Imaging the Nuclear Structure in Ultra-Relativistic Nuclear Collisions

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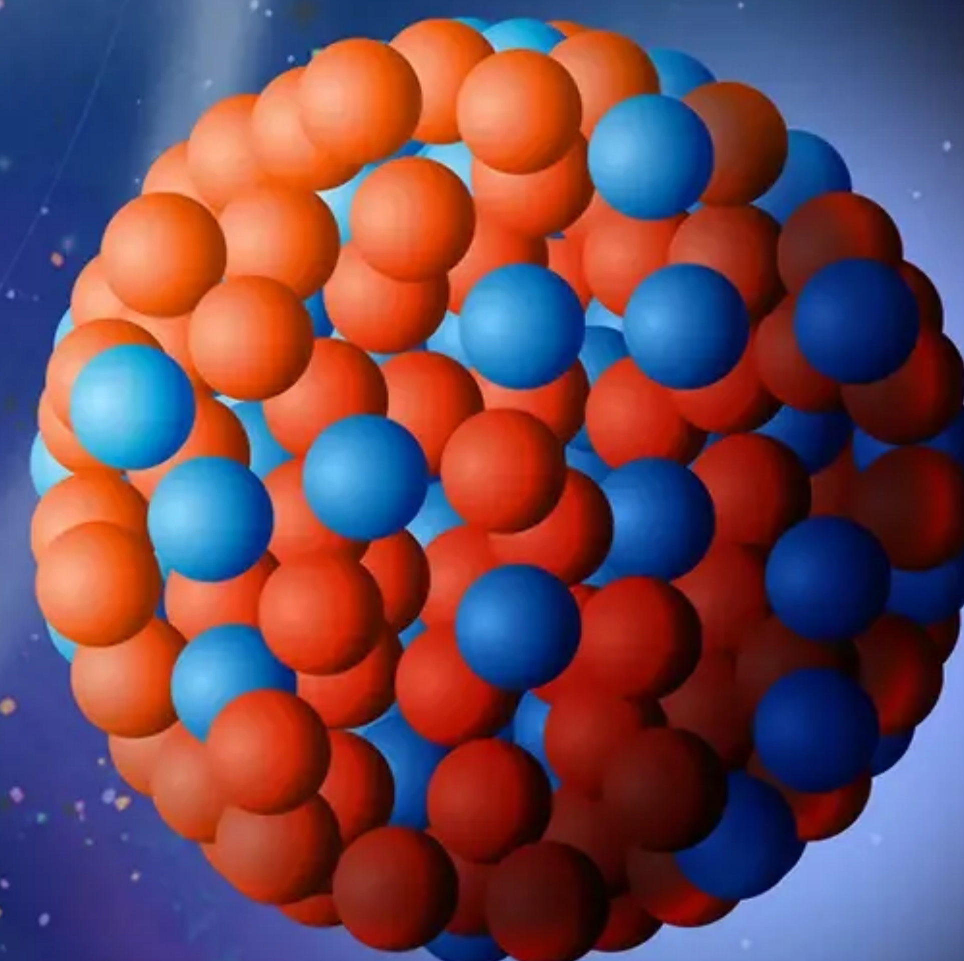
Niels Bohr Institute



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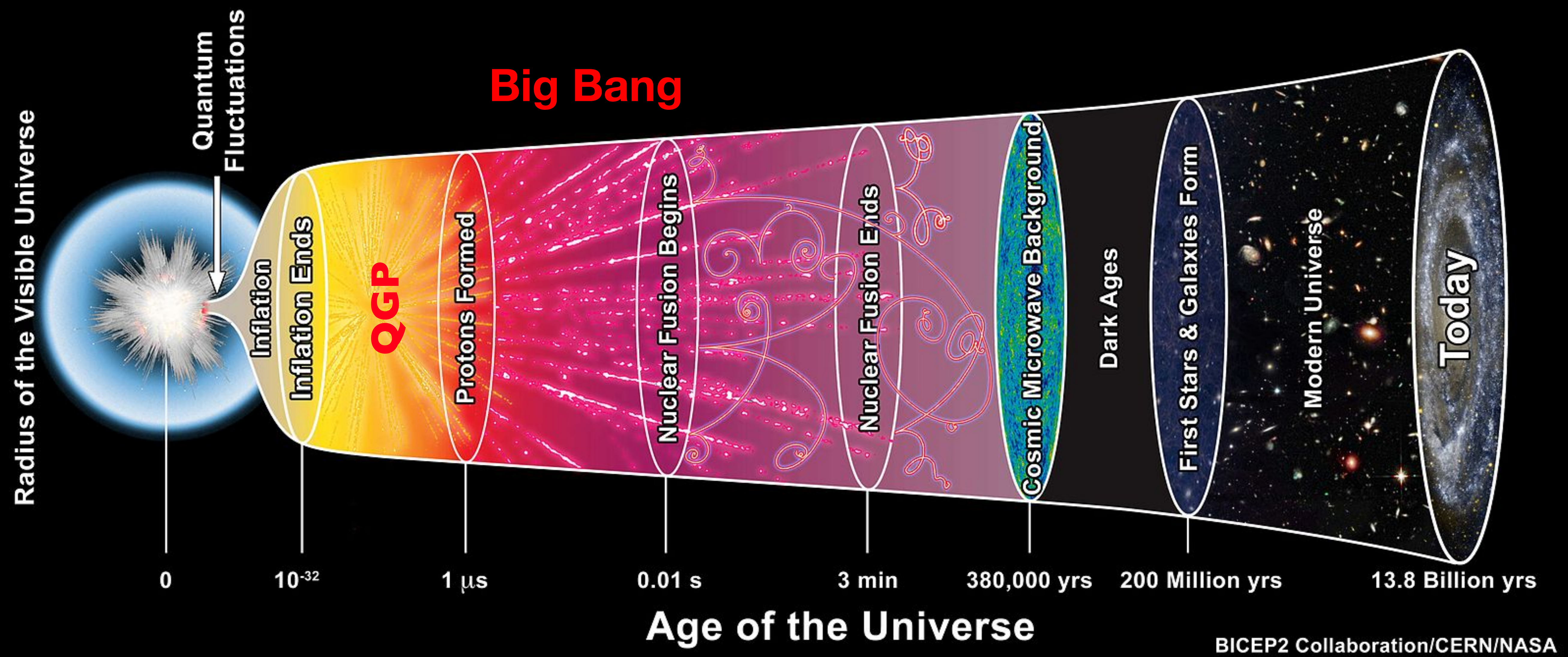
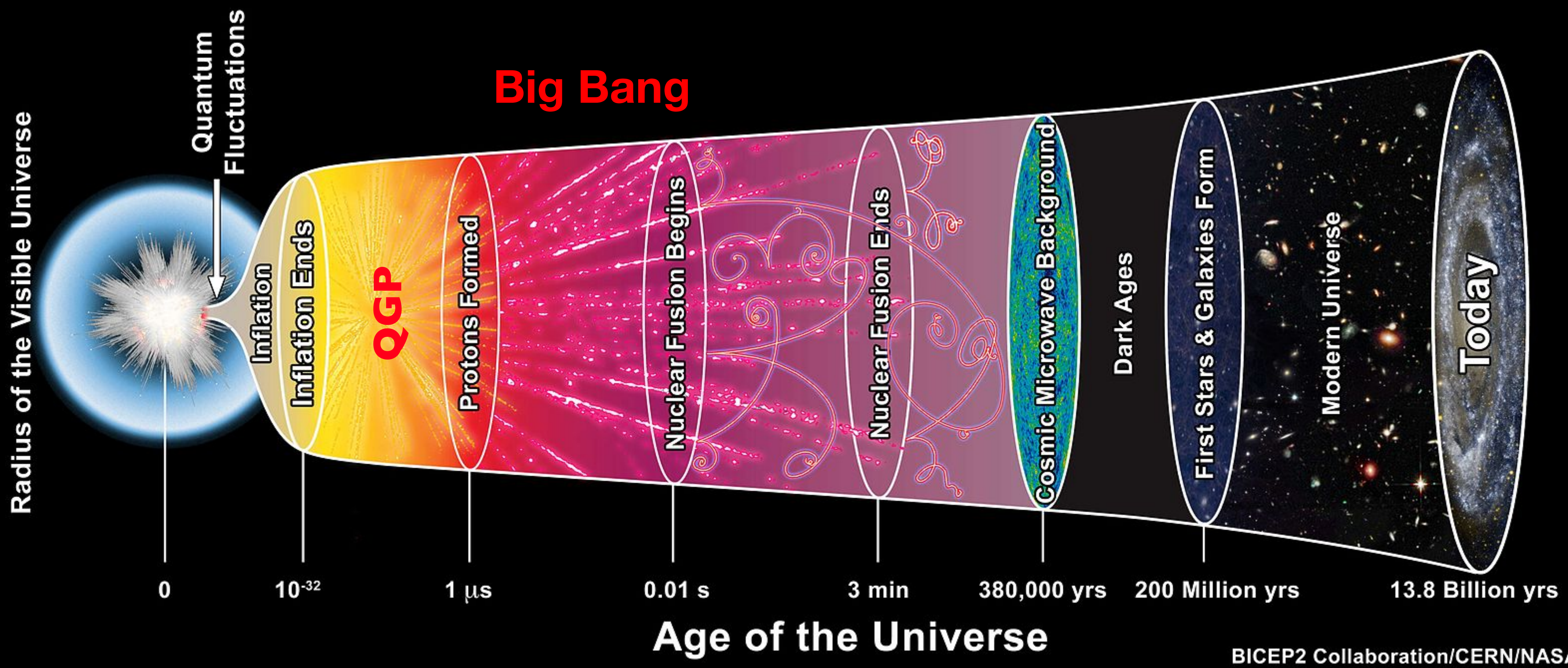
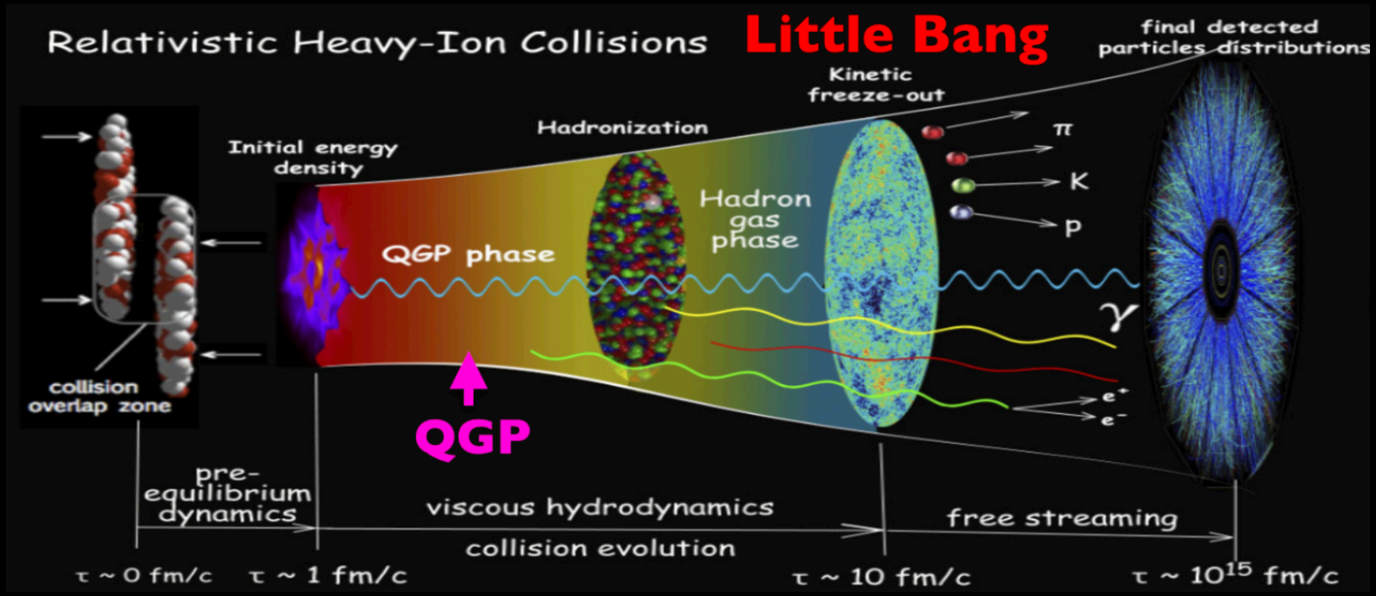


Big Bang
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
QGP
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10-32
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA

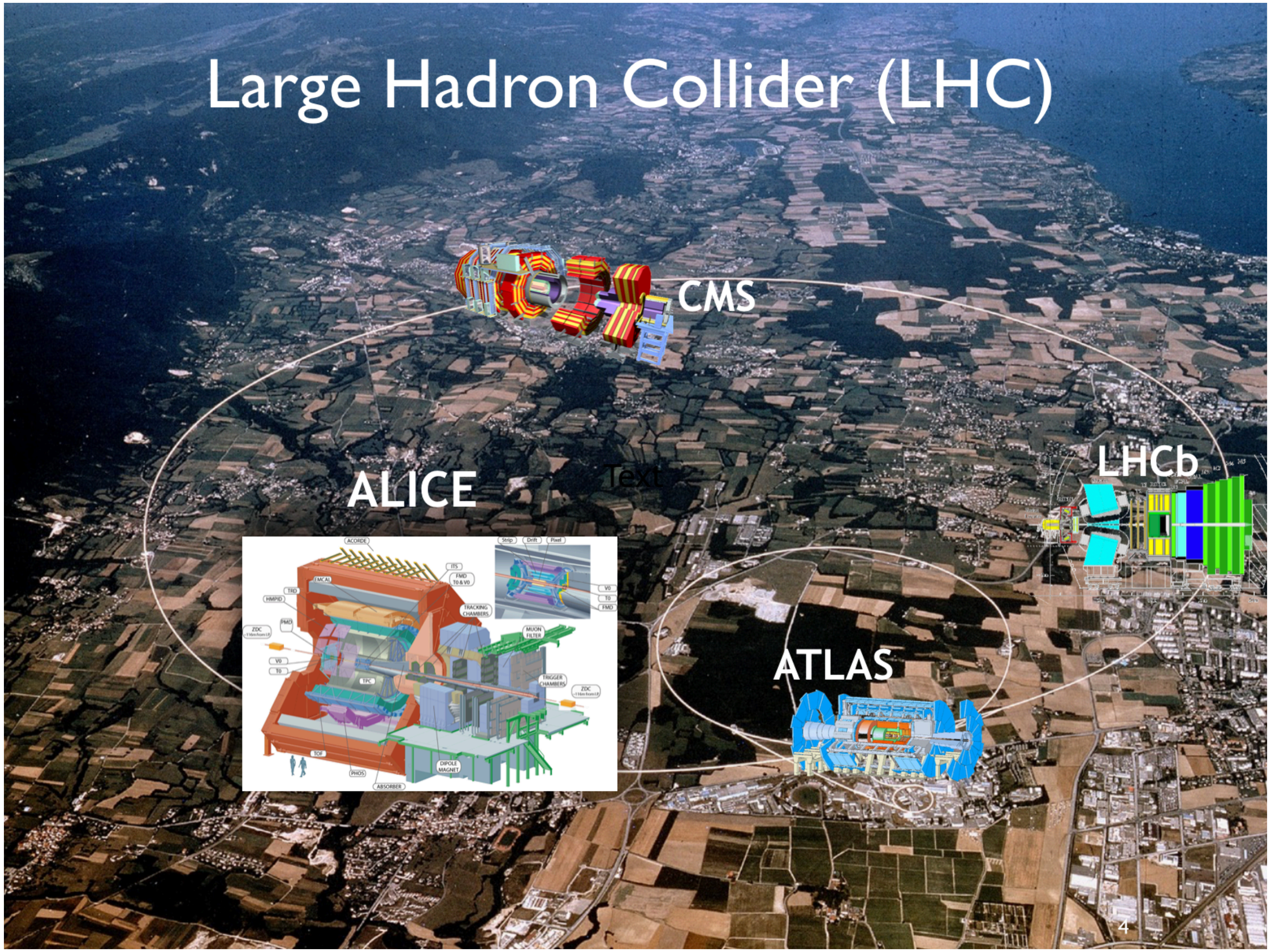


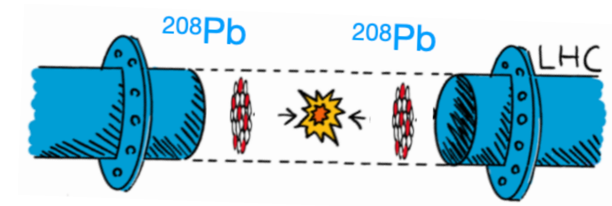


T~ 5.5 thousand billion Kelvin
(350,000 times hotter than sun's core)

