A proposal for additions to the BM@N paper draft on p,d,t

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A supplement to the uploaded document "Proposal_to_draft_addition.pdf"

Analysis and Detector Meeting of the BM@N Experiment
12-13 March 2024

Topics I’d like to address in the talk (plans and reality):

- Several analysis details
  - pT-spectra, slopes, extrapolations
  - dn/dy for p, d, t, comparison to world data

- Longitudinal dynamics and baryon rapidity loss
  - Baryon rapidity spectra → Npart estimates
  - Rapidity loss, energy dependence, comparison to world data
  - Energy loss

- Transverse dynamics
  - pT (mT) spectra, mass dependence, <pT>, comparison to world data
  - Blast-wave analysis, freezeout parameters, estimates for source density and velocity profiles

- Mass dependence of particle yields
  - Penalty factor in Ar+A collisions, comparison to world data
  - QCD phase diagram mapping
  - Freezeout Baryon (nucleon density estimates)
  - Entropy (per baryon) estimates

Ar+A data analysis

- Analysis starting point – fully corrected 2-dim (pT-y) phase space distributions of identified p, d, t given to me by Michail
- No changes/comments/objections to the analysis methods / corrections / etc. before this point
- Additional estimates for N_part for each Ar+A reaction and centrality interval provided by Genis (DCM model)

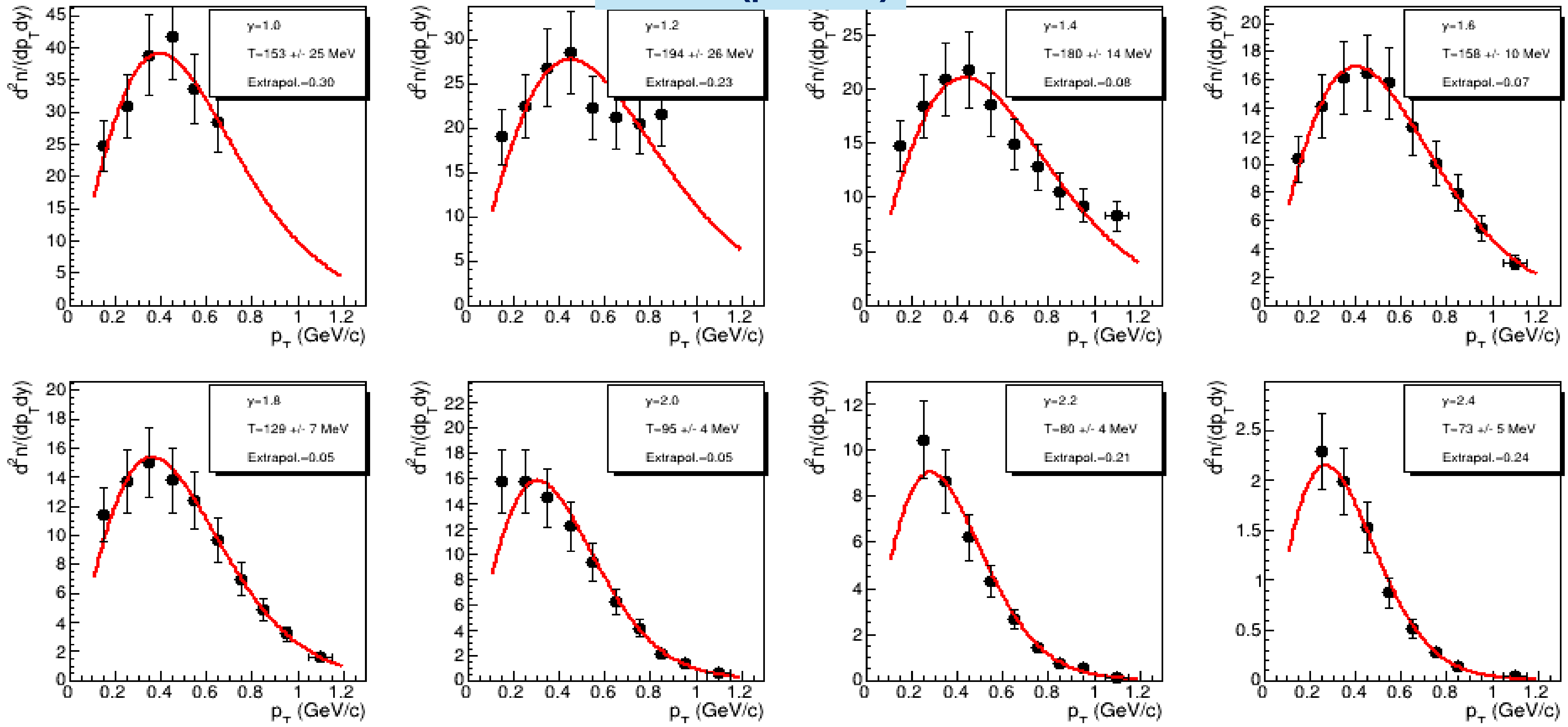
N_p - projectile N_t - target, N_S - sum

Centrality	Ar+C			Ar+Al			Ar+Cu			Ar+Sn			Ar+Pb		
	N_p	N_t	N_S	N_p	N_t	N_S	N_p	N_t	N_S	N_p	N_t	N_S	N_p	N_t	N_S
0 - 0.4	20.7	9.3	30.0	26.0	19.5	45.5	32.0	45.3	77.3	35.3	80.3	115.6	37.4	131.7	169.1
0.4 – 1.0	5.6	3.5	9.1	6.9	6.1	13.0	9.4	12.2	21.6	11.7	19.4	31.1	14.7	32.6	47.3

pT-spectra of protons

- Fit pT-spectra in rapidity bins by thermal function (*C * pT * exp{- (mT-m)/T}*)
- Rapidity density ***dn/dy*** = sum_of_data_points + extrapolation from fit function (i.e. integrals over unmeasured regions)

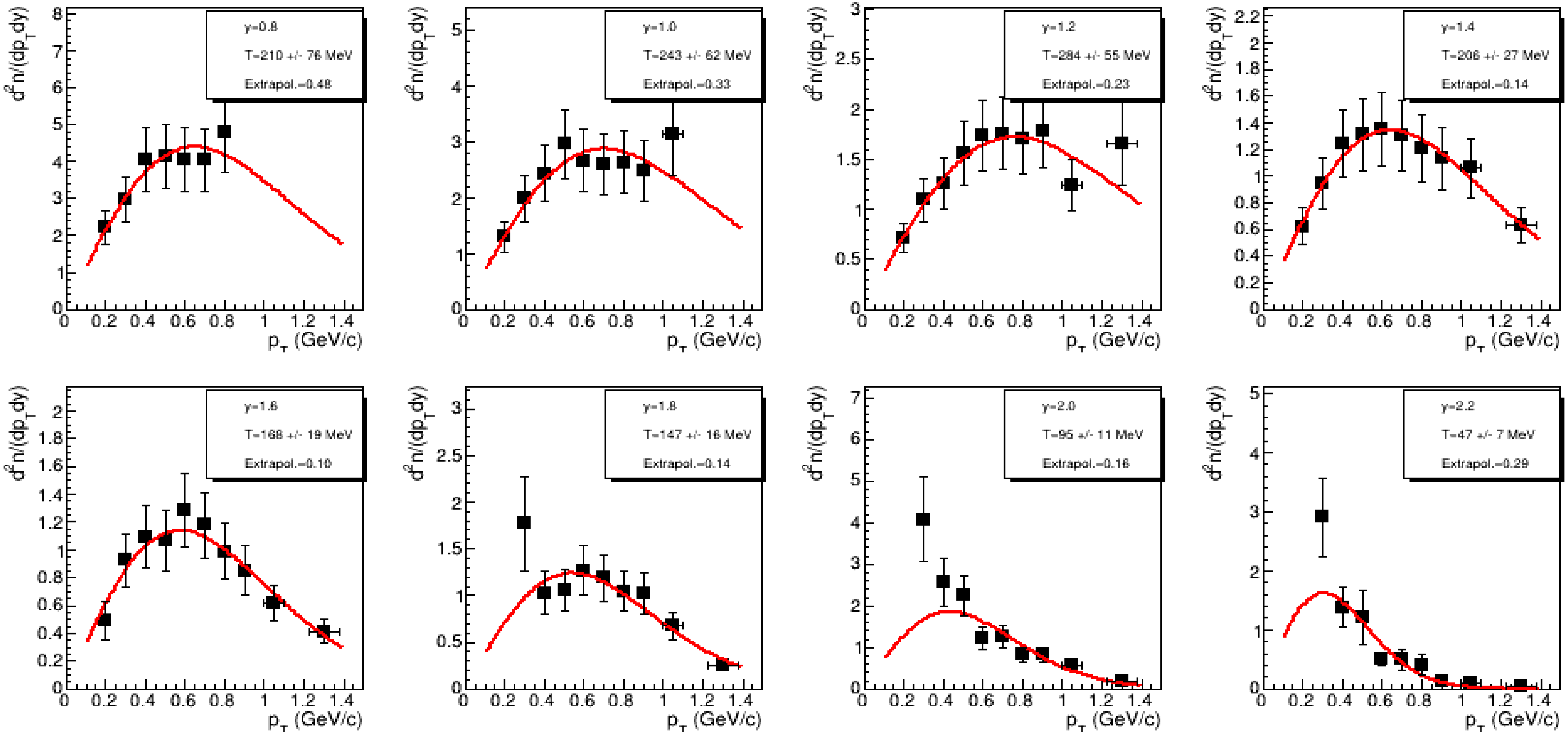
Ar + Sn (protons)



pT-spectra of deuterons

- Fit pT-spectra in rapidity bins by thermal function (*C * pT* exp{- (mT-m)/T}*)
- Rapidity density ***dn/dy*** = sum_of_data_points + extrapolation from fit function (i.e. integrals over unmeasured regions)

