Shaping the nuclear structure at the relativistic energies

Thanks to the organisers for the wonderful event

You Zhou (周铀)

Niels Bohr Institute

UNIVERSITY OF COPENHAGEN

European Research Council
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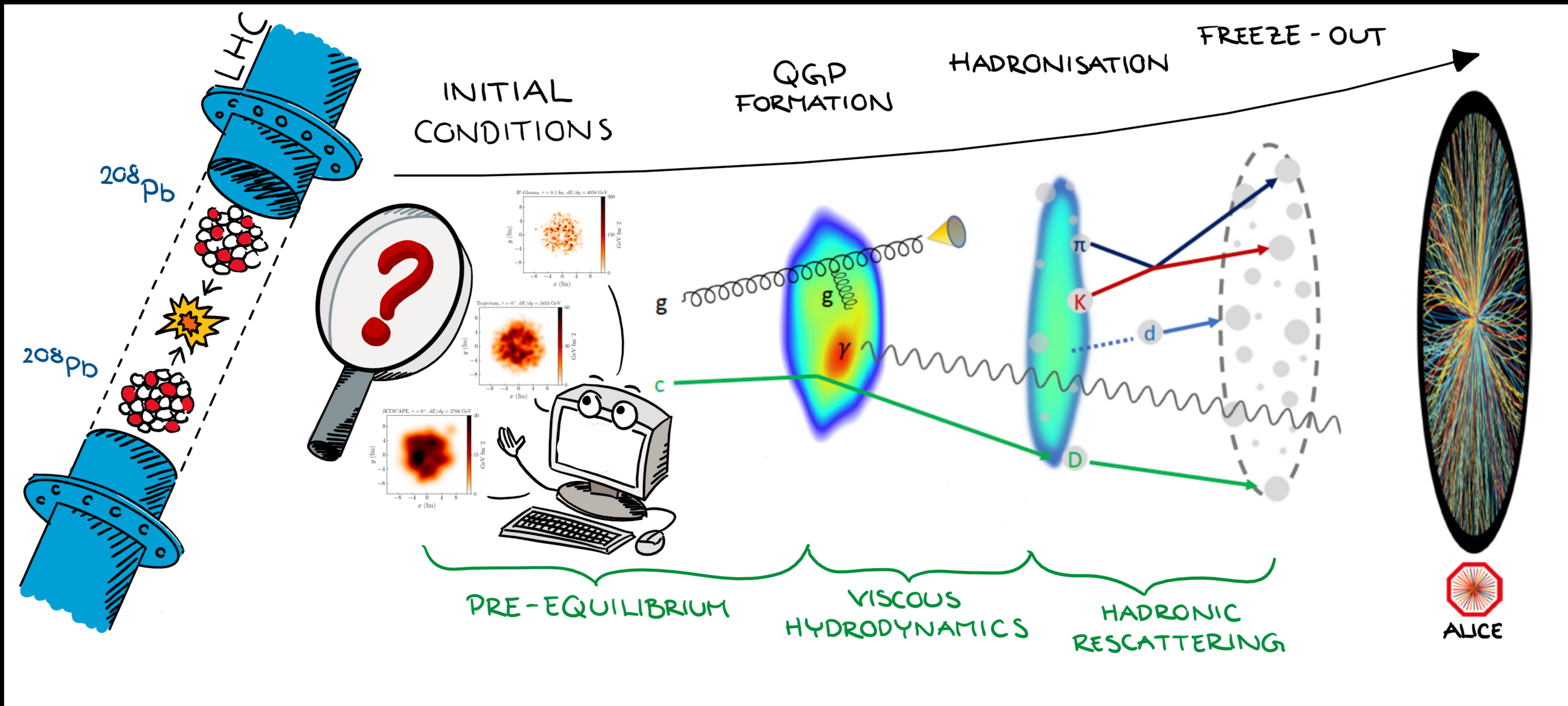
THE VELUX FOUNDATIONS
VILLUM FONDEN VELUX FONDEN

Evolution in the *Little Bang*



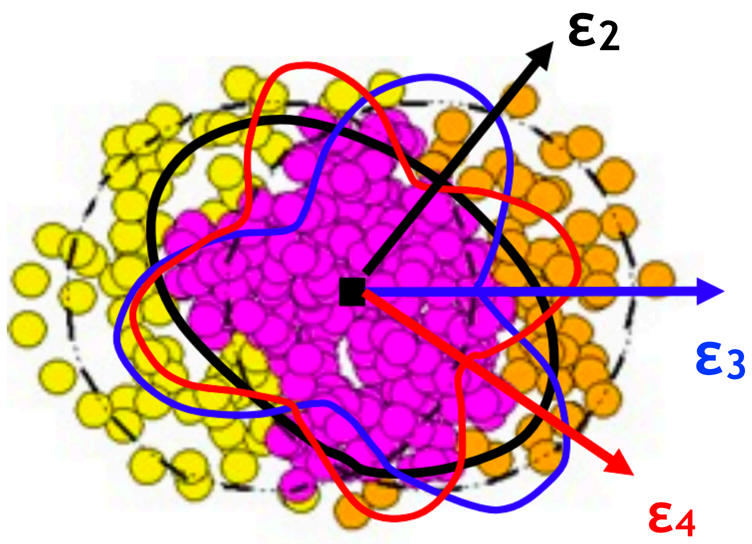
LHC operation programs

- ★ ^{208}Pb-^{208}Pb 2.76 TeV (2010, 2011), 5.02 TeV (2015, 2018), 5.36 TeV (2022,2023)
- ★ ^{129}Xe-^{129}Xe 5.44 TeV (2017)
- ★ ^{16}O-^{16}O 6.8 TeV (2024)

From initial anisotropy to anisotropic flow

Initial state

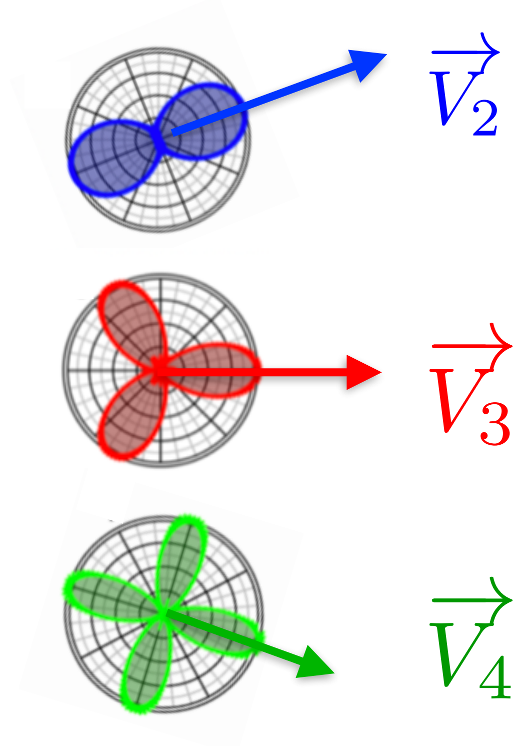
$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$



System expansion

Final state

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

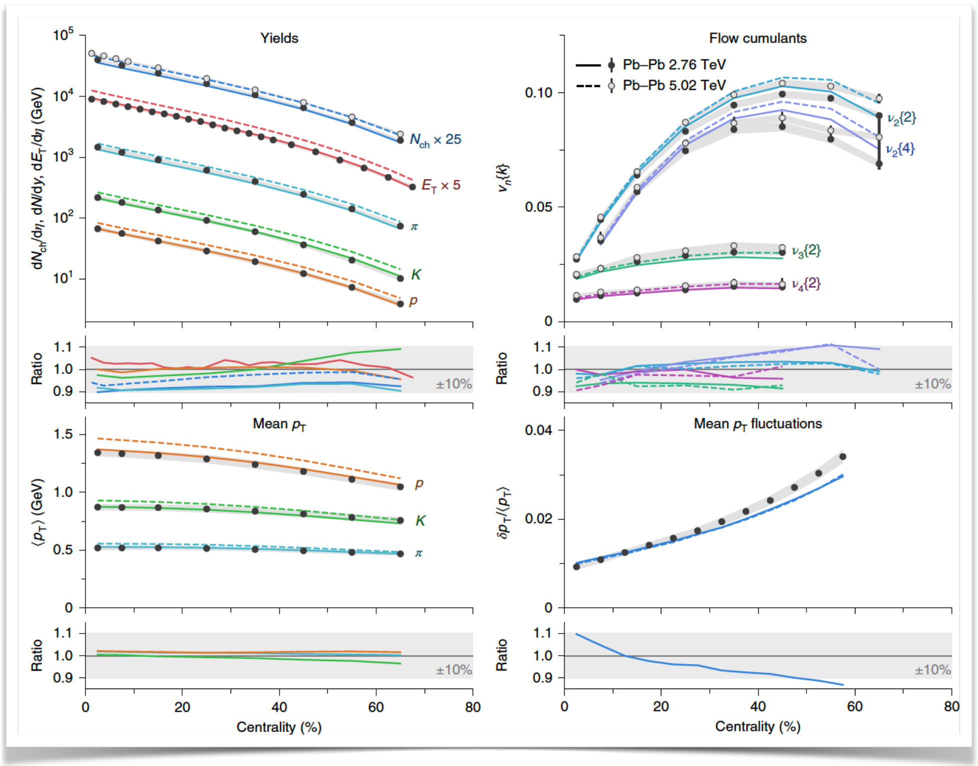


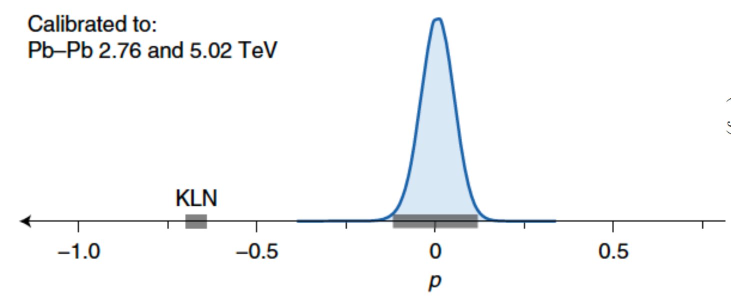
$$P(\varepsilon_m, \varepsilon_n, \varepsilon_k, ..., \Phi_m, \Phi_n, \Phi_k, ...) \Rightarrow P(v_m, v_n, v_k, ..., \Psi_m, \Psi_n, \Psi_k, ...)$$

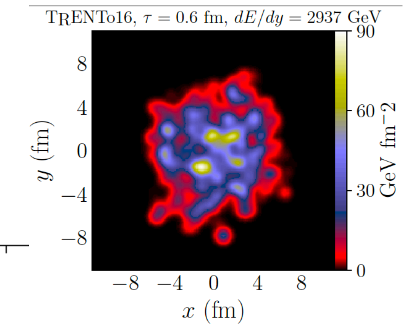
How does v_n fluctuate	How does ψ_n fluctuate	How do v_n and v_m correlate	How do ψ_n and ψ_m correlate
$P(v_n)$	$P(\Psi_n)$	$P(v_m, v_n, v_k, ...)$	$P(\Psi_m, \Psi_n, \Psi_k, ...)$

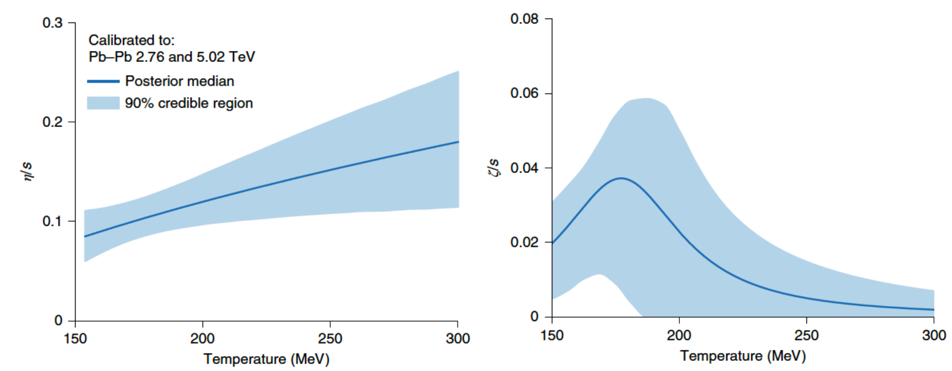
Bayesian analyses with simple v_n and $[p_T]$

J.E. Bernhard etc, Nature Physics,15, 1113 (2019)

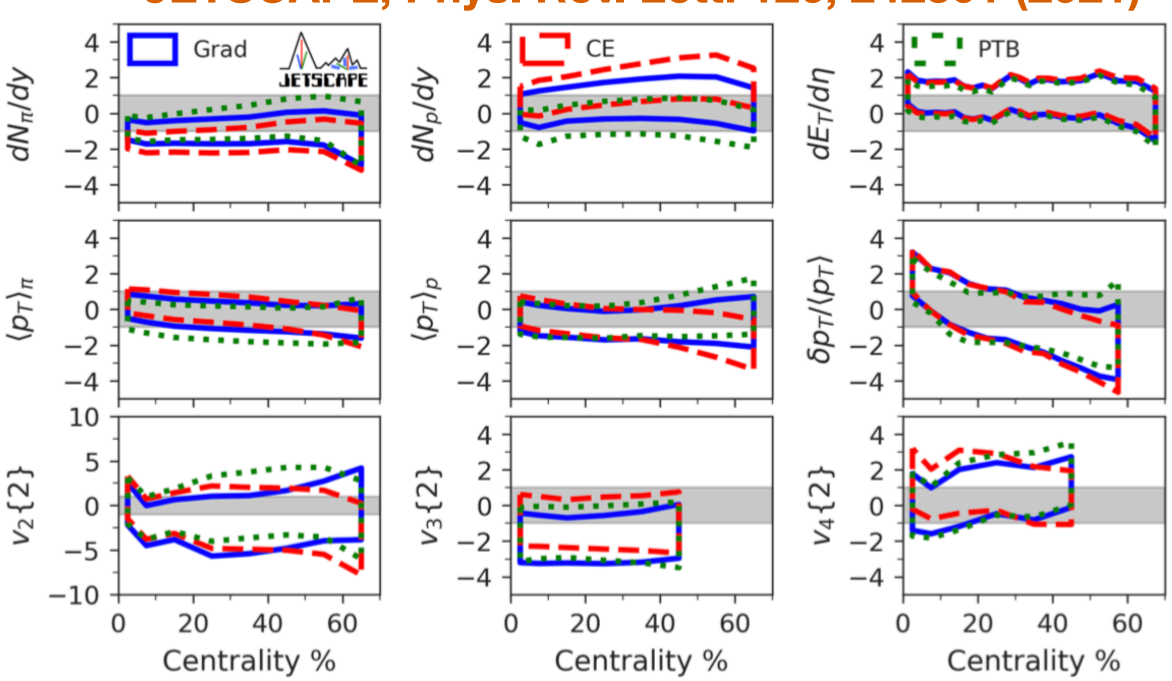


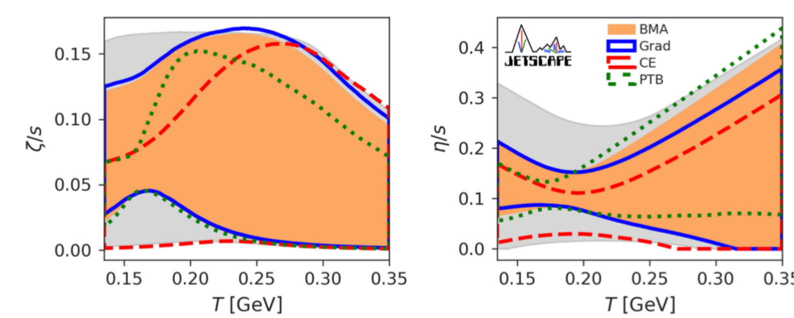


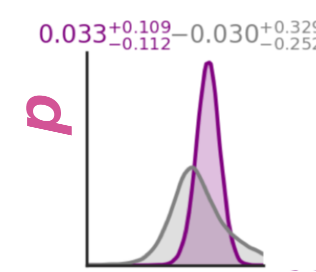


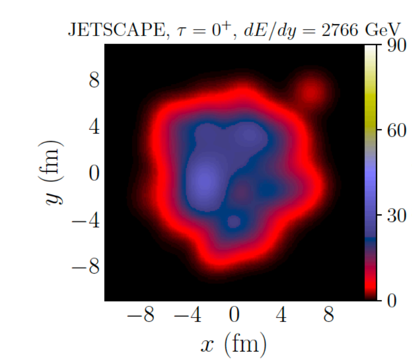


JETSCAPE, Phys. Rev. Lett. 126, 242301 (2021)

