

Imaging-By-Smashing: New Frontiers of Nuclear Structure from MeV to TeV



UNIVERSITY OF
COPENHAGEN

You Zhou

Niels Bohr Institute, University of Copenhagen



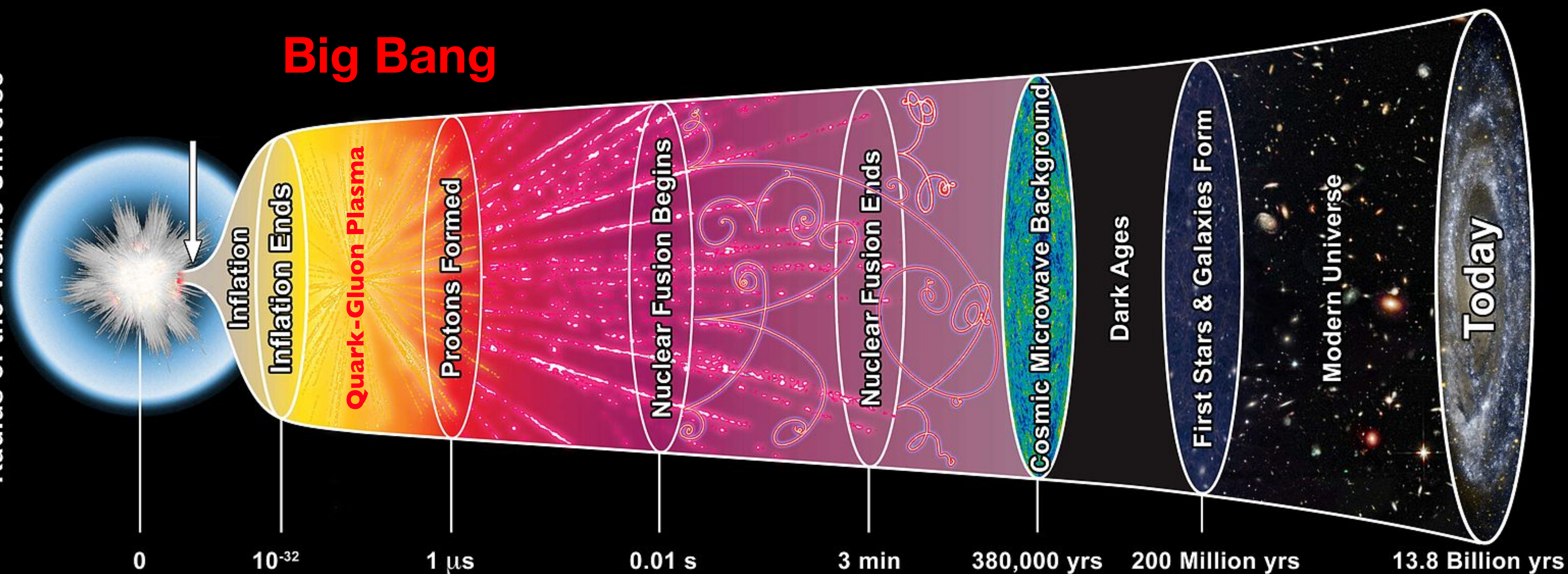
European Research Council
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**INDEPENDENT
RESEARCH FUND
DENMARK**

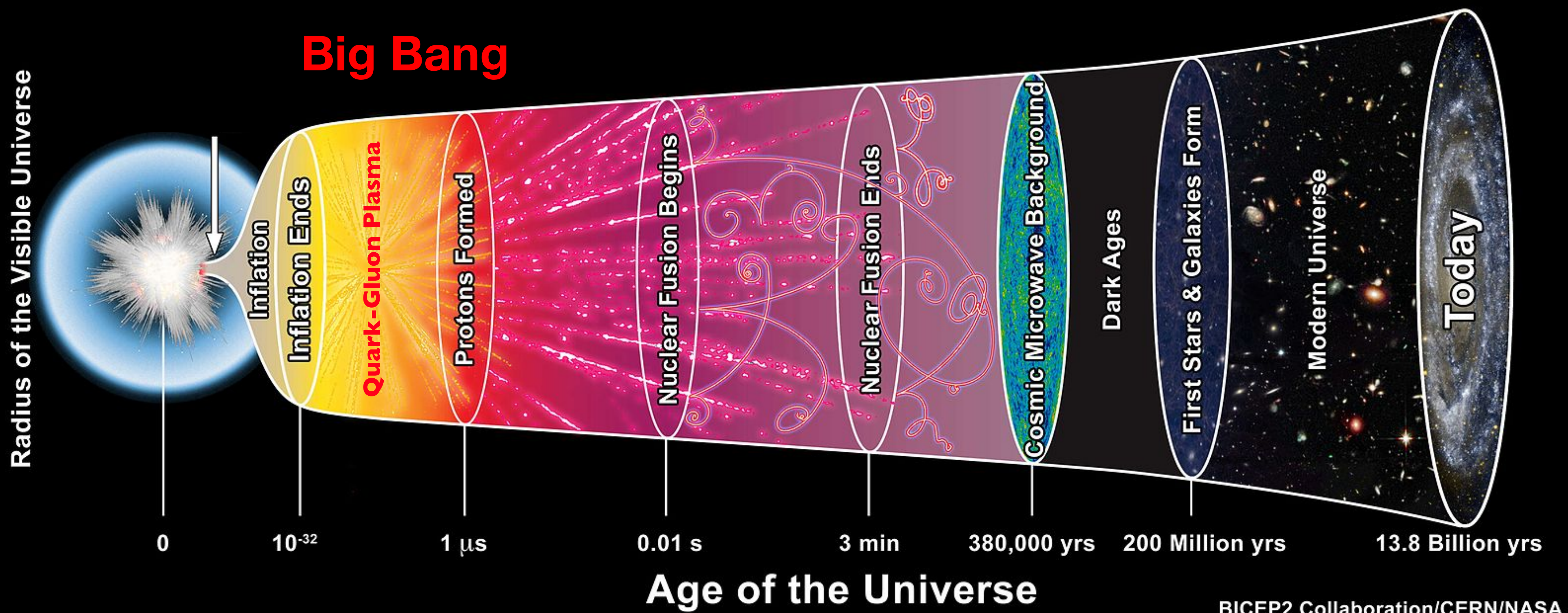
Big Bang

Radius of the Visible Universe

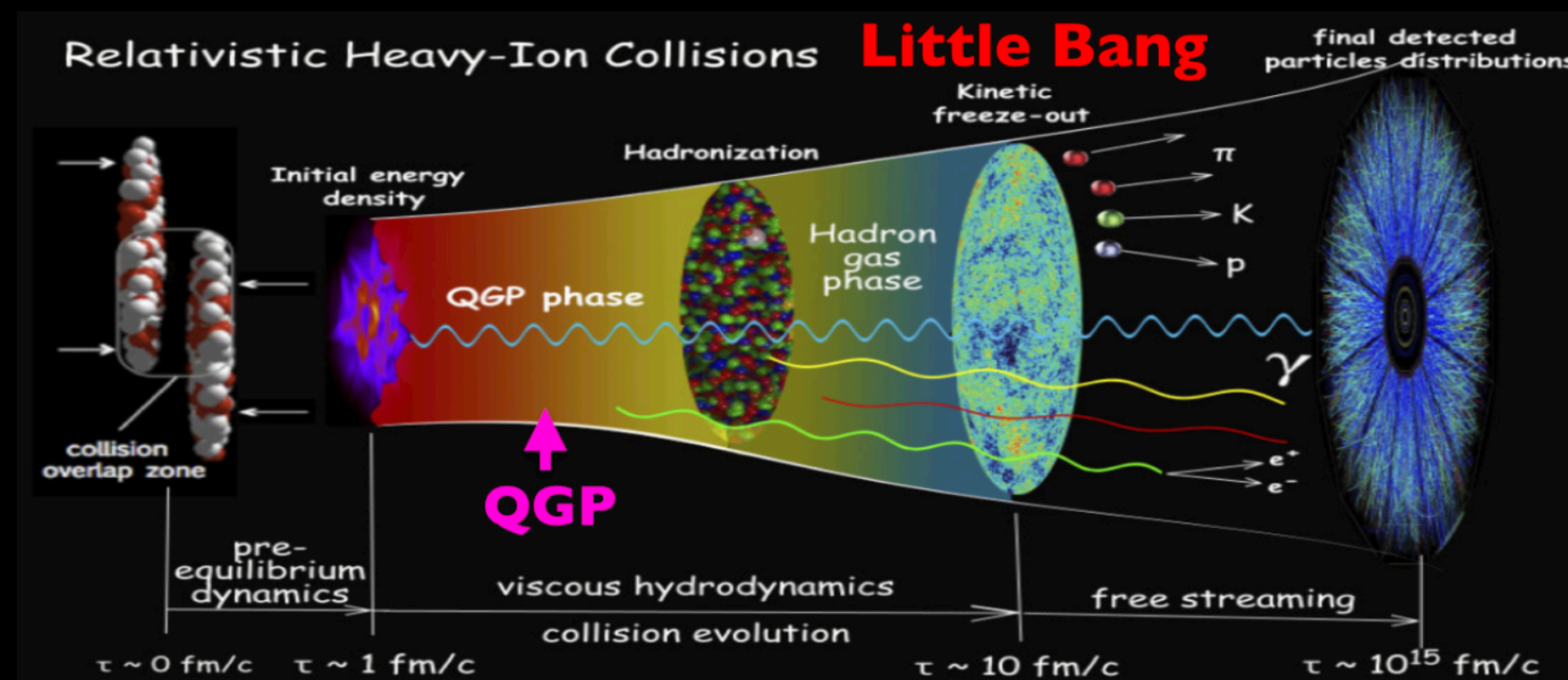


Age of the Universe

BICEP2 Collaboration/CERN/NASA



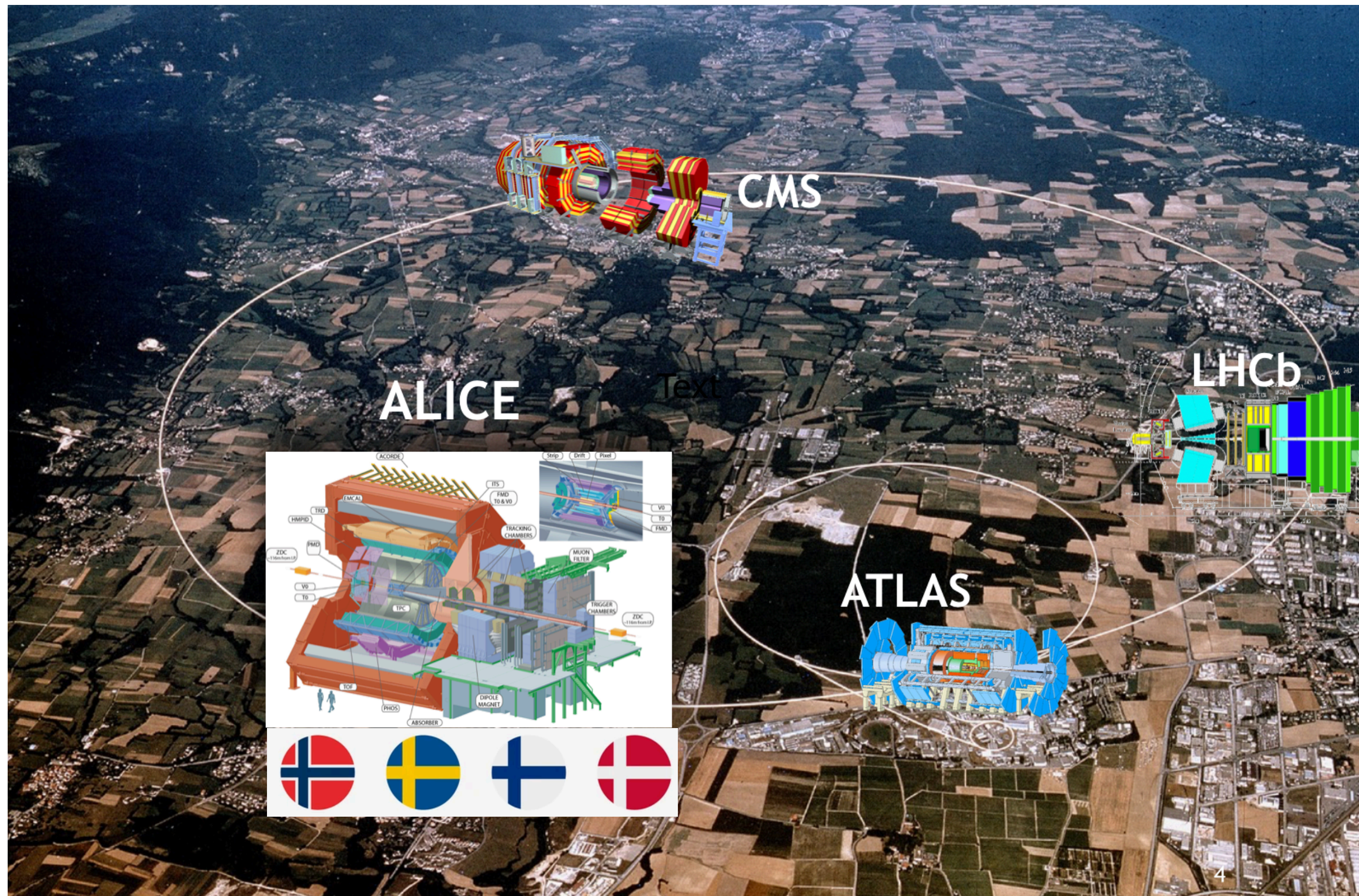
BICEP2 Collaboration/CERN/NASA



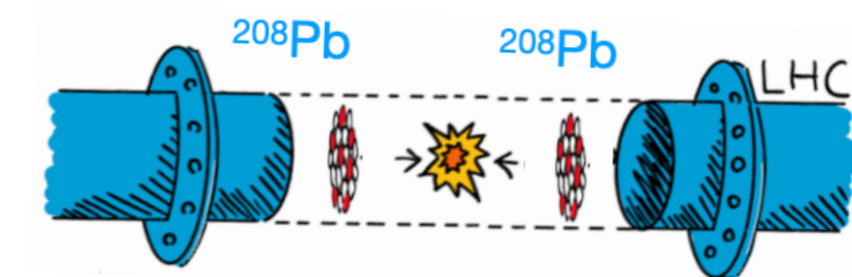
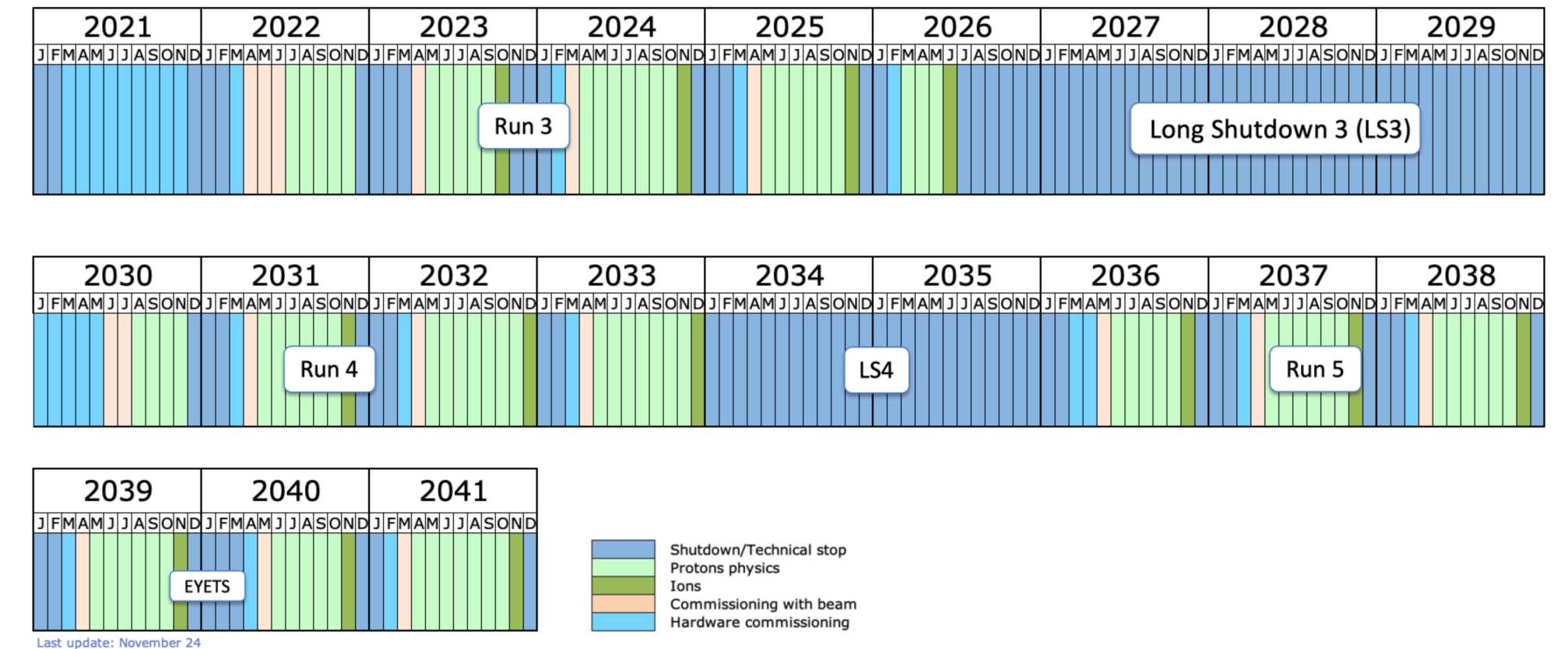
T ~ 5.5 thousand billion Kelvin (350,000 times hotter than sun's core)

Large “Heavy-ion” Collider @ CERN

Large Hadron Collider, CERN, Geneva



$v \sim 99.999992\% c$



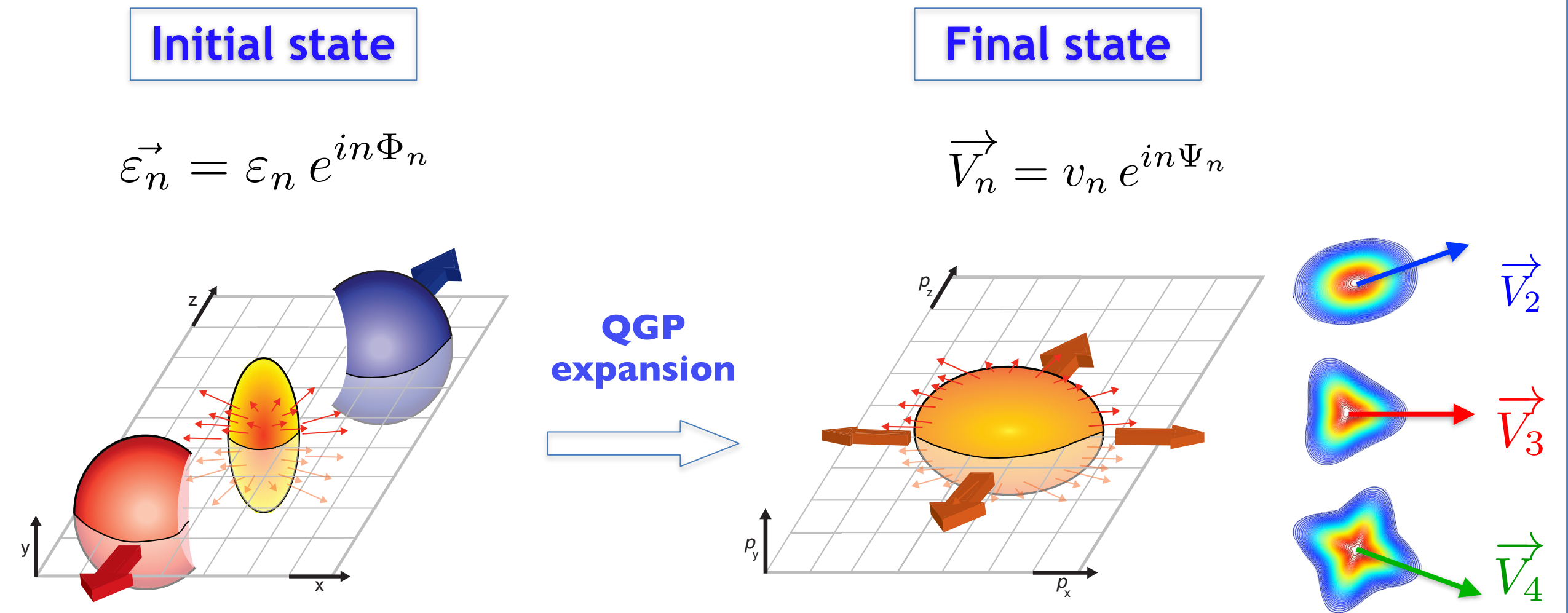
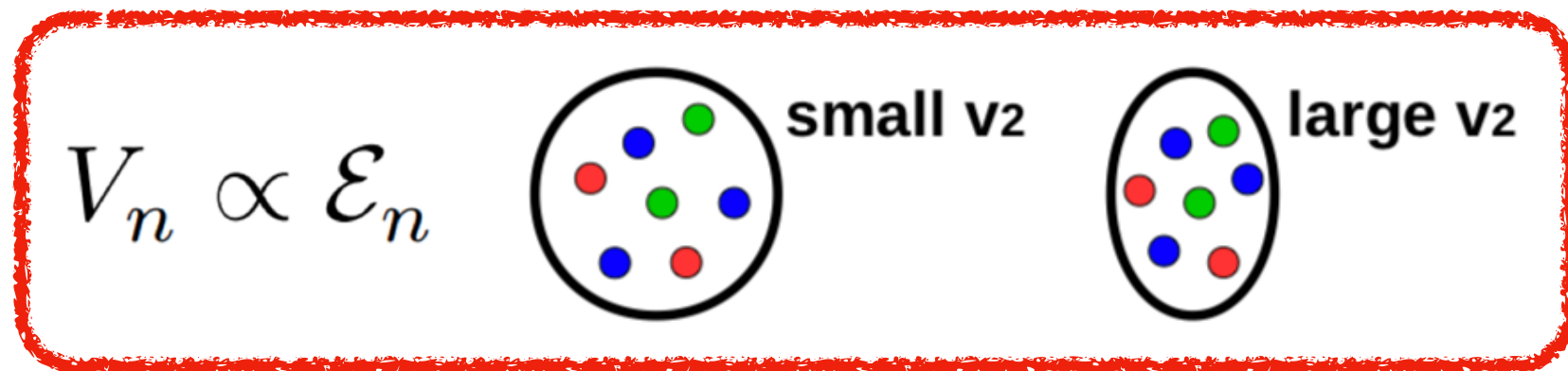
Pb-Pb 2.76 TeV (Run 1)
5.02 TeV (Run 2)
5.36 TeV (Run 3)



Xe-Xe 5.44 TeV

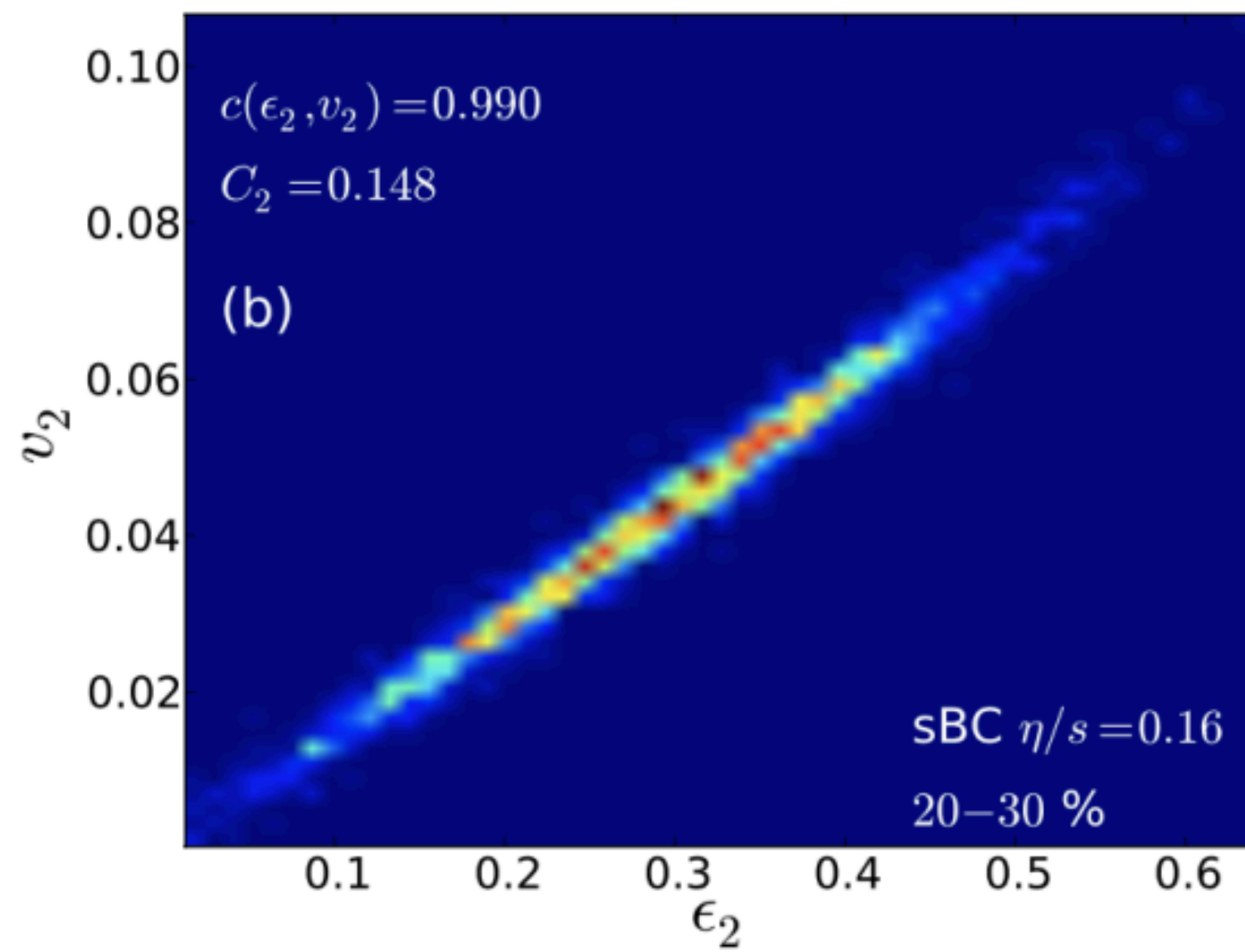
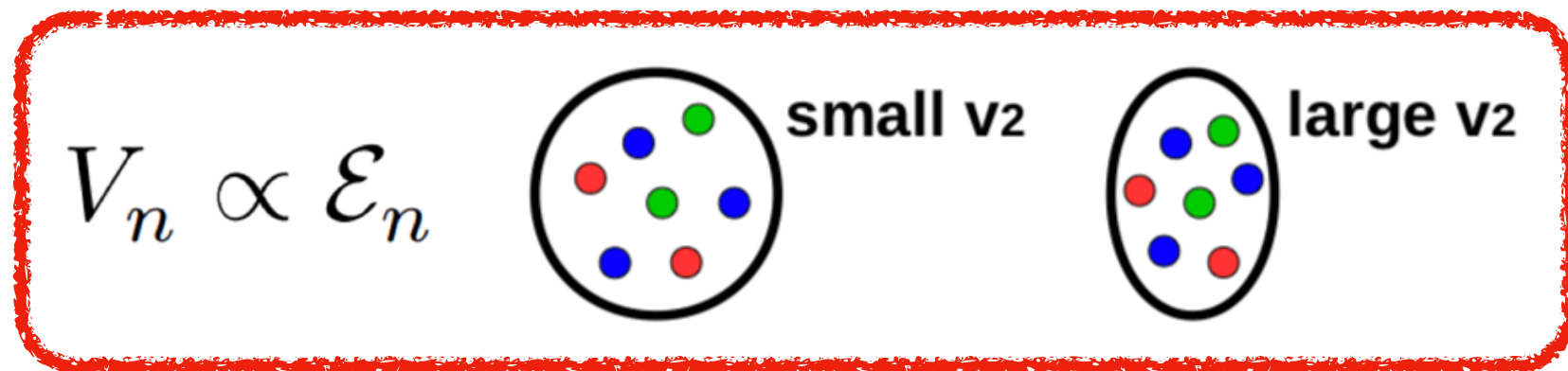
Anisotropic flow \rightarrow QGP properties

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

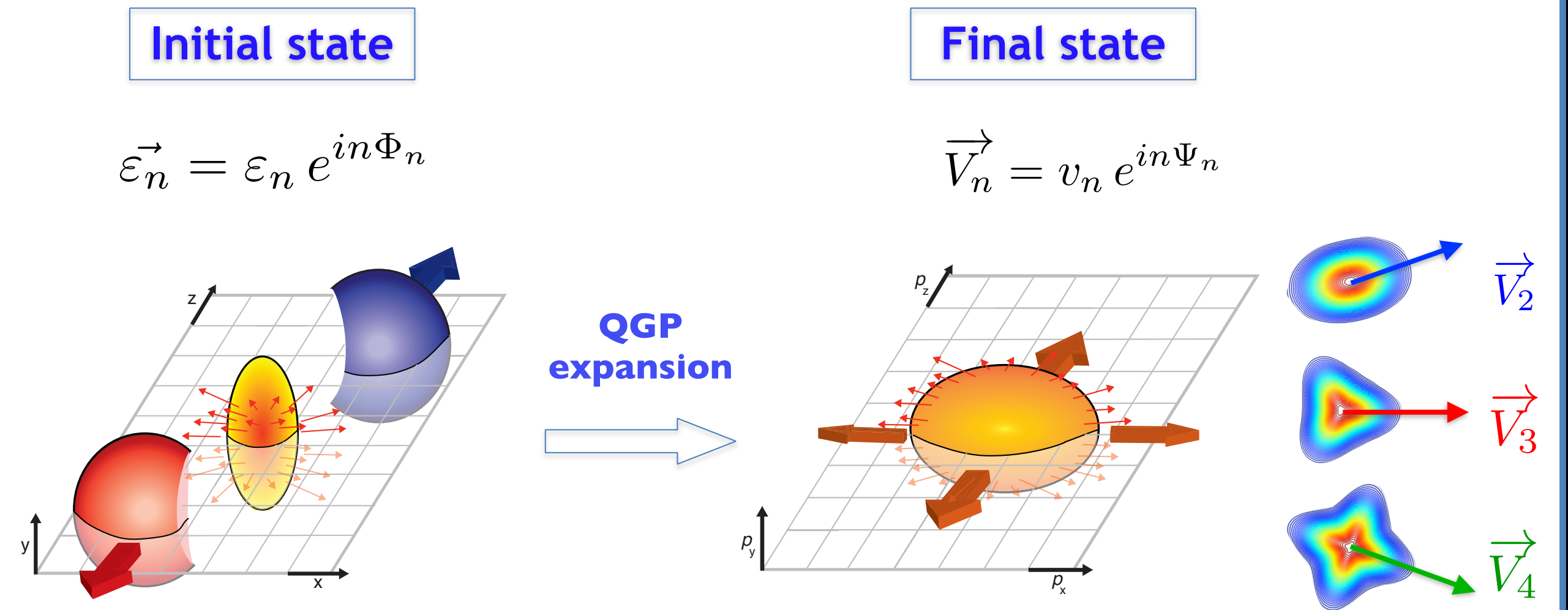


Anisotropic flow -> QGP properties

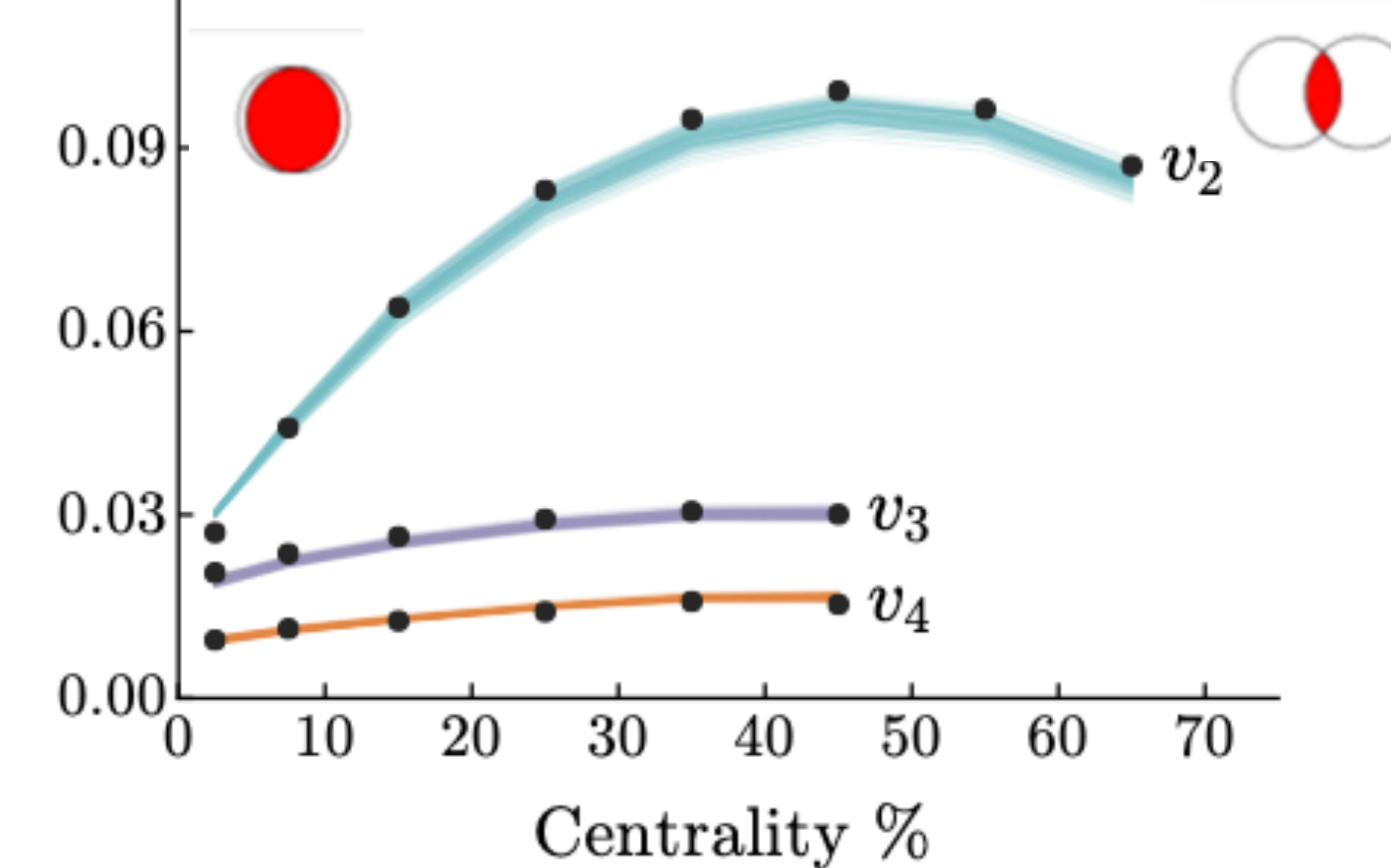
❖ **Shape** of the fireball: **Anisotropic flow**



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



ALICE, Phys. Rev. Lett 116, 132302 (2016)



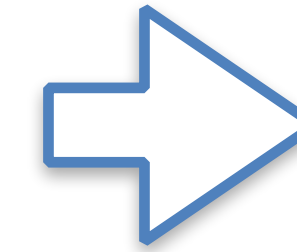
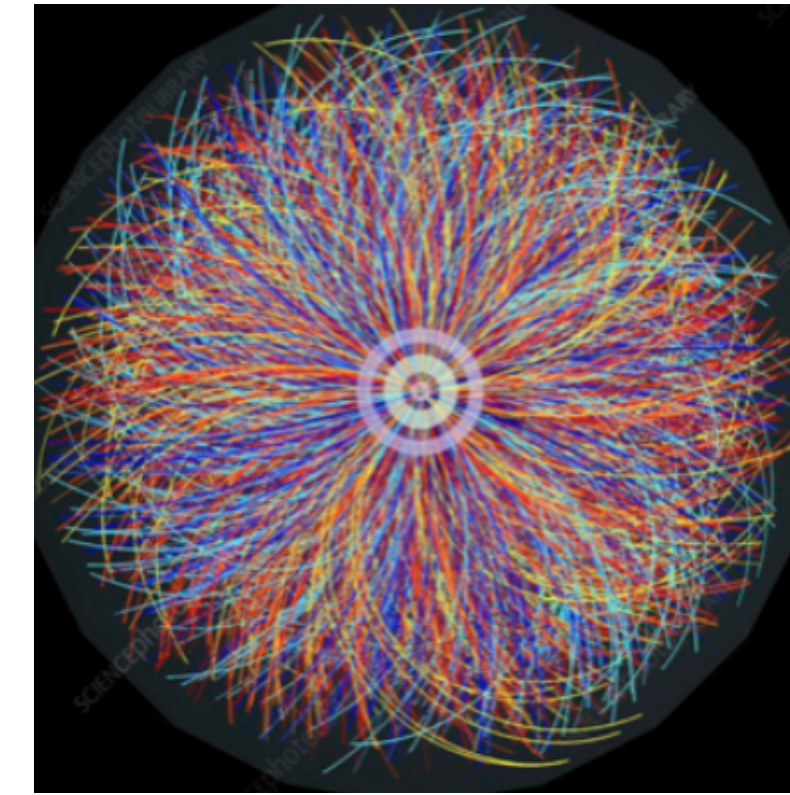
➔ QGP properties

Radial flow \rightarrow QGP properties

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

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

small $\langle p_t \rangle$ large $\langle p_t \rangle$

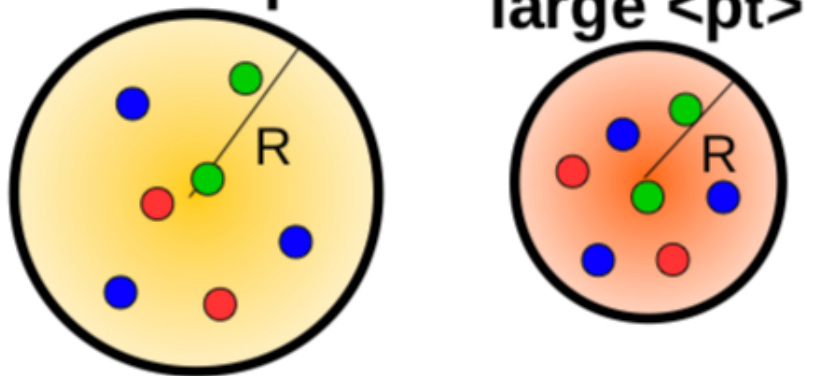


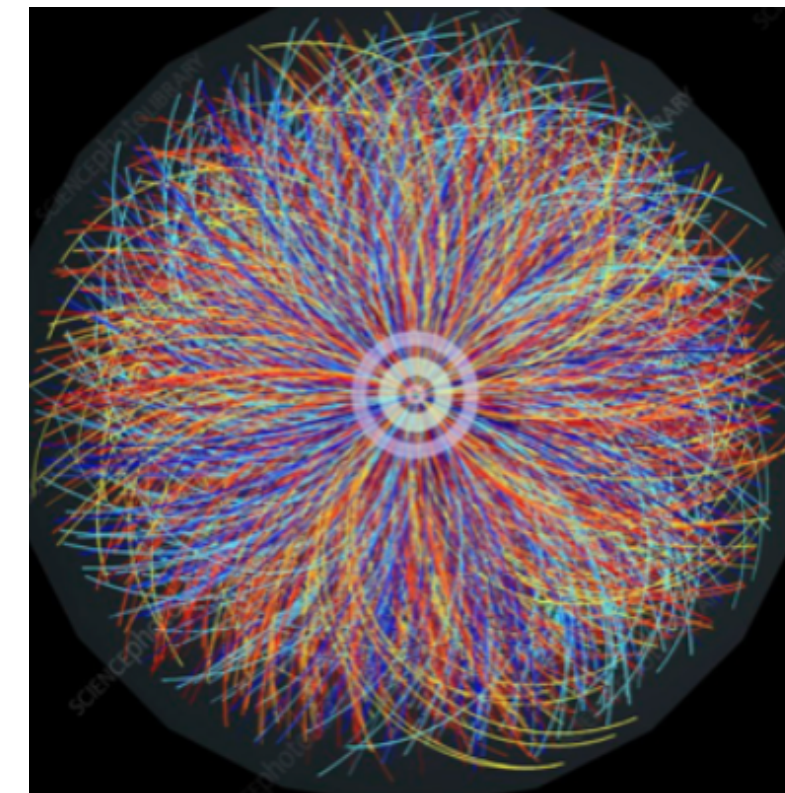
$[p_T]$
 $[p_T^2]$
 $[p_T^3]$
 $[p_T^4]$
 \vdots
 $[p_T^m]$

Radial flow \rightarrow QGP properties

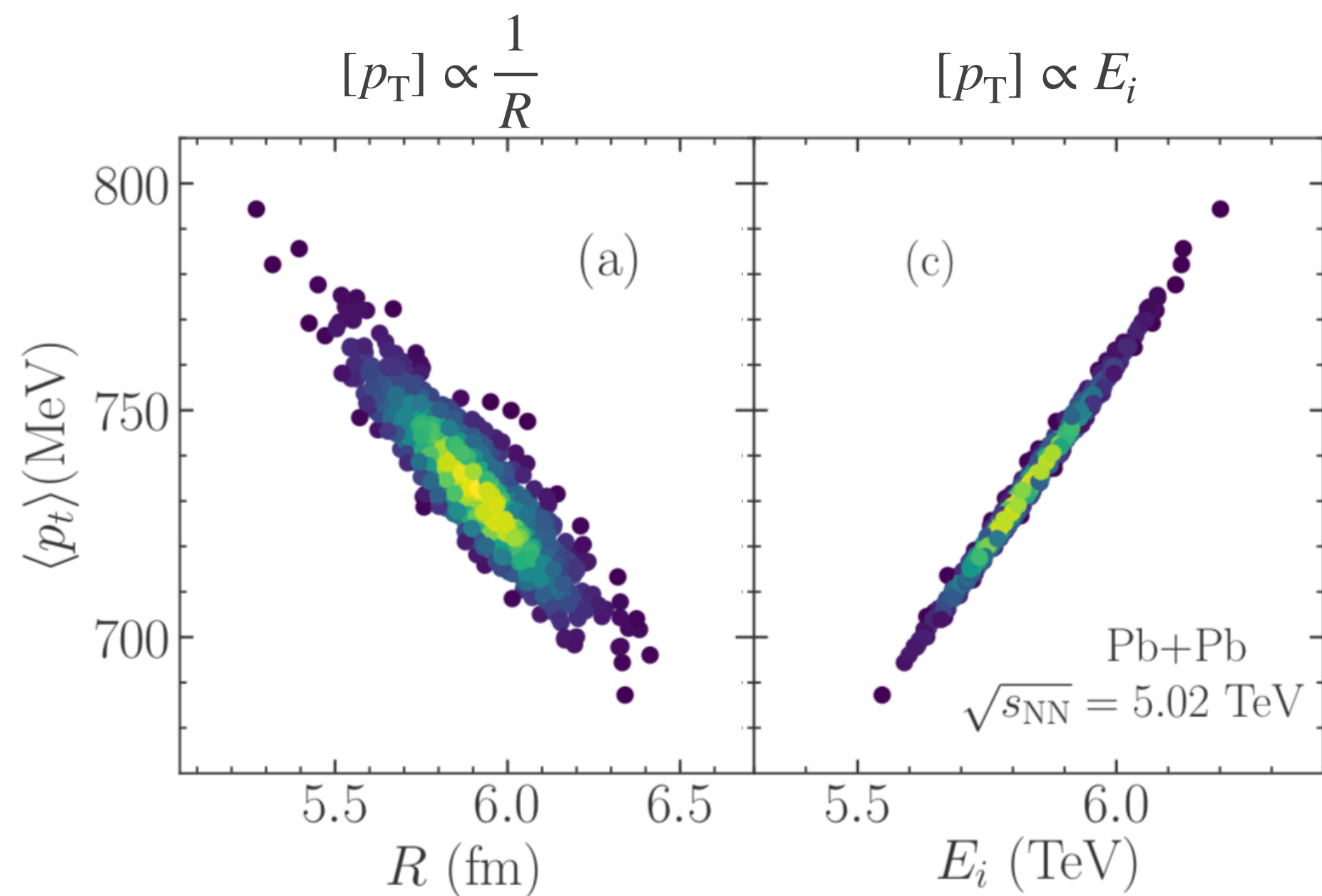
❖ Size of the fireball: radial flow, $[p_T]$

