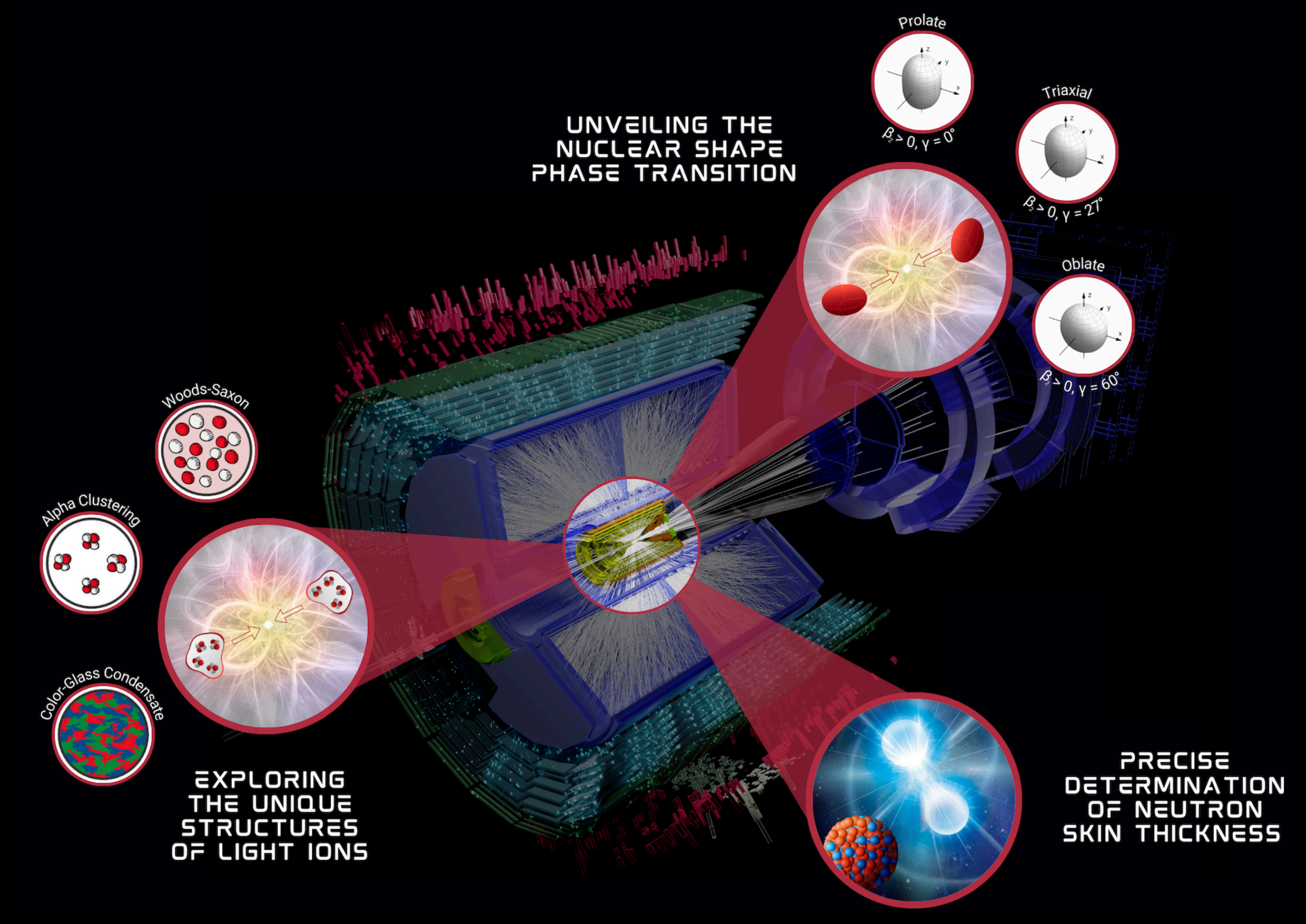
Imaging the nuclear structure at the TeV energy scale using reverse engineering



Based on papers:

- Phys. Lett. B 868 (2025) 139698
- Phys. Rev. Lett. 133, 192301 (2024)
- arXiv: 2504.03044
- arXiv: 2404.09780

EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

UNIVERSITY OF COPENHAGEN

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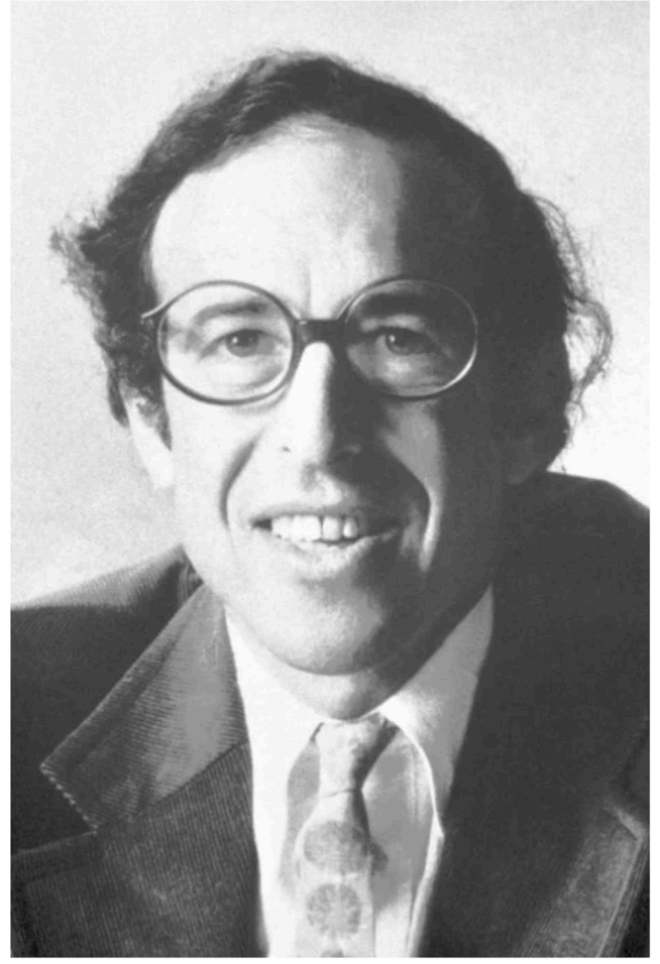
INDEPENDENT RESEARCH FUND DENMARK

50 Years since 1975

The Nobel Prize in Physics 1975


Photo from the Nobel Foundation archive.
Aage Niels Bohr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Ben Roy Mottelson


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Leo James Rainwater

"for the discovery of the connection between ***collective motion*** *and* ***structure of the atomic nucleus****…"*

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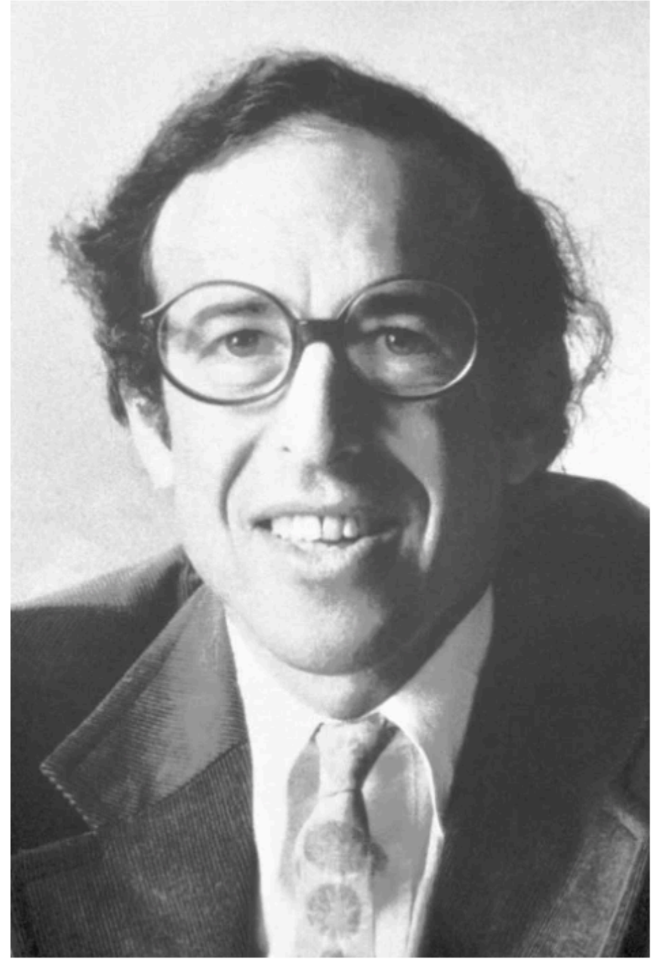

Photo from the Nobel Foundation archive.
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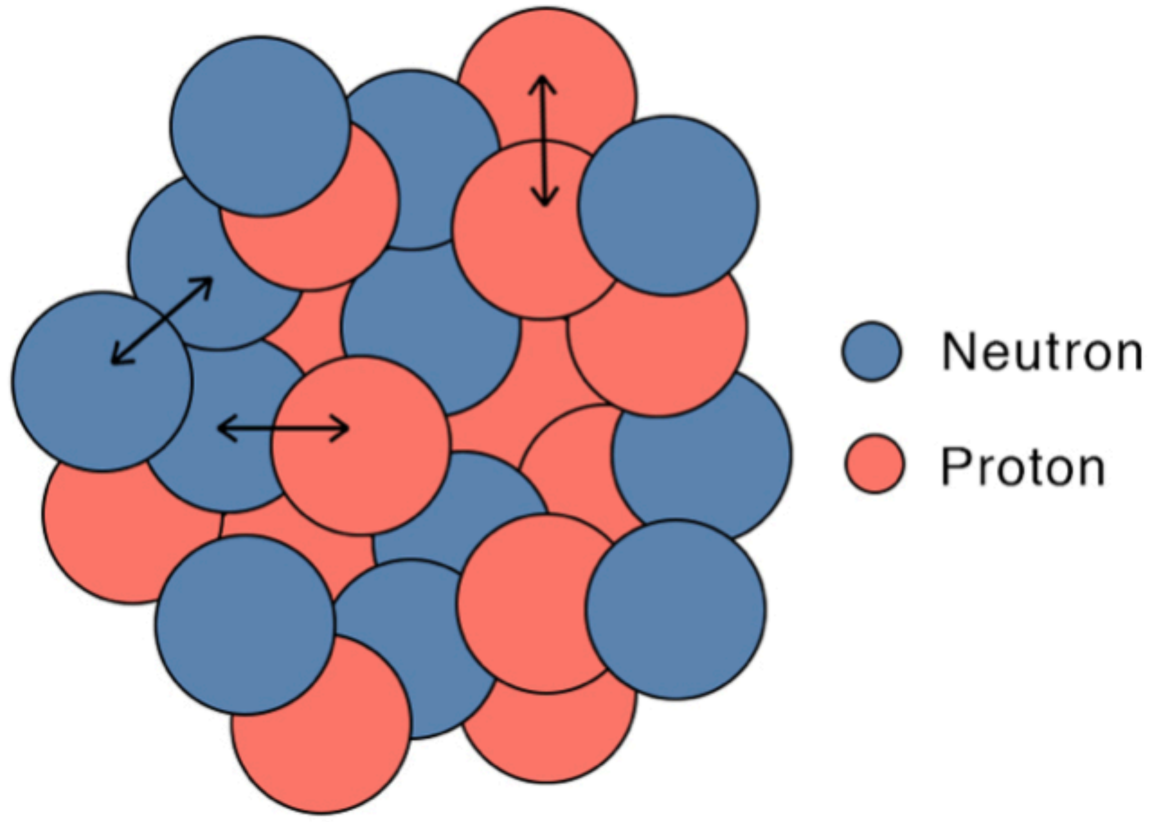
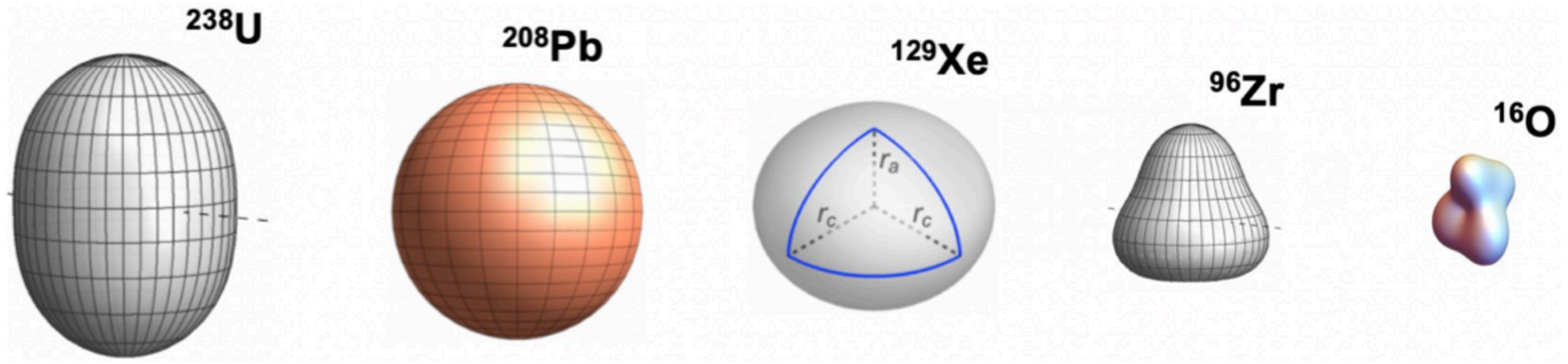
"for the discovery of the connection between ***collective motion*** *and* ***structure of the atomic nucleus***…*"*

Strong interactions described by QCD

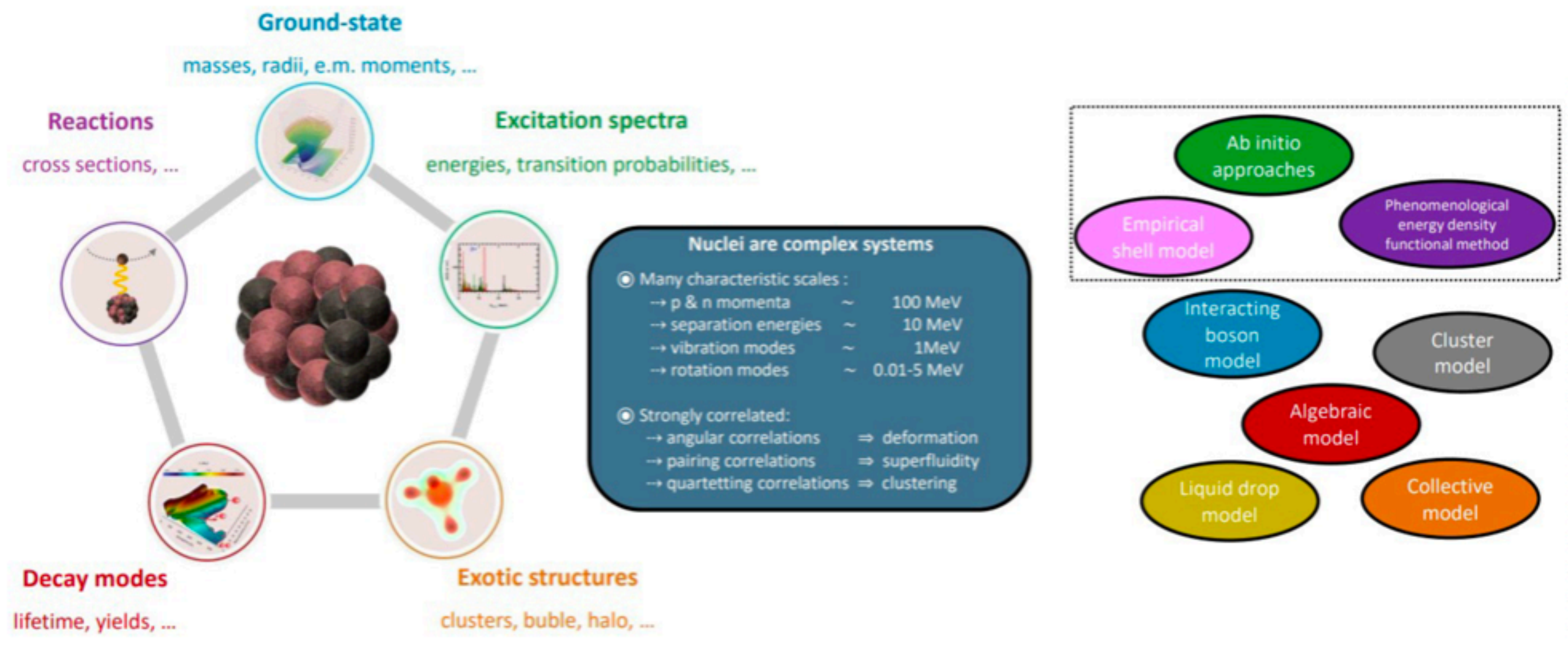


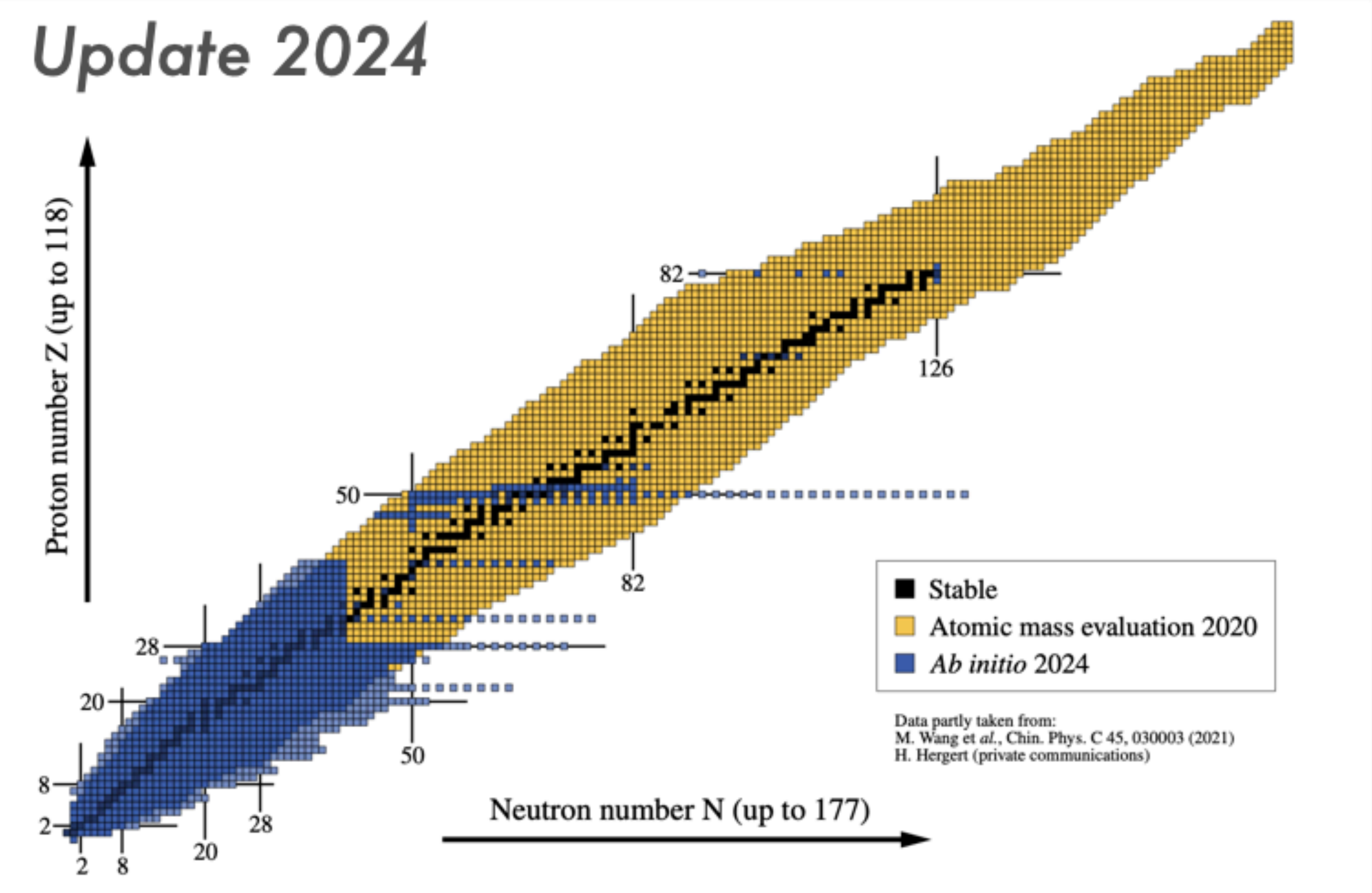
Many-body interactions



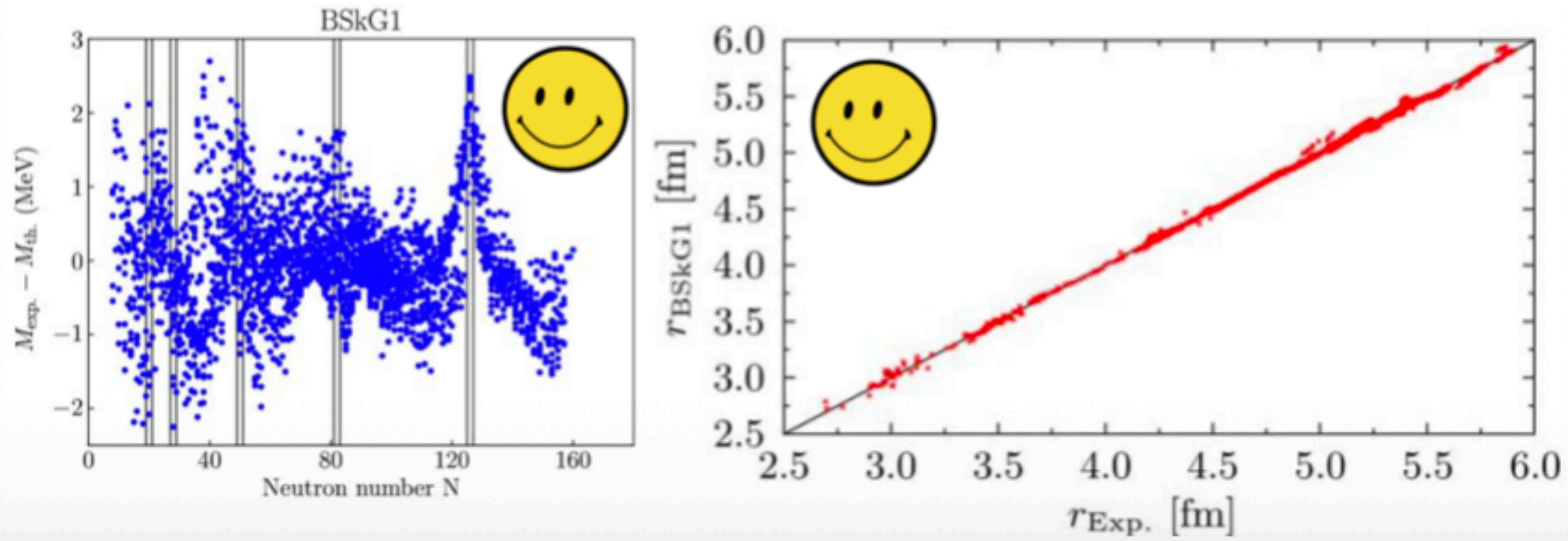
Nuclear Structure at low energies

Atomic nuclei have rich phenomenology. Rooted in the strong nuclear force.
Nuclear structure is a very old field. Many different approaches.

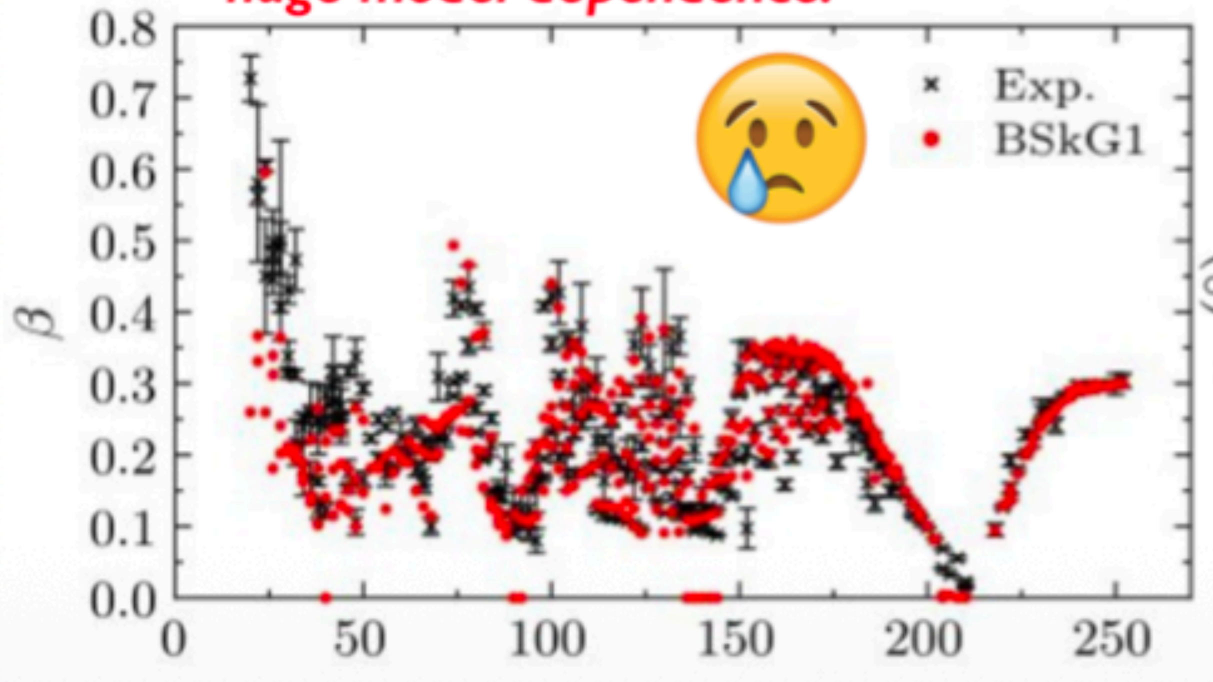


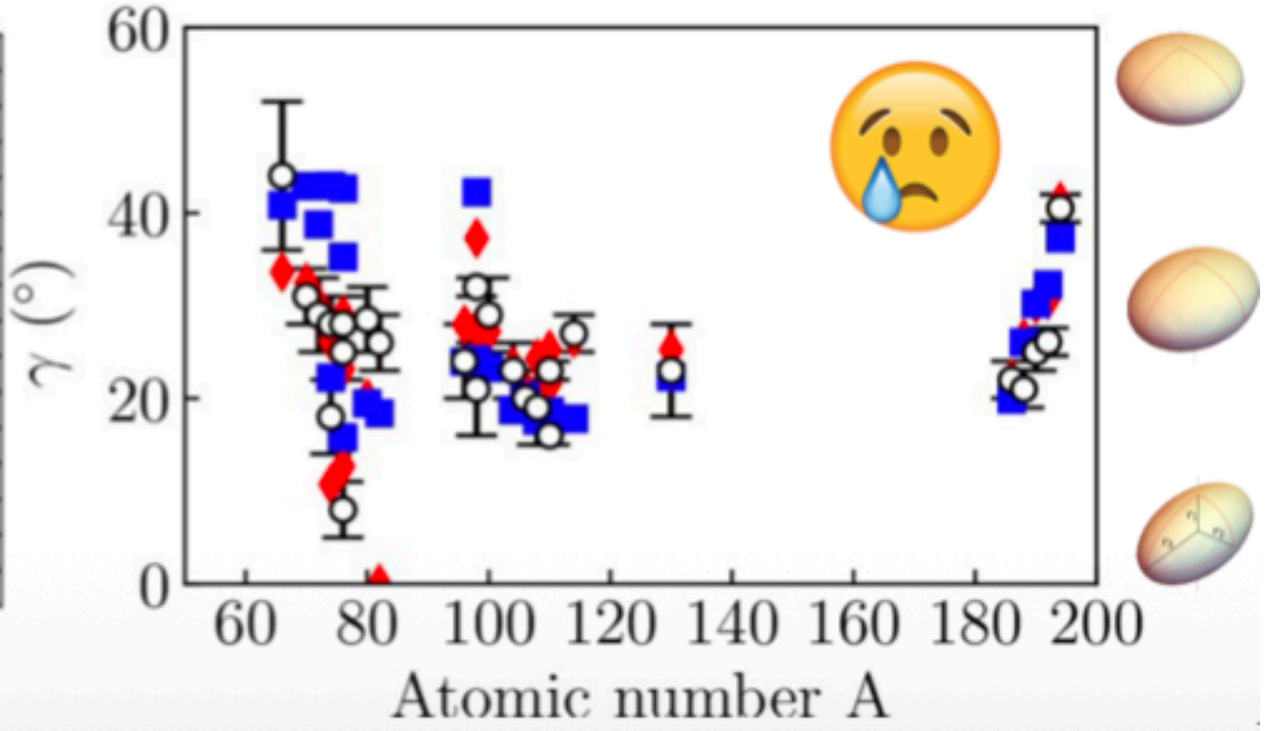


Energy density function method : accurate description of masses and radii

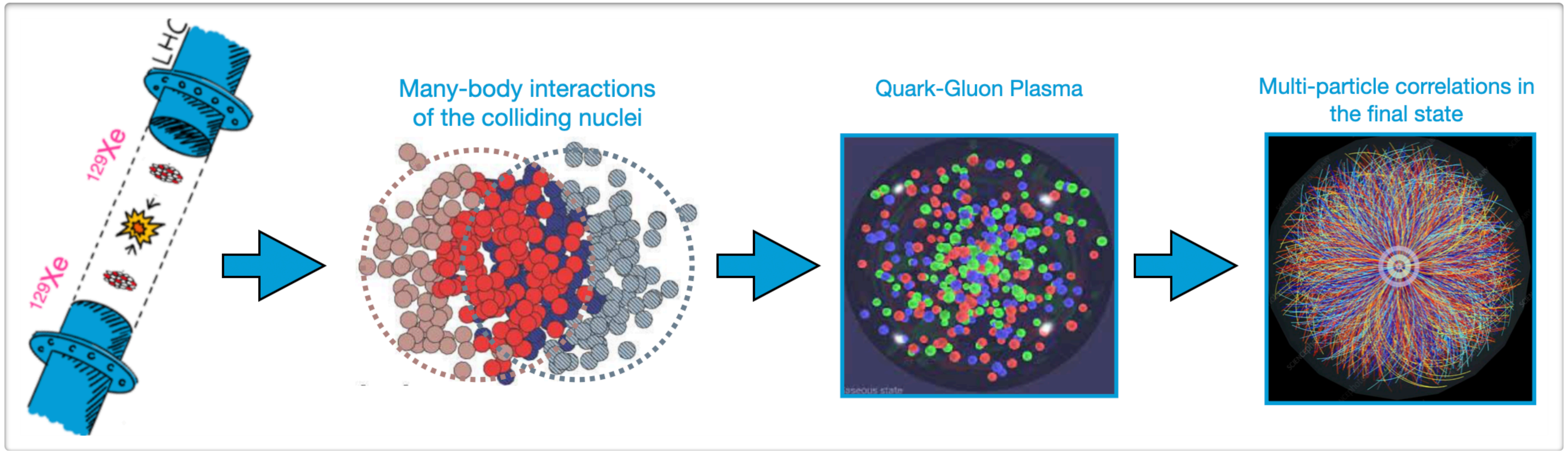


- *there are no real probes of multi-nucleon correlations*
- *huge model dependence.*