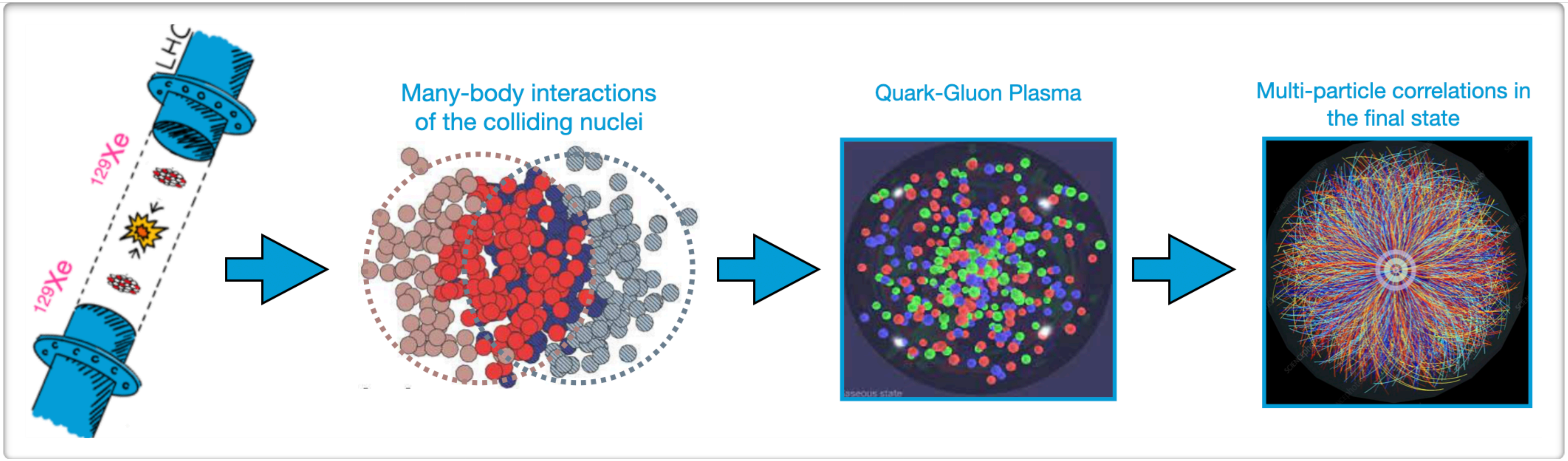






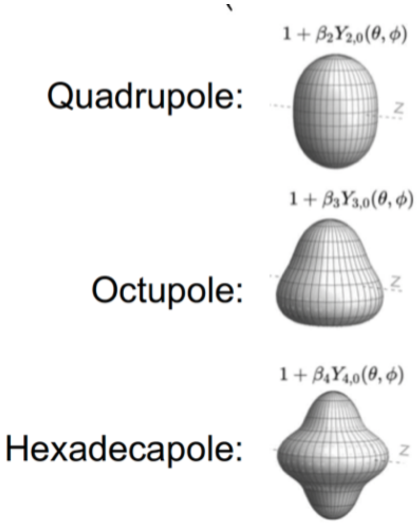


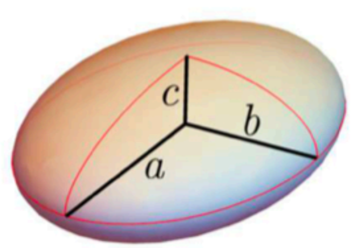
Nuclear structure at high energies



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

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



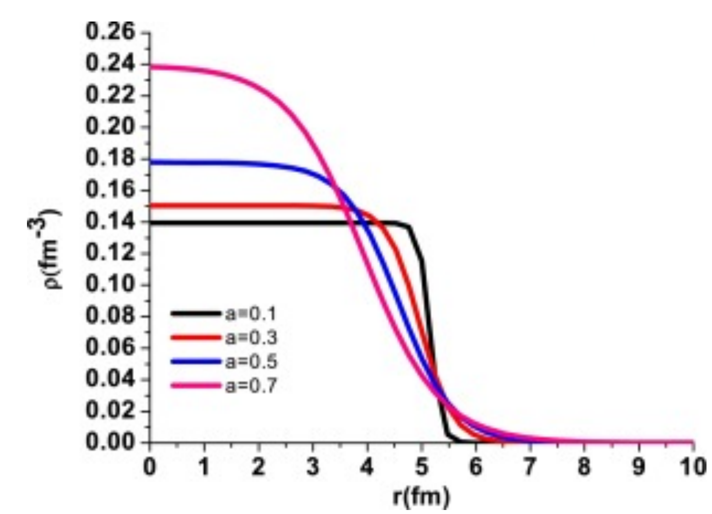


$0 \leq \gamma \leq \pi/3$

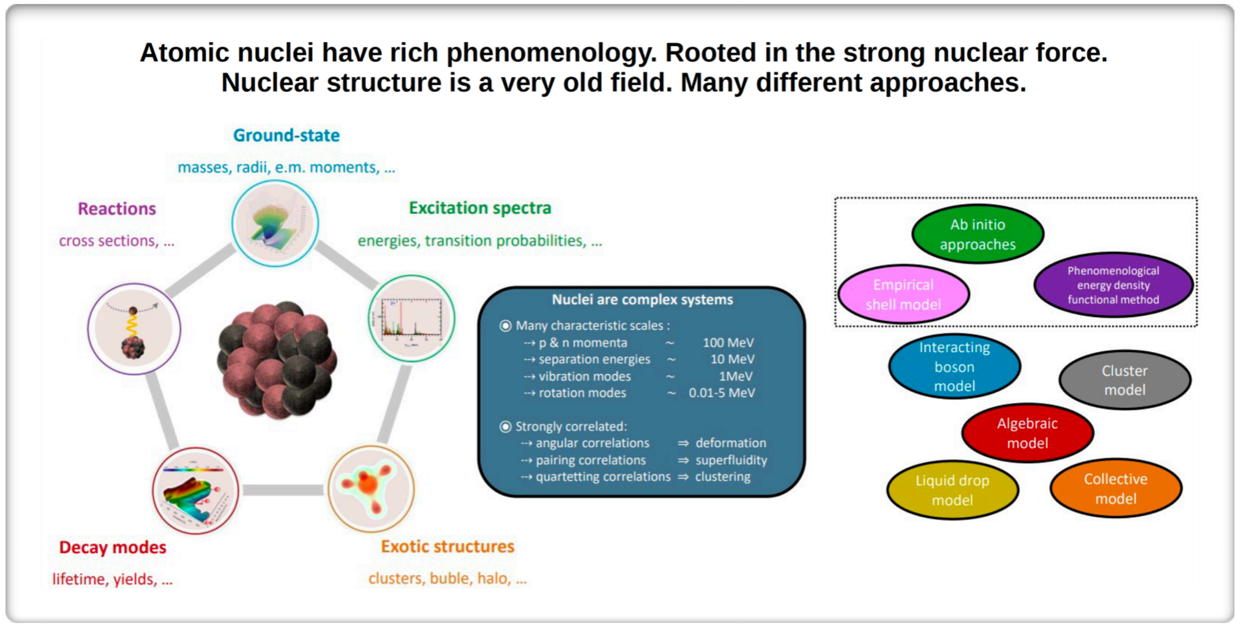
Prolate: a=b<c → β_2, γ=0

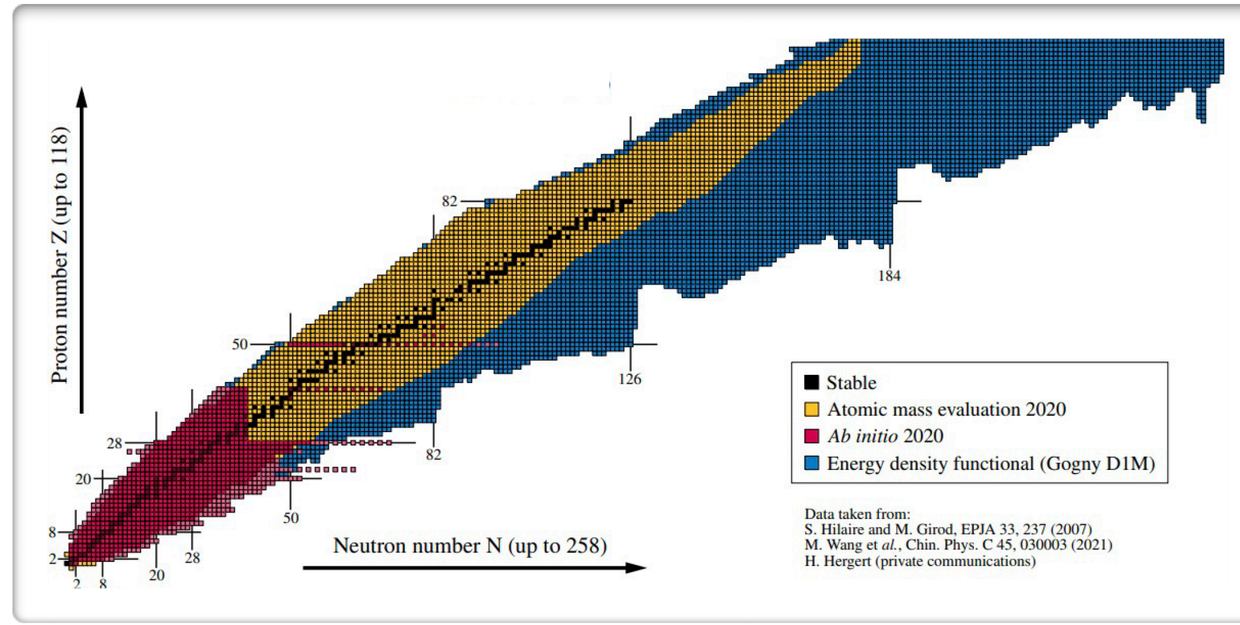
Oblate: a<b=c → β_2, γ=π/3

Triaxial: a<b<c → β_2, γ=π/6

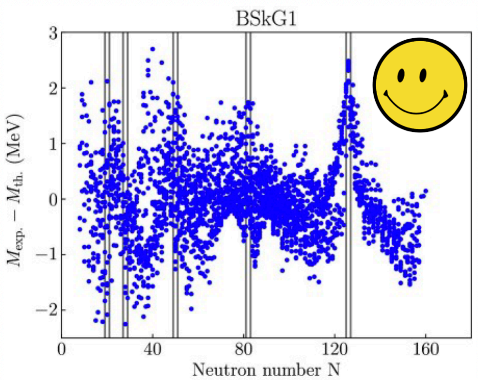


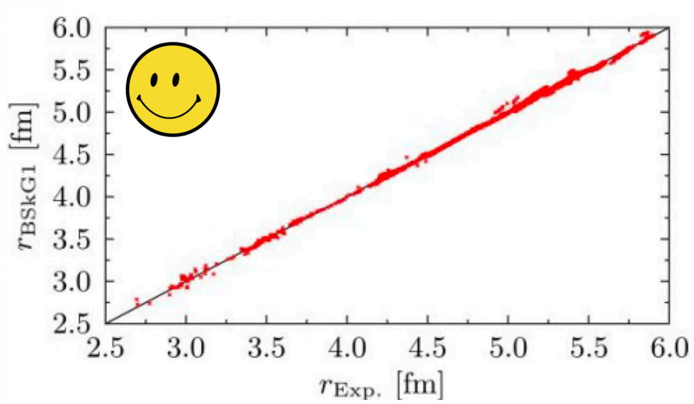
Nuclear structure at low energies



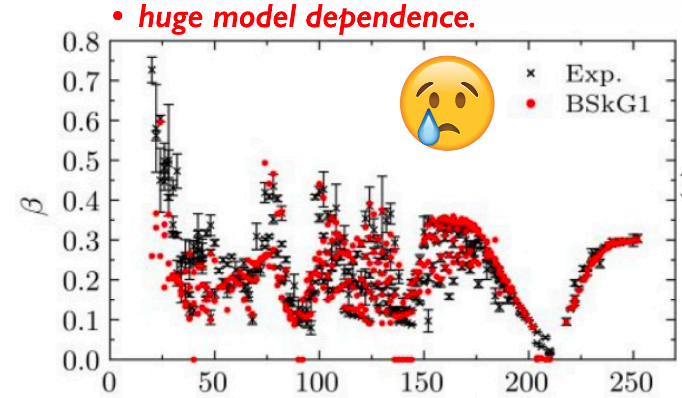


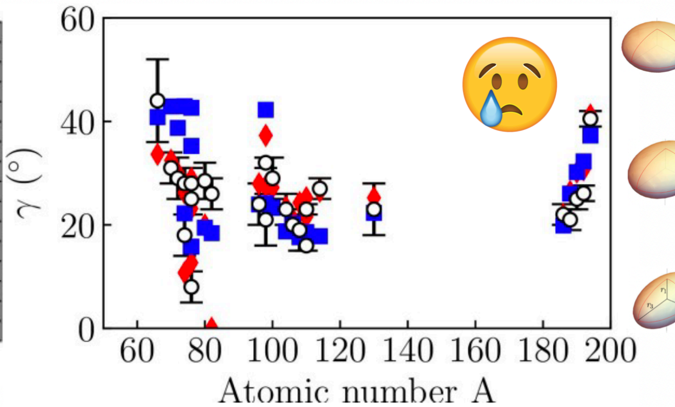
Energy density function method : accurate description of masses and radii





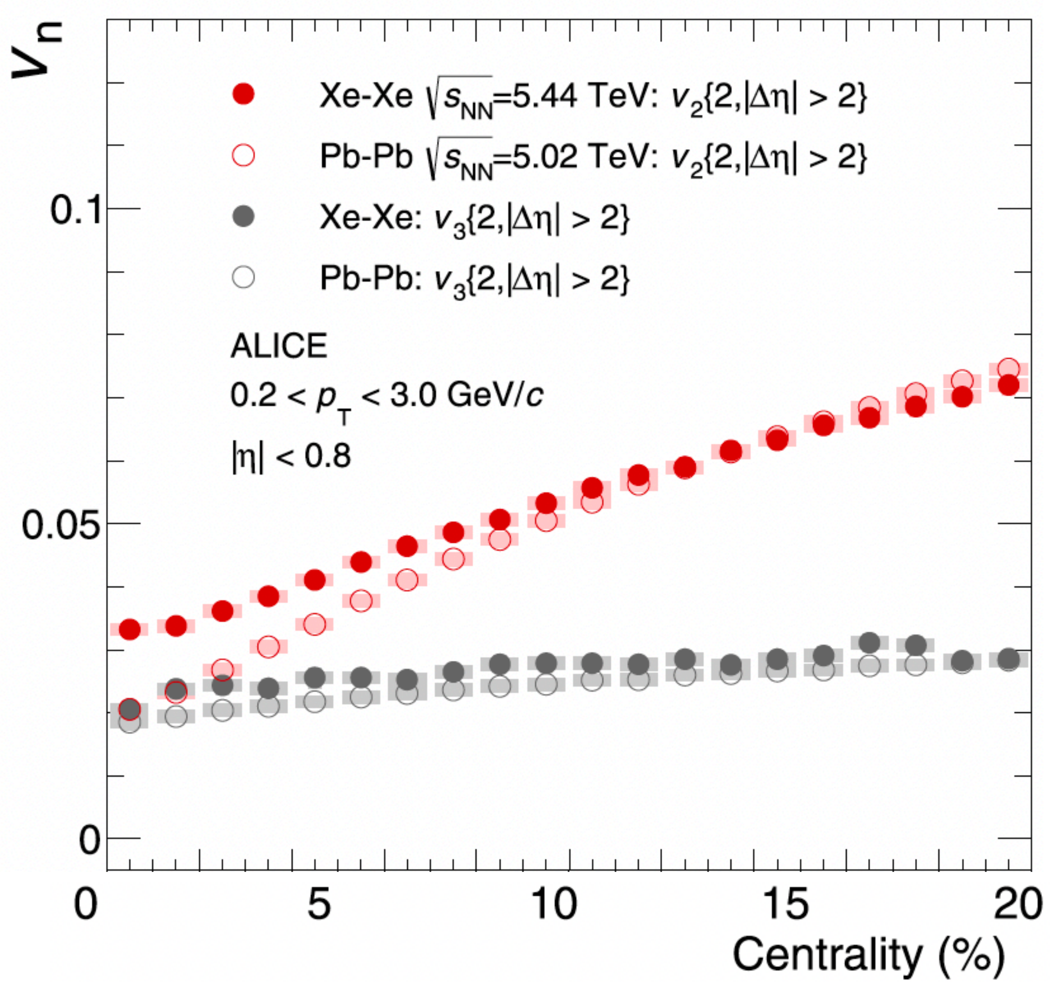
- *there are no real probes of multi-nucleon correlations*
- *huge model dependence.*

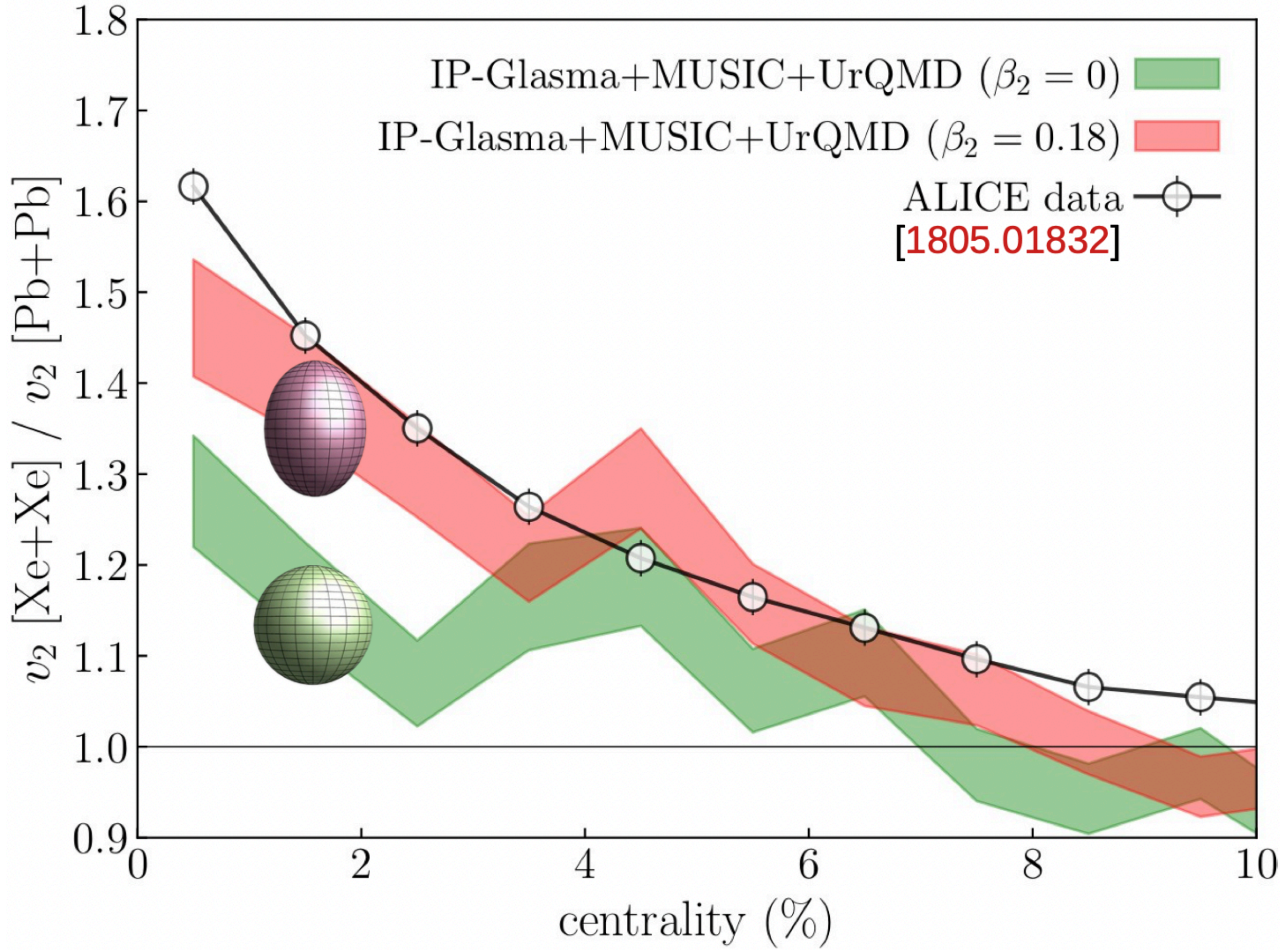




Probe nuclear structure of ^{129}Xe with v_n

ALICE, Physics Letters B 784 (2018) 82





- Significant v_2 enhancements in central Xe-Xe collisions, originated from large deformation
- Help to constrain β_2