Heavy-ion collisions at the LHC

Large Hadron Collider, CERN, Geneva





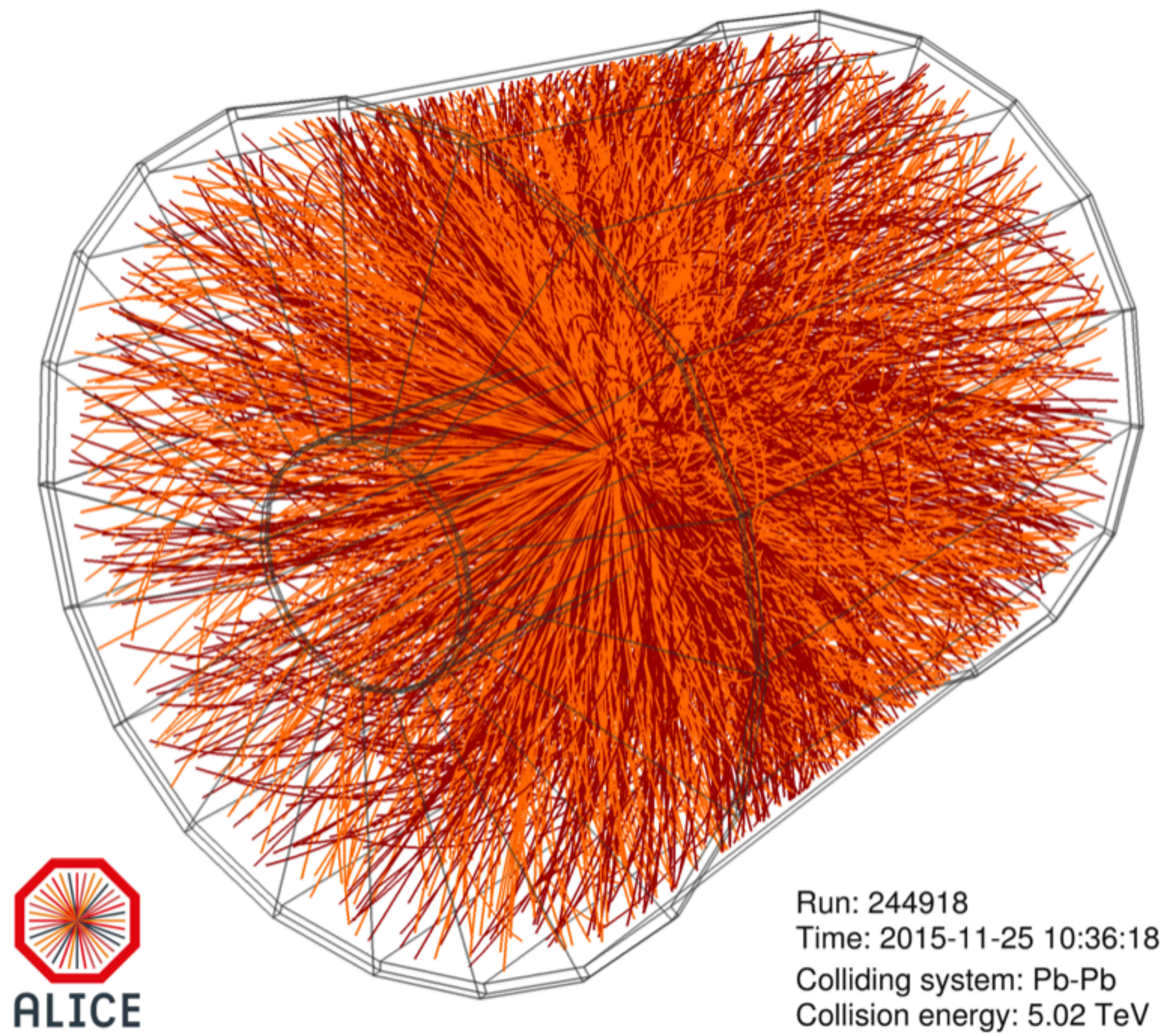
Pb-Pb 2.76 TeV

5.02 TeV

5.36 TeV

Xe-Xe 5.44 TeV

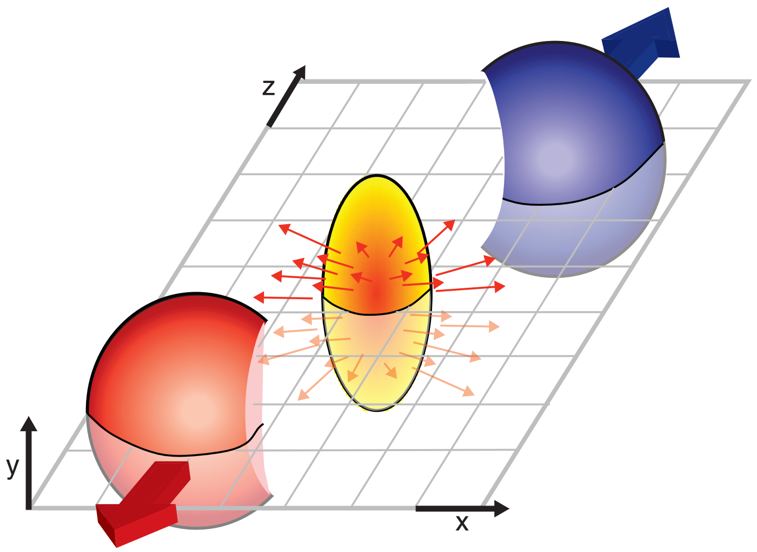
Heavy-ion collision



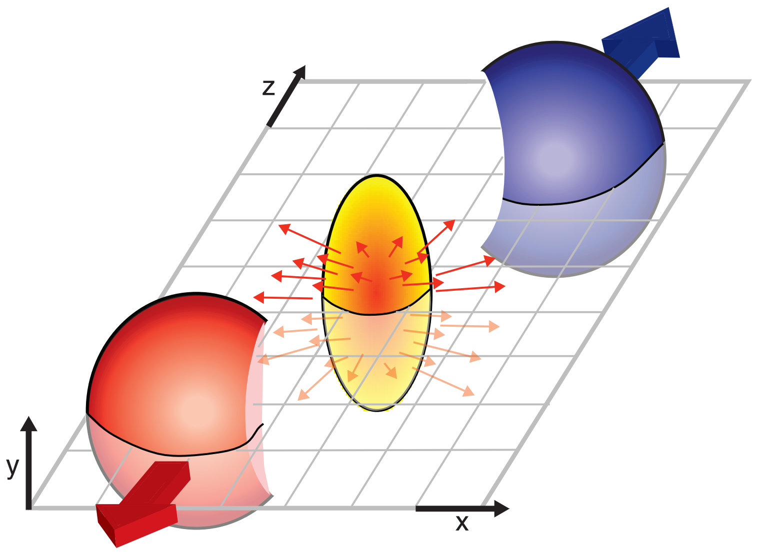
More than 35.000 particles produced in a single Lead-Lead collisions event

How can we study the QGP from this event?

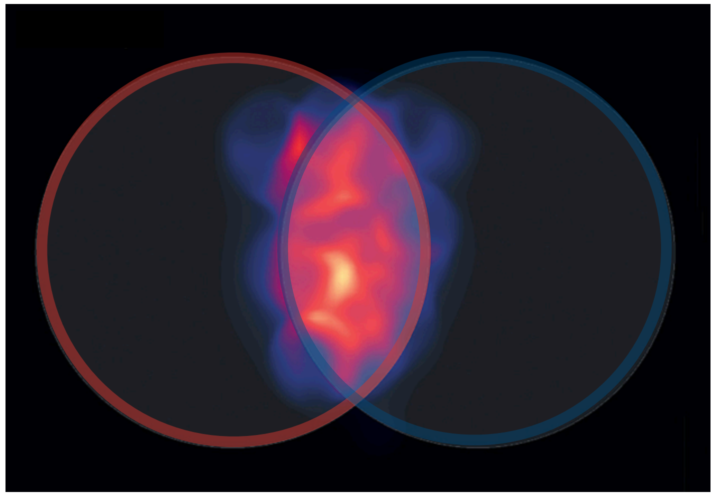
Anisotropic flow



Anisotropic flow

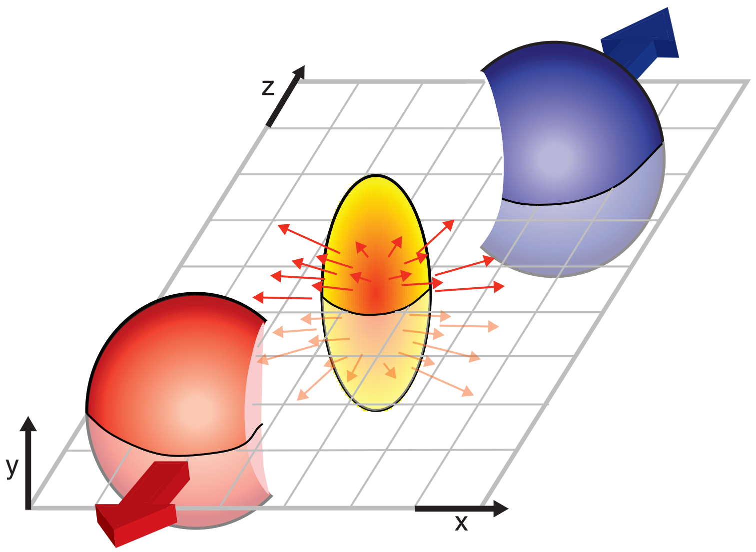


Initial state
(shortly after the collision)

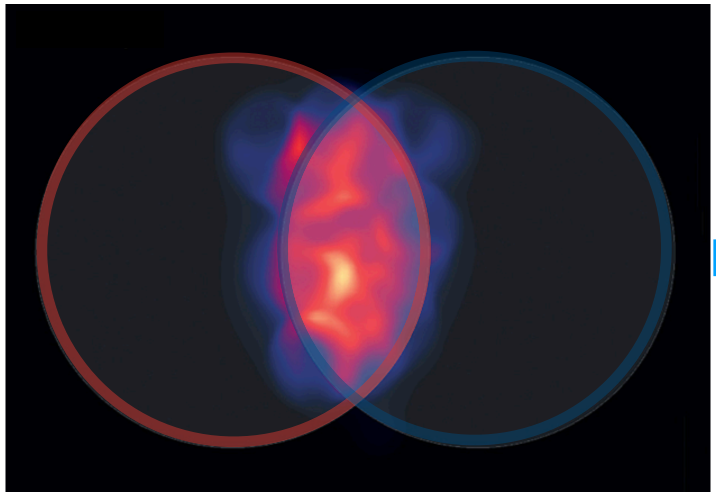


Initial Eccentricity

Anisotropic flow

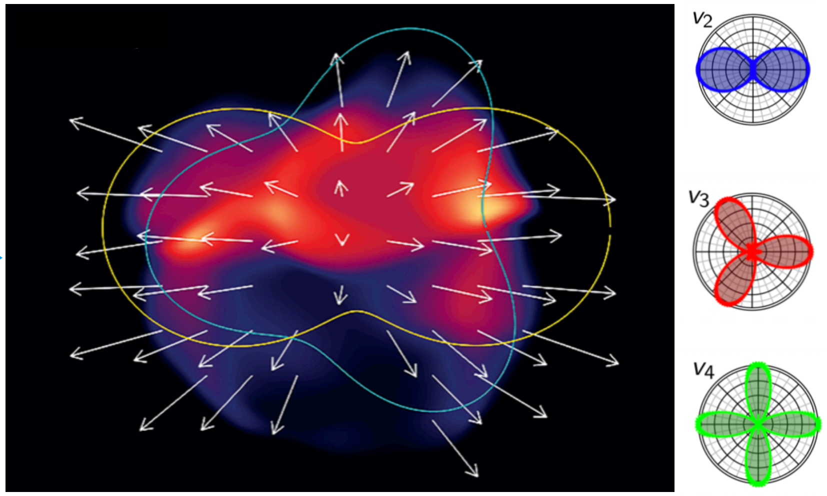


Initial state
(shortly after the collision)



Initial Eccentricity

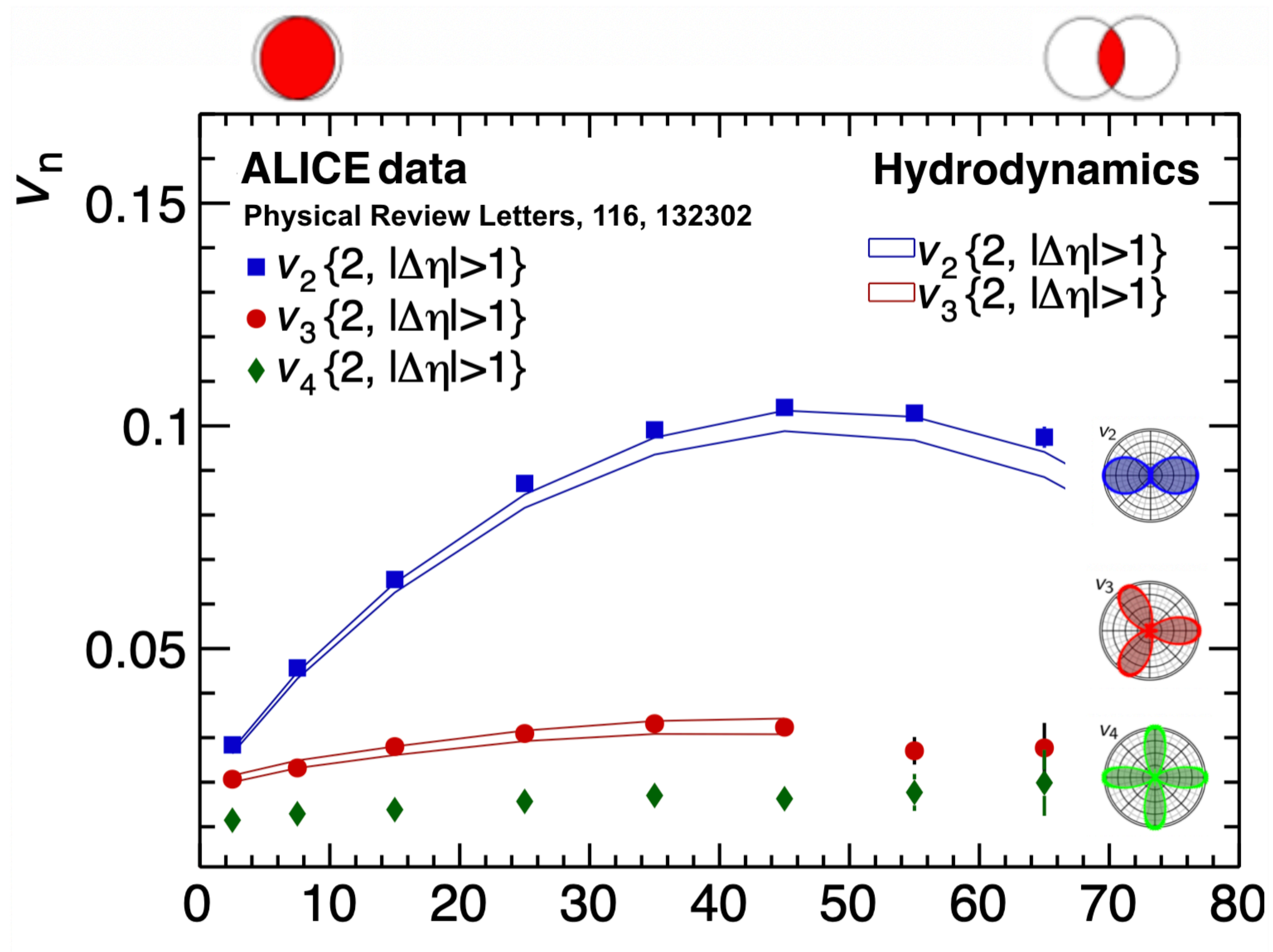
Final state
(what detector recorded)



Final state particle anisotropic expansions, **Anisotropic flow**

Early Universe is a **Fluid**

ALICE, Physical Review Letters 116, 132302 (2016)

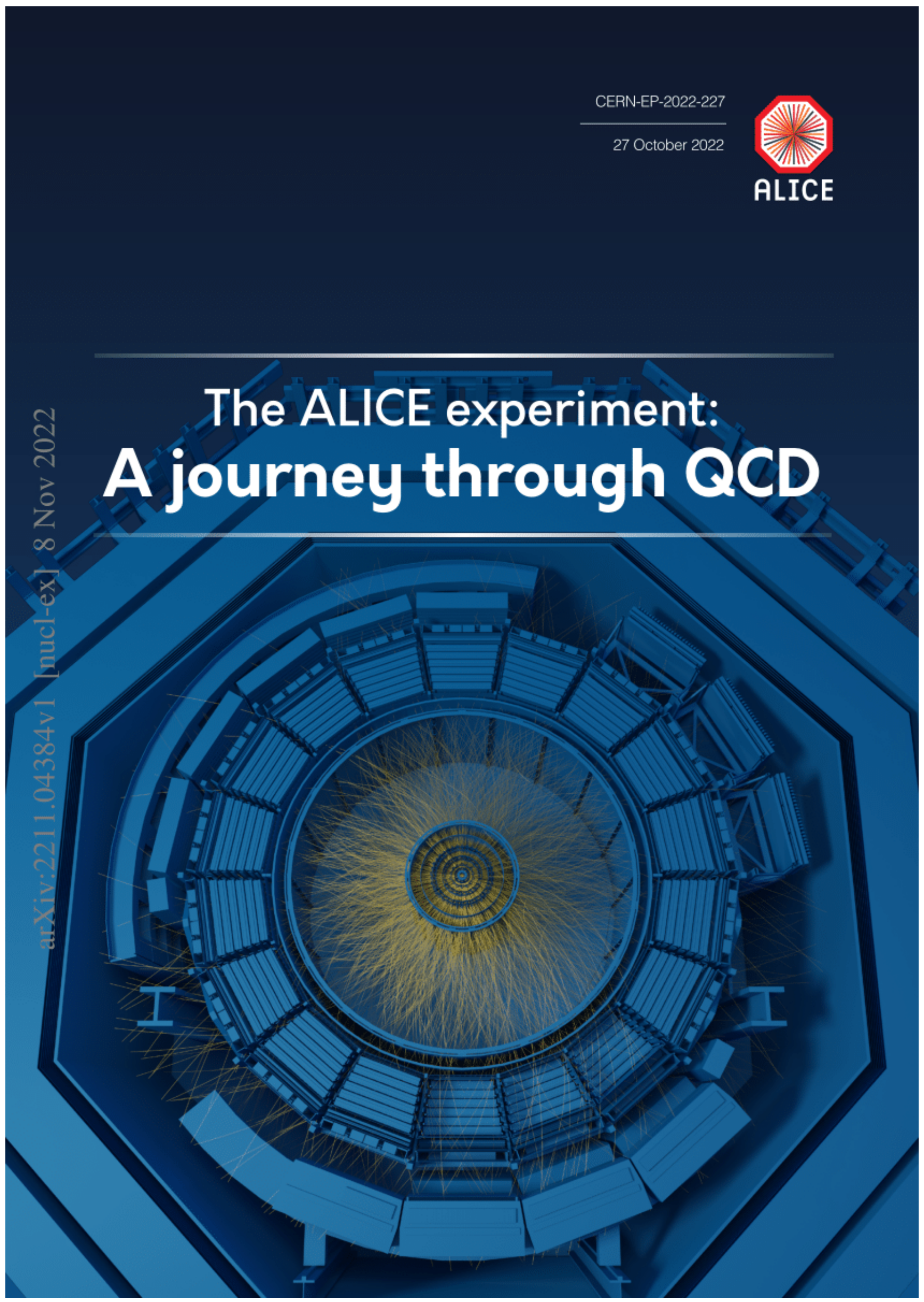


450+ citations

❖ Measurements agree with hydrodynamic predictions
- **The Quark-Gluon Plasma (Early Universe) behaves like a fluid**

