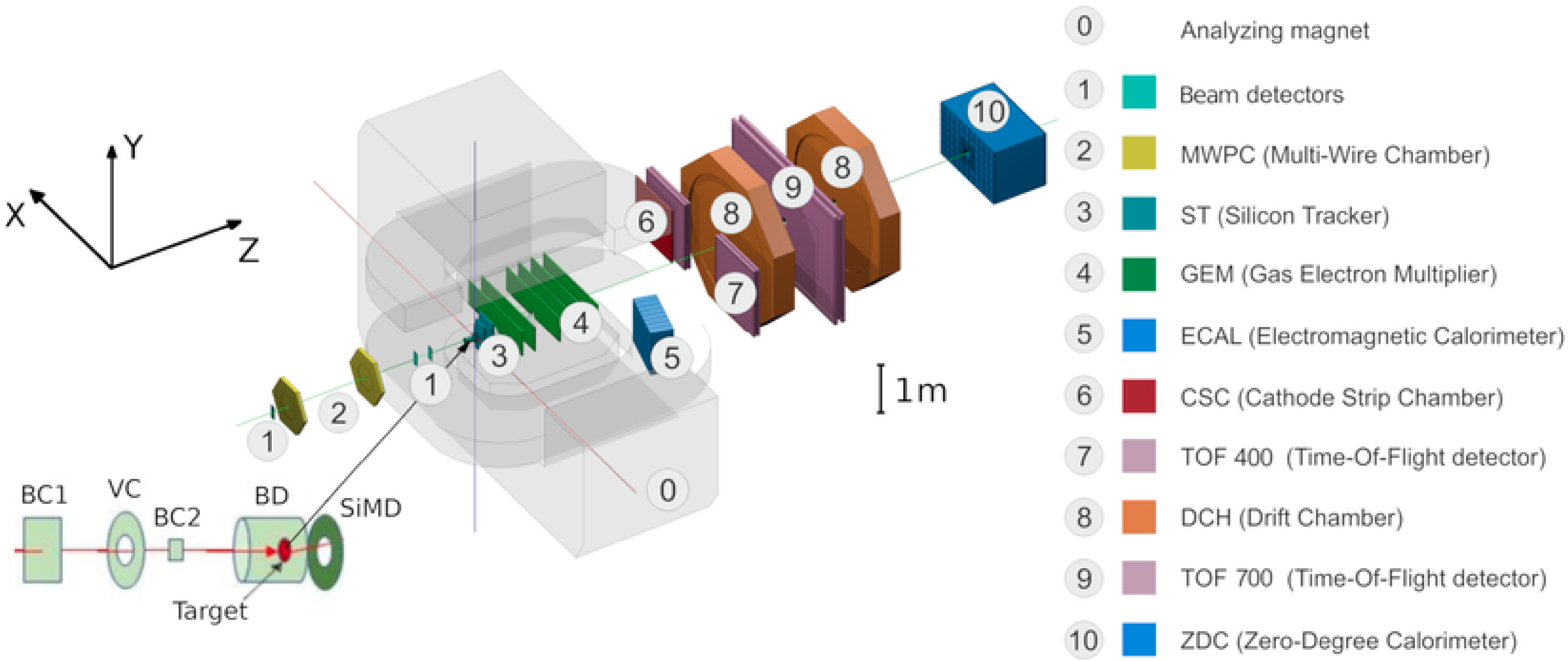
Production of protons, deuterons, tritons in argon-nucleus interactions at 3.2 AGeV



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Outline

1) Selection criteria

2) Data – MC agreement

3) Reconstruction and trigger efficiencies

4) Centrality classes

5) Cross sections, multiplicities and systematic uncertainties

6) Rapidity and transverse mass spectra

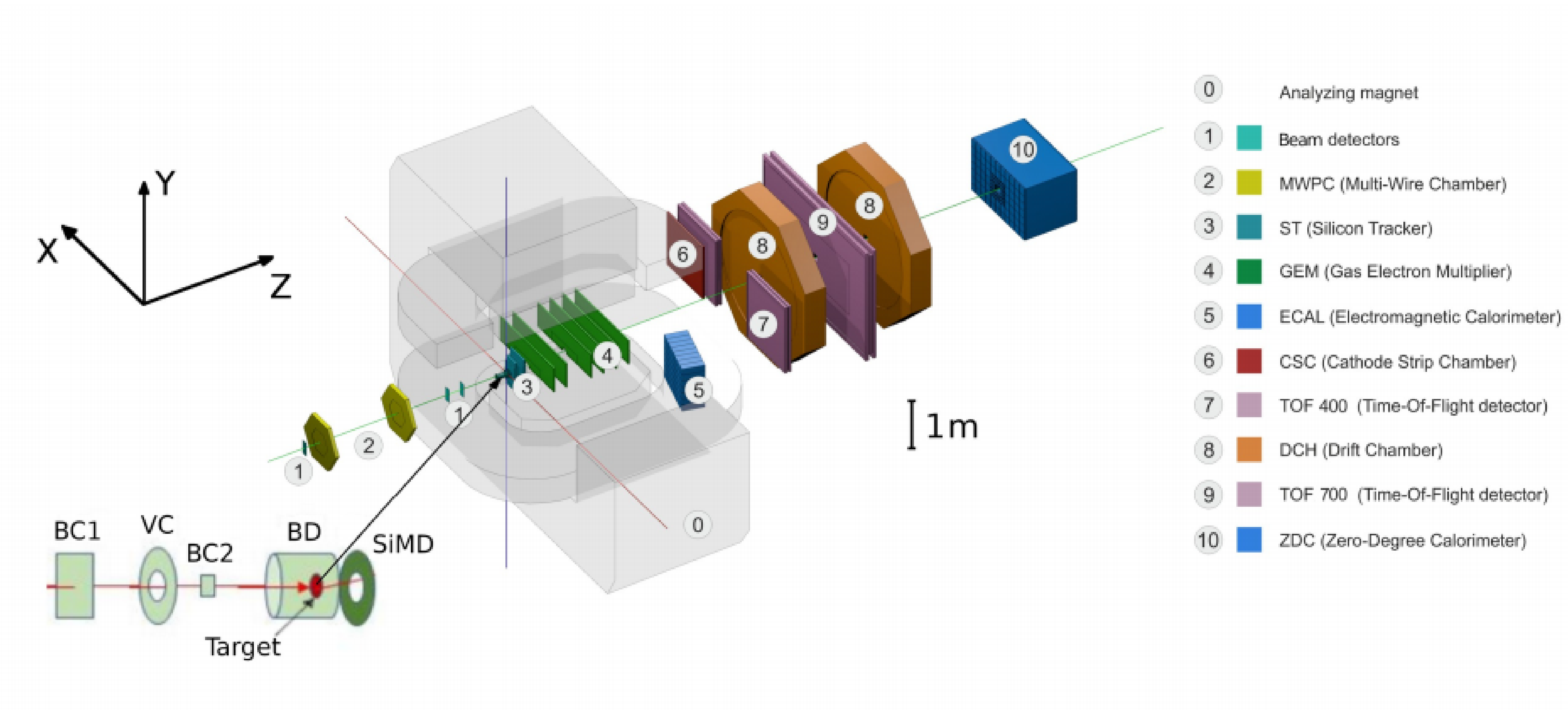
7) Coalescence factors

8) Summary

BM@N Setup

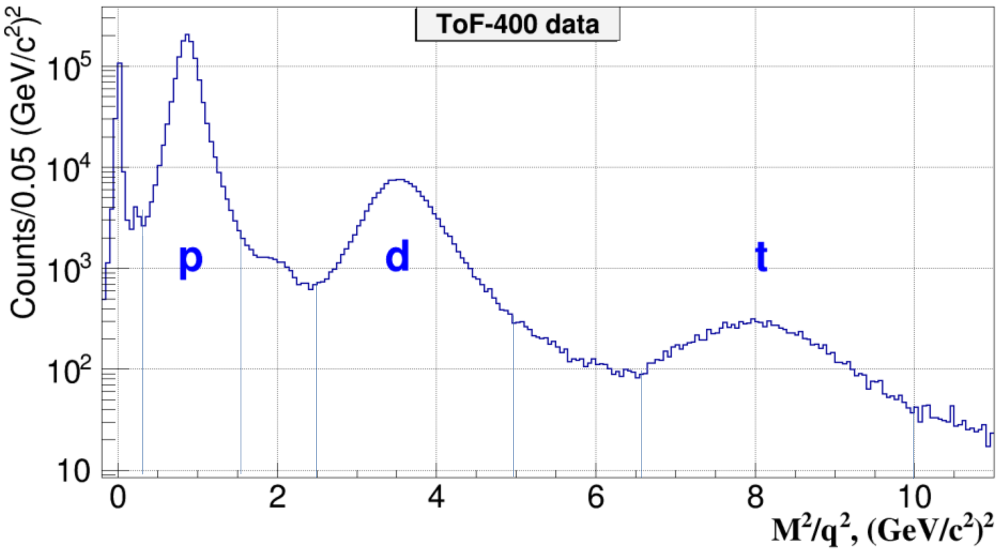
Run with argon beam (March 2018)

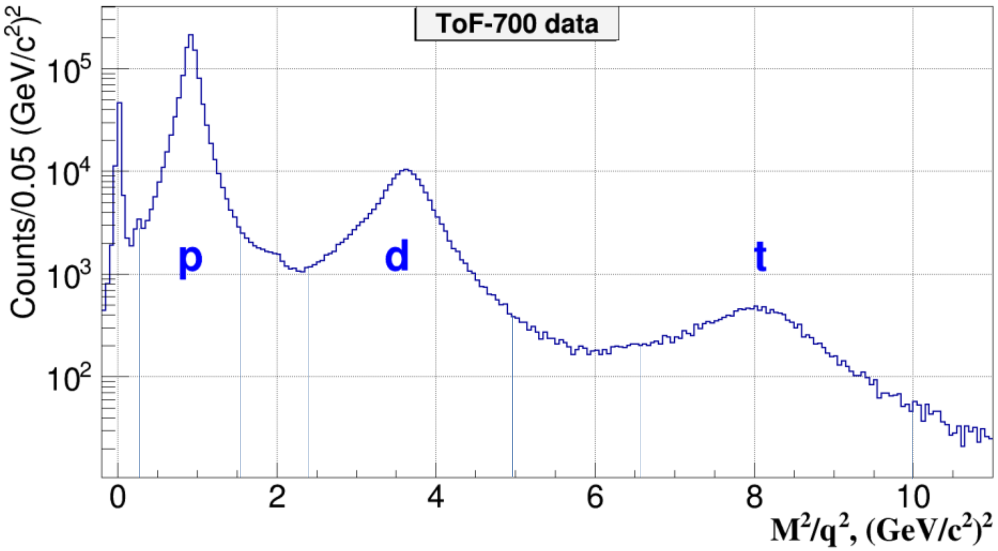
(Ar+C, Ar+Al, Ar+Cu, Ar+Sn, Ar+Pb at 3.2A GeV)



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





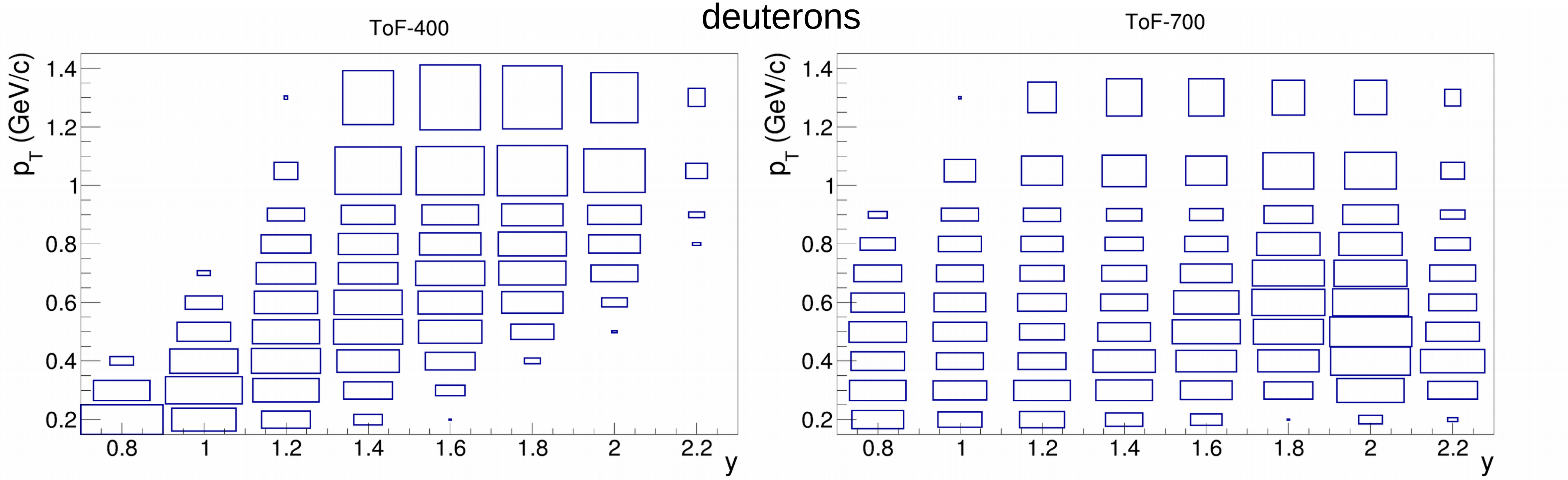
$$sig = hist - bg$$

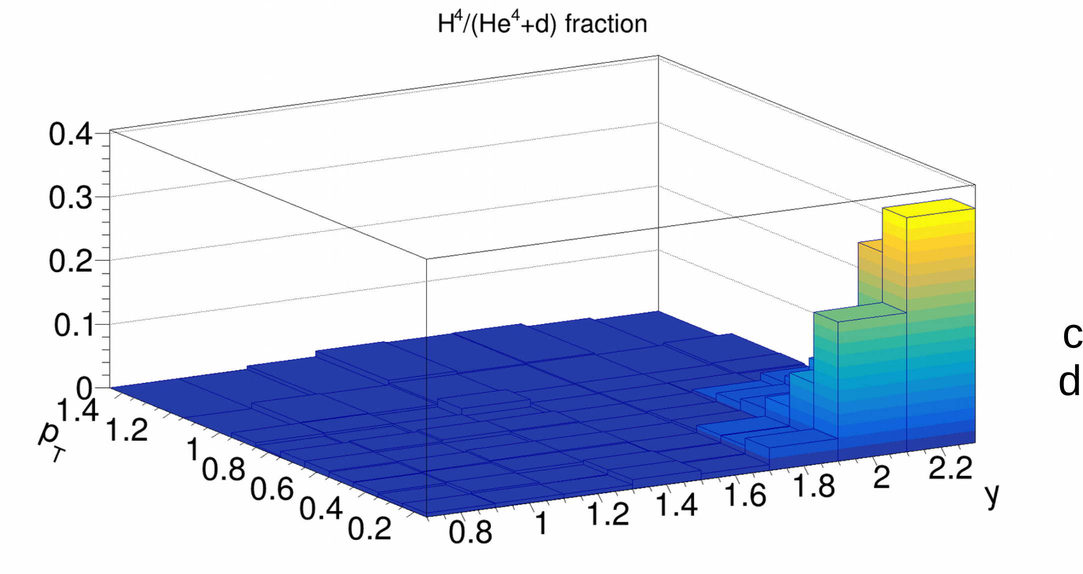
$$err_{stat} = \sqrt{hist + bg}$$

Where hist and bg represent the histogram and background integral yields within the selected m^2 windows