Probe Nuclear structure with NSC

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

Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations

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[2]*Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[3]*Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands*

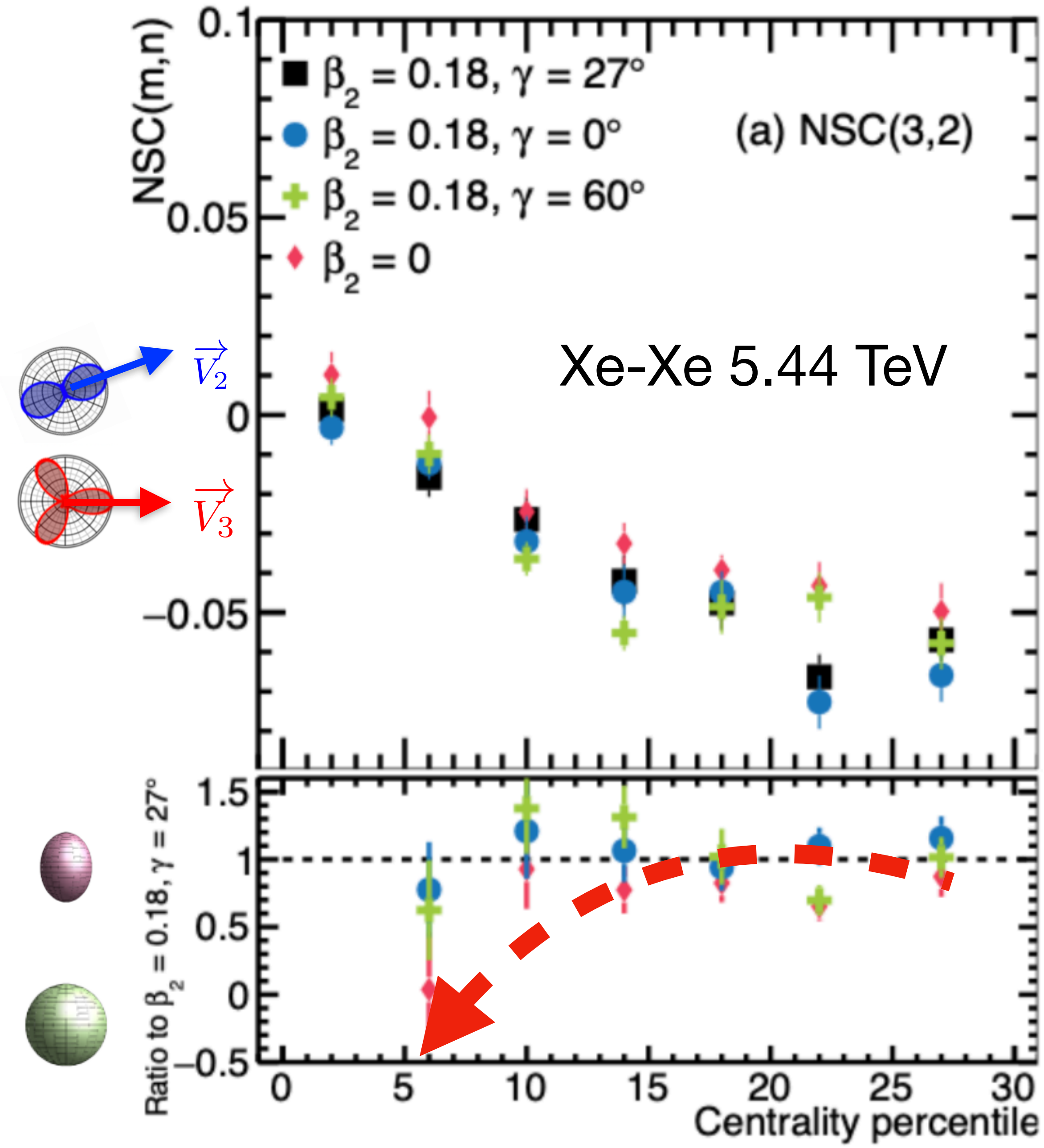
Normalised Symmetric cumulants:

$$v_2 \propto \varepsilon_2$$
$$v_3 \propto \varepsilon_3$$

$$\frac{\langle v_2^2\, v_3^2\rangle - \langle v_2^2\rangle \langle v_3^2\rangle}{\langle v_2^2\rangle \langle v_3^2\rangle} = \frac{\langle \varepsilon_2^2\, \varepsilon_3^2\rangle - \langle \varepsilon_2^2\rangle \langle \varepsilon_3^2\rangle}{\langle \varepsilon_2^2\rangle \langle \varepsilon_3^2\rangle}$$

Or: $NSC^{v}(3,2) = NSC^{\varepsilon}(3,2)$

Z. Lu, M.Zhao, J. Jia, YZ, Eur. Phys. J. A (2023) 59, 279

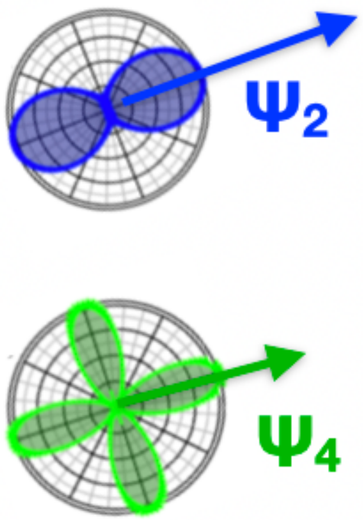


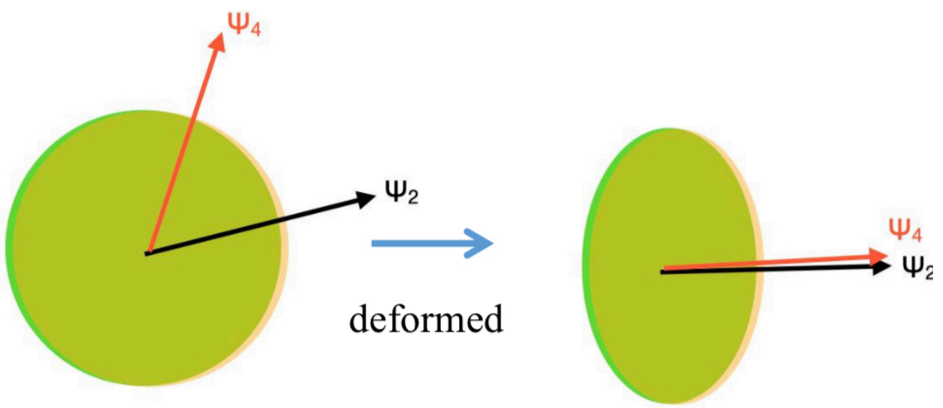
❖ Different results due to nuclear deformation observed in NSC(3,2)

❖ New measurements should allow the constrain the β_2 but not γ

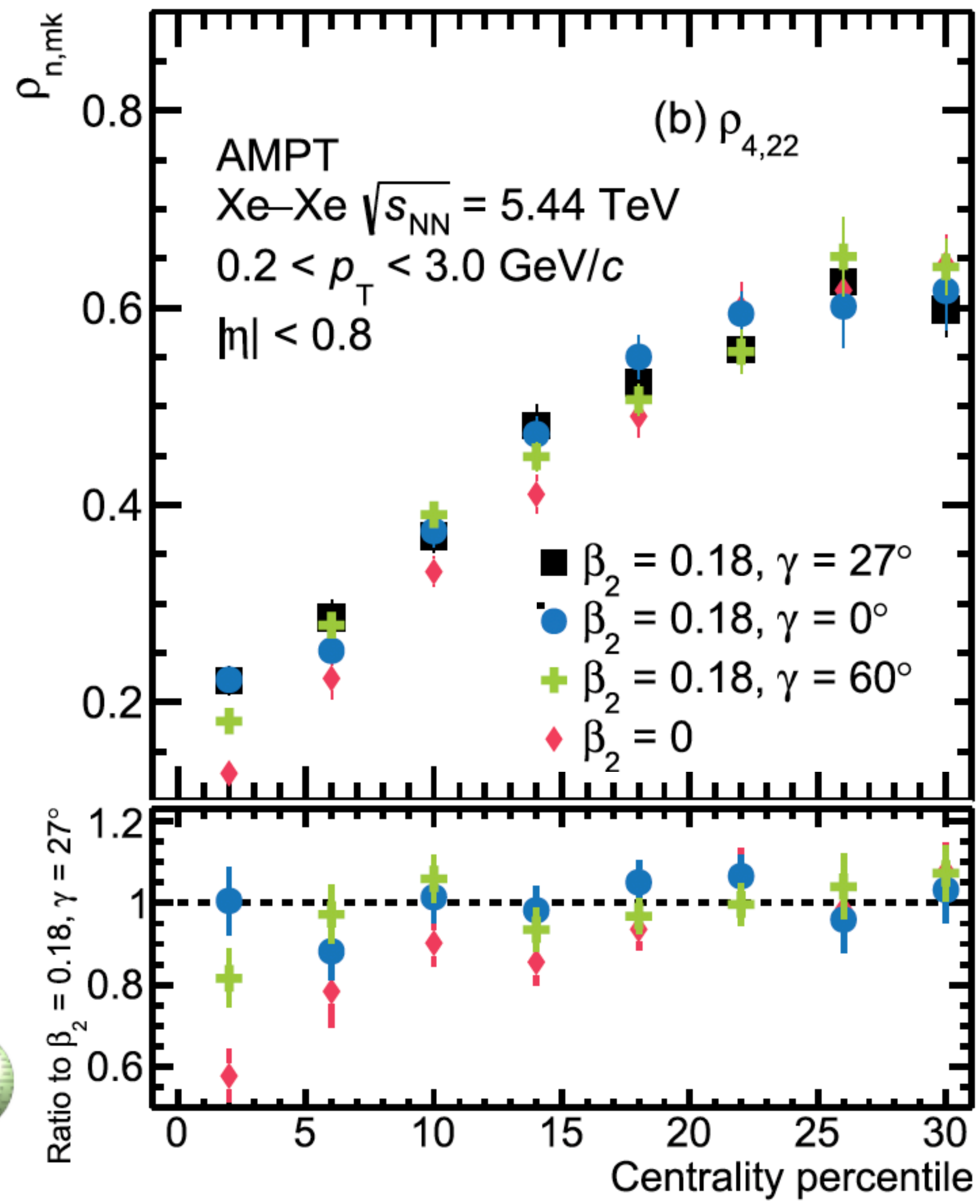
Enhanced ψ_n correlations in models

- $\rho_{4,22}$ probes correlations between Ψ_2 and Ψ_4 ~ $\langle \cos 4(\Psi_2 - \Psi_4) \rangle$





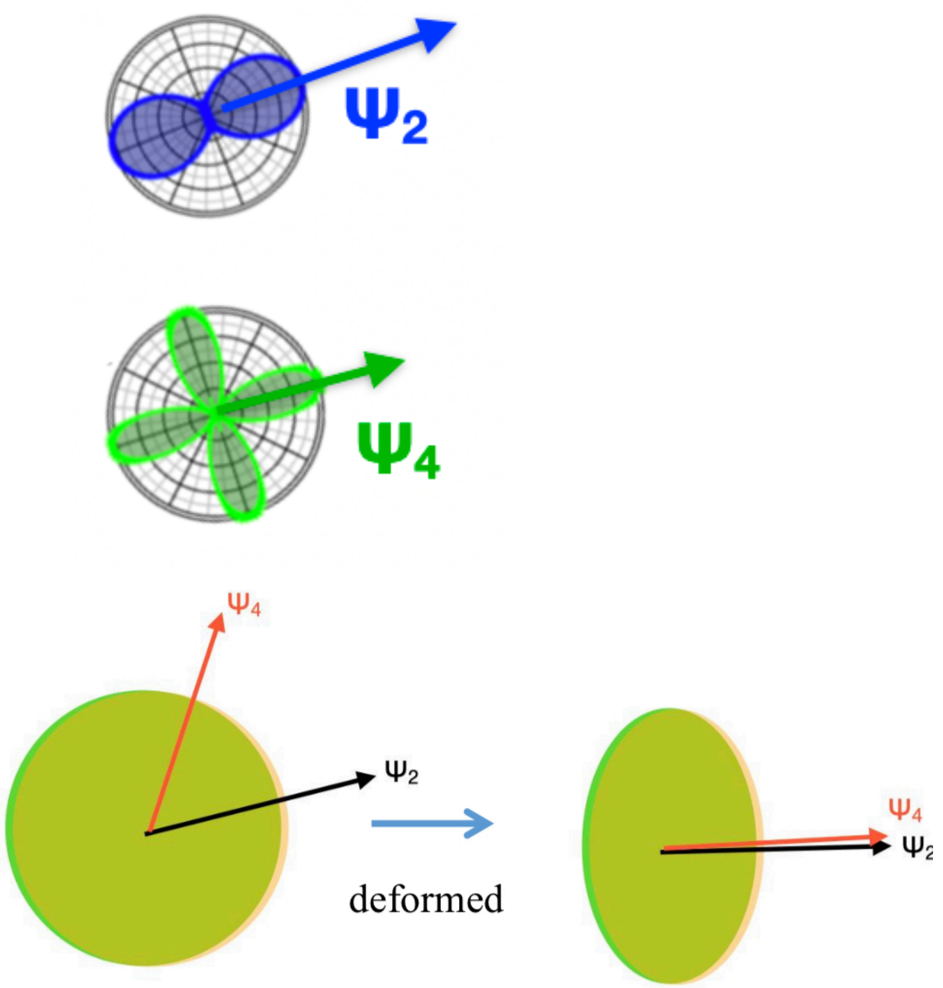
Z. Lu, M.Zhao, J. Jia, YZ, Eur. Phys. J. A (2023) 59, 279

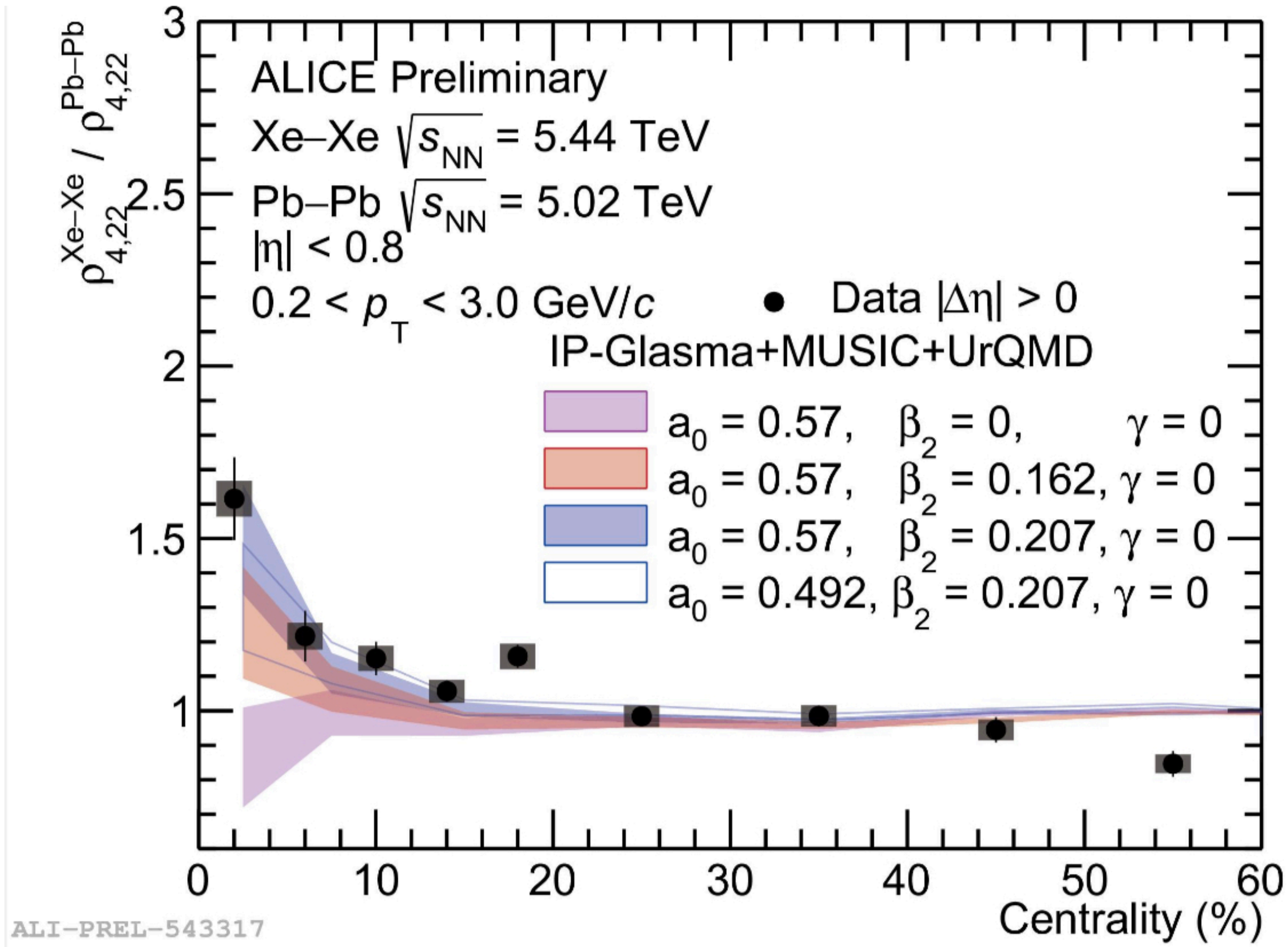


- A Stronger correlation is predicted for the deformed nuclei using hydrodynamic framework

