Nuclear structure for high-energy nuclear physics

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INSTITUTE for NUCLEAR THEORY

INT PROGRAM INT-23-1A

Intersection of nuclear structure and high-energy nuclear collisions

January 23, 2023 - February 24, 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

cea
ESNT
Espace de Structure Nucléaire Théorique
DSM - DAM

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

INSTITUTE for NUCLEAR THEORY

→ 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.

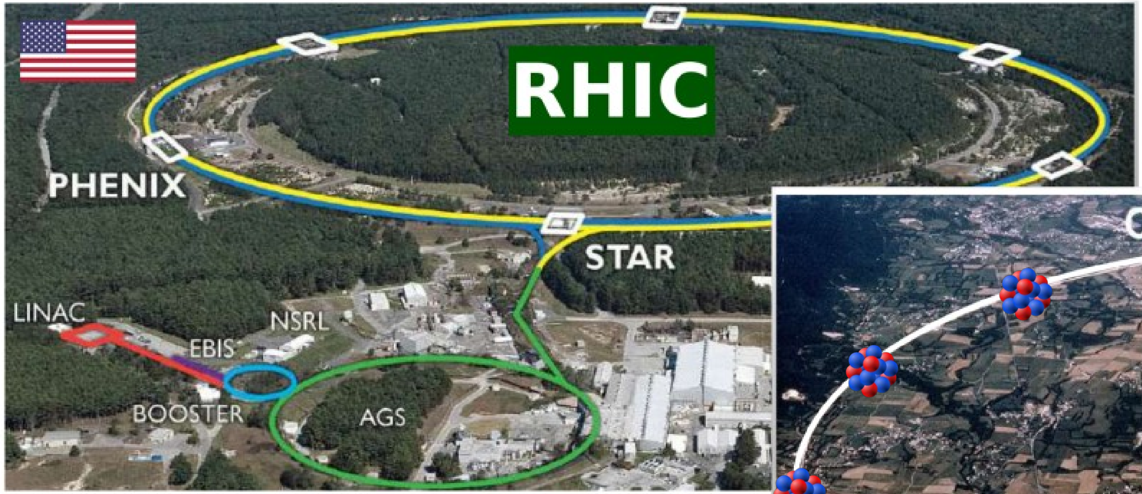
3 – Nuclear shapes in high-energy nuclear experiments.

4 – Prospects: theory and experiment.

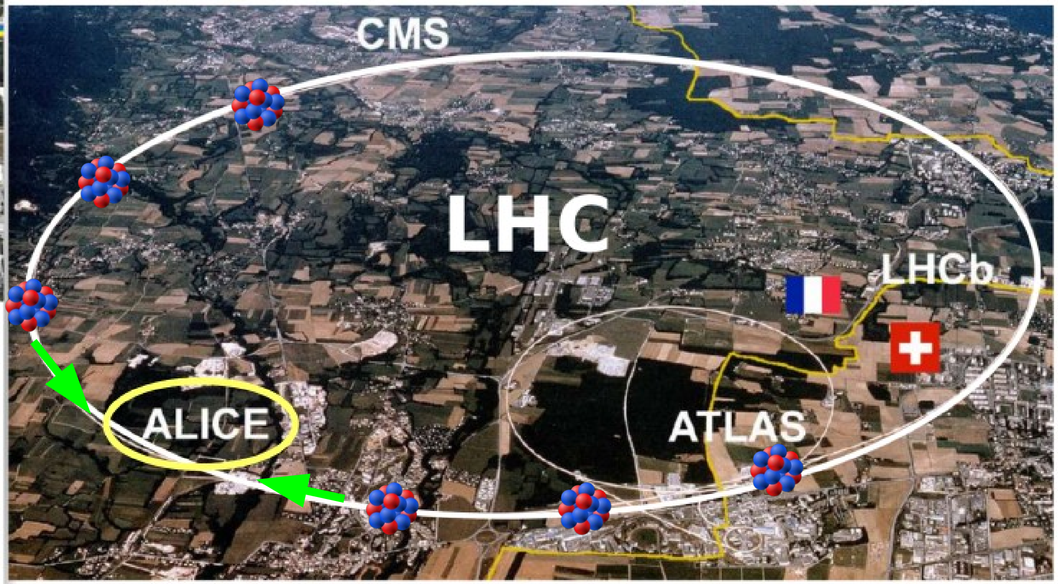
1 – High-energy nuclear physics and collision geometry.

HIGH ENERGY NUCLEAR PHYSICS

Long Island (NY)

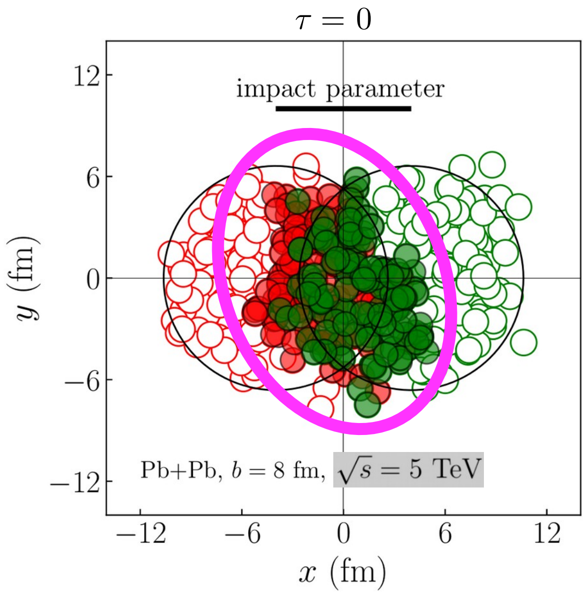


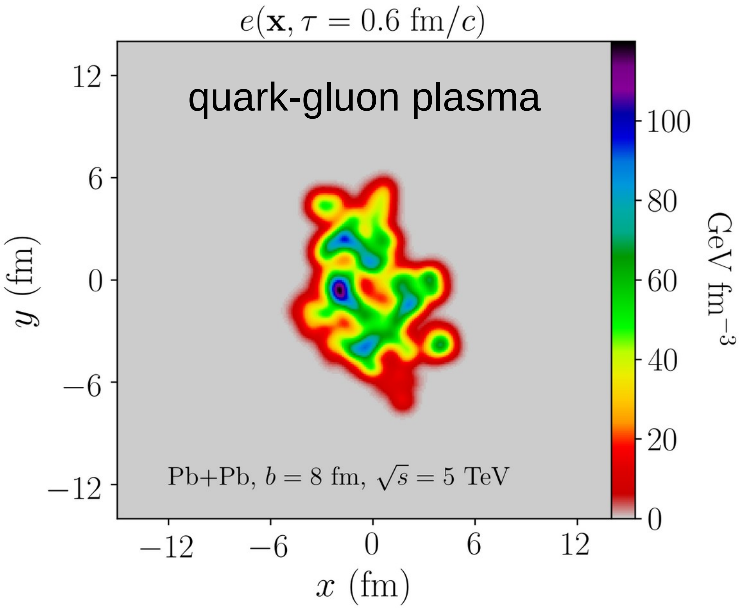
Geneva (CH)



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.

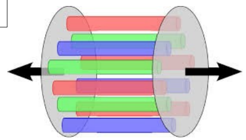
[HoTQCD collaboration, PRD **90** (2014) 094503]

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.

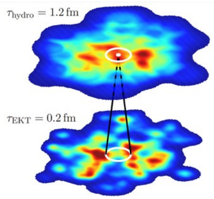
2 Effective theory of highly coherent gluon states: *"Glasma"*



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

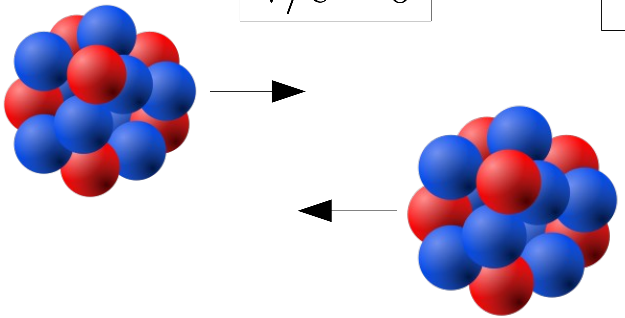
3 Effective QCD kinetic theory

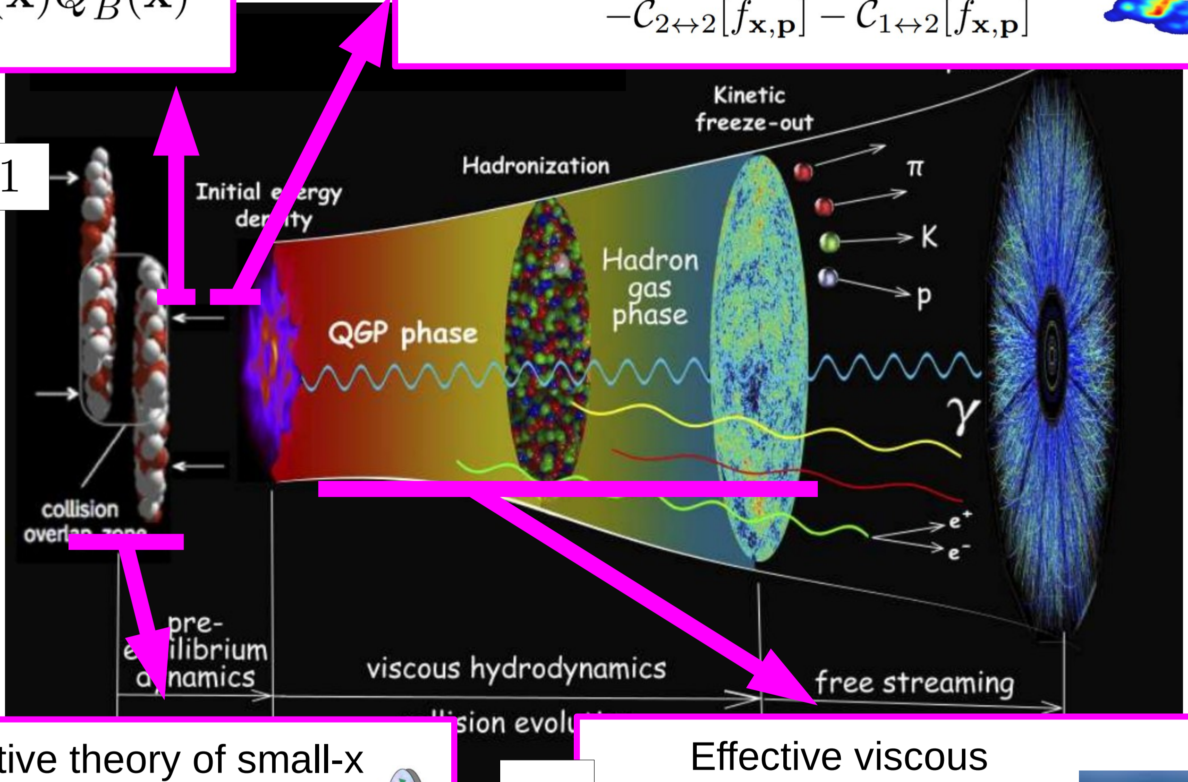
$$\partial_\tau f_{\mathbf{x},\mathbf{p}} + \frac{\mathbf{p}}{|\mathbf{p}|}\cdot\nabla_{\mathbf{x}} f_{\mathbf{x},\mathbf{p}} - \frac{p^z}{\tau}\partial_{p^z} f_{\mathbf{x},\mathbf{p}} = -\mathcal{C}_{2\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}] - \mathcal{C}_{1\leftrightarrow 2}[f_{\mathbf{x},\mathbf{p}}]$$



v/c ~ 0

v/c = 1

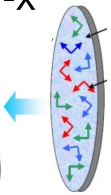




HEAVY-ION COLLISIONS
=
A TOWER OF EFFECTIVE THEORIES

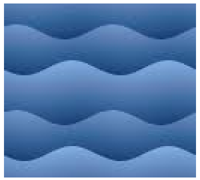
1 Effective theory of small-x degrees of freedom
CGC

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

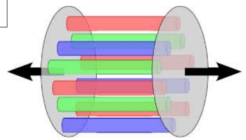


4 Effective viscous hydrodynamic description

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



2 Effective theory of highly coherent gluon states: *“Glasma”*



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3 Effective QCD kinetic theory

