Why is it interesting to study central collisions of heavy projectiles with light targets at the BM@N?

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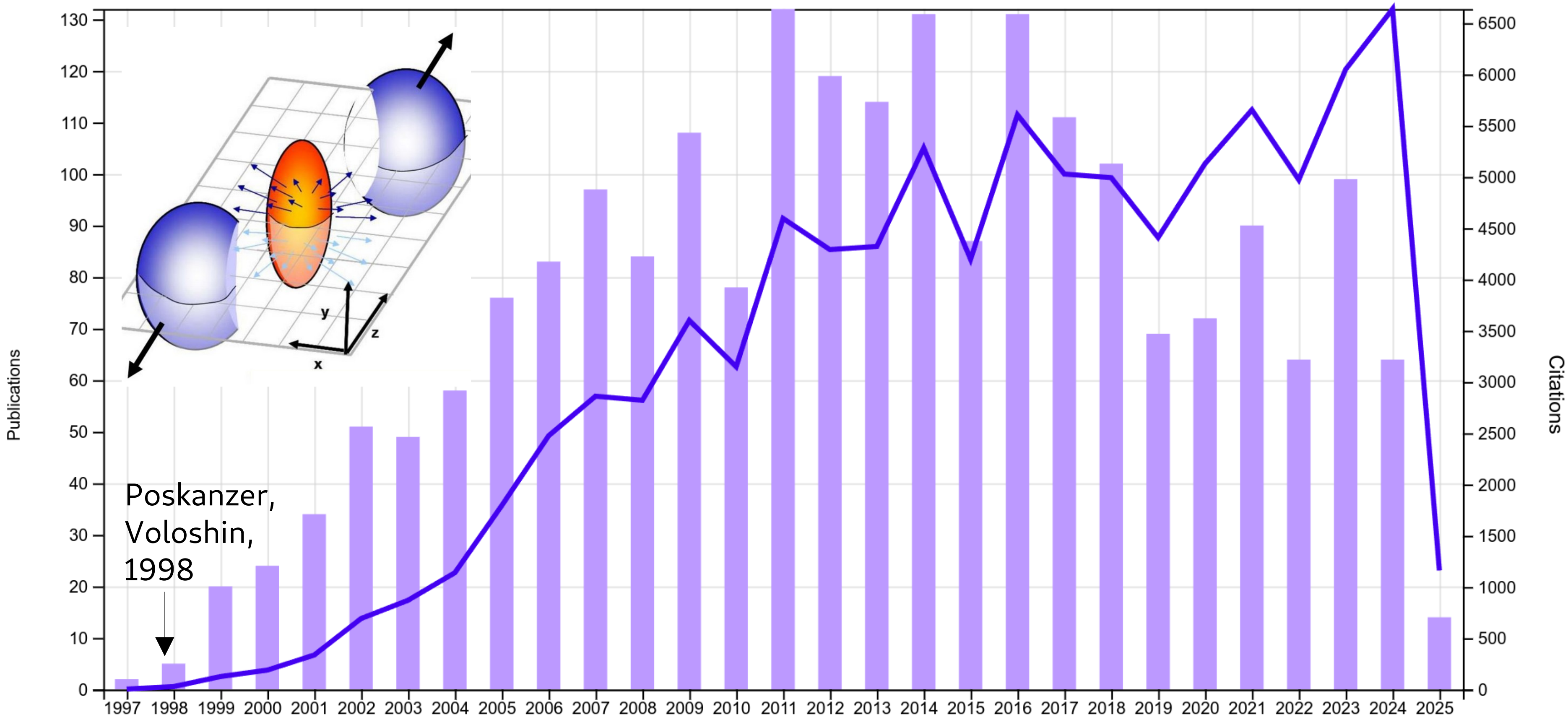
Outline

- Over the past 30 years, experiments and theorists have mostly focused on symmetric collisions of same-size (heavy) nuclei to study:
  - Elliptic flow (v_2) which develops in non-central collisions (2000+ papers)
  - Anisotropic flow in general: v_1, v_2, v_3, v_4, v_5 …. (700+ papers)
  - Global vorticity of nuclear matter translated to the polarization of produced Λ (200+ papers)
  - Measurements were successfully described by numerous models
- While the BM@N and MPD experiments at NICA will add new data to all of this, entirely new topics for study can also be considered:
  - Local vorticity rings created at the boundary between participant and spectator domains in central collisions
  - Development of vorticity in asymmetric collisions of heavy projectiles with lighter target nuclei
  - Translation of the anomalous n/p ratio at far nuclear periphery (neutron skin/neutron halo) to an unusual ratio between spectator neutrons and protons in central collisions, including asymmetric ones
  - Sensitivity of characteristics of asymmetric collisions to EoS of nuclear matter

Symmetric non-central HI collisions

Search in Web of Science Core collection with **"Elliptic flow heavy-ion collisions"** returns **2 168** journal papers, cited **92 410** times in total

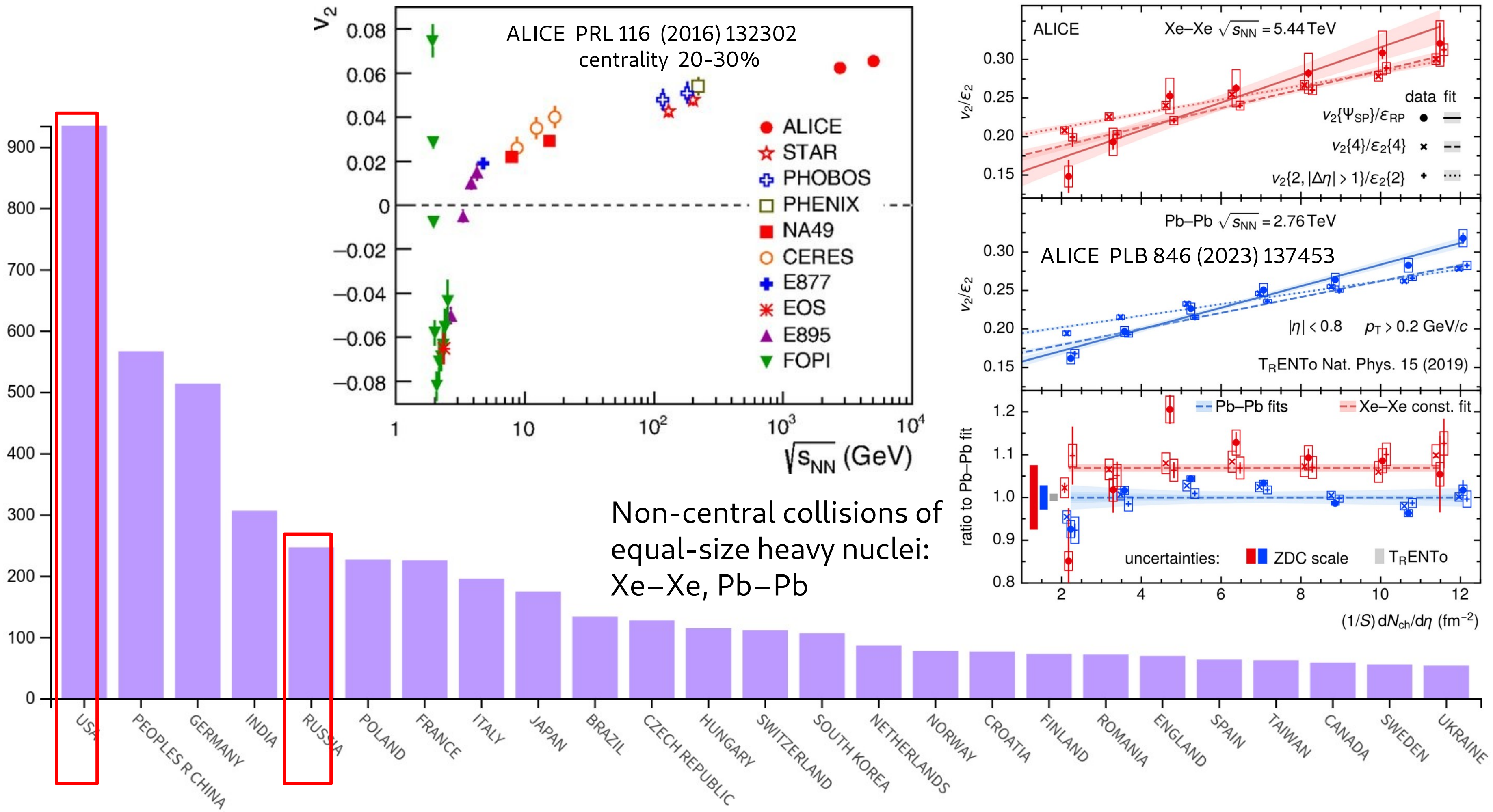


$$E\frac{d^3N}{d^3p}=\frac{d^2N}{2\pi p_T dp_T dy}\left\{1+2\sum_{n=1}^{\infty} v_n(p_T)\cos[n(\varphi-\psi_n)]\right\}$$

Radial flow v_1 – direct flow, v_2**- elliptic flow**

Inspired also by RHIC findings in 2005, "perfect fluid"

