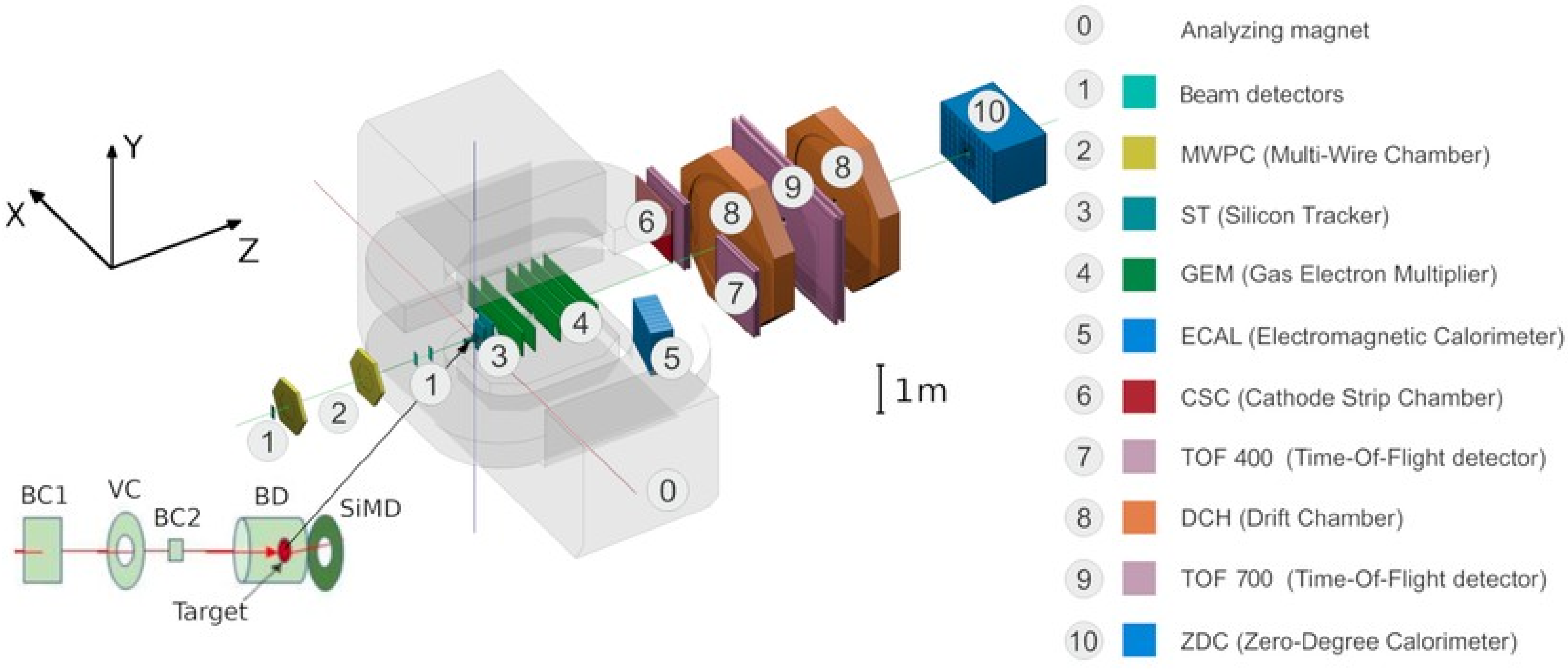
Production of protons, deuterons, tritons in argon-nucleus interactions at 3.2 AGeV



L.Kovachev[1,2] on behalf of the BM@N Collaboration

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2. IMech Bulgarian Academy of Sciences, Bulgaria

Outline

1) Run with argon beam (March 2018)

- ✓BM@N detector set-up

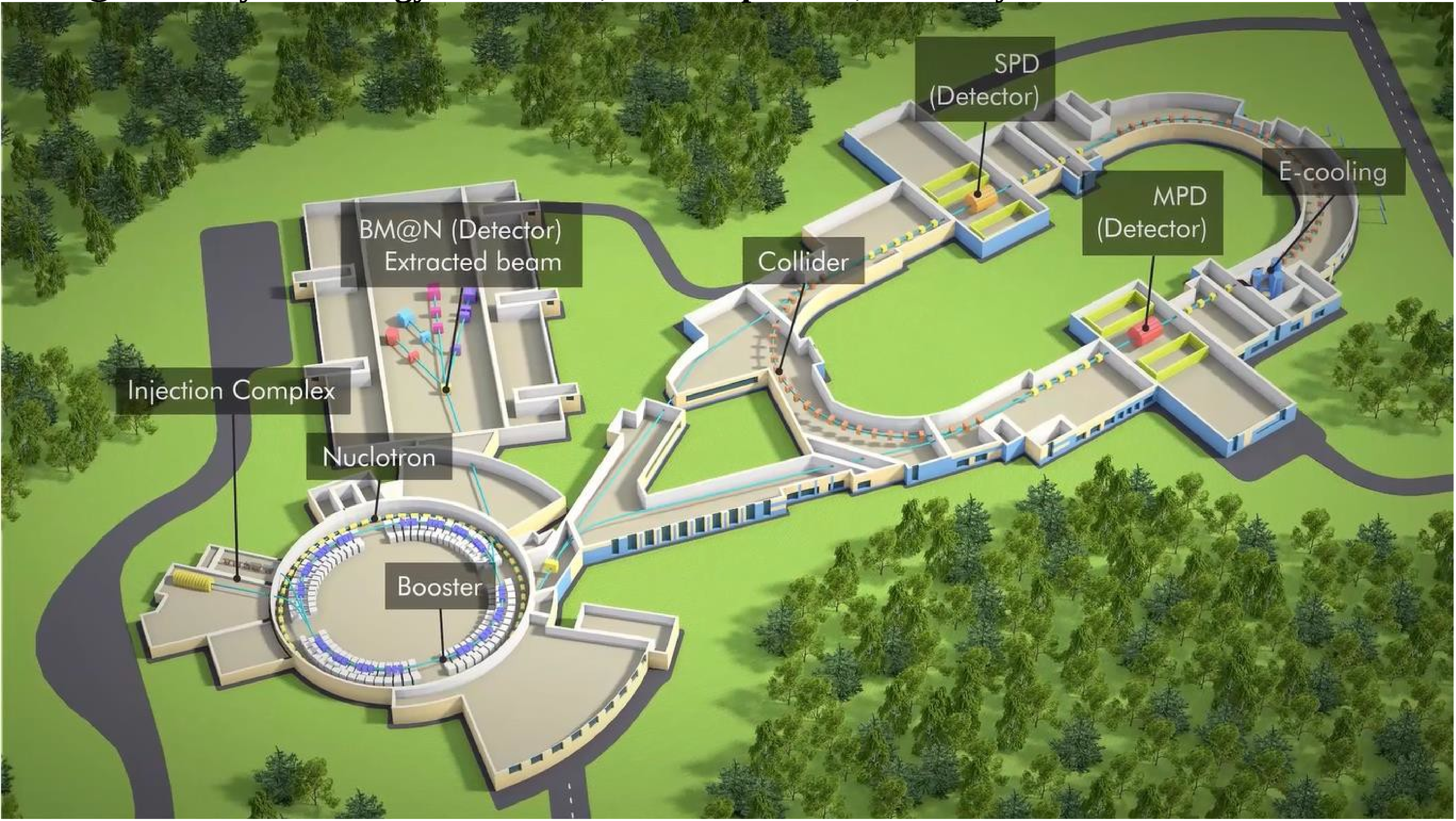
2) Physics results (Ar+C, Ar+Al, Ar+Cu, Ar+Sn, Ar+Pb at 3.2A GeV)

- ✓Cross sections and multiplicities of p, d, t
- ✓Transverse mass and rapidity spectra
- ✓Coalescence factors

3) Summary

NICA Accelerator Complex

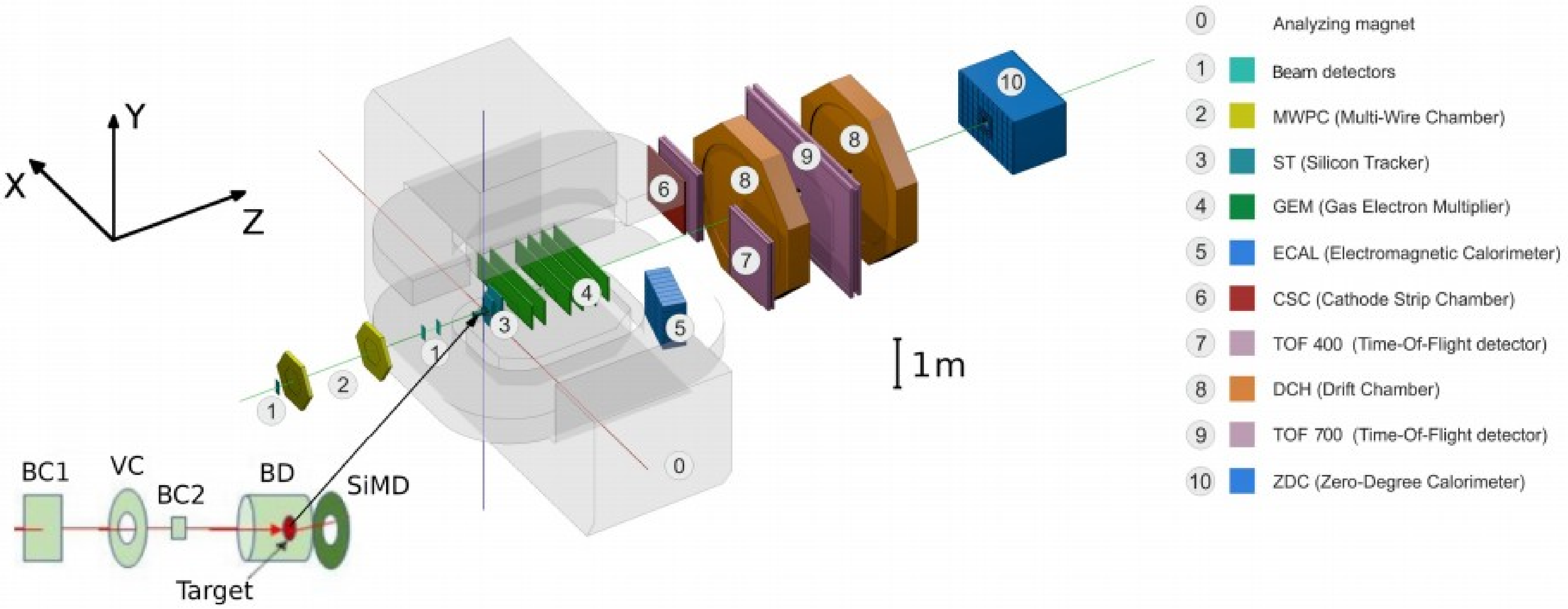
BM@N: heavy ion energy 1-4 GeV/n, beams: p to Au, Intensity ~10^6 /s



BM@N Setup

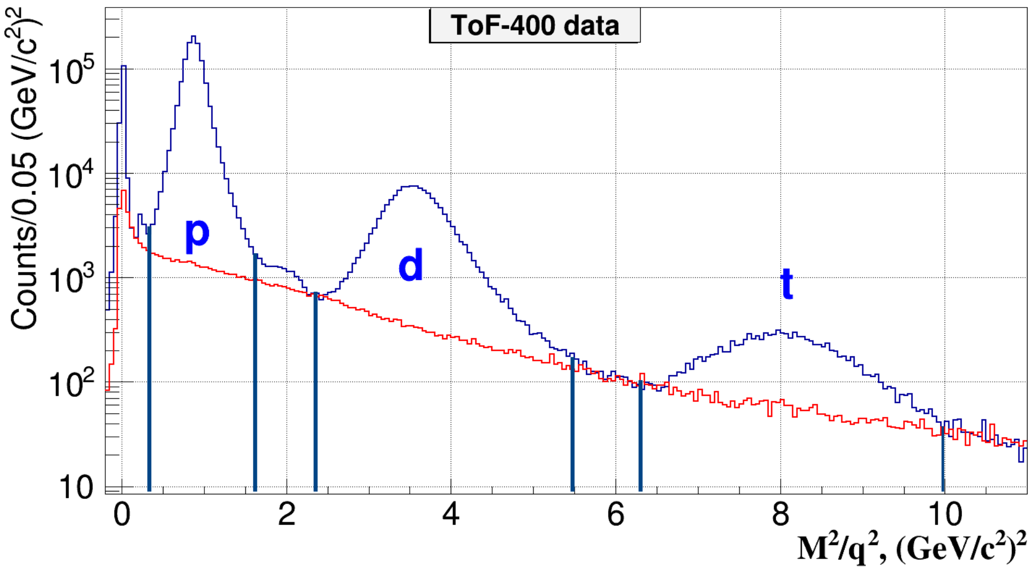
Run with argon beam (March 2018)

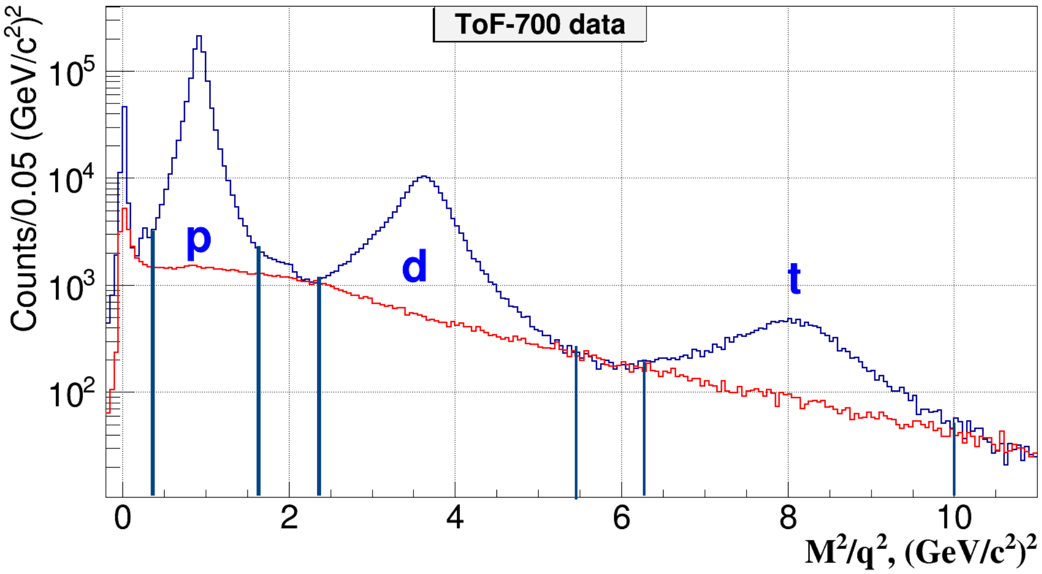
(Ar+C, Ar+Al, Ar+Cu, Ar+Sn, Ar+Pb at 3.2A GeV)



Detectors used in the analysis: Beam detectors (1), Multiplicity Detectors, ST (3), GEM (4),CSC (6), TOF 400 (7), DCH (8), TOF 700 (9)

m^2 spectra of positive particles produced in argon-nucleus interactions





Vertical blue lines indicate the signal ranges of identified protons, deuterons, and tritons. Red lines show the background estimated from "mixed" events.

