Probing Lepton Number Violation in (e-,e+) Reactions on Nuclei

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NUMEN

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Institut für Theoretische Physik

Motivation and Goals

- **Research on Nuclear Isotensor Modes within the NUMEN*@LNS Catania Project**

- **Rank-2 Isotensor Response by Heavy Ion Double Charge Exchange (DCE) Reactions:**
  Hard Collisonal Hadronic DCE Processes

- **New Approaches to Lepton Number Violation**
  Weak Lepton Double Charge Exchange (LDCE) Reactions on Accelerators

Probing Nuclear Isotensor Response in
Strong and Weak Interactions
as Tools for LNV Research

*__NU__clear __M__atrix __E__lements for __N__eutrinoless Double Beta Decay,
see Eur. Phys. J. A 62:151 (2026)

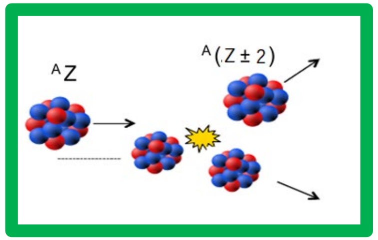
Topics

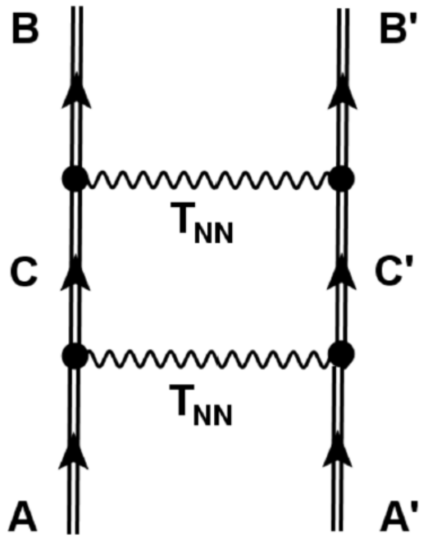
- NUMEN Activities on Isotensor Modes by Heavy Ion Double Single Charge Exchange (DSCE) and Majorana Double Charge Exchange (MDCE) Reactions

- New Paths towards Direct Studies of Lepton Number Violation (LNV) with Lepton Beams

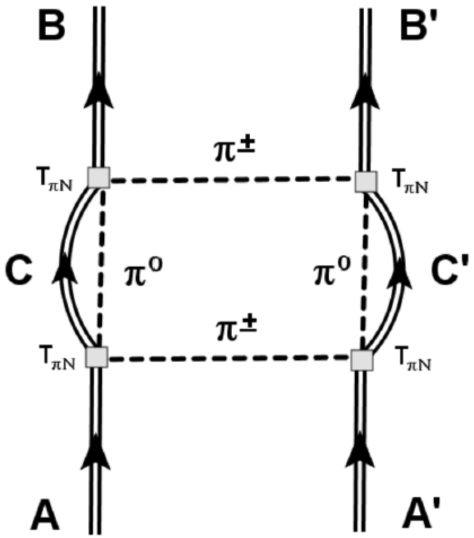
  → A(e-,e+)X Inclusive Lepton Double Charge Exchange (LDCE) Reactions at Accelerator Facilities: Jlab, EIC…

Probing Isotensor Nuclear Spectroscopy in Heavy Ion DCE Reactions



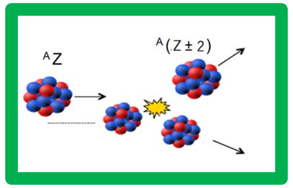


Double Single Charge Exchange
(DSCE)

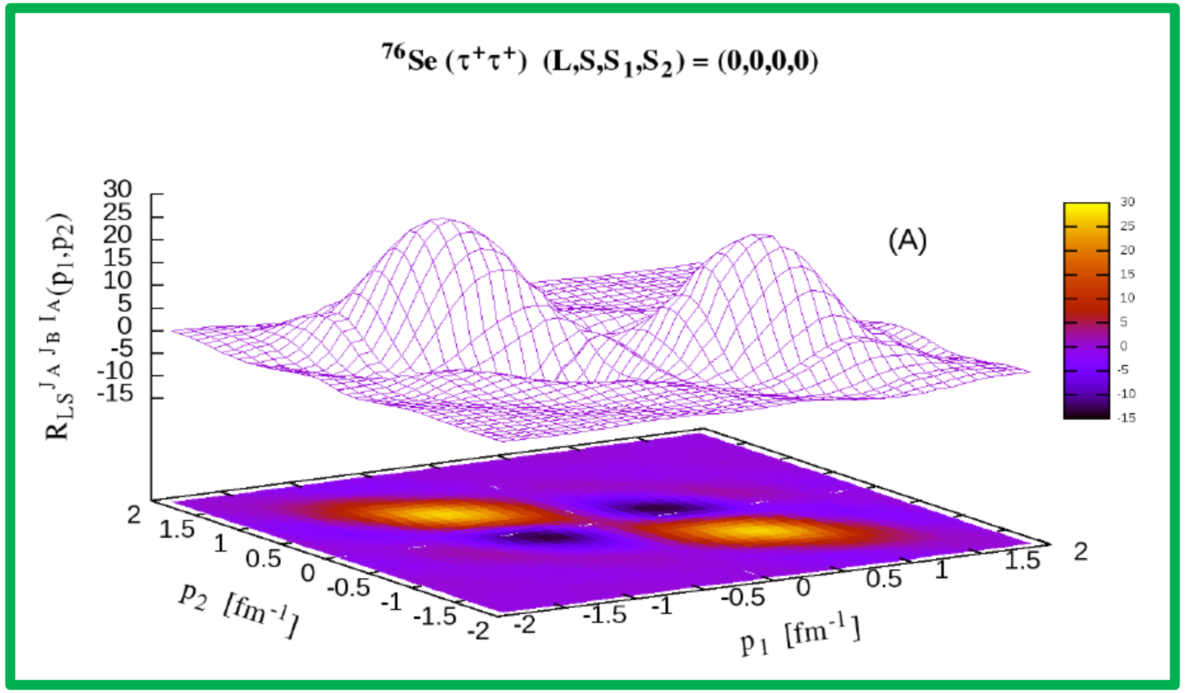


Majorana Double Charge Exchange
(MDCE)

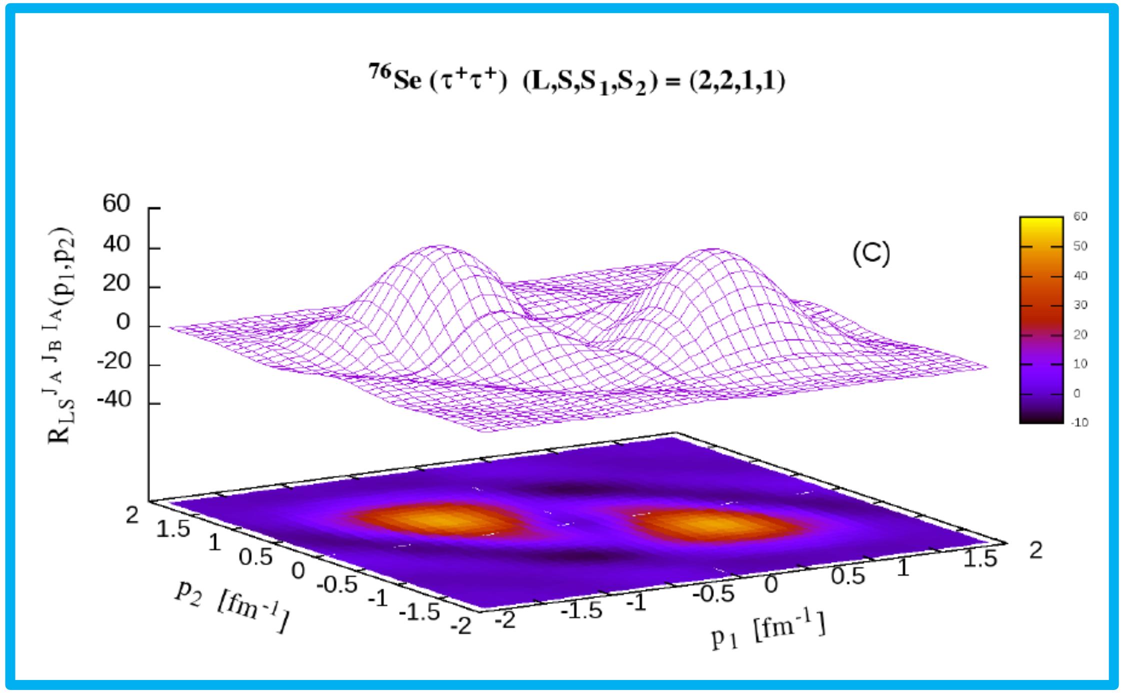
DSCE Study of Isotensor Two-Body Transition Densities (TBTD)
$^{76}\mathrm{Se}_{g.s.} \rightarrow {}^{76}\mathrm{Ge}_{g.s.}$



