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Theoretical aspects of fundamental symmetries and conservation laws

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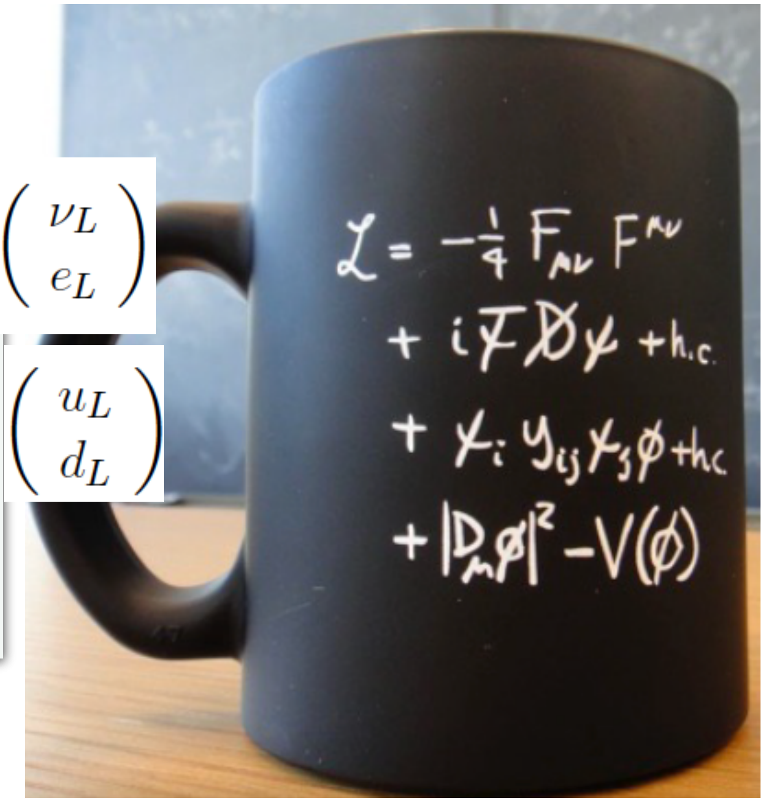
Outline

- Global and discrete symmetries in the Standard Model and beyond
    - High-level overview of expt. probes and their merits
- Lepton Number Violation and neutrinoless double beta decay
    - Recent theoretical developments & impact on phenomenology
- Conclusions & Outlook

The fate of symmetries in the SM

- Global symmetries:
  - U(3)^5 symmetry of the fermion's gauge-kinetic term is broken by Yukawa couplings $Y_{e,u,d}$: origin of flavor

$$\psi_i = \begin{pmatrix} \ell_L \\ e_R \\ q_L \\ u_R \\ d_R \end{pmatrix}_i \quad i=1,2,3 \qquad \ell_L \rightarrow \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad q_L \rightarrow \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$



- When the dust settles, baryon number (B) and individual lepton family numbers ($L_{\alpha=e,\mu,\tau}$) survive as "accidental" symmetries

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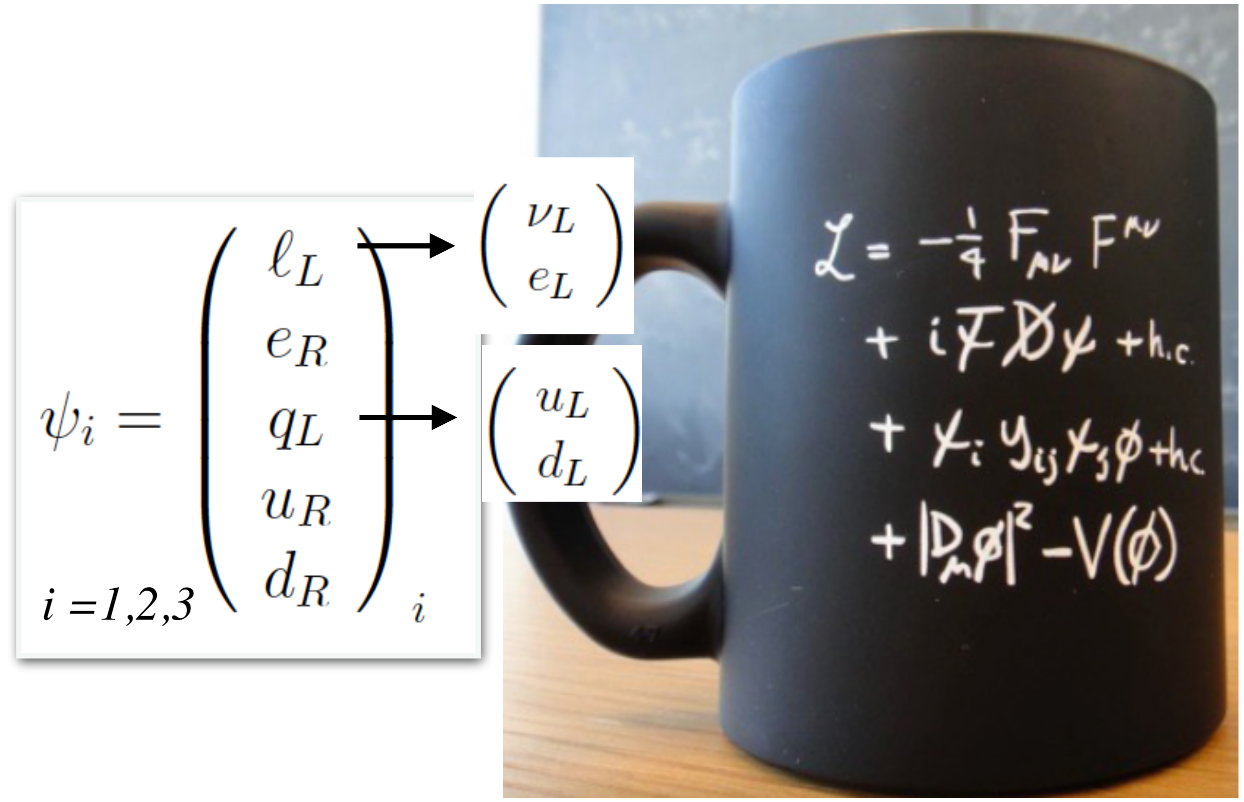
  - $U(3)^5$ symmetry of the fermion's gauge-kinetic term is broken by Yukawa couplings $Y_{e,u,d}$: origin of flavor

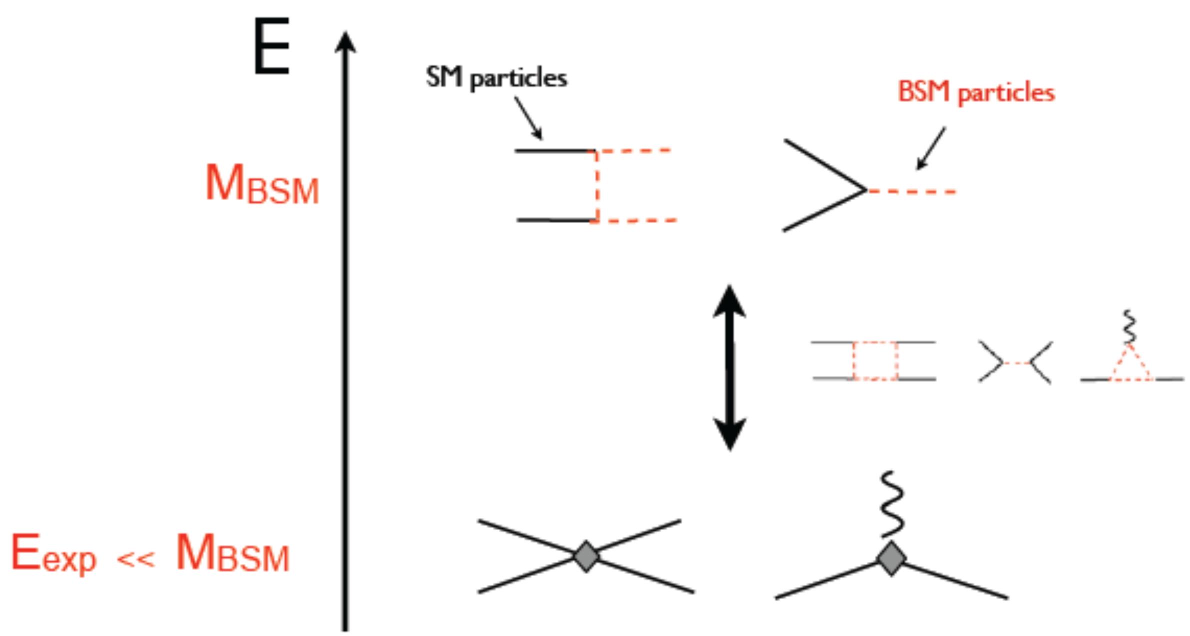


  - When the dust settles, baryon number (B) and individual lepton family numbers ($L_{\alpha=e,\mu,\tau}$) survive as "accidental" symmetries

- Discrete symmetries:
  - P, C maximally violated by weak interactions
  - CP (T) violated by V_{CKM} ($\leftarrow$Yukawa + $SU(2)_W$) and QCD θ-term $\Rightarrow$ specific pattern of CPV in flavor sector and EDMs

Symmetry violation and new physics

- The SM accidental (B, $L_{e,\mu,\tau}$) and approximate (CP) symmetries are not necessarily preserved by new physics



[$\Lambda \leftrightarrow M_{BSM}$]

Weinberg 1979   Wilczek-Zee1979   Buchmuller-Wyler 1986 ....

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

ΔL=2   ΔB=1, LFV, CPV

$$L_\alpha^T C \epsilon H \; H^T \epsilon L_{\alpha'}$$

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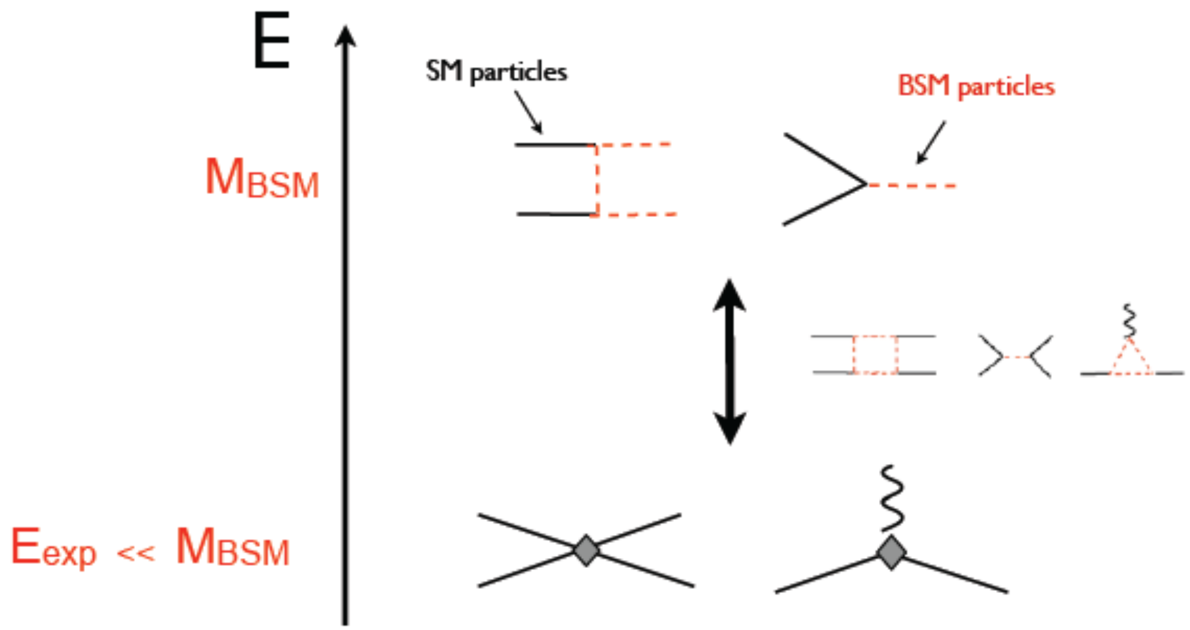

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- B, $L \equiv L_e+L_\mu+L_\tau$, $L_{e,\mu,\tau}$, CP can be probed across many energy scales

Low-E

Proton decay, n-nbar oscillations, $0\nu\beta\beta$, $\mu \to eX$, $\tau \to \mu X$, $\tau \to eX$, ν oscillations, meson decays, EDMs, ...

$pp \to eejj$, $pp \to e_a \bar{e}_b X$, $h \to \tau\mu$, ...
$ep \to \tau X$, $\mu p \to \tau X$ ...
Jet angular distribution in $pp \to hjj$, ...

High-E

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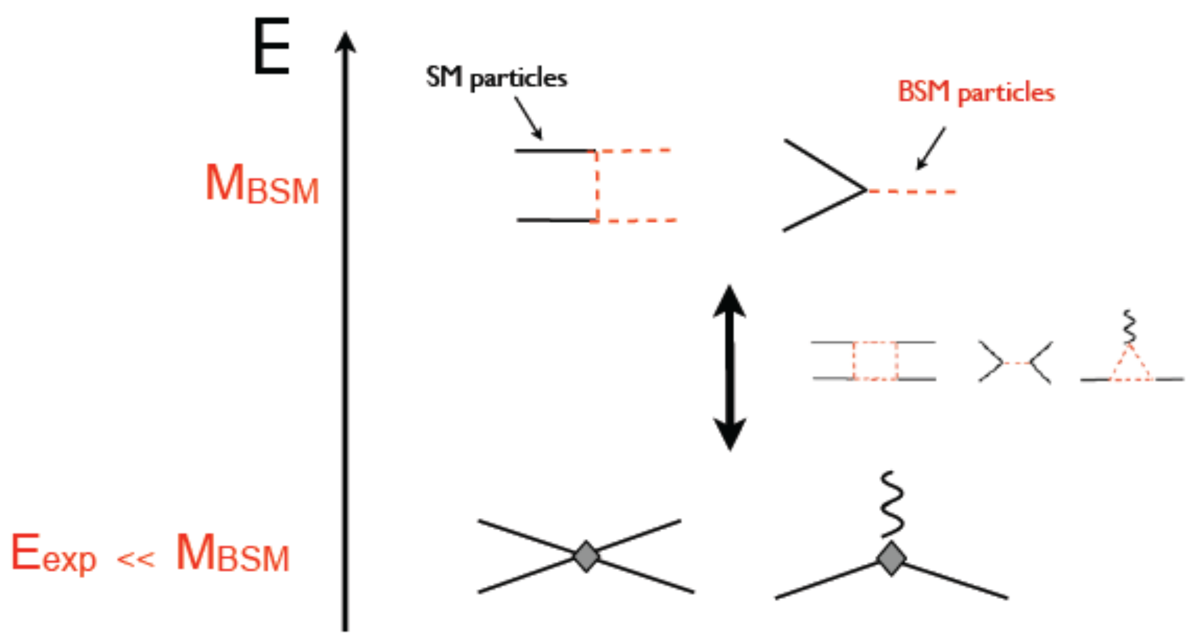

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- Generally, the strongest sensitivity comes from low-E, but if BSM scale is not too high collider observables can be competitive
- Vibrant low-E experimental program Talks by K. Kirch and T. Lasserre

Physics reach

- Merits of observables that violate B, L, $L_{e,\mu,\tau}$, CP:
  - Essentially 'background free' discovery tools

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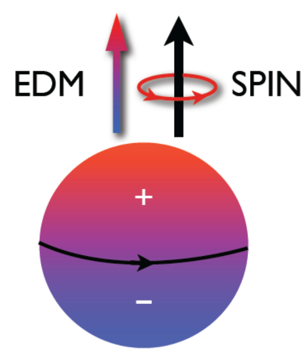
EDMs in $e \cdot cm$

Th0 → e

System	current limit	projected	SM (CKM)
e	$\sim 10^{-29}$	$\sim 5 \times 10^{-30}$	$\sim 10^{-38}$
μ	$\sim 10^{-19}$		$\sim 10^{-35}$
τ	$\sim 10^{-16}$		$\sim 10^{-34}$
n	$\sim 10^{-26}$	10^{-28}	$\sim 10^{-31}$
p	$\sim 10^{-23}$	10^{-29}	$\sim 10^{-31}$
^{199}Hg	$\sim 6 \times 10^{-30}$	10^{-30}	$\sim 10^{-33}$
^{129}Xe	$\sim 10^{-27}$	10^{-29}	$\sim 10^{-33}$
^{225}Ra	$\sim 10^{-23}$	10^{-26}	$\sim 10^{-33}$
...	...		...



For a recent review: Chupp, Fierlinger, Ramsey-Musolf, Singh, 1710.02504

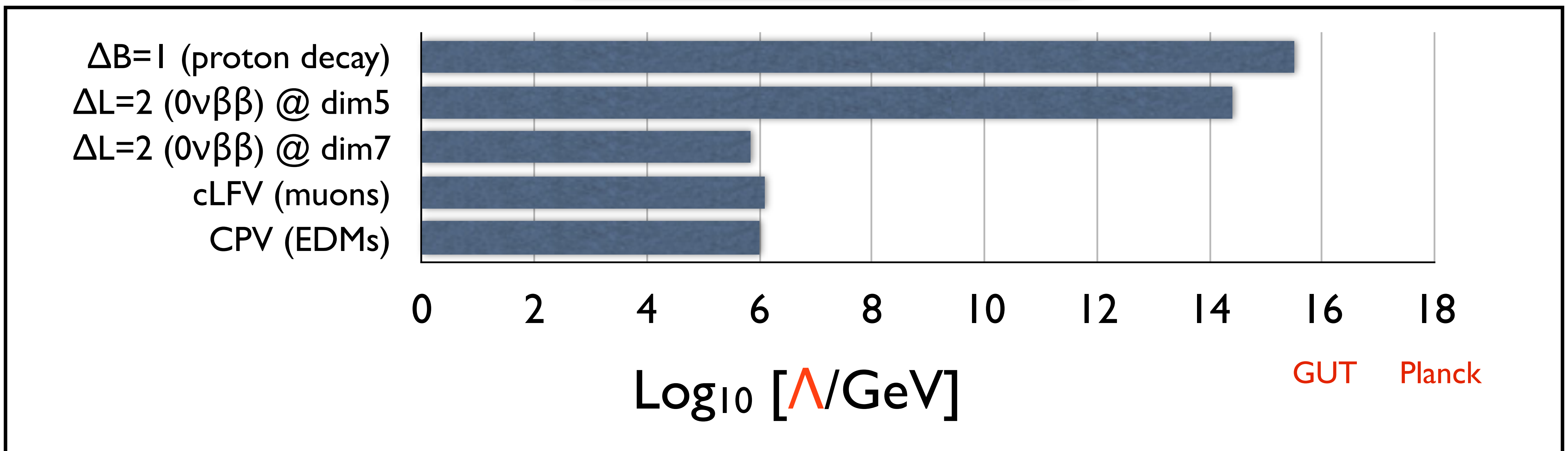
* Observation would signal new physics or a tiny QCD θ-term ($< 10^{-10}$).
Multiple measurements + theoretical input can disentangle the two effects and point to underlying sources of CP violation

Physics reach

- Merits of observables that violate B, L, $L_{e,\mu,\tau}$, CP:
  - Essentially ‘background free’ discovery tools
  - Probe very high scales (conversely, strong constraints on TeV physics)

$\sim (v_{EW}/\Lambda)^n \quad n=2,4,..$

$$\boxed{\delta O_{\rm BSM}(\Lambda) \ \lesssim \ (O_{\rm exp} - O_{\rm SM})}$$



Λ ~ *maximal* scale probed by a given measurement, assuming O(1) couplings (for all probes) and one-loop factor for EDMs and LFV

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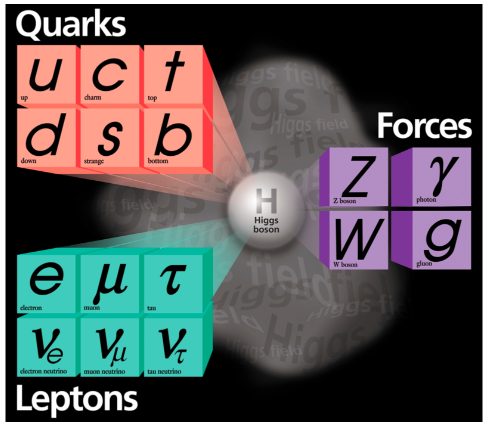
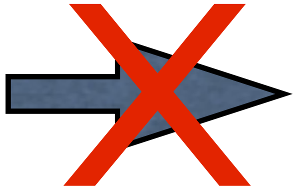
  - Essentially 'background free' discovery tools
  - Probe very high scales (conversely, strong constraints on TeV physics)
  - Can shed light on open questions such as
    - the origin of neutrino mass (L, $L_{e,\mu,\tau}$ violation)
    - the generation of the baryon asymmetry in the universe: B (L) & CP violation required by Sakharov conditions





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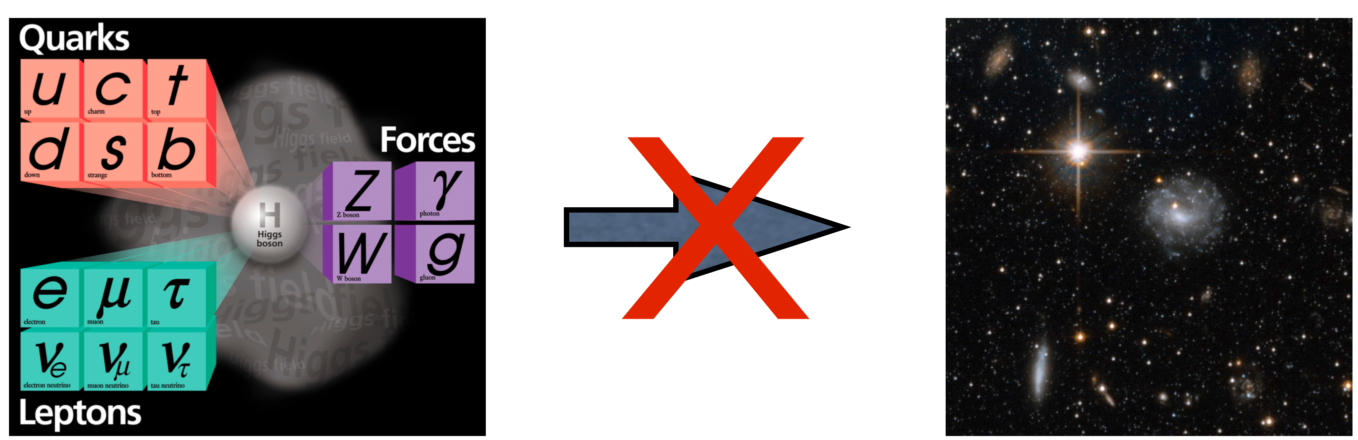


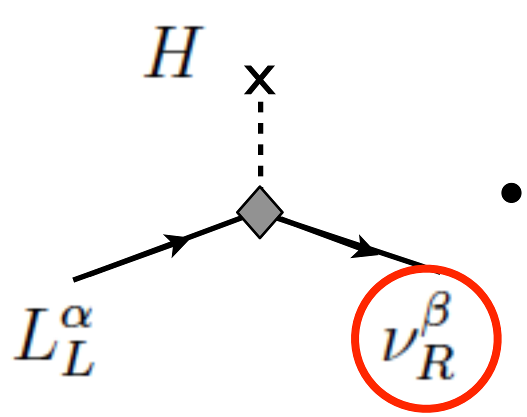
Focus on this for the rest of the talk

Neutrino mass and symmetries

- Lorentz invariance ⇒ two options: Dirac or Majorana
- $SU(2)_W$ invariance ⇒ need new degrees of freedom

Dirac mass:

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



...

