

1 **BM@N Analysis Note 3**
2 **Production of π^+ , K^+ mesons in**
3 **3.2 A GeV argon-nucleus interactions**

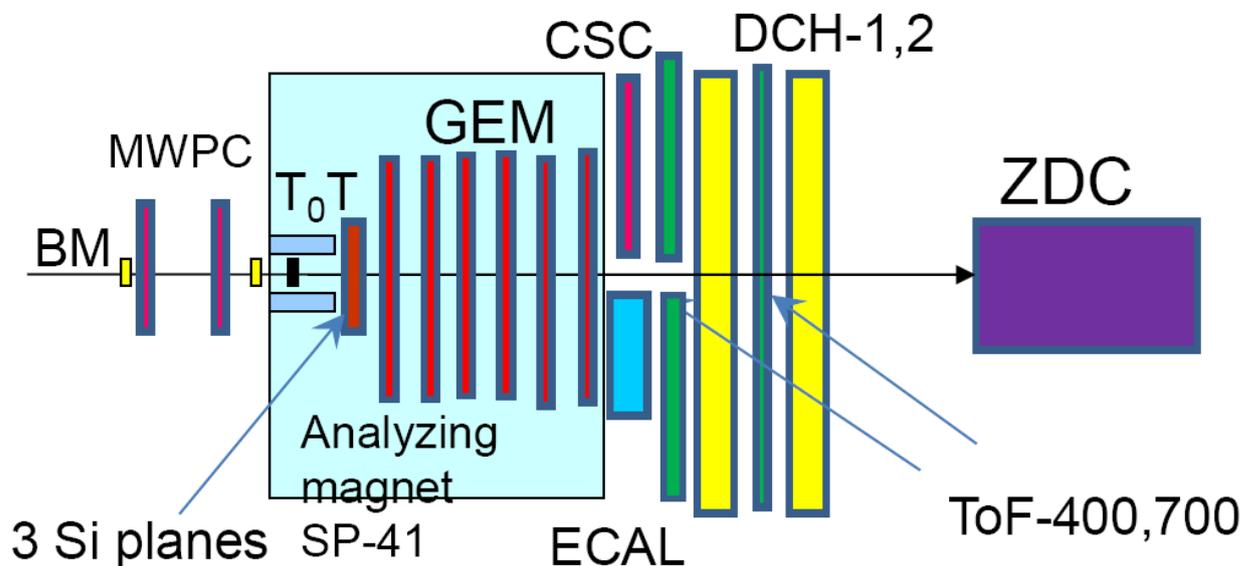
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7 **Abstract**

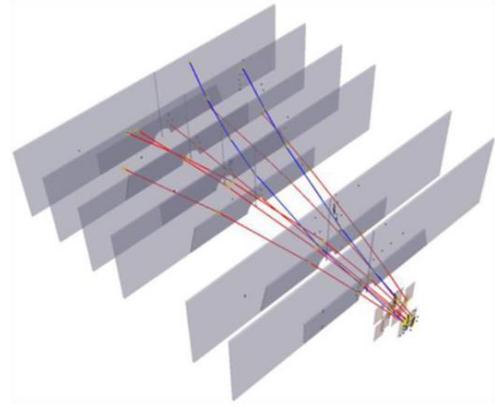
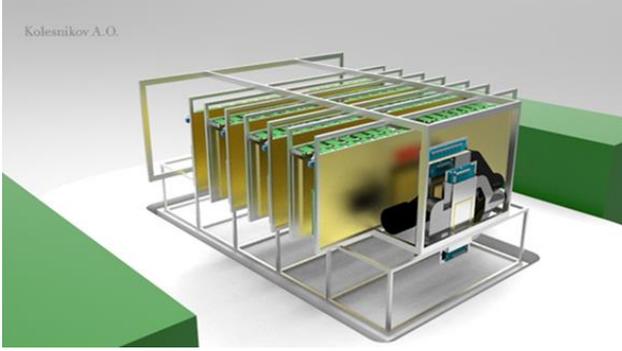
8 Production of π^+ , K^+ mesons in interactions of the argon beam with the kinetic energy 3.2 AGeV
9 with the *C, Al, Cu, Sn, Pb* targets was studied with the BM@M detector at the Nuclotron. The
10 analysis procedure is described in details. Results on π^+ , K^+ meson yields have been obtained
11 and compared with model predictions and data available.

12 **BM@N configuration in the argon beam run**

13 The technical run of the BM@N detector was performed with the argon beam in March 2018.
14 The view of the BM@N setup used in the run is presented in Fig. 1. The configuration of the
15 central tracker was based on three planes of forward silicon detectors and six stations consisted
16 of GEM detectors with the size of 163x45 cm² [GEMTDR]. The GEM tracking stations were
17 arranged to cover the upper part of the magnet acceptance. The beam passed the GEM detectors
18 through the arc holes (Fig. 2). Each successive GEM station was rotated by 180° around the
19 vertical axis. It was done to have the opposite electron drift direction in the successive stations in
20 order to avoid a systematic shift of reconstructed tracks due to the Lorentz angle in the magnetic
21 field. The research program was devoted to measurements of inelastic reactions $Ar+A \rightarrow X$ with
22 the beam kinetic energy of 3.2 AGeV and different targets: *C, Al, Cu, Sn, Pb*.



23
24 Fig. 1. BM@N set-up in the argon beam run.



25

26 Fig.2. Left: Schematic view of the central tracking detectors (3 forward silicon and 6 GEM
 27 detectors). Right: Event of $Ar+A \rightarrow X$ interaction reconstructed in the central tracking detectors.

28 In the present analysis the experimental data from the forward silicon detectors, GEM detectors,
 29 trigger barrel BD and silicon multiplicity FD detectors around the target, beam and T0 counters
 30 and two sets of the time-of-flight detectors ToF-400 and ToF-700 were analyzed. To confirm
 31 matching of extrapolated tracks reconstructed in the central detectors to the ToF detectors, hits in
 32 the outer tracking detectors: cathode strip chamber CSC or drift chambers DCH were used. The
 33 argon beam intensity was few 10^5 per the spill, the spill duration was 2-2.5 sec. The magnetic
 34 field in the center of the analyzing magnet was 0.61 T. Number of triggered events, beam fluxes
 35 and integrated luminosities collected in interactions of the argon beam with different targets are
 36 given in Table 1a and 1b for the ToF-400 and ToF-700 data sample, respectively. The data
 37 samples included “good quality” runs where the CSC (DCH) and ToF-400 (ToF-700) detectors
 38 were fully operational.

39 **Event reconstruction**

40 The track reconstruction method was based on the so-called “cellular automaton” approach
 41 [CBM1]. The tracks found were used to reconstruct primary and secondary vertices using the
 42 “KF-particle” formalism [CBM2]. π^+ and K^+ were identified using the time of flight from the
 43 ToF detectors, the length of the trajectory and the momentum reconstructed in the central
 44 tracker. The π^+ and K^+ candidates should originate from the primary event vertex, correlate
 45 with hits in the CSC / DCH detectors and match hits in the ToF-400 / ToF-700 detectors.
 46 Herewith, the CSC (DCH) hits were used to confirm the quality of the tracks matched to ToF-
 47 400 (ToF-700) hits. Events were recorded with different conditions on the minimum number of
 48 fired channels in the barrel BD and multiplicity silicon FD trigger detectors, ranging from zero to
 49 4.

50 Table 1a. Number of triggered events, beam fluxes and integrated luminosities collected in
 51 interactions of the argon beam of 3.2 AGeV with different targets (ToF-400 data sample).

Interactions, target thickness	Number of triggers / 10^6	Integrated beam flux / 10^7	Integrated luminosity / 10^{30} cm^{-2}
$Ar+C$ (2 mm)	11.7	10.9	2.06
$Ar+Al$ (3.33 mm)	30.6	15.4	2.30

<i>Ar+Cu</i> (1.67 mm)	30.9	15.9	1.79
<i>Ar+Sn</i> (2.57 mm)	30.0	15.1	1.11
<i>Ar+Pb</i> (2.5 mm)	13.7	7.0	0.50

52 Table 1b. Number of triggered events, beam fluxes and integrated luminosities collected in
53 interactions of the argon beam of 3.2 AGeV with different targets (ToF-700 data sample).

Interactions, target thickness	Number of triggers / 10^6	Integrated beam flux / 10^7	Integrated luminosity / 10^{30} cm^{-2}
<i>Ar+C</i> (2 mm)	11.3	8.7	1.97
<i>Ar+Al</i> (3.33 mm)	29.2	10.2	2.05
<i>Ar+Cu</i> (1.67 mm)	28.7	11.3	1.60
<i>Ar+Sn</i> (2.57 mm)	25.9	9.5	0.91
<i>Ar+Pb</i> (2.5 mm)	13.7	4.9	0.40

54 **π^+ and K^+ selection criteria:**

- 55 • Each track has at least 4 hits in GEM detectors (6 detectors in total), where hit is a
56 combination of two strip clusters on both readout sides (X and X' views) on each detector
57 [GEMTDR]
- 58 • Tracks are originated from the primary event vertex, the deviation of the reconstructed
59 vertex from the position of the target along the beam direction $-3.4 < |Z_{\text{vertex}} - Z_0| < 1.7$ cm.
60 A harder upper limit is aimed to remove background due to interactions in a scintillator
61 counter behind the target.
- 62 • Distance of the closest approach of tracks from the vertex in the direction perpendicular
63 to the beam at Z_{vertex} : $dca < 1$ cm
- 64 • χ^2 / ndf for tracks from the primary vertex $< 3.5^2$
- 65 • Momentum range of positive tracks: $p_{\text{pos}} > 0.5, 0.7$ GeV/ c for analysis of the ToF-400 and
66 ToF-700 data, respectively
- 67 • Correlation of extrapolated tracks with the CSC / DCH hits as well as with the ToF-400 /
68 ToF-700 hits should be within $\pm 2.5\sigma$ of the residual distributions.

69 **Event simulation:**

70 The Monte Carlo event samples of $Ar+A$ collisions were produced with the DCM-SMM event
71 generator. The passage of particles through the setup volume was simulated with the GEANT
72 program integrated into the BmnRoot software framework. To properly describe the GEM
73 detector response in the magnetic field, the microsimulation package Garfield++ was used. The
74 package gives very detailed description of the processes inside the GEM detector, including the
75 drift and diffusion of released electrons in electric and magnetic fields and the electron
76 multiplication in GEM foils, so that the output signal from the readout plane can be reproduced.
77 To speed up the simulation, dependencies of the Lorentz shifts and the charge distributions on
78 the readout planes on the drift distance were parameterized and used in the GEM digitization part
79 of the BmnRoot package. The details of the detector alignment, Lorentz shift corrections are

80 described in the paper [DeuteronPaper]. Examples of experimental and Monte Carlo
81 distributions of the distance of the closest approach of tracks to the vertex, χ^2 of reconstructed
82 tracks, number of tracks reconstructed in the primary vertex, number of hits per track are
83 presented in Fig.3a. Distributions of the total momentum p and transverse momentum p_T of
84 π^+ and K^+ for ToF-400 and ToF-700 data and simulation are presented in Fig.3b and 3c,
85 respectively.

86 The detector effects in simulation were controlled by reproducing the track reconstruction
87 efficiency evaluated from data. Efficiency distributions in 3 Si and 6 GEM stations measured
88 with reconstructed experimental tracks are shown in Fig.4. For each station they were estimated
89 using the following approach:

- 90 1. Select good quality tracks with the number of hits per track (excluding the station under
91 study) not less than N ;
- 92 2. Check that track crosses the detector area, if yes, add one track to the denominator;
- 93 3. If there is a hit in the detector, which belongs to the track, add one track to the numerator;
- 94 4. Detector efficiency is equal to the ratio of number of tracks in numerator to number of
95 tracks in denominator.

96 These efficiencies were applied to reduce the number of hits of tracks reconstructed in
97 simulation. The experimental and simulated distributions of Si and GEM hit residuals to tracks in
98 X and Y projections are presented in Fig.5a and Fig.5b, respectively. The RMS of distributions
99 are in a reasonable agreement between data and simulation. The mean values and sigma of the
100 residuals of CSC hits in the X and Y projections with respect to reconstructed positive tracks
101 identified in ToF-400 are given in Fig.6a - Fig.6d in dependence on the particle momentum. The
102 mean values and sigma of the residuals of ToF-400 hits in the X and Y projections with respect
103 to reconstructed positive tracks are given in Fig.7a - Fig.7d in dependence on the particle
104 momentum. The mean values and sigma of the residuals of DCH hits in the X and Y projections
105 with respect to reconstructed positive tracks identified in ToF-700 are given in Fig.8a - Fig.8b in
106 dependence on the particle momentum. The mean values and sigma of the residuals of ToF-700
107 hits in the X and Y projections with respect to reconstructed positive tracks are given in Fig.9a -
108 Fig.9b in dependence on the particle momentum.

109 **Signals of π^+ and K^+ in experimental data:**

110 The mass squared spectrum of positive particles identified in ToF-400 and ToF-700 in
111 experimental and simulated events of A_r+A interactions are illustrated in Fig.10a and 10b,
112 respectively. Signals of π^+ and K^+ were extracted in windows of the mass squared from -0.09 to
113 $0.13 (\text{GeV}/c^2)^2$ and from 0.18 to $0.32 (\text{GeV}/c^2)^2$, respectively. Numbers of π^+ and K^+ were taken
114 from the content of the histogram bins within the corresponding mass windows. To estimate the
115 background in the π^+ and K^+ mass windows, the "mixed event" method was used, i.e. the shape
116 of the mass squared background distribution was evaluated by matching tracks to hits in the ToF-
117 400 and ToF-700 detectors originated from independent events. Signals of π^+ and K^+ in the
118 intervals of the transverse momentum p_T and rapidity y_{lab} were reconstructed using the same
119 procedure. The errors of the π^+ and K^+ signals include the uncertainty of the background
120 subtraction. The statistical and systematic errors were calculated according to the formula:
121 $sig=hist-bg$, $err(stat)=\sqrt{hist+bg}$, assuming the background uncertainty of \sqrt{bg} . Here $hist$ and bg

122 denote the histogram integral and the background integral within the π^+ and K^+ mass squared
 123 windows. To estimate the π^+ and K^+ signal systematic errors due to the background subtraction
 124 method, the distributions were fitted to the 1st degree polynomial (background) in the mass
 125 squared range $-0.14-0.4$ (GeV/c²)². The variation of the background integral in the π^+ (K^+) mass
 126 squared window taken from mixed events relative to the bg integral taken from the fit of the
 127 mass squared spectra was treated as a systematic error.

128 The π^+ and K^+ mass squared windows were excluded from the fit. Spectra of mass squared
 129 shown in Fig.10c and 10d in bins of y of π^+ and K^+ identified in ToF-400 in Ar+Cu interactions
 130 illustrate the background subtraction method using a linear fit. The mixed event method is
 131 illustrated in Fig.10e and 10f. Spectra of mass squared in bins of rapidity y of π^+ and K^+
 132 identified in ToF-400 in Ar+Sn interactions: left) experimental events, right) simulated events.
 133 Background (blue histogram) is taken from mixed events and normalized to the red signal
 134 histogram in the mass squared range between the π^+ and K^+ peaks and above the K^+ peak.

135 The statistics of π^+ and K^+ reconstructed in ToF-400 (ToF-700) in $Ar+C$, $Ar+Al$, $Ar+Cu$,
 136 $Ar+Sn$, $Ar+Pb$ interactions are summarized in Table 2. Number of reconstructed π^+ (K^+) in
 137 interactions of 3.2 AGeV argon beam with C , Al , Cu , Sn , Pb targets in bins of y_{lab} and p_T are
 138 shown in Fig. 11a (11b) for ToF-400 data. The corresponding 2-dimensional (y_{lab} , p_T)
 139 distributions are given in Fig.11c and 11d.

140 Table 2. Signals of π^+ and K^+ mesons reconstructed in ToF-400 and ToF-700 in argon-nucleus
 141 interactions. The error presents the statistical uncertainty.

Target	<i>ToF-400</i>				
	<i>C</i>	<i>Al</i>	<i>Cu</i>	<i>Sn</i>	<i>Pb</i>
π^+	4020±66	21130±152	28010±175	32060±186	22420±156
K^+	45±10	278±25	538±31	729±36	570±32
Target	<i>ToF-700</i>				
	<i>C</i>	<i>Al</i>	<i>Cu</i>	<i>Sn</i>	<i>Pb</i>
π^+	1070±34	5640±80	8090±95	9450±104	6830±86
K^+	31±6	117±16	193±21	346±23	221±20

142 **π^+ / K^+ reconstruction efficiency from simulation:**

143 The π^+ / K^+ reconstruction efficiency is the ratio of the number of reconstructed π^+ / K^+ to the
 144 number of generated ones in the intervals of (p_T, y), where y is measured in the laboratory frame
 145 (y_{lab}). The reconstruction efficiency can be decomposed into the following components: $\epsilon_{rec} =$
 146 $\epsilon_{acc} \cdot \epsilon_{cuts}$. The definition of every term is given in Table 4 and their determination procedure is as
 147 follows.

148 After the event simulation and reconstruction the successfully reconstructed π^+ / K^+ were
 149 counted in the numerator N_{acc} . The detector acceptance was taken as N_{acc} / N_{gen} , where N_{gen} is the
 150 total number of generated MC events. The number of π^+ / K^+ after applying kinematic and
 151 spatial cuts (N_{cuts}) gave the “selection cuts” efficiency with respect to the number of accepted
 152 ones from above.

153 Table 4. Decomposition of the π^+ / K^+ reconstruction efficiency.

Reconstruction efficiency	$\epsilon_{rec} = \epsilon_{acc} \cdot \epsilon_{cuts}$
π^+ / K^+ geometrical acceptance in detectors	$\epsilon_{acc} = N_{acc}(y, p_T) / N_{gen}(y, p_T)$
Efficiency of reconstruction of π^+ / K^+ within the detector geometrical acceptance after applying kinematic and spatial cuts	$\epsilon_{cuts} = N_{cuts}(y, p_T) / N_{acc}(y, p_T)$

154 The actual values of the efficiencies (ϵ_{acc} , ϵ_{cuts}) and combined reconstruction efficiencies ϵ_{rec}
 155 calculated in the y , p_T and 2-dinotional (y , p_T) bins are shown in Figs. 12a – 12b for π^+ , K^+
 156 mesons reconstructed in ToF-400 in $Ar+A$ interactions.

157 **Trigger efficiency:**

158 Different conditions on the minimum number of fired channels in the barrel BD and multiplicity
 159 silicon FD trigger detectors, ranging from zero to 4 were applied to record experimental data.
 160 The mean efficiency ϵ_{trig} of the BD and FD trigger detectors for events with reconstructed $\pi^+ /$
 161 K^+ produced in interactions of the argon beam with the whole set of C , Al , Cu , Sn , Pb targets is
 162 given in Table 5a and 5b, respectively. The dependence of the BD and FD trigger efficiency on
 163 the number of tracks from the primary vertex for events with reconstructed π^+ / K^+ is presented
 164 in Fig.13a and 13b, respectively. The systematic errors used in the analysis cover the differences
 165 in the π^+ , K^+ signals obtained by using the mean values of the trigger efficiency values instead
 166 of the efficiency dependences on the number of the vertex tracks and the Y position of the
 167 primary vertex. The trigger efficiency of BD (FD) detectors was evaluated using experimental
 168 event samples recorded with an independent trigger based on FD (BD): $\epsilon(BD \geq m) =$
 169 $[N(BD \geq m \ \& \ FD \geq n)] / N(FD \geq n)$ for every target. The efficiency for the combined BD and FD
 170 triggers was calculated as a product of the BD and FD trigger efficiencies.

171 Table 5a. Mean BD trigger efficiency evaluated for events with reconstructed π^+ / K^+ in
 172 interactions of the argon beam with the whole set of C , Al , Cu , Sn , Pb targets.

