Study of hadron and light nuclei production at NICA

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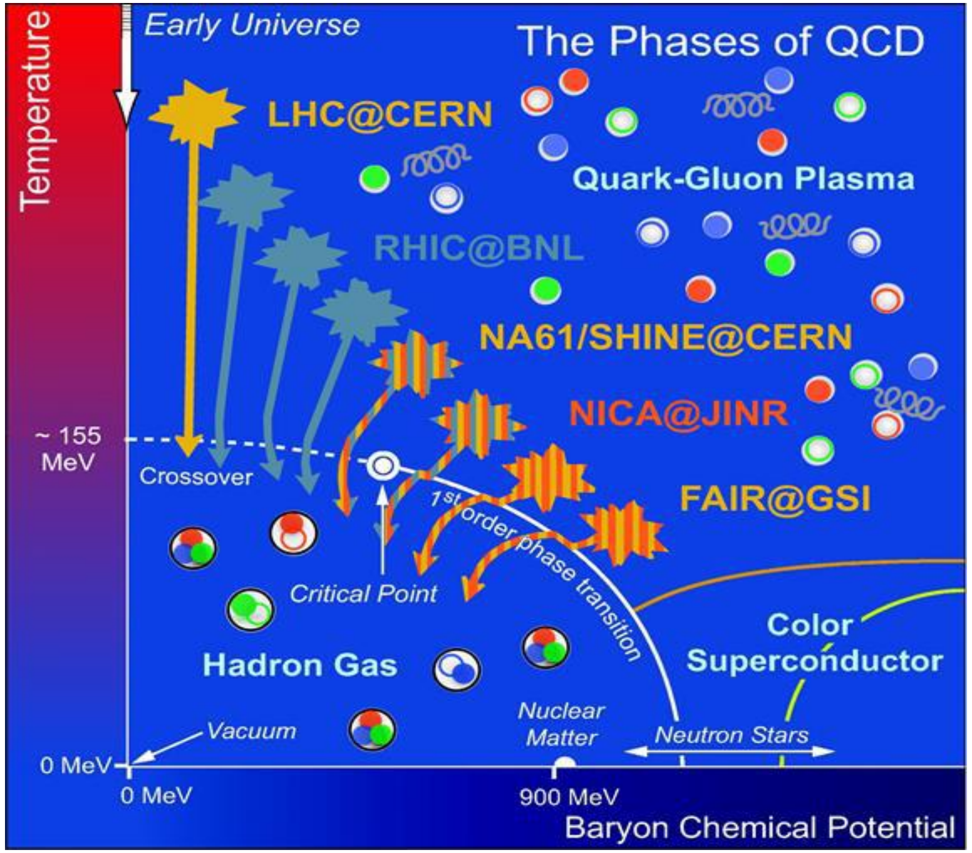
Outline

- 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

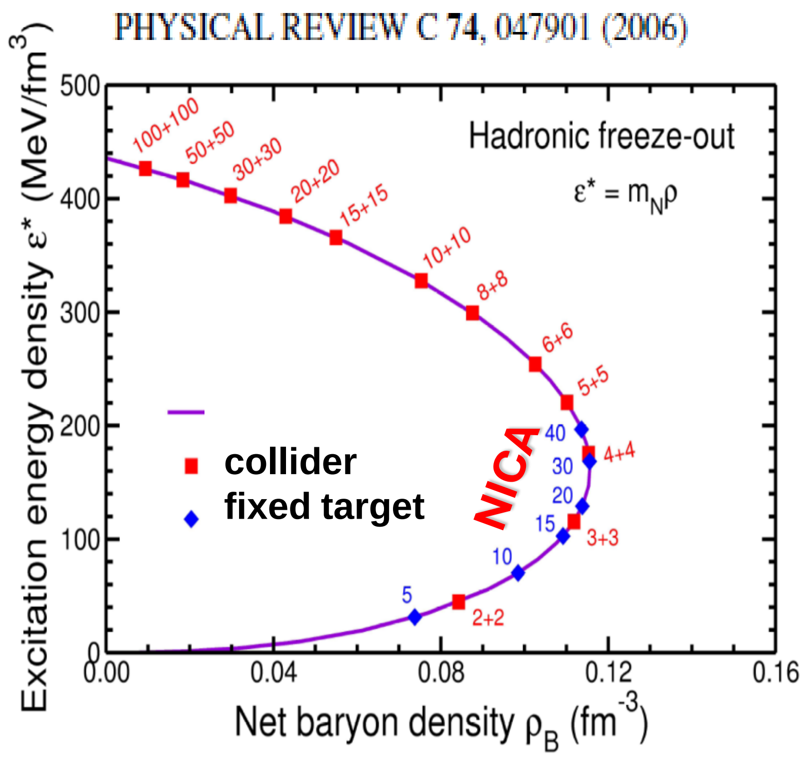
  MPD (collider mode) 4-11 GeV and

  ‘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
- μ_B = (300 - 750) MeV, T_{ch} ~ (120-150) MeV
- Fixed target (BM@N) - 2-6A GeV, Collider (MPD) - $\sqrt{s_{NN}}$=3-11 GeV



At low NICA energies:

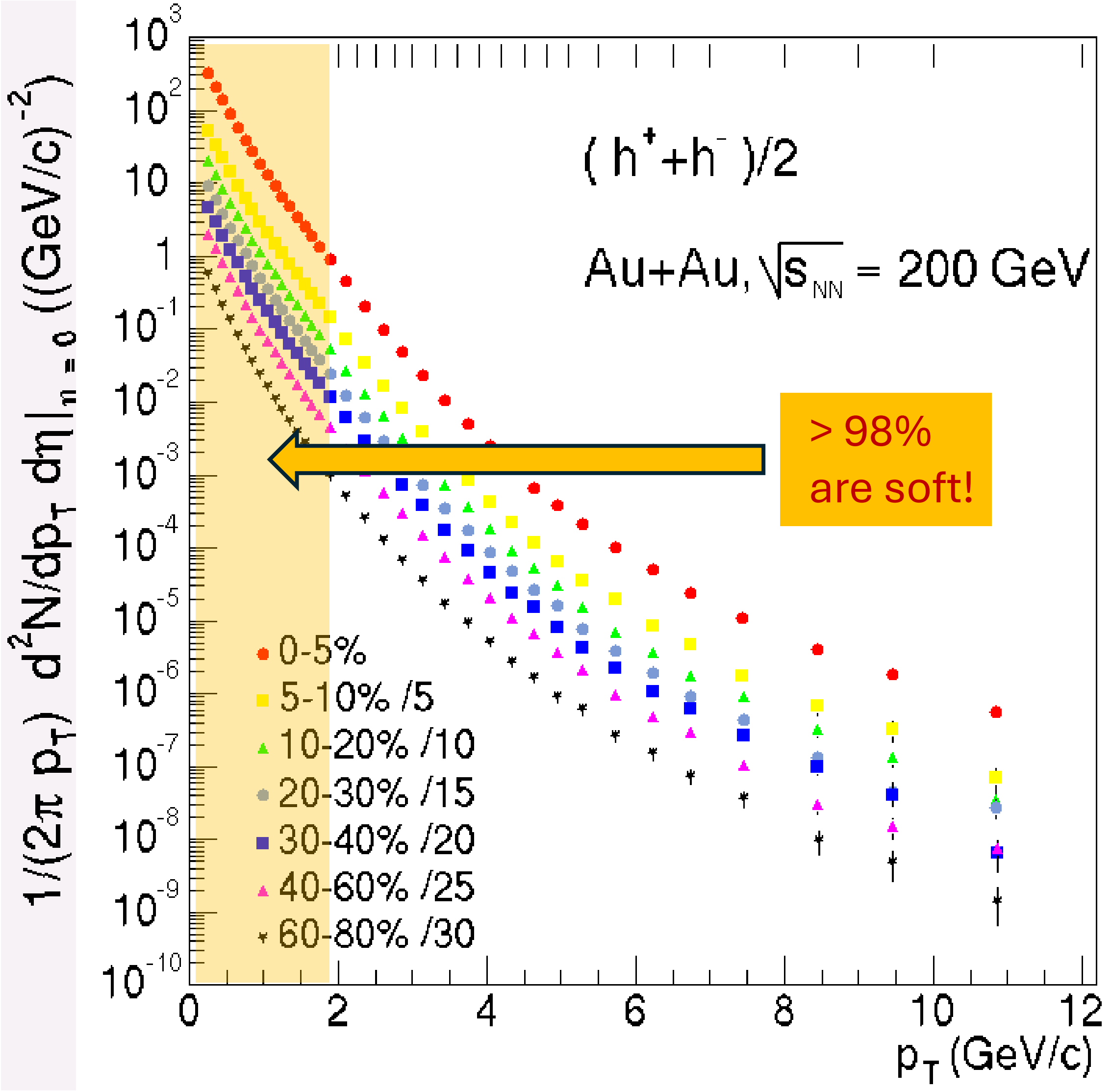
- baryon dominated nuclear matter is formed:
- particle production process mainly through excitation and decay of baryon resonances
- in-medium effects play a role in hadron production
- up to 30% of the total baryon number is contained in clusters

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 pT < 2 GeV/c



<u>Hadrons from bulk</u>: particles containing most abundant quark specie (*u, d, s* + their anti-partners):

π, K, p, Λ, Ξ, K*, d, t, ^{3}He, $^3H_\Lambda$

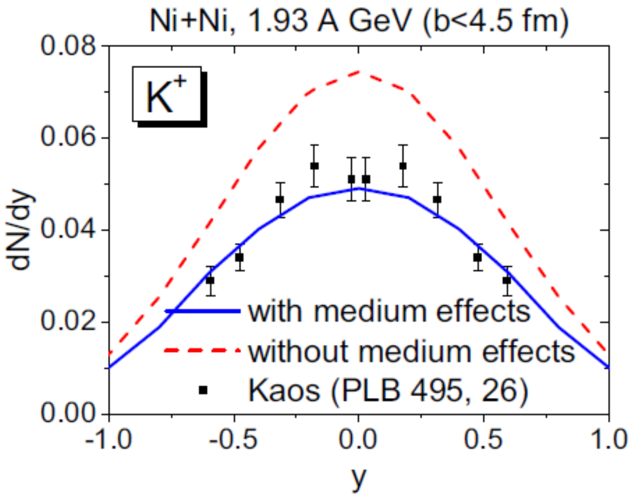
Measurements of hadrons and light nuclei allow to address reaction dynamics and medium properties:

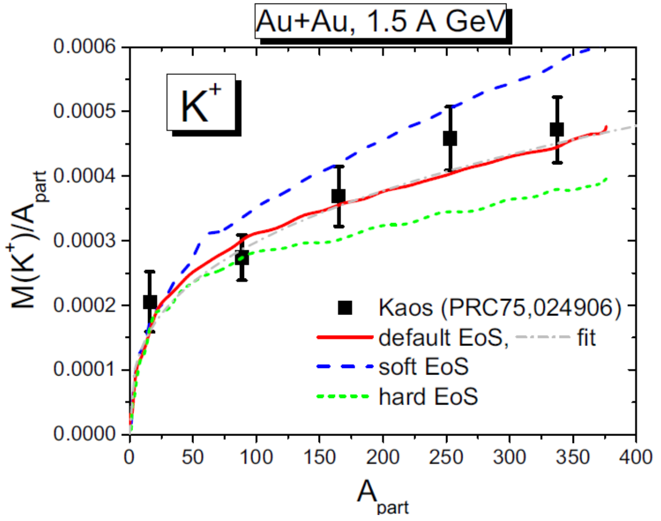
- Important geometrical quantities of the reaction
- Baryon number transfer, baryon and energy density in the reaction zone
- Phase transformations and CEP
- Chemical composition and thermalization
- Space-time extent and collective effects

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
- EOS, phase transformations and chemical equilibration can be probed

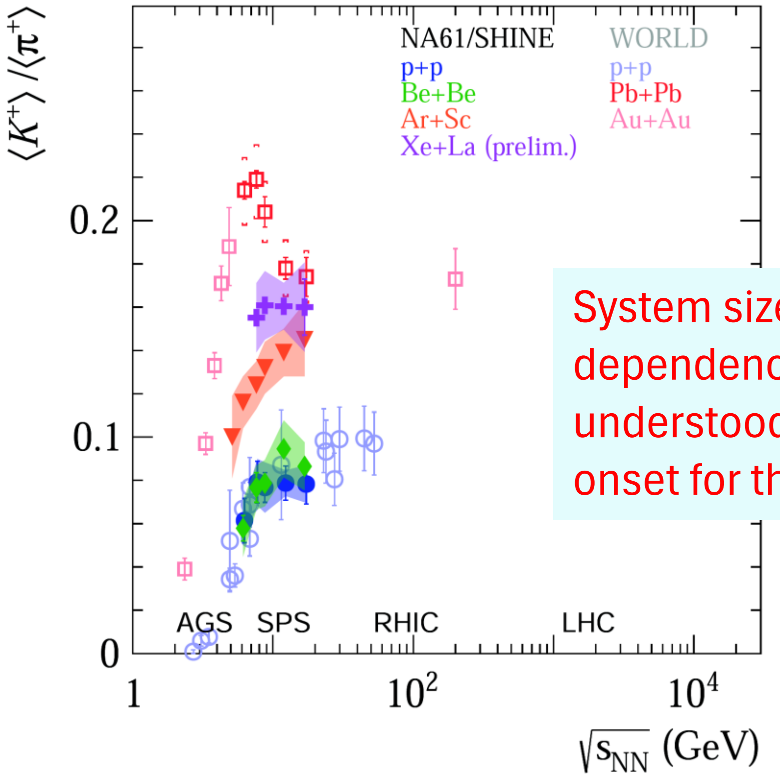
PRC 103, 044901 (2021))





- 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)
- Precise measurements of strangeness essential to confine models

- 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)*)



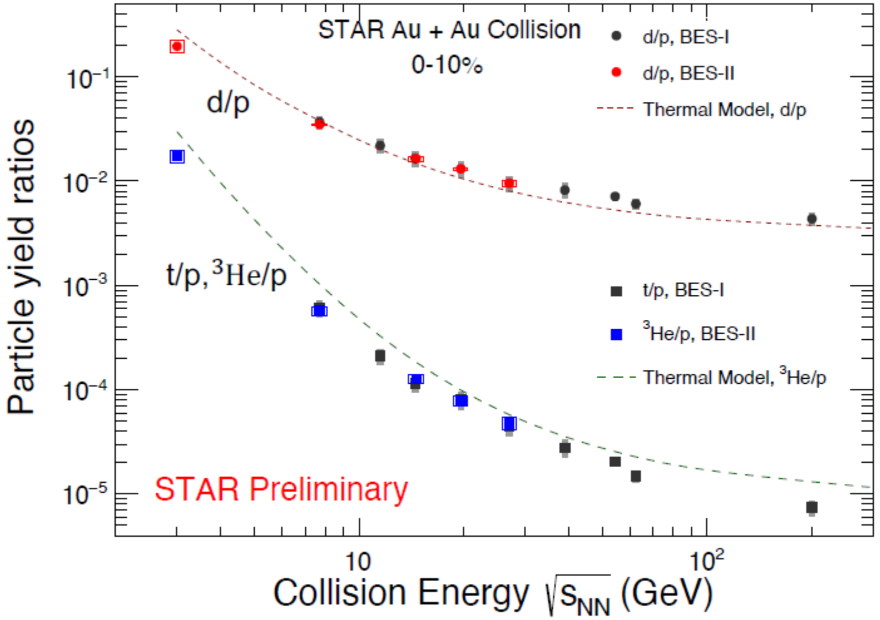
System size of the energy dependence is not fully understood : where is the onset for the Horn?

