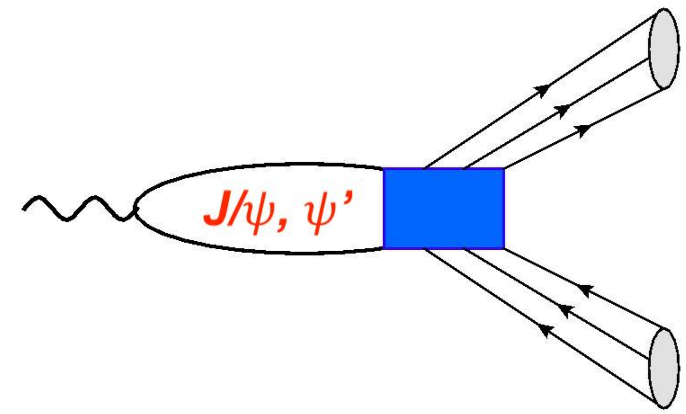
Workshop on form factor, polarization and CP violation in quantum correlated hyperon-antihyperon production

Fudan University,
Shanghai, 7-8 July 2019



Neutrinoless double beta decays of hyperons: $B_i^- \to B_f^+ \ell^- \ell'^-$

G. López Castro (Cinvestav, México)

Simpler HME (than Nuclear $0\nu\beta\beta$ decays)

	$\Delta S = 0$	$\Delta S = 1$	$\Delta S = 2$
$\Sigma^- \to$	$\Sigma^+ e^- e^-$	$p e^- e^-$	-
	-	$p \mu^- e^-$	-
	-	$p \mu^- \mu^-$	-
$\Xi^- \to$	-	$\Sigma^+ e^- e^-$	$p e^- e^-$
	-	$\Sigma^+ \mu^- e^-$	$p \mu^- e^-$
	-	-	$p \mu^- \mu^-$
$\Omega^- \to$	-	-	$\Sigma^+ e^- e^-$
	-	-	$\Sigma^+ \mu^- e^-$
	-	-	$\Sigma^+ \mu^- \mu^-$

⬇

Effective Majorana masses: $\langle m_{ee} \rangle, \langle m_{e\mu} \rangle, \langle m_{\mu\mu} \rangle$

Based on three old papers on $\Delta L = 2$ hyperon decays:

BLNV-03: C. Barbero, GLC and A. Mariano, Phys. Lett. B566,98 (2003)

BLNV-07: C. Barbero, L. F. Li, GLC and A. Mariano, Phys Rev D76, 116008 (2007)

BLNV-13: C. Barbero, L. F. Li, GLC and A. Mariano, Phys Rev D87, 036010 (2013)

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Little experimental information (PDG 2018)

	BR (90% c. l.)	Ref.
$\Xi^- \to p\mu^-\mu^-$	$< 4.0 \times 10^{-8}$	HyperCP Collab (2005)
	$< 3.7 \times 10^{-4}$	Schrock-Littenberg (1992)
$\Lambda_c^+ \to \Sigma^-\mu^+\mu^+$	$< 7.0 \times 10^{-4}$	E653 Collab (1995)

Hai-Bo Li, Front Phys (2017): can reach 10^{-7} sensitivity at BESIII

Plan:

* $\Delta L = 2$ processes and Majorana neutrinos

* $2\nu\beta\beta$ hyperon decays (rare, background)

* $0\nu\beta\beta$ hyperon decays (forbidden)
  - Model-independent bound
  - Loop-model
  - Matrix elements within a Bag Model

* Final comments

Main motivation: Majorana neutrinos

- No fundamental reason for L (and B) conservation (unlike Q, C)
- Profoundly important to observe $\not{L}$ & $\not{B}$ (BAU)

$$\Delta B = 1, \quad \Delta L = \pm 1 \quad : p \to e^+ \pi, \text{ single nucleon decay}$$
$$\Delta B = 2, \quad \Delta L = 0 \quad : n \leftrightarrow \bar{n}, \text{ oscillations}$$
$$\Delta B = 0, \quad \Delta L = 2 \quad : B^- \to B'^+ \ell^- \ell'^-, \ 0\nu\beta\beta \text{ decays}$$

- Majoranas look unavoidable for massive neutrinos. $\overline{\nu_R^c} M \nu_R \Rightarrow |\Delta L| = 2$

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$$\overline{\nu_R^c} M \nu_R \Rightarrow |\Delta L| = 2$$

	N mass	ν masses	eV ν anoma–lies	BAU	DM	M_H stability	direct search	experi–ment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

Different mass scales are technically possible and worth exploring!

Drewes, 1303.6912;
de Gouvea, 0706.1732

Intensive experimental searches of $\Delta L = 2$

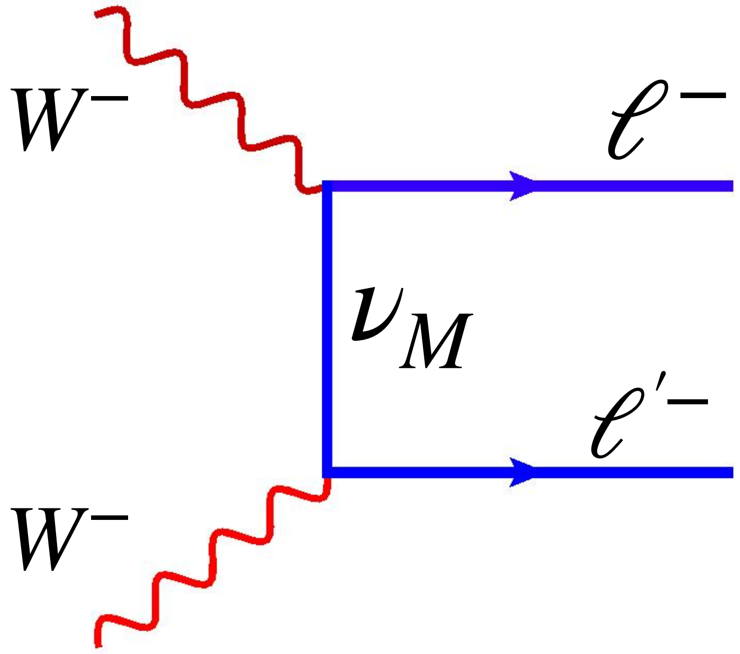
- $(\mathrm{A}, \mathrm{Z}) \to (\mathrm{A}, \mathrm{Z}+2) e^- e^-$
- $\mathrm{M}_1^{\pm} \to \mathrm{M}_2^{\mp} \ell^{\pm} \ell'^{\pm}$ $\quad (\mathrm{M} = \text{meson}, \quad \ell = e\mu, \tau)$
- $\tau^{\pm} \to \ell^{\mp} M_1^{\pm} M_2^{\pm}$
- $e^- \to \mu^+$ conversion in nuclei
- $pp, \; p\bar{p} \to \ell^{\pm} \ell'^{\pm} X$
- $B_i^{\mp} \to B_f^{\pm} \ell^{\mp} \ell'^{\mp}$

Sensitivities to different mass scales and mixings, complementary

Sterile neutrinos would couple to matter only through the mixing with active neutrinos vía charged currents

$$\nu_\ell = \sum_{i=1}^{3} U_{\ell i}\nu_i + \sum_{M=4}^{n+4} V_{\ell M}\nu_M$$

$$\mathscr{L}^{\rm cc} = \frac{G_F}{\sqrt{2}}\bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\ell W_\mu + \mathrm{h.c.}$$



+ crossed channels

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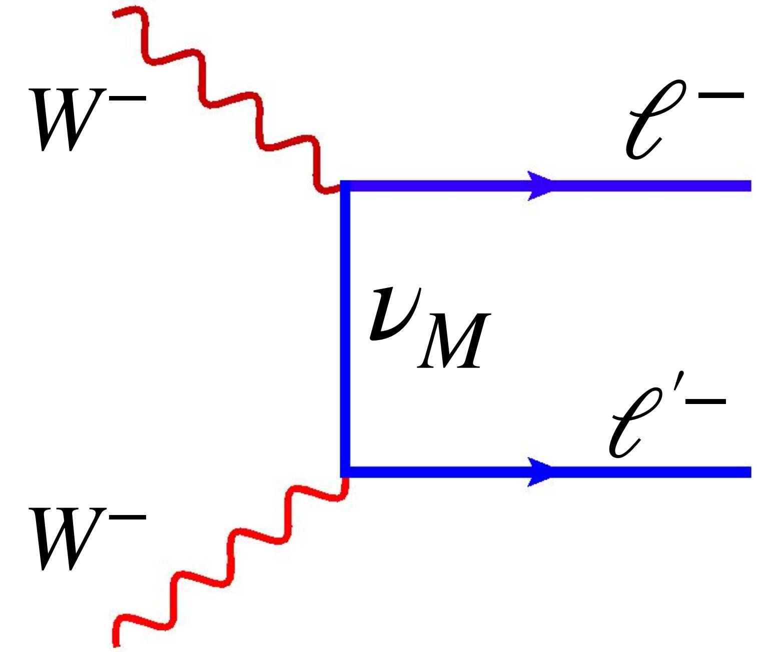


+ crossed channels

LNV driven by an Effective Majorana mass parameter

- **Very light neutrinos:** $\langle m_{\ell\ell'}\rangle = \sum_i U_{i\ell}U_{\ell' i}m_i$
- **Very heavy neutrinos:** $\langle m^{-1}_{\ell\ell'}\rangle = \sum_k \frac{V_{k\ell}V_{\ell' k}}{m_k}$
- **Resonant neutrinos:** $\langle m^{R}_{\ell\ell'}\rangle \sim \sum_k \frac{V_{k\ell}V_{\ell' k}m_k}{\Gamma_k}$

