Relativistic nuclear collisions as a new laboratory to test effective theories for nuclei

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IsoQuant
SFB1225

EMMI Workshop and International Workshop XLIX on Gross Properties of Nuclei and Nuclear Excitations

Intersection of nuclear structure and high-energy nuclear collisions: a new research direction.

ExtreMe Matter Institute EMMI

EMMI Rapid Reaction Task Force

Nuclear Physics Confronts Relativistic Collisions of Isobars

Heidelberg University, Germany, May 30 – June 3 & October 12-14 2022

Organizers:
Giuliano Giacalone
Jiangyong Jia
Vittorio Somà
You Zhou

Deciphering nuclear phenomenology across energy scales

https://esnt.cea.fr/Phocea/Page/index.php?id=107 **Sep 20th - Sep 23rd 2022**

Organizers:
Giuliano Giacalone (ITP Heidelberg)
Jean-Yves Ollitrault (IPhT Saclay)
You Zhou (Niels Bohr Institute)

Intersection of nuclear structure and high-energy nuclear collisions

Organizers:
Jiangyong Jia (Stony Brook & BNL)
Giuliano Giacalone (ITP Heidelberg)
Jacquelyn Noronha-Hostler (Urbana-Champaign)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Fuqiang Wang (Purdue)

Jan 23rd - Feb 24th 2023

→ Next Initial Stages conference (Copenhagen, 2023) will have a track related to nuclear structure.

→ Input to Nuclear Physics LRP in the US, both hot QCD (e.g. arXiv link) and nuclear theory.

→ Contributed input to NUPECC LRP 2024 [with Y. Zhou (NBI Copenhagen)]

→ Just started a Topical Issue on EPJA on the intersection of the two areas (~20 papers in 2023) [T. Duguet, G. Giacalone, V. Somà, Y. Zhou]

OUTLINE

1 – High-energy nuclear physics and collision geometry.

2 – Nuclear structure input.

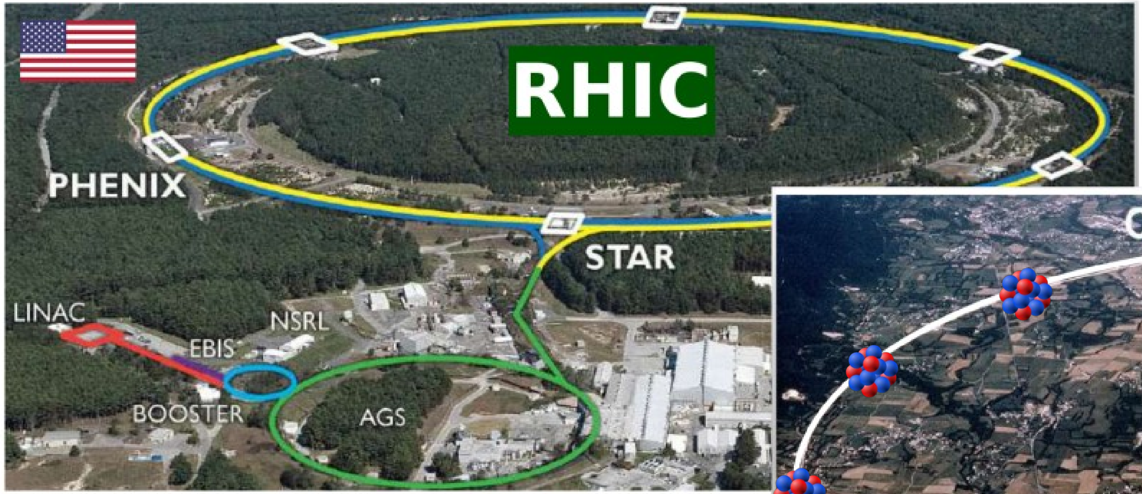
3 – Nuclear shapes in high-energy nuclear experiments.

4 – Prospects: light nuclei and *ab initio* calculations.

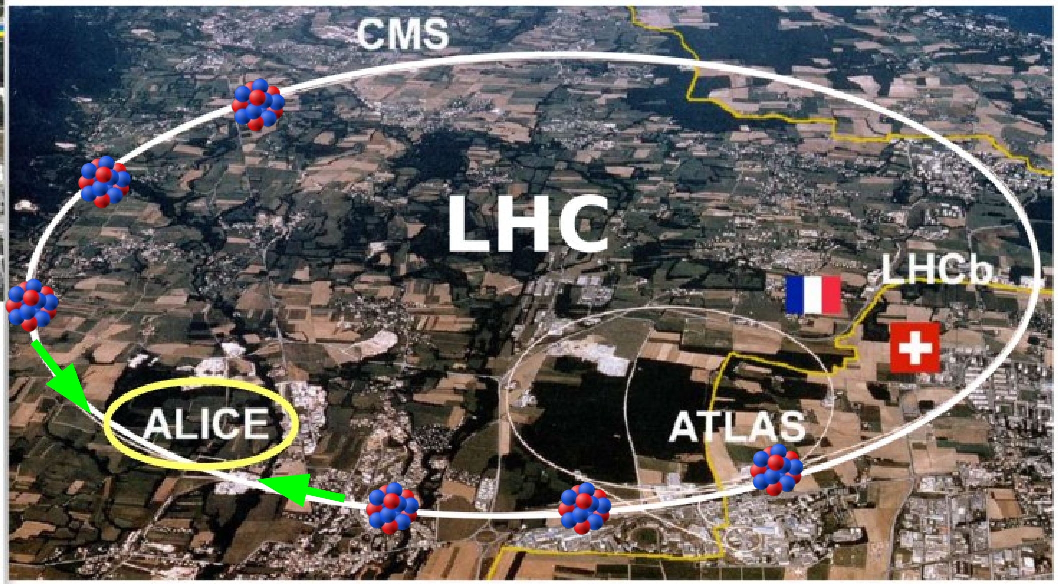
1 – High-energy nuclear physics and collision geometry.

HIGH ENERGY NUCLEAR PHYSICS

Long Island (NY)

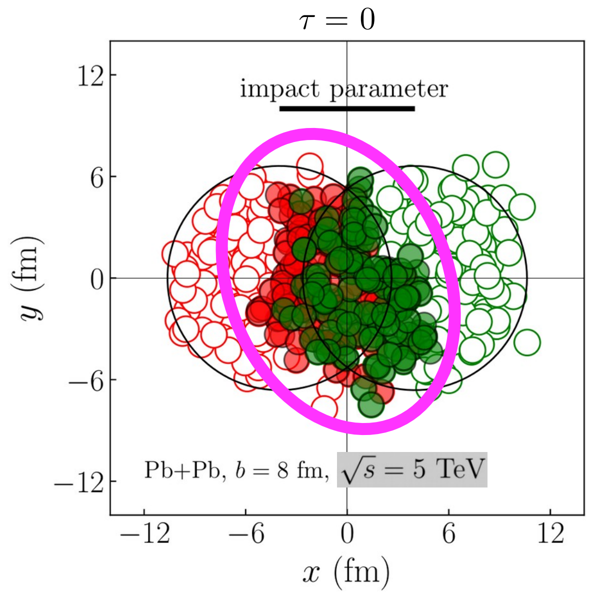


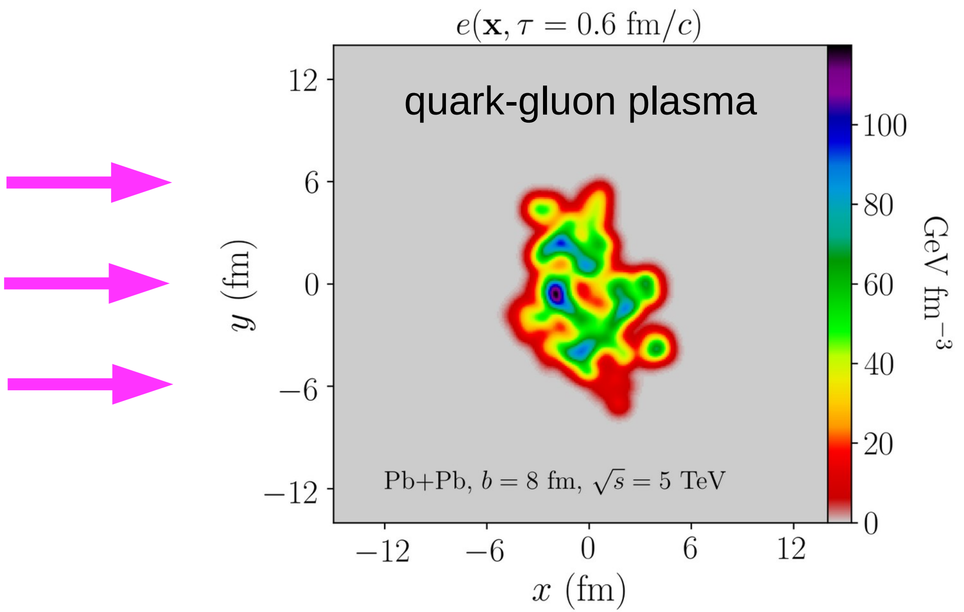
Geneva (CH)



Huge experimental program.

Emergent phenomena in strong-interaction matter.





Effective fluid description: $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu}$ + transport (η/s , ζ/s, ...)

[Romatschke & Romatschke, arXiv:1712.05815]

Equation of state from lattice QCD. Large number of DOF (~40): QGP.