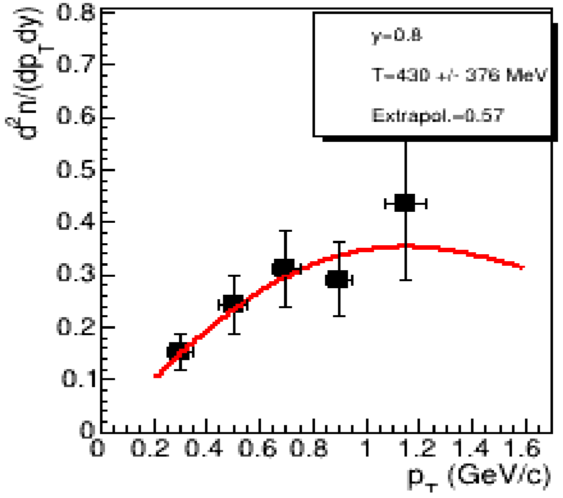
Ar + Sn (deuterons)

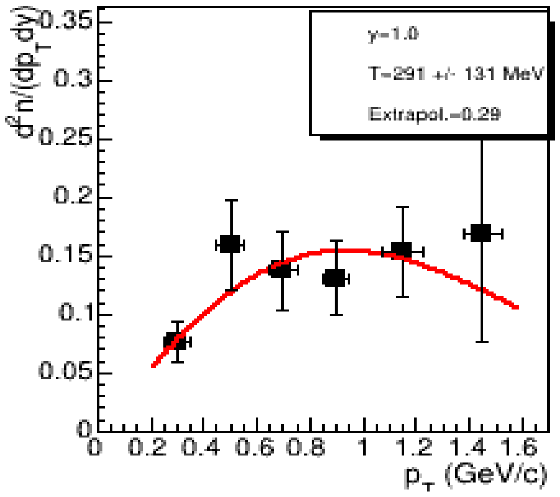


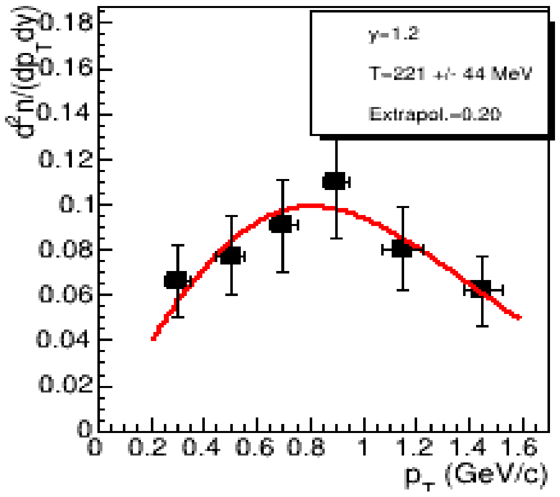
pT-spectra of tritons

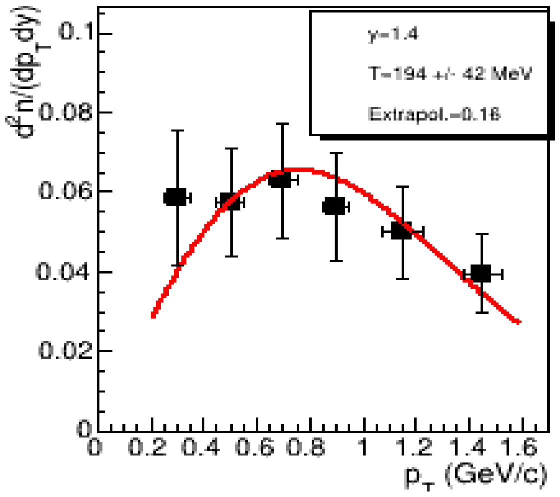
- Fit pT-spectra in rapidity bins by thermal function (*C * pT* exp{- (mT-m)/T}*)
- Rapidity density ***dn/dy*** = sum_of_data_points + extrapolation from fit function (i.e. integrals over unmeasured regions)

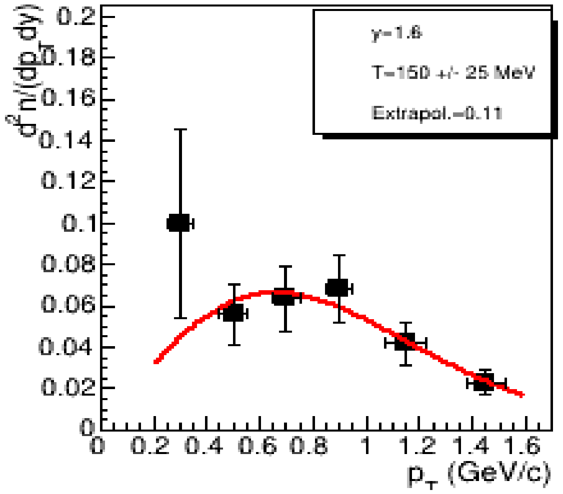
Ar + Sn (tritons)

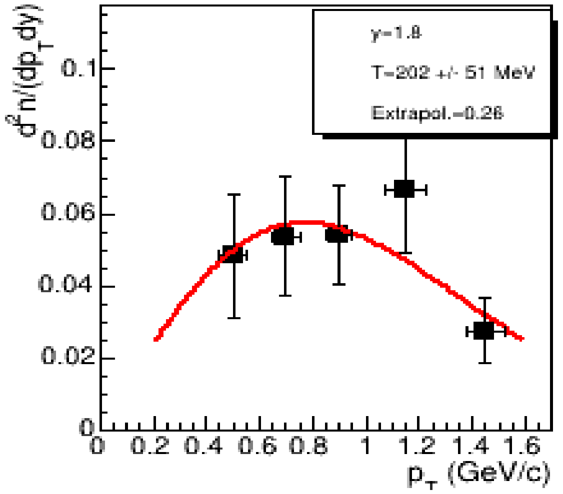












Summary on pT-spectra:

- No problems found for p,t
- deuterons: low pT-part of spectra at beam rapidity (is He4 contamination properly accounted for?)
- Thermal fit describes the shape of pT-spectra and can be used for extrapolation (dn/dy and <pT>)
- Extrapolation varies from 10% to 50%

BM@N results on spectra and yields

(a comparison to world data)

- Recently, STAR experiment published results on p, d, t, He3, He4 production in centrality selected Au+Au at 3 GeV from the RHIC/STAR Fixed Target Program. The publication can be found under arXiv:2311.11020v1 [nucl-ex].

- The same collision energy, but different system size and collision geometry!

- Nevertheless, a comparison among two experiments can be performed

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

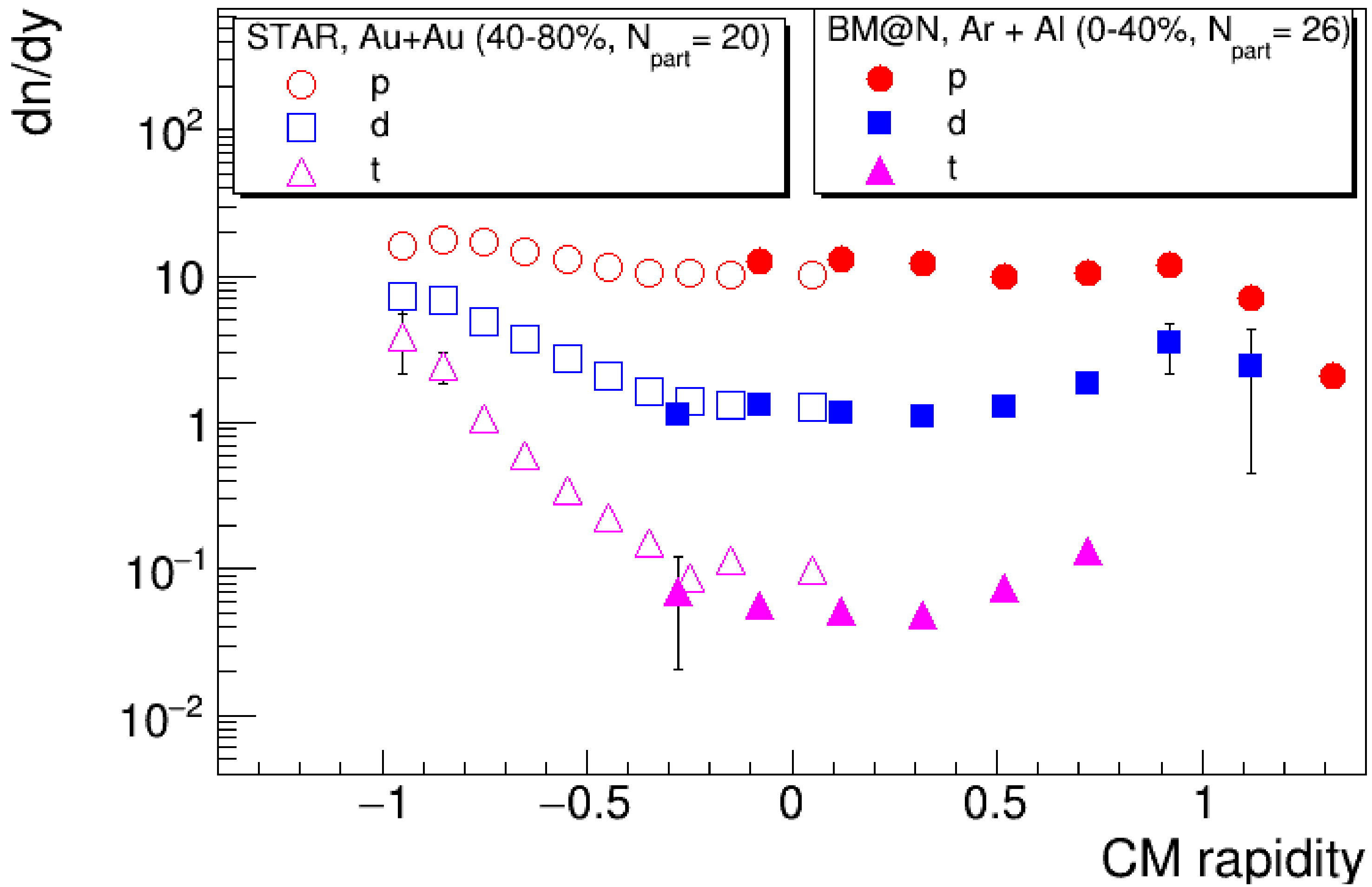
The STAR Collaboration

TABLE I. Centrality definition and the corresponding mean value of $\langle N_{\mathrm{Part}} \rangle$ along with the statistical and systematic uncertainties in Au+Au collisions at $\sqrt{s_{NN}} = 3\,\mathrm{GeV}$.