- Violates $L_{e,\mu,\tau}$, conserves L

See also talk by P. Hernandez

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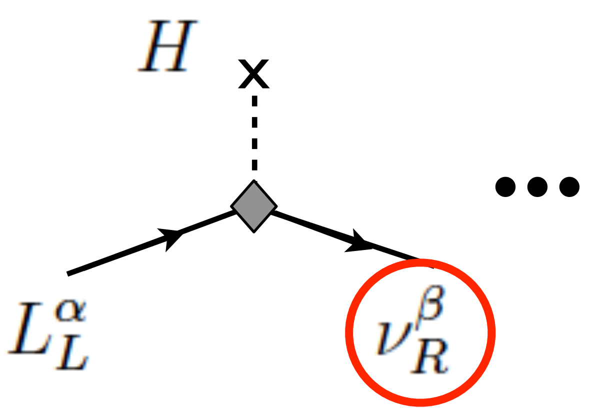
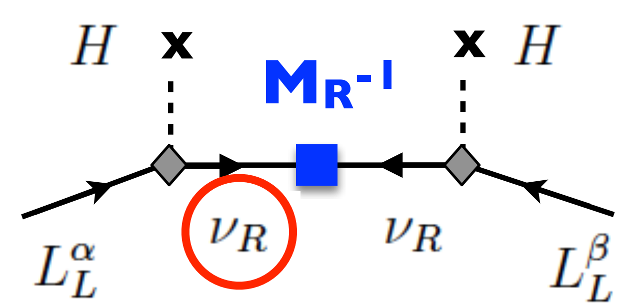
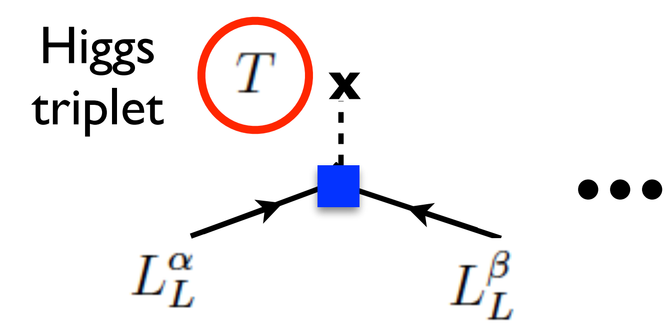


Majorana mass:

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





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

See also talk by P. Hernandez

Neutrino mass and symmetries

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}} + \ldots$$

- Is Lepton Number a good symmetry of the new dynamics?

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

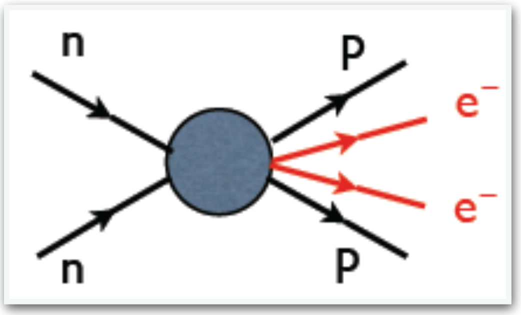
Among *neutrino-less* processes ($K^+ \to \pi^- e^+ e^+$, $pp \to e^+ e^+$ +2 jets ,…, 0νββ), 0νββ is the strongest* probe — "Avogadro's number wins"(P. Vogel)

* For certain models, collider processes and meson decays can be competitive

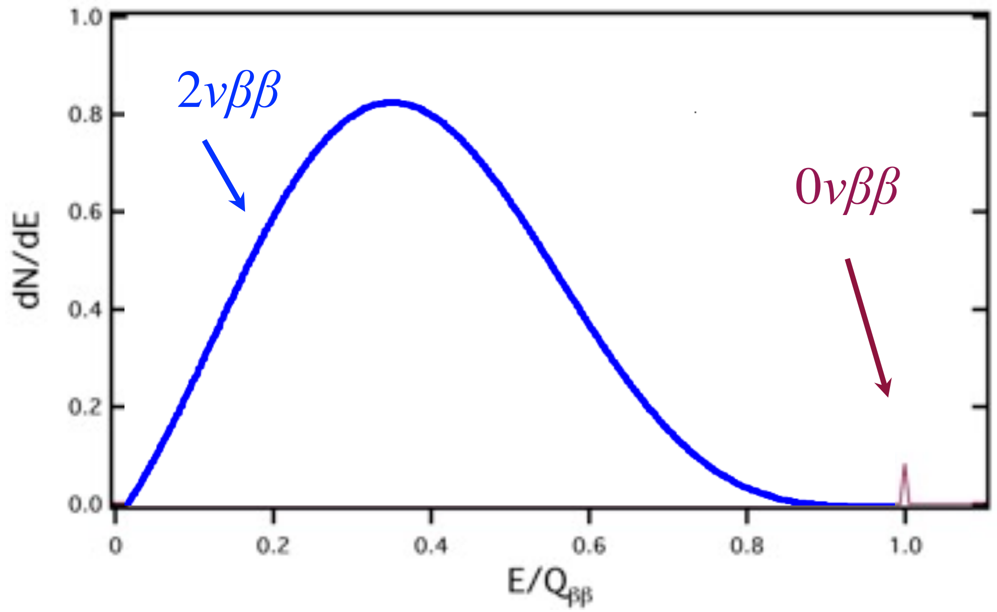
Neutrinoless double beta decay

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

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



ΔL=2



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

See talk by T. Lasserre

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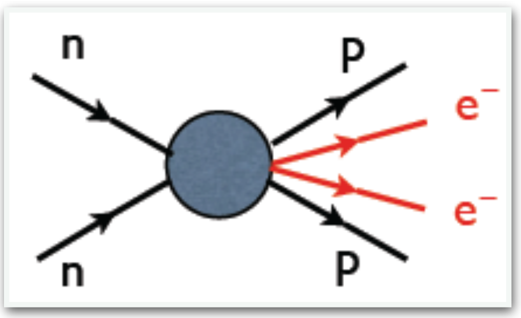

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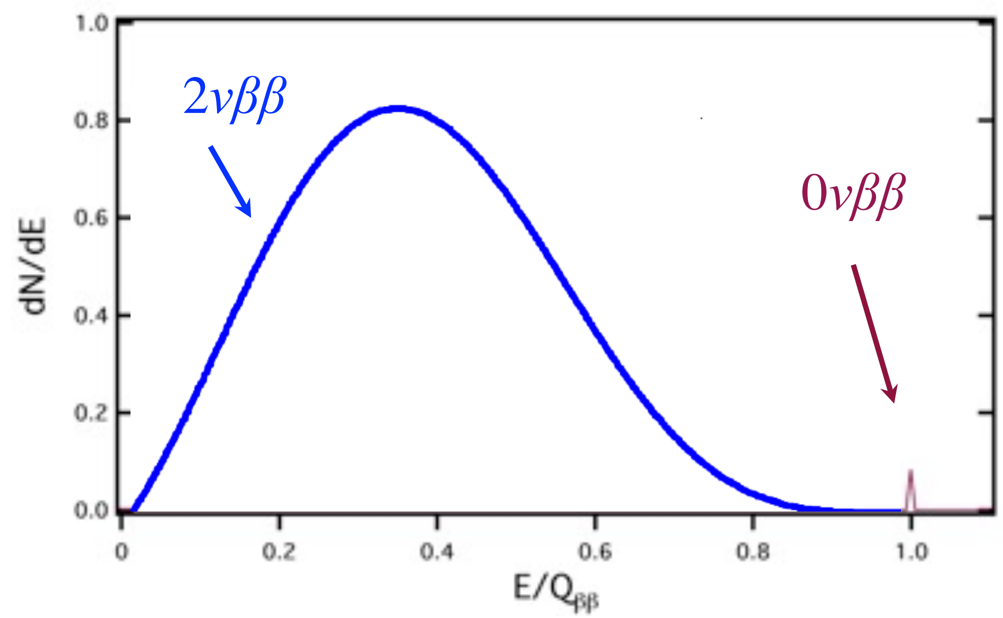

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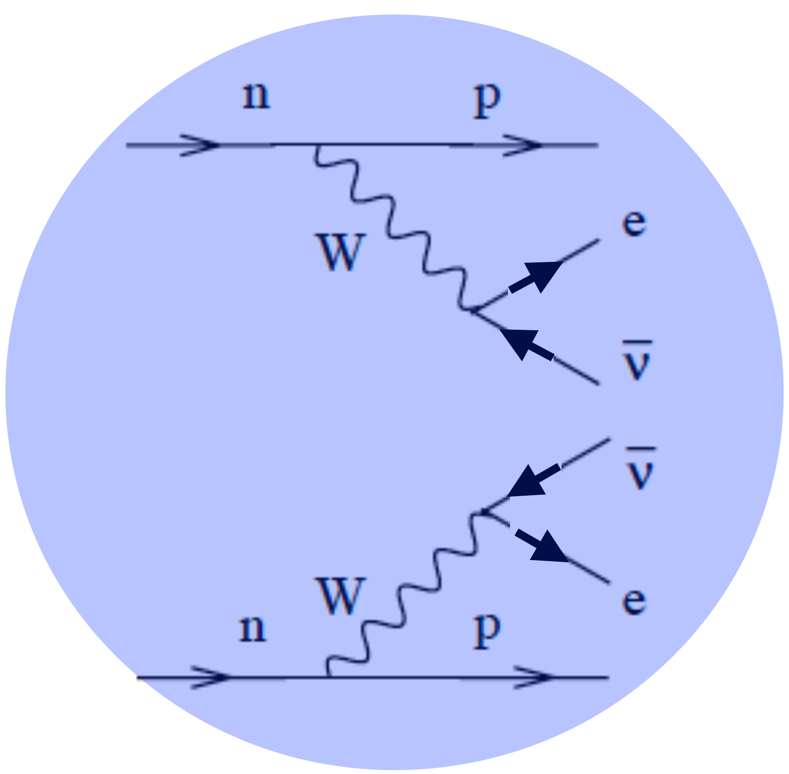
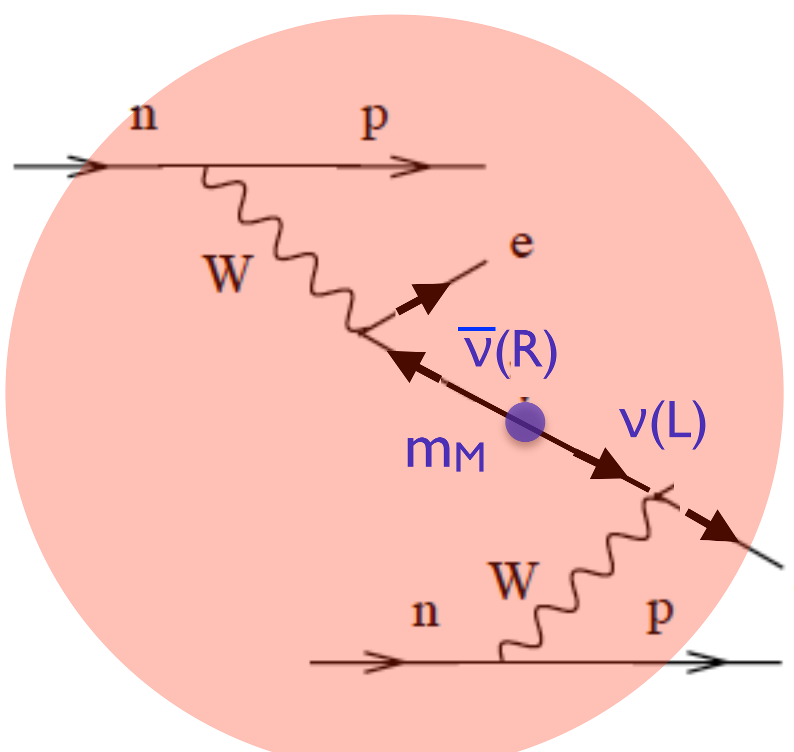


