Neutrino-less Double Beta Decays

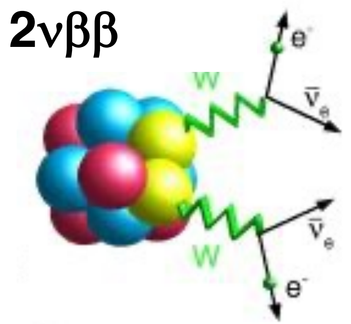
Manfred Lindner

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

Sep. 5-10, 2021 @Zoom

Double Beta Decay: SM and BSM

SM allowed process:



- 2n → 2p and Z → Z+2
- hidden behind single β-decays

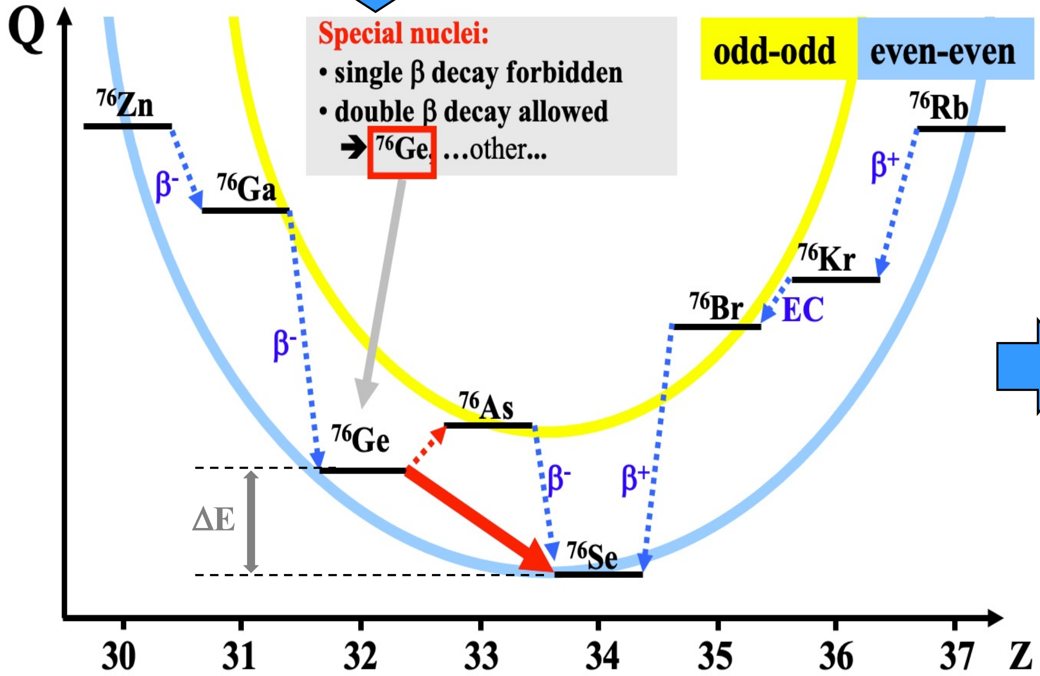
BSM add ➔

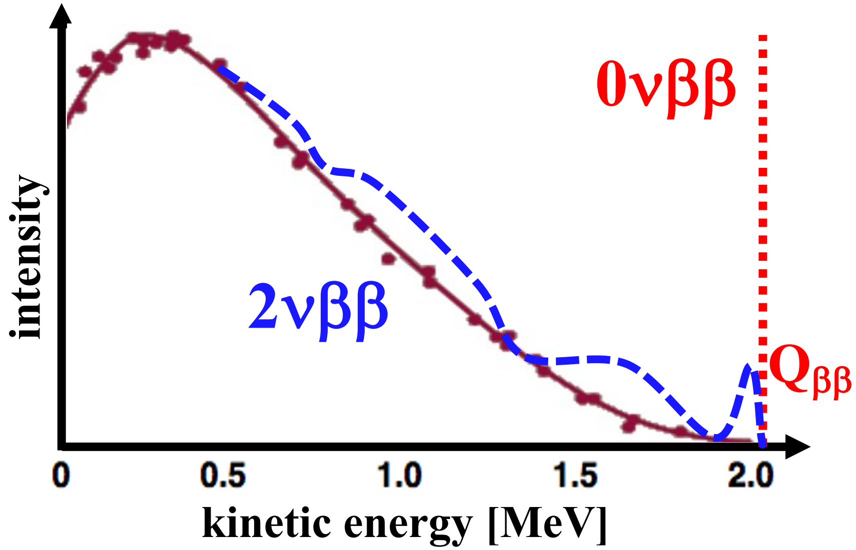
- SM: 2e+2ν ➔ spectrum

- BSM, Z→Z+2, $Q_{\beta\beta}$ ~ MeV-ish
  ➔ requires 2 electrons:

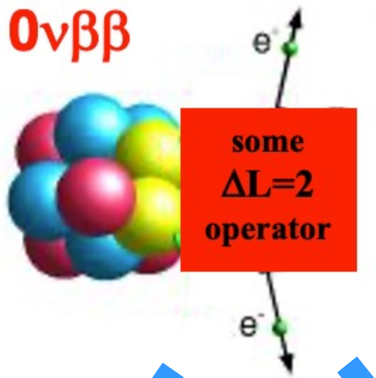
- 2e + no other particles
  ➔ line @ $Q_{\beta\beta}$ and ΔL=2

- 2e + X
  ➔ modified spectrum ≤ $Q_{\beta\beta}$

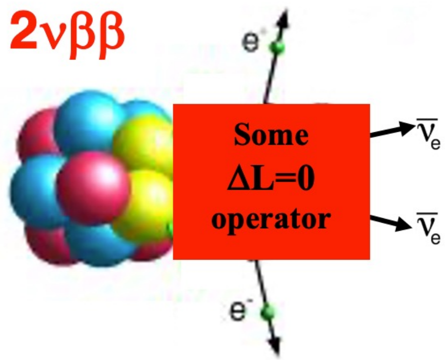




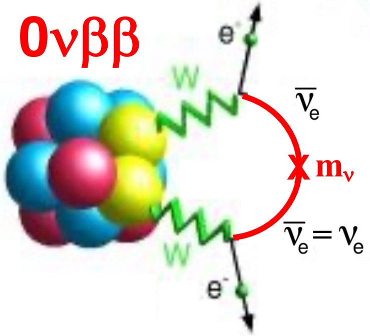
Double Beta Decay and BSM Physics



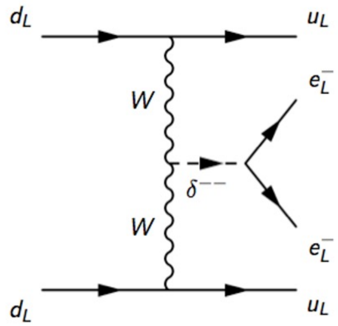
or



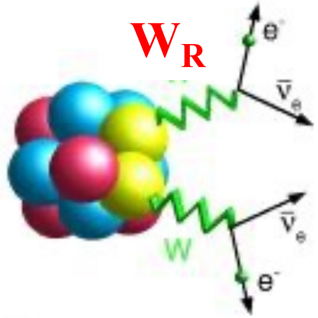
Z→ Z+2 : $\Delta q = 2$
energy @detector
MeV-ish
➔ charged & light
➔ only electrons



e.g.



e.g.



contributes to line at $Q_{\beta\beta}$

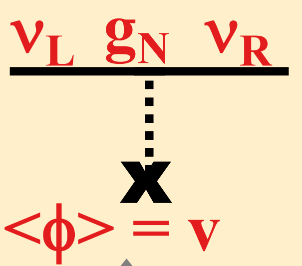
contributes to spectrum

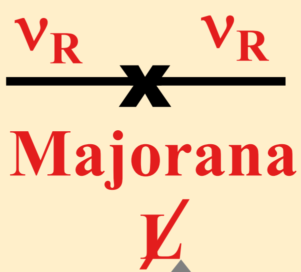
- many reasons for BSM physics with and w/o ΔL=2
- if one ignores all other reasons ➔ neutrino masses
- many BSM models affect both 0νββ and 2νββ

➔ why think only about neutrinos?

Bottom-Up from a Neutrino Perspective

Simplest: Another copy of SM field → new representation → extra gauge group → ...
➔ Simplest and suggestive possibility: right handed neutrinos





➔

$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

like quarks & charged leptons
➔ Dirac masses
(including NMS mixing)

Majorana masses
➔ new scales
lepton number violation

6x6 block mass matrix
Diagonalization ➔ see-saw
M_R heavy ➔ 3 light ν's

Assumptions:

- 3 right handed neutrino states
  ➔ complete gauge singlet $(1_c, 1_L, Y=0)$
- no extra symmetry which forbids L violation

Consequences:

- new parameters
- modified symmetries: L violation
- nice explanation of light neutrinos
- multi-scale theory

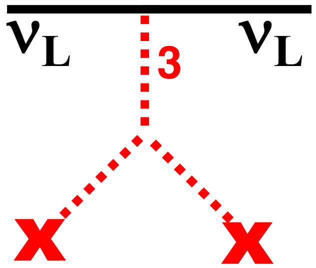
➔ SM+

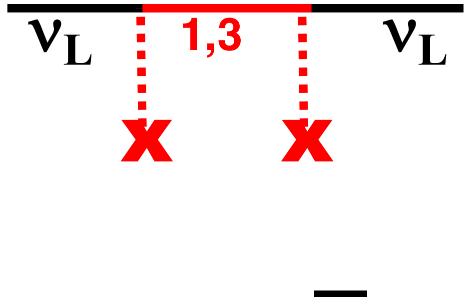
Many other Possibilities

- add scalar triplets (3_L) or add fermionic (1_L) or (3_L)

→ Majorana masses without ν_R:

$M_L LL^c$





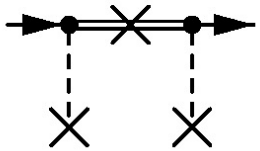
- add both ν_R and new singlets / triplets:

