

Benchmarking nuclear matrix elements of $0\nu\beta\beta$ decay with heavy-ion collisions

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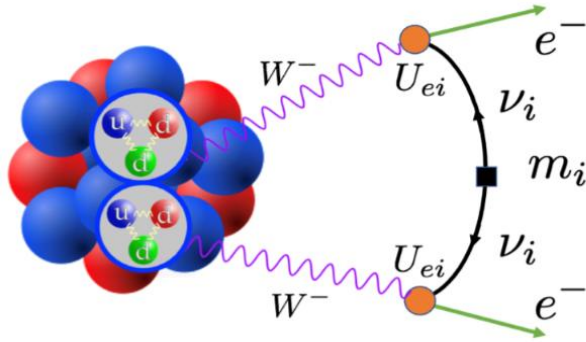
Spicy Gluons 2026: Workshop for Young Scientists on the Quark-Gluon Matter in Extreme Conditions
Wuhan 2026.10.17-2026.10.20

- ❑ Motivation
- ❑ Theoretical framework
- ❑ Results of correlation analysis
- ❑ Summary

Neutrinoless double beta ($0\nu\beta\beta$) decay

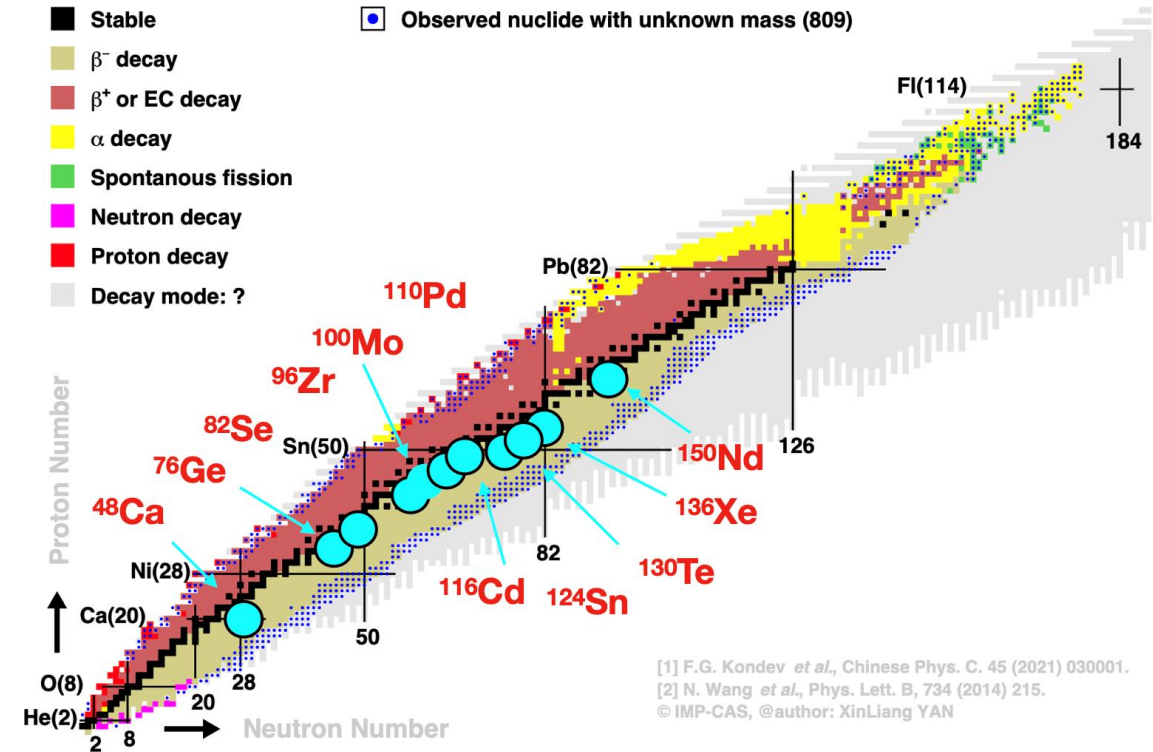
- Neutrinoless double beta ($0\nu\beta\beta$) decay:

$$(A, Z) \rightarrow (A, Z + 2) + 2e^{-}$$



- Determine the nature of the neutrino (Dirac or Majorana)
- Determine the effective neutrino mass $\langle m_{\beta\beta} \rangle$
- Demonstrate the violation of the lepton number in nature
- Understand the origin of the matter-antimatter asymmetry

Nuclear Chart: decay mode of the ground state nuclide(NUBASE2020)



Neutrinoless double beta ($0\nu\beta\beta$) decay



$$\langle m_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^3 U_{ei}^2 m_i \right| = \left[\frac{m_e^2}{g_A^4 G_{0\nu} T_{1/2}^{0\nu} |M^{0\nu}|^2} \right]^{1/2}$$

↑
↑
↑

effective neutrino mass
experimental half-life
Nuclear matrix element (NME)

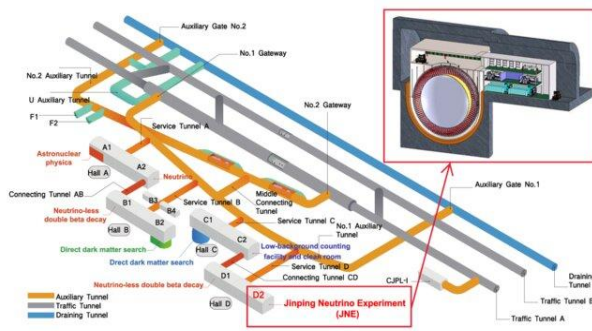
$$M^{0\nu} = \langle \Psi_F(0_1^+) | \hat{O}^{0\nu} | \Psi_I(0_1^+) \rangle$$

