Università di Catania

INFN LNS

NUMEN

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Lepton Double Charge Exchange Reactions as Probes for Lepton Number Violation

F. Cappuzzello, A. Spatafora and H. Lenske

CLAS Collaboration June/July 2026

29 giu 2026, 08:00 → 2 lug 2026, 20:00 US/Eastern

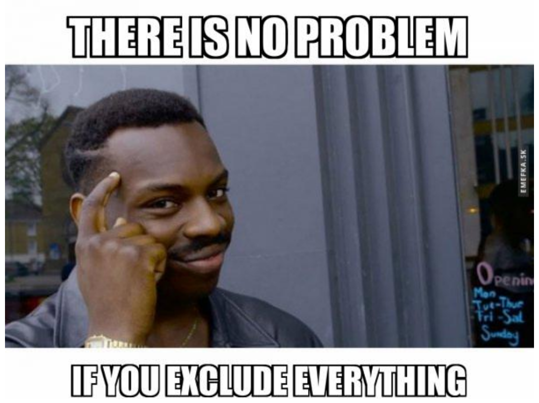
F113 (JLab)

Annalisa D'Angelo (University of Rome Tor Vergata and INFN Roma Tor Vergata), Bryan McKinnon (University of Glasgow), Maria Zurek (Argonne National Laboratory), Nathan Baltzell (Jefferson Lab), Raphaël Dupré (IJCLab, Paris-Saclay U.), Stepan Stepanyan (Jefferson Lab)

Outline

- Context: Lepton Number Violation physics
- Idea: LDCE reactions as LNV probe
- A possible JLAB experiment
- Conclusions

The lepton number violation scenario

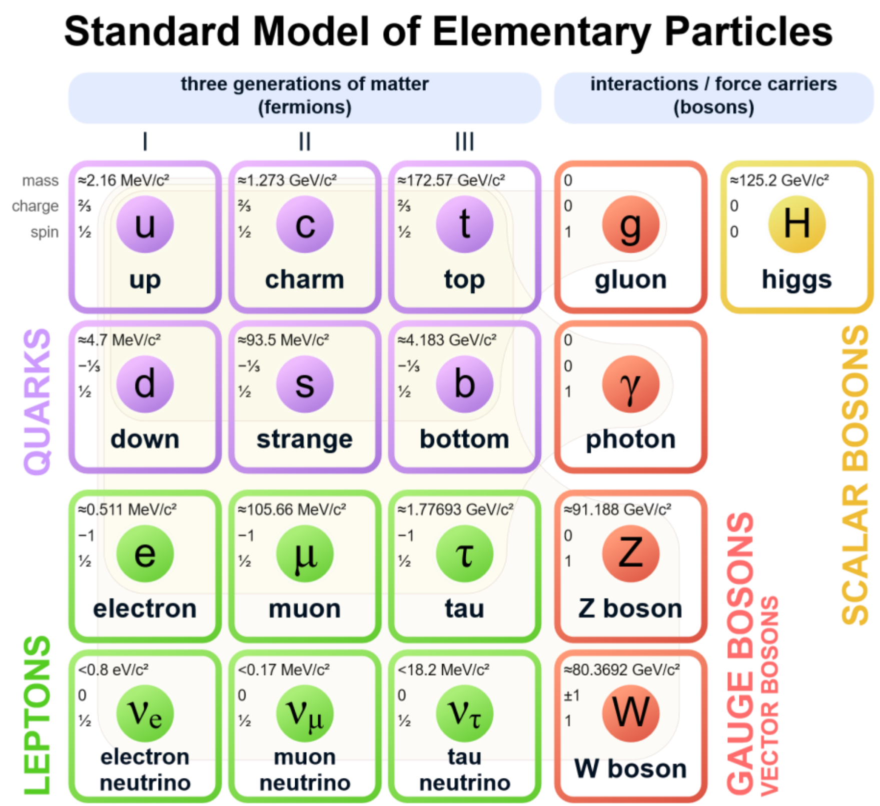


The SM has no problem (for today)!

- Measurements agrees with theory

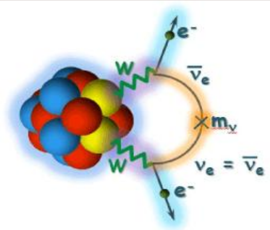
However:

- Hierarchy of scales
- Dark matter
- Neutrinos have masses
- Matter-antimatter asymmetry and baryogenesis



Search for **lepton number violation (LNV)**. Its observation would have profound impact in our understanding of the cosmos, since the same interactions can lead to **baryon-antibaryon asymmetry** of the universe via **leptogenesis**. (M. Fukugita and T. Yanagida, Physics Letters B 174, 45(1986))

The LNV at MeV scale mainly via 0νββ decay



Neutrinoless double beta decay**

$$ {}^{A}_{Z}X_{N} \rightarrow {}^{\;\;\;A}_{Z+2}Y_{N-2} + 2e^{-} $$
$$ {}^{A}_{Z}X_{N} \rightarrow {}^{\;\;\;A}_{Z-2}Y_{N+2} + 2e^{+} $$

Not yet observed!

**E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys. Rev. 56 (1939) 1184

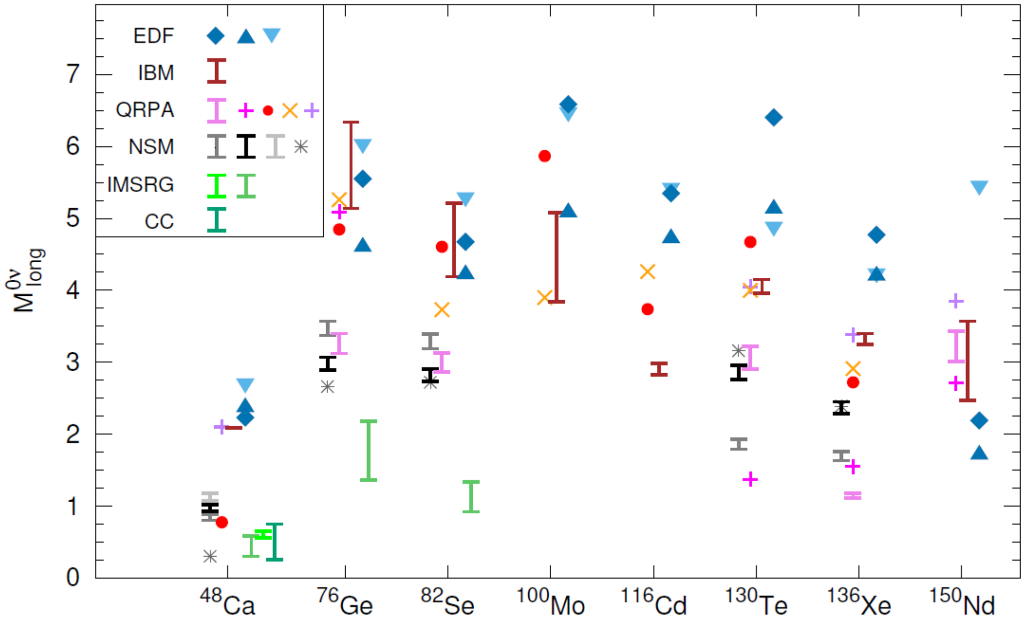
- Beyond the **standard model**
  - **Lepton number violation**
  - **CP violation** in lepton sector
- Way to **leptogenesis** and **Grand Unification Theories**
- Access to effective **neutrino masses**

$$ \frac{1}{T^{0\nu}_{1/2}}(0^{+} \rightarrow 0^{+}) = g_A^4 G_{0\nu} \left| M^{0\nu\beta\beta} \right|^2 \left| \frac{\langle m_{\beta\beta} \rangle}{m_e} \right|^2 $$

Nuclear Matrix Elements (NMEs):

Nuclear transition probability

$$|M^{0\nu\beta\beta}|^2 = |\langle\Psi_f|\hat{O}^{0\nu\beta\beta}|\Psi_i\rangle|^2$$



M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023)
H. Ejiri et al., Phys. Rep. 797 (2019) 1–102

Measurements (still not conclusive for 0νββ)

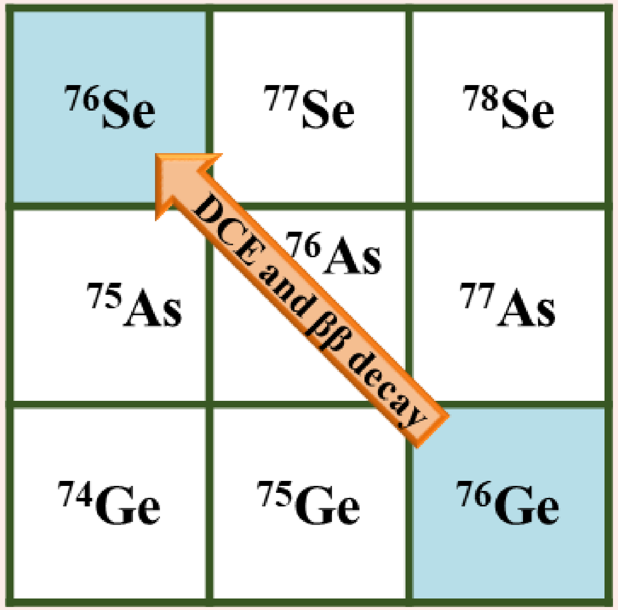
- ✓ β-decay and **2νββ** decay
- ✓ **(π$^+$, π$^-$)**, single charge exchange (^{3}He,t), (d,^{2}He), HI-SCE, electron capture, **transfer reactions**, ordinary μ-capture, γ-ray spectroscopy, **γγ-decay**, hadron resonance spectroscopy …
- ✓ A promising experimental tool: **Heavy-Ion Double Charge-Exchange (HI-DCE)**

1st order isospin probes

2nd order isospin probes

Double Charge Exchange reactions (DCE)

$$^{A}_{Z}x_{N} + ^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z\mp2}y_{N\pm2} + {}^{A}_{Z\pm2}Y_{N\mp2}$$



Why to study DCE?

- Population of exotic nuclei from stable target and projectile
- Nuclear response to second order isospin operator
- **Connection with second order weak processes**

Nuclear **Double Charge Exchange reactions (DCE)** to stimulate in the laboratory the same nuclear transition (**g.s. to g.s.**) occurring in $0\nu\beta\beta$

F. Cappuzzello et al., EPJ A (2018) 54:72

Differences | Similarities

The NUMEN project

Neutrinoless double beta decay**

$$\frac{1}{T_{1/2}^{0\nu}}(0^+ \rightarrow 0^+) = G_{0\nu}\left|M^{0\nu\beta\beta}\right|^2 \left|\frac{\langle m_\nu \rangle}{m_e}\right|^2$$

**E. Majorana, Il Nuovo Cimento 14 (1937) 171
W. H. Furry, Phys. Rev. 56 (1939) 1184

Nuclear **Double Charge Exchange reactions (DCE)** to stimulate in the laboratory the same nuclear transition (**g.s. to g.s.**) occurring in 0νββ

F. Cappuzzello et al., EPJ A (2018) 54:72

Why?

To extract **"data-driven" information** on NME for all the systems candidate for 0νββ:

- Constraints to the existing theories of NMEs (nuclear wave functions)
- Model-independent comparative information on the sensitivity of half-life experiments
- Complete study of the reaction mechanism

Where?