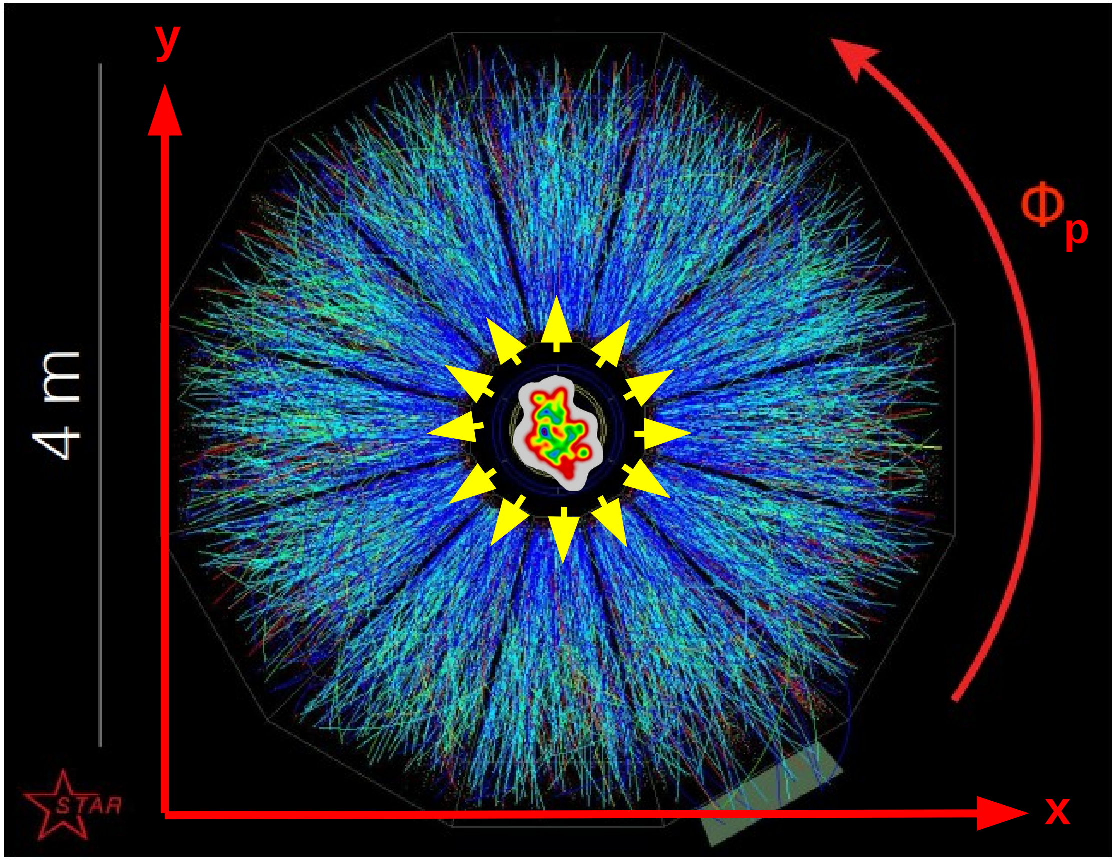
[HoTQCD collaboration, PRD **90** (2014) 094503]

Relevant temperature at top LHC energy: ≈ 220 MeV (2.6 x 10^{12} K).

[Gardim, Giacalone, Luzum, Ollitrault, Nature Phys. **16** (2020) 6, 615-619]

Main goals: understanding initial condition/transport properties/hadronization.

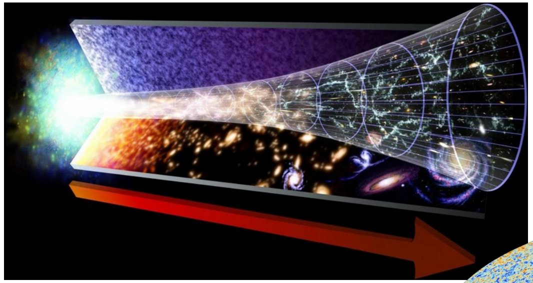
How do we reconstruct the initial condition of the QGP?

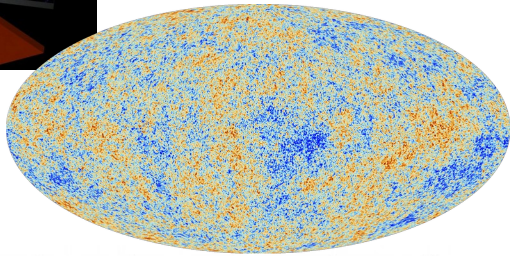


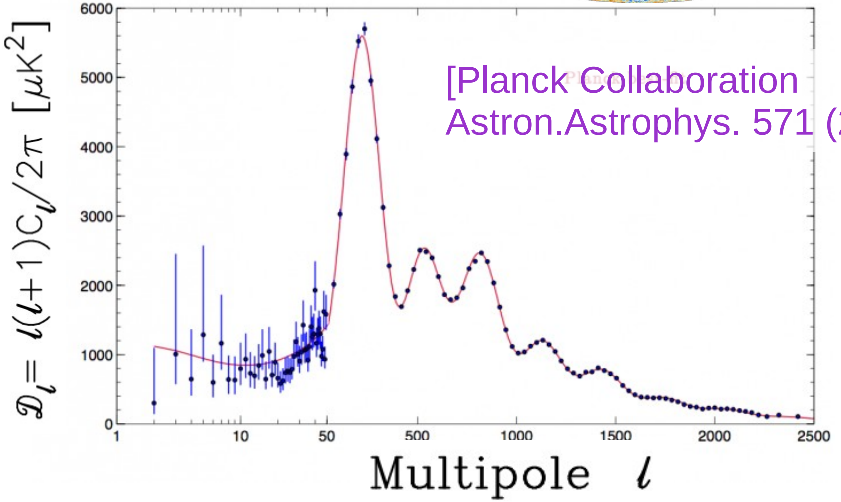
Low-momentum particles follow the hydrodynamic expansion.

$$\frac{d^2N}{dp_T d\phi} = \underbrace{\frac{dN}{2\pi dp_T}}_{\text{EXPLOSIVENESS OF THE EXPANSION}} \underbrace{\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)\right)}_{\text{ANISOTROPY OF AZIMUTHAL DISTRIBUTION}}$$

The Big Bang

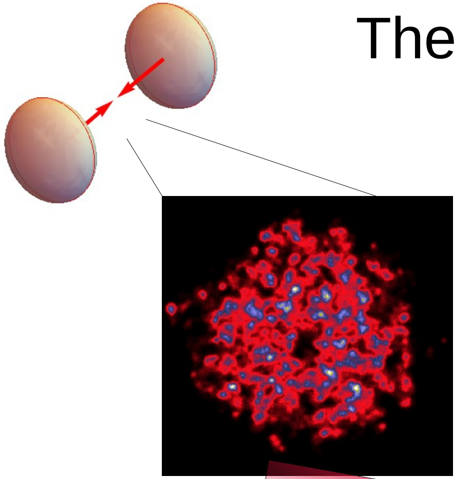


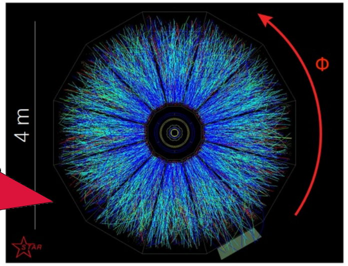


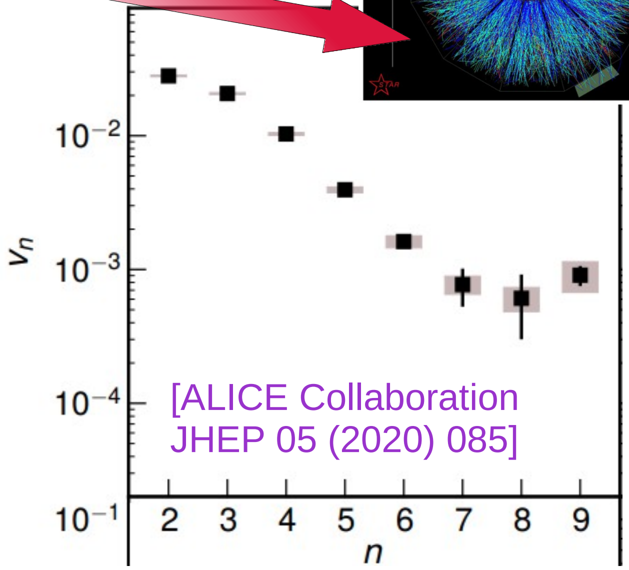


[Planck Collaboration
Astron.Astrophys. 571 (2014) A16]

The Little Bang(s)





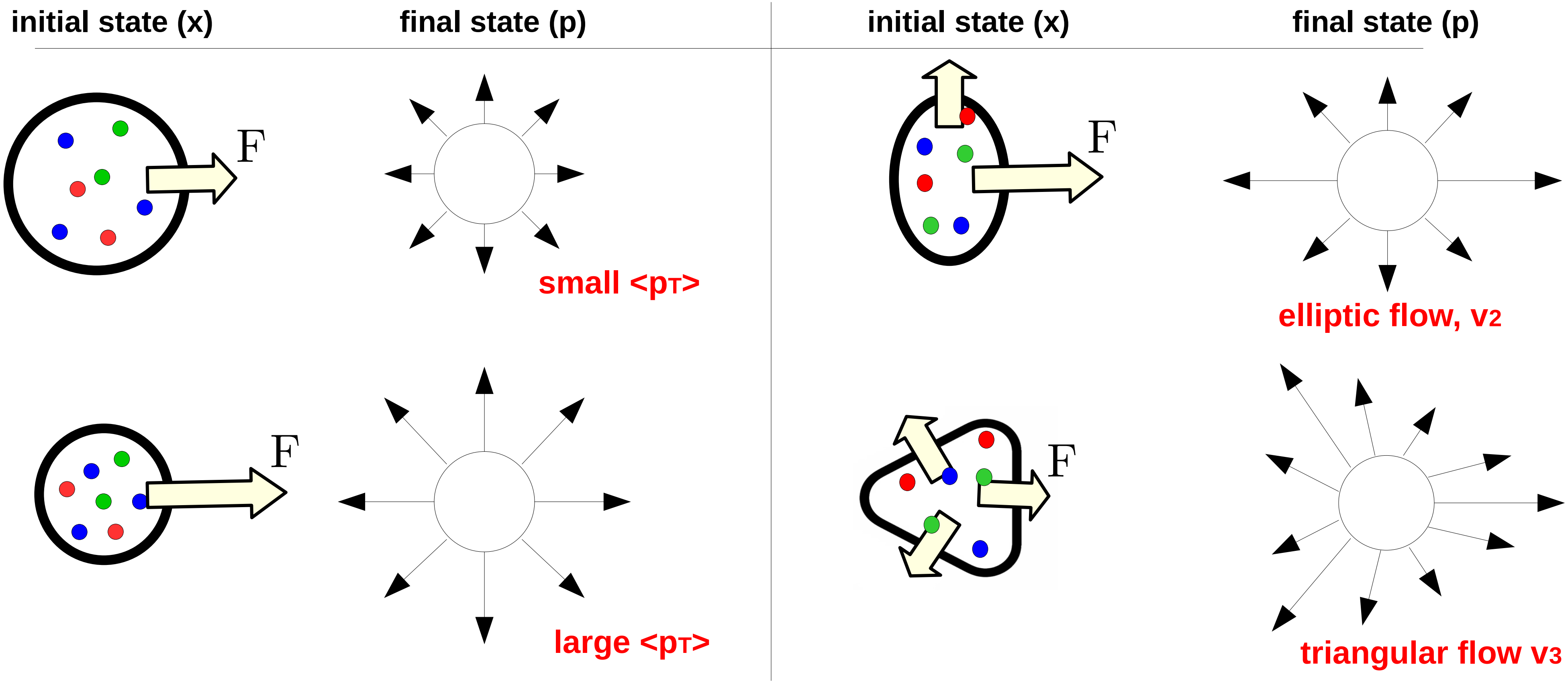


[ALICE Collaboration
JHEP 05 (2020) 085]