Trigger / Target 3.2 AGeV π^+ mesons	C	Al	Cu	Sn	Pb
$\epsilon_{trig} (BD \geq 2)$	0.80±0.03	0.96±0.01	0.98±0.01	0.99±0.01	0.99±0.01
$\epsilon_{trig} (BD \geq 3)$	0.66±0.02	0.92±0.01	0.97±0.01	0.98±0.01	0.99±0.01
$\epsilon_{trig} (BD \geq 4)$	0.48±0.02	0.88±0.01	0.95±0.01	0.97±0.01	0.98±0.01

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Trigger / Target 3.2 AGeV, K^+ mesons	C	Al	Cu	Sn	Pb
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$\epsilon_{trig} (BD \geq 2)$	0.67 ± 0.15	0.97 ± 0.02	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01
$\epsilon_{trig} (BD \geq 3)$	0.67 ± 0.15	0.96 ± 0.02	0.98 ± 0.01	0.99 ± 0.01	0.99 ± 0.01
$\epsilon_{trig} (BD \geq 4)$	0.67 ± 0.15	0.94 ± 0.02	0.95 ± 0.02	0.99 ± 0.01	0.98 ± 0.01

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Table 5b. Mean FD trigger efficiency evaluated for events with reconstructed π^+ / K^+ in interactions of the argon beam with the whole set of *C, Al, Cu, Sn, Pb* targets.

Trigger / Target 3.2 AGeV π^+ mesons	<i>C</i>	<i>Al</i>	<i>Cu</i>	<i>Sn</i>	<i>Pb</i>
$\epsilon_{trig} (FD \geq 2)$	0.28 ± 0.01	0.40 ± 0.01	0.56 ± 0.01	0.65 ± 0.01	0.73 ± 0.01
$\epsilon_{trig} (FD \geq 3)$	0.14 ± 0.01	0.22 ± 0.01	0.37 ± 0.01	0.49 ± 0.01	0.58 ± 0.01
$\epsilon_{trig} (FD \geq 4)$	0.08 ± 0.01	0.11 ± 0.01	0.23 ± 0.01	0.34 ± 0.01	0.46 ± 0.01

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Trigger / Target 3.2 AGeV, K^+ mesons	<i>C</i>	<i>Al</i>	<i>Cu</i>	<i>Sn</i>	<i>Pb</i>
$\epsilon_{trig} (FD \geq 2)$	0.30 ± 0.06	0.40 ± 0.03	0.64 ± 0.03	0.74 ± 0.03	0.82 ± 0.03
$\epsilon_{trig} (FD \geq 3)$	0.17 ± 0.04	0.23 ± 0.02	0.45 ± 0.03	0.61 ± 0.03	0.73 ± 0.03
$\epsilon_{trig} (FD \geq 4)$	0.08 ± 0.03	0.12 ± 0.02	0.35 ± 0.03	0.44 ± 0.03	0.58 ± 0.03

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Luminosity uncertainty (see separate document Lumi.pdf)

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Impact parameter distribution:

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Distributions of the impact parameters of minimum bias interactions generated with the DCM-SMM model all generated events with π^+ (K^+) are shown in Fig.14a and 14b. The impact parameter distributions for events with π^+ (K^+) in the measured kinematical range as well as the impact parameters of simulated events with reconstructed π^+ (K^+) are presented for comparison. The measured kinematical ranges in the rapidity spectra of π^+ and K^+ generated with the DCM-SMM model in minimum bias interactions of the 3.2 AGeV argon beam with the Cu target, are given in Fig.14c.

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Evaluation of π^+ / K^+ cross sections and spectra:

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The inclusive cross section σ_{π^+} and yield Y_{π^+} of π^+ production in $Ar+C$, $Ar+Al$, $Ar+Cu$, $Ar+Sn$, $Ar+Pb$ interactions are calculated in bins of y (p_T) according to the formulae:

$$\sigma_{\pi^+}(y, p_T) = N_{rec}(y, p_T) / (\epsilon_{rec}(y, p_T) \cdot \epsilon_{trig} \cdot L) \quad Y_{\pi^+}(y, p_T) = \sigma_{\pi^+}(y, p_T) / \sigma_{inel}$$

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where L is the luminosity (Table 1), N_{rec} – the number of reconstructed π^+ (Table 2), ϵ_{rec} – the combined efficiency of the π^+ reconstruction, ϵ_{trig} – the trigger efficiency (Table 5), σ_{inel} – the cross section for minimum bias inelastic $Ar+A$ interactions (Table 7). The same formulas are used to calculate the K^+ inclusive production cross section and yield in bins of y (p_T). The cross

sections in (y, p_T) bins are calculated as weighted averaged of the results obtained with ToF-400 and ToF-700 data taking into account the statistical errors ($w \sim 1/\sigma^2$). The cross sections for inelastic $Ar+Al$, $Ar+Cu$, $Ar+Sn$, $Ar+Pb$ interactions are taken from the predictions of the DCM-SMM model which are consistent with the results calculated by the formula: $\sigma_{inel} = \pi R_0^2 (A_P^{1/3} + A_T^{1/3})^2$, where $R_0 = 1.2$ fm is an effective nucleon radius, A_P and A_T are atomic numbers of the beam and target nucleus [HadesL0]. The uncertainties for $Ar+Al$, $Ar+Cu$, $Ar+Sn$, $Ar+Pb$ inelastic cross sections are estimated by using the alternative formula: $\sigma_{inel} = \pi R_0^2 (A_P^{1/3} + A_T^{1/3} - b)^2$ with $R_0 = 1.46$ fm and $b = 1.21$ [AngelovCC].

Table 7. Inelastic cross sections for argon-nucleus interactions.

Interaction	$Ar+C$	$Ar+Al$	$Ar+Cu$	$Ar+Sn$	$Ar+Pb$
Inelastic cross section, mb	1470±50	1860±50	2480±50	3140±50	3970±50

The yields of π^+ / K^+ in minimum bias $Ar+C$, $Ar+Al$, $Ar+Cu$, $Ar+Sn$, $Ar+Pb$ interactions are measured in the kinematic range on the transverse momentum of $0.1 < p_T < 0.6$ GeV/c for π^+ ($0.1 < p_T < 0.5$ GeV/c for K^+) and the rapidity in the laboratory frame of $1.5 < y_{lab} < 3.2$ for π^+ ($1.0 < y_{lab} < 2.0$ for K^+). The rapidity of the beam-target nucleon-nucleon CM system calculated for an interaction of the argon beam with the kinetic energy of 3.2 GeV/nucleon with a fixed target is $y_{CM}=1.08$. The transformation of the y distribution to c.m.s. gives $y^*=y_{lab}-y_{CM}$. The differential spectra of the π^+ (K^+) yields in y_{lab} are measured in the π^+ (K^+) transverse momentum range of $0.1 < p_T < 0.6$ GeV/c ($0.1 < p_T < 0.5$ GeV/c). The corrected differential y_{lab} spectra of π^+ / K^+ yields are presented in Figs. 15a and 15b, respectively. Due to low statistics of the K^+ meson signal in $Ar+C$ interactions, the results are given only for the whole measured range in y_{lab} and p_T . Predictions of the DCM-SMM, URQMD and PHSD models are shown for comparison. The corrected invariant differential p_T spectra of π^+ , K^+ yields are presented in Fig. 16a, 16b-c, respectively. The measured spectra of the π^+ / K^+ yields in p_T are parameterized by the form: $1/p_T \cdot d^2N/dp_T dy = N \cdot \exp(-(m_T - m_{\pi^+})/T)$, where $m_T = \sqrt{(m_{\pi^+})^2 + p_T^2}$ is the transverse mass, the normalization N and the inverse slope parameter T are free parameters of the fit, dy corresponds to the measured y_{lab} range. In Fig.17a and 17b the inverse slopes T of the experimental invariant p_T spectra of π^+ / K^+ mesons are compared with the predictions of the DCM-SMM, URQMD and PHSD models. In Table 12b the inverse slopes T of the invariant p_T spectra of K^+ mesons are given for the whole measured range in y_{lab} and p_T .

223 Systematic uncertainties:

224 The systematic error of the π^+ / K^+ yields in every p_T and y bin is calculated as a quadratic sum
225 of uncertainties coming from the following sources:

- 226 • Sys1: Systematic error of the trigger efficiency evaluated as a function of the number of
227 tracks from the primary vertex and the primary vertex position.
- 228 • Sys2: Systematic errors of the reconstruction efficiency due to the remaining difference
229 in the X/Y primary vertex distribution in the simulation relative to the experimental data.
- 230 • Sys3: Systematic errors of the background subtraction under the π^+ and K^+ signals in the
231 mass squared spectra of identified particles as described in section on **Signals of π^+ and
232 K^+ in experimental data.**

233 The π^+ / K^+ yield normalization uncertainty calculated as a quadratic sum of uncertainties of the
 234 trigger efficiency, tracking efficiency, luminosity and inelastic nucleus-nucleus cross section.
 235 The normalization error is valid for the whole measured kinematical range. The luminosity
 236 uncertainty is estimated to be within 2%. The normalization uncertainty of the trigger efficiency
 237 is 28% for K^+ detection in Ar+C interactions and between 7.5% (Ar+Al) and 4% (Ar+Pb) for
 238 K^+ detection in interactions of argon with more heavy targets. The trigger efficiency uncertainty
 239 for π^+ detection ranges between 4.5% (Ar+C) and 0.9% (Ar+Pb). The uncertainty of the central
 240 tracking detector efficiency is estimated to be within 3%. The uncertainty of matching of
 241 extrapolated tracks with the CSC (DCH) hits as well as with the ToF-400 (ToF-700) hits is
 242 within 5%. The tracking and outer detector uncertainties are estimated from the remaining
 243 differences between the efficiencies obtained in experimental and Monte-Carlo events.

244 Relative difference of π^+ (K^+) yields measured in (y, p_T) bins using combined ToF-400 and ToF-
 245 700 data are given in Fig.14d and 14e, respectively. Relative difference of π^+ (K^+) yields
 246 measured in (y, p_T) bins originated from different sources of systematic uncertainties are given in
 247 Fig.14f and 14i, respectively. The average values of systematic uncertainties π^+ (K^+) yields in
 248 Ar+C, Al, Cu, Sn, Pb interactions are summarized in Table 10.

249 Table 10. Total systematic uncertainty of the π^+ and K^+ yields measured argon-nucleus
 250 interactions.

Target Systematics	π^+					Target	K^+				
	C sys%	Al sys%	Cu sys %	Sn sys%	Pb sys%		C sys%	Al sys%	Cu sys%	Sn sys%	Pb sys%
Sys1-Sys3	14	11	12	9	9		28	26	14	12	16
Norm (trigger + tracking + luminosity)	7.8	6.3	6.2	6.2	6.2		29	10	8.4	7.6	7.4

251 **Integrated yields and cross sections:**

252 The integrated yields of π^+ / K^+ produced in the kinematic range of $0.1 < p_T < 0.6$ GeV/c for π^+
 253 ($0.1 < p_T < 0.5$ GeV/c for K^+) and $1.5 < y_{lab} < 3.2$ for π^+ ($1.0 < y_{lab} < 2.0$ for K^+) in minimum bias
 254 Ar+C, Al, Cu, Sn, Pb interactions are summarized in Tables 12a and 12b. To extrapolate the
 255 measured yields to the full kinematic range the predictions of the DCM-SMM model are used.
 256 The rapidity spectra of π^+ and K^+ generated in the DCM-SMM model are shown in Fig.14c.
 257 The model extrapolation factors, the full yields of the π^+ and K^+ production in Ar+C, Ar+Al,
 258 Ar+Cu, Ar+Sn, Ar+Pb minimum bias interactions with beam energy of 3.2 AGeV are also given
 259 in Tables 12a and 12b. The ratios of K^+ to π^+ yields are given in Table 12b.

260 Table 12a. Extrapolation factors to the full kinematic range and π^+ yields for 3.2 AGeV argon-
 261 nucleus data in the measured and full kinematical ranges. The first errors given are statistical, the
 262 second errors are systematic.

3.2 AGeV, π^+	C	Al	Cu	Sn	Pb
DCM-SMM extrap. factor				4.98	5.64

	3.43	3.86	4.51		
Yield in $0.1 < p_T < 0.6$ GeV/c, $1.5 < y_{lab} < 3.2$	$0.275 \pm 0.006 \pm 0.02$ 7	$1.00 \pm 0.01 \pm 0.07$	$1.14 \pm 0.01 \pm 0.08$	$1.28 \pm 0.01 \pm 0.09$	$1.25 \pm 0.01 \pm 0.085$
Yield in the full kin. range	$0.943 \pm 0.019 \pm 0.09$ 2	$3.86 \pm 0.04 \pm 0.27$	$5.15 \pm 0.05 \pm 0.35$	$6.35 \pm 0.05 \pm 0.44$	$7.03 \pm 0.07 \pm 0.48$

263 Table 12b. Extrapolation factors to the full kinematic range , K^+ yields and K^+ to π^+ yield
264 ratios for 3.2 AGeV data in the measured and full kinematical ranges. The first errors given are
265 statistical, the second errors are systematic. Also the inverse slope parameters T of the invariant
266 p_T spectra are given.

3.2 AGeV K^+	<i>C</i>	<i>Al</i>	<i>Cu</i>	<i>Sn</i>	<i>Pb</i>
DCM-SMM extrap. factor	2.33	2.51	2.84	3.21	3.67
Yield in $0.1 < p_T < 0.5$ GeV/c, $1.0 < y_{lab} < 2.0$	$0.0094 \pm 0.0018 \pm$ 0.0035	$0.0390 \pm 0.0028 \pm 0$.0061	$0.0417 \pm 0.0021 \pm 0$.0066	$0.056 \pm 0.0022 \pm 0.00$ 75	$0.051 \pm 0.0022 \pm 0.$ 0092
Yield in the full kin. range	$0.0219 \pm 0.0042 \pm$ 0.0081	$0.098 \pm 0.007 \pm 0.0$ 15	$0.119 \pm 0.006 \pm 0.0$ 19	$0.180 \pm 0.007 \pm 0.0$ 24	$0.188 \pm 0.008 \pm 0.0$ 34
K^+ / π^+ ratio, measured range	$0.0343 \pm 0.0066 \pm$ 0.0125	$0.0390 \pm 0.0028 \pm 0$.0055	$0.0366 \pm 0.0019 \pm 0$.0053	$0.0439 \pm 0.0018 \pm 0$.0051	$0.0411 \pm 0.0018 \pm 0$.0068
K^+ / π^+ ratio, full kin. range	$0.0233 \pm 0.0045 \pm$ 0.0085	$0.0253 \pm 0.0018 \pm 0$.0035	$0.0230 \pm 0.0012 \pm 0$.0033	$0.0283 \pm 0.0012 \pm 0$.033	$0.0268 \pm 0.0012 \pm 0$.0044
K^+ inverse slope T , MeV measured range	$73 \pm 14 \pm 13$	$80 \pm 7 \pm 5$	$81 \pm 5 \pm 5$	$81 \pm 5 \pm 4$	$78 \pm 5 \pm 4$

267 In general, the transport models describe the shape of the differential spectra on y and p_T , but
268 predict more abundant yields of π^+ and K^+ in Ar+C interactions than measured in the
269 experiment. The BM@N results could be compared with the results of other experiments
270 studied argon-nucleus interactions at lower energies, shown in Table 13.

271 Table 13. Yields of K^+ , π^+ production and effective inverse slopes of invariant m_T spectra
272 measured in in interactions of light and medium nucleus.

Interacting nucleus / Beam kinetic energy / Experiment	π^+ , K^+ yields	K^+ / π^+ yield ratio, $\cdot 10^{-2}$	T_{eff} at $y^* = 0$, MeV, K^+ / π^+
Ar+KCl, 1.76 AGeV, [HADES1]	$3.9 \pm 0.1 \pm 0.1$ (π^-) $(2.8 \pm 0.2) \cdot 10^{-2}$ (K^+)		$82.4 \pm 9.1 - 4.6$ (π^-) $89 \pm 1 \pm 2$ (K^+)
Ar+KCl, 1.93 AGeV	$3.9 \pm 0.14 \pm 0.08$ (π^+)		
Ni+Ni, 1.93 AGeV [FOPI1,FOPI3]	$3.6 \cdot 10^{-2}$ (K^+ , Apart= 46.5) $8.25 \cdot 10^{-2}$ (K^+ , Apart = 75)	$7.59 \pm 0.49 \cdot 10^{-3}$ (Apart = 46.5)	101.9 ± 1.0
Ni+Ni, , 1.93 AGeV	87 ± 10 mb, $3 \cdot 10^{-2}$ (K^+)		97 ± 7 (non-central)

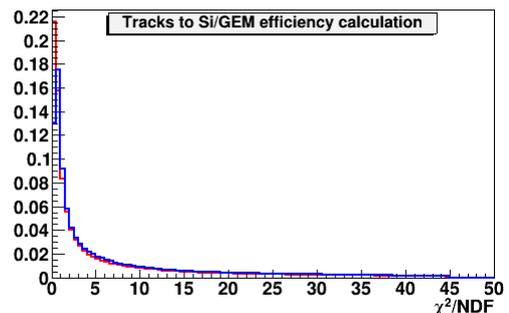
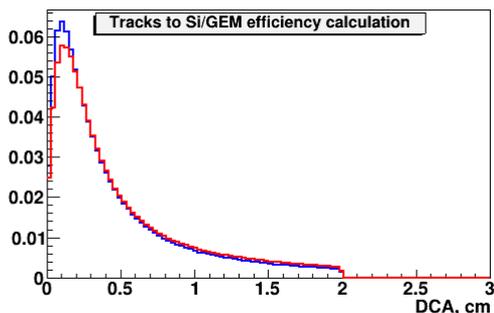
[KaoS1, KaoS2]			107±10 (central)

273 Summary

274 Production of π^+ and K^+ in interactions of the argon beam with *C*, *Al*, *Cu*, *Pb* targets was
 275 studied with the BM@N detector. The analysis procedure is described including details of the
 276 π^+ reconstruction, efficiency and systematic uncertainty evaluation. First physics results are
 277 presented on π^+ / K^+ yields in minimum bias argon-nucleus interactions at the beam kinetic
 278 energies of 3.2 AGeV. The results are compared with models of nucleus-nucleus interactions.

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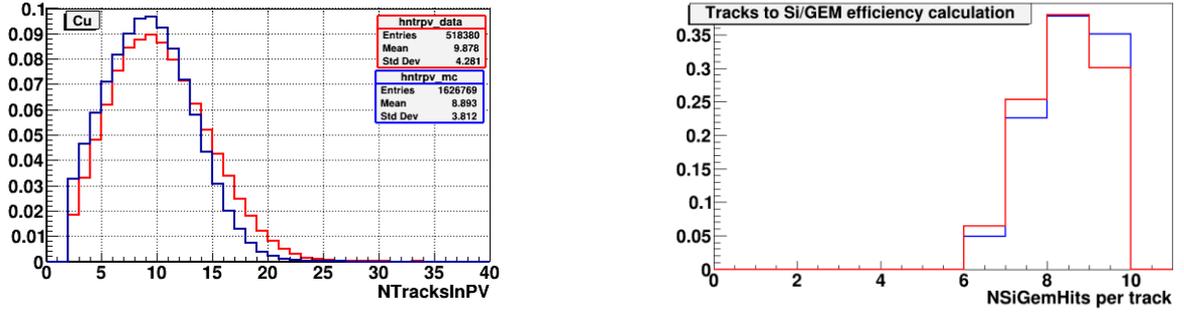


Fig.3a. $Ar+Ar$ interactions at 3.2 AGeV argon beam energy: comparison of experimental distributions (red lines) and Monte Carlo GEANT distributions of events generated with the DCM-SMM model (blue lines): Distribution of the distance of the closest approach DCA between tracks and the vertex in the plane perpendicular to the beam direction; χ^2 of reconstructed tracks; number of tracks reconstructed in the primary vertex; number of hits per track reconstructed in 3 Si + 6 GEM detectors.