Catania, LNS-INFN

- **K800** Superconducting Cyclotron
- **MAGNEX** magnetic spectrometer
- Experience in **nuclear reactions**

F. Cappuzzello et al., EPJ A 52 (2016) 167

Relevant aspects of Heavy-Ion Double-Charge Exchange

F. Cappuzzello et al., Progr. Part. and Nucl. Physics 128 (2023) 103999

Progress in Particle and Nuclear Physics 128 (2023) 103999

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

Shedding light on nuclear aspects of neutrinoless double beta decay by heavy-ion double charge exchange reactions

F. Cappuzzello [a,b], H. Lenske [c], M. Cavallaro [b,*], C. Agodi [b], N. Auerbach [d], J.I. Bellone [a,b], R. Bijker [e], S. Burrello [f], S. Calabrese [b], D. Carbone [b], M. Colonna [b], G. De Gregorio [g,l], J.L. Ferreira [h], D. Gambacurta [b], H. García-Tecocoatzi [e], A. Gargano [g], J.A. Lay [i,j], R. Linares [h], J. Lubian [h], E. Santopinto [k], O. Sgouros [b], V. Soukeras [a,b], A. Spatafora [a,b], on behalf of the NUMEN collaboration

New challenges for 0νββ research

Two relevant issues emerging recently

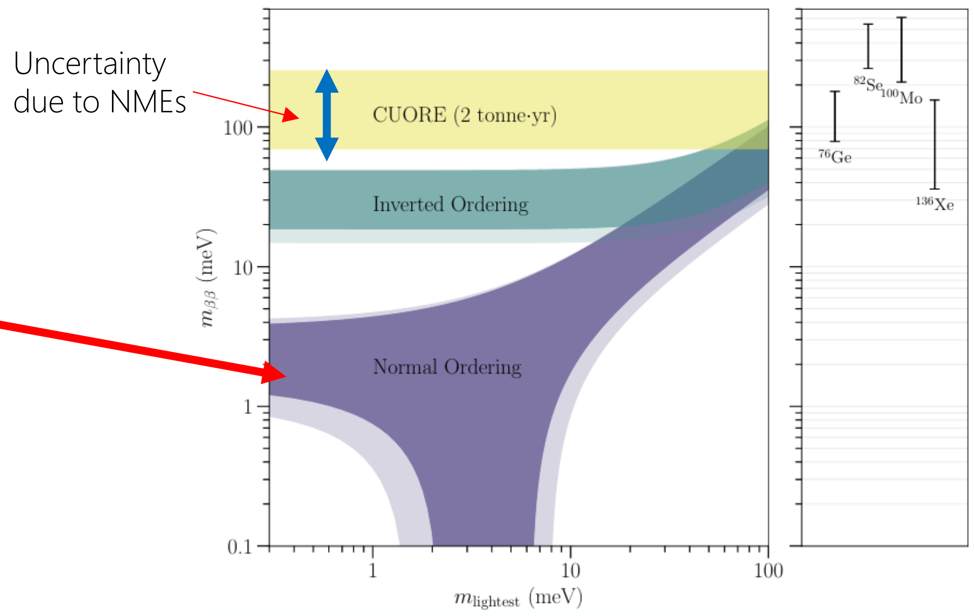
The normal hierarchy seems to be more favored!

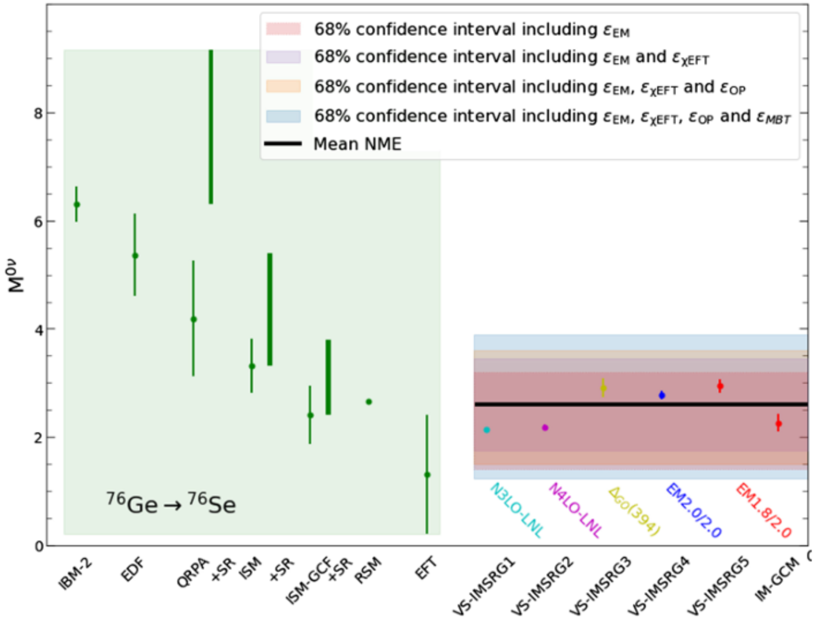
See recent global analyses [R. Jimenez et al. arXiv:2606.18987v1 17 Jun 2026]

$\Sigma m_\nu < 0.0642\ eV$ at 95% CL close to $\Sigma m_\nu^{NH} \sim 0.059\ eV$

but different from $\Sigma m_\nu^{IH} \sim 0.099\ eV$

Cuore collaboration, Science, 390 (2025) 1029



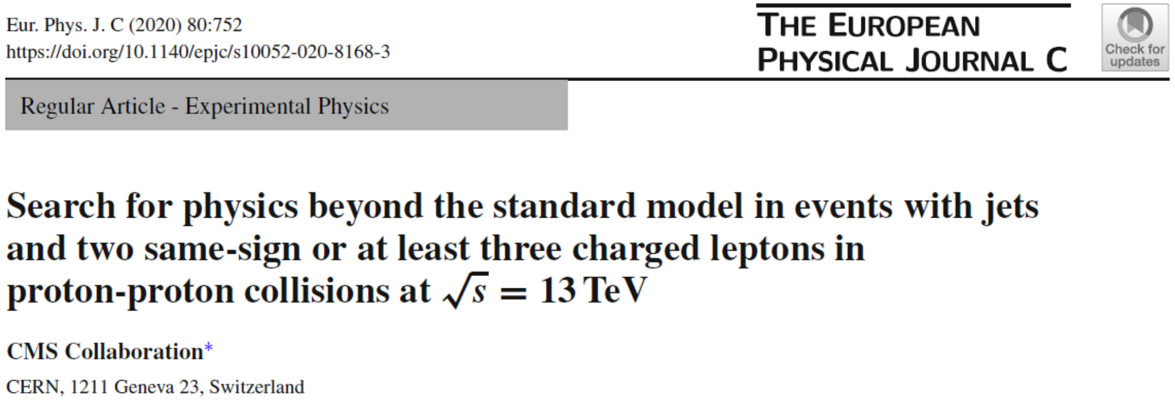


- ✓ The **NMEs from ab-initio** calculations are typically **smaller** than those, typically adopted, from nuclear structure models**!** See for example [A. Belley et al. PRL 132, 182502 (2024) 182]

If so, **0νββ signals could be much less likely to be observed** than initially expected, even with future ton-scale detectors

The LNV at TeV scale

✓ Searching for same sign two-lepton plus di-jet $l^{\pm}l^{\pm}jj$ signals in p +p collisions at LHC



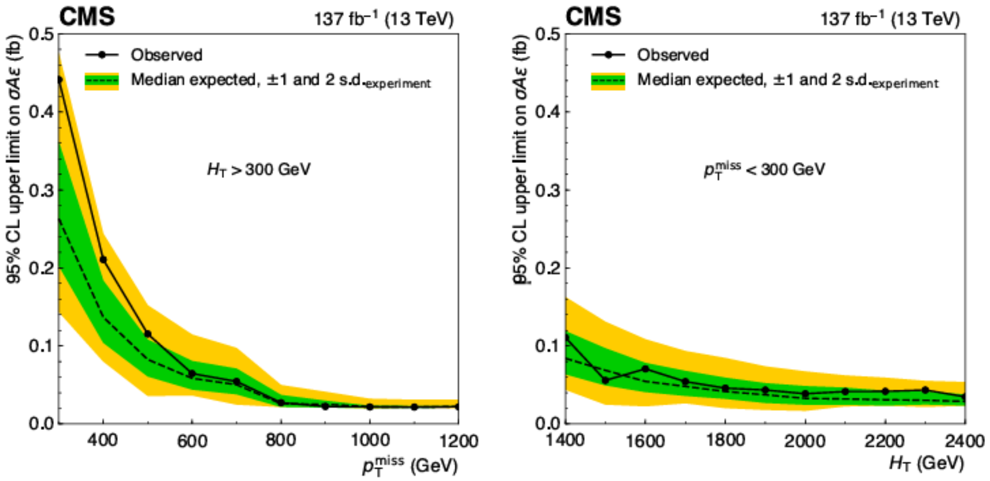
Eur. Phys. J. C (2020) 80:752
https://doi.org/10.1140/epjc/s10052-020-8168-3

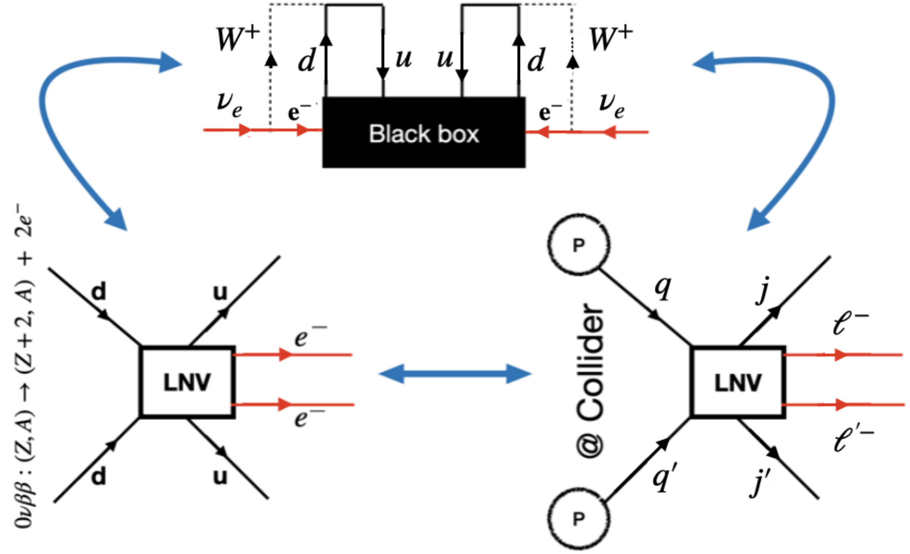
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Search for physics beyond the standard model in events with jets and two same-sign or at least three charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration*
CERN, 1211 Geneva 23, Switzerland





K.S. Babu et al., JHEP 06 (2024) 132

✓ **A growing interest from the theory**

✓ **Presently no signals** from LHC form p +p collisions at $\sqrt{S} = 13\ TeV$ up to 137 fb^{-1}

✓ A compelling physics case for the long-termed **Future Circular Collider**

Context: **0νββ** decay and **DCE** reactions

Idea: **LDCE** reactions as **LNV** probe

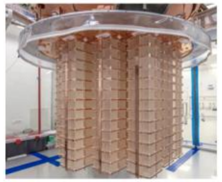
A possible **JLAB** experiment

Conclusions

Search for Alternative LNV Probes

…beside

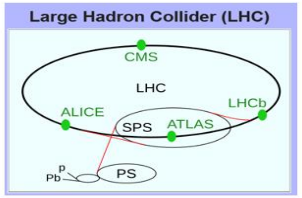
Double Beta Decay@MeV and Collisional $\ell^2 j^2$ Production@TeV



