High-Energy Nuclear Structure Tomography (HENST) at the LHC

Intersection of nuclear structure and high-energy nuclear collisions 2026

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UNIVERSITY OF COPENHAGEN

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Niels Bohr & Yukawa

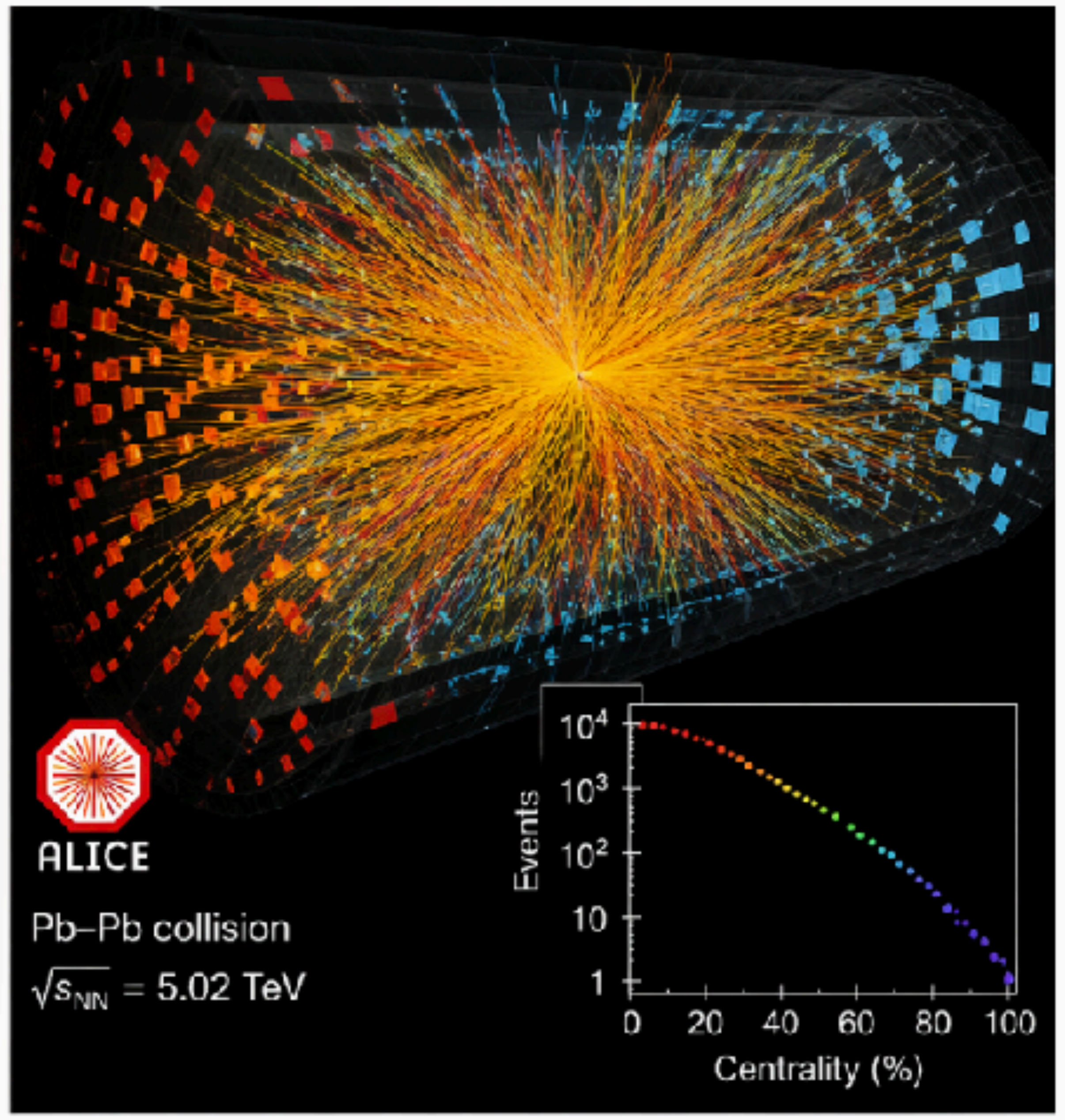
Niels Bohr, Hideki Yukawa, Sumi Yukawa and J. Robert Oppenheimer

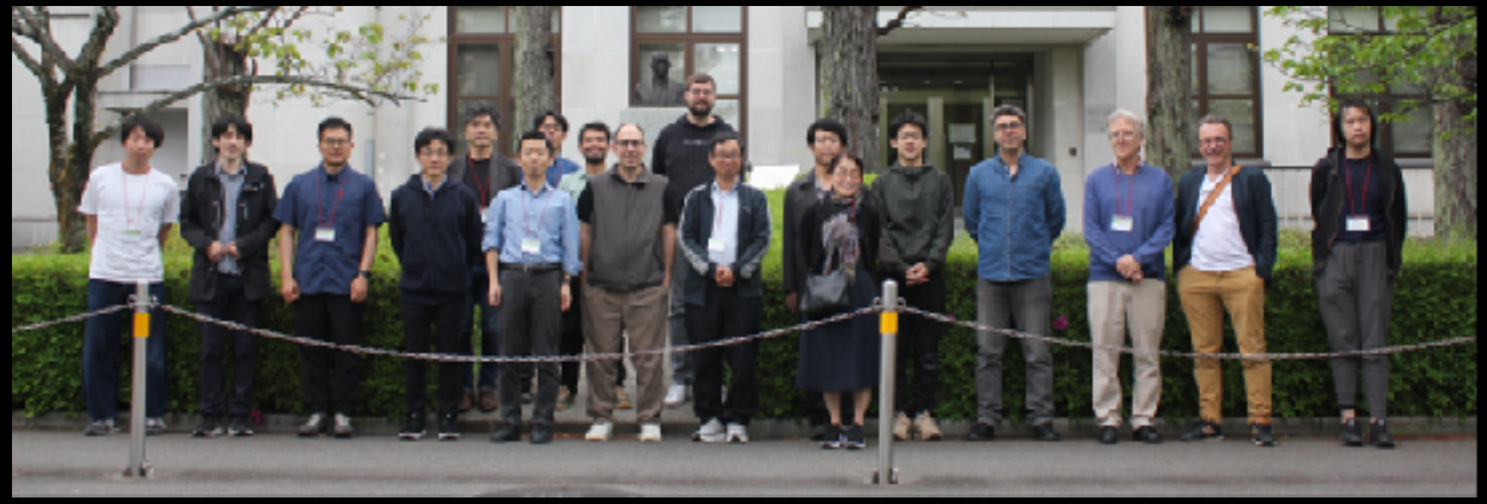
Hideki Yukawa, Niels Bohr

Leading Japanese physicist at Niels Bohr Institute

Yoshio Nishina (にしな よしお) in Copenhagen

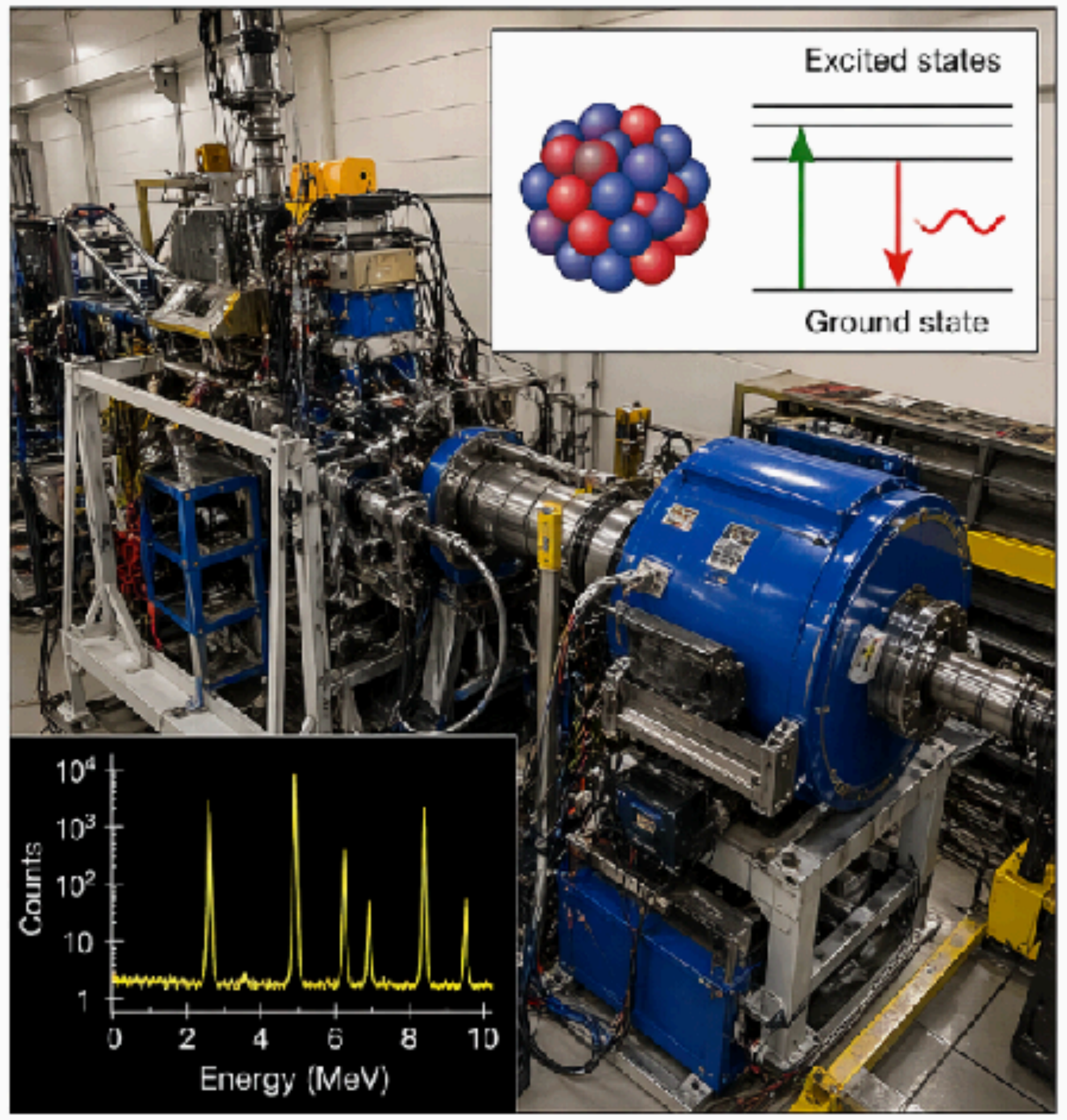
High-energy heavy-ion physics (at the LHC)



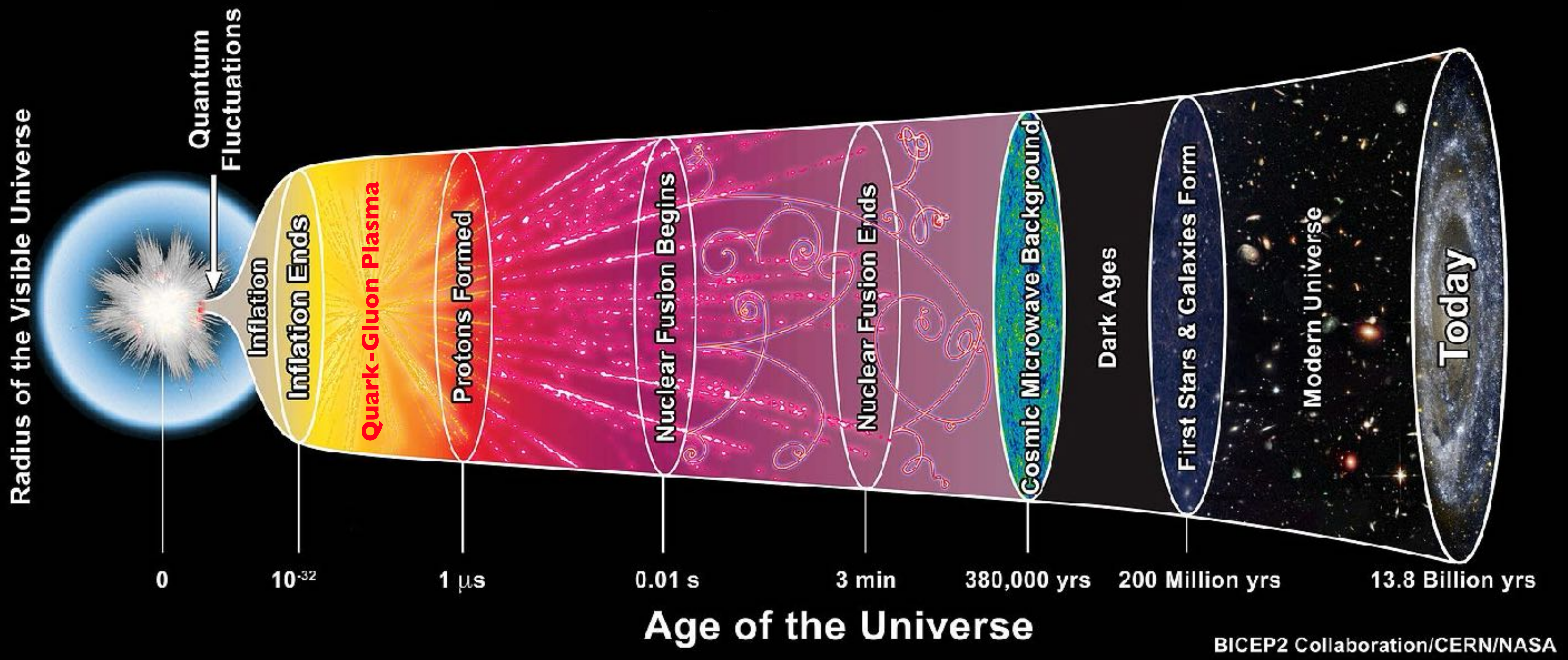


Intersection

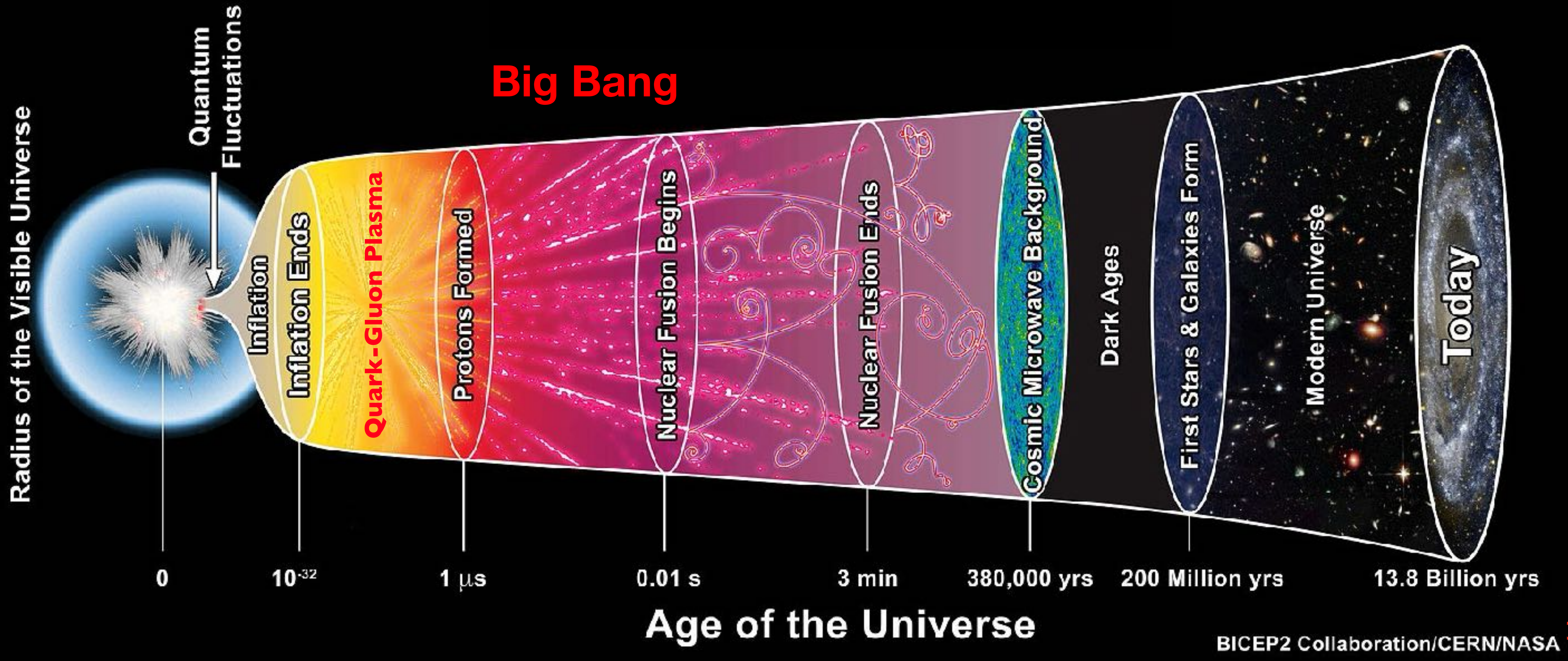
Low-energy nuclear structure physics



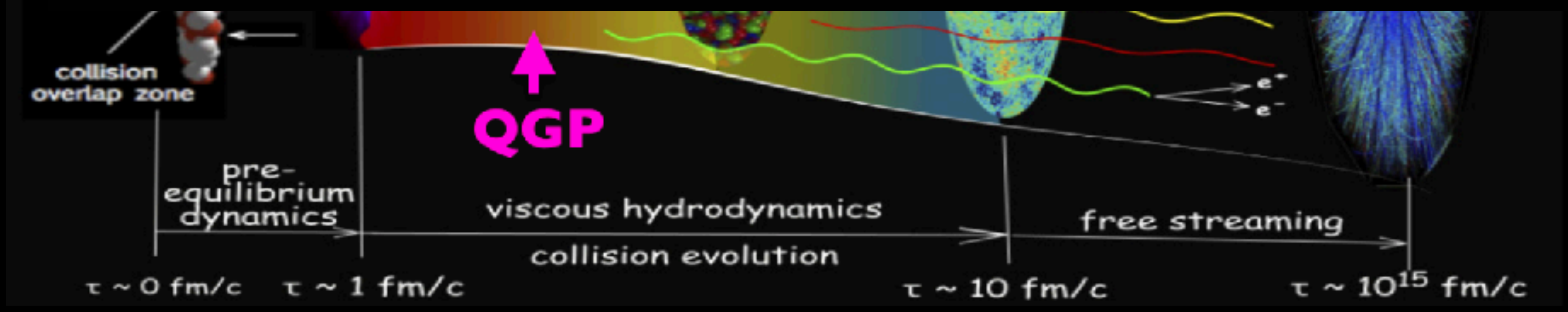
* picture generated by ChatGPT for illustration only


Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Quark-Gluon Plasma
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

v ≈ 99.9999991% c

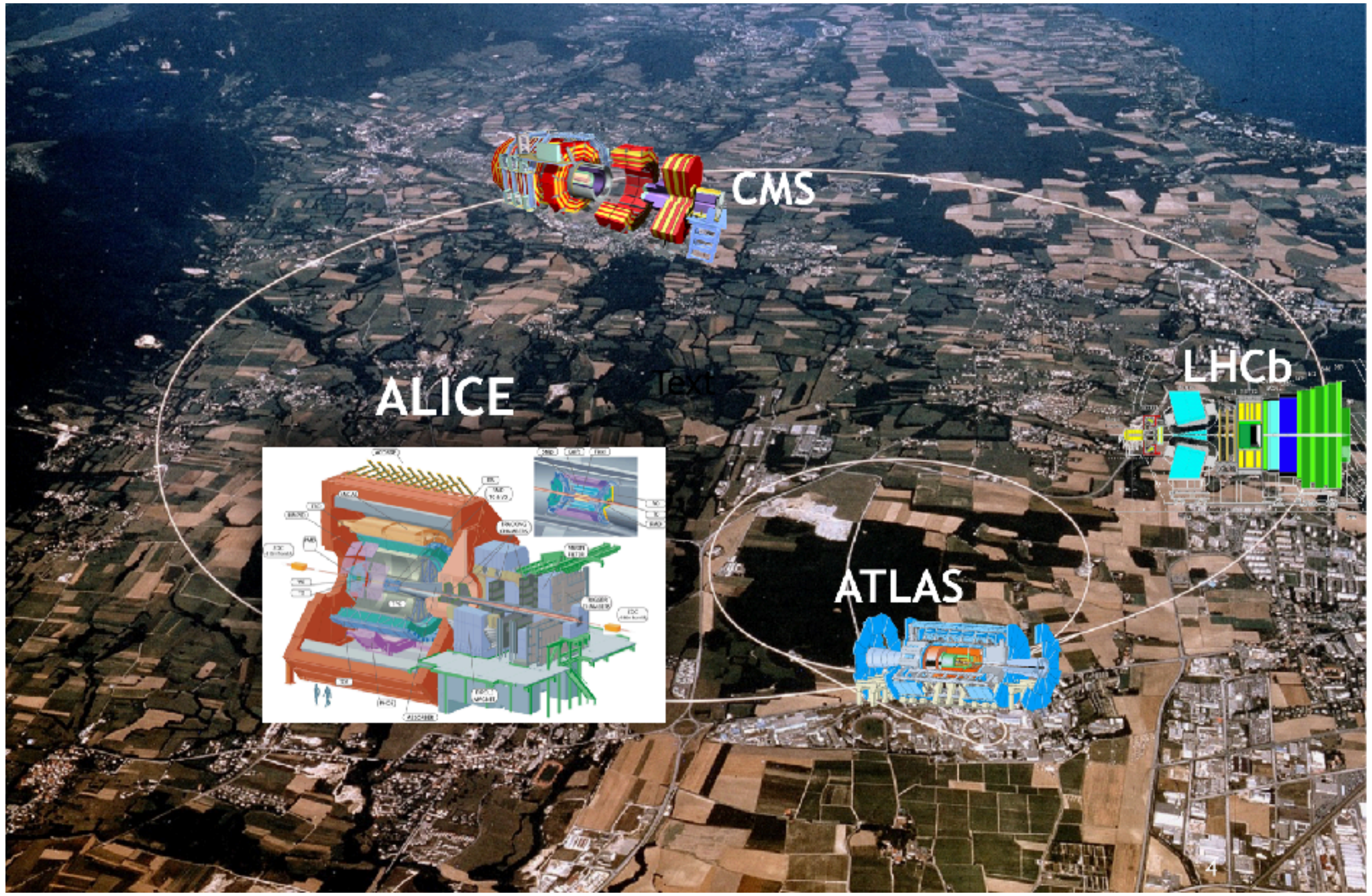


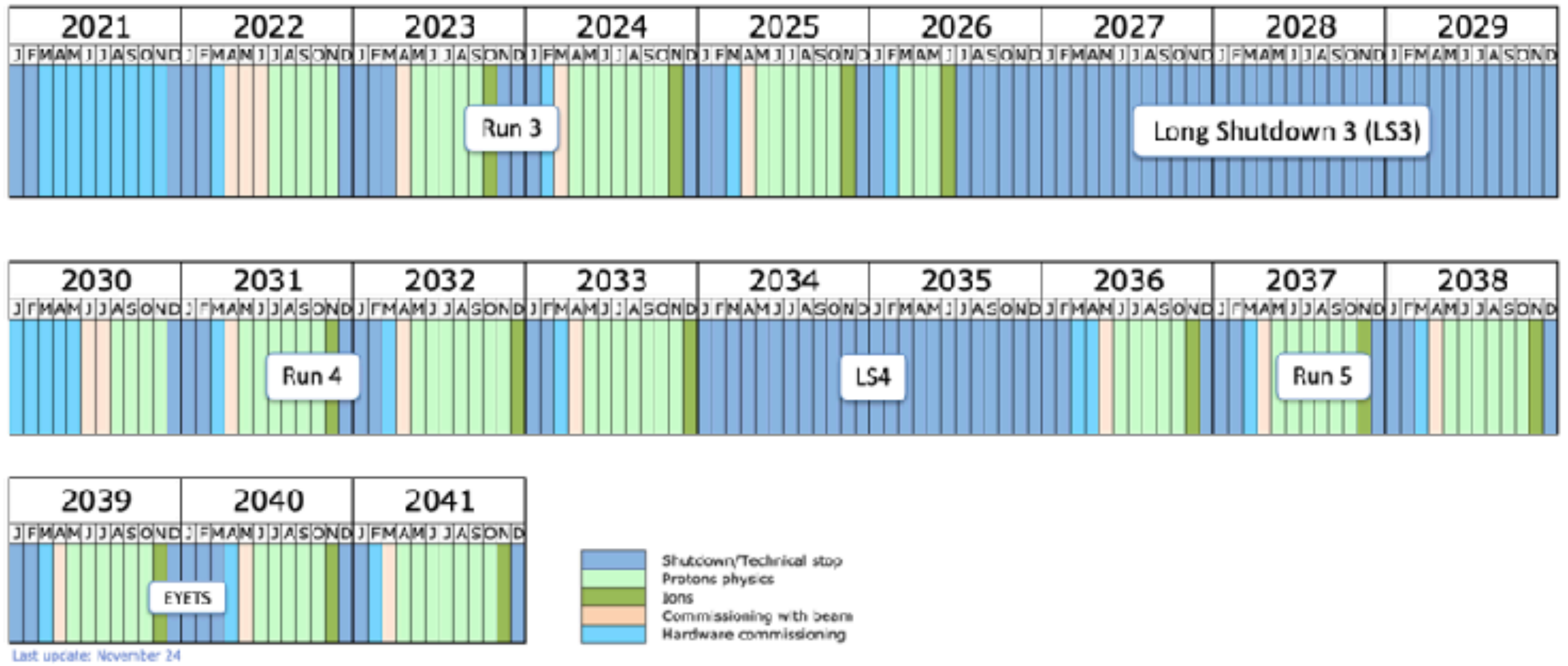
n (350,000 times
core)

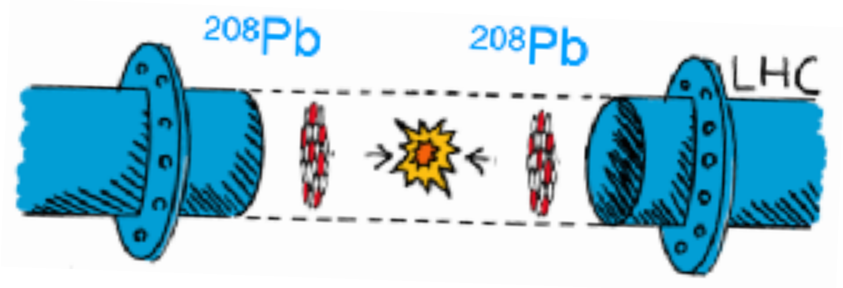


Large "Heavy-ion" Collider @ CERN

Large Hadron Collider, CERN, Geneva



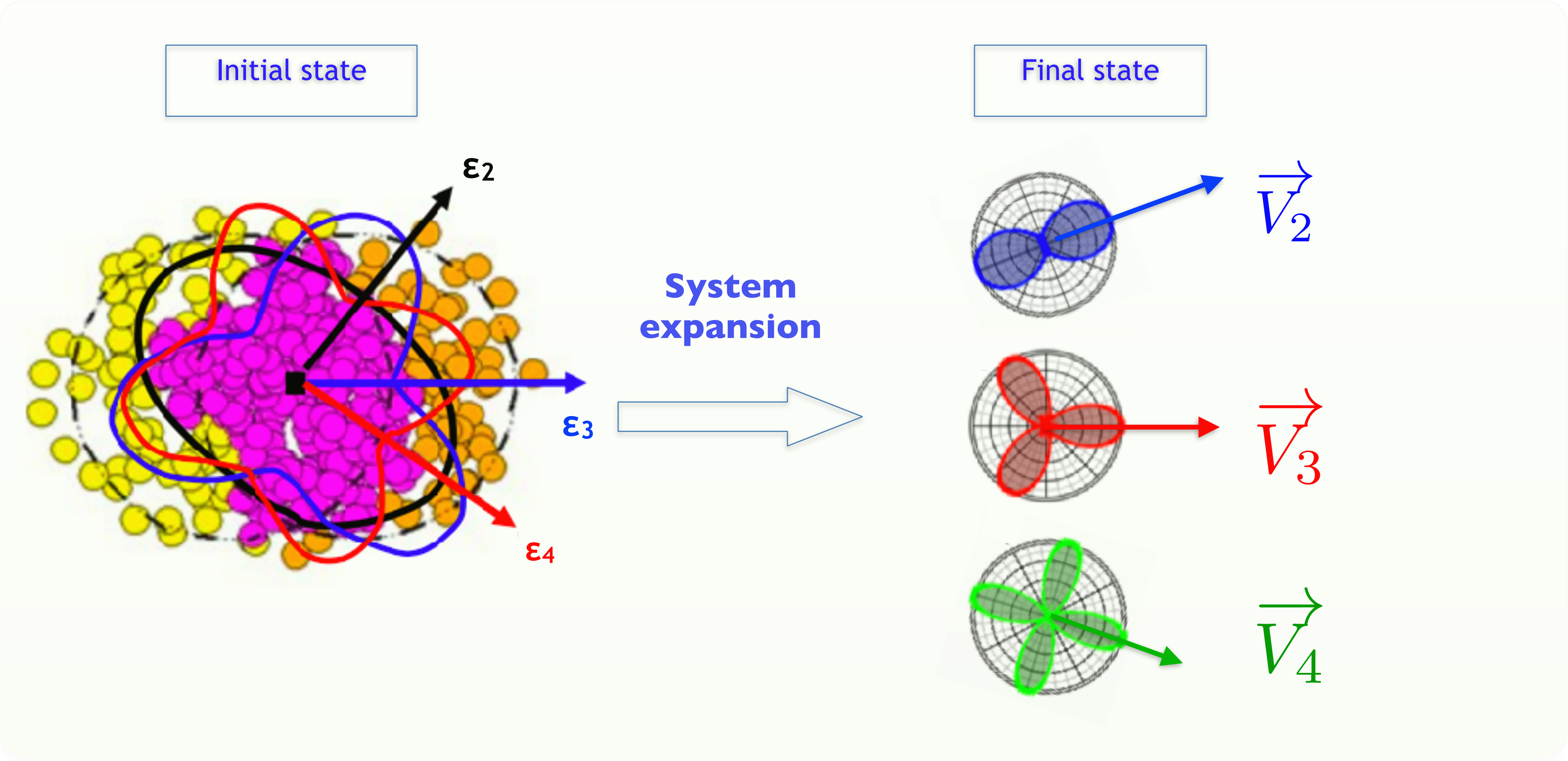


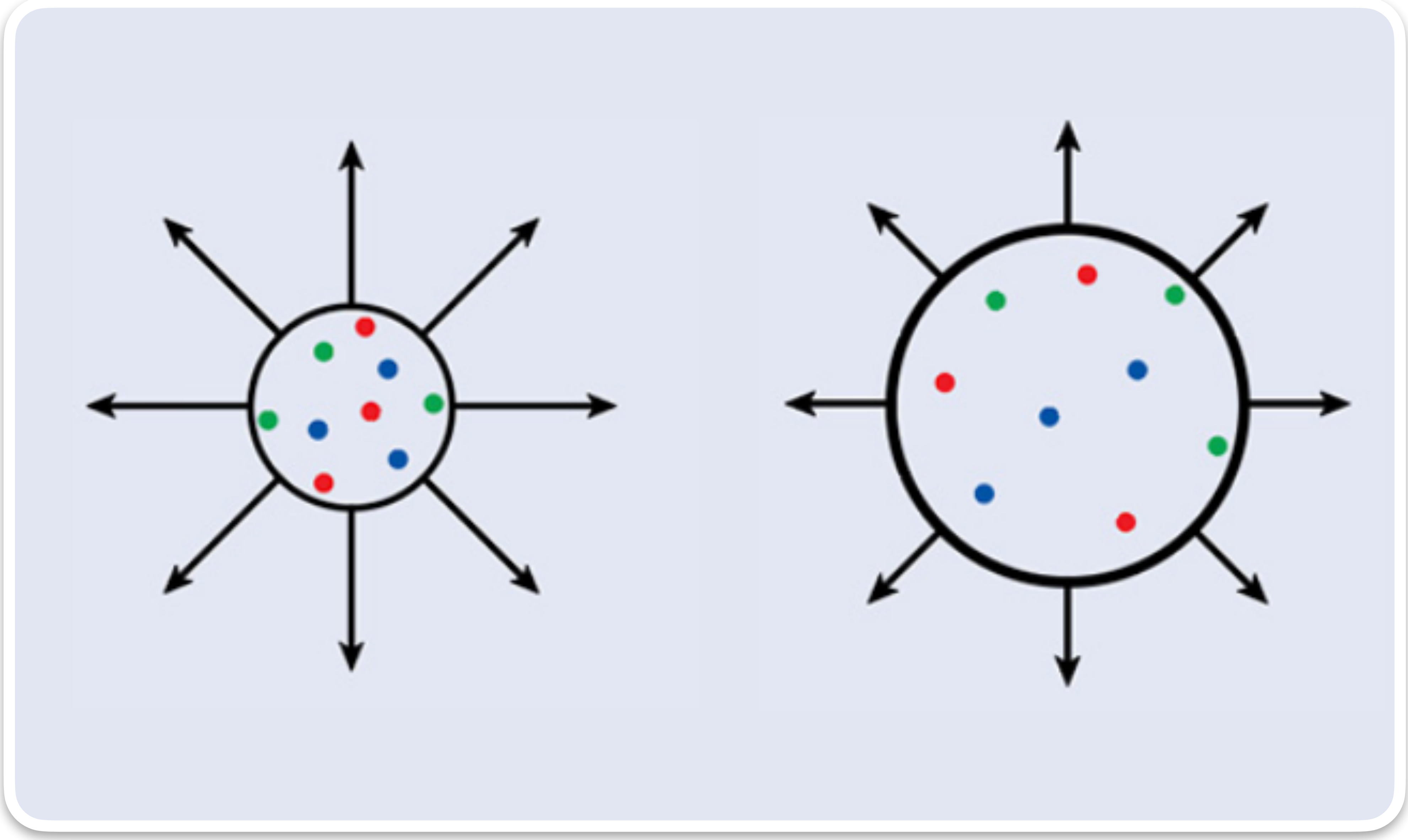


Pb-Pb 2.76 TeV (Run 1)
5.02 TeV (Run 2)
5.36 TeV (Run 3)

Xe-Xe 5.44 TeV

Study the QGP transport properties with collective flow

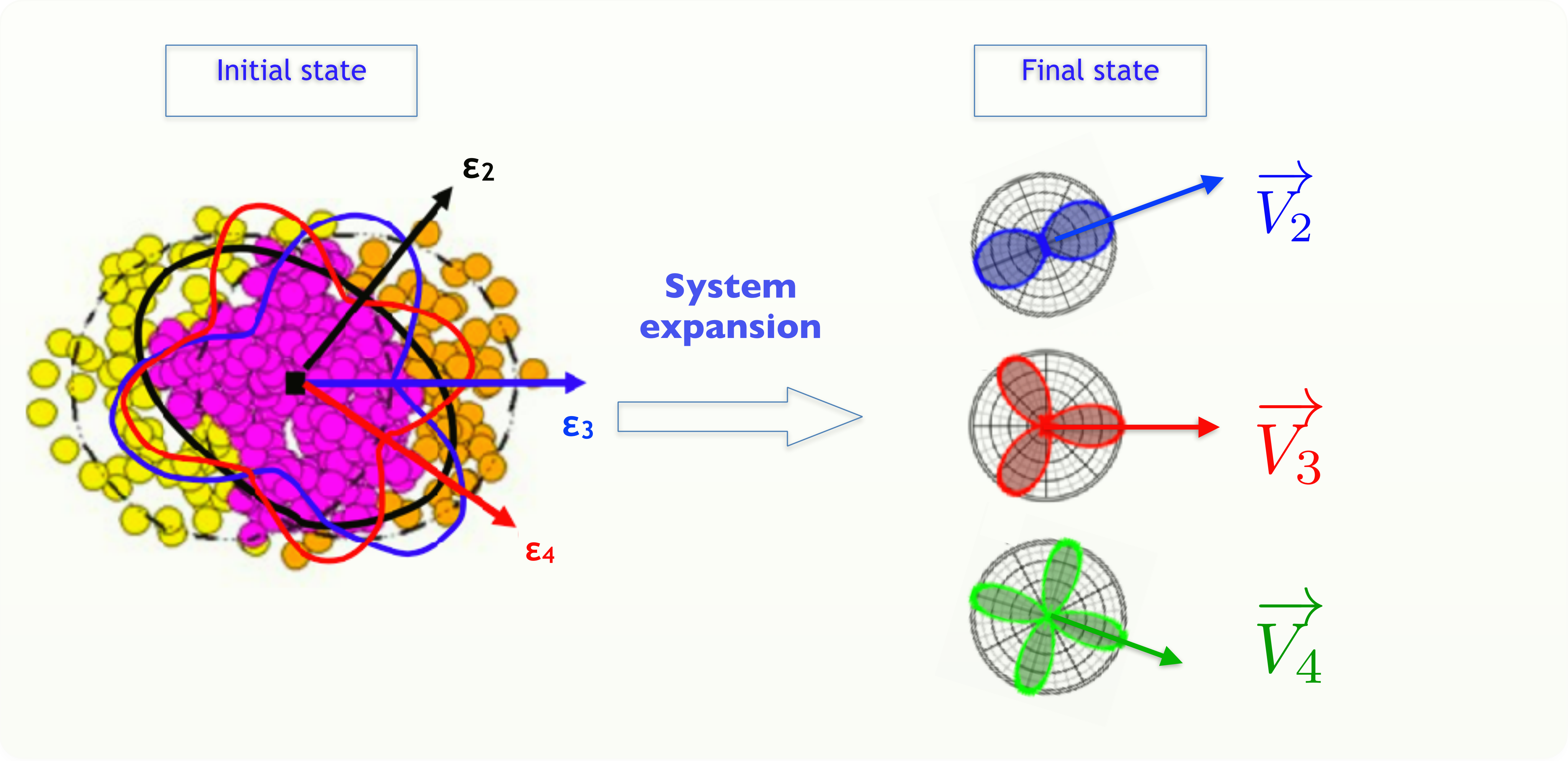


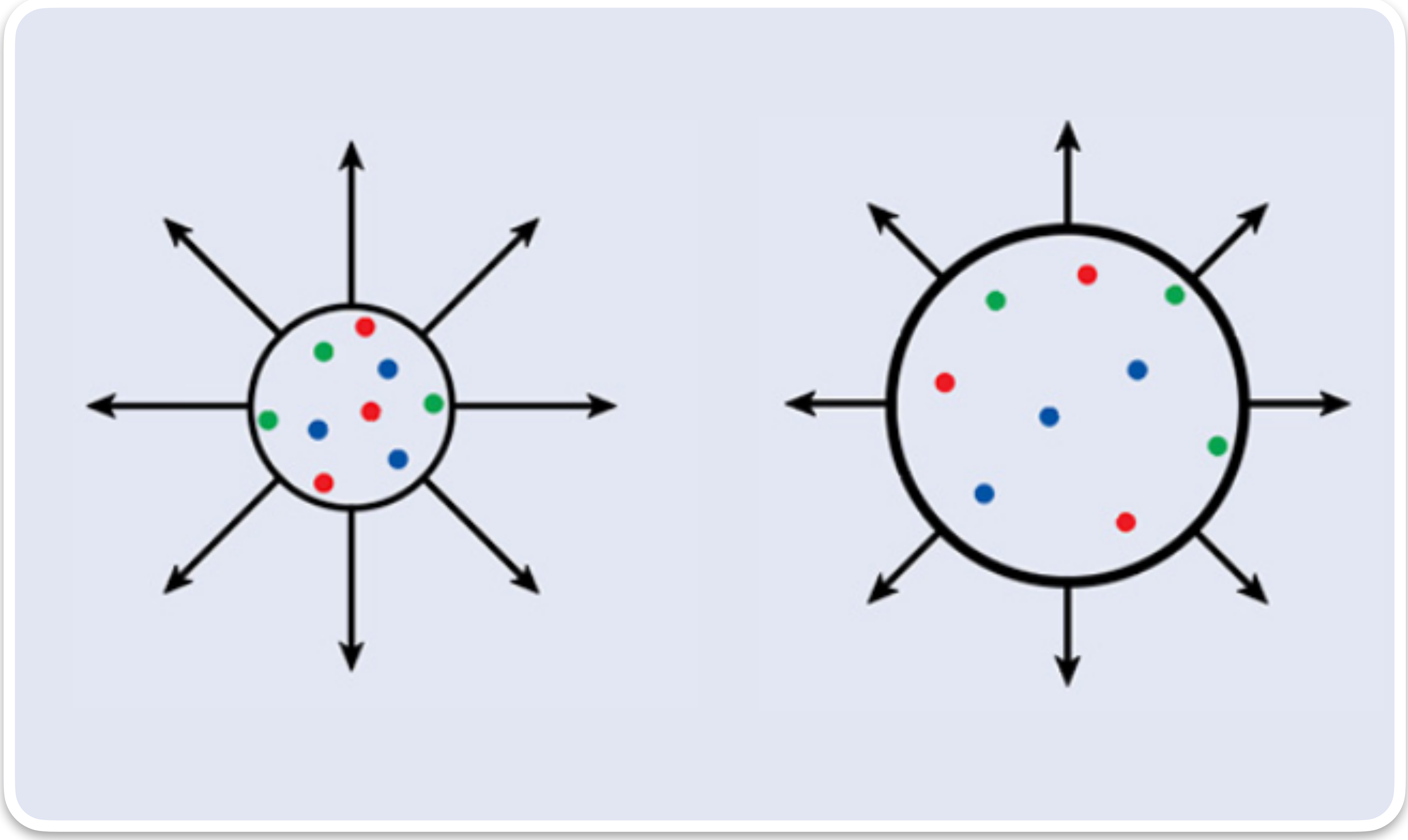


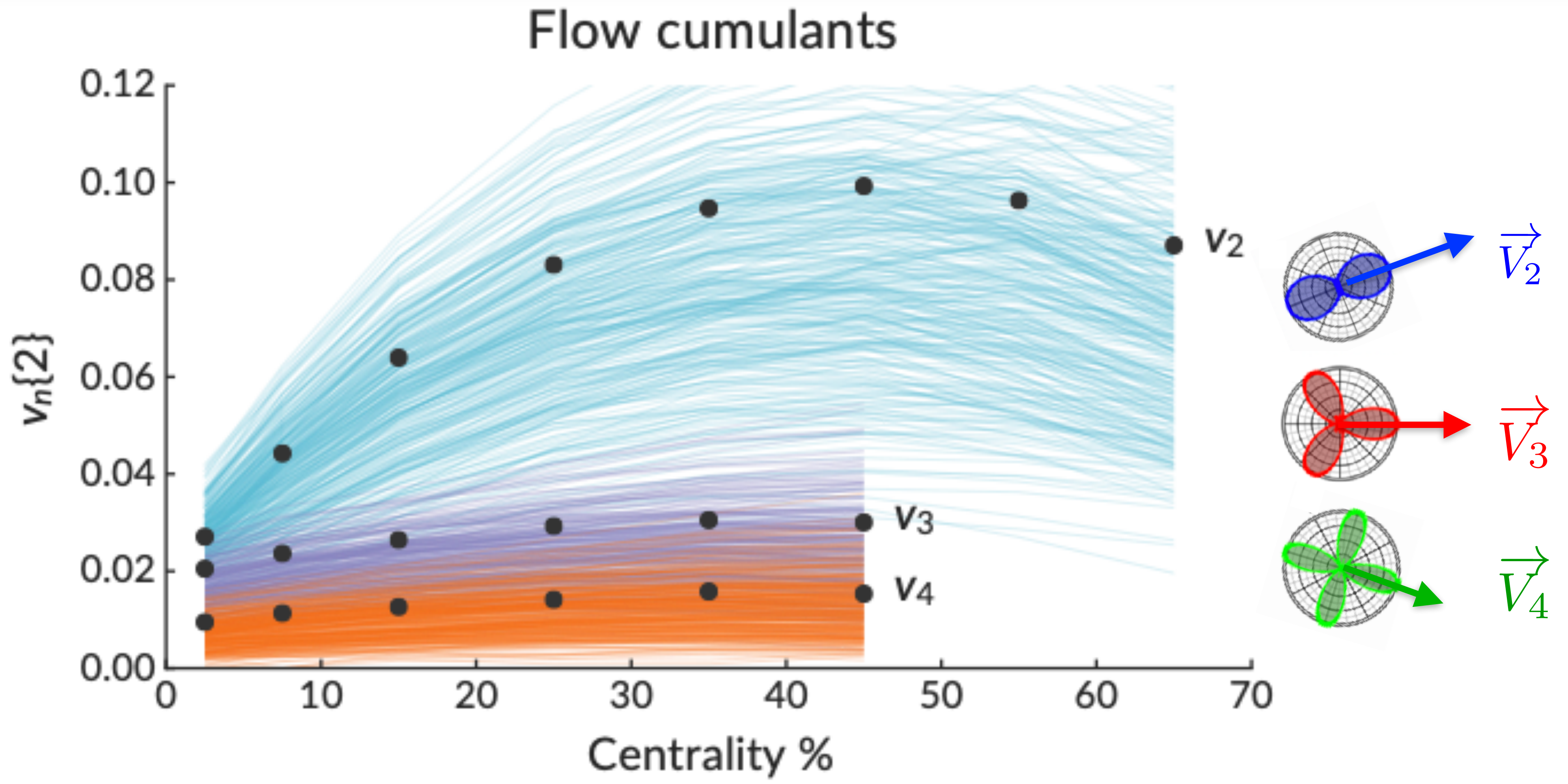
Initial shape ← Anisotropic flow → shear viscosity of QGP