Perfect fluid

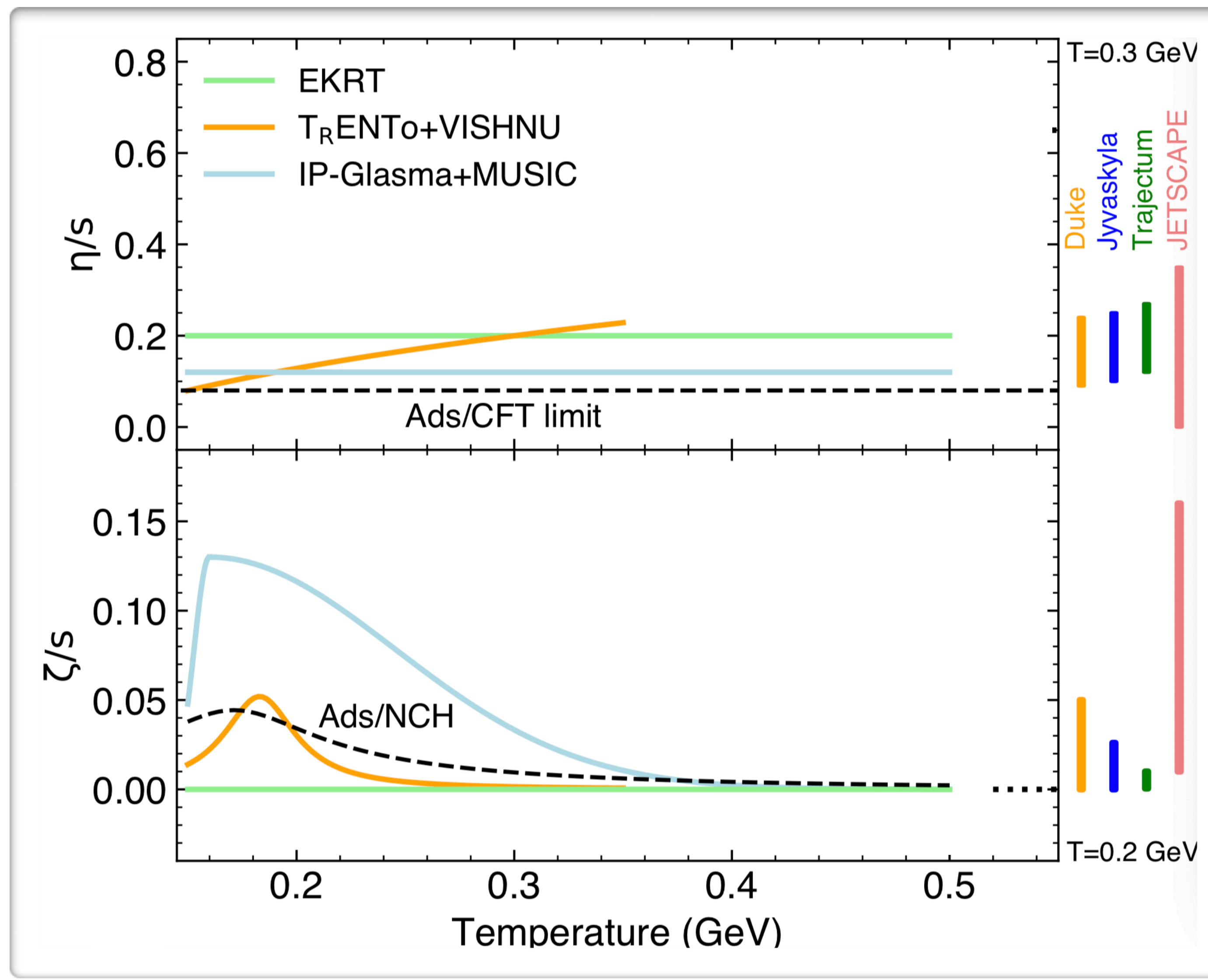
Eur. Phys. J. C 84 (2024) 813
200+ citations



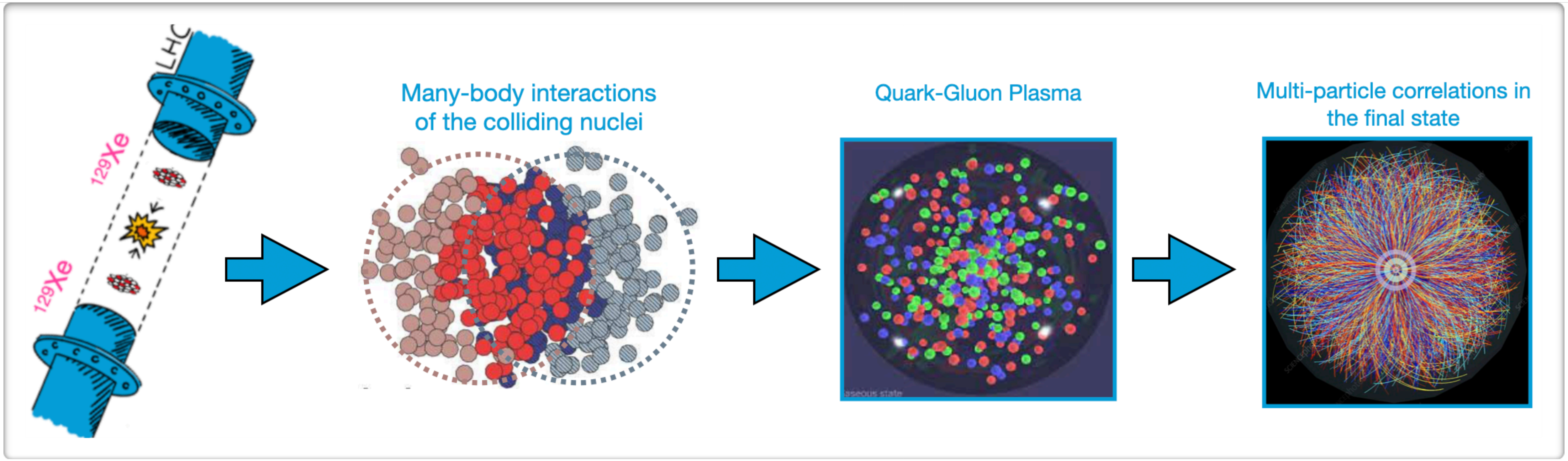
Extracted viscosities of QGP

- shear viscosity η/s
- bulk viscosity ζ/s

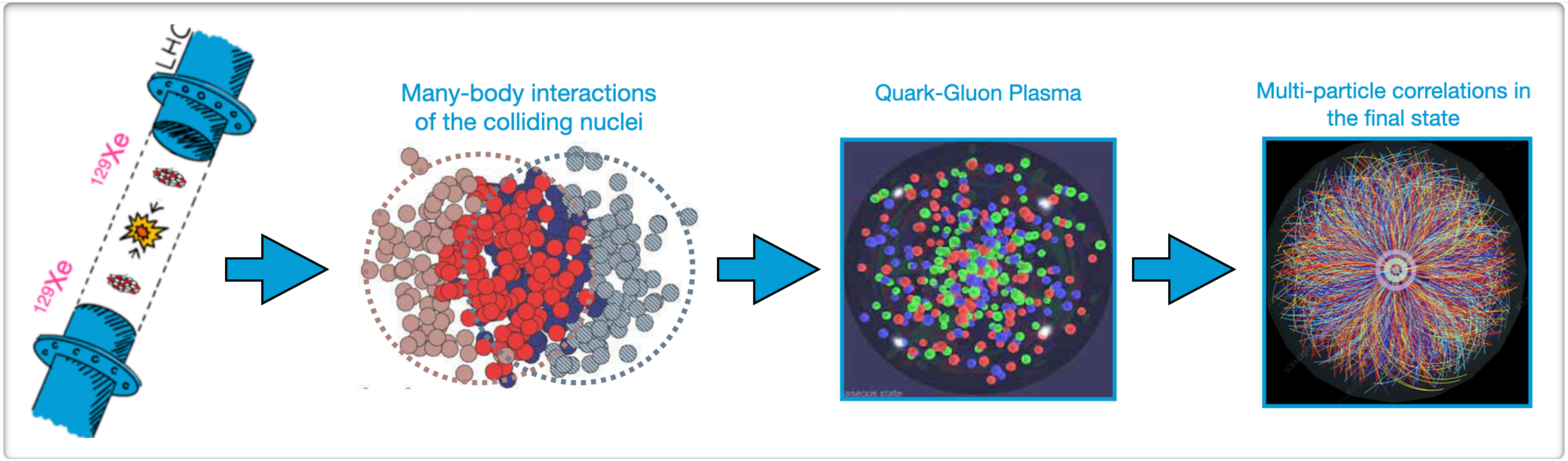
Duke: *Nature Phys.* 15 (2019) 11, 1113
Jyväskylä: *Phys. Rev. C 104, 054904 (2021)*
Trajectum: *Phys. Rev. Lett. 126, 202301 (2021)*
JETSCAPE: *Phys. Rev. Lett. 126, 242301 (2021)*
IP-Glasma: *Phys. Rev. Lett. 128, 042301 (2022)*

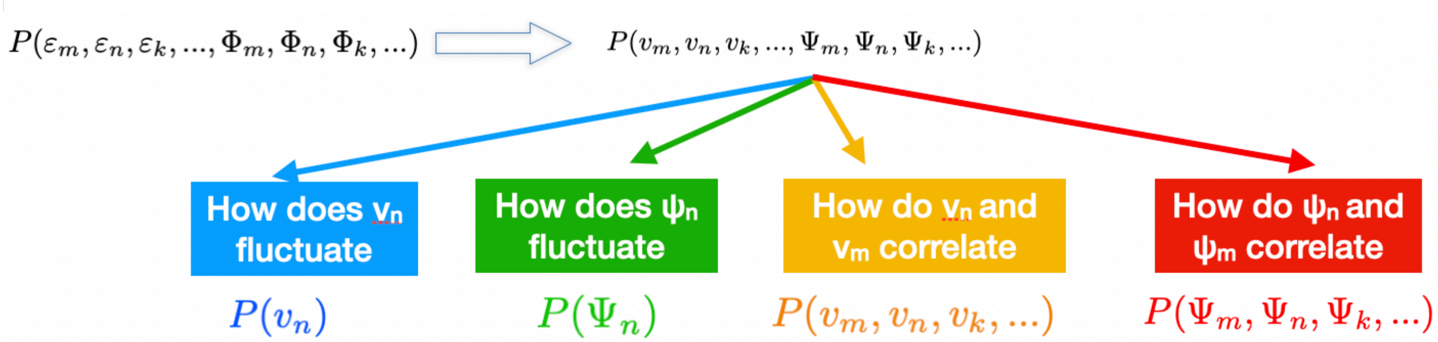


Imaging power of high energy nuclear collisions



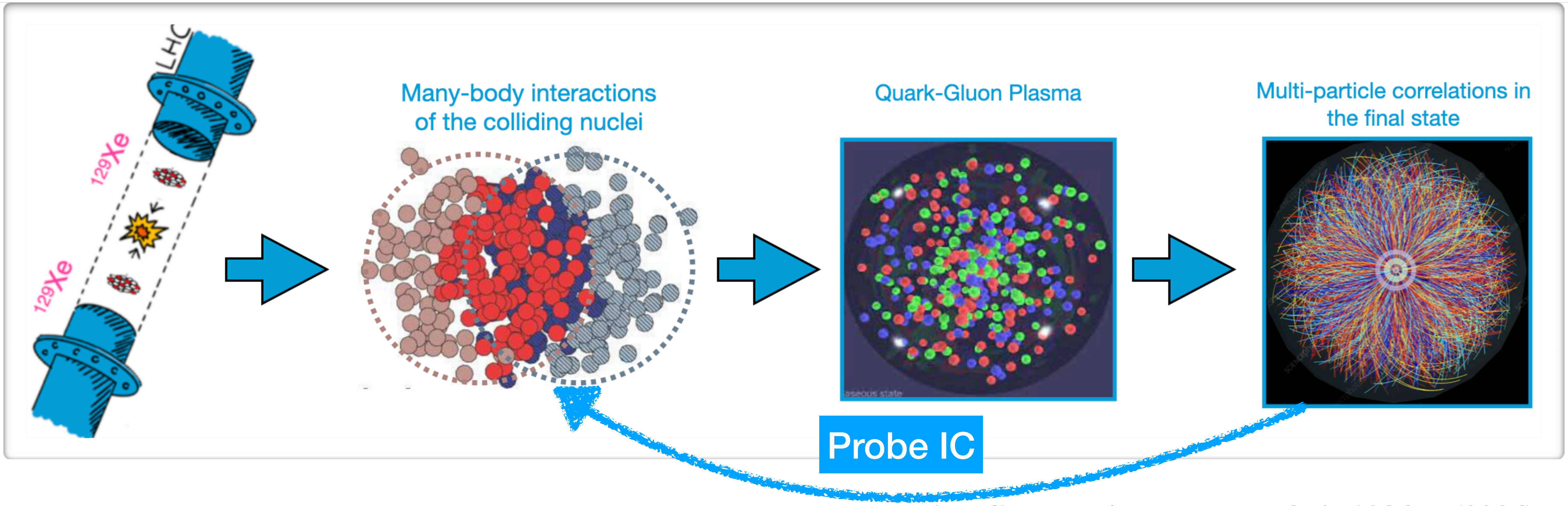
Imaging power of high energy nuclear collisions





ALICE, Physics Letters B 850, 138477 (2024)
ALICE, JHEP 05 (2023) 243
ALICE, Phys. Rev. C Letters, 107 (2023) 051901
ALICE, Physics Letters B 834, 137393 (2022)
ALICE, Physics Letters B 818, 136354 (2021)
ALICE, Phys. Rev. C 104, 024903 (2021)
ALICE, Phys. Rev. C 103, 024913 (2021)
ALICE, ALICE-PUBLIC-2021-004 (2021)
ALICE, JHEP 06, 147 (2020)
ALICE, JHEP 05, 085 (2020)
ALICE, Eur. Phys. J. C 80, 846 (2020)
ALICE, Physics Letters B784 (2018) 82
ALICE, Phys. Rev. C 97, 024906 (2018)
ALICE, JHEP07 (2018) 103

Imaging power of high energy nuclear collisions



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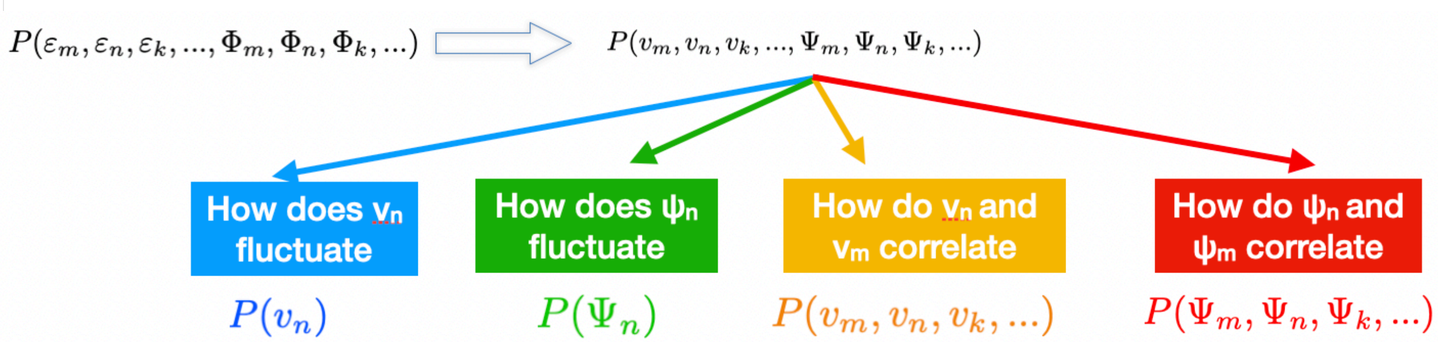

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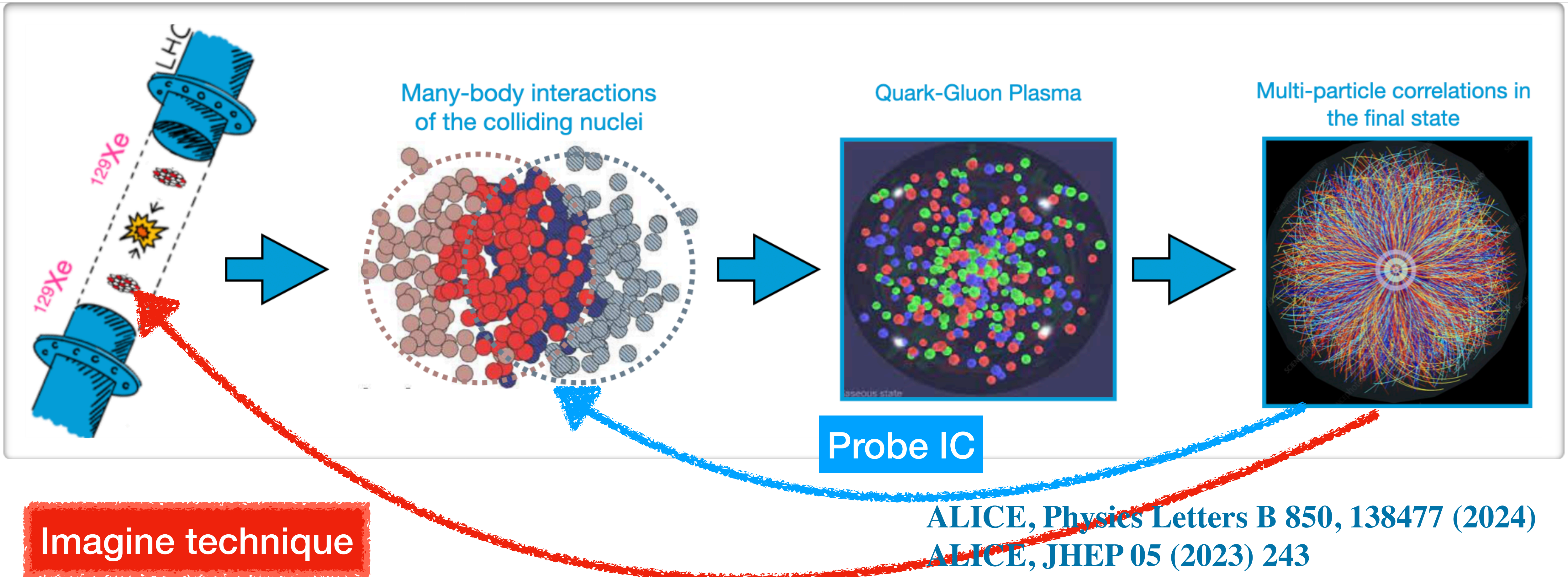