LEGEND, NEXO, CUPID, …

LDCE@GeV

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

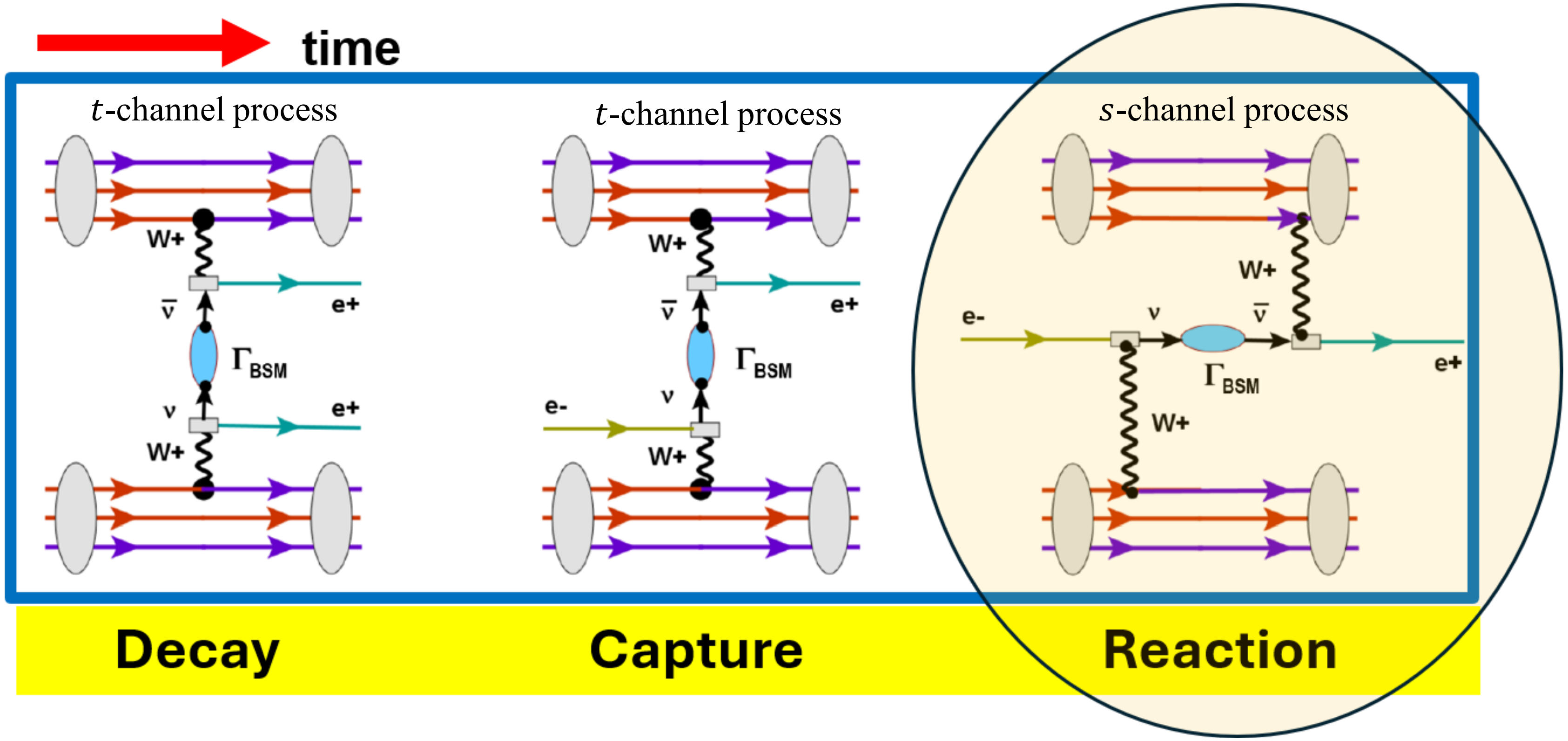


ATLAS & CMS

A new kid on the block: the lepton DCE reactions

The $(l^{\pm}, l^{\mp})$ reactions $l^{\pm} \in \{e^{\pm}, \mu^{\pm}, \tau^{\pm}\}$ at multi-GeV incident energy: **a new access to lepton number violation (LNV)**

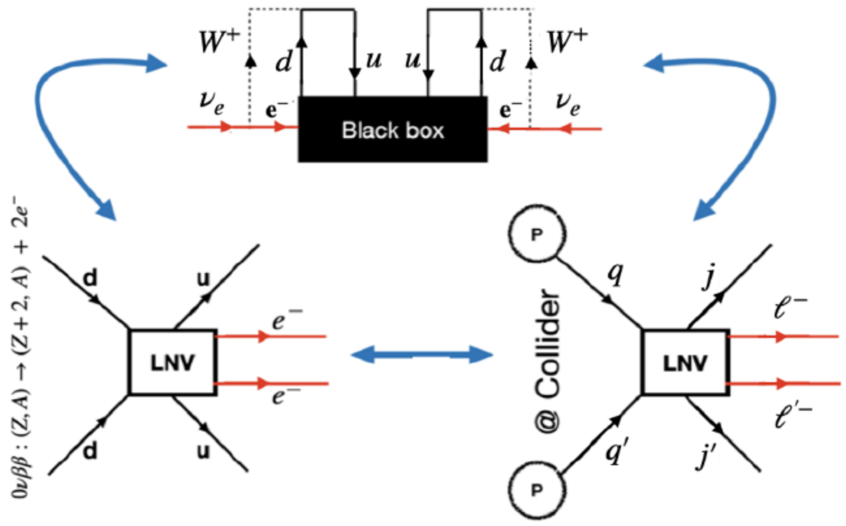
- ✓ **$0\nu\beta\beta$-decay protected from outside interferences**. No way to stimulate the decay from external. A strong dependence on NMEs as well as from Q-values and neutrino mass hierarchy.



- ✓ **LDCE LNV may be manipulated**, for examples changing the lepton beam and or the beam energy. No real limitation due to specific properties of nuclei and to neutrino mass hierarchy

H. Lenske, F. Cappuzzello and A. Spatafora, *Lepton Double Charge Exchange Reactions as Probes for Lepton Number Violation, arXiv:2603.21997v1 2026*

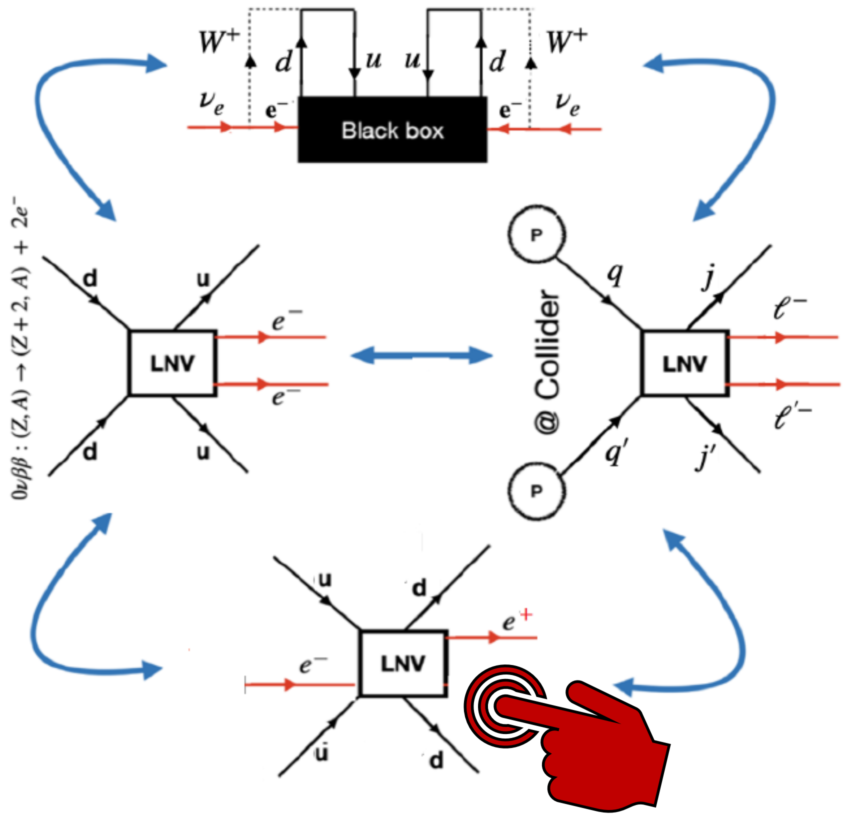
The Black Box Theorem (BBT)



The **Black Box Theorem** (BBT) establishes that **whatever** the mechanism at the origin of $0\nu\beta\beta$ or **high-energy LNV-dijet** emission it is, the observation of such events will prove that the **neutrinos** are **Majorana fermions**. (J. Schechter and J.W.F. Valle, PRD 25 (1982) - K.S. Babu, et al., JHEP 06 (2024) 132.)

In other words, $\boldsymbol{0\nu\beta\beta}$, LNV-dijet processes they either exist altogether, or they do not exist altogether!

The Black Box Theorem (**BBT**)



The **Black Box Theorem** (BBT) establishes that **whatever** the mechanism at the origin of $\mathbf{0\nu\beta\beta}$ or **high-energy LNV-dijet** emission or **LDCE** it is, the observation of such events will prove that the **neutrinos** are **Majorana fermions**. (J. Schechter and J.W.F. Valle, PRD 25 (1982) - K.S. Babu, et al., JHEP 06 (2024) 132.)

In other words, $\mathbf{0\nu\beta\beta}$, LNV-dijet and LDCE processes they either exist altogether, or they do not exist altogether!

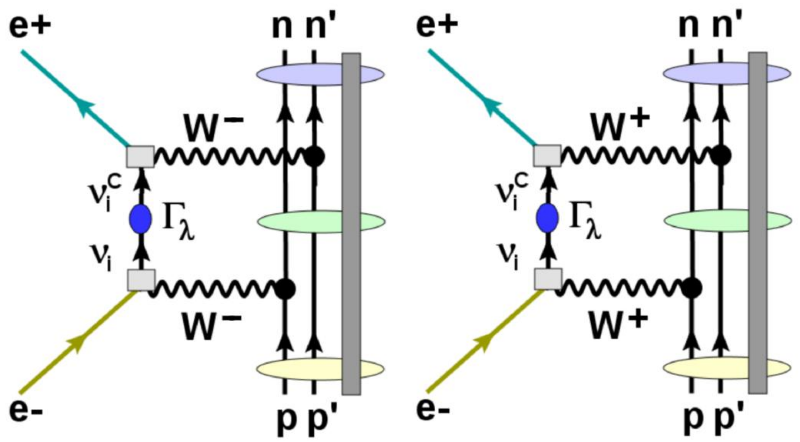
The three classes of processes pertain at different energy scales, i.e. **MeV** for $\mathbf{0\nu\beta\beta}$, multi **TeV** for the **LNV-dijet** and, bridging the gap among these, **GeV** for the **LDCE**.