Cross sections and multiplicities of p, d t

The differential cross sections $d^2\sigma_{p,d,t}(y, p_T)/dydp_T$ and multiplicities $d^2N_{p,d,t}(y, p_T)/dydp_T$ of protons,deuterons and tritons produced in Ar+C, Al, Cu, Sn, Pb interactions are calculated in bins of (y, p_T) according to the formulae:

$$d^2\sigma_{p,d,t}(y,p_T)/dydp_T=\sum[d^2n_{p,d,t}(y,p_T,N_{tr})/(\varepsilon_{trig}(N_{tr})\,dydp_T)]\times 1/(L\varepsilon^{rec}_{d,p,t}(y,p_T))$$

$$d^2N_{p,d,t}(y,p_T)/dydp_T=d^2\sigma_{p,d,t}(y,p_T)/(\sigma_{inel}\,dydp_T)$$

where L is the luminosity,

n – the number of reconstructed p, d, t in intervals dy and dp_T ,

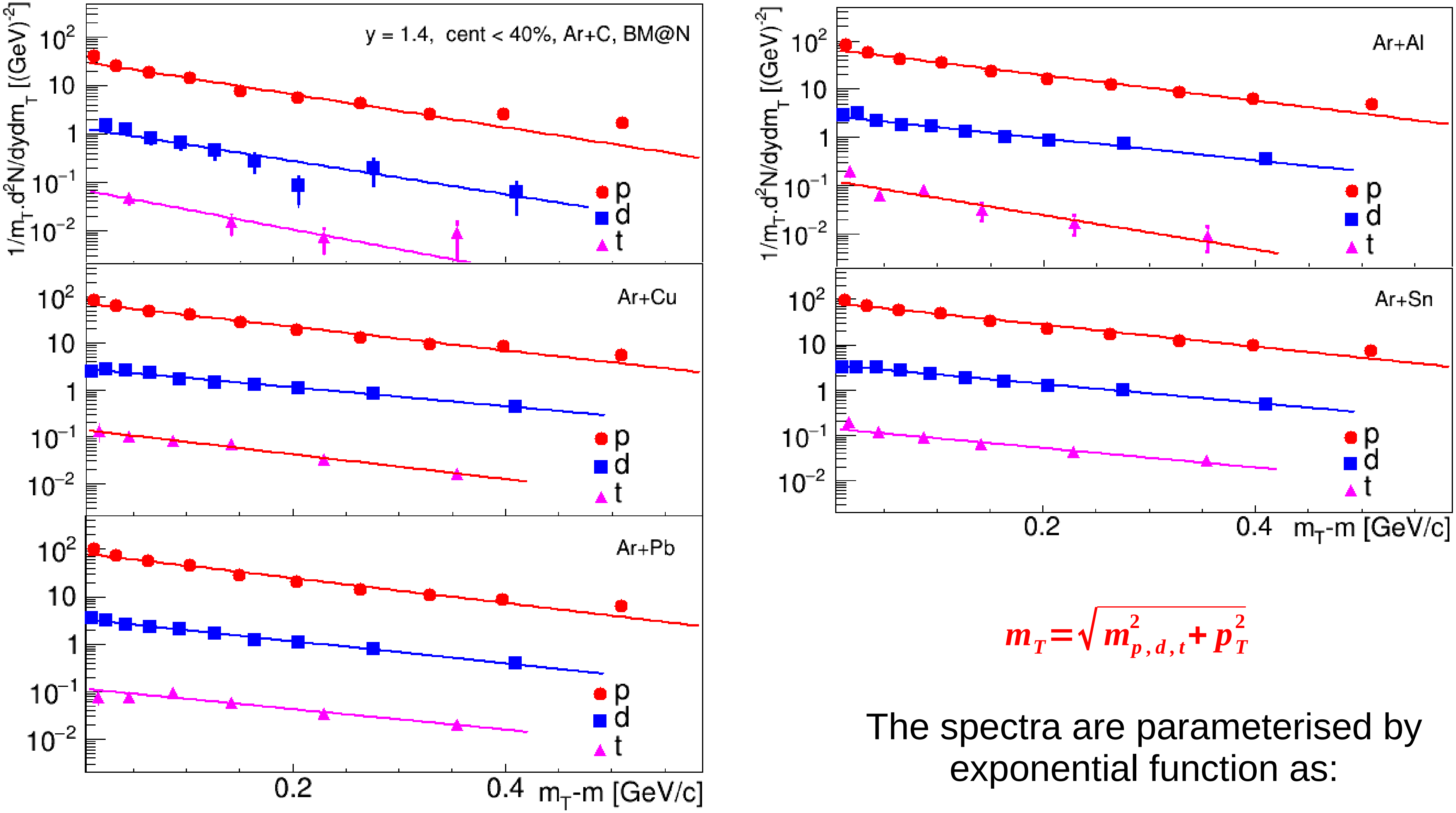
ε_{rec} – the efficiency of the p, d, t reconstruction,

$\varepsilon_{trig}(N_{tr})$– the track-dependent trigger efficiency,

σ_{inel}– the cross section for minimum bias inelastic Ar+A interactions. The cross sections for inelastic Ar+C, Al, Cu, Sn, Pb interactions are taken from the predictions of the DCM-SMM model

The cross sections and multiplicities are evaluated for two classes of a collision centrality: less and above than 40%

Transverse mass spectra of protons, deuterons, tritons produced at rapidity = 1.4 in Ar+A interactions with centrality less than 40%



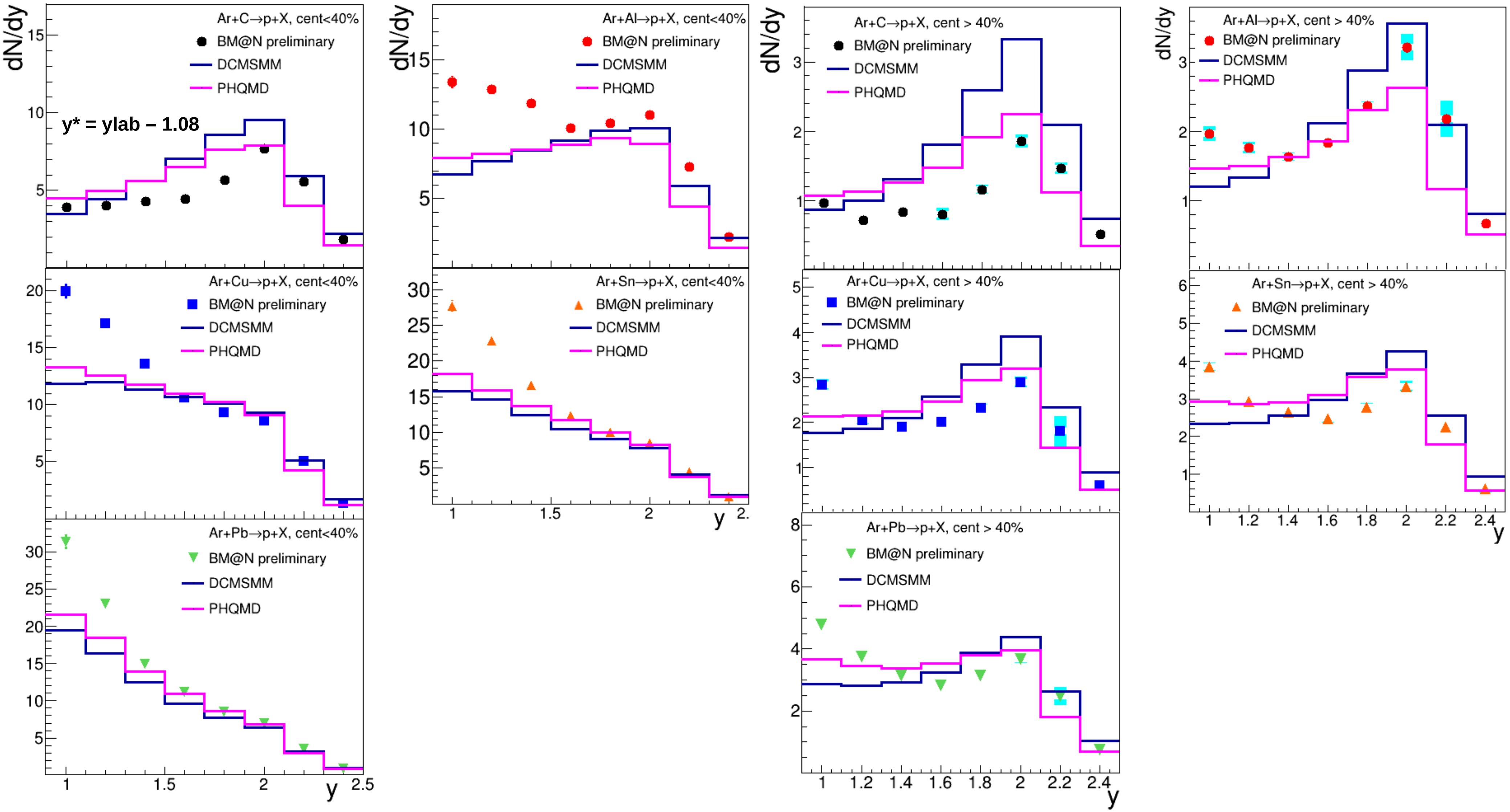
$$m_T = \sqrt{m^2_{p,d,t} + p^2_T}$$

The spectra are parameterised by exponential function as:

$$1/m_T \cdot d^2N/dydm_T = \frac{dN/dy}{T_0(T_0+m)} \cdot \exp(-(m_T-m)/T_0)$$

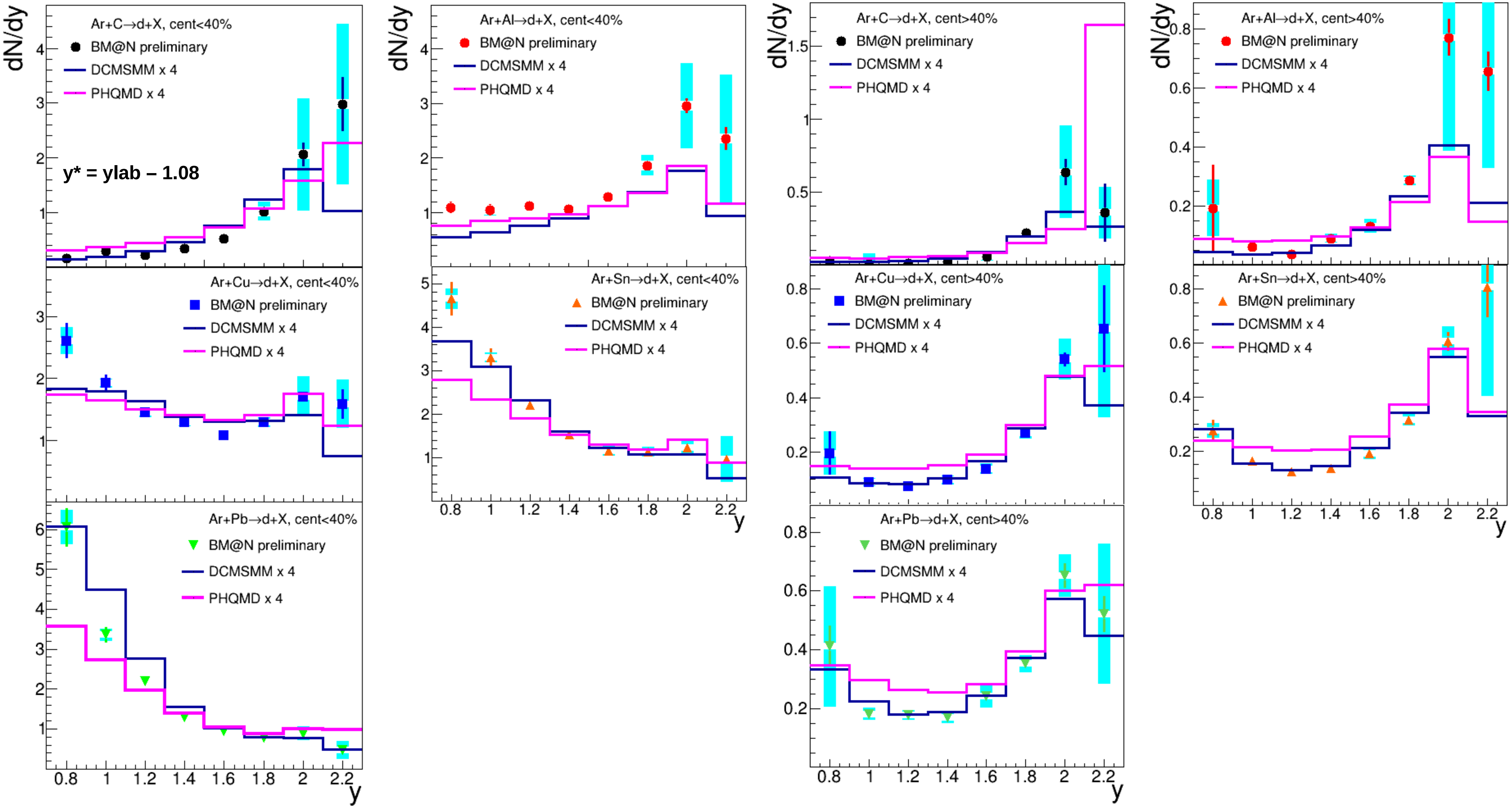
where fitting parameters are the integral of the m_T spectrum, dN/dy, and the inverse slope, T0.