Imaging the nuclear structure in nuclear collisions



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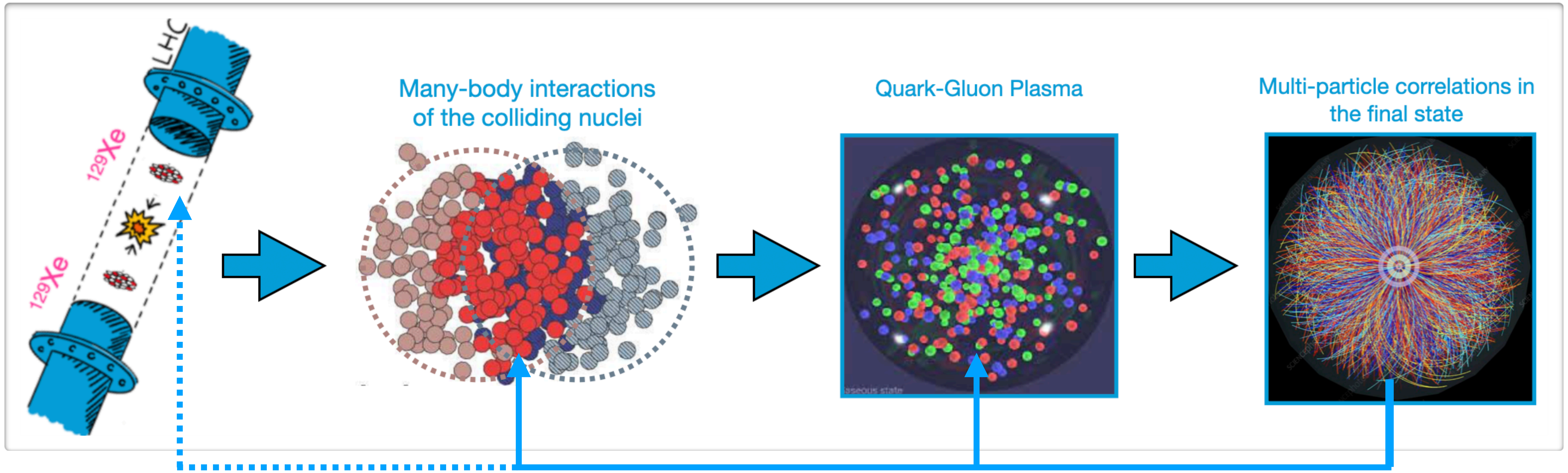

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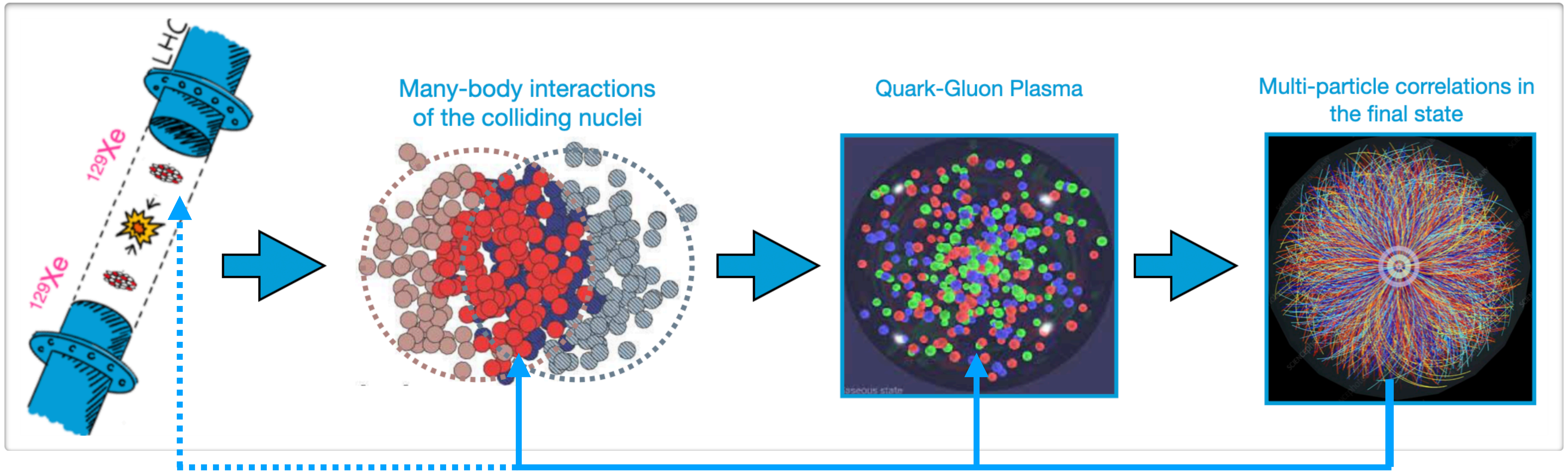

^{208}Pb-^{208}Pb

^{129}Xe-^{129}Xe

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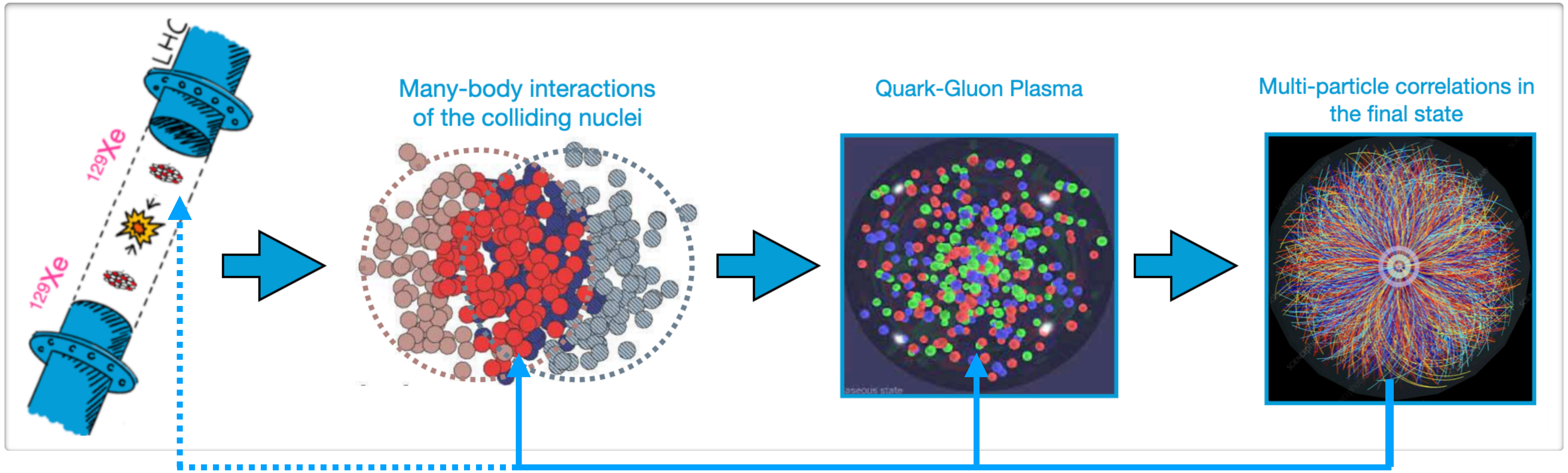

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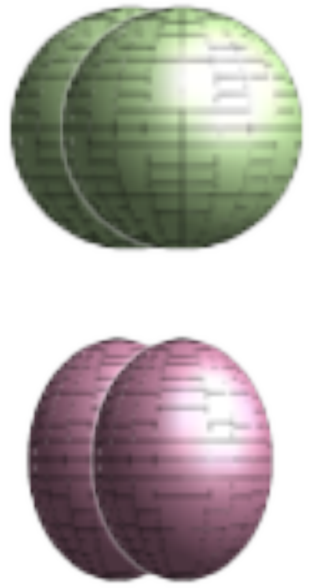
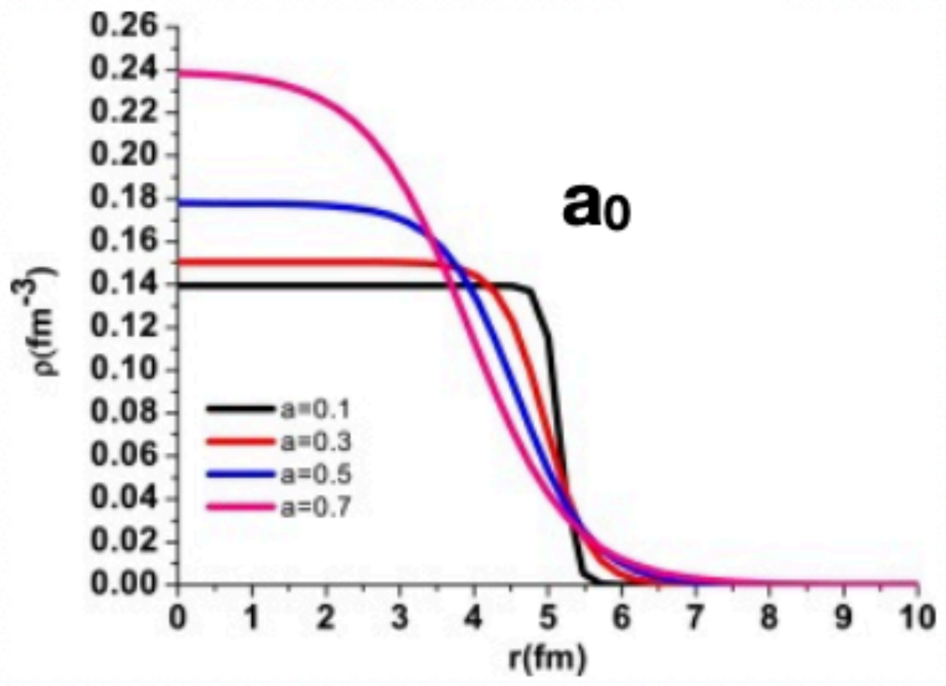
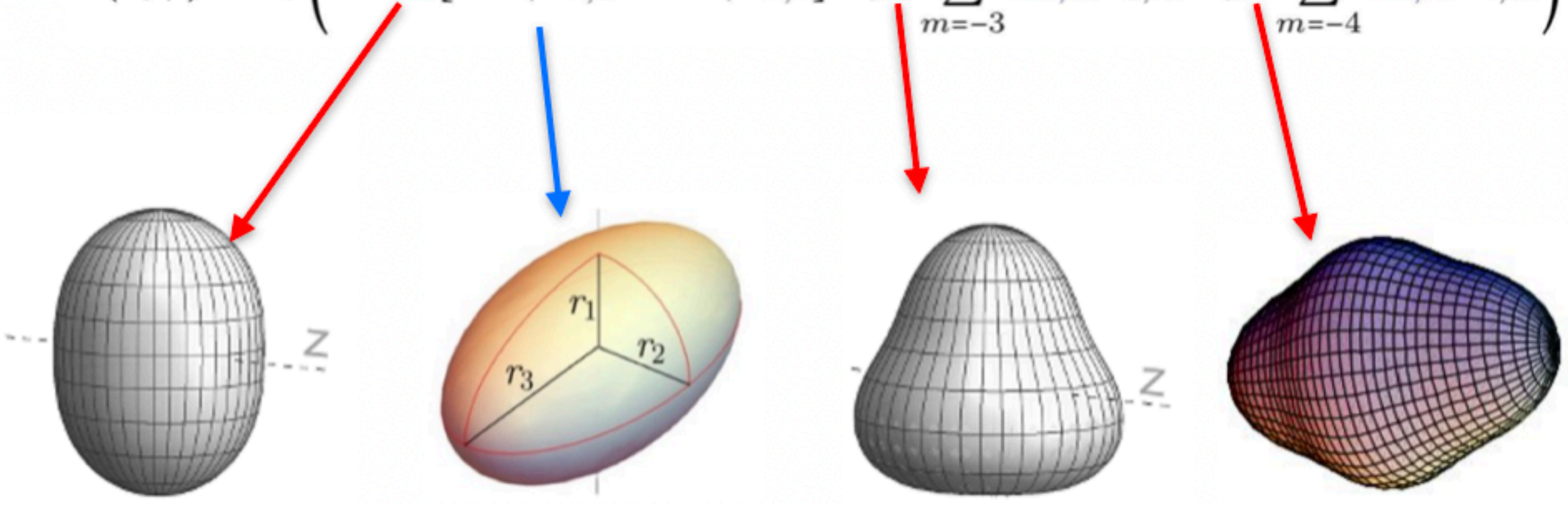


$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$



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



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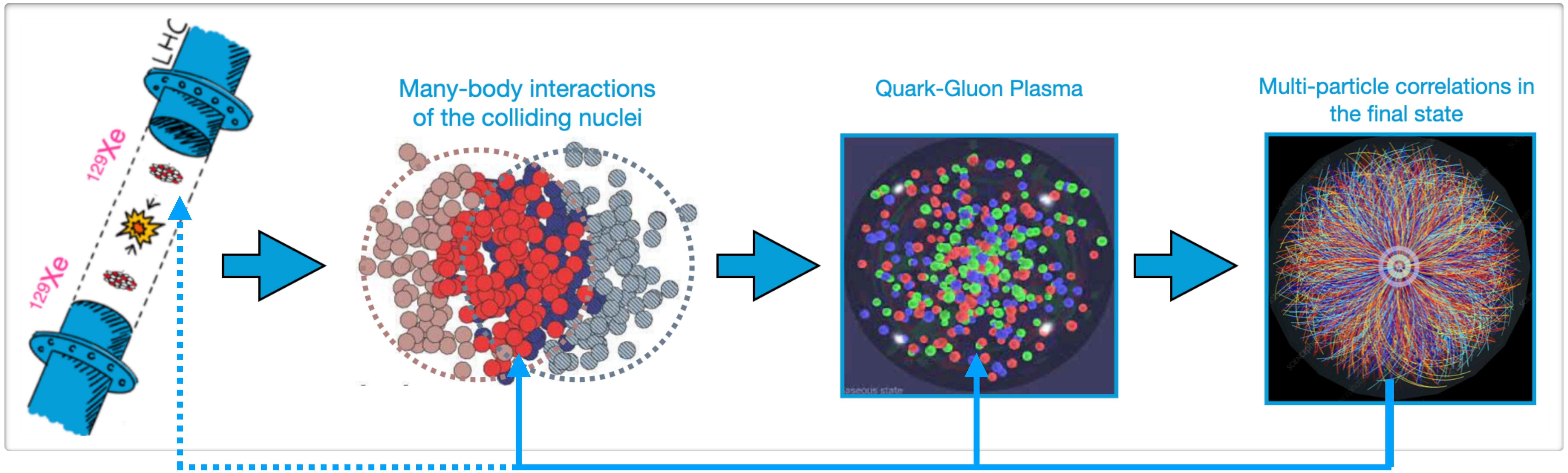

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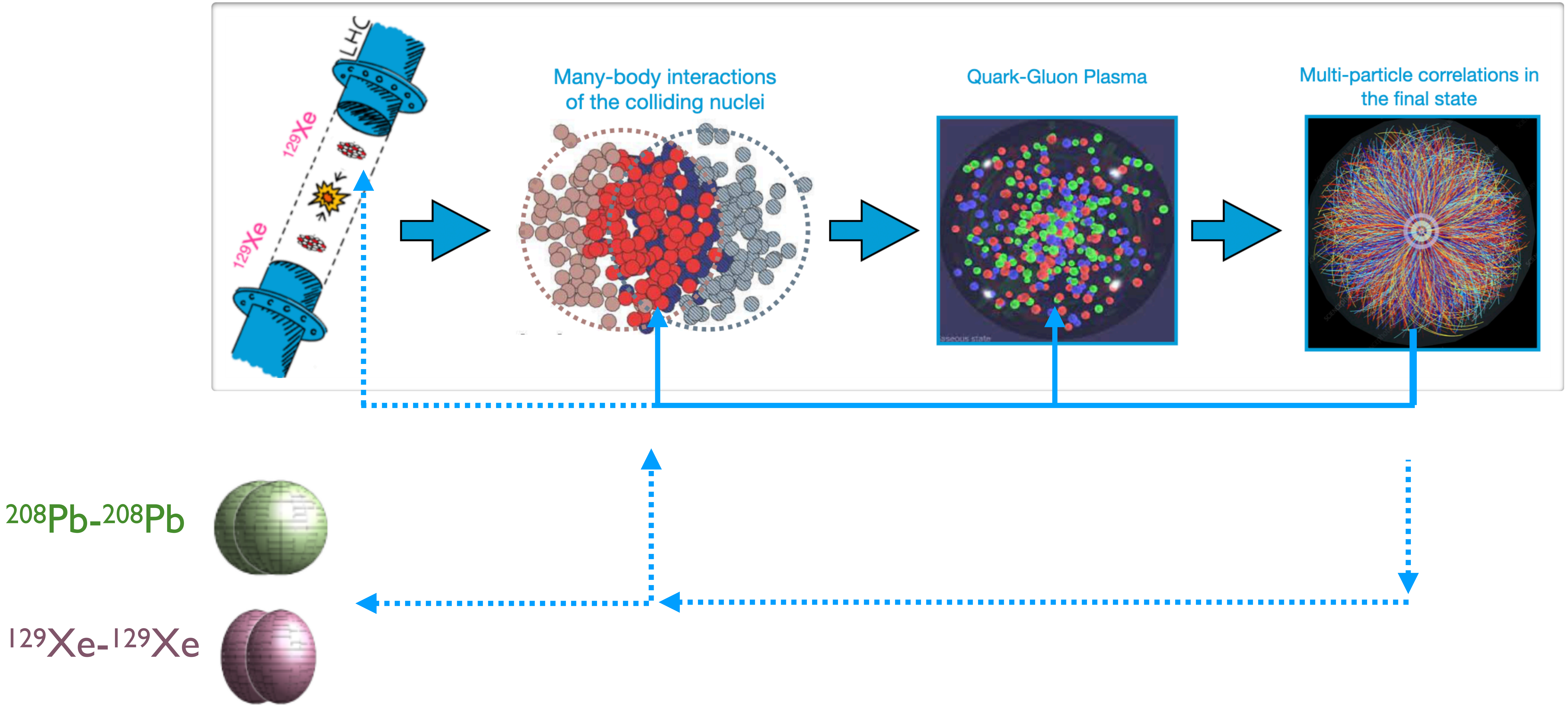
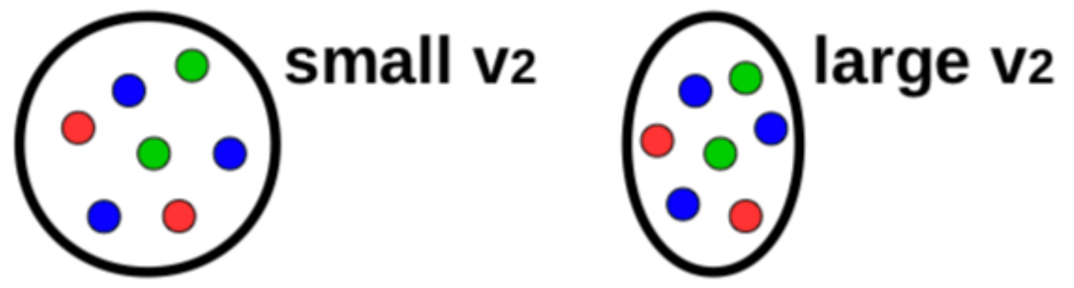


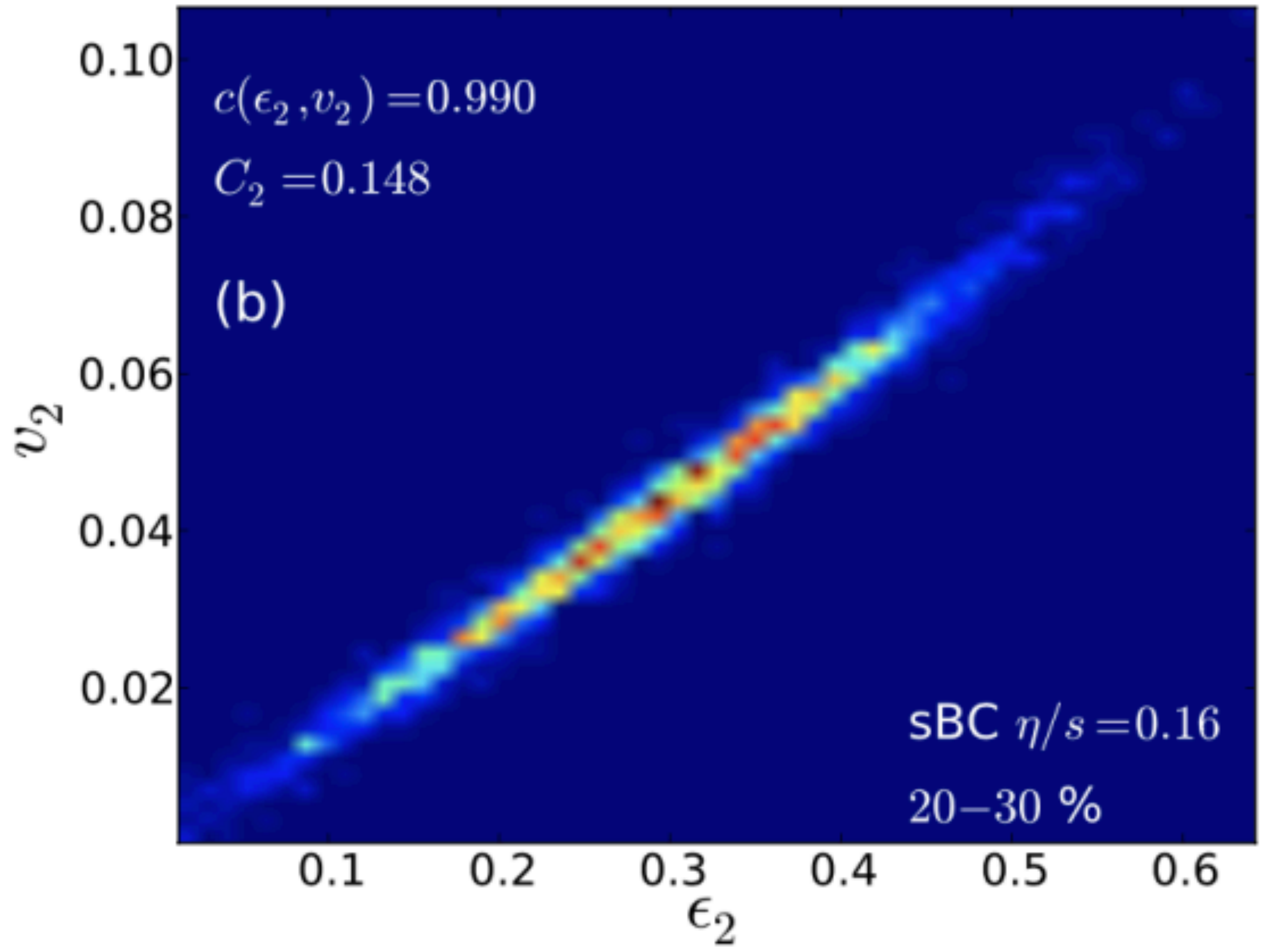
Can we build the connection between final state ***collective motion*** *and* ***structure of the atomic nuclei*** *we collided*

"Reverse engineering" with collective motion

❖ Shape of the fireball: Anisotropic flow

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





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

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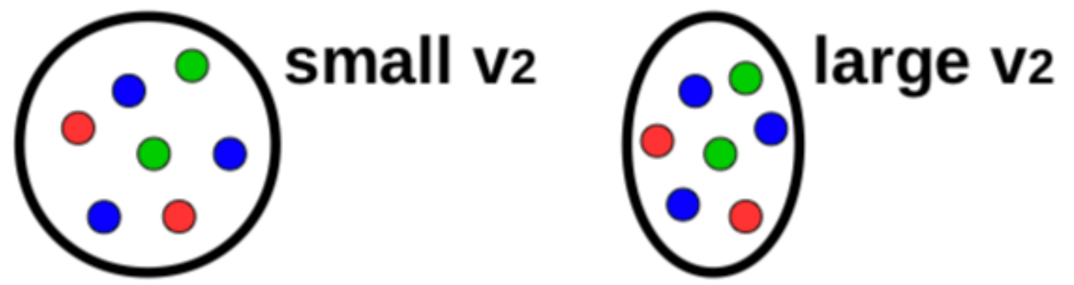
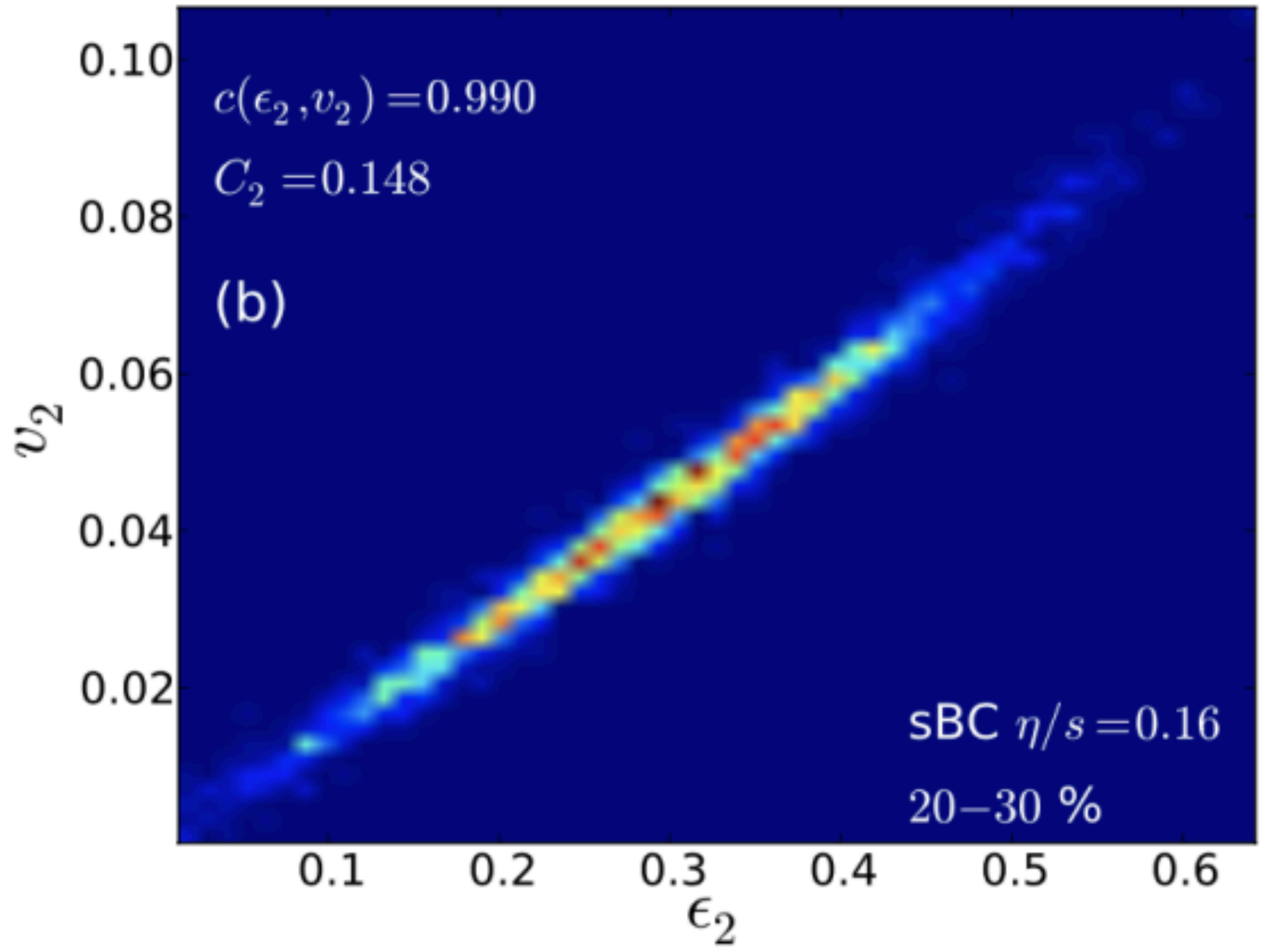