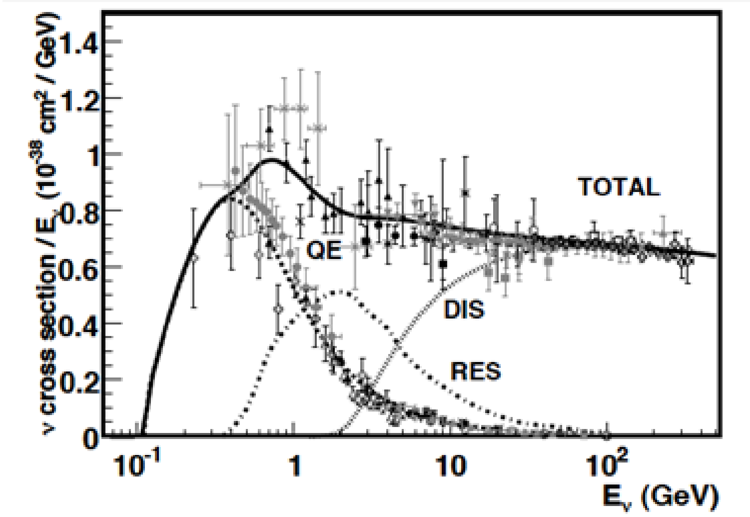
Jefferson Lab

Major efforts for $\mathbf{0\nu\beta\beta}$ and **LNV-dijet**, but nothing for LDCE. **LDCE can be explored today at Jlab, practically with no competition for years, due to the interplay of energy and luminosity available**

LDCE cross section

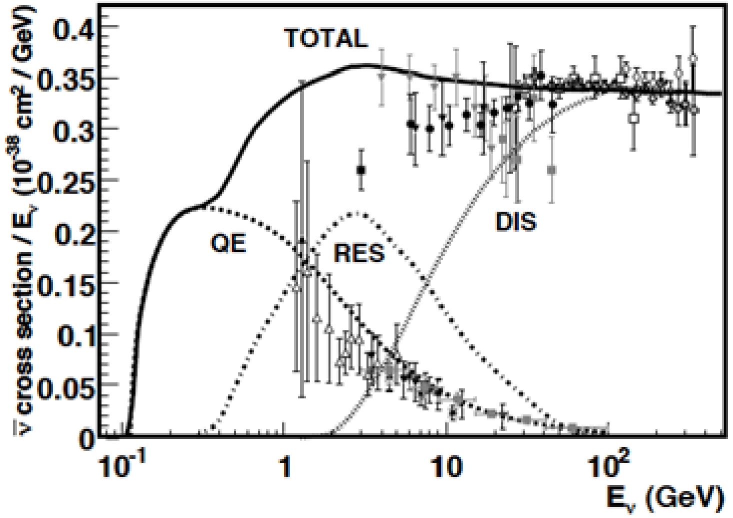
Calculations in the **semi-phenomenological approach** utilizing the Left-Right Symmetric Model (**LRSM**) to explore the **cross-section** vs **beam energy** and **target mass** dependence (performed by **H. Lenske**)





$\boldsymbol{\nu_\mu + N \to \mu^- + X}$

$\boldsymbol{\bar{\nu}_\mu + N \to \mu^+ + Y}$



✓ Resembling the $0\nu\beta\beta$ case, LDCE cross section is factorizable, to leading order, into unknown (normalized) Beyond the Standard Model matrix elements $|\Gamma_{BSM}|^2$ and in principle known reduced cross sections of reaction-dynamical content

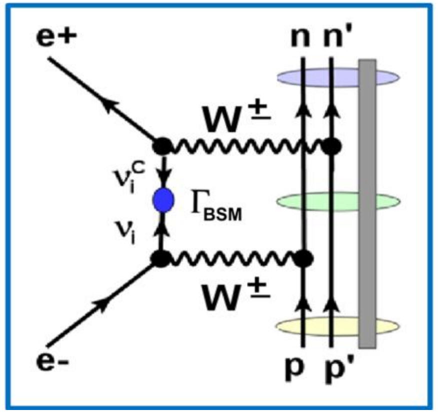
LDCE Amplitude and Cross Section

Dominant in ***LDCE***   Dominant in **$0\nu\beta\beta$-decay**

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

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

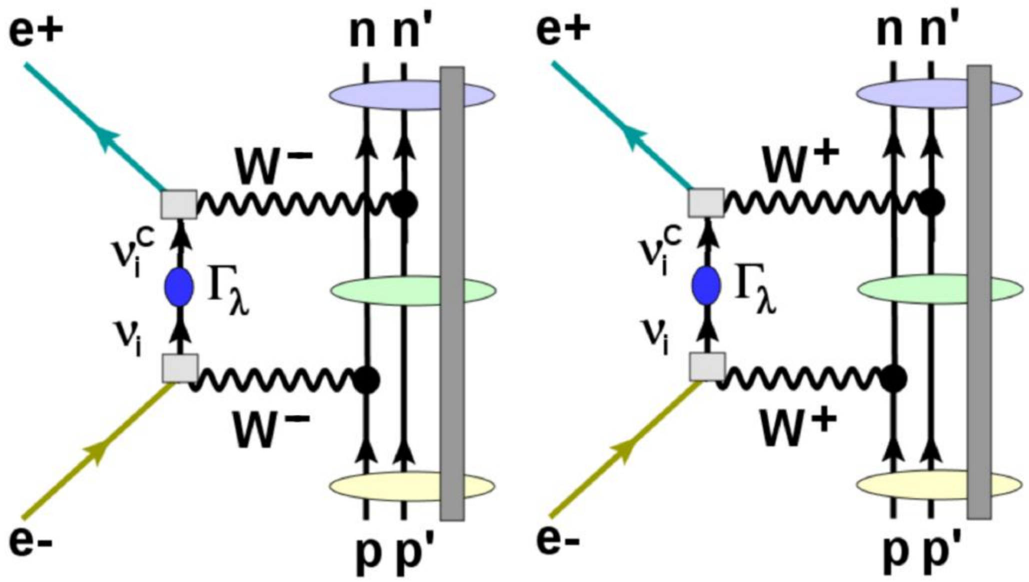
LL/RR Diagonal - No LR Mixing
Majorana Masses m_i



LDCE cross section

Calculations in the **semi-phenomenological approach** utilizing the Left-Right Symmetric Model (**LRSM**) to explore the **cross-section** vs **beam energy** and **target mass** dependence (performed by **H. Lenske**)

s-channel process

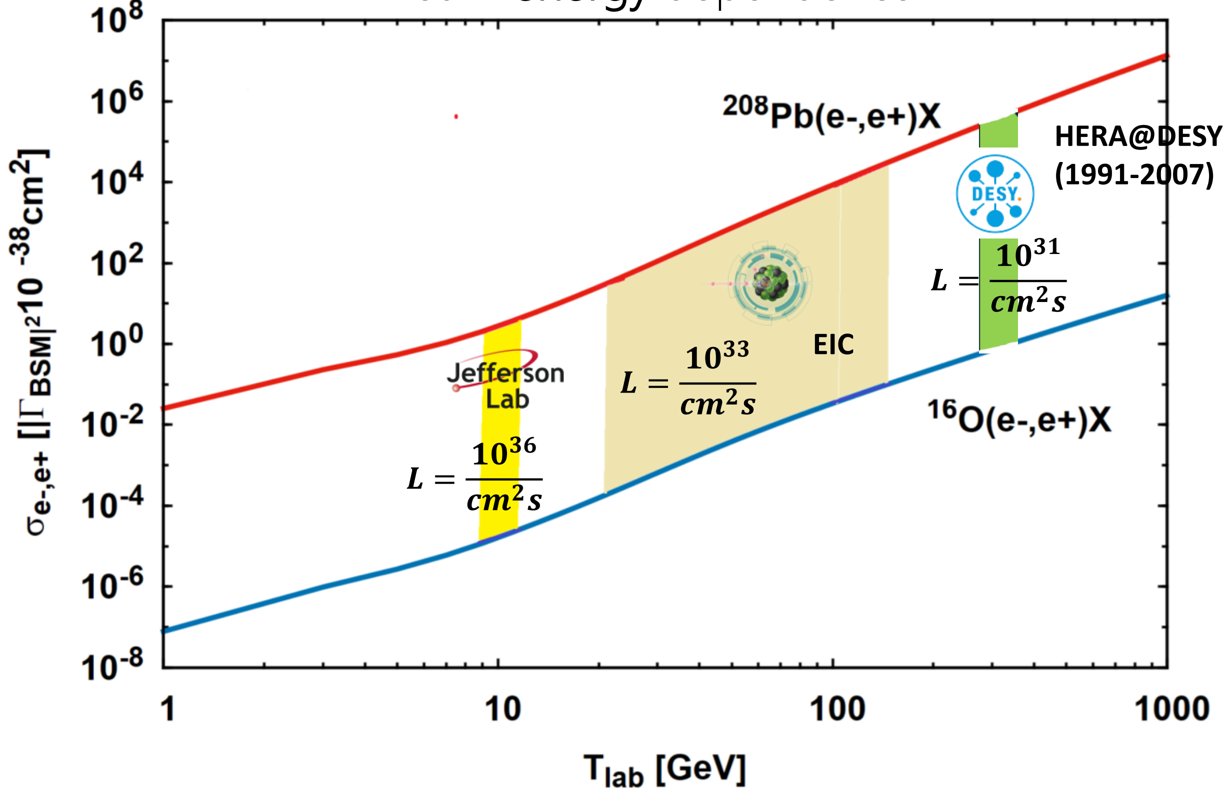


- ✓ Majorana **mass term dominant** in the $0\nu\beta\beta$: to date, experiments indicate $|\Gamma_{\nu\bar{\nu}}|^2 \leq 10^{-13}$ in units of the electron mass
- ✓ **Other BSM operators** (**energy dependent**, dim-7 and dim-9) will lead to significantly **larger values** for LDCE and **di-jet**
- ✓ Irrespective of direct LNV signals, **unique experimental constraints can be derived on** $|\Gamma_{BSM}|^2$ **from LDCE cross section measurement at Jlab**

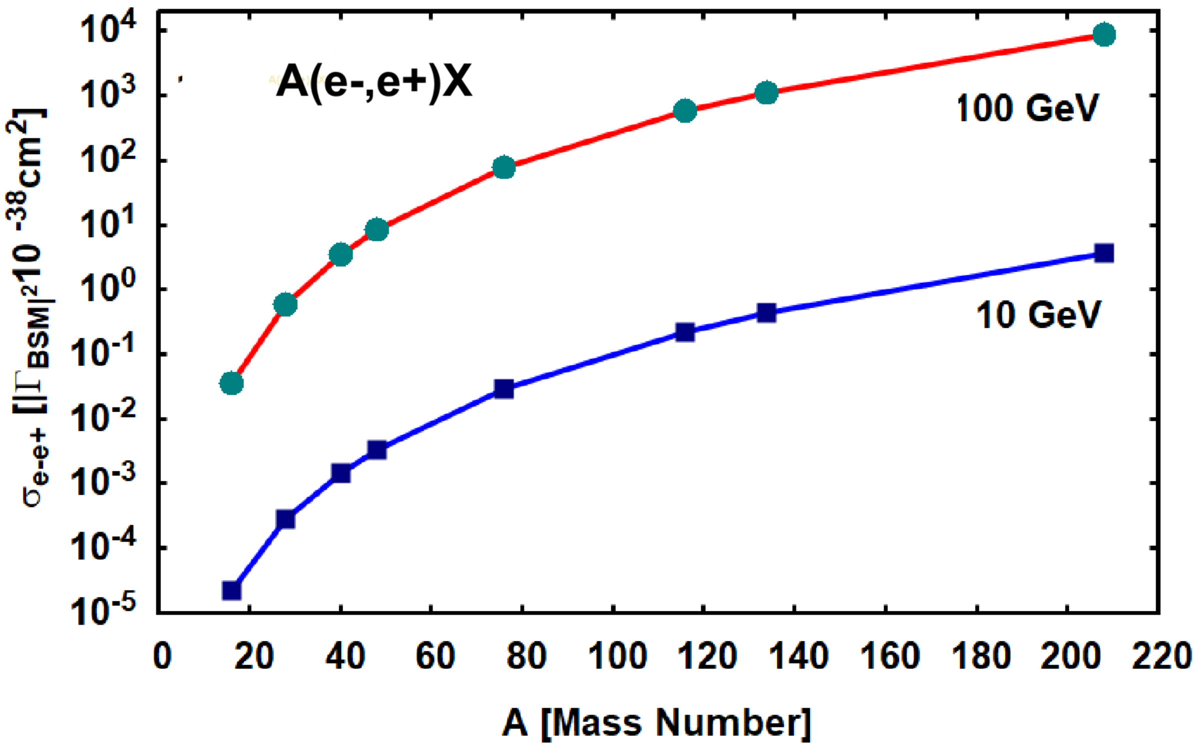
LDCE cross section

Calculations in the **semi-phenomenological approach** utilizing the Left-Right Symmetric Model (**LRSM**) to explore the **cross-section** vs **beam energy** and **target mass** dependence (performed by **H. Lenske**)