Rapidity spectra dN/dy of protons produced in Ar+A interactions with less and above than 40% centrality . The results are integrated over p_T



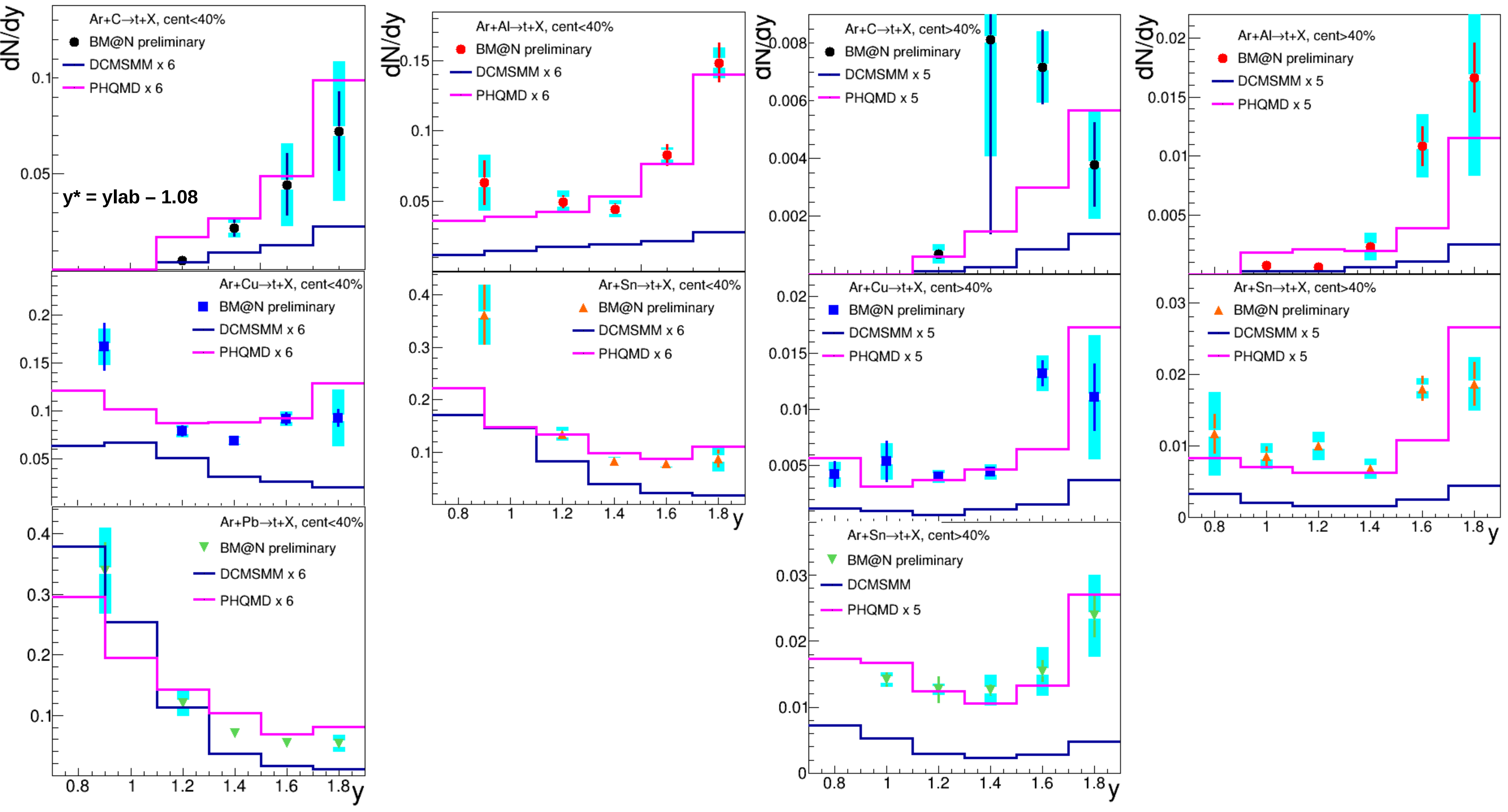
The models reasonable describes the experimental results in the forward y range. At mid-rapidity the models under-estimate the data for interactions with the targets heavier than the carbon.

Rapidity spectra dN/dy of deuterons produced in Ar+A interactions with less and above than 40% centrality. The results are integrated over p_T



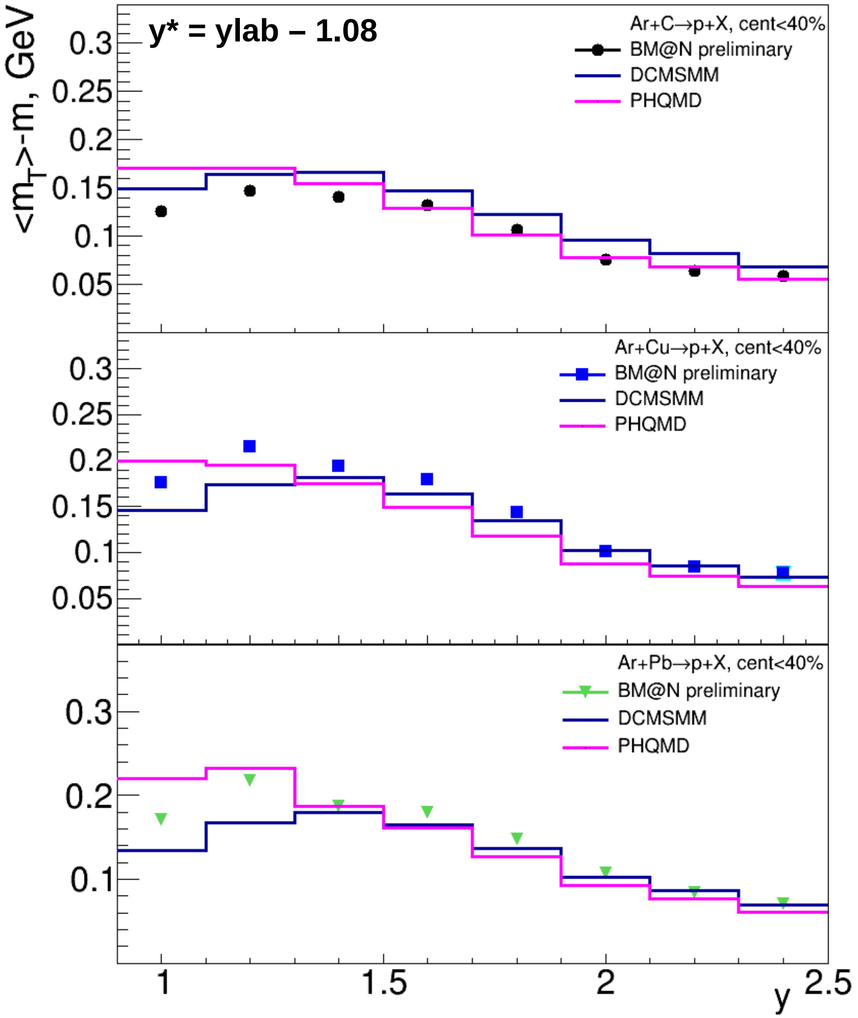
The spectra of deuterons dominate in the beam fragmentation range for Ar+C and Ar+Al interactions, whereas the spectra become more central for interactions with heavier targets. The models reasonably describe the shape of the experimental spectra, but under-predict the normalization of the data by factors of 4

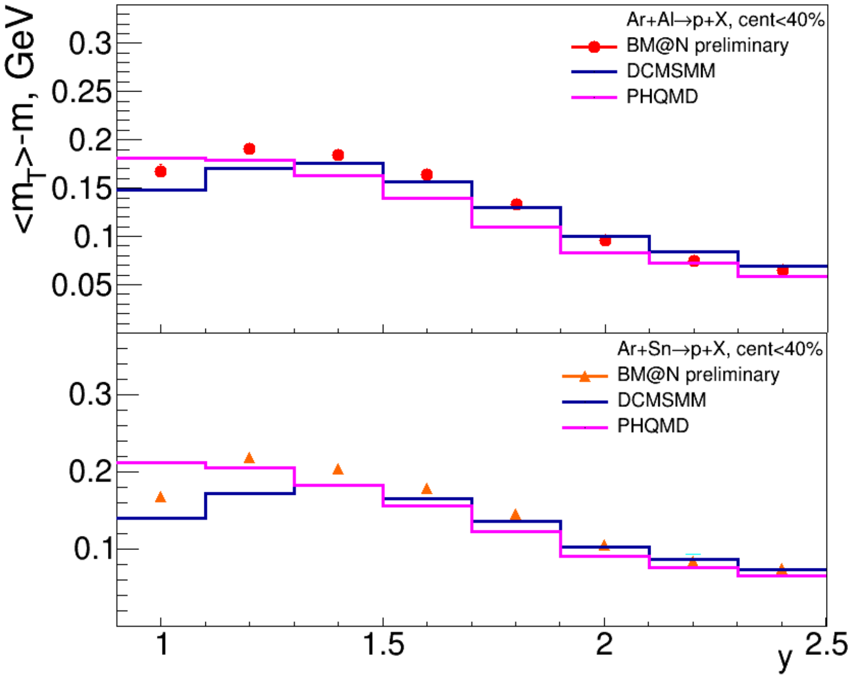
Rapidity spectra dN/dy of tritons produced in Ar+A interactions with less and above than 40% centrality. The results are integrated over p_T



The models reasonably describe the shape of the experimental spectra, but under-predict the normalization of the data by factors of 5-6

Rapidity dependence of the mean transverse kinetic energy $\langle m_T \rangle - m$ obtained from the fits of the m_T spectra of protons in Ar+A interactions with centrality 0-40%





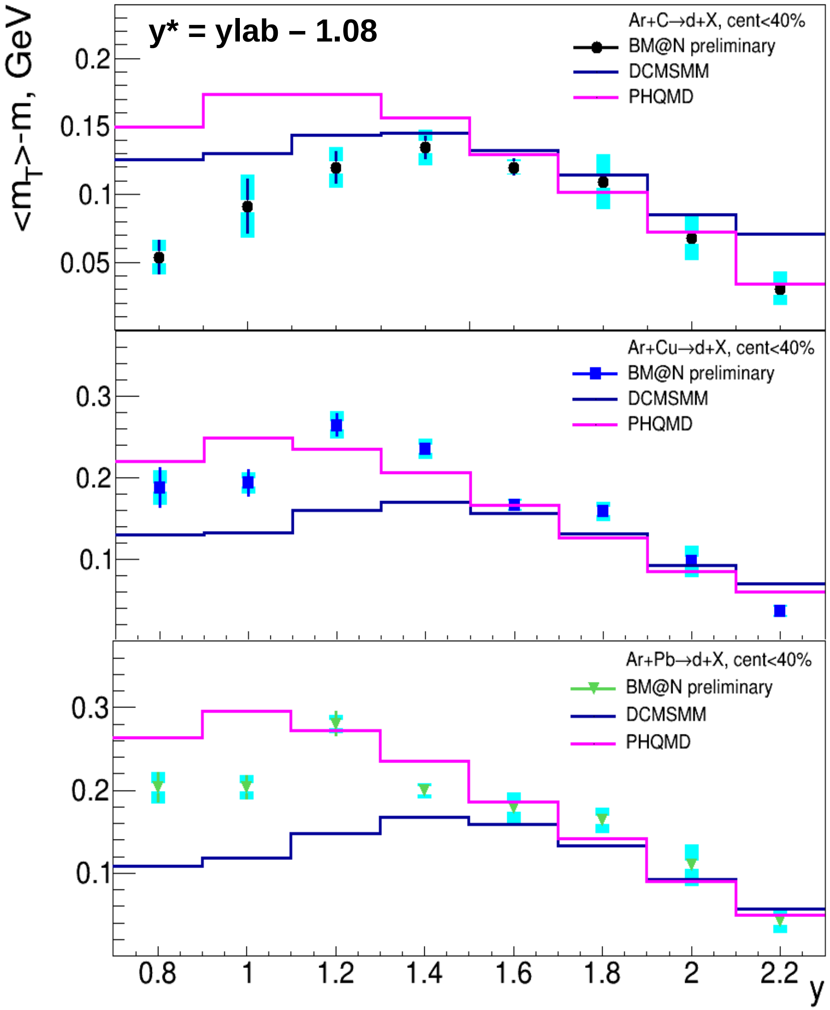
$$\langle E_T \rangle = \langle m_T \rangle - m$$

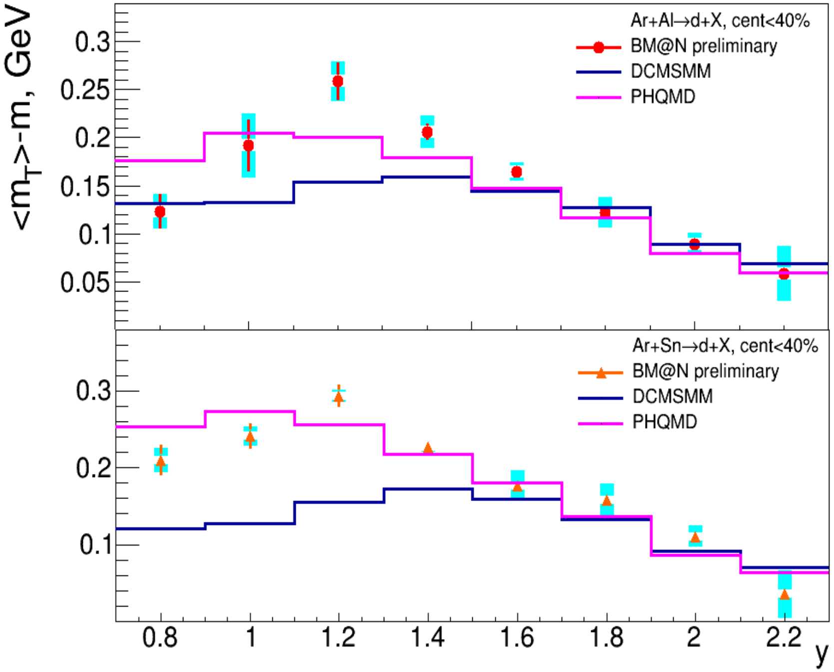
Is related to T0 by the following equation

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

The maximal values of $\langle E_T \rangle$ are measured at rapidity $1.0 < y < 1.3$. In general, the y dependence of $\langle E_T \rangle$ for protons is consistent with predictions of the DCM-SMM and PHQMD models.