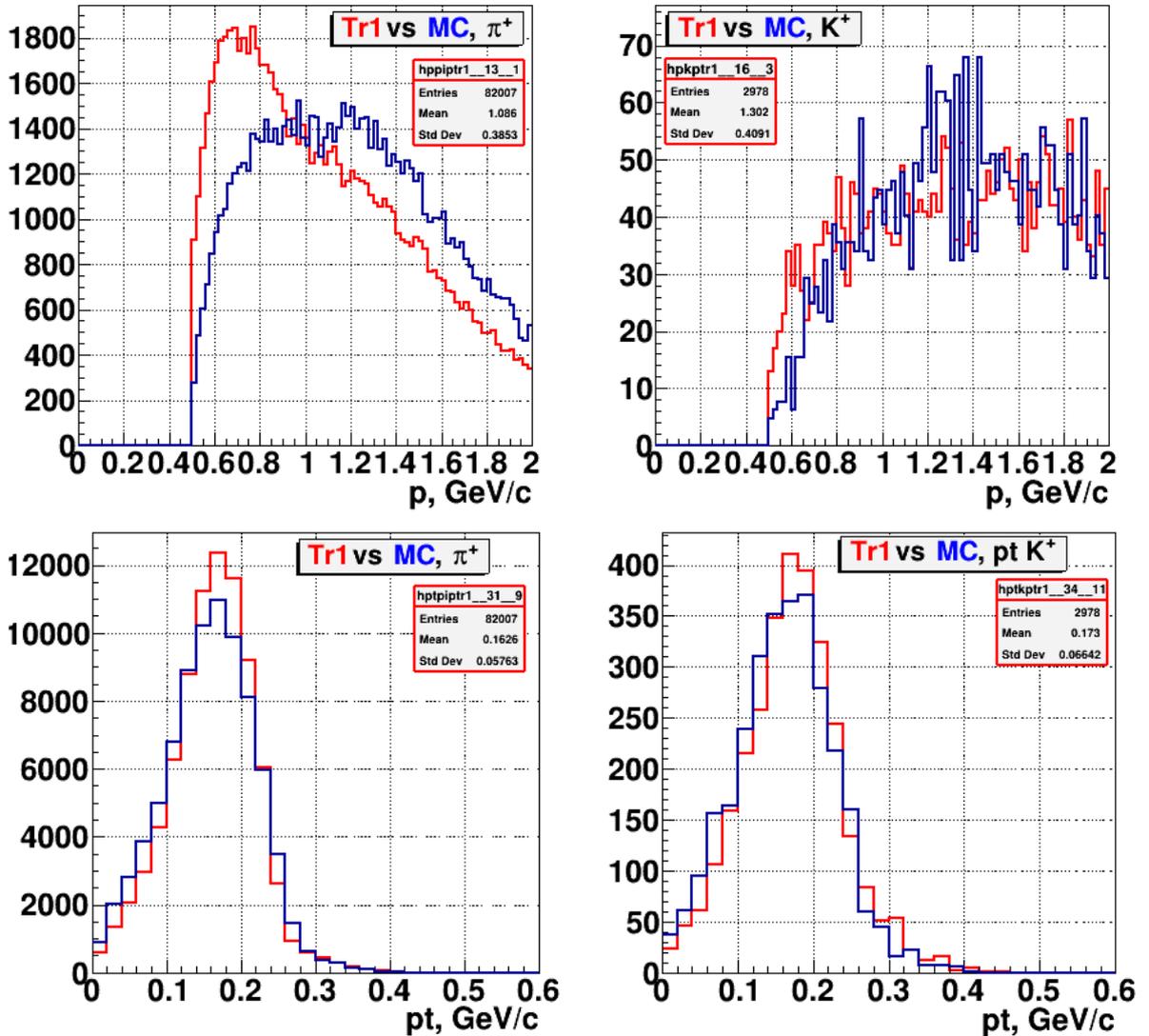


Fig. 3b. $Ar+Ar$ interactions at 3.2 AGeV argon beam energy: comparison of ToF-400 experimental data (red curves) and DCM-SMM + GEANT Monte Carlo simulation (blue curves): total momentum of identified π^+ and K^+ (upper plots); transverse momentum of π^+ and K^+ (lower plots).

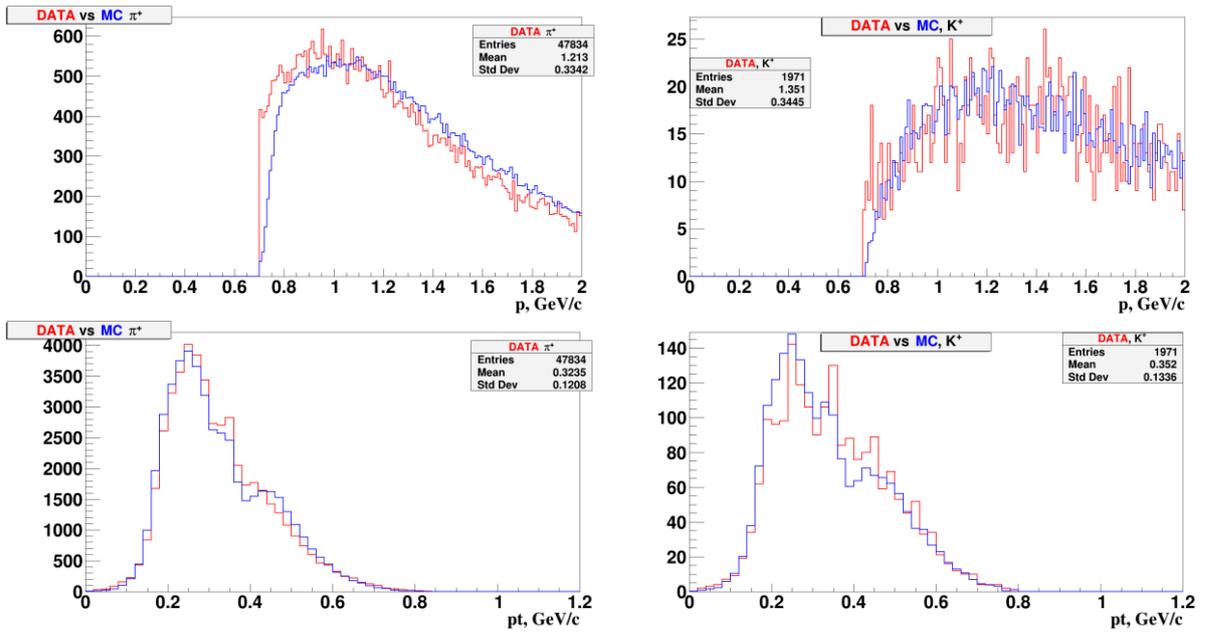
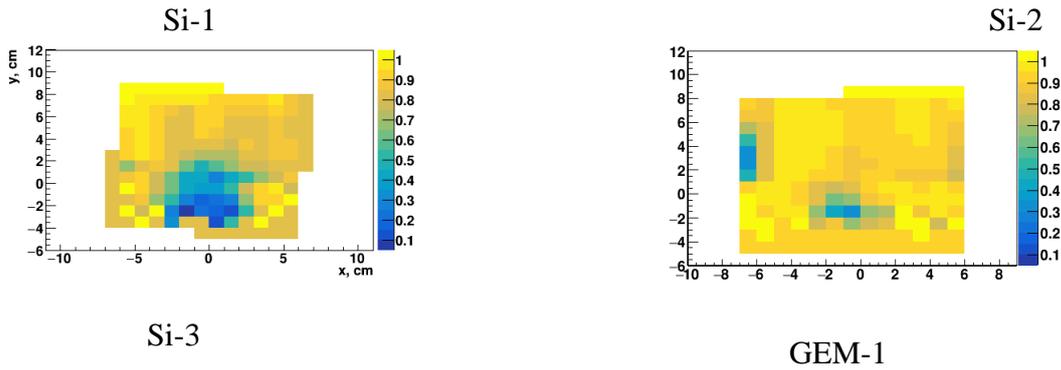
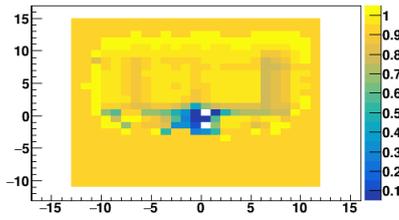
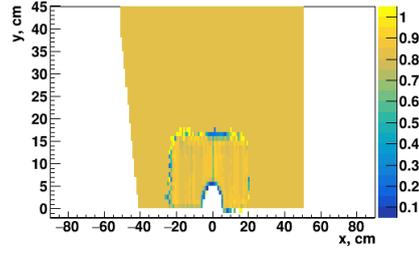


Fig. 3c. Ar+A interactions at 3.2 AGeV argon beam energy: comparison of ToF-700 experimental data (red curves) and DCM-SMM + GEANT Monte Carlo simulation (blue curves): total momentum of identified π^+ and K^+ (upper plots); transverse momentum of π^+ and K^+ (lower plots).

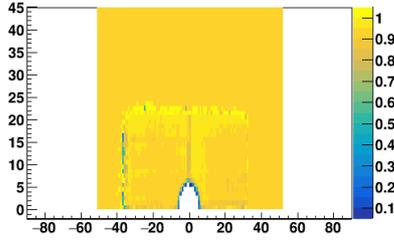




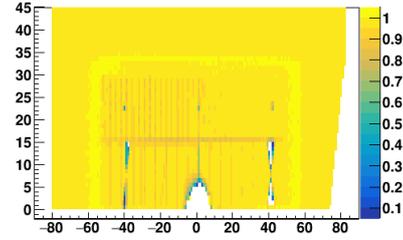
GEM-2



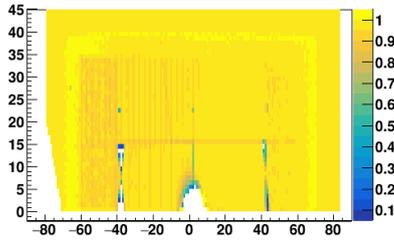
GEM-3



GEM-4



GEM-5



GEM-6

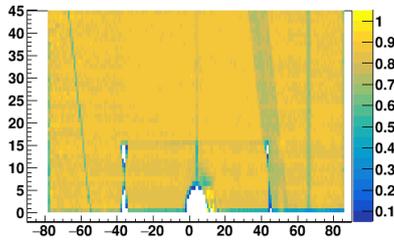
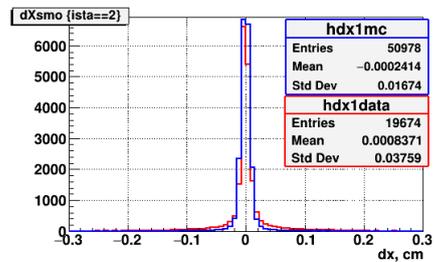
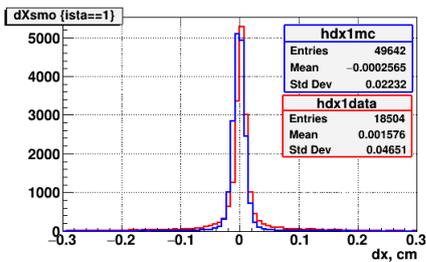


Fig. 4. 2-dimensional efficiency distributions in 3 Si and 6 GEM stations measured with experimental tracks and implemented into Monte Carlo simulation.



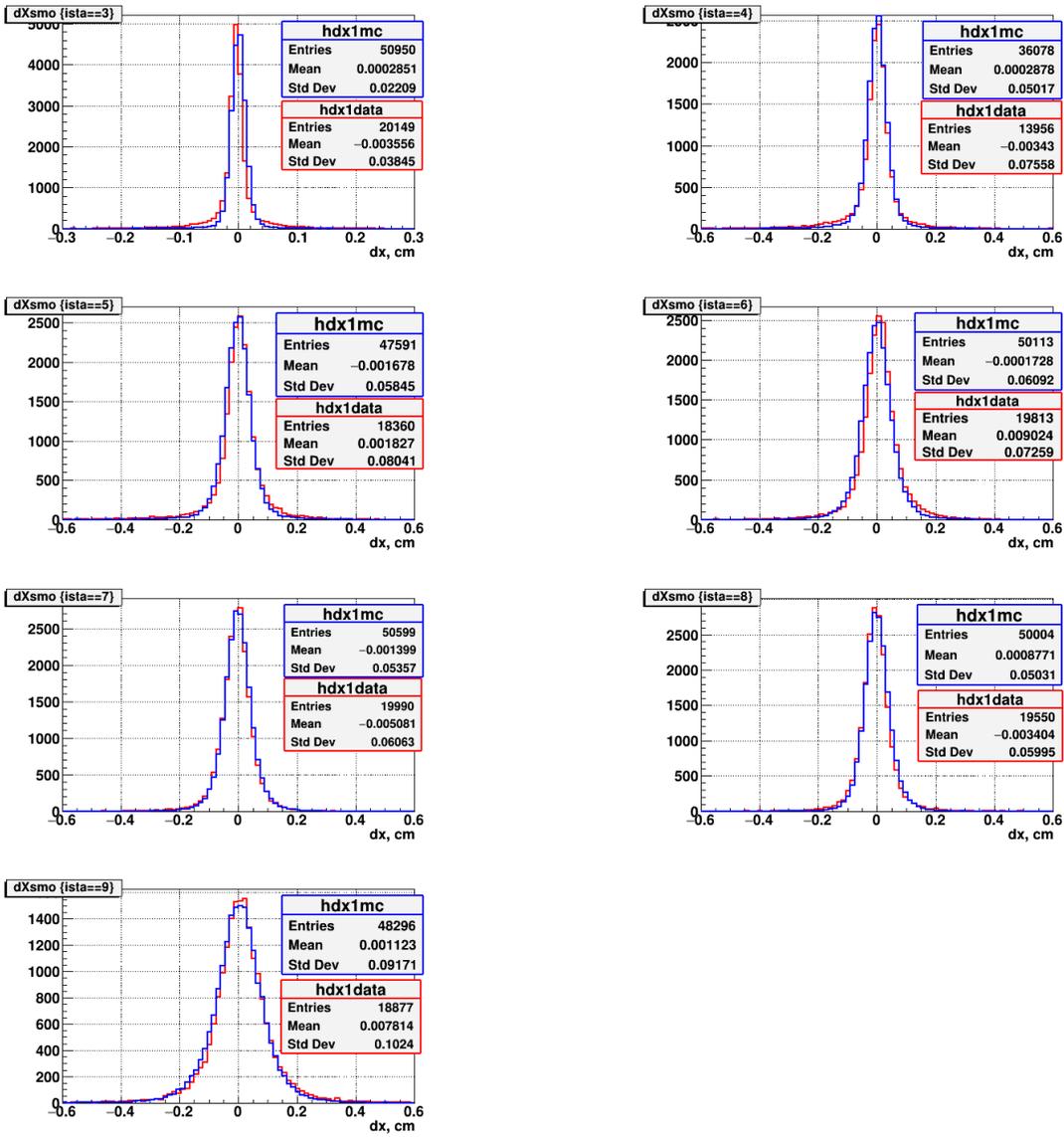
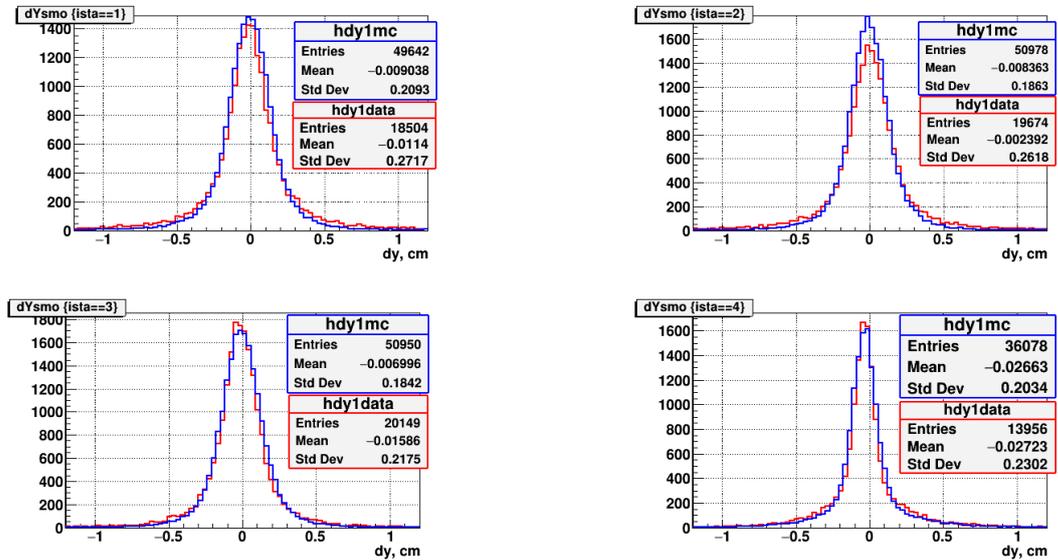


Fig. 5a. Residual distributions of hits in X projection with respect to reconstructed tracks in 3 Si (ista=1-3) and 6 GEM detectors (ista=4-9): experimental data (red histograms), simulated tracks (blue histograms).



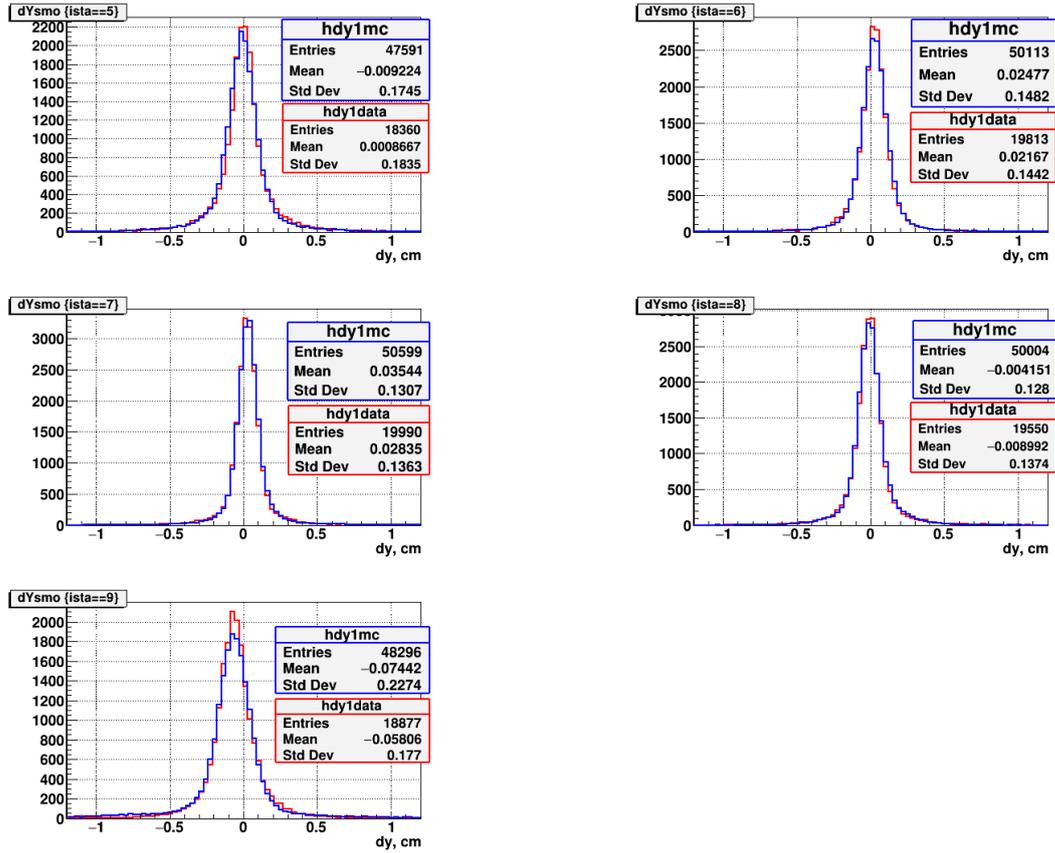


Fig. 5b. Residual distributions of hits in Y projection with respect to reconstructed tracks in 3 Si (ista=1-3) and 6 GEM detectors (ista=4-9): experimental data (red histograms), simulated tracks (blue histograms).

