

# Overview of neutrinoless double beta decay

**Julia Harz**

GDR Deep Underground Physics kick-off meeting  
31/05/2021



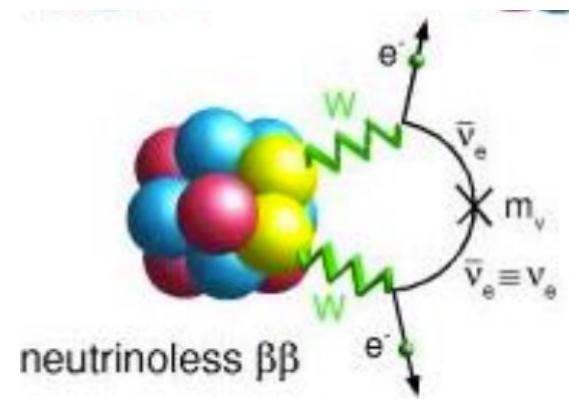
Technische Universität München



# Outline

- **Introduction**
- **Neutrinos and Lepton Number Violation**
- **Neutrinoless Double Beta Decay**
- **Neutrinoless Double Beta Decay and Standard Interactions**
- **Neutrinoless Double Beta Decay and Non-Standard Interactions**
- **Neutrinoless Double Beta Decay and the LHC**
- **Neutrinoless Double Beta Decay and Baryogenesis**

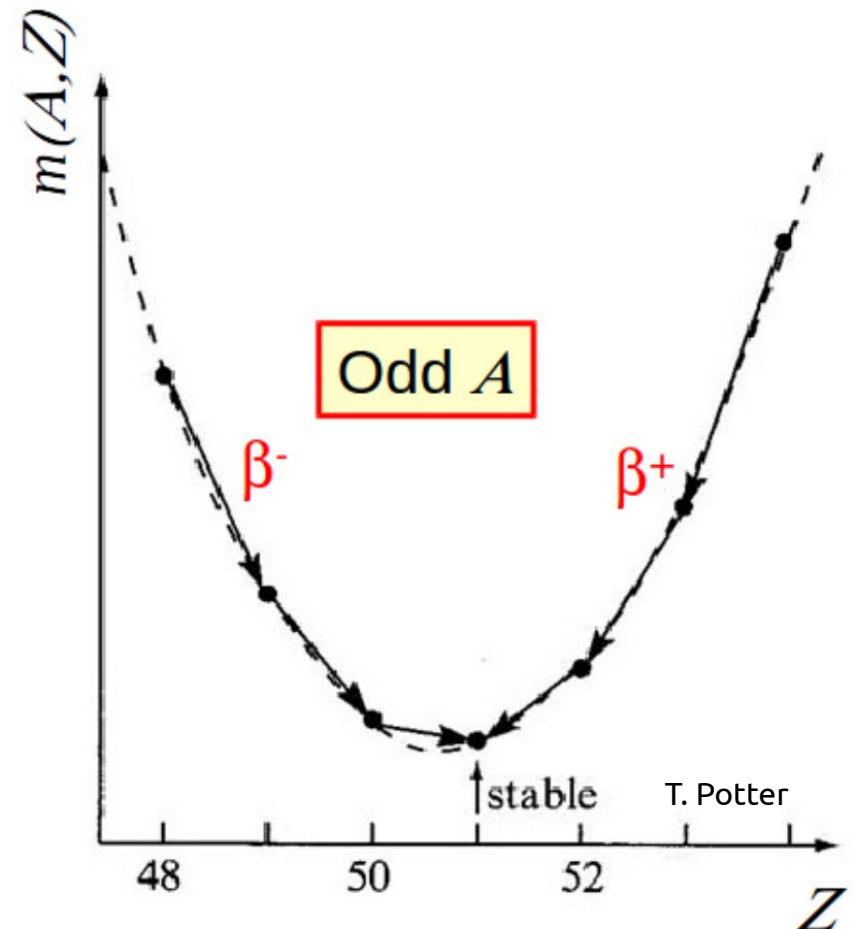
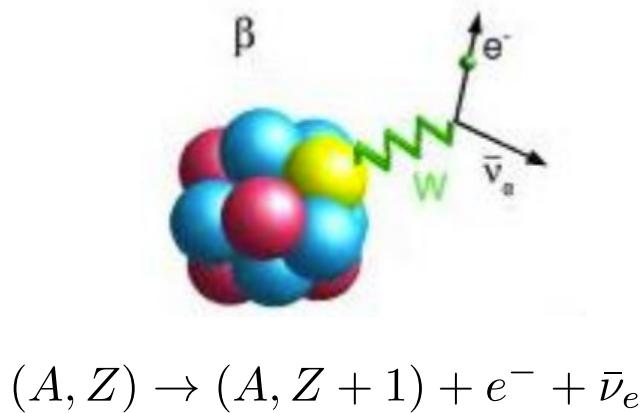
# Introduction



# Single Beta Decay

Standard single beta decay can occur in three different forms

- **$\beta^-$  decay**  $n \rightarrow p + e^- + \bar{\nu}_e$
- **$\beta^+$  decay**  $p \rightarrow n + e^+ + \nu_e$
- **Electron capture (EC)**  $e^- + p \rightarrow n + \nu_e$

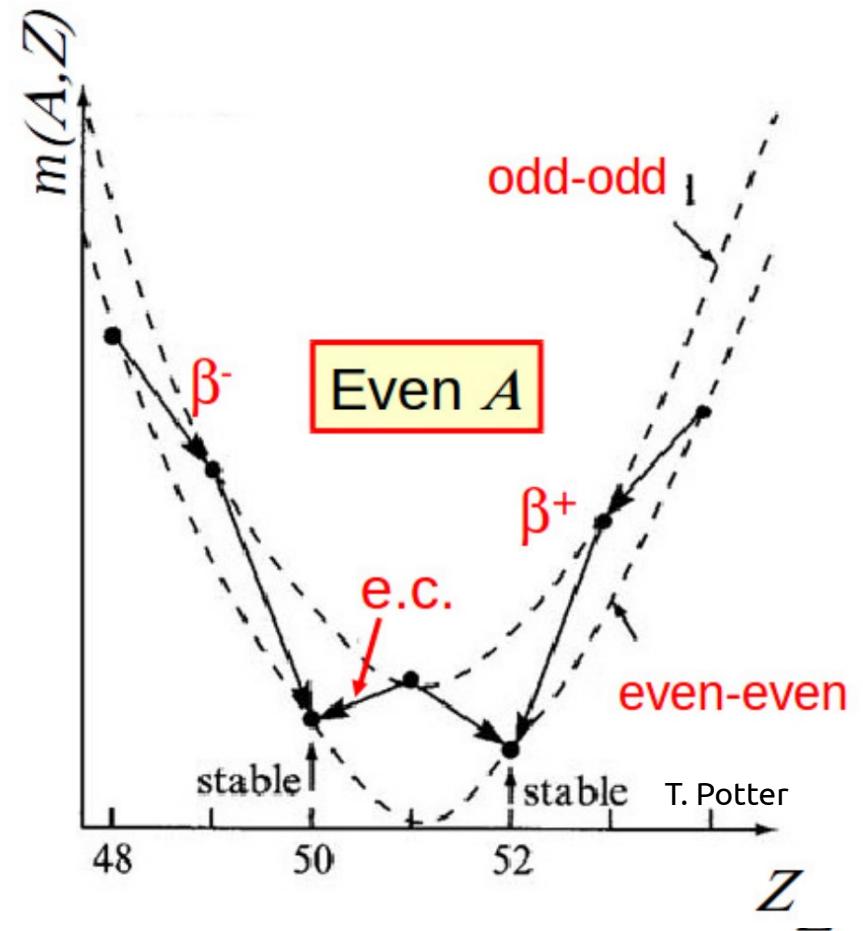
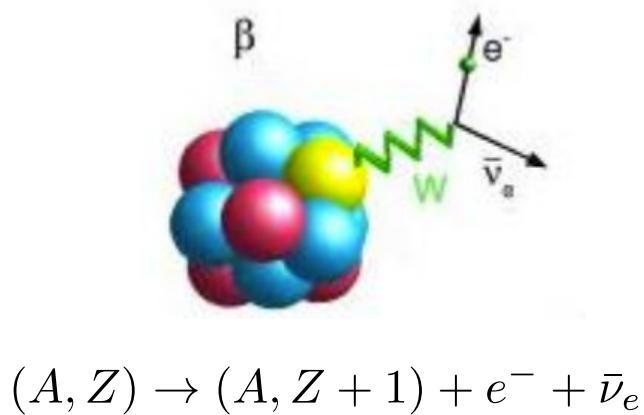


If the decay is possible  $M(A, Z) > M(A, Z + 1)$ , it is the dominant contribution.

# Single Beta Decay

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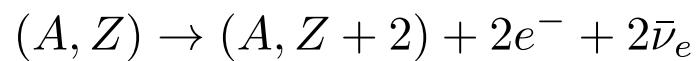
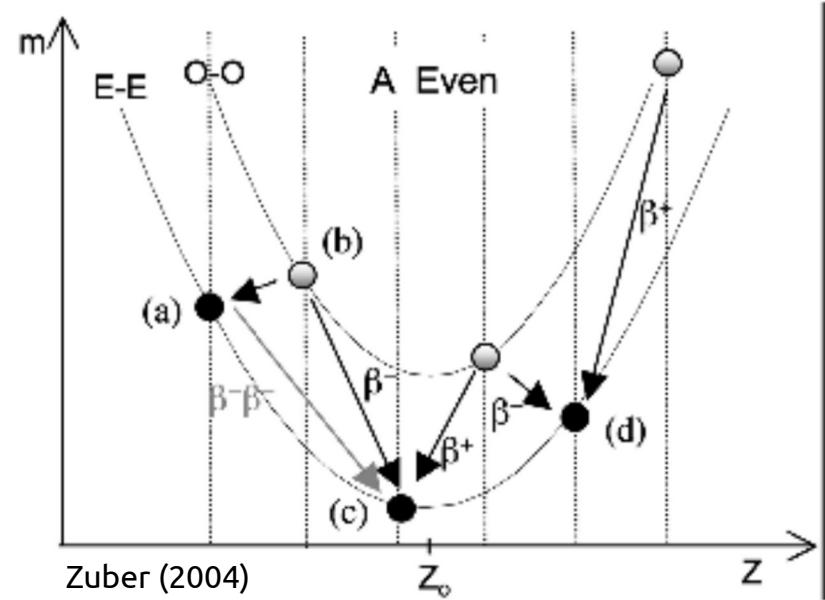
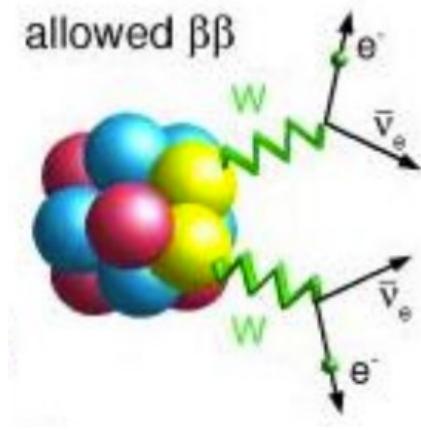
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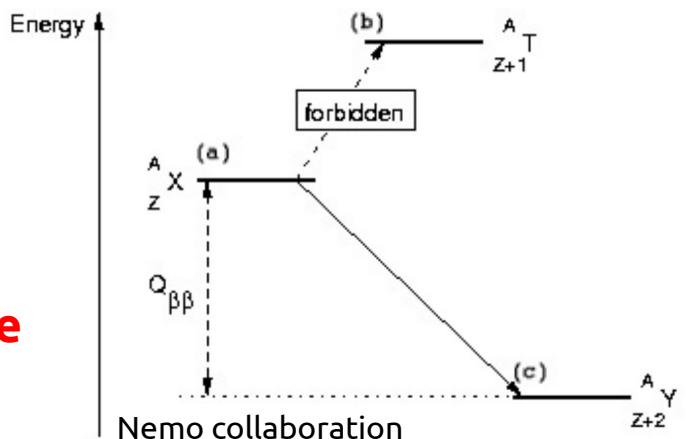
If the decay is possible  $M(A, Z) > M(A, Z + 1)$ , it is the dominant contribution.

# Double Beta Decay

For 35 nuclides (even A, even Z), the standard single beta decay is **not energetic possible**.

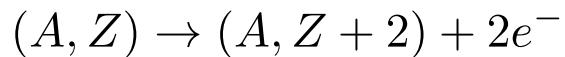
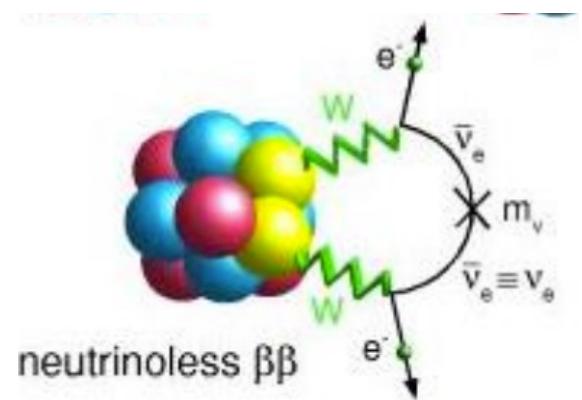


In this case, the second order two neutrino double beta decay can be the dominant contribution!

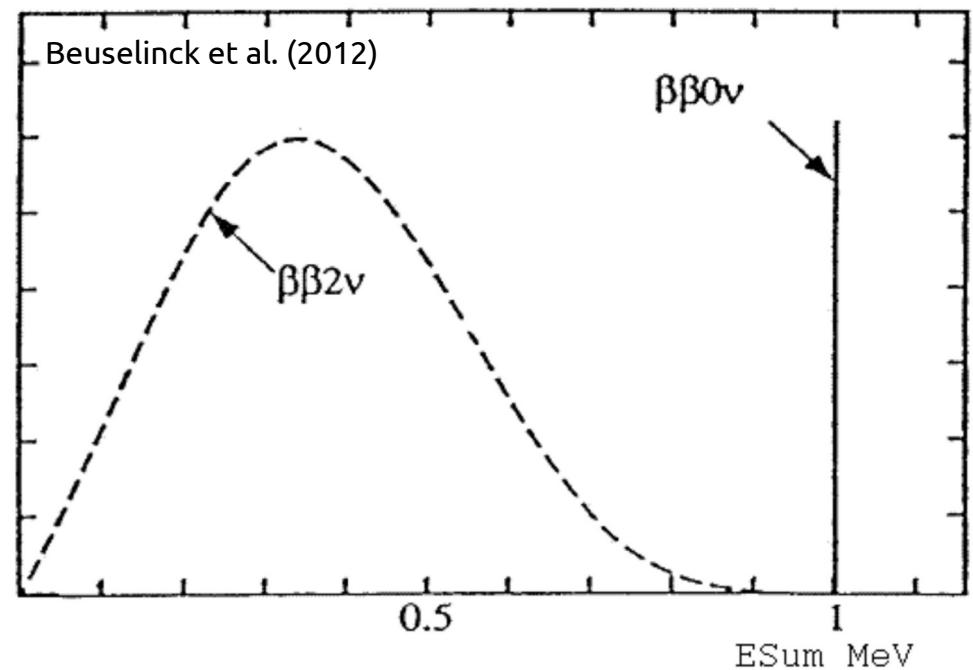


# Neutrinoless double beta decay

For these 35 nuclides (even A, even Z), there is potential to probe **new physics** via neutrinoless double beta decay.



**Lepton Number violating (LNV)**  
 $\Delta L = 2$



**Besides the continuous  $\beta\beta 2\nu$  spectrum, a monochromatic line at the maximal energy could be a hint for a possible lepton-number violating  $\beta\beta 0\nu$  decay process.**

# Neutrinoless double beta decay



Wikipedia



AIP

SEPTEMBER 15, 1935

PHYSICAL REVIEW

VOLUME 48

## Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*

(Received May 20, 1935)

From the Fermi theory of  $\beta$ -disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over  $10^{17}$  years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

DECEMBER 15, 1939

PHYSICAL REVIEW

VOLUME 56

## On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY

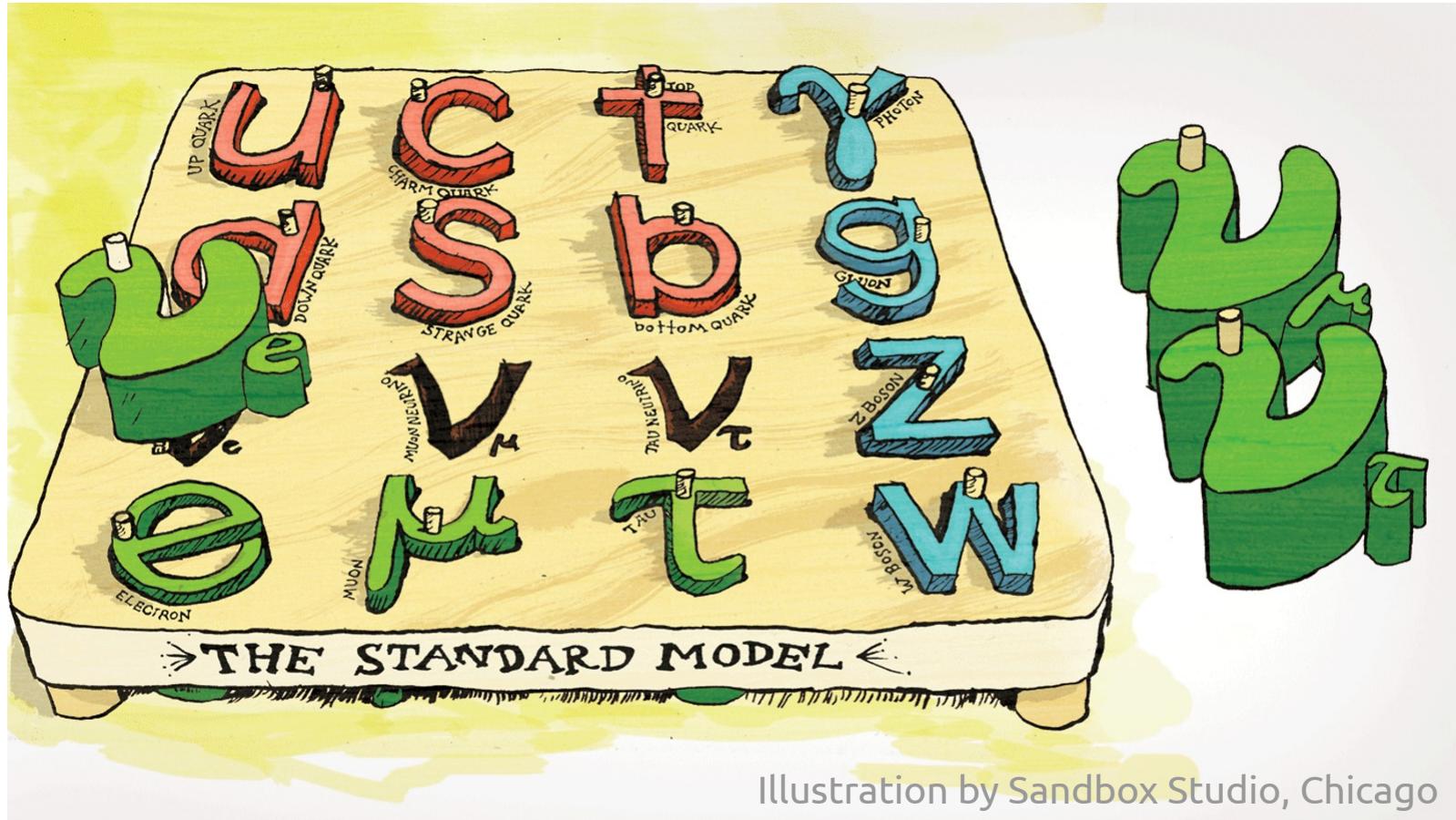
*Physics Research Laboratory, Harvard University, Cambridge, Massachusetts*

(Received October 16, 1939)

The phenomenon of double  $\beta$ -disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double  $\beta$ -disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with  $\Delta i = \pm 1, 0$ . The results obtained with the Majorana theory indicate that it is not at all certain that double  $\beta$ -disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ( $\epsilon \gtrsim 20$ ,  $\Delta M \gtrsim 0.01$  unit).

# **Neutrinos & Lepton Number violation**

# Neutrinos – what do we know?



**"Neutrinos, the Standard Model misfits"**

# Neutrinos – what do we know?

2015 NOBEL PRIZE  
*in Physics*

- Neutrinos in the Standard Model are **massless**

$$L_i \rightarrow \begin{pmatrix} \nu_i \\ \ell_i \end{pmatrix} \quad m_\nu = 0$$

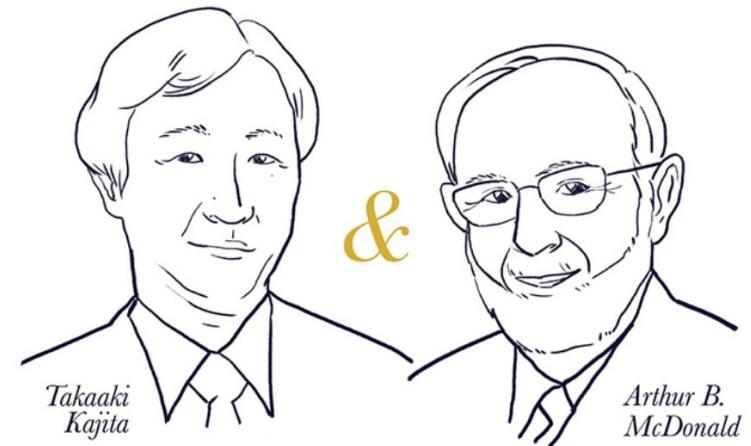
- Neutrino **mixing**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Neutrino **oscillations** require **massive** neutrinos

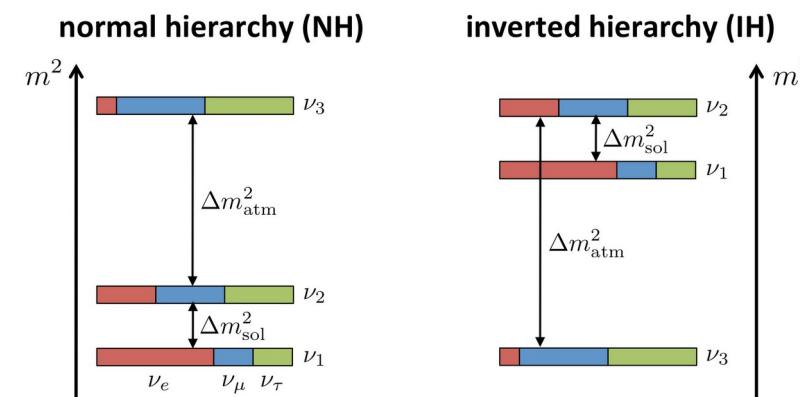
$$P(\nu_i \rightarrow \nu_j) \propto \Delta m_{ij}^2 \quad \Delta m_{12}^2 \sim 7.59 \times 10^{-5} \text{ eV}^2$$
$$\Delta m_{23}^2 \sim \Delta m_{31}^2 \sim 2.3 \times 10^{-3} \text{ eV}^2$$

- **Normal vs. inverted hierarchy**



## NEUTRINO OSCILLATIONS

The discovery of these oscillations shows that neutrinos have mass.



How do neutrinos get their masses?

What nature do neutrinos have? Are they their own anti-particles?

# Right-handed Neutrinos as New Physics

Quarks			
Left	$\frac{2}{3}$ 2.4 MeV <b>u</b> up	Right	$\frac{2}{3}$ 1.27 GeV <b>c</b> charm
Left	$-\frac{1}{3}$ 4.8 MeV <b>d</b> down	Right	$-\frac{1}{3}$ 104 MeV <b>s</b> strange
Left	$-\frac{1}{3}$ 171.2 GeV <b>t</b> top	Right	$-\frac{1}{3}$ 4.2 GeV <b>b</b> bottom
Leptons			
Left	$0\nu_e$ <0.0001 eV electron neutrino	Right	$0\nu_1$ $\sim$ keV sterile neutrino
Left	$0\nu_\mu$ $\sim$ 0.01 eV muon neutrino	Right	$0\nu_2$ $\sim$ GeV sterile neutrino
Left	$0\nu_\tau$ $\sim$ 0.04 eV tau neutrino	Right	$0\nu_3$ $\sim$ GeV sterile neutrino
Left	-1 0.511 MeV <b>e</b> electron	Right	-1 105.7 MeV <b><math>\mu</math></b> muon
Left	-1 1.777 GeV <b><math>\tau</math></b> tau	Right	

Right-handed neutrinos could explain the neutrino masses

# Why Lepton-Number Violation?

## Dirac mass

$$y_\nu L \epsilon H \nu_R^c \supset m_D \nu_L \nu_R^c$$

1/2	
-1/2	0

*hypercharge*

## Majorana mass

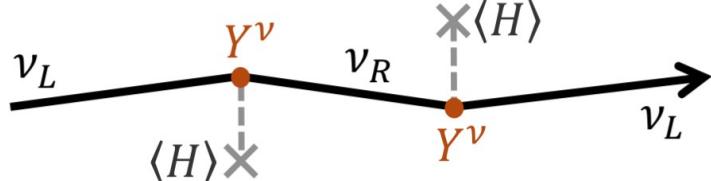
$$m_M \bar{\nu}_R \nu_R^c$$

0	0
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- tiny Yukawa couplings

$$m_\nu / \Lambda_{EW} \leq 10^{-12}$$

- Lepton number no accidental symmetry anymore**



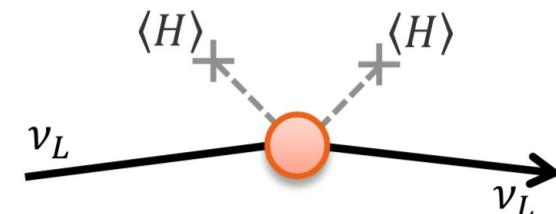
$$m_M \bar{\nu}_L \nu_L^c$$

1/2	1/2
-----	-----

-1/2	1/2
LLHH	
-1/2	1/2

not at tree-level within  
the SM possible

- higher dimensional operator
- Lepton number violation (LNV)**



# Majorana Neutrino Masses

$$\begin{aligned}\mathcal{L} &\supset Y_\nu^{ij} L_i N_j \phi + M^{ij} N_i N_j \\ &= M_D^{ij} \nu_i N_j + M_M^{ij} N_i N_j\end{aligned}$$

$$M_\nu = \begin{pmatrix} \delta m_\nu^{1\text{loop}} & M_D \\ M_D^T & M_M \end{pmatrix}$$

Diagonalisation with  $M_M \gg M_D$ :

$$\nu \simeq \nu_L + \theta v_R^c$$

$$m_\nu \simeq \frac{M_D^2}{M_M}$$

mainly **active**  $SU(2)_L$  doublet states with **light** masses

$$N \simeq \nu_R + \theta^T v_L^c$$

$$m_N \simeq M_M$$

mainly **sterile** singlet states with **heavy** masses

*"naturally"* small neutrino masses

**Seesaw type I**



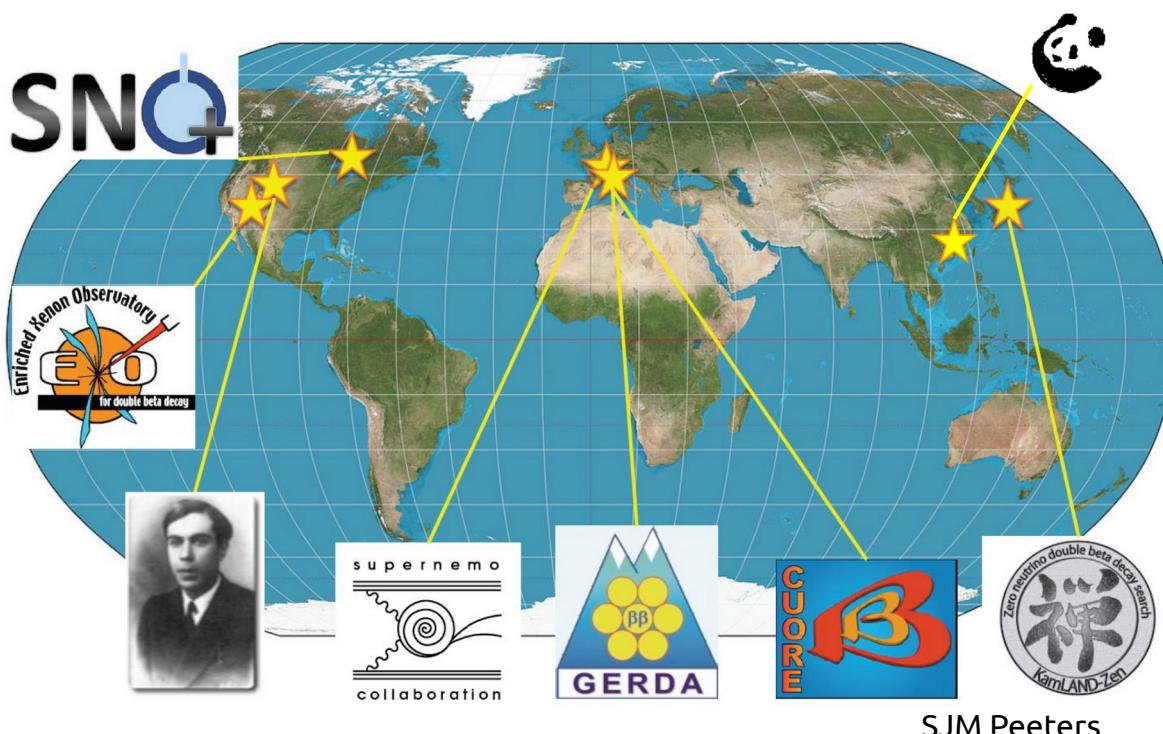
**How can one test if neutrinos have a Majorana or Dirac nature?**

