Nuclear phenomenology at the intersection of nuclear structure and high-energy nuclear collisions

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UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

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EMMI Nuclear and Quark Matter Seminar 2023

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 for Nuclear Physics LRP in the US, arXiv link

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

OUTLINE

1 – High-energy nuclear physics and anisotropic flow.

2 – Nuclear structure input to high-energy nuclear collisions.

3 – Nuclear shapes in high-energy nuclear experiments.

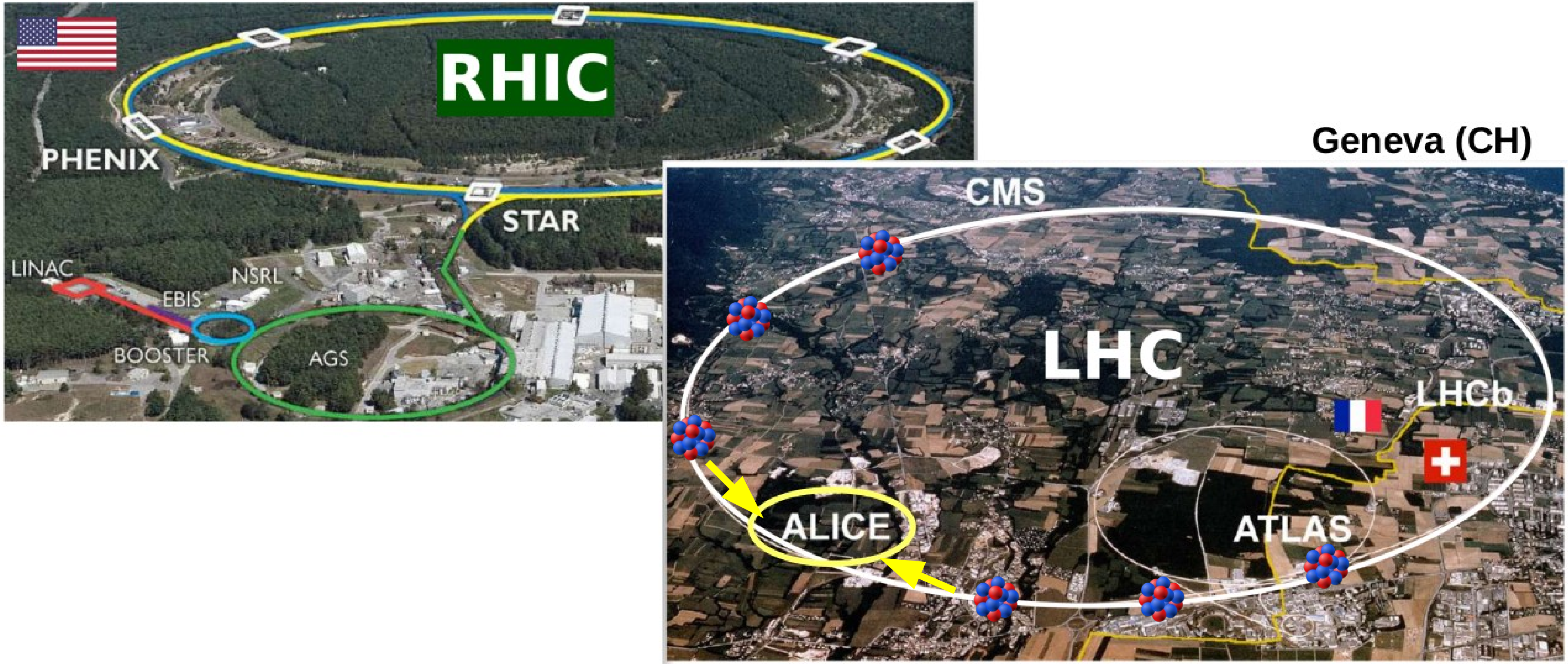
4 – Prospects: theory and experiment.

1 – High-energy nuclear physics and anisotropic flow.

HIGH ENERGY NUCLEAR PHYSICS

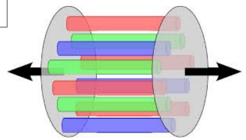
Long Island (NY)

Geneva (CH)



GOAL: studying emergent properties and phase diagram of strong-interaction matter.

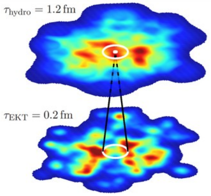
2 Effective theory of highly-occupied gluon fields: *“Glasma”*

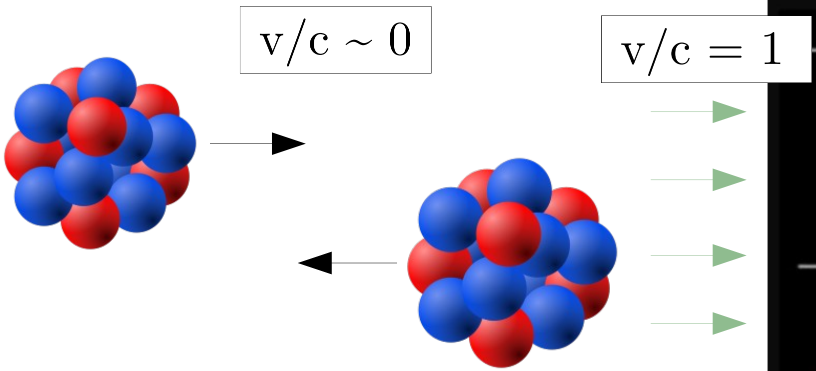


$$\langle T^{00}\rangle \propto Q_A^2(\mathbf{x})Q_B^2(\mathbf{x})$$

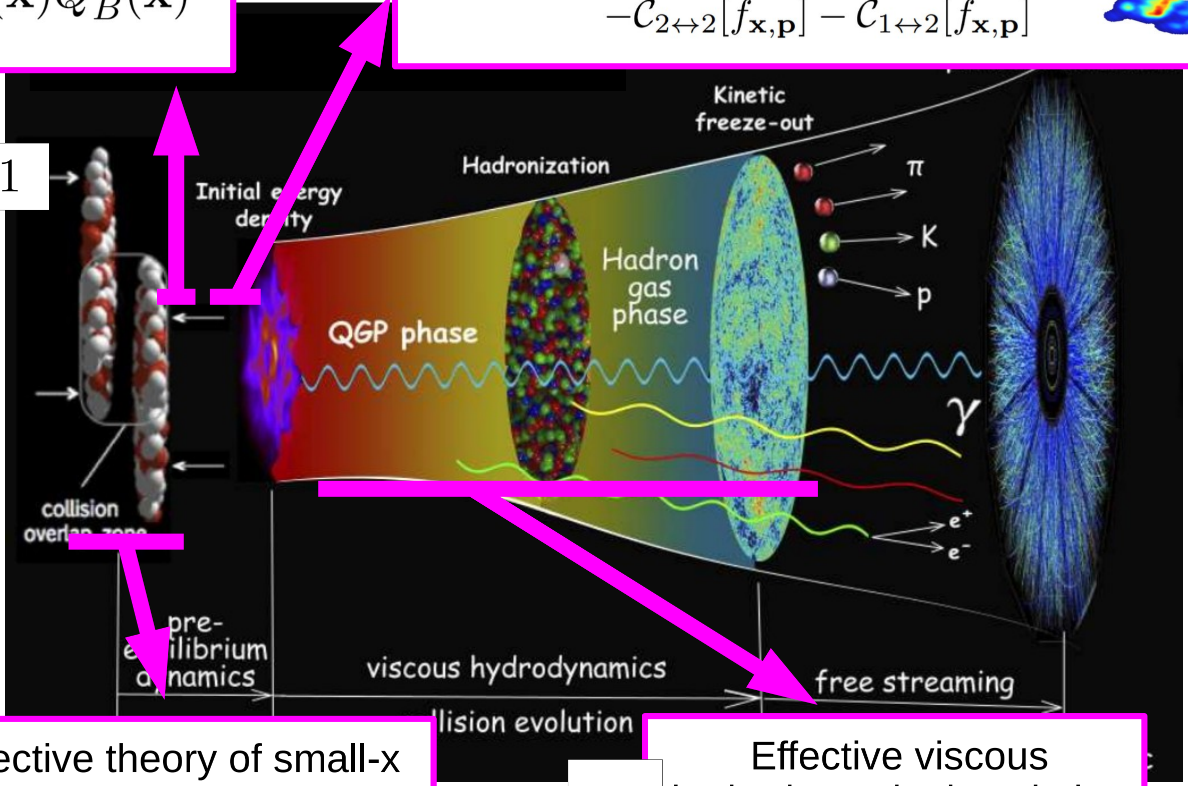
3 Effective QCD kinetic theory

$$\partial_\tau f_{\mathbf{x},\mathbf{p}} + \frac{\mathbf{p}}{|\mathbf{p}|}\cdot\nabla_{\mathbf{x}} f_{\mathbf{x},\mathbf{p}} - \frac{p^z}{\tau}\partial_{p^z} f_{\mathbf{x},\mathbf{p}} = -\mathcal{C}_{2\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}] - \mathcal{C}_{1\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}]$$





HEAVY-ION COLLISIONS
=
A TOWER OF EFFECTIVE THEORIES



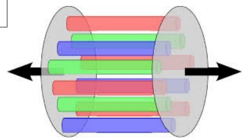
1 Effective theory of small-x degrees of freedom
CGC

$$A^\mu_{1,2}(x) \qquad Q_s^2(\mathbf{x})$$

4 Effective viscous hydrodynamic description

$$\vec{F} = -\vec{\nabla}P \qquad \eta/s$$

2 — Effective theory of highly-occupied gluon fields: *"Glasma"*



$$\langle T^{00}\rangle \propto Q_A^2(\mathbf{x})Q_B^2(\mathbf{x})$$

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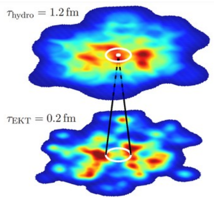
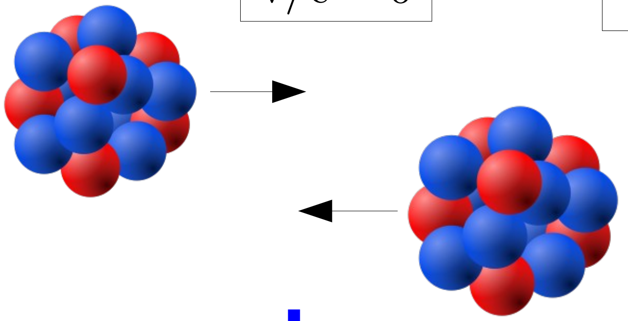
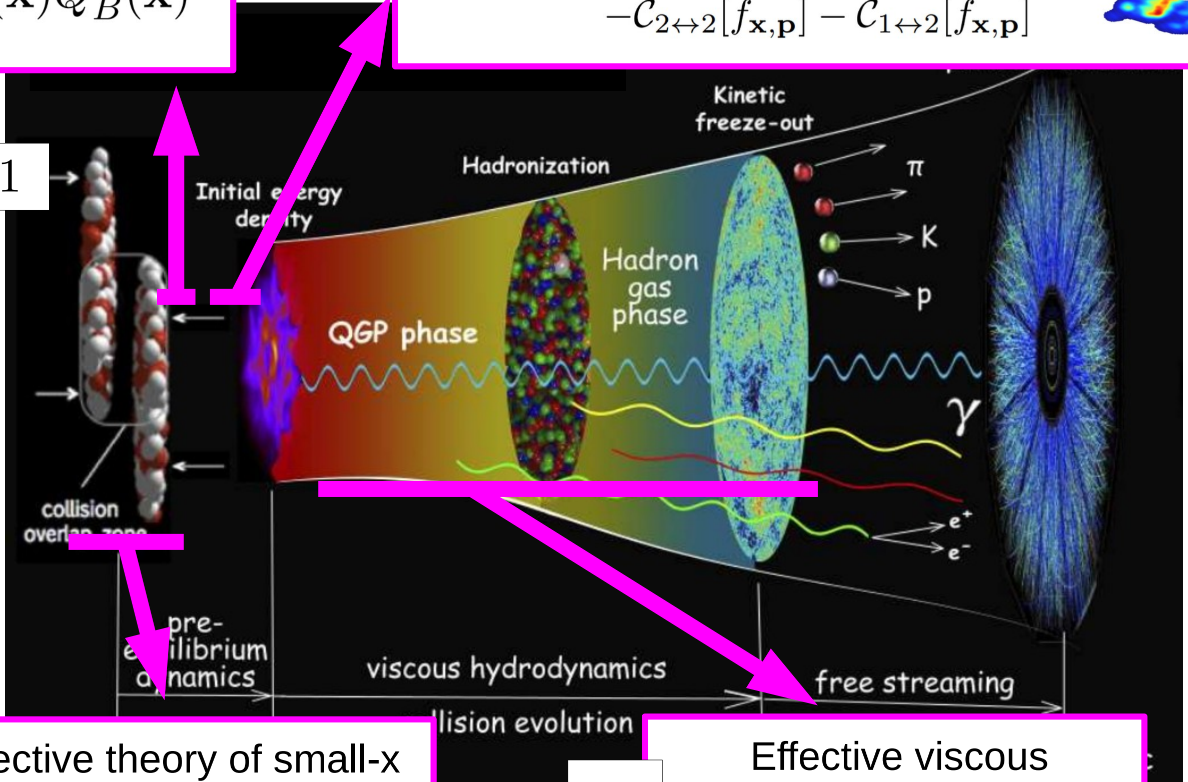