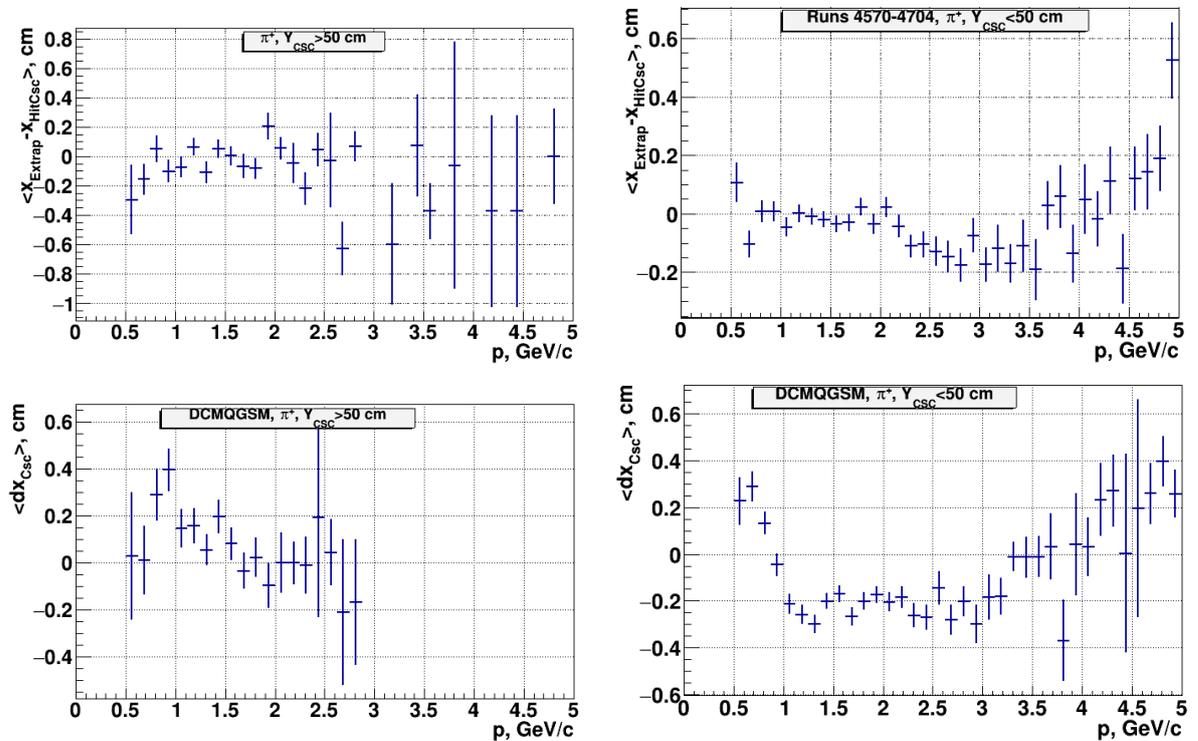


Fig. 6a. ToF-400 data and simulation: Mean values of residuals of CSC hits in X projection with respect to reconstructed positive tracks in dependence on the particle momentum for two ranges in Y: upper plots experimental data, lower plots – simulated tracks.

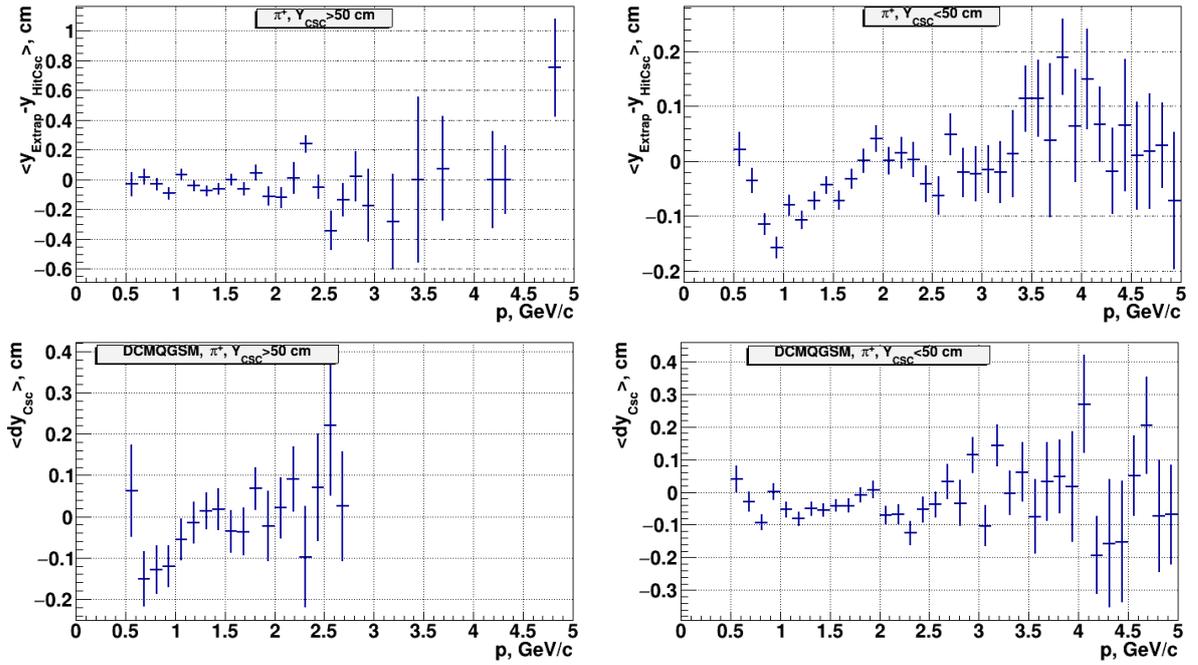


Fig. 6b. ToF-400 data and simulation: Mean values of residuals of CSC hits in the Y projection with respect to reconstructed positive tracks in dependence on the particle momentum for two ranges in Y: upper plots - experimental data, lower plots – simulated tracks.

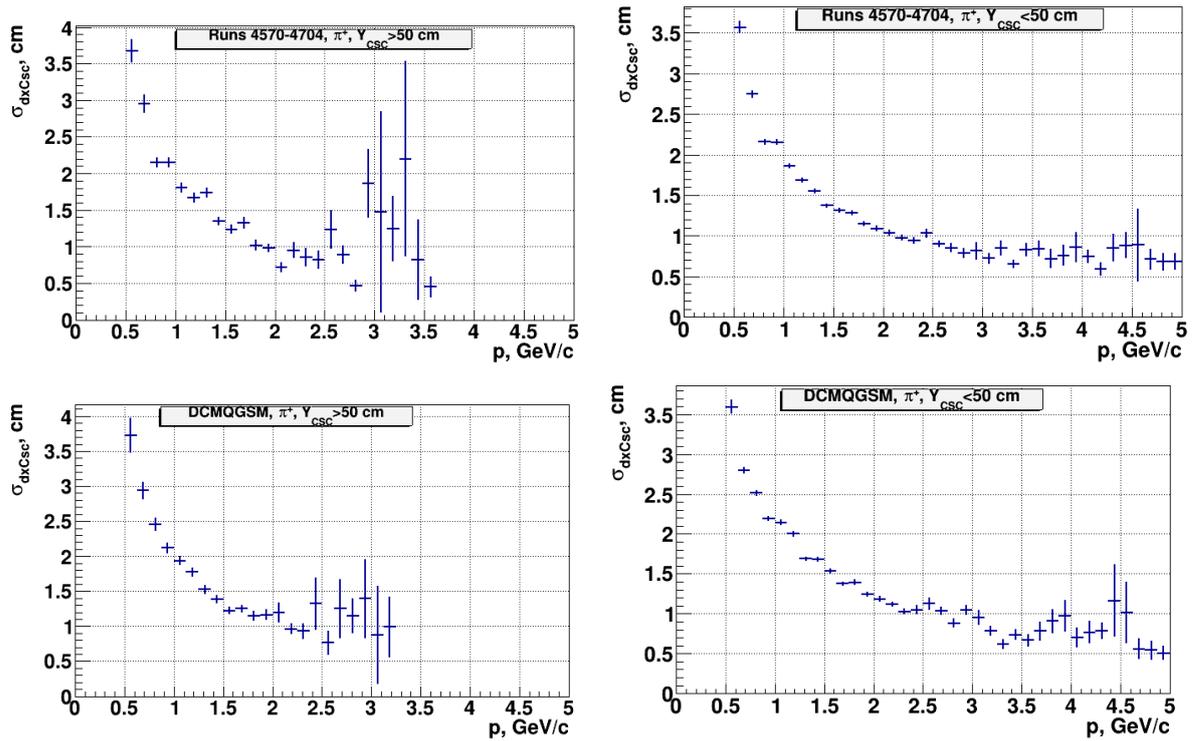


Fig. 6c. ToF-400 data and simulation: Sigma of residuals of CSC hits in the X projection with respect to reconstructed positive tracks in dependence on the particle momentum for two ranges in Y: upper plots - experimental data, lower plots – simulated tracks.

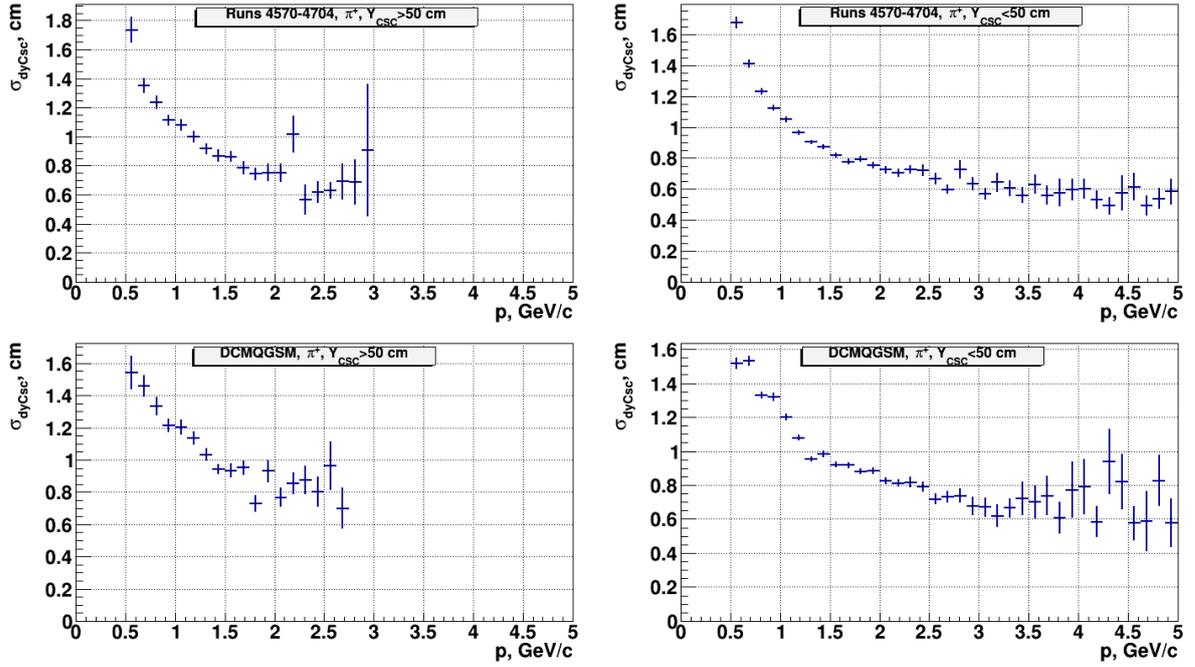


Fig. 6d. ToF-400 data and simulation: Sigma of residuals of CSC hits in the Y projection with respect to reconstructed positive tracks in dependence on the particle momentum for two ranges in Y: upper plots - experimental data, lower plots – simulated tracks.

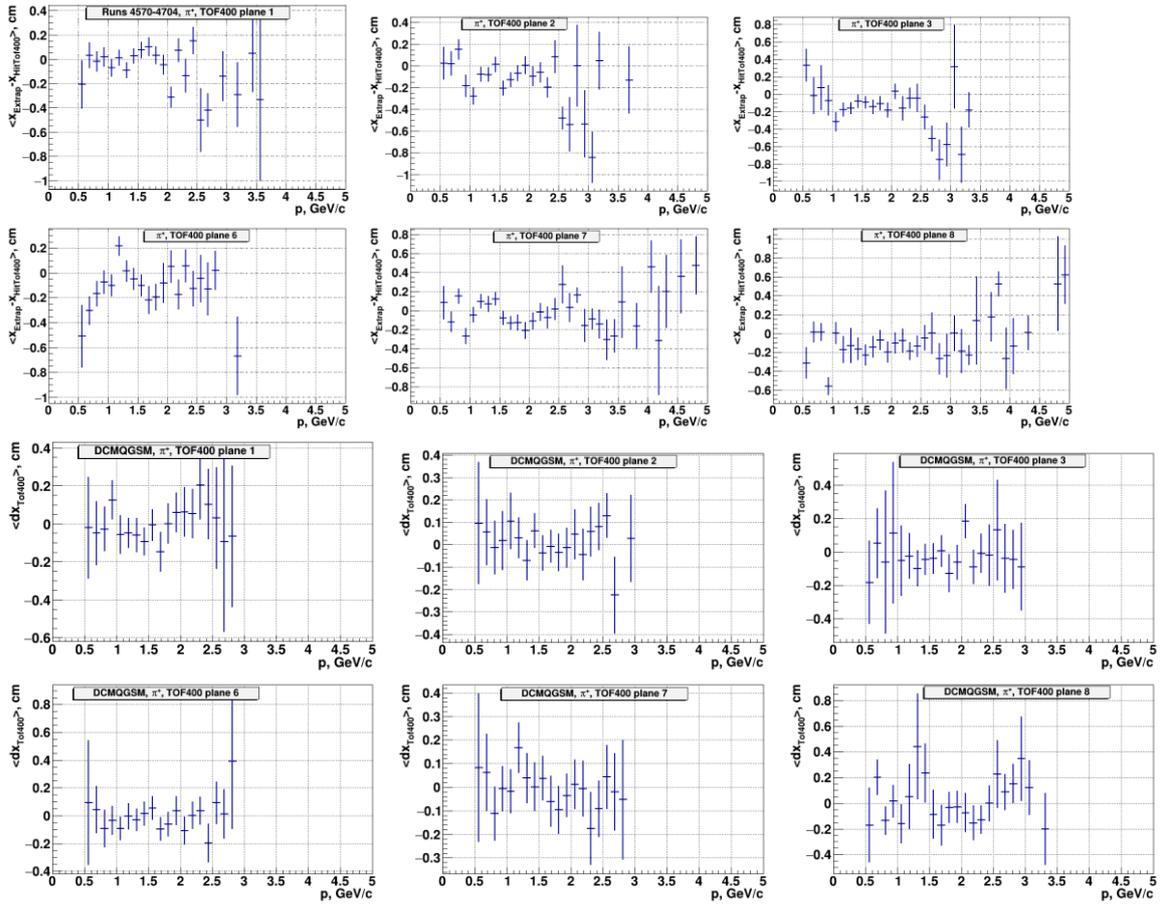


Fig. 7a. Mean values of residuals of ToF-400 hits in the X projection with respect to reconstructed positive tracks in dependence on the particle momentum: upper 6 plots - experimental data, lower 6 plots - simulated tracks.

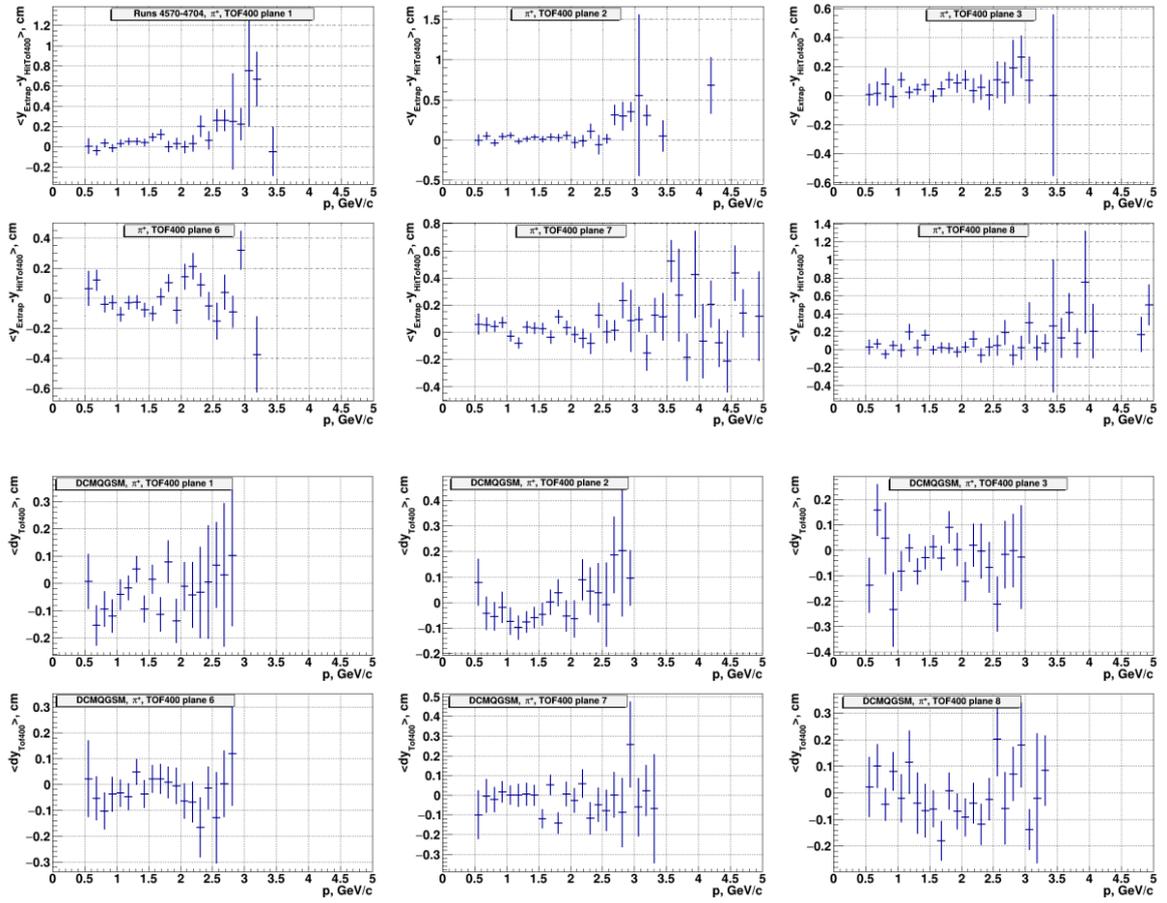
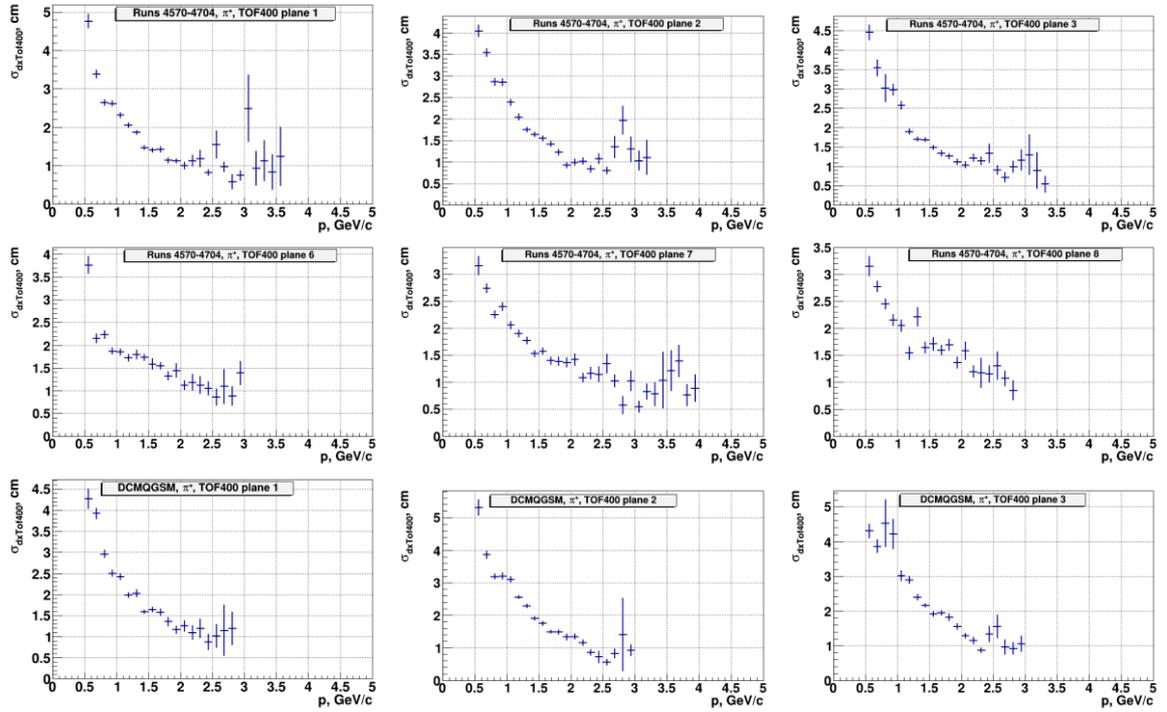


Fig. 7b. Mean values of residuals of ToF-400 hits in the Y projection with respect to reconstructed positive tracks in dependence on the particle momentum: upper 6 plots - experimental data, lower 6 plots - simulated tracks.