→ see-saw type II, III

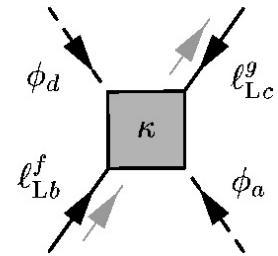
$m_\nu = M_L - m_D M_R^{-1} m_D^T$

- add higher dimensional operators: d=5, …

→ model independence



$\Rightarrow$

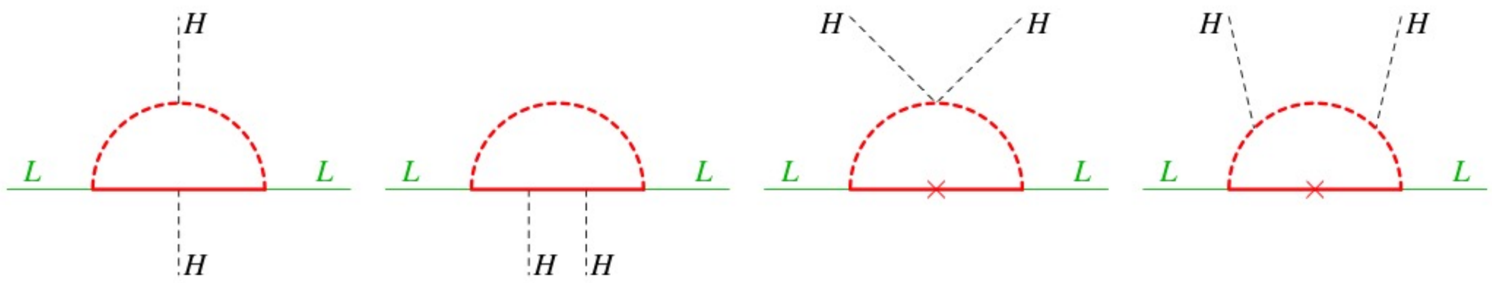


$\Leftrightarrow$

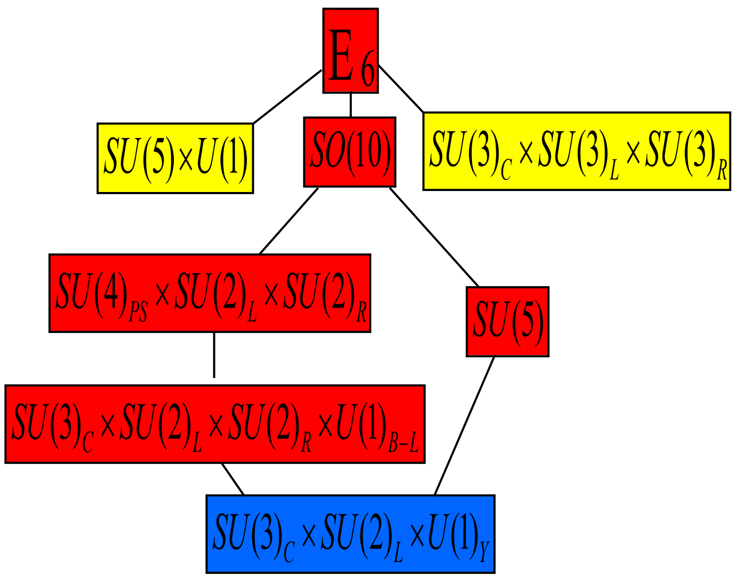
$\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}_L^C \nu_L \Phi^T \Phi$

→ $M_L \overline{L} L^c$

- Radiative neutrino mass generation ←→ BSM

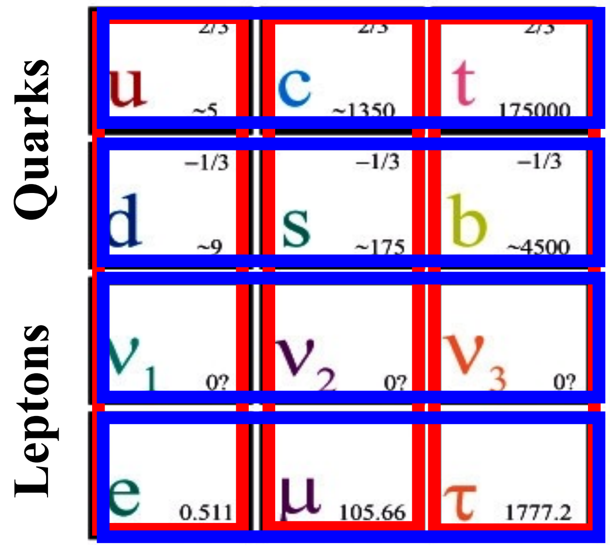


- Gauge unification, GUTs and Flavour symmetries



Generations are only copies
➔ horizontal symmetries?
A4, S3, D5, T‘, ...
breaking...
➔ explain regularities

more options ←→ more constrains, precision



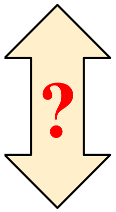
generation 1. 2. 3.

- **More:** further ν‘s, SUSY, gauge groups, extra d, strings,…

What is realized in Nature?

A huge number of options and a huge parameter space...
... but we know little: 2x Δm^2, mixings, ~mass, unitarity bounds, astro/cosmo

- **choose a 'minimal model' and explain all there is (so far...)**



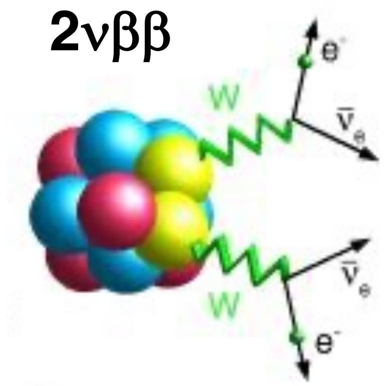
  - three ν_R to explain only masses and mixings
  - νMSM → keV neutrinos as DM, BAU (Shaposhnikov et al.)
  - often leaves other questions out (e.g. unification, inflation, DE, flavour, ...)

- **many wider and very well motivated BSM options & hints**
  - often connected to other fields ➔ involves well motivated new physics
  - must explain all existing data in neutrino physics and in other fields
    - ➔ connections to other fields: LFV, LHC, DM
  - must be consistent with diverse theoretical contraints
    - ➔ BBN, cosmology, SN explosions, ...
    - ➔leptogenesis ←→ variants, other BAU
    - ➔ keV sterile ν's as warm dark matter ←→ other DM candidates

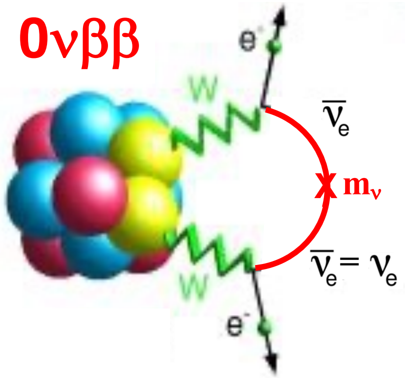
WE DON'T KNOW ➔ be open minded!

Majorana Neutrino Interpretation of 0νββ

SM

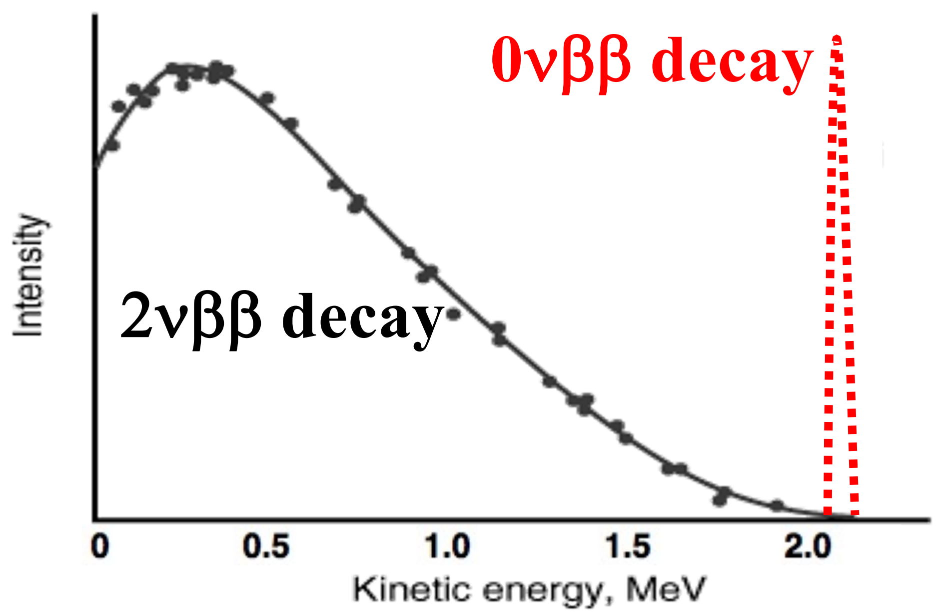


assume Majorana mass



2νββ decay seen for different isotopes

$T^{1/2} = O(10^{18} - 10^{21}$ years) ➔ up to $10^{11} \otimes T_{Universe}$



$$1/\tau = G(Q,Z)\,|M_{nucl}|^2 <m_{ee}>^2$$

lifetime τ

NMEs have uncertainties…

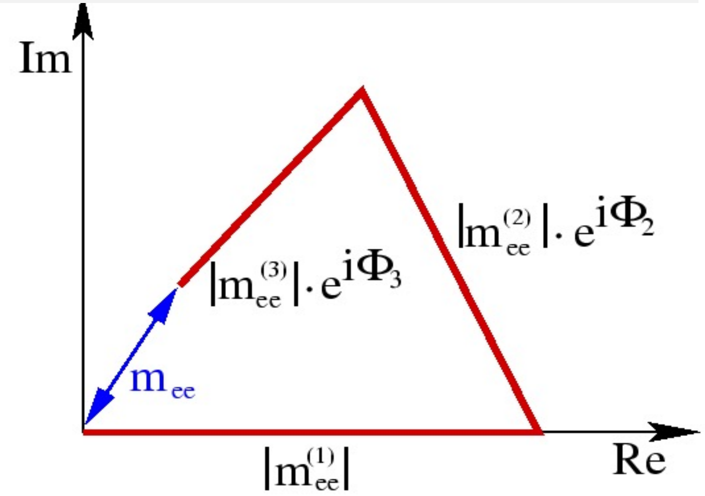
- observe expected 2νββ signal
- look for a line at $Q_{\beta\beta}$