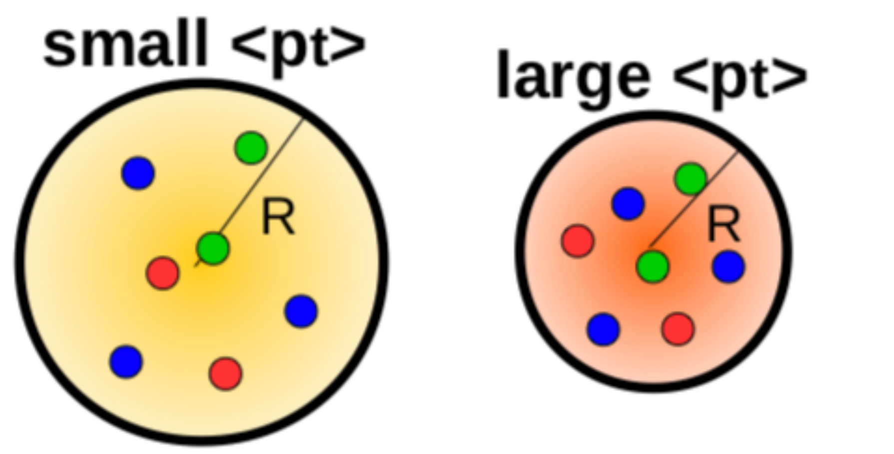


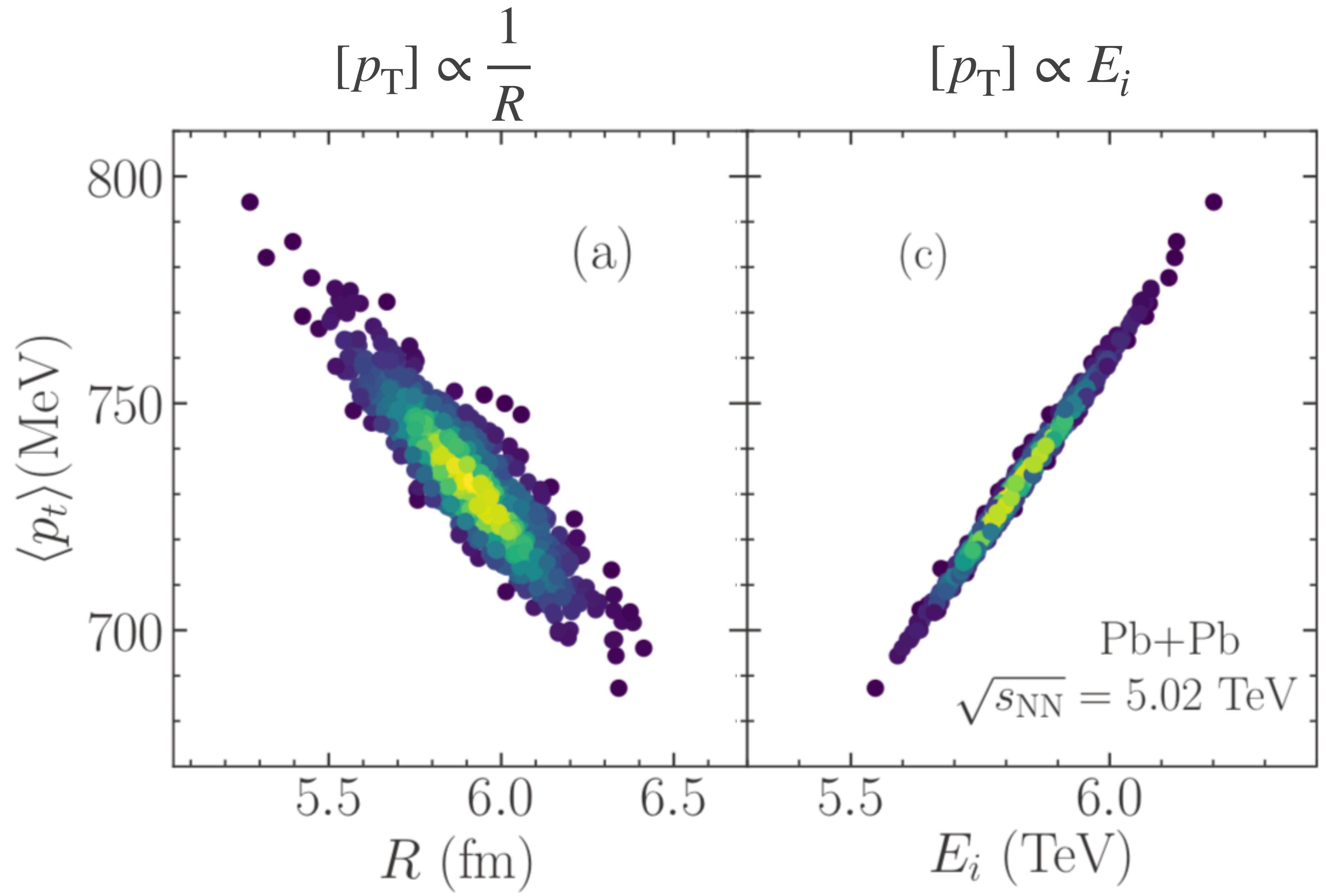
[H. Niemi et al., PRC 87 (2013) 5, 054901]

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

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

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





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

"Reverse engineering" with collective motion

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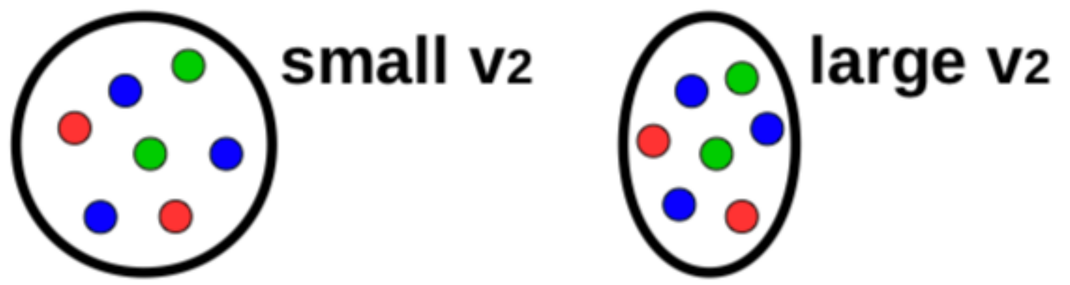

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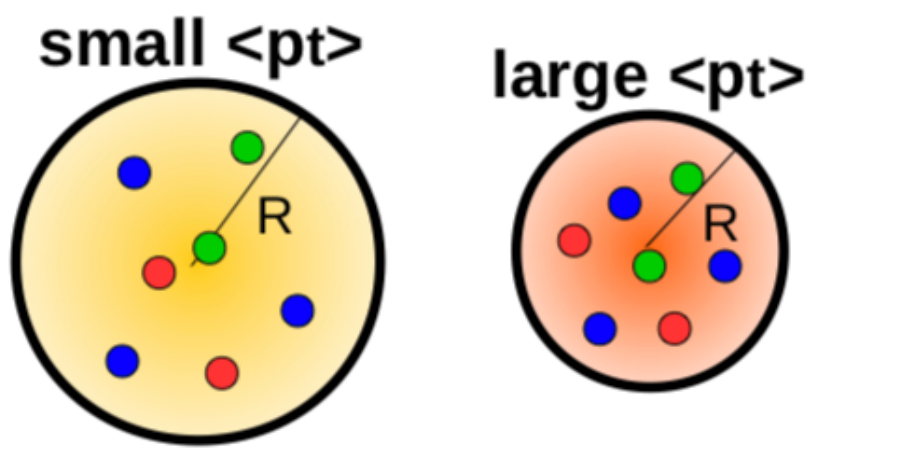

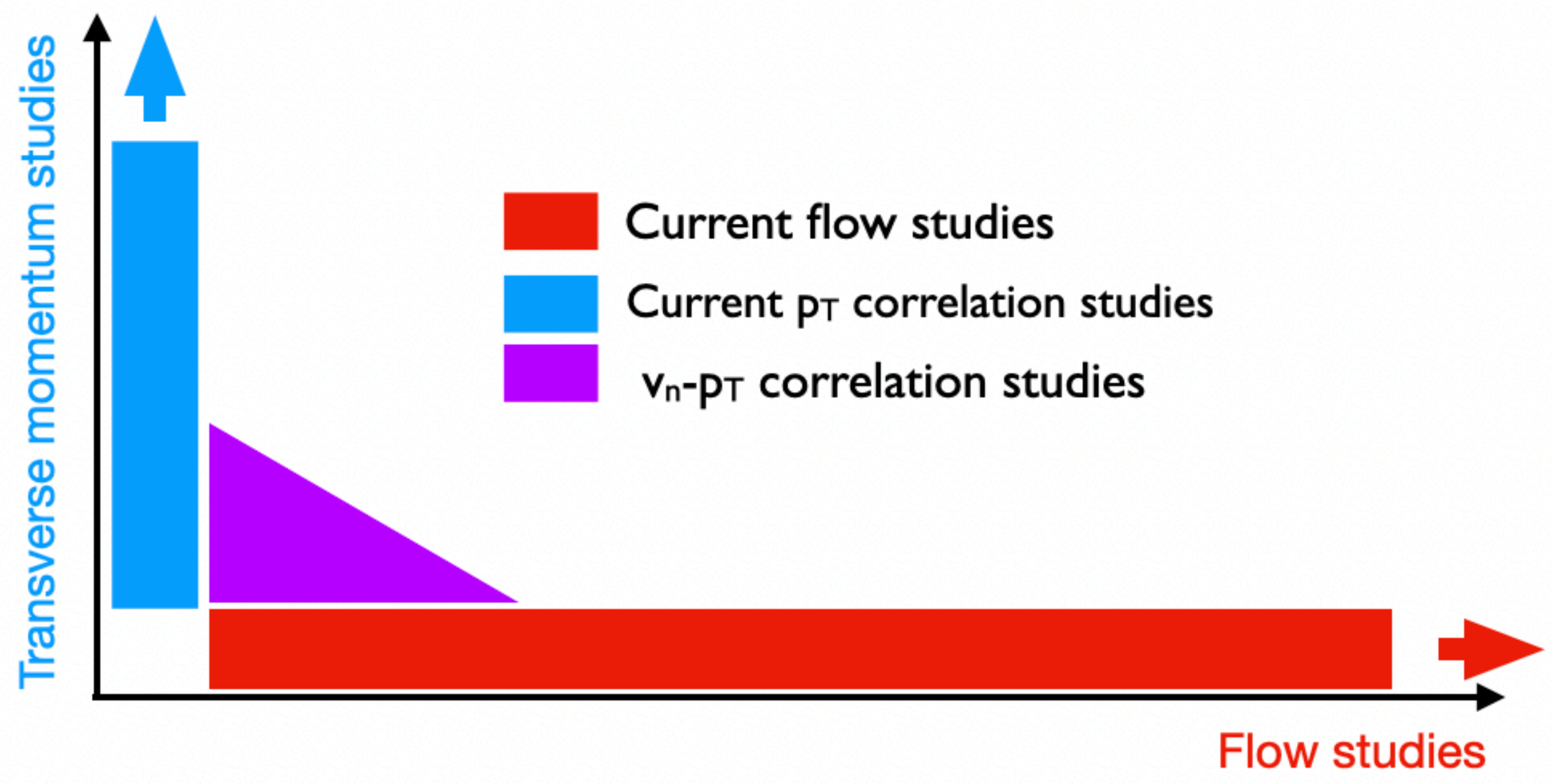

$$\rho(v_n^2, [p_\mathrm{T}]) = \frac{cov(v_n^2, [p_\mathrm{T}])}{\sqrt{var(v_n^2)}\sqrt{var([p_\mathrm{T}])}}$$

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

"Reverse engineering" with collective motion

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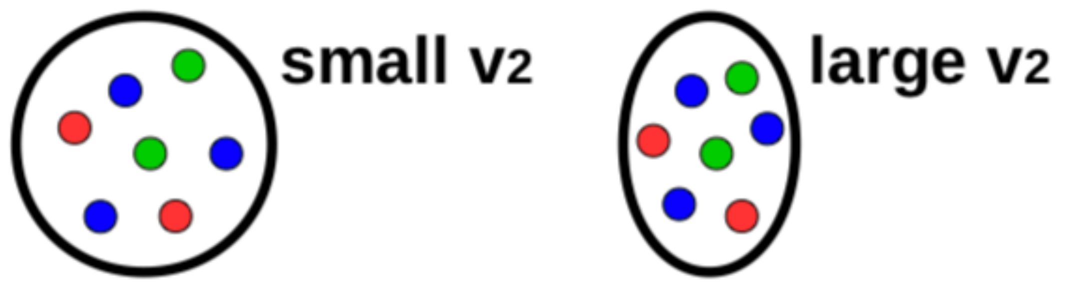

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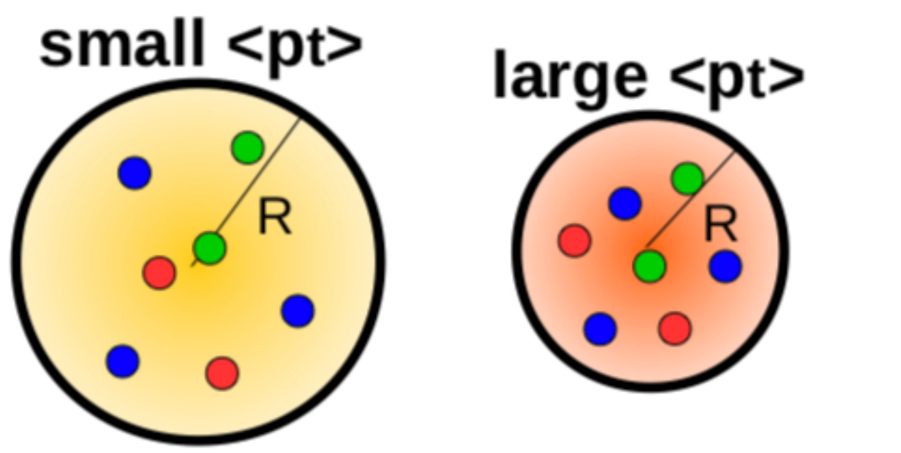
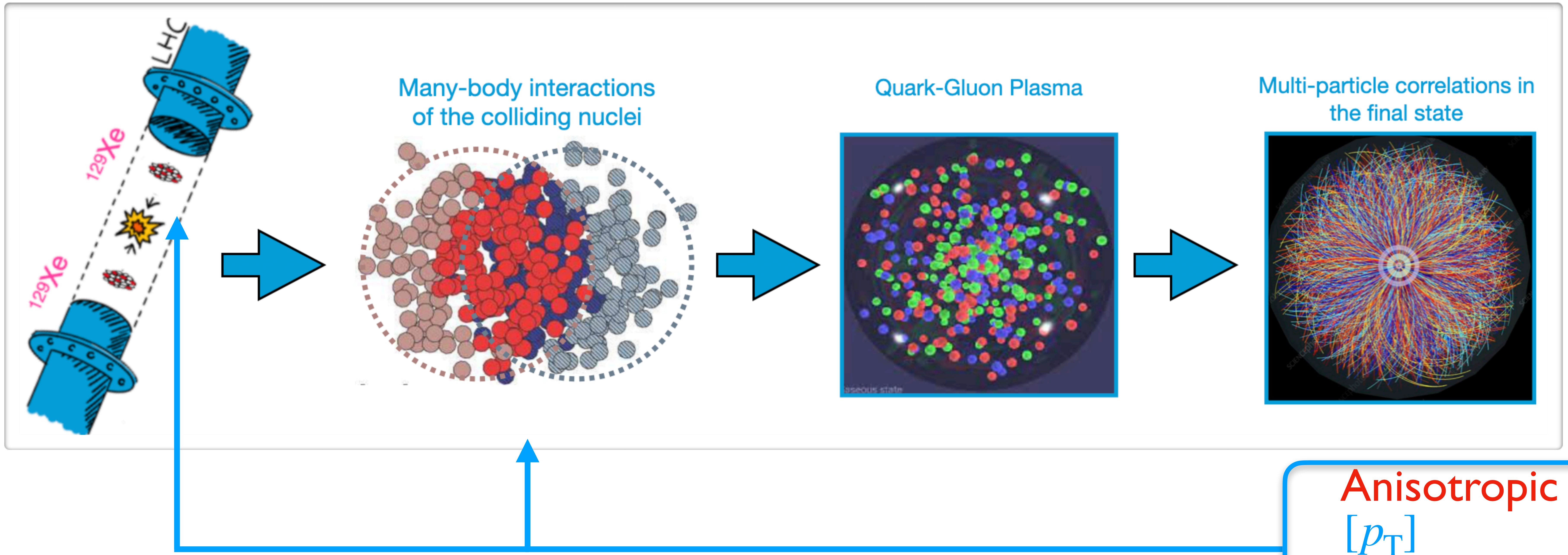
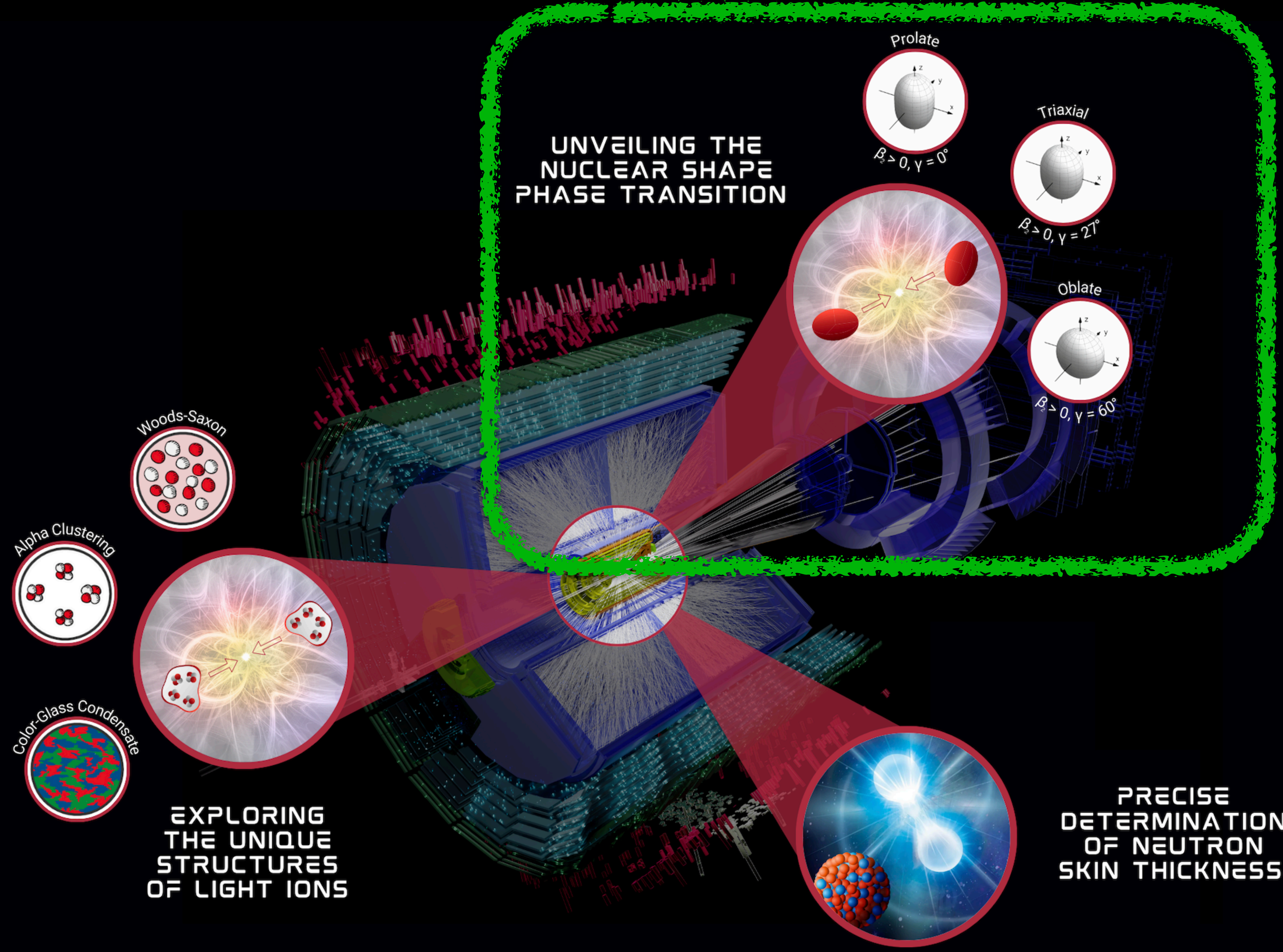




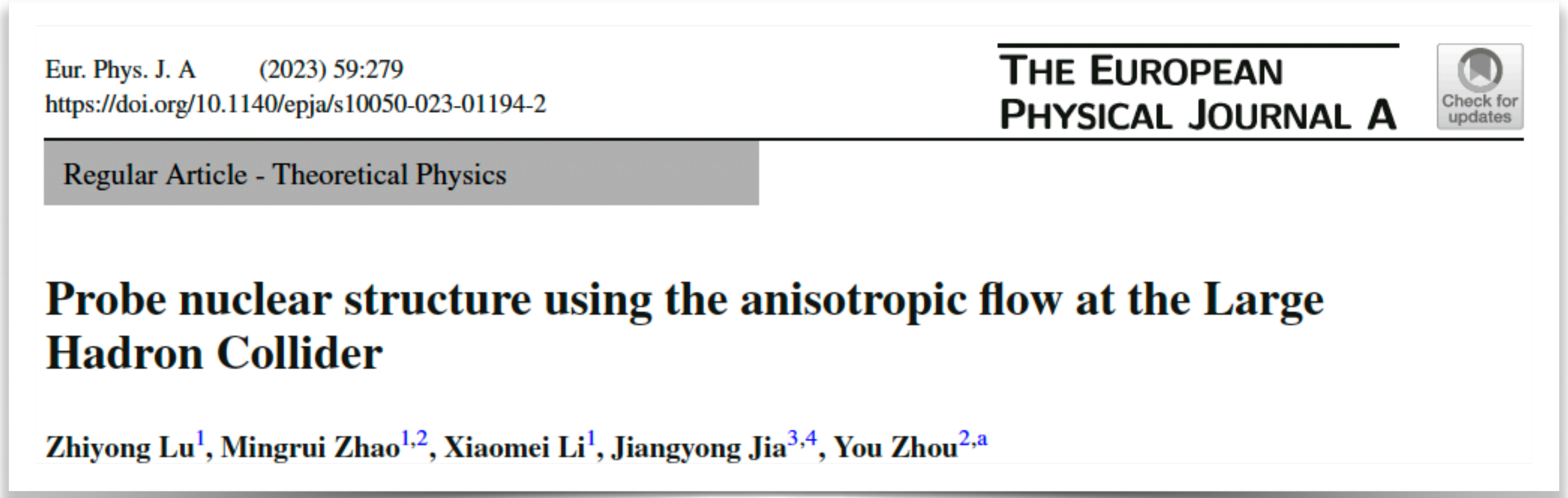
Anisotropic flow
$[p_{\mathrm{T}}]$
flow & $[p_{\mathrm{T}}]$ correlations

Reverse engineering



Heavy nuclei

Probe structure of ^{129}Xe with simple v_n


Eur. Phys. J. A (2023) 59:279
https://doi.org/10.1140/epja/s10050-023-01194-2
The European Physical Journal A
Check for updates
Regular Article - Theoretical Physics

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

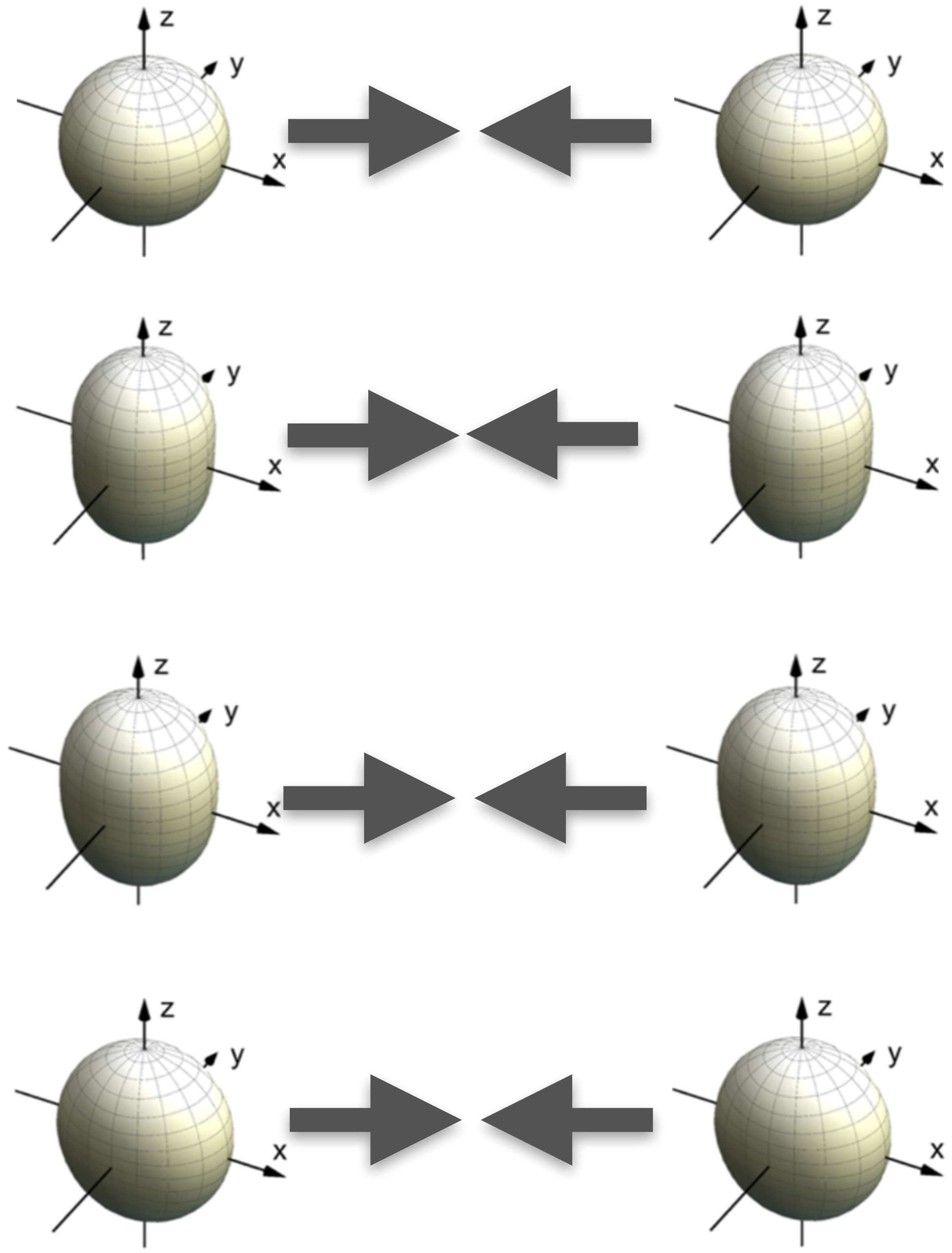
Zhiyong Lu[1], Mingrui Zhao[1,2], Xiaomei Li[1], Jiangyong Jia[3,4], You Zhou[2,a]

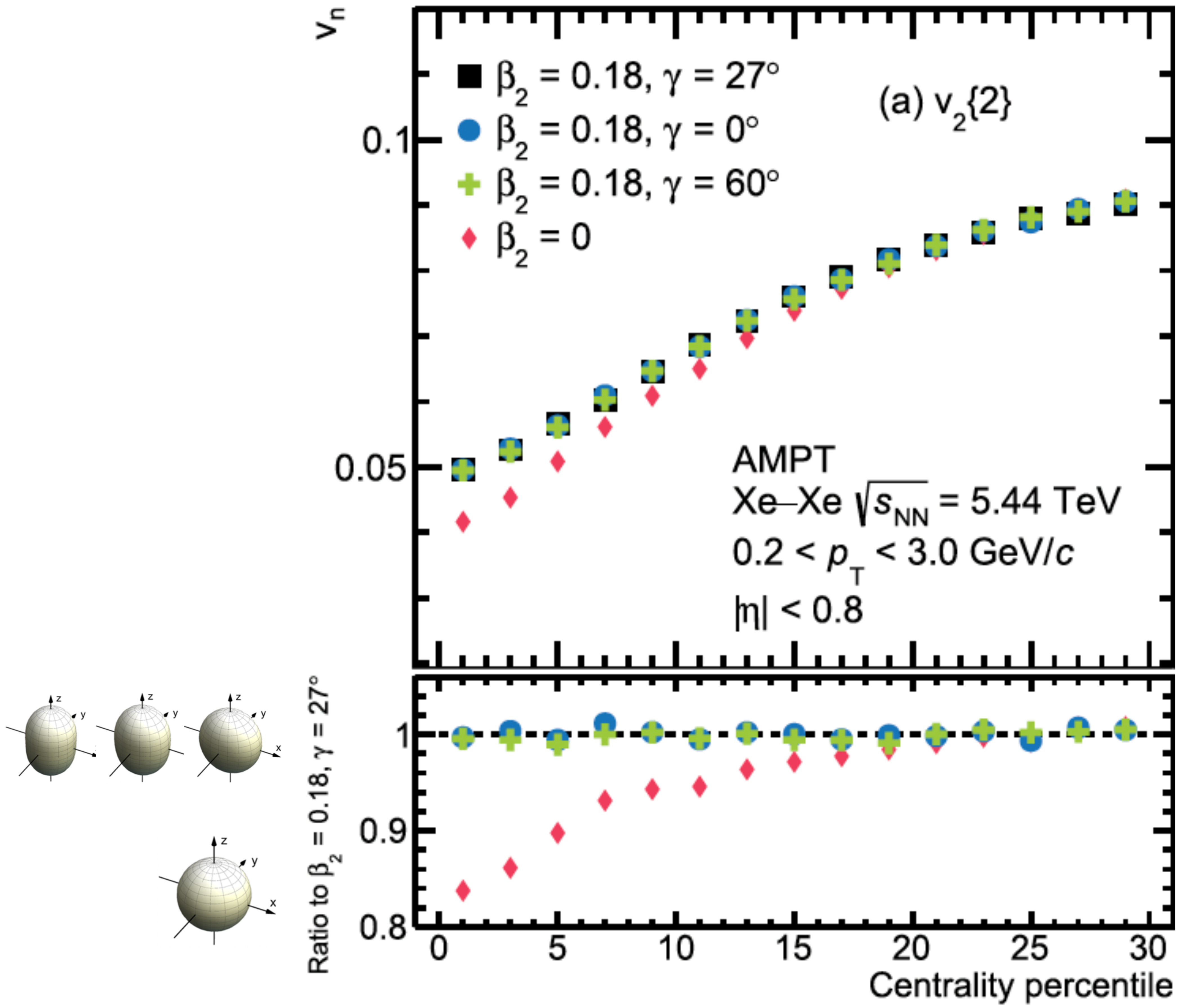
spheric
($\beta_2 = 0$)

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

Triaxial
($\beta_2 > 0, \gamma=30°$)

Oblate
($\beta_2 > 0, \gamma=60°$)