# Neutrinoless Double Beta Decay

# Neutrinoless Double Beta Decay Experiments

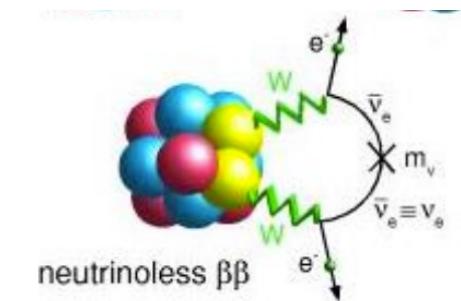
Most stringent constraints on neutrinoless double beta decay half life:

- **GERDA:**  $T_{1/2}^{\text{Ge}} \geq 1.8 \times 10^{26}$  y
- **Kamland-Zen:**  $T_{1/2}^{\text{Xe}} \geq 1.07 \times 10^{26}$  y

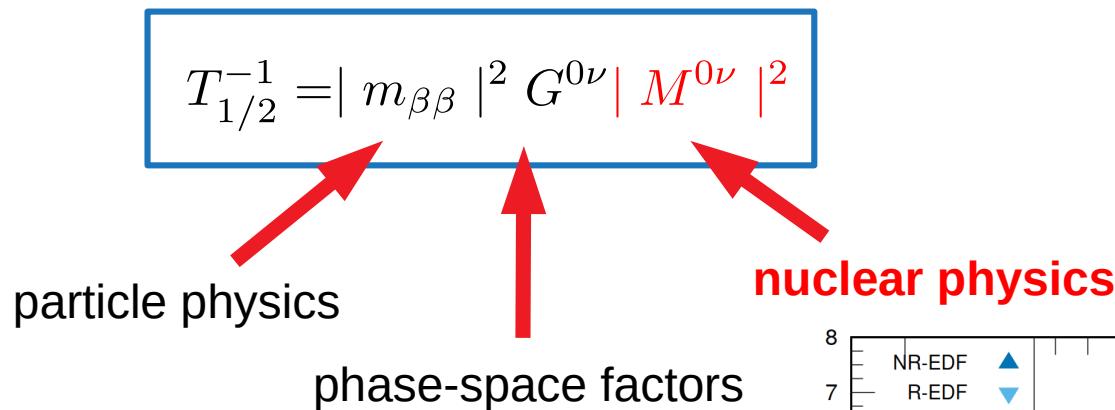


## Future prospects:

Experiment	Iso.	$3\sigma$ disc. sens. $\hat{T}_{1/2}$ [yr]	$\hat{m}_{\beta\beta}$ [meV]
LEGEND 200 [60, 61]	${}^{76}\text{Ge}$	$8.4 \cdot 10^{26}$	40–73
LEGEND 1k [60, 61]	${}^{76}\text{Ge}$	$4.5 \cdot 10^{27}$	17–31
SuperNEMO [67, 68]	${}^{82}\text{Se}$	$6.1 \cdot 10^{25}$	82–138
CUPID [57, 58, 69]	${}^{82}\text{Se}$	$1.8 \cdot 10^{27}$	15–25
CUORE [51, 52]	${}^{130}\text{Te}$	$5.4 \cdot 10^{25}$	66–164
CUPID [57, 58, 69]	${}^{130}\text{Te}$	$2.1 \cdot 10^{27}$	11–26
SNO+ Phase I [65, 70]	${}^{130}\text{Te}$	$1.1 \cdot 10^{26}$	46–115
SNO+ Phase II [66]	${}^{130}\text{Te}$	$4.8 \cdot 10^{26}$	22–54
KamLAND-Zen 800 [59]	${}^{136}\text{Xe}$	$1.6 \cdot 10^{26}$	47–108
KamLAND2-Zen [59]	${}^{136}\text{Xe}$	$8.0 \cdot 10^{26}$	21–49
nEXO [71]	${}^{136}\text{Xe}$	$4.1 \cdot 10^{27}$	9–22
NEXT 100 [63, 72]	${}^{136}\text{Xe}$	$5.3 \cdot 10^{25}$	82–189
PandaX-III 200 [64]	${}^{136}\text{Xe}$	$8.3 \cdot 10^{25}$	65–150
PandaX-III 1k [64]	${}^{136}\text{Xe}$	$9.0 \cdot 10^{26}$	20–46



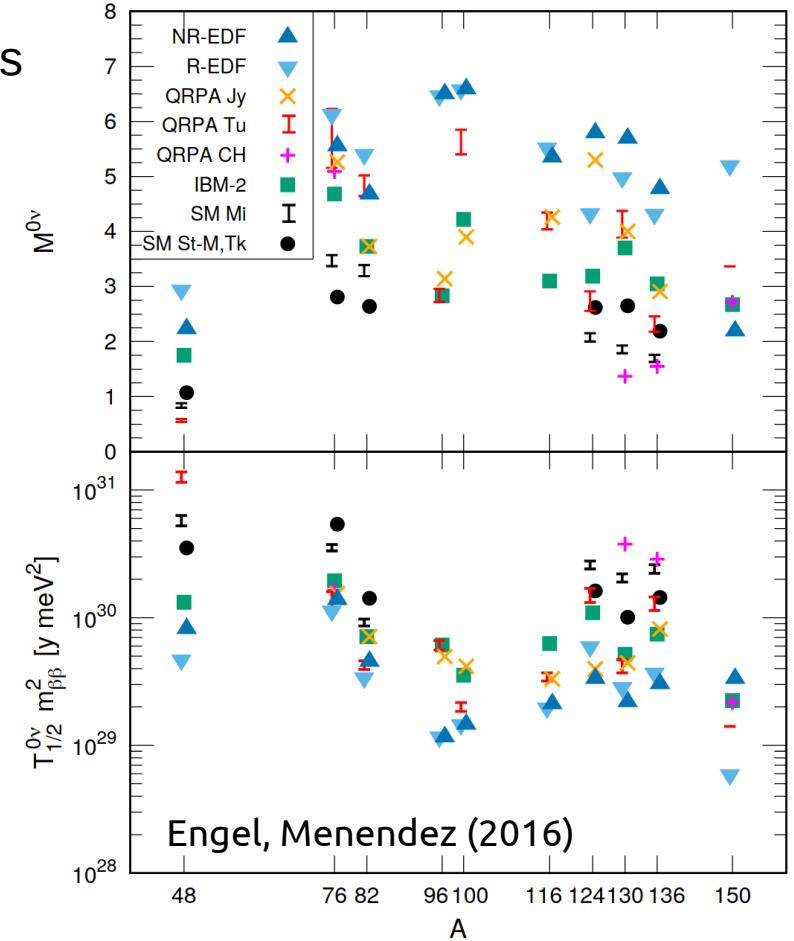
# Half life of Neutrinoless Double Beta Decay



- Dependence on isotope and specific operator
- Differences between different nuclear models
- “the  $g_A$  problem” quenching of the axial-vector coupling

$$\mathcal{M} = \mathcal{M}_{GT} - \frac{g_V^2}{g_A^2} \mathcal{M}_F + \mathcal{M}_T$$

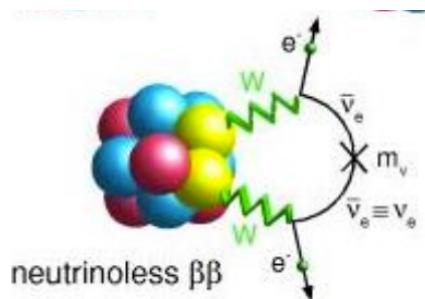
→ sizeable uncertainties



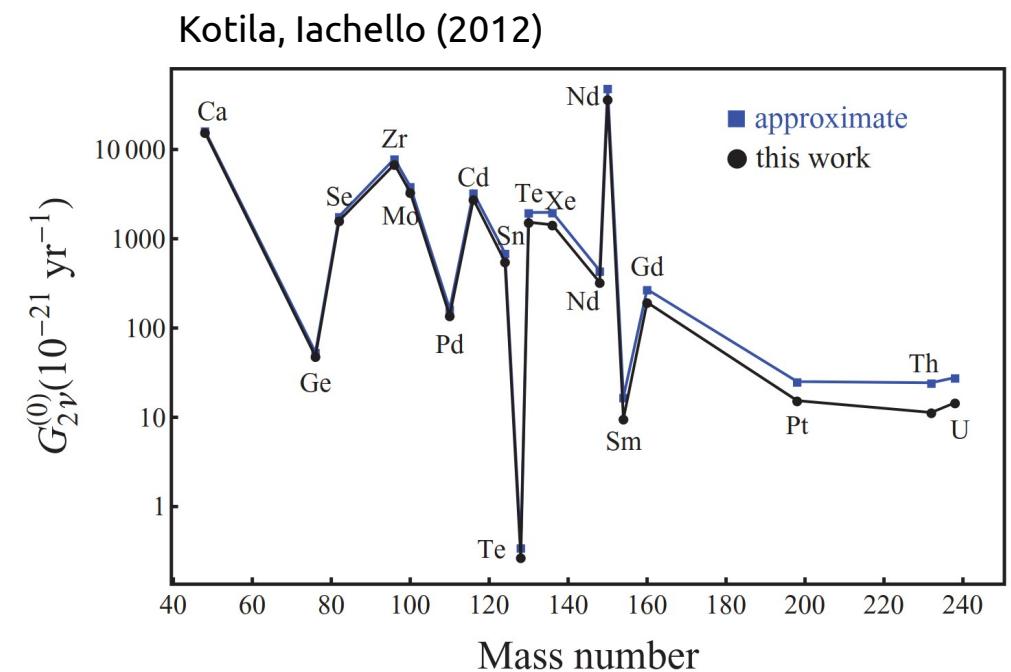
# Half life of Neutrinoless Double Beta Decay

$$T_{1/2}^{-1} = | m_{\beta\beta} |^2 G^{0\nu} | M^{0\nu} |^2$$

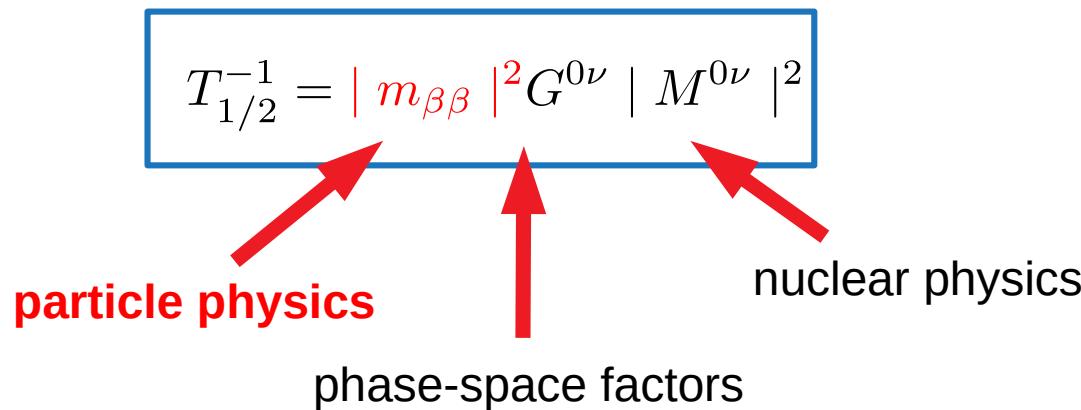
particle physics    nuclear physics  
phase-space factors



- known and calculated to good accuracy
- **Dependent on new physics!**

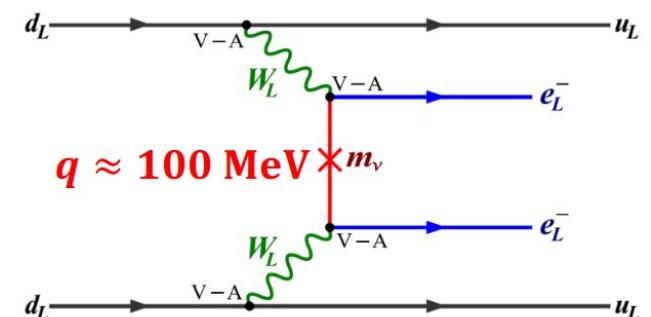


# Half life of Neutrinoless Double Beta Decay



$$A_{\mu\nu}^{\text{lep}} = \frac{1}{4} \sum_{i=1}^3 U_{ei}^2 \gamma_\mu (1 + \gamma_5) \frac{q + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1 - \gamma_5)$$

$$\approx \frac{\gamma_\mu (1 + \gamma_5) \gamma_\nu}{4q^2} \sum_{i=1}^3 U_{ei}^2 m_{\nu_i} m_{\beta\beta}$$



$$T_{1/2}^{0\nu} = (G |\mathcal{M}|^2 \langle m_{\beta\beta} \rangle^2)^{-1} \simeq 10^{27-28} \left( \frac{0.01 \text{ eV}}{\langle m_{\beta\beta} \rangle} \right)^2 \text{ y}$$

# **Neutrinoless Double Beta Decay & Standard interactions**

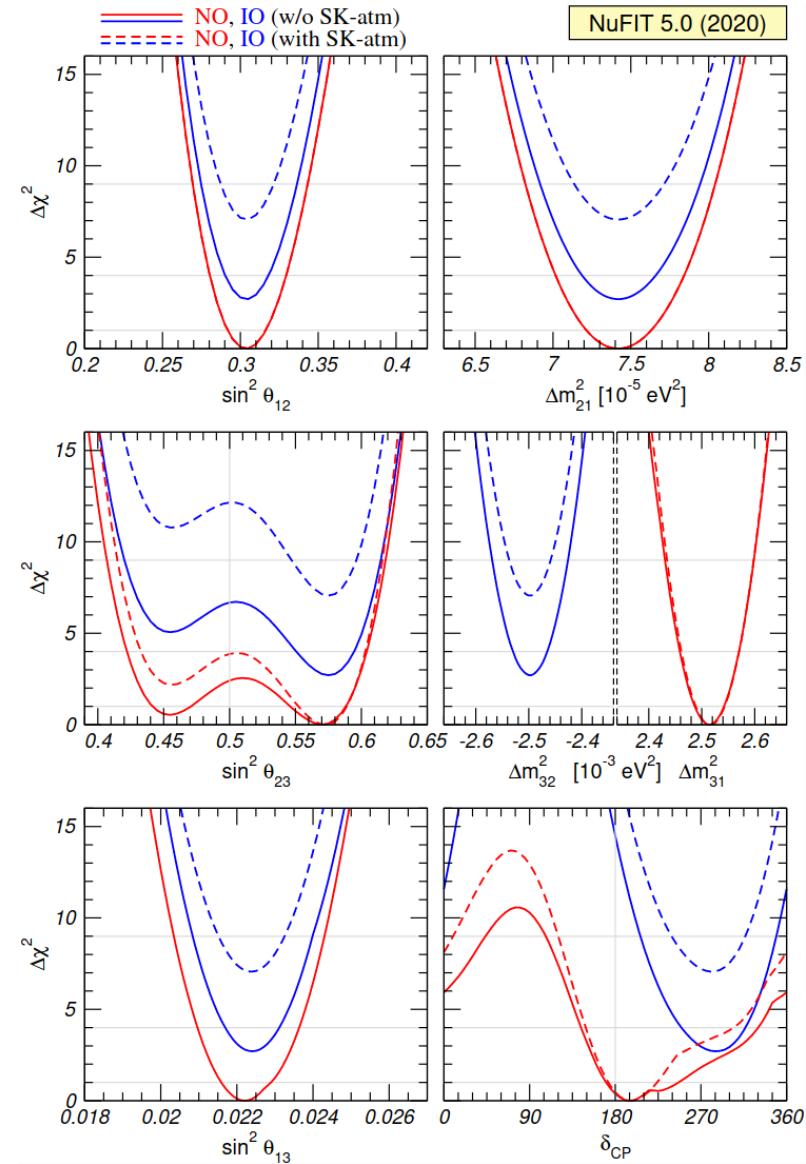
# Neutrino Oscillations & $0\nu\beta\beta$

$$|\nu_i\rangle = \sum_{\alpha} U_{\alpha i} |\nu_{\alpha}\rangle$$

$|\nu_{\alpha}\rangle$  flavour eigenstates

$|\nu_i\rangle$  mass eigenstates

**Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix**



- Solar experiments**

*Homestake, Chlorine, Gallex/GNO, SAGE, (Super) Kamiokande, SNO, Borexino*

- Atmospheric experiments**

*IceCube, ANTARES, DeepCore, Super-Kamiokande*

- Reactor experiments**

*KamLAND, Double Chooz, Daya Bay*

- Accelerator experiments**

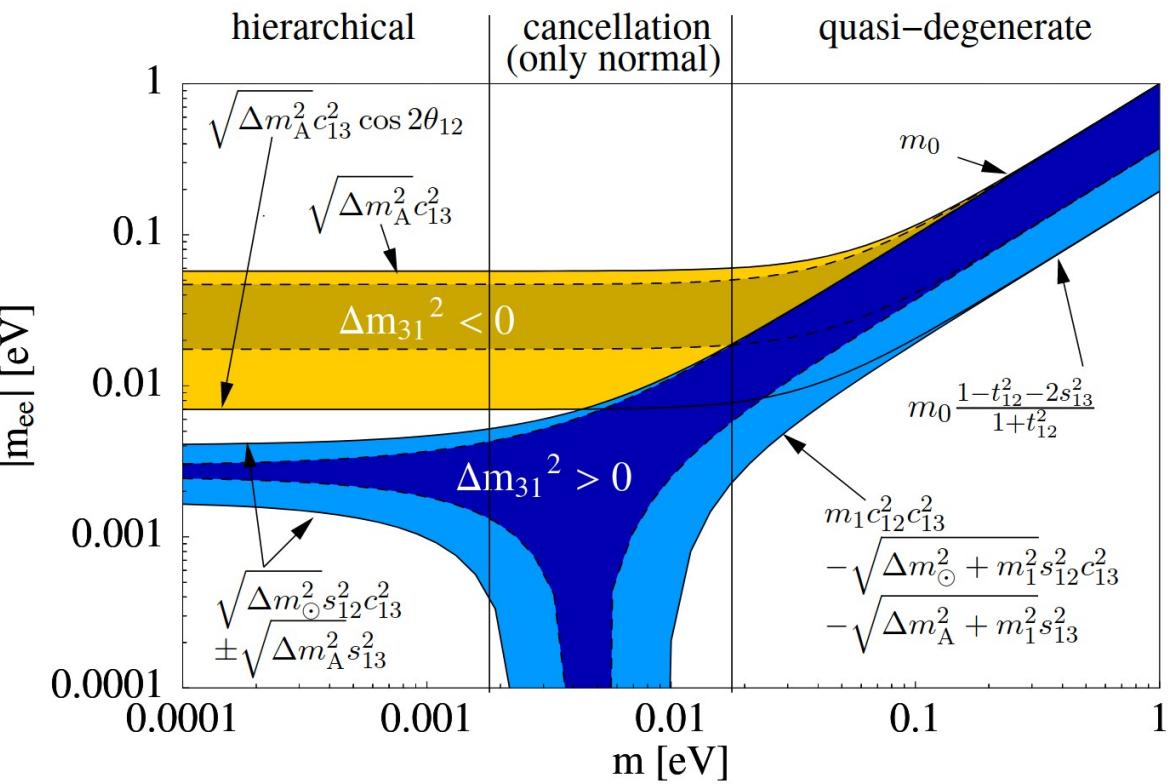
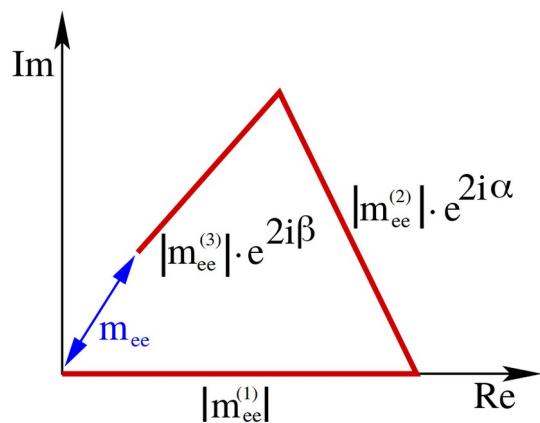
*T2K, MINOS, NOvA*

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

# Mass hierarchy & $0\nu\beta\beta$

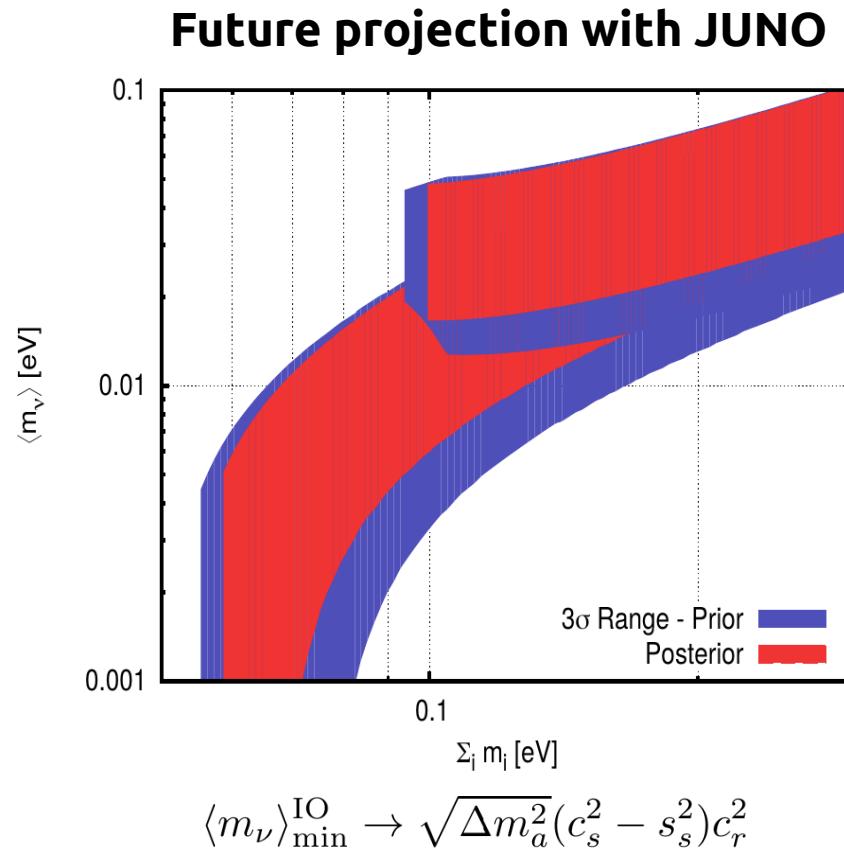
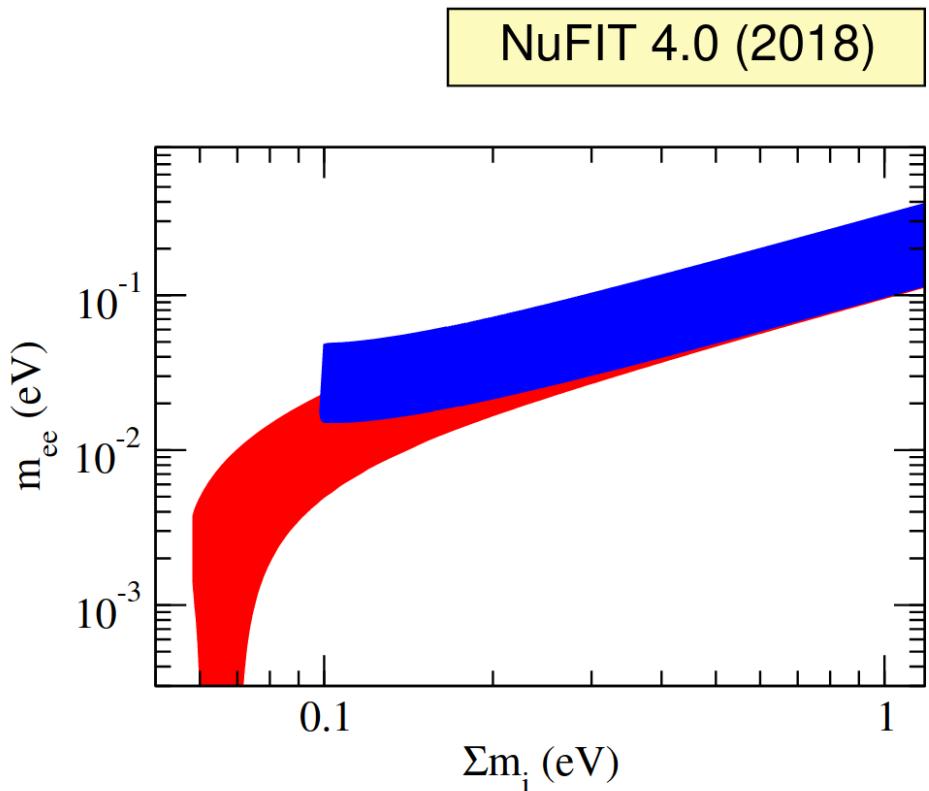
$$\langle m_{ee} \rangle = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{2i\phi_{12}} + s_{13}^2 m_3 e^{2i\phi_{13}}|$$

- Uncertainty from **unknown Majorana phase**
- **Quasi-degenerate** region above 0.2 eV
- Accidental **cancellation** for NO



Lindner, Merle, Rodejohann (2006)

# Mass hierarchy & $0\nu\beta\beta$



JUNO can determine **minimal value** of the effective mass with **almost no uncertainty** → fixes the half life that needs to be addressed