Phase space coverage

deuterons

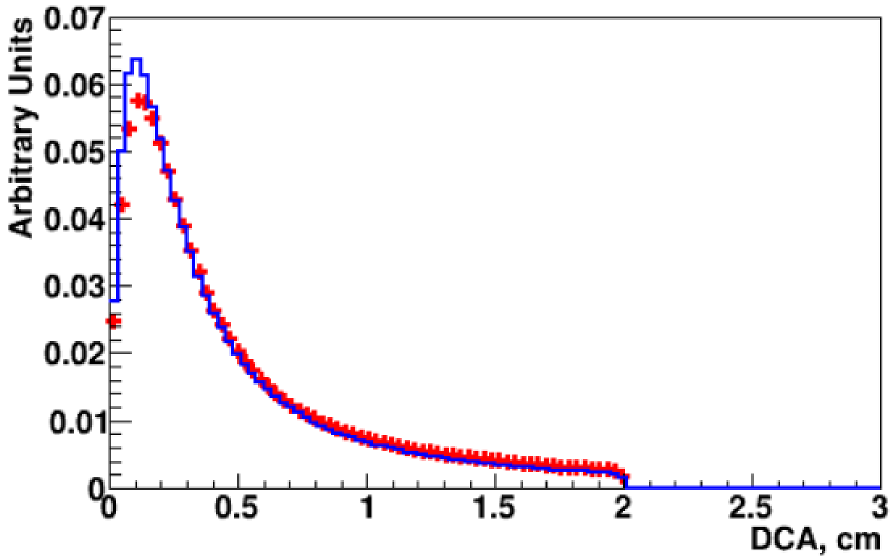


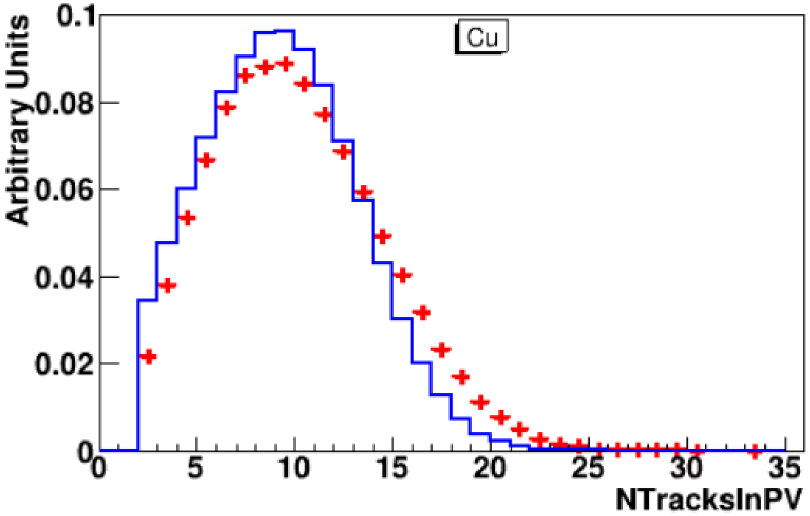


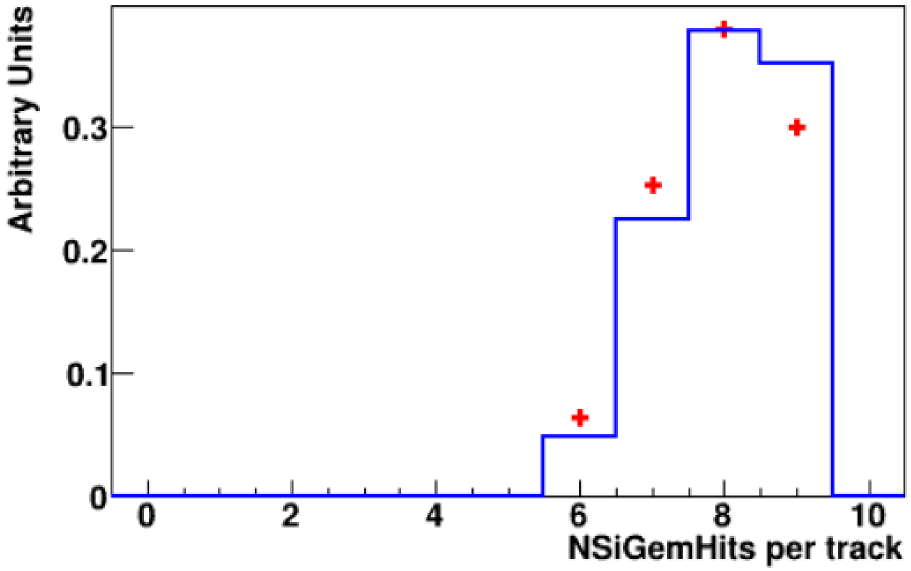
The ToF-400 and ToF-700 detectors cover different ranges of rapidity and transverse momentum of detected particles

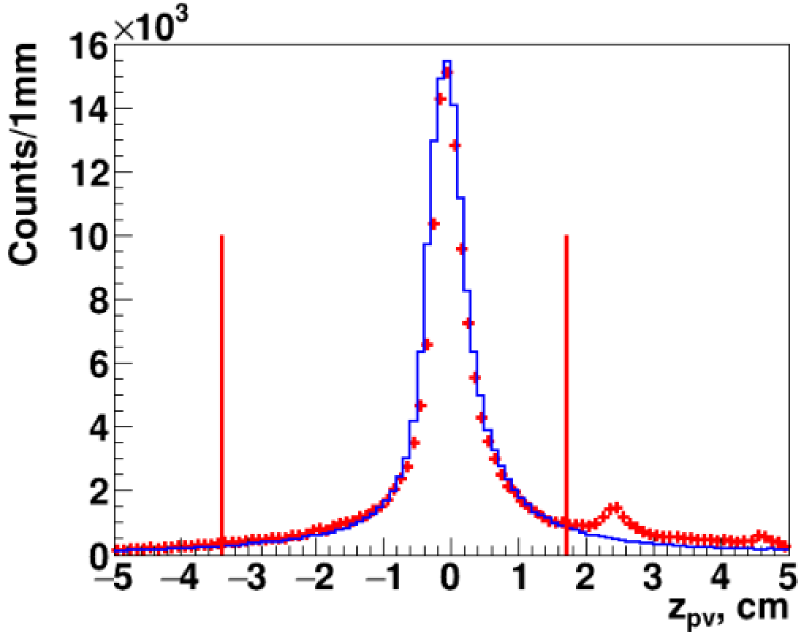
Fraction of He_4 in the total He_4+d sample is calculated using signal amplitudes (dE/dx) in GEM detectors in the rapidity and transverse momentum bins and subtracted from the data signals.

Comparison between experimental data and MC







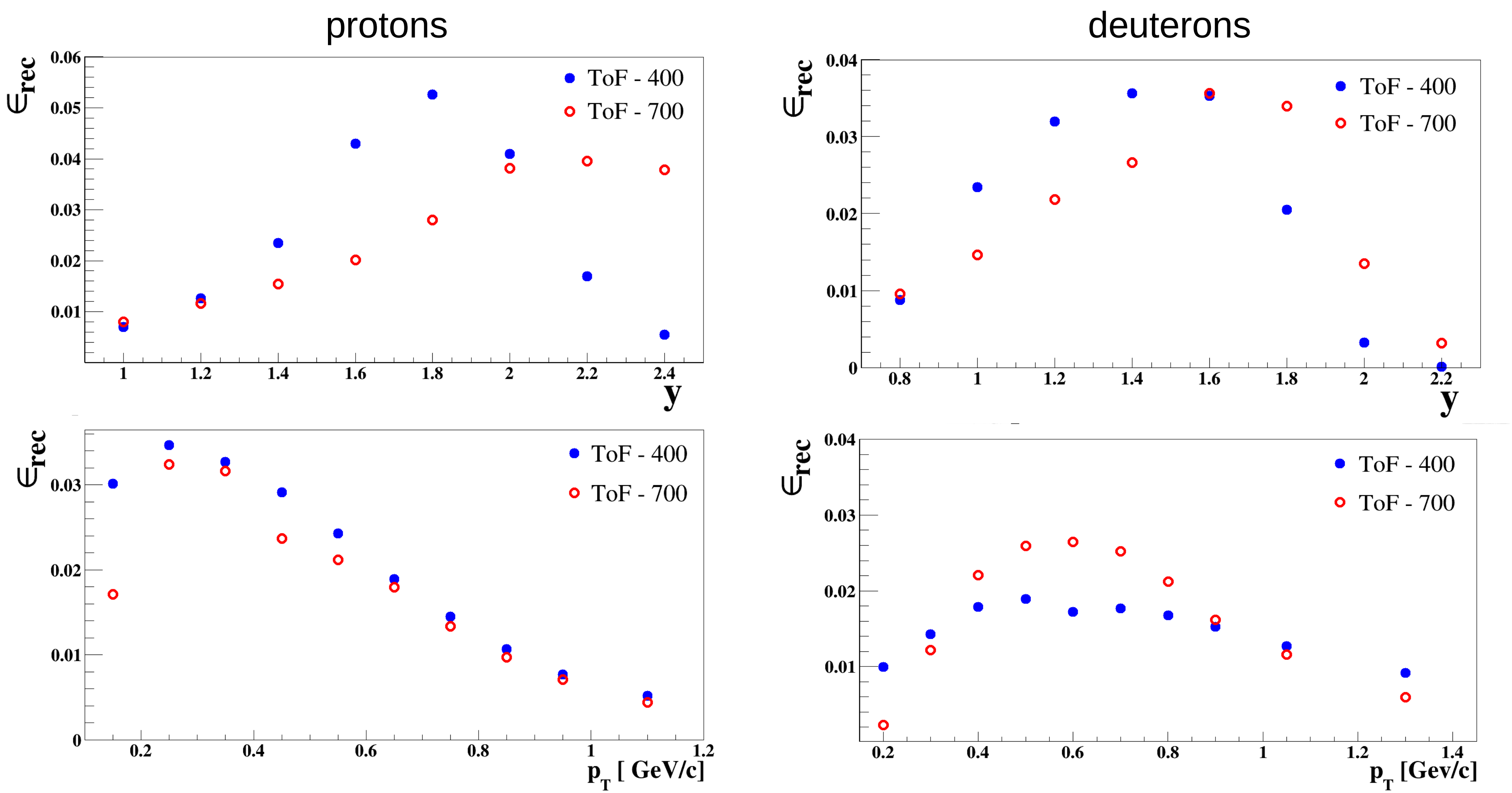


Selection Criteria for experimental data and MC

- ✔ Number of hits in 6 GEM per track > 3
- ✔ Tracks from PV: -3.4 < ZPV – Z0 < 1.7 cm
- ✔ Momentum range of tracks for ToF-400 (ToF-700):

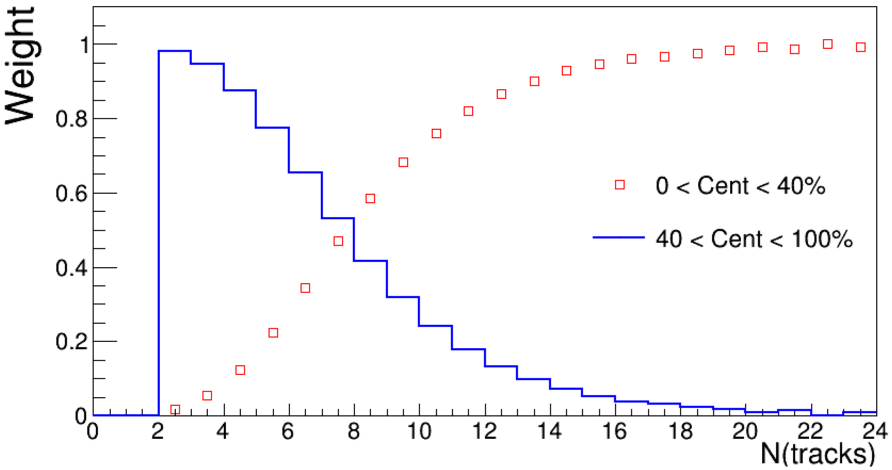
  p > 0.5 (0.7) GeV/c
- ✔ Distance from a track to PV in the X-Y plane: dca< 1 cm
- ✔ Distance of extrapolated tracks to CSC (DCH) and ToF400 (ToF-700): |residX,Y| < 3 σ of hit-track residual distribution

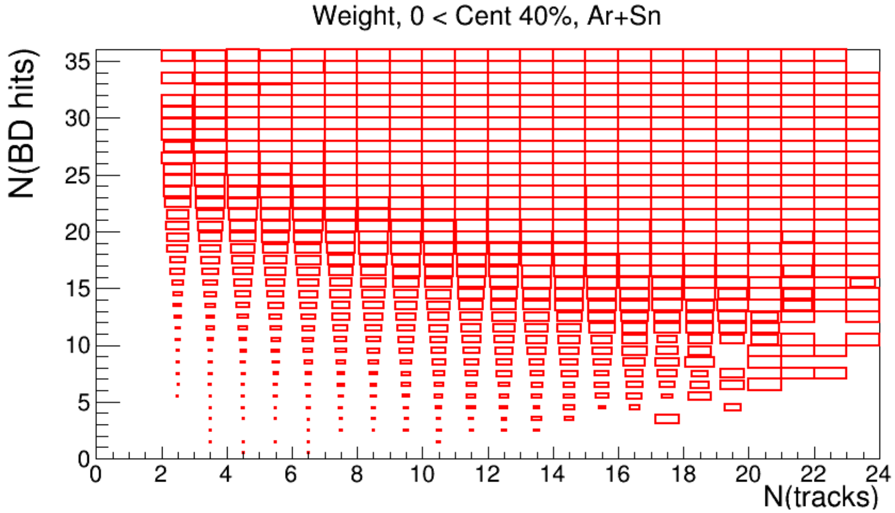
Reconstruction Efficiency for protons and deuterons for TOF400 and TOF700

