Extending physics reach of HI studies with nuclei around A~80

Physics cases for a second ion injector

⬇

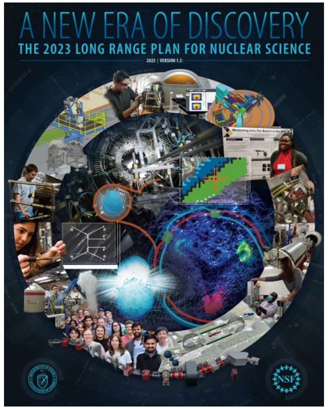
Nuclear Matrix Elements of Neutrinoless Double Beta (0νββ) Decay

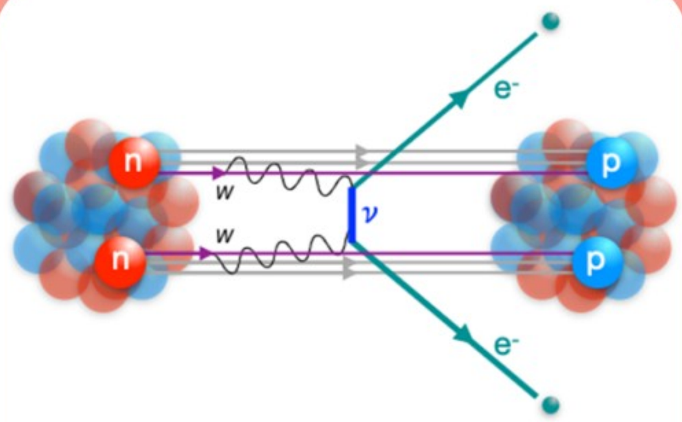
CERN

Giuliano Giacalone

December 3, 2025

Box 4.5: Neutrinoless double beta decay research





A NEW ERA OF DISCOVERY | THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

link

RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

In the hypothetical neutrinoless double beta decay ($0\nu\beta\beta$) two neutrons in the nucleus transform into two protons, and only two electrons are emitted. This process is forbidden in the Standard Model of particle physics, as two matter particles are created without any antimatter. $0\nu\beta\beta$ is expected to be mediated by the exchange of a neutrino (see upper panel) that must be its own antiparticle (i.e., a Majorana particle). Hence, the detection and subsequent study of $0\nu\beta\beta$ would deeply impact our understanding of neutrinos, physics beyond the Standard Model, and why the observed universe is formed by matter. Searching for this extremely rare decay is the goal of several ongoing and future experimental programs. However, a main uncertainty for predicting $0\nu\beta\beta$ half-lives comes from the nuclear matrix elements (NMEs) connecting the initial and final nuclear states. NMEs are calculated with many-body techniques routinely used to describe nuclear structure (e.g., nuclear shell model, energy density functional, QRPA)
up to a factor of 3-4 for the isotopes of interest (
methods (Coupled cluster, In-medium SRG, PG
$0\nu\beta\beta$ with a more consi
become essential to prov
promising way is to extra
charge exchange react
electromagnetic transitio
the NMEs of $0\nu\beta\beta$ and th

