Review of $0\nu\beta\beta$ Theory Mini Workshops

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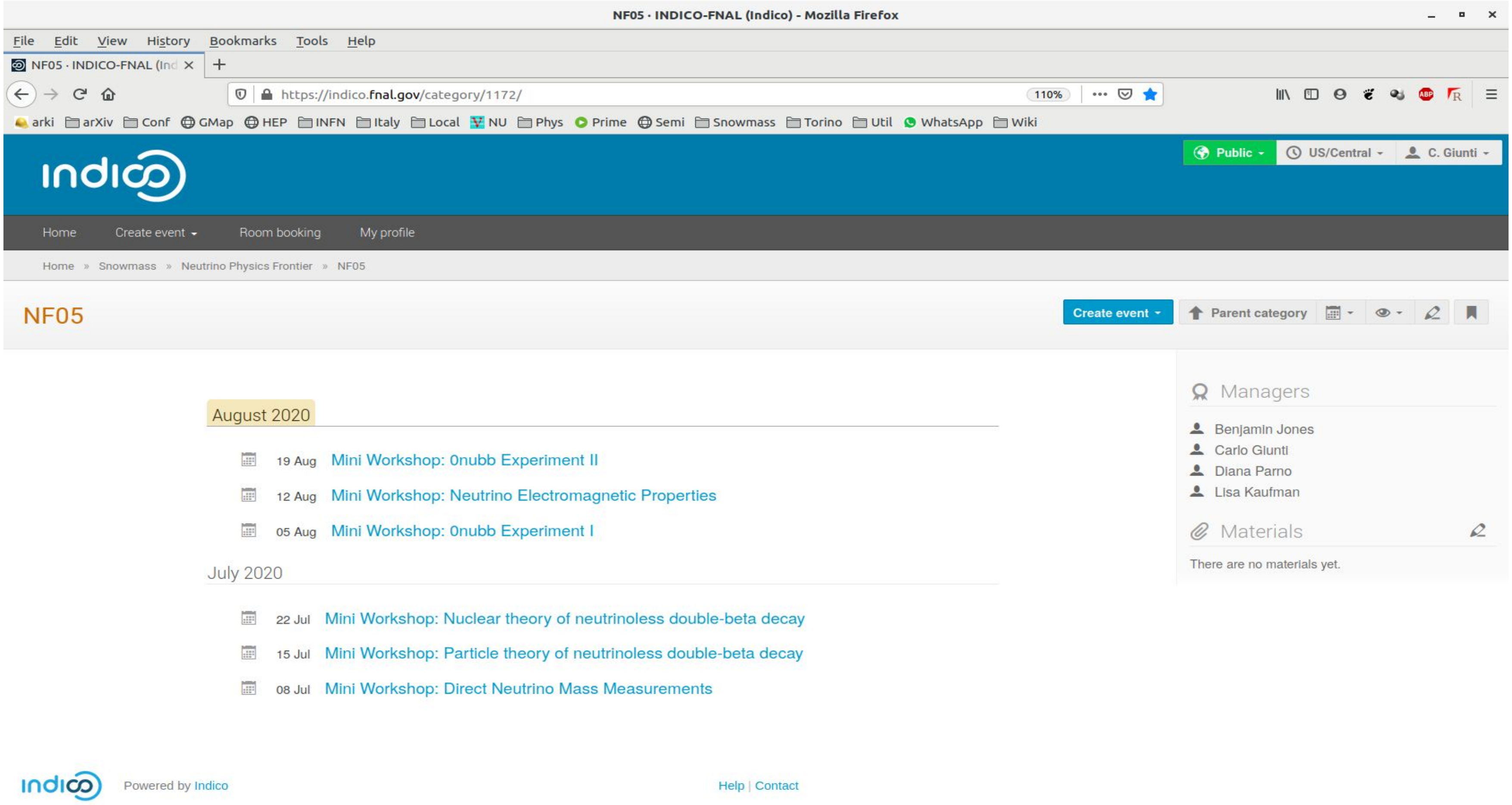
For the Snowmass 2021 Topical Group on Neutrino Properties (NF05)
Conveners: Ben Jones, Carlo Giunti, Diana Parno, Lisa Kaufman

Snowmass 2021 Mini Workshops on Neutrino Properties



NF05

August 2020

- 19 Aug Mini Workshop: 0nubb Experiment II
- 12 Aug Mini Workshop: Neutrino Electromagnetic Properties
- 05 Aug Mini Workshop: 0nubb Experiment I

July 2020

- 22 Jul Mini Workshop: Nuclear theory of neutrinoless double-beta decay
- 15 Jul Mini Workshop: Particle theory of neutrinoless double-beta decay
- 08 Jul Mini Workshop: Direct Neutrino Mass Measurements

Managers

- Benjamin Jones
- Carlo Giunti
- Diana Parno
- Lisa Kaufman

Materials

There are no materials yet.

15 July Mini Workshop: Particle theory of $0\nu\beta\beta$ decay

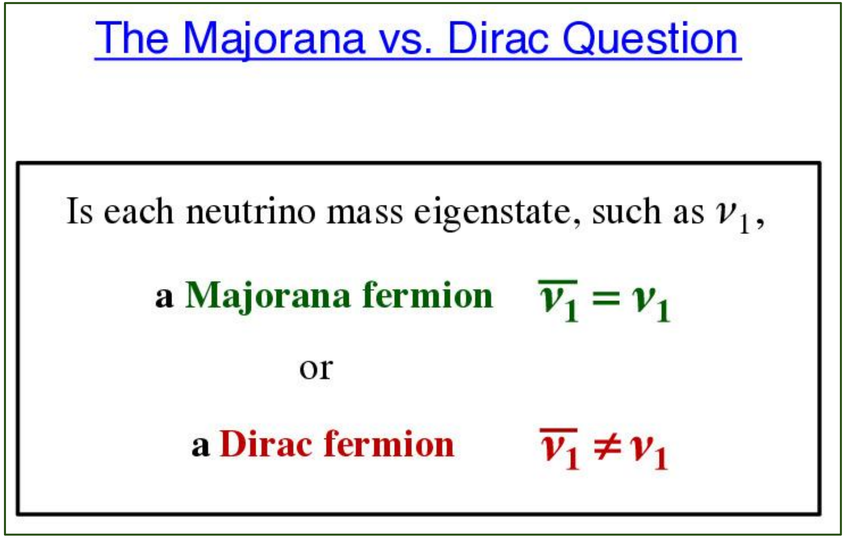
1. **Boris Kayser** (Fermilab)
   Introduction to $0\nu\beta\beta$ theory