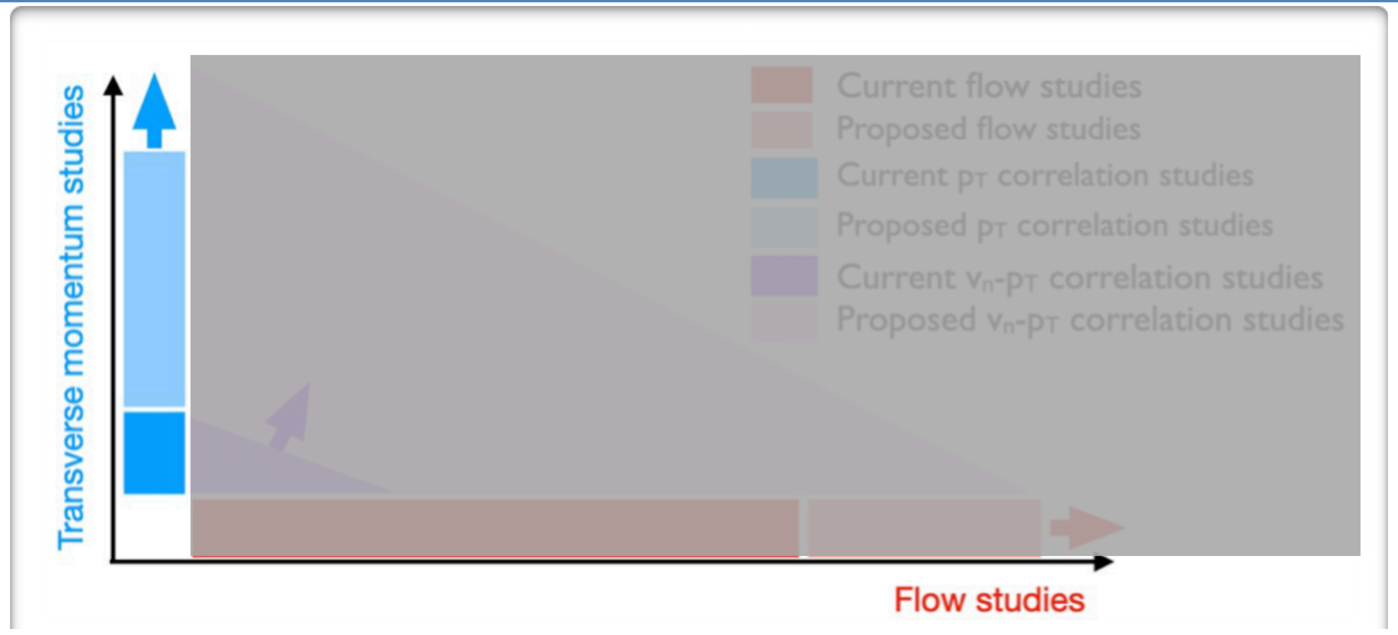
- Significant v_2 enhancements in central Xe-Xe collisions, originated from large deformation β_2
- No difference observed from the results with different γ values, no impact of triaxial structure in v_2

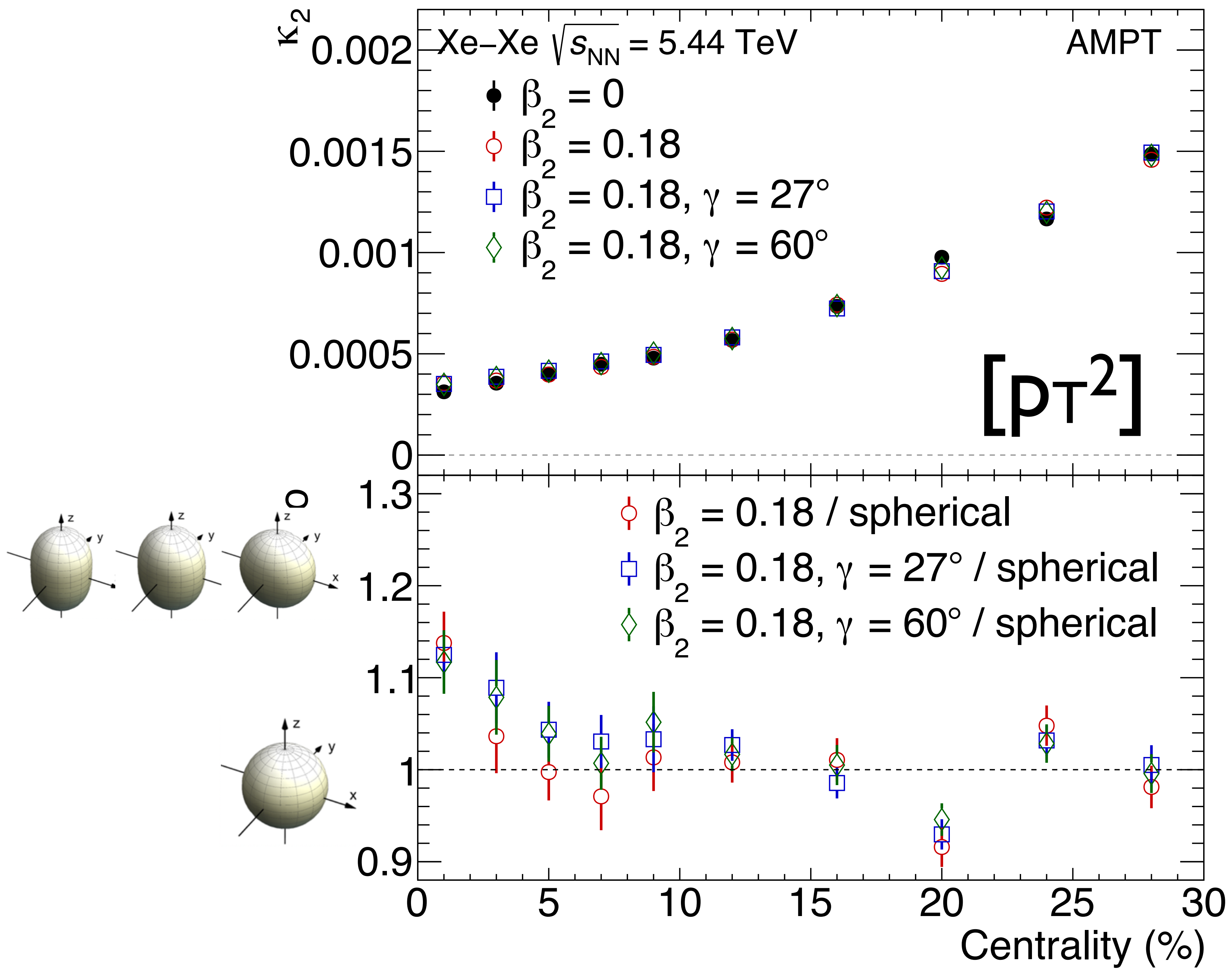
Probe structure of ^{129}Xe with [p_T] fluctuations

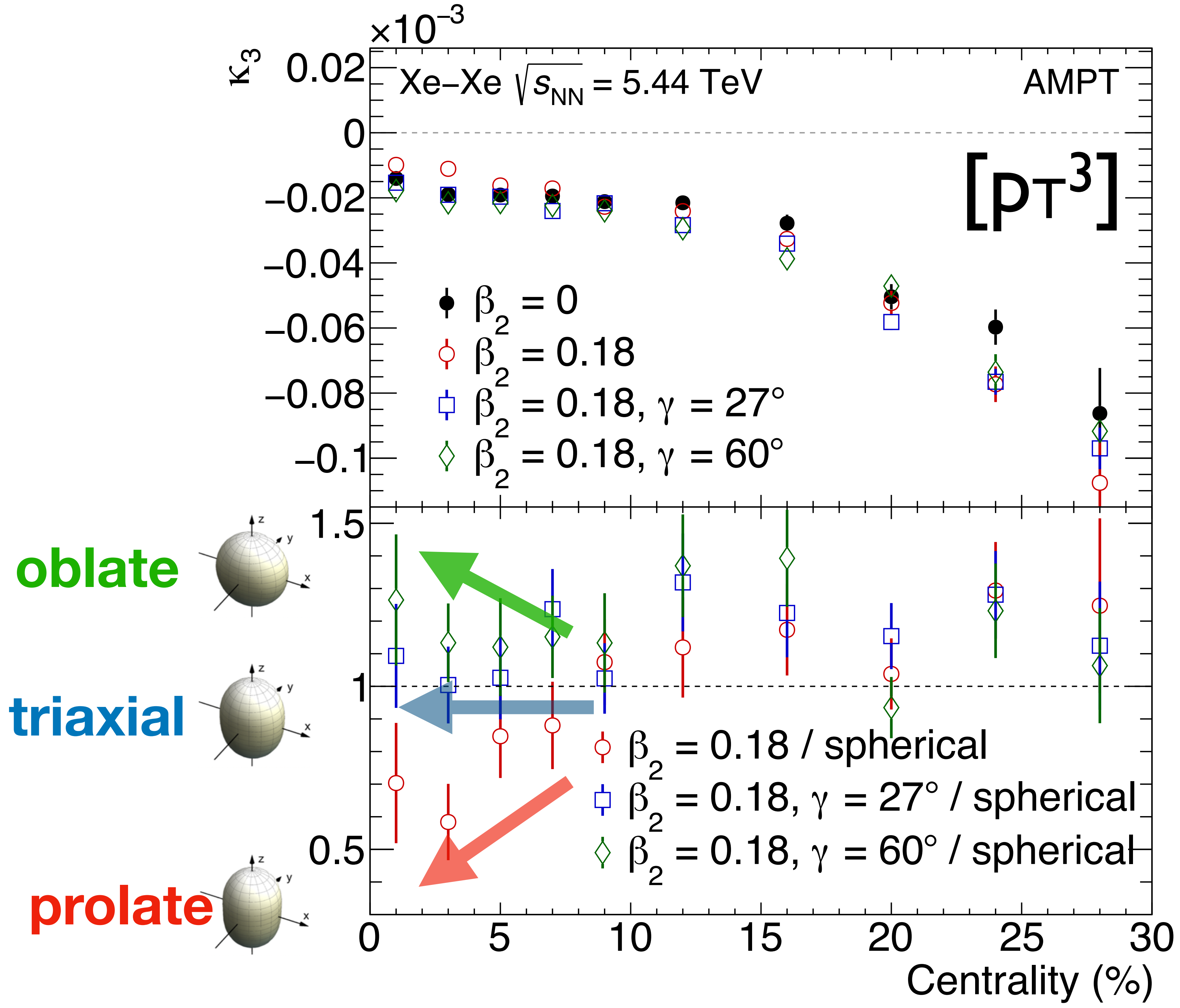
Eur. Phys. J. A (2024) 60:38
https://doi.org/10.1140/epja/s10050-024-01266-x
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Theoretical Physics

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

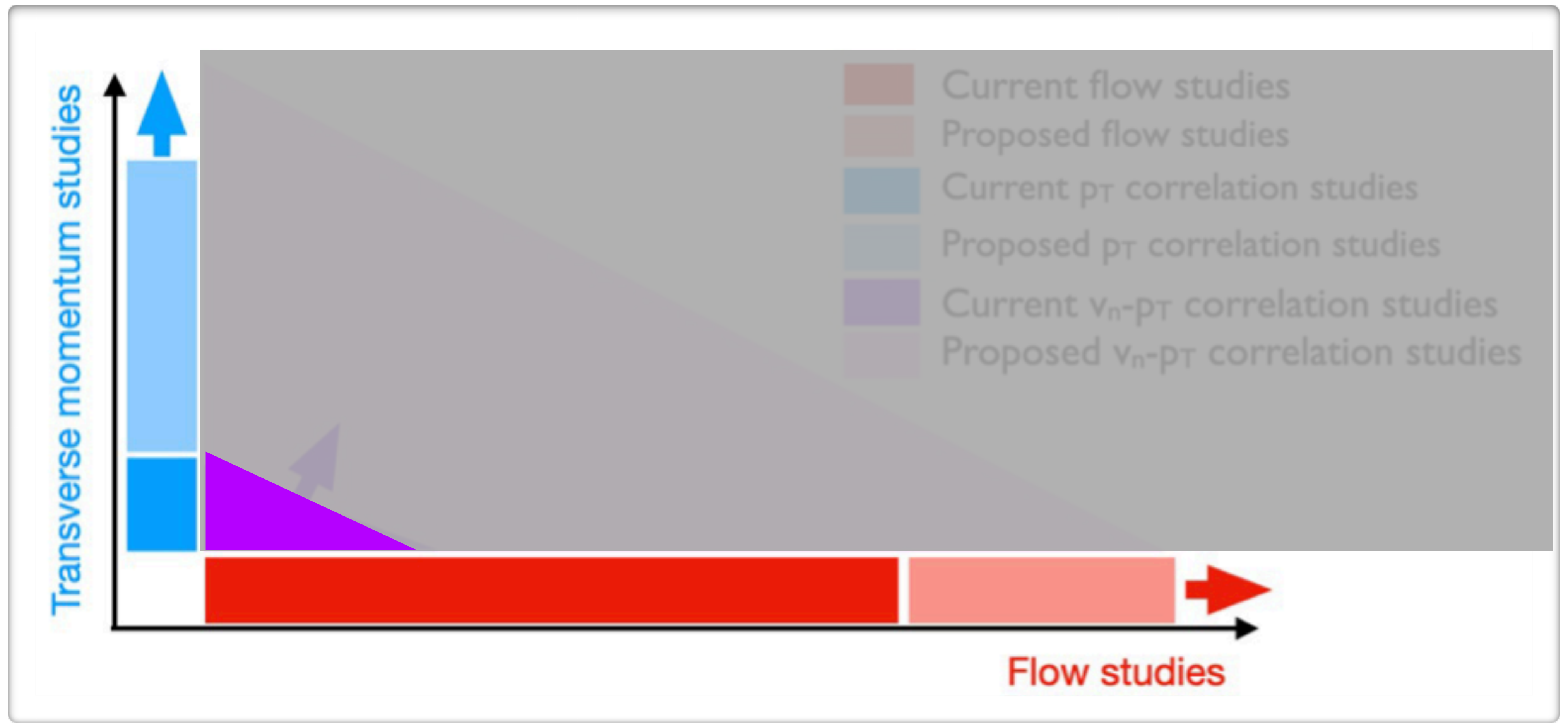


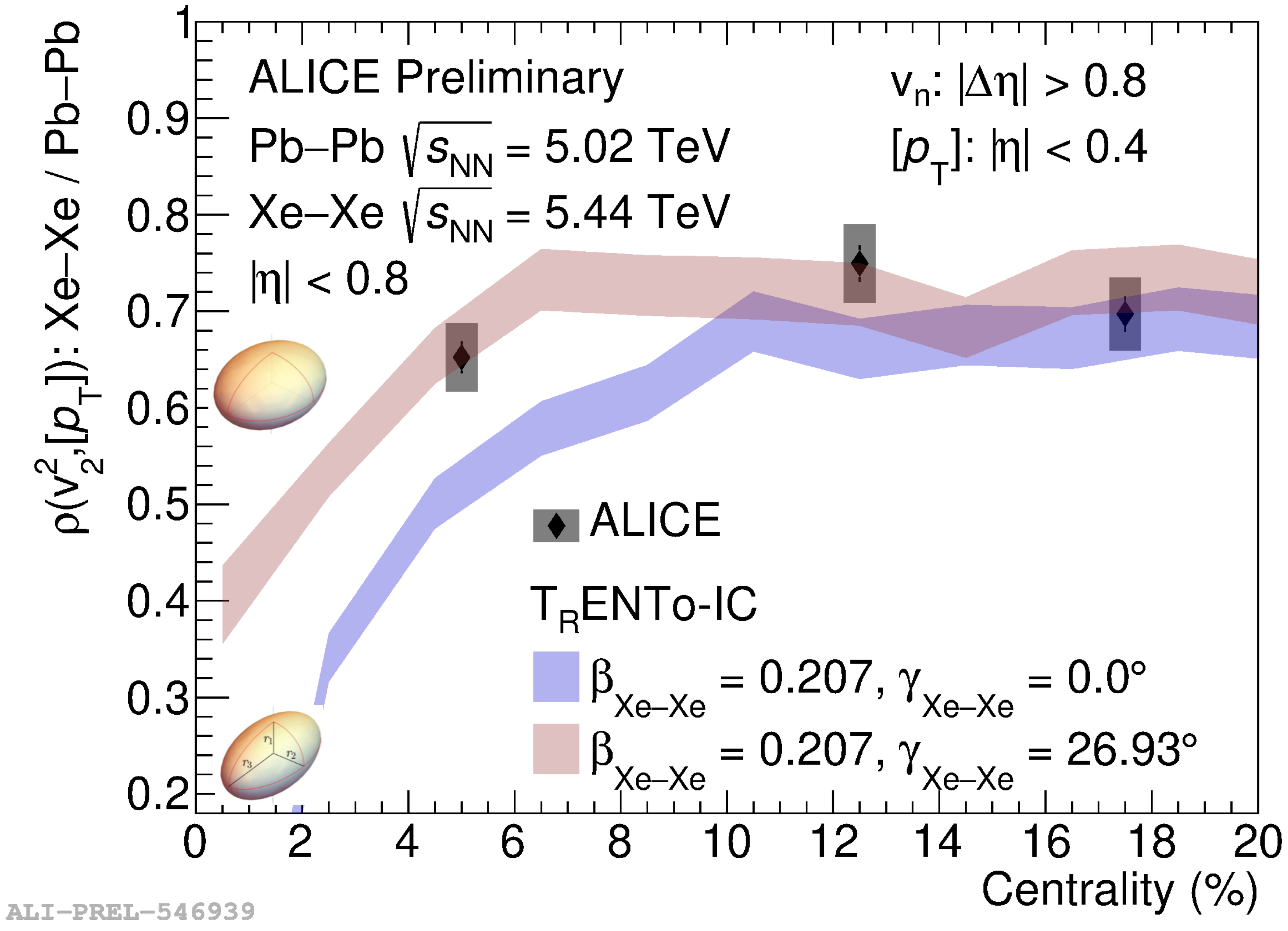




- [p_T] fluctuations, which reflect the initial size fluctuations, also bring new information on the NS.

Probe triaxial structure of ^{129}Xe

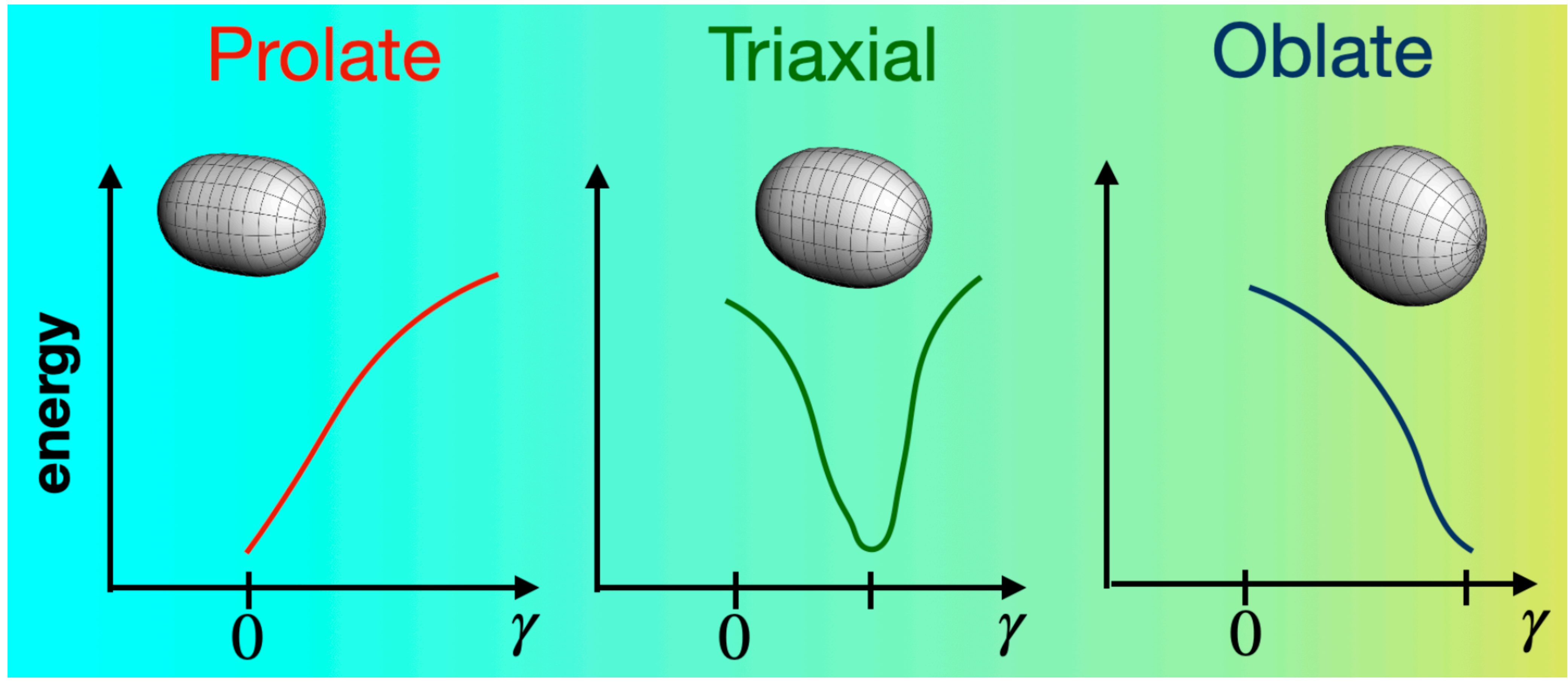




- Better agreement between ALICE data and calculations with γ = 26.93°
  - First study of triaxial structure of ^{129}Xe at high energy collisions at the LHC
  - Similar results confirmed by ATLAS
  - ***Evidence of triaxial structure of ^{129}Xe?*** **B. Bally etc, PRL128 (2022) 8, 082301**

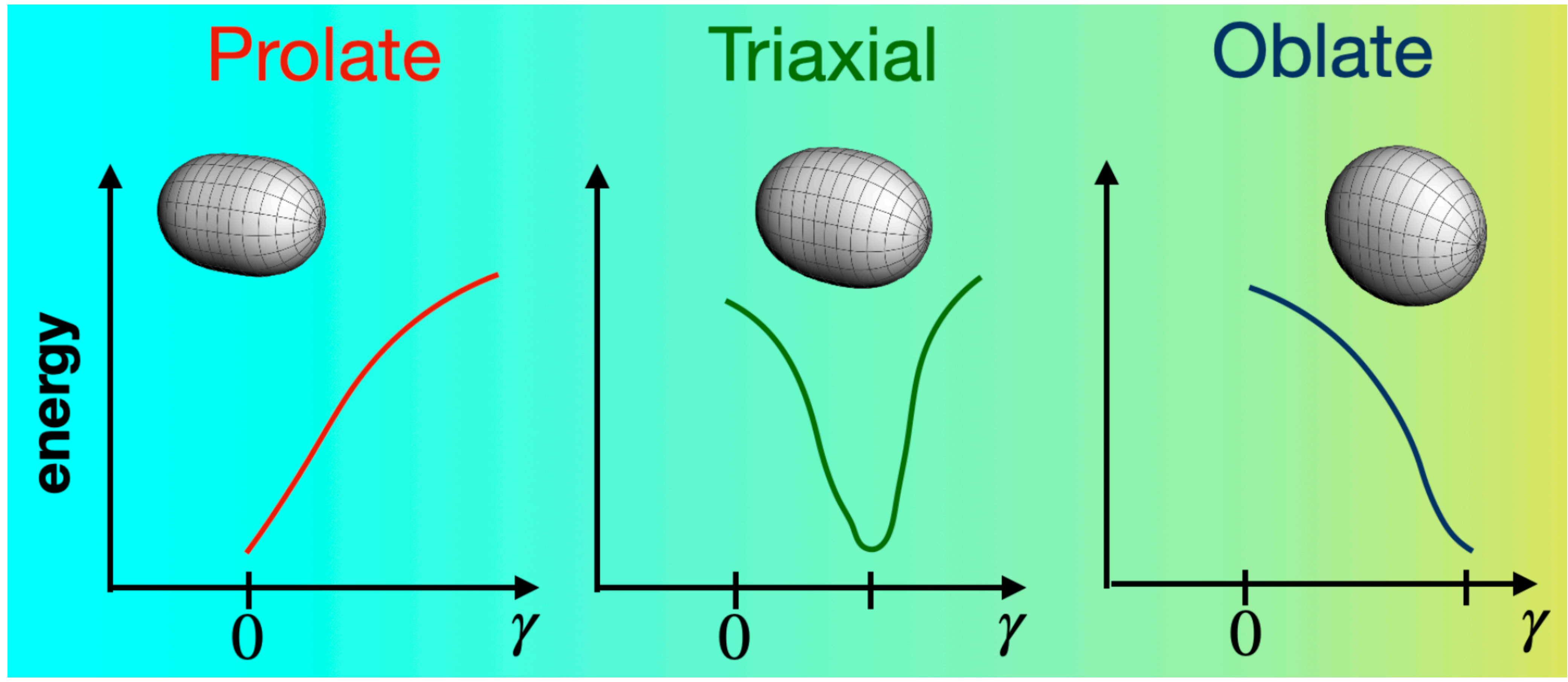
Nuclear Shape Phase Transition

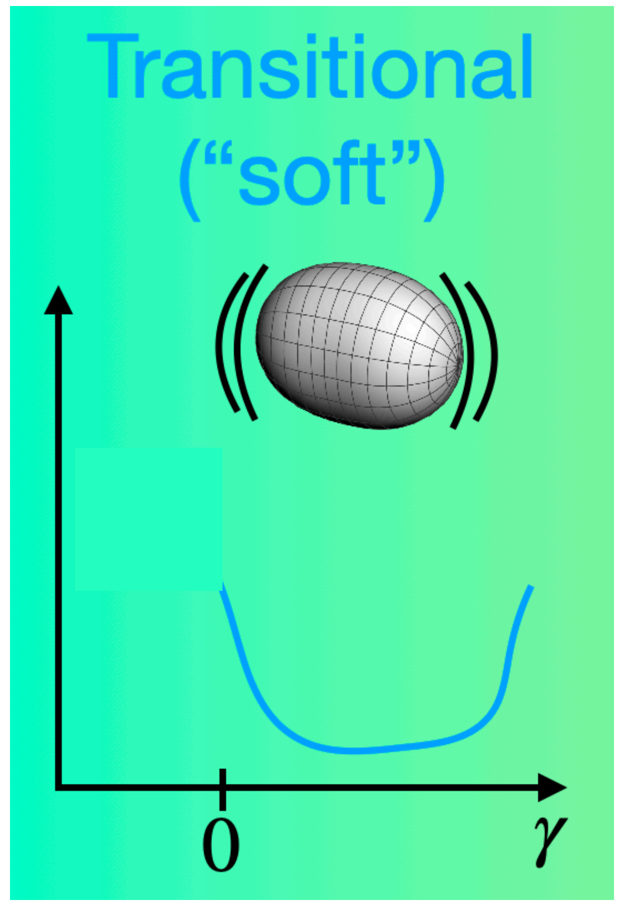
Nuclear Shape Phase Transition



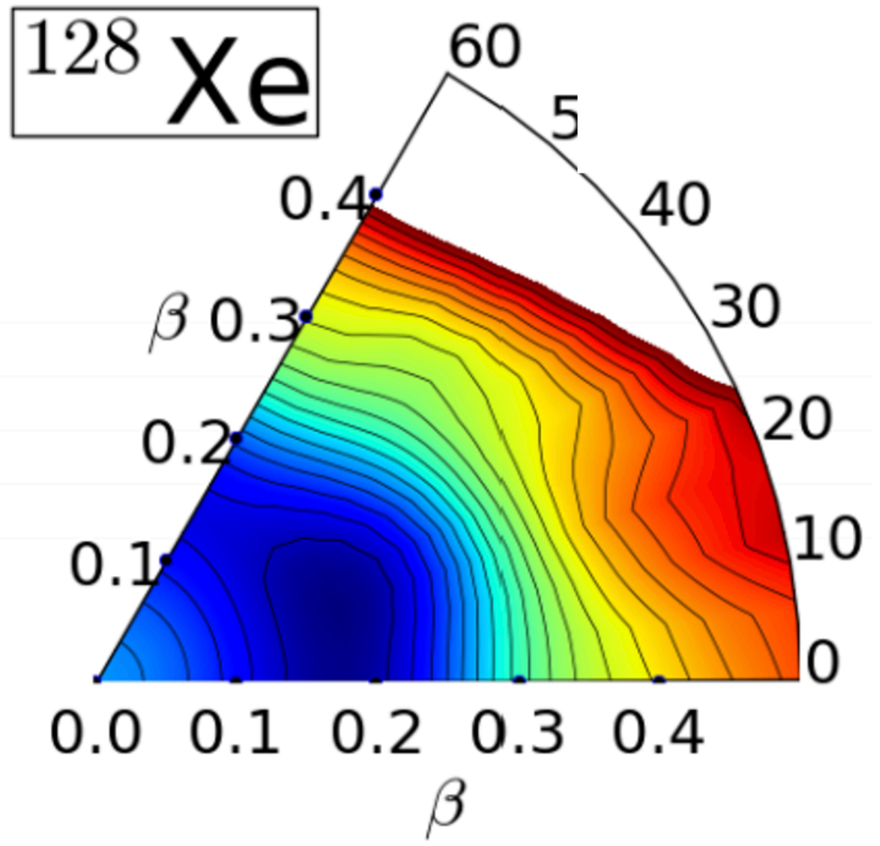
Nuclear Shape Phase Transition

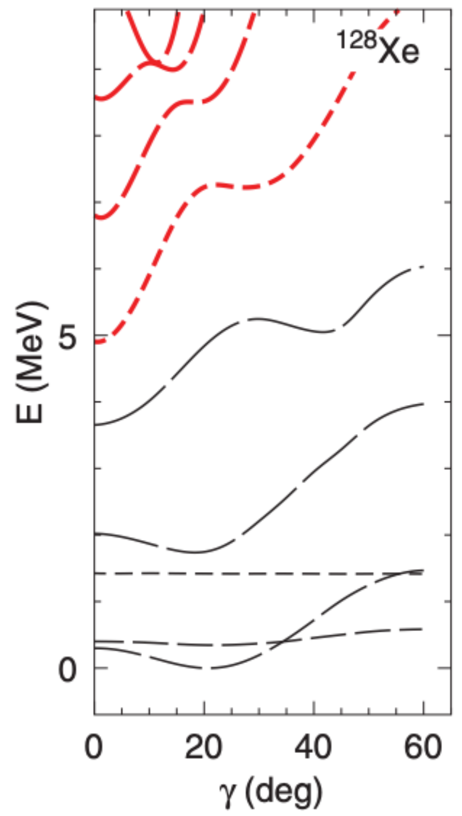
Nuclear Shape Phase diagram





^{128}Xe – ^{132}Xe





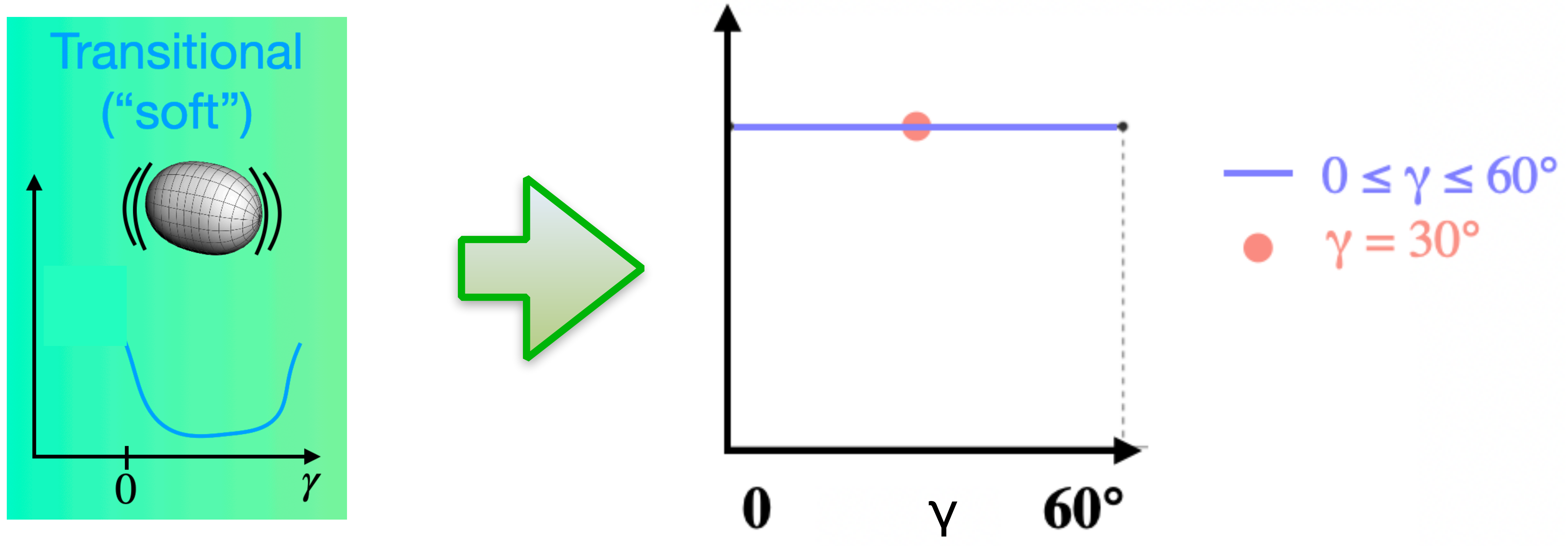
Explore nuclear shape phase transition with ^{129}Xe