Simplest mechanism:
Majorana mass term

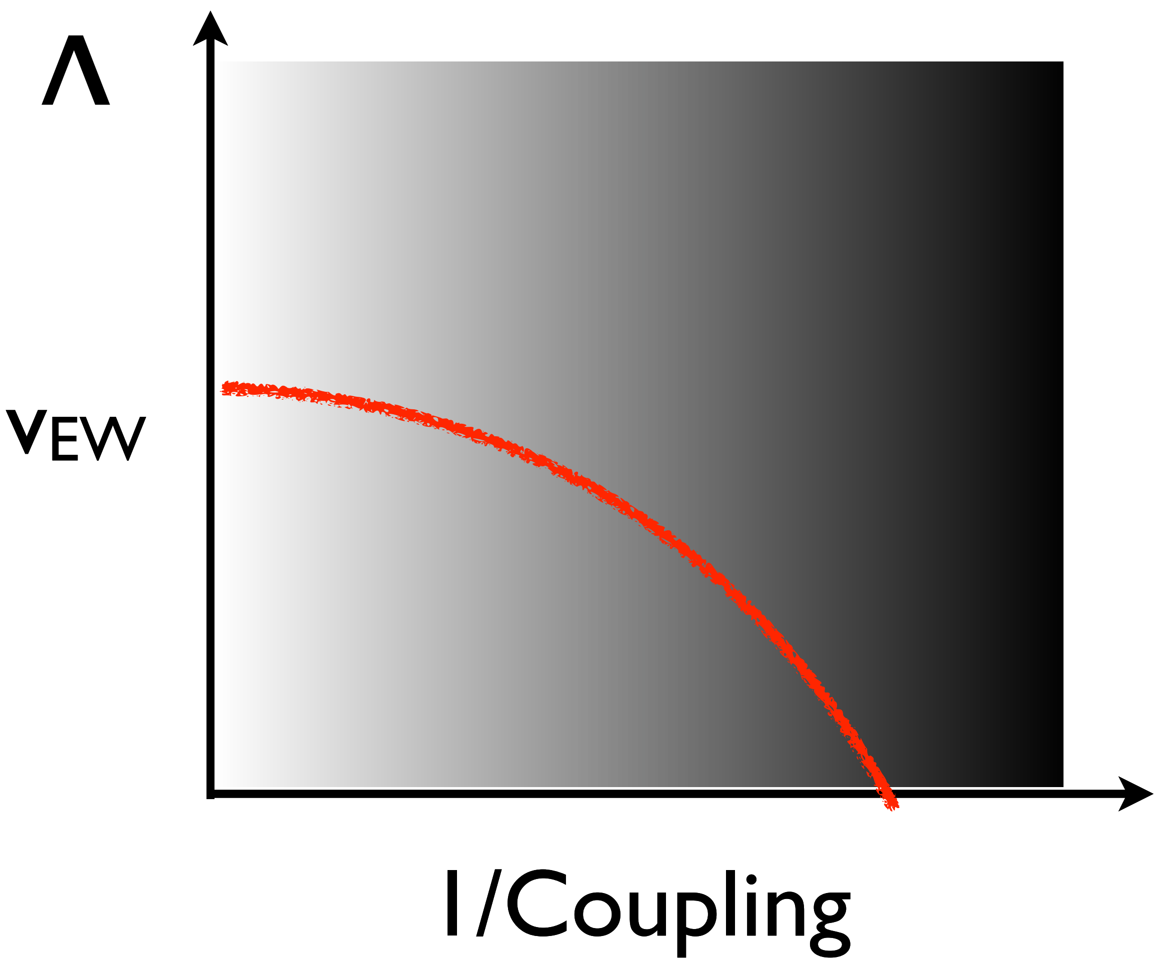
But not the only one…

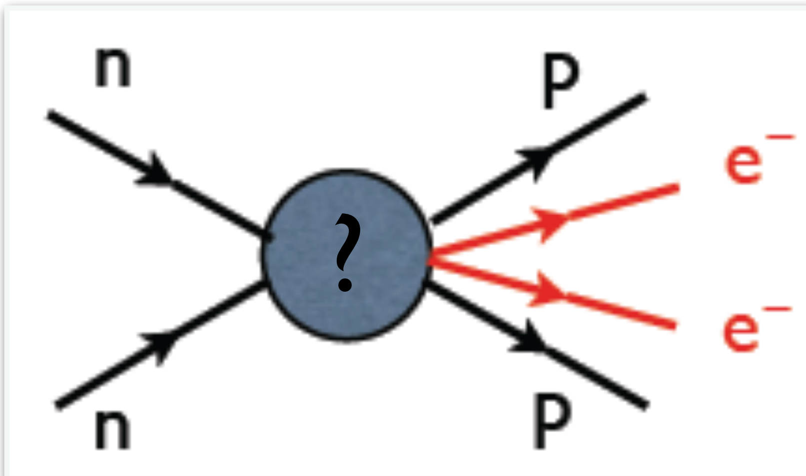


See talk by T. Lasserre

0νββ physics reach

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





See talk by M. Lindner

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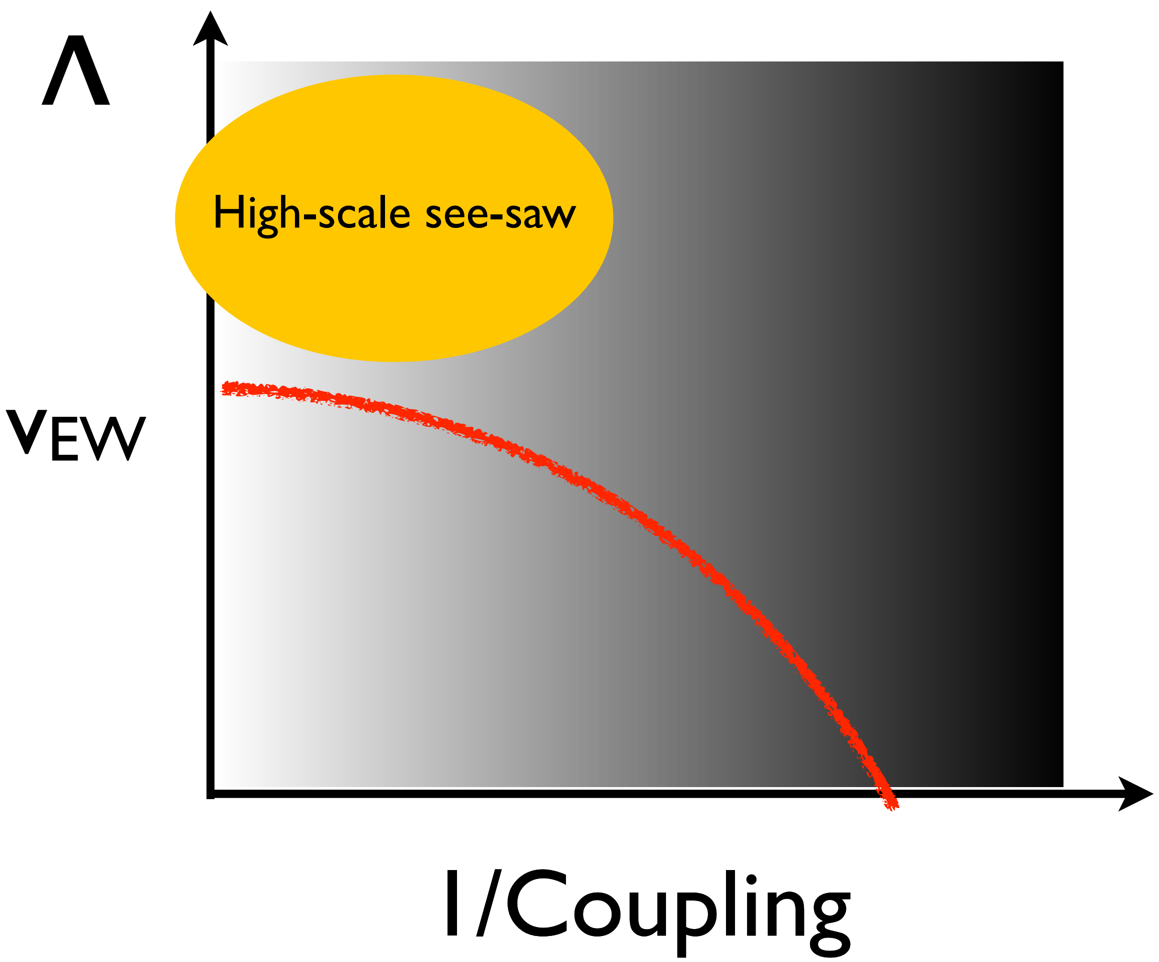
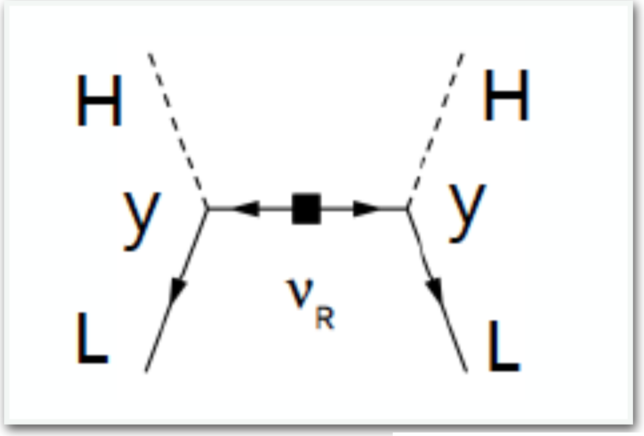
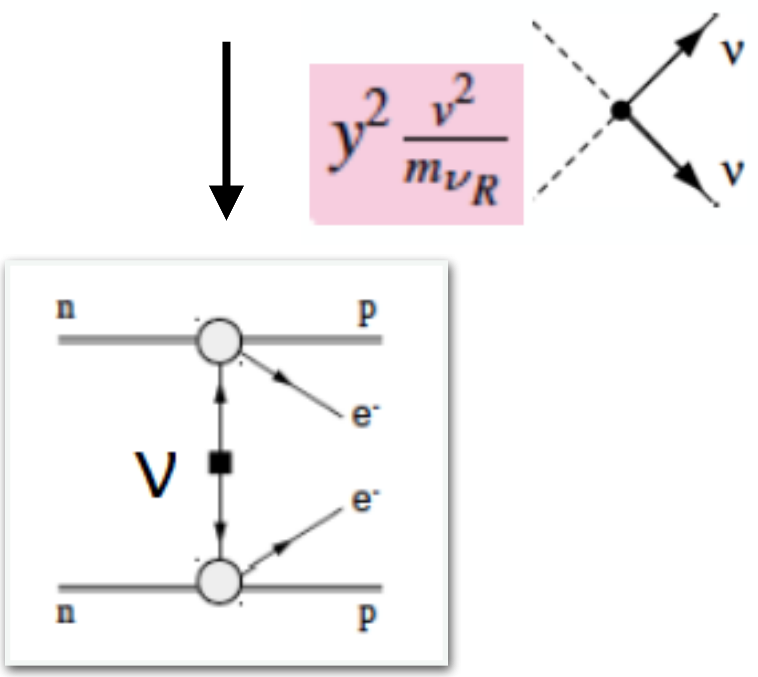




dim5
Majorana
Mass for light
ν's



Only low-E remnant of LNV
is the neutrino mass

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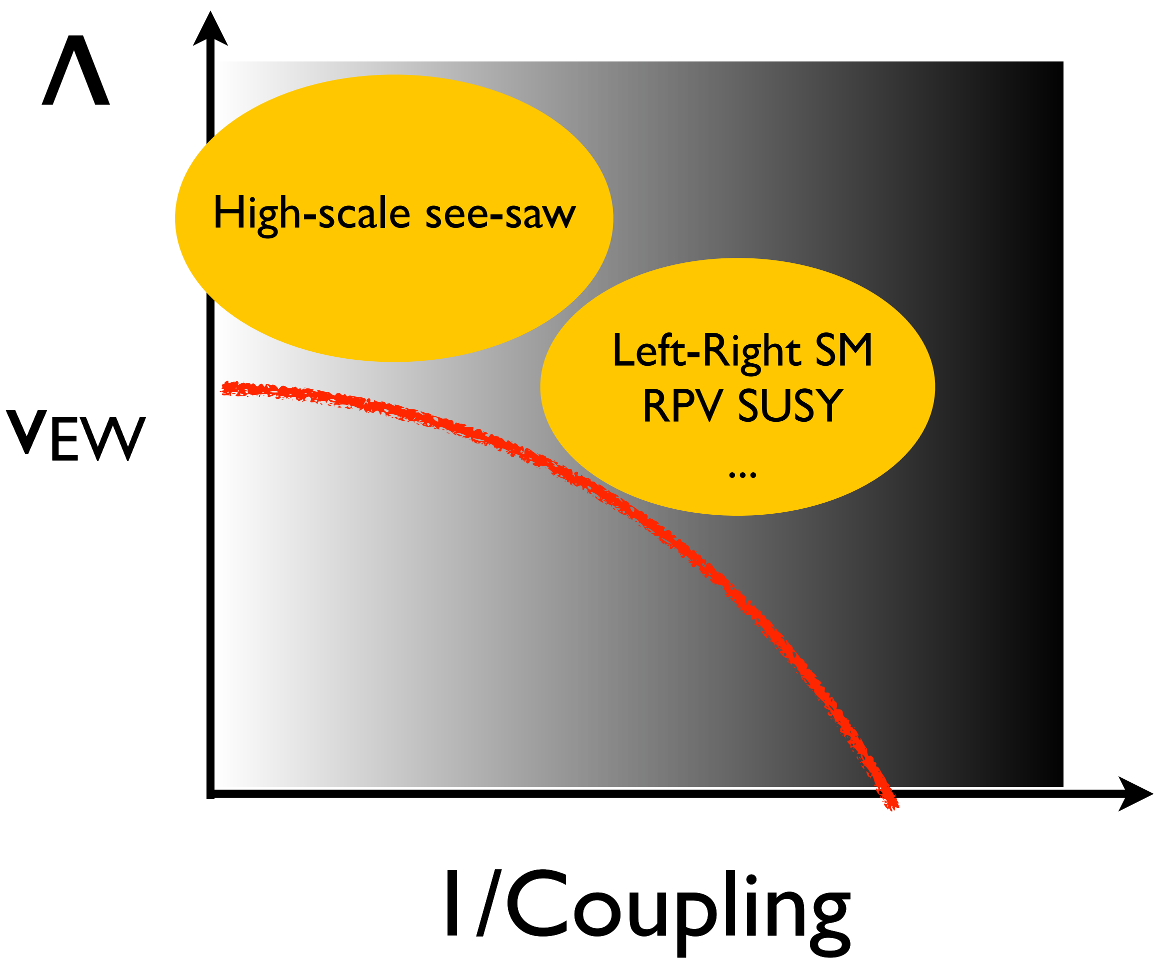

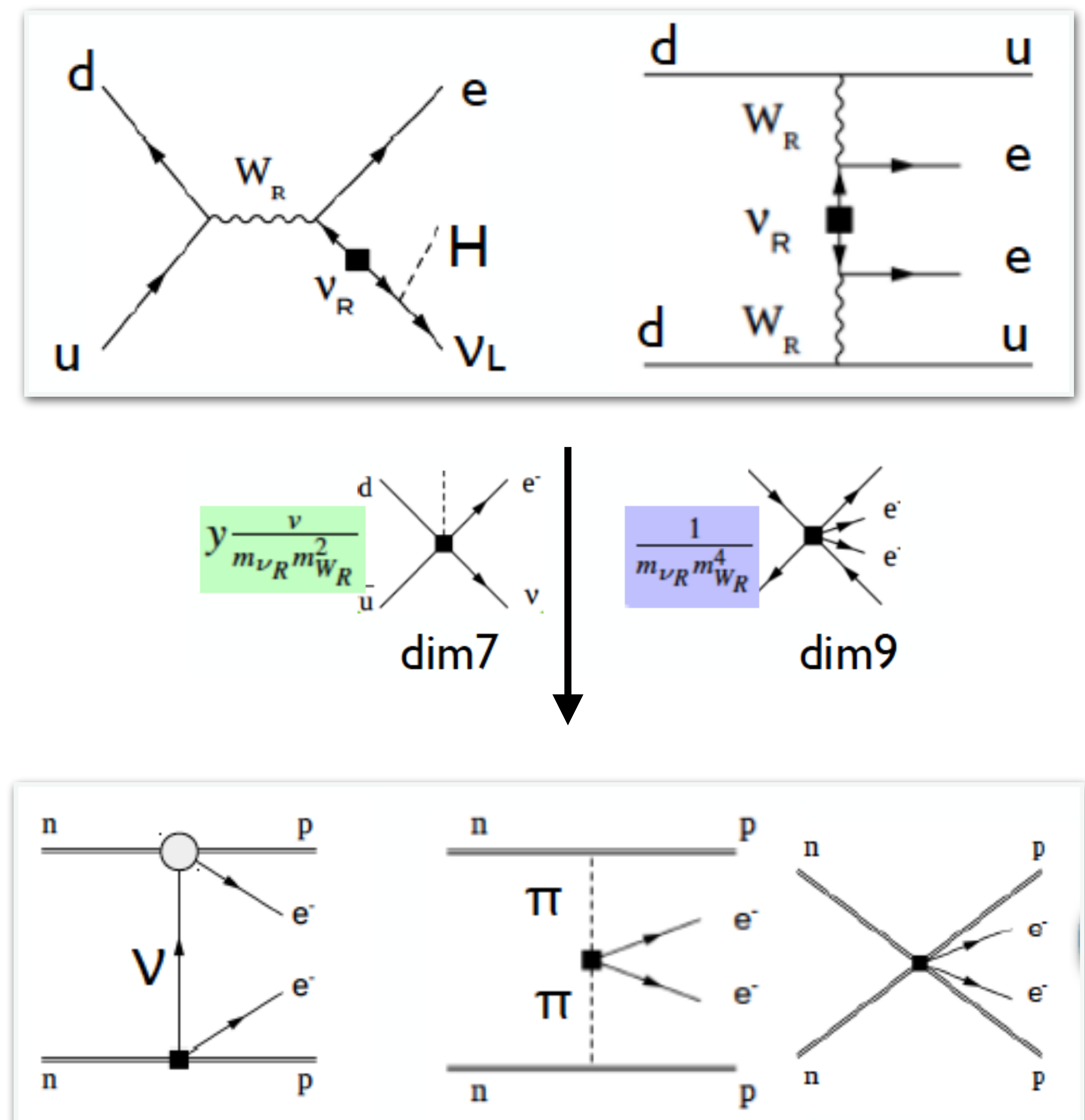

These contributions can compete with if scale is not too high and lead to new mechanisms at the nuclear scale

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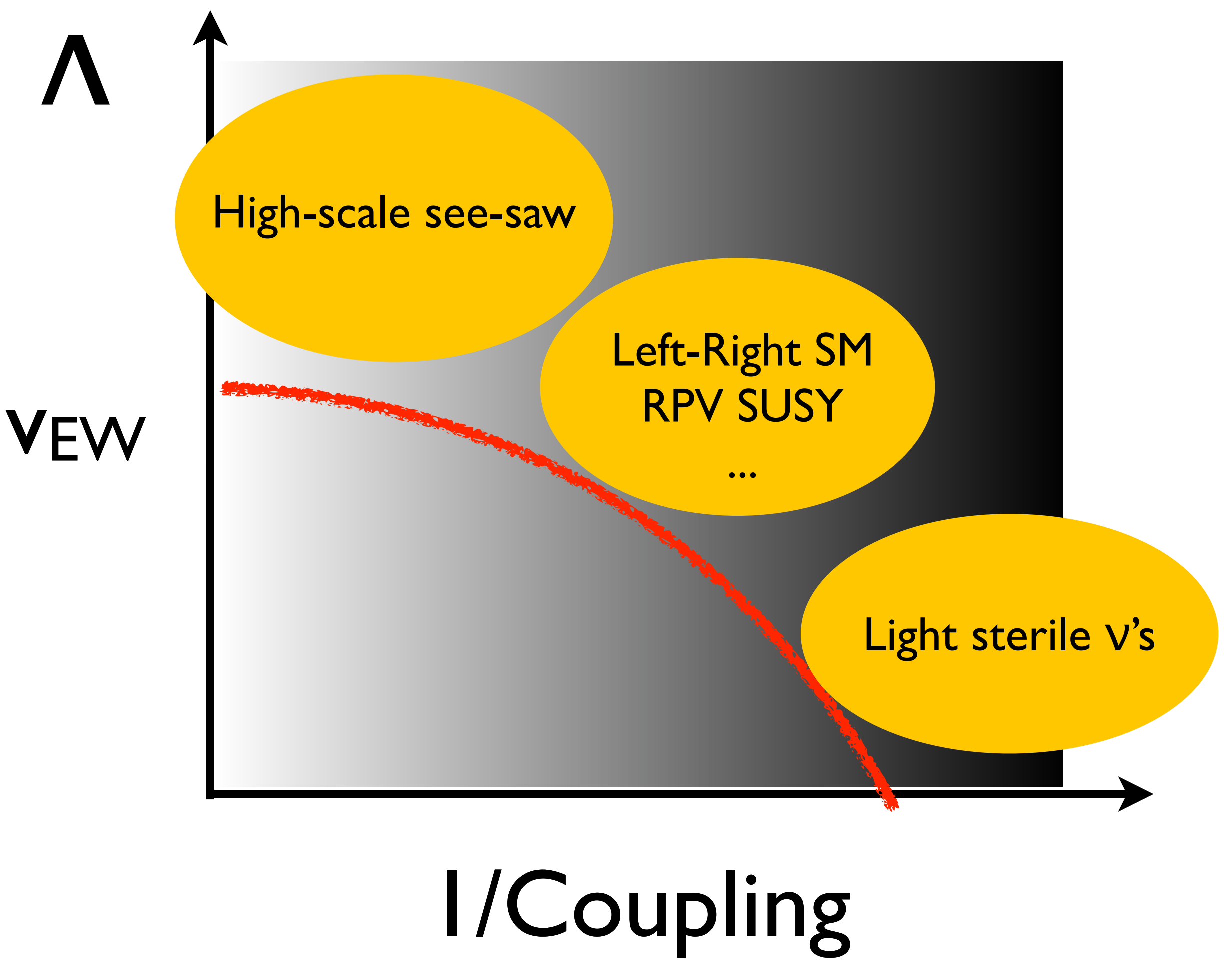
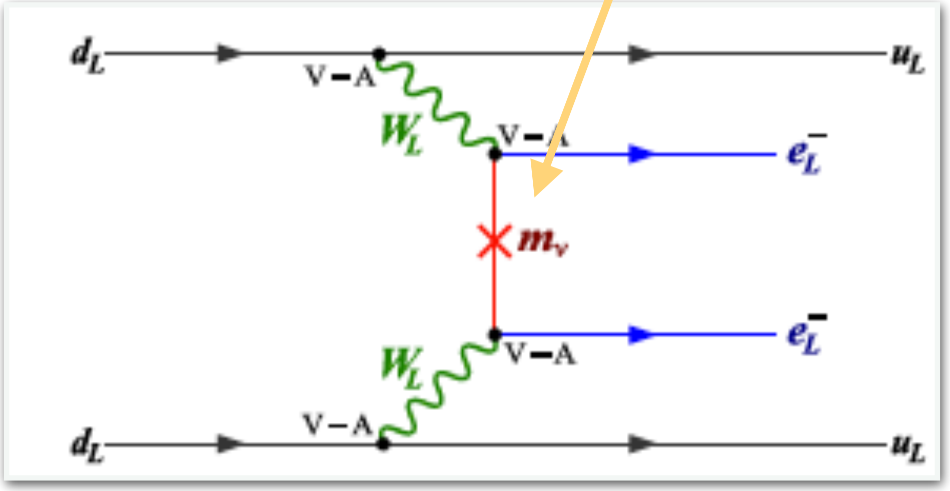


Light (nearly sterile) Majorana neutrinos:
M_R ~ eV → GeV:



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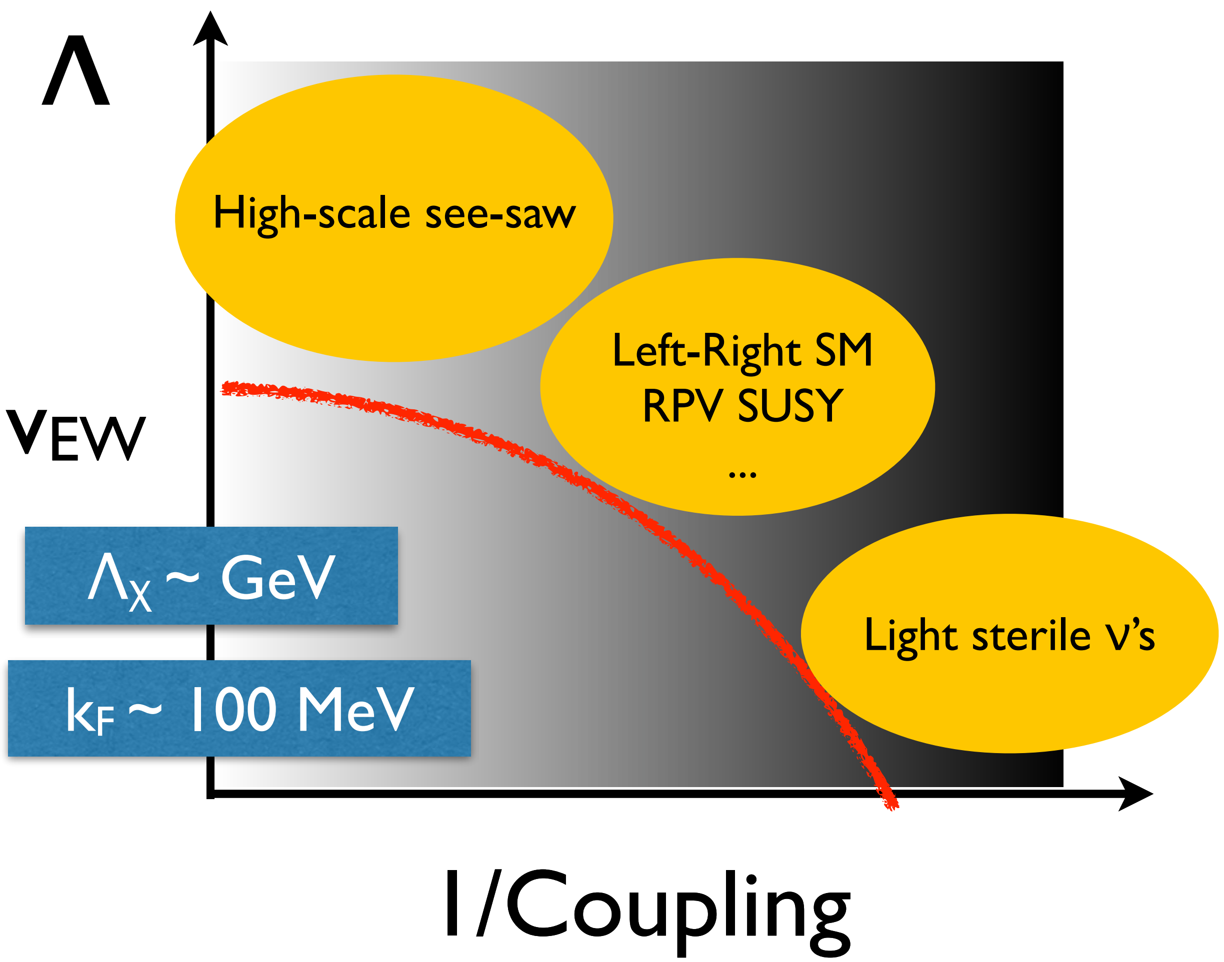


- Connecting sources of LNV to nuclei: multi-scale problem
- Best tackled by using EFT to bridge scales, combined with hadronic and nuclear matrix elements