$$R^{AB}_{LS(S_1S_2)}(\vec{p}_1,\vec{p}_2) \simeq \int d^3r_1 \int d^3r_2\, e^{i(\vec{p}_1\cdot\vec{r}_1+\vec{p}_2\cdot\vec{r}_2)} \rho_{L_2S_2}(\vec{r}_2)\rho_{L_1S_1}(\vec{r}_1)\langle B|\left[A^{\dagger}_{L_2S_2}\otimes A^{\dagger}_{L_1S_1}\right]_{LS}|A\rangle$$



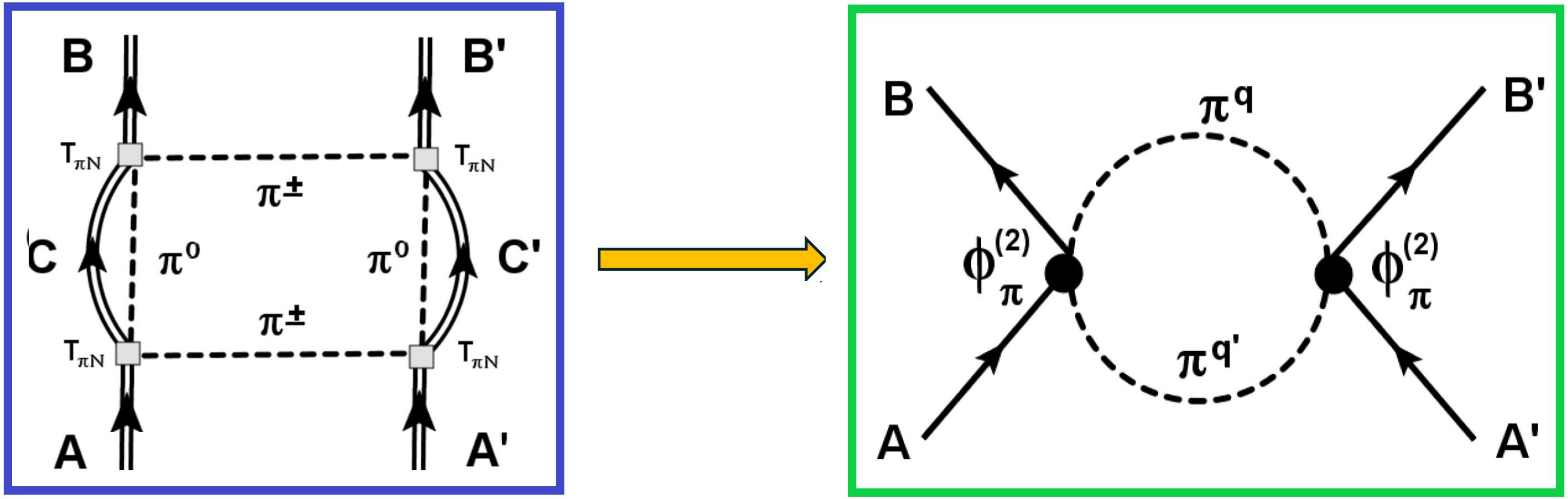
Double Fermi TBTD
(L=S=0 , S_1=S_2=0)



Double Gamow-Teller TBTD
(L=S=2 , S_1=S_2=1)

PHYSICAL REVIEW C 111, L061602 (2025), J. Bellone, H.L. et al.

Exploring New Territory:
MDCE 4-Point 3-Loop Box Diagram → Two-point 1-Loop Isotensor Pion Potential