Isotope	$G_{0\nu}$ [10^{-14} yr^{-1}]	$M^{0\nu}$ [min, max]	$T_{1/2}^{0\nu}$ [yr]	$\langle m_{\beta\beta} \rangle$ [meV]	Experiments with best sensitivity References
^{76}Ge	0.24	[2.38, 6.64]	$> 1.8 \cdot 10^{26}$	[73, 180]	GERDA: PRL125, 252502(2020)
^{82}Se	1.01	[2.72, 5.30]	$> 4.6 \cdot 10^{24}$	[277, 540]	CUPID-0: PRL129, 111801 (2023)
^{100}Mo	1.59	[3.84, 6.59]	$> 2.9 \cdot 10^{24}$	[210, 610]	AMoRE-I: PRL134, 082501 (2025)
^{130}Te	1.42	[1.37, 6.41]	$> 2.2 \cdot 10^{25}$	[90, 305]	CUORE: Nature 604, 53(2022)
^{136}Xe	1.46	[1.11, 4.77]	$> 3.8 \cdot 10^{26}$	[28, 122]	KamLAND-Zen: arXiv:2406.11438v1 (2024)



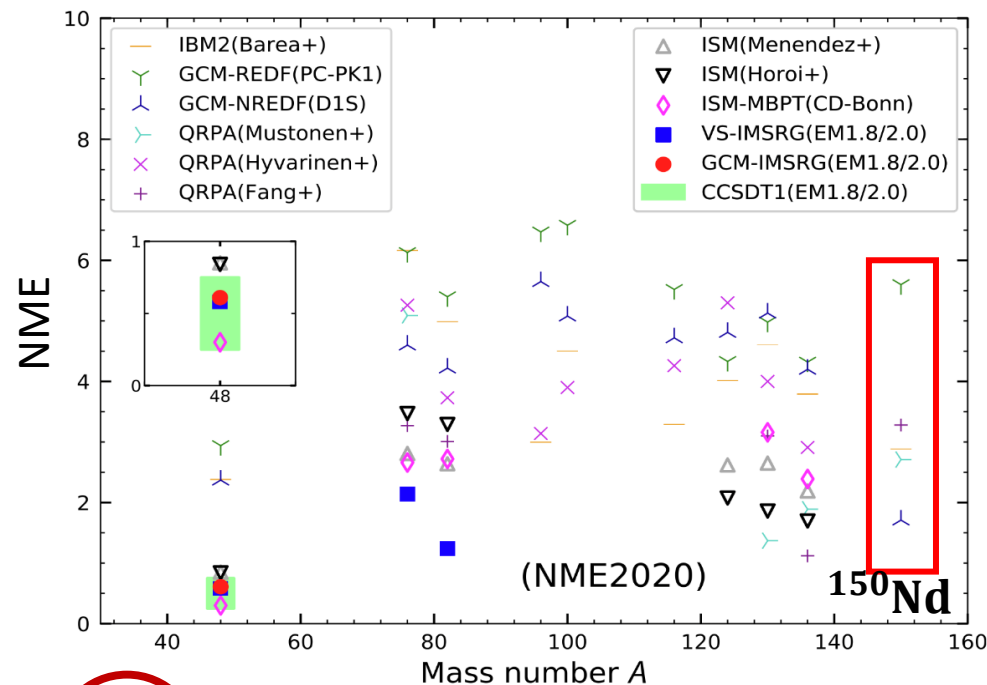
江门地下中微子实验 (JUNO)

- JUNO: $^{130}\text{Te}/^{136}\text{Xe}$



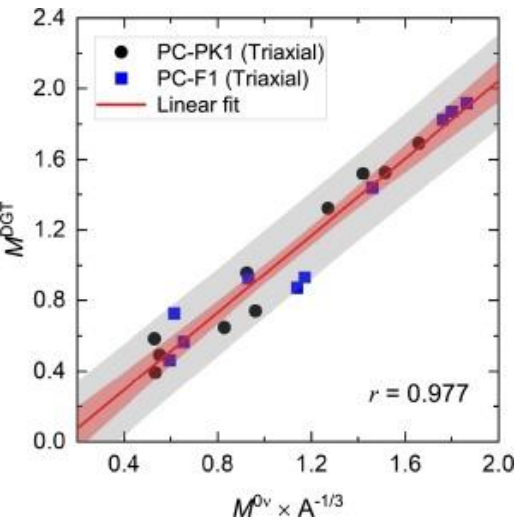
中国锦屏地下实验室 (CJPL)

- CDEX: ^{76}Ge PandaX: ^{136}Xe



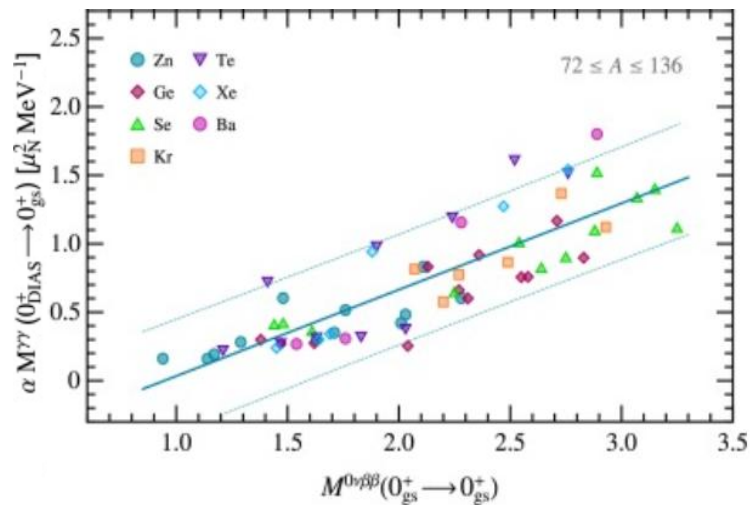
The NMEs calculated using different models differs by 2 to 3 times !