SMEFT LEFT Chiral EFT

$$T_{1/2} \propto (m_W/\Lambda)^A \ (\Lambda_X/m_W)^B \ (k_F/\Lambda_X)^C$$

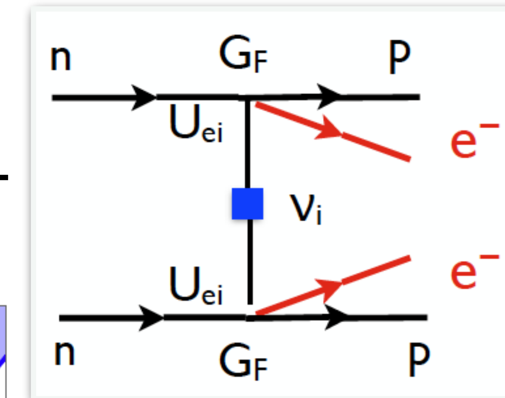
High-scale seesaw: discovery potential

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

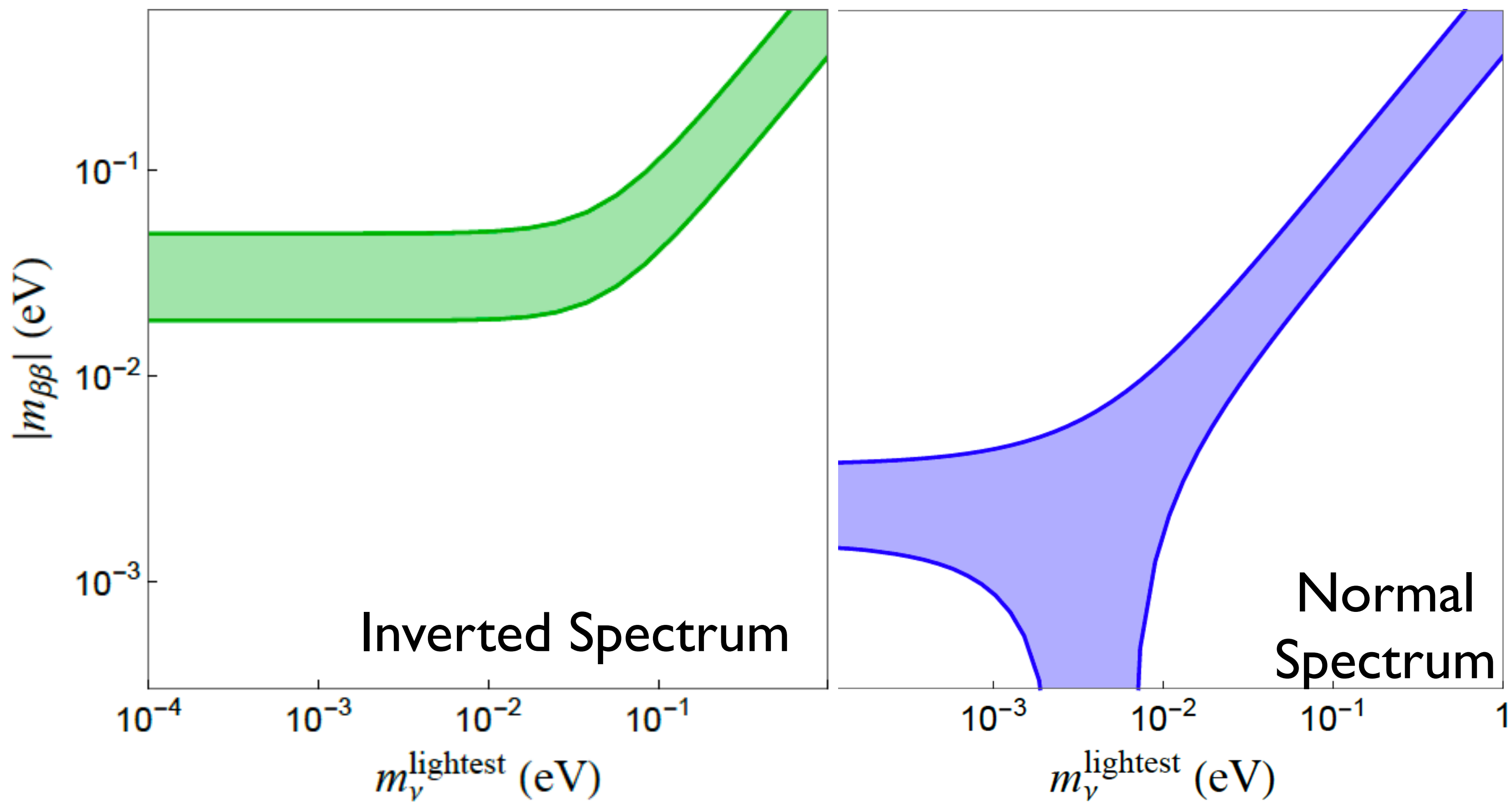
Strong correlation with oscillation parameters

(See talks by P. Hernandez and T. Lasserre)

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



Bands: unknown phases



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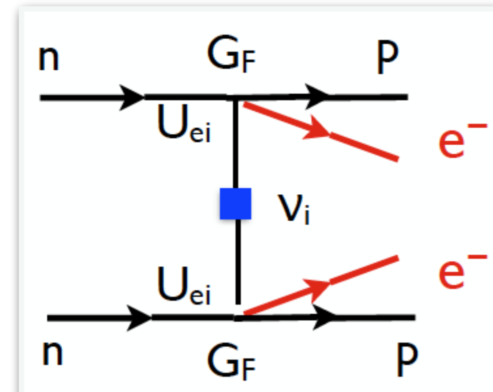
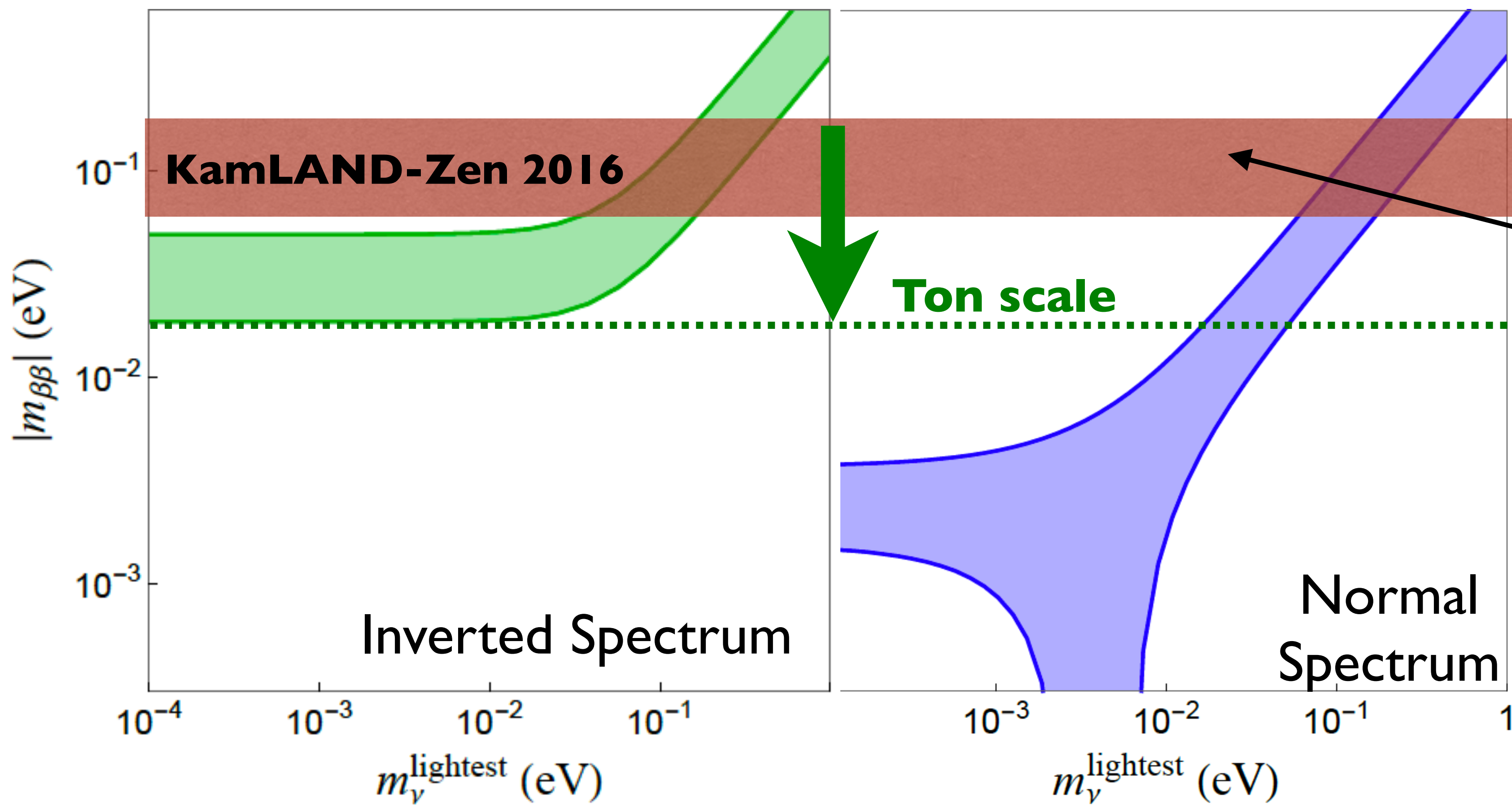




Bands: unknown phases

Assume range for nuclear matrix elements from different many-body methods

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"

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

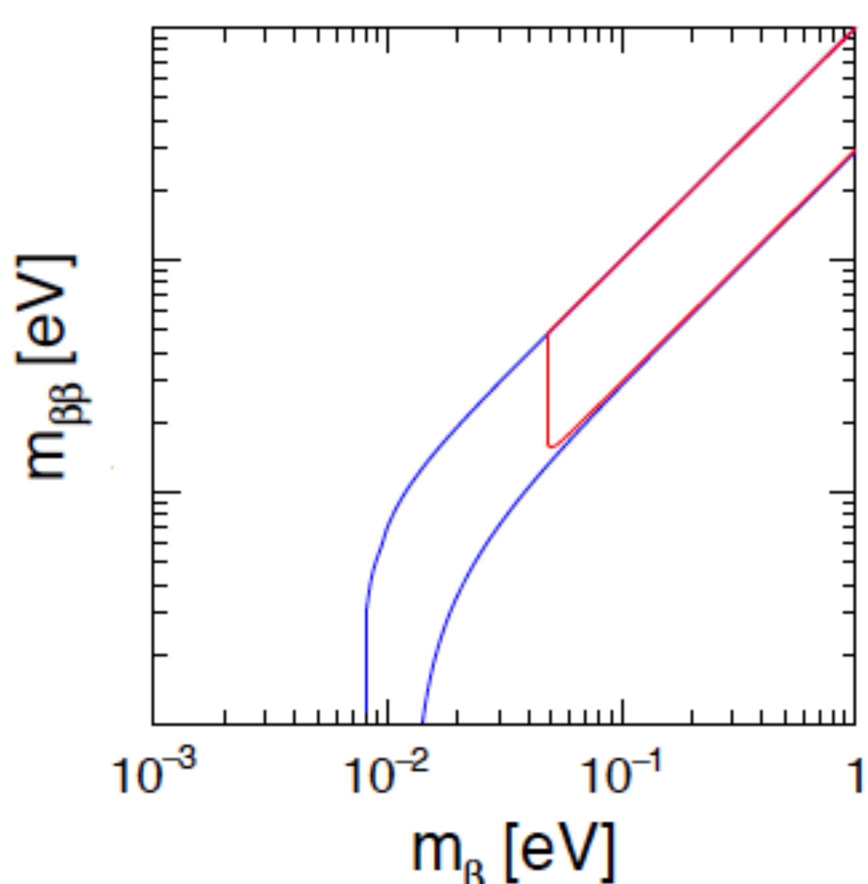
0νββ decay

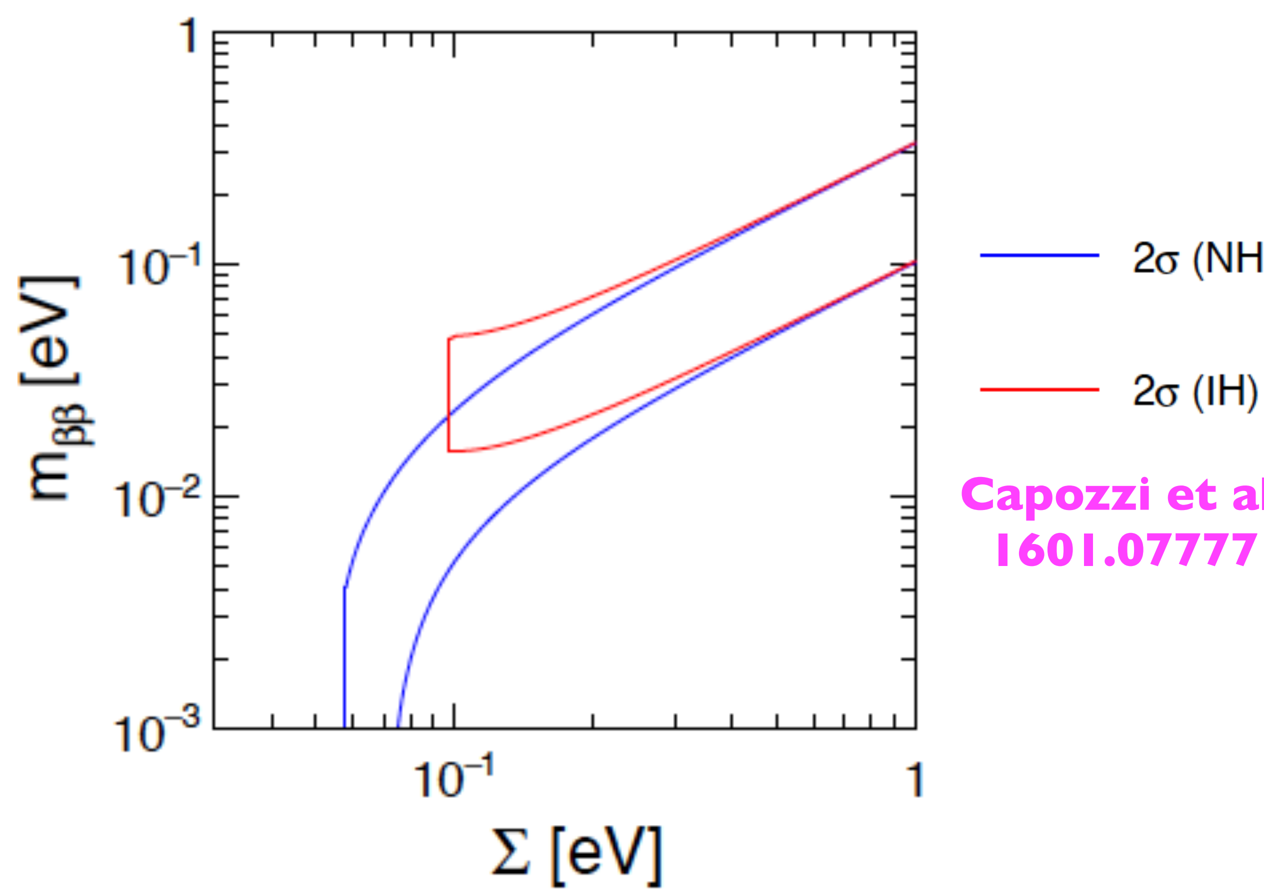
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





Capozzi et al, 1601.07777

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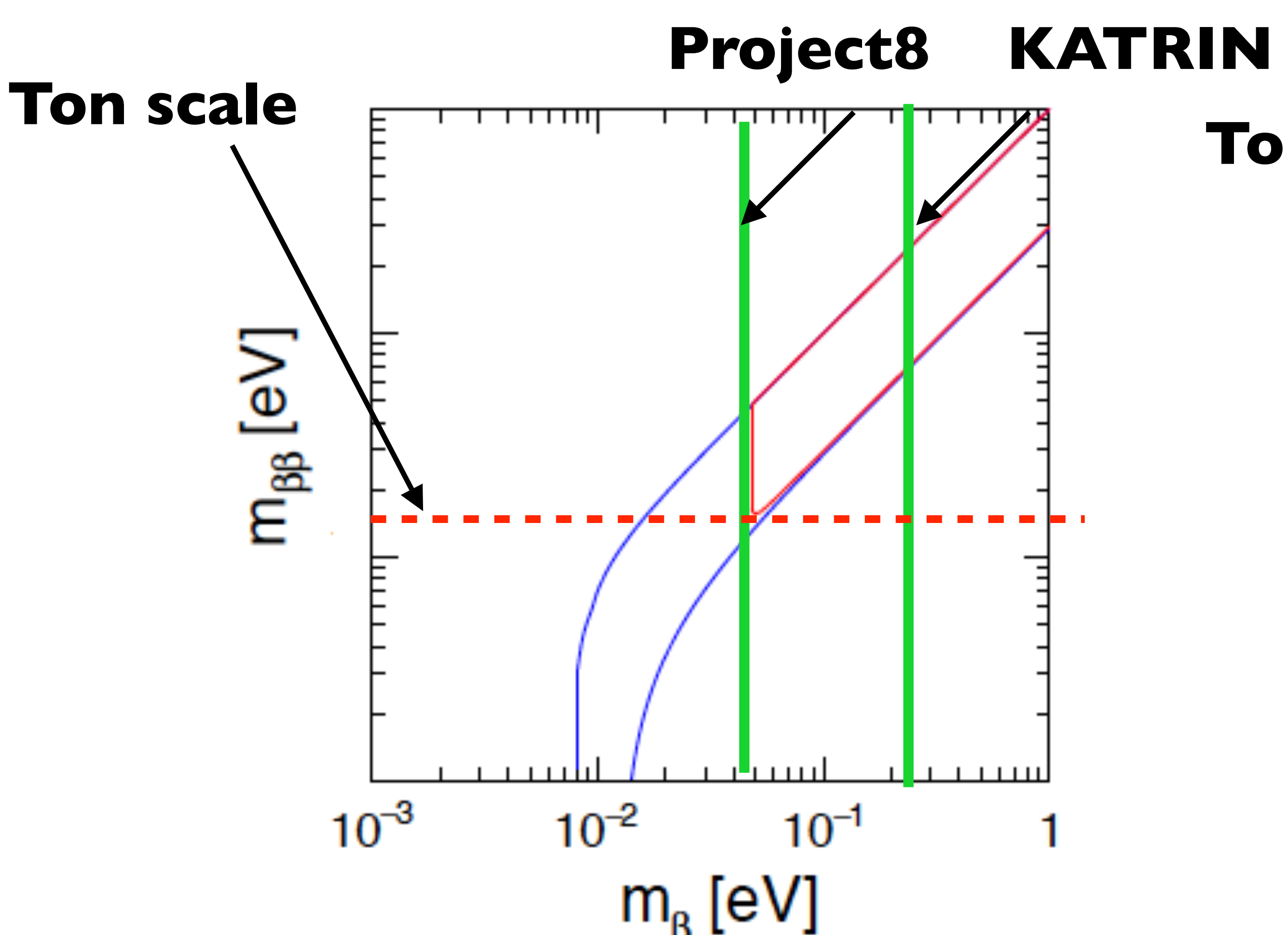

