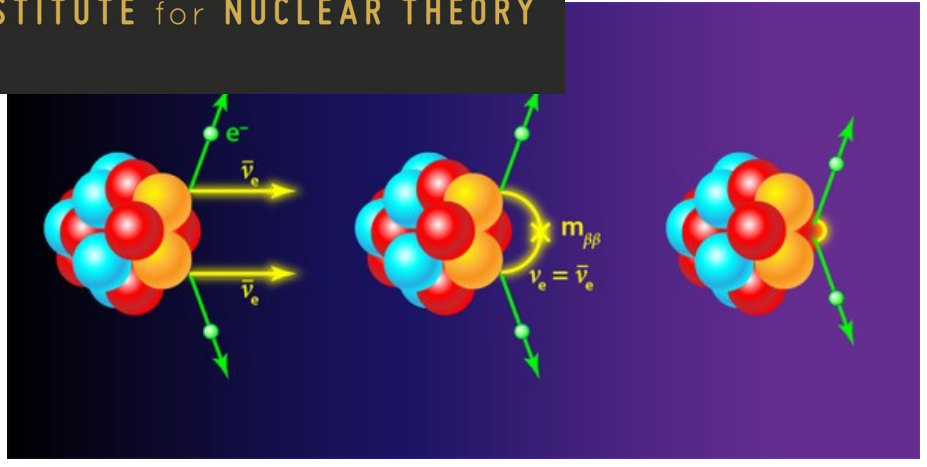
Probing nuclear correlations relevant for NMEs in high-energy nuclear collisions

Giuliano Giacalone

July 22, 2026

INSTITUTE for NUCLEAR THEORY



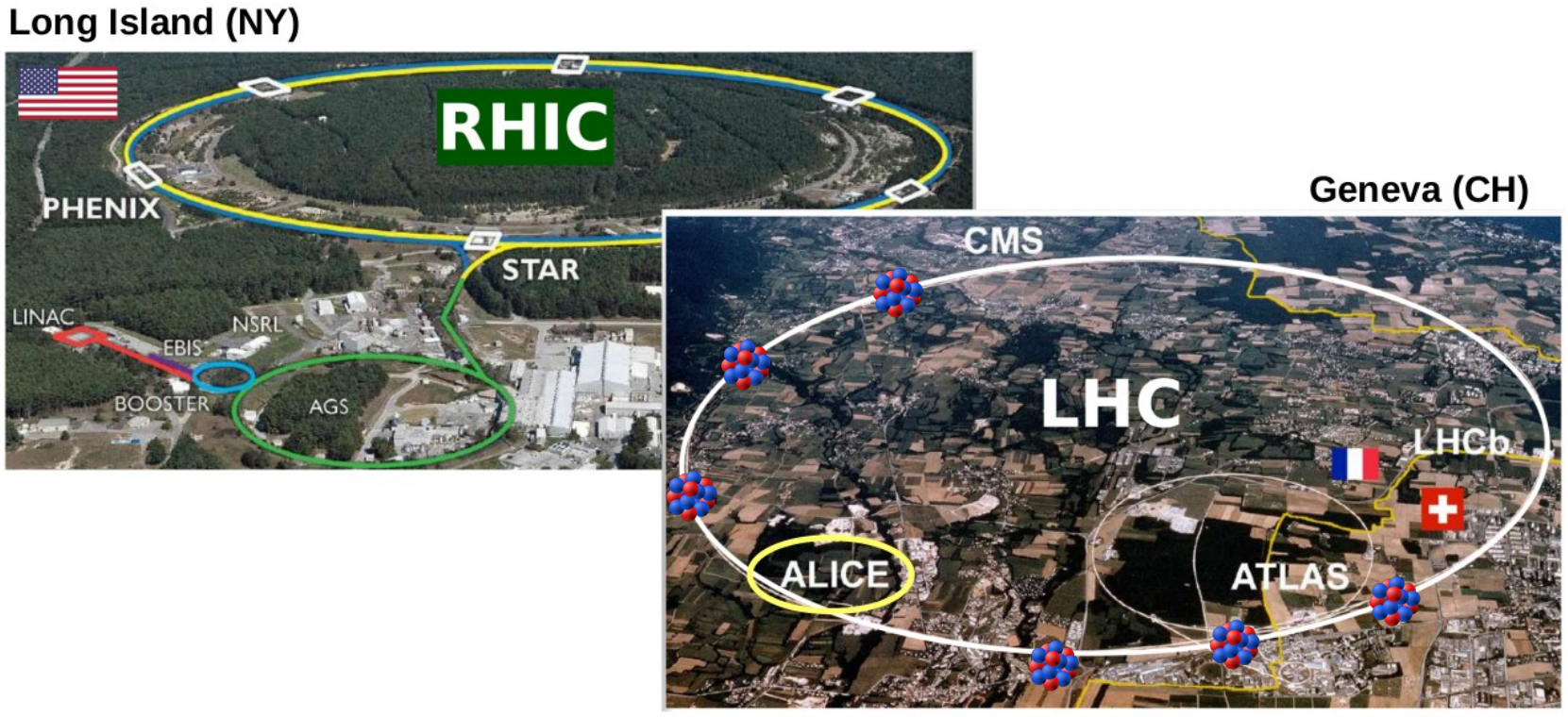
INT Program – INT-26-2a

Recommended Values for

Neutrinoless Double-Beta Decay

Nuclear Matrix Elements

High-energy (ultra-relativistic) nuclear (“heavy-ion”) collisions



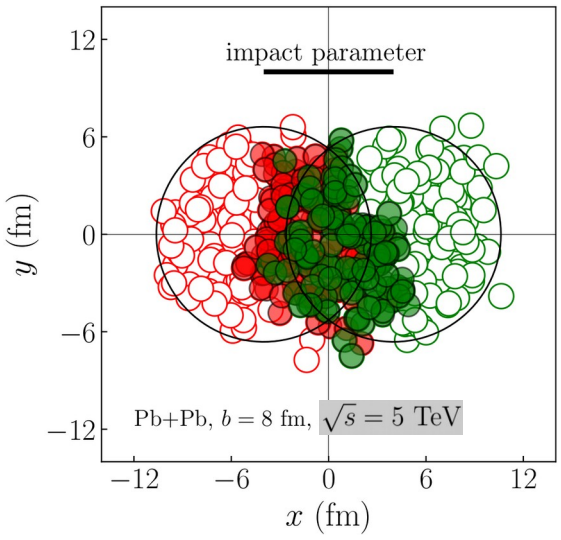
– From 2000 at Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider (RHIC)

PROGRAM ENDED FEBRUARY 2026

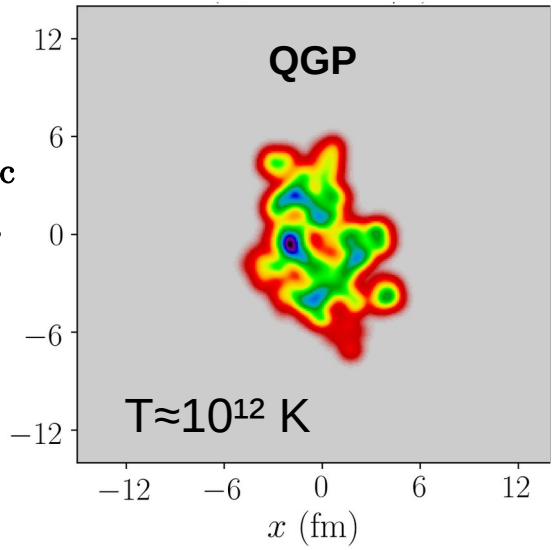
– Nuclear collisions about 1 month/year at the CERN Large Hadron Collider (LHC)

SHOULD KEEP COLLIDING NUCLEI UNTIL ~2042

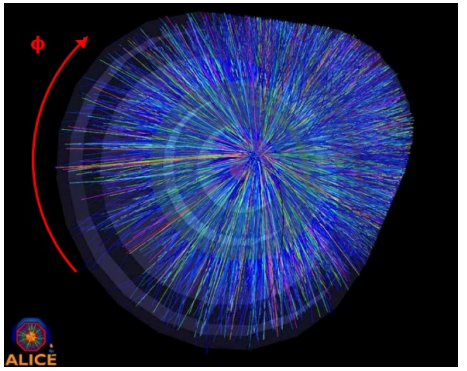
The perfect QCD fluid – 25 years later



≈ 1 fm/c



hydro



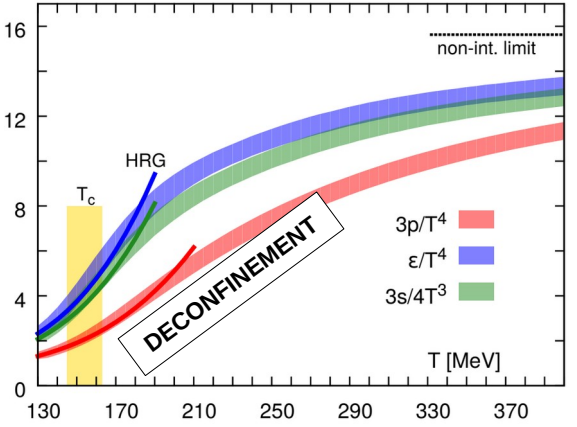
Relativistic fluid description: $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$

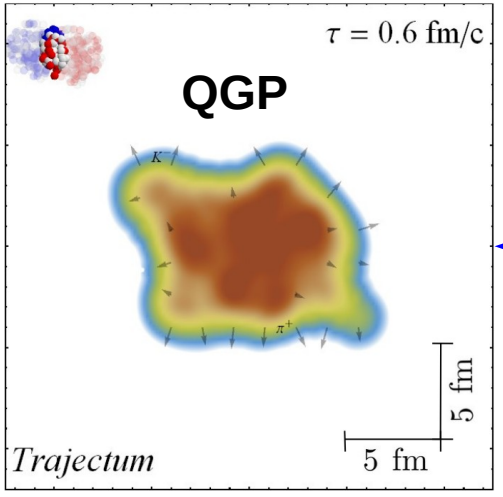
Equation of state from lattice QCD

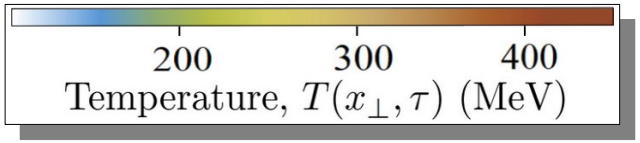
[HoTQCD collaboration, PRD **90** (2014) 094503]