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,ǁ]



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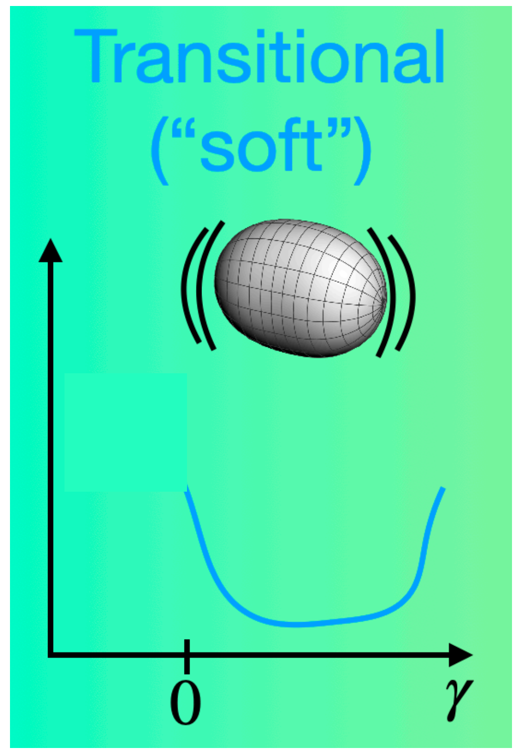
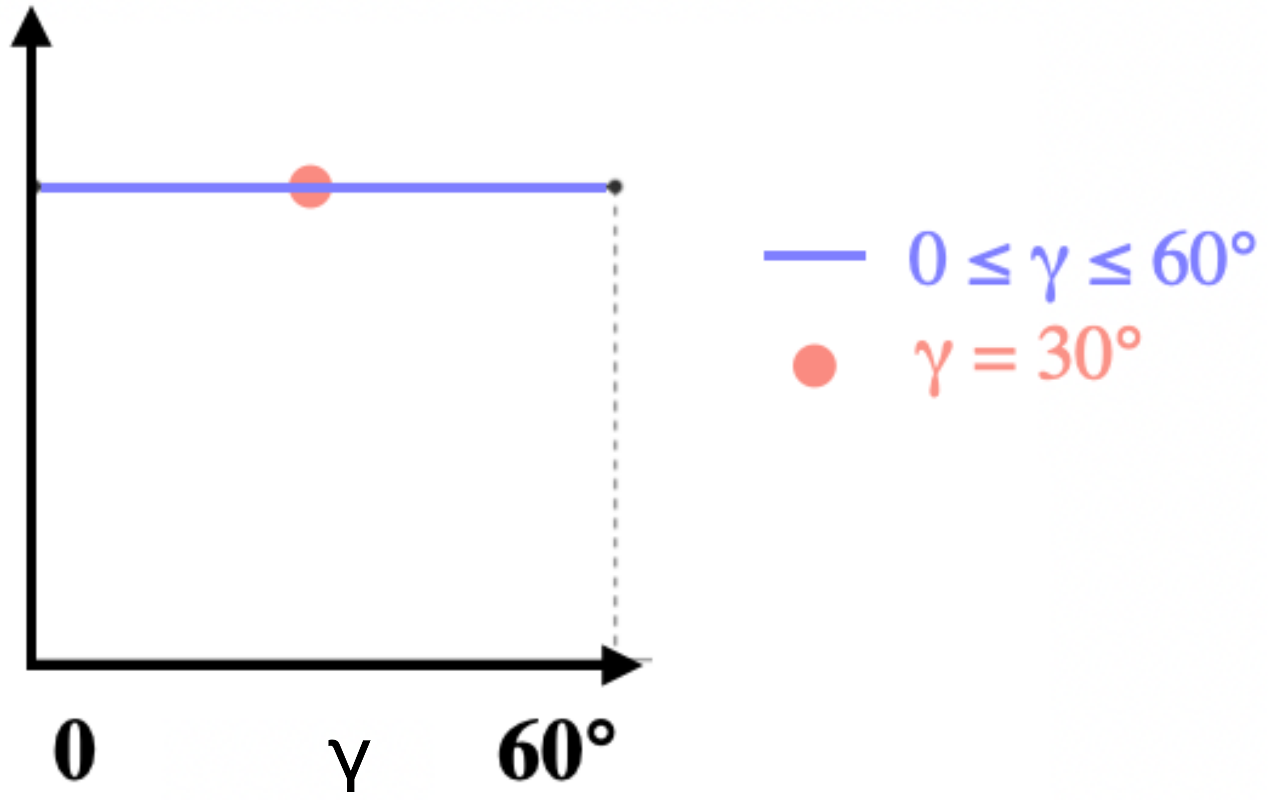
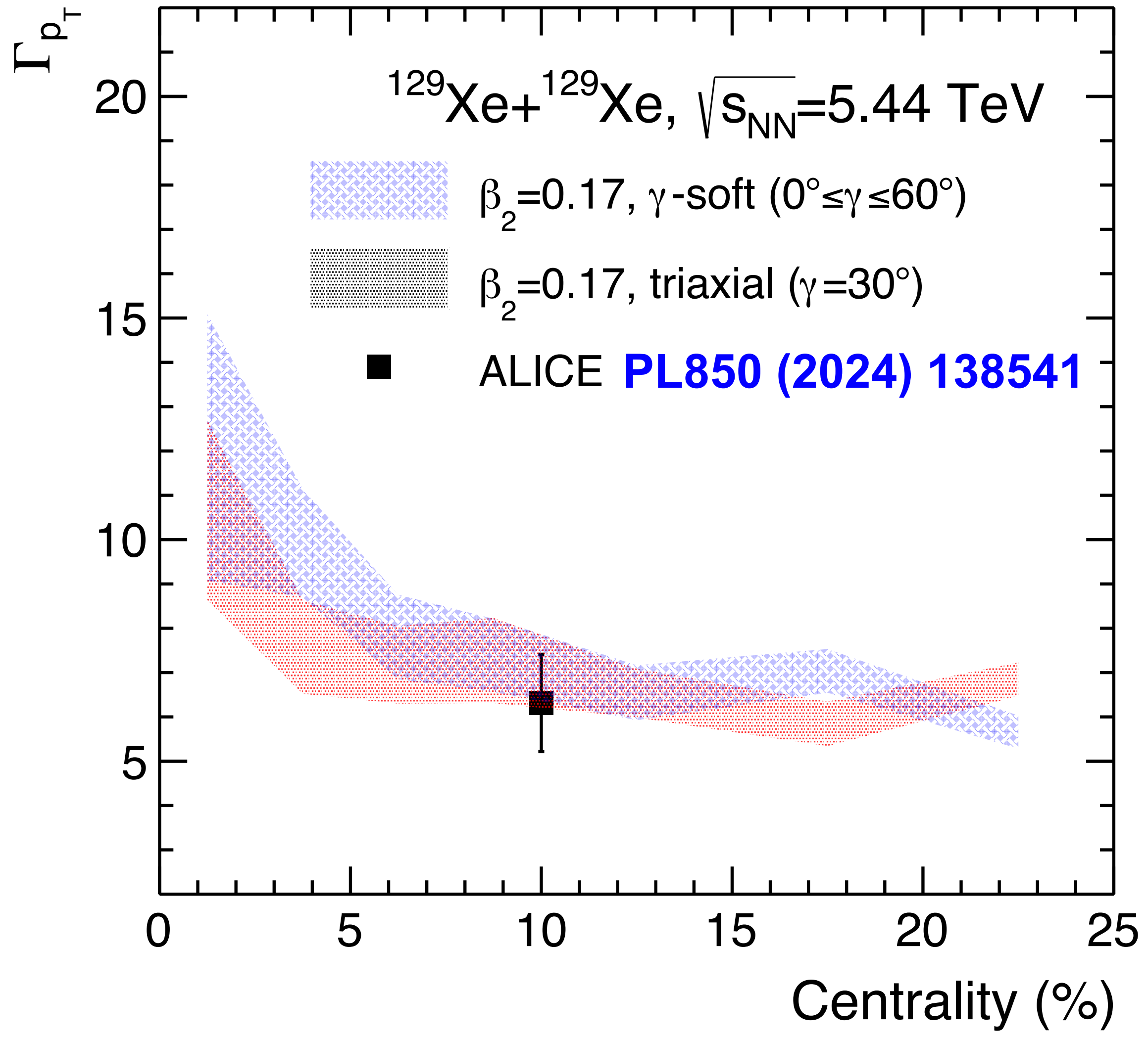




Size fluctuation

3-particle p_T correlation

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



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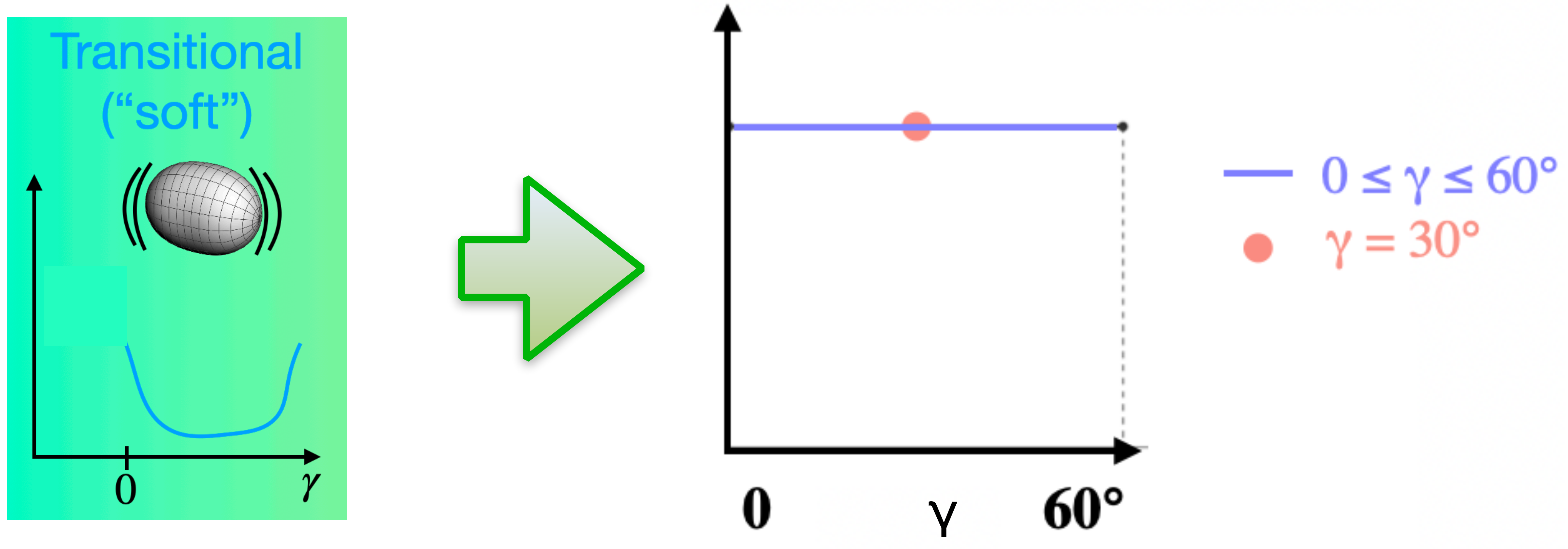
Phys. Rev. Lett. 133 (2024) 192301



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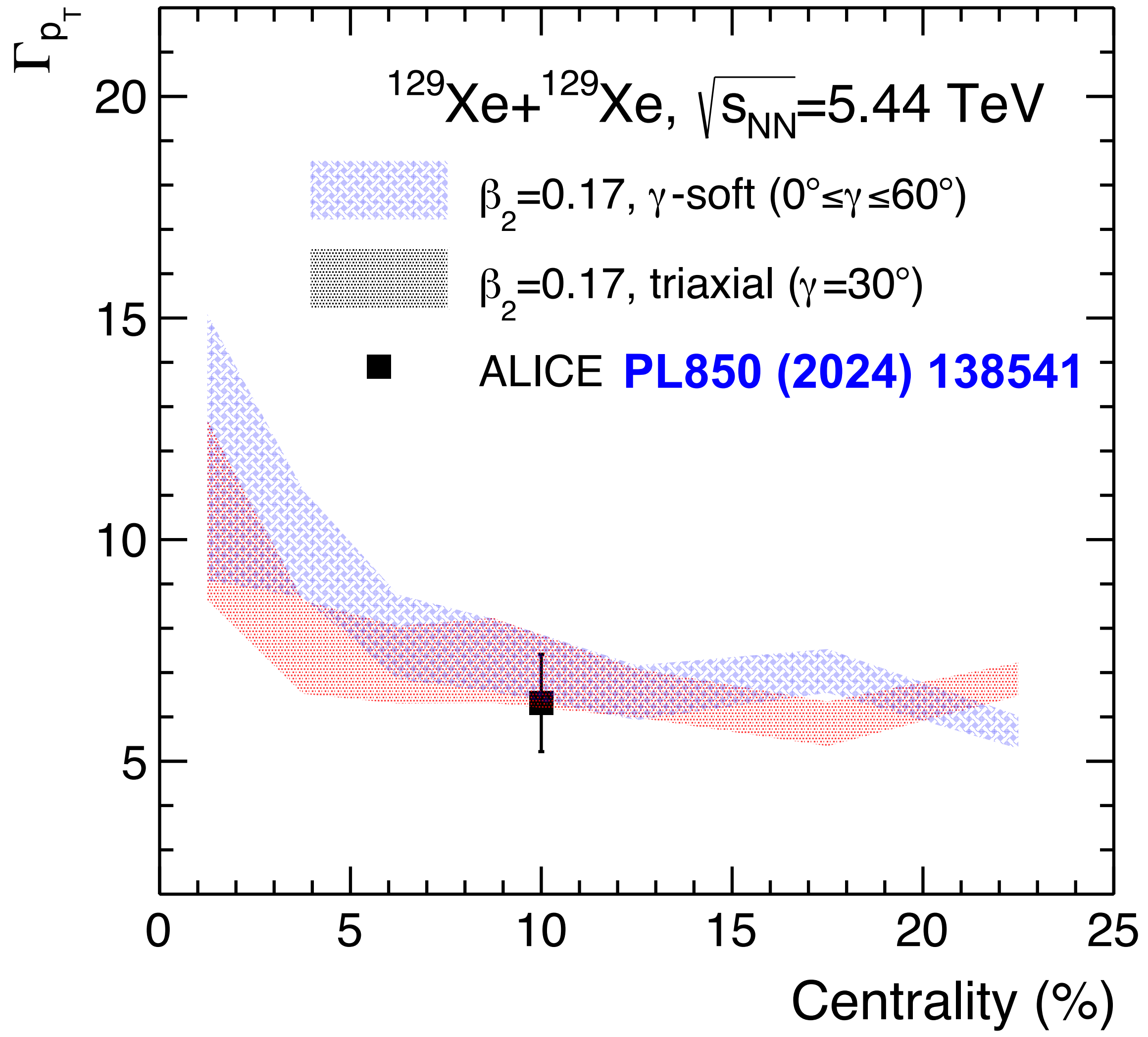
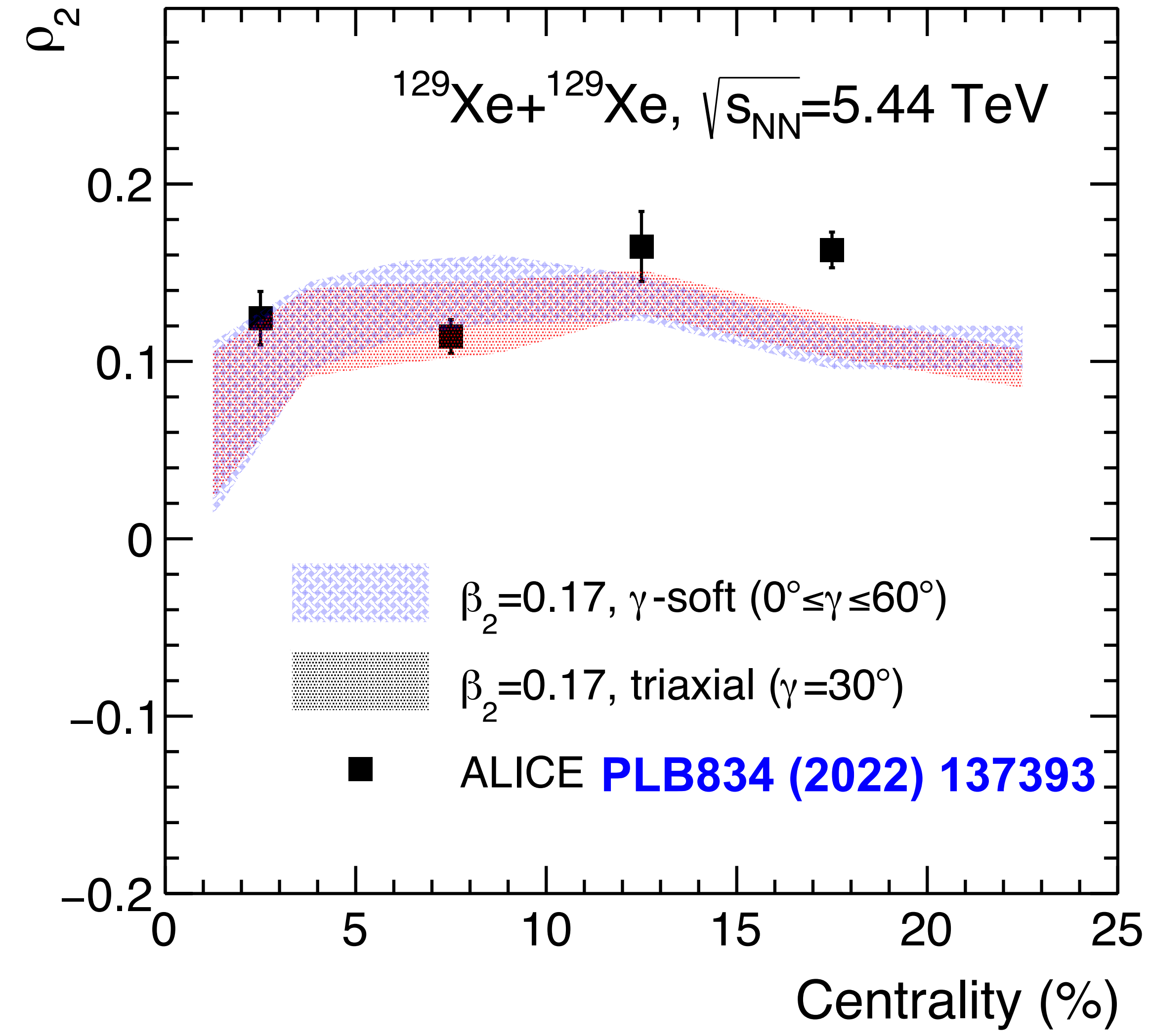


Shape-size correlations

3-particle v_n^2 — $[p_T]$ correlation

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



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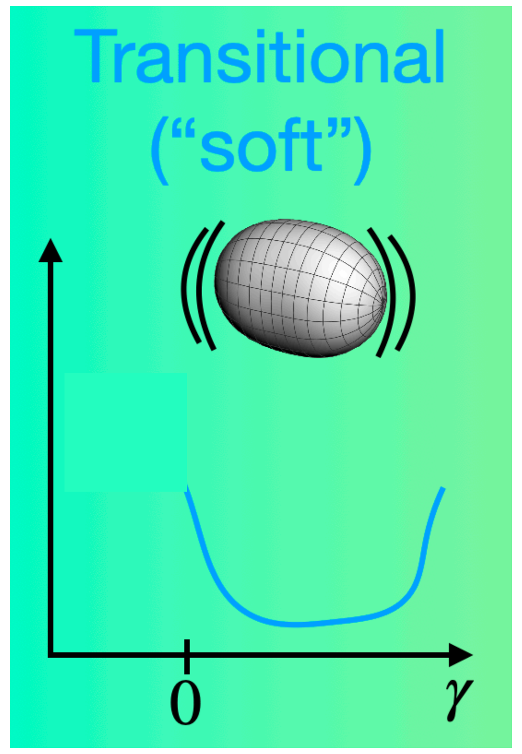
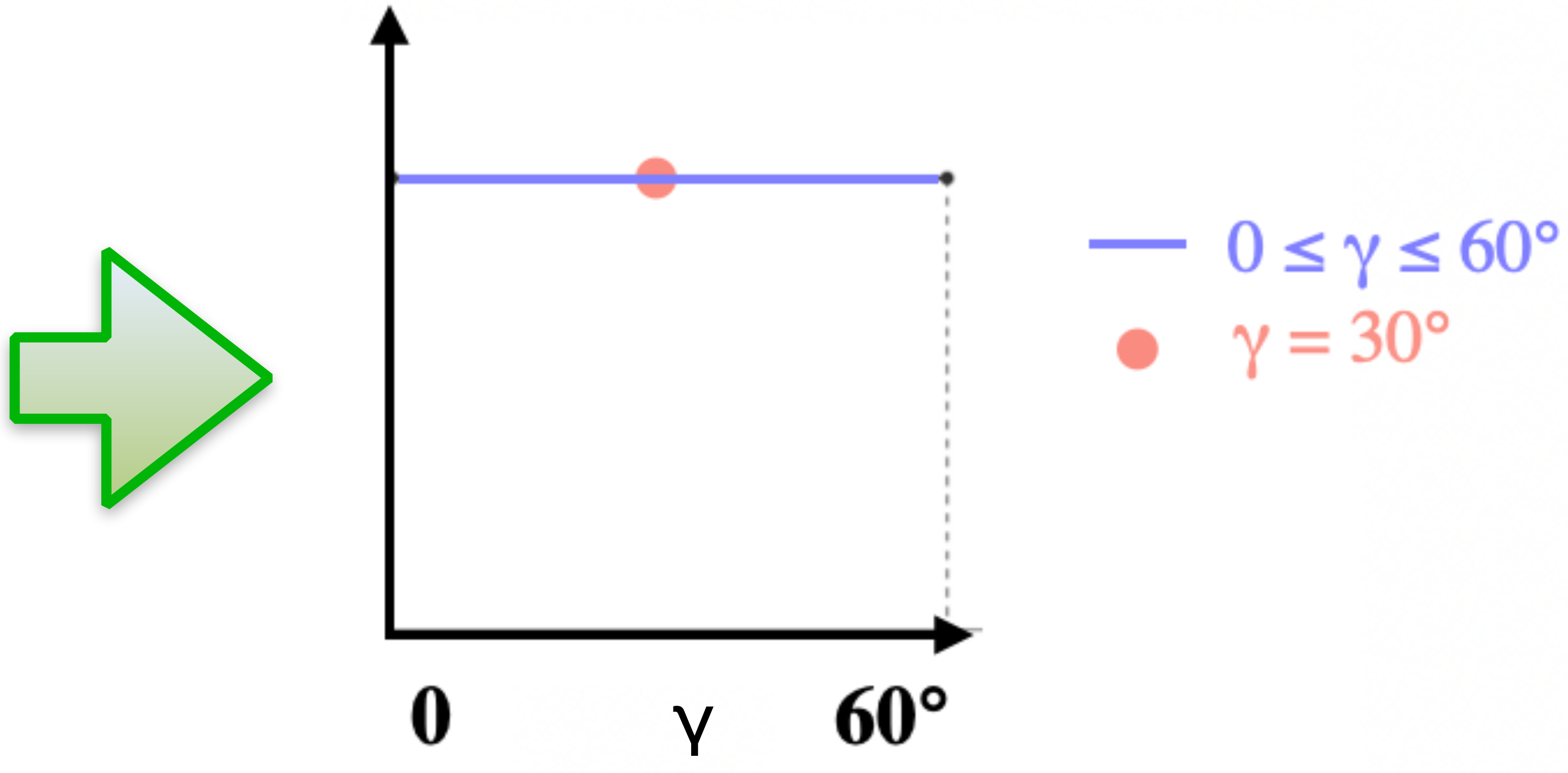
Shujun Zhao[1,2,*], Hao-jie Xu[2,3,†], You Zhou[4,‡], Yu-Xin Liu[1,5,6,§], and Huichao Song[1,5,6,ı]



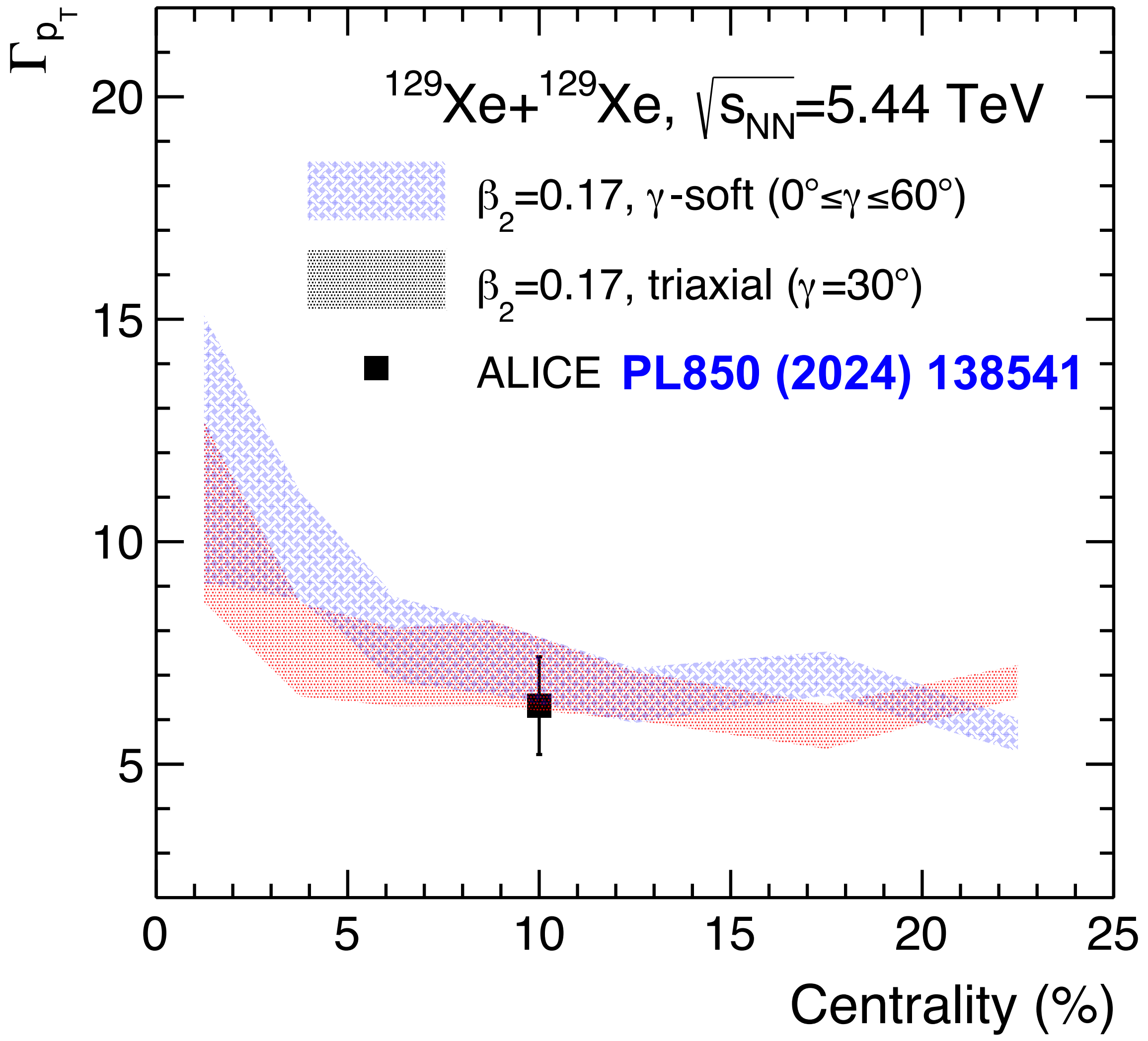


❖One can ***NOT*** distinguish triaxial (fixed γ = 30°) and γ-soft (fluctuating γ) structures with existing 3-particle correlations measurements

