

Study of hadron and light nuclei production at NICA

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for the NICA/MPD Collaboration

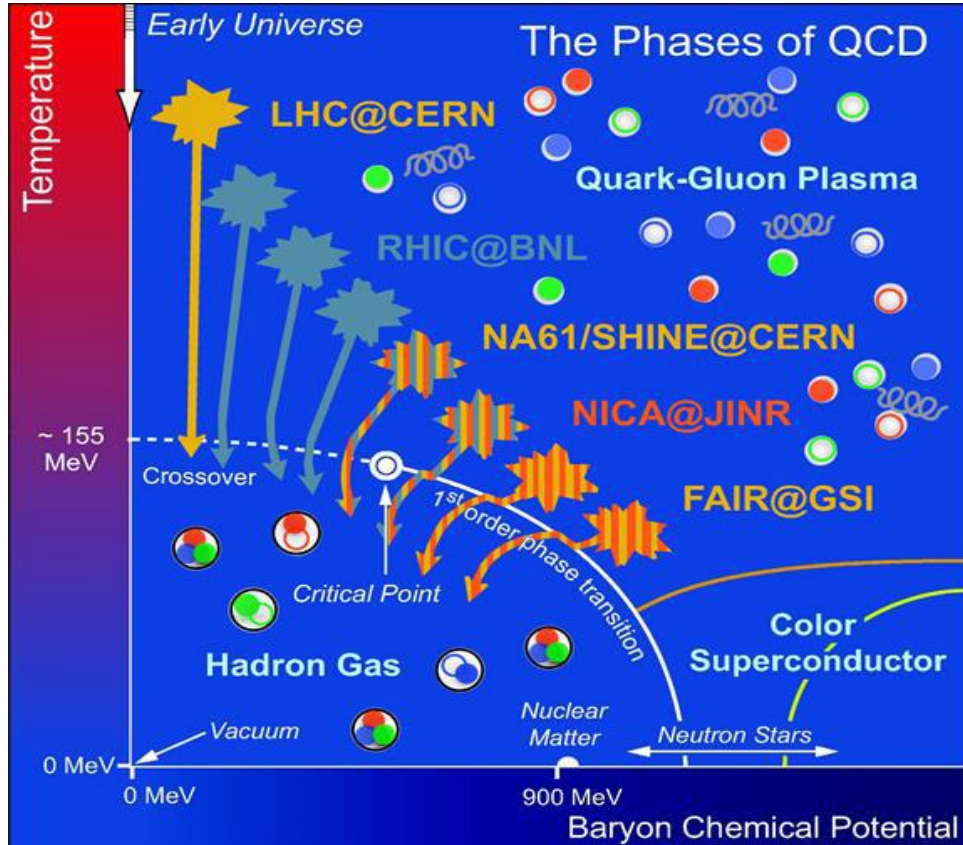


The 2nd China-Russia Joint China-Russia Workshop on NICA Facility
Shandong University, Qingdao, China, September 10 – 13, 2024

Outline

- Introduction
- NICA physics cases: hadrons and light nuclei
- Recent results from BM@N/NICA on p, d, t production in Ar+A
- MPD feasibility study for hadrons and light nuclei in Bi+Bi at 9 GeV
- Summary

A+A collisions and QCD phase diagram

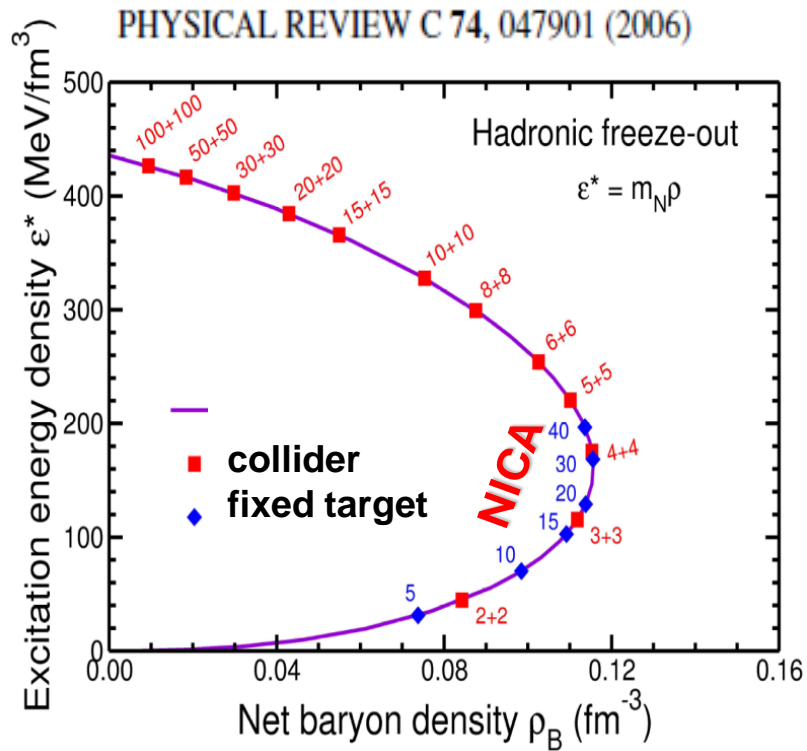


- QCD phase diagram: rich structure and variety of conditions. Experimental searching of characteristic points (CEP) and transition lines is crucial - limiting confirmation so far.
- Several running and future experimental programs worldwide
- Experiments at NICA :
 - BM@N** (fixed target) $E/A = 2-6$ GeV
 - MPD** (collider mode) 4-11 GeV and 'fixed target mode' $E/A > 2$ GeV

Heavy-ion collisions at NICA: our niche

NICA energy range – dense matter at non-zero μ_B and moderate T

- ➡ baryon density ρ up to $10\rho_0$, freeze-out net-baryon density – the highest
- ➡ $\mu_B = (300 - 750)$ MeV, $T_{\text{ch}} \sim (120-150)$ MeV
- ➡ Fixed target (BM@N) - 2-6A GeV, Collider (MPD) - $\sqrt{s_{\text{NN}}}=3-11$ GeV



At the lowest NICA energy:

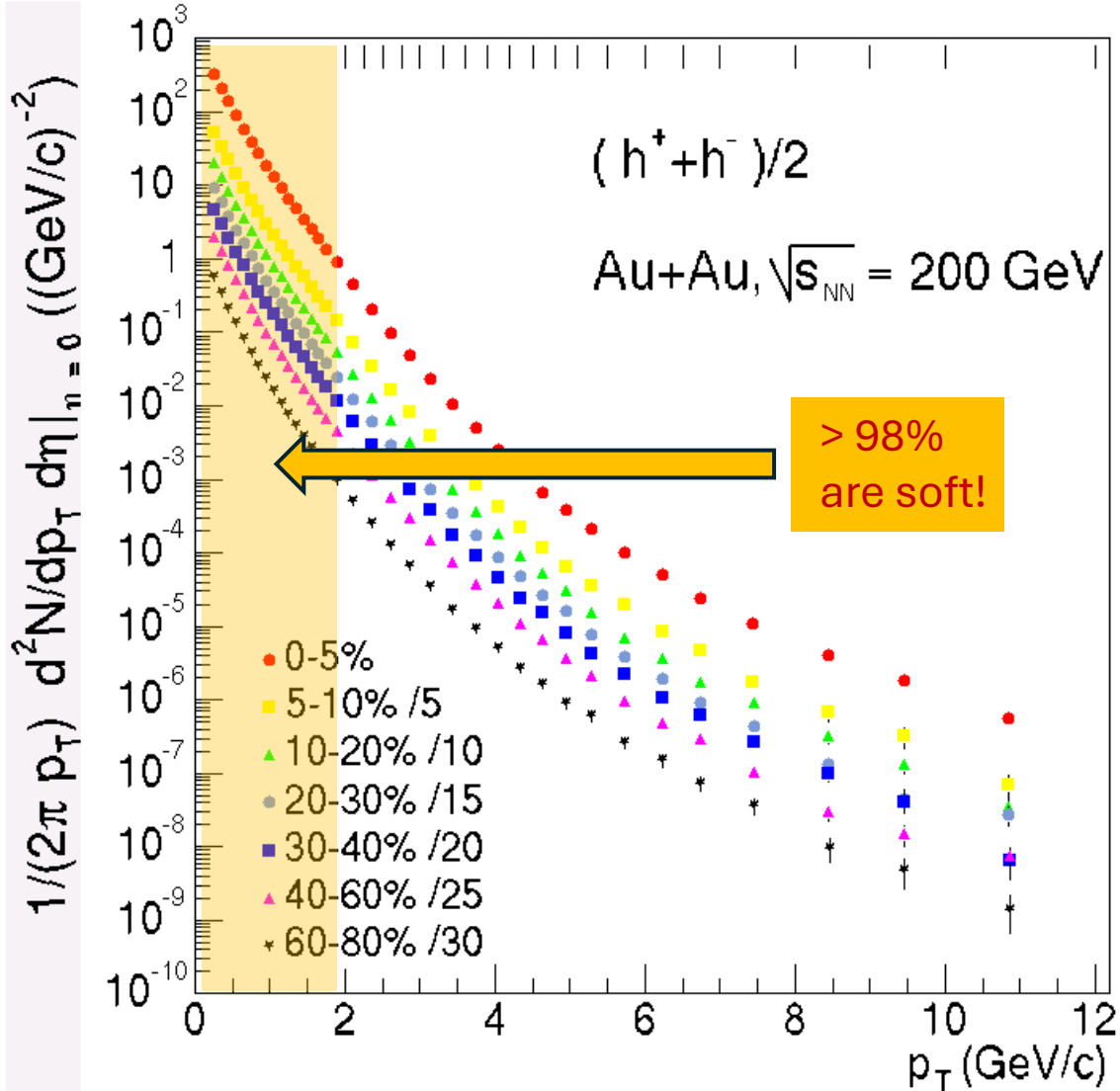
- baryon dominated nuclear matter is formed:
- particle production process mainly through excitation and decay of baryon resonances
- in-medium effects in hadron production properties
- up to 30% of the total baryon number is accumulated in clusters

At higher NICA energies:

- Transition from baryon-rich to meson-dominated matter
- QGP droplets can be formed and mixed phase (QGP+HG) is expected in central A+A

Light hadron production in A+A collisions

- Bulk of the produced matter in HIC are hadrons with $p_T < 2 \text{ GeV}/c$



Hadrons from bulk: particles containing most abundant quark specie (u, d, s + their anti-partners):
 $\pi, K, p, \Lambda, \Xi, K^*, d, t, {}^3\text{He}, {}^3\text{H}_\Lambda$

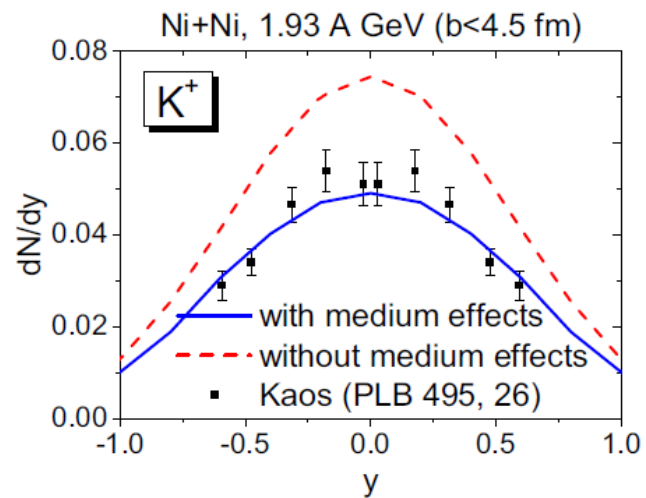
Measurements of hadrons and light nuclei allow to address reaction dynamics and medium properties:

- Important geometrical quantities of the reaction
- Baryon number transfer, baryon and energy density in the reaction zone
- Phase transformations and CEP
- Chemical composition and thermalization
- Space-time extent and collective effects

NICA physics cases: strange hadrons (kaons)

- Excitation function of hadrons, including strangeness (yields, spectra, and ratios)
- In-medium modifications of (anti)kaons properties have been seen in their abundances and spectra
- Phase transformations and chemical equilibration can be probed

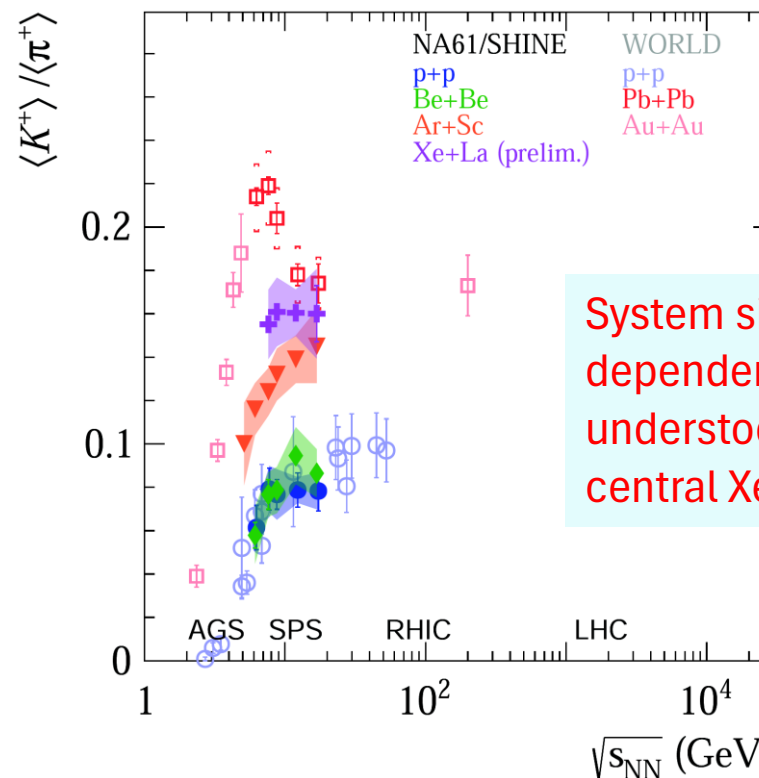
PRC 103, 044901 (2021)



- Strangeness production at threshold energies is sensitive to the EoS of nuclear matter and can provide comprehensive information about the compressibility of nuclear matter

- Kaon-nucleon interaction in dense medium is of importance for astrophysics (NS)

- Non-monotonic strangeness-to-entropy: 1) transition from baryon-dominated to meson-dominated matter; 2) phase transition to QGP; 3) CSR (PRC 94, 044912 (2016))