Centrality	FXTMult	$\langle N_{\mathrm{Part}} \rangle$
0 – 10%	195 – 119	$310.7 \pm 0.1 \pm 8.3$
10 – 20%	118 – 86	$224.2 \pm 0.1 \pm 8.0$
20 – 40%	85 – 41	$135.0 \pm 0.1 \pm 5.3$
40 – 80%	40 – 5	$39.7 \pm 0.1 \pm 1.9$

BM@N and STAR-FXT rapidity spectra

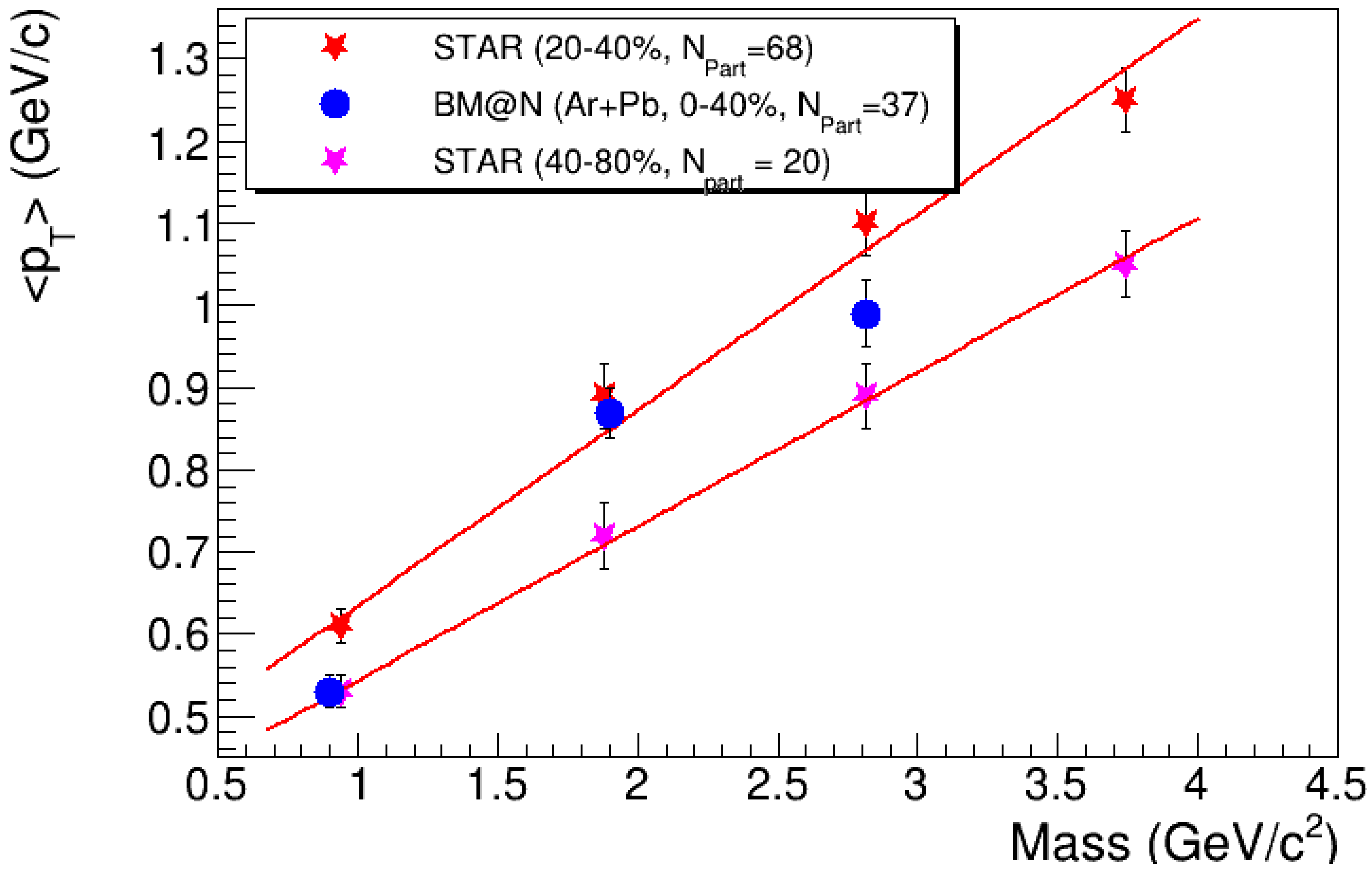
- Ar+Al 0-40% data set from BM@N (projectile Npart = 26) and 40-80% Au+Au (projectile Npart = 20) were used for comparison. Particle yields (approx.) scale with Npart



Collision geometry in Ar+Al and Au+Au is not fully identical, but the yields on p, d, t agree within 20% at midrapidity

BM@N and STAR-FXT <pT>

- Unfortunately, Npart-scaling can not be used for pT-spectra
- <pT> from BMN 0-40% Ar+Pb was tested against STAR in the range <u>bounded</u> by 20-40% and 40-80% Au+Au



- BM@N and STAR measurements for <pT> agree numerically
- STAR: <pT> in Au+Au rises linearly with particle mass
- BM@N : <pT> vs mass in central Ar+Pb has a convex shape
- Different density (collective velocity) profiles? Input from theory (model predictions) is required to make a conclusion….

Transverse dynamics at NICA

- Shapes of (pT)mT-spectra and slope parameters (<pT>) can be sensitive to the density and velocity profiles in the source

- Different density and flow profiles result in a different A-dependence of $\langle m_t \rangle$-m (<pT>) for clusters

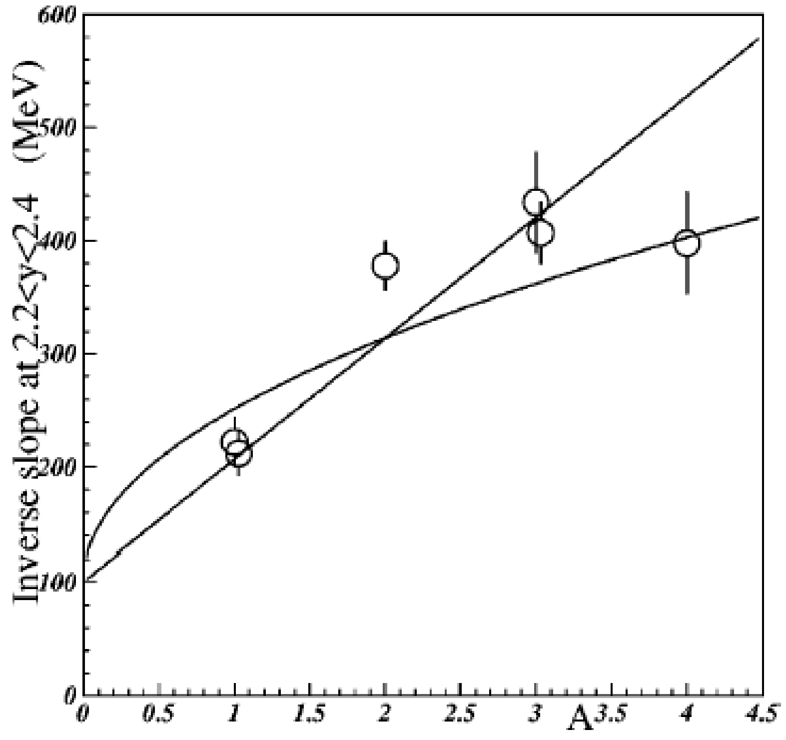
- Two of the most used ones give rise of $\langle m_t \rangle$-m (<pT>) vs A:
  1) Box spatial profile with a linear velocity profile ($\langle m_t \rangle - m \sim A$)
  2) Gaussian density profile with a velocity profile
  $$v(r)=v_f(r/R)^{\alpha},\ \alpha\sim[0.4\text{-}0.6]\ (\langle m_t \rangle - m \sim A^{1-\alpha})$$
  Polleri et al. PRC 61,064908

- The latter (i.e. density and velocity profiles) are crucial in blast-wave analysis of spectra (freezeout parameters)

- **Potentially can be addressed in the collisions of light and heavy nuclei, but requires an input from theory (models)**

At present, only and idea without realization

PHYSICAL REVIEW C, VOLUME 61, 064908



4 Baryon rapidity distributions, stopping and rapidity loss in Ar+A

The incoming nucleon loses its momentum during the collision and the mechanism of baryon transfer over finite rapidity distances (baryon stopping [1]) is an important theoretical problem for many years [2]-[4]. The baryon density, attained in high energy nuclear collisions, is a crucial quantity governing the reaction dynamics and the overall system evolution, including eventual phase transformations in dense nuclear matter. The measurement of rapidity distributions of stopped baryons in heavy ion collisions for different combinations of projectile and target as well as at different impact parameters provides essential constrains for the possible dynamical scenarios of baryon charge transfer. The advantage of the BM@N experiment at NICA is that the experimental arrangement of the detector makes it possible to measure the distribution of protons and light nuclei (d, t) over a rapidity interval y = (1.0 - 2.2). This rapidity range is wide enough to include particle rapidity density not only near the midrapidity (y_{CM} = 1.08), but also at the rapidity of the incoming nucleus, in contrast to the situation at the collider, where the acceptance of collider experiments does not include this range. Together with a sufficient p_T-coverage for nuclear clusters in BM@N, it makes possible to better determine the shape of the rapidity density distribution and derive information about rapidity and energy loss in the reaction.