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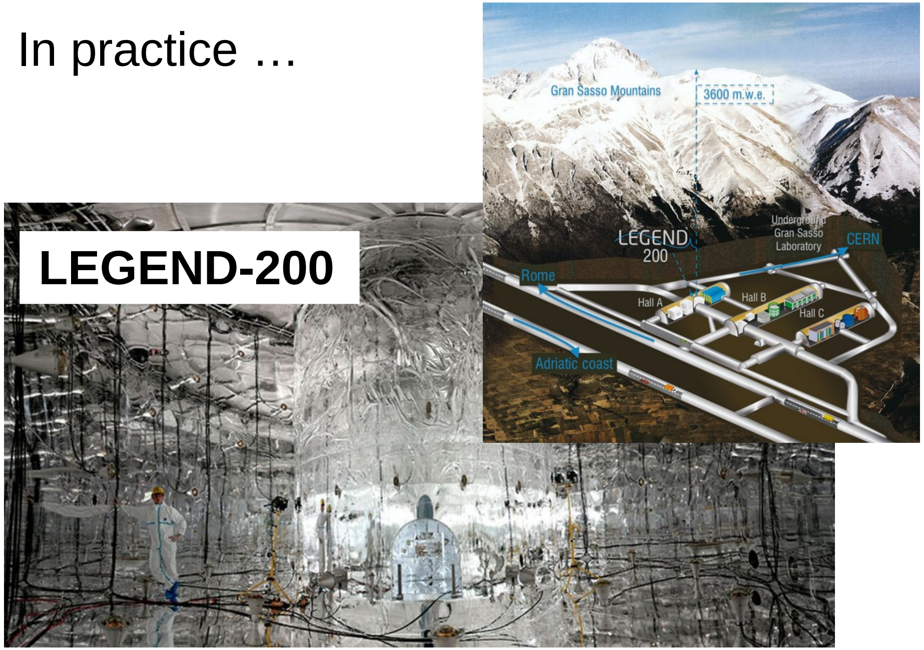
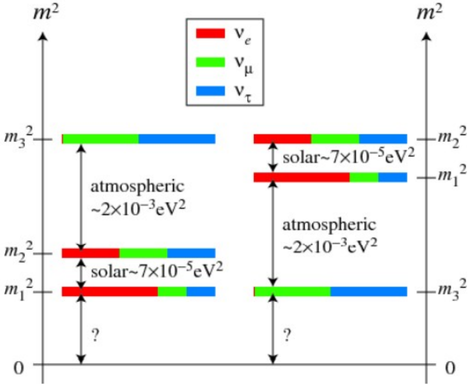
In practice …

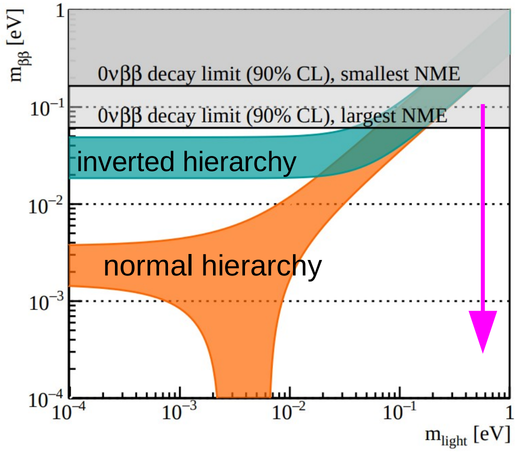


observation — nuclear structure — new physics

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \qquad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

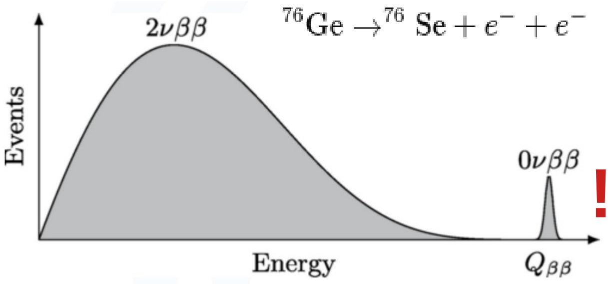
$$m_{\beta\beta} = \left|\sum U_{ek}^2 m_k\right|$$





$^{48}Ca \rightarrow {}^{48}Ti$
$^{76}Ge \rightarrow {}^{76}Se$
$^{82}Se \rightarrow {}^{82}Kr$
$^{96}Zr \rightarrow {}^{96}Mo$
$^{100}Mo \rightarrow {}^{100}Ru$
$^{110}Pd \rightarrow {}^{110}Cd$
$^{116}Cd \rightarrow {}^{116}Sn$
$^{124}Sn \rightarrow {}^{124}Te$
$^{130}Te \rightarrow {}^{130}Xe$
$^{136}Xe \rightarrow {}^{136}Ba$
$^{150}Nd \rightarrow {}^{150}Sm$

… what we hope to see



~ 2 MeV

Future proposals (e.g. LEGEND-1000) are O(1B)$ endeavors

[Agostini *et al.*, RMP **95** (2023) 2, 025002]