1.Very light Majorana neutrino

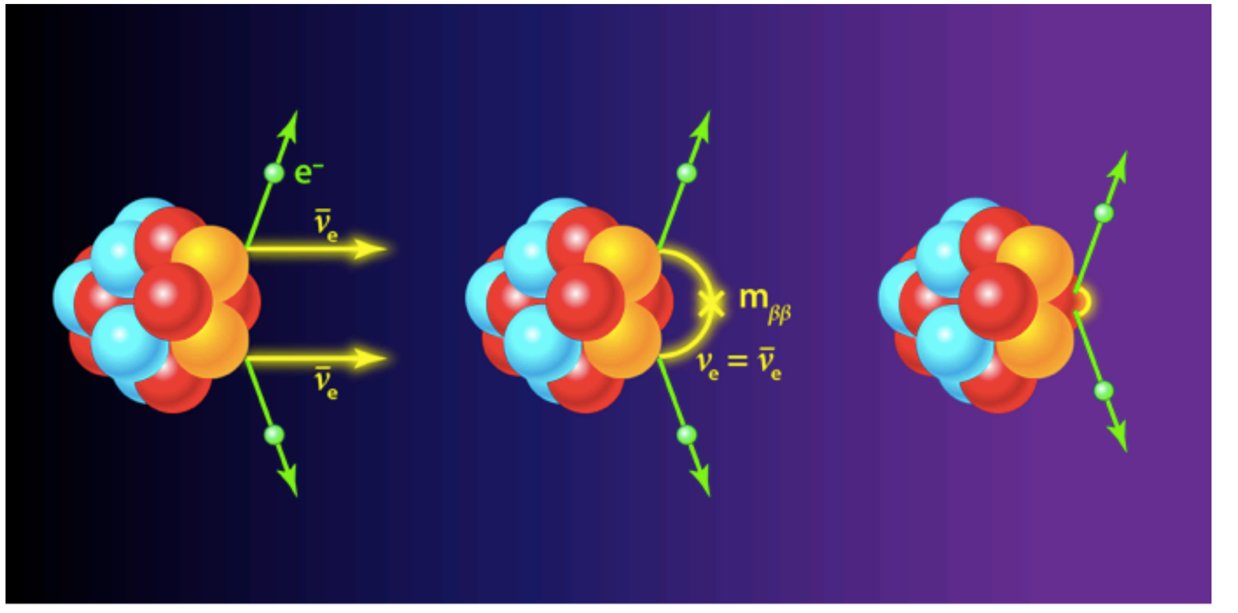
Most sensitive is neutrinoless nuclear double-beta decay

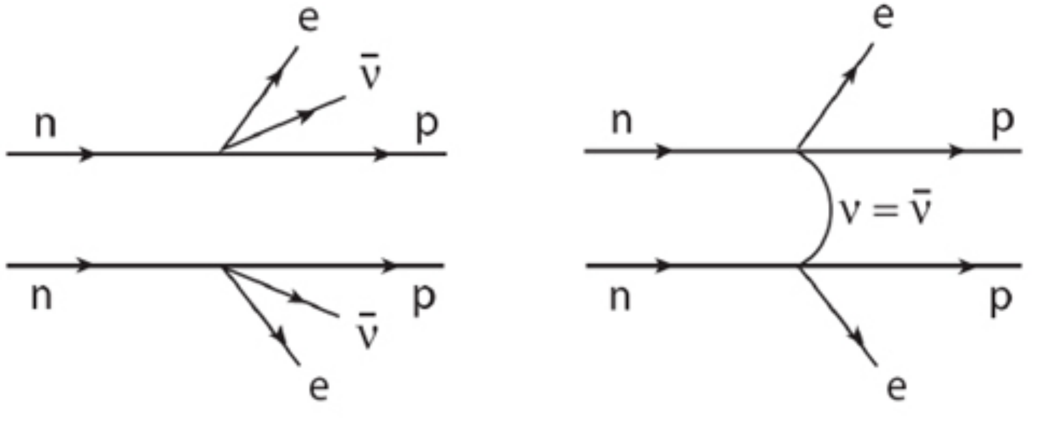
Tree- or loop-level phenomenon?

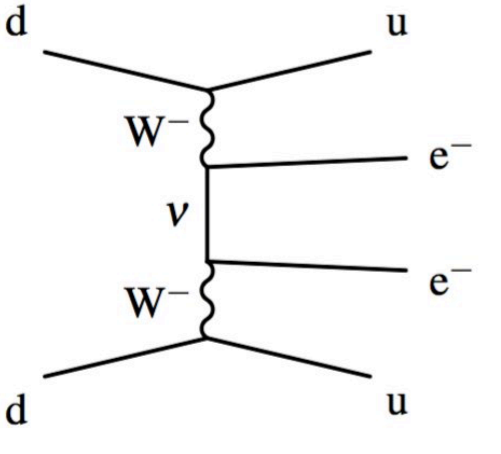
Nuclear matrix elements difficult to calculate & g_A in nuclei

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot \left|\mathcal{M}^{0\nu}\right|^2 \cdot \langle m_{ee}\rangle^2$$

$$|\langle m_{ee}\rangle| \sim O(0.1 - 0.2)\ \mathrm{eV}$$

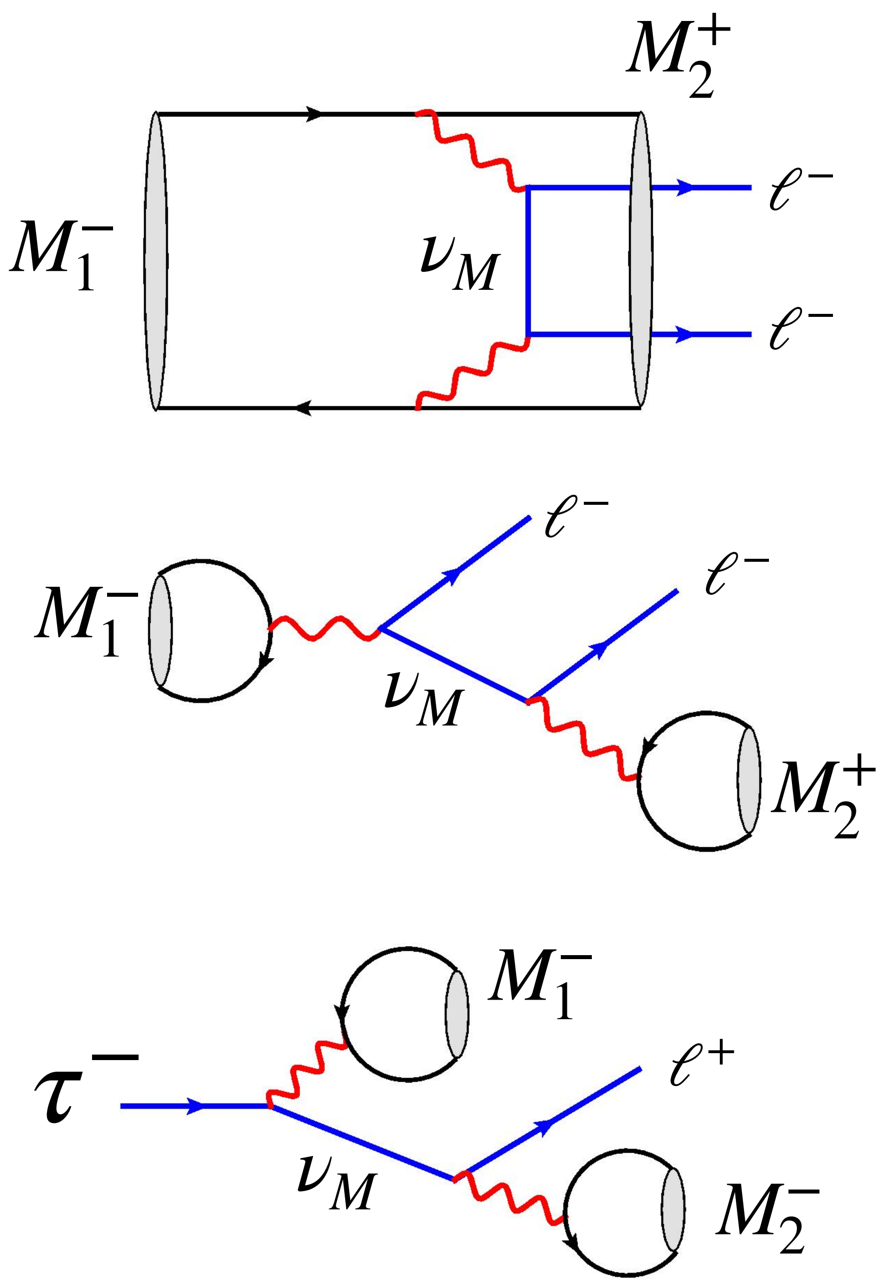






2. Intermediate mass neutrinos (0.1~ 5 GeV)

A. Atre et al, JHEP05, 030 (2009) +many others



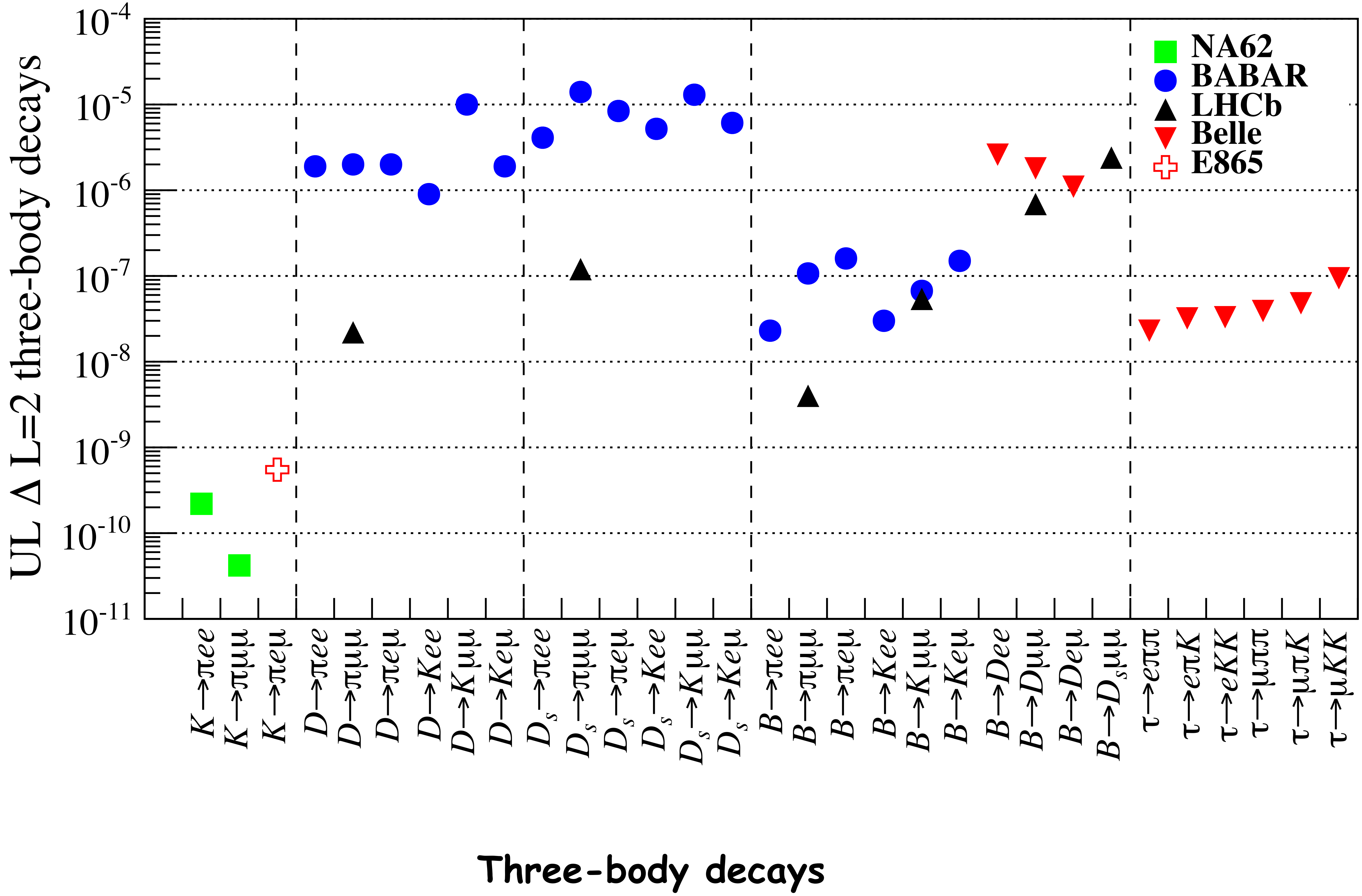
Contribution of only one Majorana neutrino N

$$\sim G_F^2 V_{ij}^{CKM} V_{kl}^{*VCKM} f_{M_1} f_{M_2} \frac{U_{\ell N} U_{\ell' N} m_N}{q^2 - m_N^2 + i m_N \Gamma_N}$$

