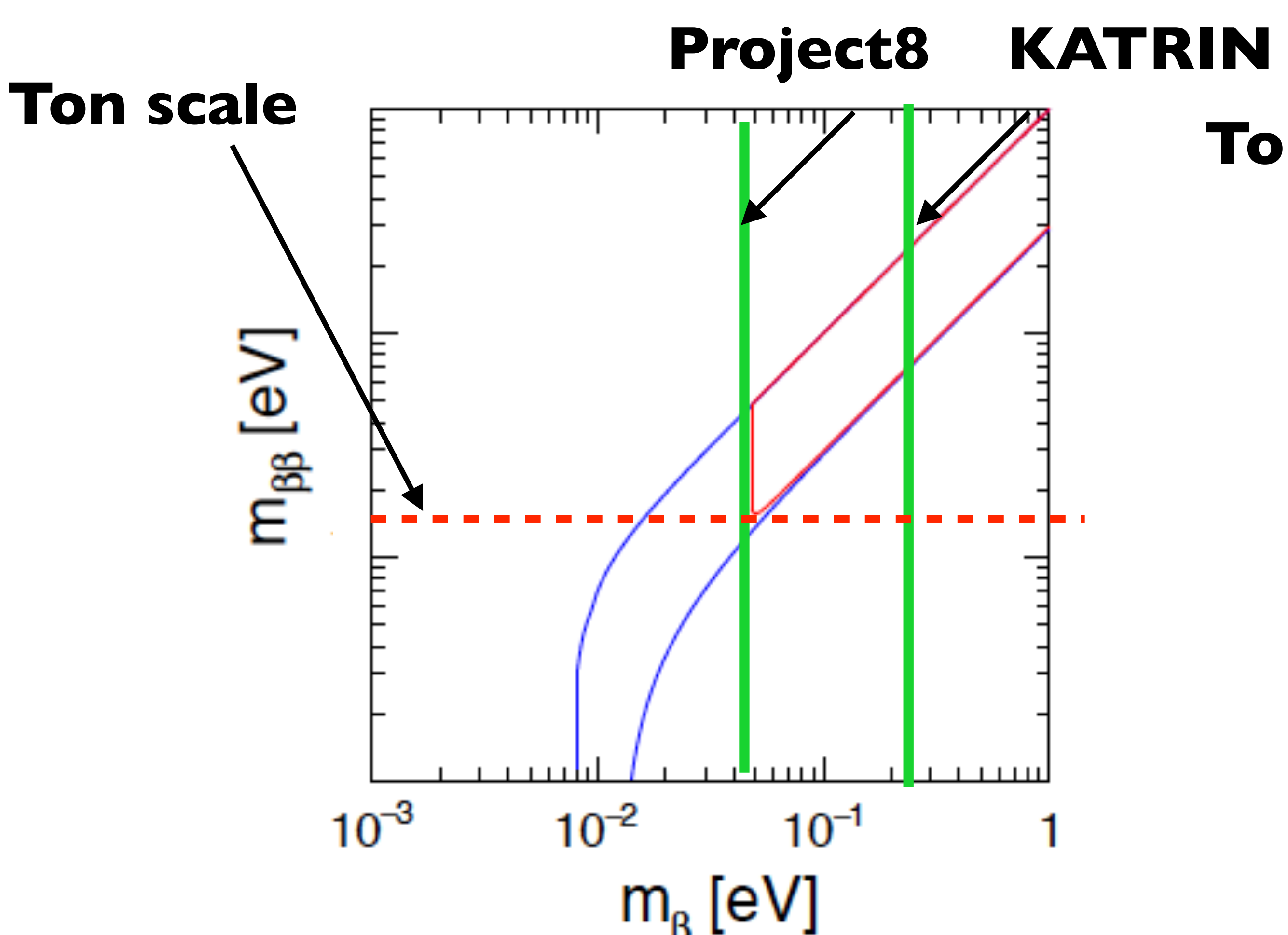
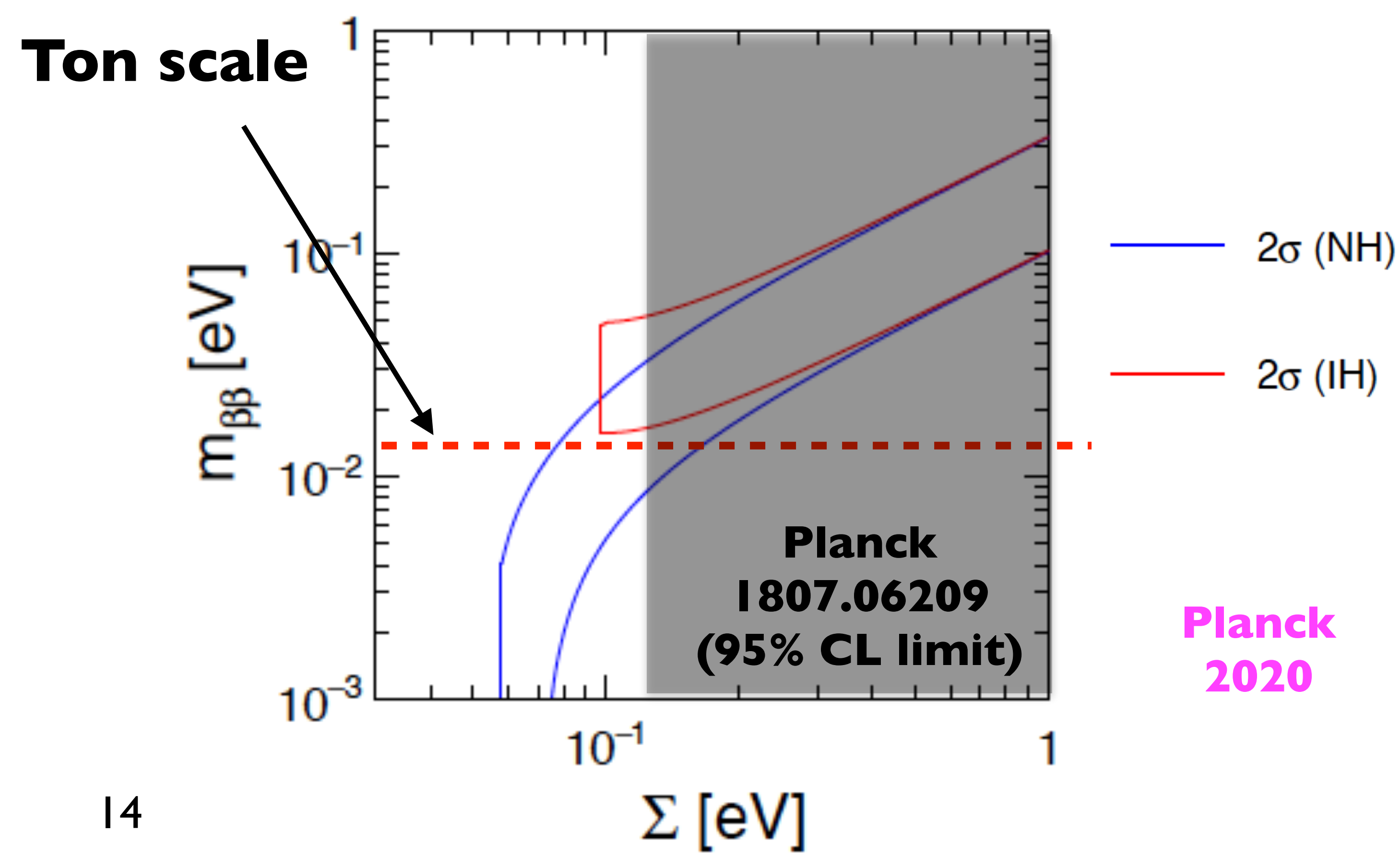




Diagnosing power

- 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

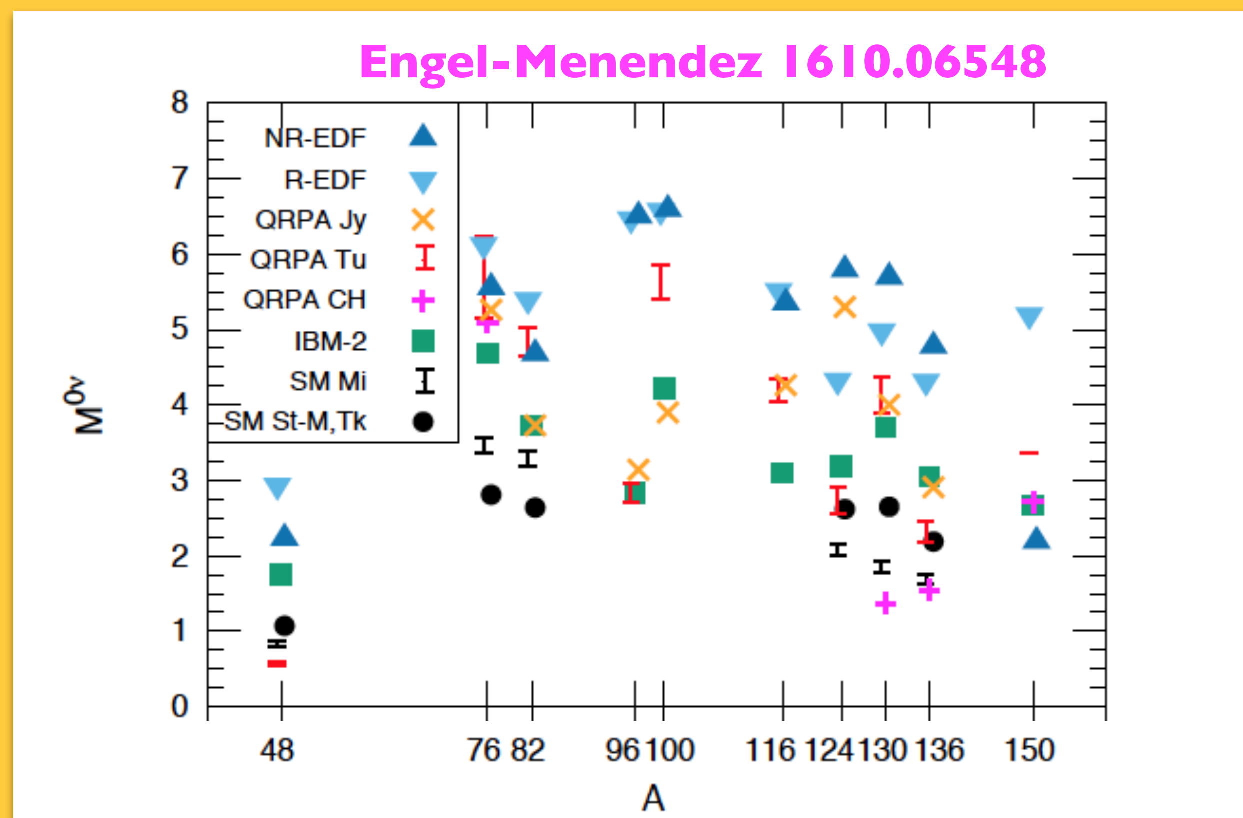
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology

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

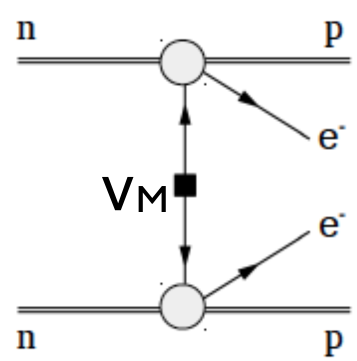


New insights from EFT

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



$$V_\nu^{(a,b)} = \tau^{+,a}\tau^{+,b}\,\frac{1}{\mathbf{q}^2}\left(J_V^{(a)}(\mathbf{q})J_V^{(b)}(-\mathbf{q}) + J_A^{(a)}(\mathbf{q})J_A^{(b)}(-\mathbf{q})\right)$$

$$J_V \sim 1$$
$$J_A \sim g_A\,\sigma$$

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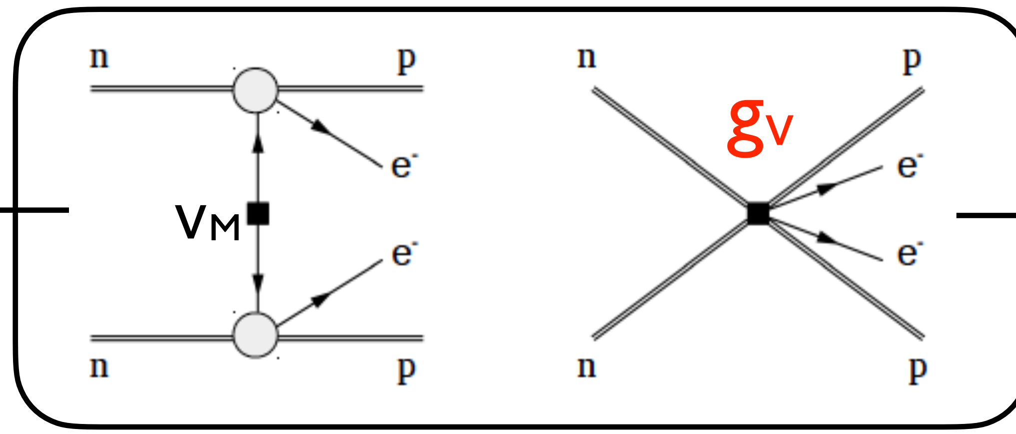
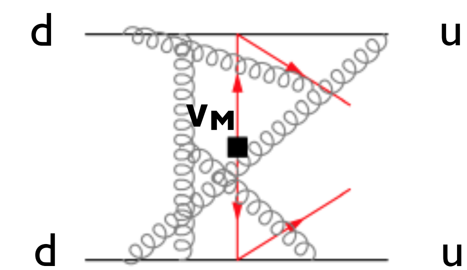


'New': short-range coupling $g_V \sim 1/Q^2$



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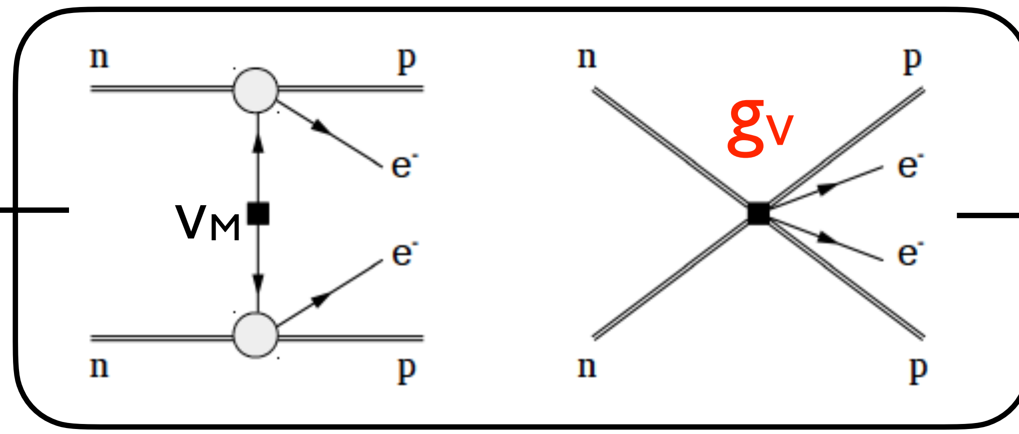

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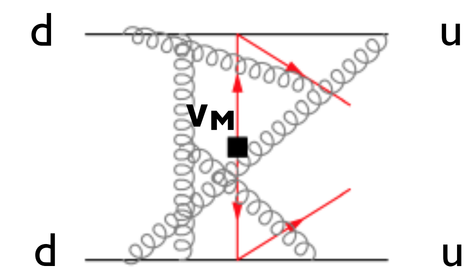
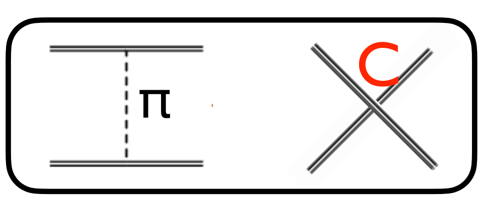


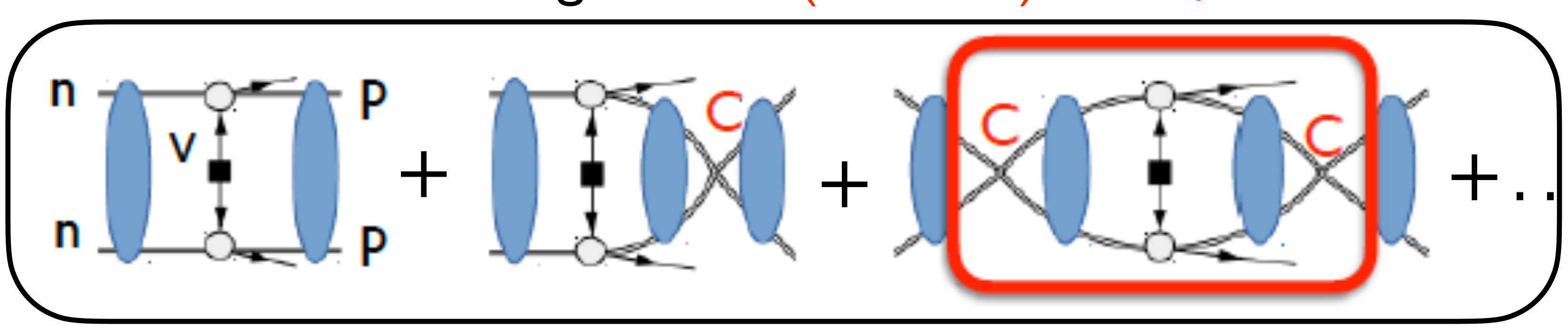
- Required by renormalization of $nn \to pp$ amplitude in presence of strong interactions

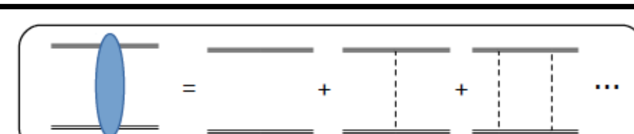
LO strong potential



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

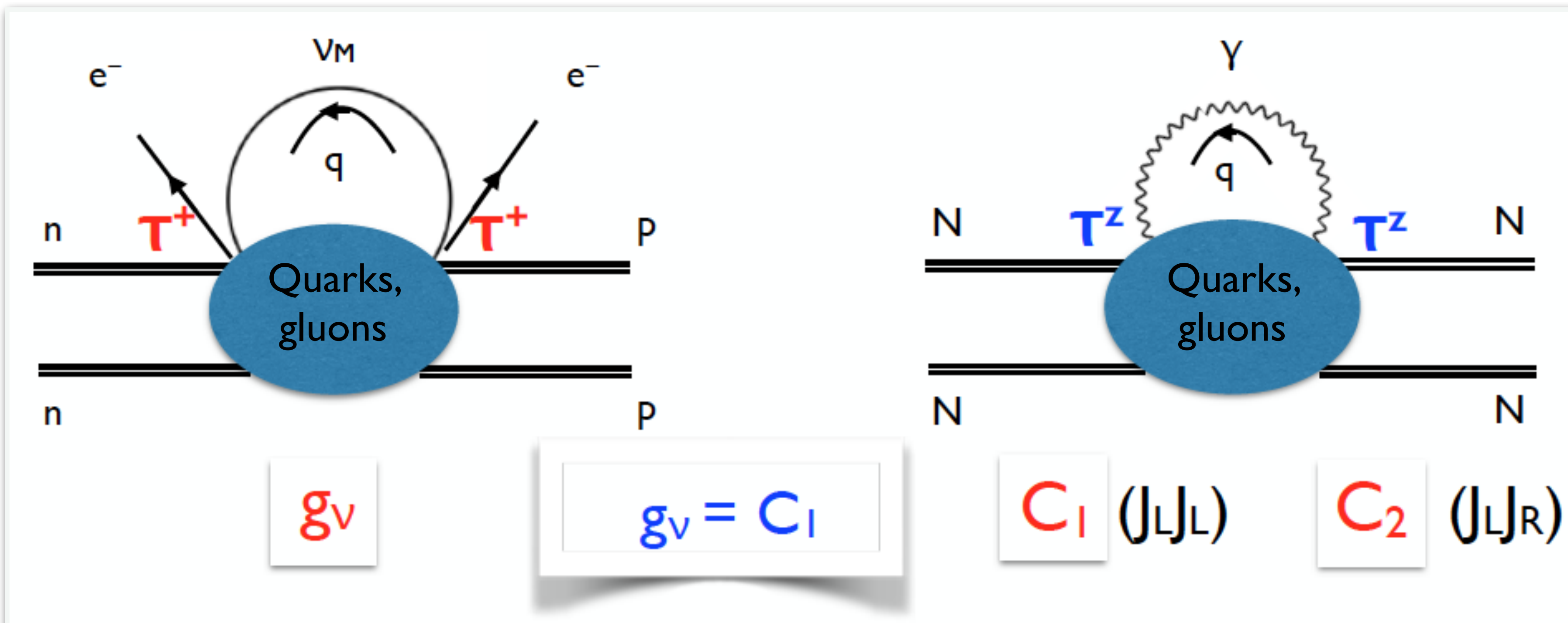
UV divergence $\propto (m_N C/4\pi)^2 \sim 1/Q^2$





Connection with data?