Enhanced ψ_n correlations observed in EXP

❖ $\rho_{4,22}$ probes correlations between Ψ_2 and Ψ_4
~ $\langle \cos 4(\Psi_2 - \Psi_4) \rangle$

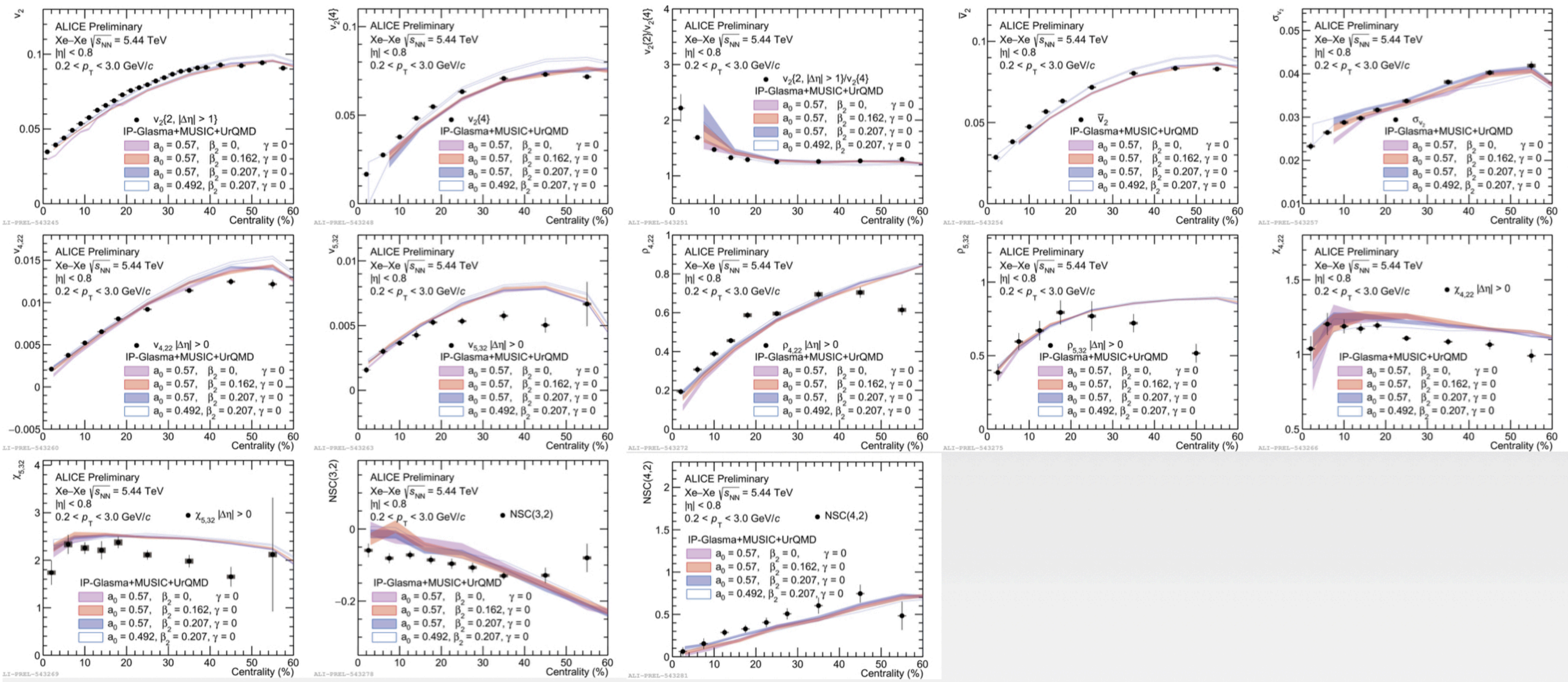




❖ A Stronger correlation has been observed in Xe-Xe collisions
- confirm the deformed ^{129}Xe

Nuclear structure with Standard flow studies

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
$P(v_n)$	$P(\Psi_n)$	$P(v_m, v_n, v_k, \ldots)$	$P(\Psi_m, \Psi_n, \Psi_k, \ldots)$

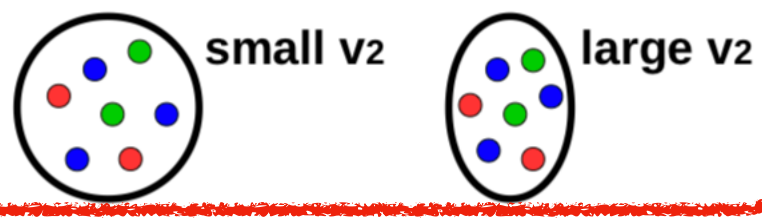


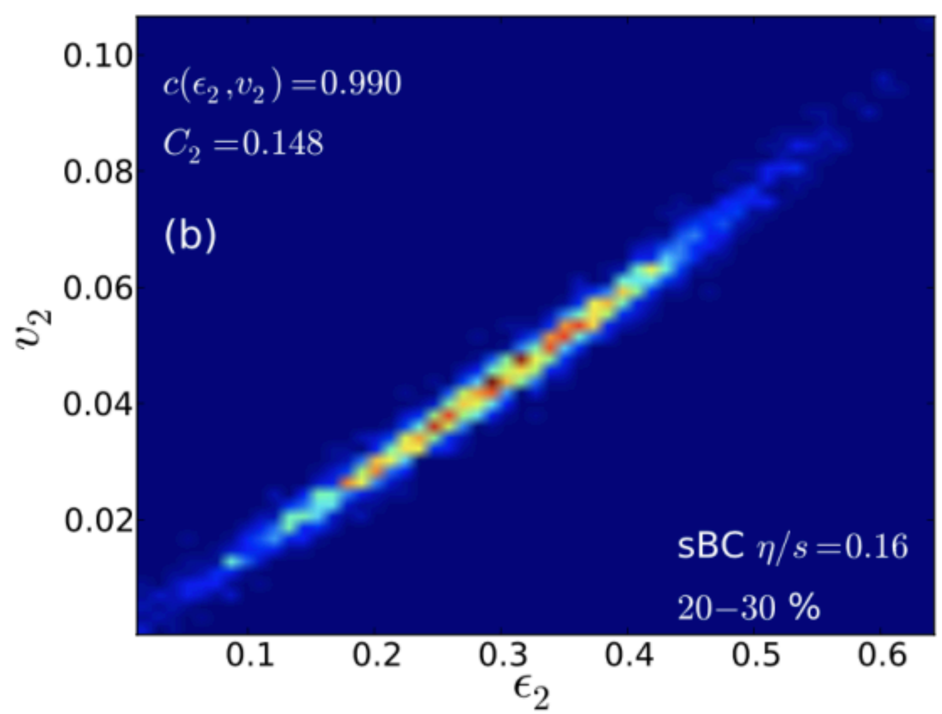
- ***Several*** observable are sensitive to the nuclear ***deformation*** β_2 in central Xe-Xe collisions
- ***None*** of the existing anisotropic flow observables have sensitivity to the ***triaxial*** structure

Initial conditions through $[p_T]$

❖Shape of the fireball: Anisotropic flow

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



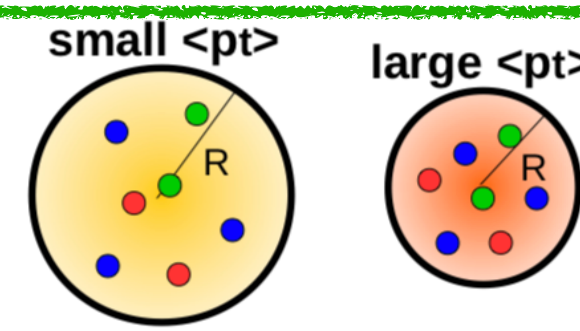


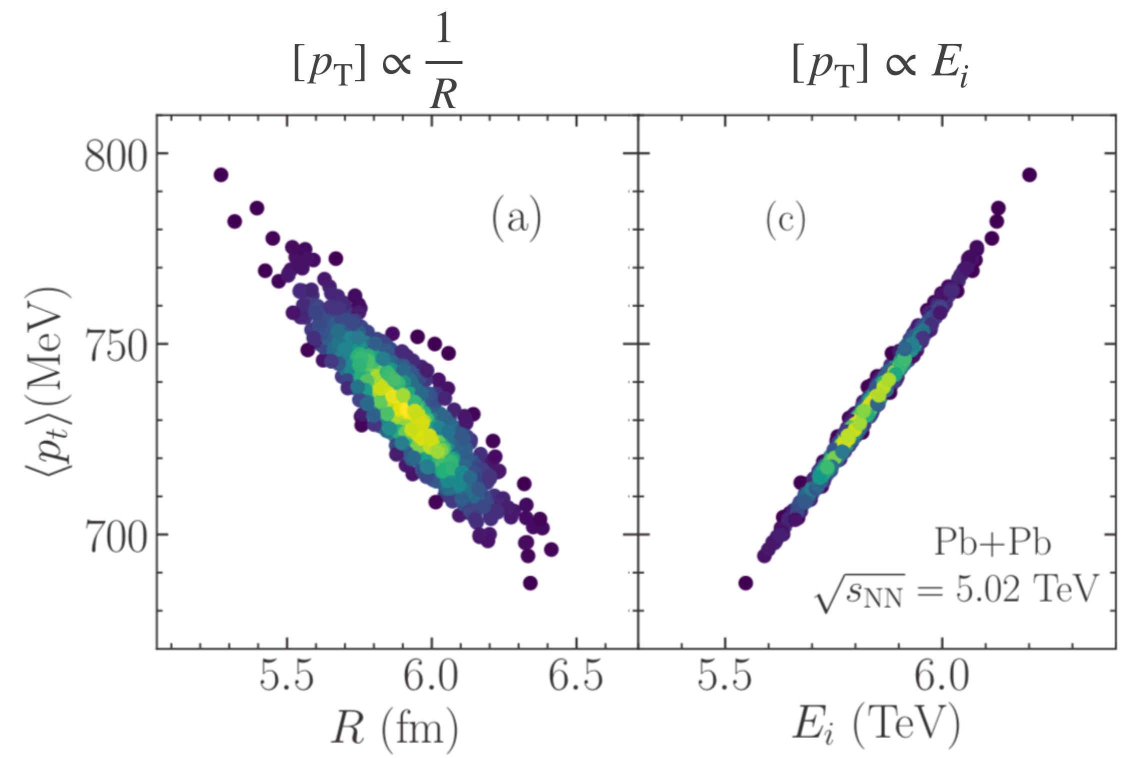
[H. Niemi et al., PRC 87 (2013) 5, 054901]

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

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

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

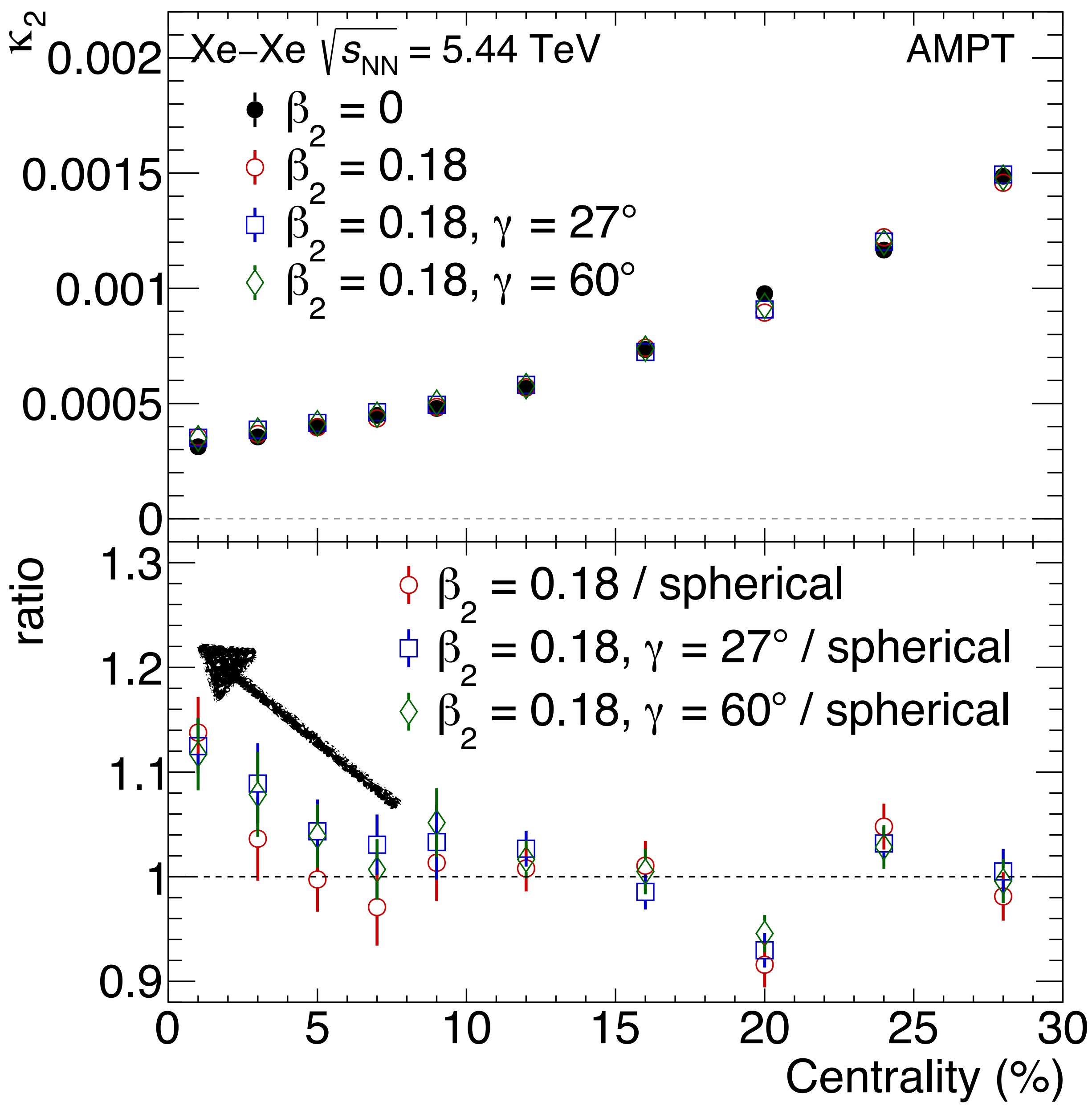


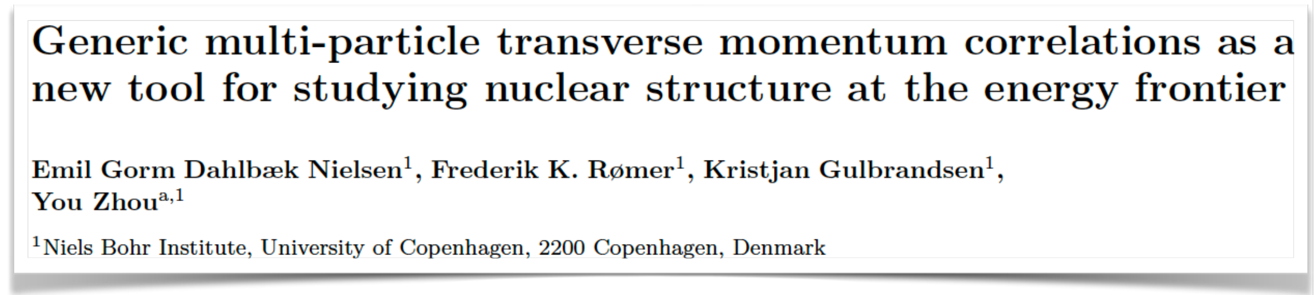


[G. Giacalone et al., PRC103 (2021) 2, 024909]

Two-particle p_T correlations

E. G. Nielsen etc, arXiv: 2312.00492





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

Emil Gorm Dahlbæk Nielsen[1], Frederik K. Rømer[1], Kristjan Gulbrandsen[1], You Zhou[a,1]

[1]Niels Bohr Institute, University of Copenhagen, 2200 Copenhagen, Denmark

$$\kappa(p_T'^2) = \langle\langle p_T'^2 \rangle\rangle - \langle\langle p_T'^1 \rangle\rangle^2$$

Final state cumulant	Liquid-drop model
κ_2	$\frac{1}{32\pi}\langle\beta_2^2\rangle$