Fluid is viscous (η/s , ζ/s , …)

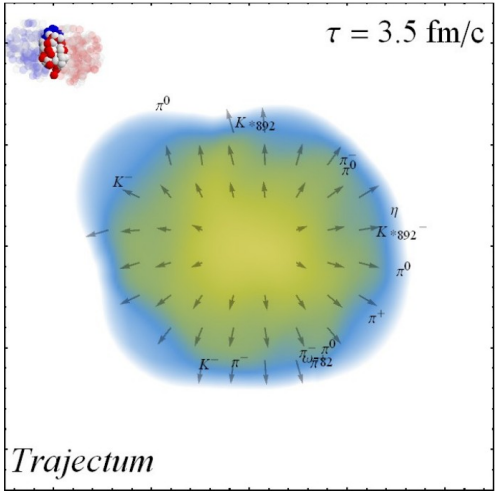
[Romatschke & Romatschke, 1712.05815]

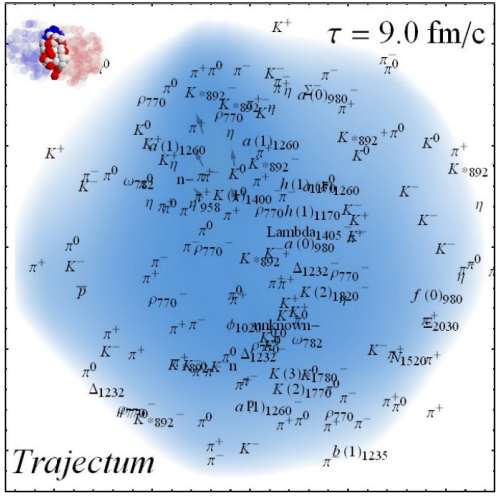




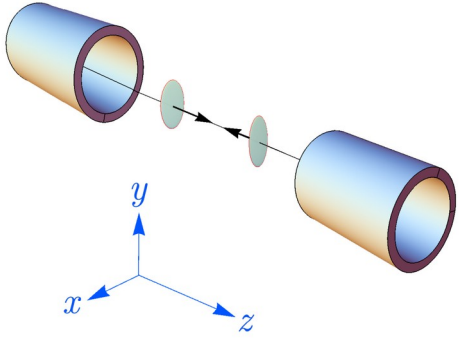


THE ART OF BACKWARD PROPAGATION





OBSERVABLES

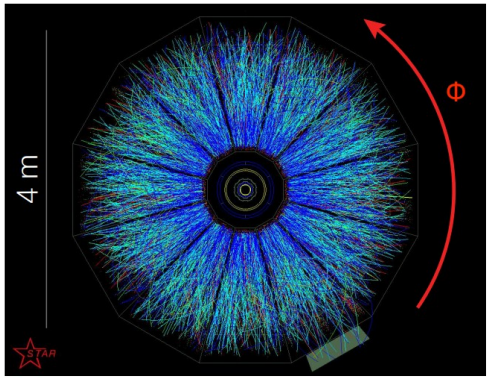


How ?

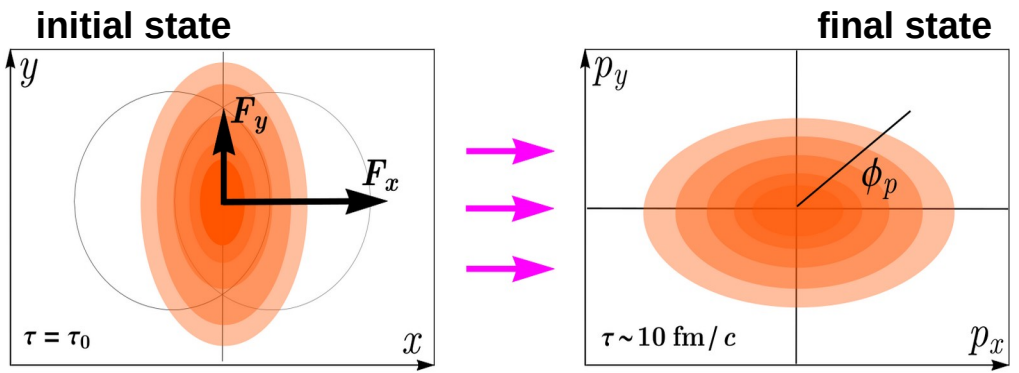
Soft spectra, hydrodynamics, initial-state geometry

[Ollitrault, 1992]

[Heinz, Snellings, 2013]



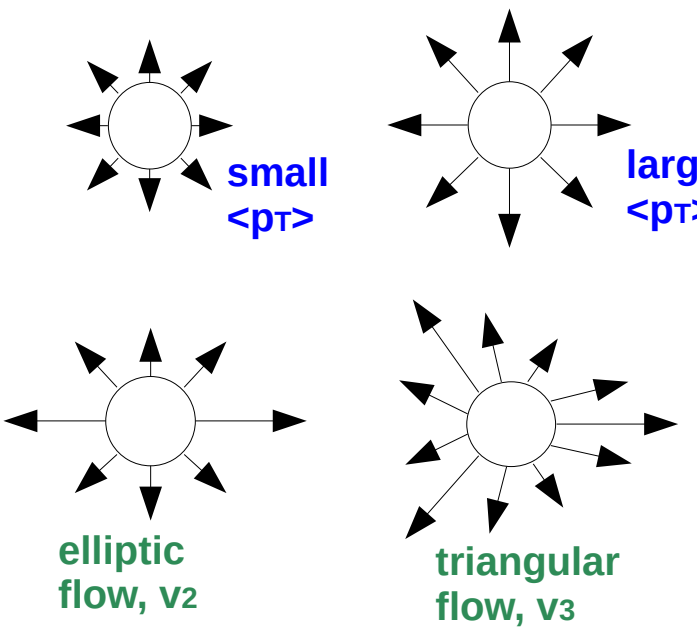
Reconstructing initial conditions and geometry from final particle distributions



$$F = -\nabla P$$

1/R

$$v_2 \propto \int_\phi e^{i2\phi} \frac{dN}{d\phi}$$



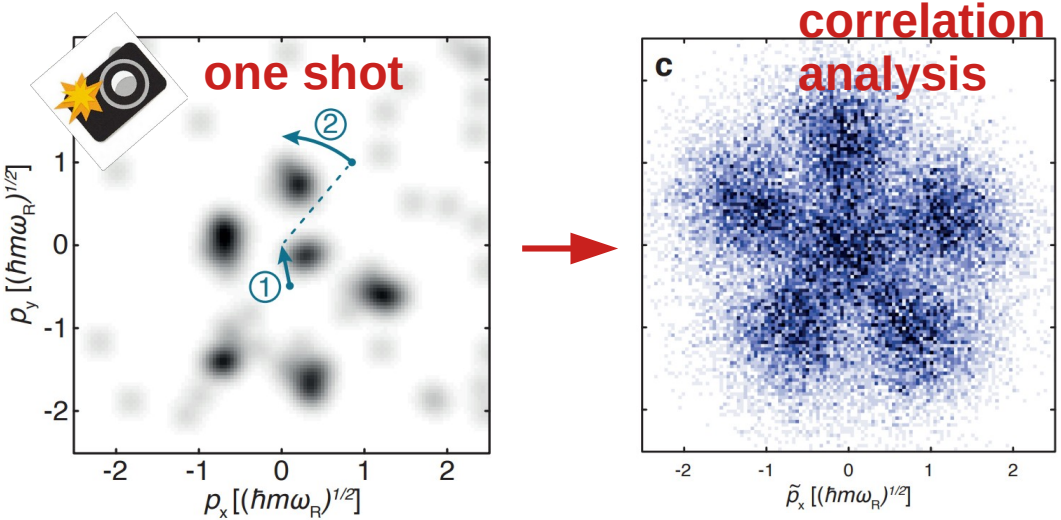
Imaging (static) many-body systems

Classical – one picture with sufficient resolution

Quantum – Statistical analysis

Example – The Pauli crystal

[Holten *et al.*,Phys. Rev. Lett. **126**, 020401 (2021)]



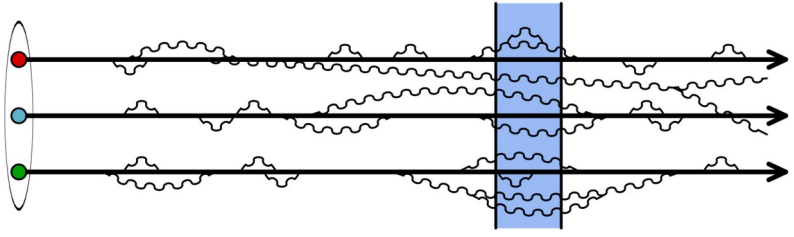
e.g. two-body densities

$$\rho^{(2)}(\mathbf{r}_1,\mathbf{r}_2) = \frac{\langle \psi^\dagger(\mathbf{r}_2)\psi^\dagger(\mathbf{r}_1)\psi(\mathbf{r}_1)\psi(\mathbf{r}_2)\rangle}{n^2}$$

Can we similarly image atomic nuclei ?