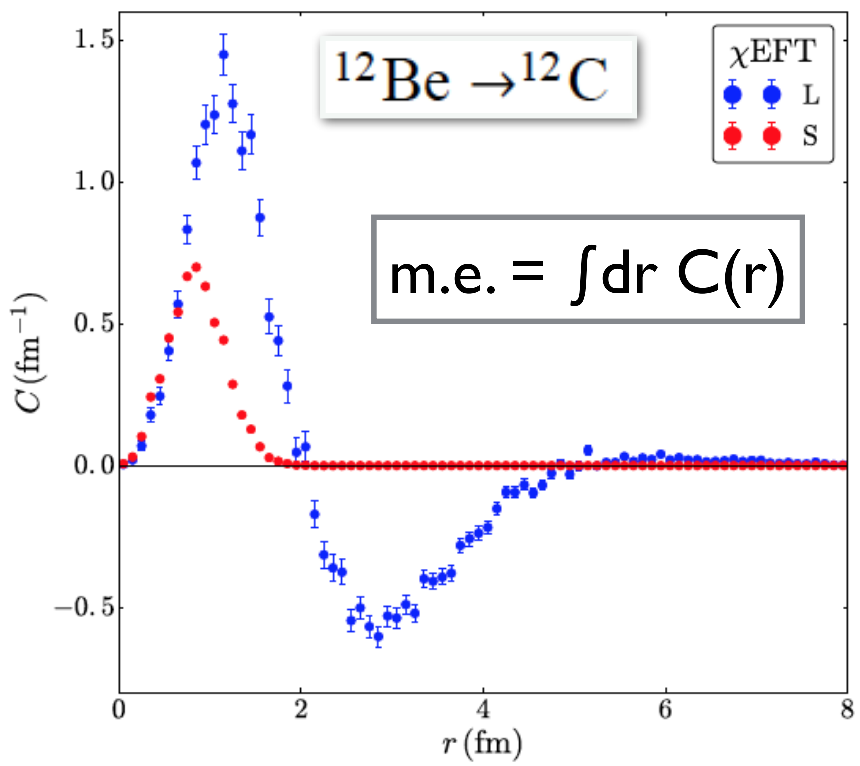
- Isospin symmetry relates g_V to one of two I=2 e.m. couplings (hard γ's & ν's)



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

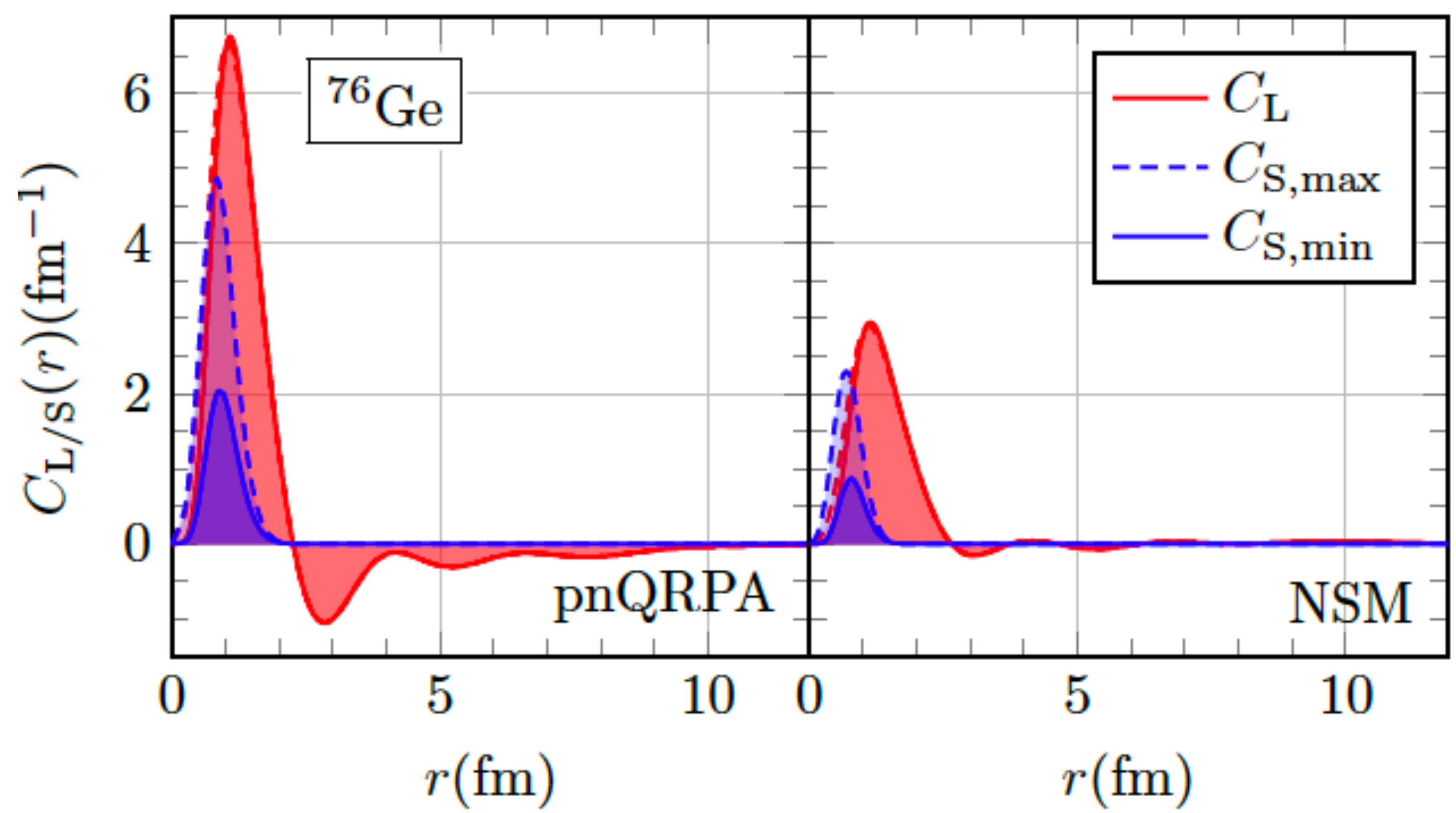
Impact on nuclear matrix elements

- *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

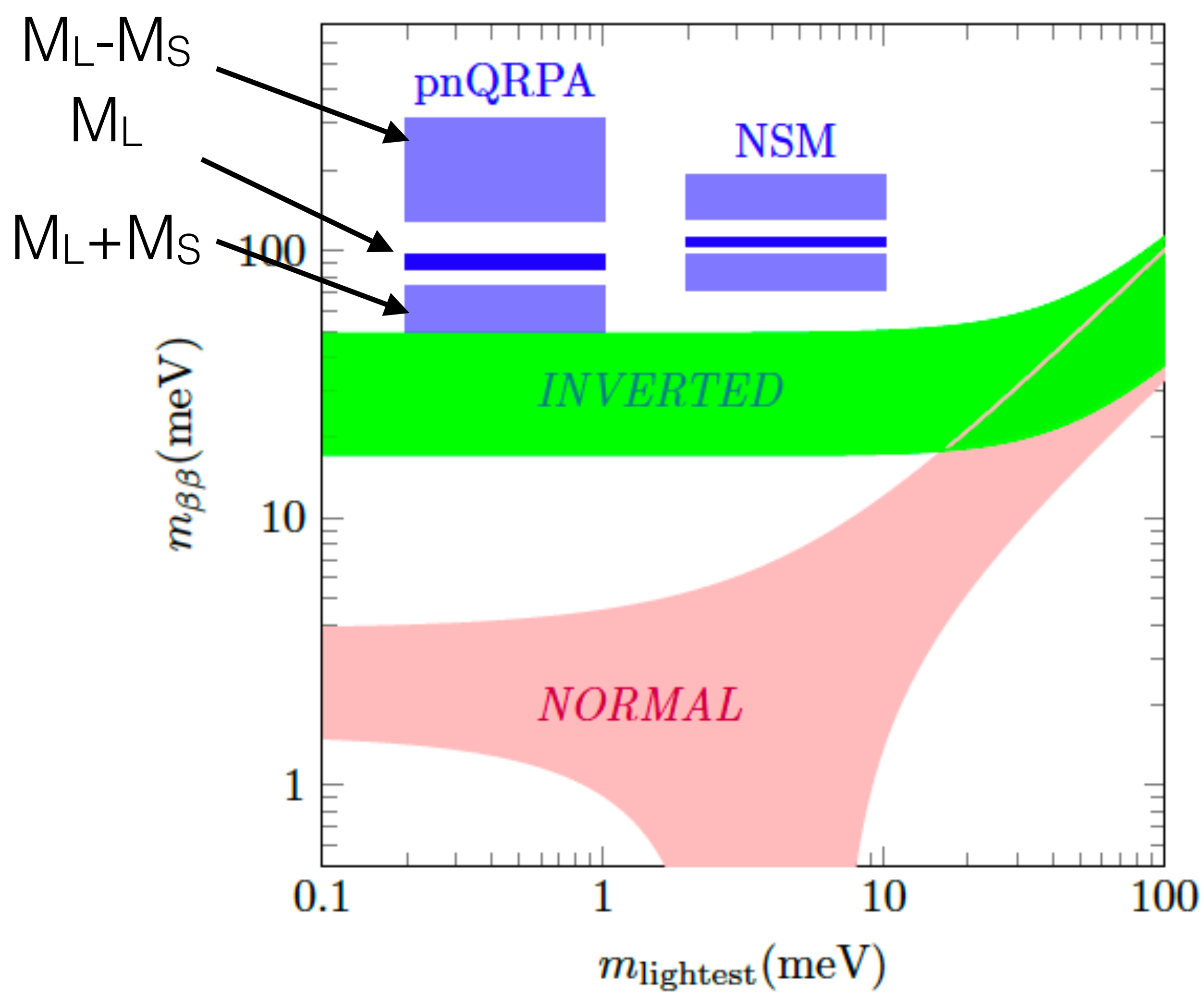


30-70% effect in QRPA and 15-45% in NSM. Similar or larger in other isotopes

Jokiniemi-Soriano-Menendez, 2107.13354

Impact on nuclear matrix elements

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



Key question:
is the interference constructive or destructive?

Jokiniemi-Soriano-Menendez, 2107.13354

Towards determining 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)

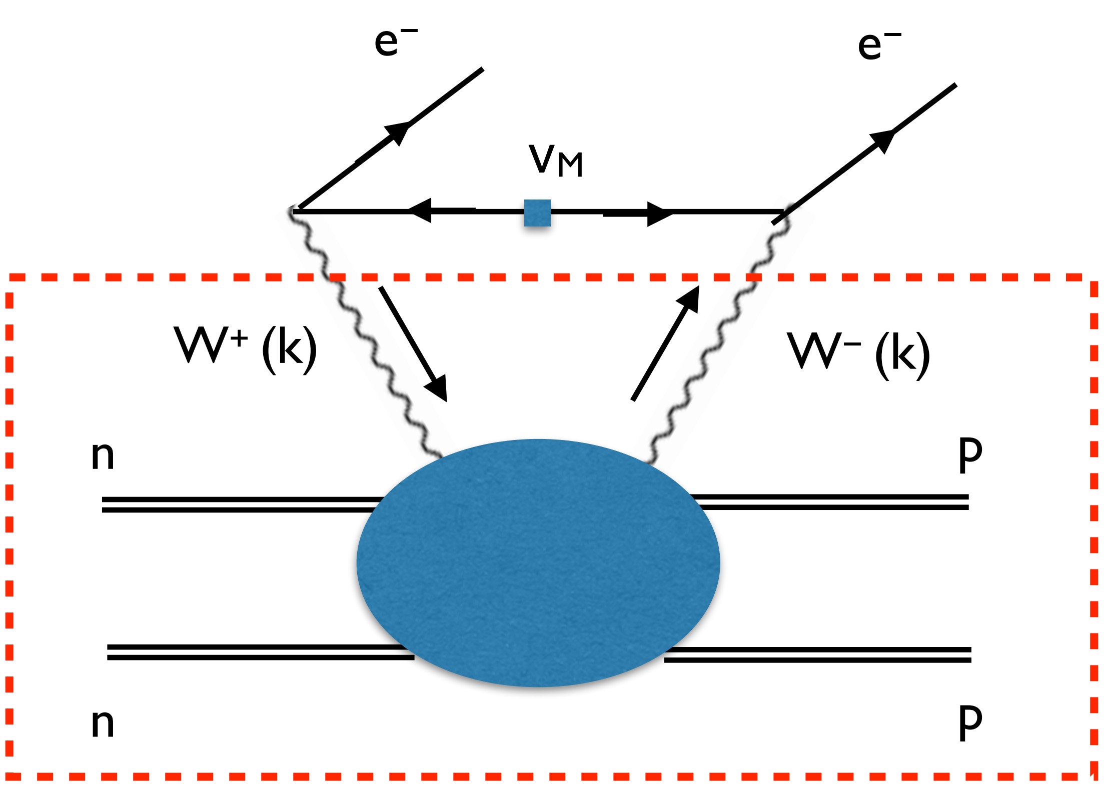
VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

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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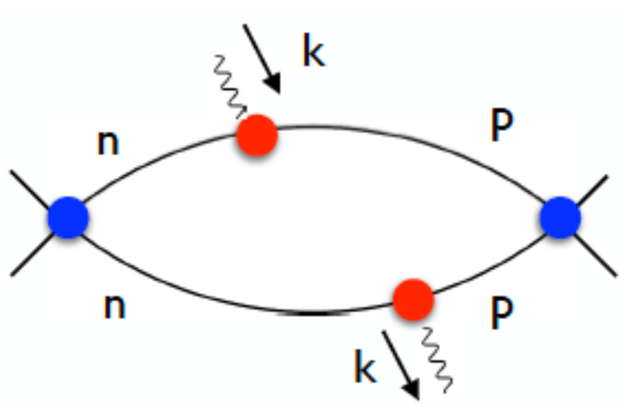
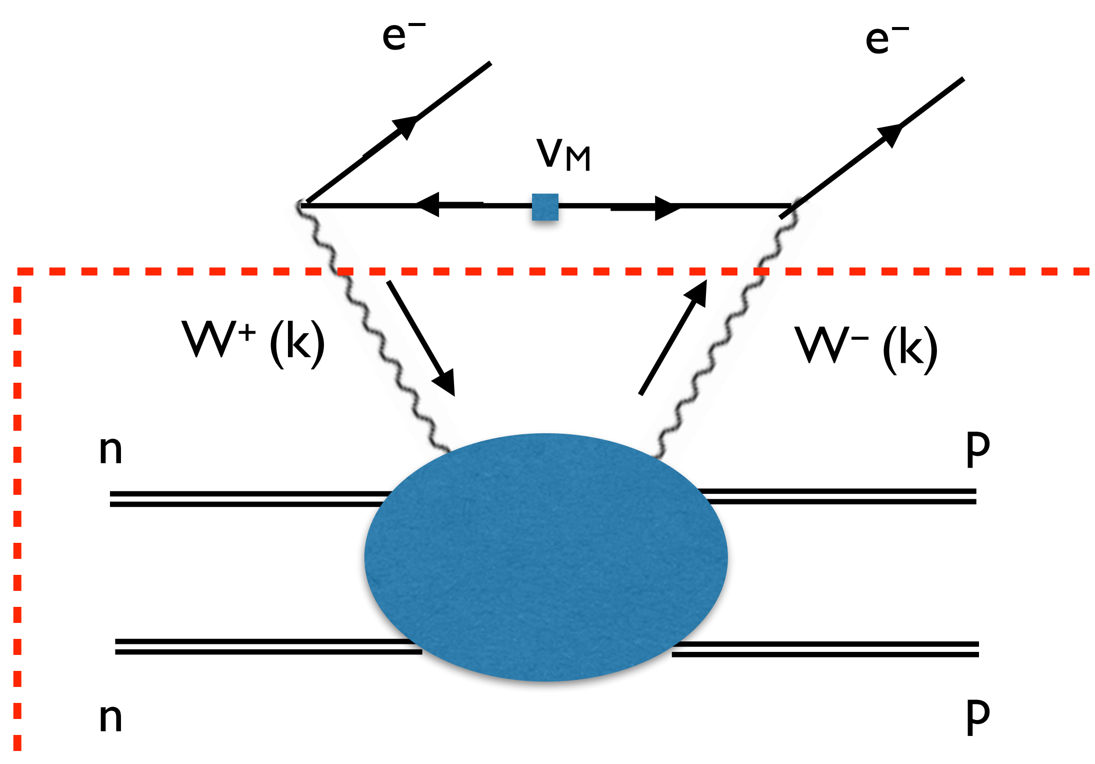
Low k: chiral EFT to NLO