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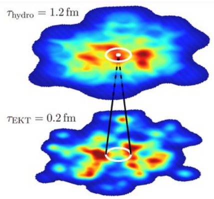
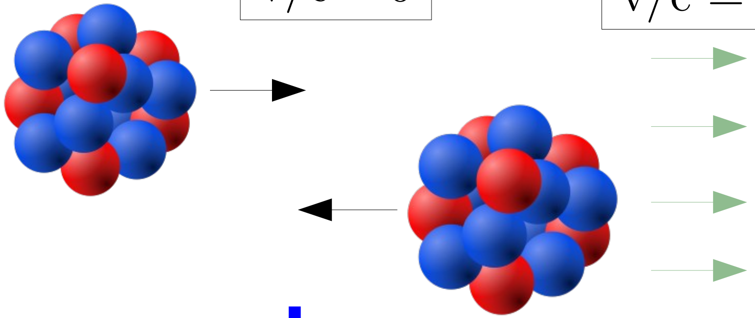
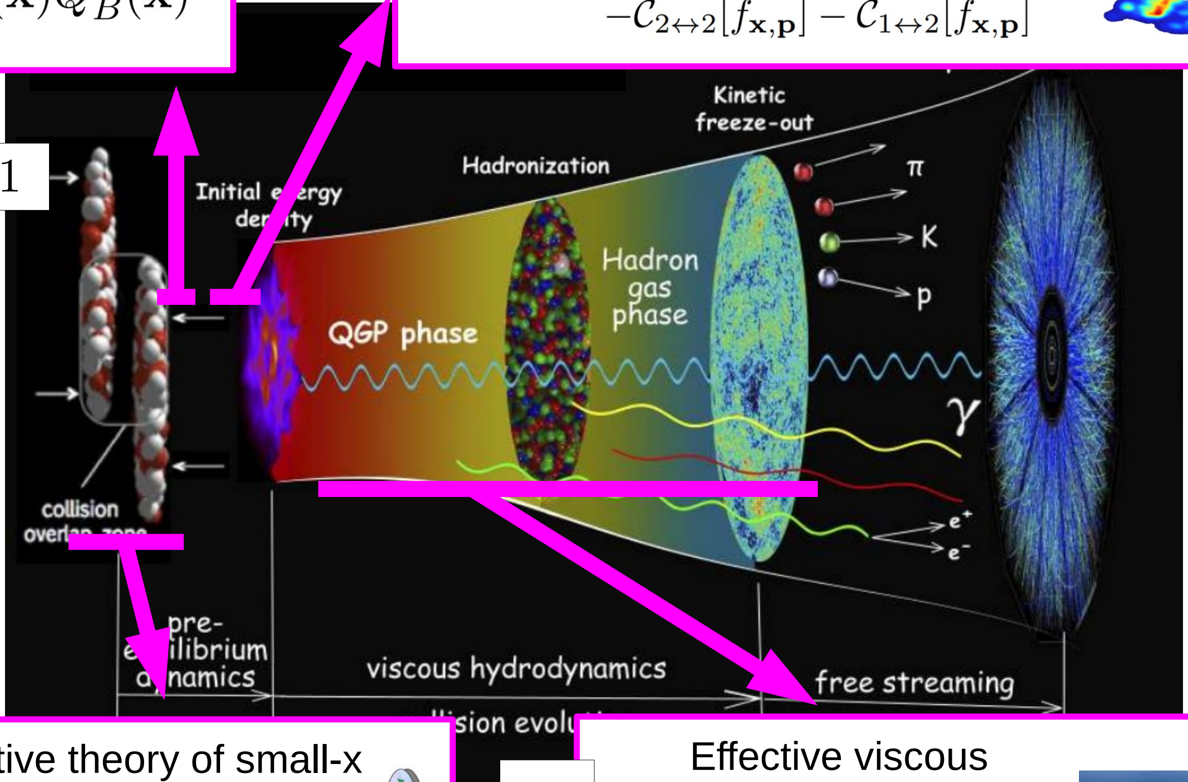


$\mathrm{v/c} \sim 0$

$\mathrm{v/c} = 1$





0 **THIS PROGRAM**

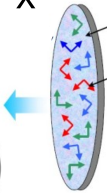
Effective theories of QCD for spatial distribution of large-x degrees of freedom

→ nuclear structure

1 Effective theory of small-x degrees of freedom

CGC

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



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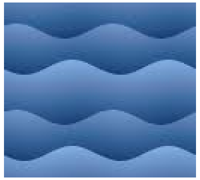
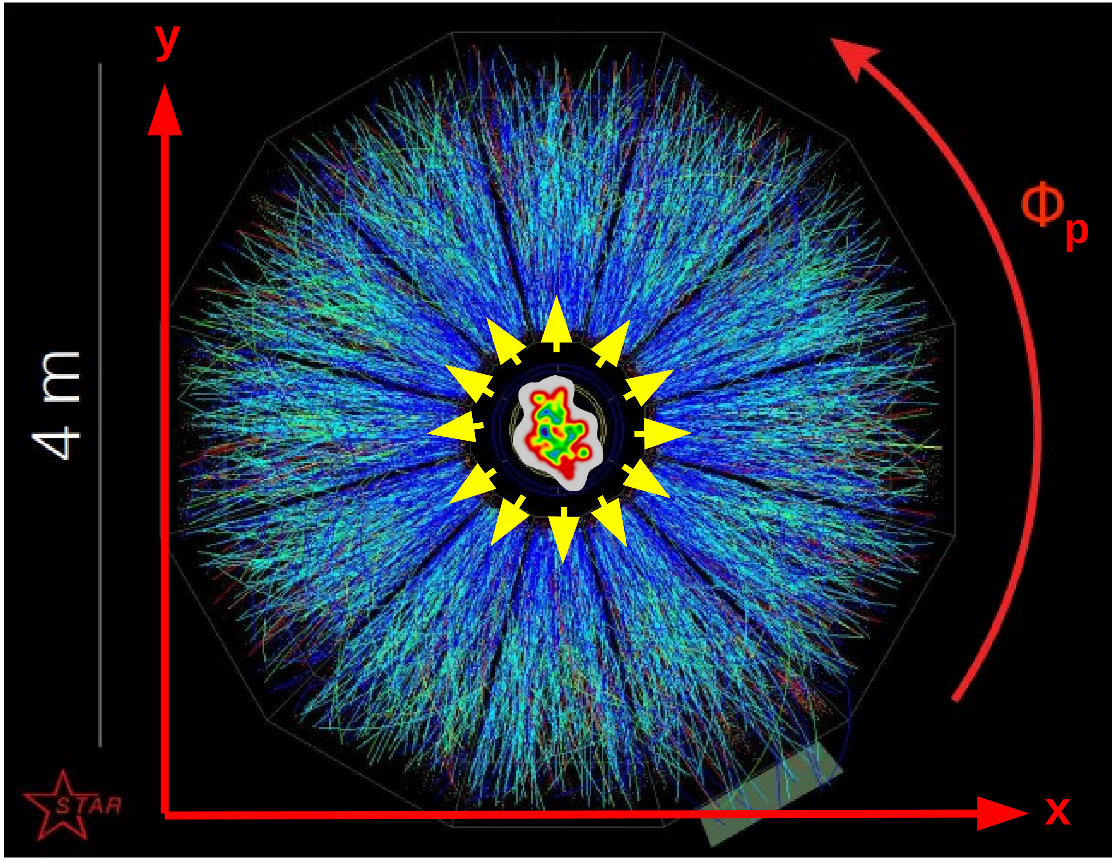


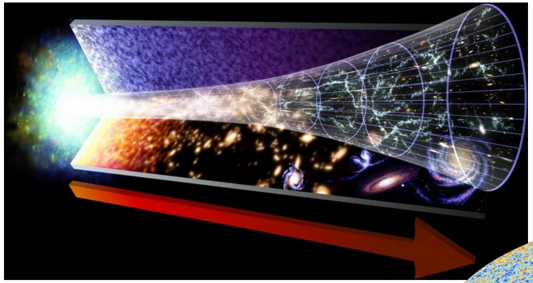
How do we reconstruct the initial condition of the QGP?

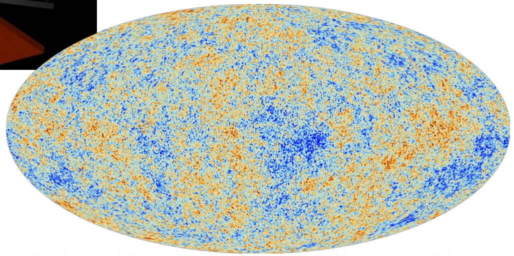


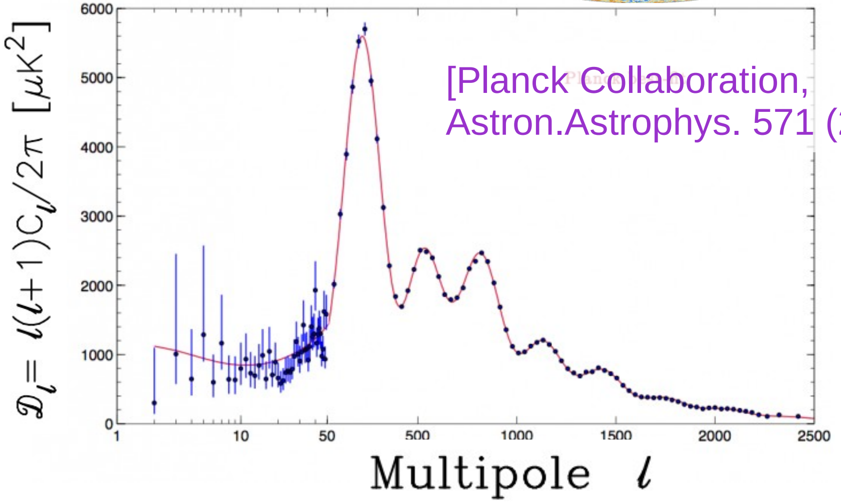
Low-momentum particles follow the hydrodynamic expansion.

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

The Big Bang

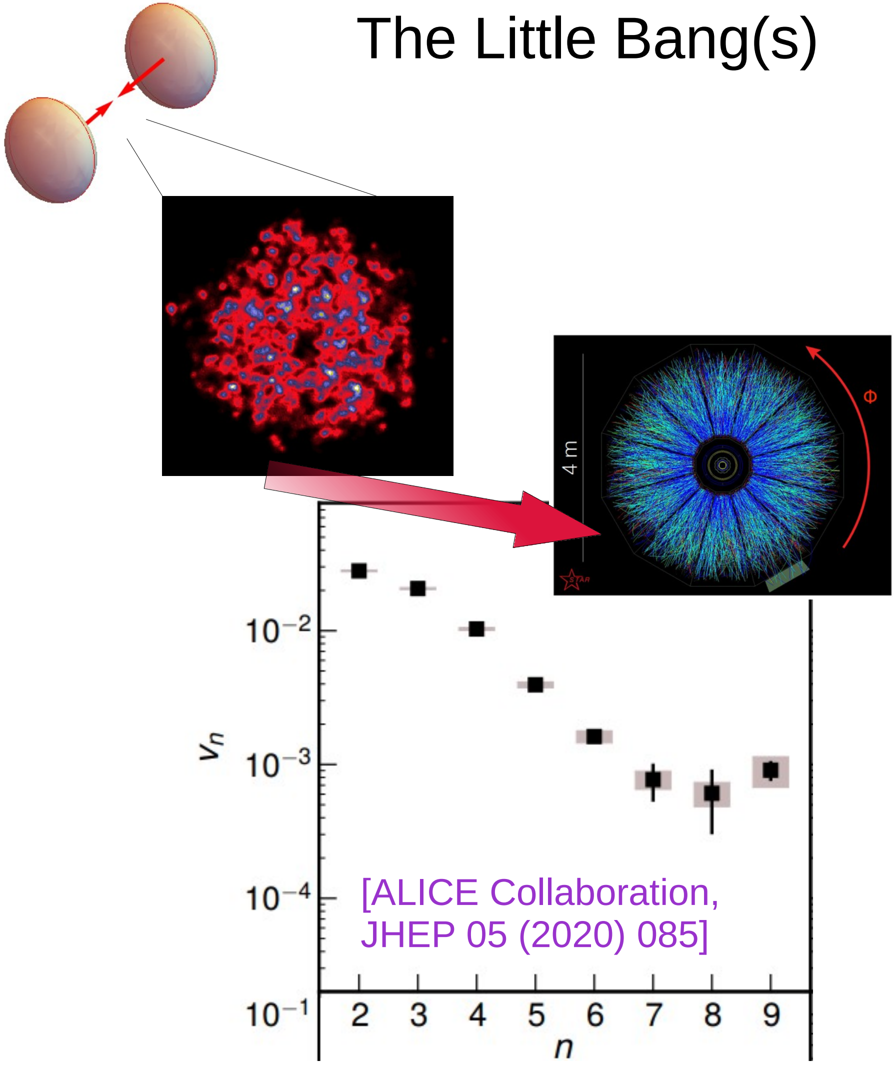






[Planck Collaboration, Astron.Astrophys. 571 (2014) A16]

The Little Bang(s)



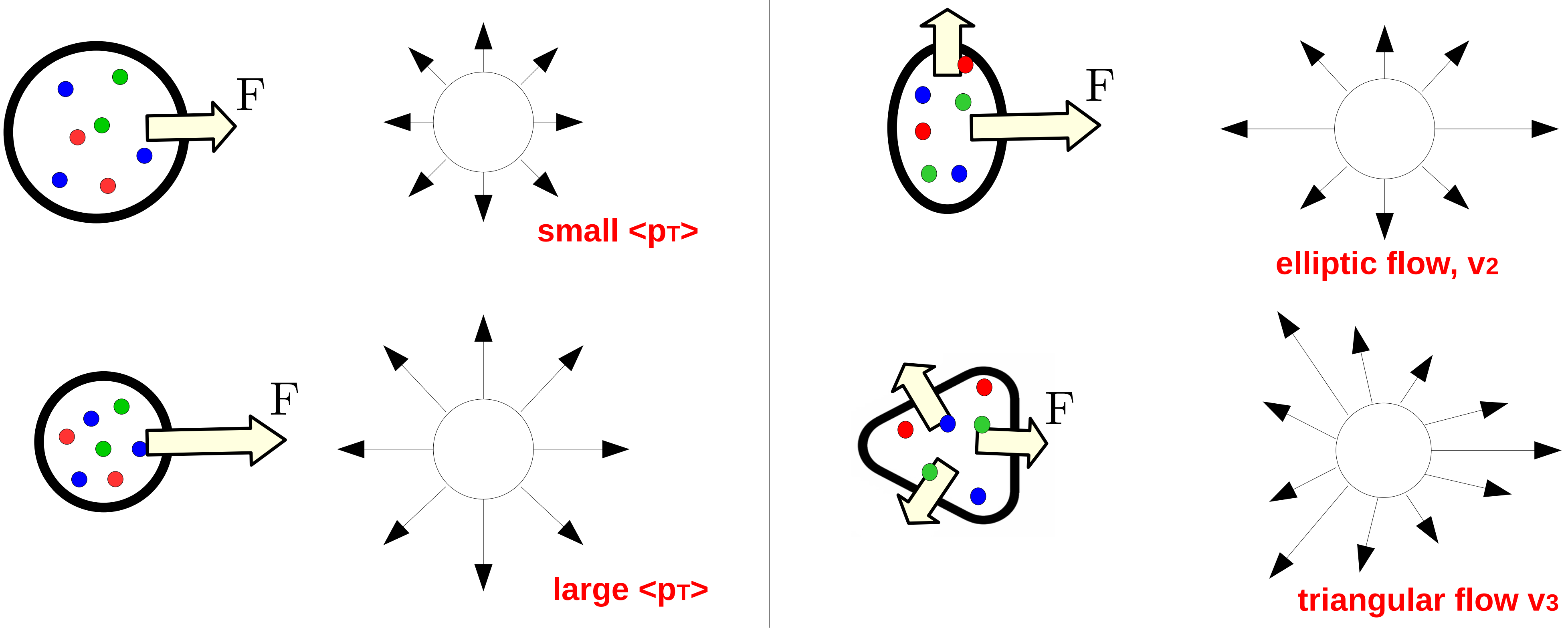
[ALICE Collaboration, JHEP 05 (2020) 085]