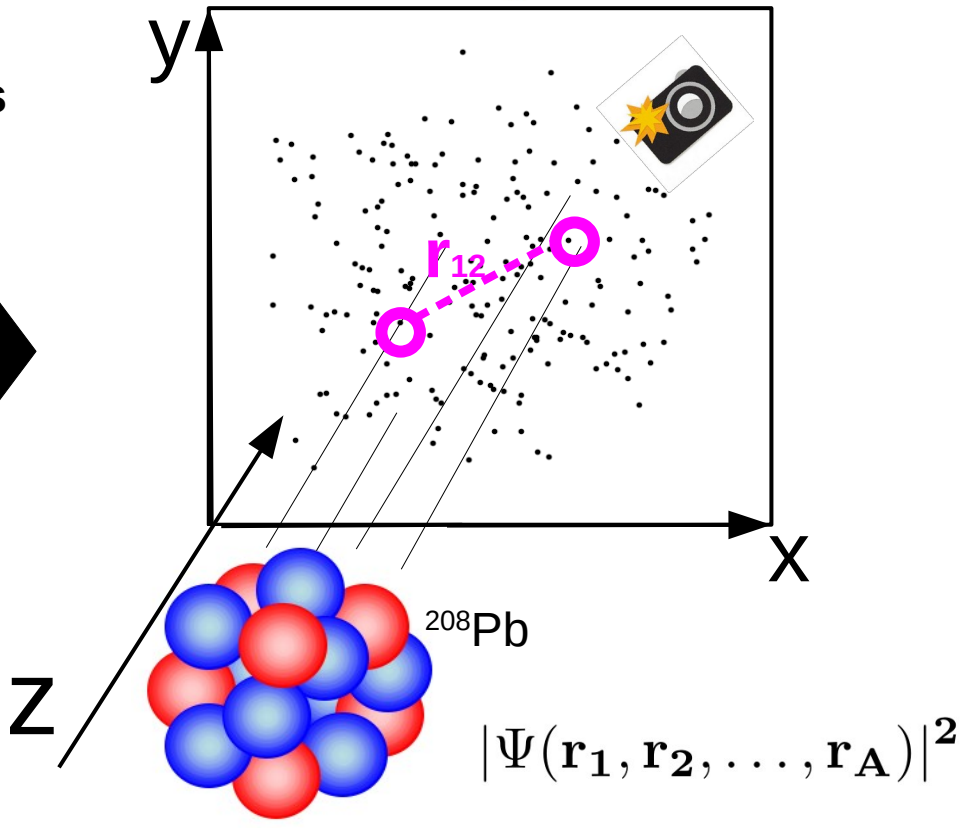
Connection to nuclear structure?

High-energy collisions as imaging processes



[Gelis, IJMPE **24** (2015) 10, 1530008]

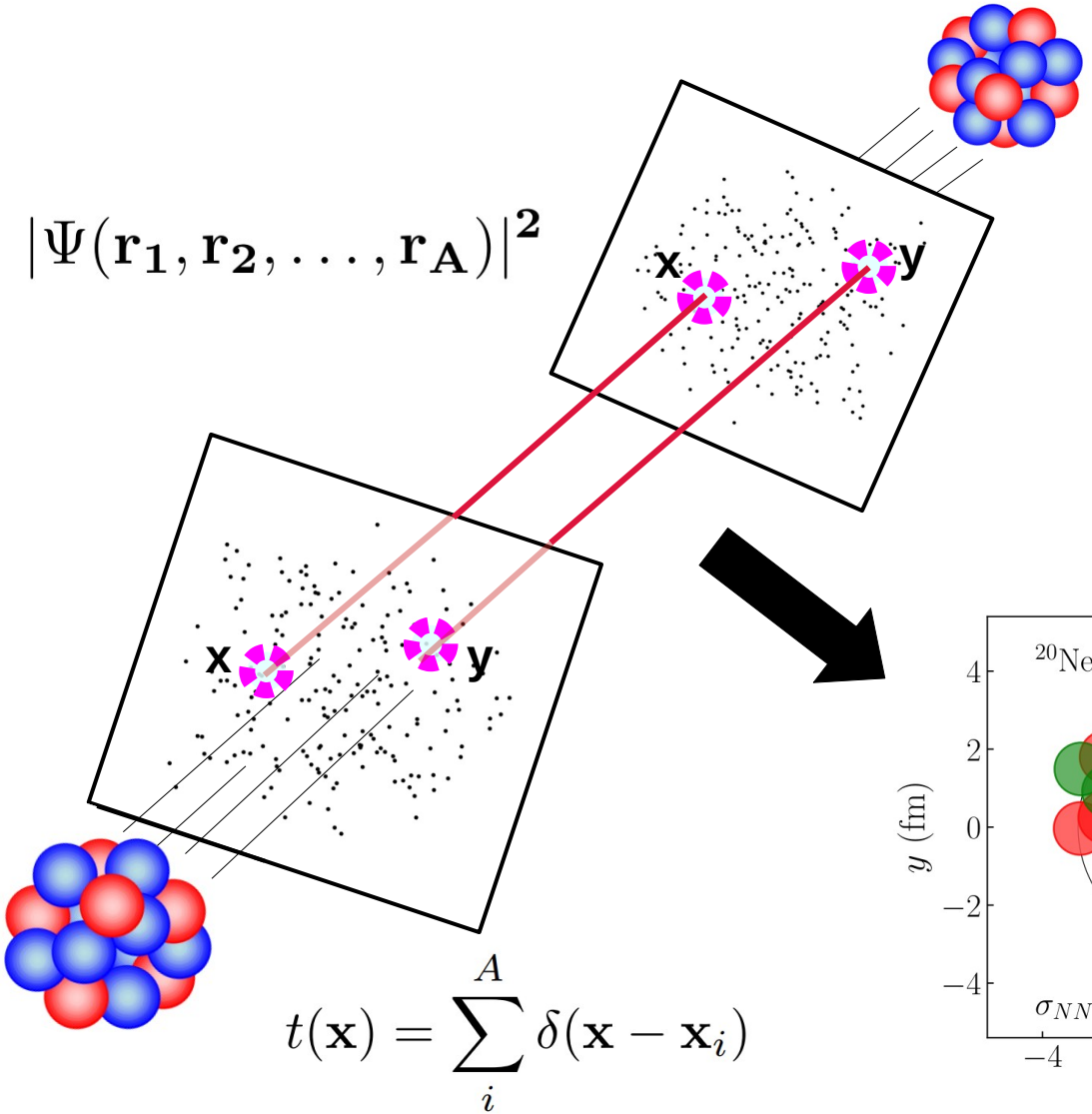
$$t(\mathbf{x}) = \sum_i^A \delta(\mathbf{x} - \mathbf{x}_i)$$



Time scale of collisions faster than any internal dynamics

Instantaneous snapshot of the positions of the colliding nucleons

$$|\Psi(\mathbf{r_1}, \mathbf{r_2}, \ldots, \mathbf{r_A})|^2$$



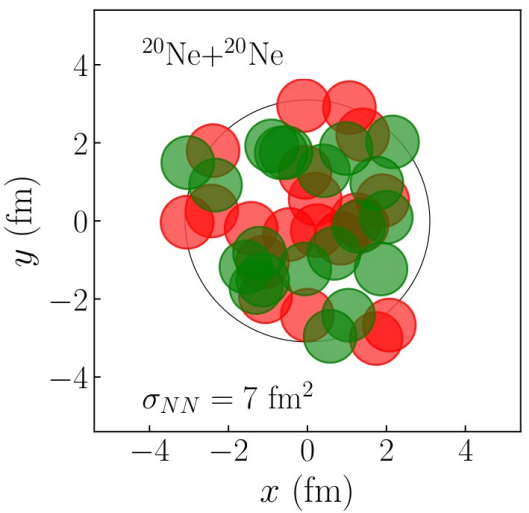
$$t(\mathbf{x}) = \sum_{i}^{A} \delta(\mathbf{x} - \mathbf{x}_i)$$

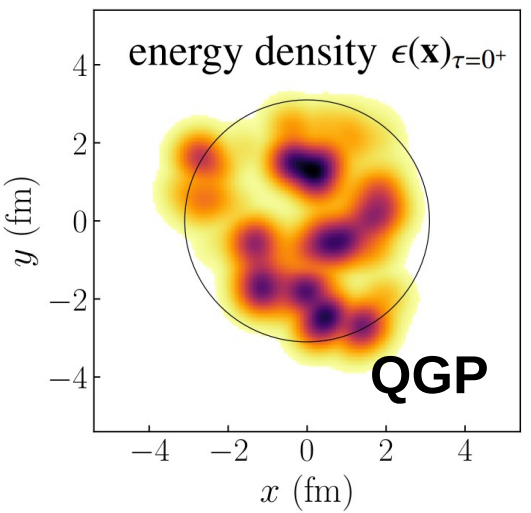
Physics of ultra-central collisions

Time scale of scattering ~0.1 fm/c

Typical transverse kick Qs~1GeV

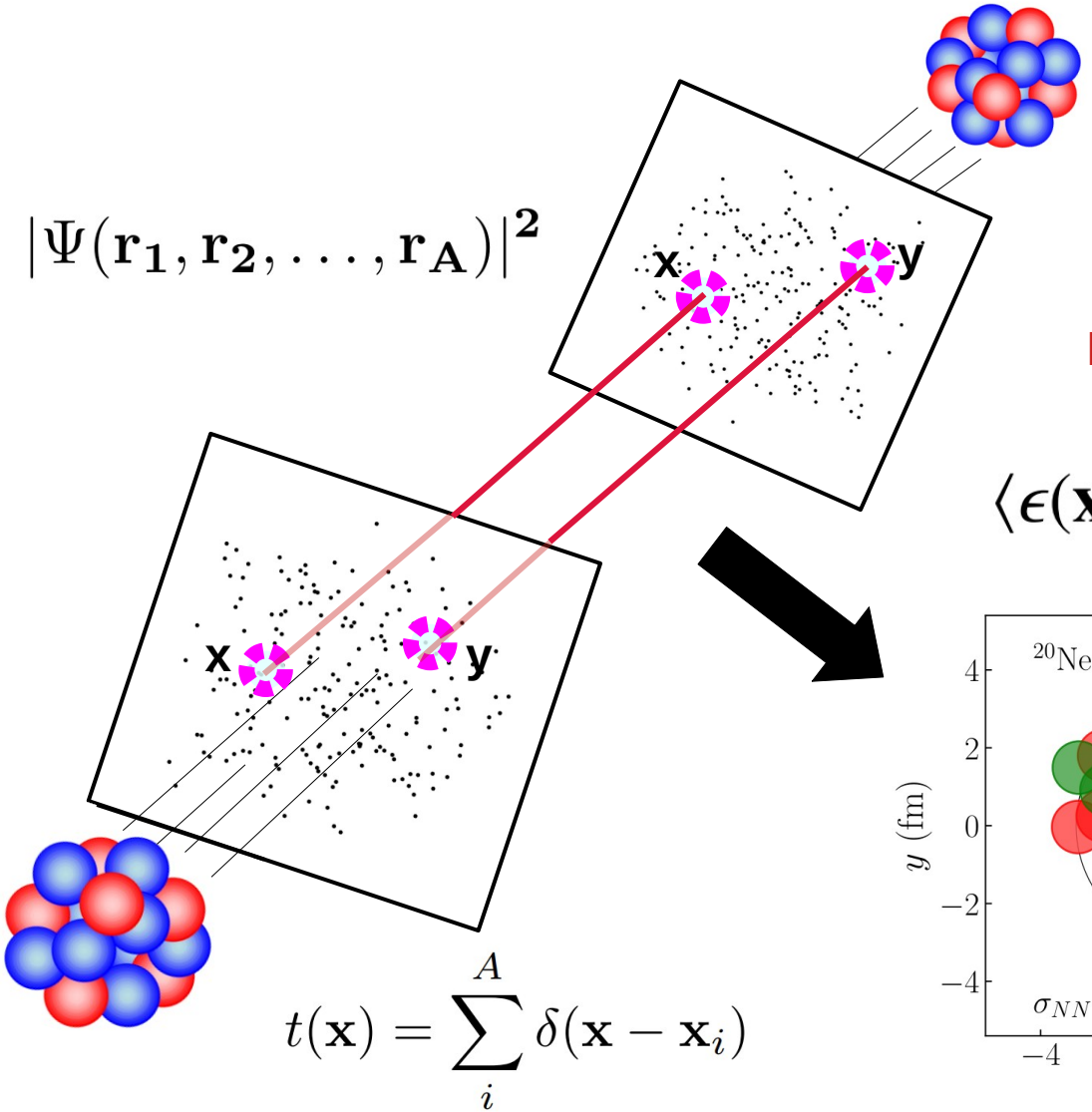
Nucleon positions dictate large-scale structures in the QGP