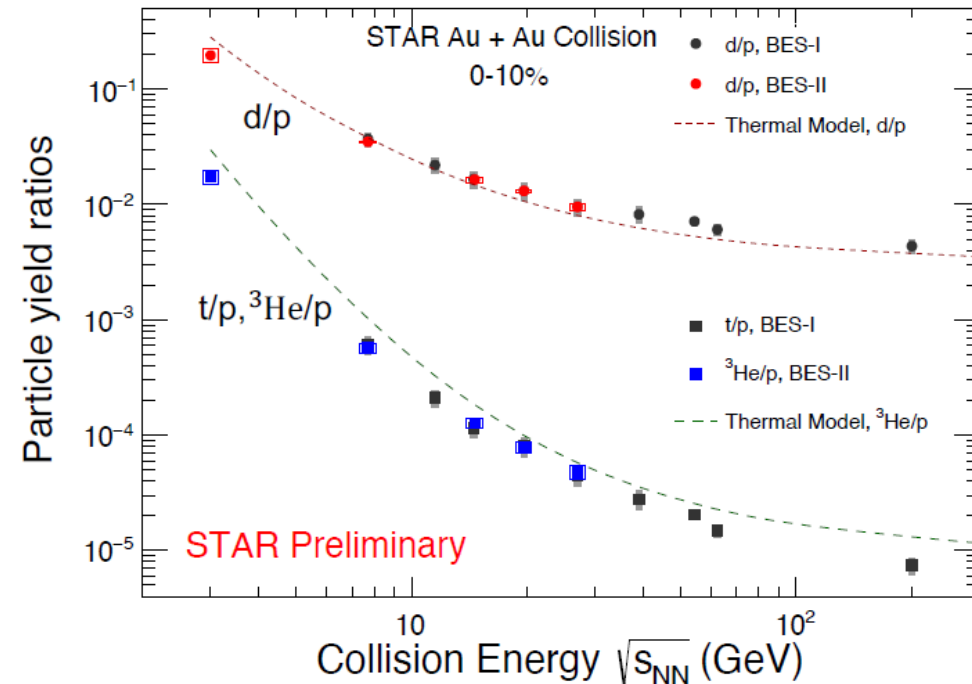
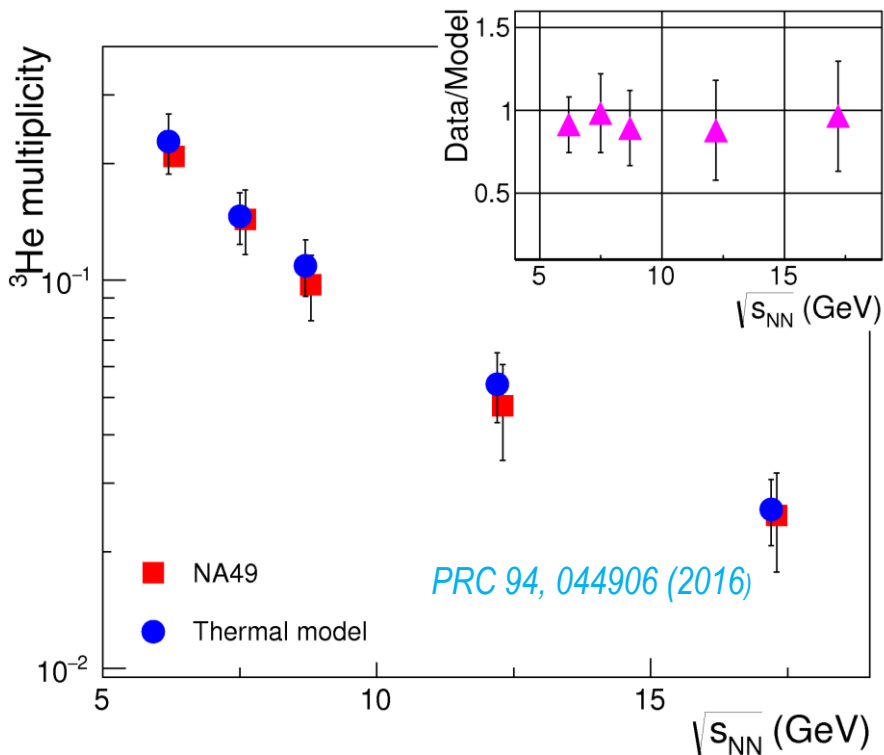
NICA physics cases: Light nuclei

- Light nuclei : weakly bound objects are copiously formed in hot & dense matter
- Production of nucleon clusters (p, d, t, ^3He) allow addressing the reaction dynamics, cluster formation mechanism, homogeneity volume size, momentum-space correlations in the source, etc.

Thermal fits reproduce yields of light nuclei (SPS/NA49)

Puzzle?

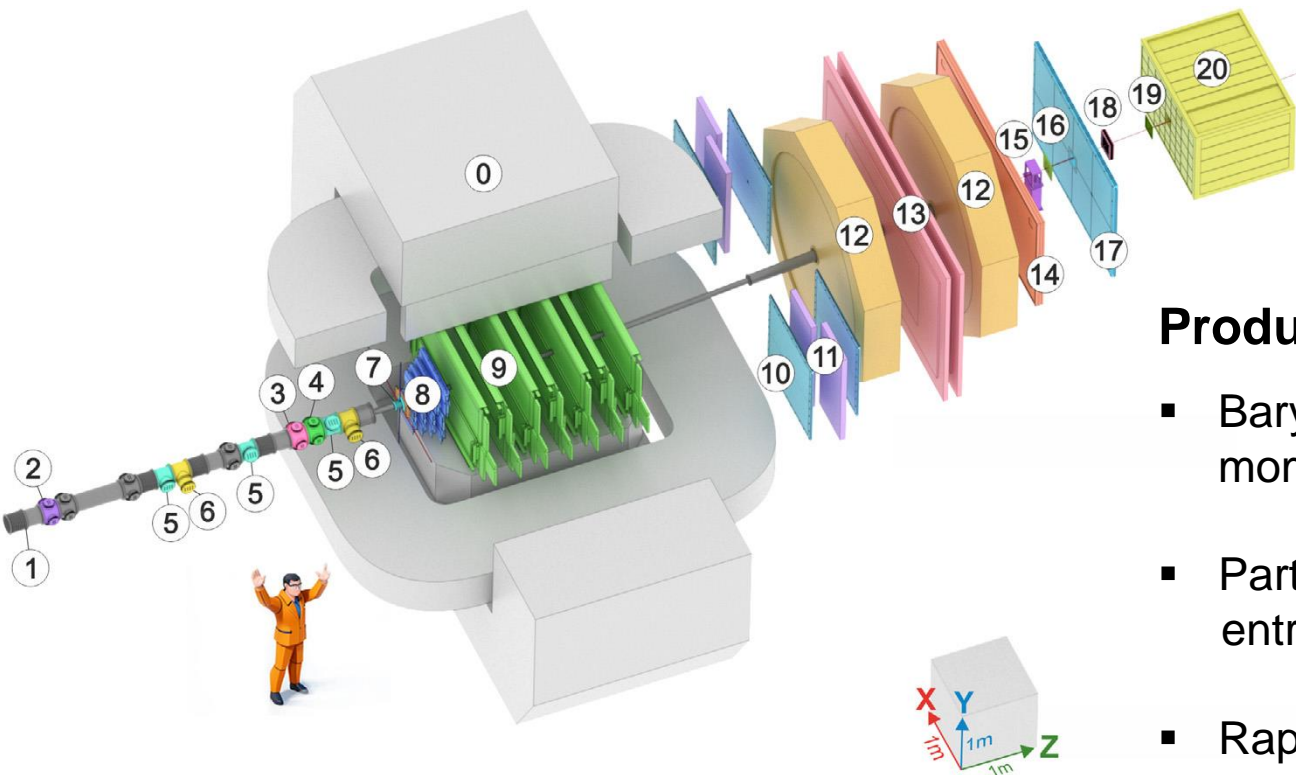
Thermal model overestimate t/p and $^3\text{He}/p$ ratios (STAR/BES)



Baryonic Matter at Nuclotron experiment at NICA: first results and lessons from BM@N

- Tracking : ST + GEMs + CSC/CSC ($\delta p / p \sim 2 \cdot 10^{-2}$)
- PID : MRPC TOF400/700 ($\sigma_{\text{TOF}} \sim 85 / 115$ ps)
- Trigger and centrality: multiplicity detectors BD+SiMD

NIMA 1065 (2024) 169532



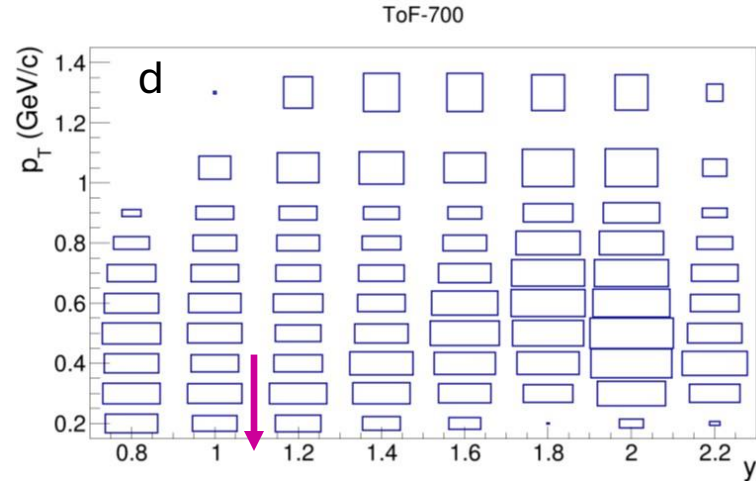
- Data taking from 2016
- Available data sets:
 - C + C, Al, Cu, Pb at 4.5(4.0)A GeV
 - Ar + C, Al, Cu, Sn, Pb at 3.2A GeV
 - Xe + CsI at 3.8A GeV
- Results on charged hadron yields (π , K), protons, light nuclei, Lambda-hyperons
JHEP 07 (2023) 174, e-Print: 2303.16243 [hep-ex]

Production of p,d,t at low NICA energies ($E/A=3.2$ GeV):

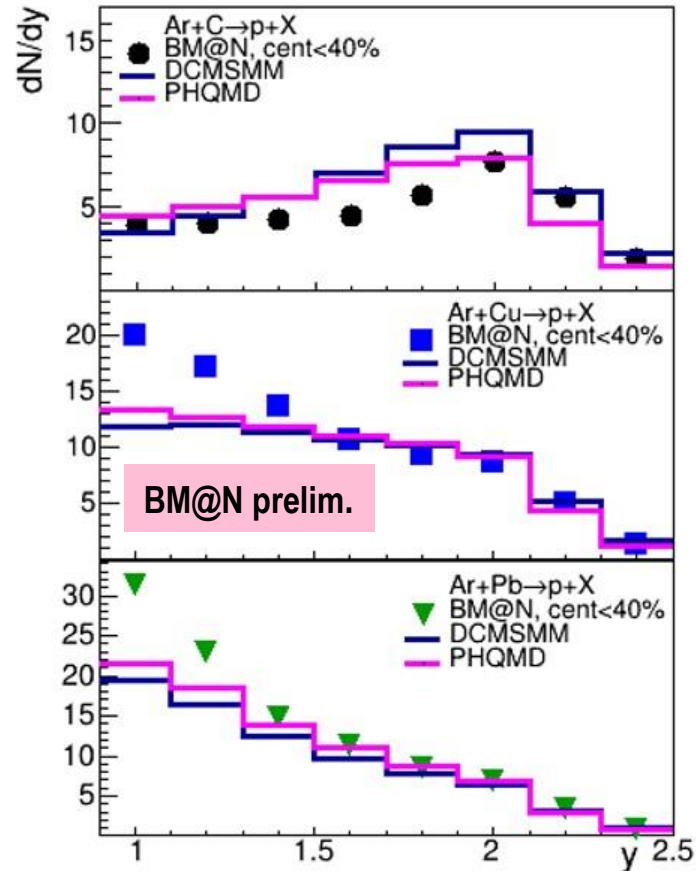
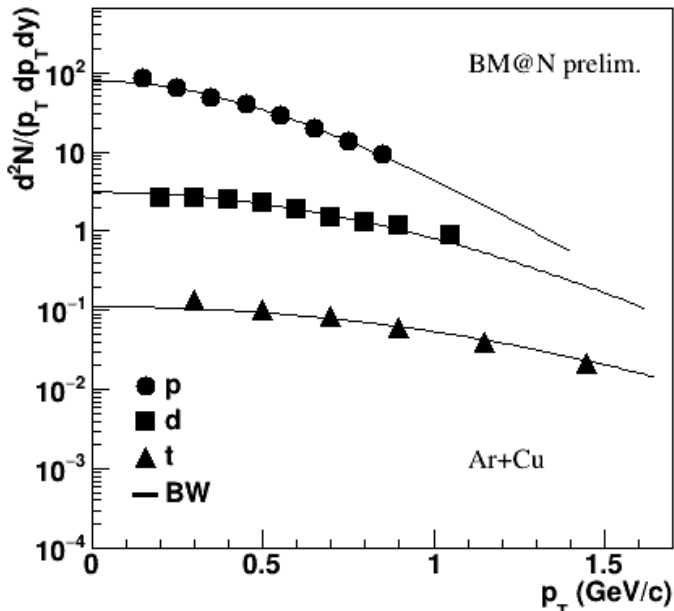
- Baryon rapidity distributions and p_T -spectra – reaction dynamics, momentum loss, fireball parameters, etc.
- Particle ratios – nucleon phase-space density, CEP, entropy-per-baryon S/A , source size, etc.
- Rapidity and energy loss – baryon density in the reaction zone, baryon number transfer mechanism

BM@N : Rapidity and pT-spectra in Ar+A at 3.2A GeV

Data sets: $\sim 16 \cdot 10^6$ Ar + C, Al, Cu, Sn, Pb at $E/A = 3.2$ GeV ($y_{CM} = 1.08$); centrality 0-40% and >40%
 p,d,t are selected by TOF, analysis details in *JHEP 07 (2023) 174*