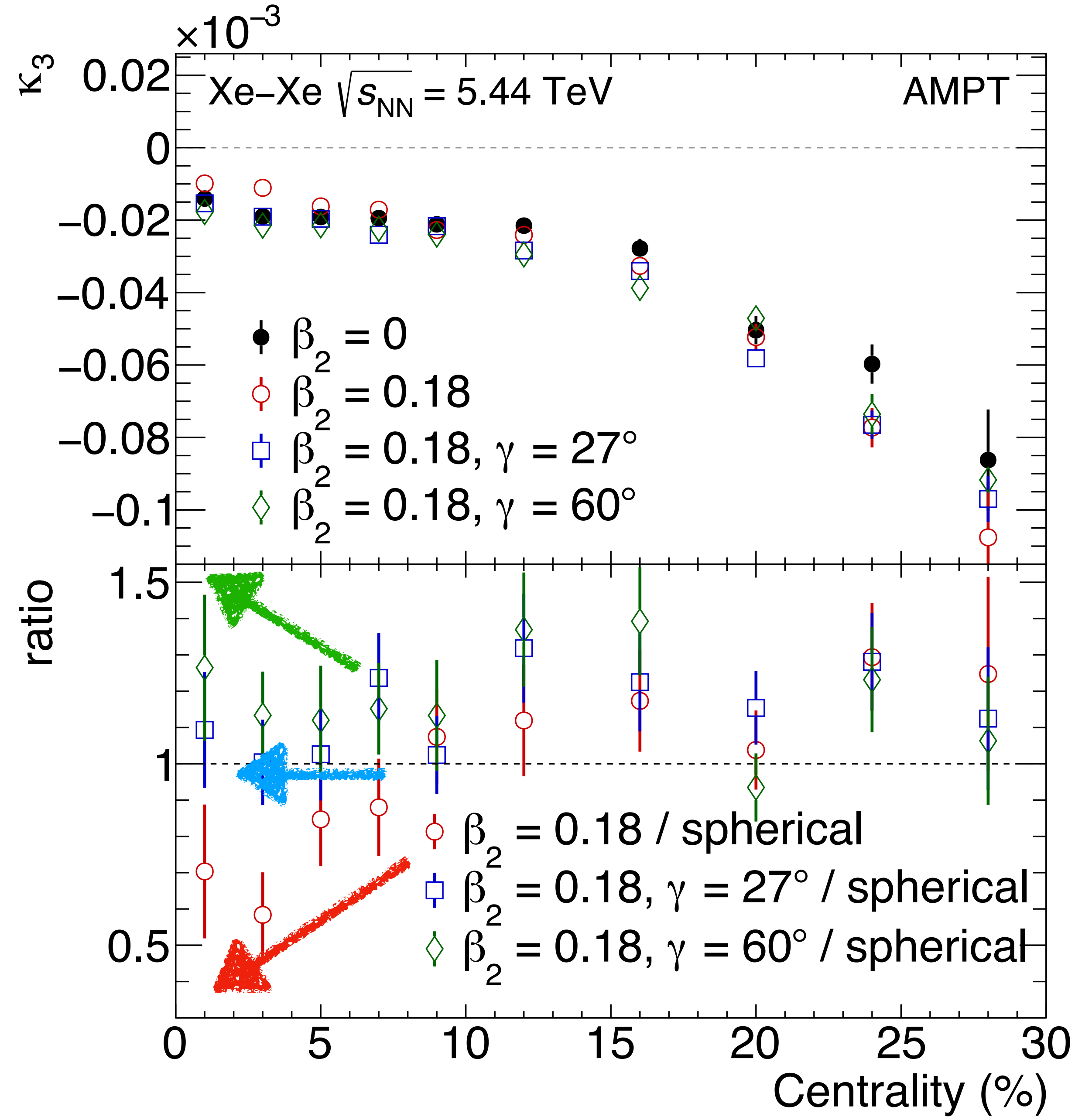
- ❖[P_T] and its fluctuations can be studied via multi-particle p_T fluctuations.
- ❖These multi-particle p_T correlations provide a new way to probe ***deformation*** of ^{129}Xe.

Multi-partile p_T correlations

E. G. Nielsen etc, arXiv: 2312.00492

$$\kappa(p_T'^3) = \langle\langle p_T'^3 \rangle\rangle - 3\langle\langle p_T'^1 \rangle\rangle\langle\langle p_T'^2 \rangle\rangle + 2\langle\langle p_T'^1 \rangle\rangle^3$$

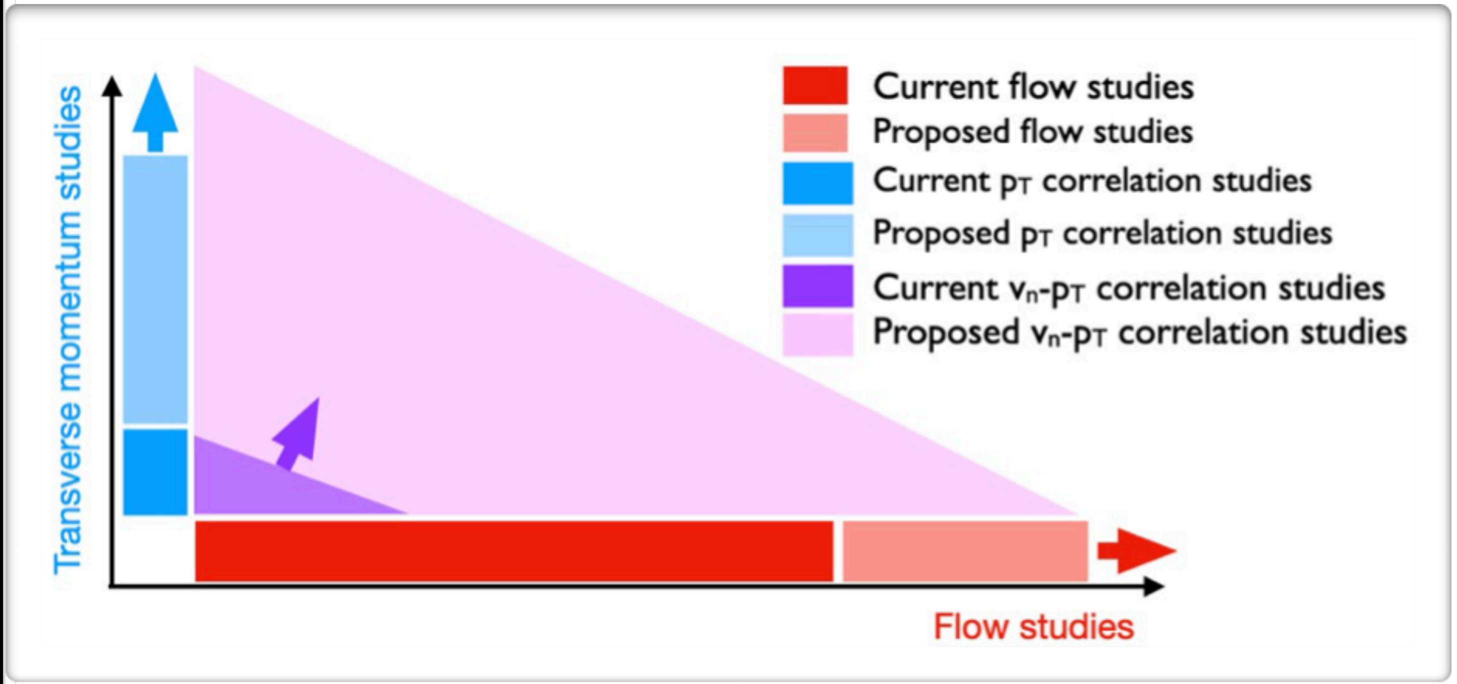
Final state cumulant	Liquid-drop model
κ_2	$\frac{1}{32\pi}\langle\beta_2^2\rangle$
κ_3	$\frac{\sqrt{5}}{896\pi^{3/2}}\langle\cos(3\gamma)\beta_2^3\rangle$



❖The first time to observe sensitive to triaxial structure with κ_3

❖These multi-particle p_T correlations provide a new way to probe ***deformation*** and ***triaxial*** structures of ^{129}Xe.

v_n-$[p_T]$ correlations



❖ **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

❖ Assuming $v_n \propto \varepsilon_n$, $[p_T] \propto E_0$

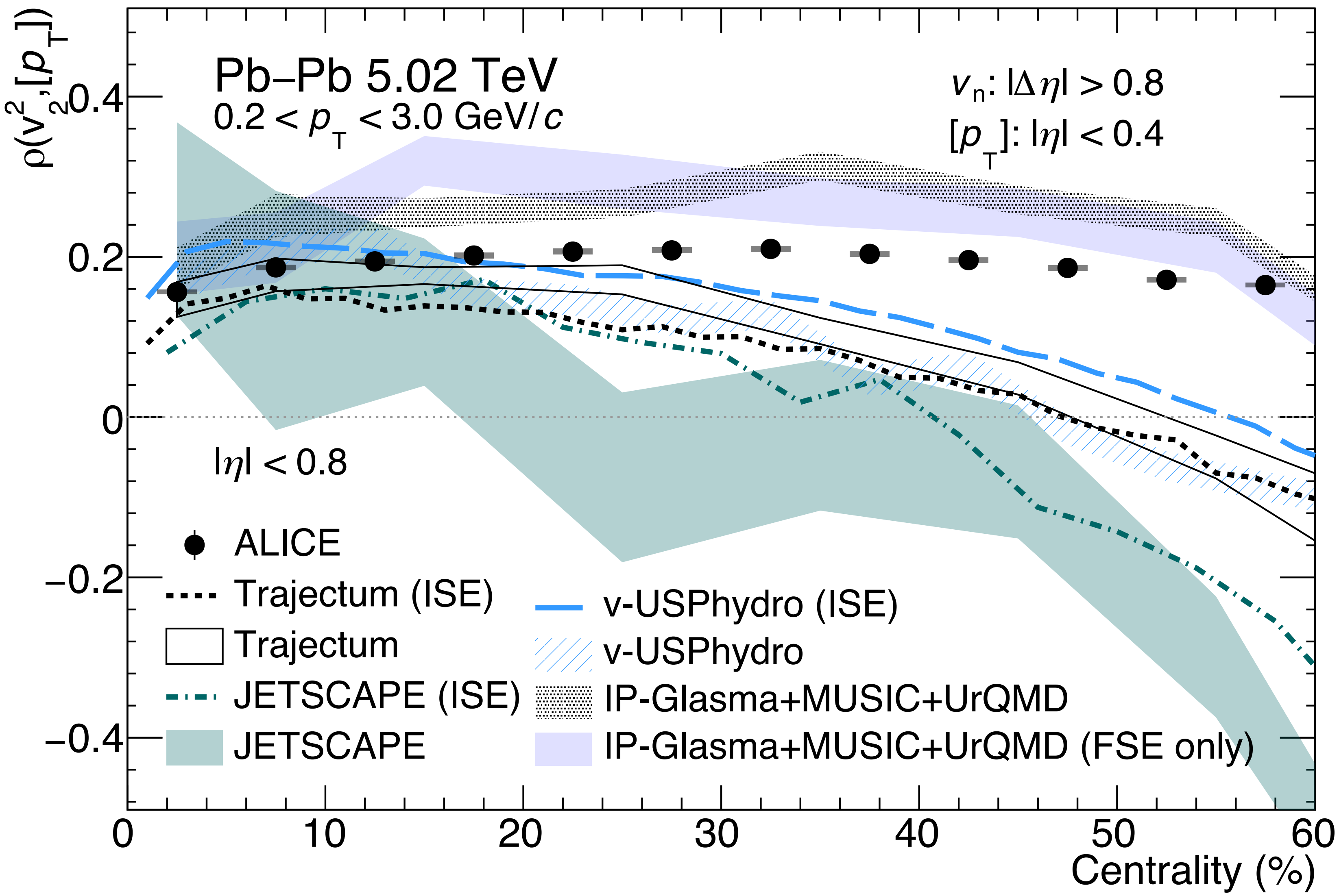
$$\rho(v_n^2, [p_T]) = \rho(\varepsilon_n^2, [E_0])$$

final-state model calculation

Initial-state model estimation

❖ One can compare $\rho(v_n^2, [p_T])$ measurements to $\rho(\varepsilon_n^2, [E_0])$ calculations, to constrain the initial state model

ρ_2 in Pb-Pb



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

ALICE, PLB 834 (2022) 137393

v-USPhydro, PRC103 (2021) 2, 024909

IP-Glasma, PRC102, 034905 (2020)

JETSCAPE, PRL126, 242301 (2021) Privation communication

Trajectum, PRL126, 202301 (2021) Privation communication

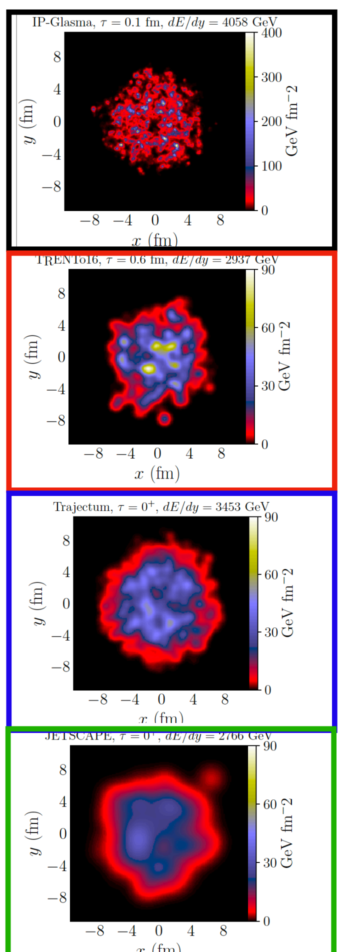
❖ IP-Glasma+MUSIC+UrQMD shows a weak centrality dependence and describe the data fairly well

❖ TRENTo-IC based calculations (v-USPhydro, Trajectum, JETSCAPE) all show strong centrality dependence, negative values for centrality >40%

Accessing the initial conditions

❖ Sensitive to the nucleon width parameter (size of nucleon)

- IP-Glasma ~ 0.4 fm; v-USPhydro ~ 0.5 fm; Trajectum~0.7 fm; JETSCAPE (TRENTo) ~ 1.1 fm
- w(IP-Glasma) < w(v-USPhydro) < w(Trajectum) < w(JETSCAPE)
- New constraints on the ***nucleon size***