$v/c \sim 0$



$v/c = 1$



0 — THIS TALK

Effective theories of QCD for spatial distribution of large-x degrees of freedom

→ nuclear structure

1 — Effective theory of small-x degrees of freedom

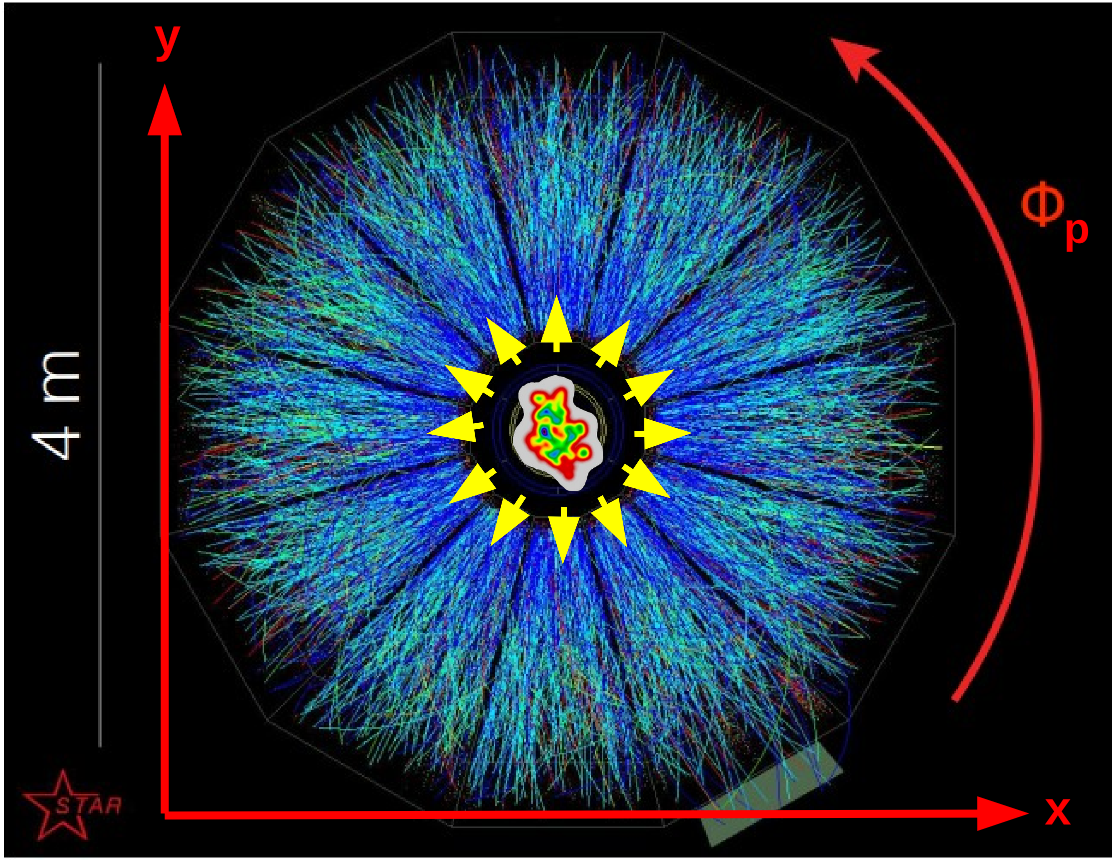
CGC

$$A^\mu_{1,2}(x) \qquad Q_s^2(\mathbf{x})$$

4 — Effective viscous hydrodynamic description

$$\vec{F} = -\vec{\nabla}P \qquad \eta/s$$

How do we reconstruct the initial condition of the QGP?



Hydrodynamics describes the motion of the bulk of the produced particles.

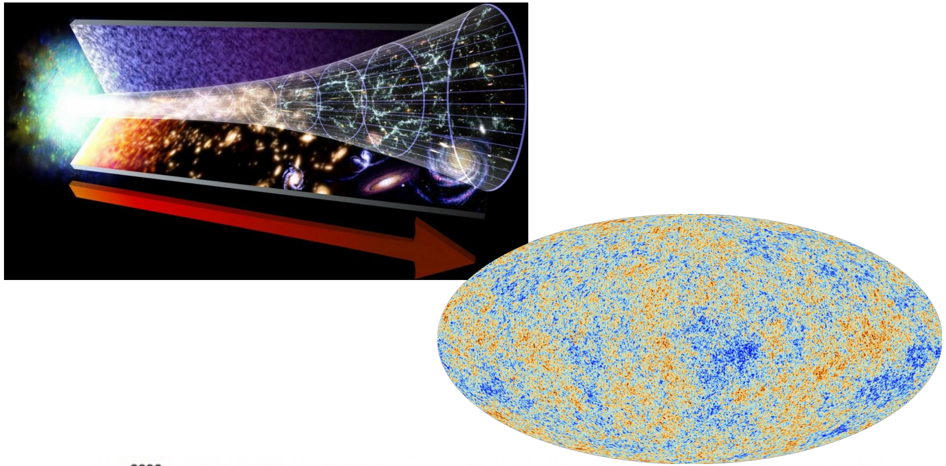
They sit at low momenta and follow the collective expansion of the system.

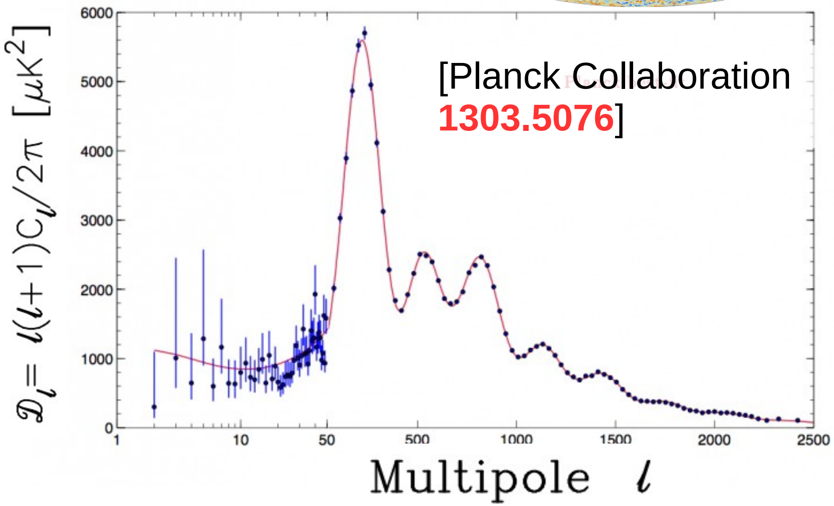
$$\frac{d^2N}{dp_T d\phi} = \frac{dN}{2\pi dp_T}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\phi - \Phi_n)\right)$$

EXPLOSIVENESS OF THE EXPANSION

ANISOTROPY OF AZIMUTHAL DISTRIBUTION

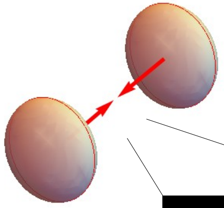
The Big Bang

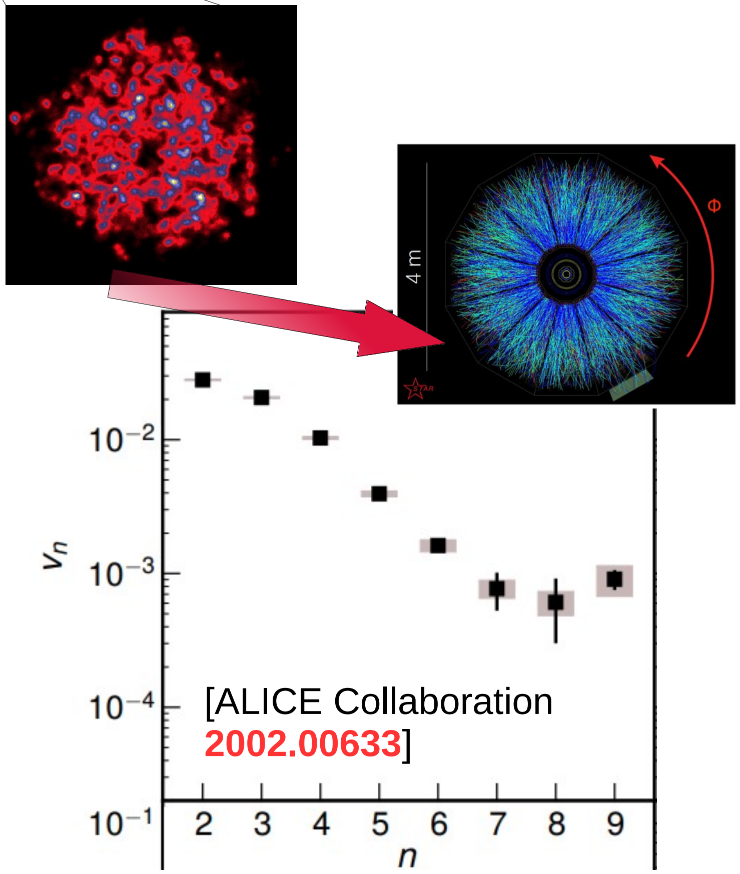




[Planck Collaboration 1303.5076]

The Little Bang(s)



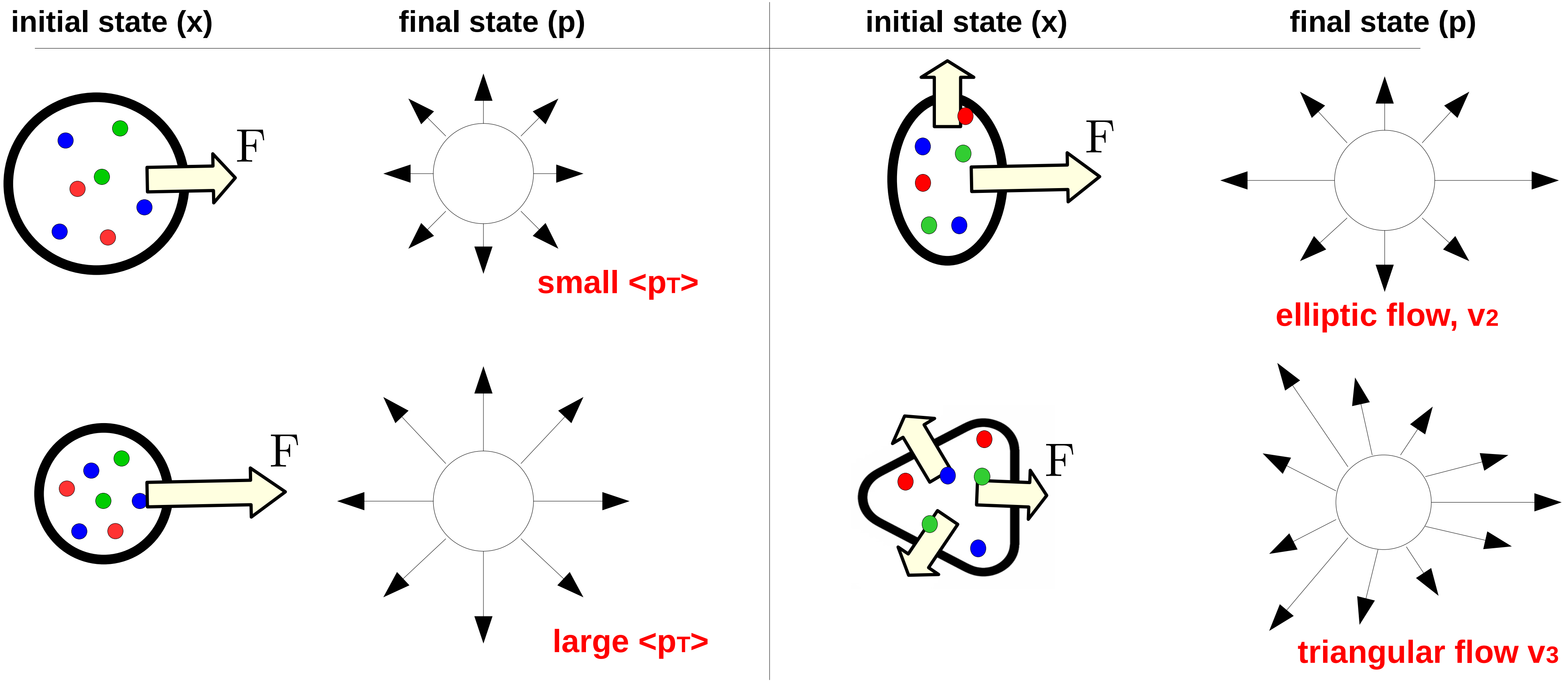


[ALICE Collaboration 2002.00633]