Rapidity dependence of the mean transverse kinetic energy ⟨m_T⟩−m obtained from the fits of the m_T spectra of deuterons in Ar+A interactions with centrality 0-40%





$$\langle E_T \rangle = \langle m_T \rangle - m$$

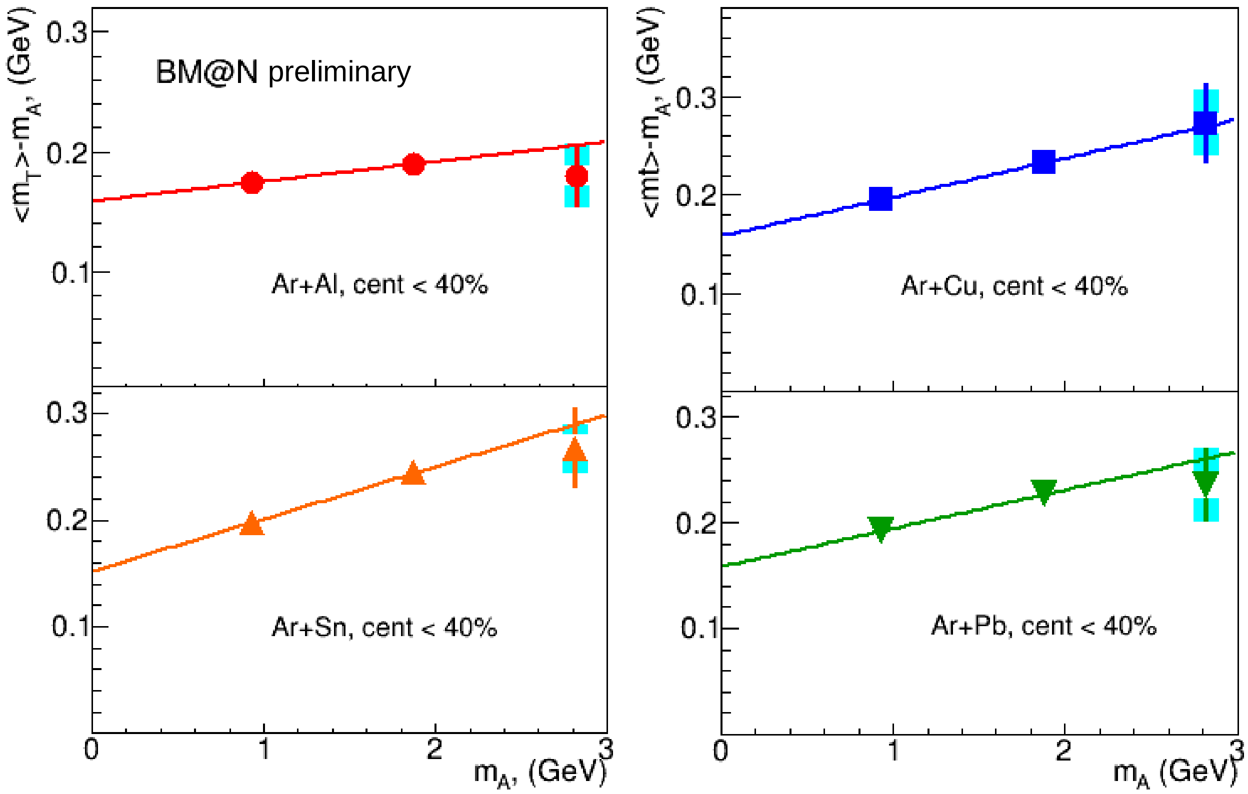
Is related to T0 value extracted from the fit of the m_T spectrum

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

The PHQMD model reproduces the rise of the data at mid-rapidity in CM, while the DCM-SMM model predict the values which are lower than the experimental results.

Dependence of the mean transverse kinetic energy $\langle m_T \rangle - m$ on the mass of the nuclear fragment measured in Ar+A collisions with centrality less than 40%.

The mid-rapidity value of $\langle E_T \rangle$ is calculated as the average value for three points at y=1.0, 1.2 and 1.4



$$\langle E_T \rangle = \langle m_T \rangle - m$$

$$\langle E_T \rangle \approx E_{therm} + E_{flow} = 3/2\,T^* + (\gamma - 1)\,m$$

Where $\gamma = 1/\sqrt{1 - \langle \beta \rangle^2}$

$\langle \beta \rangle$ is the average radial collective velocity and T^* is the temperature of the thermal motion

$$T^* = T\sqrt{(1 + \langle \beta \rangle)/(1 - \langle \beta \rangle)}$$

Rises approximately linearly with the mass of the nuclear fragment

The average radial velocity $\langle \beta \rangle$ and source temperature at the kinetic freeze-out extracted from these fits are given in table

	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
T , MeV	89 ± 3	91 ± 5	80 ± 5	76 ± 5	80 ± 5
$\langle \beta \rangle$	0.0 ± 0.05	0.17 ± 0.05	0.27 ± 0.03	0.30 ± 0.03	0.26 ± 0.03

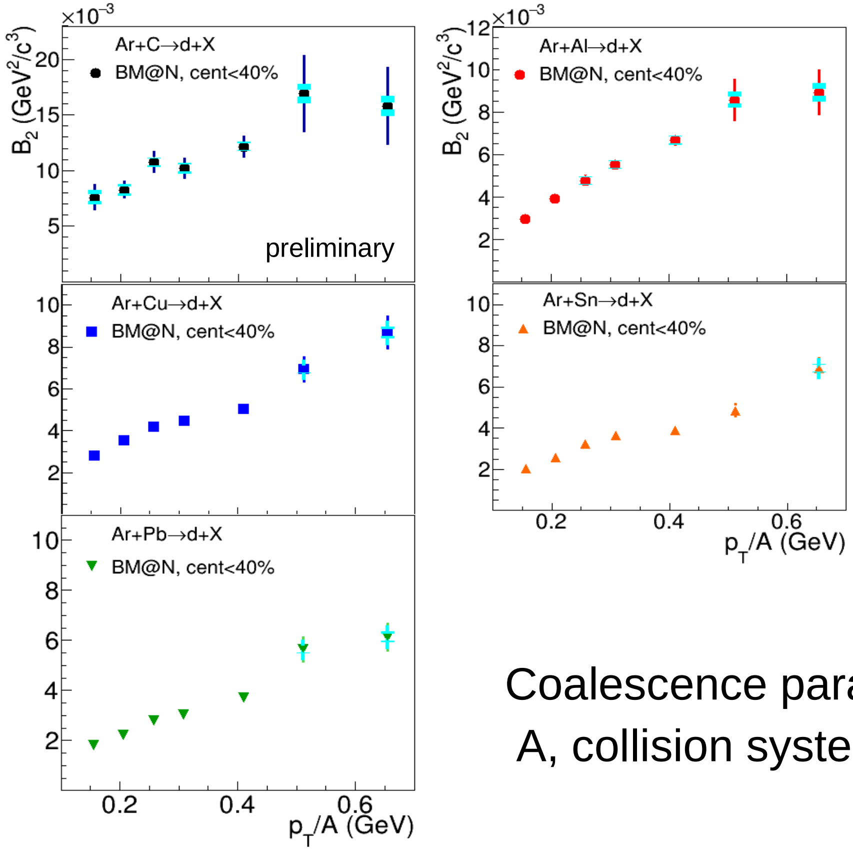
Coalescence factors B_2 and B_3

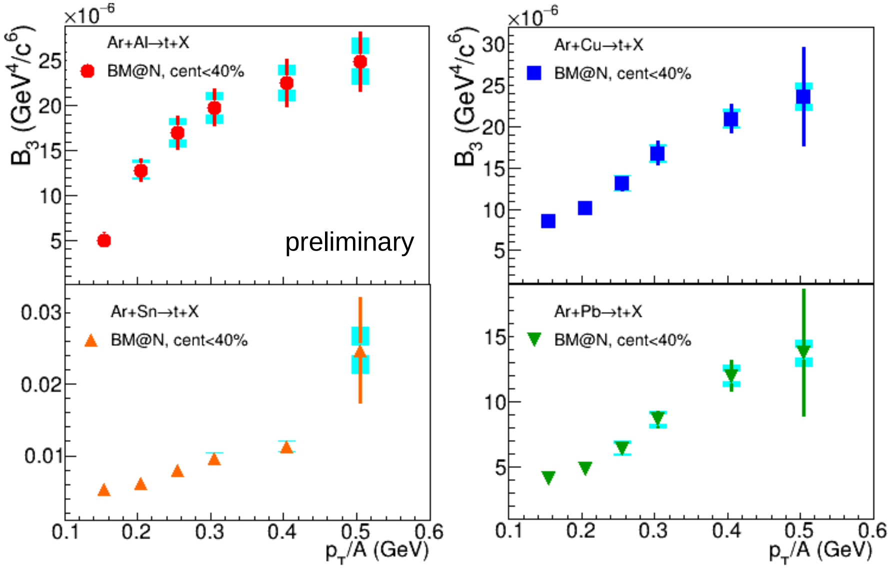
$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^Z \left(E_n \frac{d^3 N_n}{dp_n^3} \right)^{A-Z}$$

$$\approx B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A, B_A \propto V_{eff}^{1-A}$$

$$\rightarrow B_A = d^2 N_A / 2\pi p_{T,A} dp_{T,A} dy / [d^2 N_p / 2\pi p_T dp_T(p) dy]^A, A = 2(d), 3(t)$$

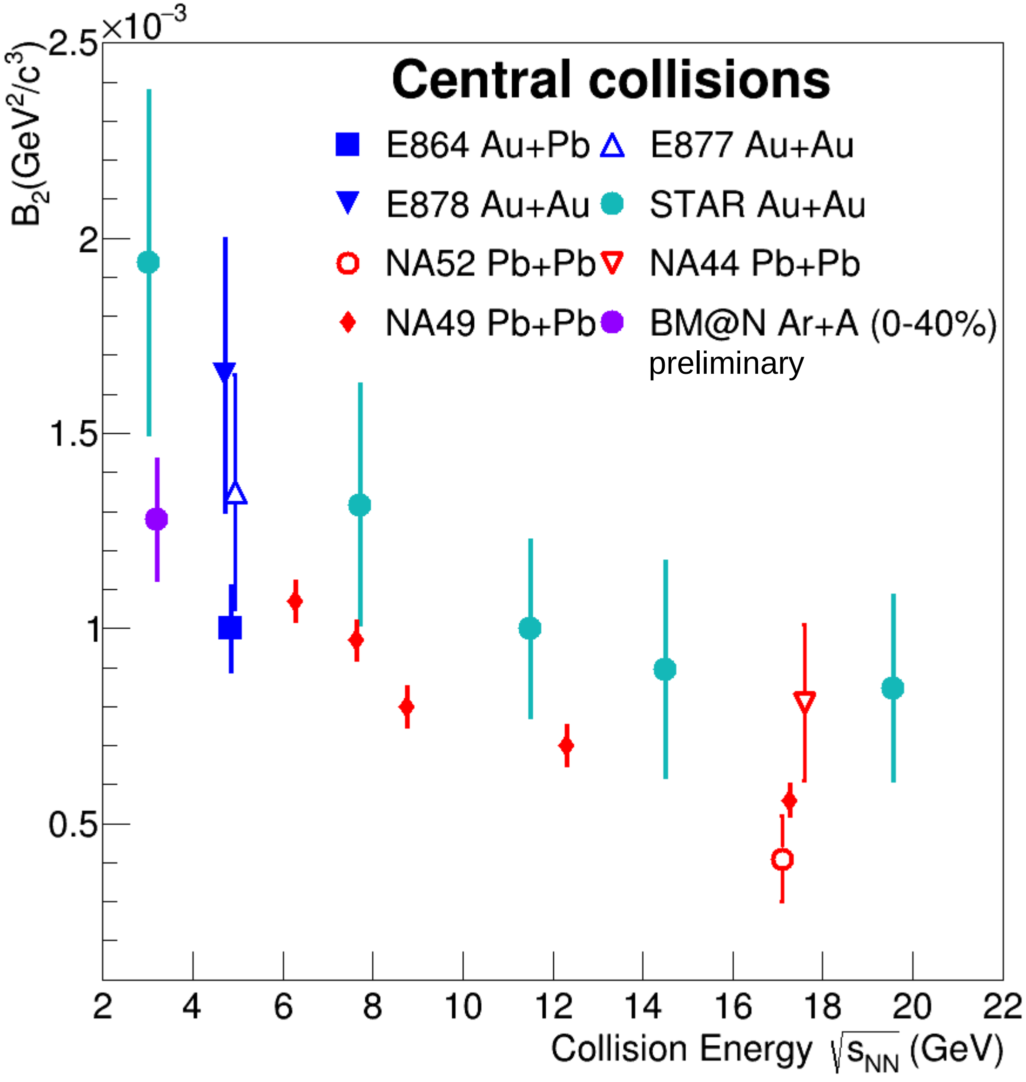
B_A is the coalescence parameter that characterizes the probability of nucleons to form a nucleus.