Tremendous efforts worldwide to understand elliptic flow phenomenon

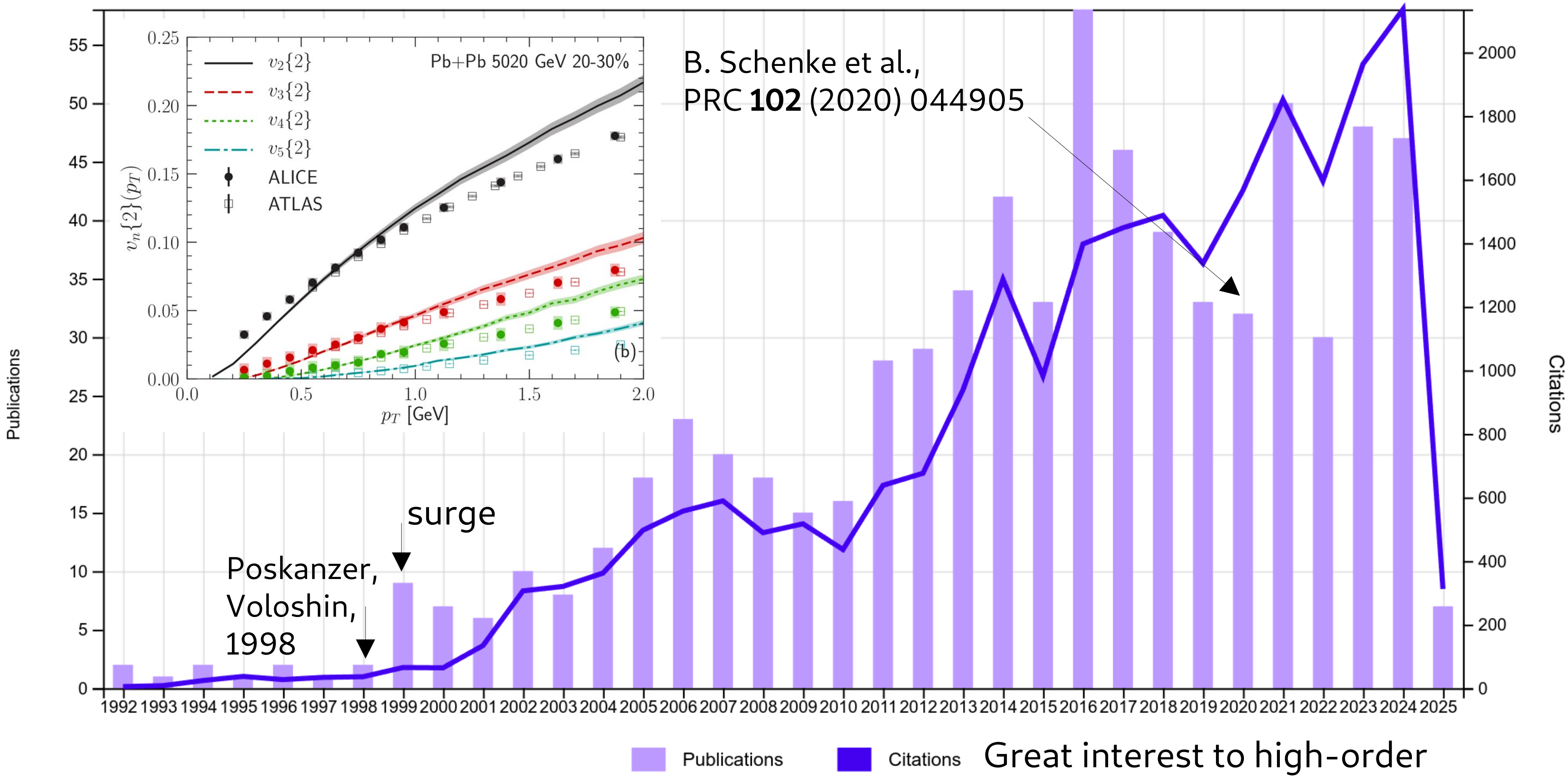


Non-central collisions of equal-size heavy nuclei: Xe–Xe, Pb–Pb

papers by authors from ...

More general: v_2, v_3, v_4, v_5 ..., theory, review papers

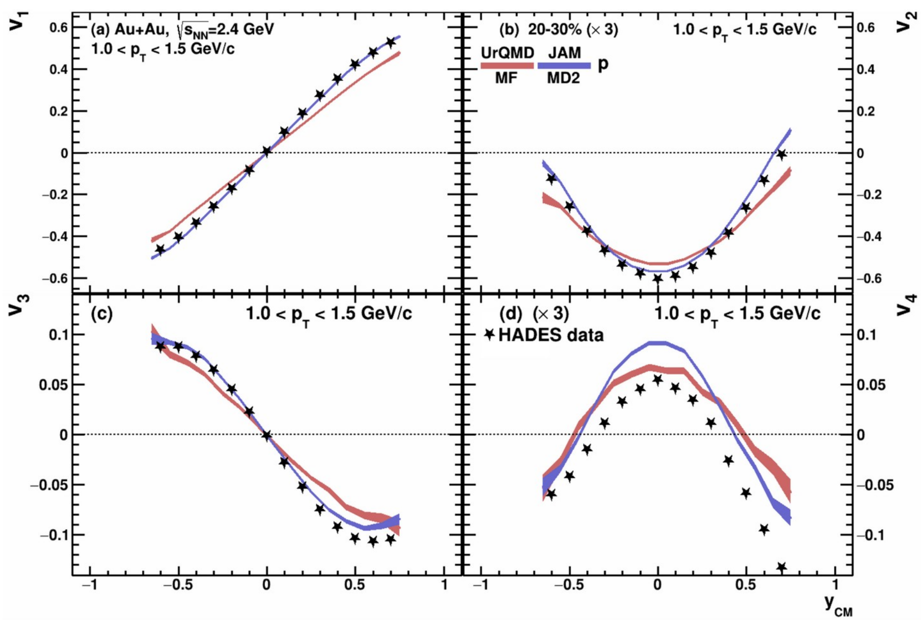
Search with **"Anisotropic flow heavy-ion collisions"** returns **729** journal papers, cited **9 570** times in total



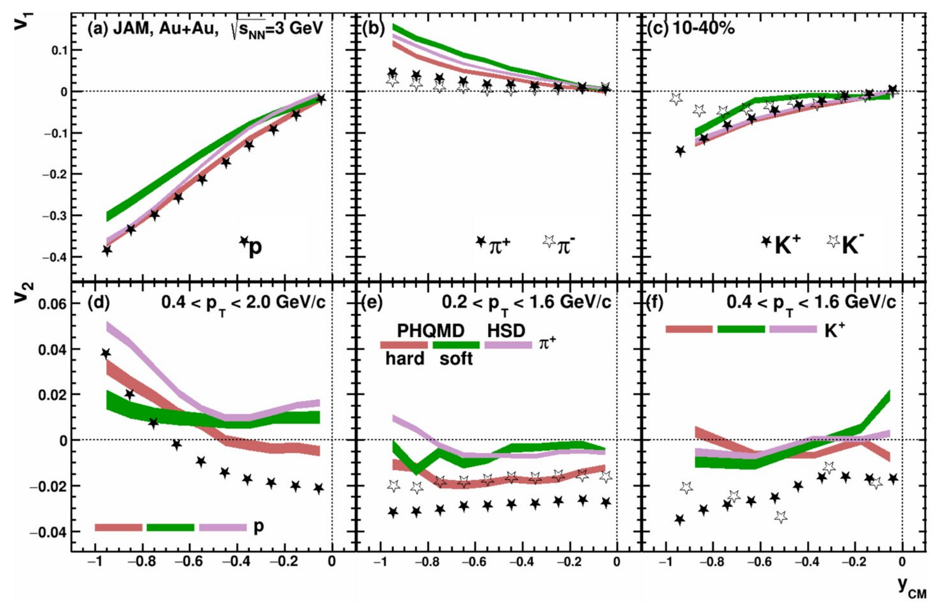
Great interest to high-order harmonics of φ in the last decade

Present HADES and STAR data on v_n relevant to NICA energy are described by models ...