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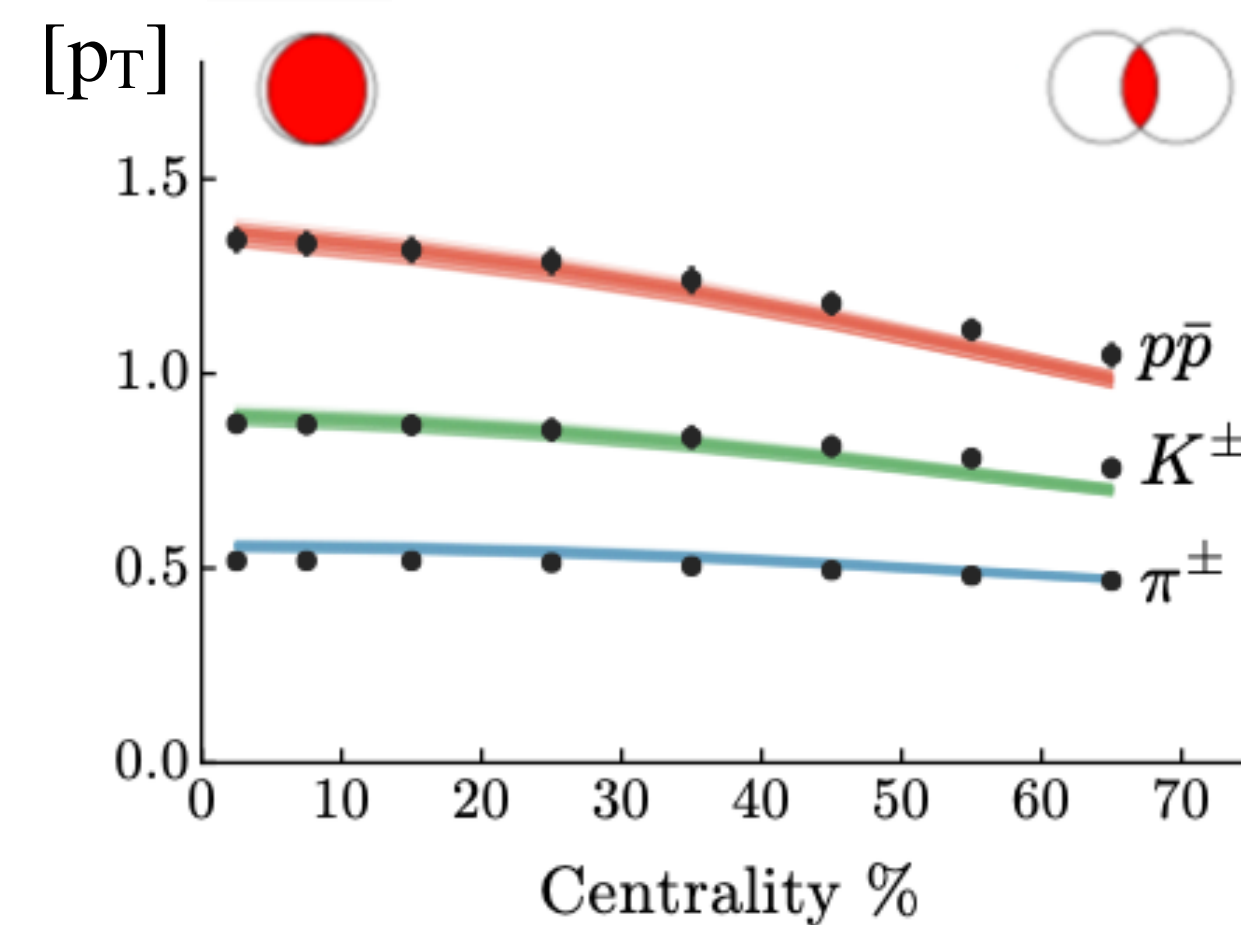
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 $[p_T^2]$
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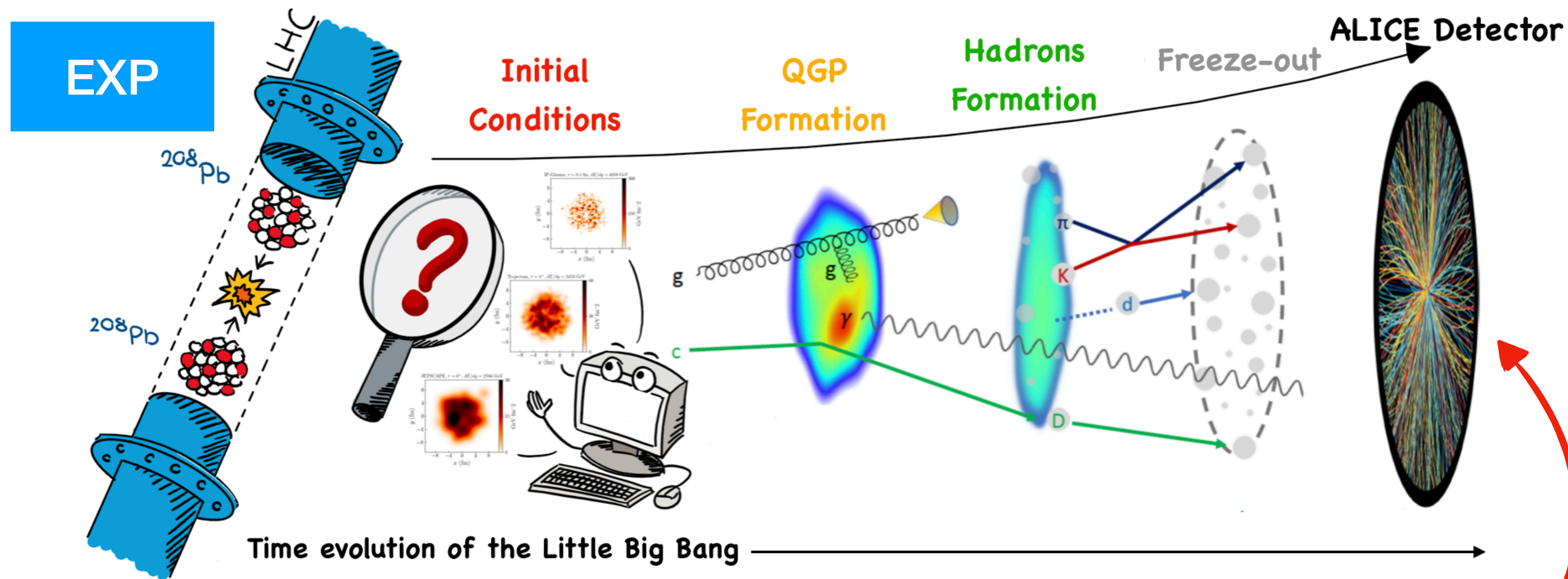


[G. Giacalone et al., PRC103 (2021) 2, 024909]



QGP properties

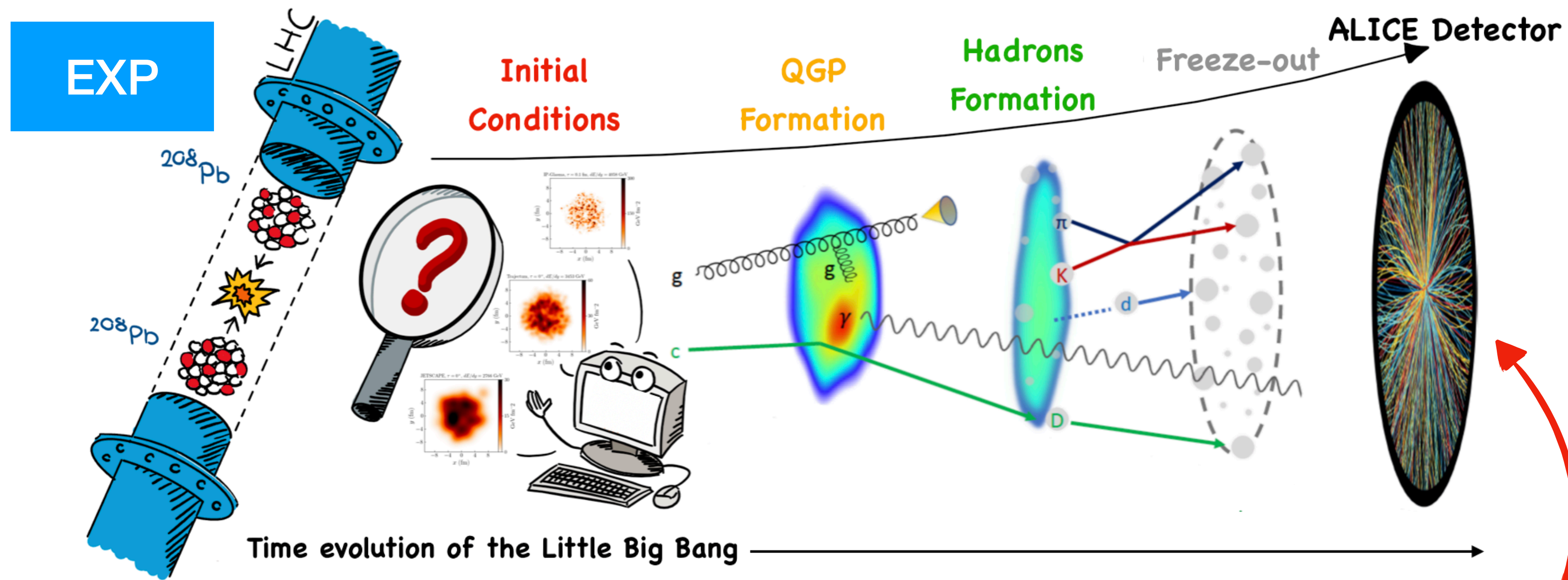
Data and model comparisons



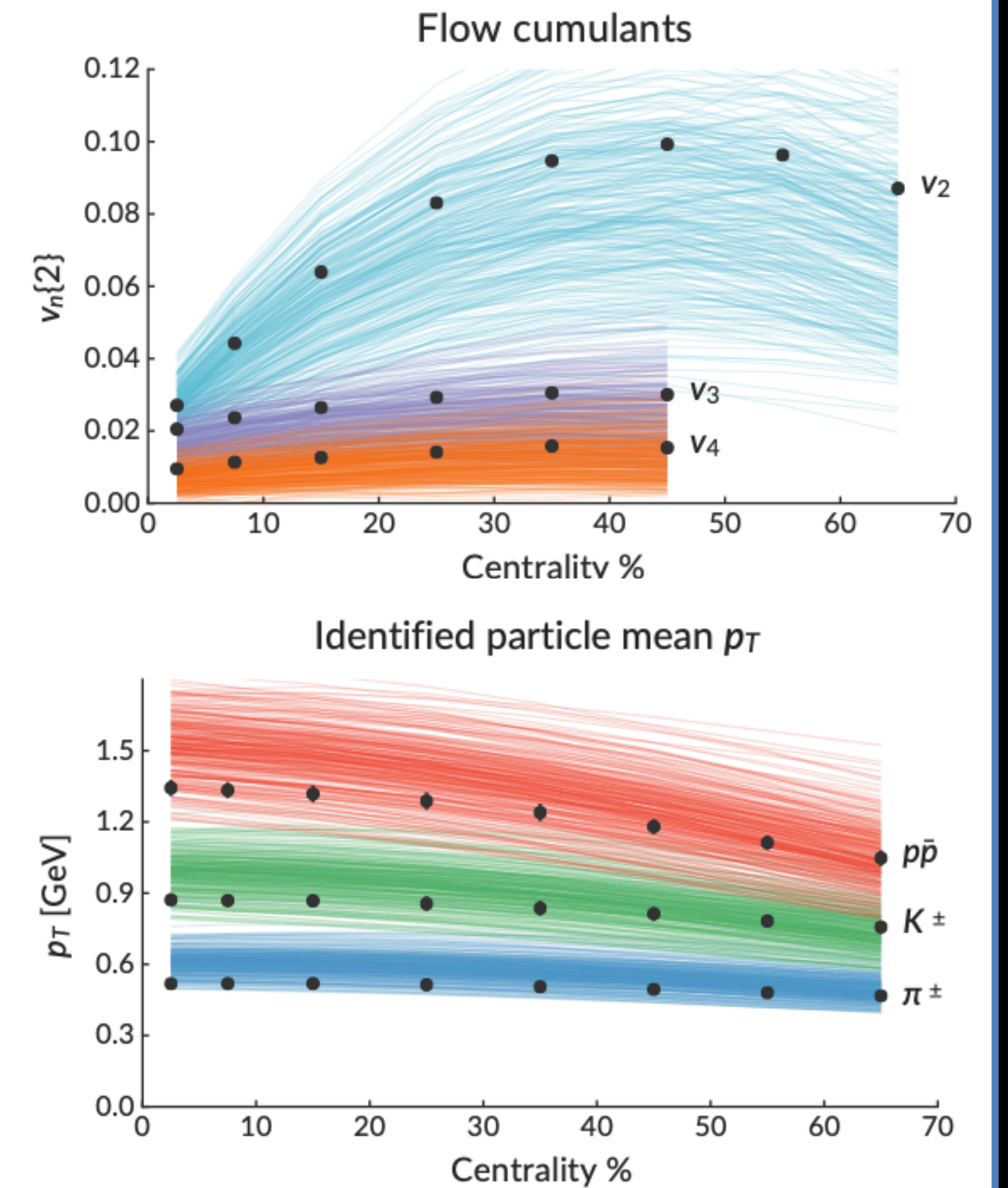
From ALICE@NBI group

- ALICE, Nature Communications 17, 2585 (2026)
- ALICE, arXiv:2603.13217, accepted by JHEP
- ALICE, arXiv:2602.10645, submitted to JHEP
- ALICE, arXiv:2509.06428, submitted to PRL
- ALICE, arXiv:2504.02359, submitted to PRL
- ALICE, JHEP 11, 076 (2025)
- ALICE, Physics Letters B 869 (2025) 139855
- ALICE, Physics Letters B 850 (2024) 138477
- ALICE, Phys. Rev. C 109, 065202 (2024)
- ALICE, JHEP 05, 243 (2023)
- ALICE, Phys. Rev. C Letters, 107 (2023) 051901
- ALICE, Physics Letters B 834, 137393 (2022)
- ALICE, Physics Letters B 818, 136354 (2021)
- ALICE, Phys. Rev. C 104, 024903 (2021)
- ALICE, Phys. Rev. C 103, 024913 (2021)
- ALICE, JHEP 06, 147 (2020)
- ALICE, JHEP 05, 085 (2020)
- ALICE, Eur. Phys. J. C 80, 846 (2020)

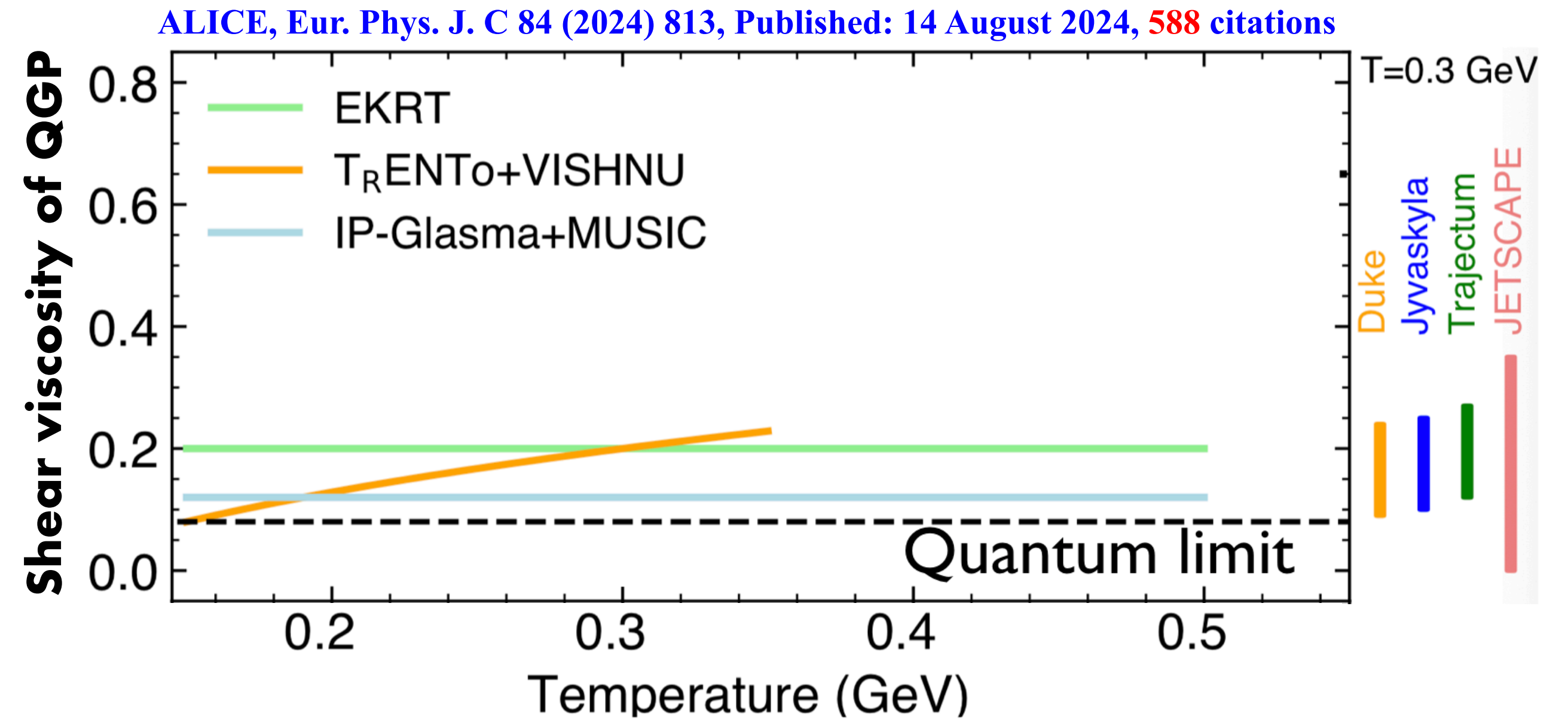
Data and model comparisons



Global Bayesian Analysis



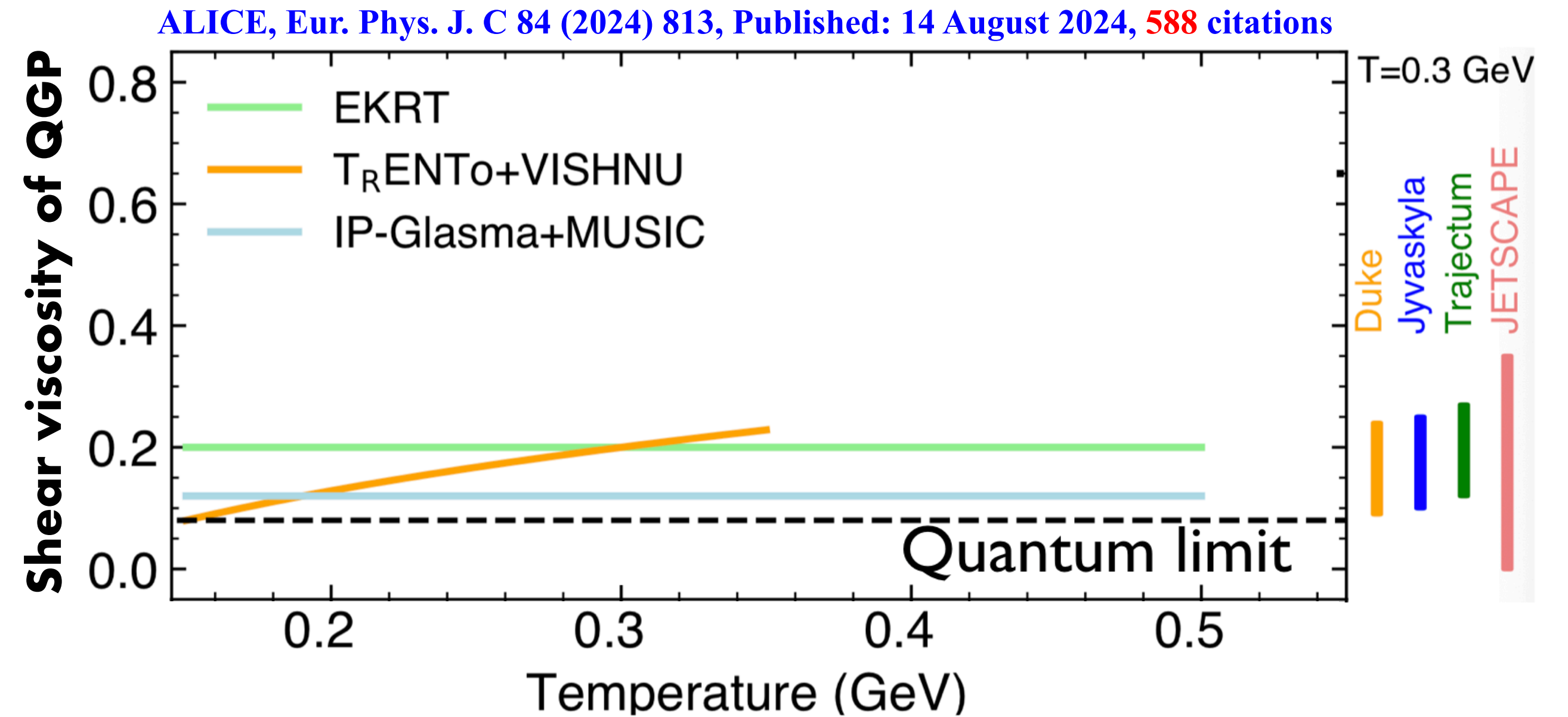
Primary goal of high-energy nuclear collisions: QGP



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

$\eta/s(T)$ is very close to $1/4\pi$ (Quantum limit) \rightarrow Perfect fluid

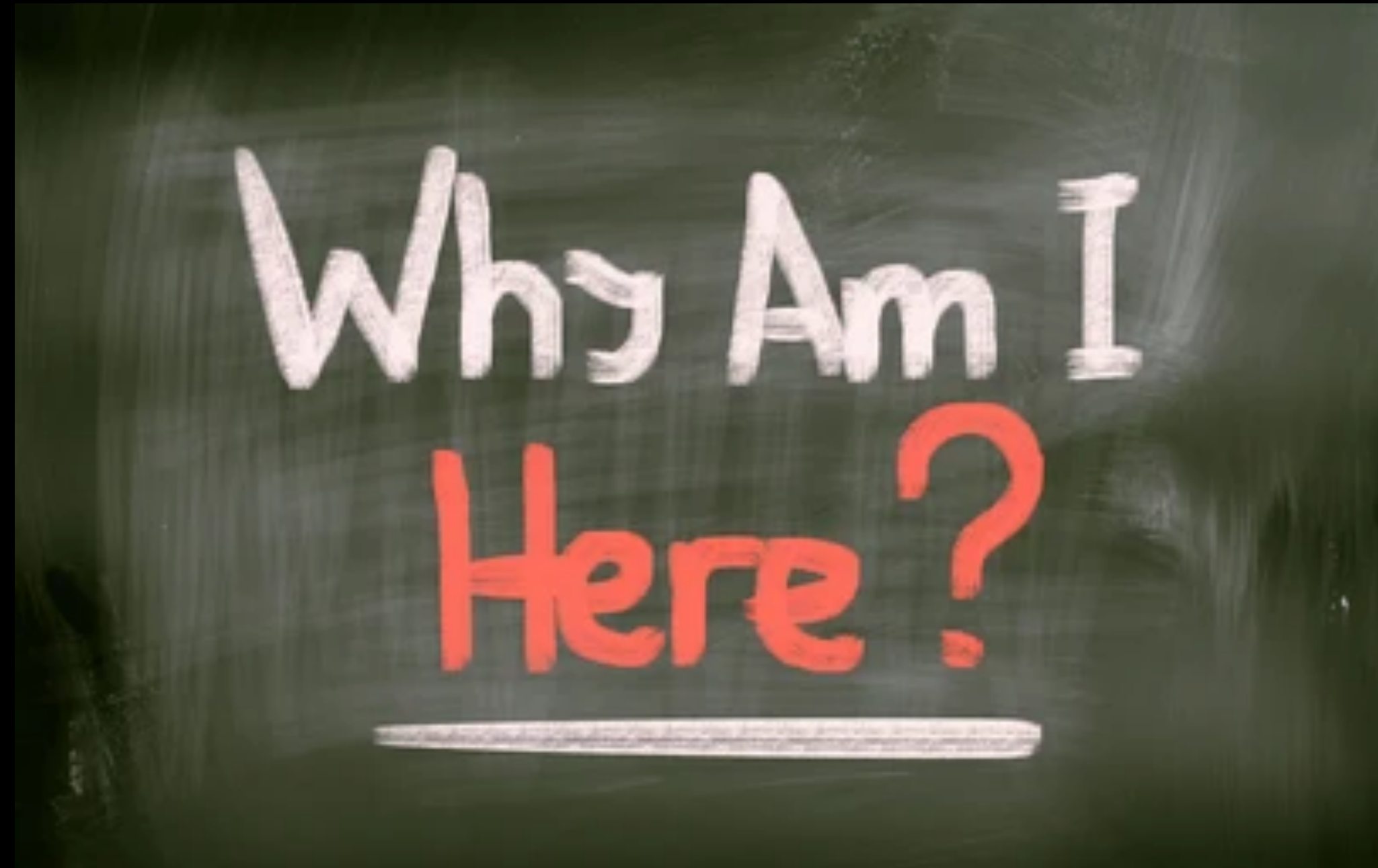
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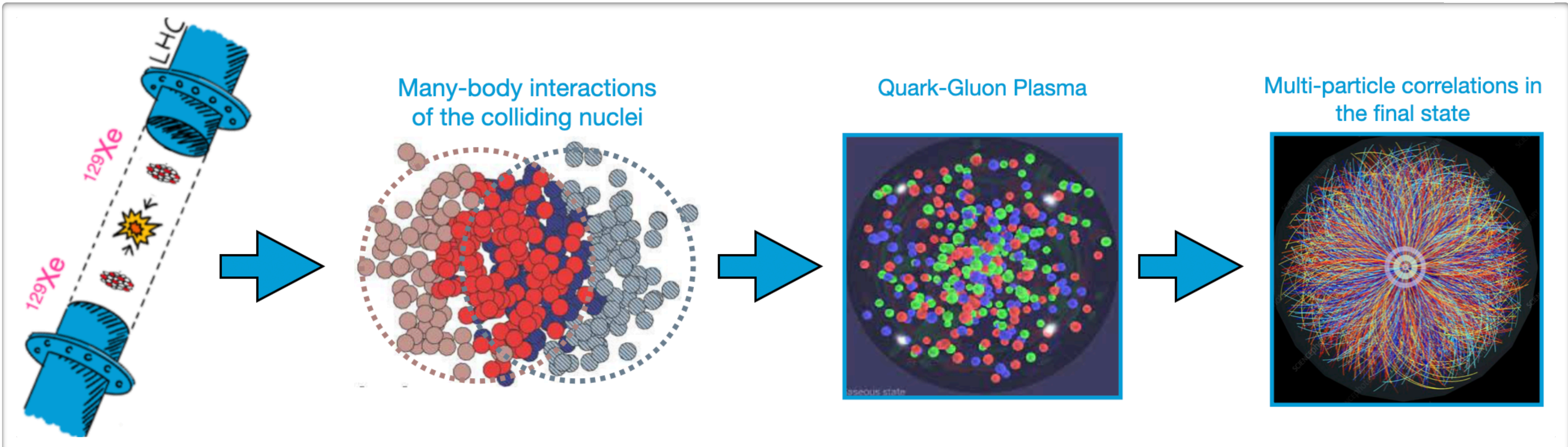
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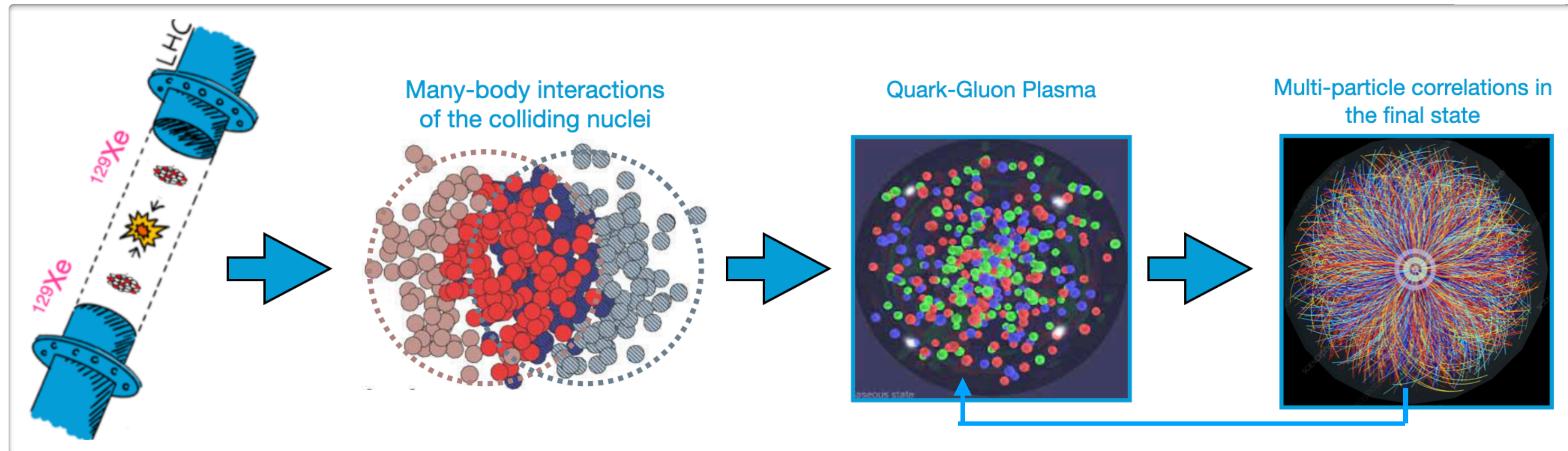
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Quark-Gluon Plasma? Not Nuclear Structure?

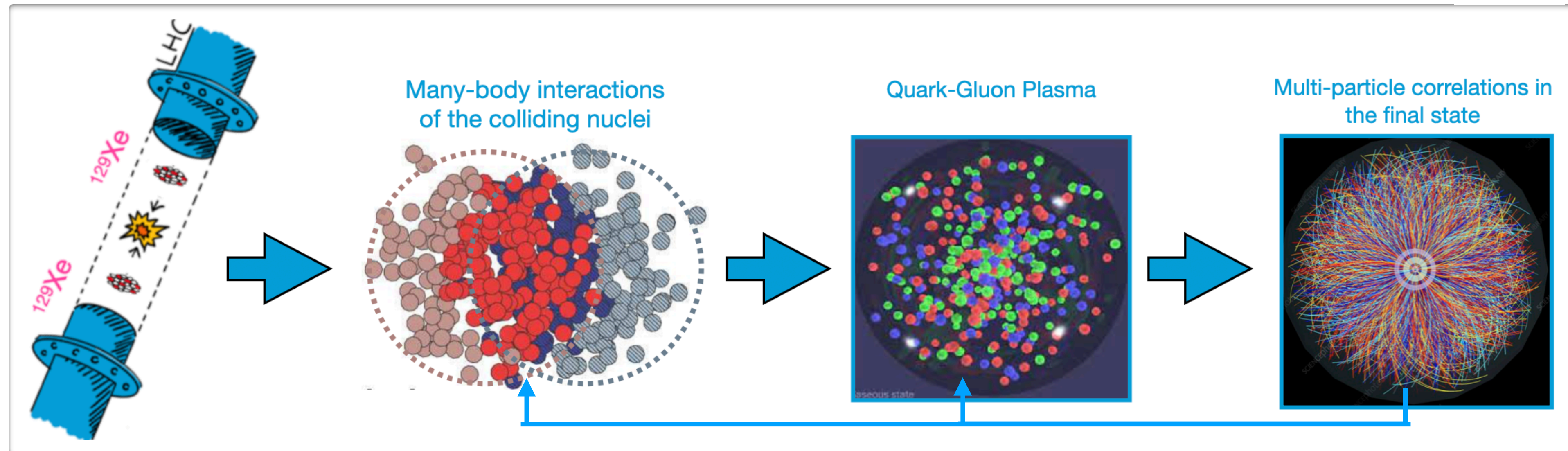


Collective flow

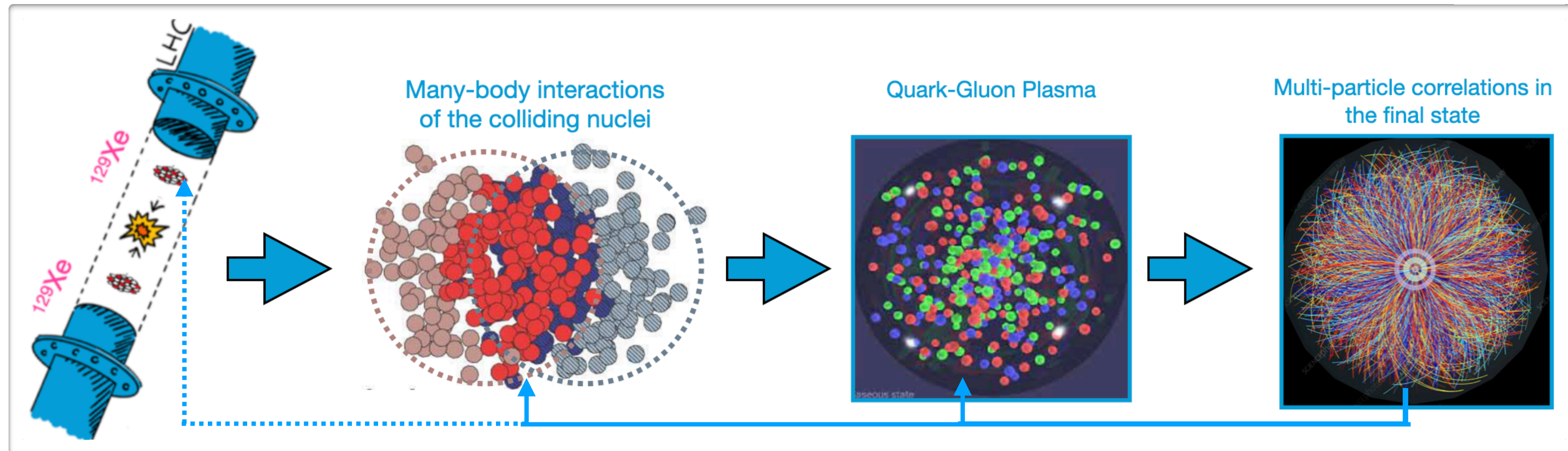




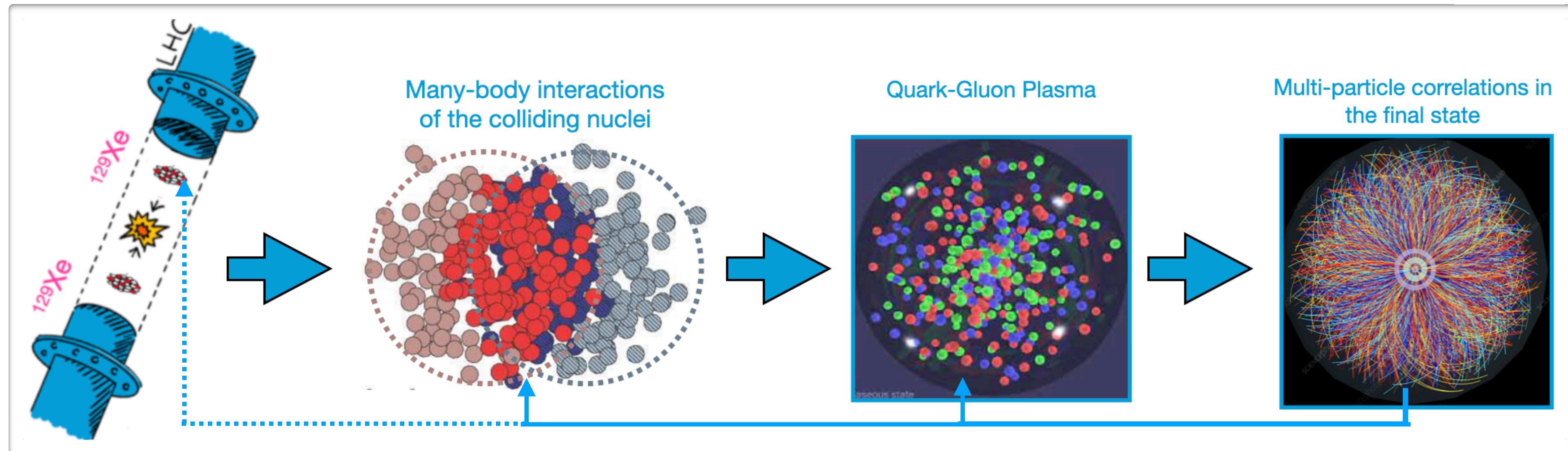
initial conditions \leftarrow QGP \leftarrow Collective flow



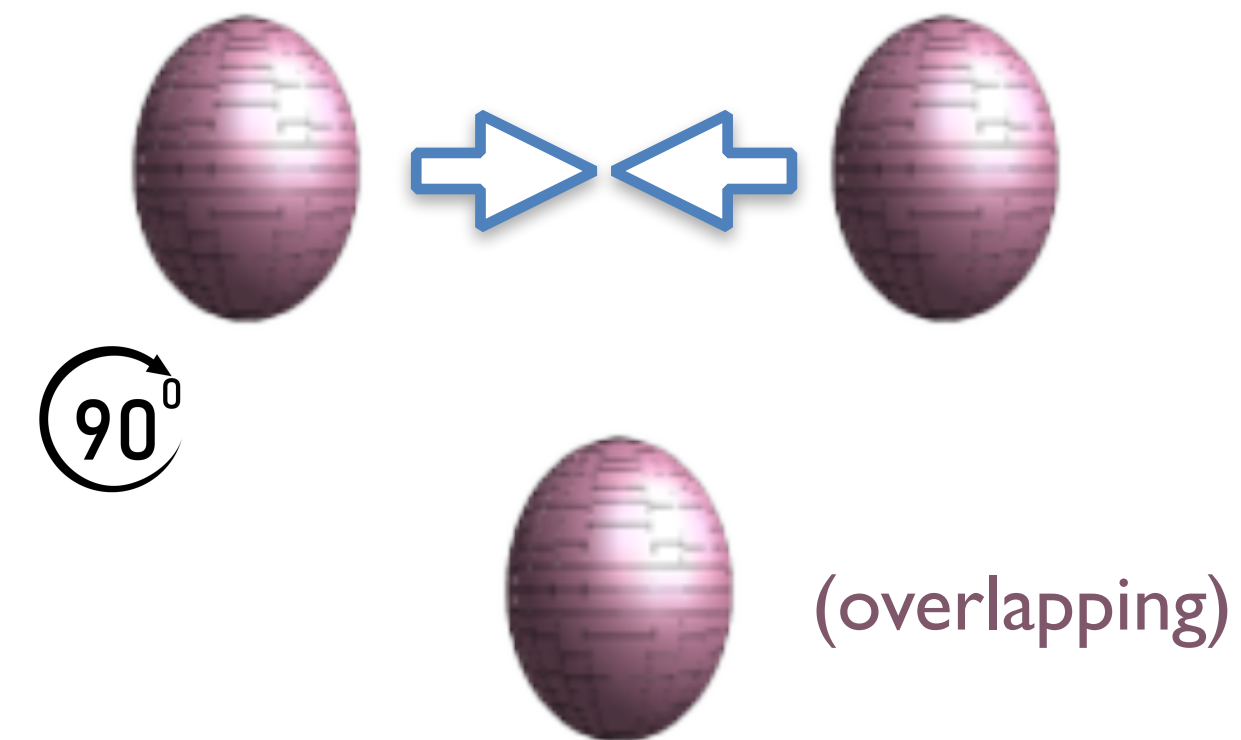
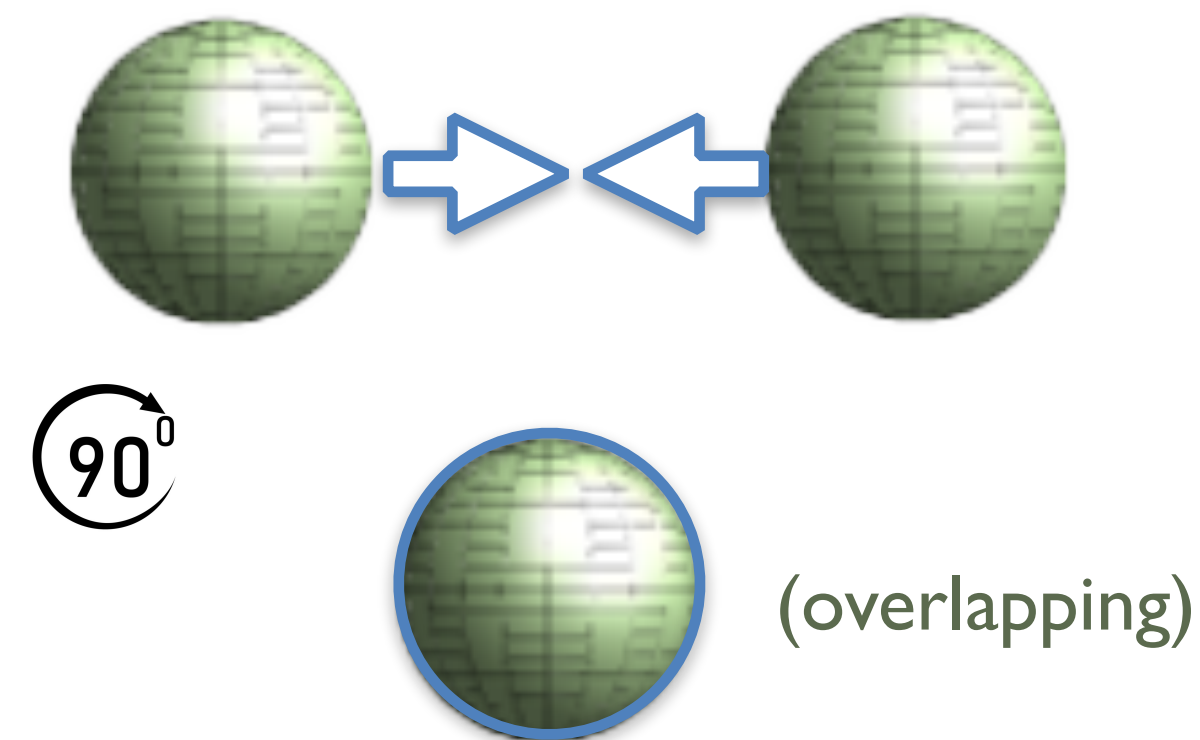
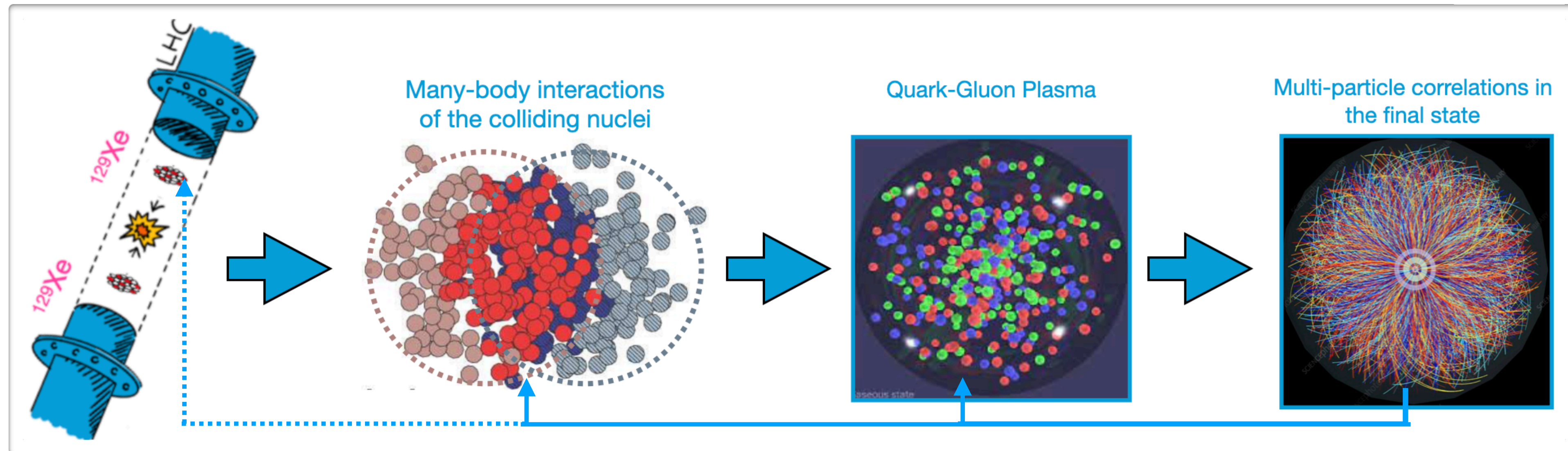
Nuclear Structure \leftarrow initial conditions \leftarrow QGP \leftarrow Collective flow