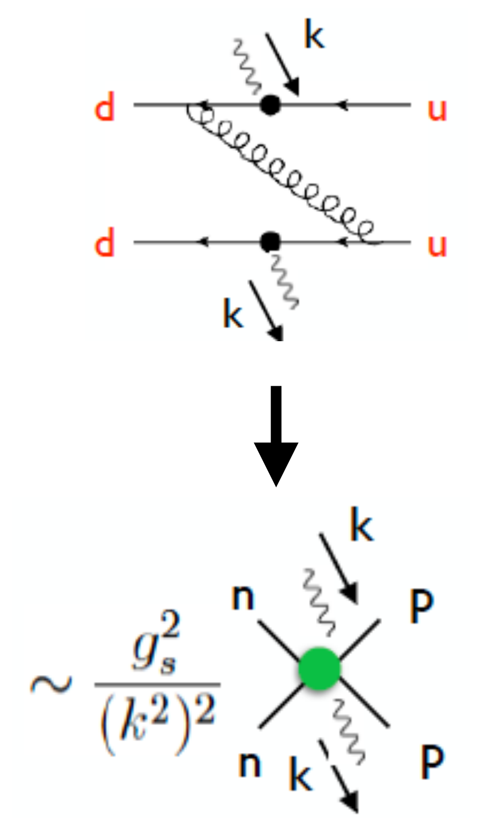


Intermediate k: resonance contributions in and , πNN intermediate state, …



Forward “Compton” amplitude

High k: QCD OPE

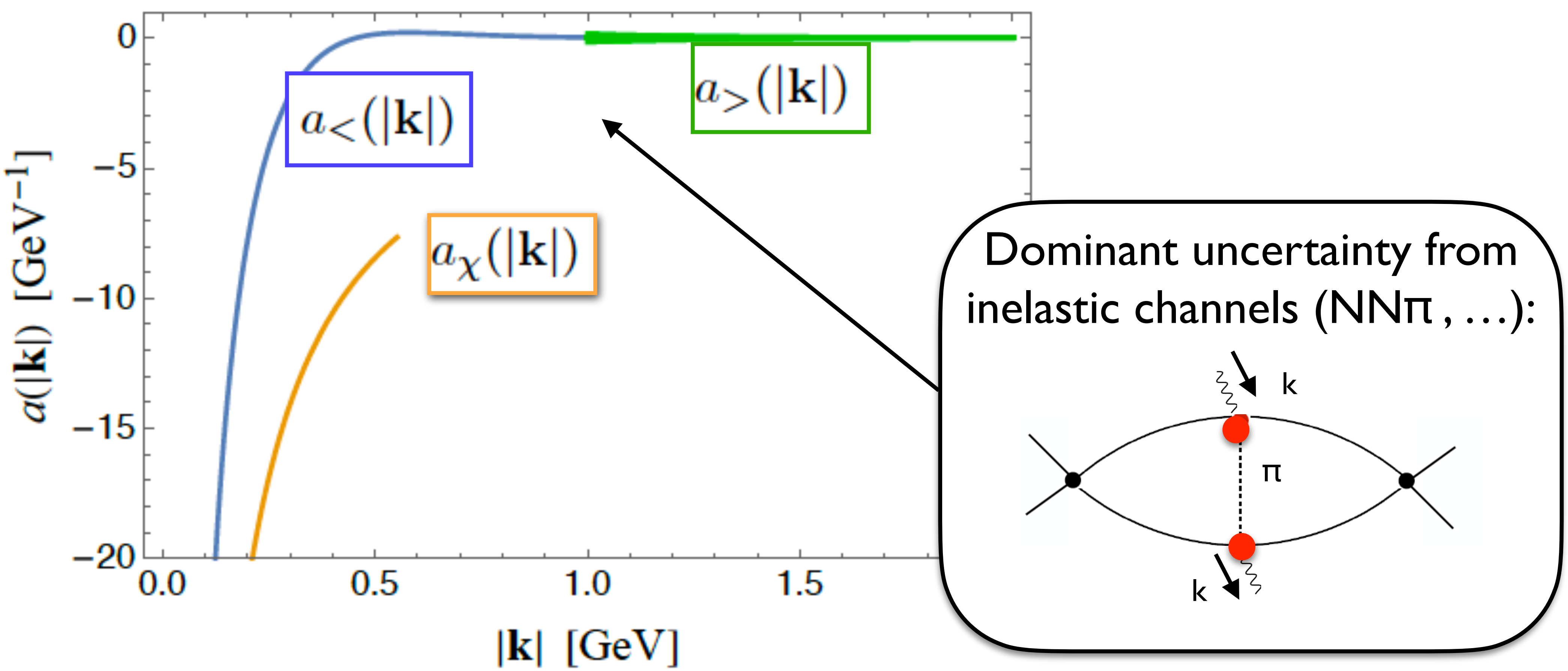


Estimating the contact term (2)

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

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

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



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- 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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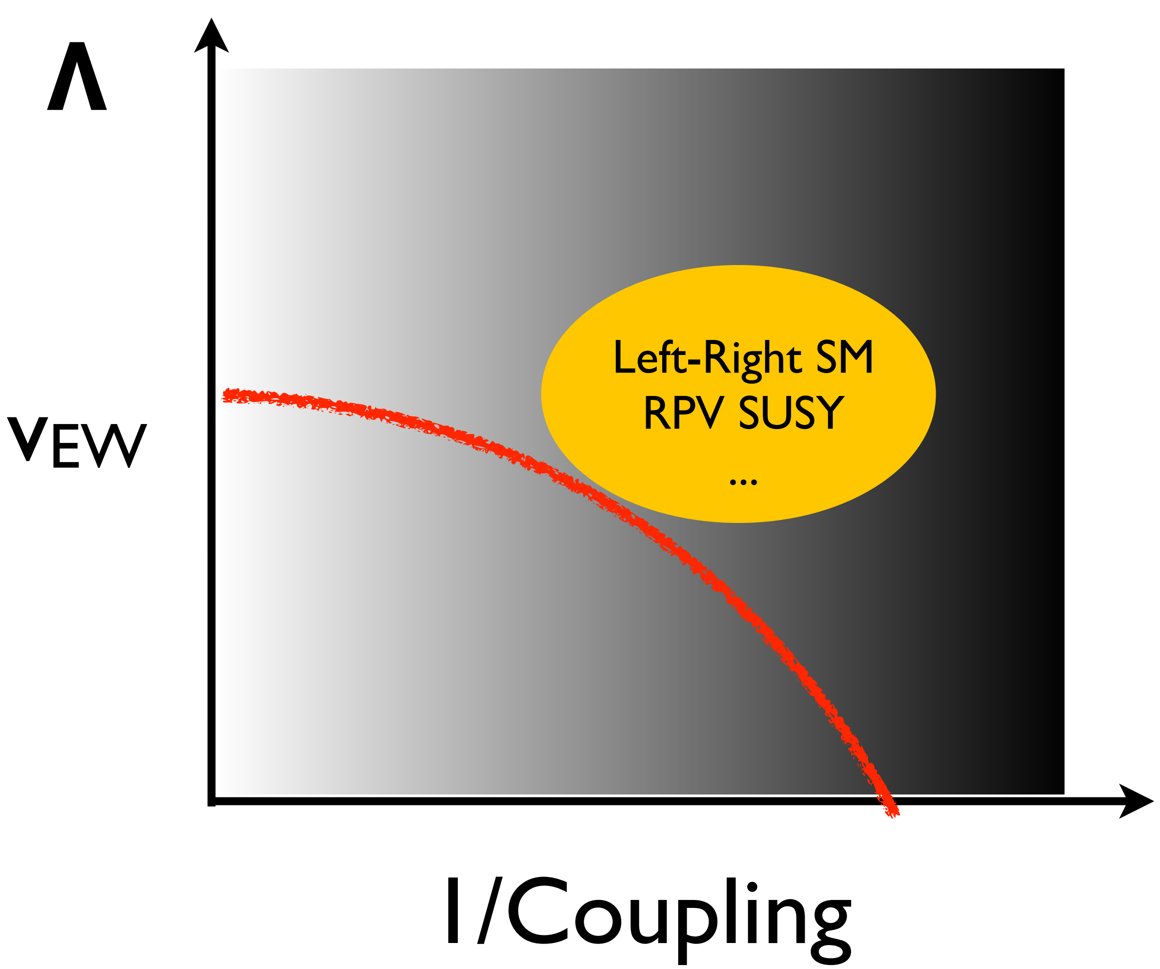
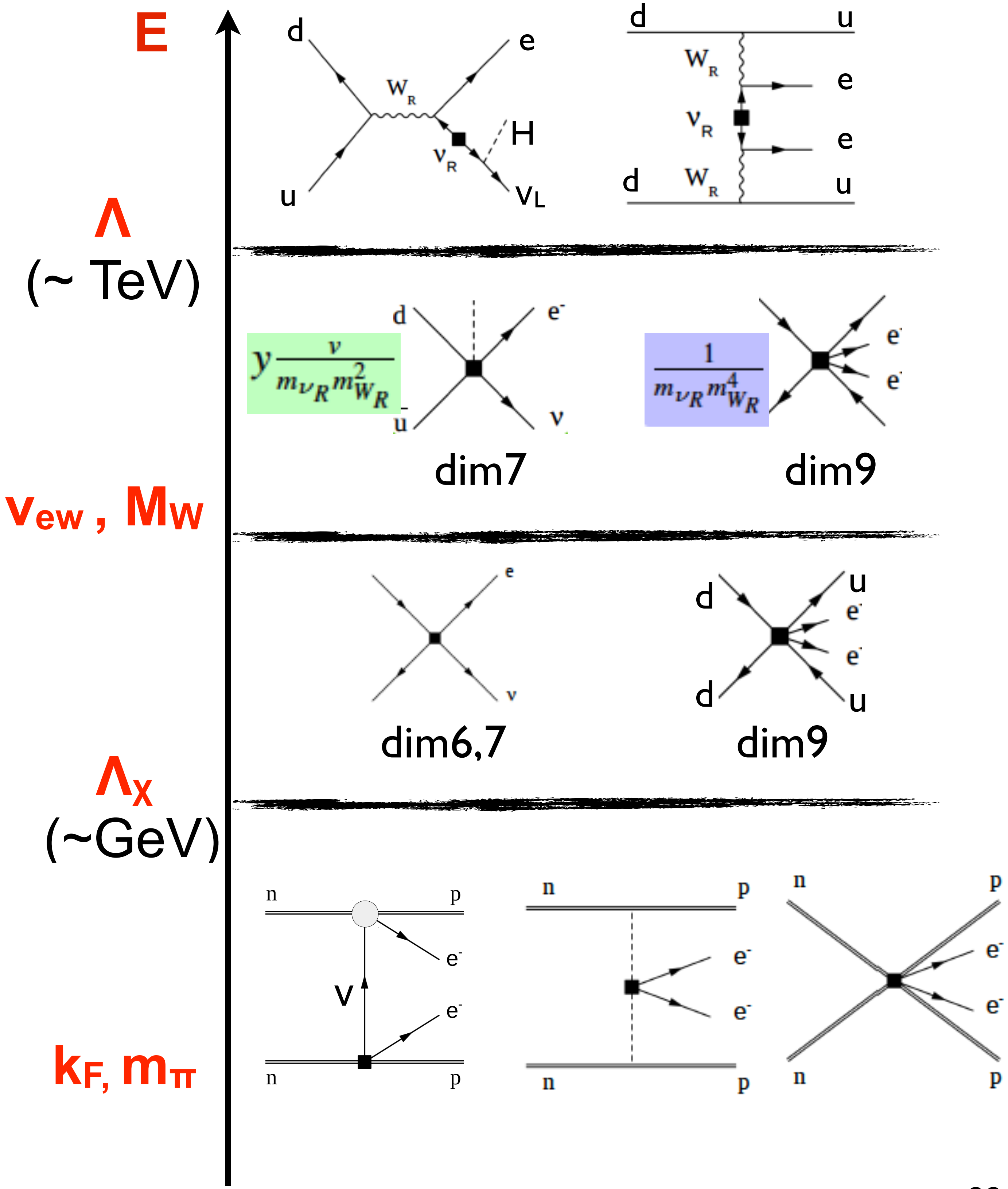
Wirth, Yao, Hergert, 2105.05415

Good news, while we wait for lattice results

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

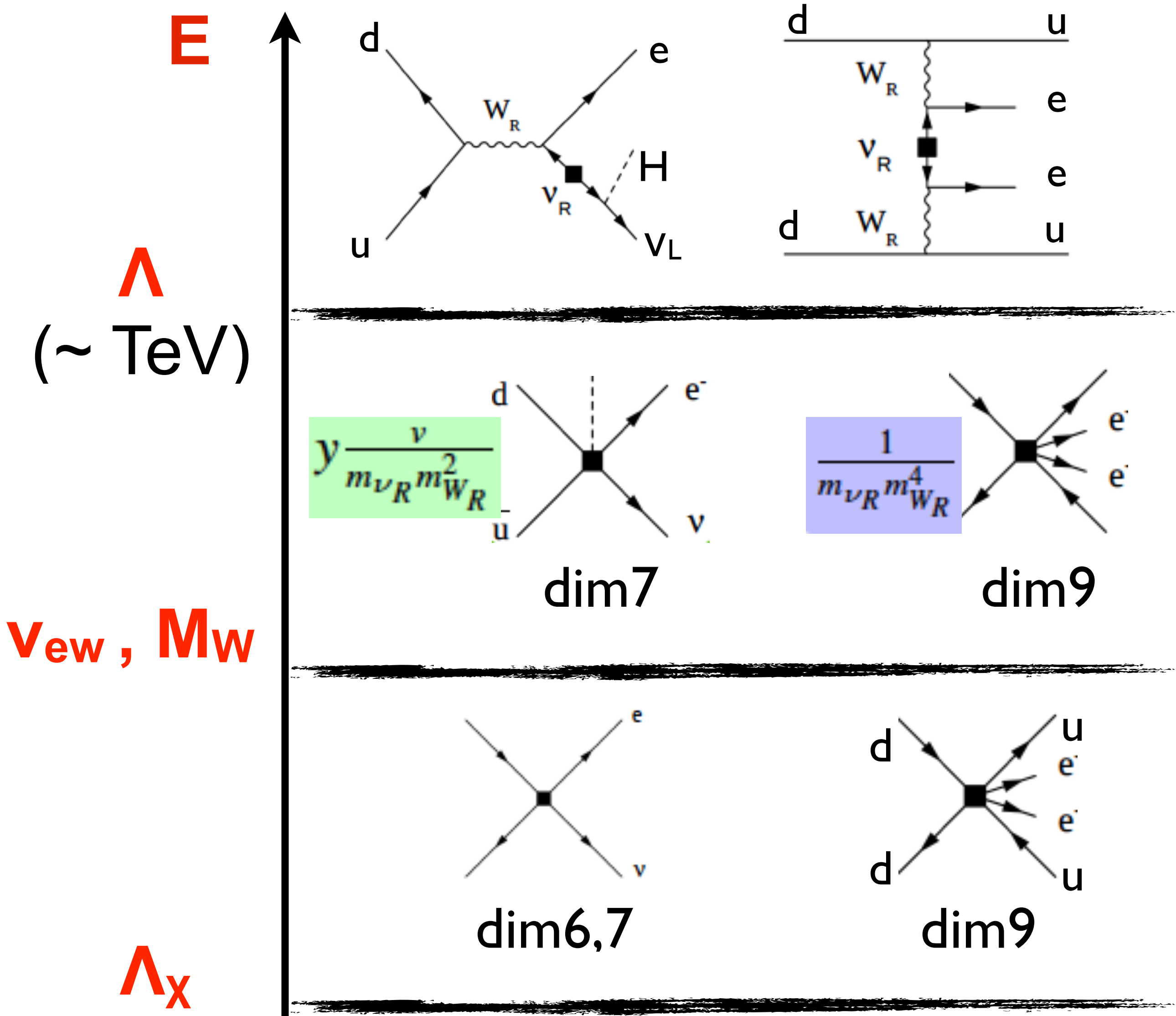


~TeV-scale LNV



- Higher dim operators arise in well motivated models
- 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!

~TeV-scale LNV



- Higher dim operators arise in well motivated models
- 31 operators up to dimension 9

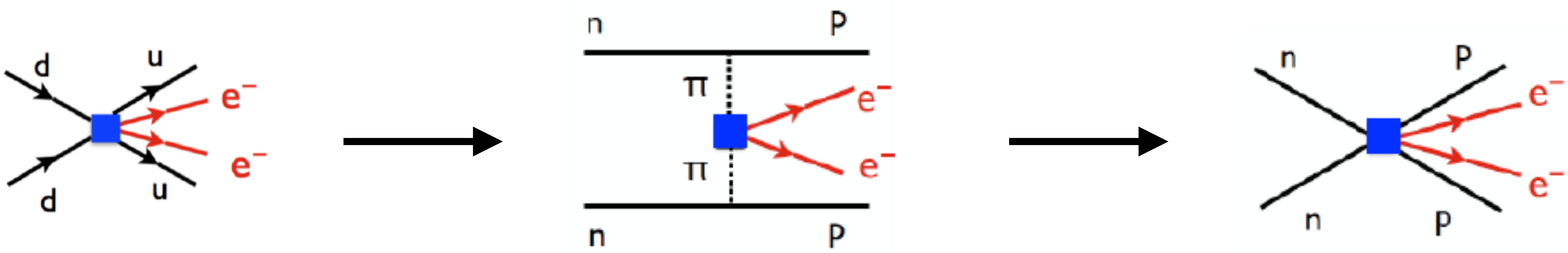
Vast literature, with varying degree of enthusiasm for EFT tools (SM-EFT, chiral EFT)

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
...

Hadronic theory developments

- Leading order hadronic realization of dim-9 operators:



In Weinberg's counting, pion-exchange contribution dominates

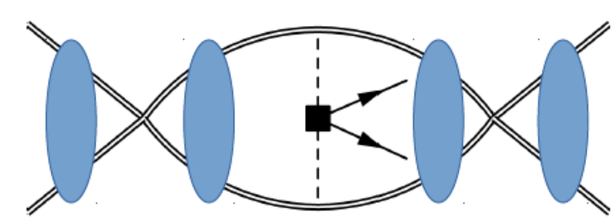
Prezeau, Ramsey-Musolf, Vogel
hep-ph/0303205

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!