Differential v_1, v_2, v_3, v_4



v_1, v_2 for identified hadrons

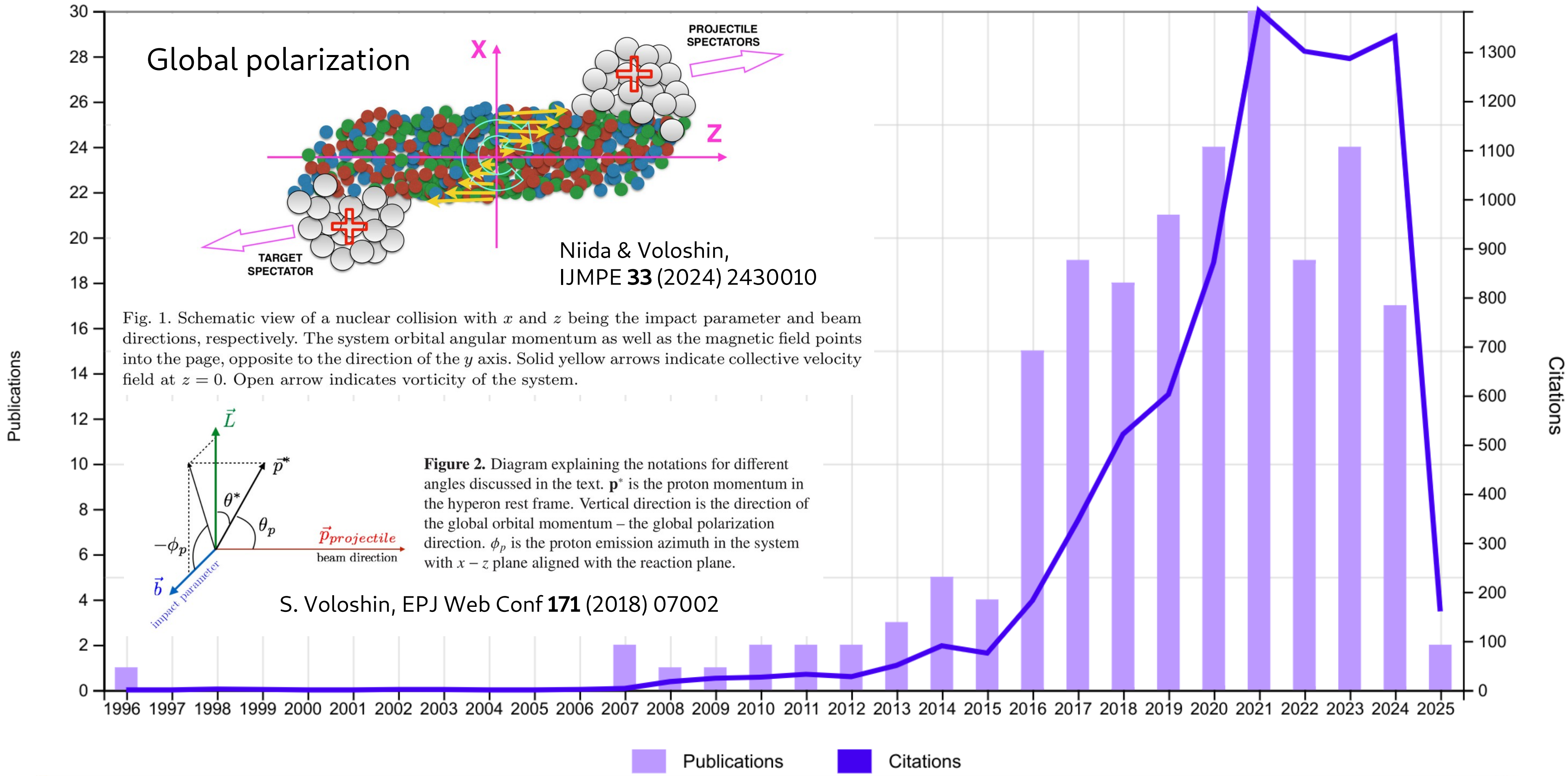


P. Parfenov, Particles **5** (2022) 561:
"We have found that transport models JAM and UrQMD in the mean-field mode can qualitatively reproduce the recently published HADES and STAR v_n measurements of protons from Au + Au collisions at $\sqrt{s_{NN}}$ = 2.4 and 3 GeV."

Will future NICA data on Bi-Bi spoil the party?

Global angular momentum of the nuclear system, Λ polarization in HIC

Search with **“Vorticity heavy-ion collisions”** returns **212** journal papers, cited **8 332** times in total, mostly on global polarization.

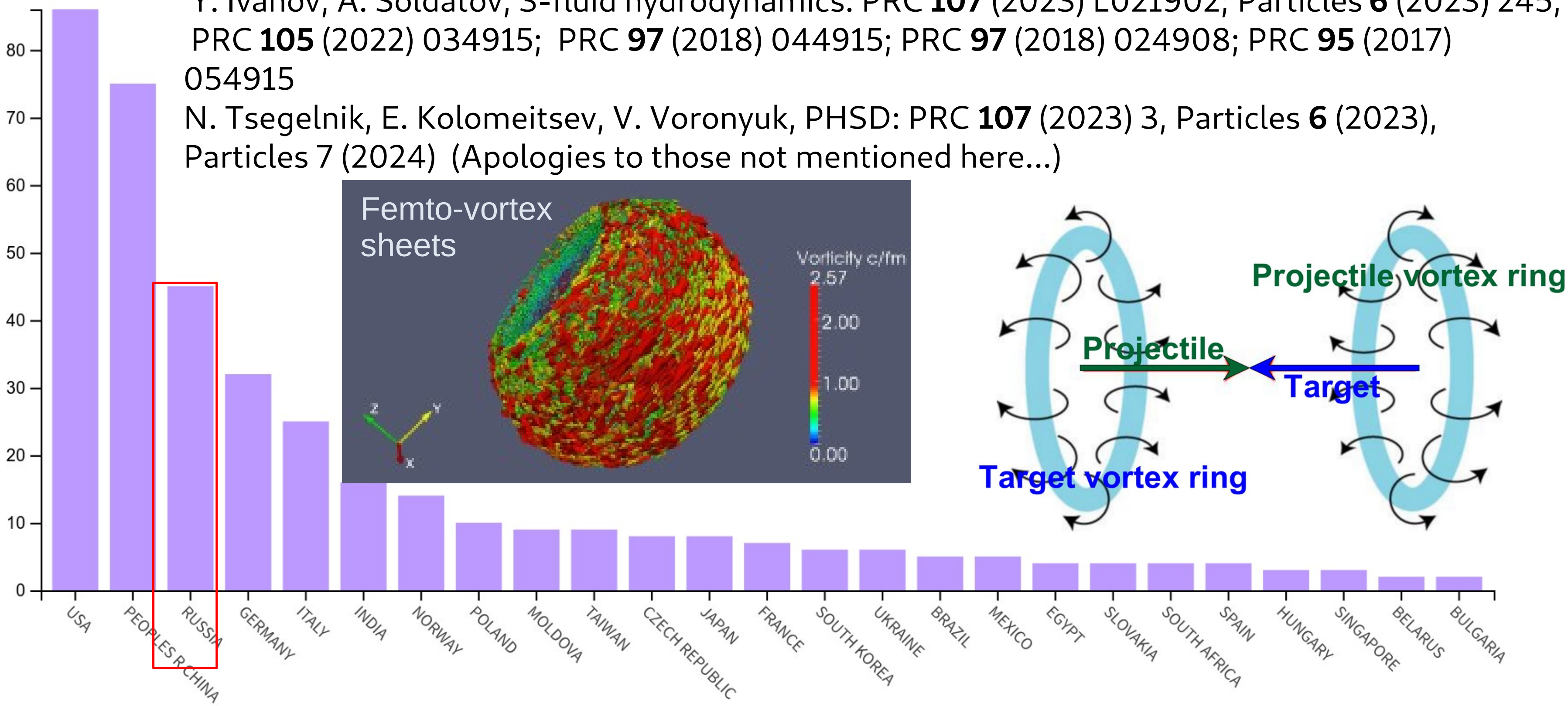


Vorticity studies: countries

M. Baznat, K. Gudima, A. Sorin, O. Teryaev, kinetic QGS model : PRC 88 (2013) 061901R; PRC 93 (2016) 031902R

Y. Ivanov, A. Soldatov, 3-fluid hydrodynamics: PRC **107** (2023) L021902; Particles **6** (2023) 245; PRC **105** (2022) 034915; PRC **97** (2018) 044915; PRC **97** (2018) 024908; PRC **95** (2017) 054915

N. Tsegelnik, E. Kolomeitsev, V. Voronyuk, PHSD: PRC **107** (2023) 3, Particles **6** (2023), Particles 7 (2024) (Apologies to those not mentioned here…)



- As calculated, higher vorticity values (and Λ polarization) are expected at the boundary between participant and spectator (fragmentation) domains in collisions of same-size heavy nuclei.

- Vorticity in bulk participant matter at mid-rapidity (where more Λ are produced) is lower.

Vorticity of matter translates into global polarization of emitted Λ

- Interesting, but a very subtle effect to be measured by detecting the angular anisotropy of protons from decays of Λ w.r.t. the reaction plane

- NICA will study the polarization of Λ. HADES and STAR results are expected to be confirmed.

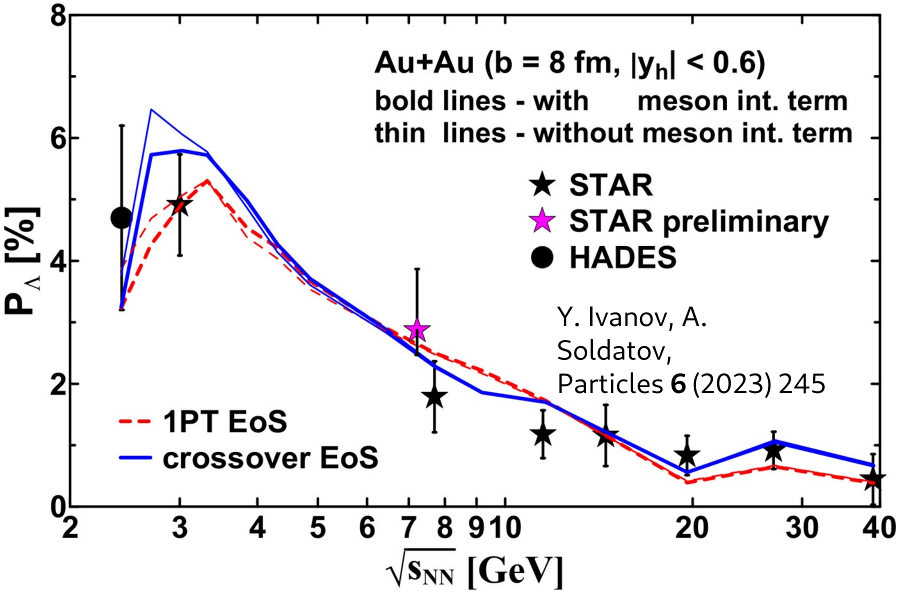


Figure 1. Global Λ polarization in midrapidity regions $|y_h| < 0.6$, originating from the thermal vorticity with (bold lines) and without (thin lines) the meson-field contribution in Au+Au collisions at $b = 8$ fm as a function of the collision energy $\sqrt{s_{NN}}$. The results for different EoSs are presented. Data are from Refs. [28,35,36] (STAR) and [37] (HADES).