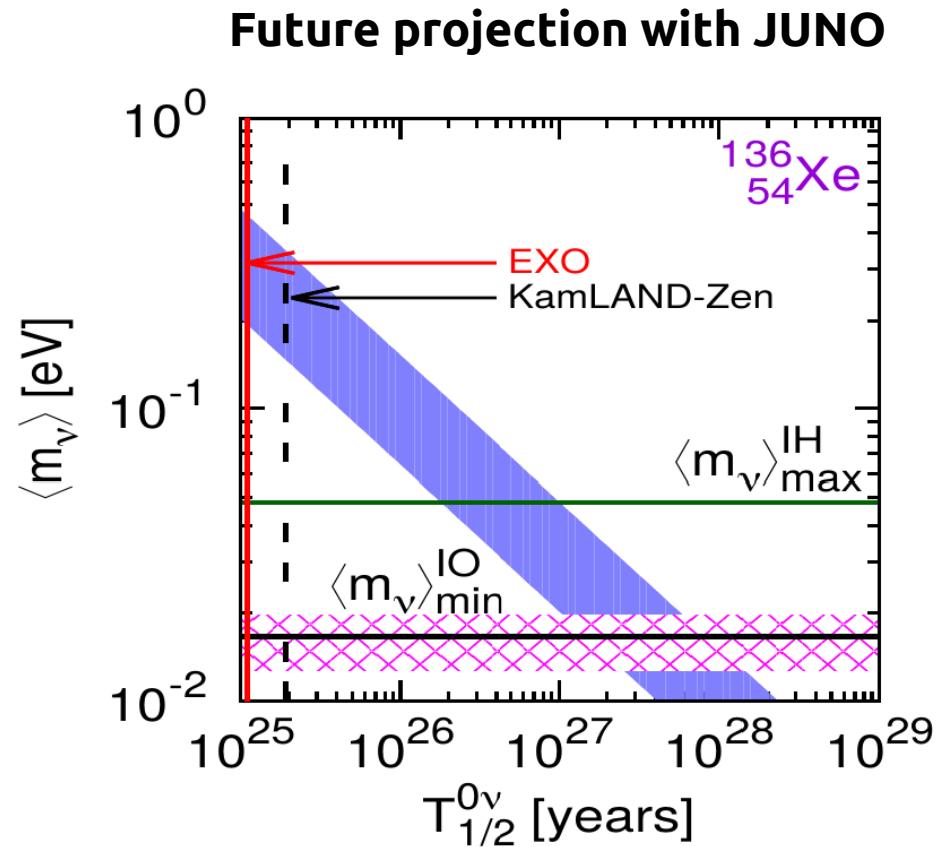
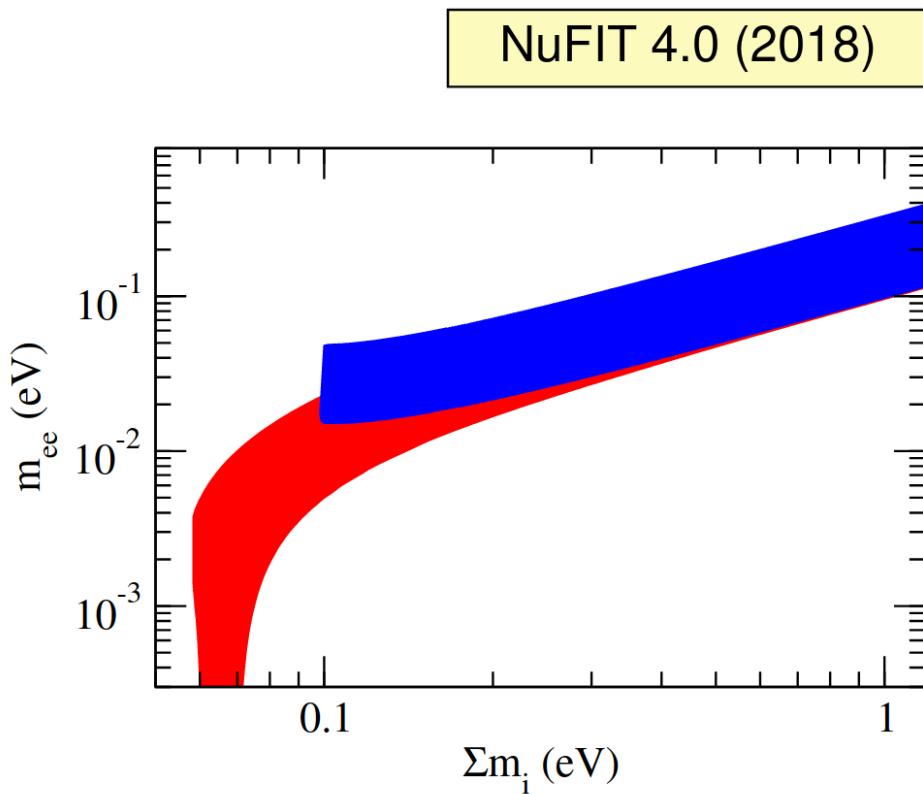
Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni, Schwetz (2018+)

Anamiati, Romeri, Hirsch, Ternes, Tortola (2019+)

Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo (2017+)

Ge, Rodejohann (2018)

# Mass hierarchy & $0\nu\beta\beta$



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Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni, Schwetz (2018+)

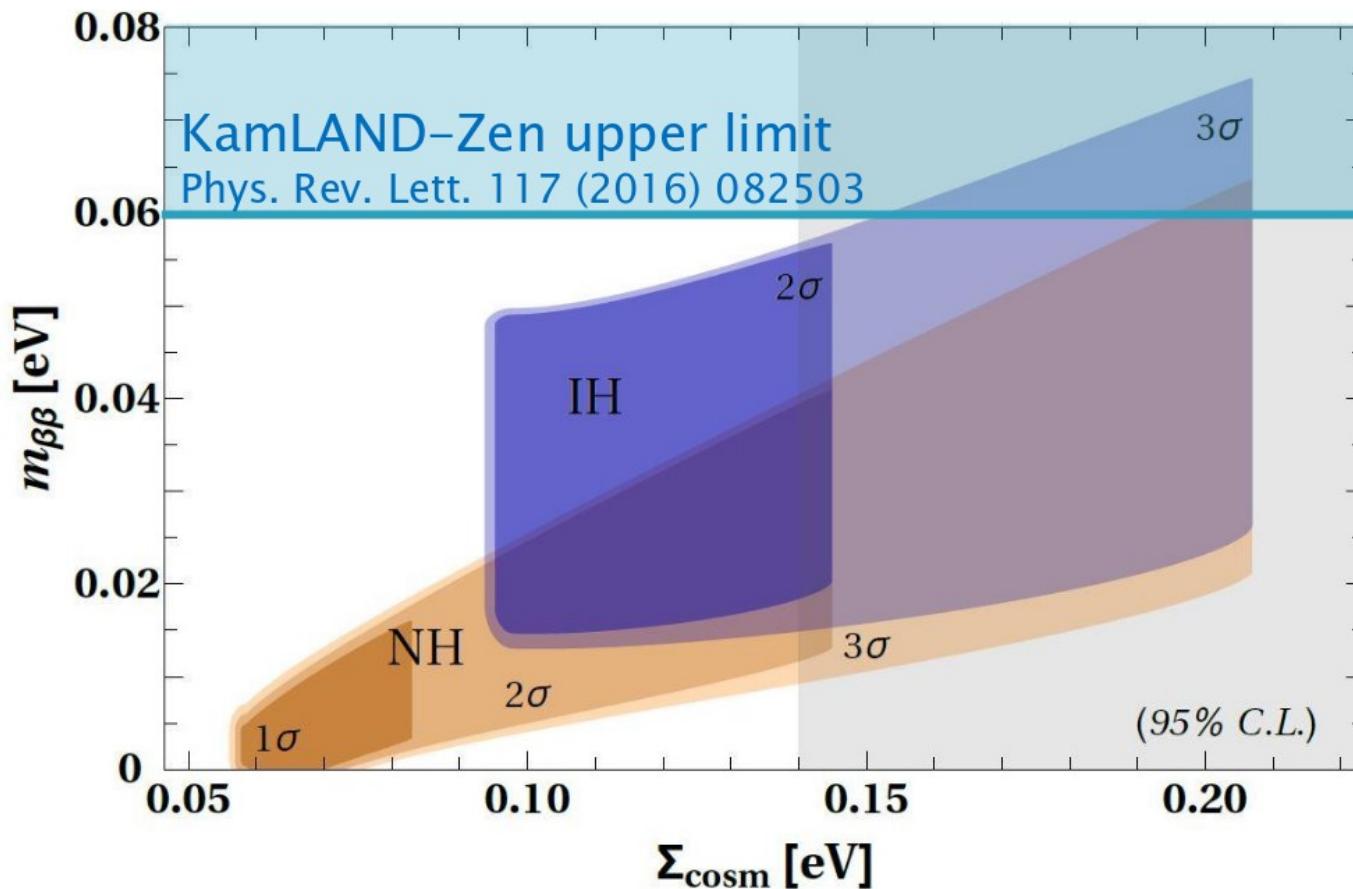
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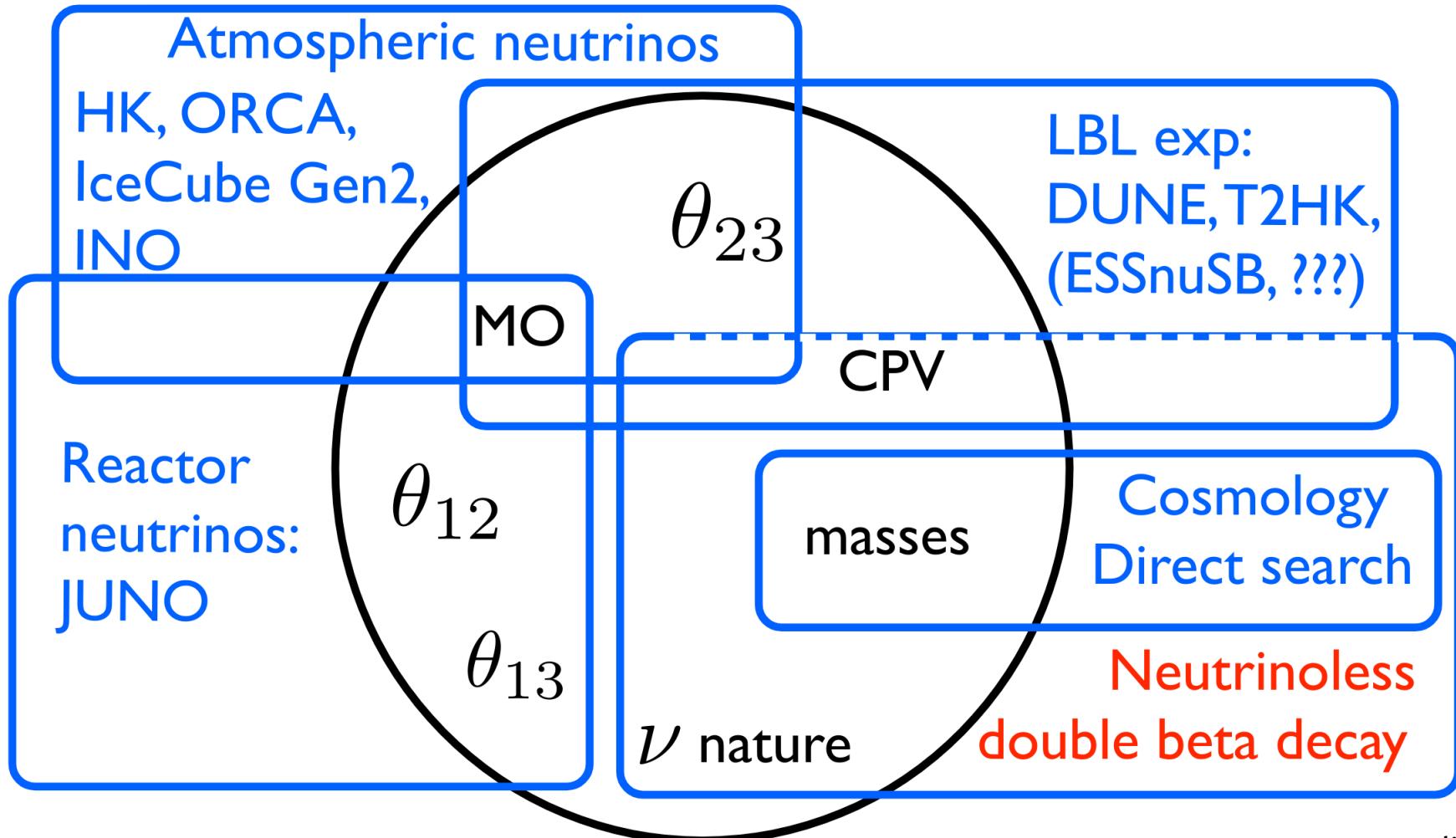
Ge, Rodejohann (2015+)

# Mass hierarchy & $0\nu\beta\beta$ & Cosmology

Dell'Oro, Marcocci, Viel, Vissani (2016)



# Complementarity

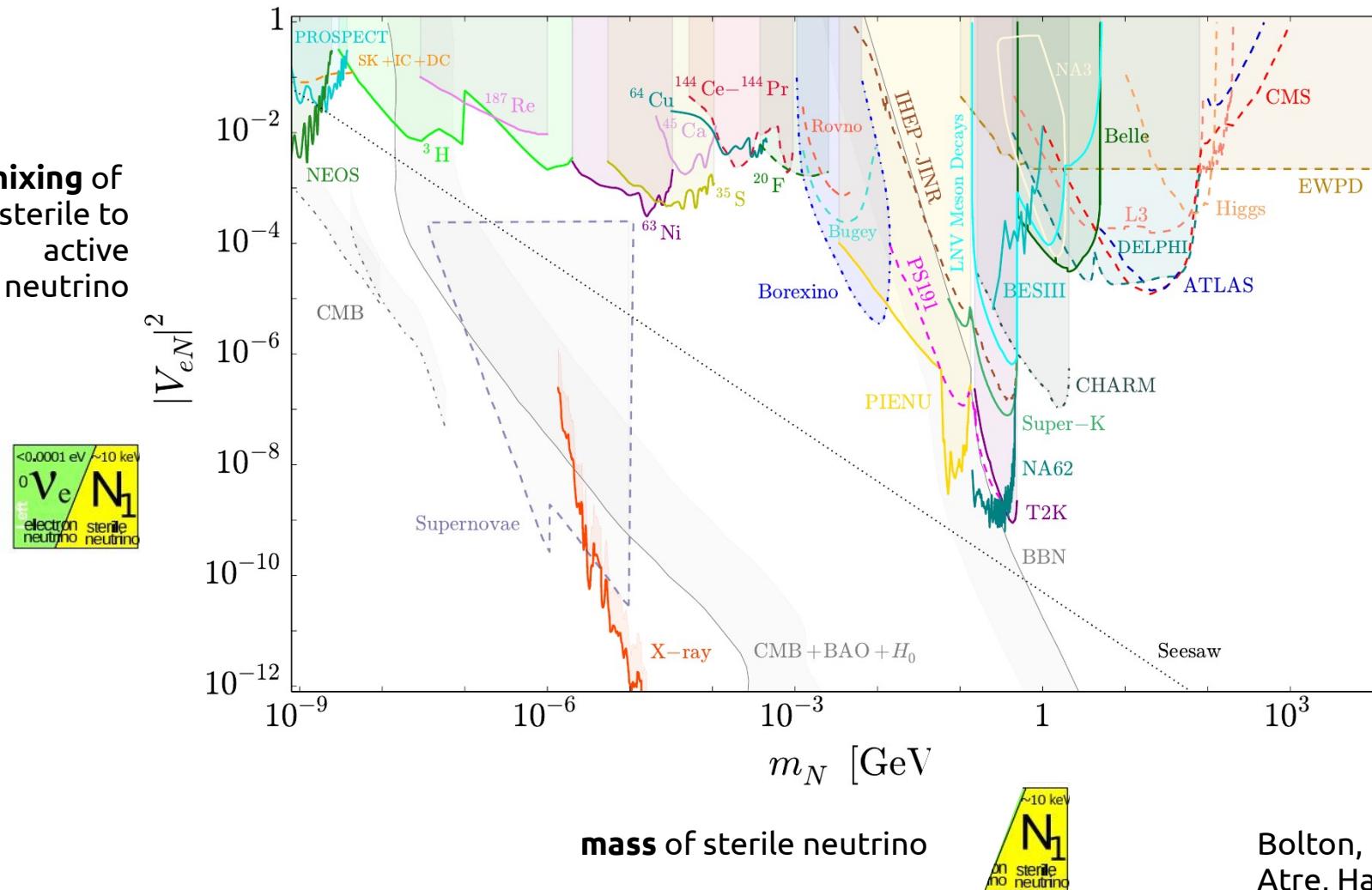


S. Pascoli

# Heavy Sterile Neutrinos

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} g_A^4 m_p^2 |\mathcal{M}_N^{0\nu}|^2 \left| \sum_{i=1}^3 \frac{U_{ei}^2 m_i}{\langle \mathbf{p}^2 \rangle} + \sum_{i=1}^{n_S} \frac{V_{eN_i}^2 m_{N_i}}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2} \right|^2$$

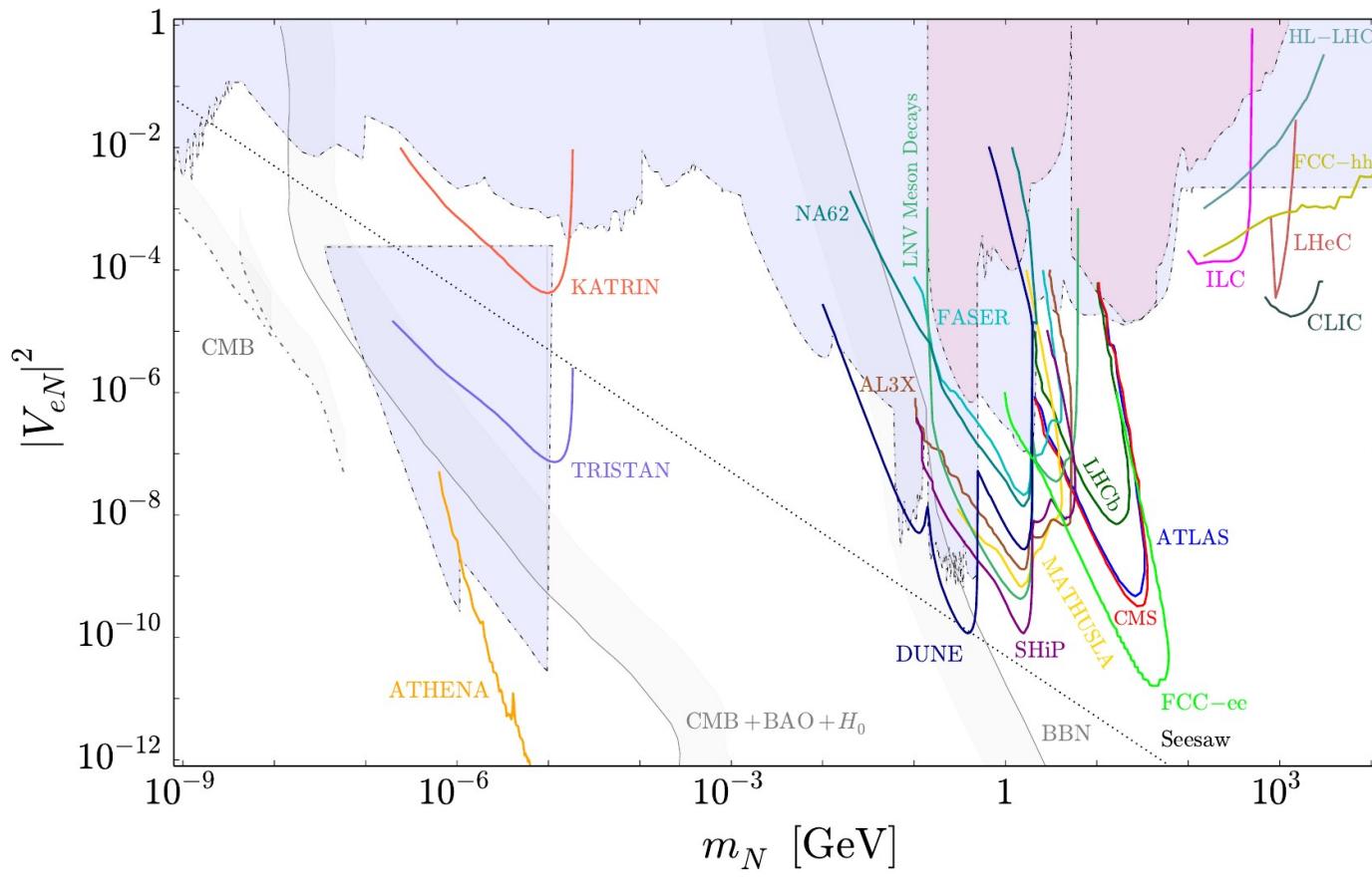
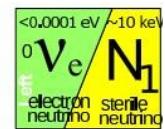
**mixing of  
sterile to  
active  
neutrino**



# Heavy Sterile Neutrinos

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**mixing of  
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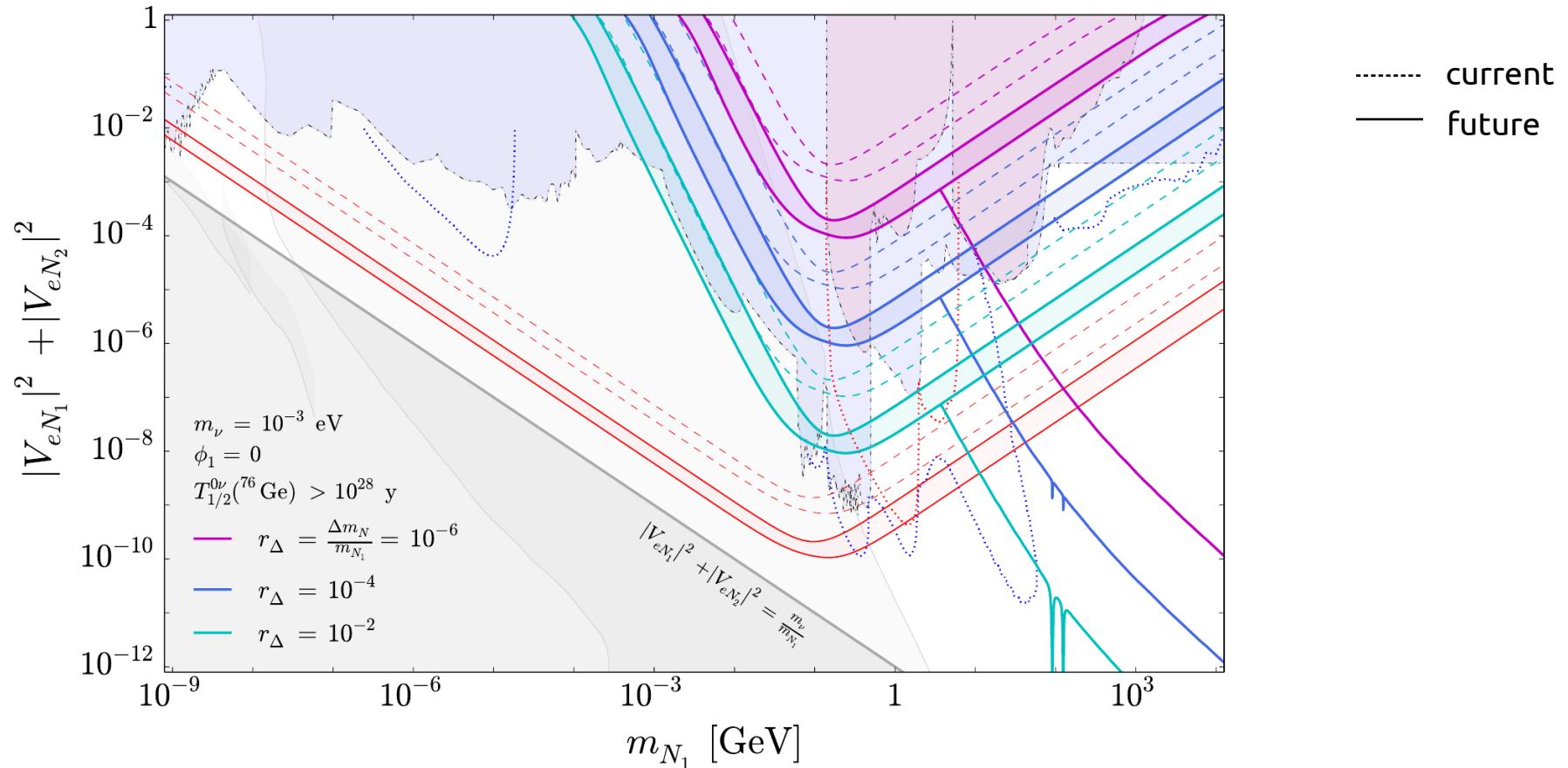
**mass of sterile neutrino**



Bolton, Deppisch, Dev (2019)

# Heavy Sterile Neutrinos

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu} g_A^4 m_p^2 |\mathcal{M}_N^{0\nu}|^2 \left| \sum_{i=1}^3 \frac{U_{ei}^2 m_i}{\langle \mathbf{p}^2 \rangle} + \sum_{i=1}^{n_S} \frac{V_{eN_i}^2 m_{N_i}}{\langle \mathbf{p}^2 \rangle + m_{N_i}^2} \right|^2$$



$\Delta r \rightarrow 0$  leads to **pseudo-Dirac limit** where lepton number is approximately conserved and  $0\nu\beta\beta$  forbidden

Bolton, Deppisch, Dev (2019)

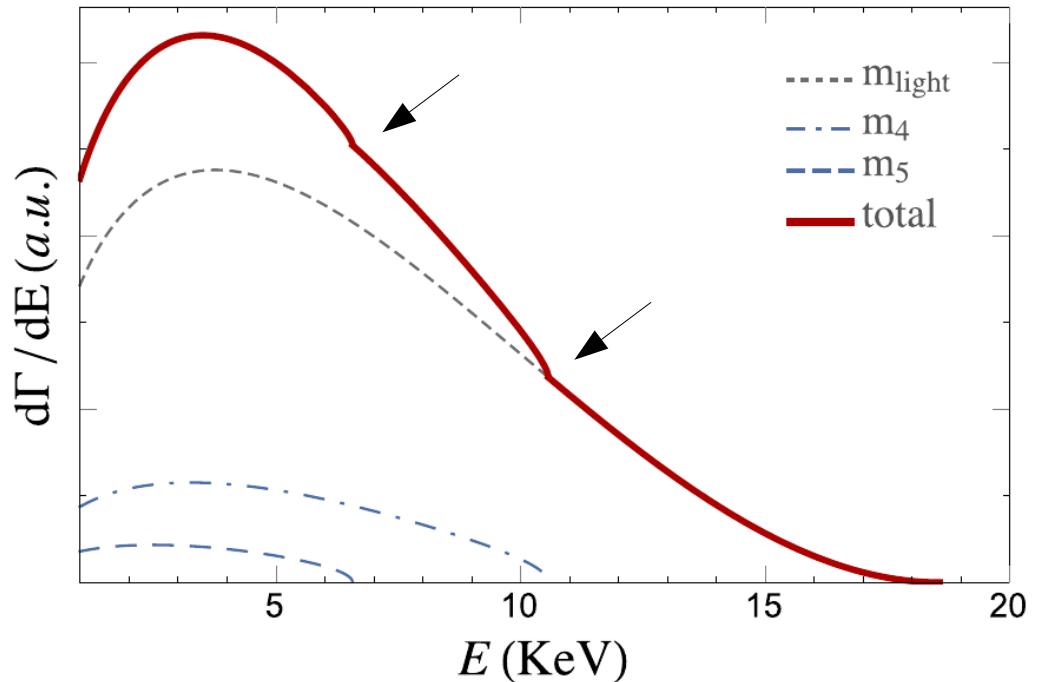
# Light Sterile Neutrinos

**Hypothesis:** KATRIN sees a kink

**Assumption:** 3 active + 1 sterile neutrino

$$m_4 \in [1 \text{ KeV}, 18.5 \text{ KeV}]$$

$$|U_{e4}|^2 > 10^{-6}.$$



**Impact on neutrinoless double beta decay:**

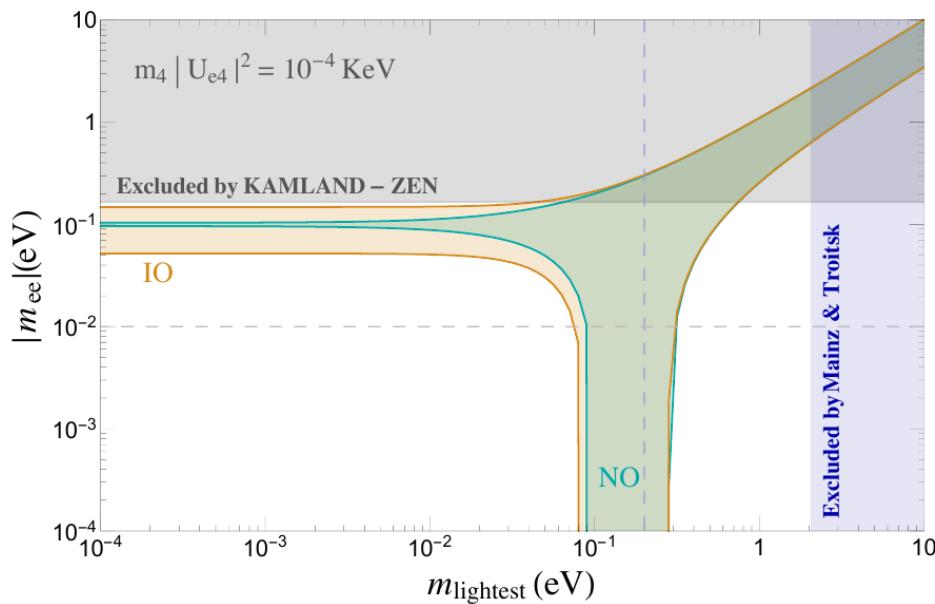
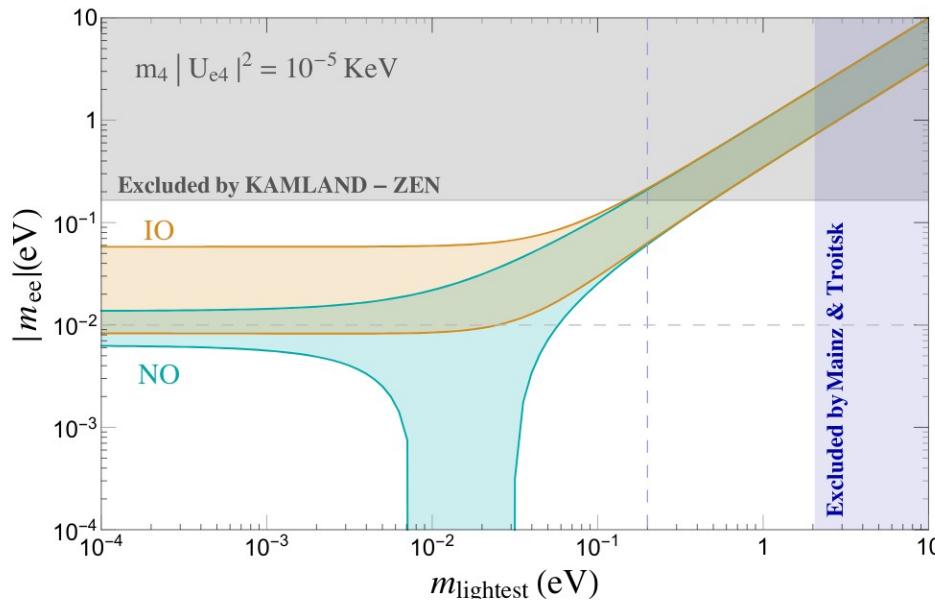
$$m_{ee}^{(3+1)} = \sum_{i=1}^4 U_{ei}^2 p^2 \frac{m_i}{p^2 - m_i^2} \simeq \sum_{i=1}^4 U_{ei}^2 m_i \equiv m_{ee}^{(\text{SM}_\nu)} + m_4 U_{e4}^2$$