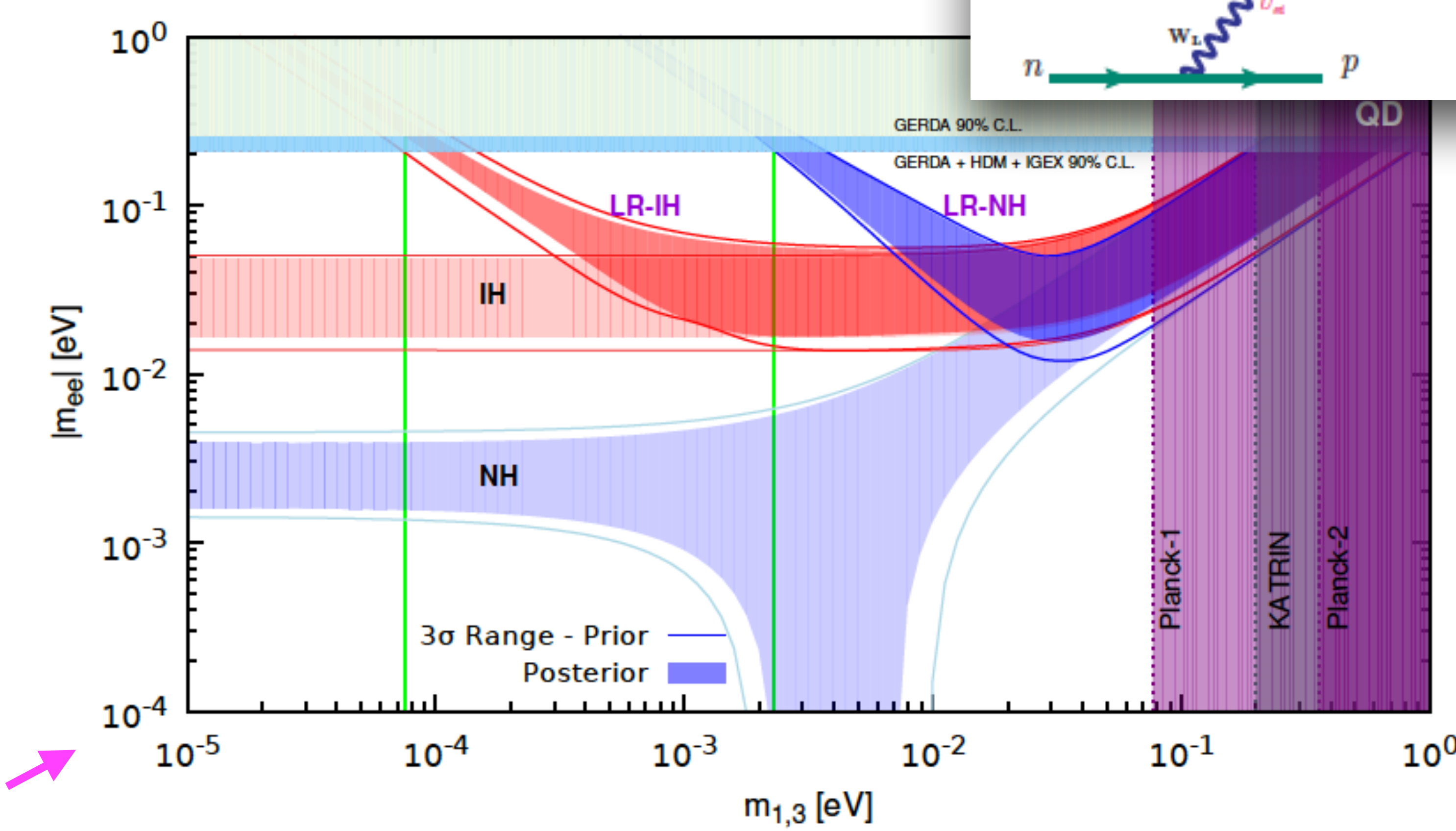
VC, W. Dekens, J. de Vries, M. Graesser,
E. Mereghetti [1806.02780]

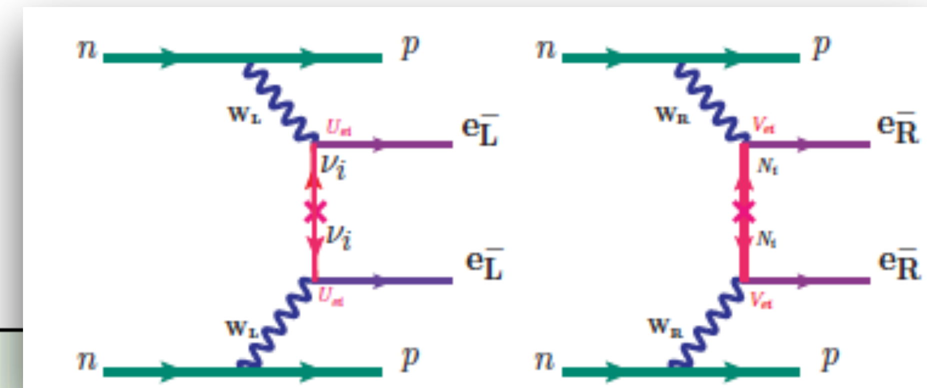
- Several unknown LO NN contact couplings! Opportunity for LQCD

Phenomenological interest (1)

- TeV-scale LNV induces *contributions to 0νββ* ***not directly related to the exchange of light neutrinos,*** within reach of planned experiments

Example: left-right symmetric model with type-II seesaw





$$M_i \propto m_i$$

$$V_R^{PMNS} = V_L^{PMNS}$$

$$M_i = \frac{m_i}{m_3} M_3, \text{ for NH}$$
$$M_i = \frac{m_i}{m_2} M_2, \text{ for IH.}$$

$M_{2,3}$ = 1 TeV

Tello-Nemevesek-Nesti-Senjanovic-Vissani 1011.3522

Ge-Lindner-Patra 1508.07286

...

Phenomenological interest (2)

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

Keung-Senjanovic '83

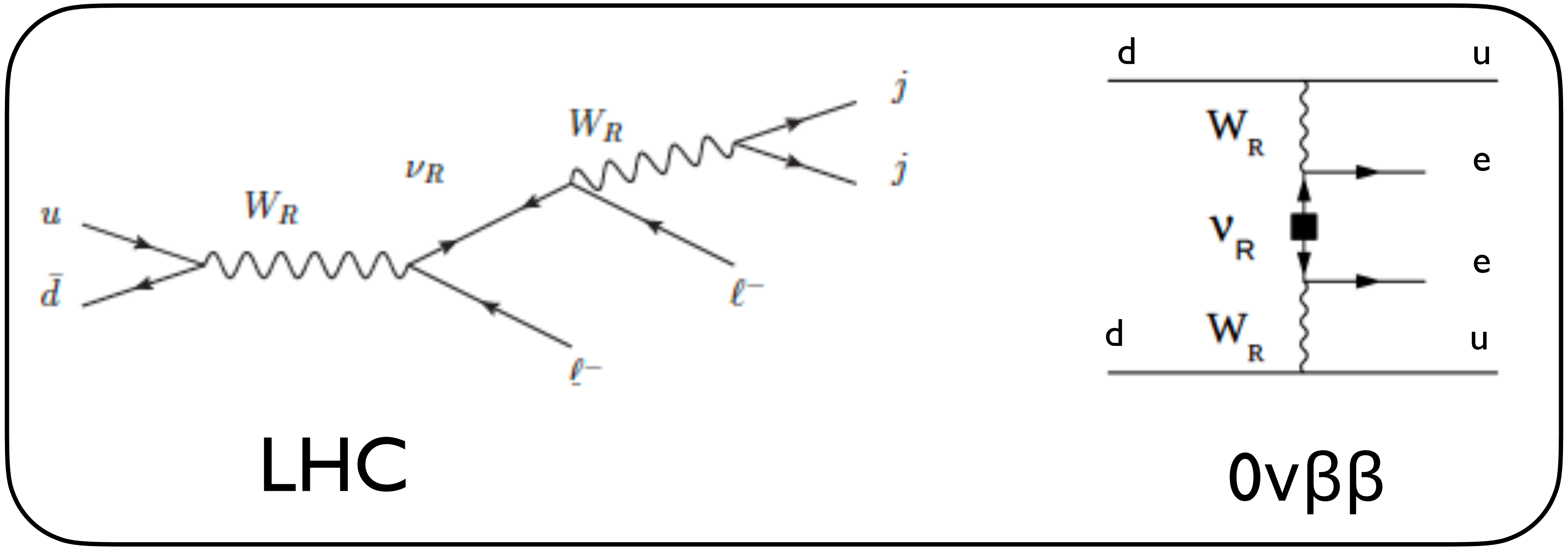
Maiezza-Nemevesek-Nesti- Senjanovic 1005.5160

Helo-Kovalenko-Hirsch-Pas 1303.0899, 1307.4849

Cai, Han, Li, Ruiz 1711.02180

...

Classic LRSM example



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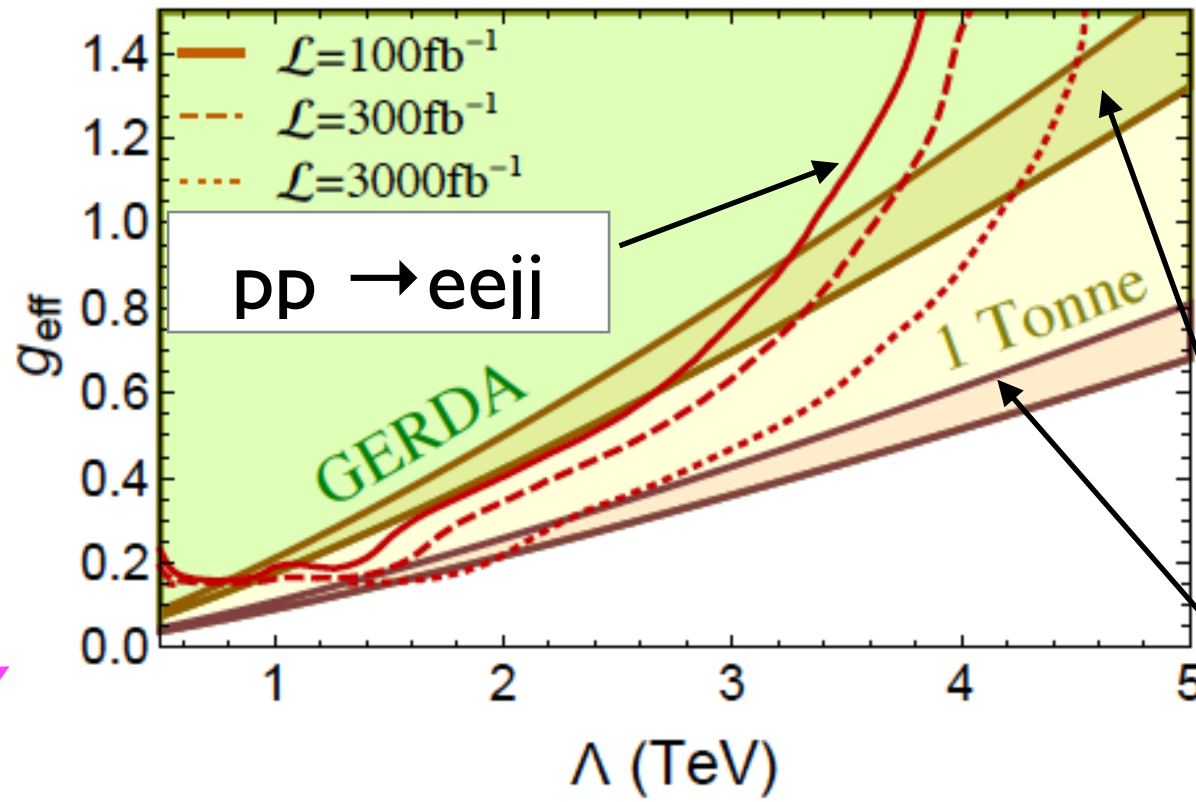
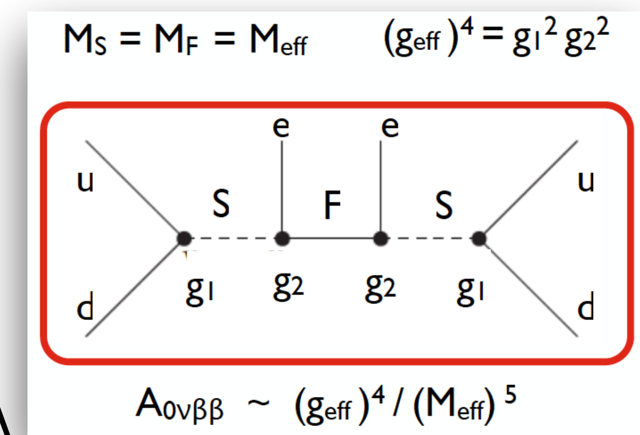
Cai, Han, Li, Ruiz 1711.02180

Peng, Ramsey-Musolf, Winslow, 1508.0444

...



Simplified model



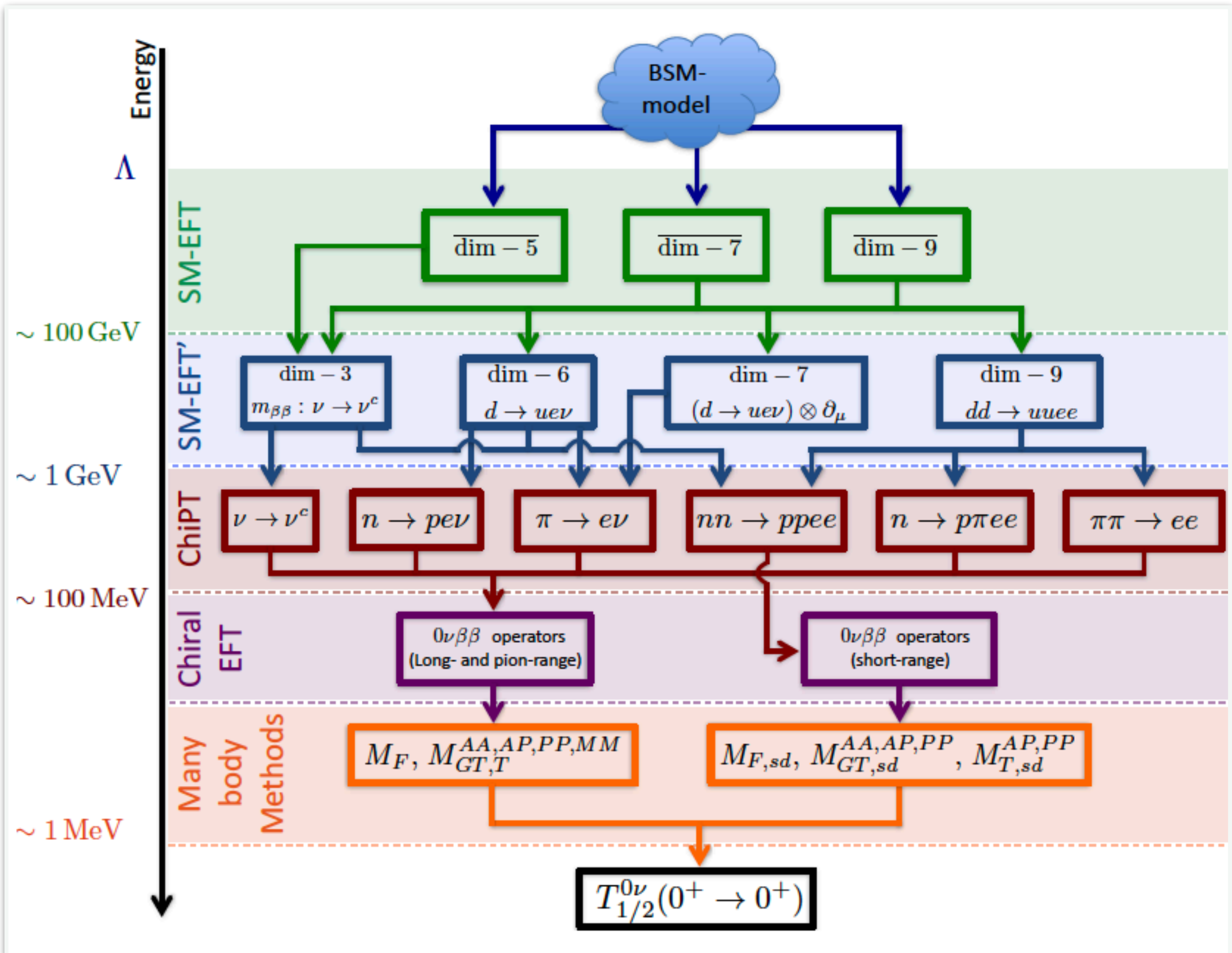
Hadronic / nuclear uncertainty

- 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, et al 2106.10838 , ...

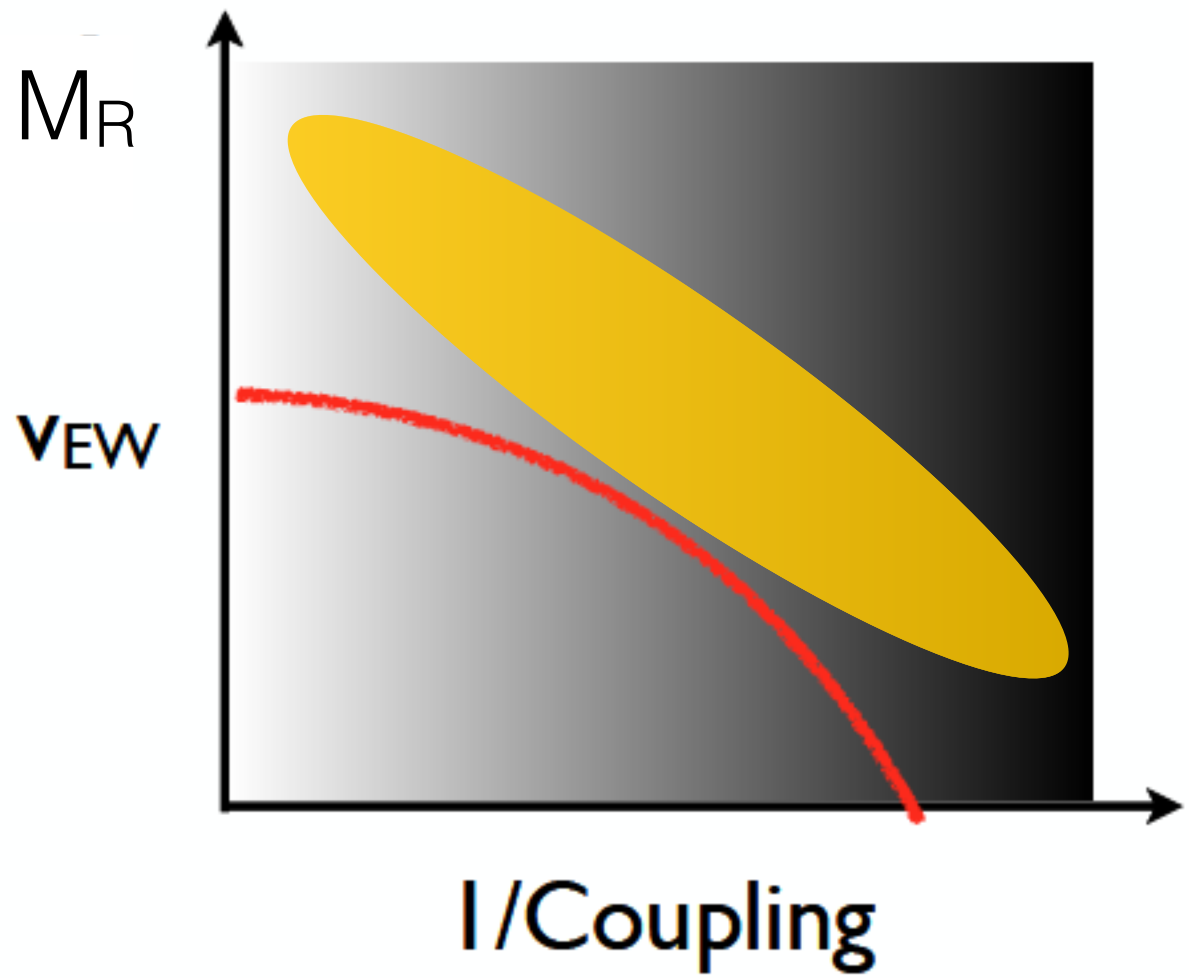
Summary: EFT-based master formula

- 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]

0vββ and sterile neutrinos

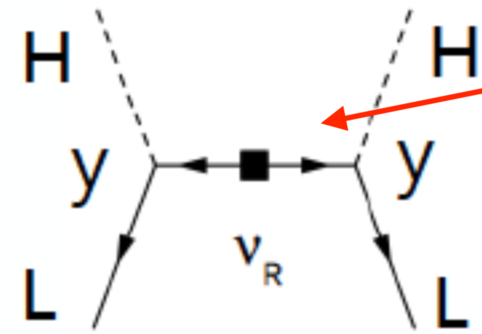


Phenomenological interest

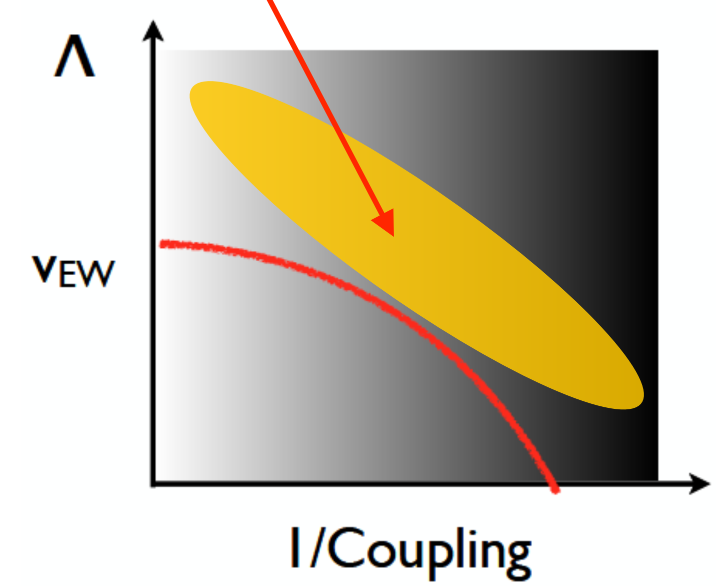
Akhmedov. Rubakov, Smirnov
hep-ph/9803255

Canetti, Drewes, Shaposhnikov
1204.3902

...