Non-relativitic vorticity : $\omega = \frac{1}{2}\nabla \times \mathbf{v}$

Thermal vorticity: $\hat{\omega}_{\mu\nu} = \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu)$

$\beta_\mu = u_\mu / T$, T is the local temperature

u_μ - collective local 4-velocity

Average polarization $\perp$ reaction plane:

$$\langle P_\Lambda \rangle = \frac{1}{2m_\Lambda}\left(E_\Lambda - \frac{1}{3}\frac{\mathbf{p}_\Lambda^2}{E_\Lambda + m_\Lambda}\right)\hat{\omega}_{xz}$$

E. Kolomeitsev, V. Toneev, V. Voronyuk, PRC **97** (2018) 064902

So far we considered only global vorticity in symmetric nucleus-nucleus collisions ...

Shell we expect surprises from future NICA data?

Next step: where to ?

- “We can conclude that the 3FD model describes the available data on the global polarization in and around the NICA energy range reasonably well.”
- “Keeping this in mind, we can proceed to an even less-explored topic, i.e., the production of vortical rings in heavy-ion collisions.”

  Y. Ivanov, A. Soldatov, Particles **6** (2023) 245

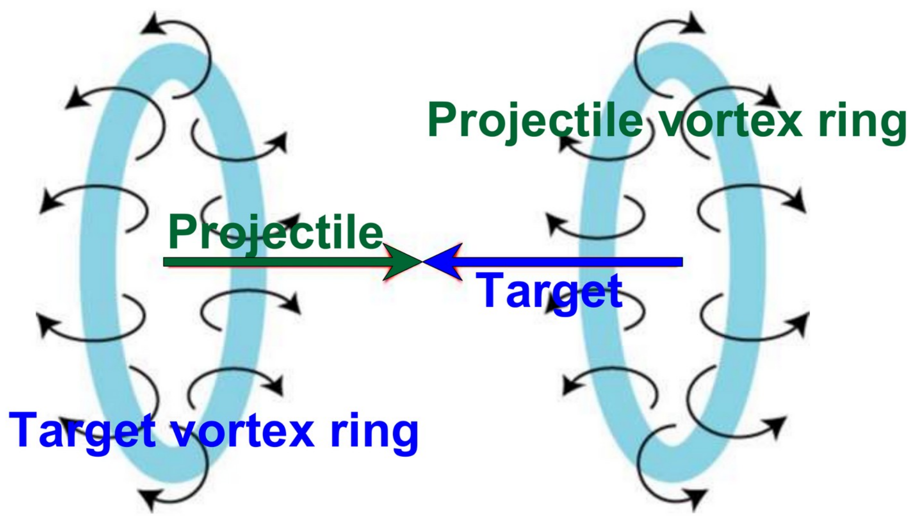


Figure 4. Schematic picture of the vortex rings at forward/backward rapidities. Curled arrows indicate the direction of the circulation of the matter.

Vortex rings in asymmetric central collisions ?

- "We mention another very interesting possibility for vorticity studies in **asymmetric nuclear collisions** such as Cu+Au."

- "For **relatively central collisions**, when during the collision a smaller nucleus is fully "absorbed" by the larger one (e.g. such collisions can be selected by requiring no signal in the zero degree calorimeter in the lighter nucleus beam direction), one can easily imagine a configuration with **toroidal velocity field**, and as a consequence, a vorticity field in the form of a circle."

S. Voloshin, EPJ Web Conf **171** (2018) 07002
(points to vorticity in asymmetric collisions for the first time?)

Vortex rings from central pA collisions

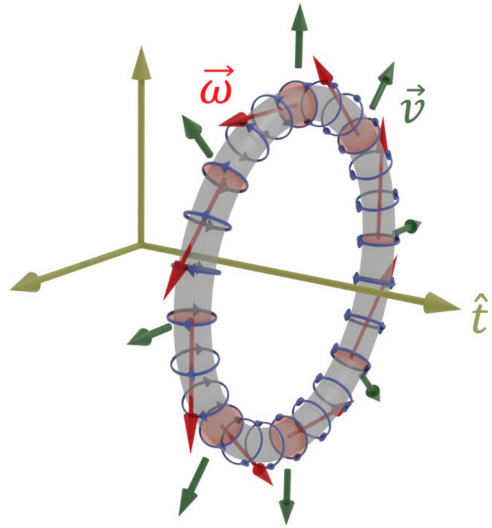


FIG. 1. The vortex structure of an expanding smoke ring.

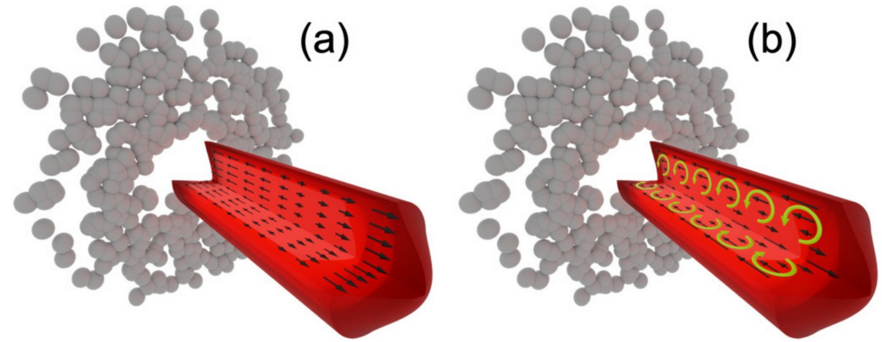


FIG. 2. Sketch of the initial conditions for the plasma formed just after a proton drills through the center of a gold nucleus. The thermalized fluid tube is initialized with two possible flow patterns. Left: initial condition (a) a boost-invariant flow distribution with more matter in the Au-going direction. Right: initial condition (b) the edges of the cylinder flow more in the Au-going direction than do fluid cells at the center of the cylinder. Transverse flow rapidly develops hydrodynamically but is not present in the initial condition.

The vortical structure of the expanding smoke ring sketched in Fig. 1 may be naturally quantified by

$$\overline{\mathcal{R}}^{\hat{t}}_{\mathrm{NR}} \equiv \left\langle \frac{\vec{\omega}_{\mathrm{NR}} \cdot (\hat{t} \times \vec{v}_{\mathrm{cell}})}{|\hat{t} \times \vec{v}_{\mathrm{cell}}|} \right\rangle_{\phi}, \tag{1}$$

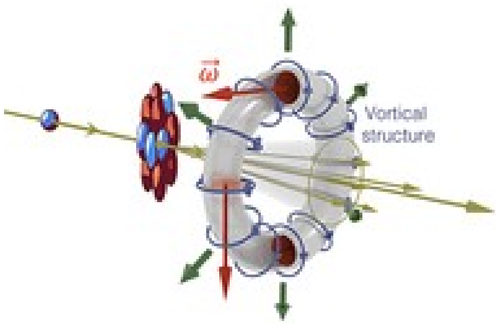
where $\vec{\omega}_{\mathrm{NR}} = \frac{1}{2}\vec{\nabla} \times \vec{v}$ is the nonrelativistic vorticity and $\vec{v}_{\mathrm{cell}}$ is the velocity of one fluid cell of smoke. The axis of the ring is $\hat{t}$, and the structure is averaged over the azimuthal angle about the ring axis.

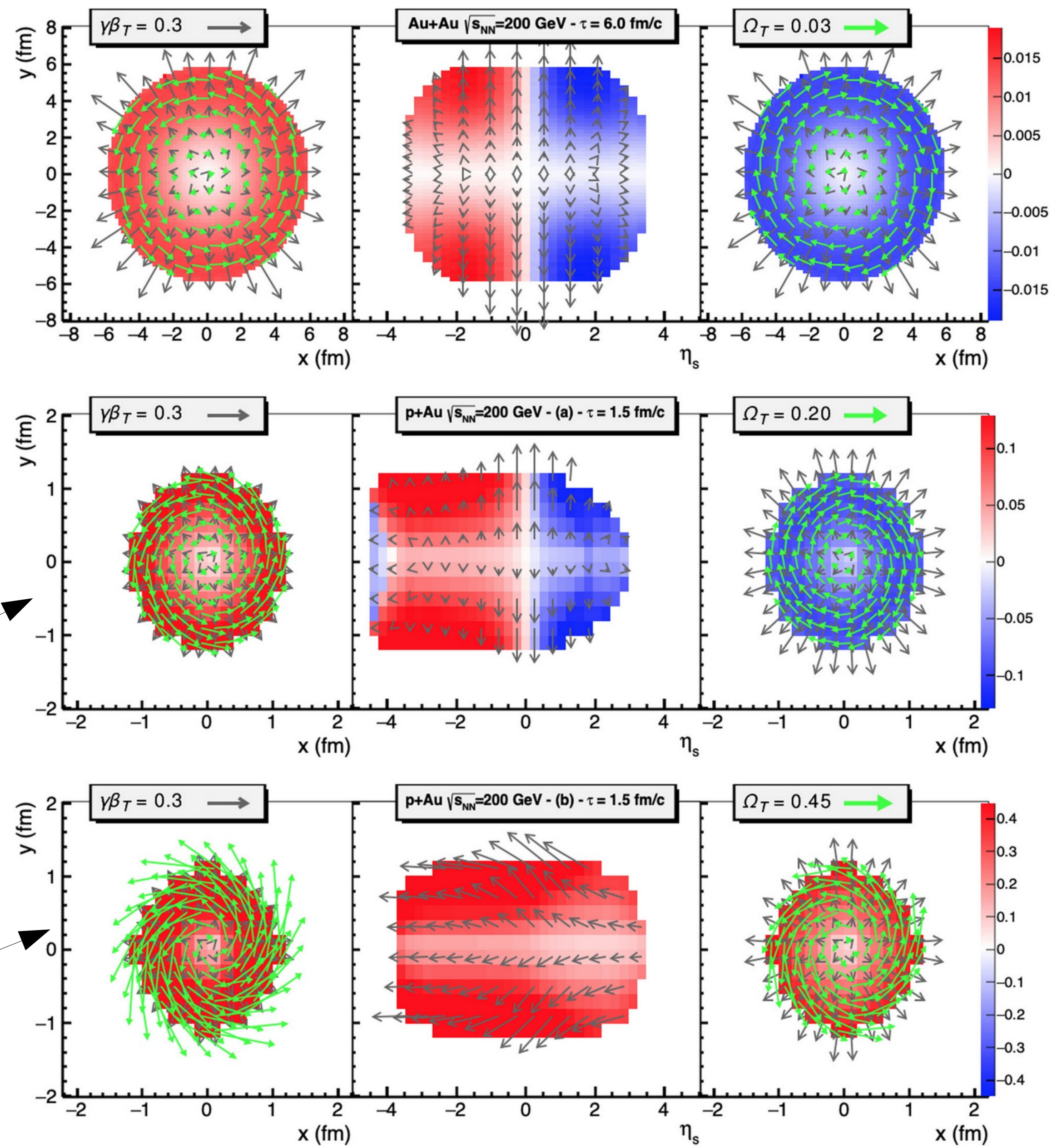
Ring observable: to account for transverse momentum dependence of polarized Λ at given rapidity.