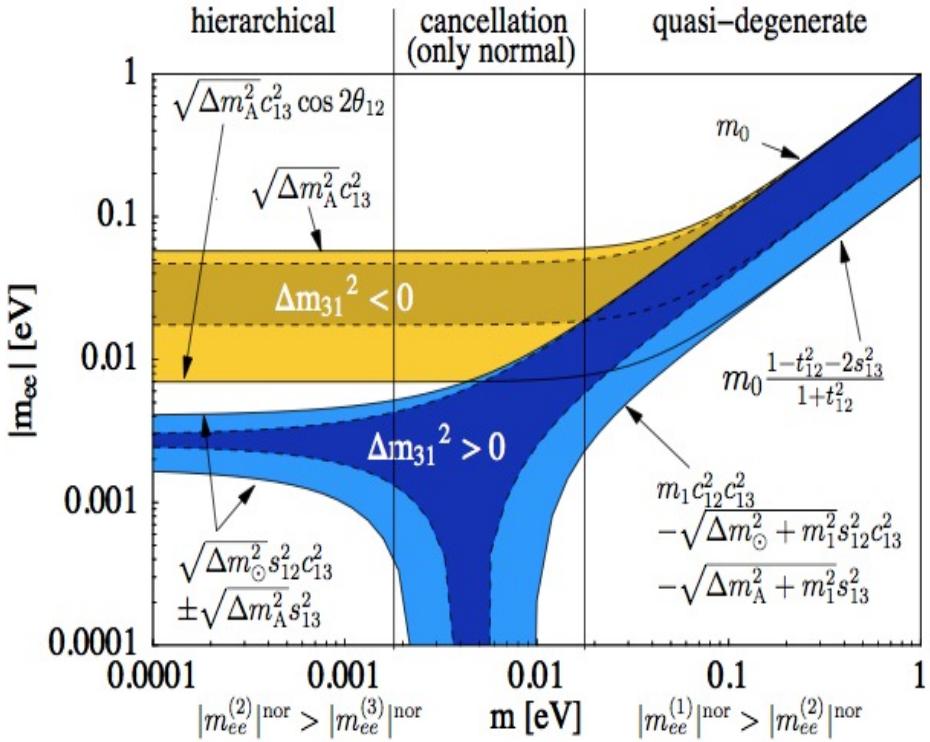
interprete signal ➔ **Majorana mass**

m_{ee}: The Effective Neutrino Mass

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}| \cdot e^{i\Phi_2} + |m_{ee}^{(3)}| \cdot e^{i\Phi_3}$$

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1$$
$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2}$$
$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2}$$





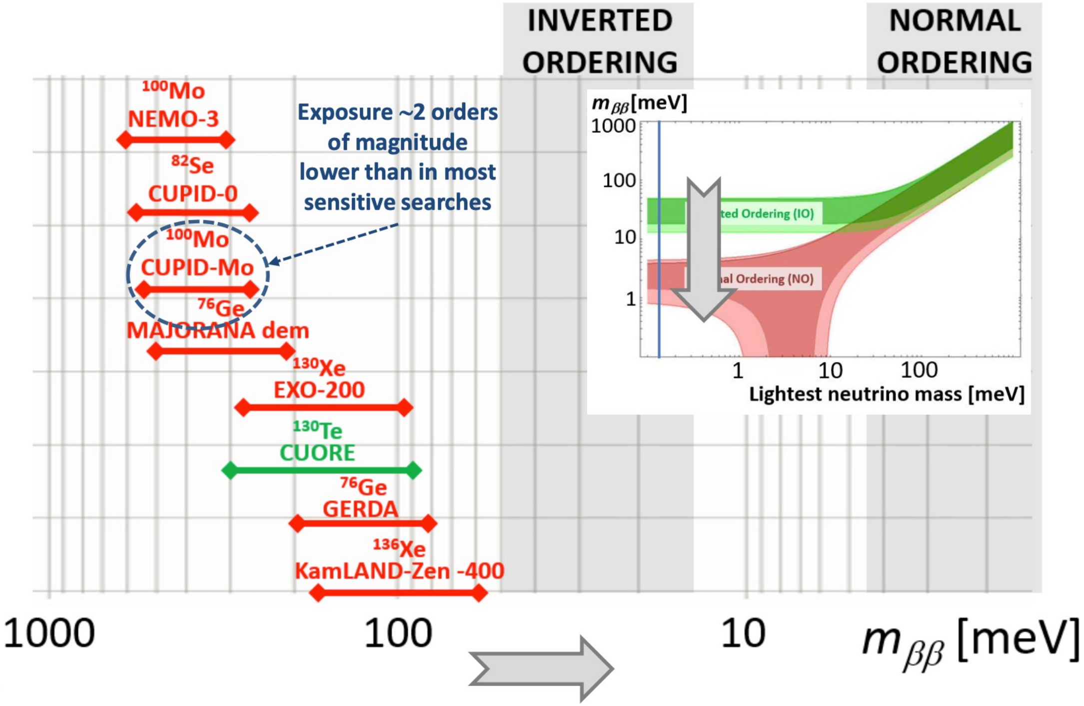
Comments:
- NMEs ➔ unavoidable theory errors
- known Δm^2 from oscillations
  TH + EX errors → bands

- ton-scale projects aim at covering IH
- global fits ...NH?
- cosmology...

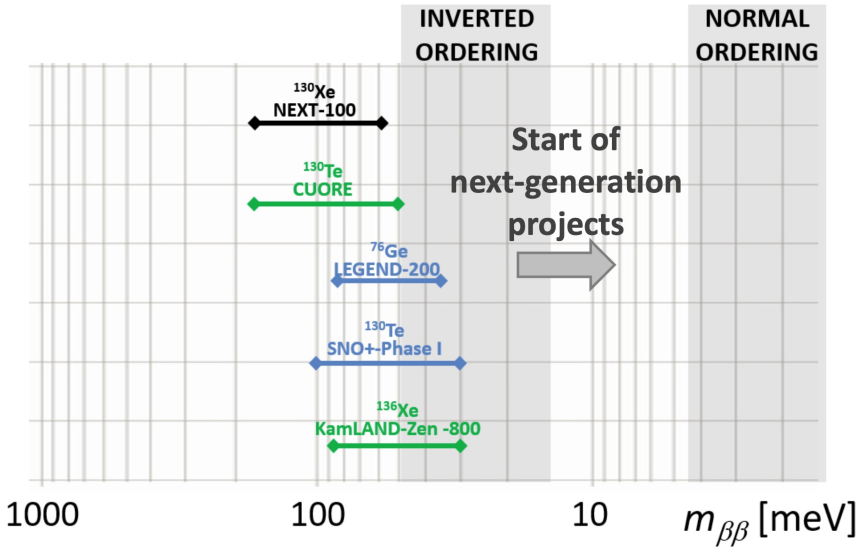
- **Assumption:** No other BSM physics...!

Experimental Status & Outlook

A. Giuliani, talk at TAUP2021, https://indico.ific.uv.es/event/6178/

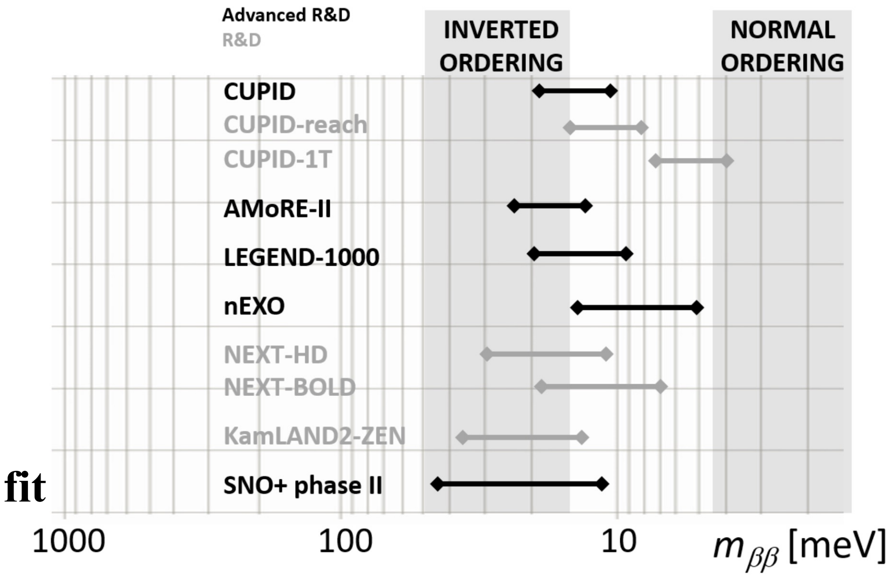


possible ~5y situation

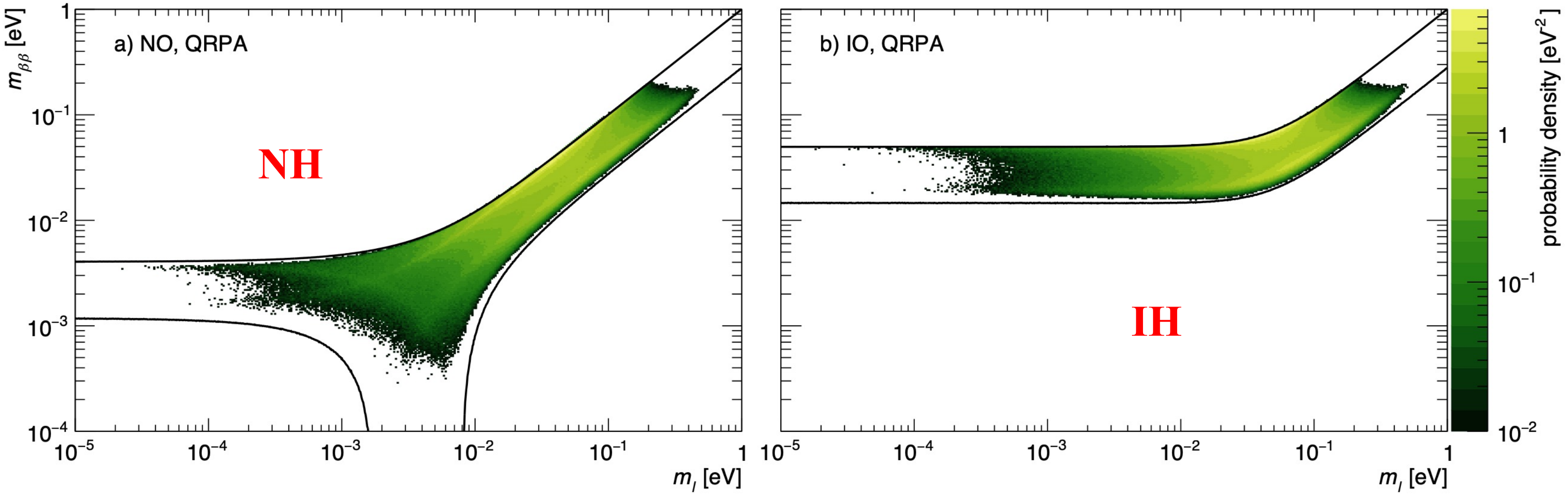


- ➢ next years: start to cov er all IH
- ➢ in the long run:
  - will cover all of IH
  - improved BSM tests
  - so far no convincing project to test (most) NH
- ➢ while waiting: watch NH preference
  now: global fits prefer NH weakened by T2K/NoVA CP fit

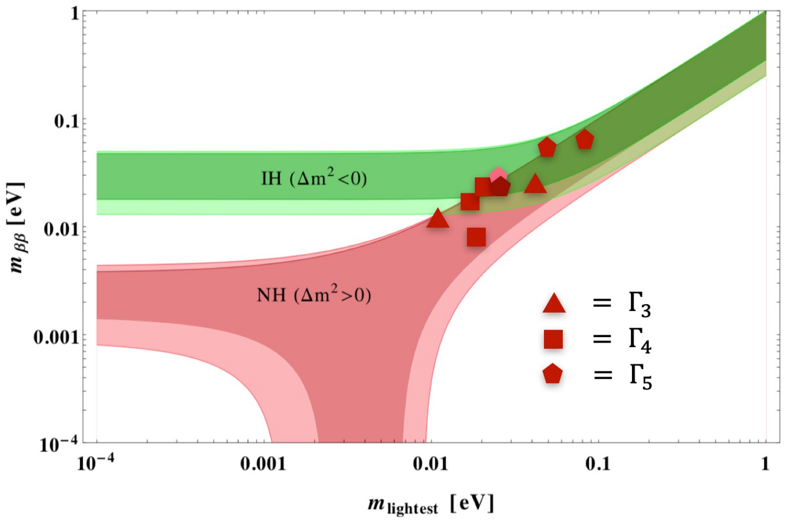
long term goals of next generation projects



A lower or Limit?