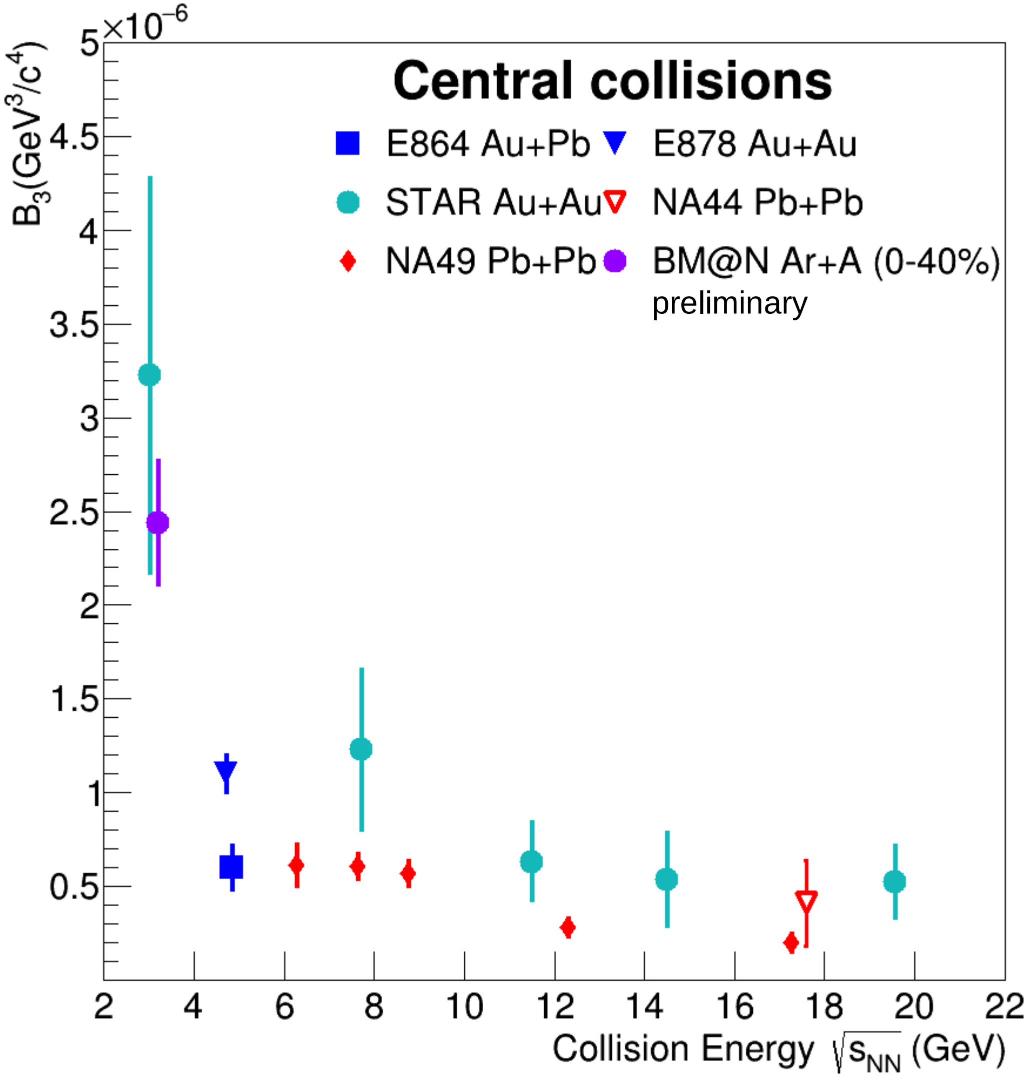




Coalescence parameter B_A depends on the nucleus mass number A, collision system, centrality, energy, and transverse momentum

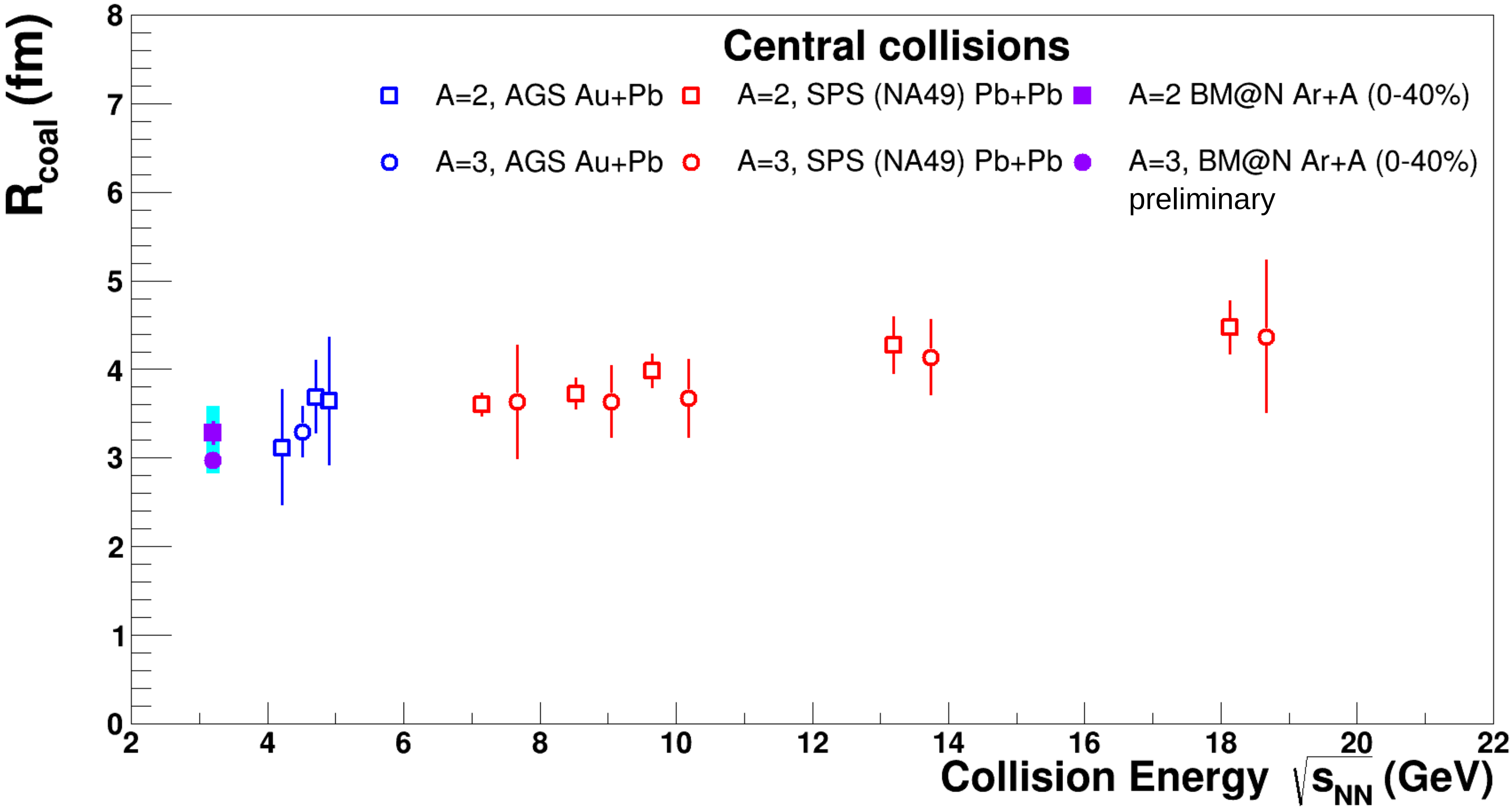
Preliminary Results: Coalescence parameter B_2 and B_3





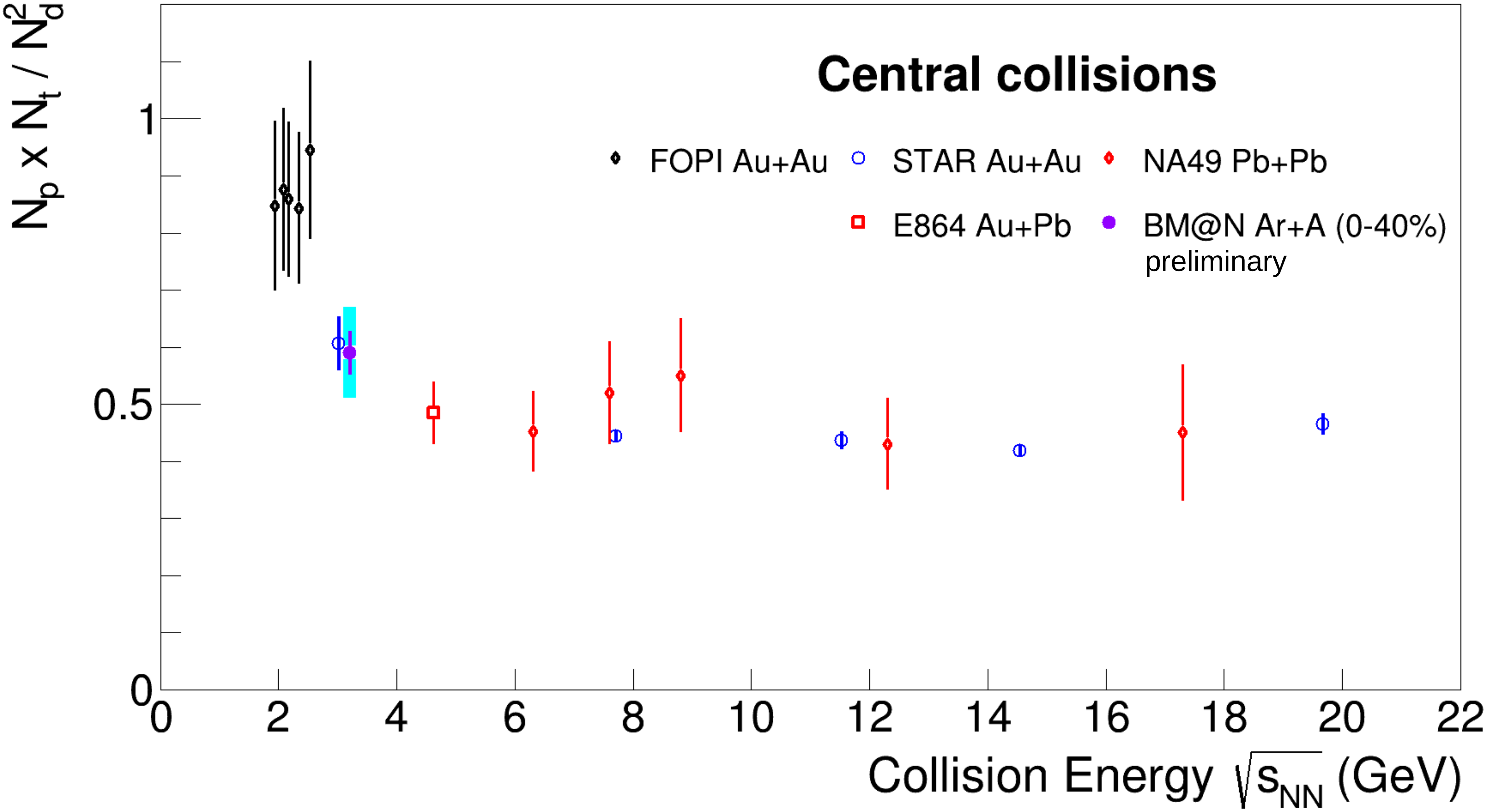
The BM@N result is calculated as a weighted average of Ar+Al,Cu,Sn,Pb

Preliminary Results: Coalescence source radii



The coalescence radii calculated from B_2 and B_3 for deuterons and tritons produced in Ar+A interactions (centrality 0-40%) align with values ranging from 3 to 3.5 fm

Preliminary Results: $N_p \cdot N_t / N^2_d$ ratio



The result of the BM@N experiment fall between the values obtained from experiments done at lower and higher energies.

Summary

1. Results of the BM@N experiment at the Nuclotron/NICA complex are presented on proton , deuteron and triton production in interactions of an argon beam of 3.2 AGeV with fixed targets of C, Al, Cu, Sn and Pb.

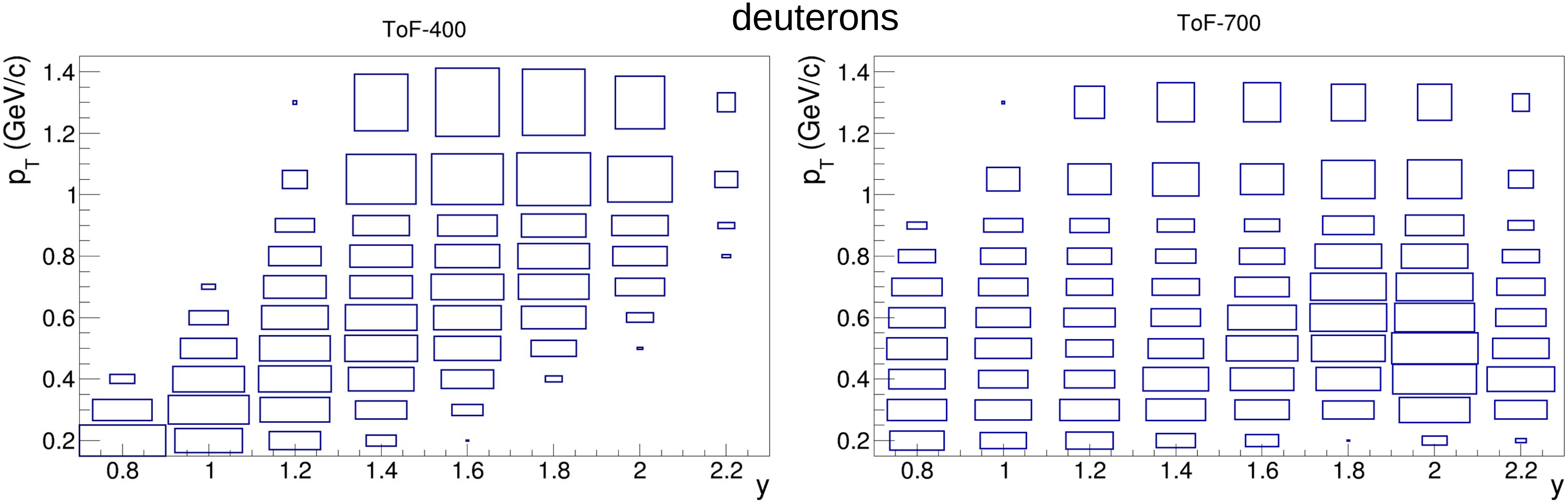
2. Transverse mass distributions, rapidity spectra and multiplicities of protons, deuterons and tritons are measured. The results are treated within a coalescence approach and compared with predictions of theoretical models and with other measurements.

Thank you for your attention !