Physics of ultra-central collisions

$$|\Psi(\mathbf{r_1}, \mathbf{r_2}, \ldots, \mathbf{r_A})|^2$$

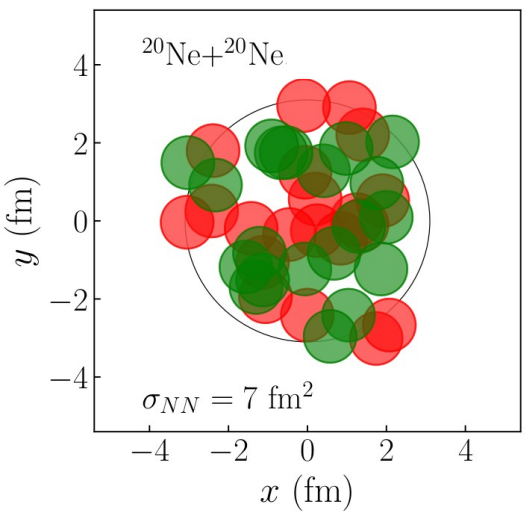


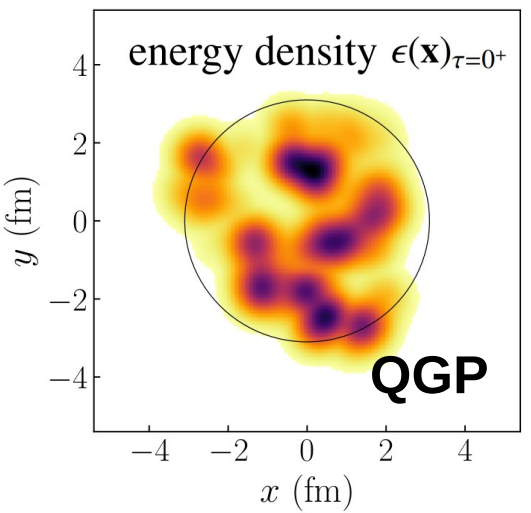
$$t(\mathbf{x}) = \sum_i^A \delta(\mathbf{x} - \mathbf{x}_i)$$

Keyword = Correlations!

$$\langle \epsilon(\mathbf{x})\epsilon(\mathbf{y}) \rangle \qquad |\mathbf{x} - \mathbf{y}| > 1/Q$$

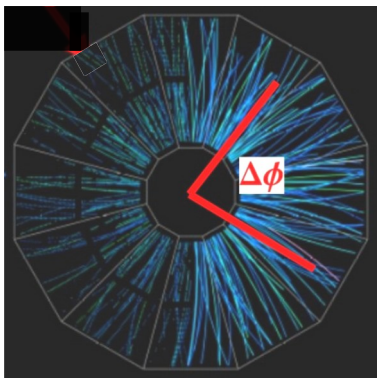
large scales from low-energy physics!



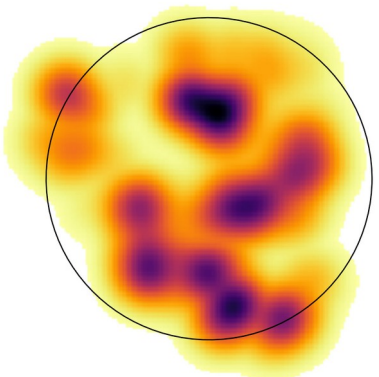


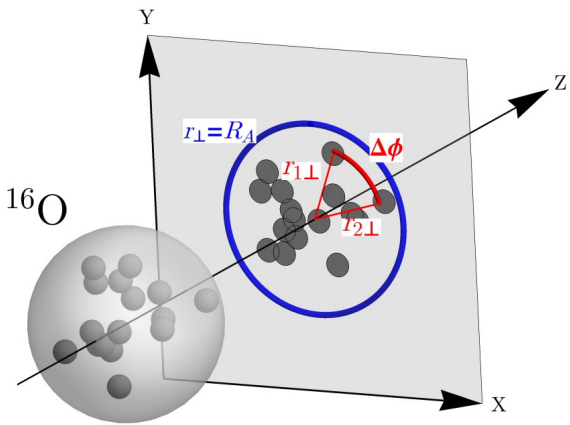
Many-body (angular) correlations – From final-state hadrons to initial nuclei

[Duguet, Giacalone, Jeon, Tichai, Phys. Rev. Lett. **135** (2025) 18, 182301]
[Blaizot, Giacalone, Lovato, 2512.18926]



QGP





Final-state two-particle correlations

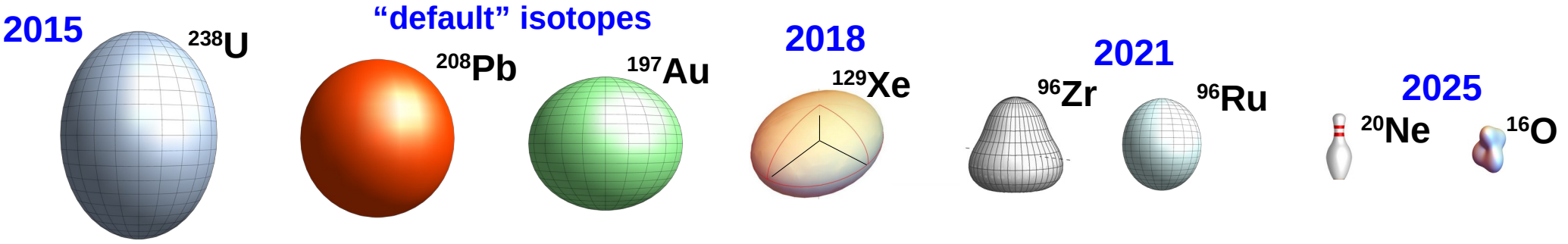
Two-point correlation of the energy density

Nuclear two-body correlation

$$\left\langle \frac{\sum_{i\neq j} e^{in(\phi_i-\phi_j)}}{N_{\rm ch,ev}(N_{\rm ch,ev}-1)} \right\rangle \Rightarrow \int_{\mathbf{x},\mathbf{y}} \langle \epsilon(\mathbf{x})\epsilon(\mathbf{y})\rangle\, x^n\, y^n\, e^{in(\phi_x-\phi_y)} \Rightarrow \int_{\mathbf{r}_1,\mathbf{r}_2} \rho^{(2)}(\mathbf{r}_1,\mathbf{r}_2)\, r_{1\perp}^n\, r_{2\perp}^n\, e^{in(\phi_1-\phi_2)}$$

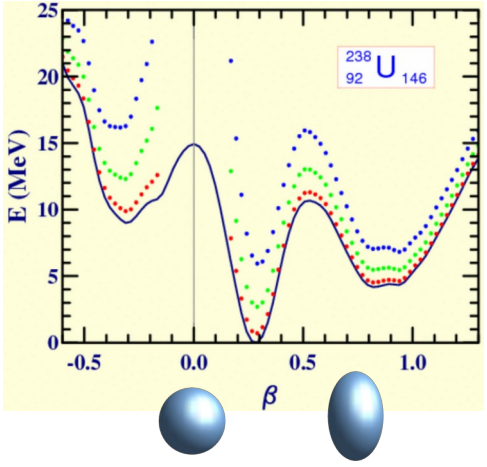
The unexpected uses of particle colliders – Imaging colliding states

Manifestation of many-body correlations – Classical pictures



"Redescovering" the nuclear shape in collider smashups

[Verney, EPJA **61** (2025) 4, 82]



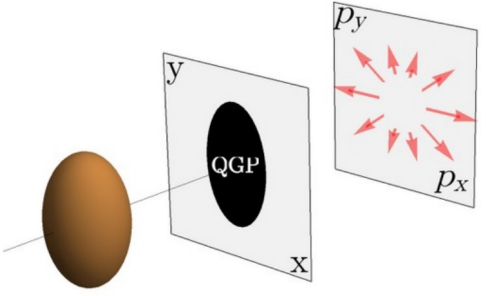
$$\beta \propto \langle \Phi | \hat{Q}_{20} | \Phi \rangle$$

$$\hat{Q}_{20}(\mathbf{r}) \propto r^2 \, Y_{20}(\theta)$$

quadrupole operator

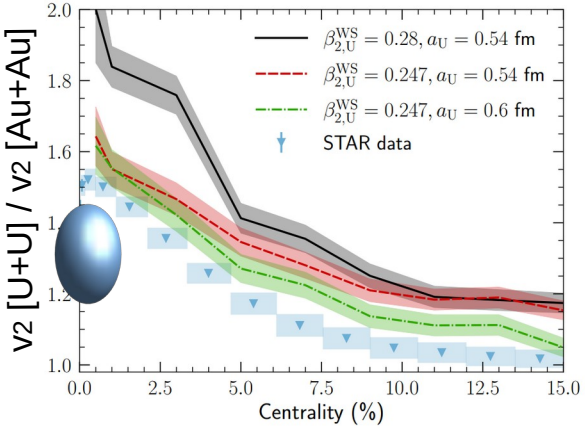
$$|\Psi_K^{JM}\rangle \propto \int d\Omega \, D^{J*}_{MK}(\Omega) \, \hat{R}(\Omega) |\Phi\rangle$$