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

$$F = -\nabla P$$

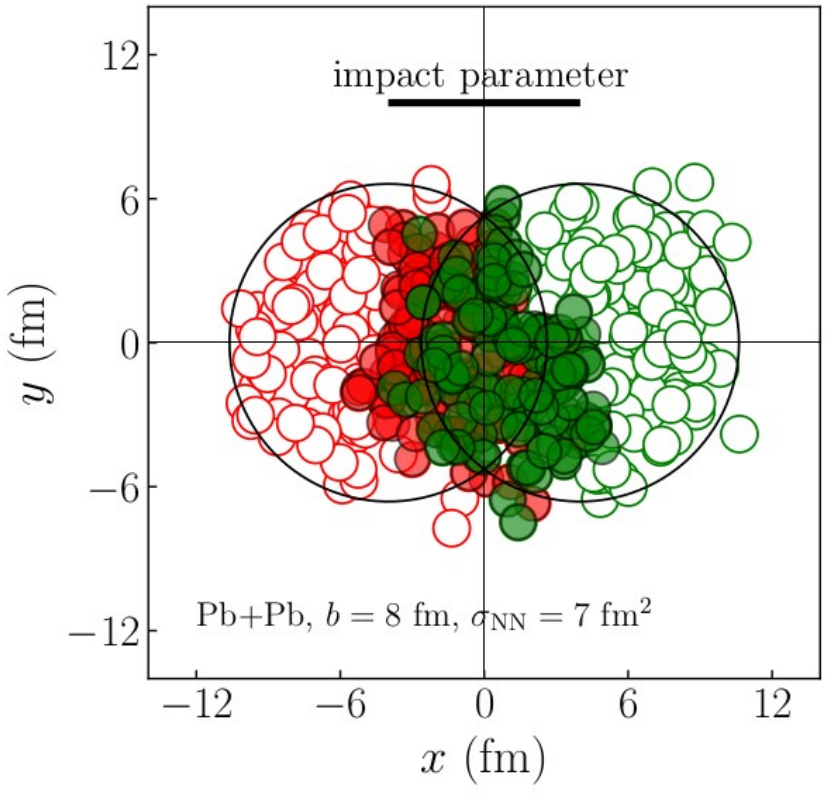
[Ollitrault, PRD **46** (1992) 229-245]



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

2 – Nuclear structure input to high-energy nuclear collisions.

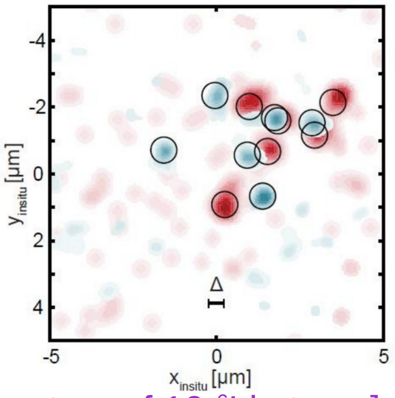
Formation of QGP starts with an input from nuclear structure.



High-energy model

Scattering occurs mainly within nucleons.

“quantum measurement” of the nucleon positions.



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

Origin of nucleon positions for “spherical” systems like ^{208}Pb.
Effective description: independent sampling in common potential (mean field) is appropriate.

INDEPENDENT PARTICLE PROBLEM

FULL PROBLEM

$$H|\psi\rangle = E|\psi\rangle$$

$$h_i|\phi_k^i\rangle = \varepsilon_k^i|\phi_k^i\rangle$$

$$h_i = \frac{p_i^2}{2m} + V(r_i)$$

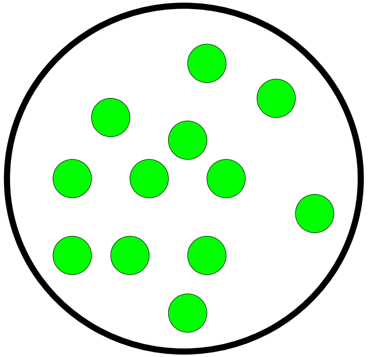
$$V(r_i) = -\frac{V_0}{1+\exp\left(\frac{r_i - R}{a}\right)}$$

Woods-Saxon

Ground state from variational equation with Ansatz of independent Fermions.

$$\delta \frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\Psi\rangle} = 0$$

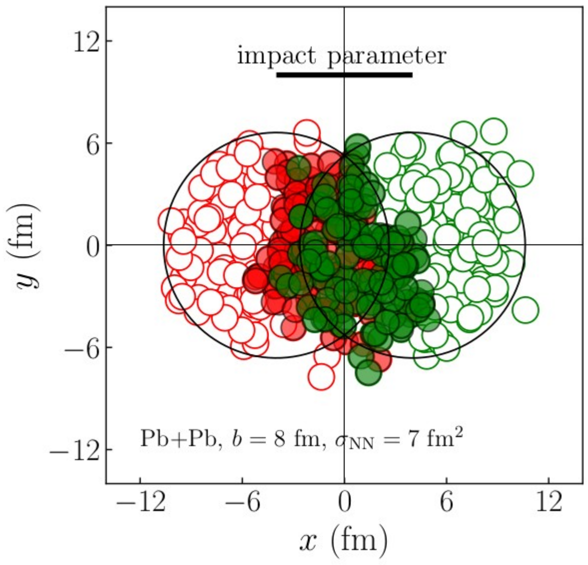
Slater determinant
(+ pairing)

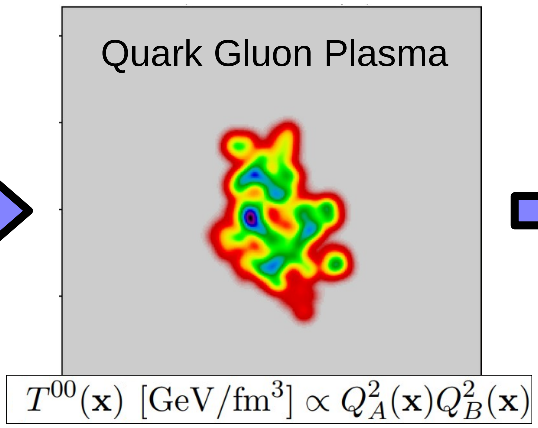


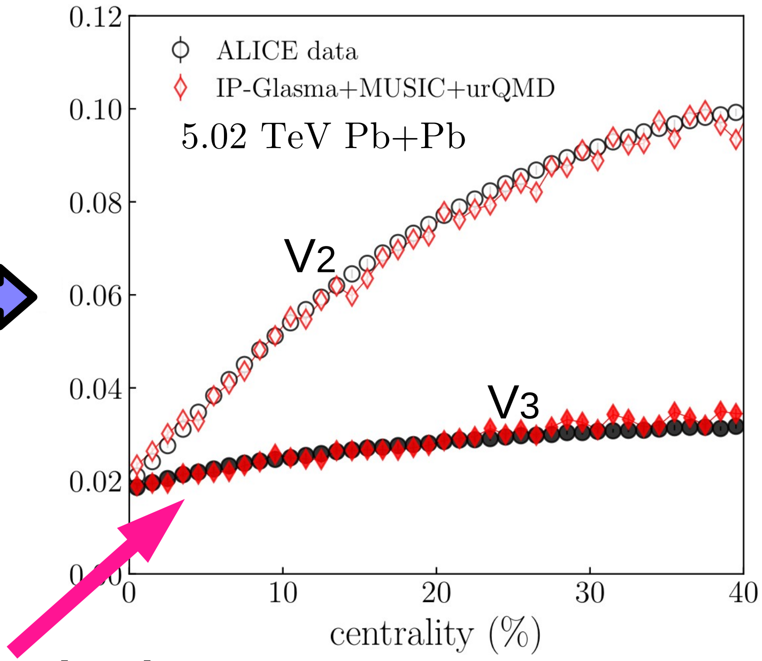
More realistic: Potential generated from effective nucleon-nucleon interaction (Gogny force, Skyrme force, etc.), in “Energy Density Functional” theory.

Mean-field-based approach works at high energy (justifies the MC Glauber approach).

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

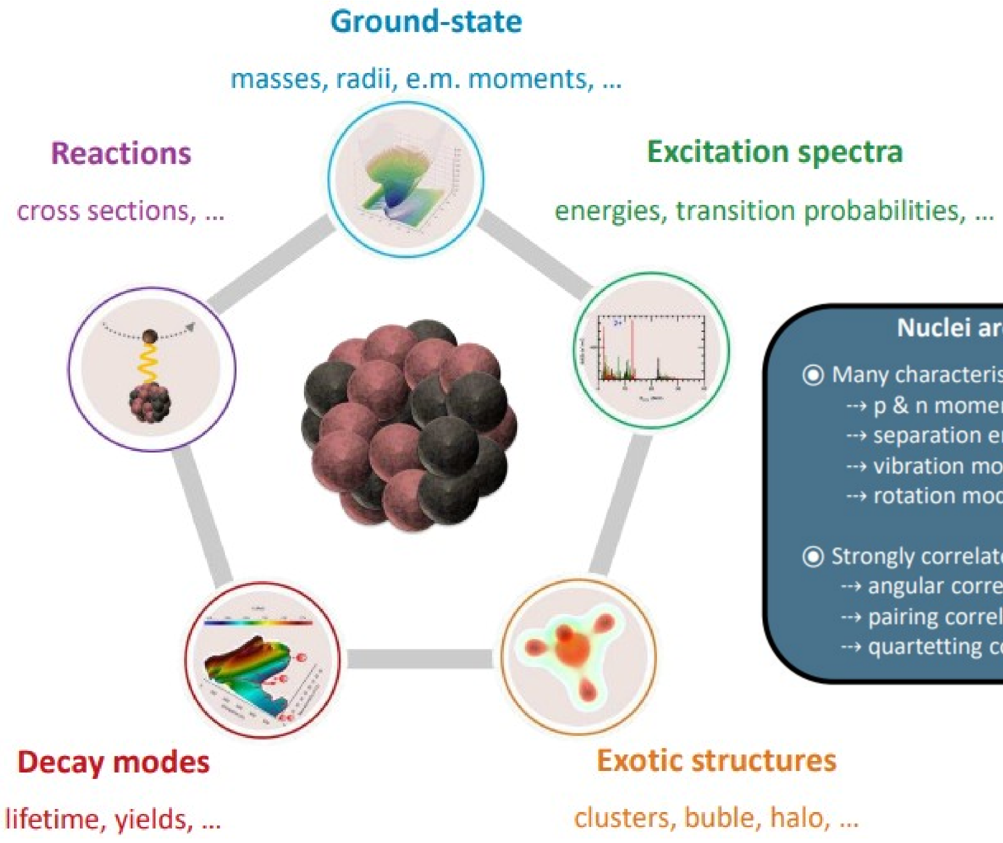






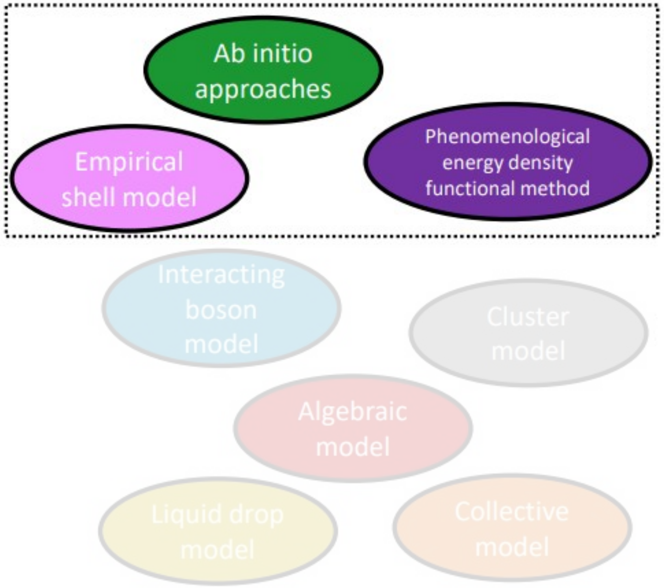
precision physics!