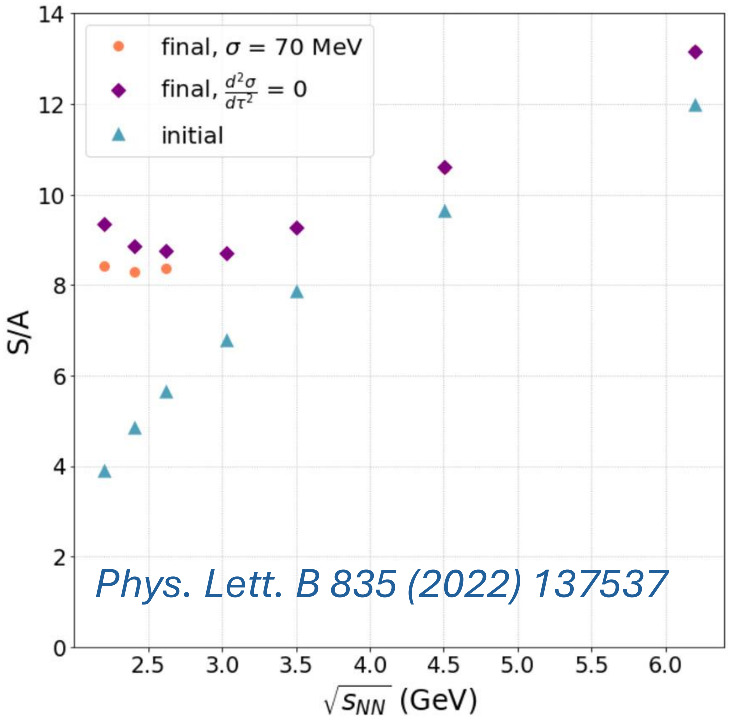
NICA physics cases: Light nuclei

- Light nuclei : weekly bound objects are copiously formed in hot and dense matter (up to 30% of N_{bar} at NICA)
- Production of nucleon clusters (p, d, t, 3He) allows addressing reaction dynamics, testing cluster formation mechanism, defining homogeneity volume size and momentum-space correlations, etc.
- Production rates and ratios can be sensitive to dynamical fluctuations due to PT or CEP

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

- A non-equilibrium phase transition indicates a gain in the final *S/A* due to the dynamical nature of phase transition and stochastic fluctuations during the fireball evolution
- Relative neutron density fluctuation is related to spinodal instability (1st PT) or CEP

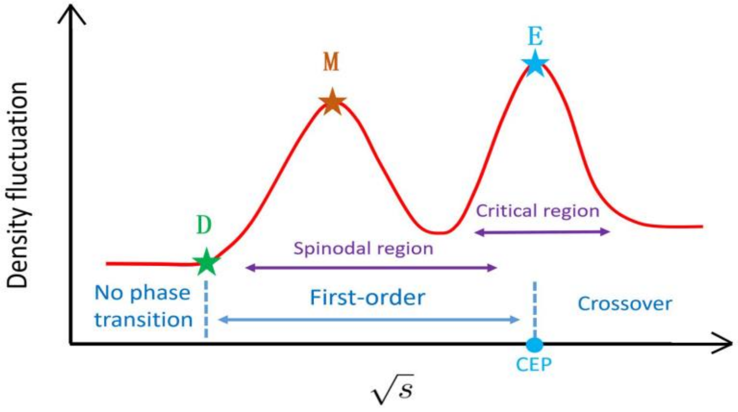




Phys. Lett. B 835 (2022) 137537

Phys. Lett.B 781 (2018) 499–504

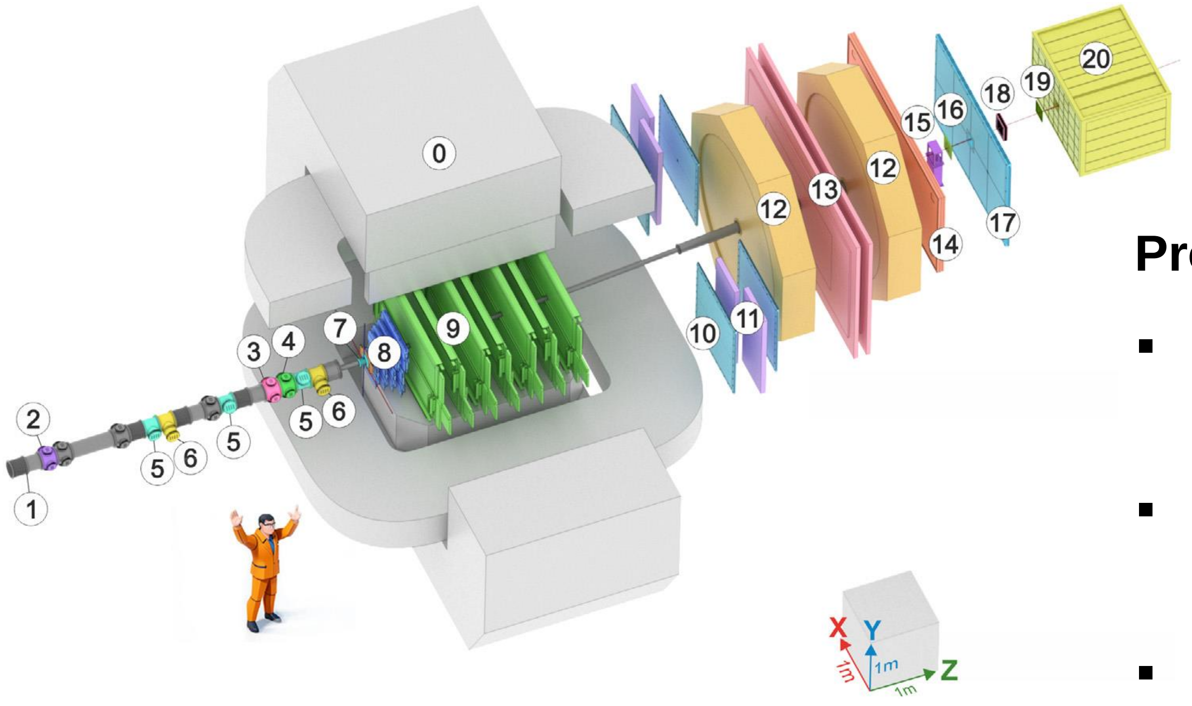
$O_{pdt}=(N_pN_t)/(N_d^2)$



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 ($\sigma_{TOF} \sim 85 / 115$ ps)
- Trigger and centrality: multiplicity detectors BD+SiMD

NIM A 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):

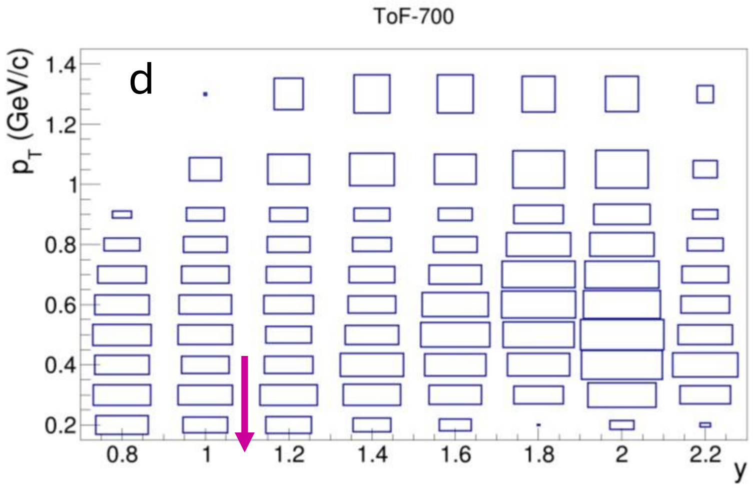
- Baryon rapidity distributions and pT-spectra – reaction dynamics, momentum loss, fireball parameters, etc.

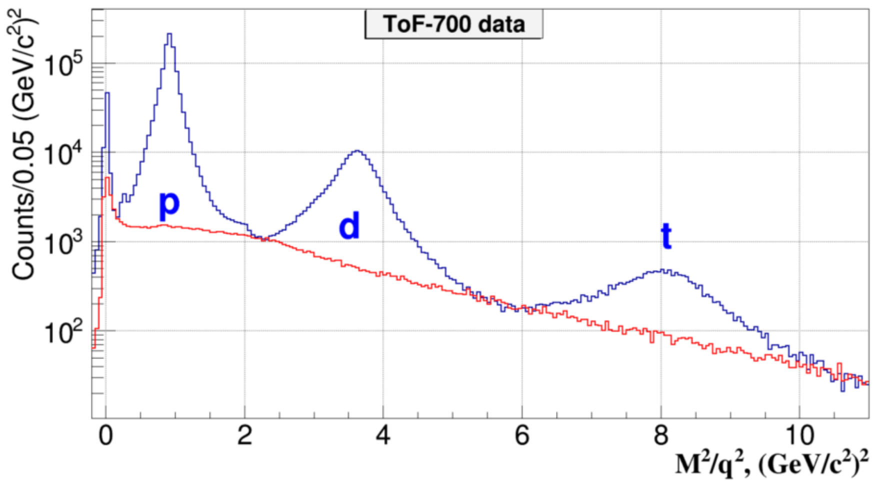
- Particle ratios – nucleon phase-space density, CEP, entropy-per-baryon S/A, source size, etc.

- Rapidity loss – baryon density in the reaction zone, baryon number transfer mechanism

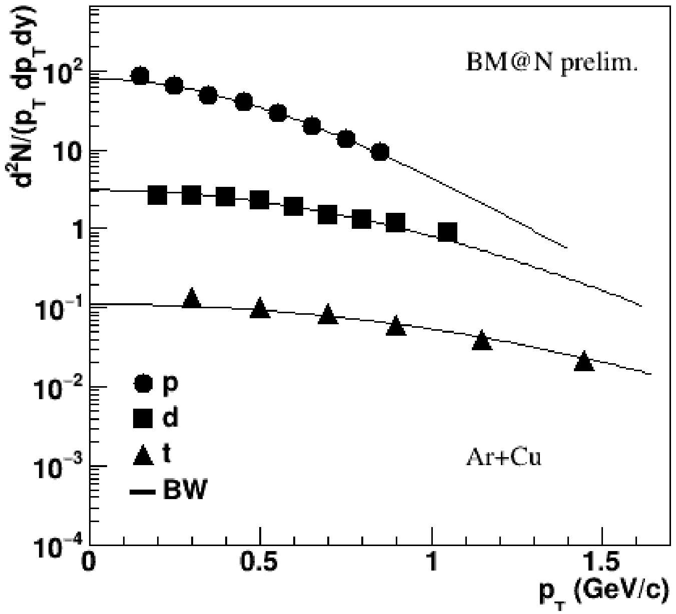
BM@N : Rapidity and pT-spectra in Ar+A at 3.2A GeV

Data sets: ~16·10^6 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; corrections from MC; analysis details in *JHEP 07 (2023) 174*





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



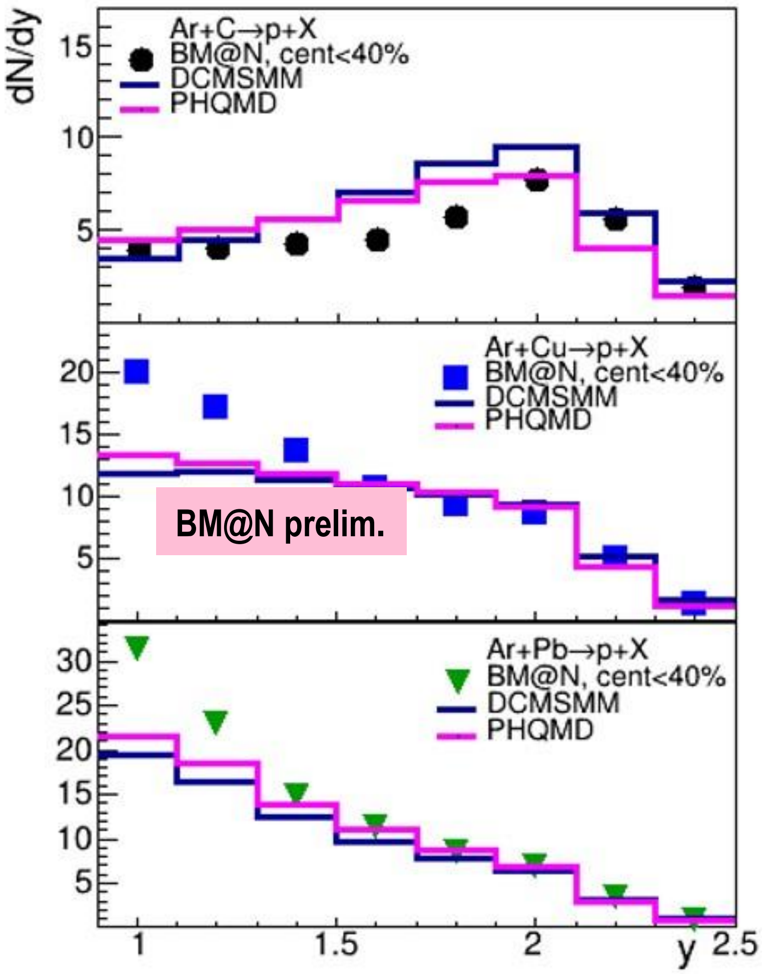
pT-spectra of p,d,t in 0-40% Ar+A:

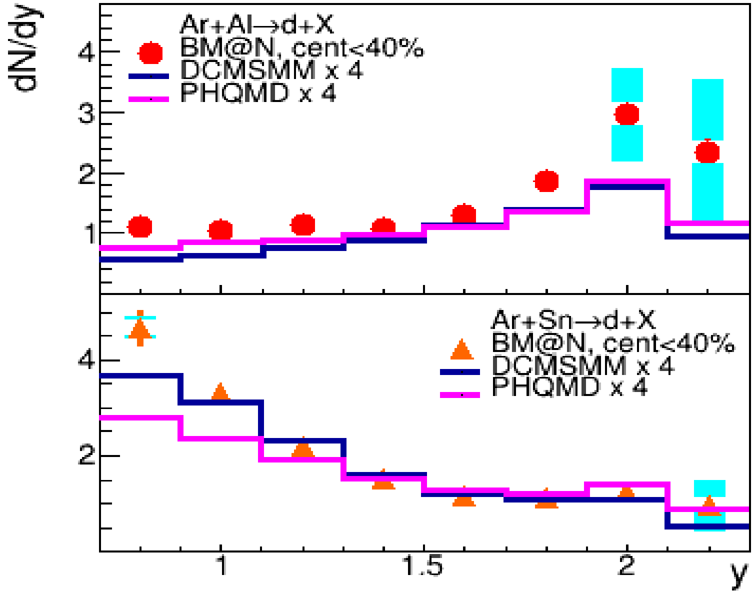
- BW fits: T~105-110 MeV <β>~0.3

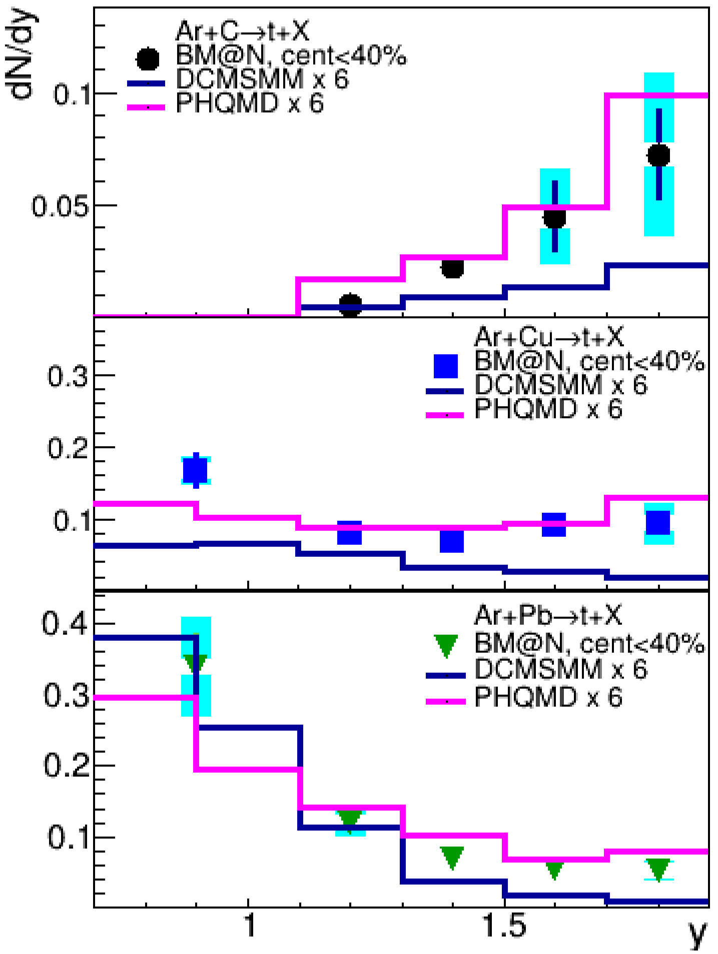
BM@N : Rapidity spectra of *p,d,t* in Ar+A at 3.2A GeV

