BM@N results on light nuclei and prospects for the study of the production of nuclear clusters at NICA energies

V.I. Kolesnikov
VBLHEP, JINR

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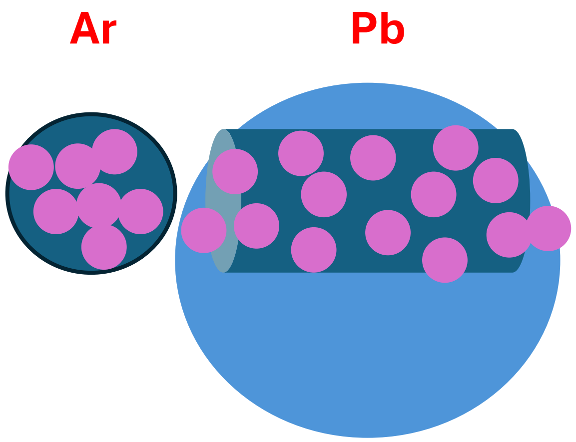
Topics I'd like to address in the talk

- Longitudinal dynamics and baryon rapidity loss
  - Baryon rapidity spectra
  - Rapidity loss $<\delta y>$ and its system size dependence
  - Energy dependence of $<\delta y>$, comparison to world data
  - Energy loss $<\delta E>$, $<\delta y>$ and $<\delta E>$ correlation

- Particle yield ratio and mass dependence of particle abundances
  - d/p ratio, its rapidity and system size dependence
  - Nucleon phase-space density in Ar+A collisions
  - Entropy-per-baryon *S/A*
  - Penalty factor in Ar+A and QCD phase diagram mapping

All listed topics are described in the recent version of the pdt-paper draft

Ar+A collisions : system size, N_{part} scaling , etc.

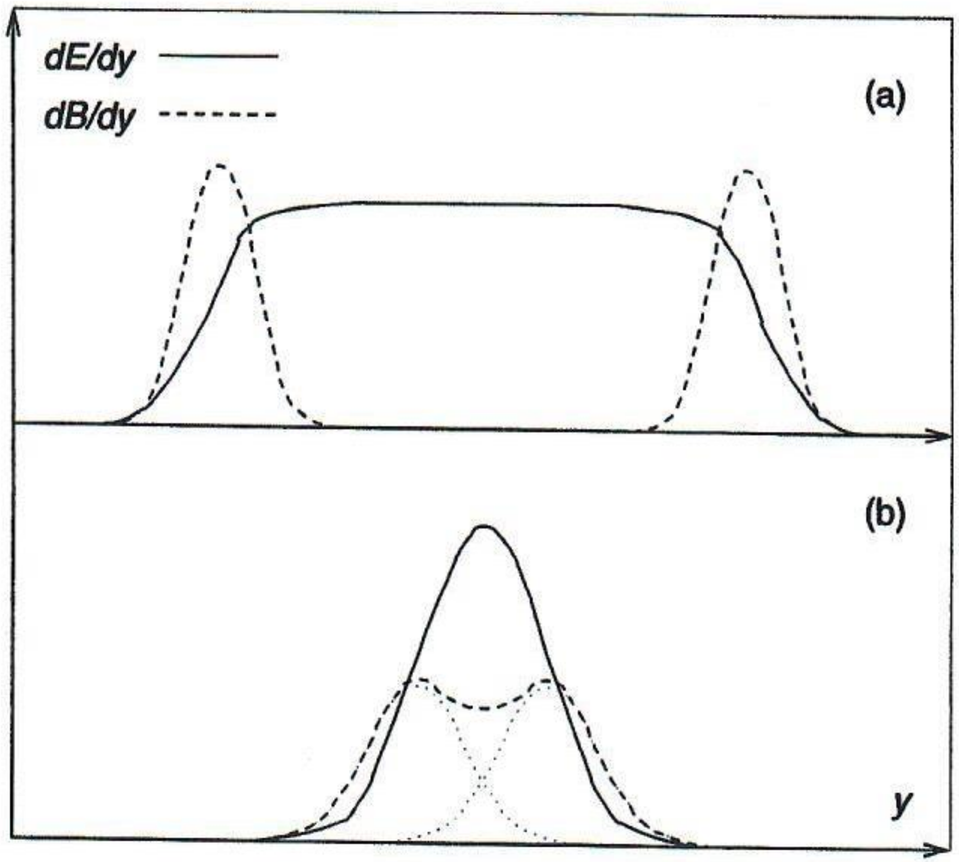


The size of the reaction zone (fireball) in A_1+A_2 is defined by:

- Atomic mass numbers $\boldsymbol{A_1, A_2}$
- Impact parameter ***b*** (collision centrality)
- Nucleon-nucleon cross-section

- The fireball volume is proportional to the number of participating nucleons N_{part} , while its shape is determined by *A* and *b*
- N_{part} can be obtained from a Glauber model
- *System size dependence* is a variation of an observable value as a function of *A, b*, or both
- It has been firmly established that the particle multiplicity in A+A is proportional to N_{part}
- N_{part}-scaling allows one to relate pion abundancies in minbias Ar+A (published by BM@N in JINST recently) to those in 0-40% central collisions by a scaling factors $(N_{part})^{0\text{-}40\%}$ / $(N_{part})^{minbias}$

Rapidity & energy loss in HIC



a) Bjorken picture : transparent for baryons medium, the only trail of energy (i.e. particle multiplicity) between y_p and y_t

b) **Fermi-Landau picture** : full stopping, i.e. initial longitudinal energy Inelastically transferred to produced particles, so, particle multiplicity(energy) and baryon number centered at y_{CM}

- In a full stopping scenario distribution of energy and baryon number in the longitudinal and transverse directions are similar

- But experimental data (FOPI) indicate that the full stopping does not appear to happen even in very central A+A at low energies *(see Phys. Rev. Lett. 92, 232301 (2004))*

Rapidity and energy loss mechanism (or baryon number transfer process in general) is crucial for understanding collisions dynamics, dense nuclear matter properties (compressibility, EOS etc.), entropy production, collective effects and phase transformations.

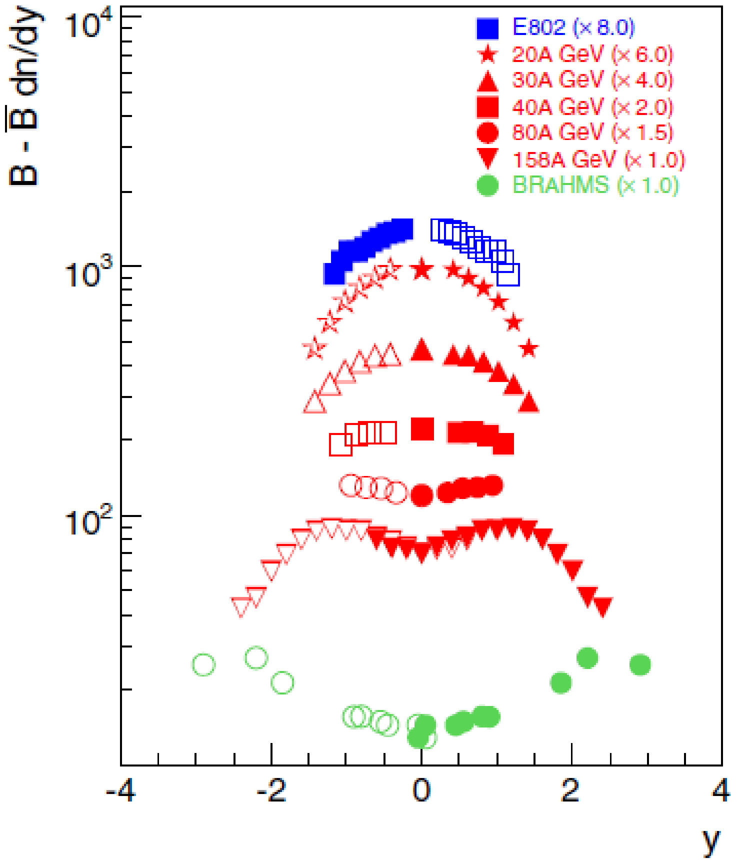
Stopping in A+A collisions: state of art

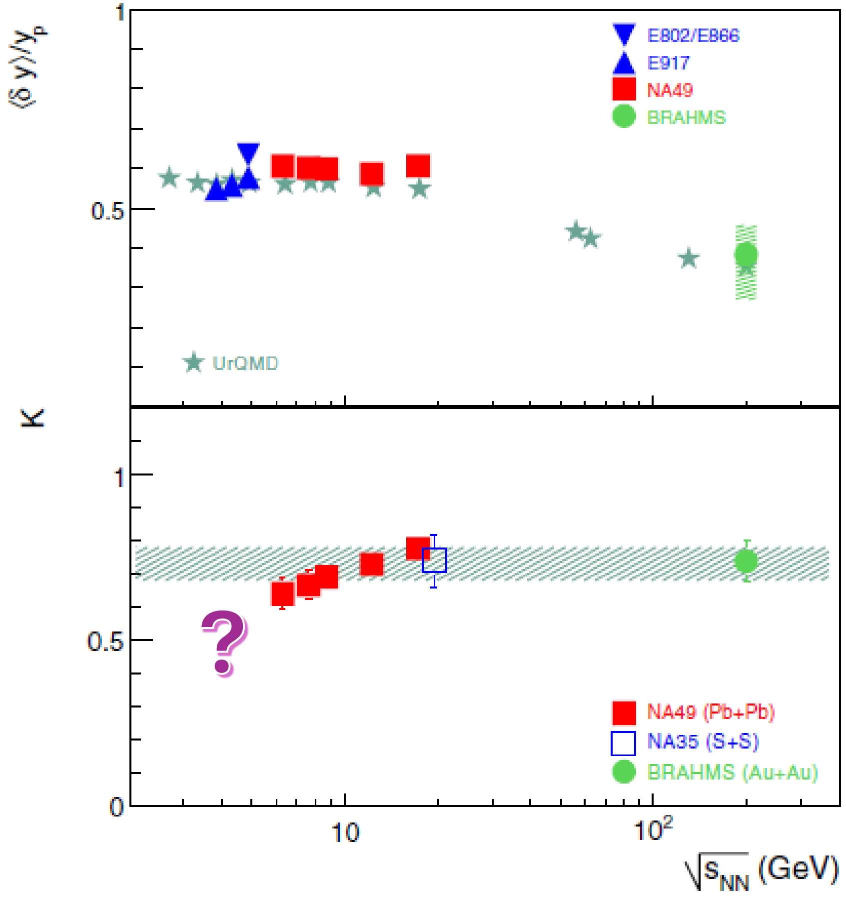
$$\langle \delta y \rangle = y_{\mathrm{p}} - \frac{2}{N_{\mathrm{part}}} \int_0^{y_{\mathrm{p}}} y \frac{\mathrm{d}N_{(\mathrm{B}-\bar{\mathrm{B}})}}{\mathrm{d}y}\,\mathrm{d}y$$

$$K = 2\,E_{\mathrm{inel}}/(\sqrt{s_{\mathrm{NN}}} - 2m_{\mathrm{p}})$$

$$E_{\mathrm{inel}} = \frac{\sqrt{s_{\mathrm{NN}}}}{2} - \frac{1}{N_{(\mathrm{B}-\bar{\mathrm{B}})}} \int_{-y_{\mathrm{p}}}^{y_{\mathrm{p}}} \langle m_{\mathrm{t}} \rangle \frac{\mathrm{d}N_{(\mathrm{B}-\bar{\mathrm{B}})}}{\mathrm{d}y} \cosh y\,\mathrm{d}y$$

Ch. Blume J.Phys. G: Nucl. Part. Phys. 34 S951 (2007)





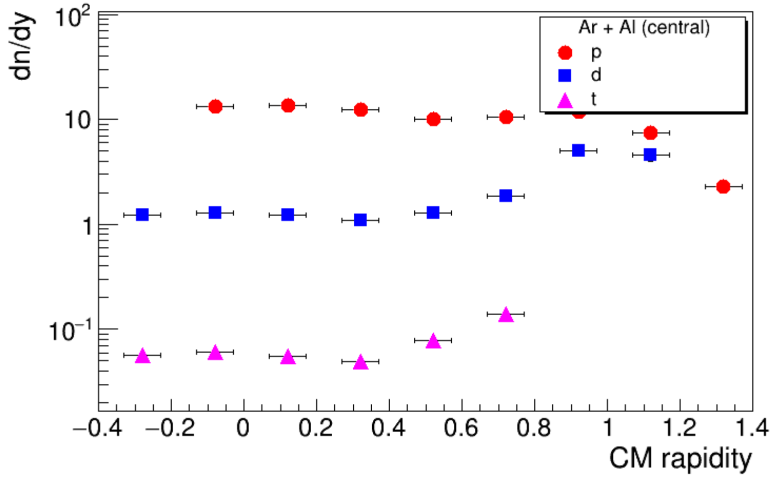
Overall picture:

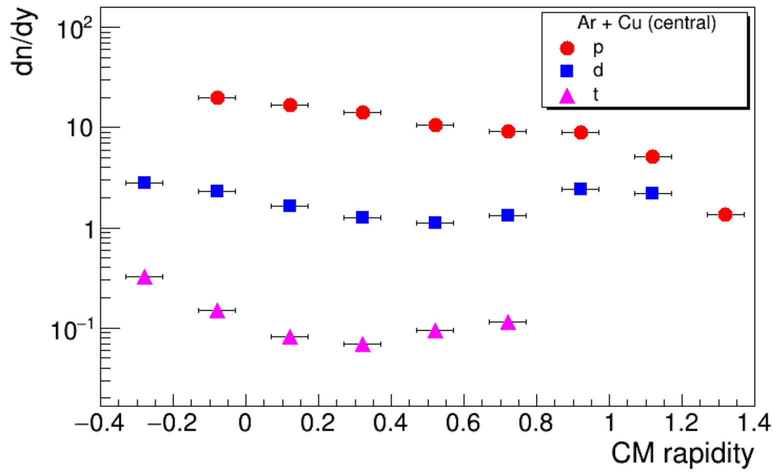
- As energy increases, a central (non-Gaussian) peak developing into a double-hump structure that widens toward RHIC leaving a plateau about mid-rapidity
- Rapidity scaling is working up to the top SPS energy. Decrease in opacity (i.e. nuclear transparency) and breaking of rapidity scaling above SPS energies.
- Inelasticity rises gradually up to SPS and levels off above

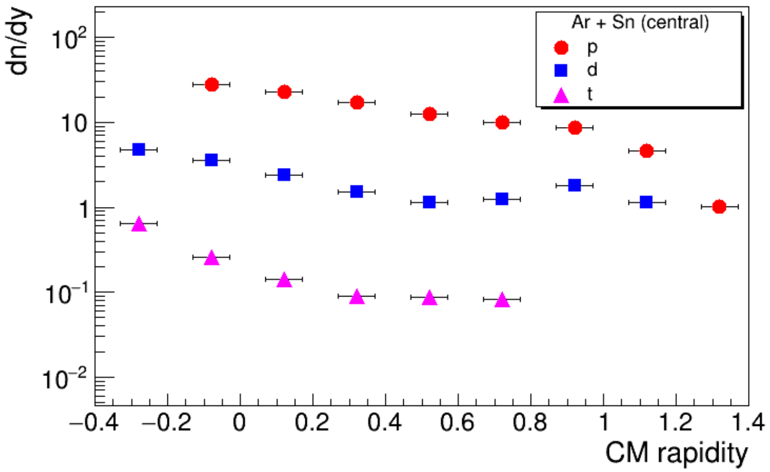
BM@N paper draft...