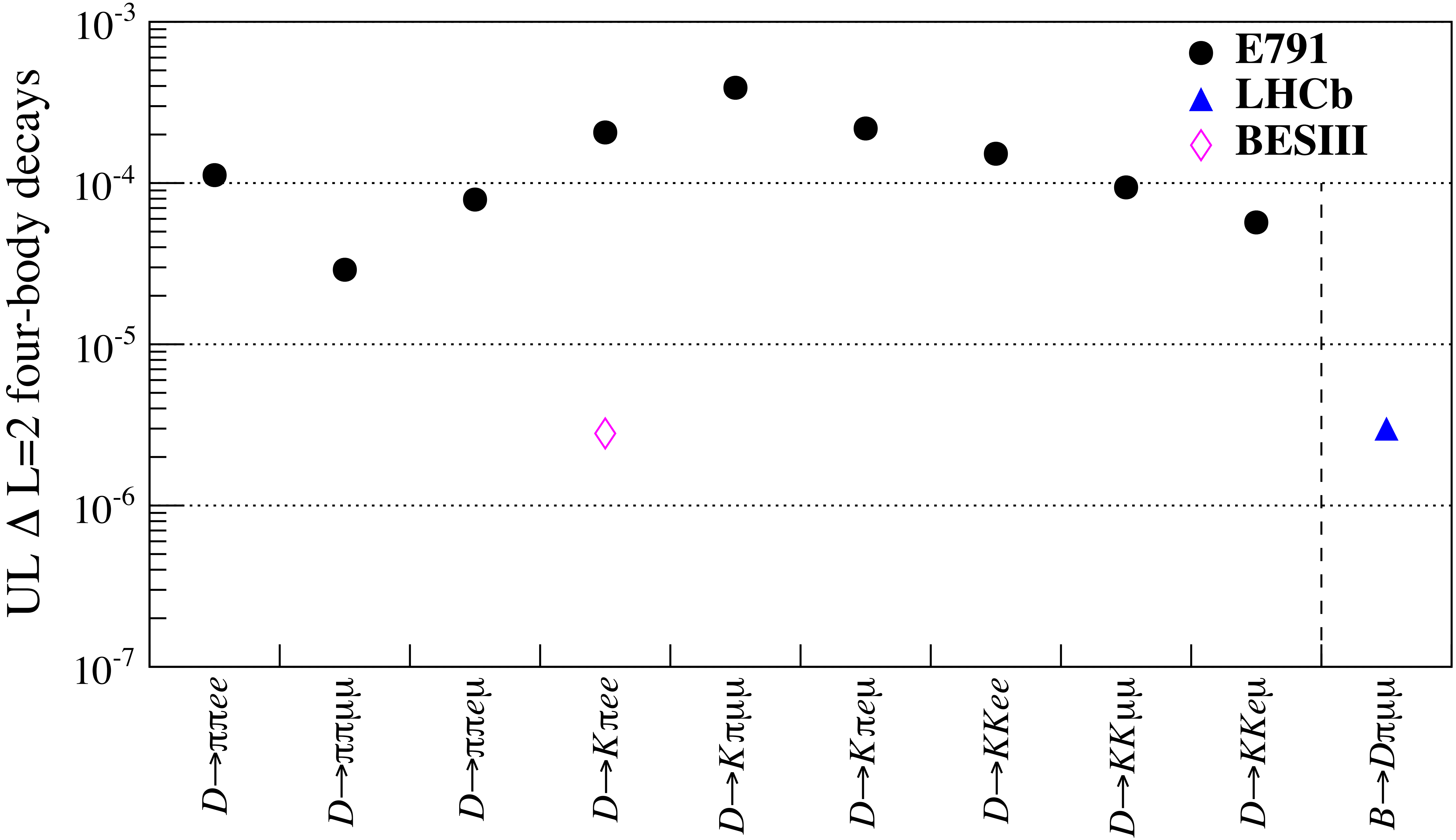
Resonance enhancement

$$BR = \frac{G_F^4 \left| U_{\ell N} U_{\ell' N} \right|^2 m_N^2}{\Gamma_N^2} \left| V_1^{CKM} V_2^{CKM} \right|^2 f(m_N, \cdots)$$