Mapping initial-state geometry to final-state observables via pressure-gradient force.

$$F = -\nabla P$$

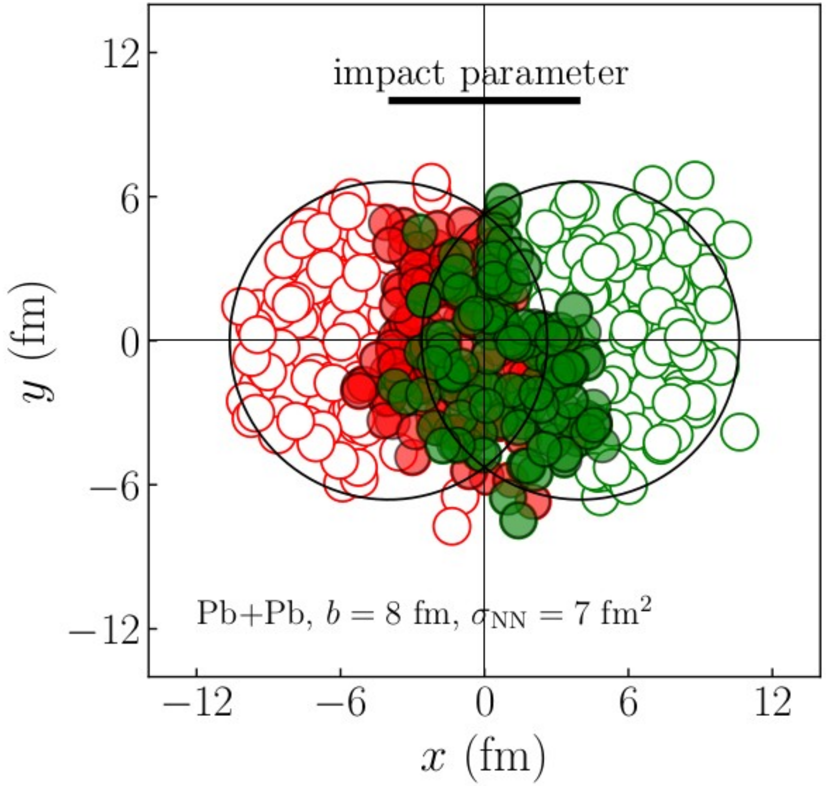
[Ollitrault, PRD **46** (1992) 229-245]



[Shape and size of the QGP can be reconstructed from data!]

2 – Nuclear structure input.

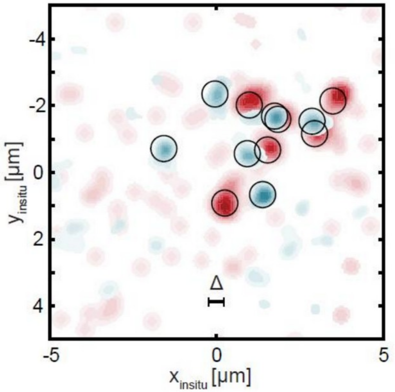
Formation of QGP starts with an input from nuclear structure.



High-energy model

Scattering occurs mainly within nucleons.

“quantum measurement” of the nucleon positions.

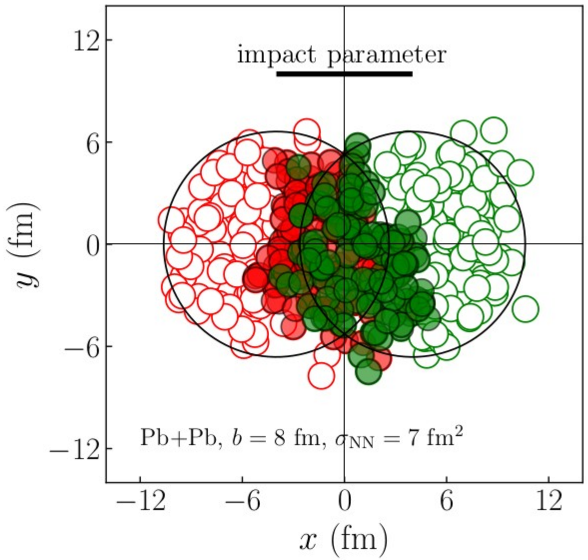


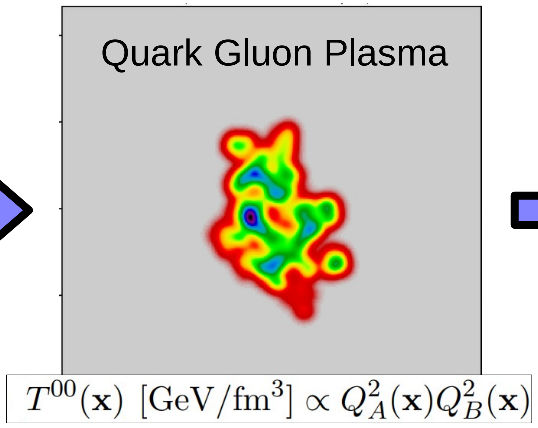
[from Sandra Brandstetter (Heidelberg), Collapsed wave function of a system of 10 ^{6}Li atoms]

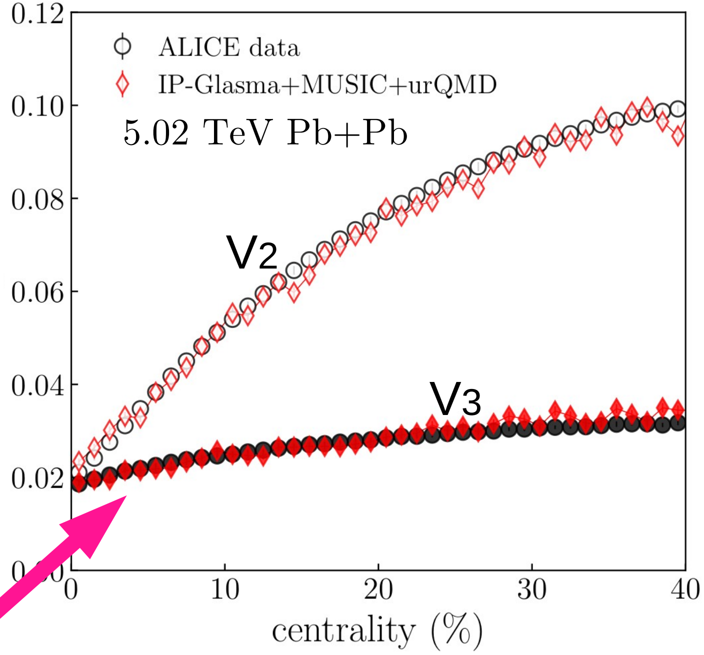
Mean-field-based approach. Independent nucleons from Woods-Saxon density

$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-R}{a}\right)}$$

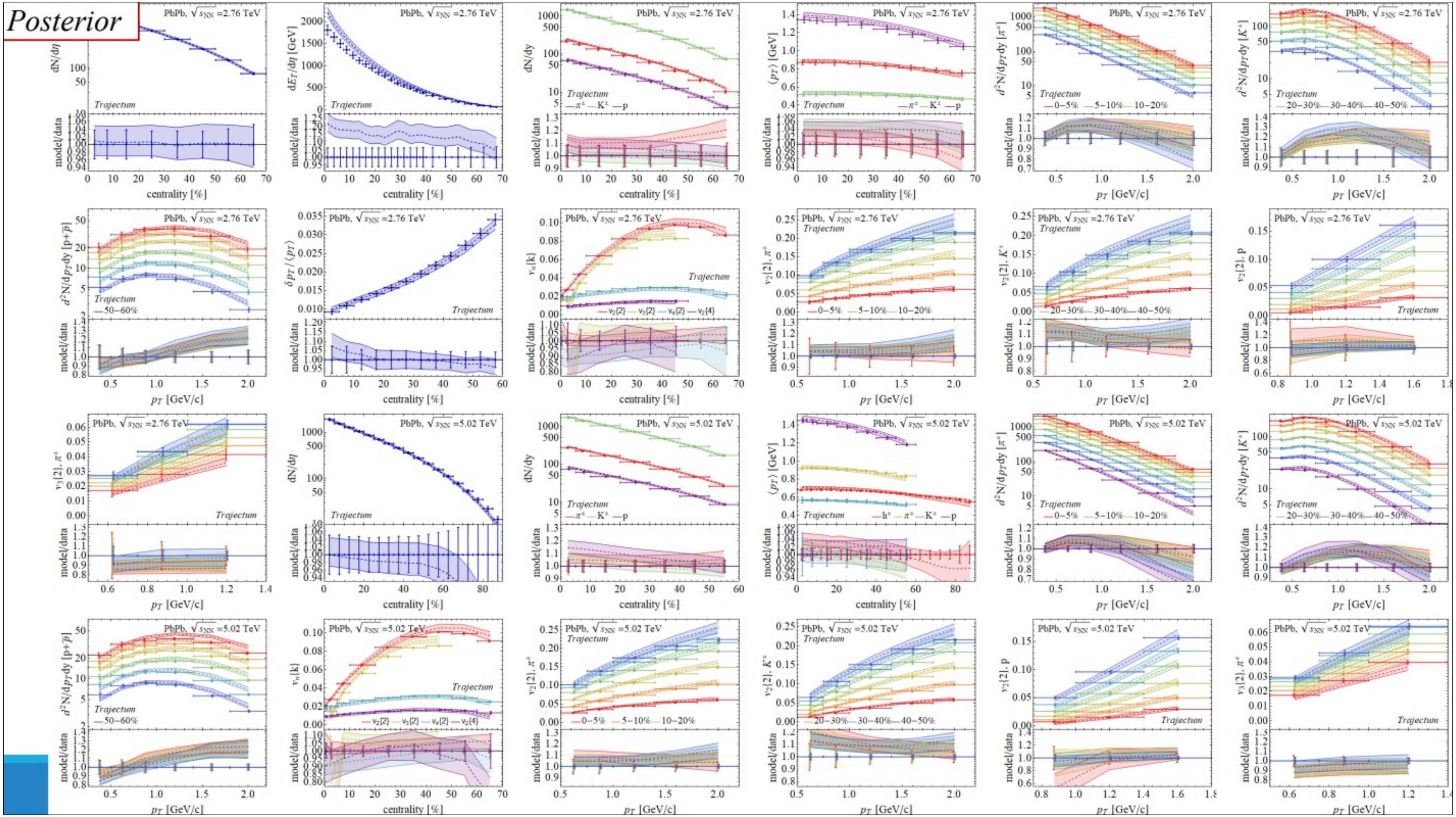
Nucleus-nucleus interaction does not modify the shape of the interaction region on large scales.







precision physics!