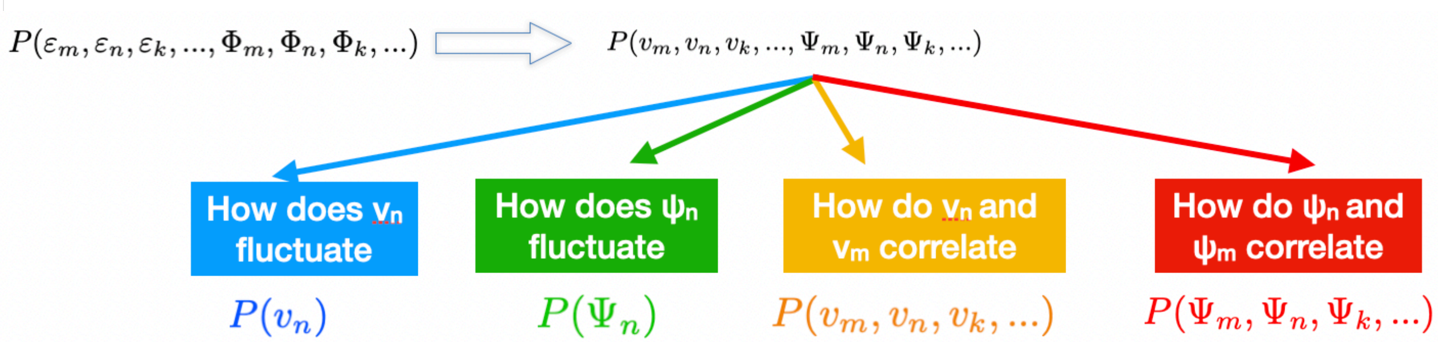

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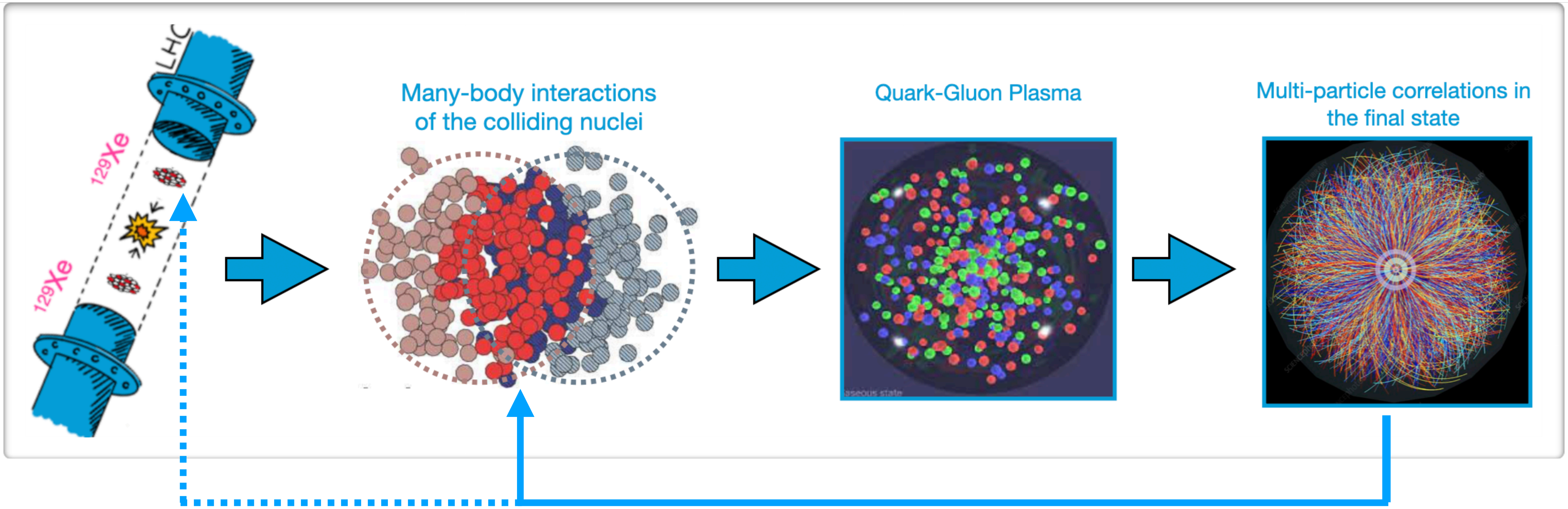
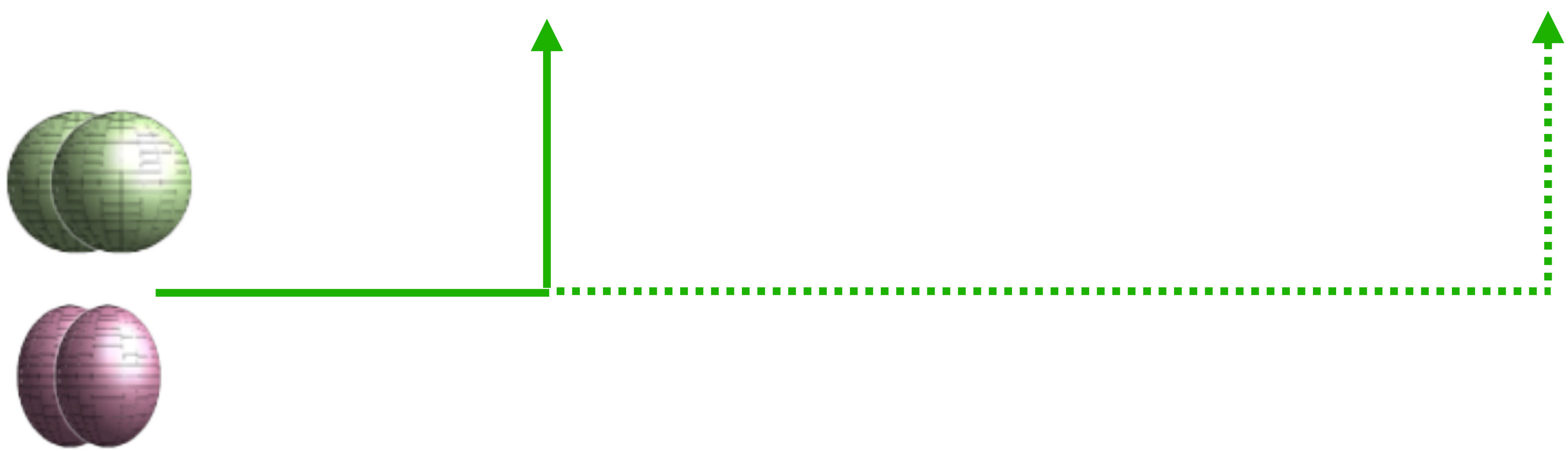
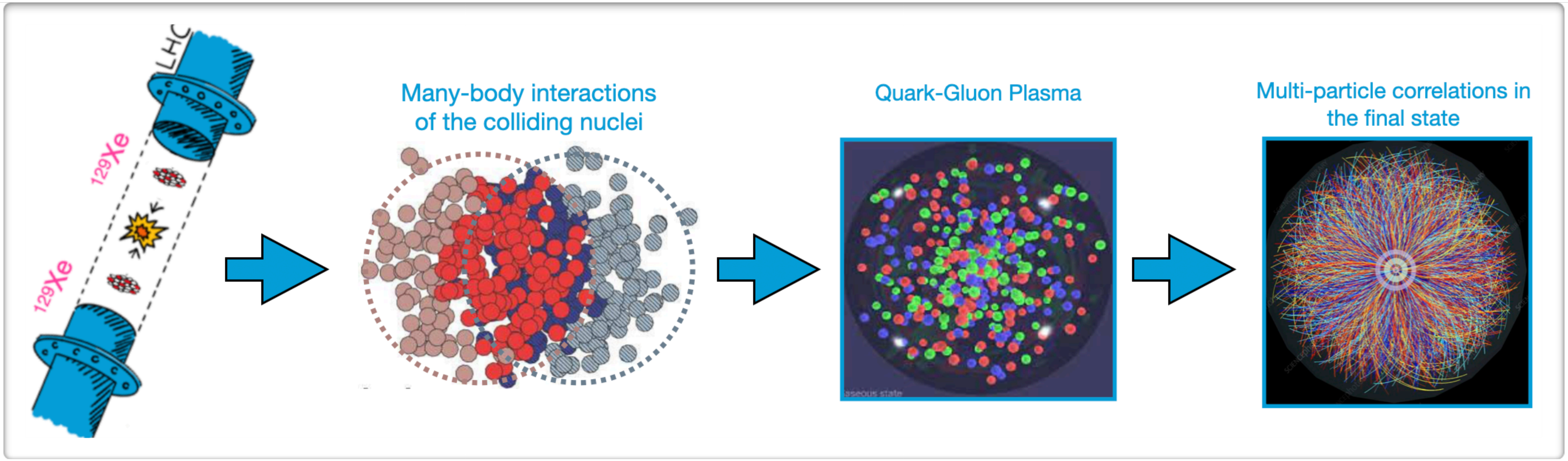
ALICE, JHEP07 (2018) 103

Nuclear structure at high energies





Nuclear structure at high energies



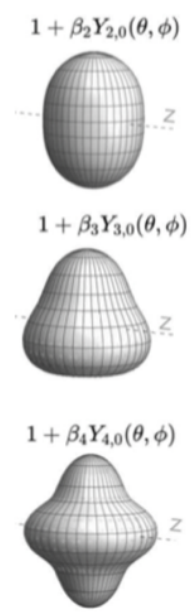
$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

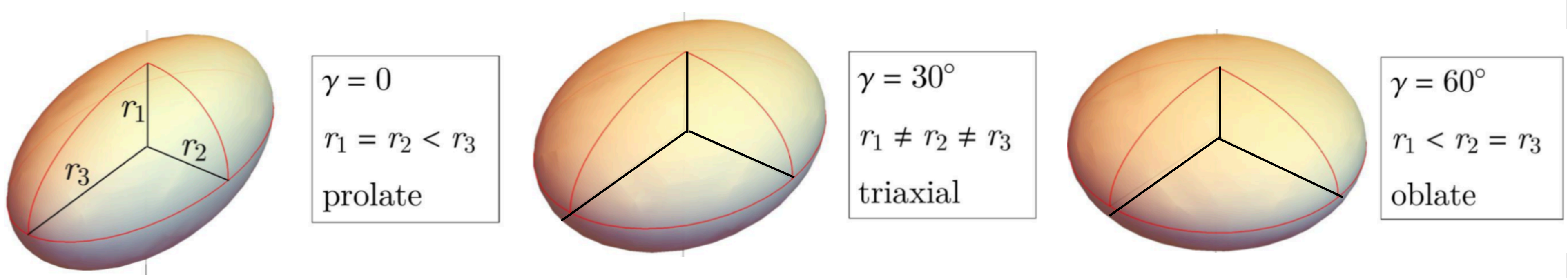
$$R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3\sum_{m=-3}^{3}\alpha_{3,m}Y_{3,m}+\beta_4\sum_{m=-4}^{4}\alpha_{4,m}Y_{4,m}\right)$$

Quadrupole:

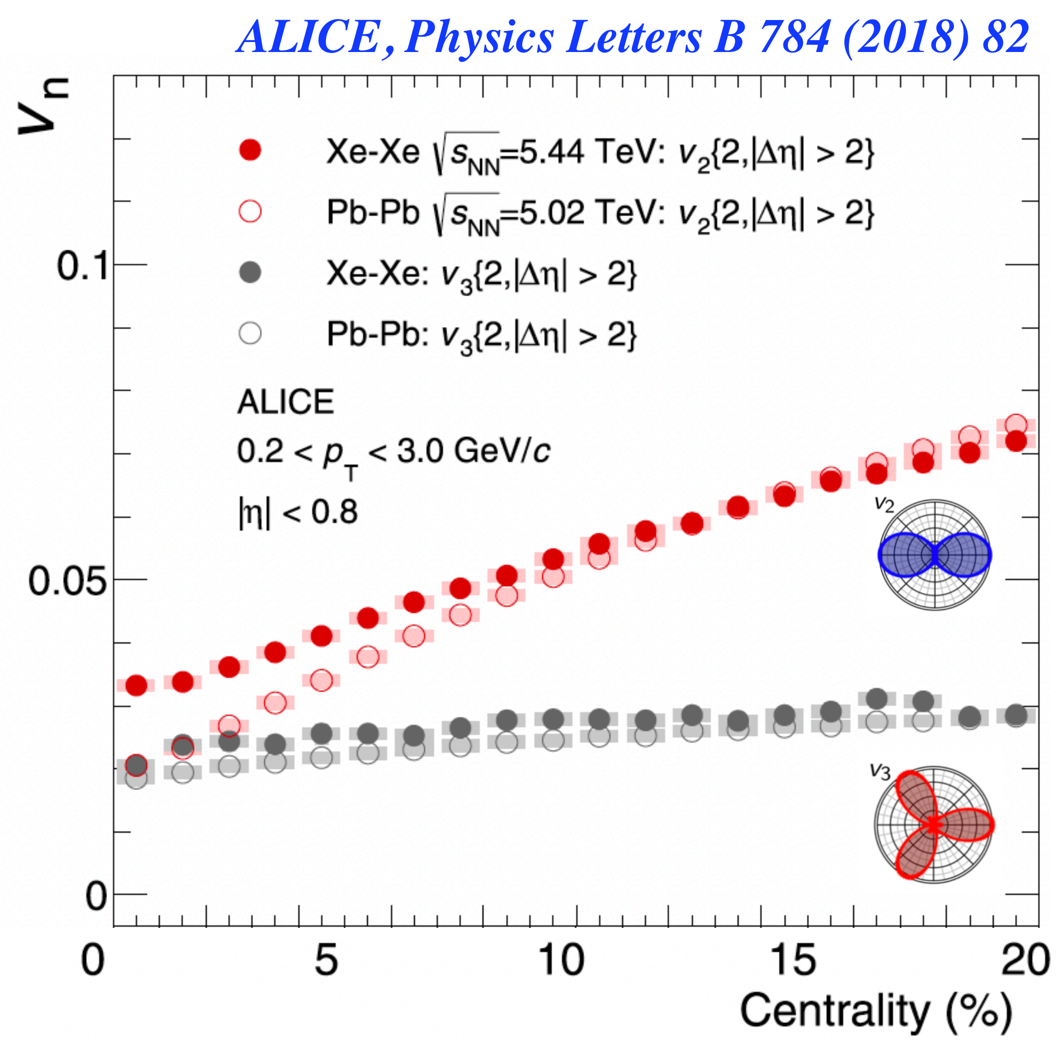
Octupole:

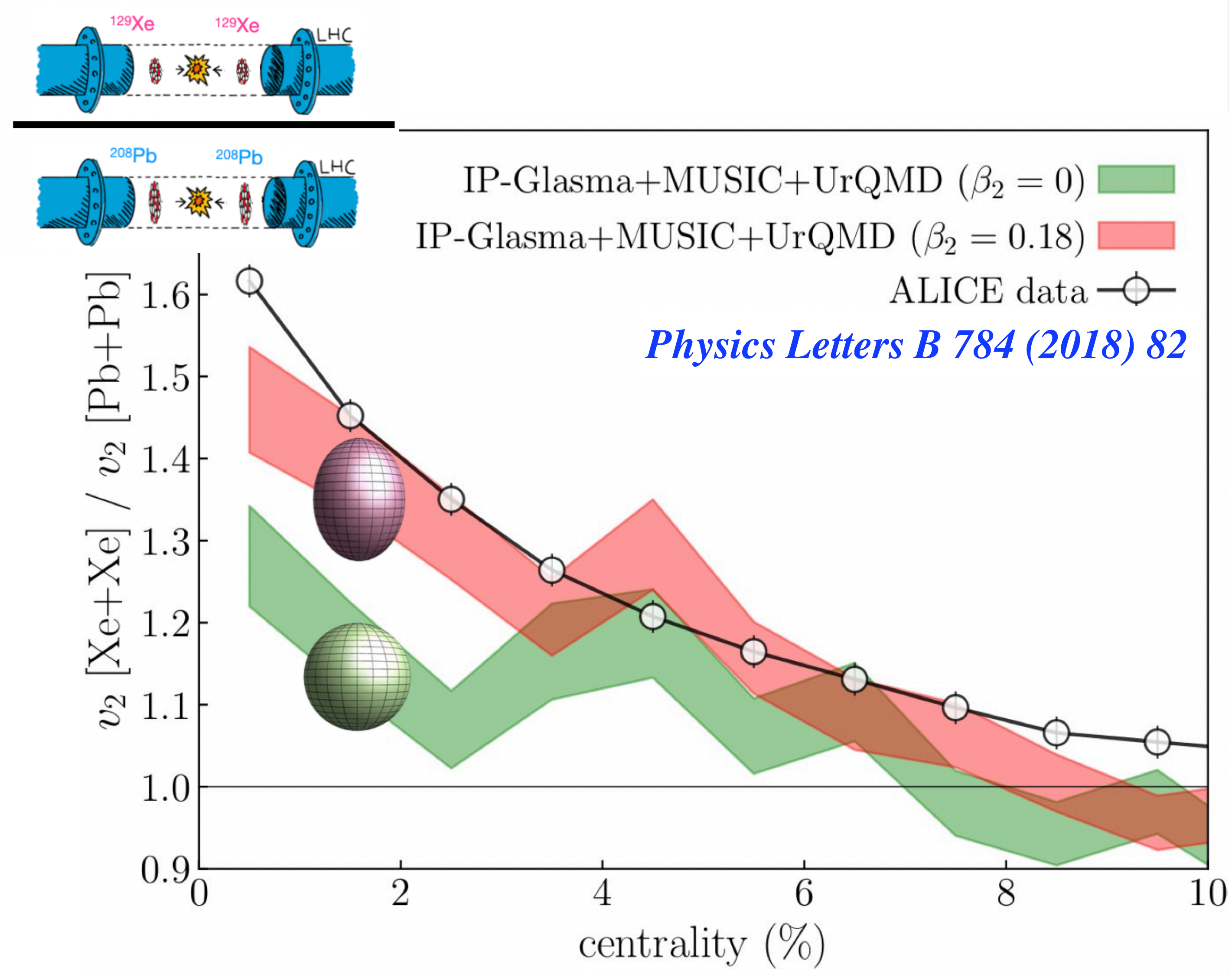
Hexadecapole:





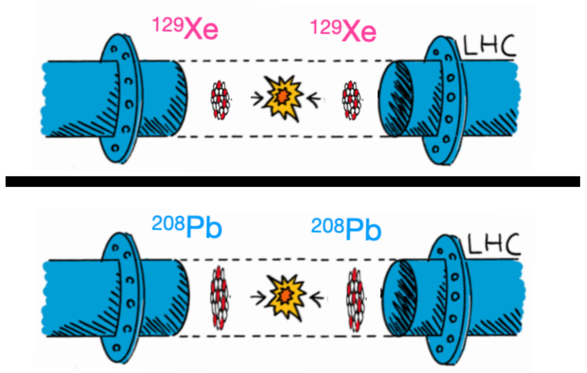
Nuclear structure of ^{129}Xe with flow v_n