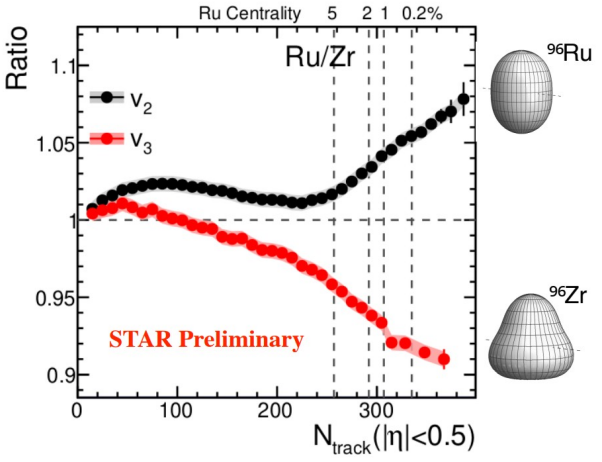
lab — projection — intrinsic

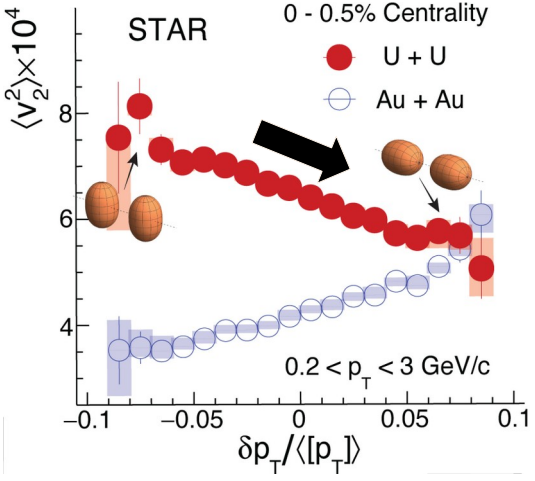


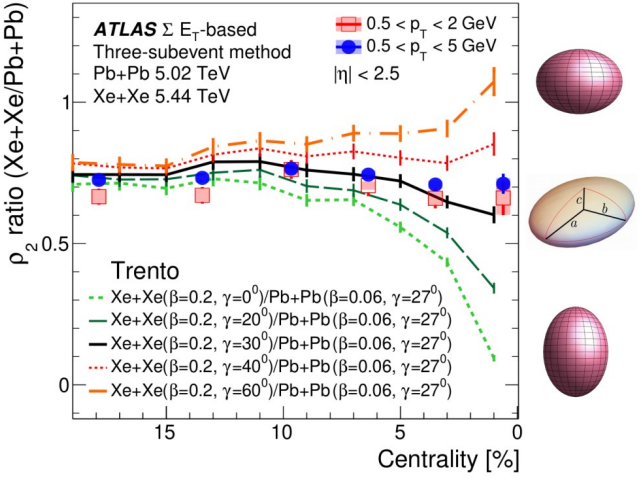
Rigid-rotor interpretation of collider results

Results align well with low-energy theo /exp expectations









[STAR collaboration, PRL **115**, no.22, 222301 (2015)]

[ALICE collaboration, PLB **784**, 82-95 (2018)]

[CMS collaboration, PRC **100**, no.4, 044902 (2019)]

[ATLAS collaboration, PRC **100**, no.4, 044902 (2019)]

[STAR collaboration, PRC **105**, no.1, 014901 (2022)]

[ALICE collaboration, PLB **834**, 137393 (2022)]

[ATLAS collaboration, PRC **107**, no.5, 054910 (2023)]

[STAR collaboration, Nature **635**, no.8037, 67-72 (2024)]

[ATLAS collaboration, PRL **133** (2024) 25, 252301]

[ALICE collaboration, PLB **869** (2025) 139855]

[STAR collaboration, Rept.Prog.Phys. **88** (2025) 108601]

[CMS collaboration, PLB **876** (2026) 140359]

[ATLAS collaboration, arXiv:2509.05171]

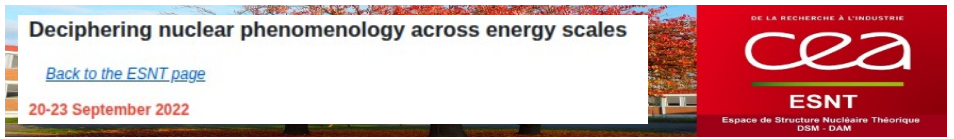
[ALICE collaboration, arXiv:2509.06428]

[CMS collaboration, arXiv:2510.02580]

…

EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 1/2)

EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 2/2)



Check progress over the past 4 years

Program Overview

INSTITUTE for NUCLEAR THEORY

Intersection of nuclear structure and high-energy nuclear collisions

January 23, 2023 - February 24, 2023

Exploring nuclear physics across energy scales 2024: intersection between nuclear structure and high energy nuclear collisions

Apr 15 – 27, 2024
Asia/Shanghai timezone

Enter your search term

Intersection of nuclear structure and high-energy nuclear collisions: 2025 Program and Workshop

12–22 mag 2025
Jiangwan Campus, Fudan University
Asia/Shanghai fuso orario

Inserisci il termine di ricerca

Intersection of nuclear structure and high-energy nuclear collisions 2026

13–24 apr 2026
Yukawa Institute for Theoretical Physics
Asia/Tokyo fuso orario

Inserisci il termine di ricerca

Intersection of nuclear structure and high-energy nuclear collisions 2027

29–31 Mar 2027
Daejeon
Asia/Seoul timezone

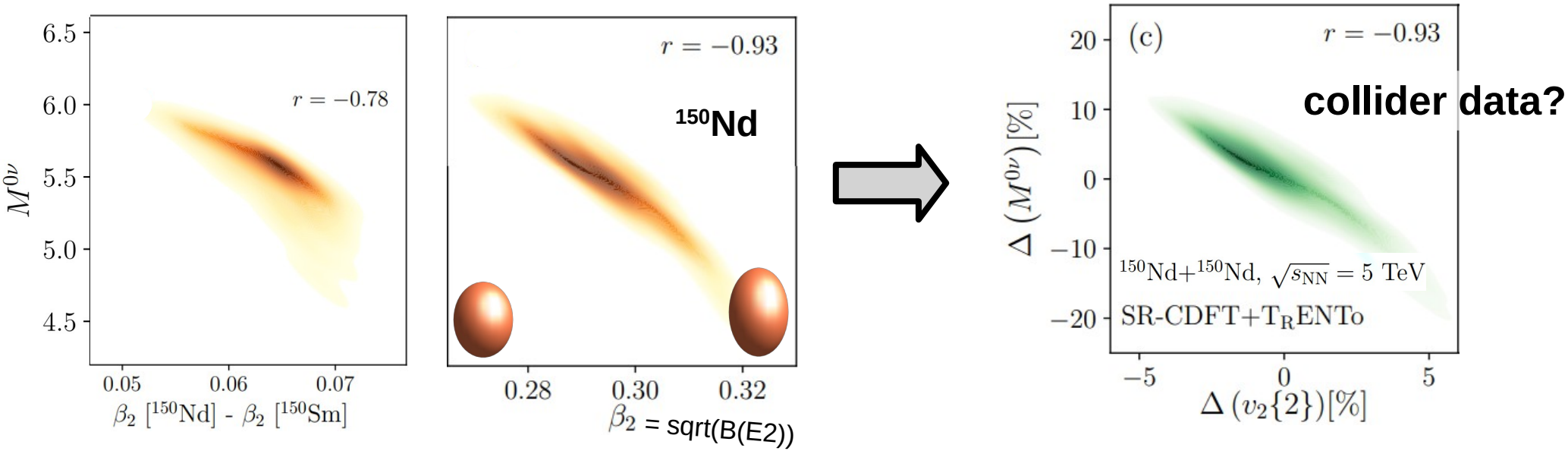
Enter your search term

+ more not listed / upcoming

All right, so … Why NMEs of 0ν2β decay?

Statistical evaluations in the CDFT framework

[Zhang *et al.*, PRC **112** (2025) 2, L021302]



[Li *et al.*, Phys. Rev. Lett. **135** (2025) 2, 022301]

Strong correlation between nuclear shape parameter and the NME in deformed ^{150}Nd

What is the role of many-body properties/correlations in the parent?

Why NMEs of 0ν2β decay?

Statistical evaluations “ab initio”

[Belley *et al.*, PRC **113** (2026) 1, 014319]

Upper panel:

“Elliptic flow” observable correlated with LECs for 16O

[in progress with Ekström, Hagen…]

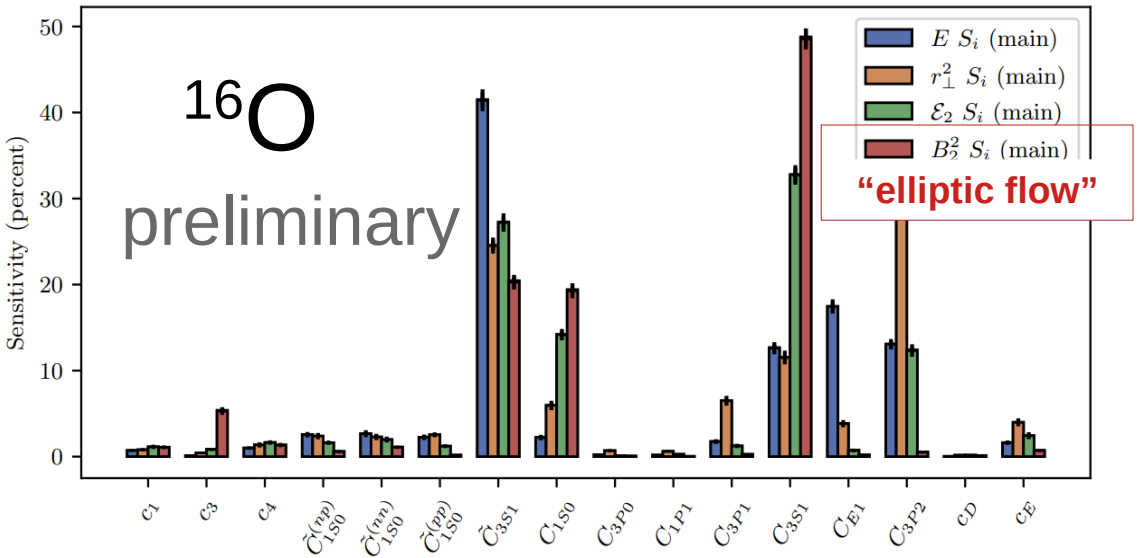
Lower panel:

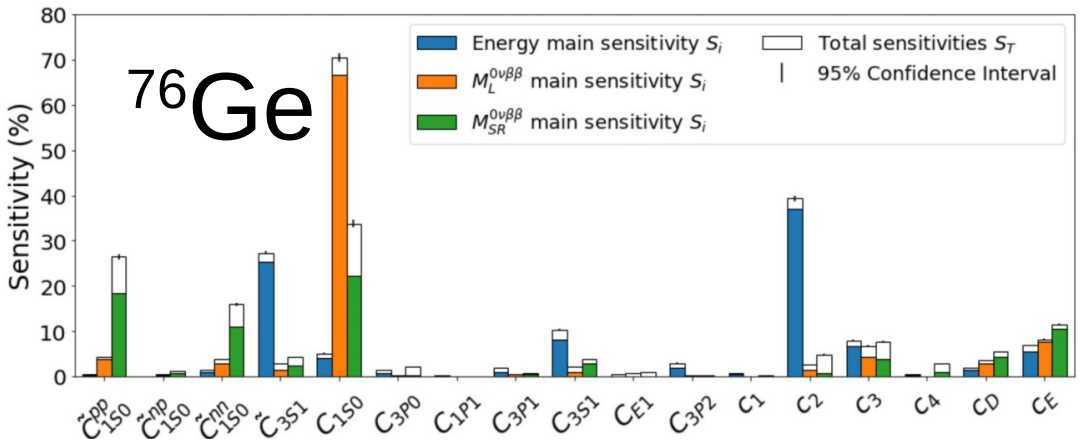
NME correlated with LECs for 76Ge

[Belley *et al.*, PRC **113** (2026) 1, 014319]

Combining the analyses?

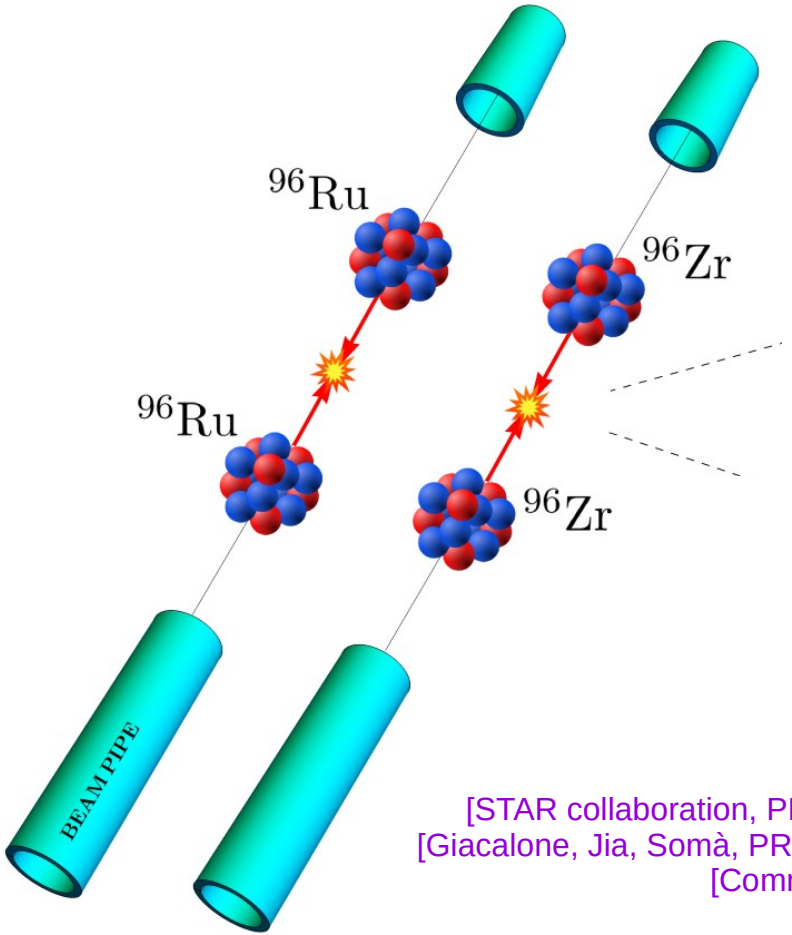
[in progress with Belley, Holt …]





Overarching question – Can information from collider runs pin down NME evaluations?

NB – The setup of “isobar collisions” is ideally suited for the purpose



Basic idea – Eliminating uncertainties via ratios

$$\frac{\overbrace{F_X}^{\text{observable in } X+X}}{\underbrace{F_Y}_{\text{observable in } Y+Y}} = \boxed{\frac{\overbrace{\kappa_X}^{\text{medium response in } X+X}}{\underbrace{\kappa_Y}_{\text{medium response in } Y+Y}}} \frac{\overbrace{I_X}^{\text{initial-state geometry of } X+X}}{\underbrace{I_Y}_{\text{initial-state geometry of } Y+Y}}$$

≈ 1

Ratios of observables (O) should be unity…

$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \stackrel{?}{=} 1$$

… up to nuclear structure effects!

[STAR collaboration, PRC **105** (2022) 1, 014901]
[Giacalone, Jia, Somà, PRC **104** (2021) 4, L041903]
[Community paper 2507.01454]

Stable, isobars, ground states … perfect match to scenario of 0ν2β!

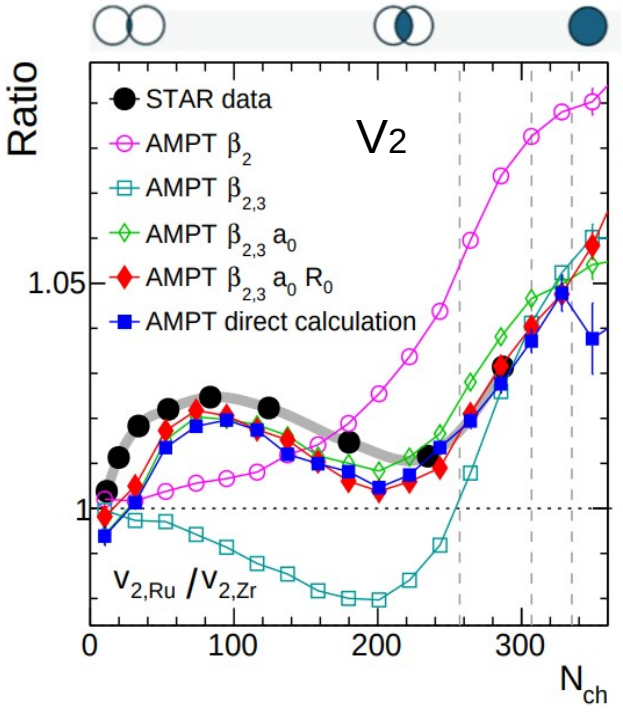
Practical application using RHIC data

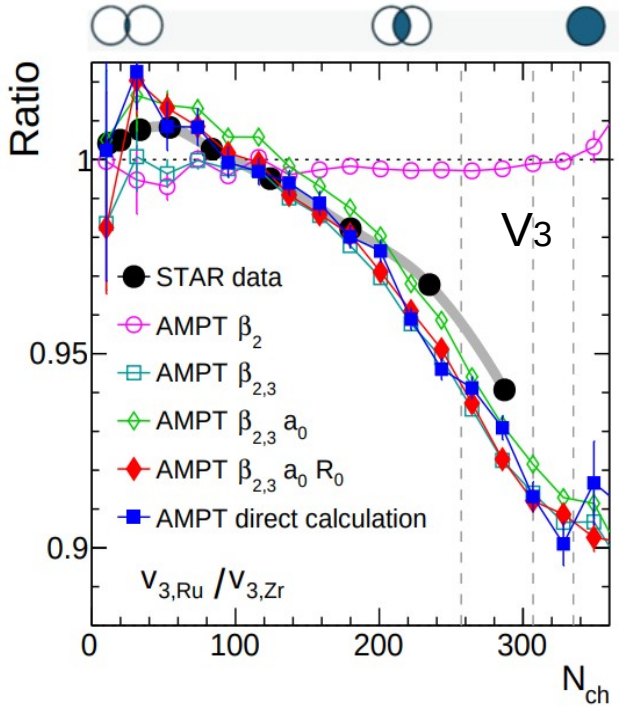
[STAR collaboration, PRC **105**, no.1, 014901 (2022)]

Taylor-expansion approach

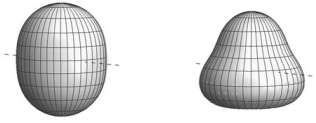
$$R_{\mathcal{O}} \equiv \frac{\mathcal{O}_{\mathrm{Ru}}}{\mathcal{O}_{\mathrm{Zr}}} \approx 1 + c_1\Delta\beta_2^2 + c_2\Delta\beta_3^2 + c_3\Delta R_0 + c_4\Delta a$$