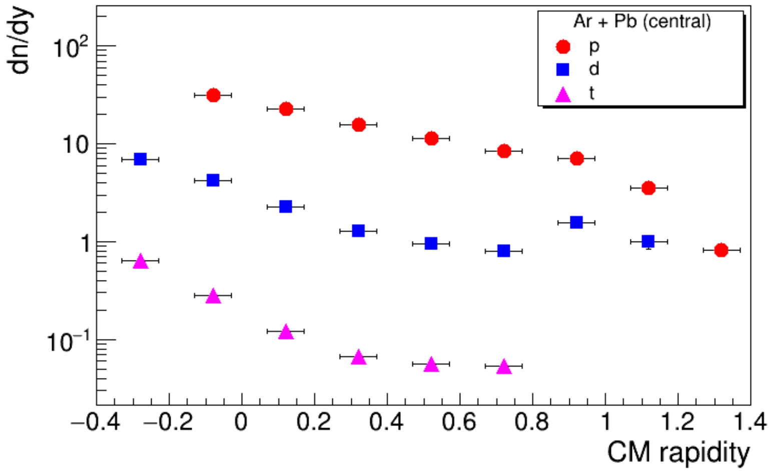
9 Baryon rapidity distributions, stopping and rapidity loss in Ar+A

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. The measured yield for every particle sort was multiplied by the number of nucleons in the compound system. The number of nucleons bound in clusters contribute to the total number of baryons up to about 15% and 25% in central Ar+C and Ar+Pb reactions, respectively. The obtained distribution should then be corrected for the fraction of unmeasured baryons: neutrons, hyperons and ^{3}He nuclei. Calculations with the PHQMD and UrQMD models indicate that for



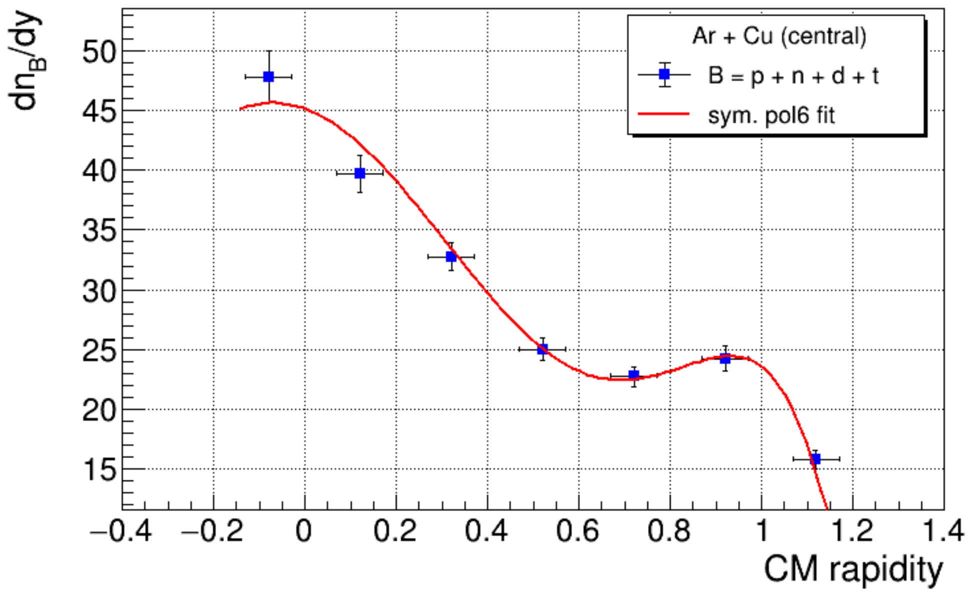






Rapidity loss (stopping) in Ar+A collisions. Analysis details.

The total number of baryons B in a rapidity bin was then calculated as
B = p + n + 2.0 · d + 5.7 · t,
where the coefficient in front of t is 5.7 = 3.0 (for tritons) + 3.0/1.1 (for 3He)



- Number of neutrons was estimated from UrQMD
- Tritons/helium-3 = n/p
- dn/dy fitted to 3rd degree in y^2 allowing integration in the chosen rapidity interval (as suggested by the BRAHMS/RHIC experiment)
- Issues related to midrapidity shifts and projectile-target mixing in asymmetric Ar+A were addressed (see supplementary slides)

Rapidity losses <δy> are obtained from the analysis of the shapes of baryon rapidity distributions utilizing the parameterization function

(For more baryon distributions see supplementary slides)

The average 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

$$\langle y \rangle = \int_{y_0}^{y_b} y \frac{dn}{dy} dy \Big/ \int_{y_0}^{y_b} \frac{dn}{dy} dy$$

Rapidity loss (stopping) in Ar+A collisions : system size dependence

Table 6: The average rapidity loss $\langle \delta y \rangle$ in Ar+A reactions

	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
0-40%	0.47 ± 0.03	0.54 ± 0.03	0.60 ± 0.03	0.62 ± 0.04	0.64 ± 0.04
>40%	0.39 ± 0.03	0.42 ± 0.03	0.47 ± 0.03	0.53 ± 0.04	0.55 ± 0.04

Discussion:

- Rapidity loss (or nuclear opacity) increases with the size of the source
- $<\delta y>$ has similar values in reactions producing similar fireball volumes (defined by N_{part}).

For example, peripheral Ar+Pb ($<\delta y>$=0.55, N_{part}=**47(3)**) and central Ar+Al ($<\delta y>$=0.54,N_{part} = **45.5 (3)**); or peripheral Ar+Cu ($<\delta y>$=0.47, N_{part} ~ **22**) and central Ar+C ($<\delta y>$=0.47, N_{part} = **30**)

DCM model (Genis)

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	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**

Rapidity loss in A+A collisions : excitation function

A thought : not only the total number of participants (system size) but also a number of multiple collisions should play a role. Moreover, with increasing energy nuclear matter becomes more transparent (see state-of-art slide).

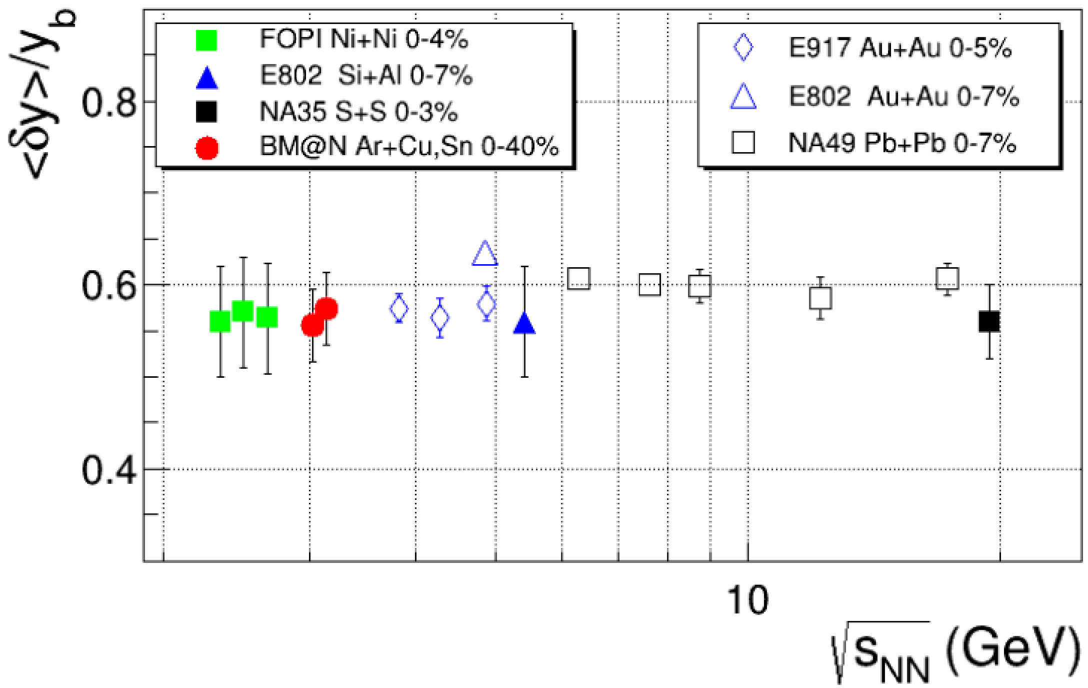


Figure 9: The excitation function of the scaled average rapidity loss $\langle \delta y \rangle / y_b$ in A+A collisions. Medium-size colliding systems are drawn by solid symbols, while heavy systems are shown by open ones. Centrality intervals are indicated in the legends. BM@N points for Ar+Cu and Ar+Sn reactions are displaced horizontally for the clarity.

Discussion:

- In medium size A+A collisions $<\delta y>$ scales with y_b
  (Note : in the shown by solid symbols systems #of_multiple_collisions is approx. the same)

- Surprisingly, similar trend in observed in heavy systems (Au+Au, Pb+Pb) – nuclear transparency begins to play a role even at low energies?

Prospects for the study rapidity and/or energy loss @ NICA (BM@N & MPD)

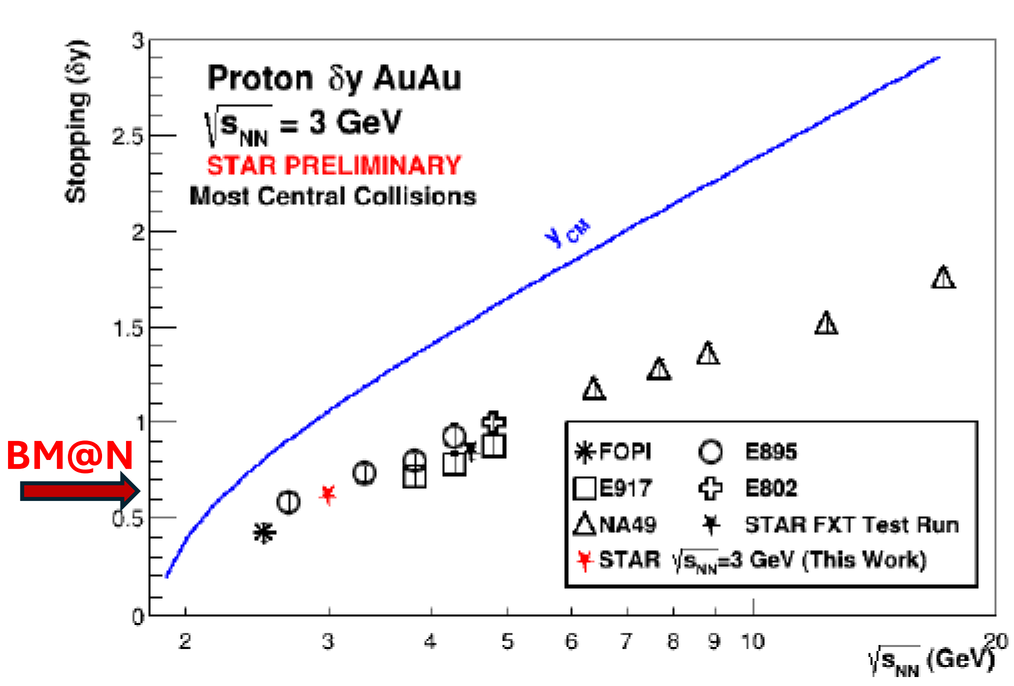
- Large phase-space coverage for nucleons and nuclear clusters (from midrapidity up to $y_{beam)}$ is crucial

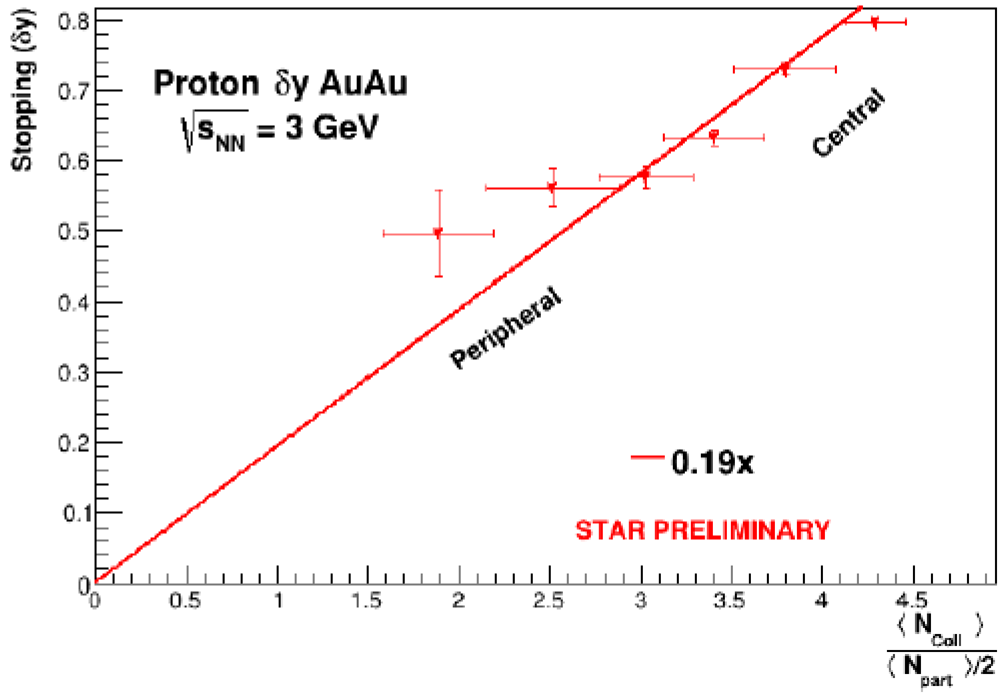
- Complementing centrality selected collisions of heavy nuclei (Au, Bi, Pb) with medium-size collisions allows one to perform consistency checks and extent the range of effective target opacity

- Extension of cluster nomenclature to He3, He4 allows more precise determination of the total baryon number in the reaction

- With all this – fill gap in the NICA energy range (and varying the system size) with the measurements of the rapidity and energy losses and $\langle\delta y\rangle$ - $\langle\delta E\rangle$ correlations

(Preliminary) results on stopping from STAR. Au+Au at 3 GeV (FXT program)



