Study of proton and light nuclei production in Ar-nucleus collisions in the BM@N experiment at NICA

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on behalf of the BM@N experiment

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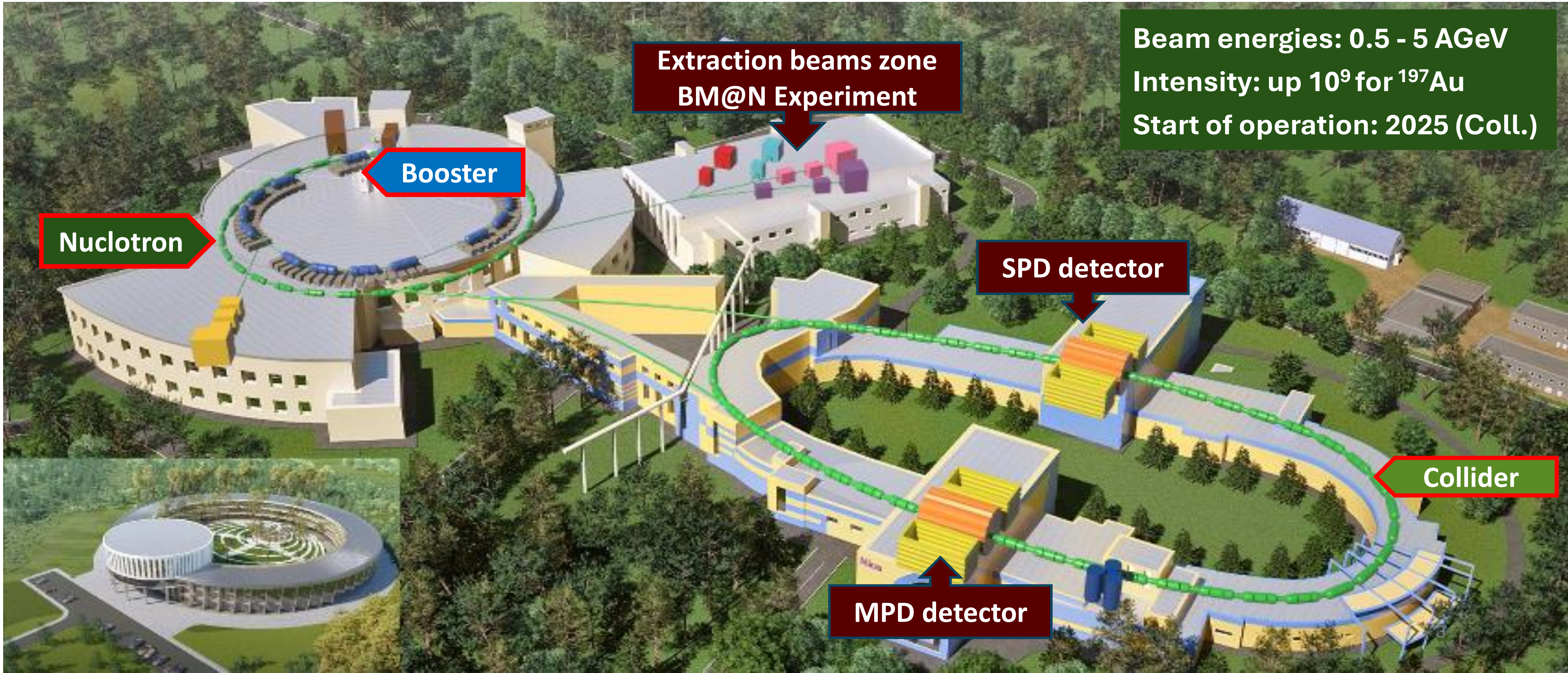
Outline

- NICA accelerator complex and prospects for cluster measurements
- Recent results on *p*,*d*,*t* production in Ar+A from the BM@N experiment at NICA
- Summary

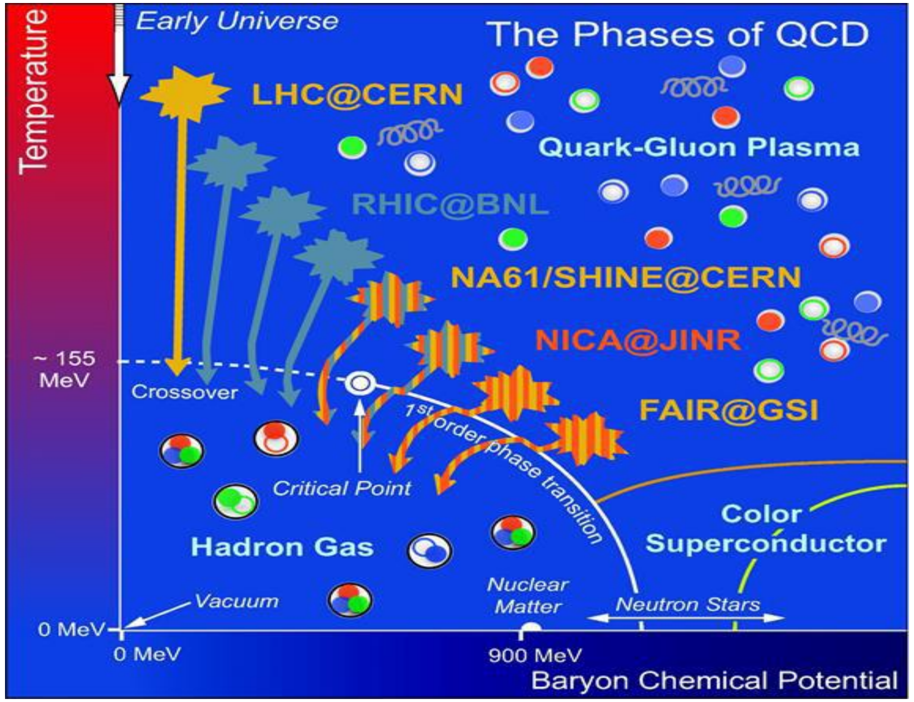
NICA – Nuclotron-based Ion Collider

- Chain of accelerators providing ion beams (from *p* to Au) for fundamental physics studies & applied research
- Modern detectors for study dense nuclear matter and spin phenomena (MPD, SPD, BM@N)
- Experimental zone with beam lines for physics study and applied research
- Cryogenic infrastructure for production, testing and supply superconducting elements



Heavy-ion collisions and QCD phase diagram

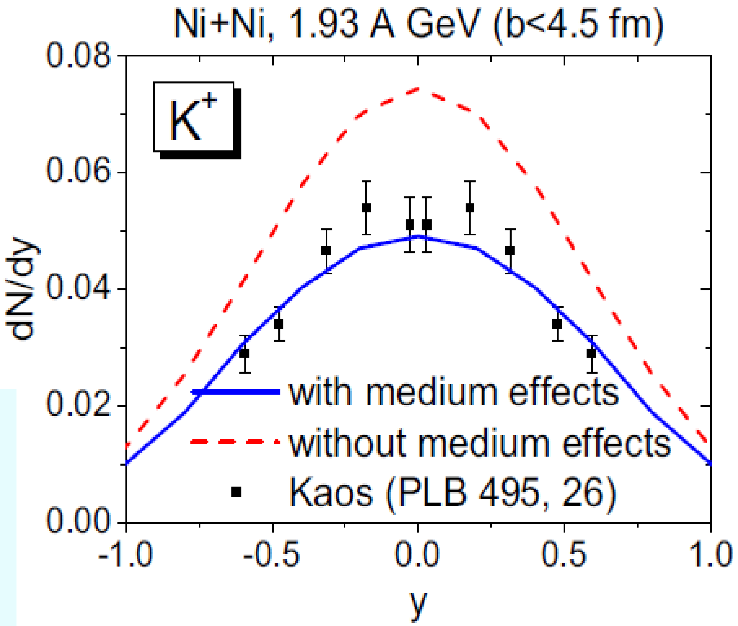
- QCD phase diagram: rich structure and variety of conditions (from Early Universe to Neutron Stars)
- Experimental searching of characteristic points and transition lines is crucial - limiting confirmation so far

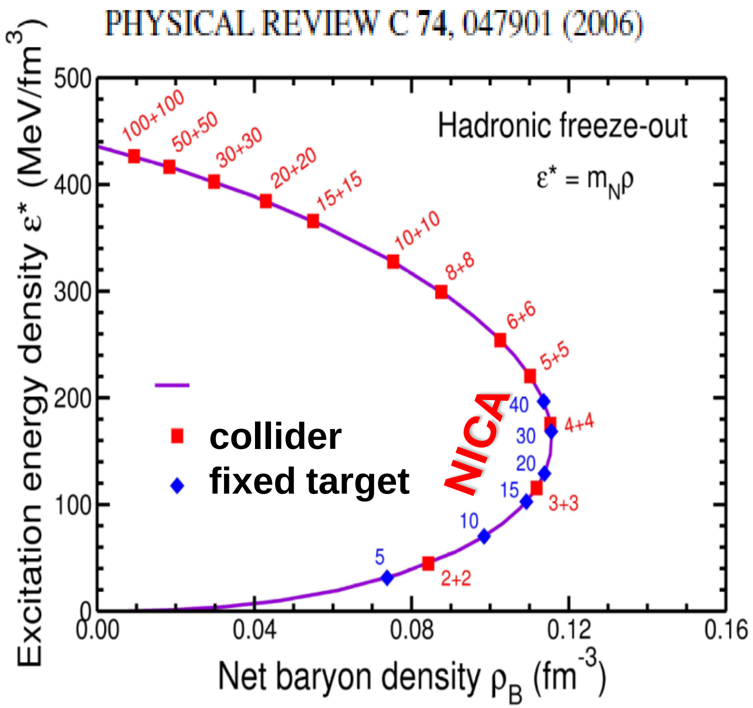


NICA: dense matter at non-zero μ_B and moderate T

- baryon density 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) - 2-4.5A GeV, Collider (MPD) - $\sqrt{s_{NN}}$=3-11 GeV