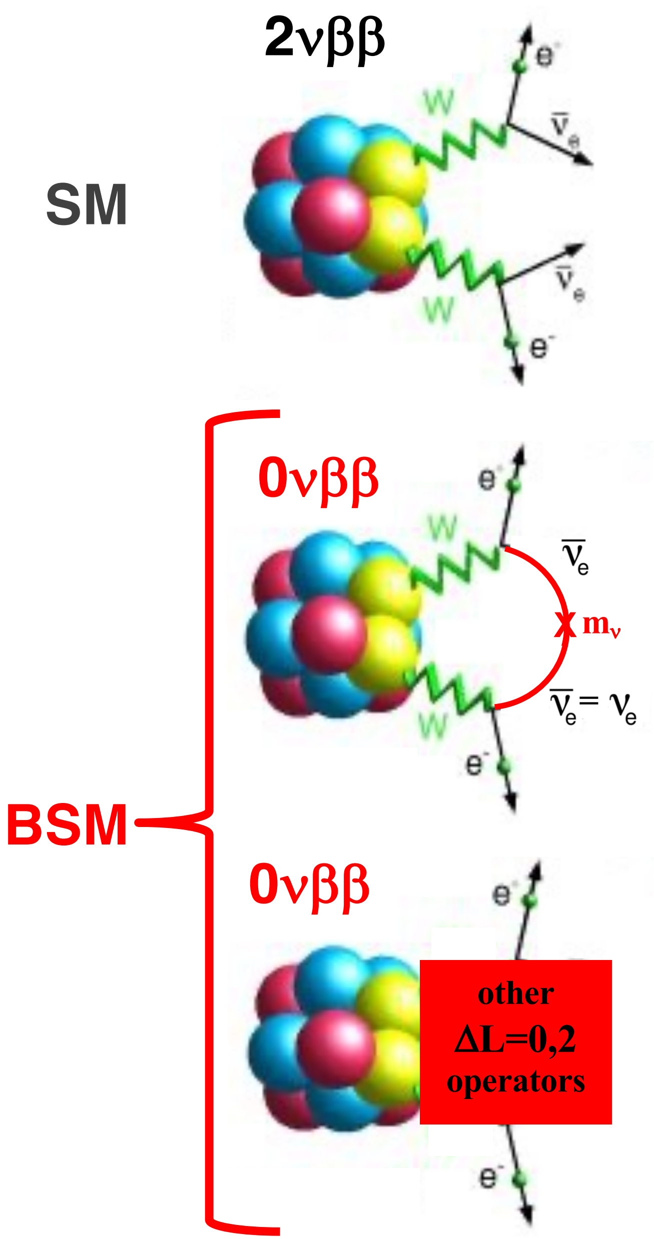
Agostini, Benato, Detwiler PRD 96 (2017) 053001 ; similar: Caldwell, Ettengruber, Merle, Schulz,Totzauer, PRD 96 (2017) 7, 073001

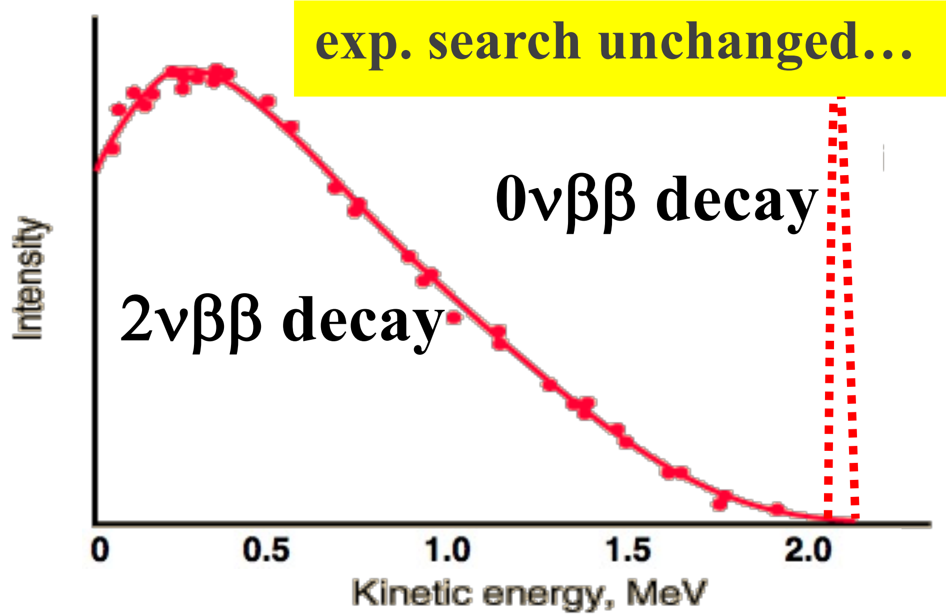


Feruglio, FLASY 2019, http://indico.cern.ch/event/795851

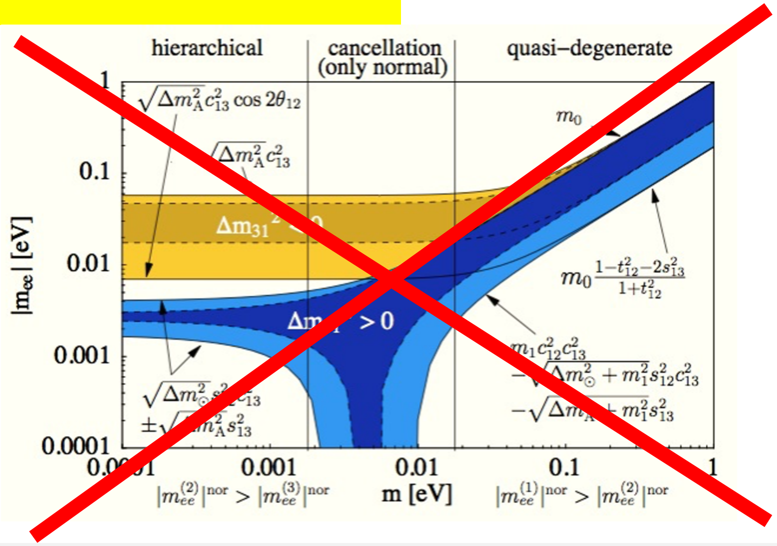
- **global fits of neutrino parameters**
  - ➔ constrain model parameters (NH ←→ IH)
  - ➔ weak preference for NH (2.7σ in NuFit 5.0)
  - ➔ data: no lower limit
  - ...and 0νββ may be other physics ➔ $m_{\beta\beta}$= 0, tiny
- **theory: there is no probability**
  - ➔ SM+m_ν: any number per se equally good
  - ➔ no theory measure (linear, log, ...)
  - ➔ discrete symmetries: added assumptions
  - ➔ depends on symmetry ➔ no generic preference
- **same methods do not work for quarks, e,μ,τ**

More general: L Violating Processes



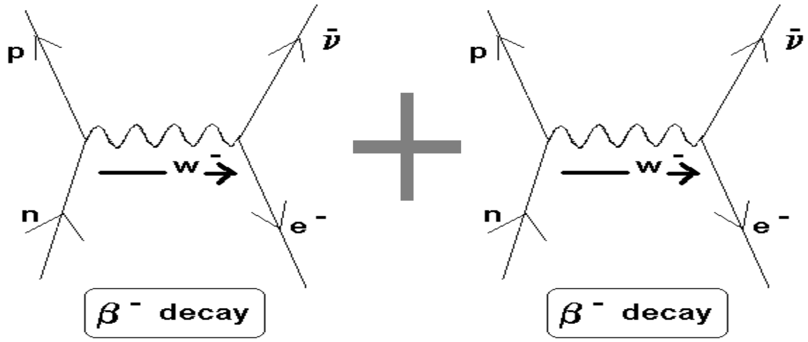


…interpretation changes:



Other Double Beta Decay Processes

Standard Model:

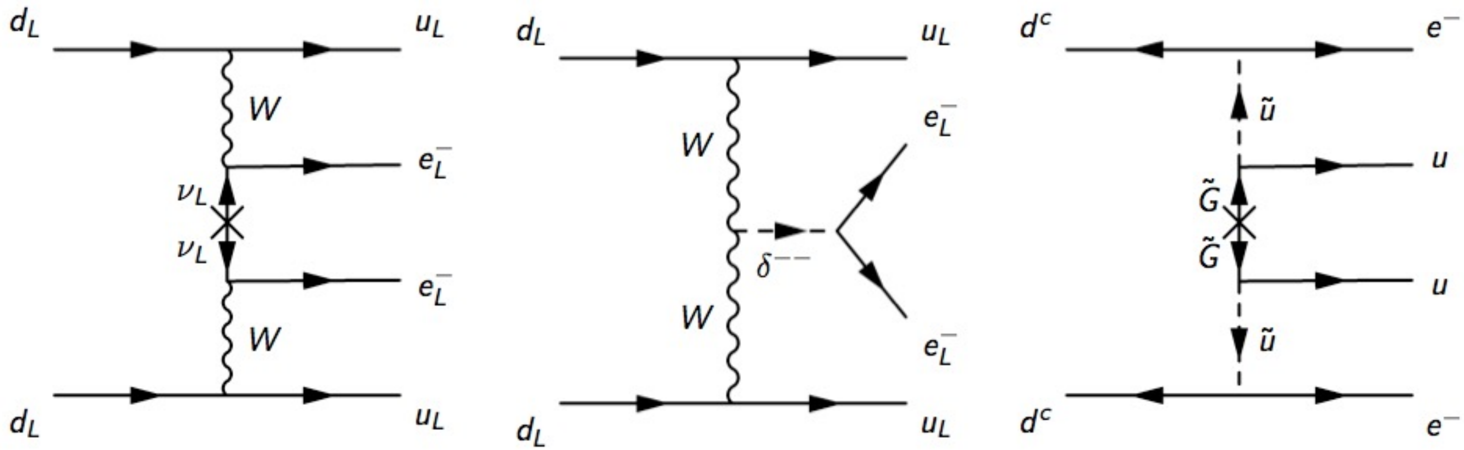


➔ 2 electrons + 2 neutrinos

2νββ

Majorana ν-masses or other ΔL=2 physics: ➔ 2 electrons

0νββ



…

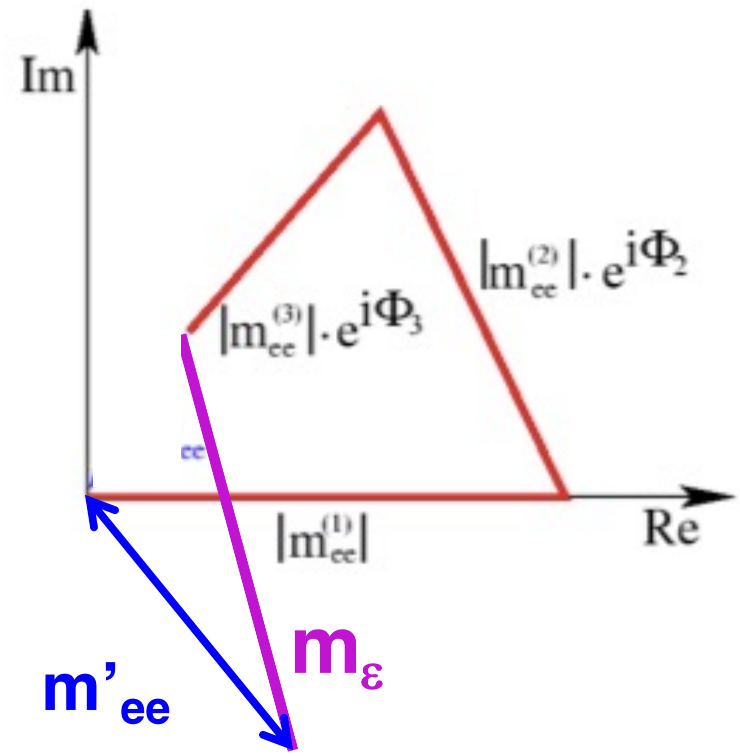
Majorana neutrino masses ←→ Dirac?

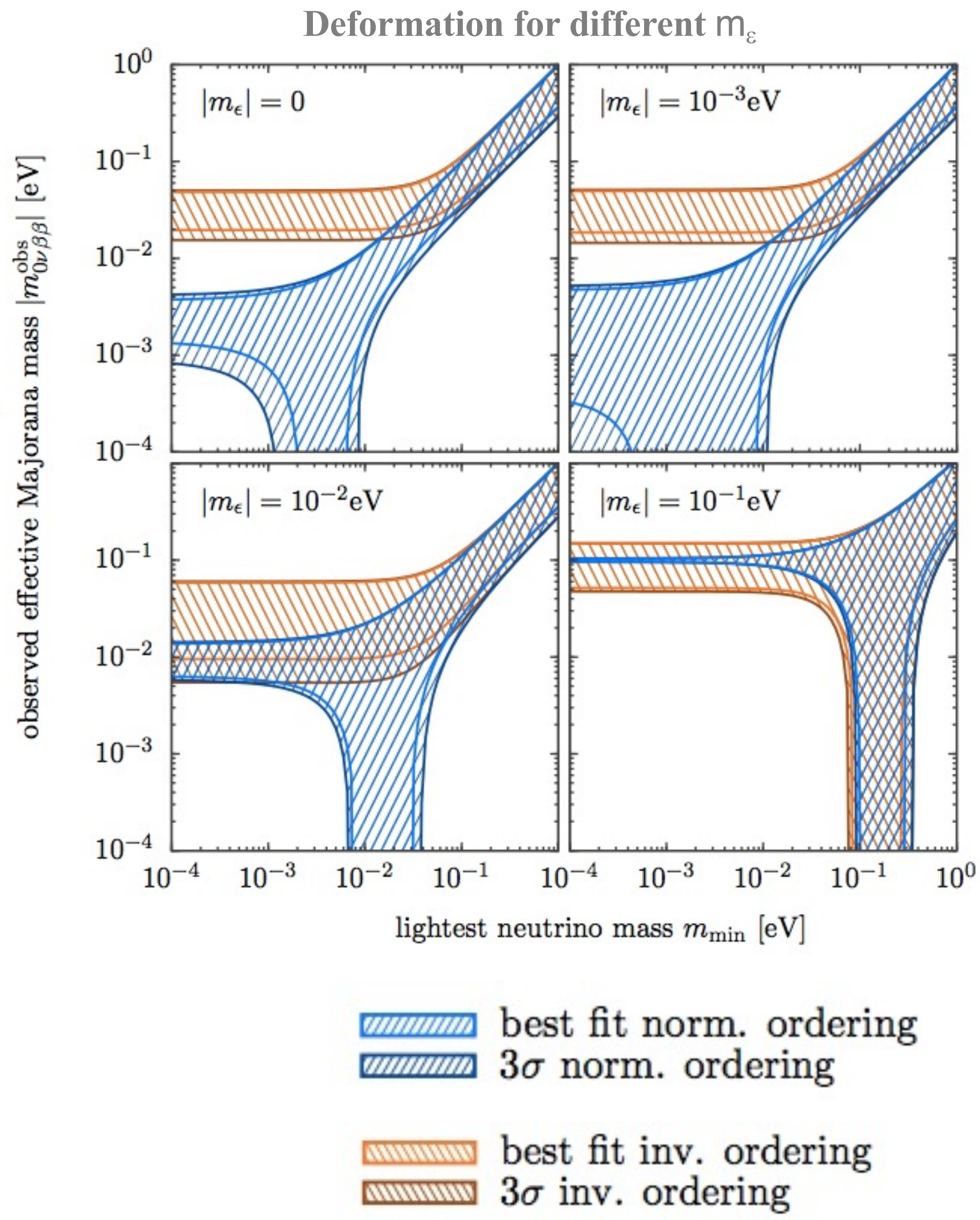
SM + Higgs triplet

SUSY

important connections to LHC and LFV …

sub eV Majorana mass ←→ TeV scale physics





Interferences:

total $0\nu\beta\beta$

- neutrino contribution
- m_ε ←→ other $\Delta L=2$ physics
- shifts masses, mixings, CP phases

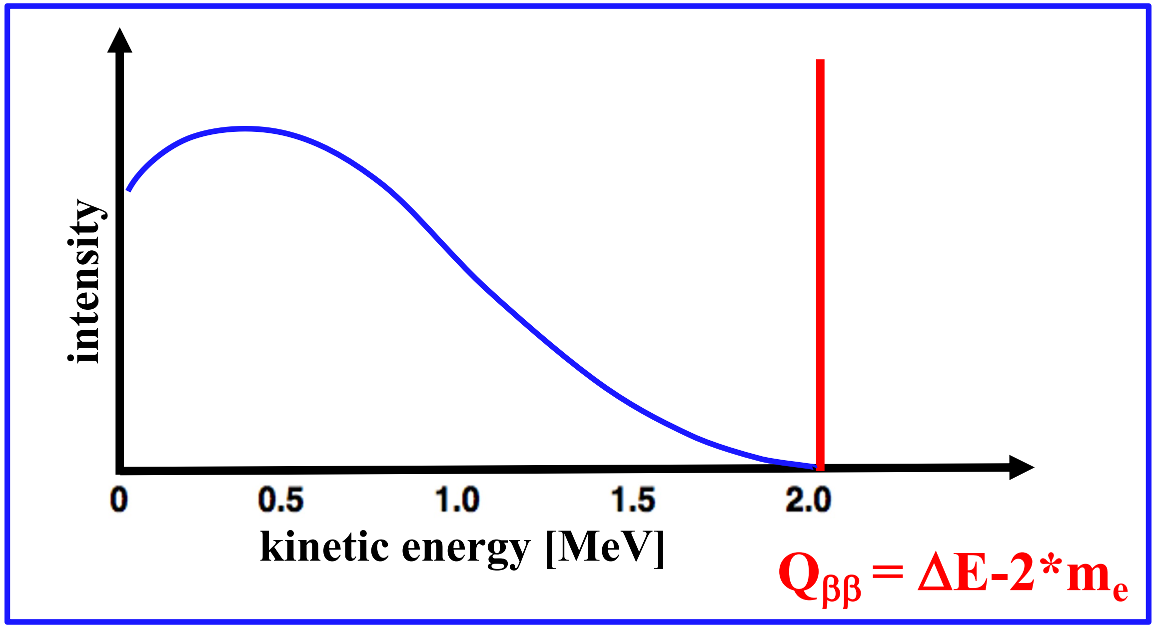
➔ deformation due to TeV physics

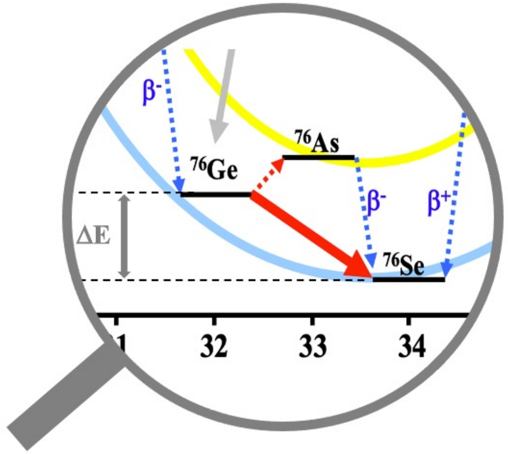
Extreme case:

- Dirac neutrino masses

  ➔ all due to other $\Delta L=2$ physics

Modifications of the Energy Spectrum





BSM can affect:

- ➢ amplitudes of both 2νββ and 0νββ ←→ NME uncertainties
- ➢ shape
- ➢ line position