[Wilke van der Schee, ESNT workshop]

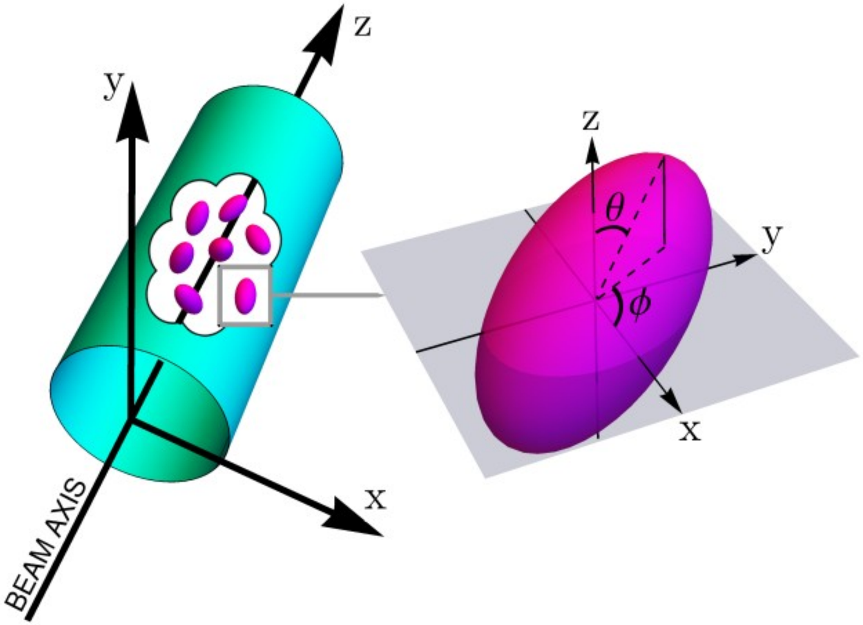
We are in a precision era. Nuclear structure input becomes an issue!

Describing heavy-ion collisions requires *a priori* knowledge of all spatial correlations,

$$\rho_k^{\mathrm{JMNZ}}(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r}_4) \equiv \langle \Psi_k^{\mathrm{JMNZ}} | c^\dagger(\vec{r}_1) c^\dagger(\vec{r}_2) c(\vec{r}_3) c(\vec{r}_4) | \Psi_k^{\mathrm{JMNZ}} \rangle$$

2-body correlation function

Help from low-energy nuclear physics:
Spatial correlations encapsulated in “intrinsic shapes”.
Instead of A-body correlation functions, use 1-body density with a deformed shape.

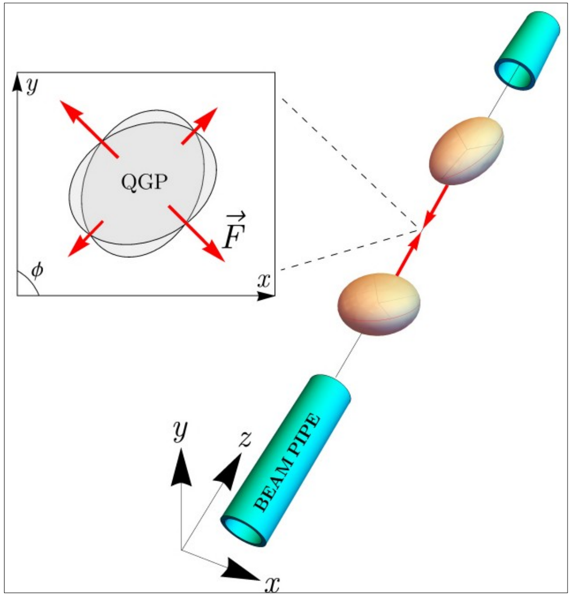


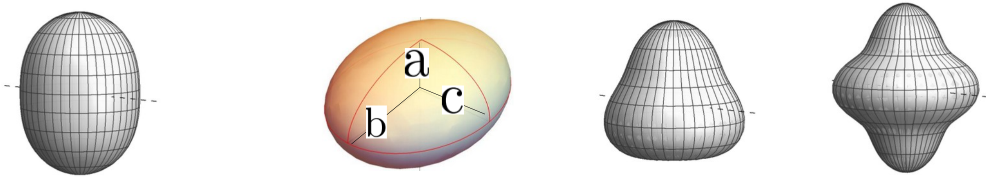
The bag of nucleons is now deformed and with a random orientation.

The collision selects one such orientation.

Generalize the Woods-Saxon profile to include intrinsic deformations:

$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \quad , \quad R(\Theta,\Phi) = R_0\left[1+\underline{\beta_2}\left(\cos\underline{\gamma} Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\underline{\beta_3} Y_{30}(\Theta)+\underline{\beta_4} Y_{40}(\Theta)\right]$$





Intrinsic shapes are non-observable for direct measurements, but they leave their fingerprint on virtually all nuclear observables and phenomena

Michael Bender – RBRC Workshop Jan 2022

2 – Nuclear shapes in high-energy nuclear experiments.

Species that have been collided so far (excludes p-A, d-A, He-A):

LHC

@ 2.76-5.02 TeV

- 208Pb, main species → "spherical baseline"
- 129Xe, data released in 2018

RHIC

@ 200 GeV

- 197Au, main species
- 238U, data released in 2015
- 96Ru, 96Zr, data released in 2021

(- 63Cu, very old data set)

→ deformed ions

New questions to address:

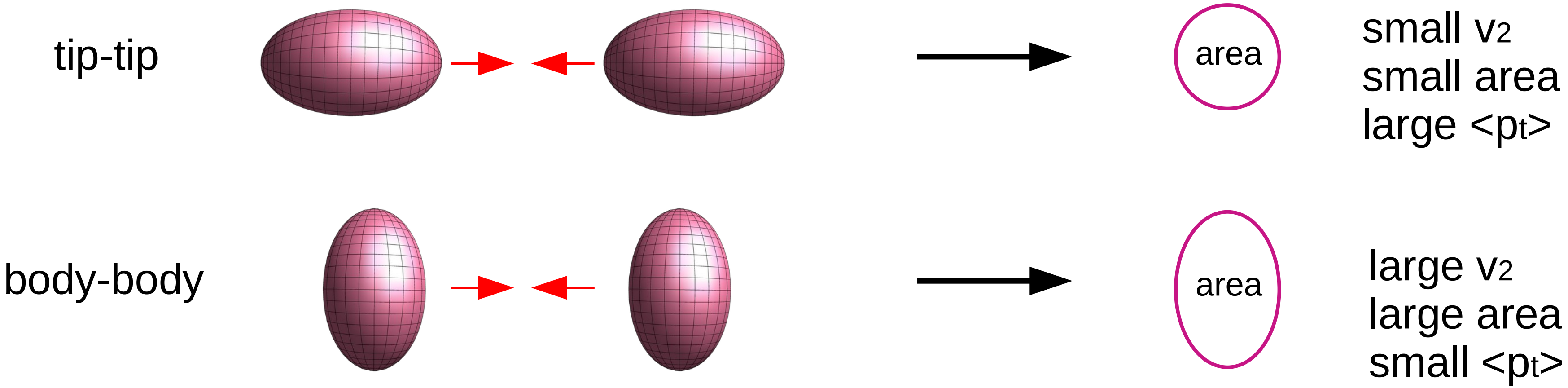
Testing high-energy model via crosscheck of nuclear deformation effects.

Are low-energy expectations compatible with high-energy observations?

HOW TO DO THAT? SHAPE-SIZE CORRELATION.

A new "classical phenomenon".

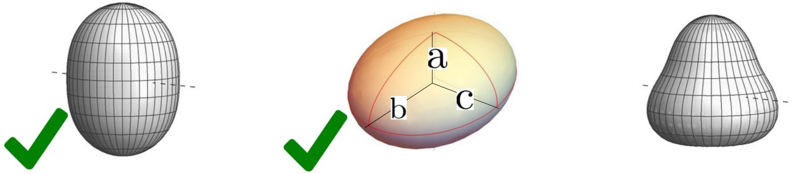
[Giacalone, PRL **124** (2020) 20, 202301
PRC **102** (2020) 2, 024901]



CENTRAL COLLISIONS OF (PROLATE) DEFORMED IONS

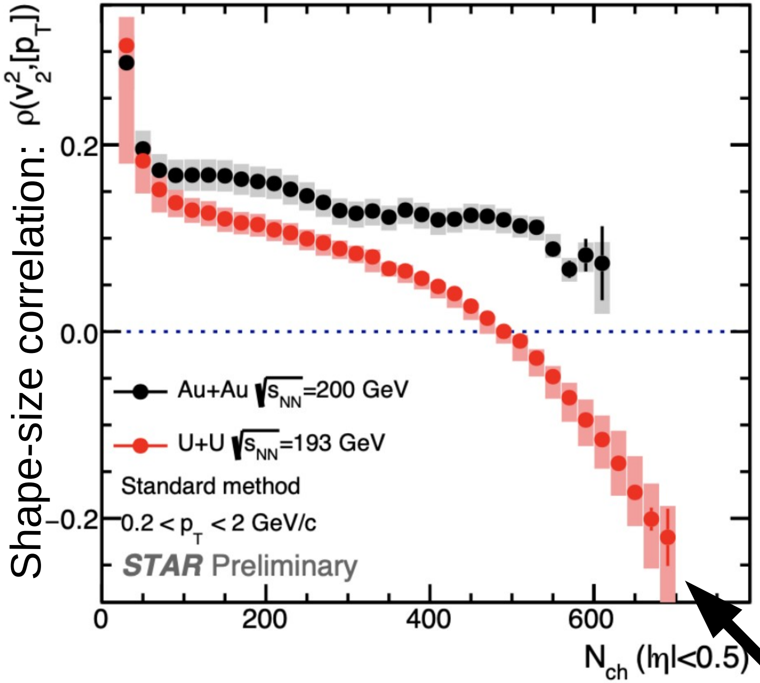
The ellipticity of the quark-gluon plasma is positively correlated with its area.