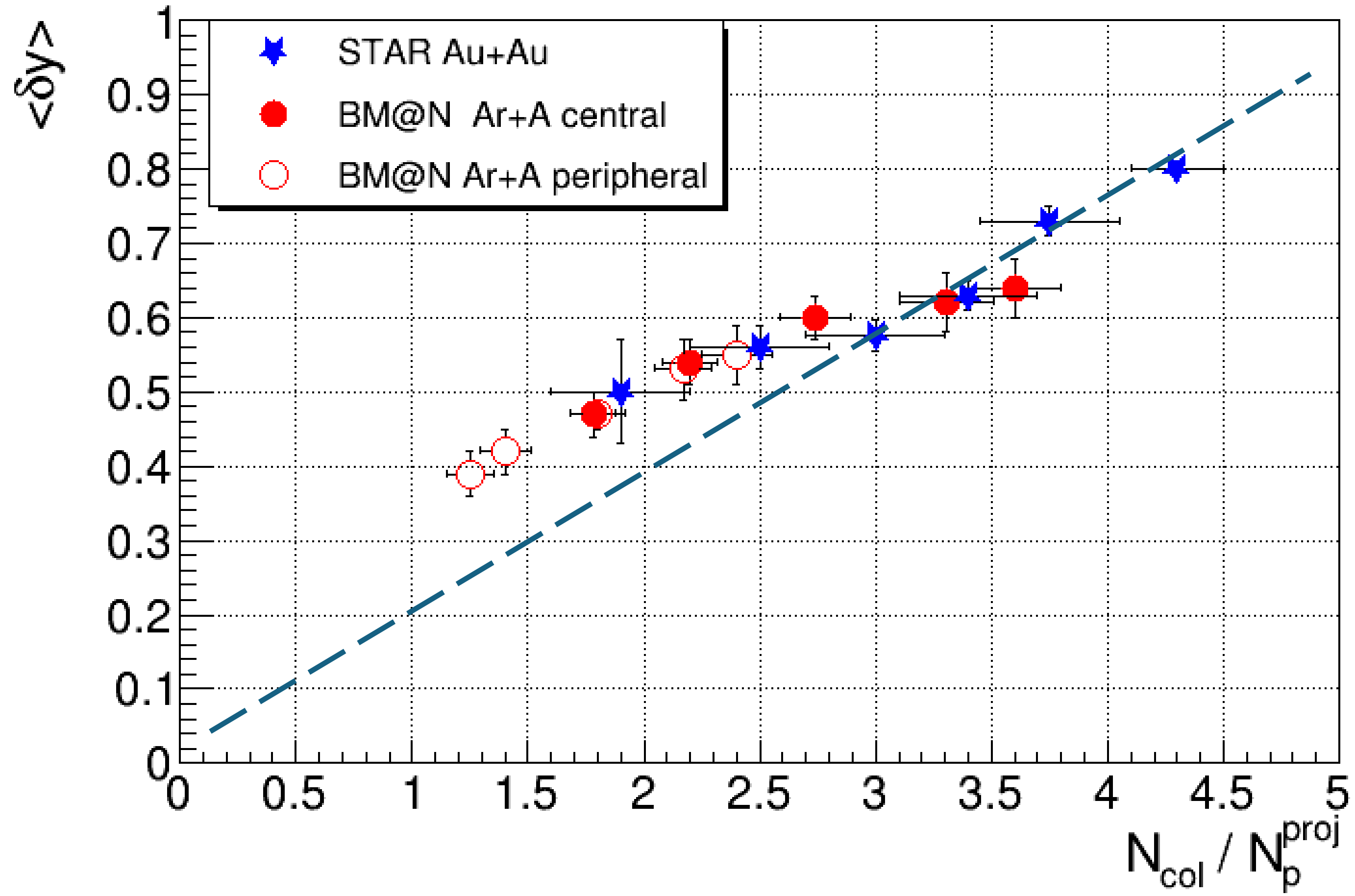


- Stopping at $\sqrt{s_{NN}} = 3.0$ GeV is consistent with measurements at similar energies
- Average loss of 0.19 ± 0.01 units of rapidity per nucleon-nucleon collision[6]

[1] W. Reisdorf *et al.* (FOPI Collaboration), Nucl. Phys. A **848**, 366 (2010)
[2] J. Klay *et al.* (E895 Collaboration), Phys. Rev. Lett. **88**, 102301 (2002)
[3] B. Back *et al.* (E917 Collaboration), Phys. Rev. Lett. **86**, 1970 (2001)
[4] L. Ahle *et al.* (E802 Collaboration), Phys. Rev. C **60** , 064901 (1999)
[5] C. Blume. (NA49 Collaboration) J. Phys. G **34**, S951 (2007)
[6] F.Videbæk and O. Hansen, Phys. Rev. C **52**, 2684 (1995)

BM@N vs STAR comparison of the stopping results : system size

- In A_p+A_t collisions the degree of target's opacity can be characterized by the number of collisions per participant
- Number of collisions per participant for Ar+A (BM@N) is obtained from a Glauber model



- Results on the system size dependence for <δy> in Au+Au (STAR) and Ar+A (BM@N) are consistent

- But the deviation from the *'0.19 per collision'* line can be more fundamental : no good explanation yet.
  It seems that there are 2 lines (trends): for light and for heavy systems (+ a transition region between them).
  As an idea: every successive collision is less "efficient" in the rapidity loss process
  <δy> ~ 0.45 for Ncol/Npart = [1..2]
  <δy> ~ 0.55 for Ncol/Npart = [2..3]
  <δy> ~ 0.67 for Ncol/Npart = [3..4]

Energy loss in Ar+A collisions. Analysis details and prelim. results.

The study of the rapidity loss can be complemented by results on the loss in energy. The average energy loss (inelastic energy per baryon) is calculated as

$$\langle \delta E \rangle = E_b - \int_{y_0}^{y_b} E(y) \frac{dn}{dy} dy \Bigg/ \int_{y_0}^{y_b} \frac{dn}{dy} dy, \quad (1)$$

where $E_b = 1.54$ GeV (total initial energy per nucleon in the center-of-mass system) and $E(y) = m_T\, cosh(y)$. The transverse mass value was calculated as $m_T = m + T + T^2/(m + T)$, where T is the slope parameter and m is the proton's rest mass. As can be seen from Table 7, the average energy loss increases

Table 7: Average energy loss $\langle \delta E \rangle$ (GeV) in Ar+A reactions.

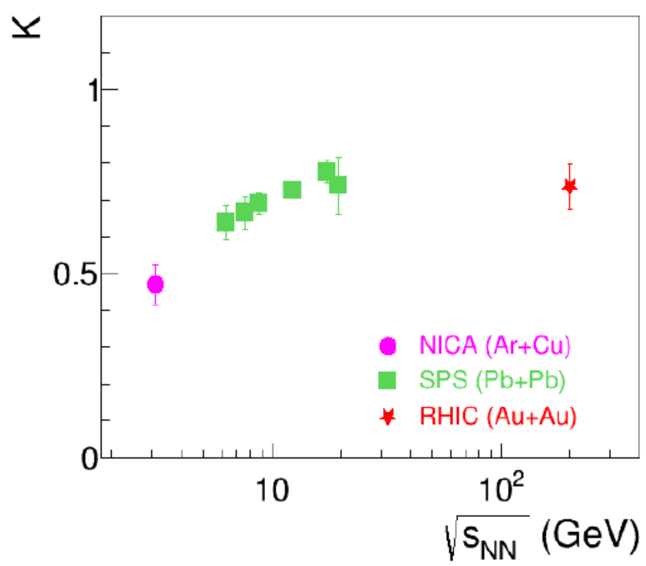
	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
0-40%	0.275 ± 0.015	0.295 ± 0.010	0.347 ± 0.006	0.37 ± 0.008	0.384 ± 0.013
>40%	0.259 ± 0.018	0.266 ± 0.012	0.289 ± 0.012	0.310 ± 0.005	0.327 ± 0.006

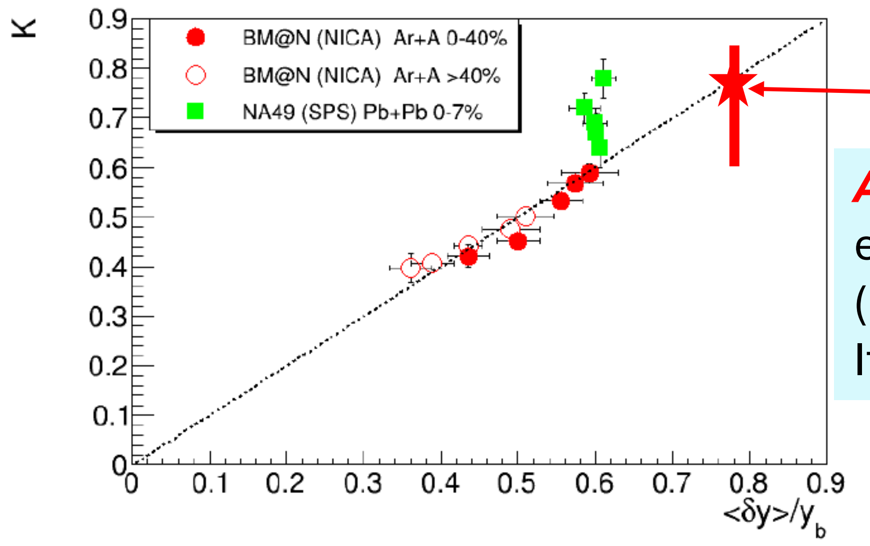
- The average energy loss is larger in more central collisions and increases with the target mass number

Energy loss in Ar+A collisions

Inelasticity ***K*** – fraction of the initial kinetic energy (per nucleon) transferred to entropy production in the reaction(i.e. particle production and their thermal motion)

$$K = 2\,\langle \delta E \rangle / (\sqrt{s_{NN}} - 2\,m_p)$$





A note: the correlation does not evolve smoothly with energy (i.e.from read to green symbols) Its actual trace is not known!

Figure 10: Left: The energy dependence of the reaction in-elasticity K (see text for detail) in central A+A collisions. The value from central Ar+Cu collisions represents BM@N results. Right: K as a function of relative rapidity loss.

- Up to 50% of the initial kinetic energy is transferred to the energy of produced matter in Ar+A at NICA/BM@N
- Relative rapidity and energy losses are perfectly correlated in the NICA energy range → an indication that baryon number transfer defines the overall reaction dynamics. Correlation may break down if gluon dof start playing a role?

Some more results on

- Particle ratios
- Nucleon phase-space density
- Entropy
- Penalty factor and QCD phase-diagram mapping

Deuteron-to-proton ratio R_{dp}

Following the prescription from M.J. Murray , J. Phys. G 28, 2069 (2002)

Particle phase-space density is defined as $f(\mathbf{x},\mathbf{p}) \equiv \frac{(2\pi\hbar)^3}{(2J+1)} \frac{d^6N}{dp^3dx^3}$

Spatial-averaged phase-space density <f> related to the ratio of deuterons to protons as $\langle f_i(\boldsymbol{p})\rangle = \frac{\int f_i^2(\boldsymbol{p},\boldsymbol{x})d\boldsymbol{x}}{\int f_i(\boldsymbol{p},\boldsymbol{x})d\boldsymbol{x}} = \frac{1}{3}\left(E_d\frac{d^3N_d}{dp_d^3}\right)\Big/\left(E_p\frac{d^3N_p}{dp_p^3}\right).$

Several assumption in phase-space density estimates should be underlined

1) For an equilibrated system: $f(E) = \frac{1}{e^{(E-\mu)/T} \pm 1},$

2) If the particle source is diluted (f << 1): $f \sim e^{-(E-\mu)/T} = e^{-E/T} e^{\mu/T}$

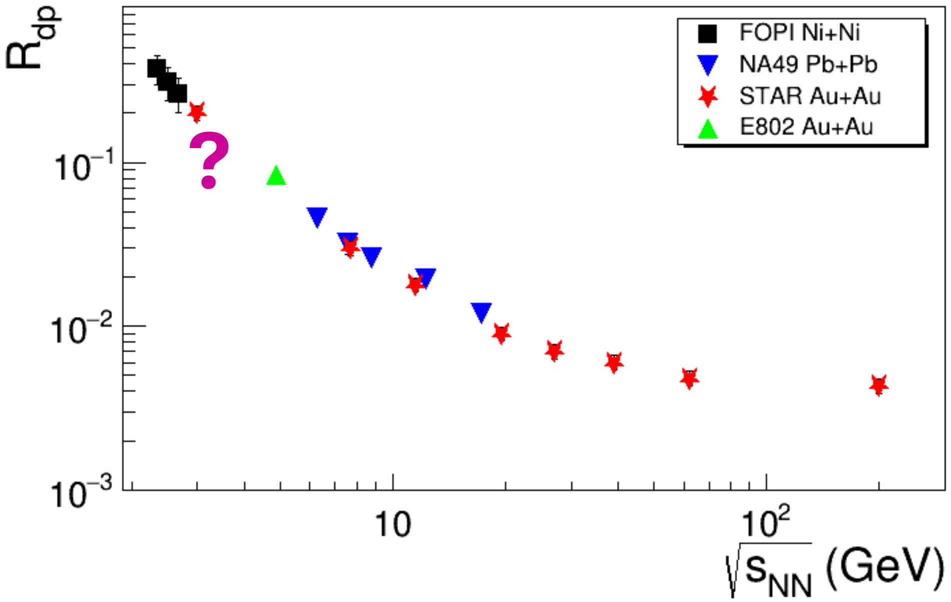
- Thus, an interplay between baryochemical potential μ/T (fugacity) and E/T defines rapidity and pT dependence of <*f*> (and R_{dp})

- In particular, at a given rapidity <*f*> decreases exponentially with mT (since $E = m_T cosh(y)$) with a slope T which includes the strength of radial flow

- At forward rapidity <*f*> and R_{dp} rise exponentially if the factor $e^{\mu/T}$ toward the beam rapidity overcomes

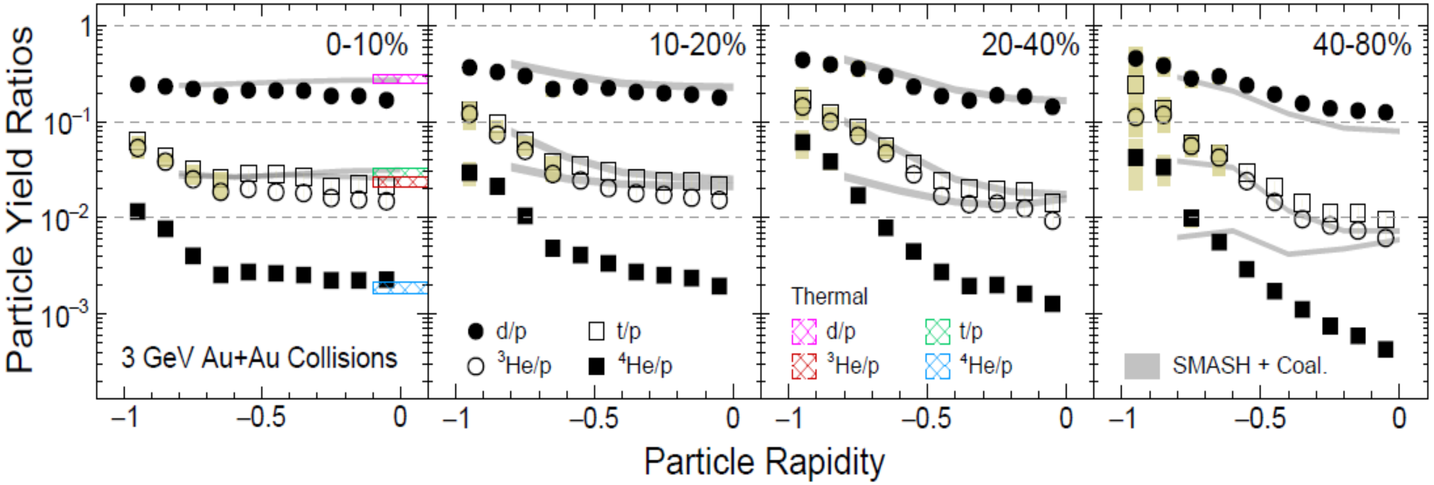
State-of-art : phase-space density <f> and R_{dp} in HIC

Midrapidity R_{dp} (and <*f*>) decrease with energy. Fireball expansion cause the baryons occupy a bigger volume and spread over a wider momentum range. More diluted medium at the freezeout at AGS/SPS/RHIC.