Inspired by non-relativistic ansatz

M. Lisa et al., PRC **104** (2021) L011901

Modeling: Au-Au vs pAu





Case (a): initially "laminar"

Case (b): with rotation

M. Lisa et al., PRC **104** (2021) L011901

Studies of vorticity rings can be very complicated ...

- Let's first see if the neutron-proton content of the nuclear periphery is reflected in the n/p ratio of the spectator matter in collisions of nuclei of approximately the same size.

- Note: the case of Pb—Pb collisions at the LHC has been already considered. It requires advanced Zero Degree Calorimeters)

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https://doi.org/10.1140/epja/s10050-022-00832-5

THE EUROPEAN PHYSICAL JOURNAL A

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Regular Article - Theoretical Physics

Peeling away neutron skin in ultracentral collisions of relativistic nuclei

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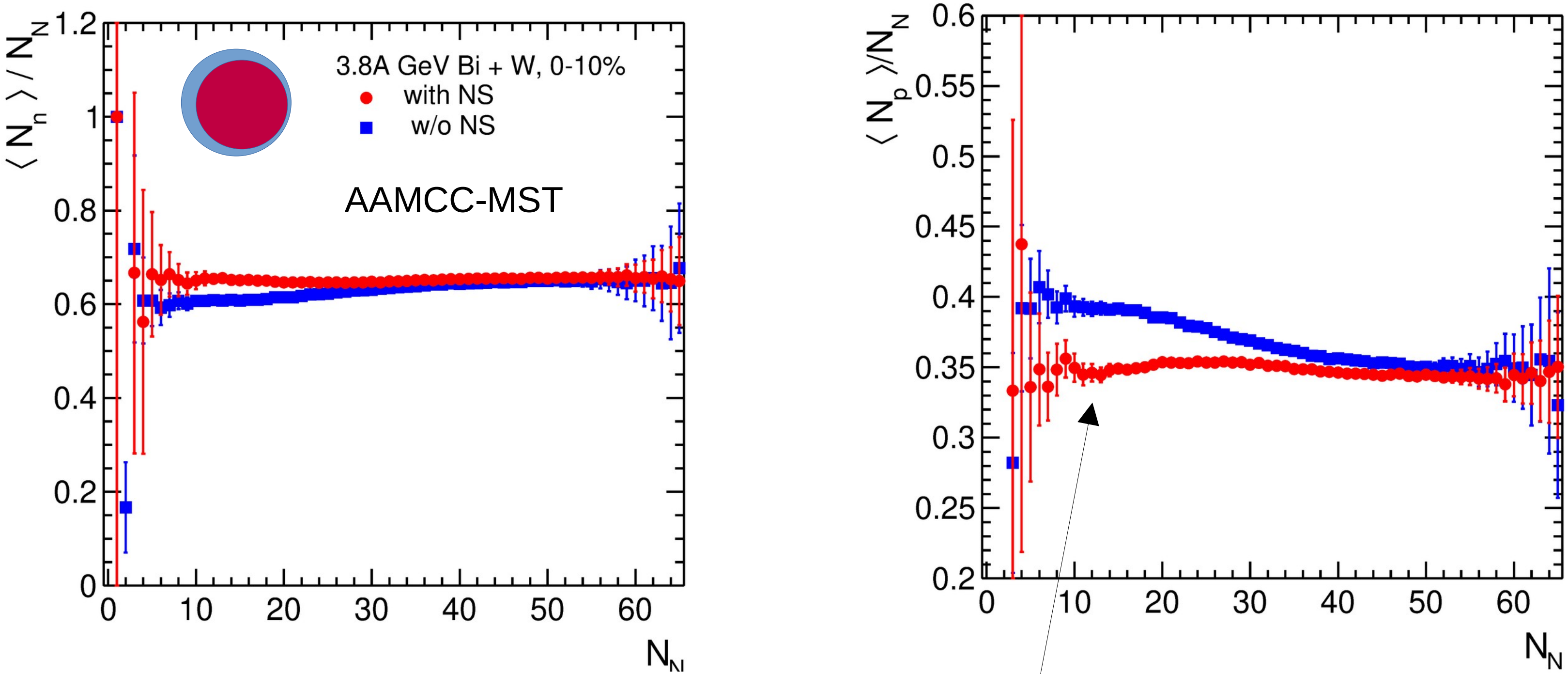
Our AAMCC-MST to model spectators and probe the neutron skin in projectile nuclei

- Nucleus-nucleus collisions are simulated by means of the Glauber Monte Carlo model [1)]. Non-participated nucleons form spectator matter (prefragment)
- Excitation energy of prefragment can be calculated via three options:
  - Ericson formula based on the particle-hole model[2)]
  - parabolic ALADIN approximation[3)] adjusted to describe the data for light and heavy nuclei
  - Hybrid approximation: a combination of Ericson formula for peripheral collisions and ALADIN approximation otherwise
- Deexcitation is simulated via MST-clusterisation[4)] accomplished with Fermi Break Up mode from Geant4[5)] for ultracentral collisions

1) C. Loizides, J.Kamin, D.d'Enterria Phys. Rev. C **97** (2018) 054910
2) T. Ericson Adv. In Phys. **9** (1960) 737
3) A. Botvina et al. NPA **584**
4) R. Nepeivoda, et al., Particles **5** (2022) 40
5) J. Alison et al. Nucl. Inst. A **835** (2016) 186

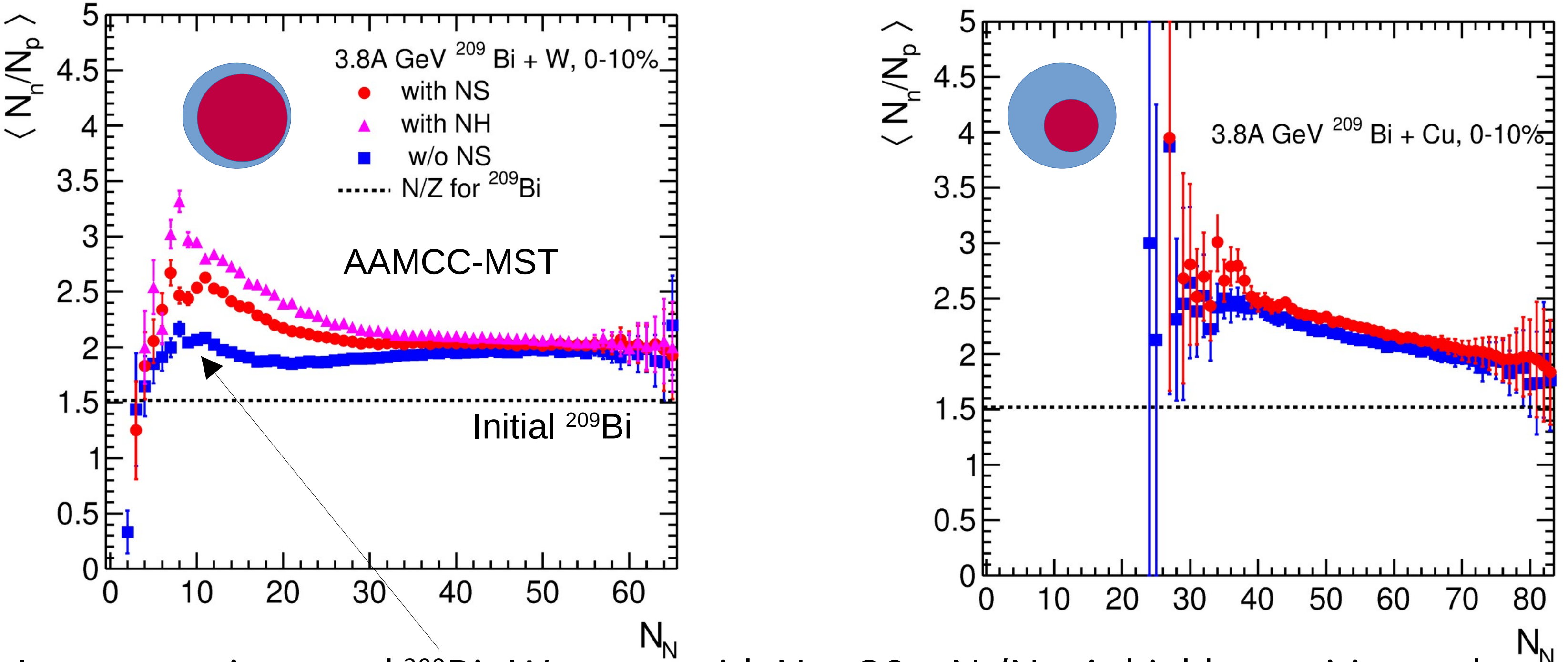
AAMCC-MST: average numbers of spectator neutrons and protons per total number of spectators in ^{209}Bi+W