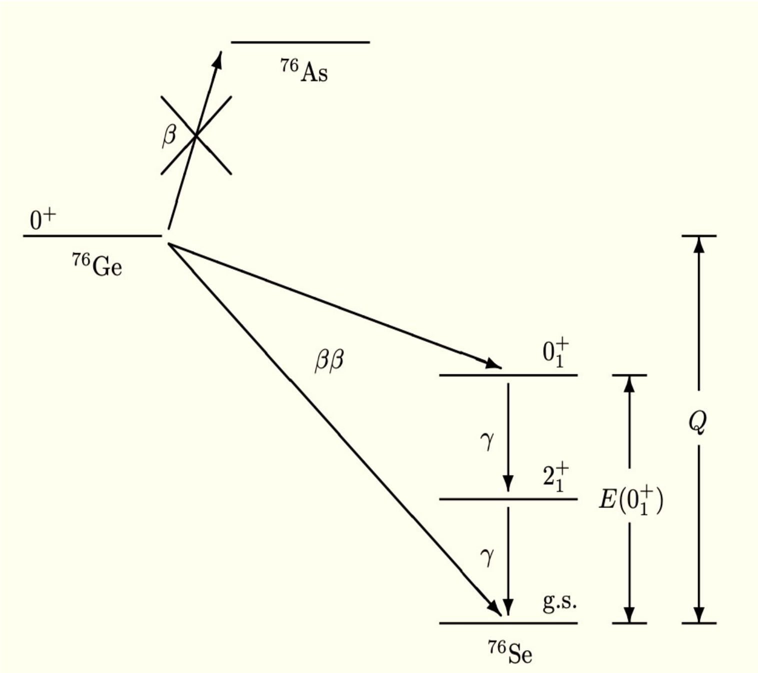
backgrounds in a real experiment ←→ what can be detected

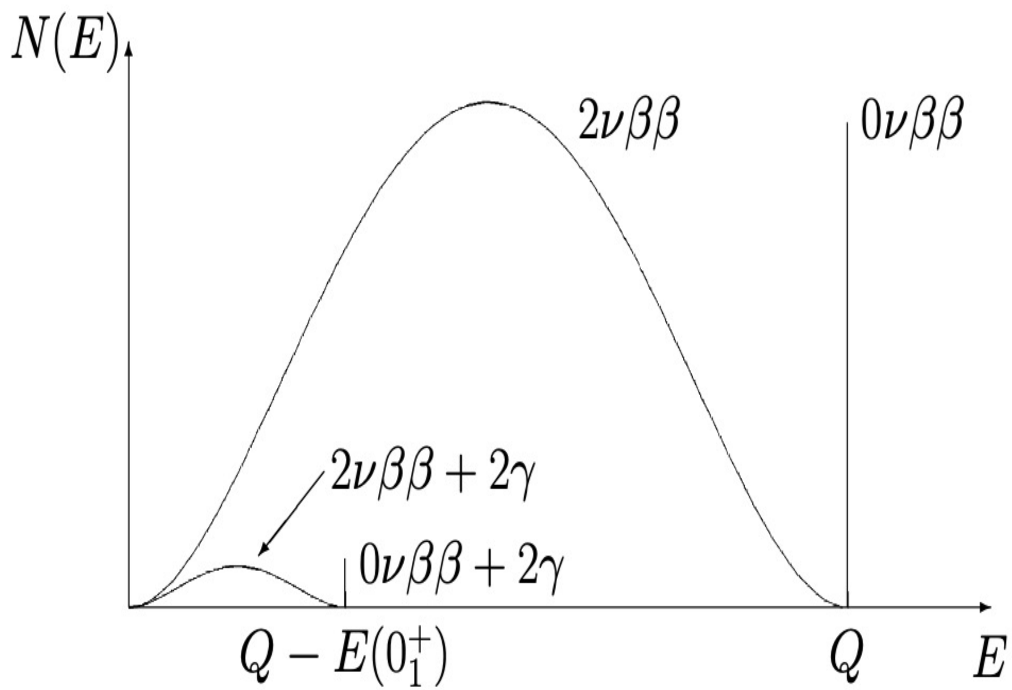
Examples:

- o sterile neutrinos with masses $\simeq$ MeV and 2νββ
- o right-handed currents → M_{WR}
- o …

Consistency Test of 0νββ with one Isotope

0νββ can also go to excited states Duerr, ML, Zuber, PRD 84 (2011) 093004





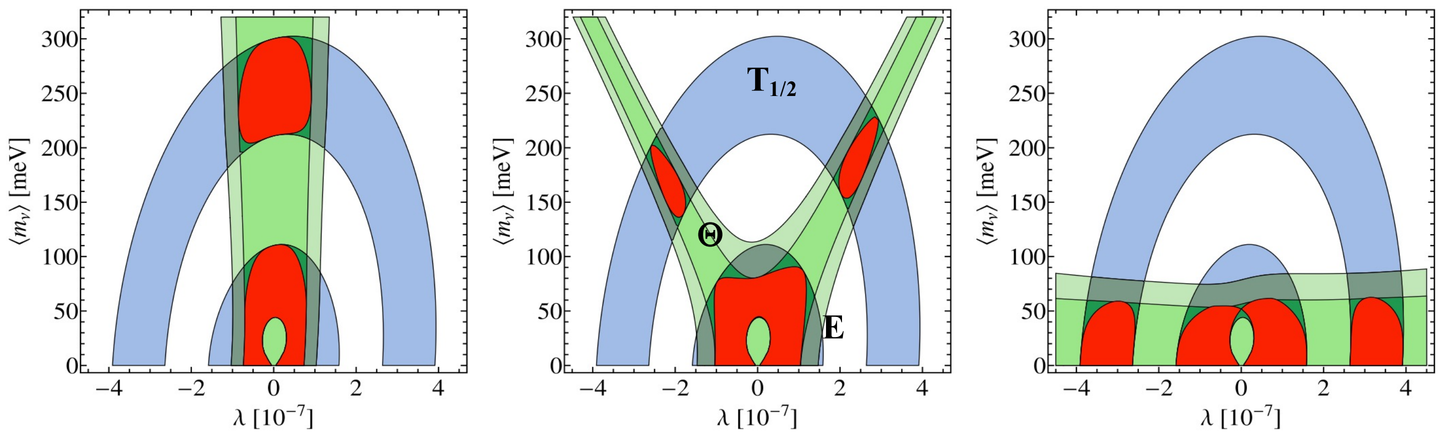
**➔ small corrections to the 0νββ spectrum
from sub-leading SM allowed transitions – not BSM**

A nice consistency test with one isotope
ΔE ←→ known energy levels → does not depend on NME uncertainties

Resolving the Origin of 0νββ

- **Over-constraining neutrino parameters**
    - m_ν from 0νββ ←→ other determinations: KATRIN, cosmology, ...
  - **so far only bounds and no discrepancy ➔ future:**
    - perfect match ➔ just Majorana neutrinos?
    - mismatch ➔ something else must contribute
    - finite mass and no 0νββ ➔ Dirac mass?

- **Further information in 0νββ experiments**
    - microscopic physics ←→ angular distribution (SuperNEMO, NEXT)



Arnold et al., Eur. Phys. J. C (2010) 70: 927

left-right symmetry
➔ right handed currents

$$\lambda \approx \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sqrt{\frac{m_\nu}{M_R}}$$

a) pure MM contribution
b) 30% RHC_λ admixture
c) pure RHC_λ

Combine 0νββ and 2νββ

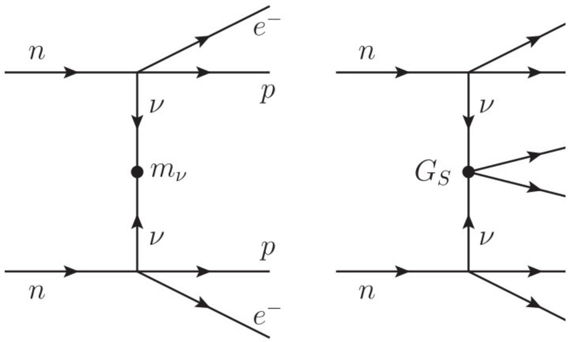
Future experiments will measure 2νββ spectrum very precisely
➔ combine 0νββ and 2νββ (effects on top of high statistics SM signal)

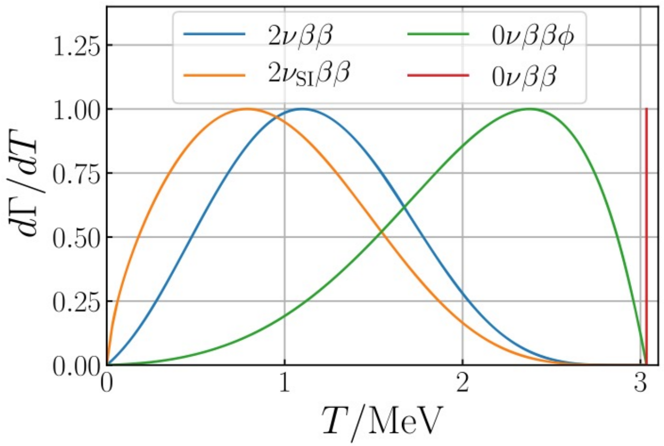
- **Lepton-number conserving right-handed currents**
  Deppisch, Graf, Simkovic, PRL 125 (2020) 17, 171801

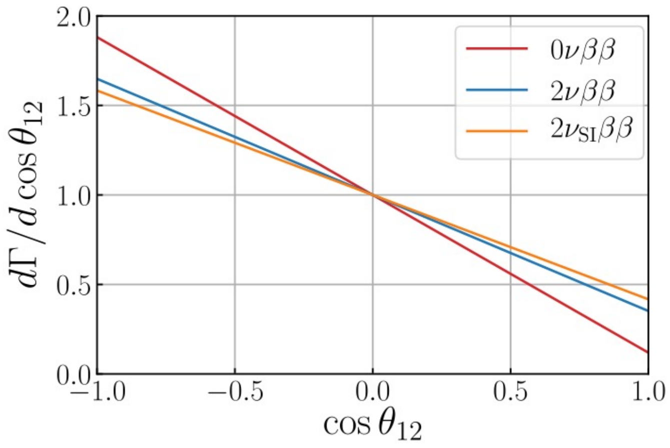
- **Sterile neutrino and light fermion searches through energy end point**
  Bolton, Deppisch, Graf, Simkovic, PRD 103 (2021) 5, 055019, Agostini, et al.,PLB 815 (2021) 136127

- **Neutrino self-interactions**
  Deppisch, Graf, Rodejohann, Xu, PRD 102 (2020) 5, 051701