Abada, Hernandez-Cabezudo, Marcano (2019)

# Light Sterile Neutrinos – Interplay $0\nu\beta\beta$ & KATRIN

**Assumption:** 3 active + 1 sterile neutrino:

- possible kink @ KATRIN would imply that IO and NO might **not be distinguishable** anymore with  $0\nu\beta\beta$
- **Observation** of  $0\nu\beta\beta$  would not necessarily imply IO
- **Non-observation** would not rule out IO due to cancellations for large enough  $m_4 |U_{e4}|^2$



Abada, Hernandez-Cabezudo, Marcano (2019)

# **Neutrinoless Double Beta Decay & Non-standard interactions**

# Lepton-Number Violation

- LNV occurs only at odd mass dimension:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1} \mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3} \mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5} \mathcal{O}_i^{(9)} + \dots$$

$$\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho} \epsilon_{\beta\sigma}$$

$$\mathcal{O}_{14b}^{(9)} = L^\alpha L^\beta \bar{Q}_\alpha \bar{u}^c Q^\rho d^c \epsilon_{\beta\rho}$$

$$\mathcal{O}_{3a}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\beta} \epsilon_{\rho\sigma}$$

Babu, Leung (2001), de Gouvea, Jenkins (2007), Deppisch, Graf, JH, Huang (2017)

# Lepton-Number Violation

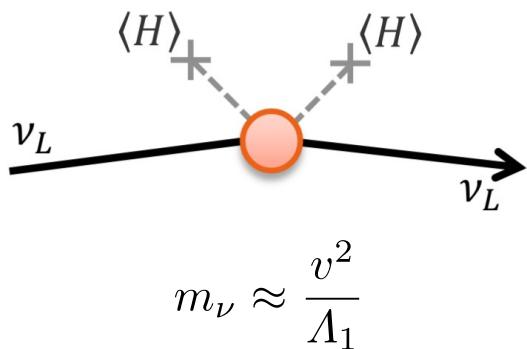
- LNV occurs only at odd mass dimension:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1} \mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3} \mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5} \mathcal{O}_i^{(9)} + \dots$$

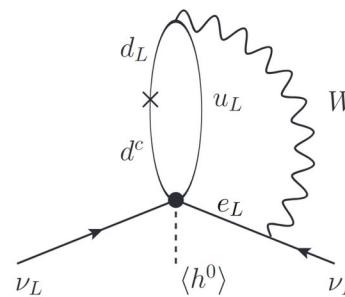


$$\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho} \epsilon_{\beta\sigma}$$

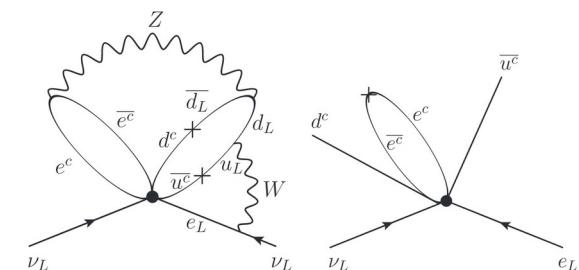
$$\mathcal{O}_{14b}^{(9)} = L^\alpha L^\beta \bar{Q}_\alpha \bar{u}^c Q^\rho d^c \epsilon_{\beta\rho}$$



$$\mathcal{O}_{3a}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\beta} \epsilon_{\rho\sigma}$$



$$m_\nu \approx \frac{y_d g^2}{(16\pi^2)^2} \frac{v^2}{\Lambda_{3a}}$$



$$m_\nu \approx \frac{y_d y_u g^4}{(16\pi^2)^4} \frac{v^2}{\Lambda_{16}}$$

Deppisch, Graf, JH, Huang (2017)



# Half life of Neutrinoless Double Beta Decay

$$T_{1/2}^{-1} = | m_{\beta\beta} |^2 G^{0\nu} | M^{0\nu} |^2$$

The equation is framed by a blue rectangle. Three red arrows point from the text below to the corresponding terms in the equation:

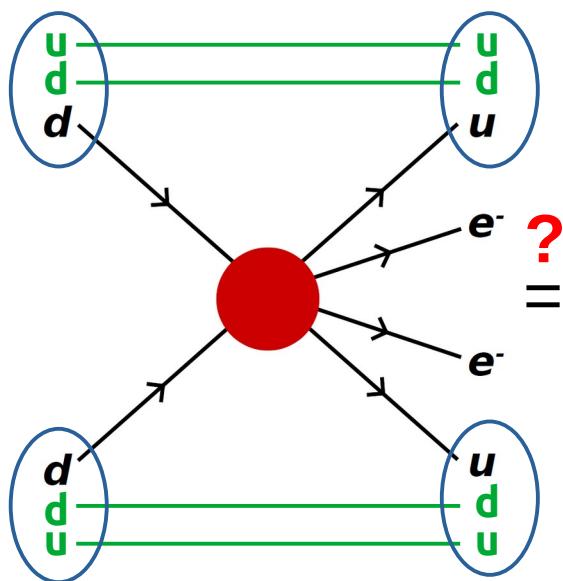
- A red arrow points from the text "particle physics" to the term  $| m_{\beta\beta} |^2$ .
- A red arrow points from the text "nuclear physics" to the term  $| M^{0\nu} |^2$ .
- A single red arrow points from the text "phase-space factors" to the term  $G^{0\nu}$ .

# Half life of Neutrinoless Double Beta Decay

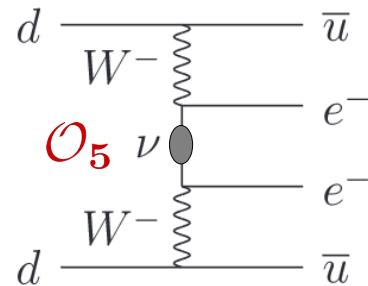
$$T_{1/2}^{-1} = |\epsilon_\alpha^\beta|^2 G^{0\nu} |M^{0\nu}|^2$$

phase-space factors

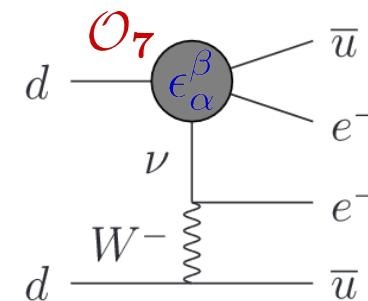
particle physics    nuclear physics



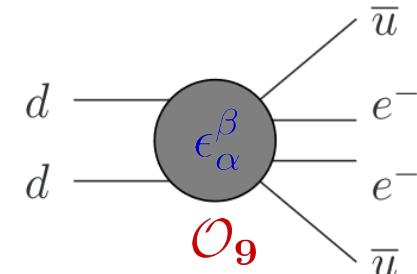
standard mass mechanism



long range contribution



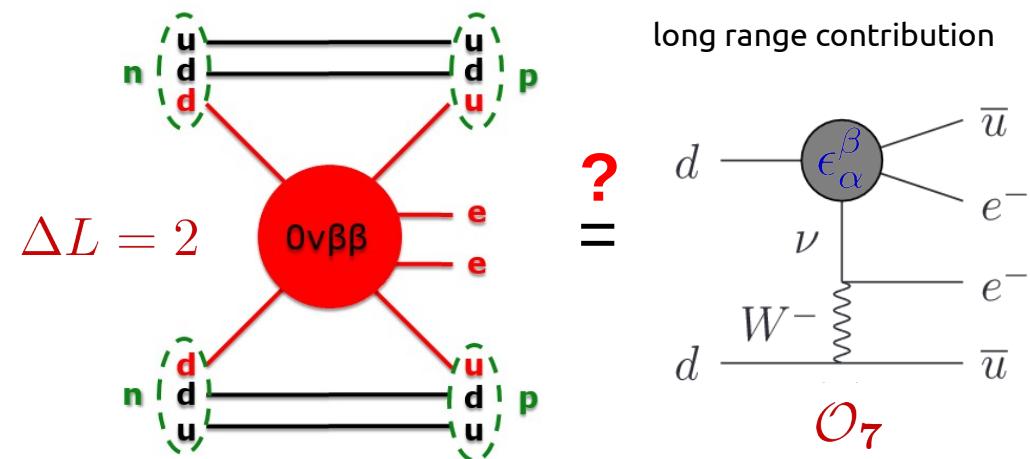
short range contribution



# Long-range contributions to $0\nu\beta\beta$ decay

$$T_{1/2}^{-1} = G_{0\nu} |\mathcal{M}|^2 |\epsilon_\alpha^\beta|^2$$

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \{ j_{V-A}^\mu J_{V-A,\mu}^\dagger + \sum_{\alpha,\beta} \epsilon_\alpha^\beta j_\beta J_\alpha^\dagger \}$$



**Leptonic and hadronic current with different chirality structure:**

$$j_\beta = \bar{e} \mathcal{O}_\beta \nu$$

with

$$J_\alpha^\dagger = \bar{u} \mathcal{O}_\alpha d$$

$$\mathcal{O}_{V\pm A} = \gamma^\mu (1 \pm \gamma_5)$$

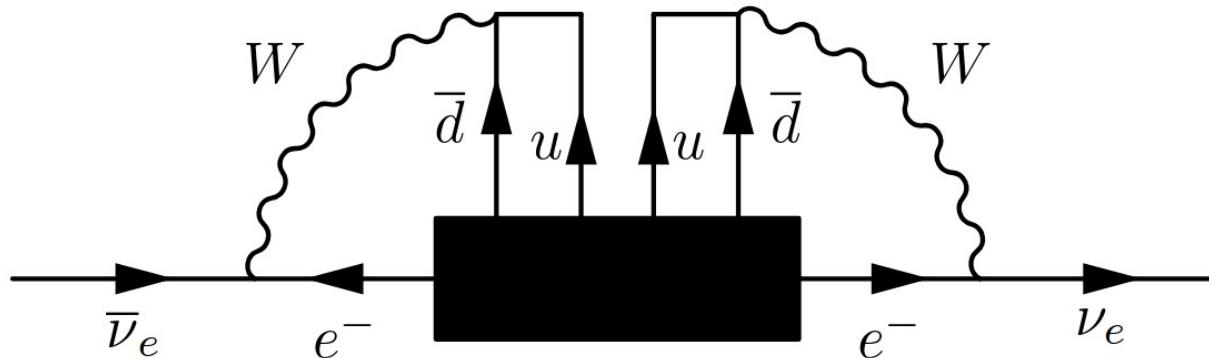
$$\mathcal{O}_{S\pm P} = (1 \pm \gamma_5)$$

$$\mathcal{O}_{T_{R,L}} = \frac{i}{2} [\gamma_\mu, \gamma_\nu] (1 \pm \gamma_5)$$

$ \epsilon  \times 10^8$	$\epsilon_\nu$	$\epsilon_{V-A}^{V+A}$	$\epsilon_{V+A}^{V+A}$	$\epsilon_{S\pm P}^{S+P}$	$\epsilon_{T_R}^{T_R}$
${}^{76}\text{Ge}$	41	0.21	37	0.66	0.07
${}^{76}\text{Xe}$	26	0.11	22	0.26	0.03

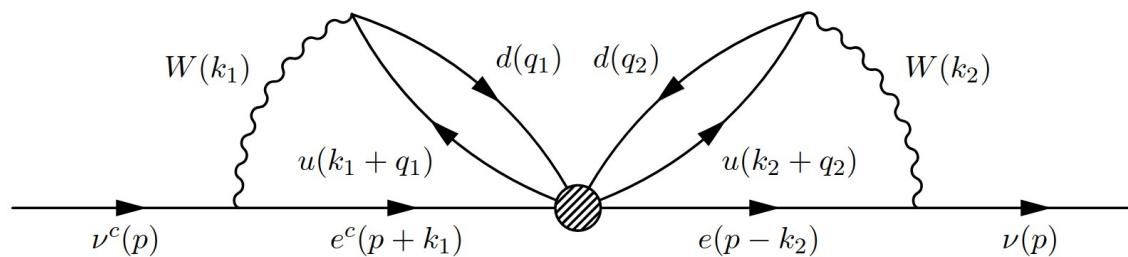
Deppisch, Hirsch, Päs (2012)

# Schechter-Valle Theorem – Black Box Theorem



Schechter, Valle (1982)

**Any  $\Delta L = 2$  operator** that leads to 0vbb will induce a **Majorana mass contribution** via loop

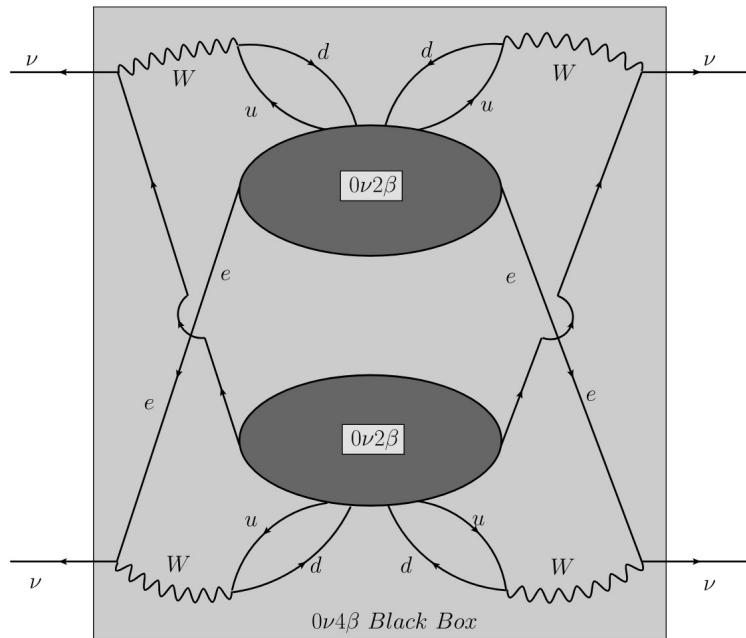


**9-dim  $\Delta L = 2$  operator** will lead to 0vbb but only **tiny contribution** to neutrino mass

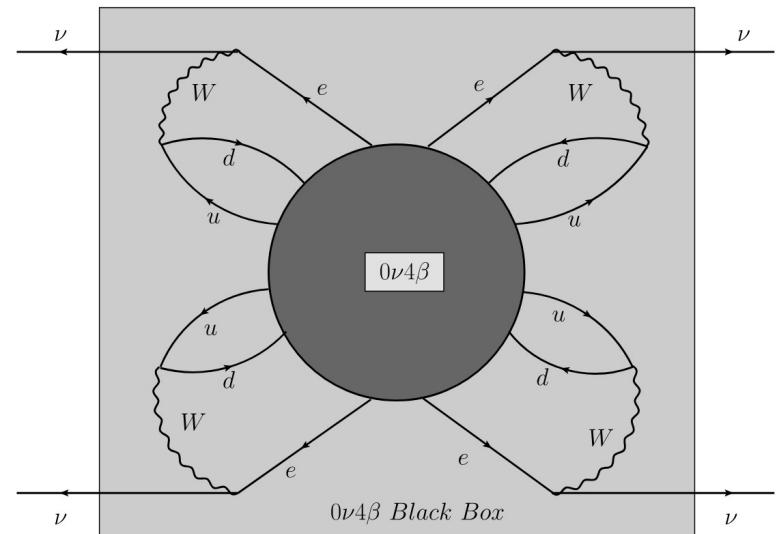
$$\delta m_\nu = 10^{-28} \text{ eV}$$

Dürr, Merle, Lindner (2011)

# Can one ever prove neutrinos are Dirac?



$$R = \frac{\Gamma_{0\nu2\beta}}{\Gamma_{0\nu4\beta}}$$



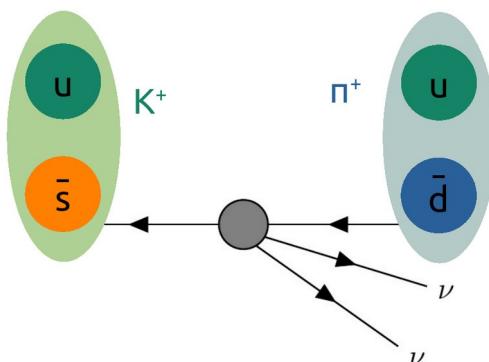
$$R = \frac{Q_{\beta\beta}^5 (\frac{1}{\Lambda^5})^2 q^6}{Q_{4\beta}^{11} (\frac{1}{\Lambda^{14}})^2 q^{18}} \sim 10^{82},$$

Should a **0ν4β decay** signal ever be established, **unaccompanied by 0ν2β decays**, then one would **rule out Majorana neutrinos**

*Caveats may exist?*

Hirsch, Srivastava, Valle (2018)

# Distinguishing Majorana vs Dirac nature?



## Golden Channel

$$\text{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{\text{SM}} = (8.5^{+1.0}_{-1.2}) \times 10^{-11}$$

Buras, Buttazzo, Girrbach-Noe, Knegjens (2015)

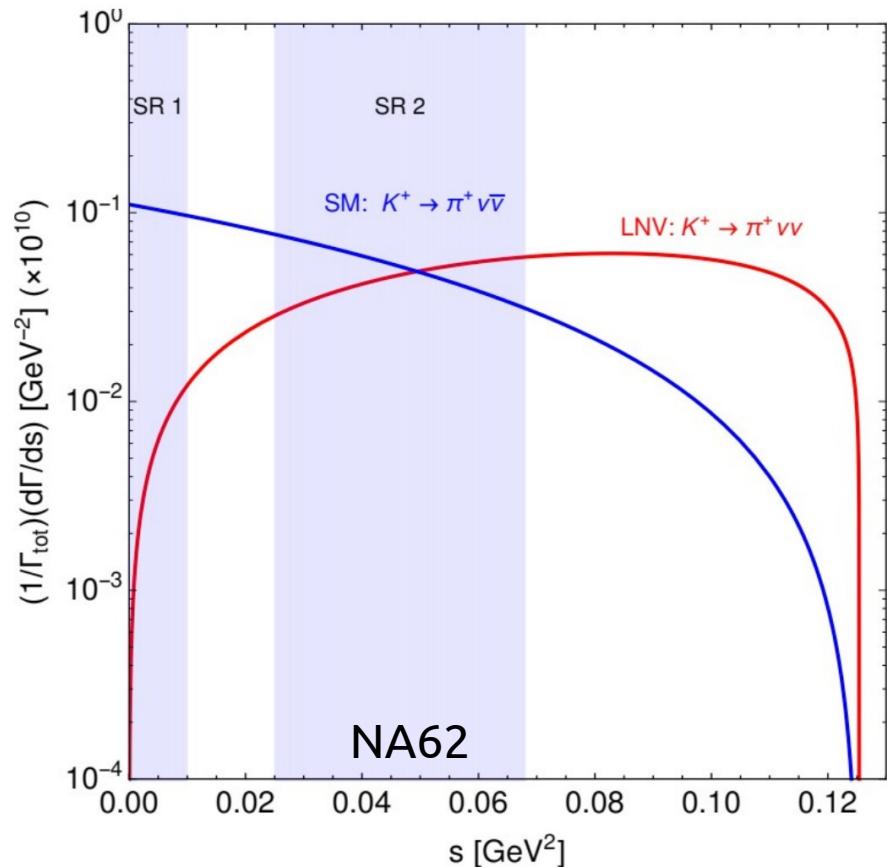
**NA62 aims to reach SM precision!**

- **SM**, lepton number **conserving vector** current

$$\mathcal{L}_{\text{SM}}^{K \rightarrow \pi \nu \bar{\nu}} = \frac{1}{\Lambda_{\text{SM}}^2} (\bar{\nu}_i \gamma^\mu \nu_i) (\bar{d} \gamma_\mu s)$$

- **BSM**, lepton number **violating scalar** current

$$\mathcal{L}_{\text{BSM}}^{K \rightarrow \pi \nu \nu} = \frac{v}{\Lambda_{\text{BSM}}^3} (\nu_i \nu_j) (\bar{d} s)$$

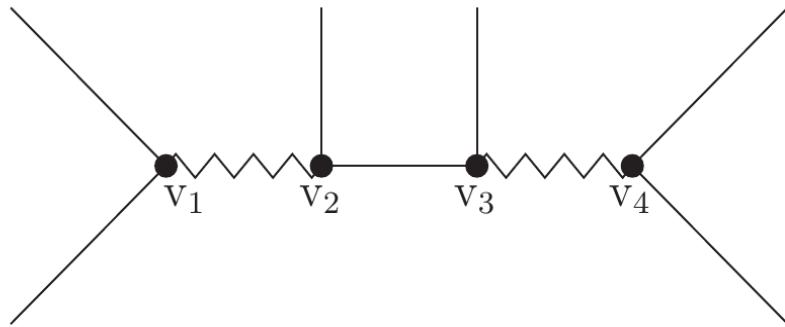


$$s = (E_K - E_\pi)^2$$

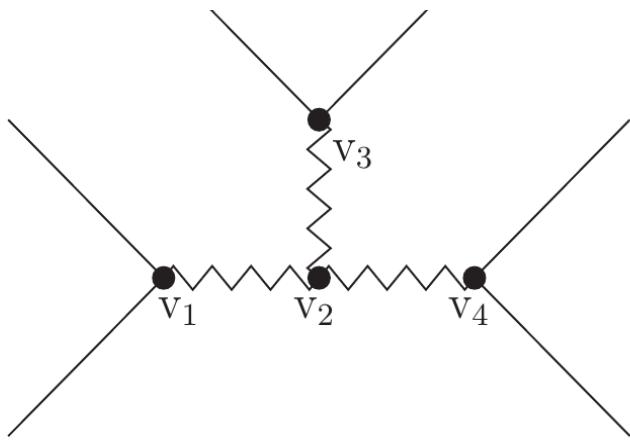
→ **different phase space distribution**

Deppisch, Fridell, JH (2020)

# Topologies for Neutrinoless Double Beta Decay



Topology I



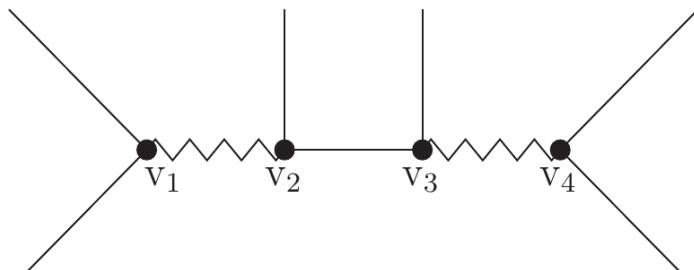
Topology II

#	Decomposition	Long Range?	Mediator ( $U(1)_{\text{em}}, SU(3)_c$ )			Models/Refs./Comments
			$S$ or $V_\rho$	$\psi$	$S'$ or $V'_\rho$	
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(-1, \mathbf{1})$	Mass mechan., RPV [58][60], LR-symmetric models [39], Mass mechanism with $\nu_S$ [61], TeV scale seesaw, e.g., [62][63]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, \mathbf{8})$ $(+1, \mathbf{1})$	$(0, \mathbf{8})$ $(+5/3, \mathbf{3})$	$(-1, \mathbf{8})$ $(+2, \mathbf{1})$	[64]
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, \mathbf{8})$ $(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$ $(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$ $(+2, \mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, \mathbf{1})$ $(+1, \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$ $(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$ $(+1/3, \overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1, \mathbf{1})$ $(+1, \mathbf{8})$	$(0, \mathbf{1})$ $(0, \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$ $(+1/3, \overline{\mathbf{3}})$	RPV [58][60], LQ [65][66]
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1, \mathbf{1})$ $(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$ $(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$ $(+2/3, \mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1, \mathbf{1})$ $(+1, \mathbf{8})$	$(0, \mathbf{1})$ $(0, \mathbf{8})$	$(+2/3, \mathbf{3})$ $(+2/3, \mathbf{3})$	RPV [58][60], LQ [65][66]
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, \overline{\mathbf{3}})$ $(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1})$ $(0, \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$ $(+1/3, \overline{\mathbf{3}})$	RPV [58][60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3, \overline{\mathbf{3}})$ $(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3})$ $(-1/3, \overline{\mathbf{6}})$	$(+1/3, \overline{\mathbf{3}})$ $(+1/3, \overline{\mathbf{3}})$	RPV [58][60]
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3, \overline{\mathbf{3}})$ $(+4/3, \mathbf{6})$	$(+1/3, \overline{\mathbf{3}})$ $(+1/3, \mathbf{6})$	$(-2/3, \overline{\mathbf{3}})$ $(-2/3, \mathbf{6})$	only with $V_\rho$ and $V'_\rho$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3, \overline{\mathbf{3}})$ $(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$ $(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$ $(+2, \mathbf{1})$	only with $V_\rho$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3, \mathbf{3})$ $(+2/3, \overline{\mathbf{6}})$	$(+4/3, \overline{\mathbf{3}})$ $(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$ $(+2, \mathbf{1})$	only with $V_\rho$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3, \overline{\mathbf{3}})$ $(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1})$ $(0, \mathbf{8})$	$(+2/3, \mathbf{3})$ $(+2/3, \mathbf{3})$	RPV [58][60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3, \overline{\mathbf{3}})$ $(+4/3, \mathbf{6})$	$(+5/3, \mathbf{3})$ $(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$ $(+2/3, \mathbf{3})$	only with $V_\rho$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3, \overline{\mathbf{3}})$ $(+4/3, \mathbf{6})$	$(+1/3, \overline{\mathbf{3}})$ $(+1/3, \mathbf{6})$	$(+2/3, \mathbf{3})$ $(+2/3, \mathbf{3})$	see Sec. 4 (this work)
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3, \mathbf{3})$ $(-1/3, \mathbf{3})$	$(0, \mathbf{1})$ $(0, \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$ $(+1/3, \overline{\mathbf{3}})$	RPV [58][60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3, \mathbf{3})$ $(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}})$ $(+1/3, \mathbf{6})$	$(-2/3, \overline{\mathbf{3}})$ $(-2/3, \mathbf{6})$	only with $V'_\rho$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3, \mathbf{3})$ $(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$ $(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}})$ $(-2/3, \mathbf{6})$	only with $V'_\rho$

Bonnet, Hirsch, Ota, Winter (2014)

# **Neutrinoless Double Beta Decay & the LHC**

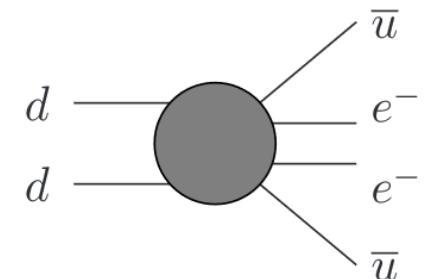
# Neutrinoless Double Beta Decay at the LHC