R_{dp} is flat vs rapidity in central Au+Au (saturation of <*f*>) and rises towards yb in peripheral collisions (effect of $e^{\mu/T}$?)

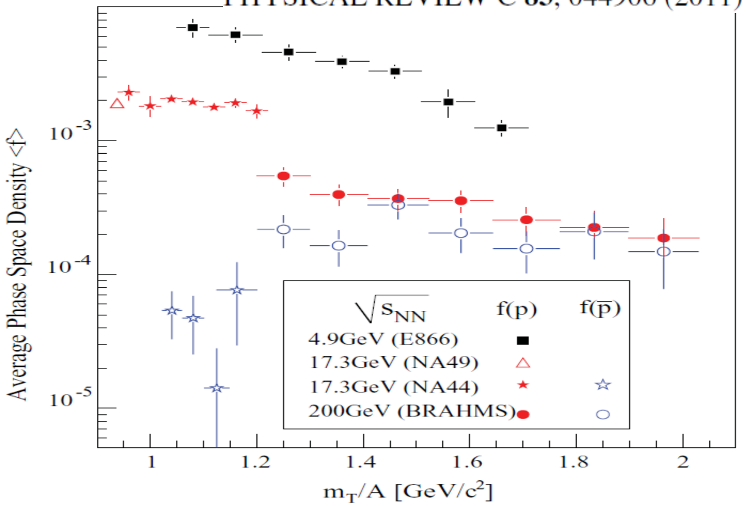
STAR, Au+Au @ 3 GeV (FXT), arXiv:2311.11020v1



An aim of the study at BM@N:
what is the R_{dp} (<*f*>) dependence on system size at NICA energies?

- Average phase-space density <*f*> depends strongly on mT.
- The larger collision energy and stronger radial expansion the flatter is the mT-dependence

PHYSICAL REVIEW C **83**, 044906 (2011)



BM@N results. Deuteron-to-proton ratio R_{dp}

- R_{dp} is simple, but potentially fruitful probe to test nuclear matter properties
- It proportional to the baryon phase-space density and governs nuclear cluster formation process

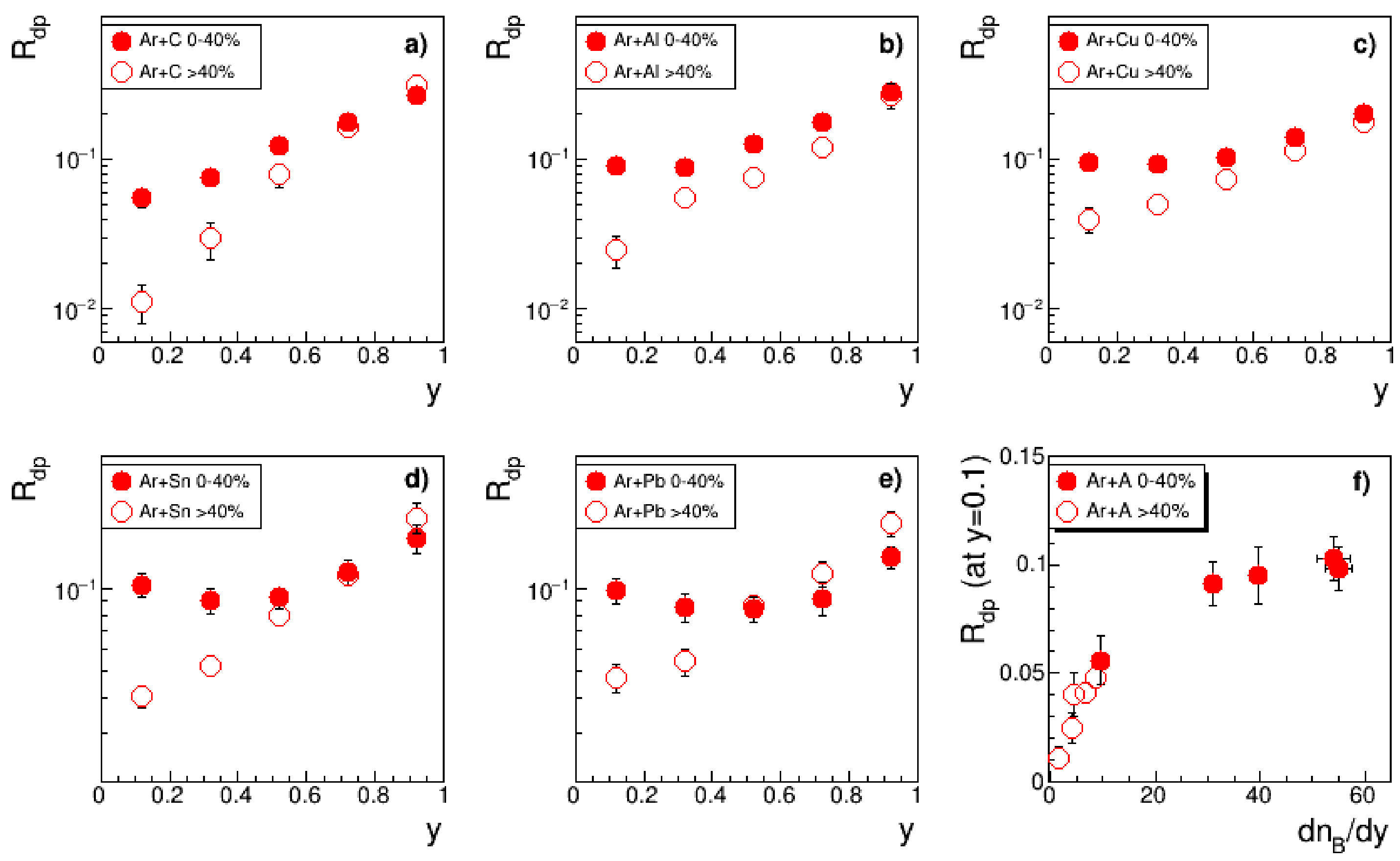


Figure 11: R_{dp} as a function of center-of-mass rapidity y in Ar+C (a), Ar+Al (b), Ar+Cu (c), Ar+Sn (d), and Ar+Pb (e) collisions. Central and peripheral collisions are shown by solid and open symbols, respectively. f): Midrapidity R_{dp} as a function of midrapidity baryon density dnB /dy in Ar+A collisions

- R_{dp} rises with rapidity in peripheral Ar+A collisions (baryochemical potential plays a role)
- R_{dp} indicates a plato in central Ar+A. The saturation region in Ar+Pb extends up to y_b.
- System size dependence of the midrapidity R_{dp} indicates a saturation in central Ar+A

Averaged nucleon phase-space density <*f*> in Ar+A

- Midrapidity d/p-ratios obtained in central Ar+A at 3 pT/A values (data points shifted along x for clarity)

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

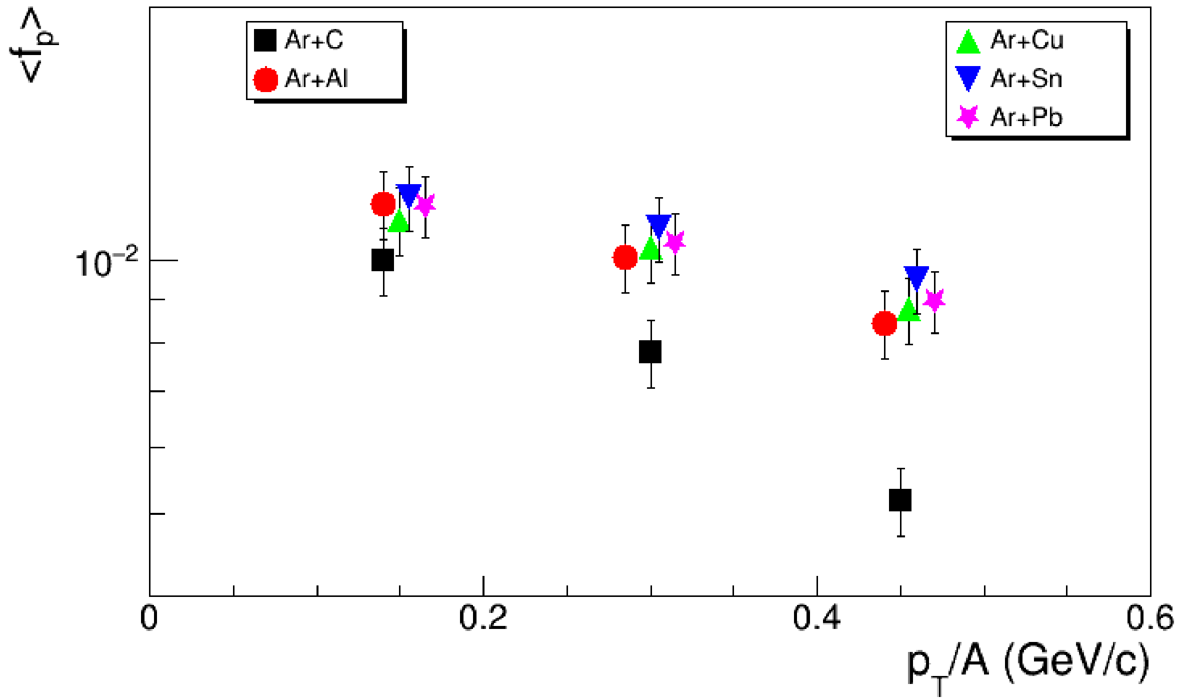


Figure 12: Average proton phase-space density for central Ar+A collisions as a function of pT /A within the rapidity range 0.05< y <0.45. The shown results are obtained at pT = 0.15, 0.3, 0.45 GeV/c, but displaced horizontally for the clarity

- Exponential decrease with pT; the slope is determined by the strength of radial flow : the larger flow is the harder is the observed distribution
- Thus, the observed trend for Ar+C (little radial flow) and Ar+Al, Cu, Sn, Pb (approx. the same flow pattern) is in line with expectations

Results from the paper draft

Table 3: T and $\langle\beta\rangle$ values evaluated from the linear fit of the $\langle E_T\rangle = \langle m_T\rangle - m$ values of protons, deuterons and tritons produced in Ar+A interactions with centrality 0-40%.

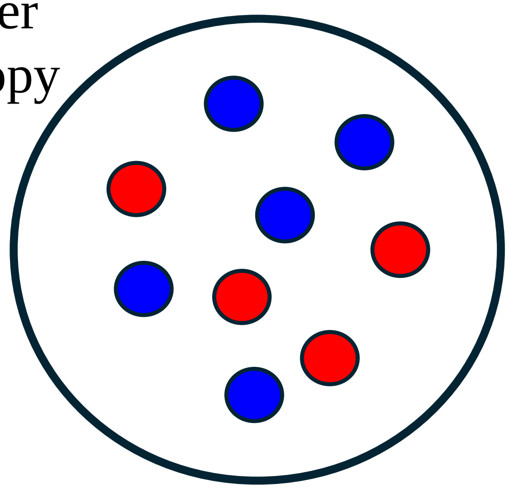
	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
T , MeV	89 ± 3	76 ± 8	80 ± 5	74 ± 9	80 ± 10
$\langle\beta\rangle$	0.0 ± 0.04	0.26 ± 0.05	0.27 ± 0.03	0.30 ± 0.04	0.26 ± 0.05

Entropy and cluster production in HIC

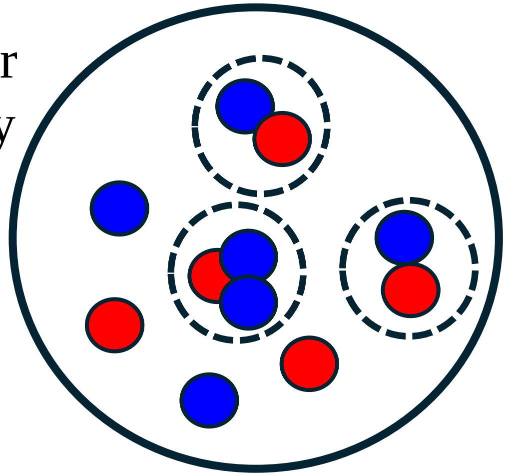
Entropy ***S*** ~ # of microstates in the system

S is defined by:

- ✓ *E, V*, or in general, by the phase-space volume: the larger is the phase-space the greater is the number of positions to occupy
- ✓ Number of particles *N*
- ✓ Phase – some phases (as QGP) or mixing of phases (QGP+HG) have larger #dof and #of_microstates



- Entropy is a measure of particle disorder or randomness: the larger is the cluster abundances in a system the smaller is the entropy value



- In HIC, the entropy once produced does not change during further evolution. Thus, the final-state entropy is defined by the one produced in the first moments of the reaction. So, an abrupt increase in ***S*** due to PT might be fixed in the experiment

- Specific entropy ***S/A*** (entropy per baryon) can be deduced from the d/p-ratio

Entropy in heavy-ion collisions

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

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

Specific entropy (entropy per baryon) *S/A* can be deduced from R_{dp}.

Despite of the fact that at BM@N energies ~80% of the particle multiplicity is defined by protons and light nuclei, the pion contribution to the total entropy should be estimated. Following *L.Landau:*

$$\frac{S_\pi}{A} = 4.1 \frac{N_\pi}{N_N}$$

where N_π is the number pions and N_N is the number of nucleons

All numbers are obtained in the rapidity range $0 < y < 0.4$

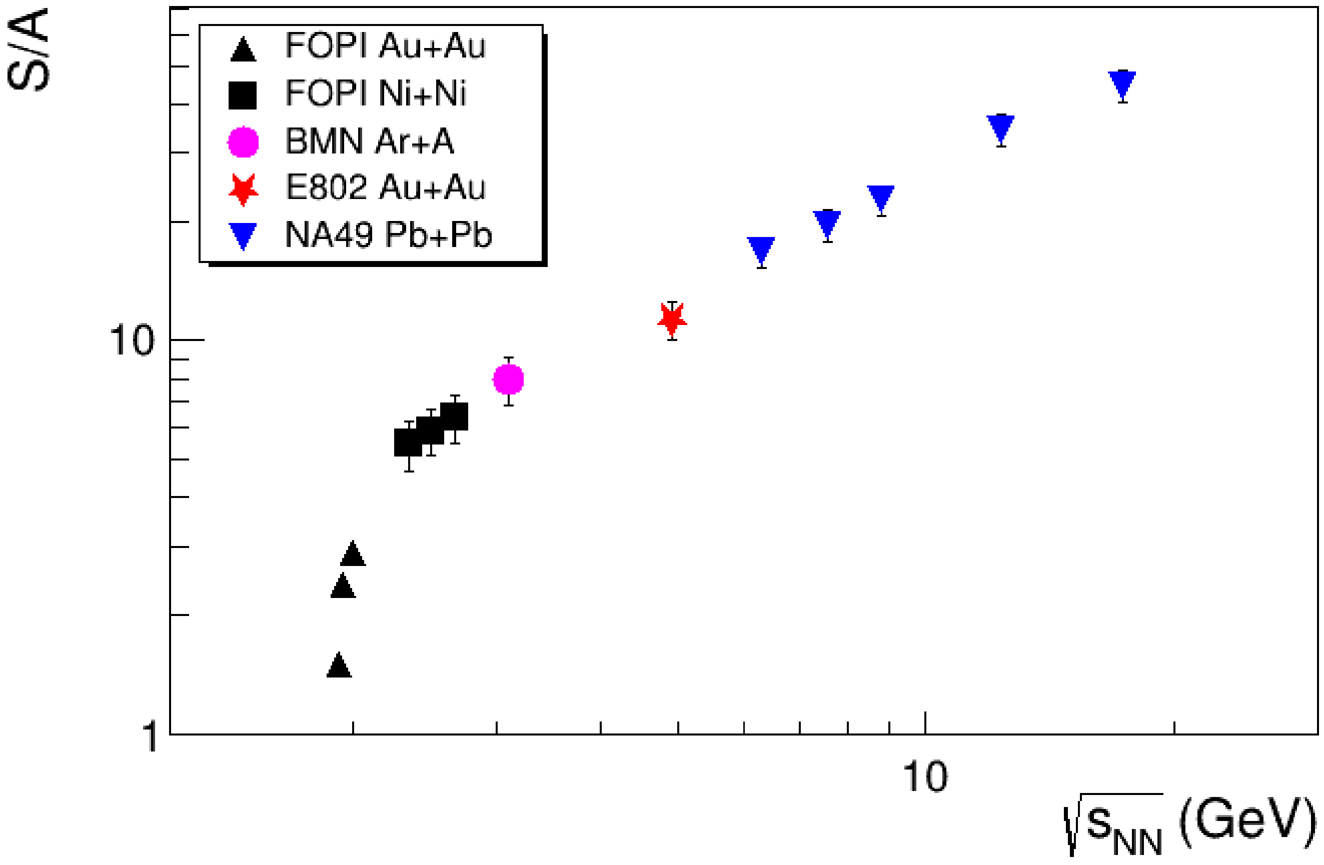
The pion yields were estimated from BM@N data for π^+ and UrQMD model for π^- and π^0