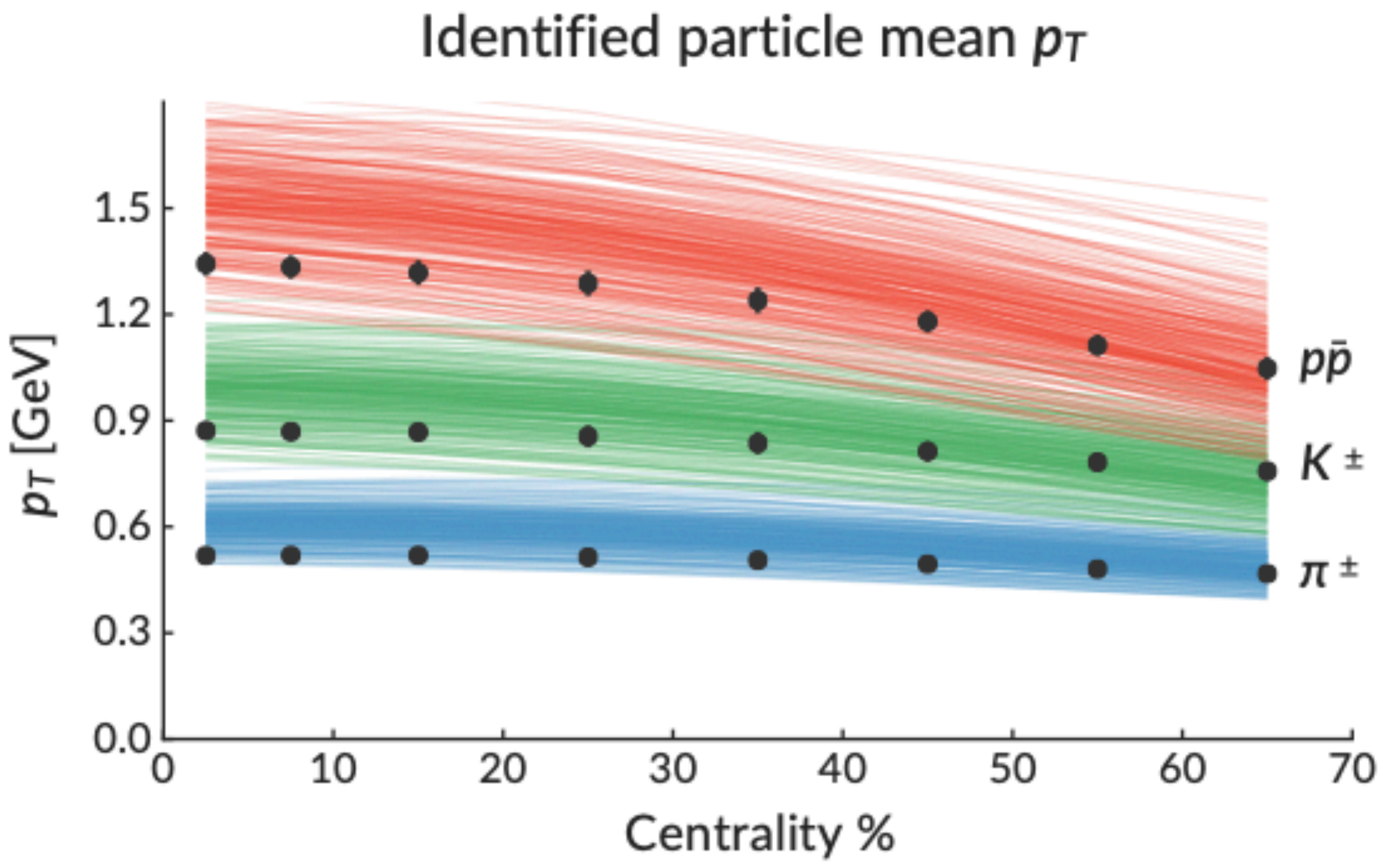
Initial size ← Radial flow → Bulk viscosity of QGP

Study the QGP transport properties with collective flow







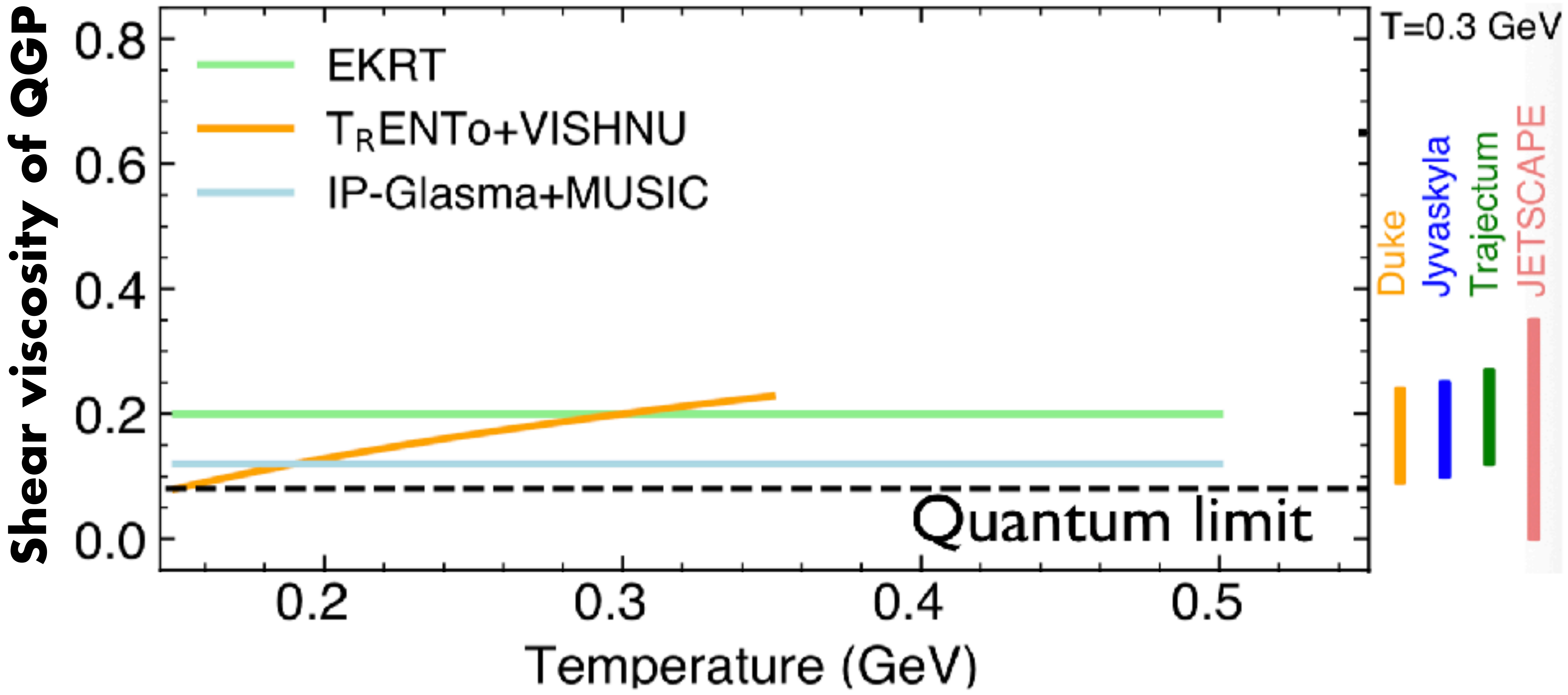


Primary goal of high-energy nuclear collisions: QGP

Perfect fluid

ALICE, Eur. Phys. J. C 84 (2024) 813
(571 citations)

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)*

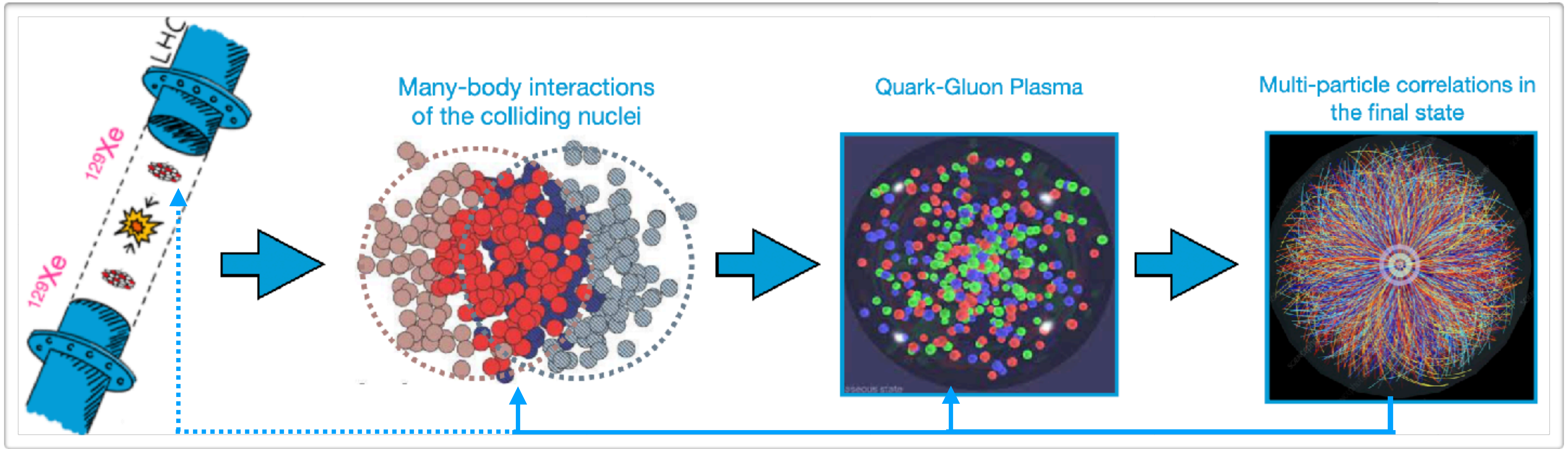


Current best understanding on the time evolution of QGP (Early Universe)

η/s(T) is very close to 1/4π (Quantum limit) -> Perfect fluid

Details, also see talk: Huichao Song @ Wednesday
Maxim Virta @ Thursday

Nuclear Structure <— initial conditions <— QGP

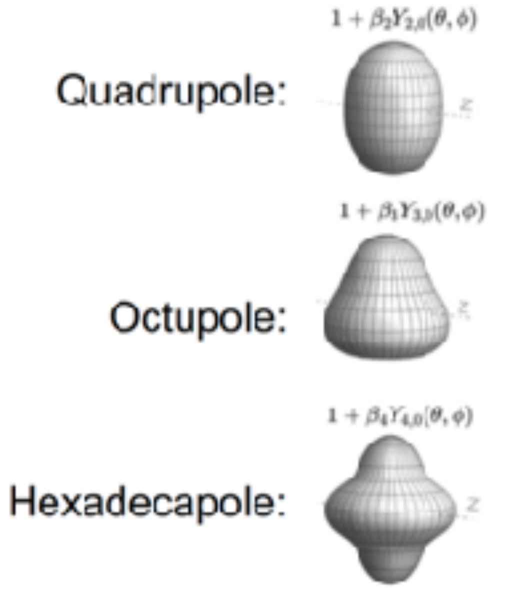


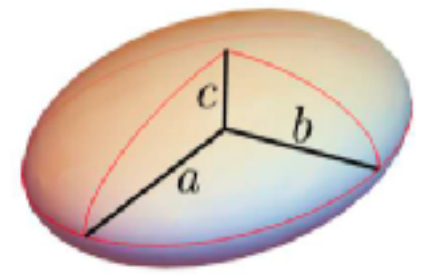
Starting point:

✓ One-body nucleon density distributions with W-S including NS parameters

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

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



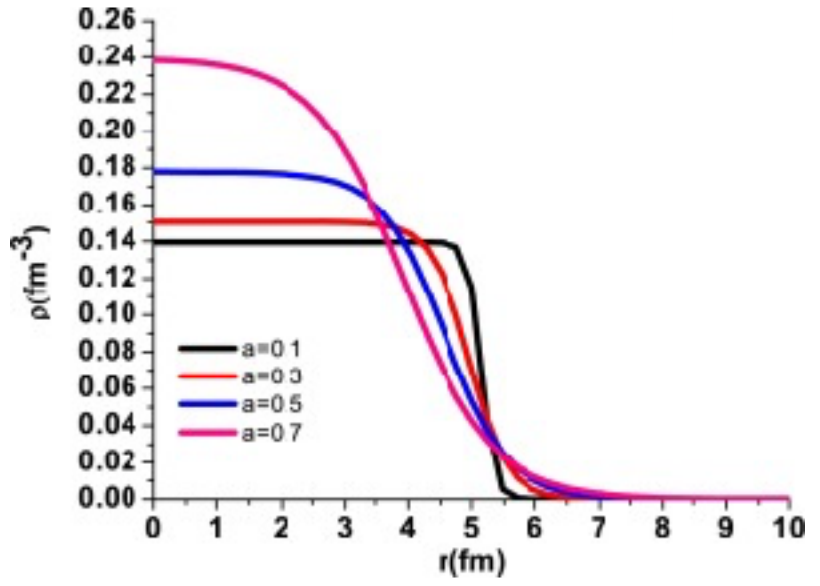


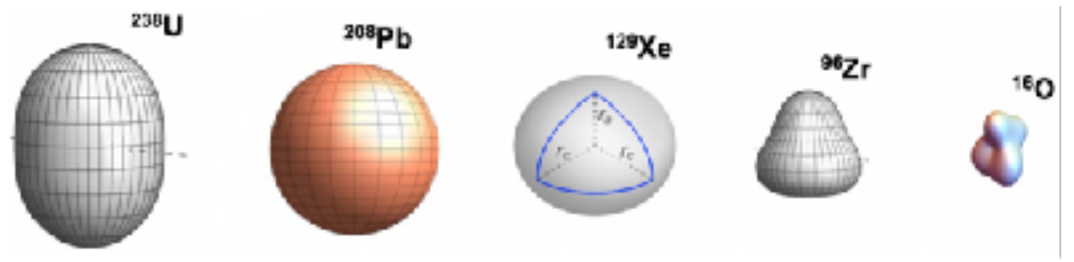
$0 \leq \gamma \leq \pi/3$

Prolate: a=b<c → β_2, γ=0

Oblate: a<b=c → β_2, γ=π/3

Triaxial: a<b<c → β_2, γ=π/6





New research directions

Venue	Workshop	Participants	
BNL (2022.01)	RIKEN BNL Research Center Physics Opportunities from the RHIC Isobar Run This workshop will be held virtually. January 25–28, 2022	30 participants	
GSI (2022.05 & 10)	EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 1/2)	50 participants	
Saclay (2022.09)	 Deciphering nuclear phenomenology across energy scales	30 participants	
INT (2023.2)	INSTITUTE for NUCLEAR THEORY INT PROGRAM INT-23-1A Intersection of nuclear structure and high-energy nuclear collisions	30 participants	
NBI (2023.6)	 The VII-th International Conference on the Initial Stages of High-Energy Nuclear Collisions (IS2023), Copenhagen.	220+ participants	← New Track
PKU (2024.4)	Exploring nuclear physics across energy scales 2024: intersection between nuclear structure and high energy nuclear collisions	200+ participants	
CERN (2024.10)	Light ion collisions at the LHC	200+ participants	
Frankfurt (2025.4)	Quark Matter 2025	1100+ participants	← New Track
Fudan (2025.5)	Intersection of nuclear structure and high-energy nuclear collisions: 2025 Program and Workshop	100+ participants	
Taipei (2025.8)	The VIII[th] International Conference on the INITIAL STAGES of High-Energy Nuclear Collisions Taipei, Taiwan	150+ participants	← New Track
CERN (2025.12)	Light Ion Collisions at the LHC 2025	200+ participants	

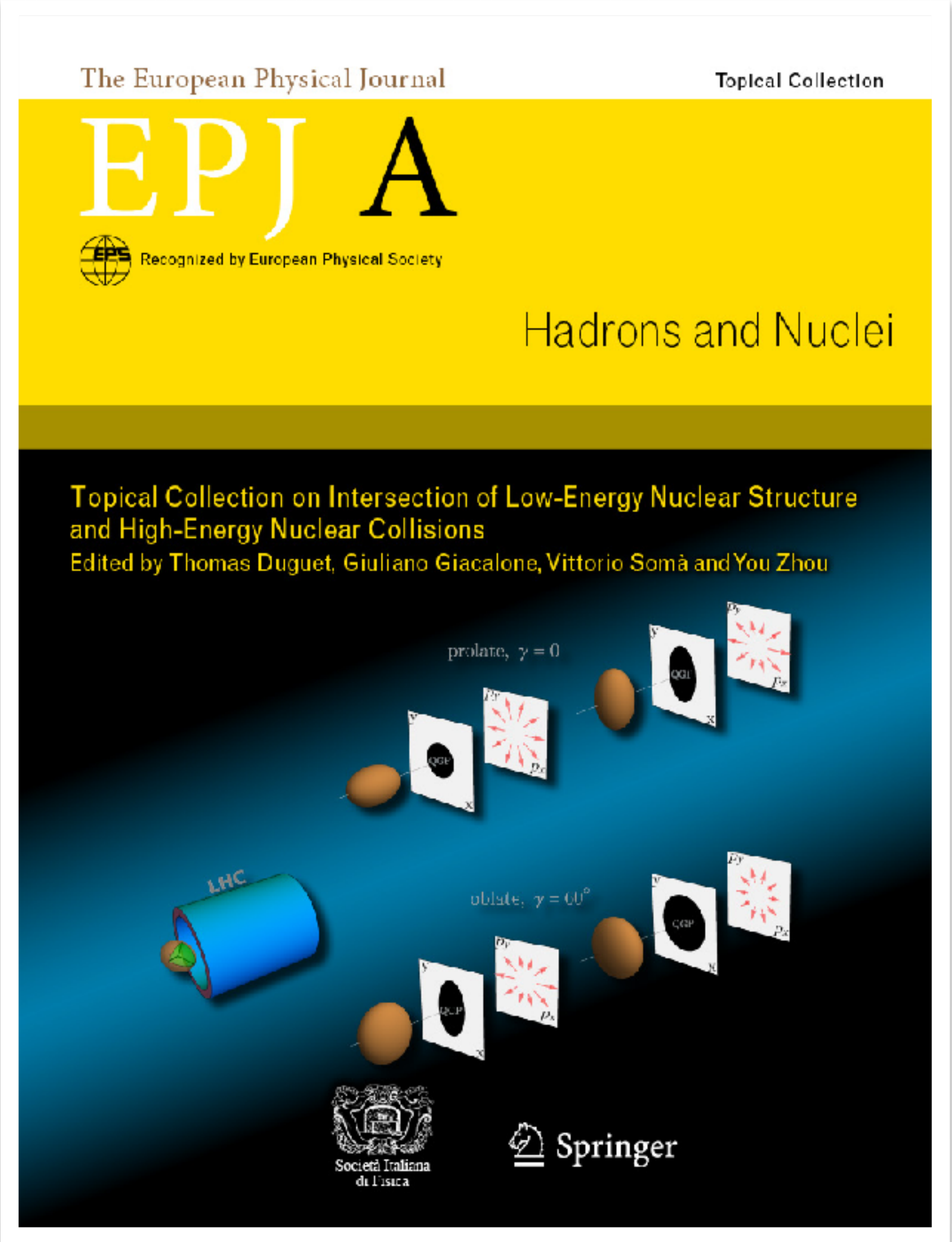
A topical collection

EPJA Topical Collection: Intersection of Low-Energy Nuclear Structure and High-Energy Nuclear Collisions

Published on 10 February 2026

Guest Editors: Thomas Duguet, Giuliano Giacalone, Vittorio Somà, You Zhou

High-energy heavy-ion physics and low-energy nuclear structure physics have historically been disconnected fields. The hydrodynamic description of the quark-gluon plasma (QGP) requires input from nuclear structure to model the initial states of the colliding nuclei, but until 2015 or so, most phenomenological studies have relied on simplified nuclear models, assuming spherical charge distributions and ignoring features like neutron skins or deformations. Advances in both theory and experiment now show that the hydrodynamic evolution of the QGP is sensitive to the detailed features of the colliding nuclei, with remarkable consequences for experimental observables.



Nuclear Structure @ HE: a paradigm-shift research

❖ Phase I: **Emergence**

➡ Emergence of Nuclear Structure Effects in Ultra-Relativistic Collisions

❖ Phase II: **Sensitivity → Extraction**

➡ From Sensitivity to Extraction: Probing Nuclear Structure with Collective Flow

❖ Phase III: **Unification and validation**

➡ Toward a Unified Framework: nuclear structure across energy scale

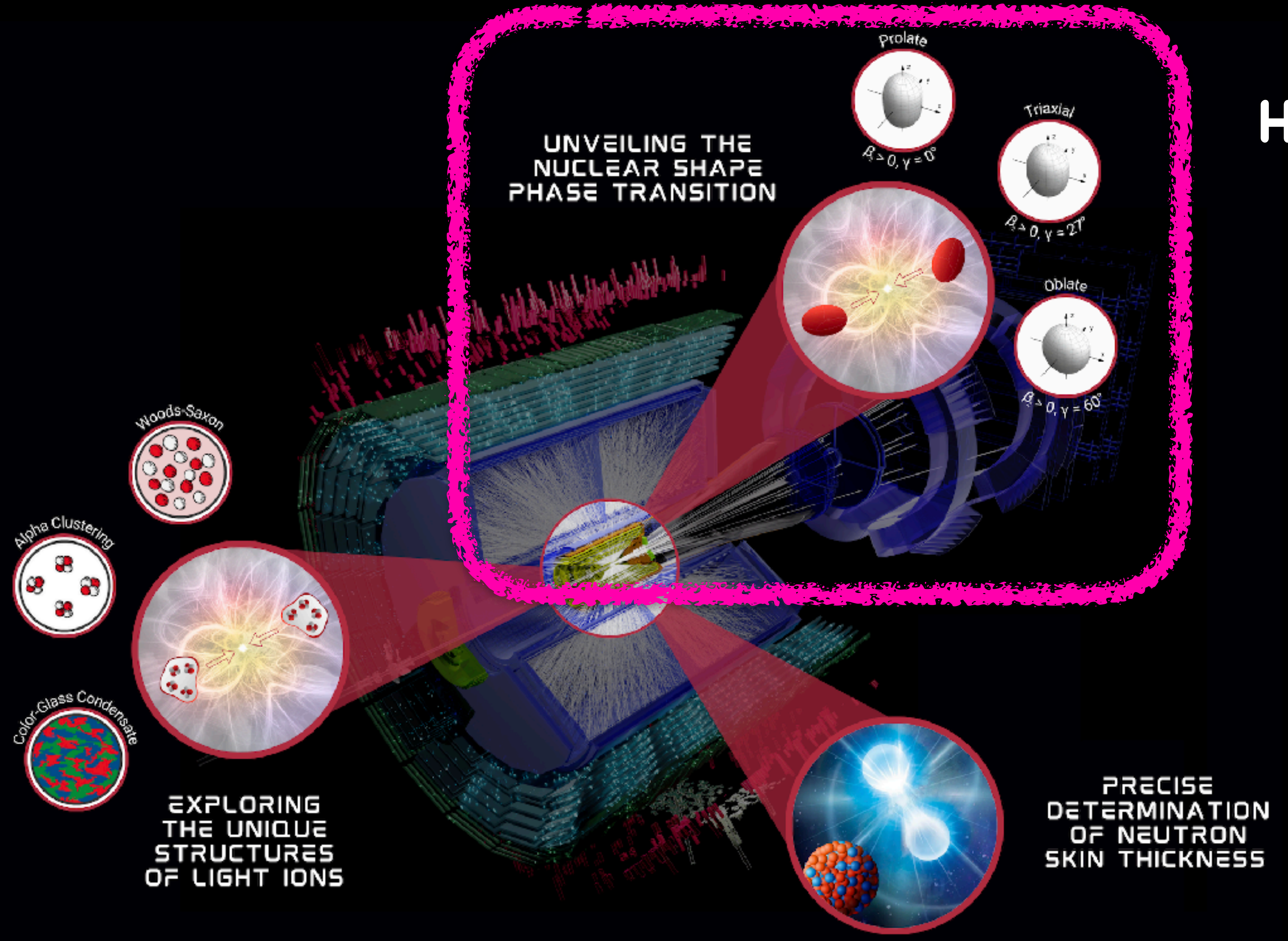
➡ Validation with Light-Ion Collisions

❖ Phase IV: **Tomography / Precision Era**

➡ Toward Nuclear Structure Tomography at the LHC

❖ Phase I: **Emergence**

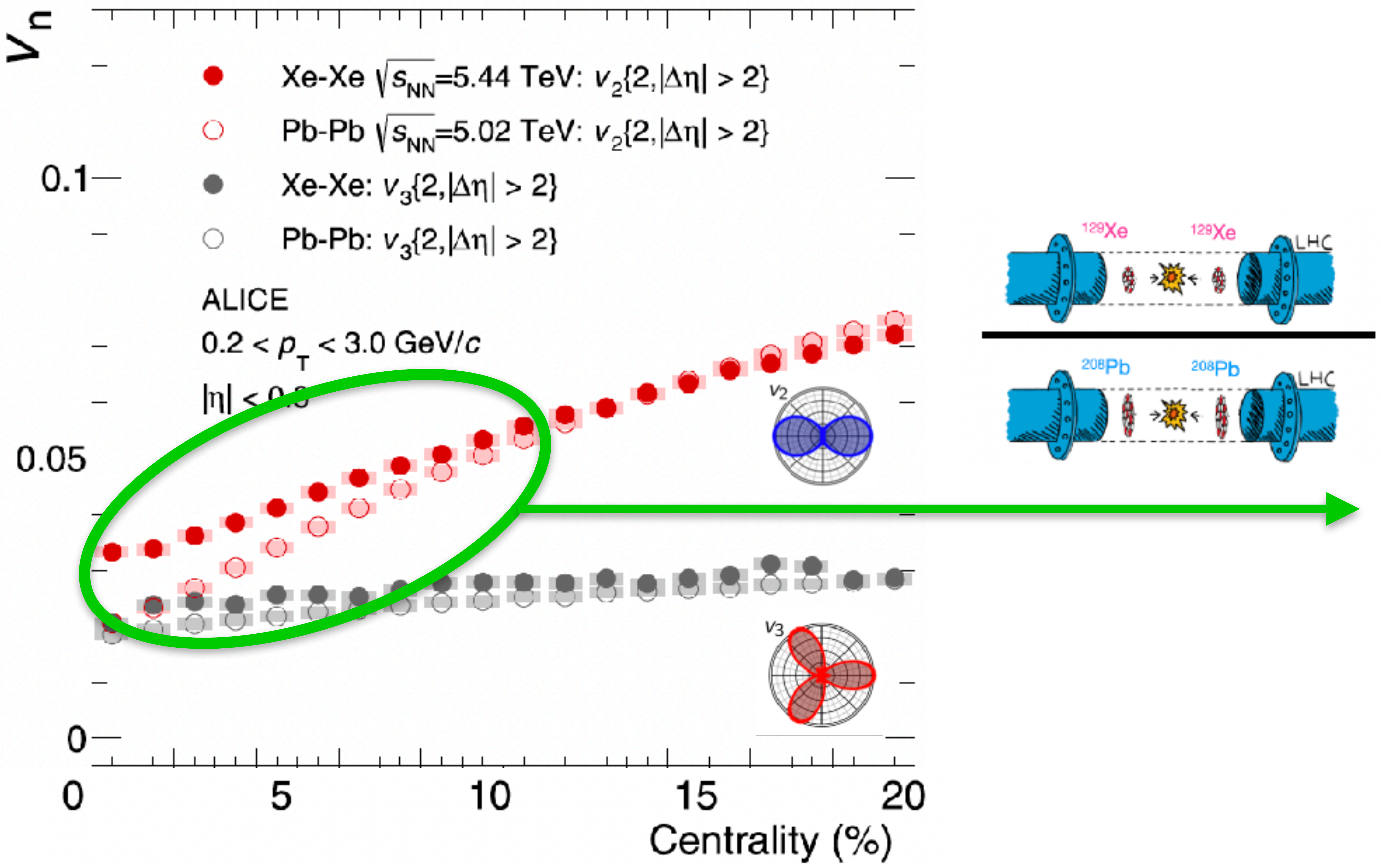
➡ Emergence of Nuclear Structure Effects in Ultra-Relativistic Collisions



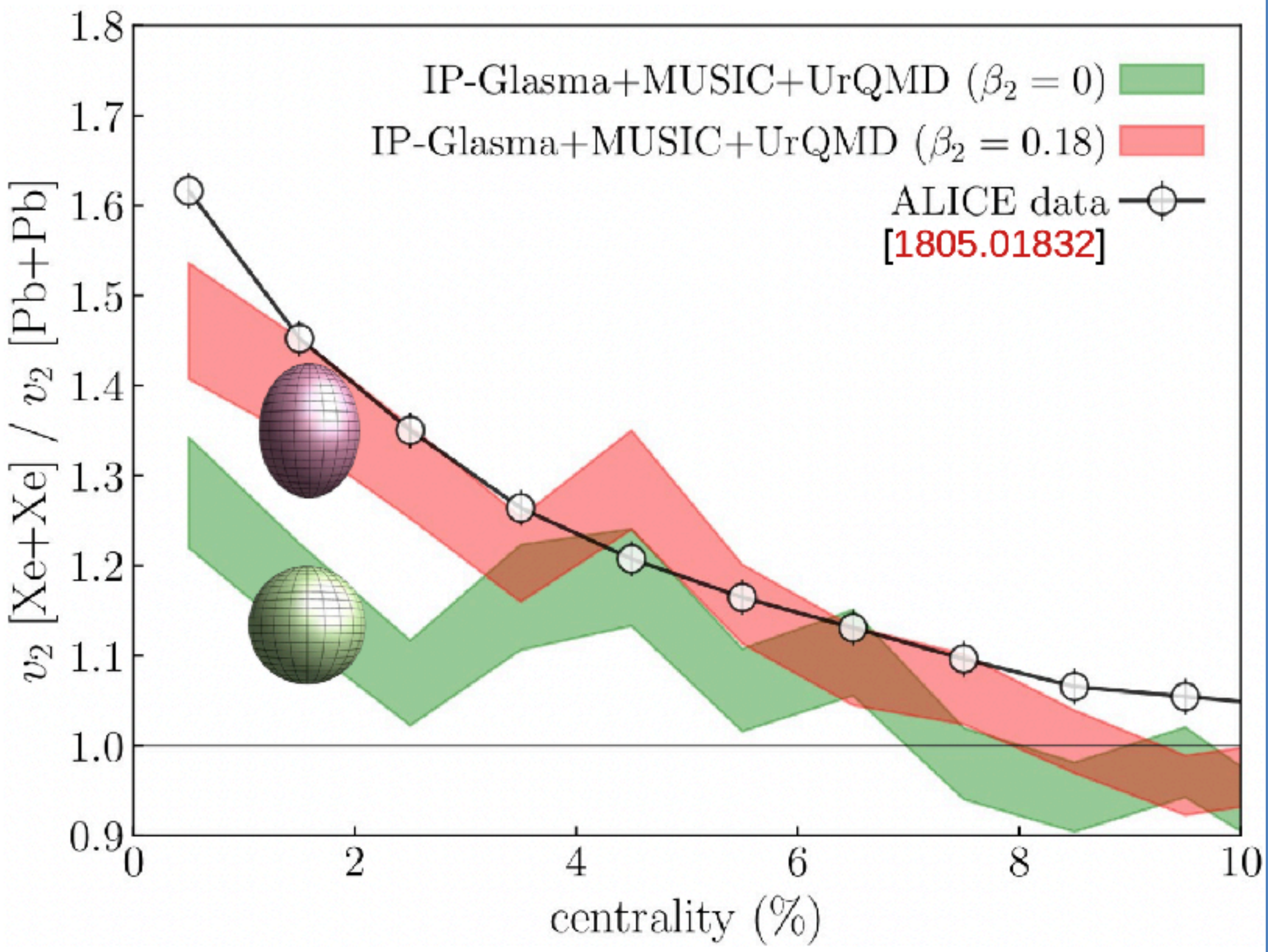
Heavy nuclei

Effect of Nuclear structure of ^{129}Xe with flow v_n

ALICE, Physics Letters B 784 (2018) 82



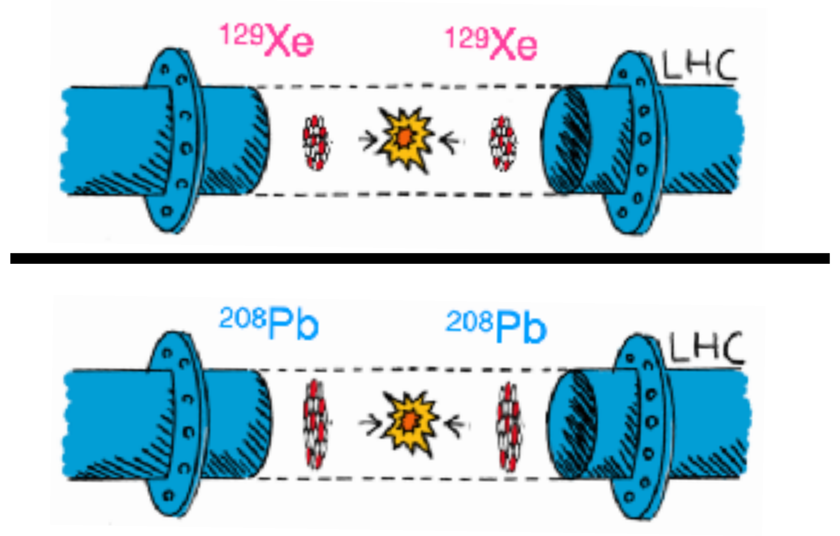
Physics Letters B 784 (2018) 82

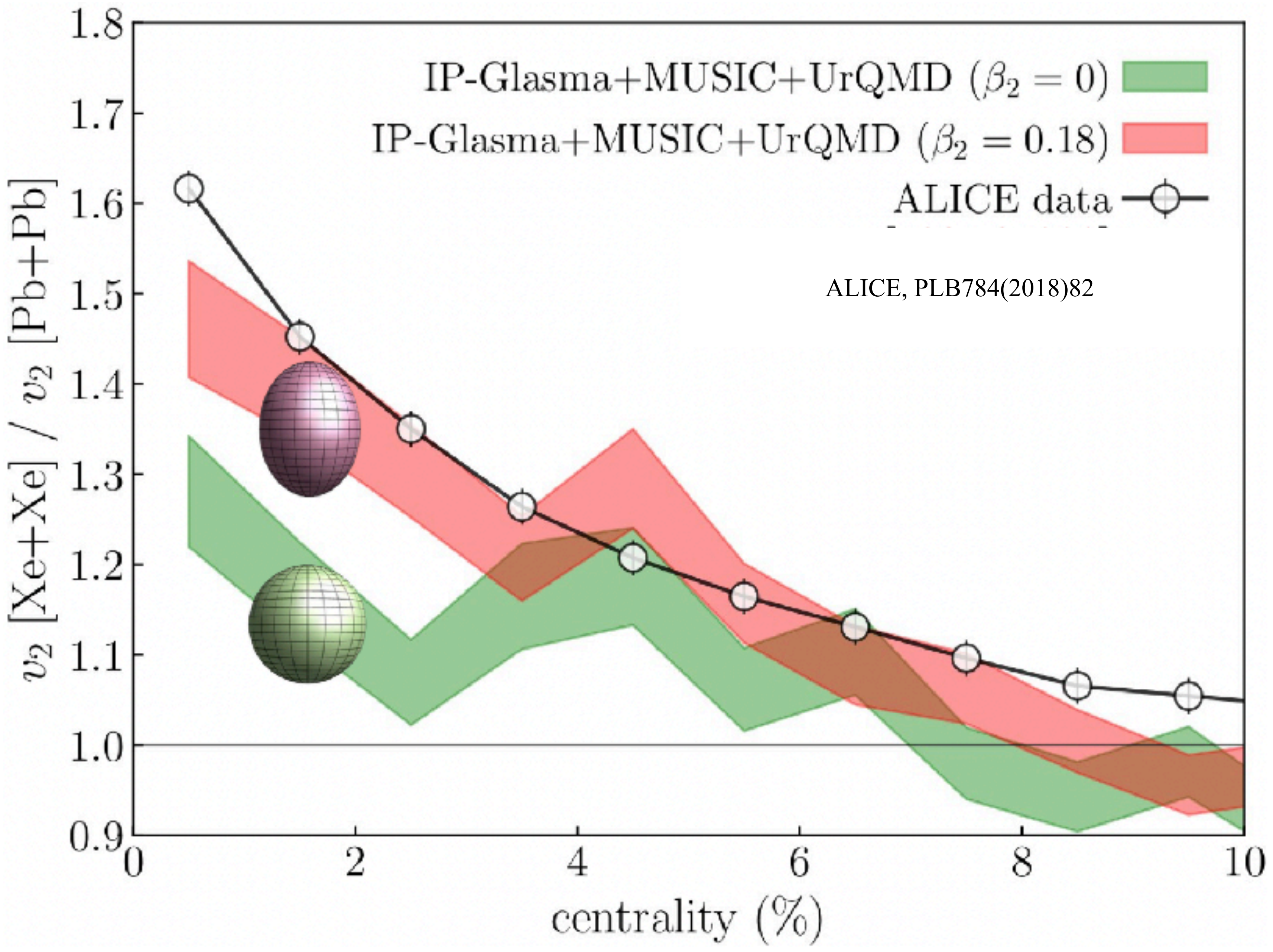


❖ Significant v_2 enhancements in central Xe-Xe collisions than in Pb-Pb collisions

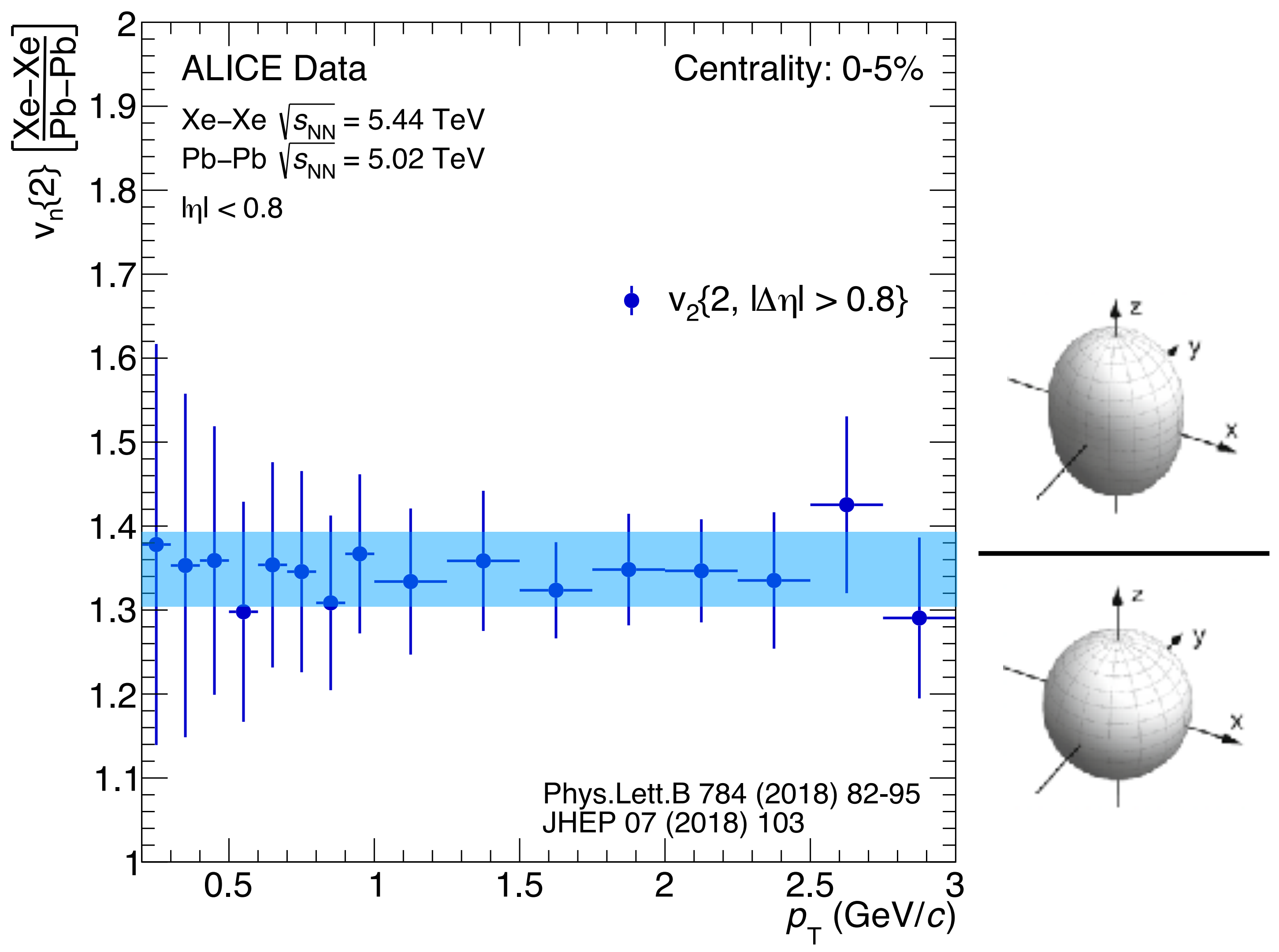
- The ratio between two similar systems (in size) cancel out most final state effect -> initial conditions
- The observed enhancement is due to the NS effect, originated from large β_2 deformation