<u>Spectra of *p,d,t* in 0-40% Ar+A:</u>

- Rapidity spectra of protons in data indicate more stopping than in models
- Models underestimate the yields of light nuclei. Discrepancy could be due to feed-down from excited nuclear states (*Phys. Lett. B 809 (2020) 135746)*



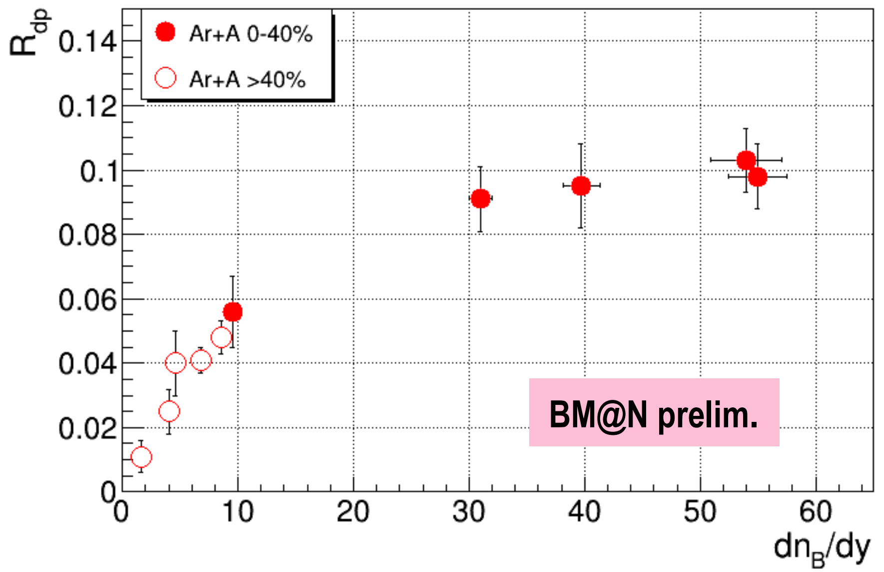


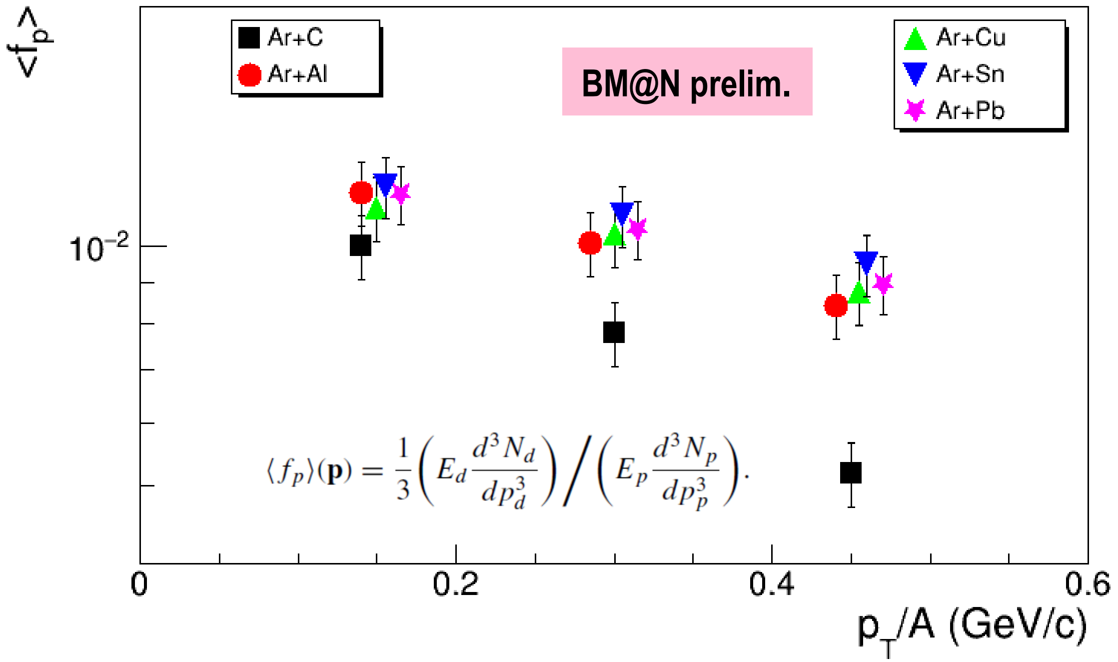


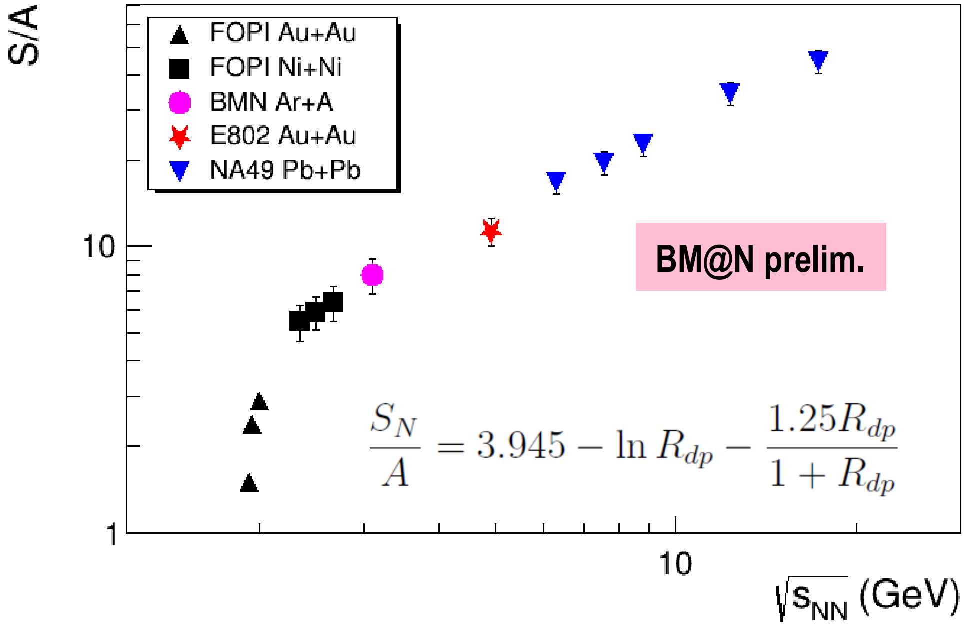
BM@N : R_{dp} in Ar+A - system size dependence and related observables

- R_{dp} is related to nucleon phase-space density and entropy-per-baryon in the source

- The midrapidity R_{dp} rises in small systems and saturates in central Ar+A
- <f> decreases exponentially with pT 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 ~ 8.0*** in 0-40% Ar+A follows the general trend in the excitation function



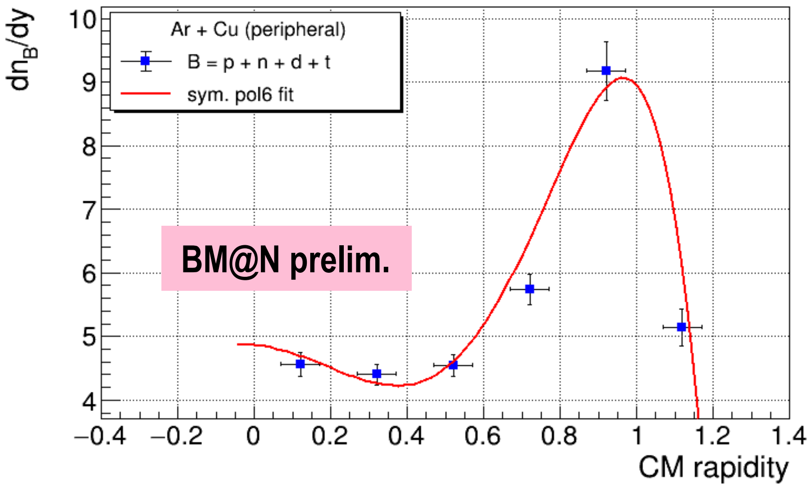


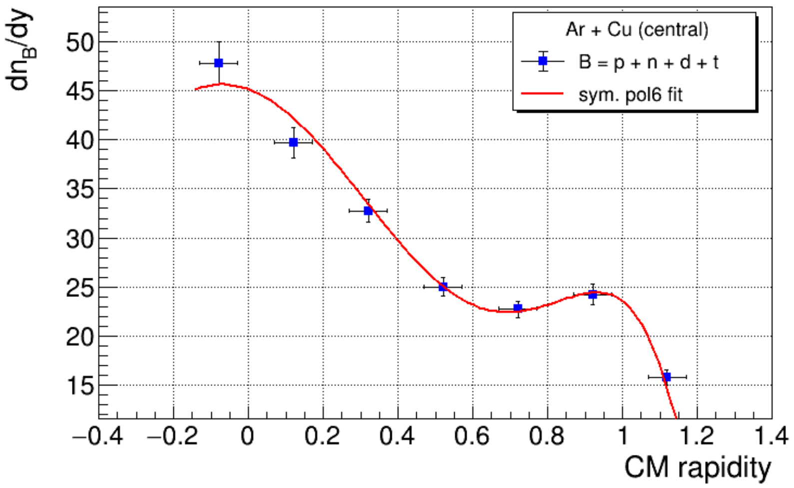


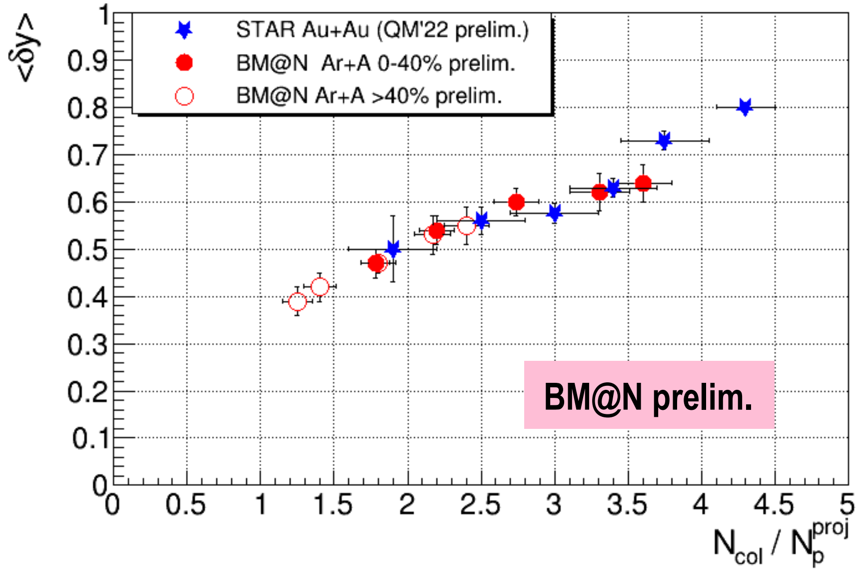
BM@N: Rapidity loss in Ar+A at 3.2A GeV

- 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

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

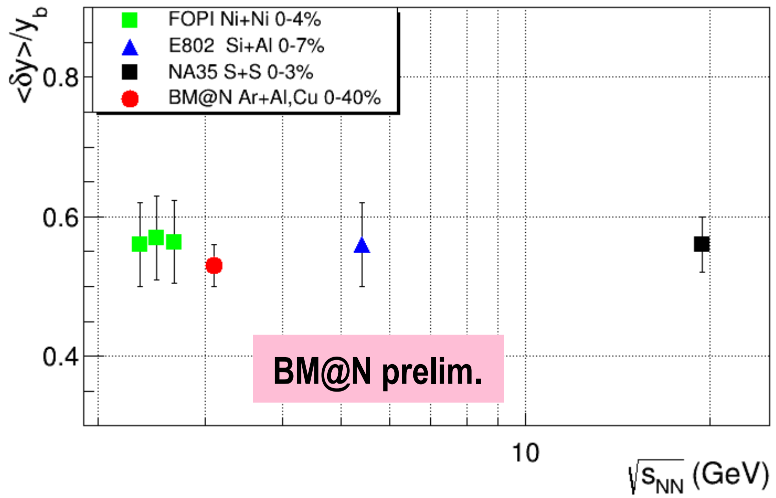






- Rapidity loss (nuclear opacity) increases with the size of the reaction zone. Ar+A (BM@N) and Au+Au (STAR, QM'22) agree on a proper scale

- <δy> scales with the beam rapidity in medium-size A+A over a broad energy range.