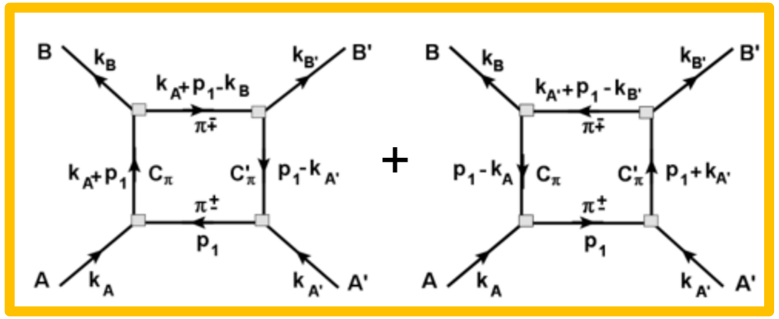


Two MDCE Scenarios:
Scattering (MSS) and Decay (MDS) Scenarios

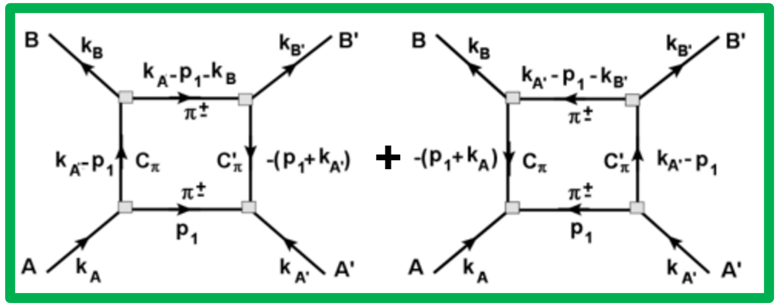
C. Garofalo, H.L., in preparation

MDCE Modes and Box Diagram

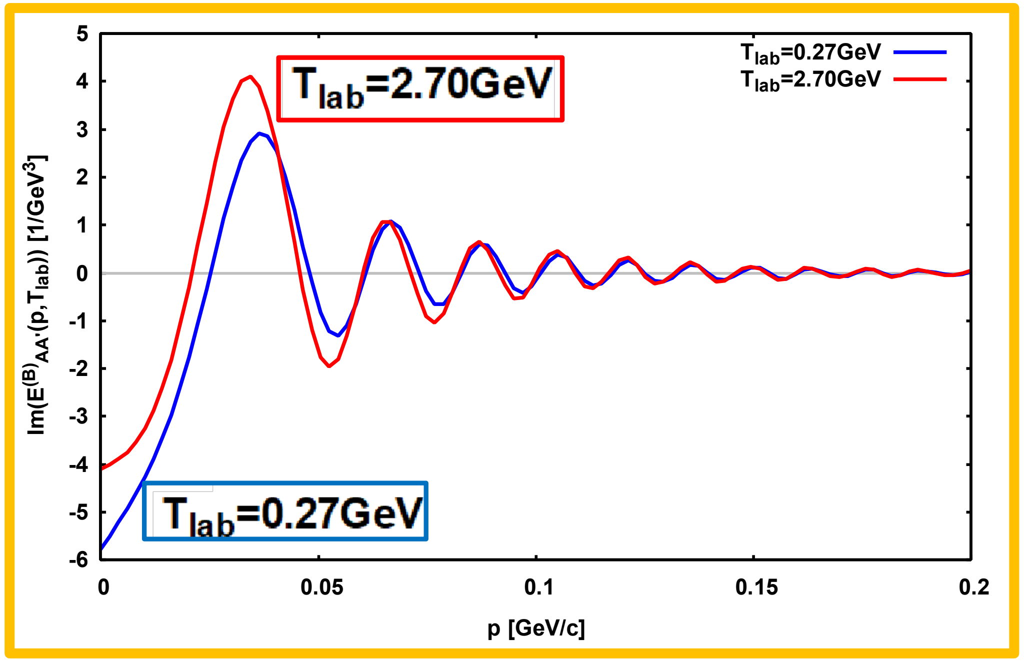
$^{76}Se(^{18}O,^{18}Ne)^{76}Ge$

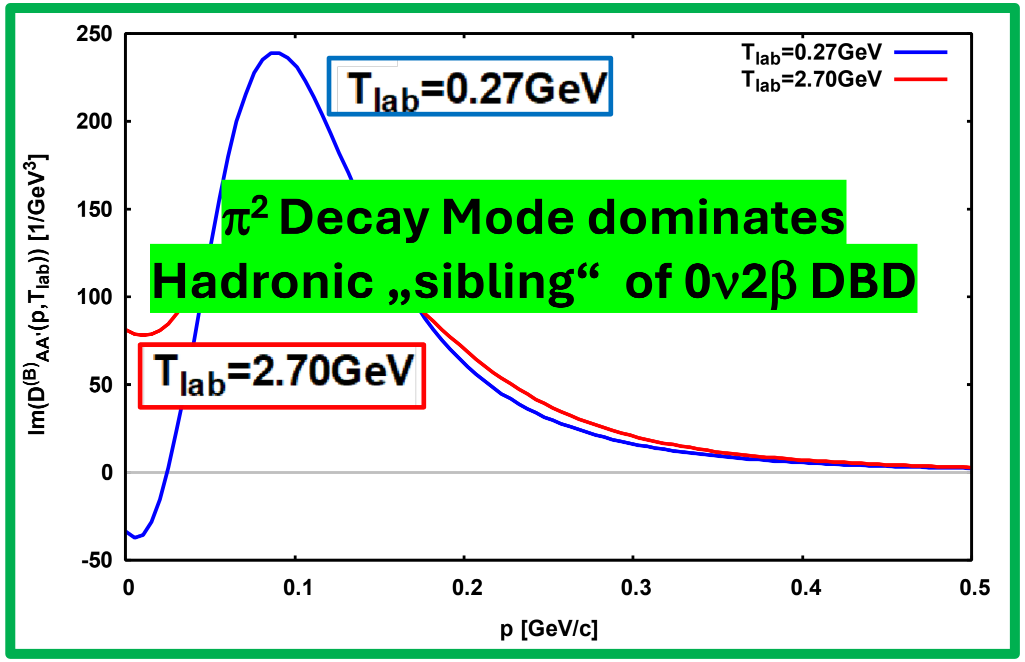


$[\pi^+\pi^-]$-Scattering Mode (MSS)



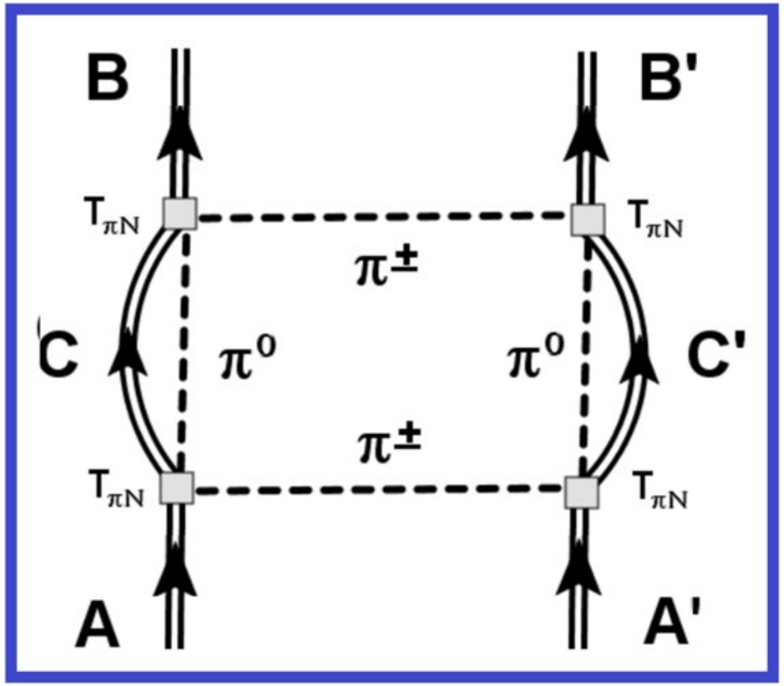
$[\pi^\pm\pi^\pm]$ - Decay Mode (MDS)

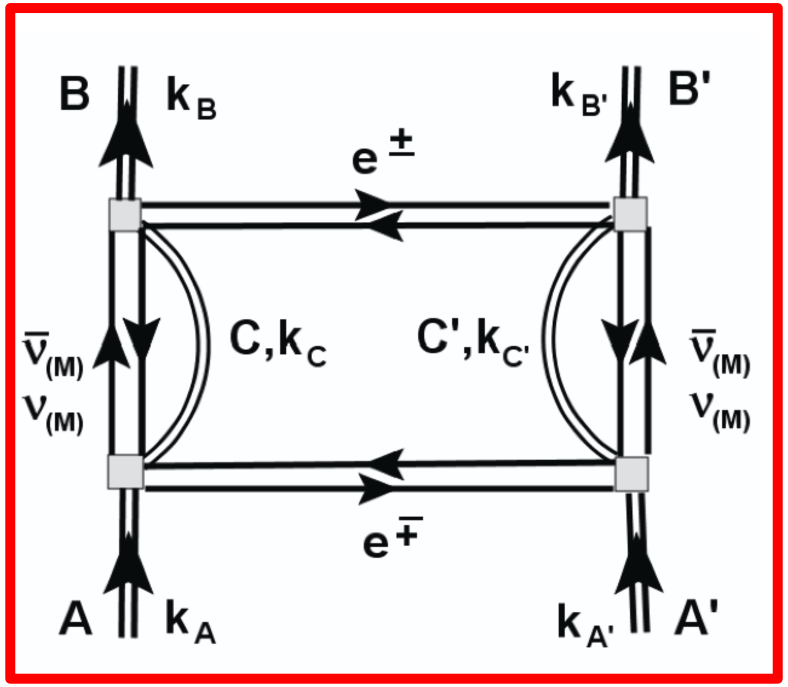




...with Caterina Garofalo

...from Hadronic MDCE Reactions to „*Lepton MDCE*“ aka LDCE Reactions:





..taken from ***Theory of Majorana-Type Heavy Ion Double Charge Exchange Reactions by Pion–Nucleon Isotensor Interactions,***
H.L. et al., Universe Universe 10 (2024) 5, 202

Search for New Physics

Beyond the Standard Model

(BSM)

“The discovery of nonzero neutrino masses is among the most important particle physics results of the last two decades: It indicates that the Standard Model of particle physics is incomplete. After 20 years of intense experimental and theoretical research, we still do not know the physics that leads to nonzero neutrino masses.”

(André de Gueva, Annu. Rev. Nucl. Part. Sci. 2016. 66:197)

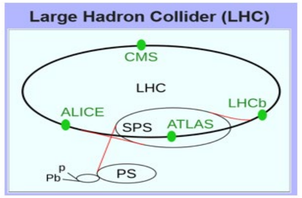
Search for Alternative LNV Probes

...beside

Double Beta Decay@MeV and **$\ell^{\pm 2}j^2$ Production@TeV**

GERDA & CUORE

Gap of $10^{6...9}$ (!) eV



ATLAS & CMS

Motivations and Aims

Bridging the Gap between LNV@MeV and LNV@TeV
by using
***Non-Exotic* Methods for eploring *Exotic* BSM Physics**

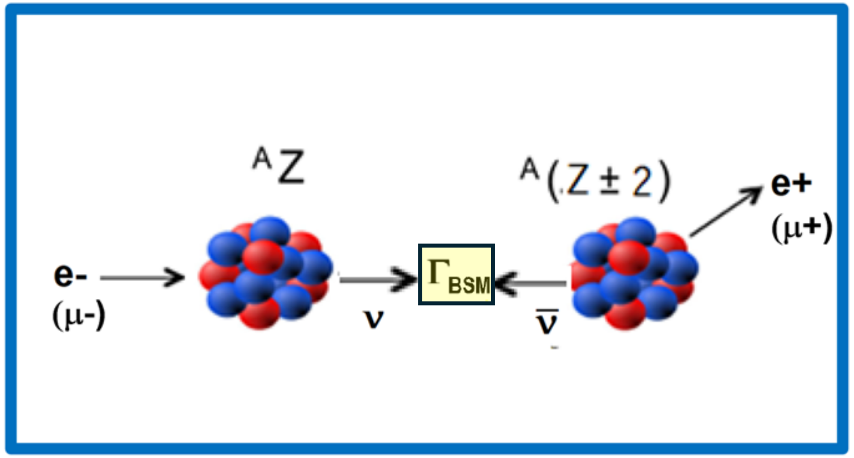
- **Lepton DCE Reactions : New independent probe for Lepton Number Violation**
  → A(e-,e+)B reactions on accelerator facilities

Disclaimer:
LDCE reactions are not for measuring or investigating nuclear DBD matrix elements!