Effect of Nuclear structure of ^{129}Xe on ***differential*** flow

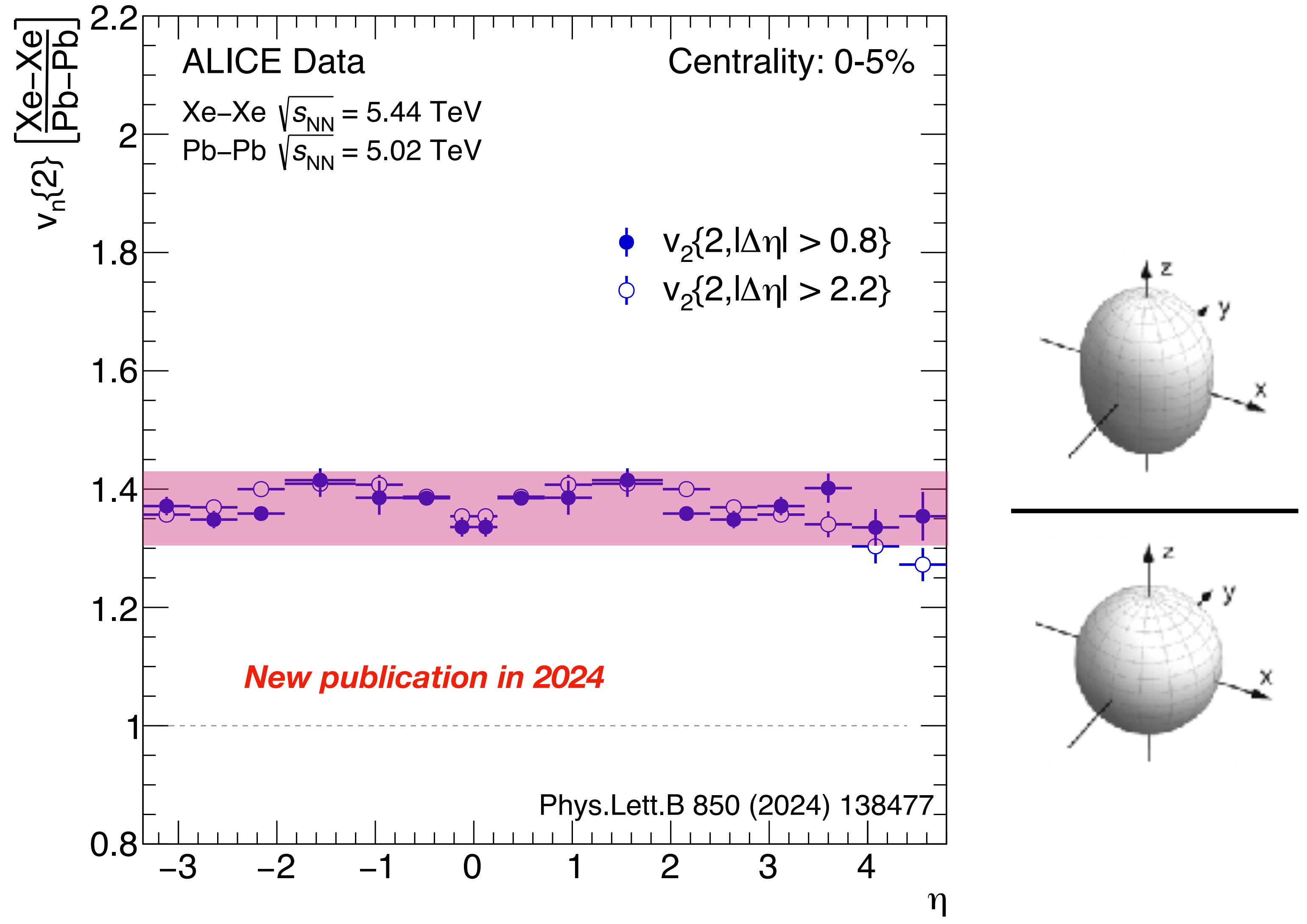




p_T-differential



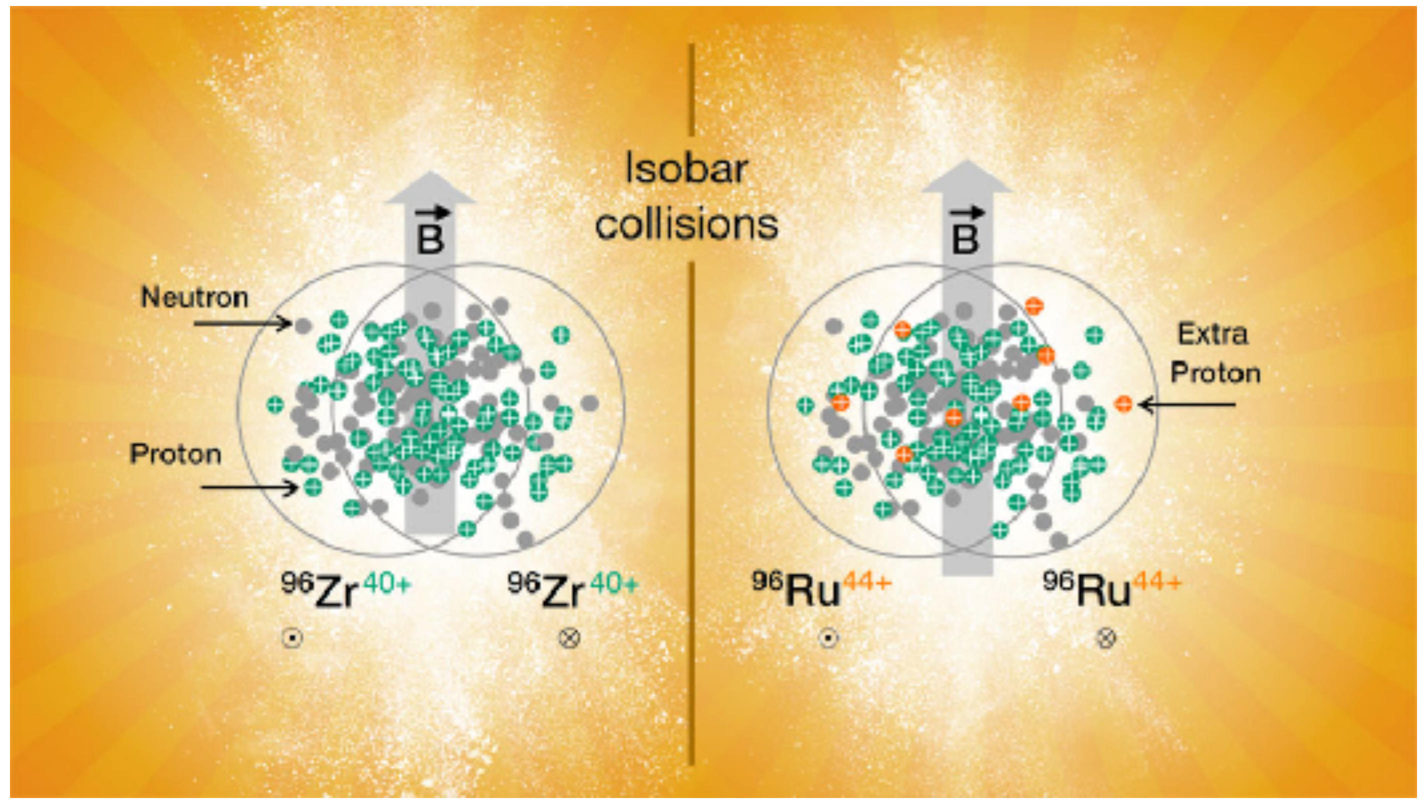
η-differential



❖For the first time observe the impact of NS over a very wide kinematic range ($-3.5 < \eta < 5.0$)

- New input for the low-x physics

Meanwhile at RHIC: isobar runs



Since then, pioneering work has been done,
many of which are done by the participants in this workshop!

- Hydrodynamical flow and geometrical response, with a focus on connection to nuclear structure
- Chiral Magnetic Effect (CME), vorticity, and effects of strong EM field
- Longitudinal fluctuations and correlations related to the transport of conserved charges
- Nuclear PDF and transition from collective flow to jet quenching

ExtreMe Matter Institute EMMI

EMMI Rapid Reaction Task Force

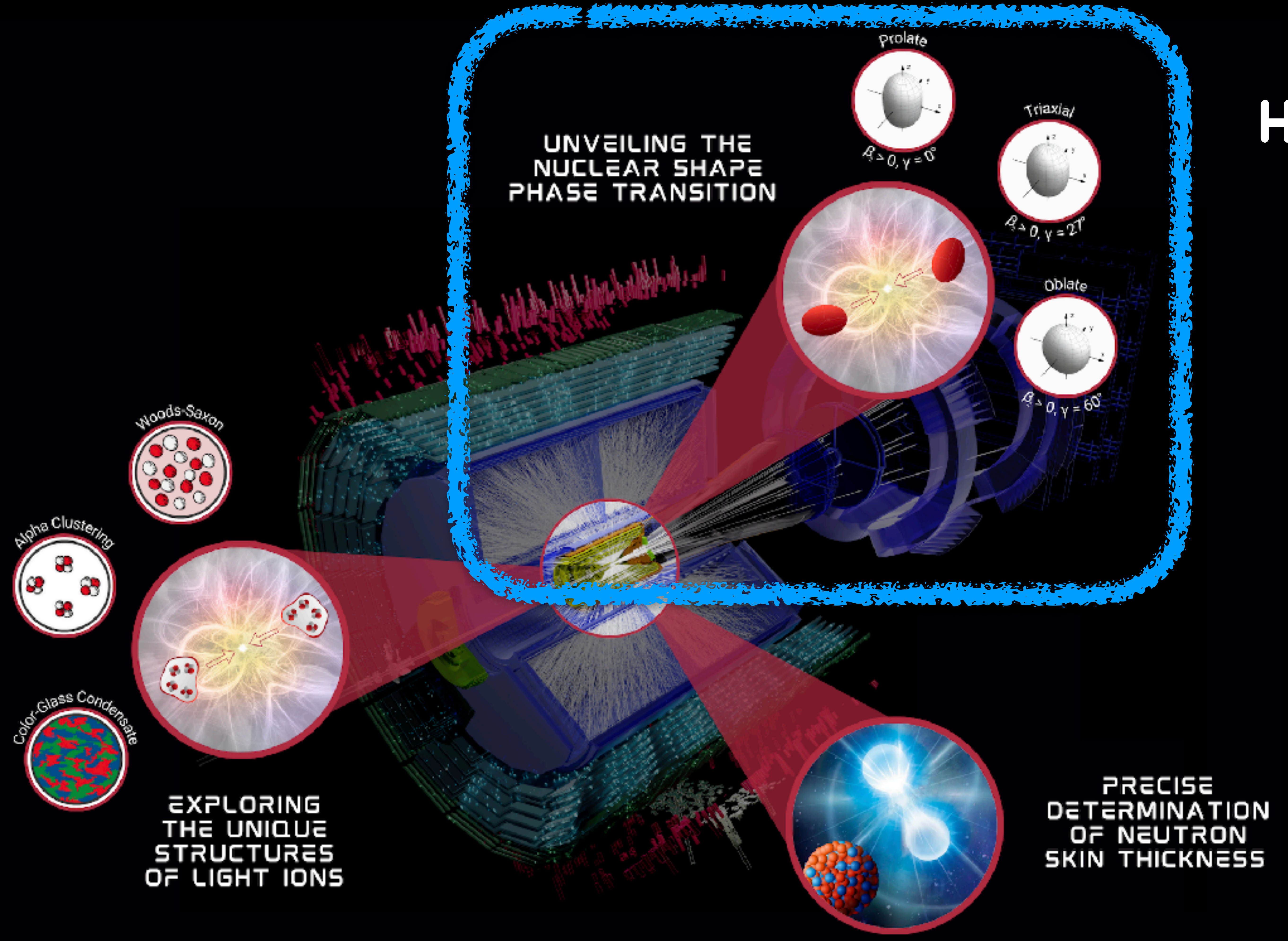
Nuclear Physics Confronts Relativistic Collisions of Isobars

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

High-energy collisions of the A=96 isobars ^{96}Zr and ^{96}Ru have been performed in 2018 at the Relativistic Heavy Ion Collider (RHIC) as a means to probe effects of local parity violation in the strong sector, that would manifest as deviations from unity in the ratio of observables taken between $^{96}Zr+^{96}Zr$ and $^{96}Ru+^{96}Ru$ collisions. Recently released measurements of such ratios reveal deviations from unity. However, such observations are primarily caused by the two collided isobars having different radial profiles and intrinsic deformations. To make progress in understanding RHIC data, we will gather nuclear physicists across the energy spectrum to answer the following question: Does the combined effort of state-of-the-art low-energy nuclear structure physics and high-energy heavy-ion physics allow us to understand the observations made in isobar collisions at RHIC?

❖Phase II: **Sensitivity → Extraction**

➡ From Sensitivity to Extraction: Probing Nuclear Structure with Collective Flow

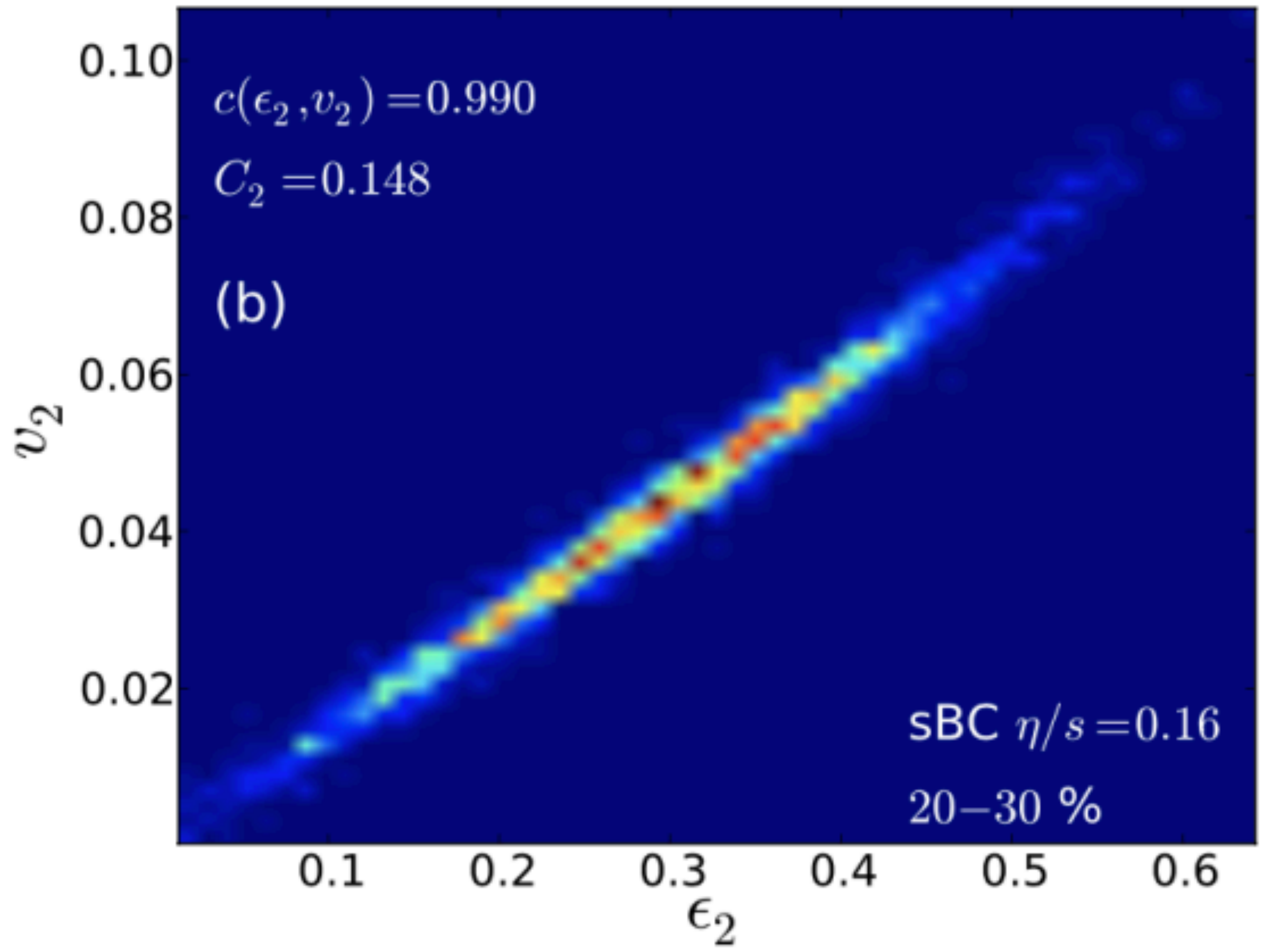


Heavy nuclei

Probe Nuclear Structure with anisotropic flow

❖ Shape of the fireball: Anisotropic flow

$V_n \propto \mathcal{E}_n$



[H. Niemi et al., PRC 87 (2013) 5, 054901]

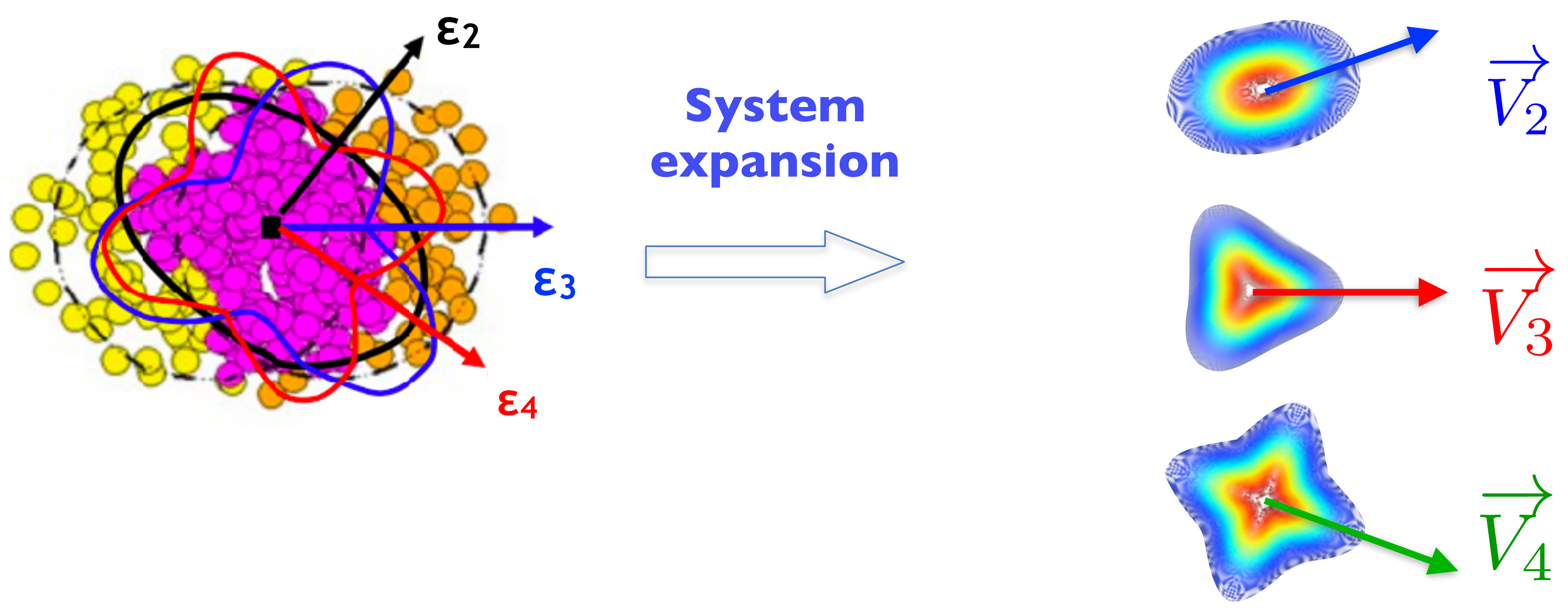
Details, also see talk:
Giuliano Giacalone @ Monday
Wenyao Ke @ Monday

Initial state

$\vec{\varepsilon_n} = \varepsilon_n \, e^{in\Phi_n}$

Final state

$\vec{V_n} = v_n \, e^{in\Psi_n}$



$P(\varepsilon_m, \varepsilon_n, \varepsilon_k, ..., \Phi_m, \Phi_n, \Phi_k, ...)$ ⇒ $P(v_m, v_n, v_k, ..., \Psi_m, \Psi_n, \Psi_k, ...)$

How does v_n fluctuate	How does ψ_n fluctuate	How do v_n and v_m correlate	How do ψ_n and ψ_m correlate
$P(v_n)$	$P(\Psi_n)$	$P(v_m, v_n, v_k, ...)$	$P(\Psi_m, \Psi_n, \Psi_k, ...)$

observables:

- $v_n\{m\}$
- Flow decorrelation $r_n(p_T^a, p_T^b)$
- Symmetric cumulant SC(m,n)
- Non-linear flow $\rho_{m,nk}$

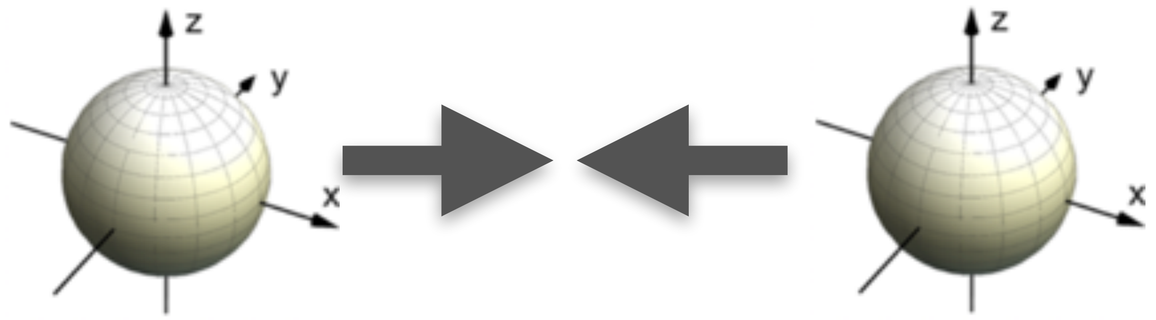
sensitivity of anisotropic flow to nuclear structure

Eur. Phys. J. A (2023) 59:279
https://doi.org/10.1140/epja/s10050-023-01194-2
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Theoretical Physics

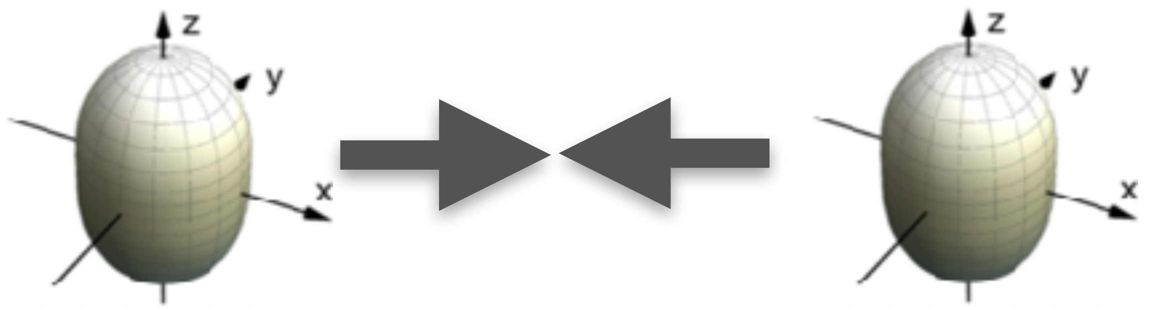
Probe nuclear structure using the anisotropic flow at the Large Hadron Collider

Zhiyong Lu[1], Mingrui Zhao[1,2], Xiaomei Li[1], Jiangyong Jia[3,4], You Zhou[2,a]

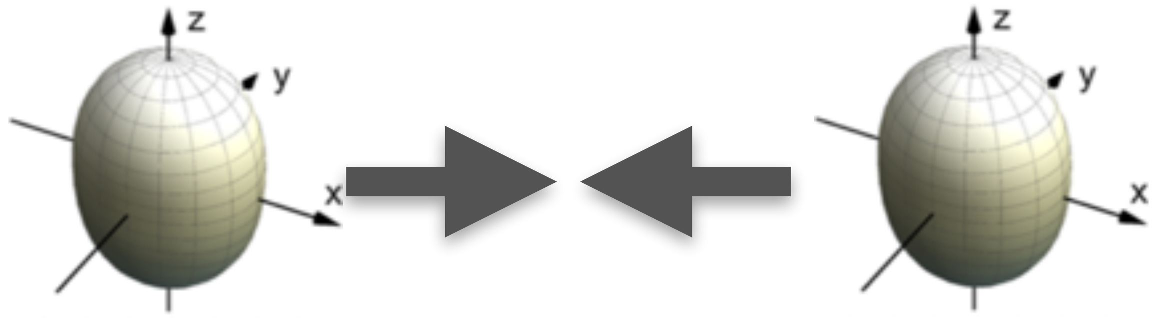
spheric
($\beta_2 = 0$)



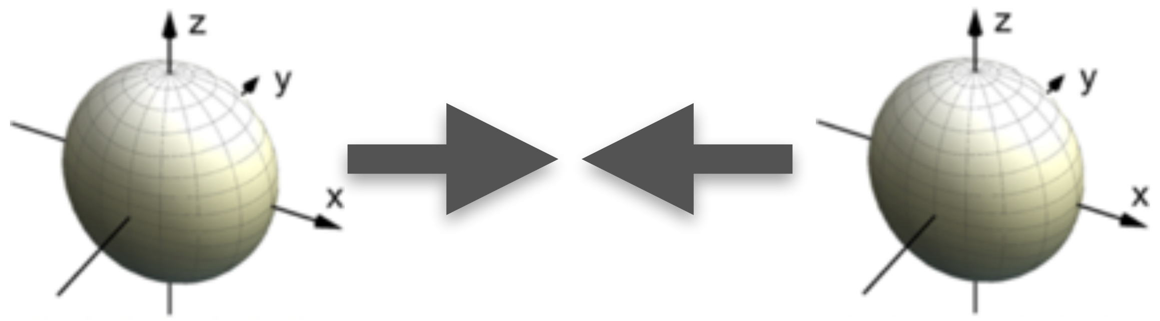
Prolate
($\beta_2 > 0, \gamma=0$)

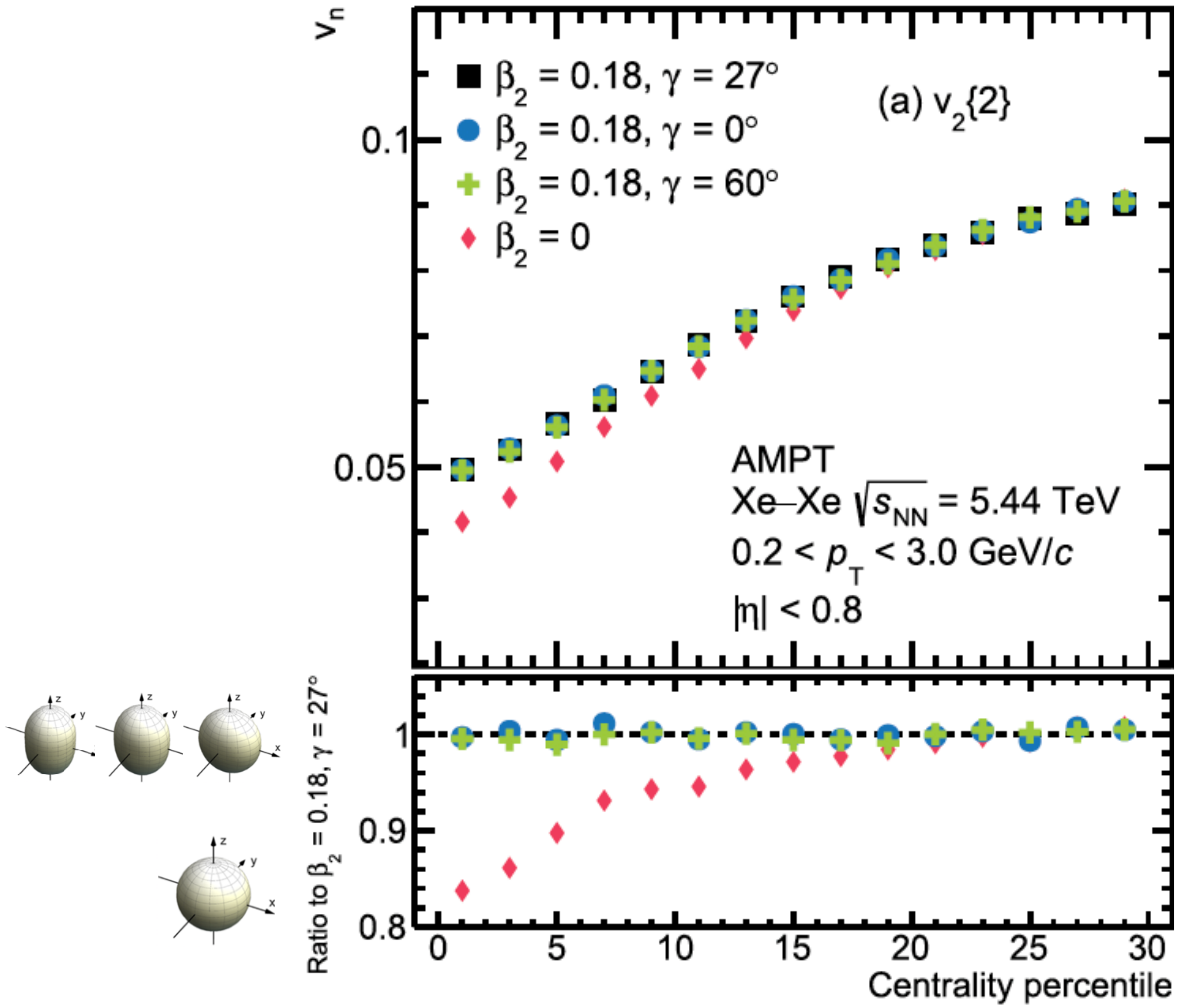


Triaxial
($\beta_2 > 0, \gamma=30°$)



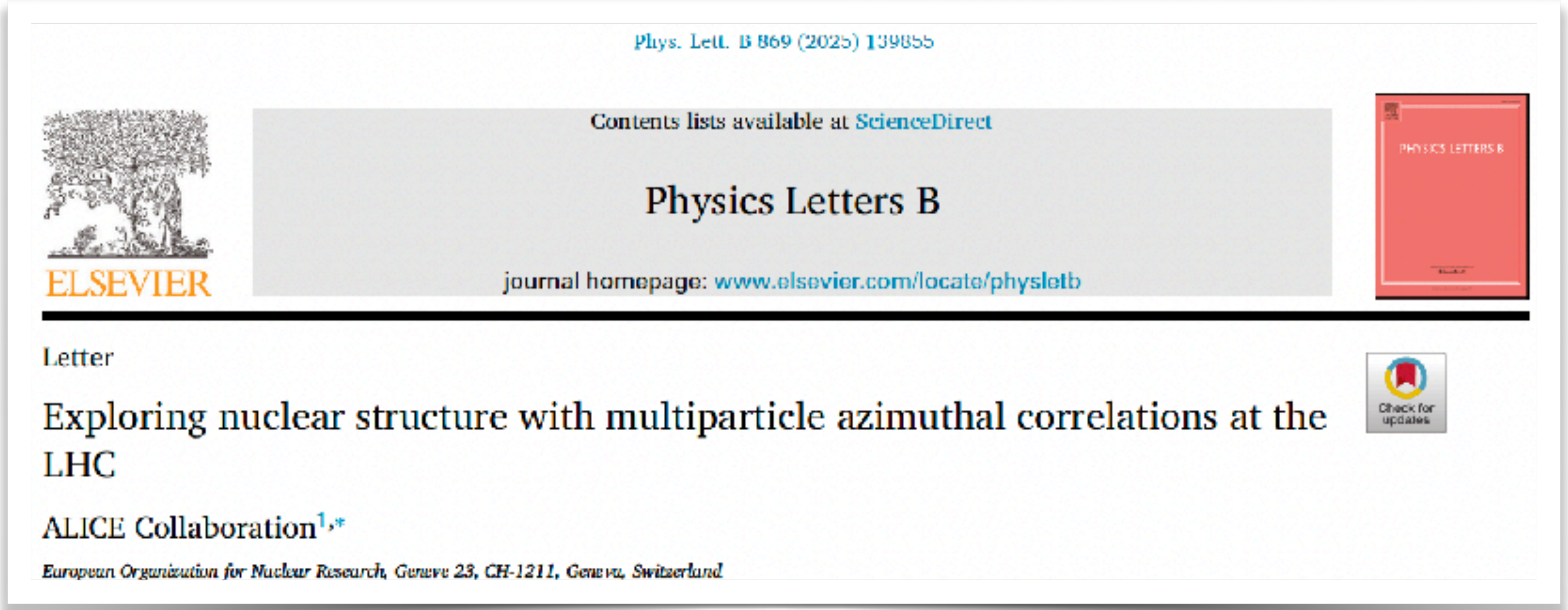
Oblate
($\beta_2 > 0, \gamma=60°$)





- ❖ Significant v_2 enhancements in central Xe-Xe collisions, originated from large deformation β_2
- ❖ No difference observed from the results with different γ values, no impact of triaxial structure in v_2

Nuclear structure of ^{129}Xe with systematic flow measurements


Phys. Lett. B 869 (2025) 139855

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

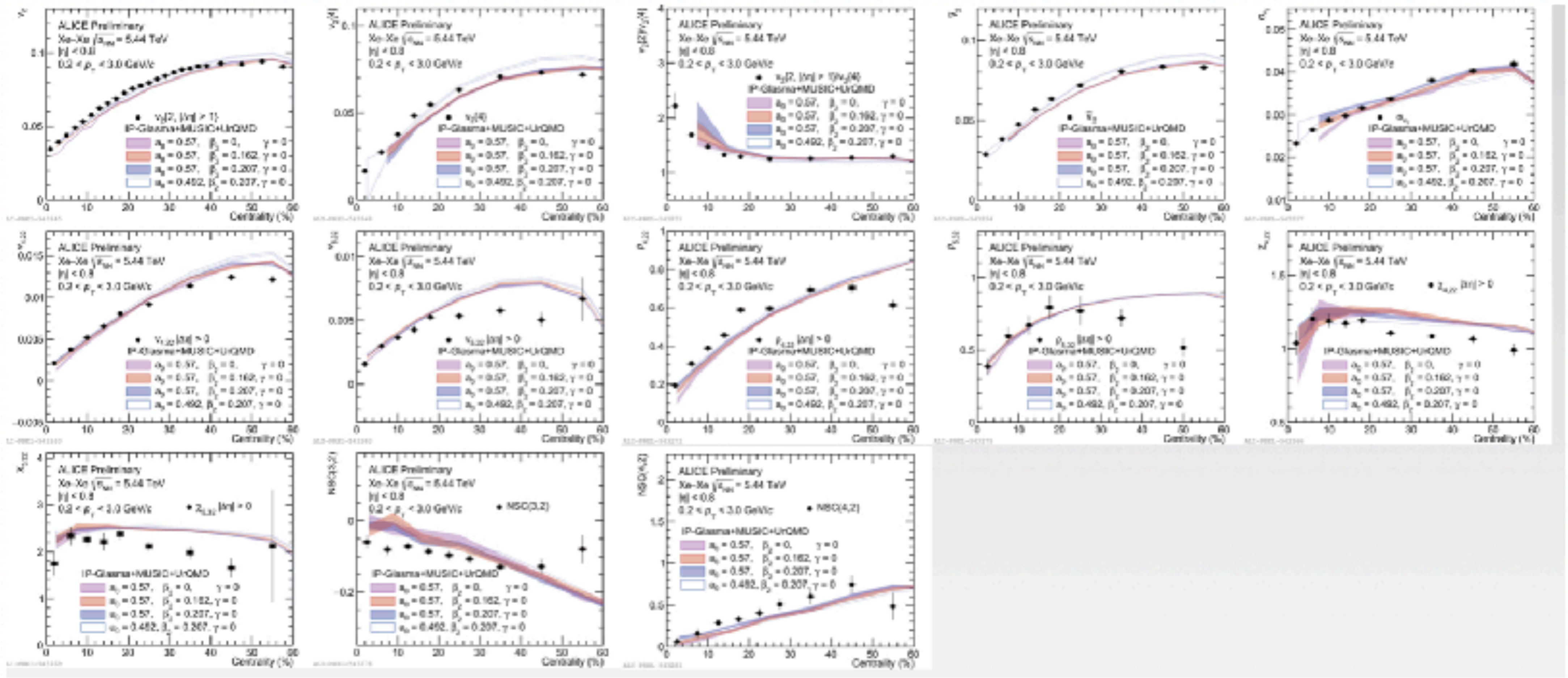
ELSEVIER

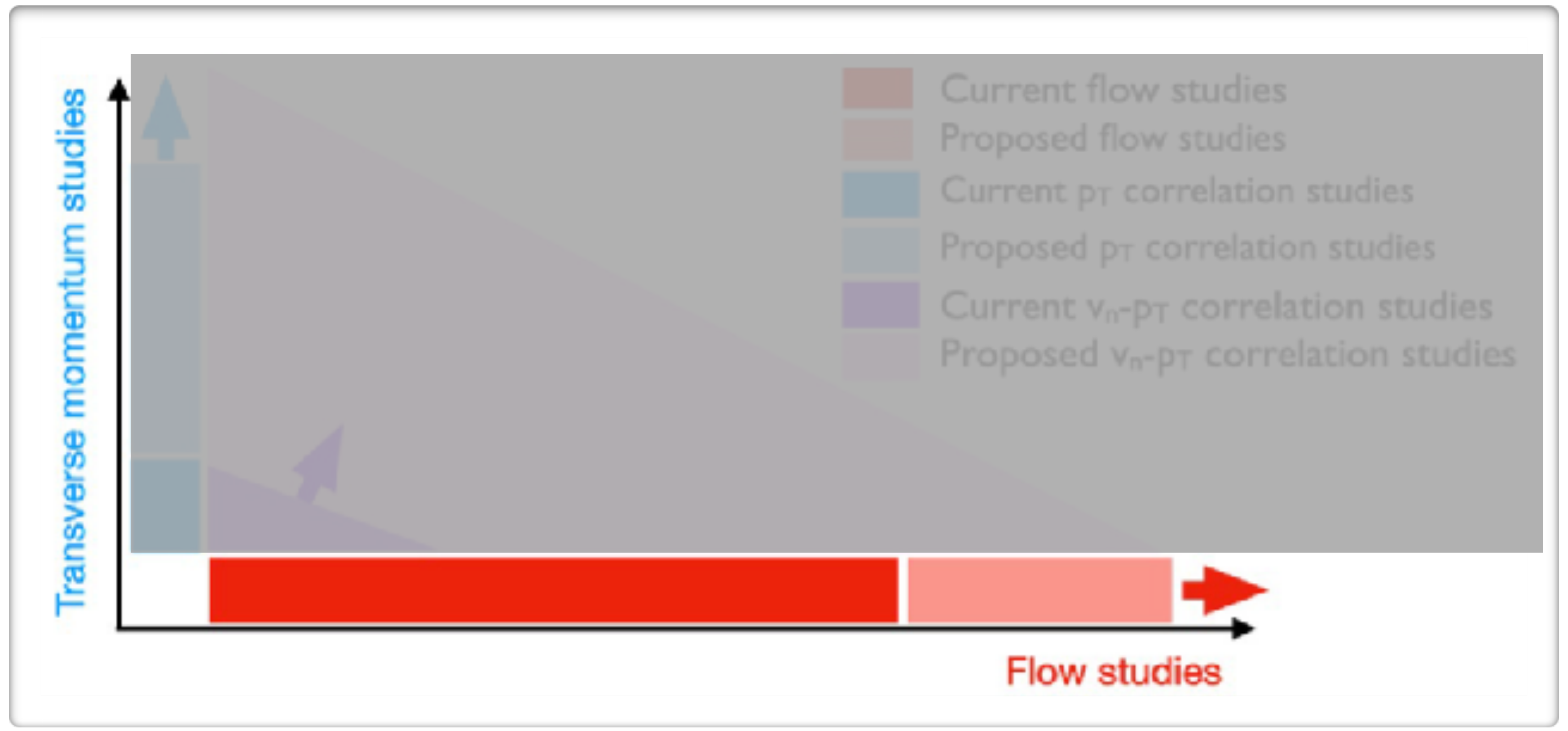
Letter

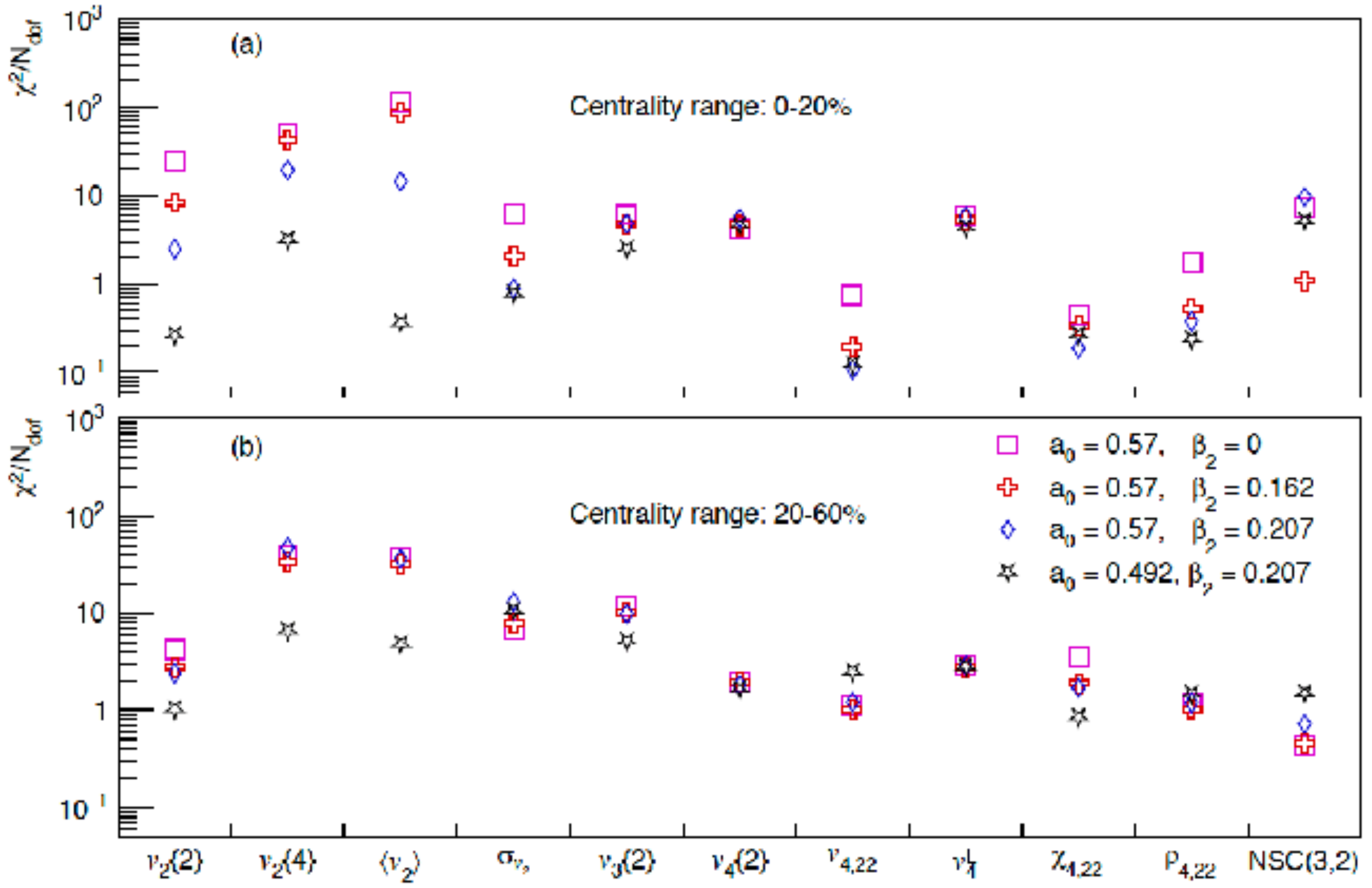
Exploring nuclear structure with multiparticle azimuthal correlations at the LHC

ALICE Collaboration[1,*]

European Organization for Nuclear Research, Geneva 23, CH-1211, Geneva, Switzerland

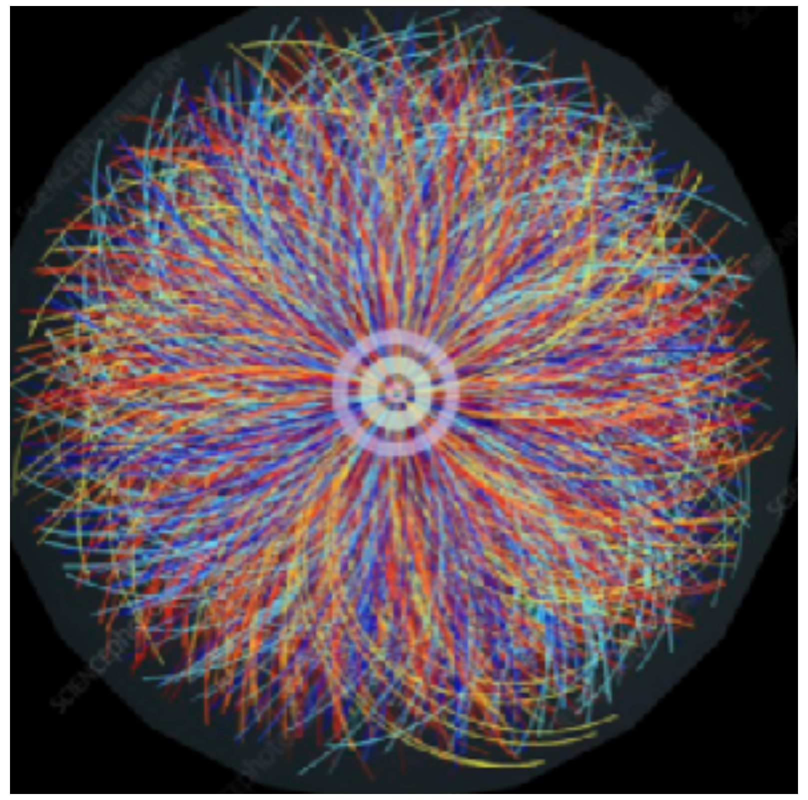






- ❖Overall, calculations with a_0 = 0.492 and β_2 = 0.207 describes the flow measurements better in Xe–Xe collisions
  - Compatible with low-energy nuclear structure (MeV energy scale).