Reminder: ^{208}Pb is particular case of doubly-magic system.
Atomic nuclei have rich phenomenology rooted in the strong nuclear force.



Nuclei are complex systems

- Many characteristic scales :
  - ⇢ p & n momenta ~ 100 MeV
  - ⇢ separation energies ~ 10 MeV
  - ⇢ vibration modes ~ 1MeV
  - ⇢ rotation modes ~ 0.01-5 MeV
- Strongly correlated:
  - ⇢ angular correlations ⇒ deformation
  - ⇢ pairing correlations ⇒ superfluidity
  - ⇢ quartetting correlations ⇒ clustering



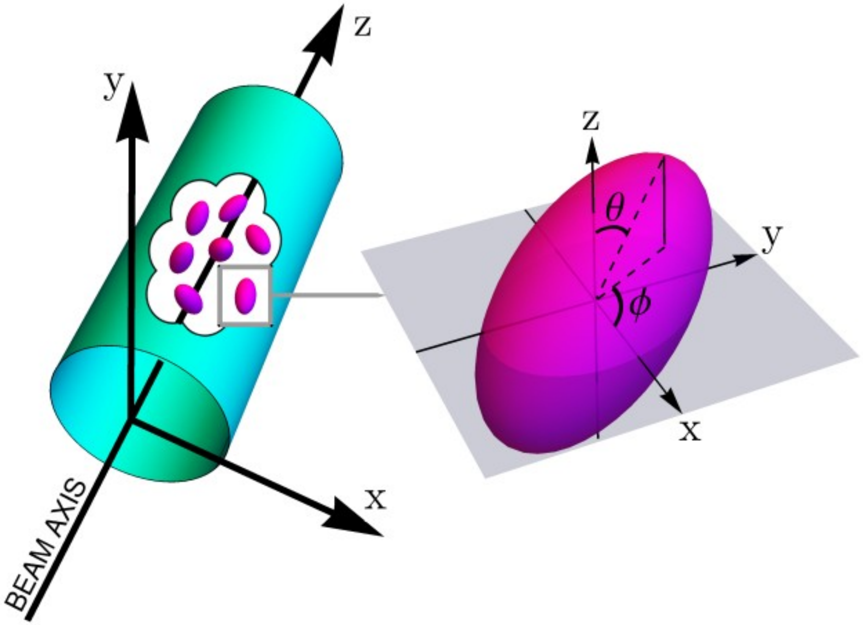
[from Jean-Paul Ebran (CEA Bruyères-le-Châtel)]

Describing heavy-ion collisions requires *a priori* knowledge of A-body correlation functions, e.g.,

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

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.



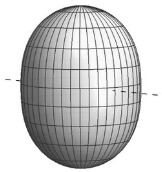
Keep a mean field approach.

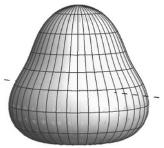
The bag of nucleons is now deformed and with a random orientation.

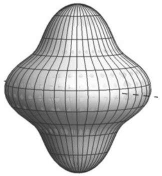
The interaction selects one such orientation.

Generalize the Woods-Saxon profile to include intrinsic deformations:

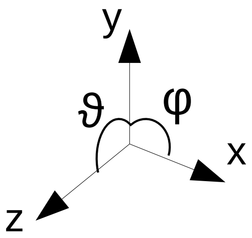
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)} \quad , \quad R(\Theta,\Phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\beta_3 Y_{30}(\Theta)+\beta_4 Y_{40}(\Theta)\right]$$

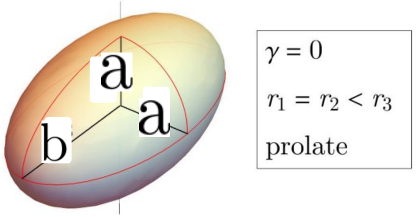


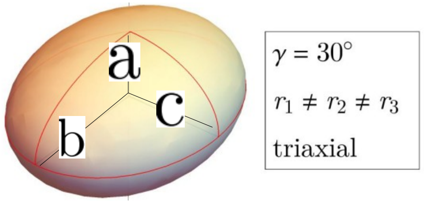


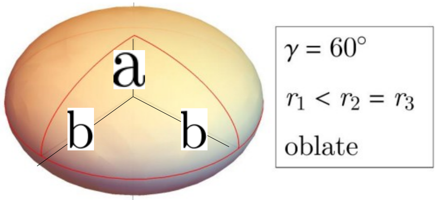


For $\beta_2 > 0$, the nucleus is prolate ($\gamma=0$), triaxial ($\gamma=30^0$), or oblate ($\gamma=60^0$).









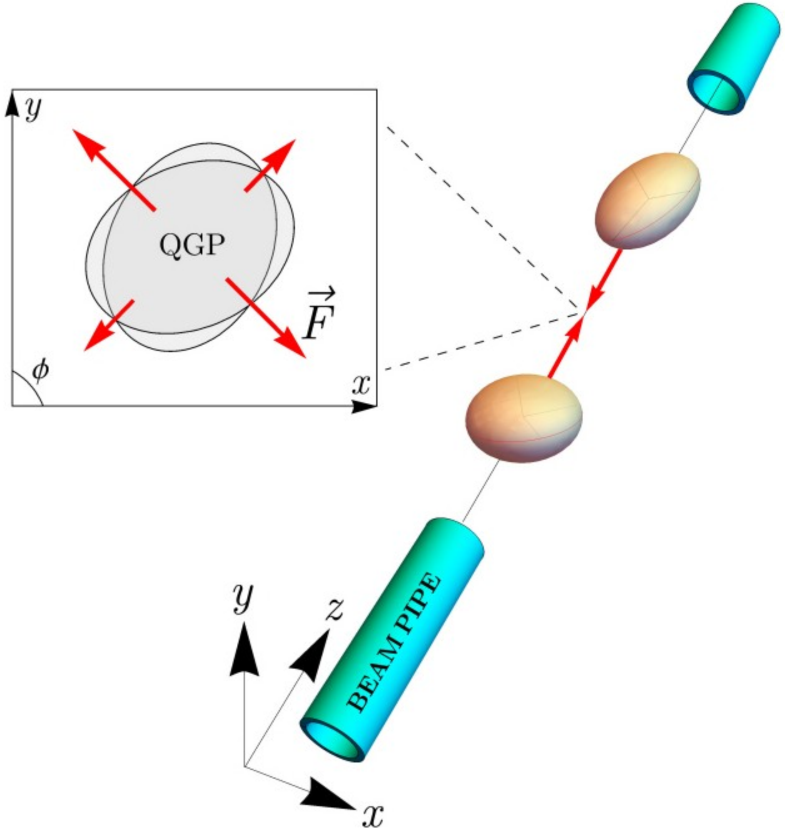
Intrinsic shapes are non-observable for direct measurements, but they leave their fingerprint on virtually all nuclear observables and phenomena

Michael Bender – RBRC Workshop Jan 2022

They will show up as well at high energy.

↓

THIS TALK!



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)

(129Xe, 238U, 96Ru, 96Zr, 63Cu) → deformed ions

New questions to address:

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

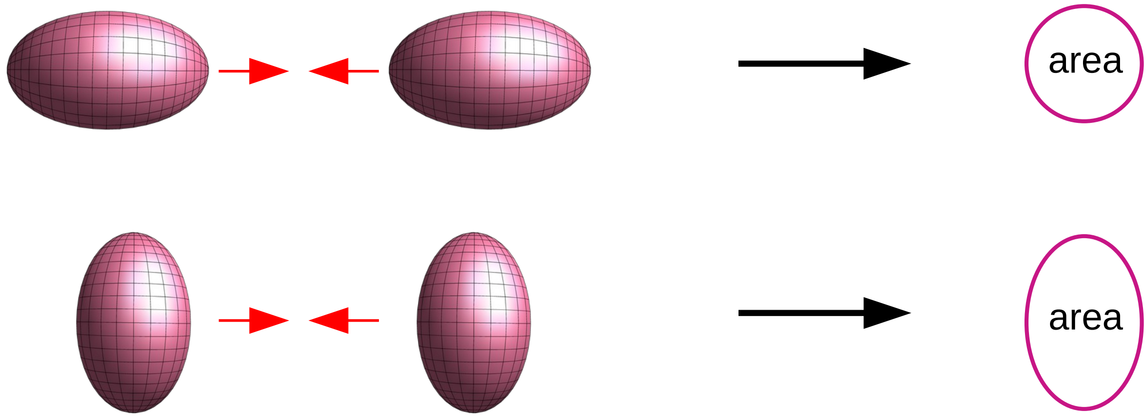
Are low-energy expectations compatible with high-energy observations?

HOW TO DO THAT? SHAPE-SIZE CORRELATION.

A new “classical phenomenon”.

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

tip-tip



small v_2
small area
large $<p_t>$

body-body

large v_2
large area
small $<p_t>$

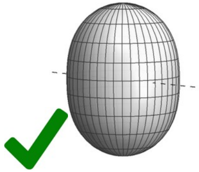
CENTRAL COLLISIONS OF (PROLATE) DEFORMED IONS

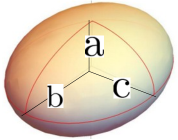
The ellipticity of the quark-gluon plasma is positively correlated with its area.

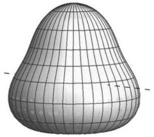
Deformation yields a negative correlation between v_2 and the $<p_t>$.

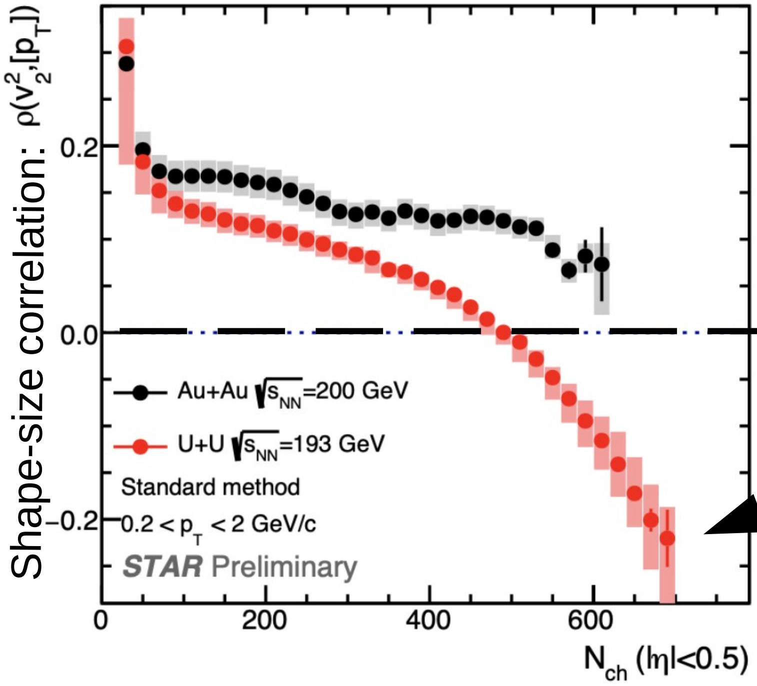
Signature of the strong prolate deformation of uranium-238.