Beam **energy** dependence

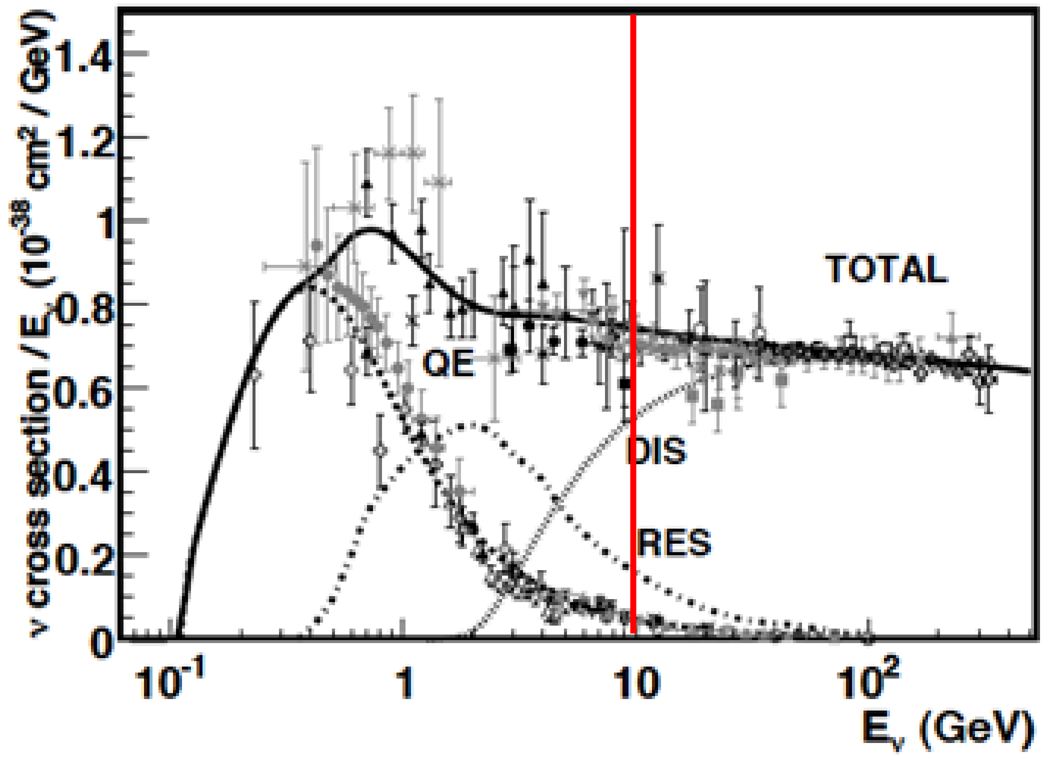


Target **mass** dependence



The calculations do not account for heavy-neutrino recoil effect nor for contributions from dimension-7 and dimension-9 operators, which could be significant. So, one can consider them as lower limits for the expected cross section.

LDCE reaction mechanism



J. A. Formaggio and G. P. Zeller., Rev. Mod. Phys., 84 (2012) 1307

- ✓ At ~ 10 GeV scale the LDCE reaction can proceed via **Quasi Elastic** (QE), **Resonant** (RES) and **Deep Inelastic Scattering** (DIS) competing mechanisms
- ✓ Since LDCE is a second order process one should consider different combinations. For instance QE-QE or RES-DIS and so on
- ✓ A possible experiment is thus in principle in line with typical **inleastic scattering** studies **conducted at Jlab**

Context: $0\nu\beta\beta$ decay and DCE reactions

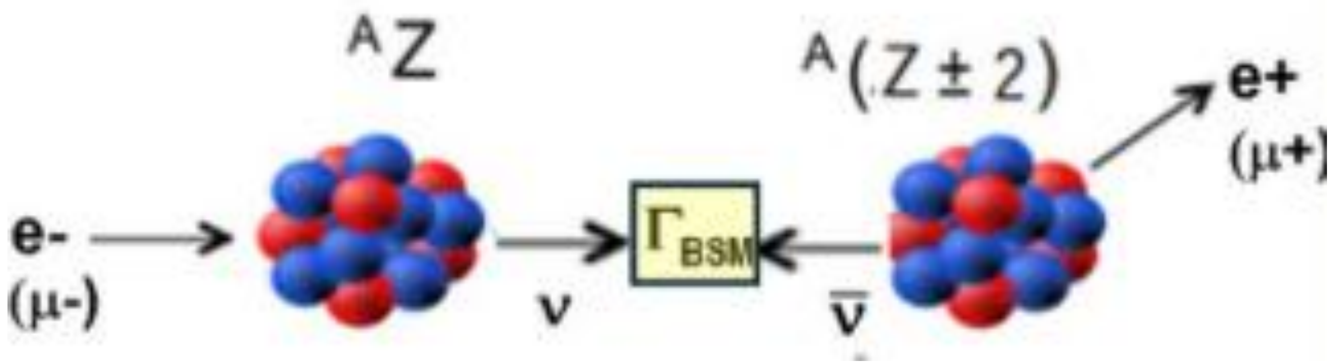
Idea: LDCE reactions as LNV probe

A possible JLAB experiment

Conclusions

Featuring aspects of LDCE reactions

- ✓ **LDCE processes are second order reactions** of the kind $\boldsymbol{e^-} + {}^{A}_{Z}X_N \rightarrow \nu_M + {}^{A}_{Z}X^*_N \rightarrow \boldsymbol{e^+} + {}^{\bar{A}}_{\bar{Z}}X^*_{\bar{N}} + \boldsymbol{2n} + \boldsymbol{mesons} + \ \ldots$



- ✓ **LDCE events require that a positron is generated**. However, even at high momentum, positron background from electromagnetic interactions is, by far, more than LDCE signals

- ✓ Two nucleons are also emitted. These can be measured to reduce background

- ✓ Finally, mesons, typically pions, can be emitted depending on the specific reaction mechanism

Signatures of LDCE QE-QE events

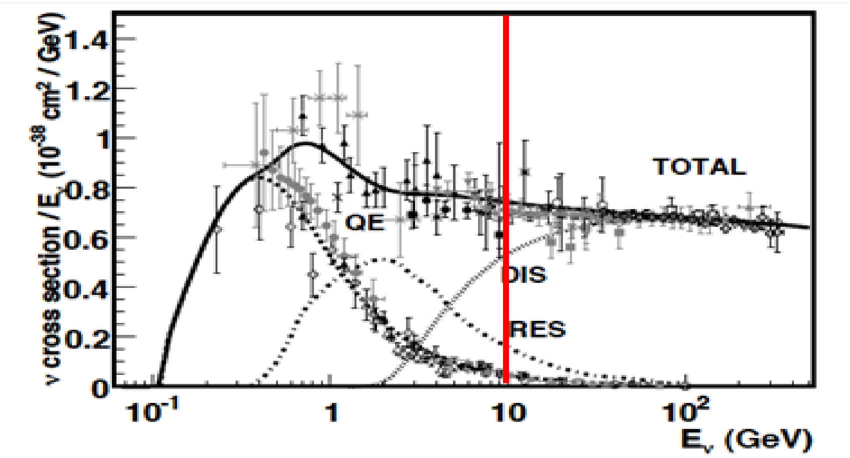
- ✓ **The simplest LDCE mechanism is a second order quasielastic process (QE-QE)** of the kind $e^- + {}^{A}_{Z}X_N \rightarrow \nu_M + {}^{A-1}_{Z-1}X^*_N + N \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + 2N$

- ✓ In the first step the electron collides on a proton generating the Majorana neutrino and an energetic neutron. In the second step the neutrino collides on a second proton generating a second energetic neutron and the positron.

- ✓ Electric charge conservation requires that only the protons of the target nucleus can be affected

- ✓ In this case the **LDCE signature is the coincident detection of a positron and two neutrons with the proper momenta (multiplicity = 3)**

- ✓ However this process is not the most probable, at 10 GeV it should account for about 1% of the LDCE cross section



J. A. Formaggio and G. P. Zeller., Rev. Mod. Phys., 84 (2012) 1307

Signatures of LDCE resonant and deep inelastic events

- ✓ When resonant and deep inelastic proceeses occur in one or both the vertices **(QE-RES, RES-RES, QE-DIS, RES-DIS, DIS-DIS)** also neutrons of the target nucleus can drive the process

- ✓ ***For example, in a double resonant process RES-RES we can have the following reaction routes:***

$$
\begin{cases}
e^- + {}^{A}_{Z}X_N \rightarrow \nu_M + {}^{A-1}_{Z-1}X^*_N + \Delta^0 \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + 2\Delta^0 \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + 2n + 2\pi^0 (2\ protons\ affected) \\
e^- + {}^{A}_{Z}X_N \rightarrow \nu_M + {}^{A-1}_{Z-1}X^*_N + \Delta^0 \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + 2\Delta^0 \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + 2p + 2\pi^- (2\ protons\ affected) \\
e^- + {}^{A}_{Z}X_N \rightarrow \nu_M + {}^{A-1}_{Z-1}X^*_N + \Delta^0 \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + 2\Delta^0 \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + p + n + \pi^- + \pi^0 (2\ protons\ affected) \\
e^- + {}^{A}_{Z}X_N \rightarrow \nu_M + {}^{A-1}_{Z}X^*_{N-1} + \Delta^- \rightarrow e^+ + {}^{A-2}_{Z}X^*_{N-2} + 2\Delta^- \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + 2n + 2\pi^- (2\ neutrons\ affected) \\
e^- + {}^{A}_{Z}X_N \rightarrow \nu_M + {}^{A-1}_{Z-1}X^*_N + \Delta^0 \rightarrow e^+ + {}^{A-2}_{Z-1}X^*_{N-1} + \Delta^0 + \Delta^- \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + 2n + \pi^- + \pi^0 (1\ proton\ and\ 1\ neutron\ affected) \\
e^- + {}^{A}_{Z}X_N \rightarrow \nu_M + {}^{A-1}_{Z-1}X^*_N + \Delta^0 \rightarrow e^+ + {}^{A-2}_{Z-1}X^*_{N-1} + \Delta^0 + \Delta^- \rightarrow e^+ + {}^{A-2}_{Z-2}X^*_N + n + p + 2\pi^- (1\ proton\ and\ 1\ neutron\ affected)
\end{cases}
$$

- ✓ One can see that in absence of DIS mechanisms two nucleons and neutral or negative pions are present in the final state. No positive pions, due to charge conservation!