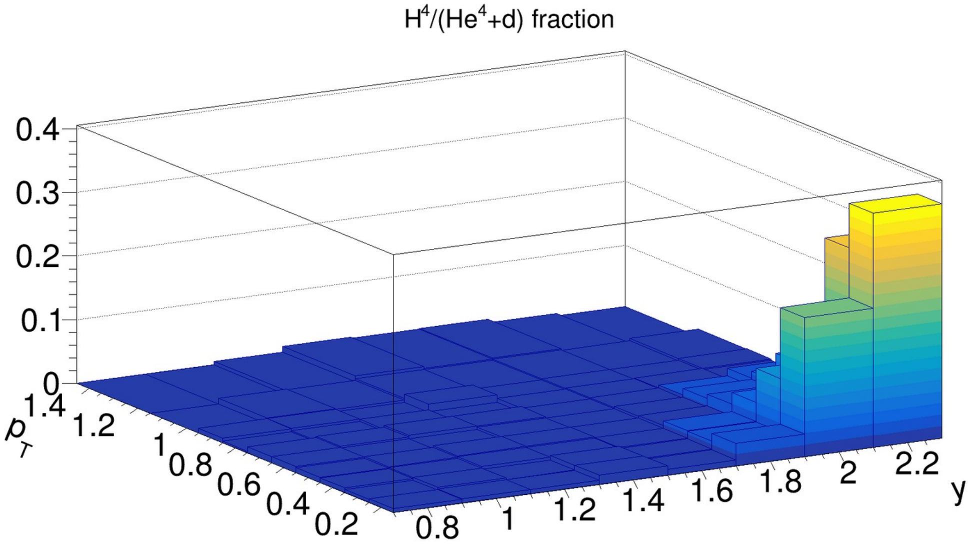
BACKUP

Phase space coverage

deuterons

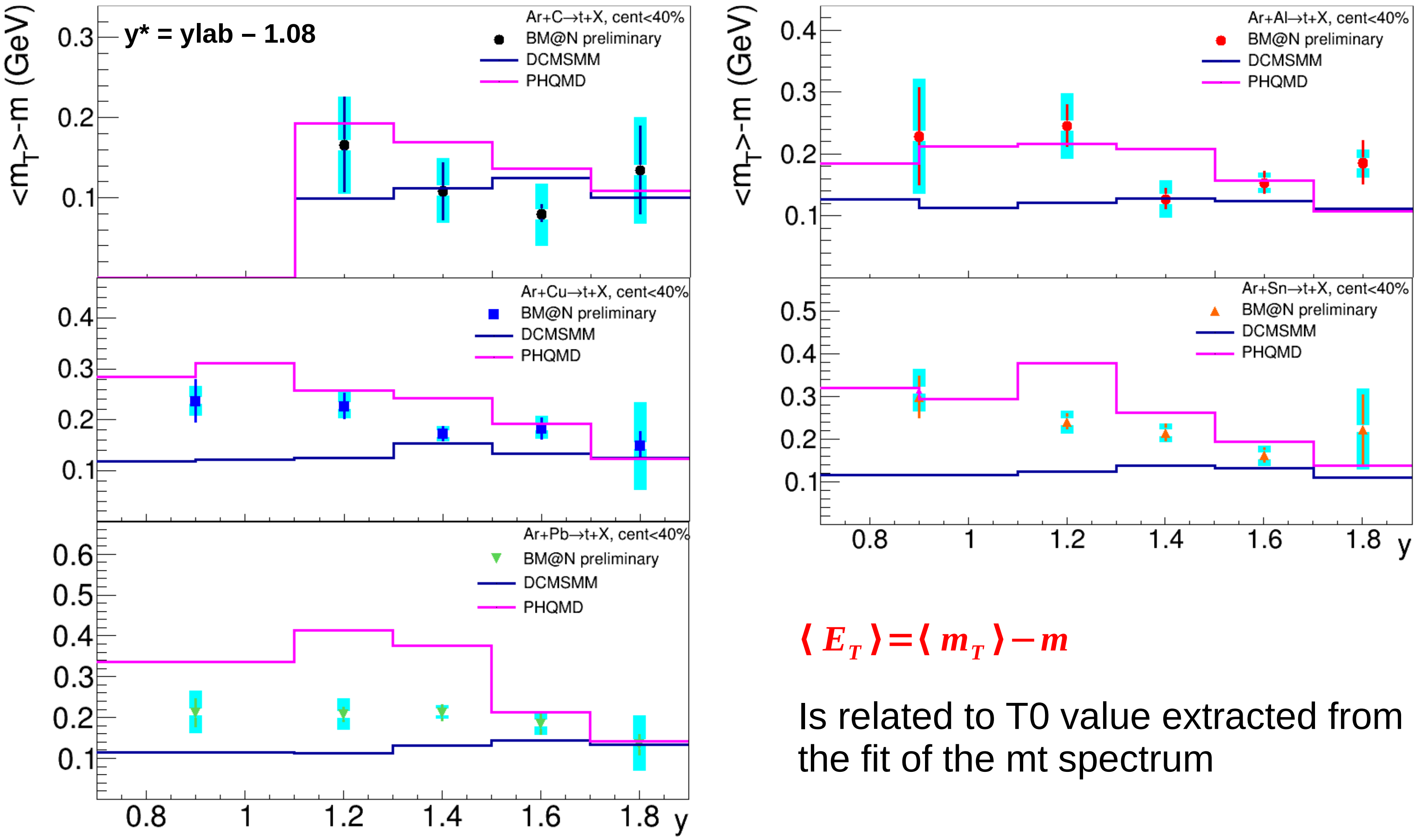


The ToF-400 and ToF-700 detectors cover different ranges of rapidity and transverse momentum of detected particles



Fraction of He_4 in the total He_4+d sample is calculated using signal amplitudes (dE/dx) in GEM detectors in the rapidity and transverse momentum bins and subtracted from the data signals.

Rapidity dependence of the mean transverse kinetic energy ⟨mT ⟩−m obtained from the fits of the m_T spectra of tritons in Ar+A interactions with centrality 0-40%



$$\langle E_T \rangle = \langle m_T \rangle - m$$

Is related to T0 value extracted from the fit of the mt spectrum

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The PHQMD model reproduces the rice of the data at mid-rapidity in CM, while the DCM-SMM model predict the values which are lower than the experimental results.

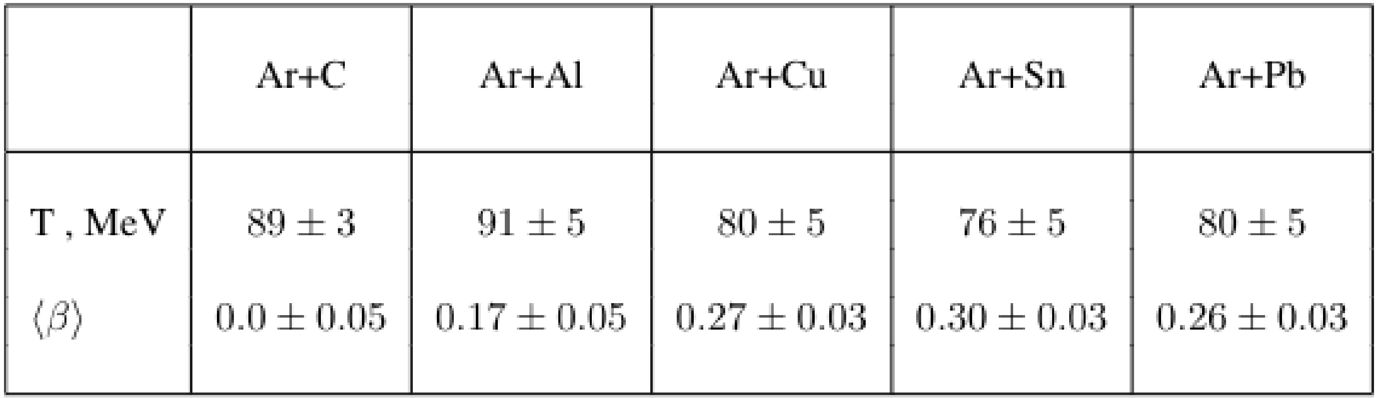
Results: (T) and ⟨β⟩ measurements

1) In Ar+C interactions BM@N observes no collective radial flow, i.e. ⟨β⟩ ~ 0

2) The measurements of temperature (T) and ⟨β⟩ obtained by BM@N for interactions with middle-sized nuclei (from Ar+Al to Ar+Pb) are lower than the values observed in experiments with heavy nuclei (such as Pb+Pb and Au+Au) at higher energies, where T is around 95-110 MeV and ⟨β⟩ is approximately 0.46 in experiments like NA-49 and STAR BES.

3) The FOPI experiment measured T ~ 100 MeV and ⟨β⟩ ~ 0.35 in Au+Au collisions at 1.2 AGeV and found that the radial flow decreases rapidly in interactions of middle size nuclei.

4) The results from BM@N align with the general trend of thermal temperature and radial flow increasing with the size and energy of the collision system.



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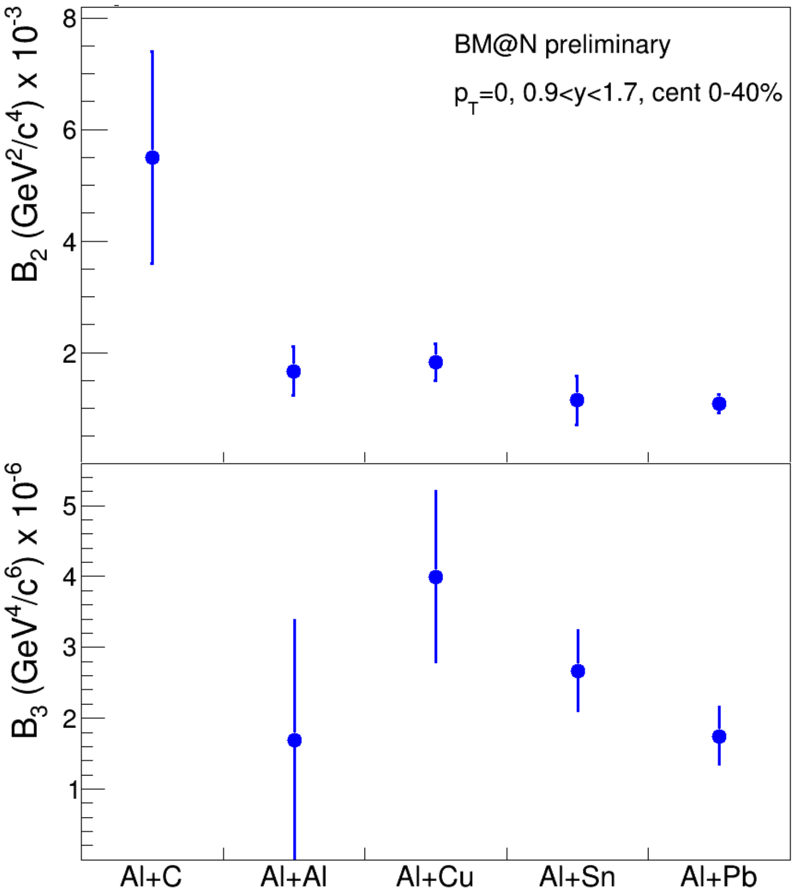
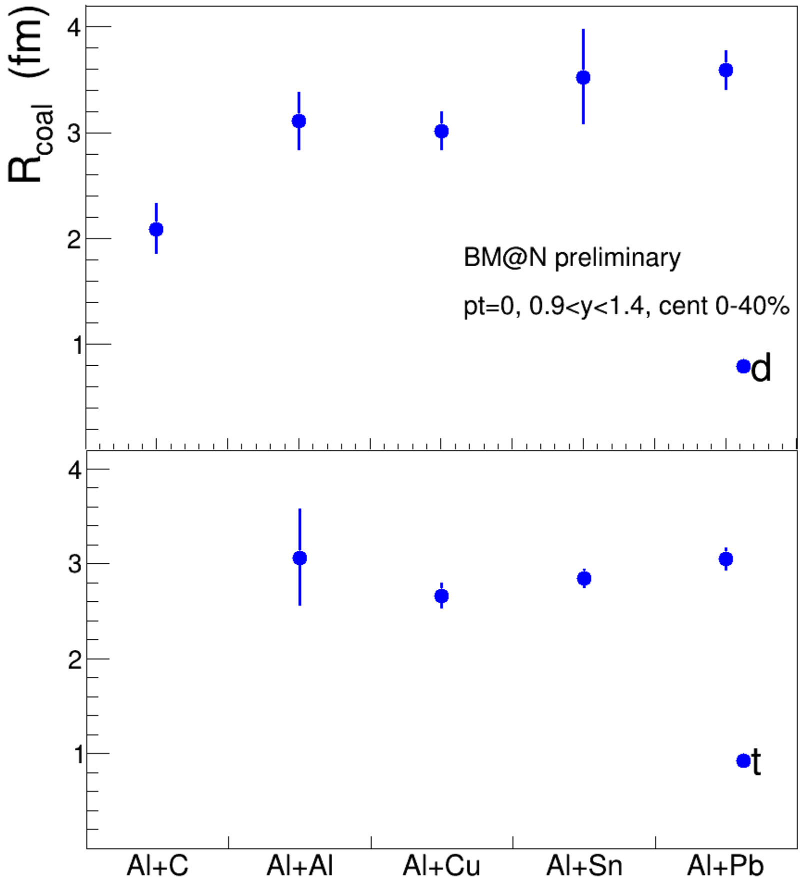
$\langle\beta\rangle$	0.0 ± 0.05	0.17 ± 0.05	0.27 ± 0.03	0.30 ± 0.03	0.26 ± 0.03

Coalescence parameters $B_2(p_T = 0)$ and $B_3(p_T = 0)$ and coalescence radii $R^d_{coal}(p_T = 0)$ and $R^t_{coal}(p_T = 0)$ for deuterons and tritons produced in Ar+A interactions.





The B_2(pT) and $B_3(p_T)$ values given in the previous slide are extrapolated down to $p_T = 0$ using an exponential fit of the form **$B_A(p_T = 0)\exp(a \cdot p_T)$** as predicted by the coalescence model. To evaluate the uncertainty of the parameter $B_A(p_T = 0)$, the data errors are scaled by a factor $\sqrt{\chi^2/ndf}$ from the first iteration of the fit.