2. **Michele Maltoni** (UAM/CSIC, Madrid)
   Neutrino masses and $0\nu\beta\beta$ from neutrino oscillations

3. **Silvia Pascoli** (Durham U.)
   CP violation in $0\nu\beta\beta$

4. **Michael Ramsey-Musolf** (Massachusetts U., Amherst)
   Non-standard contributions to $0\nu\beta\beta$

Boris Kayser: Introduction to $0\nu\beta\beta$ theory



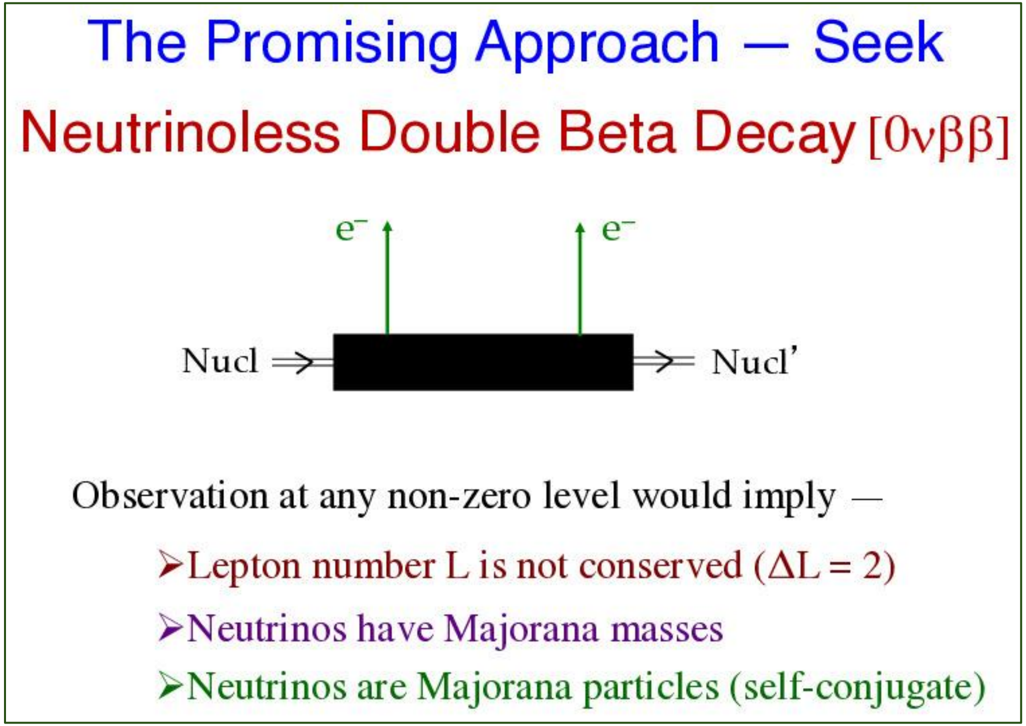
The Majorana vs. Dirac Question

Is each neutrino mass eigenstate, such as ν_1,

a **Majorana fermion** $\overline{\nu_1} = \nu_1$

or

a **Dirac fermion** $\overline{\nu_1} \neq \nu_1$



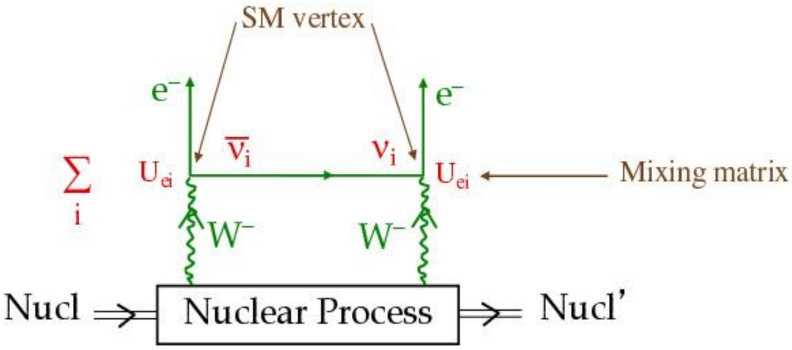
The Promising Approach — Seek Neutrinoless Double Beta Decay [$0\nu\beta\beta$]

Observation at any non-zero level would imply —

- Lepton number L is not conserved ($\Delta L = 2$)
- Neutrinos have Majorana masses
- Neutrinos are Majorana particles (self-conjugate)

Boris Kayser: Introduction to 0νββ theory

If the dominant mechanism is —

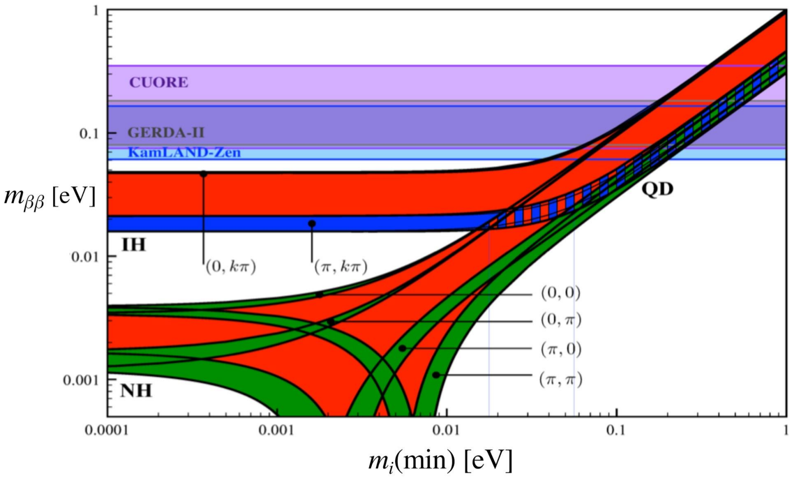


Then —

$$\mathrm{Amp}[0\nu\beta\beta] \propto \left|\sum \overset{\text{Mass }(\nu_i)}{m_i} U_{ei}^{2}\right| \equiv m_{\beta\beta}$$

$$\text{Thus } m_{\beta\beta} = \left| m_1 c_{12}^2 c_{13}^2 e^{i\alpha_1} + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_2} + m_3 s_{13}^2 e^{-2i\delta} \right| .$$