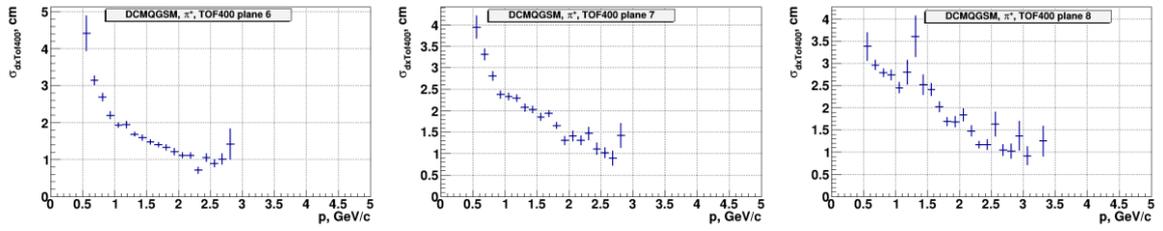


Fig. 7c. Sigma of residuals of ToF-400 hits in the X projection with respect to reconstructed positive tracks in dependence on the particle momentum: upper 6 plots - experimental data, lower 6 plots - simulated tracks.

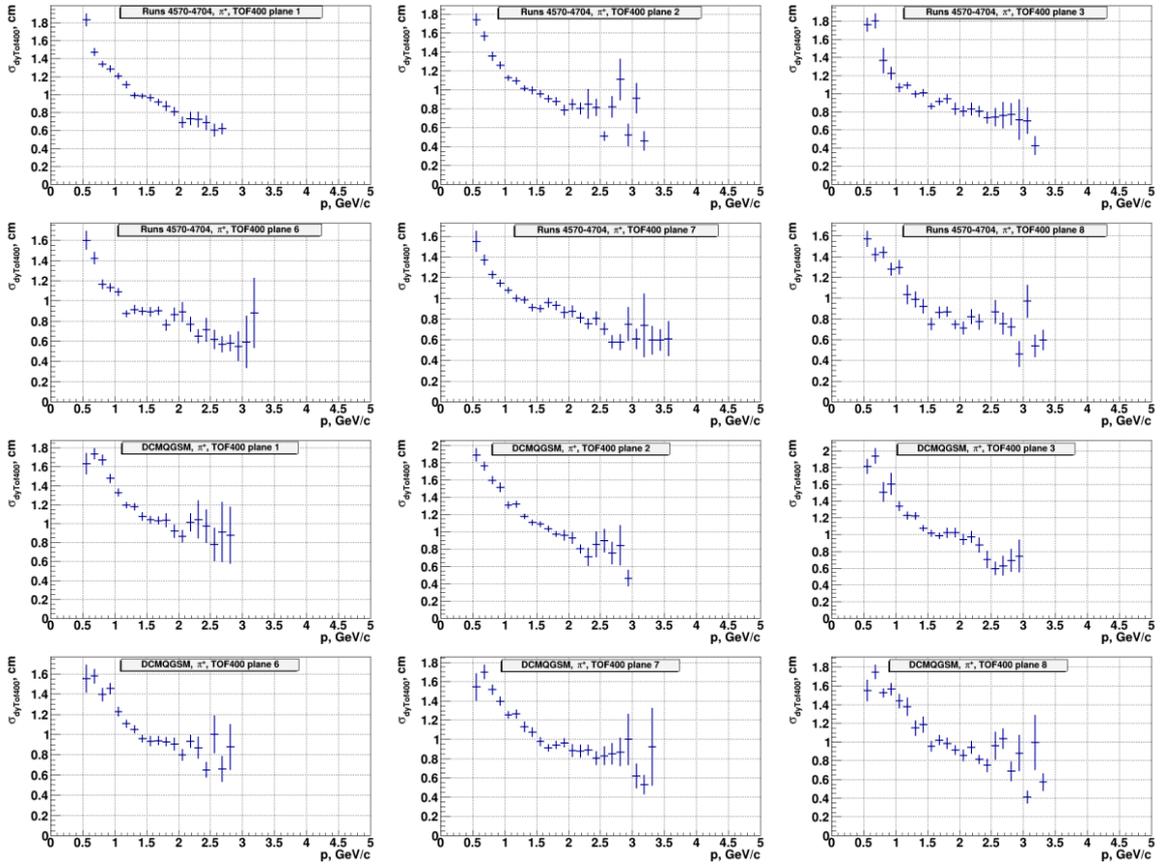
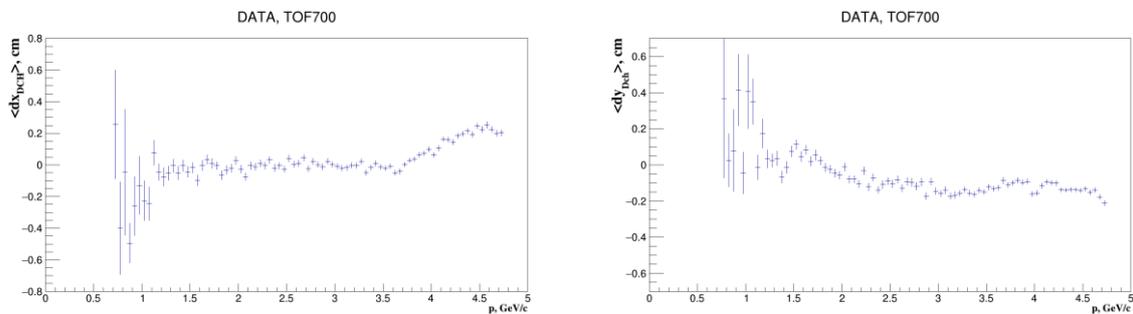


Fig. 7d. Sigma of residuals of ToF-400 hits in the Y projection with respect to reconstructed positive tracks in dependence on the particle momentum: upper 6 plots - experimental data, lower 6 plots - simulated tracks.



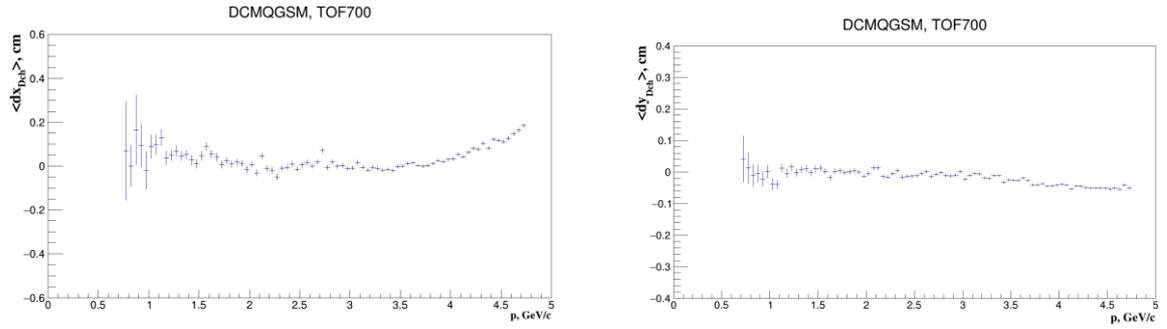


Fig. 8a. ToF-700 data and simulation: Mean values of residuals of DCH hits in X and Y projections with respect to reconstructed positive tracks in dependence on the particle momentum: upper plots experimental data, lower plots – simulated tracks.

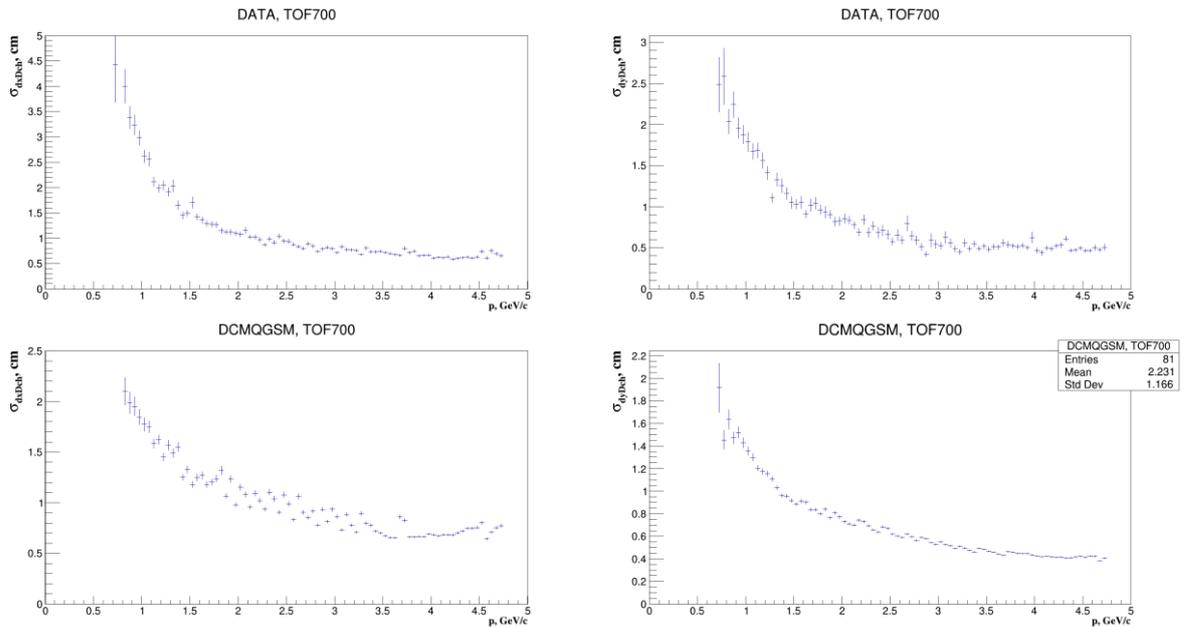


Fig. 8b. ToF-700 data and simulation: Sigma of residuals of DCH hits in the X and Y projections with respect to reconstructed positive tracks in dependence on the particle momentum: upper plots - experimental data, lower plots – simulated tracks.

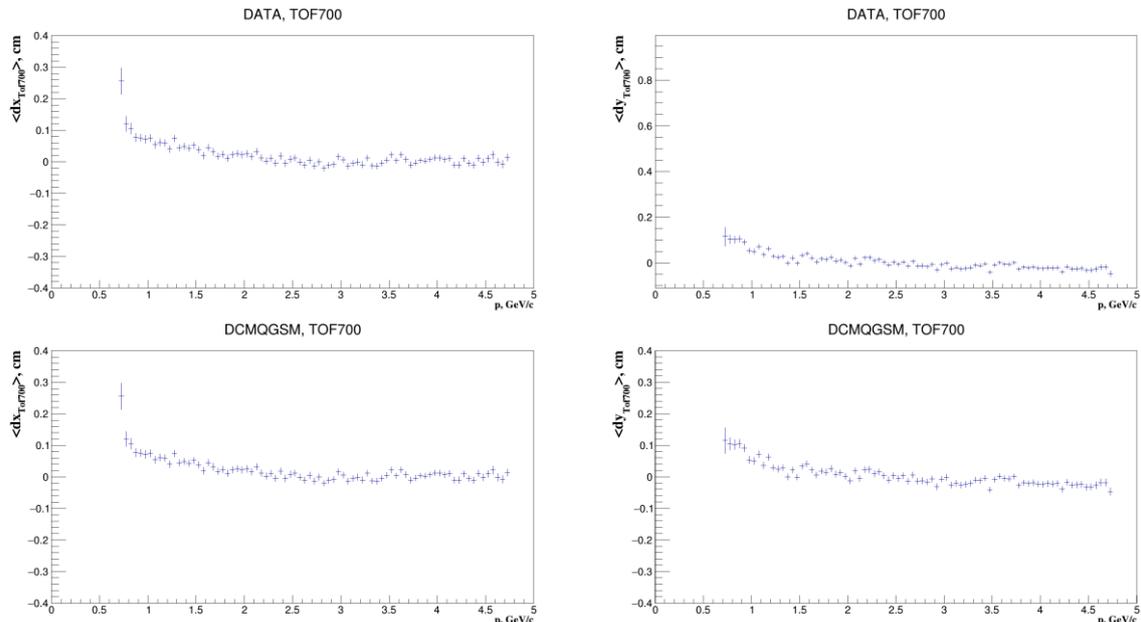


Fig. 9a. Mean values of residuals of ToF-700 hits in the X and Y projections with respect to

reconstructed positive tracks in dependence on the particle momentum: upper plots - experimental data, lower plots - simulated tracks.

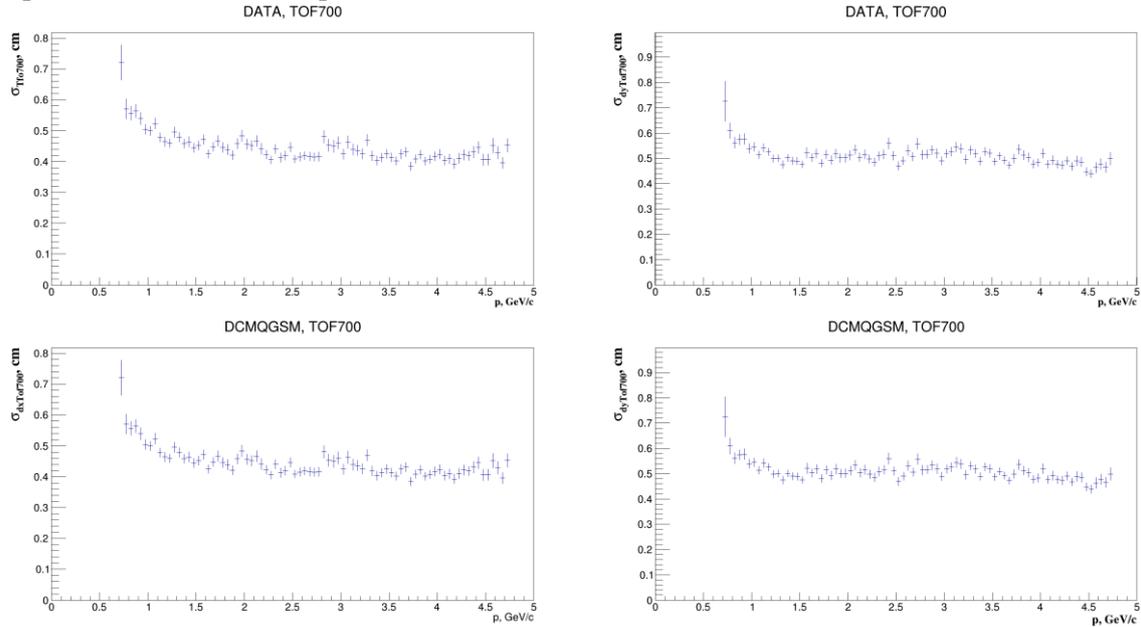


Fig. 9b. Sigma of residuals of ToF-700 hits in the X and Y projections with respect to reconstructed positive tracks in dependence on the particle momentum: upper plots - experimental data, lower plots - simulated tracks.

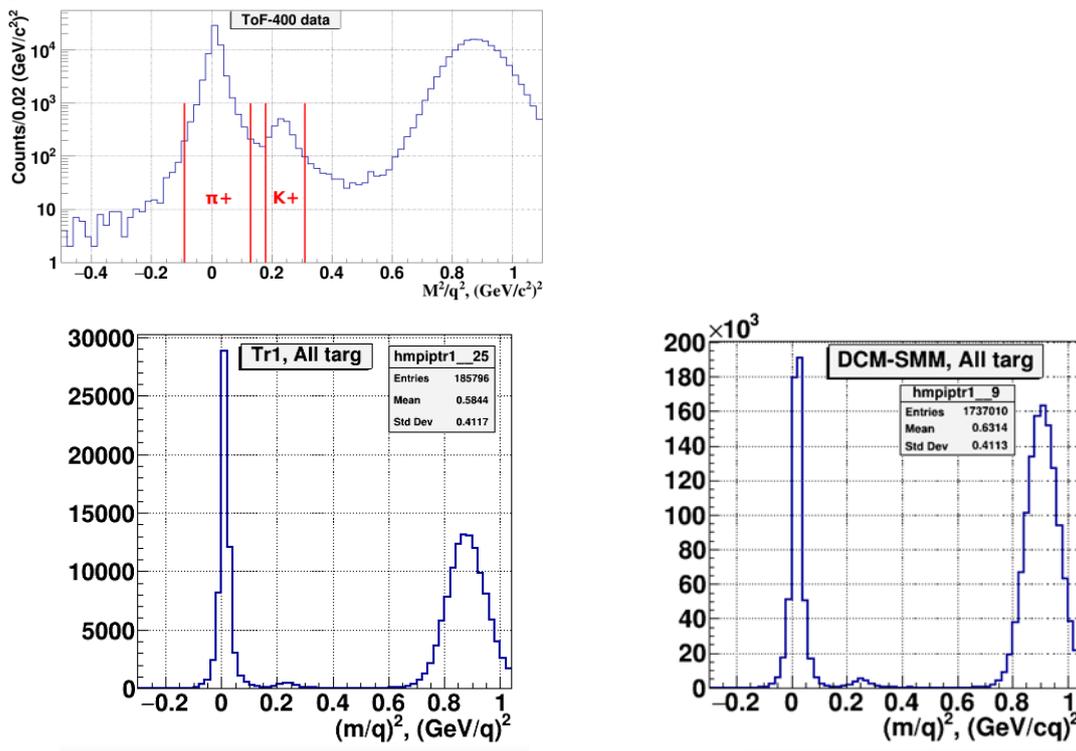


Fig. 10a. Spectrum of mass squared of particles identified in ToF-400 in Ar+A interactions at 3.2 AGeV argon beam energy: left) experimental events, right) simulated events.

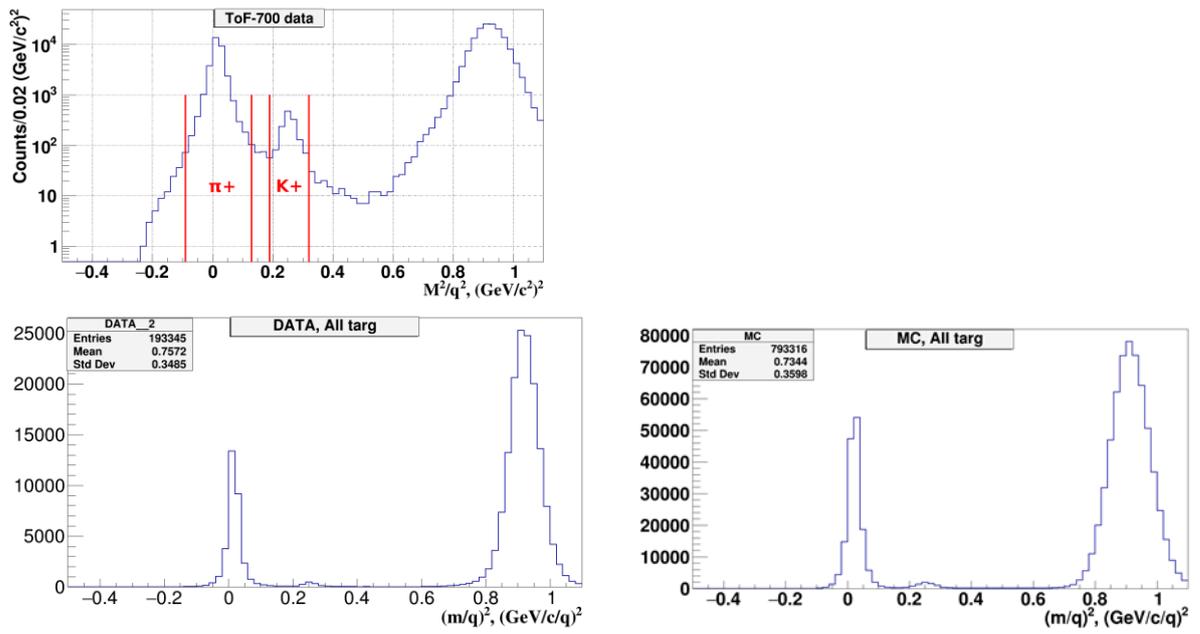


Fig. 10b. Spectrum of mass squared of particles identified in ToF-700 in Ar+A interactions at 3.2 AGeV argon beam energy: left) experimental events, right) simulated events.