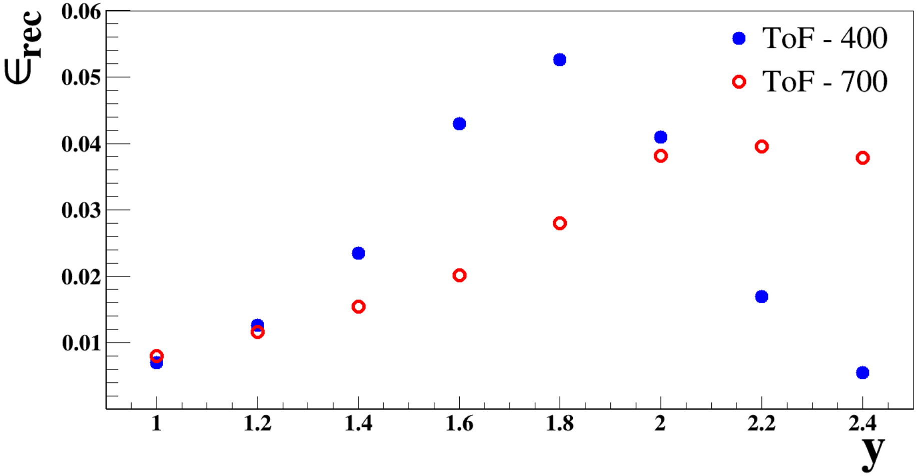
Using prescriptions in **I.G.Bearden et al. (NA44 Collaboration), Eur. Phys. J. C 23, 237–247 (2002)** based on **R. Scheibl and U. Heinz, Phys. Rev. C 59, 1585 (1999).**

The coalescence source radius $R_{coal} = \sqrt[3]{3/2R_{\|}R_{\perp}^2}$ is calculated from the B_2(pT = 0)and B_3(pT = 0) values

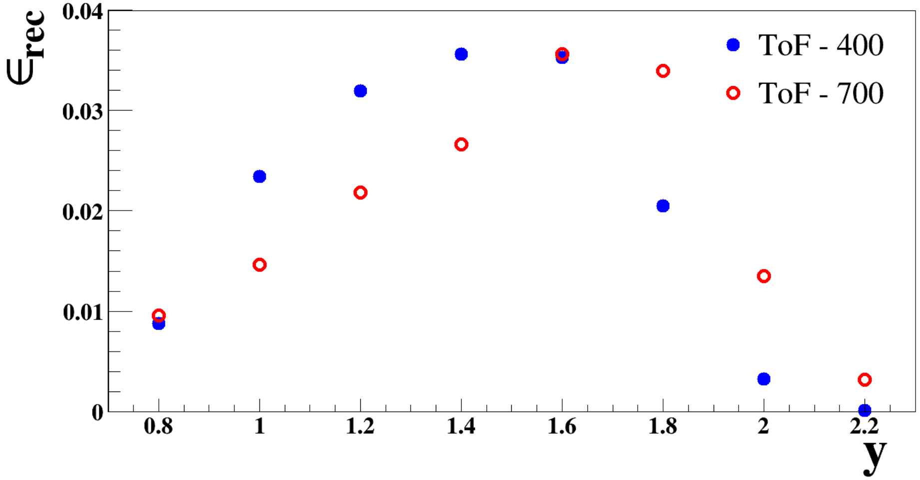
The expression $B_A \propto \exp[m_T(1/T_p - 1/T_A)]/(m_T R \| (m_T) R \perp^2 (m_T)) A^{-1}$ describes the relationship between the coalescence factor B_A and various parameters in the context of nuclear fragment formation.

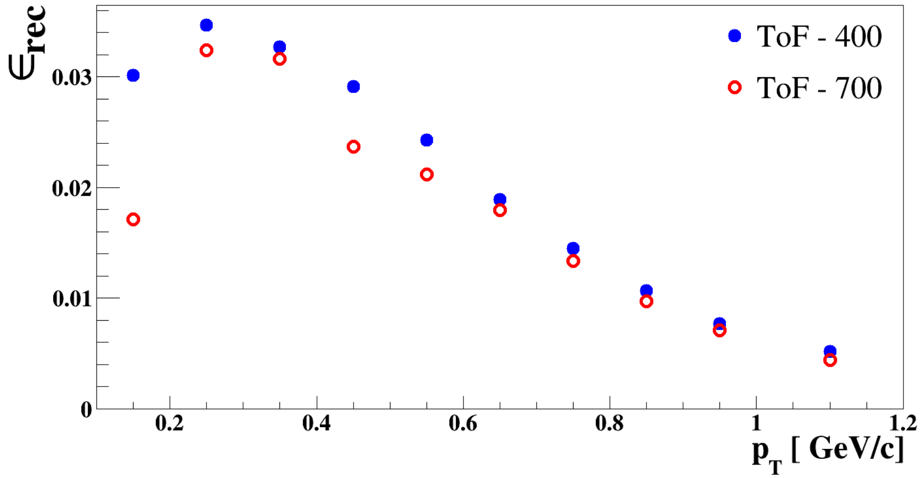
Reconstruction Efficiency for protons and deuterons for TOF400 and TOF700

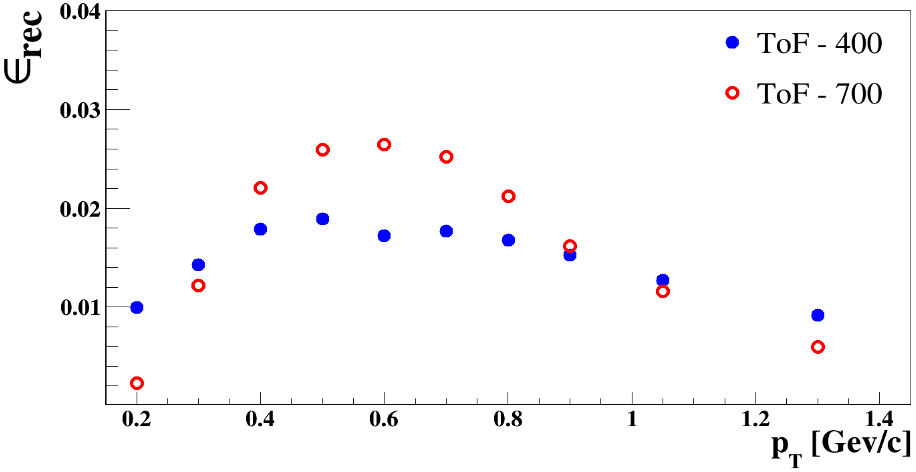
protons



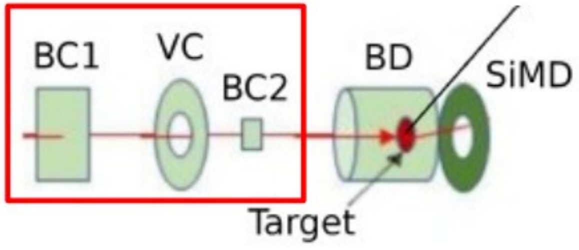
deuterons







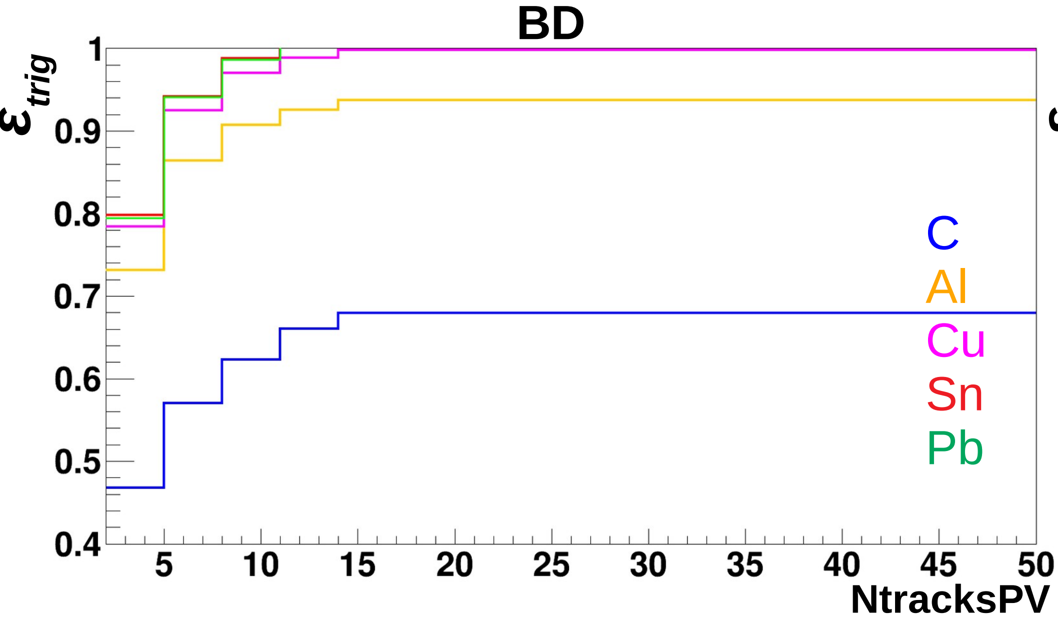
Trigger Efficiency

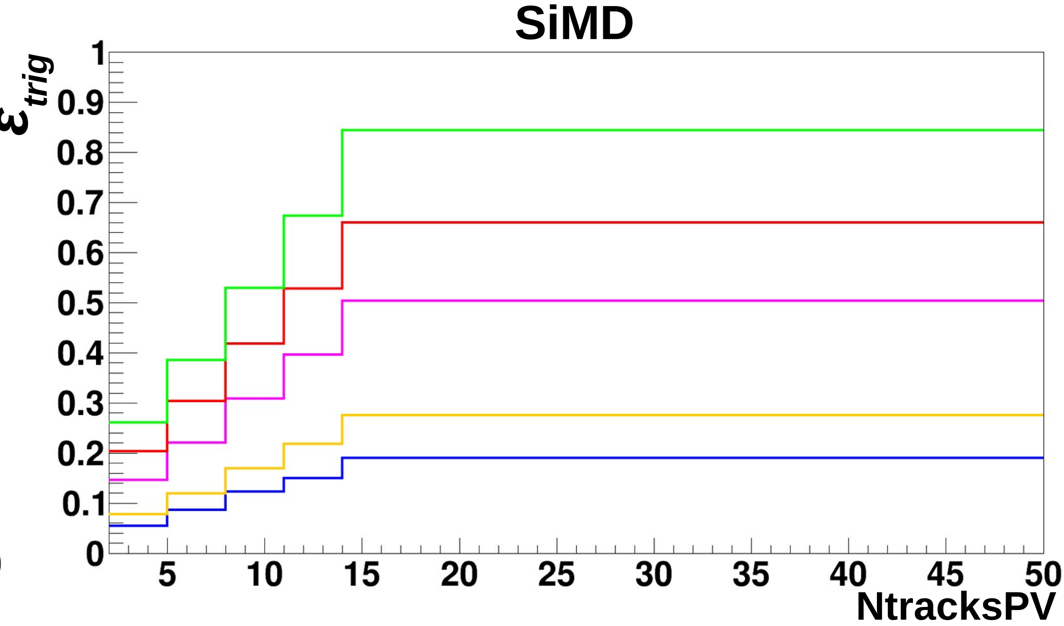


The efficiency to get a trigger signal based on multiplicities of fired channels in the BD (SiMD) detectors εtrig was calculated for events with reconstructed protons, deuterons and tritons using experimental event samples recorded with an independent trigger based on the SiMD(BD)detectors:

$$\varepsilon trig(BD \geq m) = N(BD \geq m,\ SiMD \geq n)/N(SiMD \geq n),$$

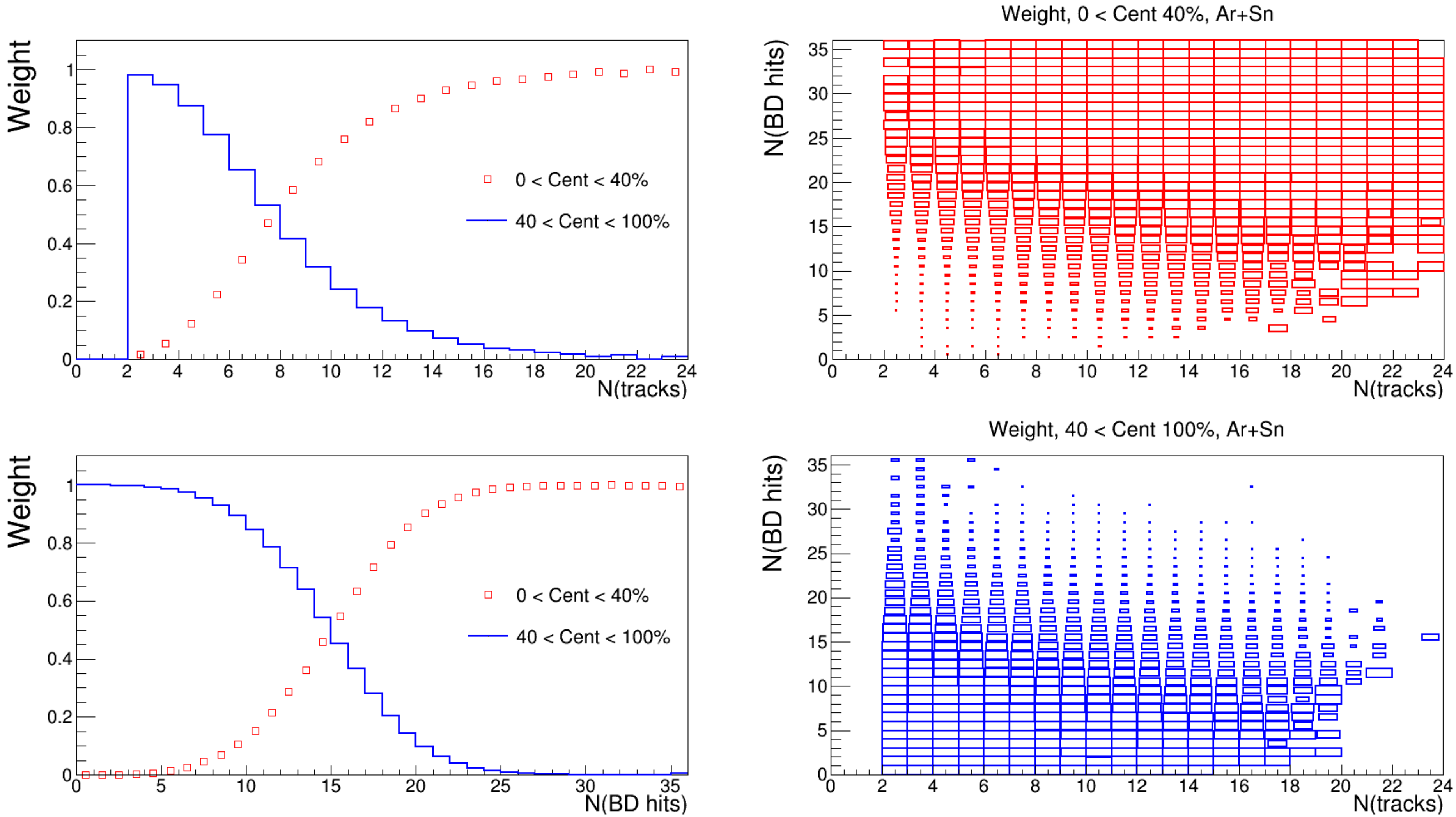
where **m** and **n** are the minimum number of fired channels in BD and SiMD varied in the range from 2 to 4. The dependences of the trigger efficiency on the track multiplicity in the primary event vertex and the X/Y vertex position were taken into account. The efficiency for the combined BD and SiMD triggers was calculated as a product of the BD and SiMD trigger efficiencies.