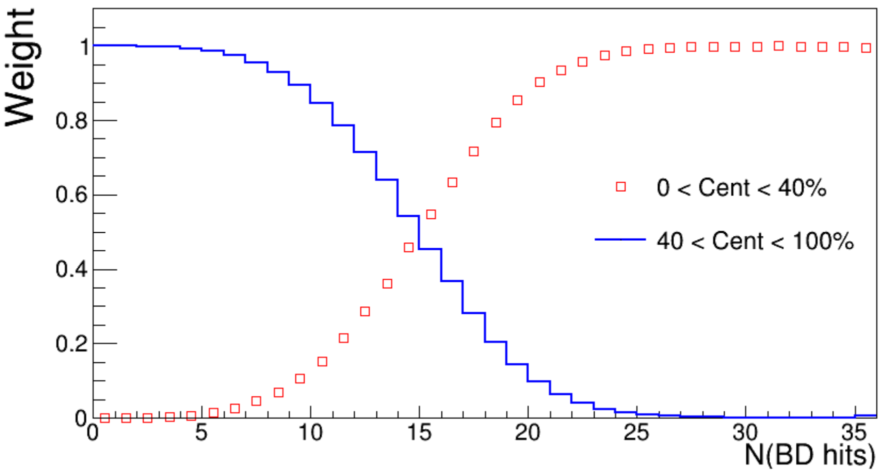


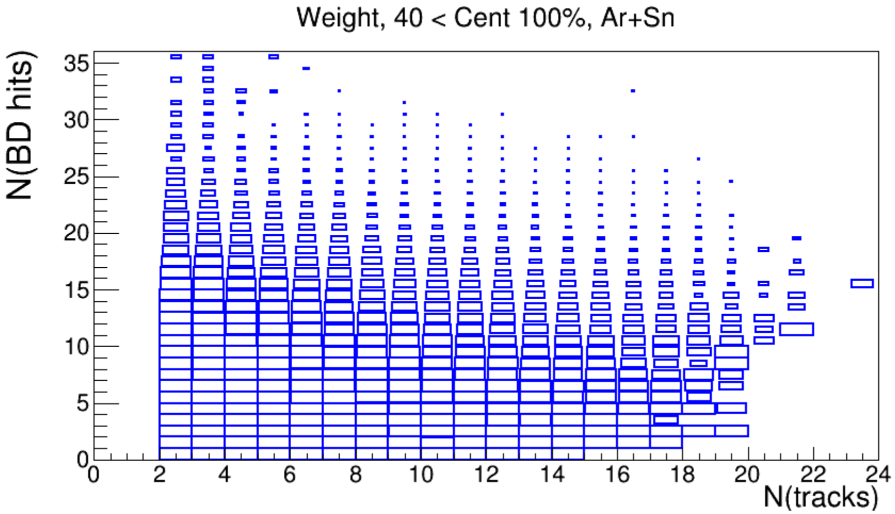
Centrality classes

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



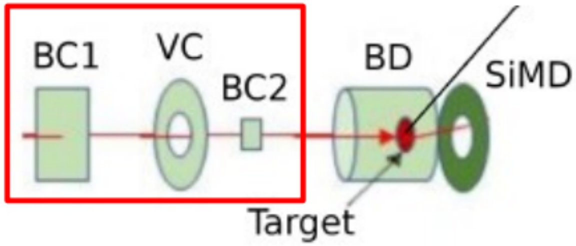






Fractions(probabilities) of events taken from the two-dimensional distributions are used as event weights to define the weighted number of reconstructed p, d, t in the y and p_T bins in data and simulation

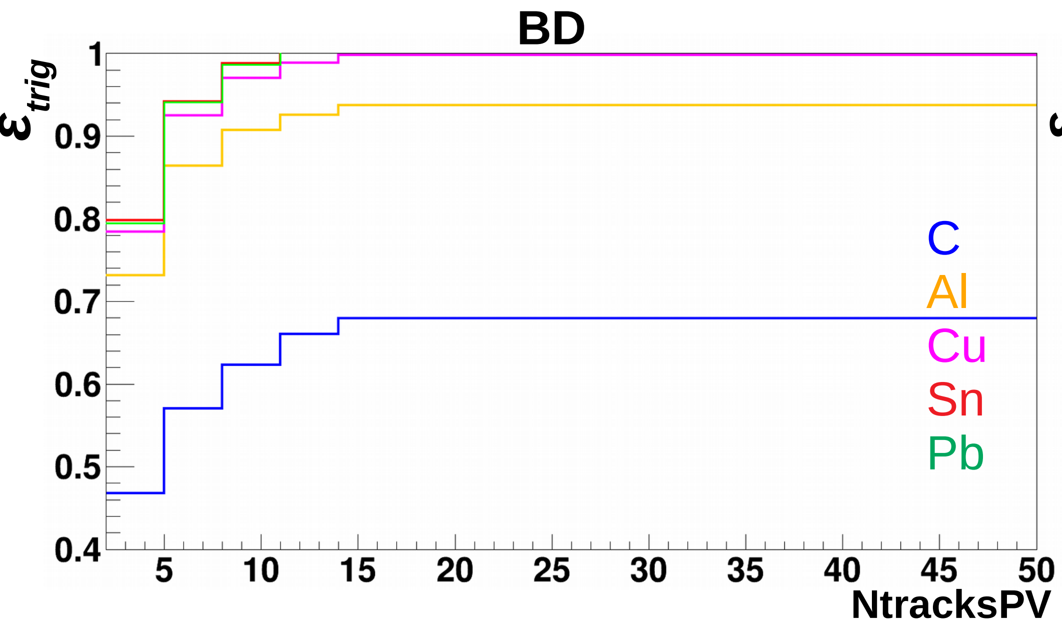
Trigger Efficiency

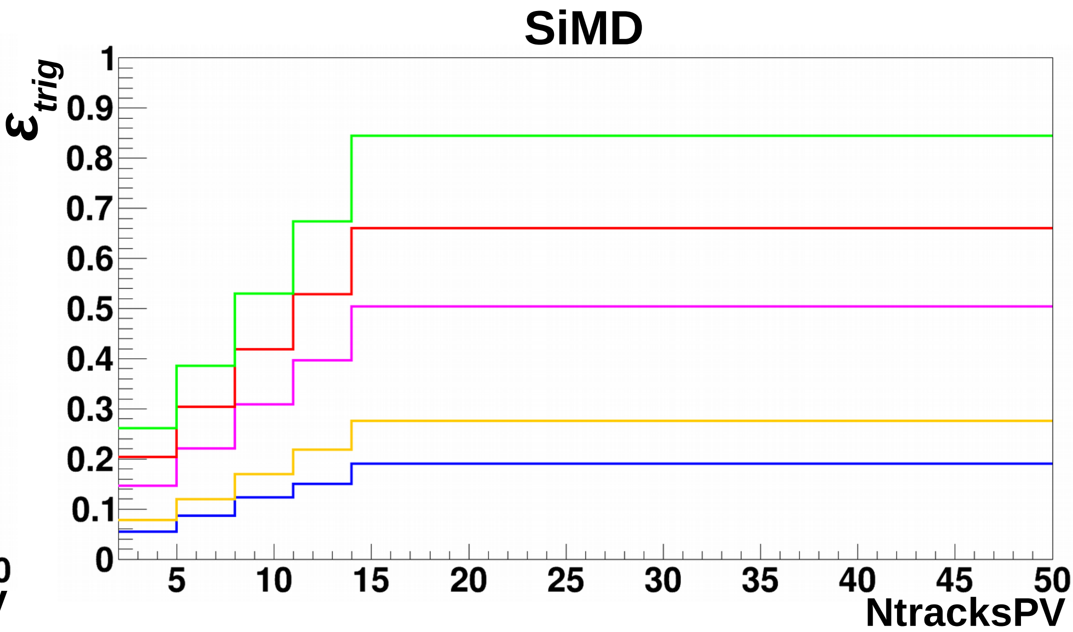


The efficiency to get a trigger signal based on multiplicities of fired channels in the BD (SiMD) detectors εtrig was calculated for events with reconstructed protons, deuterons and tritons using experimental event samples recorded with an independent trigger based on the SiMD(BD)detectors:

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

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.





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: 0-40% and 40-100%

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.

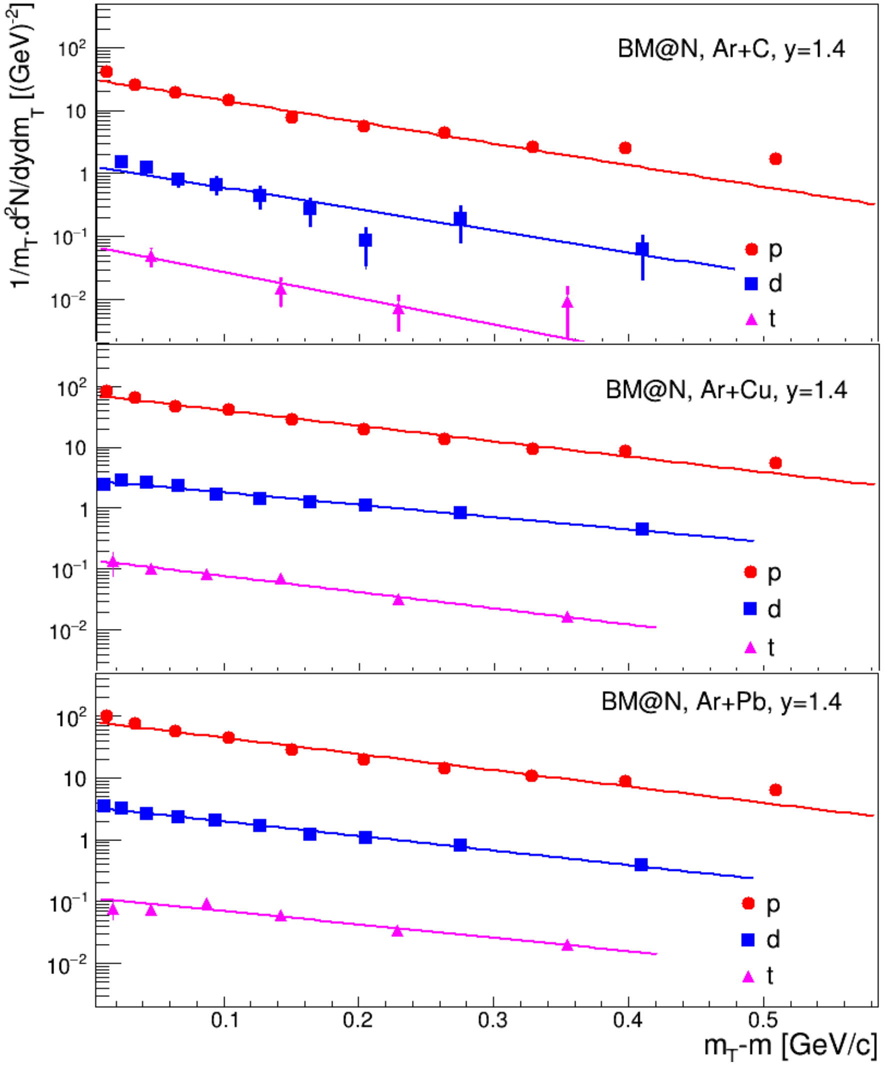
Sys4: systematic errors of the background subtraction under the p, d, t signals in the mass squared spectra of identified particles.

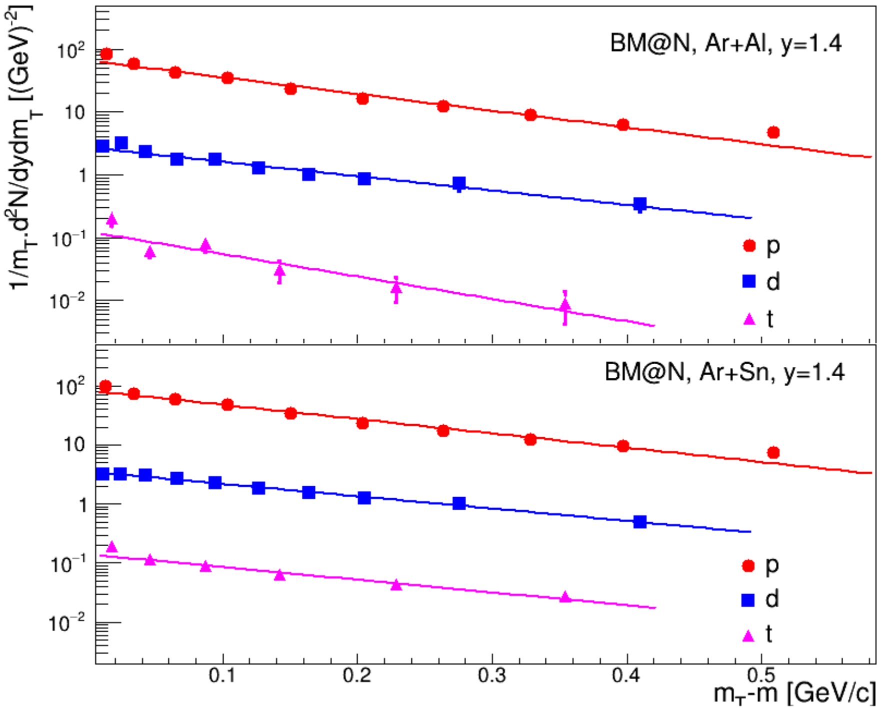
Sys5:Systematic uncertainty calculated as half of the difference of the p, d, t yields measured in bins of rapidity y in the ToF-400 and ToF-700 detectors

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**

Transverse mass spectra of protons, deuterons, tritons produced at rapidity = 1.4 in Ar+A interactions with centrality 0-40%