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

$$F = -\nabla P$$

[Ollitrault, PRD **46** (1992) 229-245]
[Broniowski, Chojnacki, Obara, PRC **80** (2009) 051902]
[Alver, Roland, PRC **81** (2010) 054905]

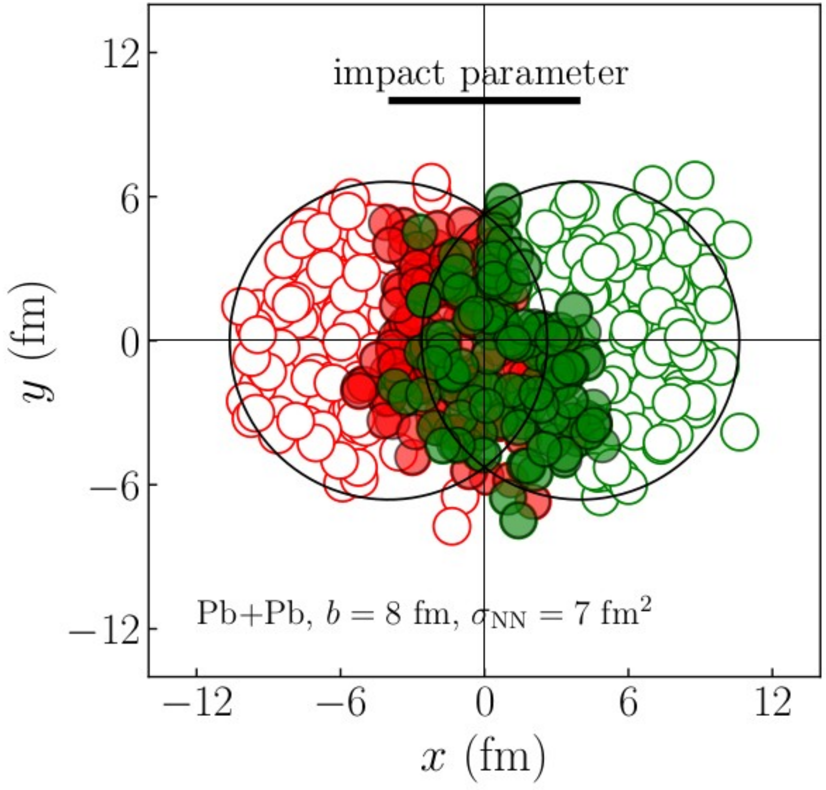
initial state (x)	final state (p)	initial state (x)	final state (p)



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

2 – Nuclear structure input.

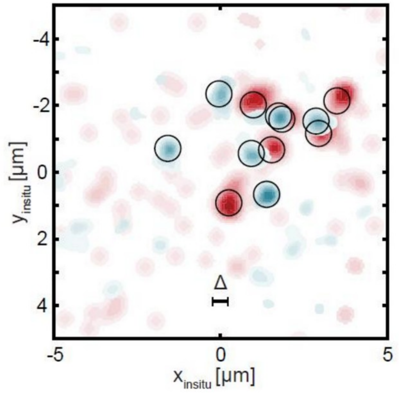
Formation of QGP starts with an input from nuclear structure.



High-energy model

Scattering occurs mainly within nucleons.

“quantum measurement” of the nucleon positions.



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

Origin of nucleon positions: for “spherical” systems like 208Pb, independent sampling in common potential (<u>mean field</u>) is appropriate.

INDEPENDENT PARTICLE PROBLEM

FULL PROBLEM

$$H|\psi\rangle = E|\psi\rangle \longrightarrow \begin{array}{l} h_i|\phi_k^i\rangle = \varepsilon_k^i|\phi_k^i\rangle \\ h_i = \dfrac{p_i^2}{2m} + V(r_i) \end{array}$$

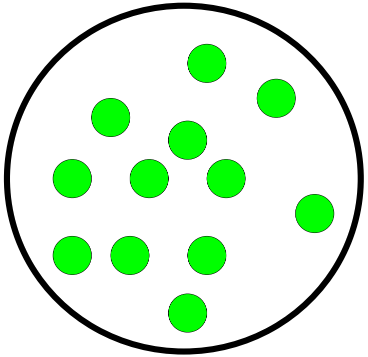
$$V(r_i) = -\frac{V_0}{1+\exp\left(\frac{r_i - R}{a}\right)}$$

Woods-Saxon

Nuclear state from variational equation.

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

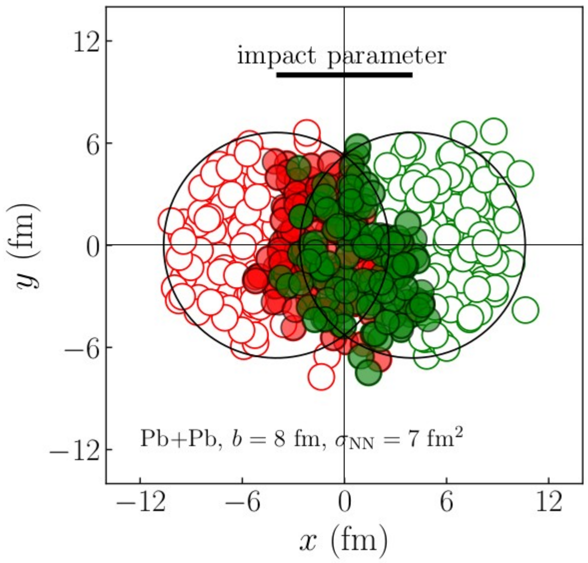
Slater determinant
(+ pairing)

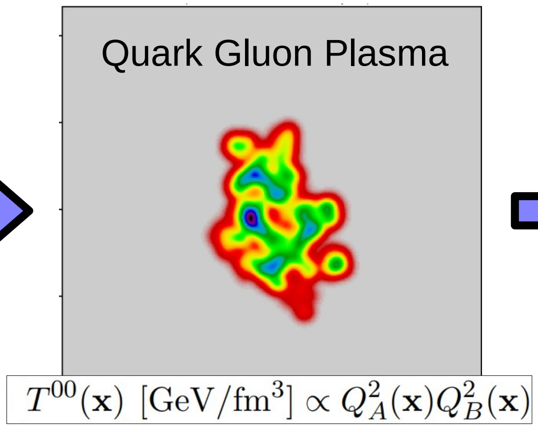


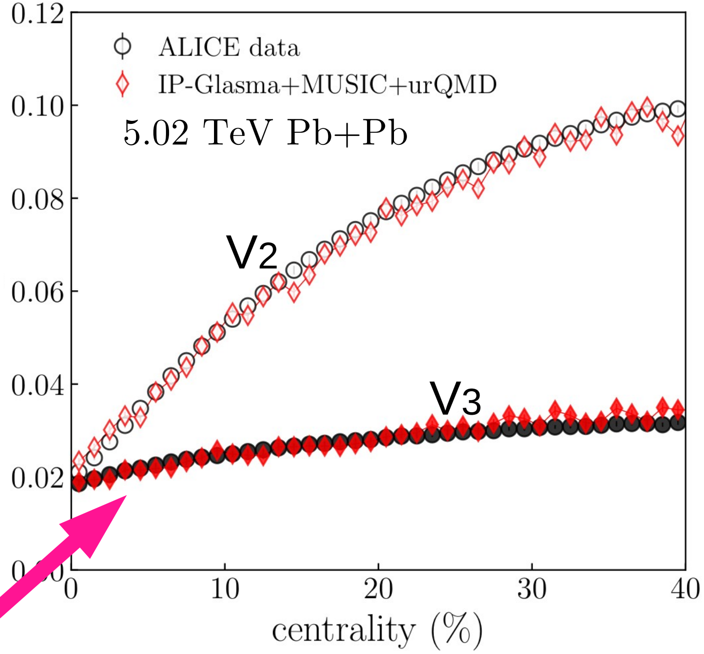
More realistic: Potential generated by effective nucleon-nucleon interaction (Gogny force, Skyrme force, etc.), in “Energy Density Functional” theory.

Goodness of mean field description justifies the Glauber Monte Carlo approach.

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







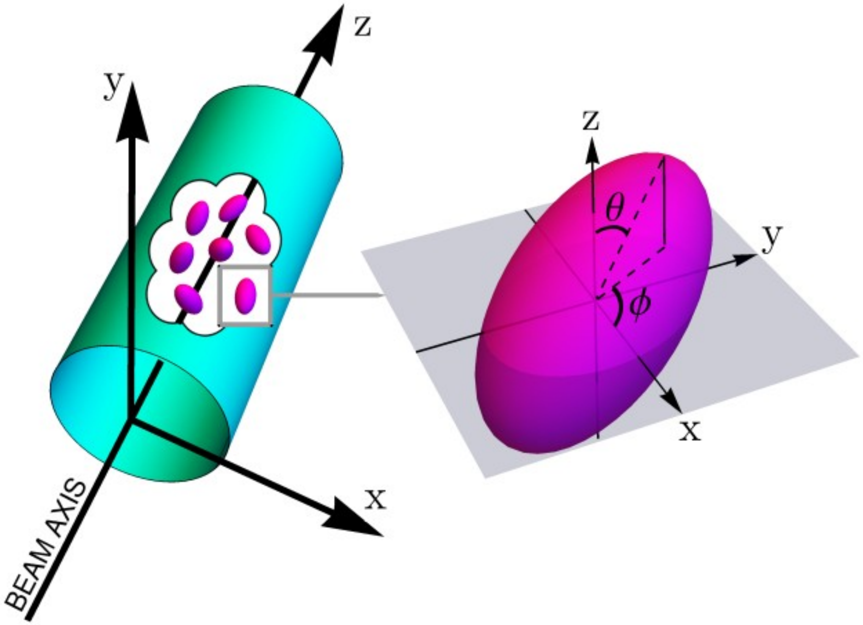
precision physics!

Beyond ^{208}Pb? Heavy-ion collisions require *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.

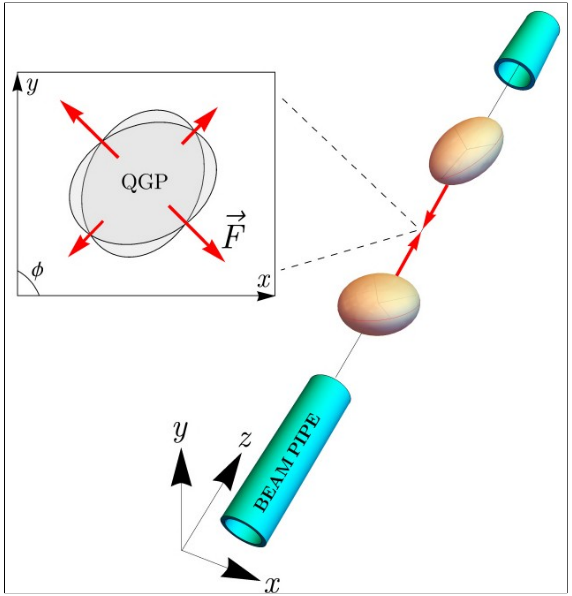


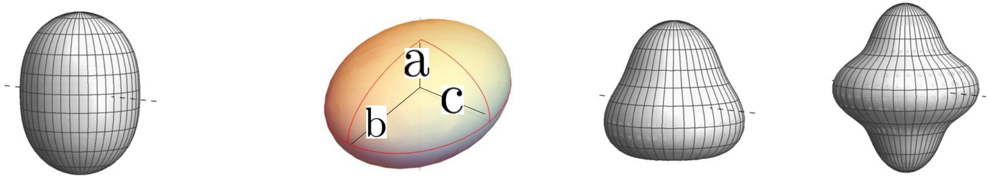
The bag of nucleons is now deformed and with a random orientation.

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:

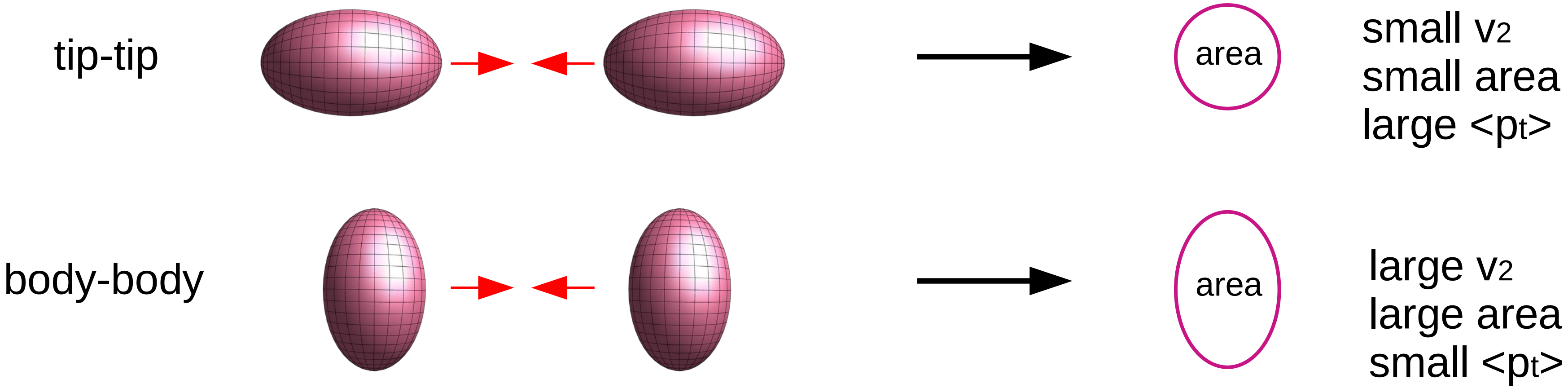
Testing high-energy model via crosscheck of nuclear deformation effects.