Probe Nuclear Structure with radial flow



$[p_T]$
$[p_T^2]$
$[p_T^3]$
$[p_T^4]$
.
.
.
$[p_T^m]$

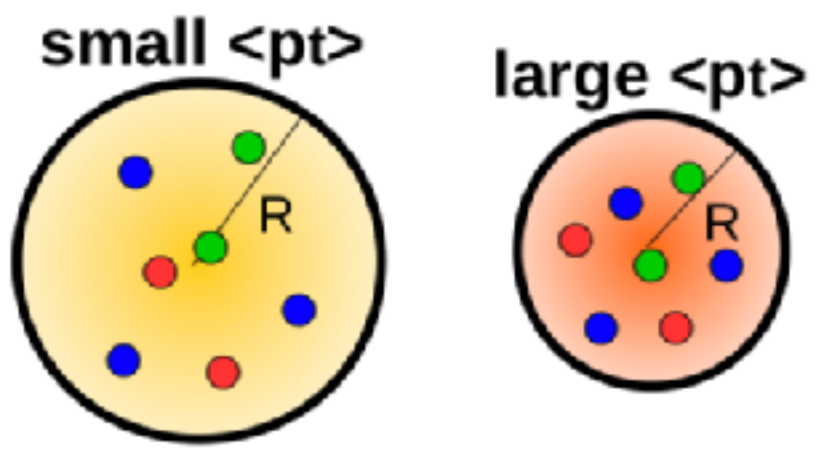
S. Bhatta etc., PRC 105 (2022) 2, 024904
E. G. Nielsen etc., EPJA (2024) 60, 38

Final state Cumulant	Initial state Cumulant	Liquid-drop Model
κ_2	$\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle$	$\frac{1}{32\pi}\langle\beta_2^2\rangle$
κ_3	$\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^3\right\rangle$	$\frac{\sqrt{5}}{896\pi^{3/2}}\langle\cos(3\gamma)\beta_2^3\rangle$
κ_4	$\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^4\right\rangle-3\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle^2$	$-\frac{3}{14336\pi^2}(7\langle\beta_2^2\rangle^2-5\langle\beta_2^4\rangle)$
κ_5	$\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^5\right\rangle-10\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^3\right\rangle\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle$	$-\frac{5\sqrt{5}}{315392\pi^{5/2}}(11\langle\cos(3\gamma)\beta_2^3\rangle\langle\beta_2^2\rangle-5\langle\beta_2^5\rangle)$
κ_6	$\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^6\right\rangle-15\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^4\right\rangle\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle$	$\frac{5}{918412504\pi^3}(42042\langle\beta_2^2\rangle^3-5720\langle\cos(3\gamma)\beta_2^3\rangle^2$
	$+30\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle^3-10\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^3\right\rangle^2$	$-45045\langle\beta_2^2\rangle\langle\beta_2^4\rangle+8575\langle\beta_2^6\rangle+700\langle\cos(6\gamma)\beta_2^6\rangle)$
κ_7	$\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^7\right\rangle-21\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^5\right\rangle\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle$	$-\frac{15\sqrt{5}}{524812288}(2002\langle\beta_2^2\rangle^2\langle\cos(3\gamma)\beta_2^3\rangle$
	$+210\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^3\right\rangle\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle^2$	$+715\langle\cos(3\gamma)\beta_2^3\rangle\langle\beta_2^4\rangle$
	$-35\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^3\right\rangle\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^4\right\rangle$	$+910\langle\cos(3\gamma)\beta_2^5\rangle\langle\beta_2^2\rangle-175\langle\cos(3\gamma)\beta_2^7\rangle)$
κ_8	$\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^8\right\rangle-28\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^6\right\rangle\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle$	$\frac{5}{142748942336\pi^4}(2144142\langle\beta_2^2\rangle^4-3063060\langle\beta_2^2\rangle^2\langle\beta_2^4\rangle$
	$+420\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^4\right\rangle\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle^2$	$-340\langle\beta_2^2\rangle\Big(2288\langle\cos(3\gamma)\beta_2^3\rangle^2-35(49\langle\beta_2^6\rangle$
	$-35\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^4\right\rangle^2-630\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle^4$	$+4\langle\cos(6\gamma)\beta_2^6\rangle)\Big)+25\Big(21879\langle\beta_2^4\rangle^2$
	$+560\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^3\right\rangle^2\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^2\right\rangle$	$+14144\langle\cos(3\gamma)\beta_2^3\rangle\langle\cos(3\gamma)\beta_2^5\rangle$
	$-56\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^5\right\rangle\cdot\left\langle\left(\frac{\delta d_\perp}{d_\perp}\right)^3\right\rangle$	$-35(79\langle\beta_2^8\rangle+16\langle\cos(6\gamma)\beta_2^8\rangle)\Big)$

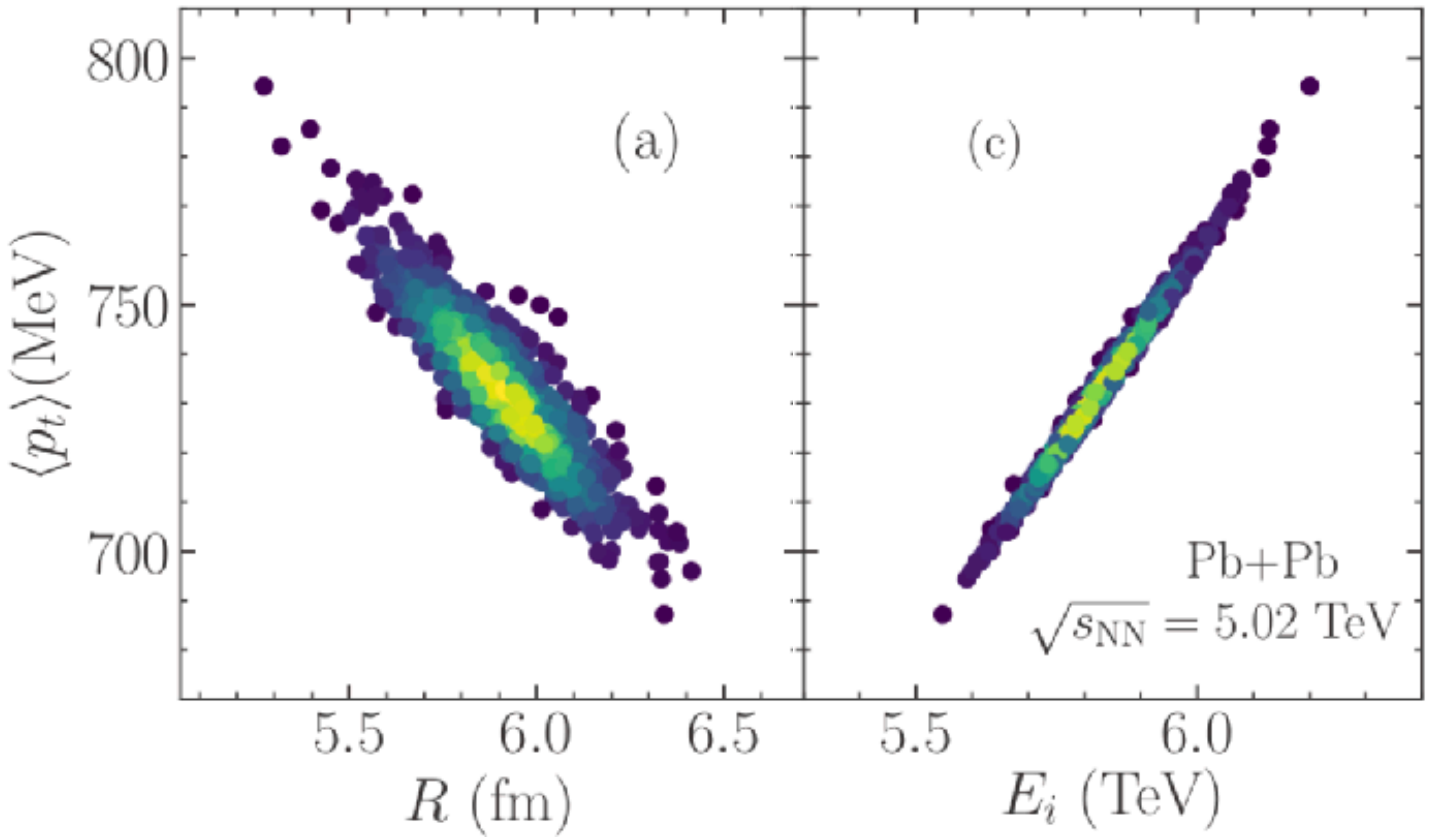
❖ Size of the fireball: radial flow, $[p_T]$

$$\frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto \frac{dE}{E}$$

$$\frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto -\frac{dR}{R}$$

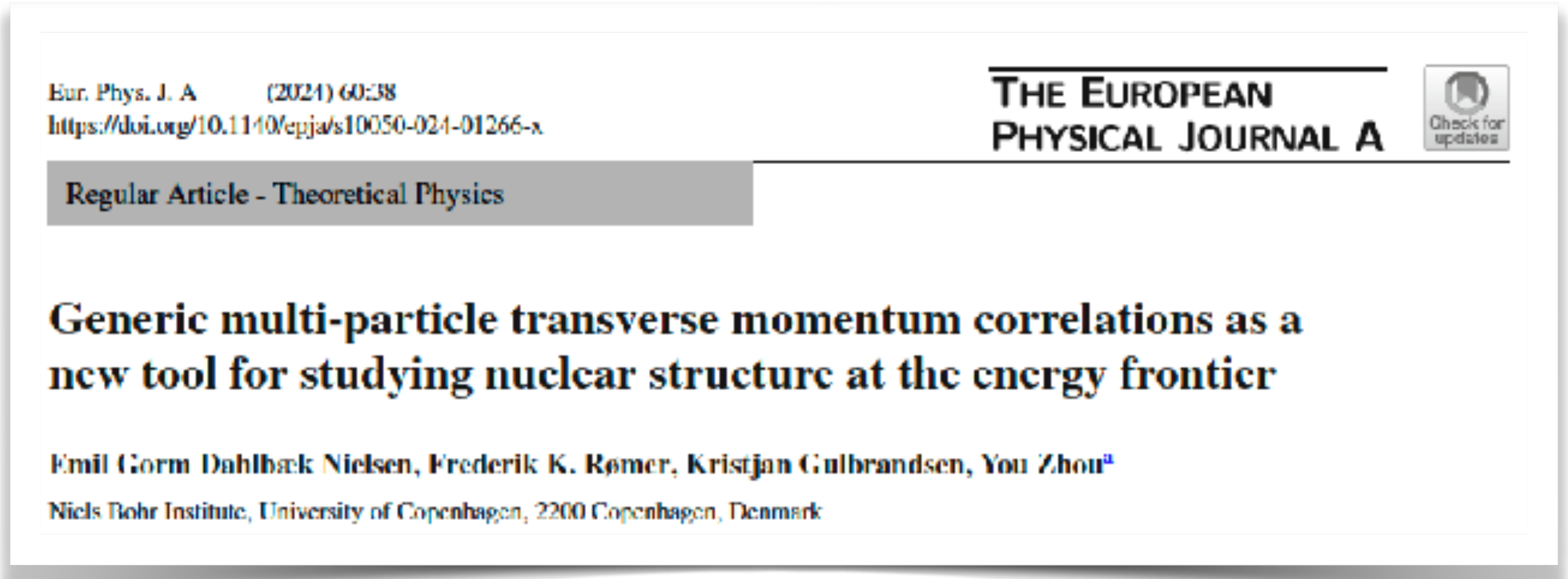


$[p_T] \propto \frac{1}{R}$ $\qquad$ $[p_T] \propto E_i$



[G. Giacalone et al., PRC103 (2021) 2, 024909]

sensitivity of radial flow ([pT] fluctuations) to nuclear structure


Eur. Phys. J. A (2024) 60:38
https://doi.org/10.1140/epja/s10050-024-01266-x

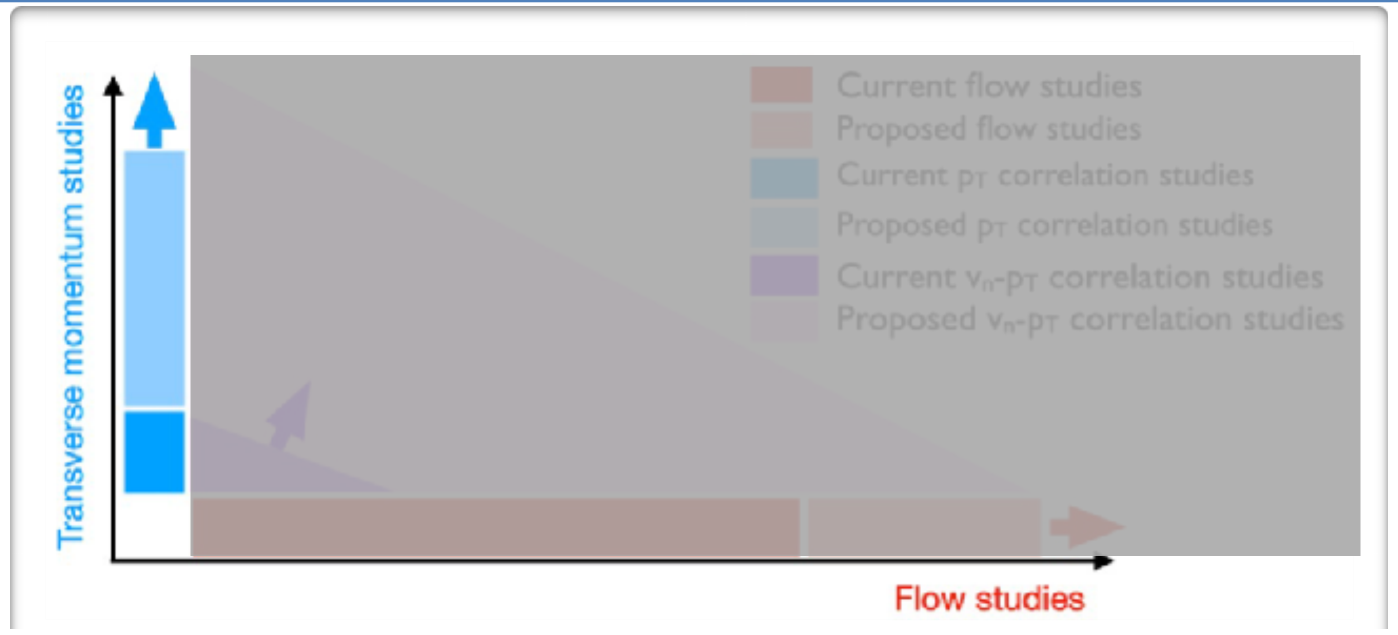
THE EUROPEAN PHYSICAL JOURNAL A

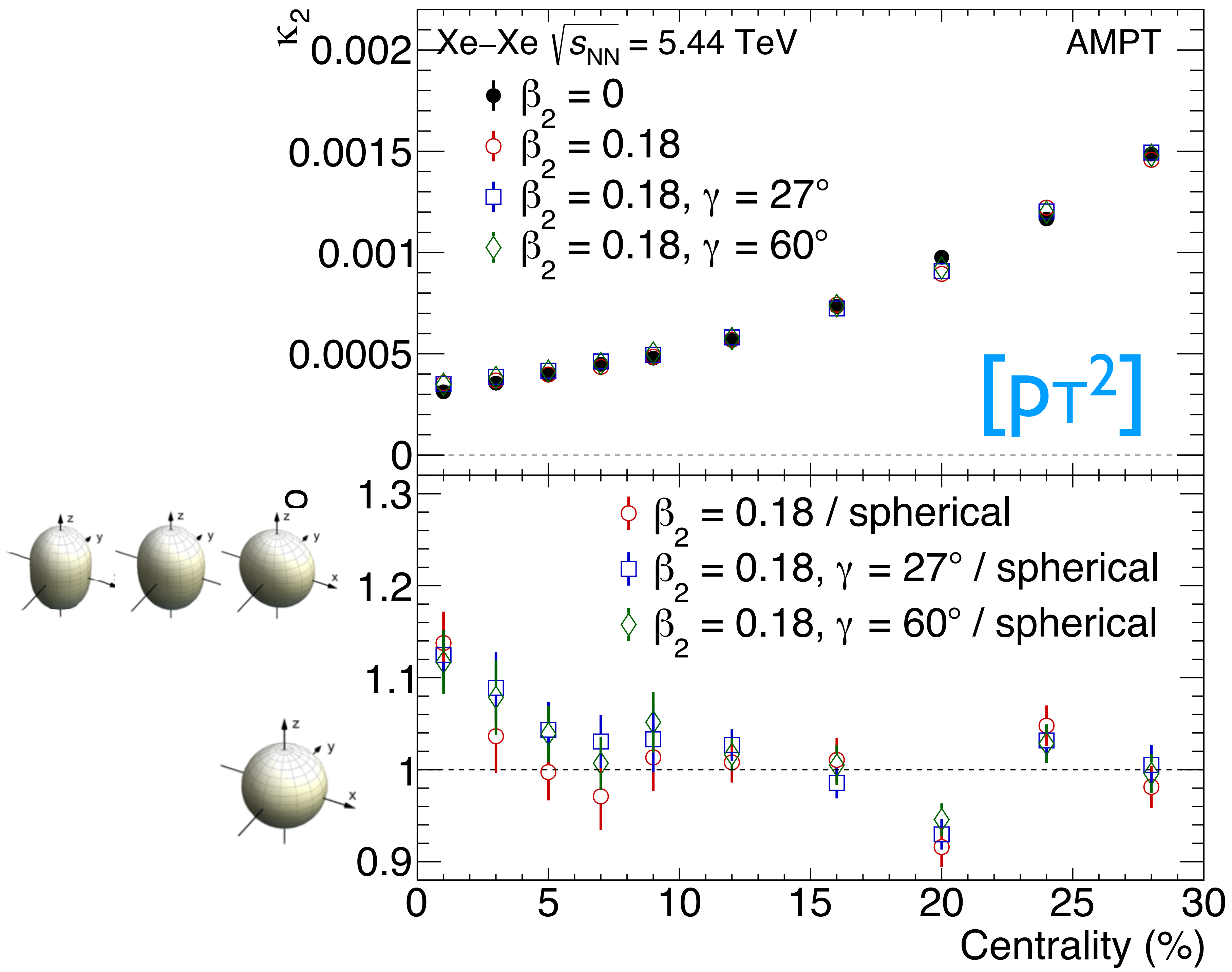
Regular Article - Theoretical Physics

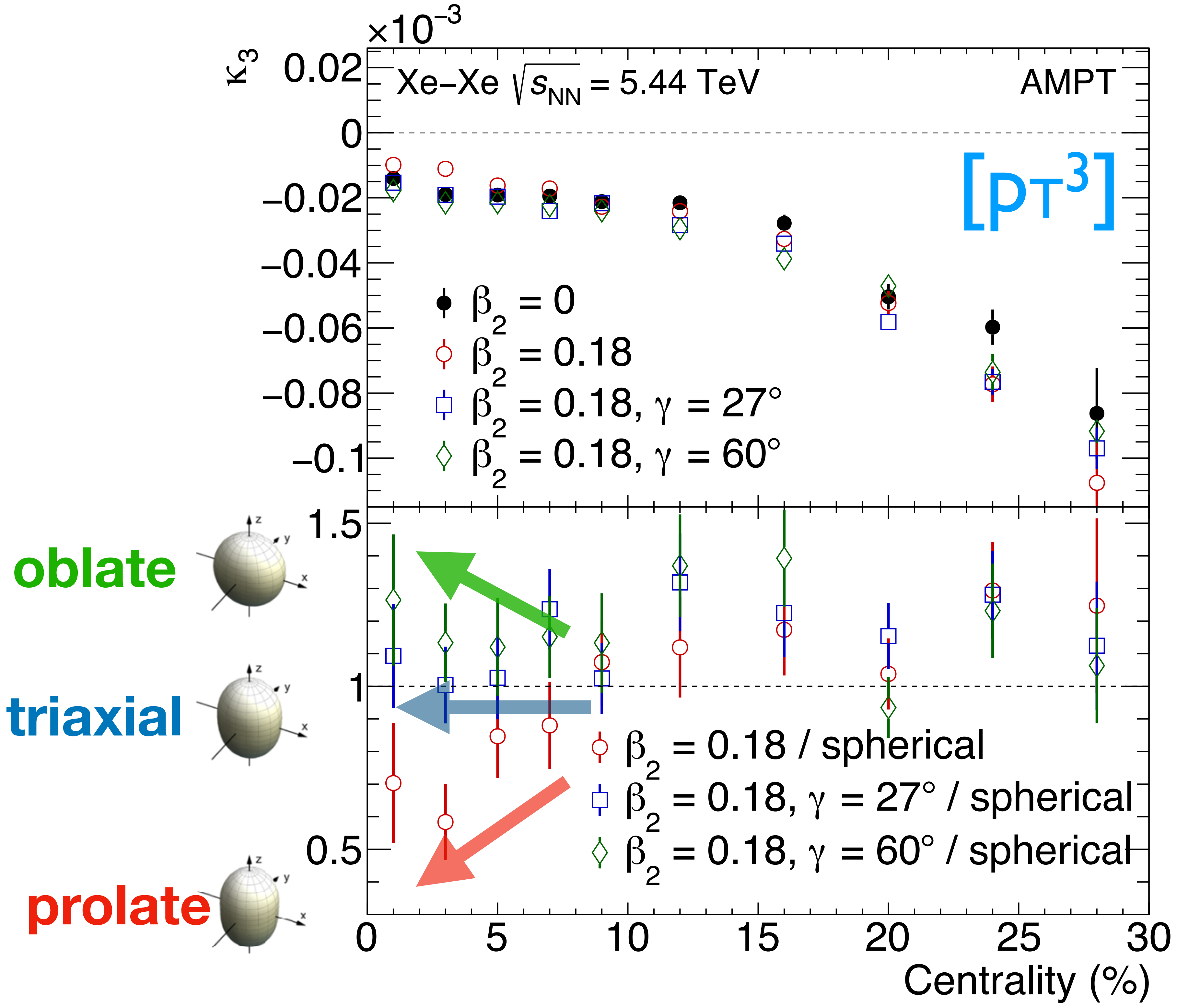
Generic multi-particle transverse momentum correlations as a new tool for studying nuclear structure at the energy frontier

Emil Gorm Dahlbæk Nielsen, Frederik K. Rømer, Kristjan Gulbrandsen, You Zhou[a]

Niels Bohr Institute, University of Copenhagen, 2200 Copenhagen, Denmark



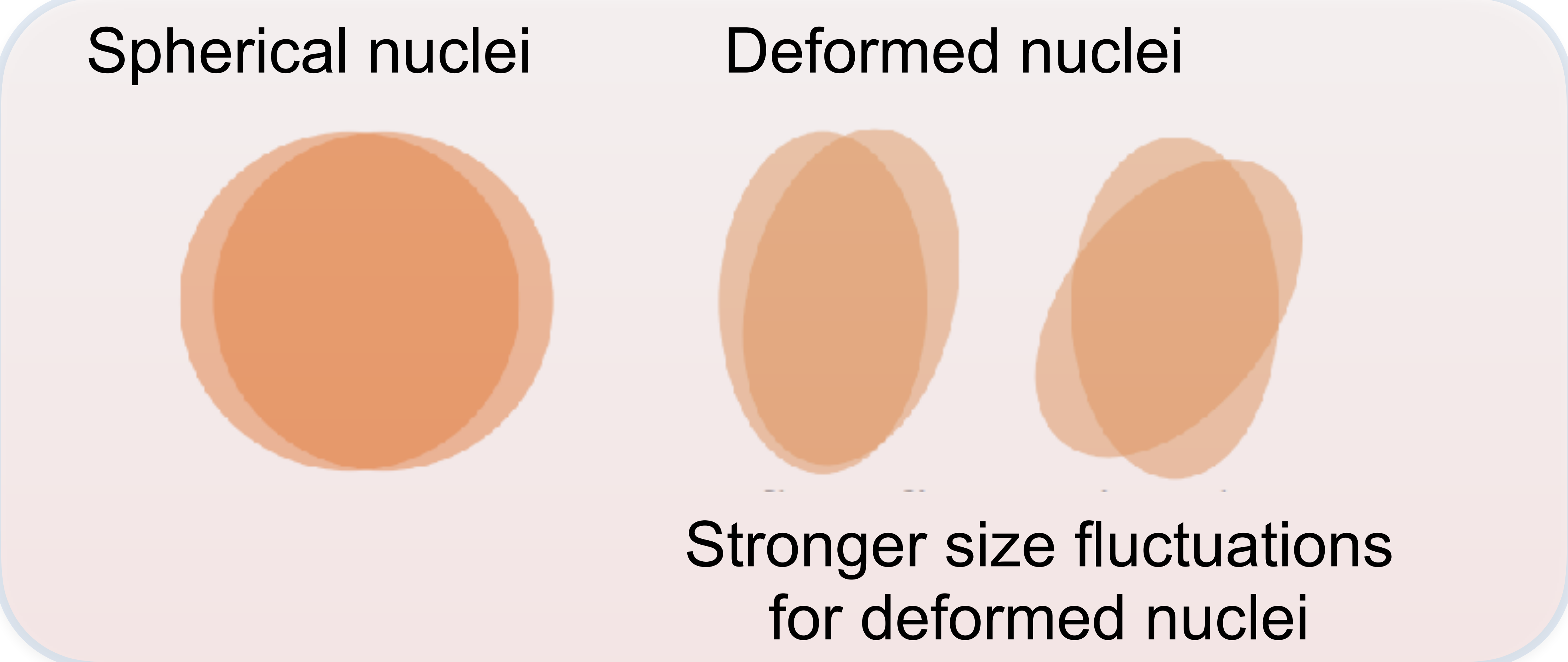




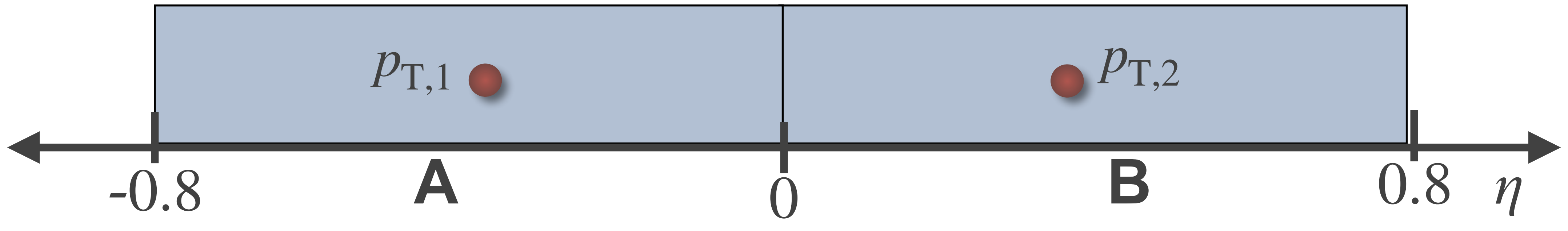
- [pT] fluctuations, which reflect the initial size fluctuations, also bring new information on the NS.

Latest measurements of $[p_T^k]$

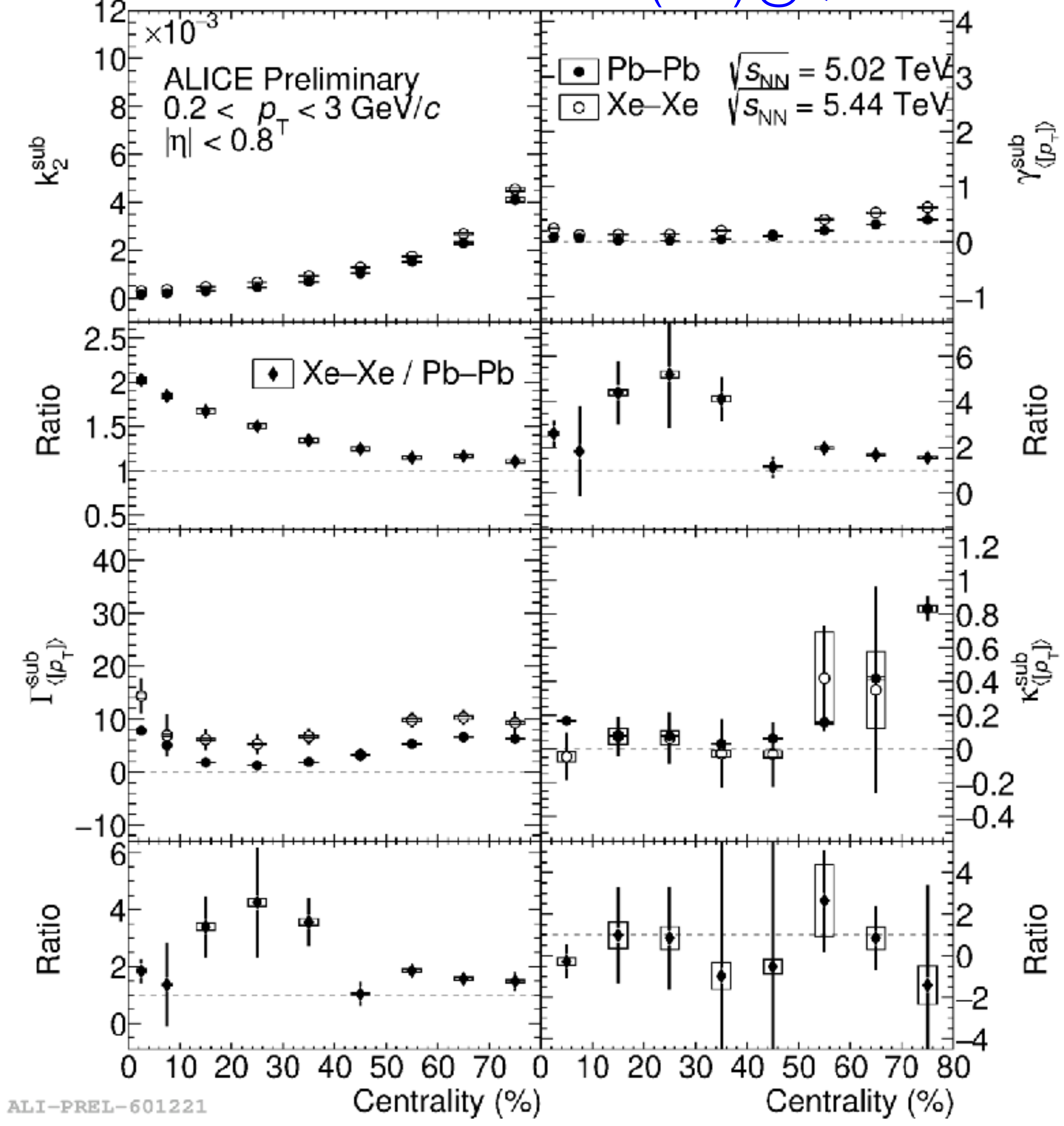
- $[p_T]$ and its event-by-event fluctuations measured in heavy-ion collisions at the LHC
  -> probe initial ***size*** and ***size fluctuations***



No bias from non-collective effects: Resonance decays, global momentum conservation, etc.



Emil G.N (NBI) @QM2025



"Reverse engineering" with collective motion

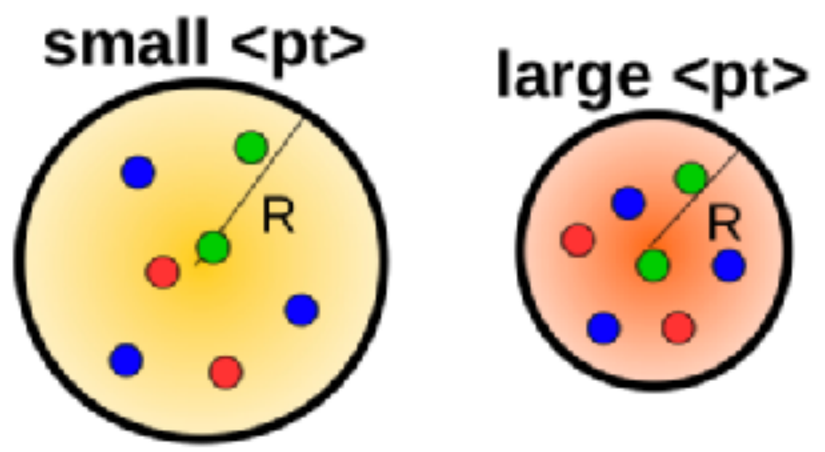
❖ Shape of the fireball: Anisotropic flow

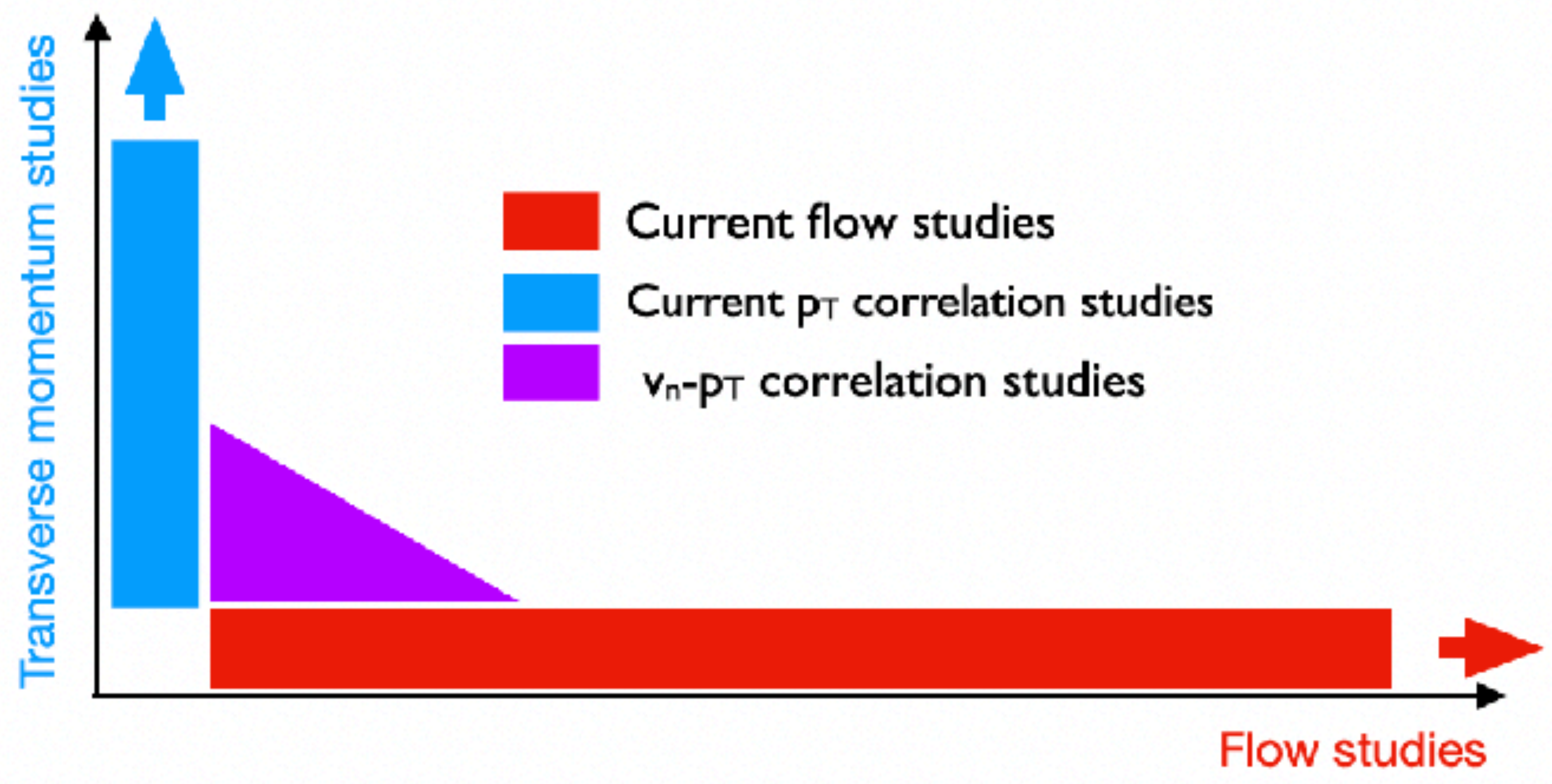
$$V_n \propto \mathcal{E}_n$$

❖ Size of the fireball: radial flow, $[p_{\mathrm{T}}]$

$$\frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto \frac{dE}{E}$$

$$\frac{d\langle p_t\rangle}{\langle p_t\rangle} \propto -\frac{dR}{R}$$





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

P. Bozek etc, PRC96 (2017) 014904

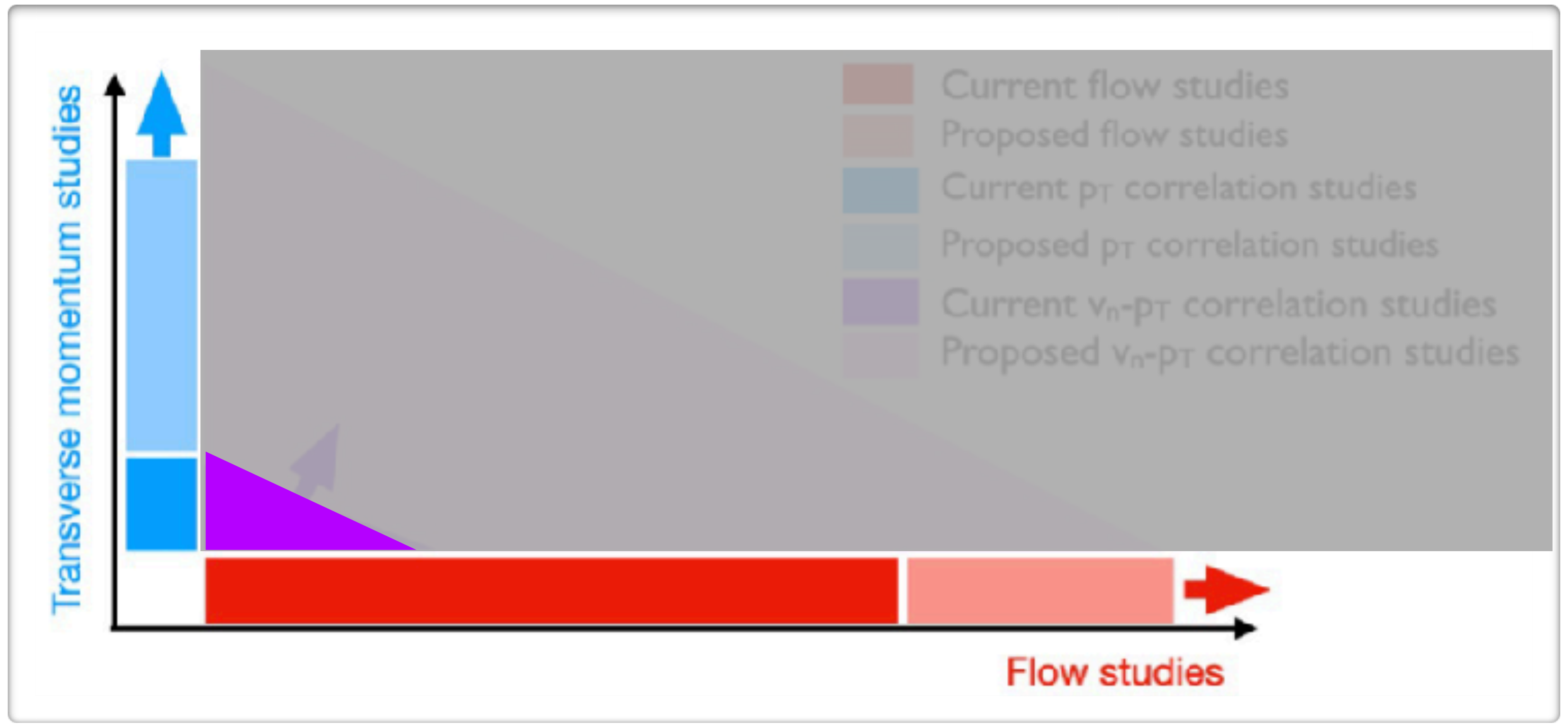
❖ Considering $v_n \propto \varepsilon_n$, $[p_{\mathrm{T}}] \propto E_0$