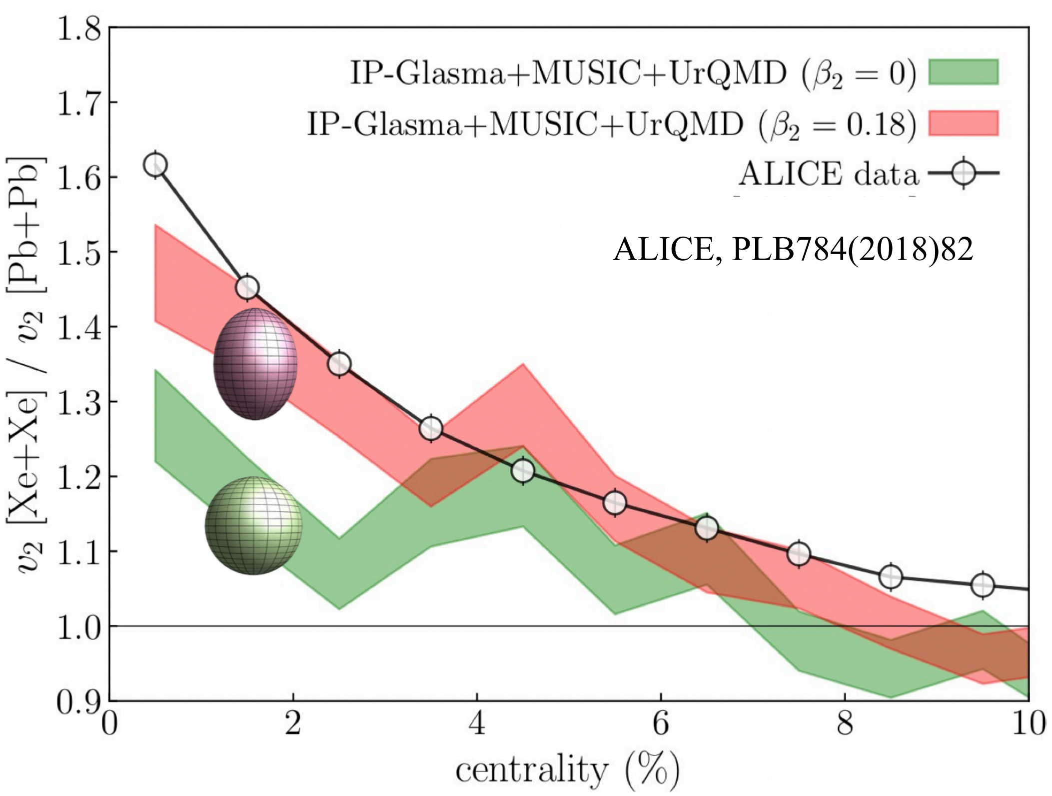


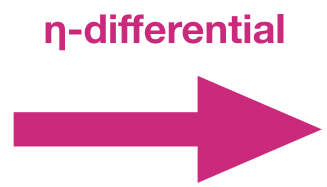


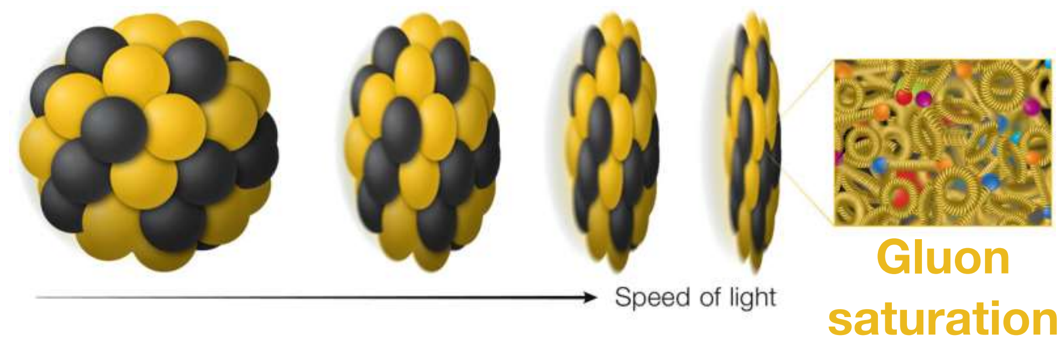
❖ Significant v_2 enhancements in central Xe-Xe collisions, originated from large deformation

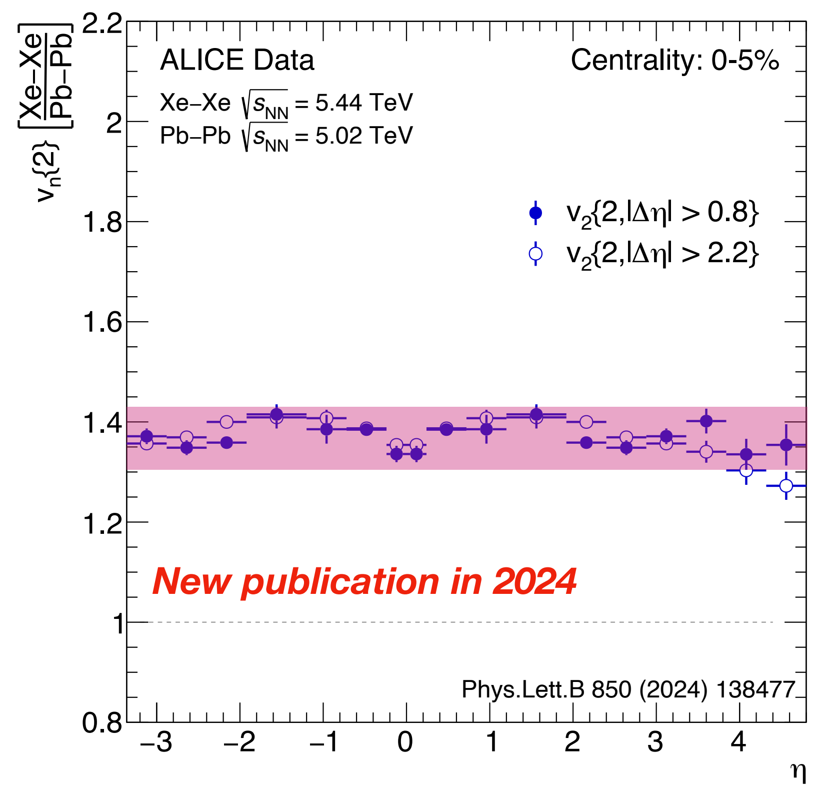
Nuclear structure at low-x physics

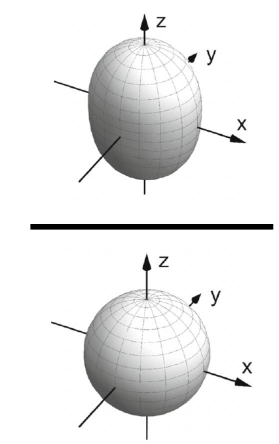












- ❖ For the first time observe the impact of NS over a very wide pseudorapidity range (-3.5 < η < 5.0)
  - New input for the low-x physics

Nuclear structure of ^{129}Xe with detailed studies

ALICE, submitted to *Phys. Lett. B*

arXiv > nucl-ex > arXiv:2409.04343

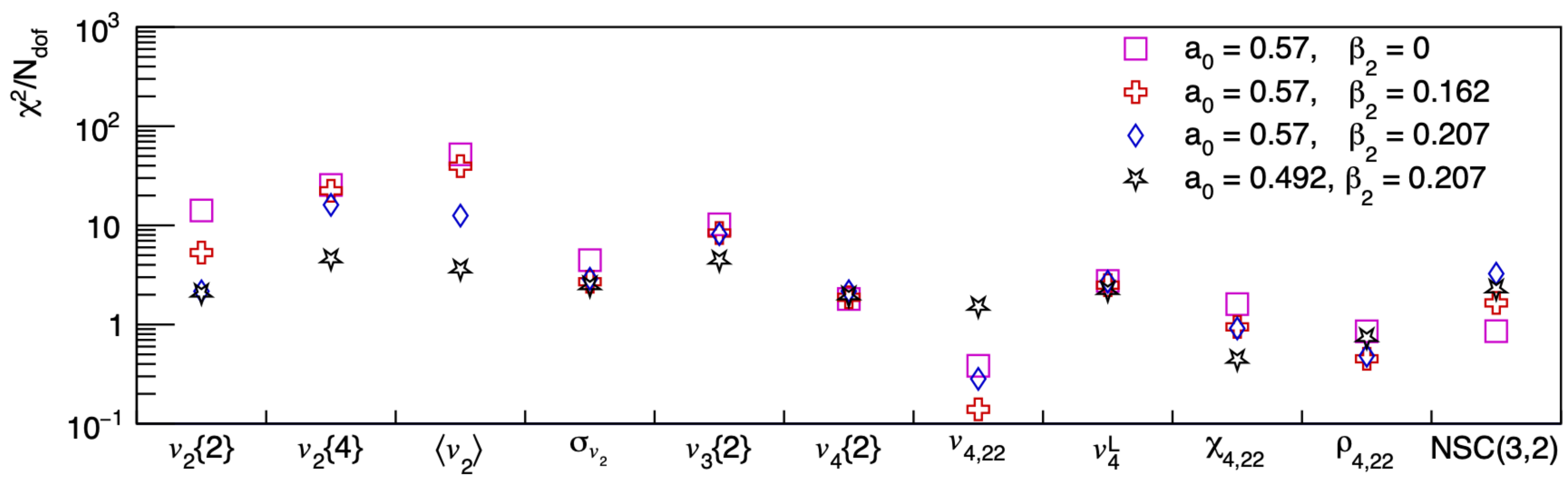
Nuclear Experiment

[Submitted on 6 Sep 2024]

Exploring nuclear structure with multiparticle azimuthal correlations at the LHC

ALICE Collaboration

Understanding nuclear structure provides essential insights into the properties of atomic nuclei. In this paper, details of the nuclear structure of ^{129}Xe, such as the quadrupole deformation and the nuclear diffuseness, are studied by extensive measurements of anisotropic-flow-related observables in Xe−Xe collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.44$ TeV with the ALICE detector at the LHC. The results are compared with those from Pb−Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for a baseline, given that the ^{208}Pb nucleus is not deformed. Furthermore, comprehensive comparisons are performed with a state-of-the-art hybrid model using IP-Glasma+MUSIC+UrQMD. It is found that among various IP-Glasma+MUSIC+UrQMD calculations with different values of nuclear parameters, the one using a nuclear diffuseness parameter of $a_0 = 0.492$ and a nuclear quadrupole deformation parameter of $\beta_2 = 0.207$ provides a better description of the presented flow measurements. These studies represent an important step towards a thorough exploration of the imaging power of nuclear collisions at ultrarelativistic energy and the search for the imprint of nuclear structure on various flow observables in heavy-ion collisions at the LHC. The findings demonstrate the potential of nuclear structure studies at the TeV energy scale and highlight that the LHC experiments can complement existing low-energy experiments on nuclear structure studies.



❖ Systematic studies show that the extracted nuclear structure parameters at the LHC (TeV energy scale) agree with low-energy nuclear structure study (MeV energy scale).

Probe triaxial structure of ^{129}Xe

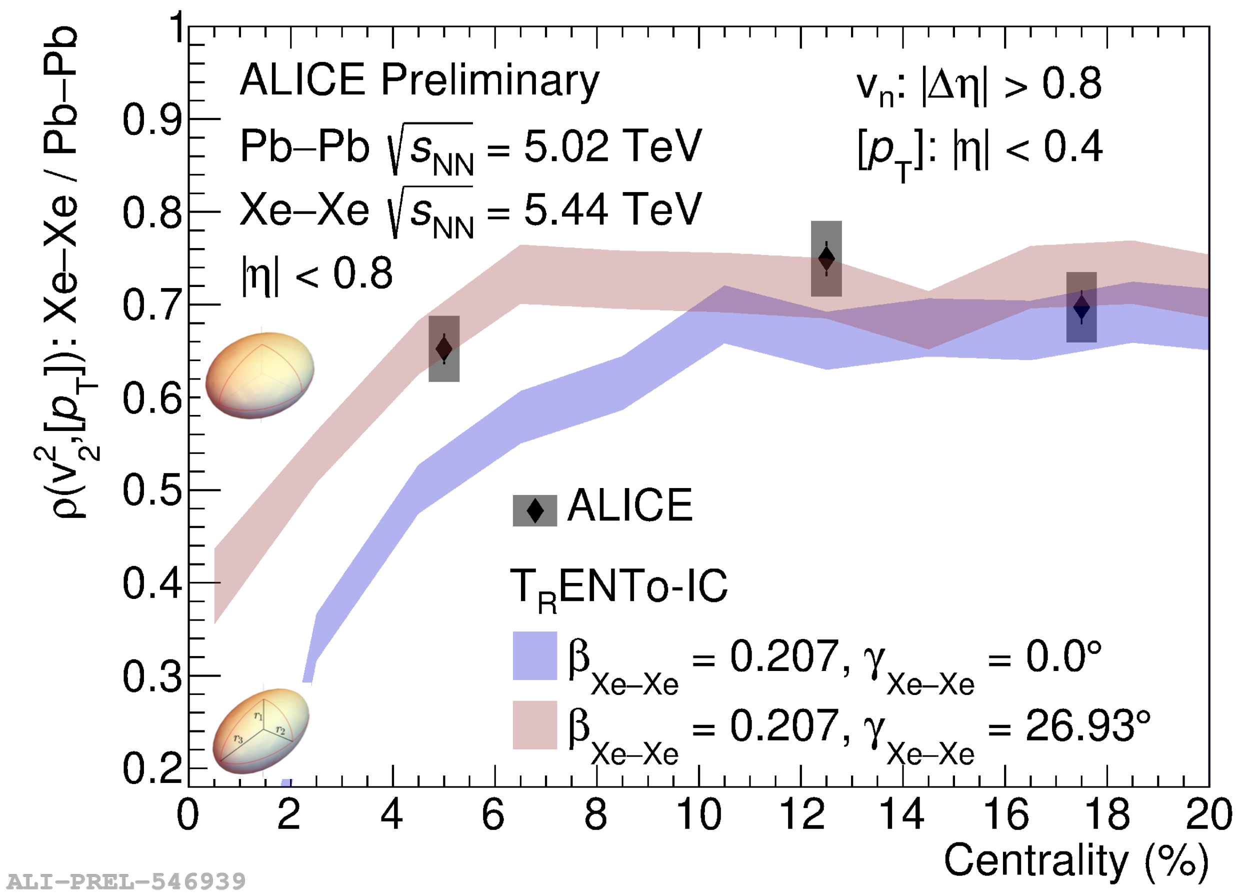
❖ **Shape** of the fireball: Anisotropic flow

❖ **Size** of the fireball: radial flow, $[p_T]$

❖ Final state: correlation between v_n and p_T

$$\rho(v_n^2, [p_T]) = \frac{cov(v_n^2, [p_T])}{\sqrt{var(v_n^2)}\sqrt{var([p_T])}}$$

P. Bozek etc, PRC96 (2017) 014904

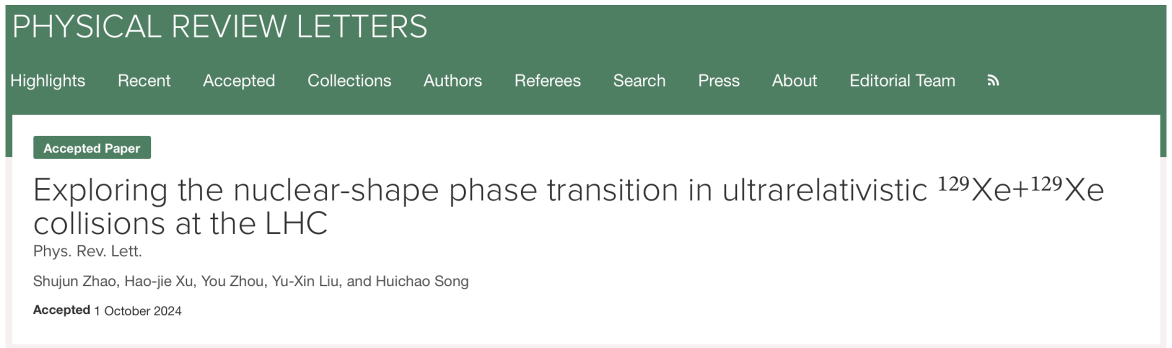


❖ Better agreement between LHC data and calculations with γ = 26.93°

- First study of triaxial structure of ^{129}Xe at high energy collisions at the LHC
- Similar results confirmed by ATLAS
- ***Evidence of triaxial structure of ^{129}Xe?*** B. Bally etc, PRL128 (2022) 8, 082301

Probe γ-soft structure of ^{129}Xe

arXiv:2403.07441, accepted by PRL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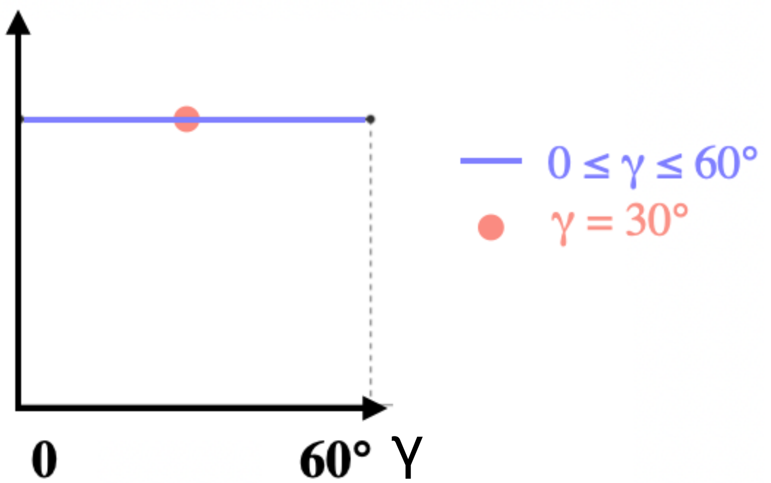
Accepted Paper

Exploring the nuclear-shape phase transition in ultrarelativistic ^{129}Xe+^{129}Xe collisions at the LHC

Phys. Rev. Lett.