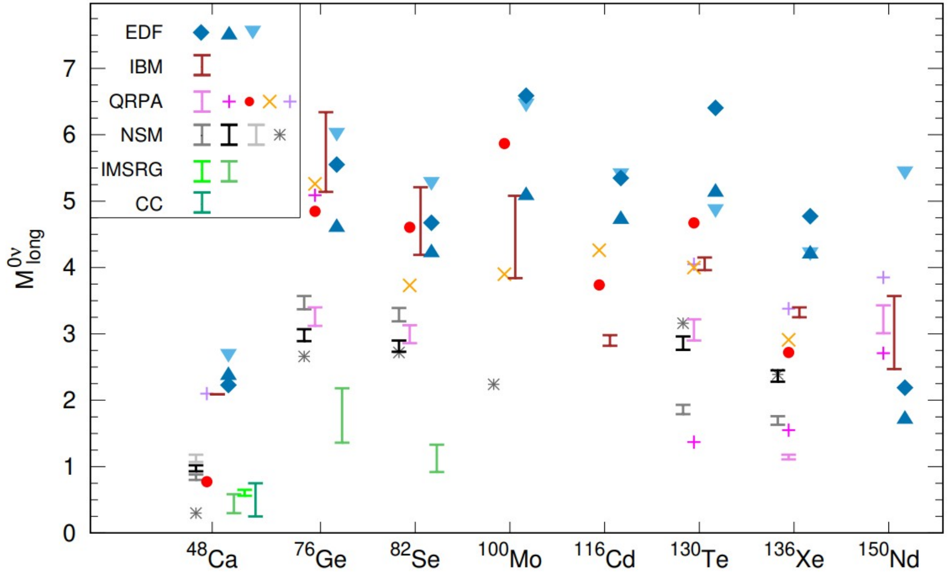
Bottleneck for interpretation/design – NMEs

observation **NME**

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu} \left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2 \quad \langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$$

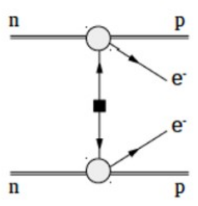
new physics

$$\langle\Psi_F|\hat{O}^{0\nu}(\mathbf{r}_1,\mathbf{r}_2)|\Psi_I\rangle$$



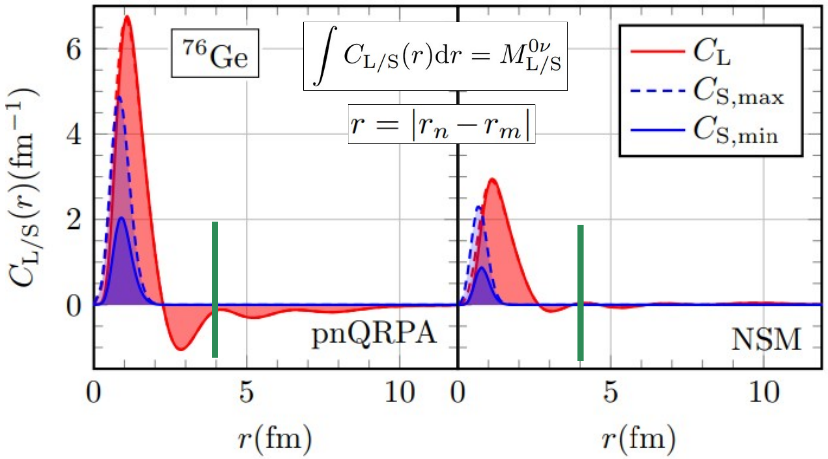
Two-body properties of ground states at various length scales

Jordy de Vries (UVA)
CERN-TH Colloquium
Feb 25

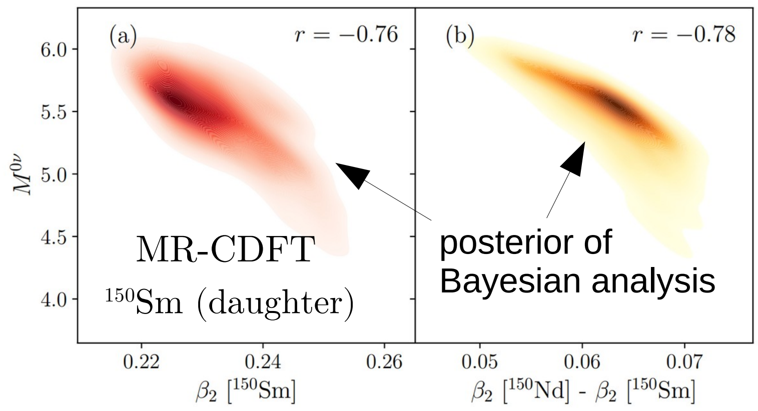


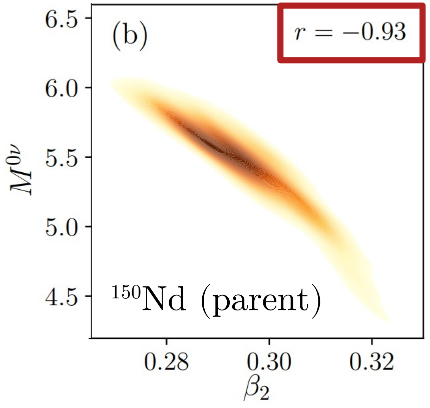
- Large nuclei —> complicated many-body nuclear matrix elements
- Nuclear methods and codes are benchmarked on 'single-nucleon-currents' physics