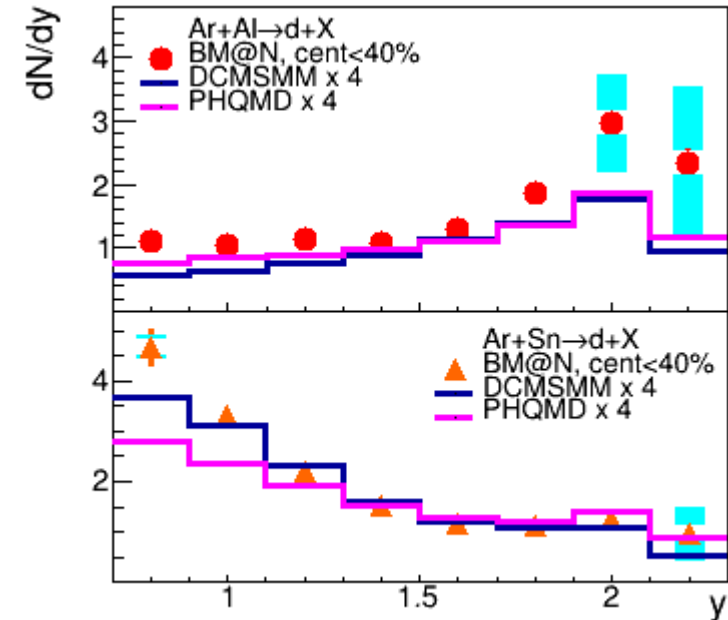


BM@N has a large phase-space coverage in the forward hemisphere



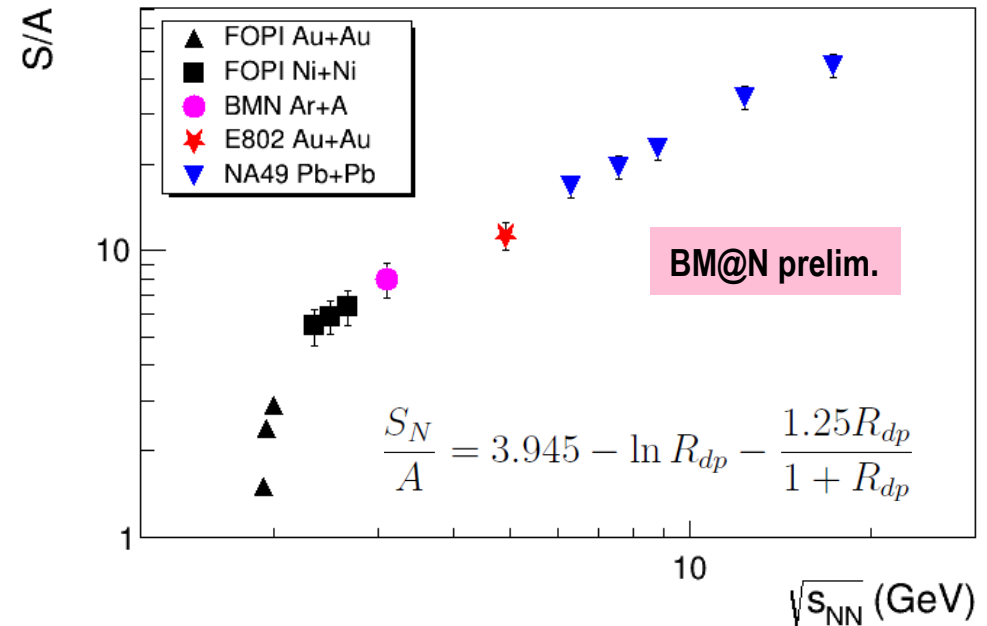
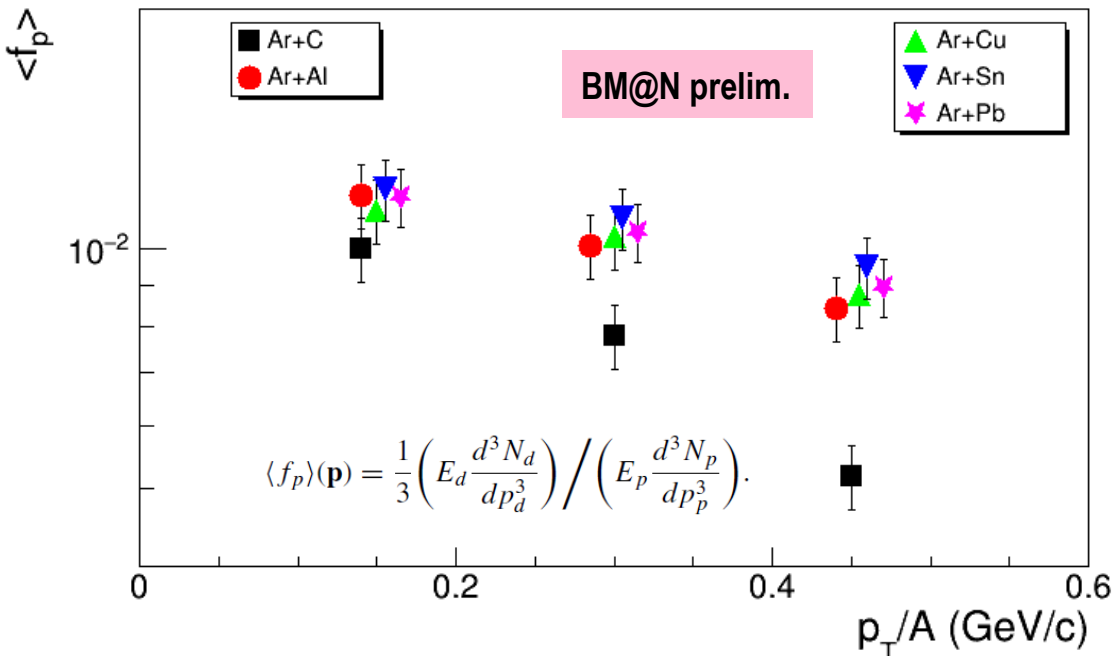
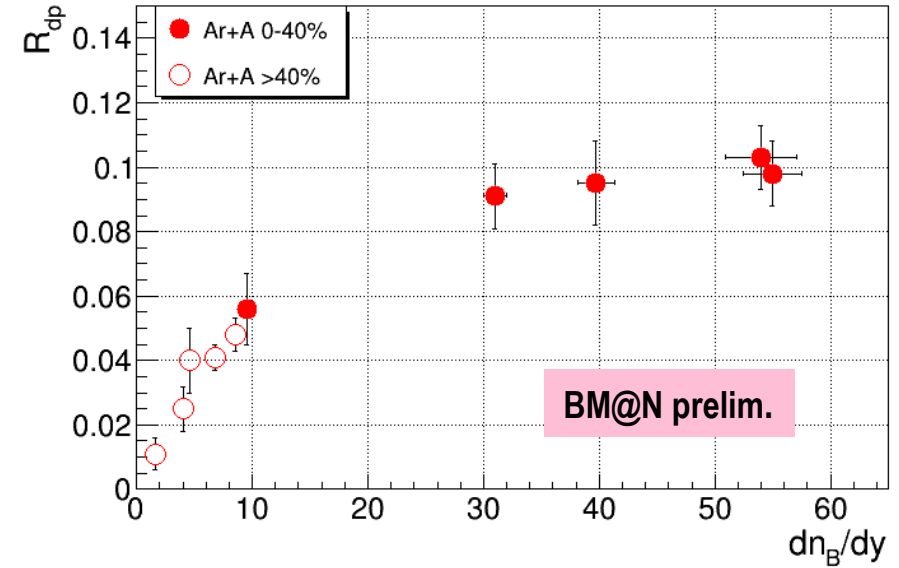
Spectra and yields of p,d,t in 0-40% Ar+A

- BW fits: $T \sim 105-110$ MeV $\langle \beta \rangle \sim 0.3$
- Rapidity spectra of protons (data) indicate more stopping than models
- Models underestimate the yields of light nuclei (factor from 2 to 5)



BM@N : R_{dp} in Ar+A - system size dependence and related observables

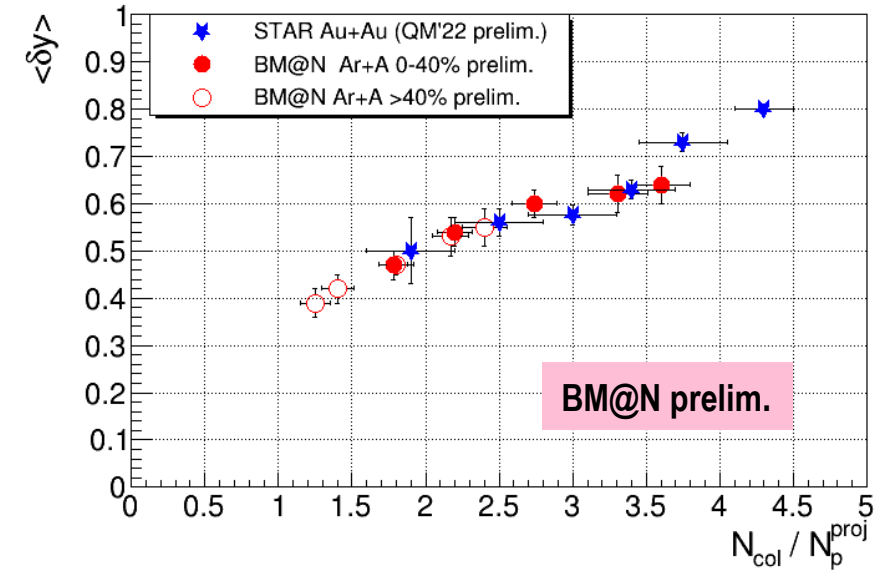
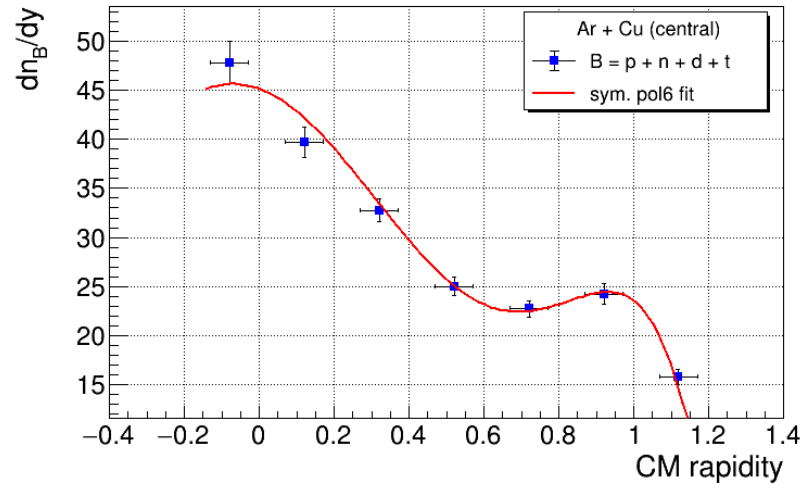
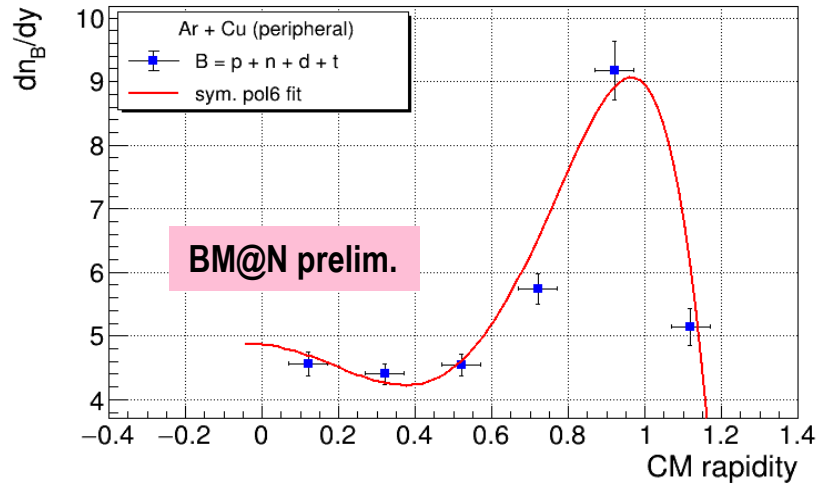
- The midrapidity R_{dp} rises in small systems and saturates in central Ar+A
- $\langle f_p \rangle$ decreases exponentially with p_T indicating a weak (if any) variation with the target mass in Ar+A (except Ar+C). Might be an indication of balancing of stopping power and the outward flow at BM@N.
- The entropy per baryon $S/A \sim 8.0$ in 0-40% Ar+A follows the general trend in the excitation function



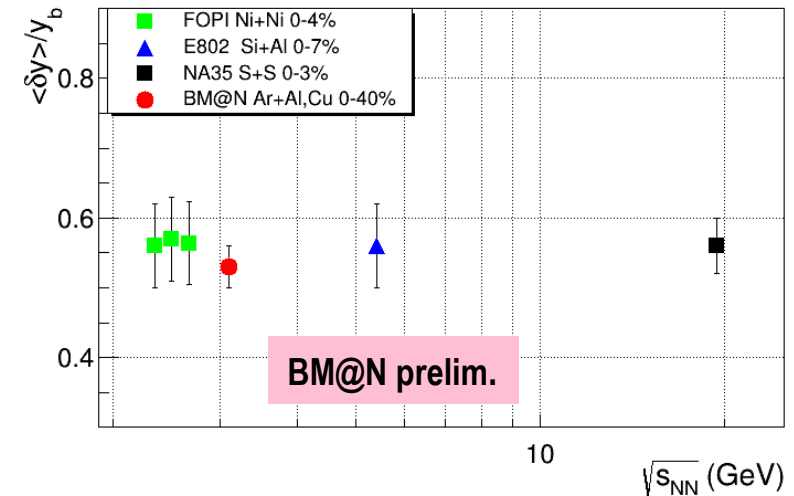
BM@N: Rapidity loss in Ar+A at 3.2A GeV

- Nucleons loss their momentum during the reaction. Baryon rapidity loss mechanism (baryon number transfer) is crucial for understanding collision dynamics. It reflects the baryon density achieved in HIC and related to nuclear matter properties: compressibility, EOS, and entropy production

$$\langle \delta y \rangle = y_b - \langle y \rangle,$$



- Rapidity loss (nuclear opacity) increases with the size of the reaction zone. Ar+A (BM@N) and Au+Au (STAR, QM'22) agree on a proper scale
- $\langle \delta y \rangle$ scales with the beam rapidity in medium-size A+A over a broad energy range.

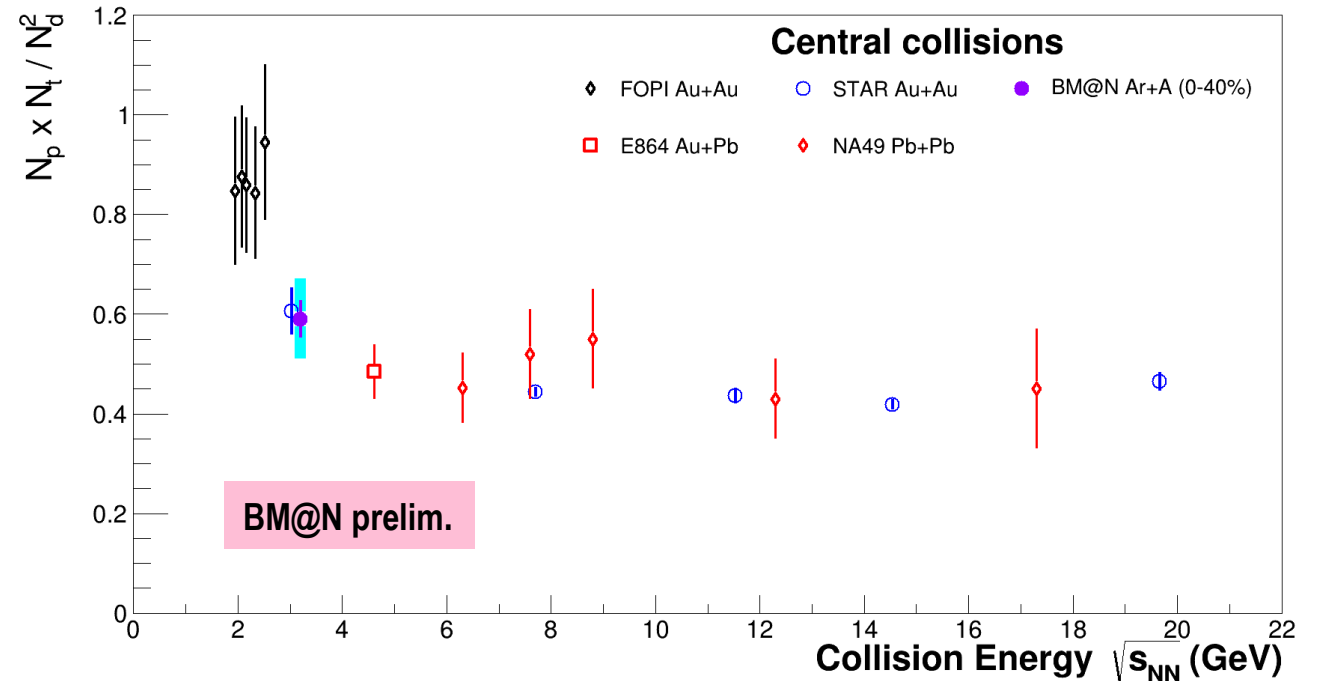
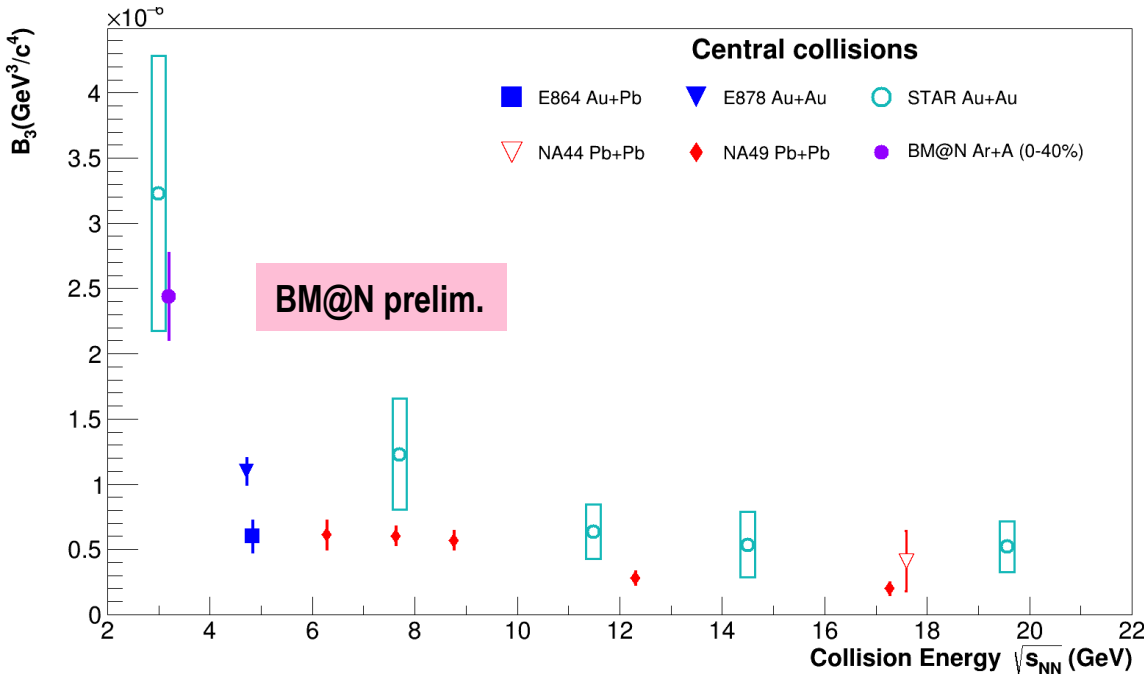