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]

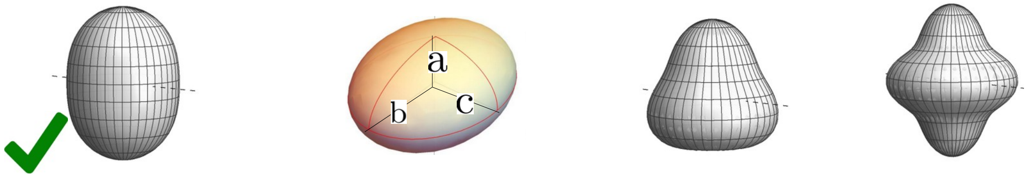


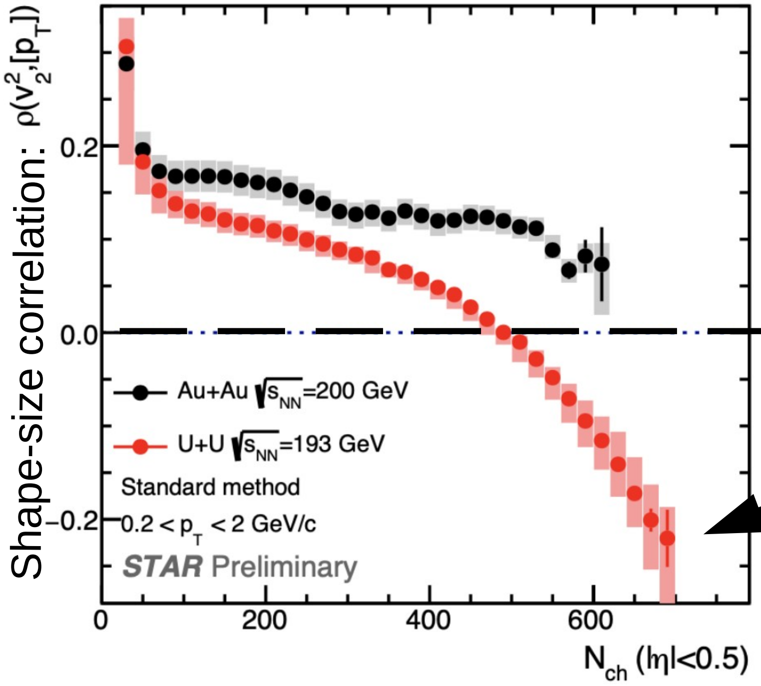
CENTRAL COLLISIONS OF (PROLATE) DEFORMED IONS

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

Signature of the prolate deformation of uranium-238.

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

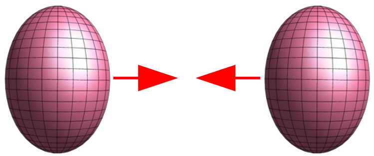




Shape is correlated with size

v_2 is anti-correlated with <p_t>

Limit of fully-overlapping shapes.



Signature of the hexadecapole deformation of uranium-238.

Circumstantial evidence that hydro simulations do not capture v_2 [U+U] / v_2 [Au+Au].

[Giacalone, Jia, Zhang, PRL **127** (2021) 24, 242301]

$$v_2^2 = a_0 + a_1 \beta_2^2$$

Woods-Saxon parametrization should include quadrupole-hexadecapole coupling.

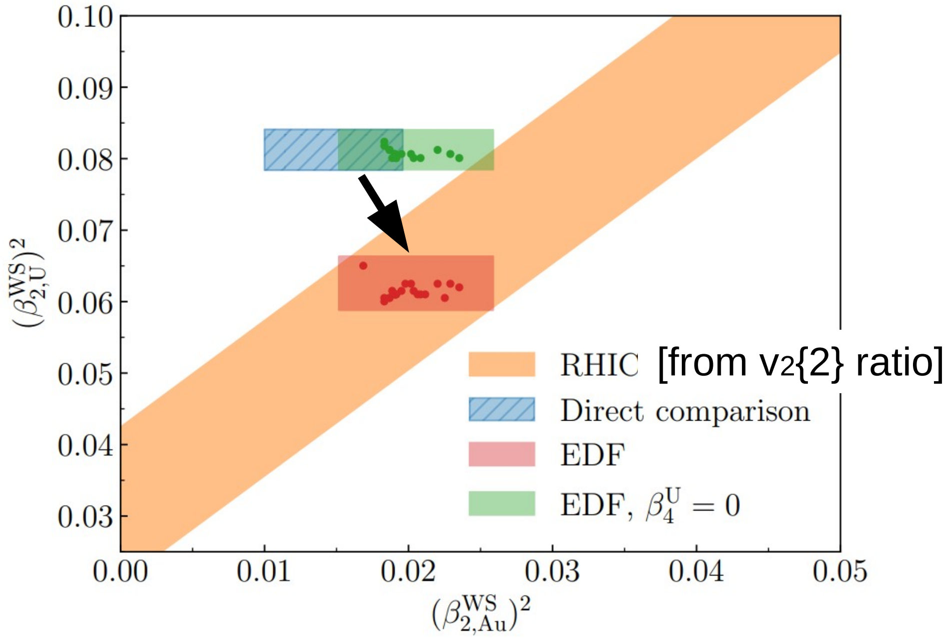
$$\beta_{20} = \frac{R_d^2}{R_0^2}\left[\beta_{20}^{\rm WS} + \frac{4}{7}\sqrt{\frac{5}{4\pi}}\left((\beta_{20}^{\rm WS})^2 + \frac{6}{\sqrt{5}}\beta_{20}^{\rm WS}\beta_{40}^{\rm WS}\right)\right]$$

Measured for Uranium-238

$\beta_2 \approx 0.28$
$\beta_4 \approx 0.1$

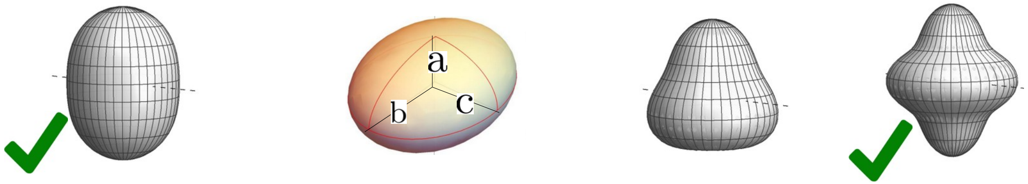
$$\beta_2^{\rm WS} \approx 0.25$$

[Ryssens, Giacalone, Schenke, Shen, in preparation]



Signature of the triaxial deformation of xenon-129.

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



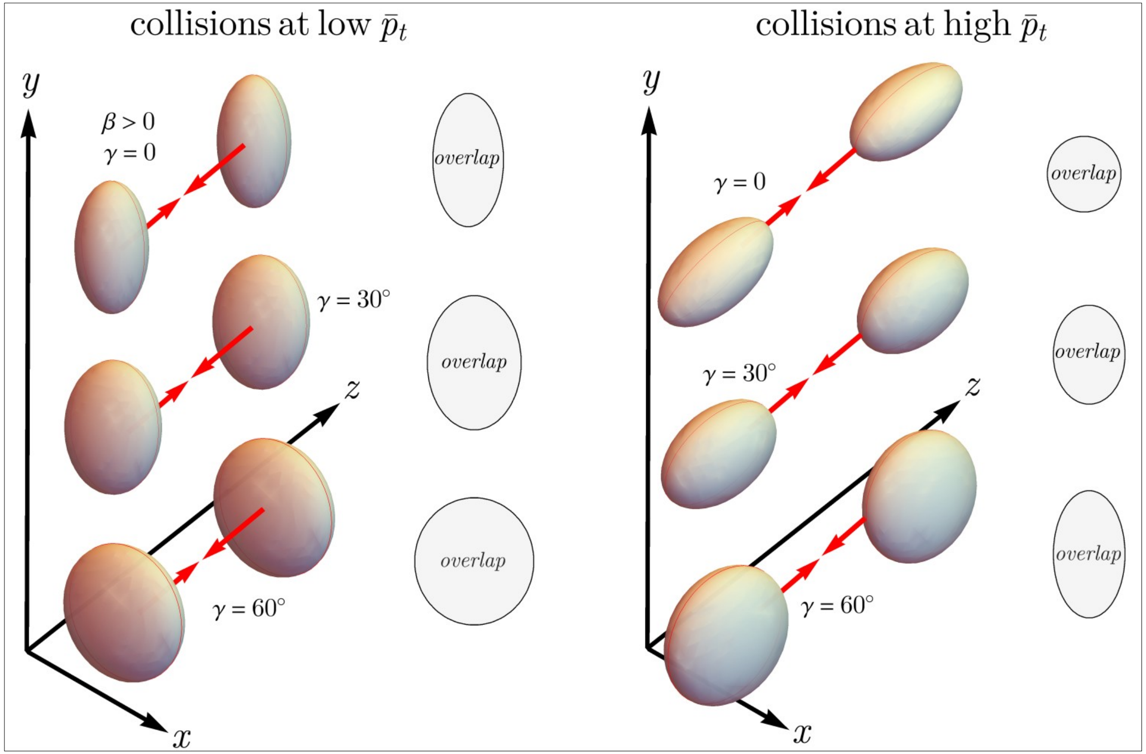
Shape-size correlation is sensitive to the triaxiality, γ.

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

Leading order correction:

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

[Jia, PRC **105** (2022) 4, 044905]



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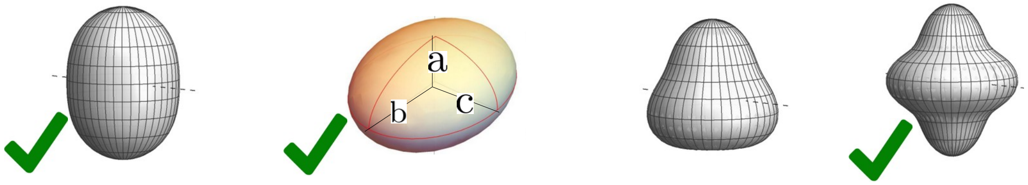
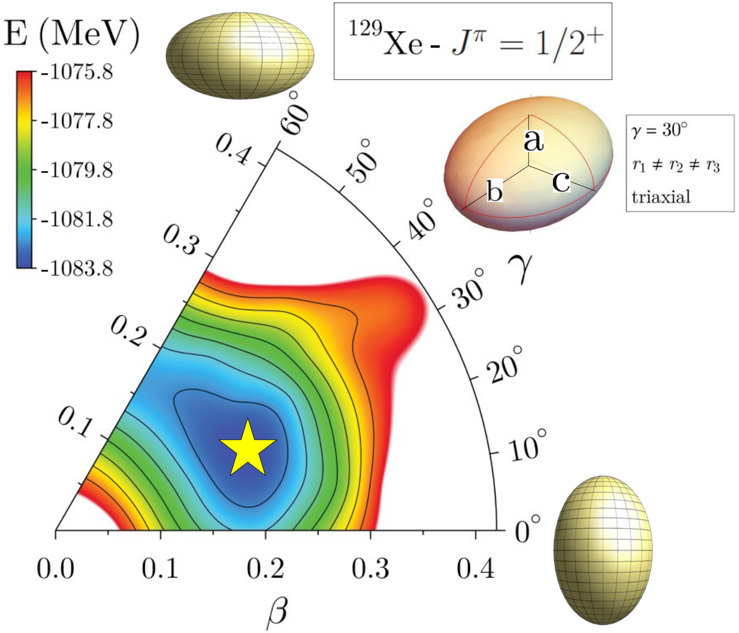
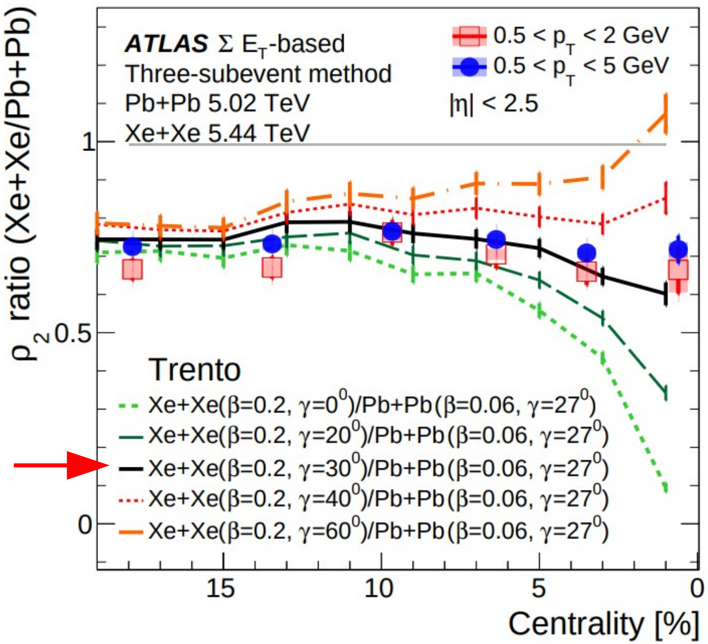