- A weak sensitivity of $\langle N_n \rangle / N_N$ and $\langle N_p \rangle / N_N$ to the presence of neutron skin in ^{209}Bi is expected in central ^{209}Bi+W events with a small number of spectator nucleons ($N_N < 20$)

A. Svetlichnyi, S. Savenkov, R. Nepeivoda, I. P., Int. J. Mod. Phys. E **33** (2024) 2441027

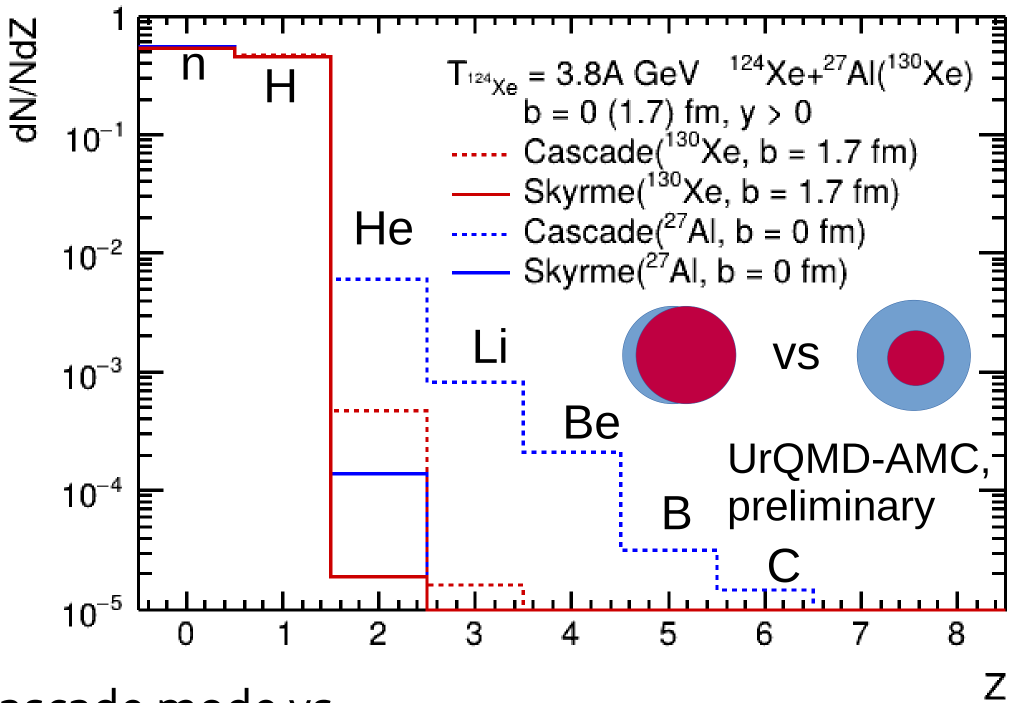
AAMCC-MST: average n/p ratio for spectator nucleons vs their total number in central collisions



- In contrast, in central ^{209}Bi+W events with $N_n < 30$ $\langle N_n/N_p \rangle$ is highly sensitive to the presence of neutron skin/halo in ^{209}Bi.
- A method to peel away surface neutrons from ^{209}Bi in asymmetric collisions
- This sensitivity is washed out in central ^{209}Bi+Cu events due to involving a thicker layer of matter in ^{209}Bi.

A. Svetlichnyi, S. Savenkov, R. Nepeivoda, I. P., Int. J. Mod. Phys. E **33** (2024) 2441027

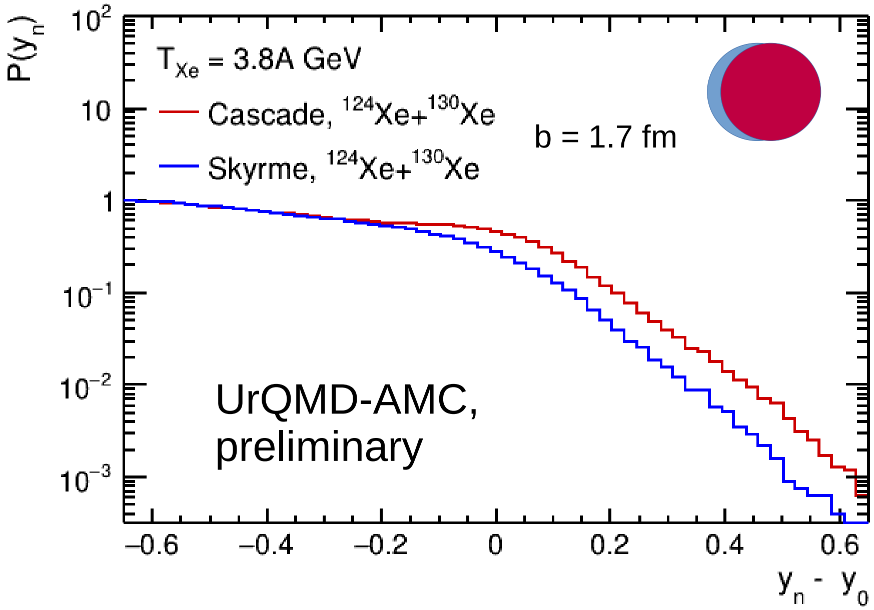
UrQMD-AMC: using MST-clustering to recognize nuclear fragments in final state

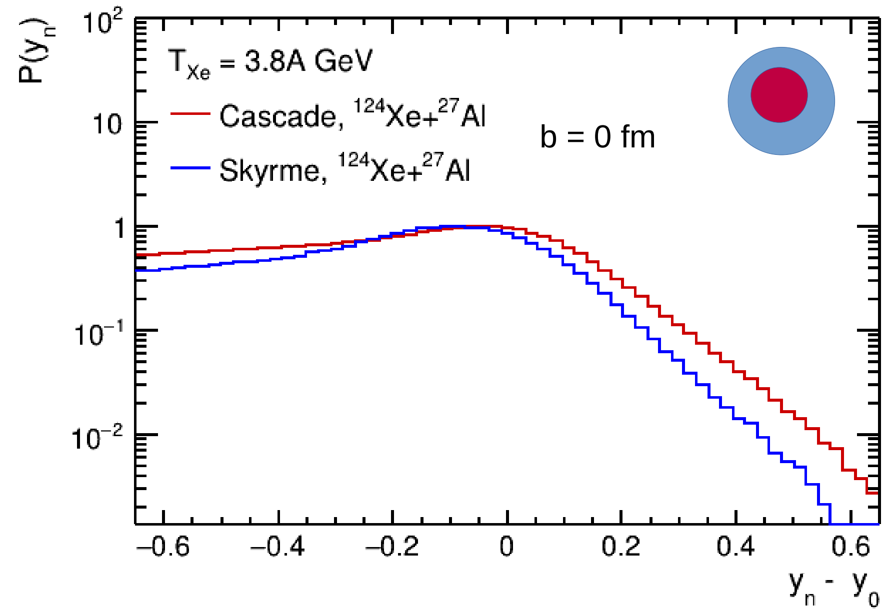


UrQMD in cascade mode vs
UrQMD with the density-dependent Skyrme-type EoS (eos=1):

- n, p, d, t, He, Li, Be, B, C in central ^{124}Xe+^{130}Xe and ^{124}Xe+^{27}Al collisions
- same numbers of protons and neutrons, but the rates of production of light nuclei are sensitive to the target size and EoS

UrQMD-AMC: rapidity distribution of neutrons – a task for HGND





UrQMD in cascade mode vs
UrQMD with density-dependent Skyrme-type EoS (eos=1), central collisions:

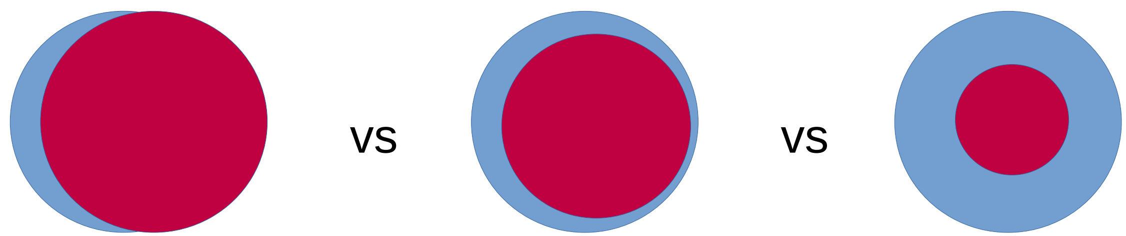
- More forward neutrons are produced on ^{130}Xe as well as on ^{27}Al in cascade mode
- The general shapes are different
- Target-size dependence is obvious

Conclusions

- It seems promising to look into a less explored domain of central collisions, where the famous v_2 disappears

- Collisions of heavy projectiles with lighter target nuclei in the fixed target mode are of special interest

- In this mode a target size scan can be conducted to compare the results for:
  - ^{209}Bi+Bi, ^{209}Bi+W, ^{209}Bi+Cu
  - ^{124}Xe+CsI, ^{124}Xe+Al