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

BM@N results:

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 collisions 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

Prospects for the study particle ratios and *S/A* @ NICA (BM@N & MPD)

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Enhanced pion-to-proton ratio at the onset of the QCD phase transition

Thiranat Bumnedpan [a], Jan Steinheimer [b], Marcus Bleicher [c,d], Ayut Limphirat [a],
Christoph Herold [a,*]

- A non-equilibrium phase transition indicates a gain in *S/A* (and pion-to-proton ratio) due to the dynamical nature of phase transition (PT) and stochastic fluctuations during the fireball evolution. Predictions made for the two freezeout lines defined by *S/A=const*

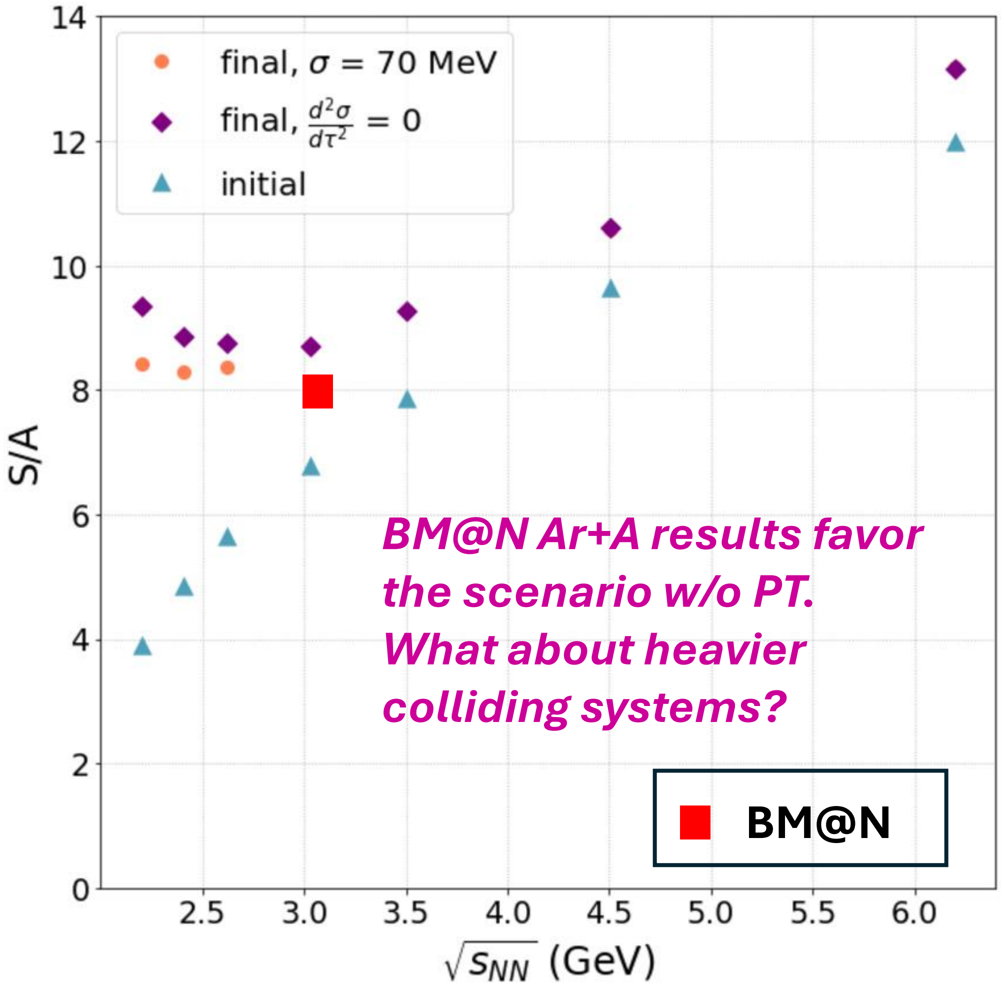
- The effect, i.e. the difference between two scenarios (w/ PT and w/o PT) is larger at low collision energies

- The authors predict that a beam energy scan around these values of $\sqrt{s_{NN}}$, where the FOPT is reached should then reveal a sudden increase of the pion-to-proton ratio at the collision that passes through that transition.

Specific entropy and phase transition in Ar+A?

- Study the production of charged pions, protons, and light nuclei by varying collisions energies and system size and over a large phase-space is crucial

Physics Letters B 835 (2022) 137537



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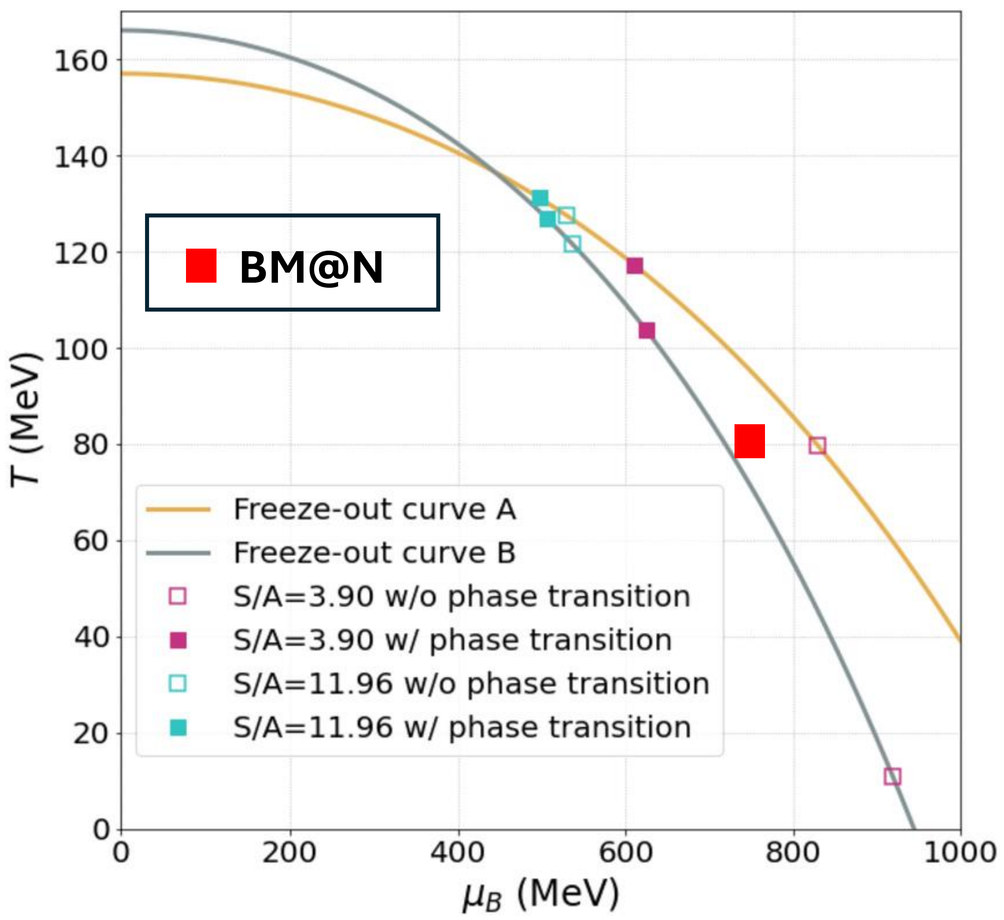

Specific entropy and phase transition in Au+Au?

Energy (+system size) scan in the NICA energy range can reveal this ratio and its relation to FOPT further!

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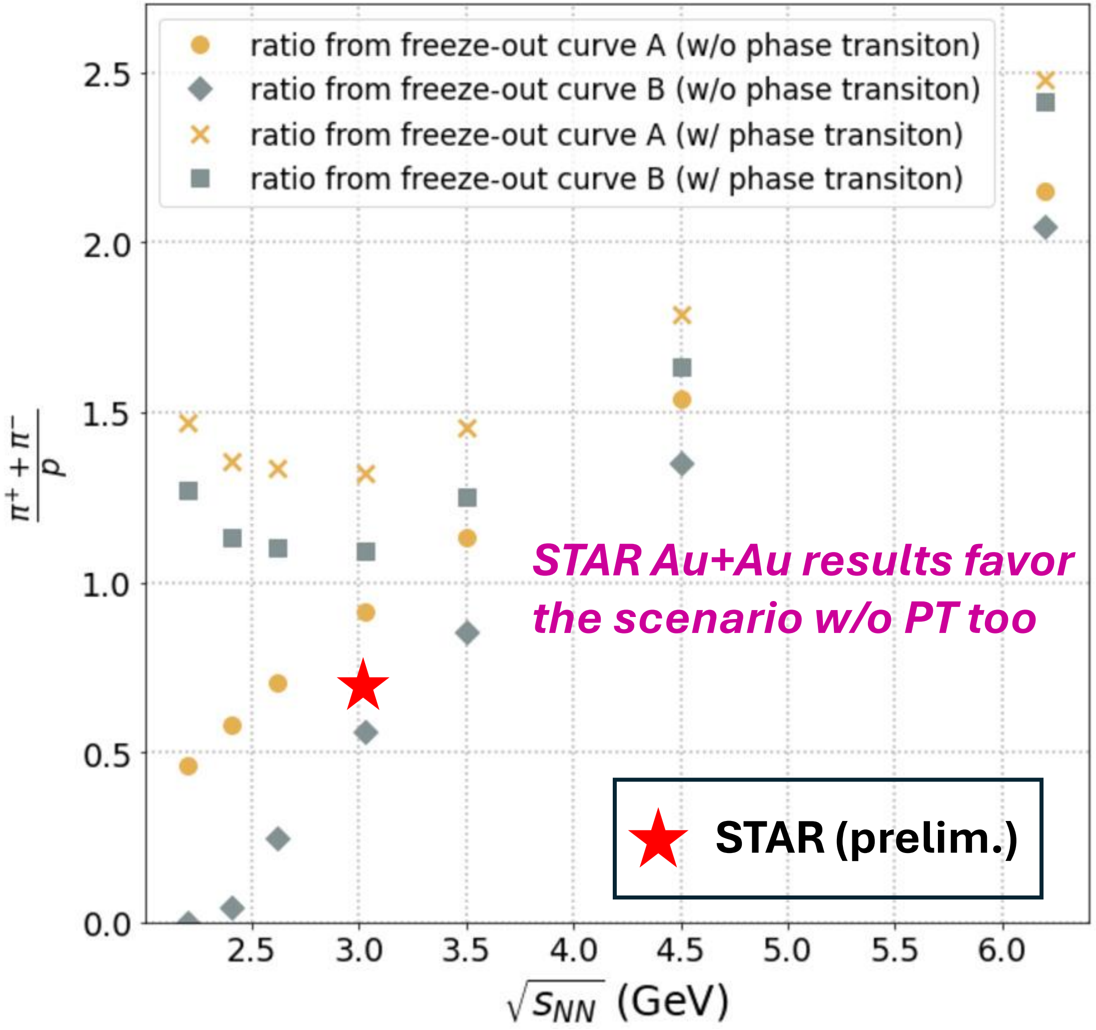
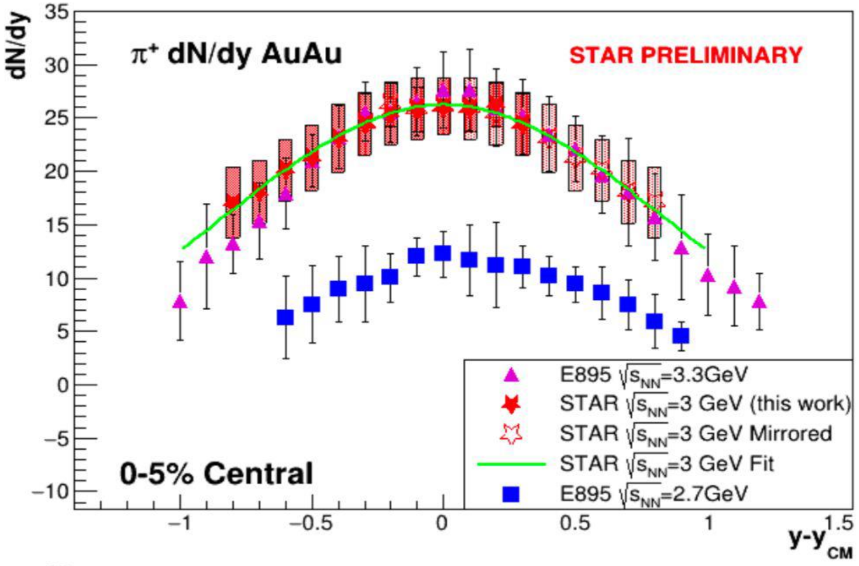
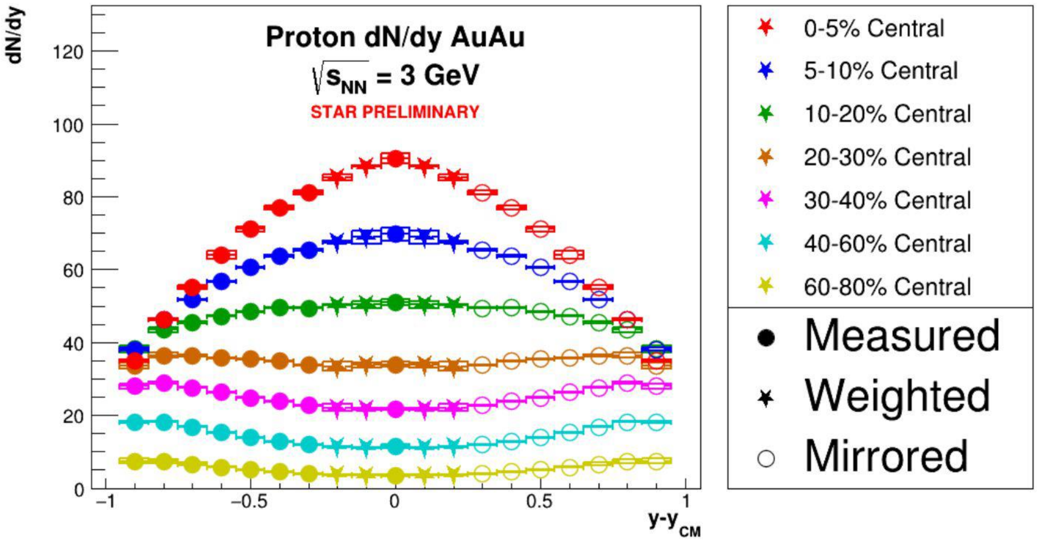