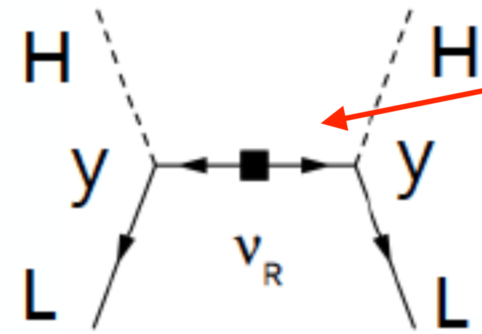
Arbitrary scale $M_R \leftrightarrow \Lambda$



- 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
- In general $m_{\beta\beta} \neq (m_{\beta\beta})_{active}$, with strong dependence on ν_R spectrum

Phenomenological interest

Drewes-Garbrecht 1502.00477
Drewes-Eijima 1606.06221
Hernandez et al 1606.06719
...



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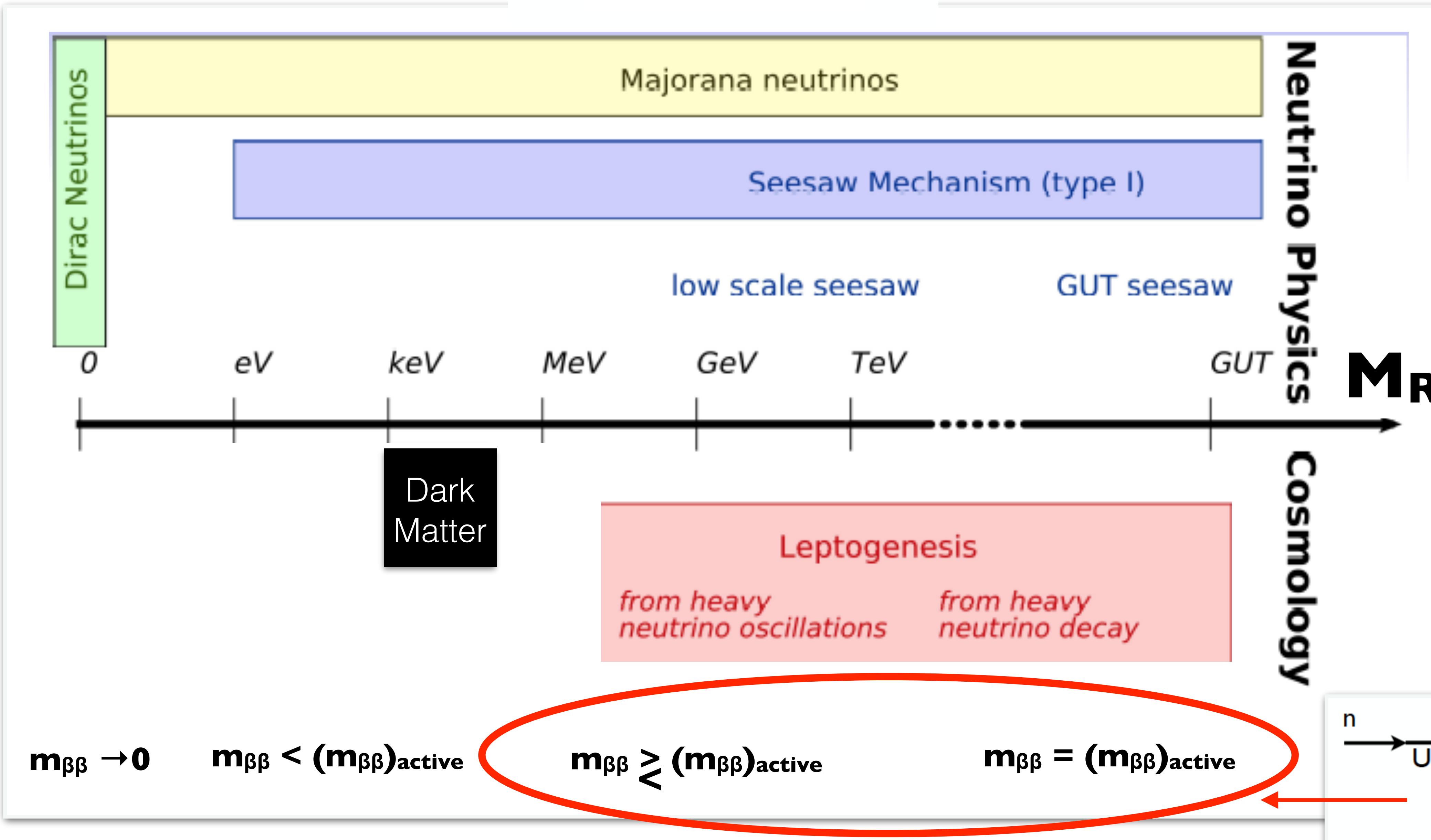
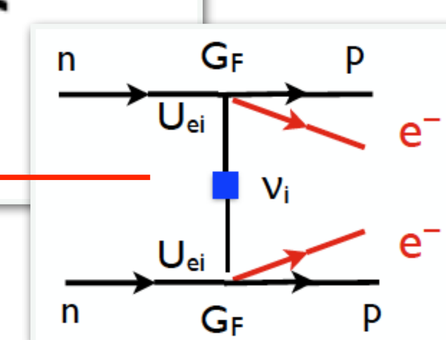
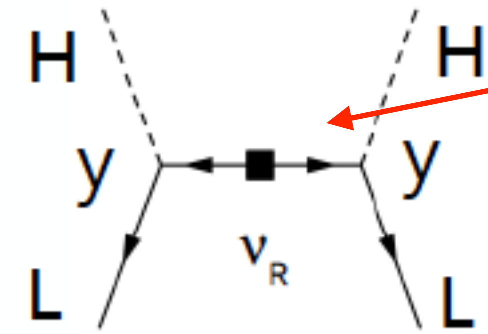




Plot by Marco Drewes

Phenomenological interest



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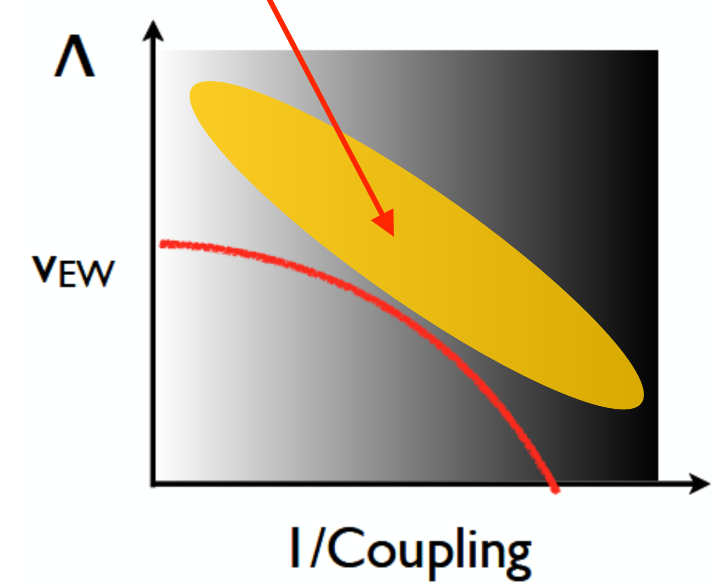

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  - ν_R can provide a dark matter candidate
  - ν_R can generate the baryon asymmetry through leptogenesis
- In general $m_{\beta\beta} \neq (m_{\beta\beta})_{active}$, with strong dependence on ν_R spectrum
- Can be probed at colliders, beam dump, semileptonic decays, EWPO, …

See e.g. Bolton, Deppisch, Dev 1912.03058

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

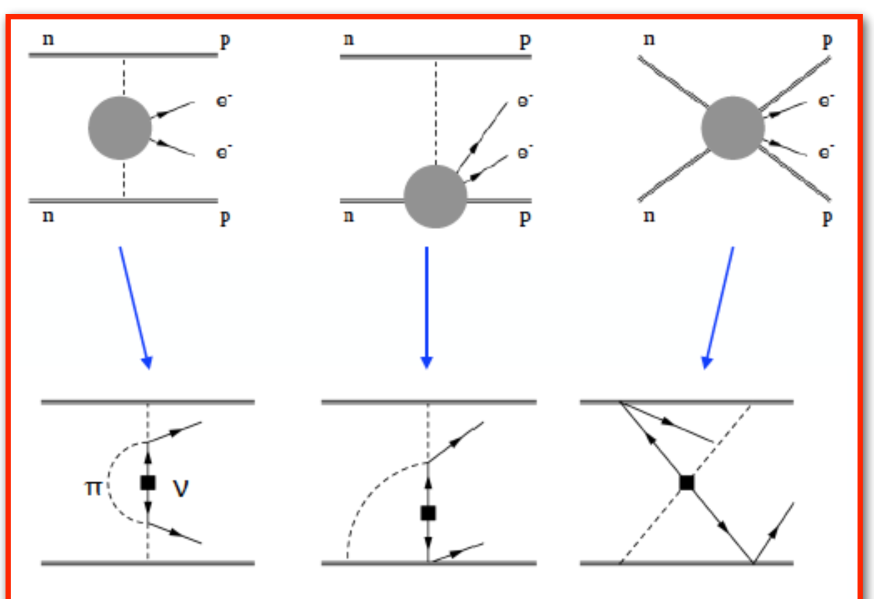
Improving the theory uncertainty is challenging, but there are exciting prospects thanks to advances in EFT, lattice QCD, and nuclear structure

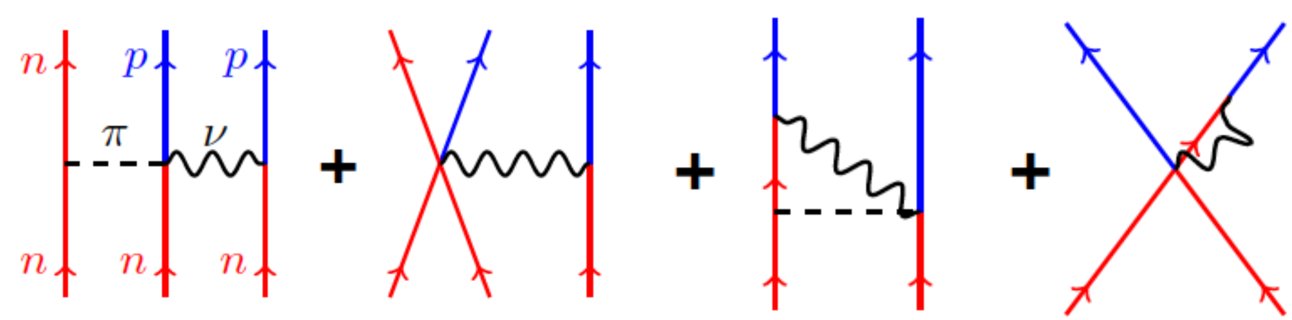
Backup

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

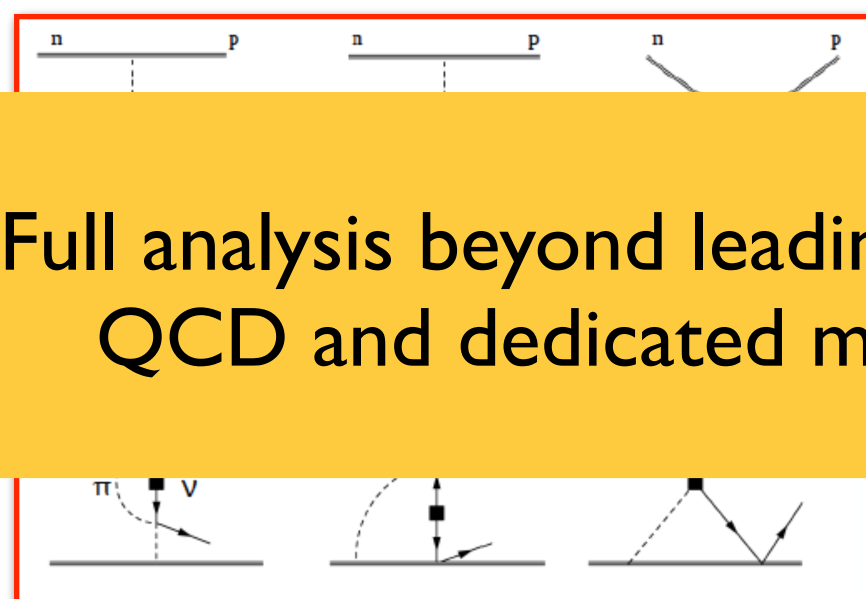




LNV@dim5: What about higher orders?

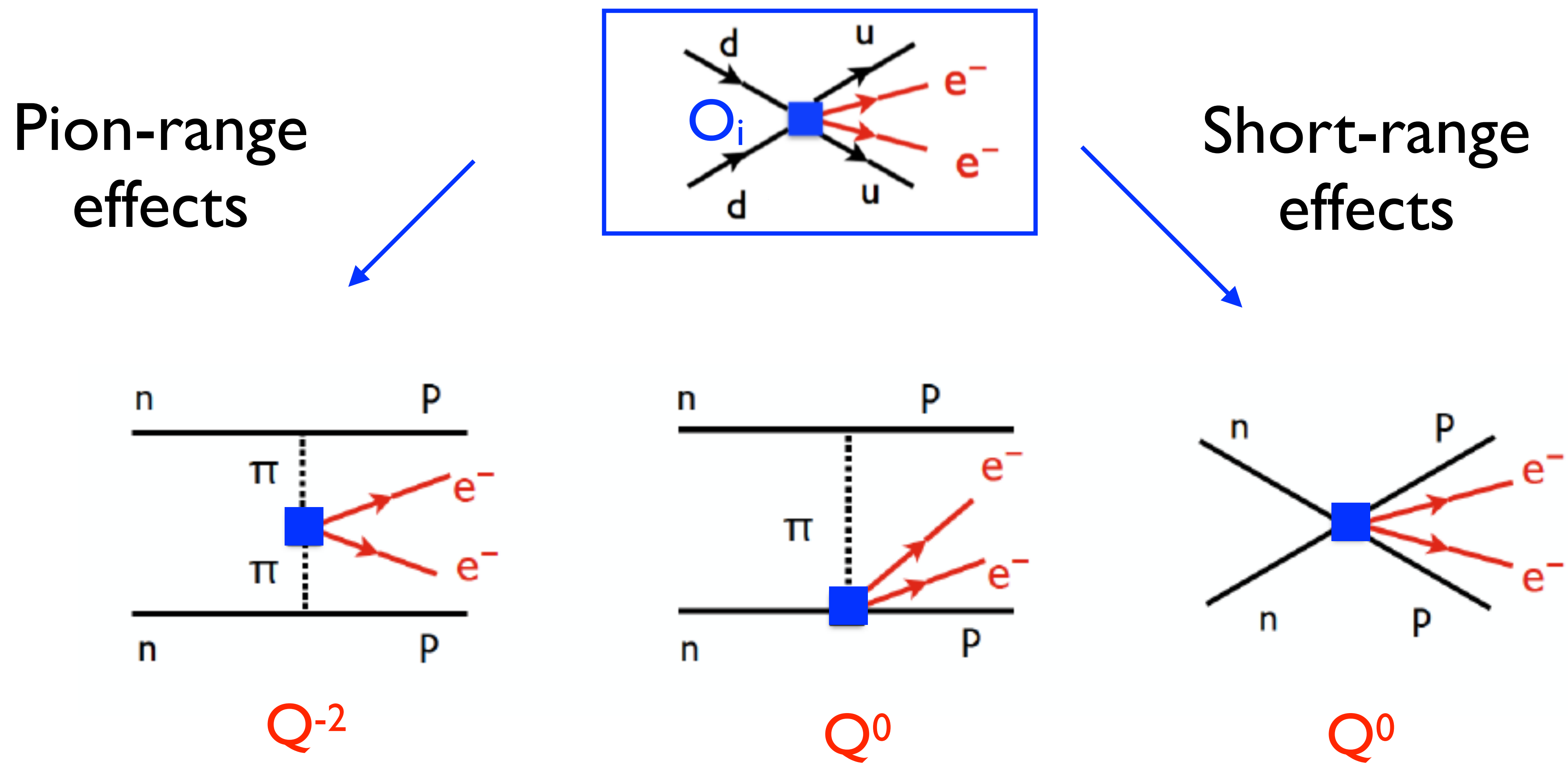
- N2LO
  - πN loops + new contact — VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729
  - 2-body **x** 1-body current (and a new contact) — Wang-Engel-Yao 1805.10276
  - Neglecting contact terms, calculations in light and heavy nuclei find O(10%) corrections: encouraging!