Size fluctuation

3-particle p_T correlation

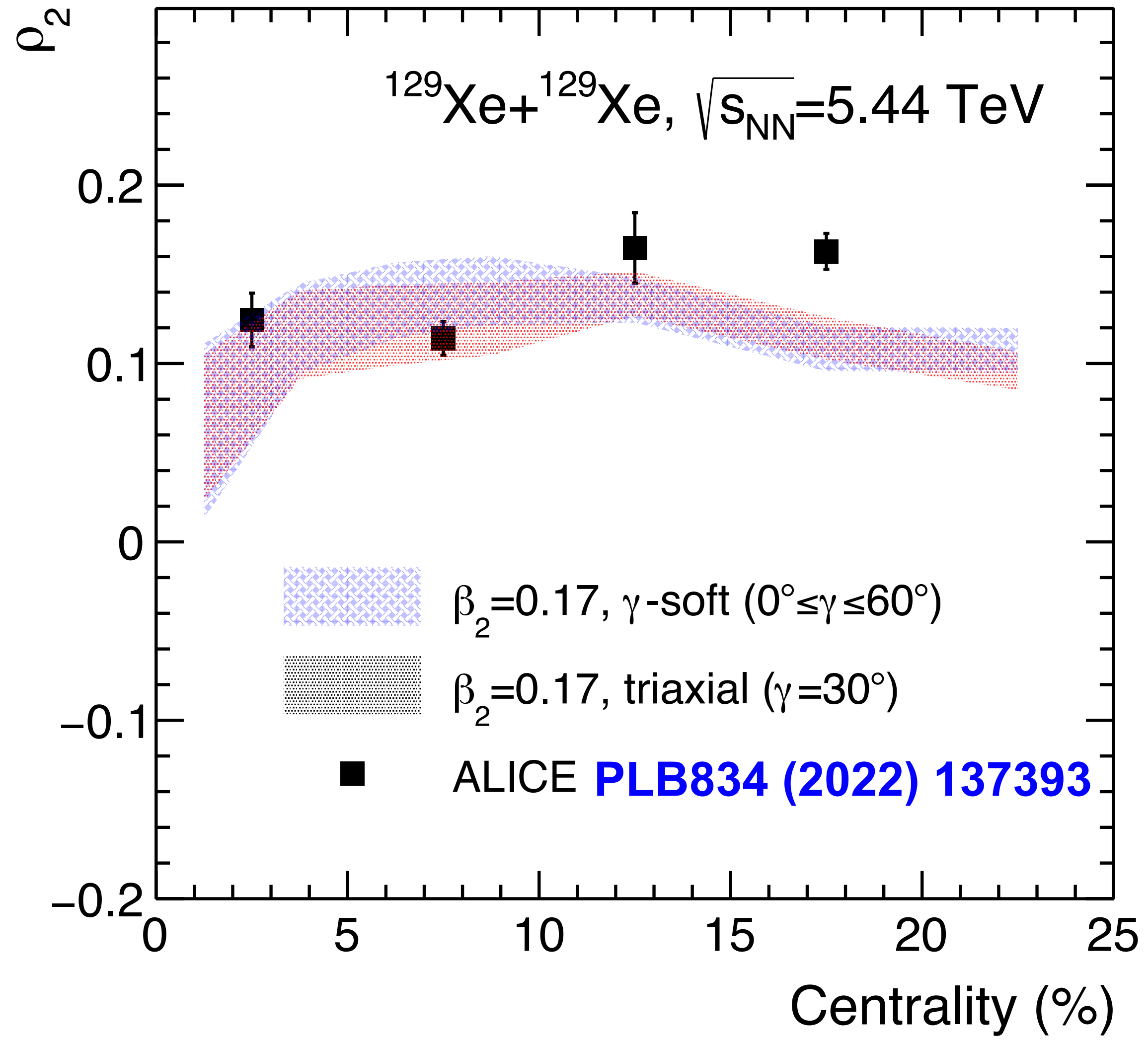
$$\Gamma_{p_T} = \frac{\langle \delta p_{T,i}\delta p_{T,j}\delta p_{T,k}\rangle \langle [p_T]\rangle}{\langle \delta p_{T,i}\delta p_{T,j}\rangle^2}$$



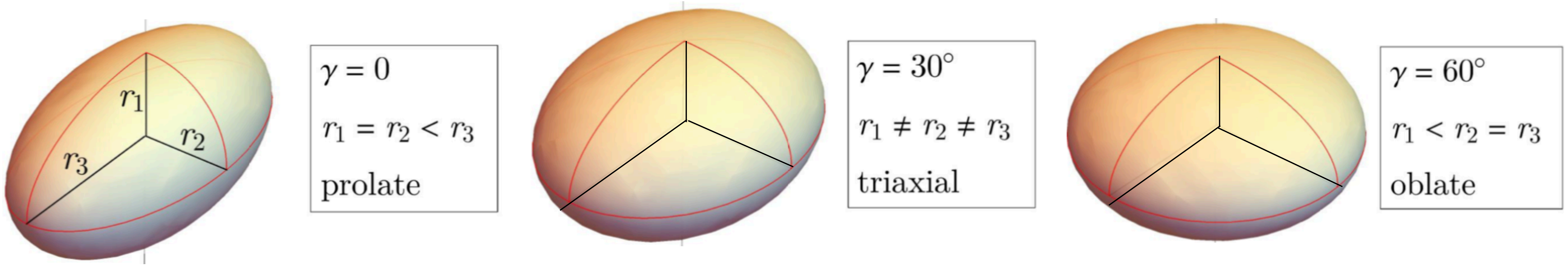
Shape-size correlations

3-particle v_n^2 — $[p_T]$ correlation

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



Shape transition via high-order correlations of v_n and p_T



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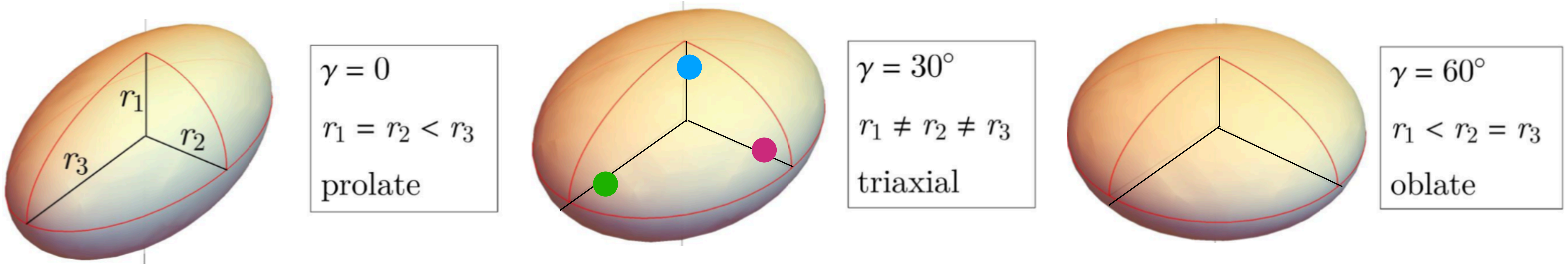
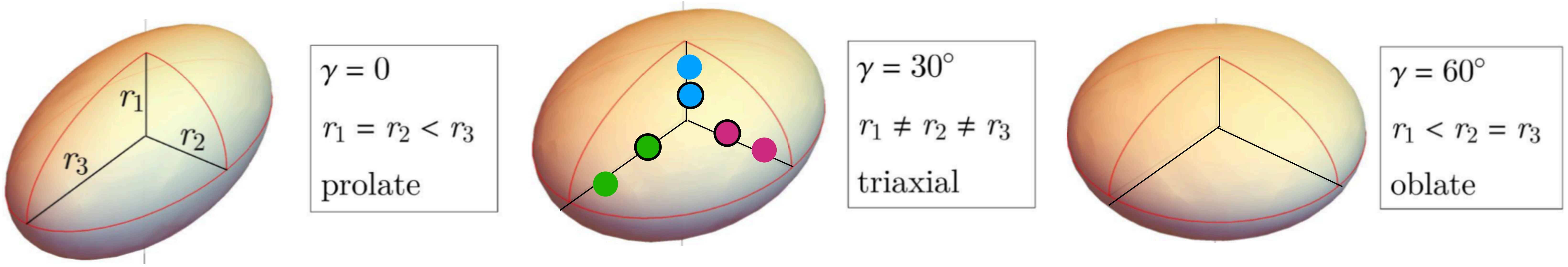


❖ To probe the relation of r_1, r_2 and r_3, we need 3-particle correlations

Shape transition via high-order correlations of v_n and p_T



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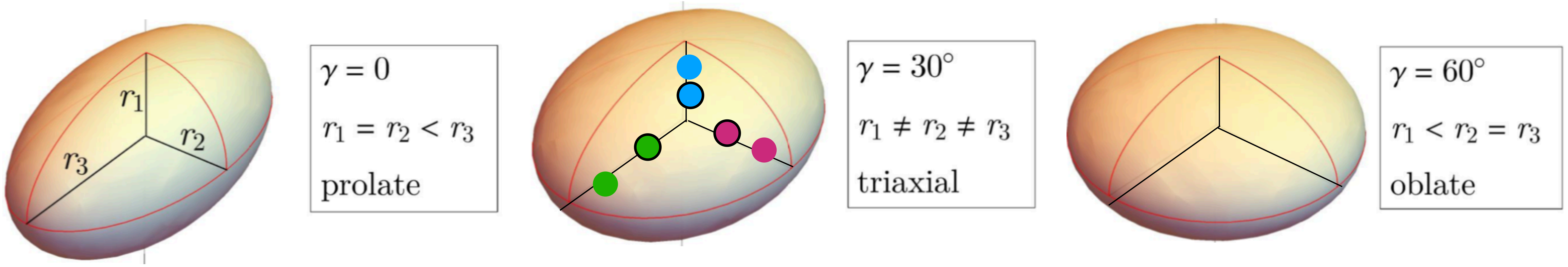
Shape transition via high-order correlations of v_n and p_T



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

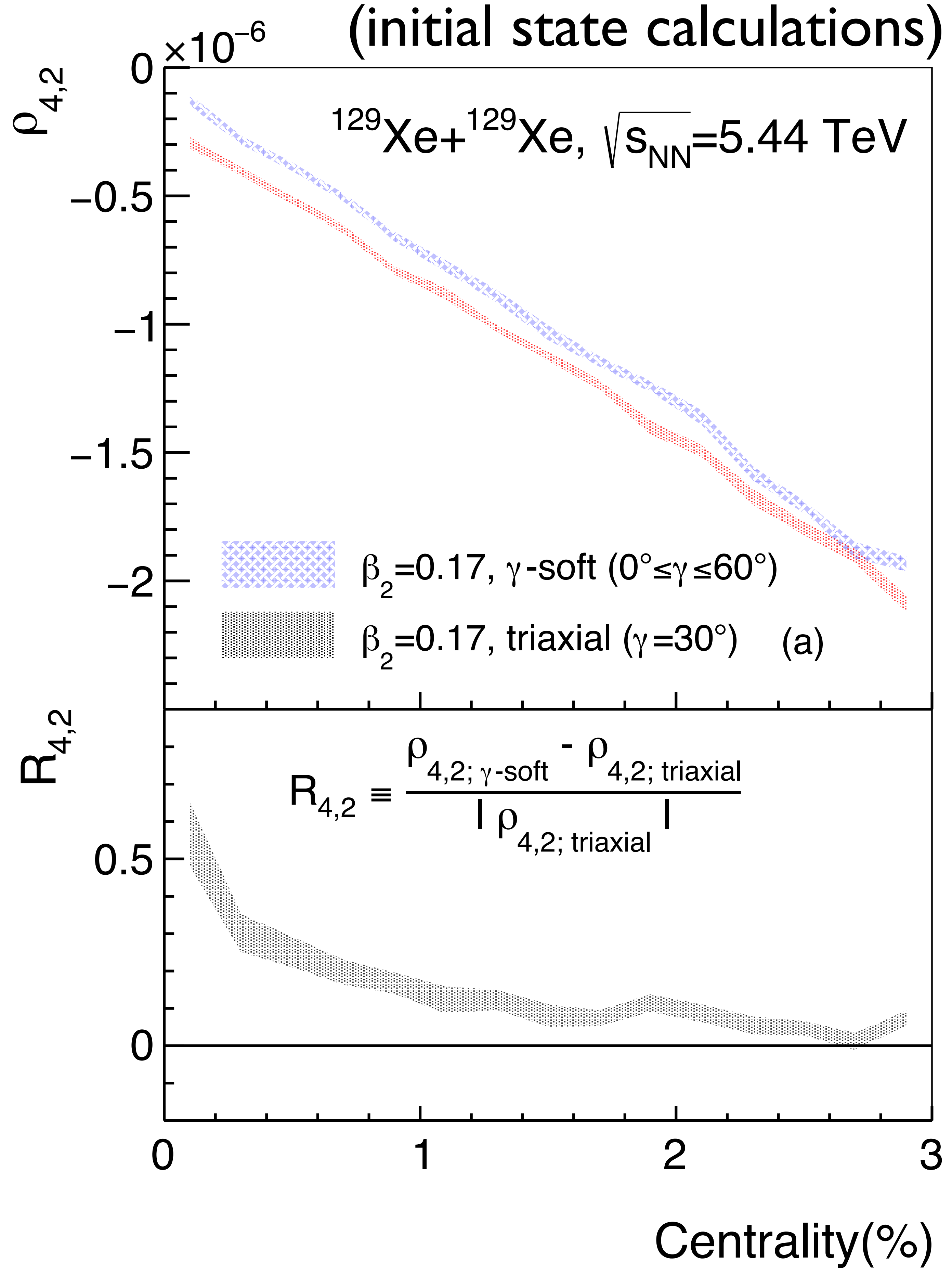
❖ To probe the γ fluctuations, we need 6-particle correlations

New proposal:

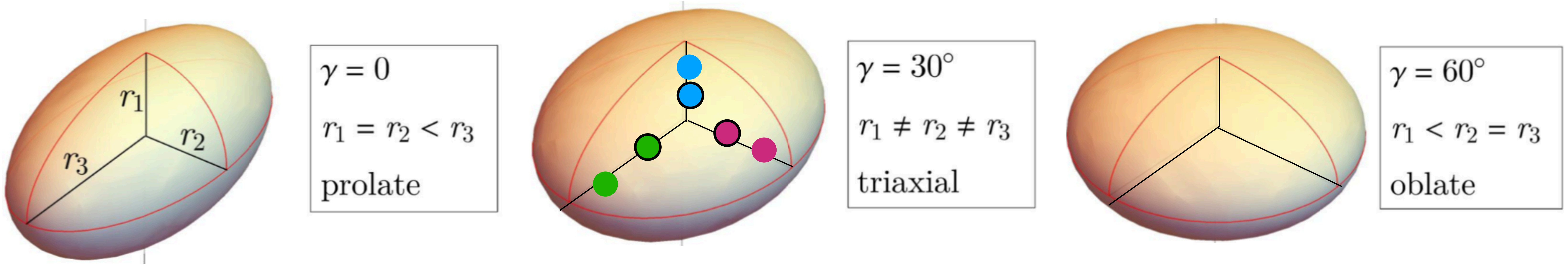
$$\rho_{4,2} \equiv \left(\frac{\langle \varepsilon_2^4 \delta d_\perp^2\rangle}{\langle \varepsilon_2^4\rangle\langle d_\perp\rangle^2}\right)_c \equiv \frac{1}{\langle \varepsilon_2^4\rangle\langle d_\perp\rangle^2}\left[\langle \varepsilon_2^4 \delta d_\perp^2\rangle + 4\langle \varepsilon_2^2\rangle^2\langle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

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

Phys. Rev. Lett. 133 (2024) 192301



Shape transition via high-order correlations of v_n and p_T



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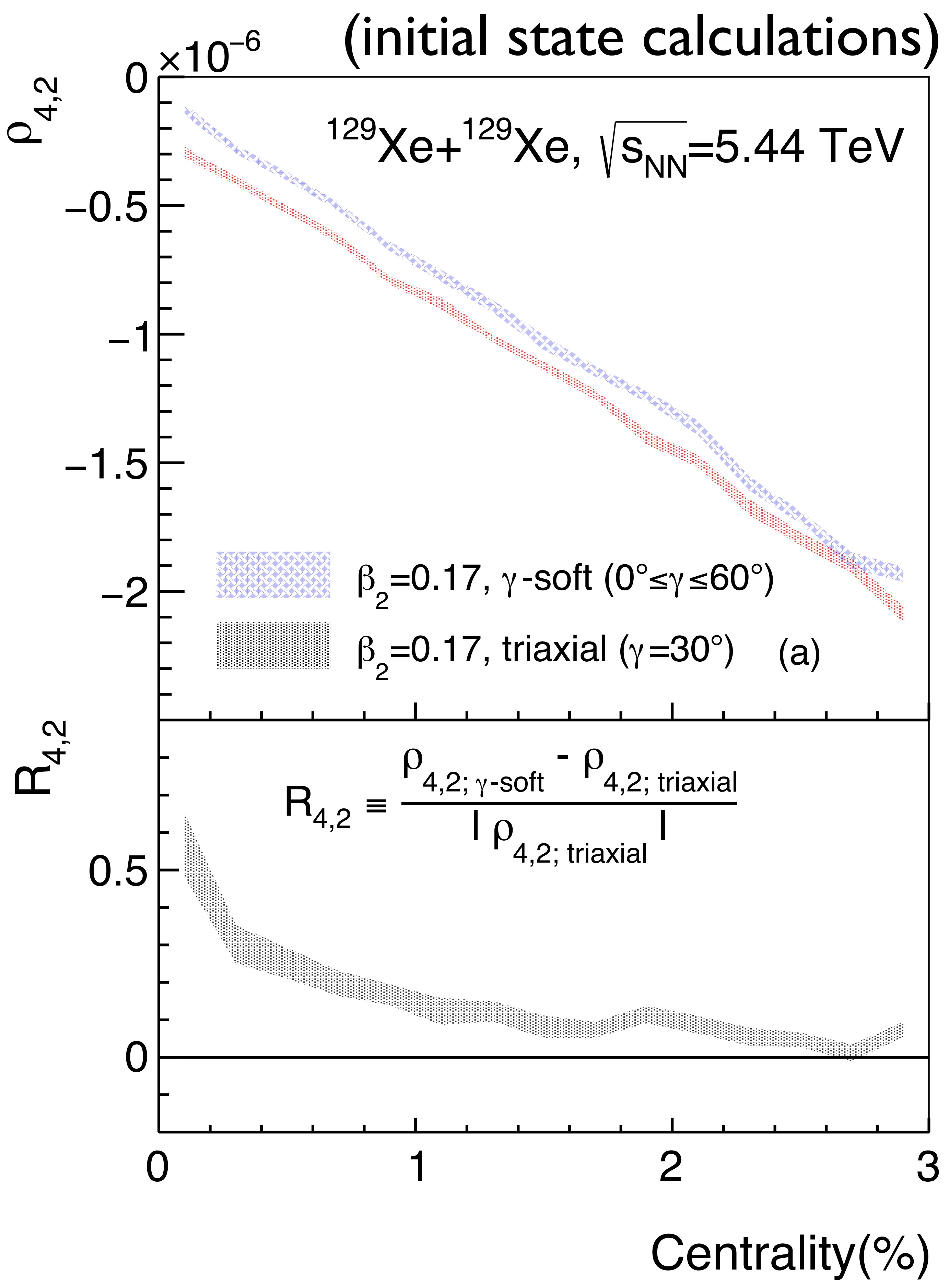
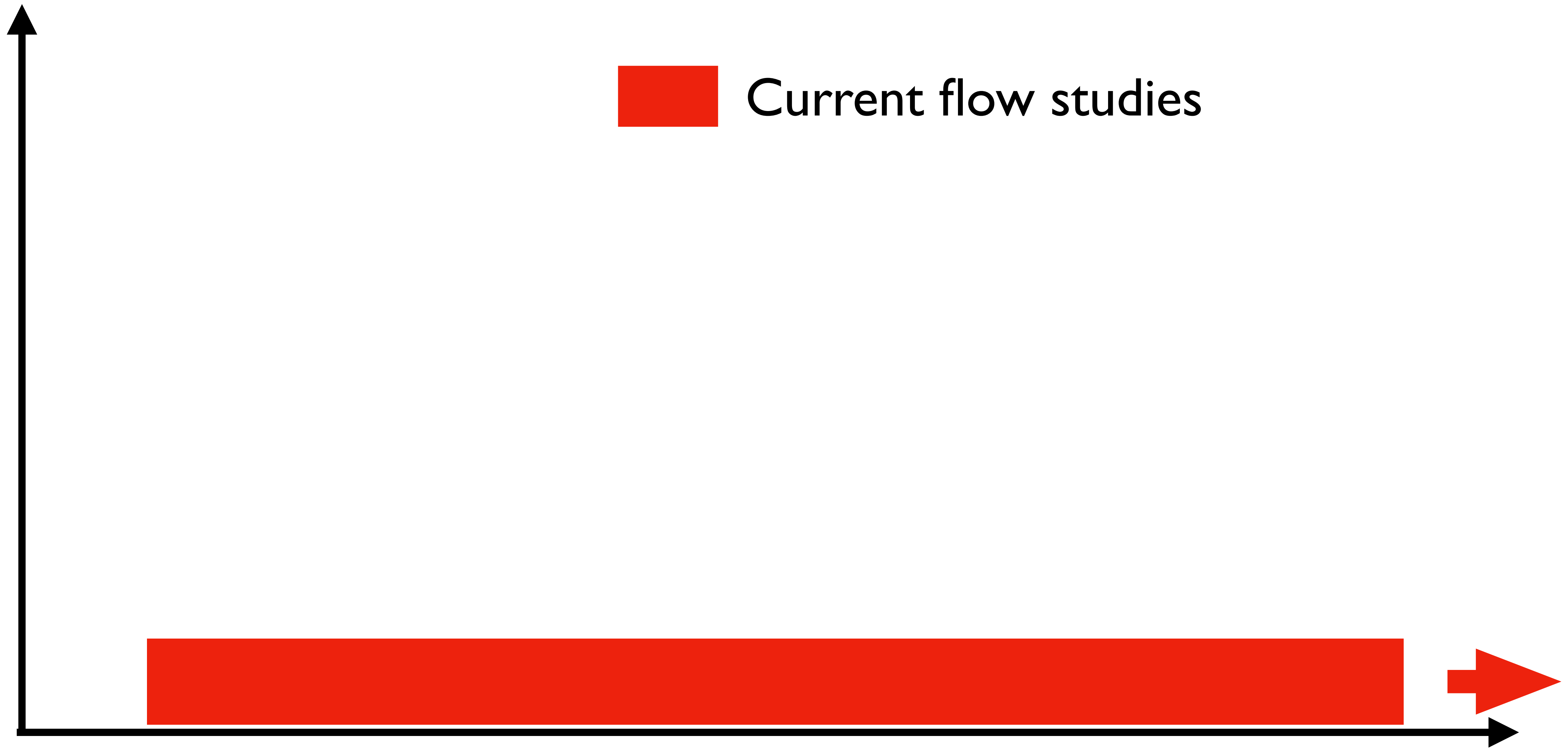
➡The six-particle correlations allow to differentiate triaxial (fixed γ = 30°) and γ-soft (fluctuating γ) structures.

❖Higher-order v_n and p_T correlations allows to probe nuclear shape phase transition, but their implementations are highly non-trivial!

Phys. Rev. Lett. 133 (2024) 192301



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



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†
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A *Unified Algorithm* makes them all possible

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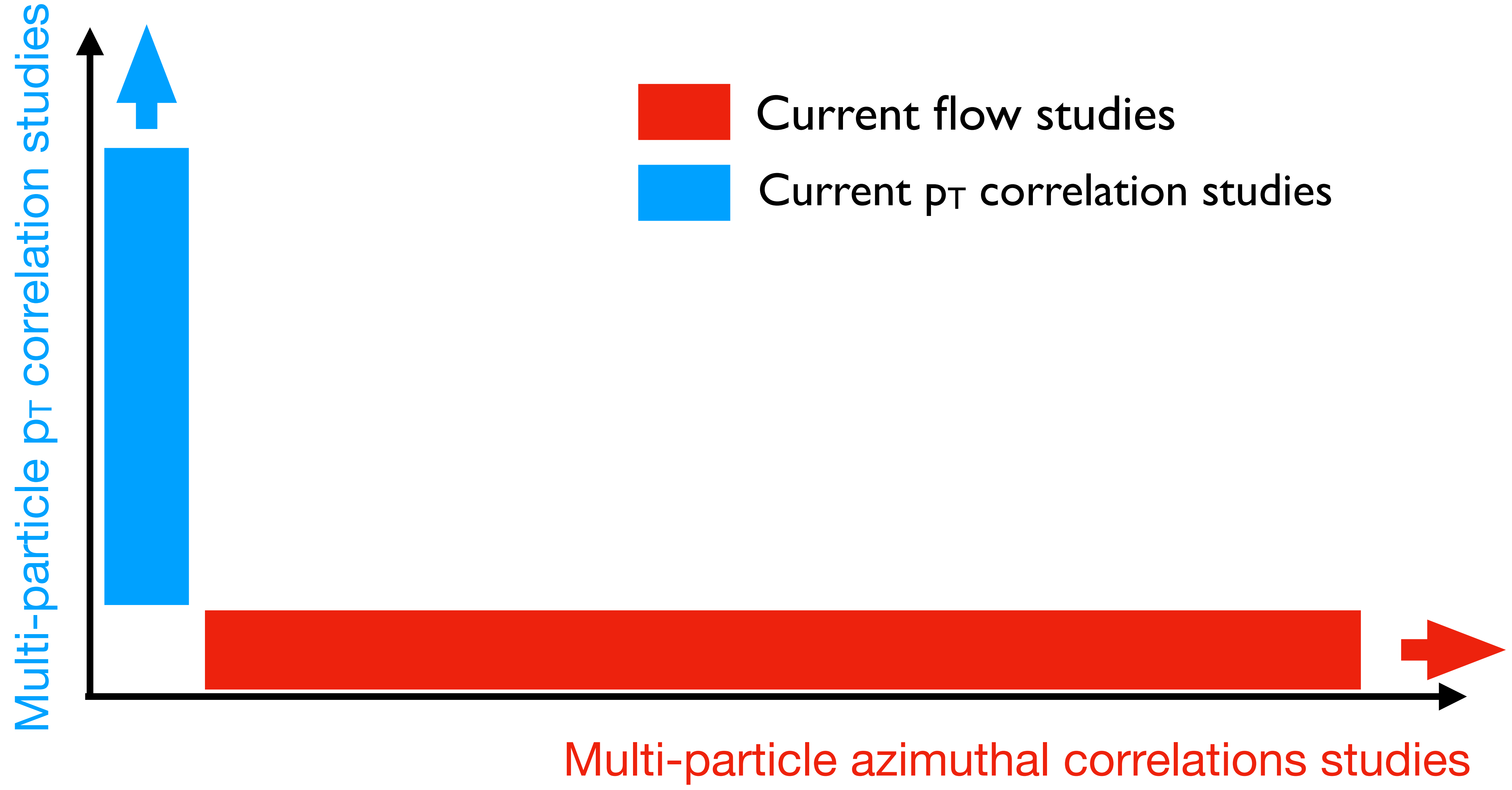
Eur. Phys. J. A (2024) 60:38
https://doi.org/10.1140/epja/s10050-024-01266-x
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Theoretical Physics

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



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THE EUROPEAN PHYSICAL JOURNAL A

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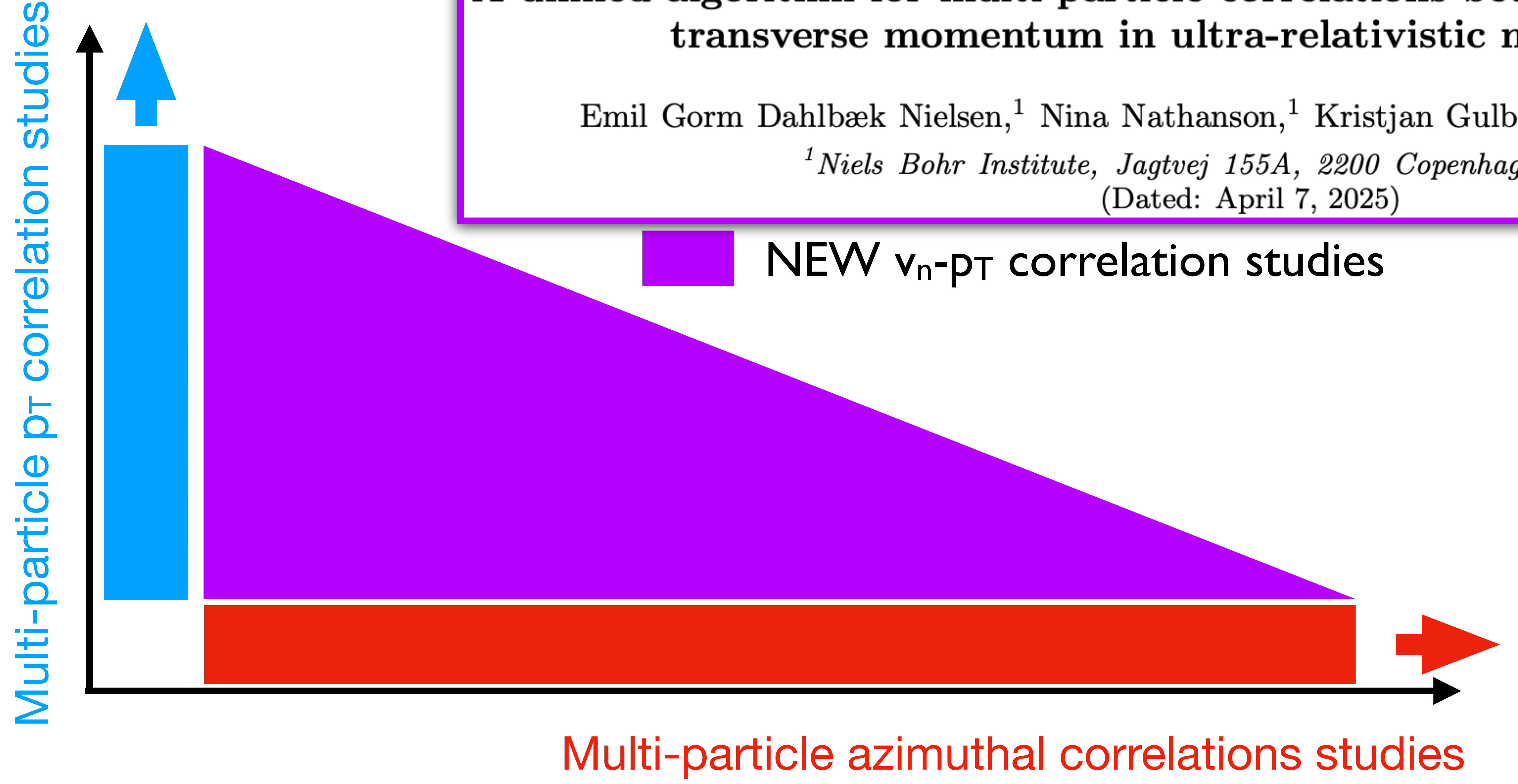
Niels Bohr Institute, University of Copenhagen, 2200 Copenhagen, Denmark

arXiv:2504.03044, submitted to EPJC

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

Emil Gorm Dahlbæk Nielsen,[1] Nina Nathanson,[1] Kristjan Gulbrandsen,[1] and You Zhou[1,*]
[1] *Niels Bohr Institute, Jagtvej 155A, 2200 Copenhagen, Denmark*
(Dated: April 7, 2025)