Possible Size of $m_{\beta\beta}$



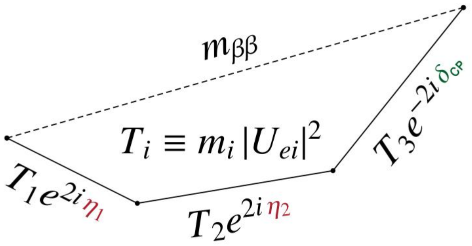
Pascoli

Absolute neutrino mass scale and $0\nu\beta\beta$

- Quantities sensitive to absolute ν masses: $m_\beta = \sqrt{\sum_i m_i^2 \left|U_{ei}\right|^2}$ and $m_{\beta\beta} = \left|\sum_i m_i U_{ei}^2\right|$;
- these new quantities depend on:
  - new parameters: lightest neutrino mass (m_0) and Majorana phases (η_1 and η_2);
  - oscillation parameters: mass-squared (Δm^2_{21}, Δm^2_{31}) and mixings (θ_{12}, θ_{13}, δ_{CP});
- notice that:
  - θ_{23} does not appear in U_{ei} $\Rightarrow$ irrelevant for m_β and $m_{\beta\beta}$;
  - only combinations $(\delta_{\text{CP}} + \eta_i)$ enter $m_{\beta\beta}$ $\Rightarrow$ specific δ_{CP} value is not relevant;
- hence, phenomenological picture only affected by $(\theta_{13}, \theta_{12}, \Delta m^2_{21}, \Delta m^2_{31})$.

NO:
$$\begin{cases} m_3^2 = m_1^2 + \Delta m^2_{31} \\ m_2^2 = m_1^2 + \Delta m^2_{21} \\ m_1^2 = m_0^2 \end{cases}$$

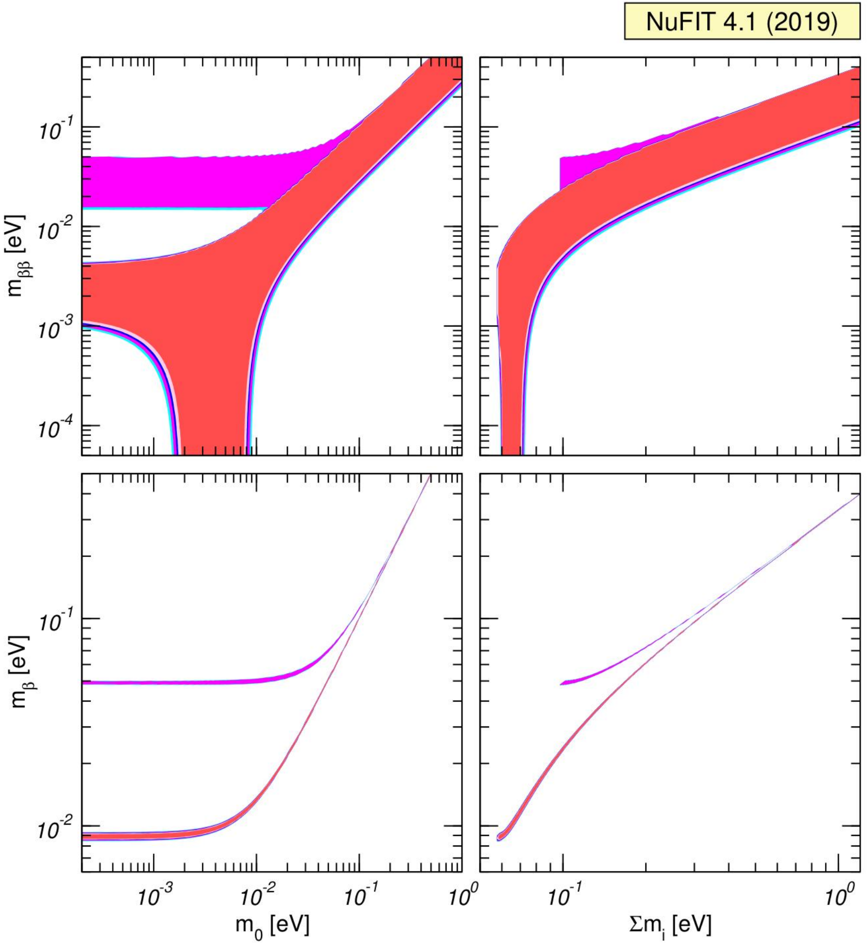
IO:
$$\begin{cases} m_2^2 = m_3^2 + \left|\Delta m^2_{32}\right| \\ m_1^2 = m_2^2 - \Delta m^2_{21} \\ m_3^2 = m_0^2 \end{cases}$$



Michele Maltoni: Neutrino masses and $0\nu\beta\beta$ from neutrino oscillations

Status of m_β and $m_{\beta\beta}$

- Results of the global fit of oscillation data can be projected onto m_β and $m_{\beta\beta}$ as a function of lightest ν mass m_0 (or $\sum m_i$);
- no neutrino ordering assumed: both cases considered on equal footing ⇒ **IO** region disfavored at $\Delta\chi^2 = 6.2$ by oscillation data (growing to $\Delta\chi^2 = 10.4$ if Super-K atmospheric data also included);
- extension of $m_{\beta\beta}$ regions dominated by unknown η_i ⇒ flat χ^2 valley closed by steep walls ⇒ 1σ, 2σ, 3σ, … ranges very similar.