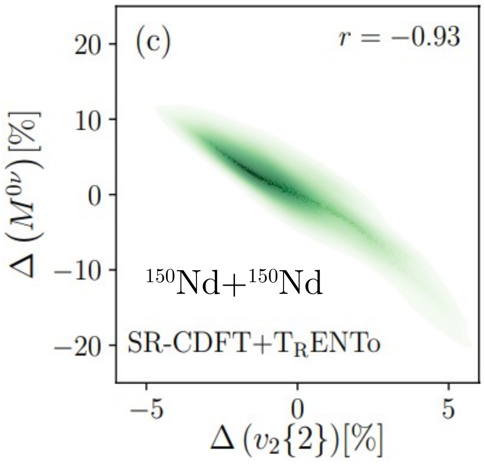
[Jokiniemi, Soriano, Menéndez, PLB **823** (2021) 136720]



Example with deformed 150Nd-Sm – Strong correlation with parent isotope deformation

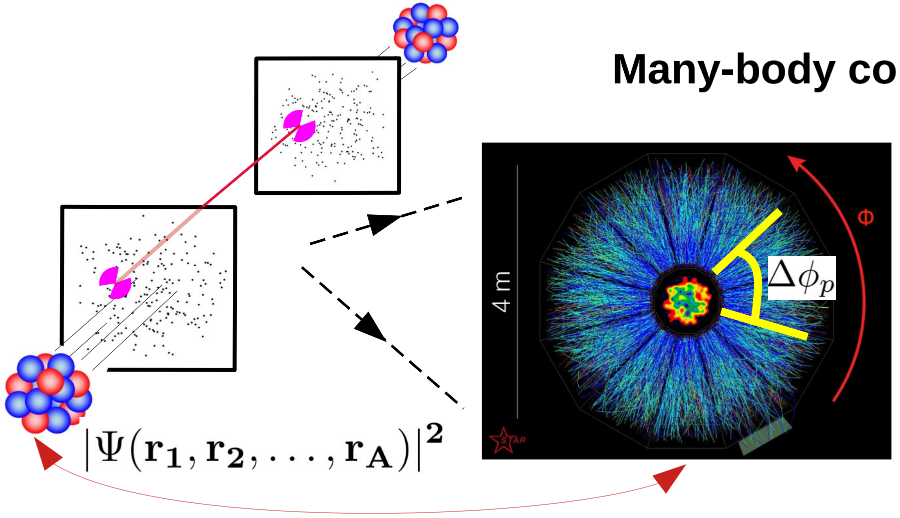






[Li, Giacalone, Yao, Zhang, PRL **135** (2025) 2, 022301]

Many-body correlations – Unique capability of high-energy collisions



$$\frac{dN_{\rm pairs}}{d\Delta\phi_p} \propto 1 + 2\,v_2^2\,\cos(2\Delta\phi_p) + \ldots$$

elliptic flow

$$\langle v_2^2\rangle \longrightarrow \int_{\mathbf{r}_1,\mathbf{r}_2} r_{\perp 1}^2\, r_{\perp 2}^2\, e^{i\,2(\phi_1-\phi_2)}\, \rho^{(2)}(\mathbf{r}_1,\mathbf{r}_2)$$

$\langle \hat{\mathcal{E}}_2 \rangle$

nucleon-nucleon correlation!