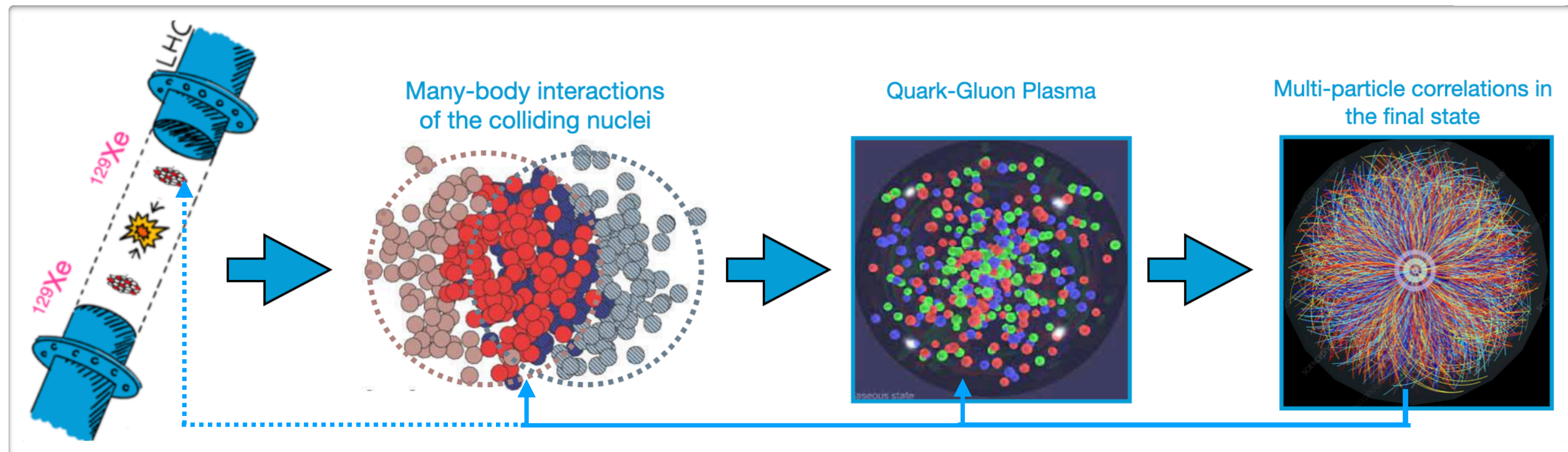
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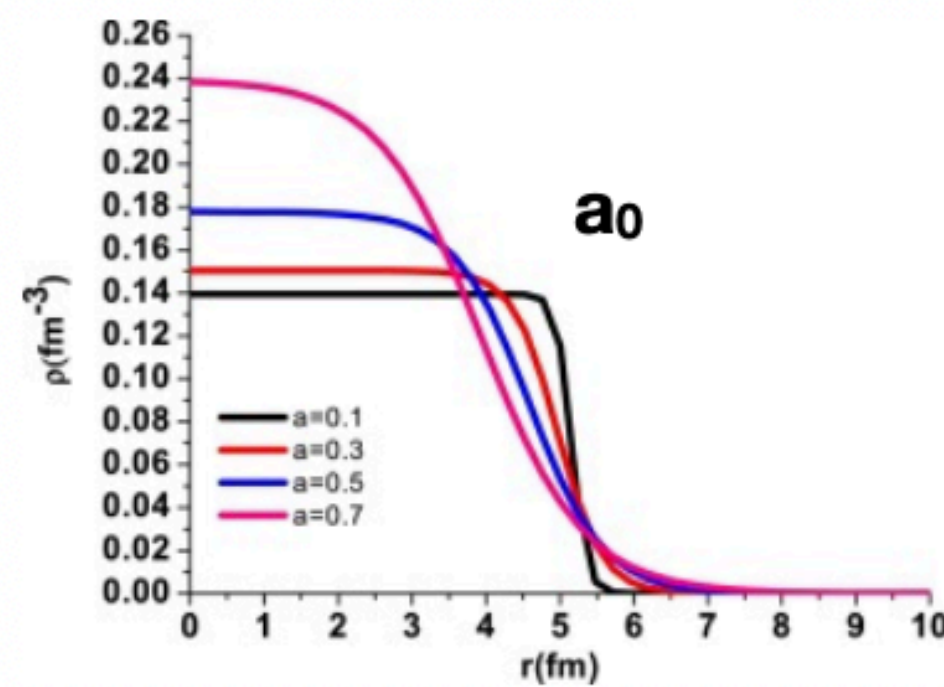
Nuclear Structure ← initial conditions ← QGP ← Collective flow



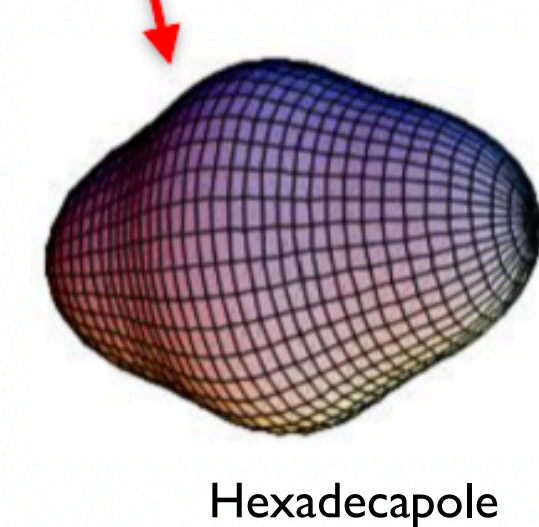
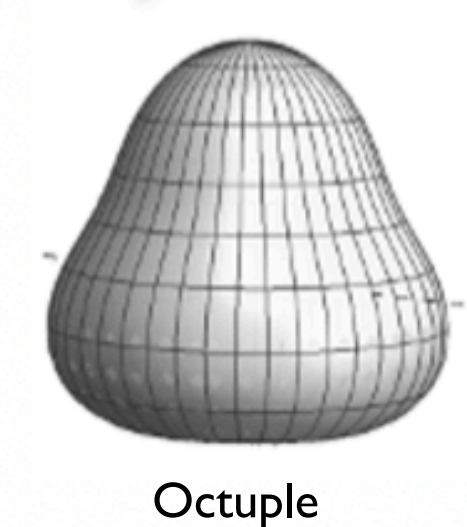
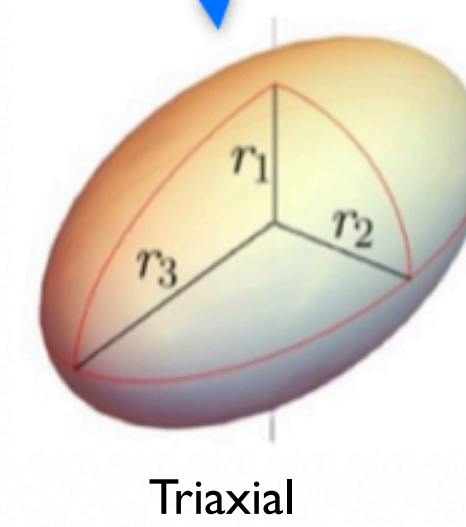
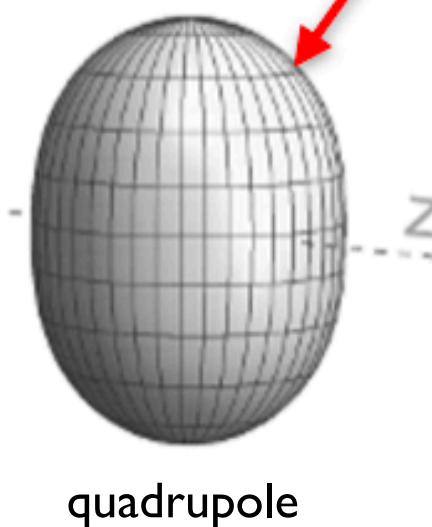
Starting point:

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

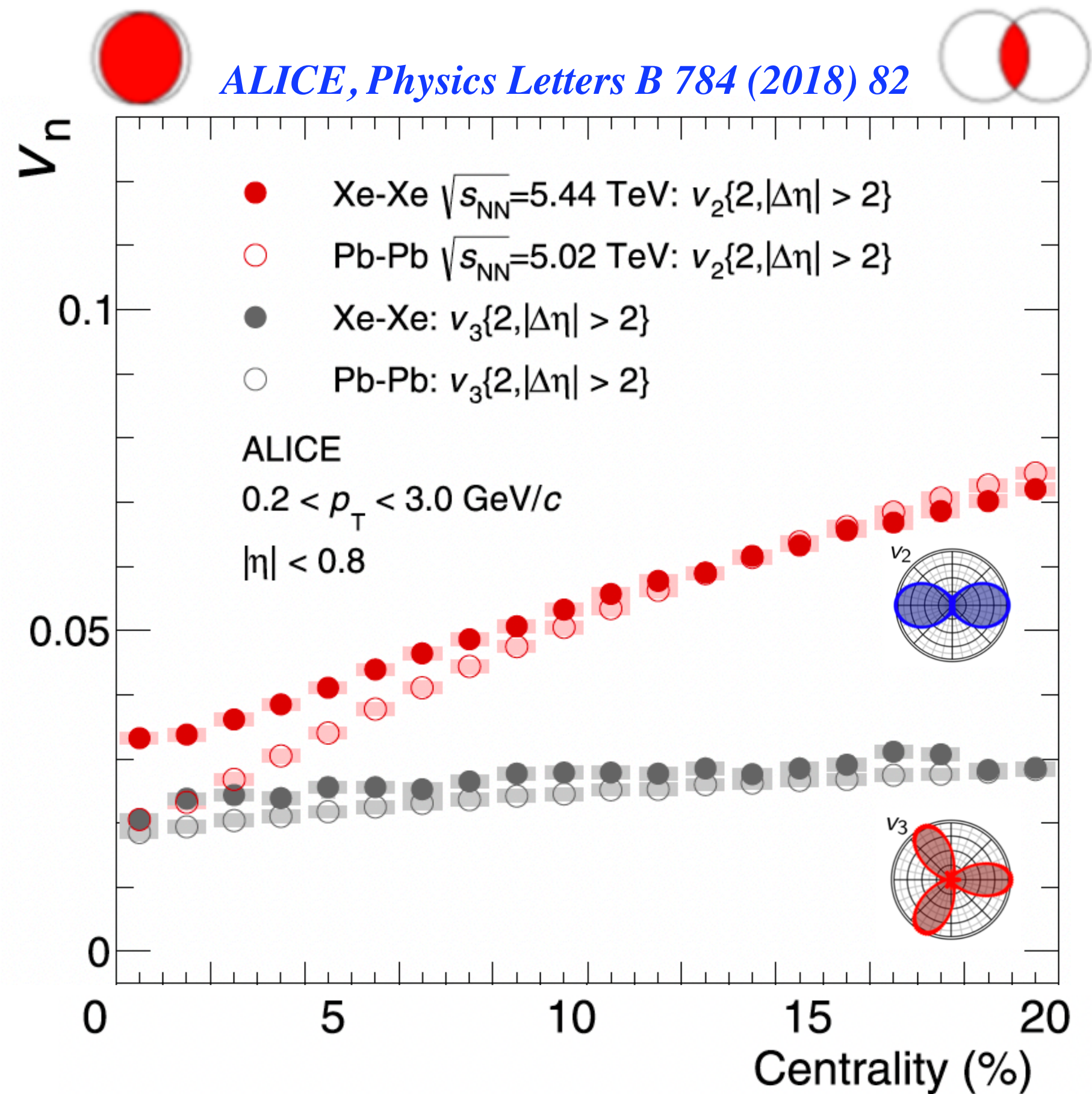
$$\rho(r, \theta, \phi) = \frac{\rho_0}{1 + e^{(r-R(\theta, \phi))/a_0}}$$



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

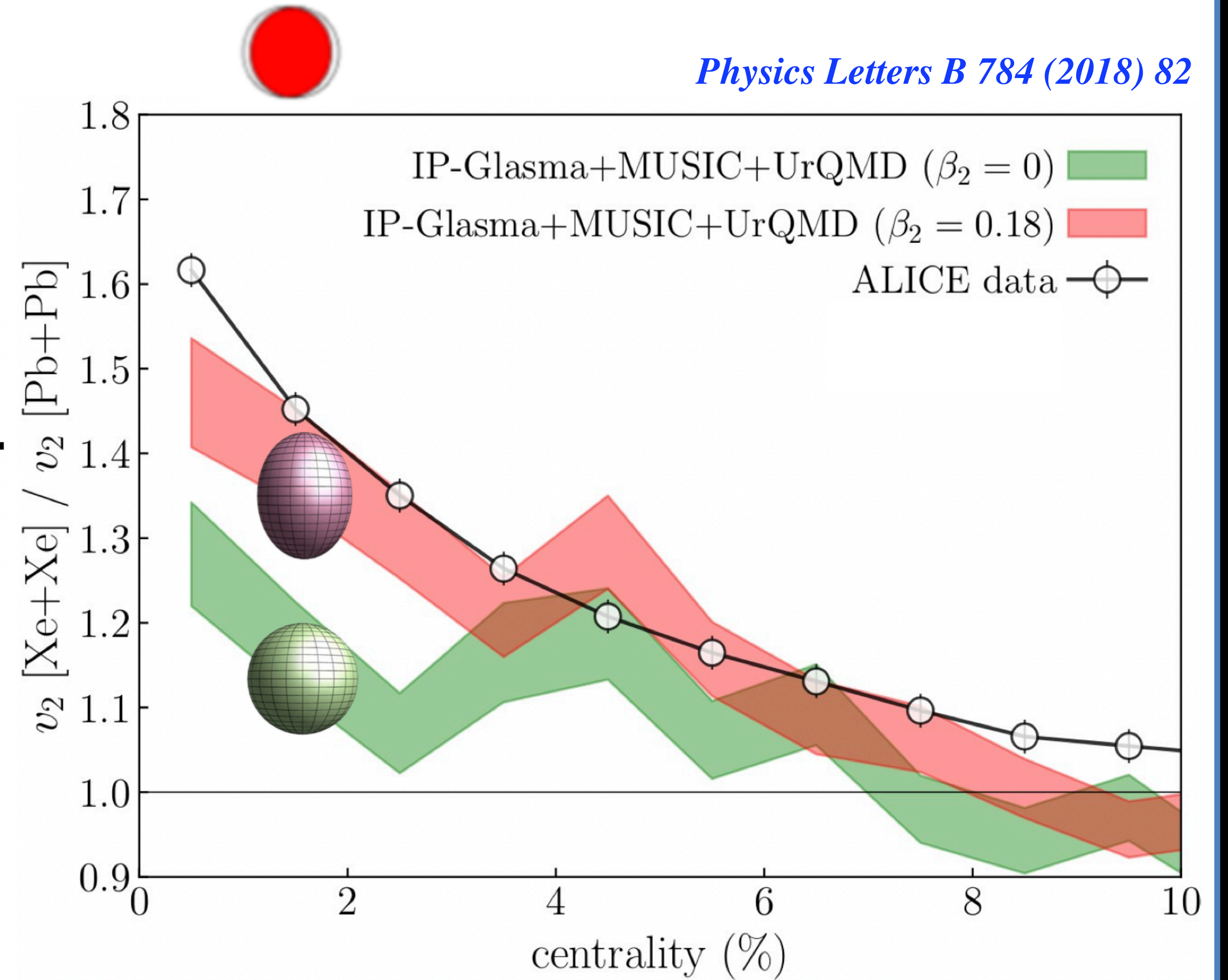
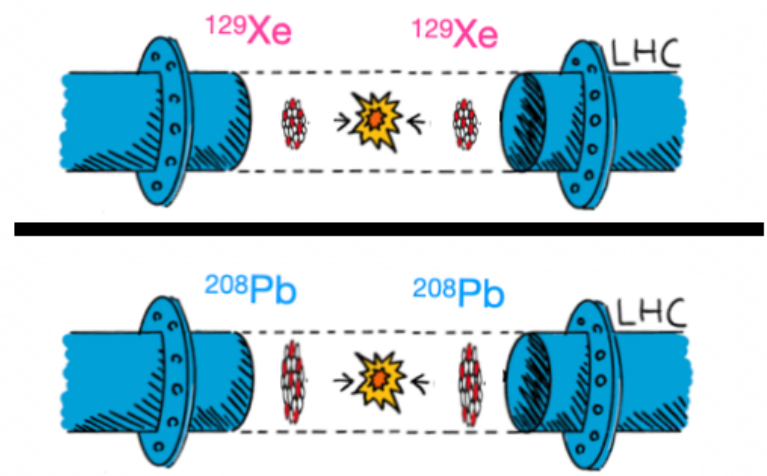
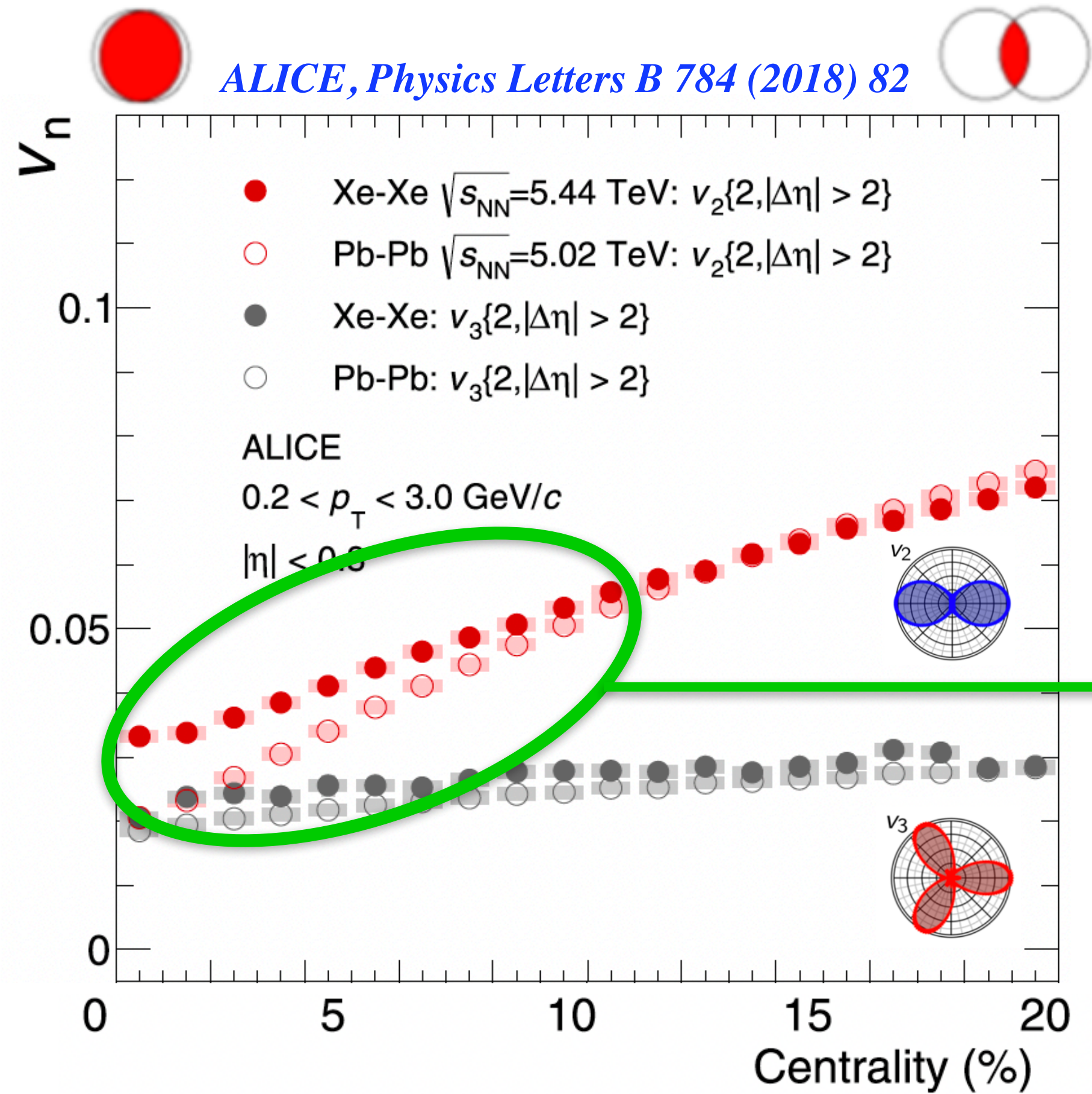


Emergence of Nuclear structure effect via **Anisotropic Flow**



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

Emergence of Nuclear structure effect via **Anisotropic Flow**



- ❖ Significant v_2 enhancements in central Xe-Xe collisions than in Pb-Pb collisions
 - It was realised that such enhancement is due to the NS effect, originated from large β_2 deformation

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

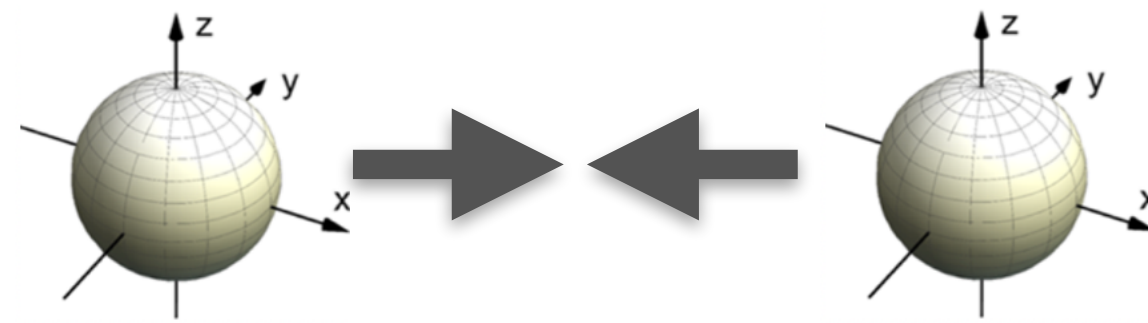


Regular Article - Theoretical Physics

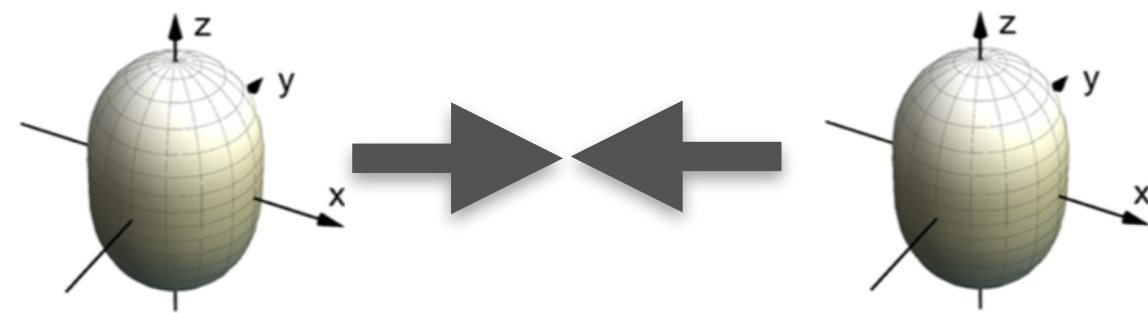
Probe nuclear structure using the anisotropic flow at the Large Hadron Collider

Zhiyong Lu¹, Mingrui Zhao^{1,2}, Xiaomei Li¹, Jiangyong Jia^{3,4}, You Zhou^{2,a}

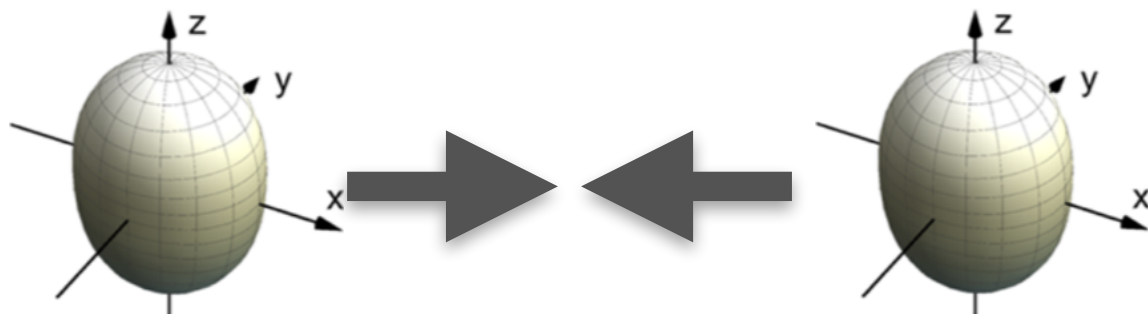
spheric
 $(\beta_2 = 0)$



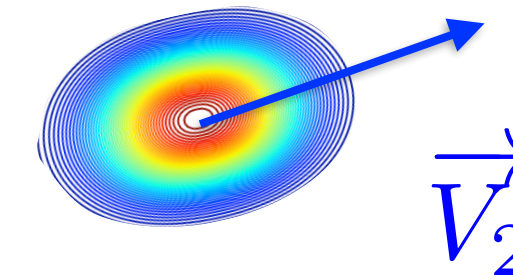
Prolate
 $(\beta_2 > 0, \gamma=0)$



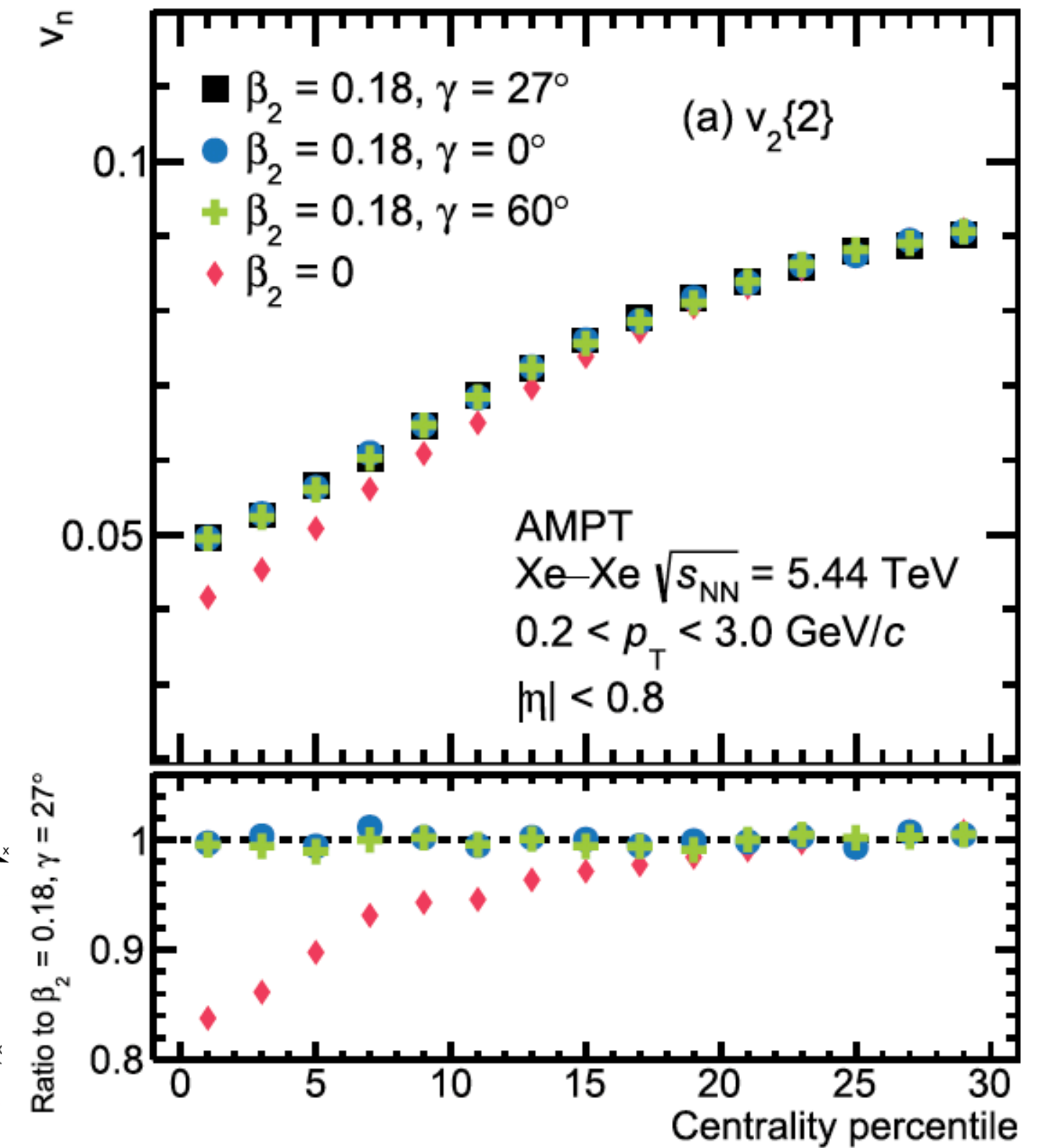
Triaxial
 $(\beta_2 > 0, \gamma=30^\circ)$



Oblate
 $(\beta_2 > 0, \gamma=60^\circ)$



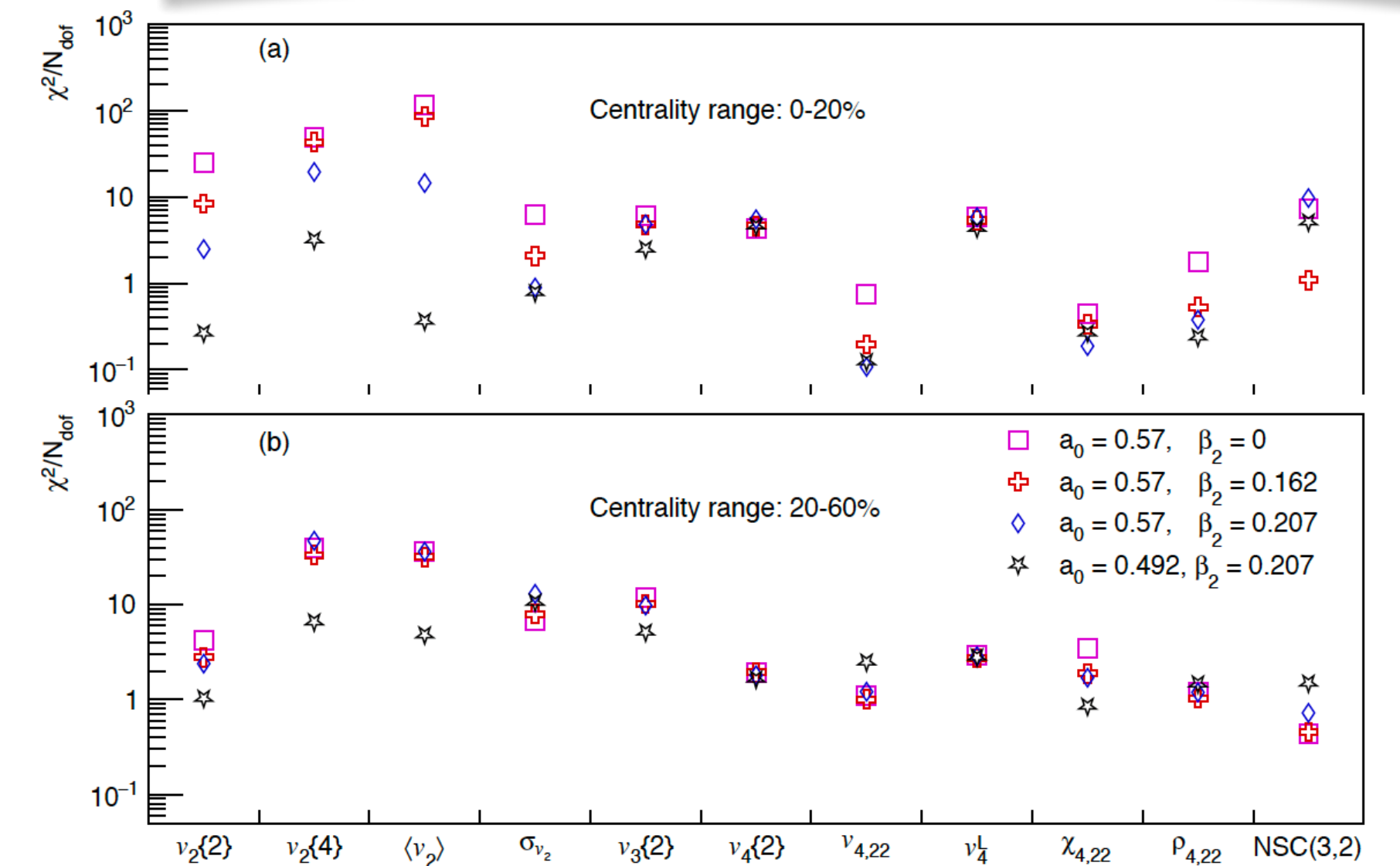
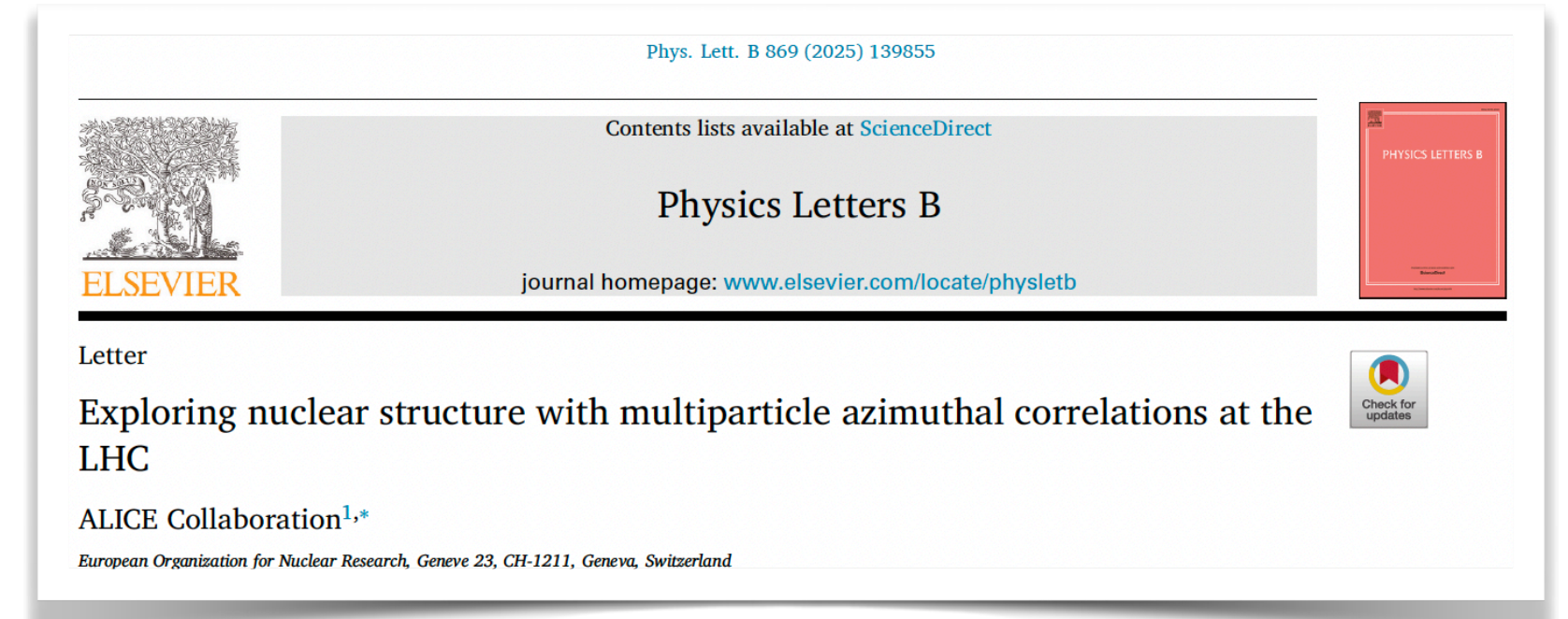
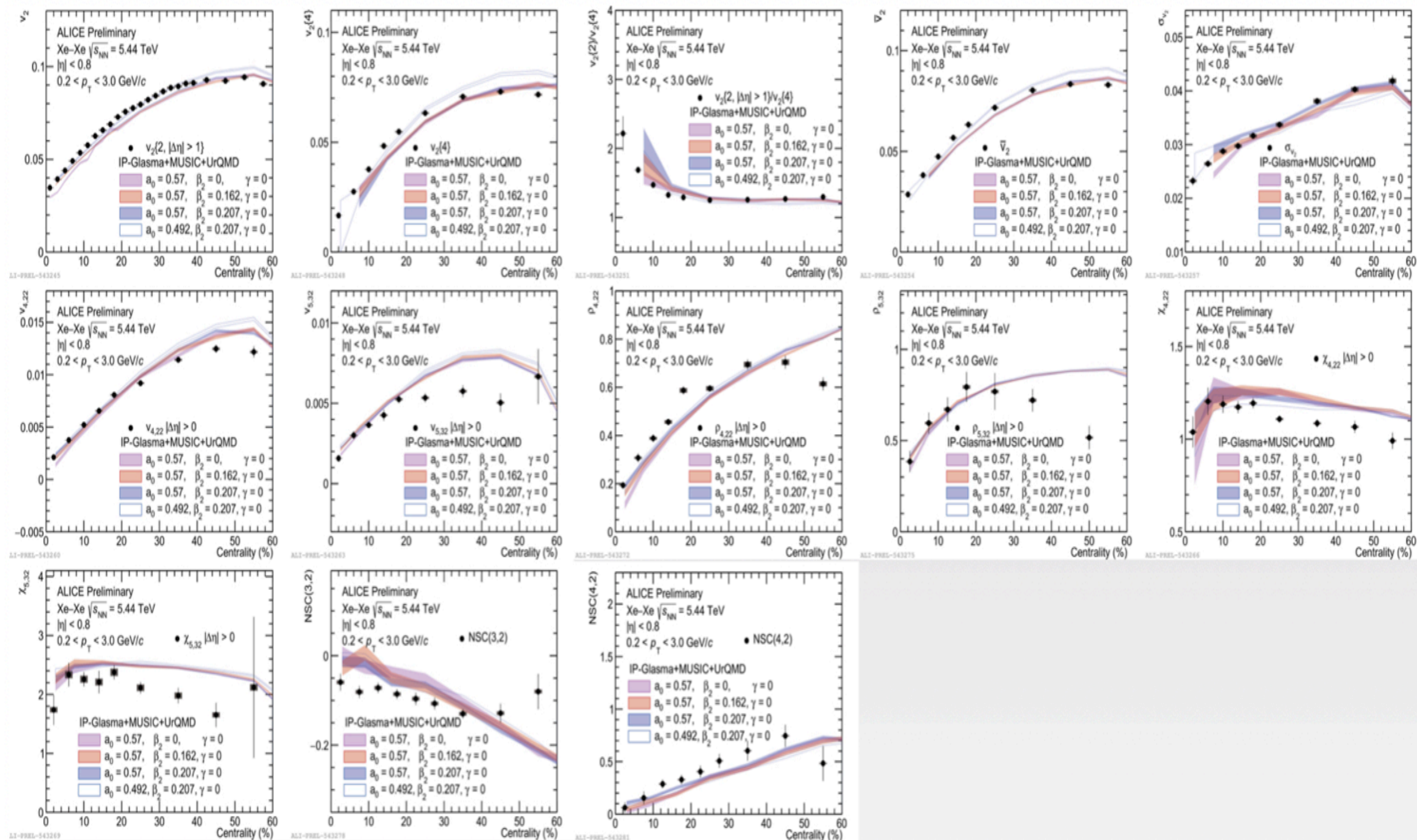
$$\langle v_2^2 \rangle \rightarrow \frac{3}{4\pi} \langle \beta_2^2 \rangle$$



- ❖ Significant v_2 enhancements \rightarrow large β_2
- ❖ No difference from different γ , no impact of triaxial structure in v_2



Nuclear structure of ^{129}Xe with **Anisotropic Flow**



- ❖ Overall, calculations with $a_0 = 0.492$ and $\beta_2^{\text{W-S}} = 0.207$ describes the flow measurements better in Xe–Xe collisions
 - Compatible with low-energy nuclear structure (MeV energy scale).