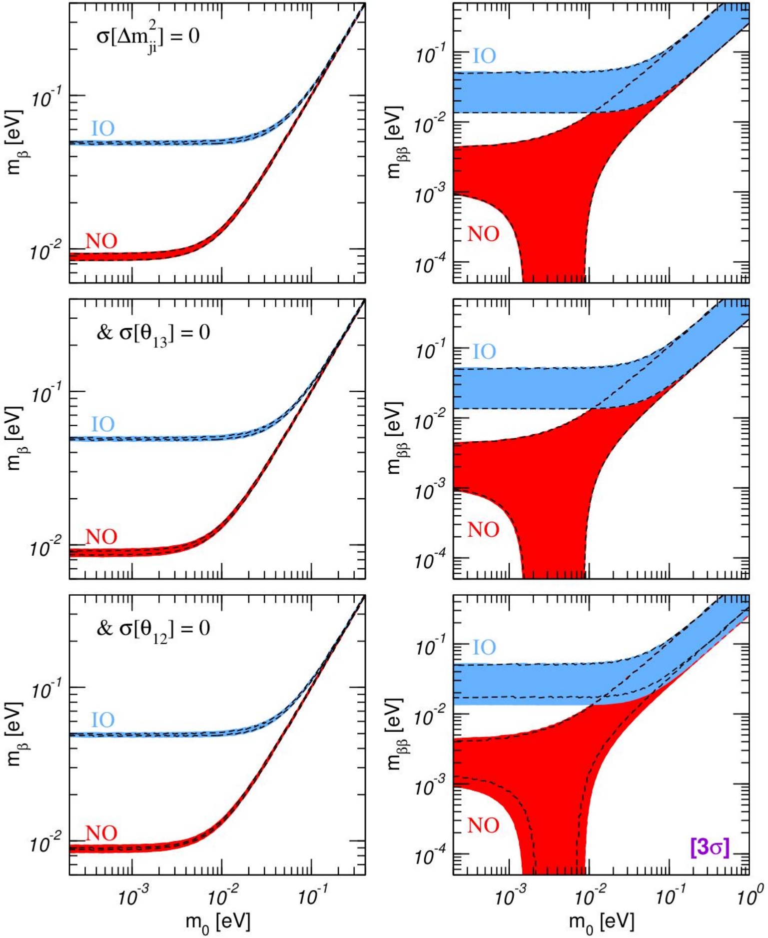


Michele Maltoni: Neutrino masses and $0\nu\beta\beta$ from neutrino oscillations

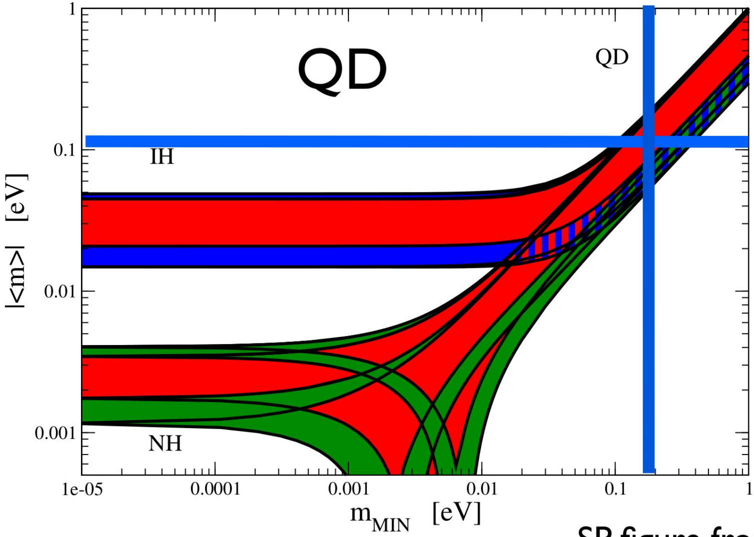
Impact of osc. parameters

- Uncertainty on Δm^2_{21} and Δm^2_{31} has negligible impact on the extension of the m_β and $m_{\beta\beta}$ regions;
- uncertainty on θ_{13} marginally affect m_β, and is irrelevant for $m_{\beta\beta}$;
- the only oscillation parameter whose precision has a visible (albeit small) impact on m_β and $m_{\beta\beta}$ ranges is θ_{12};

⇒ the present phenomenological picture will not be significantly affected by future improvements in the determination of the oscillation parameters, **except for what concerns the neutrino mass ordering**.

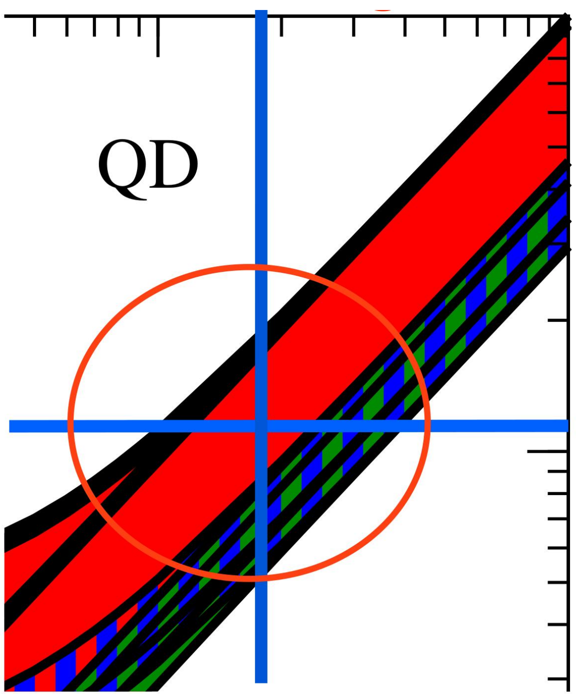


Silvia Pascoli: CP violation in $0\nu\beta\beta$



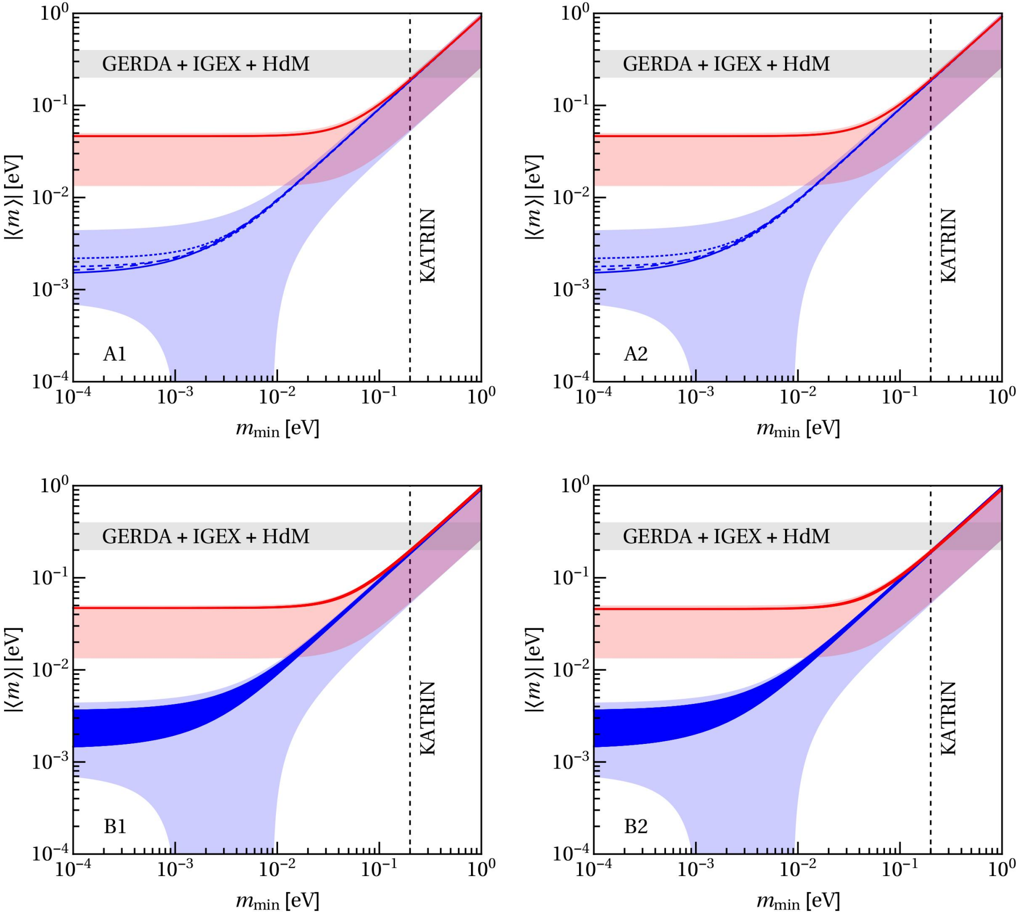
SP, figure from PDG

If m_{ee} and neutrino masses are measured with sufficient precision, then it may be possible to establish CPV due to Majorana phases.