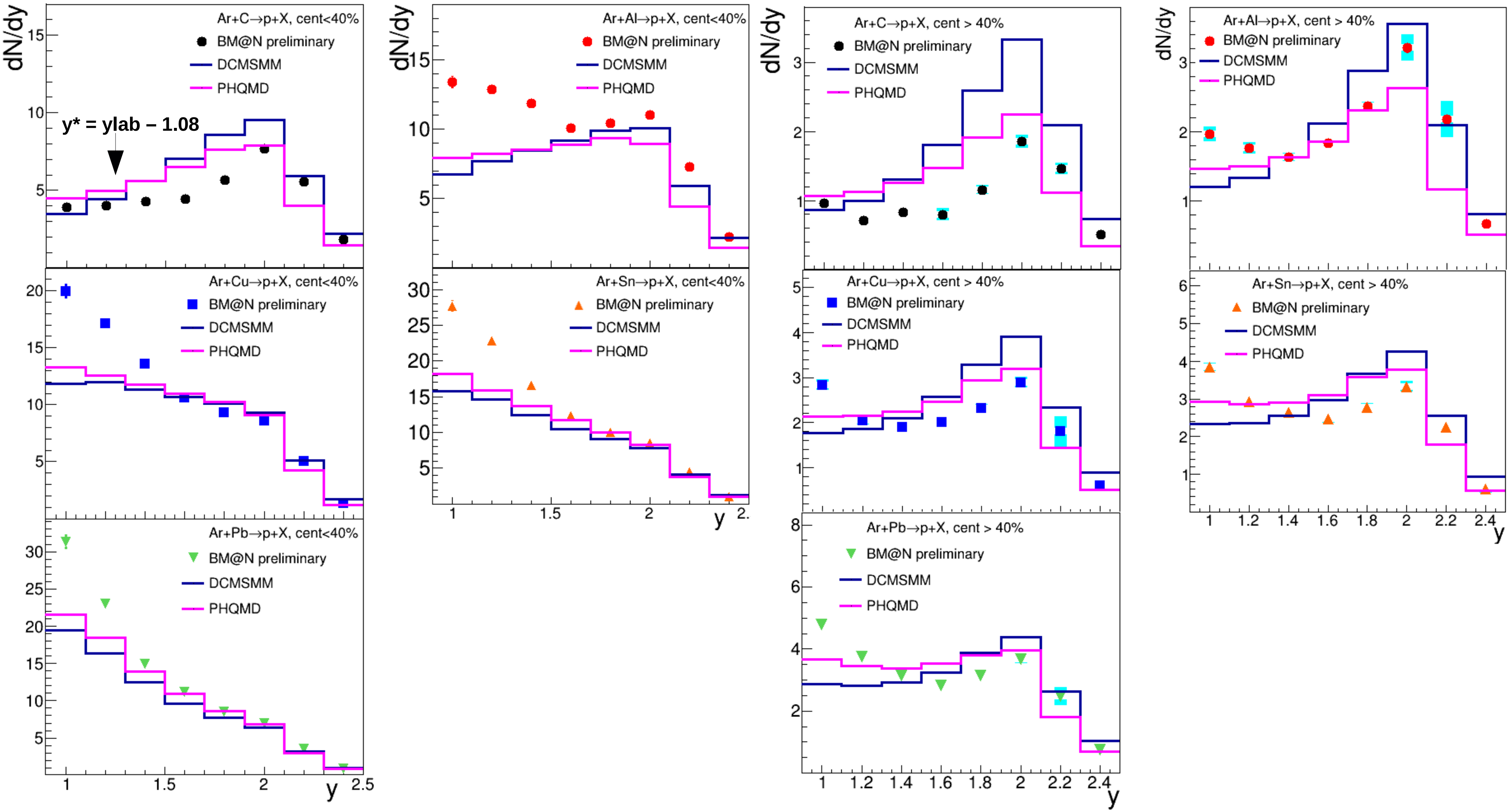
$$m_T=\sqrt{m_{p,d,t}^2+p_T^2}$$

The spectra are parameterised by exponential function as:

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

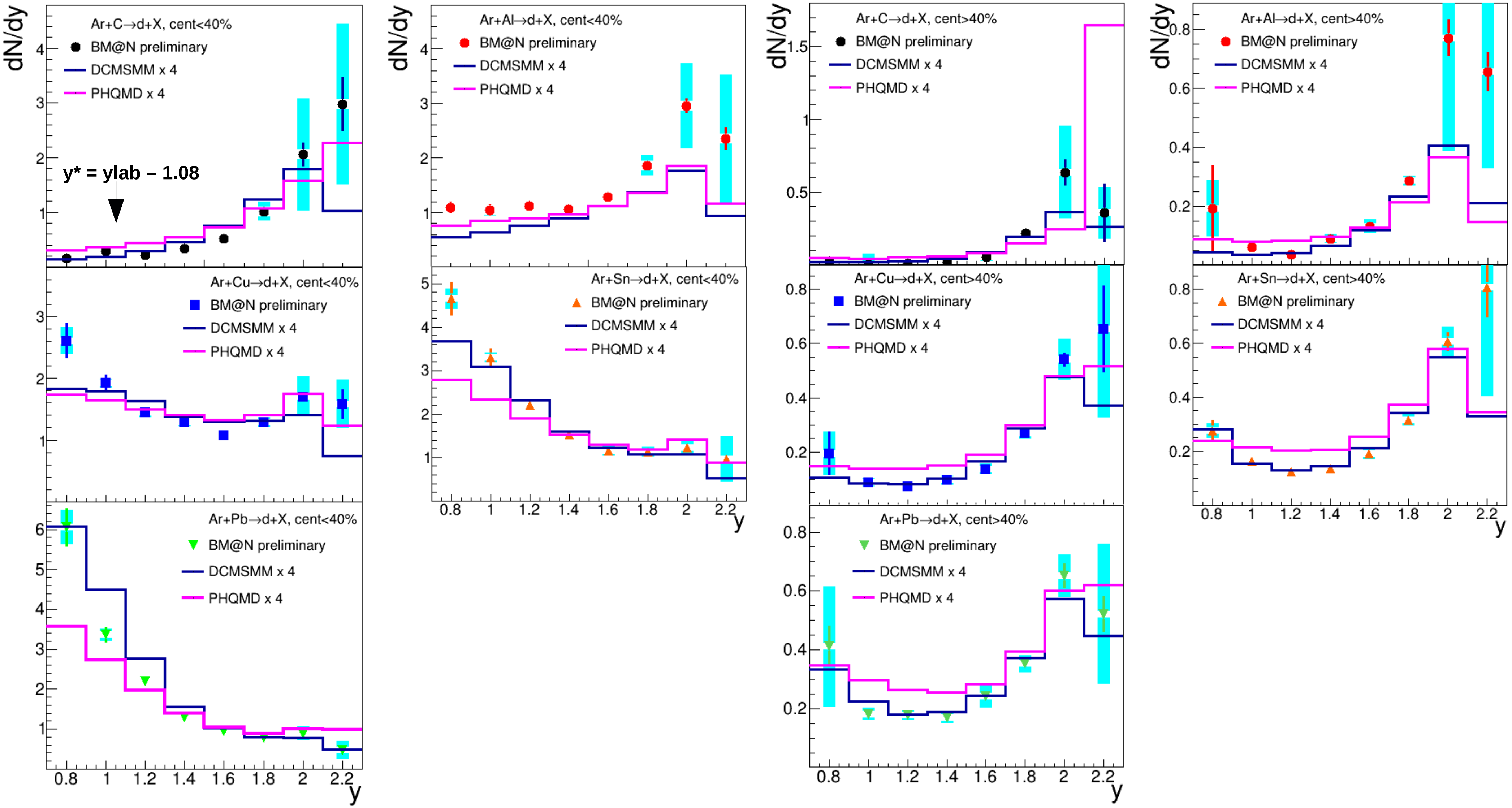
where fitting parameters are the integral of the m_T spectrum, dN/dy, and the inverse slope, T0.

Rapidity spectra dN/dy of protons produced in Ar+A interactions with centrality 0-40% and 40-100%. The results are integrated over p_T



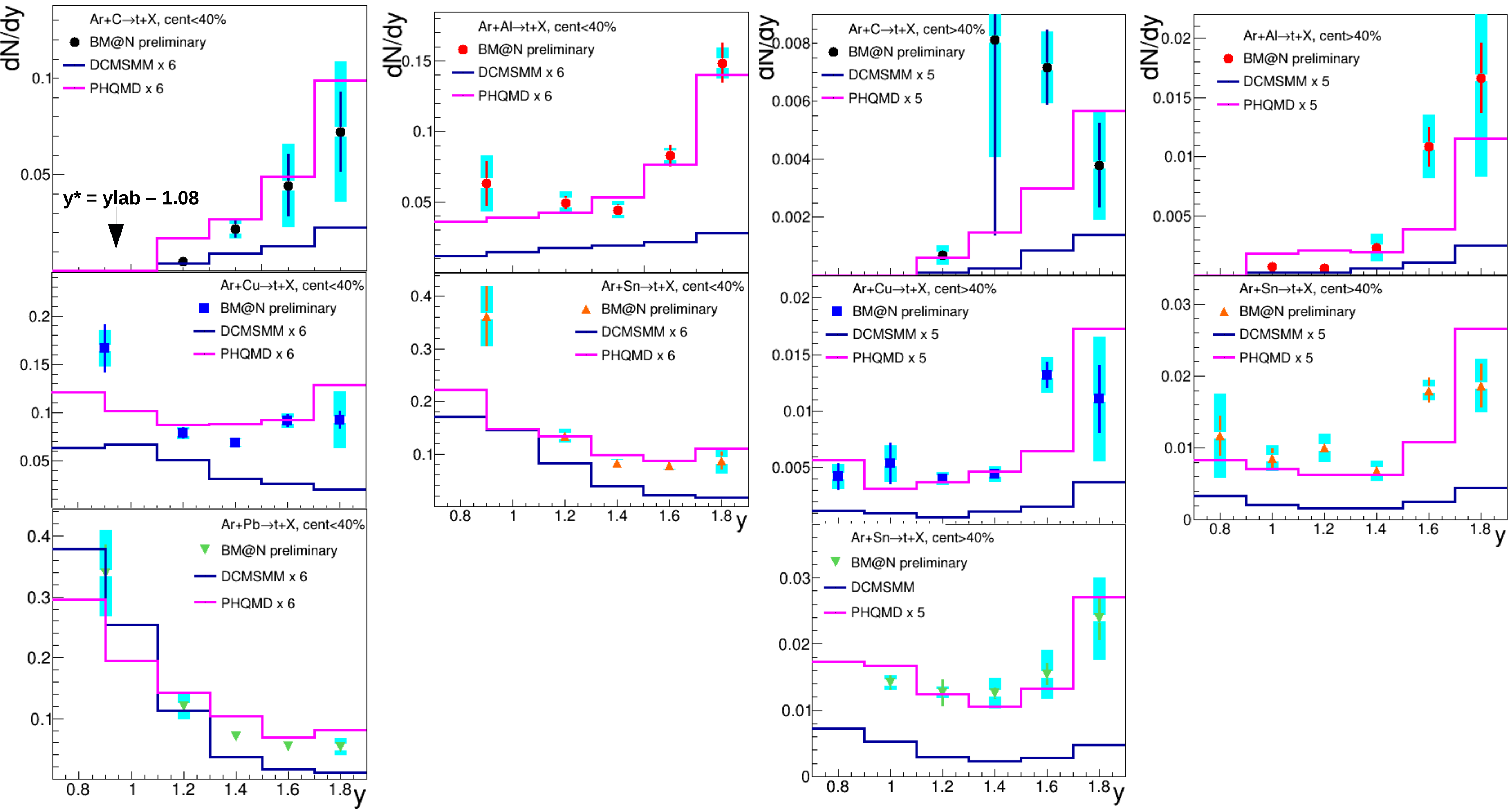
The models reasonable describes the experimental results in the forward y range. At mid-rapidity the models under-estimate the data for interactions with the targets heavier than the carbon.

Rapidity spectra dN/dy of deuterons produced in Ar+A interactions with centrality 0-40% and 40-100%. The results are integrated over p_T



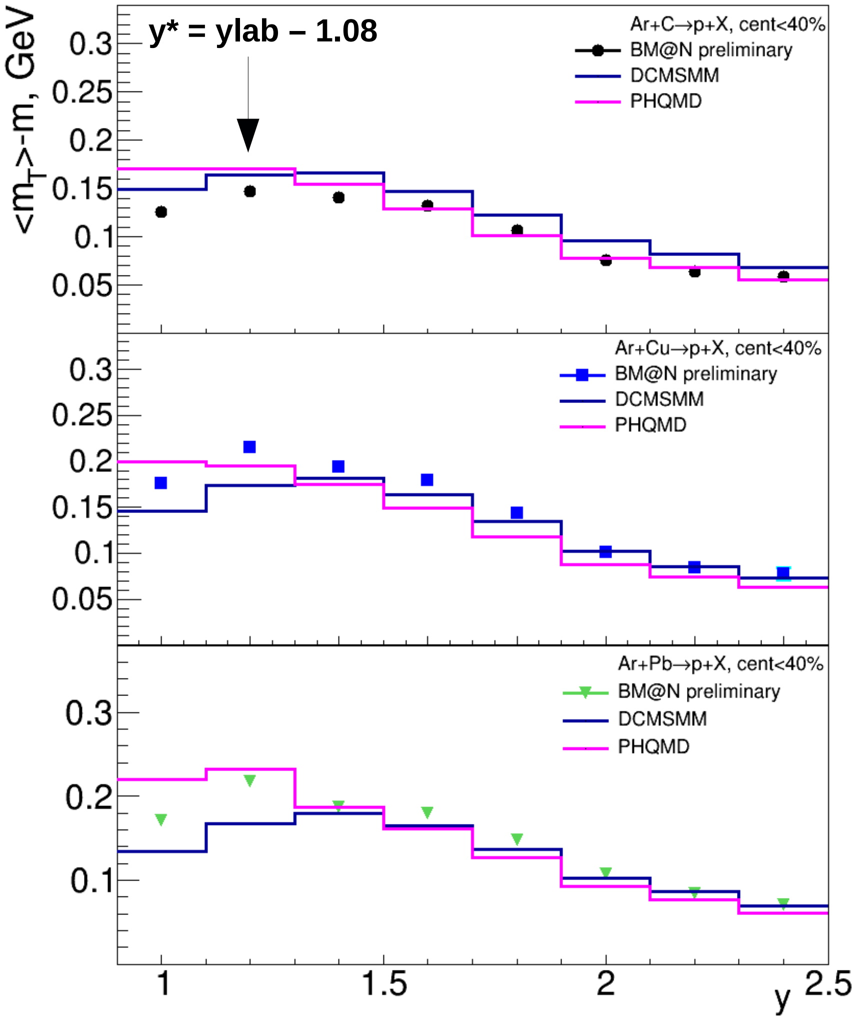
The spectra of deuterons dominate in the beam fragmentation range for Ar+C and Ar+Al interactions, whereas the spectra become more central for interactions with heavier targets. The models reasonably describe the shape of the experimental spectra, but under-predict the normalization of the data by factors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