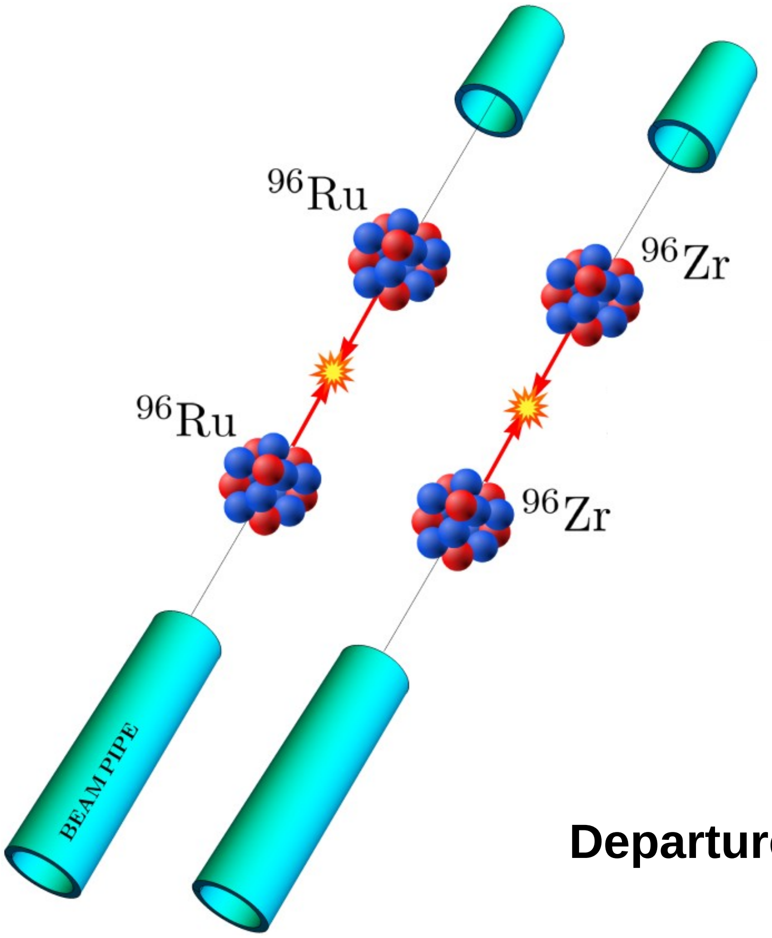
[Bally et al., PRL **128** (2022) 8, 082301]

[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:

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

elliptic flow from fluctuations

response coefficient

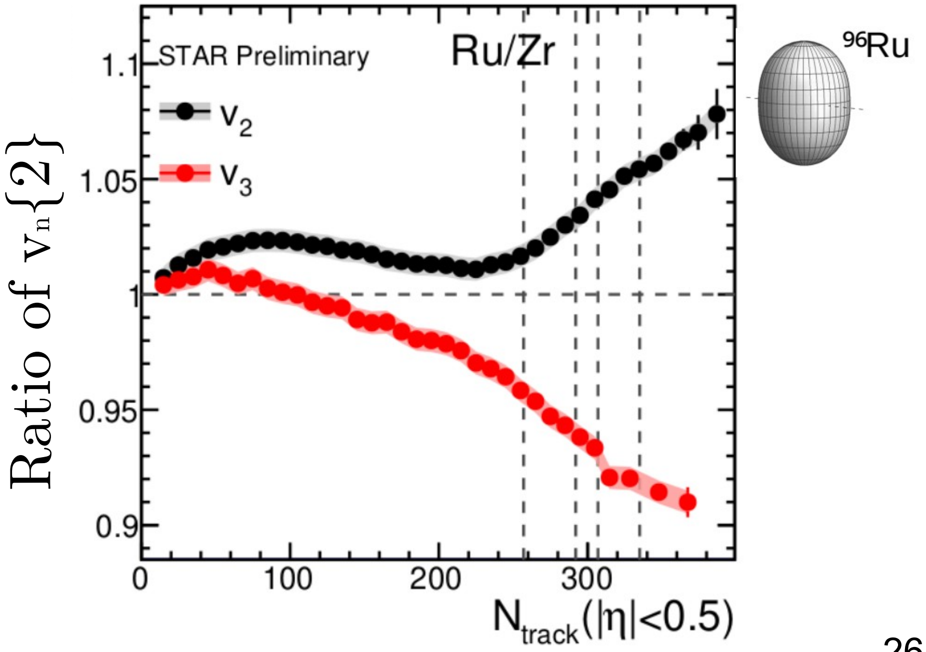
quadrupole deformation

[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.

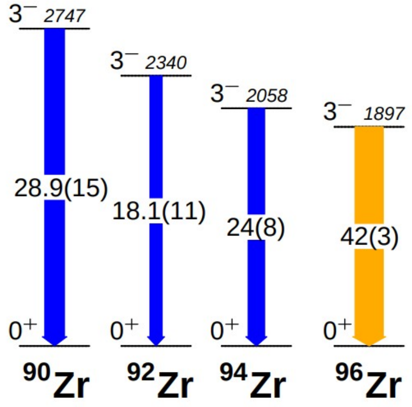
Same logic follows for octupole-deformed nuclei:

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

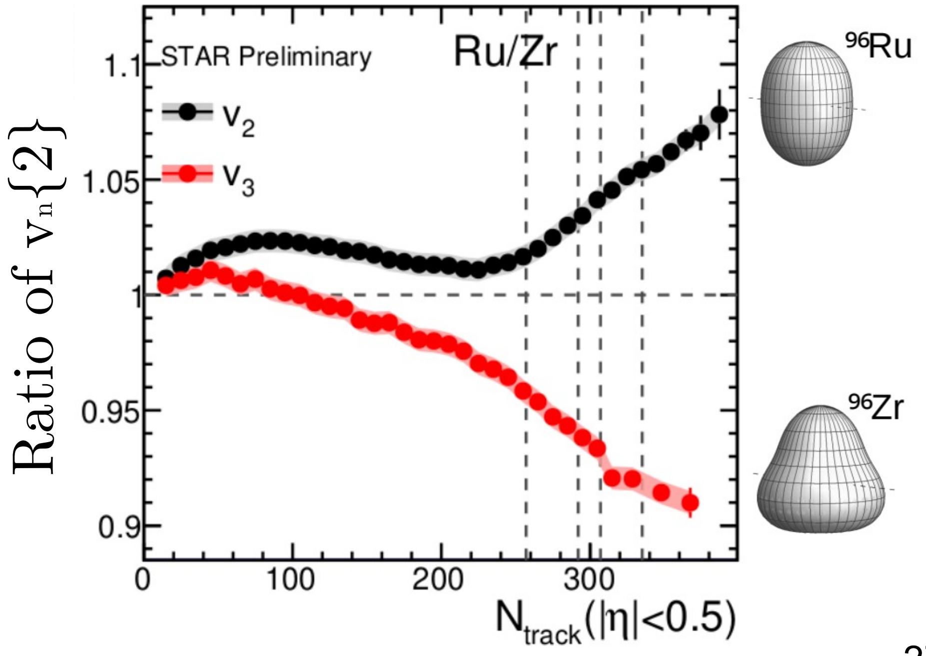
[Jia, Zhang, PRL **128** (2022) 2, 022301]

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

No experimental information about ^{96}Ru.



[from M. Zielinska, ESNT workshop]

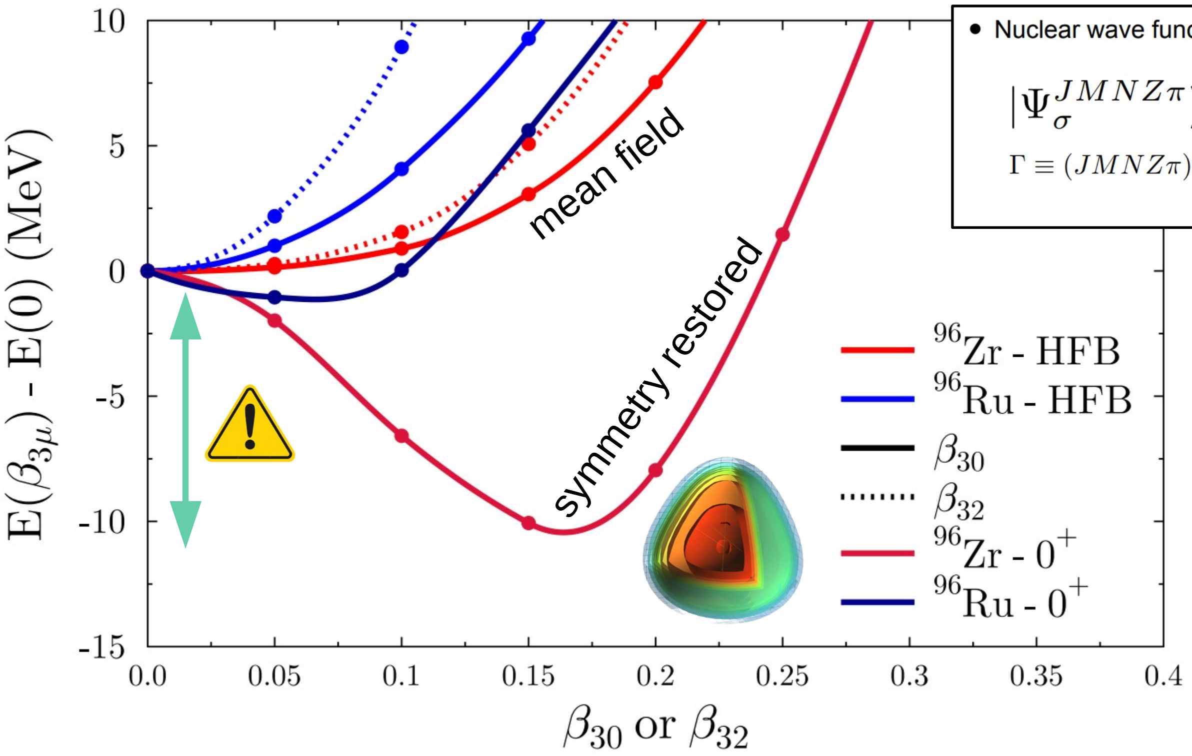


RHIC data implies $\beta_{3,\mathrm{Zr}}^2 \gg \beta_{3,\mathrm{Ru}}^2$

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

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

$\Gamma \equiv (JMNZ\pi)$

[from T. Rodriguez]

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

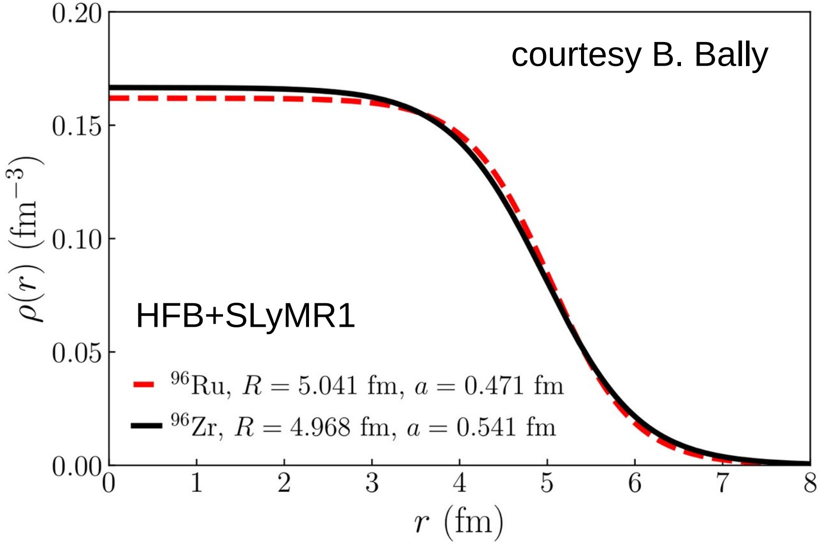
Benjamin Bally (Paris-Saclay)

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.

Signature of skin differences between isobars.



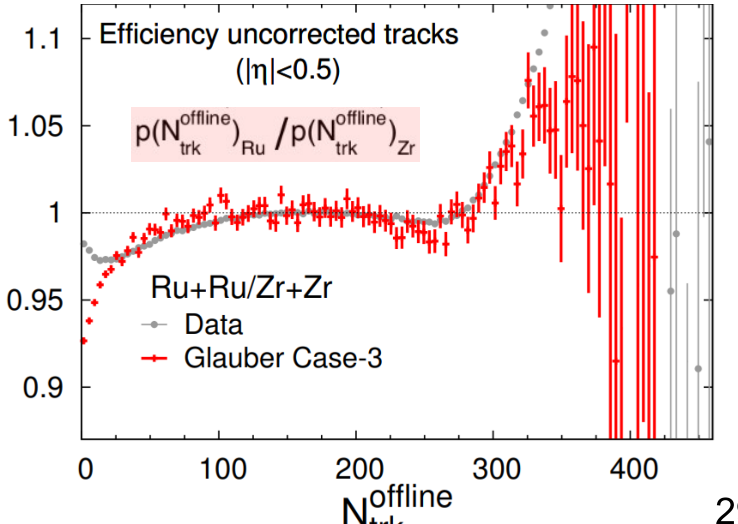
Radial profiles are different:

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

skin thickness

- 96Zr, more diffuse **due to larger N**.
- 96Ru, sharper surface.

Most immediate evidence: Size differences show up in probabilities of multiplicities.