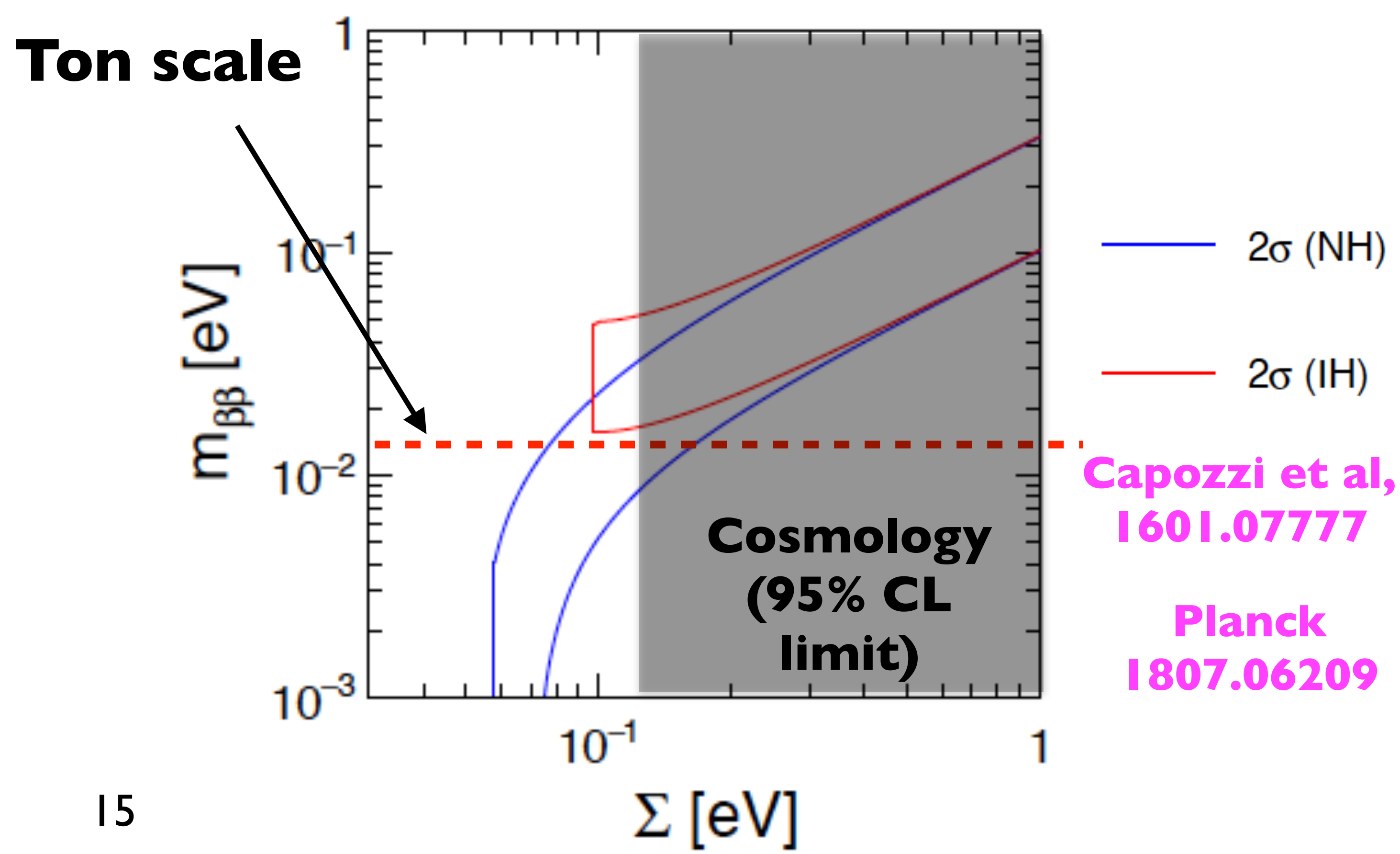

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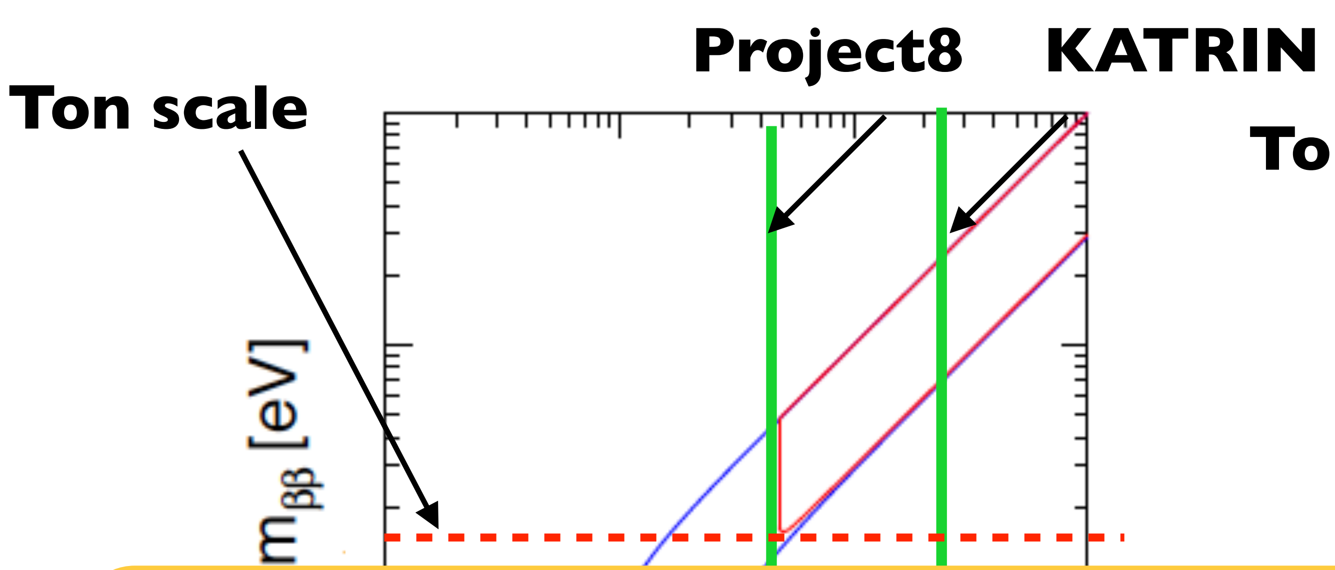
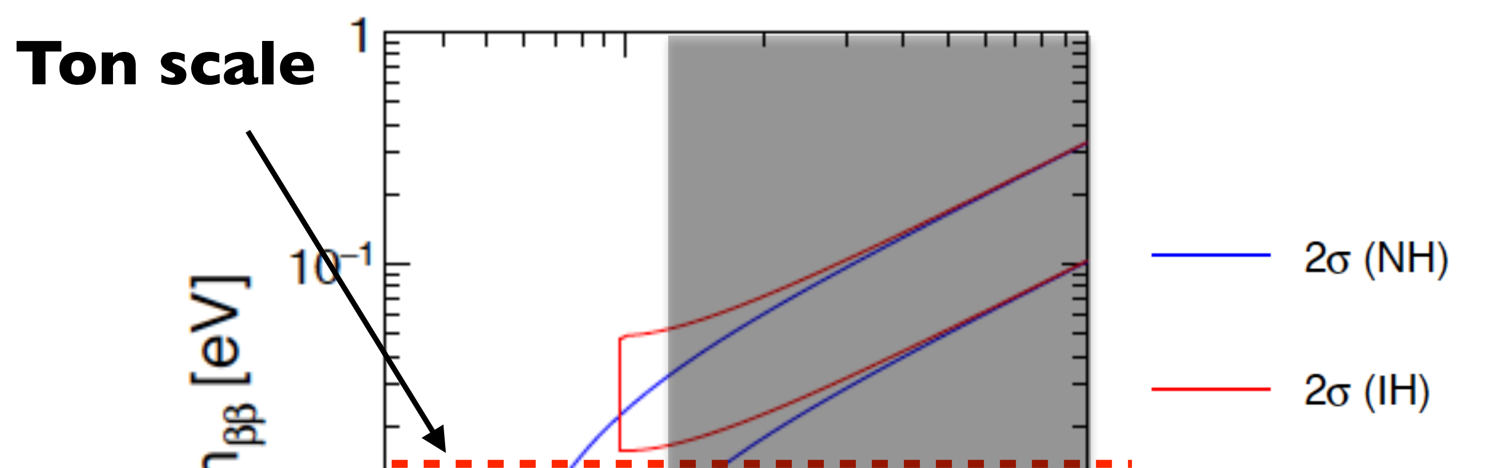


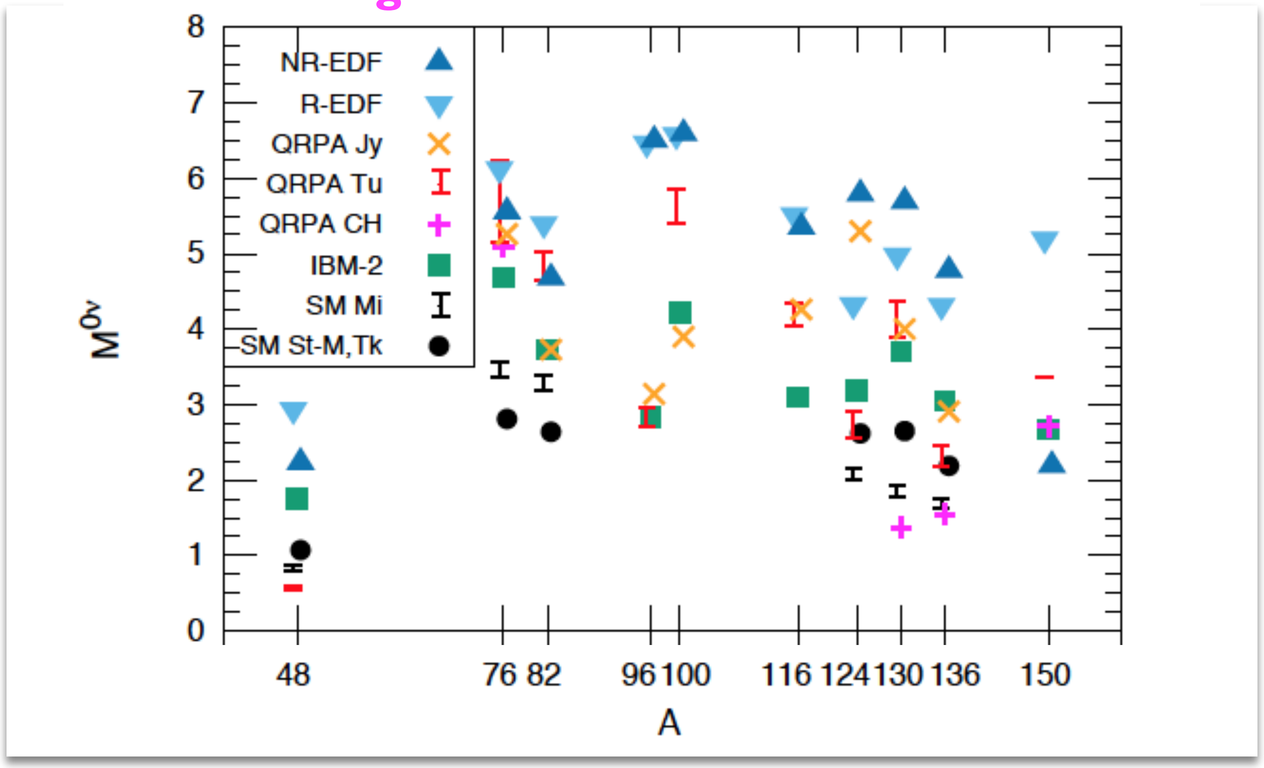


But these interesting connections require knowing matrix elements and their uncertainties!

High-scale seesaw: theory developments

- Snapshot as of a few years ago [recall $\Gamma \propto |M_{0\nu}|^2 \, (m_{\beta\beta})^2$]

Engel-Menendez 1610.06548



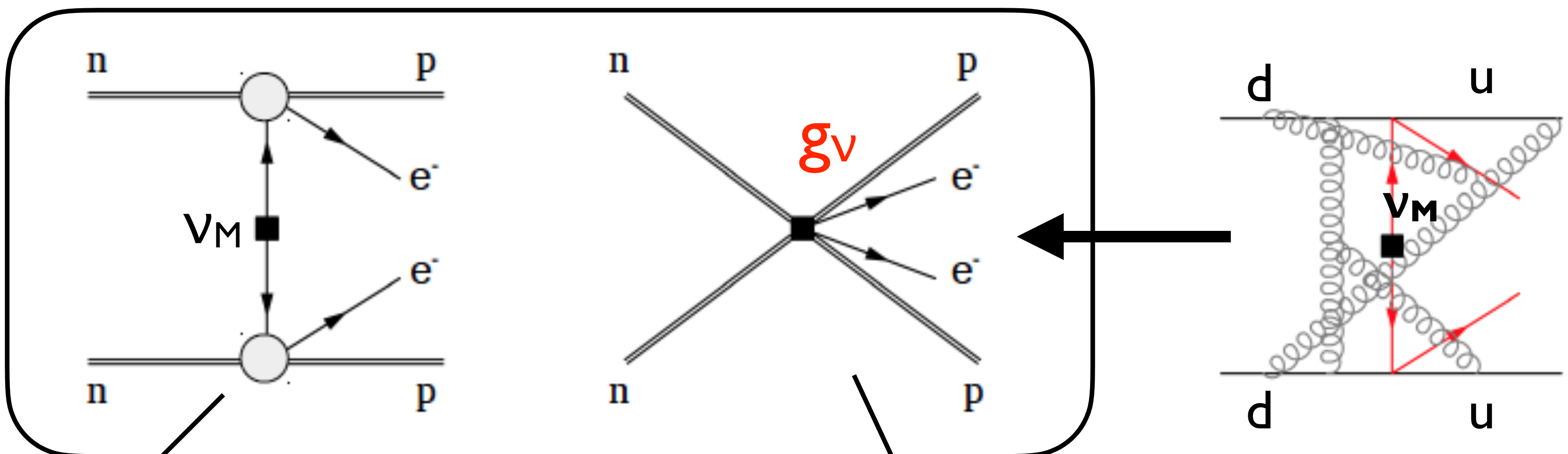
- Steps towards controlled uncertainties in matrix elements:
  - Use chiral EFT as guiding principle
  - Compute hadronic matrix elements with QCD-based methods
  - First-principles nuclear structure calculations: light nuclei, ^{48}Ca , ^{76}Ge, …

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 $\sim 1/Q^2$
Coulomb-like potential

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

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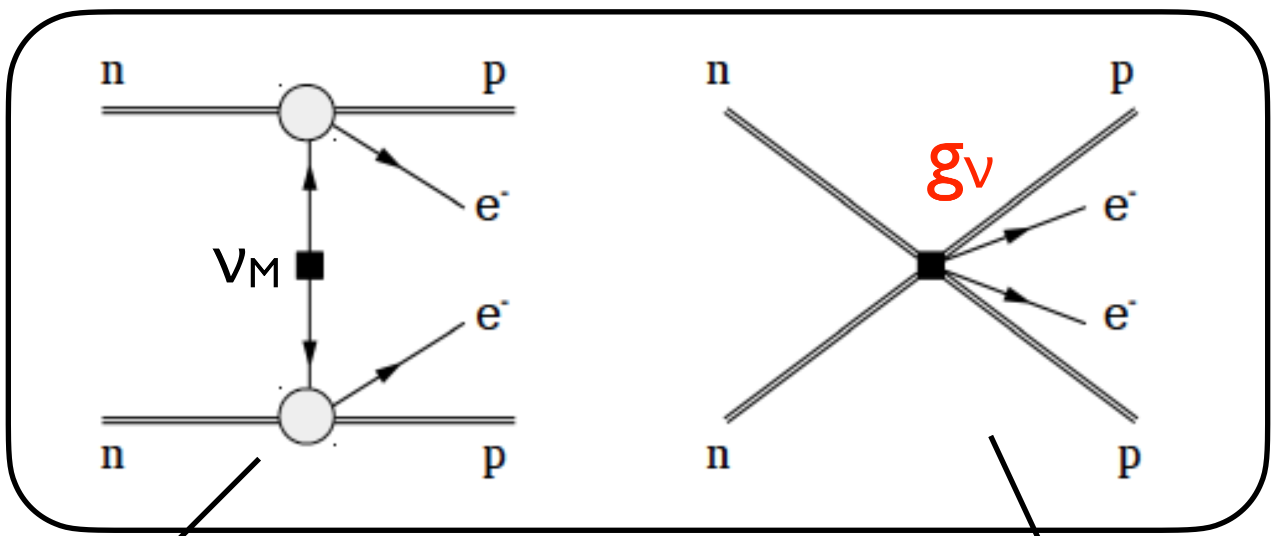


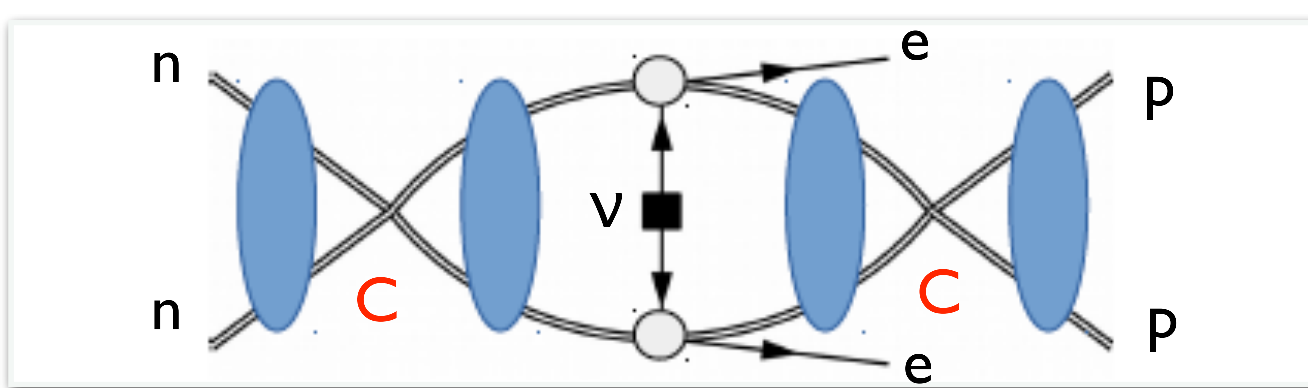
'Usual' ν_M exchange $\sim 1/Q^2$
Coulomb-like potential

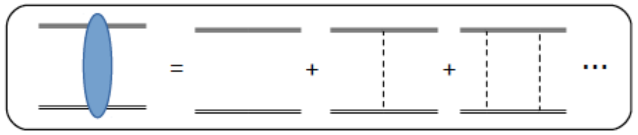
'New': short-range coupling $g_\nu \sim 1/Q^2$
Required by renormalization of $nn \to ppee$
amplitude in presence of strong interactions

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

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

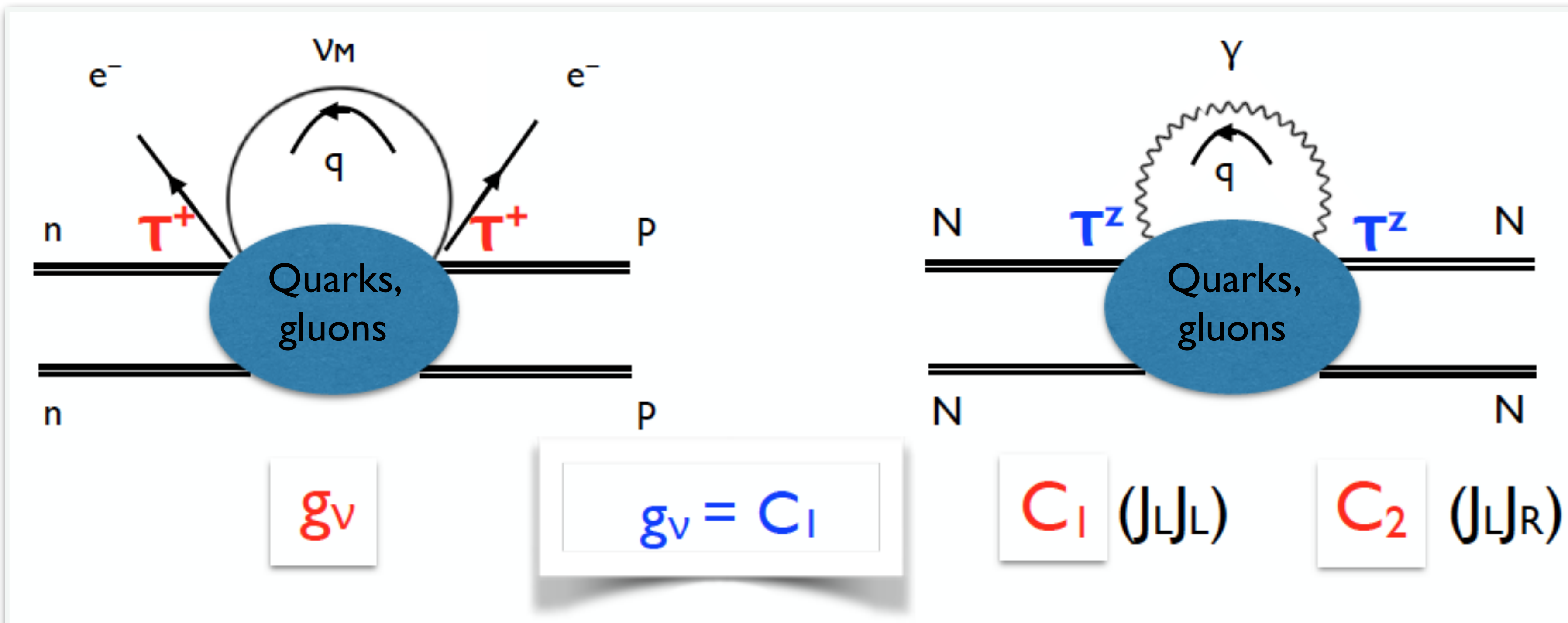
Strong $^1S_0$ short-range interaction





Connection with data?