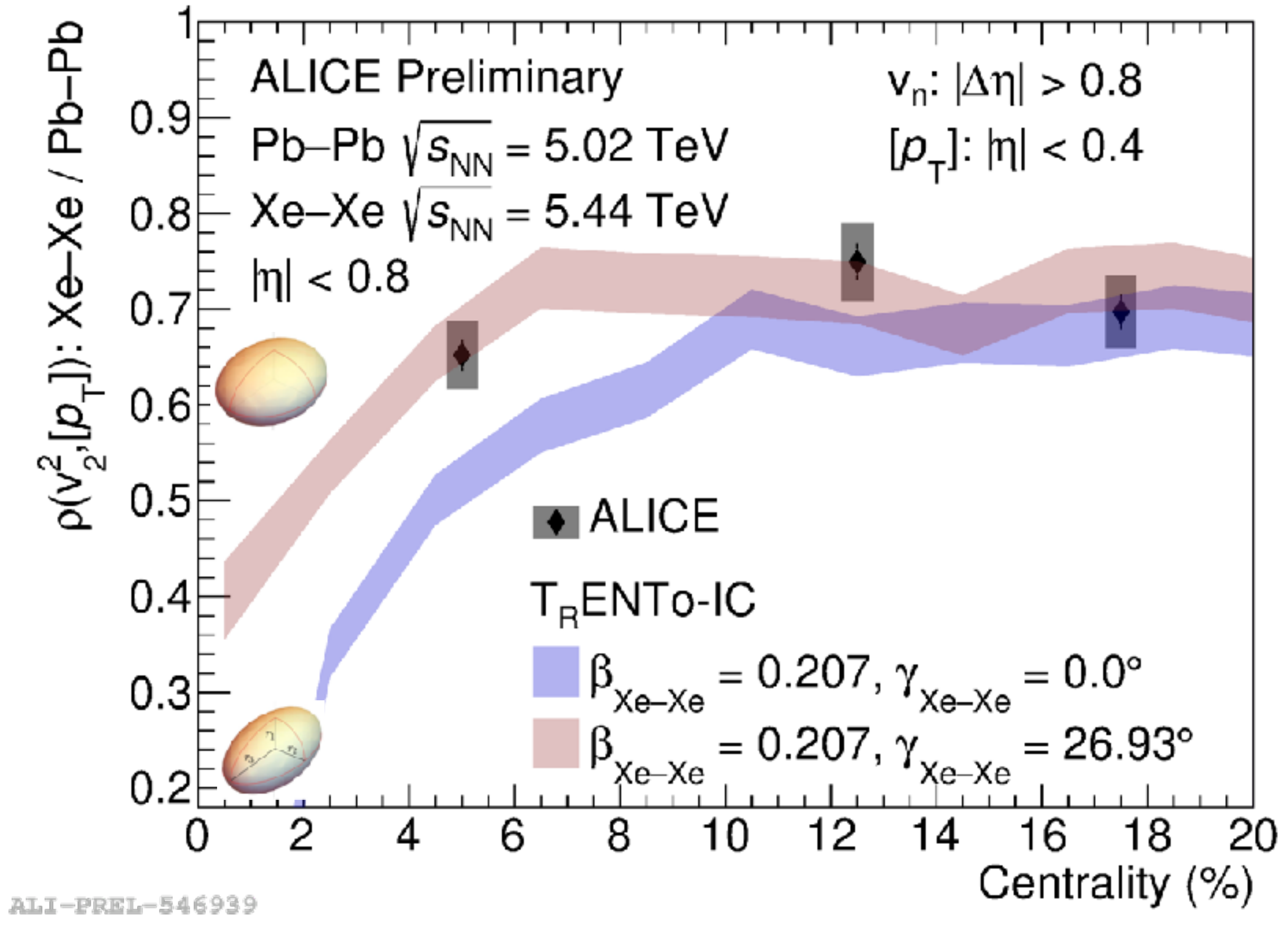
$$\rho(v_n^2, [p_{\mathrm{T}}]) = \rho(\varepsilon_n^2, [E_0])$$

final-state model calculation

Initial-state model estimation

Probe triaxial structure of ^{129}Xe



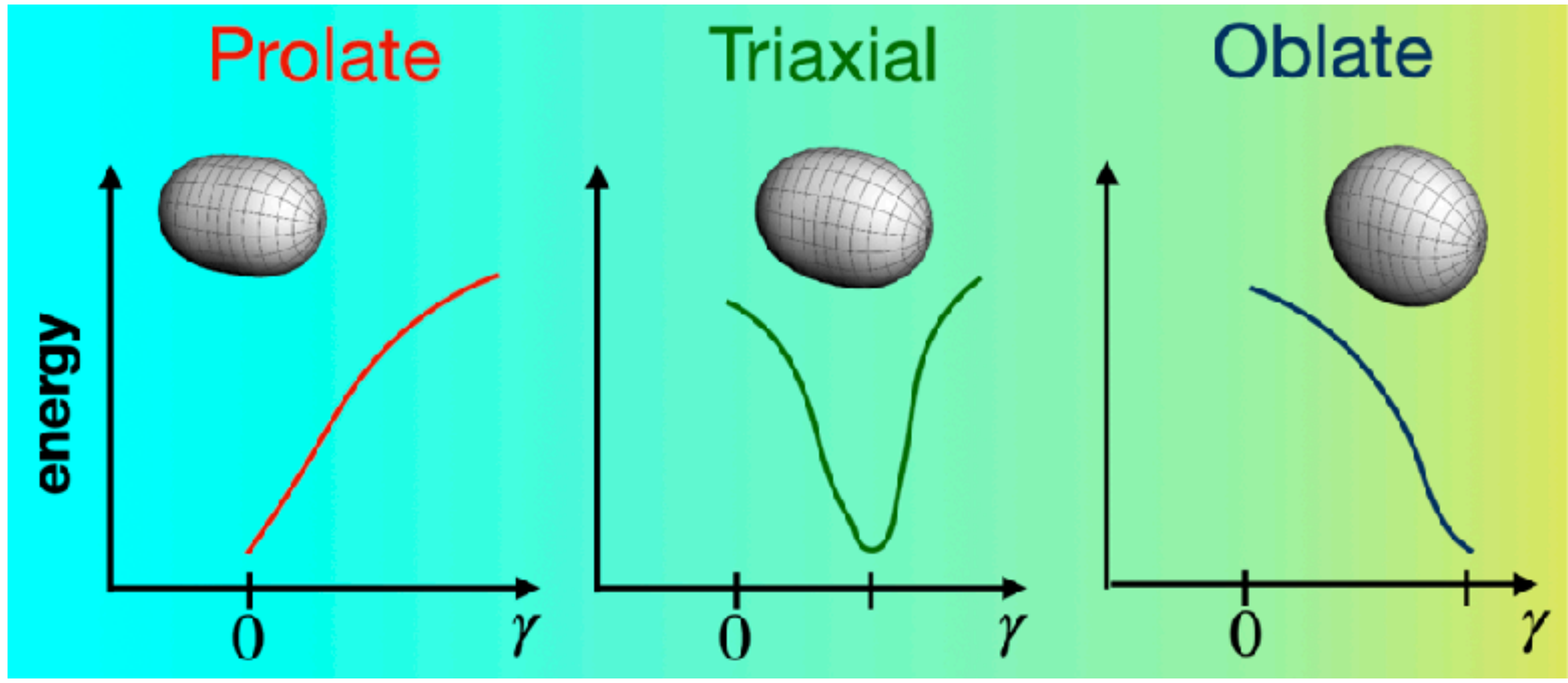


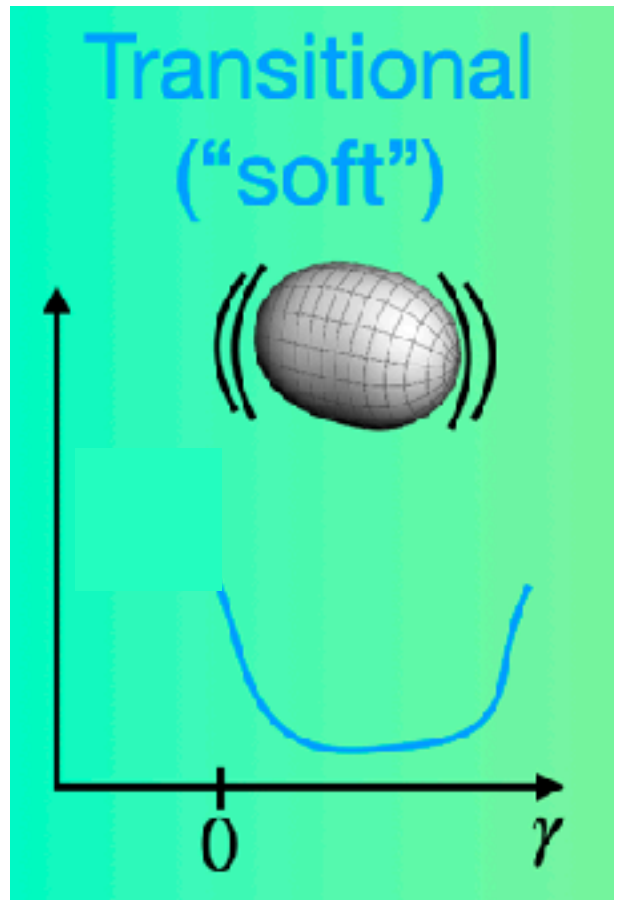
❖ Better agreement between LHC data and calculations with $\gamma = 26.93°$

- 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**

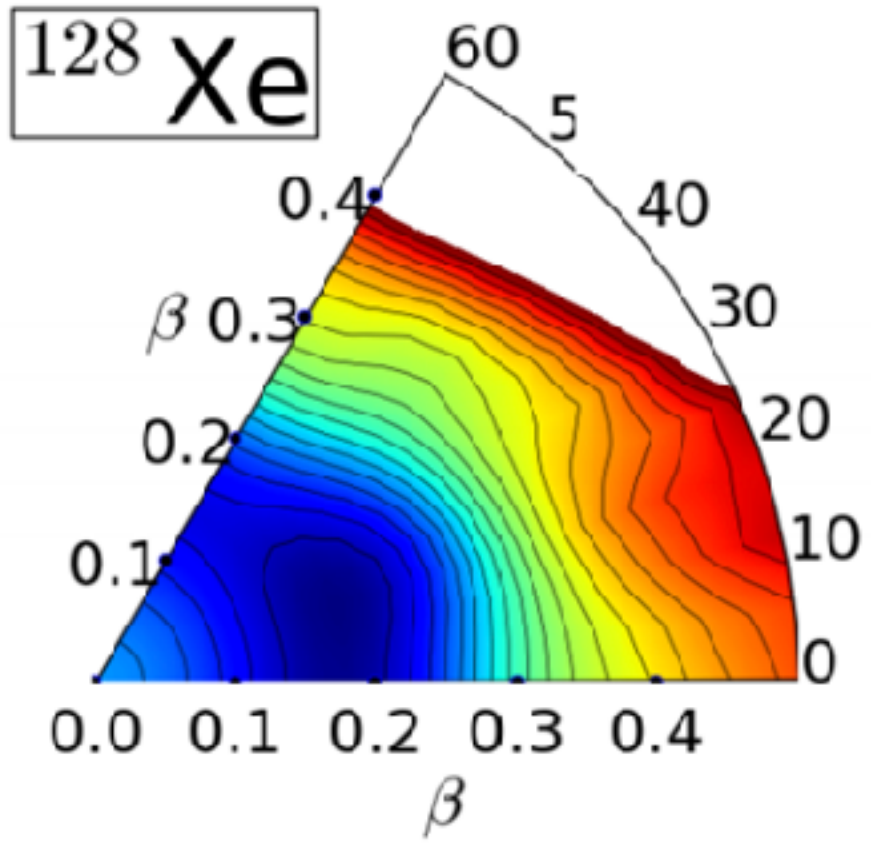
Nuclear Shape Phase Transition

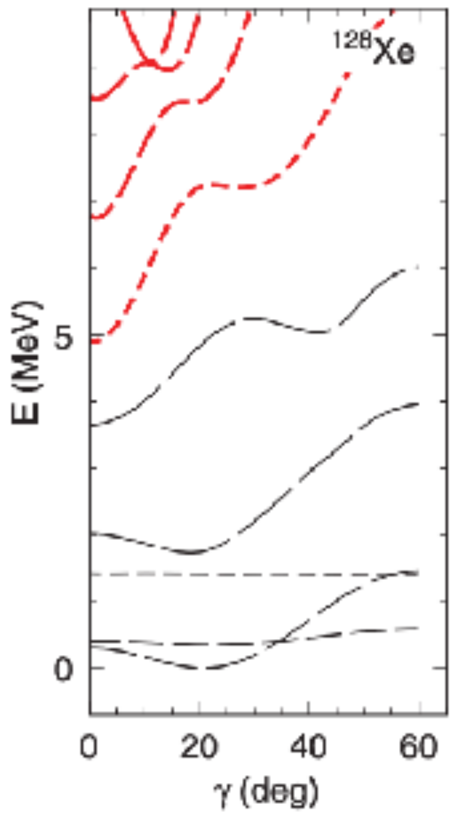
Nuclear Shape Phase diagram





^{128}Xe – ^{132}Xe





Details, also see talk:
Huichao Song @ Wednesday

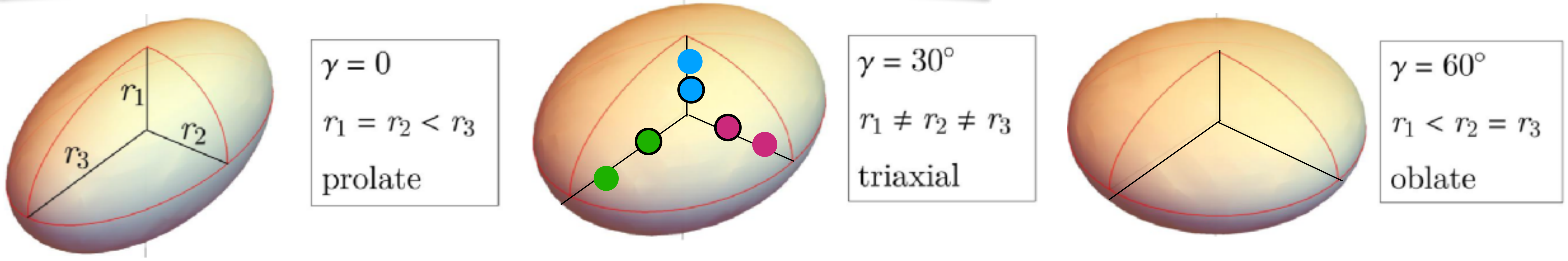
Shape transition via high-order correlations of v_n and p_T

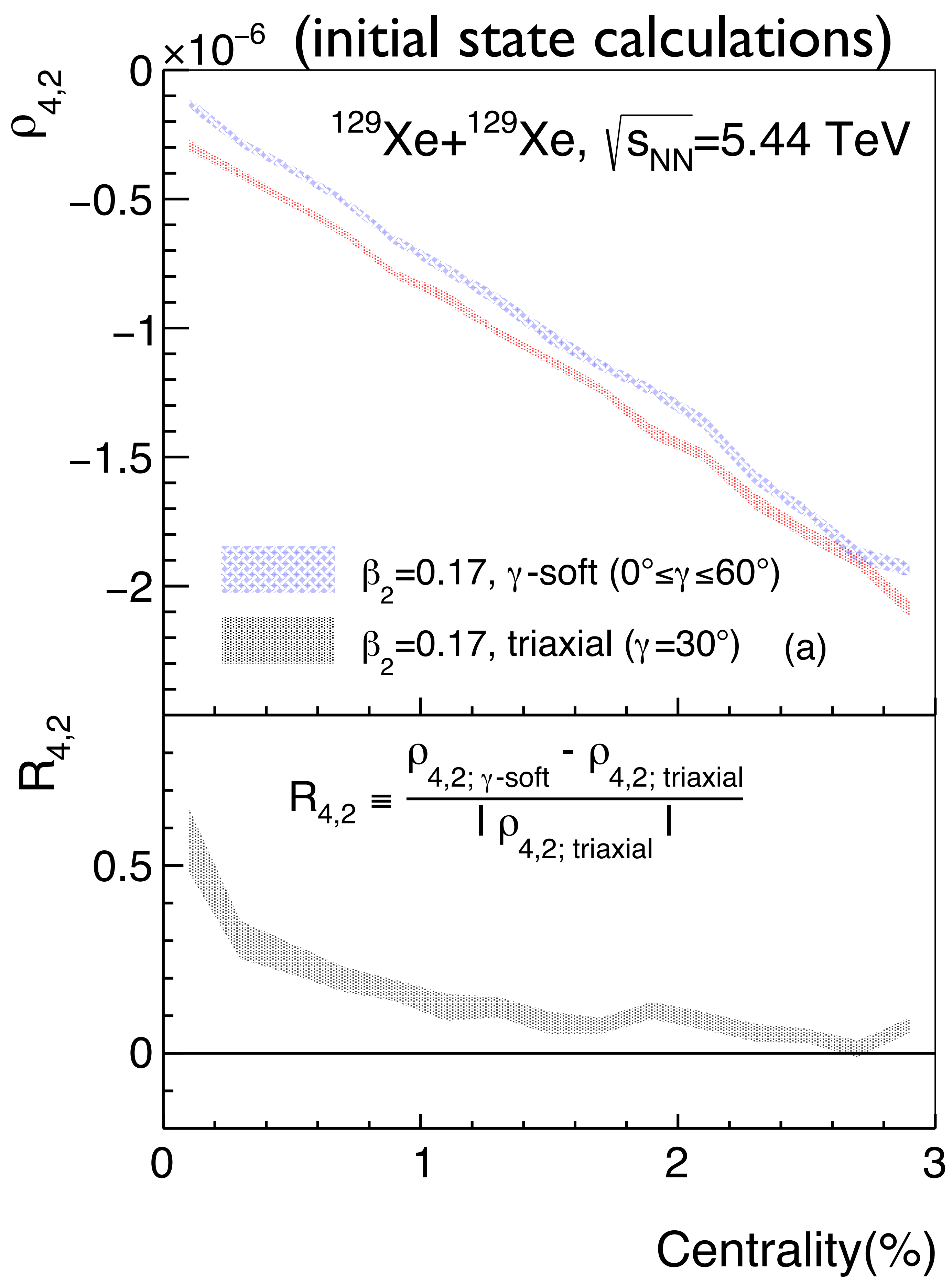
Physical Review Letters

Exploring the Nuclear-Shape Phase Transition in Ultrarelativistic ^{129}Xe + ^{129}Xe Collisions at the LHC

Shujun Zhao[1,2,*], Hao-jie Xu[2,3,†], You Zhou[4,‡], Yu-Xin Liu[1,5,6,§], and Huichao Song[1,5,6,∥]

Phys. Rev. Lett. 133 (2024) 192301





❖ 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 proposal:

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

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

➡The implementation is highly non-trivial!

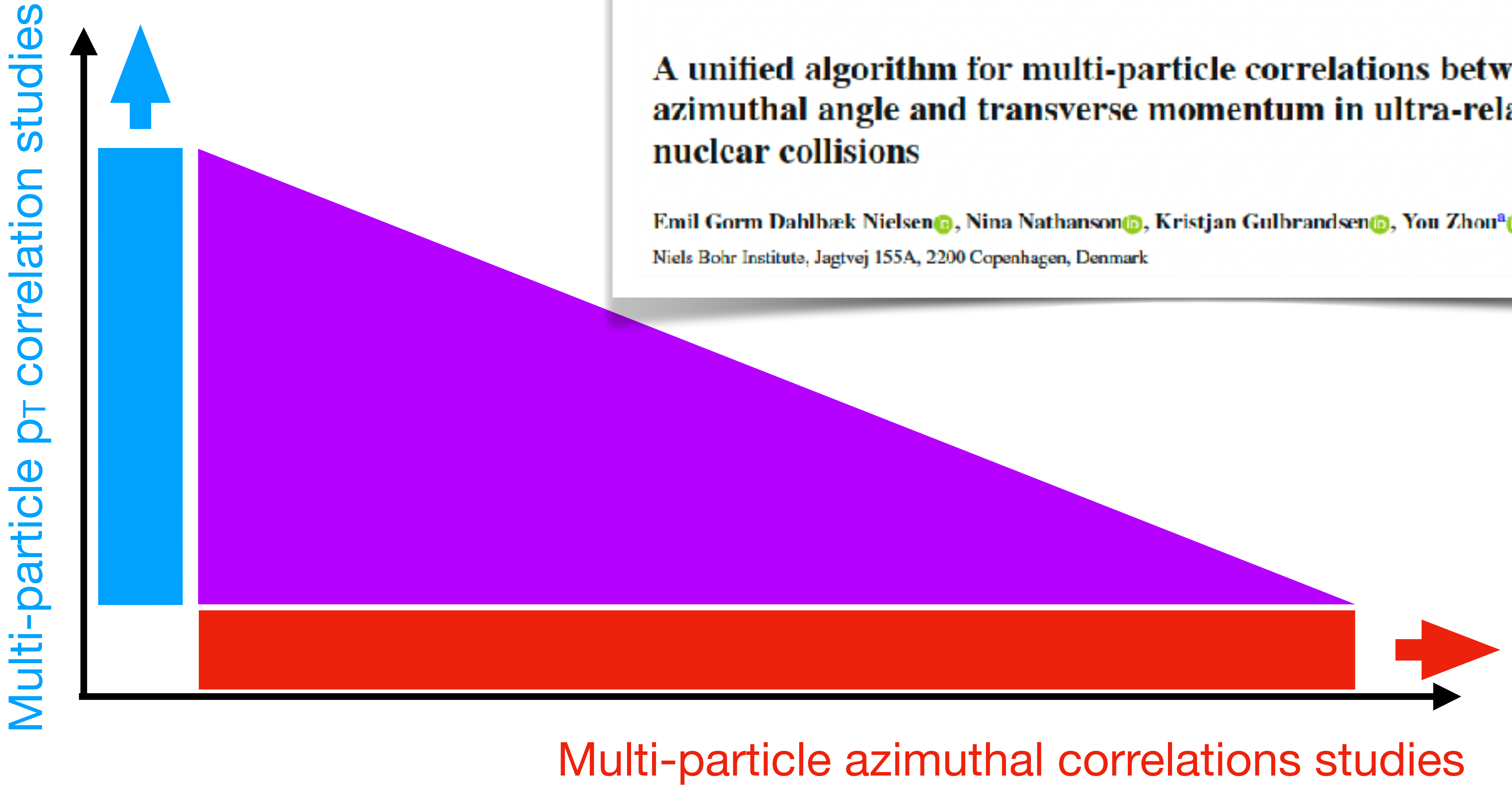
A ***Unified Algorithm*** makes them all possible

multi-particle $\mathbf{p_T}$ correlation:
Generic Algorithm (2024)

Eur. Phys. J. A (2024) 60:38
https://doi.org/10.1140/epja/s10050-024-01266-x
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Theoretical Physics

Generic multi-particle transverse momentum correlations as a new tool for studying nuclear structure at the energy frontier

Emil Gorm Dahlbæk Nielsen, Frederik K. Rømer, Kristjan Gulbrandsen, You Zhou[a]
Niels Bohr Institute, University of Copenhagen, 2200 Copenhagen, Denmark



Eur. Phys. J. C (2025) 85:1016
https://doi.org/10.1140/epjc/s10052-025-14681-1
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

A unified algorithm for multi-particle correlations between azimuthal angle and transverse momentum in ultra-relativistic nuclear collisions

Emil Gorm Dahlbæk Nielsen, Nina Nathanson, Kristjan Gulbrandsen, You Zhou[a]
Niels Bohr Institute, Jagtvej 155A, 2200 Copenhagen, Denmark

PHYSICAL REVIEW C 89, 064904 (2014)

Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations

Ante Bilandzic,[1] Christian Holm Christensen,[1] Kristjan Gulbrandsen,[1] Alexander Hansen,[1] and You Zhou[2,3]
[1] Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark
[2] Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands
[3] Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands

multi-particle ***azimuthal*** correlation:
Generic Framework (2014)
Generic Algorithm (2021)

PHYSICAL REVIEW C 103, 024913 (2021)

Generic algorithm for multiparticle cumulants of azimuthal correlations in high energy nucleus collisions

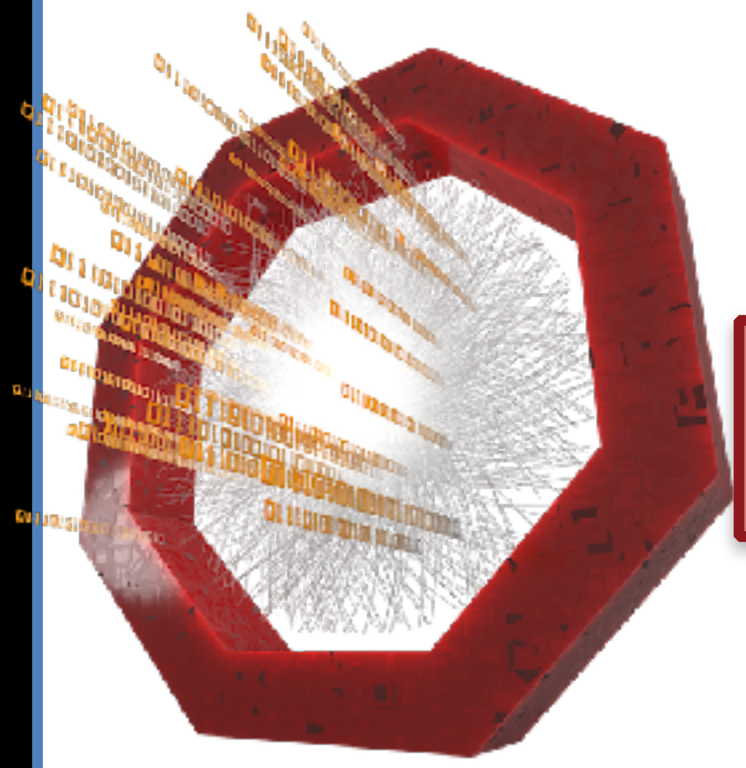
Zuzana Moravcova, Kristjan Gulbrandsen, and You Zhou[*]
Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark

Also see: Masakiyo Kitazawa etc., arXiv: 2510.13838

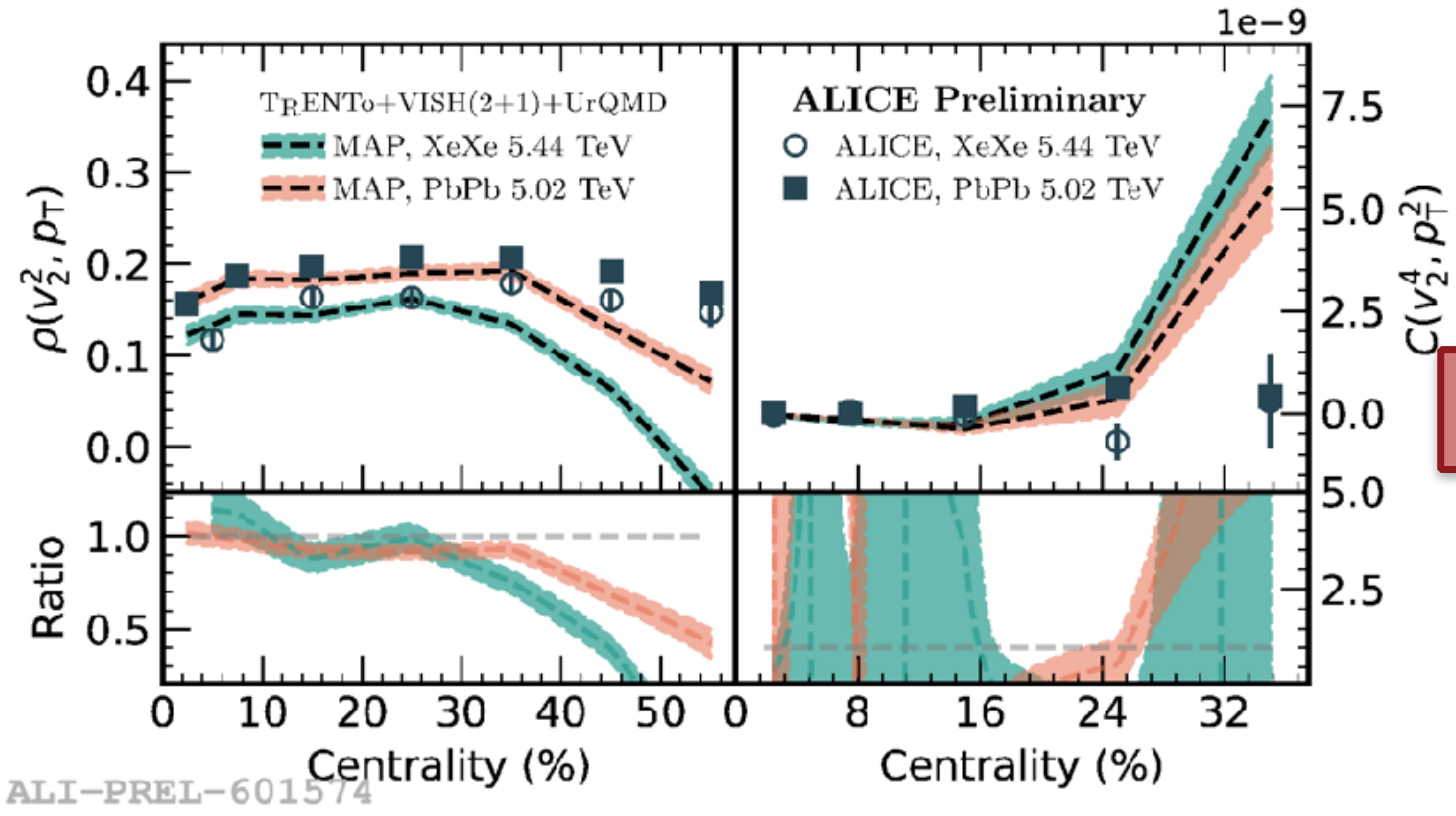
Exploring nuclear shape phase transition

❖ First ever experimental measurement on the multi-particle correlations of v_n and p_T

ALICE data



Unified algorithm



Bayesian Fit

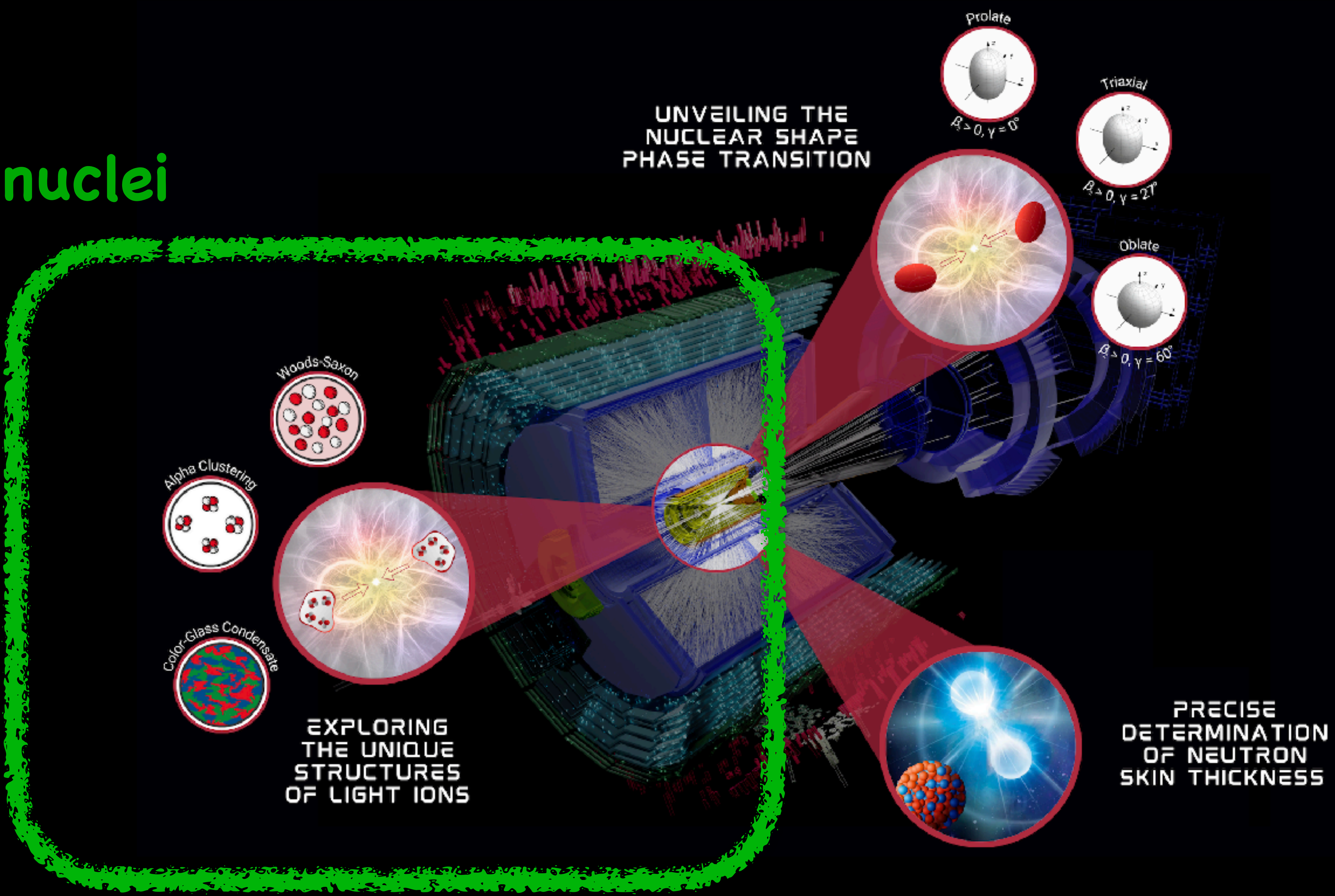
Maxim's talk

❖ Phase III: **Unification and validation**

➡ Toward a Unified Framework: nuclear structure across energy scale

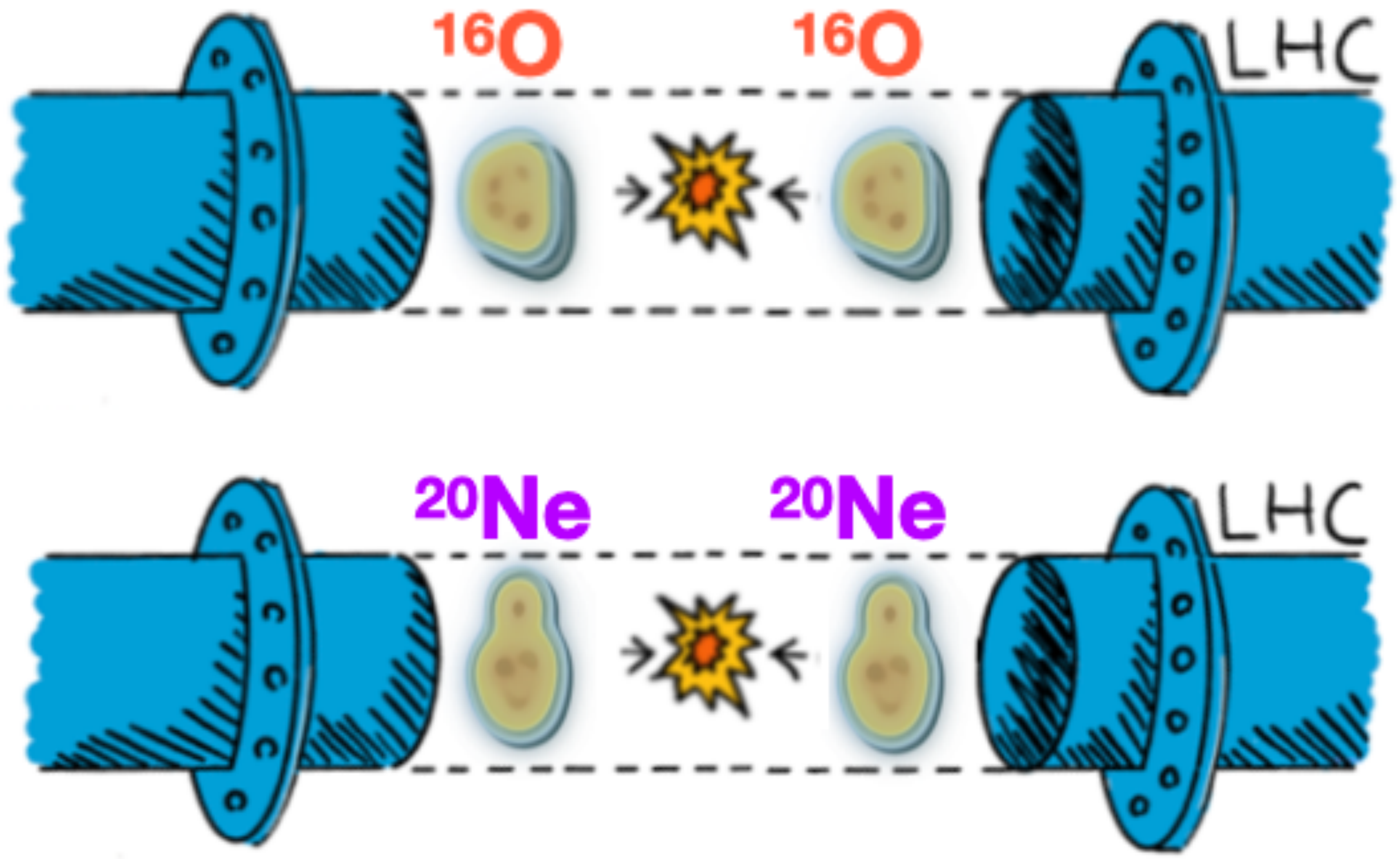
➡ Validation with Light-Ion Collisions

Light nuclei

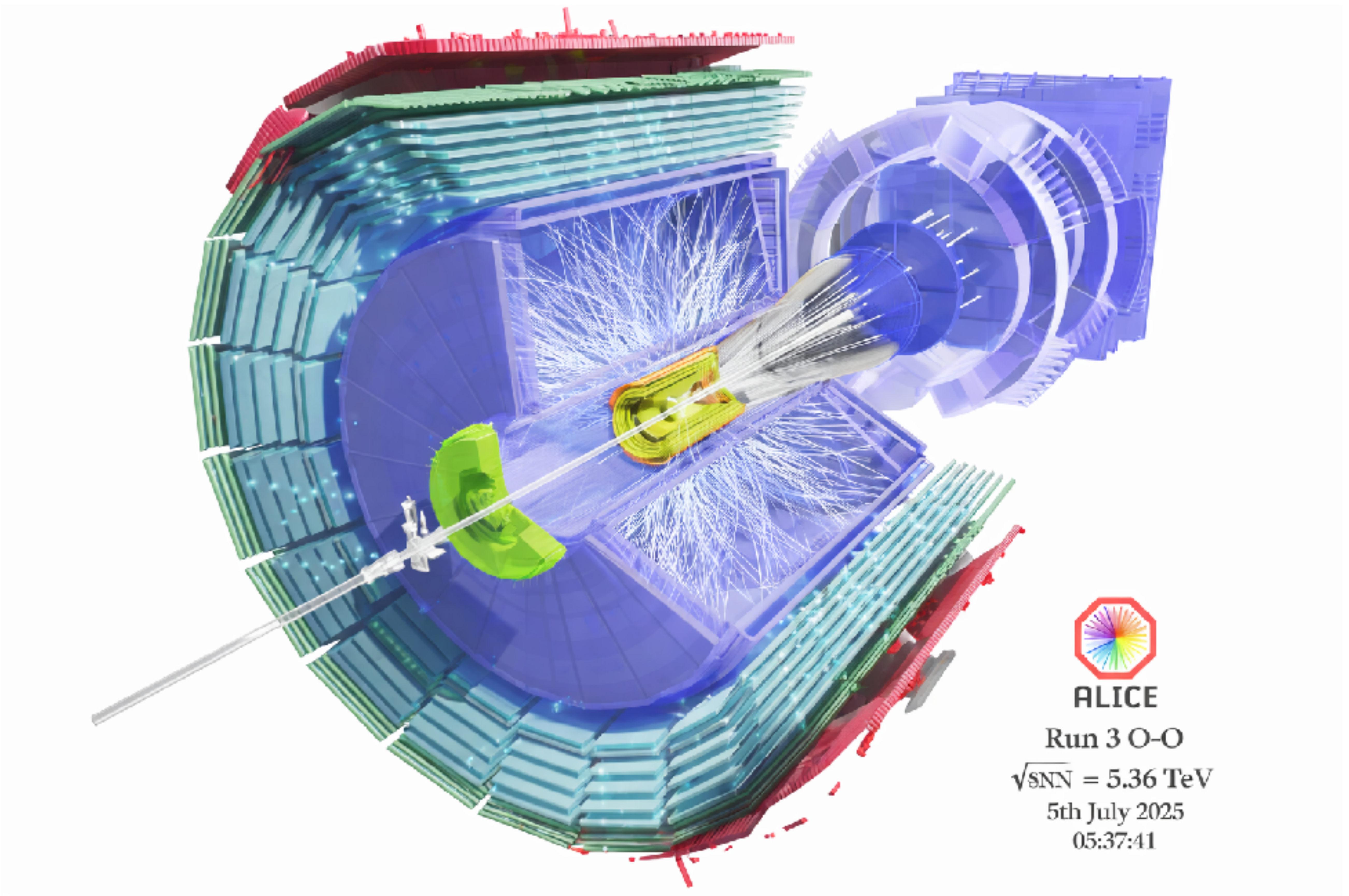


LHC: Large ligHt-ion Collider @ CERN

July, 2025!