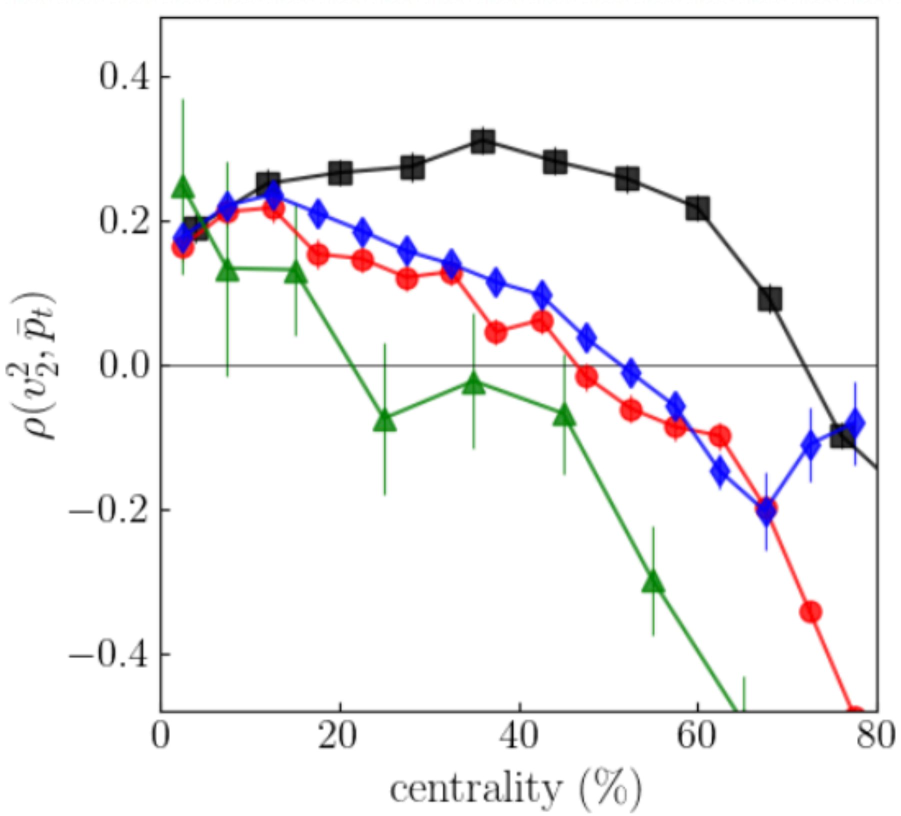


w ~ 0.4

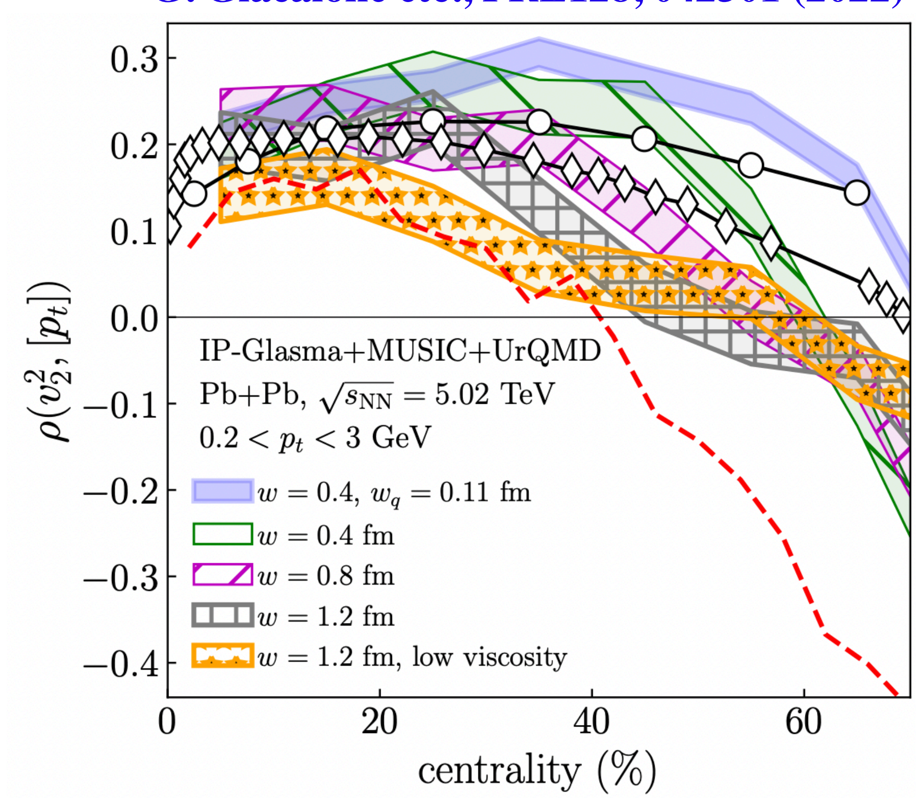
w ~ 0.5

w ~ 0.7

w ~ 1.1

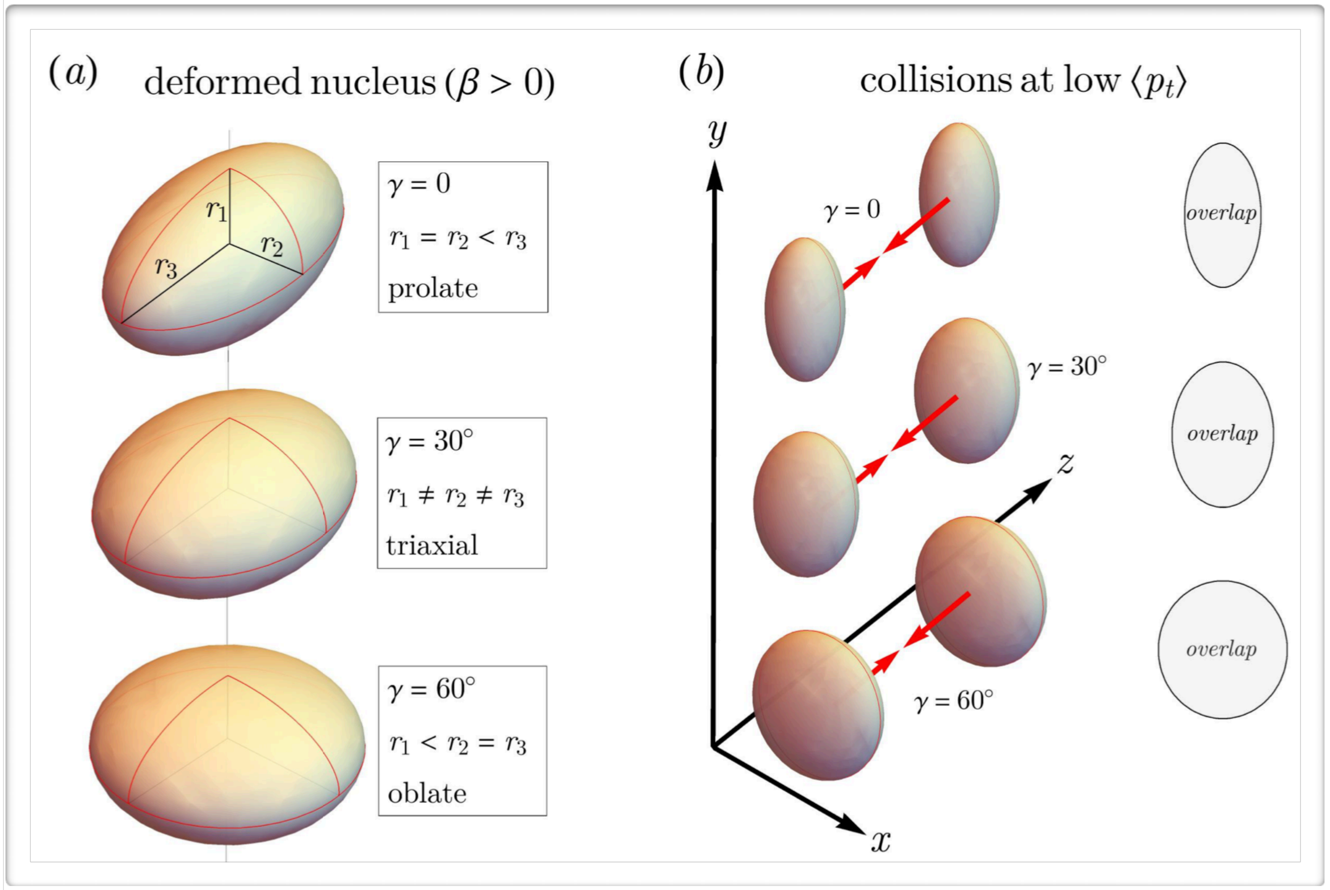


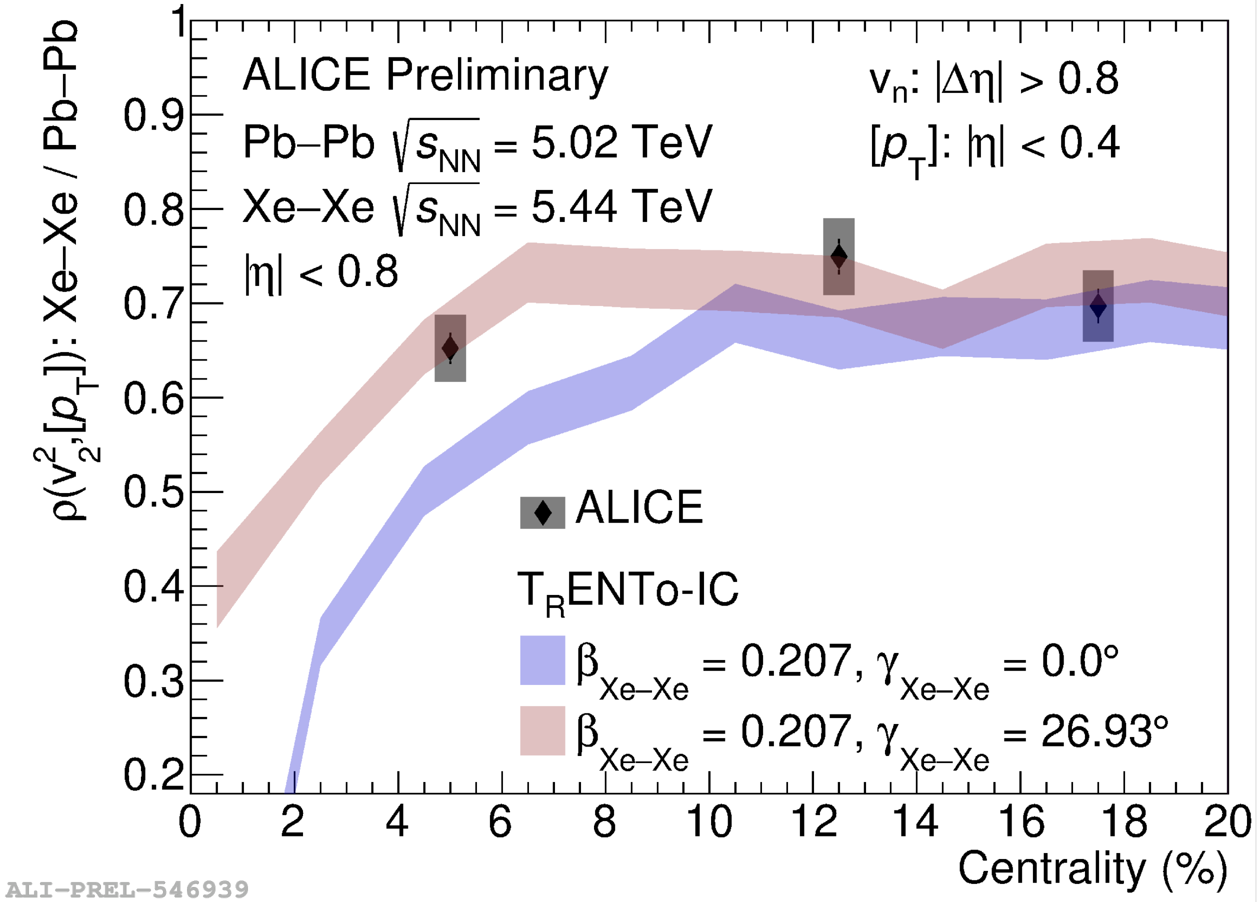
G. Giacalone etc., PRL128, 042301 (2022)



Probe triaxial structure of ^{129}Xe

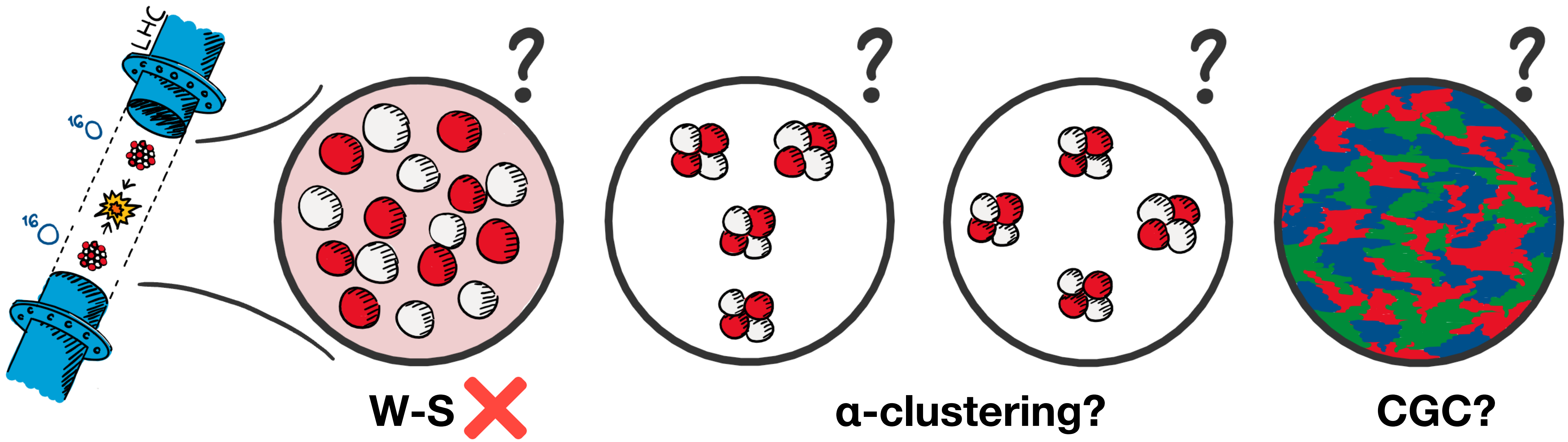
B. Bally etc, PRL128 (2022) 8, 082301





- Better agreement between LHC data and calculations with $\gamma = 26.93°$
  - ***First observation of triaxial structure of ^{129}Xe at high energy collisions at the LHC***
  - New connection of high-energy heavy-ion physics and low-energy nuclear (structure) physics

O-O collisions at the LHC Run 3 (2024)



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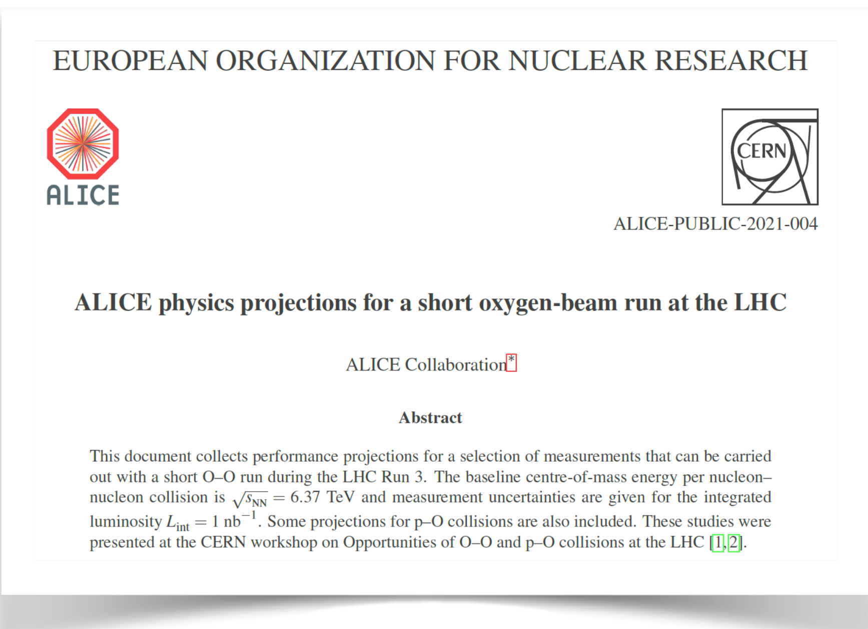
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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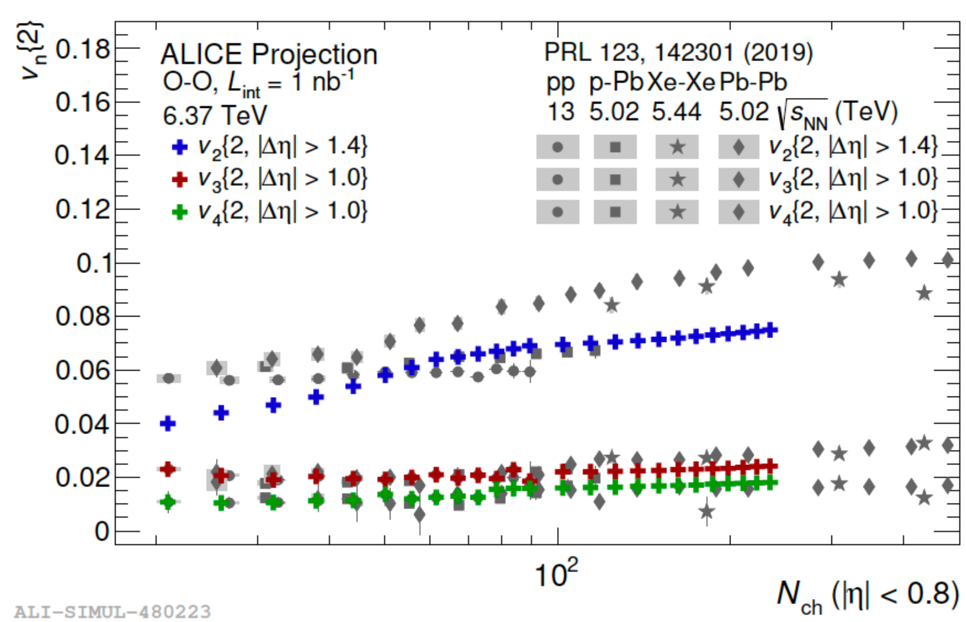
ALICE-PUBLIC-2021-004

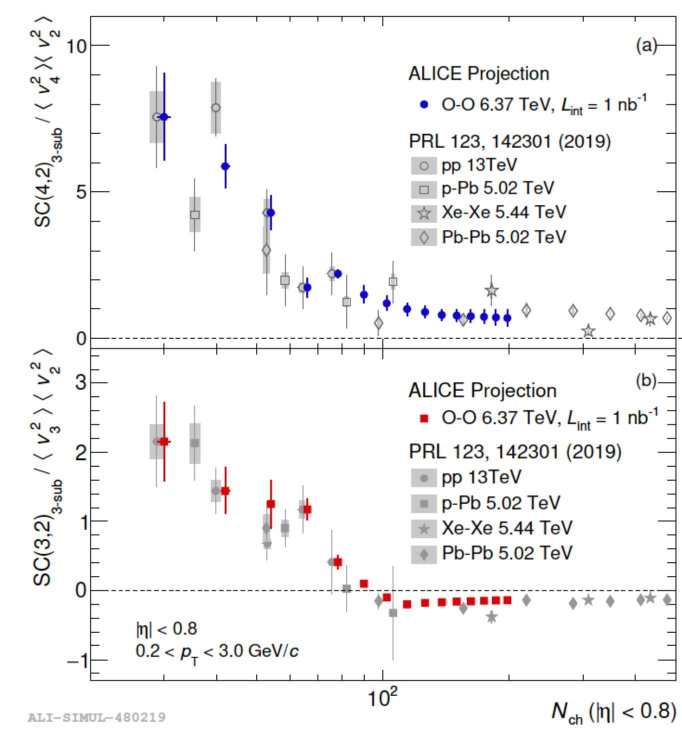
ALICE physics projections for a short oxygen-beam run at the LHC

ALICE Collaboration

Abstract

This document collects performance projections for a selection of measurements that can be carried out with a short O–O run during the LHC Run 3. The baseline centre-of-mass energy per nucleon–nucleon collision is $\sqrt{s_{NN}} = 6.37$ TeV and measurement uncertainties are given for the integrated luminosity $L_{int} = 1\ nb^{-1}$. Some projections for p–O collisions are also included. These studies were presented at the CERN workshop on Opportunities of O–O and p–O collisions at the LHC [1, 2].