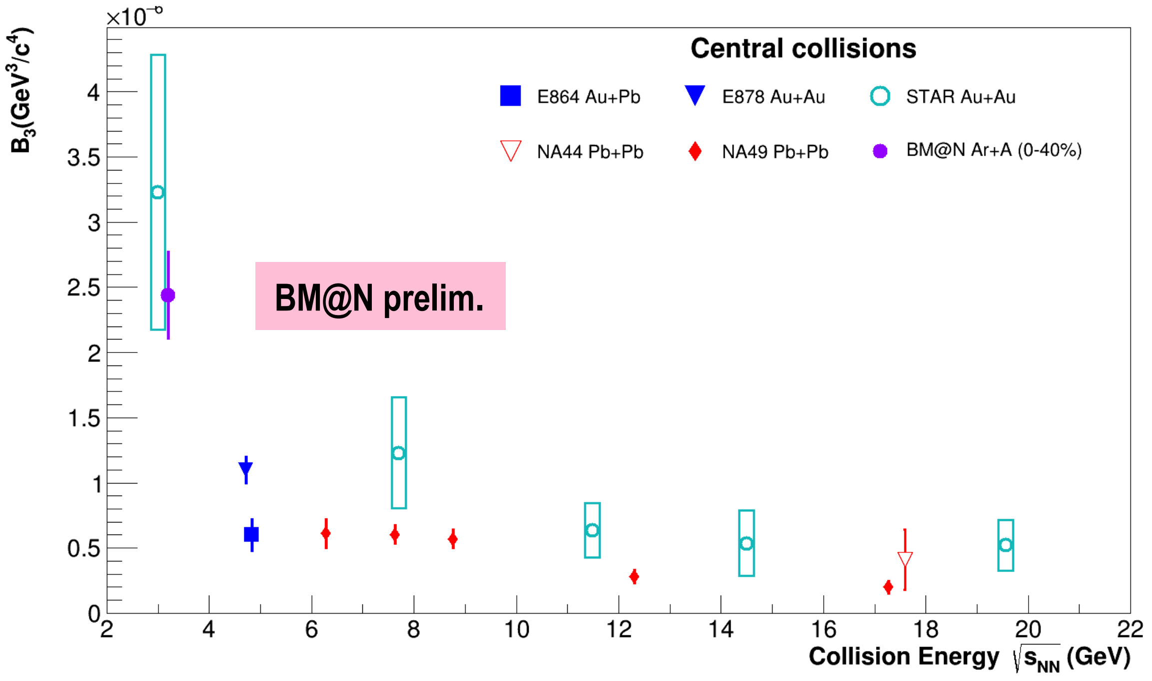


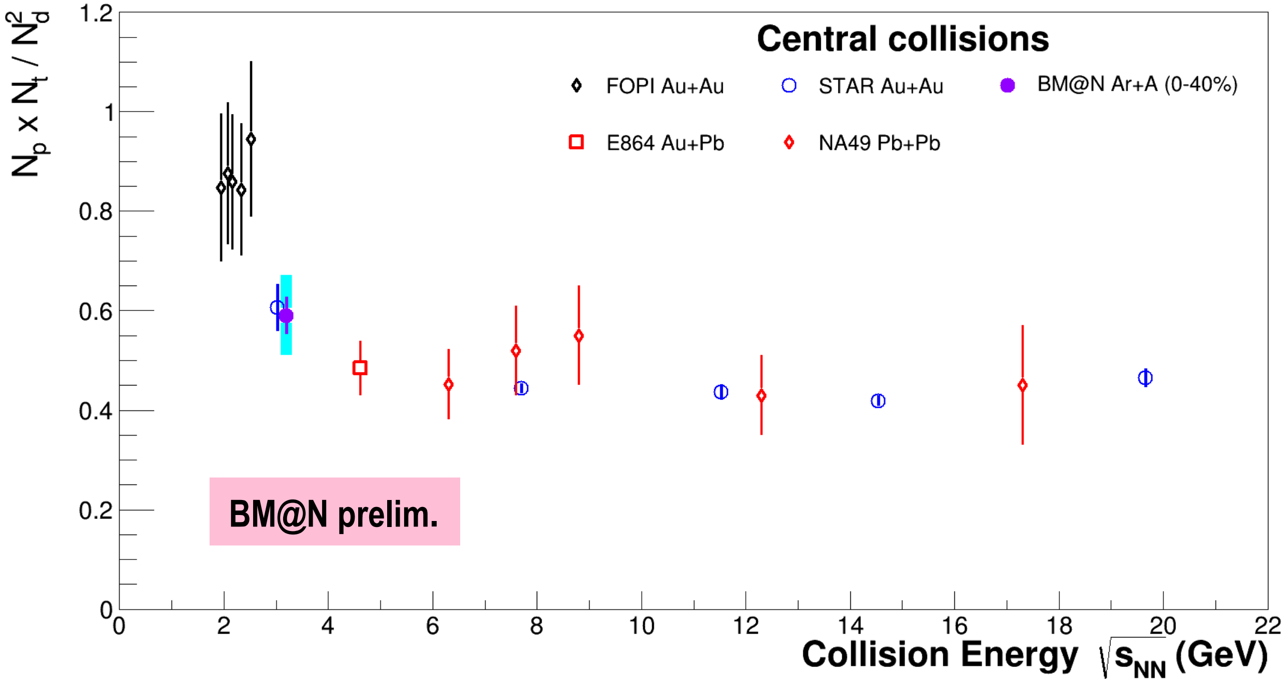
BM@N: coalescence parameter B_A and O_{pdt}

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

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

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

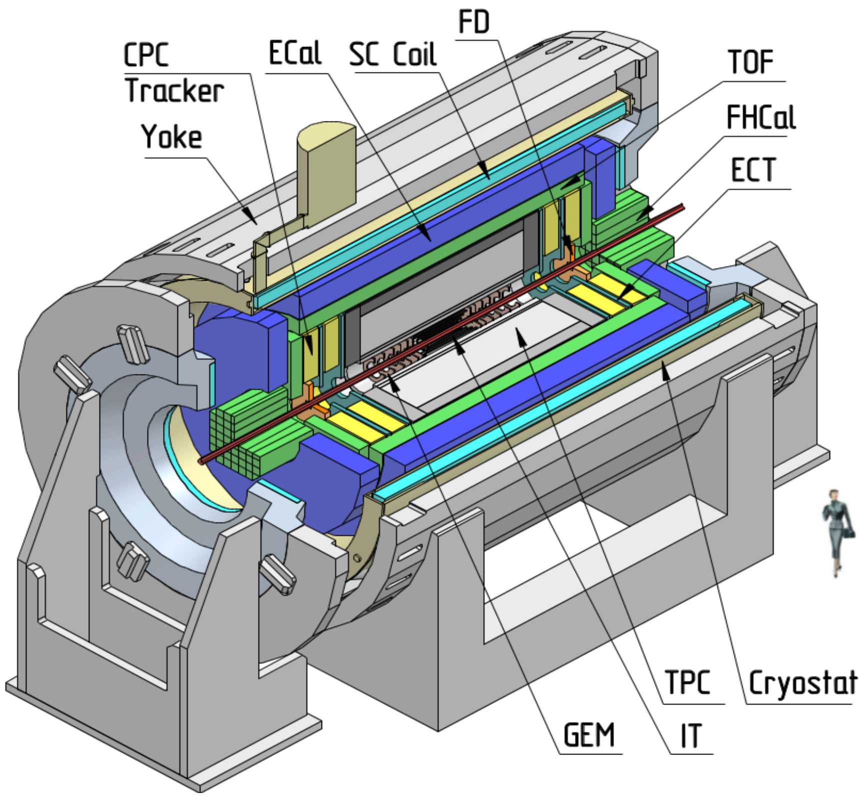




BM@N results from 0-40% central Ar+A follow the general trend of the excitation function for B_A and O_{dpt}

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**

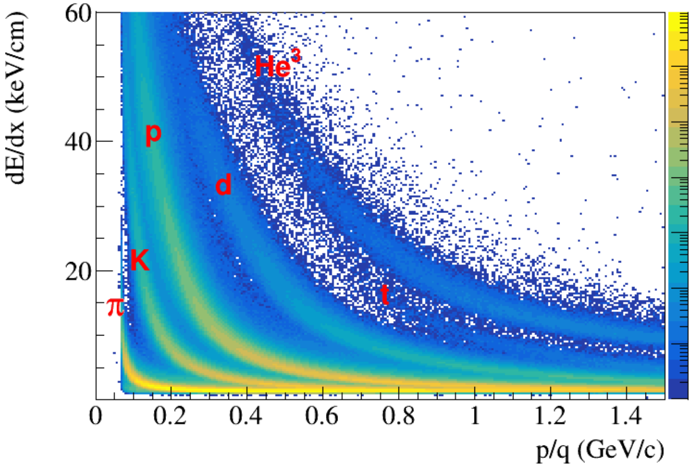
Bi+Bi at 9 GeV (collider mode) or

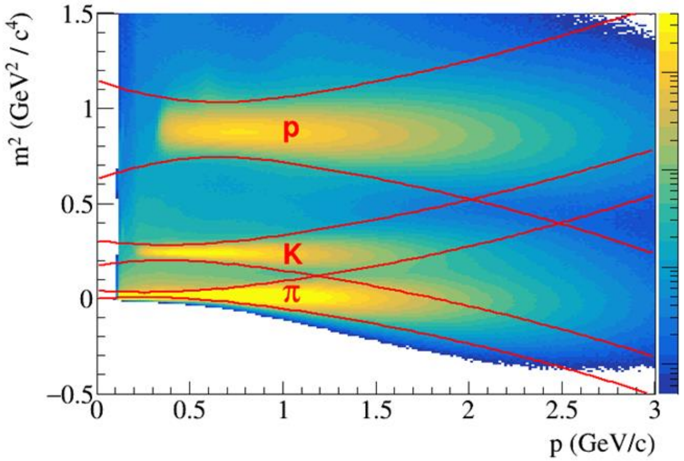
Xe+W at E/A=2.5 GeV (FXT fixed target)

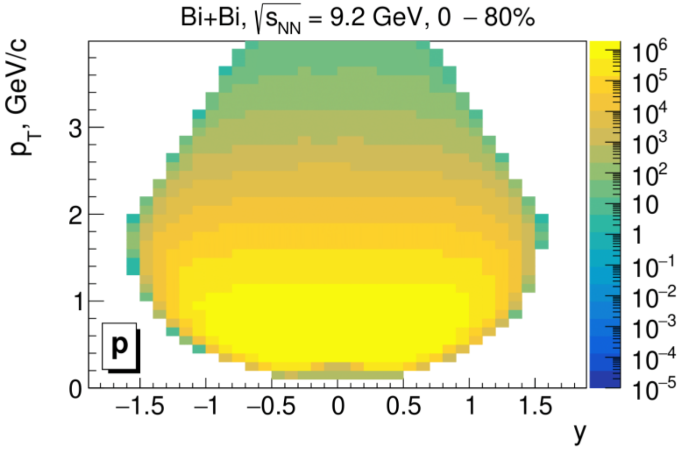
MPD-FXT and BM@N at NICA are complementary for STAR-FXT at RHIC.
New data on small- or medium-size A+A collisions.

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

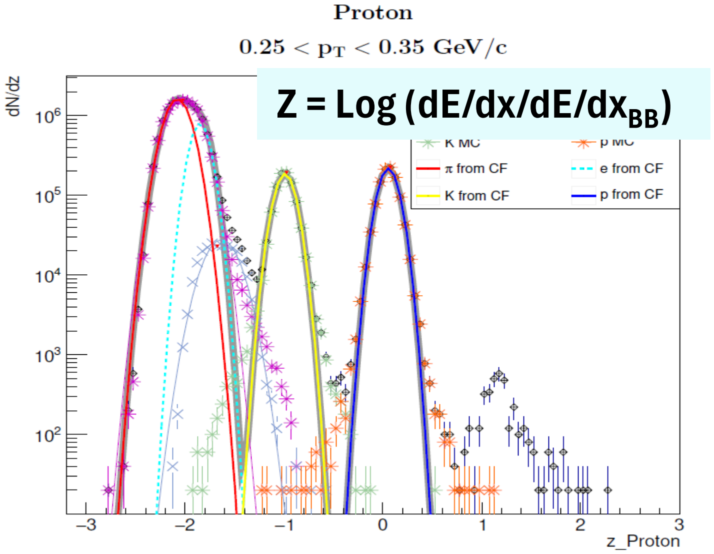
- PHQMD model as an input, full simulation and reconstruction chains (MpdROOT)
- dE/dx+TOF – large phase-space coverage but low pT-cutoff at forward rapidity

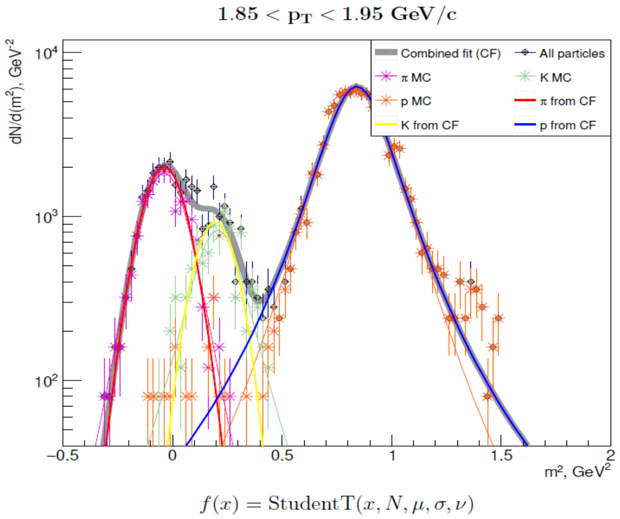


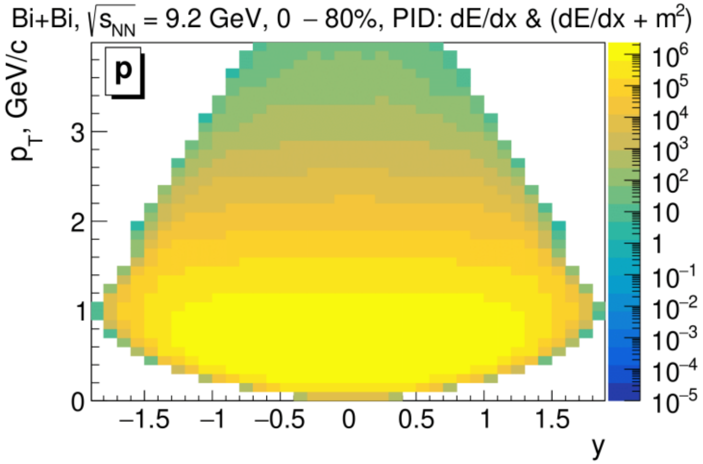




- dE/dx ($p < p_{low}$) and TOF ($p > p_{low}$) provides an extra acceptance at low-pT (a gain in y-coverage ~ 0.2)



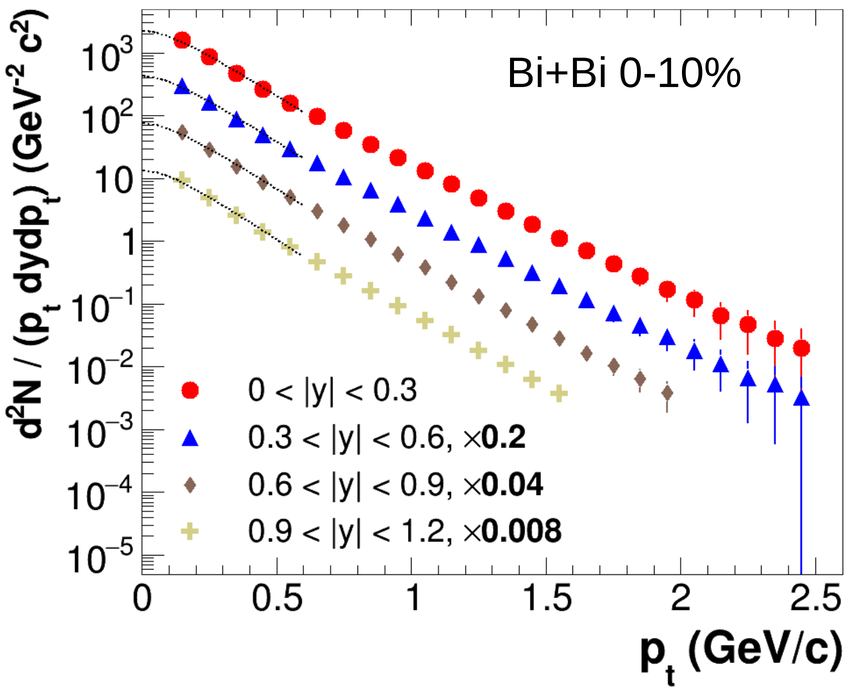


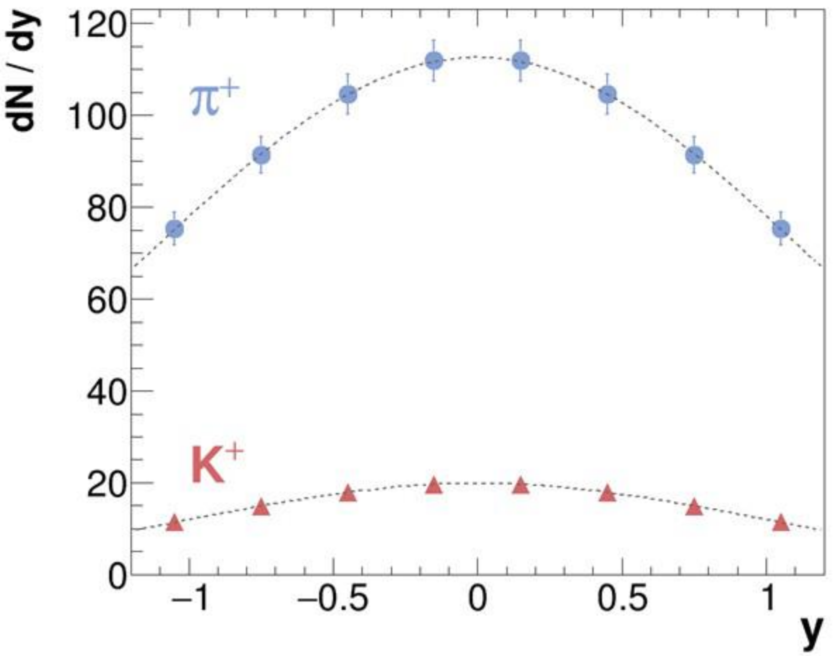


MPD: Hadron spectra and yields from central A+A collisions (pions)