[Shou *et al.*, PLB **749** (2015) 215-220]

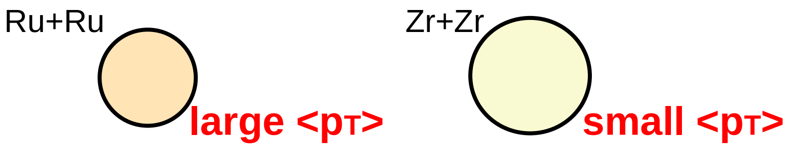
[Li *et al.*, PRC **98** (2018) 5, 054907]

[Li *et al.*, PRL **125** (2020) 22, 222301]

[Xu *et al.*, PLB **819** (2021) 136453]

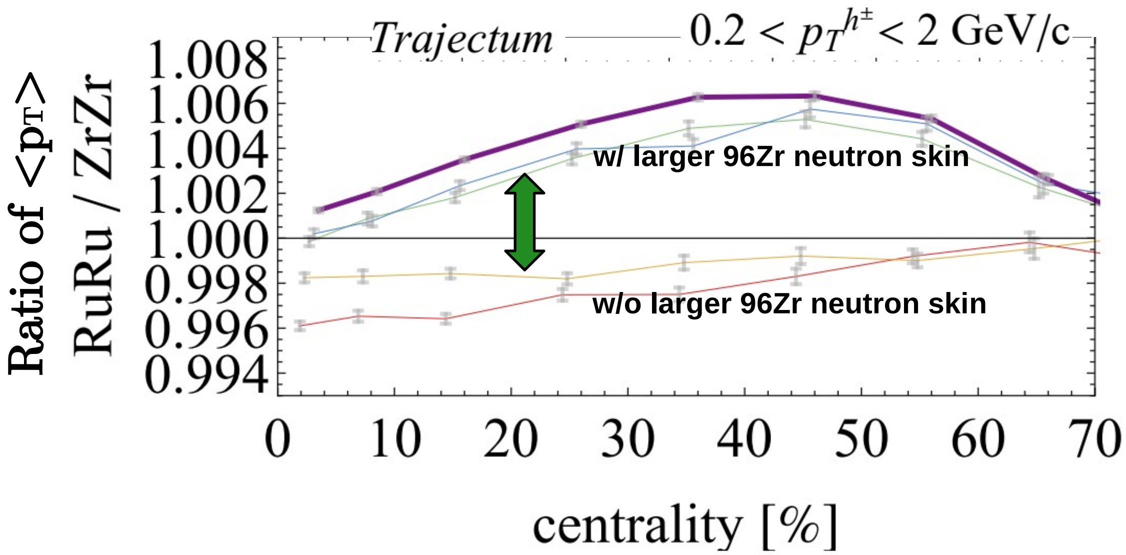
Due to the smaller neutron skin, Ru+Ru systems are more compact. <p_t> is enhanced.

$$F = -\nabla P \Longrightarrow$$

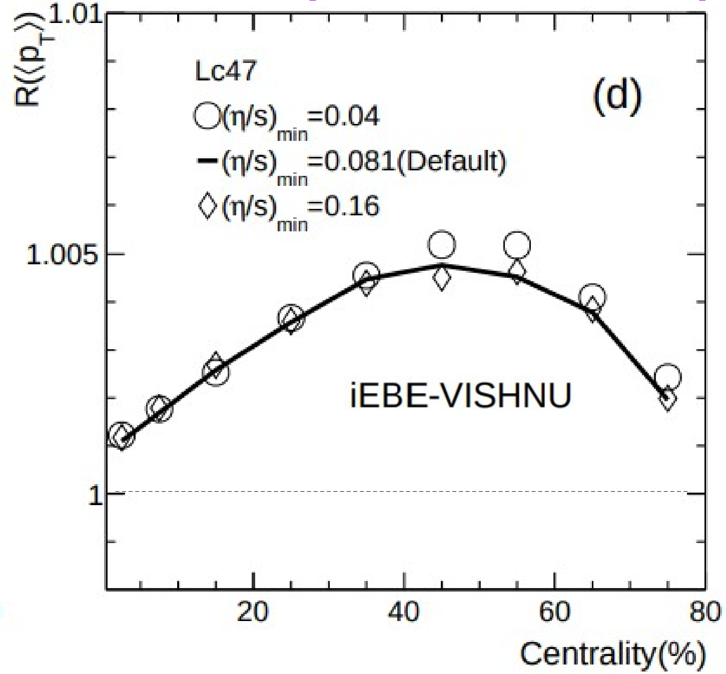


Minor impact from deformations and viscous corrections during hydro.

[Nijs, van der Schee, arXiv:2112.13771]



[Xu *et al.*, arXiv:2111.14812]



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:

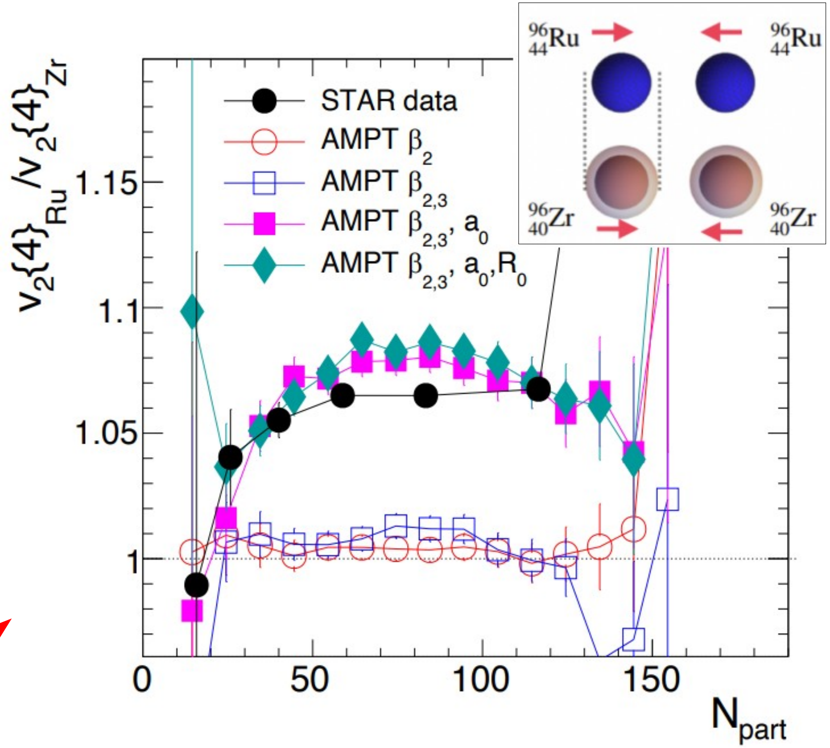
$$p(v_{2x}, v_{2y}) = \frac{1}{\pi\delta^2}\exp\left[-\frac{(v_{2x}-v_2^{rp})^2+v_{2y}^2}{\delta^2}\right]$$

Higher-order cumulants isolate elliptic flow in the reaction plane: [Voloshin *et al.*, PLB **659** (2008) 537-541]

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

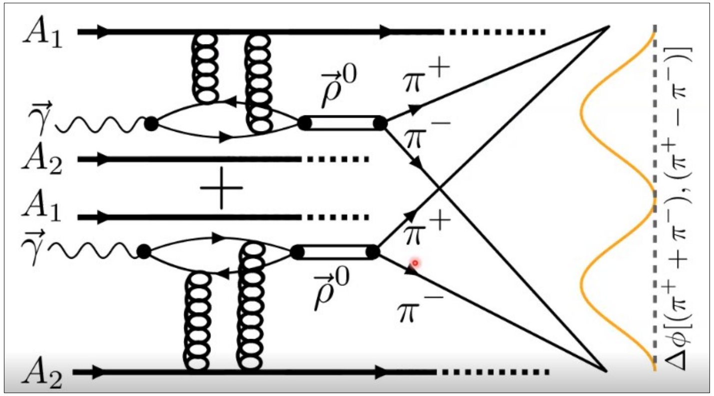
Intrinsic ellipticity:
- sensitive to nuclear thickness
- insensitive to nuclear deformation

[Jia, Giacalone, Zhang, arXiv:2206.10449]



New technique by STAR collaboration to probe gluon densities in UPCs.

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



ScienceAdvances

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HOME > SCIENCE ADVANCES > VOL. 9, NO. 1 > TOMOGRAPHY OF ULTRARELATIVISTIC NUCLEI WITH POLARIZED PHOTON-GLUON COLLISIONS

RESEARCH ARTICLE | PHYSICS

Tomography of ultrarelativistic nuclei with polarized photon-gluon collisions

STAR COLLABORATION Authors Info & Affiliations

SCIENCE ADVANCES • 4 Jan 2023 • Vol 9, Issue 1 • DOI: 10.1126/sciadv.abq3903

11.941

$$f(t) = A_c|\mathcal{F}\left[\rho_A(r;R,a)\right](|t|)|^2 + \frac{A_i/Q_0^2}{(1+|t|/Q_0^2)^2}$$

FT of gluon density
(Woods-Saxon)

Measured skin of gold:

$$\Delta r_{np}[\mathrm{STAR}] = 0.17 \pm 0.03\ (\mathrm{stat.}) \pm 0.08\ (\mathrm{syst.})\ \mathrm{fm}$$

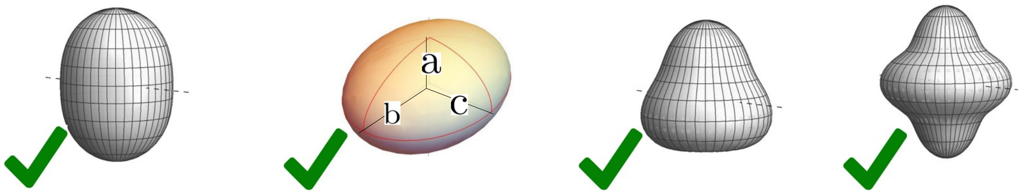
Fully consistent with state-of-the-art density functional results:

$$\Delta r_{np}[\mathrm{MREDF}] = 0.17\ \mathrm{fm}$$

[Bally, Giacalone, Bender, arXiv:2301.02420]

Wrapping up:

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

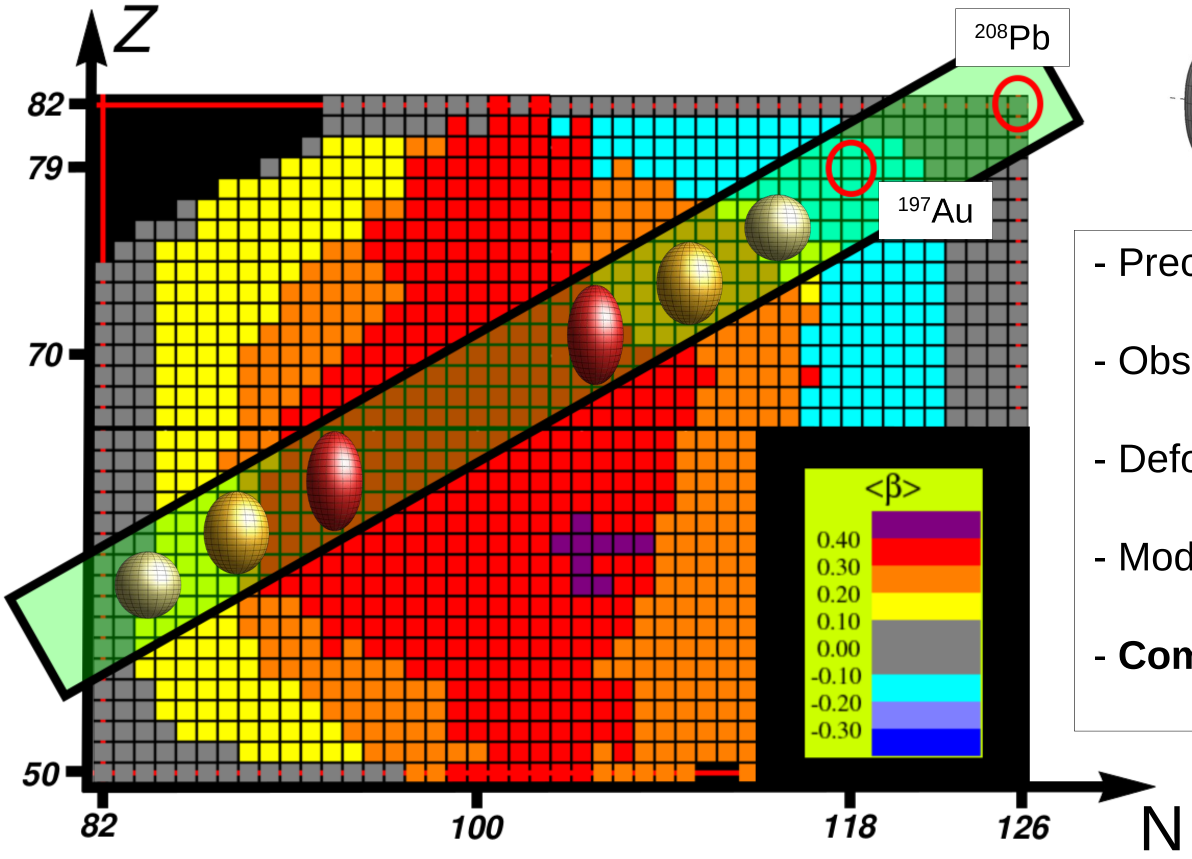


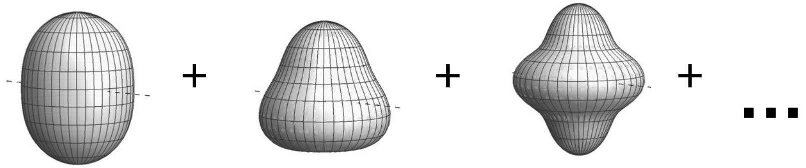
Answers to the initial questions:

- **Great confidence that high-energy model is appropriate.**
- **No clear indication of modifications of nuclear geometry from enhanced gluon fluctuations (Lorentz boost).**

IN CONCLUSION – NEW METHOD TO IMAGE NUCLEI

The ultimate nuclear shape experiment? Exploration of rare earth nuclei.





- Precise determination of relative deformations.
- Observation of small triaxial deformations.
- Deformations beyond hexadecapole (β_4).
- Model-independent constraints for *ab-initio* theory.
- **Complementary knowledge about nuclei.**

4 – Prospects: theory and experiment.