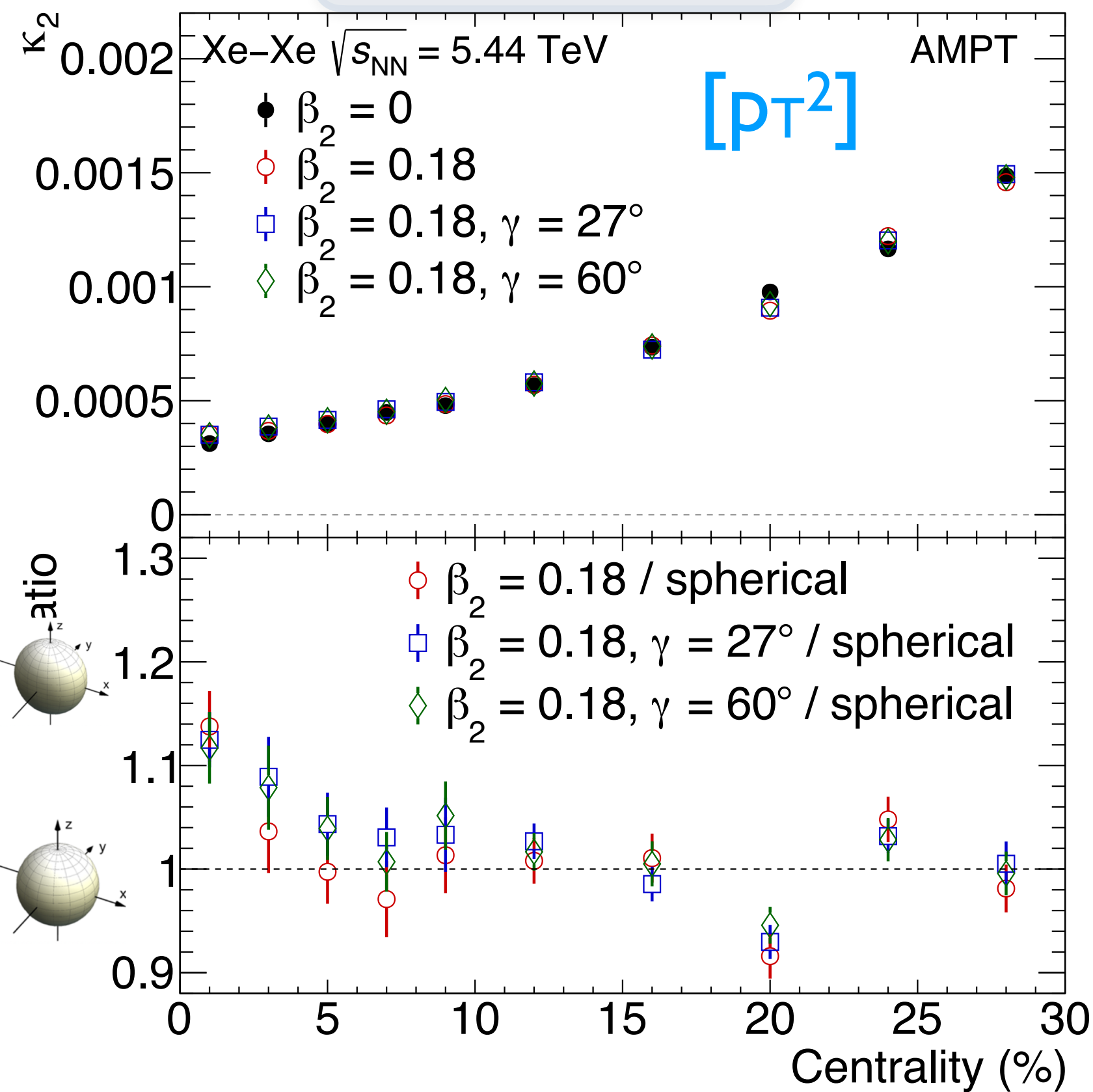
Nuclear structure of ^{129}Xe with **Radial Flow**

- $[\rho_T]$ and its event-by-event fluctuations measured in heavy-ion collisions at the LHC

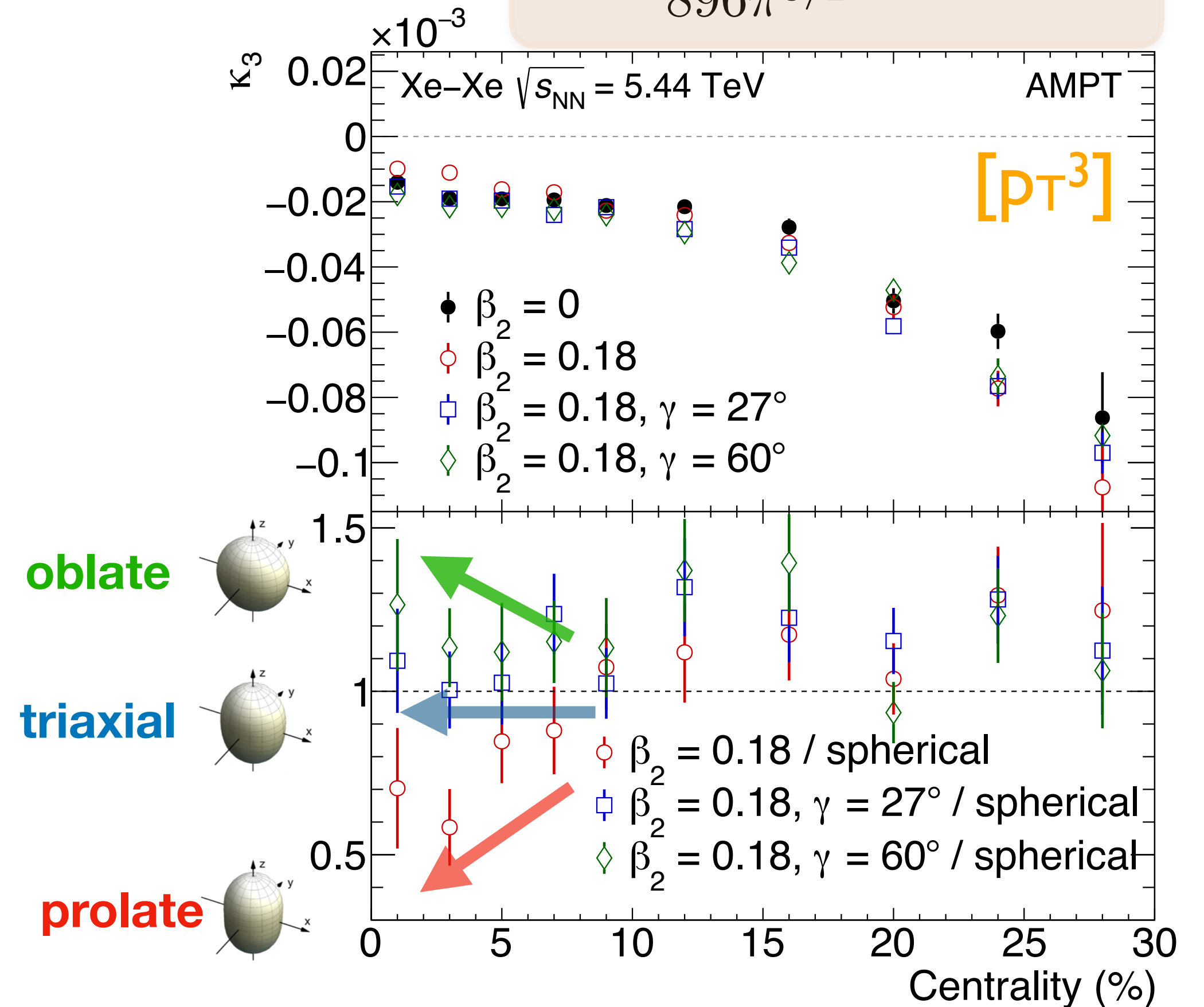
-> probe initial **size** and **size fluctuations** -> **NS**

E. G. Nielsen et al., EPJA (2024) 60, 38

$$\kappa_2 \rightarrow \frac{1}{32\pi} \langle \beta_2^2 \rangle$$

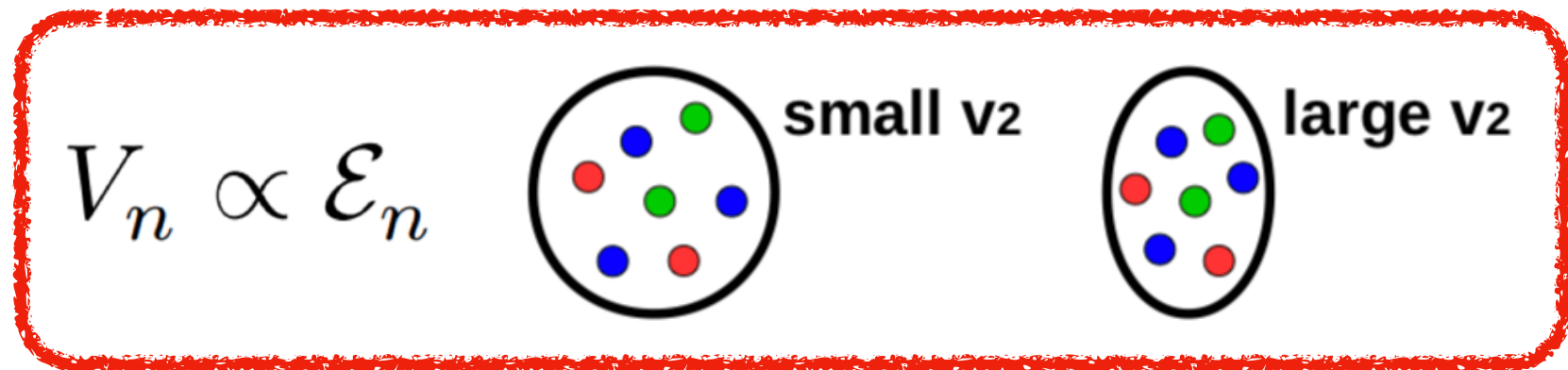


$$\kappa_3 \rightarrow \frac{1}{896\pi^{3/2}} \langle \cos(3\gamma) \beta_2^3 \rangle$$

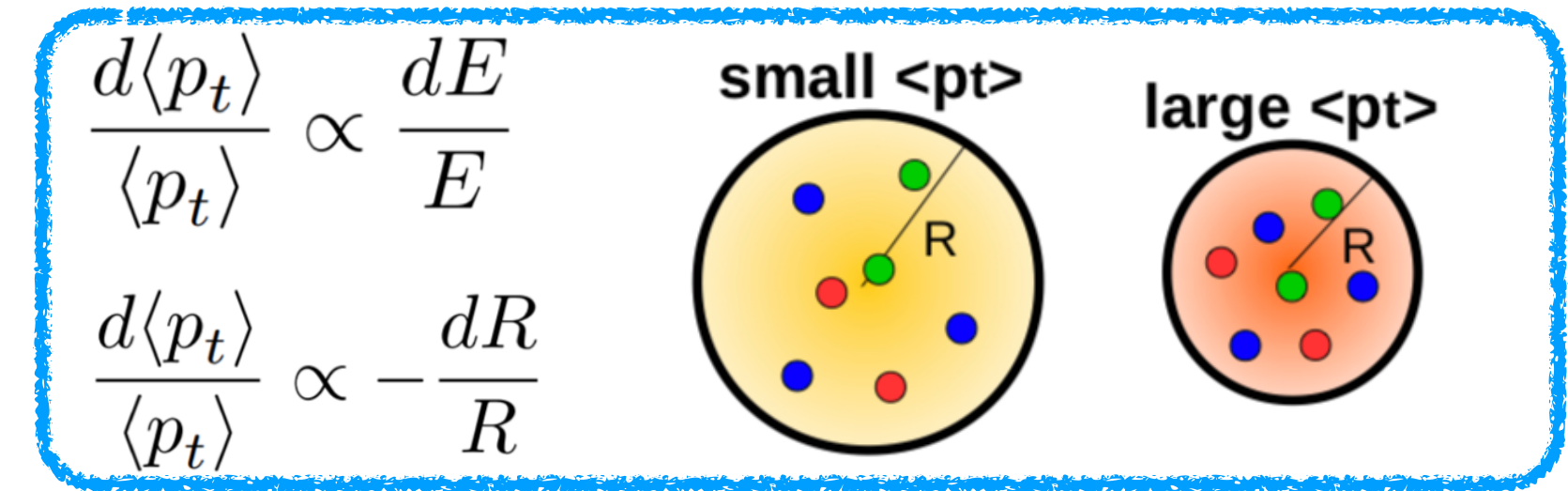


Nuclear structure with “Shape-Size correlation”

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

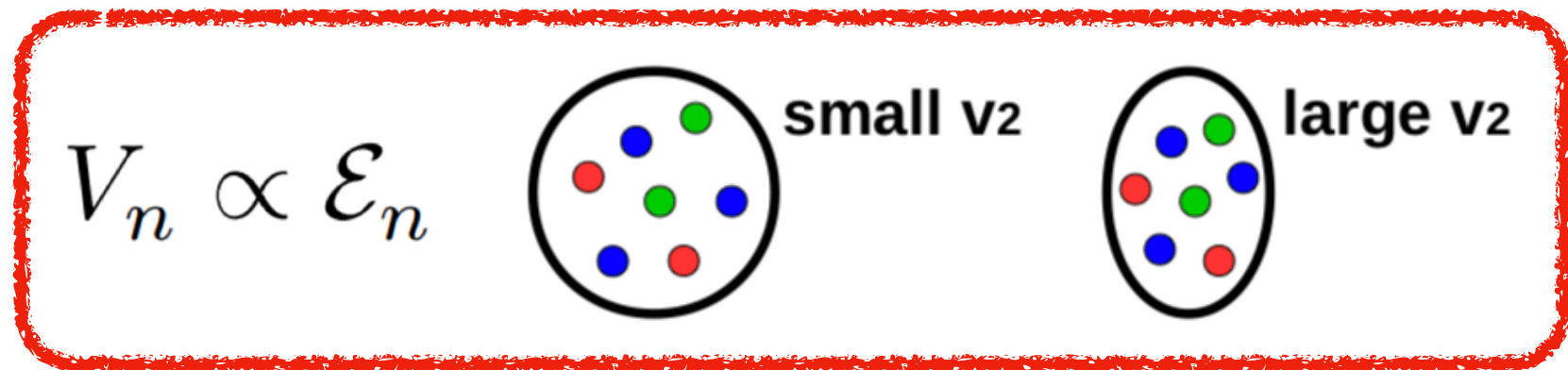


❖ **Size** of the fireball: **Radial Flow, $[p_T]$**

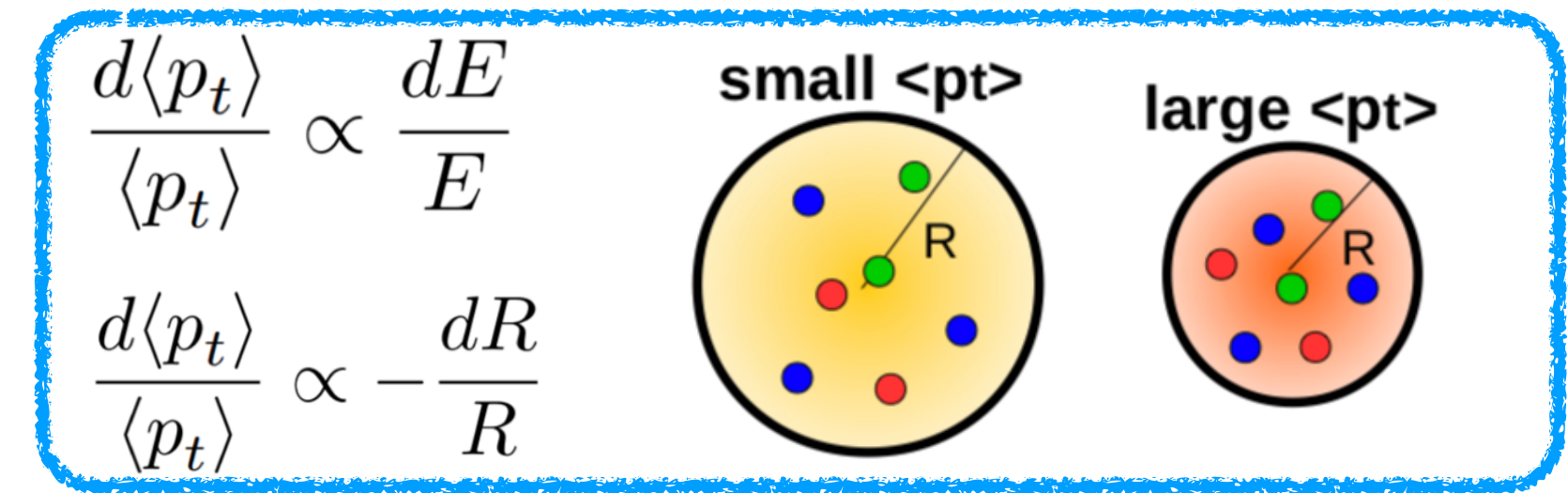


Nuclear structure with “Shape-Size correlation”

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



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❖ **Shape-Size** correlation: $\rho(v_n^2, [p_T])$

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

P. Bozek etc, PRC96 (2017) 014904

❖ Considering $v_n \propto \epsilon_n$, $[p_T] \propto E_0$

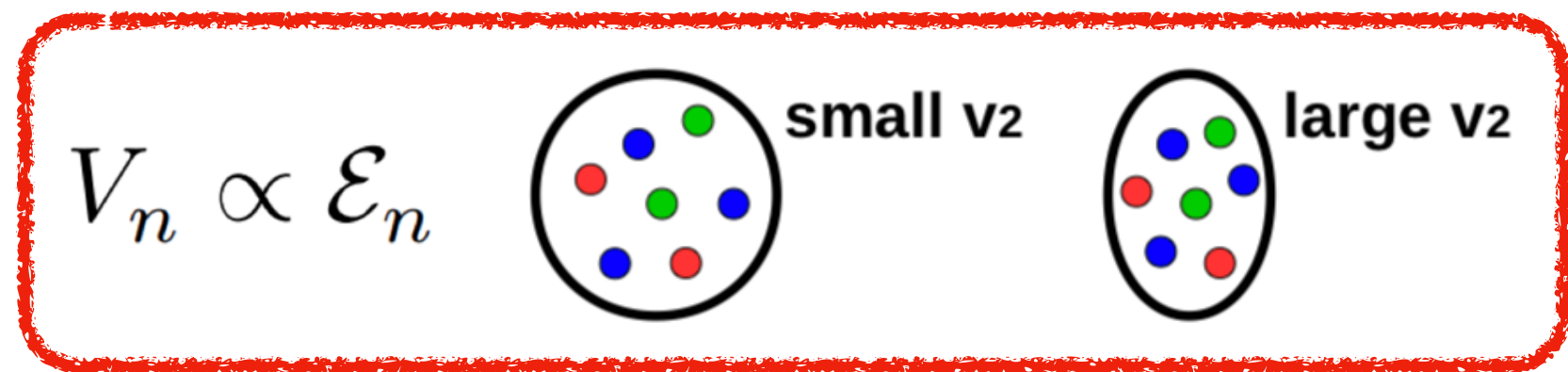
$$\rho(v_n^2, [p_T]) = \rho(\epsilon_n^2, [E_0])$$

final-state model
calculation

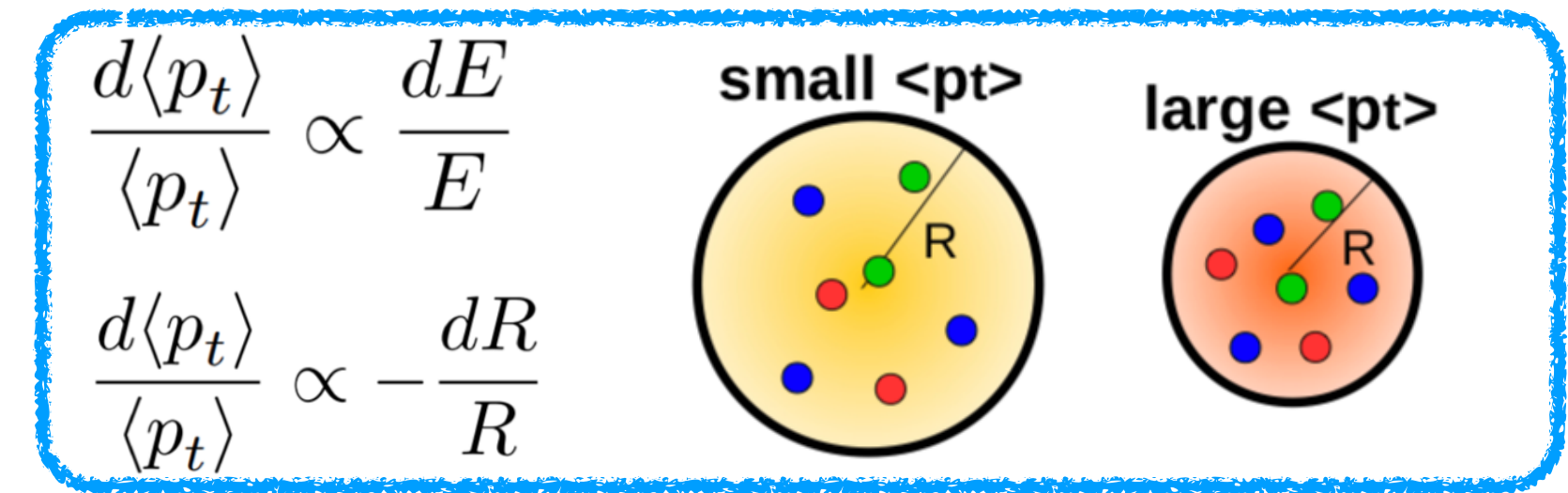
Initial-state model
estimation

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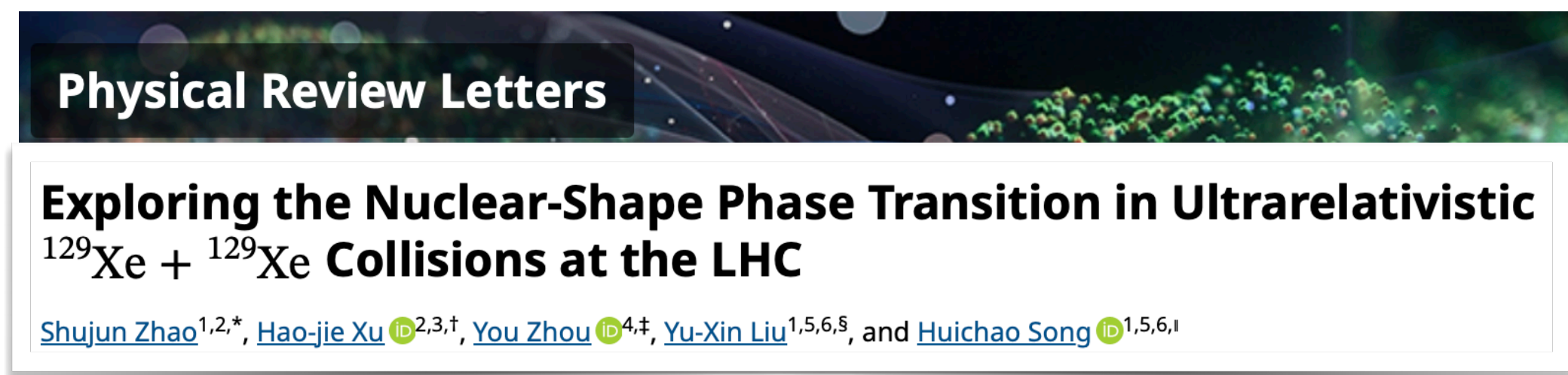
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final-state model
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S. Zhao etc., Phys. Rev. Lett. 133 (2024) 192301



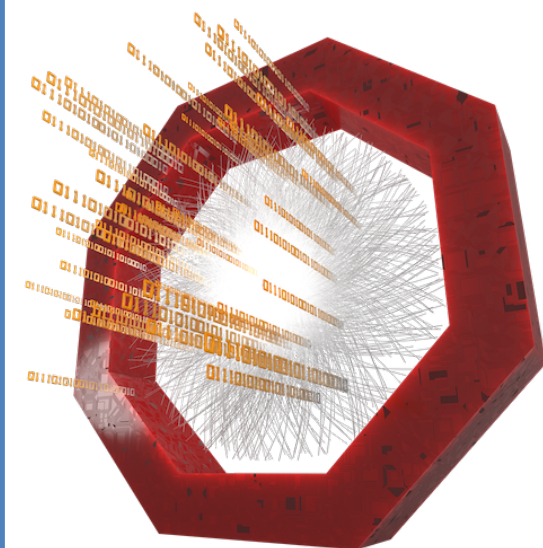
$$\rho(v_2^2, [p_T]) \rightarrow -\frac{3\sqrt{5} \langle \cos(3\gamma) \beta_2^3 \rangle}{28\pi^{3/2}}$$

$$\rho(v_2^4, p_T^2) \rightarrow A\beta_2^6 [53 + 16 \langle \cos(6\gamma) \rangle] + B [\beta_2^6, \langle \cos(3\gamma) \rangle]$$

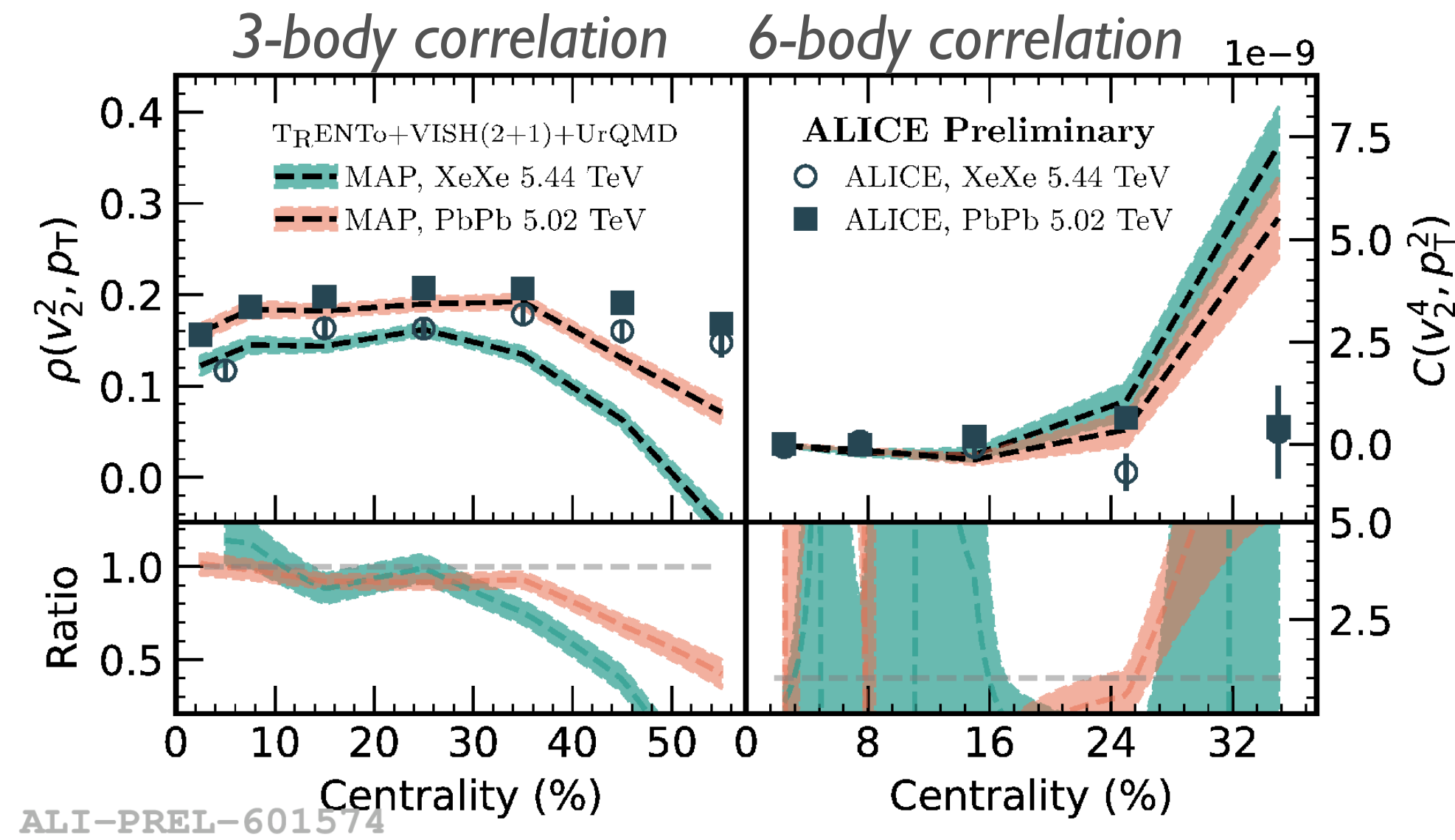
Extract precise Nuclear Structure with Bayesian Fit

❖ Precise imaging of nuclear structure with collective flow

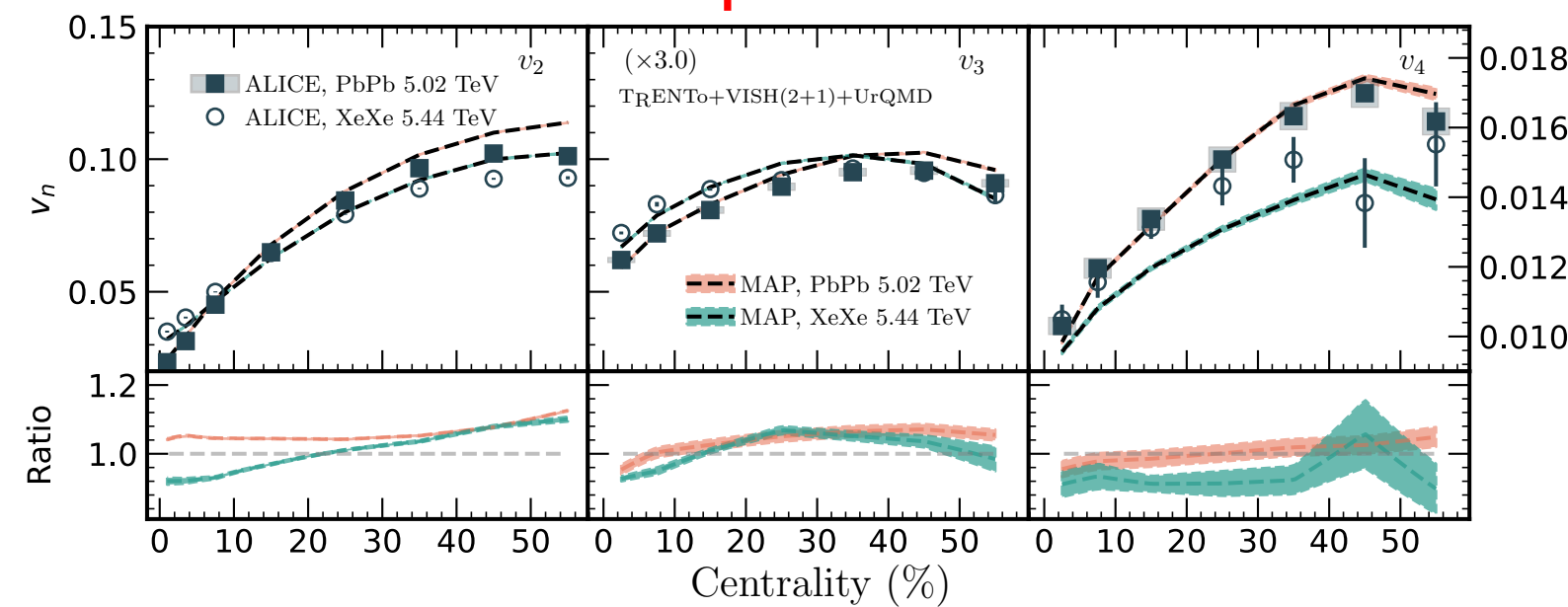
ALICE data



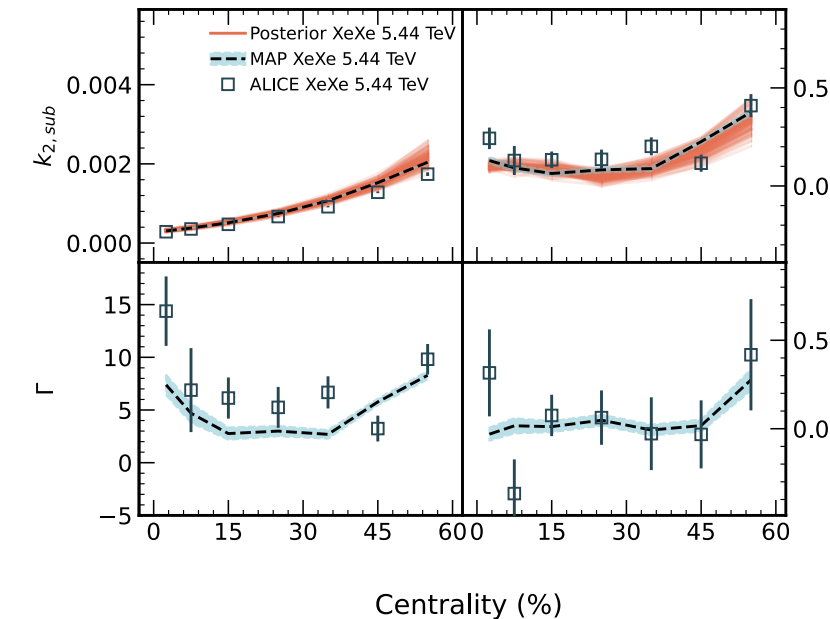
Unified algorithm



Anisotropic flow



Radial flow

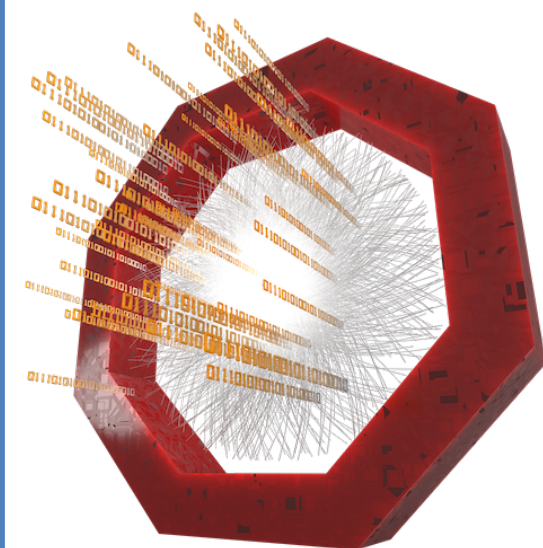


ALICE, in preparation for
Report on Progress in Physics

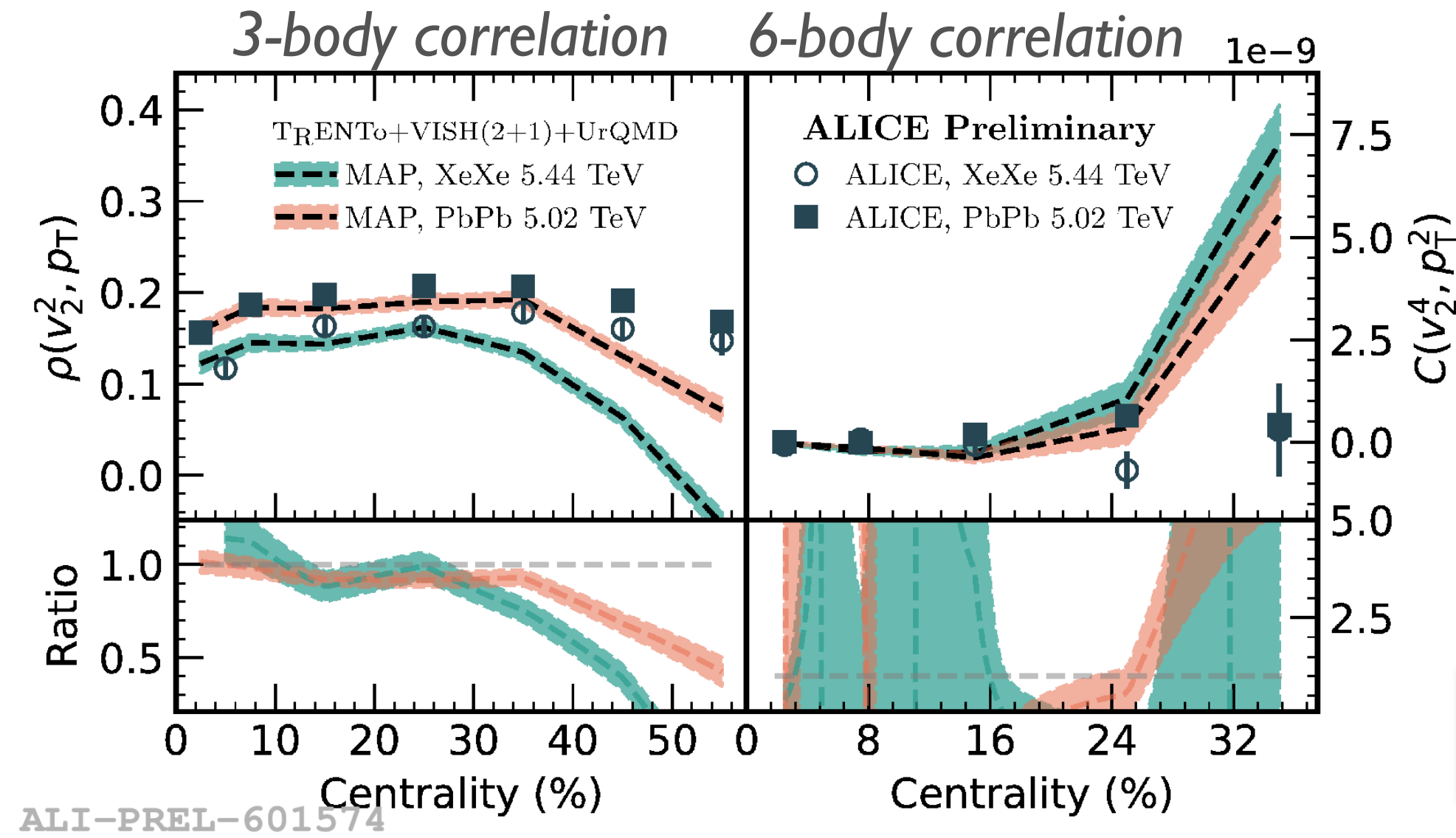
Extract precise Nuclear Structure with Bayesian Fit