Correlation between NMEs and low-energy nuclear observables



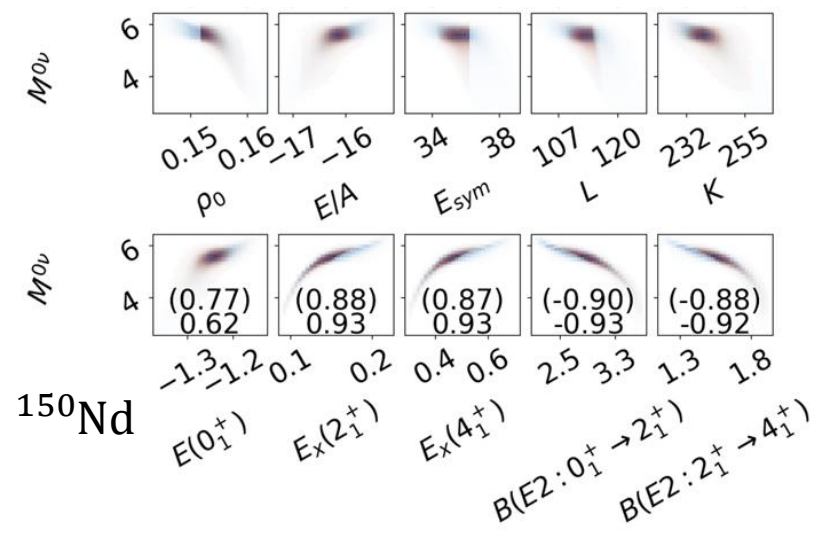
Phys. Lett. B 855, 138796 (2024)

Double Gamow-Teller transitions



Phys. Lett. B 827, 136965 (2022)

Double gamma ($\gamma\gamma$) transitions



Phys. Rev. C 112, L021302(2025)

Properties of nuclear low-lying states

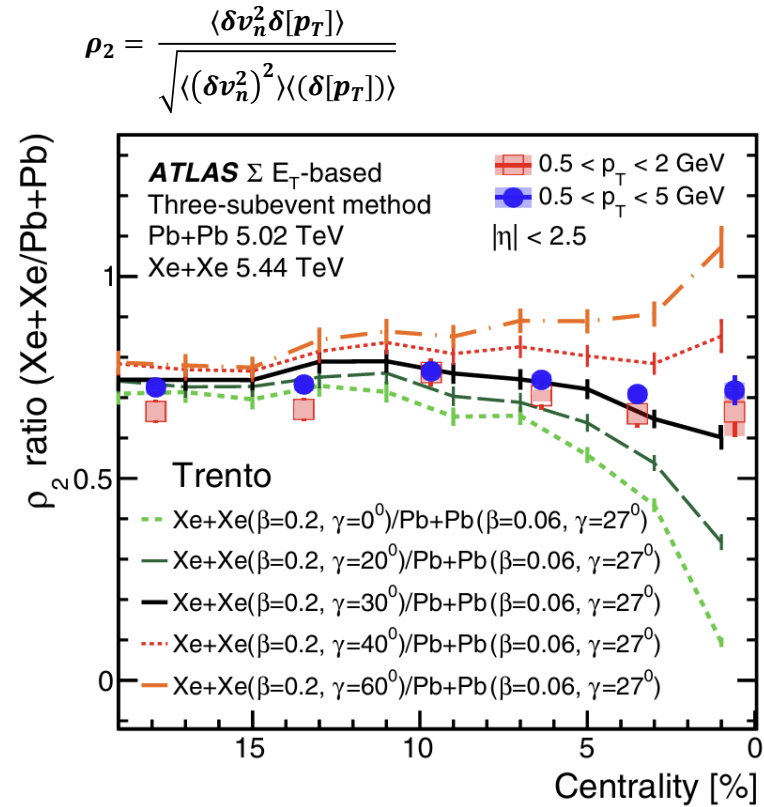
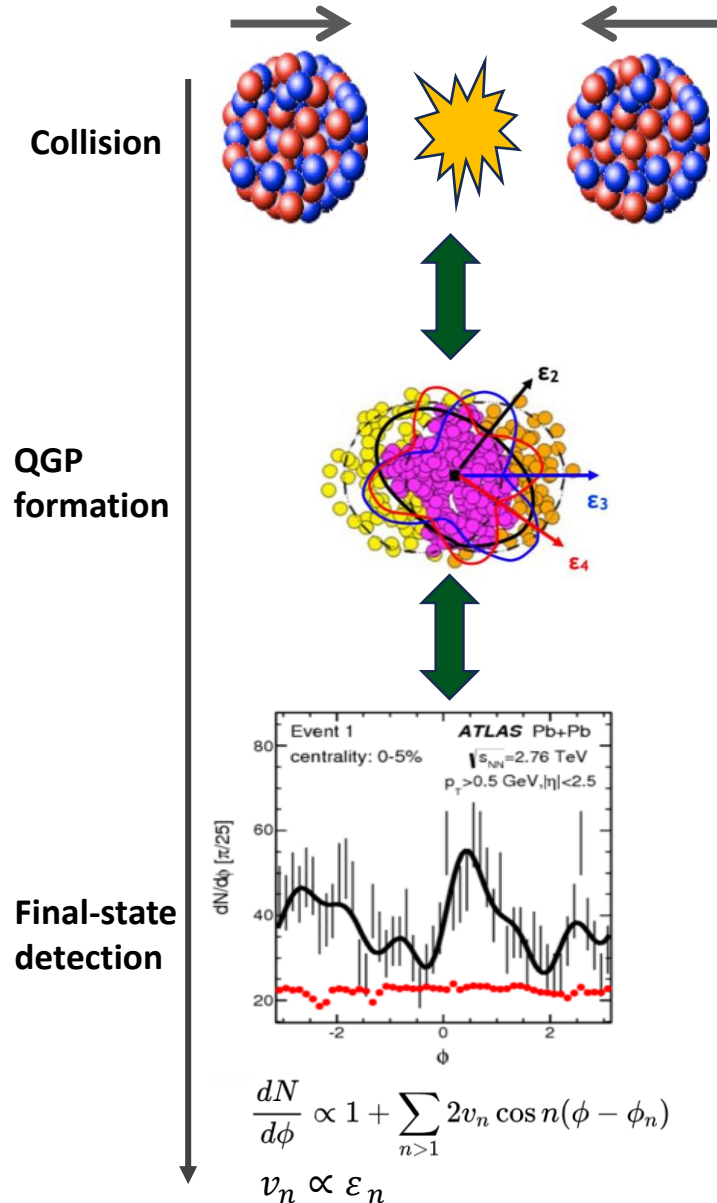


✓ The NME exhibits a correlation with these low-energy experimental observables.