[Zhang, Jia, PRC **107** (2023) 2, L021901



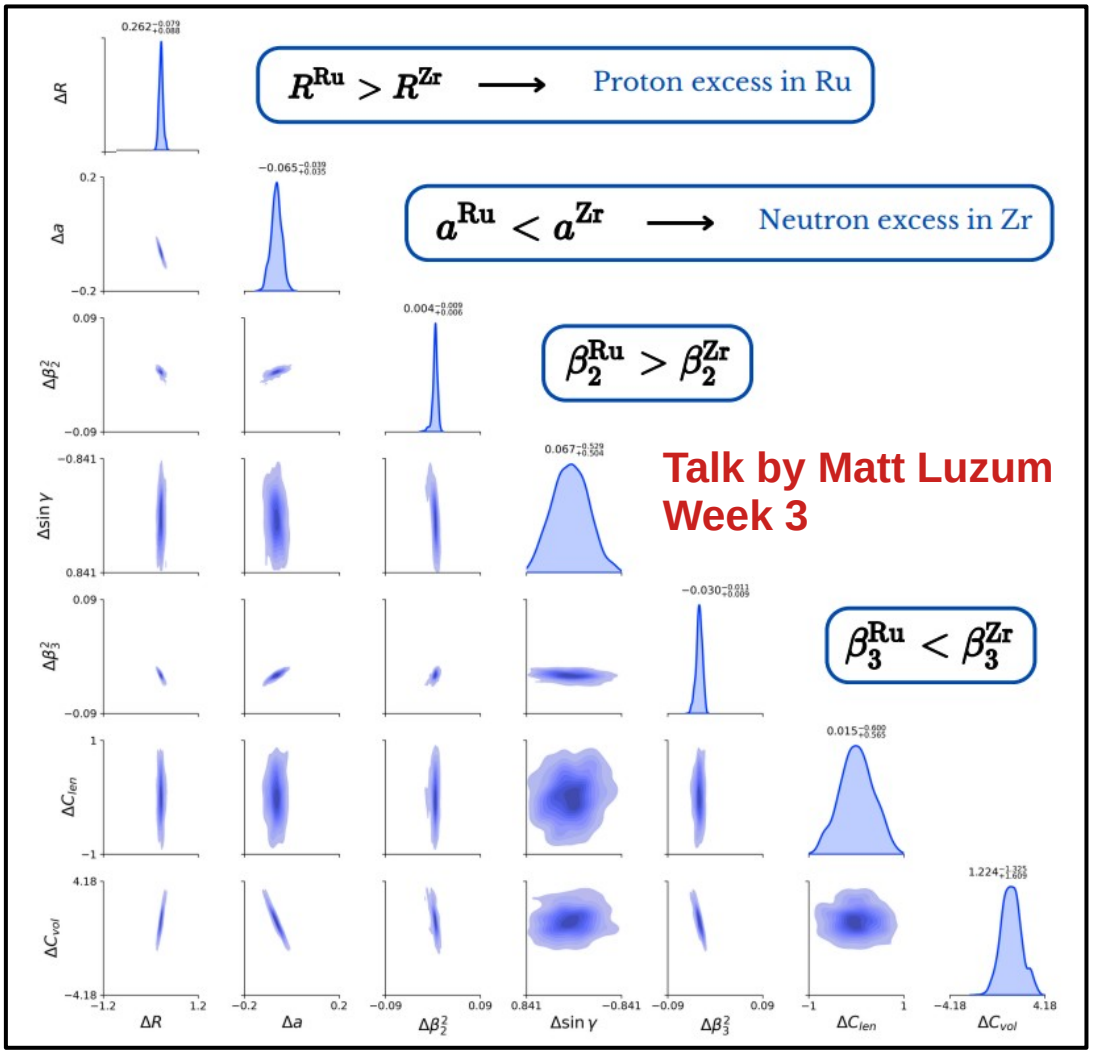


$$\rho(r,\theta,\phi) \propto \frac{1}{1+e^{[r-R_0(1+\beta_2 Y_2^0(\theta,\phi)+\beta_3 Y_3^0(\theta,\phi))]/a}}$$



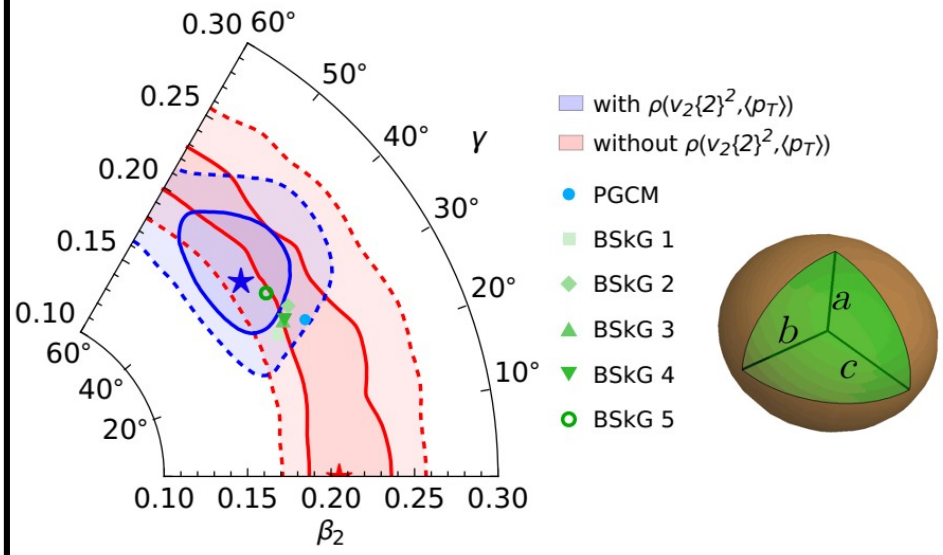
	R_0 (fm)	a_0 (fm)	β_2	β_3
Case 1: ^{96}Ru	5.09	0.46	0.162	0
Case 2	5.09	0.46	0.06	0
Case 3	5.09	0.46	0.06	0.20
Case 4	5.09	0.52	0.06	0.20
Case 5: ^{96}Zr	5.02	0.52	0.06	0.20
Ratios	$\frac{\text{Case 1}}{\text{Case 2}}$	$\frac{\text{Case 1}}{\text{Case 3}}$	$\frac{\text{Case 1}}{\text{Case 4}}$	$\frac{\text{Case 1}}{\text{Case 5}}$
Case 1 and 5 difference	ΔR_0	Δa	$\Delta\beta_2^2$	$\Delta\beta_3^2$
	0.07 fm	-0.06 fm	0.0226	-0.04

State-of-the-art – Bayesian inference of parameters related to nuclear structure



[Giacalone, Nijs, van der Schee, 2606.03993]

^{129}Xe, Many-body correlations consistent with a triaxial shape



$$\frac{\langle r_{1\perp}^2 r_{2\perp}^2 e^{i2(\phi_1-\phi_2)}\rangle_2}{\langle r_{1\perp}^2\rangle_1^2} = 0.0131(1)_{\rm stat}(19)_{\rm syst}$$

<$Q_{2,2}$ $Q_{2,-2}$> invariant

Prediction for a potential collider run with ^{76}Ge and ^{76}Se

Kumar quadrupole invariants [Kumar, **PRL** 1972]

$$Q^2 = \sqrt{5}\,[Q_2 \times Q_2]^0 \quad Q_{2\mu} = r^2 Y_{2\mu}$$

$$\langle Q^2 \rangle = \sum_i B(E2, 0^+_{GS} \to 2^+_i)$$

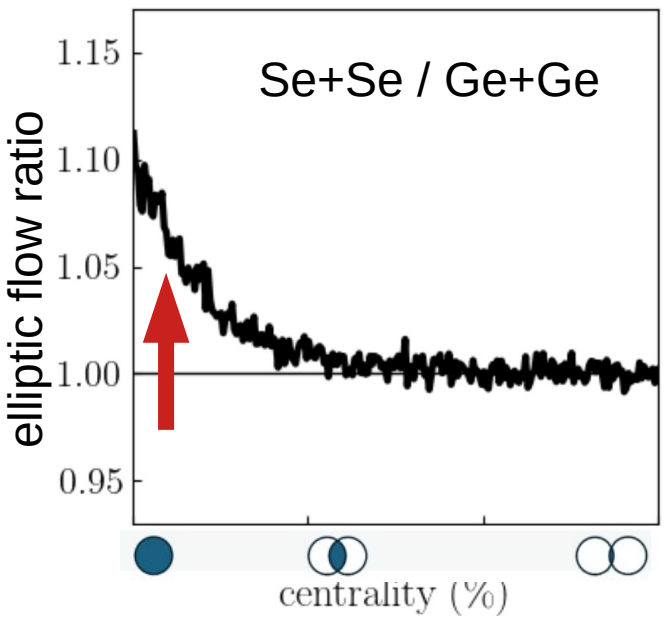
$$\beta_2 = \frac{4\pi}{3R^2 A}\sqrt{\langle Q^2 \rangle}$$

$$\rho^{\mathrm{WS}}(\mathbf{r}) \propto \left[1 + \exp\left(\frac{r - R(\theta,\phi)}{a}\right)\right]^{-1}$$

$$R(\theta,\phi) = R_0\,\{1 + \beta\,[\cos\gamma Y_{20}(\theta,\varphi) + \sin\gamma Y_{22}(\theta,\phi)]\}$$

Shell model calculations

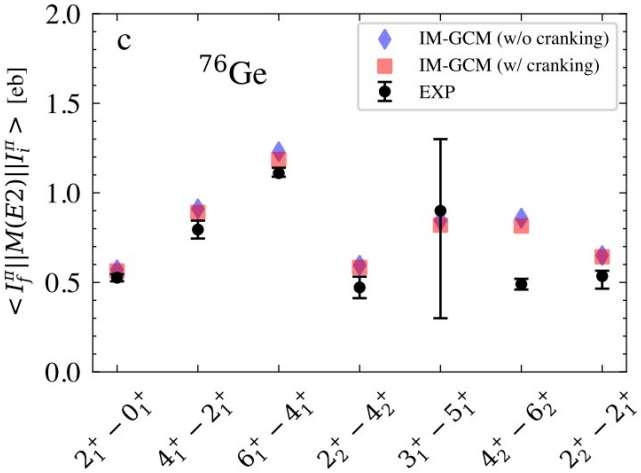
		^{76}Ge			^{76}Se		
Interaction	a^{WS}	R_0^{WS}	β^{WS}	γ^{WS}	R_0^{WS}	β^{WS}	γ^{WS}
JJ4BB	0.52	4.53	0.283	33.5	4.50	0.345	34.5
JUN45	0.52	4.53	0.267	31.0	4.55	0.322	35.6
GCN	0.52	4.53	0.267	32.3	4.54	0.322	32.5
RG	0.52	4.54	0.265	31.5	4.51	0.310	29.3

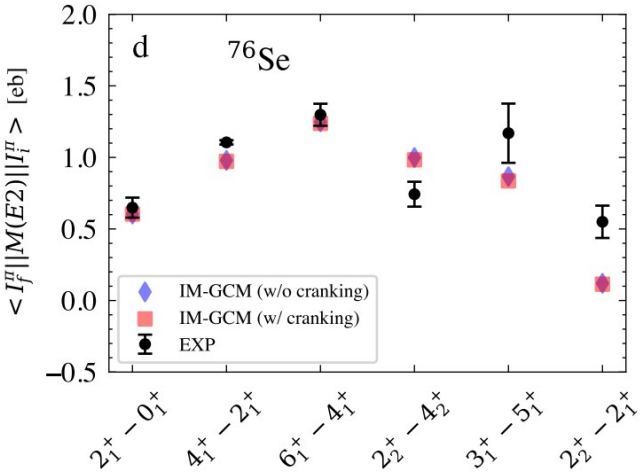


[in progress with Frycz, Menendez …]

Unicity and complementarity of probes

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





■ low-energy approach

$$\langle Q^2 \rangle = \sum_i B(E2, 0^+_{GS} \to 2^+_i)$$

- Probes protons
- Many levels needed?
- Higher-order correlators (e.g. triaxiality) increase complexity
- Study of octupole correlations?