❖ Precise imaging of nuclear structure with collective flow

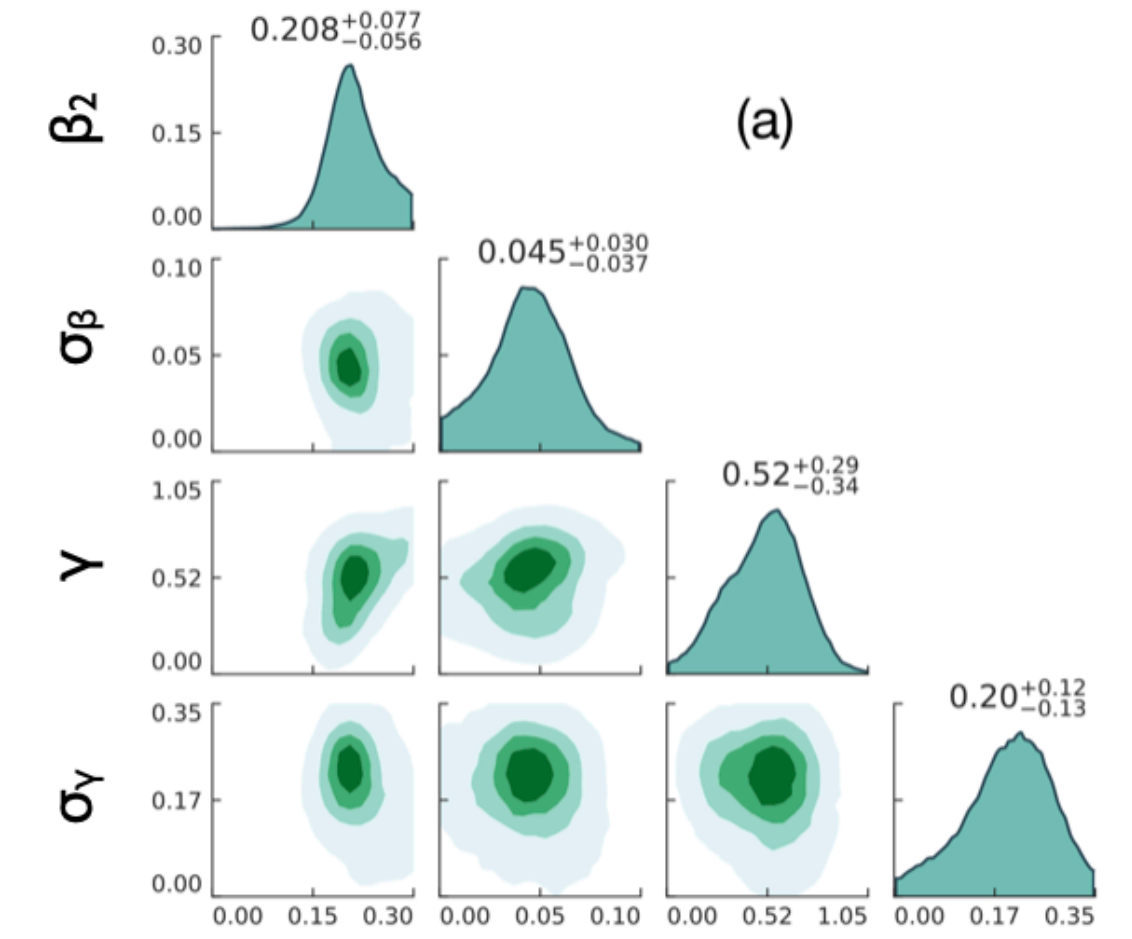
ALICE data



Unified algorithm



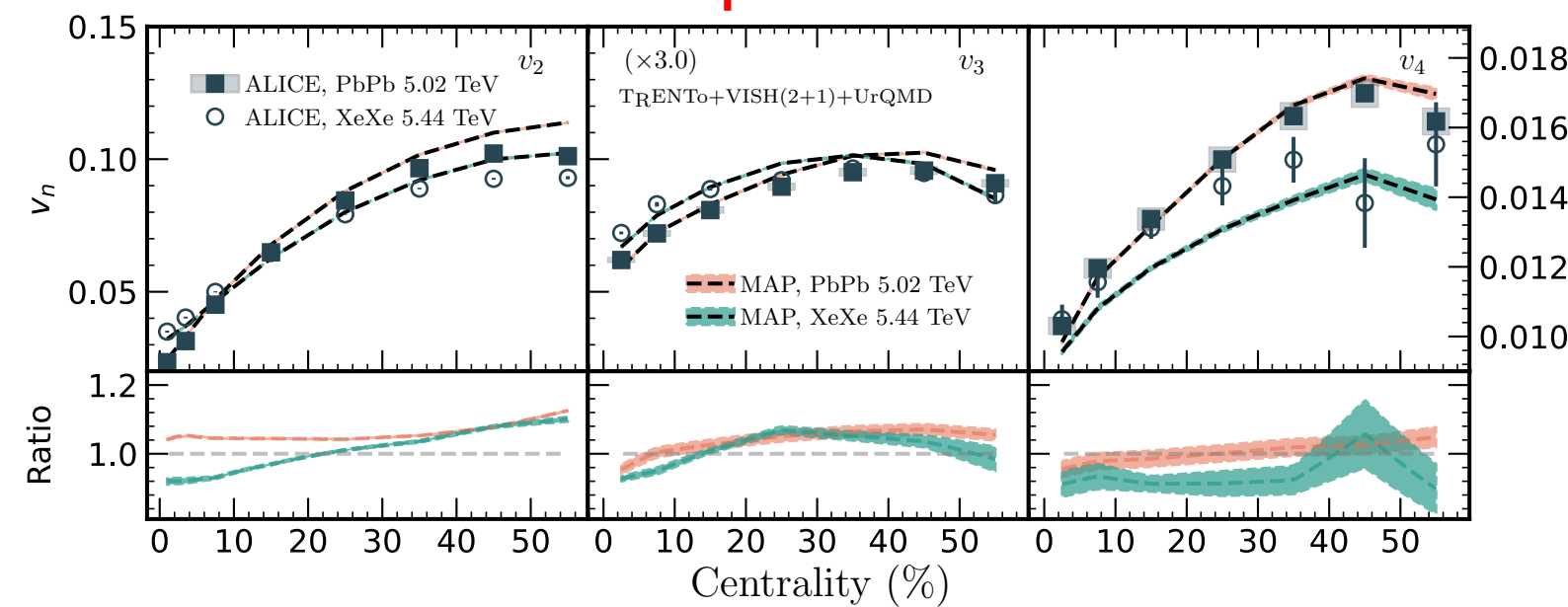
Bayesian Fit



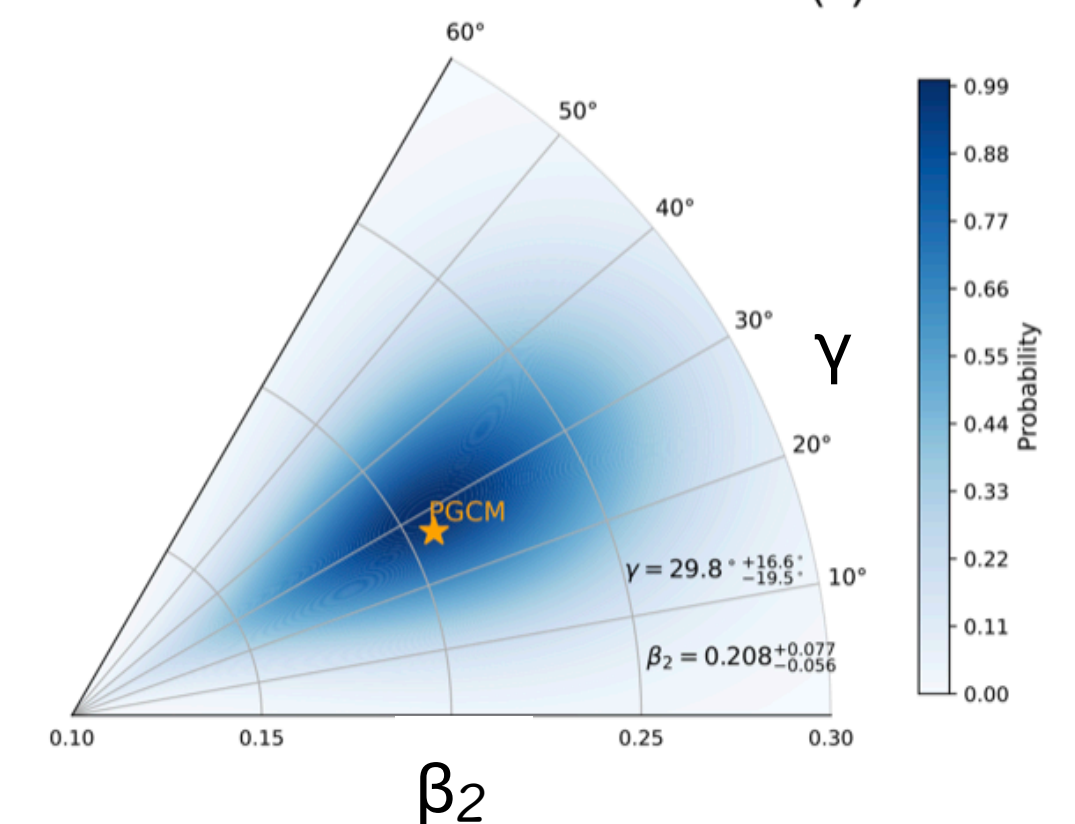
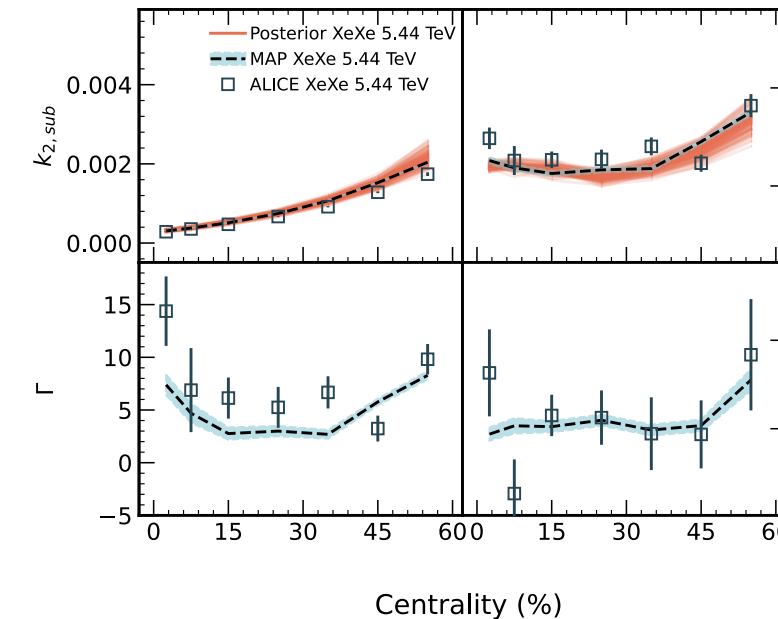
ALICE

(b)

Anisotropic flow



Radial flow



ALICE, in preparation for Report on Progress in Physics

Combining NS + “heavy-ion theory”

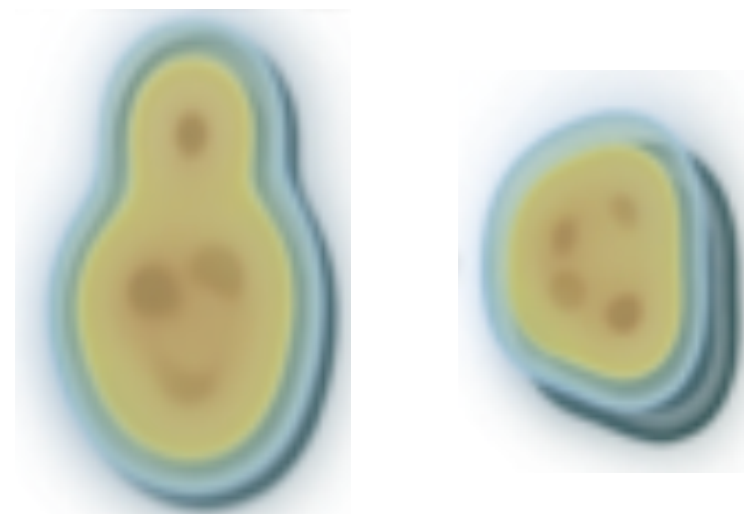
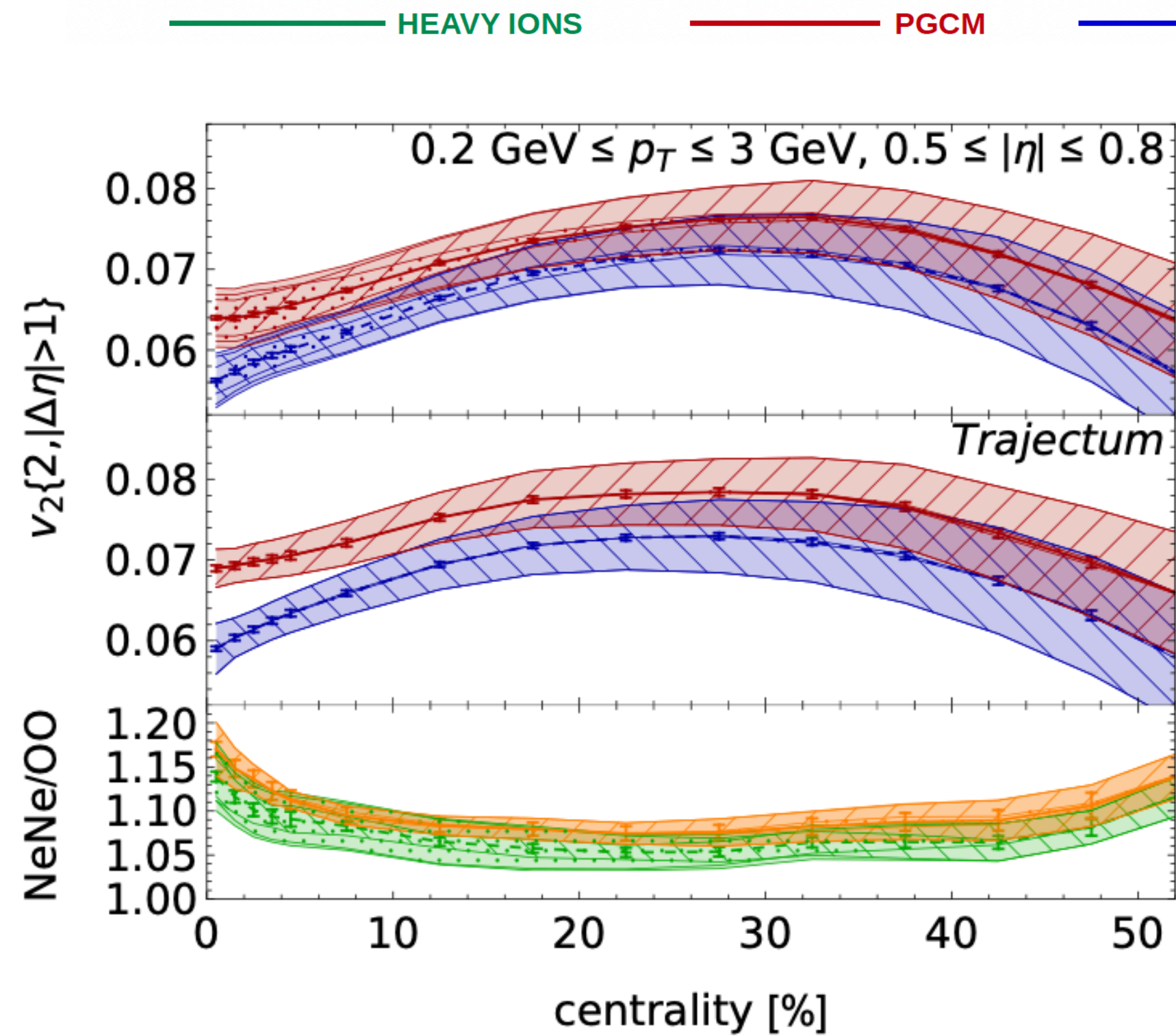
Hydrodynamic

*PRL*135 (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 Somà⁵



Low-energy NS

Hydrodynamic



Combining NS + “heavy-ion theory”

Hydrodynamic

*PRL*135 (2025) 012302

Parton Transport

In preparation

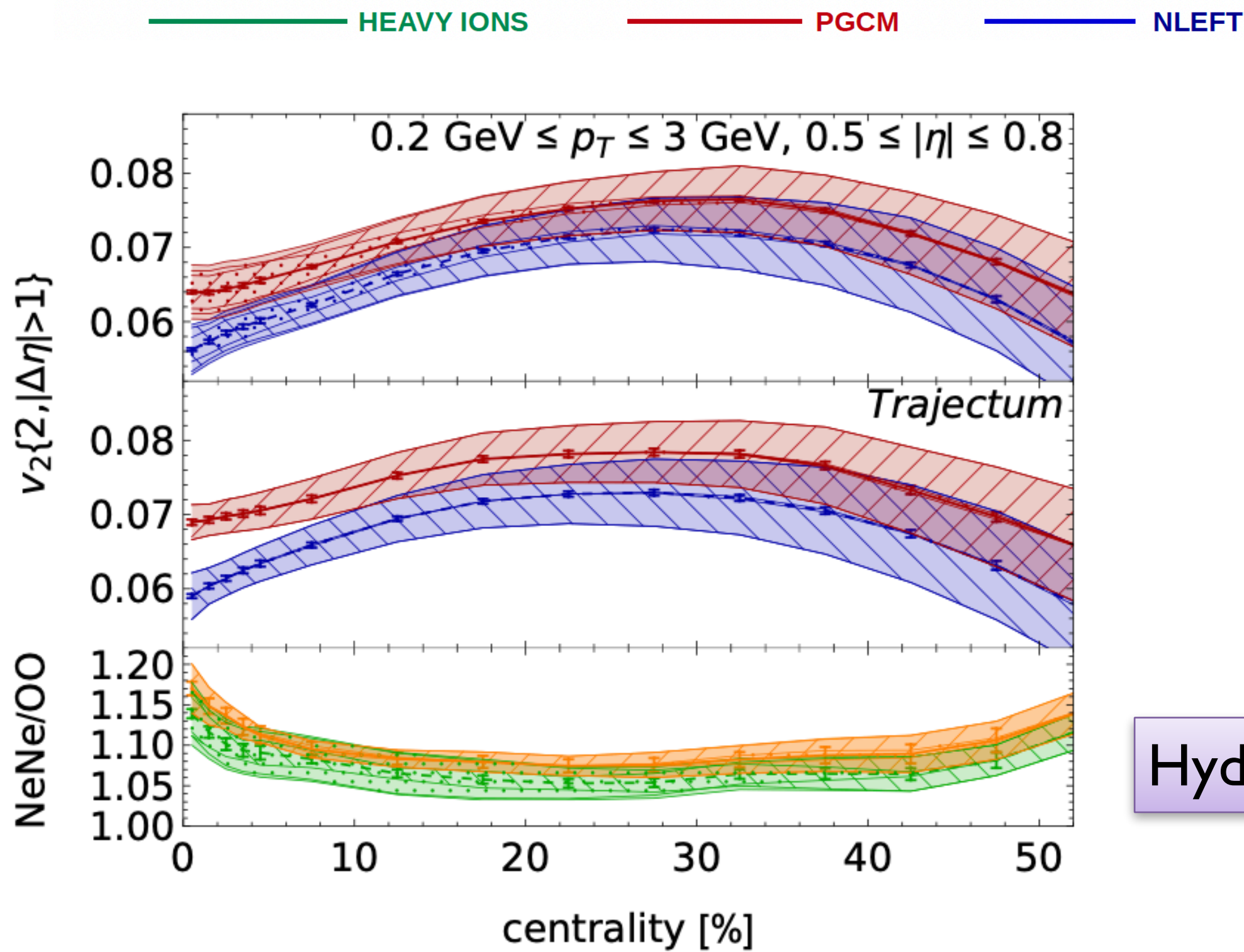
CERN-TH-2024-021

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

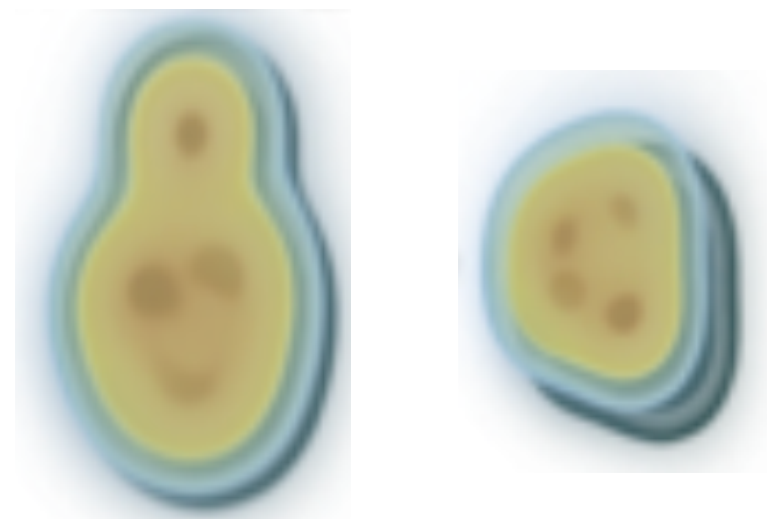
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 Christopher Plumberg,¹⁹ Tomás R. Rodríguez,²⁰ Robert Roth,^{21,22} Wilke van der Schee,^{3,23,24} and Vittorio Somà⁵

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 Zhang⁸



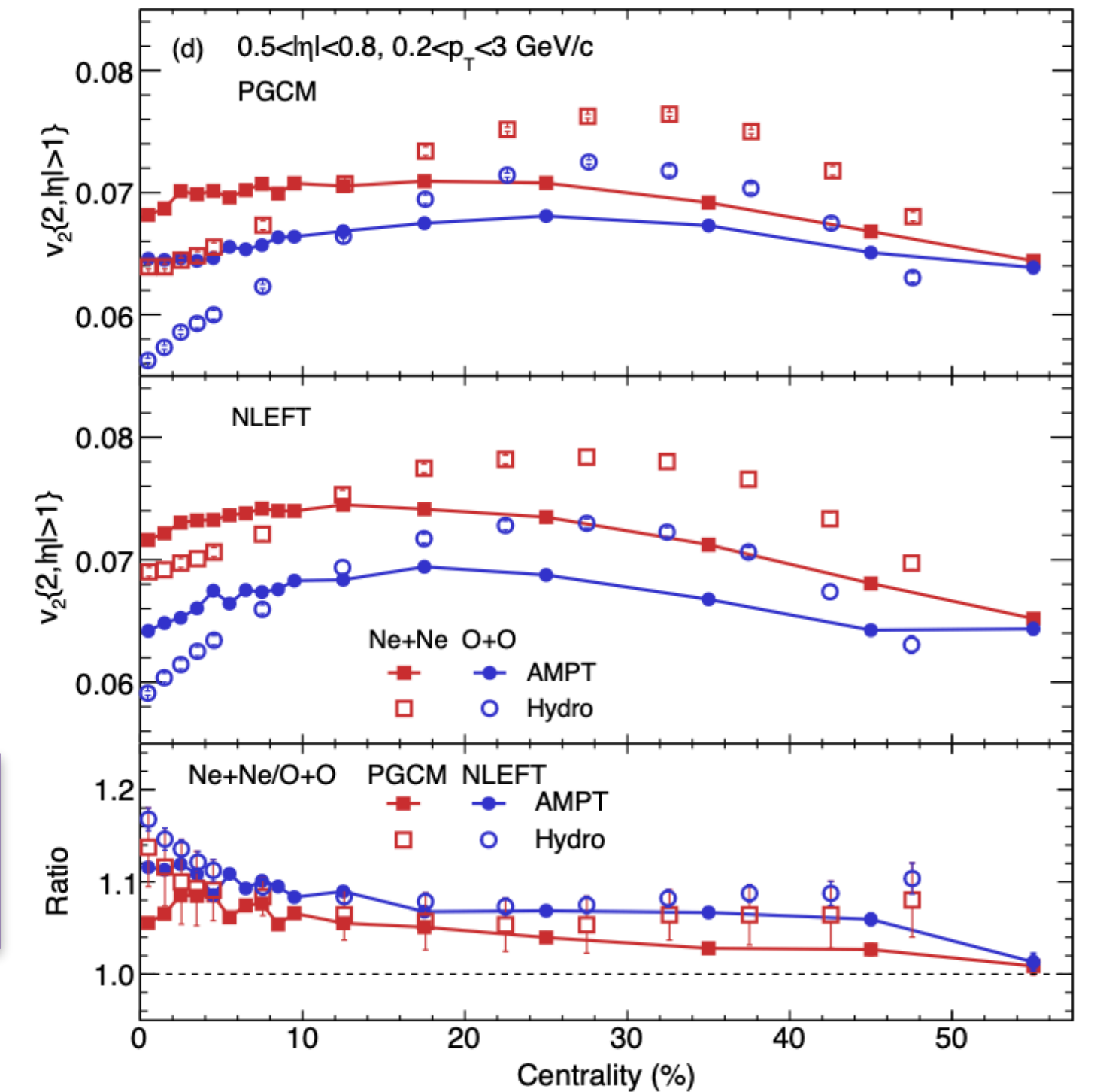
— Theorists — Experimentalists (ALICE, ATLAS, STAR)



Low-energy NS

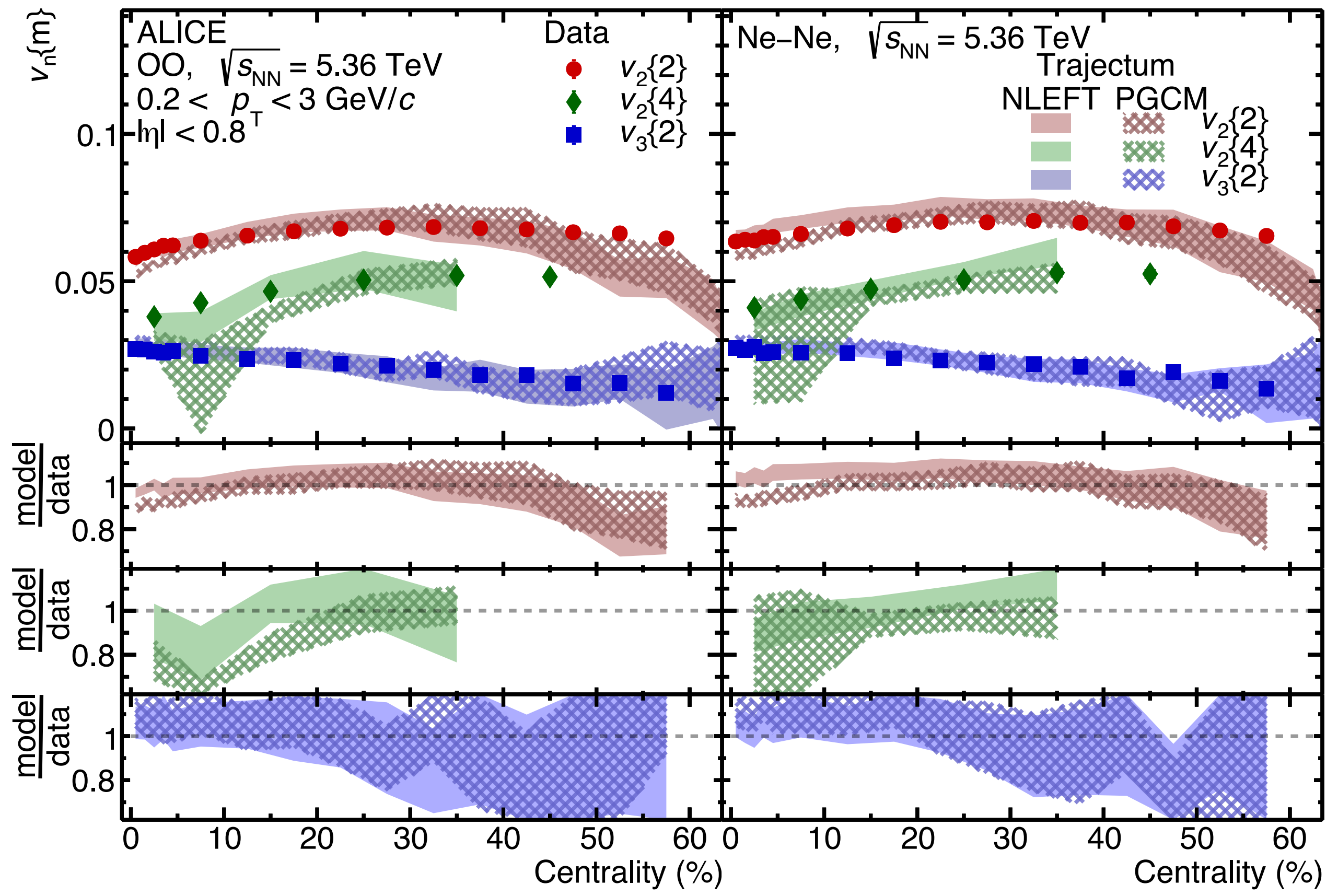
Hydrodynamic

Parton Transport



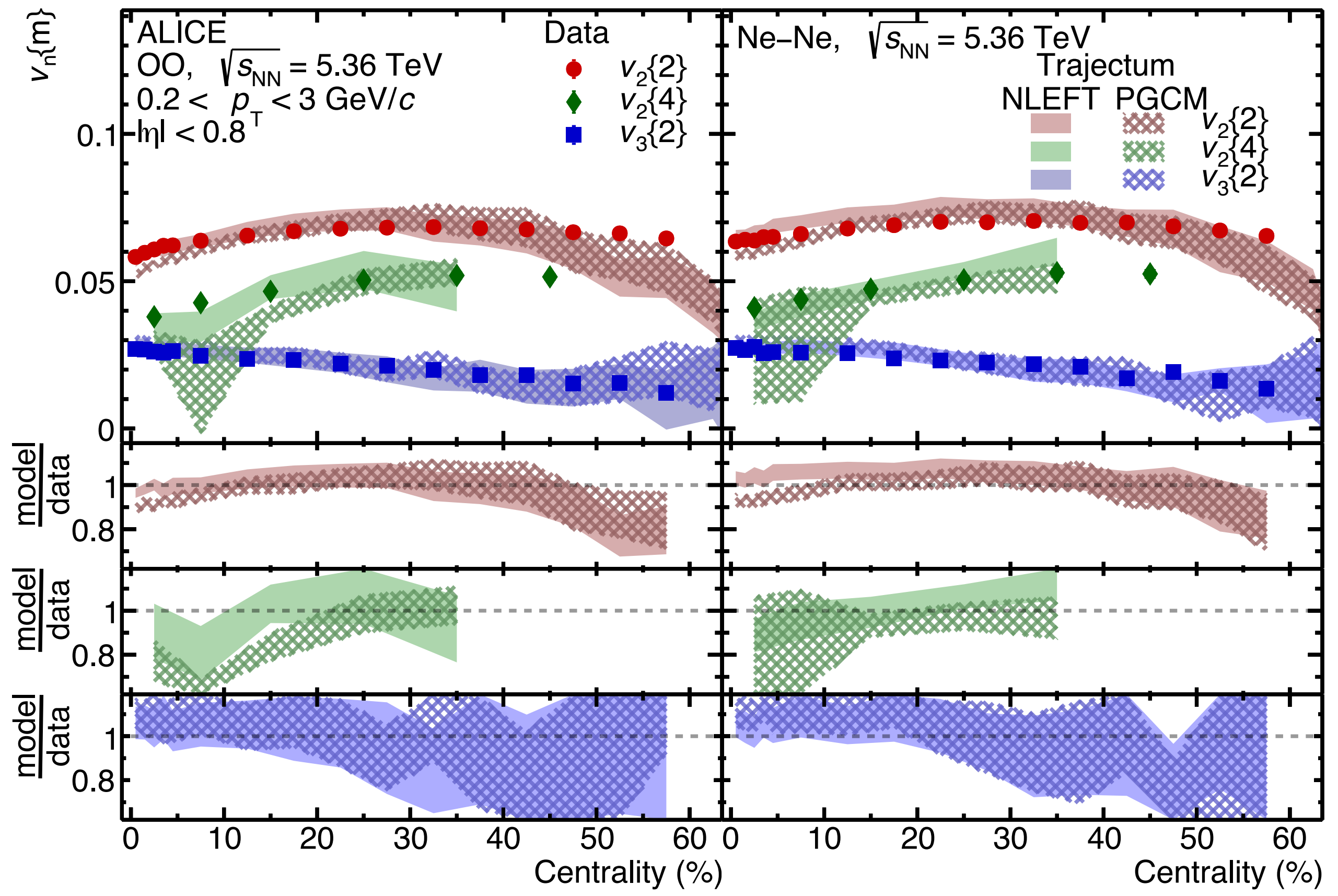
Evidence of nuclear geometry driven flow in light ion collisions

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



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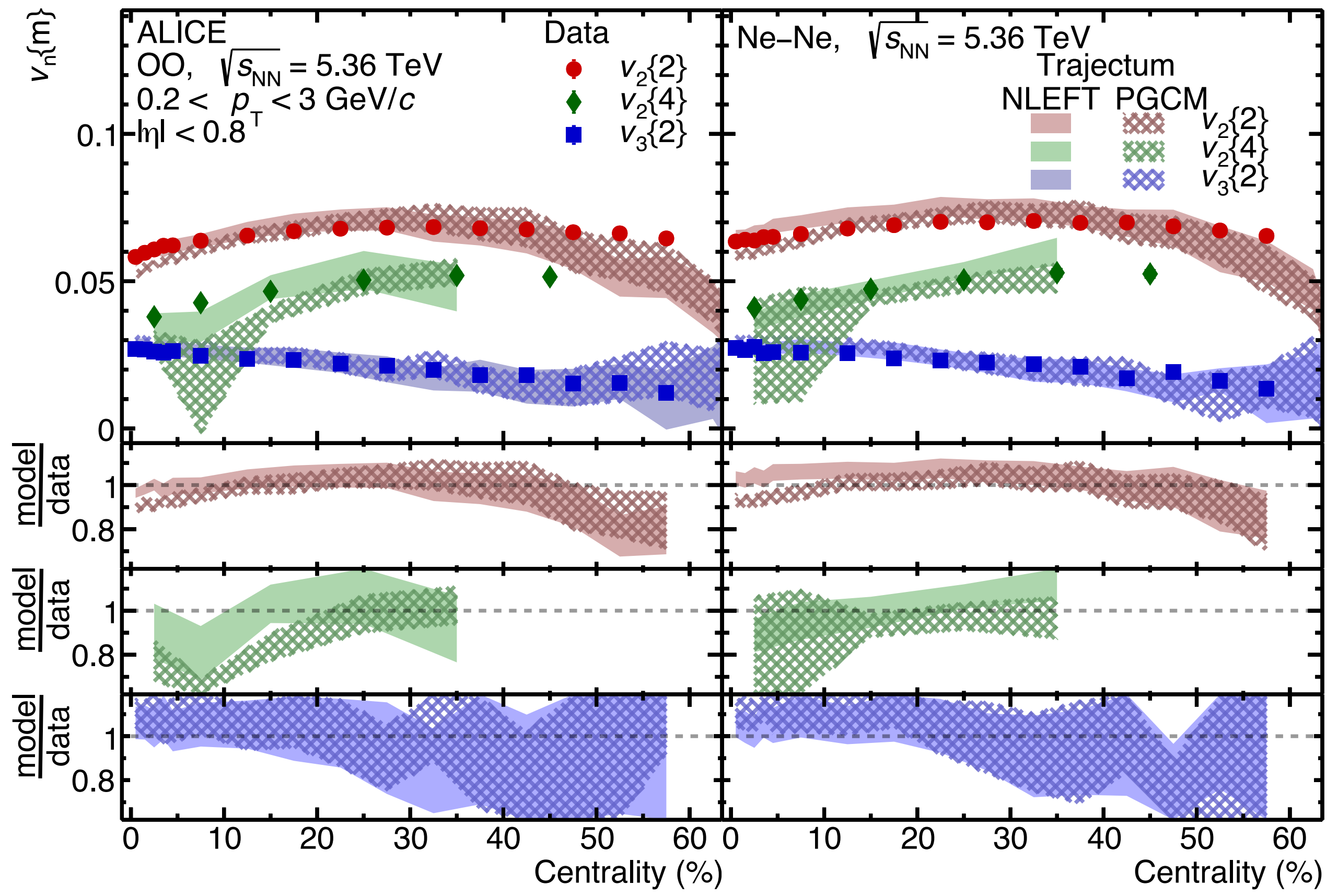


- ❖ **Unified Framework:** nuclear structure across energy scale
- ❖ Nicely described by predictions from Trajectum(NS+hydro)
 - Nuclear geometry driven hydrodynamic flow observed in light ion collisions
 - *For the first time excellent agreement (equivalent if not better than Pb-Pb) between hydro predictions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



Evidence of nuclear geometry driven flow in light ion collisions

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



- ❖ **Unified Framework:** nuclear structure across energy scale
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- ✓ **Validation** with Light-Ion Collisions

Evidence of nuclear geometry driven flow in light ion collisions

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

Also see **CERN Headline (Sept. 19th, 2025)**

CERN Accelerating science

Signed in as: yozhou (Drupal)