- Double Gamow-Teller transitions and double gamma decays have weak signals and are difficult to measure.
- The correlations between NMEs and the properties of low-lying nuclear states depend on the nucleus.

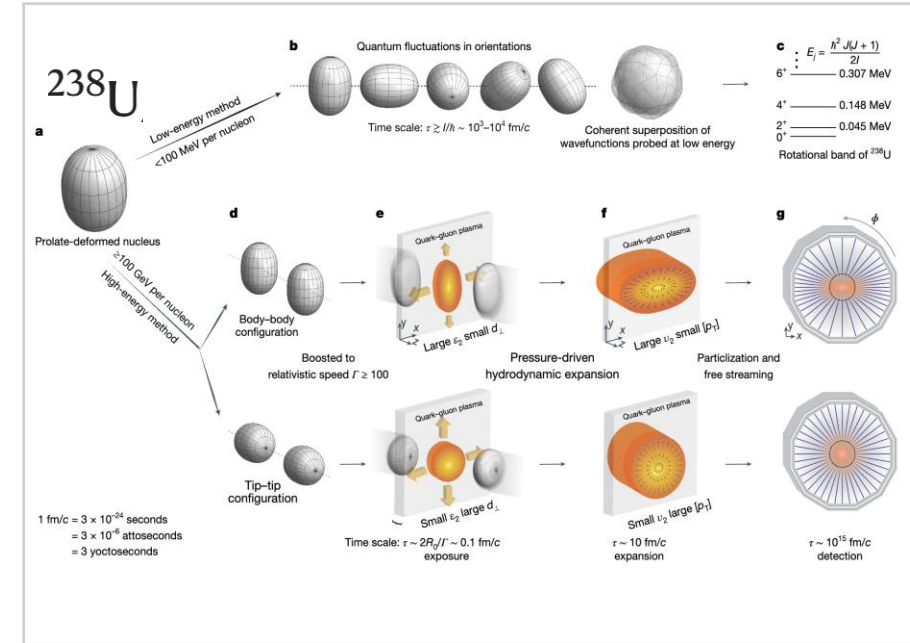
Probing nuclear structure with heavy-ion collisions

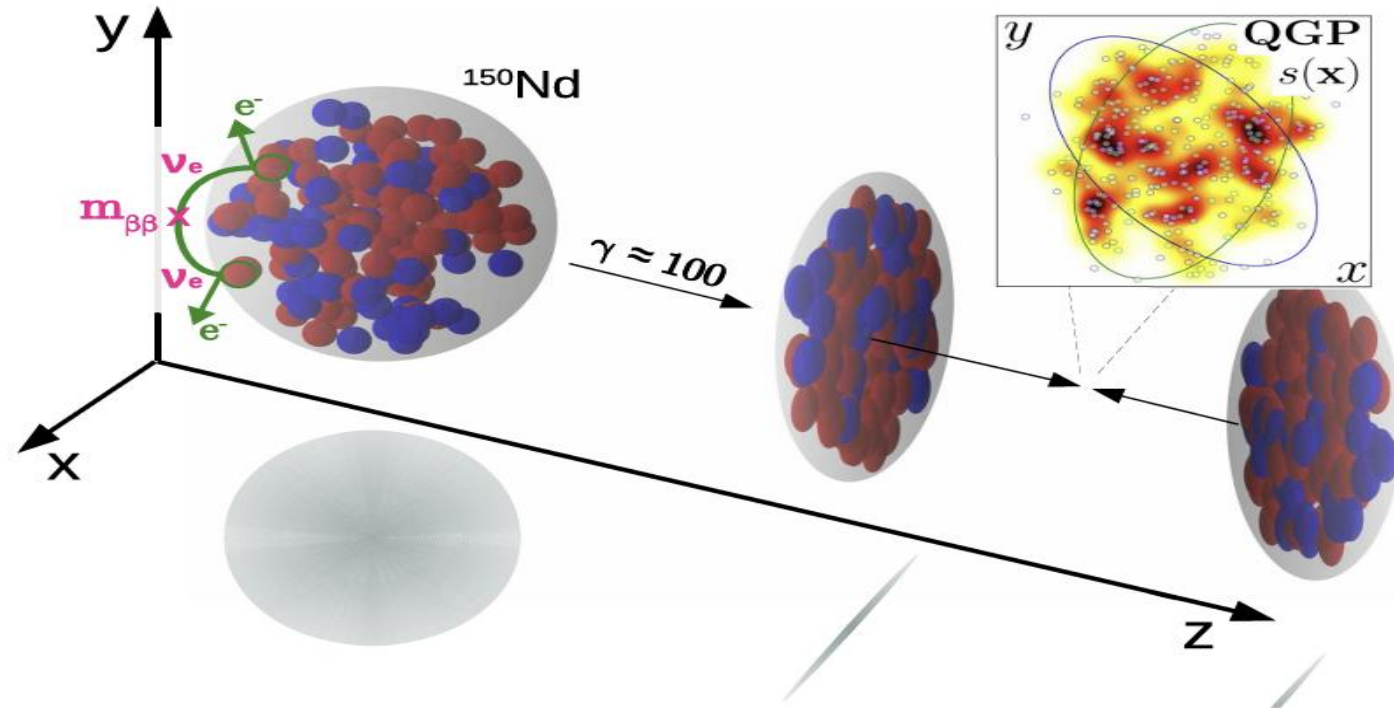


ATLAS Collaboration *Phys. Rev. C* 107, 054910 (2023)

STAR Collaboration *Nature* 635, 67 (2024)

- ✓ The initial shape of the nuclei can be inferred from the observables of the collision final state.