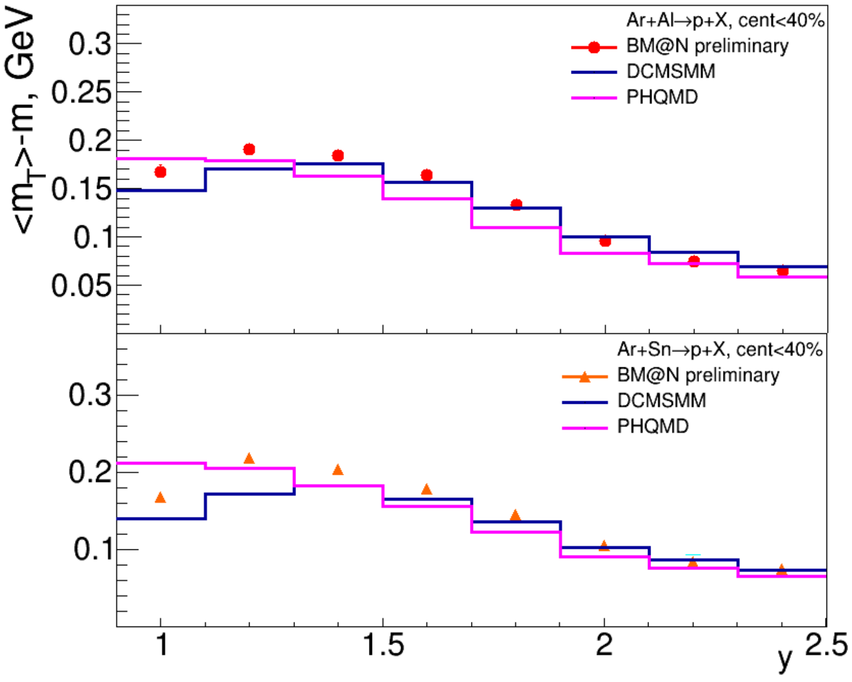
Rapidity spectra dN/dy of tritons produced in Ar+A interactions with centrality 0-40% and 40-100%. The results are integrated over p_T



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%





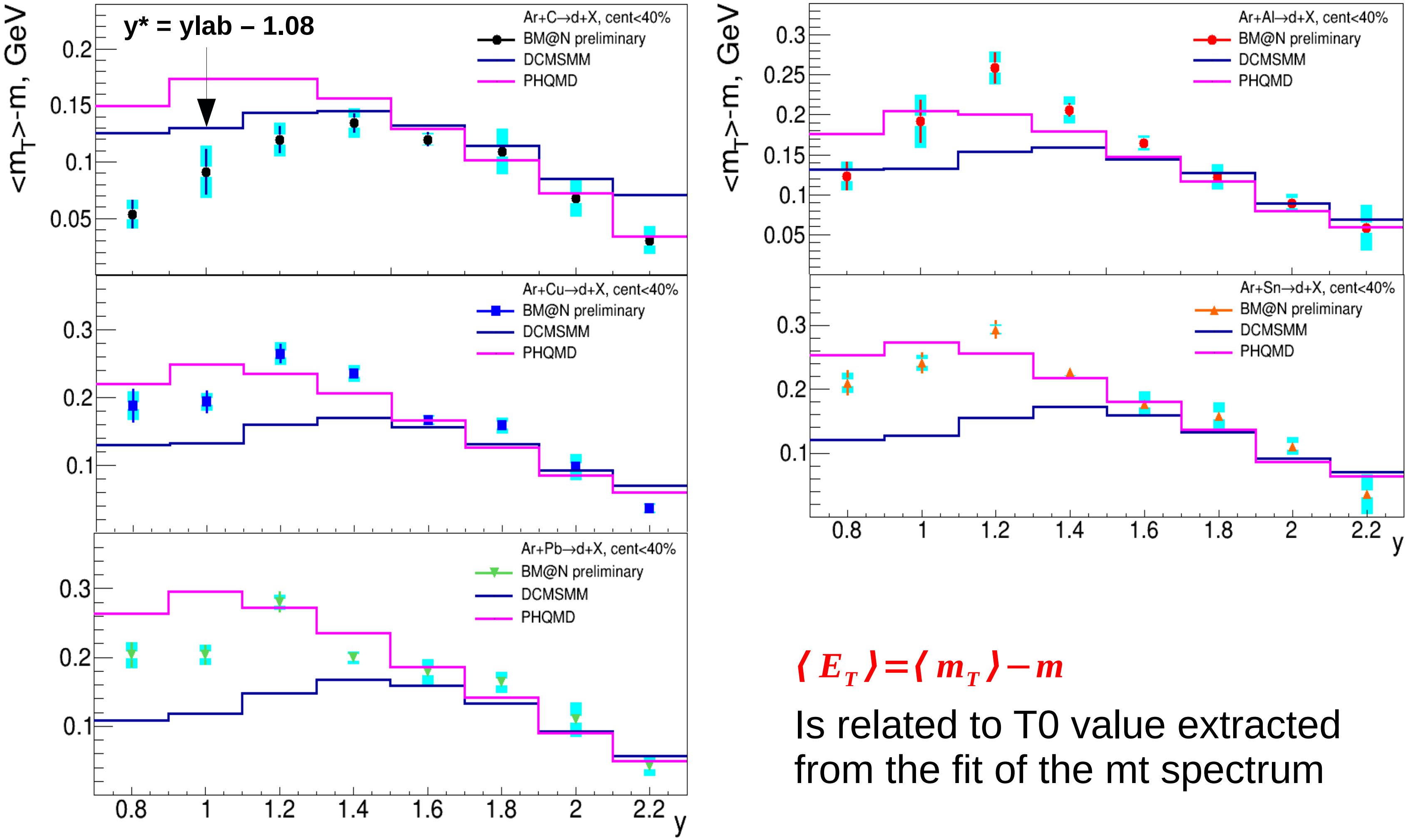
$$\langle E_T \rangle = \langle m_T \rangle - m$$

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 $\langle m_T \rangle - m$ obtained from the fits of the m_T spectra of deuterons in Ar+A interactions with centrality 0-40%



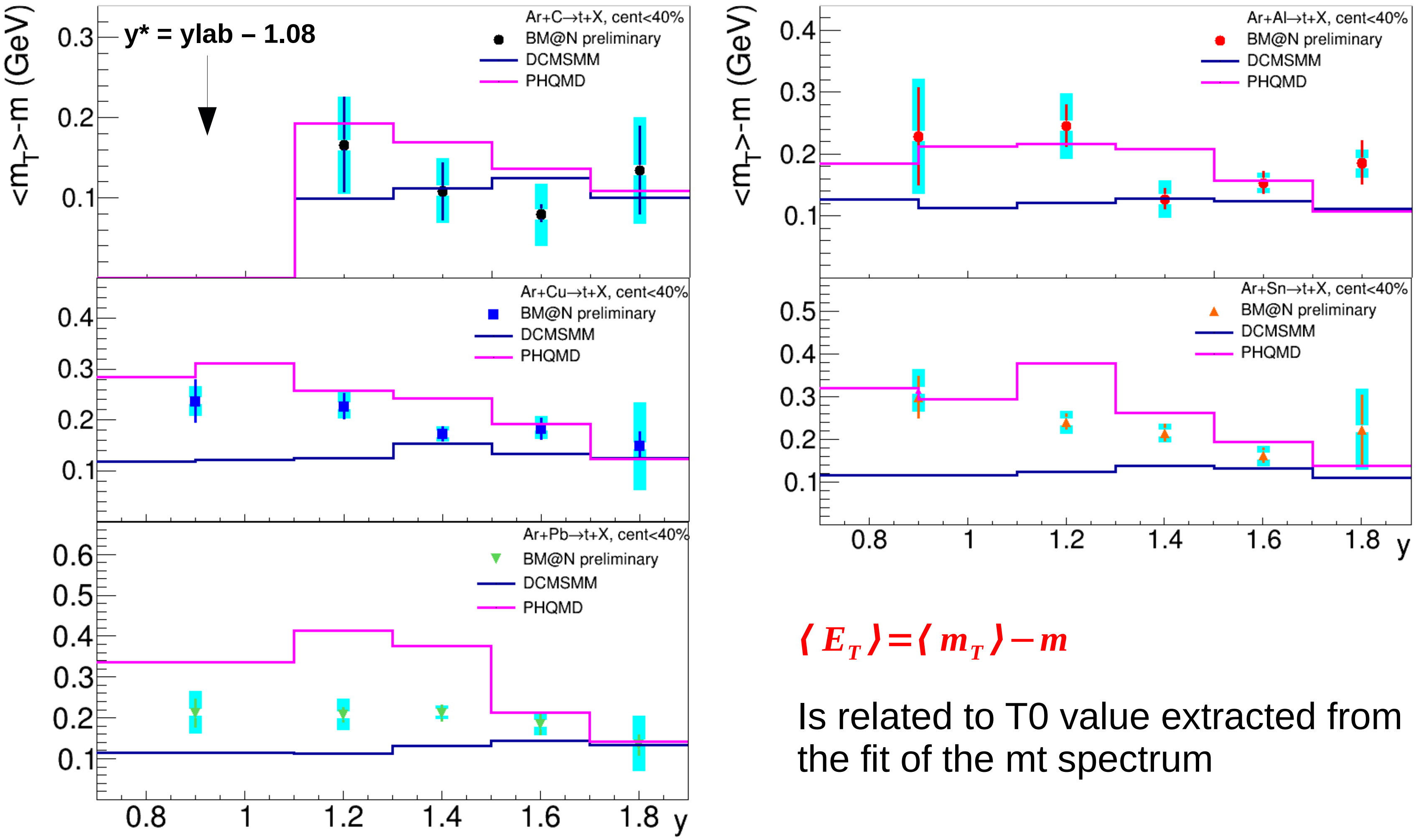
$$\langle E_T \rangle = \langle m_T \rangle - m$$

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

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%



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

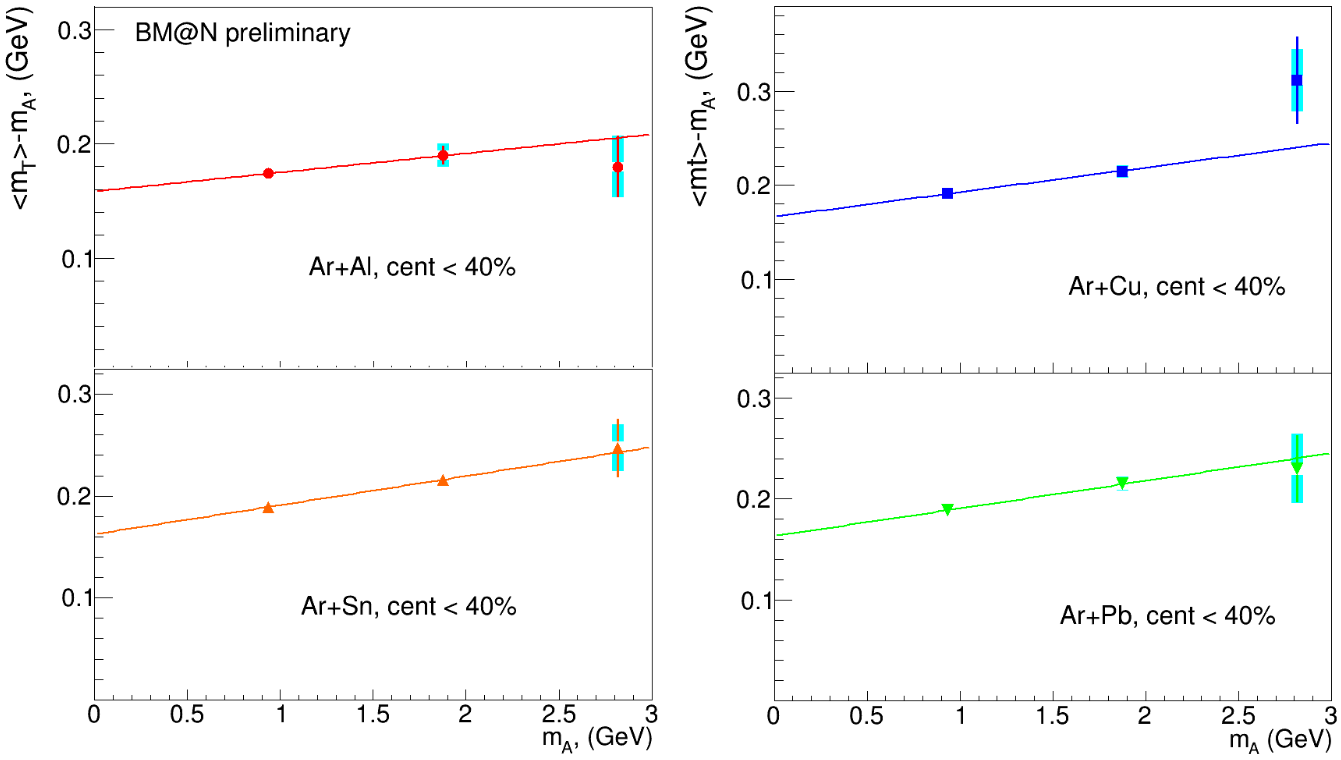
Is related to T0 value extracted from the fit of the mt spectrum

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

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.

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 0-40%.