Sign out Directory



ABOUT

NEWS

SCIENCE

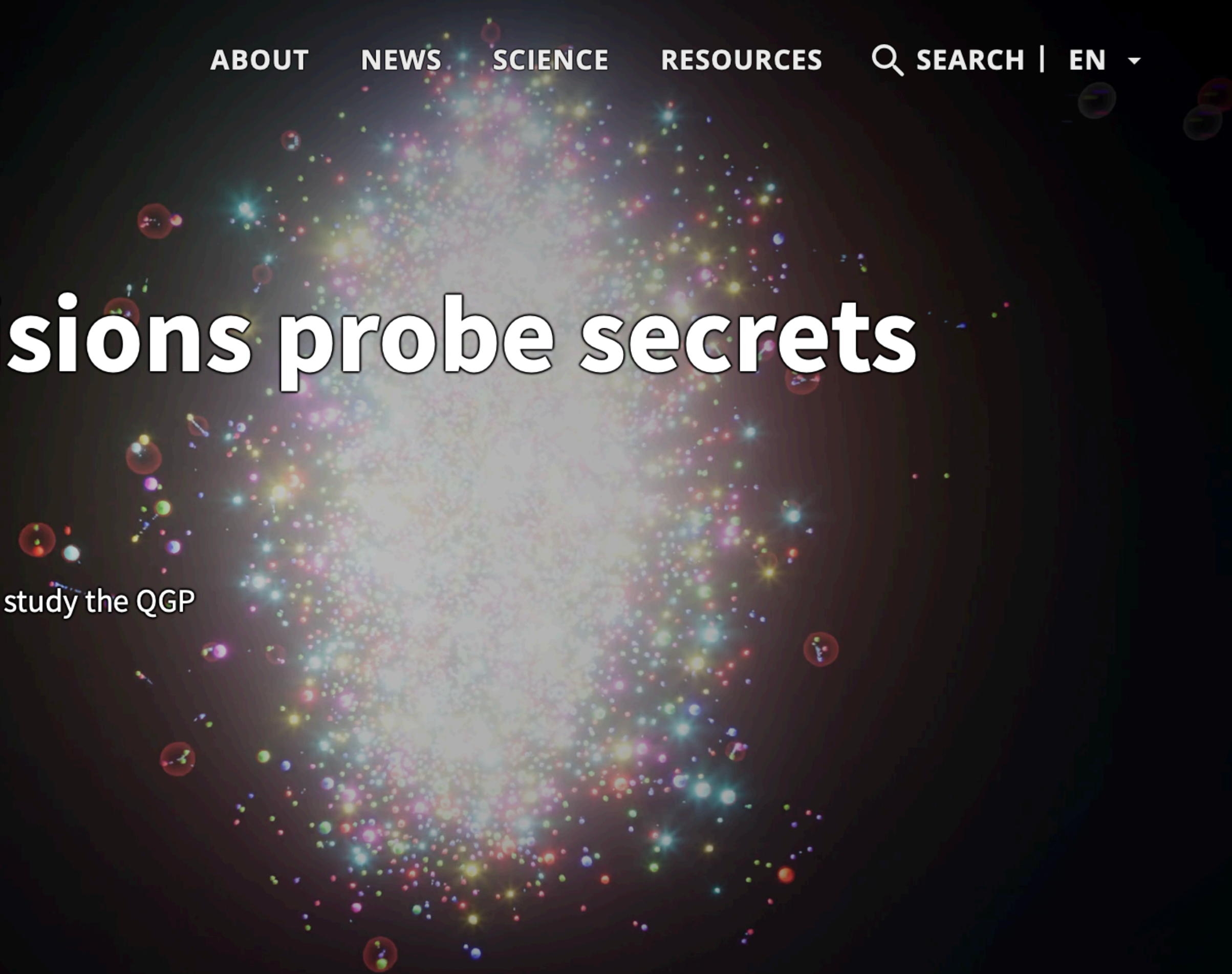
RESOURCES

SEARCH | EN

Shape-shifting collisions probe secrets of early Universe

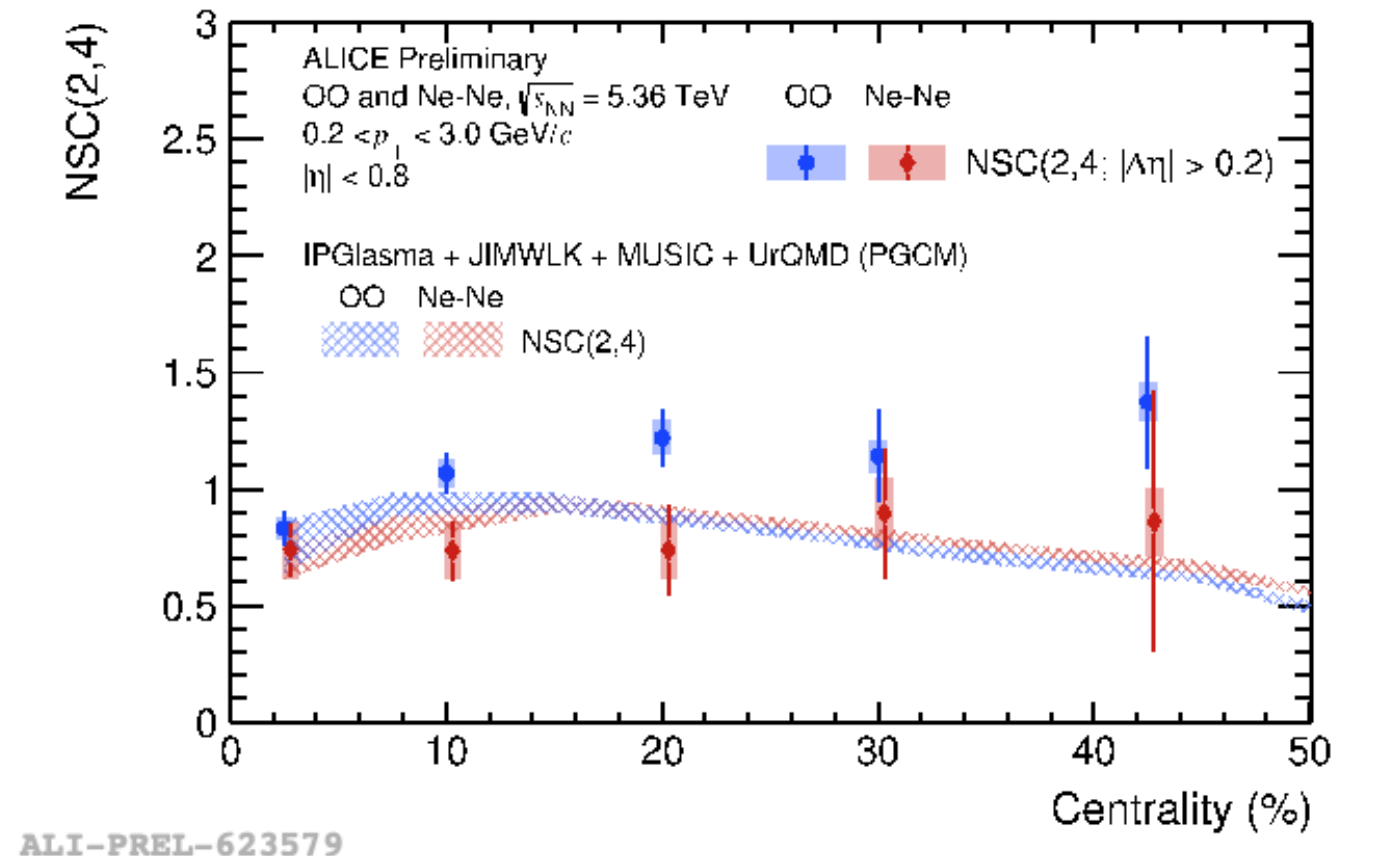
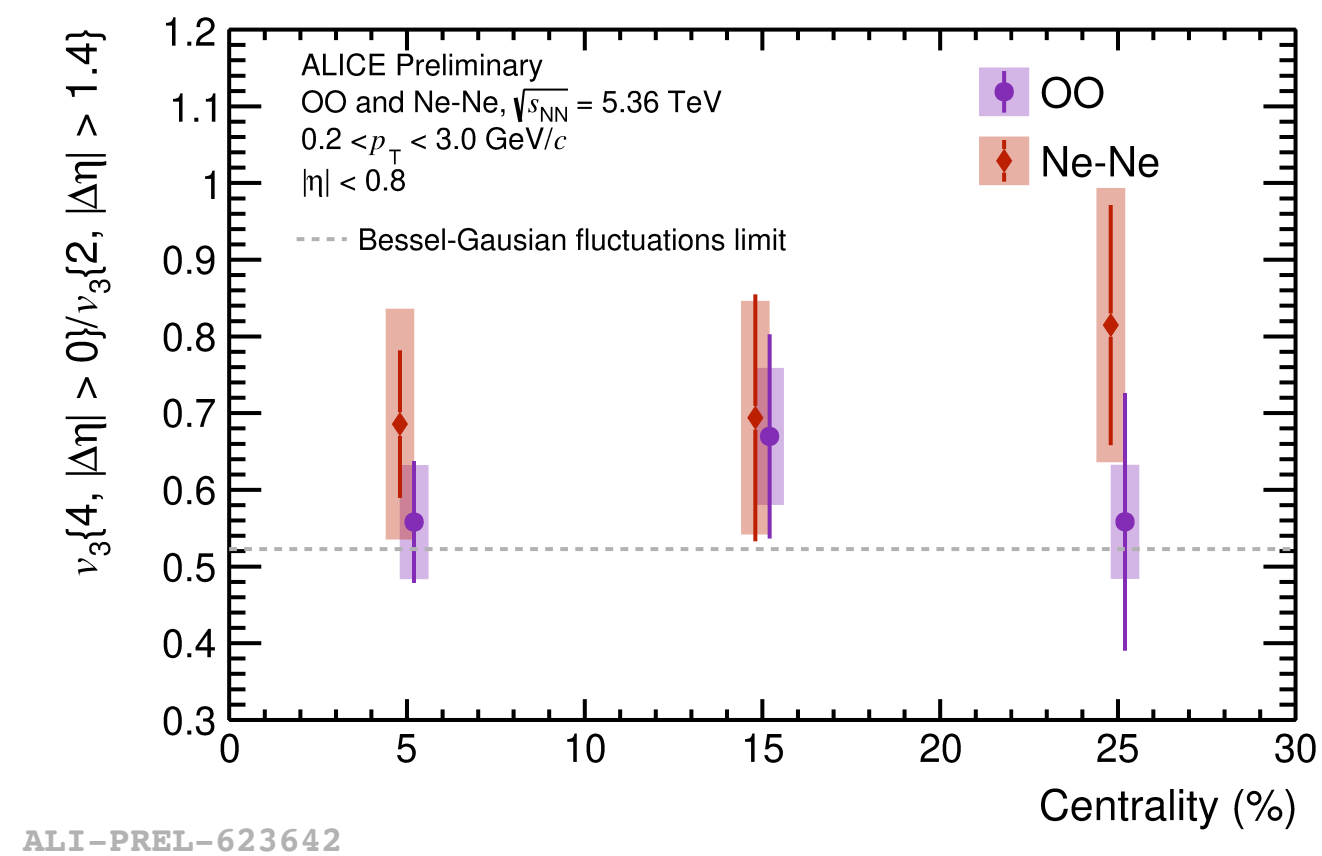
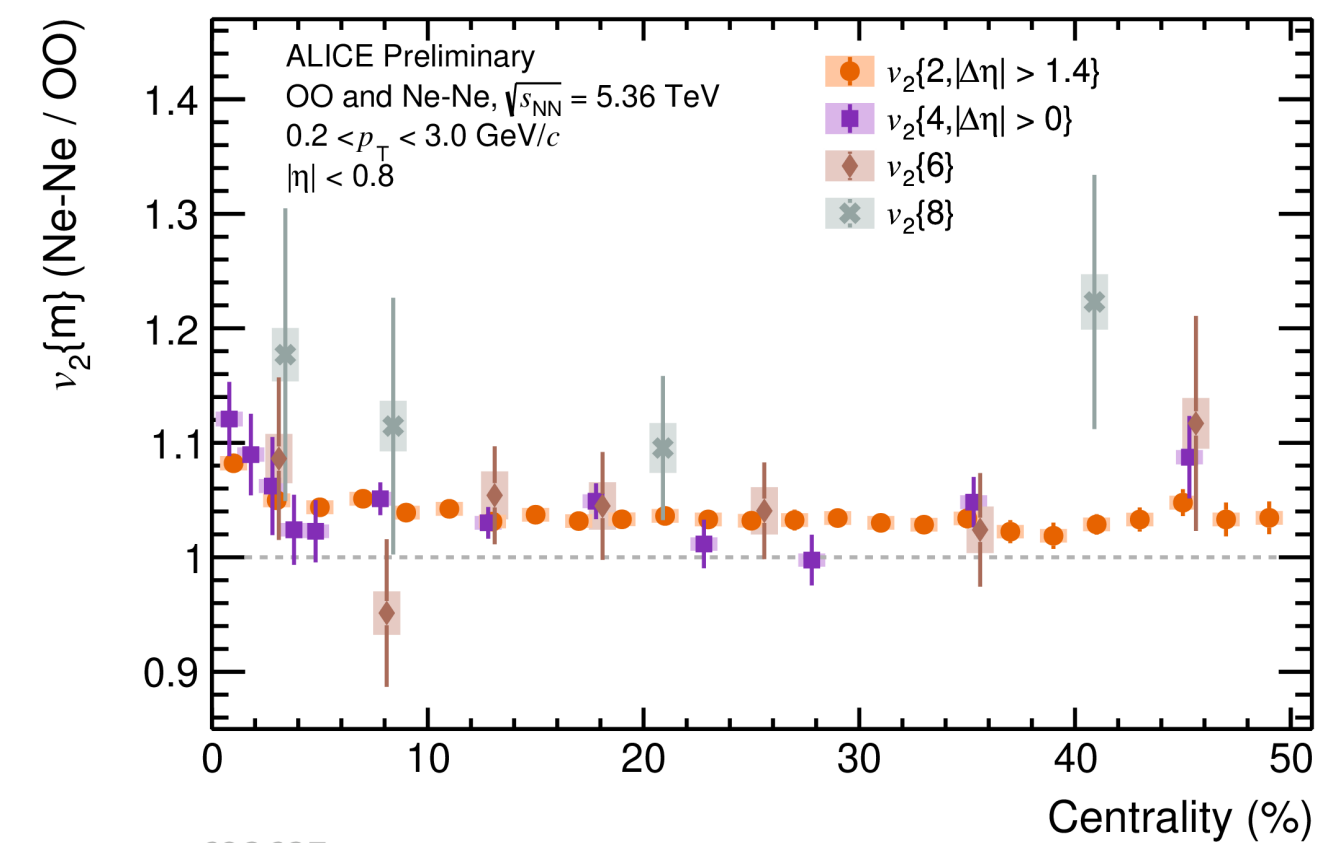
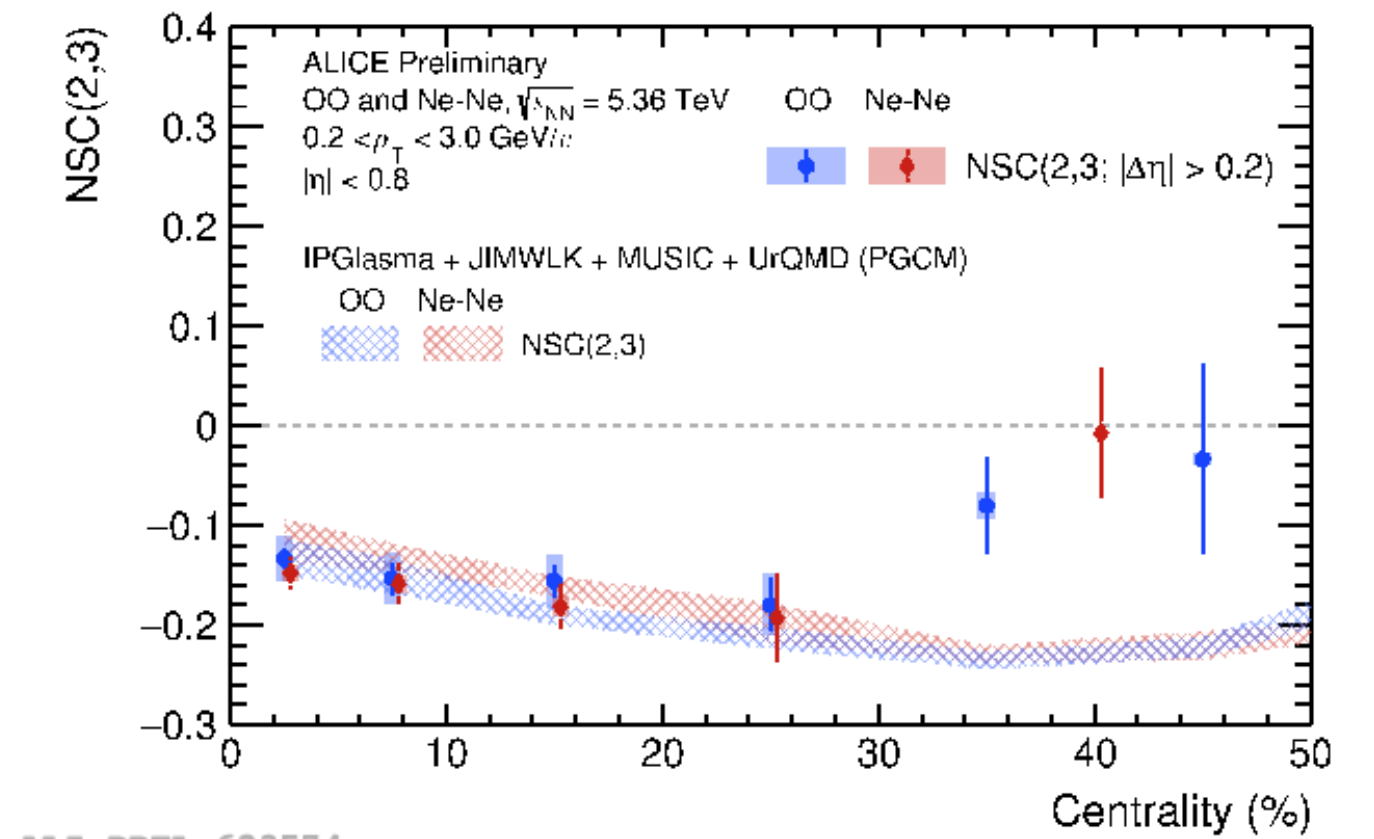
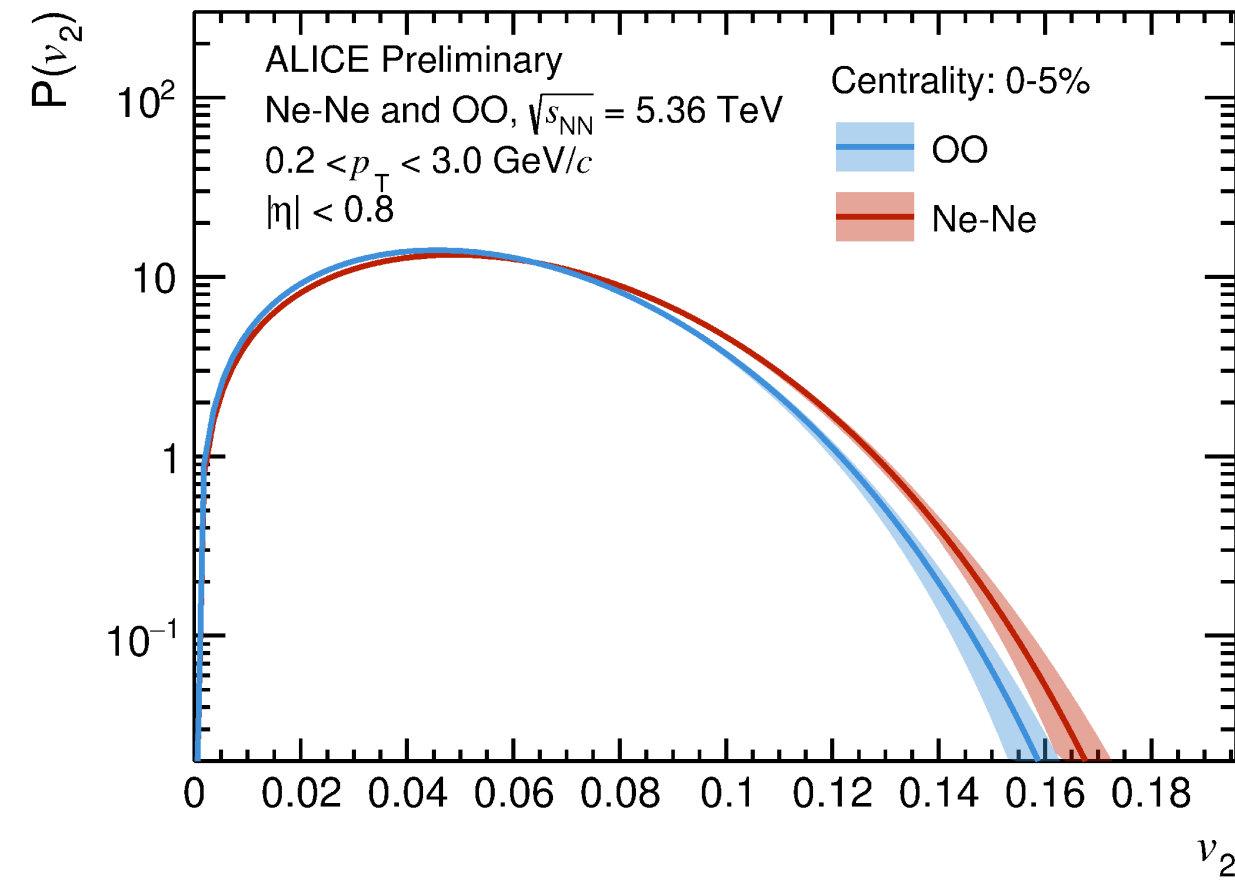
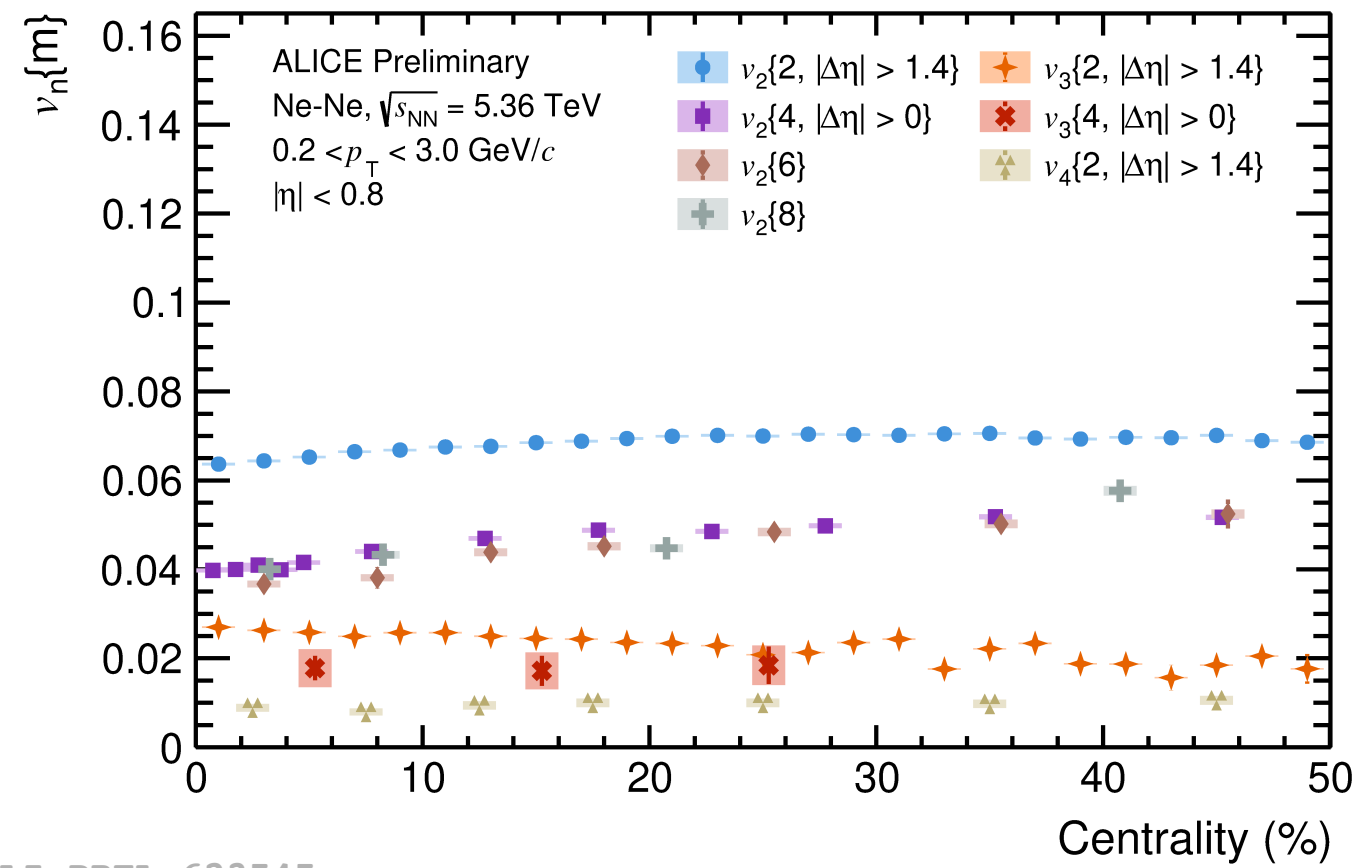
First collisions between light nuclei at the LHC offer up a new tool to study the QGP

Read more →



Many new OO & Ne-Ne measurements available in 2026

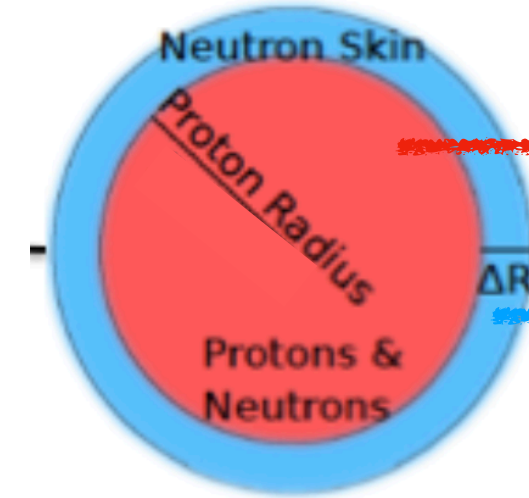
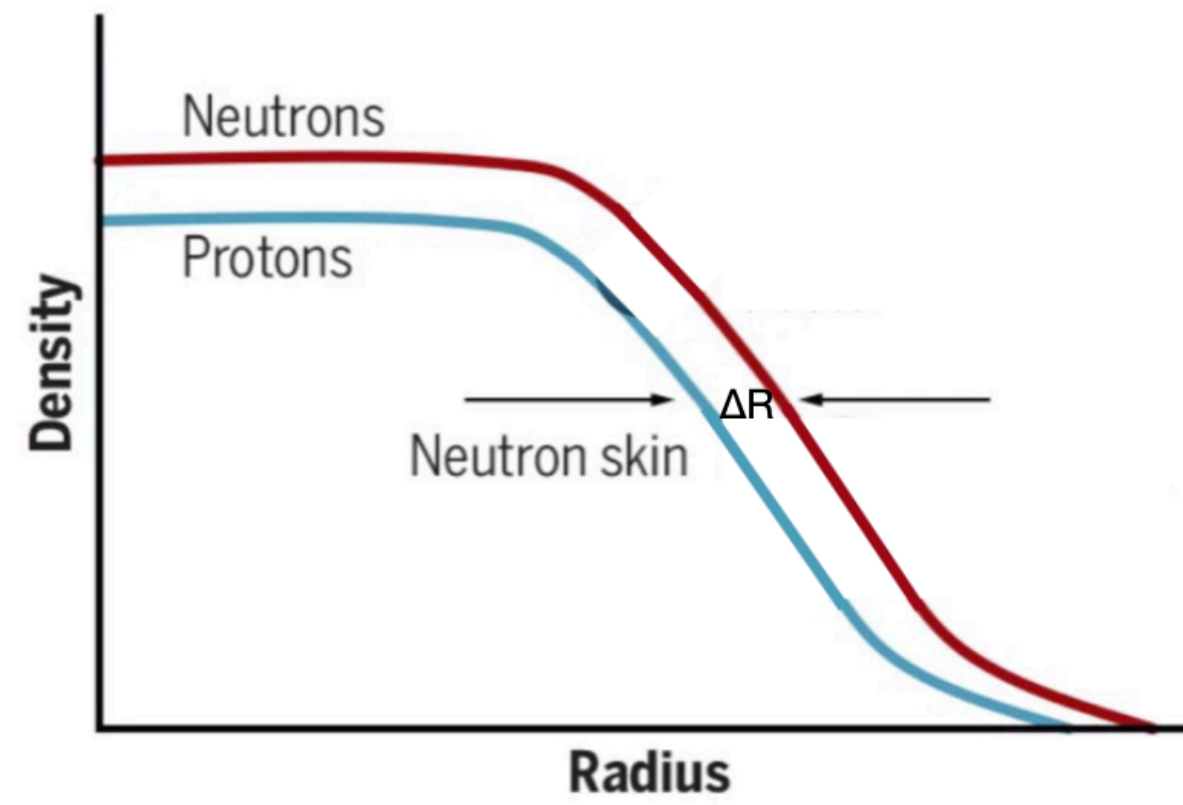
+ many more to be available before this summer



✍️ Toward precise nuclear structure imaging (5- α vs $\alpha + {}^{16}\text{O}$)

(ALICE, *Phys. Rev. Lett.* in preparation)

Neutron skin study at Relativistic Nuclear Collisions

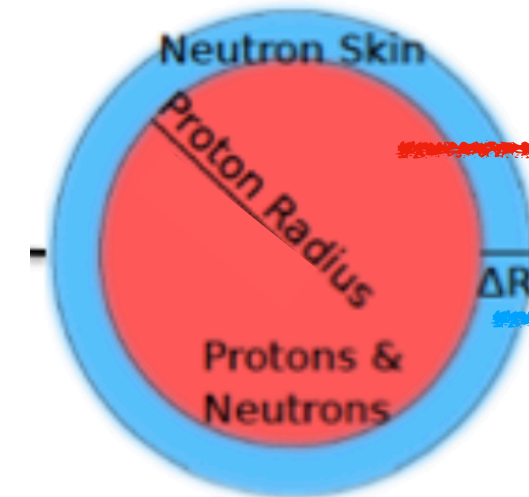
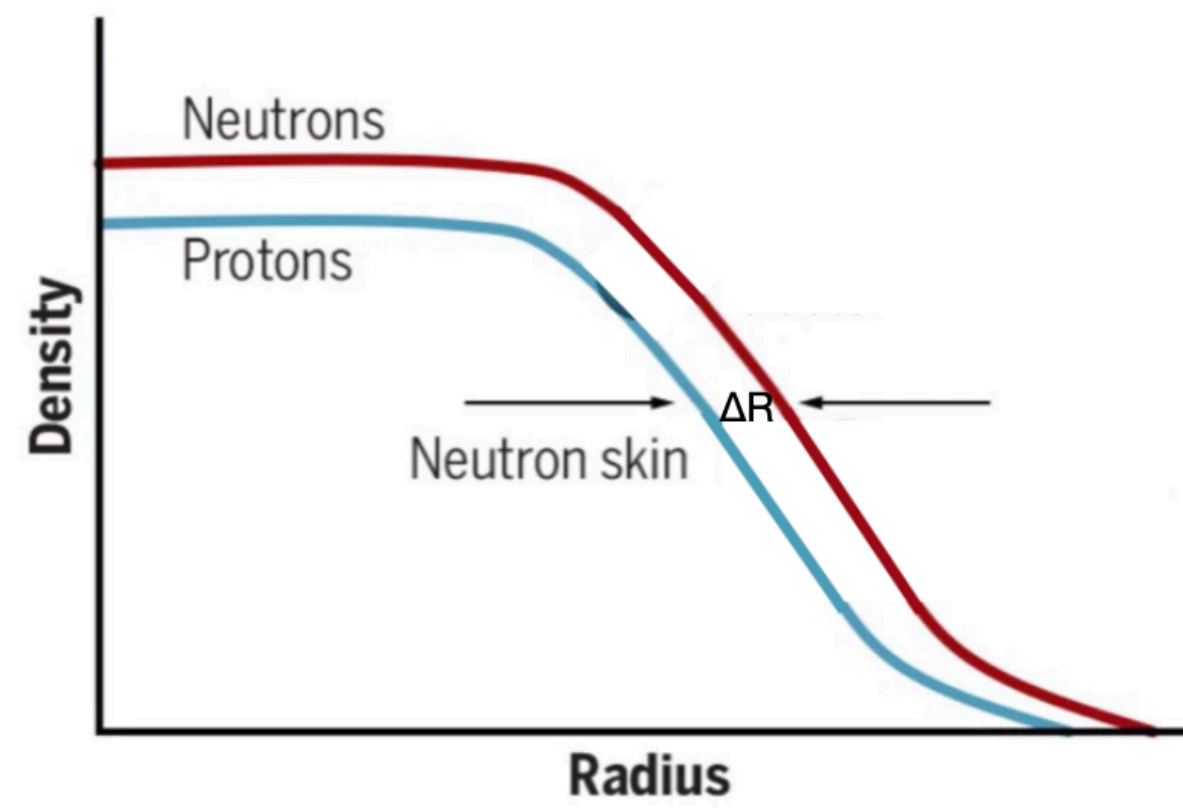


$$\rho(r, \Theta, \Phi) \propto \frac{1}{1 + \exp([r - R(\Theta, \Phi)] / a)}$$

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

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

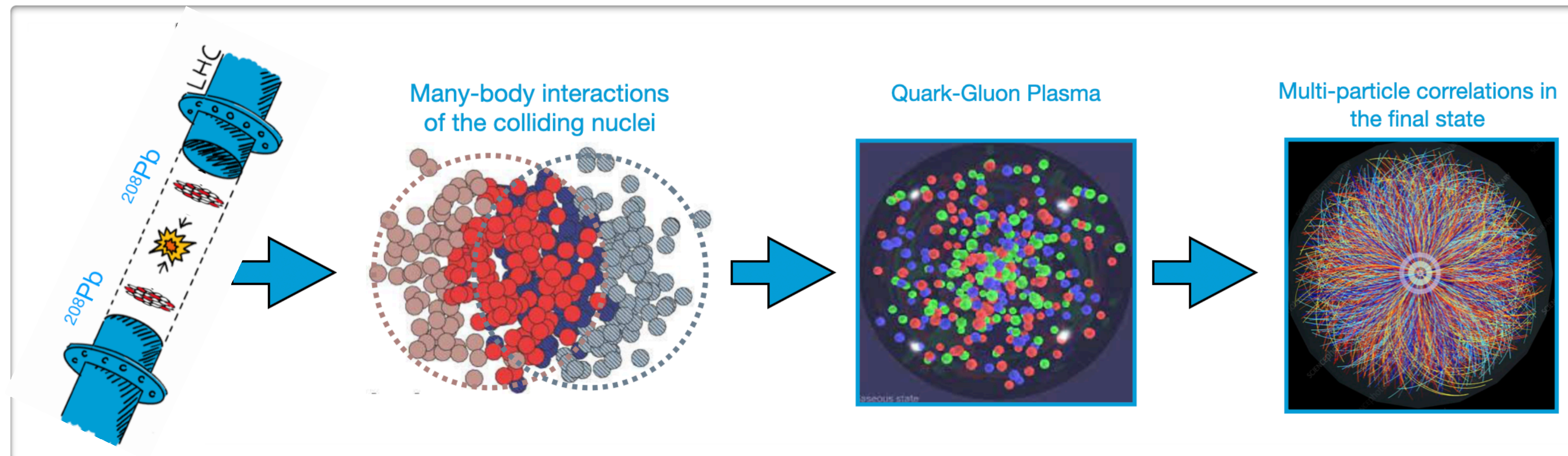
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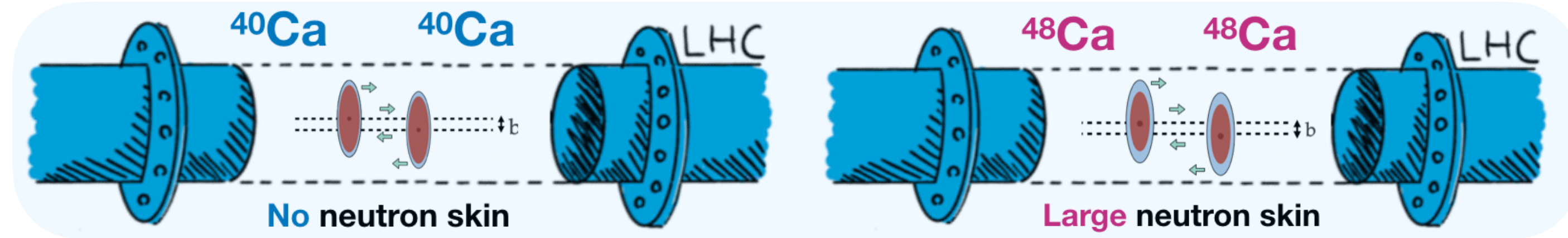
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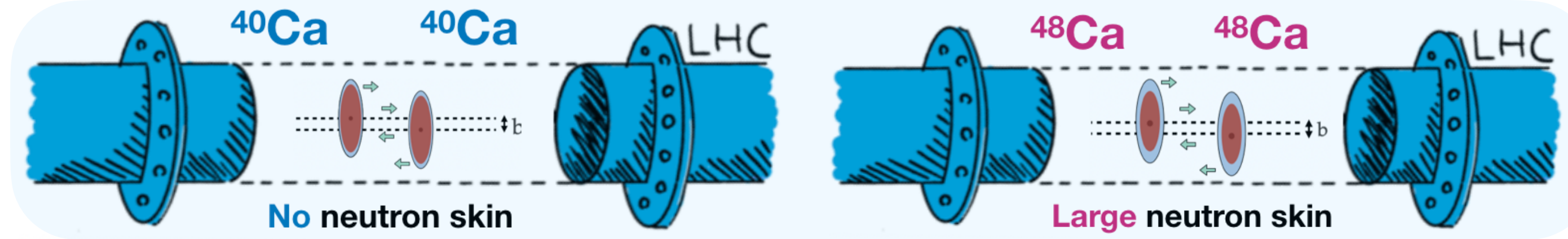
$$\rho_n(r, \Theta, \Phi) \propto \frac{1}{1 + \exp([r_n - R_n(\Theta, \Phi)] / a_n)}$$



What can we learn from ^{48}Ca - ^{48}Ca vs ^{40}Ca - ^{40}Ca



What can we learn from ^{48}Ca - ^{48}Ca vs ^{40}Ca - ^{40}Ca

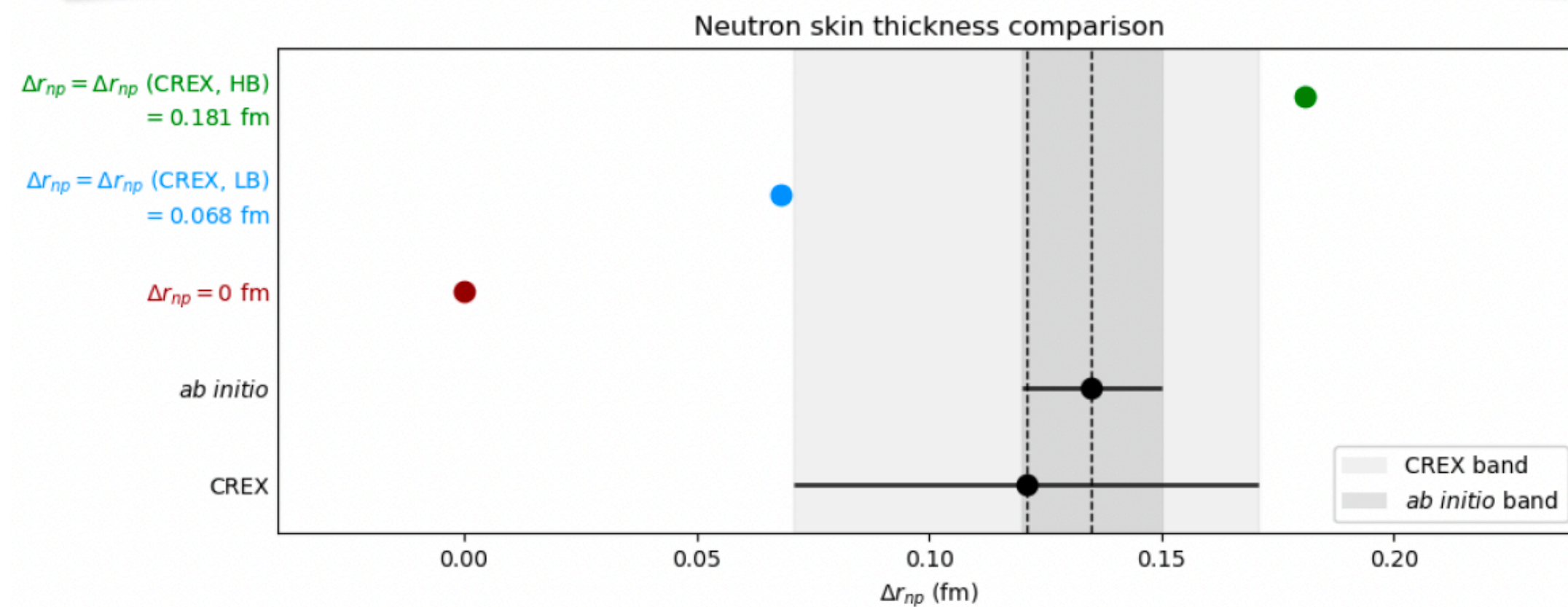


Characterizing the Neutron Skin of ^{48}Ca Through Collective Flow at the CERN Large Hadron Collider

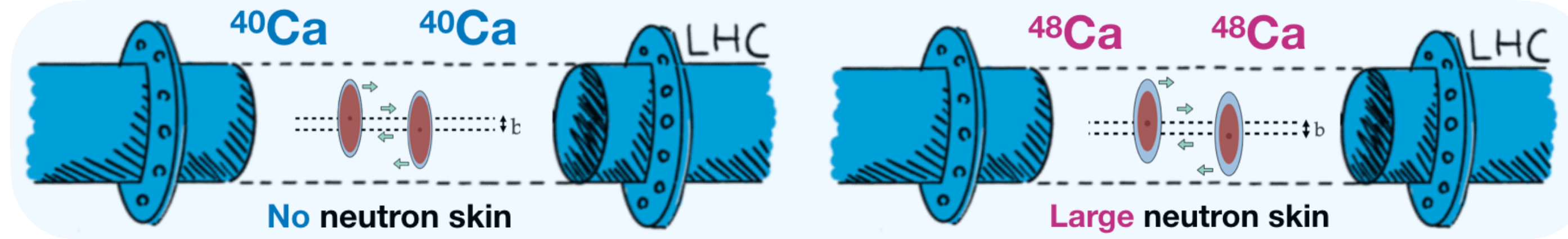
Andreas Vitsos¹, Leonora Misciattelli Mocenigo Soranzo¹, Emil Gorm Dahlbæk Nielsen¹, You Zhou^{1,a}

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

[arXiv: 2512.00114](https://arxiv.org/abs/2512.00114), accepted by EPJC



What can we learn from ^{48}Ca - ^{48}Ca vs ^{40}Ca - ^{40}Ca

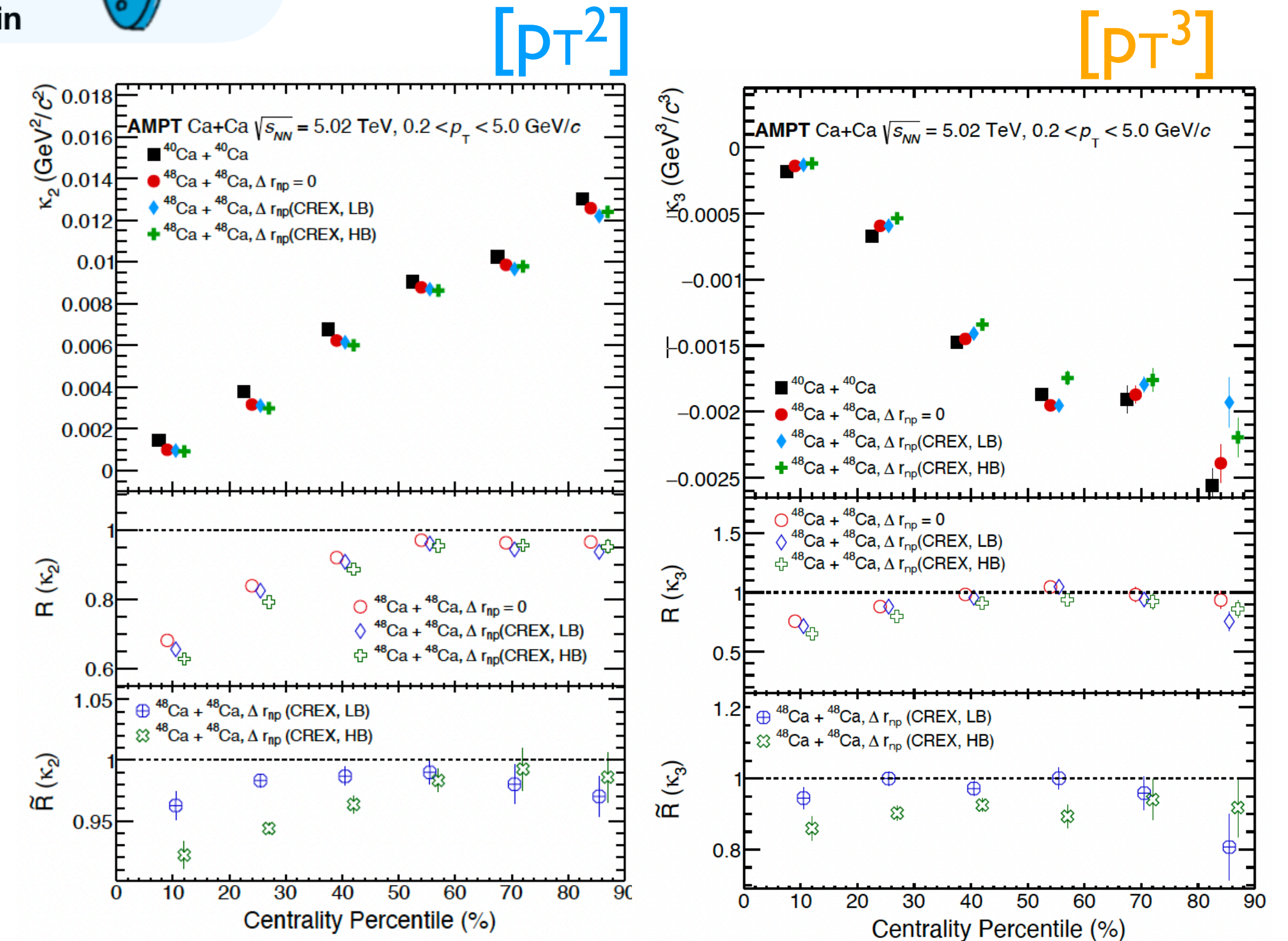
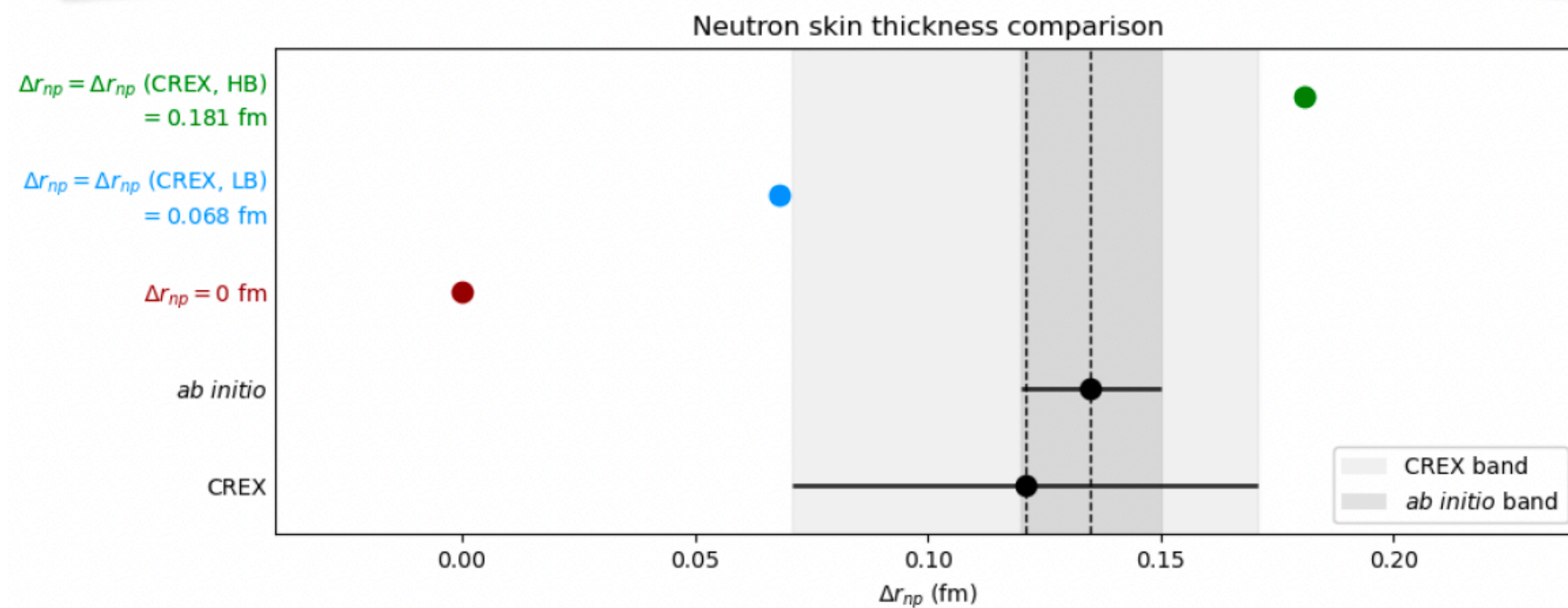