- Chiral+isospin symmetry relates g_ν to I=2 e.m. couplings (hard γ's & ν's)

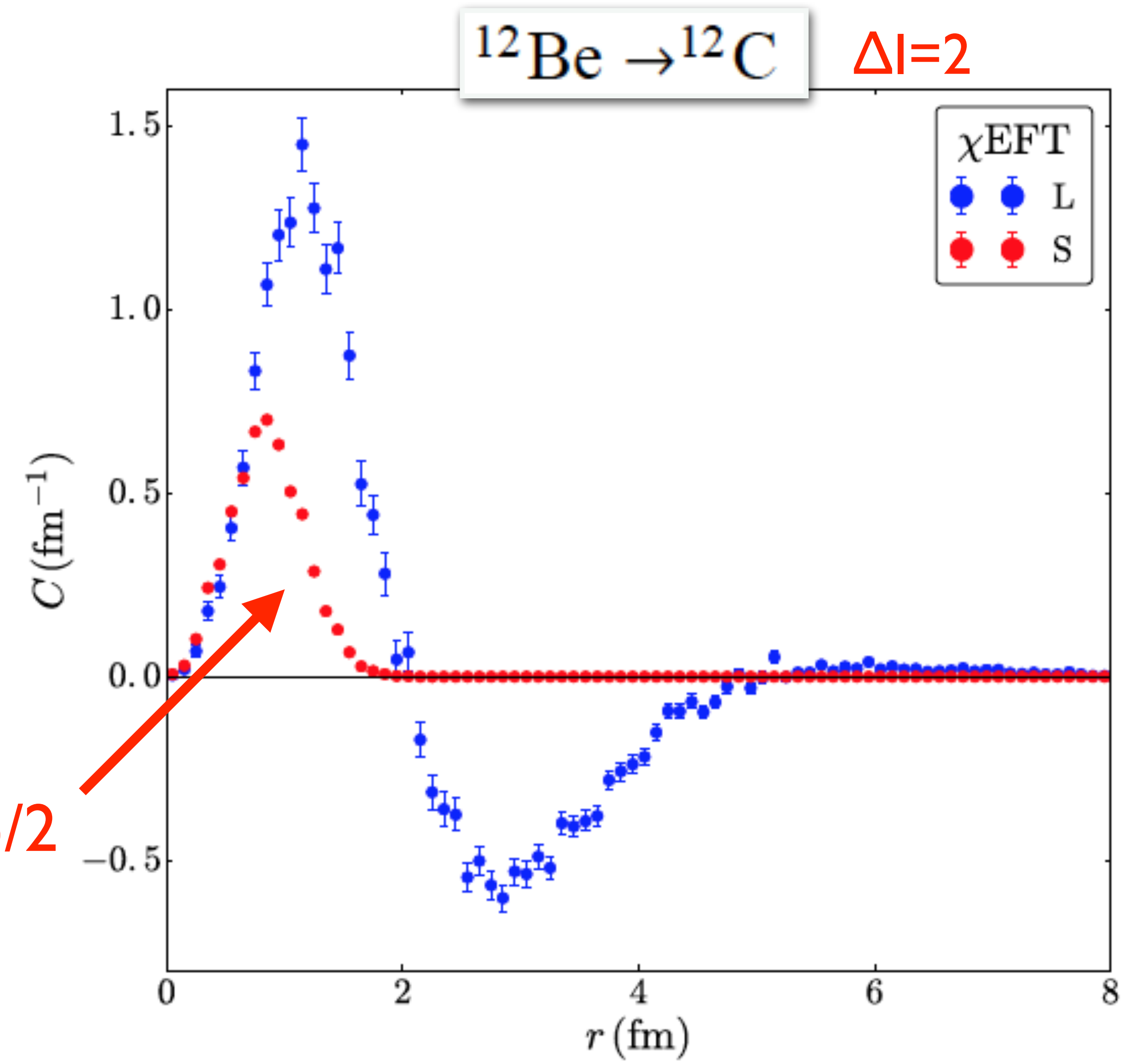


- NN data ($a_{nn}+a_{pp}-2a_{np}$) determine C_1+C_2, confirming LO scaling!
- Assuming $g_\nu \sim (C_1+C_2)/2$, what is the impact on $m_{\beta\beta}$ extraction?

Impact on nuclear matrix elements (I)

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

Amplitude = $\int$ dr C(r)



$g_V \sim (C_1+C_2)/2$

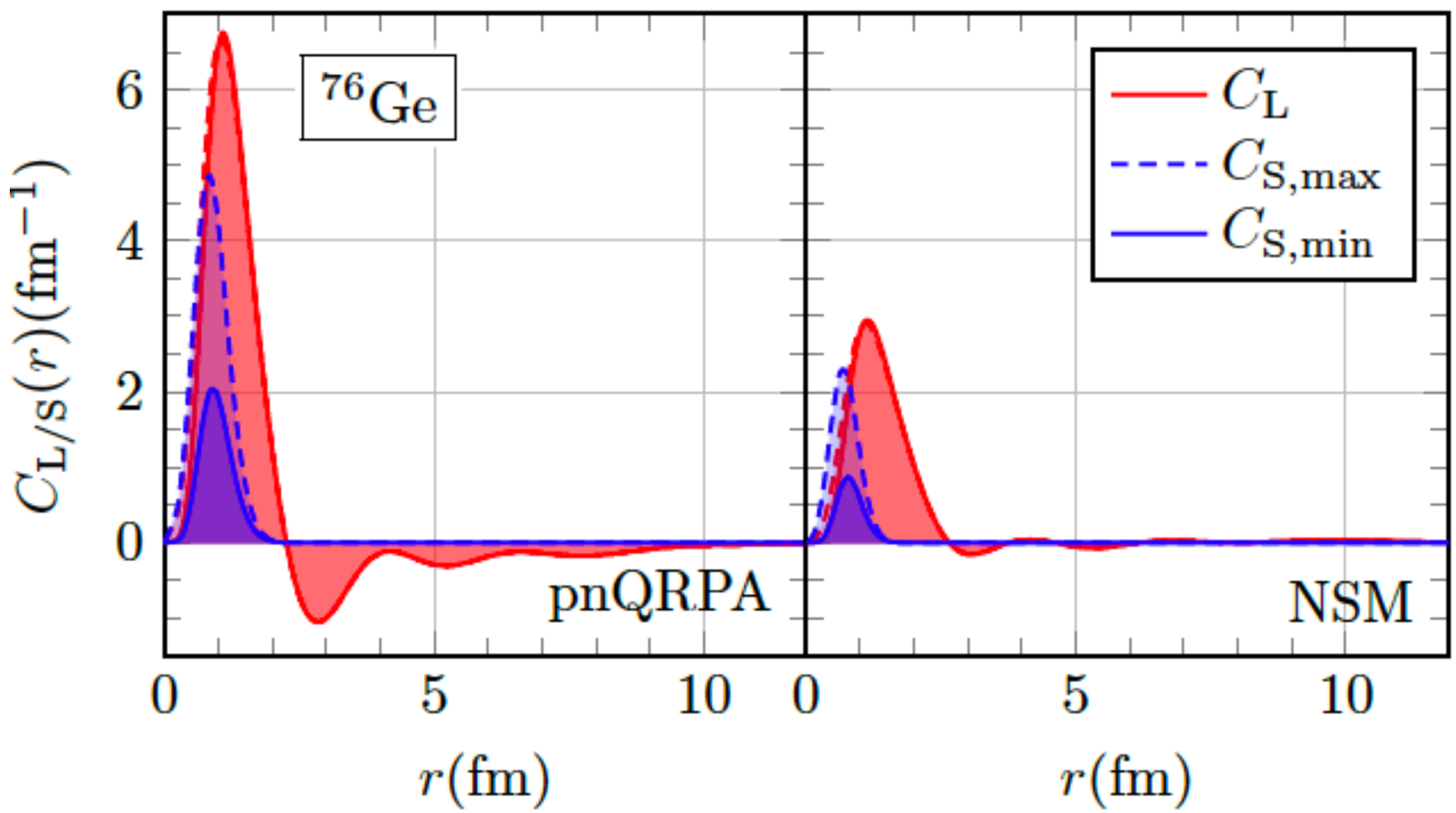
Light nuclei with Norfolk chiral potential [1606.06335]

g_V contribution large in ΔI=2 transition: for A=12, $A_S/A_L = 0.75$

Transitions of experimental interest (^{76}Ge→ ^{76}Se, …) have node (ΔI=2) ⇒ expect significant effect!

Impact on nuclear matrix elements (2)

- Similar large effects for nuclei of experimental interests are found with other methods as well (QRPA, nuclear shell model), taking $g_\nu \sim (C_1+C_2)/2$



Jokiniemi-Soriano-Menendez, 2107.13354

Impact on nuclear matrix elements (2)

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Nucleus	pnQRPA $M_L^{0\nu}$	pnQRPA $M_S^{0\nu}$	pnQRPA $M_S^{0\nu}/M_L^{0\nu}(\%)$	NSM $M_L^{0\nu}$	NSM $M_S^{0\nu}$	NSM $M_S^{0\nu}/M_L^{0\nu}(\%)$
^{48}Ca				0.96 – 1.05	0.22 – 0.65	23 – 62
^{76}Ge	4.72 – 5.22	1.49 – 3.80	32 – 73	3.34 – 3.54	0.52 – 1.49	15 – 42
^{82}Se	4.20 – 4.61	1.27 – 3.24	30 – 70	3.20 – 3.38	0.48 – 1.38	15 – 41
^{96}Zr	4.22 – 4.63	1.24 – 3.19	29 – 69			
^{100}Mo	3.40 – 3.95	1.66 – 4.26	49 – 108			
^{116}Cd	4.26 – 4.45	1.10 – 2.80	26 – 63			
^{124}Sn	4.72 – 5.29	1.69 – 4.28	36 – 81	3.20 – 3.41	0.54 – 1.58	17 – 46
^{128}Te	3.92 – 4.50	1.37 – 3.45	35 – 77	3.56 – 3.80	0.61 – 1.76	17 – 46
^{130}Te	3.46 – 3.89	1.18 – 3.05	34 – 77	3.26 – 3.48	0.57 – 1.64	17 – 47
^{136}Xe	2.53 – 2.80	0.76 – 1.95	30 – 70	2.62 – 2.79	0.45 – 1.31	17 – 47

r(fm) r(fm)

Jokiniemi-Soriano-Menendez, 2107.13354

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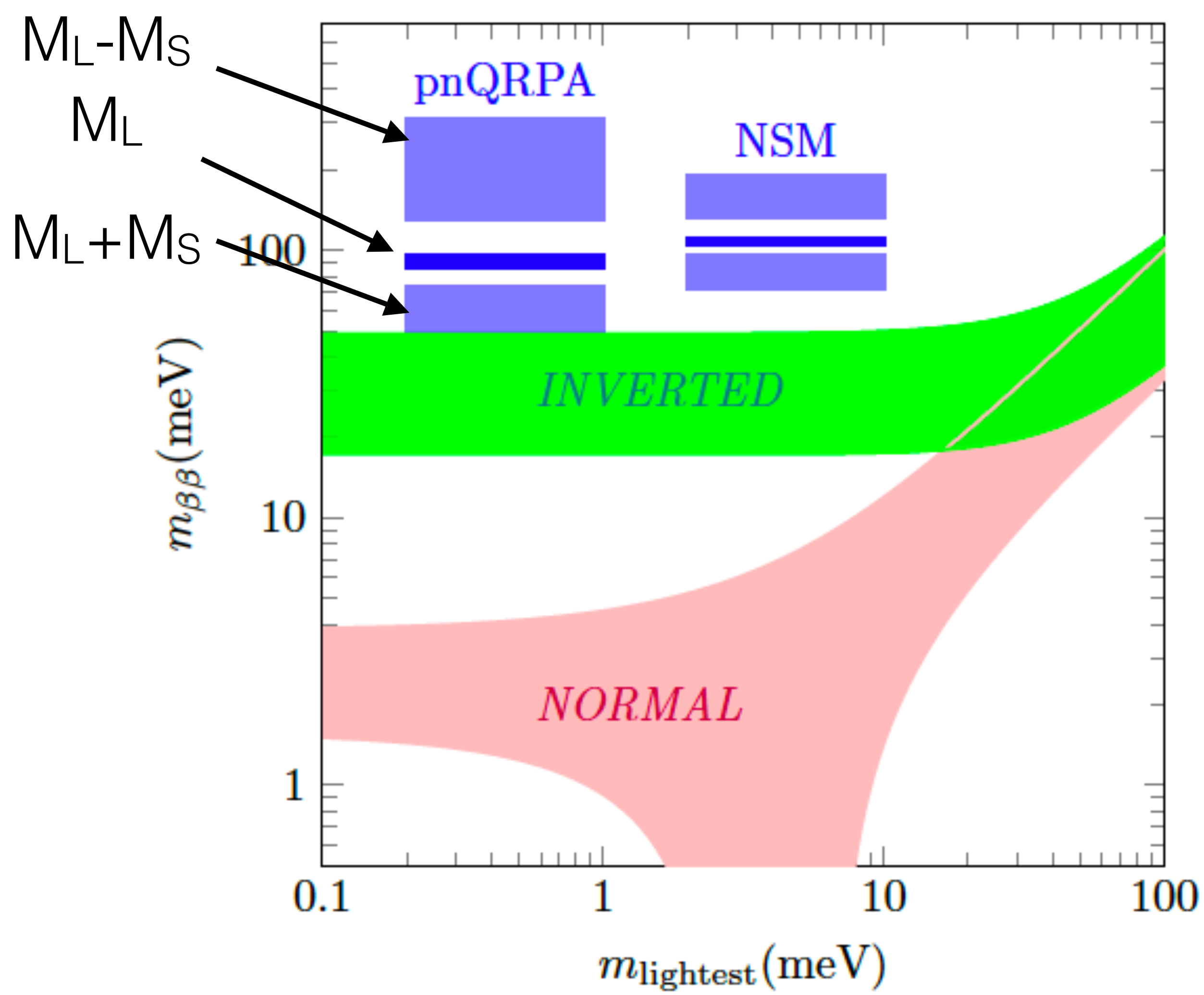


Key question: is the interference constructive or destructive?

Jokiniemi-Soriano-Menendez, 2107.13354

Towards determining of g_ν

- Large-N_C arguments point to $g_\nu \sim (C_1+C_2)/2 + O(1/N_C)$

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)

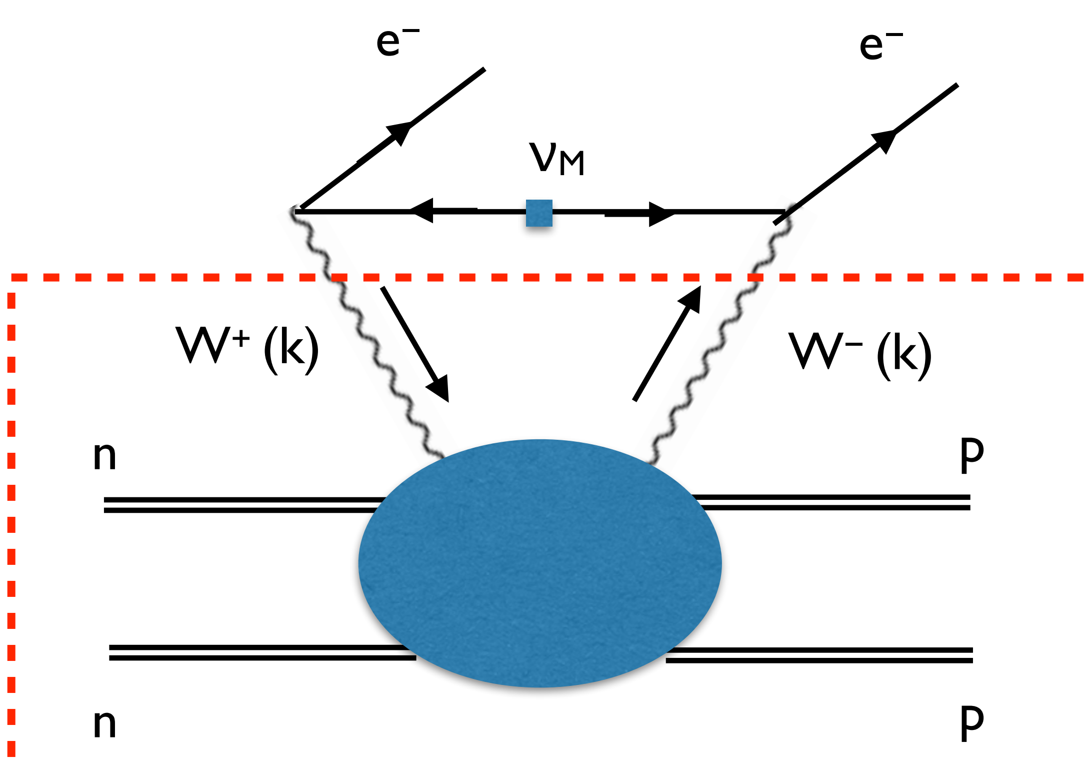
VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

Estimating the contact term (1)

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

- Useful representation of the amplitude

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



Forward "Compton" amplitude

Estimating the contact term (I)

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

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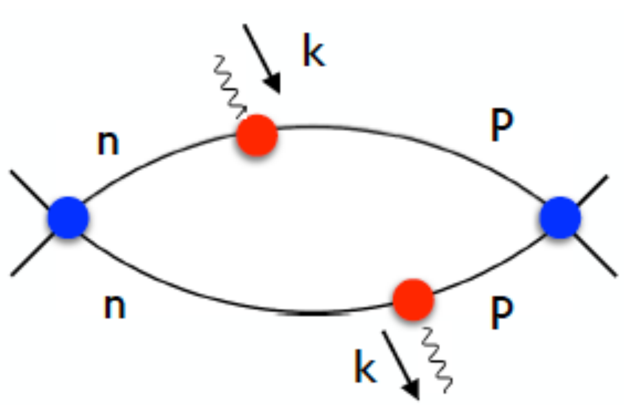
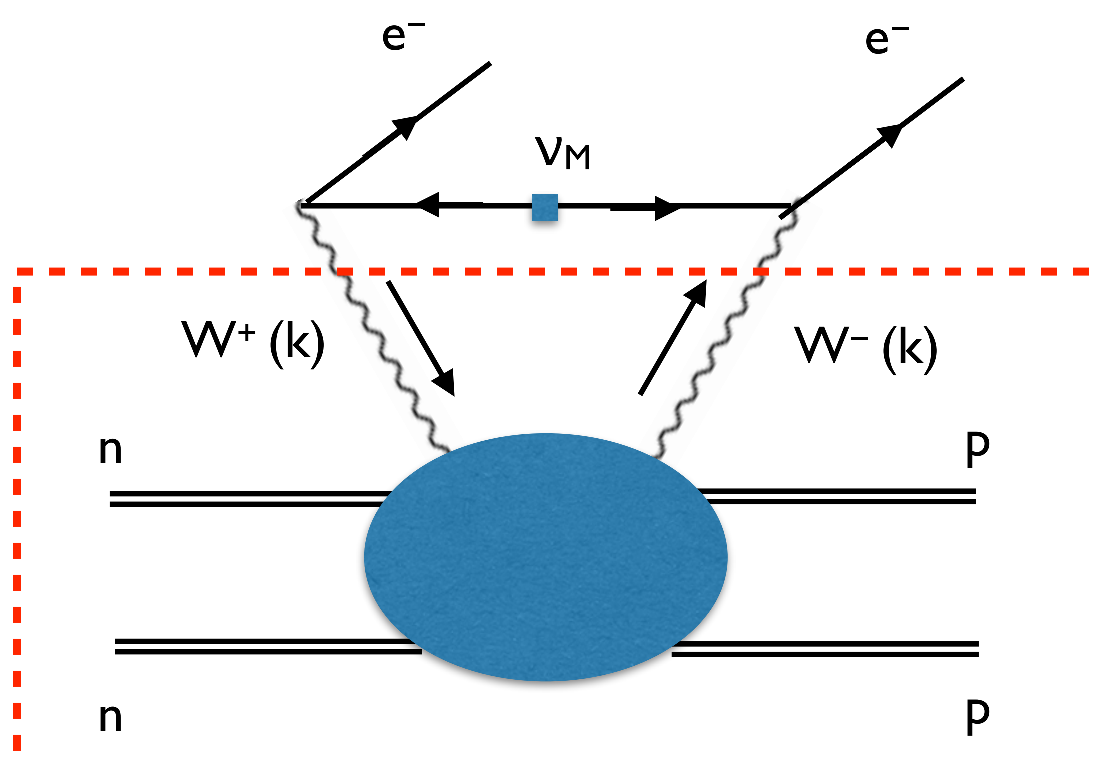
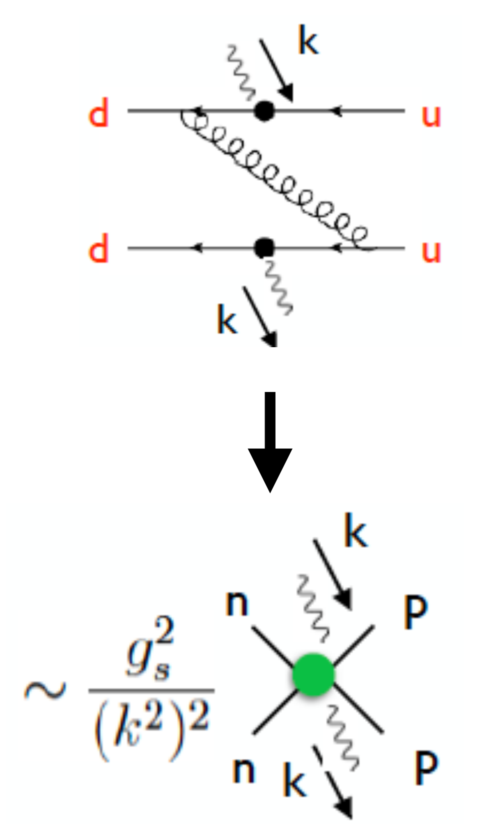
Low k: chiral EFT to NLO