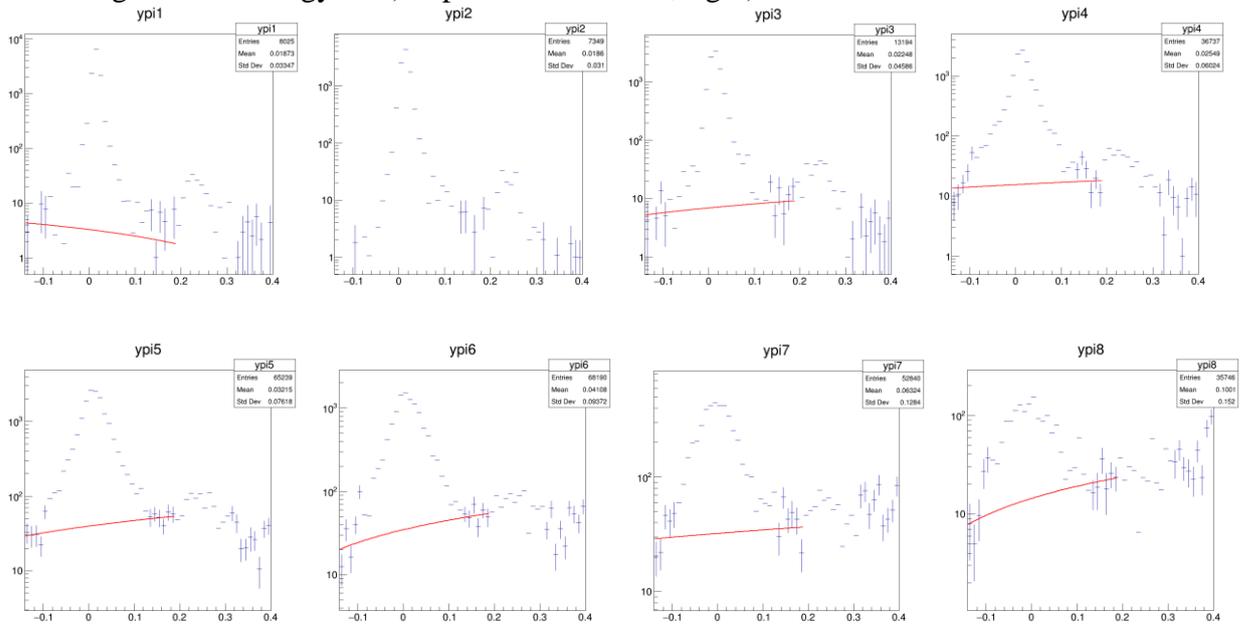


Fig. 10c. Spectrum of mass squared in bins of y of π^+ identified in ToF-400 in Ar+Cu interactions: background subtraction by the linear fit described in the text.

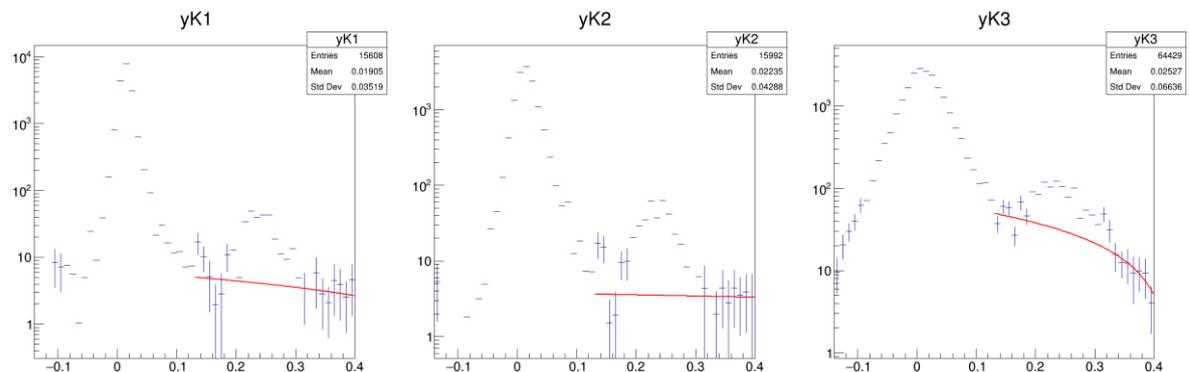


Fig. 10d. Spectrum of mass squared in bins of y of K^+ identified in ToF-400 in Ar+Cu interactions: background subtraction by the linear fit described in the text.

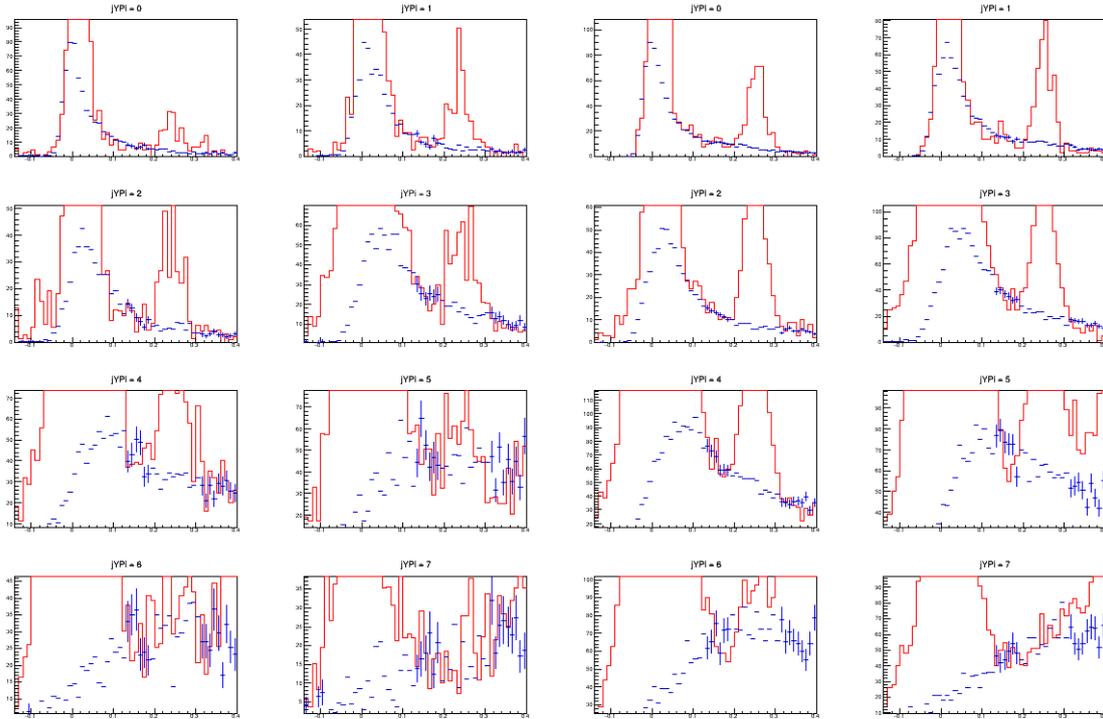


Fig. 10e. Spectrum of mass squared in bins of y of π^+ identified in ToF-400 in Ar+Sn interactions at 3.2 AGeV argon beam energy: left) experimental events, right) simulated events. Background (blue histogram) is taken from mixed events and normalized to the red signal histogram in the mass squared range between the π^+ and K^+ peaks.

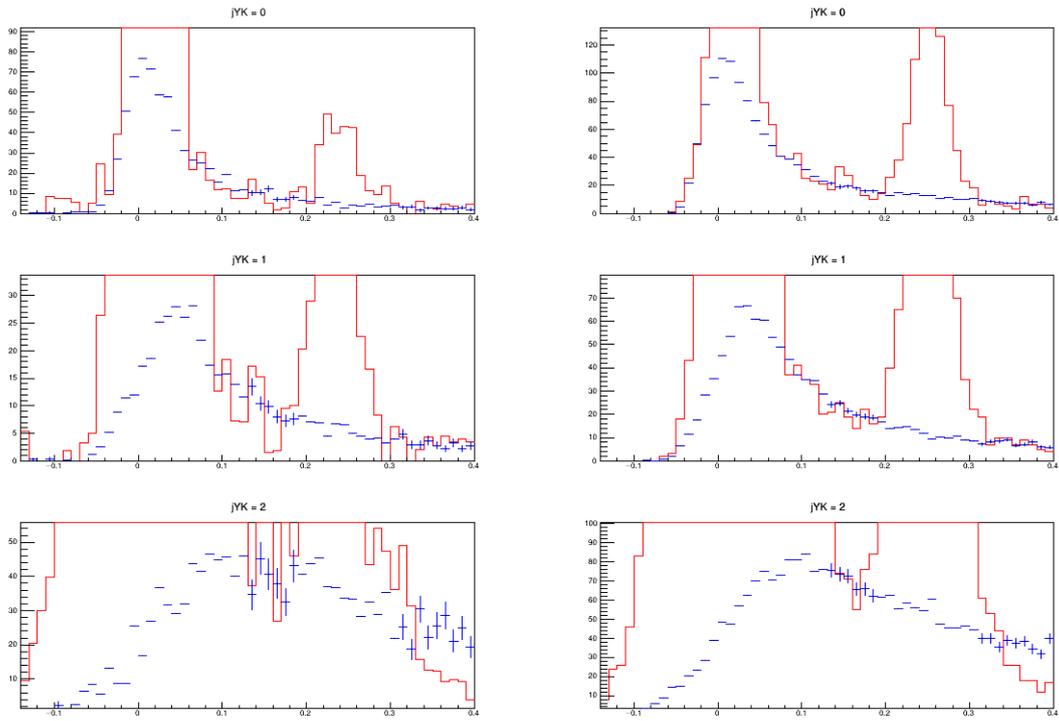


Fig. 10f. Spectrum of mass squared in bins of y of K^+ identified in ToF-400 in Ar+Sn interactions: left) experimental events, right) simulated events. Background (blue histogram) is taken from mixed events and normalized to the red signal histogram in the mass squared range below and above the K^+ peak.

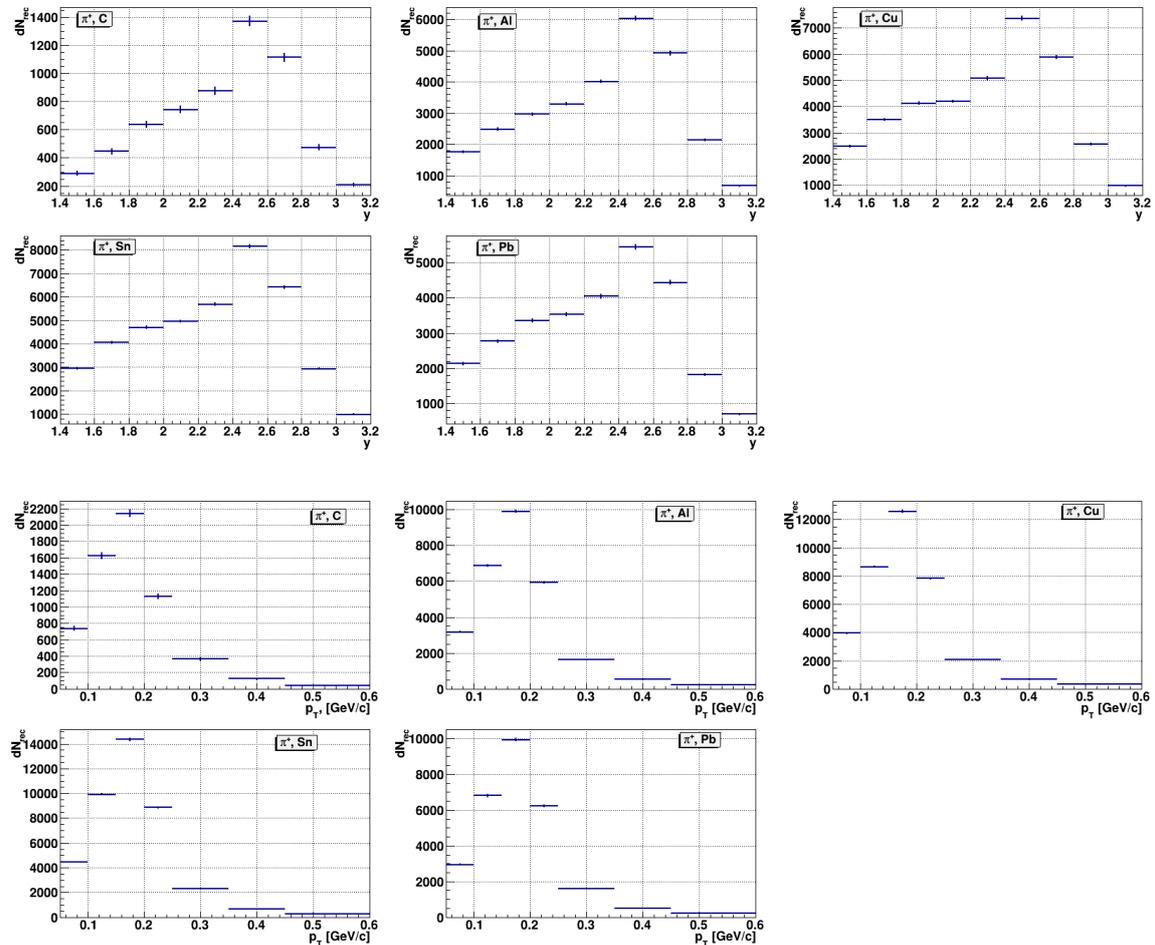


Fig.11a. Number of reconstructed π^+ in ToF-400 in interactions of 3.2 AGeV argon beam with C, Al, Cu, Sn, Pb targets in bins of y_{lab} (upper plots) and p_T (lower plots).

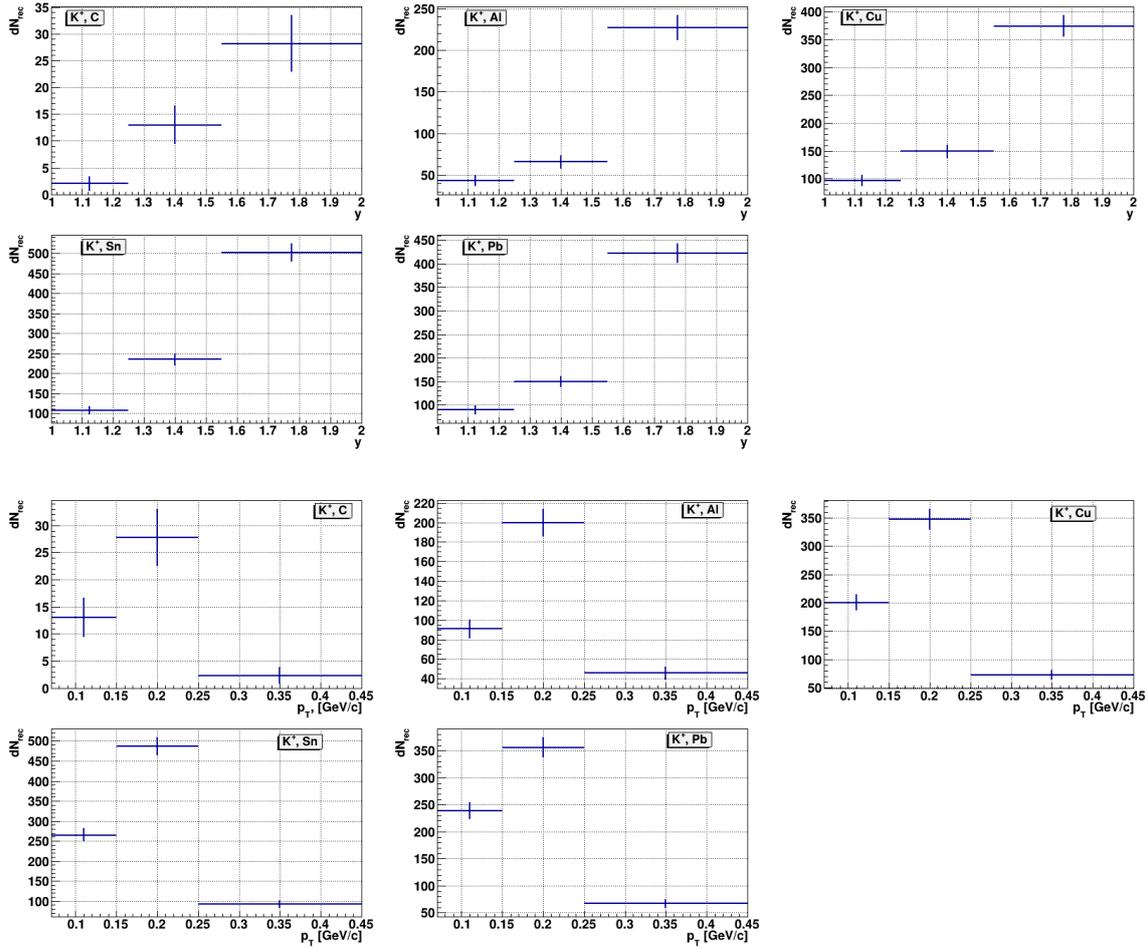


Fig.11b. Number of reconstructed K^+ in ToF-400 in interactions of 3.2 AGeV argon beam with C, Al, Cu, Sn, Pb targets in bins of y_{lab} (upper plots) and p_T (lower plots).

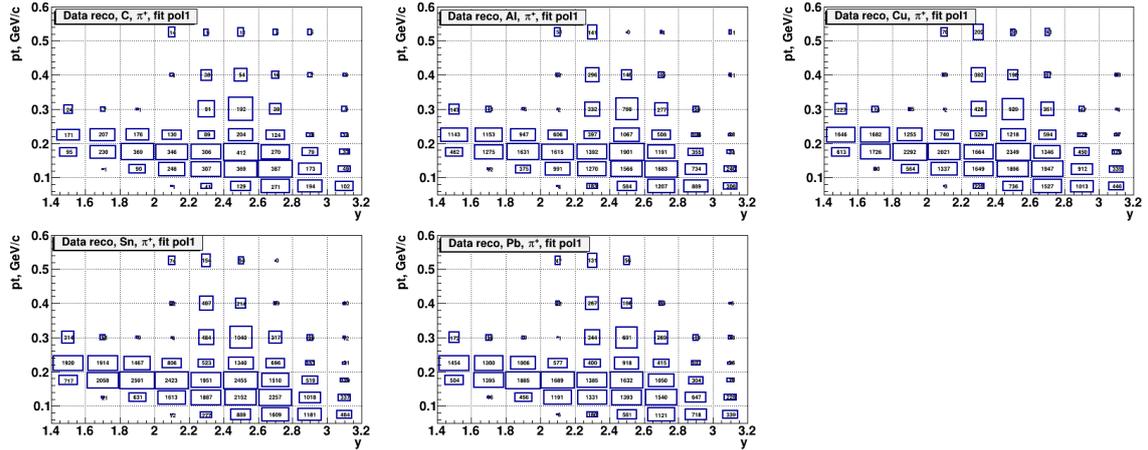


Fig.11c. Number of reconstructed π^+ in ToF-400 in interactions of 3.2 AGeV argon beam with C, Al, Cu, Sn, Pb targets in bins of (y_{lab}, p_T) .