Event display of O-O collisions in ALICE



Unification: Combining NS + "heavy-ion theory"

Hydrodynamic *PRL135 (2025) 012302*

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]

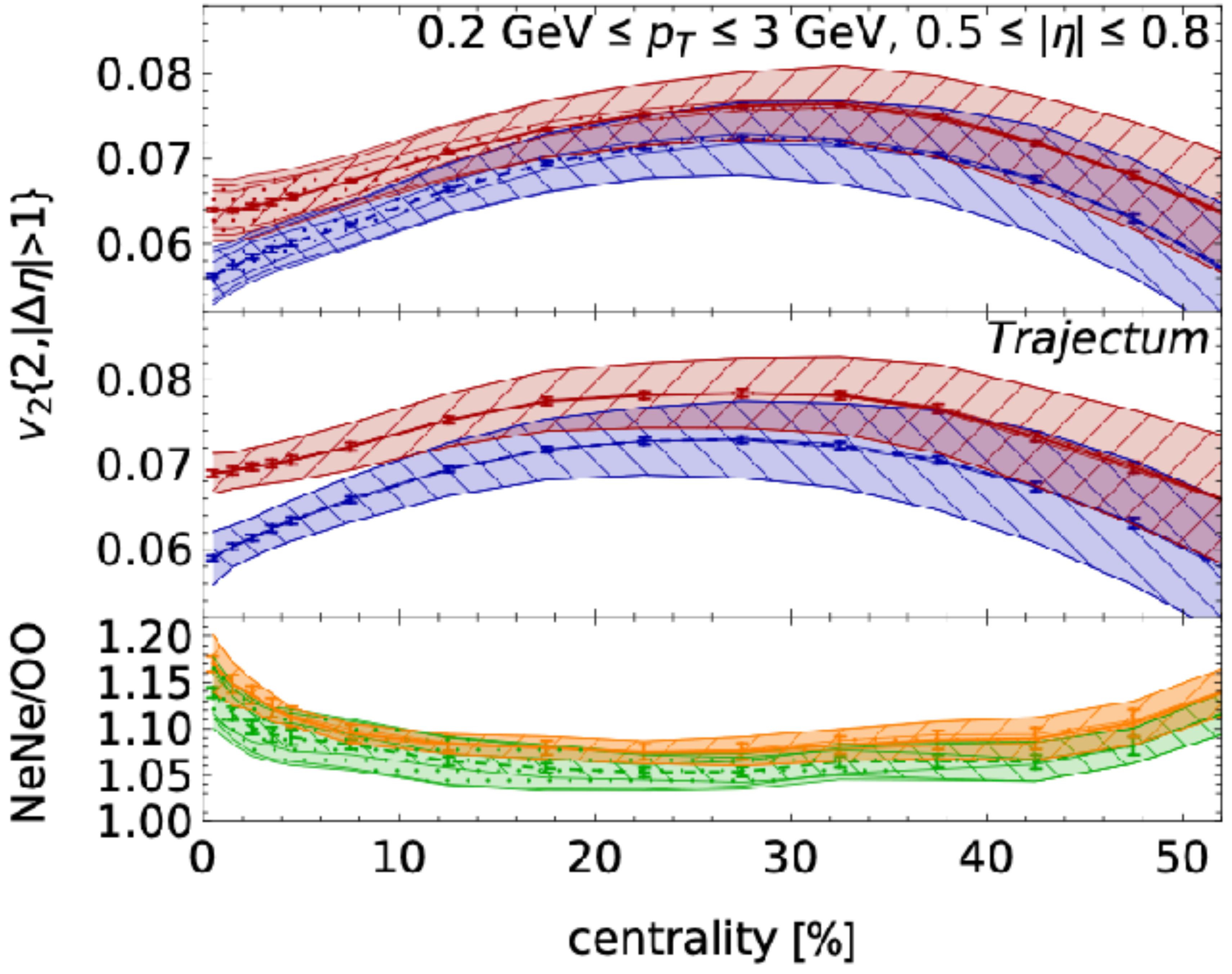
HEAVY IONS — PGCM — NLEFT

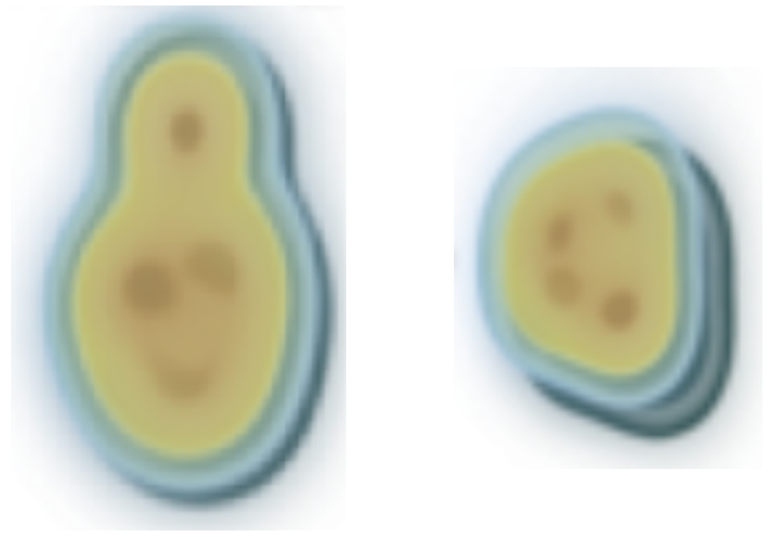
Parton Transport *In preparation*

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)

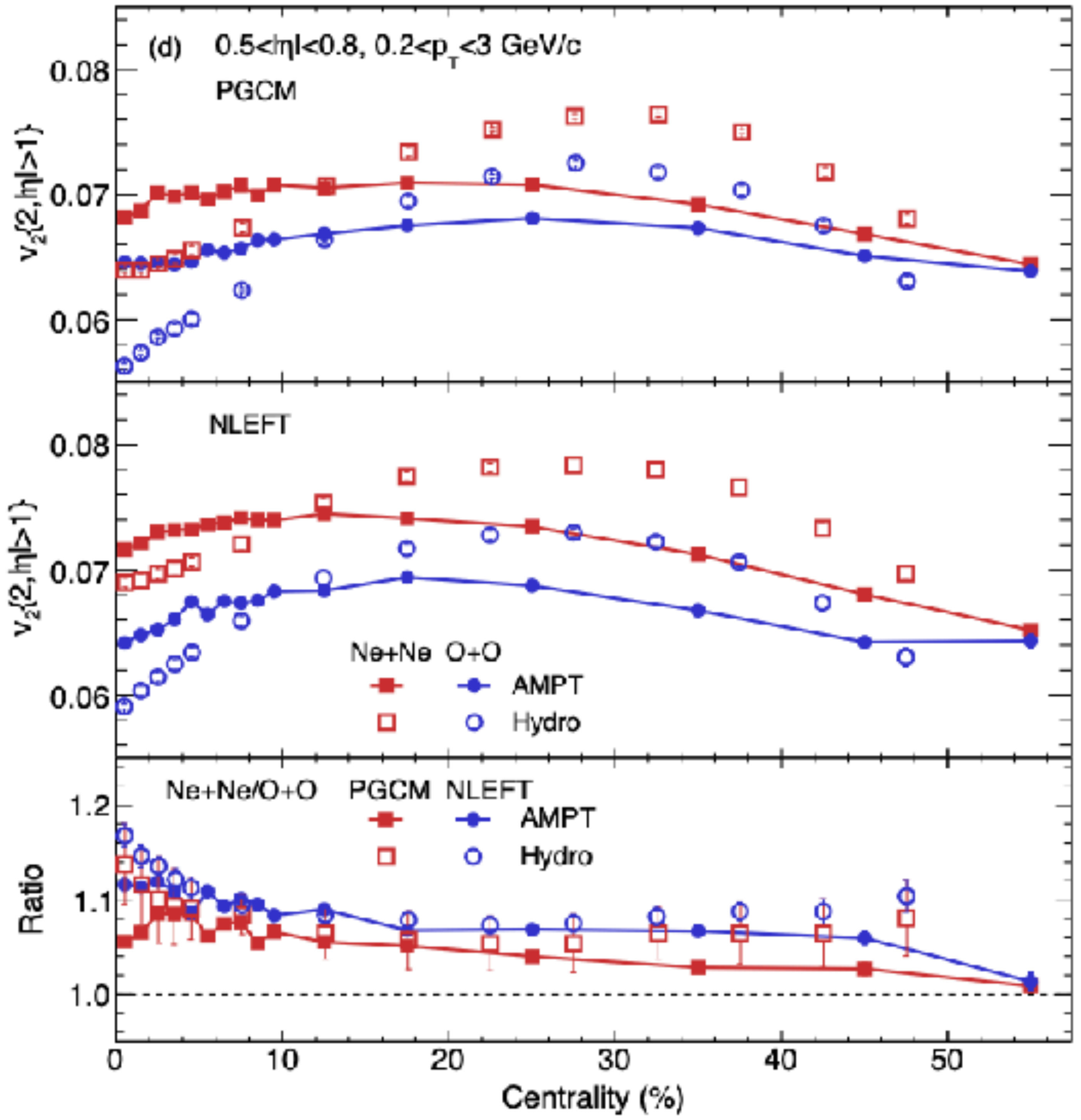




Low-energy NS

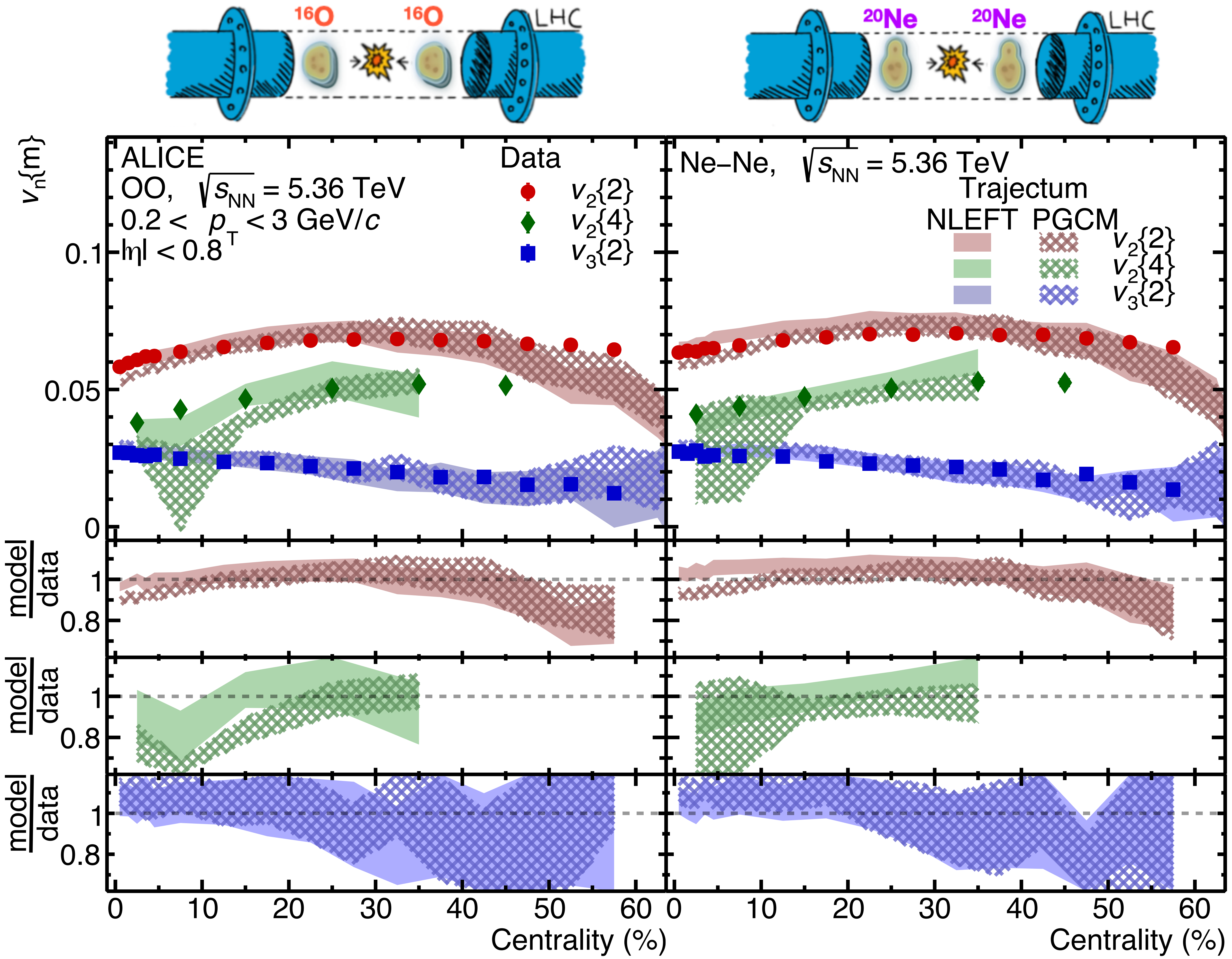
Hydrodynamic

Parton Transport



Validation: Evidence of nuclear geometry driven flow

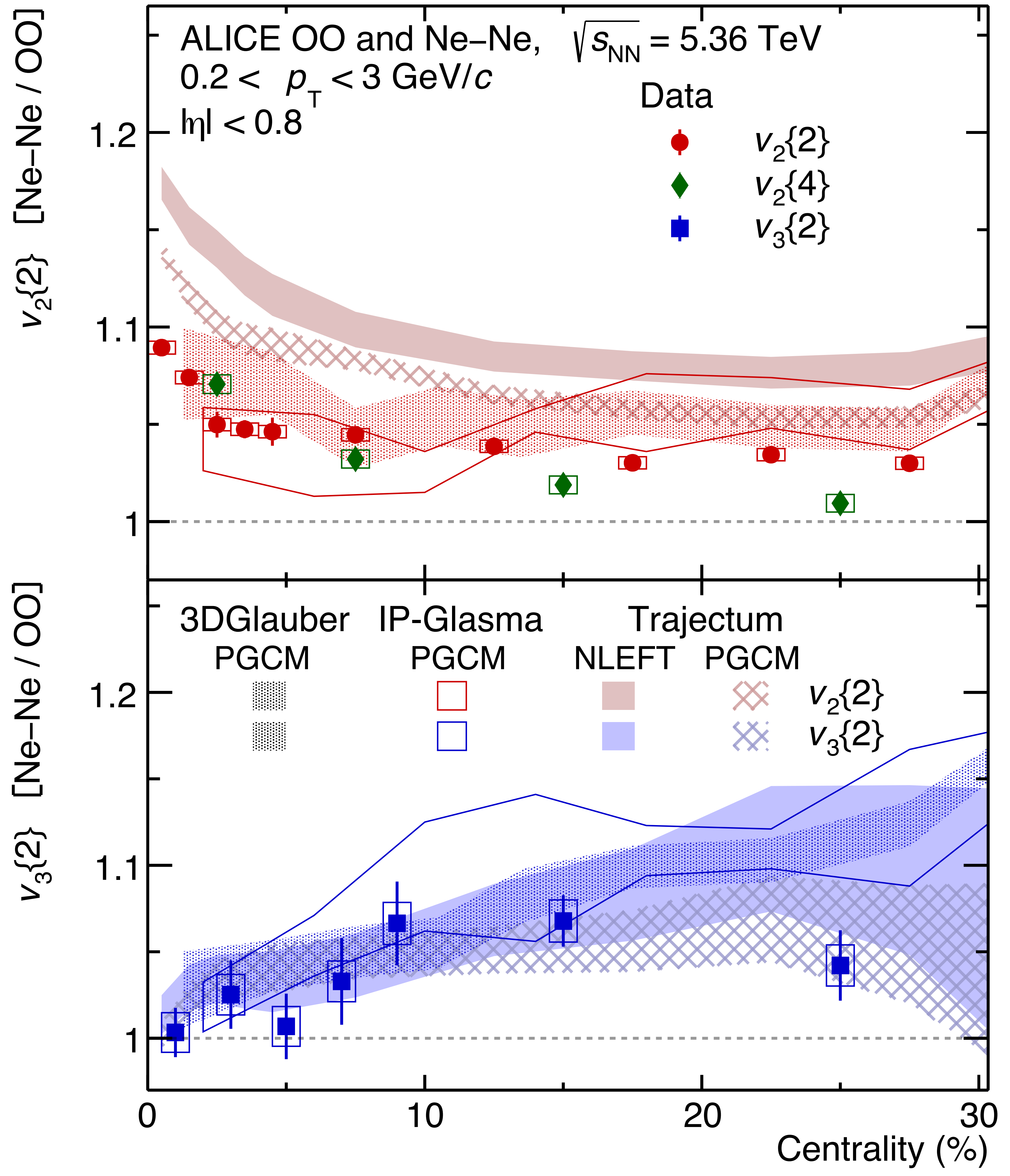
ALICE, arXiv:2509.06428, submitted to Phys. Rev. Lett.



- **Unified Framework**: nuclear structure across energy scale
- Nicely described by predictions from Trajectum(NS+hydro)
  - Nuclear geometry driven hydrodynamic flow observed in light ion collisions
  - *For the first time reasonable agreement (equivalent if not better than Pb-Pb) between hydro predictions and data in small systems*

✓ Validation with Light-Ion Collisions

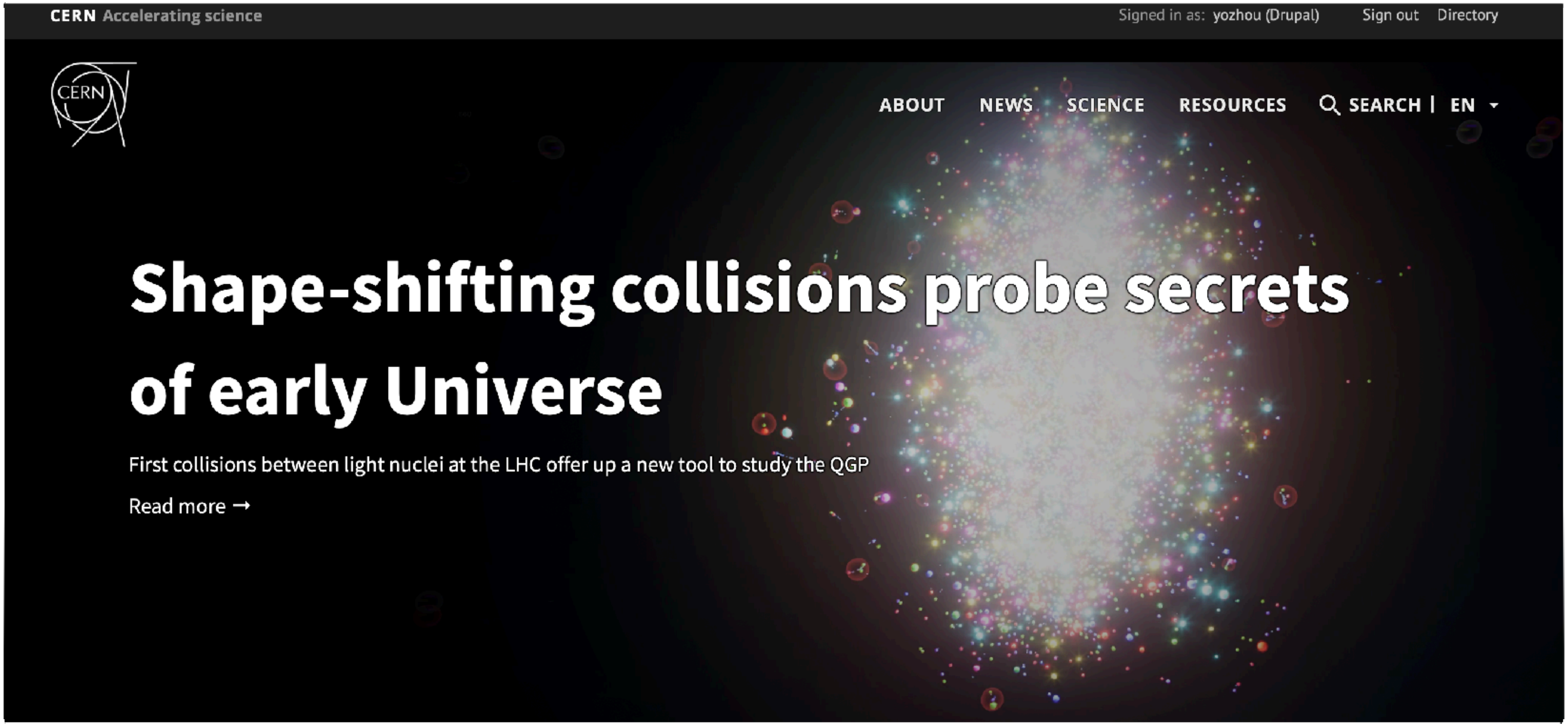
Flow ratios (Ne-Ne / OO) tell us more



ALICE, arXiv:2509.06428, submitted to Phys. Rev. Lett.

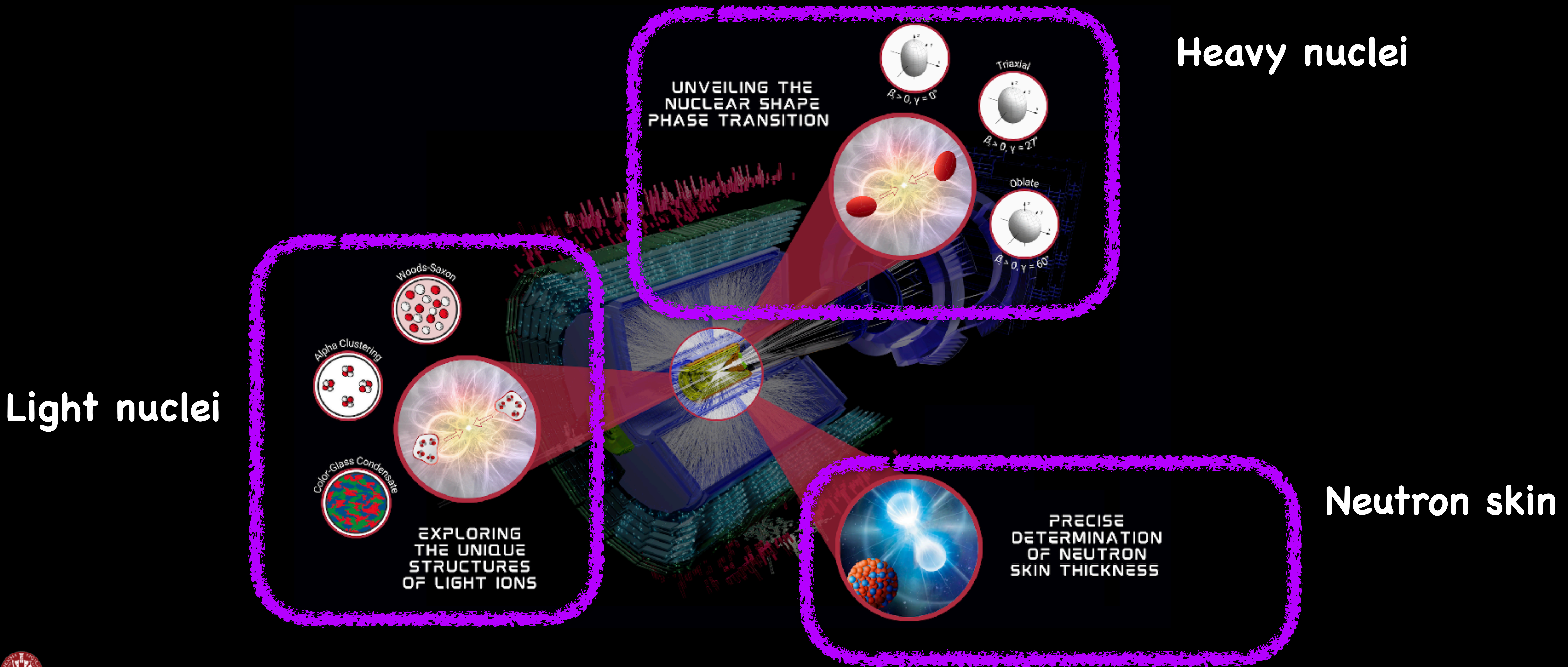
- Enhanced v_2 in Ne-Ne than OO
  - Driven by nuclear geometrical shape of ^{20}Ne (larger deformation compared to ^{16}O)
  - Trajectum prediction using NLEFT-NS overestimates the ratio
  - Trajectum prediction using PGCM-NS agrees better although still overestimates the ratio
  - predictions from 3DGlauber and IP-Glasma using PGCM describes the data
  - Data better described by the models using a smaller sub-nucleon (~ 0.1 fm)
- v_3 ratio is close to unity in the central collisions due to large β_3 from tetrahedral shape of ^{16}O, then increases toward peripheral collisions

CERN Headline (Sept. 19th, 2025)



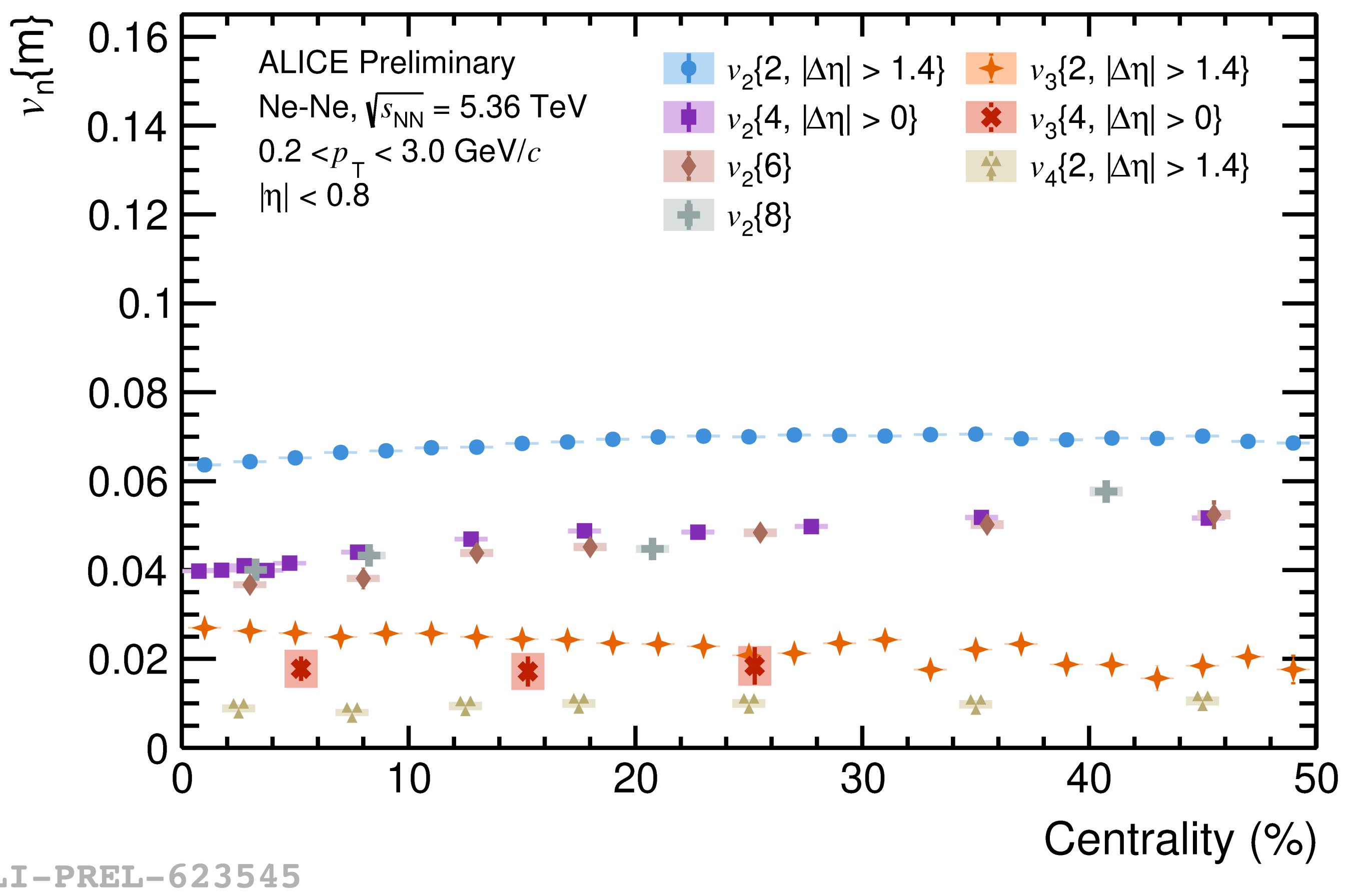
❖ Phase IV: **Tomography / Precision Era**

➡ Toward ***Precision Nuclear Structure Tomography*** at the LHC

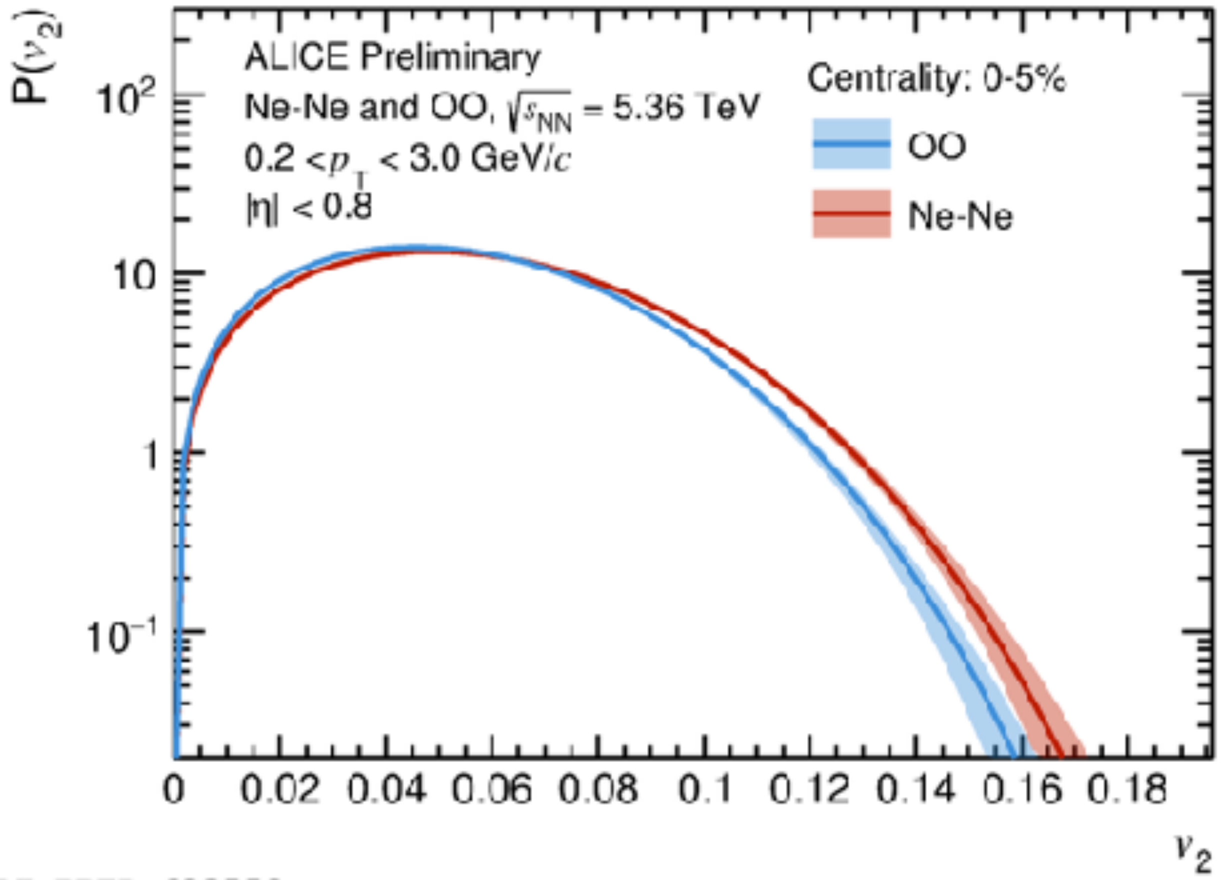


Many new OO & Ne-Ne results

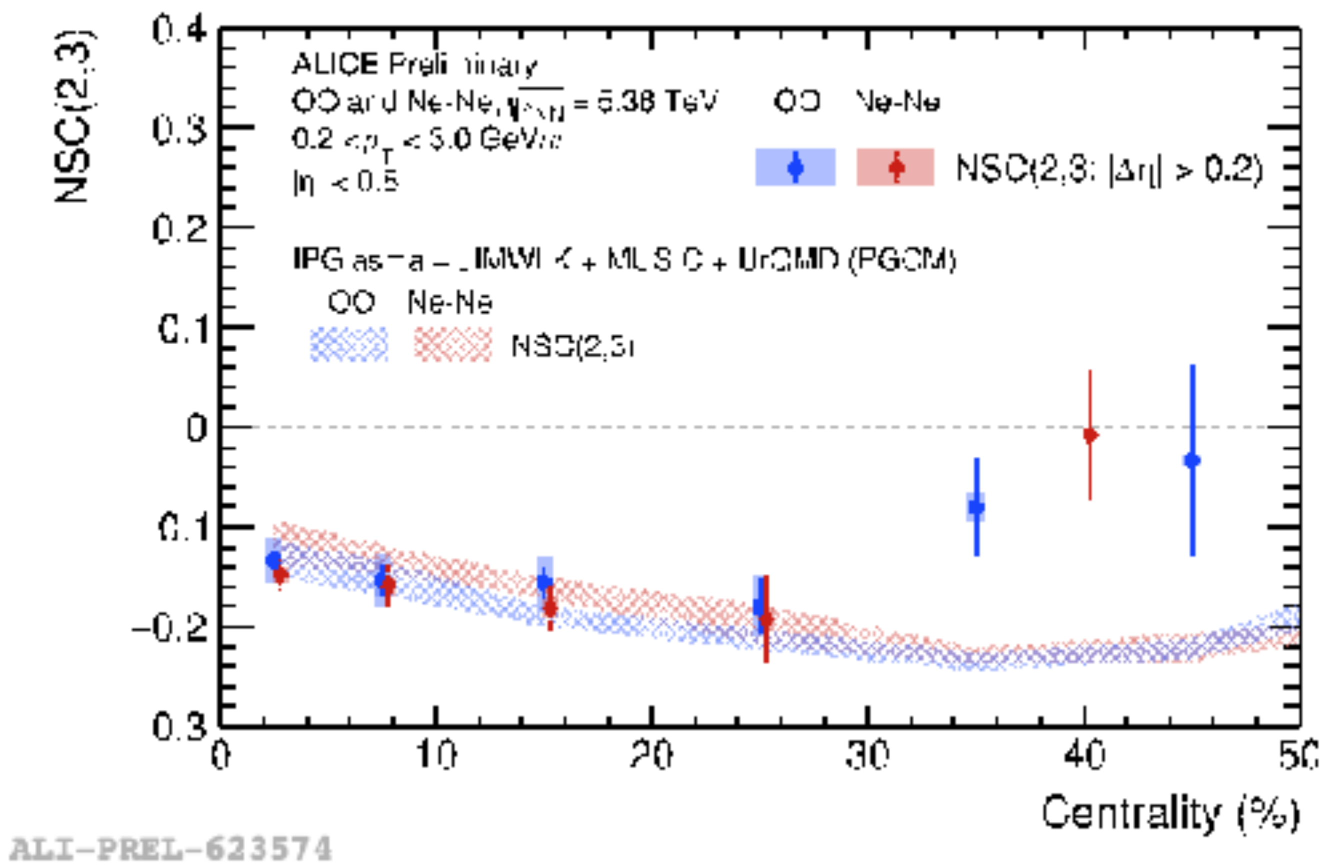
New results released for SQM2026+ many more to be available before this summer



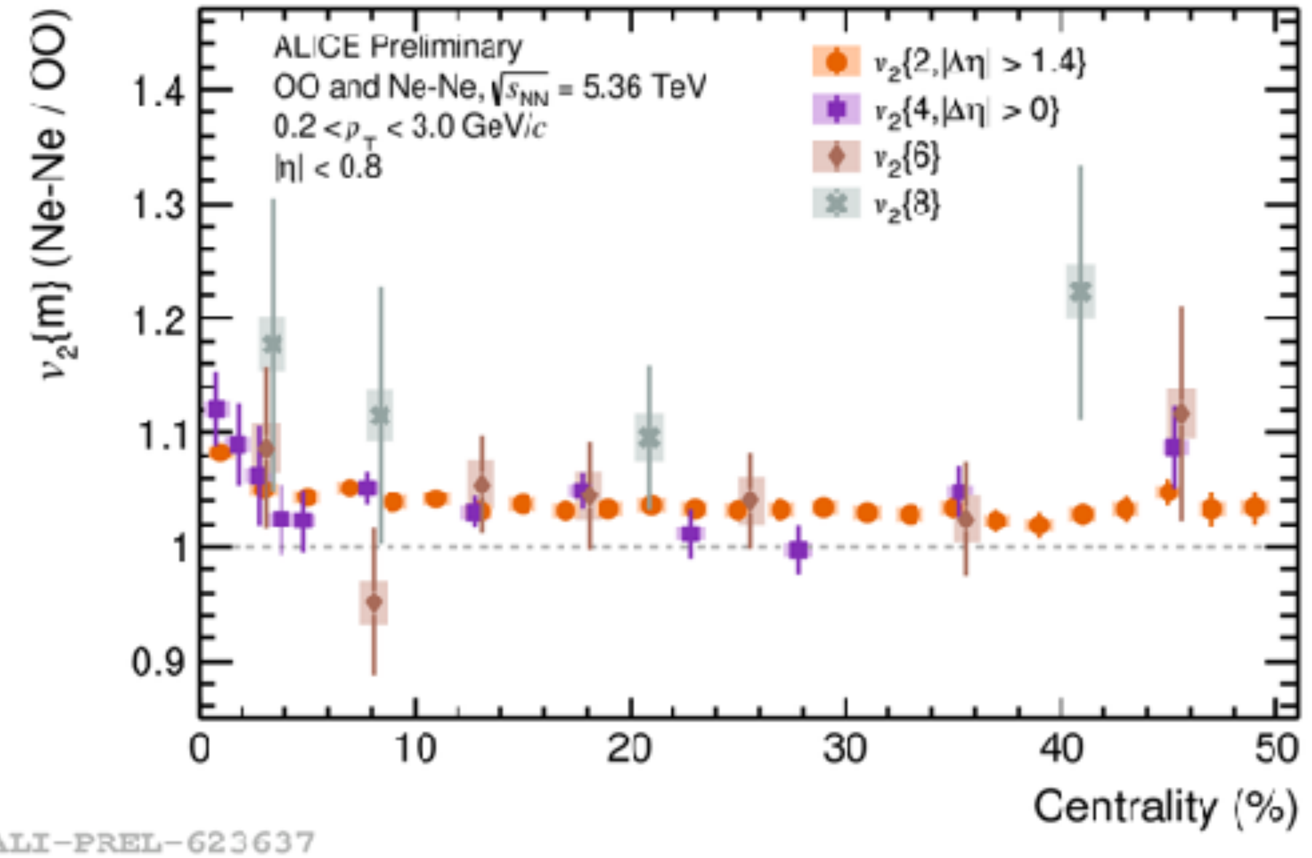
ALI-PREL-623545



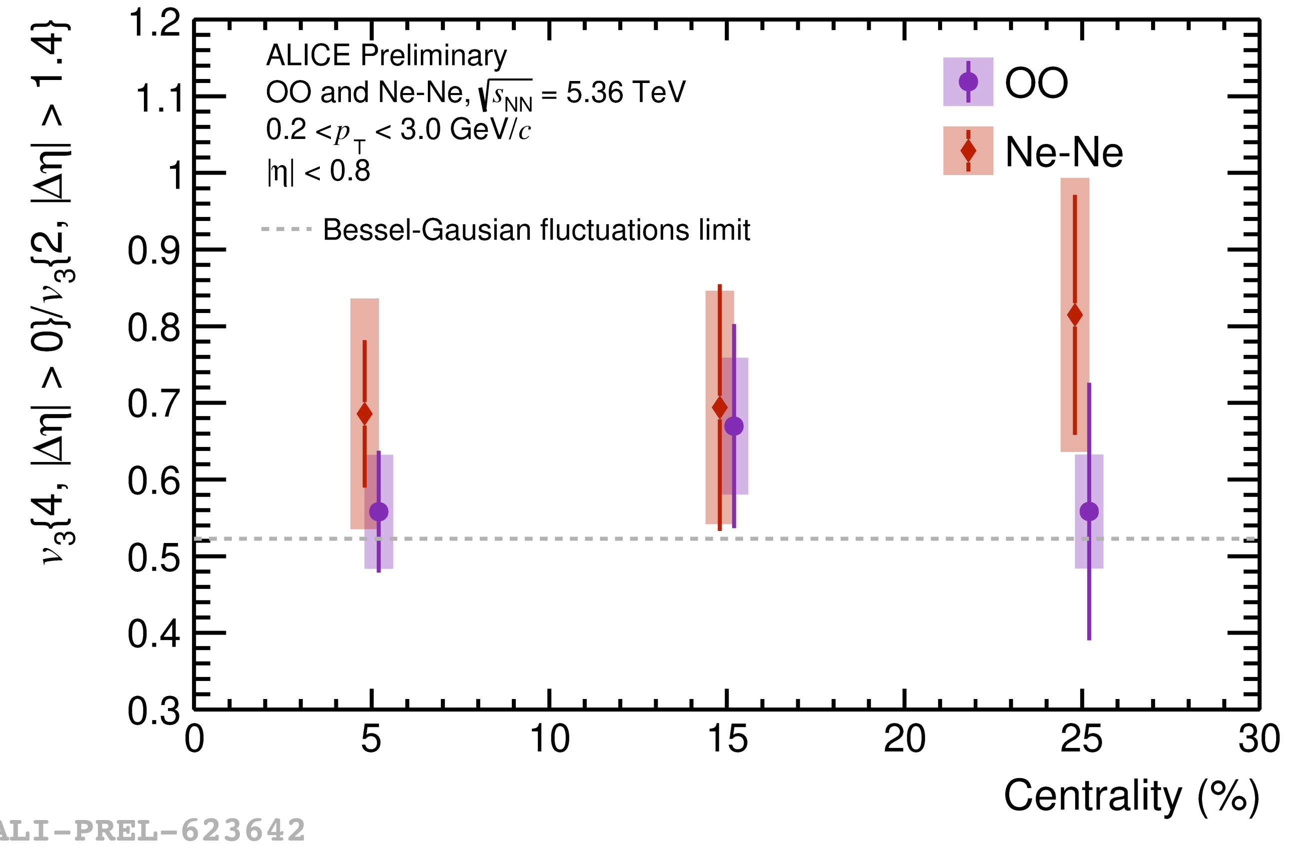
ALI-PREL-623559



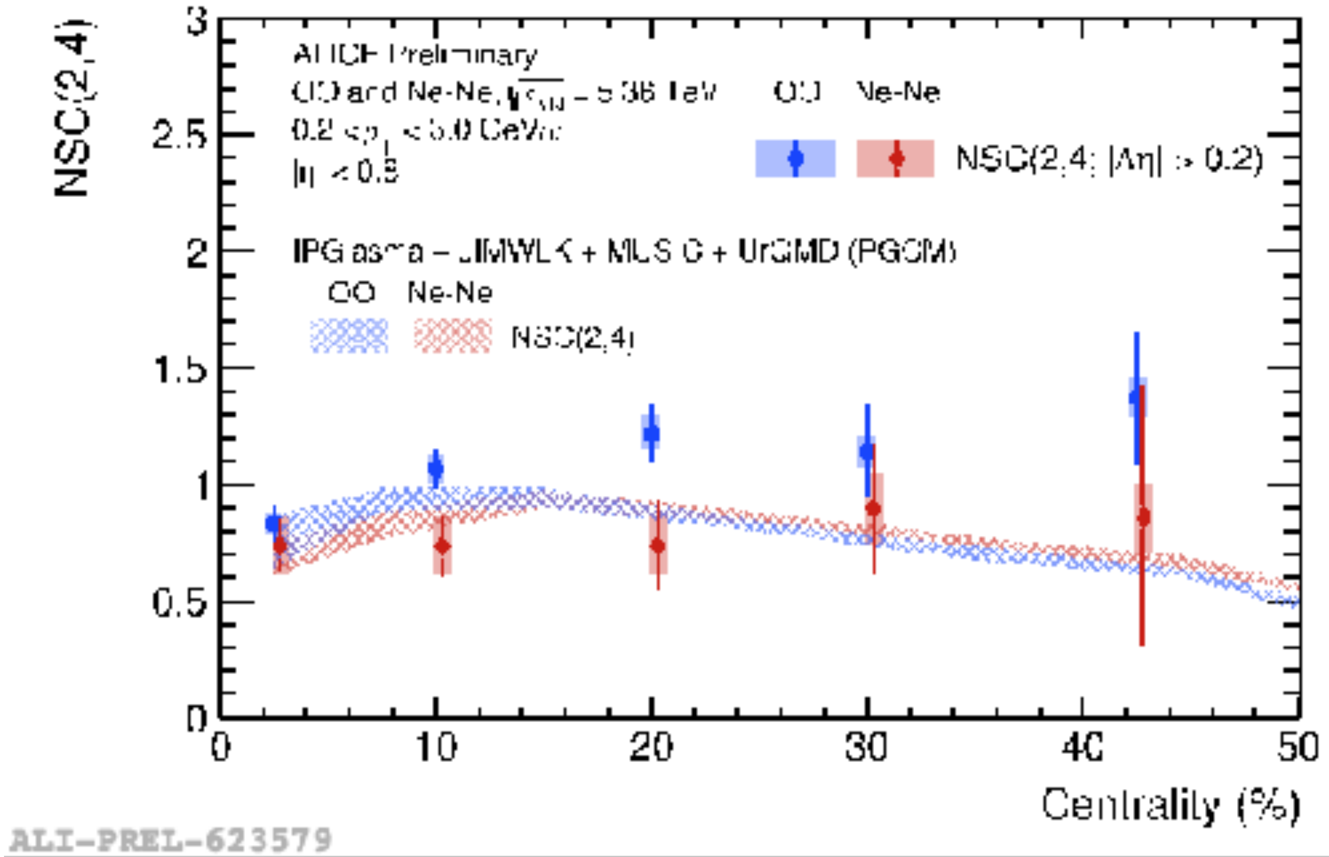
ALI-PREL-623574



ALI-PREL-623637



ALI-PREL-623642



ALI-PREL-623579

✍ Discrimination power? (PGCM vs NLEFT vs other models)