PRC 103, 044901 (2021))





NICA/BM@N energies:

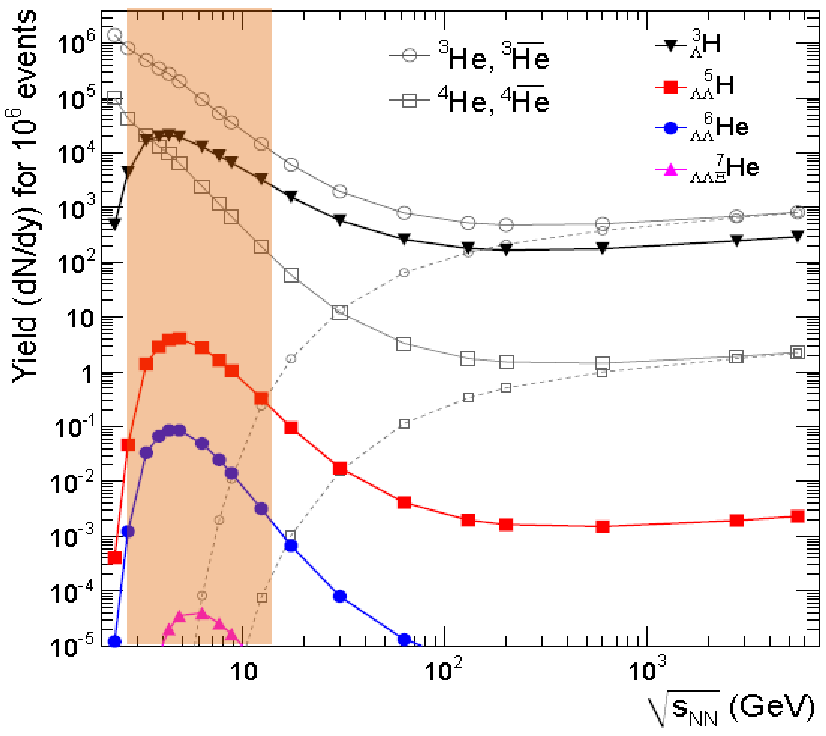
- Baryon dominated nuclear matter: particle production mainly through excitation and decay of baryon resonances
- In-medium effects play a role in hadron production

Why proton and light nuclei at NICA?

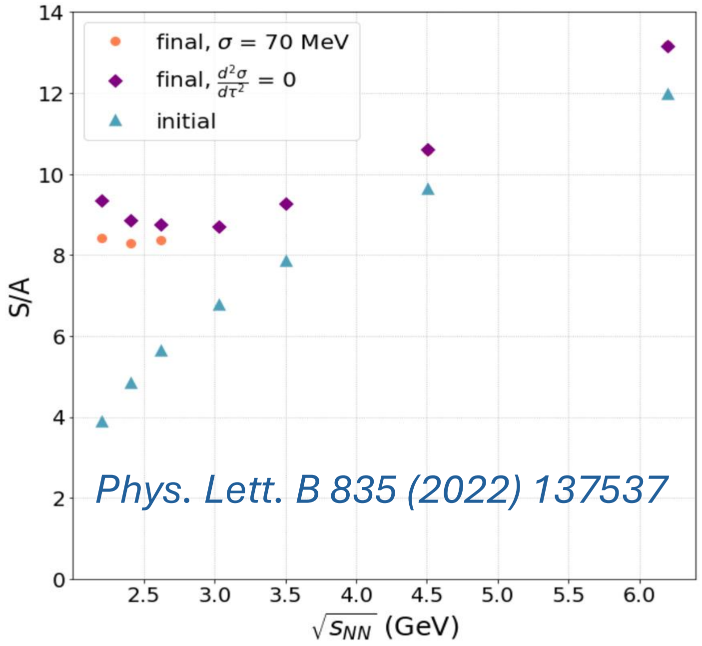
- **Protons**: baryon number transfer, baryon and energy density in the reaction zone, collective effects, phase transition and CEP
- **Light nuclei**: weekly bound objects are copiously formed in hot and dense matter. Production rates and ratios can be sensitive to dynamical fluctuations due to PT and/or CEP; allow testing formation mechanism in models, estimating homogeneity volume and momentum-space correlations

Enhanced yield of (hyper)nuclei at NICA due to high baryon density

A. Andronic et al, PLB 697 (2011) 203



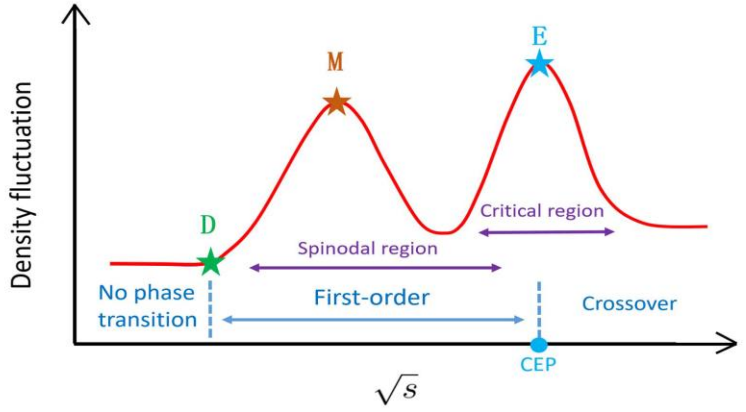
- A non-equilibrium phase transition indicates a gain in the final *S/A* due to the dynamical nature of phase transition and stochastic fluctuations during the fireball evolution
- Relative neutron density fluctuation is related to spinodal instability (PT or CEP)



Phys. Lett. B 835 (2022) 137537

Phys. Lett.B 781 (2018) 499–504

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

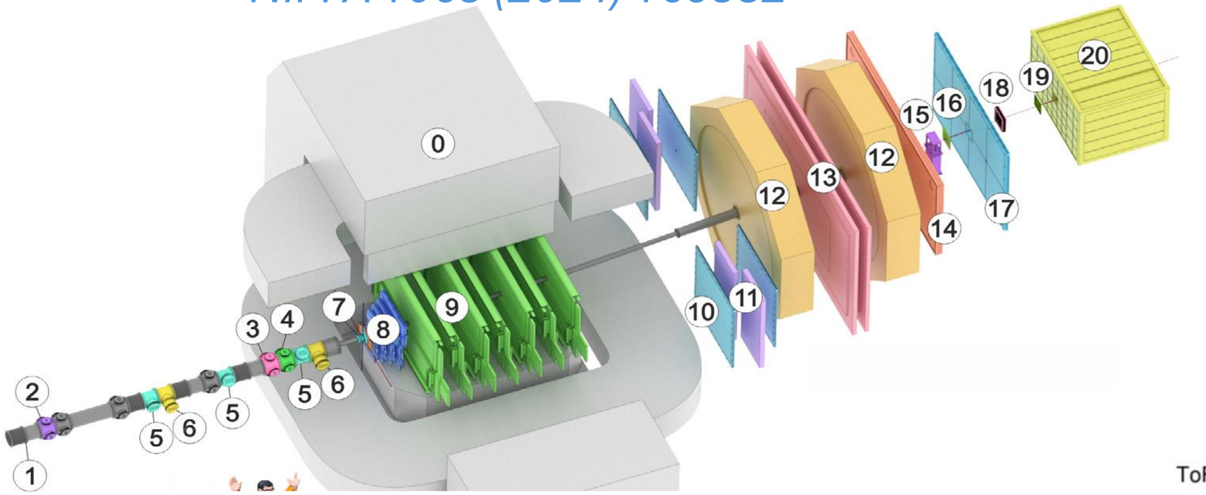


Baryonic Matter at Nuclotron experiment at NICA

more about BM@N in the talk of M.Kapishin on Tue. 22/10 at 12.10

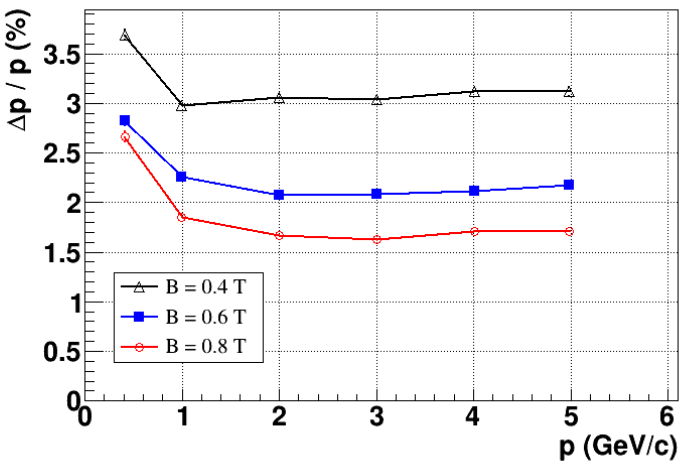
- Tracking : ST + GEMs + CSC/CSC ($\delta p / p \sim 2 \cdot 10^{-2}$)
- PID : MRPC TOF400/700 ($\sigma_{TOF} \sim 85/115$ ps)
- Trigger and centrality: multiplicity detectors BD+SiMD