■ high-energy approach

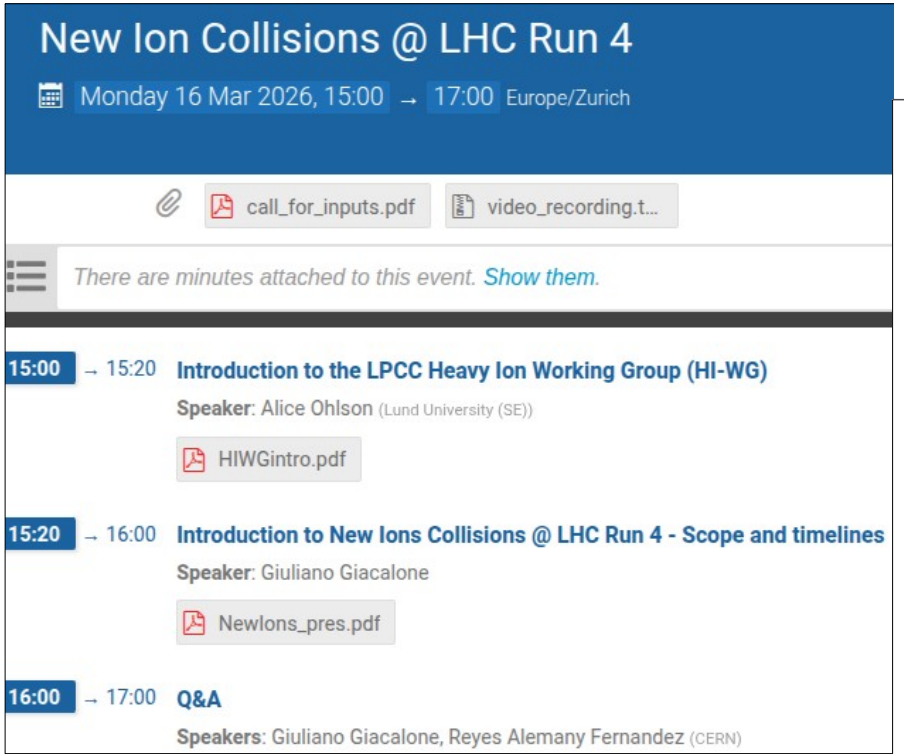
- Probes protons + neutrons
- Expectation directly in the ground state
- Higher-order correlators are straightforward
- Octupole and quadrupole on equal footing

^{129}Xe [Giacalone, Nijs, van der Schee, 2606.03993]

$$\langle Q_2^2 \rangle = \frac{\langle r_{1\perp}^2 r_{2\perp}^2 e^{i2(\phi_1 - \phi_2)} \rangle_2}{\langle r_{1\perp}^2 \rangle_1^2} = 0.0131(1)_{\text{stat}}(19)_{\text{syst}}$$

$$\langle Q_3^2 \rangle = \frac{\langle r_{1\perp}^3 r_{2\perp}^3 e^{i3(\phi_1 - \phi_2)} \rangle_2}{\langle r_{1\perp}^3 \rangle_1^2} = 0.0043(1)_{\text{stat}}(26)_{\text{syst}}$$

Towards multi-species ion campaigns in LHC Run 4 – Community effort



in collaboration with Reyes Alemany Fernandez (CERN)

- **Roadmap and timelines**
- **Phase 1** – Collecting ideas for science cases to be pursued **MAY 26**
  [deadline in two months from now, May 18]
- **Phase 2** – Call for abstracts on physics studies related to science cases **SEP 26**
  List of contributions that will constitute the White Paper
  [deadline with Heidelberg workshop Sept 21-25 / but submissions welcome afterward]
  → **[review progress in LPCC workshop Sep 27]**
- **Phase 3** – Completion of scientific studies to appear in White Paper **SEP 28**
  Publication-style results. They can of course appear in journals and arXiv
  [deadline around end of 2028] → **[LPCC workshop]**
- **Phase 4** – Assembly of the White Paper [deadline in Spring 2029] **MAR 29**
- **Submission to experimental collaborations and relevant boards**

Emerging consensus for

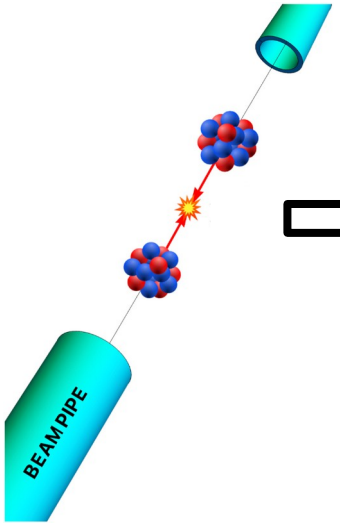
Species: ^{4}He, ^{12}C, ^{16}O, ^{24}Mg, ^{40}Ar, ^{40,44,48}Ca, ^{76}Ge, ^{86}Kr, ^{136}Ba, ^{136}Xe

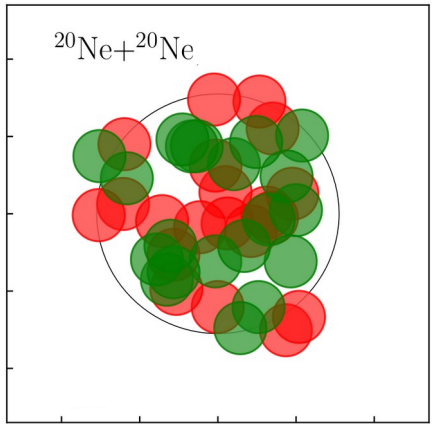
0ν2β candidates are in the final list

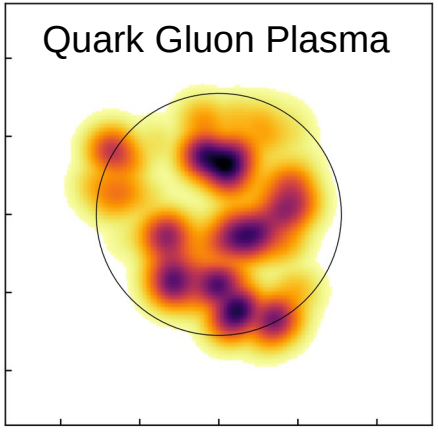
SUMMARY

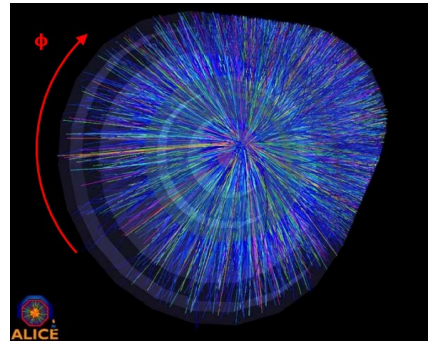
MULTI-NUCLEON CORRELATIONS IN NUCLEI

MULTI-PARTICLE CORRELATIONS IN FINAL STATE



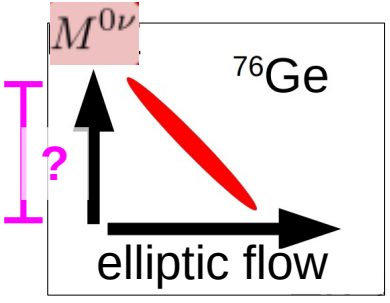


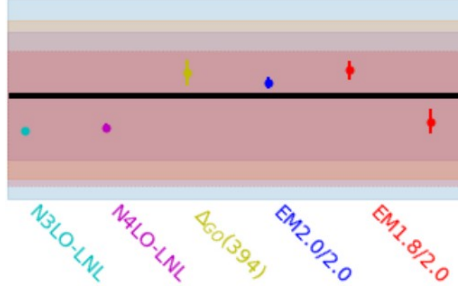




Imaging the low-energy structure of colliding states

Broad reach into many-body quantum physics
(EFTs of QCD, NME of 0νββ ...)





?

Exciting experimental prospects – Multi-ion program @ LHC in the next decade

EMMI Workshop: Light-ion collisions 2026

https://indico.gsi.de/event/25022/

21–25 Sept 2026
Kirchhoff-Institut für Physik (KIP)
Europe/Berlin timezone

Enter your search term

One session related to 0v2β decay
Jordy de Vries [Amsterdam]
Benjamin Bally [Darmstadt]
Susanne Mertens [MPIK, LEGEND]
Dorian Frycz [Barcelona]

Payment information and financial support
Venue and Travel Information
Childcare
Accommodation
EMMI Code of Conduct
ExtreMe Matter Institute EMMI

Support
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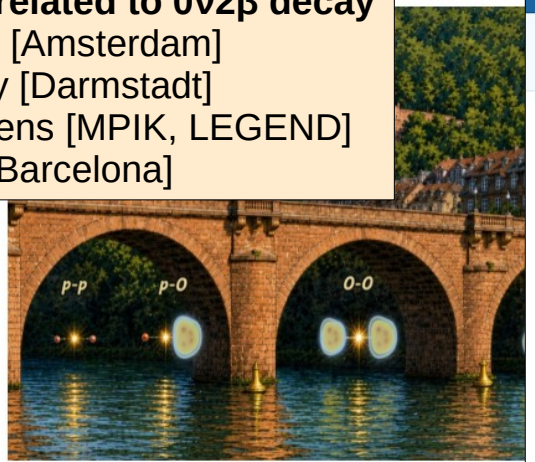

Recent light-ion collision campaigns – proton-oxygen, oxyge
and oxygen–oxygen collisions at RHIC – have opened a
collective behavior in small QCD systems, and in the study o
gluon plasma. Simultaneously, high-energy collisions offe
structure, with implications potentially extending from nuc
searches for neutrinoless double beta decay.

Intersection of nuclear structure and high-energy nuclear collisions 2027

https://indico.cern.ch/event/1686349/

29 March 2027 to 1 April 2027
Daejeon
Asia/Seoul timezone

Enter your search term

Overview
Timetable
VISA Information
Conference Venue & Accommodation
Organizing Committee

We are happy to announce the 2027 edition of the workshop on the ***Intersection of nuclear structure and high-energy nuclear collisions***. The workshop aims to foster and deepen connections between the fields of high-energy heavy-ion collisions and low-energy nuclear structure, and discuss physics opportunities recently opened up at this rapidly evolving interface.