Centrality classes

Two classes of centrality 0-40% and 40-100% based on barrel detector and track multiplicities



Fractions(probabilities) of events taken from the two-dimensional distributions are used as event weights to define the weighted number of reconstructed p, d, t in the y and p_T bins in data and simulation

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

describes the relationship within a coalescence model for nuclear fragment formation. Here is a breakdown of the components of this equation:

$E_A d^3 NA/d^3 p_A$: This term represents the invariant momentum spectra for the nuclear fragment with atomic mass number A.

B_A: The coalescence factor B_A characterizes the nuclear fragment formation process within the coalescence model.

$E_p d^3 N_p/d^3{}_p$: This part corresponds to the momentum spectra of the nucleon with momentum p, which is involved in the formation of the nuclear fragment.

Z: Represents the charge of the nuclear fragment being formed.

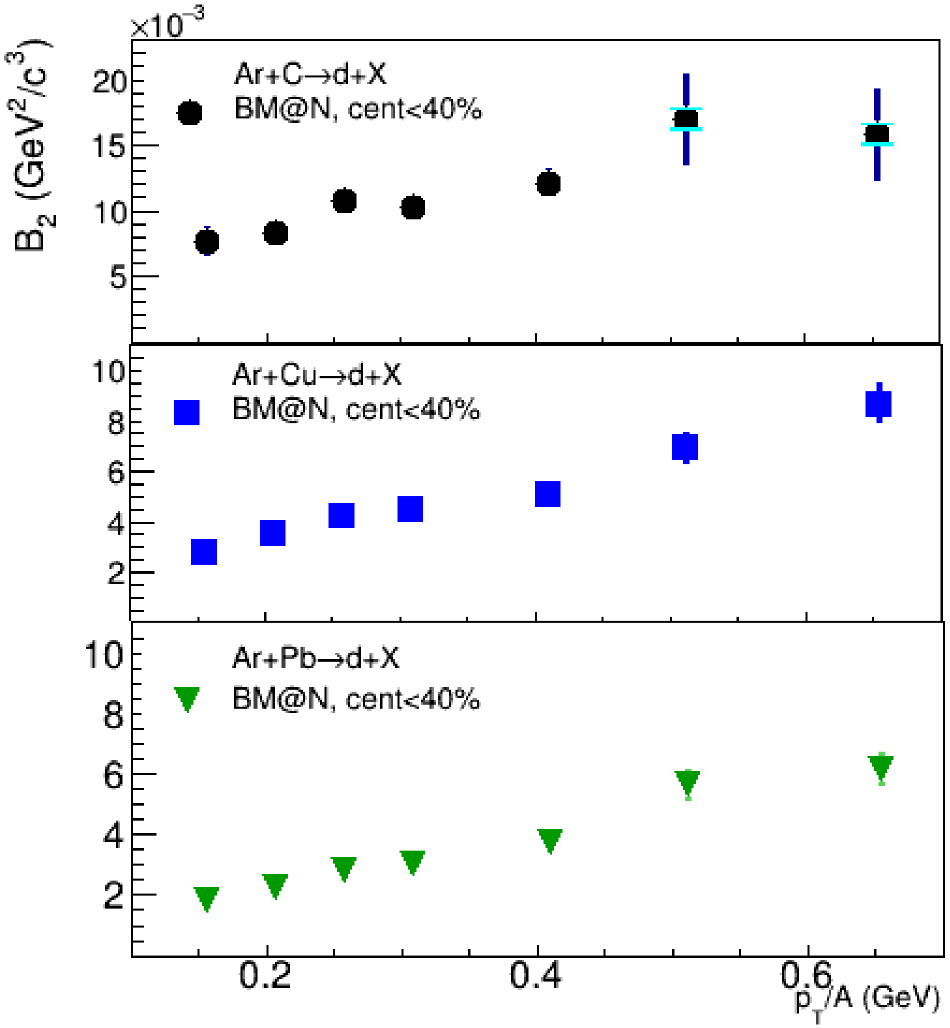
$E_n d^3 N_n/d^3{}_p$: Refers to the momentum spectra of the neutron involved in the coalescence process.

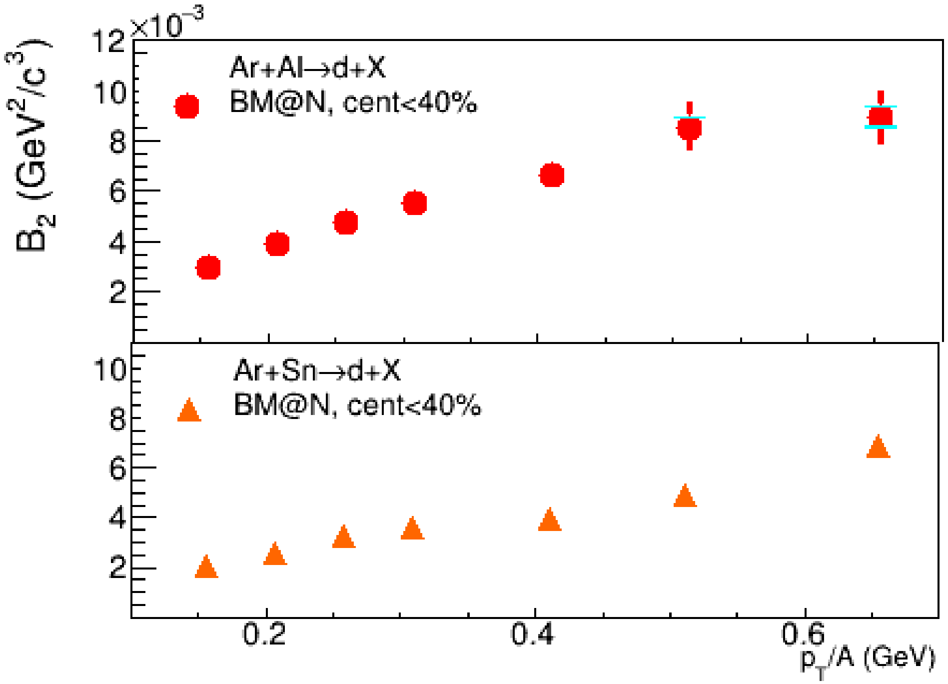
A-Z: Denotes the difference between the atomic mass number A and the charge Z, representing the number of neutrons in the nuclear fragment.

$_{pA}$: Momentum of the nuclear fragment.

p_A/A: Momentum of the nucleon normalized by the atomic mass number A.

Coalescence parameter B_2 for deuterons measured as a function of p_T /A in Ar+A collisions with centrality 0-40%.



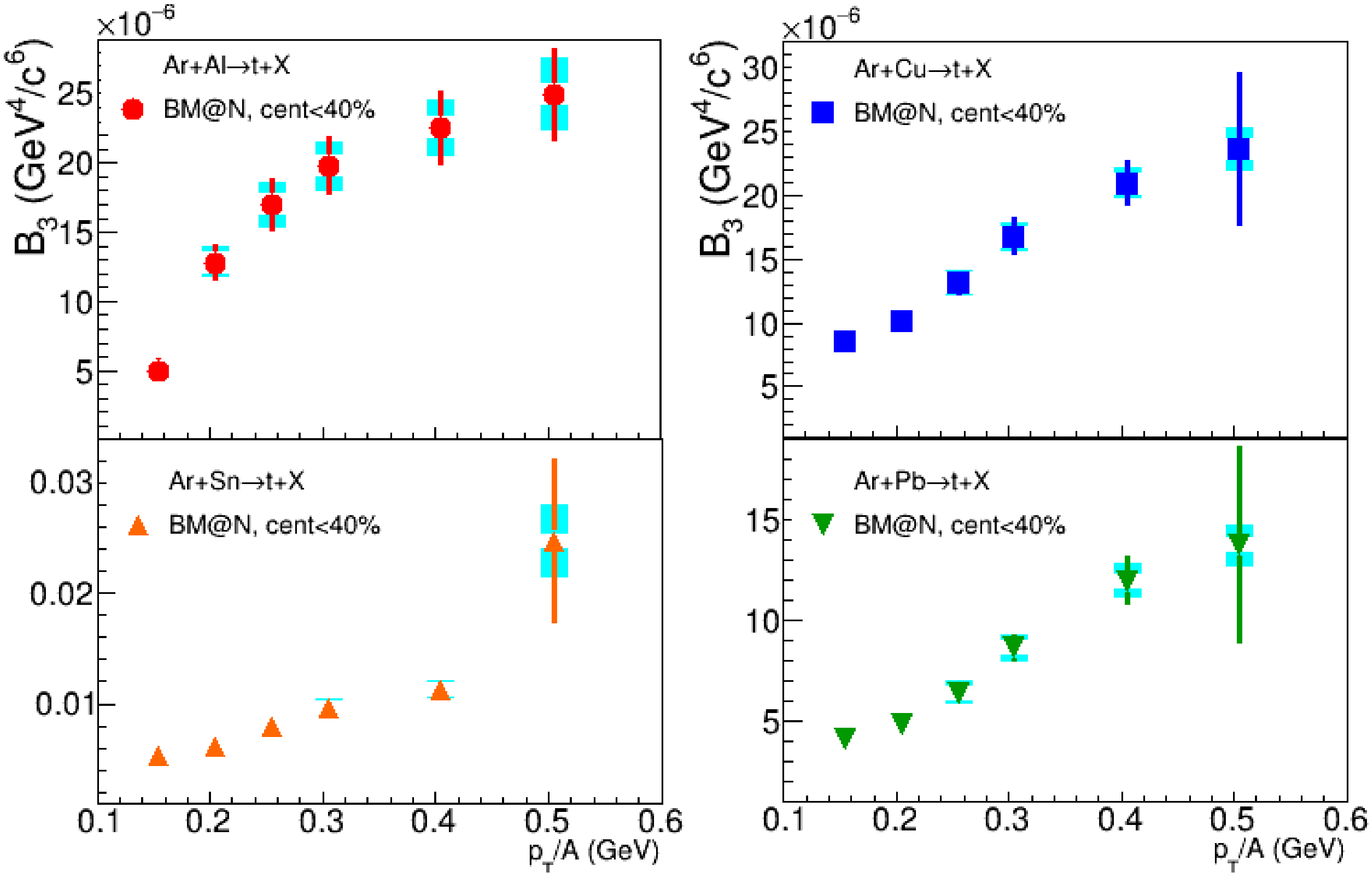


$$B_A = d^2 N_A / 2\pi p_{T,A}\, dp_{T,A}\, dy / \left(d^2 N_p / 2\pi p_T\, dp_T\, dy \right)^A$$

This equation relates the coalescence parameter B_A for deuterium (A=2) and tritium (A=3) to the measured yields of these nuclei and protons in the p_T and y bins.

The yields of protons and deuterons are measured in the same rapidity range, $0.9 < y < 1.7$ ($-0.18 < y_* < 0.62$)
The coalescence parameter B_2 rises with p_T but the dependence is close to linear rather than exponential.

Coalescence parameter B_3 for tritons measured as a function of p_T /A in Ar+A collisions with centrality 0-40%.



Statistics of tritons are not sufficient to present B_3 for Ar+C interactions

The yields of protons and tritons are measured in the same rapidity range, $0.9 < y < 1.7$ ($-0.18 < y_* < 0.62$)

The coalescence parameter B_3 rises with p_T but the dependence is close to linear rather than exponential.

Systematic uncertainties

The systematic uncertainty of the p, d, t yields and ε_{rec} in every p_T and y bin is calculated as a root square of quadratic sum of uncertainties coming from the following sources:

Sys1: systematic uncertainty of the central tracking detector efficiency.

Sys2: systematic uncertainty of the matching of central tracks to outer trackers and ToF detectors

Sys3: systematic errors of the reconstruction efficiency due to the remaining difference in the X/Y primary vertex distribution in the simulation relative to the experimental data.

Sys4: systematic errors of the background subtraction under the p, d, t signals in the mass squared spectra of identified particles.

Sys5:Systematic uncertainty calculated as half of the difference of the p, d, t yields measured in bins of rapidity y in the ToF-400 and ToF-700 detectors

Sys6:Systematic uncertainty in event centrality weights

	Ar+C %	**Ar+Al %**	**Ar+Cu %**	**Ar+Sn %**	**Ar+Pb %**
protons Total	**18**	**9**	**11**	**16**	**13**
deuterons Total	**33**	**23**	**21**	**20**	**23**
tritons Total	**44**	**23**	**21**	**21**	**23**

Systematic uncertainties

- Systematic uncertainty of the central tracking detector efficiency: it is timated from the remaining difference in the number of track hits in the central detectors in the simulation relative to the data (see Fig. 5d) and found to be within 3%

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- Systematic uncertainty of the matching of central tracks to the CSC (DCH) hits and ToF-400 (ToF-700) hits: it is estimated from the remaining differ270 ence in the matching efficiency in the simulation relative to the data and found to be within 5%.

- Systematic uncertainty of the reconstruction efficiency due to the remain273 ing difference in the X/Y distribution of primary vertices in the simulation relative to the data.

- Systematic uncertainty of the background subtraction in the mass-squared M2 spectra of identified particles: it is estimated as the difference between the background integral under the p, d, t mass-squared windows taken from "mixed events" and from the fitting of the M2 spectra by a linear function. The latter is done in the M2 range, excluding the proton, deuteron, triton signal windows.

Systematic uncertainties

Systematic uncertainty calculated as half of the difference of the proton, deuteron, triton yields measured in bins of rapidity y in the ToF-400 and ToF-700 detectors

- Systematic uncertainy of the event centrality weights estimated

1) from the remaining difference in the shape of the N(track) and N(BD) distributions in the y and pT bins in the data and the simulation;
2) from the difference in the event centrality weights taken from the two-dimensional N(track)/N(BD) distribution relative to the one-dimensional N(BD) distribution.

The total systematic uncertainty of the yield and reconstruction efficiency for the various targets, calculated as the quadratic sum of these uncertainties

For the evaluation of the systematic uncertainty of the trigger efficiency ϵtrig, the following sources are considered:

- The systematic uncertainty associated with the factorization assumption of the two trigger factors, BD and SiMD, was estimated from the difference of ϵtrig evaluated as described in Section 4, with the result evaluated using the limited amount of events registered with the beam trigger BT.

- To estimate a possible distortion of ϵtrig (BD ≥ m) due to the selection of events with the hardware-set condition N(SiMD ≥ n), ϵtrig was also evaluated using the events recorded with the beam trigger BT. The difference between the results is treated as another source of systematic uncertainty of the trigger efficiency.
- Variations of the trigger efficiency on the track multiplicity in the primary vertex and on the X/Y vertex position.

Comparison between experimental data and MC