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



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



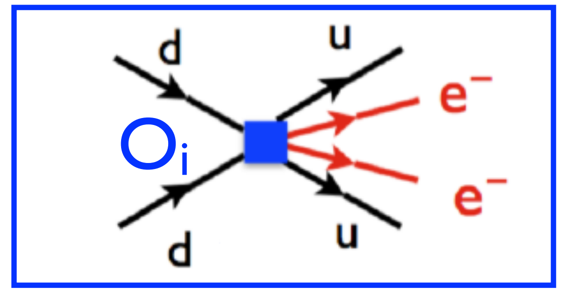
Hadronic realization of dim-9 operators in chiral EFT

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

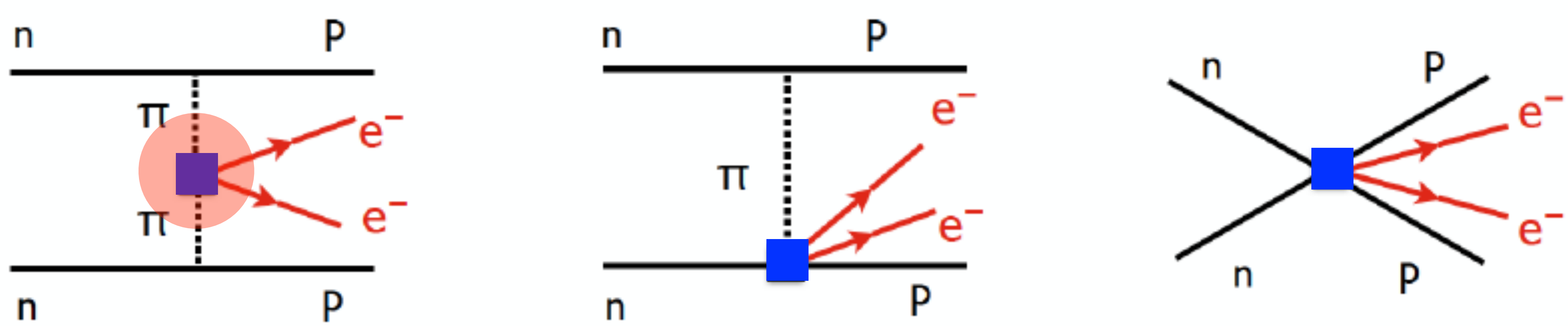
Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

TeV-scale LNV: hadronic theory developments

Pion-range effects

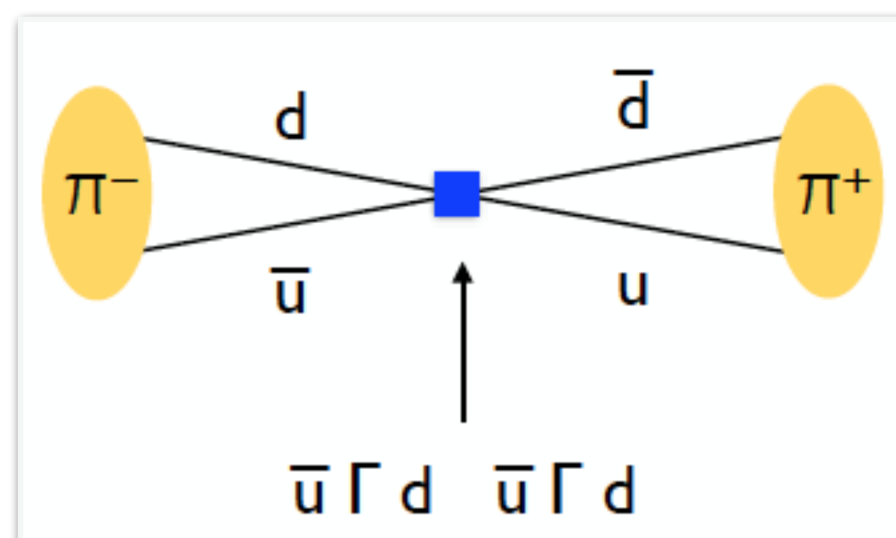


Short-range effects



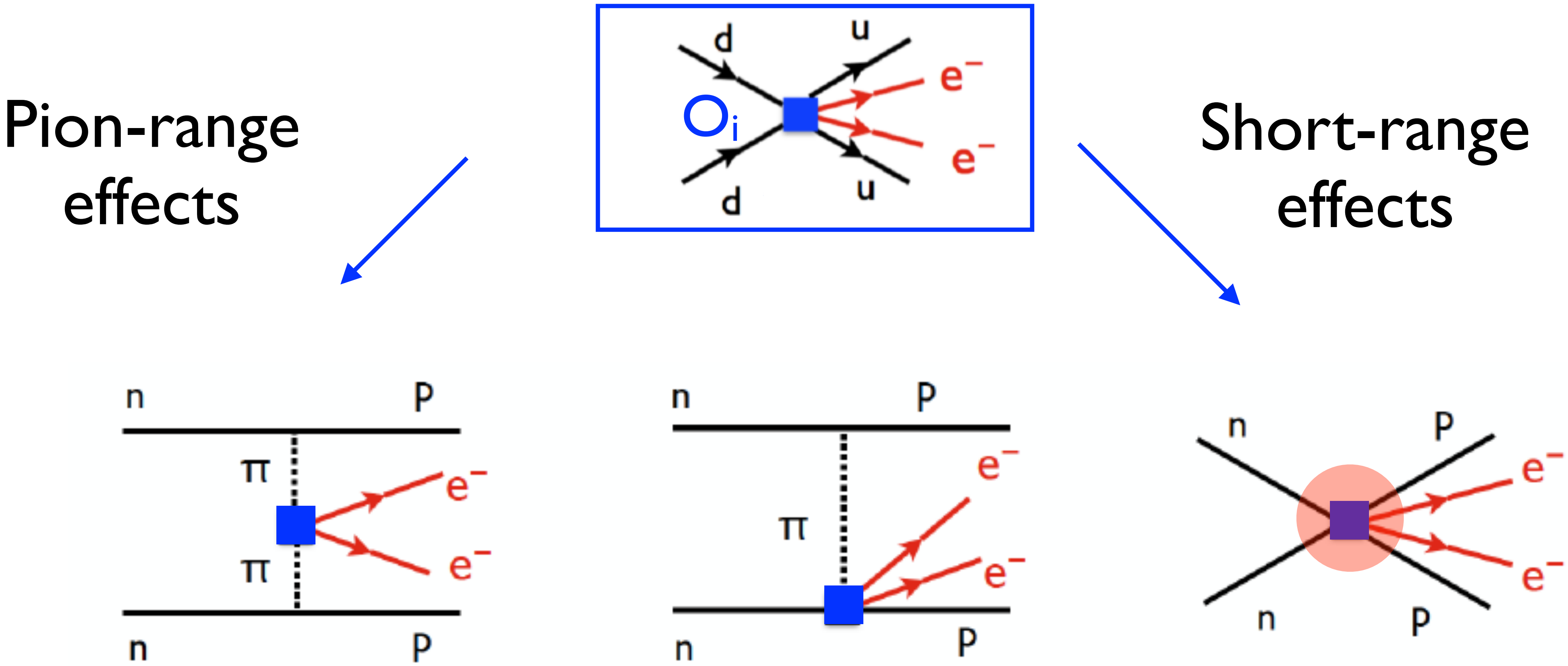
- Two recent developments:

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



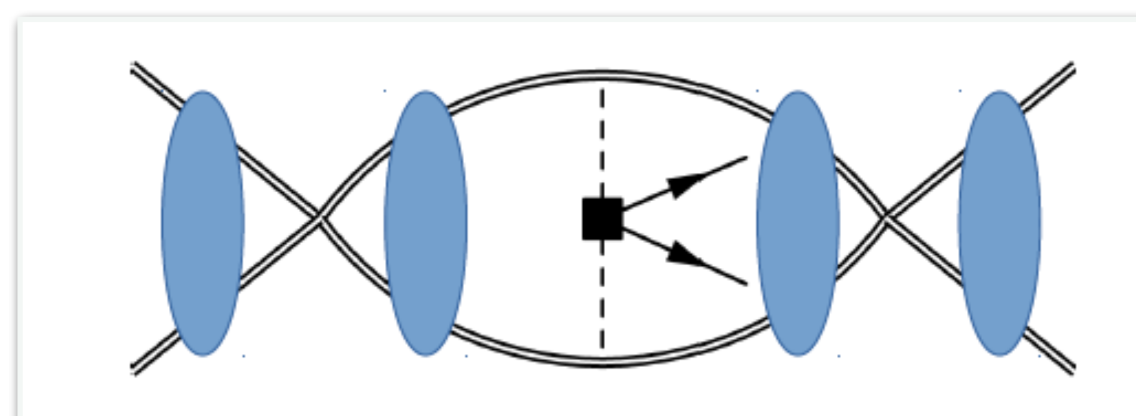
Nicholson et al (CalLat), 1805.02634, PRL

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

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

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

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

Dimension 9 operators

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

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

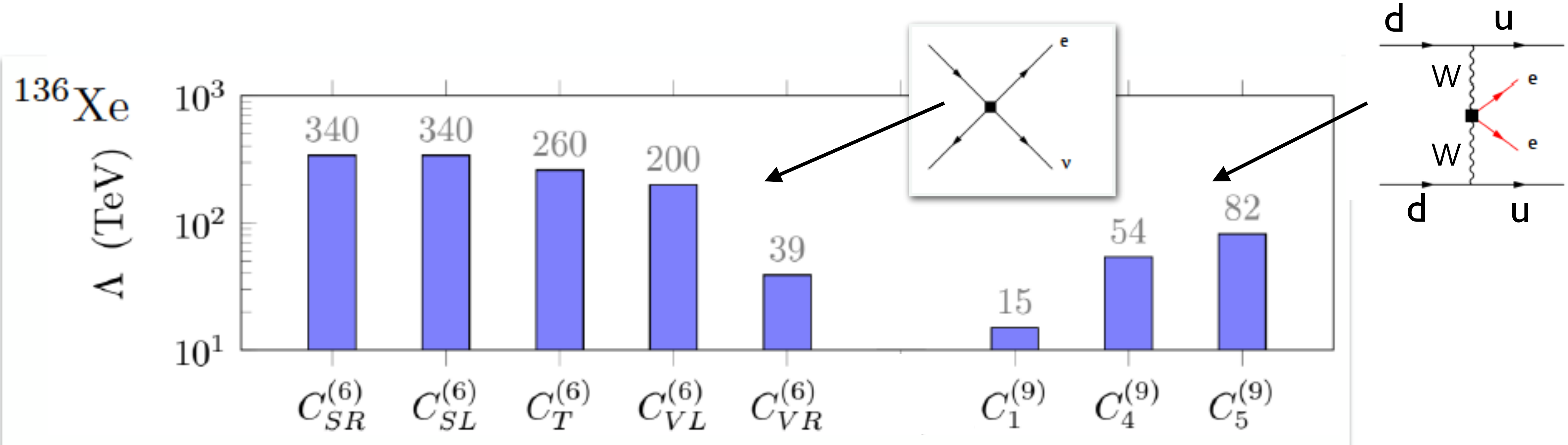
$$\begin{aligned}
O_6^\mu &= (\bar{q}_L \tau^+ \gamma^\mu q_L)(\bar{q}_L \tau^+ q_R)\,, & O_6^{\mu\prime} &= (\bar{q}_R \tau^+ \gamma^\mu q_R)(\bar{q}_R \tau^+ q_L)\,, \\
O_7^\mu &= (\bar{q}_L t^a \tau^+ \gamma^\mu q_L)(\bar{q}_L t^a \tau^+ q_R)\,, & O_7^{\mu\prime} &= (\bar{q}_R t^a \tau^+ \gamma^\mu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

What scales are we probing?

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

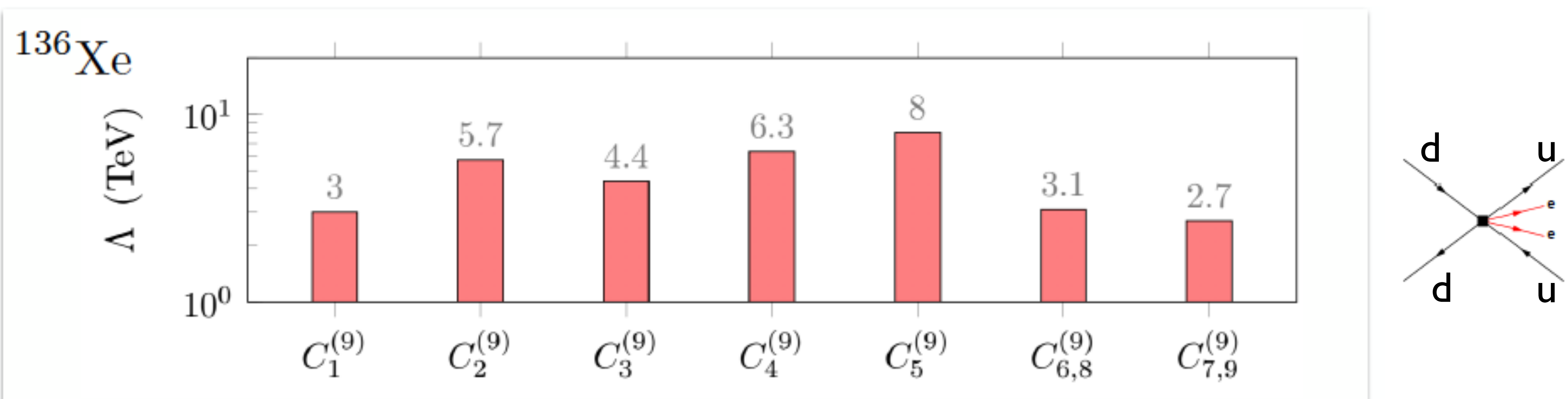
Dim 7 in SM-EFT

$(v/\Lambda)^3$



Dim 9 in SM-EFT

$(v/\Lambda)^5$

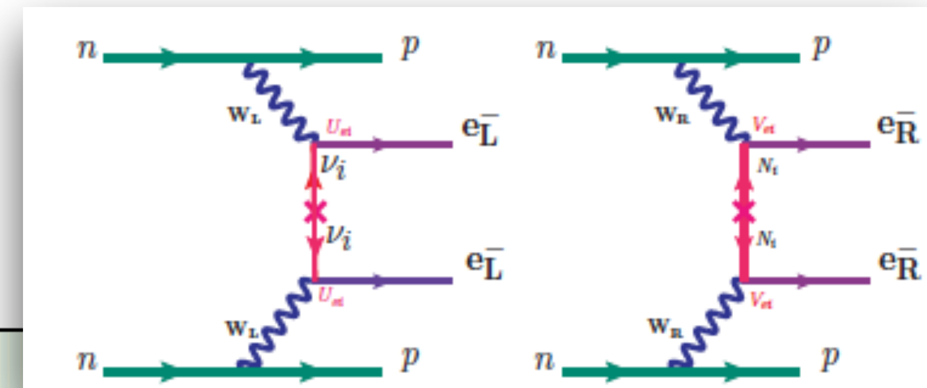


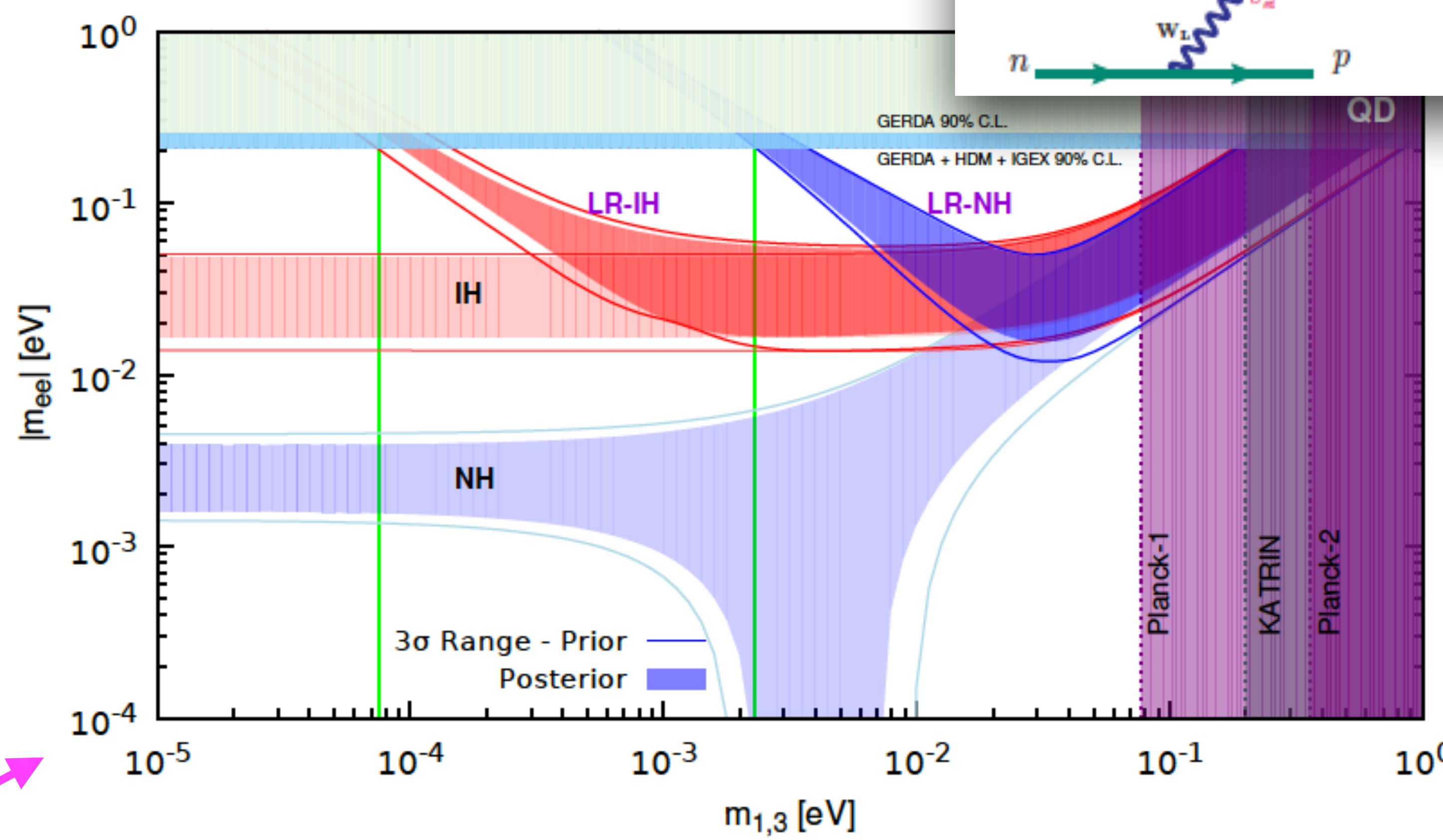
Bounds reflect dependence on Λ_χ / Λ and Q/Λ_χ

Phenomenological interest (1)

- TeV-scale LNV induces contributions to 0νββ *not directly related to the exchange of light neutrinos,* within reach of planned experiments

Example: left-right symmetric model with type-II seesaw





$$M_i \propto m_i$$

$$V_R^{PMNS} = V_L^{PMNS}$$

$$M_i = \frac{m_1}{m_3} M_3, \text{ for NH}$$
$$M_i = \frac{m_1}{m_2} M_2, \text{ for IH.}$$

$M_{2,3}$ = 1 TeV

Tello-Nemevesek-Nesti-Senjanovic-Vissani 1011.3522

Ge-Lindner-Patra 1508.07286

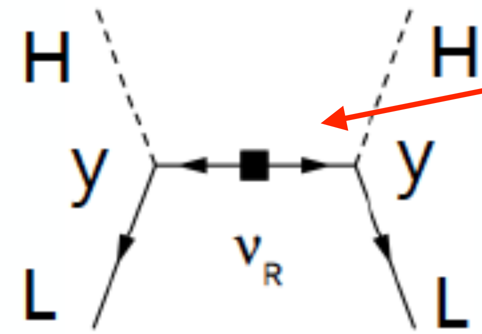
...