$$R(\Theta, \Phi) = R_0 \left[1 + \underline{\beta_2} \left(\cos \gamma Y_{20}(\Theta) + \sin \underline{\gamma} Y_{22}(\Theta, \Phi) \right) + \underline{\beta_3} Y_{30}(\Theta) + \beta_4 Y_{40}(\Theta) \right]$$

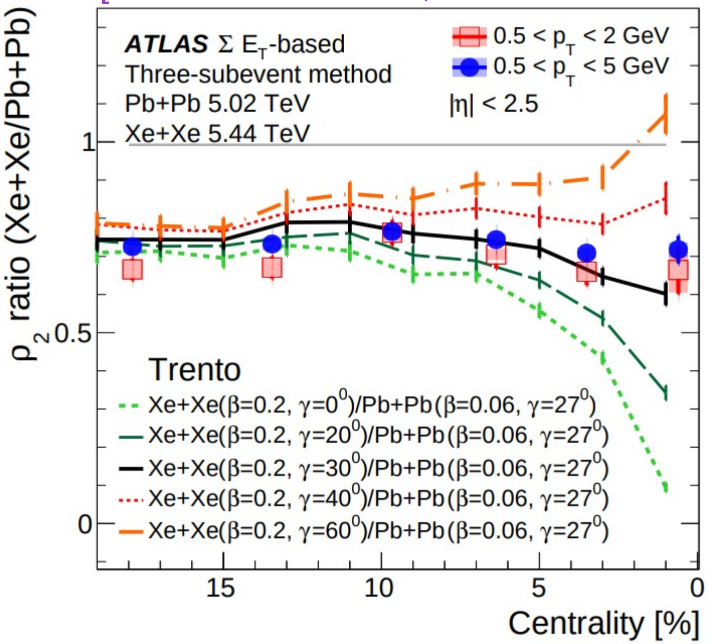


Triaxial structure of ^{129}Xe recently predicted:
[Bally et al., PRL **128** (2022) 8, 082301]

[STAR collaboration, Quark Matter 2022]

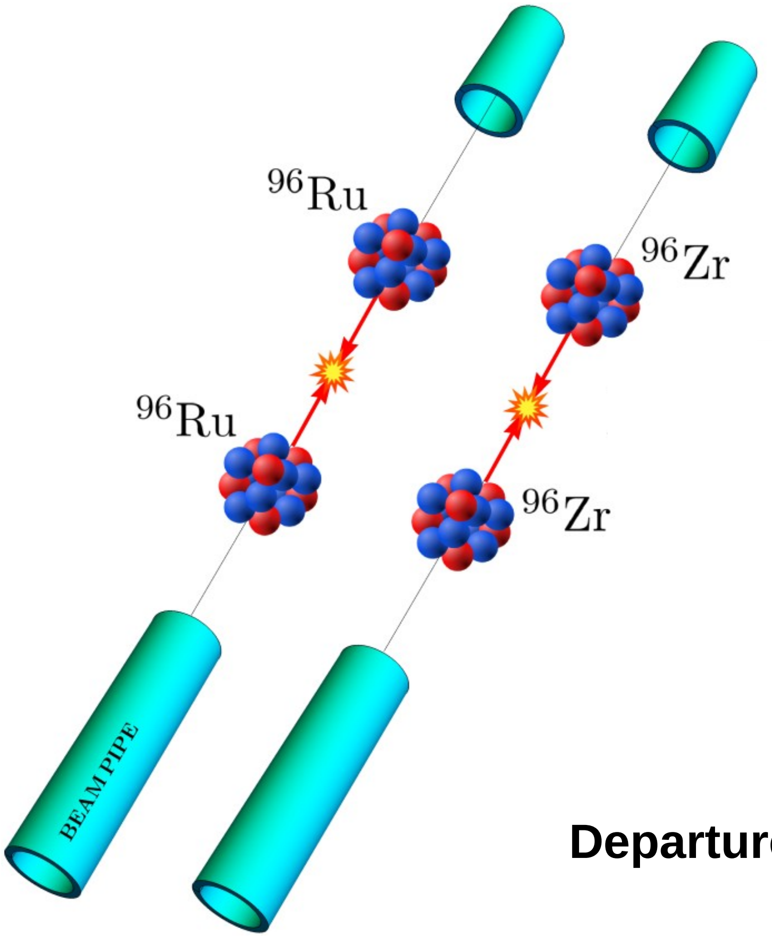


[ATLAS collaboration, arXiv:2205.00039]



Limit of fully-overlapping shapes.

Breakthrough of 2021: data from "isobar collisions" is released.



X and Y are isobars.

X+X collisions produce QGP with same properties as Y+Y collisions.

Ratios of observables (O) should be unity…

$$\frac{\mathcal{O}_{\mathrm{X+X}}}{\mathcal{O}_{\mathrm{Y+Y}}} \stackrel{?}{=} 1$$

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

Departure from unity is mainly due to nuclear structure.

Extremely precise measurements.

Signature of the quadrupole deformation of ruthenium-96.

In full generality, for quadrupole-deformed nuclei, at fixed multiplicity one has:

$$\langle v_2^2 \rangle = a + b\beta_2^2$$

elliptic flow from fluctuations

response coefficient

quadrupole deformation

[Giacalone, PRC **99** (2019) 2, 024910]
[Giacalone, Jia, Somà, PRC **104** (2021) 4, L041903]
[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]
[Jia, PRC **105** (2022) 1, 014905]

Isobar ratio and expand around the fluctuations:

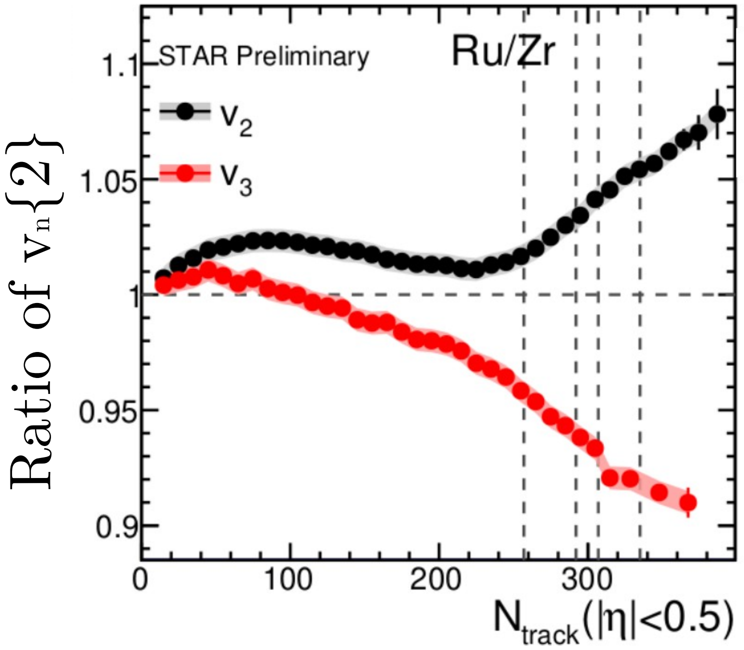
$$\frac{\langle v_2^2 \rangle_{\mathrm{Ru+Ru}}}{\langle v_2^2 \rangle_{\mathrm{Zr+Zr}}} = 1 + c\left(\beta_{2,\mathrm{Ru}}^2 - \beta_{2,\mathrm{Zr}}^2\right)$$

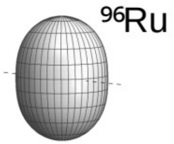
positive coeff

Low-energy nuclear physics tells us:

$$\beta_{2,\mathrm{Ru}}^2 \gg \beta_{2,\mathrm{Zr}}^2$$

Ratio should be above unity.





Signature of the octupole deformation of zirconium-96.

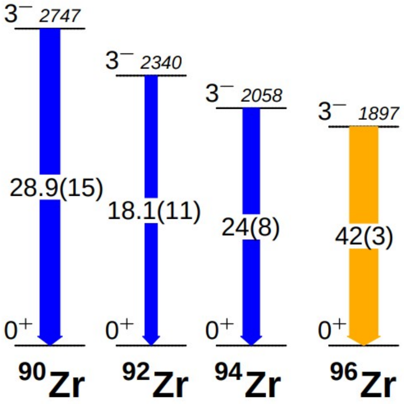
Same logic follows for octupole-deformed nuclei:

$$\frac{\langle v_3^2 \rangle_{\mathrm{Ru+Ru}}}{\langle v_3^2 \rangle_{\mathrm{Zr+Zr}}} = 1 + c\left(\beta_{3,\mathrm{Ru}}^2 - \beta_{3,\mathrm{Zr}}^2\right)$$

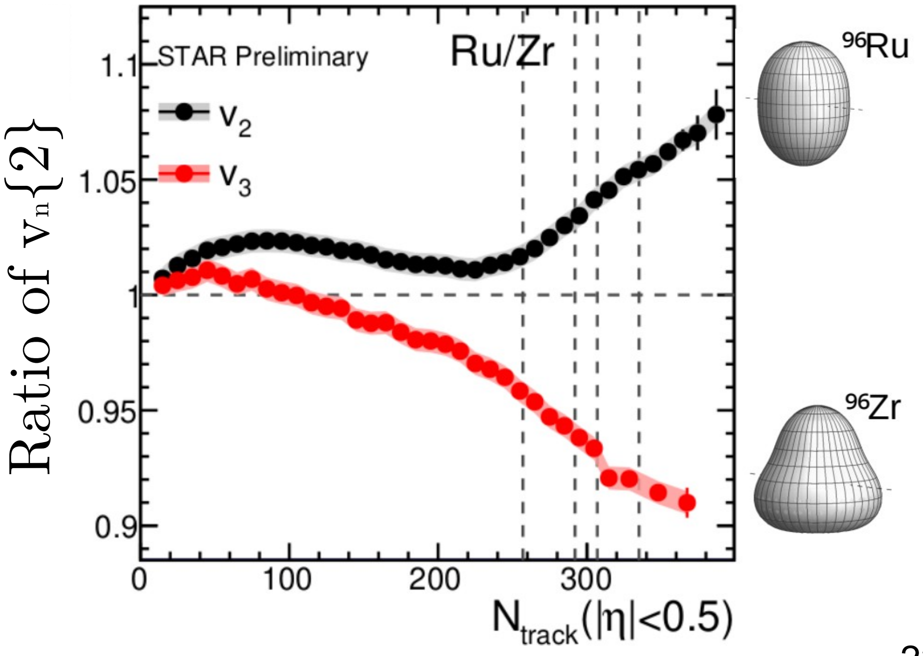
[Jia, Zhang, PRL **128** (2022) 2, 022301]

Significant octupole deformation from low-lying first 3^- state in ^{96}Zr.