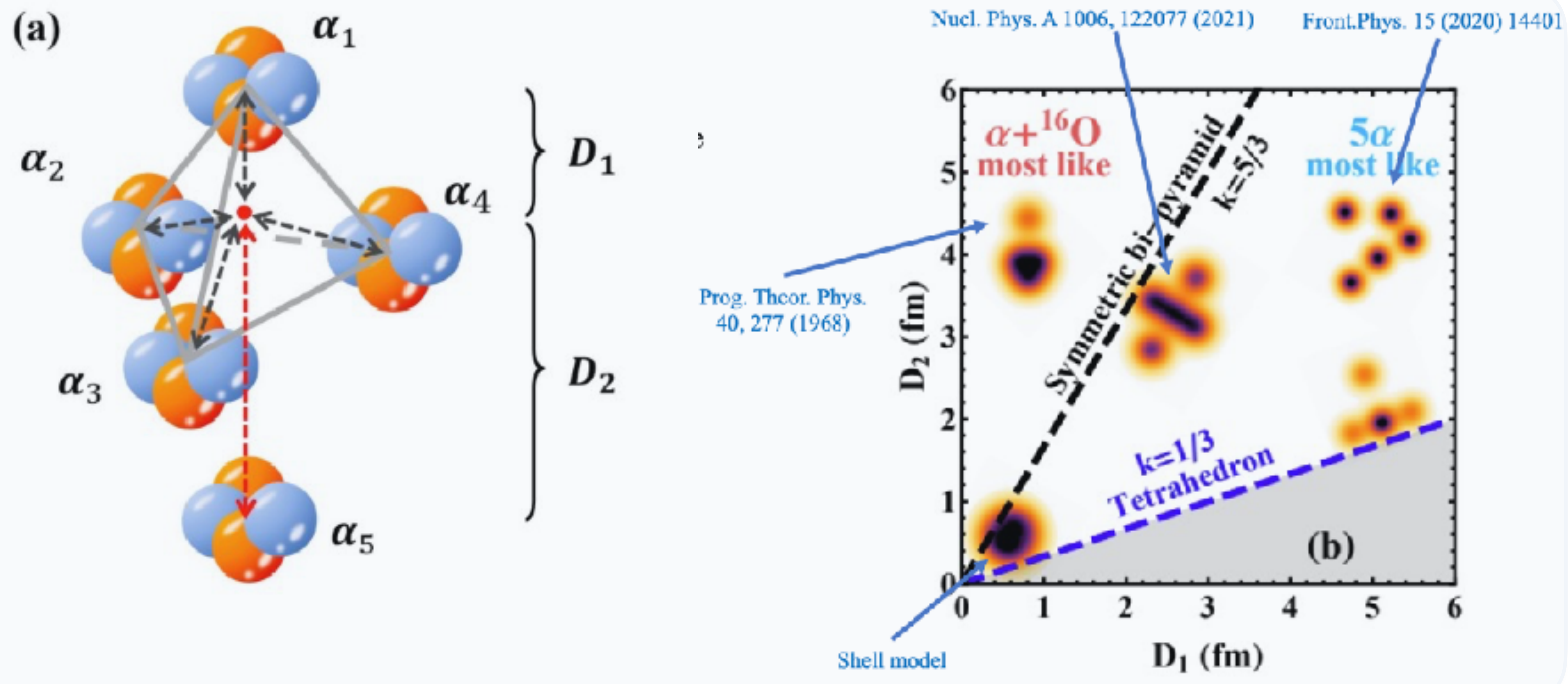
One novel idea

Identifying α-Cluster Configurations in ^{20}Ne via Ultracentral Ne + Ne Collisions

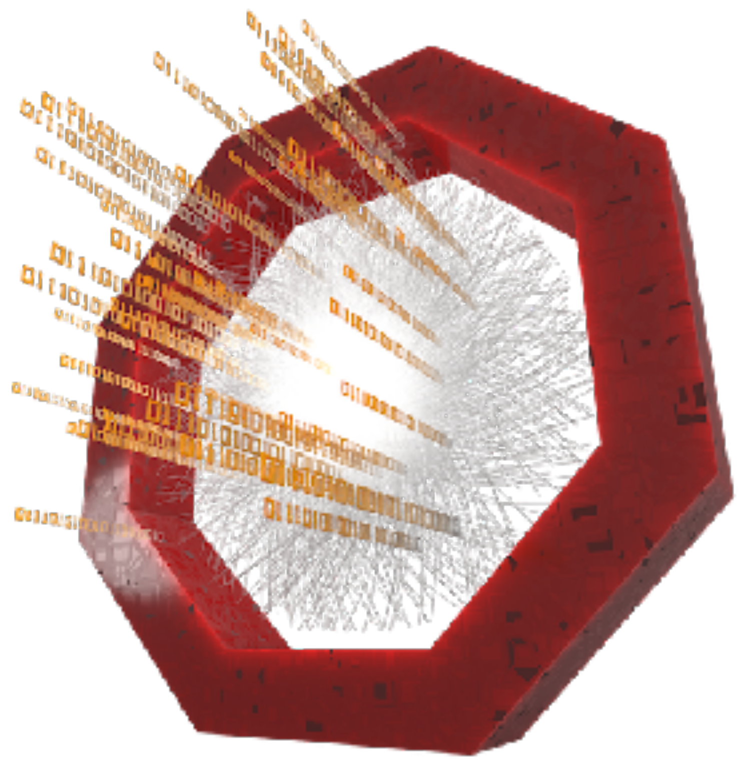
Pei Li (李沛), Bo Zhou (周波)*, and Guo-Liang Ma (马国亮)†

Show more

Phys. Rev. Lett. **136**, 082302 – **Published 27 February, 2026**



ALICE data

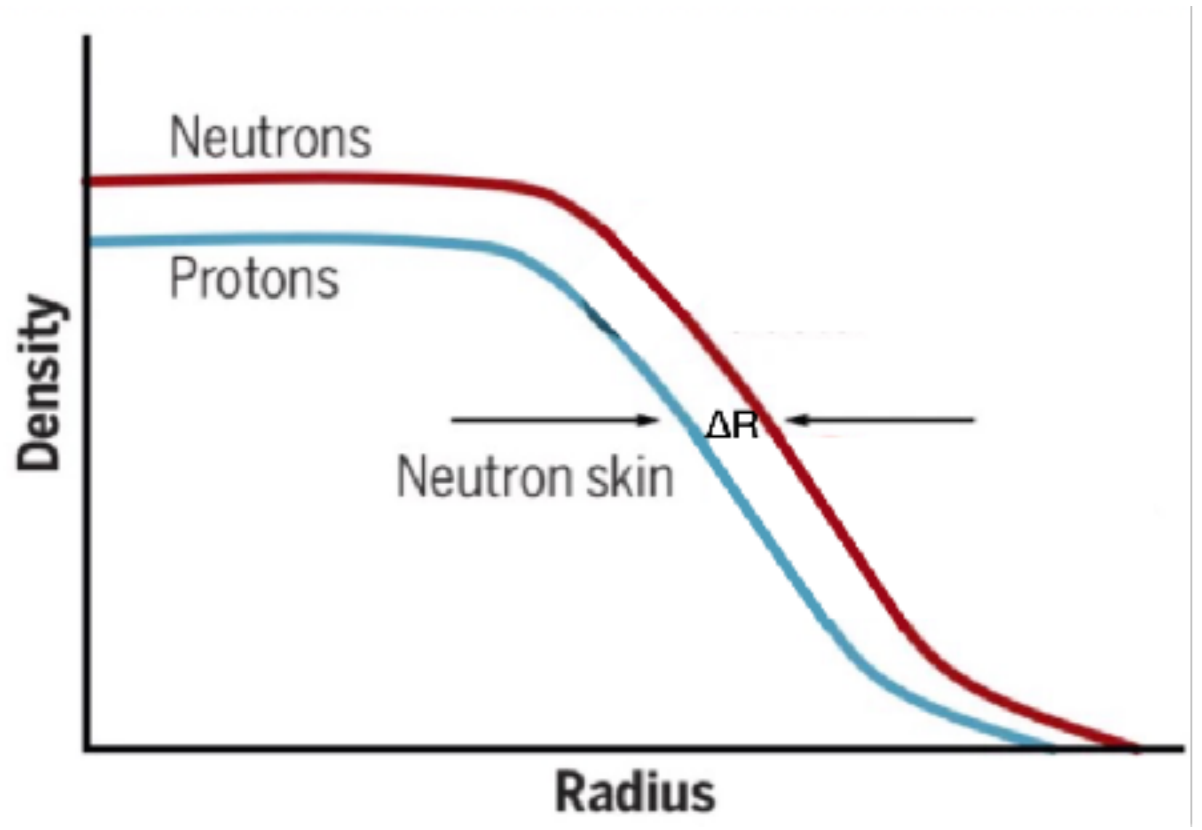


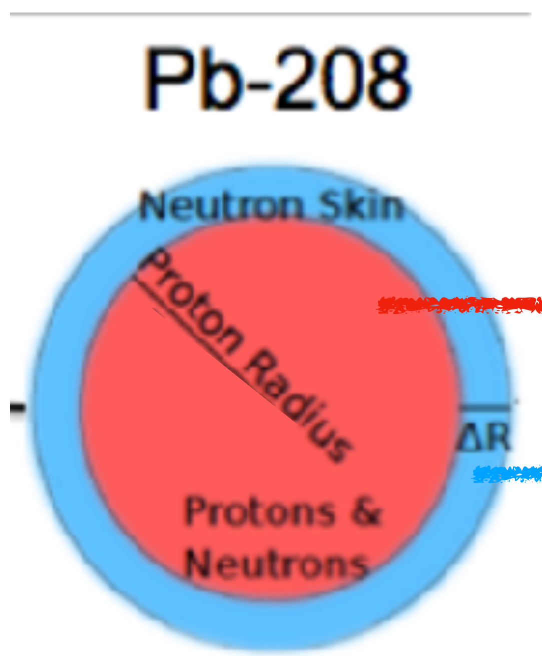
ALICE measurements

(To be available)

5-α or α+^{16}O ?

Neutron skin study at High Energy



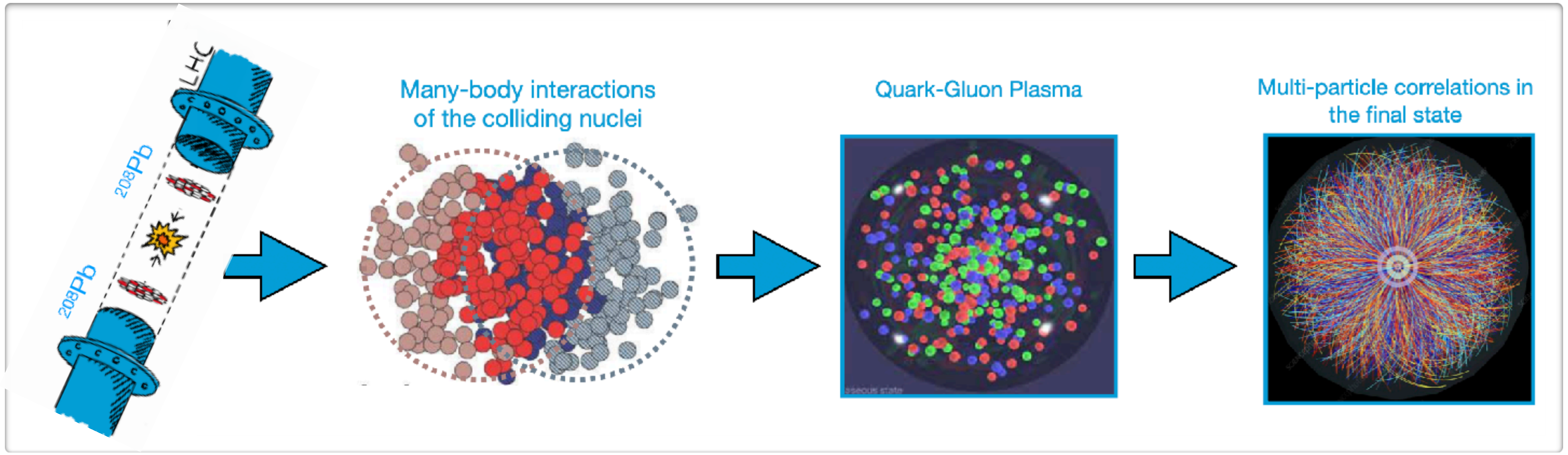


$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)}$$

$$\rho_p(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r_p-R_p(\Theta,\Phi)\right]/a_p\right)}$$

$$\rho_n(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r_n-R_n(\Theta,\Phi)\right]/a_n\right)}$$

a_p = 0.448 fm,
R_p = 6.680 fm,
r_p = 5.436 fm,
R_n = 6.690 fm



Large neutron skin → Large Initial size → Smaller [p_T] & stronger [p_T] fluctuations; → Weaker flow fluctuations

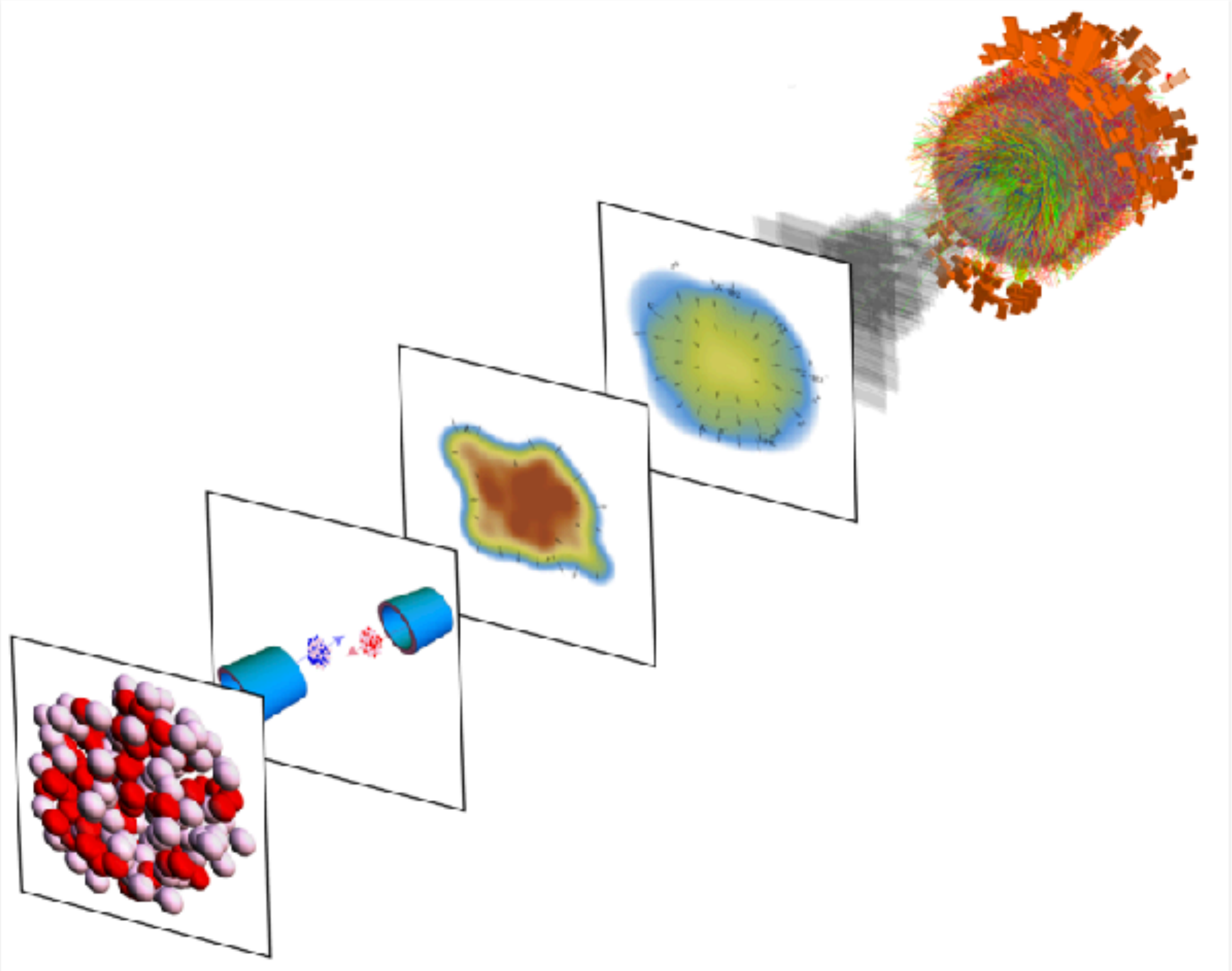
Talks on neutron skin:
- *Xavier R.M, Monday*
- *Huichao S., Tuesday*
- *Bjoern S., Wednesday*

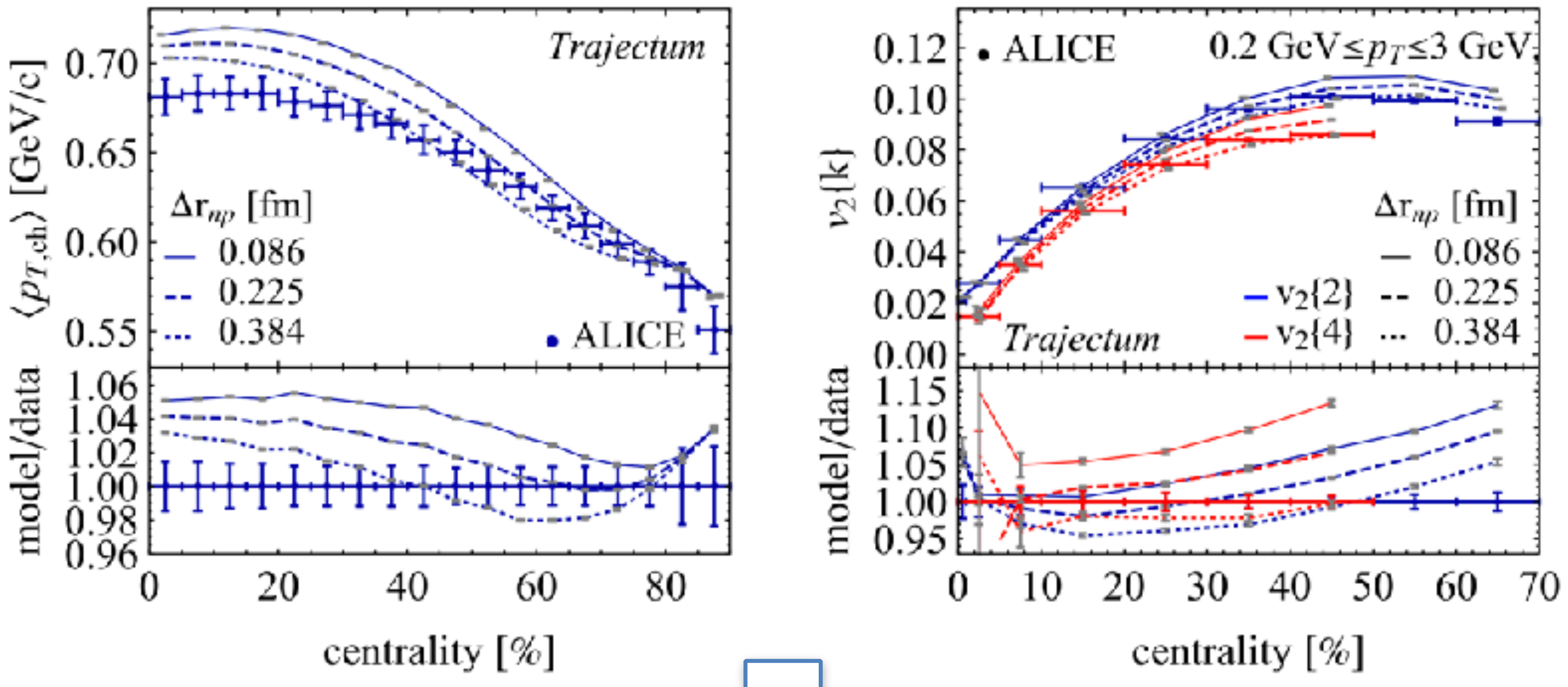
Extracting neutron skin of ^{208}Pb at the LHC

Thick-skinned: Using heavy-ion collisions at the LHC, scientists determine the thickness of neutron "skin" in lead-208 nuclei

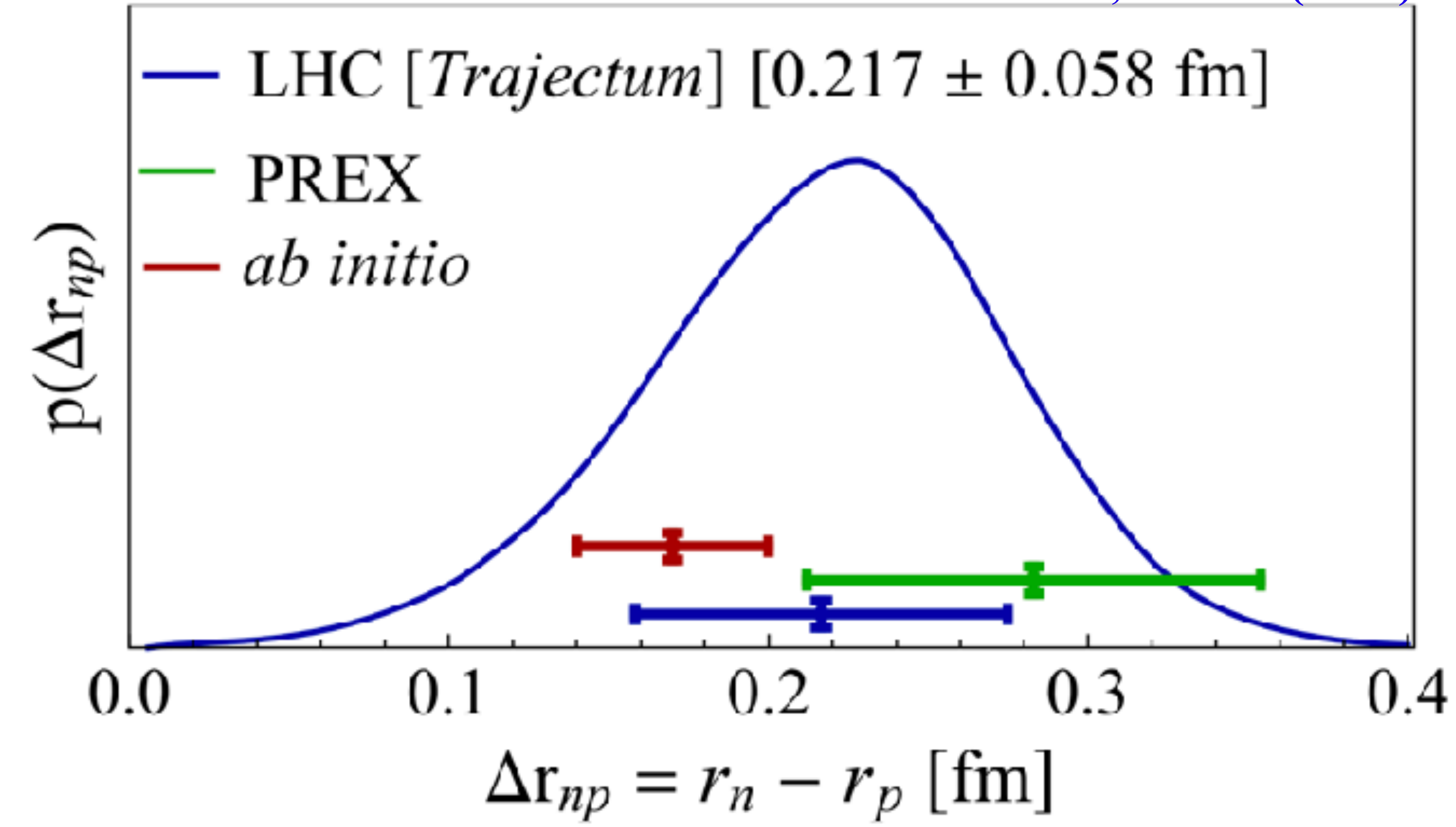
This is the first measurement of the neutron skin of lead-208 using exchanges predominantly involving gluons and it can provide insight into the structure of nuclei and neutron stars

15 NOVEMBER, 2023 | By Naomi Dinmore

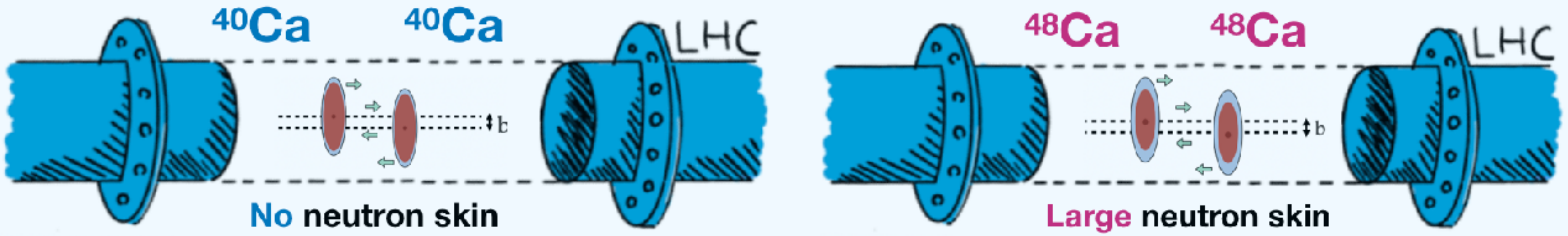




PRL131, 202302 (2023)



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

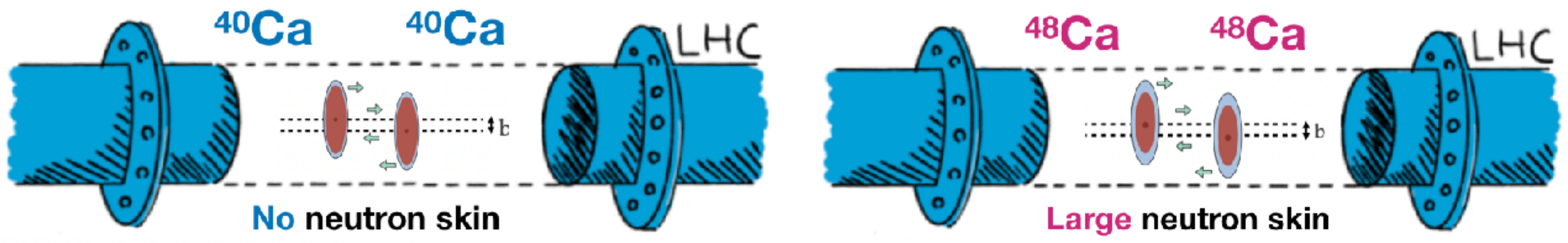


Resolve the tension between PREX and CREX (Current puzzle in low-energy nuclear physics)

Large neutron skin → Large Initial size → Smaller $[p_T]$ & stronger $[p_T]$ fluctuations

Large Initial size → Weaker flow fluctuations

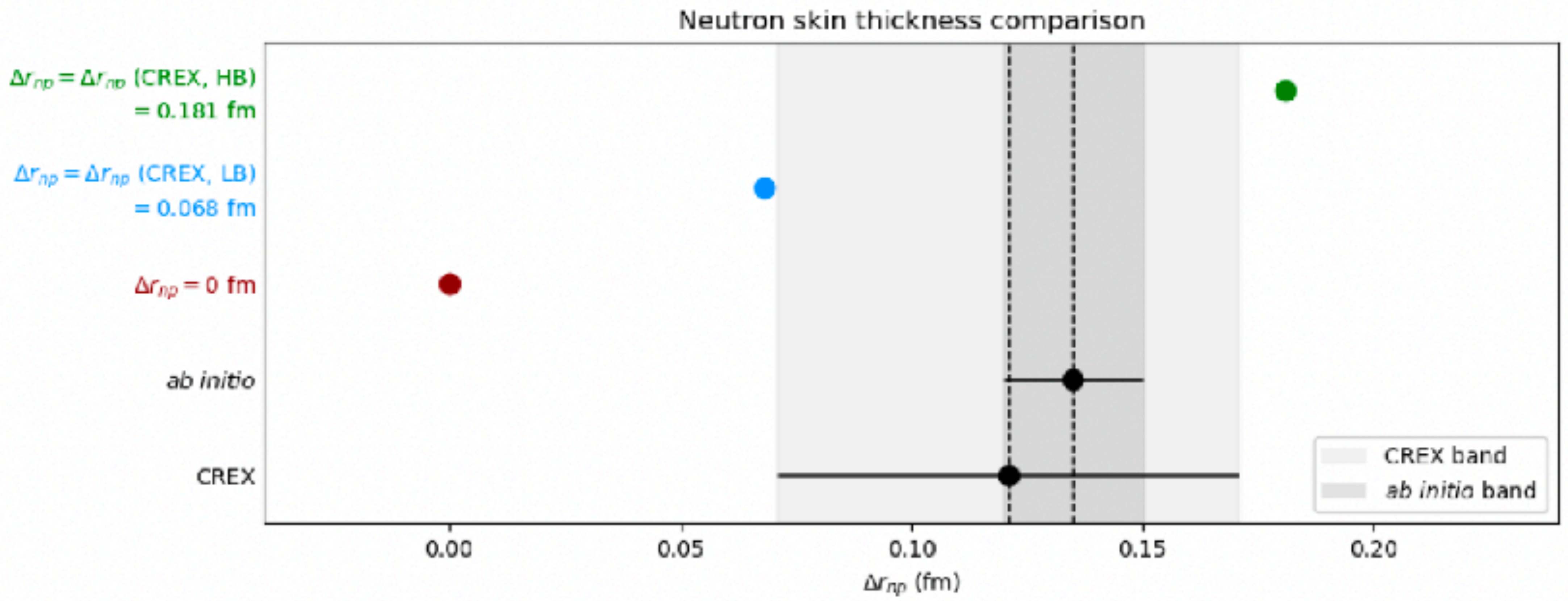
AMPT results for ^{48}Ca-^{48}Ca vs ^{40}Ca-^{40}Ca



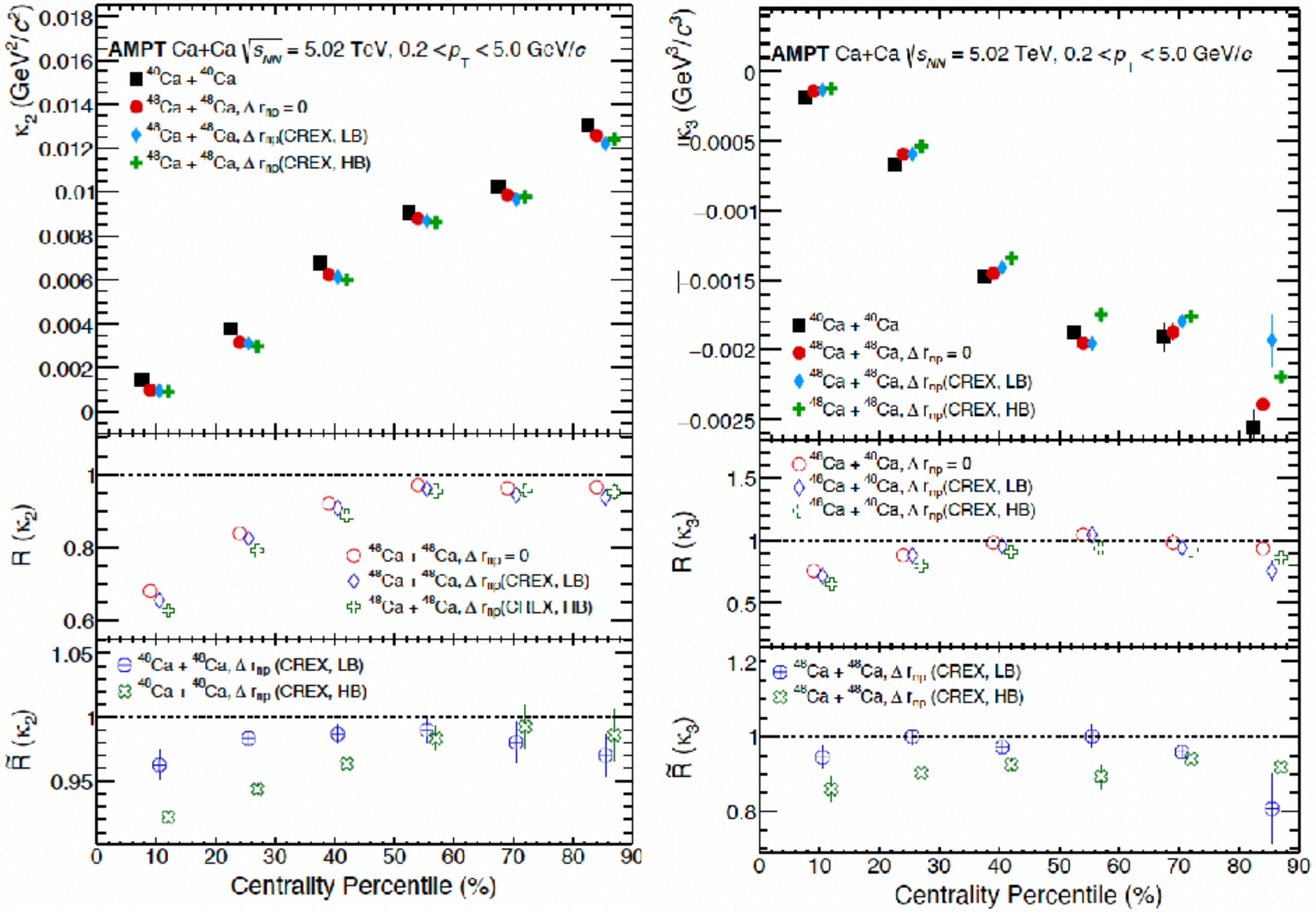

Characterizing the Neutron Skin of ^{48}Ca Through Collective Flow at the CERN Large Hadron Collider

Andreas Vitsos [1], Leonora Misciattelli Mocenigo Soranzo [1], Emil Gorm Dahlbæk Nielsen [1], You Zhou [1,a]

[1]Niels Bohr Institute, Jagtvej 155A, 2200 Copenhagen, Denmark

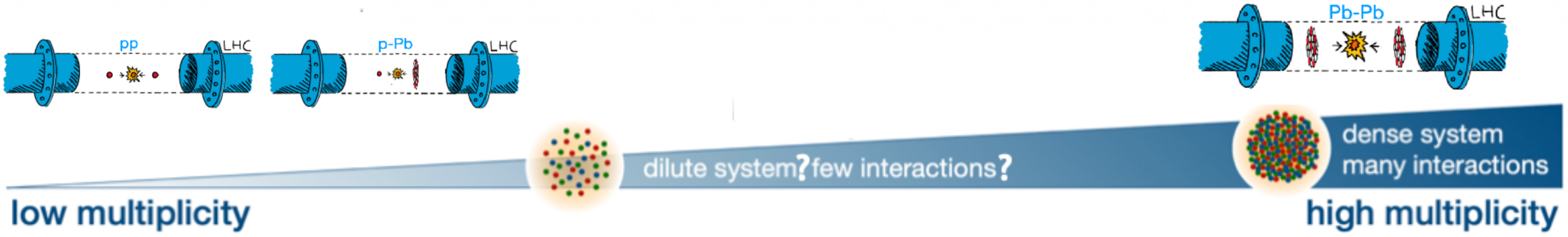


arXiv: 2512.00114, submitted to EPJC



- Highly non-trivial differences observed when using large and small neutron skin
    - *^{48}Ca-^{48}Ca as a promising candidate for the future light-ion runs at the LHC-Run4*

Searching for a tiny droplet of QGP



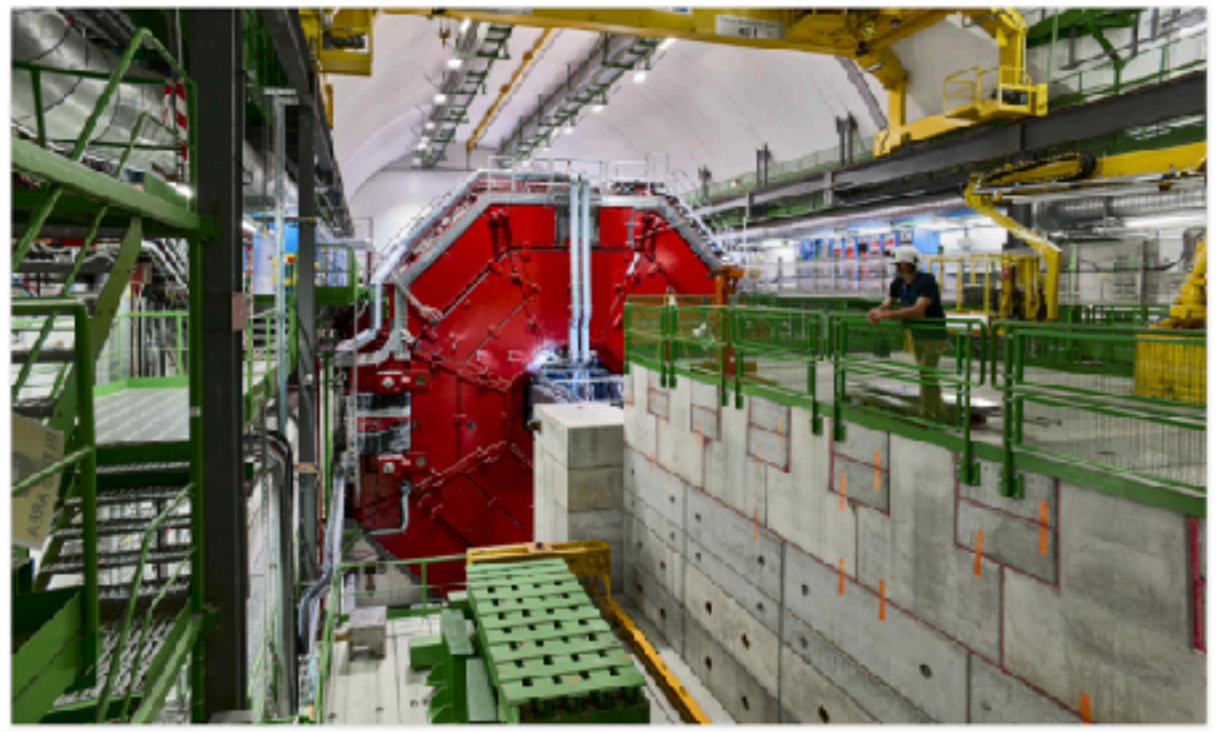
ABOUT NEWS SCIENCE

Voir en français

ALICE sees new sign of primordial plasma in proton collisions

The ALICE Collaboration takes a step further in addressing the question of whether a quark–gluon plasma can be formed in proton–proton and proton–nucleus collisions

20 MARCH, 2026 | By ALICE collaboration



nature communications

Article https://doi.org/10.1038/s41467-025-67796-1

Observation of partonic flow in proton–proton and proton–nucleus collisions

Received: 12 July 2025

Accepted: 3 December 2025

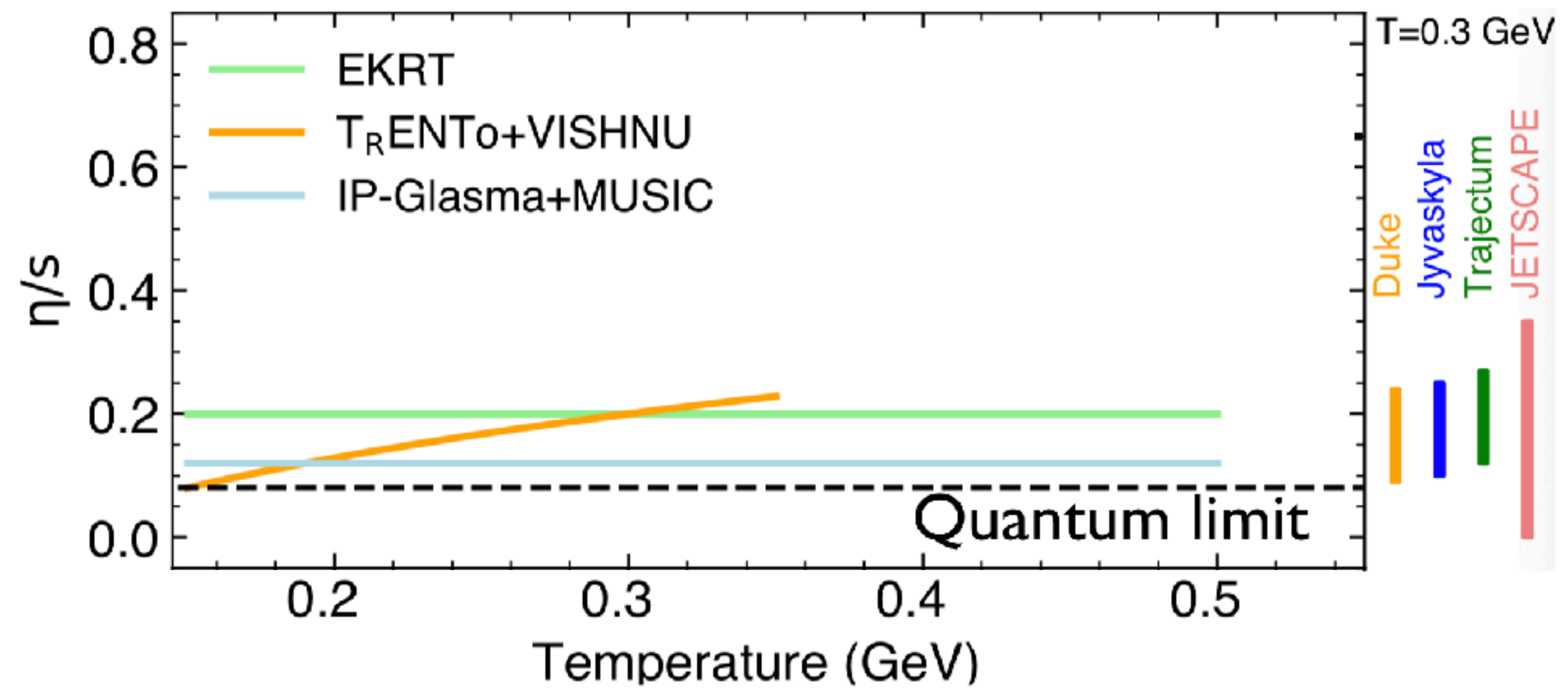
Published online: 20 March 2026

Check for updates

The ALICE Collaboration *

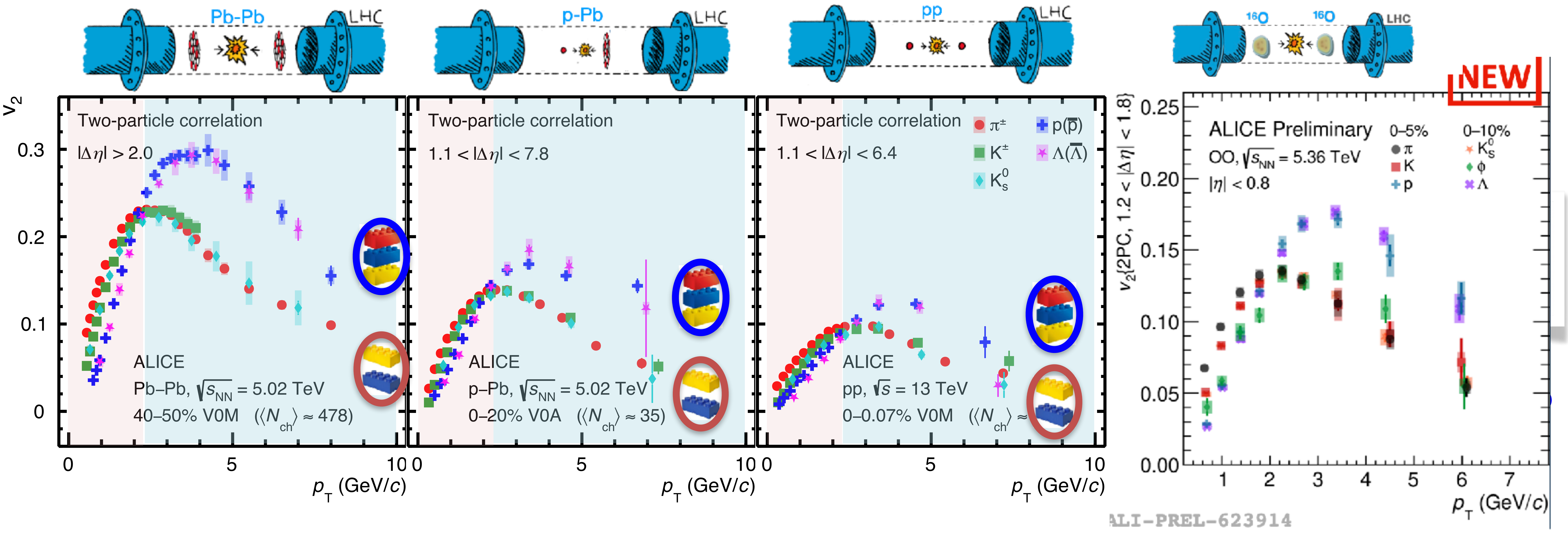
Quantum Chromodynamics predicts a phase transition from hadronic matter to quark–gluon plasma (QGP) at high temperatures and energy densities, where quarks and gluons (partons) are no longer confined within hadrons. The QGP forms in ultrarelativistic heavy-ion collisions. Anisotropic flow coefficients, quantifying the azimuthal expansion of produced matter, probe QGP properties. Flow measurements in high-energy heavy-ion collisions show a distinctive grouping of anisotropic flow for baryons and mesons at intermediate transverse momentum – a feature associated with flow imparted at the quark level, confirming QGP existence. The observation of QGP-like features in proton–proton and proton–ion collisions has sparked debate about QGP formation in smaller systems. For the first time, we demonstrate the distinctive grouping of anisotropic flow for baryons and mesons in high-multiplicity proton–lead and proton–proton collisions at the Large Hadron Collider (LHC). These results are described by a model including hydrodynamic flow followed by hadron formation via quark coalescence, consistent with the formation of partonic flowing systems in these collisions.