- *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 pT=0.2 to 2.5 GeV/c
- Extrapolation to full pT-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*

- MPD has large phase-space coverage for identified pions and kaons (> 60% of the full phase-space for K at 9 GeV in central collisions)
- Hadron spectra can be measured from pT=0.2 to 2.5 GeV/c
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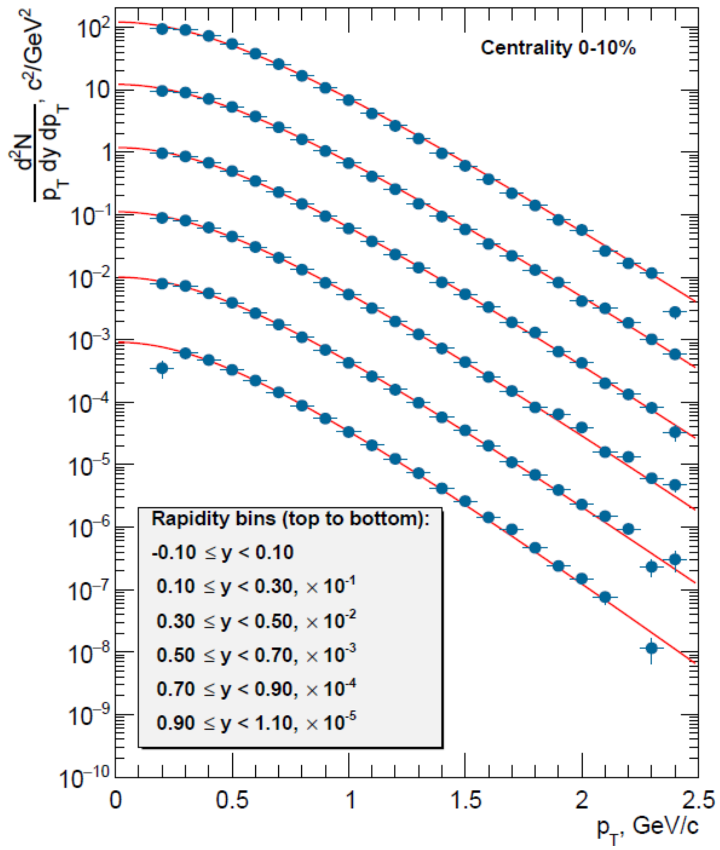
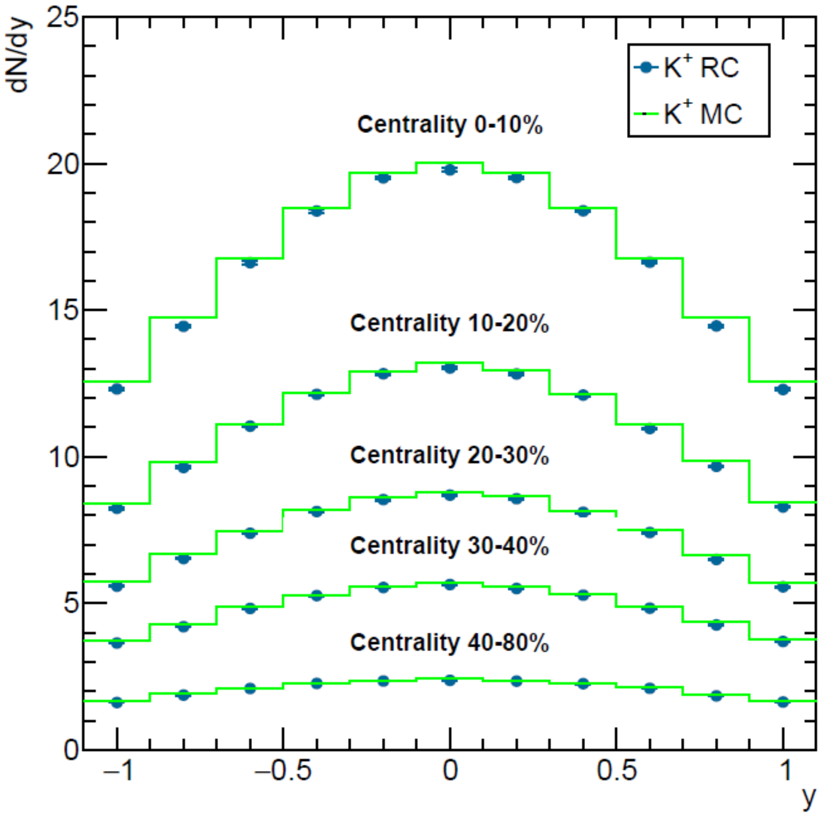
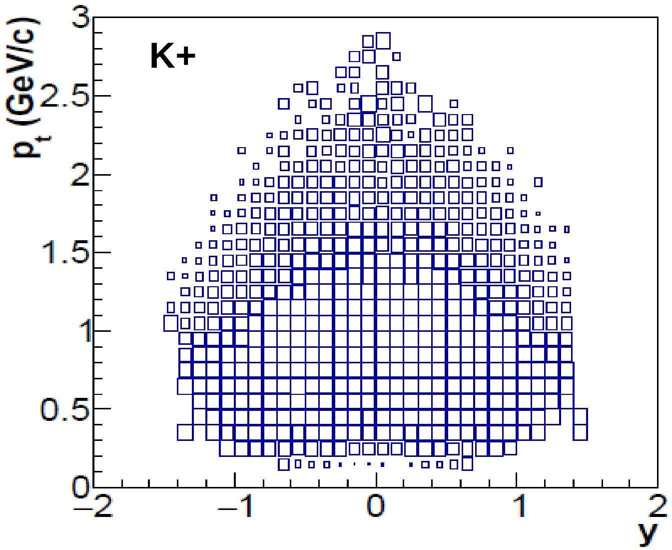


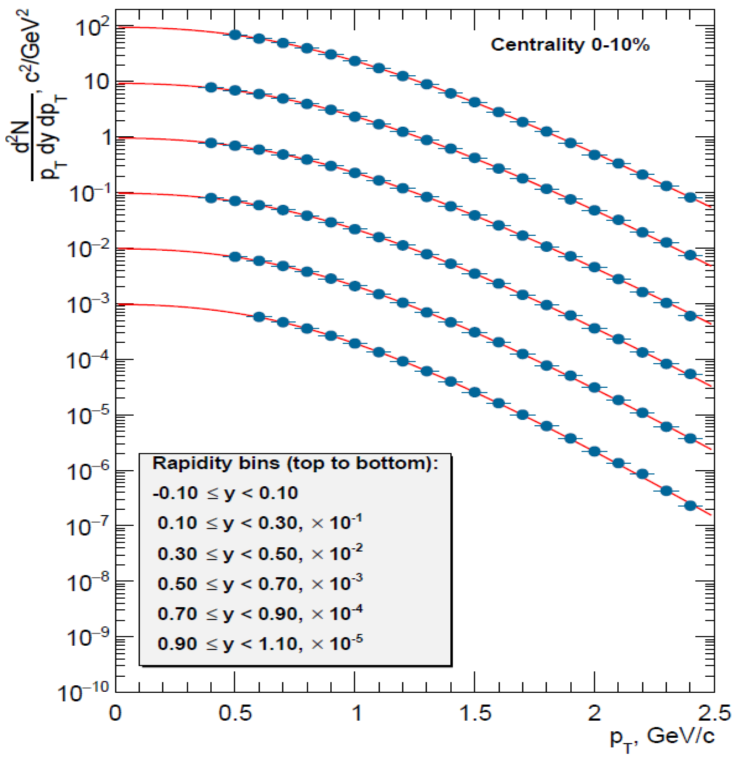


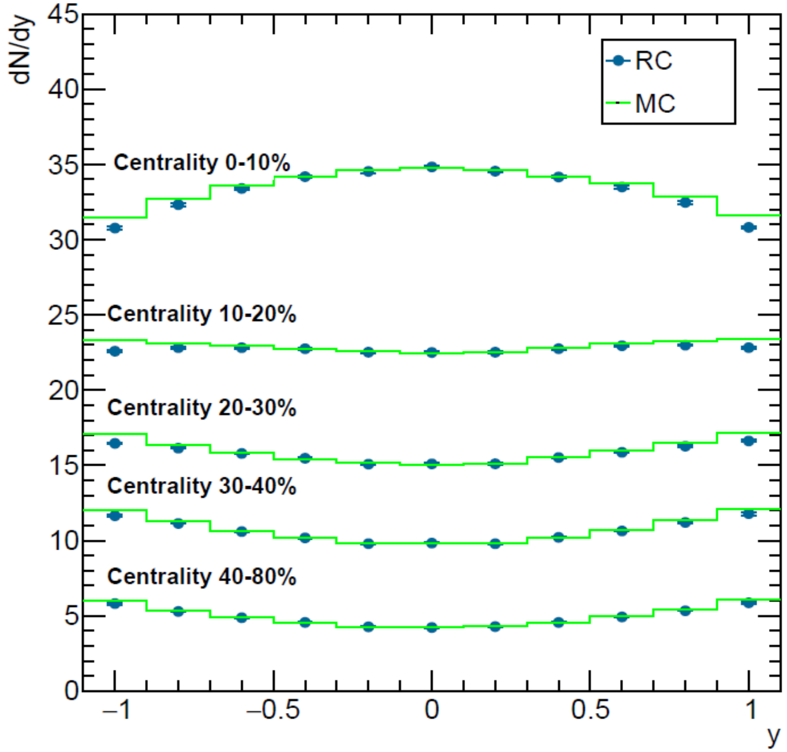


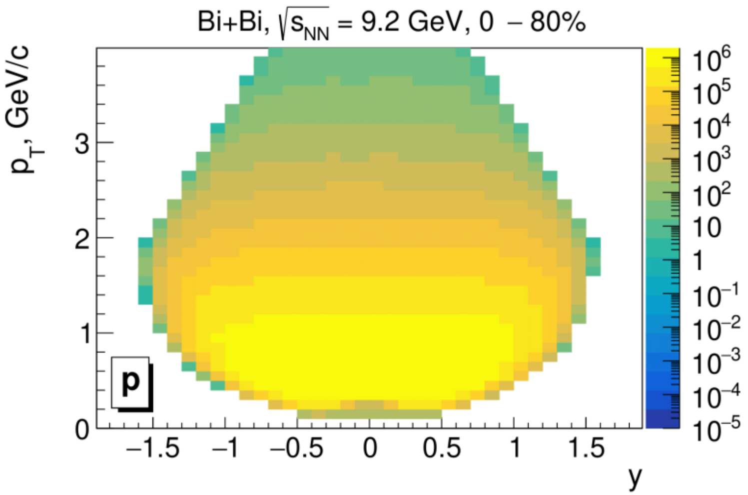
NICA/MPD advantages for hadron measurements – a large phase-space coverage and homogeneous acceptance

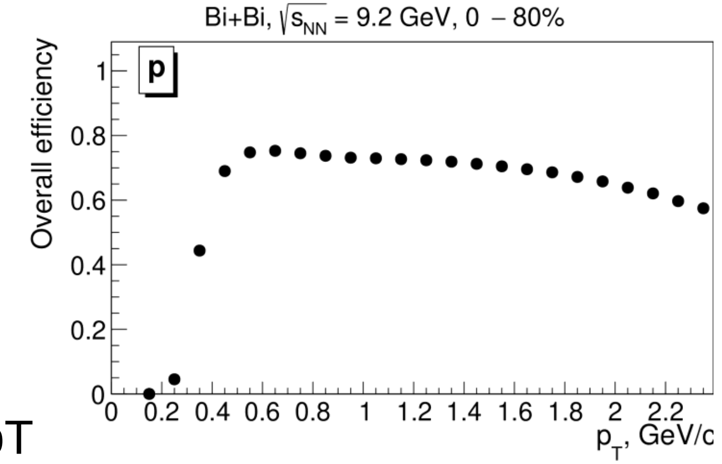
MPD: hadron spectra and yields from central A+A collisions (protons)

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





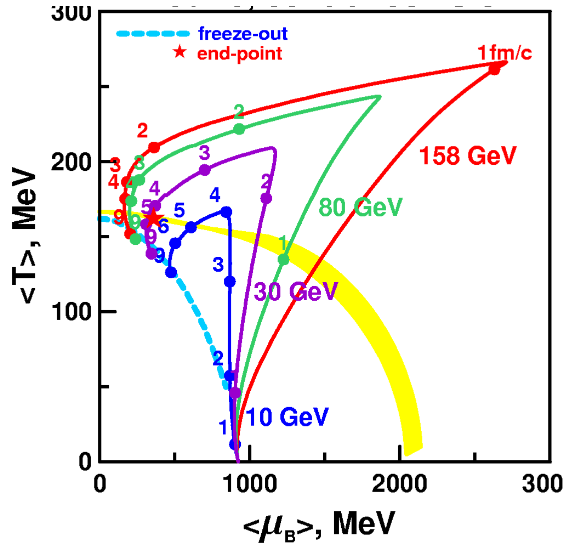


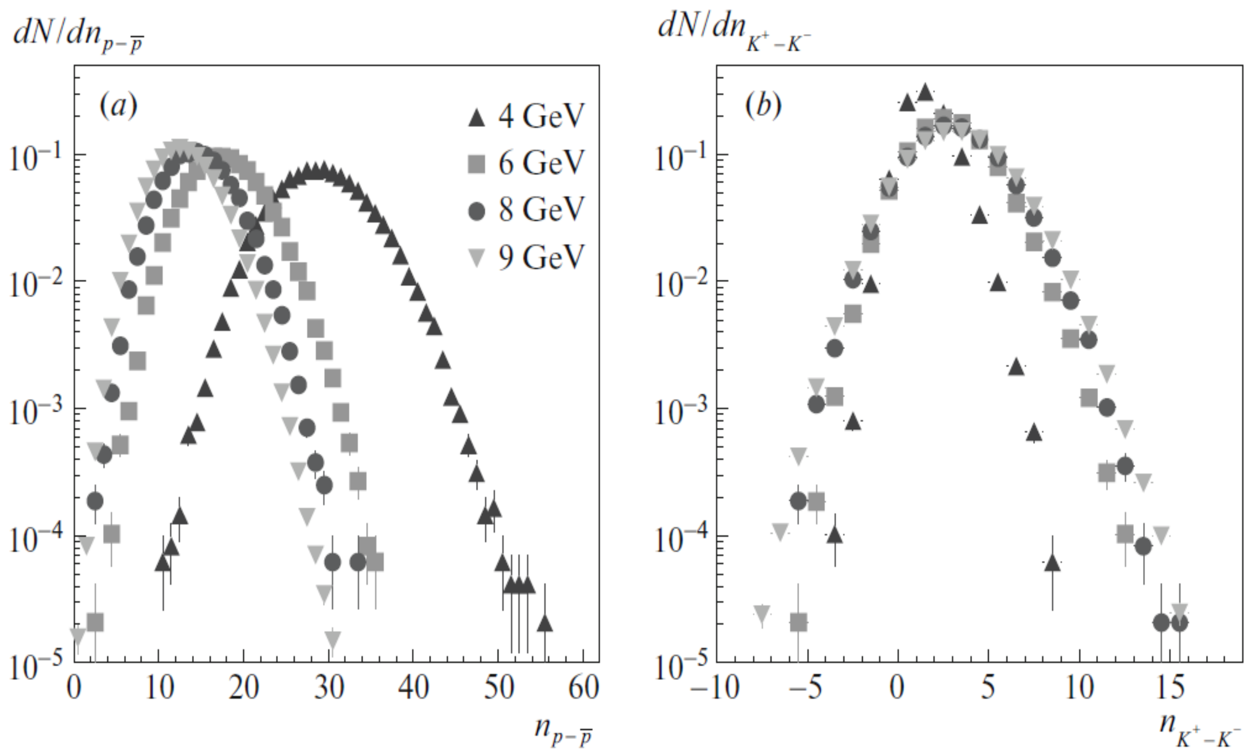


- Midrapidity |y|<1 coverage for protons
- Uncertainty in dn/dy at forward rapidities (~ 5%) due to lack of points at low pT
- Limiting capability in determination of the variation of the shapes (stopping and 4π yields)
- A forward tracker with PID capability may provide a substantial increase of MPD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