BM@N: coalescence parameter B_A and O_{pdt}

- Coalescence parameter B_A is related to the homogeneity volume in the source
- A peak structure in the excitation function of O_{pdt} (\sim relative neutron density fluctuations) as a probe of the QCD phase diagram structure – *K.J.Sun et al, Phys. Lett. B 781, 499 (2018)*

$$E_A d^3 N_A / d^3 p_A = B_A (E_p d^3 N_p / d^3 p)^Z (E_n d^3 N_n / d^3 p)^{A-Z} \Big|_{p=p_A/A}$$

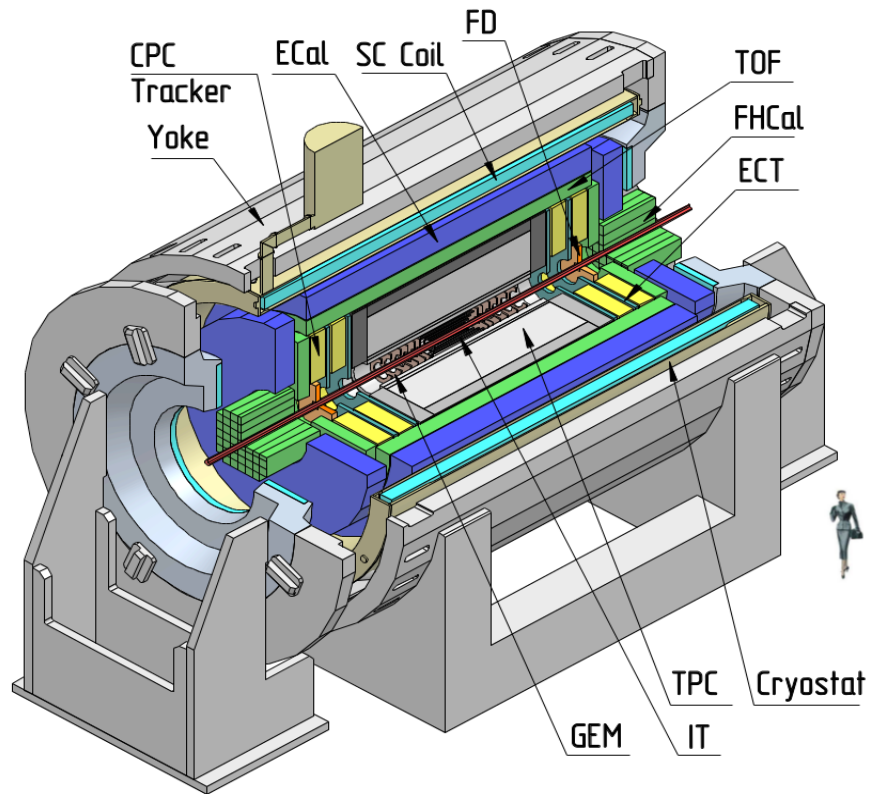
$$O_{pdt} = (N_p N_t) / (N_d^2)$$



BM@N results from 0-40% central Ar+A follow the general trend of the excitation function for B_A and O_{pdt}

MultiPurpose Detector (MPD) for A+A collisions @ NICA

Eur. Phys. J. A 58 (2022)



- 3D tracking (TPC), uniform acceptance
- Powerful PID (TPC, TOF, ECAL)
- Precise event characterization (FHCAL)
- Fast timing and triggering (FD)

Start of operation in **2025**

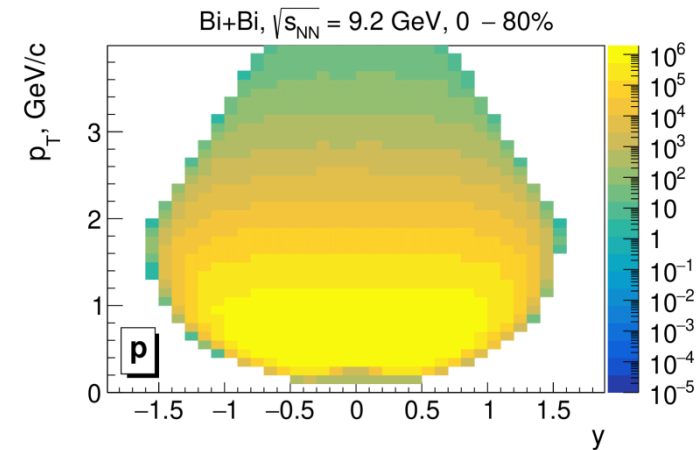
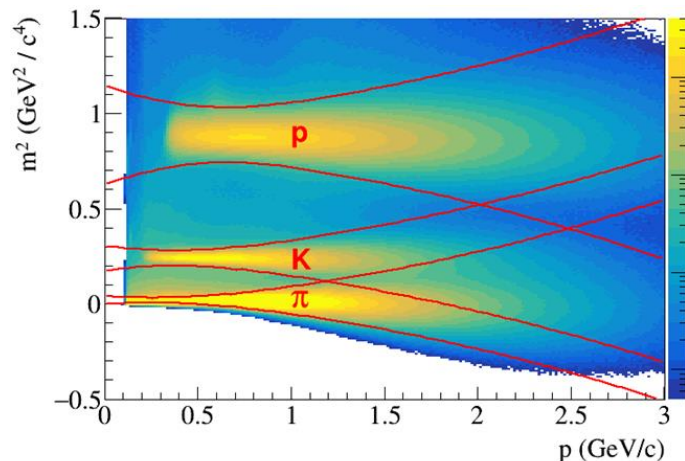
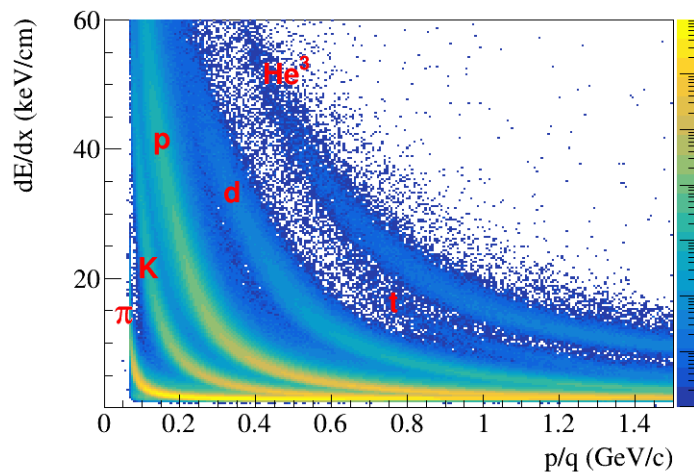
Bi+Bi at 9 GeV (collider mode) or

Xe+W at $E/A=2.5$ GeV (FXT fixed target)

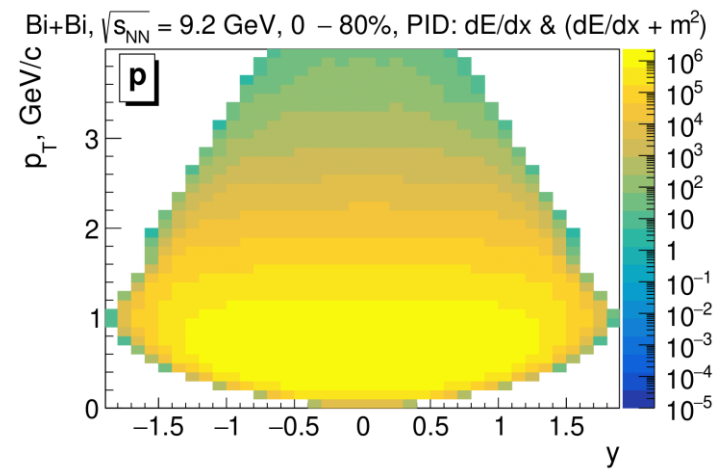
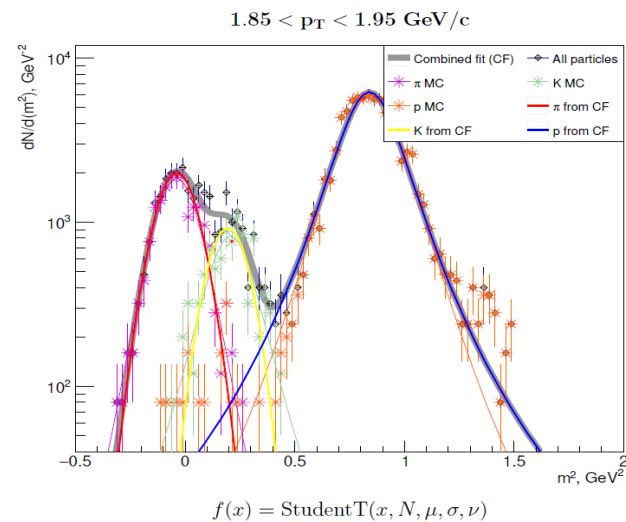
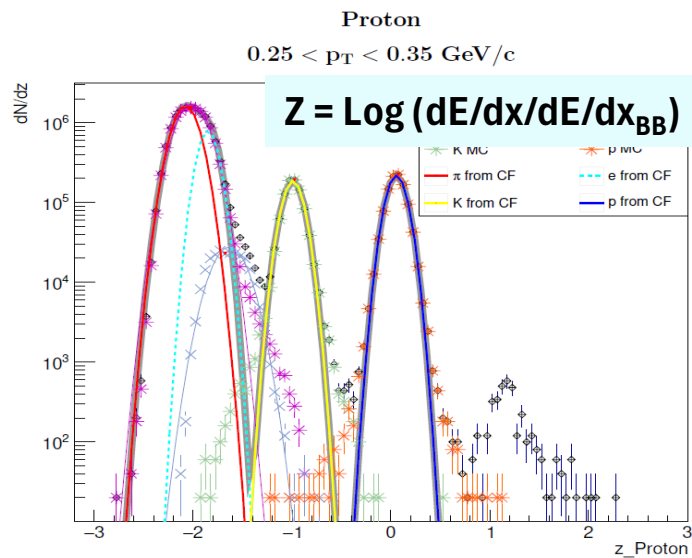
MPD-FXT and BM@N at NICA are complementary for STAR-FXT at RHIC.
New data on small- or medium-size A+A collisions.

MPD: PID in Bi+Bi at 9.2 GeV (collider mode)

- dE/dx+TOF – large phase-space coverage but low p_T -cutoff at forward rapidity



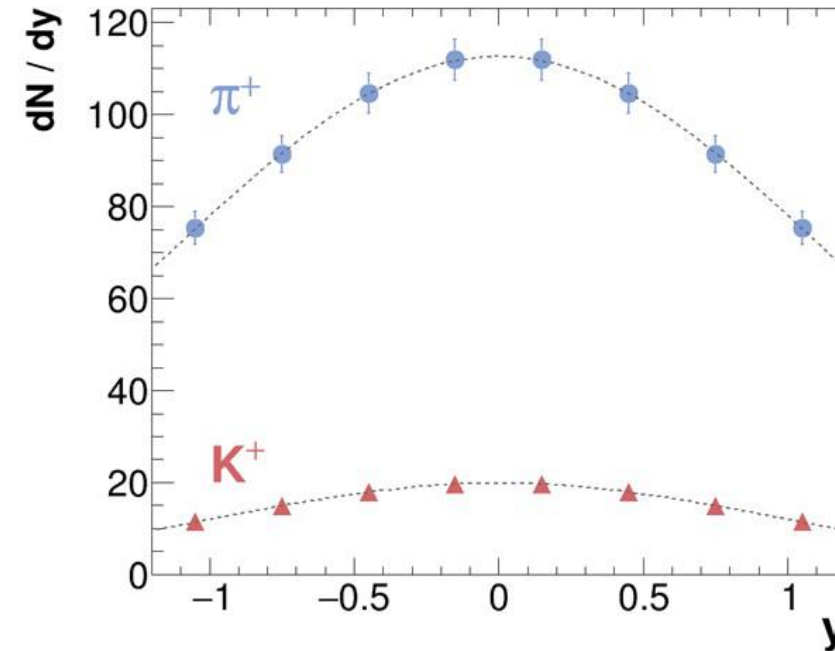
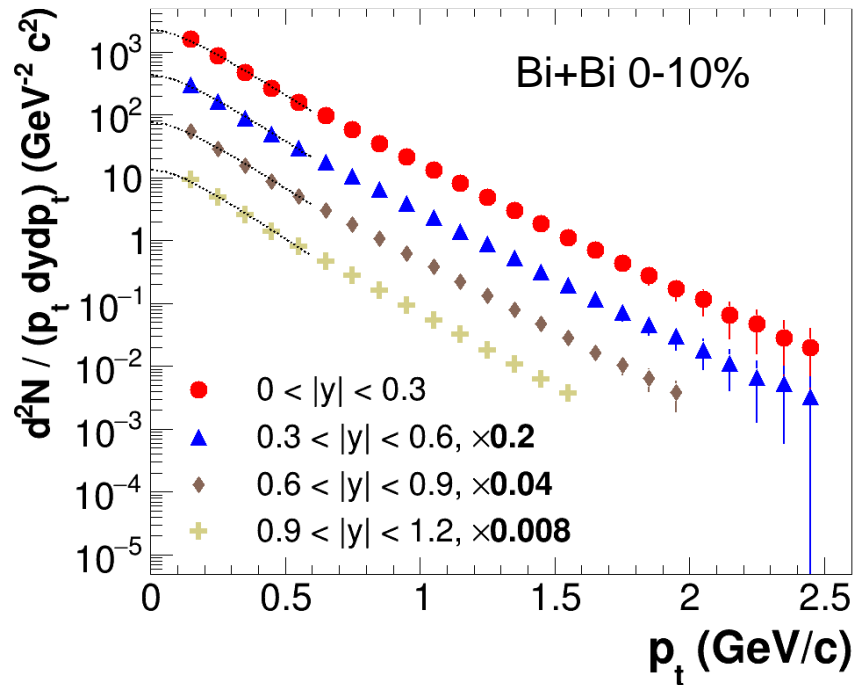
- dE/dx ($p < p_{low}$) and TOF ($p > p_{low}$) provides an extra acceptance at low- p_T (a gain in y -coverage ~ 0.2)



MPD: Hadron spectra and yields from central A+A collisions (π , K)

- *Recent reconstruction chain, combined $dE/dx+TOF$ particle ID, spectra analysis*

- MPD has a large phase-space coverage for identified pions and kaons (> 60% of the full phase-space for π at 9 GeV in central collisions)
- Hadron spectra can be measured from $p_T=0.2$ to 2.5 GeV/c
- Extrapolation to full p_T -range and to the full phase space (4π yields) can be performed exploiting the spectra shapes