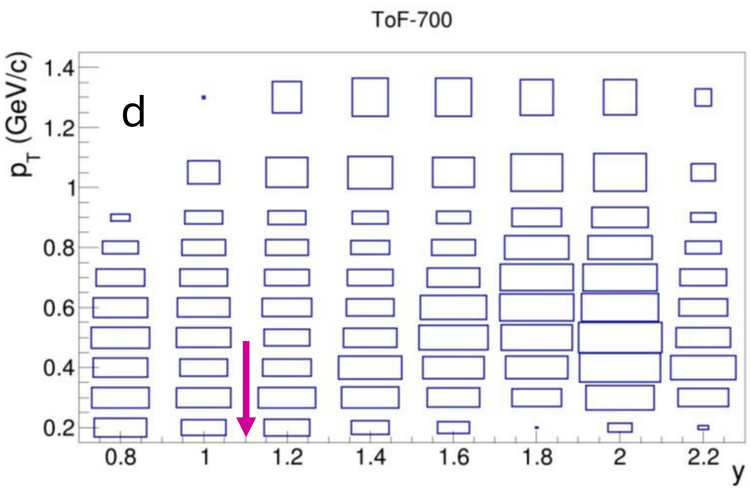
NIM A 1065 (2024) 169532

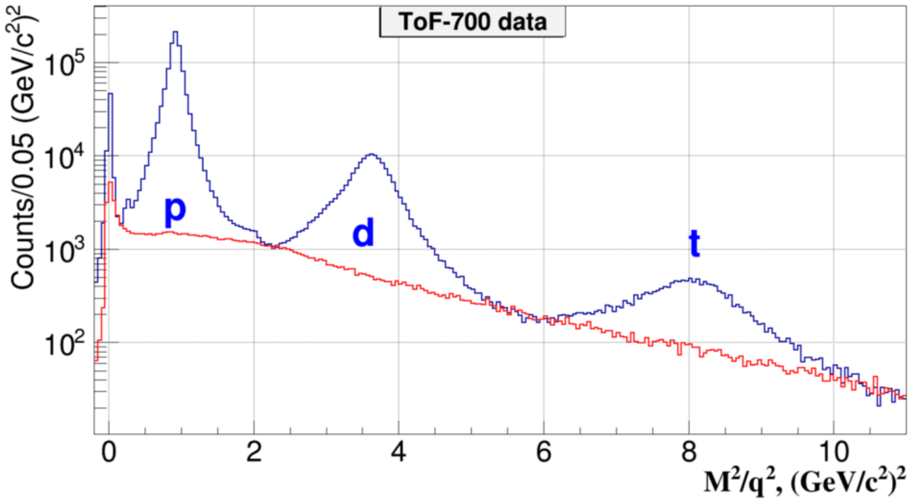


- Commissioning & data taking from 2018
- Available data sets:
  - C + C,Al,Cu,Pb at 4.5(4.0)A GeV
  - Ar + C,Al,Cu,Sn,Pb at 3.2A GeV
  - Xe + CsI at 3.8A GeV
- Results on charged hadrons (π, K), protons, light nuclei, Lambda-hyperons

JHEP 07 (2023) 174, e-Print: 2303.16243 [hep-ex]

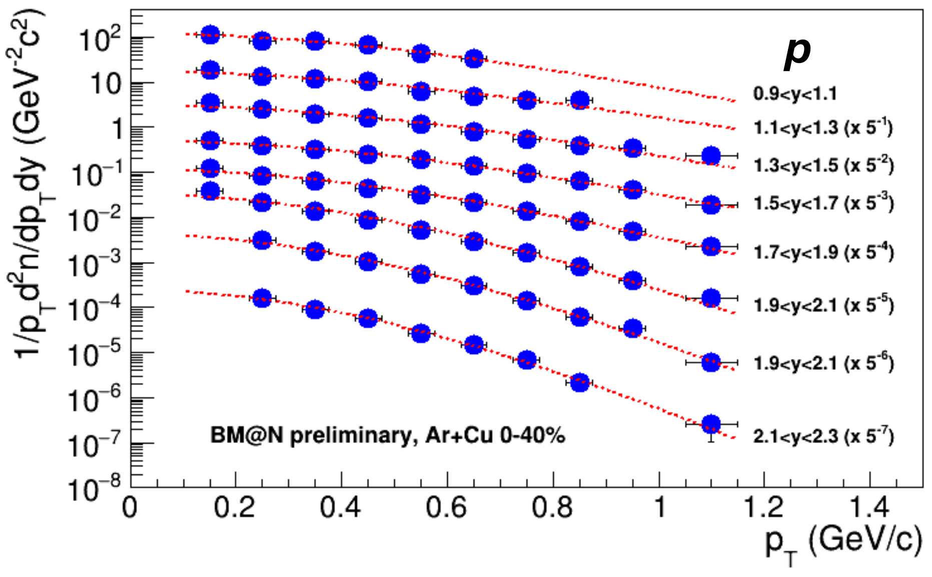




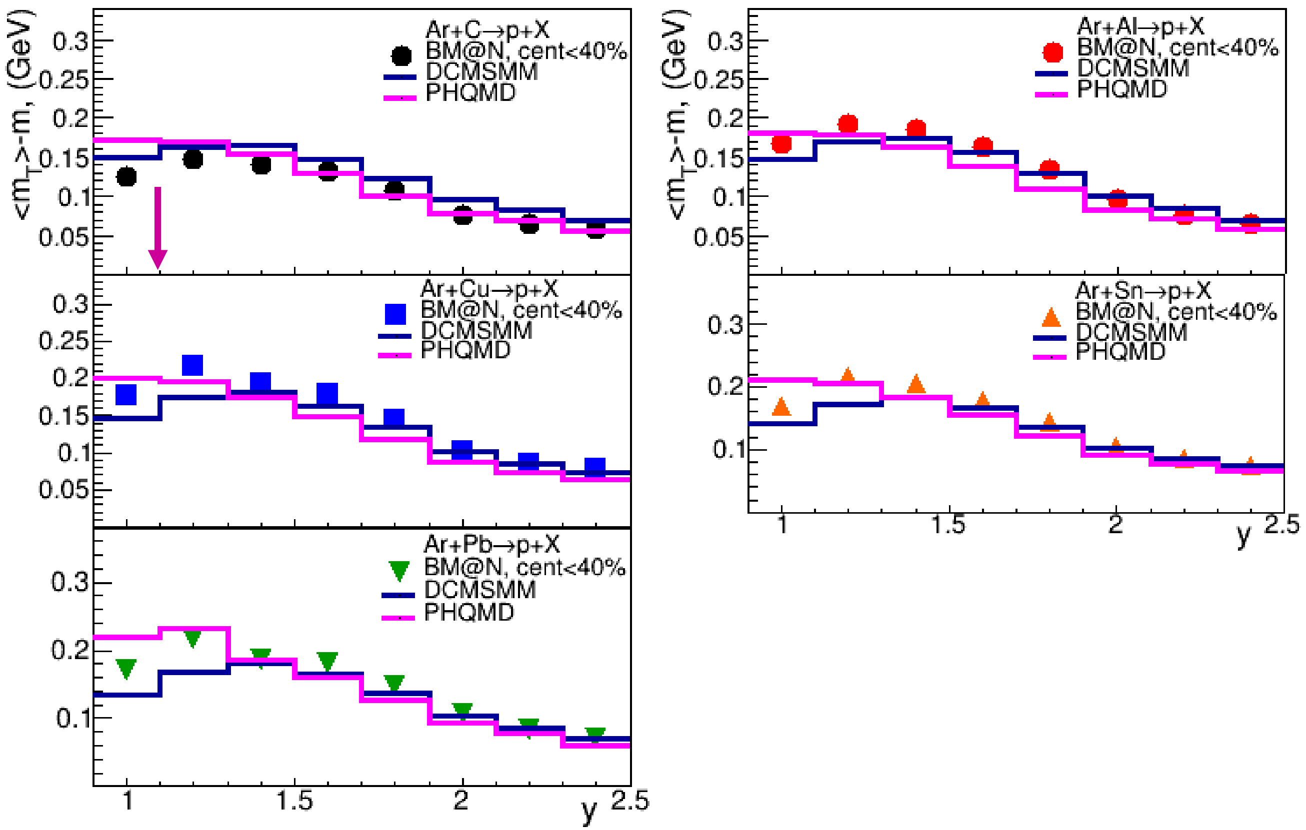


BM@N results: particle pT-spectra in Ar+A at 3.2A GeV

- Data set: ~16·10^6 Ar + C, Al, Cu, Sn, Pb at E/A = 3.2 GeV (y_{CM} = 1.08)
- Centrality: 0-40% and >40% by charged track multiplicity and #of_hits in the multiplicity detector
- PID: *p,d,t* are selected by m^2 from TOF; corrections from MC; analysis details in *JHEP 07 (2023) 174*