Forward “Compton” amplitude

High k: QCD OPE



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

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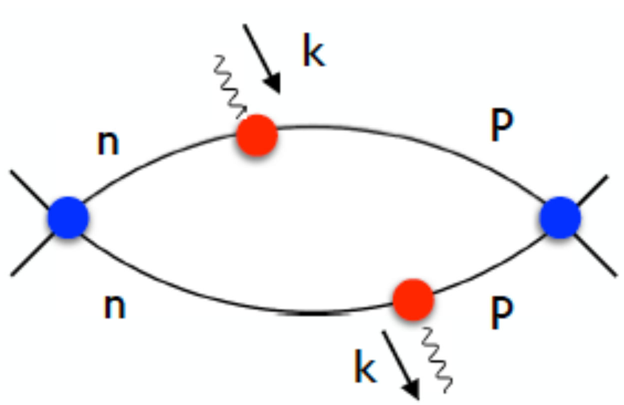
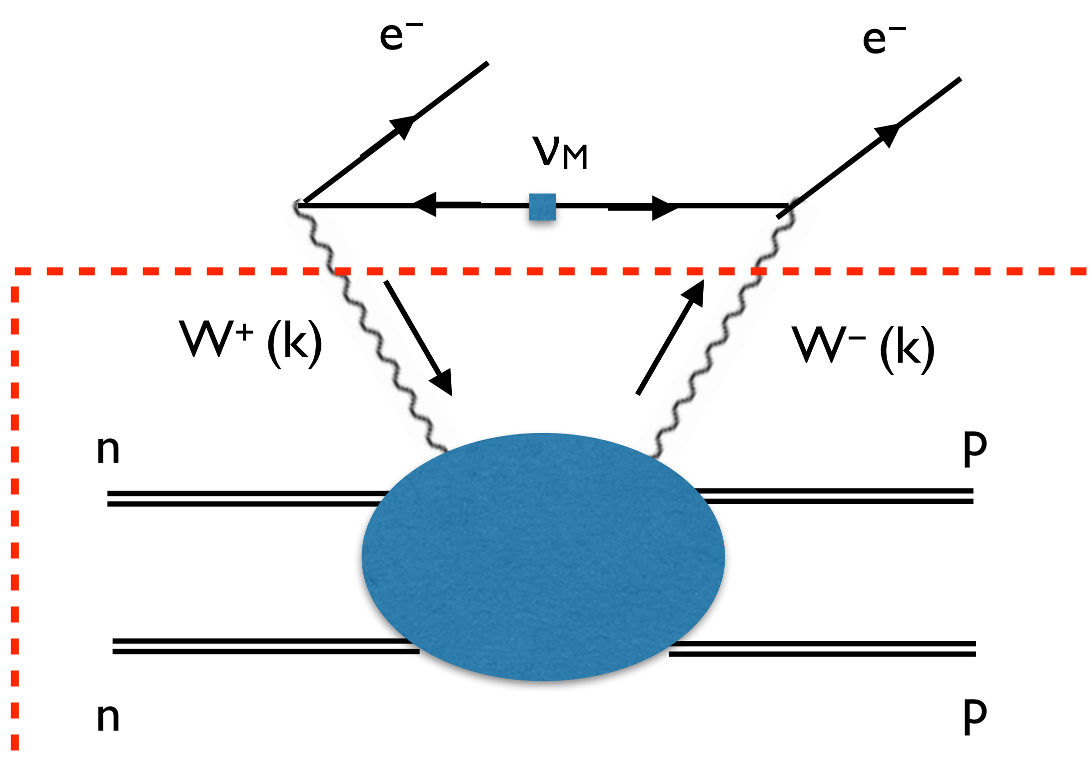
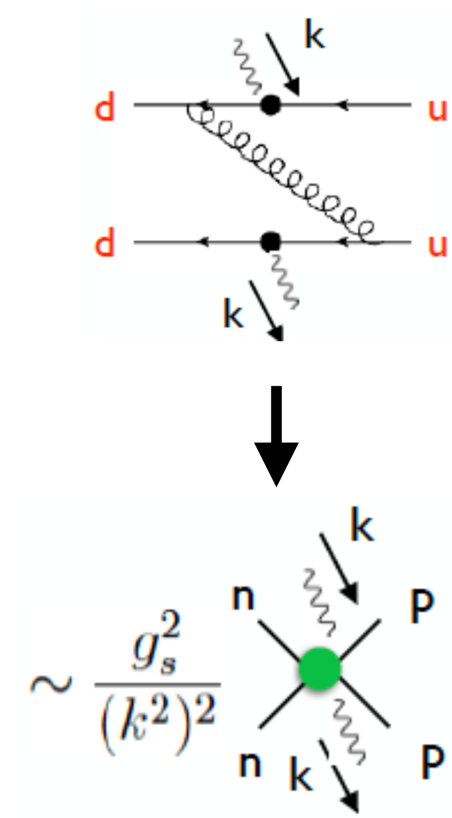


Intermediate k: resonance contributions in and , πNN intermediate state, …



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)

- 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 to be used to fit g_ν with regulators suitable for many-body nuclear calculations

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

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

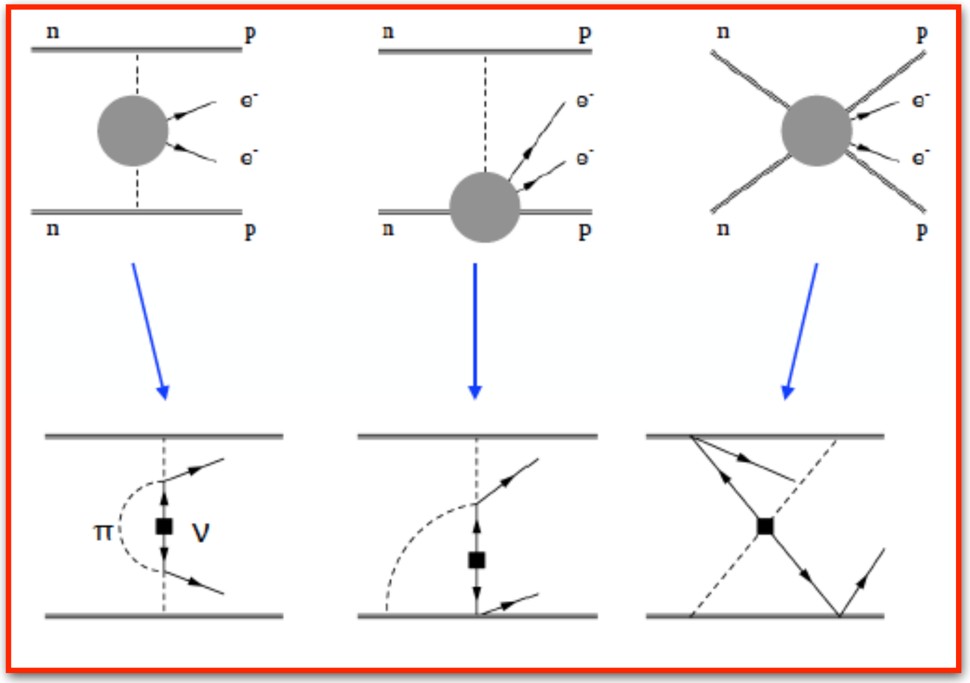
- First calculation of $^{48}Ca \rightarrow {}^{48}Ti$ with contact fitted to synthetic data ⇒ contact term enhances nuclear matrix element by (43±7)%

Wirth, Yao, Hergert, 2105.05415

What about higher orders?

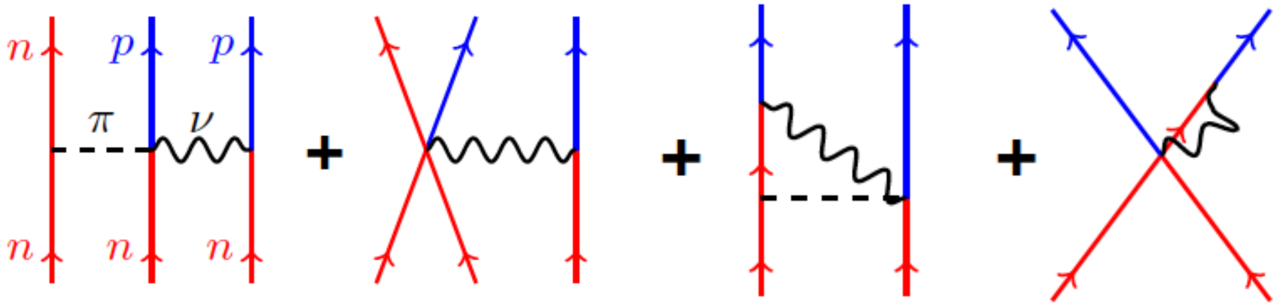
- N2LO

  - πN loops + new contact



VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

  - 2-body **x** 1-body current



Wang-Engel-Yao 1805.10276

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

S. Pastore, J. Carlson, V.C., W. Dekens, E. Mereghetti, R. Wiringa 1710.05026
V.C., J. Engel, j. Menendez, E. Mereghetti, in preparation

What about higher orders?

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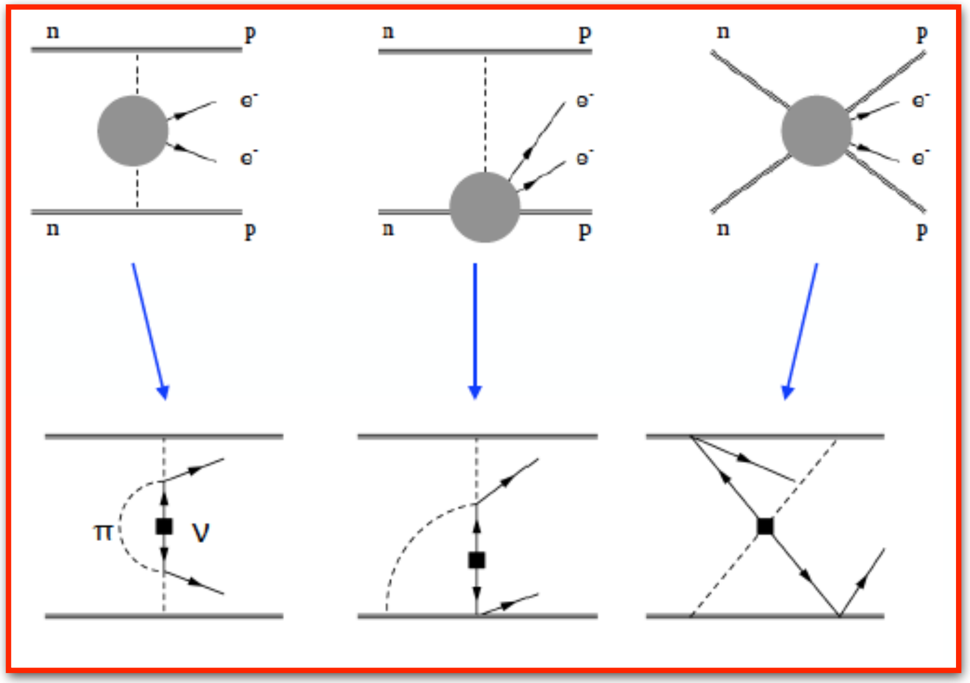
  - πN loops + new contact



VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

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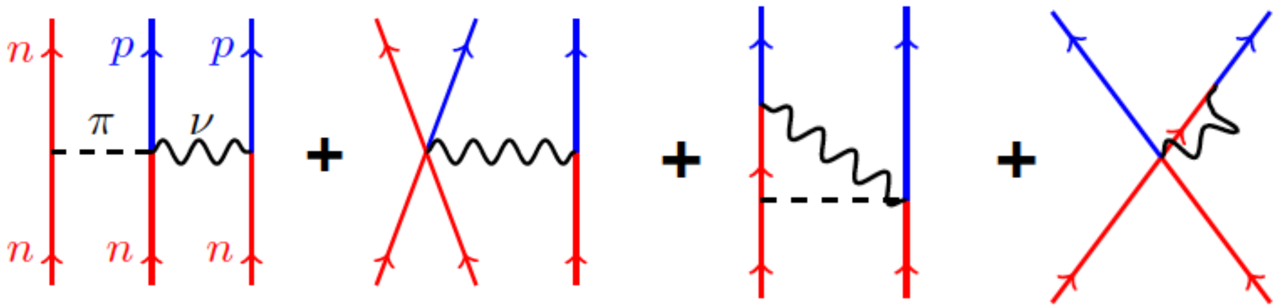

Chiral EFT + estimate of contact term + many-body →

Significant step towards reduction of matrix element uncertainty & interpretation of a positive or null result in terms of $m_{\beta\beta}$

LNV from multi-TeV scale physics

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

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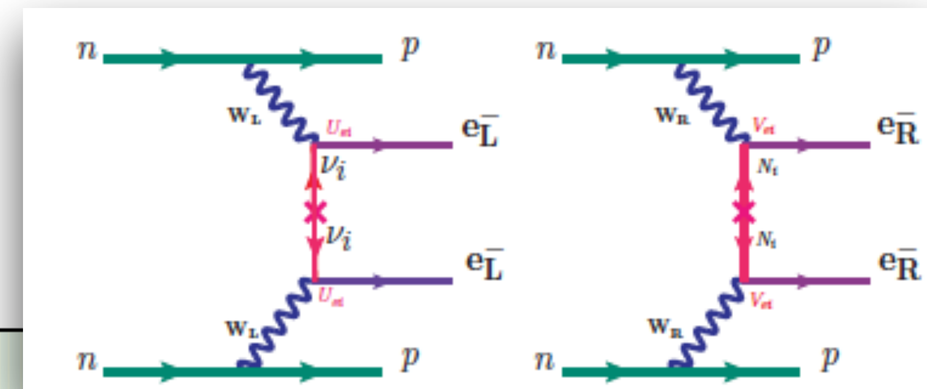
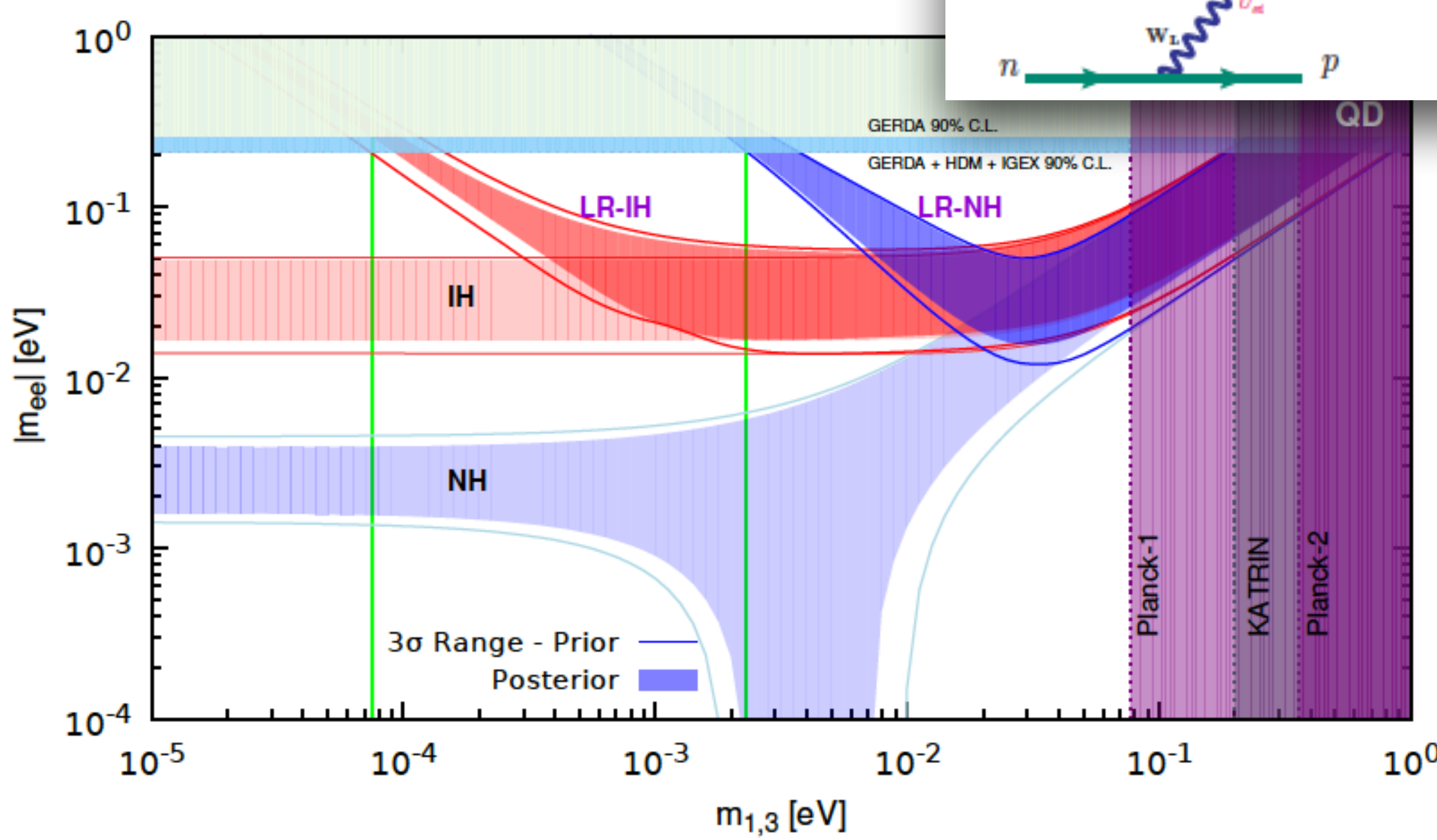
Example: left-right symmetric model with type-II seesaw





$$M_i \propto m_i$$

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

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

$M_{2,3}$ = 1 TeV

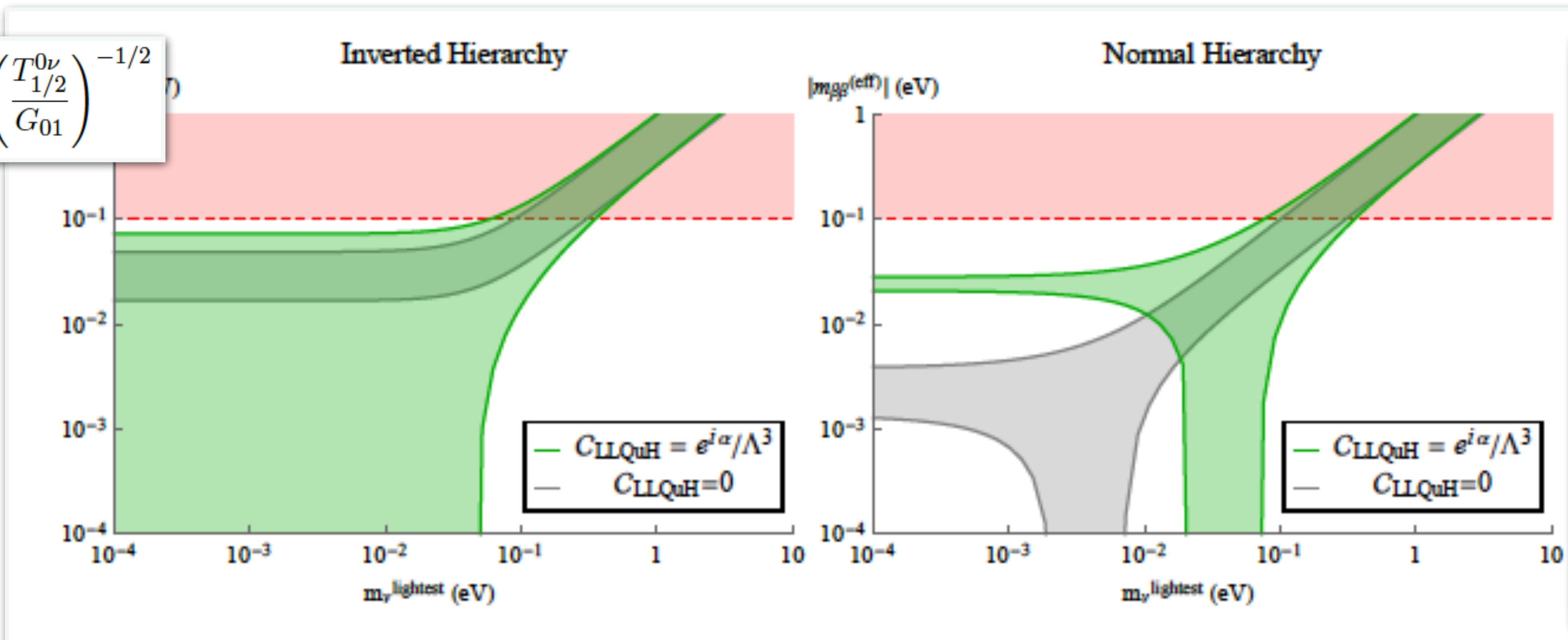
Tello-Nemevesek-Nesti-Senjanovic-Vissani 1011.3522
Ge-Lindner-Patra 1508.07286. **
...