- Nucleons in the Incoming nucleus loss their momentum in the reaction
- Simultaneous stopping of many nucleons within the interaction volume → baryon density can reach critical values for quark deconfinement and/or CSR
- Stopping has also strong impact on baryon number transport dynamics and building up of collective flow in (baryon rich) dense nuclear matter
- An important key to experimental exploration of these phenomena is systematic measurements of the rapidity distributions of baryons over a broad range of initial conditions (i.e. collision energy, system size and centrality)

BM@N advantage is a large phase space coverage (the whole forward rapidity range) and PID for baryons

Rapidity loss (stopping) in A+A collisions (II)

What must be analyzed?

- The average rapidity loss of the projectile is used as the characteristic quantity of the process
- Usually, one counts only leading baryons, so net-baryon distributions are analyzed. At BM@N energies the contribution of produced baryons is small – it's good!

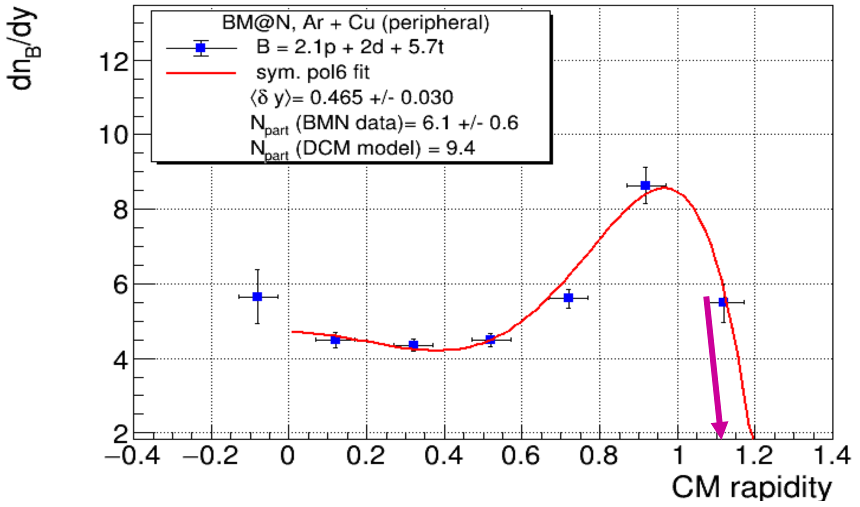
Potential problems / worries for BM@N:

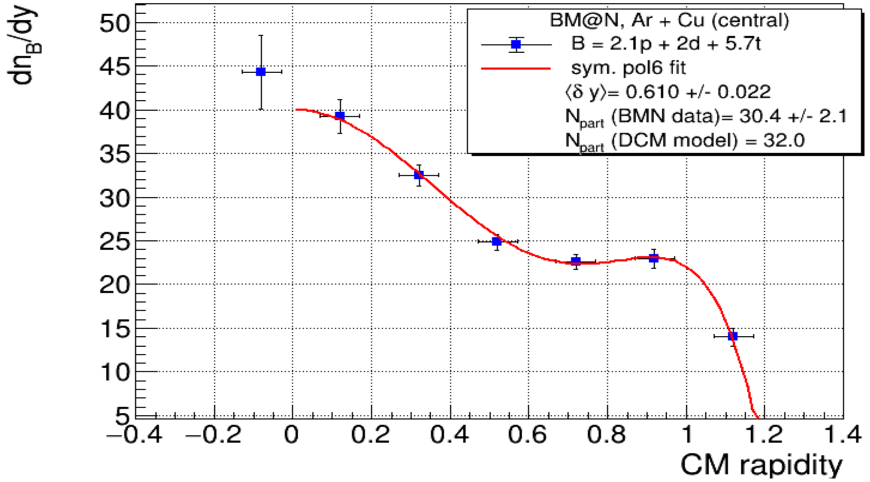
- For symmetric A1 + A2 collisions (A1 = A2) center-of-mass rapidity is the point of symmetry for rapidity spectra. If A1 != A2, however, and due to mixing of projectile and target nucleons the situation is more difficult.
- For example, in strongly asymmetric collisions, midrapidity does not have a well-defined kinematic definition and can vary with centrality
- If A1 != A2 beam-target contributions to rapidity spectra are not equal → a special treatment for contamination estimates

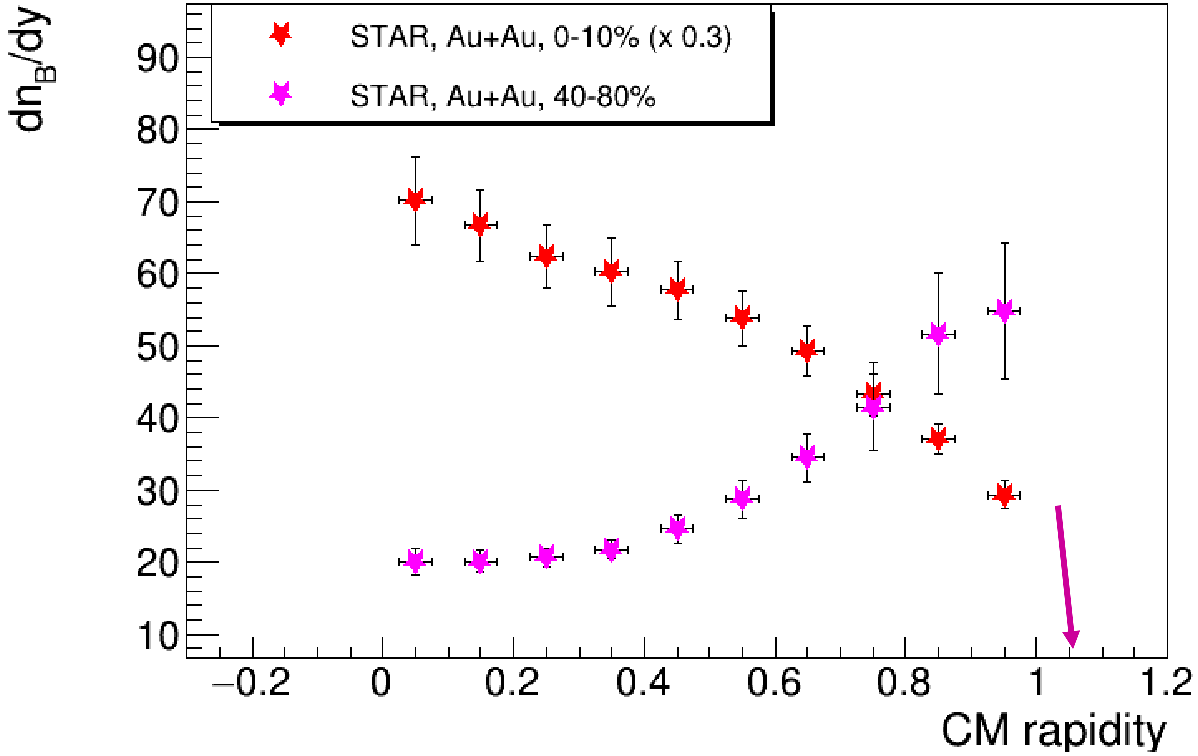
Rapidity loss (stopping) in A+A collisions (III)

- Before the collision, the baryon rapidity distribution consists of two peaks, centered near beam/target rapidity
- After the collision, the baryon rapidity distribution extends from below the beam rapidity (y=0) to somewhat has a complicated shape, which varies with centrality

[1] The STAR Collaboration, arXiv:2311.11020v1 [nucl-ex]