- ✓ When DIS mechanisms are activated more pions are emitted at each vertex, being positive pions also possible, although always in conjunction with negative pions

- ✓ In all these cases the LDCE signature is the coincident detection of a positron, two nucleons and two or more pions with the proper momenta and electric charge (multiplicity >3)

Signatures of LDCE events

- ✓ In summary, an experimental **signature of LDCE requires a coincident detection of the energetic positron emitted at forward angle with almost the full beam energy, and a swarm of hadrons**, nucleons and mesons (typically pions) such that energy, momentum and charge conservation are verified

- ✓ Since each of the LDCE reaction mechanism may generate the discovery events, **one should in principle look at each of them**

- ✓ **A crucial question is the** amount of **background** present in each of these LDCE routes, which of course strongly depends on the experimental set-up

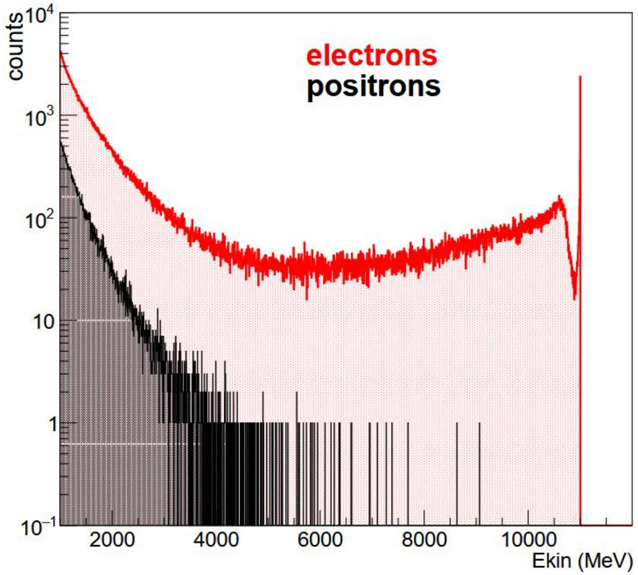
Challenges in the study of LDCE background

The investigation of background sources in LDCE events is a **challenging task, not yet solved**

Where is my mobile phone?

- ✓ **Hard to find data** of e^- induced reactions on nuclear targets triggered by the detection of e^+, preferentially emitted at forward angles with kinetic energies not far from the beam energy

- ✓ **Data triggered by energetic scattered e^- are not much reliable** and could also be misleading due to the very different energy spectra of e^+ and e^- at high momentum



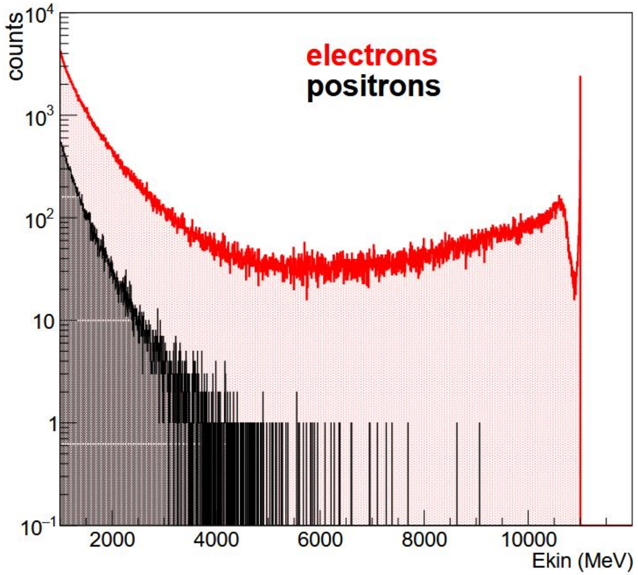
Challenges in the study of LDCE background

The investigation of background sources in LDCE events is a **challenging task, not yet solved but mandatory**

That is better!

- ✓ **Hard to find data** of e^- induced reactions on nuclear targets triggered by the detection of e^+, preferentially emitted at forward angles with kinetic energies not far from the beam energy

- ✓ **Data triggered by energetic scattered e^- are not much reliable** and could also be misleading due to the very different energy spectra of e^+ and e^- at high momentum

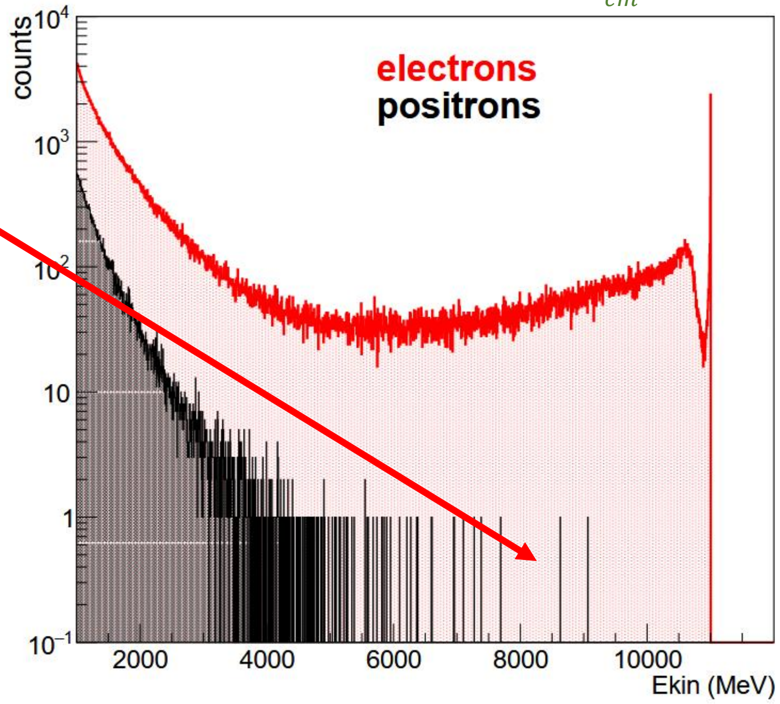


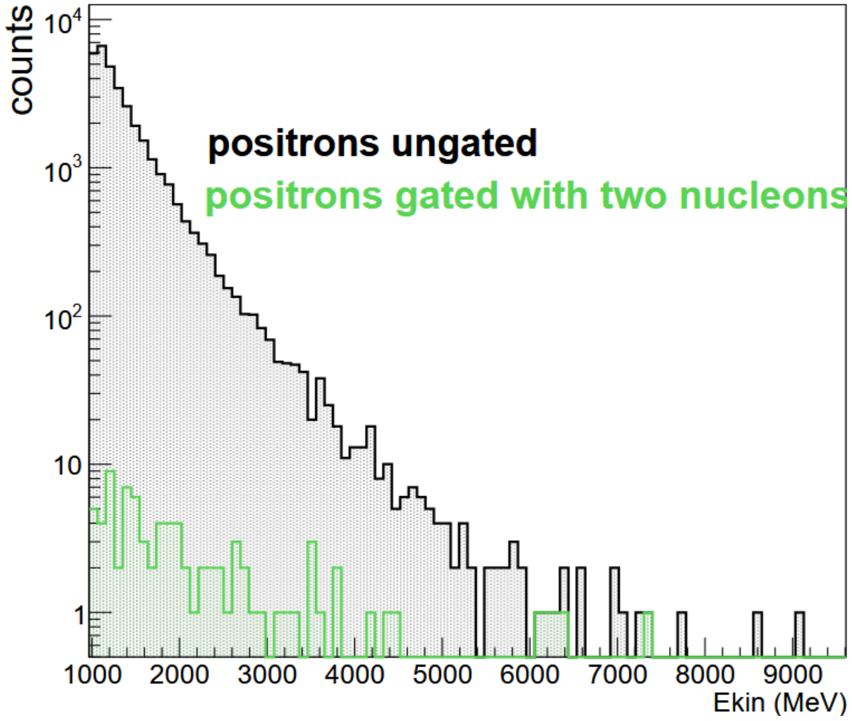
Challenges in the study of LDCE background

✓ **Simulations of background sources are also challenging** and not very reliable, mainly due to the very low cross section of background processes mimicing the LDCE

The simulation corresponds to about $0.1\ s$ full power experiment at CLAS12 or 0.3 ms in Hall C, while taking one day processing time

$10^{11}\ e^{-}$ beam particles on a ^{208}Pb $1\ \frac{g}{cm^2}$



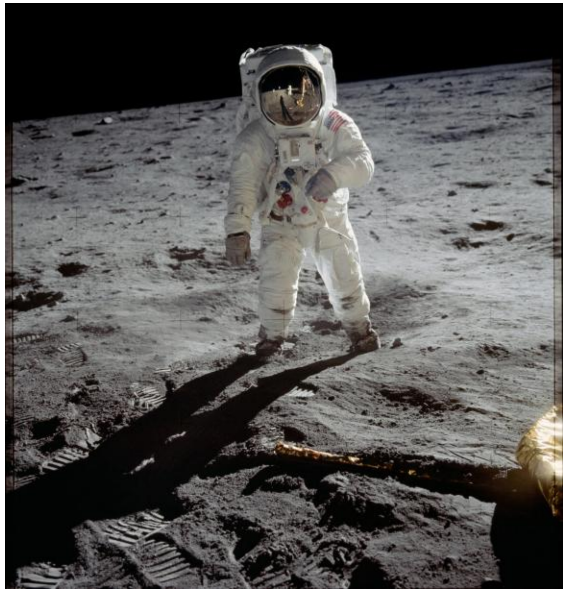


✓ **Hard to** give a quantitative assessment of background suppression strategies with poor statistical datasets

A possible wayout

A short (1 - 2 days) data taking with CLAS12 on a ^{208}Pb $1\,\frac{\mathrm{g}}{\mathrm{cm}^2}$ with the help of the CLAS collaboration, would be a milestone for a real assessment of LDCE background

This data would serve as a key factor for future projects of LDCE discovery also with CLAS12



Context: **$0\nu\beta\beta$** decay and **DCE** reactions

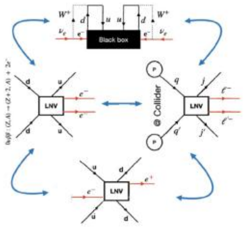
Idea: **LDCE** reactions as **LNV** probe

A possible **JLAB** experiment

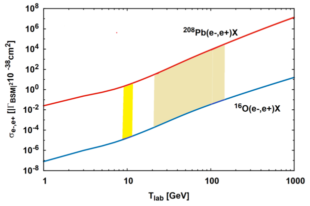
Conclusions

Conclusions

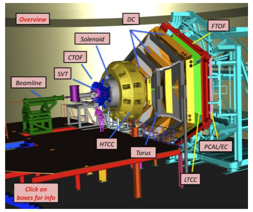
- **LDCE** is a **new (!)** promising way to **LNV** and **physics BSM**

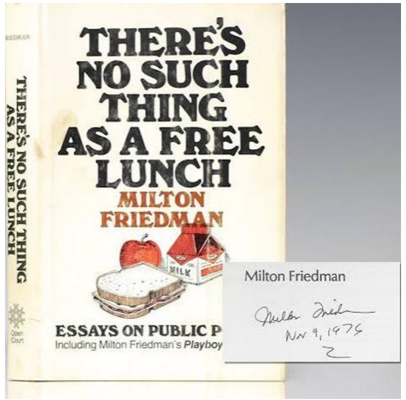


- A **new (!)** **semi-phenomenological theory**, based on the **LRSM**, gives reliable and encouraging **cross-section estimates** (H. Lenske, F. C., A. Spatafora, ArXiv_2603.21997v1)



- Today, **JLAB is the only place where,** without developing new detectors or technologies, it is possible to perform a measurement with **interesting sensitivity on** $|\Gamma_{BSM}|^2$ in a reasonable time. CLAS12 seems to be the most sensitive setup for the first steps in this enterprise





Legacy from Mullah Nasruddin and Galileo

A proud and visiting scholar arrived at the court and boasted of his immense knowledge, challenging the locals with an impossible riddle: **"How many stars are in the sky?"**

While the rest of the court was baffled, Mullah Nasruddin stepped forward and casually replied, *"There are exactly as many stars in the sky as there are hairs on my donkey."*

The scholar scoffed and demanded to know how Nasruddin could prove such an absurd claim.