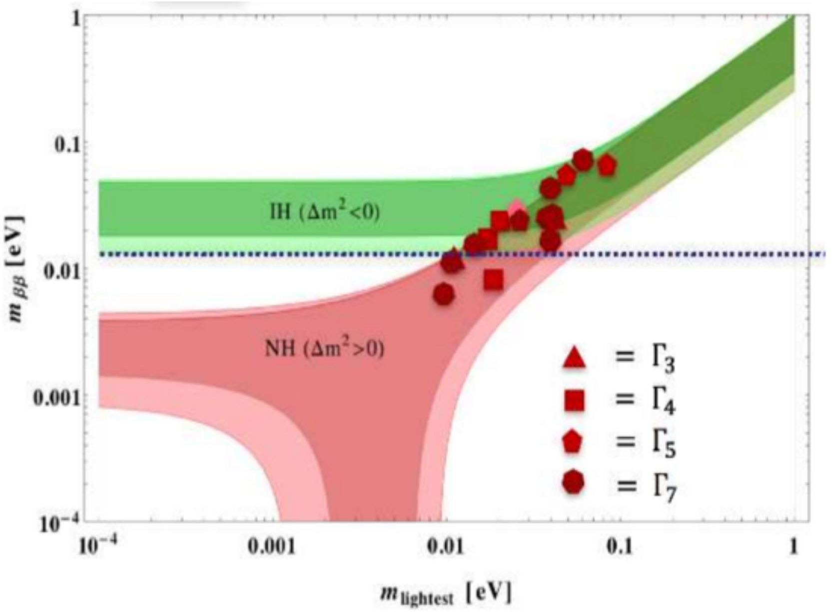
However, this requires also a very precise determination of NME.

Silvia Pascoli: CP violation in $0\nu\beta\beta$



I. Girardi, S. T. Petcov, A. Titov, 1605.04172

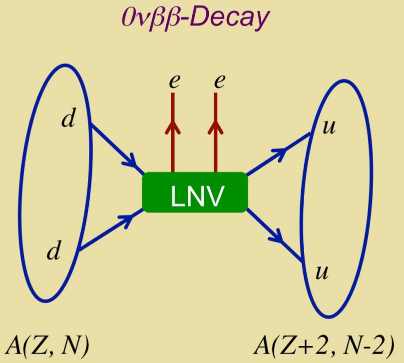
Examples of model predictions

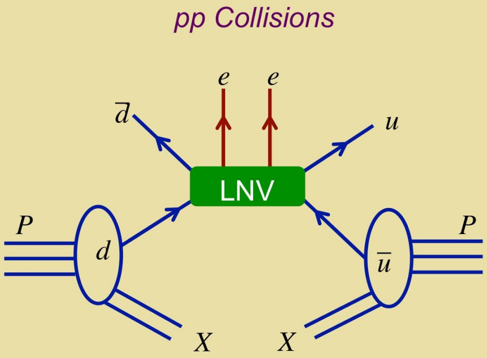


F. Feruglio, Bethe Colloquium, 18 June 2020,

Michael Ramsey-Musolf: Non-standard contributions to $0\nu\beta\beta$

TeV Scale LNV: $0\nu\beta\beta$-Decay & Colliders





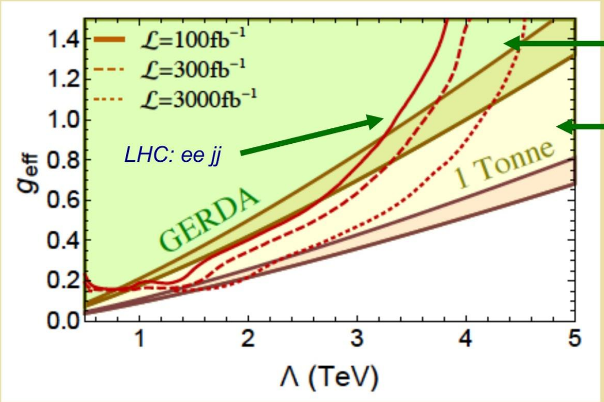
Simplified Model: Illustrative Case

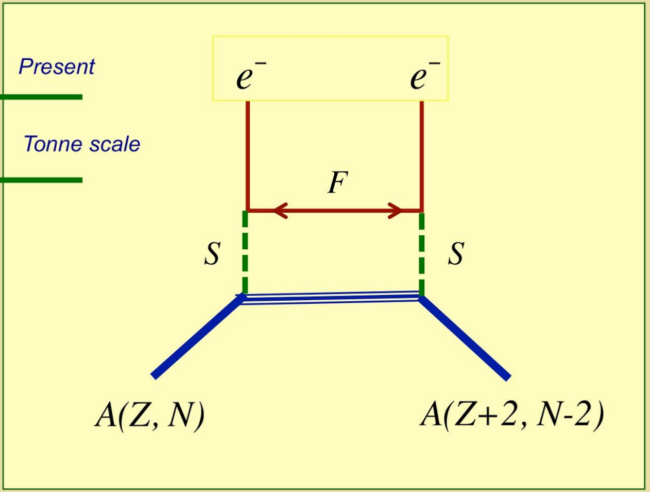
$$\mathcal{L}_{\rm INT} = g_1 \bar{Q}_i^a d^a S_i + g_2 \epsilon^{ij} \bar{L}_i F S_j^* + \mathrm{H.c.}$$

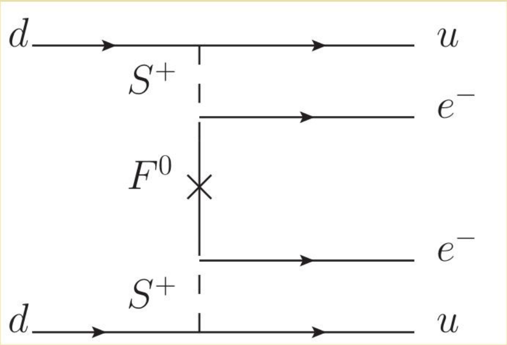
S: (1, 2, ½)