Phenomenological interest

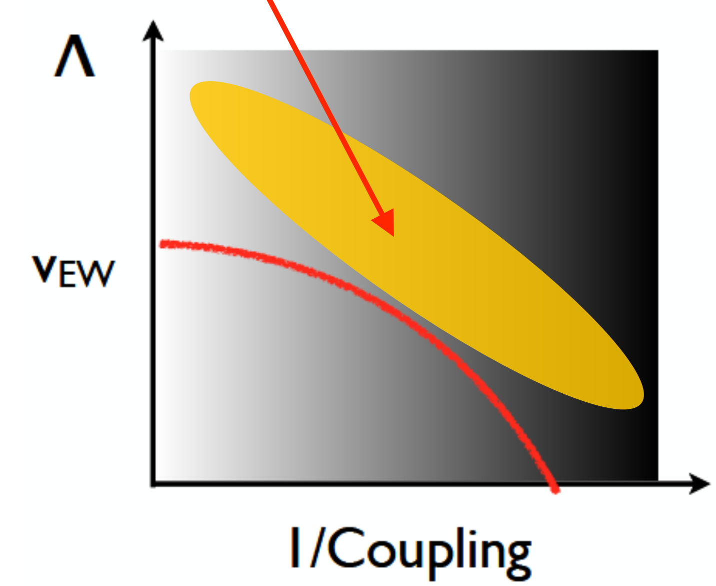
Akhmedov. Rubakov, Smirnov
hep-ph/9803255

Canetti, Drewes, Shaposhnikov
1204.3902

...



Arbitrary scale $M_R \leftrightarrow \Lambda$



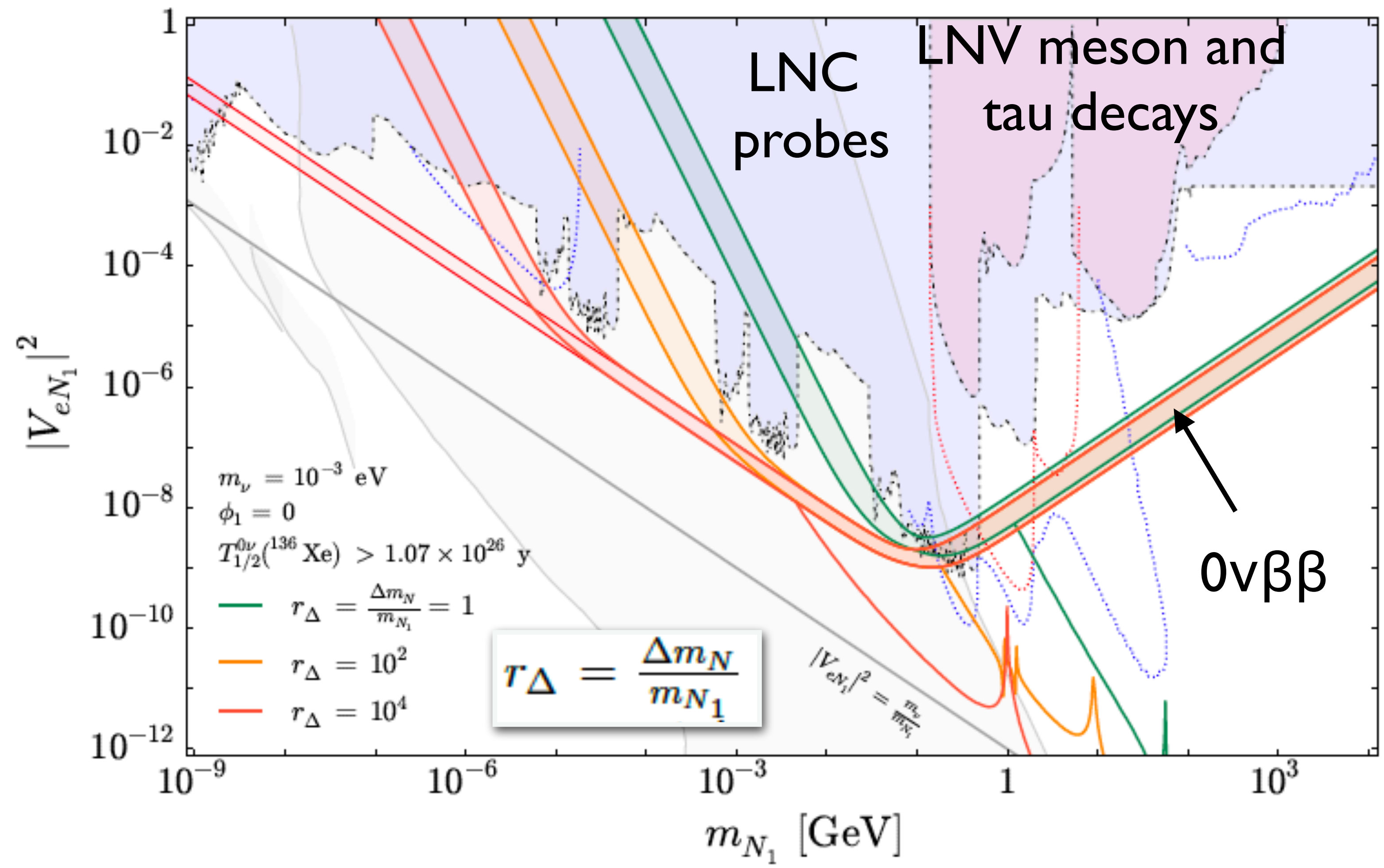
- Attractive class of "minimal" models
  - ν_R can give rise to light neutrino masses
  - ν_R can provide a dark matter candidate
  - ν_R can generate the baryon asymmetry through leptogenesis
- In general $m_{\beta\beta} \neq (m_{\beta\beta})_{active}$, with strong dependence on ν_R spectrum
- Can be probed at colliders, beam dump, semileptonic decays, EWPO, ...

See e.g. Bolton, Deppisch, Dev 1912.03058

Theory developments and challenges

- Rich literature on 0νββ versus other probes of sterile ν_R's in various mass ranges

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



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

$K^+ \to \pi^- \ell_1^+ \ell_2^+$	$B^+ \to h^- \ell_1^+ \ell_2^+$	$\tau^- \to \ell^+ h_1^- h_2^-$
$\ell_{1,2} = e, \mu$	$h = \pi, K \quad \ell_{1,2} = e, \mu$	$\ell = e, \mu \quad h_{1,2} = \pi, K$
$\mathrm{BRs} < \#10^{-10}$	$\mathrm{BR}\ (\pi^- \mu^+ \mu^+) < \#10^{-9}$	$\mathrm{BRs} < \#10^{-8}$

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

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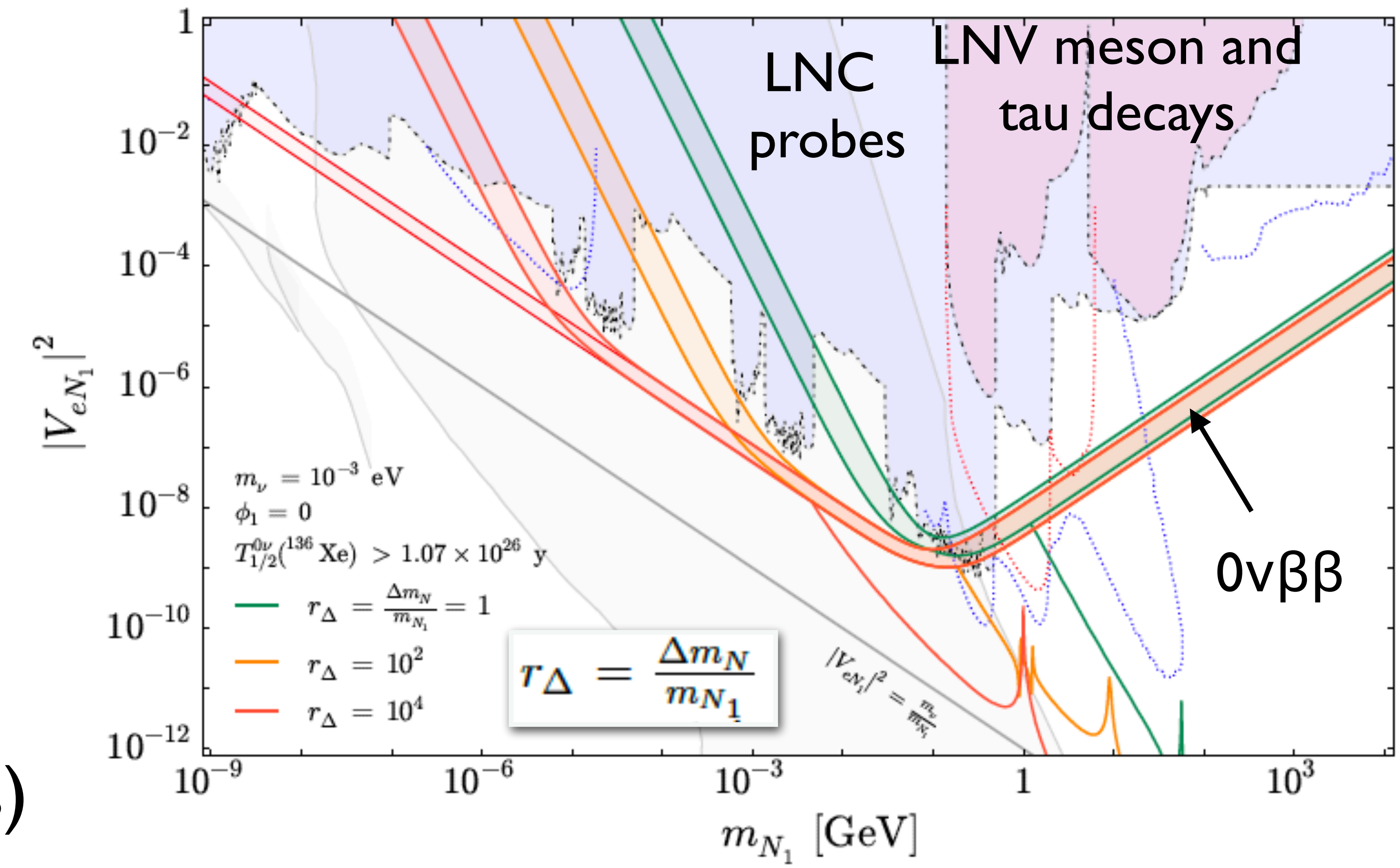

- Beyond pure see-saw (ν_R's interaction beyond Yukawas)

Dekens et al. 2002.07182
...

- Challenges from hadronic and nuclear effects:
  - Refine dependence of matrix elements on ν_R mass spectrum
  - Systematic EFT approach (new LECs, …)

...
deGouvea et al hep-ph/0608147
Faessler et al, 1408.6077
Dekens et al. 2002.07182
...

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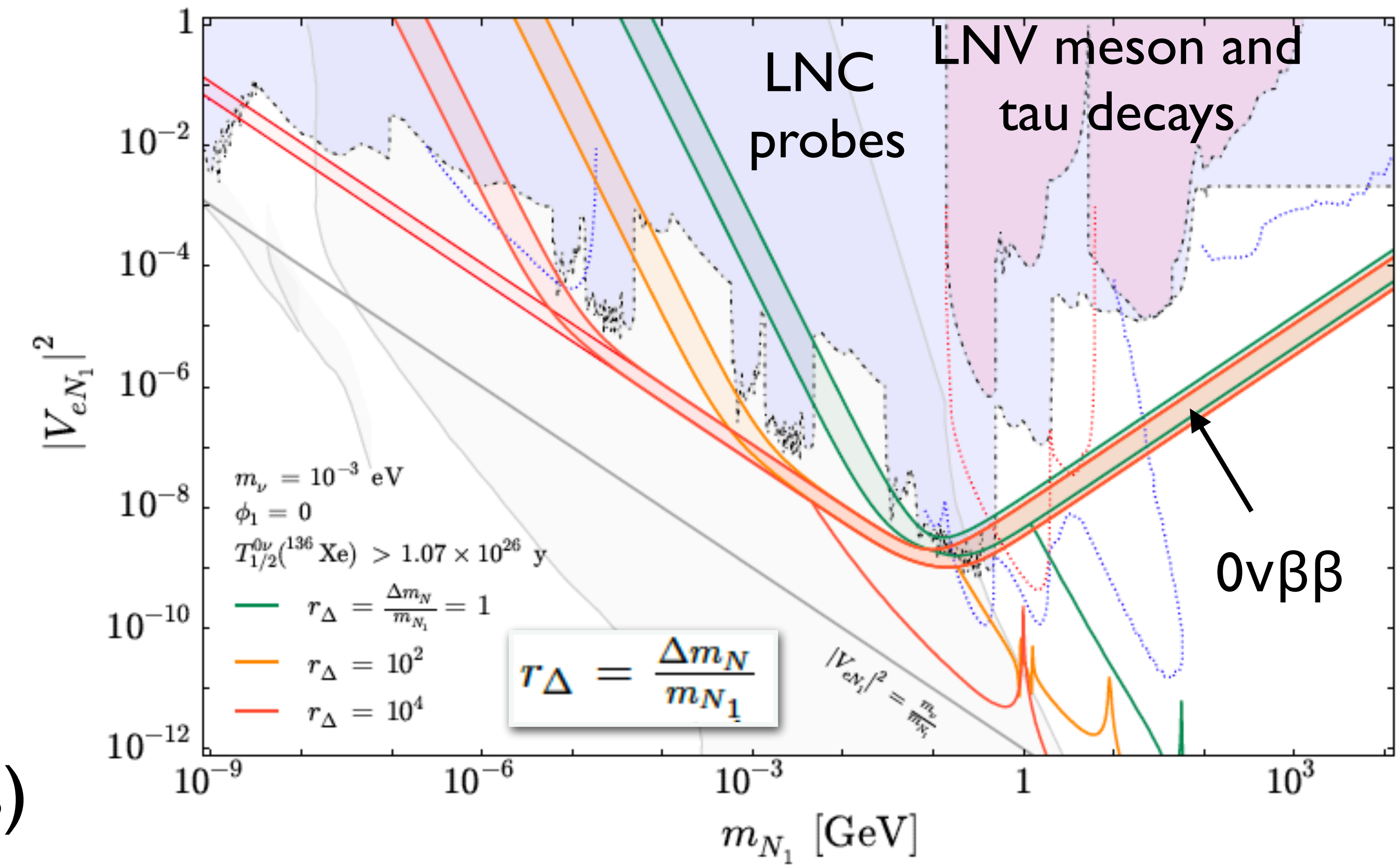

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Dekens et al. 2002.07182
...

See Jordy de Vries' talk on July 8

EFT developments and challenges

- νSMEFT + chiral EFT analysis

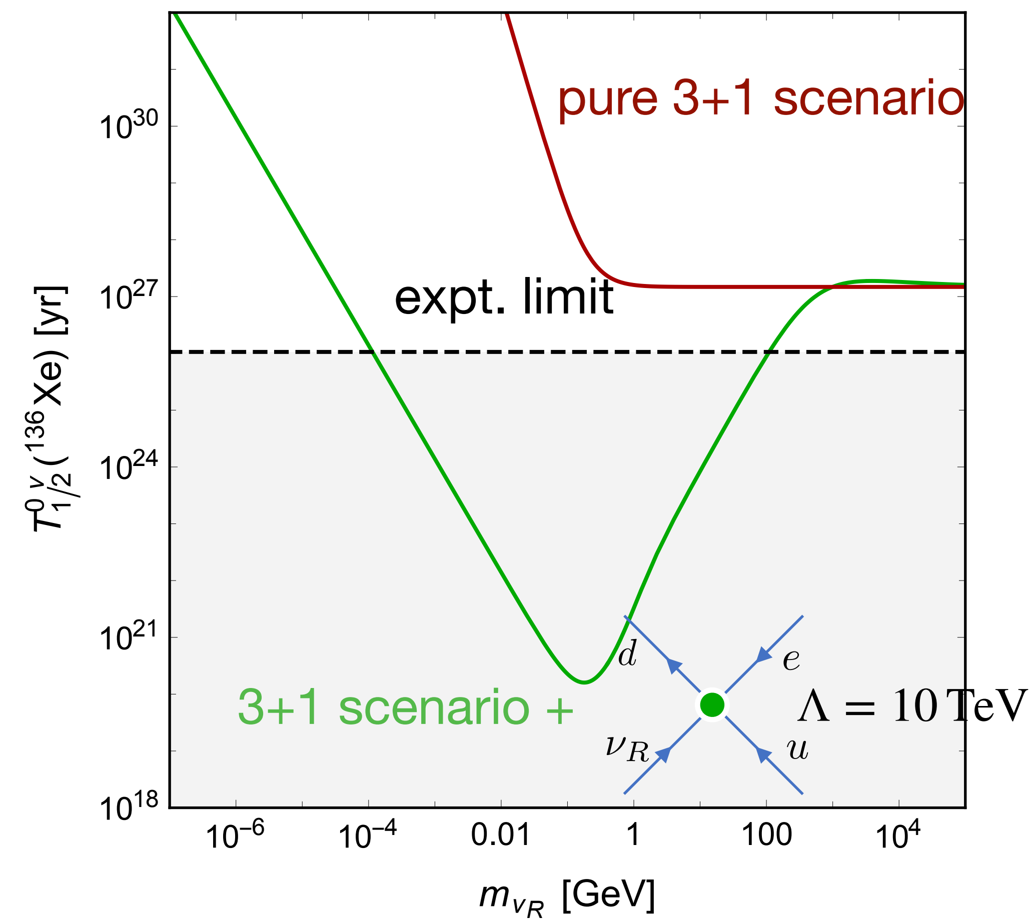
Dekens et al. 2002.07182

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

- ν_R's interaction beyond Yukawa can have large impact

- Challenges:
  - New LECs in hadronic EFT
  - Dependence of m.e. and LECs on ν_R mass

O(100%) uncertainties not shown



Plot courtesy of Wouter Dekens

…
deGouvea et al hep-ph/0608147
Faessler et al, 1408.6077
Dekens et al. 2002.07182
…

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 observable? (single electron spectra, relative angle of outgoing electrons)