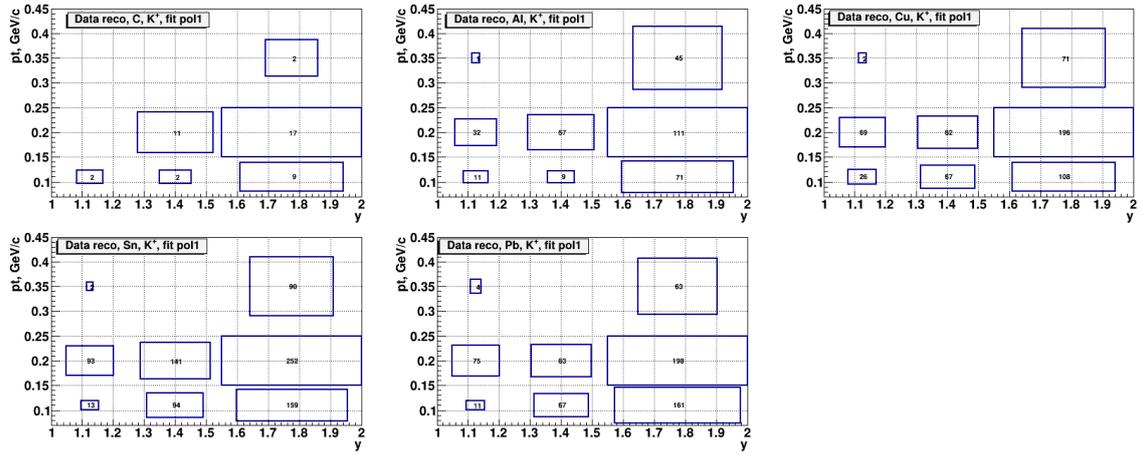


Fig.11d. Number of reconstructed K^+ in ToF-400 in interactions of 3.2 AGeV argon beam with C, Al, Cu, Sn, Pb targets in bins of (y_{lab}, p_T) .

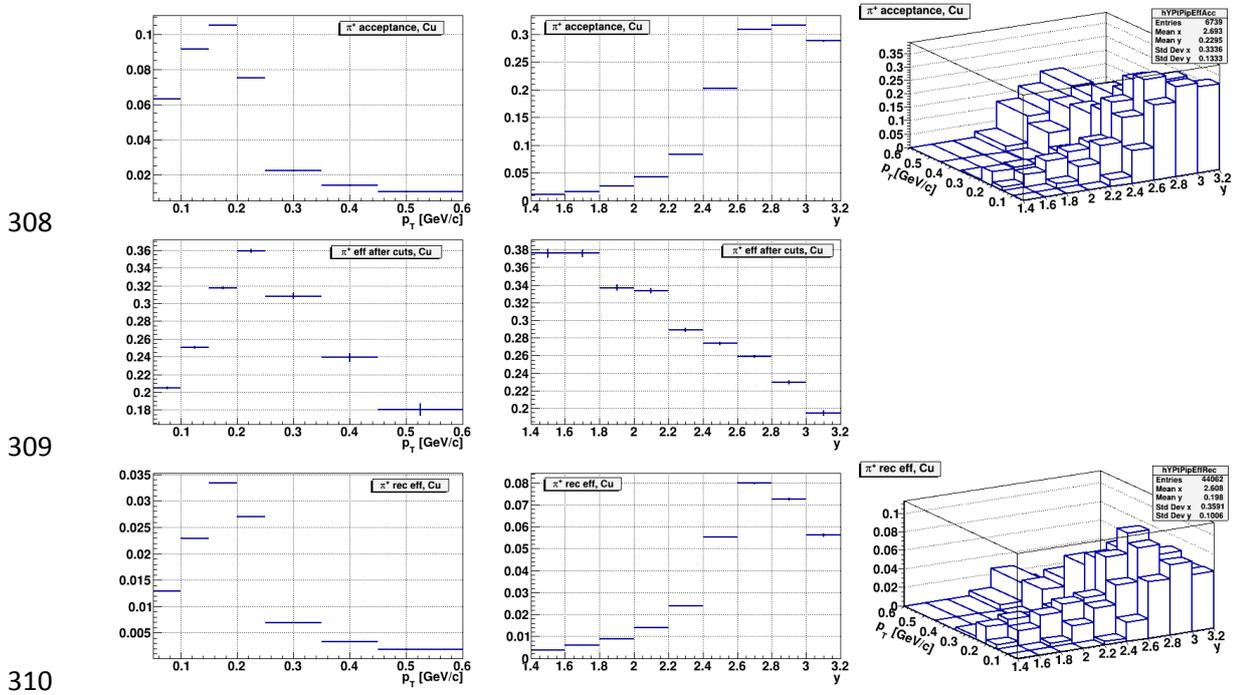
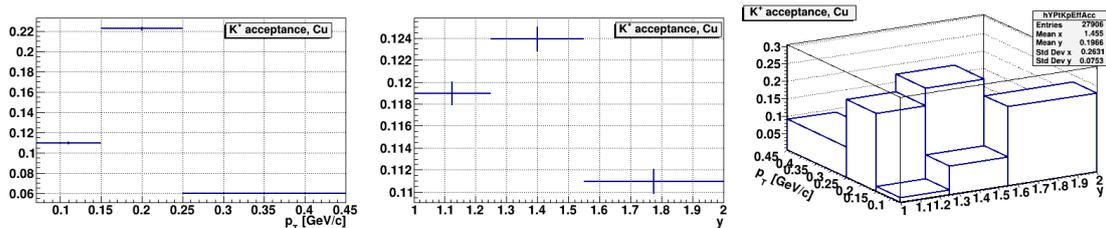


Fig.12a. π^+ geometrical acceptance (upper plots); efficiency of reconstruction of accepted π^+ after applying kinematic and spatial cuts (middle plots) and full reconstruction efficiency (lower plots) shown in bins of rapidity y_{lab} in the laboratory system, transverse momentum p_T and (y, p_T) . Results are shown for Ar+Cu interactions at 3.2 AGeV argon beam energy.



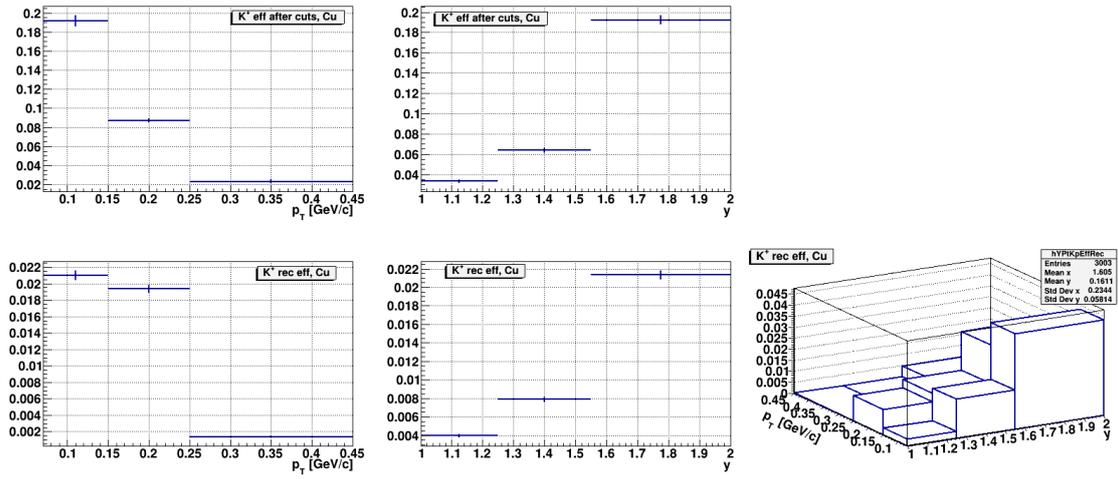


Fig.12b. K^+ geometrical acceptance (upper plots); efficiency of reconstruction of accepted K^+ after applying kinematic and spatial cuts (middle plots) and full reconstruction efficiency (lower plots) shown in bins of rapidity y_{lab} in the laboratory system, transverse momentum p_T and (y, p_T) . Results are shown for Ar+Cu interactions at 3.2 AGeV argon beam energy.

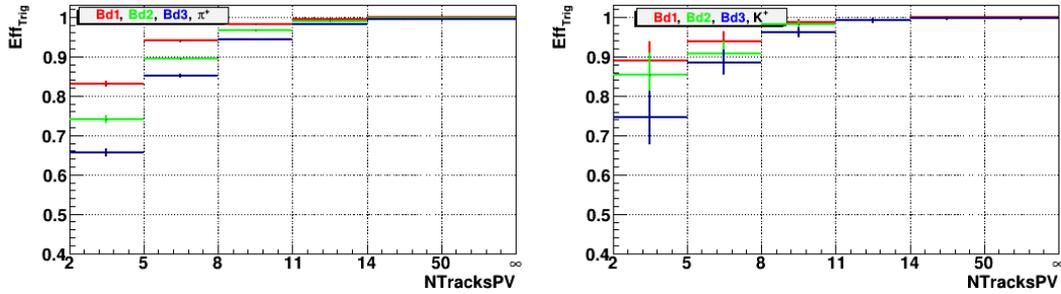


Fig.13a. Dependence of the BD trigger efficiency on the number of tracks from the primary vertex calculated in events with π^+ (left plot) and K^+ (right plot) produced in interactions of the argon beam with the *C, Al, Cu, Sn, Pb* targets.

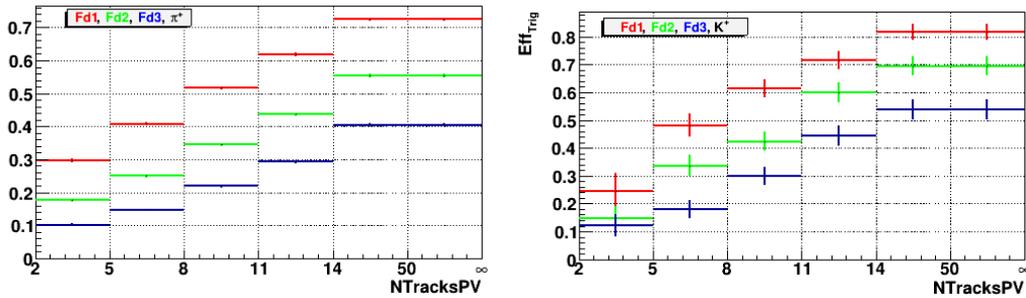
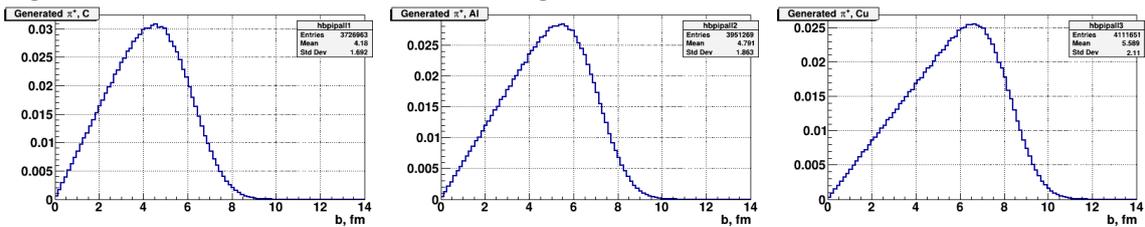


Fig.13b. Dependence of the FD trigger efficiency on the number of tracks from the primary vertex calculated in events with π^+ (left plot) and K^+ (right plot) produced in interactions of the argon beam with the *C, Al, Cu, Sn, Pb* targets.



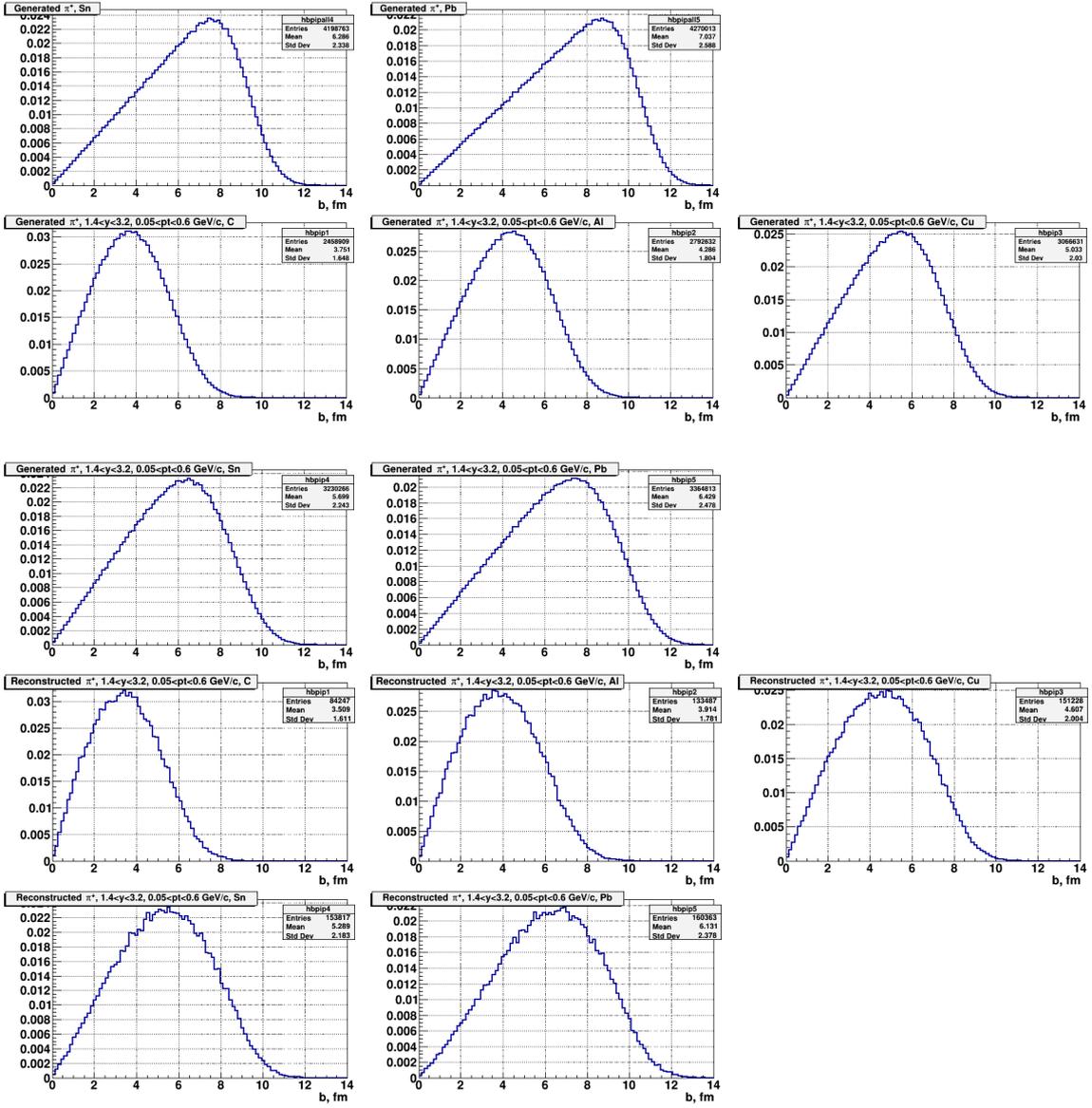
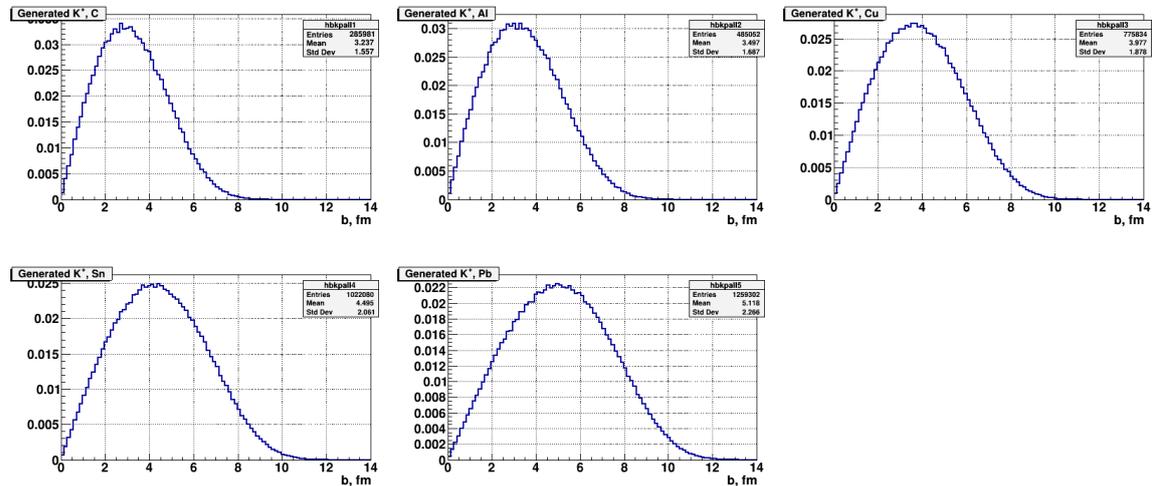


Fig. 14a. Impact parameter distributions of minimum bias interactions of 3.2 AGeV argon beam with C, Al, Cu, Pb targets, with π^+ generated with the DCM-SMM model in the full kinematical range (upper plots). Impact parameter distribution of minimum bias events with π^+ generated with the DCM-SMM model in the kinematical range of the BM@N measurement (middle plots). Impact parameter distribution of DCM-SMM minimum bias events with reconstructed π^+ (lower plots).



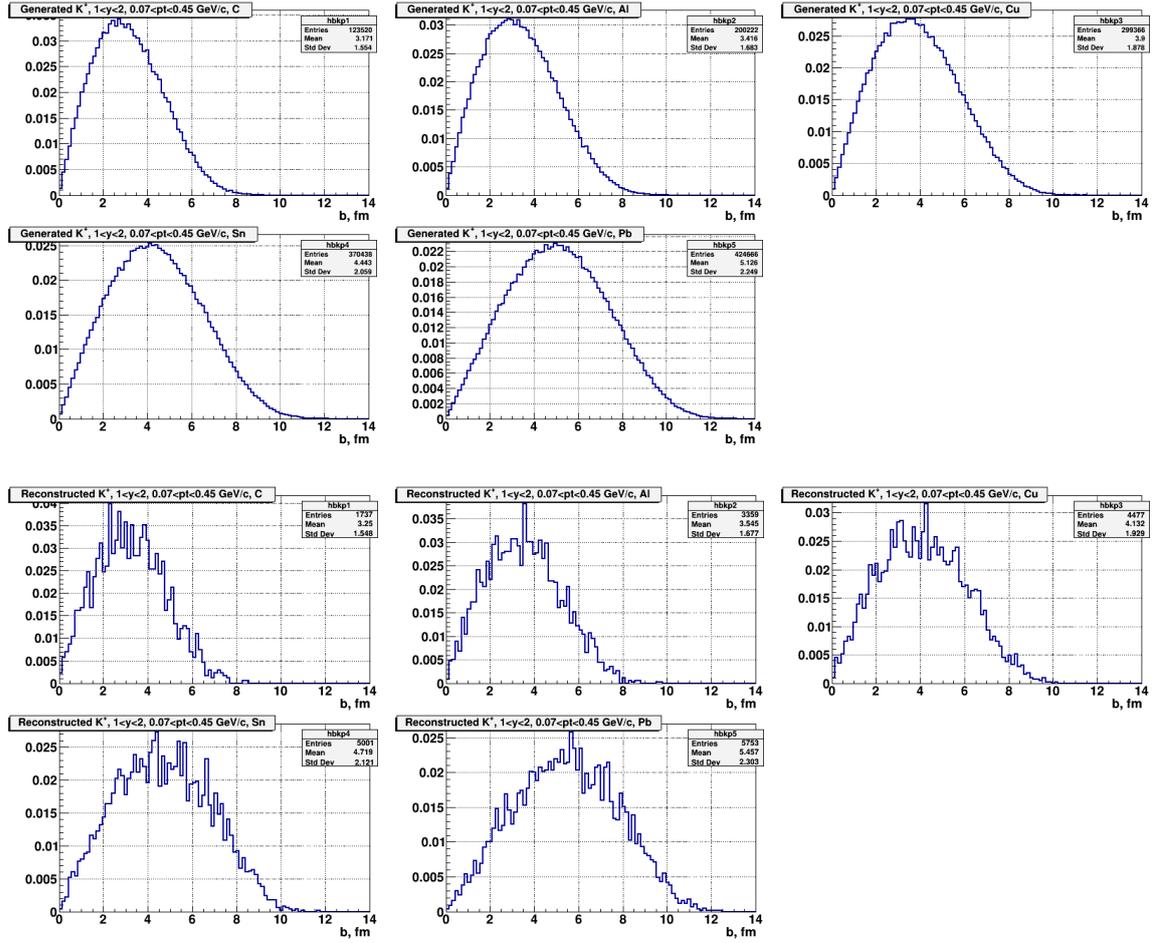


Fig. 14b. Impact parameter distributions of minimum bias interactions of 3.2 AGeV argon beam with C, Al, Cu, Pb targets, with K^+ generated with the DCM-SMM model in the full kinematical range (upper plots). Impact parameter distribution of minimum bias events with K^+ generated with the DCM-SMM model in the kinematical range of the BM@N measurement (middle plots). Impact parameter distribution of DCM-SMM minimum bias events with reconstructed K^+ (lower plots).