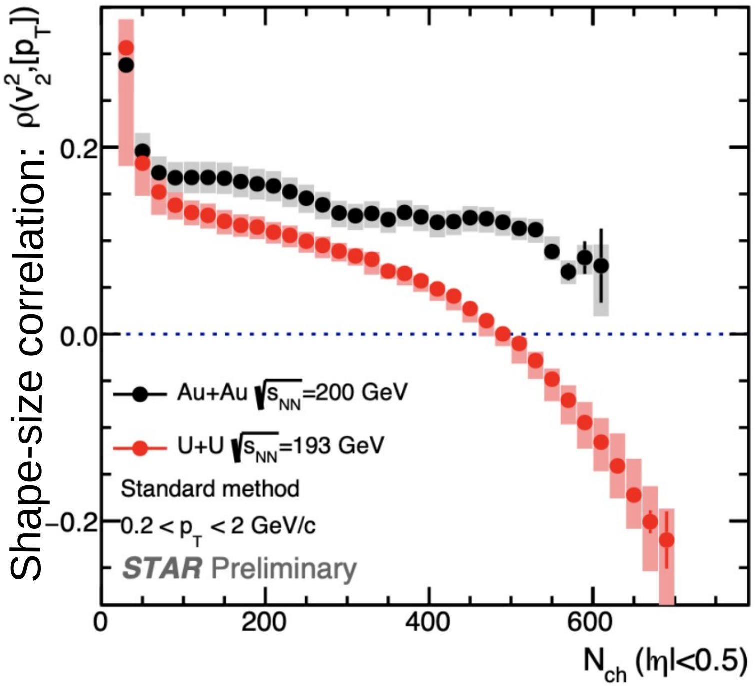
Extract nuclear structure from Bayesian analyses of high-energy data.
Check consistency with low-energy expectations

$$\Pr(p\,\&D) = \Pr(p) \times \Pr(D|p) = \Pr(D) \times \Pr(p|D)$$

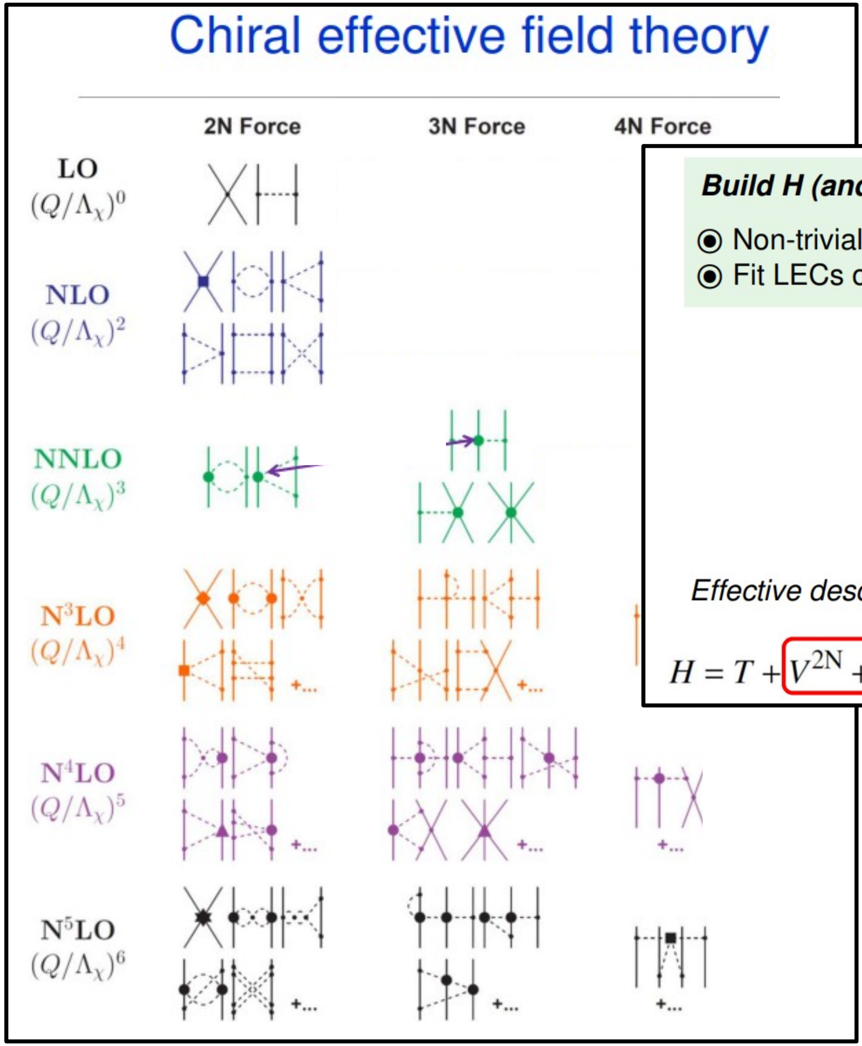
$$\text{prior} \times \text{likelihood} = \text{evidence} \times \text{posterior}$$

[see e.g. Matt Luzum, ESNT workshop]

Enabled by strong dependence of observables on structural properties.



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



Build H (and other operators) with $\boxed{\chi\text{EFT at various orders}}$

- ◉ 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

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

[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]

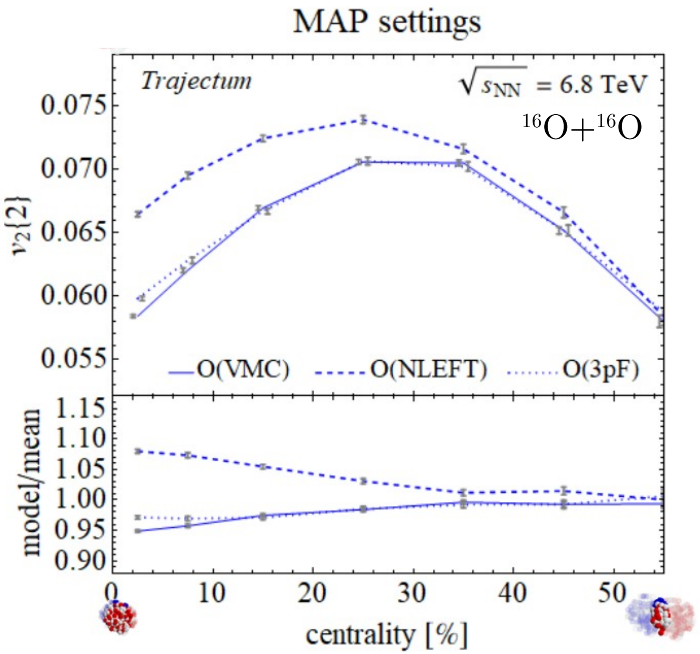
Exploiting ab initio predictions. Opportunity from $^{16}O+^{16}O$ collisions @ RHIC and LHC.

- 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]
[Rybczyński, Broniowski, PRC **100** (2019) 6, 064912]

- 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]



Different N-body correlations.

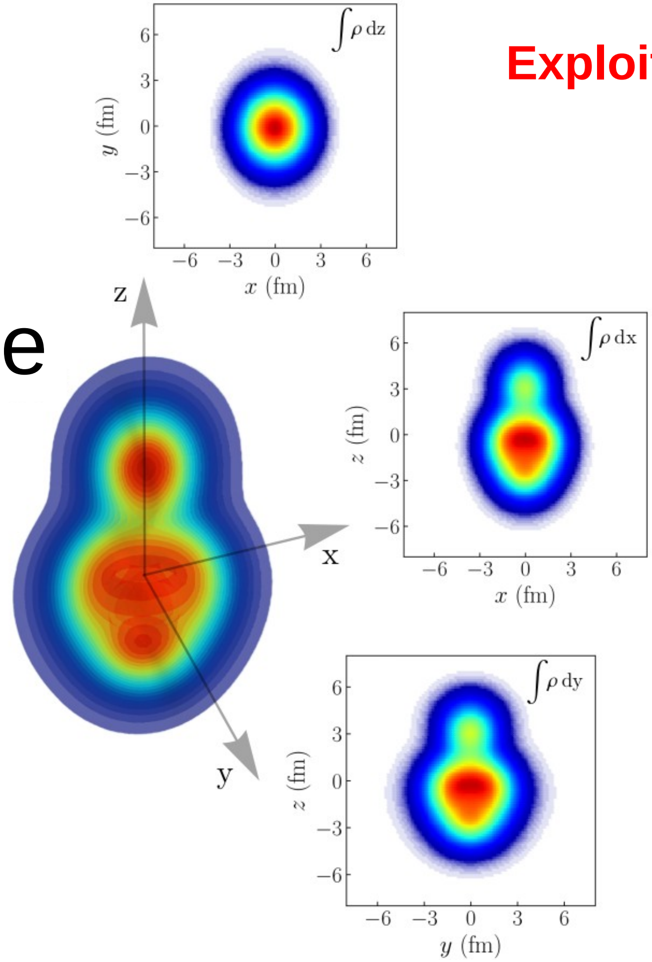
Hamiltonian or many-body solution?

[Trajectum (G Nijs, W van der Schee)
+ Nuclear Lattice EFT (D. Lee, B-N. Lu)
+ G Giacalone, in progress]

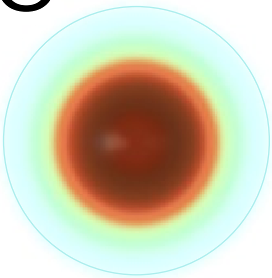
Transparent evidence of the “geometric” origin of flow in a small system?

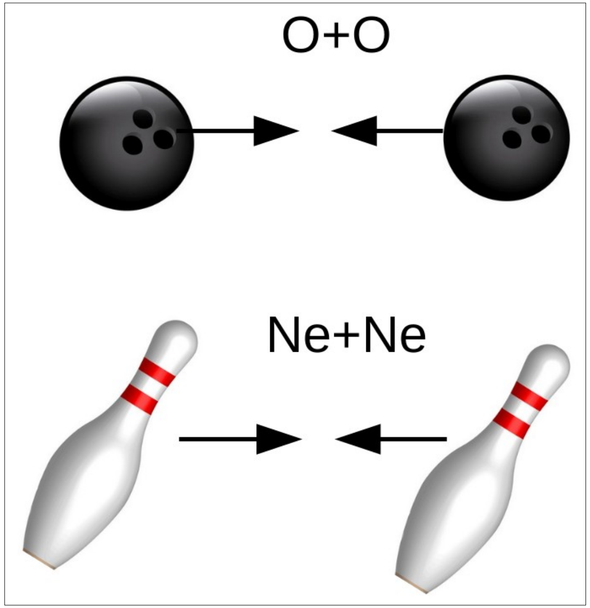
Exploiting bowling-pin-shaped ^{20}Ne.

^{20}Ne



^{16}O





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

Bands are systematical uncertainties (η/s, ζ/s, …)

Large 20% effect on rms v_2.

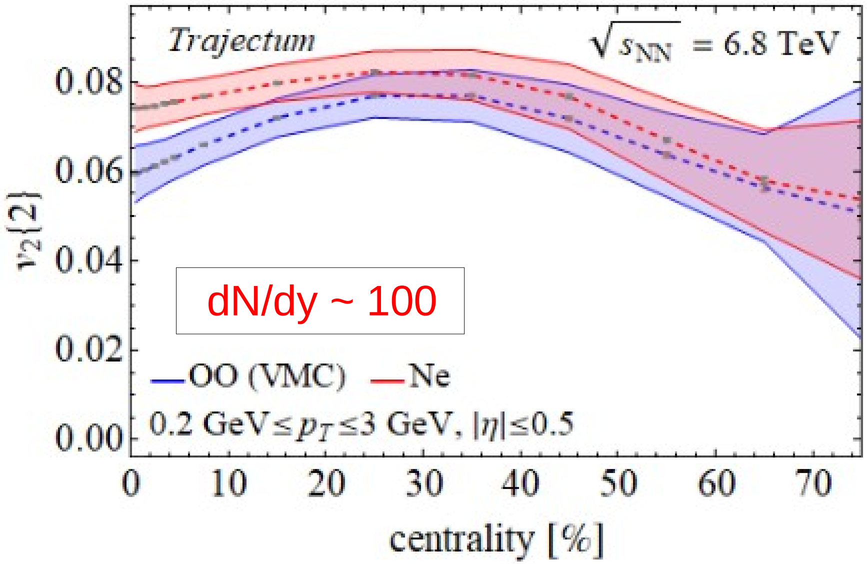
Systematical uncertainty on ratio at % level!
(“isobar criterion”)

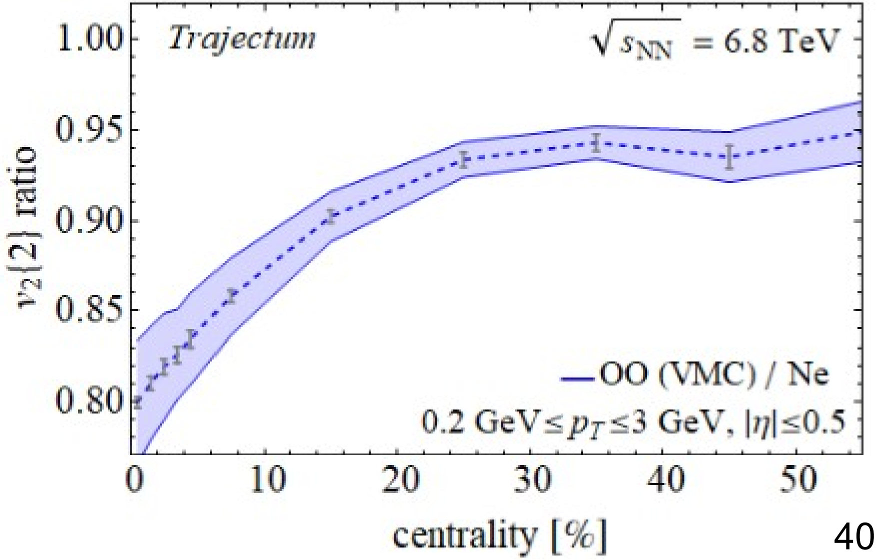
<u>Unambiguous “geometric” interpretation.</u>

<u>OUR POINT</u>

Central A-A 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 (Bally, Duguet, Ebran, Frosini, Rodriguez, Somà)
+ G. Giacalone, in progress]