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





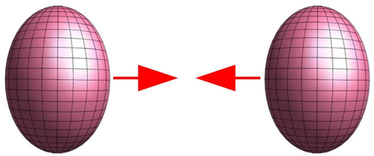




Shape is correlated with size

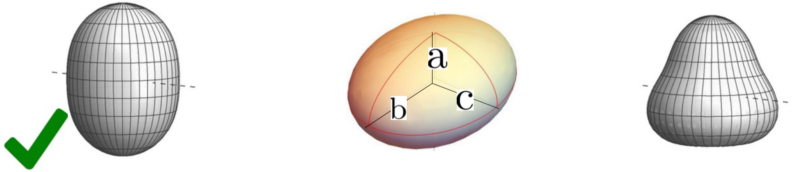
v_2 is anti-correlated with <p_t>

Limit of fully-overlapping shapes.



Signature of the triaxial deformation of xenon-129.

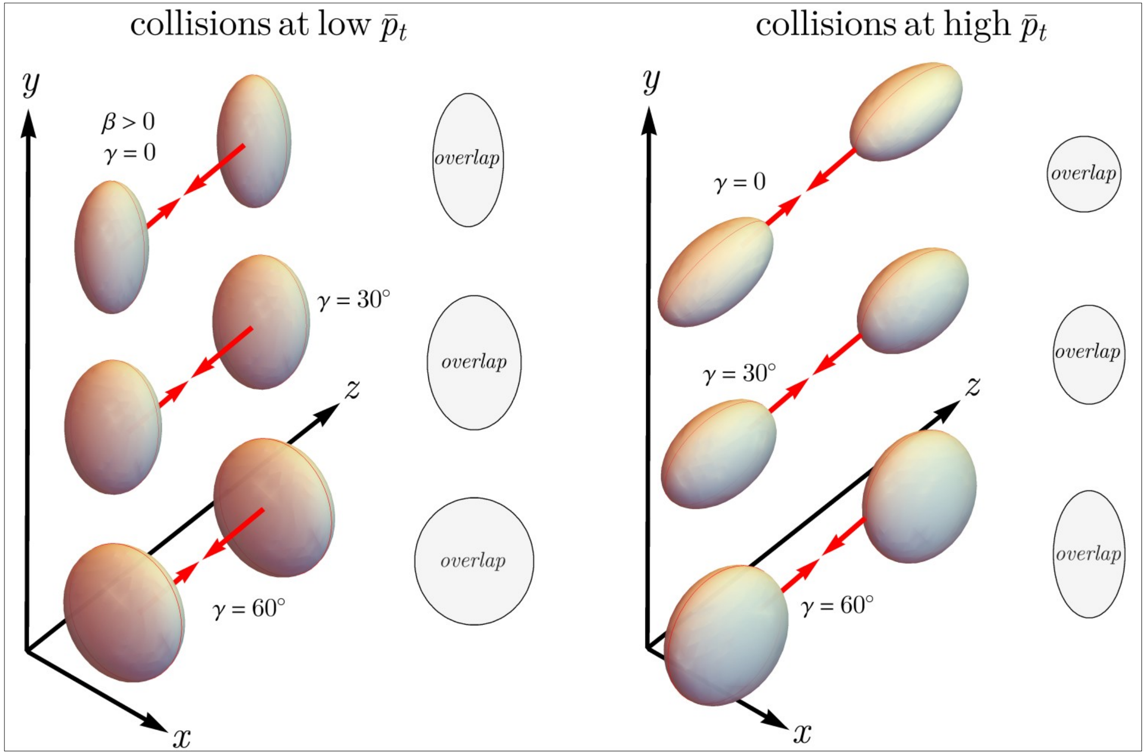
$$R(\Theta,\Phi) = R_0\left[1 + \underline{\beta_2}\left(\cos\gamma Y_{20}(\Theta) + \sin\underline{\gamma}Y_{22}(\Theta,\Phi)\right) + \underline{\beta_3}Y_{30}(\Theta) + \beta_4 Y_{40}(\Theta)\right]$$



Shape-size correlation is sensitive to the triaxiality, γ.

$$\rho_2 \propto -\cos(3\gamma)\beta_2^3$$

[see e.g. Jia, PRC **105** (2022) 4, 044905]



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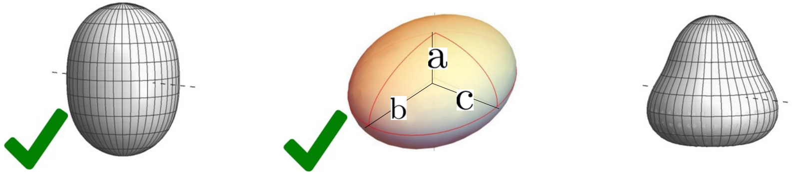
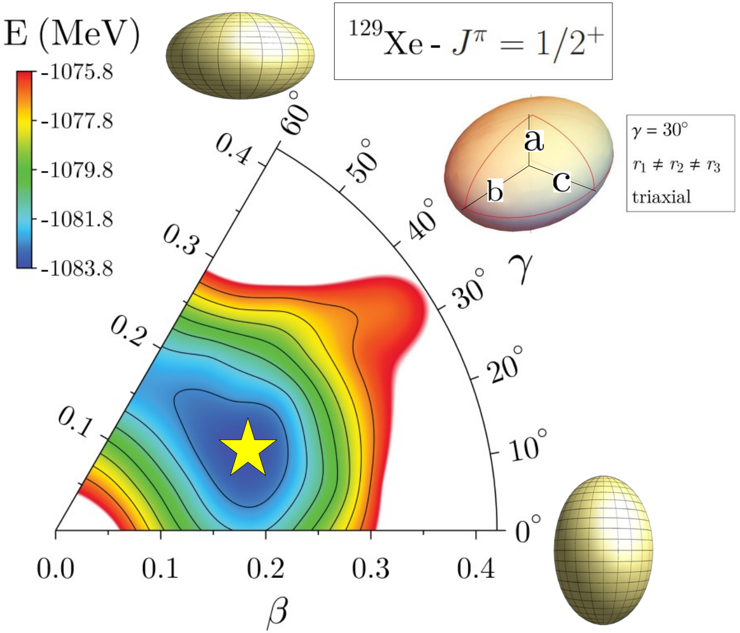
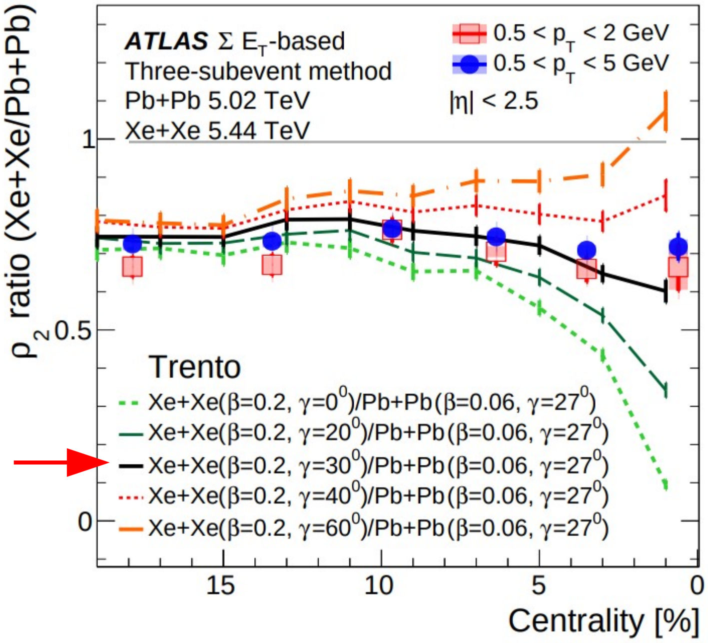




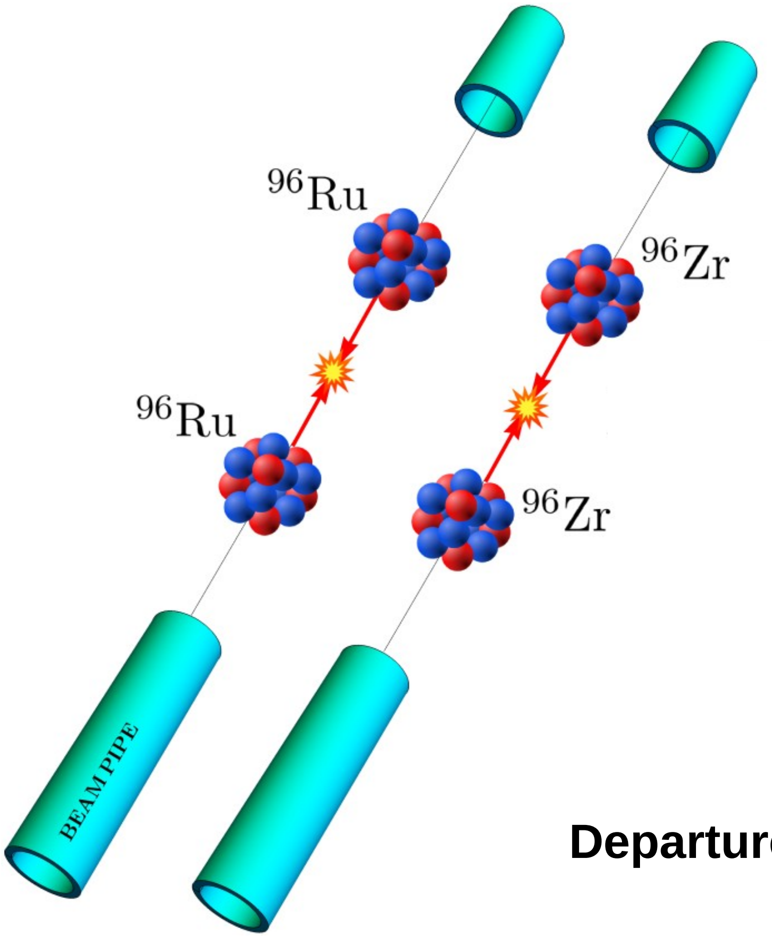
[Bally et al., PRL **128** (2022) 8, 082301]

[ATLAS collaboration, arXiv:2205.00039]

triaxial



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:

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

- a: elliptic flow from fluctuations
- b: response coefficient
- β_2^2: 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:

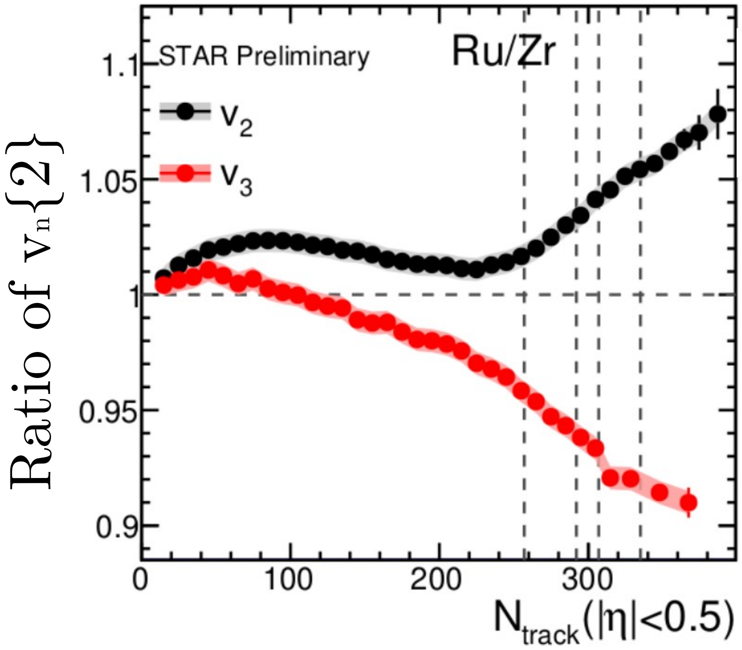
$$\frac{\langle v_2^2 \rangle_{\rm Ru+Ru}}{\langle v_2^2 \rangle_{\rm Zr+Zr}} = 1 + c\left(\beta^2_{2,\rm Ru} - \beta^2_{2,\rm Zr}\right)$$

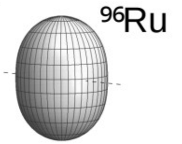
- c: positive coeff

Low-energy nuclear physics tells us:

$$\beta^2_{2,\rm Ru} \gg \beta^2_{2,\rm Zr}$$

Ratio should be above unity.





Signature of the octupole deformation of zirconium-96.