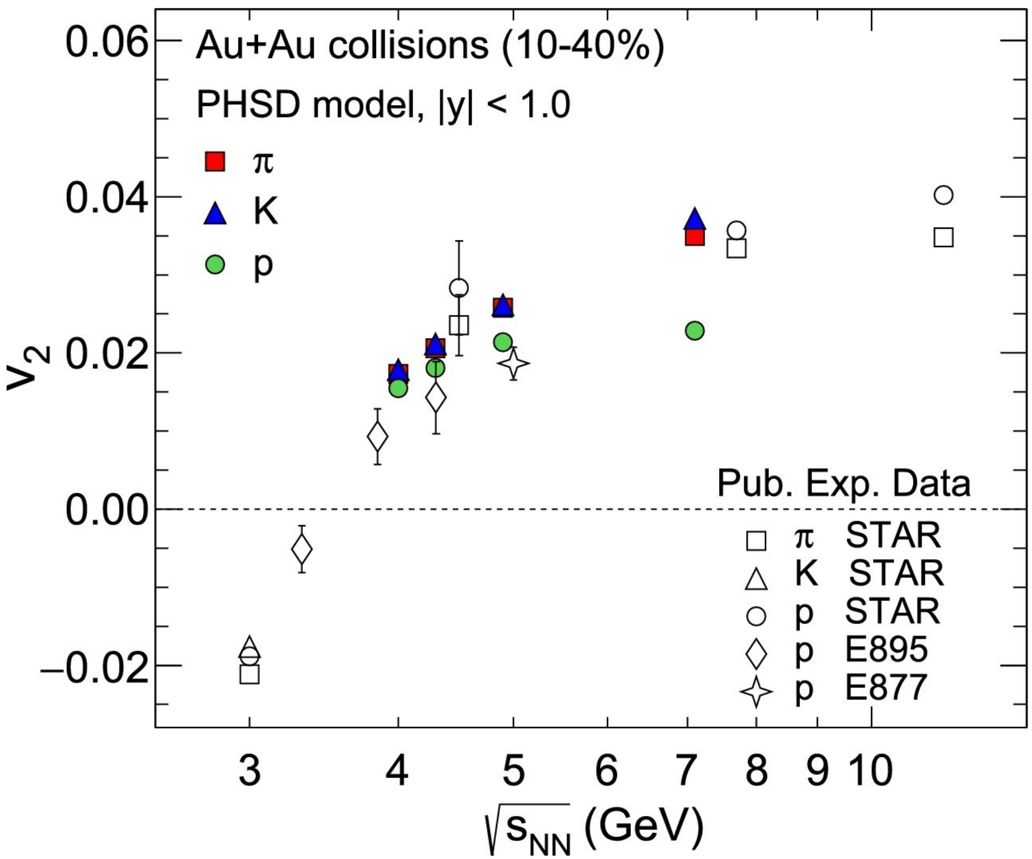
- It will be interesting to study the evolution of vortical (doughnat) spectator rings as function of the target size

- Nuclear structure effects, e.g., neutron skin/halo can be also investigated in central collisions of symmetric and asymmetric systems

Backup slides

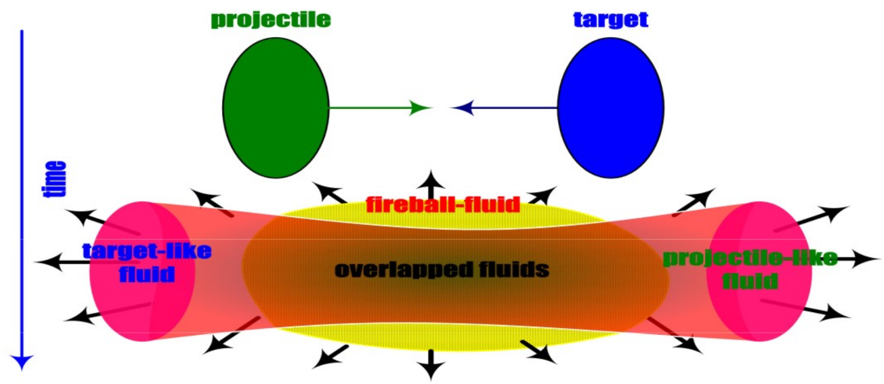
Another comparison: STAR, E895, E877 data and PHSD model

- The elliptic flow, v_2 , for pions and protons as predicted by the PHSD model, demonstrate significant similarity with the results reported by E895, E877 and STAR within $\sqrt{s_{NN}}$=4 – 6 GeV.
- NCQ – scaling to be re-confirmed by future measurements at NICA
- **Do we expect surprises in collisions of equal-size heavy nuclei at NICA ?**



T. Bhat et al., PLB **859** (2024) 139103

Notes to take home from papers by Y. Ivanov, A. Soldatov, 3FD model



- Global polarization is consistent with our understanding of collision dynamics within 3FD model

- Vorticity is pushed out to fragmentation regions. Therefore, the midrapidity polarization decreases while the total polarization increases with energy rise

- Midrapidity polarization at NICA energies is expected to be higher than at BES RHIC

- The polarization should be stronger at peripheral rapidities w.r.t. the midrapidity region. How can we measure it at forward rapidities at BM@N ?

3FD modeling of central Au-Au collisions

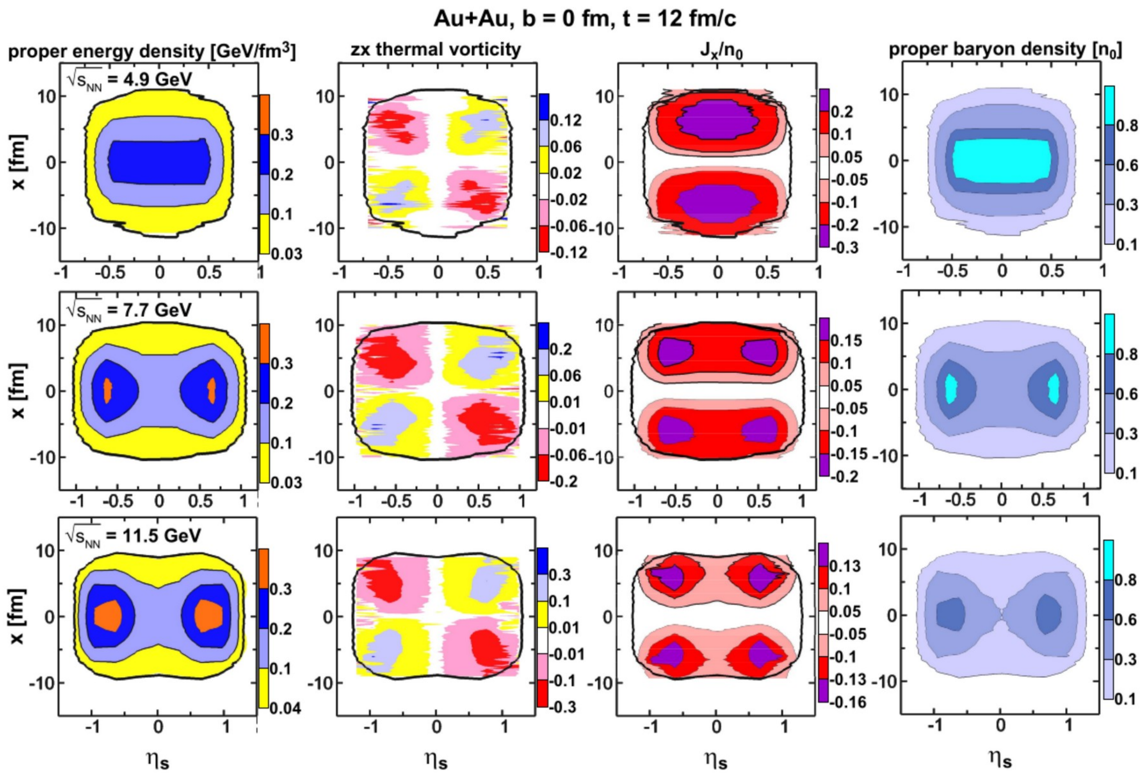


Figure 5. Columns from left to right: the proper energy density (GeV/fm^3), the proper-energy-density-weighted relativistic thermal zx vorticity, x-component of the baryon current (J_x) in units of normal nuclear density ($n_0 = 0.15$ 1/fm^3), and the proper baryon density (n_B) in units of n_0 in the $x\eta_s$ plane at time instant $t = 12$ fm/c in the ultra-central ($b = 0$ fm) Au+Au collisions at $\sqrt{s_{NN}} = 4.9$–11.5 GeV. η_s is the space–time rapidity along the beam (z-axis) direction. Calculations are performed with the crossover EoS. The bold solid contour indicates the border of the nuclear matter with $n_B > 0.1 n_0$.

Vorticity rings are clearly seen in simulations: Y. Ivanov, A. Soldatov, Particles **6** (2023) 245

Rapidity dependence of R_Λ: Au-Au

Y. Ivanov, A. Soldatov, Particles **6** (2023) 245

$$R_\Lambda(y) = \left\langle \frac{\mathbf{P}_\Lambda \cdot (\mathbf{e}_z \times \mathbf{p})}{|\mathbf{e}_z \times \mathbf{p}|} \right\rangle_y,$$

A challenge to experiments: it is necessary to identify Λ, and measure the momenta of protons from Λ decays.

Feed-down contribution from decays of other baryons to be taken into account.

MPD setup: to measure at both sides and compare ?