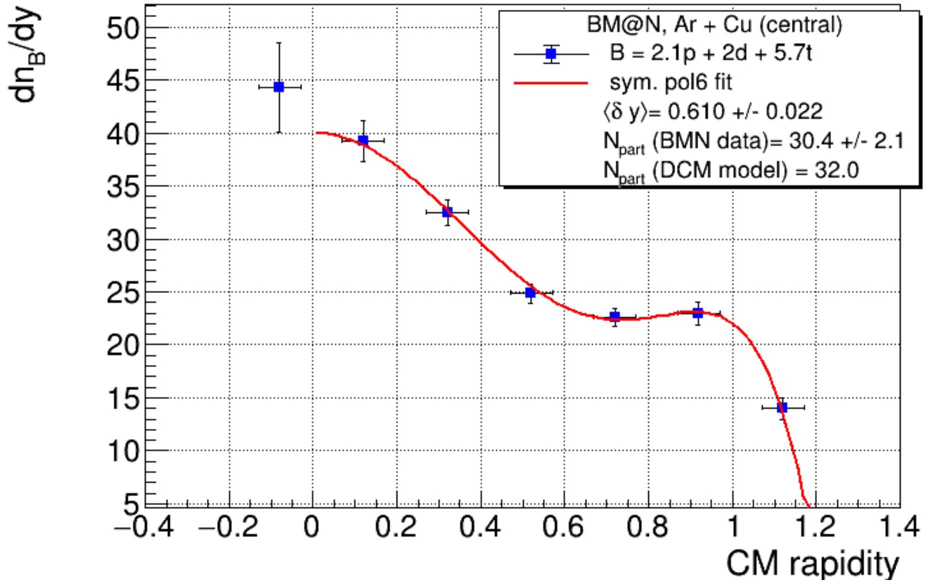


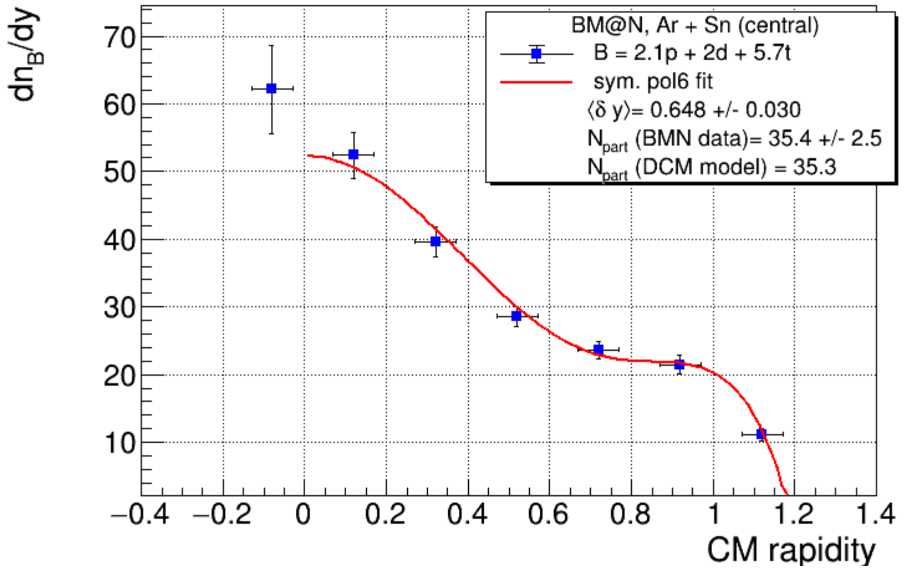


Rapidity loss (stopping) in Ar+A collisions. Analysis details.

The total baryon number in Ar+A collisions at NICA/BM@N energies is basically determined by nucleons and light nuclei ($d, t, {}^3$He). To obtain the baryon rapidity distribution, we add up the yield of protons, deuterons and tritons in every rapidity bin multiplied by the number of nucleons in compound particles. The obtained distribution should then be corrected for the fraction of unmeasured baryons: neutrons, hyperons and ^{3}He nuclei. Calculations with the PHQMD model indicate the n/p-ratio of about 1.1 in the forward hemisphere for all reactions. We assume that the $t/{}^3$He ratio is equal to n/p. Thus, the baryon yield B in a rapidity bin was then calculated as

$$B = 2.1 \cdot p + 2.0 \cdot d + 5.7 \cdot t$$





- Integrating rapidity spectra from y=0 to y_beam → an estimate for the number of (projectile) participants
- Agreement between data and model predictions in central Ar+A may indicate that contribution of target baryons in the projectiles is under control → must be validated (not done yet)!

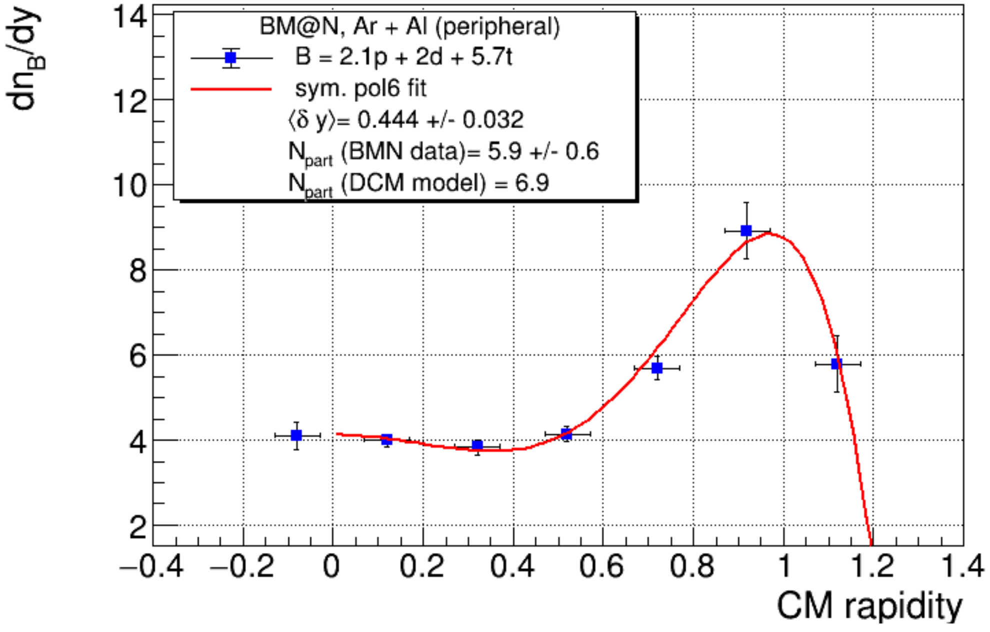
Rapidity loss (stopping) in Ar+A collisions.
Analysis details (II).

The mean rapidity loss is calculated as

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

where y_b is the rapidity of the projectile before the collisions and

$$\langle y \rangle = \frac{\int_0^{y_b} y \frac{dn}{dy} dy}{\int_0^{y_b} \frac{dn}{dy} dy}$$



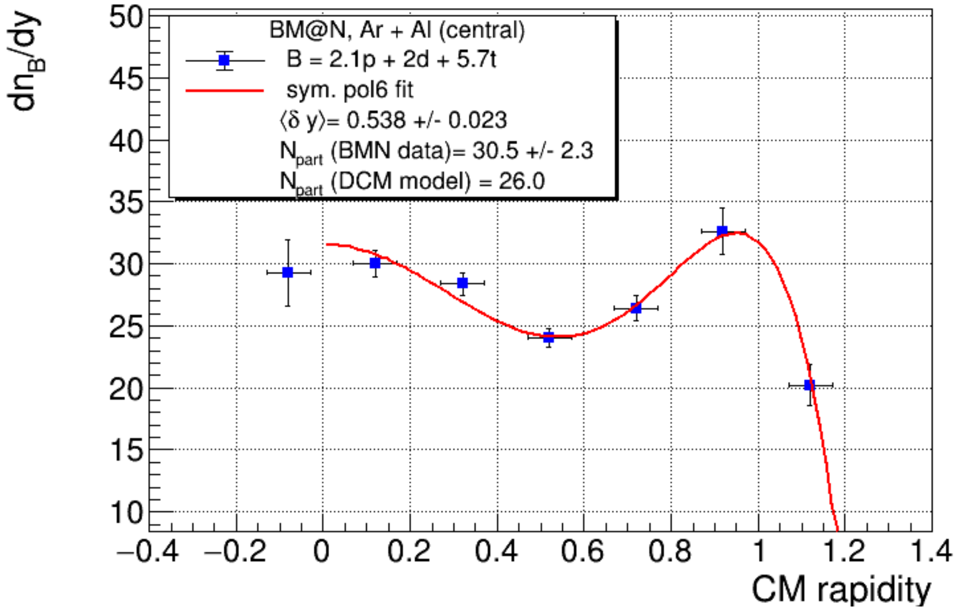


Table 2: Mean rapidity losses $\langle \delta y \rangle$ in Ar+A reactions.

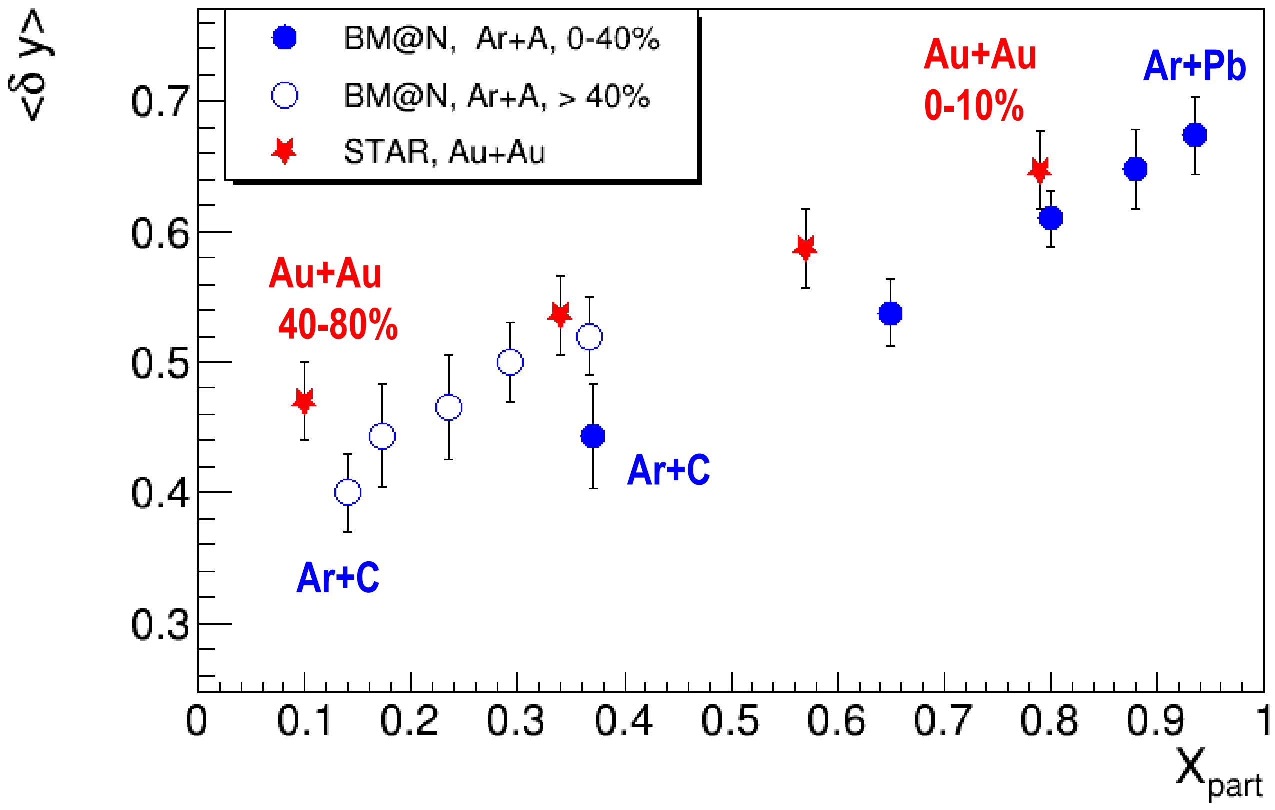
	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
0-40%	0.44 ± 0.04	0.54 ± 0.02	0.61 ± 0.02	0.65 ± 0.03	0.67 ±0.03
>40%	0.40 ± 0.02	0.44 ± 0.03	0.47 ± 0.03	0.50 ± 0.02	0.52 ± 0.02