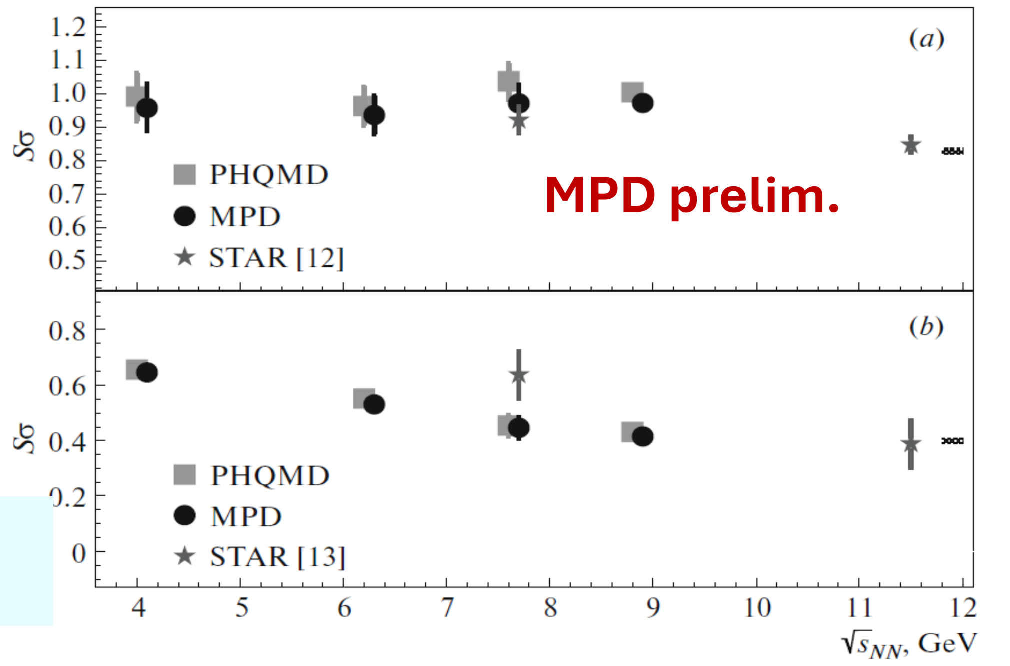
MPD: prospects for CEP search in net-proton and net-strangeness fluctuations

- 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





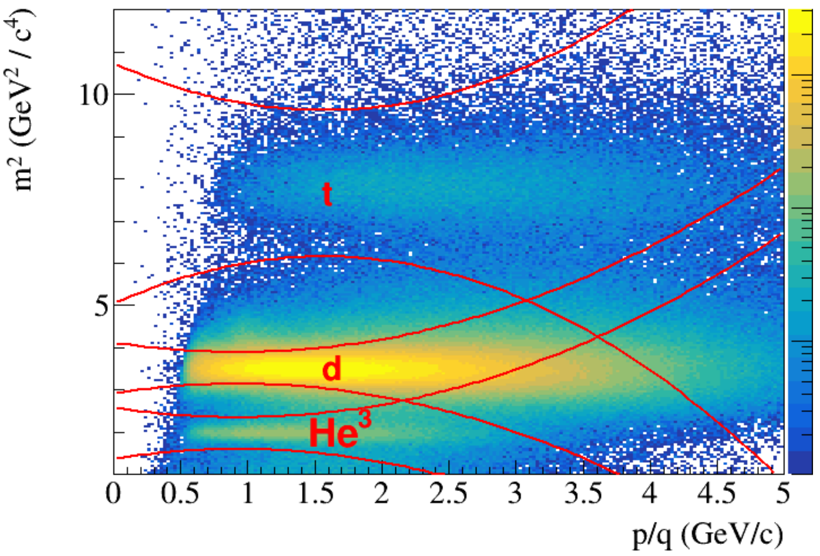
effective skewness Sσ for net-protons (a) and net-kaons (б)

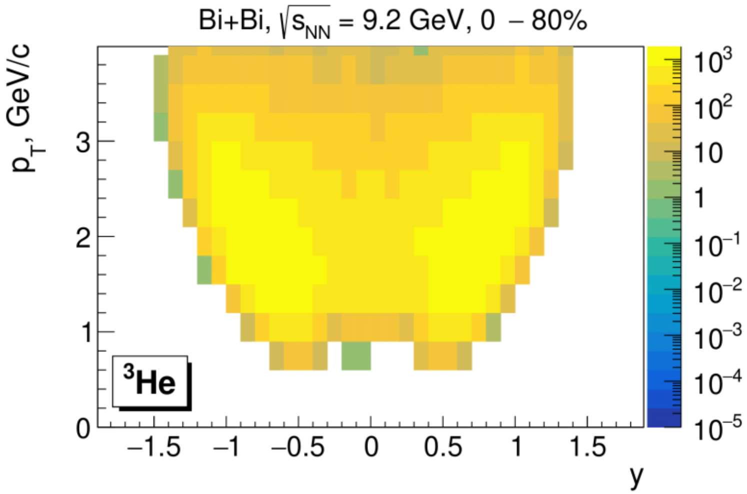


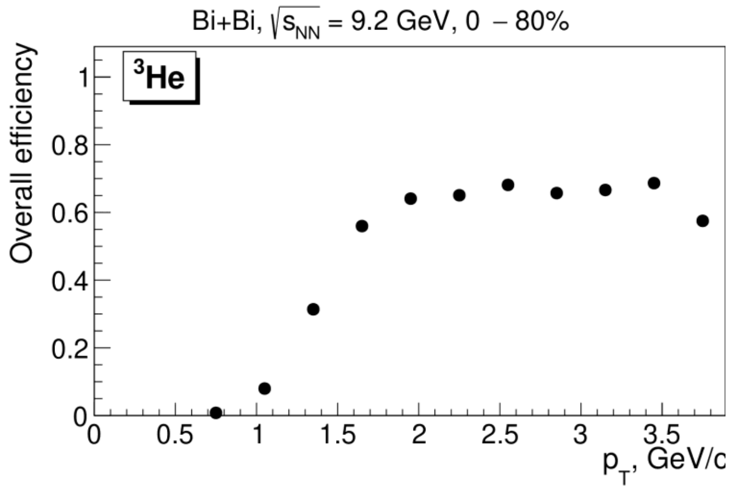
Limiting progress yet in feasibility studies due to lack of experts in the field. We are looking for cooperation with Chinese colleagues

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

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

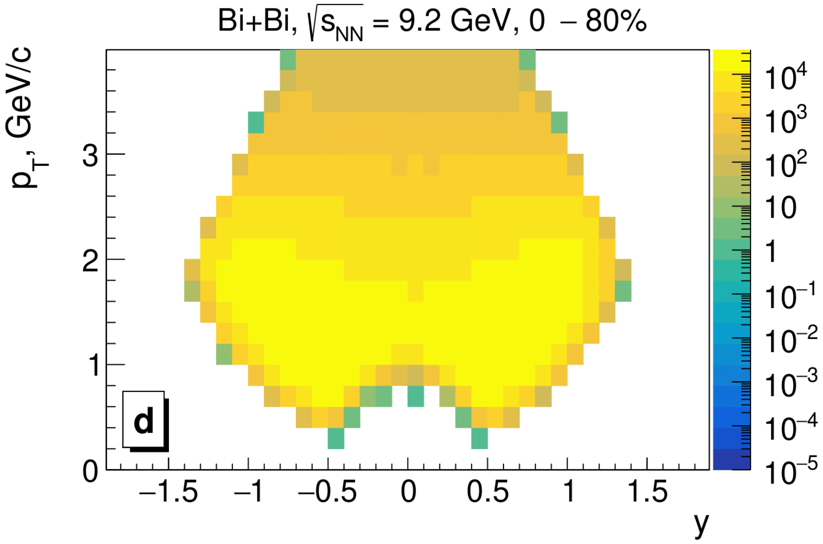


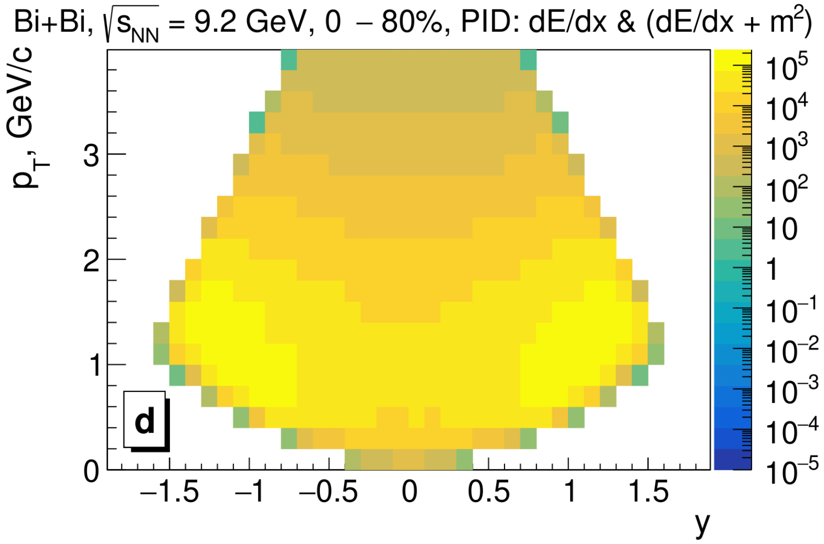




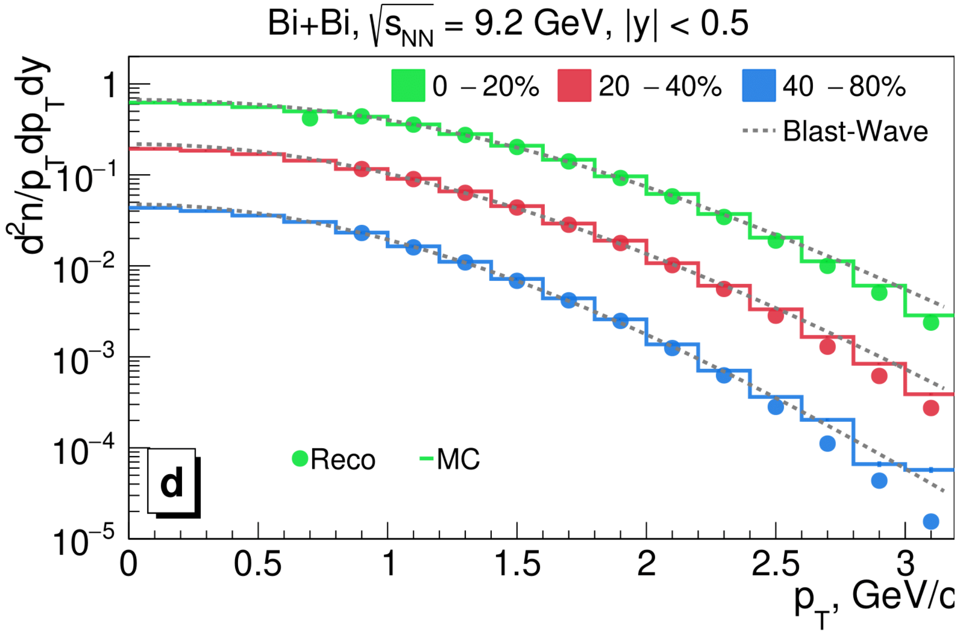
- dE/dx-only PID provides an extra acceptance at low-pT