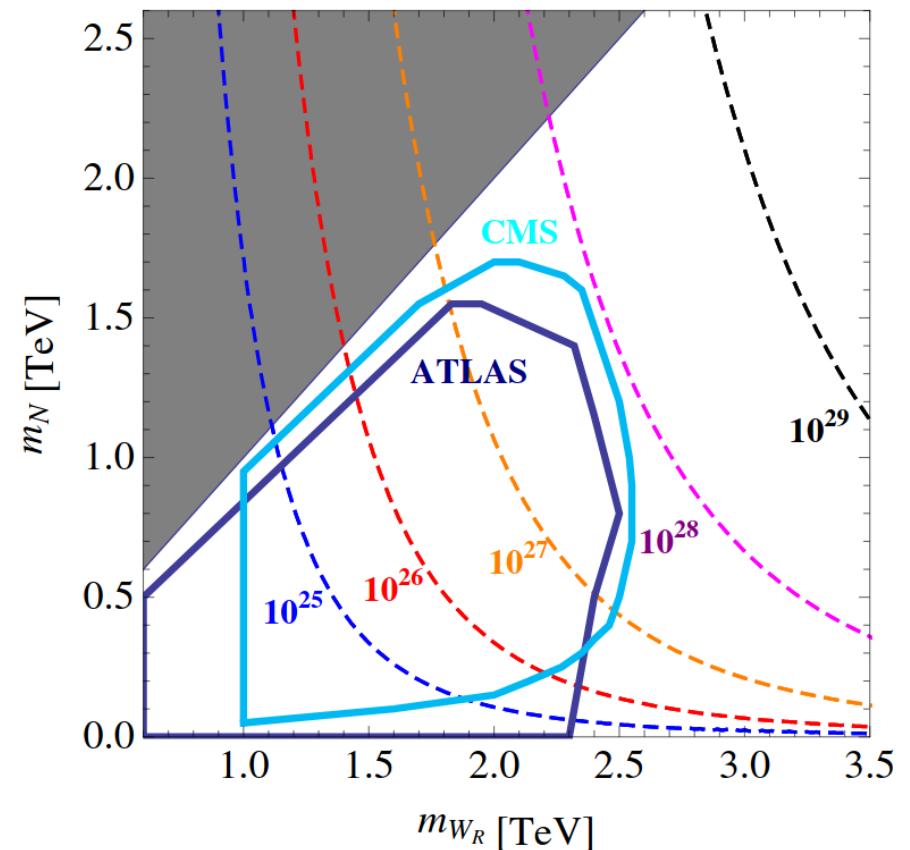
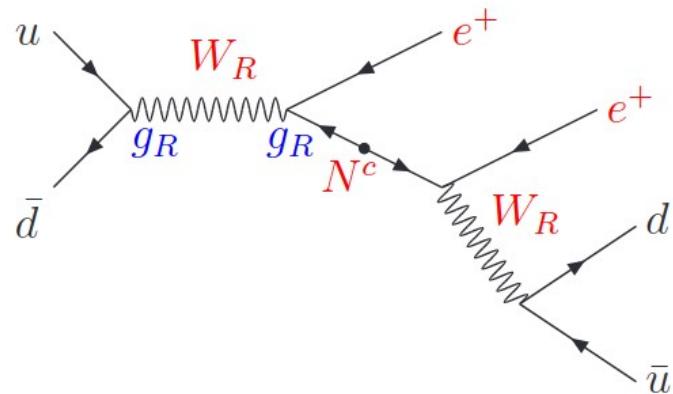
Topology I

$$\mathcal{O}_9 = \frac{c_9}{\Lambda^5} \bar{u} \bar{u} \bar{d} \bar{d} \bar{e} \bar{e}$$

$$\Lambda \geq (1.2 - 3.2) g_{\text{eff}}^{4/5} \text{TeV}$$



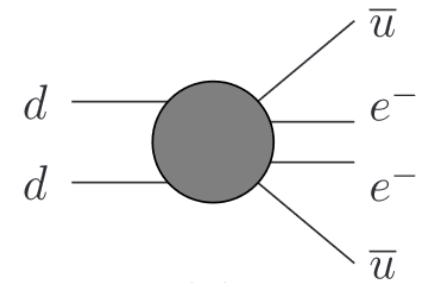
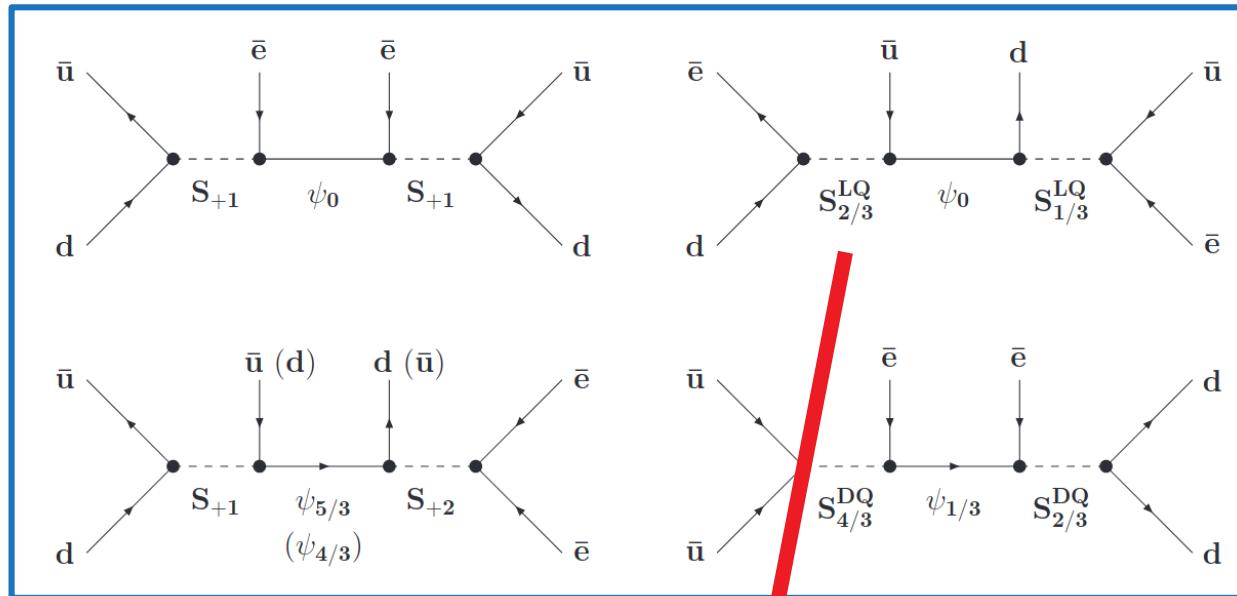
**Example:** Left-Right Symmetric Model



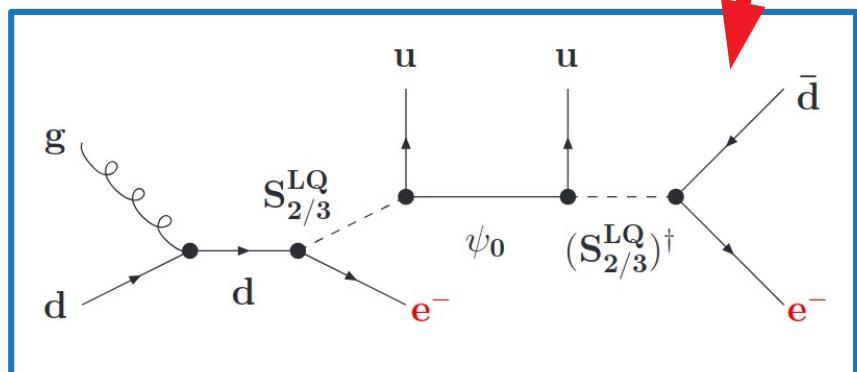
Helo, Kovalenko, Hirsch, Päs (2013)

# Neutrinoless Double Beta Decay at the LHC

Different possible contributions to 0vbb:



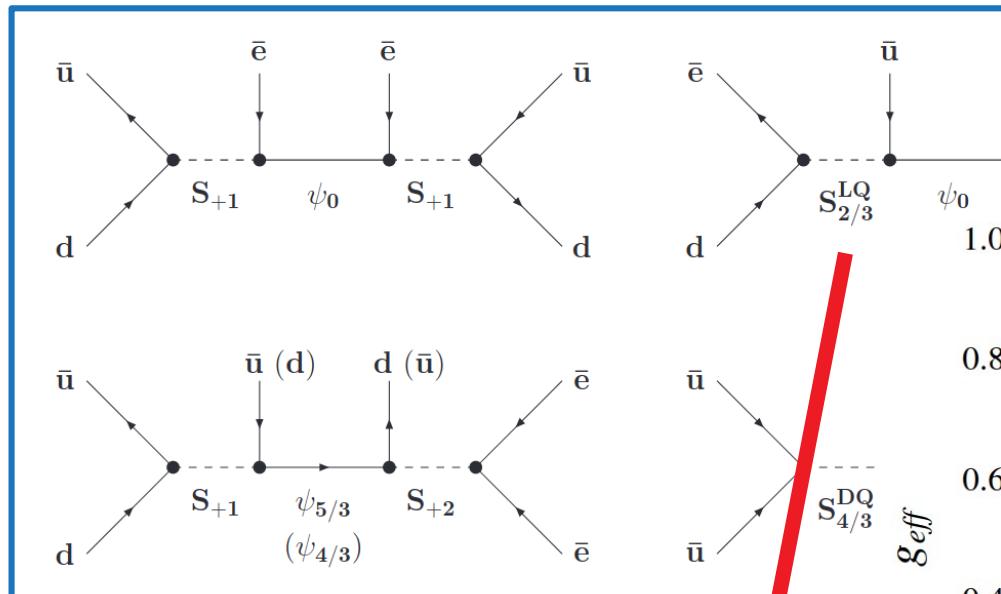
Production process at LHC:



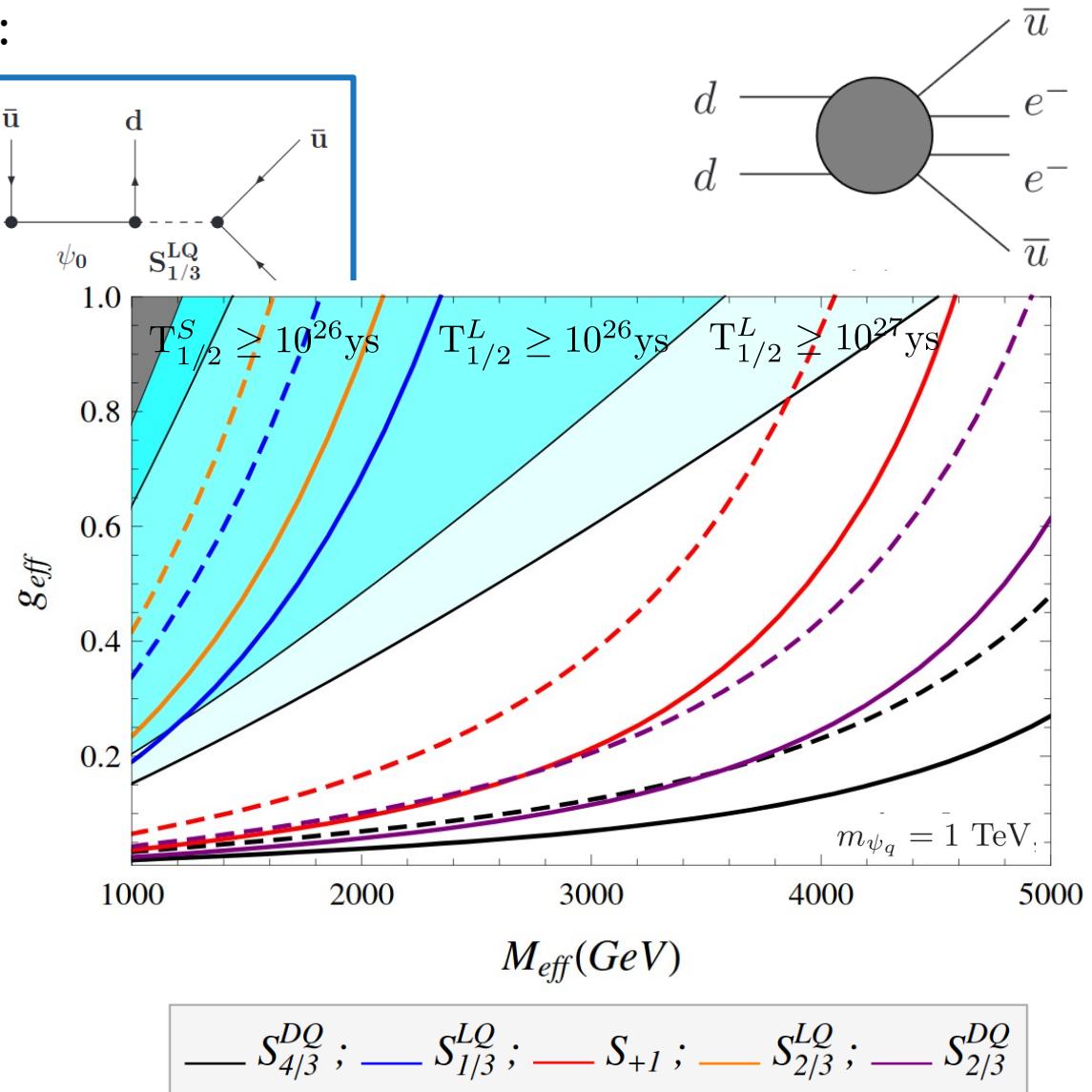
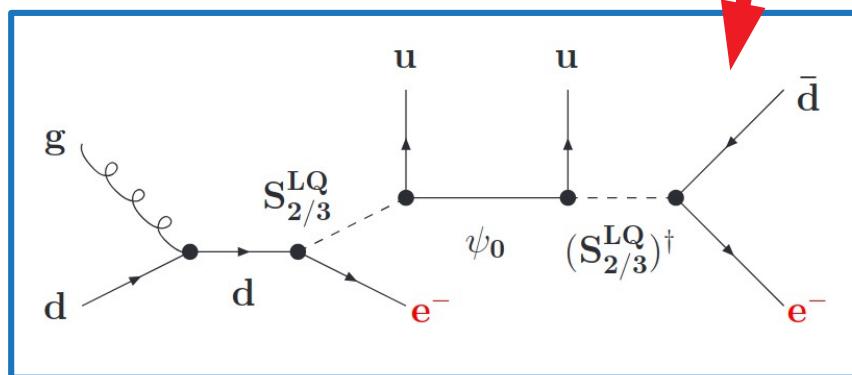
Helo, Kovalenko, Hirsch, Päs (2013)

# Neutrinoless Double Beta Decay at the LHC

Different possible contributions to 0vbb:



Production process at LHC:

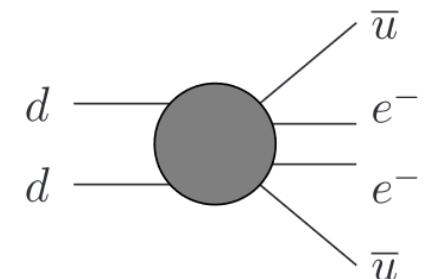


Helo, Kovalenko, Hirsch, Päs (2013)  
 Bonnet, Hirsch, Ota, Winter (2013)  
 Hirsch, Klapdor-Kleingrothaus, Kovalenko (1995)  
 Mohapatra (1986)

# Neutrinoless Double Beta Decay at the LHC

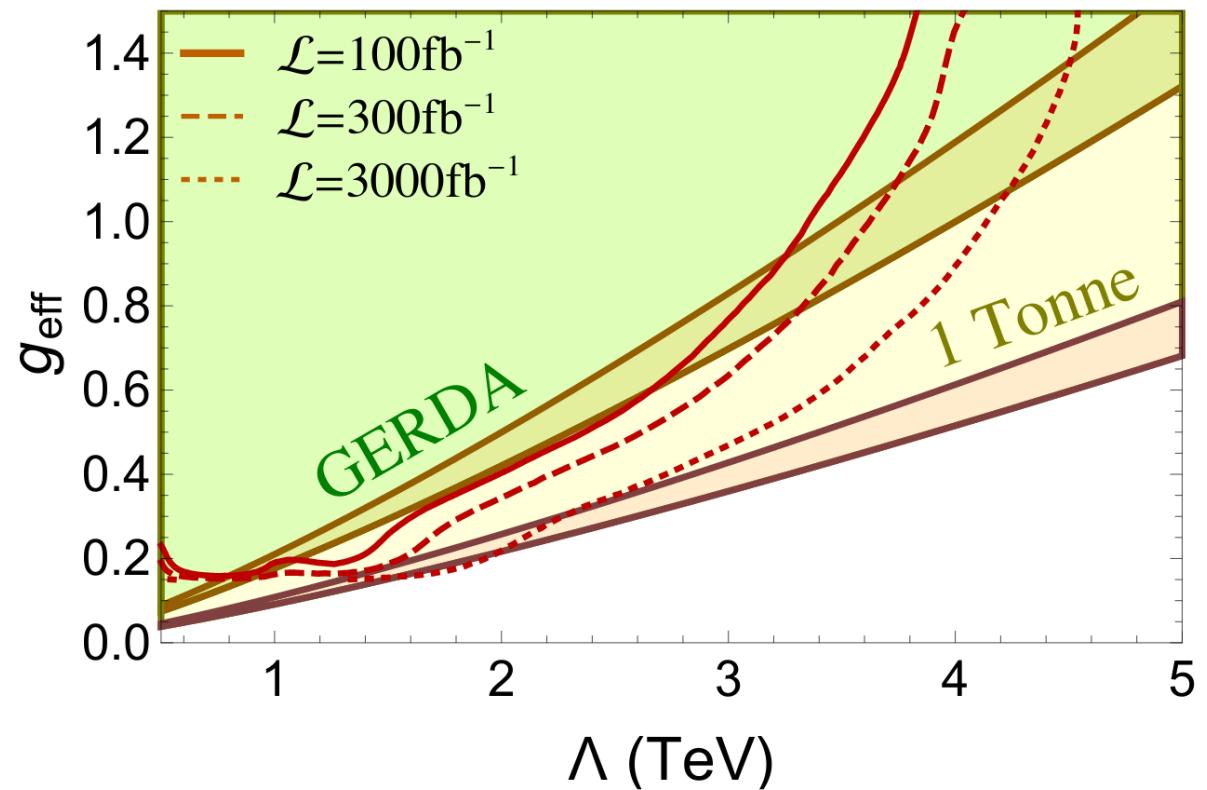
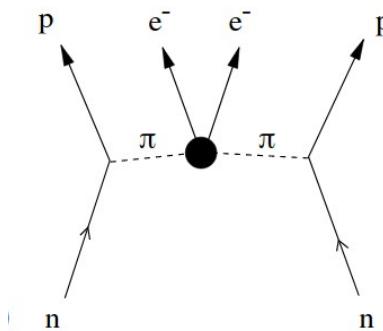
Refined study of model with greatest LHC reach:

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



Including:

- SM + detector background
- running of the operators
- long distance contributions

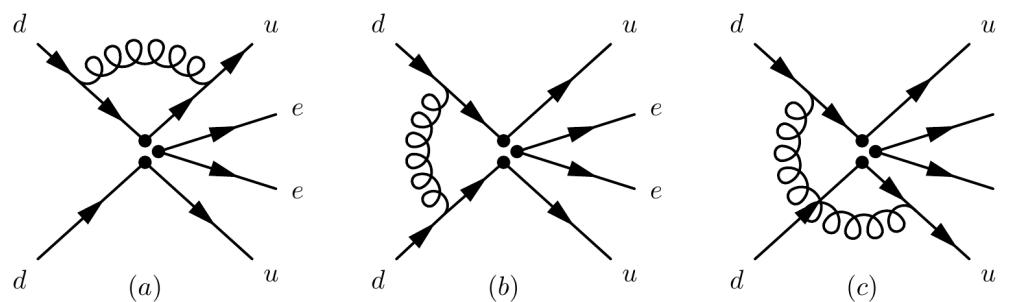


$$\frac{C_{\text{eff}}}{2\Lambda^5} (\mathcal{O}_{2+}^{++} - \mathcal{O}_{2-}^{++}) \bar{e}_L e_R^c + \text{h.c.} \rightarrow \frac{C_{\text{eff}} \Lambda_H^2 F_\pi^2}{2\Lambda^5} \pi^- \pi^- \bar{e}_L e_R^c + \text{h.c.}$$

Peng, Ramsey-Musolf, Winslow (2015)

# QCD corrections and running

Leading order QCD corrections to the **complete set of the short-range**  $d = 9$   $0\nu\beta\beta$ -operators covering the low-energy limits of any possible underlying high-energy scale model



$$\begin{aligned}\mathcal{O}_1^{XY} &= 4(\bar{u}P_Xd)(\bar{u}P_Yd) j, \\ \mathcal{O}_2^{XX} &= 4(\bar{u}\sigma^{\mu\nu}P_Xd)(\bar{u}\sigma_{\mu\nu}P_Xd) j, \\ \mathcal{O}_3^{XY} &= 4(\bar{u}\gamma^\mu P_Xd)(\bar{u}\gamma_\mu P_Yd) j, \\ \mathcal{O}_4^{XY} &= 4(\bar{u}\gamma^\mu P_Xd)(\bar{u}\sigma_{\mu\nu}P_Yd) j^\nu, \\ \mathcal{O}_5^{XY} &= 4(\bar{u}\gamma^\mu P_Xd)(\bar{u}P_Yd) j_\mu\end{aligned}$$

$$\begin{aligned}\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} &= G_1 \left| \beta_1^{XX} (C_1^{LL}(\Lambda) + C_1^{RR}(\Lambda)) + \beta_1^{LR} (C_1^{LR}(\Lambda) + C_1^{RL}(\Lambda)) + \right. \\ &\quad + \beta_2^{XX} (C_2^{LL}(\Lambda) + C_2^{RR}(\Lambda)) + \\ &\quad + \beta_3^{XX} (C_3^{LL}(\Lambda) + C_3^{RR}(\Lambda)) + \beta_3^{LR} (C_3^{LR}(\Lambda) + C_3^{RL}(\Lambda)) \left|^2 + \right. \\ &\quad + G_2 \left| \beta_4^{XX} (C_4^{RR}(\Lambda) + C_4^{RR}(\Lambda)) + \beta_4^{LR} (C_4^{LR}(\Lambda) + C_4^{RL}(\Lambda)) + \right. \\ &\quad \left. + \beta_5^{XX} (C_5^{RR}(\Lambda) + C_5^{RR}(\Lambda)) + \beta_5^{LR} (C_5^{LR}(\Lambda) + C_5^{RL}(\Lambda)) \right|^2 ,\end{aligned}$$

e.g.

$$\beta_1^{XX} = \mathcal{M}_1 U_{(12)11}^{XX} + \mathcal{M}_2 U_{(12)21}^{XX},$$

Gonzalez, Hirsch, Kovalenko (2015+)  
Arbelaez, Gonzalez, Hirsch, Kovalenko (2016)

# QCD corrections and running

- QCD corrections can give **sizeable impact** to **short range** contribution

	With QCD		Without QCD	With QCD		Without QCD
${}^A X$	$ C_1^{XX}(\Lambda_1) $	$ C_1^{XX}(\Lambda_2) $	$ C_1^{XX} $	$ C_1^{LR,RL}(\Lambda_1) $	$ C_1^{LR,RL}(\Lambda_2) $	$ C_1^{LR,RL} $
${}^{76}\text{Ge}$	$5.0 \times 10^{-10}$	$3.8 \times 10^{-10}$	$\mathbf{2.6 \times 10^{-7}}$	$1.5 \times 10^{-8}$	$9.1 \times 10^{-9}$	$\mathbf{2.6 \times 10^{-7}}$
${}^{136}\text{Xe}$	$3.4 \times 10^{-10}$	$2.6 \times 10^{-10}$	$\mathbf{1.8 \times 10^{-7}}$	$9.7 \times 10^{-9}$	$6.1 \times 10^{-9}$	$\mathbf{1.8 \times 10^{-7}}$
${}^A X$	$ C_2^{XX}(\Lambda_1) $	$ C_2^{XX}(\Lambda_2) $	$ C_2^{XX} $	—	—	—
${}^{76}\text{Ge}$	$3.5 \times 10^{-9}$	$5.2 \times 10^{-9}$	$1.4 \times 10^{-9}$	—	—	—
${}^{136}\text{Xe}$	$2.4 \times 10^{-9}$	$3.5 \times 10^{-9}$	$9.4 \times 10^{-10}$	—	—	—
${}^A X$	$ C_3^{XX}(\Lambda_1) $	$ C_3^{XX}(\Lambda_2) $	$ C_3^{XX} $	$ C_3^{LR,RL}(\Lambda_1) $	$ C_3^{LR,RL}(\Lambda_2) $	$ C_3^{LR,RL} $
${}^{76}\text{Ge}$	$1.5 \times 10^{-8}$	$1.6 \times 10^{-8}$	$1.1 \times 10^{-8}$	$2.0 \times 10^{-8}$	$2.1 \times 10^{-8}$	$1.8 \times 10^{-8}$
${}^{136}\text{Xe}$	$9.7 \times 10^{-9}$	$1.1 \times 10^{-8}$	$7.4 \times 10^{-9}$	$1.4 \times 10^{-8}$	$1.4 \times 10^{-8}$	$1.2 \times 10^{-8}$
${}^A X$	$ C_4^{XX}(\Lambda_1) $	$ C_4^{XX}(\Lambda_2) $	$ C_4^{XX(0)} $	$ C_4^{LR,RL}(\Lambda_1) $	$ C_4^{LR,RL}(\Lambda_2) $	$ C_4^{LR,RL(0)} $
${}^{76}\text{Ge}$	$5.0 \times 10^{-9}$	$3.9 \times 10^{-9}$	$\mathbf{1.2 \times 10^{-8}}$	$1.7 \times 10^{-8}$	$1.9 \times 10^{-8}$	$1.2 \times 10^{-8}$
${}^{136}\text{Xe}$	$3.4 \times 10^{-9}$	$2.7 \times 10^{-9}$	$\mathbf{7.9 \times 10^{-9}}$	$1.2 \times 10^{-8}$	$1.3 \times 10^{-8}$	$7.9 \times 10^{-9}$
${}^A X$	$ C_5^{XX}(\Lambda_1) $	$ C_5^{XX}(\Lambda_2) $	$ C_5^{XX} $	$ C_5^{LR,RL}(\Lambda_1) $	$ C_5^{LR,RL}(\Lambda_2) $	$ C_5^{LR,RL} $
${}^{76}\text{Ge}$	$2.3 \times 10^{-8}$	$1.4 \times 10^{-8}$	$\mathbf{1.2 \times 10^{-7}}$	$3.9 \times 10^{-8}$	$2.8 \times 10^{-8}$	$\mathbf{1.2 \times 10^{-7}}$
${}^{136}\text{Xe}$	$1.6 \times 10^{-8}$	$9.5 \times 10^{-9}$	$\mathbf{8.2 \times 10^{-8}}$	$2.8 \times 10^{-8}$	$2.0 \times 10^{-8}$	$\mathbf{8.2 \times 10^{-8}}$

Gonzalez, Hirsch, Kovalenko (2015)