Study of the mass dependence of particle yields

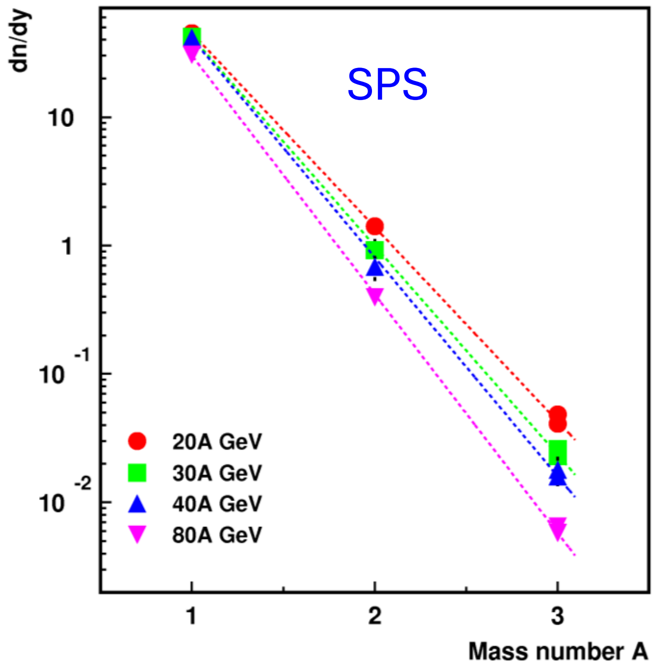
It has been established experimentally that cluster production yields decrease exponentially with the atomic mass number A [26, 61]. As an example, Fig. 14 (left panel) presents mid rapidity dn/dy for $p, d.t$ as a function of A from 0-40% central Ar+Sn collisions. The A-dependence of yields was fitted to a form:

$$\frac{dn}{dy}(A) = const/p^{A-1}, \quad (13)$$

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 (determining T and μ_B)

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



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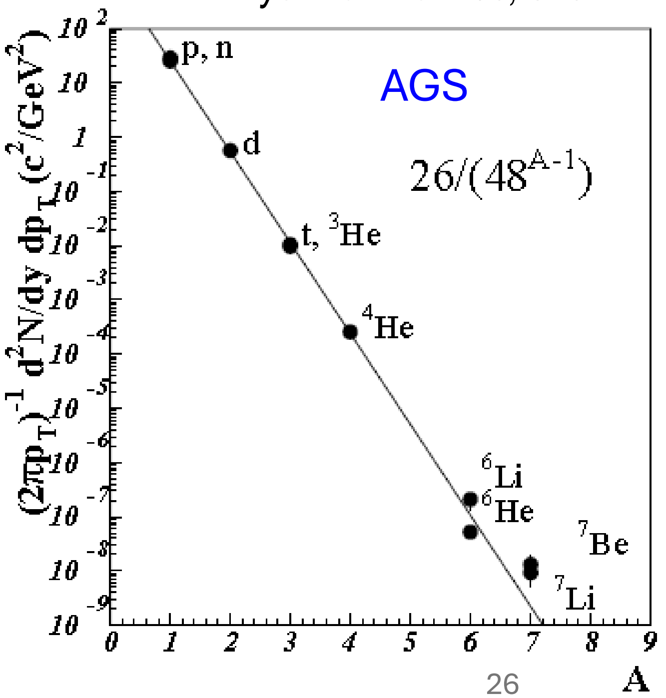
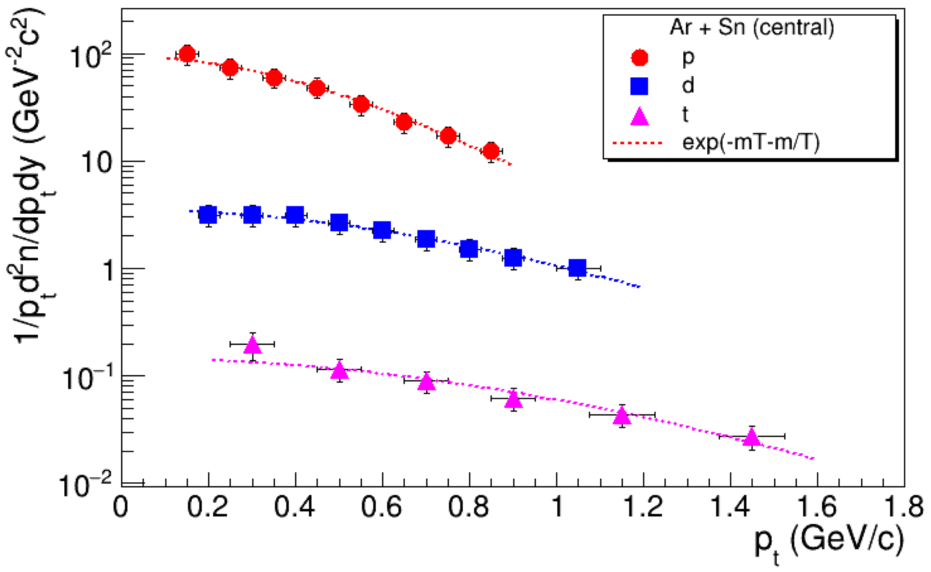
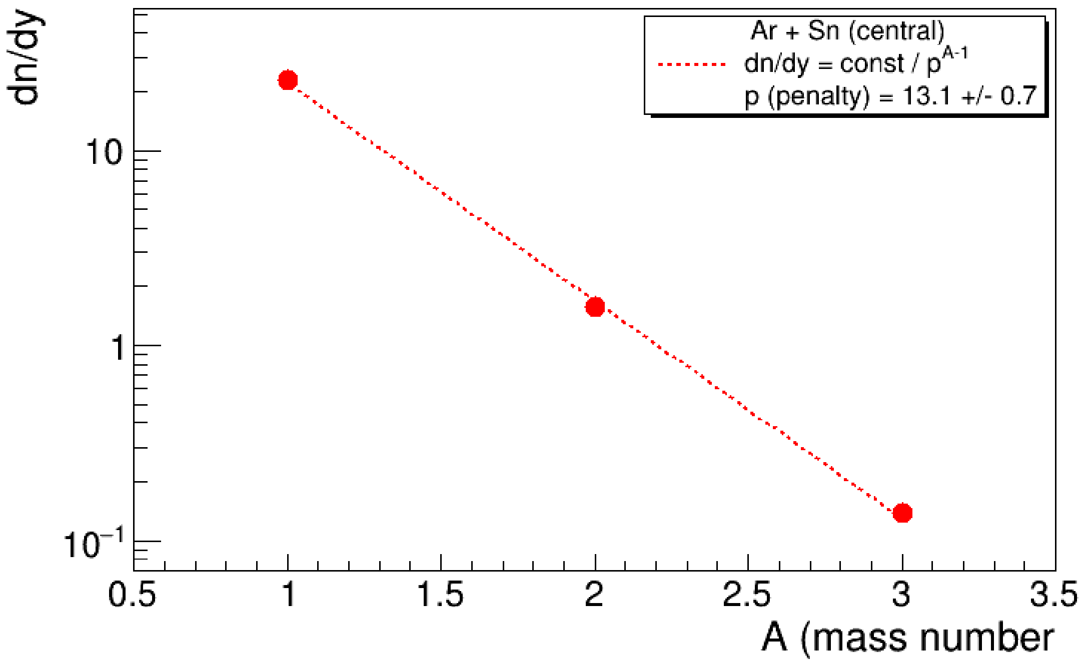
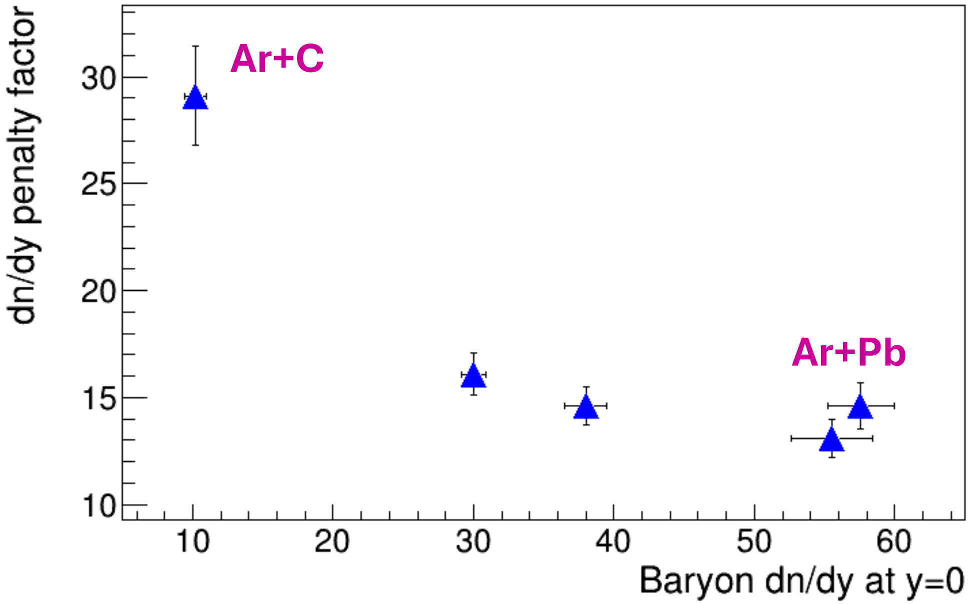


Particle yields & penalty factor in central Ar+A reaction in BM&N







- 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 (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!)

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

thus: $\mu_B = m - T \ln p$

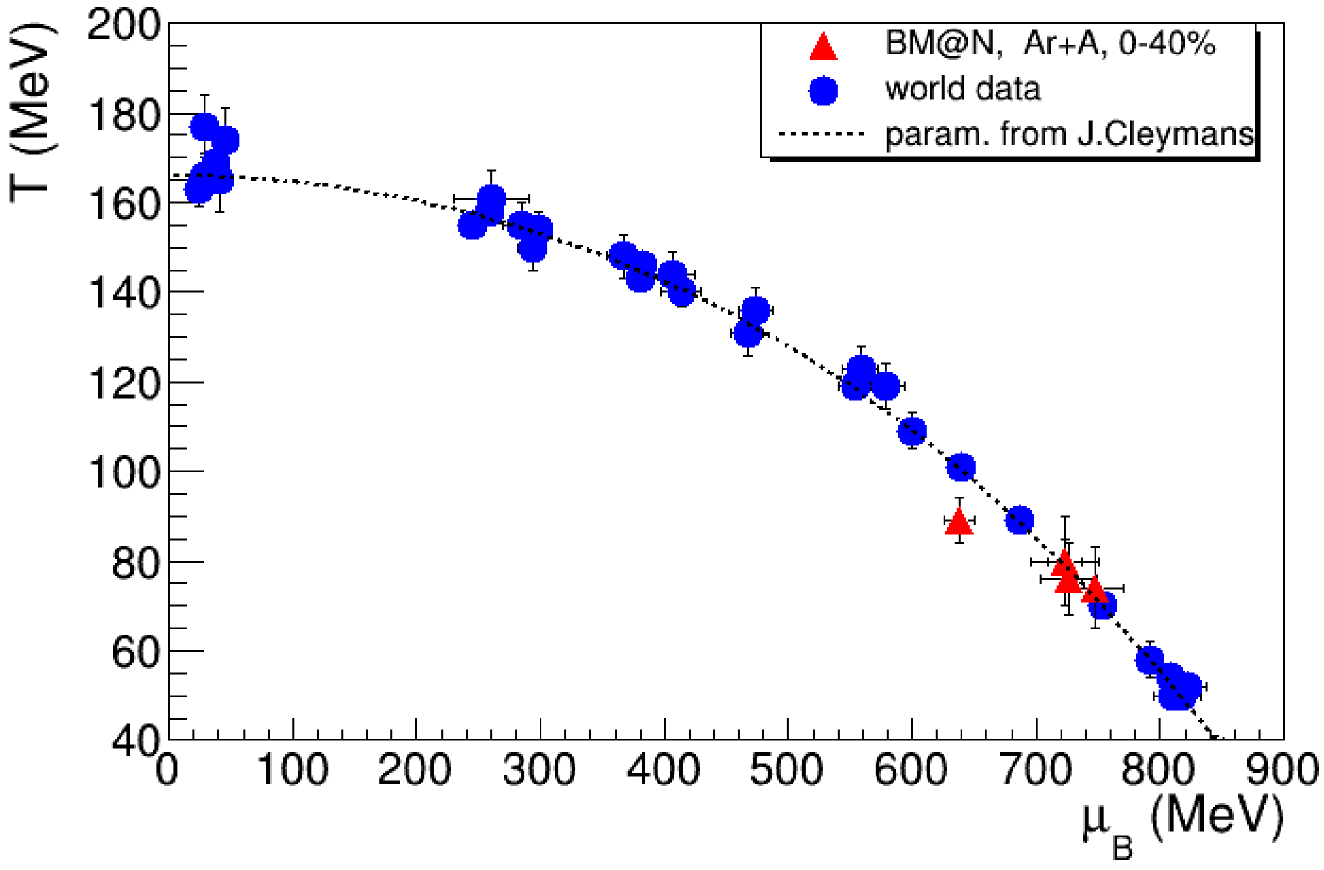


Table 8: Penalty factor p, temperature T (from Table 3), and baryochemical potential μ_B in 0-40% central Ar+A collisions.

	p	T (MeV)	μ_B(MeV)
Ar+C	29.1 ± 2.3	89 ± 3	638 ± 12
Ar+Al	16.1 ± 1.0	76 ± 8	727 ± 23
Ar+Cu	14.6 ± 0.7	80 ± 5	724 ± 14
Ar+Sn	13.1 ± 0.7	74 ± 9	748 ± 24
Ar+Pb	14.6 ± 0.8	80 ± 10	724 ± 27

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

- BM@N now has a hint about its 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

- d/p-ratio studied as a function of rapidity, centrality and system size. Nucleon phase-space density $<f>$ and entropy per baryon S/A is estimated and compared to world data

- Mass dependence of midrapidity particle yields analyzed, penalty factor obtained in central Ar+A collisions, the value of baryochemical potential was estimated

- The paper draft has updated with the analysis details and discussion included

Supplementary slides

Supplement #1 : Asymmetric Ar+A collisions and 'effective midrapidity'

First, in strongly asymmetric $A_1 + A_2(A_1! = A_2)$ collisions, midrapidity does not have a well-defined kinematic definition and can vary with centrality. In what follows we deal with an 'effective midrapidity', which has chosen as the position of the maximum in the rapidity distribution of produced pions. As calculations of microscopic models DCM and UrQMD indicate, the effective midrapidity y_{CM}^{eff} is shifted toward the projectile rapidity range in Ar+C(Al) and in the opposite direction in Ar+Cu(Sn,Pb) collisions. The estimated values of the mid rapidity shifts $\Delta y_{CM} = y_{CM}^{eff} - y_{CM}^{NN}$ in Ar+A collisions are indicated in Table 5. In peripheral collisions, the midrapidity shift is small in Ar+Cu and Ar+Al, and is of the order ± 0.1 in Ar+Pb and Ar+C reactions.