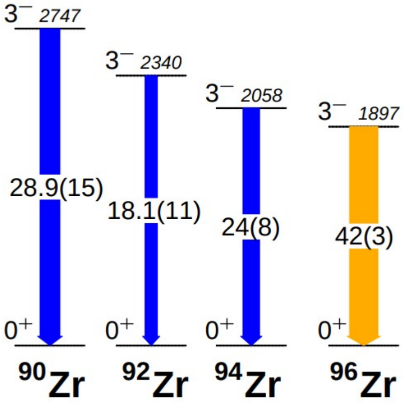
Same logic follows for octupole-deformed nuclei:

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

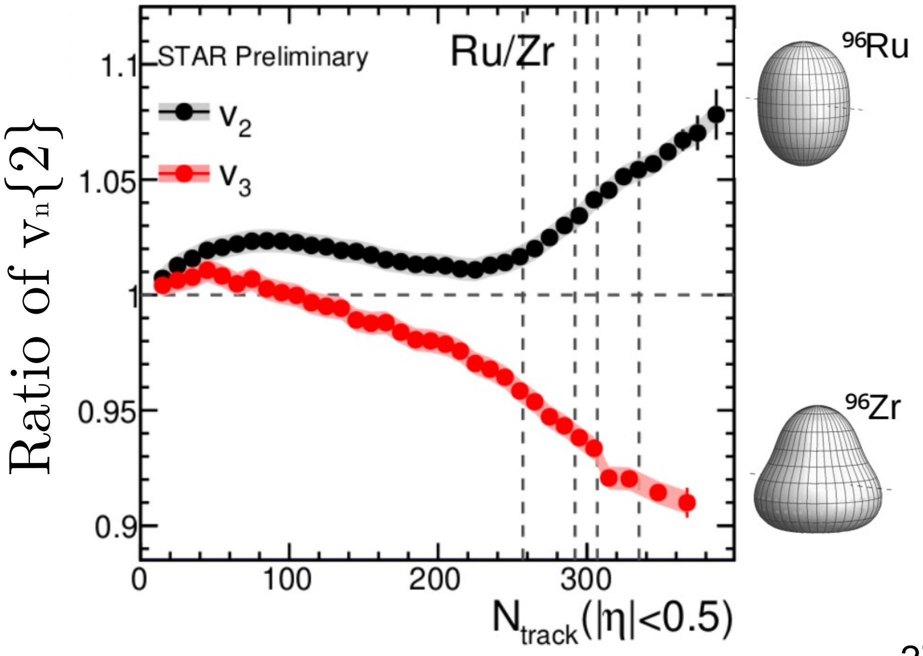
[Jia, Zhang, PRL **128** (2022) 2, 022301]

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

No experimental information about ^{96}Ru.



[from M. Zielinska, ESNT workshop]

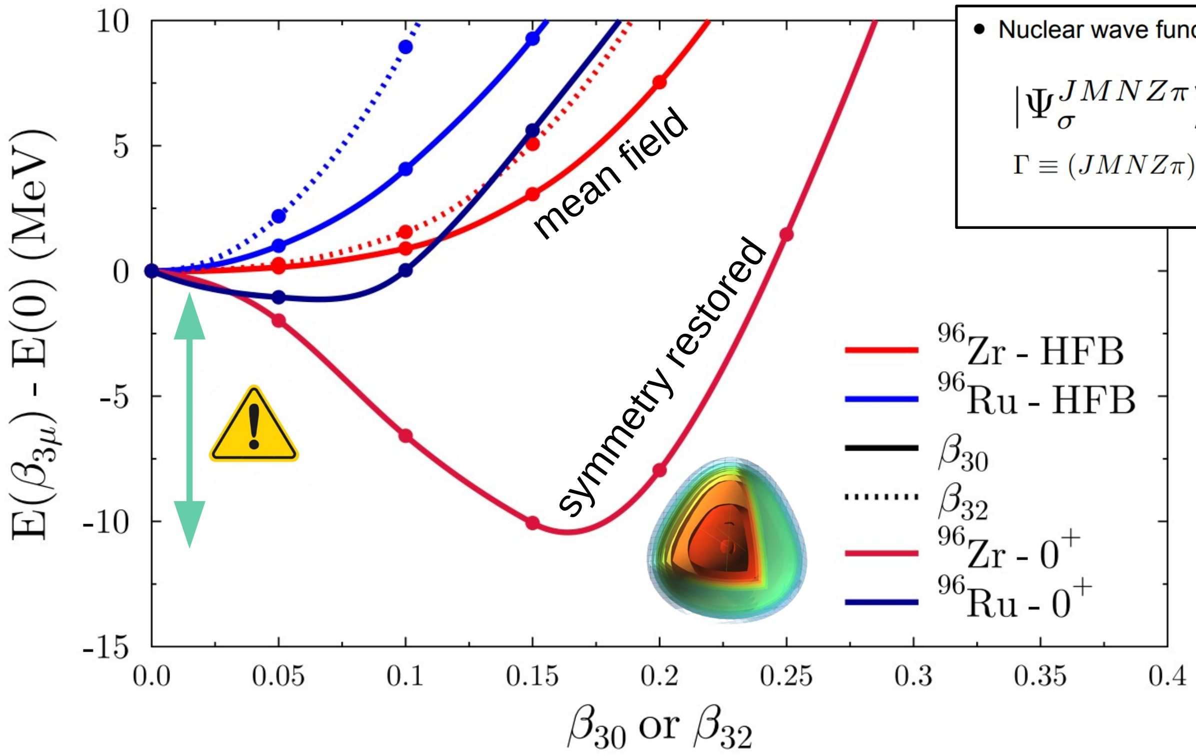


RHIC data implies $\beta_{3,\mathrm{Zr}}^2 \gg \beta_{3,\mathrm{Ru}}^2$

Explanation from nuclear structure theory?

Octupole deformation is a "beyond-mean-field" effect. Emerges from symmetry restoration.

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



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

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

$\Gamma \equiv (JMNZ\pi)$

WEIGHTS **PROJECTION** **DEFORMED MF STATE**

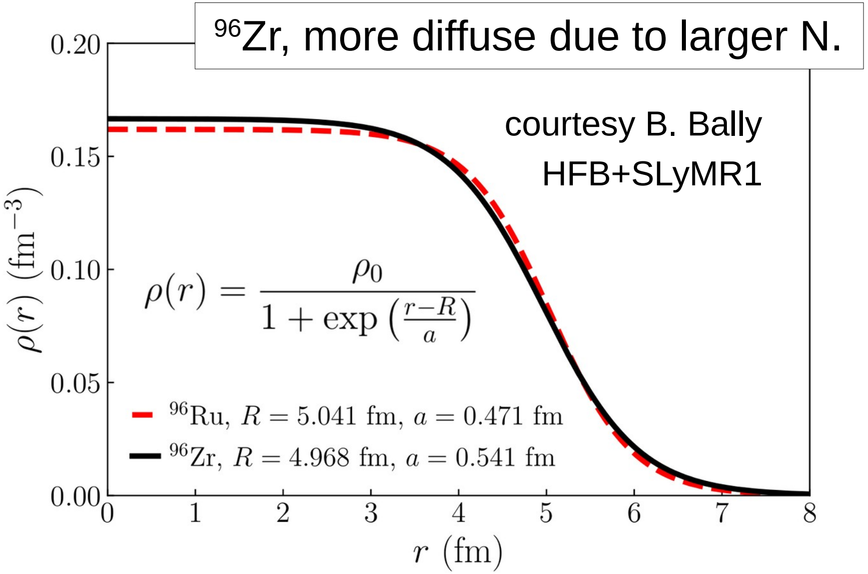
ExtreMe Matter Institute EMMI
EMMI Rapid Reaction Task Force
Nuclear Physics Confronts Relativistic Collisions of Isobars
Heidelberg University, Germany, May 30 – June 3 & October 12 – 14, 2022

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. New challenges in nuclear structure theory.

BONUS: Signature of skin thickness in (ratio of) fourth-order cumulant of v2.



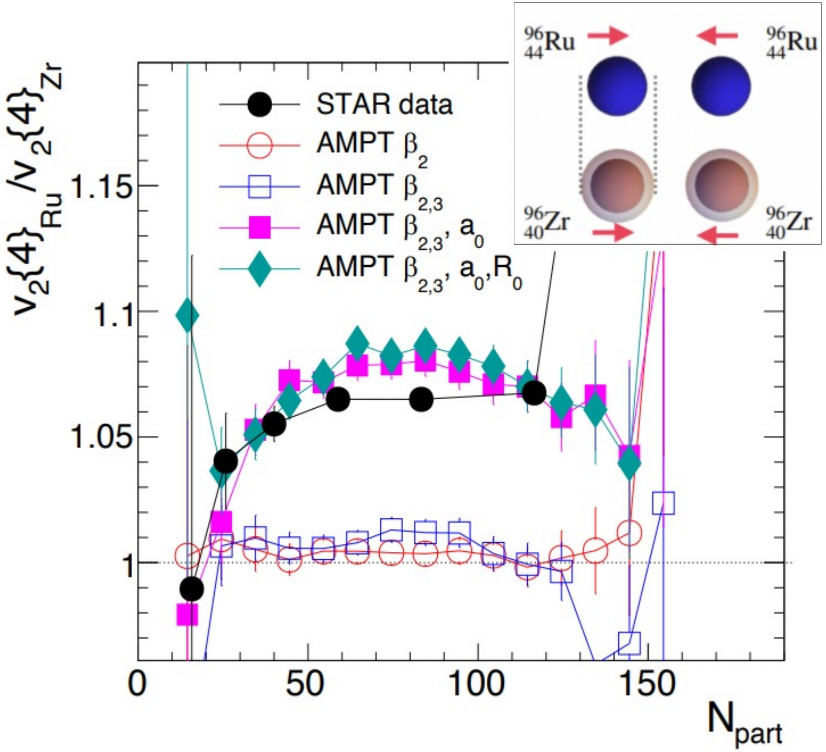
Gaussian model of $V_2=(v_x,v_y)$ fluctuations.
Reaction plane is along x:

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

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

probes the skin

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



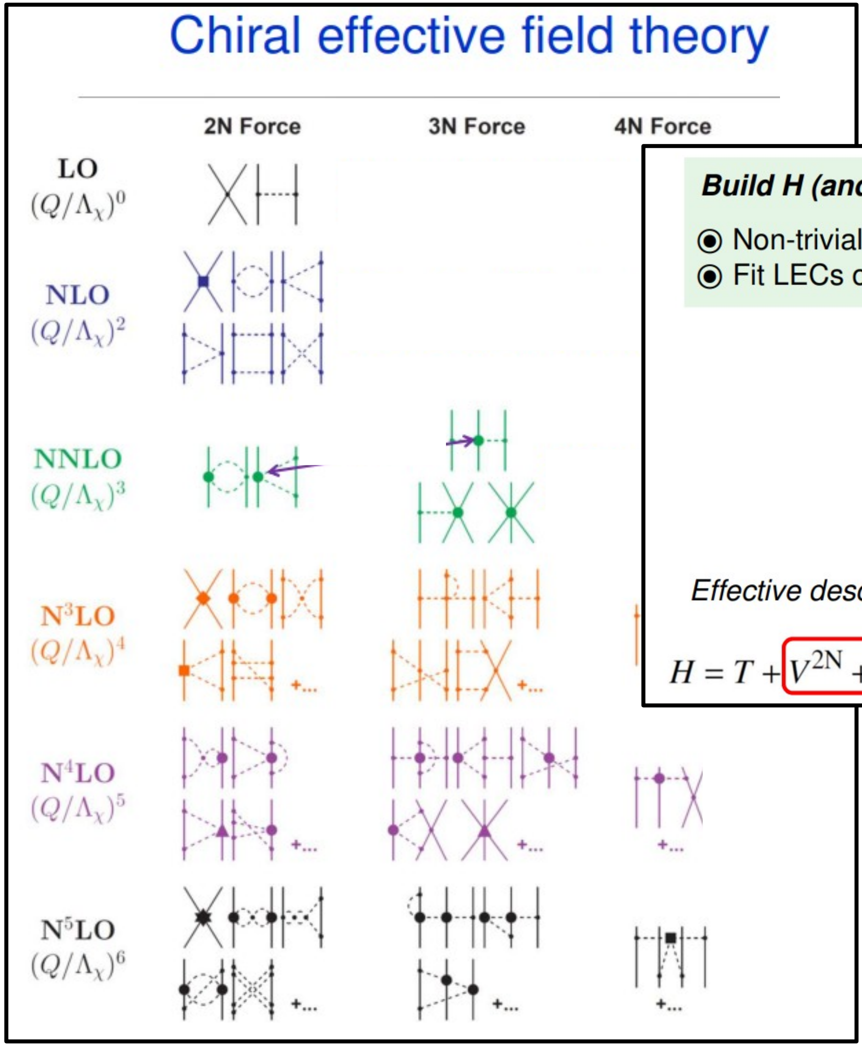
see also [Nijs, van der Schee, arXiv:2112.13771]
[Xu *et al.*, arXiv:2111.14812]
[Xu *et al.*, PLB **819**, 136453 (2021)]

Answers to the initial questions:

- Expectations from low-energy nuclear physics confirmed in high-energy data.
- Quadrupole, triaxiality, octupole (?), hexadecapole, 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).** ✓

3 – Prospects: theory and experiment

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



Build H (and other operators) with χEFT at various orders

- ◉ Non-trivial formal task whose difficulty increases with order (e.g. **3N at N²LO, 4N at N³LO**…)
- ◉ Fit LECs of mode-2k tensors to experimental data (or lattice QCD) in A = k-body systems

Organization = power counting
Importance of interaction terms

A-body Schrödinger Equation

$$H|\Psi_k^A\rangle = E_k^A|\Psi_k^A\rangle$$

Effective description = *A*-body operator in principle

$$H = T + V^{2N} + V^{3N} + V^{4N} + \ldots + V^{AN}$$

[Weinberg, Gasser, Leutwyler, van Kolck, ..]