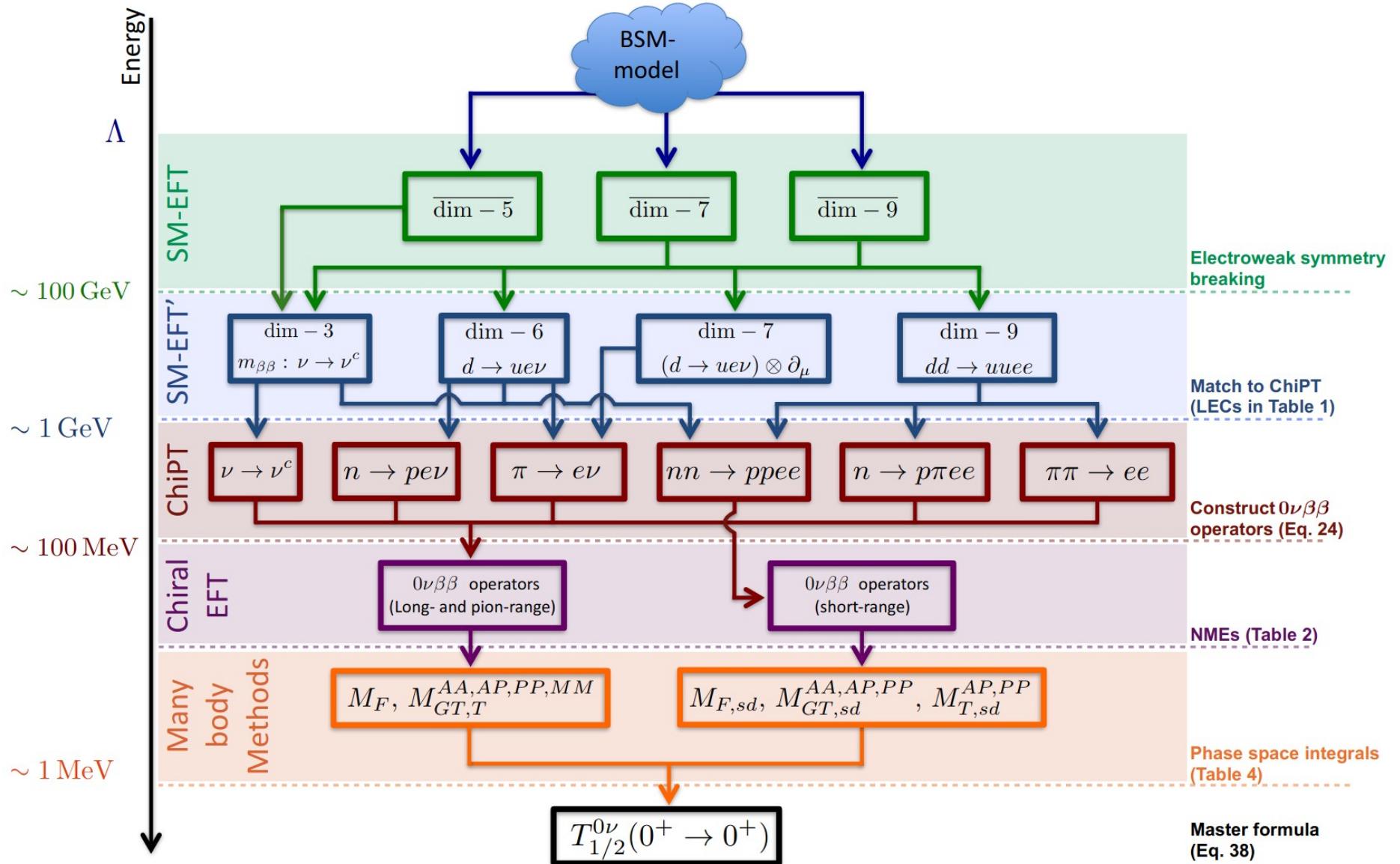
- QCD corrections **sub-dominant** for **long range** contribution (less than 60%)

Arbelaez, Gonzalez, Hirsch, Kovalenko (2016)

- Extrapolation of perturbative results to sub-GeV non-perturbative scales on the basis of **QCD coupling constant “freezing” behavior** using Background Perturbation Theory  
→ only **moderate** dependence

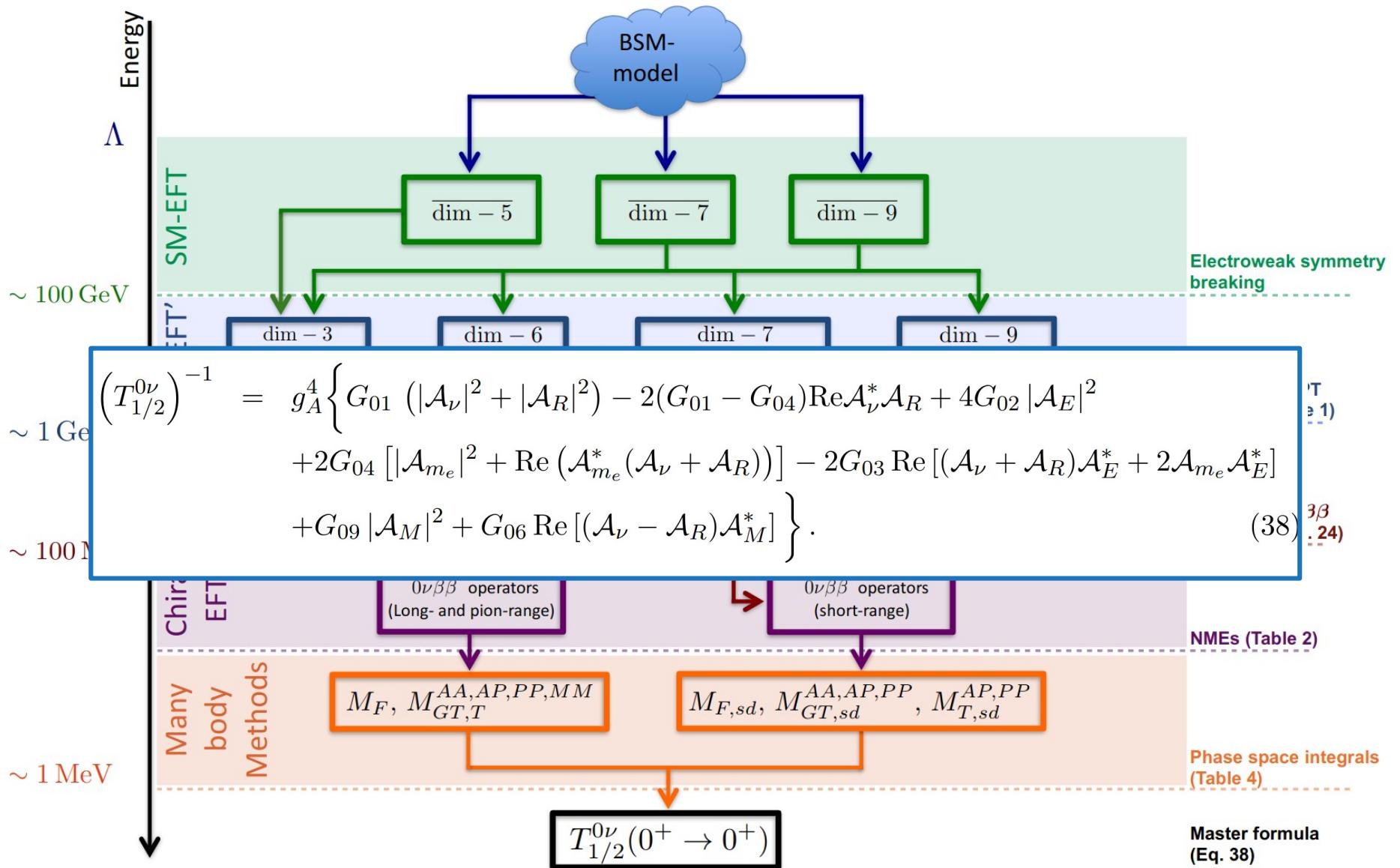
Gonzalez, Hirsch, Kovalenko (2018)

# “Master formula”



Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2018)  
Graf, Deppisch, Iachello, Kotila (2018)

# “Master formula”



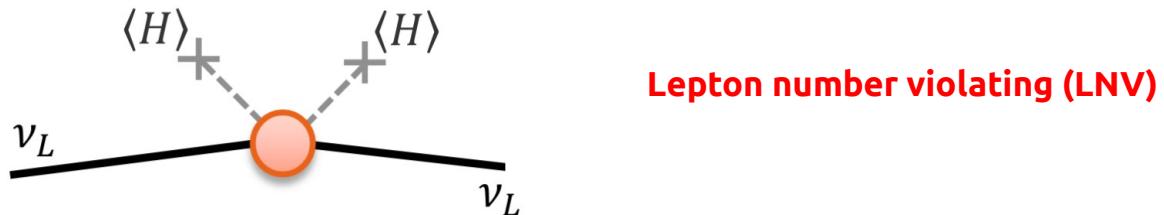
Cirigliano, Dekens, de Vries, Graesser, Mereghetti (2018)

Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastore, van Kolck (2018)

# **Neutrinoless Double Beta Decay & Baryogenesis**

# Leptogenesis and Neutrino masses

The origin of neutrino masses lies beyond the standard model



$$M_\nu \approx -\frac{v^2}{2} \lambda M_N^{-1} \lambda^T$$

$$M_\nu \simeq 0.3 \left( \frac{\text{GeV}}{M_N} \right) \left( \frac{\lambda^2}{10^{-14}} \right) \text{eV}$$

**Leptogenesis via oscillations**

Akhmedov et al. (1998)

$$M_\nu \simeq 0.3 \left( \frac{10^8 \text{GeV}}{M_N} \right) \left( \frac{\lambda^2}{10^{-6}} \right) \text{eV}$$

**High-scale Leptogenesis**

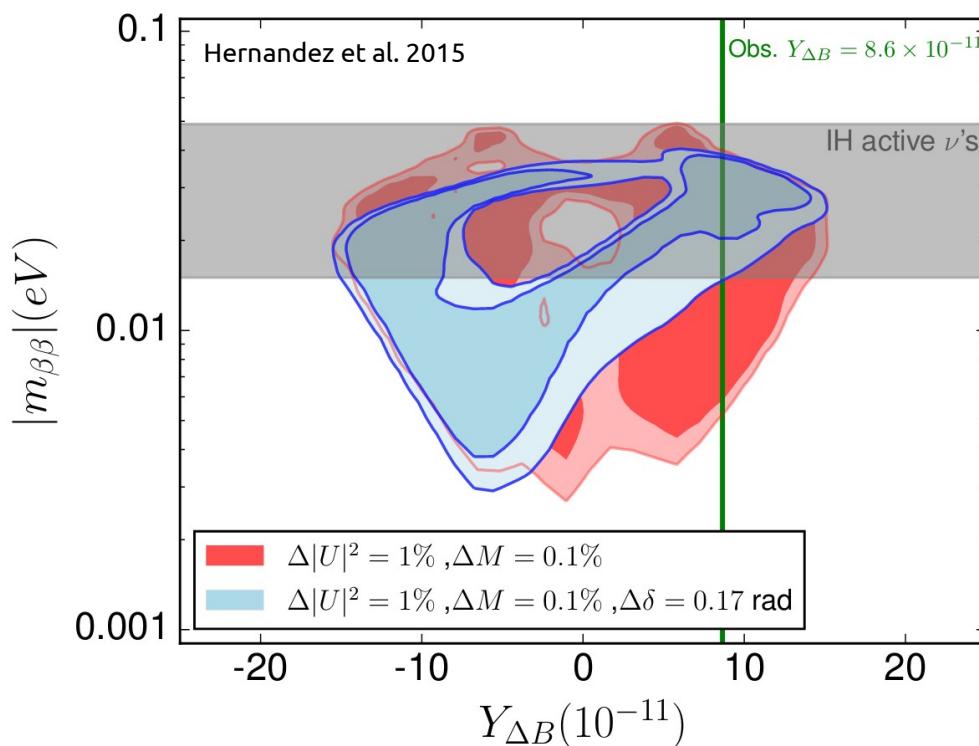
Fukugita et al. (1986)

**Combined analysis of both regimes and comparison with existing literature (Klaric et al. 2021)**

# Leptogenesis via oscillations & $0\nu\beta\beta$ decay

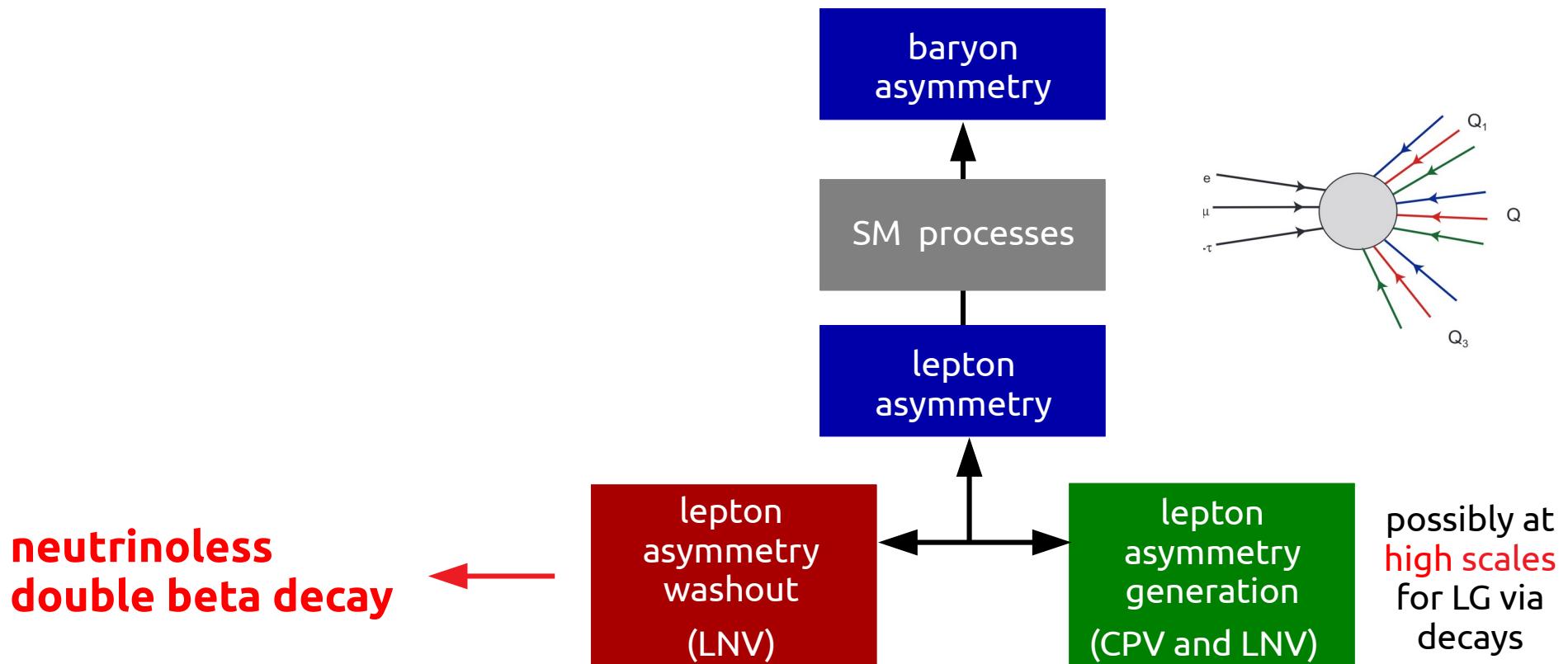
For  $N=2$ , the baryon asymmetry is predictable by combination of different experimental measurements:

- Observation of **two heavy neutral leptons** with 0.1% accuracy at SHiP
- Determination of their **mixings** to electrons and muons with a 1% accuracy
- **CP phase** determined to 0.17 rad accuracy with neutrino oscillations
- **Measurement of neutrinoless double beta decay**



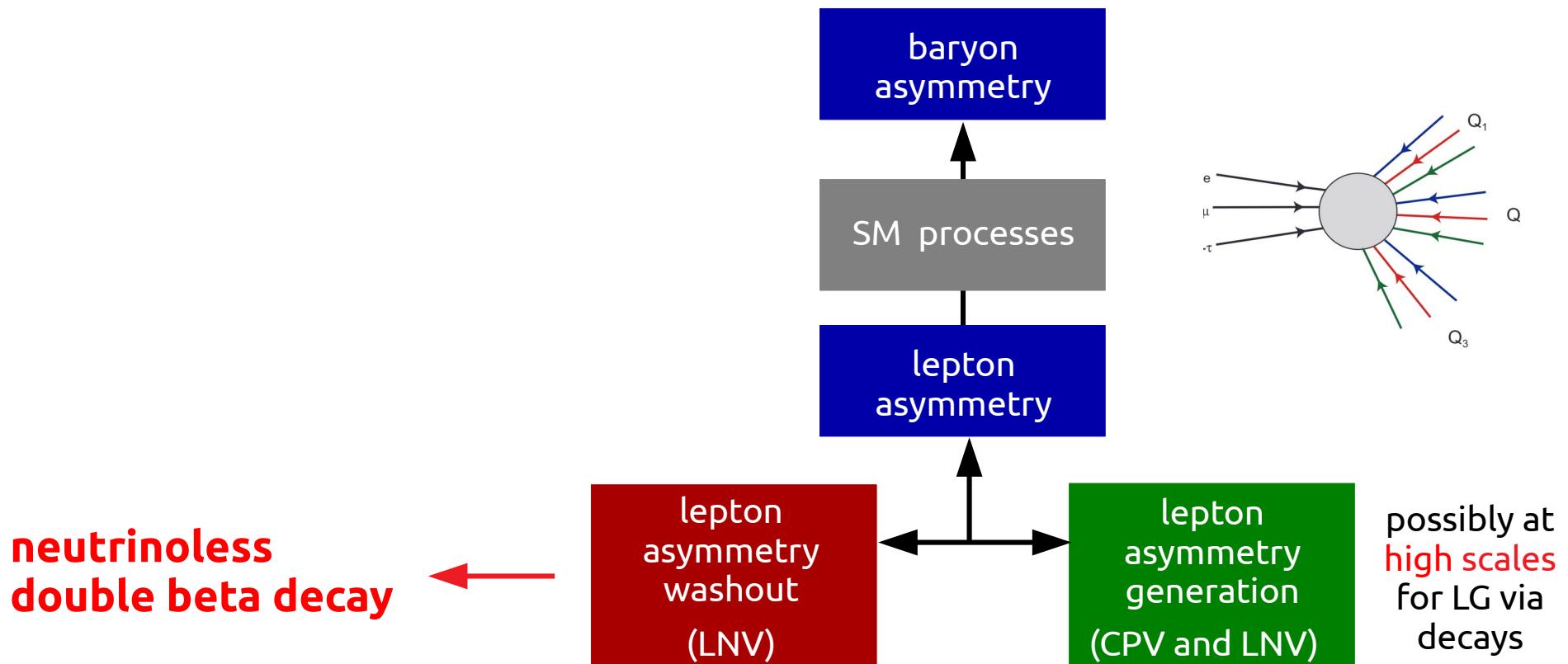
Hernandez et al. 2015, Abada et al. 2015, Drewes et al. 2016

# High-scale Leptogenesis & $0\nu\beta\beta$ decay



**Imagine we observe  $0\nu\beta\beta$ , can we make a statement about the washout strength and thus about the validity of a baryogenesis model?**

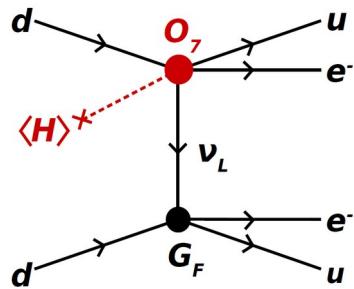
# High-scale Leptogenesis & $0\nu\beta\beta$ decay



Imagine we observe  $0\nu\beta\beta$ , can we make a statement about the washout strength and thus about the validity of a baryogenesis model?

YES!

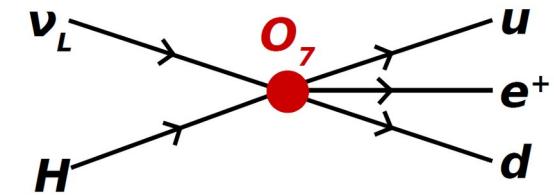
# $0\nu\beta\beta$ and Baryogenesis



$$T_{1/2}^{-1} = G_{0\nu} |\mathcal{M}|^2 |\epsilon_\alpha^\beta|^2$$

Observation would fix the **effective coupling** for one operator

$\mathcal{O}$	Operator
$1^{H^2}$	$L^i L^j H^k H^l \bar{H}^t H_t \epsilon_{ik} \epsilon_{jl}$
2	$L^i L^j L^k e^c H^l \epsilon_{ij} \epsilon_{kl}$
$3_a$	$L^i L^j Q^k d^c H^l \epsilon_{ij} \epsilon_{kl}$
$3_b$	$L^i L^j Q^k d^c H^l \epsilon_{ik} \epsilon_{jl}$
$4_a$	$L^i L^j \bar{Q}_i \bar{u}^c H^k \epsilon_{jk}$
$4_b^\dagger$	$L^i L^j \bar{Q}_k \bar{u}^c H^k \epsilon_{ij}$
8	$L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}$



$$\Lambda_7 \left( \frac{\Lambda_7}{c'_7 \Lambda_{Pl}} \right)^{\frac{1}{5}} \lambda_7 < T < \Lambda_7$$

**effective coupling** can be related to the **scale of the operator**

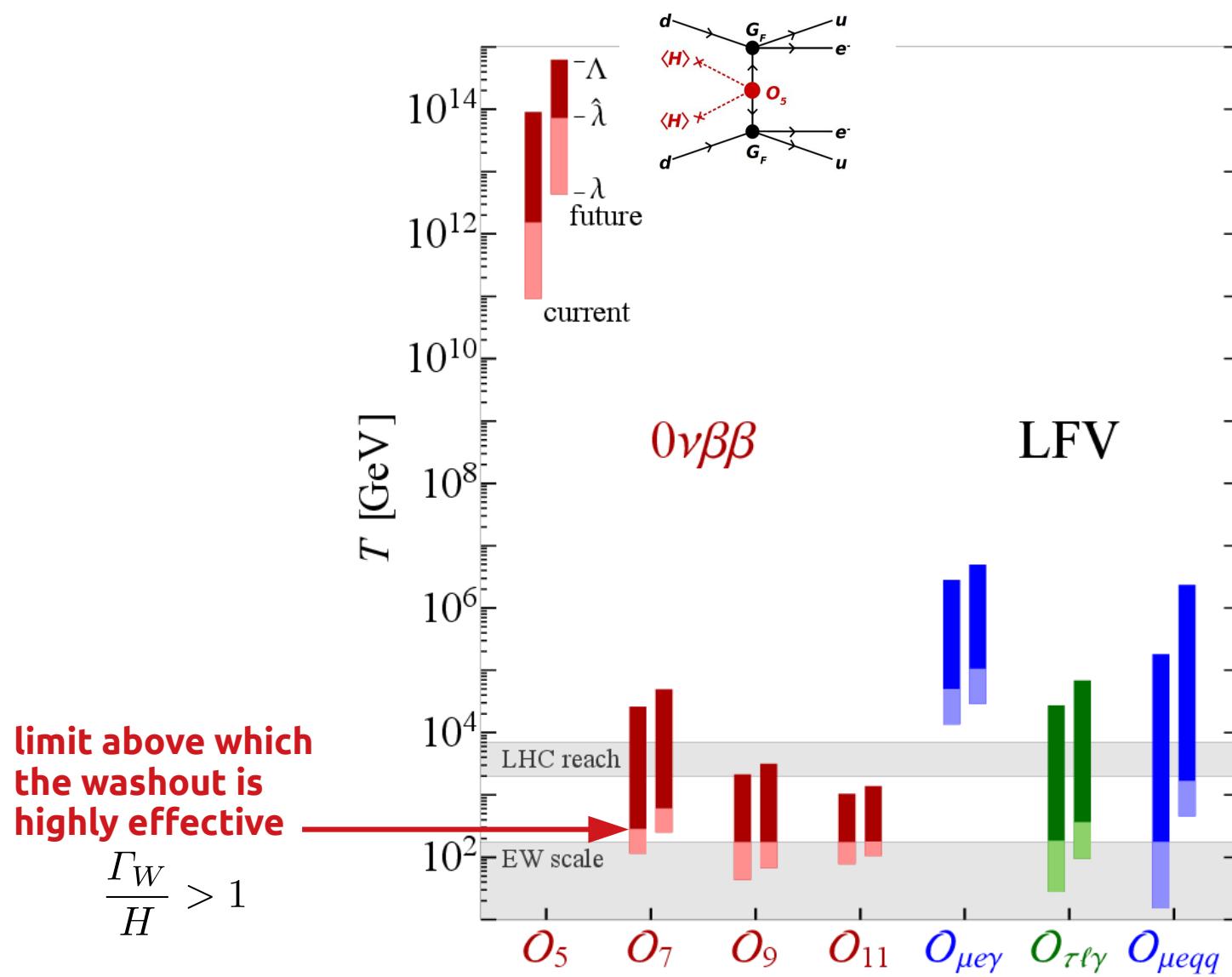
$\mathcal{O}_D$	$\Lambda_D^0$ [GeV]
$\mathcal{O}_5$	$9.1 \times 10^{13}$
$\mathcal{O}_7$	$2.6 \times 10^4$
$\mathcal{O}_9$	$2.1 \times 10^3$
$\mathcal{O}_{11}$	$1.0 \times 10^3$

**Limit above which the washout is highly effective** can be calculated in dependence of the **operator scale**

$$\frac{\Gamma_W}{H} > 1$$

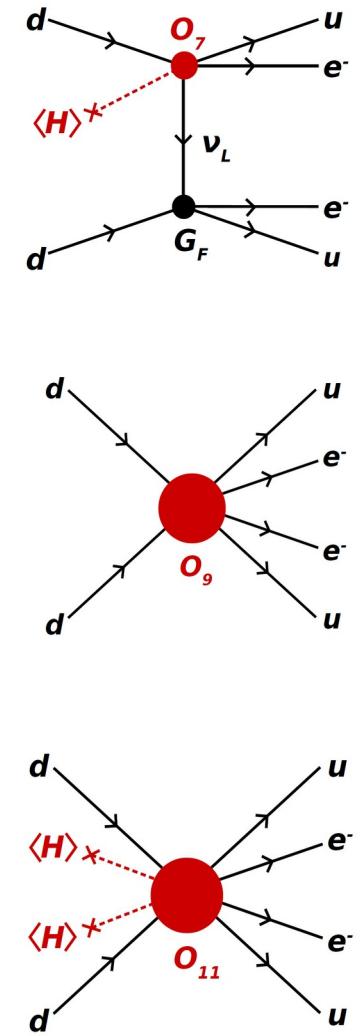
Deppisch, Graf, JH, Huang (2018)  
Deppisch, JH, Huang, Hirsch, Päs (2015)

# 0v $\beta\beta$ and Baryogenesis



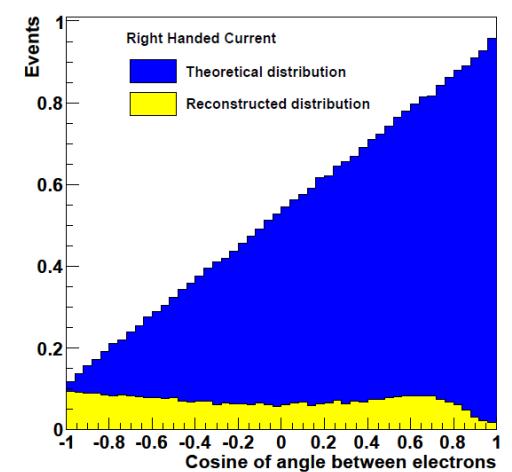
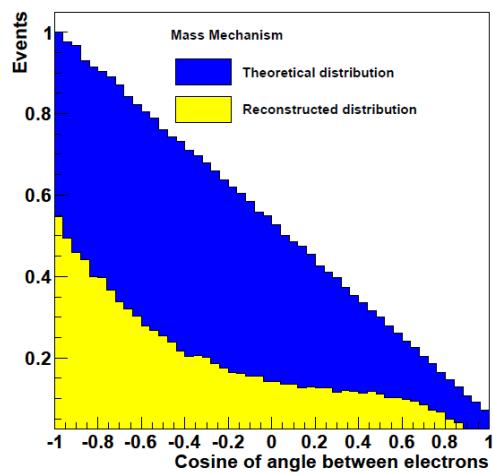
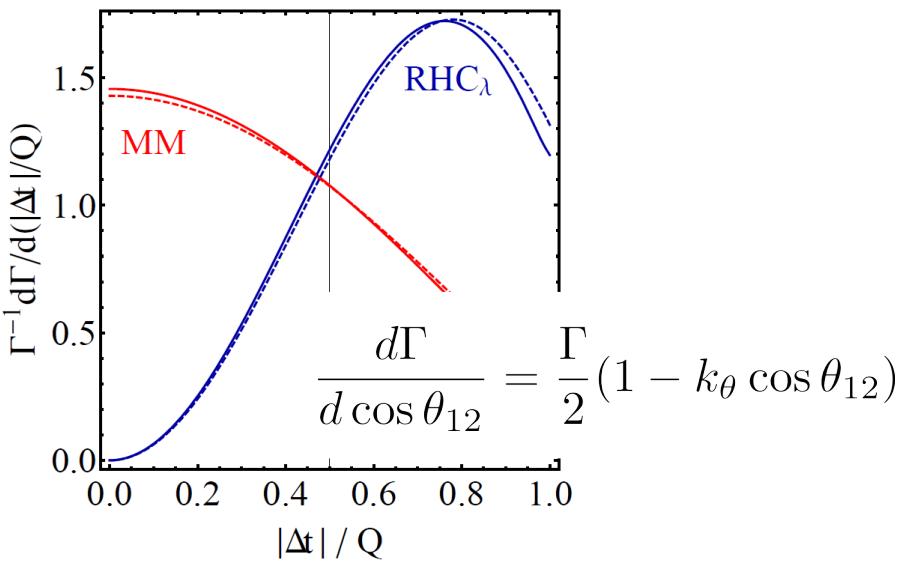
Potential to falsify baryogenesis models!