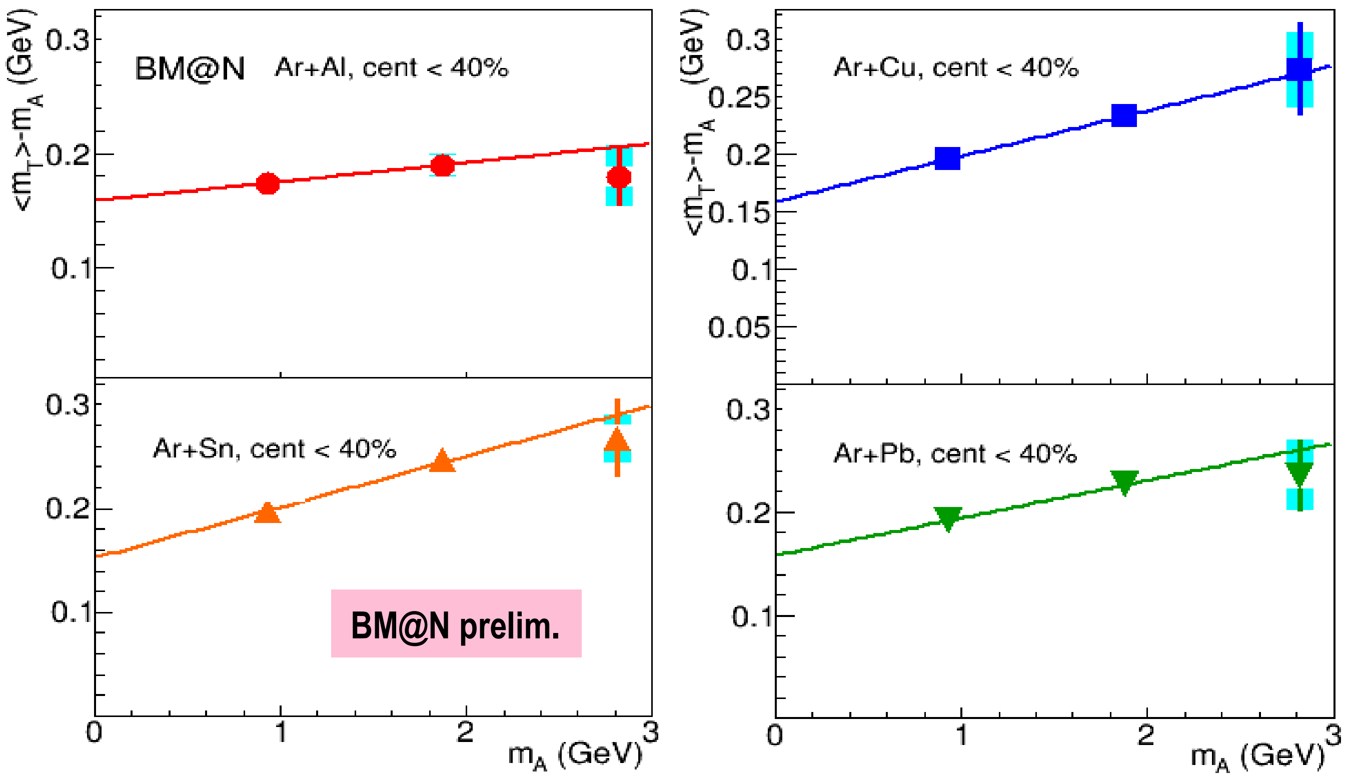
$$\langle E_T \rangle = \langle m_T \rangle - m = T_0 + T_0^2/(T_0 + m)$$



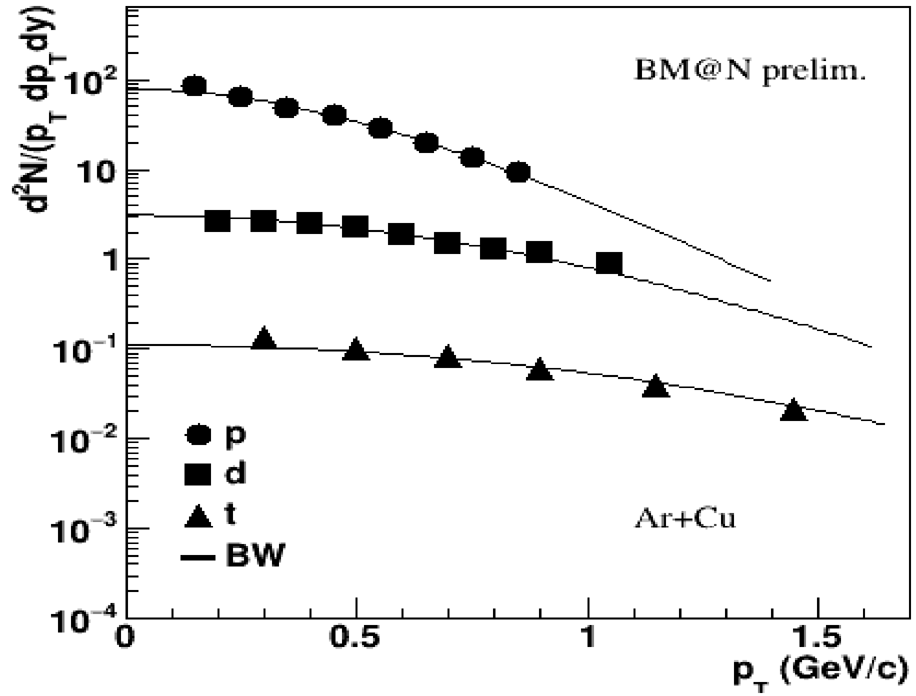
- mT-exponentials are used for extrapolation.
  The extrapolation: 5-30% (***p***), 10-40% (***d***) 12-45% (***t***)

- A bell-like $\langle E_T \rangle(y)$ dependence is reproduced by models;
  ~10% syst. error in *T* (<*mT*>) for *p,d* and ~20% for *t*

BM@N results: mass dependence for $<m_T>$-m and BW fits in Ar+A at 3.2A GeV

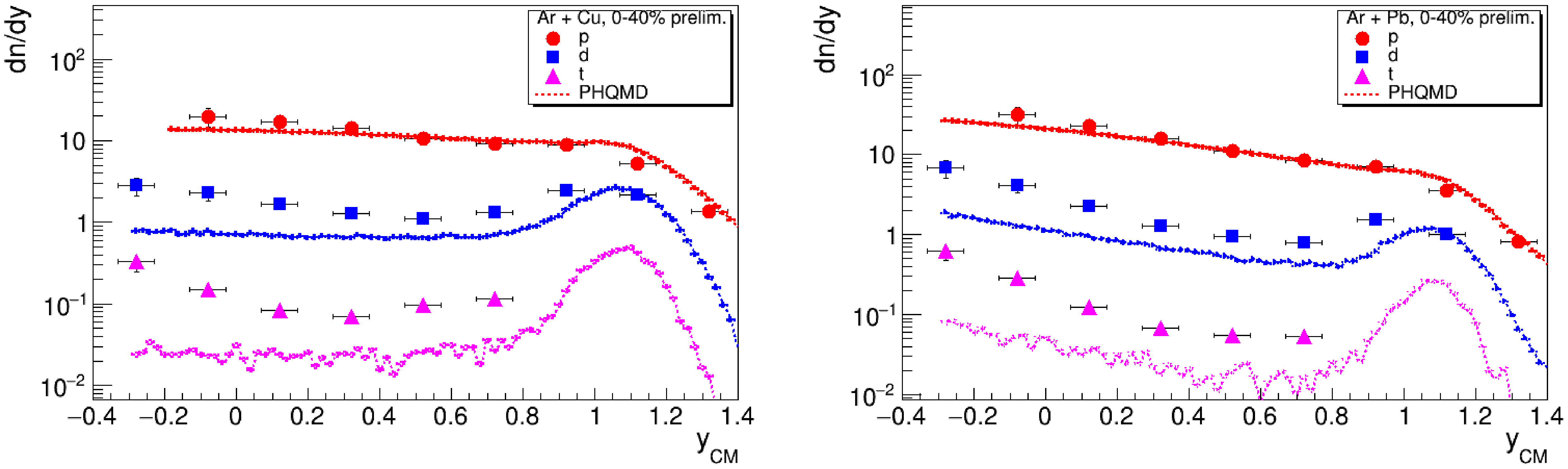


BW fit: $$C_i \int_0^1 m_t f(\xi) K_1\left(\frac{m_t \cosh(\rho)}{T}\right) I_0\left(\frac{p_t \sinh(\rho)}{T}\right) \xi d\xi$$