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



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

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

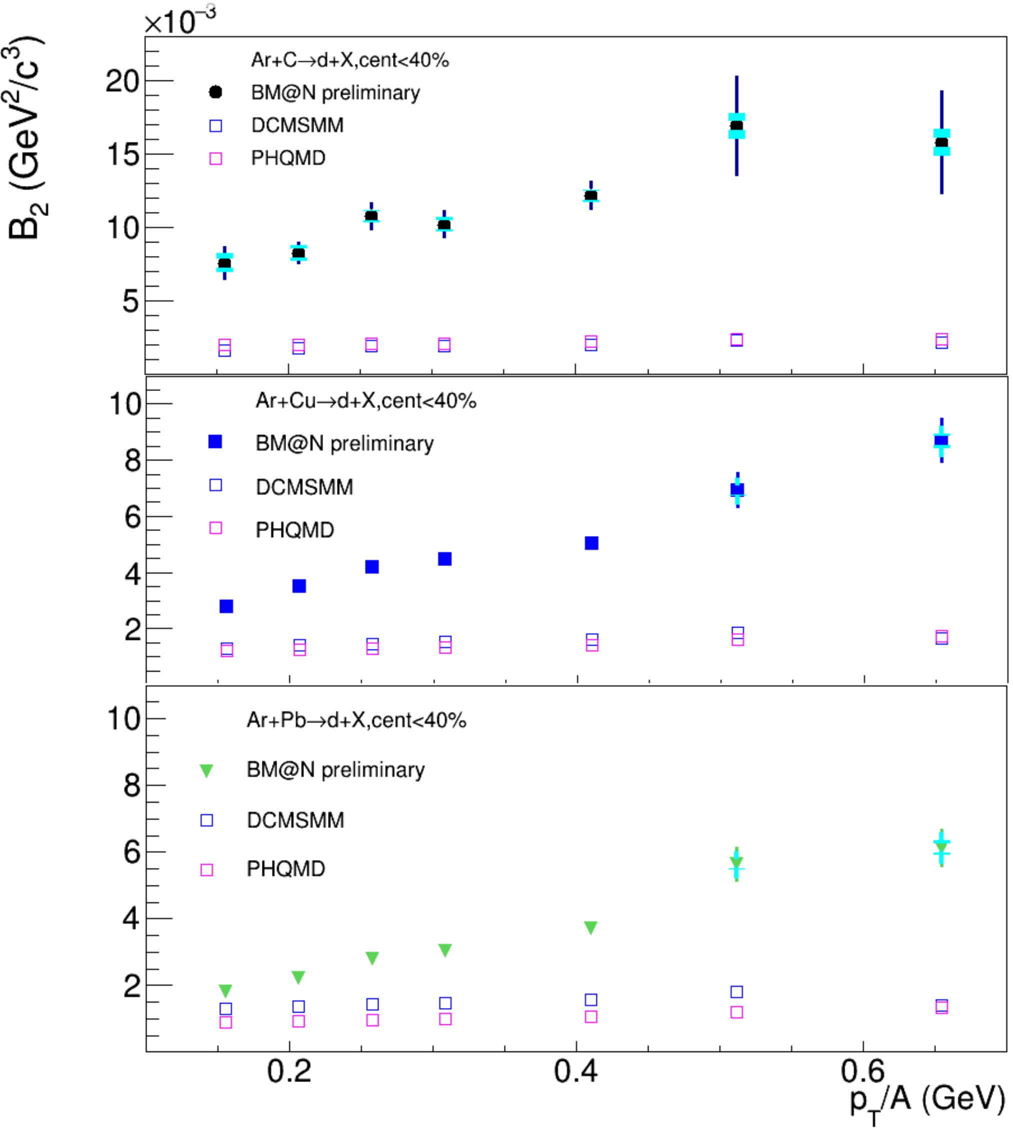
$$T^* = T\sqrt{(1+\langle \beta \rangle)/(1-\langle \beta \rangle)}$$

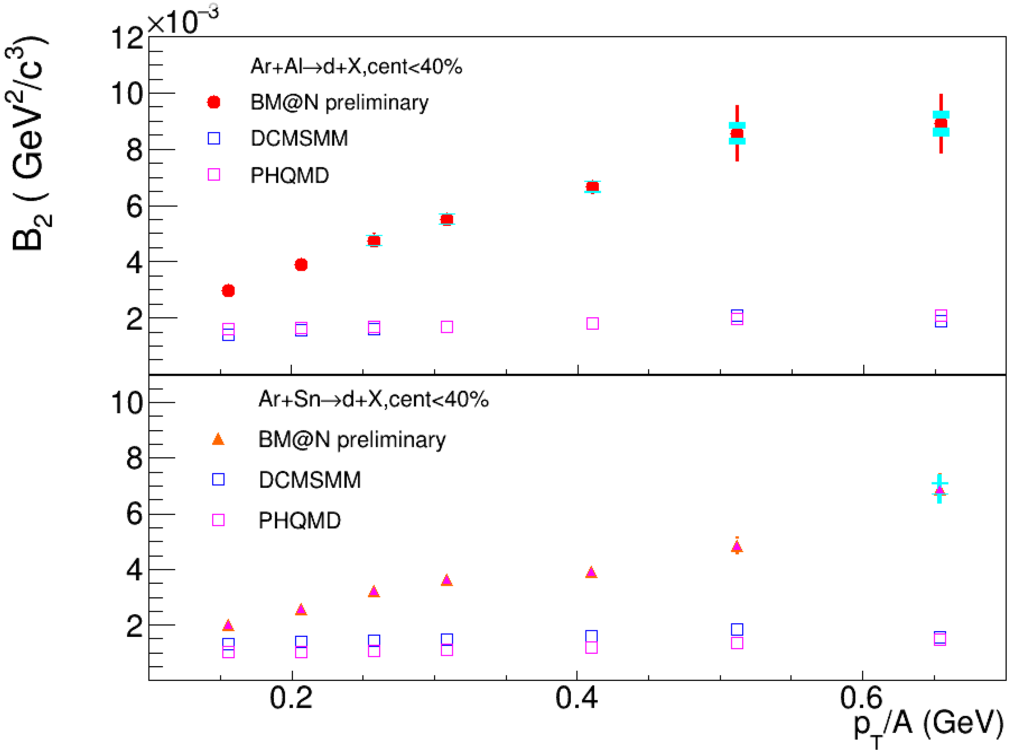
Rises approximately linearly with the mass of the nuclear fragment

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	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 ± 0.4	0.26 ± 0.5

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



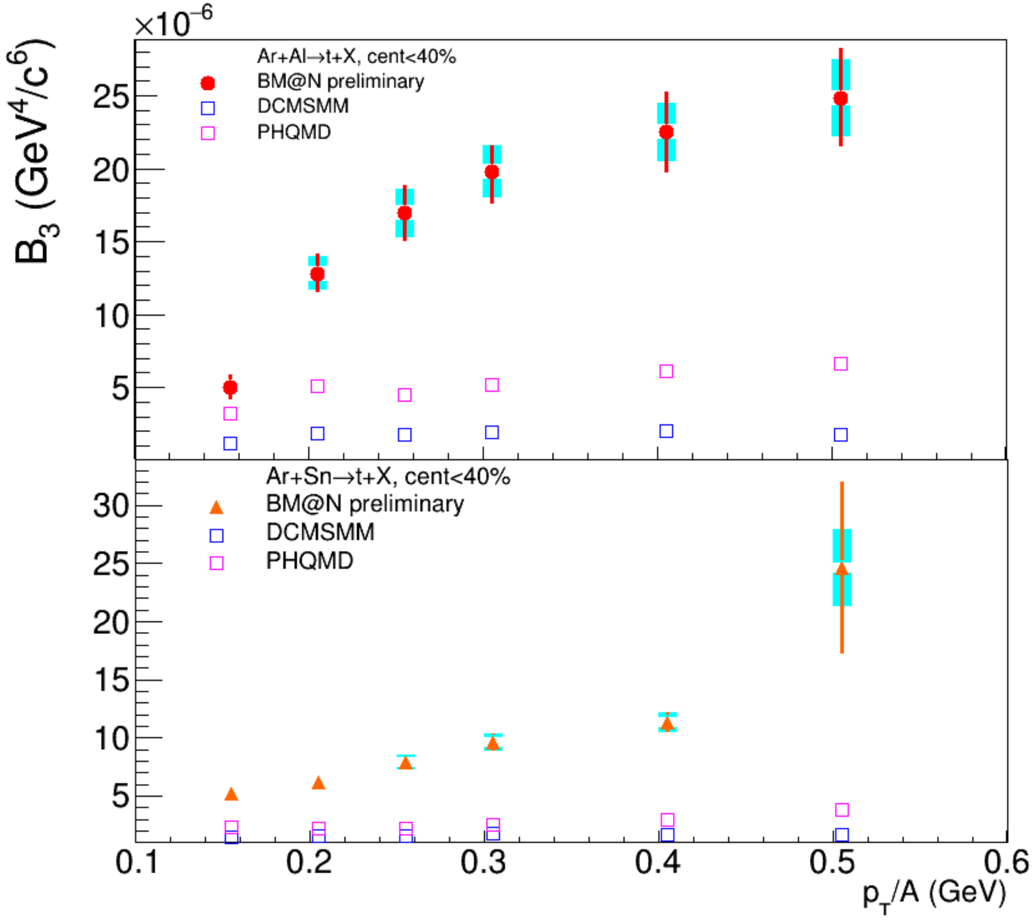


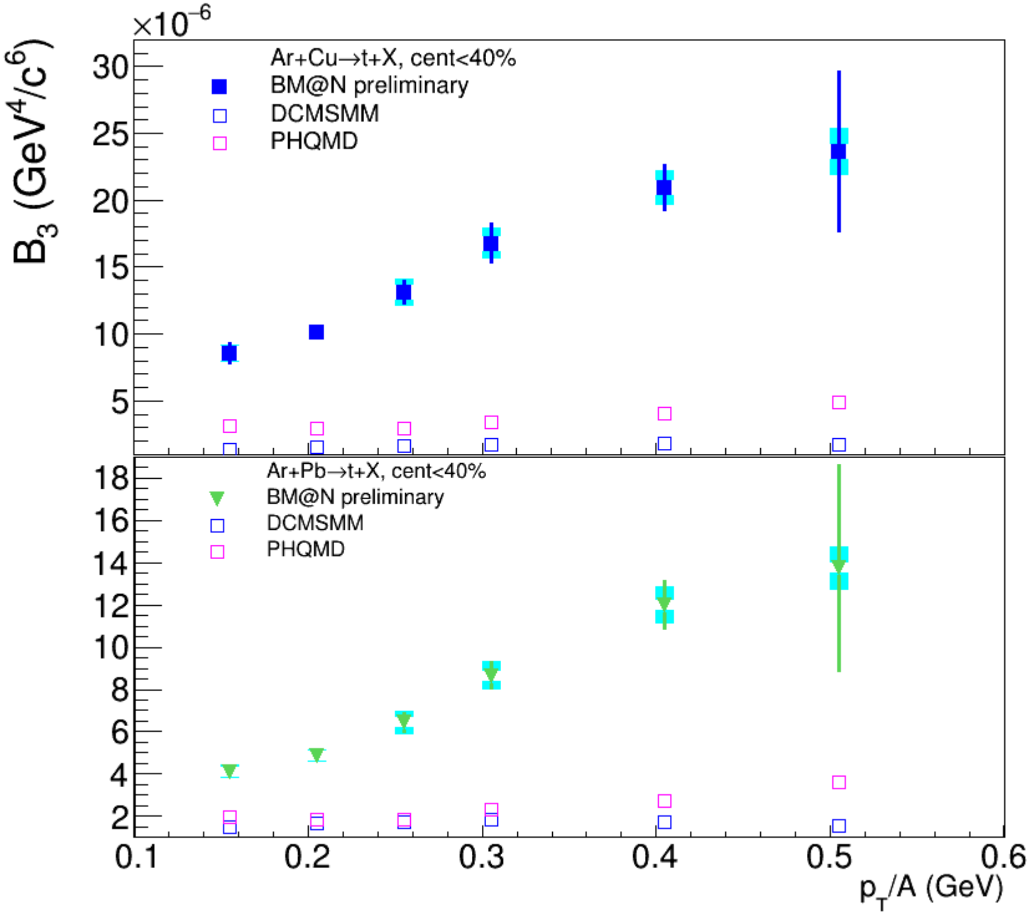
$$B_A = d^2 N_A / 2\pi p_{T,A}\, dp_{T,A}\, dy / \left(d^2 N_p / 2\pi p_T\, dp_T\, dy \right)^A$$

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.
The DCM-SMM and PHQMD models predict an almost flat dependence on p_T

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





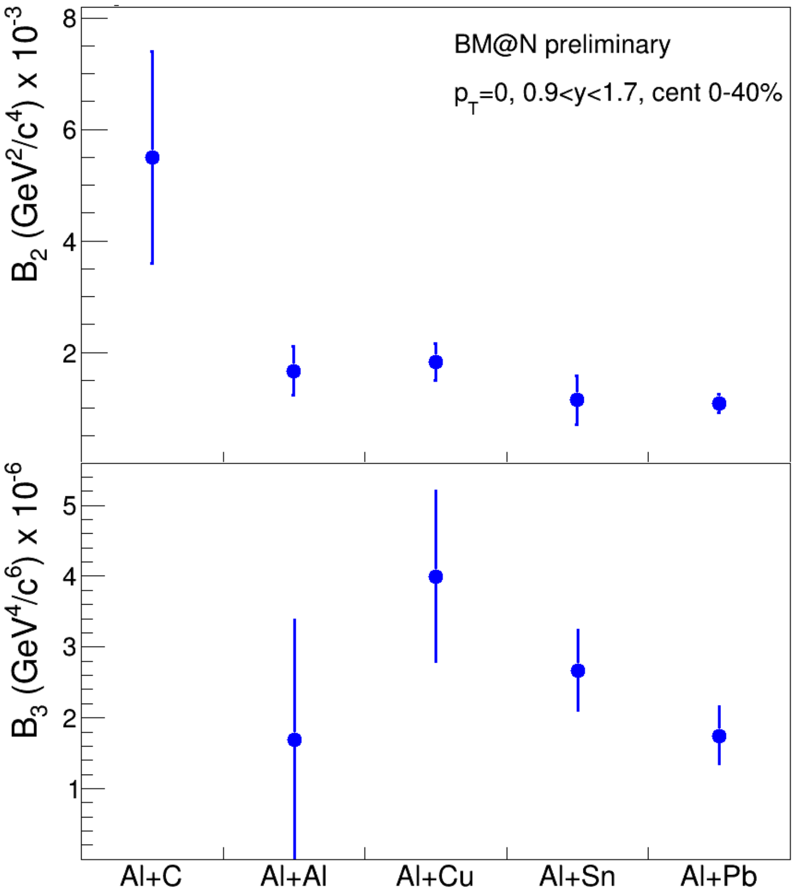
Statistics of tritons are not sufficient to present B_3 for Ar+C interactions