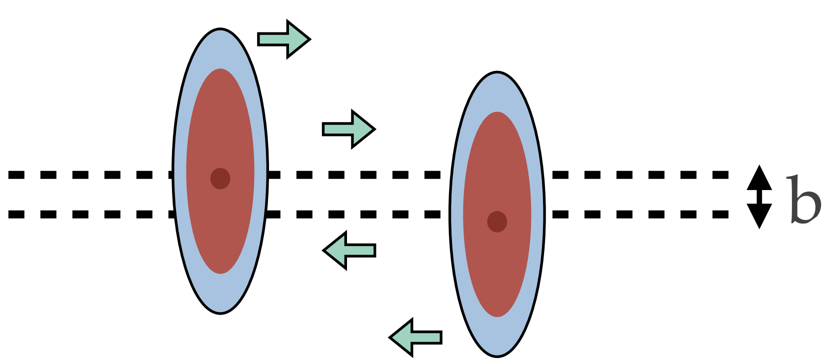




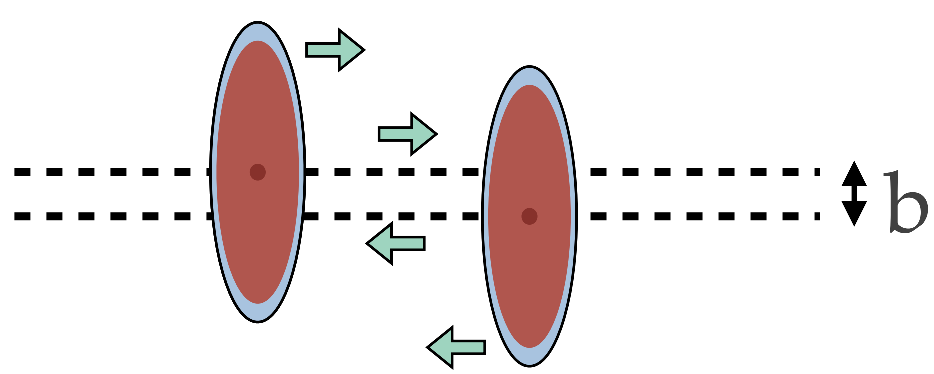
Future possibilities

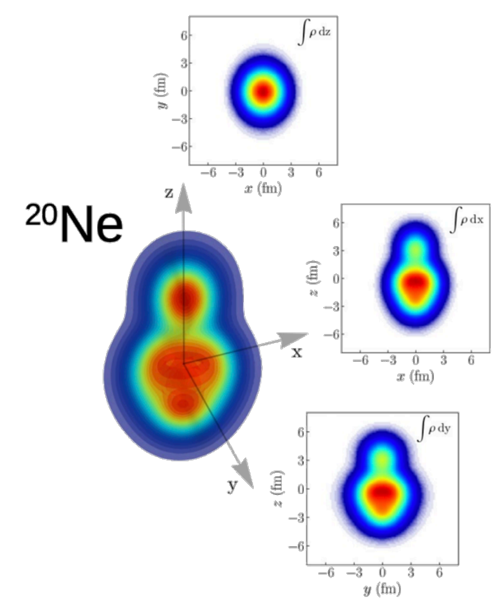
	Initial eccentricity fluctuations	Initial size (entropy) fluctuations	Nucleon width	Nuclear structure	Nuclear skin depth	Neutron skin
Anisotropic flow	✓			✓		✓
p_T correlations		✓		✓	✓	✓
v_n-p_T correlations	✓	✓	✓	✓		✓

^{48}Ca: large skin



^{40}Ca: small skin





- Neutron skin i.e., ^{208}Pb, ^{40}Ca and ^{48}Ca
- Further understanding on the α-clustering structure with ^{20}Ne
- New isobar runs ^{40}Ca vs ^{40}Ar (well within the capability of nuclear EFT calculations)

Recent Activities @ High Energies

BNL (01.2022)

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

link

GSI (05.2022)

EMMI
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

GSI (10.2022)

EMMI
EMMI Rapid Reaction Task Force: "Nuclear physics confronts relativistic collisions of isobars" (part 2/2)
12-14 October 2022
Heidelberg University

link

CEA, Saclay (09.2022)

DE LA RECHERCHE À L'INDUSTRIE
cea
ESNT
Espace de Structure Nucléaire Théorique
DSM - DAM

Deciphering nuclear phenomenology across energy scales

Back to the ESNT page

20-23 September 2022

PROGRAM ESNTprogram19Sept2022DefVf.pdf

link

INT (02.2023)

INSTITUTE for NUCLEAR THEORY

INT PROGRAM INT-23-1A

Intersection of nuclear structure and high-energy nuclear collisions

link

NBI (06.2023)

The VII-th International Conference on the **Initial Stages** of High-Energy Nuclear Collisions (IS2023), Copenhagen.

2023 IS INITIAL STAGES

link

Follow-up activities

PKU (04.2024)
Beijing

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

15–26 Apr 2024
Asia/Shanghai timezone

Enter your search term

- Overview
- Participant List
- Committees
- Meeting and Hotel Information
- About Beijing
- Visa to China
- Transportation

Contact
huichaosong@pku.edu.cn

Introduction： Recently, it has been realized that relativistic heavy ion collisions could provide new approaches to study some fundamental properties of atomic nuclei. It is therefore timely to gather scientists from both the low-energy and high-energy nuclear physics communities to discuss the recent progress and future perspective in this research direction. The two-week program+workshop on "Exploring Nuclear Physics across Energy Scales" emphasizes the intersection between nuclear structure and high-energy nuclear collisions, with a focus on the following questions: How does the low-energy structure of nuclei manifest in high-energy collisions? How do the observations made at colliders complement our knowledge of nuclear structure? During the program days (April 15-18, April 23-26) the two invited speakers each day are expected to give a one-hour seminar with sufficient time for discussions. The embedded workshop (20-22 April) will be 3 days with 25-30 invited talks and 3 short discussion sections.

The scientific program includes the following topics, which emphasises the intersections between nuclear structure and high-energy collisions.

- Manifestation of nuclear deformations across energy scales
- Neutron skin determinations and applications
- Many-body correlations and clustering in light nuclei
- Bayesian analysis for high-energy collisions and nuclear structure
- Role of nuclear structure in low- and intermediate-energy collisions
- Connection to Ultra-peripheral Collisions (UPCs) and the future Electron-Ion Collider (EIC)
- Opportunities with colliding new species at future high-energy experiments

(Program + workshop for a limited number of participants)

CERN (10.2024)
In preparation

(Hopefully) Form concrete proposals for the future HI runs @ LHC

Conclusion

❖ **Heavy-ion collisions offer a unique, precision imaging tool of the nuclear structure with cross field applications**
- Complements low-energy nuclear physics, which rely on modelling to obtain the structure

❖ **Multi-particle correlations (for anisotropic flow and mean transverse momentum) are the key tool in probing the nuclear structure**
- Higher-order correlations can reveal additional sensitivities to more complex shapes

❖ **Future runs at the LHC (i.e., O-O, Ne-Ne) allow us to test cutting edge *ab-initio* nuclear structure methods**
- Reducing our uncertainty on QGP properties while providing valuable information for hydrodynamic and transport model simulations and nuclear pdfs

❖ **Huge potential from Bayesian analysis and Machine Learning**
- To be explored when more data is available

~~Conclusion~~ Remarks

- **The nuclear structure studies at the high energies (i.e., RHIC & LHC) can not replace the efforts of NS at low energies, OBVIOUSLY.**
- **They complement each other**
  - *NS@LE covers much wider range in the nuclide chart*
  - *NS@HE enables novel opportunity to resolve some challenging questions (many-body, shape etc) with a few selected nuclei*
- **The interactions between two communities are crucial**
  - *Can we have a unified description of nuclear structure through the entire energy scale from MeV to TeV*

Thanks !

INDEPENDENT RESEARCH FUND DENMARK

- ⋆ 1 Postdoc
  - starting Later 2024
  - yearly income ~ € 86k

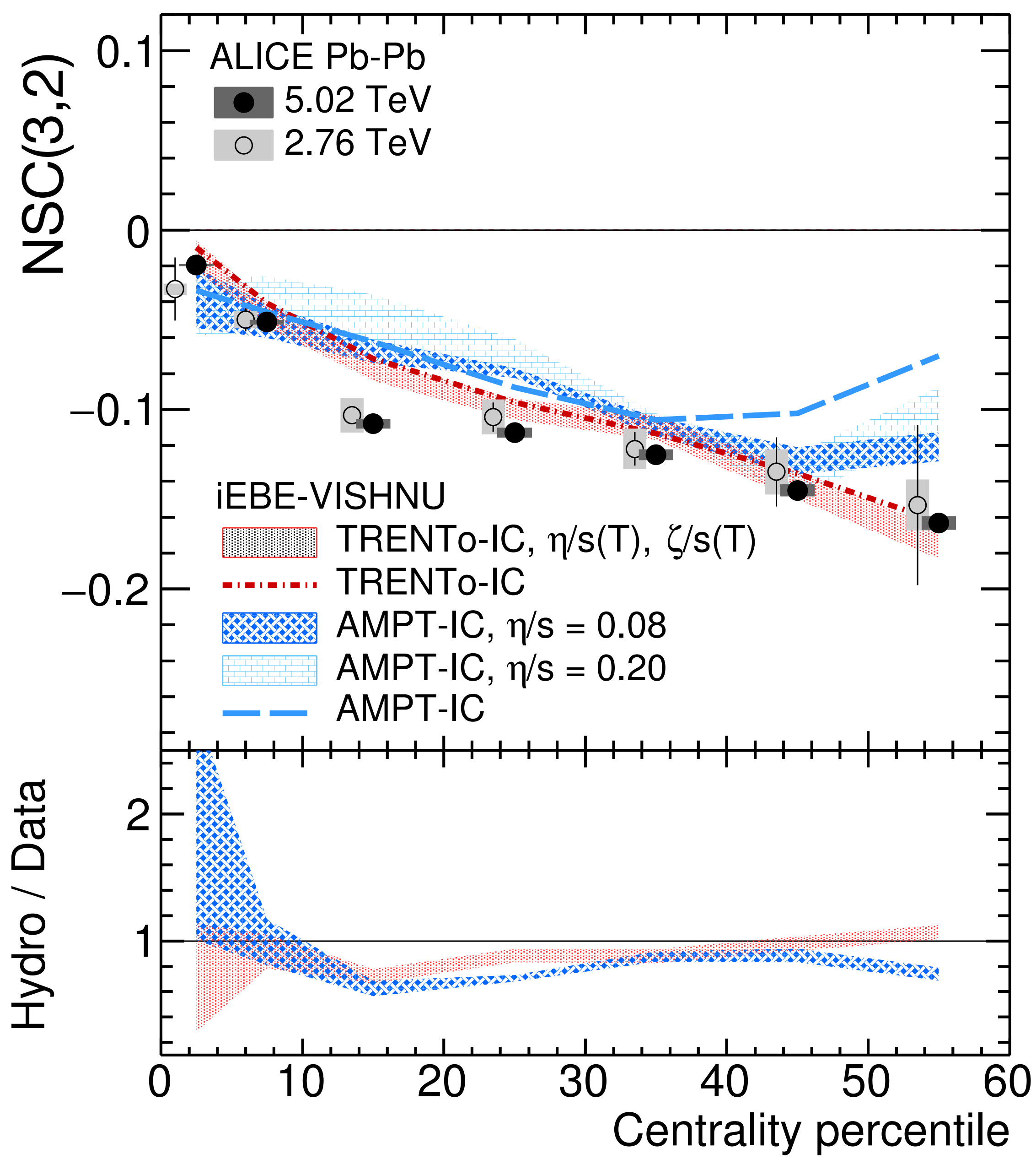
- ⋆ 1 PhD
  - starting summer 2024
  - yearly income ~ € 66k

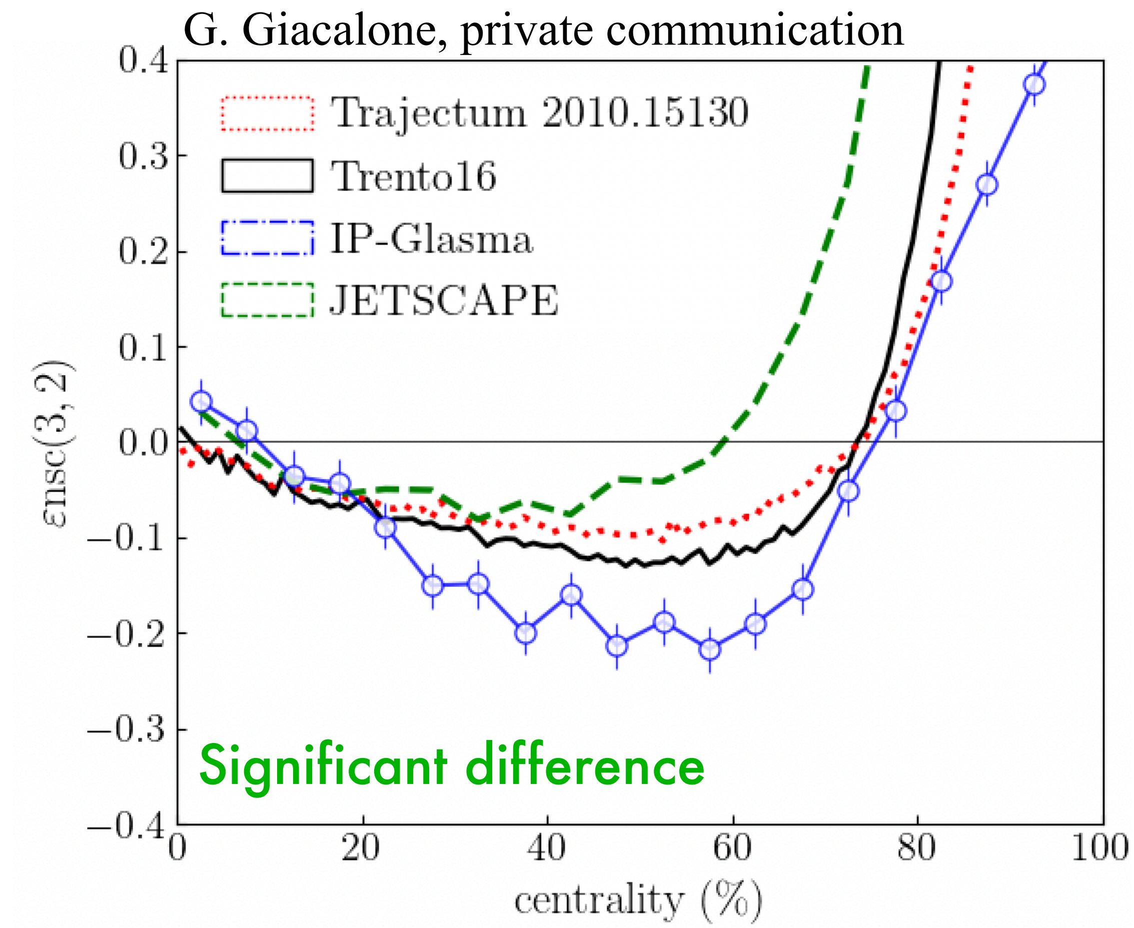
- ⋆ Contact You Zhou: You.Zhou AT cern.ch

Bakcup

Probe IC with NSC(3,2)

$$NSC^{v}(3,2) = NSC^{\varepsilon}(3,2)$$



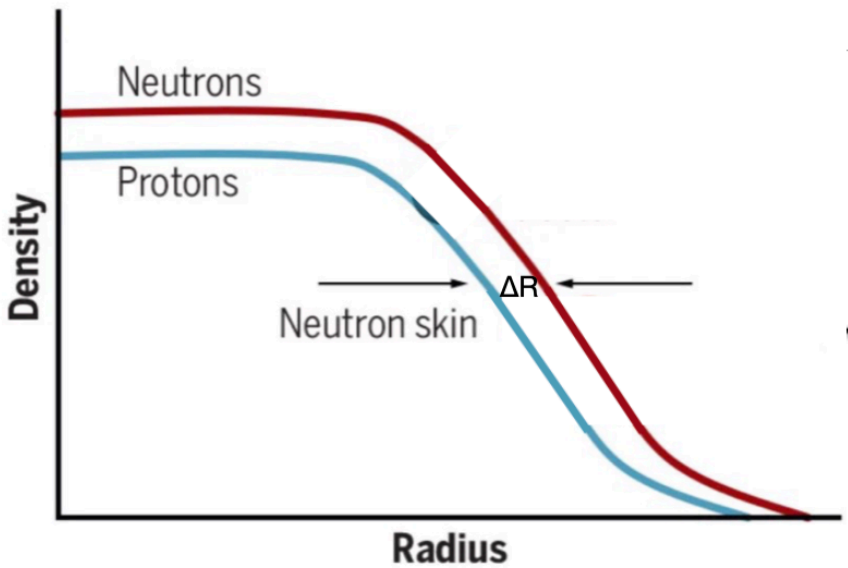


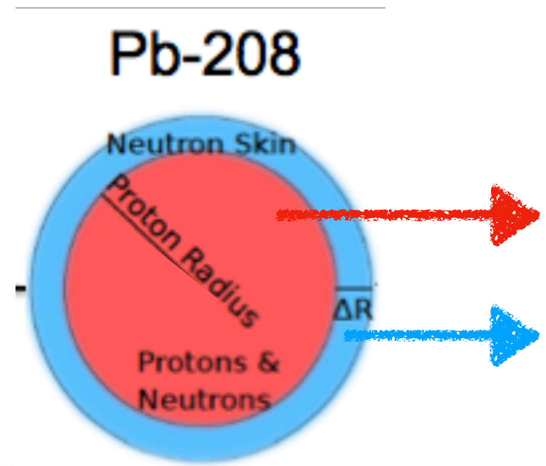
- Precision NSC(3,2) data provides tight constraints on the initial state models
- what is the general correlation between any order of v_n^k and v_m^p and the correlations among multiple flow coefficients

ALICE, PLB818 (2021) 136354

iEBE-VISHNU, M. Li, YZ etc, PRC104, 024903 (2021)