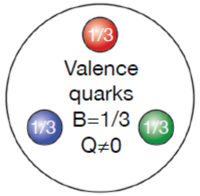
- Midrapidity $<E_T>$ increases with mass. This might be due to radial expansion in the reaction zone.
- BW fits (combined *p*+*d*+*t*): ***T*** ~ 115 MeV, <β> ~ 0.15 (0.23) for a constant (linear) velocity profile. Small variations of the BW fit parameters for 0-40% Ar+Al,Cu,Sn,Pb

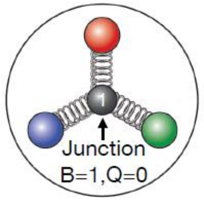
BM@N results : Rapidity spectra of *p,d,t* in Ar+A at 3.2A GeV vs. models



- Rapidity spectra of protons: BM@N data indicate more stopping than 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)*

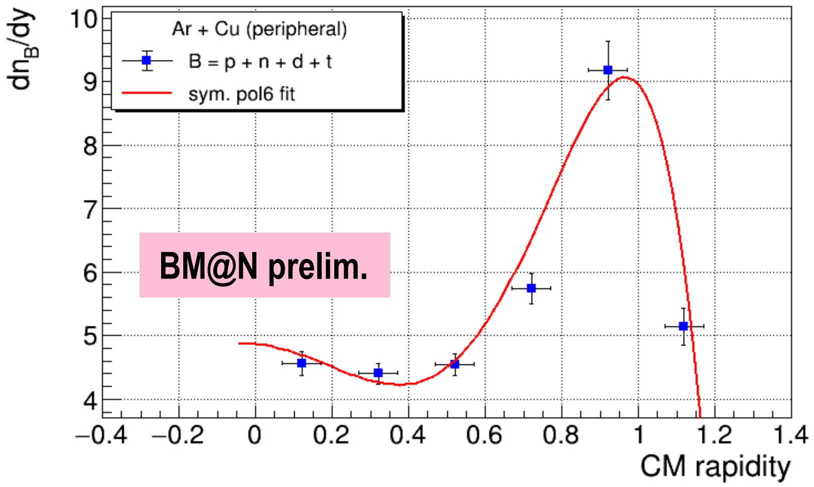
BM@N results: rapidity loss in Ar+A at 3.2A GeV

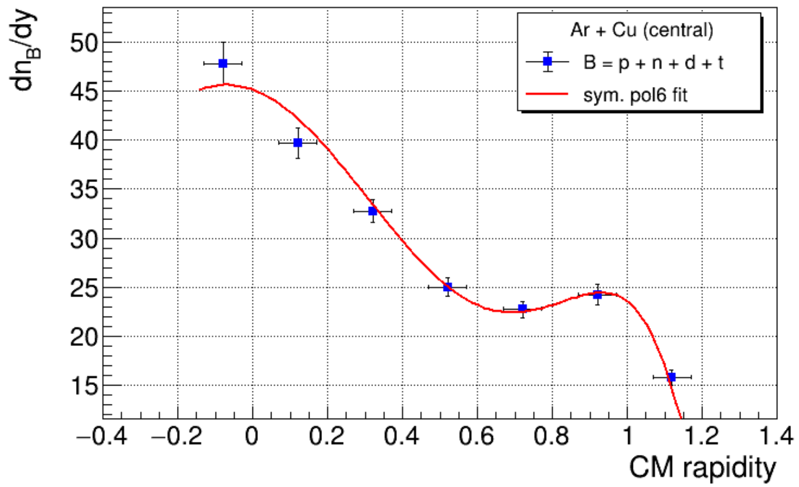


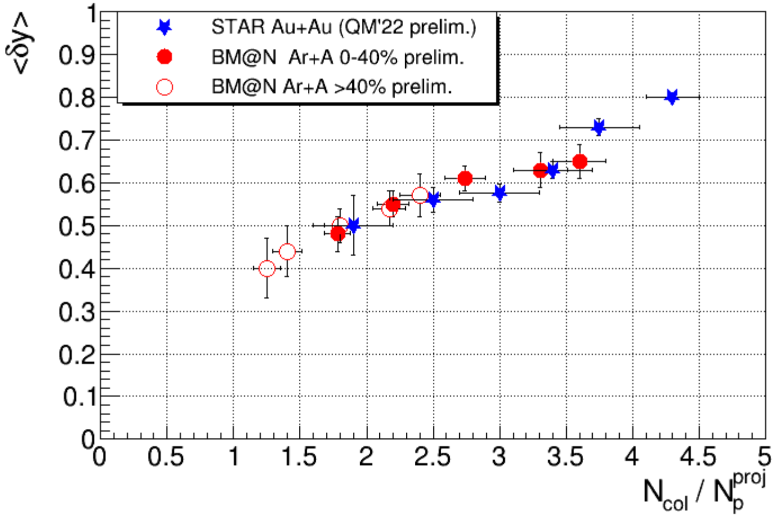


- Baryon rapidity loss mechanism (baryon number transfer) is crucial for understanding collision dynamics
- Testing baryon density achieved in reactions and nuclear matter properties (compressibility and EOS)

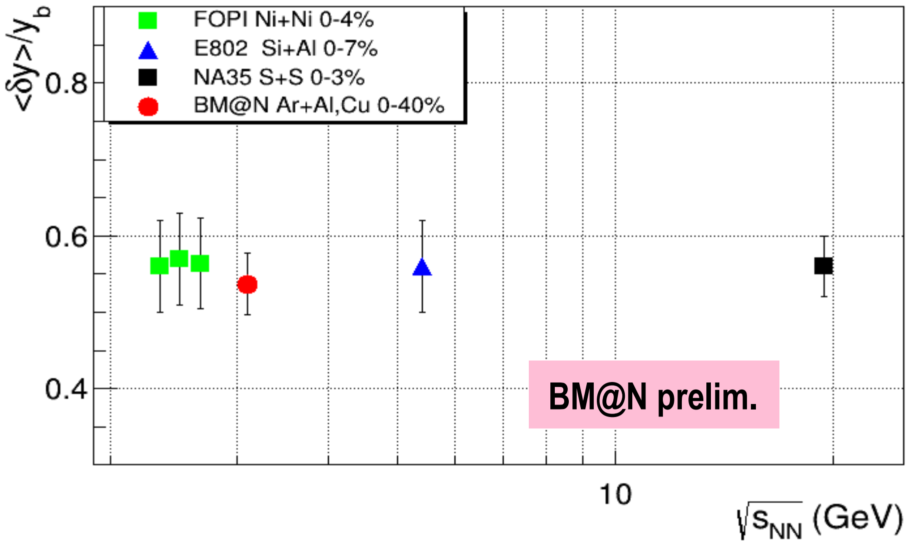
$$\langle \delta y \rangle = y_b - \langle y \rangle, \qquad \frac{dn_B}{dy} = (1+\alpha(y))\frac{dn_p}{dy} + \beta\frac{dn_d}{dy} + \gamma(1+\alpha(y)^{-1})\frac{dn_t}{dy}, \quad \alpha(y) = n/p(y),\ \beta=2,\ \gamma=3$$