Describing nuclear systems:

1) Consistently (from a single theoretical rationale?)
2) Systematically (complete phenomenology?)
3) Accurately enough (relevant to experimental uncertainty?)
4) From inter-nucleon interactions (right balance between reductionism/emergence?)
5) Rooted in QCD (sound connection to underlying EFT?)

[from Thomas Duguet, ESNT workshop]

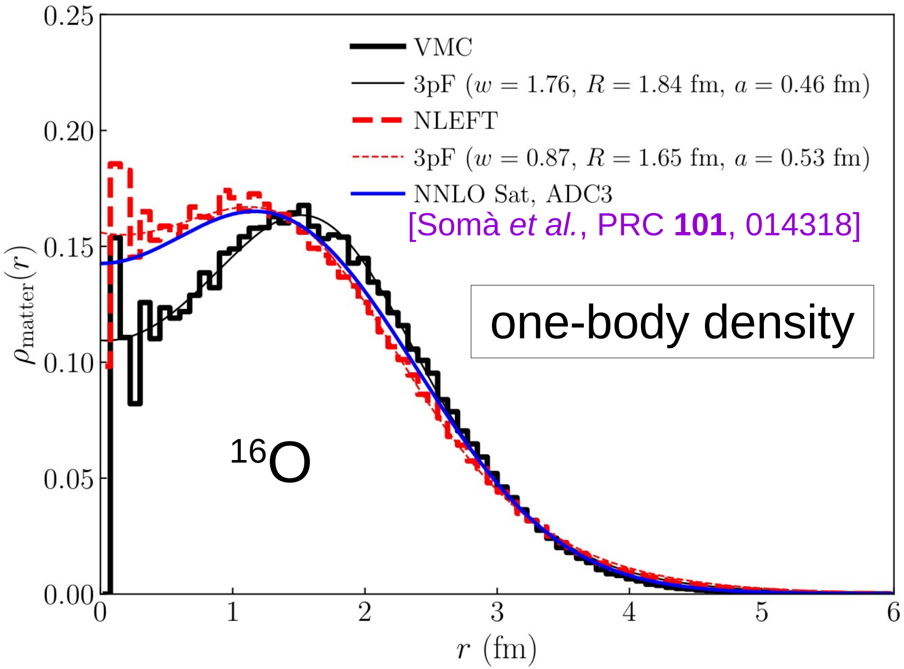
Going beyond shapes: connection with *ab initio* approaches.

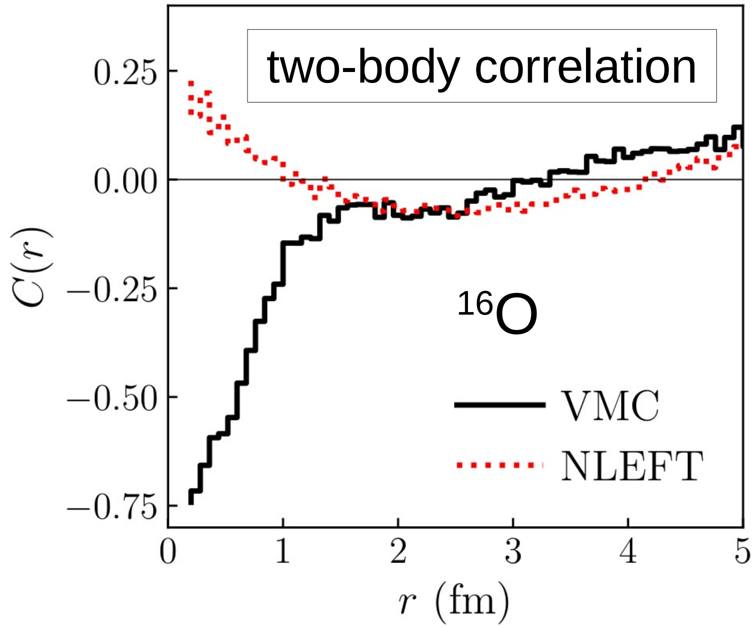
Oxygen-oxygen collisions are ideal for the purpose.

- 6000 configurations from **cluster Variational Monte Carlo (VMC)** simulations.
Interaction: AV18+UIX (not an EFT) with a repulsive core. [Lonardoni *et al.*, PRC **96** (2017) 2, 024326]

- 15359 configurations from **Nuclear Lattice Effective Field Theory (NLEFT)**.
Interaction: pionless chiral EFT. Pin-hole algorithm to determine nucleon positions.

[Summerfield *et al.*, PRC **104** (2021) 4, L041901]

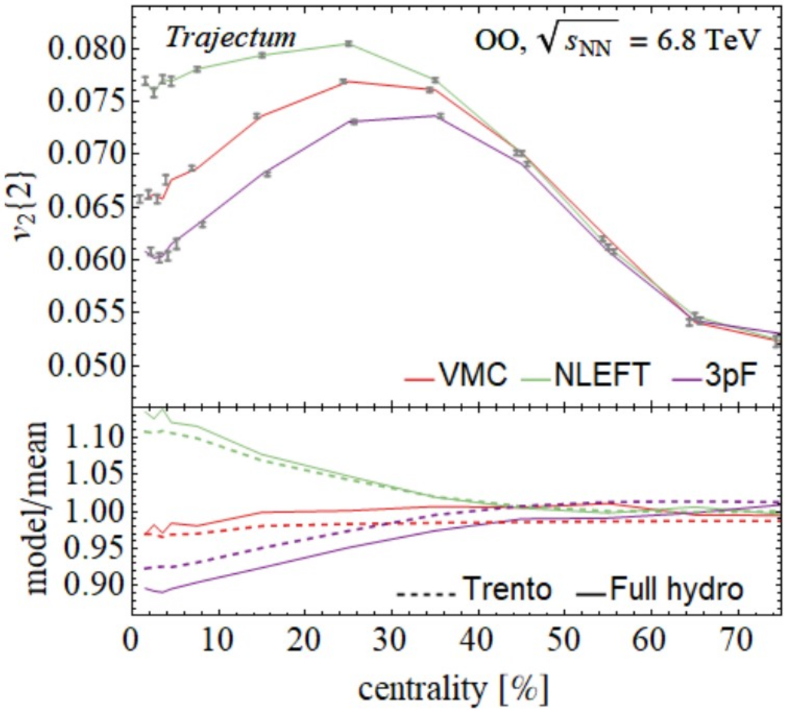


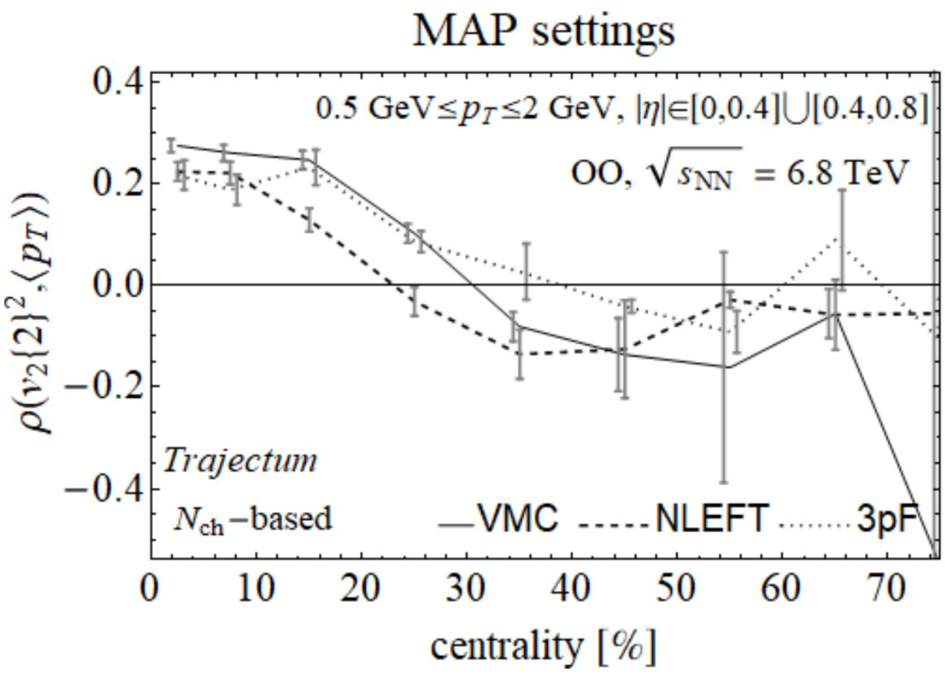


Study of shape-size correlations in oxygen collisions.

Different predictions from different frameworks… why?
Different interaction or many-body solution? Role of short-range physics?

[Giacalone, Lee, Nijs, van der Schee, in preparation]



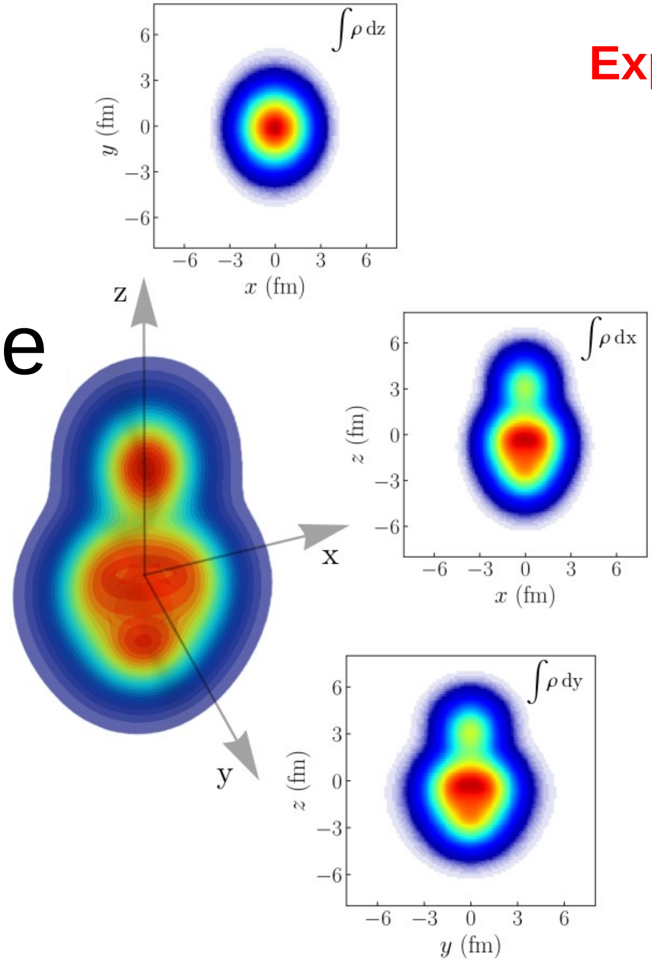


A new tool to test effective theories of QCD for nuclei.