Exploring new LNV territory with…

Nuclear LDCE Reaction Studies on Accelerator Facilities

Lepton Beams:



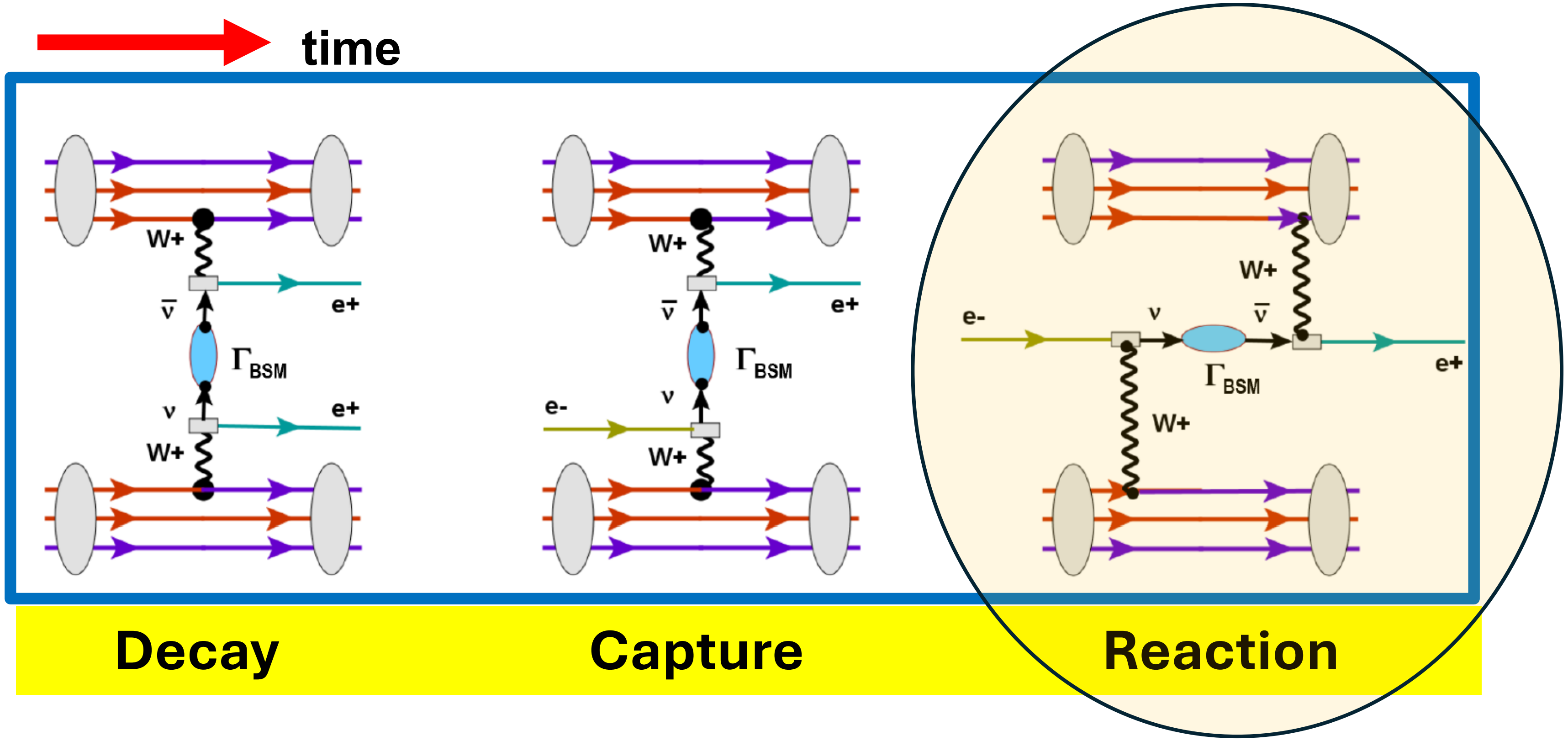
- Lepton number violation: $|\Delta L| = 2$

No Nuclear Structure Constraints!

- LNV under laboratory conditions

New access to LNV in nuclear systems @ GeV to TeV

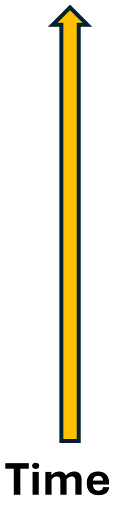
Lepton DCE Processes on Nuclei

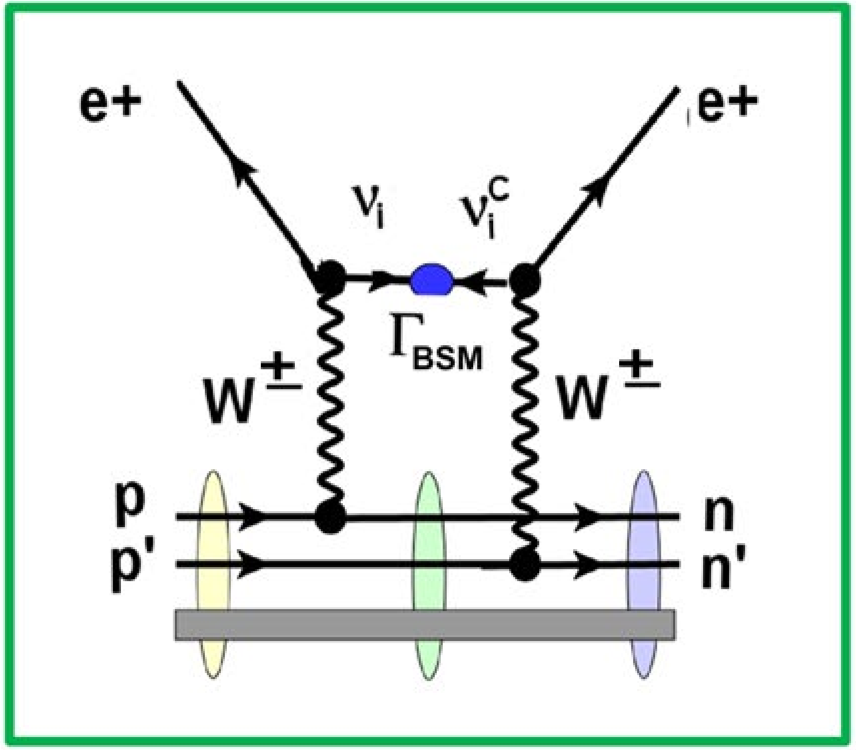


New LNV Probe

- H.L., F. Cappuzzello, A. Spatafora, 2603.21997 [nucl-th]
- H.L., 2603.21903 [nucl-th]