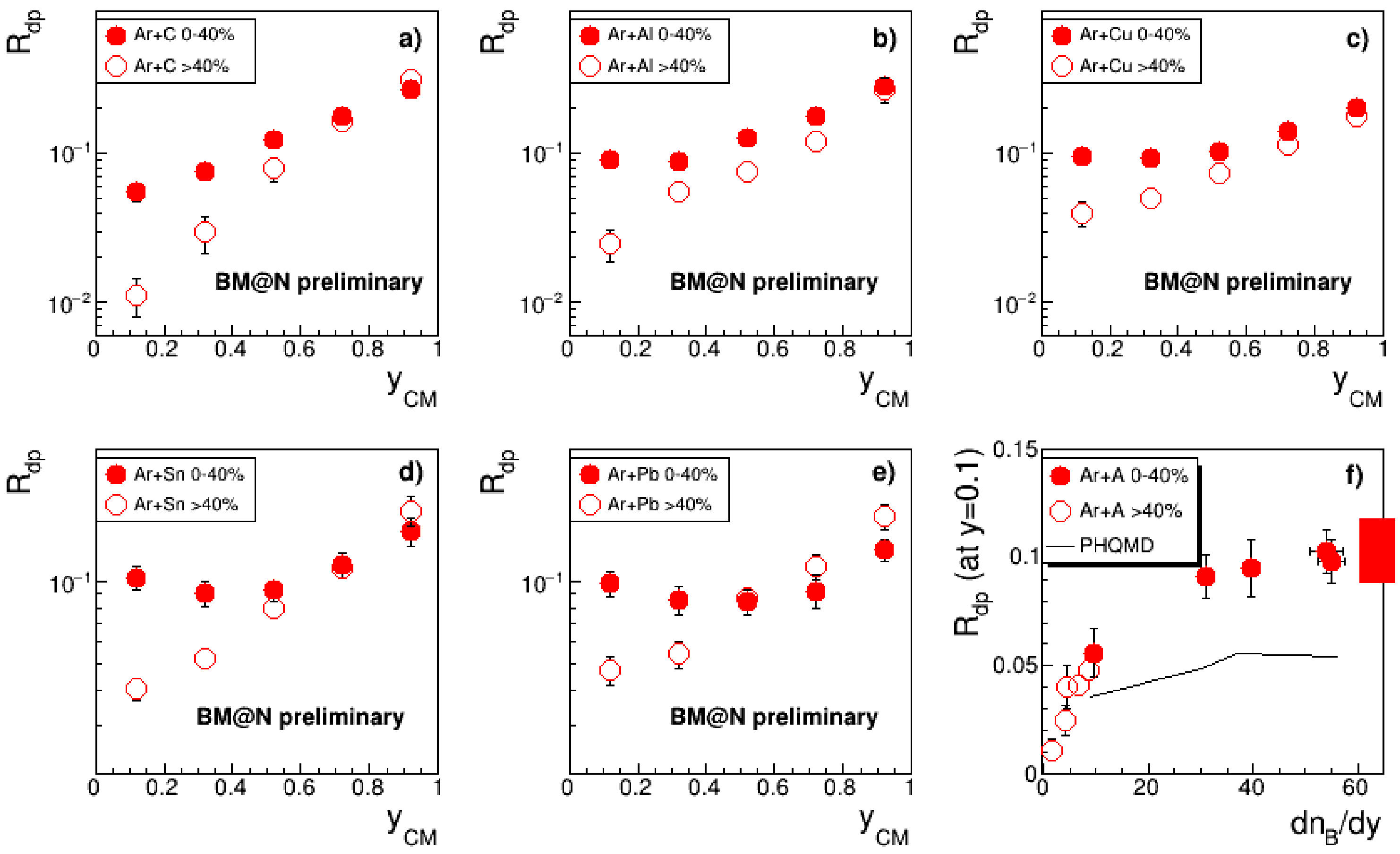


- Nuclear opacity increases slowly with the size of the reaction zone in 0-40% Ar+A (+18% gain from Ar+Al to Ar+Pb)
- <*δy*> in Ar+A and Au+Au (STAR, QM'22) agree on proper scale
- <*δy*> scales with the beam rapidity in medium-size A+A



BM@N results: deuteron-to-proton ratio R_{dp} in Ar+A

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



~25-30% syst. error in R_{dp}

- R_{dp} increases toward the beam rapidity in peripheral Ar+A and has a plateau in central collisions
- The midrapidity R_{dp} rises in small systems and saturates in central Ar+A

BM@N results: 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}

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

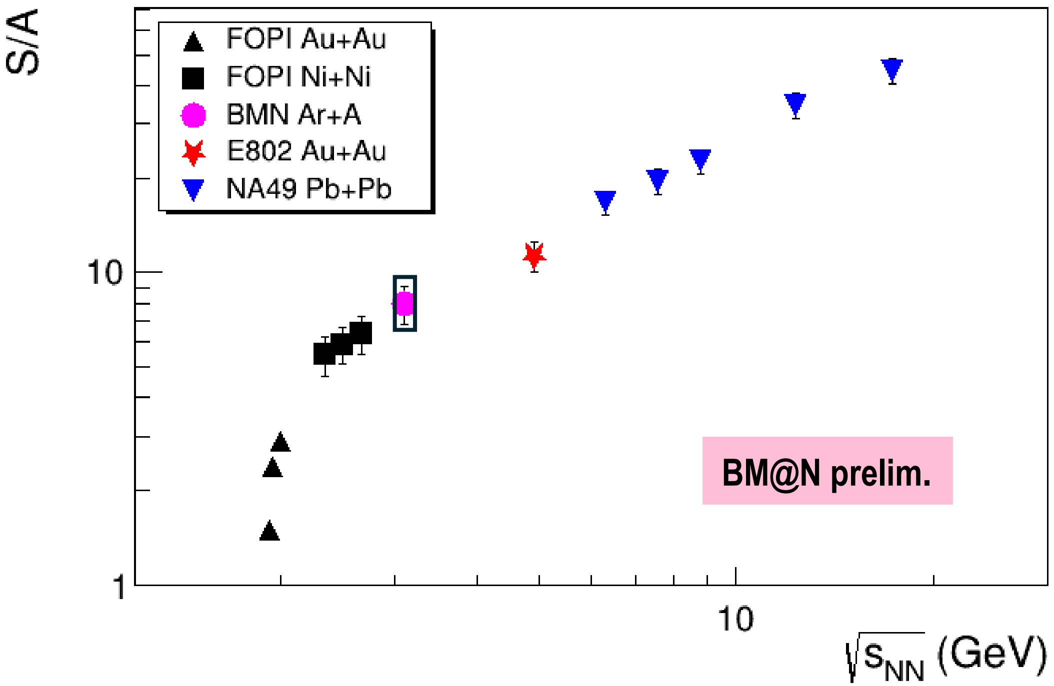
L. P. Csernai and J. I. Kapusta, Phys. Rep. 131, 4 (1986) 223-318

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 (BM@N data + models) 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
- BM@N results follow the general trend for central A+A collisions

Summary

- Heavy-ion experimental program at NICA is progressing according to plans.
  The BM@N experiment at Nuclotron/NICA has started take data
- BM@N results on *p,d,t* from Ar-nucleus at E/A = 3.2 GeV:

  - pT-spectra are measured over the forward rapidity range
  - rapidity distributions of protons are reproduced by models, *d* and *t* yields are strongly underestimated
  - average rapidity loss $<\delta y>$ increases with the size of system
  - deuteron-to-proton ratio R_{dp} saturates in central Ar-nucleus near midrapidity
  - entropy-per-baryon S/A ~ 8.0 in 0-40% Ar+A near midrapidity

- not shown (see in Spares): nucleon phase-space densities, coalescence, penalties, and O_{pdt} in Ar+A

Thank you for your attention!

Extra slides

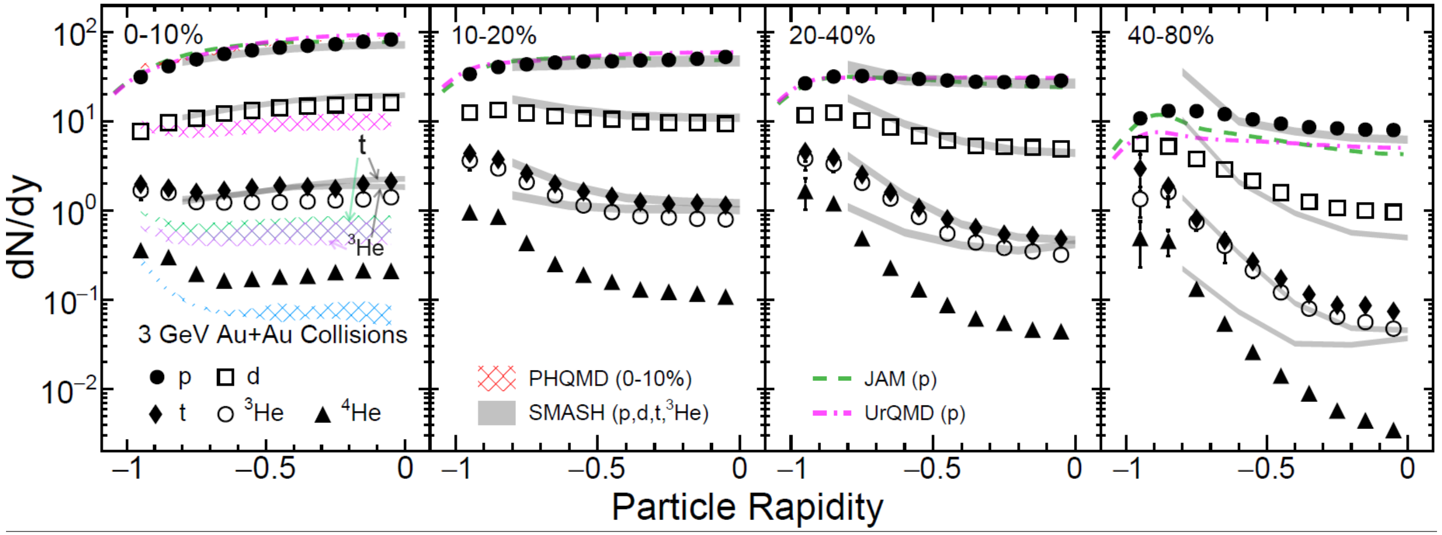
Rapidity spectra of *p,d,t* in A+A: BM@N vs STAR-FXT