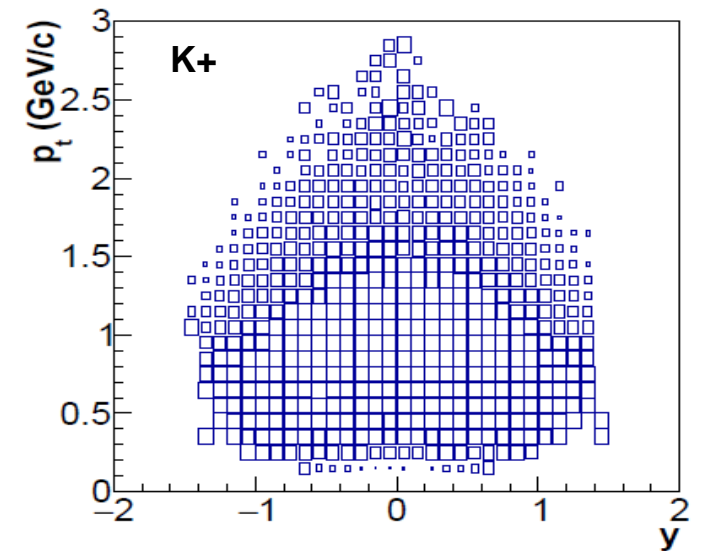
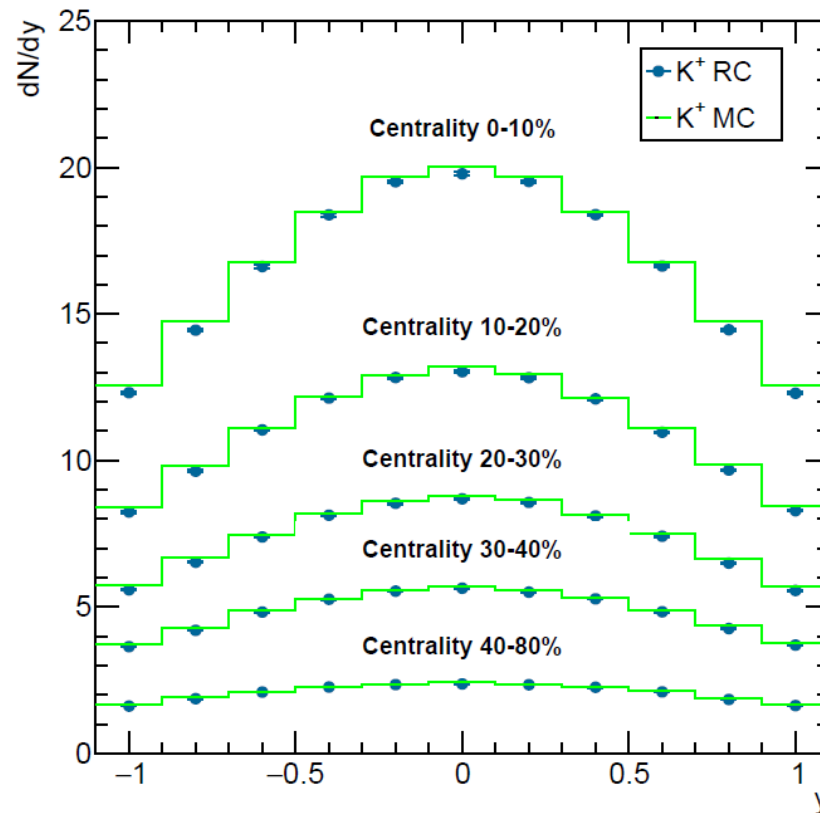
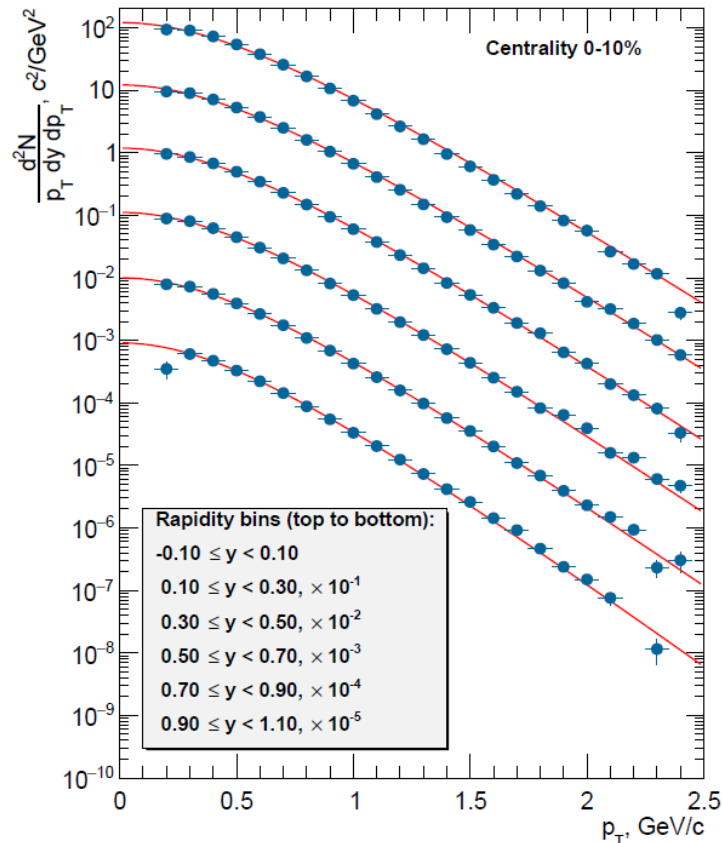


NICA/MPD advantages for hadron measurements – a large phase-space coverage and homogeneous (vs collision energy) acceptance

MPD: hadron spectra and yields from central A+A collisions (K⁺)

- Recent reconstruction chain, combined $dE/dx+TOF$ particle ID, spectra analysis

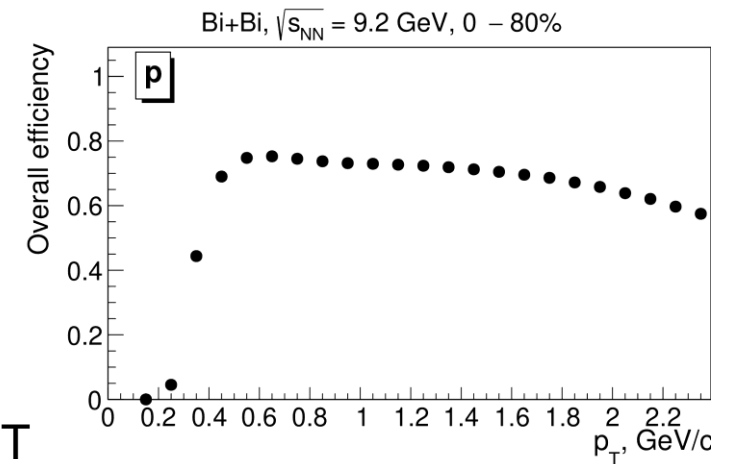
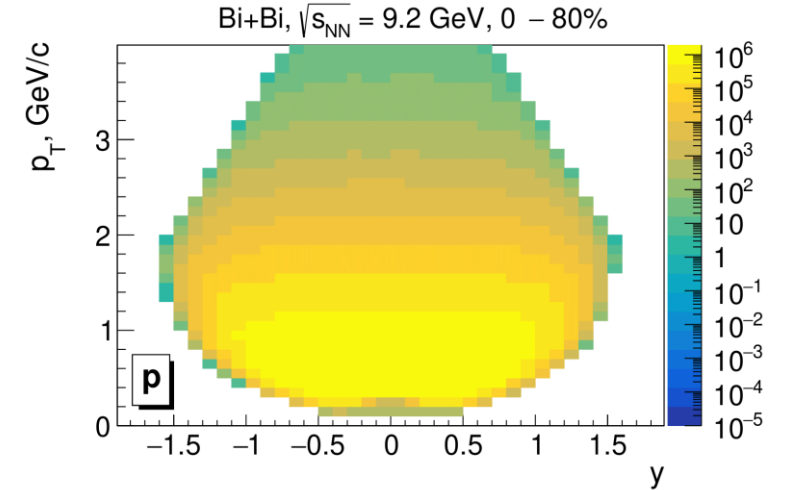
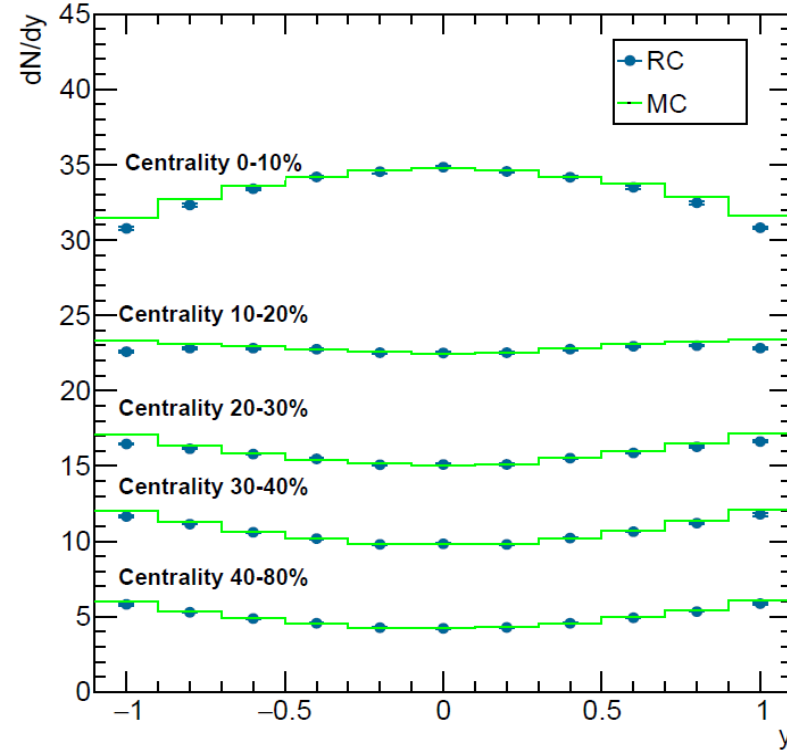
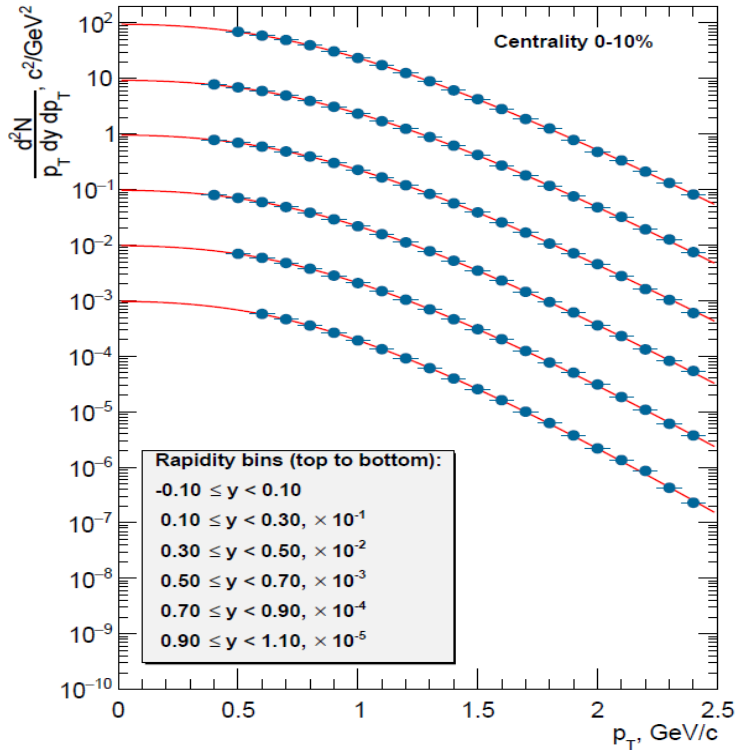
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NICA/MPD advantages for hadron measurements – a large phase-space coverage and homogeneous acceptance

MPD: hadron spectra and yields from central A+A collisions (protons)

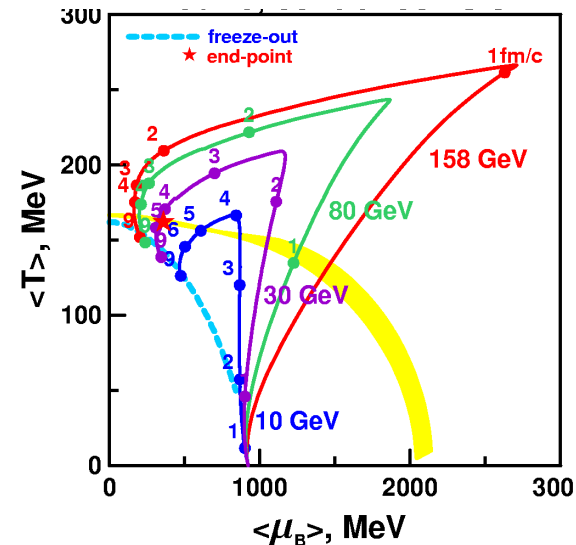
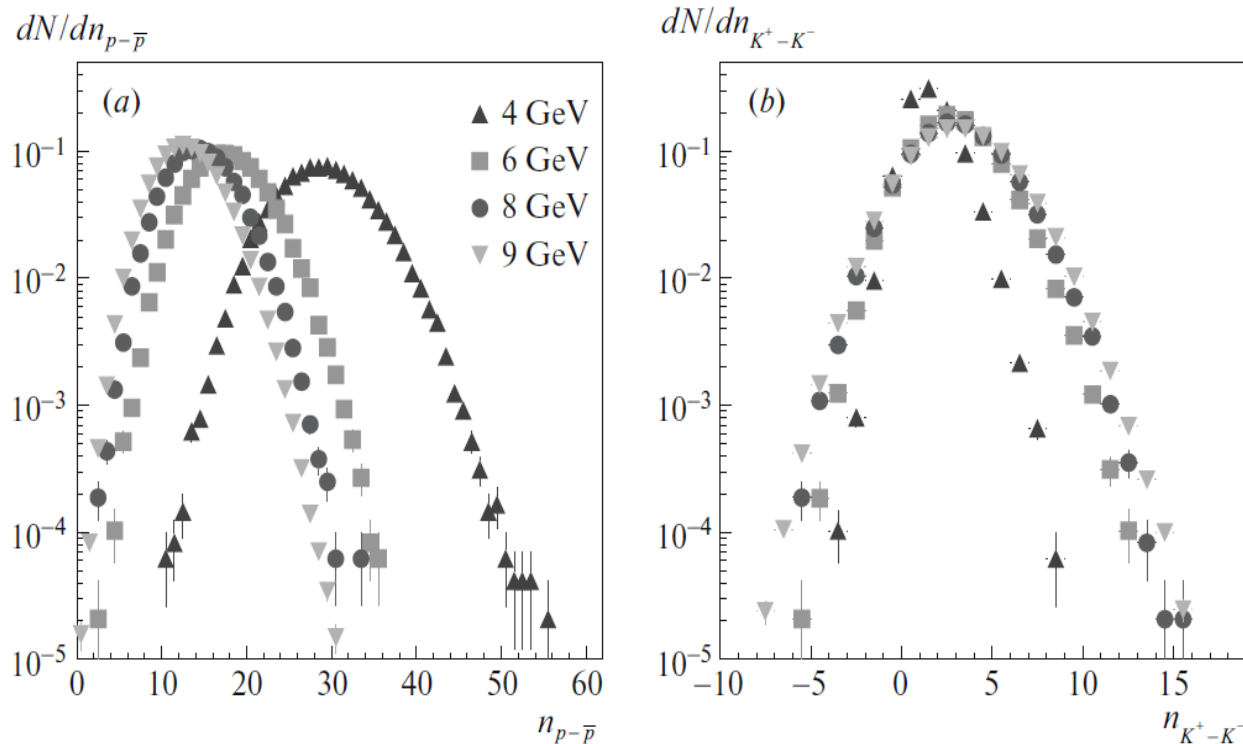
- Recent reconstruction chain, combined $dE/dx+TOF$ particle ID, spectra analysis