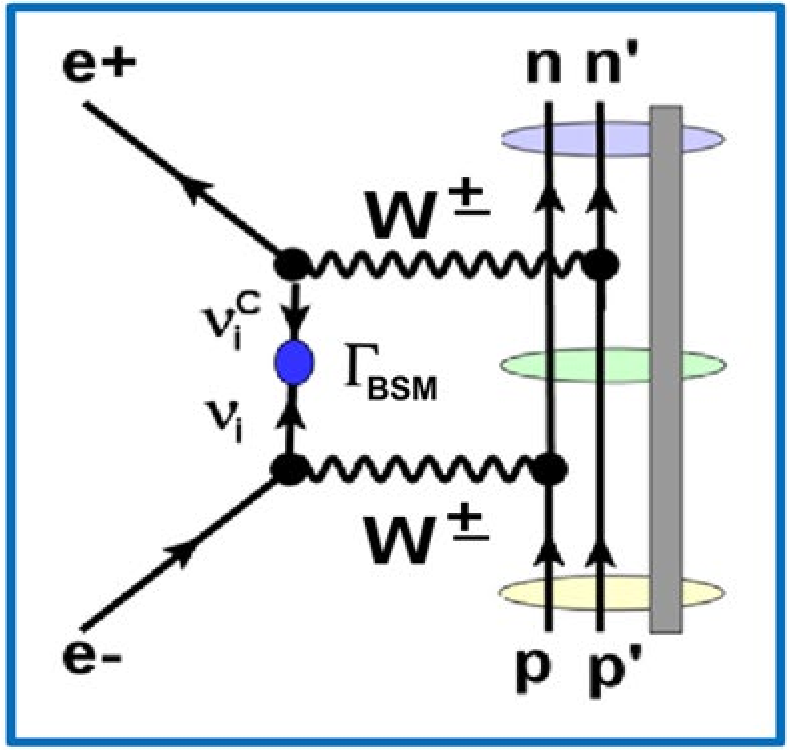
LNV (Re-)Search with Lepton Double Charge Exchange Reactions





Nuclear $0\nu2\beta^+$ Decay
A(Z,N) → B(Z-2,N+2)
Few cases, pre-defined, fixed energies
t-channel LNV
E ~ MeV

t-channel
s-channel



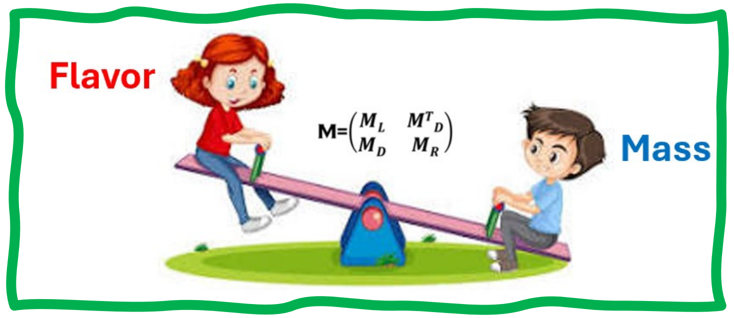
Nuclear (e-,e+) LDCE reaction
A(Z,N) → B(Z-2)
any target/energy, lab. experiment
s-channel LNV
E ~ MeV...GeV...

Neutral Leptons and Mass Eigenstates

Light Neutrino Mass Puzzle

Lepton Number Violation in nuclear $0\nu2\beta$ –decay@MeV and $l^{\pm}l^{\pm}$ jj-events@TeV:

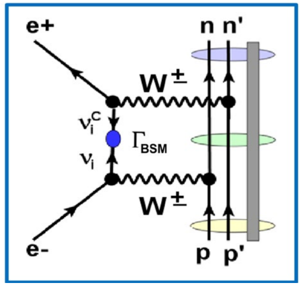
there must be a hidden sector of $N_M \geq 3$ massive Majorana Fermions $n_i = n^c_i$



Flavor ↔ Mass Eigenstates: Change of Basis by Pontecorvo–Maki–Nakagawa–Sakata (PMNS) Trafo

$$|\nu_{eh}\rangle = \sum_{i=1}^{N_M} U^{(h)}_{ei} |n_{ih}\rangle \quad ; \quad |\bar{\nu}_{eh}\rangle = \sum_{i=1}^{N_M} V^{(h)}_{ei} |n_{ih}\rangle$$

2nd Order LDCE-RME and Left-Right Symmetric Model (LRSM)



$$\mathcal{L}_{CC} = \widetilde{G}_F\left(j_{\mu L}\left(J^\mu_L + \kappa J^\mu_R\right) + j_{\mu R}\left(\lambda J^\mu_R + \eta J^\mu_L\right)\right)$$

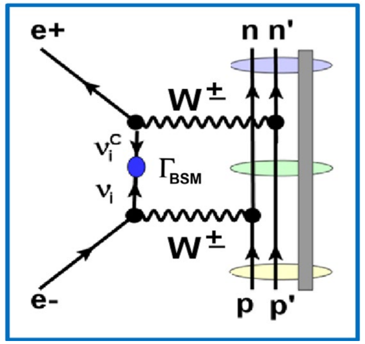
The LDCE Reaction Amplitude

$$\mathcal{M}^{(e^- e^+)}_{AX_f} = \langle e^+ X_f \left| \mathcal{L}_{CC}\mathcal{G}\mathcal{L}_{CC} \right|_{\ell} A e^- \rangle = \sum_{h_1,h_2} \underbrace{\Gamma_{h_1 h_2}}_{\text{„BSM“}} \underbrace{\mathcal{M}^{(e^- h_1, e^+ h_2)}_{AX_f}}_{\text{2nd Order PT}}.$$

…up to terms linear in LR-Mixing:

$$\mathbf{M}^{(e-,e+)}_{AX_f} \approx \mathbf{M}^{(e-e+)}_{\ell L,\ell L} + \kappa\left(\mathbf{M}^{(e-e+)}_{\ell L,\ell R} + \mathbf{M}^{(e-e+)}_{\ell R,\ell L}\right) + \lambda\left(\mathbf{M}^{(e-e+)}_{\ell L,rR} + \mathbf{M}^{(e-e+)}_{rR,\ell L}\right) + \eta\left(\mathbf{M}^{(e-e+)}_{\ell L,rL} + \mathbf{M}^{(e-e+)}_{rL,\ell L}\right) + \ldots$$

$\Rightarrow$ $\Gamma_{\ell L,\ell L} = 1$ $\quad\Gamma_{\ell L,\ell R} = \Gamma_{\ell R,\ell L} = \kappa$ $\quad\Gamma_{\ell L,\ell R} = \Gamma_{rR,\ell L} = \lambda$ $\quad\Gamma_{\ell L,\ell R} = \Gamma_{rL,\ell L} = \eta$



LDCE Partial L/R Reaction Amplitudes

$$\mathcal{M}^{(e^- h_1, e^+ h_2)}_{AX_f} = \sum_C \underbrace{\boxed{\langle e^+ X_f | \mathcal{L}^{(h_2)}_{CC} | C\bar{\nu}_e h_2}}\rangle \mathfrak{G}^{(C)}_{\bar{\nu}_e \nu_e} \underbrace{\boxed{\langle \nu_e h_1 C | \mathcal{L}^{(h_1)}_{CC} | A e^- \rangle}}$$

$$\boxed{M^{(\bar{\nu} e^+, h)}_{CX_f} = \langle e^+ X_f | \mathcal{L}^{(h)}_{CC} | C\bar{\nu}_e h \rangle}$$

$$\boxed{M^{(e^- \nu_e, h)}_{AC} = \langle \nu_e h C | \mathcal{L}^{(h)}_{CC} | A e^- \rangle}$$

$$\boxed{\mathfrak{G}(P_\alpha) = [S_F \otimes G_C]|_{P_\alpha}}$$

LDCE Reaction Amplitude

$$\mathcal{M}^{(e^- h_1, e^+ h_2)}_{AX_f}(\mathbf{k}_\alpha, \mathbf{k}_\beta) = \sum_C \int \frac{d^3k}{(2\pi)^3} \frac{M_{H_C}}{2E_C(\mathbf{k})} \mathcal{M}^{(\bar{\nu}_e e^+, h_2)}_{CX_f}(\mathbf{k}_\beta, \mathbf{k})$$

$$\times \left((1 - \delta_{h_1 h_2}) \boxed{\gamma^\mu \widetilde{K}^{(h_1,h_2)}_{H_C,\mu}(\mathbf{k})} + \delta_{h_1 h_2} \boxed{\widetilde{m}^{(h_1)}_{H_C}(\mathbf{k})} \right) \mathcal{M}^{(e^- \nu_e, h_1)}_{AC}(\mathbf{k}, \mathbf{k}_\alpha).$$

$$\widetilde{K}^{(h_1,h_2)}_{H_C,\mu}(\mathbf{k}) = \sum_{i=1}^{N_M} V^{(h_2)}_{\bar{\nu}_e i} \widehat{D}_{iH_C}(\mathbf{k}) k^\mu_i U^{(h_1)\dagger}_{\nu_e i}.$$