Shujun Zhao, Hao-jie Xu, You Zhou, Yu-Xin Liu, and Huichao Song

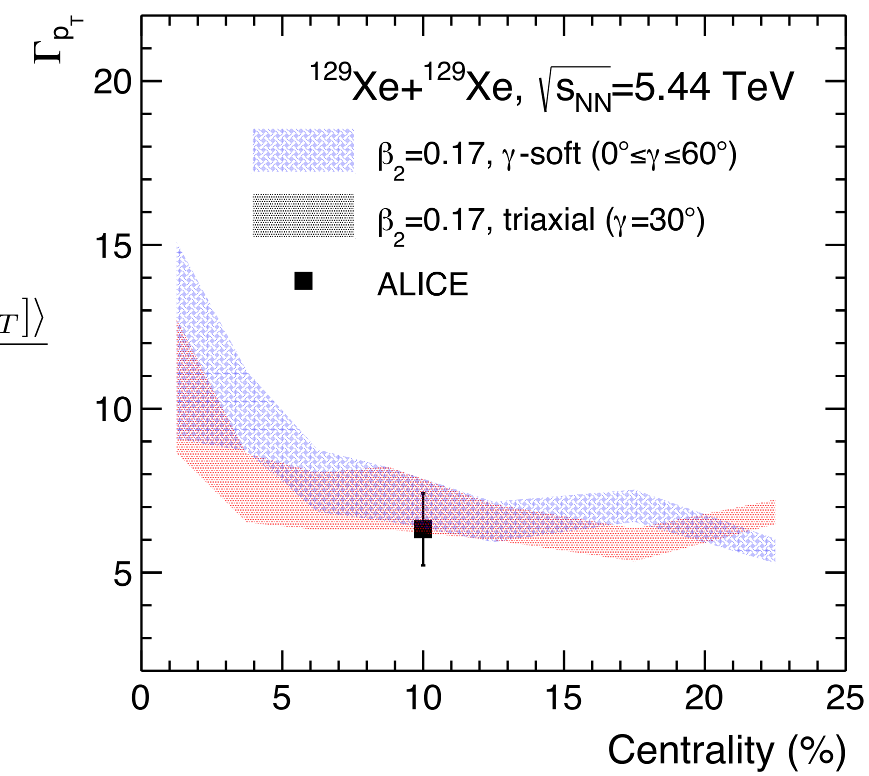
Accepted 1 October 2024



Size fluctuation

3-particle [p_T] correlation

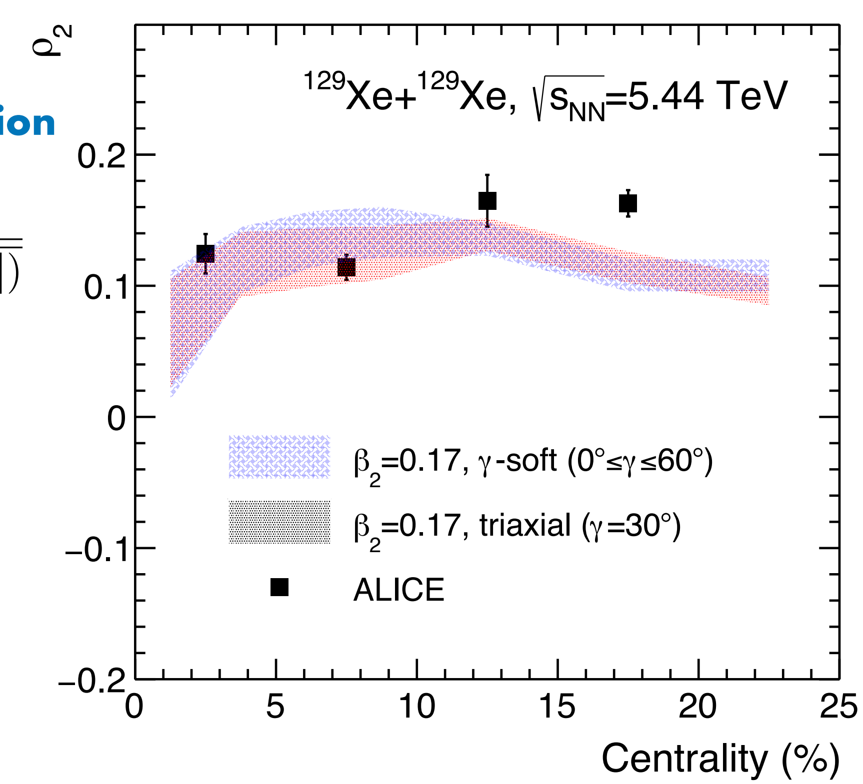
$$\Gamma_{p_T} = \frac{\langle \delta p_{T,i} \delta p_{T,j} \delta p_{T,k} \rangle \langle [p_T] \rangle}{\langle \delta p_{T,i} \delta p_{T,j} \rangle^2}$$



Shape-size correlations

3-particle v_n^2 — [p_T] correlation

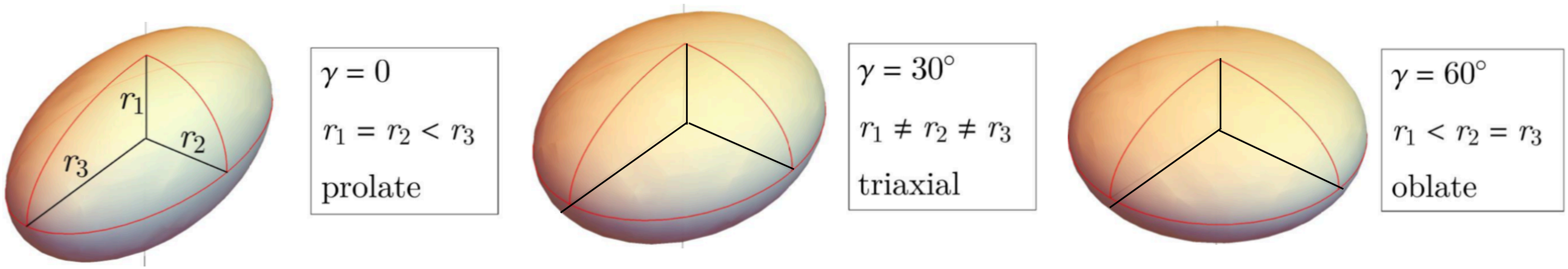
$$\rho_2 \equiv \frac{\mathrm{cov}(v_2\{2\}^2, [p_T])}{\sqrt{\mathrm{var}(v_2\{2\}^2)}\sqrt{\mathrm{var}([p_T])}}$$



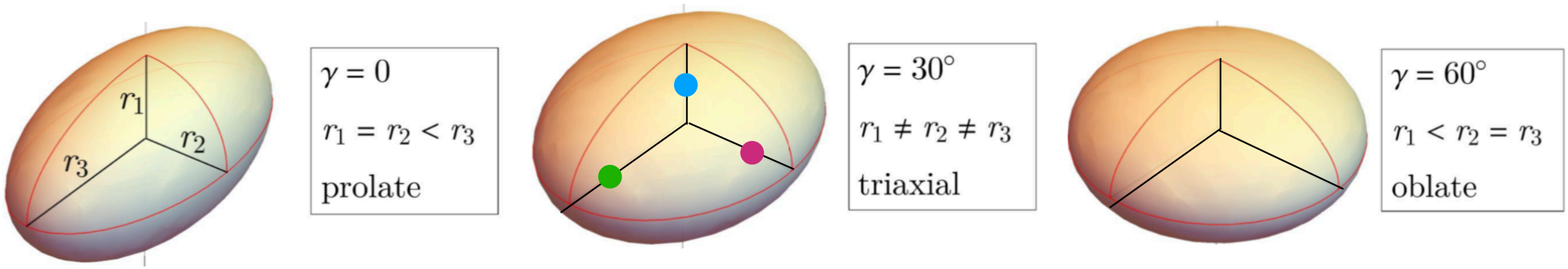
❖ For the fixed γ and γ-soft, the ρ_2 and Γ_{pt} are identical

- One can ***NOT*** distinguish triaxial (fixed γ = 30°) and γ-soft (fluctuating γ) structures with existing 3-particle correlations

Simple logic

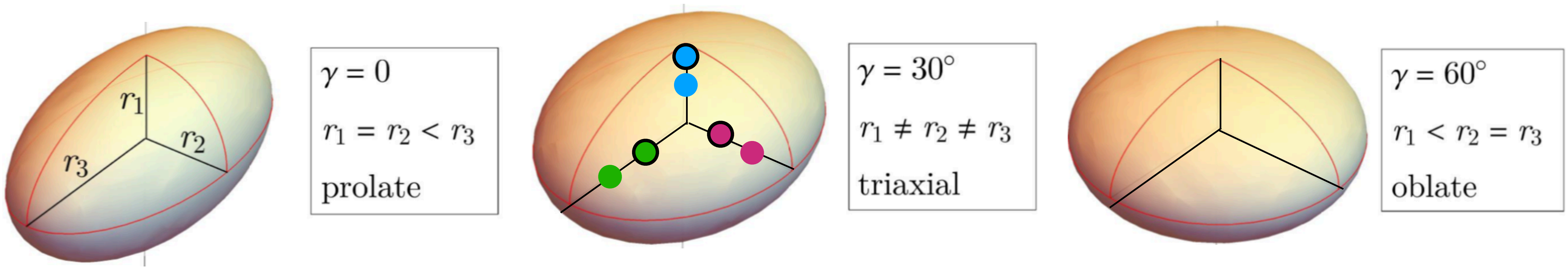


Simple logic



❖ To probe the relation of r_1, r_2 and r_3, we need 3-particle correlations

Simple logic

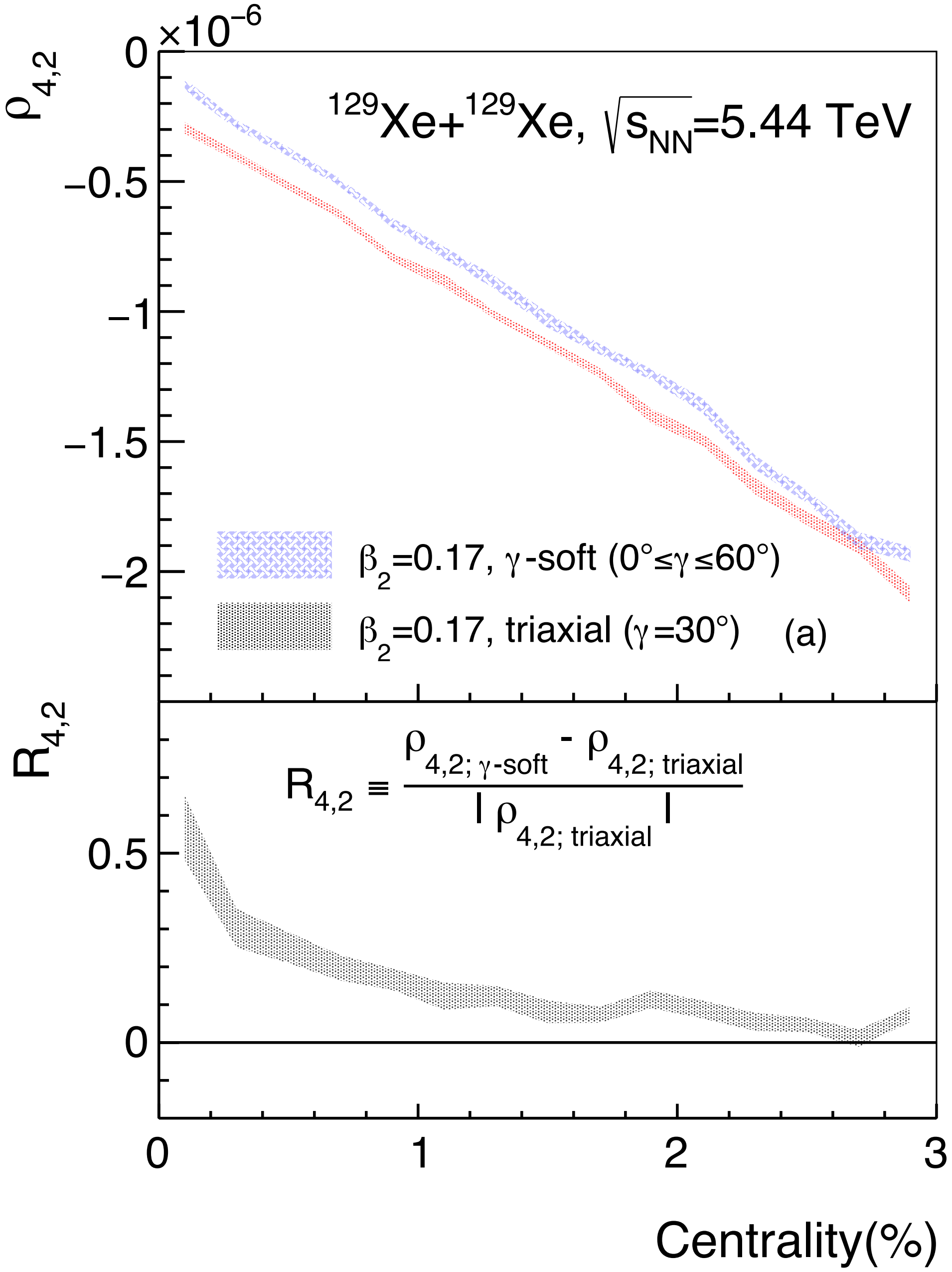


- To probe the relation of r_1, r_2 and r_3, we need 3-particle correlations
- To probe the γ fluctuations, we need 6-particle correlations

New probe for the γ-soft structure

New proposals:

$$\rho_{4,2} \equiv \left(\frac{\langle \varepsilon_2^4 \delta d_\perp^2 \rangle}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2}\right)_c \equiv \frac{1}{\langle \varepsilon_2^4 \rangle \langle d_\perp \rangle^2}\left[\langle \varepsilon_2^4 \delta d_\perp^2 \rangle + 4\langle \varepsilon_2^2 \rangle^2 \langle \delta d_\perp^2 \rangle - \langle \varepsilon_2^4 \rangle \langle \delta d_\perp^2 \rangle - 4\langle \varepsilon_2^2 \rangle \langle \varepsilon_2^2 \delta d_\perp^2 \rangle - 4\langle \varepsilon_2^2 \delta d_\perp \rangle^2\right]$$

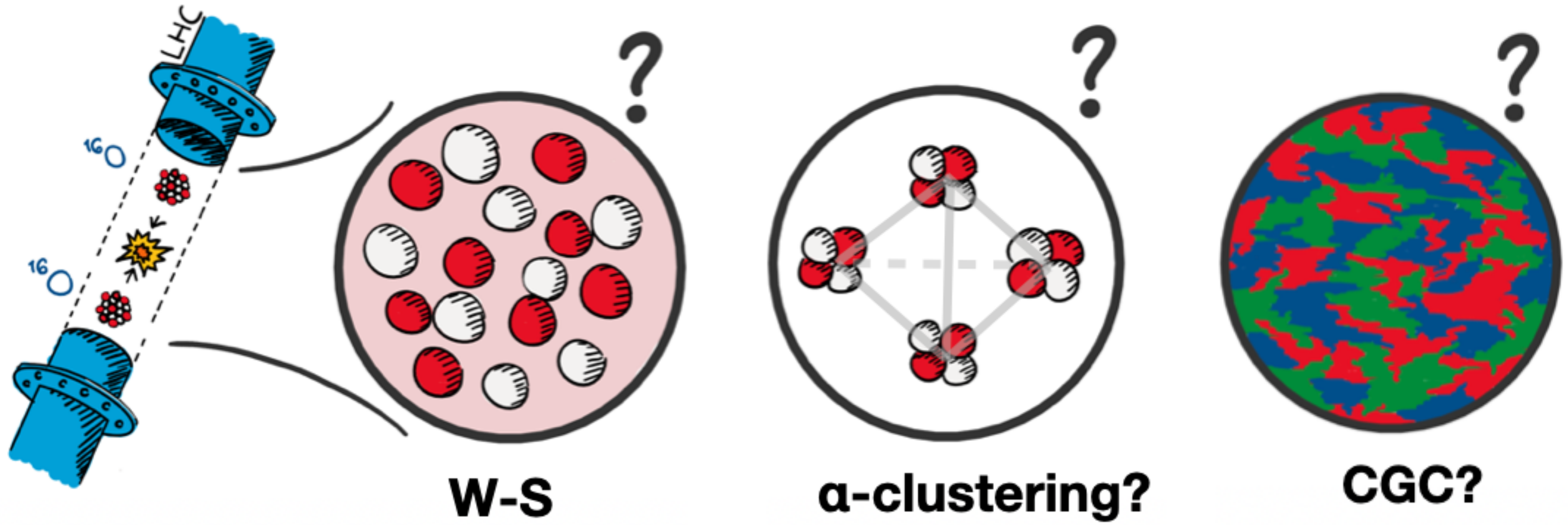


❖The six-particle correlations allow to differentiate triaxial (fixed γ = 30°) and γ-soft (fluctuating γ) structures.

❖Difference in $\rho_{4,2}$ can reach 50% in the ultra-central collisions.

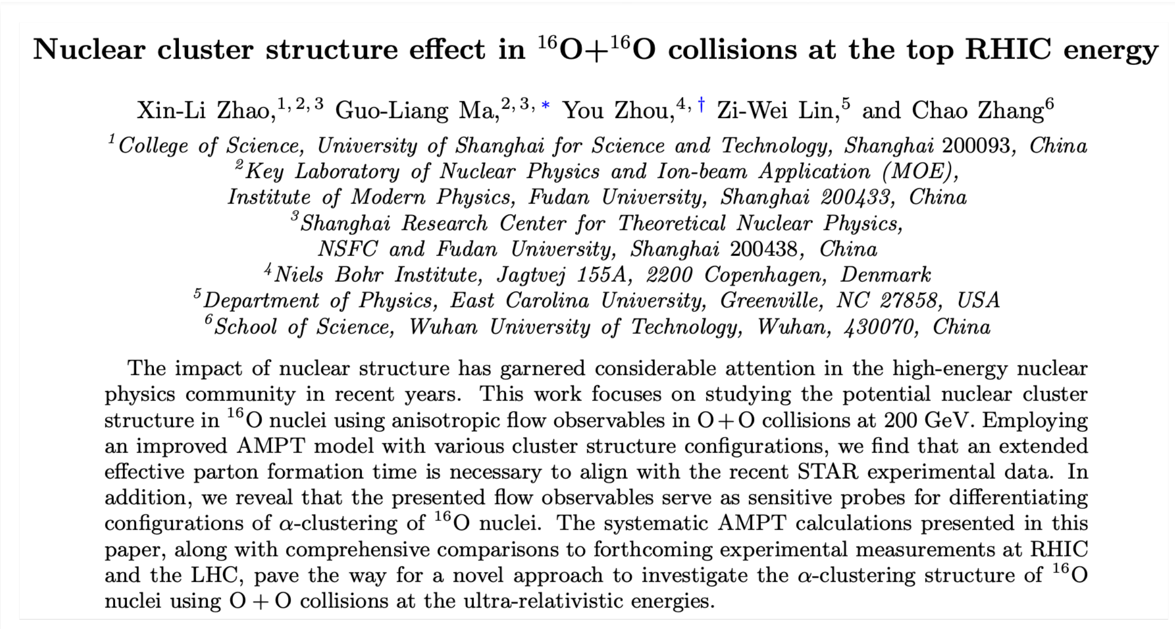
❖***Opening a new pathway to probe nuclear shape phase transition at the ultra-relativistic energies.***

^{16}O-^{16}O collisions at the LHC in 2025



Transport model predictions for ^{16}O-^{16}O

arXiv:2404.09780, submitted to Phys. Lett. B



Nuclear cluster structure effect in $^{16}O+^{16}O$ collisions at the top RHIC energy

Xin-Li Zhao,[1,2,3] Guo-Liang Ma,[2,3,*] You Zhou,[4,†] Zi-Wei Lin,[5] and Chao Zhang[6]