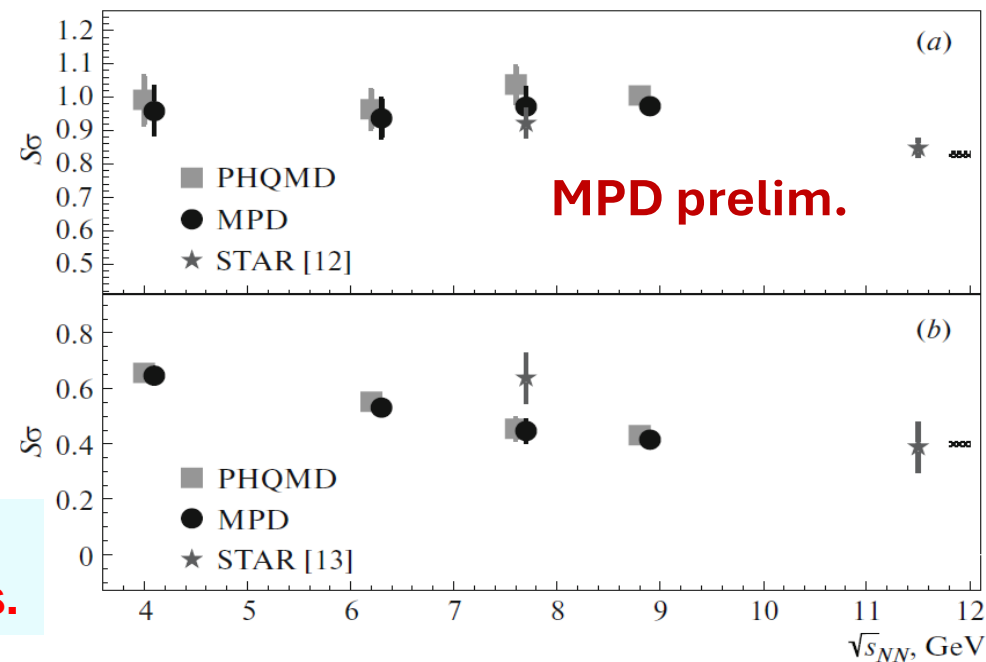
- Midrapidity $|y| < 1$ coverage for protons
- Uncertainty in dn/dy at forward rapidities ($\sim 5\%$) due to lack of points at low p_T
- Limiting capability in determination of the variation of the shapes (stopping and 4π yields)
- A forward tracker with PID capability may provide a substantial increase of MPD capability for baryon measurements**

MPD: prospects for CEP search in net-proton and net-strangeness fluctuations

- Moments of event-by-event multiplicity distributions or cumulant ratios are directly compared to susceptibilities, which diverge in the proximity of CEP
- MPD has a large uniform acceptance for hadrons and good per-event PID capability → good prospects for the study strangeness and baryon number fluctuations



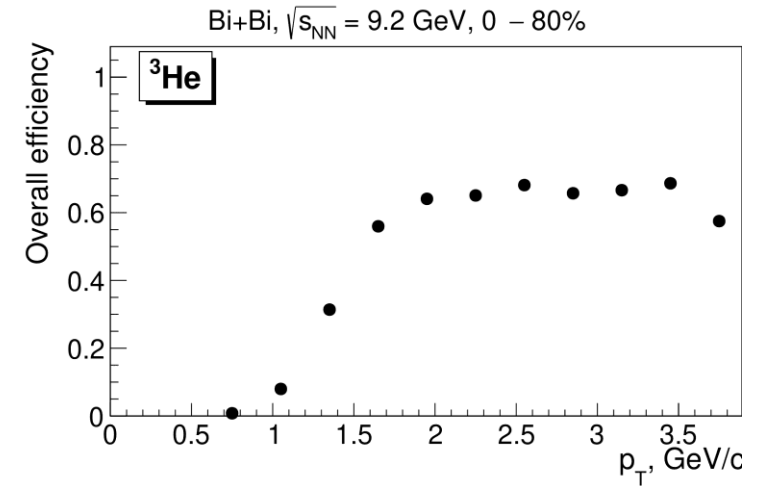
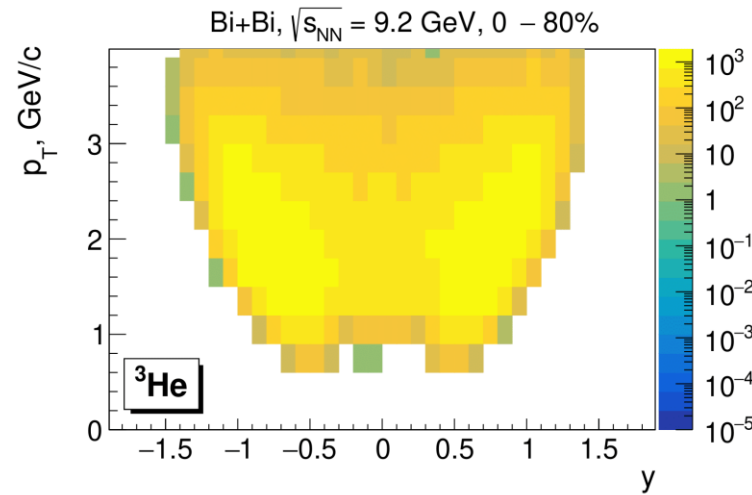
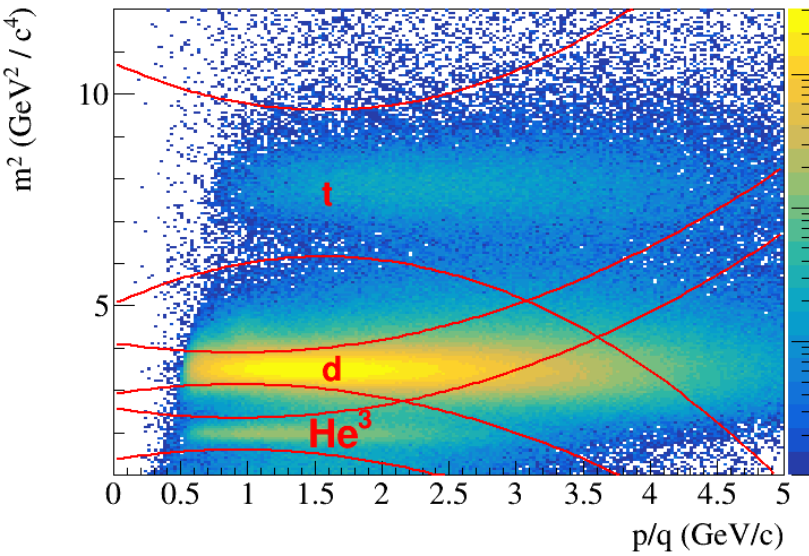
effective skewness $S\sigma$ for net-protons (a) and net-kaons (b)



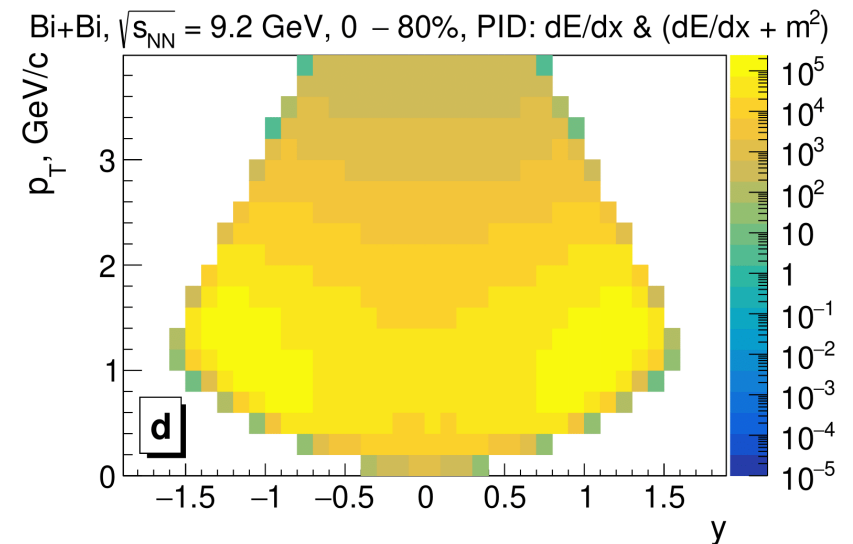
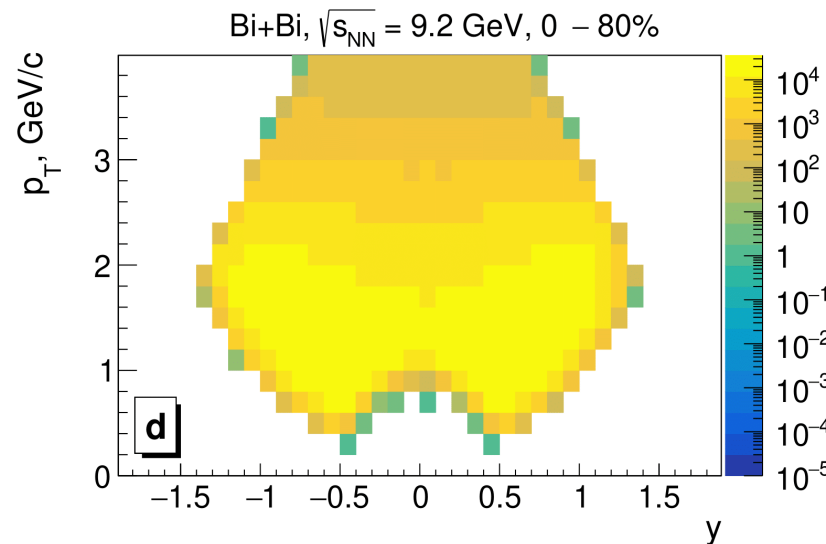
Limiting progress yet in feasibility studies due to lack of experts in the field. We are looking for cooperation with China colleagues.

MPD: light nuclei PID (collider mode, PHQMD model):

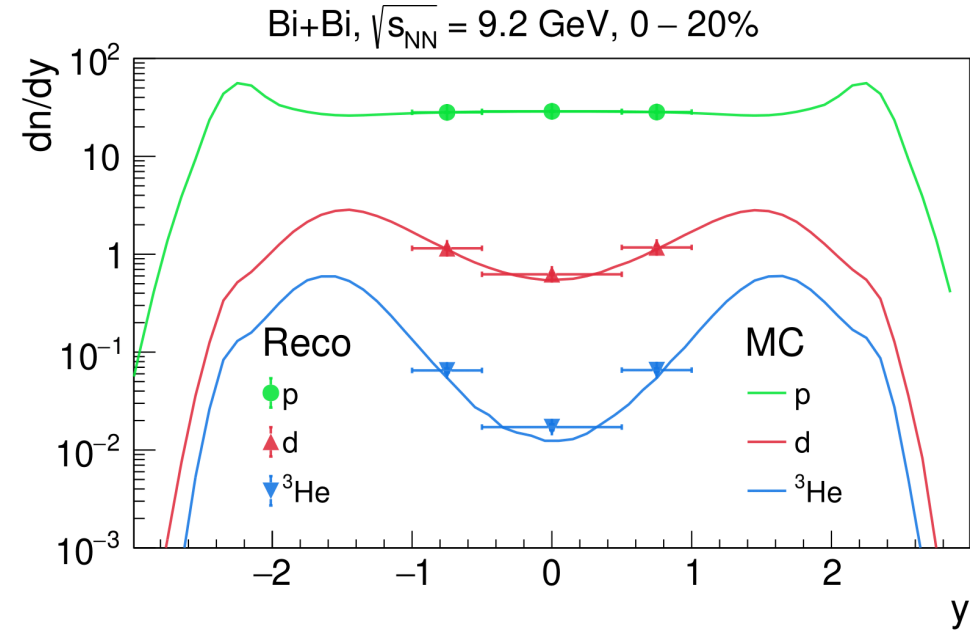
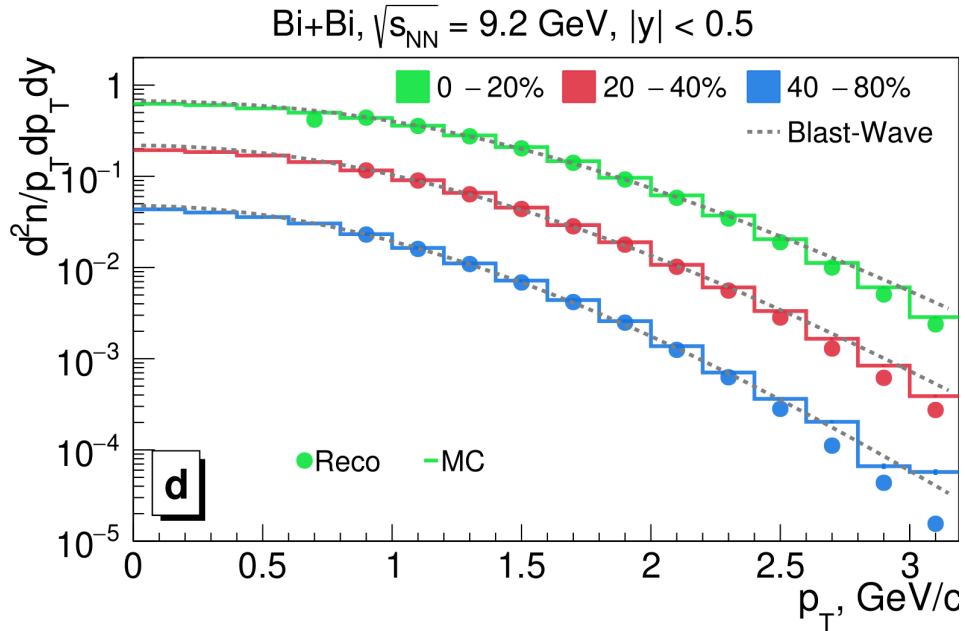
- $dE/dx+TOF$ – large phase-space coverage but low p_T -cutoff at forward rapidity for d , t , ${}^3\text{He}$



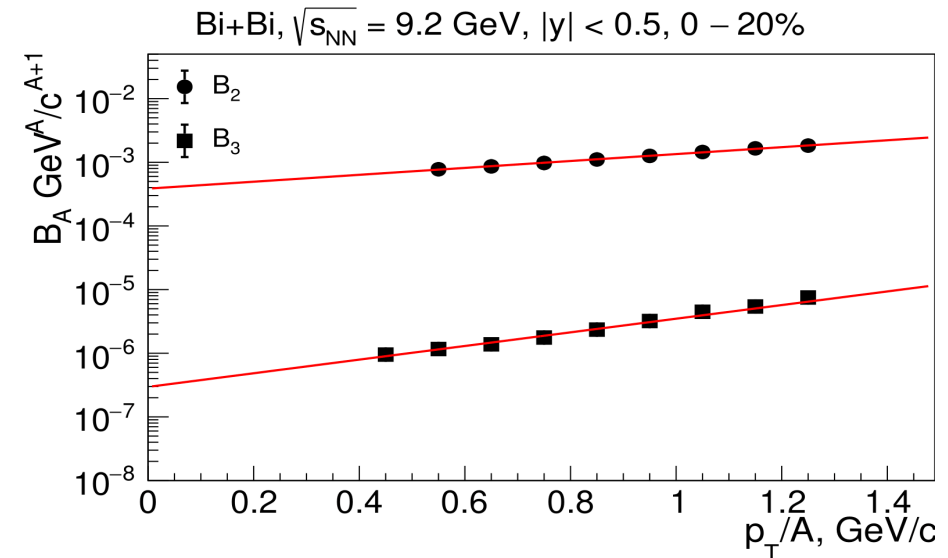
- dE/dx -only PID provides an extra acceptance at low- p_T
- A gain in y -coverage ~ 0.2