Table 5: Number of projectile participants (models and data) and midrapidity shifts in Ar+A collisions.

Reaction	Δy_{CM}	$\langle N_p^{part} \rangle$ models	$\langle N_p^{part} \rangle$ data
Ar+C (0-40%)	0.19	21.4 ± 0.6	16.7 ± 1.9
Ar+Al (0-40%)	0.07	26.1 ± 0.2	29.6 ± 0.7
Ar+Cu (0-40%)	-0.07	31.3 ± 0.7	34.9 ± 2.1
Ar+Sn (0-40%)	-0.17	34.2 ± 1.2	48.5 ± 2.5
Ar+Pb (0-40%)	-0.26	36.2 ± 1.2	70.7 ± 5.1
Ar+C (>40%)	0.09	5.6 ± 1.0	4.0 ± 0.7
Ar+Al (>40%)	0.03	6.9 ± 0.9	7.0 ± 0.8
Ar+Cu (>40%)	-0.03	8.4 ± 0.4	7.1 ± 0.9
Ar+Sn (>40%)	-0.07	11.7 ± 0.2	8.9 ± 1.3
Ar+Pb (>40%)	-0.11	13.0 ± 0.8	11.0 ± 1.1

Our estimates are supported by the studies of

F. Videbak and O.Hansen, Phys. Rev. C 95, 2684 (1995)

Indicating shifts of kaon rapidity spectra
in Si+Al, Si+Cu, Si+Au at 14.6A GeV
by approx. -0.4 going from Si+Al to Si+Au

<u>Supplement #2</u> : Asymmetric Ar+A collisions and projectile-target mixing

The second issue we'd like to address is the following. While in peripheral nucleus-nucleus collisions the projectile and target regions in the baryon rapidity distributions are well separated from each other, those are broadened and may start to overlap in central collisions. The situation may become even worse in strongly asymmetric collisions, like Ar+Pb, where projectile and target baryons can mix strongly in the forward rapidity region. To clarify the issue, we got a guidance from microscopic models, which simulated Ar+A collisions within the defined impact parameter intervals. The number of participating nucleons in these events are counted in the projectile and target nucleus separately. The average of two model predictions for the number of projectile participants is shown in the third column of Table. 5, the quoted error is the half of the difference between the DCM and UrQMD estimates. To get a filling about the degree of mixing of the projectile and target baryons in the forward hemisphere from data, the measured baryon rapidity distribution was integrated within the rapidity range from $y = y_{CM}^{eff}$ to y_{beam}. The obtained from data values of the number of projectile participants N_p^{part} are shown in Table 5 (the last column), the quoted uncertainties are the errors of the sum of experimental points within the same rapidity range. As one can see, for central Ar+C, Ar+Al, and Ar+Cu collisions the agreement between data and model predictions for the number of projectile participants is satisfactory. From that one can conclude that the overlap of target and projectile baryons is not enough to affect strongly the shape of rapidity distribution in this reactions. The situation is opposite for heavy targets: due to strong mixing the fraction of targetlike baryons in the forward (projectile) rapidity range is of about 30% and 50% in Ar+Sn and Ar+Pb reactions, respectively.

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Spares

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)

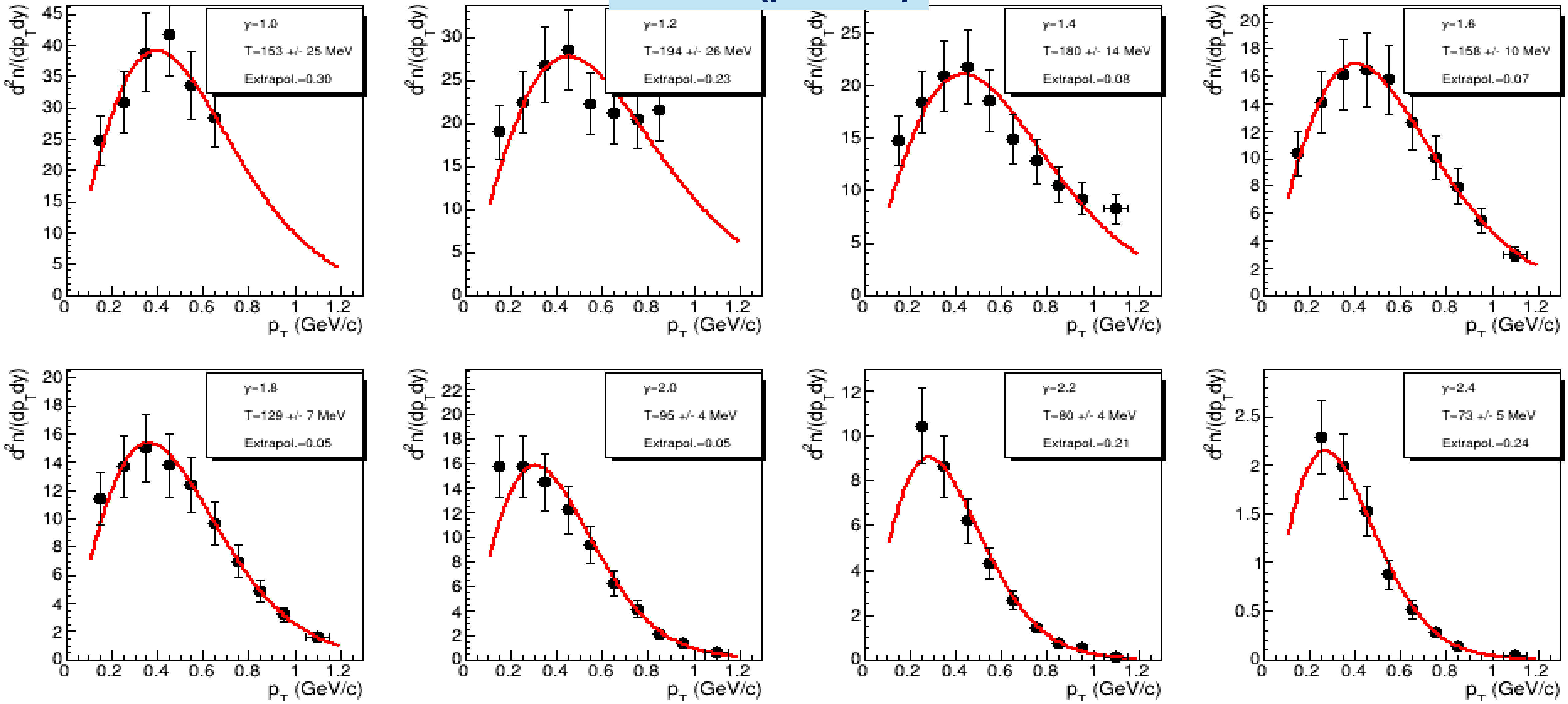
N_p - projectile N_t - target, N_S - sum

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)

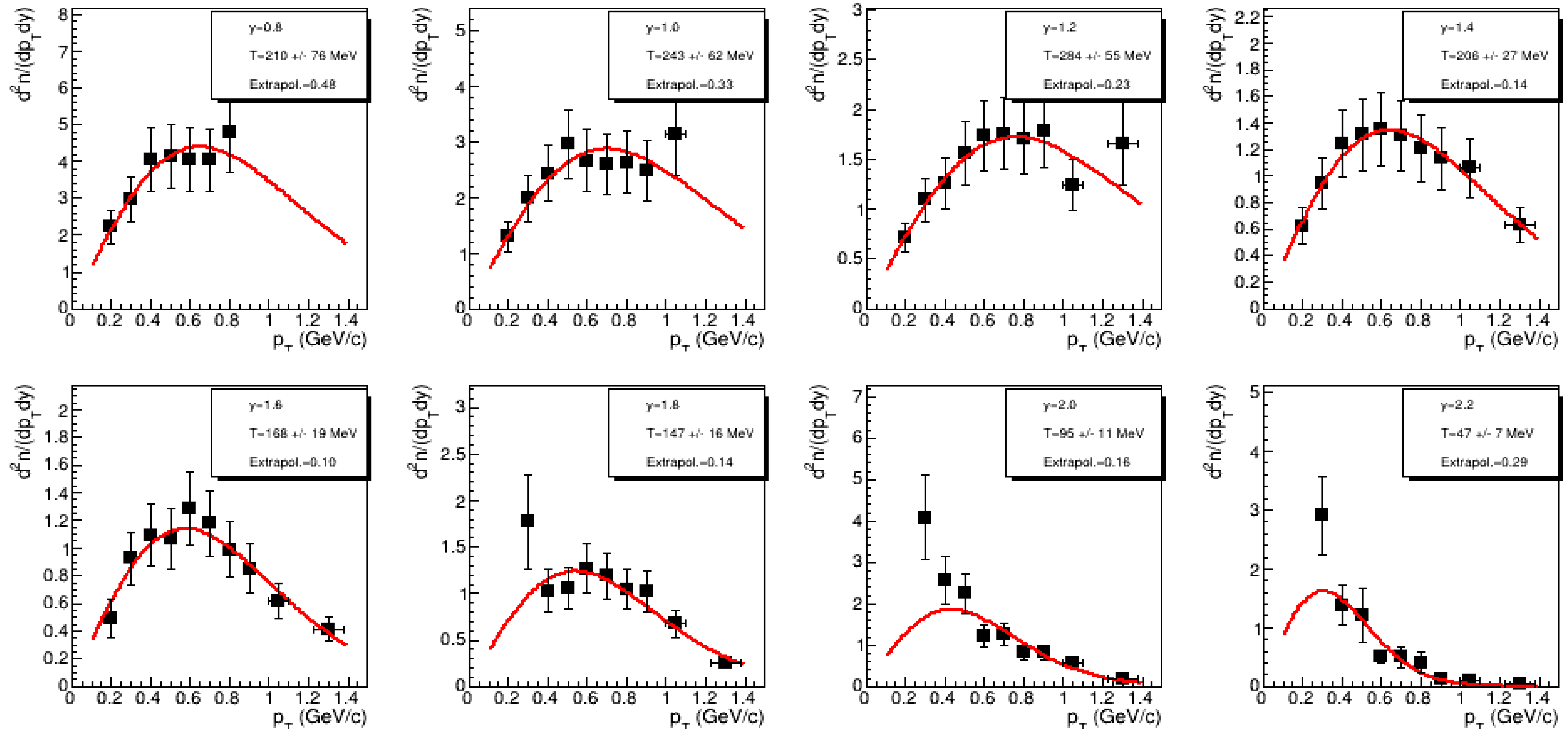
Ar + Sn (protons)



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)

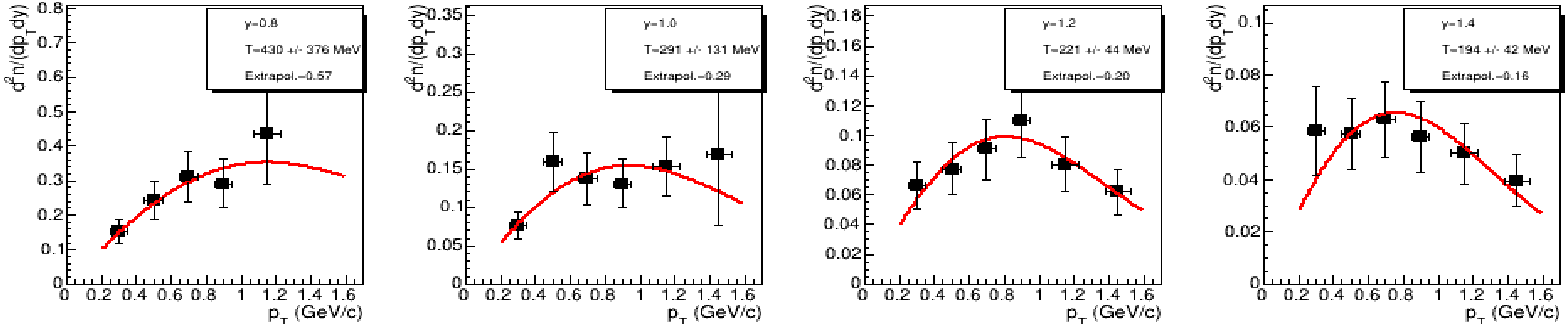
Ar + Sn (deuterons)

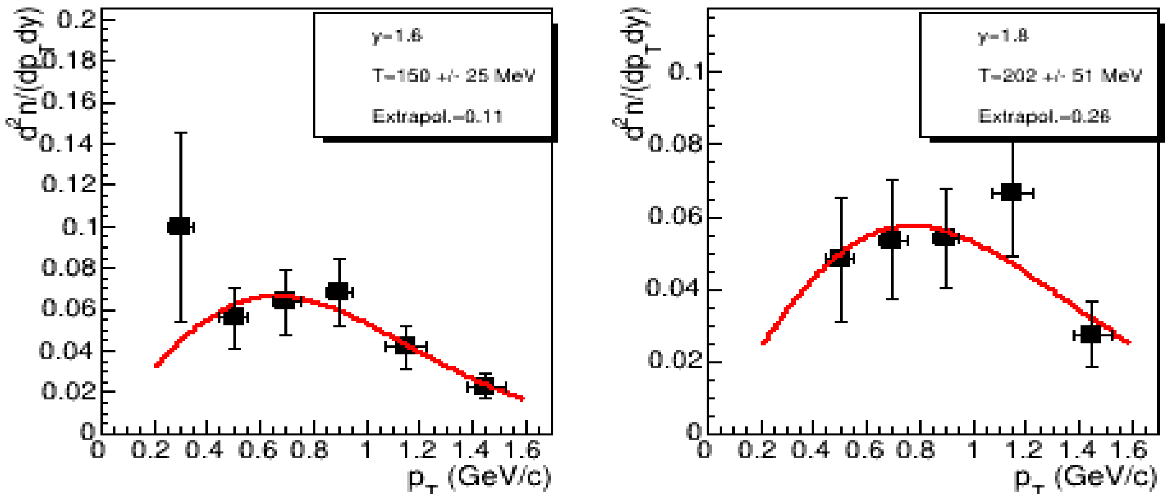


pT-spectra of tritons

- 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 $\sqrt{s_{NN}} = 3$ GeV with the STAR Detector