Nasruddin smiled and said, *"If you do not believe me, you are welcome to count the hairs on my donkey, and you will see I am right."*

When the scholar complained that it was impossible to count every hair on a donkey's hide, Nasruddin delivered the punchline: *"Exactly! And if it is impossible to count the hairs on a donkey, it is equally impossible to count the stars in the sky."*

As scientists we do count the number of stars in the sky, although it is by far the hardest way to get knowledge, as indicated by Galileo!

Thank you

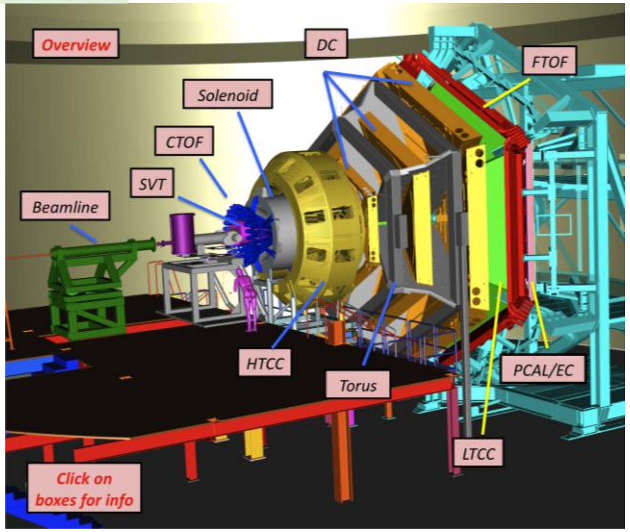
Conclusions

There are still many **open questions. Among them**:

- What is the **best signature**?
- How are the reaction products **angularly correlated**?
- What is the **background distribution**?
- How can we **verify** the results of the GEANT IV **simulations**?
- What is the **detection efficiency** for high-multiplicity events?

How to **answer questions**?

- Look at the **experimental data** (if available) for the **angular distribution** of the **backgrounds** and their time and/or angle **correlations**.
- CLAS12 would be the ideal instrument for an **initial measurement** at a **lower luminosity** and **large acceptance** conditions. A bit of luck would allow **the signal** to be observed already under



Grazie


Time for discussion!

The NUMEN Experiments

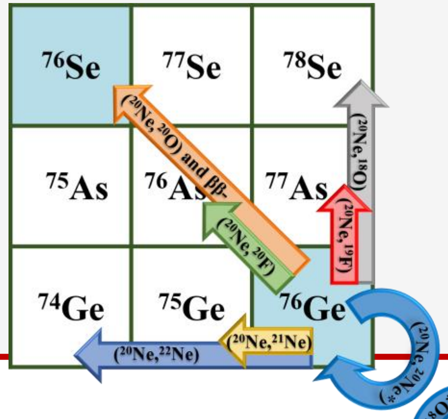
Two directions: $\beta\beta^-$ via (^{20}Ne,^{20}O) and $\beta\beta^+$ via (^{18}O,^{18}Ne)

Complete net of reactions which can contribute to the DCE cross-section: 1p, 2p, 1n, 2n transfer, SCE, elastic and inelastic

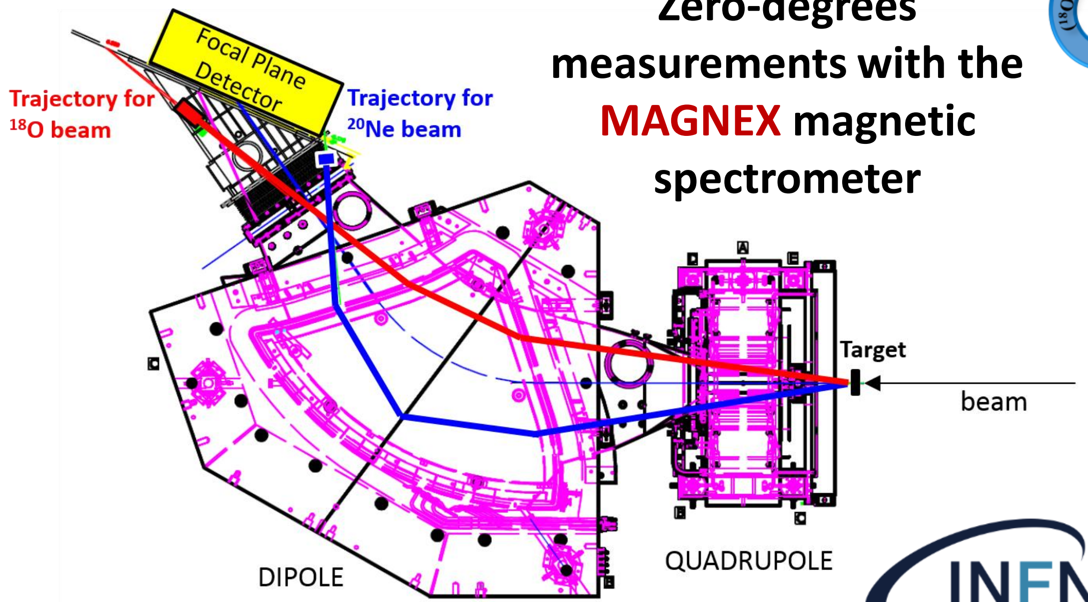
Two (or more) incident energies to study the reaction mechanism

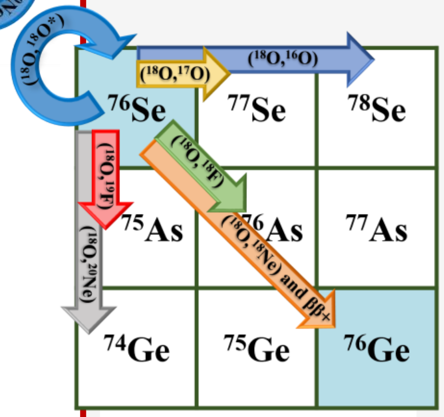
Transitions of interest for 0νββ: Limited number of targets so far, systematic exploration of all the candidates

Limitations of the past HI-DCE experiments are overcome!



Zero-degrees measurements with the MAGNEX magnetic spectrometer





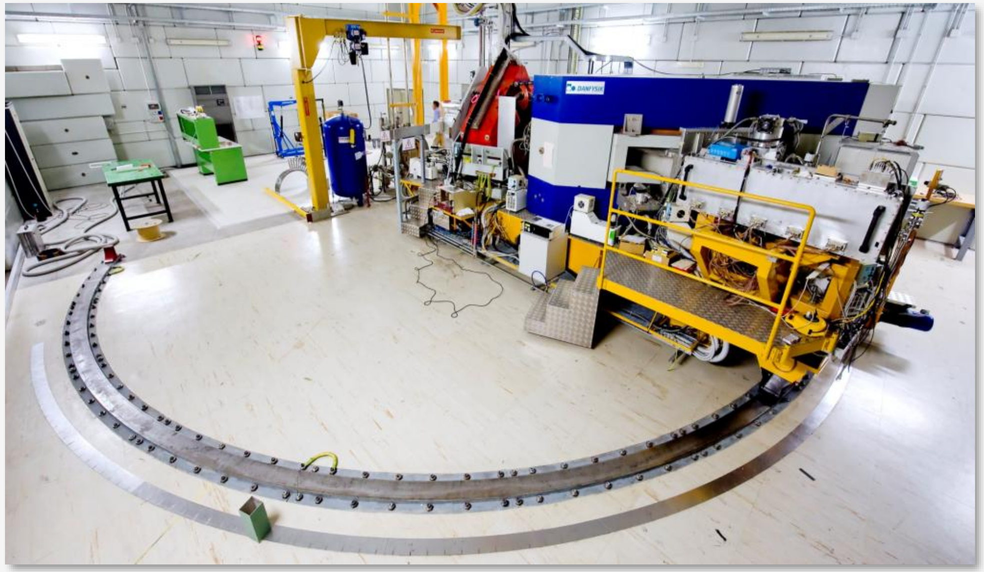
INFN LNS

NUMEN

Heavy-Ion Double-Charge Exchange **Experiments @ LNS**

MAGNEX magnetic spectrometer

F. Cappuzzello et al., EPJ A (2016) 52:167
M. Cavallaro et al., NIM B 463 (2020) 334

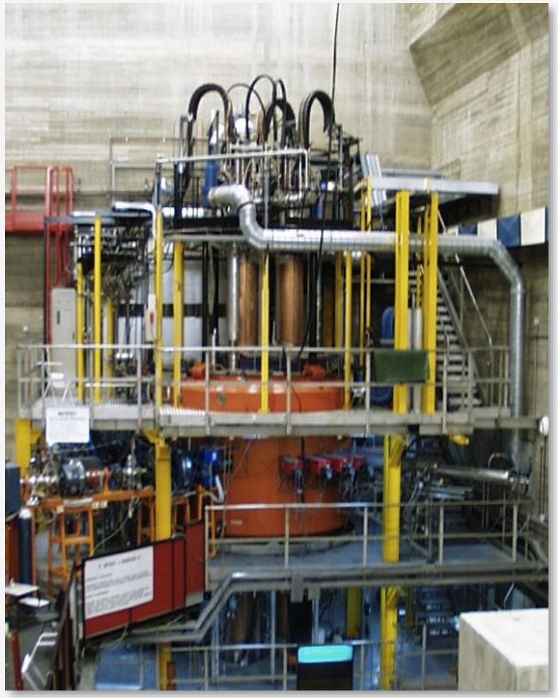


Optical characteristics	Measured values
Angular acceptance (Solid angle)	50 msr
Angular range	–20° - +85°
Momentum (energy) acceptance	-14%, +10% (-28%,+20%)
Momentum dispersion for k= - 0.104	3.68 cm/%
Maximum magnetic rigidity	1.8 T m

Measured resolution:
Energy $\Delta E/E \sim 1/1000$
Angle $\Delta\theta \sim 0.2°$
Mass $\Delta m/m \sim 1/300$

- **Wide mass range** (protons to medium-mass)
- Measurement at **zero-degrees**

A. Badalà et al., Riv. Nuovo Cim. (2020)



K800 Superconducting Cyclotron

- In operation since 1996.
- Accelerates from H to U ions
- Maximum energy 80 MeV/u.

POT lns

The Jlab LDCE experiment

$^{208}Pb(e^-, e^+)X$ cross section
(but limited to the LR term only)

$$\sigma \sim 10^{-37} |\Gamma_{LR}|^2 cm^2$$

Jefferson Laboratory Luminosity

Luminosity: we refer to the number of target nuclei (not nucleons!).

$$L \sim 10^{36} cm^{-2} s^{-1} \text{(HALL A and C)}$$
$$L \sim 10^{33} cm^{-2} s^{-1} \text{(HALL B)}$$

One can explore in principle LDCE with a sensitivity up to $10^{-42} cm^2$ in 10 days data taking, corresponding to a sensitivity in $|\boldsymbol{\Gamma_{LR}}|^2 < \mathbf{10^{-5}}$ (HALL A and C) or $|\boldsymbol{\Gamma_{LR}}|^2 < \mathbf{10^{-2}}$ in HALL B

What about detection **efficiency**?