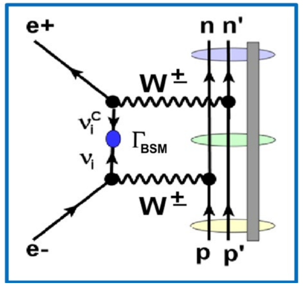
4-Vector term: grows with beam energy
LR/RL-Mixing

$$\widetilde{m}^{(h)}_{H_C}(\mathbf{k}) = \sum_{i=1}^{N_M} V^{(h)}_{\bar{\nu}_e i} m_i D^{(S)}_{iH_C}(\mathbf{k}) U^{(h)\dagger}_{\nu_e i}.$$

Mass term: inert on beam energy
LL/RR-Diagonal

$$\widehat{D}_{iH_C} = diag(D^{(T)}_{iH_C}, D^{(S)}_{iH_C}, D^{(S)}_{iH_C}, D^{(S)}_{iH_C})$$

LDCE Amplitude and Cross Section



$$\boxed{\mathcal{M}^{(e^-e^+)}_{AX_f} = \langle e^+ X_f | \mathcal{L}_{CC} \mathcal{G} \mathcal{L}_{CC} | A e^- \rangle}$$

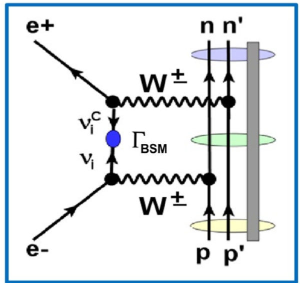
$$\mathcal{M}^{(e^-e^+)}_{AX_f} = \langle e+|\ \underbrace{\gamma_\mu \mathcal{V}^\mu_{AX_f}} + \underbrace{\mathcal{S}_{AX_f}}\ |e-\rangle$$

LR/RL Non-Diagonal – LR Mixíng
LRSM Parameters κ,λ,η

LL/RR Diagonal - No LR Mixing
Majorana Masses m_i

$\sim \mathcal{O}(\Gamma_{BSM} E_{e-}) \sim 10^{-7} E_{e-}$ **$\sim \mathcal{O}(m_\nu) \sim 10^{-7} m_e$**

Augmenting BSM Physics in LDCE Reactions:



$$\mathcal{M}^{(e^-e^+)}_{AX_f} \sim \boxed{\Gamma_{BSM}} E_e \langle e+|\, \gamma_\mu \overline{\mathcal{V}}^{\mu}_{AX_f} + \boxed{\frac{m_{ee}}{\Gamma_{BSM} E_e}} \overline{\mathcal{S}}_{AX_f}\, |e-\rangle$$

$$\left(\Gamma_{BSM} \approx 10^{-7}\right)$$

$$\left(\frac{m_{ee}}{\Gamma_{BSM} E_e} \approx \frac{m_e}{E_e}\right)$$

Complementarity of DBD and LDCE Physics!

Total Unpolarized, Spin-Averaged LDCE Cross Sections

$$|\overline{\mathcal{M}}^{(e^-e^+)}_{AX_f}|^2 = |\mathcal{V}^{(e^-e^+)}_{AX_f}|^2 + |\mathcal{S}^{(e^-e^+)}_{AX_f}|^2$$

Total Inclusive Cross section

$$\sigma_A^{(e-e+)} = \sum_{h_1h_2} \left|\Gamma_{h_1h_2}\right|^2 \left(\sigma_A^{(h_1\ h_2)}(V) + \frac{1}{\left|\Gamma_{h_1h_2}\right|^2} \sigma_A^{(h_1\ h_2)}(S) \right) \approx \sum_{h_1h_2} \left|\Gamma_{h_1h_2}\right|^2 \sigma_A^{(h_1\ h_2)}(V) + O\left(\frac{\left|m_{ee}\right|^2}{E^2} \right)$$

$$\sigma_A^{(e^-e^+)}(w_\alpha) = \int d\mathcal{N}_{X_f} \Pi_{AX_f}(k_\alpha, k_\beta) \int d\hat{\mathbf{k}}_\beta |\overline{\mathcal{M}}^{(e^-e^+)}_{AX_f}(\mathbf{k}_\alpha, \mathbf{k}_\beta)|^2$$

Estimating LDCE Reaction Yields

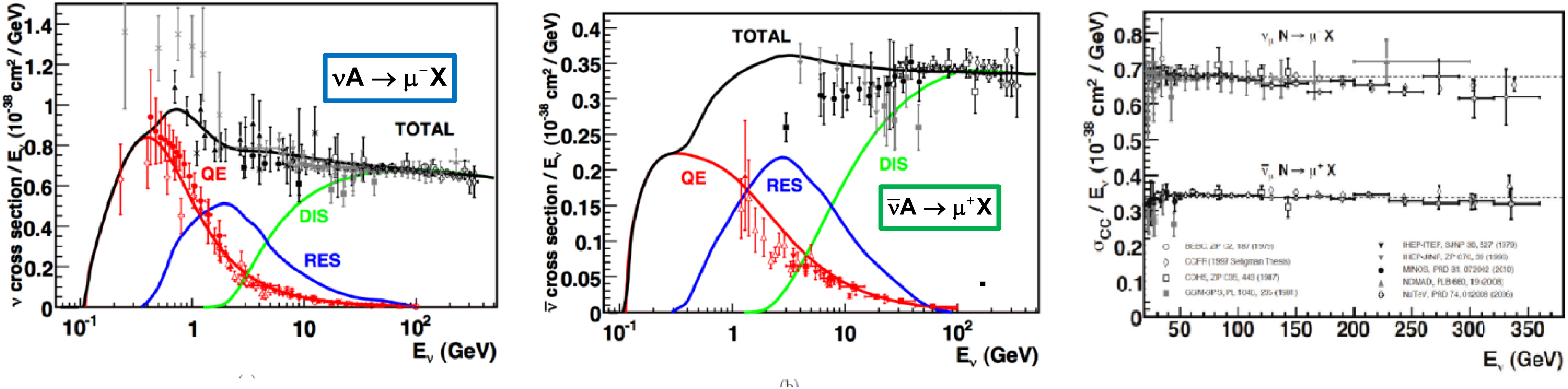
What do we know about LDCE Reactions?

...nothing!

...but $A(\nu_\ell,\ell)C$ Single Charged Current (CC) nuclear reaction data are available!