[Duguet, Giacalone, Jeon, Tichai, PRL **135** (2025) 18, 182301]

2025 – NME@LHC “Task Force”

HEP: Nuclear
(Trajectum, IP-Glasma+MUSIC)

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Wilke van der Schee (CERN/Utrecht)
Charles Gale (McGill)
Sangyong Jeon (McGill)
Noah Kakekaspan (McGill)

NUCLEAR STRUCTURE
(*ab initio*, emulators, NMEs)

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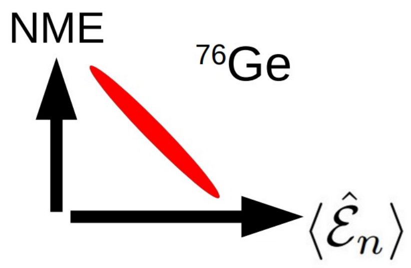
Yi Li (SYSU Zhuhai)
Jiangming Yao (SYSU Zhuhai)
Benjamin Bally (TUDarmstadt)
Alexander Tichai (TUDarmstadt)
Takayuki Miyagi (Tsukuba U)
Javier Ménendez (UBarcelona)

χEFT / BSM

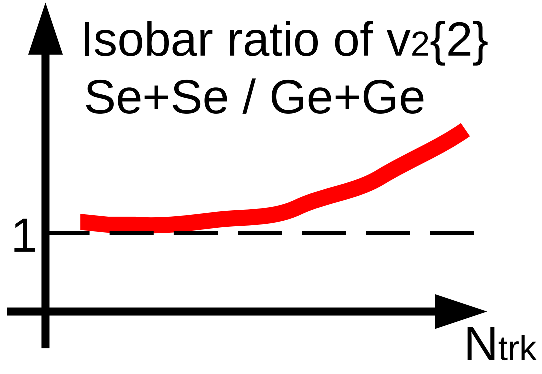
Jordy de Vries (UVAmsterdam)

Emulation and global sensitivity analysis to correlate NME with operators accessible via <vn^2>



accessible via flow measurements

Feasibility of $\langle \hat{\mathcal{E}}_n \rangle$ extraction in collider run based on hydro



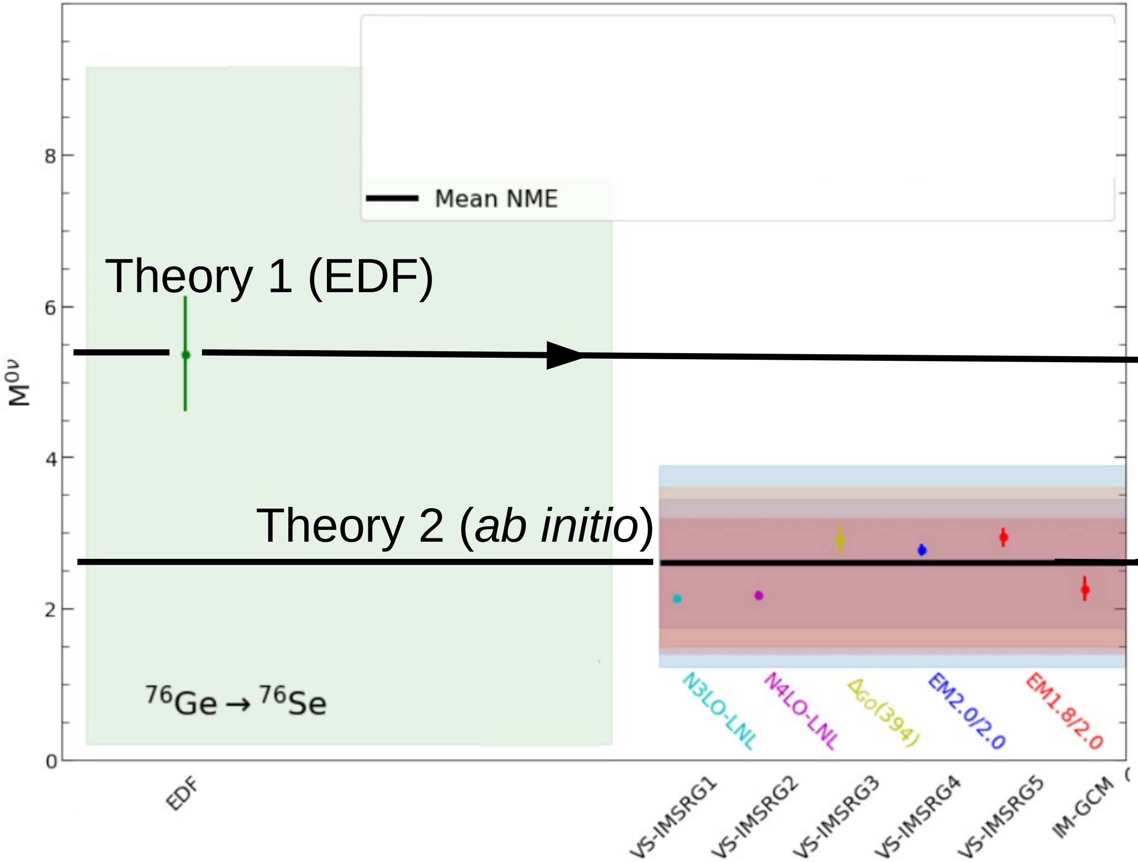
Understanding relation between NME and two-body correlations in parent species isotopes