MPD: light nuclei spectra in Bi+Bi

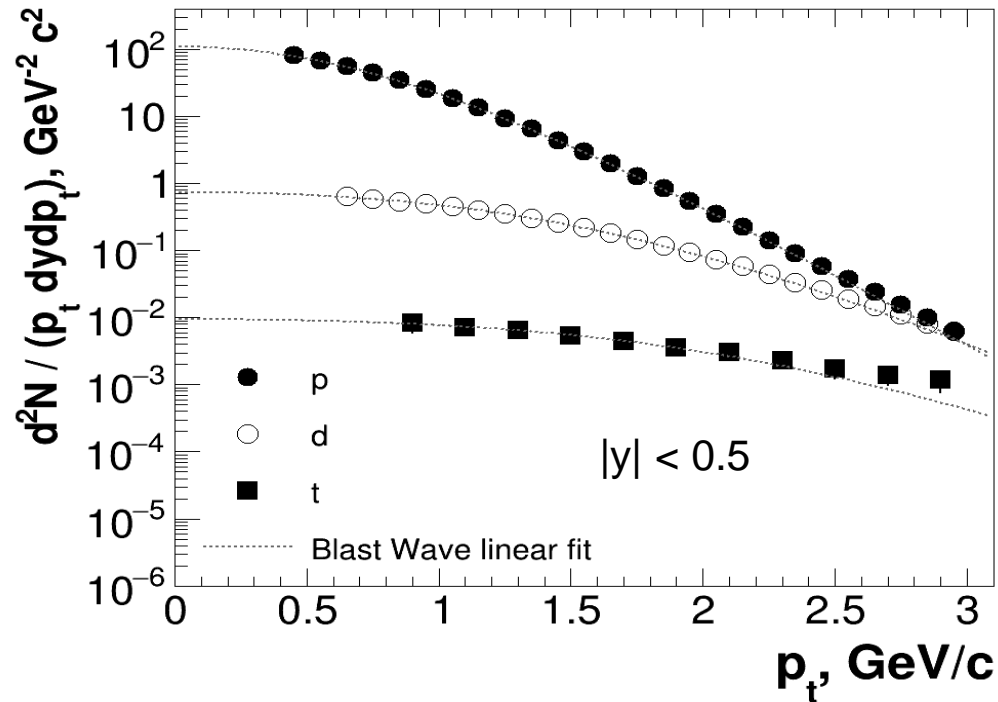


- Proton and light nuclei spectra within $|y| < 1$ for dE/dx+TOF particle ID
- Midrapidity yields, spectra, ratios
- Limiting capability for reconstruction of the full rapidity distributions → **forward tracker + PID?**

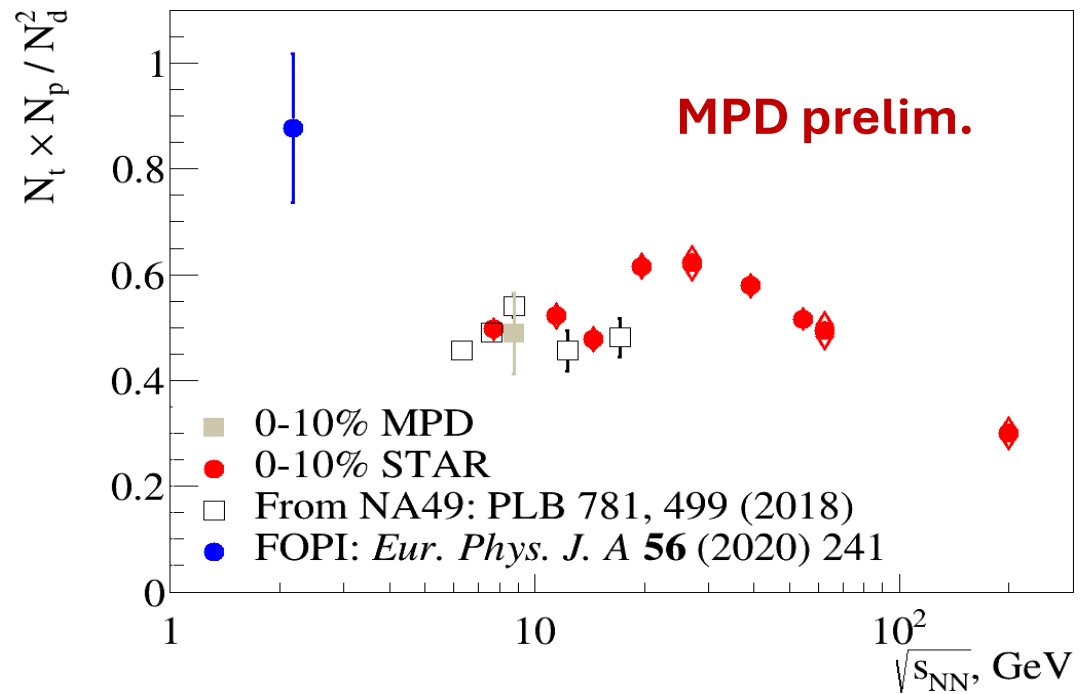


MPD: particle yields ratio in the analysis of density fluctuations

- A peak structure in the excitation function of relative neutron density fluctuations as a probe of the QCD phase diagram structure – *K.J.Sun et al, Phys. Lett. B 781, 499 (2018)*



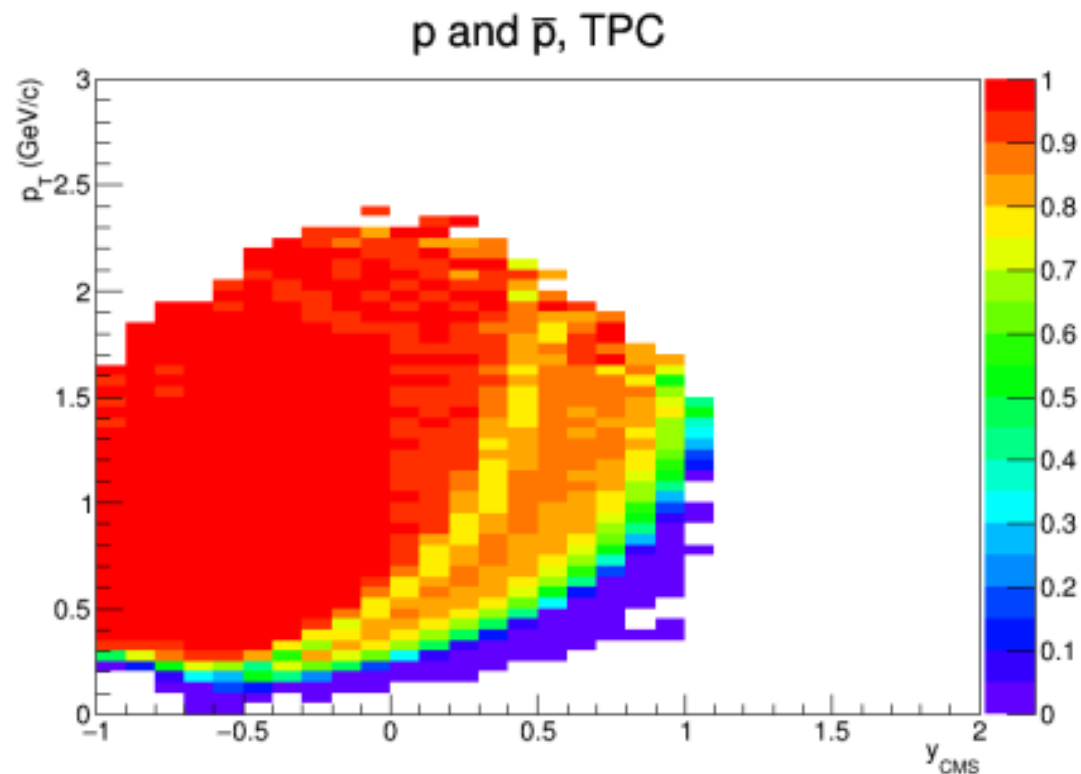
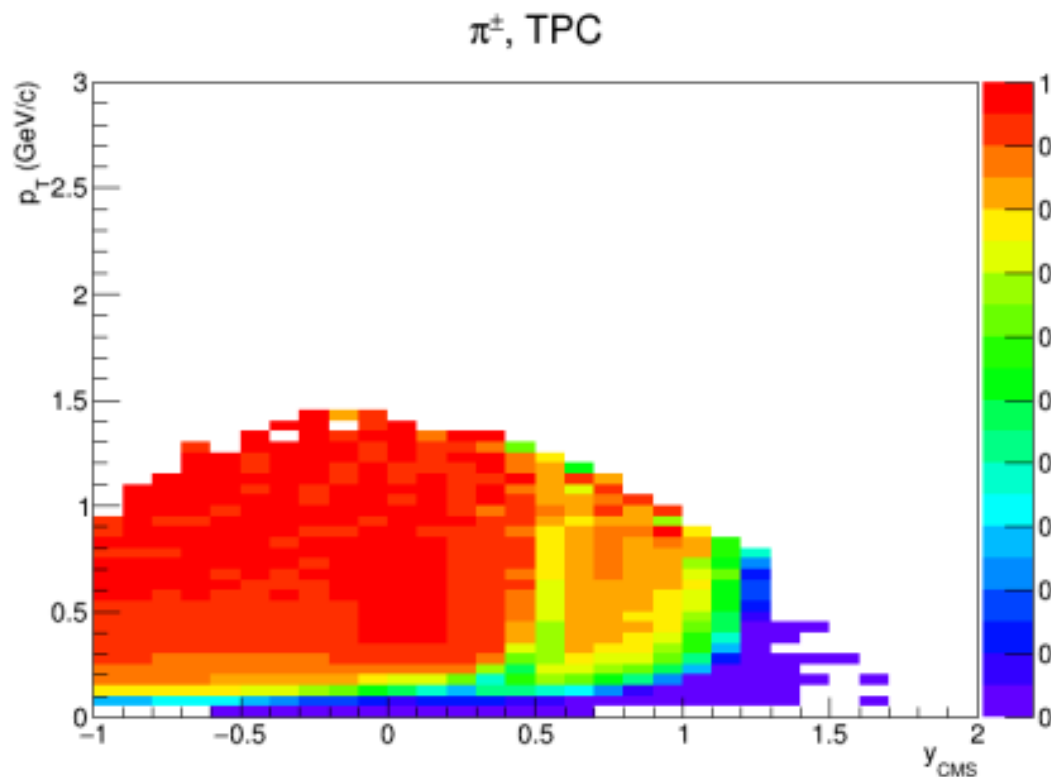
$$O_{pdt} = (N_p N_t) / (N_d^2)$$



**Limiting progress yet in feasibility studies due to lack of experts in the field.
We are looking for cooperation with China colleagues.**

MPD prospects in the FXT mode (Xe+W at 2.5A GeV)

- Xe+W at $E_{\text{kin}} = 2.5A$ GeV ($y_{\text{CM}} = 0.99$) DCM-QGSM-SMM model
- Close to a full phase-space coverage in the forward hemisphere
- Feasibility studies for the FXT mode are ongoing



Summary

- **Heavy-ion experimental program at NICA is progressing according to plans**
- **BM@N experiment : results on hadron and light nuclei yields from Ar+nucleus and Xe+CsI at E/A 3-4 GeV**
- **MPD : preparation to data taking in 2025. Feasibility studies for Bi+Bi (collider mode) and Xe+W (FXT) are ongoing**
- **MPD is looking for cooperation with China colleagues in several analysis topics**

Thank you for your attention!

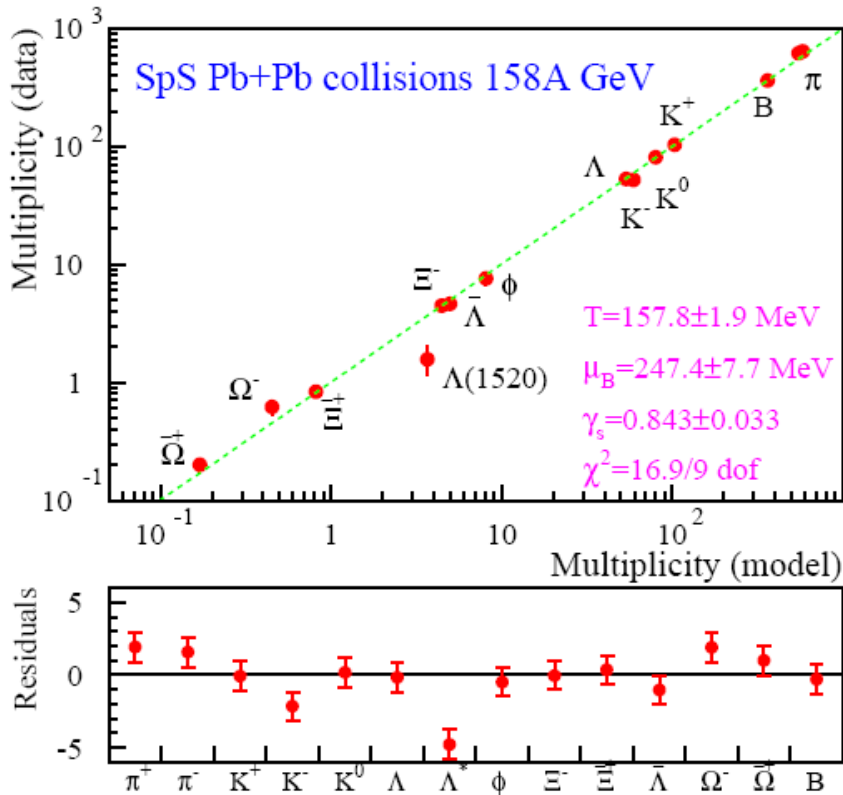
Many thanks to the organizers of this special meeting!