Searches for $\Delta L = 2$ proceses at low energies

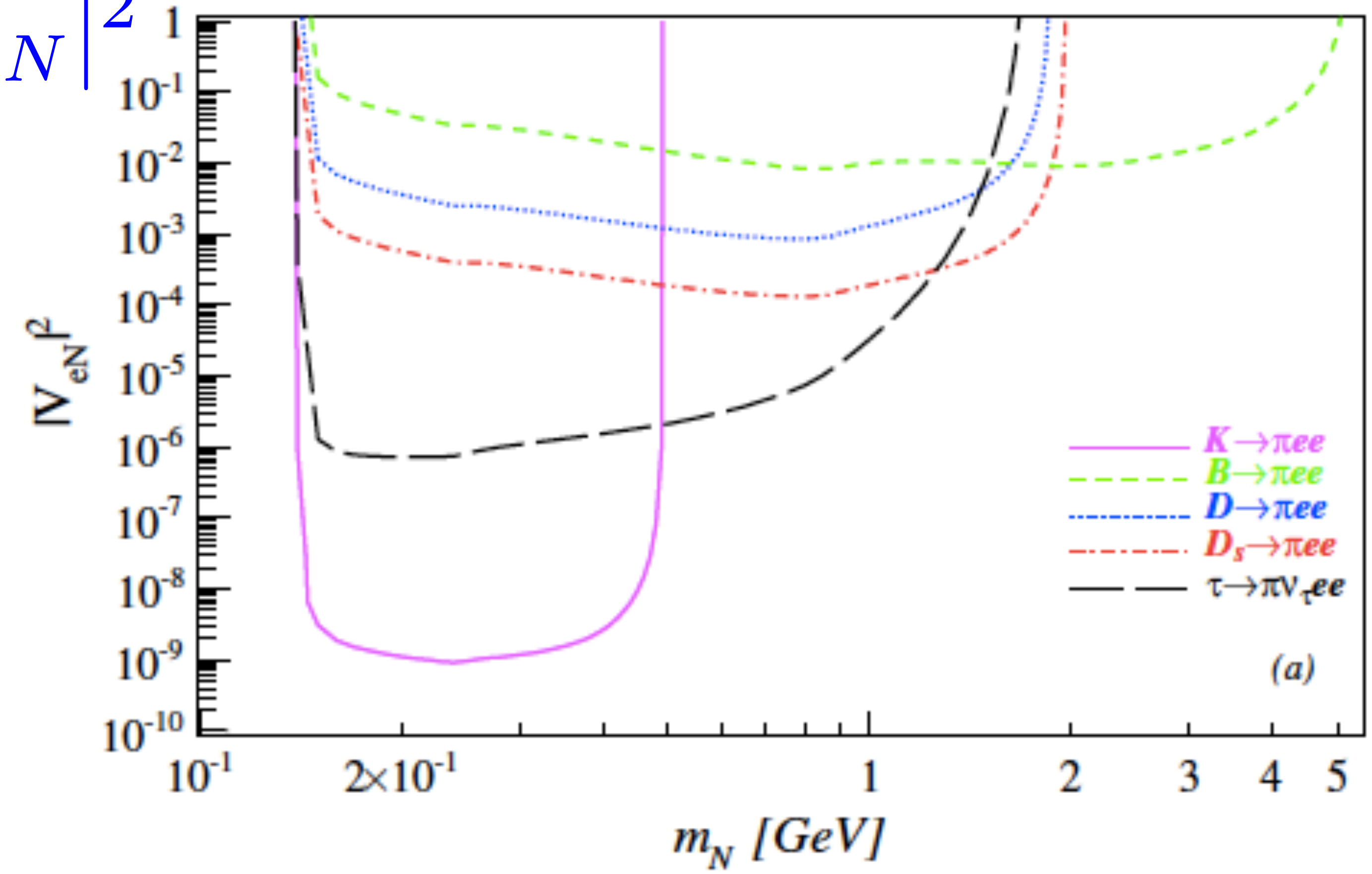


Four-body decays

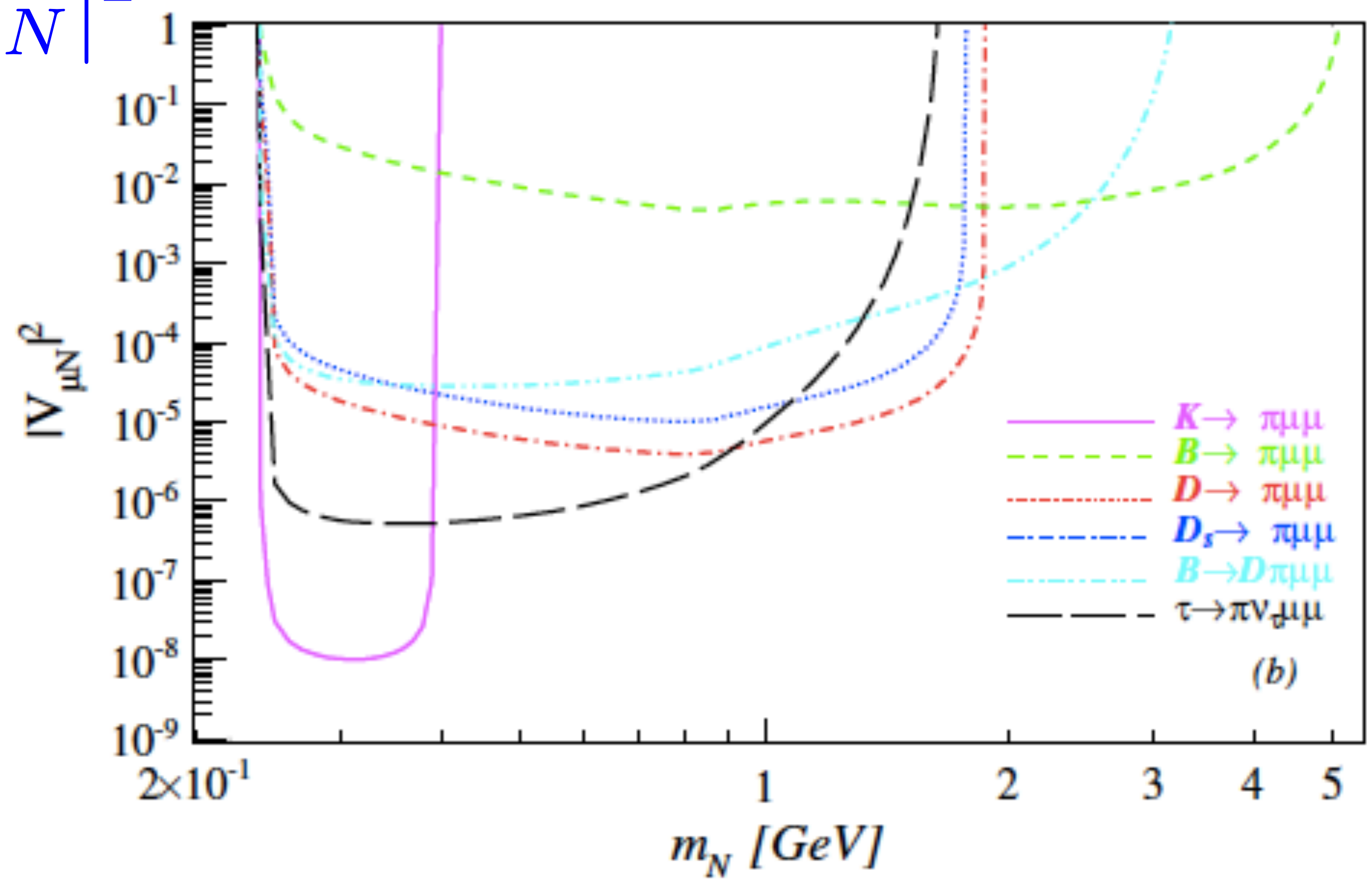


Exclusion plots

$|U_{eN}|^2$



$|U_{\mu N}|^2$



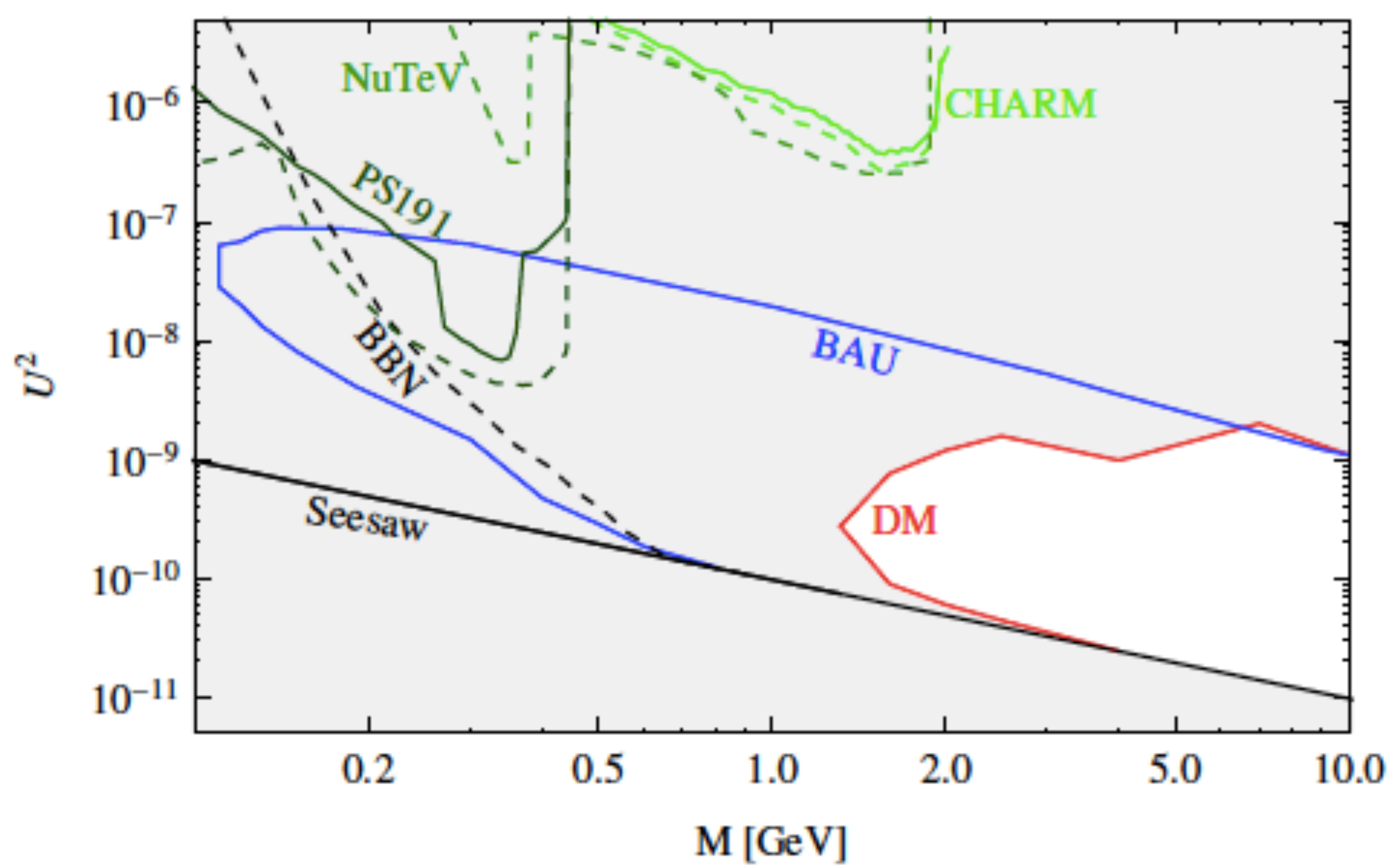
$$BR = \frac{G_F^4 \left|U_{\ell N} U_{\ell' N}\right|^2 m_N^2}{\Gamma_N^2} \times \left|V_1^{CKM} V_2^{CKM}\right|^2 f(m_N, \cdots)$$

Neutrino Minimal Standard Model (νMSM): ME + $(N_1, N_2, N_3)_R$ (estériles)

$$\nu_\ell = \sum_{j=1}^{3} V_{\ell j}^{\text{PMNS}} \nu_j + \sum_{k=1}^{3} U_{\ell k} N_k$$

$M_{N_1} \sim$ (10 - 100) keV (Dark matter)

$M_{N_{2,3}} \sim \mathcal{O}$(1 GeV) (BAU)

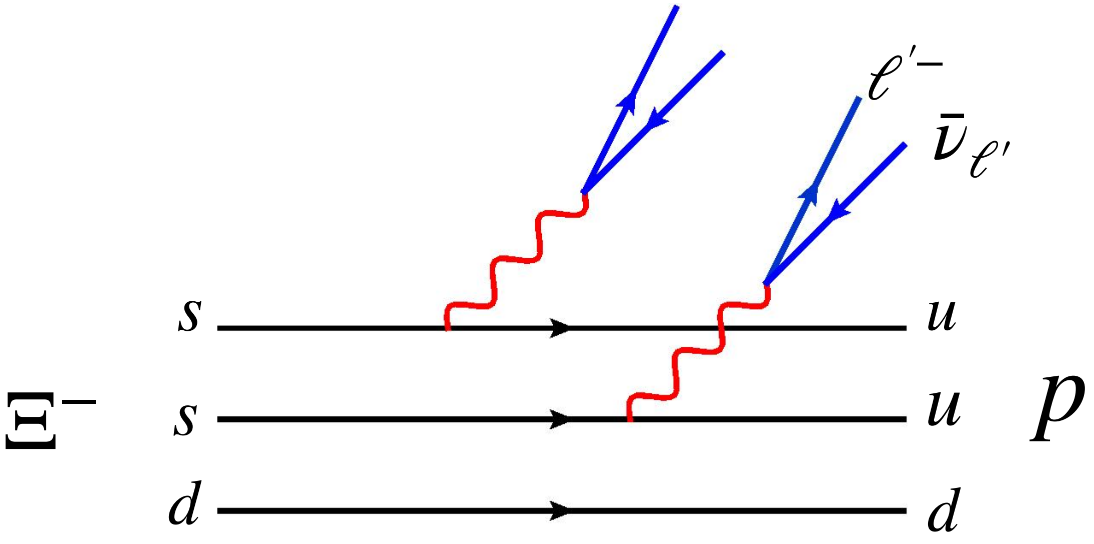


Canetti, Drewes, & Shaposhnikov PRL **110**, 061801 (2013) Canetti, Drewes, Frossard, & Shaposhnikov PRD **87**, 093006 (2013) Asaka, Blanchet, & Shaposhnikov PLB **631**, 151 (2005)