F: (1, 0, 0) Majorana

Benchmark Sensitivity: TeV LNV







LHC: pp → jj e^-e^-

T. Peng, MRM, P. Winslow 1508.04444

0νββ-Decay: TeV Scale LNV & m_ν

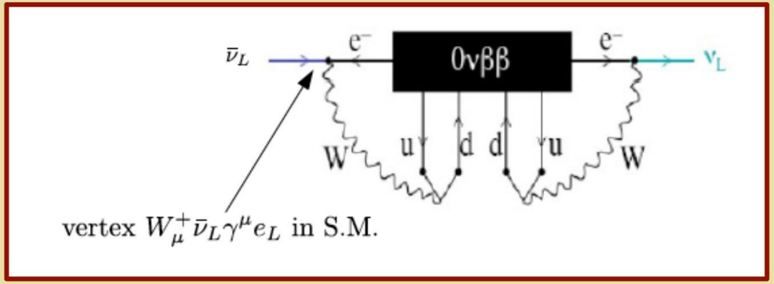
$$\mathcal{L}_{\rm mass} = y \bar{L} \tilde{H} \nu_R \; + \; \text{h.c.}$$

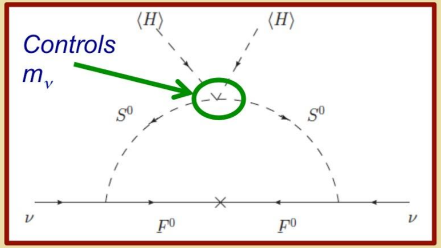
Dirac

$$\mathcal{L}_{\rm mass} = \frac{y}{\Lambda} \bar{L}^c H H^T L \; + \; \text{h.c.}$$

Majorana

Implications for m_ν:





Schecter-Valle: non-vanishing Majorana mass at (multi) loop level

Simplified model: possible (larger) one loop Majorana mass

22 July Mini Workshop: Nuclear theory of $0\nu\beta\beta$ decay

1. **Jonathan Engel** (North Carolina U.)
   Introduction to the nuclear theory aspects and problems of $0\nu\beta\beta$

2. **Jenni Kotila** (Jyvaskyla U. and Yale U.)
   Nuclear matrix elements calculations and perspectives

3. **Javier Menendez** (Barcelona U.)
   First principles calculation of $0\nu\beta\beta$

4. **Emanuele Mereghetti** (Los Alamos)
   $0\nu\beta\beta$ in effective field theory and lattice QCD

Light-ν Exchange in a Nucleus

$$[T_{1/2}^{0\nu}]^{-1} = G(Z,N)\,|M_{0\nu}|^2\, m_{\beta\beta}^2$$

Phase-space factor

Nuclear matrix element

“Traditional” part of matrix element:

$$\boxed{M_{0\nu} = M_{0\nu}^{GT} - \frac{g_V^2}{g_A^2} M_{0\nu}^{F} + \ldots} \quad \text{x } g_A^2$$

with

$$M_{0\nu}^{GT} = \langle F|\sum_{i,j} H(r_{ij})\, \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j\, \tau_i^+ \tau_j^+\ |I\rangle + \ldots$$

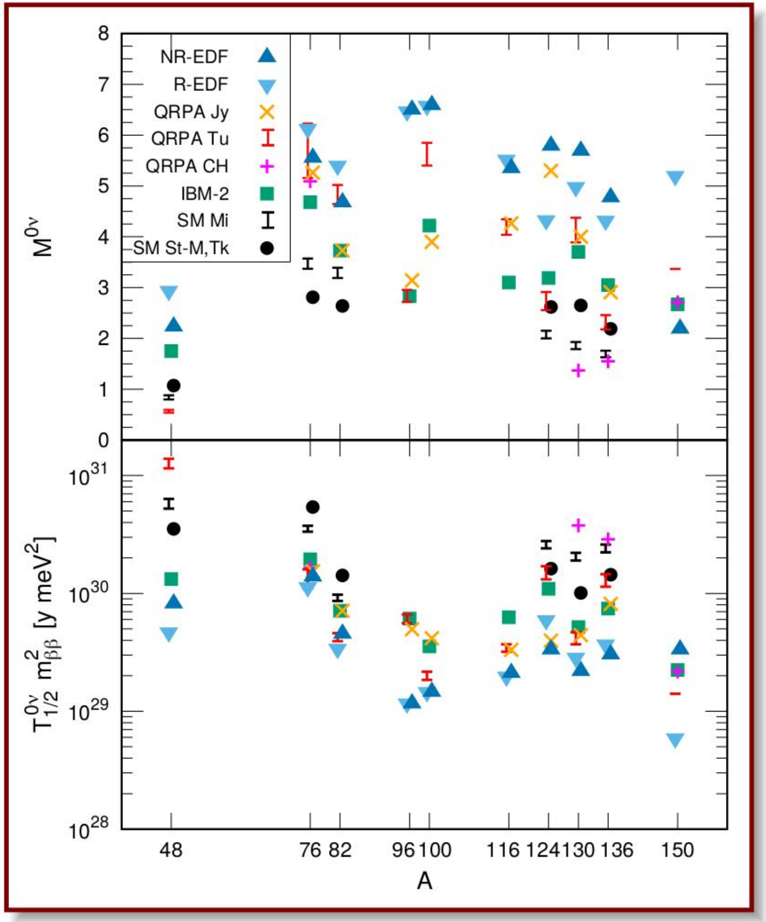
$$M_{0\nu}^{F} = \langle F|\sum_{i,j} H(r_{ij})\, \tau_i^+ \tau_j^+\ |I\rangle + \ldots$$

$$H(r) \approx \frac{2R}{\pi r}\int_0^\infty dq \frac{\sin qr}{q + \overline{E} - (E_i + E_f)/2} \quad \text{roughly} \propto 1/r$$

Corrections are from “forbidden” terms, weak nucleon form factors, many-body currents, other effects of high-energy physics that depend on framework.