World Data Set on (ν,μ) Charged Current (CC) Data

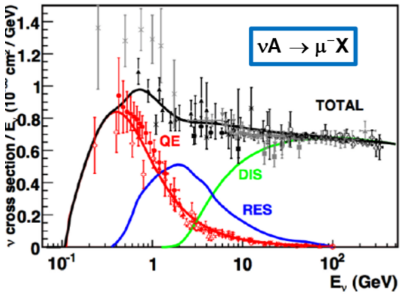
3-Component Structure



Total Cross Sections per Mass Number and per Energy

J. A. Formaggio and G. P. Zeller. *Rev. Mod. Phys.*, 84:1307–1341, 2012.

Phenomenological Modeling of CC-RME



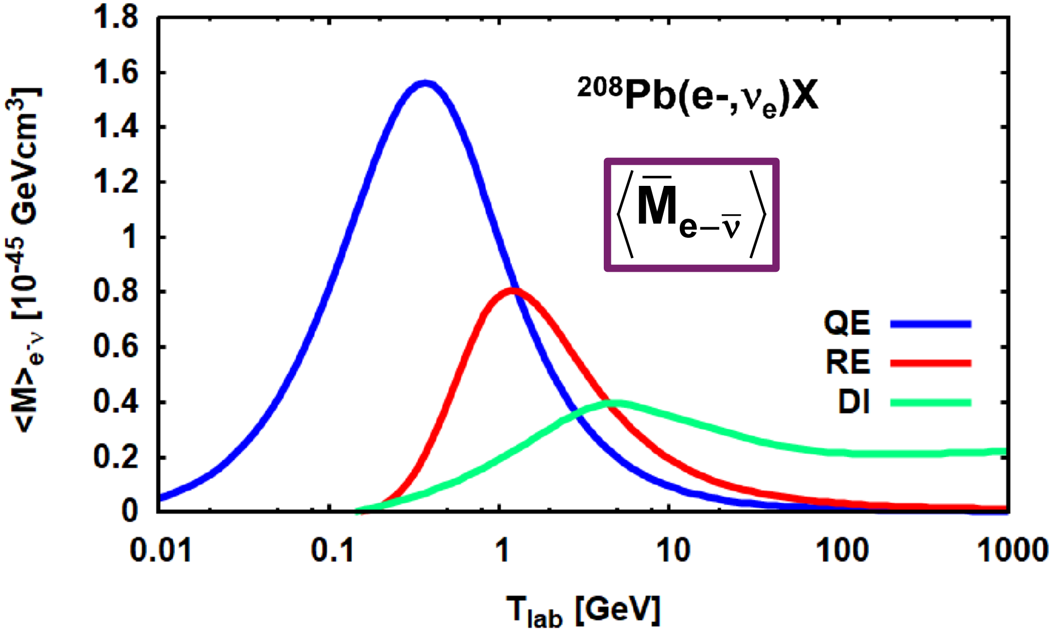
...from QE,RE,DI *data* :

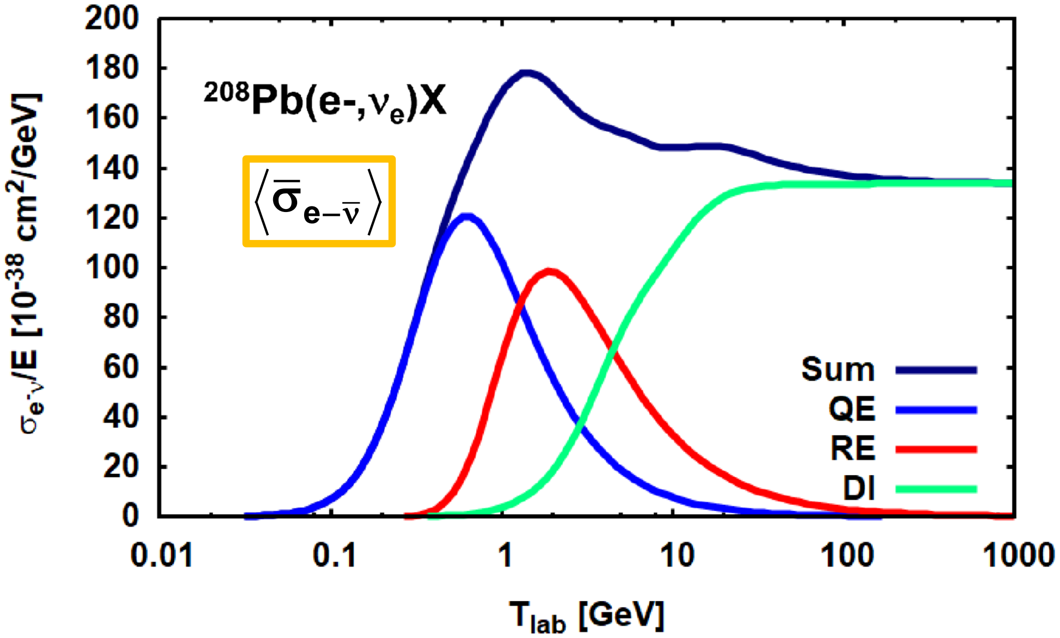
$$\boxed{\overline{M}^{\,2}_{\nu_\ell \ell}(w_\alpha)\Big|_{QE,RE,DI} = \frac{\sigma^{\nu_\ell \ell}_{\alpha\gamma}(w_\alpha)\Big|_{QE,RE,DI}}{4\pi\Pi_{\alpha\gamma}}}$$

...by exploiting lepton universality:

(e-,ν_e) mean Matrix Elements

(e-,ν_e) total Cross Sections





Estimation of LDCE Total Inclusive Cross Sections

- Phenomenological nean CC amplitudes for in- and out-channels
- off-shell form factors
- Account for 2-body effects and „N*“ mechanism
- Numerical integration over the propagators and intermediate QE,RE,DI spectra
- Use reduced unit (Γ_{BSM}=1) total inclusive vector cross section as one-for-all representative:

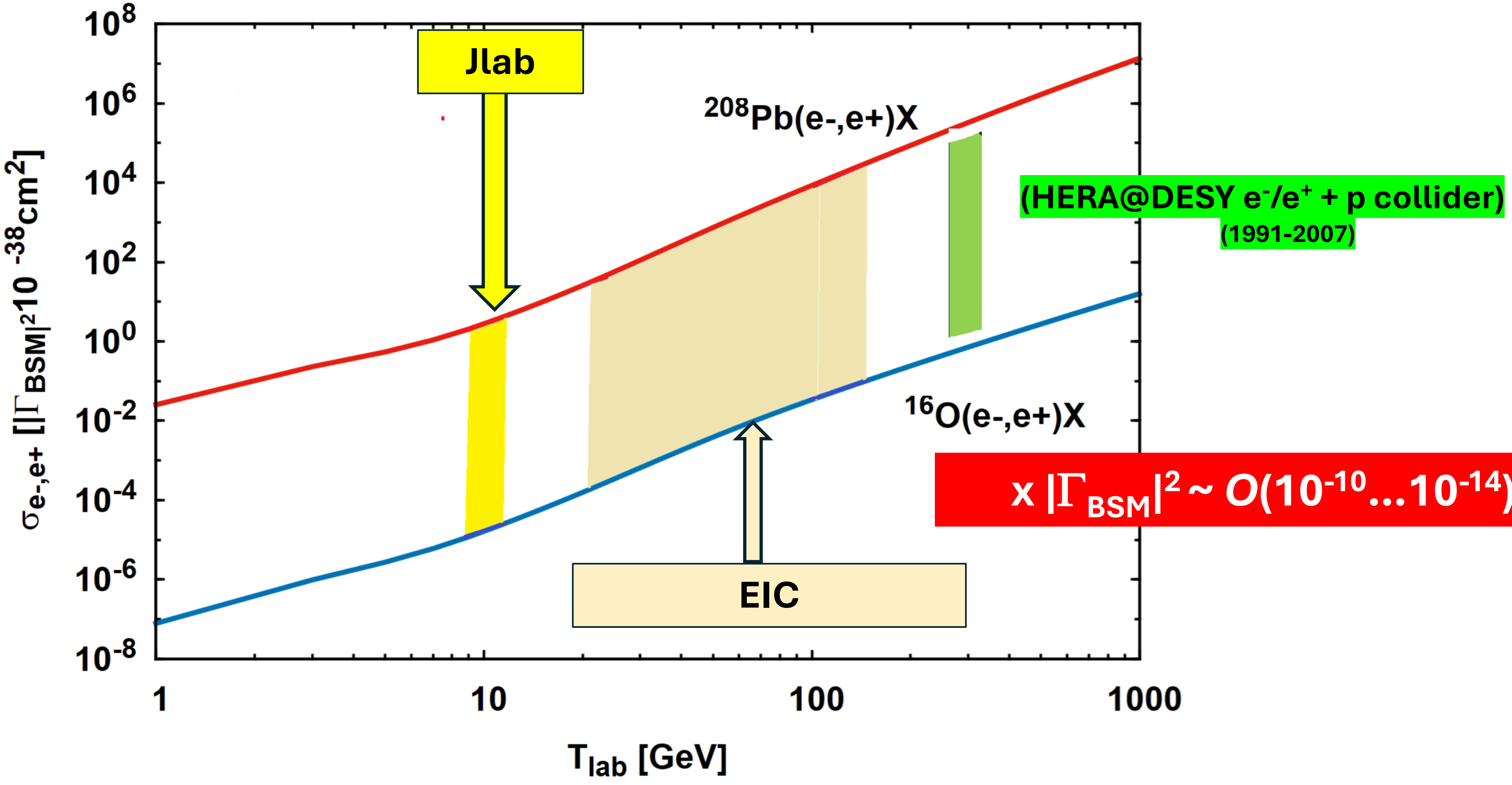
$$\boxed{\bar{\sigma}_A^{(e\text{-}e\text{+})} \sim \left|\langle e\text{+}|\,\gamma_\mu \bar{\mathcal{V}}_A^\mu\,|e\text{-}\rangle\right|^2}$$