$2\nu\beta\beta$ hyperon decays

$$B_i^- \to B_f^+ \ell^- \ell'^- \bar{\nu}_\ell \bar{\nu}_{\ell'}$$

$$dd \to uu \ell^- \ell'^- \bar{\nu}_\ell \bar{\nu}_{\ell'}$$



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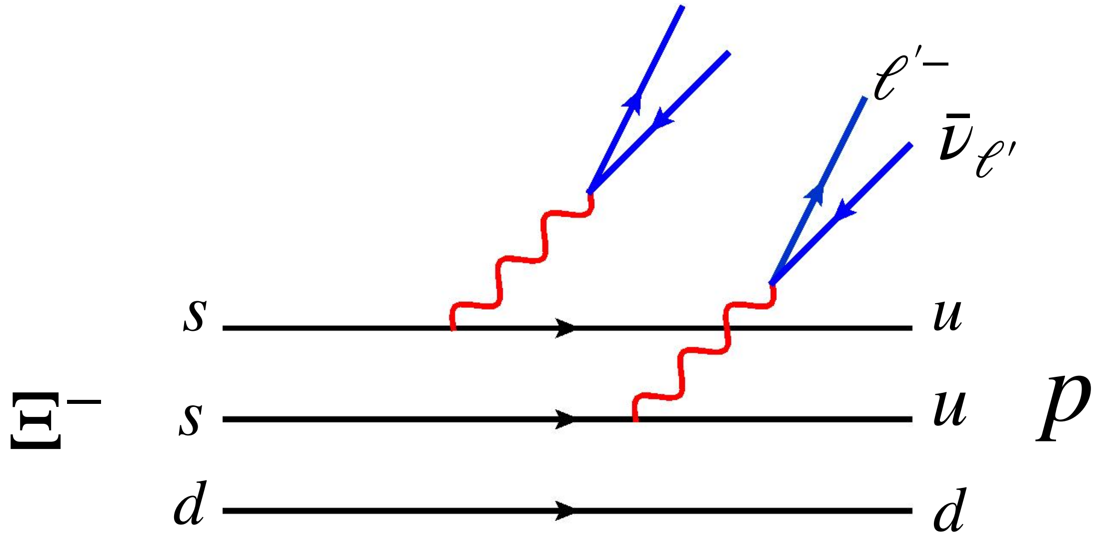
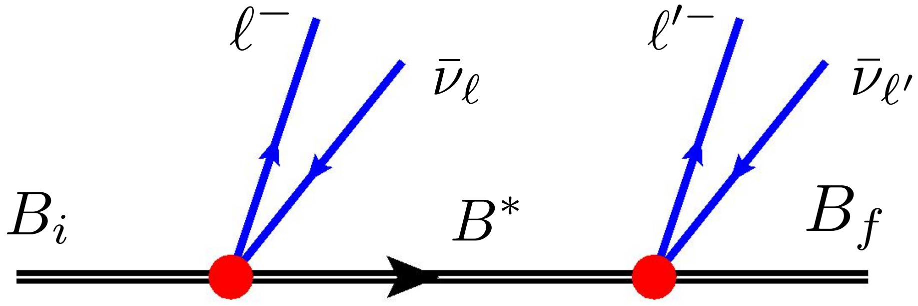


A model

- Two-step process



- Intermediate states crucial (assumption: same octet)

- Short-lived B* (Σ^0) important background for $0\nu\beta\beta$ hyperon decays. Long-lived (n) easily discriminated

- No experimental searches so far

BLNV-03, 07

- Assume decay chain: $B_i^- \to B^{*0}\ell^-\bar{\nu} \to B_f^+\ell^-\ell'^-\bar{\nu}\bar{\nu}'$

- B*=neutron decays outside detector, discriminated

BLNV-07

- B*= Σ^0 decays at same vertex ($\tau(\Sigma^0) = 7.4 \times 10^{-20}$ s)

Channel	BR	Dominant B^*
$\Sigma^- \to \Sigma^+ e^- e^- \bar{\nu}\bar{\nu}$	0.86×10^{-30}	Σ^0
$\to p e^- e^- \bar{\nu}\bar{\nu}$	4.77×10^{-8}	Λ
$\to p \mu^- e^- \bar{\nu}\bar{\nu}$	9.0×10^{-9}	Λ
$\to p \mu^- \mu^- \bar{\nu}\bar{\nu}$	~ 0	Λ
$\Xi^- \to \Sigma^+ e^- e^- \bar{\nu}\bar{\nu}$	6.59×10^{-14}	Ξ^0
$\to \Sigma^+ \mu^- e^- \bar{\nu}\bar{\nu}$	1.20×10^{-15}	Ξ^0
$\to p e^- e^- \bar{\nu}\bar{\nu}$	4.68×10^{-7}	Λ
$\to p \mu^- e^- \bar{\nu}\bar{\nu}$	3.80×10^{-7}	Λ
$\to p \mu^- \mu^- \bar{\nu}\bar{\nu}$	5.49×10^{-7}	Λ

$\Leftarrow 1.36 \times 10^{-30}$

Exact calculation
BLNV-03

Largely dominated by intermediate on-shell states

$0\nu\beta\beta$ hyperon decays

$$B_i^- \to B_f^+ \ell^- \ell'^- \qquad (dd \to uu\ell^- \ell'^-)$$

	$\Delta S = 0$	$\Delta S = 1$	$\Delta S = 2$
$\Sigma^- \to$	$\Sigma^+ e^- e^-$	$p e^- e^-$	-
	-	$p \mu^- e^-$	-
	-	$p \mu^- \mu^-$	-
$\Xi^- \to$	-	$\Sigma^+ e^- e^-$	$p e^- e^-$
	-	$\Sigma^+ \mu^- e^-$	$p \mu^- e^-$
	-	-	$p \mu^- \mu^-$
$\Omega^- \to$	-	-	$\Sigma^+ e^- e^-$
	-	-	$\Sigma^+ \mu^- e^-$
	-	-	$\Sigma^+ \mu^- \mu^-$
	$\lvert V_{ud}\rvert^4$	$\lvert V_{ud} V_{us}\rvert^2$	$\lvert V_{us}\rvert^4$

Allowed by phase space

$$B(0\nu\beta\beta) \sim \left| m_{\ell\ell'} \right|^2 |V_{ui} V_{uj}|^2 \cdot |\mathscr{M}\mathscr{E}|^2 PS$$

$0\nu\beta\beta$ hyperon decays

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	$\Delta S = 0$	$\Delta S = 1$	$\Delta S = 2$
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$\Xi^- \to$	-	$\Sigma^+ e^- e^-$	$p e^- e^-$
	-	$\Sigma^+ \mu^- e^-$	$p \mu^- e^-$
	-	-	$p \mu^- \mu^-$
$\Omega^- \to$	-	-	$\Sigma^+ e^- e^-$
	-	-	$\Sigma^+ \mu^- e^-$
	-	-	$\Sigma^+ \mu^- \mu^-$
	$\lvert V_{ud}\rvert^4$	$\lvert V_{ud} V_{us}\rvert^2$	$\lvert V_{us}\rvert^4$

Allowed by phase space

$$B(0\nu\beta\beta) \sim \left| m_{\ell\ell'} \right|^2 \lvert V_{ui} V_{uj} \rvert^2 \cdot \lvert \mathscr{ME} \rvert^2 PS$$

A model-independent estimate

Most general lagrangian for $\Delta L = 2$ semileptonic hyperon decays

$$\mathcal{L}^{\Delta L=2} = \frac{G_F^2}{\Lambda_{\beta\beta}} \left\{ c_{ij}^{\ell\ell'} (\bar{u}\Gamma_i d_i)(\bar{u}\Gamma_j d_j)(\bar{\ell}\Gamma \ell'^c) + \mathrm{h.c.} \right\}$$

Ling Fong Li, 0706.2815

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Ling Fong Li, 0706.2815

Order of magnitude estimates, $c_{ij} \sim O(1)$:

$$\frac{\Gamma(B_1 \to B_2 \ell\ell')}{\Gamma(B_1 \to B_2' \ell \nu_\ell)} = \left(\frac{G_F}{\Lambda_{\beta\beta}}\right)^2 \left| \frac{\langle B_2 | (\bar{u}\Gamma_i d_i)(\bar{u}\Gamma_j d_j) | B_1 \rangle}{\langle B_2' | \bar{u}\Gamma d | B_1 \rangle} \right|^2 \text{PS}$$

$$= \left(\frac{G_F}{\Lambda_{\beta\beta}}\right)^2 M^6 \text{PS}$$

$$\approx \left(\frac{M}{\Lambda_{\beta\beta}}\right)^2 \times 10^{-10}$$

M ~1 GeV

L. F. Li, 0706.2815

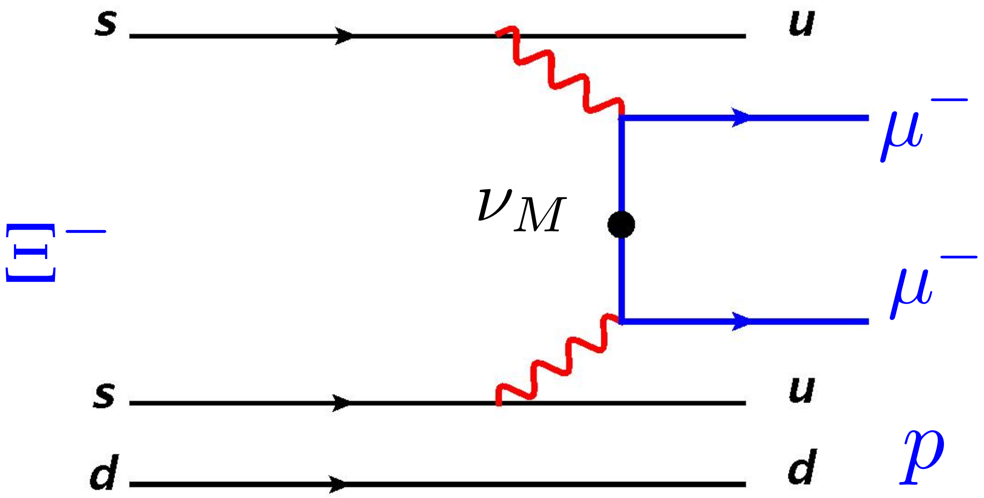
$$B(B_1 \to B_2 \ell^- \ell'^-) < 10^{-14}$$

$$\frac{1}{\Lambda_{\beta\beta}} = \frac{m_{\nu_M}}{\Lambda'^2}$$

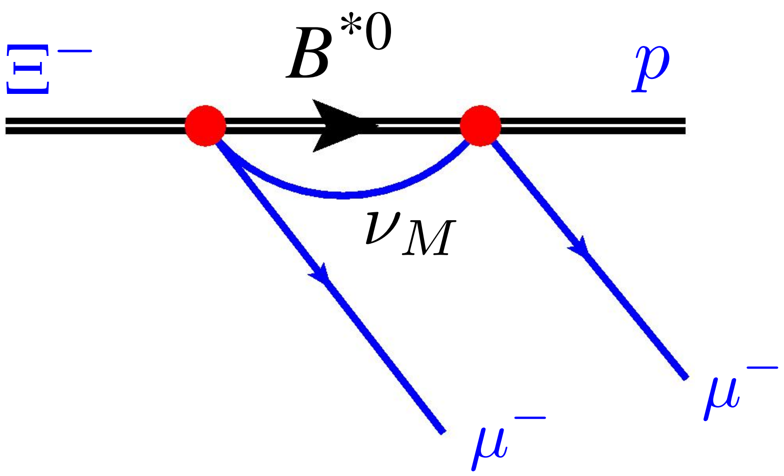
Strong suppression for light Majorana neutrinos