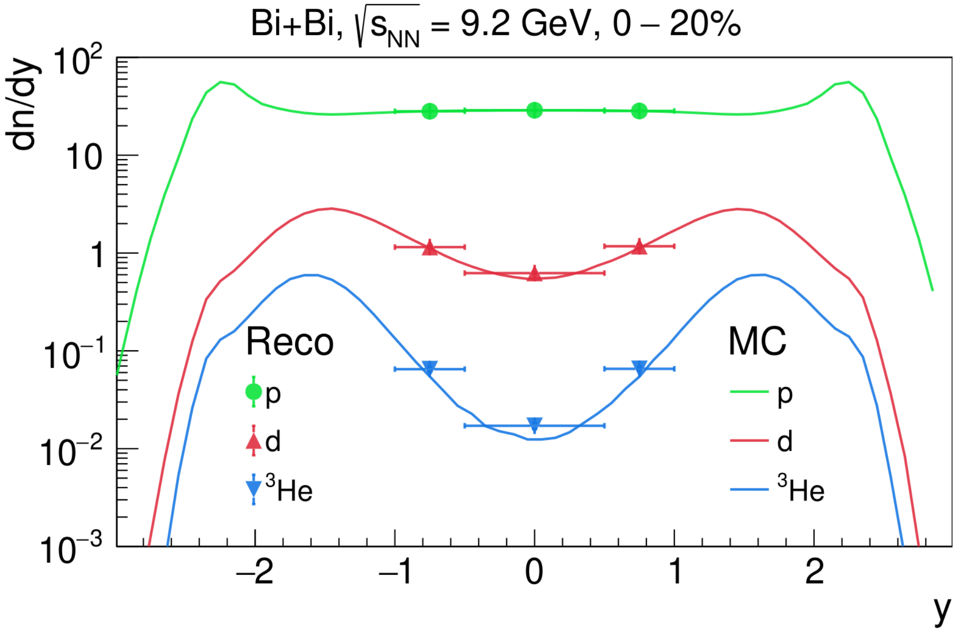
- A gain in y-coverage ~ 0.2

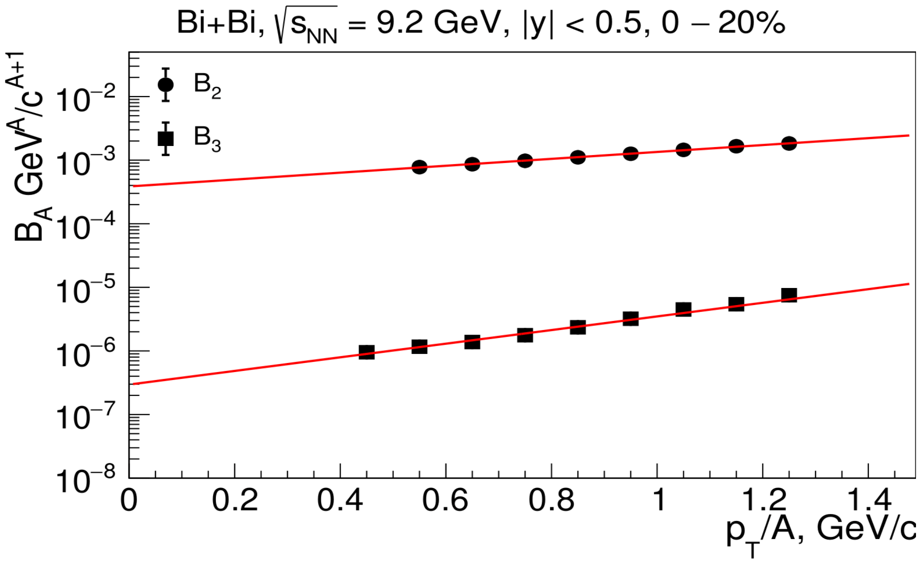




MPD: light nuclei spectra in Bi+Bi





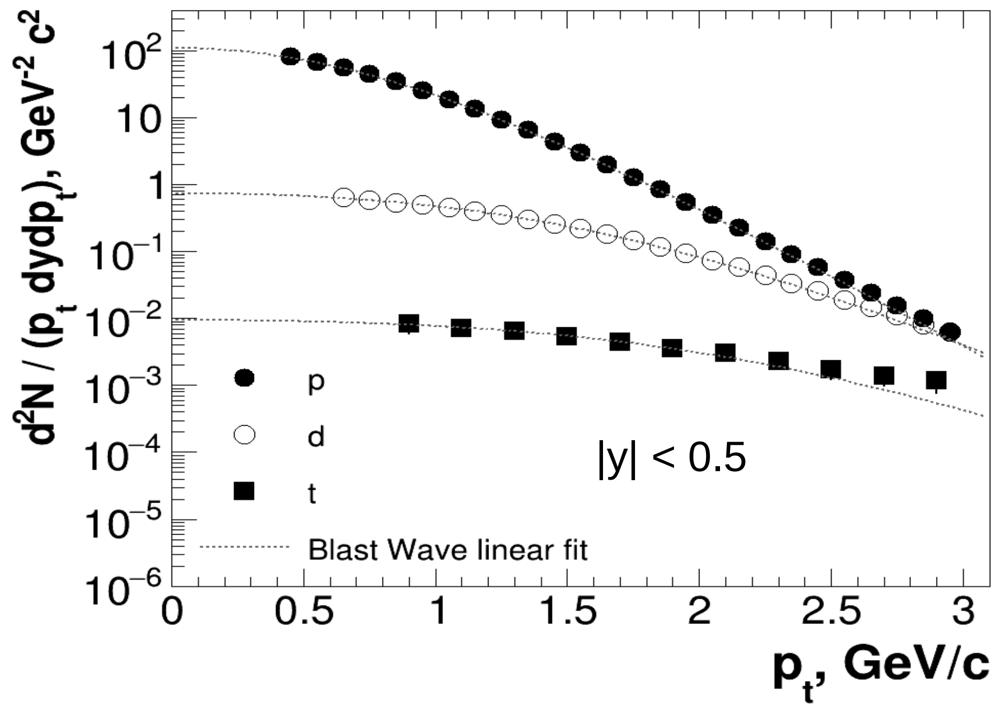


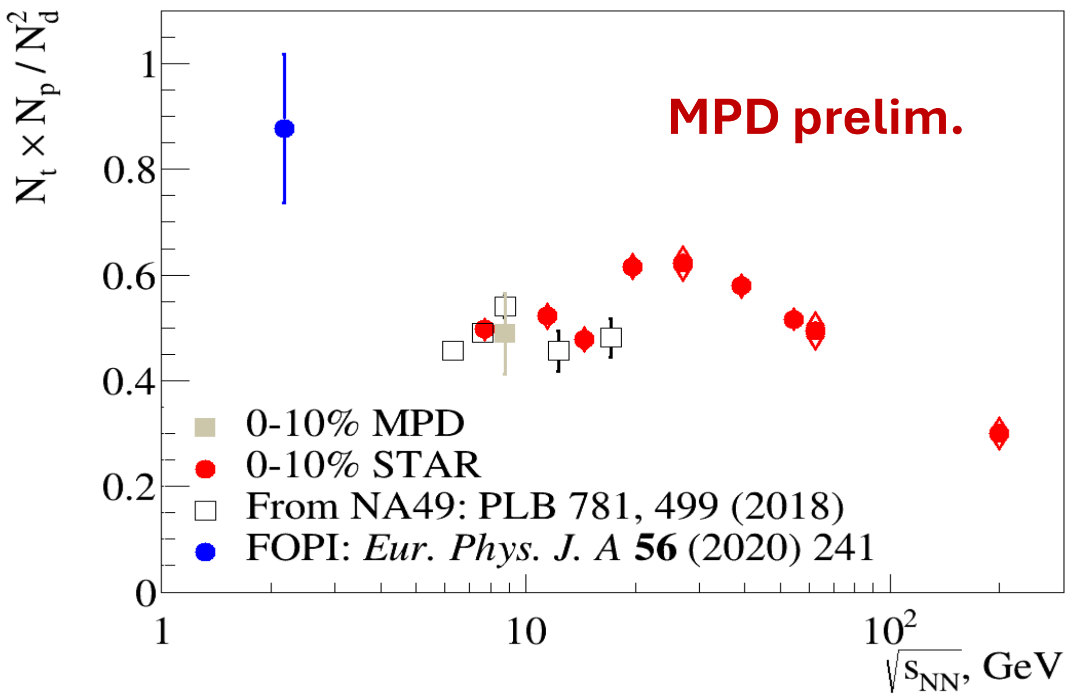
- Proton and light nuclei spectra within |y|<1 for dE/dx+TOF particle ID
- Midrapidity yields, spectra, ratios
- Limiting capability for reconstruction of the full rapidity distributions → **forward tracker + PID?**

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)*

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

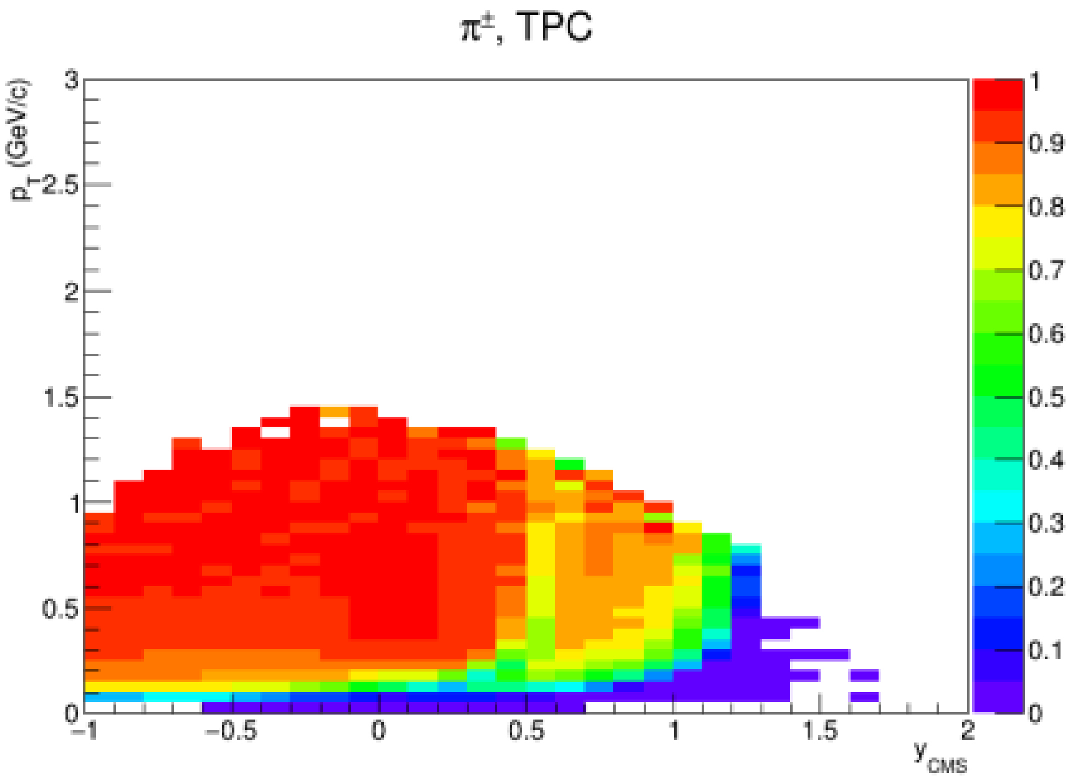


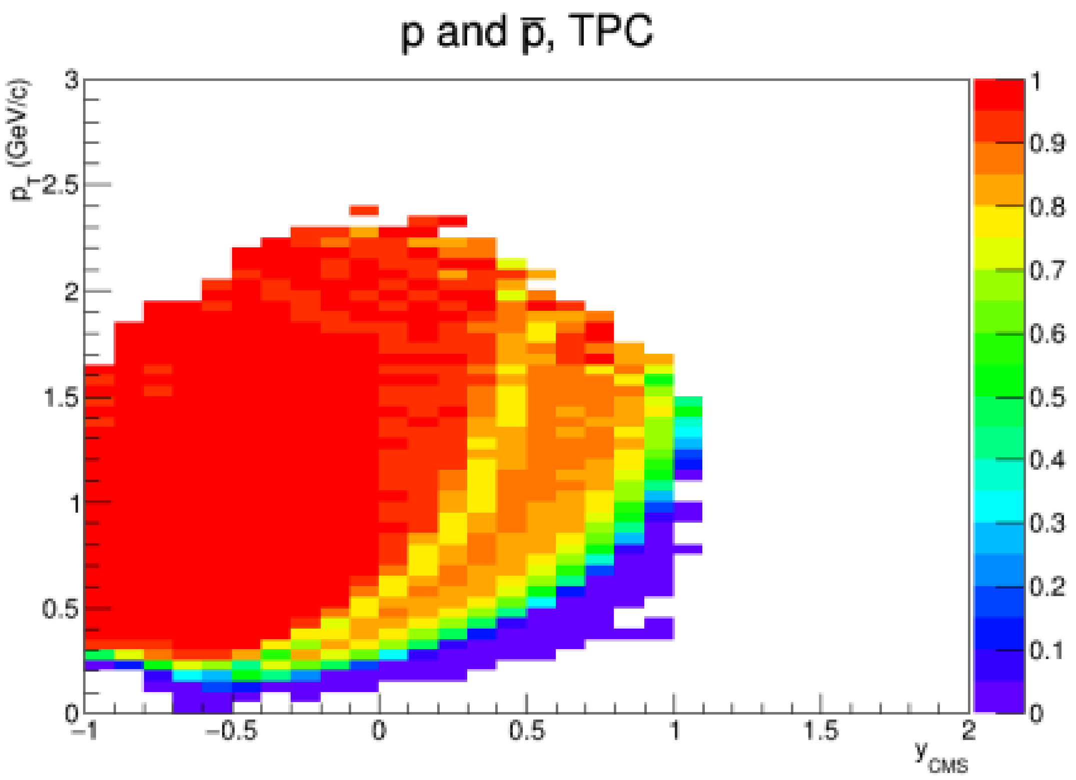


Limiting progress yet in feasibility studies due to lack of experts in the field.
We are looking for cooperation with colleagues in China

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

- Xe+W at Ekin = 2.5A GeV (y_{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 collisions at E/A 3.2 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 the analysis of data at NICA**

Thank you for your attention!

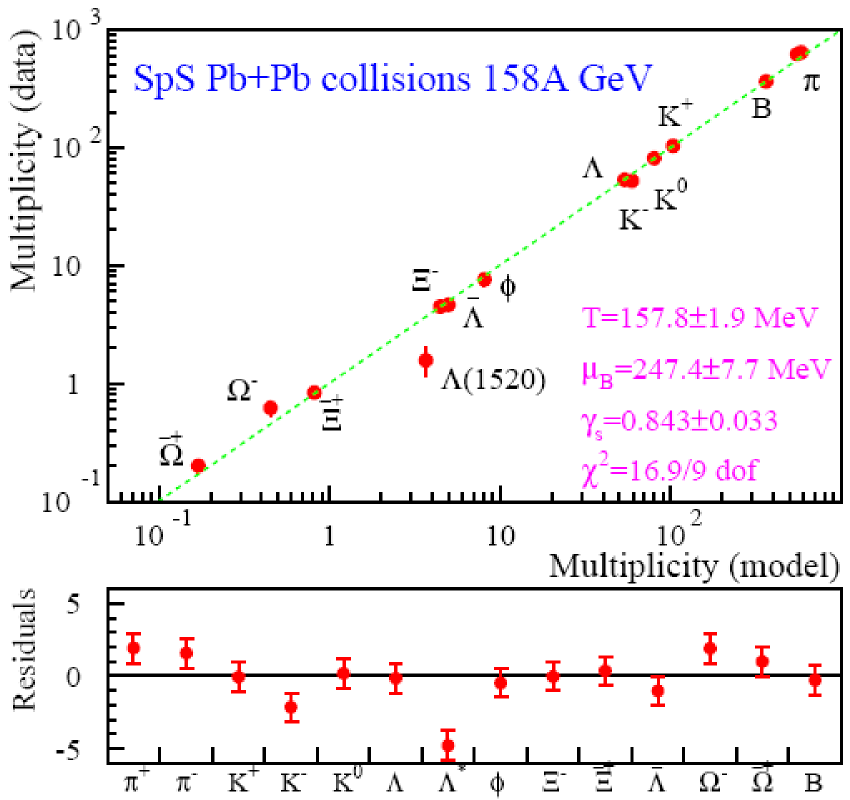
Many thanks to the organizers of this special meeting!

Extra slides

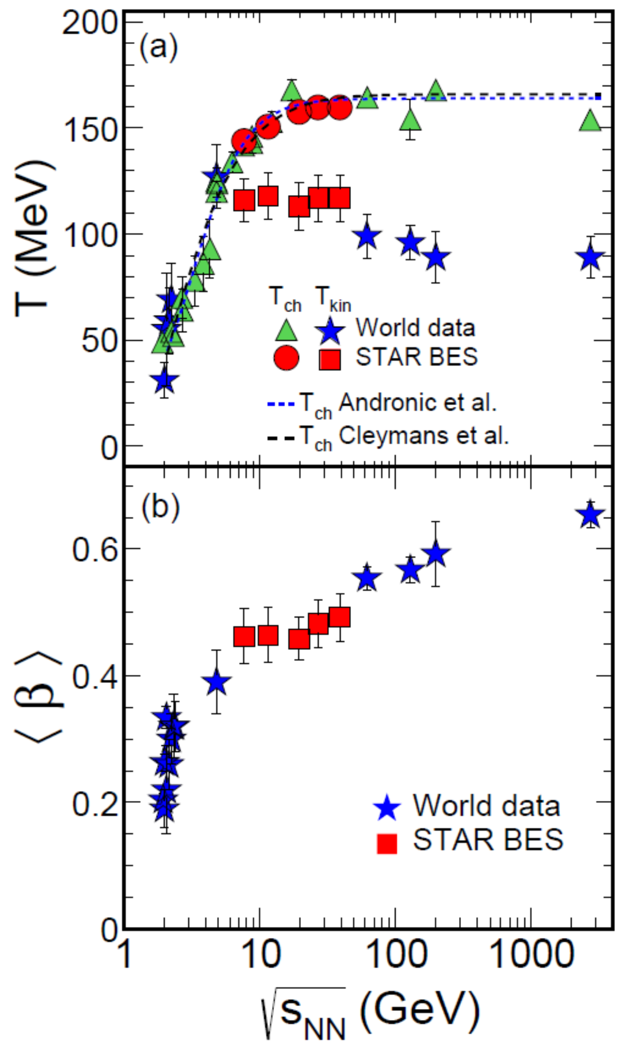
NICA physics cases: Bulk properties & phase diagram mapping