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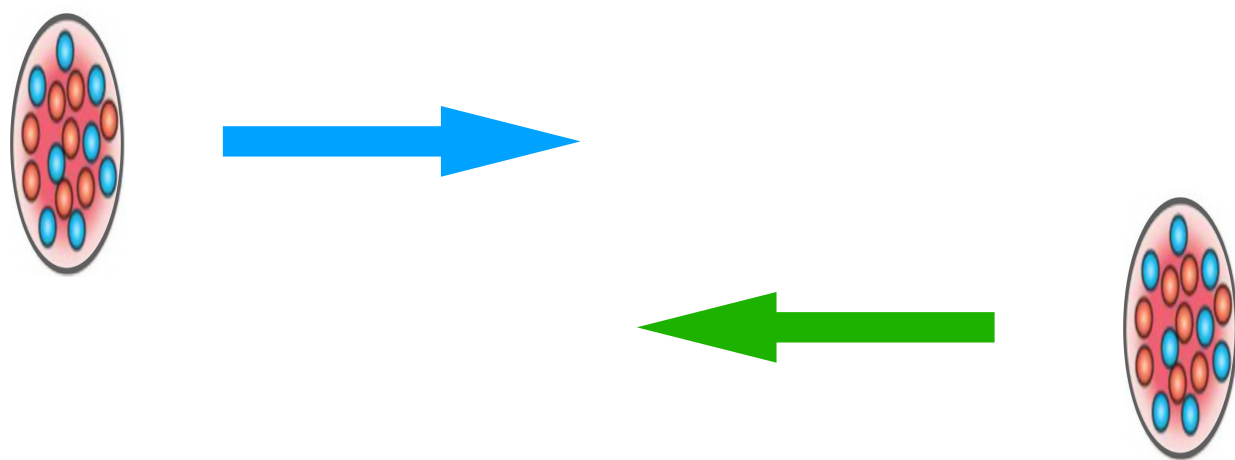
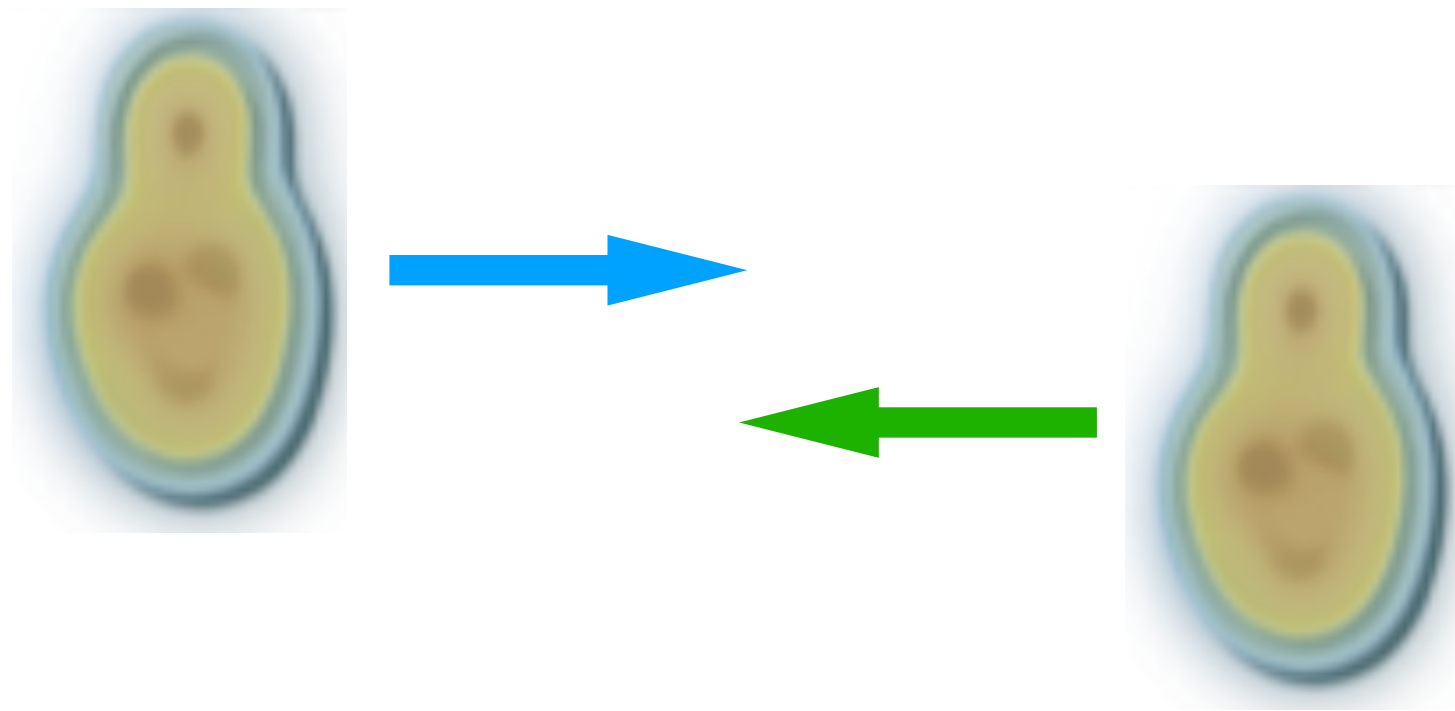


- Highly non-trivial differences observed when using large and small neutron skin
 - ^{48}Ca - ^{48}Ca as a promising candidate for the future light-ion runs at the LHC-Run4



New opportunities from 2030

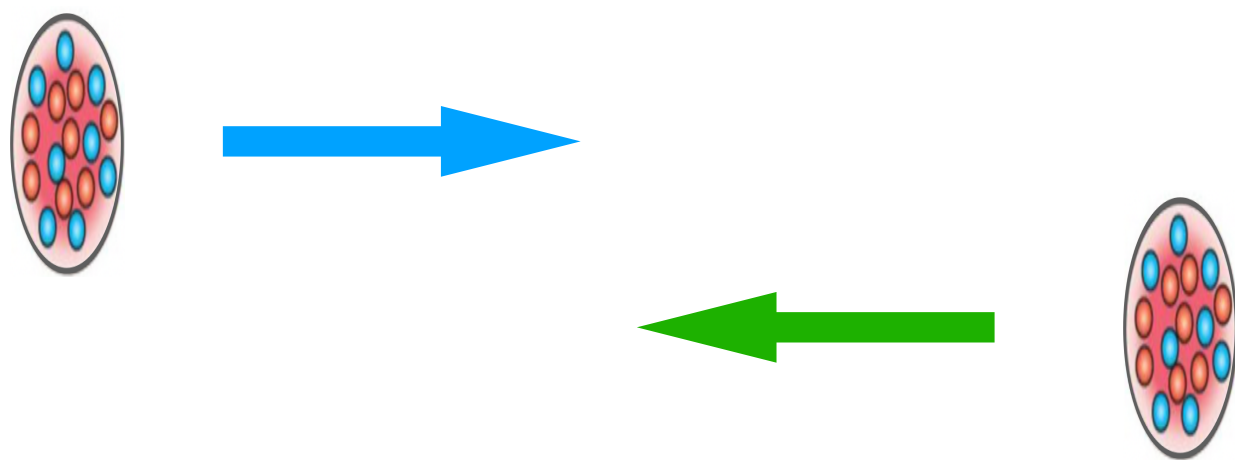
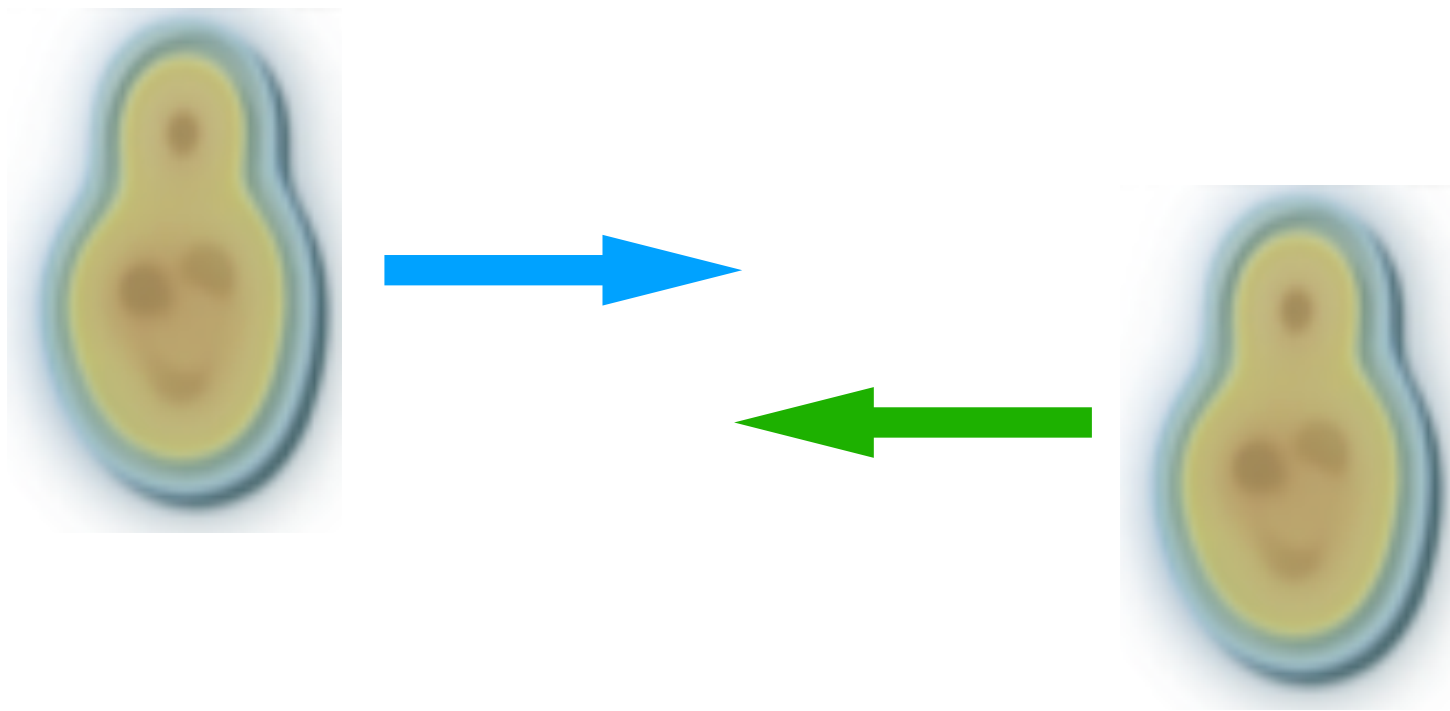
Colliding mode



New opportunities from 2030

Colliding mode

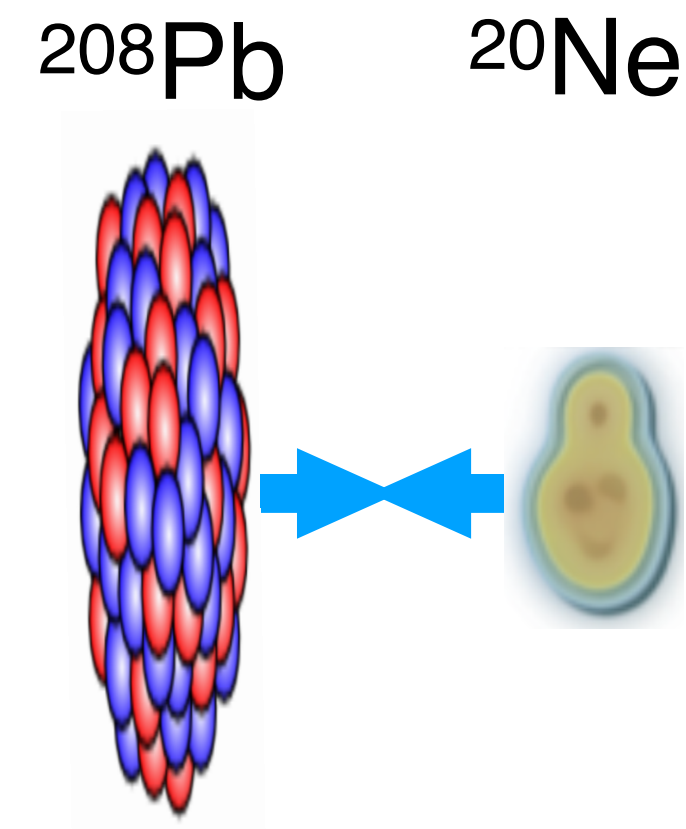
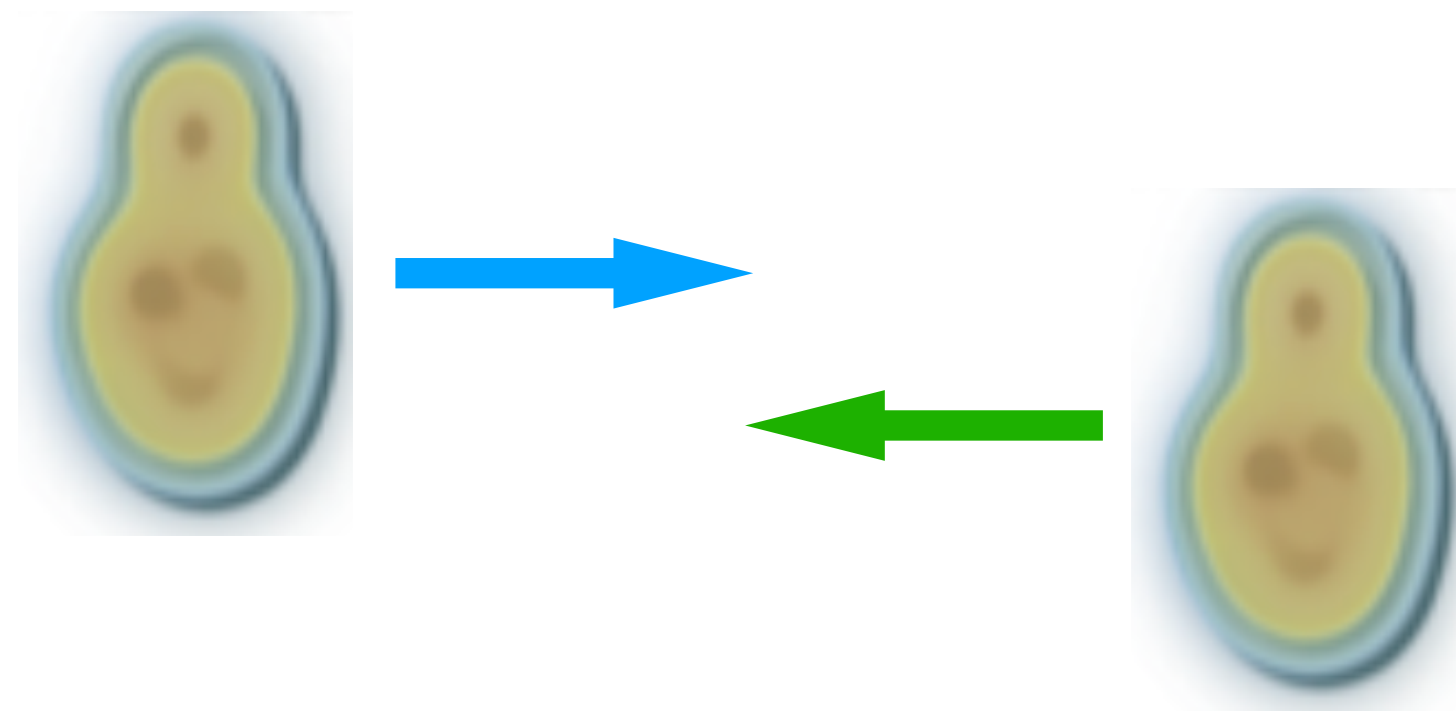
With a second injection source



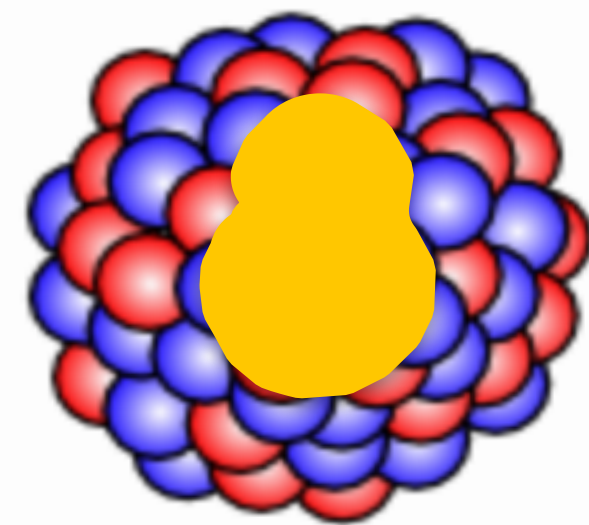
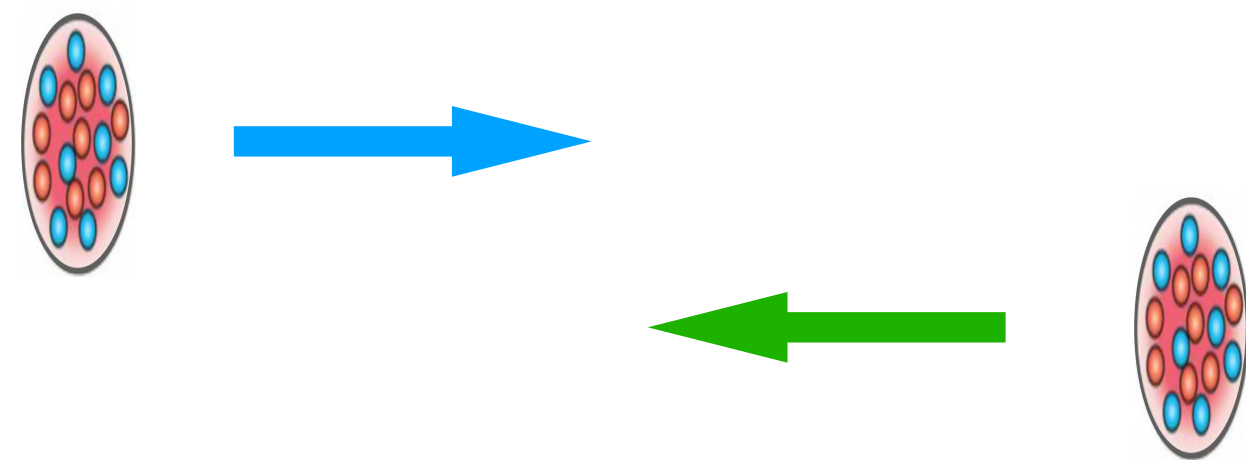
New opportunities from 2030

Colliding mode

With a second injection source



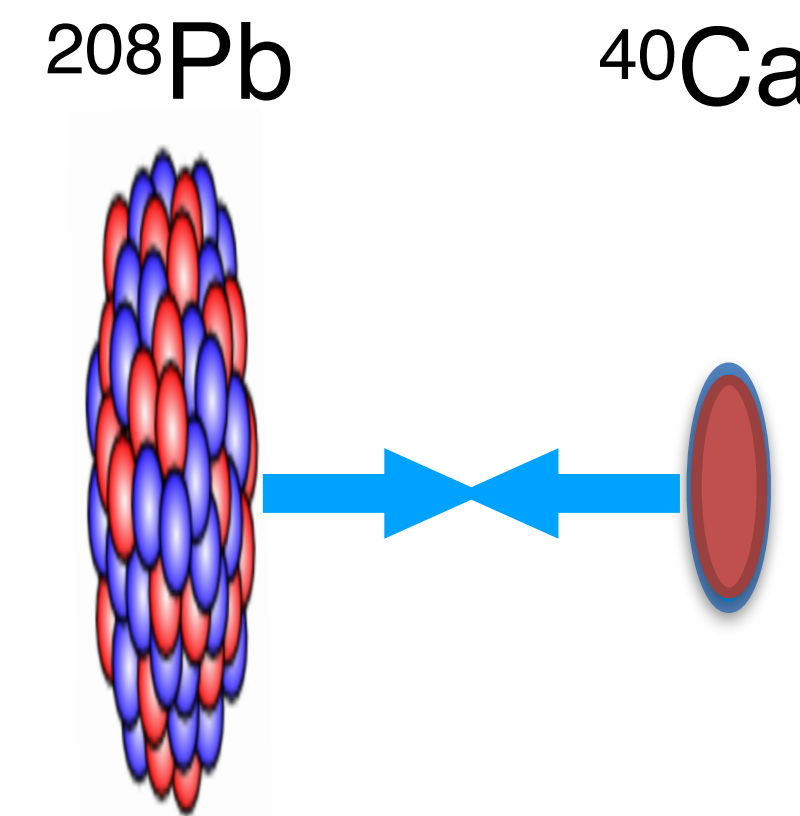
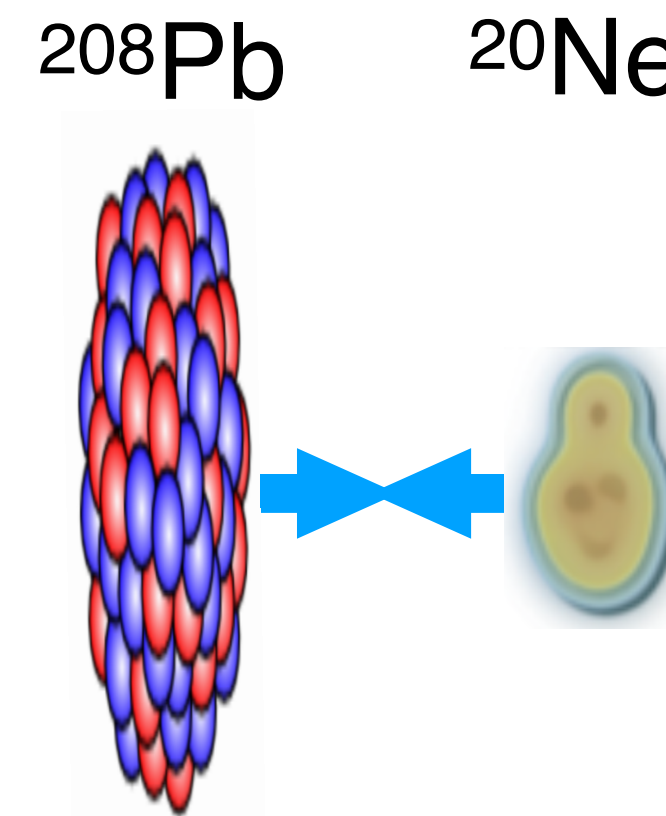
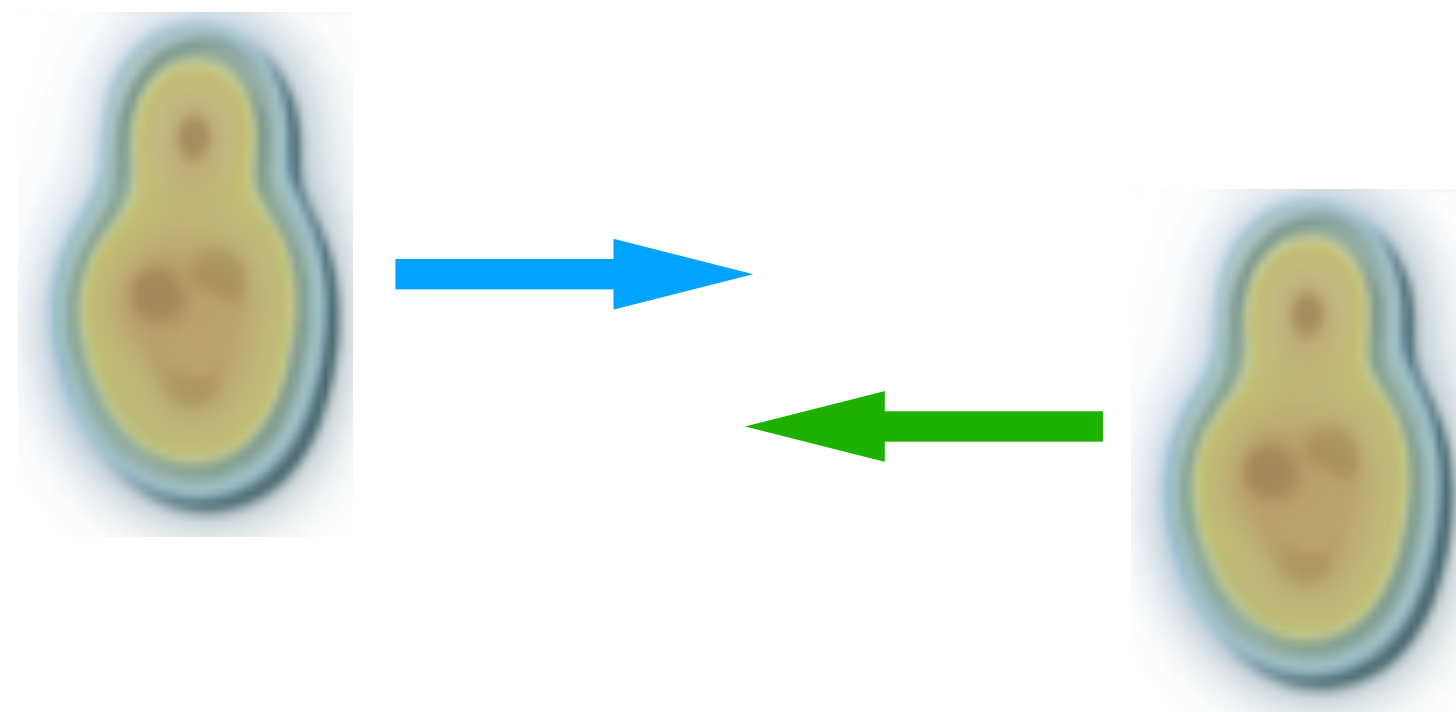
90°



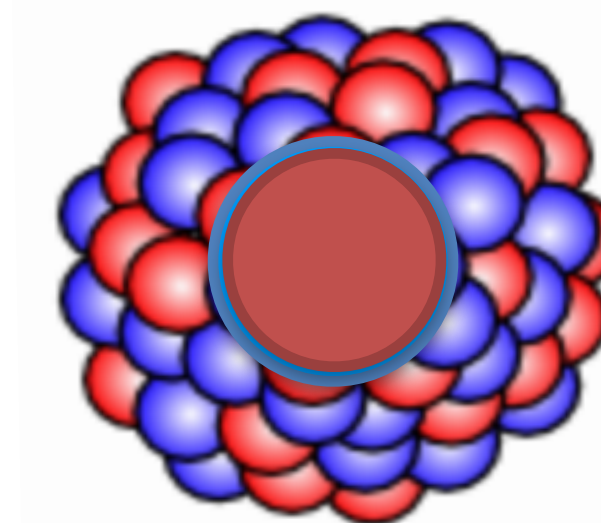
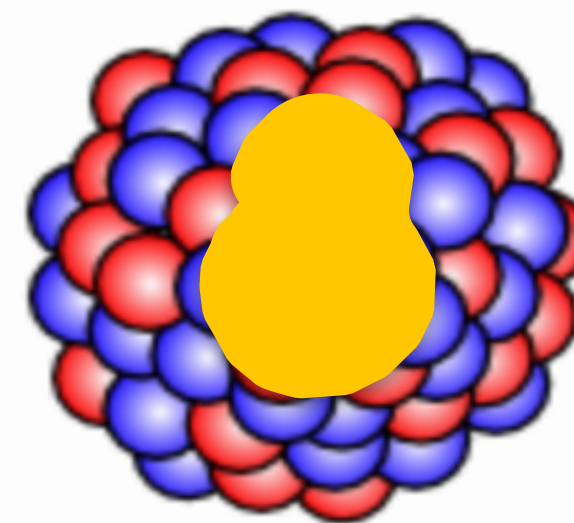
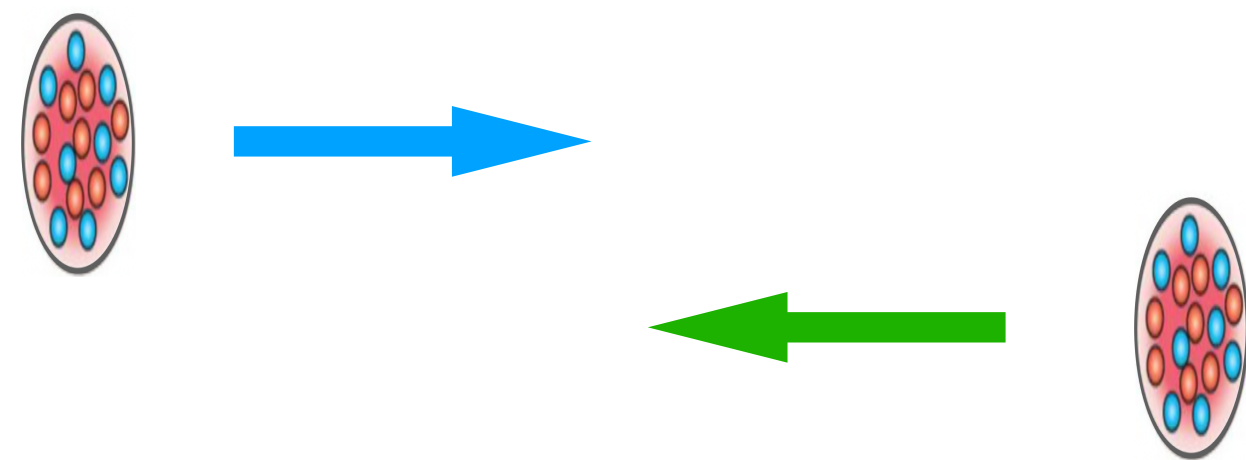
New opportunities from 2030

Colliding mode

With a second injection source



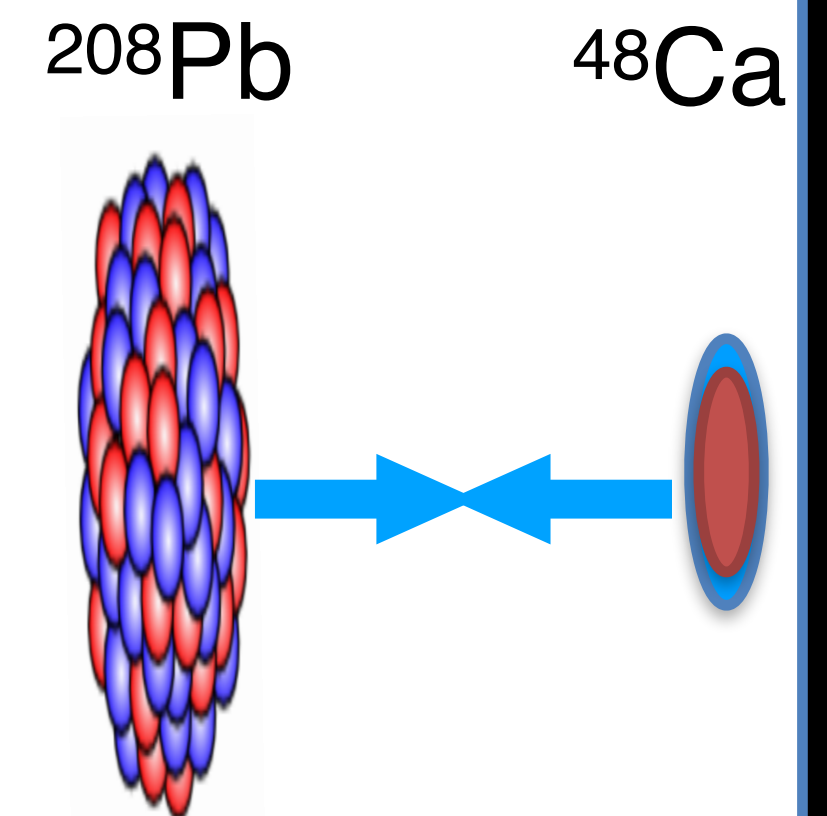
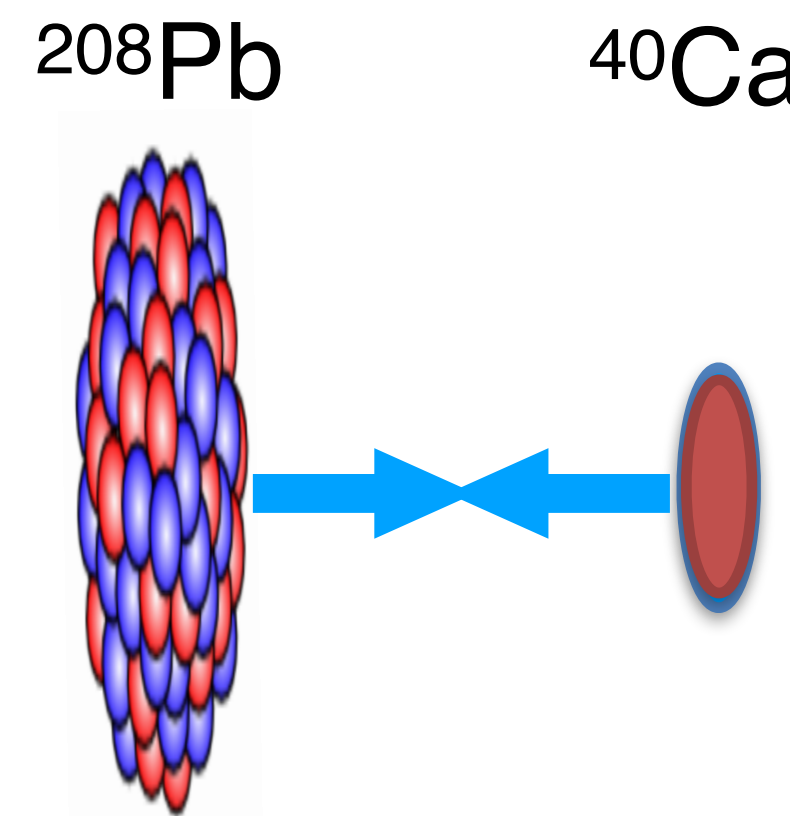
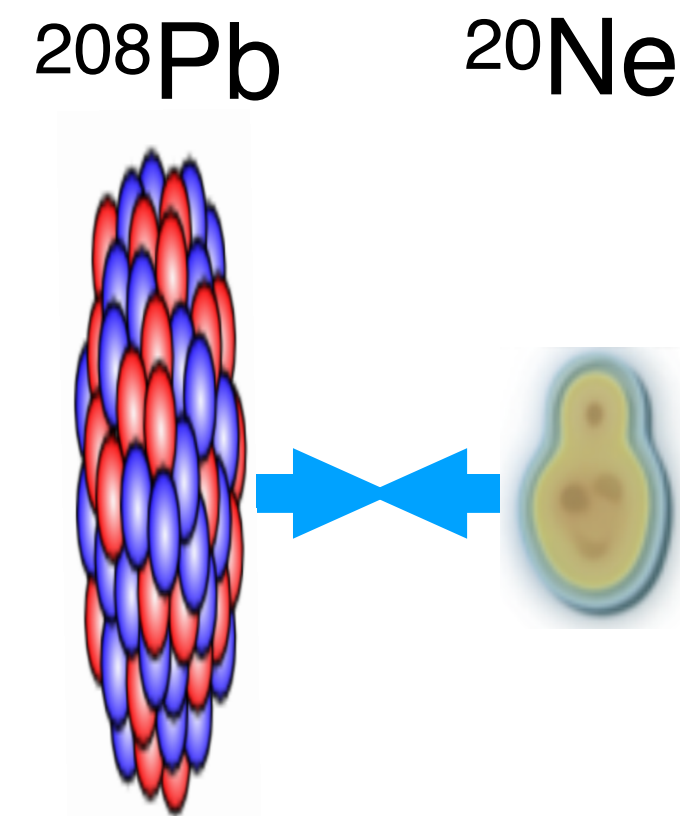
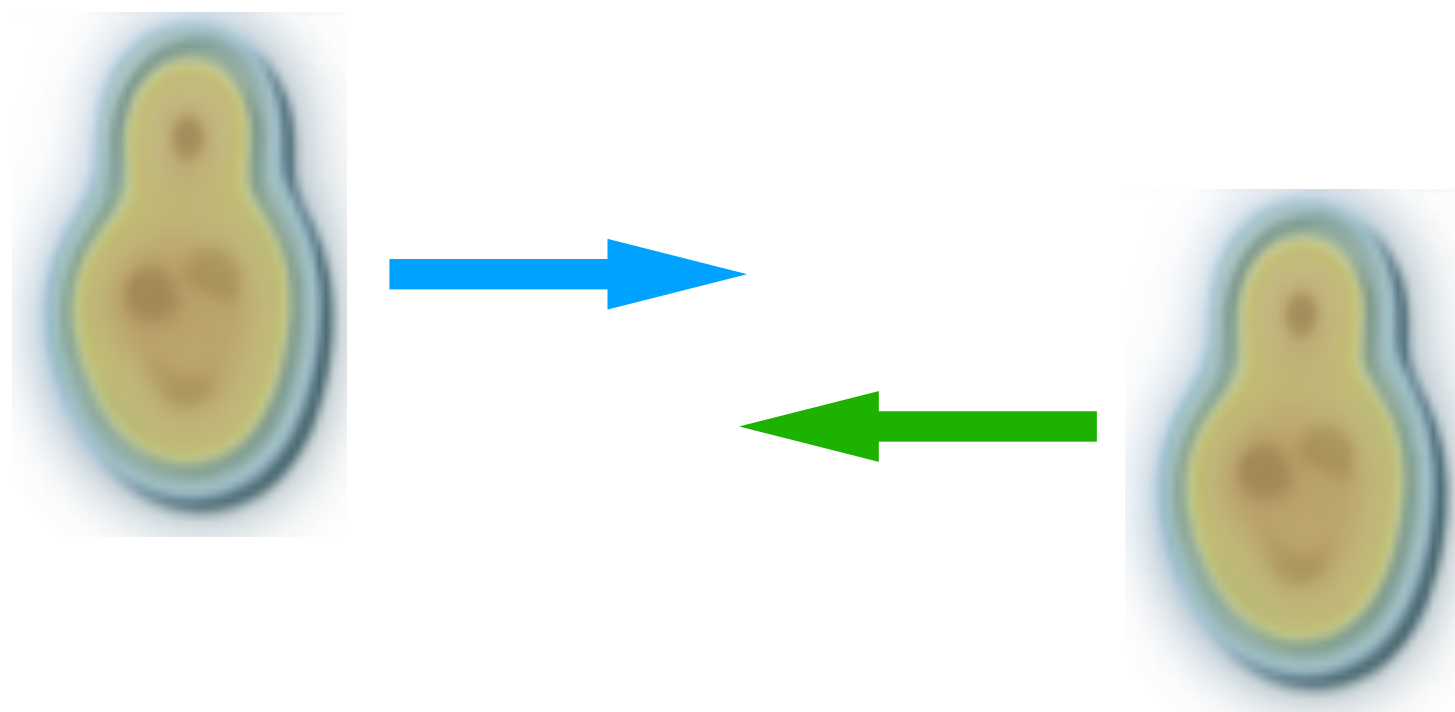
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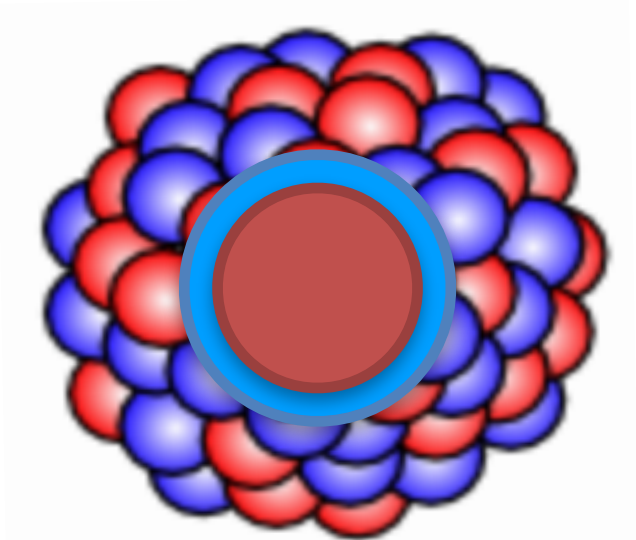
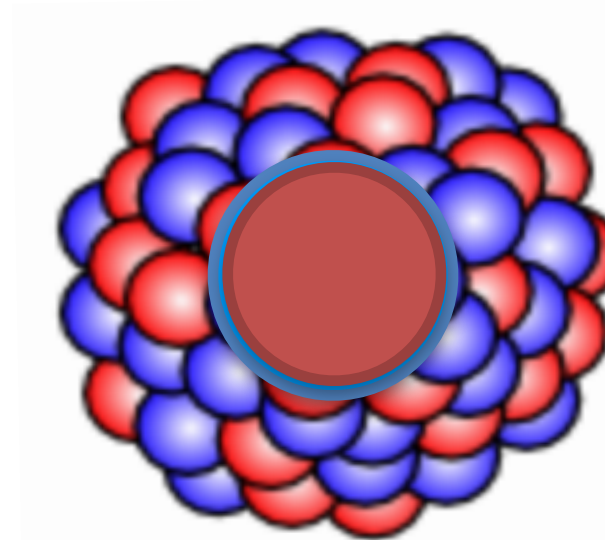
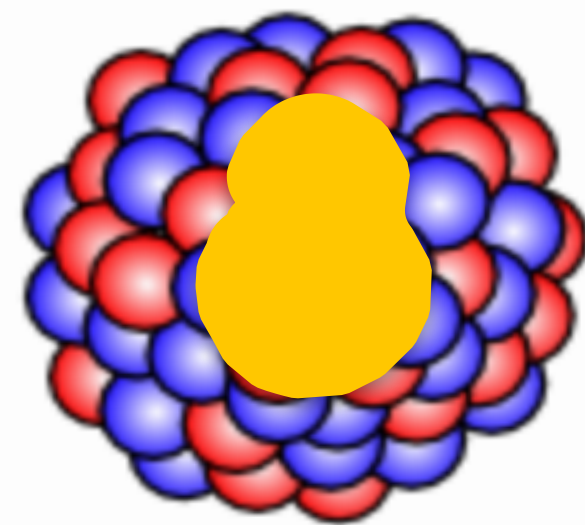
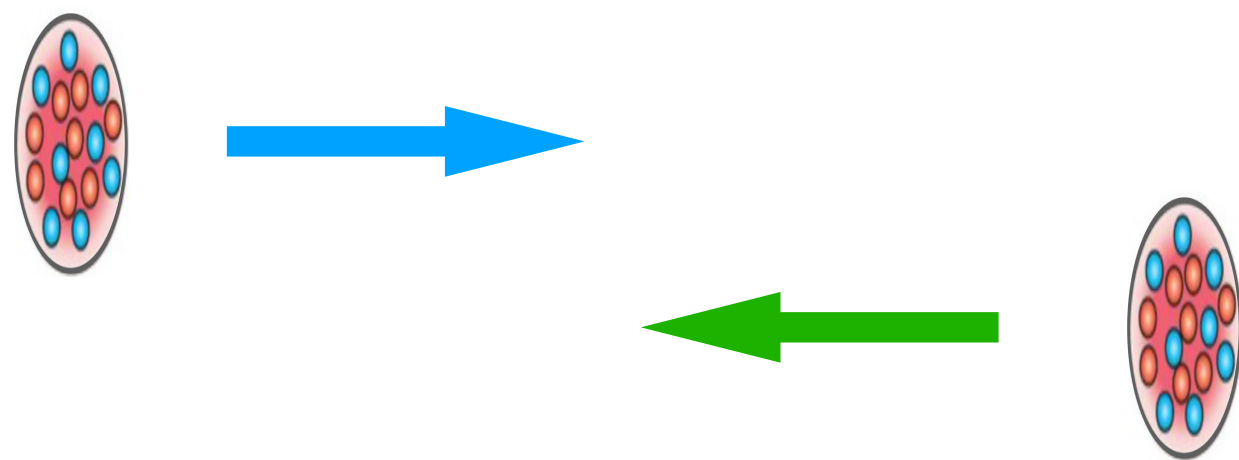
New opportunities from 2030