Recent Values

Light-ν-Exchange Matrix Elements



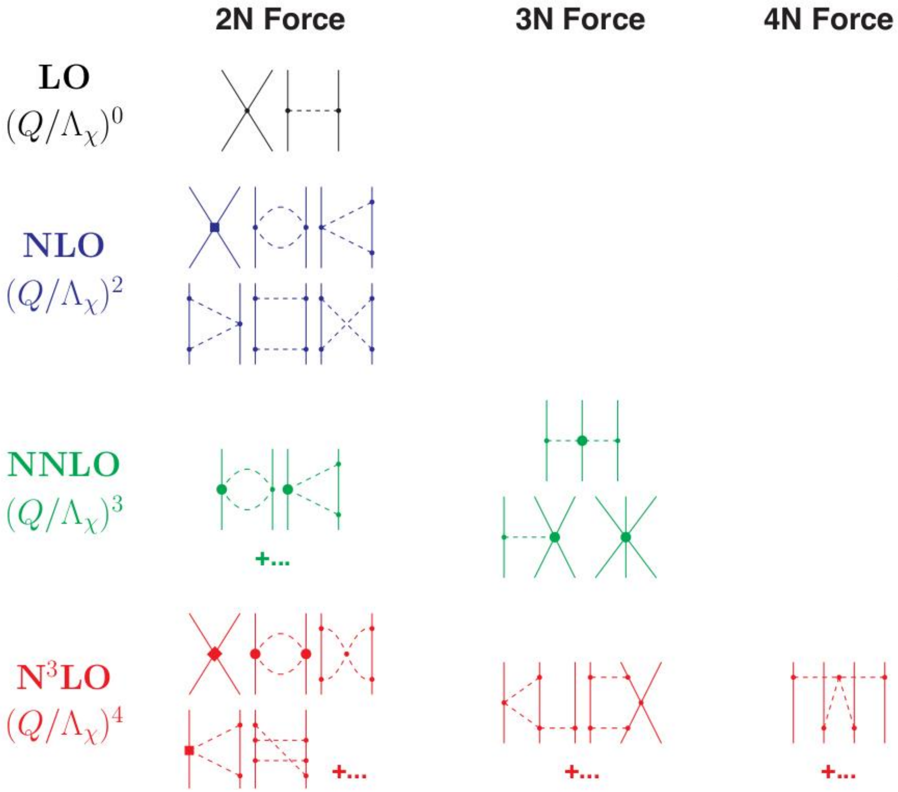
Significant spread. And all the models may miss important physics.

Uncertainty hard to quantify.

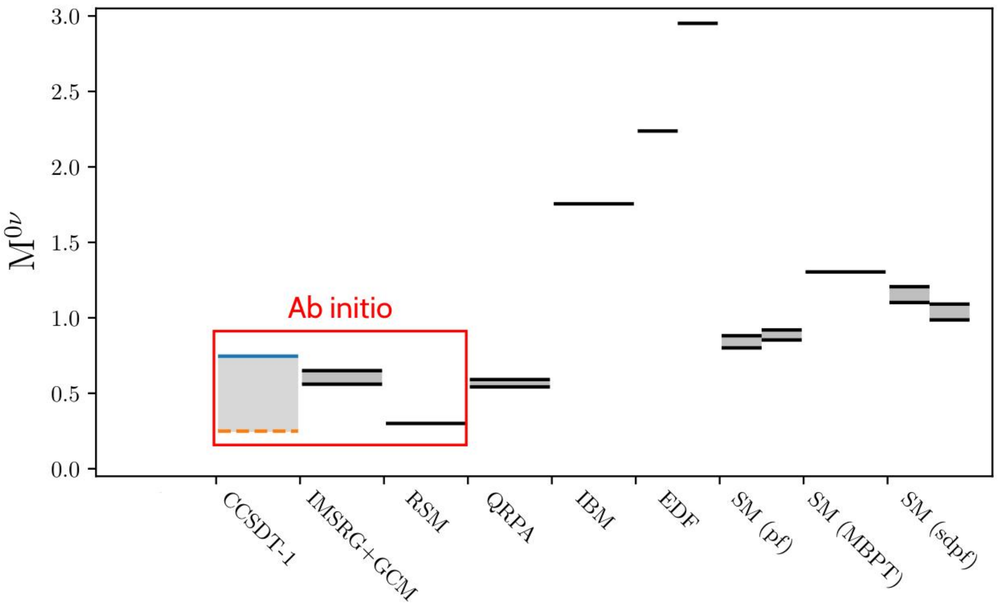
The Way Forward: Ab Initio Nuclear Theory

Starts with chiral effective field theory.

Nucleons, pions sufficient below chiral-symmetry breaking scale.



^{48}Ca: Ab-Inito $0\nu\beta\beta$ Matrix Elements vs. Older Ones



Jenni Kotila: Nuclear matrix elements calculations and perspectives

QUENCHING OF g_A

- It is well-known from single β decay/EC^* and $2\nu\beta\beta$ that g_A is renormalized in nuclei. Reasons:
  - Limited model space
  - Omission of non-nucleonic degrees of freedom($\Delta, N^*, \ldots$)

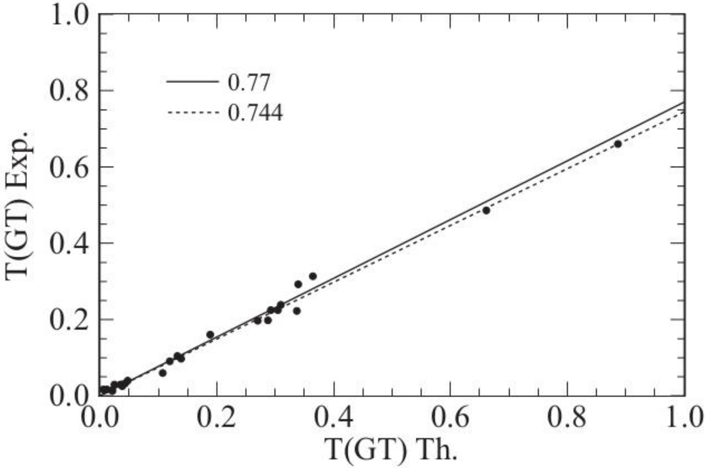
Effective value of g_A is a work in progress, since:

- Is the renormalization of g_A the same in $2\nu\beta\beta$ as in $0\nu\beta\beta$?
  - In $2\nu\beta\beta$ only the 1^+ (GT) multipole contributes. In $0\nu\beta\beta$ all multipoles 1^+, $2^-, \ldots$; 0^+, $1^-, \ldots$ contribute. Some of which could be even unquenched.
  - This is a critical issue, since half-life predictions with maximally quenched g_A are > 6 times longer due to the fact that g_A enters the equations to the power of 4!