Table 3: Mean rapidity losses $\langle \delta y \rangle$ in Au+Au collisions from the STAR experiment [5].

0-10%	10-20%	20-40%	40-80%
0.65 ± 0.03	0.59 ± 0.03	0.54 ± 0.03	0.47 ± 0.03

Rapidity loss in A+A reactions: symmetric vs asymmetric reactions

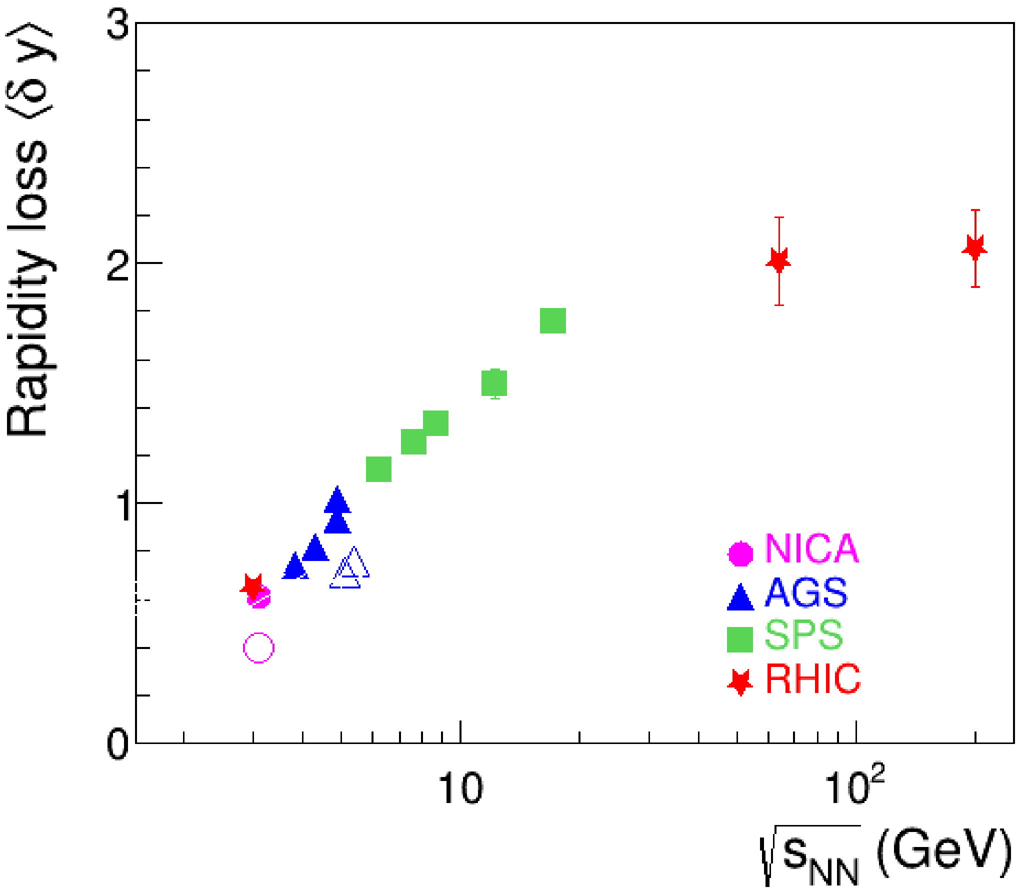
- To compare collision systems of different sizes, the results are tested against the variable: $X_{part} = N_{part}^{proj}/A_{proj}$
- Using Xpart allows putting of asymmetric and symmetric nucleus-nucleus collisions on a similar footing

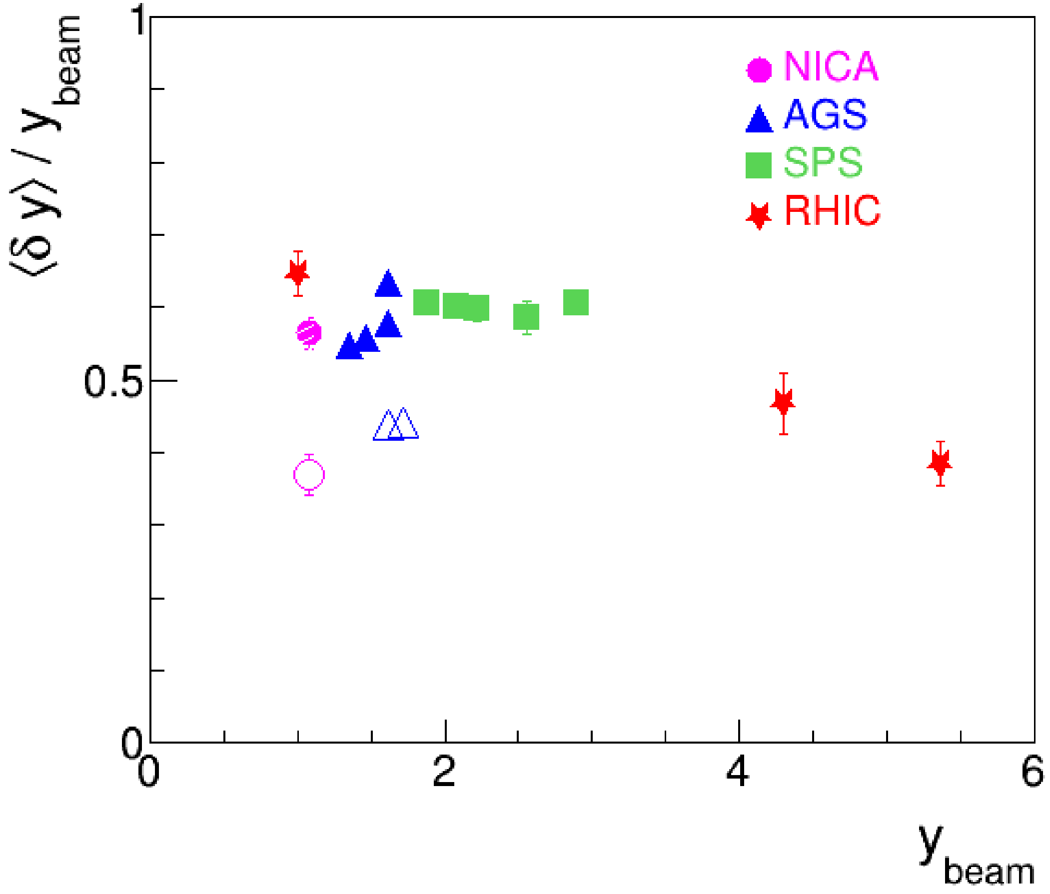


- Projectile rapidity loss rises in more central collisions and grows for heavier targets
- X_{part} indeed allows to compare systems of different geometry and size → 0-10% Au+Au and 0-40% Ar+Cu have similar <δy> values
- Asymmetric A1+A2 (A1 << A2) collisions are more effective in rapidity loss studies than collisions of heavy symmetric nuclei (must be validated after subtraction of target contribution!)

Rapidity loss in A+A reactions: excitation function

- Rapidity loss in central A+A collisions presented from low (NICA, STAR-FXT) to high energies (top RHIC)
- Data for p+p collisions are shown (see open symbols) at AGS and NICA (peripheral Ar+C)





- <δy> increases with collision energy, the rising slope changes after the top SPS
- Relative rapidity loss saturates from NICA to SPS, then drops. p+p data have no saturation.