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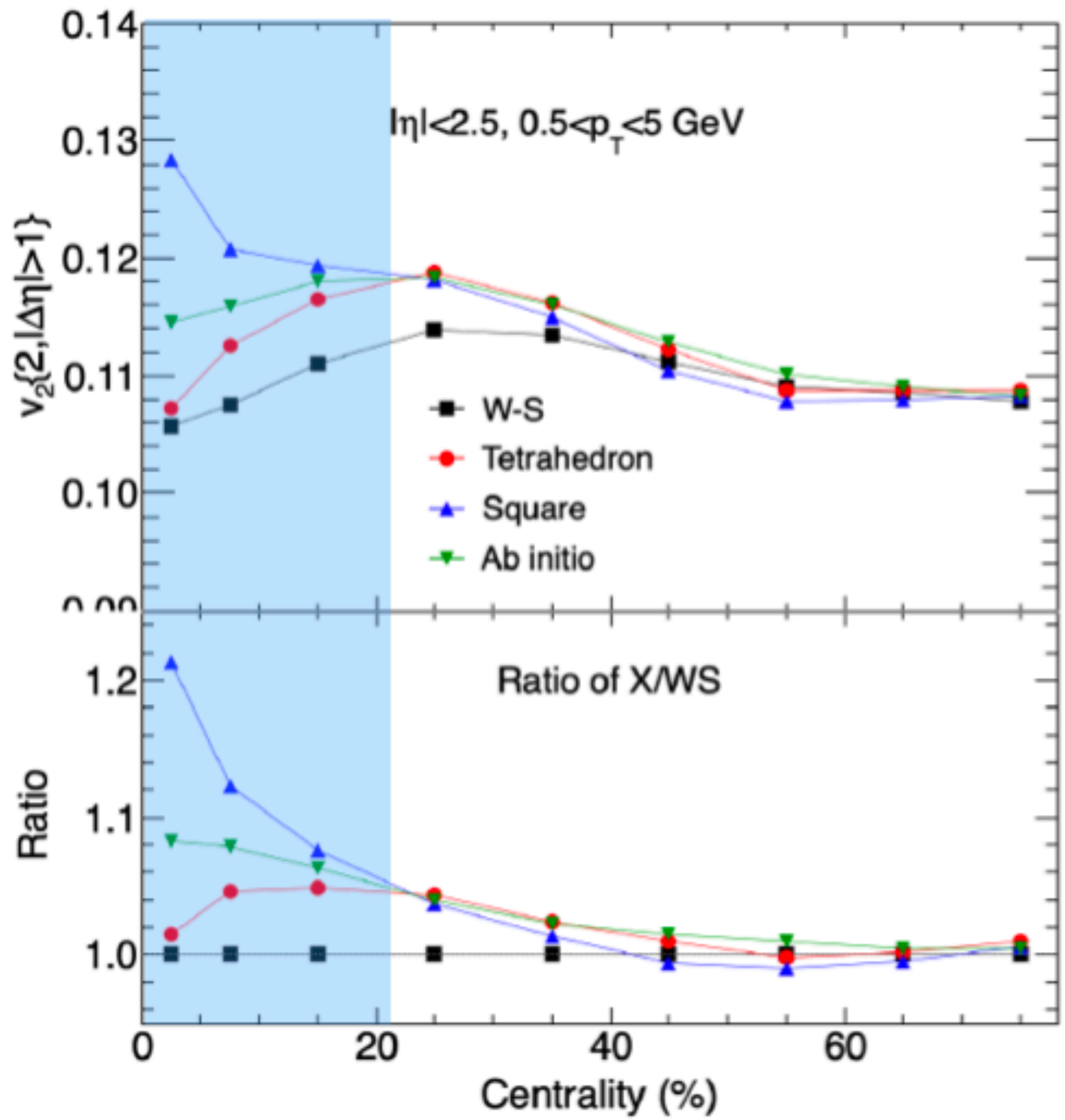
[2]Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China
[3]Shanghai Research Center for Theoretical Nuclear Physics, NSFC and Fudan University, Shanghai 200438, China
[4]Niels Bohr Institute, Jagtvej 155A, 2200 Copenhagen, Denmark
[5]Department of Physics, East Carolina University, Greenville, NC 27858, USA
[6]School of Science, Wuhan University of Technology, Wuhan, 430070, China

The impact of nuclear structure has garnered considerable attention in the high-energy nuclear physics community in recent years. This work focuses on studying the potential nuclear cluster structure in ^{16}O nuclei using anisotropic flow observables in O+O collisions at 200 GeV. Employing an improved AMPT model with various cluster structure configurations, we find that an extended effective parton formation time is necessary to align with the recent STAR experimental data. In addition, we reveal that the presented flow observables serve as sensitive probes for differentiating configurations of α-clustering of ^{16}O nuclei. The systematic AMPT calculations presented in this paper, along with comprehensive comparisons to forthcoming experimental measurements at RHIC and the LHC, pave the way for a novel approach to investigate the α-clustering structure of ^{16}O nuclei using O + O collisions at the ultra-relativistic energies.



- ❖ Predicted significant differences in v_2 from W-S and α-cluster structures
- ❖ LHC will allow precision measurements to probe the α-cluster structure.

Hydrodynamic predictions for ^{16}O-^{16}O

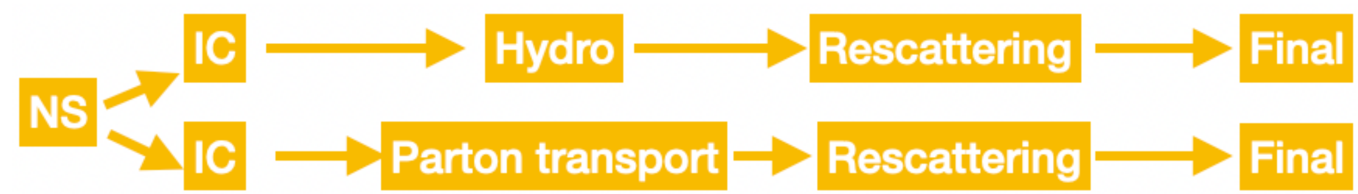
arXiv: 2110.13153

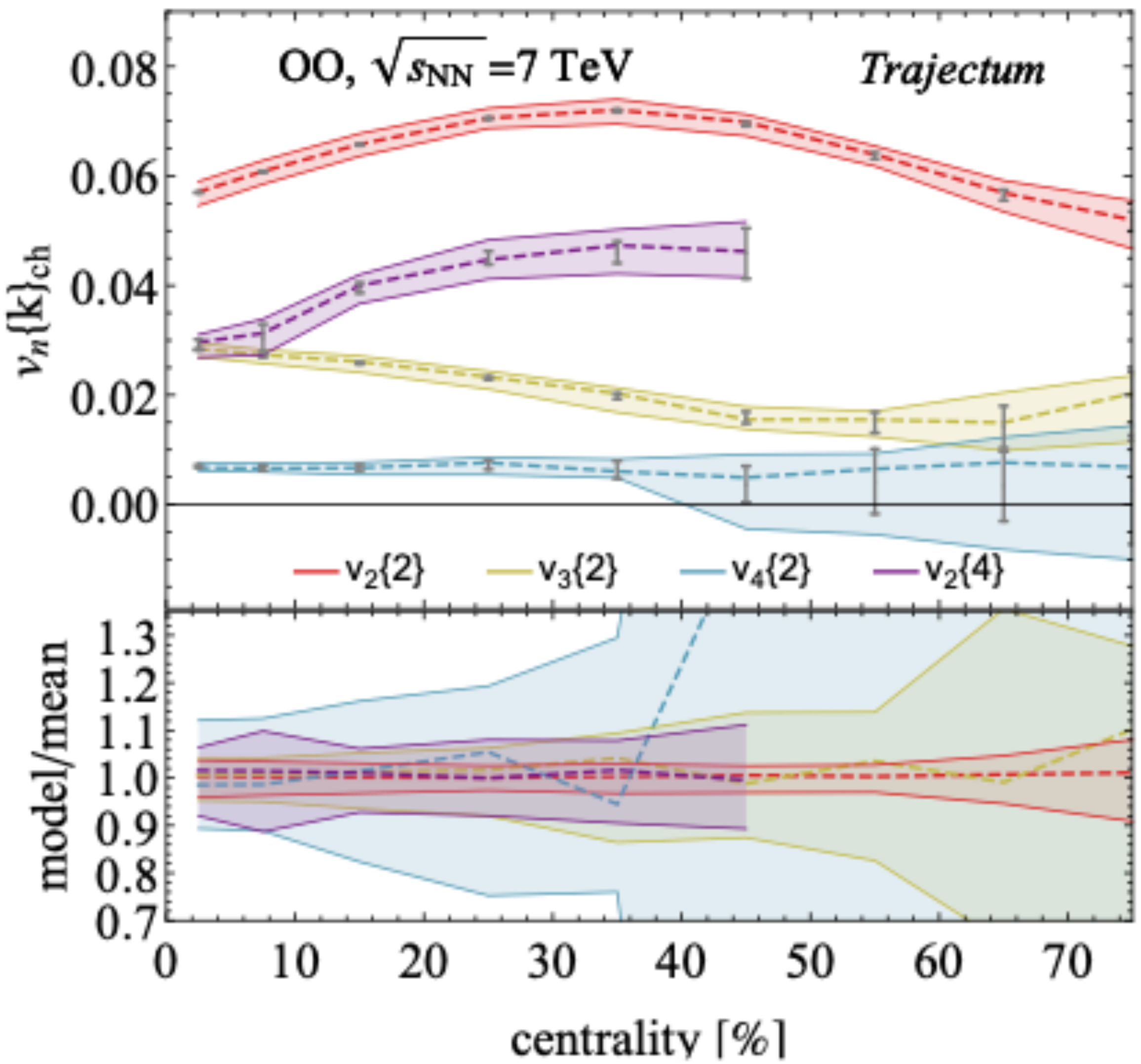
Predictions and postdictions for relativistic lead and oxygen collisions with *Trajectum*

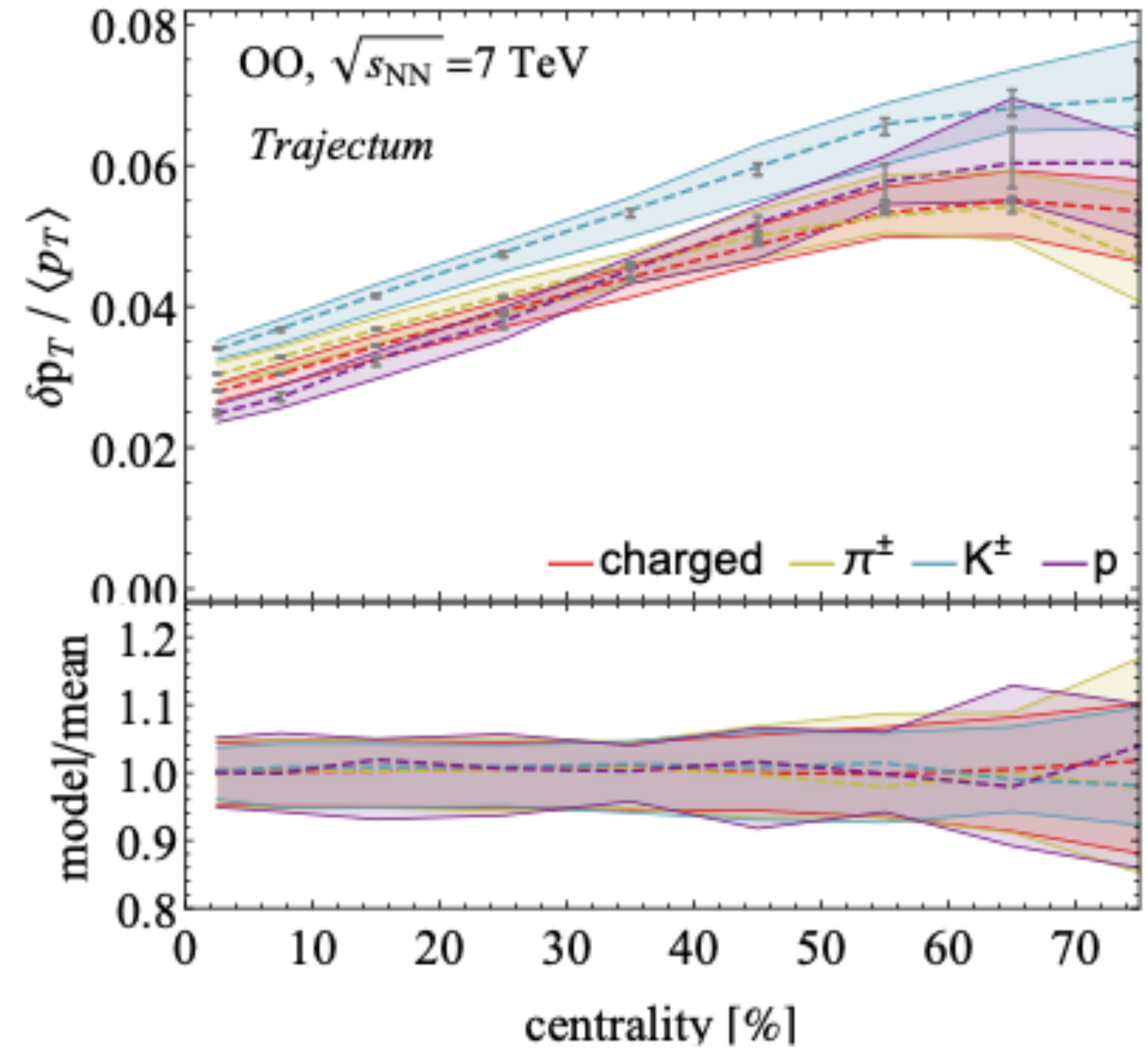
Govert Nijs[1] and Wilke van der Schee[2]

[1]*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2]*Theoretical Physics Department, CERN, CH-1211 Genève 23, Switzerland*

We introduce a global analysis of relativistic heavy ion collisions using *Trajectum* of a significantly higher precision and including a new option to vary the normalization of the centrality estimator. We use the posterior distribution of our parameters to generate a set of high statistics samples that allows us to make precise predictions including statistical and systematic uncertainties estimated from the model parameter distribution. The results are systematically compared with experiment whereby we also include many observables not included in the global analysis. This includes in particular (extremely) ultracentral anisotropic flow and mean transverse momentum, whereby we find satisfactory agreement with experiment where data is available. Lastly, we compute spectra and anisotropic flow for oxygen-oxygen collisions performed at RHIC and to be performed at the LHC and comment on how these collisions may inform us on properties of the Quark-Gluon-Plasma.







Future light ion runs at the LHC

CERN (11.2024)

- A dedicated workshop to discuss the light ion collisions
  - Existing/Coming ^{16}O-^{16}O runs
  - New possibilities at the LHC (i.e., ^{20}Ne, ^{40}Ca, ^{48}Ca)
    - Considering the extended Run 3 to 2026

Huge impact of ^{20}Ne-^{20}Ne collisions

arXiv:2402.05995

CERN-TH-2024-021

The unexpected uses of a bowling pin: exploiting ^{20}Ne isotopes for precision characterizations of collectivity in small systems

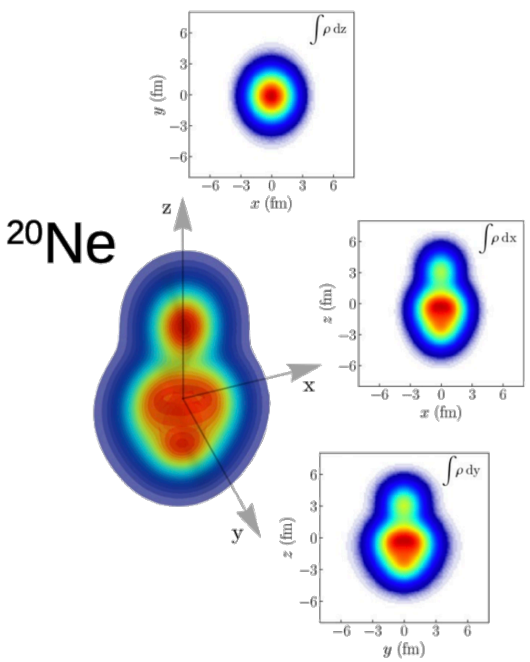
Giuliano Giacalone,[1,*] Benjamin Bally,[2] Govert Nijs,[3] Shihang Shen,[4] Thomas Duguet,[5,6] Jean-Paul Ebran,[7,8] Serdar Elhatisari,[9,10] Mikael Frosini,[11] Timo A. Lähde,[12,13] Dean Lee,[14] Bing-Nan Lu,[15] Yuan-Zhuo Ma,[14] Ulf-G. Meißner,[10,16,17] Jacquelyn Noronha-Hostler,[18] Christopher Plumberg,[19] Tomás R. Rodríguez,[20] Robert Roth,[21,22] Wilke van der Schee,[3,23,24] and Vittorio Somà[5]

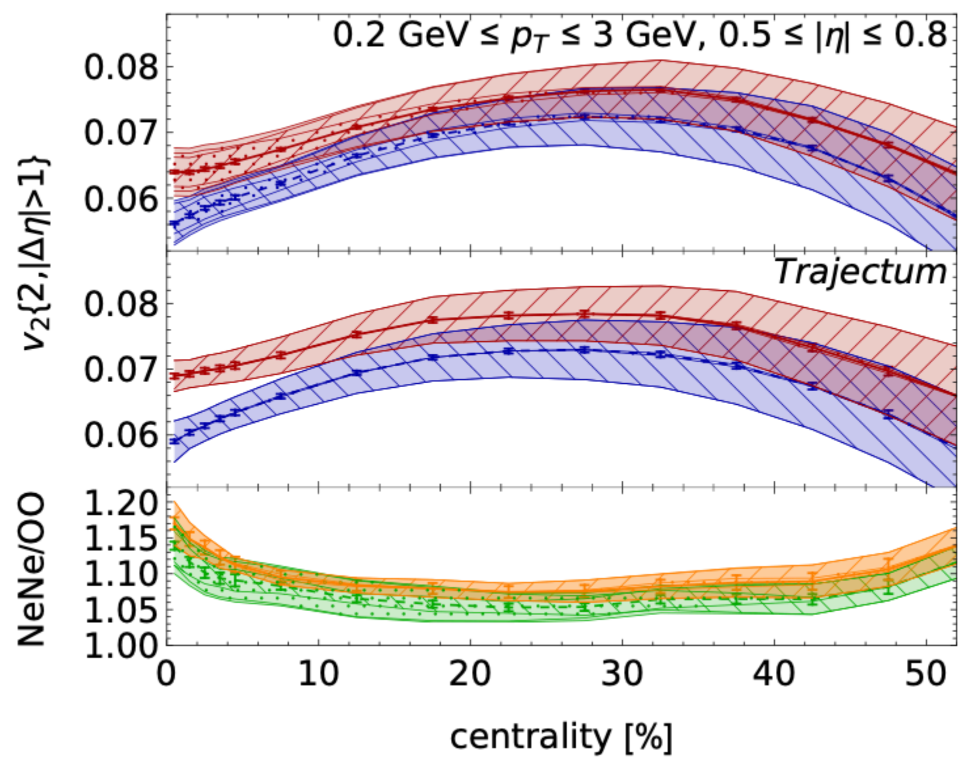
HEAVY IONS — PGCM — NLEFT

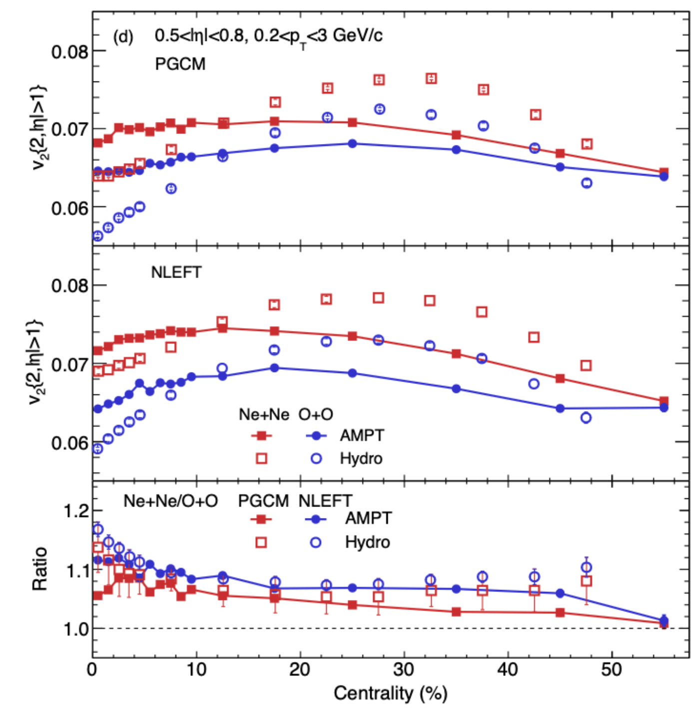
Deciphering the Origins of Anisotropic Flow in the Small Systems using unique Ne + Ne and O + O Collisions