Deppisch, Graf, JH, Huang (2018)  
Deppisch, JH, Huang, Hirsch, Päs (2015)

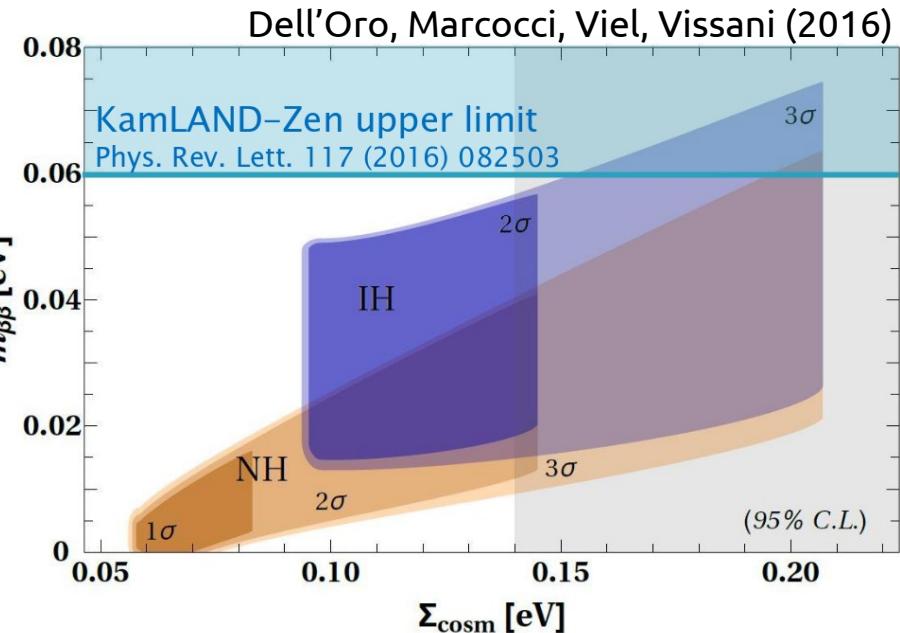


# Distinguishing different operators

- **discrepancy between sum of neutrino masses from cosmology and  $0\nu\beta\beta$  half life**  
measurements could indicate non-standard mechanism
- **Angular distributions** allows to discriminate  $O_7$  from others, due to  $e^-_R$  and  $e^+_L$  in the final state



Ali, Borisov, Zhuridov (2006),  
SuperNemo, Arnold et al. (2010)

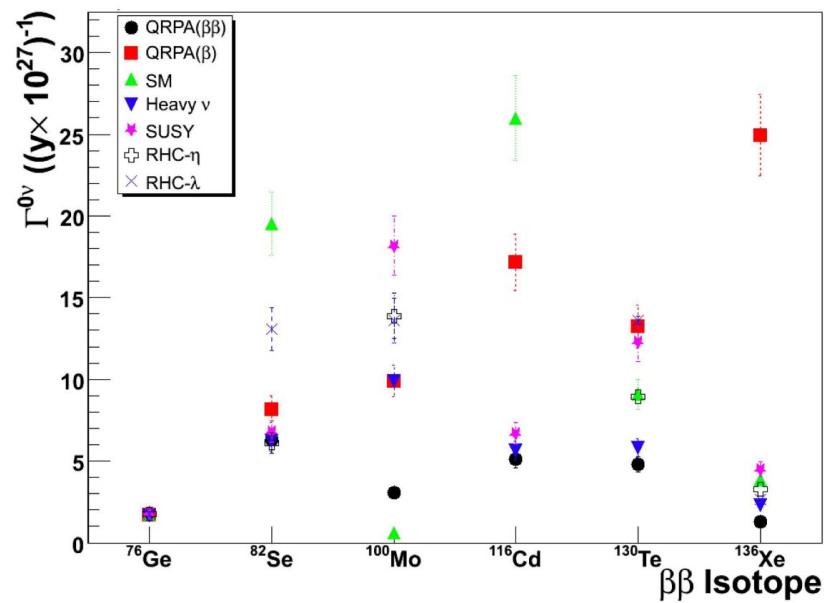
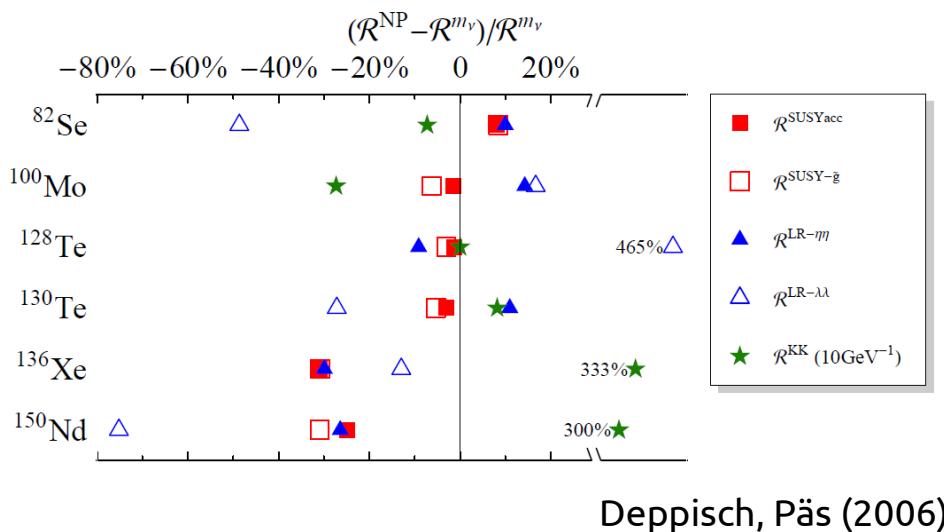


# Distinguishing different operators

- distinguishing between different mechanisms via **measurements in different isotopes**

$$[T_{1/2}^{NP}]^{-1} = \epsilon_{NP}^2 G^{NP} |\mathcal{M}^{NP}|^2$$

$$\frac{T_{1/2}(^AX)}{T_{1/2}(^{76}\text{Ge})} = \frac{|\mathcal{M}(^{76}\text{Ge})|^2 G(^{76}\text{Ge})}{|\mathcal{M}(^AX)|^2 G(^AX)}$$



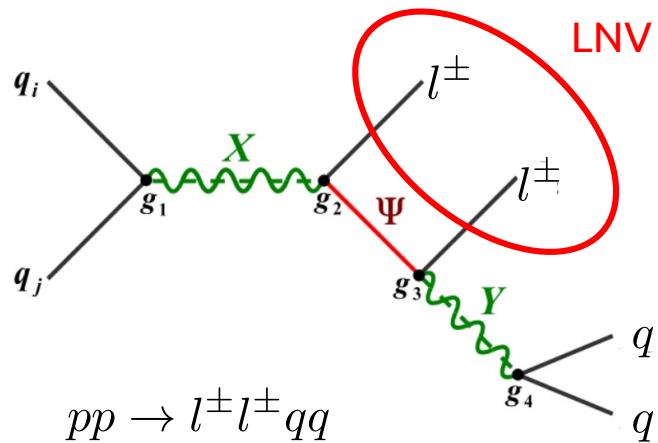
Isotope Ordering	Confidence Level	Number of Isotopes				
		2	3	4	5	6
Atomic Number	90%	<2%	8%	16%	23%	24%
	68%	<2%	19%	36%	45%	48%
$\Gamma^{0\nu}$ Spread	90%	6%	18%	27%	27%	24%
	68%	13%	29%	41%	42%	47%
Experimental Readiness	90%	3%	11%	24%	24%	24%
	68%	7%	18%	46%	47%	47%
Alternative Ordering	90%	3%	11%	17%	15%	24%
	68%	7%	18%	34%	32%	47%
Experimental Readiness (All 7 models, no $^{116}\text{Cd}$ )	90%	< 2%	6%	14%	16%	
	68%	< 2%	12%	22%	24%	

Gehman, Elliott (2007)

- observation of  $0\nu\beta\beta$  via  $O_9$  and  $O_{11}$  will imply observation of LNV at LHC

# Probing Leptogenesis at the LHC

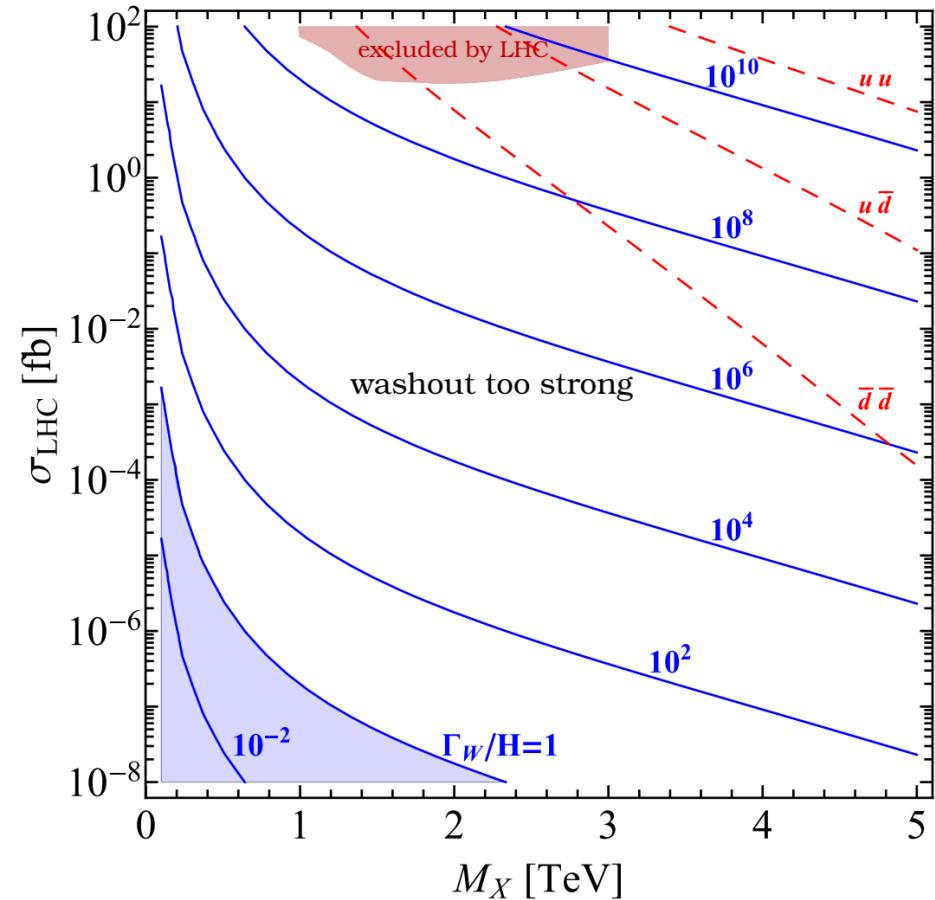
Washout processes could be observable at the LHC



$$\log_{10} \frac{\Gamma_W}{H} > 6.9 + 0.6 \left( \frac{M_X}{\text{TeV}} - 1 \right) + \log_{10} \frac{\sigma_{\text{LHC}}}{\text{fb}}$$

Observation of any washout process at LHC would falsify high scale baryogenesis!

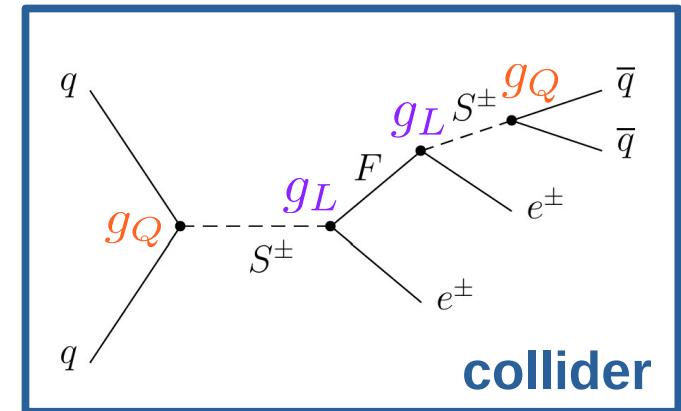
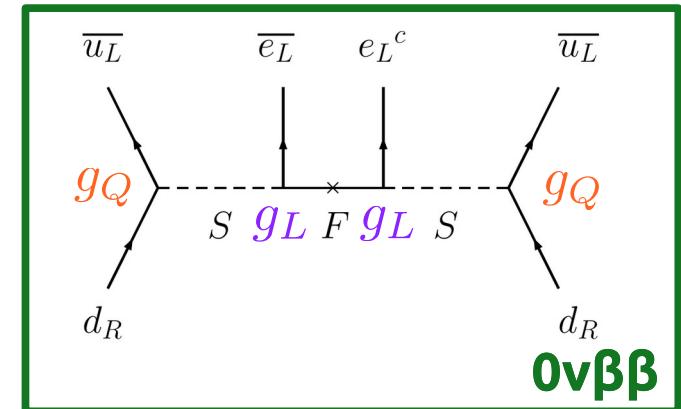
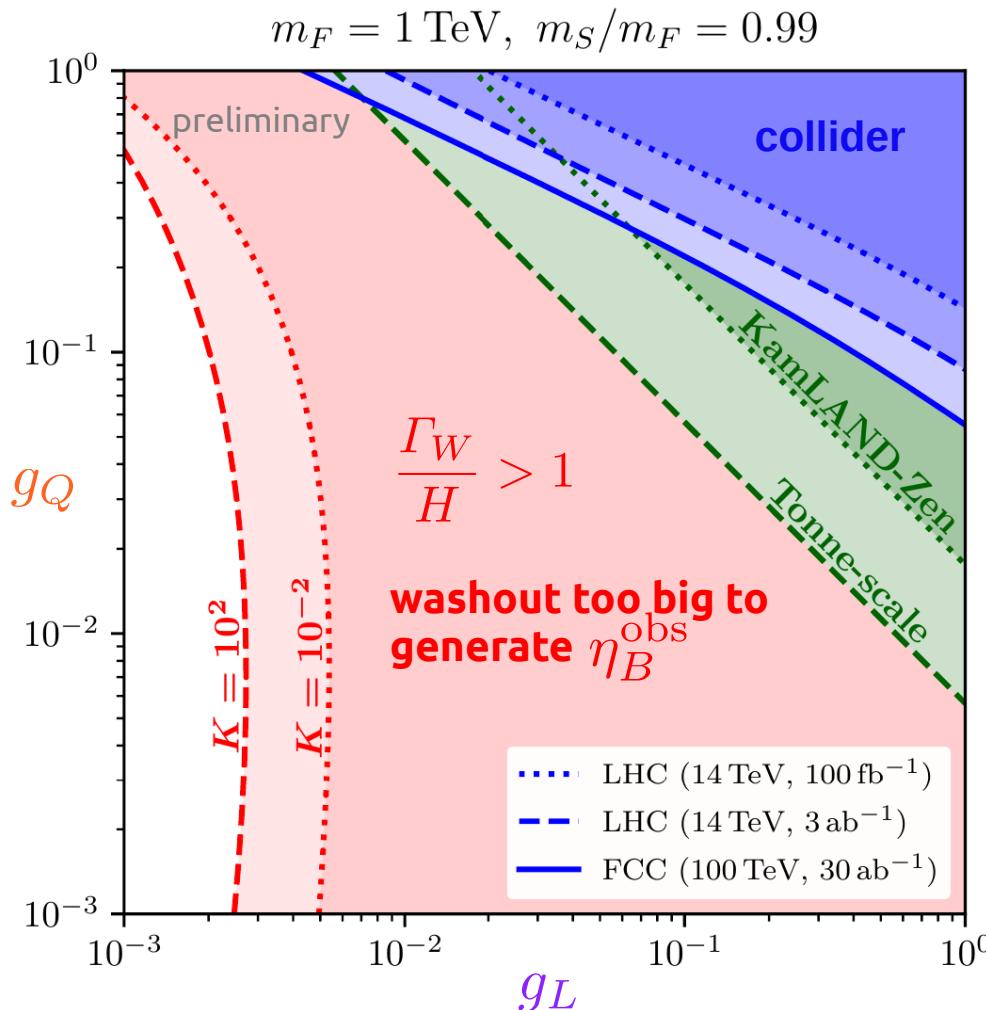
(scale of asymmetry generation *above*  $M_X$ )



Deppisch, JH, Hirsch, Phys. Rev. Lett. (2014)  
Deppisch, JH, Hirsch, Päs, Int. J. Mod. Phys. A (2015)

# Combining LHC & $0\nu\beta\beta$

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



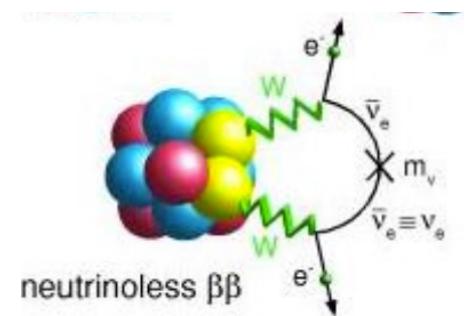
Comprehensive analysis confirms EFT results and shows interesting interplay between collider and  $0\nu\beta\beta$  reach.

JH, Ramsey-Musolf, Shen, Urrutia, in preparation

# Summary

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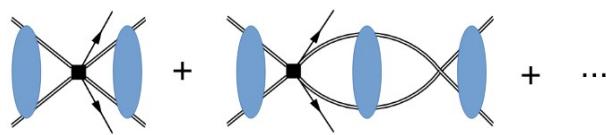
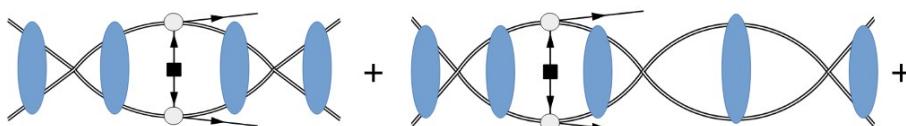
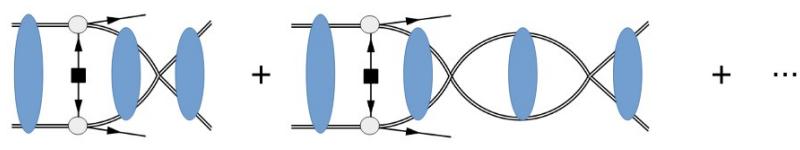
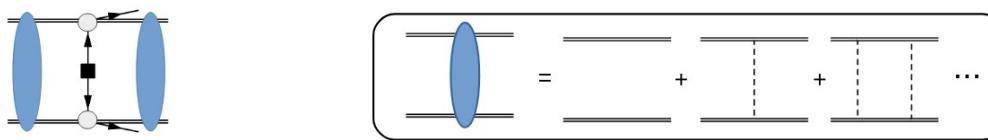
- $0\nu\beta\beta$  has huge potential to probe **LNV** and a **Majorana nature** of the neutrino
- Combination with **neutrino oscillations** powerful to constrain specific models
- Many **non-standard contributions** possible, many **topologies** and UV completions
- **$0\nu\beta\beta$  and LHC** compete against better sensitivity
- **QCD running** is important and can affect conclusions → “master formula”
- $0\nu\beta\beta$  can shed light on **baryogenesis**
- Many ideas to **disentangle different contributions**
- Open questions & uncertainties in **nuclear physics**



# **Thank you for your attention!**



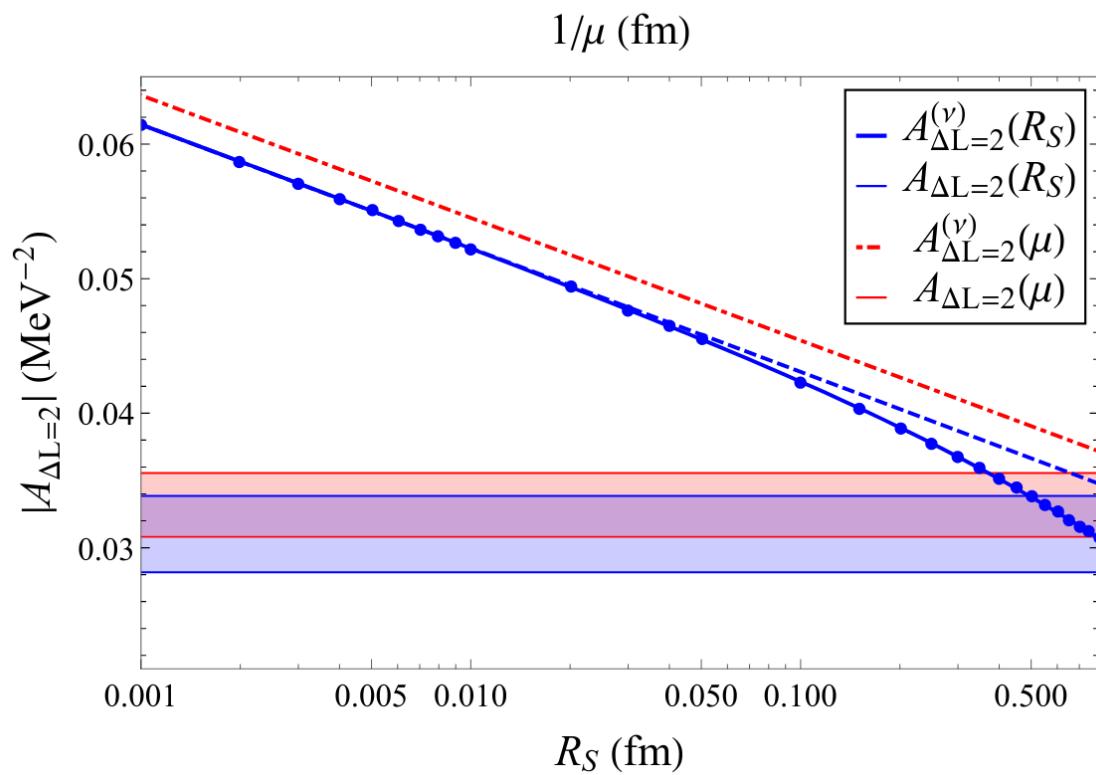
# A new leading contribution to $0\nu\beta\beta$



$$V_{\nu,CT} = -2g_\nu^{NN} \tau^{(1)+} \tau^{(2)+}$$

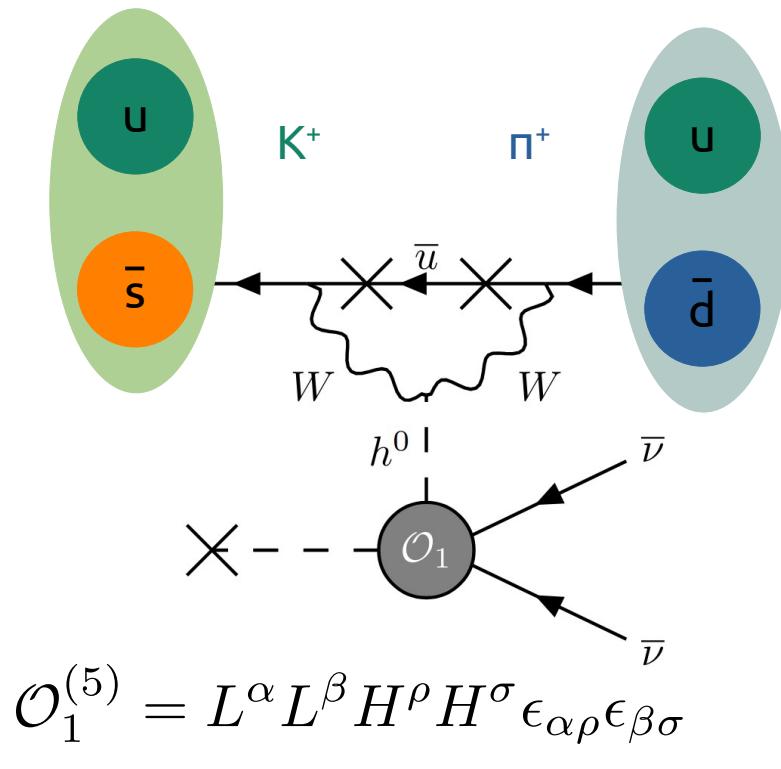
$$H_{\text{LNV}} = 2G_F^2 V_{ud}^2 m_{\beta\beta} \bar{e}_L C \bar{e}_L^T V_\nu$$

$$V_0(\mathbf{q}) = \tilde{C} + V_\pi(\mathbf{q}), \quad V_\pi(\mathbf{q}) = -\frac{g_A^2}{4F_\pi^2} \frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2}$$



Cirigliano, Dekens, de Vries, Graesser, Mereghetti, Pastore, van Kolck (2018)

# Constraining LNV interactions with rare kaon decays



- GIM suppressed

**Not explicit LNV!**

- No GIM suppression
- Includes first and second generation

**How are higher dimensional operators constraint by rare kaon decays?**

Deppisch, Fridell, JH (2020)

# Constraining power at E949

- **SM**, lepton number **conserving vector** current

$$\mathcal{L}_{\text{SM}}^{K \rightarrow \pi \nu \bar{\nu}} = \frac{1}{\Lambda_{\text{SM}}^2} (\bar{\nu}_i \gamma^\mu \nu_i) (\bar{d} \gamma_\mu s)$$

- **BSM**, lepton number **violating scalar** current

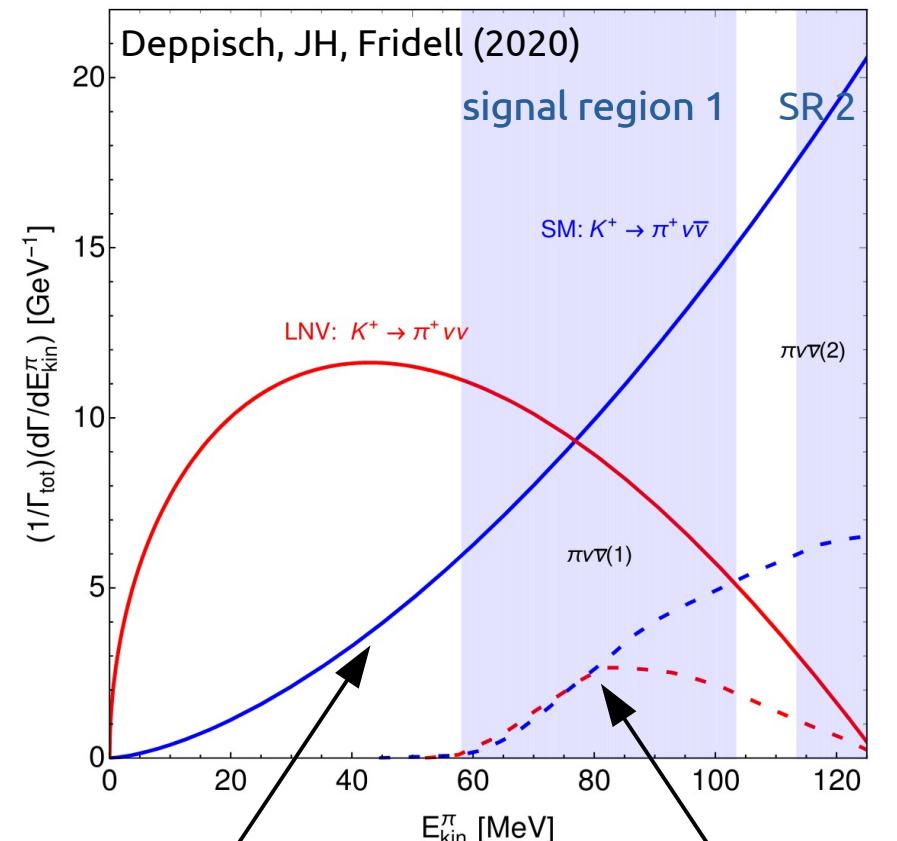
$$\mathcal{L}_{\text{BSM}}^{K \rightarrow \pi \nu \nu} = \frac{v}{\Lambda_{\text{BSM}}^2} (\nu_i \nu_j) (\bar{d} s)$$

→ **different phase space distribution**

- **different acceptance:**

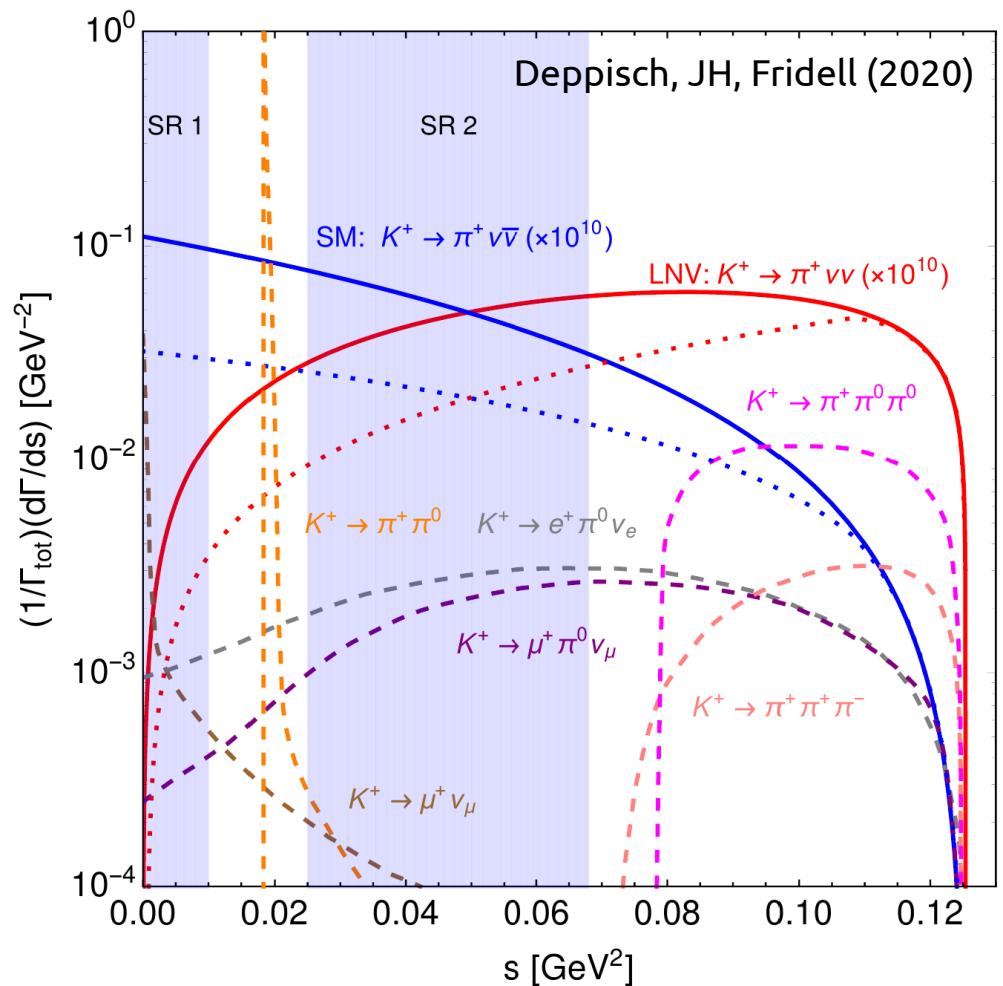
$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{E949}}^{\text{vector}} < 3.35 \times 10^{-10}$  at 90% CL

$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{E949}}^{\text{scalar}} < 21 \times 10^{-10}$  at 90% CL



Deppisch, Fridell, JH (2020)

# Constraining power at NA62



$$s = (E_K - E_\pi)^2$$

Possibility to disentangle a possible signal by improving on experimental sensitivity and strategy?