No experimental information about ^{96}Ru.



[from M. Zielinska, ESNT workshop]

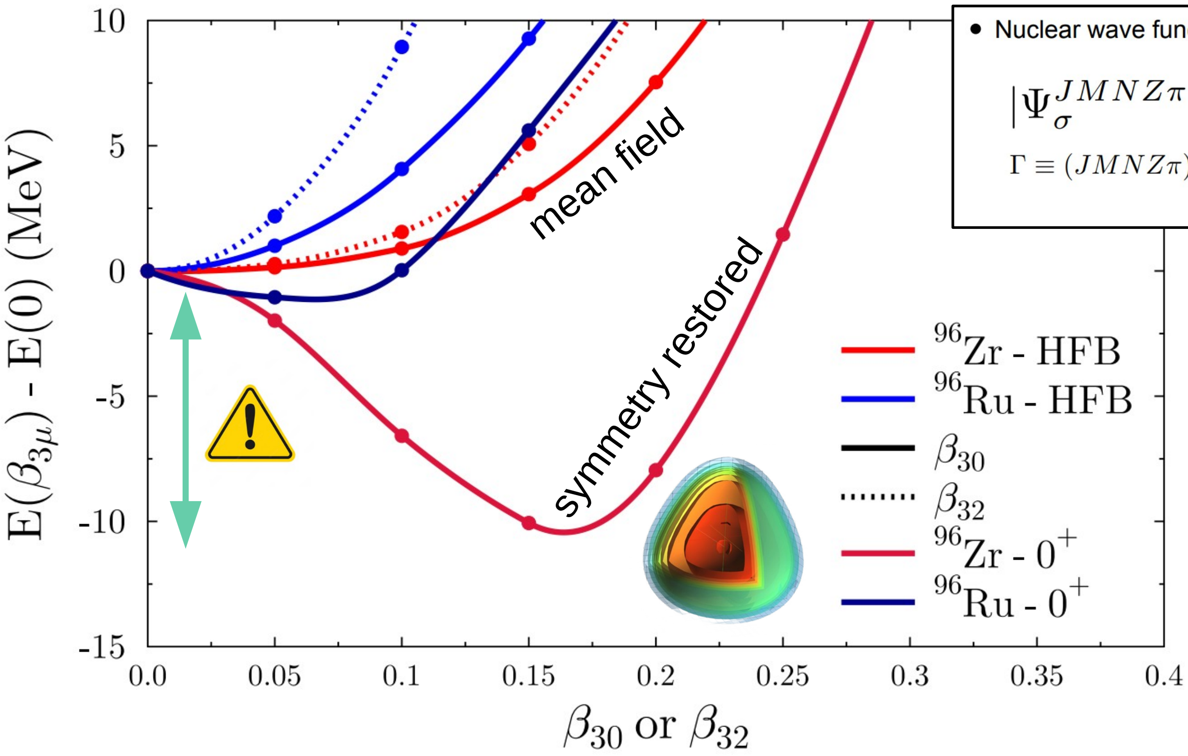


RHIC data implies $\beta_{3,\mathrm{Zr}}^2 \gg \beta_{3,\mathrm{Ru}}^2$

Explanation from nuclear structure theory?

Octupole deformation is a "beyond-mean-field" effect.

[Robledo, J.Phys.G **42** (2015) 5, 055109]



- Nuclear wave functions : Generator Coordinate Method (GCM) ansatz

$$|\Psi_\sigma^{JMNZ\pi}\rangle = \sum_{qK} f_{\sigma;qK}^{JMNZ\pi} \boxed{P^J_{MK} P^N P^Z P^\pi |\Phi(q)\rangle}$$

$\Gamma \equiv (JMNZ\pi)$

[from T. Rodriguez]

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EMMI Rapid Reaction Task Force

Nuclear Physics Confronts Relativistic Collisions of Isobars

Heidelberg University, Germany, May 30 – June 3 & October 12 – 14, 2022

Benjamin Bally (Paris-Saclay)

preliminary results

Preliminary work confirms large octupole deformation in zirconium. $\beta_{3,\mathrm{Zr}}^2 \gg \beta_{3,\mathrm{Ru}}^2$

Large energy gain from symmetry restoration.

Answers to the initial questions:

- Expectations from low-energy nuclear physics confirmed in high-energy data.
- Quadrupole, triaxiality, octupole, hexadecapole, and radial profile differences between isobars.
- **Great confidence that high-energy model is appropriate.** ✓
- **No clear indication of modifications of nuclear geometry from enhanced gluon fluctuations (Lorentz boost).** ✓

4 – Prospects: light nuclei and *ab initio* calculations.

Current works in progress:

G. Giacalone

+

G. Nijs, W. van der Schee (Trajectum hydrodynamic framework)

+

B. Bally, T. Duguet, J-P. Ebran, M. Frosini, T. Rodriguez, V. Somà
(*ab initio* PGCM)

+

D. Lee, B-N. Lu
(NLEFT)

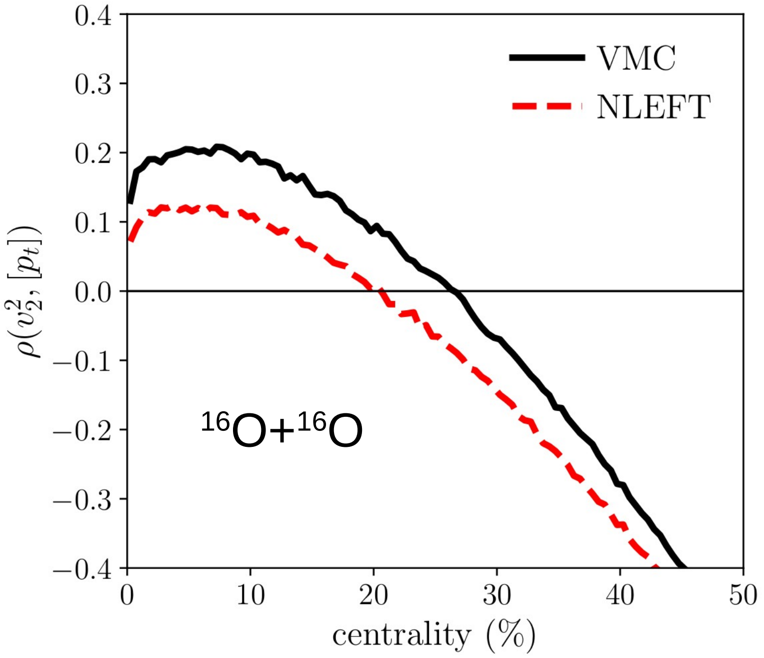
Going beyond shapes: connection with *ab initio* calculations.

Great opportunity from $^{16}O+^{16}O$ collisions from both RHIC and LHC.

- 6000 configurations from Cluster Variational Monte Carlo simulations.
Interaction: AV18+UIX. Repulsive core implemented. [Lonardoni *et al.*, PRC **96** (2017) 2, 024326] [Lim *et al.*, PRC **99** (2019) 4, 044904]

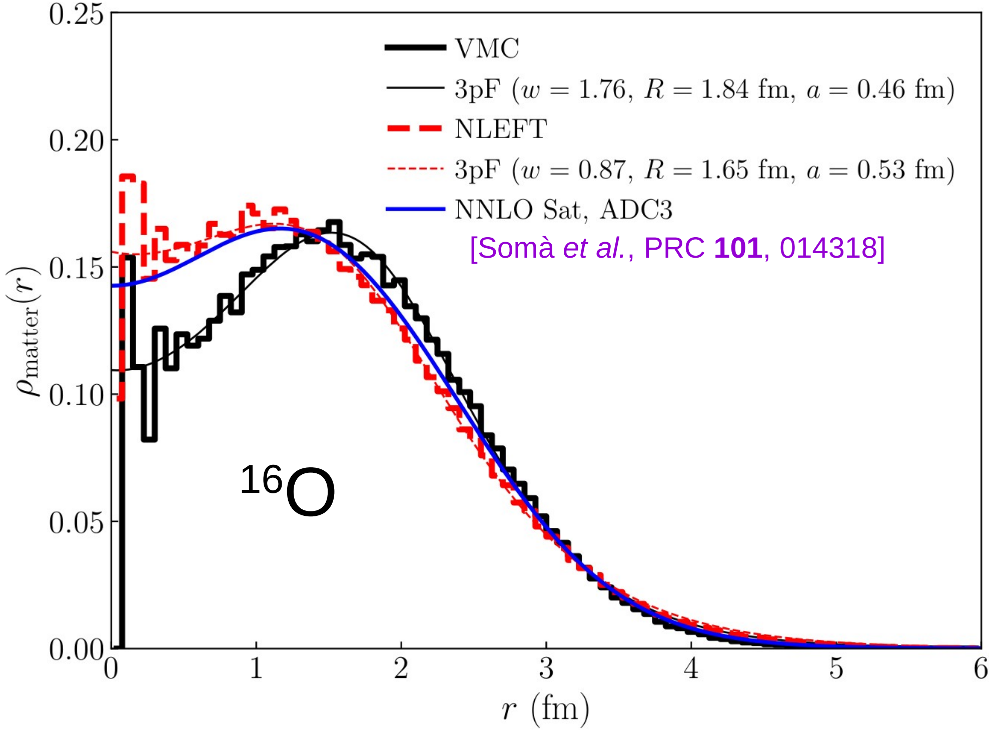
- 15359 configurations from Nuclear Lattice Effective Field Theory simulations.
Interaction: pionless EFT. Pin-hole algorithm to determine nucleon positions.