PHYSICAL REVIEW C **89**, 064904 (2014)

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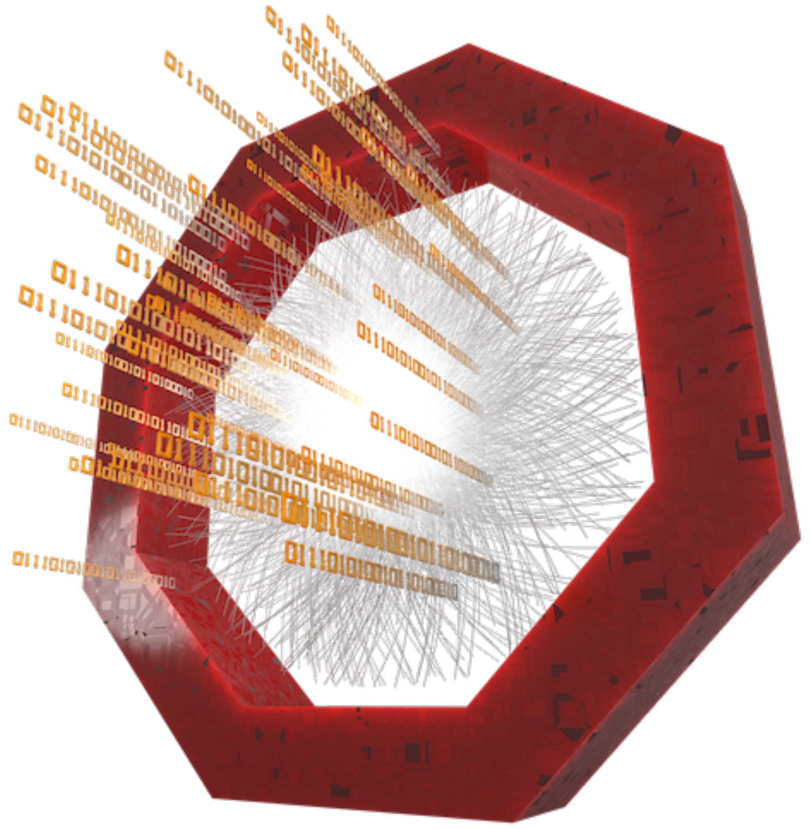
Exploring nuclear shape phase transition

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

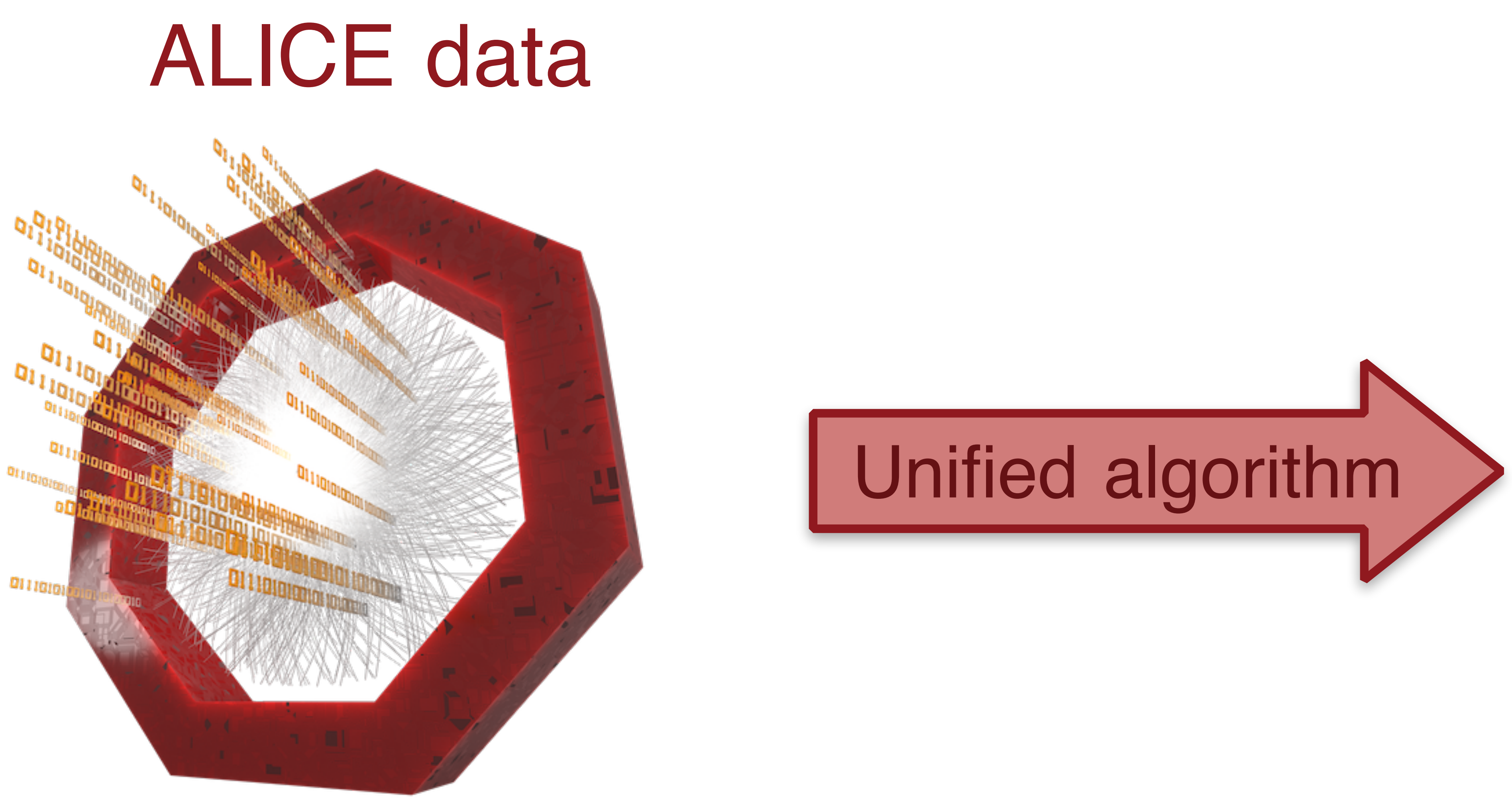


Unified algorithm

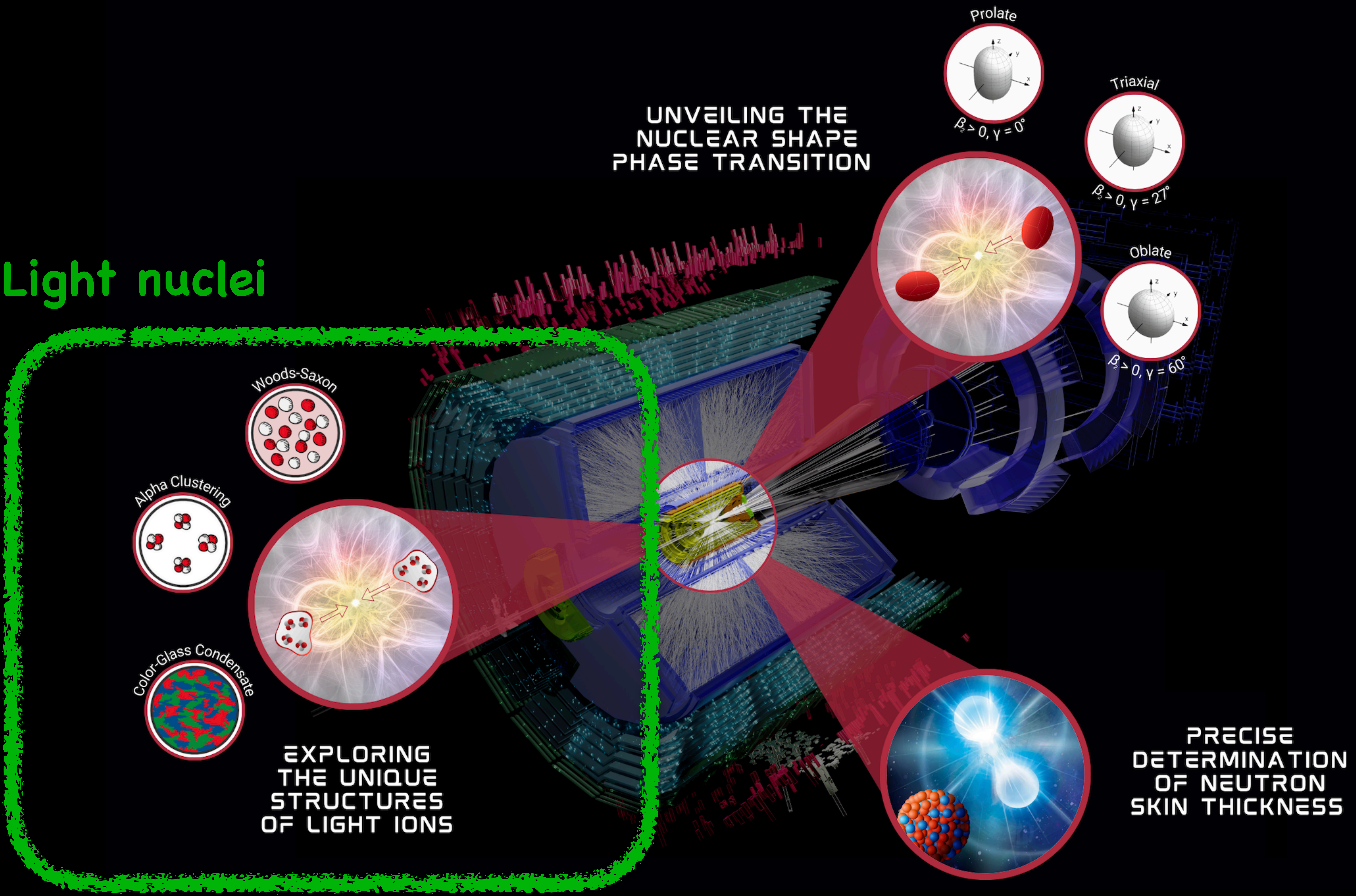
Nuclear Shape Phase Transition ?

Exploring nuclear shape phase transition

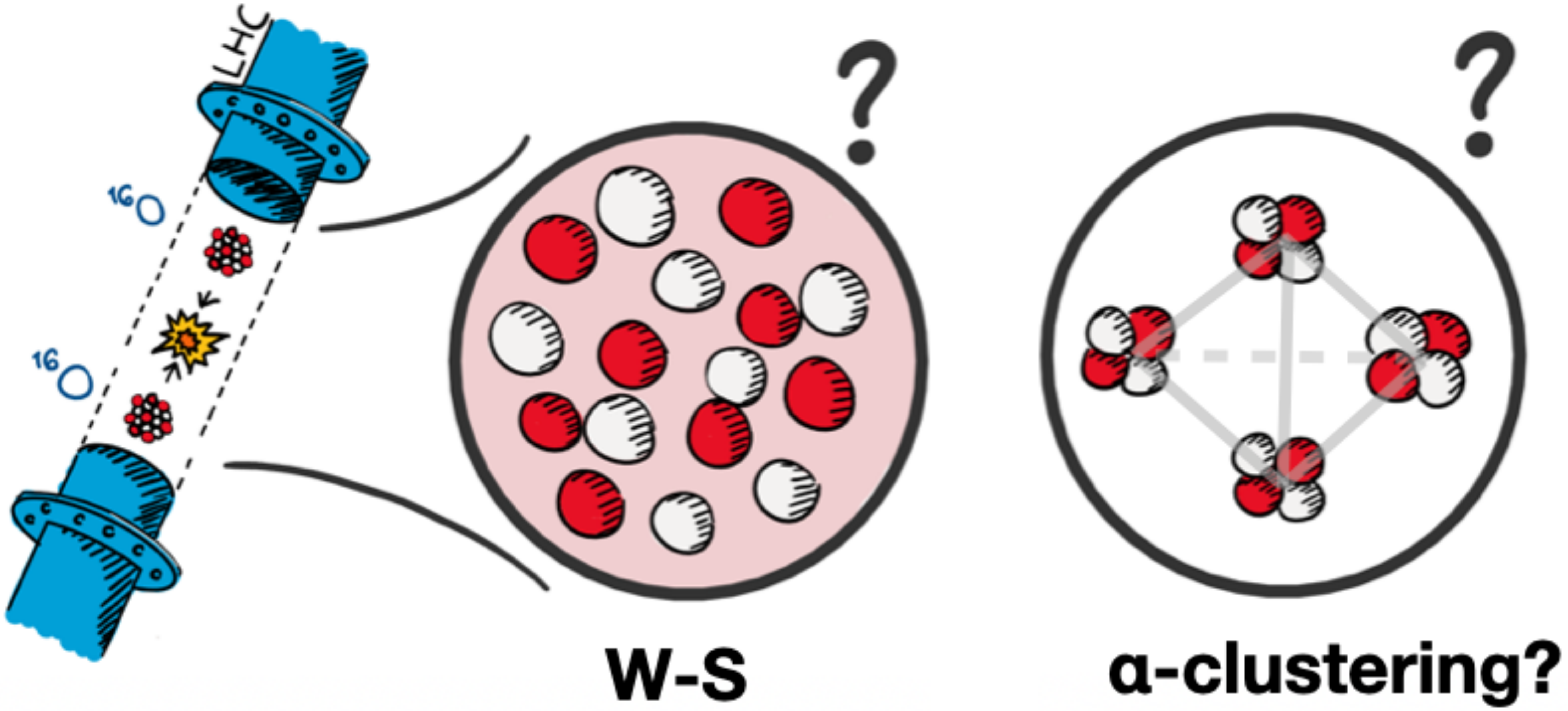
❖ First ALICE measurement on the multi-particle correlations of v_n and p_T



Light nuclei



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



Data taking last week!

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

X.L. Zhao etc., arXiv:2404.09780

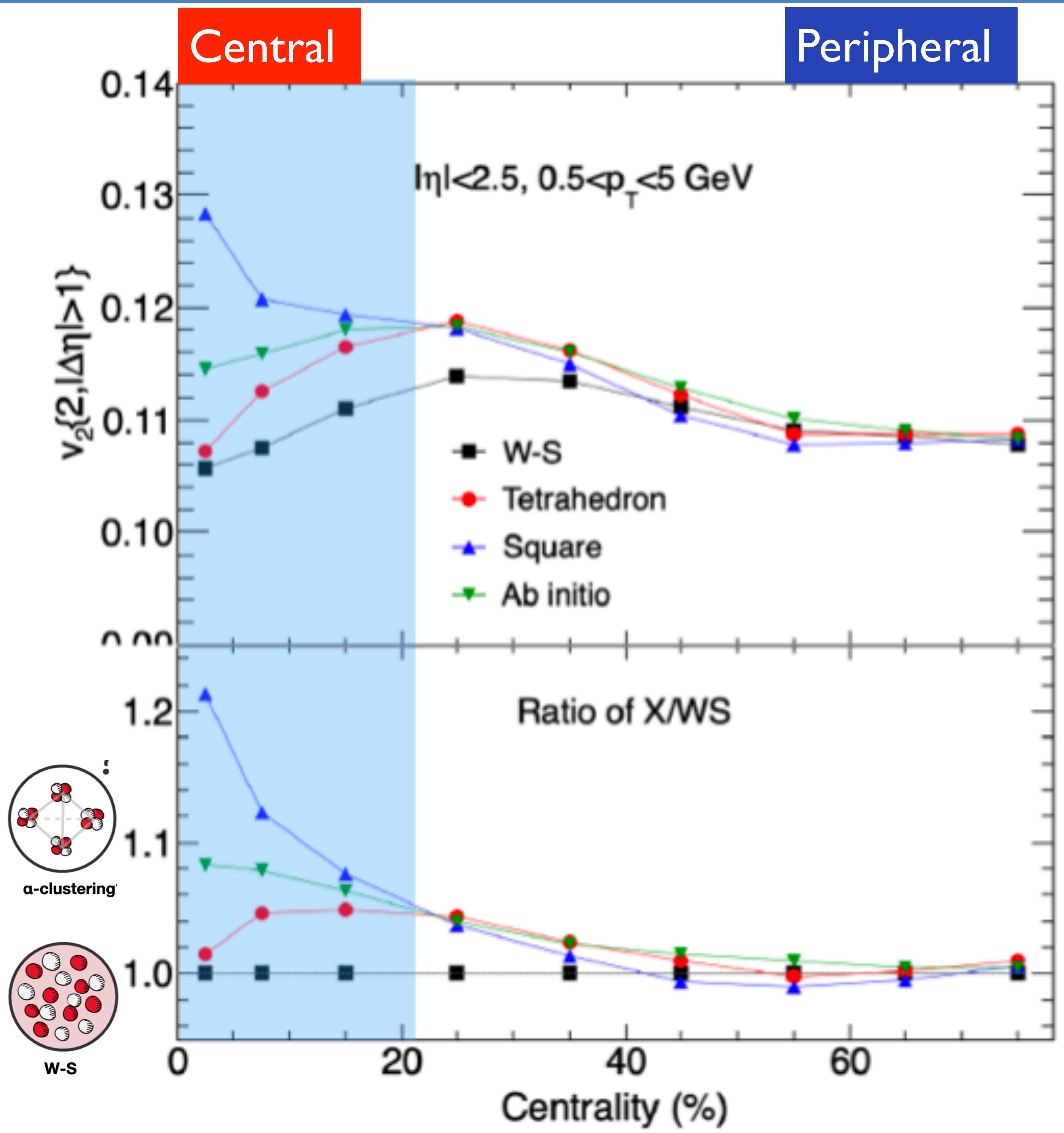
Nuclear cluster structure effect in ^{16}O+^{16}O collisions at the top RHIC energy

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

[1] *College of Science, University of Shanghai for Science and Technology, Shanghai 200093, China*
[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*

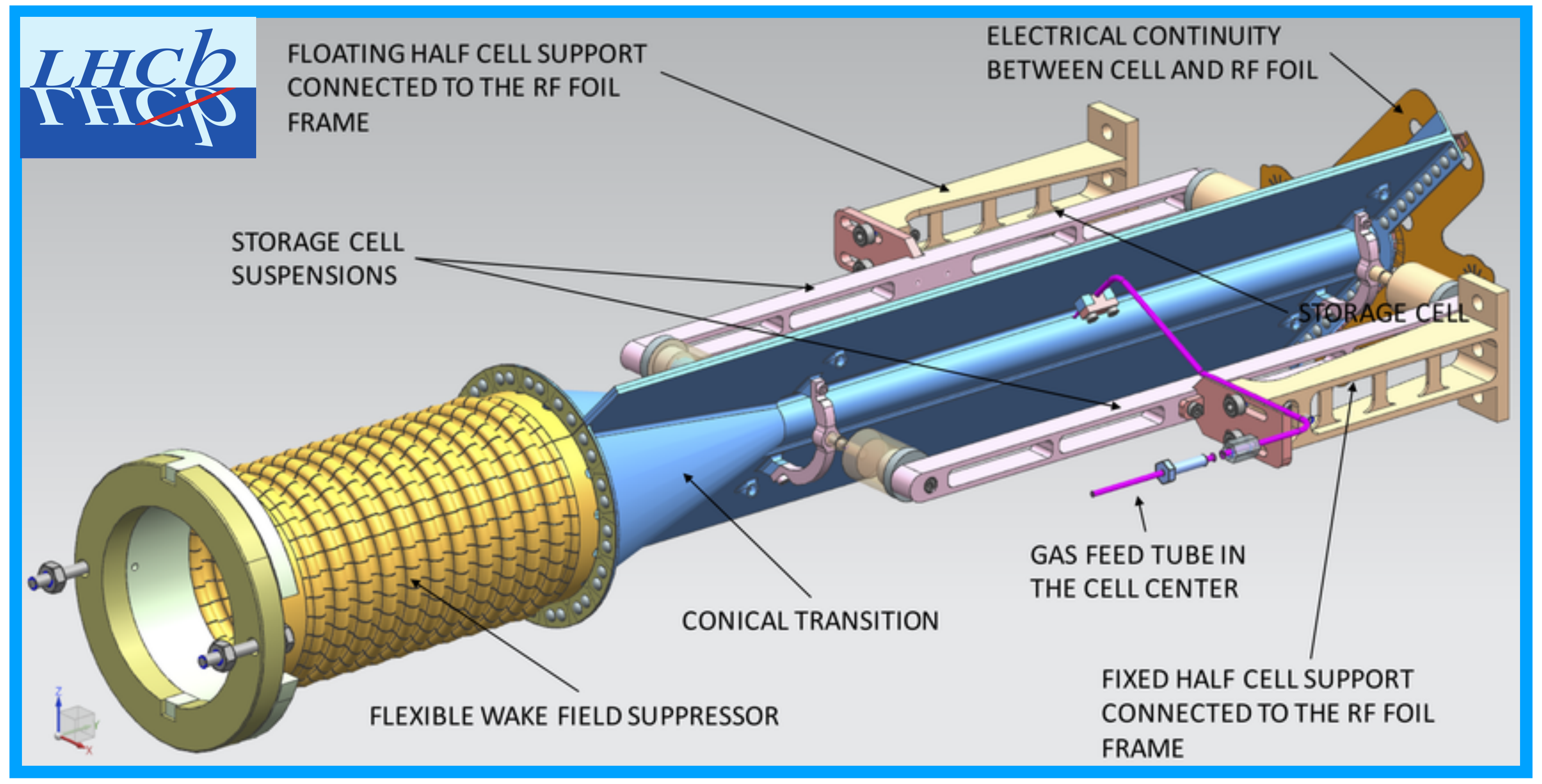
The impact of nuclear structure has garnered considerable attention in the high-energy nuclear physics community in recent years. This work focuses on studying the potential nuclear cluster structure in ^{16}O nuclei using anisotropic flow observables in O+O collisions at 200 GeV. Employing an improved 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.



Imprint of Light Nuclei Structure

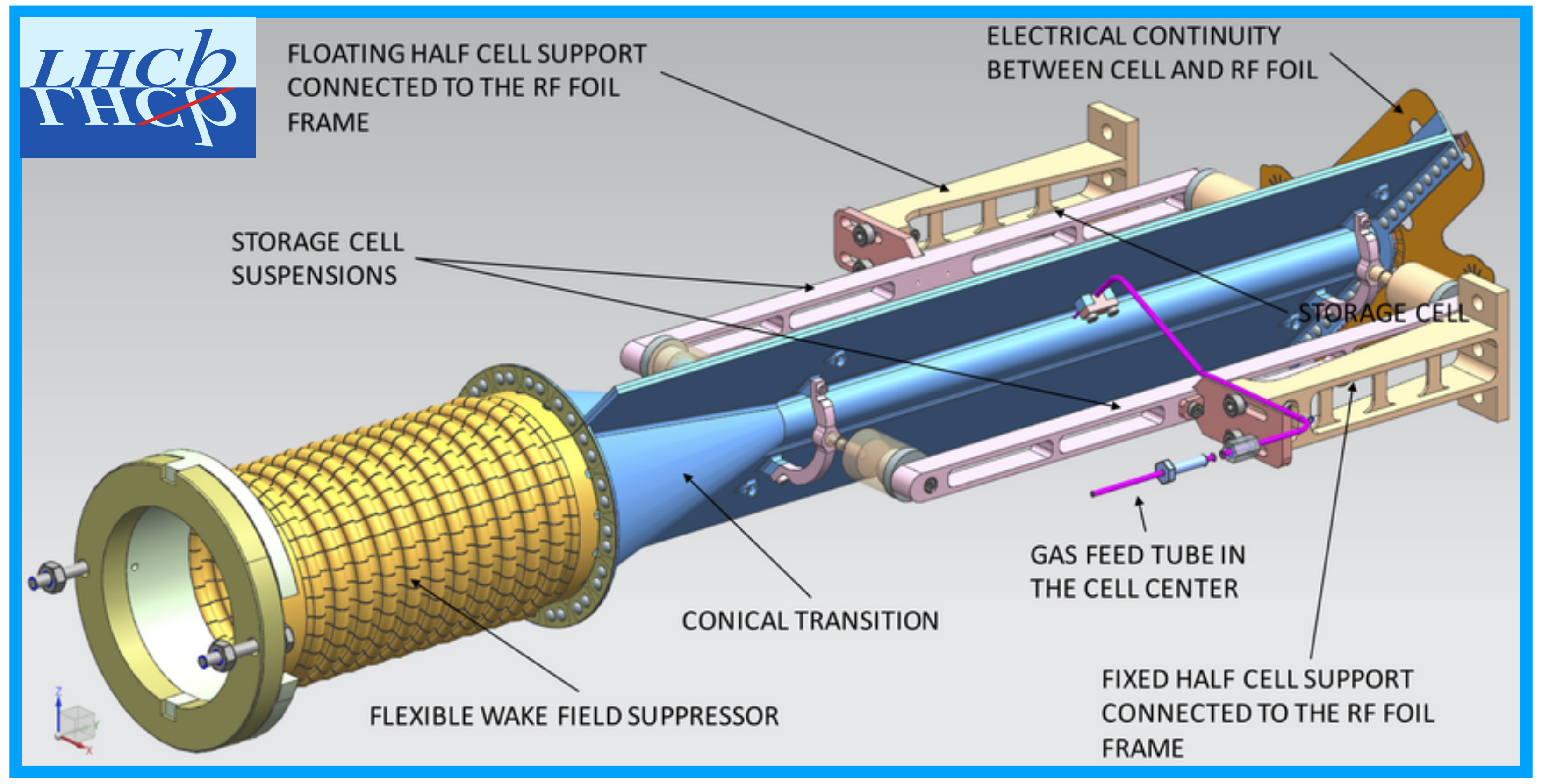
Imprint of Light Nuclei Structure



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

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

Imprint of Light Nuclei Structure



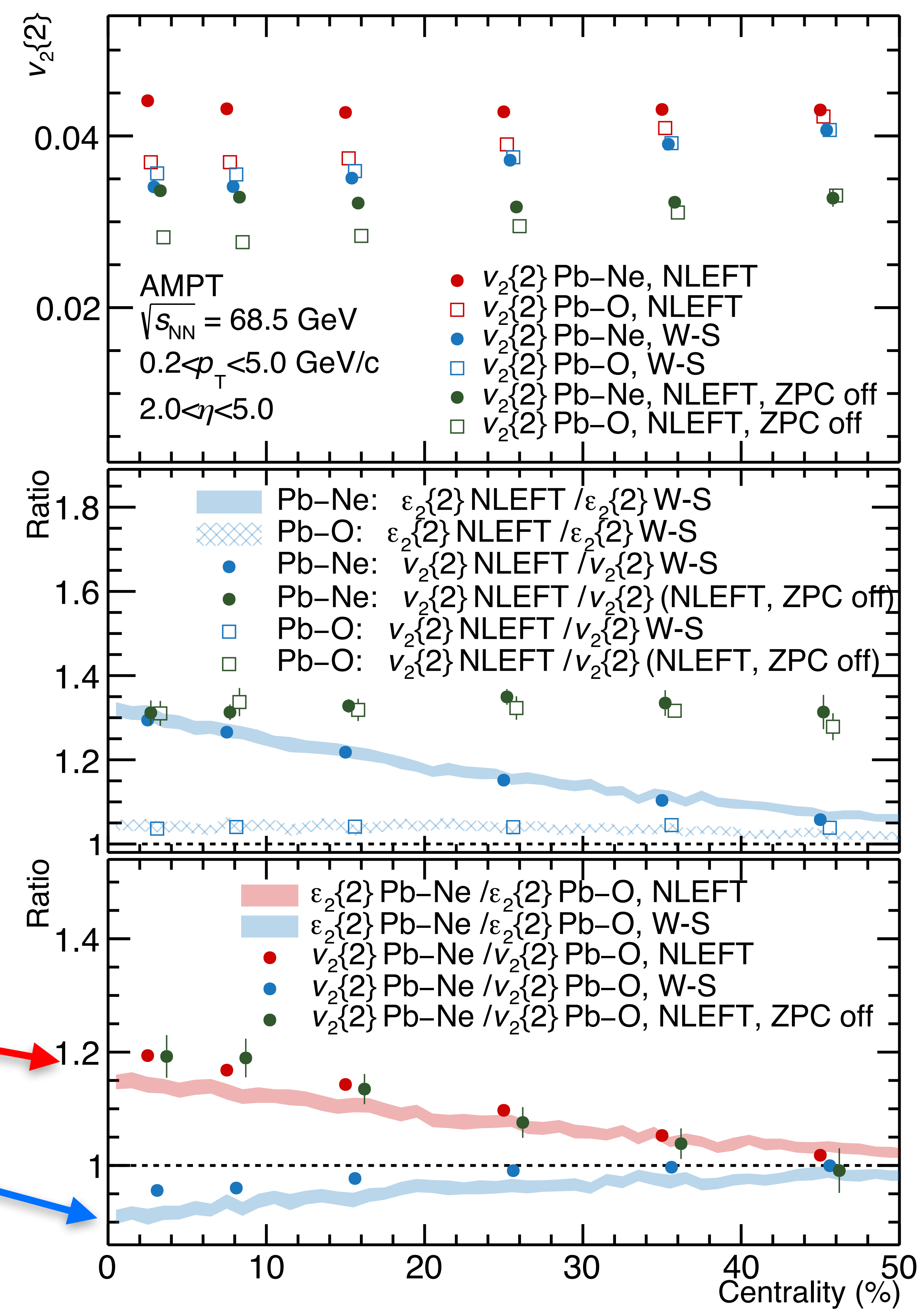
^{208}Pb-^{20}Ne @ ~68 GeV

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

❖ $v_2\{2\}$ ratio (Pb-Ne)/(Pb-O)

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

AMPT: Z. Lu etc., Phys. Lett. B 868 (2025) 139698
(Published last week)