- 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})

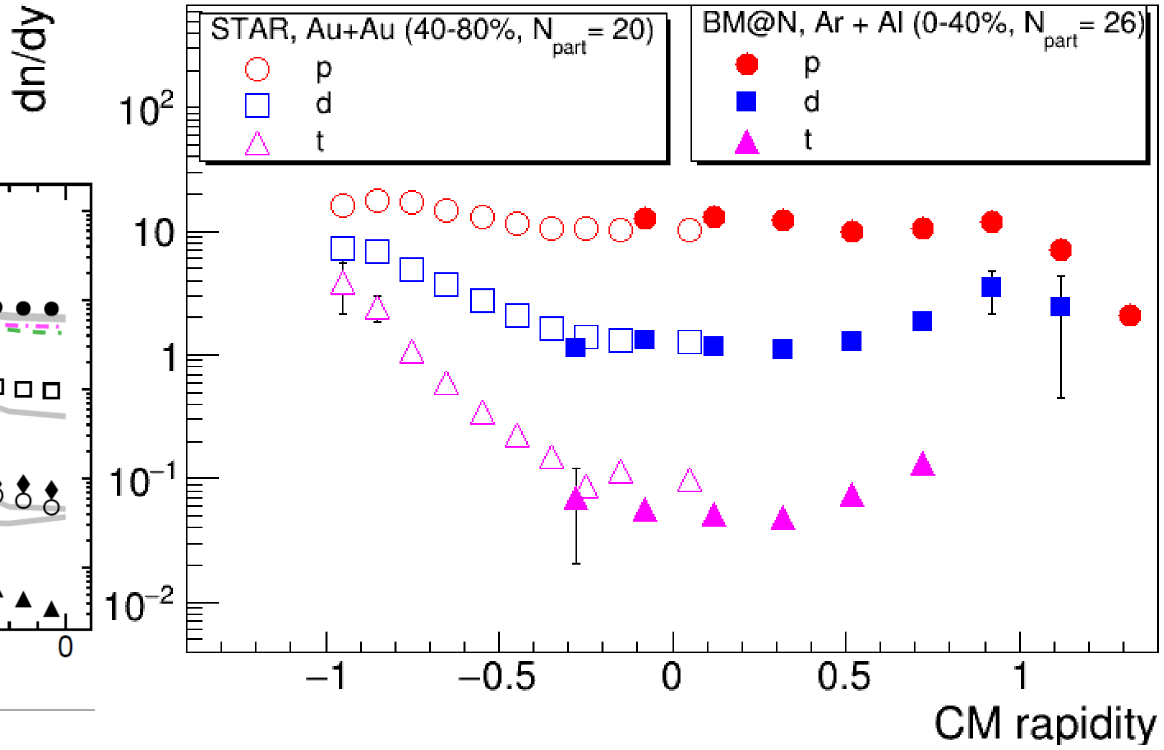
FiarXiv: 2311.11020v1 [nucl-ex]

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



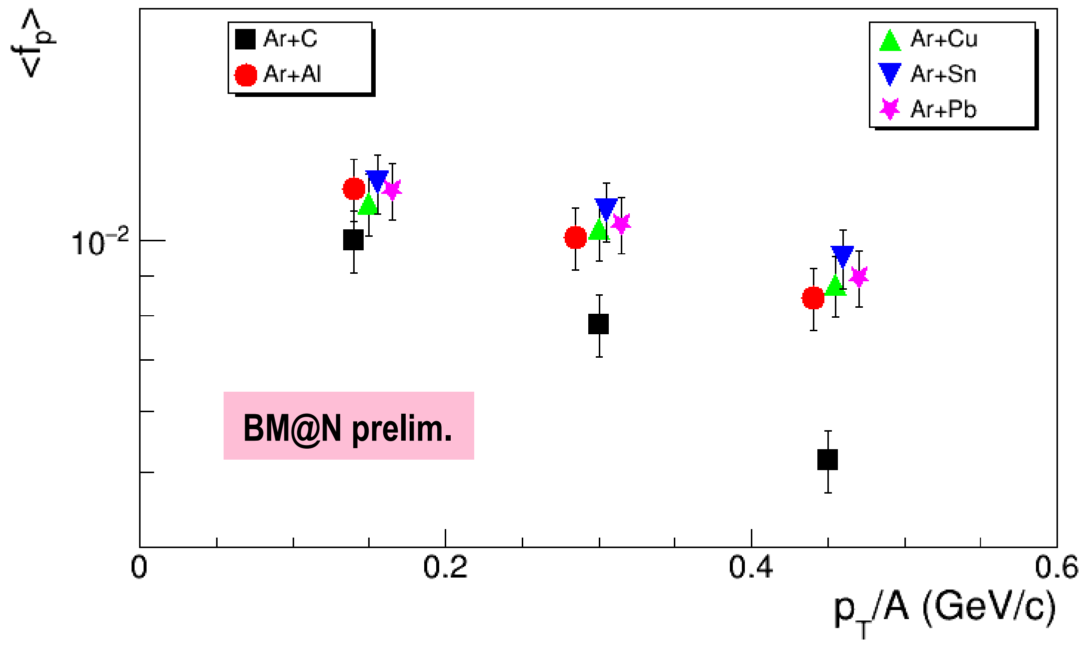
- Though the collision geometry in Ar+Al and Au+Au is different, the yields of *p, d, t* agree within 20% at midrapidity

BM@N results: nucleon phase-space density in Ar+A

- In an equilibrated source, spatial-averaged phase-space density $<f_p>$ is related to the ratio of the invariant yields of *d* and *p*. $<f_p>$ depends on the strength of stopping and on the outward flow

$$\langle f_p \rangle(\mathbf{p}) = \frac{1}{3}\left(E_d \frac{d^3 N_d}{dp_d^3}\right) \Big/ \left(E_p \frac{d^3 N_p}{dp_p^3}\right).$$

Murray and B. Holzer, Phys Rev. C 63, 054901 (2000)

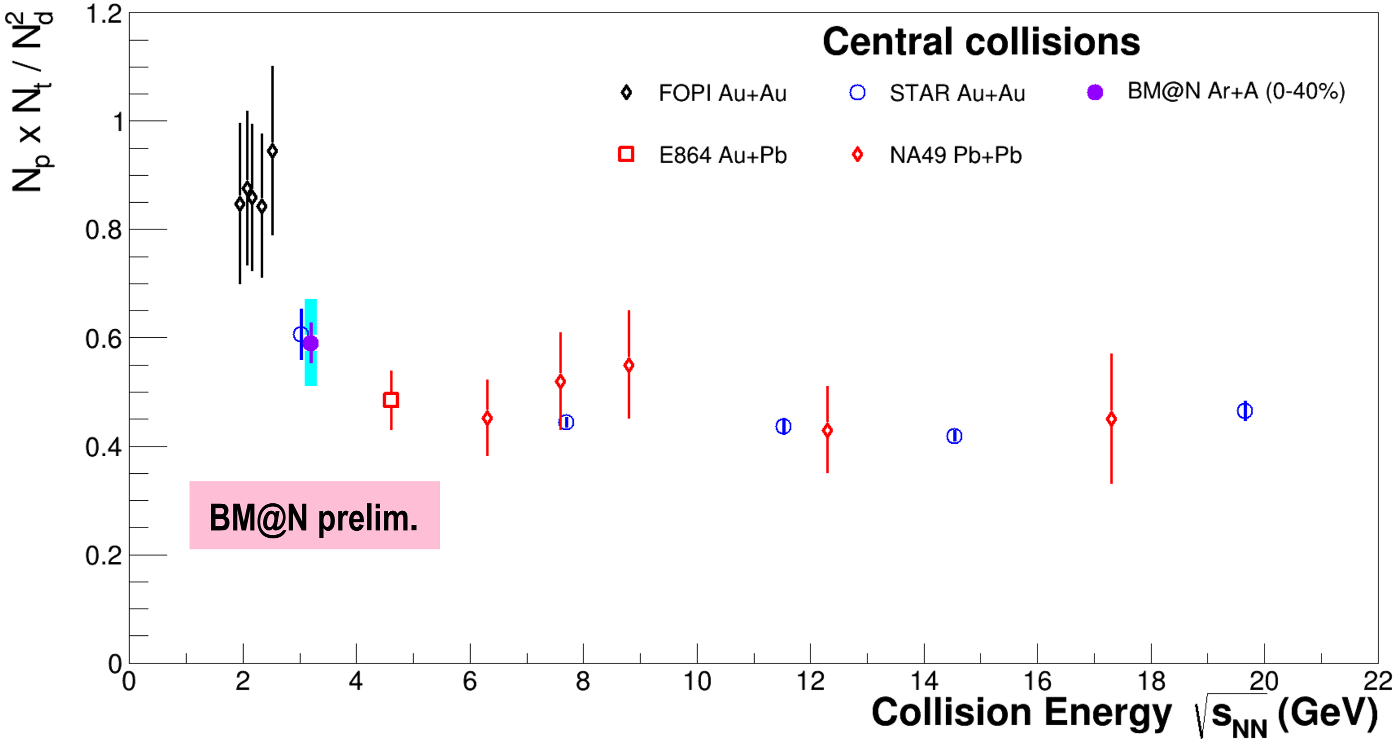


- $<f>$ decreases exponentially with pT indicating a weak (if any) variation with the target mass in Ar+A (except Ar+C). Might be an indication of balancing of stopping power and the outward flow at BM@N