A loop-model for $B_i^- \to B_f^+ \ell^- \ell'^-$

Tree: quark level



Loop: hadron level



$B^{*0} = \Lambda, \Sigma^0, \ldots$

BLNV-03, BLNV-07

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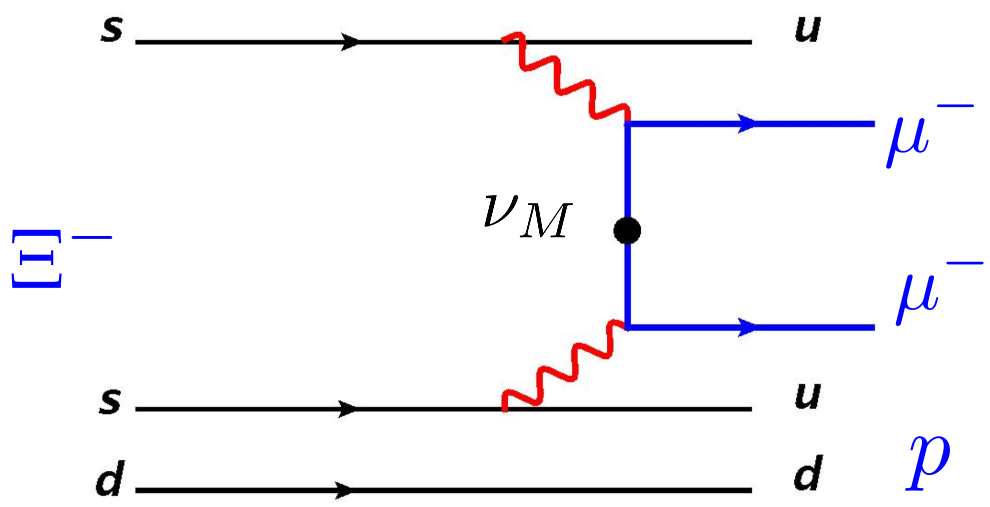

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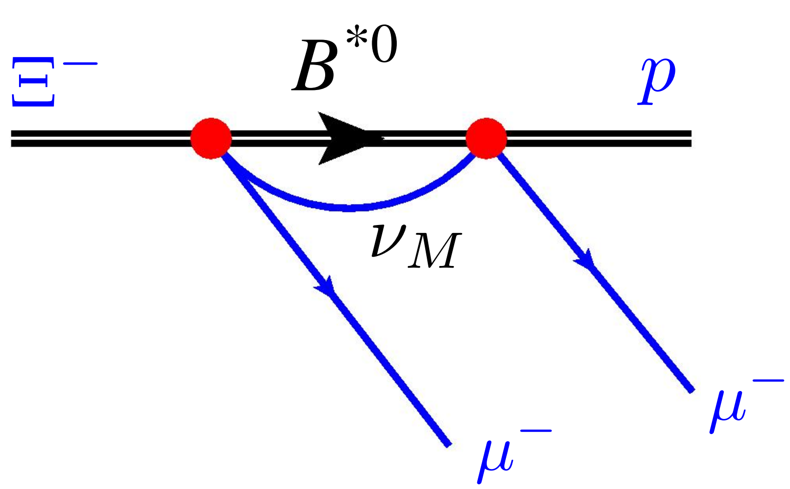


$B^{*0} = \Lambda,\ \Sigma^0, \ldots$

BLNV-03, BLNV-07

Approximated hadronic matrix element

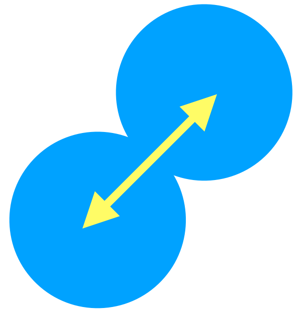
$$\langle B_f | j_\mu | B_i \rangle = \bar{u}_f \gamma_\mu \left(f^{if} + g^{if} \gamma_5 \right) u_i$$

Logarithmic divergence

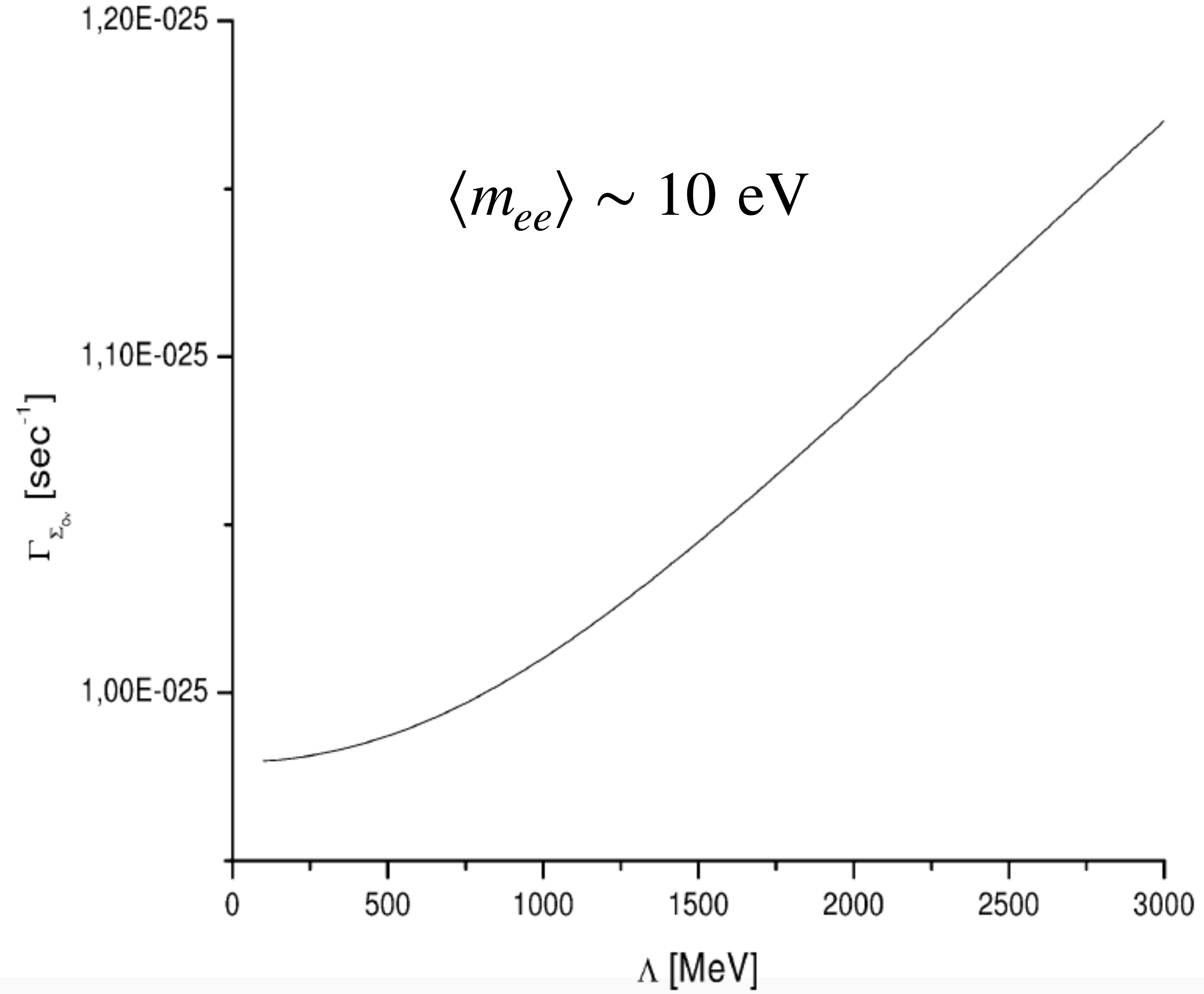
$$I_{B*}(p_\ell) \sim \int_0^1 dx \, [(\not{p}_i - \not{p}_\ell) + m_{B^*}] \int_0^{\Lambda_c} \frac{k^3 dk}{(k^2 + M^2)^2}$$

In $0\nu\beta\beta$ nuclear decays

$$\Lambda \sim 1 \text{ GeV} \sim (d_{nn})^{-1}$$



BLNV-03



For $\Lambda_c = 1$ GeV

$$B(\Sigma^- \to \Sigma^+ e^- e^-) = 1.5 \times 10^{-35}$$

Since rates scales as $\left(\Delta M_{if}\right)^5$ **, larger rates expected for other channels**

BLNV-07

$\Lambda_c = 1$ GeV

$\langle m_{ee} \rangle = 10$ eV,

$\langle m_{\mu\mu} \rangle = 10$ MeV

	$\Gamma_{0\nu}/\langle m_{\ell\ell'} \rangle^2$ [$\text{sec}^{-1}\text{MeV}^{-2}$]	$\mathcal{B}(B_i \to B_f \ell\ell)$
$\Sigma^- \to \Sigma^+ e^- e^-$	1.0×10^{-15}	1.5×10^{-35}
$\Sigma^- \to p e^- e^-$	5.0×10^{-9}	7.4×10^{-31}
$\Sigma^- \to p \mu^- \mu^-$	4.3×10^{-10}	6.3×10^{-20}
$\Xi^- \to \Sigma^+ e^- e^-$	8.4×10^{-14}	1.4×10^{-33}
$\Xi^- \to p e^- e^-$	1.1×10^{-12}	1.9×10^{-32}
$\Xi^- \to p \mu^- \mu^-$	4.8×10^{-13}	7.9×10^{-21}

BLNV-07

$\Lambda_c = 1$ GeV

$\langle m_{ee} \rangle = 10$ eV,

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$\Xi^- \to p \mu^- \mu^-$	4.8×10^{-13}	7.9×10^{-21}

HyperCP UL $B(\Xi^- \to p\mu^-\mu^-) < 4.0 \times 10^{-8} \Rightarrow$ $|m_{\mu\mu}| < 22$ TeV

$$|\langle M_{\mu\mu} \rangle| < \begin{cases} 0.04 \text{ TeV}, & \text{from } K^+ \to \pi^- \mu^+ \mu^+ \text{ (2000)} \\ 2.90 \text{ TeV}, & ep \to X\mu^+\mu^+ \text{ from HERA,} \\ & \text{W. Rodejohann (2002)} \end{cases}$$

$0\nu\beta\beta$ hyperon decays within the MIT Bag

In an effective lagrangian approach L. F. Li, 0706.2815

$$-\mathcal{L}_{\Delta L=2} = \frac{G_F^2}{\Lambda_{\beta\beta}} \left\{ c_1(\bar{u}\Gamma_i d)(\bar{u}\Gamma_j d) + c_2\left[(\bar{u}\Gamma_i d)(\bar{u}\Gamma_j s) + (\bar{u}\Gamma_i s)(\bar{u}\Gamma_j d)\right] + c_3(\bar{u}\Gamma_i s)(\bar{u}\Gamma_j s) \right\}$$
$$\times \left\{ d_1(\bar{e}\Gamma_k e^c) + d_2(\bar{\mu}\Gamma_k \mu^c) + d_3\left[\bar{e}\Gamma_k \mu^c + (\bar{\mu}\Gamma_k e^c))\right] \right\}$$

$$\langle B_f|(V-A)_\alpha(V'-A')_\beta|B_i\rangle = \bar{u}(p_f)\left[\Gamma^V_{\alpha\beta} - \Gamma^A_{\alpha\beta}\right]u(p_i)$$