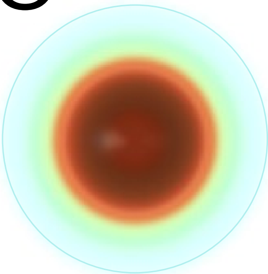
Transparent evidence of a “geometric” origin of flow in a small system?

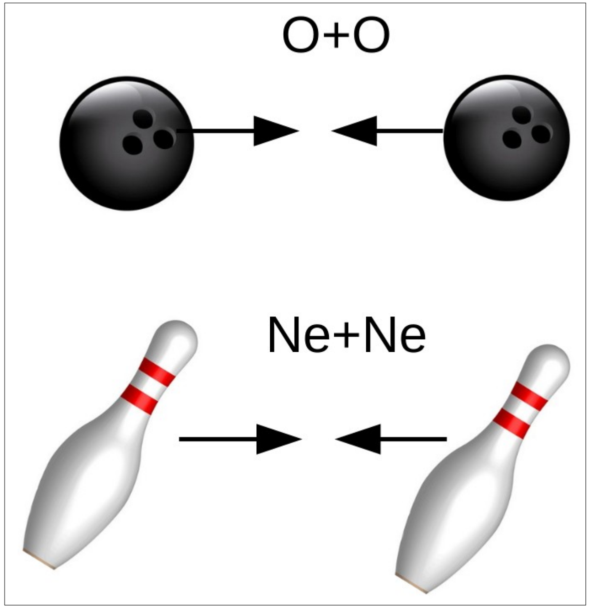
Exploit bowling-pin-shaped ^{20}Ne.

^{20}Ne



^{16}O





[Oxygen structure: VMC, Lonardoni *et al.*, PRC **96** (2017) 2, 024326]
[Neon structure: variational calculation + χEFT, Frosini *et al.*, EPJA **58** (2022) 4, 63]

Bands are systematical uncertainties, large variations in parameter space (η/s, ζ/s, ICs, …)

Large 20% effect on rms v_2.

Systematical uncertainty on ratio at % level!
(“isobar criterion”)

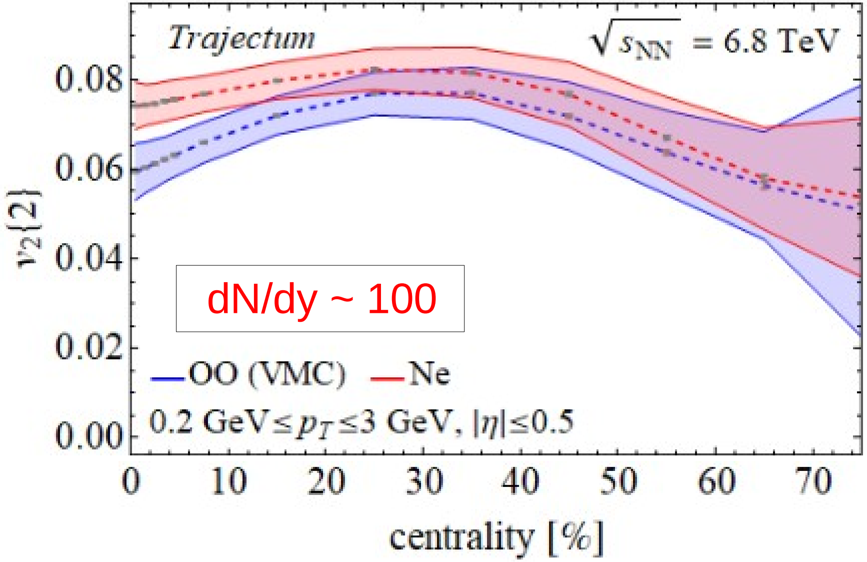
⇩

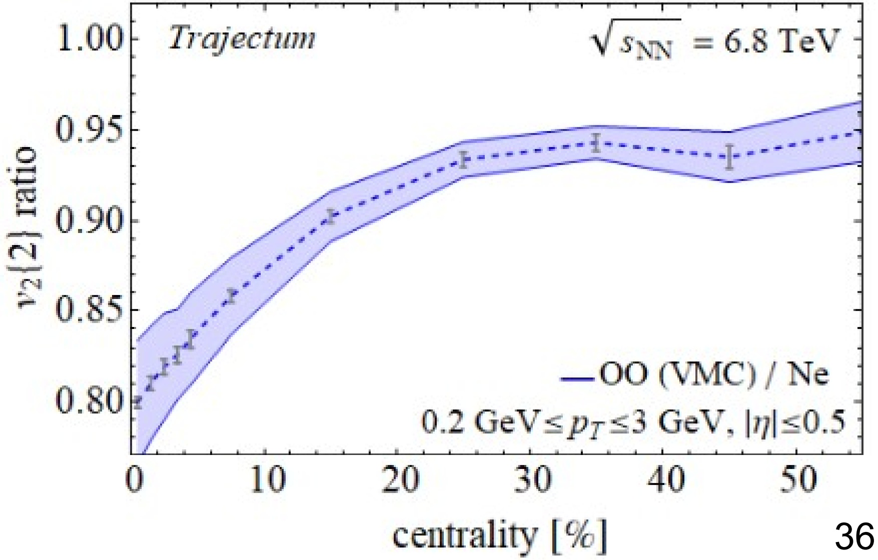
<u>Unambiguous “geometric” interpretation.</u>

<u>OUR POINT</u>

Brings more robust information than:
p+Au *vs.* d+Au
central O+O *vs.* peripheral Pb+Pb

[Trajectum (G Nijs, W van der Schee)
+ ab initio PGCM (Saclay + TU Darmstadt)
+ G Giacalone, to appear]



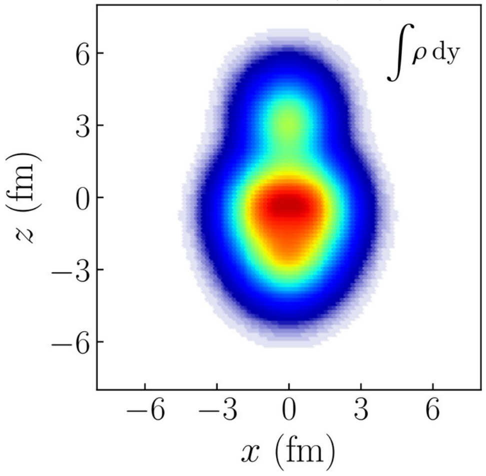


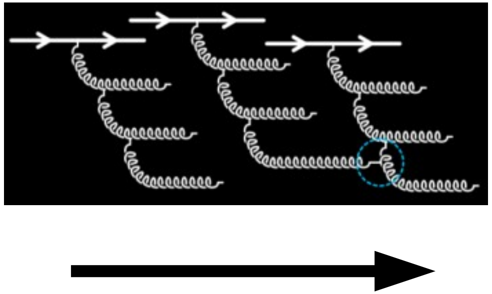
Case study: Impact of neon-neon collisions on small system program at LHC?

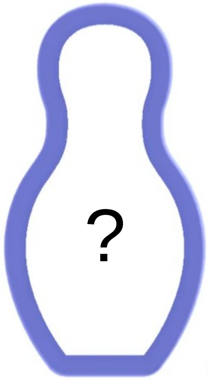
Role of small-x evolution?

neon-20 thickness

x~0.01







x~0.0001

[Giacalone, Schenke, Schlichting, Singh, in progress]

1 – ^{20}Ne in SMOG system of LHCb. Collider + fixed-target at the same time.
Collisions at sqrt(s)=7000 GeV <u>and</u> sqrt(s)=70 GeV.

2 – FOCAL upgrade of ALICE. “Dilute-dense” Ne+Ne, one small-*x*, one large-*x*.

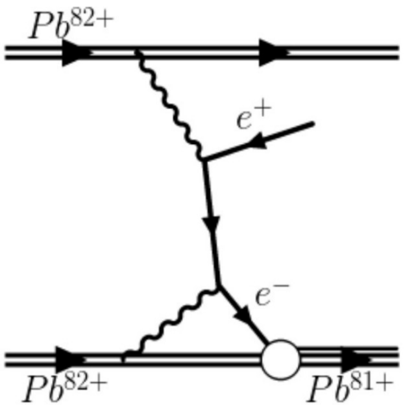
Role of quarks and gluons (QCD) for nuclear structure?

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>



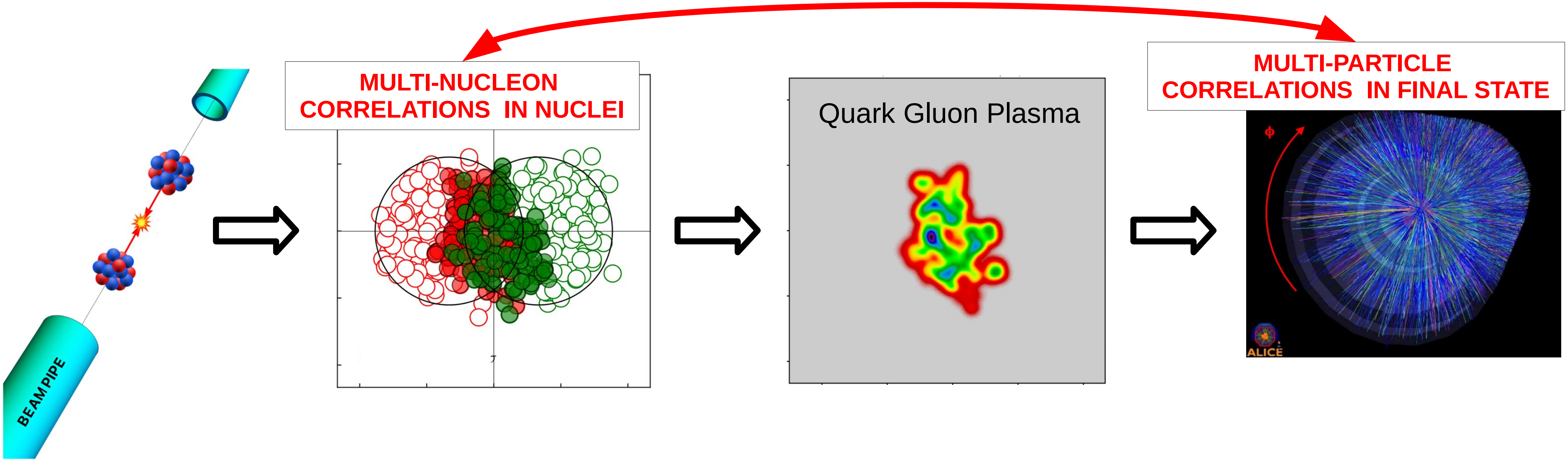
[from Alexander Kalweit, ESNT workshop]

[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 coupled with mean-field description of nuclei provides excellent description of heavy-ion data.
- Collective spatial correlations (shapes) in nuclei show up clearly at high energy.
- Prospect theory: improved initial conditions and 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: 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: $\Delta r_{np}[\,^{197}\text{Au}\,] = 0.17 \pm 0.03\ (\text{stat.}) \pm 0.08\ (\text{syst.})\ \text{fm}$
Consistent with low-energy nuclear theory.

[STAR Collaboration, arXiv:2204.01625]

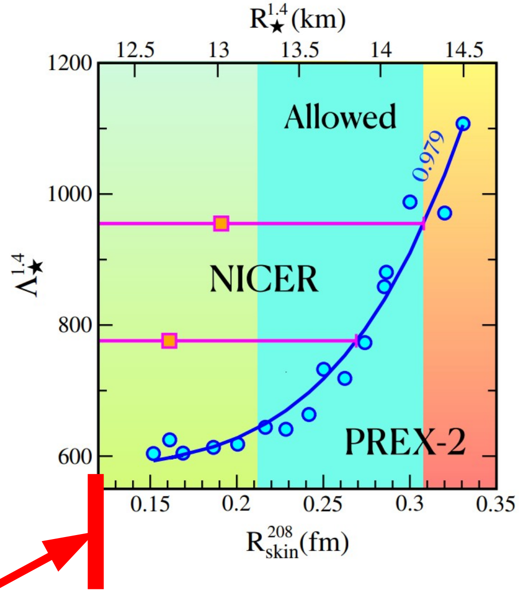
Recent measurements for ^{208}Pb from weak form factor:

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

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

[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]