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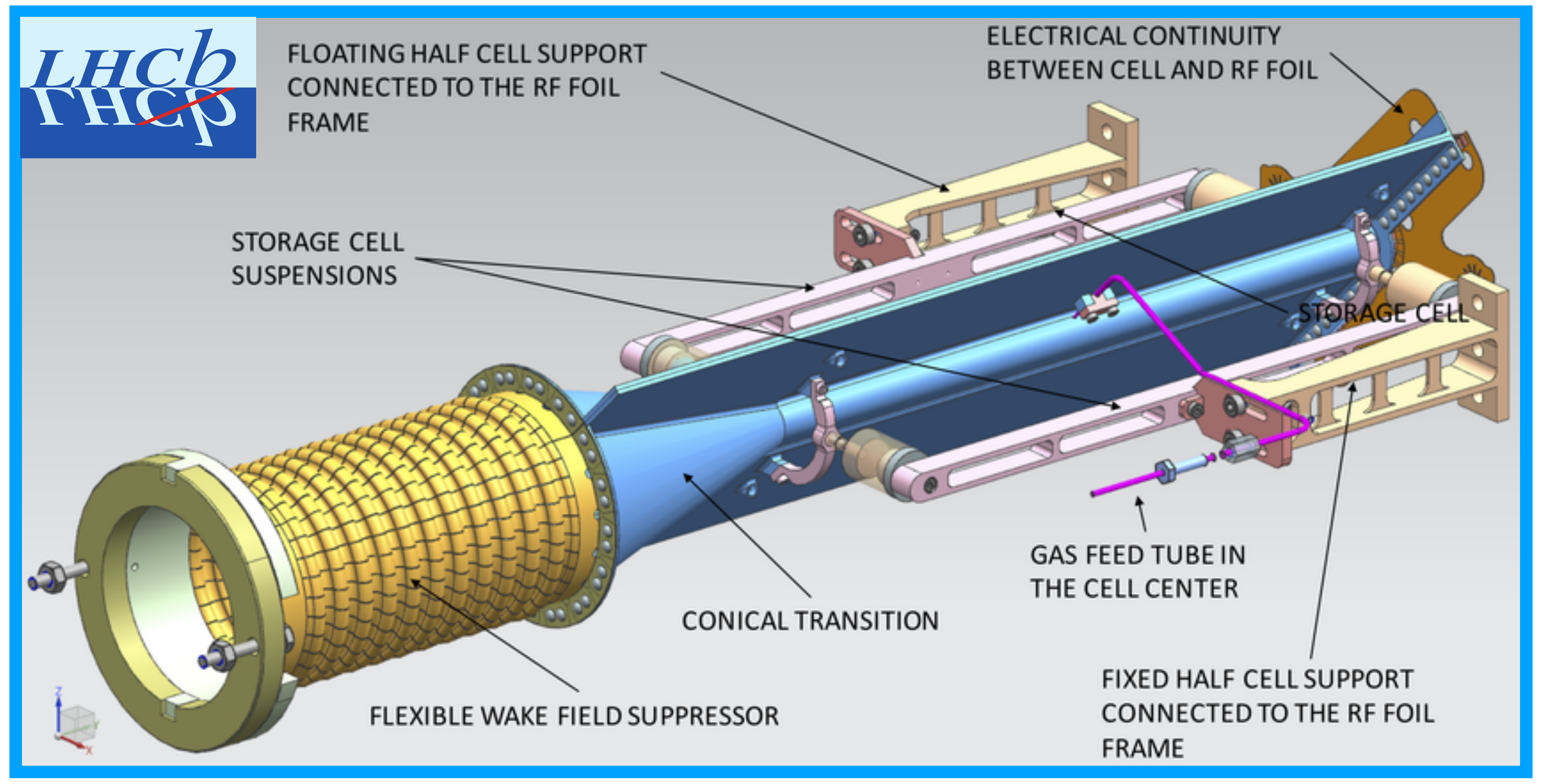

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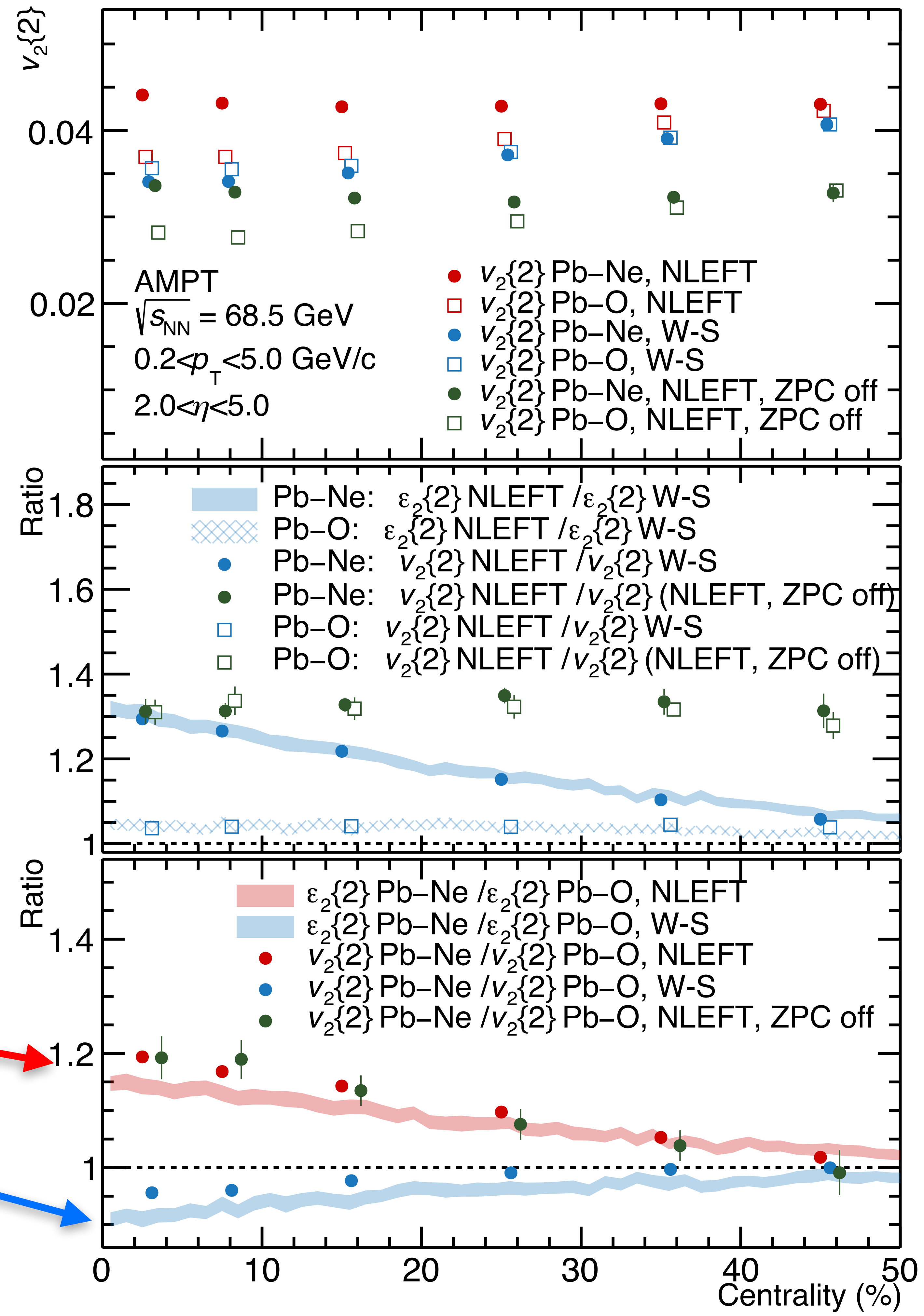
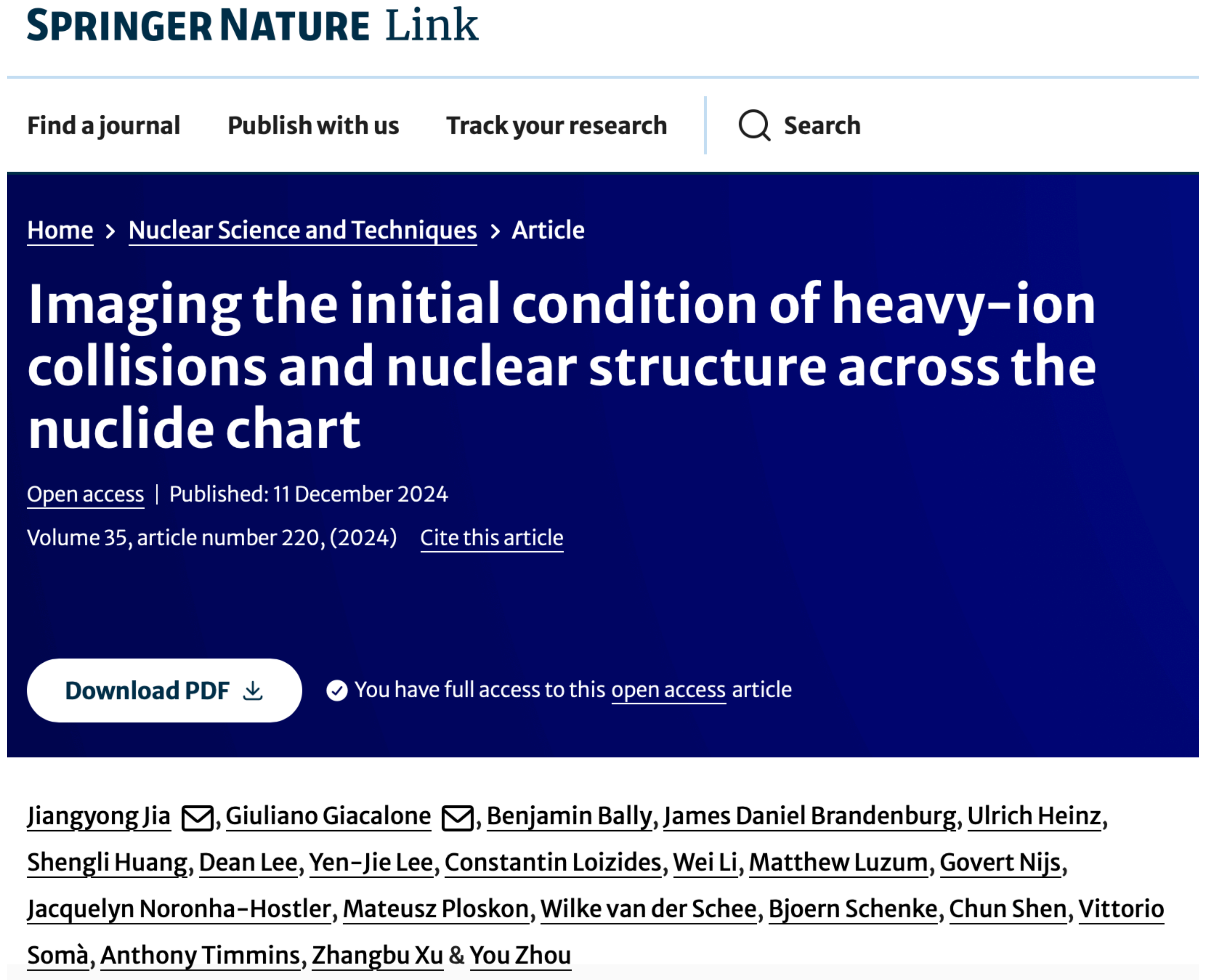


- **$v_2\{2\}$ ratio (Pb-Ne)/(Pb-O)**
  - With NLEFT, up to 20% increase in Pb-Ne
  - With W-S, down to 10% decrease in Pb-Ne
- **Imprint of Light Nuclei Structure**
  - Same picture observed in hydro and AMPT models
  - Robust signature independent on the system's evolution

Long Range Plan in Europe and US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Imaging the initial condition of heavy-ion collisions and nuclear structure across the nuclide chart

Open access | Published: 11 December 2024

Volume 35, article number 220, (2024) Cite this article

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Jiangyong Jia, Giuliano Giacalone, Benjamin Bally, James Daniel Brandenburg, Ulrich Heinz, Shengli Huang, Dean Lee, Yen-Jie Lee, Constantin Loizides, Wei Li, Matthew Luzum, Govert Nijs, Jacquelyn Noronha-Hostler, Mateusz Ploskon, Wilke van der Schee, Bjoern Schenke, Chun Shen, Vittorio Somà, Anthony Timmins, Zhangbu Xu & You Zhou

- ❖ Use the LHC as the Nuclear Structure Machine
  - presented in the ESPP update in Europe
  - discussed in Long-Range Plan in US

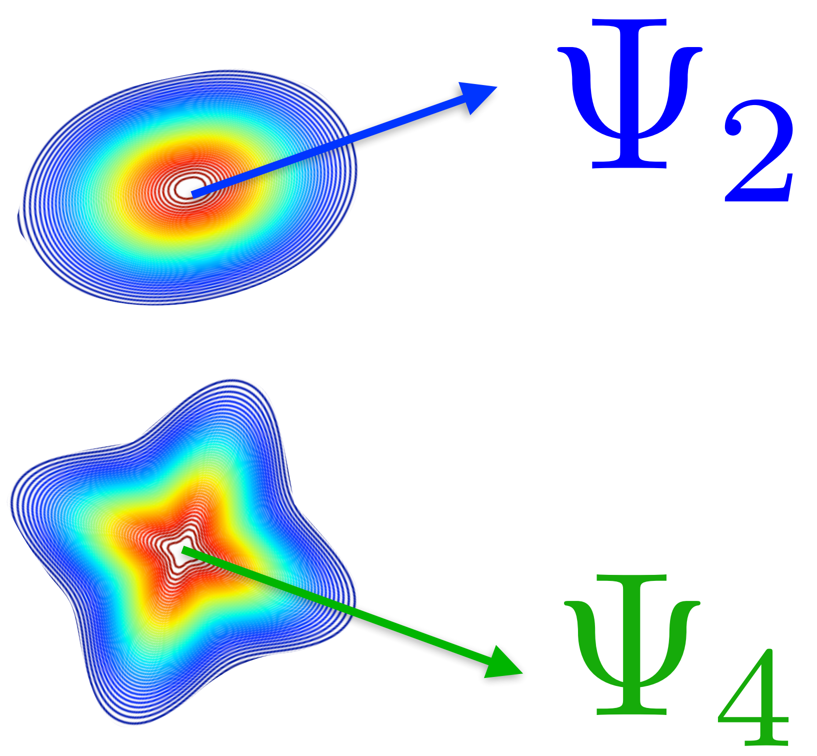
Backup

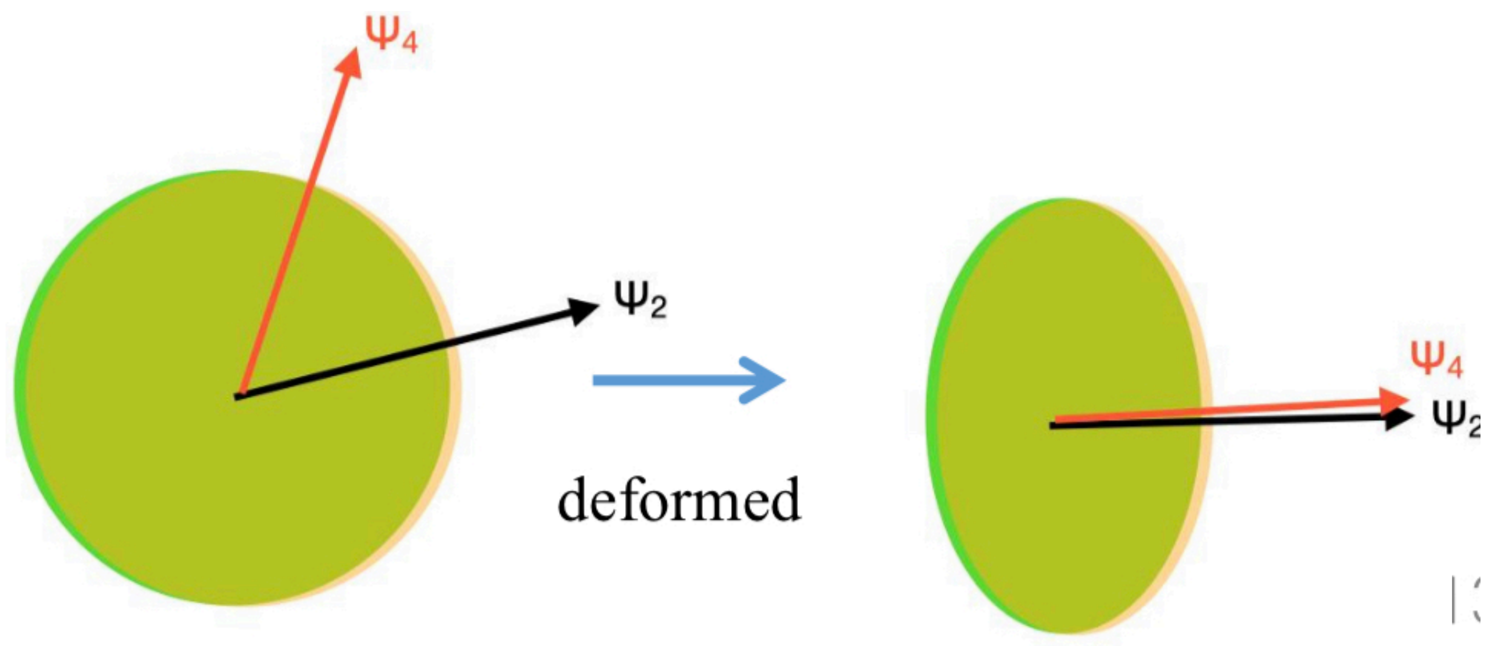
New (or old) research directions

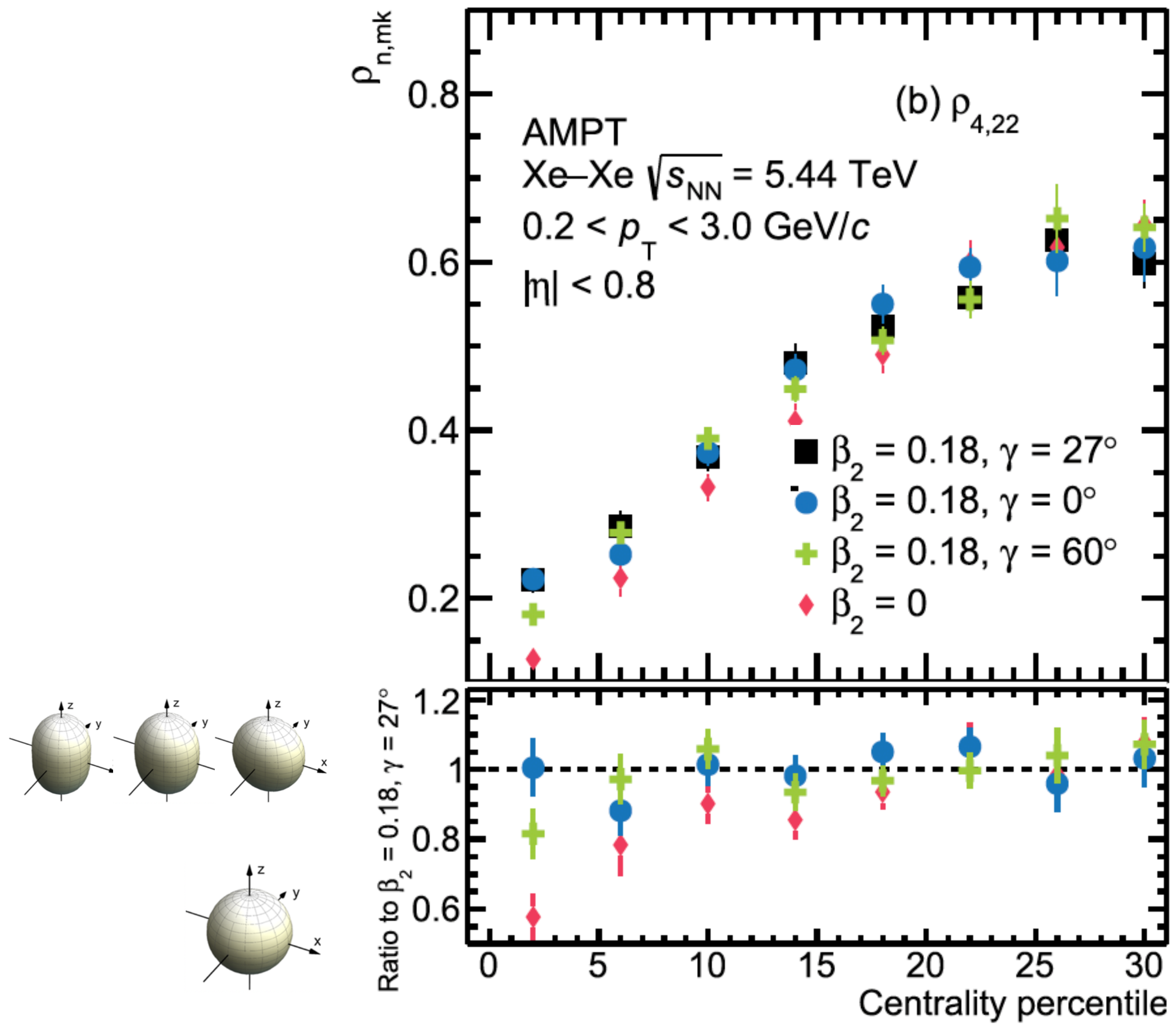
BNL (2022.01)	RIKEN BNL Research Center Physics Opportunities from the RHIC Isobar Run This workshop will be held virtually. January 25–28, 2022	30 participants
GSI (2022.05 & 10)	EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 1/2) 30 May 2022 to 3 June 2022 Heidelberg University	50 participants
Saclay (2022.09)	cea ESNT Deciphering nuclear phenomenology across energy scales 20-23 September 2022	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
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
Fudan (2025.5)	Intersection of nuclear structure and high-energy nuclear collisions: 2025 Program and Workshop	100+ participants
Taipei (2025.9)	The VIII[TH] International Conference on the INITIAL STAGES of High-Energy Nuclear Collisions Taipei	

MC studies: what flow can do and cannot do

$\rho_{4,22}$ probes <cos 4(Ψ_2 - Ψ_4) >



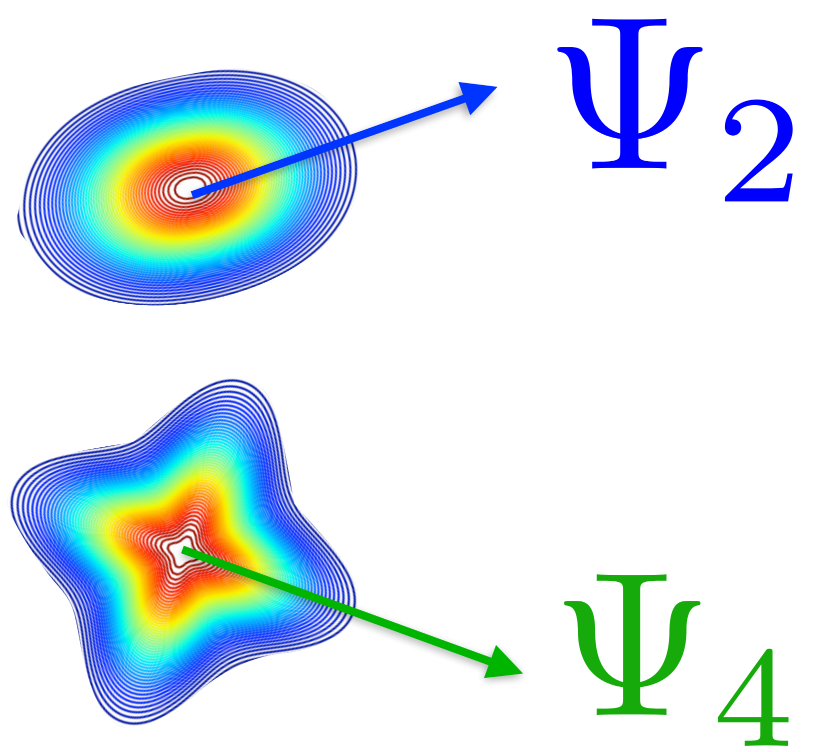


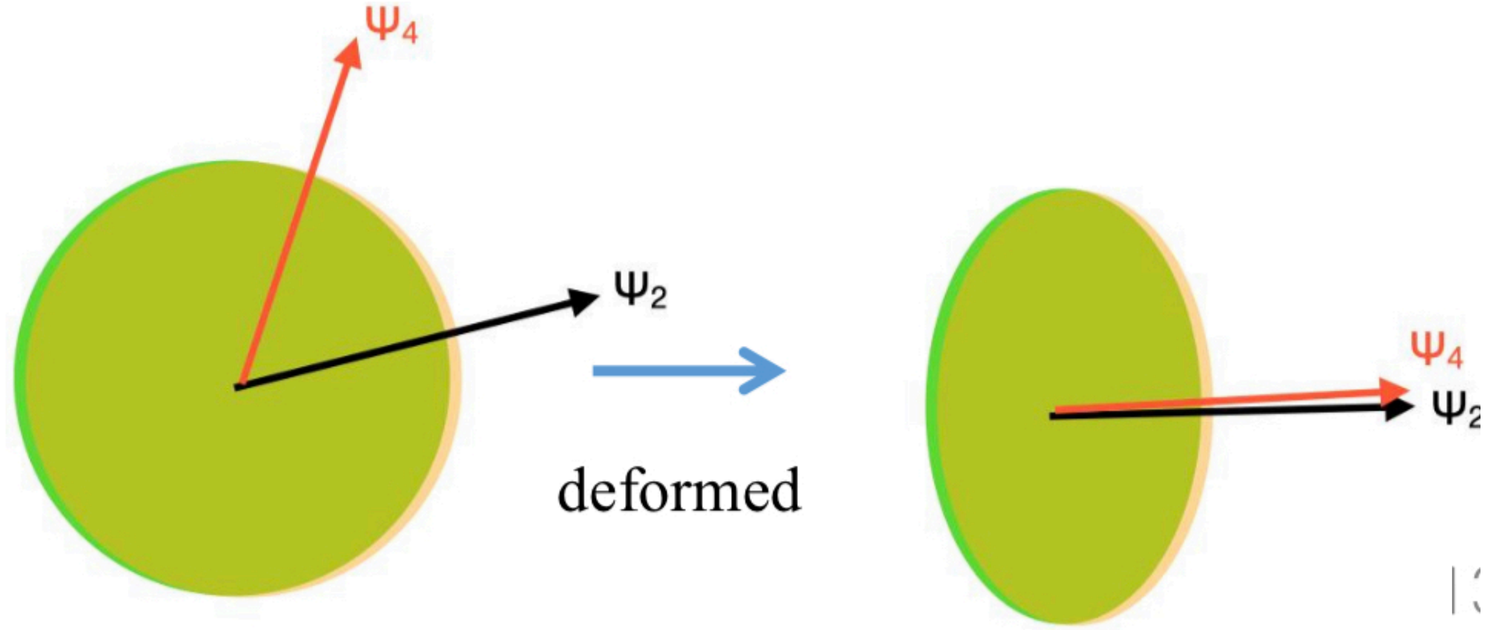


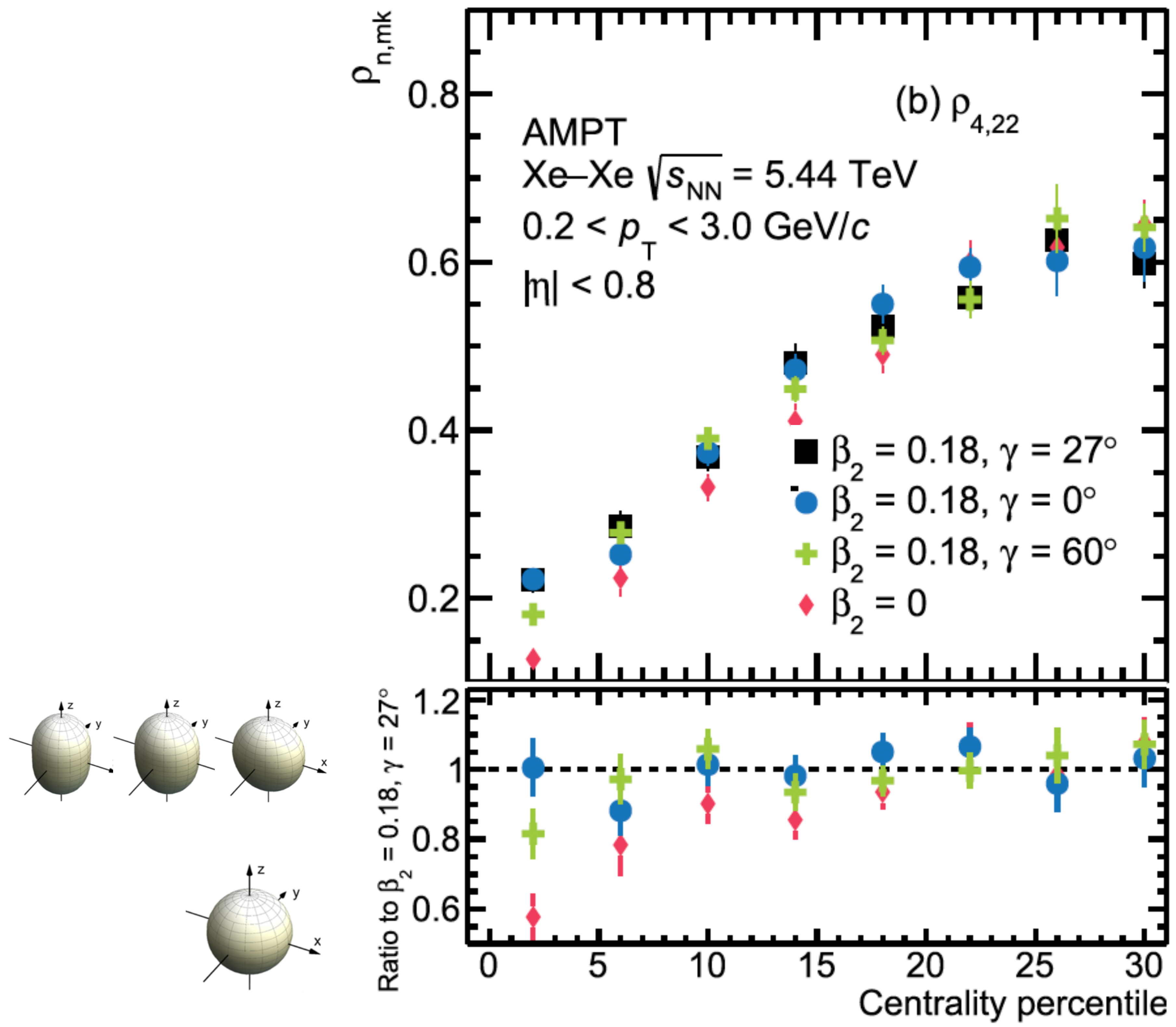
❖ An enhanced v_2 and a stronger symmetry plane correlation are found for the deformed nuclei

MC studies: what flow can do and cannot do

$\rho_{4,22}$ probes $<\cos 4(\Psi_2 - \Psi_4)>$







- ❖ An enhanced v_2 and a stronger symmetry plane correlation are found for the deformed nuclei
- ❖ None of the existing flow observable has any sensitivity to the triaxial shape.