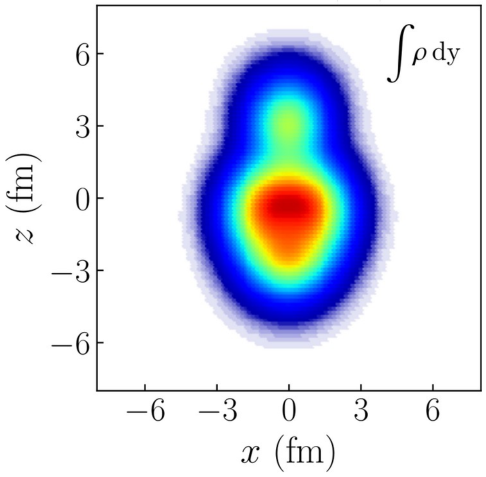


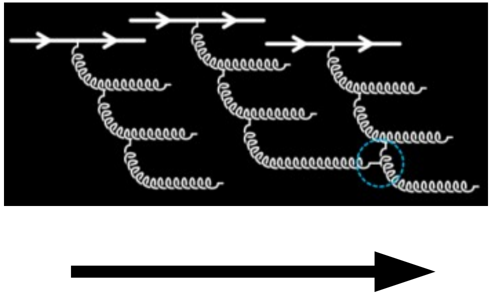


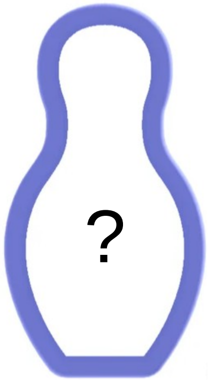
Role of small-x evolution?

neon-20 thickness

x~0.01







x~0.0001

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

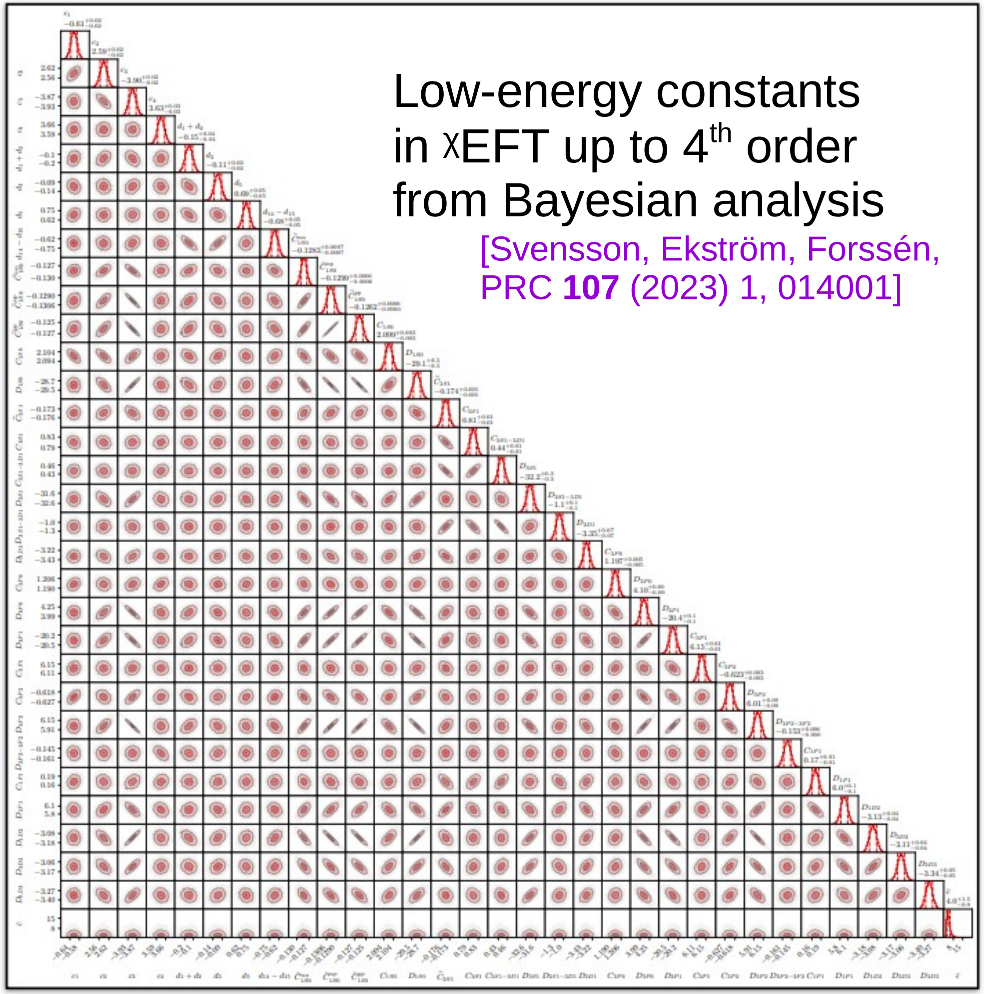
1 – ^{20}Ne in SMOG system of LHCb. Collider + fixed-target at the same time.
Collisions at sqrt(s)=7000 GeV <u>and</u> sqrt(s)=70 GeV.

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

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

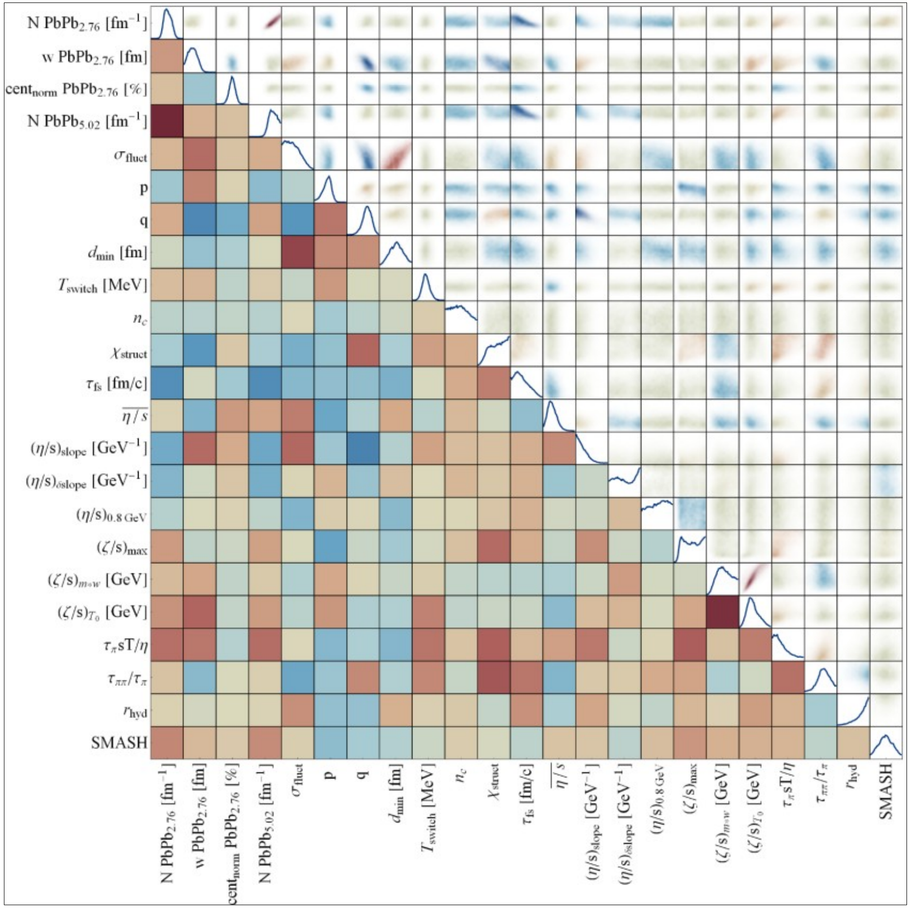
QCD across energy scales. Long term goal?

[A. Ekström, Hirschegg 2023 workshop, Jan 2023]



Low-energy constants
in χEFT up to 4th order
from Bayesian analysis
[Svensson, Ekström, Forssén, PRC **107** (2023) 1, 014001]

[Trajectum (credits W. van der Schee)]

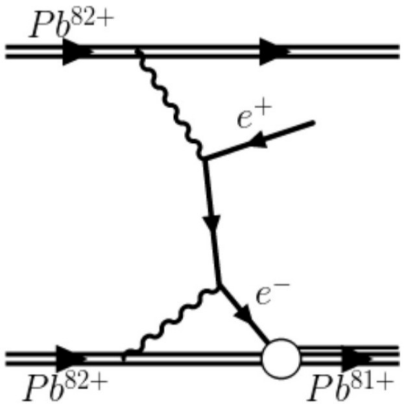


Possibility of collisions of additional species @ LHC Run 5 and Run 6?

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: $\mathcal{L}_{NN} = A^2 \cdot \mathcal{L}_{AA}$

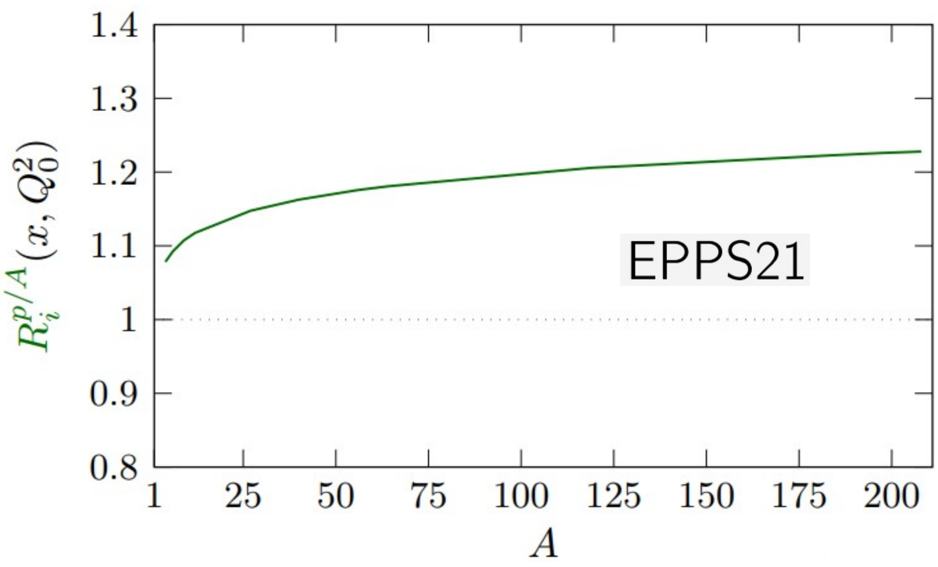
optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\langle L_{NN} \rangle$ (cm^{-2} s^{-1})	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathcal{L}_{AA}$ (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

Electron-Ion Collider – Effects of nuclear shapes should be assessed.

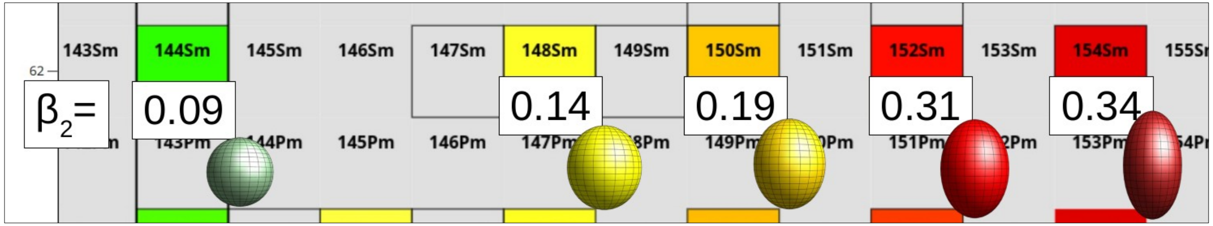
[from Petja Paakkinen, ESNT workshop]

- Define nuclear PDFs in terms of

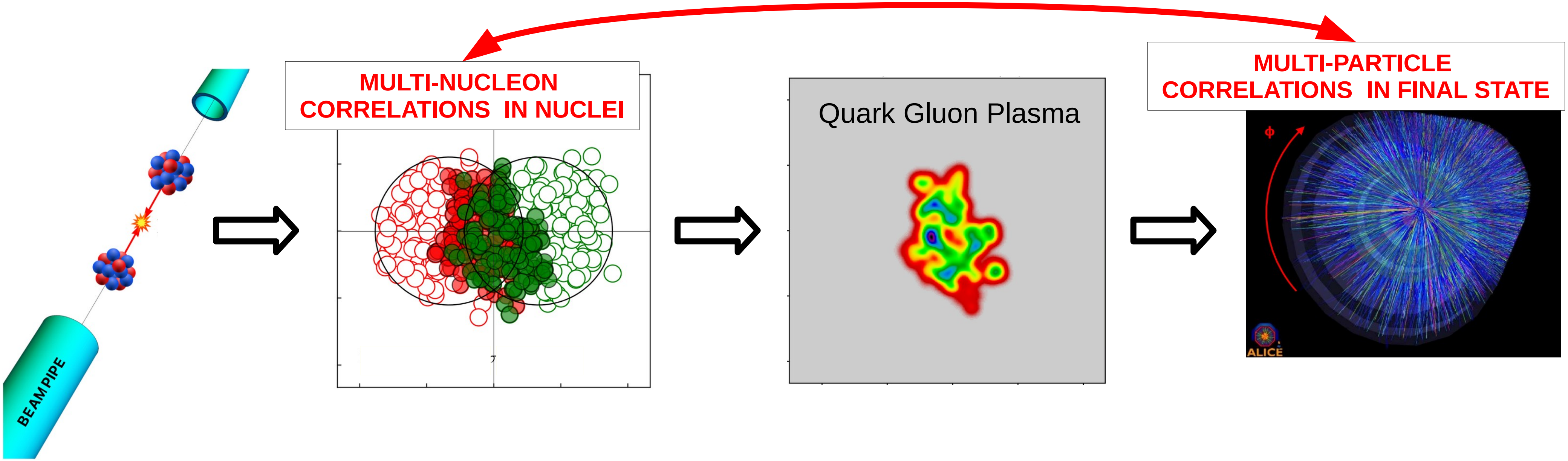
$$\underbrace{f_i^{p/A}(x,Q^2)}_{\text{bound-proton PDF}} = \overbrace{R_i^{p/A}}^{\text{nuclear modification}}(x,Q^2)\,\underbrace{f_i^{p}(x,Q^2)}_{\text{free-proton PDF}}$$



E.g.: Samarium isotopic chain. Same A (within 7%) but completely different shapes.



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

AND

ENJOY THE PROGRAM!