Lengthly most general form of vector and axial vértices BNLV-13

$$\Gamma^V_{\alpha\beta} = h_1 g_{\alpha\beta} + i h_2 \sigma_{\alpha\beta} + \frac{h_3}{2M}\gamma_\alpha P_\beta + \frac{h_4}{2M}\gamma_\alpha q_\beta + \frac{h_5}{2M}\gamma_\beta P_\alpha + \frac{h_6}{2M}\gamma_\beta q_\alpha + \frac{h_7}{4M^2}P_\alpha q_\beta + \frac{h_8}{4M^2}q_\alpha q_\beta$$
$$+ i\frac{h_9}{4M^2}P_\alpha \sigma_{\beta\mu}q^\mu + i\frac{h_{10}}{4M^2}q_\alpha \sigma_{\beta\mu}q^\mu + i\frac{h_{11}}{4M^2}P_\beta \sigma_{\alpha\mu}q^\mu + i\frac{h_{12}}{4M^2}q_\beta \sigma_{\alpha\mu}q^\mu + i h_{13}\epsilon_{\alpha\beta\mu\nu}\sigma^{\mu\nu}\gamma_5$$
$$+ \frac{h_{14}}{4M^2}\epsilon_{\alpha\beta\mu\nu}P^\mu q^\nu \gamma_5 + \frac{h_{15}}{2M}\epsilon_{\alpha\beta\mu\nu}q^\mu \gamma^\nu \gamma_5 + \frac{h_{16}}{2M}\epsilon_{\alpha\beta\mu\nu}P^\mu \gamma^\nu \gamma_5,$$

MIT Bag-model (A. Chodos et al, 1974)

- Only a few form factors contribute in the non-relativistic approximation (neglect momentum transfer $q/M \to 0,\ \ h_i(q^2) = h_i(0)$)

-Spin-flavor wavefunctions for hyperon states

BLNV-13

$\underline{\Sigma^- \to pe^- e^-}$

$$B^{\mathrm{bag}}(\Sigma^- \to pe^-e^-) = \left(\frac{c_2 d_1}{\Lambda_{\beta\beta}}\right)^2 \cdot (4.65 \times 10^{-13}\ \mathrm{MeV}^2).$$

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- Spin-flavor wavefunctions for hyperon states

BLNV-13

$\Sigma^- \to p e^- e^-$

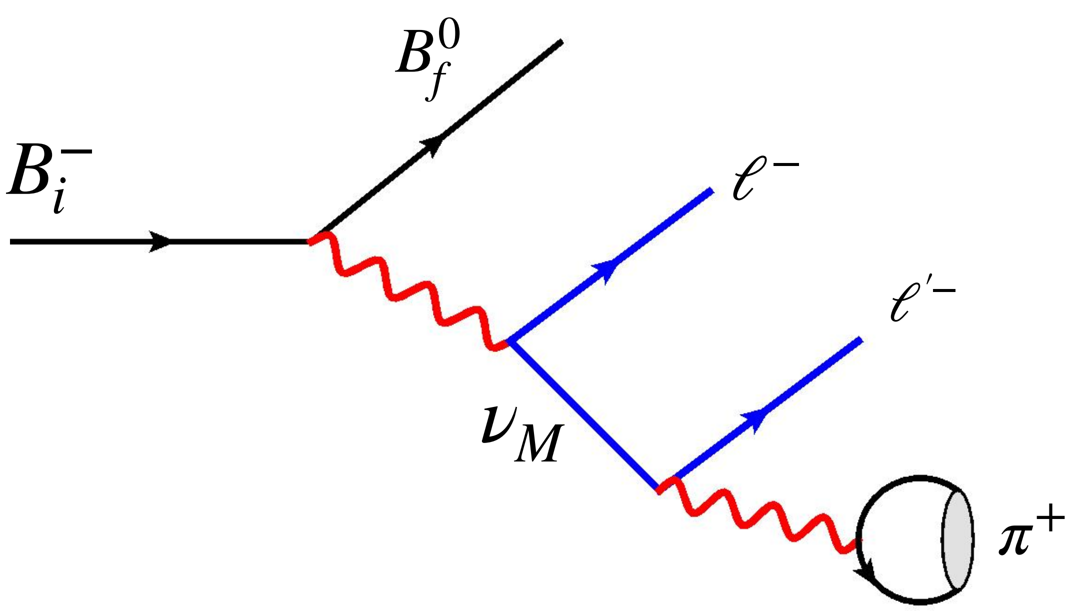
$$B^{\rm bag}(\Sigma^- \to p e^- e^-) = \left(\frac{c_2 d_1}{\Lambda_{\beta\beta}}\right)^2 \cdot (4.65 \times 10^{-13}\ {\rm MeV}^2).$$

$$\left.\begin{array}{l} c_i,\ d_i \sim O(1) \\ \Lambda_{\beta\beta} \sim 1\ {\rm TeV} \end{array}\right\} \Rightarrow \quad B^{\rm bag}(\Sigma^- \to p e^- e^-) \sim 10^{-25}$$

compared to $B^{\rm loop}(\Sigma^- \to p e^- e^-) = \left(\frac{\langle m_{ee}\rangle}{10\ eV}\right)^2 \cdot 7.4 \times 10^{-31}$ BLNV-07

Possible stronger limits on $\langle m_{\mu\mu}\rangle$ from $\Xi^- \to p \mu^- \mu^-$ in the Bag model

BLNV with a resonant Majorana neutrino



Sensitive to Majorana neutrino in the range

$$m_{\ell'} + m_\pi \leq m_N \leq m_{B_i} - m_{B_f} - m_\ell$$

w/ C.S. Kim and D. Sahoo

Only possible channels →

$$\Lambda \to p e^- e^- \pi^+$$
$$\Sigma^- \to n e^- e^- \pi^+, \; n e^- \mu^- \pi^+$$
$$\Xi^- \to \Lambda e^- e^- \pi^+$$

Final remarks

* First useful limits on forbidden $\Delta L = 2$ baryon decays can be obtained at BESIII !

* Observe for the first time $B(\Xi^- \to p\ell^-\ell'^-\bar{\nu}_\ell\bar{\nu}_{\ell'}) \sim 5 \times 10^{-7}$?

* Direct limits on effective Majorana masses $\langle m_{e\mu}\rangle$ and $\langle m_{\mu\mu}\rangle$.

* Evaluation of hadronic matrix elements of BLN decays is challenging. A more reliable evaluation is necessary and important to draw meaningfull/competitive limits on other $\langle m_{\ell\ell'}\rangle$ entries from BLNV

Thank you!

Backup slides

Decay amplitude for the loop proceses

$$\mathcal{M} = G^2 \sum_j m_j U_{\ell j} U_{\ell' j} \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2 - m_j^2} L^{\alpha\beta}(p_\ell, p_{\ell'}) H_{\alpha\beta}(Q(q))$$

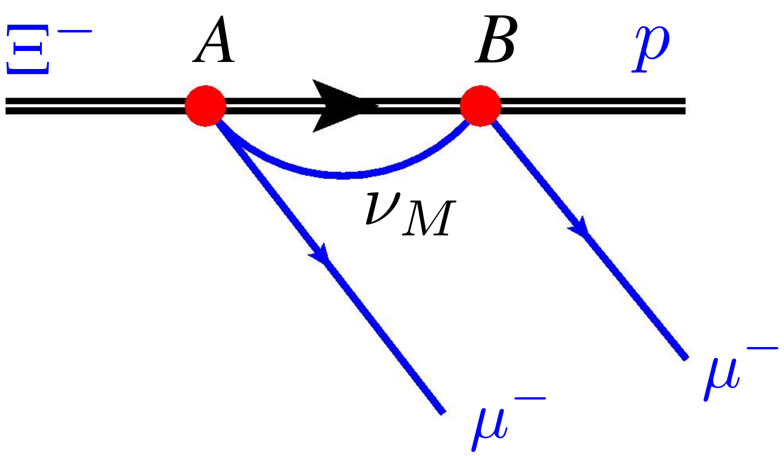
Leptonic current

$$L_{\alpha\beta}(p_1, p_2) = \bar{u}_\ell(p_1)\gamma_\beta(1-\gamma_5)\gamma_\beta u^c_{\ell'}(p_2)$$

Hadronic current

$$H_{\alpha\beta}(Q(q)) = \sum_{B^*} \bar{u}(p_f)\gamma_\alpha(f^{B^* f} + g^{B^* f}\gamma_5)\frac{\not{Q} + m_{B^*}}{Q^2 - m_{B^*}^2}\gamma_\beta(f^{B^* i} + g^{B^* i}\gamma_5)u(p_i)$$

Intermediate hyperon states contributions with leading form factors in SU(3) flavor limit



transition	η	$f_{A\eta}$	$g_{A\eta}$	$f_{B\eta}$	$g_{B\eta}$
$\Sigma^- \to \Sigma^+$	Λ	0	0.656	0	0.656
	Σ^0	$\sqrt{2}$	0.655	$\sqrt{2}$	-0.656
$\Sigma^- \to p$	n	-1	0.341	1	1.2670
	Σ^0	$\sqrt{2}$	0.655	$-1/\sqrt{2}$	0.241
	Λ	0	0.656	$-\sqrt{3/2}$	-0.895
$\Xi^- \to \Sigma^+$	Ξ^0	-1	0.341	1	1.267
	Σ^0	$1/\sqrt{2}$	0.896	$\sqrt{2}$	-0.655
	Λ	$\sqrt{3/2}$	0.239	0	0.656
$\Xi^- \to p$	Σ^0	$1/\sqrt{2}$	0.896	$-1/\sqrt{2}$	0.241
	Λ	$\sqrt{3/2}$	0.239	$-\sqrt{3/2}$	-0.895

MIT Bag Model A. Chodos et al (1974),

- Calculation of hadronic matrix element, for example

$$\Sigma^- \to p e^- e^-$$

- Spin-flavor wavefunctions for hyperons

$$\begin{aligned} X_{\alpha\beta}^{\Sigma^-\to p}(V) &= \bar{u}(p')\Gamma_{\alpha\beta}^{V}u(p) \\ &= \langle p|[M_{\alpha\beta}^{ds\to uu} + M_{\alpha\beta}^{sd\to uu}] \\ &\quad + [Q_{\alpha\beta}^{ds\to uu} + Q_{\alpha\beta}^{sd\to uu}]|\Sigma^-\rangle, \end{aligned}$$

$$\begin{aligned} X_{\alpha\beta}^{\Sigma^-\to p}(A) &= \bar{u}(p')\Gamma_{\alpha\beta}^{A}u(p) \\ &= \langle p|[N_{\alpha\beta}^{ds\to uu} + N_{\alpha\beta}^{sd\to uu}] \\ &\quad + [P_{\alpha\beta}^{ds\to uu} + P_{\alpha\beta}^{sd\to uu}]|\Sigma^-\rangle, \end{aligned}$$

$$M_{\alpha\beta}^{bd\to ac} = \int d^3x[\bar{\psi}_a(x)\gamma_\alpha\psi_b(x)]\cdot[\bar{\psi}_c(x)\gamma_\beta\psi_d(x)],$$