5 Study of the mass dependence of particle yields

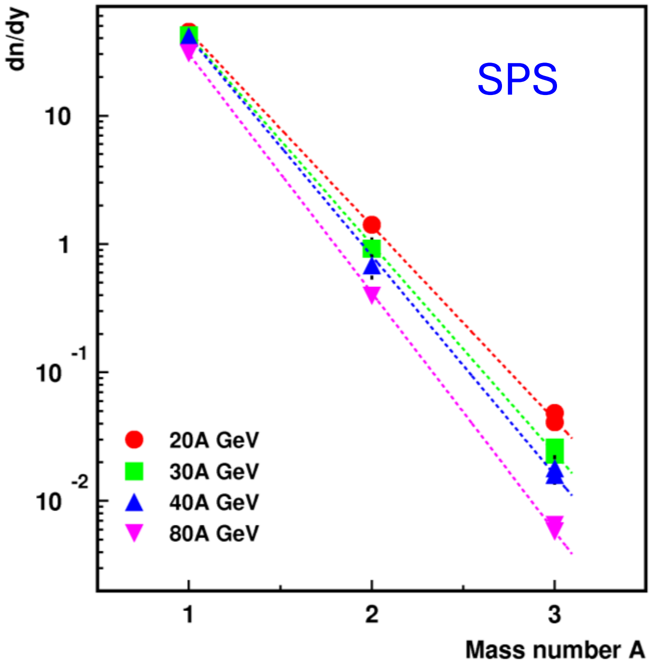
It has been established experimentally that cluster production yields decrease exponentially with the atomic mass number A [9, 10]. As an example, Figure 8 (left panel) presents midrapidity dn/dy for $p, d.t$ as a function of atomic mass number A from 0-40% central Ar+Sn collisions. The A-dependence of yields was fitted to a form:

$$dn/dy(A) = const/p^{A-1}, \qquad (4)$$

where parameter p ('penalty factor') determines the penalty of adding one extra nucleon to a system.

- 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
- In statistical thermal models, penalty factor for nucleon clusters determined by the fugacity and allows QCD phase diagram mapping (via T and μ_B)

Phys. Rev. C 94,044906 (2016).



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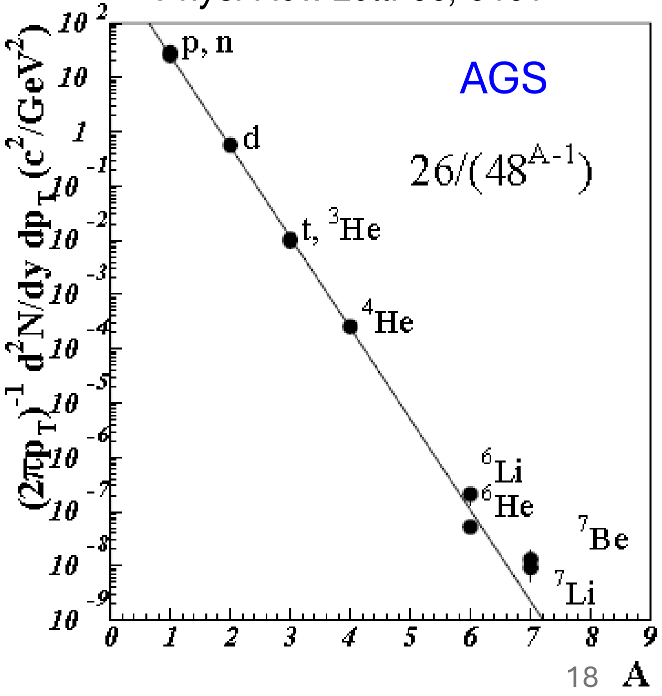
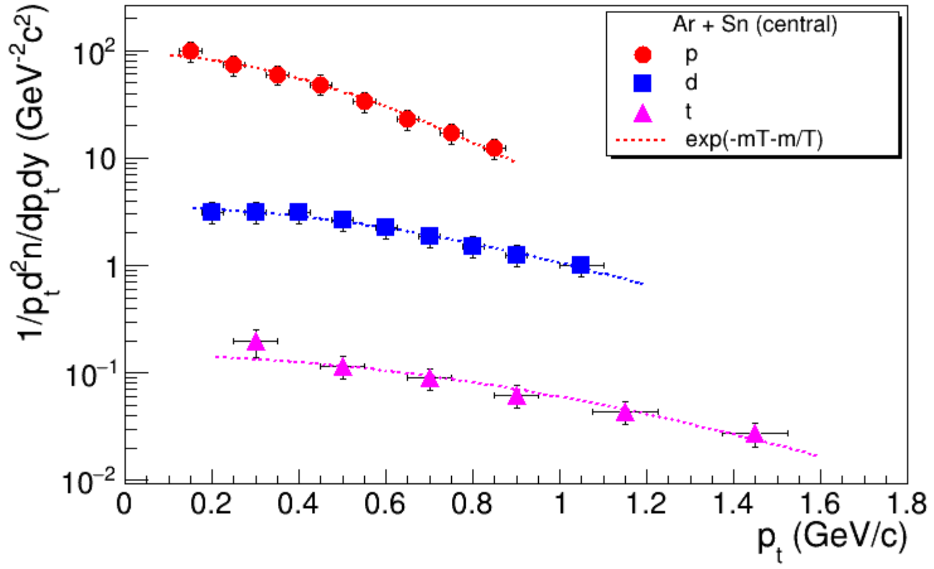
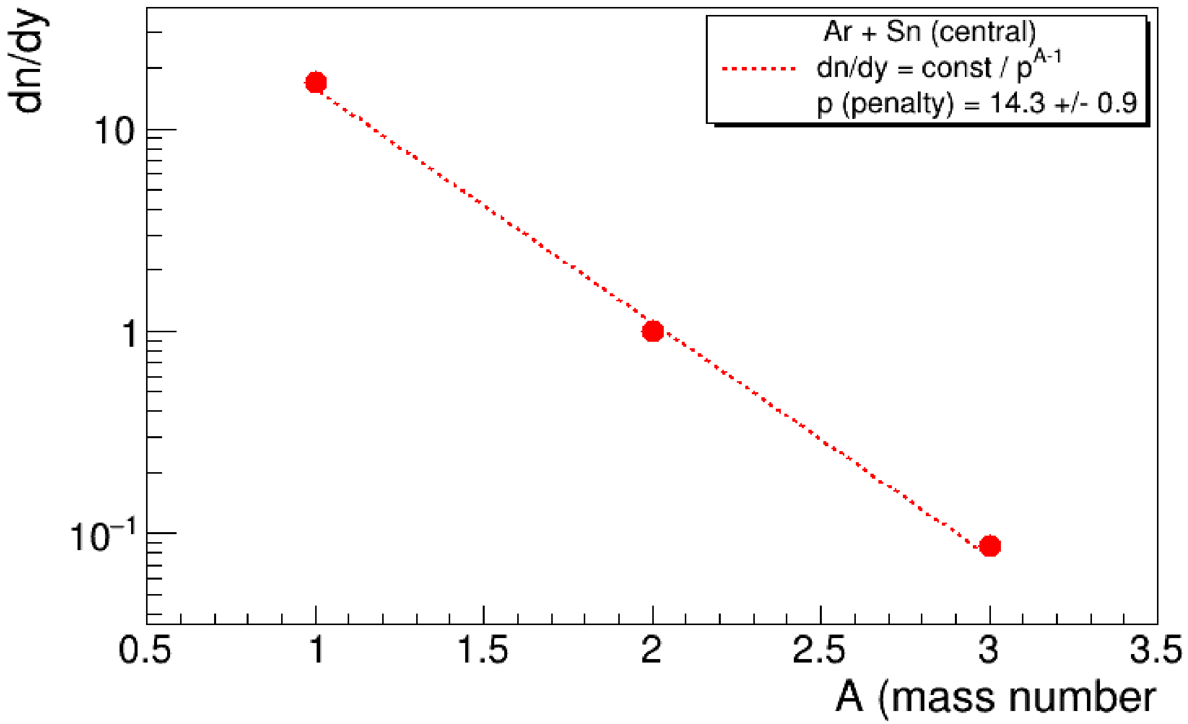
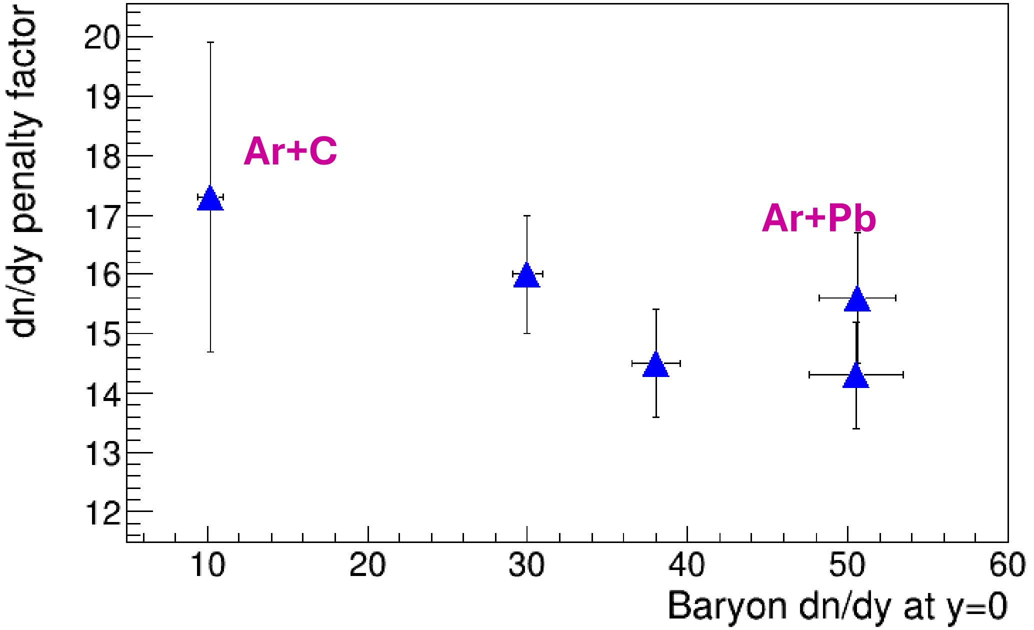


Particle yields & penalty factor in central Ar+A reaction in BM&N







Cluster formation probability favors larger baryon densities at NICA/BM&N energies (as expected, penalty less in more dense matter)

Penalty factor and QCD phase diagram mapping (an idea)