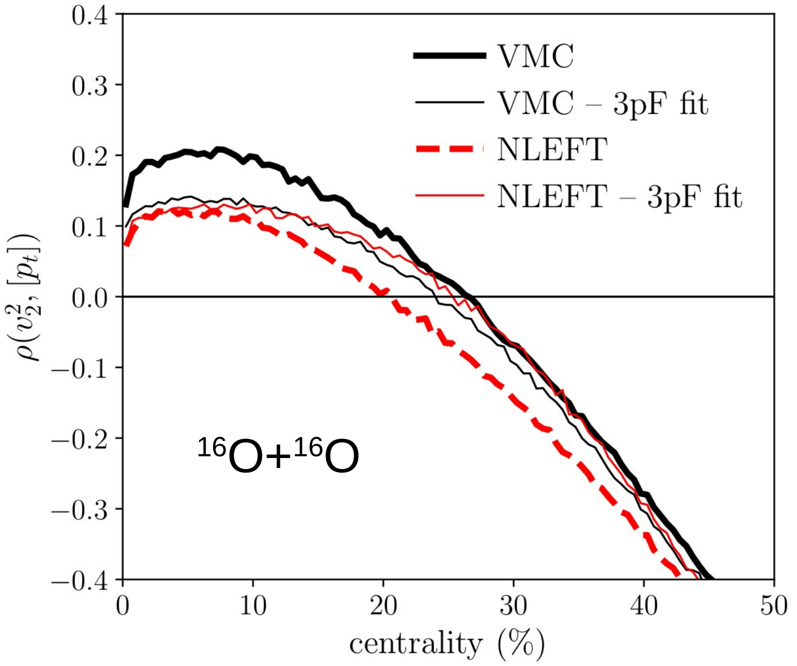
[Lu et al., PLB **797** (2019) 134863]
[Summerfield *et al.*, PRC **104** (2021) 4, L041901]



Why are they different?

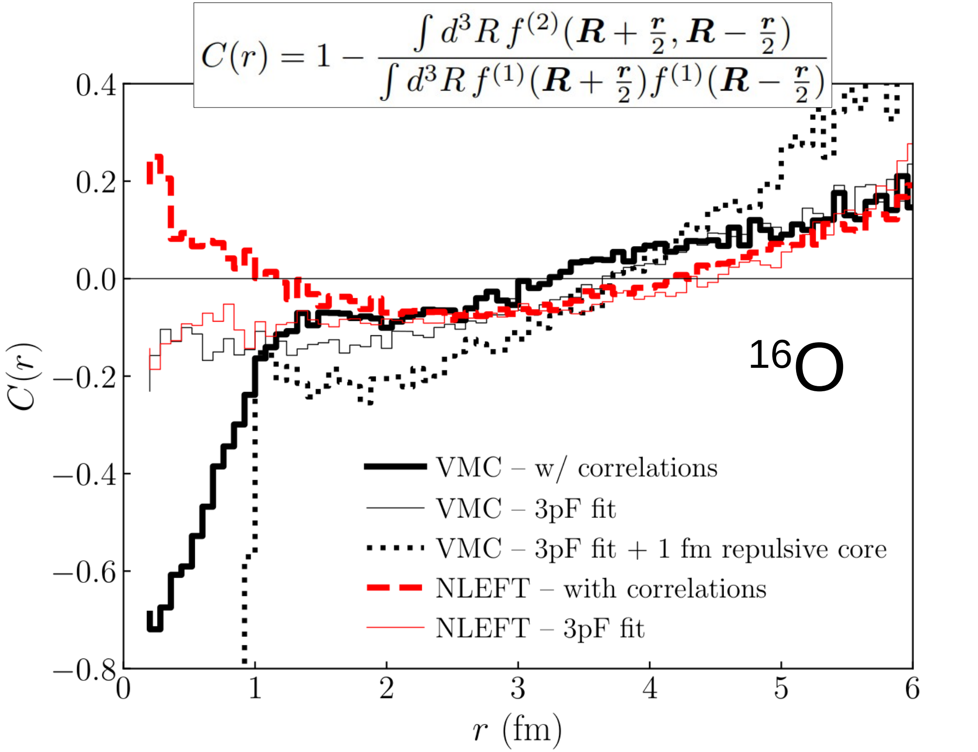
Due to the different underlying one-body density?

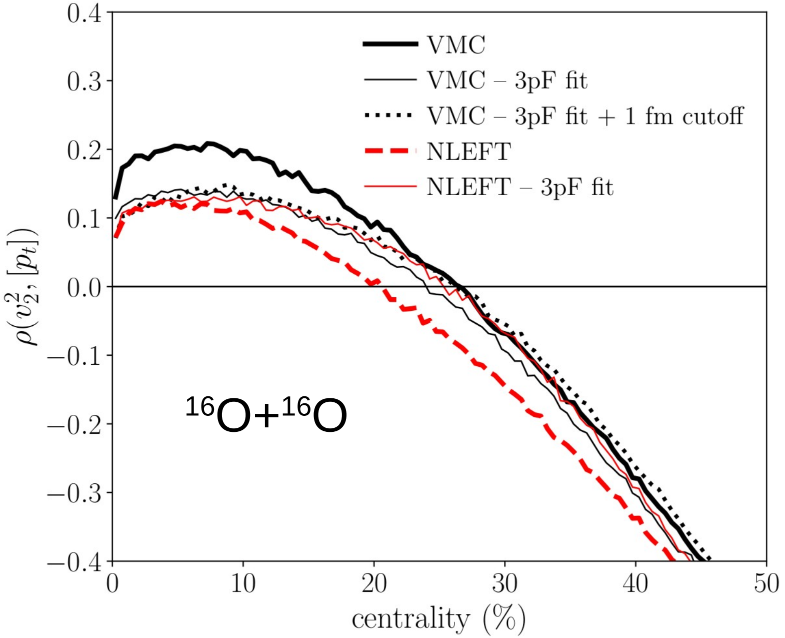




No.

Due to the short-range repulsive core?

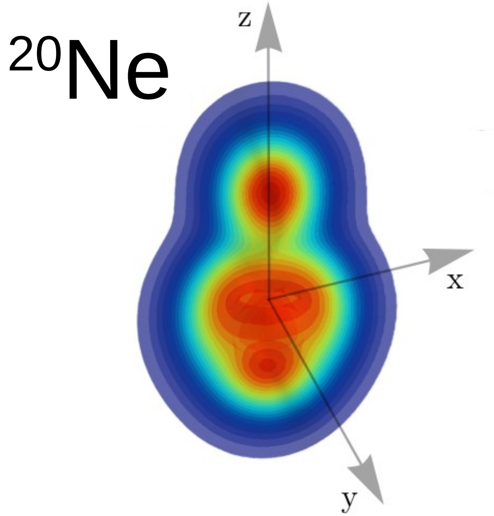


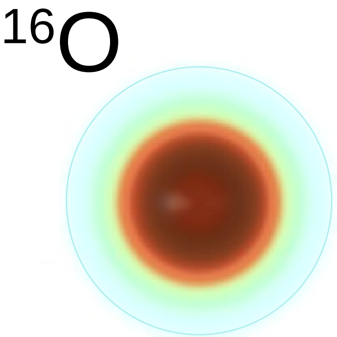


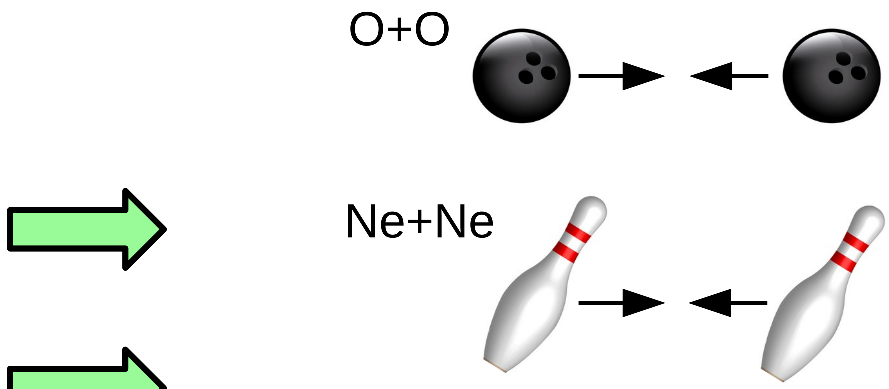
Nope. It must come from the effect of collective (spatial) correlations.
What are the relevant features?

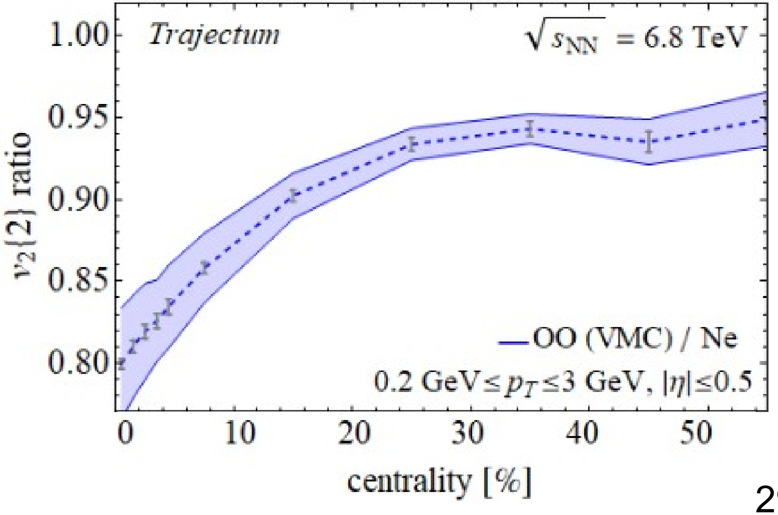
Transparent evidence of a “geometric” origin of flow in a “small system”?

Exploit bowling-pin-shaped ^{20}Ne.









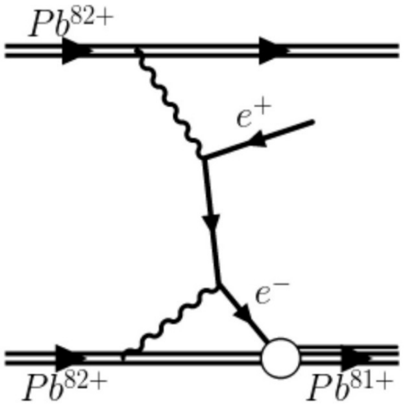
[Oxygen structure: VMC, Lonardoni *et al.*, PRC **96** (2017) 2, 024326]
[Neon structure: *ab initio* PGCM, Frosini *et al.*, EPJA **58** (2022) 4, 63]
[Nuclear Lattice Effective Field Theory?]

LHC – Run5 and Run6 (beyond 2032)

Possibility of collisions of additional species @ LHC Run 5 and Run 6?

Maximizing impact for both low- and high-energy communities?