Colliding mode

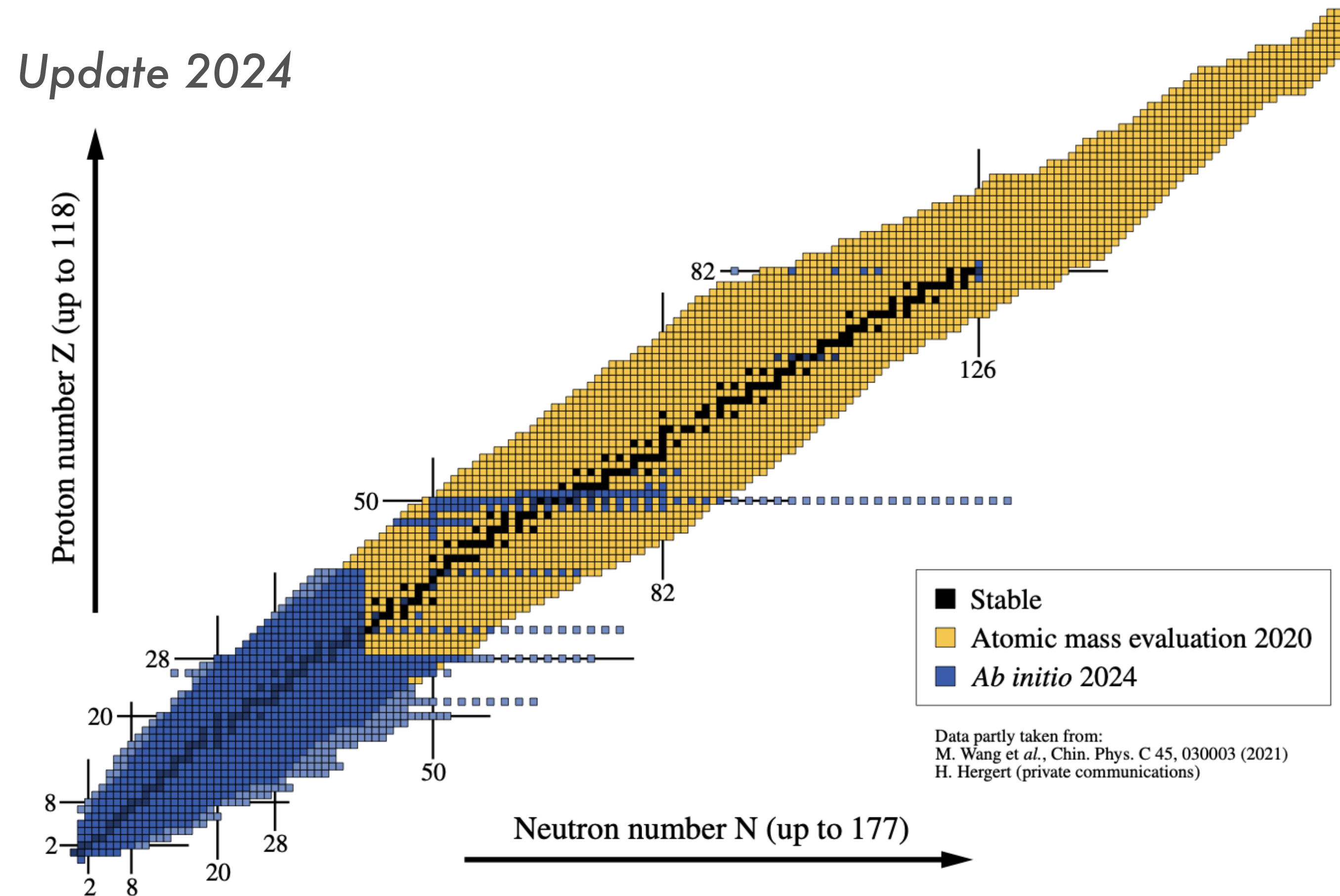
With a second injection source



90°



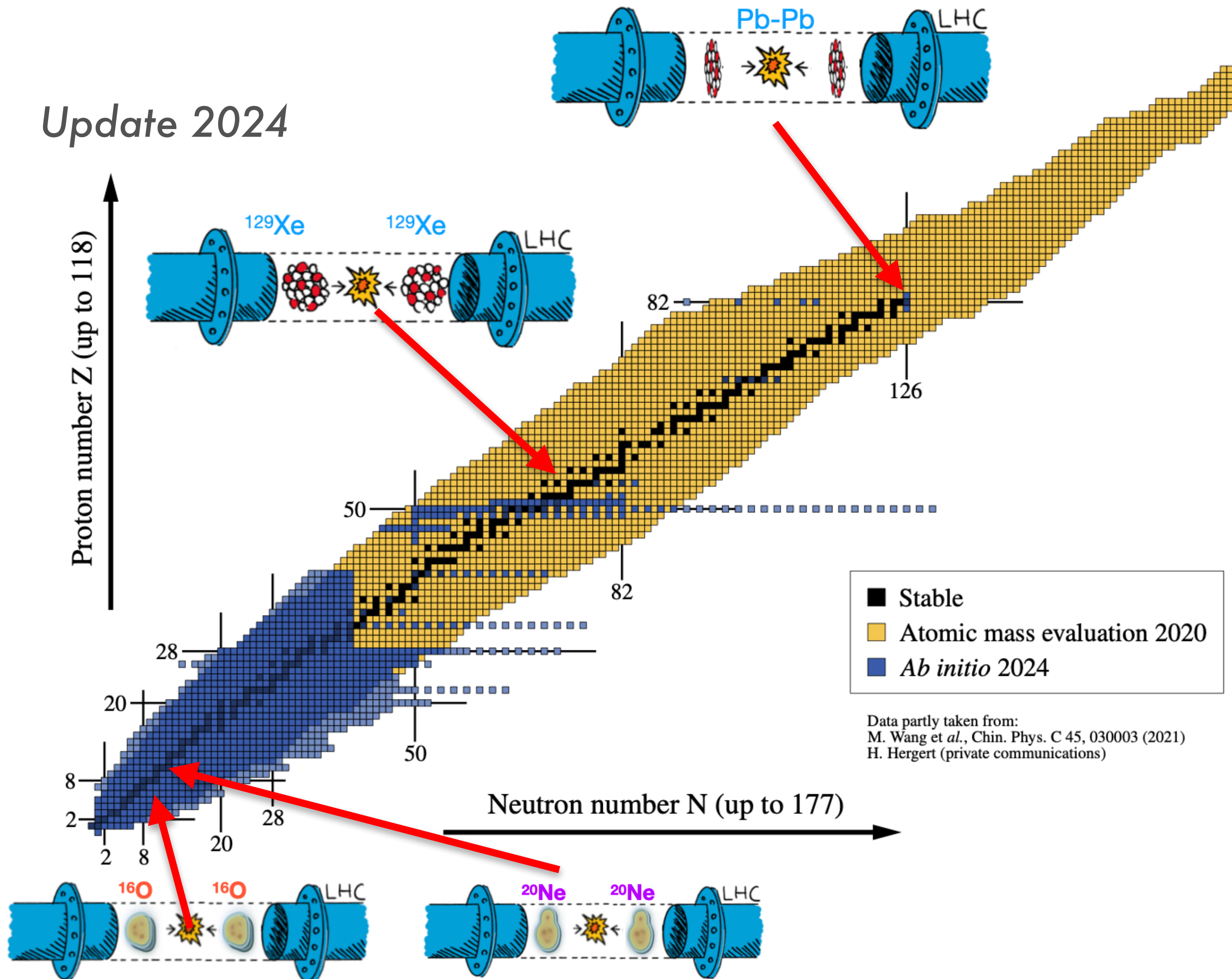
Summary



- ❖ 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!)

Summary

Update 2024



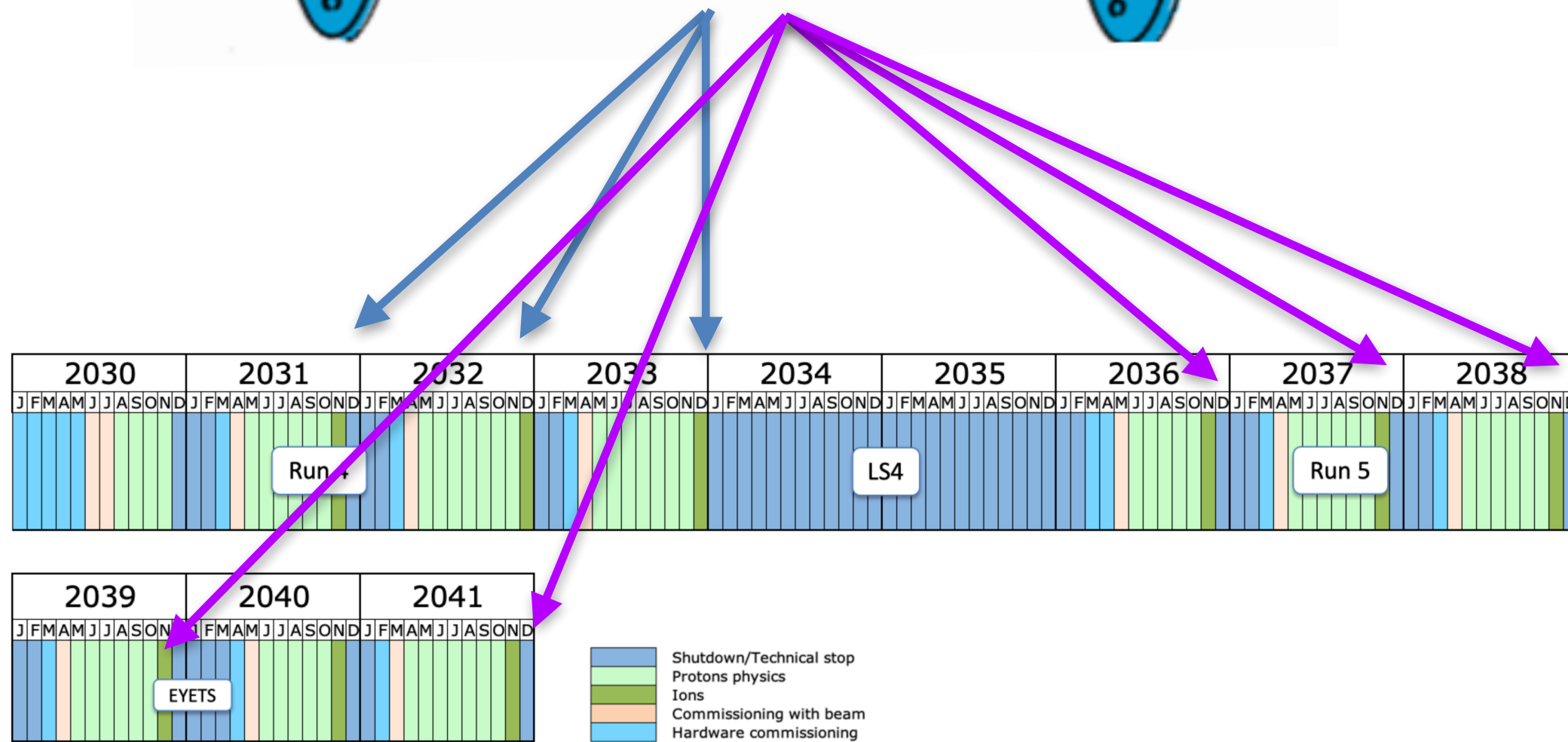
❖ With the inputs on NS from low-energy community, we have significantly improved our understanding on the Quark-Gluon Plasma (critical for the HI community!)

❖ 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.

Outlook

Question:

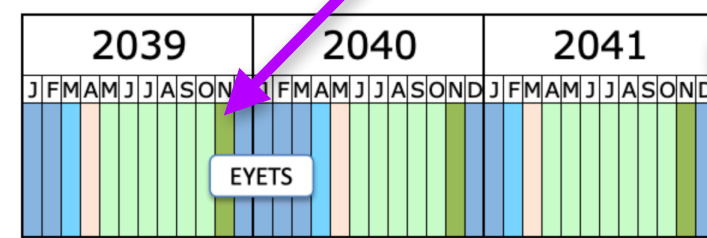
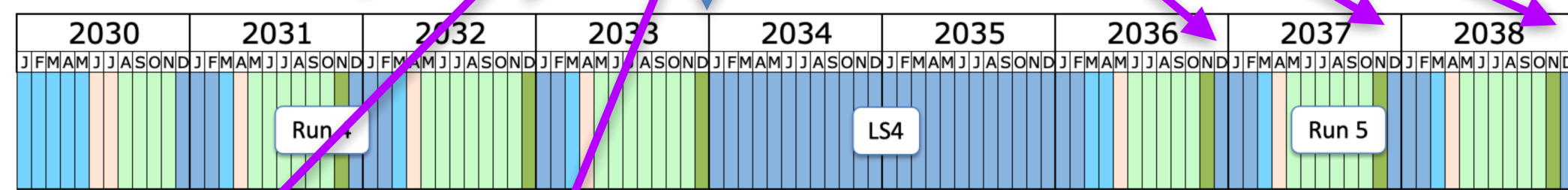
➔ What to collide at the Run 4 & Run 5 @ LHC



Outlook

Question:

➔ What to collide at the Run 4 & Run 5 @ LHC



■ Shutdown/Technical stop
■ Protons physics
■ Ions
■ Commissioning with beam
■ Hardware commissioning

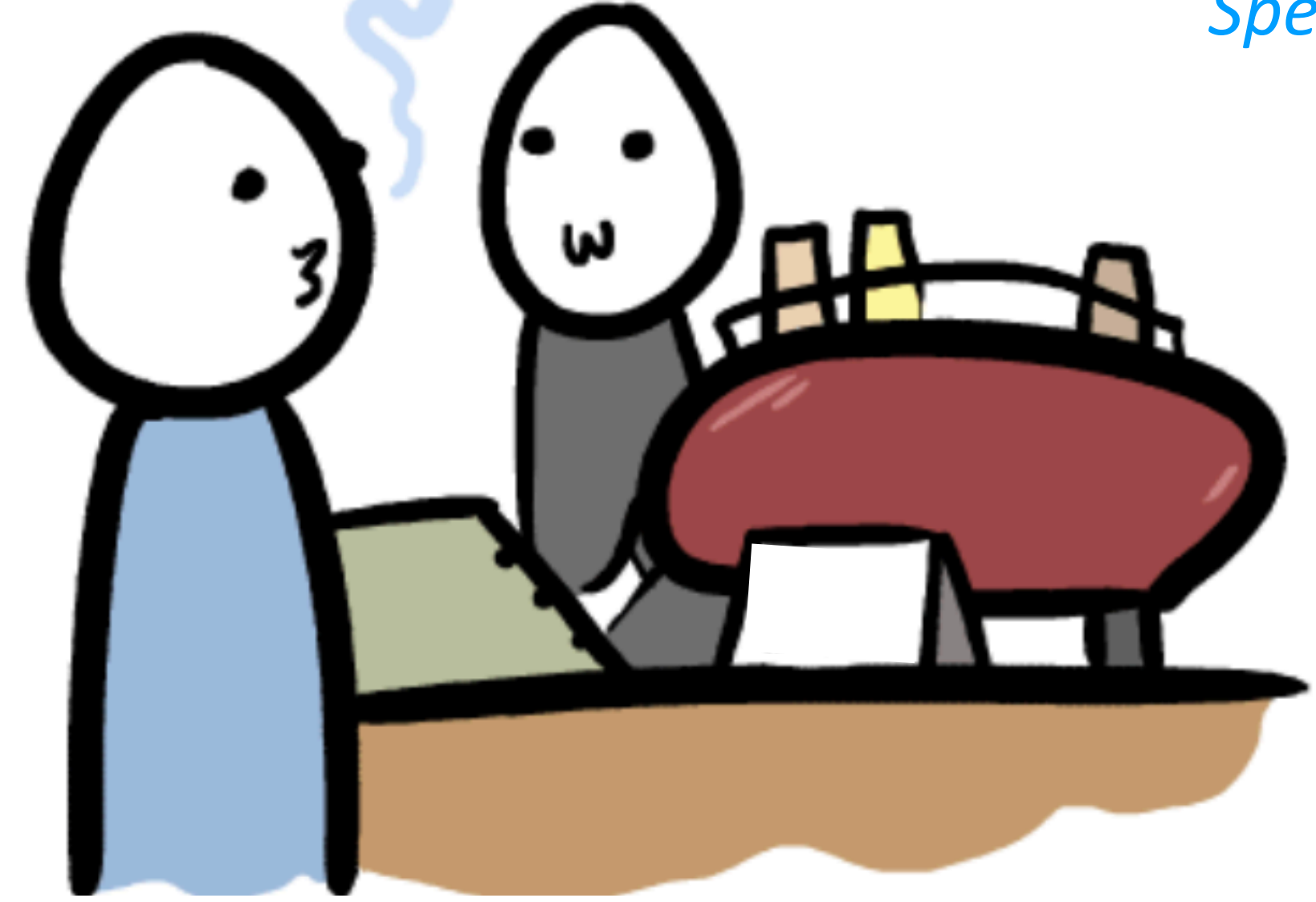
Last update: November 24

CERN MENU

5 B Boron 10.811	8 O Oxygen 15.9994	10 Ne Neon 20.1797	12 Mg Magnesium 24.305	18 Ar Argon 39.948	20 Ca Calcium 40.078	36 Kr Krypton 83.80	49 In Indium 114.818	54 Xe Xenon 131.29	82 Pb Lead 207.2
★		★		★		★		★	

NUCLEAR PHYSICS AT LHC

New collisions
Please



Special offer

He-4 Stable
4.01603
NA: 99.999%

Li-6 Stable
6.01512
NA: 7.8%

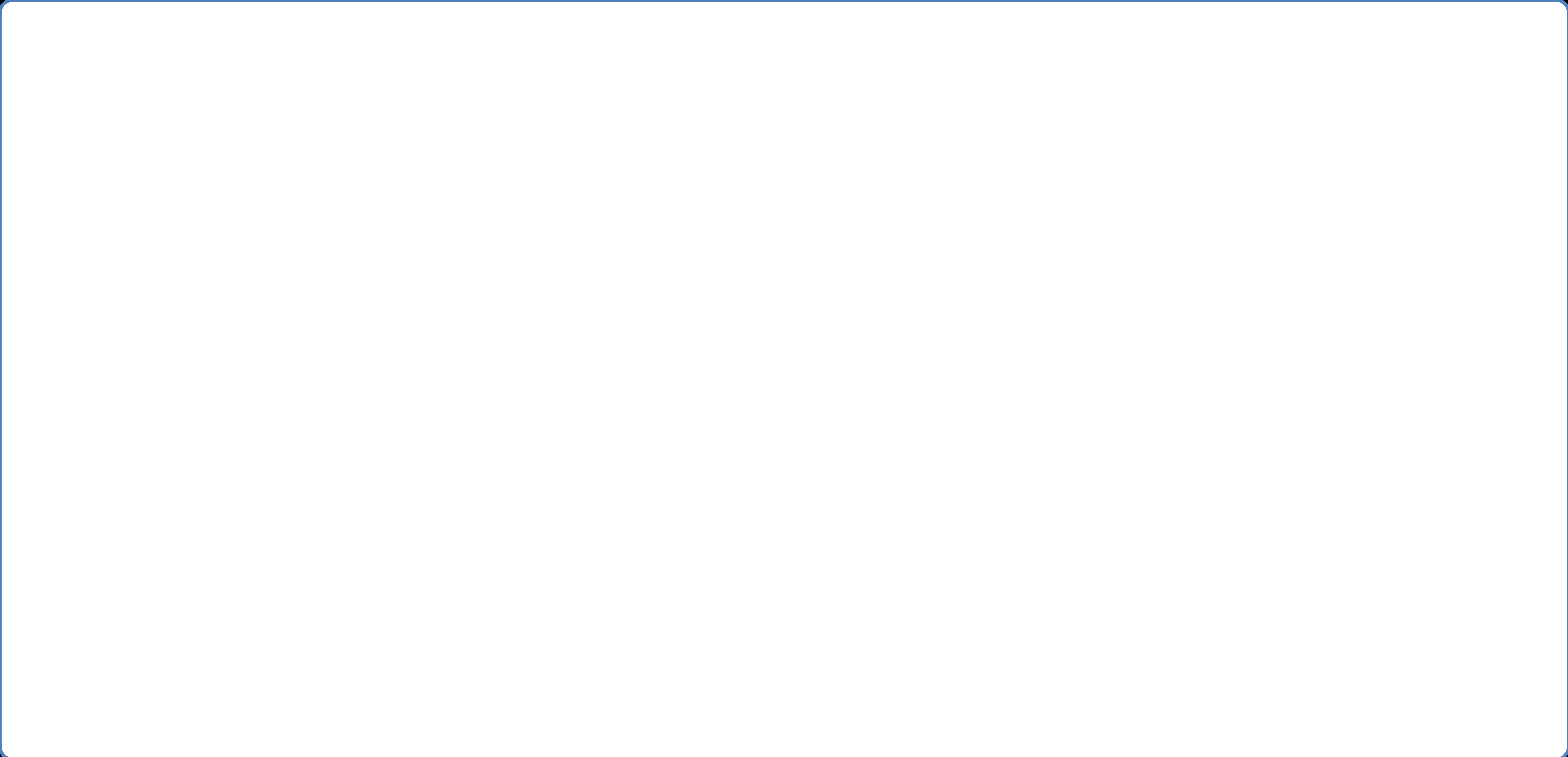
Ge-76 Stable
75.92140
NA: 7.75%

Se-76 Stable
75.91921
NA: 9.23%

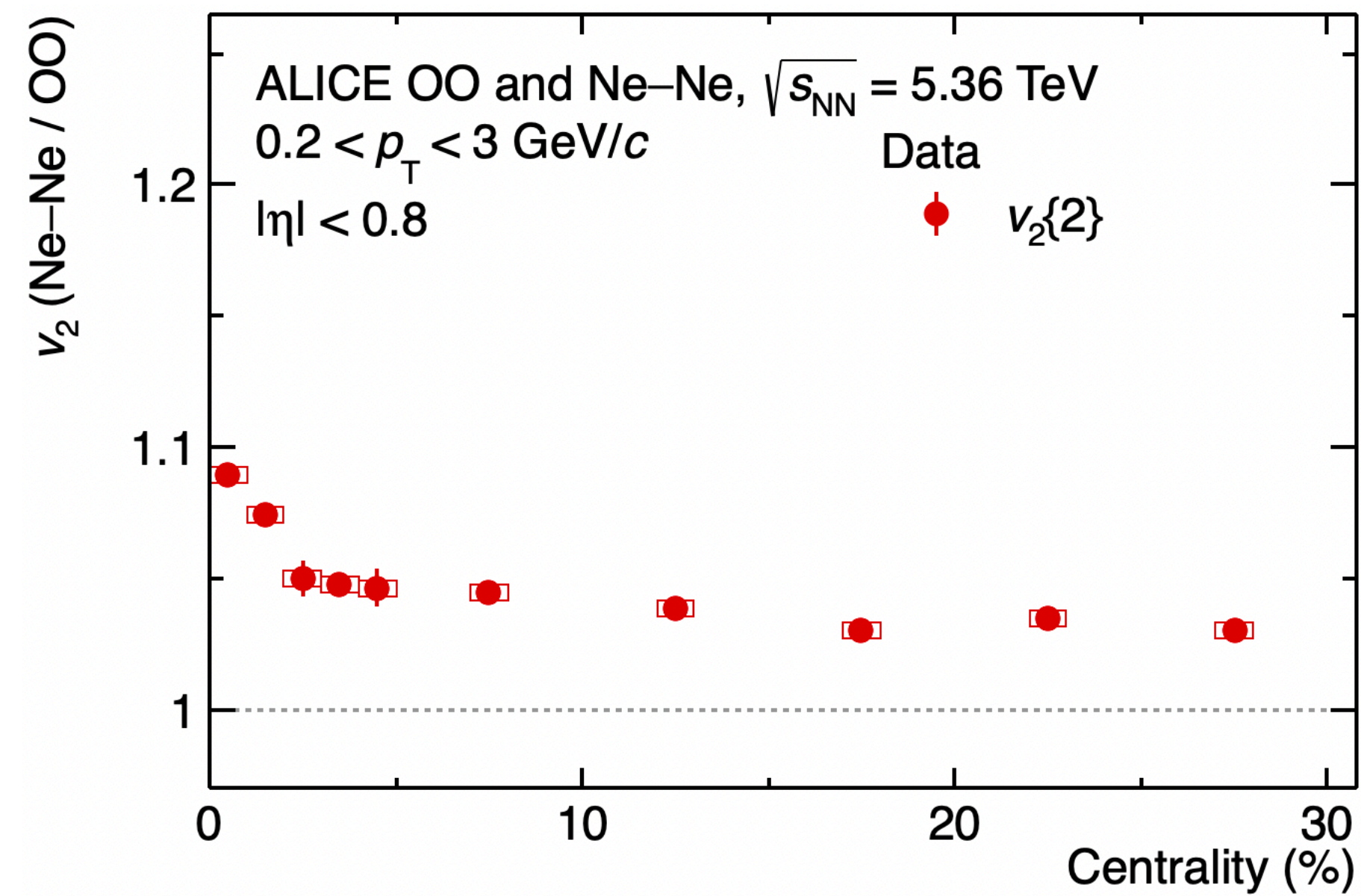
Ba-136 Stable
135.90458
NA: 7.85%

Thanks for your attention!





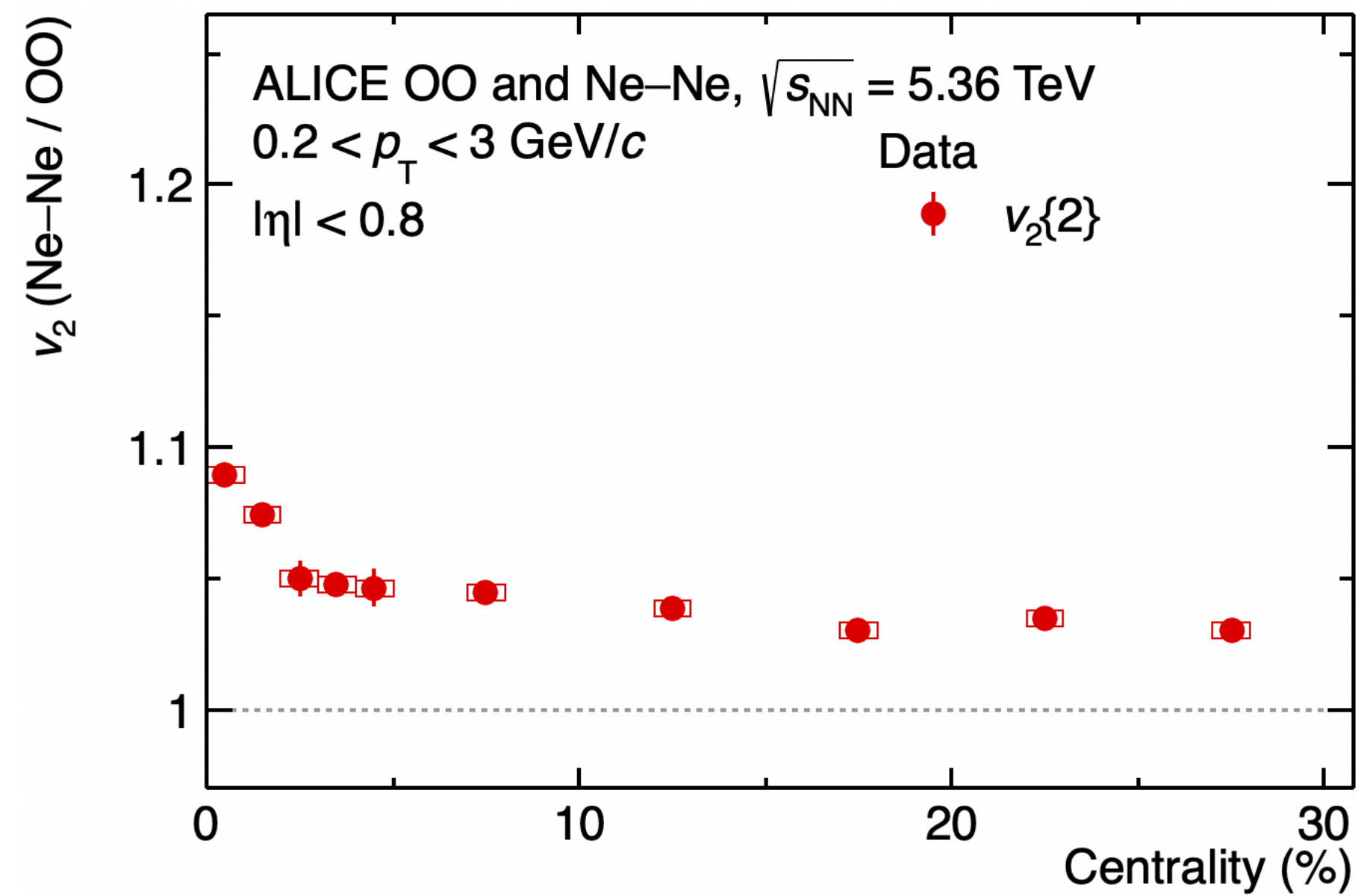
Flow ratios (Ne-Ne / OO) -> sub-structure



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



Flow ratios (Ne-Ne / OO) -> sub-structure



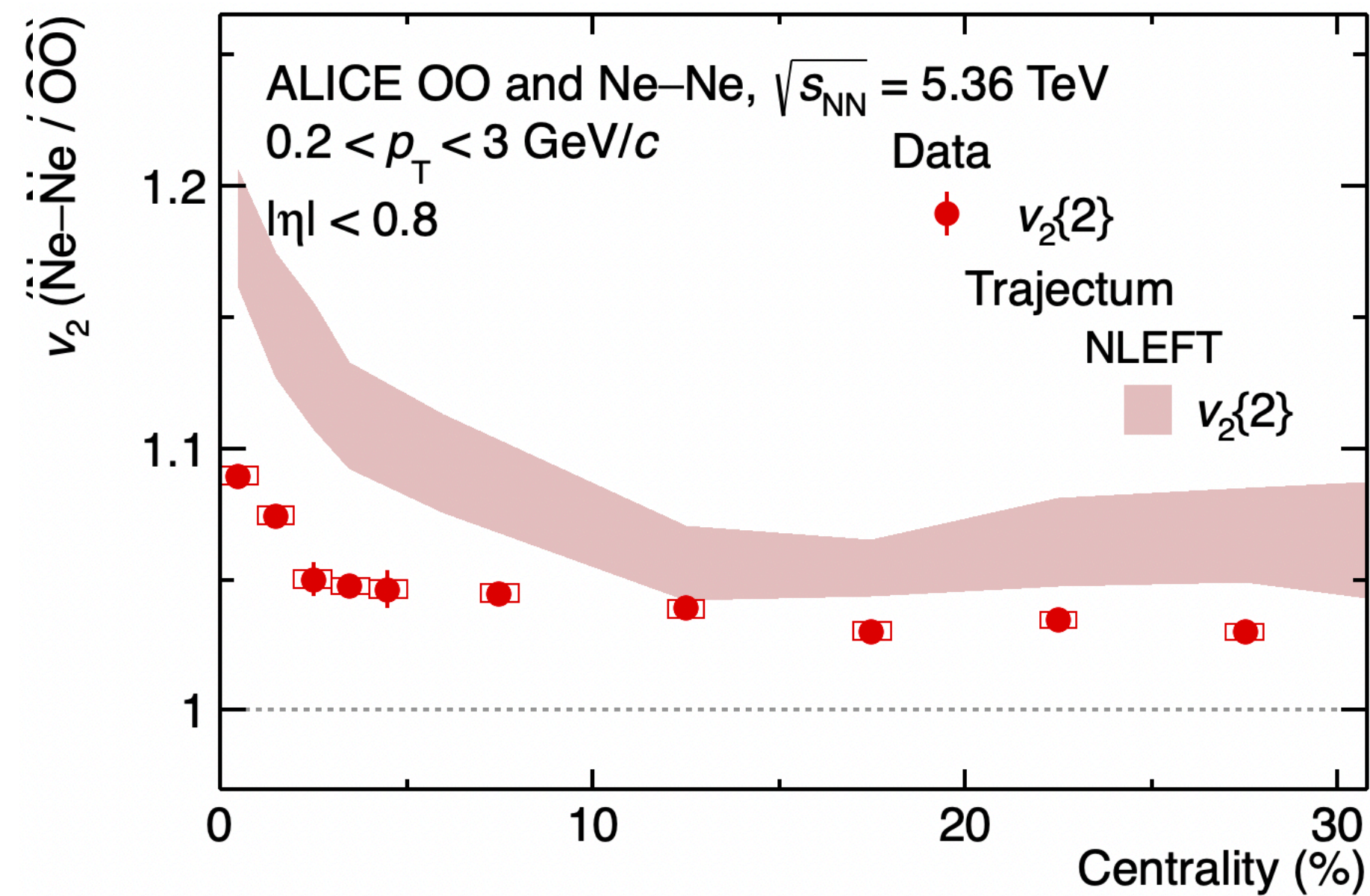
❖ Enhanced v_2 in Ne-Ne than OO

- Driven by nuclear geometrical shape of ^{20}Ne (larger deformation compared to ^{16}O)

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



Flow ratios (Ne-Ne / OO) -> sub-structure



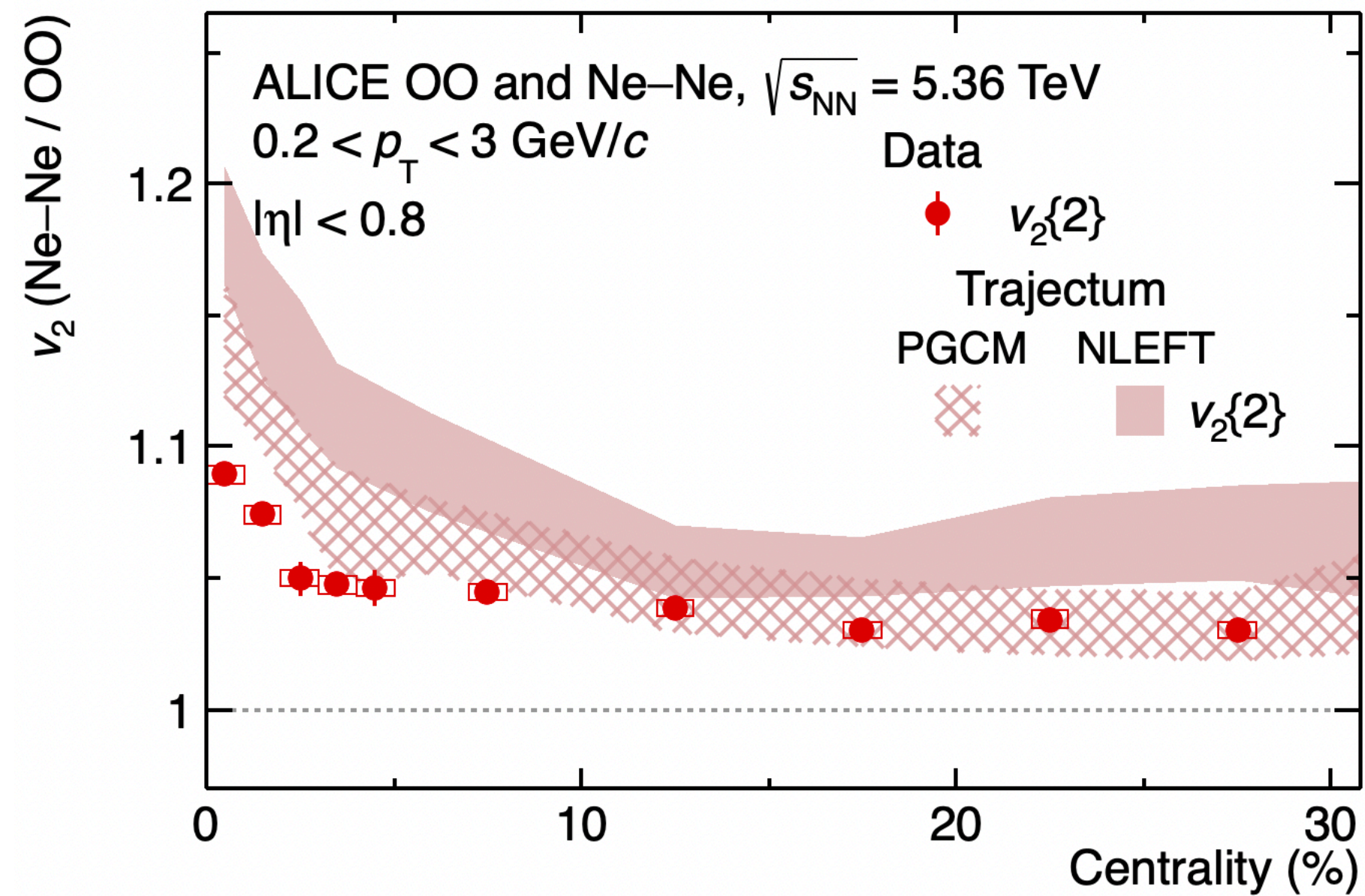
❖ Enhanced v_2 in Ne-Ne than OO

- Driven by nuclear geometrical shape of ^{20}Ne (larger deformation compared to ^{16}O)
- Trajectum prediction using NLEFT-NS overestimates the ratio

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



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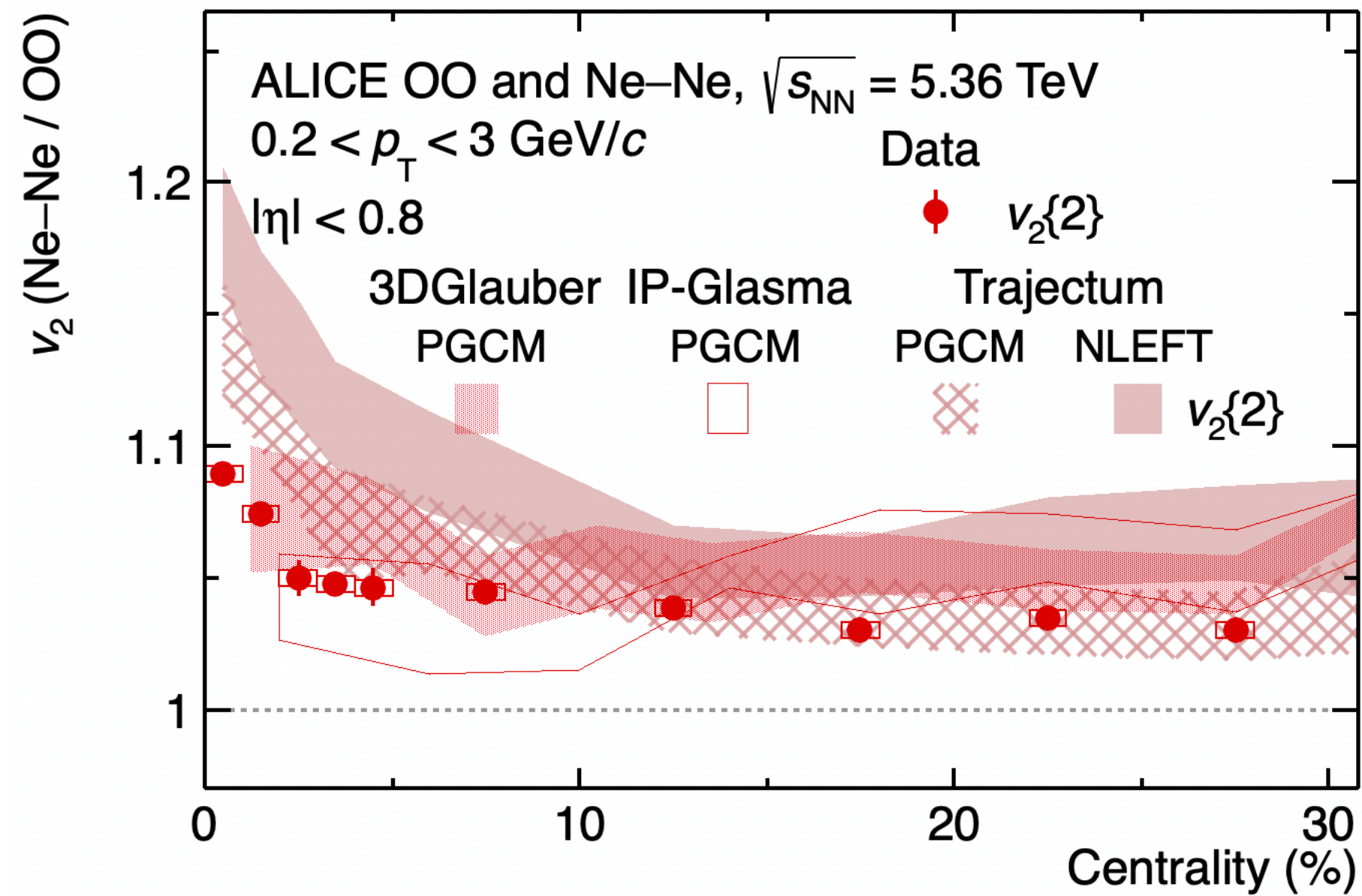
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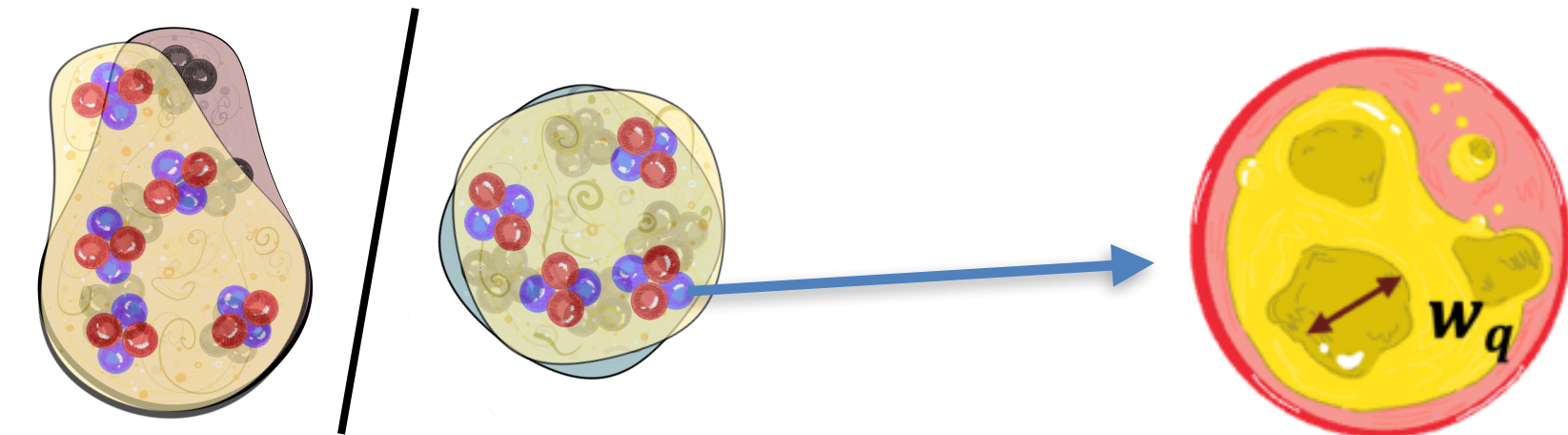
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- Trajectum prediction using NLEFT-NS overestimates the ratio
- Trajectum prediction using PGCM-NS agrees better although still overestimates the ratio
- predictions from 3DGlauber and IP-Glasma using PGCM describes the data
- Data better described by the models using a smaller sub-nucleon (~ 0.1 fm)

Difference? Subnucleon width w_q

Trajectum: $w_q \approx 0.4$ fm
 3DGlauber: $w_q \approx 0.11$ fm
 IP-Glasma: $w_q \approx 0.11$ fm

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