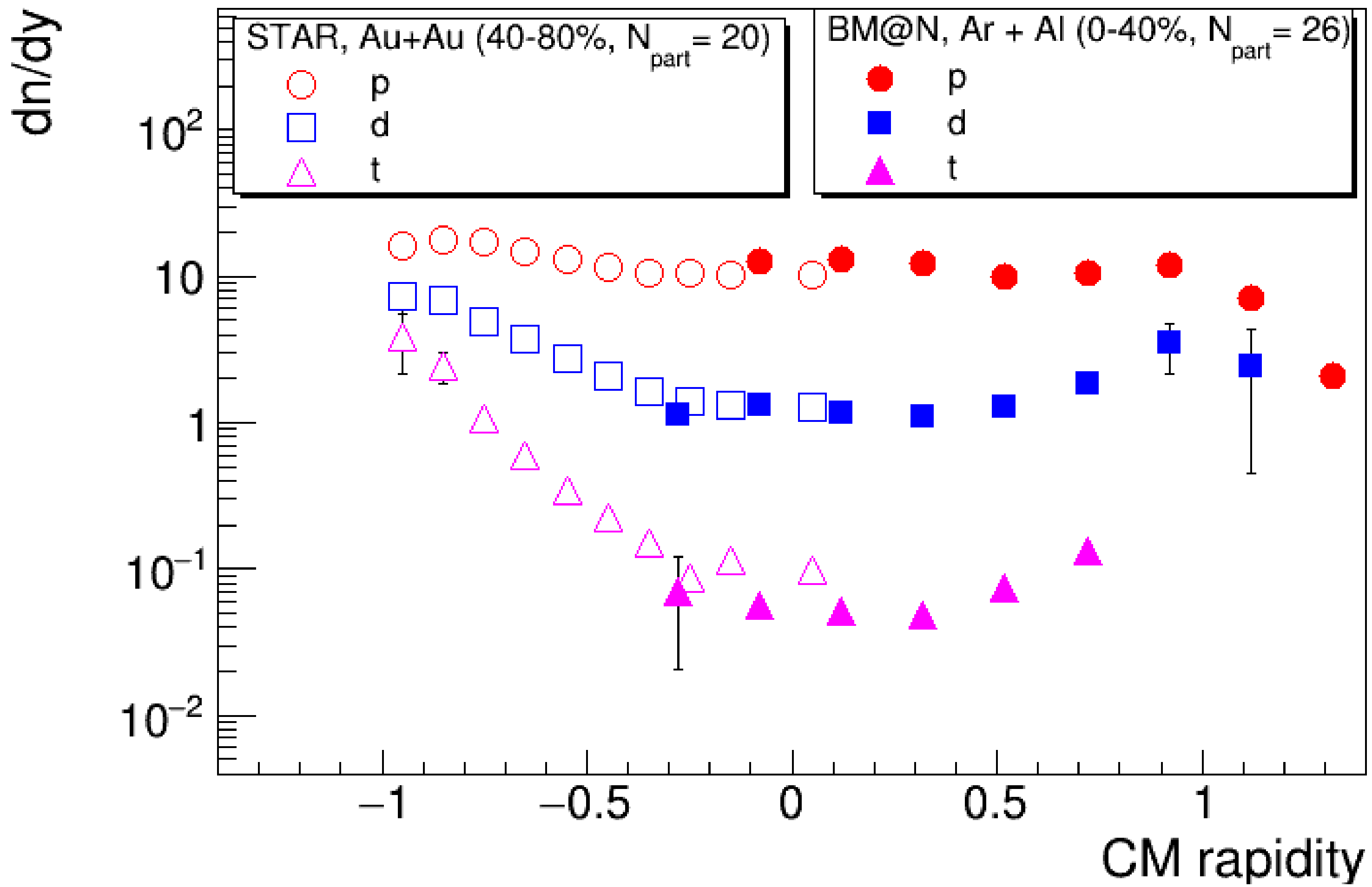
The STAR Collaboration

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

Centrality	FXTMult	$\langle N_{\rm Part} \rangle$
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

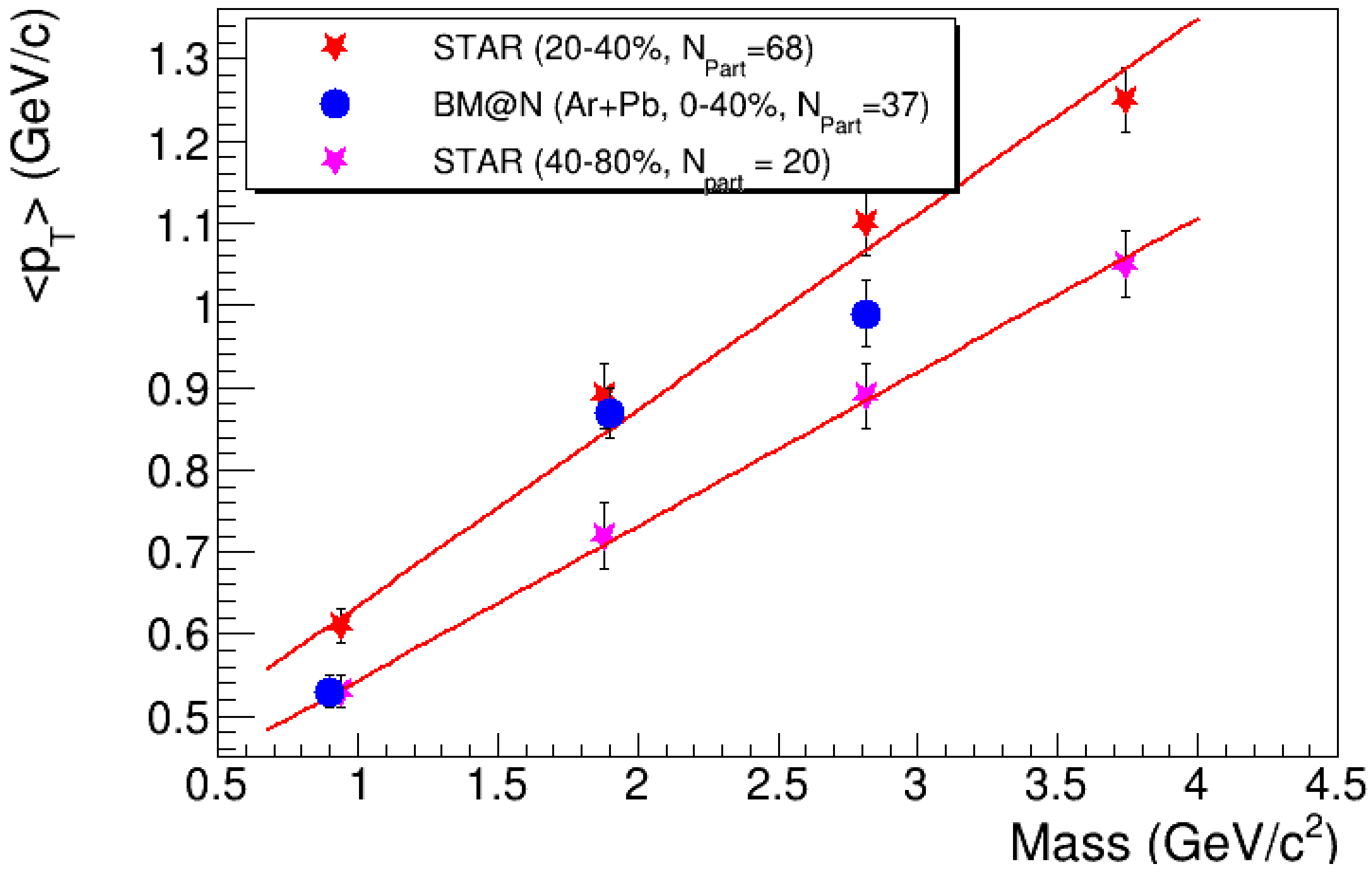
- Ar+Al 0-40% data set from BM@N (projectile Npart = 26) and 40-80% Au+Au (projectile Npart = 20) were used for comparison. Particle yields (approx.) scale with Npart



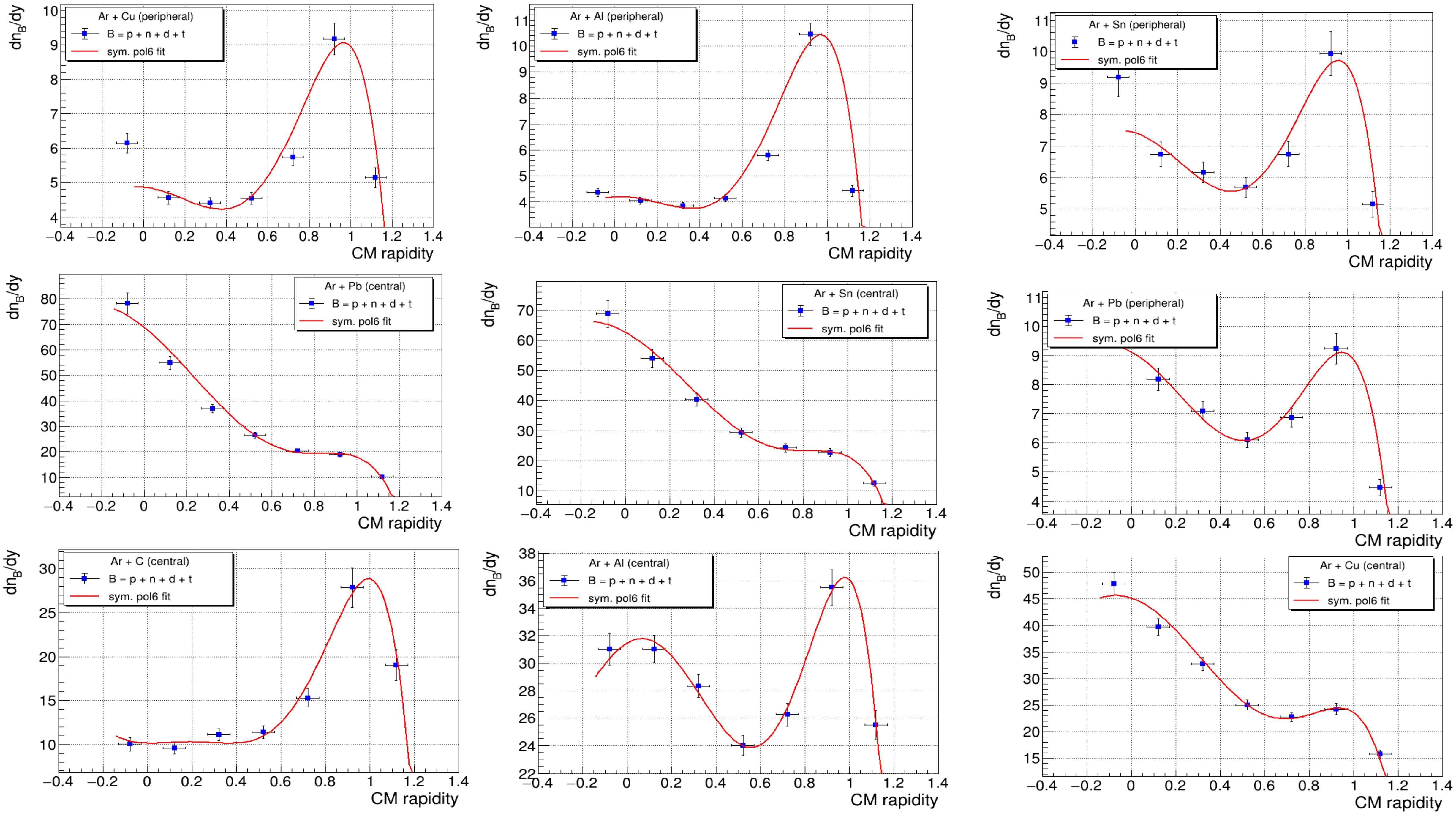
Collision geometry in Ar+Al and Au+Au is not fully identical, but the yields on p, d, t agree within 20% at midrapidity

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



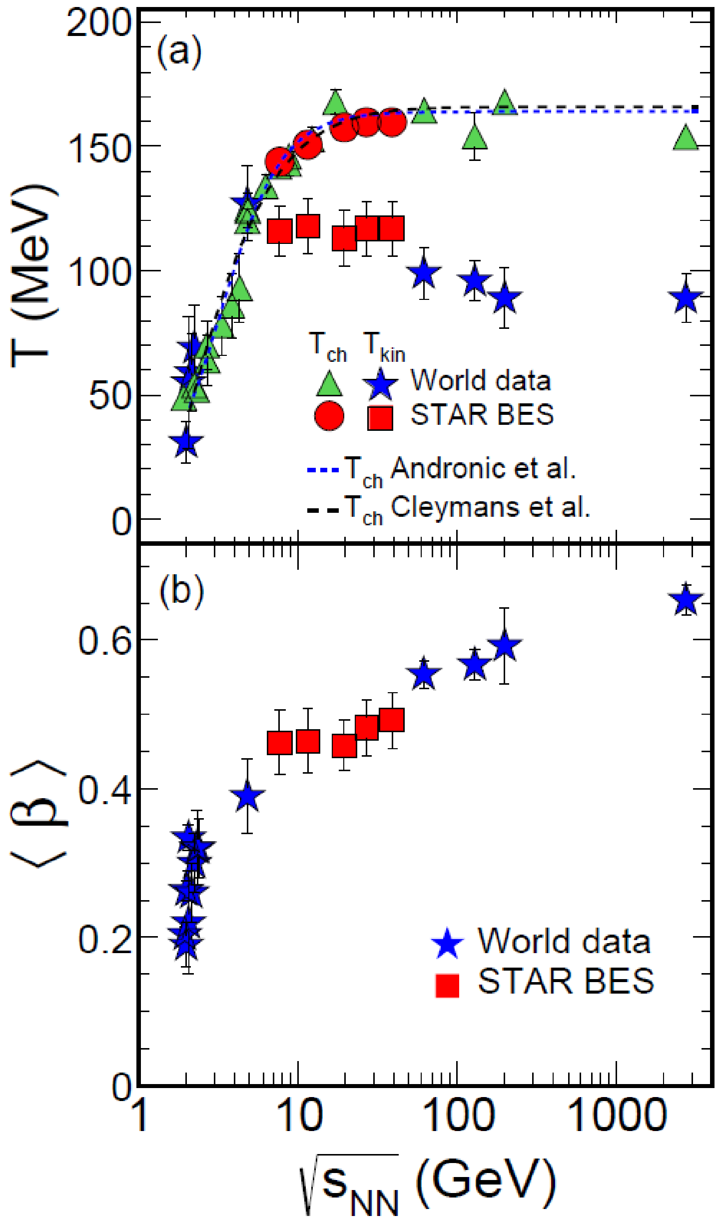
- BM@N and STAR measurements for <pT> agree numerically
- STAR: <pT> in Au+Au rises linearly with particle mass
- BM@N : <pT> vs mass in central Ar+Pb has a convex shape
- Different density (collective velocity) profiles? Input from theory (model predictions) is required to make a conclusion….



Ar + Cu (peripheral)
B = p + n + d + t
sym. pol6 fit
dn_B/dy
CM rapidity
Ar + Al (peripheral)
B = p + n + d + t
sym. pol6 fit
dn_B/dy
CM rapidity
Ar + Sn (peripheral)
B = p + n + d + t
sym. pol6 fit
dn_B/dy
CM rapidity
Ar + Pb (central)
B = p + n + d + t
sym. pol6 fit
dn_B/dy
CM rapidity
Ar + Sn (central)
B = p + n + d + t
sym. pol6 fit
dn_B/dy
CM rapidity
Ar + Pb (peripheral)
B = p + n + d + t
sym. pol6 fit
dn_B/dy
CM rapidity
Ar + C (central)
B = p + n + d + t
sym. pol6 fit
dn_B/dy
CM rapidity
Ar + Al (central)
B = p + n + d + t
sym. pol6 fit
dn_B/dy
CM rapidity
Ar + Cu (central)
B = p + n + d + t
sym. pol6 fit
dn_B/dy
CM rapidity

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