<u>Collide them in pairs (isobar strategy)?</u>



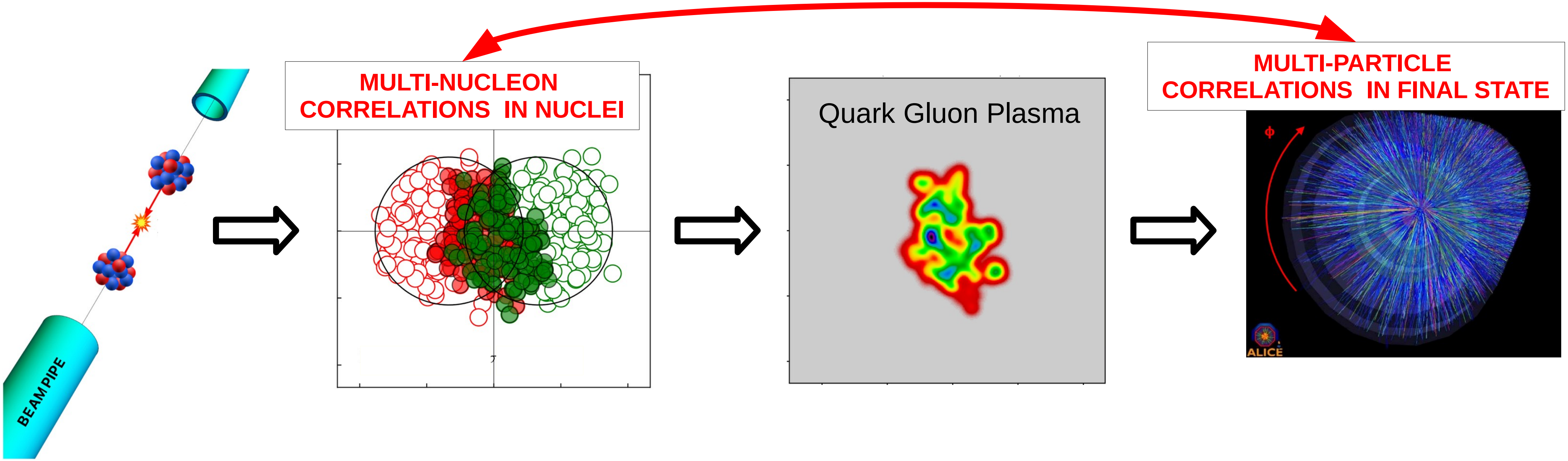
[from Alexander Kalweit (CERN), ESNT workshop]

[https://indico.cern.ch/event/1078695/]

Nucleon-nucleon luminosity: $\mathcal{L}_{NN} = A^2 \cdot \mathcal{L}_{AA}$

optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\langle L_{NN} \rangle$ (cm^{-2} s^{-1})	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathcal{L}_{AA}$ (nb^{-1} / month)	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$5.6 \cdot 10^{0}$
$\mathcal{L}_{NN}$ (pb^{-1} / month)	409	550	500	510	512	434	242

SUMMARY



- High-energy model for an excellent description of heavy-ion data.
- Collective spatial correlations (shapes) in nuclei show up clearly at high energy.
- Prospect theory: improved initial conditions from synergy with *ab-initio* nuclear theory.
- Prospect experiments: many opportunities to be discussed/investigated.

THANK YOU!

Intersection of nuclear structure and high-energy nuclear collisions

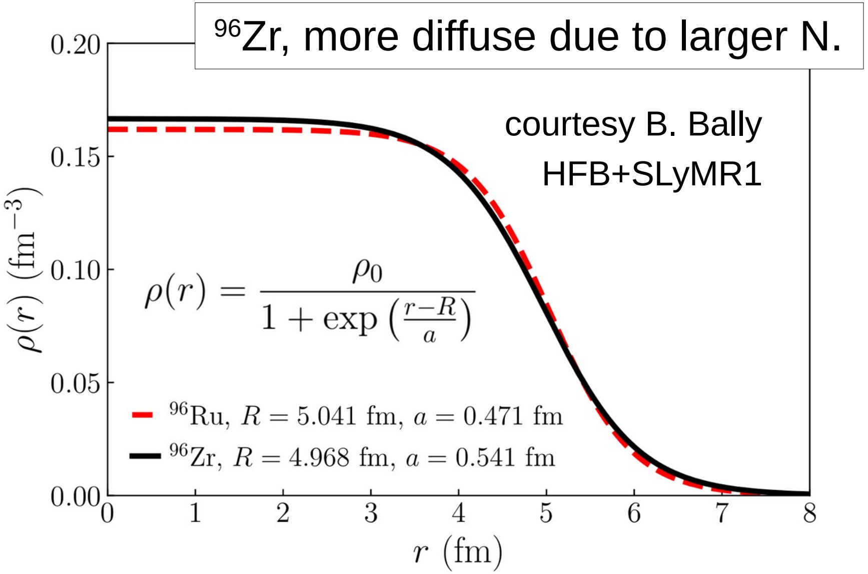
https://www.int.washington.edu/programs-and-workshops/23-1a

Jan 23rd - Feb 24th 2023

INSTITUTE for NUCLEAR THEORY

Organizers:
Jiangyong Jia (Stony Brook & BNL)
Giuliano Giacalone (ITP Heidelberg)
Jaki Noronha-Hostler (Urbana-Champaign)
Dean Lee (Michigan State & FRIB)
Matt Luzum (São Paulo)
Fuqiang Wang (Purdue)

BONUS: Signature of skin thickness in (ratio of) fourth-order cumulant of v_2.



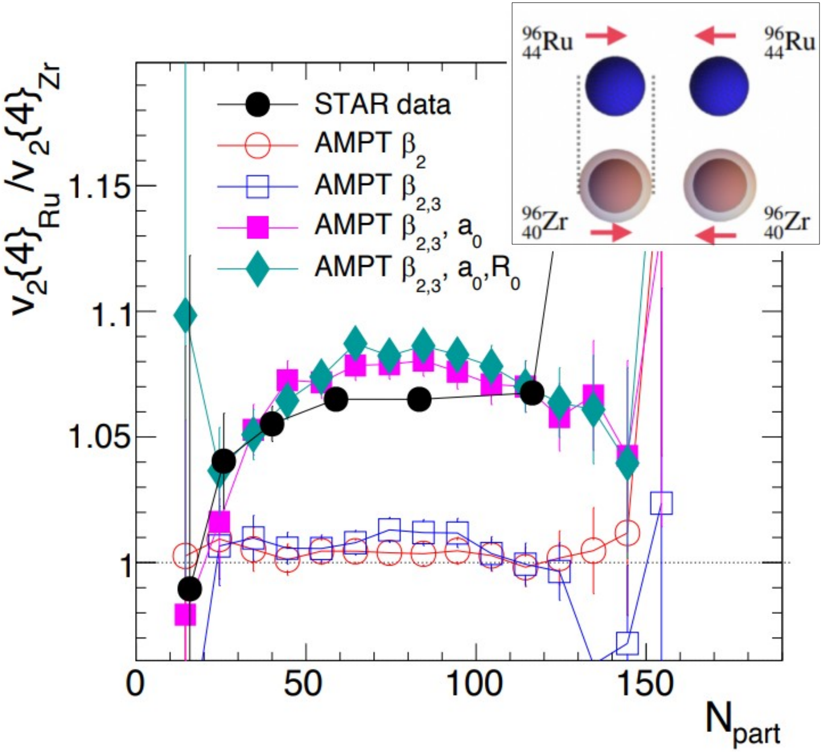
Gaussian model of $V_2=(v_x,v_y)$ fluctuations.
Reaction plane is along x:

$$p(v_{2x}, v_{2y}) = \frac{1}{\pi\delta^2} \exp\left[-\frac{(v_{2x}-v_2^{rp})^2+v_{2y}^2}{\delta^2}\right]$$

$$v_2\{4\} = v_2\{6\} = \ldots = v_2\{\infty\} = v_2^{rp}$$

probes the skin

[Voloshin *et al.*, PLB **659** (2008) 537-541]
[Jia, Giacalone, Zhang, arXiv:2206.10449]



see also [Nijs, van der Schee, arXiv:2112.13771]
[Xu *et al.*, arXiv:2111.14812]
[Xu *et al.*, PLB **819**, 136453 (2021)]

BONUS: Neutron skin estimates from high-energy collisions? Two methods.

Difference in diffuseness gives access to neutron skin difference. Use isobars.
^{208}Pb, ^{48}Ca … can high-energy nuclear physics contribute to these efforts?

[Jia & Zhang, arXiv:2111.15559]

Nice results from STAR in an individual system: $\Delta r_{np}[\,^{197}\mathrm{Au}\,] = 0.17 \pm 0.03\ (\mathrm{stat.}) \pm 0.08\ (\mathrm{syst.})\ \mathrm{fm}$
Consistent with low-energy nuclear theory.

[STAR Collaboration, Sci.Adv. 9 (2023) 1, eabq3903]

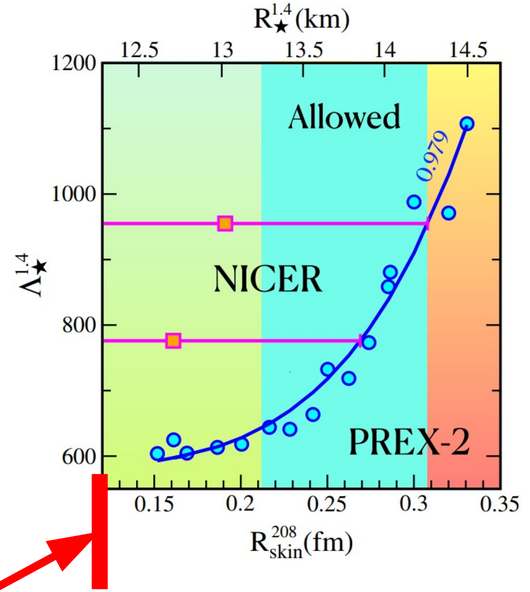
Recent measurements for ^{208}Pb from weak form factor:

$$\Delta r_{np} = 0.283 \pm 0.071\ \mathrm{fm}$$

$$L = (106 \pm 37)\ \mathrm{MeV}$$

[PREX-II experiment,
PRL **126** (2021) 17, 172502]

Stiffer EoS than expected.



From NS merger observations.

[Reed et al., PRL **126** (2021) 17, 172503]
[Fattoyev et al., PRL **120** (2018) 17, 172702]