The Jlab LDCE experiment

Experimental setup

Beam energy: 10 – 12 GeV
Beam intensity: ~ 100 μA (full intensity)
Target: ^{208}Pb 1 g/cm^2;
Experiment location: Jlab Hall C
HRMS for e^+:

$$\theta_{e^+,lab} \sim 3° - 8°$$

$$E_{e^+} \sim 8 - 11 \text{ GeV}$$

HCAL for neutrons and charged particles:

$$\theta_h \sim 30° \ (Q^2 \sim 1 - 2\ GeV^2)$$

Detection strategy

Multiple coincidence of e^+, neutrons and pions emitted in the final reaction channel to reduce the background from events originated by EM interactions

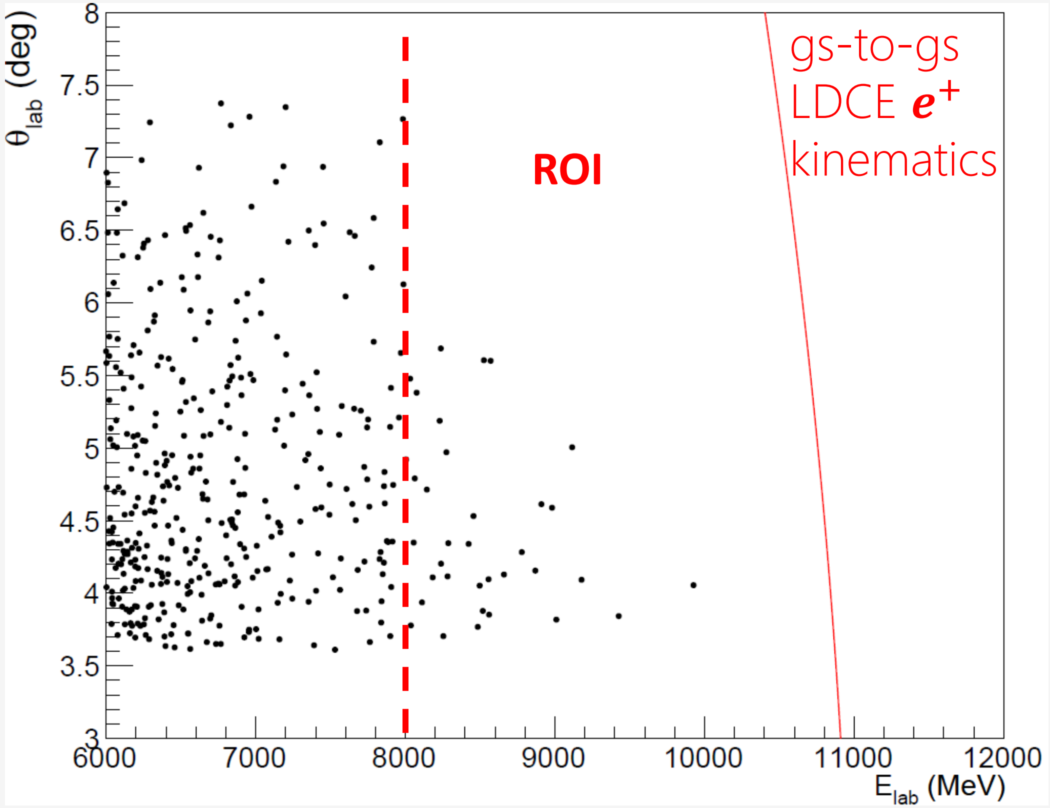
Reaction channel: $(e^-, e^+XY \ldots)$, where X and Y are the reaction products from the target, including nucleons, pions and hadronic jets

What about EM **background**?

The Jlab LDCE e^+ background

Beam: 2.3 x 10^{12} e^- @11 GeV (corresponding to **3,7 ms of beam time**)
Target: ^{208}Pb (0.5 g/cm^2);
e^+detector: HRMS at forward scattering angles $(\theta_{e^+,lab} \sim 3.5° - 7.5°)$
Overall e^+ detection efficiency: **4.2%** (100% intrinsic AND 4.2% geometric)

GEANT4
A SIMULATION TOOLKIT



e^+ count rate in the HRMS in the ROI @ 100 μA

Background: 5 kHz

Signal: $\mathbf{0.37} \cdot |\boldsymbol{\Gamma_{LR}}|^{\mathbf{2}}$ Hz

Multiple coincidences are needed!

The Jlab LDCE in a multiple-coincidence view

Beam: e^- @11 GeV
Target: ^{208}Pb (1-0.1 g/cm^2);
HRMS for e^+detection $\left(\theta_{e^+,lab} \sim 3.5° - 7.5°\right)$
HCAL for π/n detection $\theta_h \sim 30°$ $(Q^2 \sim 1-2\ GeV^2)$

Reaction channel	Luminosity (cm^{-2}s^{-1})	Detection efficiency	BR %	$\lvert\Gamma_{LR}\rvert^2$ sensitivity
(e^-, e^+nn)	$9*10^{35}$	$8*10^{-3}$	1	$3.6*10^{-2}$
$(e^-, e^+\pi)$	$9*10^{34}$	$1.7*10^{-2}$	95	1.7
$(e^-, e^+\pi\pi)$	$9*10^{34}$	$8*10^{-3}$	95	$3.6*10^{-3}$
$(e^-, e^+\pi\pi\pi)$	$9*10^{34}$	$3.8*10^{-3}$	95	$1.8*10^{-4}$

Luminosity: it refers to the number of nuclei (not nucleons!). **Target thickness** chosen to minimize the EM background according to GEANT IV simulations.

The Jlab LDCE in a multiple-coincidence view

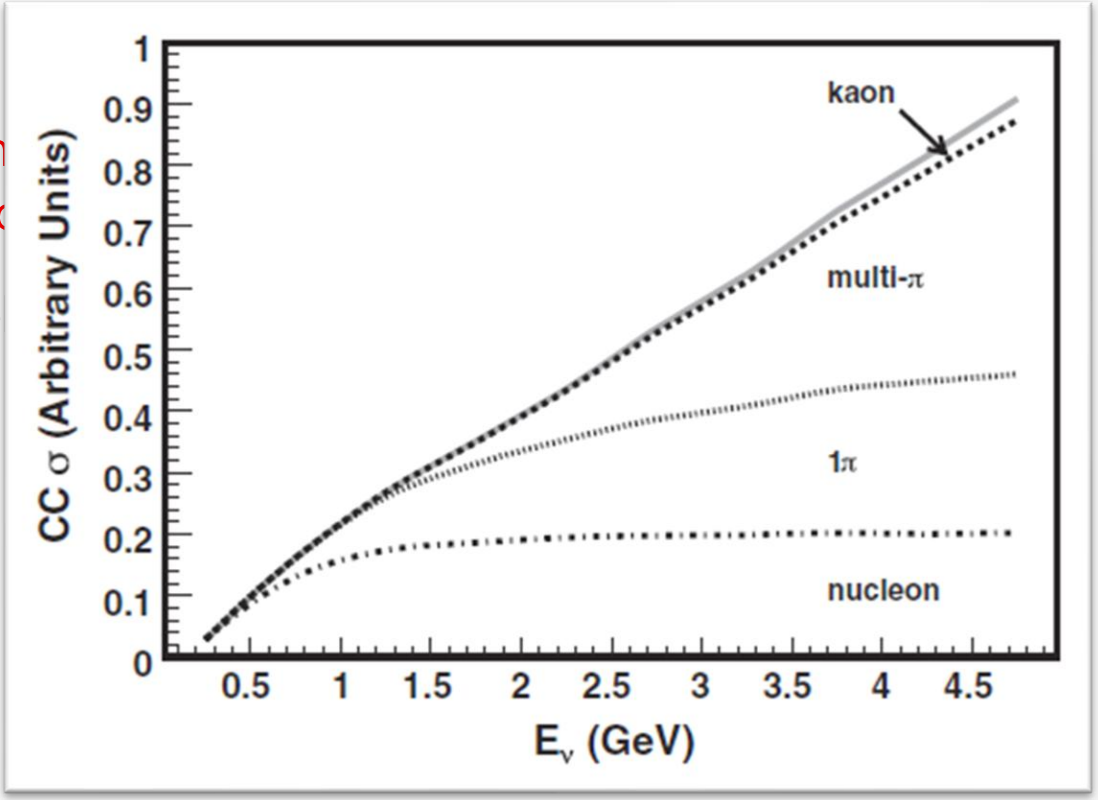
Beam: e^- @11 GeV
Target: ^{208}Pb (1-0.1 g/cm^2);
HRMS for e^+detection $(\theta_{e^+,lab} \sim 3.5° - 7.5°)$
HCAL for π/n detection $\theta_h \sim 30°$ $(Q^2 \sim 1-2\ GeV^2)$

Reaction channel	Luminosity (cm^{-2}s^{-1})	Detection efficiency	BR %	$\|\Gamma_{LR}\|^2$ sensitivity
(e^-, e^+nn)	$9*10^{35}$	$8*10^{-3}$	1	$3.6*10^{-2}$
$(e^-, e^+\pi)$	$9*10^{34}$	$1.7*10^{-2}$	95	1.7
$(e^-, e^+\pi\pi)$	$9*10^{34}$	$8*10^{-3}$	95	$3.6*10^{-3}$
$(e^-, e^+\pi\pi\pi)$	$9*10^{34}$	$3.8*10^{-3}$	95	$1.8*10^{-4}$

Detection efficiency: according to the data on HCAL on literature.

The Jlab LDCE in a multiple-coincidence view

Beam: e^- @11 GeV
Target: ^{208}Pb (1-0.1 g/c
HRMS for e^+detection
HCAL for π/n detecti



Reaction channe	BR %	$\|\Gamma_{LR}\|^2$ sensitivity
(e^-, e^+nn)	1	3.6*10^{-2}
$(e^-, e^+\pi)$	95	1.7
$(e^-, e^+\pi\pi)$	95	3.6*10^{-3}
$(e^-, e^+\pi\pi\pi)$	95	1.8*10^{-4}

BR: according to **this plot** (J. A. Formaggio and G. P. Zeller., Rev. Mod. Phys., 84 (2012) 1307) where in CC reactions the QE channel is expected to be 1% of the total cross section while the π reaction channels are expected to cover the 95% of the total cross section.

The Jlab LDCE in a multiple-coincidence view

Beam: e^- @11 GeV
Target: ^{208}Pb (1-0.1 g/cm^2);
HRMS for e^+detection $(\theta_{e^+,lab} \sim 3.5° - 7.5°)$
HCAL for π/n detection $\theta_h \sim 30°$ $(Q^2 \sim 1 - 2\ GeV^2)$

Reaction channel	Luminosity (cm^{-2}s^{-1})	Detection efficiency	BR %	$\|\Gamma_{LR}\|^2$ sensitivity
(e^-, e^+nn)	9×10^{35}	8×10^{-3}	1	3.6×10^{-2}
$(e^-, e^+\pi)$	9×10^{34}	1.7×10^{-2}	95	1.7
$(e^-, e^+\pi\pi)$	9×10^{34}	8×10^{-3}	95	3.6×10^{-3}
$(e^-, e^+\pi\pi\pi)$	9×10^{34}	3.8×10^{-3}	95	1.8×10^{-4}

$|\Gamma_{LR}|^2$ sensitivity: evaluated in a 10 days experiment at 5σ C.L. It includes background contributions both from e^+ and π/n according to GEANT IV simulations and 2 ns time windows for coincidence.