Yes,
We Can!



Details, also see talk:
Huichao Song @ Wednesday

QGP in p-Pb and pp collisions

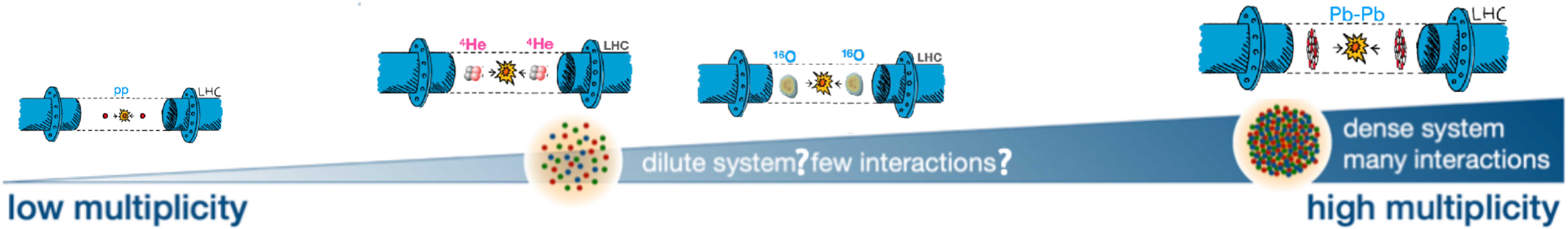


❖ Flow of identified hadrons in pp, p-Pb, OO and Pb-Pb

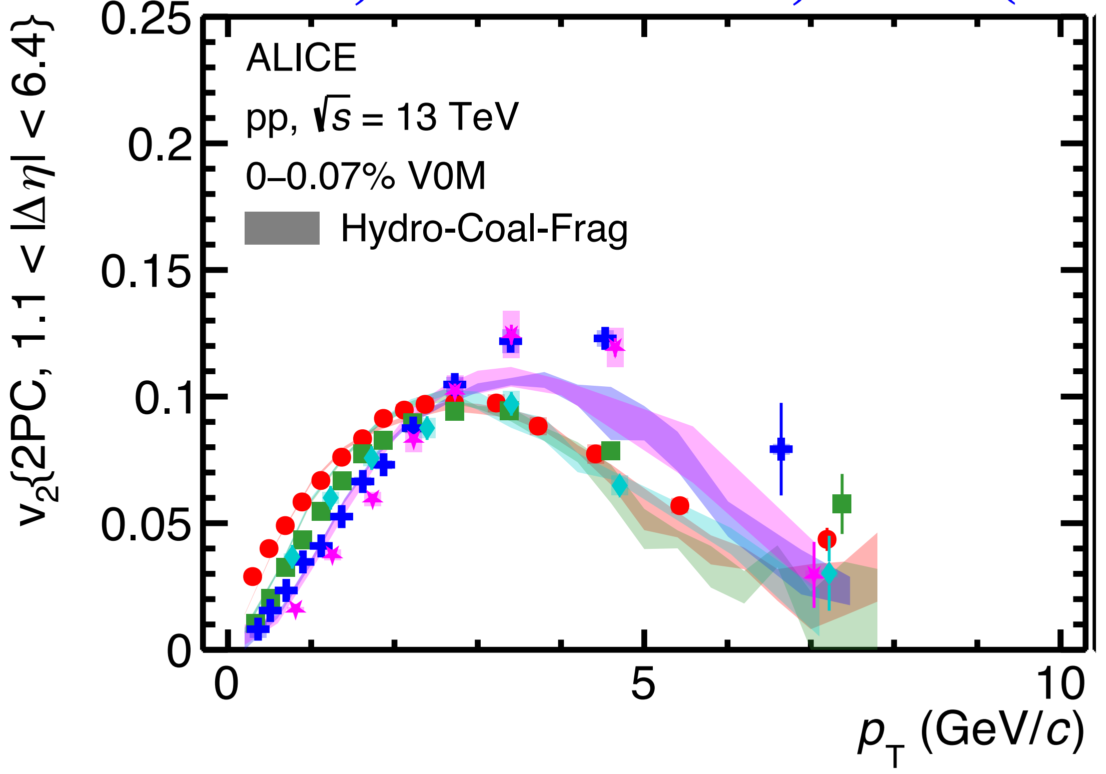
- Observation of partonic flow in small systems (> 5σ), flow developed at the parton level.

Preet P. (NBI) @SQM2026

QGP in ^{4}He-^{4}He ?

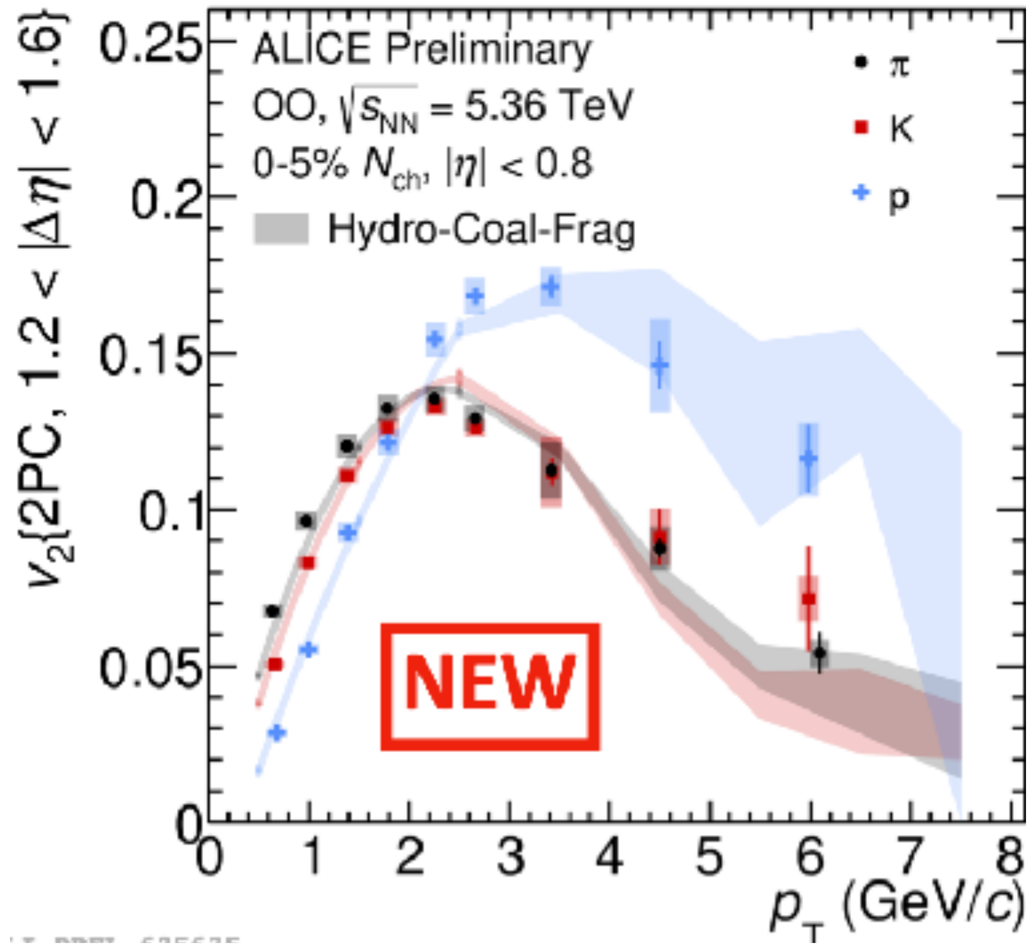


ALICE, Nat Com. 17, 2585 (2026)

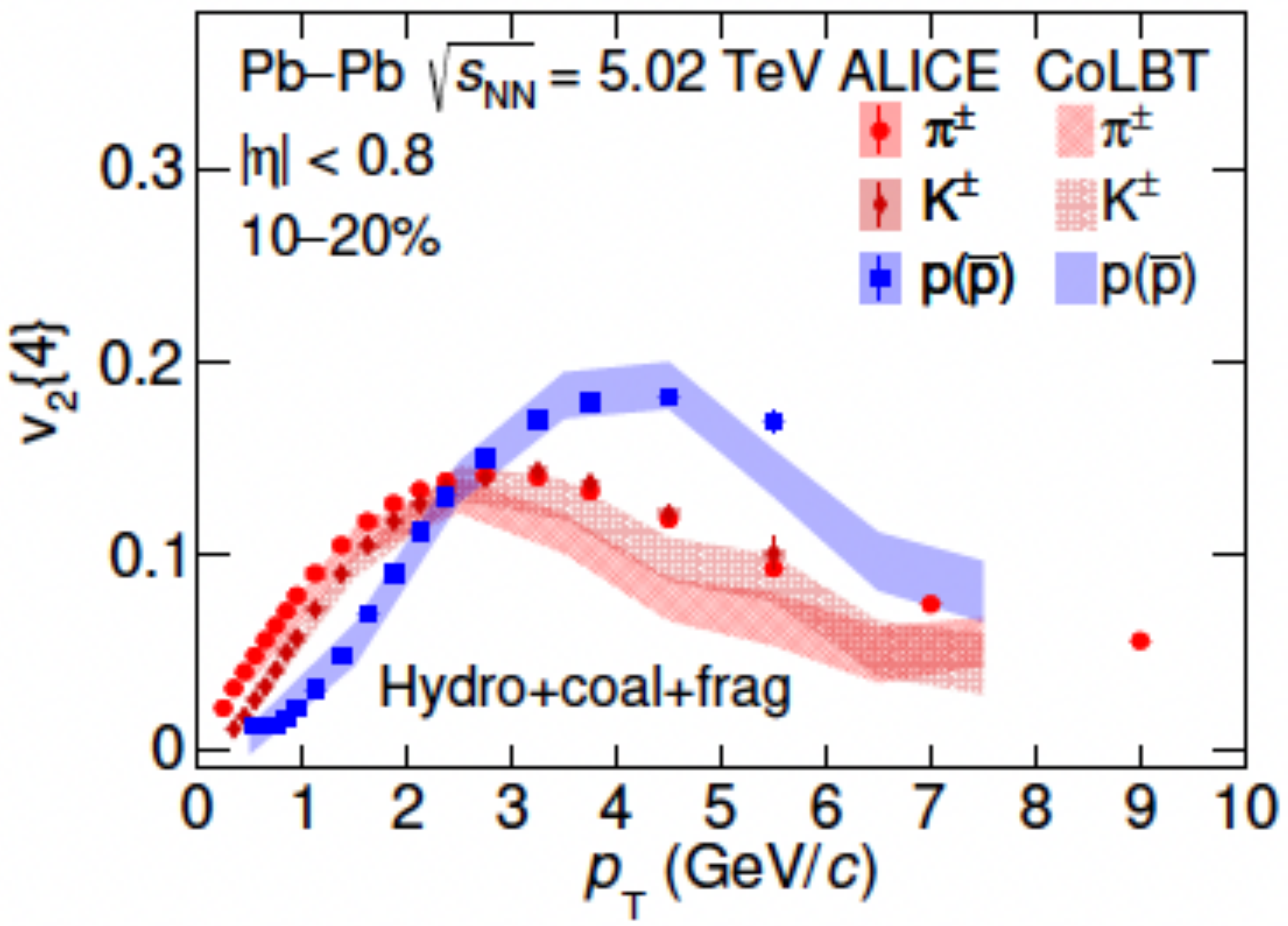


PID flow
In ^{4}He-^{4}He

Preet P. @SQM2026



ALICE, JHEP05(2023)243



Summary

❖ Phase I: **Emergence**

➡ Emergence of Nuclear Structure Effects in Ultra-Relativistic Collisions

❖Phase II: **Sensitivity → Extraction**

➡ From Sensitivity to Extraction: Probing Nuclear Structure with Collective Flow

❖ Phase III: **Unification and validation**

➡ Toward a Unified Framework: nuclear structure across energy scale

➡ Validation with Light-Ion Collisions

❖ Phase IV: **Tomography / Precision Era**

➡ Toward Nuclear Structure Tomography at the LHC

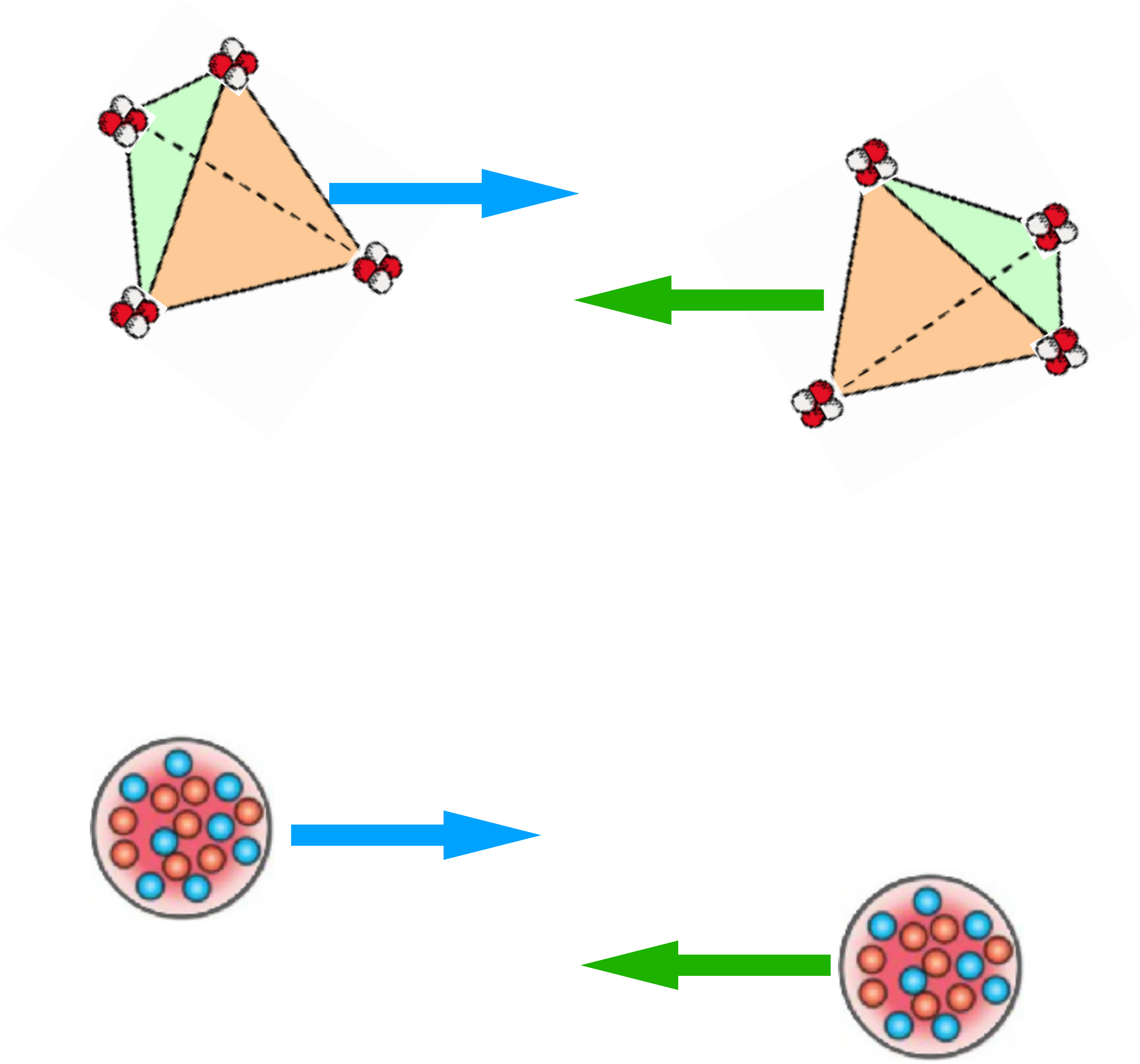
With the inputs on NS from low-energy community, we have significantly improved our understanding on the Quark-Gluon Plasma (critical for the HI community!)

With the future developments, we would like to fully explore the potential of the LHC as the most powerful Nuclear Structure experiment, ***with a few carefully-selected nuclei***.

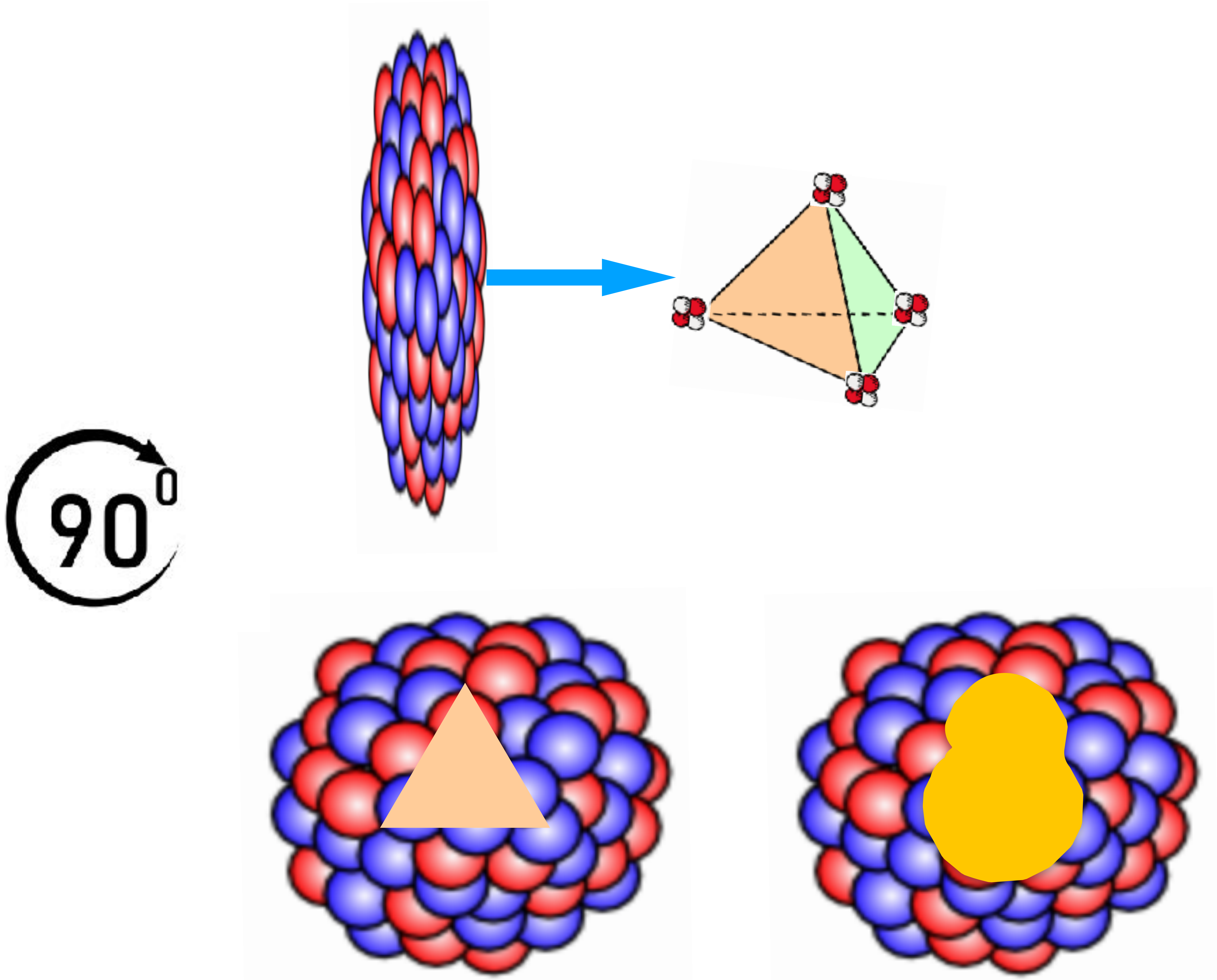
Details on the machine see talk:
Reyes Alemany Fernandez @ Tuesday

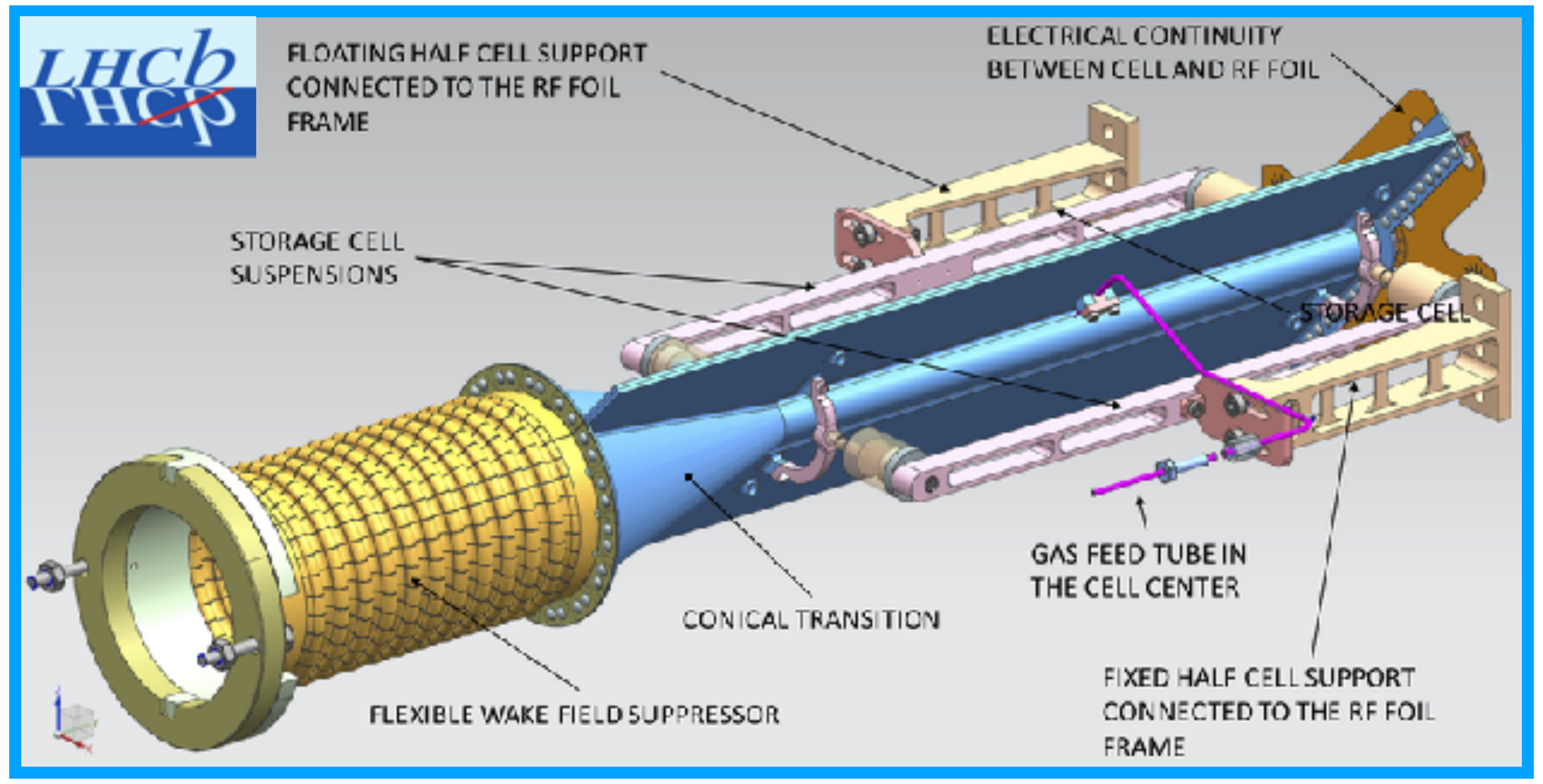
New opportunity

Colliding mode



Fixed target





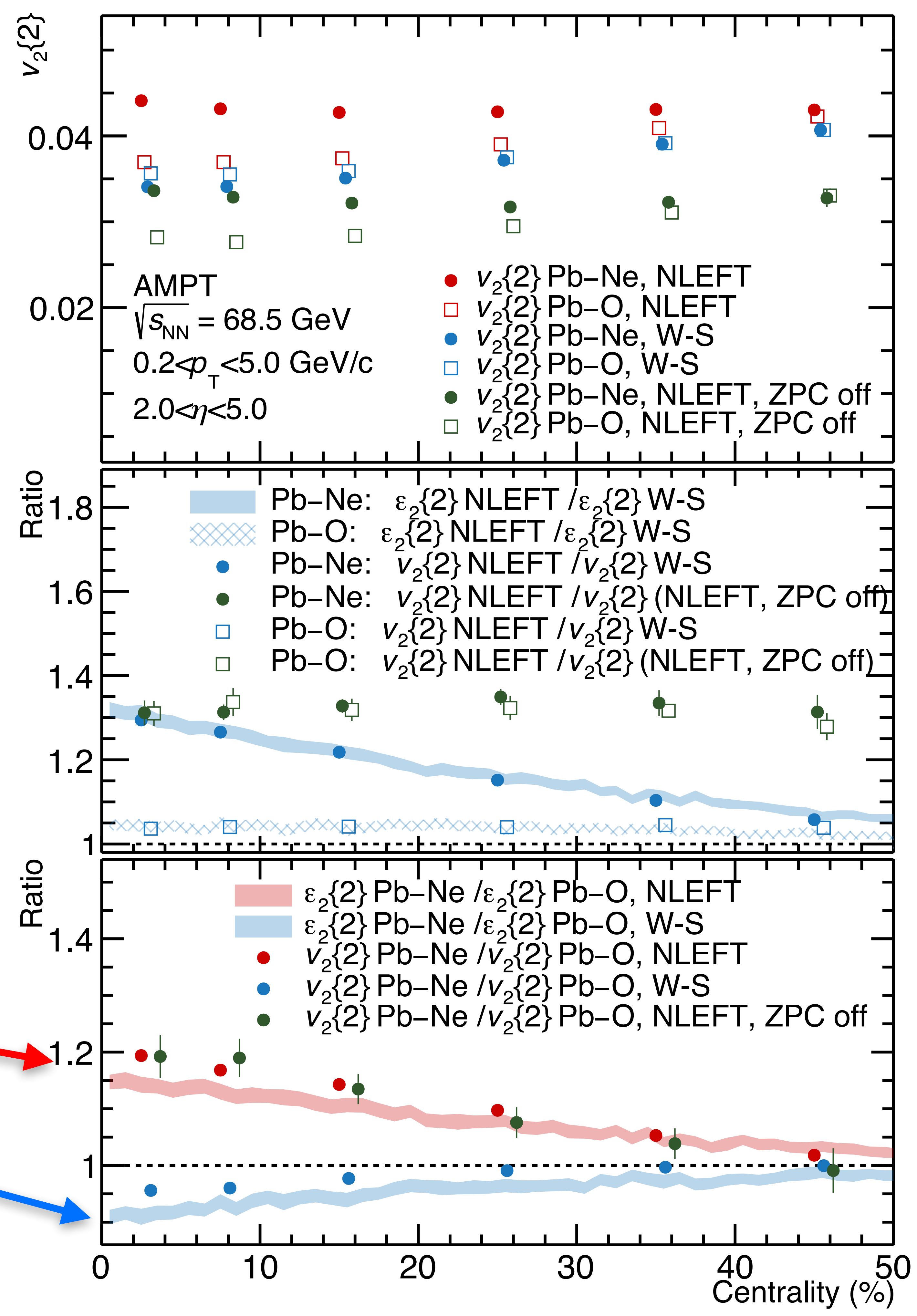
合作单位：原子能院

^{208}Pb-^{20}Ne @ ~68 GeV

^{208}Pb-^{16}O @ ~68 GeV

AMPT: Z. Lu, M. Zhao, E. Nielsen, X. Li, **YZ**

Phys. Lett. B 868 (2025) 139698



❖ **$v_2\{2\}$ ratio (Pb-Ne)/(Pb-O)**

- With NLEFT, up to 20% increase in Pb-Ne
- With W-S, down to 10% decrease in Pb-Ne

❖ **Imprint of Light Nuclei Structure**

- Same picture observed in hydro and AMPT models
- Robust signature independent on the system's evolution

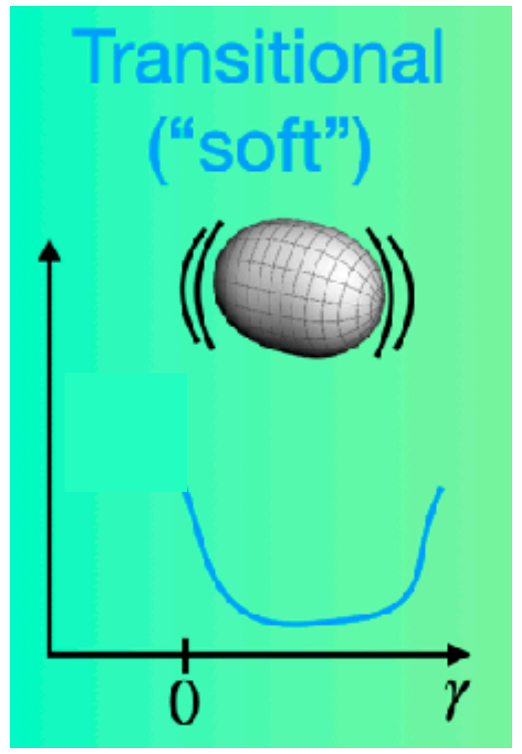
Explore nuclear shape phase transition with ^{129}Xe

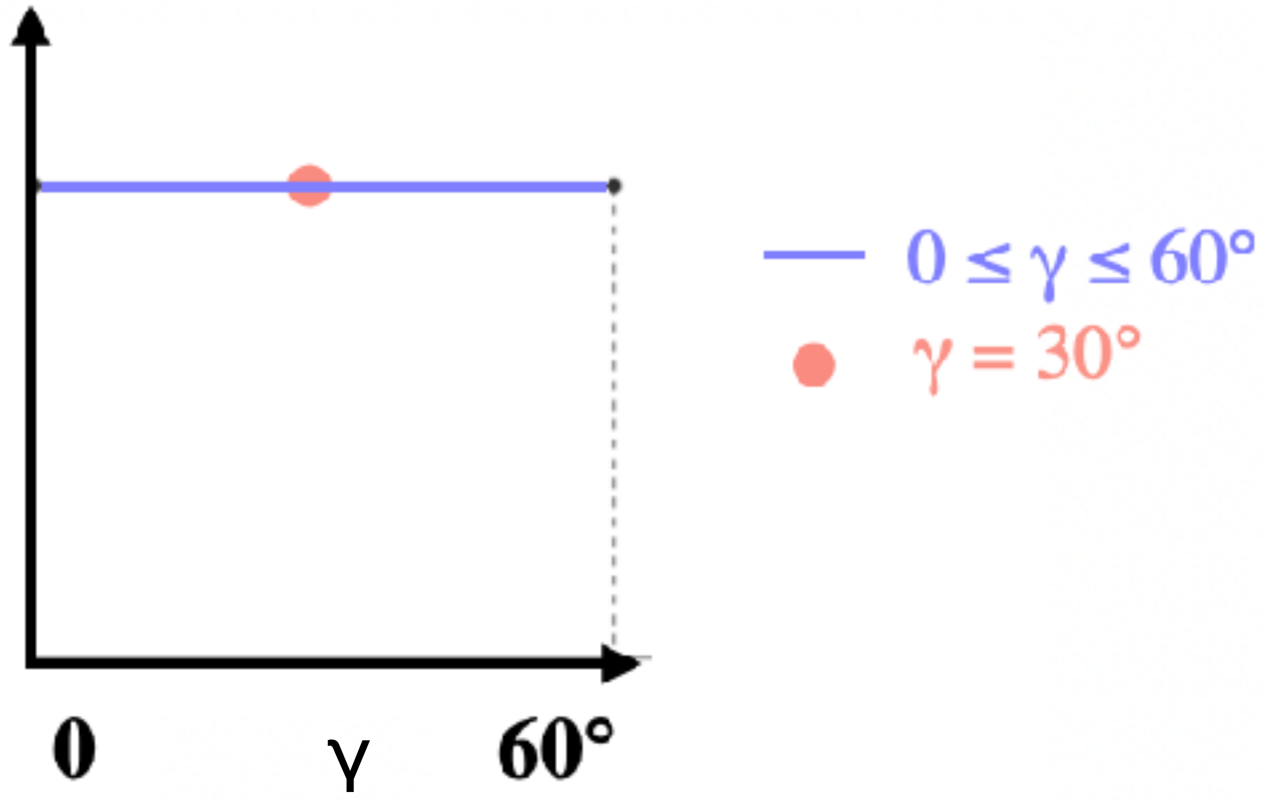
Phys. Rev. Lett. 133 (2024) 192301

Physical Review Letters

Exploring the Nuclear-Shape Phase Transition in Ultrarelativistic ^{129}Xe + ^{129}Xe Collisions at the LHC

Shujun Zhao[1,2,*], Hao-jie Xu[2,3,†], You Zhou[4,‡], Yu-Xin Liu[1,5,6,§], and Huichao Song[1,5,6,||]



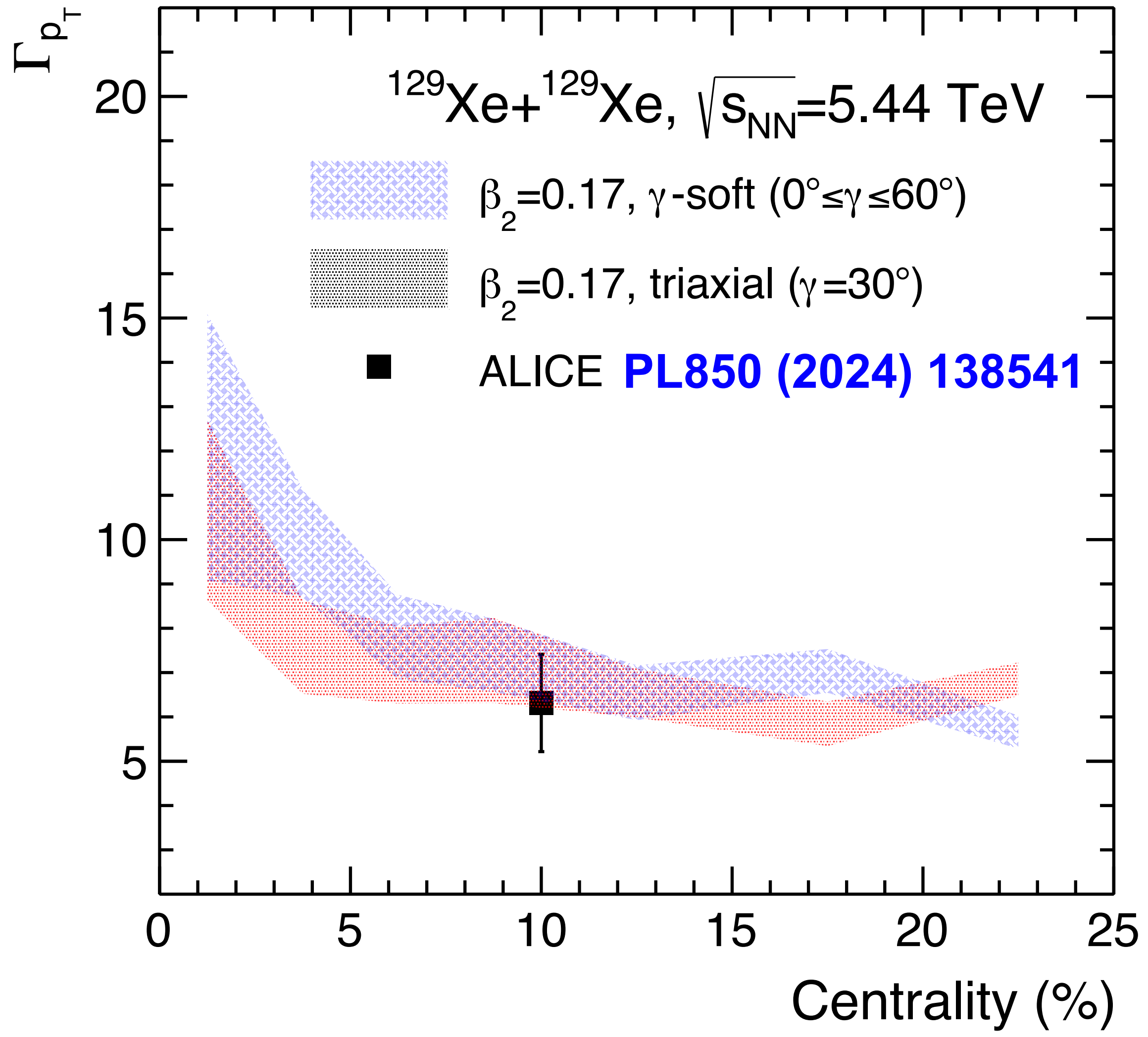


❖One can ***NOT*** distinguish triaxial (fixed γ = 30°) and γ-soft (fluctuating γ) structures with existing 3-particle correlations measurements

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

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