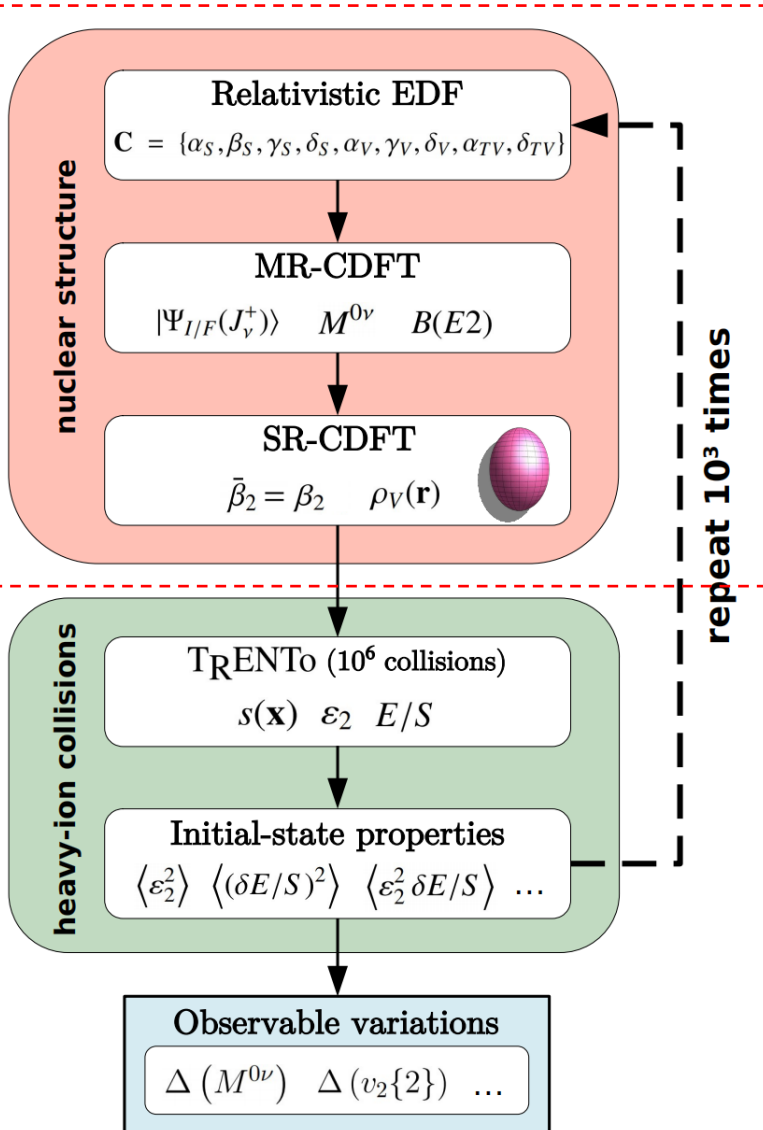


NME of $0\nu\beta\beta$

observables of HIC

💡 Are these HIC observables have correlations with the NME?

Theoretical framework of nuclear structure



Relativistic energy density functional (EDF)

- The EDF is composed of kinetic energy, electromagnetic energy and interaction energy

$$E[\tau, \rho, \nabla \rho; \mathbf{C}] = \int d^3r [\tau(\mathbf{r}) + \mathcal{E}^{\text{em}}(\mathbf{r}) + \mathcal{E}^{\text{int}}(\mathbf{r})]$$

- The NN interaction EDF

$$\begin{aligned} \mathcal{E}^{\text{int}}(\mathbf{r}) = & \frac{\alpha_S}{2} \rho_S^2 + \frac{\beta_S}{3} \rho_S^3 + \frac{\gamma_S}{4} \rho_S^4 + \frac{\delta_S}{2} \rho_S \Delta \rho_S \\ & + \frac{\alpha_V}{2} j_\mu j^\mu + \frac{\gamma_V}{4} (j_\mu j^\mu)^2 + \frac{\delta_V}{2} j_\mu \Delta j^\mu \\ & + \frac{\alpha_{TV}}{2} \mathbf{j}_{TV}^\mu \cdot (\mathbf{j}_{TV})_\mu + \frac{\delta_{TV}}{2} \mathbf{j}_{TV}^\mu \cdot \Delta (\mathbf{j}_{TV})_\mu \end{aligned}$$

- The nine free parameters

$$\mathbf{C} = \{\alpha_S, \beta_S, \gamma_S, \delta_S, \alpha_V, \gamma_V, \delta_V, \alpha_{TV}, \delta_{TV}\}$$

The **1,000 EDF parameter sets**, obtained by varying the nine parameters $\mathbf{C}$ around the PC-PK1 values, are used for correlation analysis

Theoretical framework of nuclear structure

Calculation of the NME

- Nuclear wave functions are linear combinations of particle-number (N, Z) and angular-momentum(J) projected wave functions,

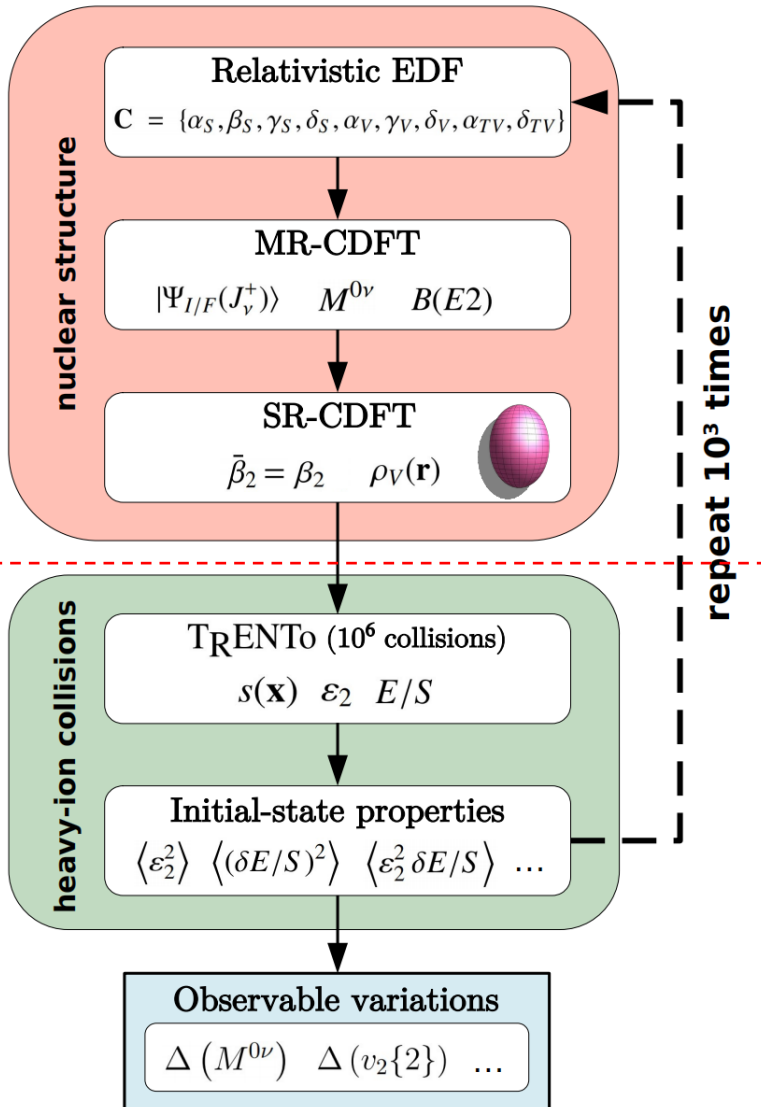
$$|\Psi_{I/F}(J_\nu^+, \mathbf{C})\rangle = \sum_{\mathbf{q}} f_\nu^{JNZ}(\mathbf{q}, \mathbf{C}) \hat{P}^N \hat{P}^Z \hat{P}^J |\Phi(\mathbf{q}, \mathbf{C})\rangle$$