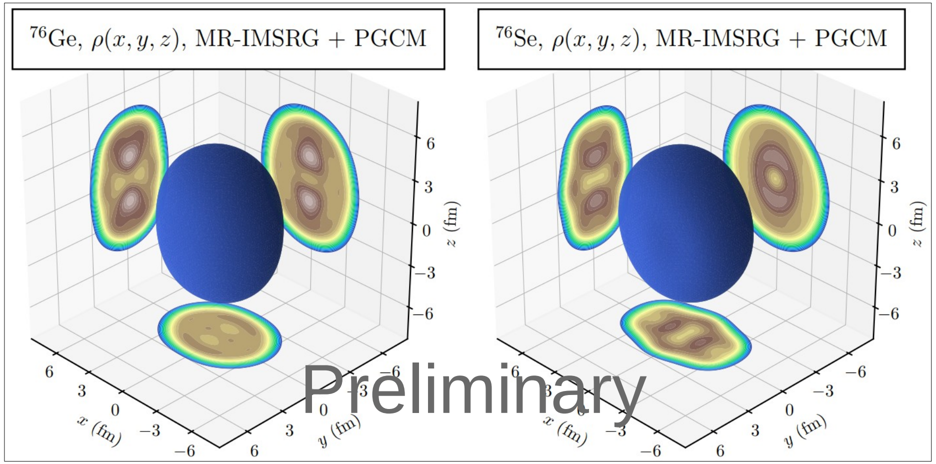
$$M^{0\nu} = \langle {}^{76}\mathrm{Se}(0_1^+) |\, \hat{O}^{0\nu} \,| {}^{76}\mathrm{Ge}(0_1^+) \rangle$$

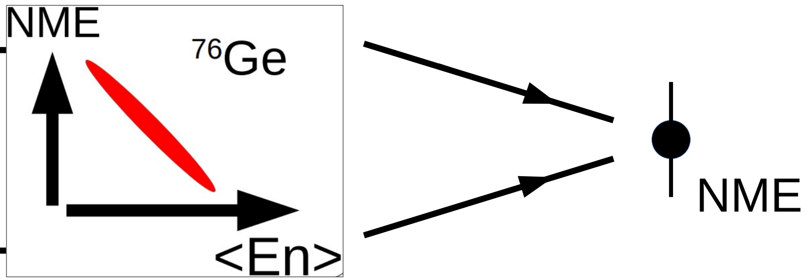
$$\rightarrow \langle \widetilde{{}^{76}\mathrm{Ge}(0_1^+)} |\, \hat{O}^{0\nu} \,| {}^{76}\mathrm{Ge}(0_1^+) \rangle + \ldots$$

GOAL

^{76}Ge, ^{76}Se are isobars, highly deformed (triaxial)
Everything is illuminated @ LHC







LHC constraint

?

[Belley *et al.*,PRL **132** (2024) 18, 182502]

CONCLUSION

- Neutrinoless double beta **($0\nu\beta\beta$) decay is the most promising avenue to discover lepton number violation and elucidate nature of neutrinos**

- **Nuclear Matrix Elements required to interpret signal and design experiments**
  They require a good theoretical control of many-body ground-state correlations

- Low-hanging fruit in high-energy collisions? **^{76}Ge and ^{76}Se are isobars with highly complex structures – Full exploitation of multi-particle correlation techniques!**

- Launched **NME@LHC project** to quantify possible impact of LHC data on NME evaluations
  Get in touch if you are interested!

- **Scientific reach very strongly enhanced if ^{76}Ge and ^{76}Se collided in “isobar mode”**
  Clear and strong physics case for a second ion injector!