→ H.L., F. Cappuzzello, A. Spatafora, 2603.21997 [nucl-th]

Incident Energy Dependence of LDCE Total Cross Sections

$\overline{\sigma}_A^{(e-e+)} \sim |\langle e+| \gamma_\mu \overline{\mathcal{V}}_A^\mu |e-\rangle|^2$

$^{16}O(e-,e+)X \leftrightarrow {}^{208}Pb(e-,e+)X$

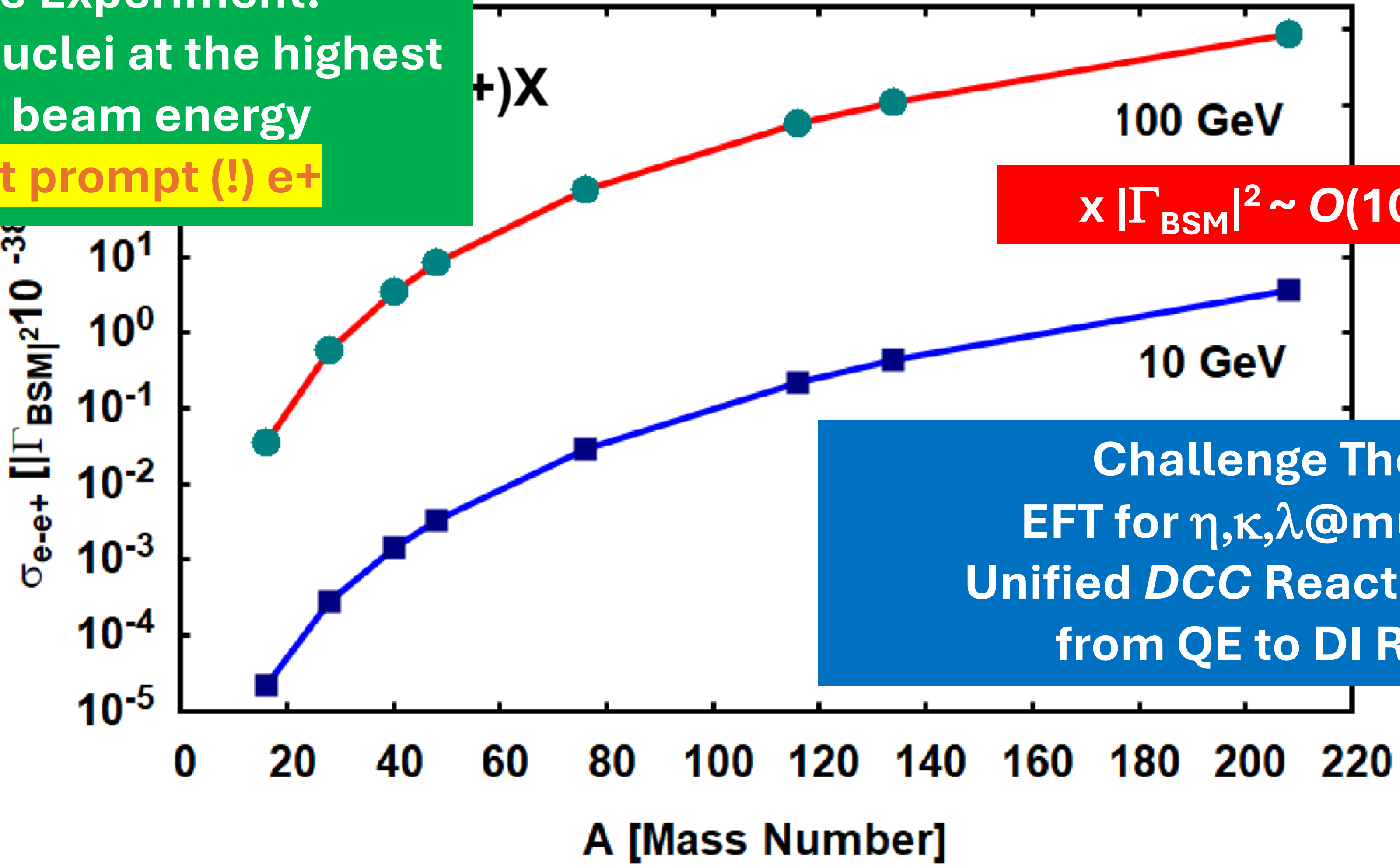


x $|\Gamma_{BSM}|^2 \sim O(10^{-10}...10^{-14})$!

Mass Dependence of LDCE Total Cross Sections

$\overline{\sigma}_A^{(e\text{-}e\text{+})} \sim |\langle e+|\, \gamma_\mu \overline{\mathcal{V}}^\mu_A \,|e-\rangle|^2$

Challenge Experiment:
Heavy target nuclei at the highest possible beam energy
single out prompt (!) e+

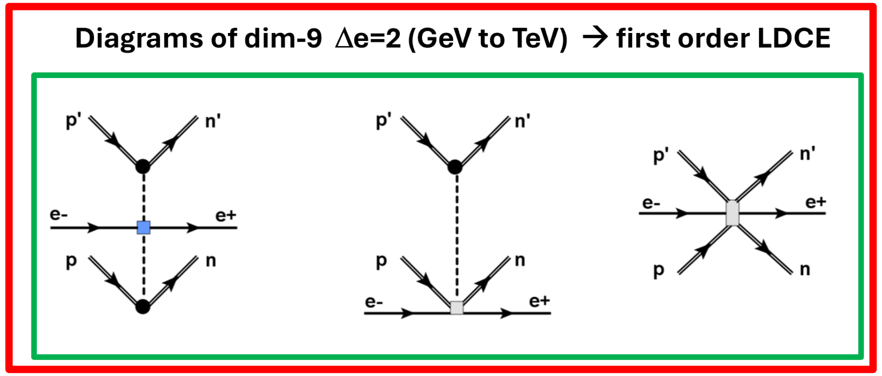


x $|\Gamma_{BSM}|^2 \sim O(10^{-10}\ldots10^{-14})$!

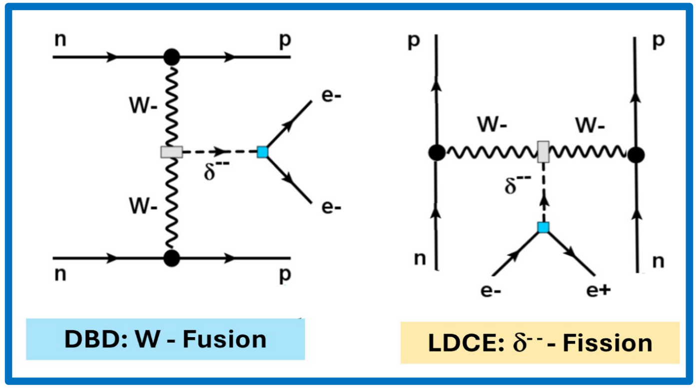
Challenge Theory:
EFT for η,κ,λ@multi-GeV
Unified *DCC* Reaction Theory
from QE to DI Regime

Status and Future

- **Nuclear Isotensor spectroscopy@NUMEN**
  (→ DGT@RIKEN: Sakaue et al., *PTEP* **12**, 123D03 (2024))
- **Lepton DCE reactions at accelerators as a new *Probe for LNV***
- ***Focus on η,κ,λ-terms by energy-momentum enhancement***
  (→ η,κ,λ@0ν-DBD: Ejiri et al., PHYS. REV. C 111, 065501 (2025)!)
- ***Outlook LDCE: Heavy Neutral Leptons, $m_{HNL} >> M_p$***
- ***Perspective LDCE : Higher-dim operators & Higgs sector***



Connection MDCE ↔ LDCE



Isotensor (!!) Higgs Boson

•**H.L., F. Cappuzzello, A. Spatafora, 2603.21997 [nucl-th]**

Supported by DFG, grant Le439/17, and INFN