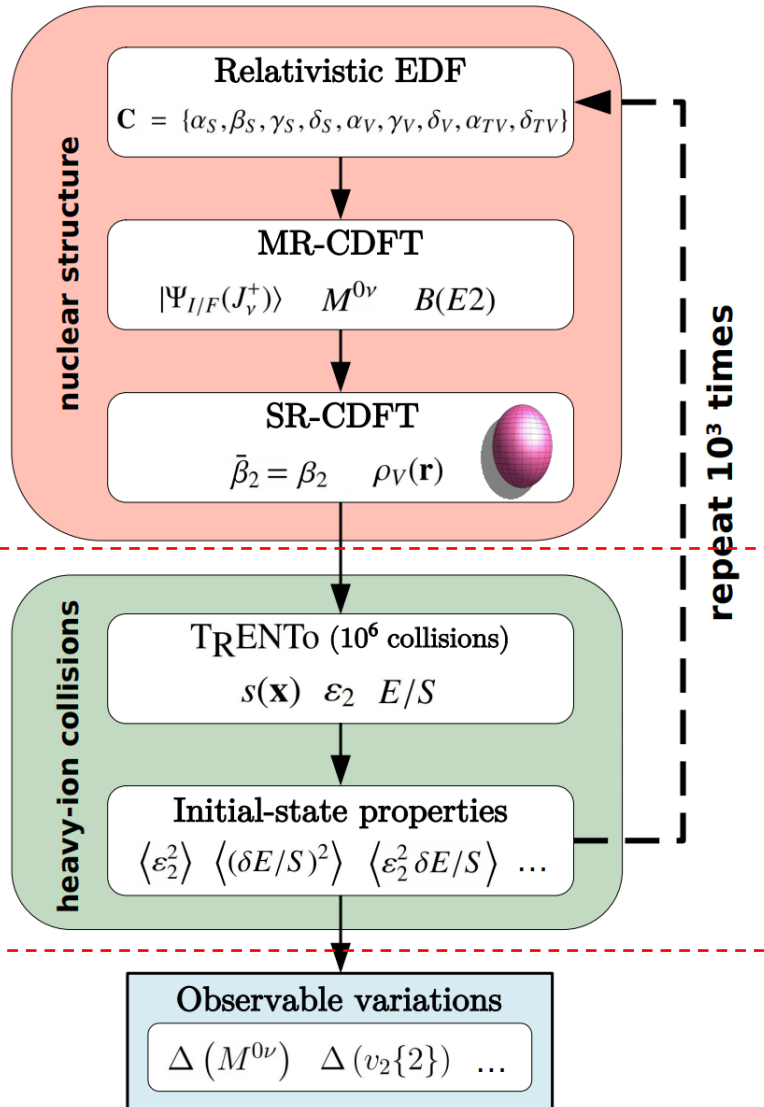
where the mean-field wave functions $|\Phi(\mathbf{q}, \mathbf{C})\rangle$ are determined by constrained relativistic mean-field (RMF) + BCS theory and the weight function f_ν^{JNZ} is determined by solving the Hill-Wheeler-Griffin (HWG) equation:

$$\sum_{\mathbf{q}'} [\mathcal{H}^C(\mathbf{q}, \mathbf{q}') - E_\nu^{JNZ} \mathcal{N}^C(\mathbf{q}, \mathbf{q}')] f_\nu^{JNZ}(\mathbf{q}', \mathbf{C}) = 0$$

- The NME of the ground-state-to-ground-state $0\nu\beta\beta$ decay is given by

$$M^{0\nu}(\mathbf{C}) = \langle \Psi_F(0_1^+, \mathbf{C}) | \hat{O}^{0\nu} | \Psi_I(0_1^+, \mathbf{C}) \rangle$$