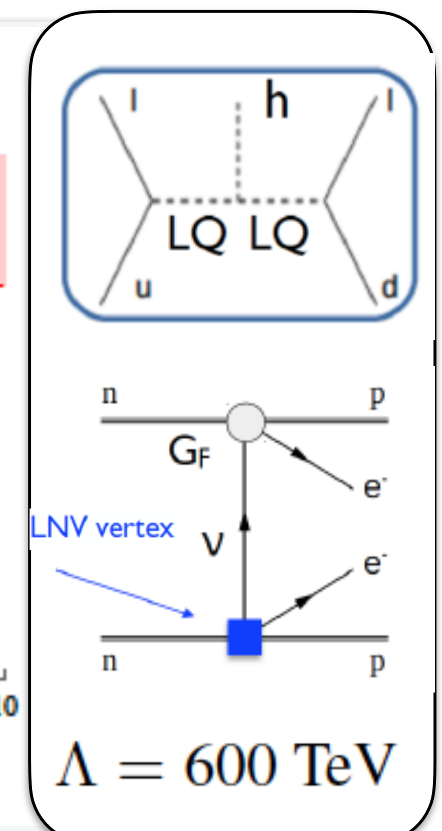
LNV from multi-TeV scale physics

- Induce 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

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





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

LNV from multi-TeV scale physics

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

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

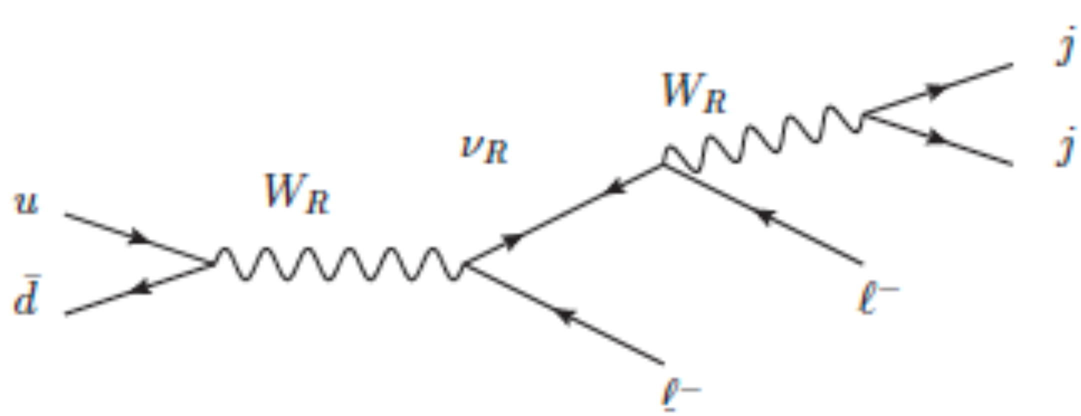
Keung-Senjanovic '83

Maiezza-Nemevesek-Nesti- Senjanovic 1005.5160

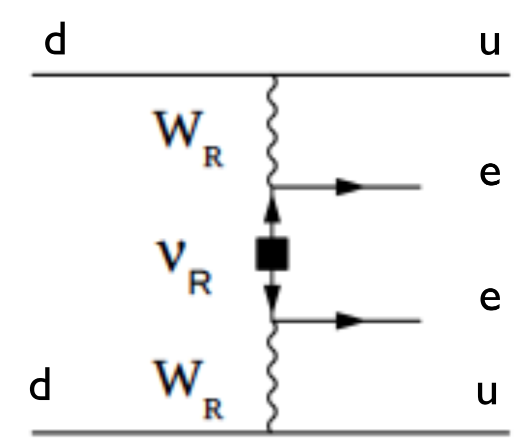
Helo-Kovalenko-Hirsch-Pas 1303.0899, 1307.4849

...

Classic LRSM example



LHC



$0\nu\beta\beta$

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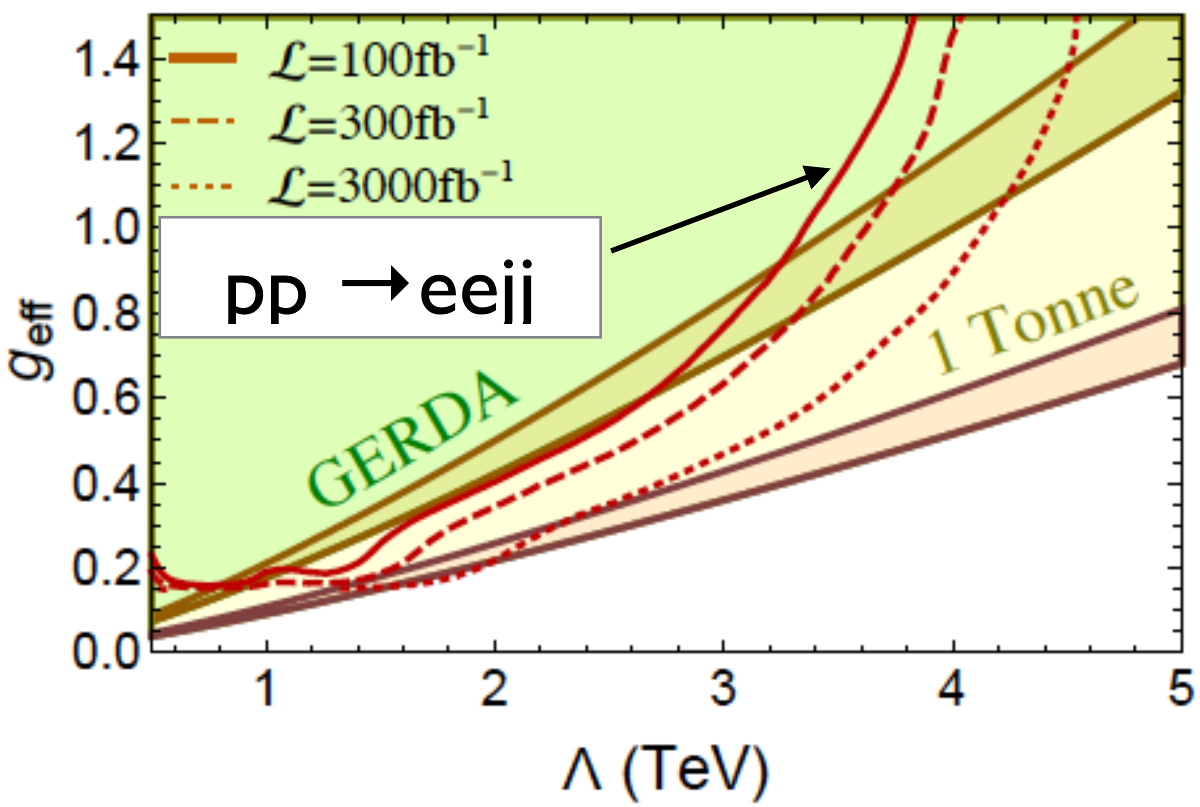
Keung-Senjanovic '83

Maiezza-Nemevesek-Nesti- Senjanovic 1005.5160

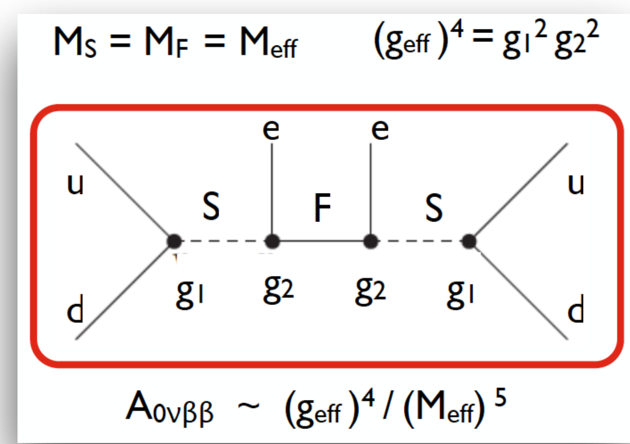
Helo-Kovalenko-Hirsch-Pas 1303.0899, 1307.4849

Peng, Ramsey-Musolf, Winslow, 1508.0444

...



Simplified model



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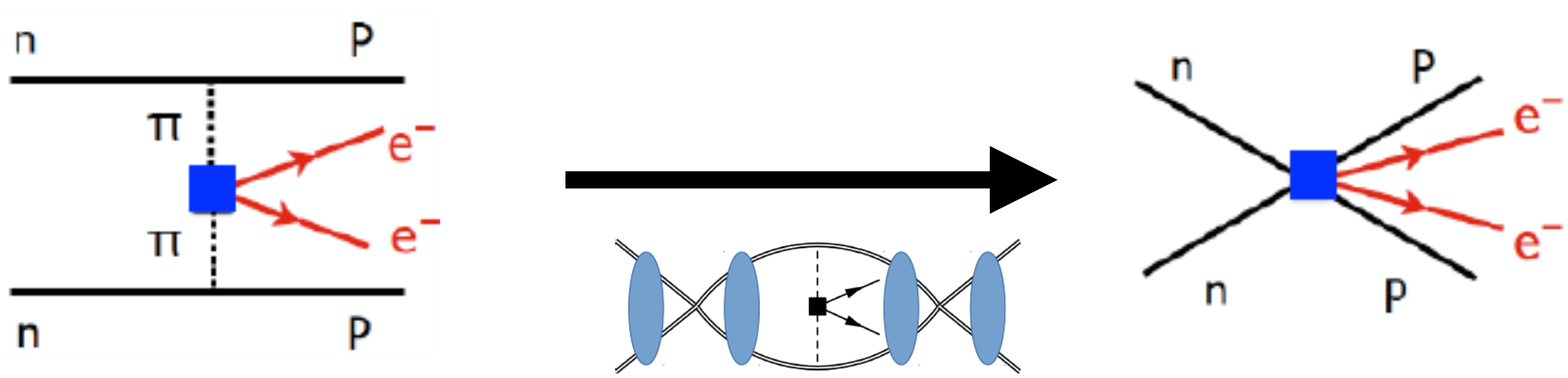
- Induce contributions to $0\nu\beta\beta$ *not directly related to the exchange of light neutrinos,* within reach of current experiments

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

- Chiral EFT: several unknown leading-order NN contact interactions. Needed to probe physics beyond high-scale seesaw and assess the complementarity to collider searches. Opportunity for lattice QCD

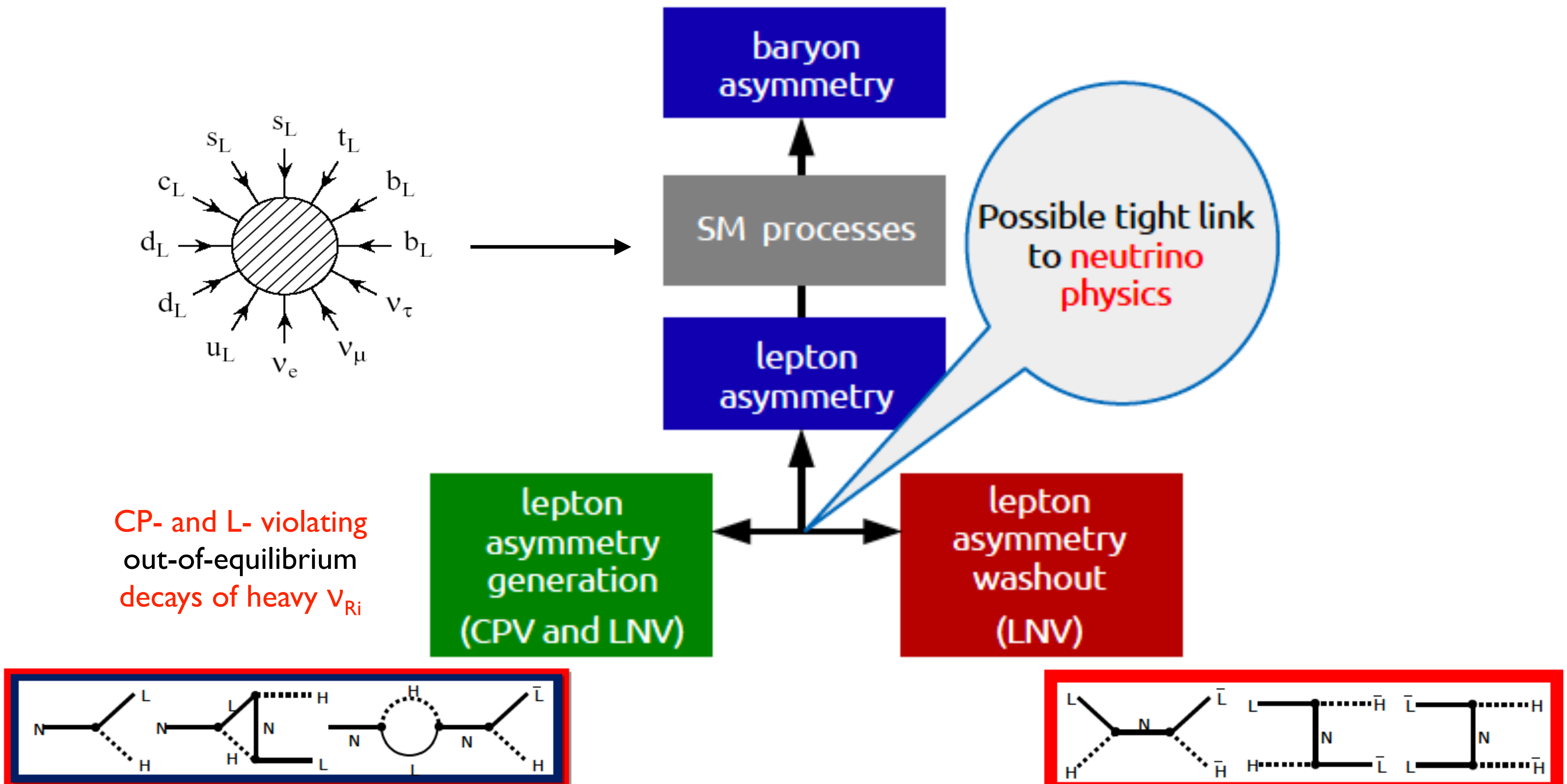


V.C, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti [1806.02780]

Connection to Leptogenesis

- LNV contributes to both generating and destroying a lepton asymmetry
  ⇒ LNV processes can be used to falsify leptogenesis

Deppisch-Harz-Hirsch 1312.4447, Deppisch-Harz-Hirsch-Huang-Pas 1503.04825, Deppisch-Graf-Harz-Huang 1711.10432, …

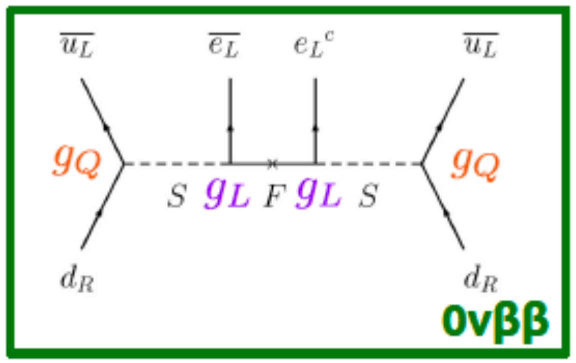


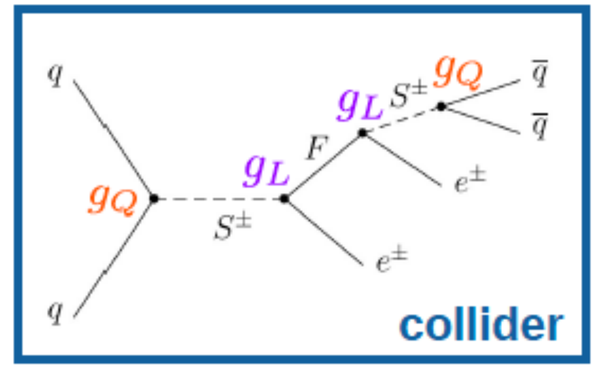
Graphic from Julia Harz

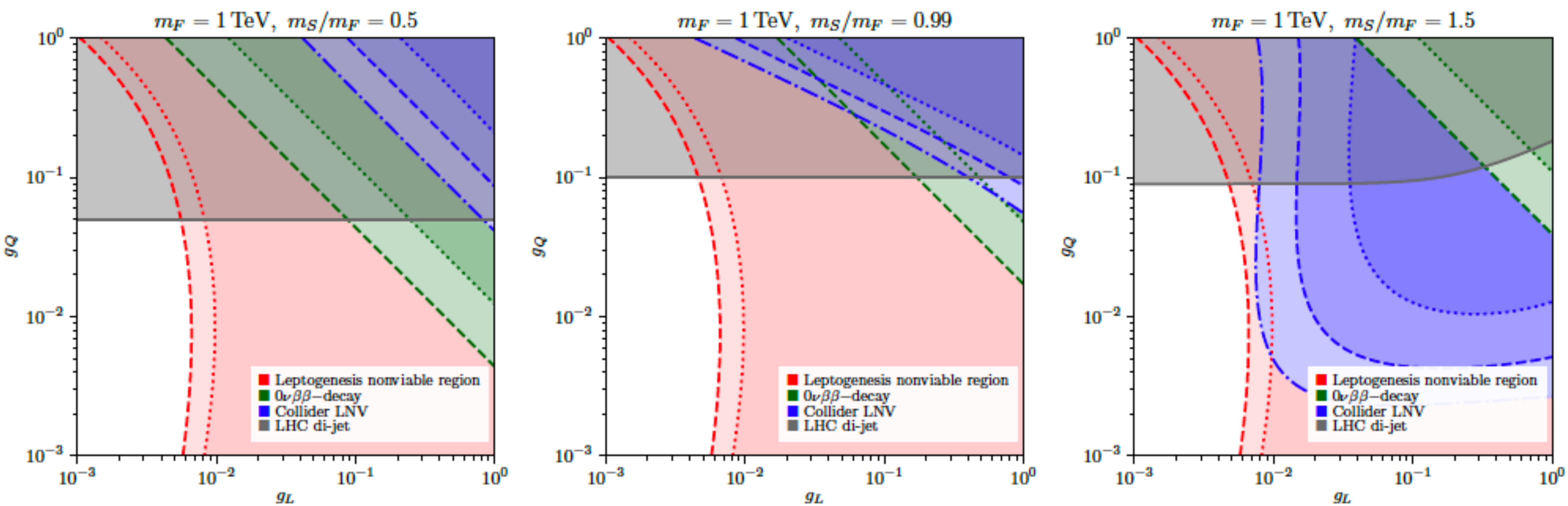
An explicit example

Harz, Ramsey-Musolf, Shen, Urrutia-Quiroga, 2106.10838

$$\mathcal{L} = g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2}\overline{F^c}F + g_S (S^\dagger S)^2 + \lambda_{HS}(S^\dagger H)^2 + \text{h.c.}$$







- Observation of LNV possible only in region where leptogenesis is not viable

$0\nu\beta\beta$ outlook

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

- Model diagnosing: what is the underlying source of LNV?
  - Within $0\nu\beta\beta$: rate variation with isotope; single electron spectra and electron's angle distribution
  - $0\nu\beta\beta$ + other probes: oscillations, direct m_ν measurements, cosmology, meson & lepton decays, LNV @ colliders, LFV, …

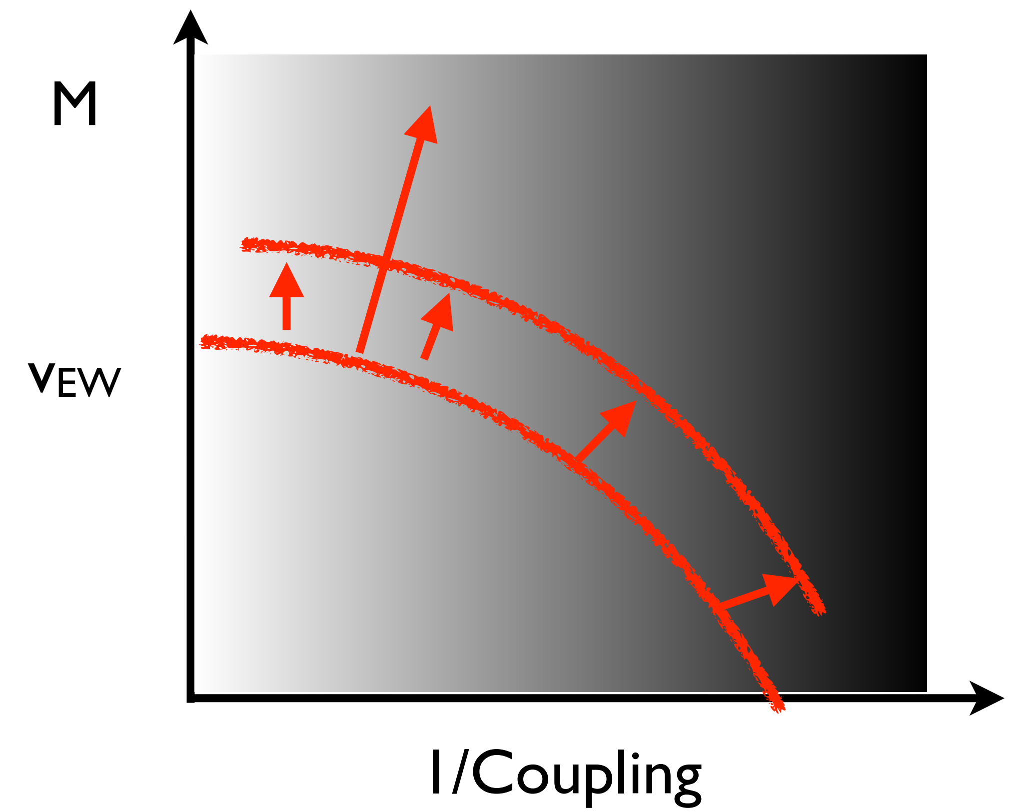
- Good prospects to control theoretical uncertainties thanks to synergy of EFT, lattice QCD, and nuclear structure

Concluding comments

- Vibrant experimental program exploring violation of Standard Model accidental symmetries (B,L, $L_{e,\mu,\tau}$) and near-symmetries (CP)

- Probe very high scales

- Can shed light on open questions (baryon asymmetry, neutrino mass, unification, …)



Looking forward to exciting experimental results!