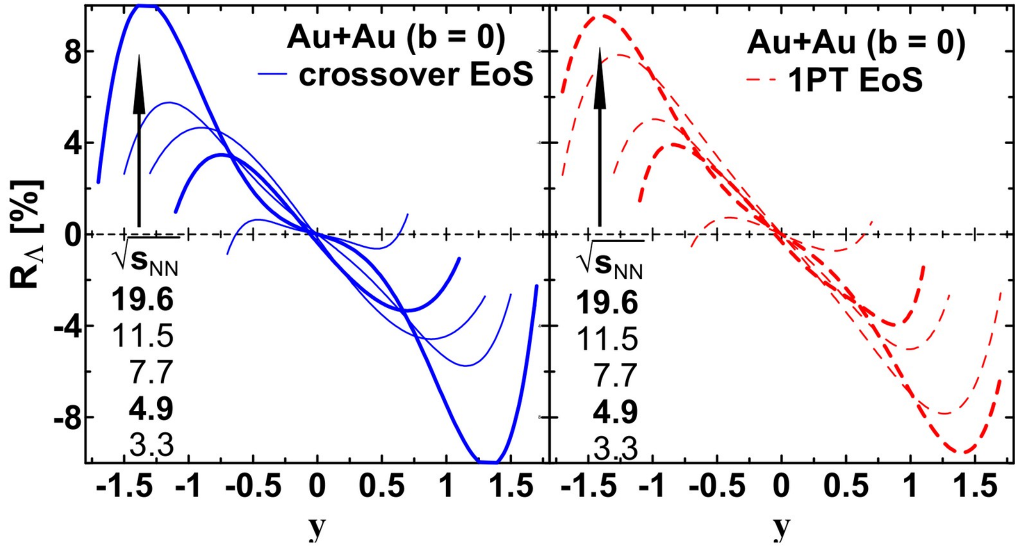
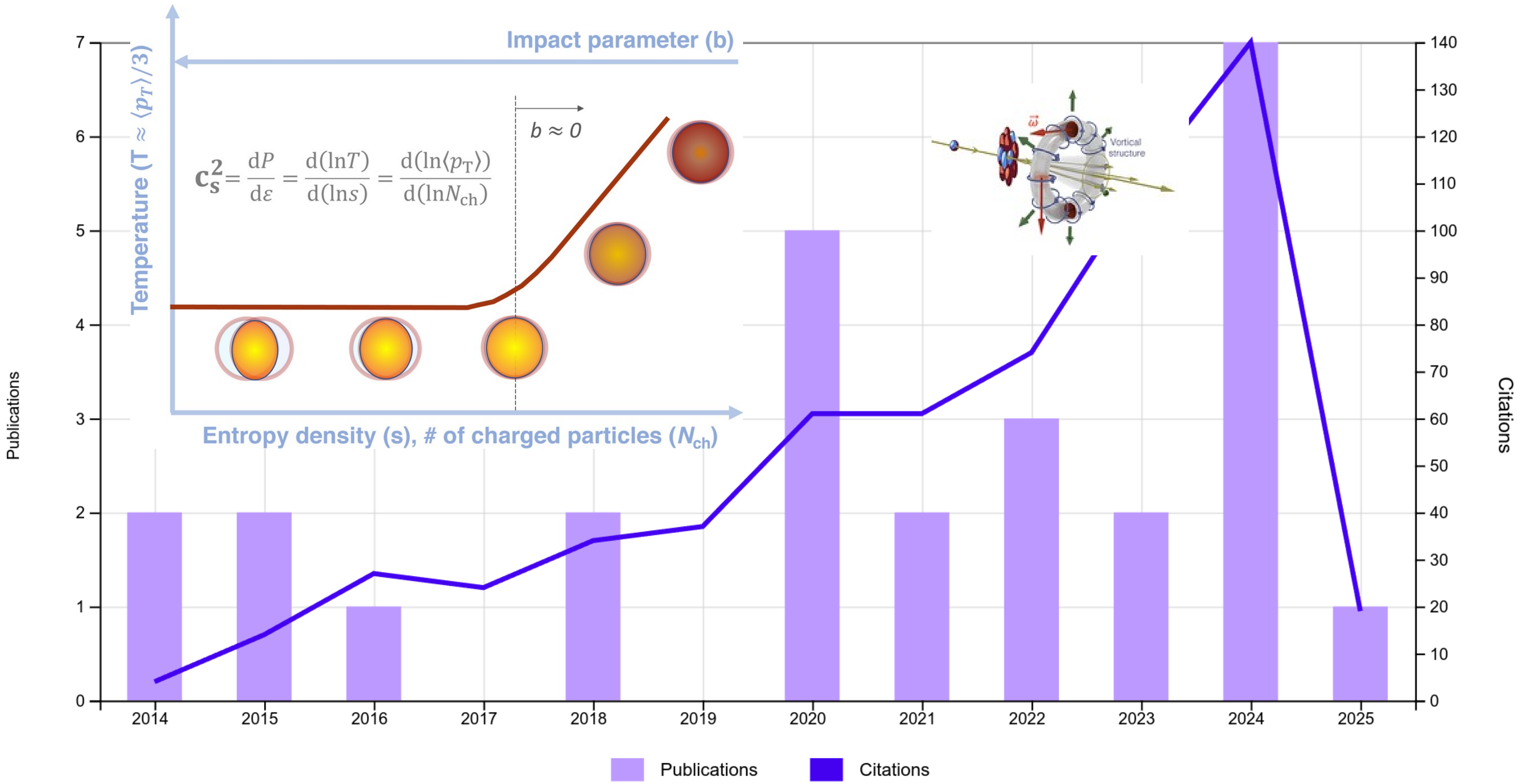


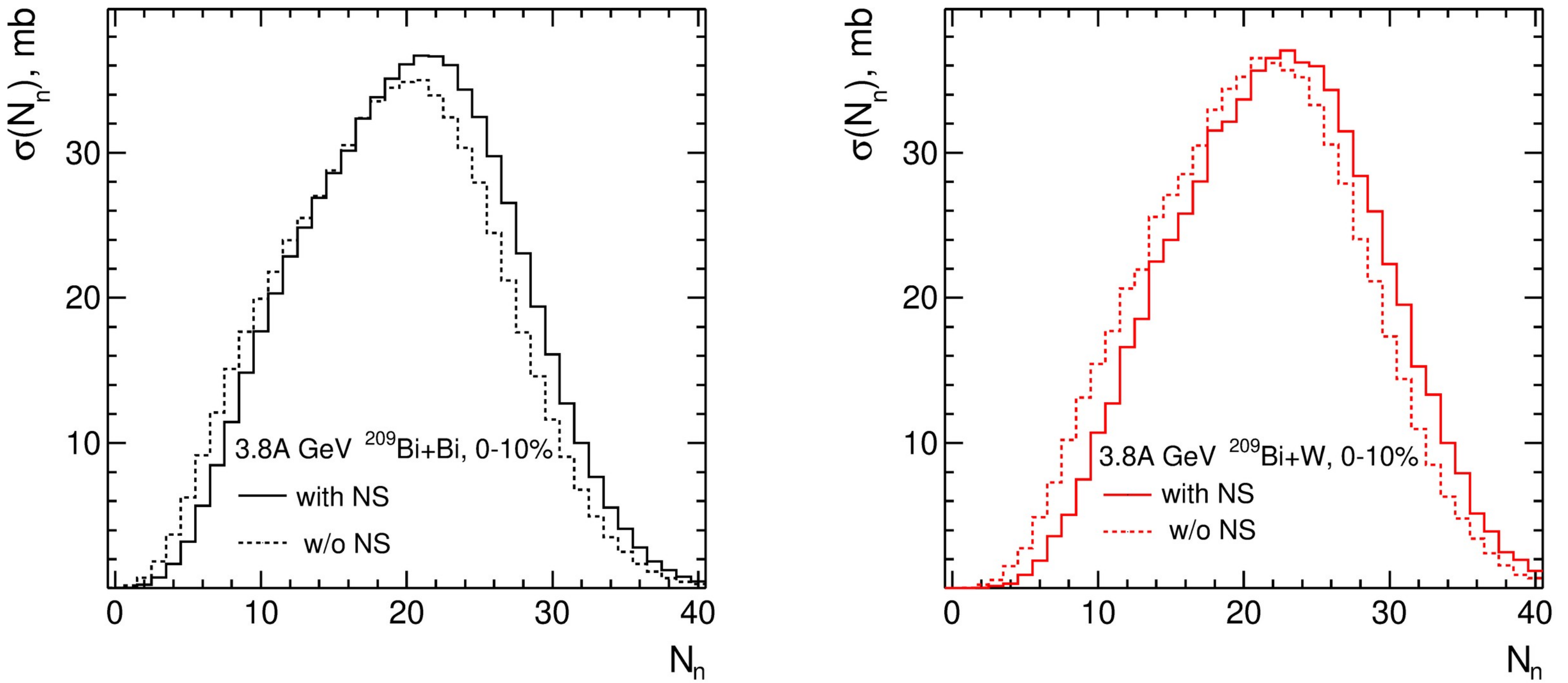
Figure 7. Rapidity dependence of the R_Λ quantity in the ultra-central ($b = 0$) Au+Au collisions at $\sqrt{s_{NN}} = 3.3$–19.6 GeV (upwards at $y \approx -1$). Distributions at 4.9 and 19.6 GeV are indicated by bold lines. Calculations are performed with the crossover (**left** panel) and 1PT (**right** panel) EoSs.

A long way ahead to understand the physics of vorticity rings ...

Studies of <u>both participant and spectator zones</u> in ultracentral collisions are very welcome. There are very few of them presently, mostly focused on fireball.



Cross sections of production of given numbers of neutrons in ^{209}Bi+Bi and ^{209}Bi+W



- These cross sections are not very sensitive to the presence of NS in ^{209}Bi

A. Svetlichnyi, S. Savenkov, R. Nepeivoda, I. Pshenichnov, Int.J.Mod.Phys. E **33** (2024) 2441027