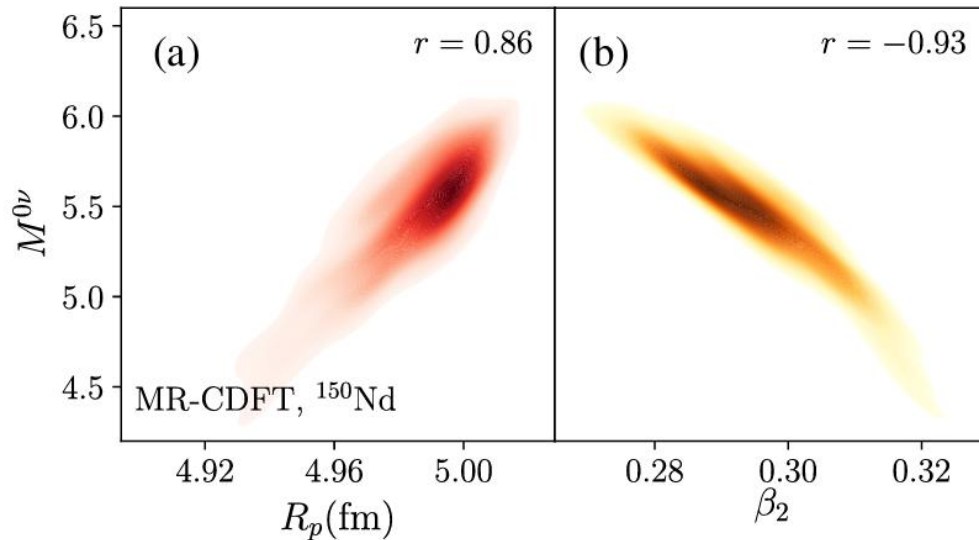
Calculation of HIC observables

- The nuclear densities are used as inputs for the **T_RENTo model** to simulate the high-energy $^{150}\text{Nd} + ^{150}\text{Nd}$ collisions.
- The simulation yields the spatial ellipticity ε_2 and the ratio of total energy to total entropy E/S of the QGP.
- The final-state angular distribution of the heavy-ion collision is obtained

$$\frac{dN_{\text{ch}}}{d^2\mathbf{p}} \propto \frac{dN_{\text{ch}}}{p_T dp_T} \left(1 + \sum_{n>1} 2v_n \cos n(\phi - \phi_n) \right)$$

where v_2 and p_T are strongly correlated with ε_2 and E/S , respectively, such that $v_2 \propto \varepsilon_2, p_T \propto E/S$.

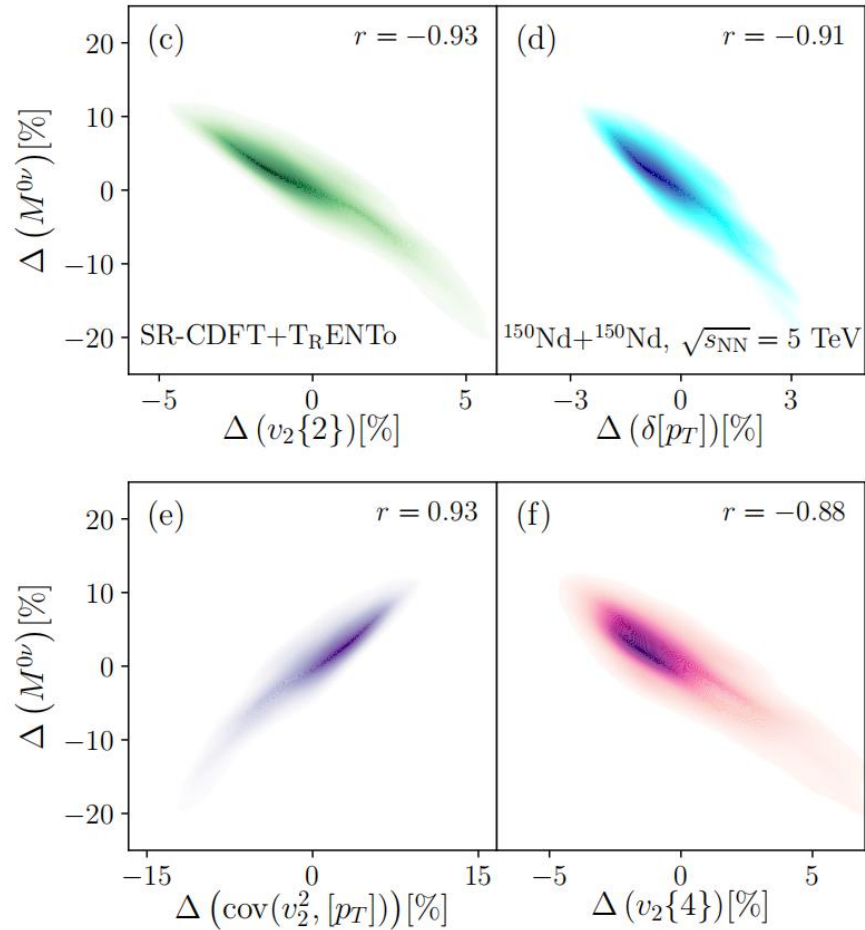
- v_2 is the elliptic flow coefficient of final-state particles.
- p_T is the transverse momentum of final-state particles.



Y. Li, X. Zhang, G. Giacalone, J.M. Yao *Phys. Rev. Lett.* 135, 022301 (2025)

- We performed the correlation analysis using 1000 sets of EDF parameters.
- ✓ The NME is correlated with the nuclear proton radius R_p and the quadrupole deformation parameter β_2

Correlation between NMEs and heavy-ion collision observables



$^{150}\text{Nd} + ^{150}\text{Nd}$, ultra-central collisions ($b=0\text{fm}$)

- v_2 is the elliptic flow coefficient of final-state particles.
- p_T is the transverse momentum of final-state particles.

Y. Li, X. Zhang, G. Giacalone, J.M. Yao *Phys. Rev. Lett.* 135, 022301 (2025)

- observables of interest
- Relative variation of an observable

$$\Delta(v_2\{2\}) \equiv \frac{1}{2} \Delta(\langle v_2^2 \rangle),$$

$$\Delta(\delta[p_T]) \equiv \frac{1}{2} \Delta(\langle (\delta[p_T])^2 \rangle),$$