BM@N results: cluster yield ratio O_{pdt}

- 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)*

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

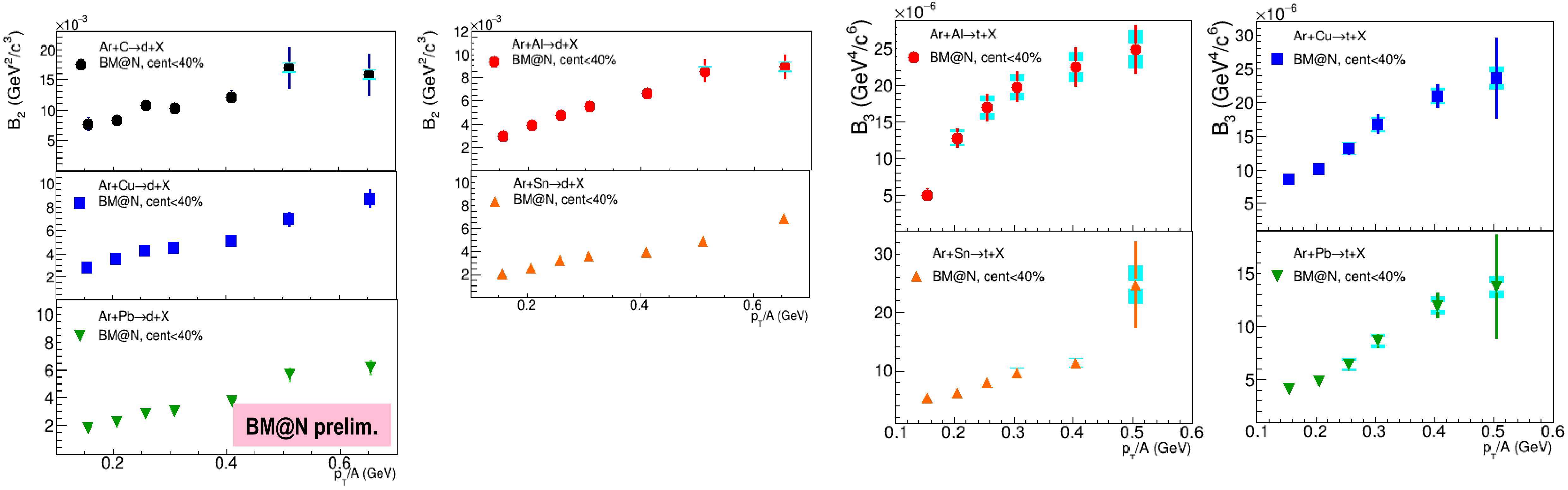


BM@N results from 0-40% central Ar+A follow the general trend of the excitation function for O_{dpt}

BM@N results: coalescence parameters B_A

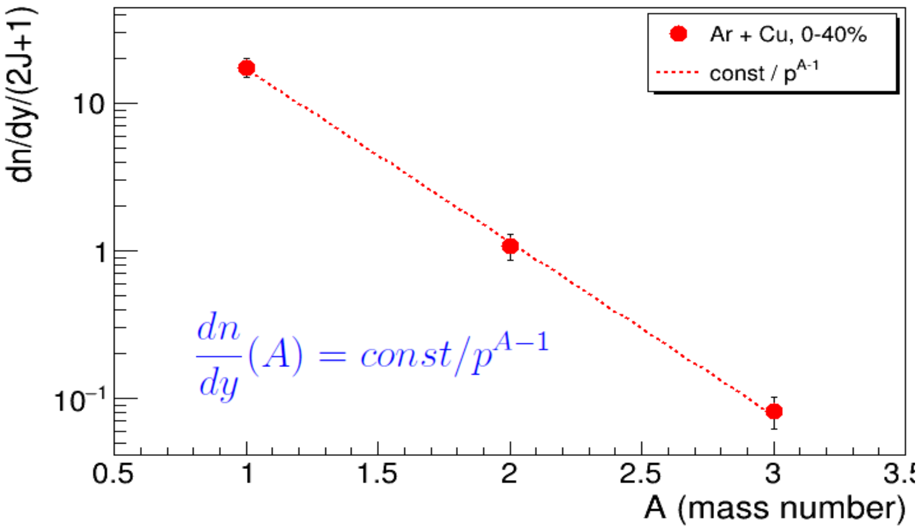
- Coalescence parameter B_A is related to the nucleon homogeneity volume in the source

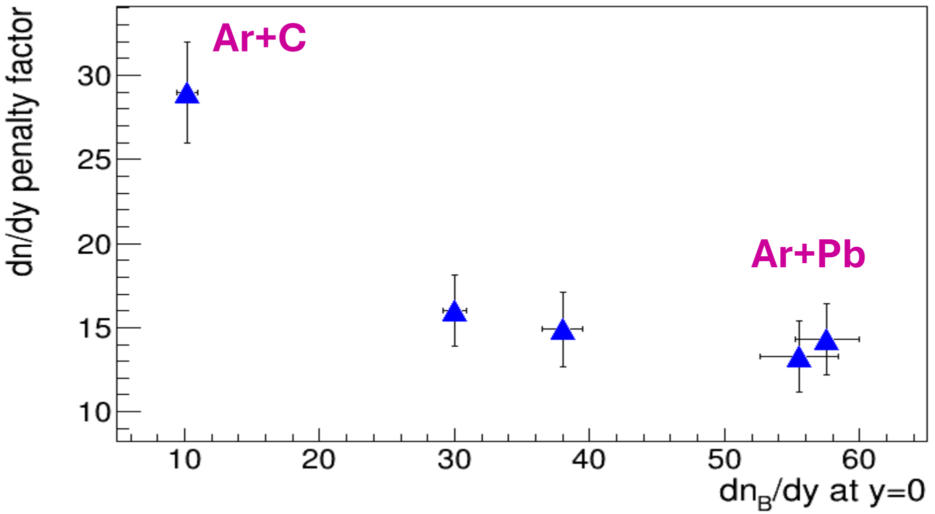
$$E_A d^3N_A/d^3p_A = B_A(E_p d^3N_p/d^3p)^Z (E_n d^3N_n/d^3p)^{A-Z}_{|p=p_A/A}$$

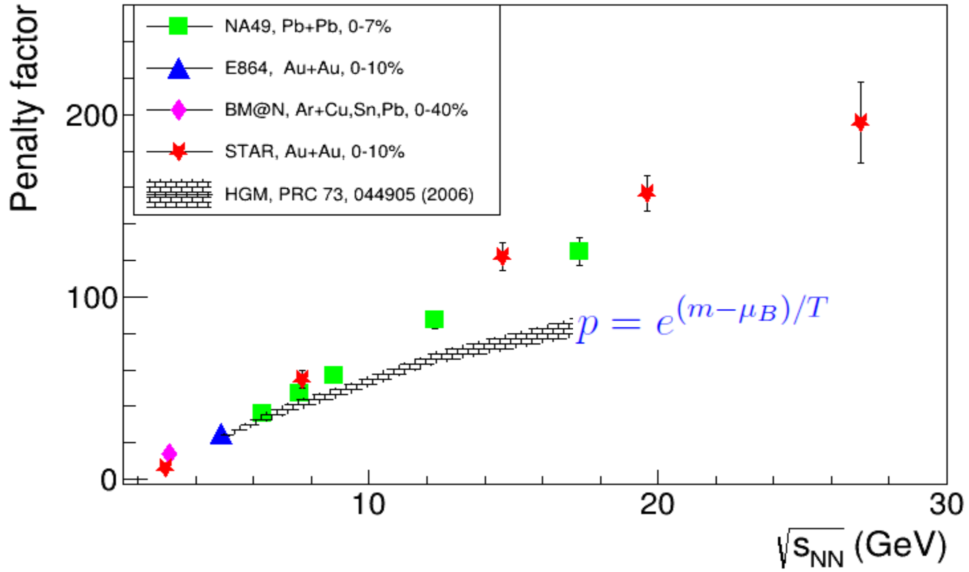


BM@N results: A-dependence of cluster yields & penalty factor in Ar+A

- Cluster yields in A+A collisions follow exponential A-dependence at all energies
- The slope parameter, penalty factor *p*, is sensitive to the nucleon phase-space density in the source







Thermal models: $p = e^{(m-\mu_B)/T}$

- Penalty factor (from dn/dy) ***p*** ~14 in central Ar+A at BM@N
- ***p*** increases (~ linearly) with collision energy, BM@N results follow the general trend
- (dn/dy) penalties and Boltzmann factors agree at low energies, but diverge at higher energies