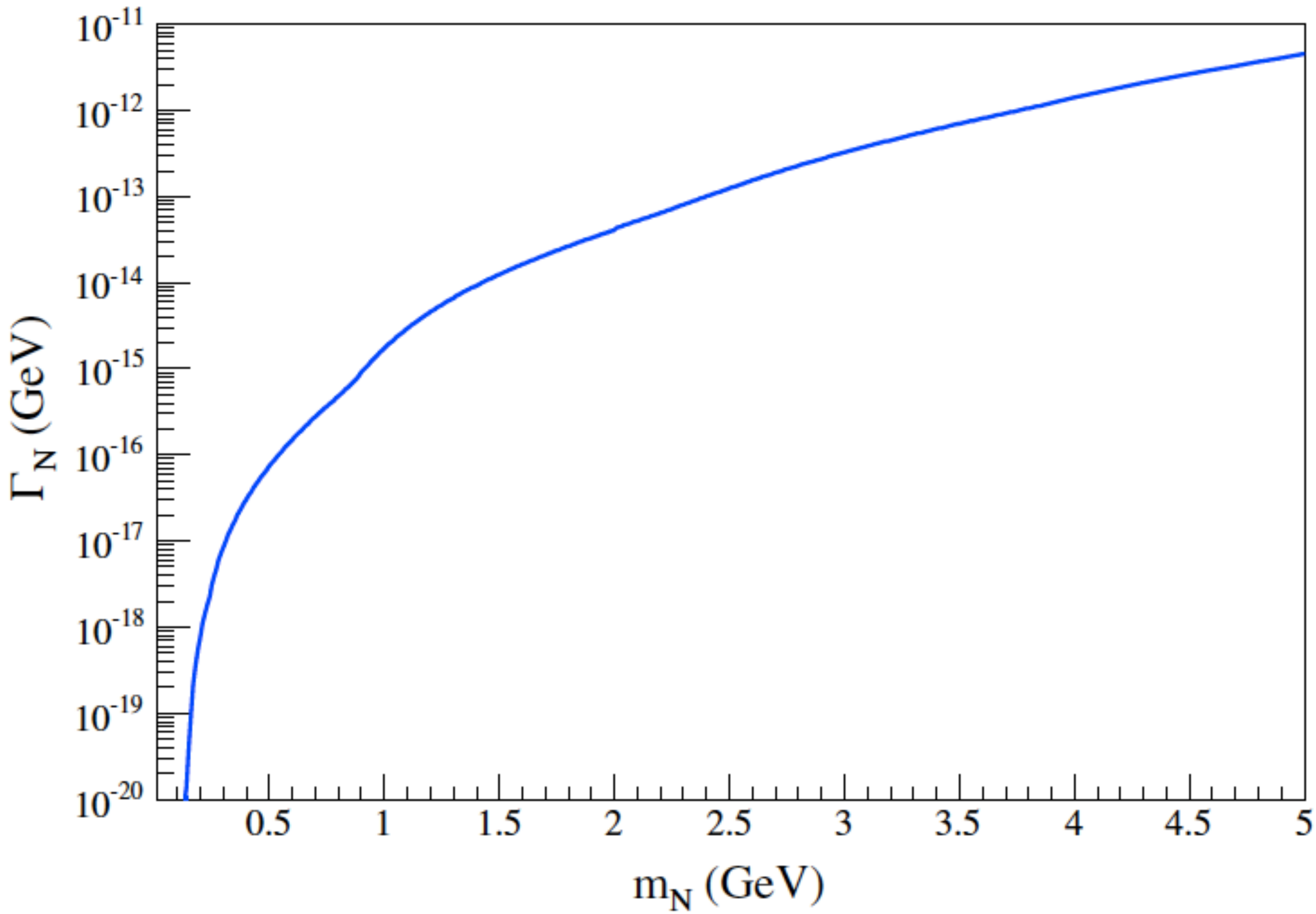
$$N_{\alpha\beta}^{bd\to ac} = \int d^3x[\bar{\psi}_a(x)\gamma_\alpha\psi_b(x)]\cdot[\bar{\psi}_c(x)\gamma_\beta\gamma_5\psi_d(x)],$$

$$P_{\alpha\beta}^{bd\to ac} = \int d^3x[\bar{\psi}_a(x)\gamma_\alpha\gamma_5\psi_b(x)]\cdot[\bar{\psi}_c(x)\gamma_\beta\psi_d(x)],$$

$$Q_{\alpha\beta}^{bd\to ac} = \int d^3x[\bar{\psi}_a(x)\gamma_\alpha\gamma_5\psi_b(x)]\cdot[\bar{\psi}_c(x)\gamma_\beta\gamma_5\psi_d(x)].$$

A. Atre et al, JHEP (2009)

$$N \to l^{\pm}P^{\mp}, \nu P^0, l^{\pm}V^{\mp}, \nu V^0,$$
$$l_1^{\pm}l_2^{\mp}\nu_{l2}, \nu_{l1}l_2^{+}l_2^{-}, \nu_{l1}\nu\bar{\nu}$$



Neutrino mass matrix and mixings

Leptonic mass terms in SM + n right-handed singlets after SSB:

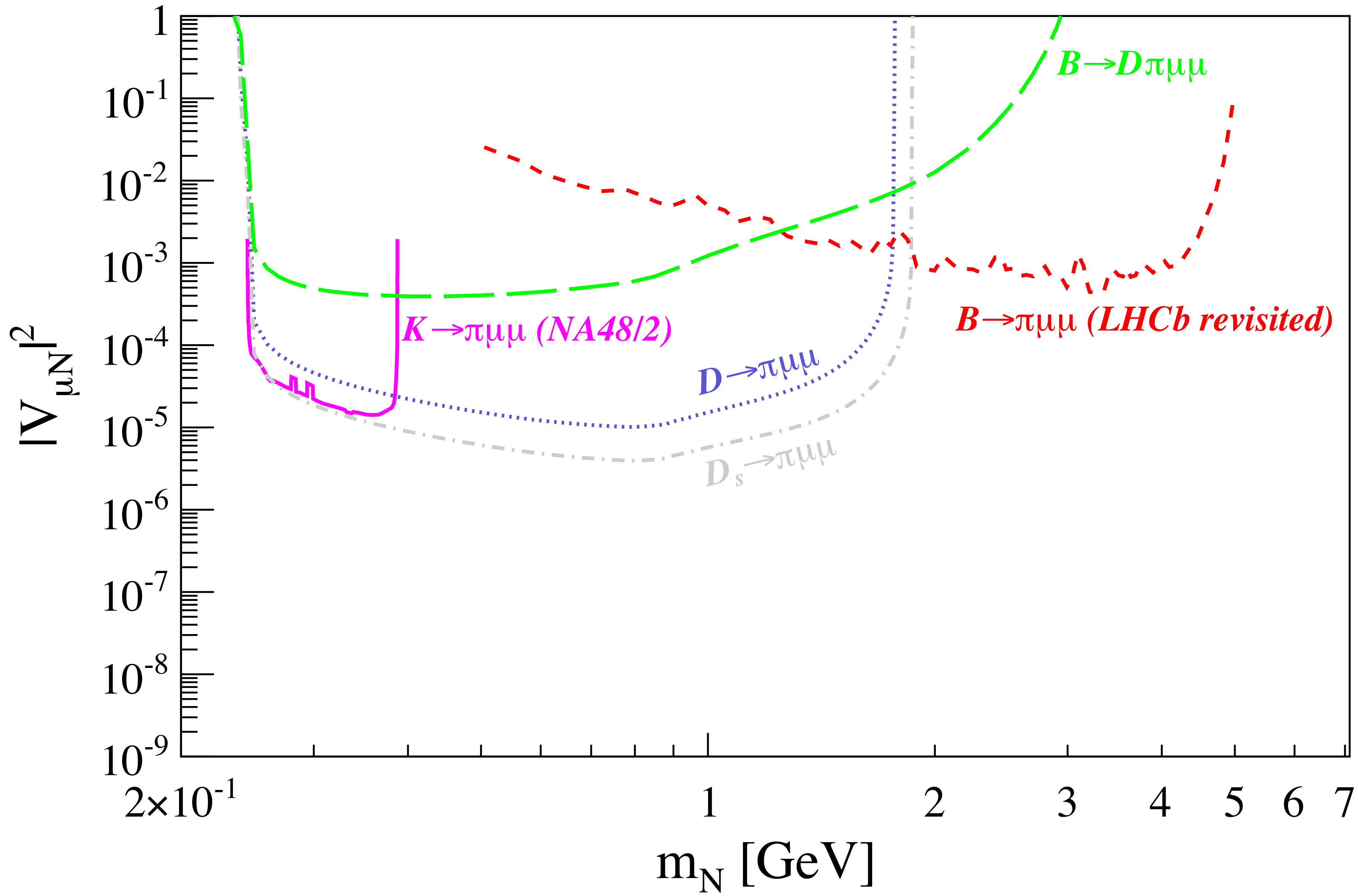
$$-L = \overline{\nu_L} m_D N_R + \frac{1}{2}\left(\overline{N_R^c} M_R N_R + \overline{\nu_L} M_L \nu_L^c\right) + h.c.$$

$$M = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}$$ Diagonalized by $$T = \begin{pmatrix} U_{3\times 3} & V_{3\times n} \\ X_{n\times 3} & Y_{n\times n} \end{pmatrix}, \quad TT^+ = 1$$

$$\begin{pmatrix} \nu_{iL}^{ph} \\ N_{iR}^{ph} \end{pmatrix} = \begin{pmatrix} U_{ij}\nu_{jL} + V_{ik} N_{kR}^c \\ X_{ij}\nu_{jL}^c + Y_{ik} N_{kR} \end{pmatrix}, \quad V \approx X \approx M_D M_N^{-1}, \quad U^+ M_R + Y^+ M_D = 0$$

$$L_{cc} = -\frac{g}{\sqrt{2}} W_\mu^+ \sum_{l=e}^{\tau}\left(\sum_{m=1}^{3} U_{lm}^* \overline{\nu_m}\gamma^\mu P_L l + \sum_{m'=4}^{3+n} V_{lm'}^* \overline{N_{m'}^c}\gamma^\mu P_L l \right) + h.c.$$

Sensitiviy reduced if N decays outside detector



N. Quintero, private