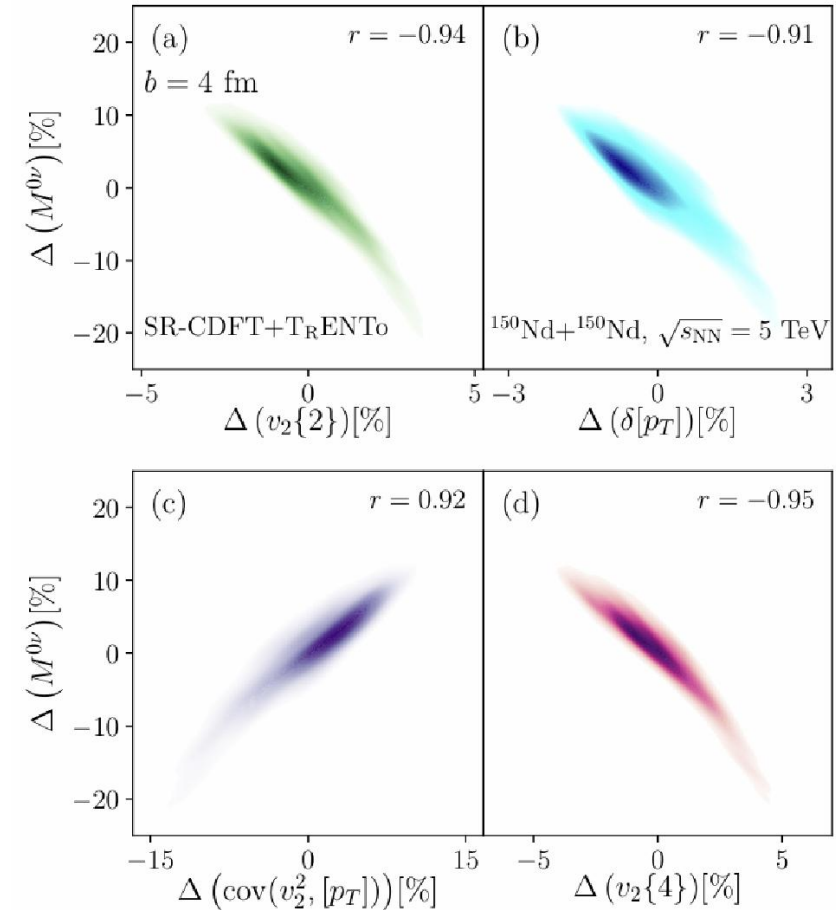
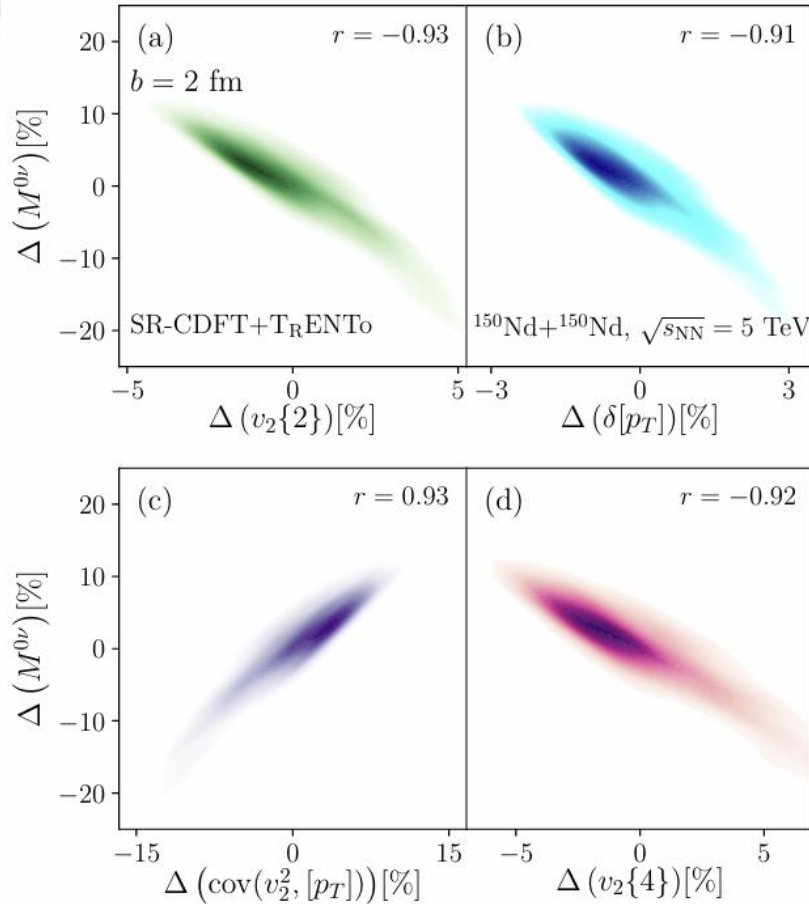
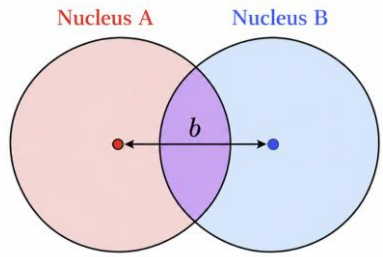
$$\Delta(\text{cov}(v_2^2, [p_T])) \equiv \frac{1}{3} \Delta(\langle v_2^2 \delta[p_T] \rangle),$$

$$\Delta(v_2\{4\}) \equiv \frac{1}{4} \Delta(2\langle v_2^2 \rangle^2 - \langle v_2^4 \rangle)$$

$$\Delta(\mathcal{O}) = \frac{\mathcal{O} - \langle \mathcal{O} \rangle_{\text{c}}}{|\langle \mathcal{O} \rangle_{\text{c}}|},$$

- ✓ There are **strong correlations** between the NME of $0\nu\beta\beta$ decay and quantities accessible at colliders.
- ✓ With the upcoming detector upgrades (such as ALICE 3), the measurement of HIC observables will be more precise. These observables could help **reduce the uncertainty** of the NME.

Correlation between NMEs and high-energy collision observables



✓ The strong correlation is still maintained as the impact parameter b increases.

Summary

- ✓ There are **significant uncertainties** in the nuclear matrix elements (NMEs) for neutrinoless double beta decay calculated using different theoretical models.
- ✓ We have conducted the first statistical analysis of the correlation between NMEs of $0\nu\beta\beta$ decay and observables from HIC using energy density functional theory (EDFT).
- ✓ The heavy-ion collision observables (of ^{150}Nd) investigated in this study exhibit a **strong correlation** with NME, offering a promising way to constrain the NME in the future.

Outlook

- Verify whether the correlation exhibits model-dependence and nucleus-dependence.
- Combine experimental data to constrain the value of NME.

Thanks !