Extra slides

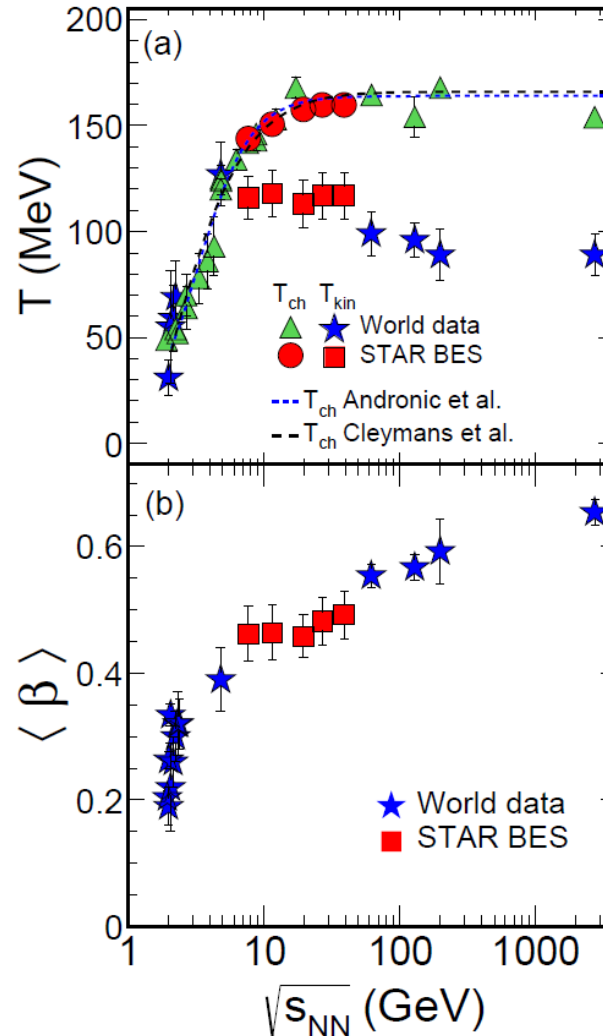
NICA physics cases: Bulk properties & phase diagram mapping

- Thermodynamical source parameters (T and μ_B) are deduced from hadron yields, spectra and ratios

Phys. Rev. C69, 024905 (2004)



Phys. Rev. C 96, 044904 (2017)



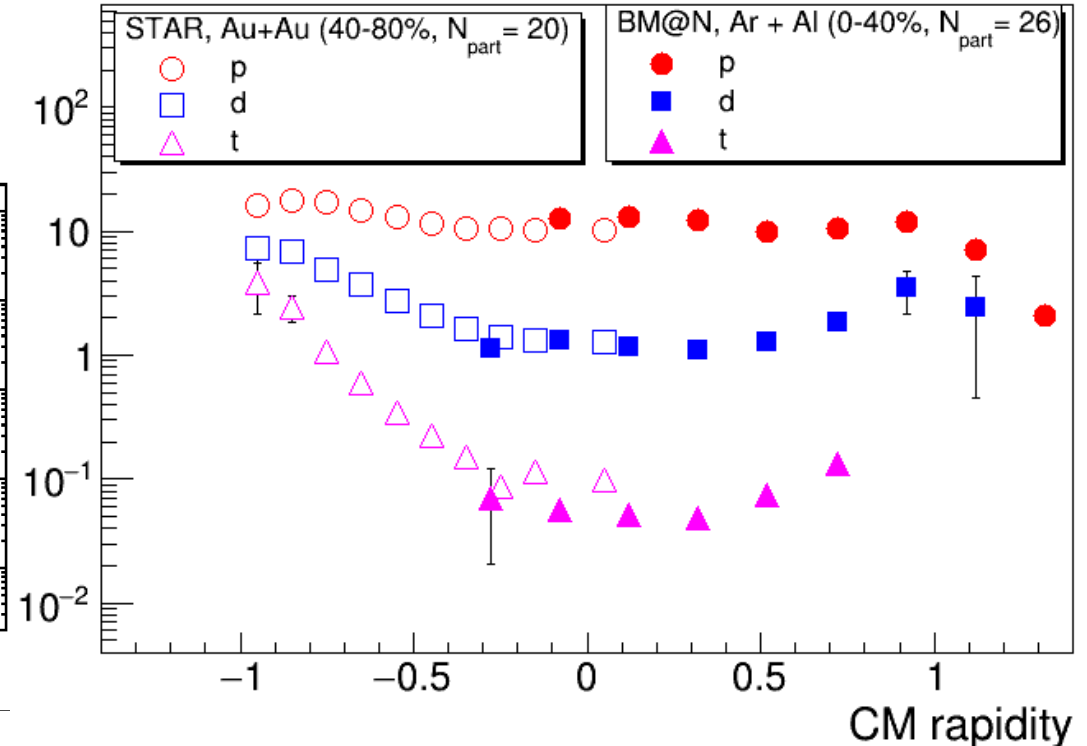
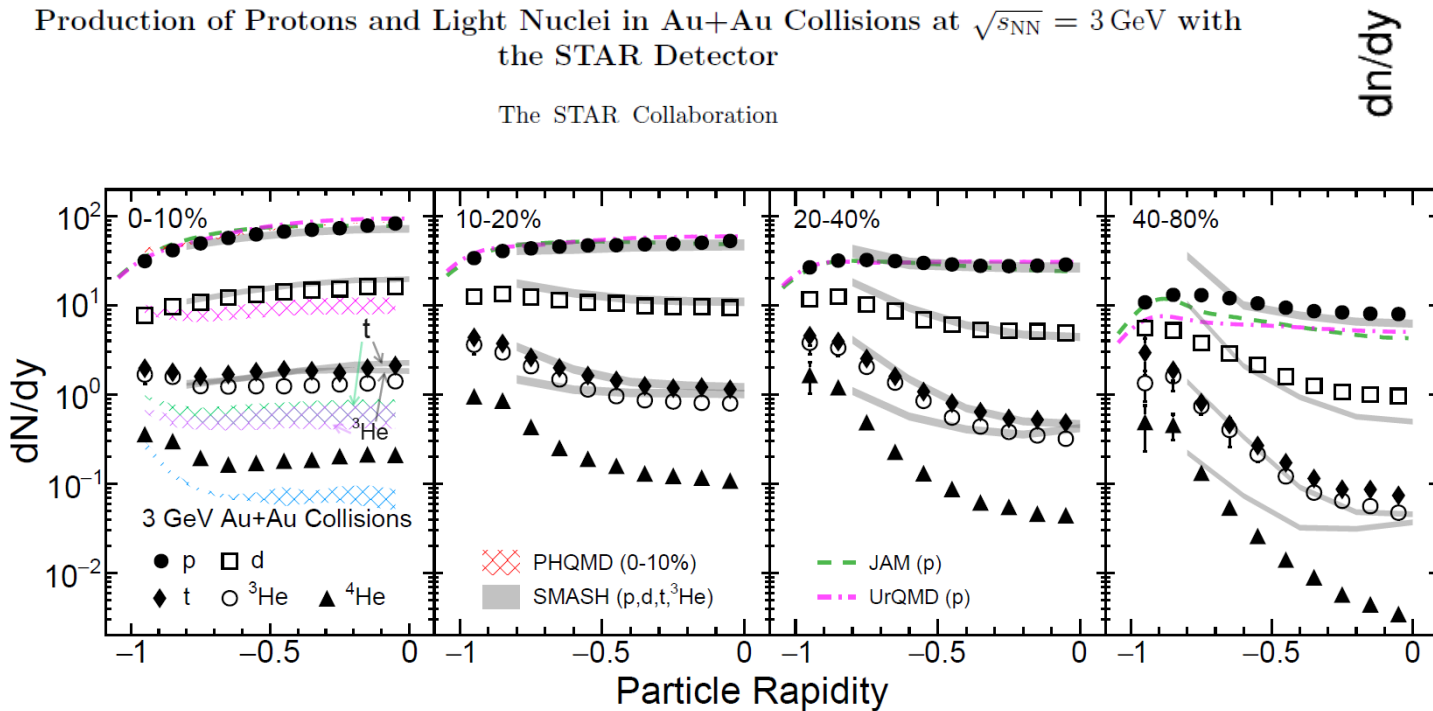
- Very detailed investigation of the fireball thermodynamical parameters in central A+A (AGS, SPS, STAR/BES) in a broad energy range
- Experiments at NICA will continue the study in the region of high baryon density by varying collisions energy and system size. Large and uniform acceptance of the apparatus is of importance

Rapidity spectra of p, d, t in A+A: BM@N vs STAR-FXT

- Ar+Al 0-40% data set from BM@N (projectile $N_{\text{part}} = 23$) and 40-80% Au+Au (projectile $N_{\text{part}} = 20$) are used for the comparison (assuming that the particle yields scale with N_{part})

arXiv: 2311.11020v1 [nucl-ex]

BM@N, this study



- Though the collision geometry in Ar+Al and Au+Au is different, the yields of p, d, t agree within 20% at midrapidity

Cluster production in HIC at low collision energies: production rate puzzle

- Discrepancy between data and models could be due to feed-down from excited nuclear states that is bigger at low collision energies (*V.Vovchenko et al, Phys. Lett. B 809 (2020)*)
- ‘3FD hydro model + UrQMD + freezeout tuning + feeddown’ qualitatively reproduces STAR data (*M.Kozhevnikova and Yu. Ivanov, PRC 109, 014913 (2024)*)

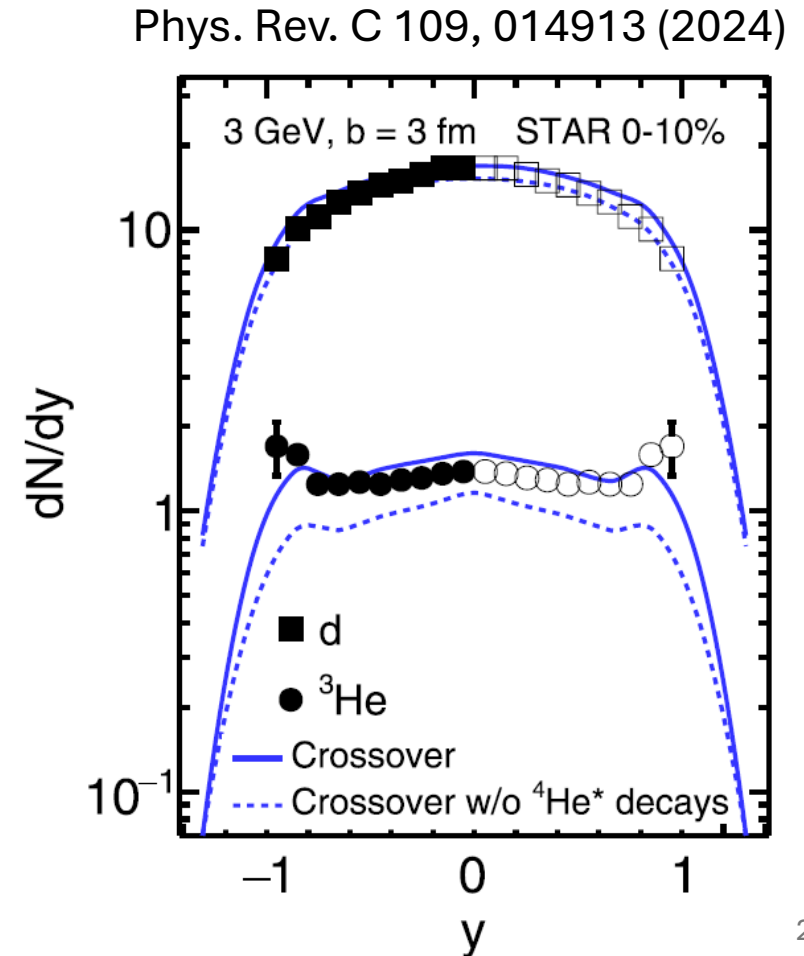
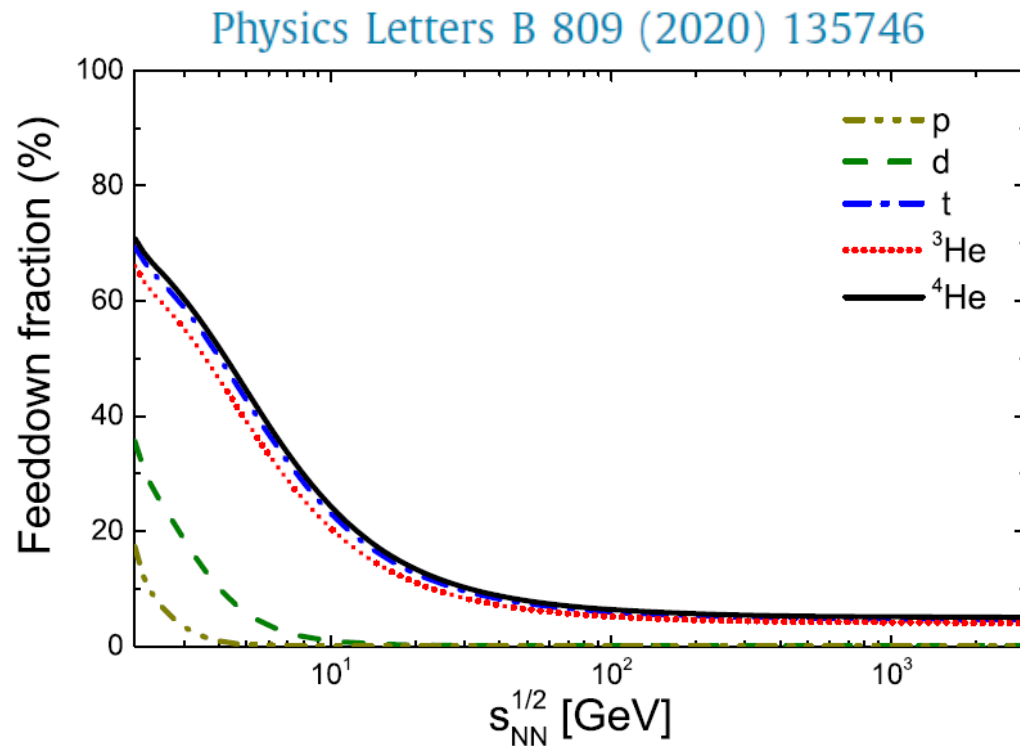


Fig. 1. Fractions of final yields of p, d, t, ^3He , and ^4He coming from decays of the excited nuclei estimated in the statistical model along the chemical freeze-out curve of Ref. [32].

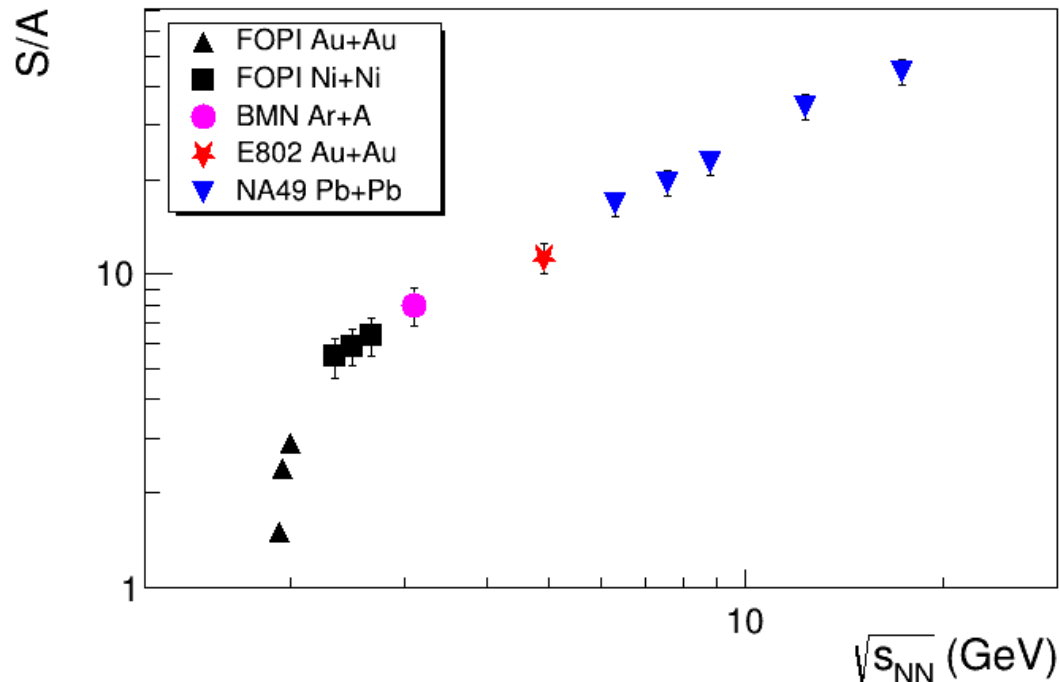
Specific entropy S/A in central A+A : energy dependence

In a thermally and chemically equilibrated system, nuclear cluster abundances and entropy attained in the reaction are related. Specific entropy (entropy per baryon) S/A can be deduced from R_{dp}

$$\frac{S_N}{A} = 3.945 - \ln R_{dp} - \frac{1.25 R_{dp}}{1 + R_{dp}} \quad L. P. Csernai and J. I. Kapusta, Phys. Rep. 131, 4 (1986) 223-318$$

In addition, the pion contribution to the total entropy is estimated (*L.Landau*): $\frac{S_\pi}{A} = 4.1 \frac{N_\pi}{N_N}$
 N_π is the number pions and N_N is the number of nucleons

Reaction	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
S/A	10.6 +/- 1.6	8.0 +/- 1.2	8.0 +/- 1.2	7.9 +/- 1.2	8.0 +/- 1.2



The entropy per baryon $S/A \sim 8.0$ in central Ar+Al,Cu,Sn,Pb at BM@N (the value near midrapidity)

- S/A increases steady with collision energy. The rate of change is higher below 2 GeV
- BM@N results follow the general trend for central A+A collisions