- …







High-Energy Collider Experiments

testing long- and short range operators

LEFT ←→ SMEFT → more information

dimension-9 short-range operators ←→ Complete set of d=9 Operators in SMEFT

scalar O_i and vector O_i^μ four-quark operators

Li, Ren, Xiao, Yu, Zheng, PRD104 (2021) 1, 015025

$$\mathcal{O}_1 = \left(\overline{u_L}^\alpha \gamma_\mu d_L^\alpha\right)\left(\overline{u_L}^\beta \gamma^\mu d_L^\beta\right), \qquad \mathcal{O}_1' = \left(\overline{u_R}^\alpha \gamma_\mu d_R^\alpha\right)\left(\overline{u_R}^\beta \gamma^\mu d_R^\beta\right),$$

$$\mathcal{O}_2 = \left(\overline{u_R}^\alpha d_L^\alpha\right)\left(\overline{u_R}^\beta d_L^\beta\right), \qquad \mathcal{O}_2' = \left(\overline{u_L}^\alpha d_R^\alpha\right)\left(\overline{u_L}^\beta d_R^\beta\right),$$

$$\mathcal{O}_3 = \left(\overline{u_R}^\alpha d_L^\beta\right)\left(\overline{u_R}^\beta d_L^\alpha\right), \qquad \mathcal{O}_3' = \left(\overline{u_L}^\alpha d_R^\beta\right)\left(\overline{u_L}^\beta d_R^\alpha\right),$$

$$\mathcal{O}_4 = \left(\overline{u_L}^\alpha \gamma_\mu d_L^\alpha\right)\left(\overline{u_R}^\beta \gamma^\mu d_R^\beta\right),$$

$$\mathcal{O}_5 = \left(\overline{u_L}^\alpha \gamma_\mu d_L^\beta\right)\left(\overline{u_R}^\beta \gamma^\mu d_R^\alpha\right),$$

$$\mathcal{O}_6^\mu = \left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{u_L} d_R\right), \qquad \mathcal{O}_6^{\mu\prime} = \left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{u_R} d_L\right),$$

$$\mathcal{O}_7^\mu = \left(\overline{u_L}\lambda^A\gamma^\mu d_L\right)\left(\overline{u_L}\lambda^A d_R\right), \qquad \mathcal{O}_7^{\mu\prime} = \left(\overline{u_R}\lambda^A\gamma^\mu d_R\right)\left(\overline{u_R}\lambda^A d_L\right),$$

$$\mathcal{O}_8^\mu = \left(\overline{u_L}\gamma^\mu d_L\right)\left(\overline{u_R} d_L\right), \qquad \mathcal{O}_8^{\mu\prime} = \left(\overline{u_R}\gamma^\mu d_R\right)\left(\overline{u_L} d_R\right),$$

$$\mathcal{O}_9^\mu = \left(\overline{u_L}\lambda^A\gamma^\mu d_L\right)\left(\overline{u_R}\lambda^A d_L\right), \qquad \mathcal{O}_9^{\mu\prime} = \left(\overline{u_R}\lambda^A\gamma^\mu d_R\right)\left(\overline{u_L}\lambda^A d_R\right),$$

d=7

$\psi^2\phi^4$

$\mathcal{O}_{l^2H^3H^\dagger}$	$\mathcal{Y}[p\,r]\,\epsilon^{im}\epsilon^{jn}(l_{pi}Cl_{rj})H_mH_n(H^\dagger H)$

$\psi^2\phi^3 D$

$\mathcal{O}_{elH^3D}$	$\epsilon^{ij}\epsilon^{km}(l_{pi}C\gamma^\mu e_r)H_jH_mD_\mu H_k$

$\psi^2\phi^2 D^2$

$\mathcal{O}^{(1)}_{l^2H^2}$	$\mathcal{Y}[p\,r]\,\epsilon^{ik}\epsilon^{jm}(l_{pi}C\sigma^{\mu\nu}l_{rj})D_\mu H_k D_\nu H_m$
$\mathcal{O}^{(2)}_{l^2H^2}$	$\mathcal{Y}[p\,r]\,\epsilon^{ik}\epsilon^{jm}(l_{pi}Cl_{rj})D_\mu H_k D^\mu H_m$

$F\psi^2\phi^2$

$\mathcal{O}^{(1)}_{Wl^2H^2}$	$\mathcal{Y}\left[\begin{smallmatrix}p\\r\end{smallmatrix}\right]\epsilon^{ik}\epsilon^{jn}(\tau^I)^m_n W^I_{\mu\nu}(l_{pi}C\sigma^{\mu\nu}l_{rj})H_kH_m$
$\mathcal{O}^{(2)}_{Wl^2H^2}$	$\mathcal{Y}[p\,r]\,\epsilon^{ik}\epsilon^{jn}(\tau^I)^m_n W^I_{\mu\nu}(l_{pi}C\sigma^{\mu\nu}l_{rj})H_kH_m$
$\mathcal{O}_{Bl^2H^2}$	$\mathcal{Y}\left[\begin{smallmatrix}p\\r\end{smallmatrix}\right]\epsilon^{ik}\epsilon^{jm}B_{\mu\nu}(l_{pi}C\sigma^{\mu\nu}l_{rj})H_kH_m$

$\psi^4 D$

$\mathcal{O}_{\bar{d}l^2uD}$	$\mathcal{Y}[r\,s]\,\epsilon^{ij}\left(\bar{d}^a_p\gamma^\mu u_{ta}\right)(l_{ri}CD_\mu l_{sj})$
$\mathcal{O}_{d^2\bar{l}qD}(\not{B})$	$\mathcal{Y}[p\,r]\,\epsilon^{abc}\left(\bar{l}^i_s D_\mu d_{rb}\right)(d_{pa}\gamma^\mu Cq_{tci})$
$\mathcal{O}_{d^3\bar{e}D}(\not{B})$	$\mathcal{Y}[p\,r\,s]\,\epsilon^{abc}(\bar{e}_t\gamma^\mu d_{pa})(d_{rb}CD_\mu d_{sc})$

$\psi^4\phi$

$\mathcal{O}_{\bar{d}eluH}$	$\epsilon^{ij}\left(\bar{d}^a_s l_{tj}\right)(e_pCu_{ra})H_i$
$\mathcal{O}^{(1)}_{\bar{d}l^2qH}$	$\mathcal{Y}\left[\begin{smallmatrix}r\\s\end{smallmatrix}\right]\epsilon^{ik}\epsilon^{jm}\left(\bar{d}^a_p l_{sj}\right)(l_{ri}Cq_{tak})H_m$
$\mathcal{O}^{(2)}_{\bar{d}l^2qH}$	$\mathcal{Y}\left[\begin{smallmatrix}r\\s\end{smallmatrix}\right]\epsilon^{ij}\epsilon^{km}\left(\bar{d}^a_p l_{sj}\right)(l_{ri}Cq_{tak})H_m$
$\mathcal{O}^{(3)}_{\bar{d}l^2qH}$	$\mathcal{Y}[r\,s]\,\epsilon^{ik}\epsilon^{jm}\left(\bar{d}^a_p l_{sj}\right)(l_{ri}Cq_{tak})H_m$
$\mathcal{O}^{(4)}_{\bar{d}l^2qH}$	$\mathcal{Y}[r\,s]\,\epsilon^{ij}\epsilon^{km}\left(\bar{d}^a_p l_{sj}\right)(l_{ri}Cq_{tak})H_m$
$\mathcal{O}^{(1)}_{\bar{e}l^3H}$	$\mathcal{Y}[r\,s\,t]\,\epsilon^{ij}\epsilon^{km}(\bar{e}_pl_{sj})(l_{ri}Cl_{tk})H_m$
$\mathcal{O}^{(2)}_{\bar{e}l^3H}$	$\mathcal{Y}\left[\begin{smallmatrix}r & s\\t\end{smallmatrix}\right]\epsilon^{ik}\epsilon^{jm}(\bar{e}_pl_{sj})(l_{ri}Cl_{tk})H_m$
$\mathcal{O}^{(3)}_{\bar{e}l^3H}$	$\mathcal{Y}\left[\begin{smallmatrix}r\\s\\t\end{smallmatrix}\right]\epsilon^{ik}\epsilon^{jm}(\bar{e}_pl_{sj})(l_{ri}Cl_{tk})H_m$
$\mathcal{O}^{(1)}_{l^2\bar{q}uH}$	$\mathcal{Y}[s\,t]\,\epsilon^{jm}\left(\bar{q}^{ai}_p u_{ra}\right)(l_{si}Cl_{tm})H_j$
$\mathcal{O}^{(2)}_{l^2\bar{q}uH}$	$\mathcal{Y}\left[\begin{smallmatrix}s\\t\end{smallmatrix}\right]\epsilon^{jm}\left(\bar{q}^{ai}_p u_{ra}\right)(l_{si}Cl_{tm})H_j$
$\mathcal{O}^{(1)}_{d^2\bar{l}uH^\dagger}(\not{B})$	$\mathcal{Y}[p\,r]\,\epsilon^{abc}\epsilon_{ij}\left(\bar{l}^i_s d_{pa}\right)(u_{tc}Cd_{rb})H^{\dagger j}$
$\mathcal{O}^{(2)}_{d^2\bar{l}uH^\dagger}(\not{B})$	$\mathcal{Y}\left[\begin{smallmatrix}p\\r\end{smallmatrix}\right]\epsilon^{abc}\epsilon_{ij}\left(\bar{l}^i_s d_{pa}\right)(u_{tc}Cd_{rb})H^{\dagger j}$
$\mathcal{O}_{d^3\bar{l}H}(\not{B})$	$\mathcal{Y}\left[\begin{smallmatrix}p & r\\s\end{smallmatrix}\right]\epsilon^{abc}\left(\bar{l}^i_t d_{rb}\right)(d_{pa}Cd_{sc})H_i$
$\mathcal{O}^{(1)}_{d\bar{l}q^2H^\dagger}(\not{B})$	$\mathcal{Y}\left[\begin{smallmatrix}p\\r\end{smallmatrix}\right]\epsilon^{abc}\left(\bar{l}^j_t d_{sc}\right)(q_{pai}Cq_{rbj})H^{\dagger i}$
$\mathcal{O}^{(2)}_{d\bar{l}q^2H^\dagger}(\not{B})$	$\mathcal{Y}[p\,r]\,\epsilon^{abc}\left(\bar{l}^j_t d_{sc}\right)(q_{pai}Cq_{rbj})H^{\dagger i}$
$\mathcal{O}_{d^2\bar{e}qH^\dagger}(\not{B})$	$\mathcal{Y}\left[\begin{smallmatrix}s\\t\end{smallmatrix}\right]\epsilon^{abc}(\bar{e}_pq_{rai})(d_{sb}Cd_{tc})H^{\dagger i}$

d=9

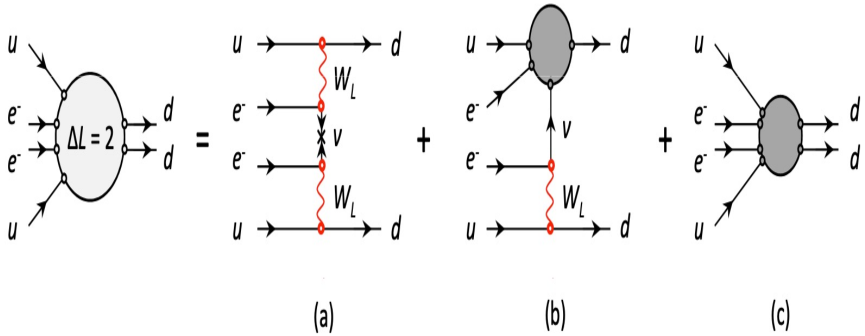
...many more...