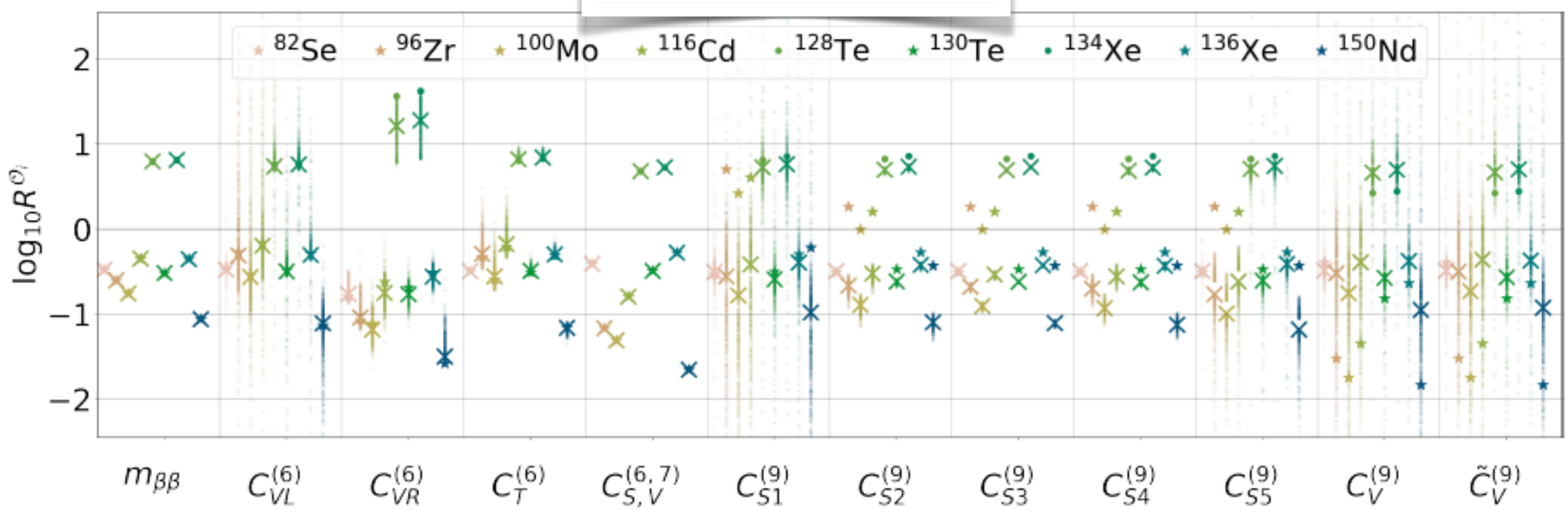
Despite degeneracies, useful diagnosing tools 'within' 0νββ

Isotope dependence

Graf, Lindner, Scholer 2204.10845

- Only 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)

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

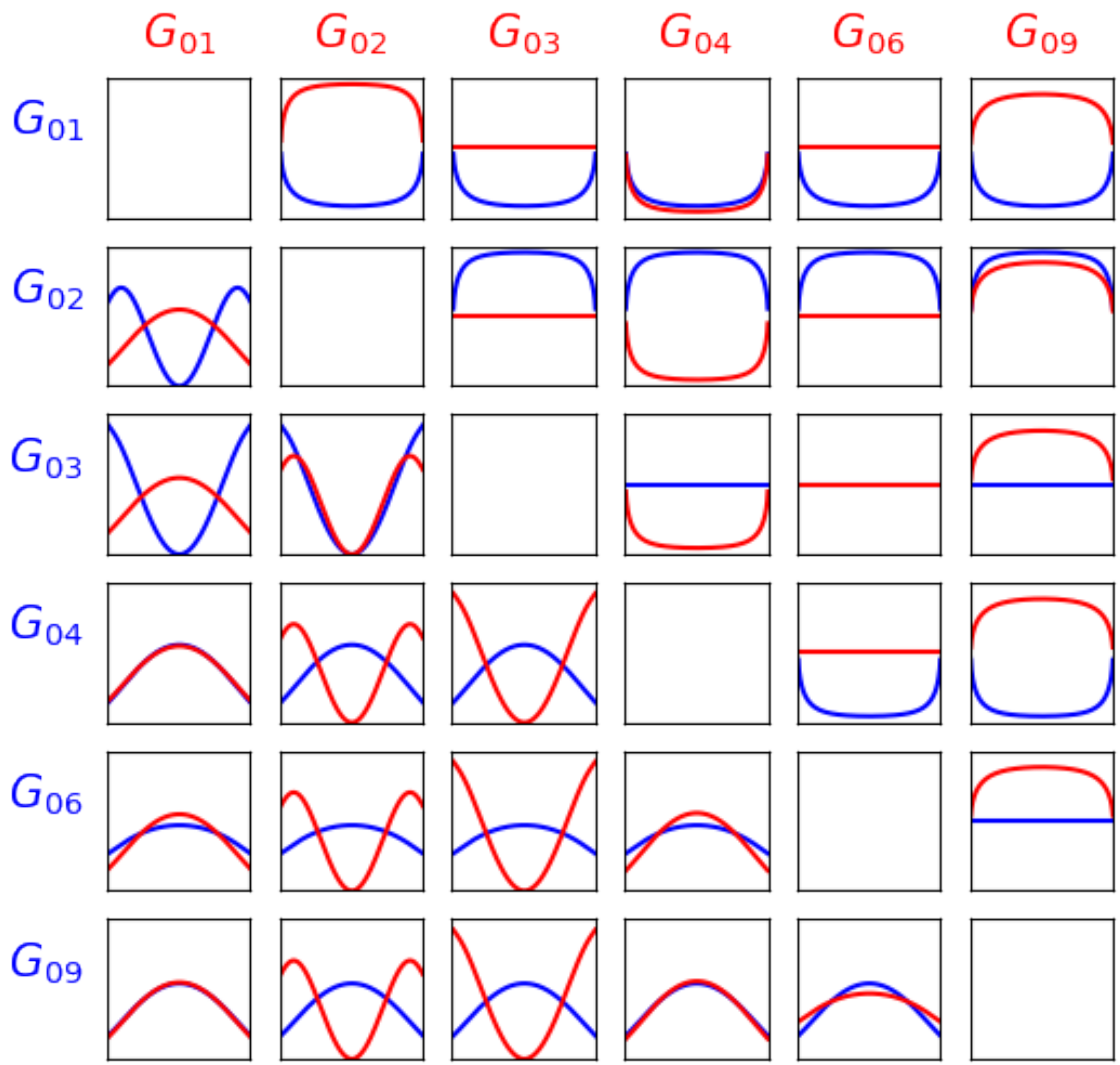


Phase space observables

Graf, Lindner, Scholer 2204.10845

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

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



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

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

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

Phase space observables

Graf, Lindner, Scholer 2204.10845

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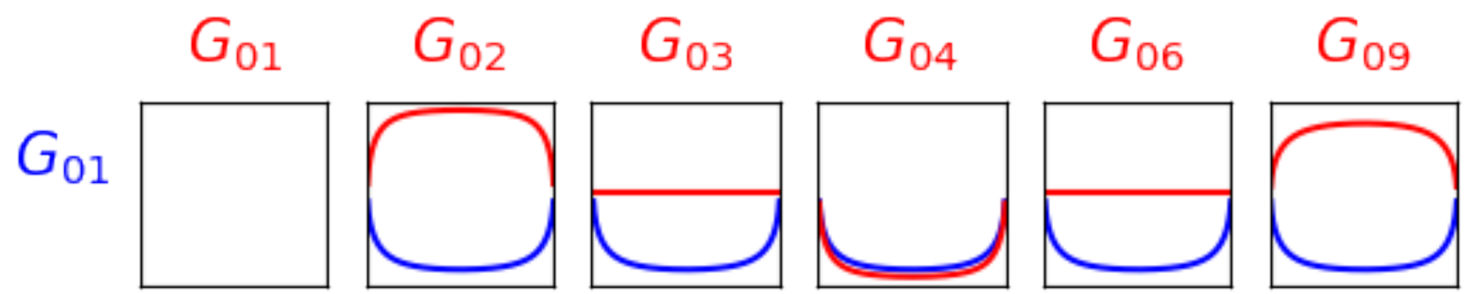
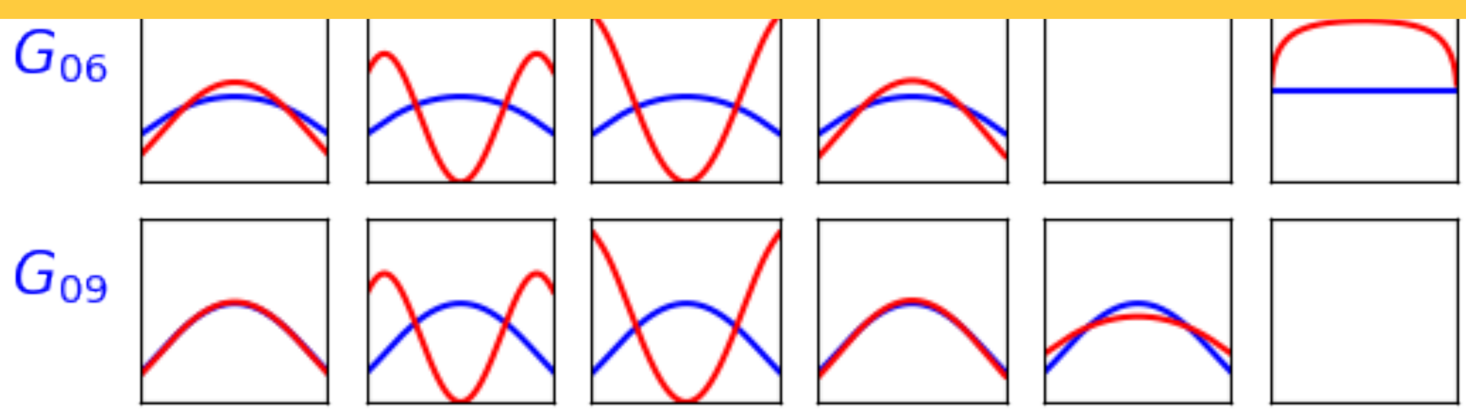


$\propto a_1(\tilde{\varepsilon})$

- Despite degeneracies, useful diagnosing tools 'within' 0νββ
- This analysis reiterates two important points:
  - Need much improved matrix elements, with O(10%) uncertainty
  - Unraveling the mechanism of LNV will also require other probes (cosmology, collider, …)



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

Phenomenological interest (1)

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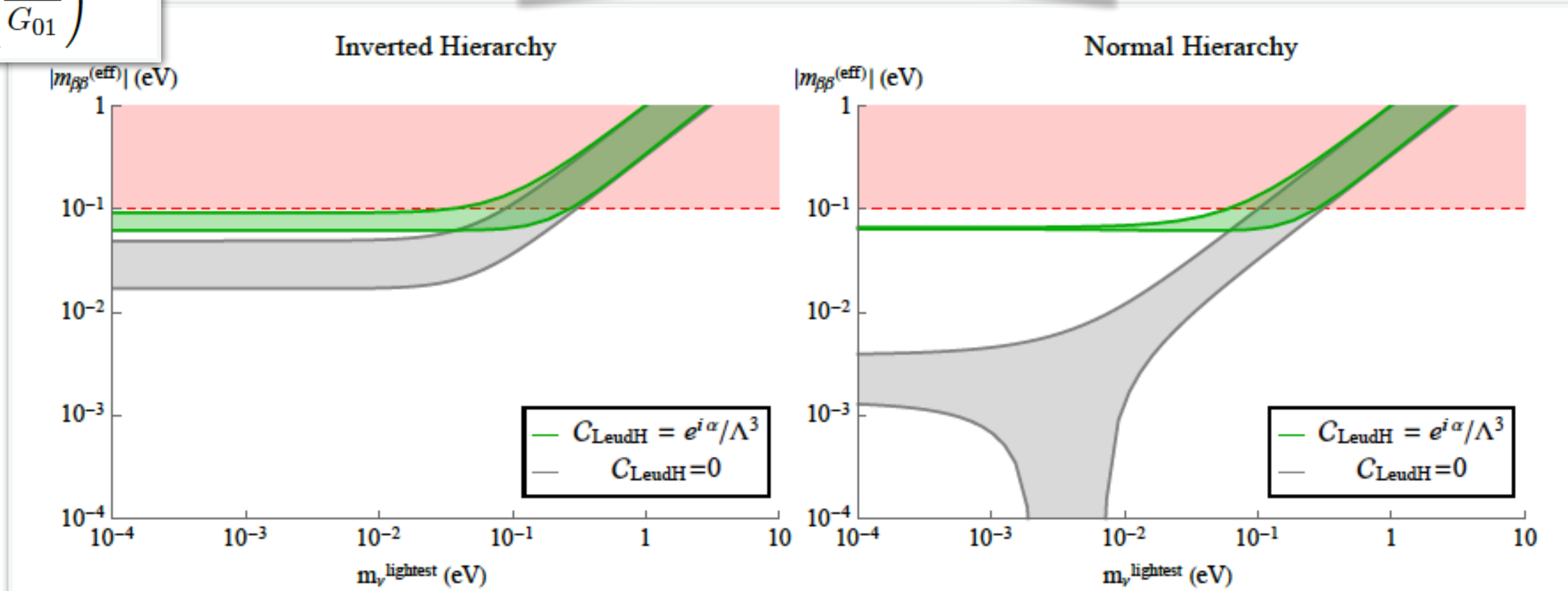
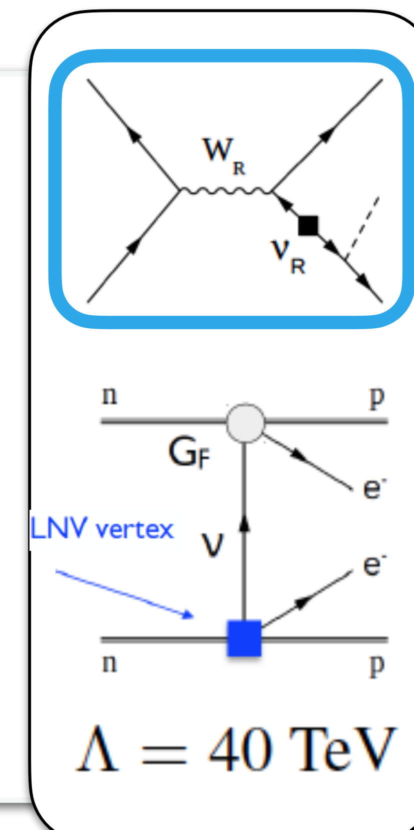
$$C_{LeudH}\, \epsilon_{ij}\, (\bar{d}\gamma^{\mu} u)\, (L_m^T C \gamma_{\mu} e)\, H_j$$

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





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

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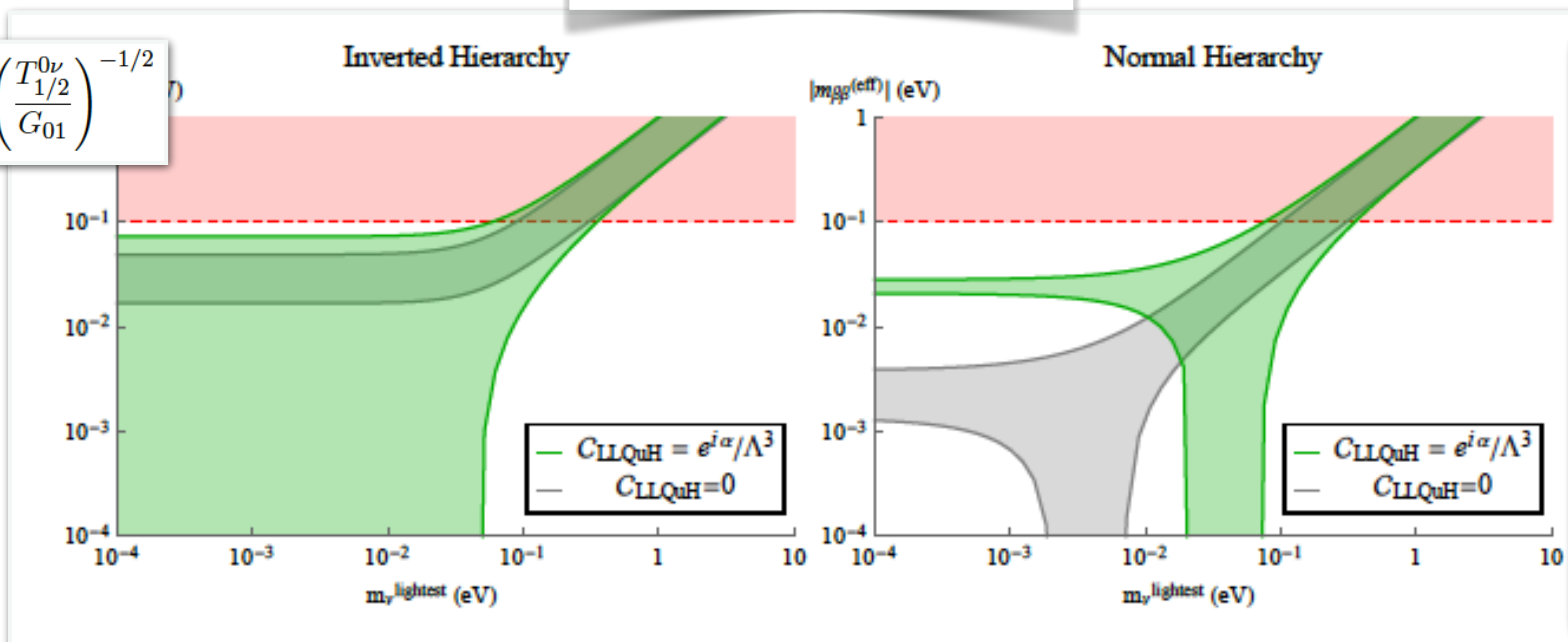
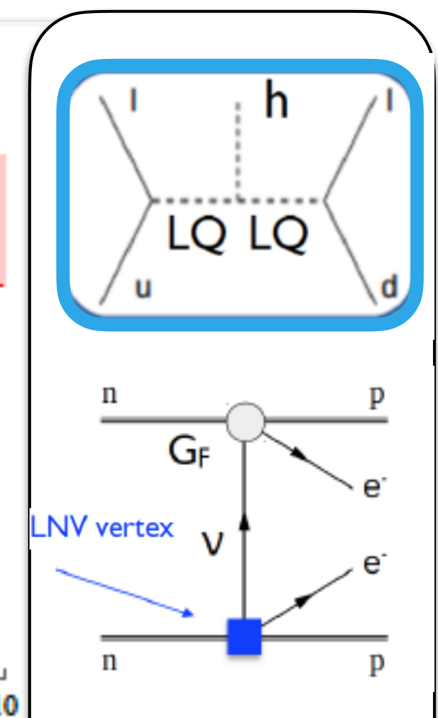
$$\mathcal{C}_{LL\bar{Q}uH}\, \epsilon_{ij}\, (\bar{Q}_m u)\, (L_m^T C L_i)\, H_j$$

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





$\Lambda = 600$ TeV

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