Deppisch, Fridell, JH (2020)

Summary of sensitivity to scalar current (based on kinematics only):

Experiment	SM (vector)	LNV (scalar)
NA62 SR 1	6%	0.3%
NA62 SR 2	17%	15%
E949 $\pi\nu\bar{\nu}(1)$	29%	2%
E949 $\pi\nu\bar{\nu}(2)$	45%	38%
KOTO	64%	30%

Experiments are generally more sensitive to vector currents

# Non-standard Majoron Emission

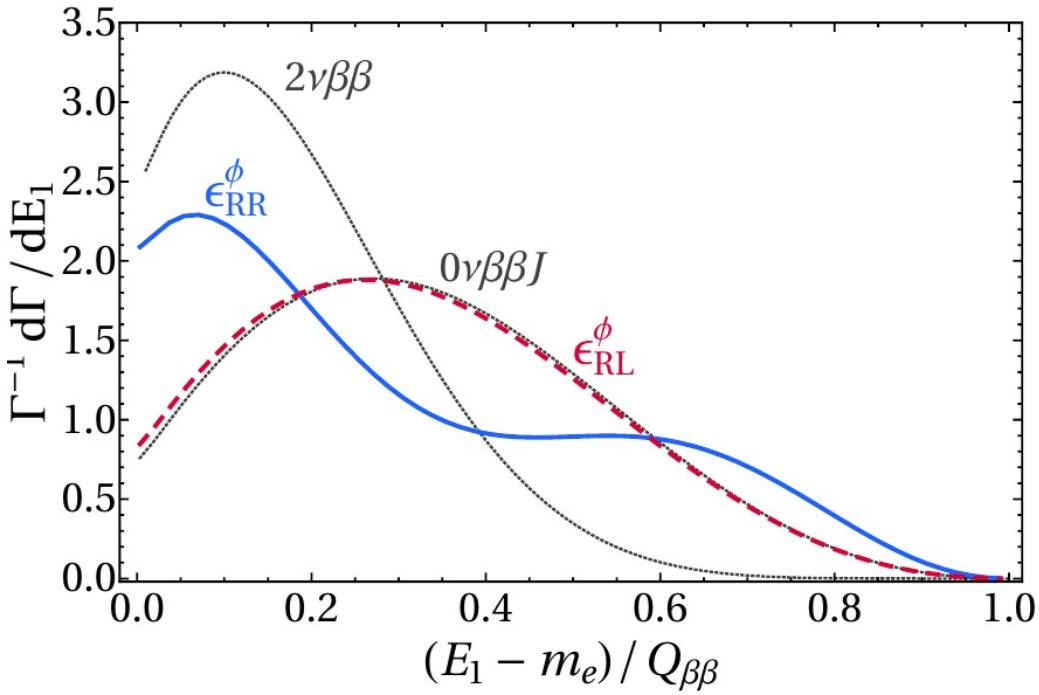
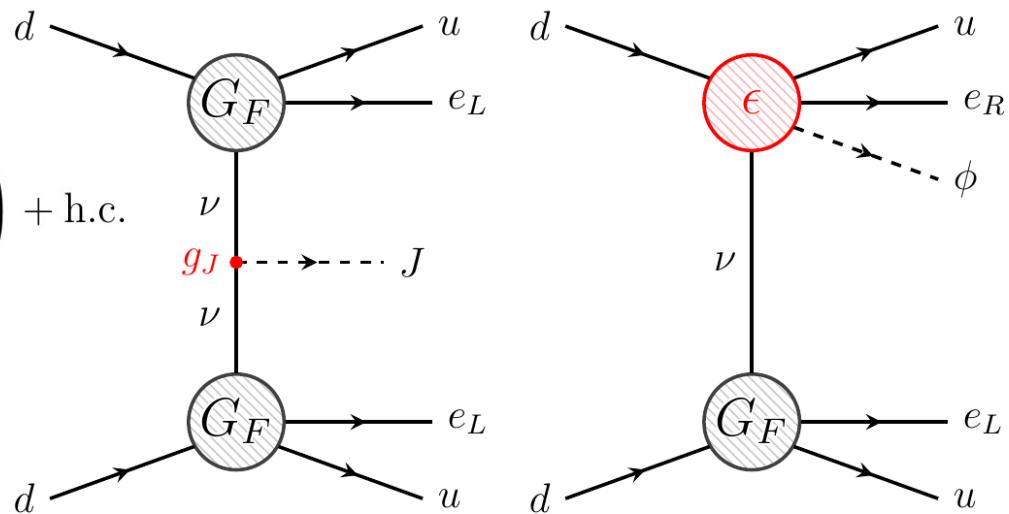
$$\mathcal{L}_{0\nu\beta\beta\phi} = \frac{G_F \cos \theta_C}{\sqrt{2}} \left( j_L^\mu J_{L\mu} + \frac{\epsilon_{RL}^\phi}{m_p} j_R^\mu J_{L\mu} \phi + \frac{\epsilon_{RR}^\phi}{m_p} j_R^\mu J_{R\mu} \phi \right) + \text{h.c.}$$

Isotope	$T_{1/2}$ [y]	$ \epsilon_{RL}^\phi $	$ \epsilon_{RR}^\phi $
$^{82}\text{Se}$	$3.7 \times 10^{22}$ [14]	$4.1 \times 10^{-4}$	$4.6 \times 10^{-2}$
$^{136}\text{Xe}$	$2.6 \times 10^{24}$ [13]	$1.1 \times 10^{-4}$	$1.1 \times 10^{-2}$
$^{82}\text{Se}$	$1.0 \times 10^{24}$	$8.0 \times 10^{-5}$	$8.8 \times 10^{-3}$
$^{136}\text{Xe}$	$1.0 \times 10^{25}$	$5.7 \times 10^{-5}$	$5.8 \times 10^{-3}$

$$\Lambda_{\text{NP},\text{RL}}^{\text{fut}} \approx 1.3 \text{ TeV}$$

$$\Lambda_{\text{NP},\text{RR}}^{\text{fut}} \approx 270 \text{ GeV}$$

**New type of interaction  
distinguishable from background**

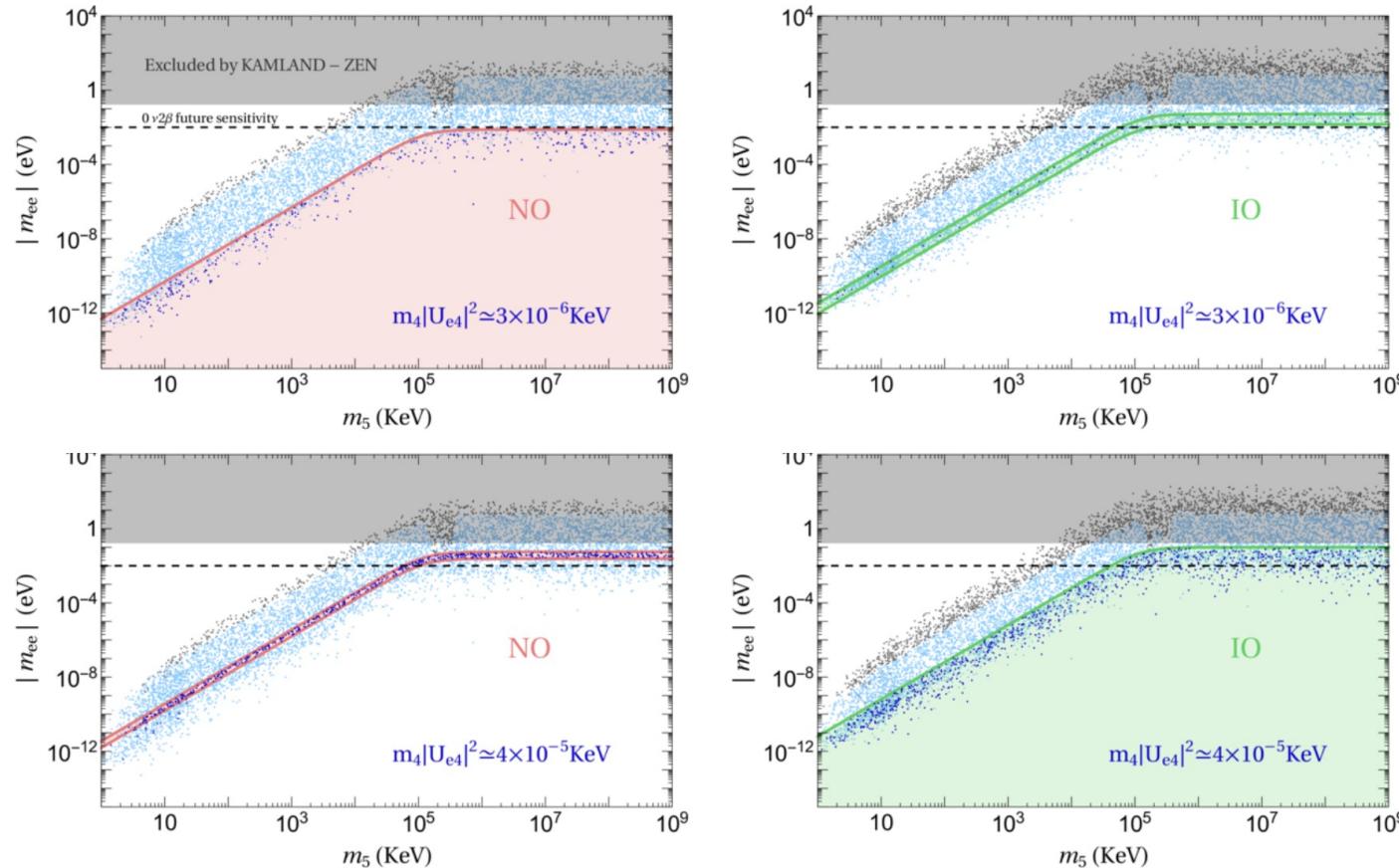


Cepedello, Deppisch, Gonzalez, Hati, Hirsch, Päs (2019)

# Light Sterile Neutrinos – Interplay $0\nu\beta\beta$ & KATRIN

**Assumption:** 3 active + 2 sterile neutrinos

1<sup>st</sup> sterile neutrino in KATRIN reach, 2<sup>nd</sup> variable



Abada, Hernandez-Cabezudo, Marcano (2019)

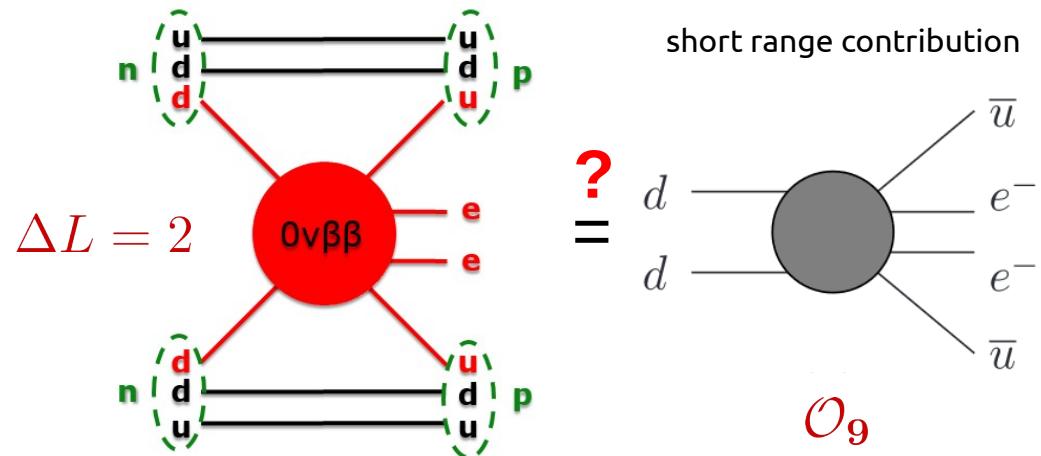
**Interesting interplay between KATRIN &  $0\nu\beta\beta$  prospects**

**Isotope dependent cancellation** between two **different** exchange mechanisms (two different NMEs)

Pascoli, Mitra, Wong (2014)

# Short-range contributions to $0\nu\beta\beta$

$$T_{1/2}^{-1} = G_{0\nu} |\mathcal{M}|^2 |\epsilon_\alpha^\beta|^2$$



$$\mathcal{L}^{\text{eff}} = \frac{G_F^2}{2} m_P^{-1} [\epsilon_1 JJJ + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_\mu j + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j_\mu]$$

Leptonic and hadronic current with different chirality structure:

$$J = \bar{u}(1 \pm \gamma_5)d, \quad J^\mu = \bar{u}\gamma^\mu(1 \pm \gamma_5)d, \quad J^{\mu\nu} = \bar{u}\frac{i}{2}[\gamma^\mu, \gamma^\nu](1 \pm \gamma_5)d$$

$$j = \bar{e}(1 \pm \gamma_5)e^C, \quad j^\mu = \bar{e}\gamma^\mu(1 \pm \gamma_5)e^C$$

${}^A X$	$ \epsilon_1 $	$ \epsilon_2 $	$ \epsilon_3^{LLz(RRz)} $	$ \epsilon_3^{LRz(RLz)} $	$ \epsilon_4 $	$ \epsilon_5 $
${}^{76}\text{Ge}$	$3.0 \cdot 10^{-7}$	$1.7 \cdot 10^{-9}$	$2.1 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$	$1.4 \cdot 10^{-7}$
${}^{136}\text{Xe}$	$2.4 \cdot 10^{-7}$	$1.3 \cdot 10^{-9}$	$1.0 \cdot 10^{-8}$	$1.6 \cdot 10^{-8}$	$1.1 \cdot 10^{-8}$	$1.1 \cdot 10^{-7}$

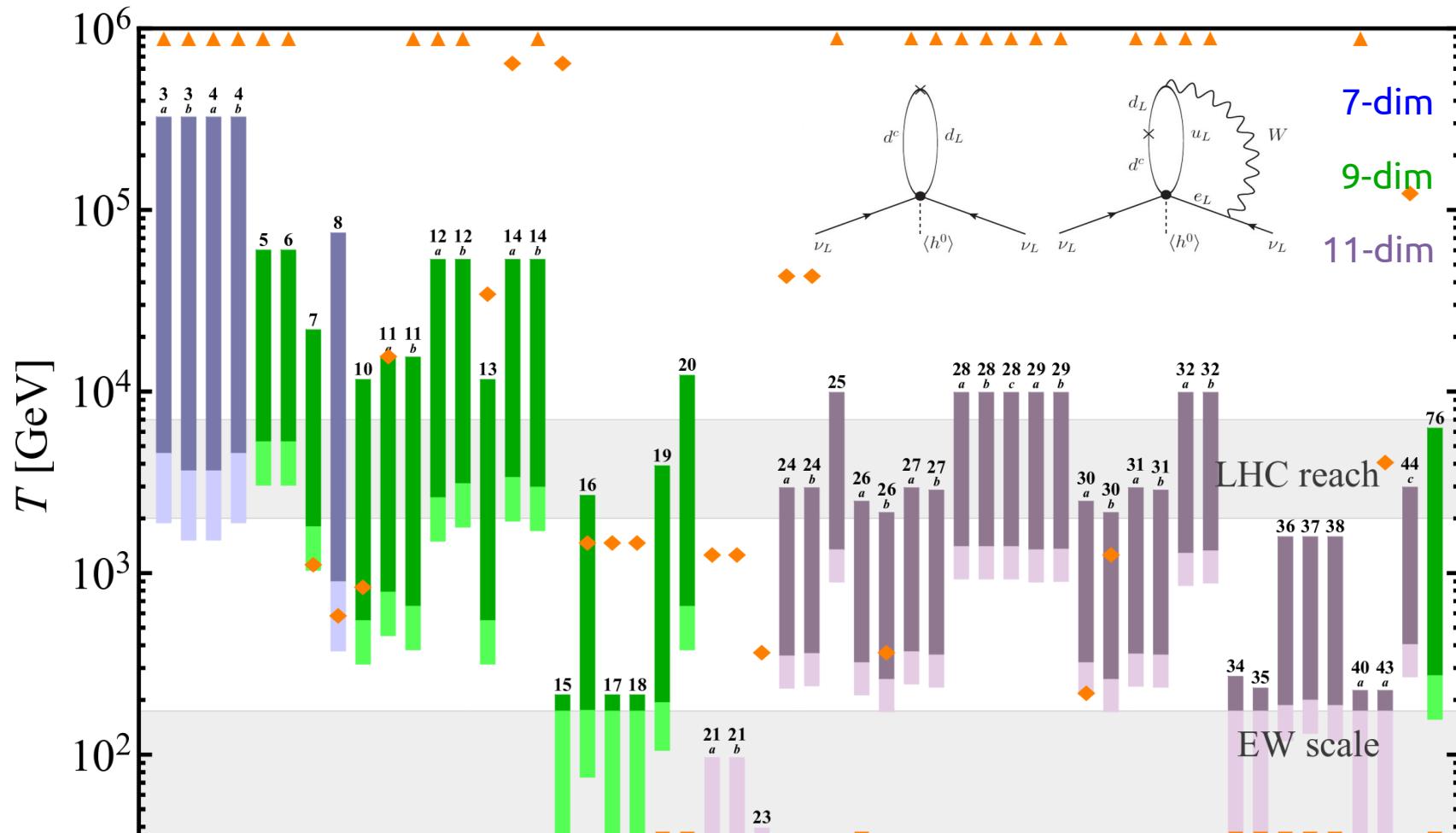
Deppisch, Hirsch, Päs (2012)

# Leptogenesis via oscillations

Akhmedov-Rubakov-Smirnov (ARS) mechanism Akhmedov et al. (1998)

production	oscillation $\cancel{CP}$	sphalerons shut off
$L_A + L_B + L_C = 0$	$L_A + L_B + L_C = 0$	$L_A + L_B \rightarrow B_{SR}$
$N_{RA}$	$L_A = 0$	$B_{SR}$
$l \rightarrow \bar{e} + N_{RA}$	$L_B = 0$	
$N_{RB}$	$L_A = 0$	
$y_\alpha \sim 10^{-8} - 10^{-6}$ not in equilibrium!	$y_{A,B} > y_c$ $N_{A,B}$ reach equilibrium before $T_{EW}$ $N_{B,H} \leftrightarrow e_L$	
		$T_{EW}$

# 0νββ and Baryogenesis



Deppisch, Graf, JH, Huang (2018)  
Deppisch, JH, Huang, Hirsch, Päs (2015)

Side remark: **Loop enhanced** rate of neutrinoless double beta decay via **virtuality** of the particle in the loop

Rodejohann, Xu (2019)

# TeV scale LNV – A simplified model study

**Right-handed neutrino decay as source of a lepton asymmetry at high scale**

$$\mathcal{L} \supset y_\nu \bar{L} H N - \frac{m_N}{2} \bar{N}^c N + \text{h.c.}$$

**LNV interaction at TeV-range**

**LNV**

$$\tilde{\mathcal{L}} \supset g_Q \bar{Q} S d_R + g_L \bar{L} (i\tau^2) S^* F + \lambda_{HS} (S^\dagger H)^2 + \text{h.c.}$$

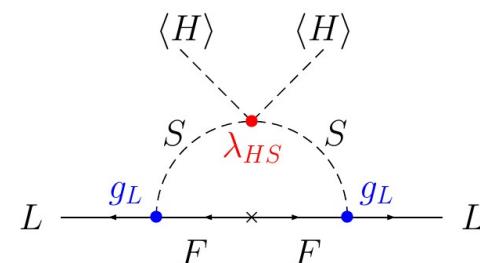
**Integrating out heavy d.o.f. leads to dim-9 LNV operator:**

$$L_{LNV}^{eff} = \frac{C_1}{\Lambda^5} \bar{Q} d^c \bar{Q} d^c \bar{L} L^C + \text{h.c.}$$

$$C_1 = g_L^2 g_Q^2$$

$$\Lambda = (m_S^4 m_F)^{1/5}$$

**Contribution to neutrino mass dependent on size of  $\lambda_{HS}$ :**

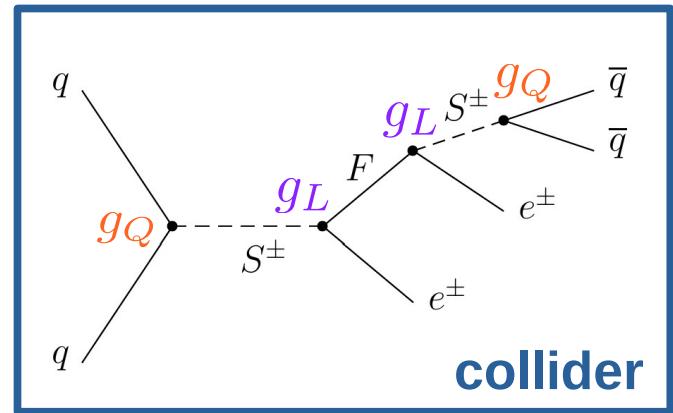
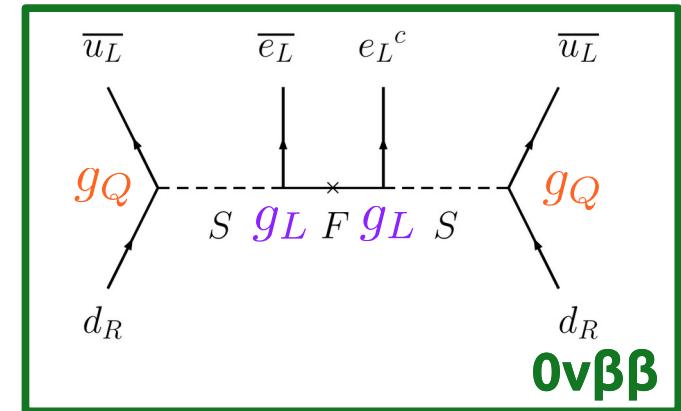
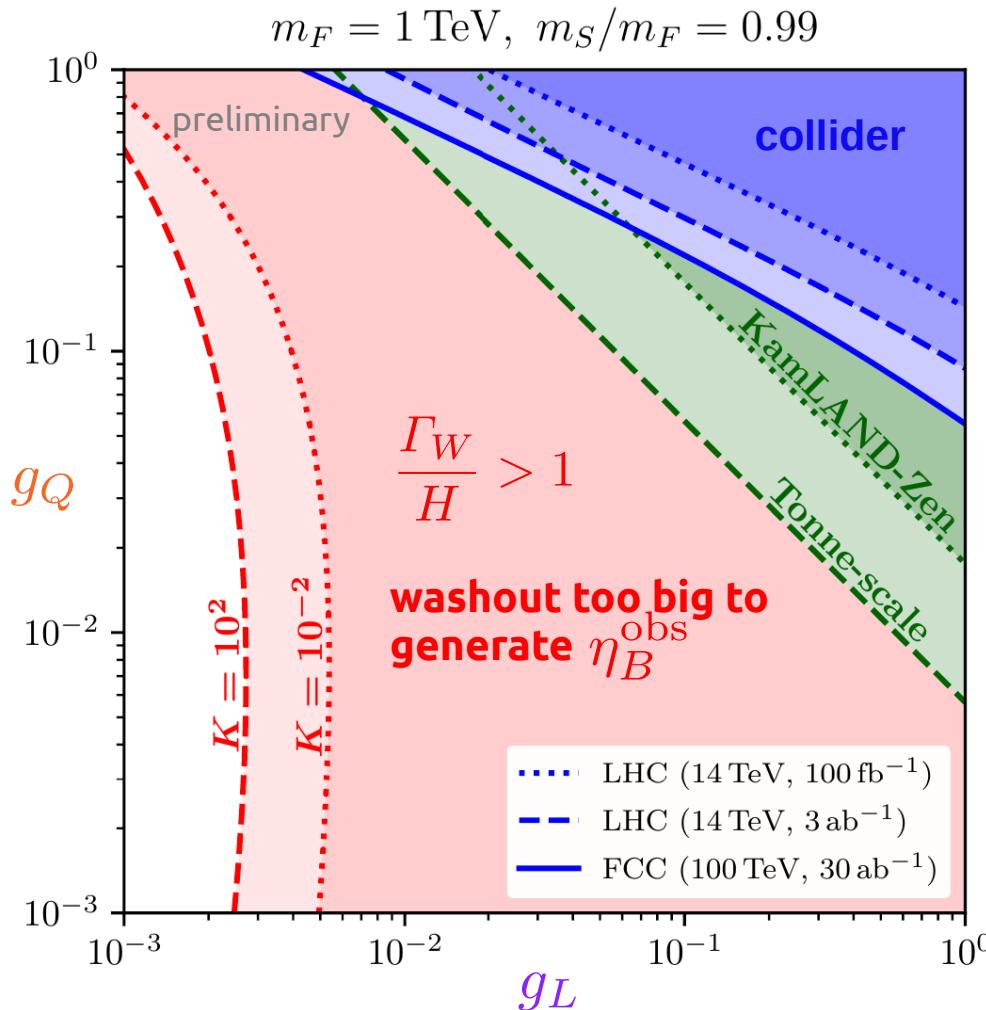


$$m_\nu \sim \frac{\lambda_{HS} g_L^2 \langle H \rangle^2}{\Lambda}$$

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga, in preparation

# Combining LHC & $0\nu\beta\beta$

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



Comprehensive analysis confirms EFT results and shows interesting interplay between collider and  $0\nu\beta\beta$  reach.

JH, Ramsey-Musolf, Shen, Urrutia, in preparation