The penalty factor is sensitive to the nucleon density attained in the reaction (the larger density the smaller penalty) and in the framework of a statistical approach it is determined as follows

$$p = e^{(m-\mu_B)/T}, \tag{5}$$

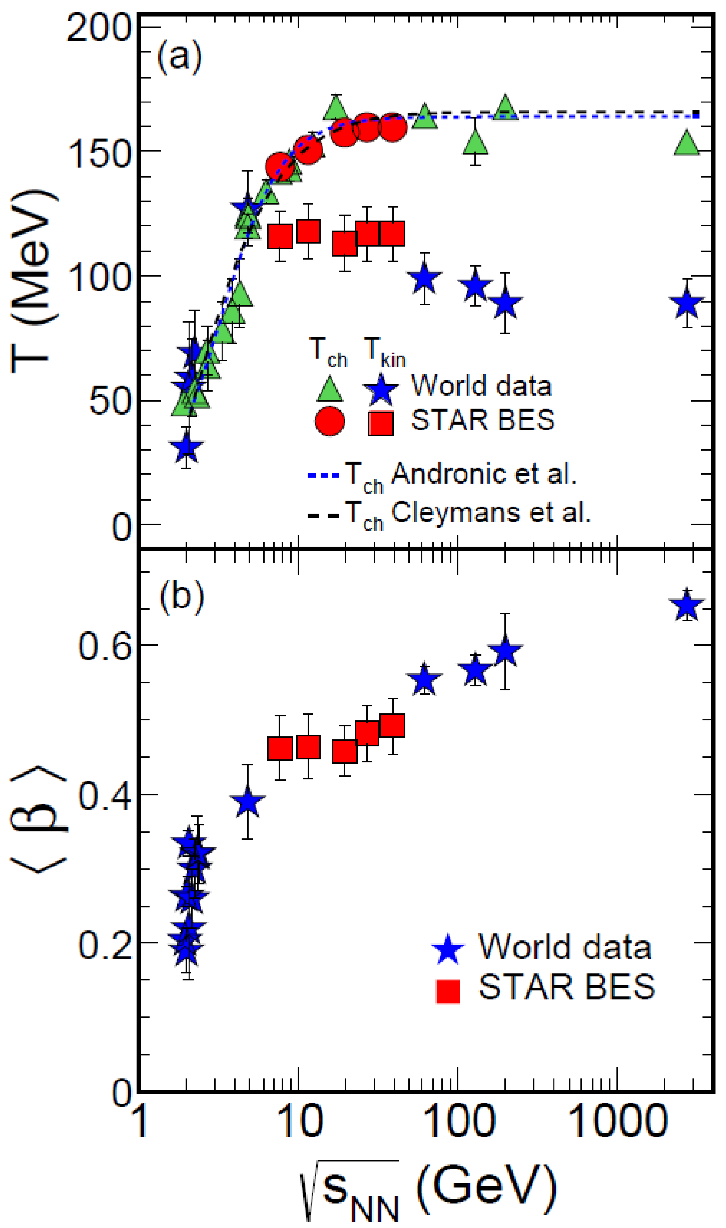
where μ_B, T, and m being the baryochemical potential, freezeout temperature, and nucleon mass, respectively. In

A practical method of freeze-out parameters estimation (T and μ_B) is analysis of hadron abundances in the framework of thermal statistical models. An alternative approach is the use of Eq. 5. As reported in Ref. [11], the values of kinetic and chemical freeze-out temperatures are similar in heavy-ion collisions below $\sqrt{s_{NN}} = 5$ GeV. Thus, we can use the value of T obtained in the analysis of transverse spectra of particles and reported in the paper draft as a good estimate for the freeze-out temperature. Converting Eq. 5, the formula for μ_B can be written as

$$\mu_B = m - T \ln p \tag{6}$$

A full collection of chemical and thermal freezeout parameters in A+A

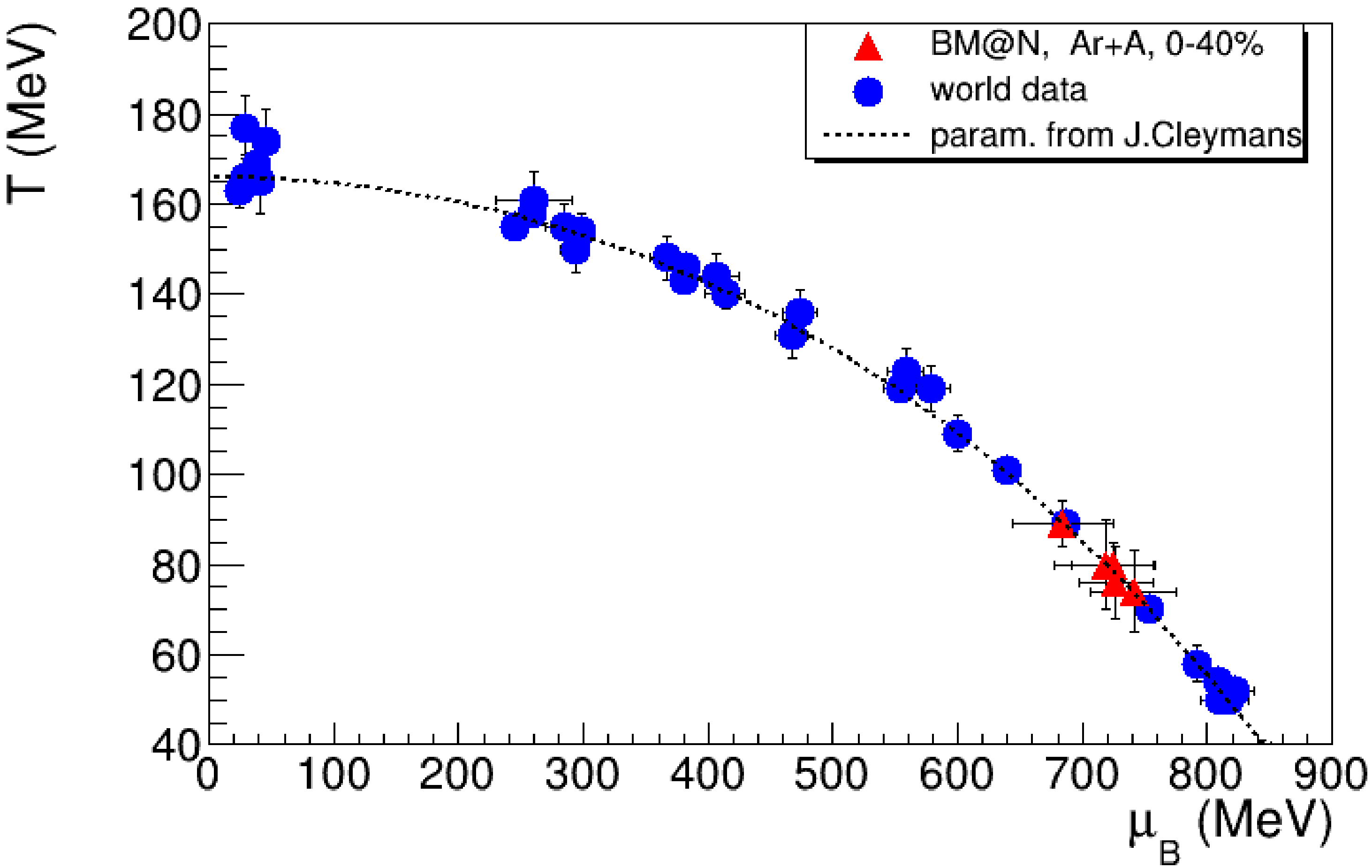
Phys. Rev. C 96, 044904 (2017)



- T_{ch} increases from 7.7 to 19.6 GeV; after that it remains almost constant and similar for all centralities
- T_{kin} increases from central to peripheral collisions suggesting longer lived fireball in central collisions
- $\langle\beta\rangle$ decreases from central to peripheral collisions suggesting stronger expansion in central collisions
- The separation between T_{ch} and T_{kin} increases with increasing energy suggesting the effect of increasing hadronic interactions between chemical and kinetic freeze-out at higher energies.
  As one can see, splitting between T_{kin} and T_{ch} is only above ~5 GeV, therefore, using at NICA/BMN energies a single T value, obtained from analysis of mT(pT)-spectra, is a reasonable approximation

Penalty factor and QCD phase diagram mapping (results)

- Data on hadron yields and ratios are analyzed in the framework of statistical model.
- An approach (parameterization) developed by J.Cleymans (a one from several!)



	p	T (MeV)	μ_B(MeV)
Ar+C	17.3 ± 2.6	89 ± 3	684 ± 40
Ar+Al	16.0 ± 1.0	76 ± 8	727 ± 30
Ar+Cu	14.5 ± 0.9	80 ± 5	724 ± 32
Ar+Sn	14.3 ± 0.9	74 ± 9	741 ± 34
Ar+Pb	15.6 ± 1.1	80 ± 10	718 ± 40

- Surprisingly, good agreement with world data and suggested parameterization
  The method is working!

- BM@N now has a hint about our niche in the QCD phase diagram!

Summary

- A post-analysis of BM@N data performed for pT-spectra and dn/dy distributions of p,d,t in Ar+A collisions – good agreement with the numbers from paper draft
- Data on particle spectra and yields from Ar+A (BM@N) tested against recent STAR measurements in Au+Au at 3 GeV – the agreement is satisfactory
- Rapidity spectra of baryons obtained, stopping power estimated, results compared to available experimental data, excitation function for $<\delta y>$ discussed
- Mass dependence of midrapidity particle yields analyzed, penalty factor obtained in central Ar+A collisions, the value of baryochemical potential was estimated
- A draft with the analysis details and discussion is prepared