Xin-Li Zhao,[1,2,3] Pei Li,[1,2] Guo-Liang Ma,[1,2,*] You Zhou,[4,†] Jiangyong Jia,[5,6,‡] Chunjian Zhang,[1,2,§] Zi-Wei Lin,[7] and Chao Zhang[8]

Theorists — Experimentalists (ALICE, ATLAS, STAR)





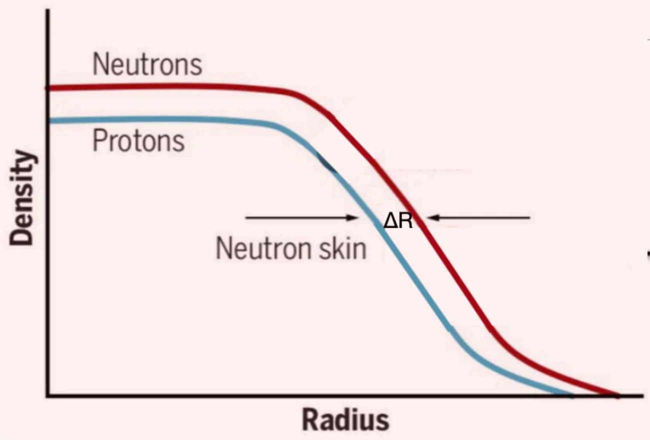


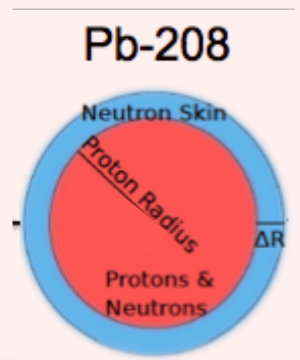
^{20}Ne-^{20}Ne vs ^{16}O-^{16}O: almost "isobar" runs at the LHC

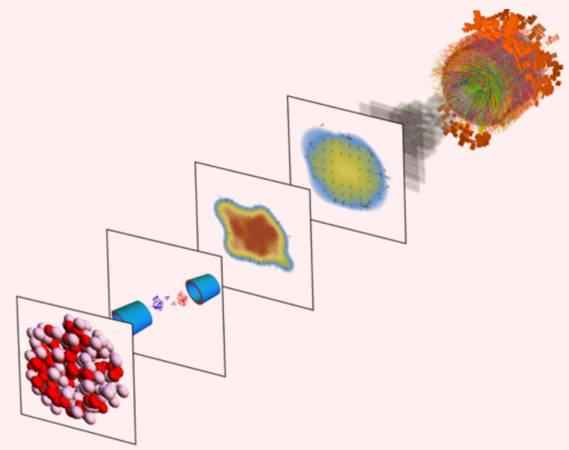
- LHC: Easy to prepare for the beam (gas), experience from ^{16}O-^{16}O run
- Precise answer on the origin of flow in small systems, with very tiny model uncertainty, the ^{20}Ne-^{20}Ne will maximize the scientific output of the ^{16}O-^{16}O run (and vice versa)

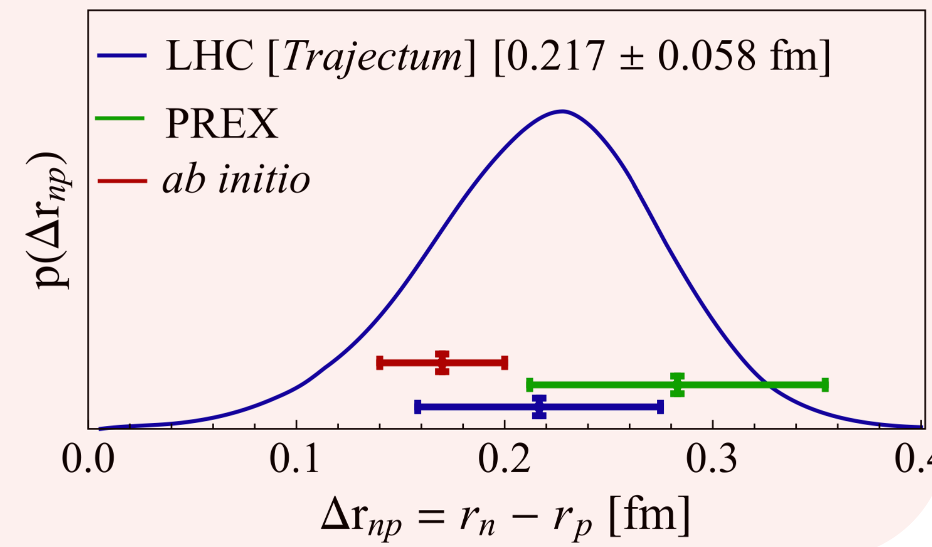
What can we learn from ^{40}Ca & ^{48}Ca

❖ Existing Neutron skin study with ^{208}Pb

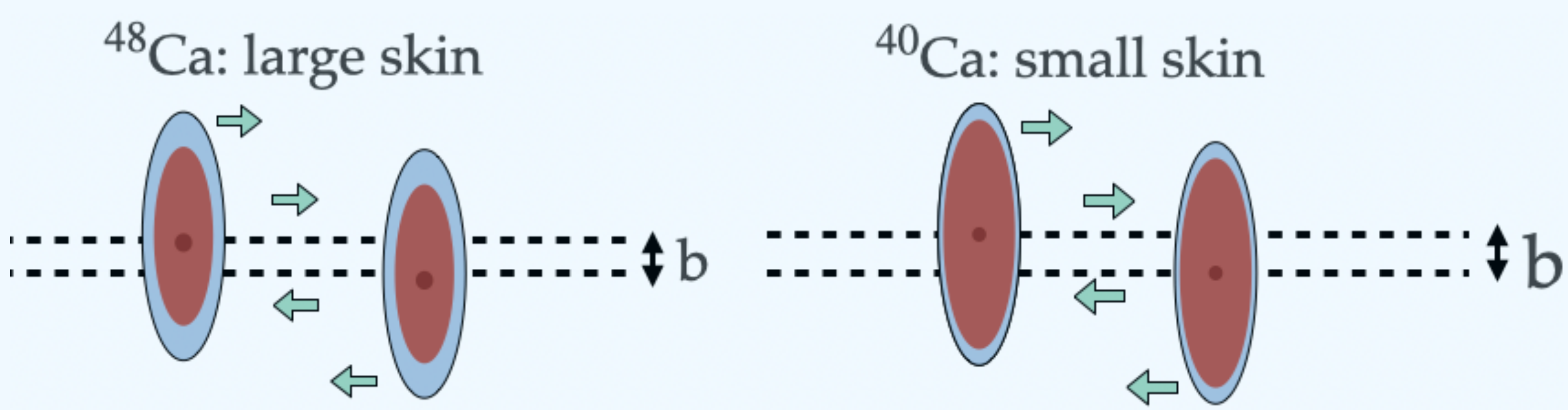






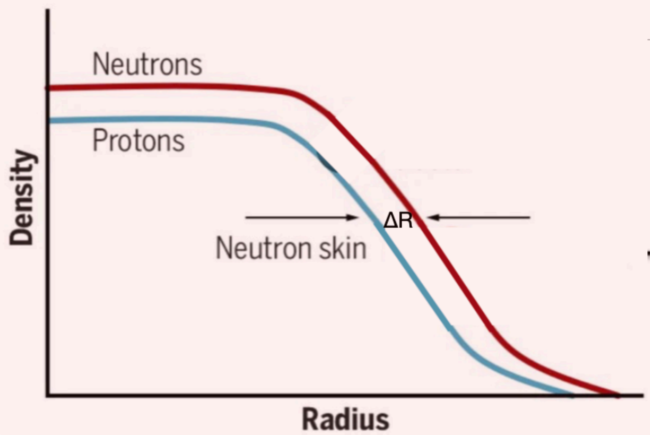


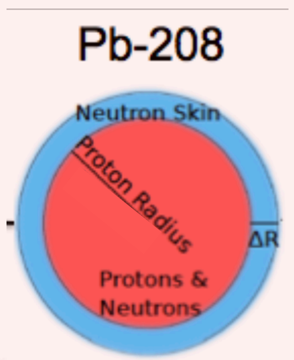
❖ New opportunity for neutron skin ^{40}Ca and ^{48}Ca

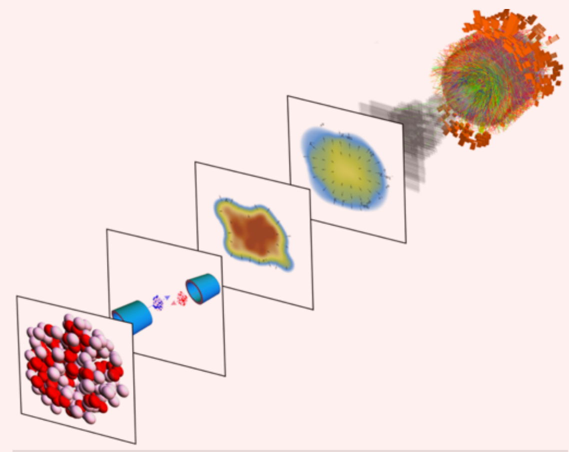


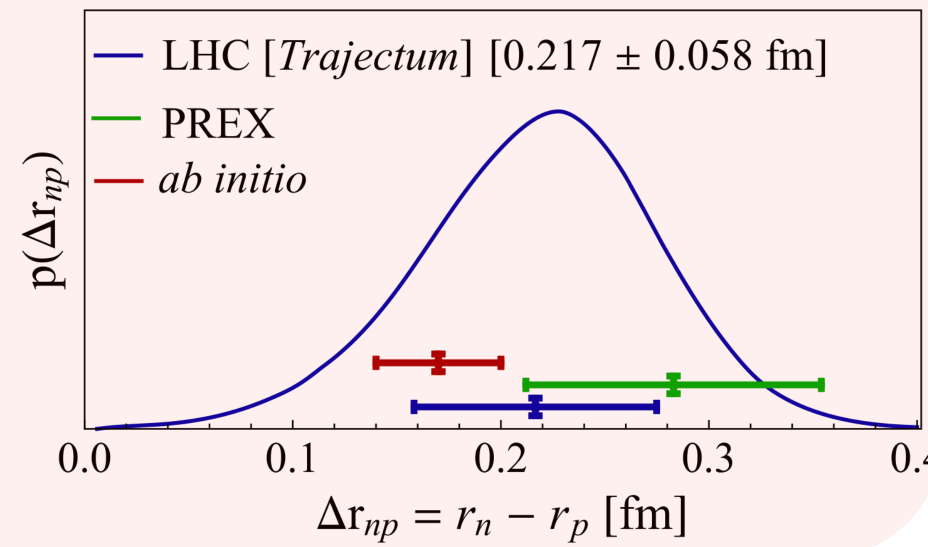
What can we learn from ^{40}Ca & ^{48}Ca

❖ Existing Neutron skin study with ^{208}Pb

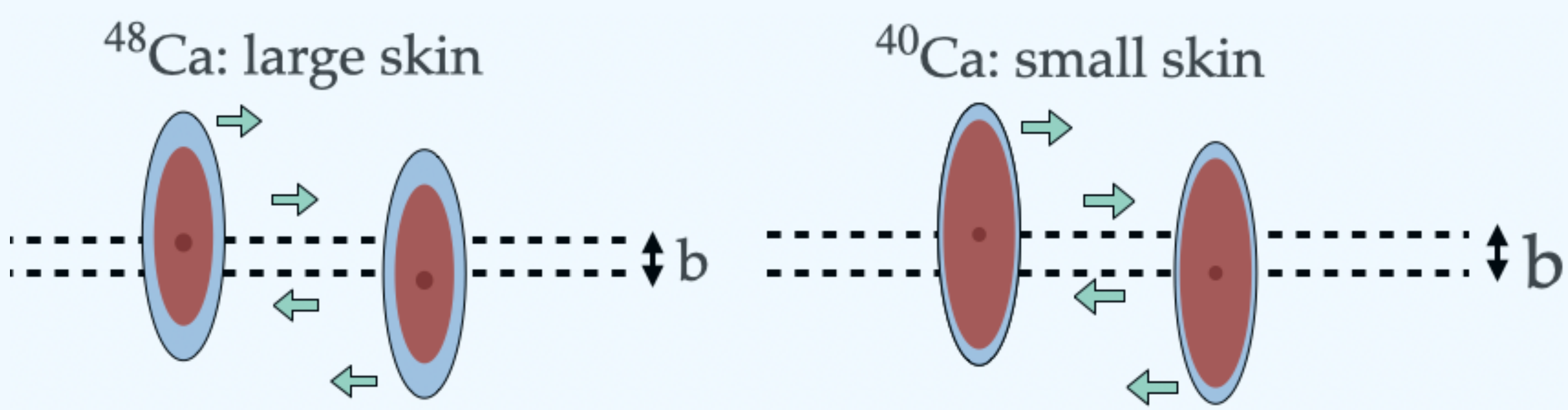








❖ New opportunity for neutron skin ^{40}Ca and ^{48}Ca



Resolve the tension between PREX and CREX (Current puzzle in low-energy nuclear physics)

Interaction between LE and HE

BNL (2022.01)

RIKEN BNL Research Center
Physics Opportunities from the RHIC Isobar Run
This workshop will be held virtually.
January 25–28, 2022

[link]

GSI (2022.05 & 10)

EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 1/2)
30 May 2022 to 3 June 2022
Heidelberg University

[link]

Saclay (2022.09)

Deciphering nuclear phenomenology across energy scales
Back to the ESNT page
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PROGRAM ESNTprogram19Sept2022DefVf.pdf

[link]

INT (2023.2)

INSTITUTE for NUCLEAR THEORY
INT PROGRAM INT-23-1A
Intersection of nuclear structure and high-energy nuclear collisions

[link]

NBI (2023.6)

[link]

PKU (2024.4)

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

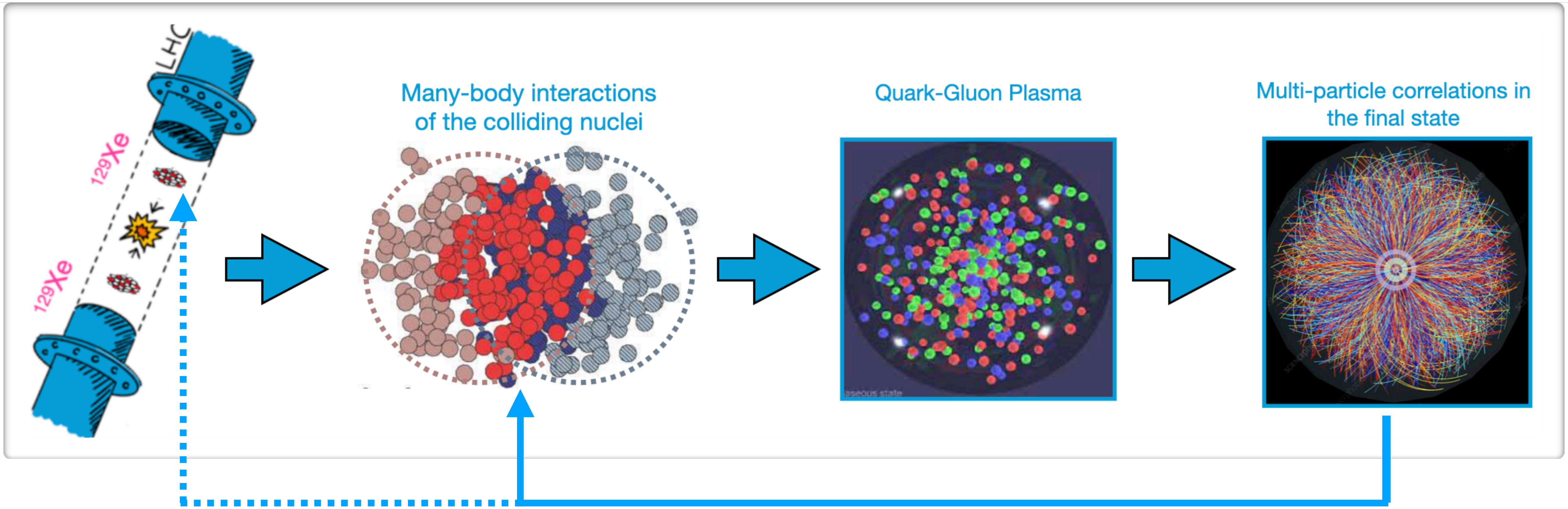
[link]

CERN (2024.10)

Light ion collisions at the LHC

Tack för
din uppmärksamhet!

Paradigm shift research in heavy-ion physics



Nobelprisen i fysik 1975

*“ for the discovery of the connection between **collective motion and particle motion** in atomic nuclei and the development of the theory of the **structure of the atomic nucleus** based on this connection”*

The Nobel Prize in Physics 1975

Photo from the Nobel Foundation archive.
Aage Niels Bohr

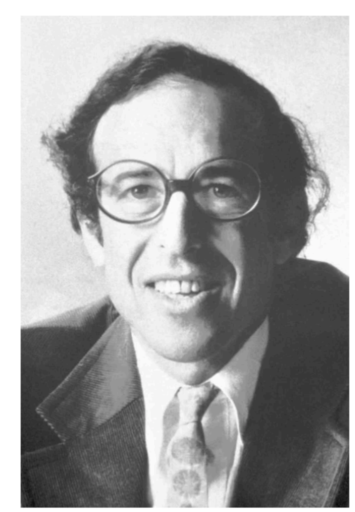


Photo from the Nobel Foundation archive.
Ben Roy Mottelson

Photo from the Nobel Foundation archive.
Leo James Rainwater