- **Same-Sign Dilepton Signals: p + p → 2e$^\pm$ + 2jets**
- **Missing Transverse Energy (MTE): p + p → e$^\pm$ +2jets + MTE**
- **Dijet with Missing Transverse Energy: p + p → 2jets + MTE**

Study / combine with other Channels

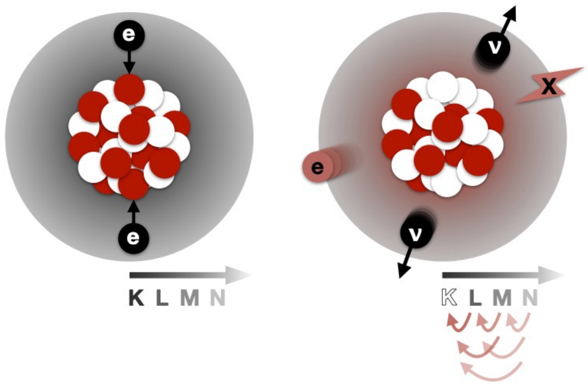
Other ΔL = 2 channels:

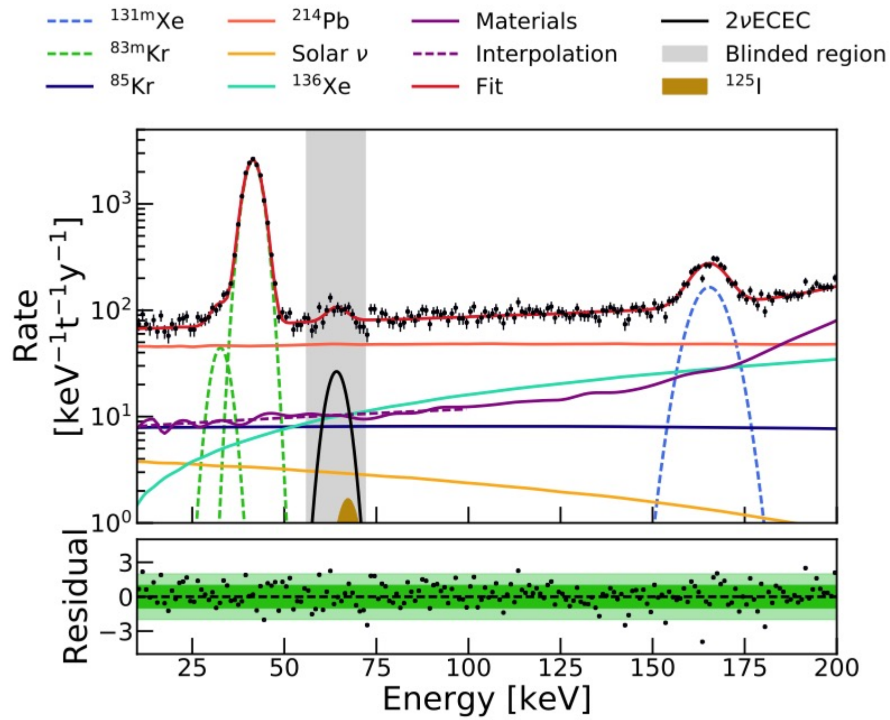
- $0\nu\beta^+\beta^+$: $A,Z \rightarrow A, Z{-}2 + 2e^+$
- $0\nu\beta^+$EC : $A,Z + e^- \rightarrow A, Z{-}2 + e^+$
- 0νECEC: $A,Z + 2e^- \rightarrow A, Z{-}2$



Observation of 2νECEC by XENON1T

E. Aprile et al., Nature 568 (2019) 7753, 532.





$T_{2\nu ECEC} = (1.8 \pm 0.5\text{stat} \pm 0.1\text{sys}) \times 10^{22}$ y

longest ever measured process

~ one trillion times the age of the Universe

Neutrino Properties from Other Experiments

You don't have to observe neutrinos to learn about them

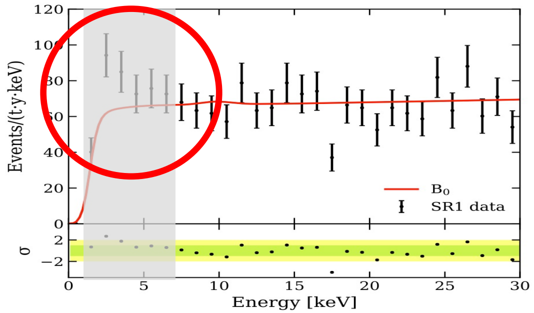
←→ impact of ν's on other observables

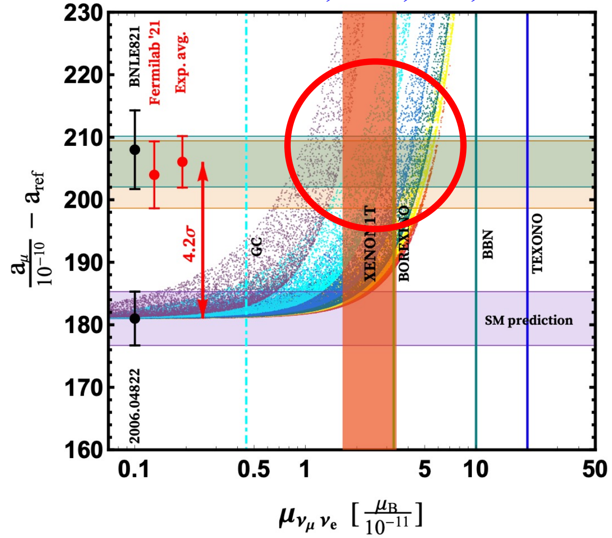
- **cosmology**
- **astrophysics**
- **0νββ decay**
- **...**

interconnections of deviations from SM: A recent example

Excess at low E_R in XENON1T

deviation of g-2 from SM





➔triggered many potential explanations

one of them: **a large neutrino magnetic moment**

Usually not expected ←→ the same diagrams induce radiatively to high neutrino masses

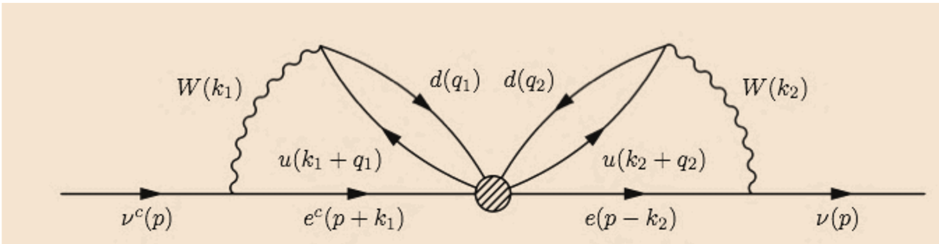
➔ symmetries which decouple μ and m_ν

➔ leads interestingly also to the required corrections to g-2

Majorana: Pro's and Con's

QFT rules the world:

- include in $\mathcal{L}$ any operator which is not forbidden by symmetry
  ... will anyway be generated by quantum corrections
- GR anomalies: Any global symmetry like L should be gauged or broken
- L: SM+ = SM+ ν_R allows $\Delta L=2$ terms ➔ Majorana terms must exist
- Schechter-Valle theorem: *Any $\Delta L=2$ operator which mediates $0\nu\beta\beta$ decay induces via loops Majorana mass terms* ➔ **Majorana masses unavoidable!**



- Calculate: 4 loops ➔ induces $\delta m_\nu = 10^{-25}$ eV Dürr, ML, Merle
  ➔ very tiny Majorana mass contribution
  ➔ academic interest: cannot explain observed neutrino masses and splitting's
  ➔ neutrinos might be predominantly Dirac with a tiny Majorana contribution

- **Global symmetries expected to be broken gravitational effects →** M_{Planck}

  lepton number L → expect at least:

$$m_\nu \approx \frac{v^2}{M_{Planck}} \approx 10^{-5}\ \mathrm{eV}$$

  Too small to explain oscillations but too large as subdominant splitting
  Connection to matter-antimatter asymmetry

- **Another hierarchy problem**
  - Dirac masses, not explained, small radiative corrections natural ←→ chiral symmetry
  - Majorana, e.g. type I see-saw →
    - naturalness: $M \leq 10^7$-10^8 GeV
    - vanilla leptogenesis; $M \geq 10^9$ GeV
    - similar arguments for other types of see-saw

$$\delta m_H^2 \simeq \frac{y_\nu^2}{16\pi^2} M^2$$

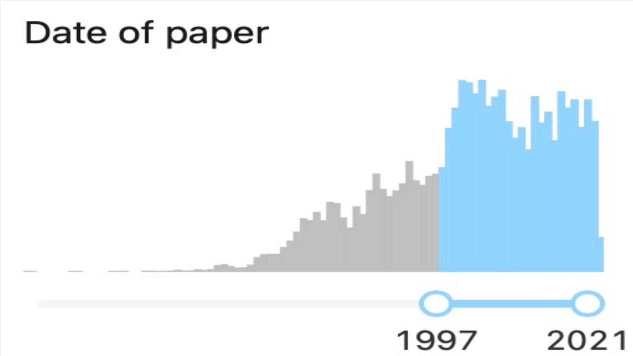
- **A henn and egg problem**

  Arguments rest on the fact that n_R does not carry any other charge
  → well motivated extensions where ν_R has some charge (e.g. horizontal S...)
  → Majorana masses forbidden if symmetry is not explicitly broken (SSB is OK)
  → models with Dirac masses – not spoiled by loops ←→ symmetry

Summary

Neutrino physics:

- will remain a hot topic in fundamental physics



INSPIRE:
'neutrino' is most frequent word in the title of papers
total: 28308 ; after 1997 = 21308
no sign of weakening

- double beta decay is and will be a very important sub-topic

To find out if 0νββ exists and what BSM mechanism is behind it:

- ➢ need better data from different types of experiments
- ➢ combine information:
  - 0νββ and 2νββ (more than one isotope, angular, ...)
  - from other ν-physics (masses, mixings, oscillations)
  - from other fields (e.g. magnetic moment & g-2, ...)
  - cosmology (leptogenesis, ...)

➔ a lot of experimental work: R&D, ..., construction

➔ further theoretical ideas and studies