Neutron skin of ^{208}Pb



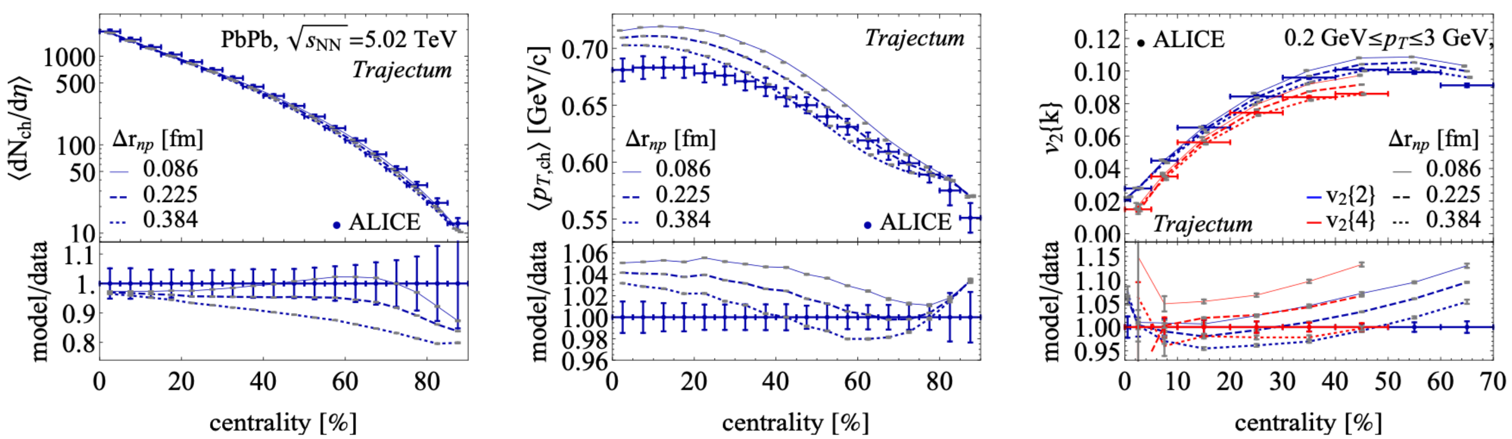


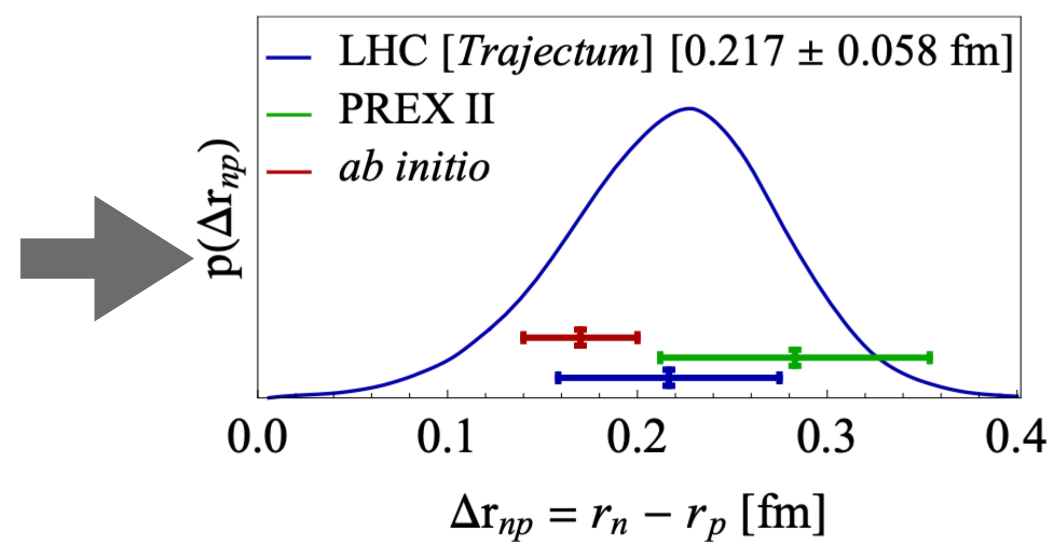
$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left(\left[r-R(\Theta,\Phi)\right]/a\right)}$$

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

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

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





❖ Extracted neutron skin of ^{208}Pb compatible with the state-of-the-art low-energy study

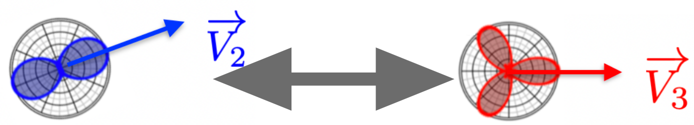
- PREX II: 0.278 ± 0.078 (exp.) + 0.012 (theo.) fm
- LHC [Trajectum]: 0.217 ± 0.058 (theo.) fm

Giacalone, Nijs, van der Schee, 2305.00015

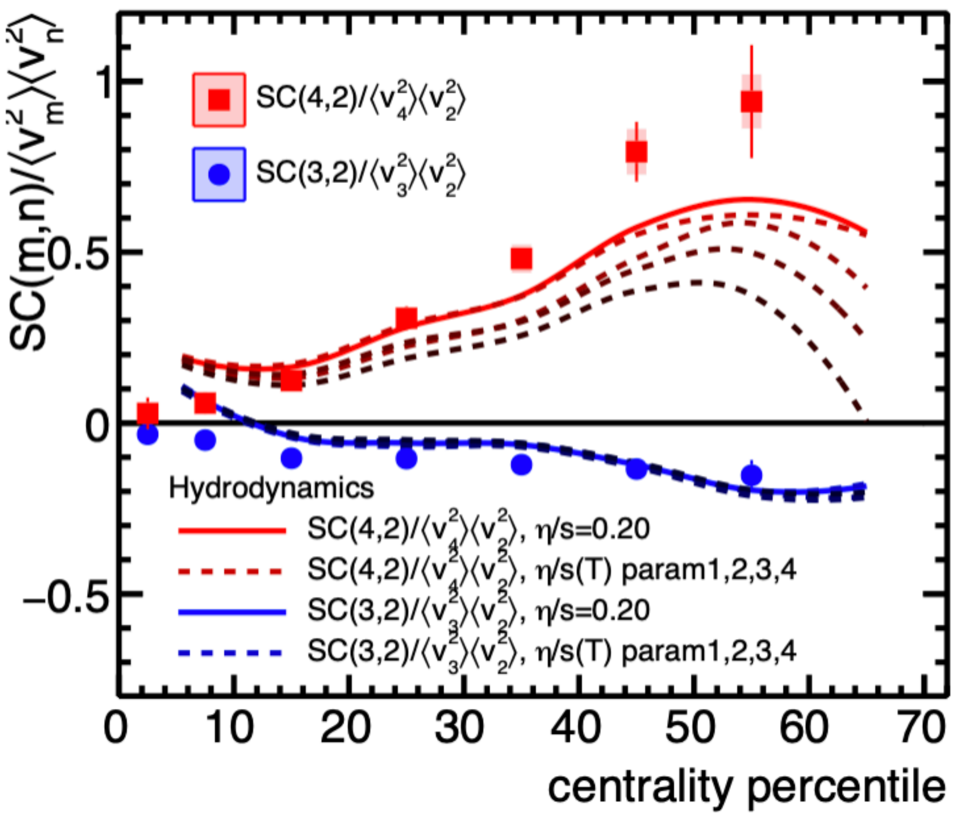
(Normalized) Symmetric Cumulant

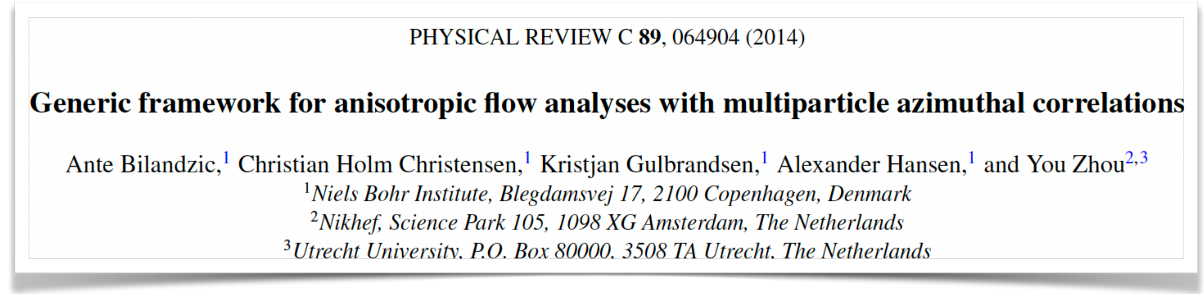
Symmetric cumulants:

$$SC(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$



ALICE, PRL117, 182301 (2016)




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]

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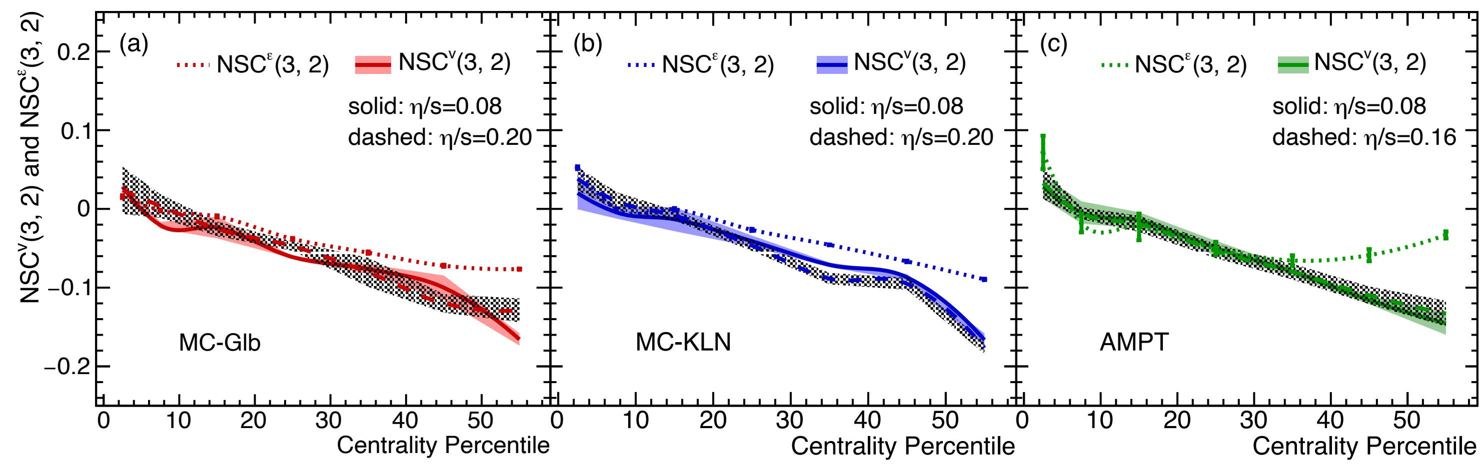
[2]*Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*

[3]*Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands*

Xiangrong Zhu, YZ, Haojie Xu, and Huichao Song, PRC95, 044902 (2017)



$$v_2 \propto \varepsilon_2 \qquad v_3 \propto \varepsilon_3$$

$$\frac{\langle v_2^2\, v_3^2\rangle - \langle v_2^2\rangle\langle v_3^2\rangle}{\langle v_2^2\rangle\langle v_3^2\rangle} = \frac{\langle \varepsilon_2^2\, \varepsilon_3^2\rangle - \langle \varepsilon_2^2\rangle\langle \varepsilon_3^2\rangle}{\langle \varepsilon_2^2\rangle\langle \varepsilon_3^2\rangle}$$

Or: $NSC^v(3,2) = NSC^\varepsilon(3,2)$

- The very first direct measurement of correlations between v_n and v_m
  - NSC(3,2) is insensitive to η/s
  - NSC(3,2) measurements provide a direct access into the initial conditions (despite details of systems evolution)
  - Can we use NSC to explore the nuclear structure?

Future possibilities

☆ Proposal for NuPECC Long-range plan

Imaging nuclear structure and quark-gluon plasma
at the Large Hadron Collider

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Abstract:

It has been established recently that nuclear collision experiments performed in high-energy collider machines, such as the CERN Large Hadron Collider (LHC), provide a novel tool to observe signatures of the shape and the radial structure of atomic nuclei. By taking *snaphots* of the state of the colliding ions at the interaction point, such experiments open an access route to a range of phenomena shaped by the collective behavior of nucleons that emerge from the strong nuclear force, such as nuclear deformations and neutron skins. The European nuclear community should explore the potential of a program of high-energy collisions across the Segrè chart to be pursued beyond LHC Run 3 to exploit the synergy between two areas of nuclear science. This will permit us, on the one hand, to advance our knowledge of the conditions that set the stage for the formation of quark-gluon plasma (QGP) in heavy-ion collisions and better constrain key physical parameters associated with the Hubble-like expansion of this medium. On the other hand, full exploitation of the LHC as an imaging tool will advance our understanding of strongly-correlated nuclear systems via probes and techniques complementary to those utilized in low-energy applications. Such studies will ultimately yield unique insight into the behavior of quantum chromodynamics (QCD) across systems and energy scales.

Proposals for ^{20}Ne, ^{40}Ca & ^{48}Ca at the LHC

☆ Proposal for US Long-range plan

arXiv > nucl-ex > arXiv:2209.11042

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Nuclear Experiment

[Submitted on 22 Sep 2022]

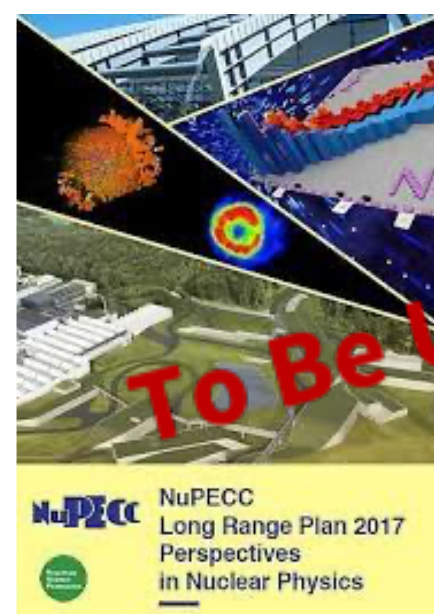
Imaging the initial condition of heavy-ion collisions and nuclear structure across the nuclide chart

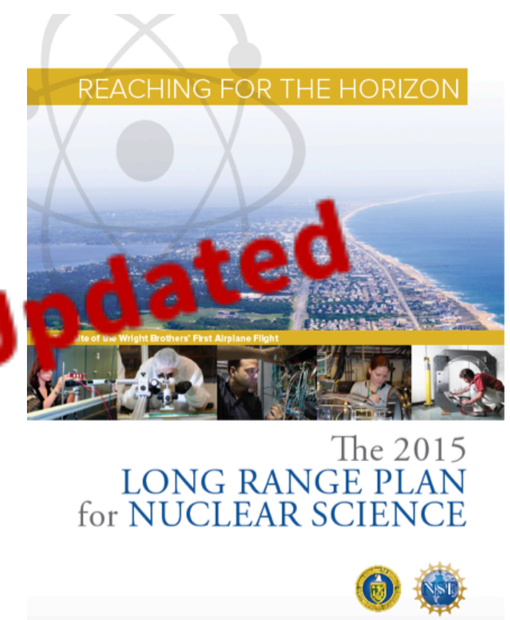
Benjamin Bally, James Daniel Brandenburg, Giuliano Giacalone, Ulrich Heinz, Shengli Huang, Jiangyong Jia, Dean Lee, Yen-Jie Lee, Wei Li, Constantin Loizides, Matthew Luzum, Govert Nijs, Jacquelyn Noronha-Hostler, Mateusz Ploskon, Wilke van der Schee, Bjoern Schenke, Chun Shen, Vittorio Somà, Anthony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

A major goal of the hot QCD program, the extraction of the properties of the quark gluon plasma (QGP), is currently limited by our poor knowledge of the initial condition of the QGP, in particular how it is shaped from the colliding nuclei. To attack this limitation, we propose to exploit collisions of selected species to precisely assess how the initial condition changes under variations of the structure of the colliding ions. This knowledge, combined with event-by-event measures of particle correlations in the final state of heavy-ion collisions, will provide in turn a new way to probe the collective structure of nuclei, and to confront and exploit the predictions of state-of-the-art ab initio nuclear structure theories. The US nuclear community should capitalize on this interdisciplinary connection by pursuing collisions of well-motivated species at high-energy colliders.

Comments: 23 pages, 6 figures
Subjects: **Nuclear Experiment (nucl-ex)**; High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)
Cite as: arXiv:2209.11042 **[nucl-ex]**
(or arXiv:2209.11042v1 **[nucl-ex]** for this version)
https://doi.org/10.48550/arXiv.2209.11042

NuPECC (2017) **NSAC (2015)**





To Be Updated

Multi-particle p_T correlations

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

Emil Gorm Dahlbæk Nielsen[1], Frederik K. Rømer[1], Kristjan Gulbrandsen[1], You Zhou[a,1]

[1]Niels Bohr Institute, University of Copenhagen, 2200 Copenhagen, Denmark

$$[p_{\mathrm{T}}^{(1)}] = \frac{P_1}{W_1} = \frac{\sum_{i=1}^{M} w_i p_{\mathrm{T},i}}{\sum_{i=1}^{M} w_i} = [p_{\mathrm{T}}],$$

$$[p_{\mathrm{T}}^{(2)}] = \frac{P_1^2 - P_2}{W_1^2 - W_2},$$

$$[p_{\mathrm{T}}^{(3)}] = \frac{P_1^3 - 3P_2P_1 + 2P_3}{W_1^3 - 3W_2W_1 + 2W_3}$$

$$[p_{\mathrm{T}}^{(4)}] = \frac{P_1^4 - 6P_2P_1^2 + 3P_2^2 + 8P_3P_1 - 6P_4}{W_1^4 - 6W_2W_1^2 + 3W_2^2 + 8W_3W_1 - 6W_4}$$

TRENTo IC

- Fully parametrised initial conditions

$$P_{\text{wounded}} = 1 - \exp\left(-\sigma_{gg}\int d\boldsymbol{x}\rho_A(\boldsymbol{x})\rho_B(\boldsymbol{x})\right), \qquad \rho_{A/B} \propto \exp\left(\frac{-|\boldsymbol{x}-\boldsymbol{x}_{A/B}|^2}{2w^2}\right)$$

- Deposit energy into each nucleus' thickness function

$$T_{A/B} = \sum_{i\in\text{wounded } A/B} \gamma \exp(-|\boldsymbol{x}-\boldsymbol{x}_i|^2/2w^2)$$

- Modify to include quark constituents $\rho_A = \frac{1}{n_c}\sum_{i=1^{n_c}} \rho_c(\boldsymbol{x}-\boldsymbol{x}_i)$

- Generalised mean of thickness functions

$$\left.\frac{dS}{d^2x_\perp d\eta}\right|_{\eta=0} \propto \left(\frac{(T_A+T_B)^p}{2}\right)^{1/p} \Rightarrow \left.\frac{dS}{d\eta}\right|_{\eta=0} \propto \begin{cases} max(T_A, T_B) & p \to +\infty \\ (T_A+T_B)/2 & p = +1 \text{ (arithmetic)} \\ \sqrt{T_AT_B} & p = 0 \text{ (geometric)} \\ 2T_AT_B/(T_A+T_B & p = -1 \text{ (harmonic)} \\ min(T_A, T_B) & p \to -\infty \end{cases}$$