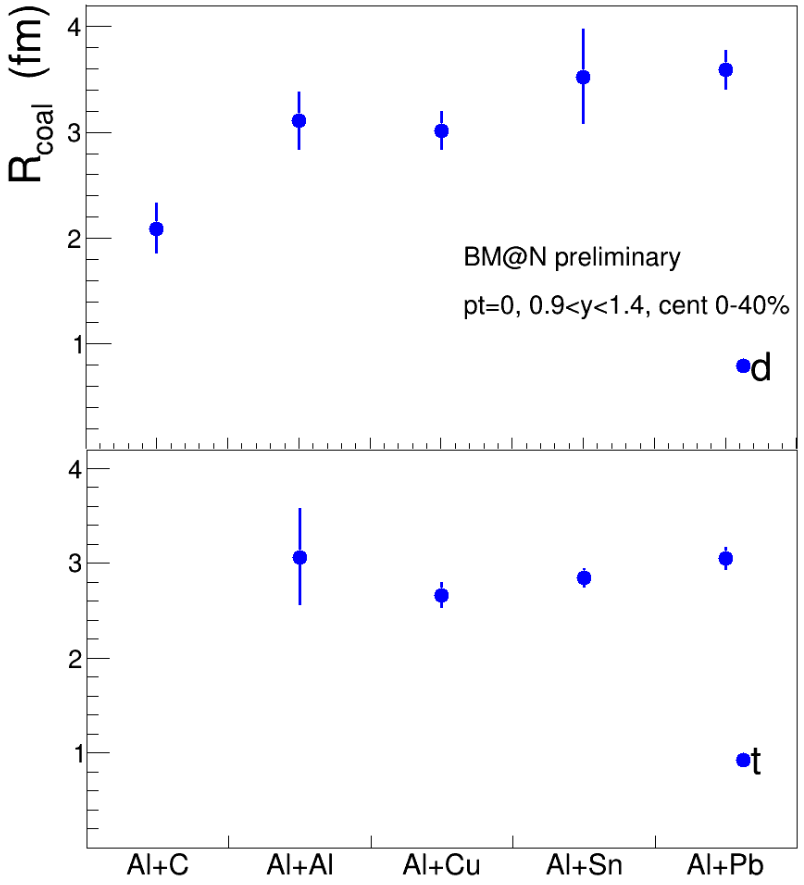
The yields of protons and tritons are measured in the same rapidity range, $0.9 < y < 1.7$ ($-0.18 < y* < 0.62$)

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

The DCM-SMM and PHQMD models predict an almost flat dependence on p_T

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. The coalescence source radius R_{coal} is calculated from the $B_2(p_T = 0)$ and $B_3(p_T = 0)$ values of deuterons and tritons.

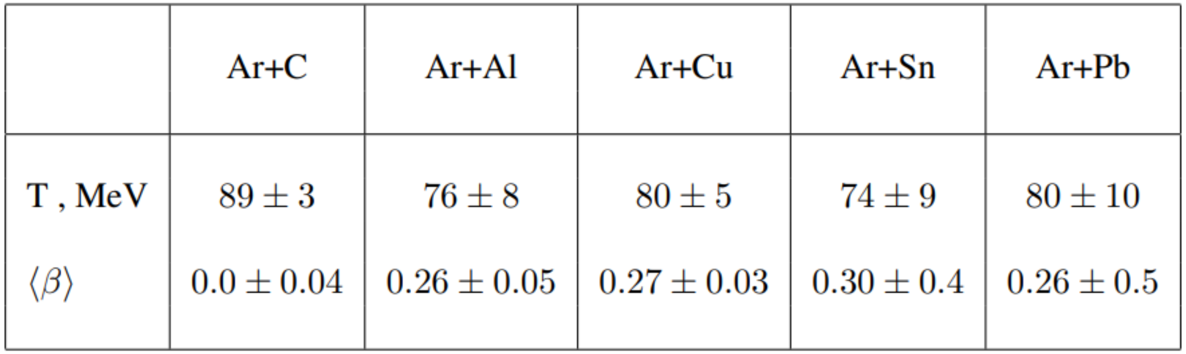
Results: (T) and ⟨β⟩ measurements

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.

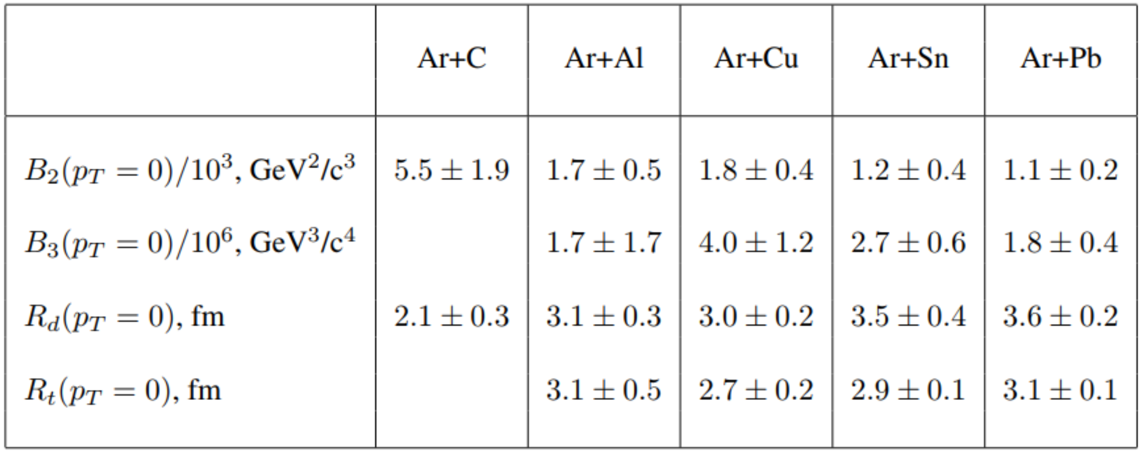


	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
T , MeV	89 ± 3	76 ± 8	80 ± 5	74 ± 9	80 ± 10
$\langle\beta\rangle$	0.0 ± 0.04	0.26 ± 0.05	0.27 ± 0.03	0.30 ± 0.4	0.26 ± 0.5

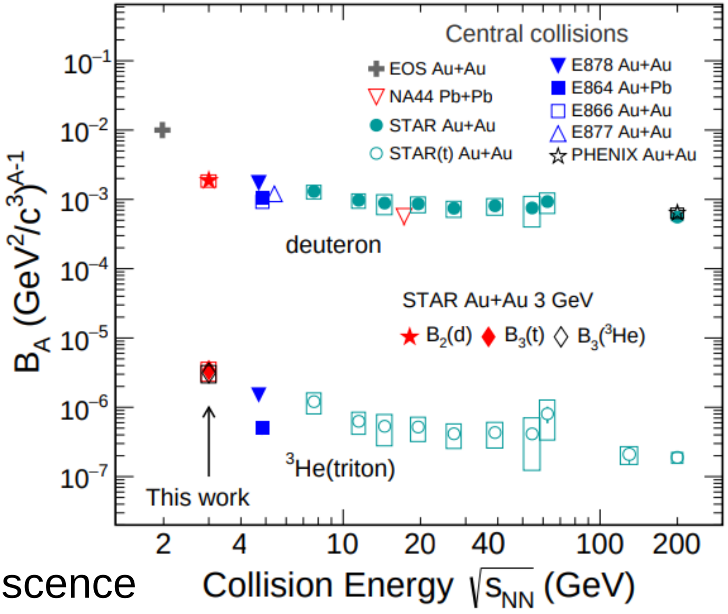
Results: B_2 B_3 and coalescence source radii

1) The results for B_2 and B_3 in Ar+A interactions (centrality 0-40%) are consistent with the energy dependence of B2 and B3 factors observed in central interactions of heavy nuclei, as shown in the NA49 analysis.

2) The coalescence source radii for deuterons and tritons produced in Ar+A interactions (centrality 0-40%) align with values ranging from 3 to 3.5 fm in accordance with the prescriptions by I.G. Bearden et al. in their study published in **Eur. Phys. J. C 23, 237–247 (2002**). except for deuterons produced in Ar+C interactions.



	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
$B_2(p_T=0)/10^3$, $\mathrm{GeV^2/c^3}$	5.5 ± 1.9	1.7 ± 0.5	1.8 ± 0.4	1.2 ± 0.4	1.1 ± 0.2
$B_3(p_T=0)/10^6$, $\mathrm{GeV^3/c^4}$		1.7 ± 1.7	4.0 ± 1.2	2.7 ± 0.6	1.8 ± 0.4
$R_d(p_T=0)$, fm	2.1 ± 0.3	3.1 ± 0.3	3.0 ± 0.2	3.5 ± 0.4	3.6 ± 0.2
$R_t(p_T=0)$, fm		3.1 ± 0.5	2.7 ± 0.2	2.9 ± 0.1	3.1 ± 0.1



STAR Collaboration: [nucl-ex] arXiv:2311.11020

3) These findings correspond to the energy dependence of coalescence source radii observed in heavy ion collisions as reported in the NA49 analysis (**Phys. Rev. C 94 (2016) 4, 044906**).

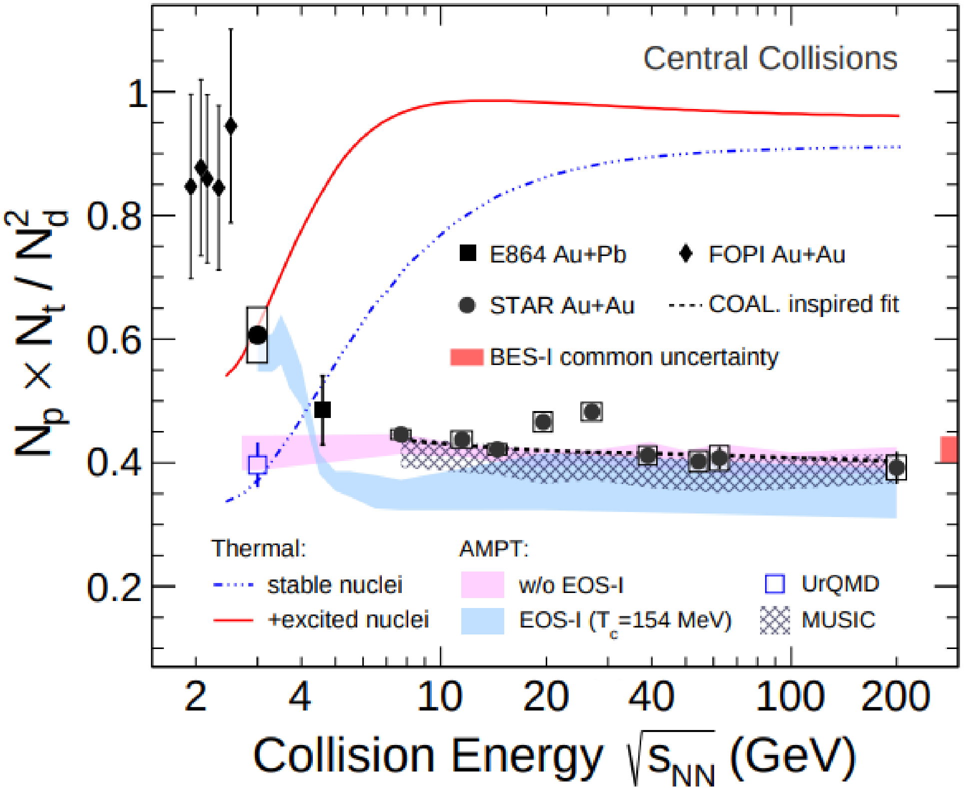
Results: $N_p \cdot N_t/N^2_d$ ratio

BM@N results: 0.53 to 0.69

Lower Energy Data (HADES and FOPI): 0.8 to 1.0

Higher Energy Data (STAR and NA49): 0.4 to 0.5

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



STAR Collaboration: [nucl-ex] arXiv:2311.11020

	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
$N_p \cdot N_t/N_d^2$	0.53 ± 0.10	0.55 ± 0.09	0.69 ± 0.11	0.60 ± 0.07	0.59 ± 0.06

Summary

The BM@N experiment presents physics results on the yields and ratios of p, d, and t in argon-nucleus interactions at a beam energy of 3.2 AGeV. These results are compare with the DCM-SMM and PHQMD models, as well as with previously published results of other experiments.

The spectra of transverse mass (m_T) are measured and the mean values $\langle m_T \rangle - m$ are presented for more central 0-40% events as functions of rapidity (y) and fragment mass. The values $\langle m_T \rangle - m$ show a linear dependence on mass. These results are parameterized as a function of the temperature and transverse velocity of the radial expansion of the source.

The rapidity spectra dN/dy of p, d, and t are presented for the entire p_T range in two centrality ranges. While the DCM-SMM and PHQMD models reproduce the shapes of the spectra, they underestimate the yields of d and t by factors of 4 and 6, respectively.

The deuteron-to-proton and triton-to-proton yield ratios are interpreted using a coalescence approach. Coalescence parameters B_2 and B_3 for d and t are calculated in dependence on the transverse momentum p_T The coalescence radii of the d and t source are extracted from the B_2 and B_3 values extrapolated to $p_T = 0$.

The compound yield ratio $N_p \cdot N_t/N^2_d$ of protons and tritons to deuterons is evaluated from the dN/dy spectra in the rapidity range $-0.18 < y* < 0.62$. The result is compared with the values measured in heavy nucleus-nucleus collisions at lower and higher energies.

Plan to discuss the paper draft and present the results at conferences as preliminary

Thank you for your attention !

BACKUP

Analysis of p,d,t production in 3.2 AGeV argon-nucleus interactions

Results of the analysis were presented at the 10th BM@N Collaboration meeting in May 2023 (L.Kovachev) and at the BM@N Analysis and Software meeting in September 2023 (L.Kovachev, M.Kapishin).
Intermediate steps of the analysis were presented at the previous Collaboration meetings (L.Kovachev, V.Plotnikov).