- Additional ways to study quenching of g_A:
  - Theoretical studies by using effective field theory (EFT) to estimate the effect of non-nucleonic degrees of freedom (two-body currents)
  - Experimental and theoretical studies of single beta decay and single charge exchange reactions involving the intermediate odd-odd nuclei
  - Double charge exchange reactions

Javier Menendez: First principles calculation of $0\nu\beta\beta$

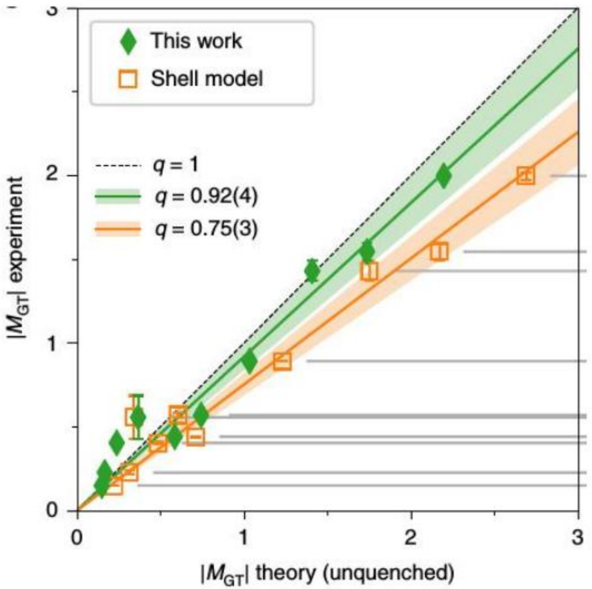
β decays (e^- capture) challenge for nuclear theory



Martinez-Pinedo et al. PRC53 2602(1996)

$$\langle F|\sum_i [g_A\, \boldsymbol{\sigma}_i \tau_i^-]^{\mathrm{eff}}\, |I\rangle\,, \quad [\boldsymbol{\sigma}_i \tau]^{\mathrm{eff}} \approx 0.7\boldsymbol{\sigma}_i \tau$$

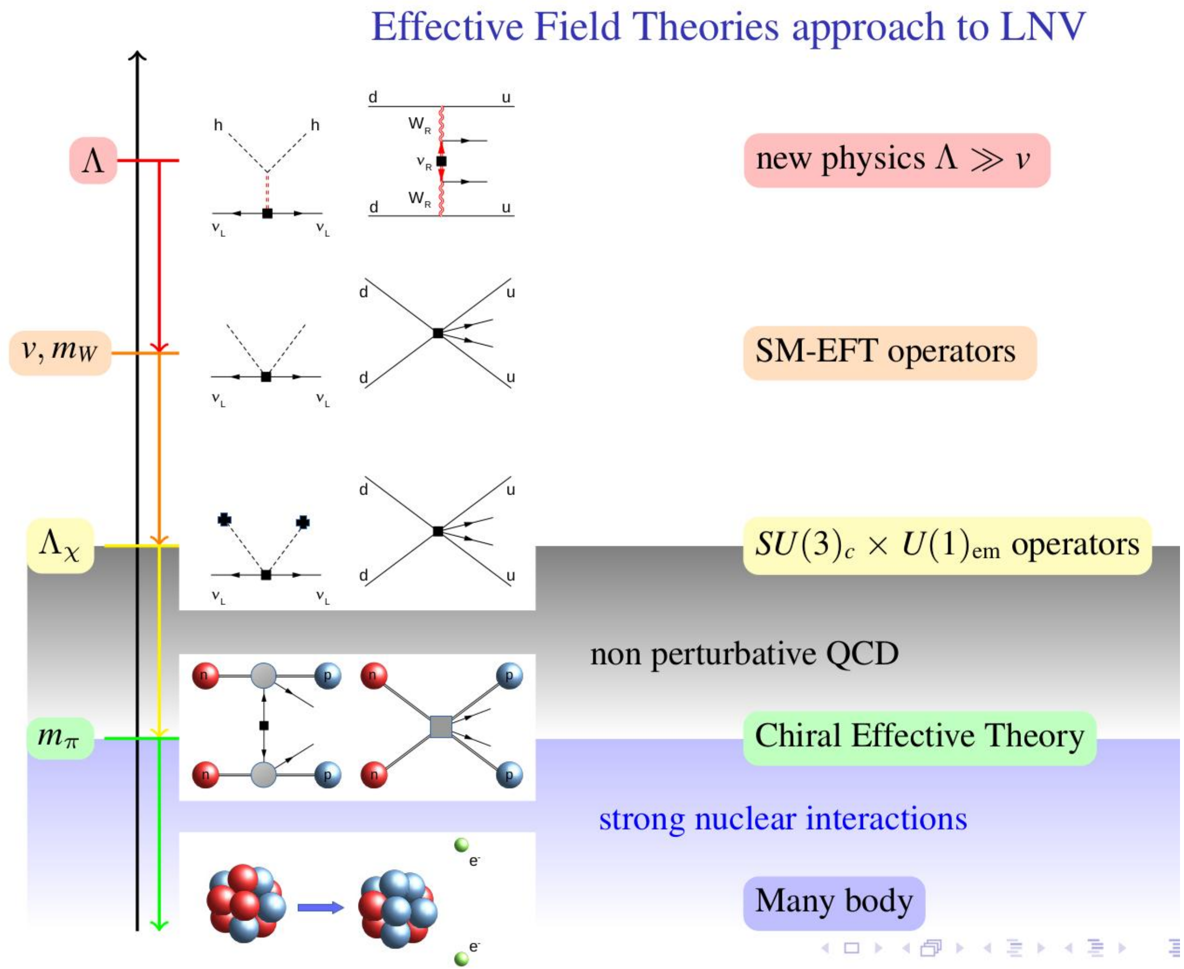
Phenomenological models
need $\boldsymbol{\sigma}_i \tau$ “quenching”



Gysbers et al. Nature Phys. 15 428 (2019)

Ab initio calculations including
meson-exchange currents
do not need any “quenching”

Emanuele Mereghetti: $0\nu\beta\beta$ in effective field theory and lattice QCD



Effective Field Theories approach to LNV

new physics $\Lambda \gg v$

SM-EFT operators

$SU(3)_c \times U(1)_{\rm em}$ operators

non perturbative QCD

Chiral Effective Theory

strong nuclear interactions

Many body

General framework to describe $0\nu\beta\beta$ generated by Lepton Number Violation at different scales

See the slides and Zoom recordings for the full discussions:

- Particle theory of $0\nu\beta\beta$ decay:

  https://indico.fnal.gov/event/43789/

- Nuclear theory of $0\nu\beta\beta$ decay:

  https://indico.fnal.gov/event/43806/

Experiments

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF$_2$ crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF$_2$ scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
Majorana Demonstrator	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF$_6$ high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	^{40}CaMoO$_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li$_2$MoO$_4$ scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li$_2$MoO$_4$ scintillating bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO$_2$ Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

R&D Construction Operating Complete

Jason Detwiler talk at Neutrino 2020

J. Detwiler

Updated from J. Wilkerson