- 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**

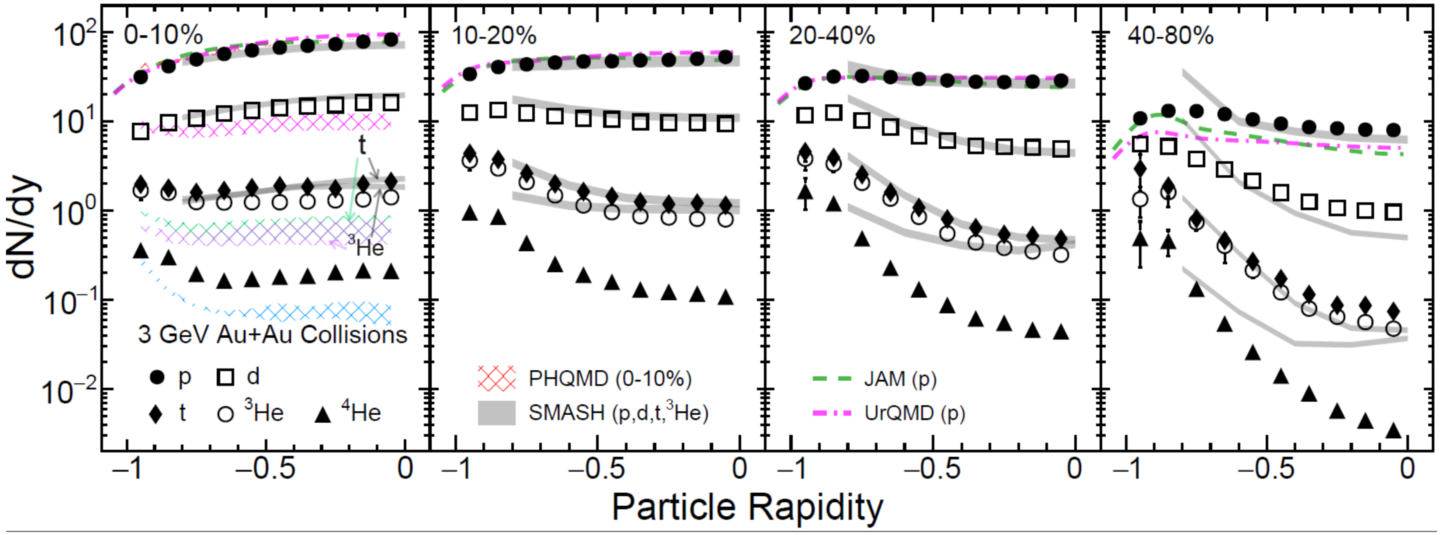
Rapidity spectra of *p,d,t* in A+A: BM@N vs STAR-FXT

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

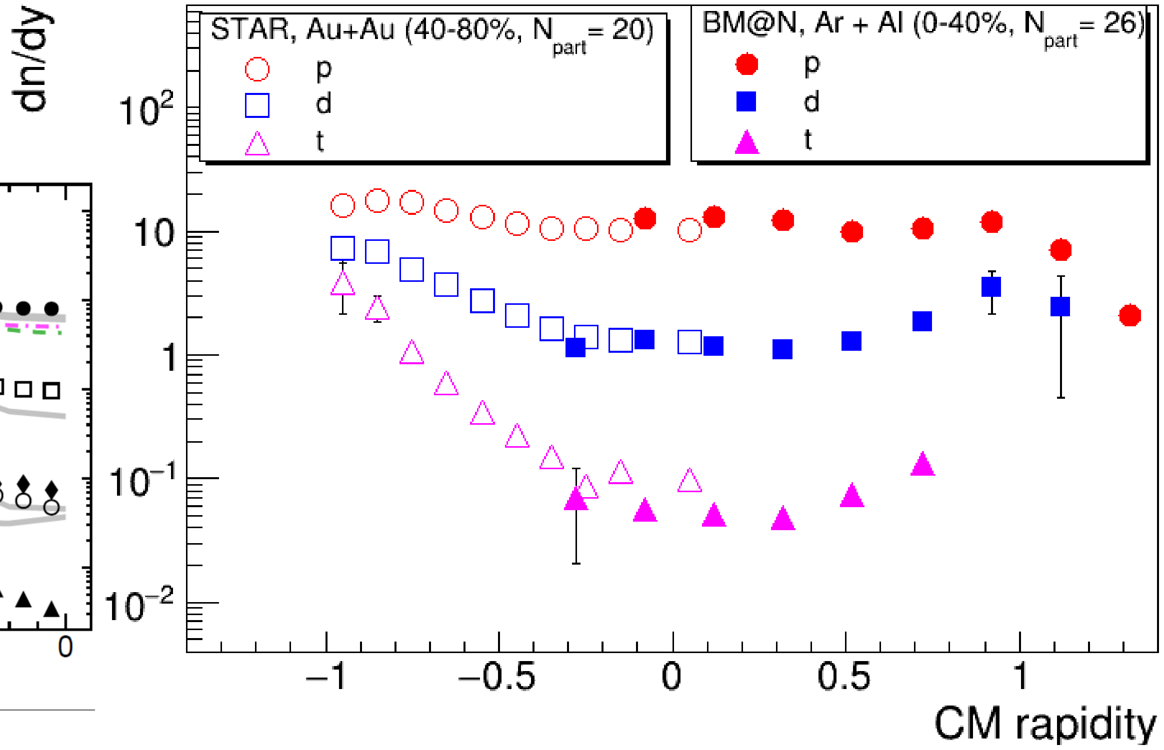
FiarXiv: 2311.11020v1 [nucl-ex]

Production of Protons and Light Nuclei in Au+Au Collisions at $\sqrt{s_{NN}} = 3$ GeV with the STAR Detector

The STAR Collaboration



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)*)

Physics Letters B 809 (2020) 135746

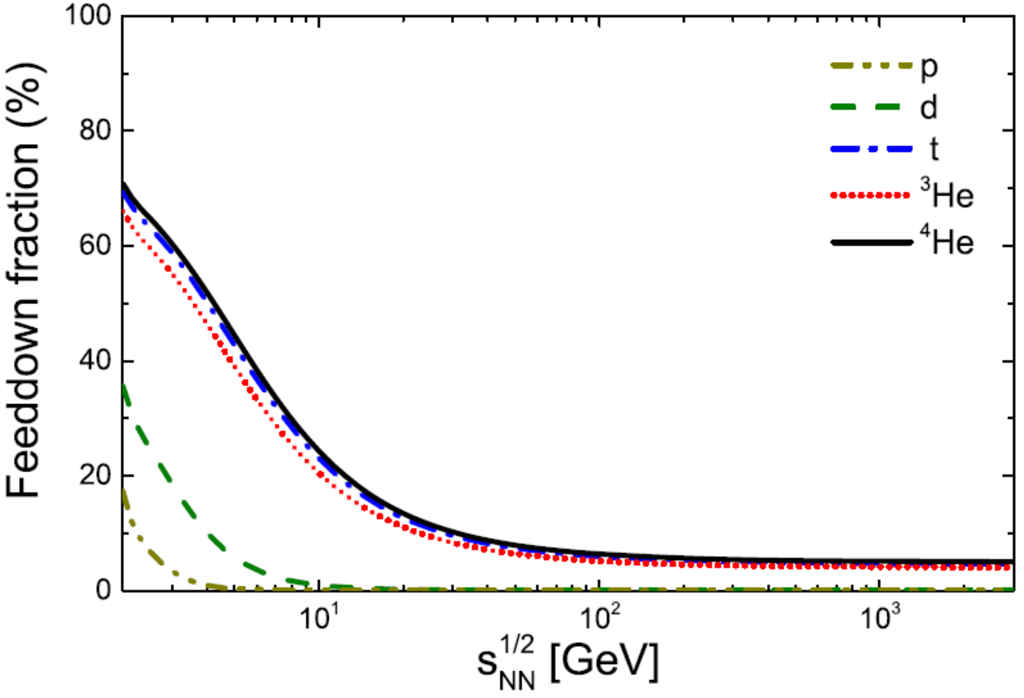
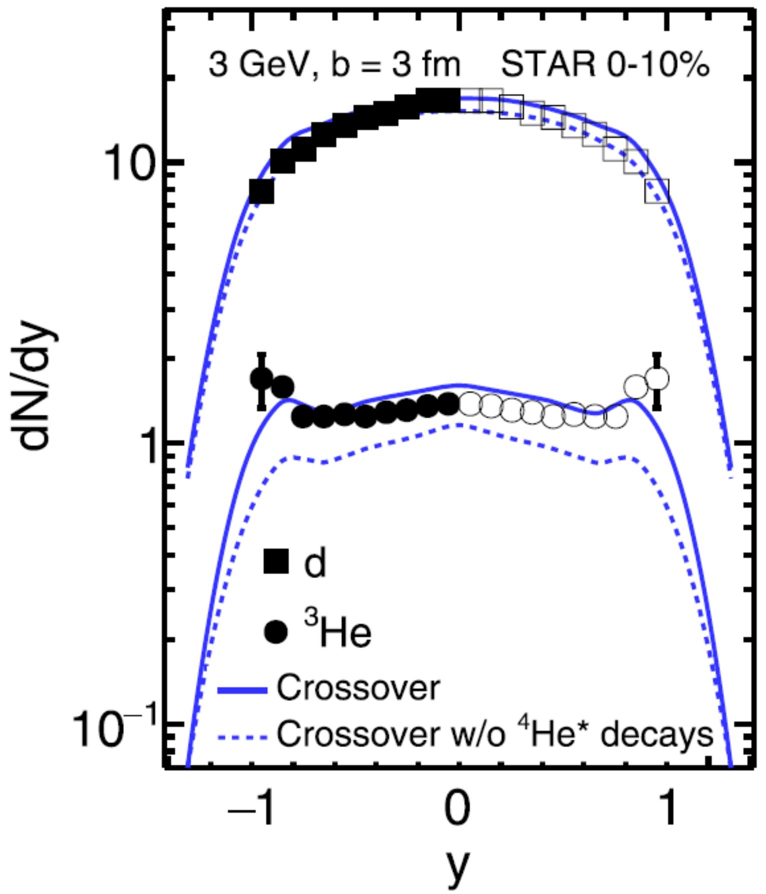


Fig. 1. Fractions of final yields of p, d, t, ^{3}He, and ^{4}He coming from decays of the excited nuclei estimated in the statistical model along the chemical freeze-out curve of Ref. [32].

Phys. Rev. C 109, 014913 (2024)



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}

$$\frac{S_N}{A} = 3.945 - \ln R_{dp} - \frac{1.25 R_{dp}}{1 + R_{dp}}$$

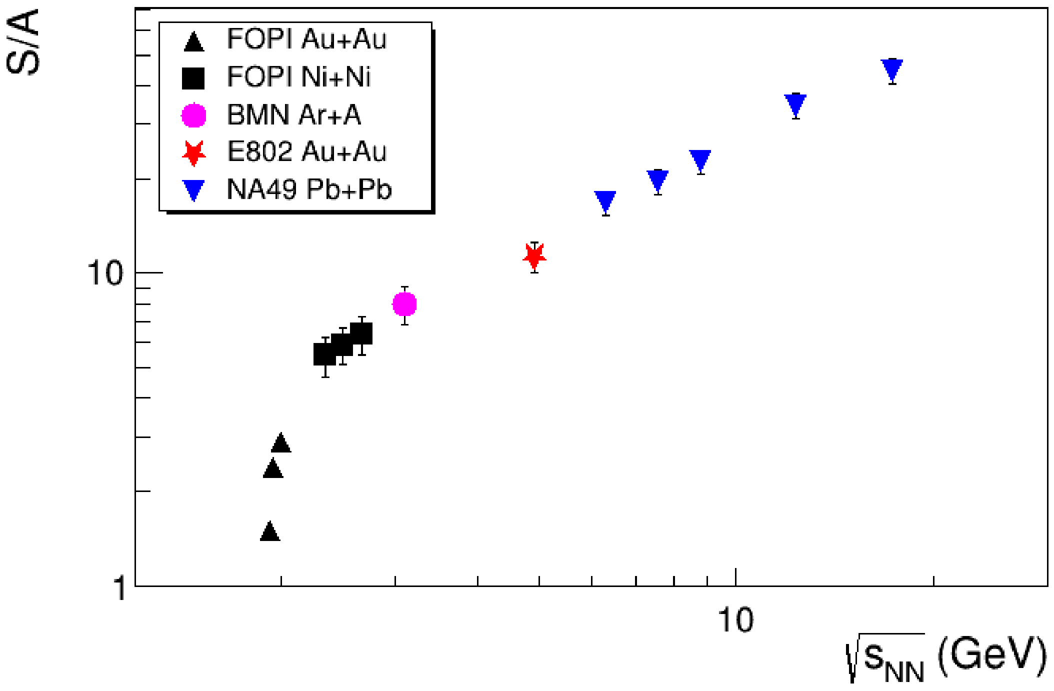
L. P. Csernai and J. I. Kapusta, Phys. Rep. 131, 4 (1986) 223-318

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**

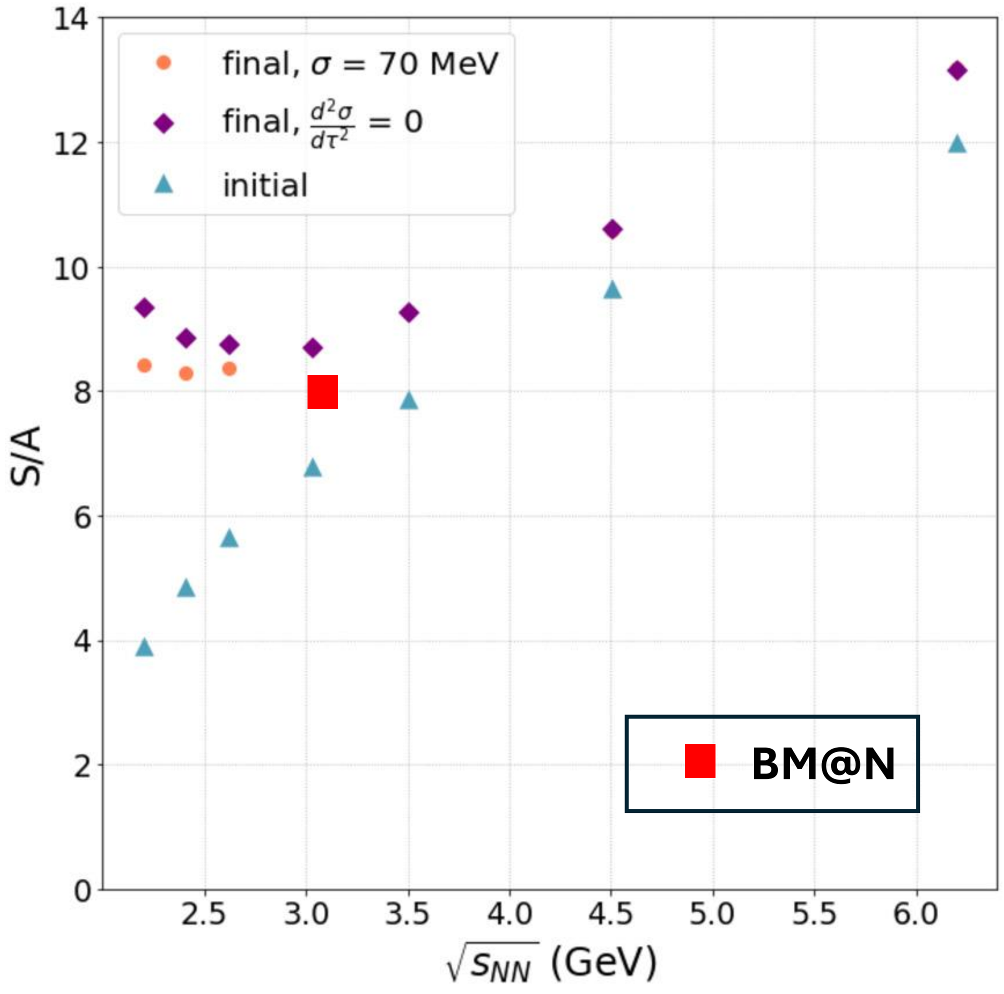


The entropy per baryon ***S/A* ~ 8.0** in central Ar+Al,Cu,Sn,Pb at BM@N (the value near midrapidity)

- *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

Specific entropy and phase transition in Ar+A

Physics Letters B 835 (2022) 137537



- A non-equilibrium phase transition indicates a gain in *S/A* due to the dynamical nature of phase transition (PT) and stochastic fluctuations during the fireball evolution. Theory predictions are made for the two freezeout lines defined by *S/A=const*
- **BM@N Ar+A results favor the scenario w/o PT**
- **Energy scan for S/A can be continued with heavier colliding systems at NICA (BM@N and MPD)**