Related analysis notes:

https://indico.jinr.ru/event/4165/attachments/17543/29918/Note_analAr_pdt3.pdf
https://indico.jinr.ru/event/4165/attachments/17543/29919/Note_centrality_pdt_text.pdf
https://indico.jinr.ru/event/4165/attachments/17543/29920/Flux_lumi_trigger.pdf
https://indico.jinr.ru/event/4165/attachments/17543/29921/lumi.pdf

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

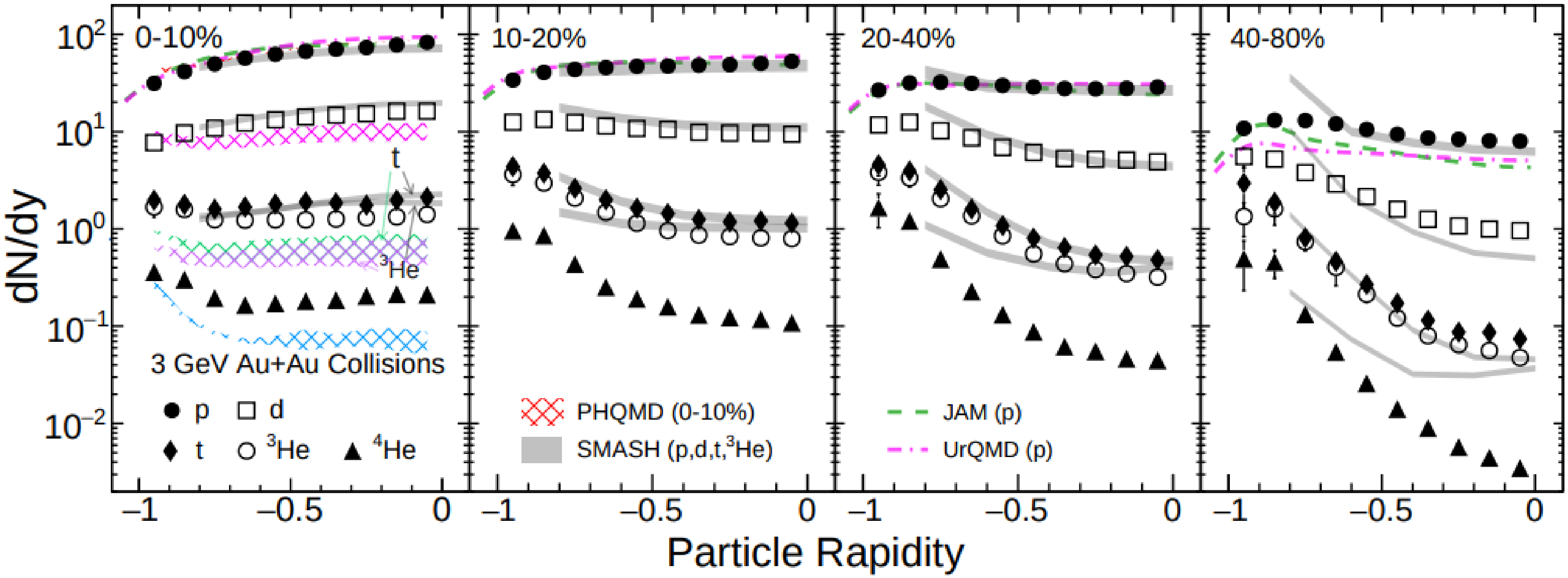


FIG. 8. Collision centrality dependence of primordial protons and light nuclei dN/dy from Au+Au collisions at $\sqrt{s_{NN}} = 3\,\mathrm{GeV}$. The vertical lines represent the orthogonal sum of statistical and systematic errors. The gray bands and colored dotted lines are results from the hadronic transport model (SMASH of p, d, t, and ^{3}He, JAM and UrQMD of p) calculations for all centralities. The colored grid bands are results from PHQMD calculations of p, d, t, ^{3}He, and ^{4}He for the top 0-10% collisions.

Nucleosynthesis of light nuclei and hypernuclei in central Au+Au collisions at $\sqrt{s_{NN}}$=3 GeV

N. Buyukcizmeci[1], T. Reichert[2,3,4], A.S. Botvina[2,3], M. Bleicher[2,3,5]

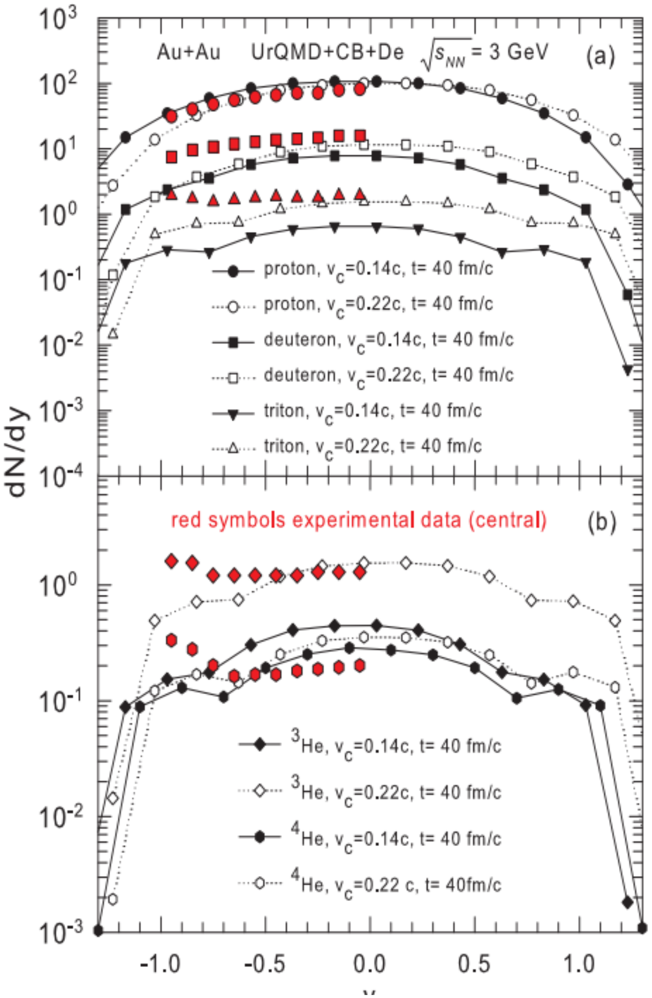
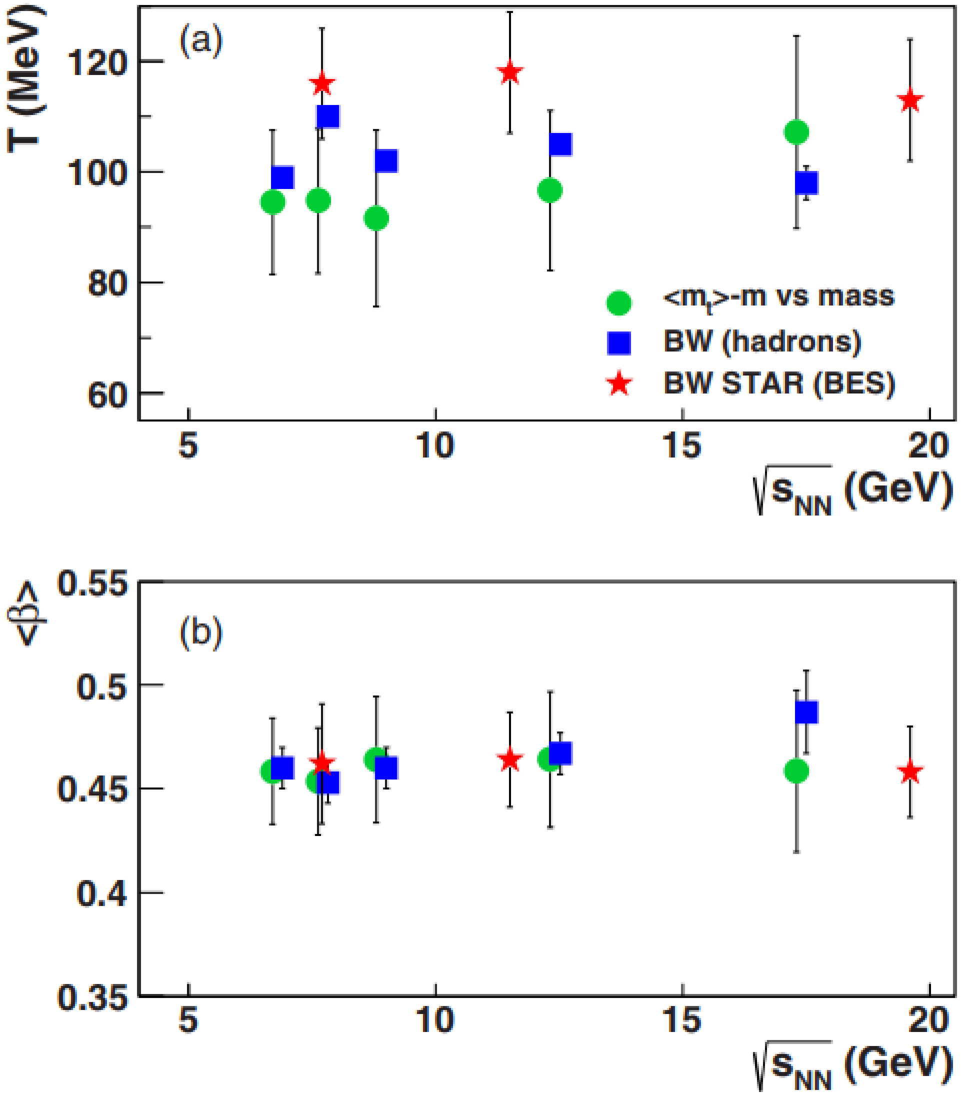


FIG. 5: (Color online.) Comparison of the calculations of the rapidity distributions of normal nuclei produced in central collisions with STAR experimental data [41]. Top panel (a) - protons, deutrons, tritons. Bottom panel (b) - ^{3}He, ^{4}He. The model parameters are indicated in the panels.

Production of deuterium, tritium, and ^{3}He in central Pb + Pb collisions at 20*A*, 30*A*, 40*A*, 80*A*, and 158*A* GeV at the CERN Super Proton Synchrotron



Energy dependence of the source temperature T (a) and average collective transverse velocity β (b) at the kinetic freeze-out in central A + A collisions. The NA49 data from the mt versus mass analysis (see text for detail) are indicated by green circles; those from blast-wave (BW) fits of mt spectra of hadrons from NA49 are depicted by blue squares; red stars are the STAR-BES results from a BW analysis of hadron spectra reported in Ref. [50].

In the context of a coalescence model for nuclear fragment formation, the coalescence factor B_A is a crucial parameter that characterizes the process. The equation provided,

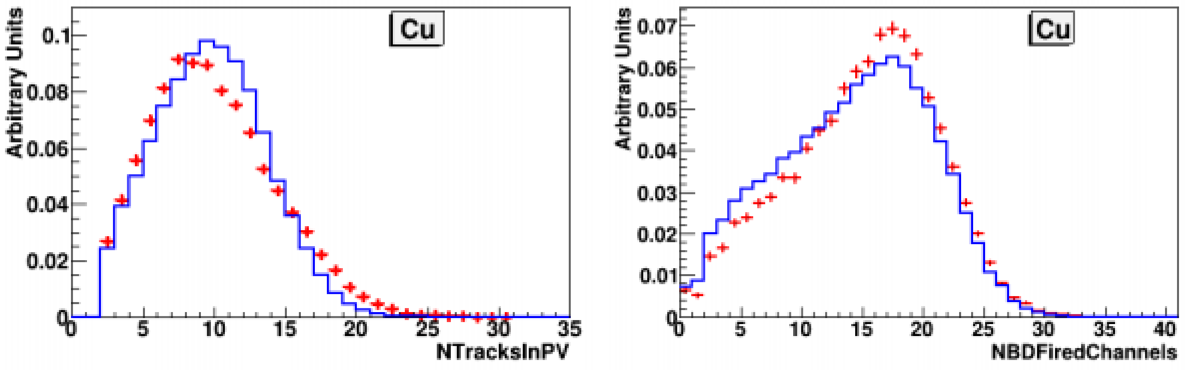
$$E_A d^3 N_A / d^3 p_A = B_A \left(E_p d^3 N_p / d_p^3 \right)^Z \left(E_n d^3 N_n / d^3 p \right)^{A-Z}_{|p = p_A / A}$$

describes how the invariant momentum spectra of the nuclear fragments (NA) with charge Z and atomic mass number A are related to the yields of the coalescing nucleons (protons Np and neutrons Nn) at the same velocity.

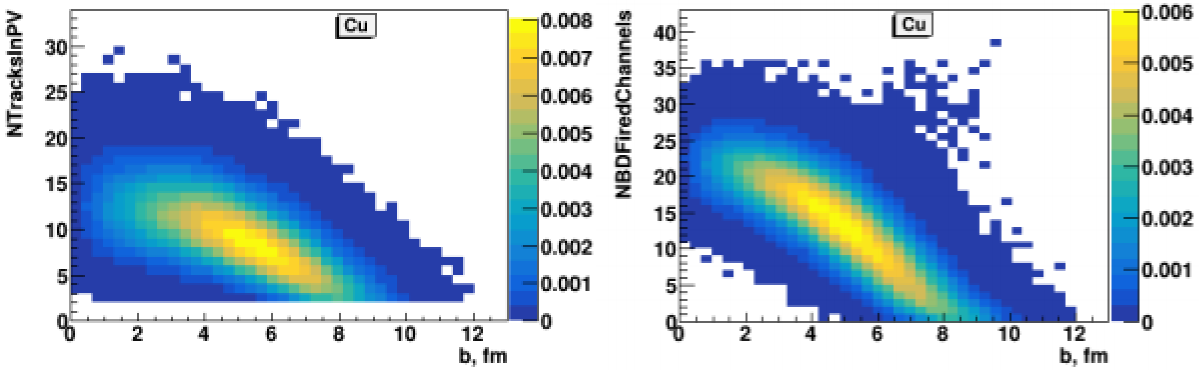
Here's a breakdown of the key components of the equation:

$E_A d^3 N_A / d^3 p_A$: Energy dependence of the differential yield of nuclear fragments with respect to their momentum.
B_A: Coalescence factor that quantifies the probability of nucleons coalescing into a nuclear fragment.
$(E_p d^3 N_p / d^3{}_p)^Z$: Energy dependence of the differential yield of protons involved in the coalescence process.
$(E_n d^3 N_n / d^3 p)^{A-Z}$: Energy dependence of the differential yield of neutrons involved in the coalescence process.
p_A and $p = p^A/A$: Momenta of the nuclear fragment and the nucleon, respectively, where pA/A represents the momentum per nucleon.

Comparison of experimental data and MC



Comparison of the experimental distributions (red crosses) and reconstructed Monte Carlo GEANT distributions of events generated with the DCM-SMM model (blue lines): number of tracks reconstructed in the primary vertex (left); number of fired BD channels (right).



Correlation obtained from the DCM-SMM model of the number of tracks in the primary vertex (left) and the number of fired channels in the BD (right) with impact parameter.

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%

.

• 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.