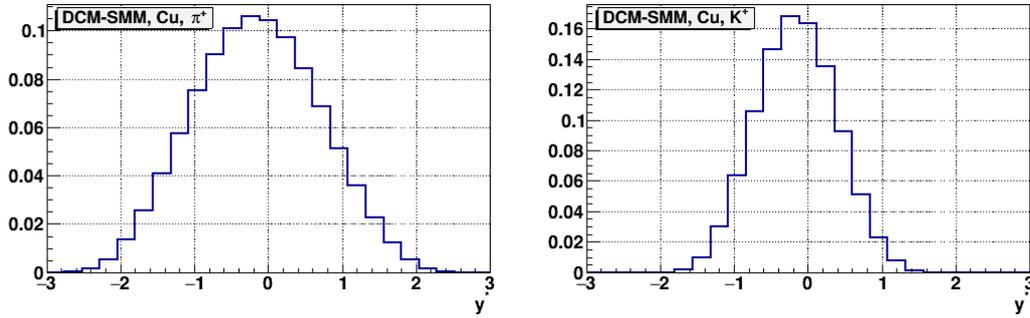


Fig.14c. Rapidity spectra of π^+ (left plot) and K^+ (right plot) in minimum bias interactions of the 3.2 AGeV argon beam with the Cu target, generated with the DCM-SMM model.

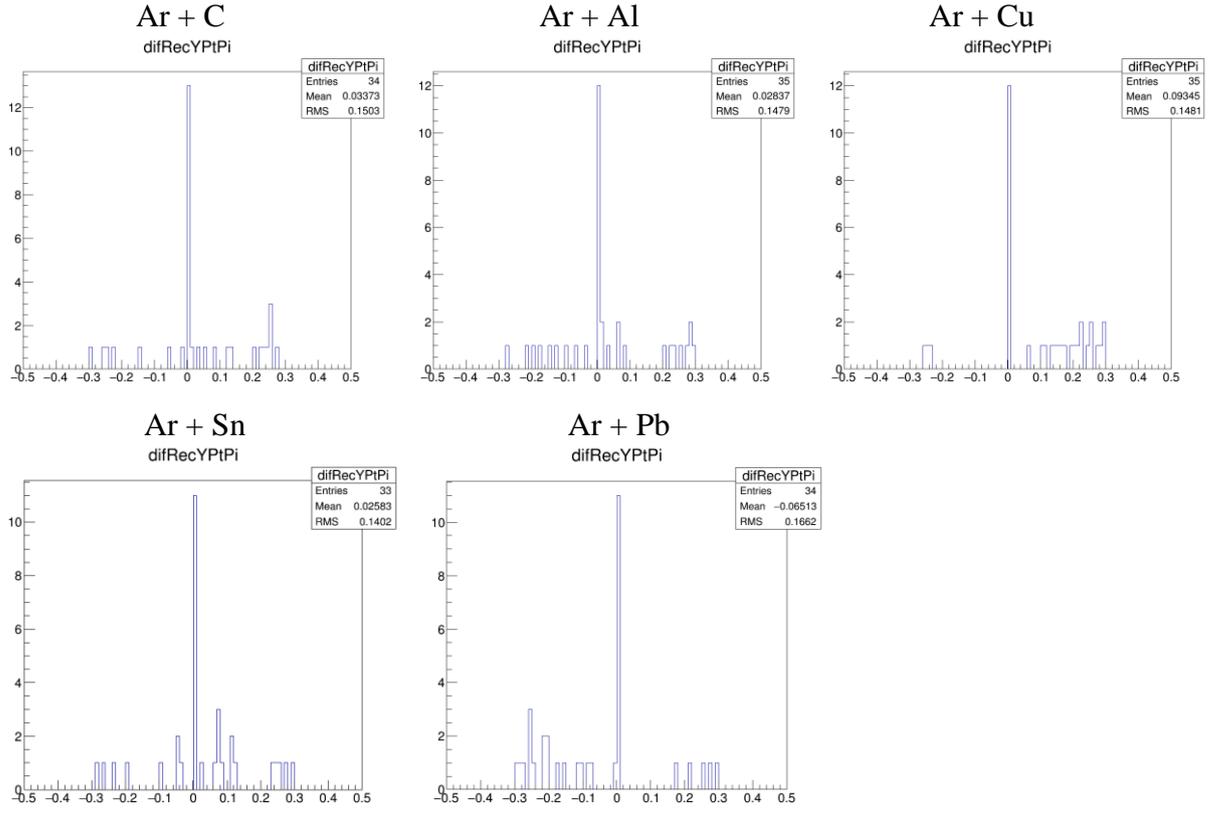


Fig.14d. Relative difference of π^+ yields measured in (y, p_T) bins using ToF-400 and ToF-700 data in Ar + C, Al, Cu, Sn, Pb interactions.

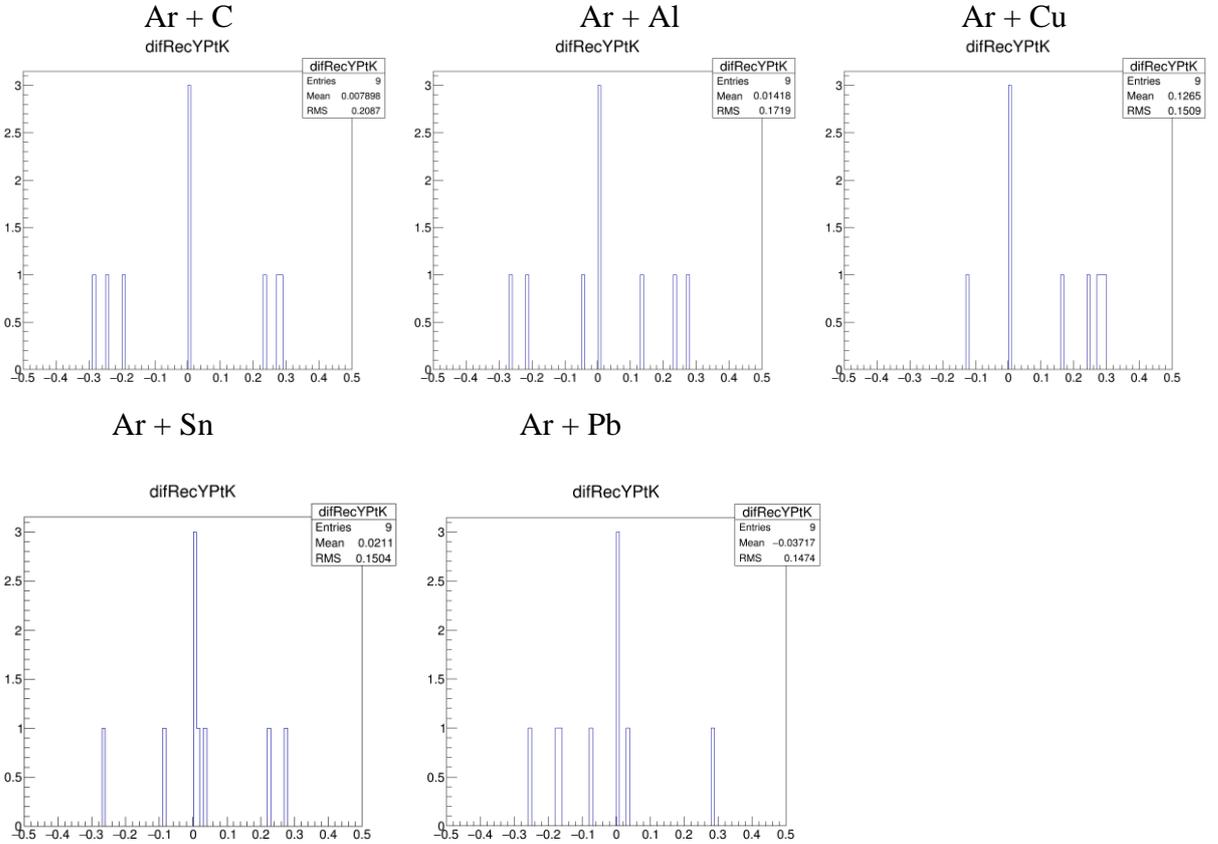


Fig.14e. Relative difference of K^+ yields measured in 9 (y, p_T) bins using ToF-400 and ToF-700 data in Ar + C, Al, Cu, Sn, Pb interactions.

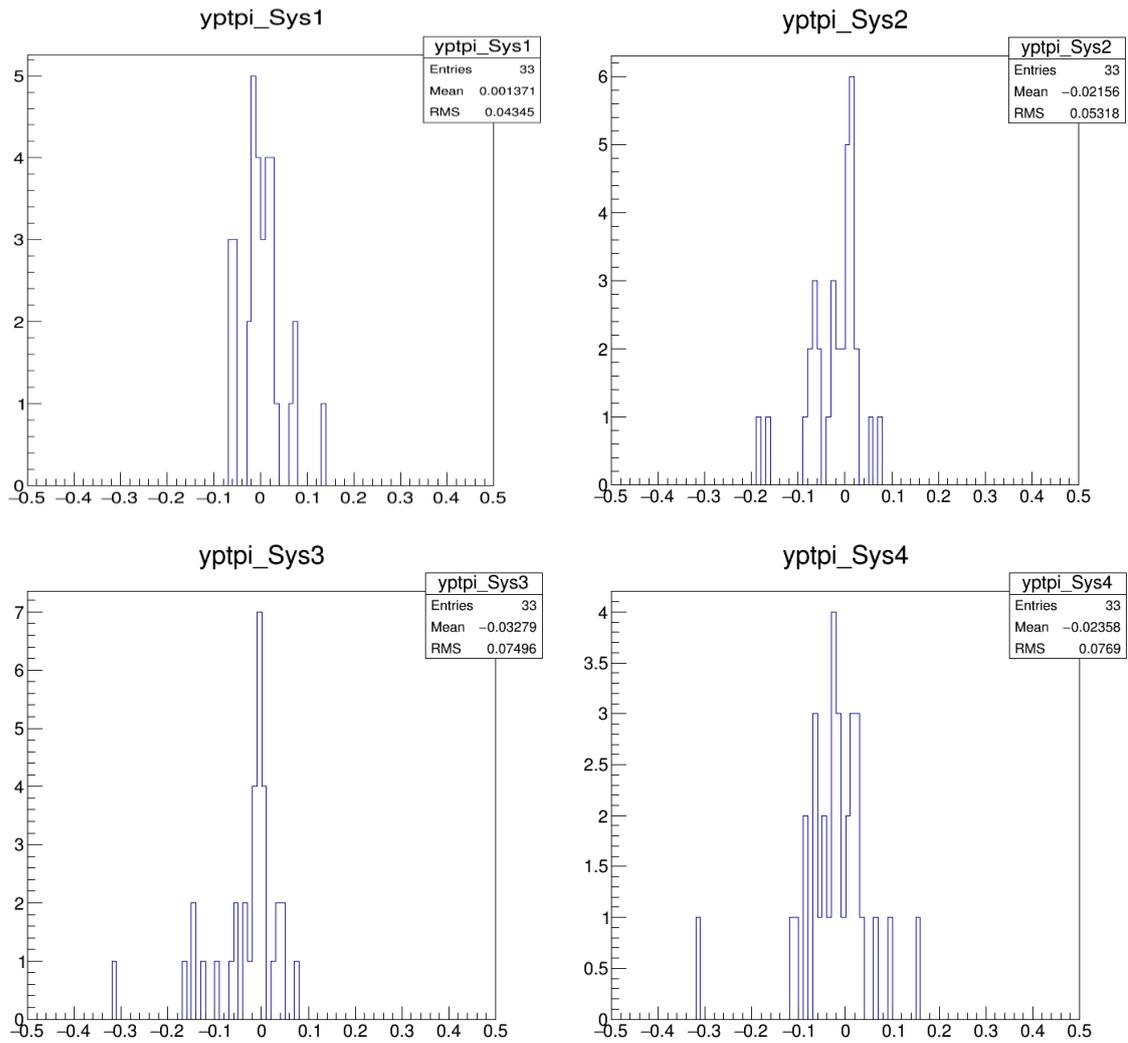
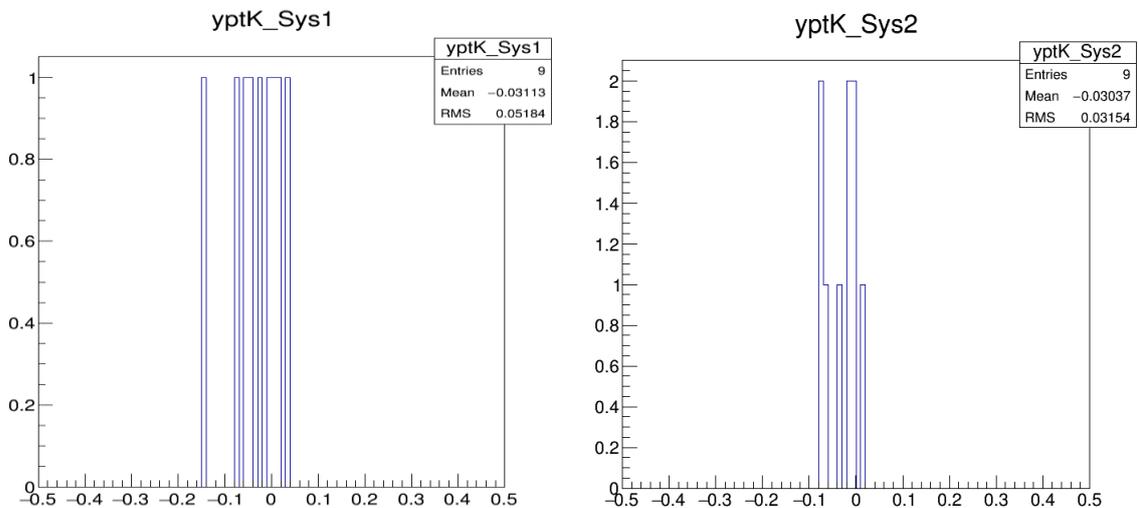


Fig.14f. Relative difference of π^+ yields in (y, p_T) bins, originated from different sources of systematic uncertainties in Ar + Sn data: Sys1 – trigger efficiency in dependence on the vertex track multiplicity and vertex position, Sys2 – X,Y vertex distribution in Data vs MC, Sys3 – method of K+ background subtraction (linear fit instead of “mixed event” method), Sys4 – data based BD trigger vs all BD+FD data.



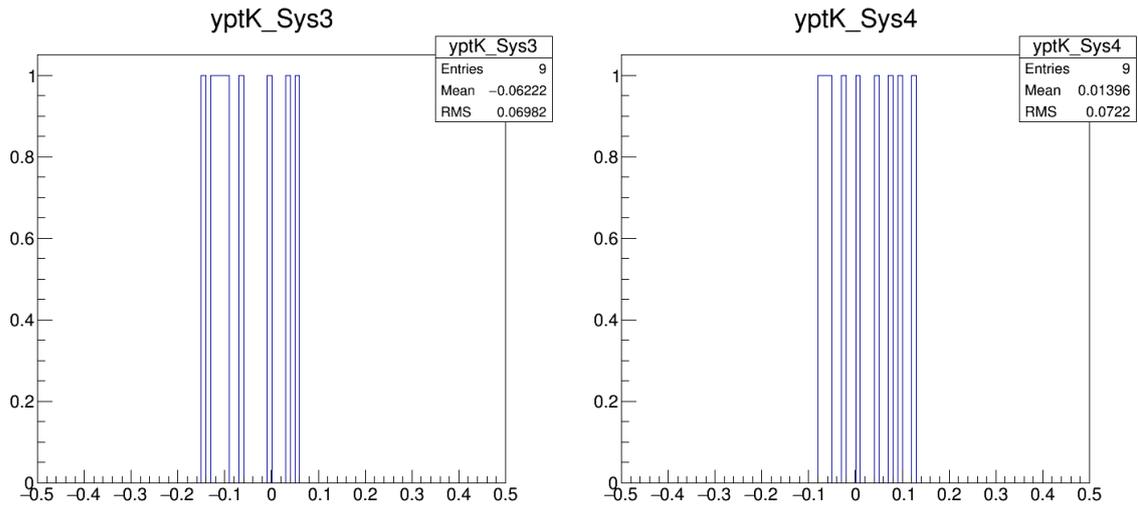
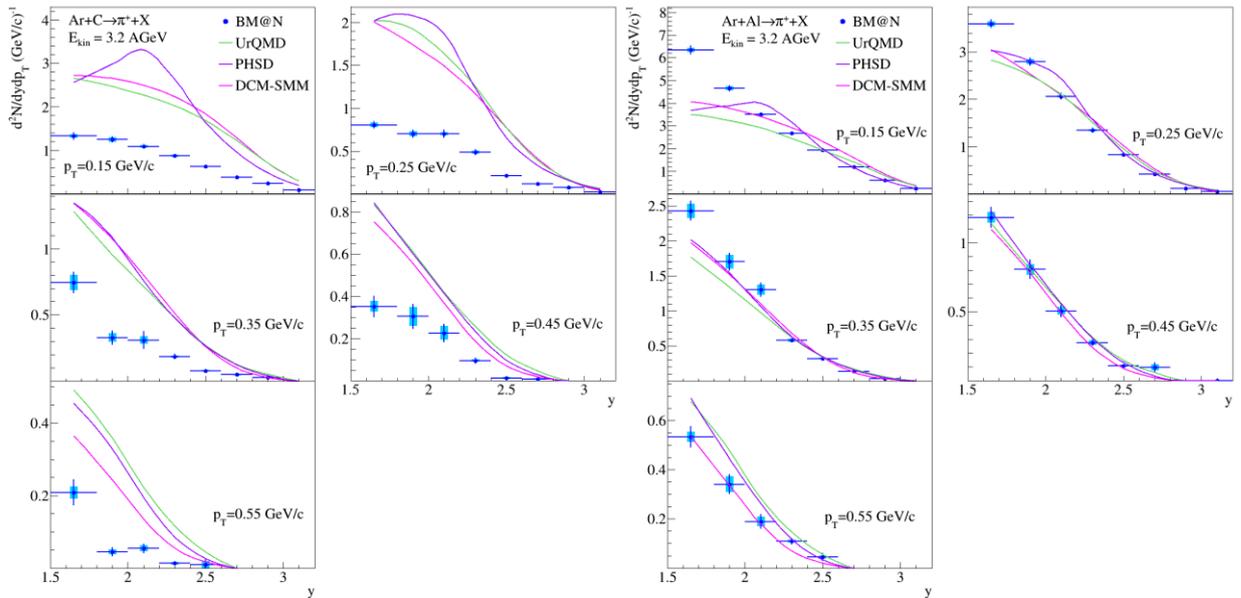


Fig.14i. Relative difference of K⁺ yields in 9 (y, p_T) bins, originated from different sources of systematic uncertainties in Ar + Sn data: Sys1 – trigger efficiency in dependence on the vertex track multiplicity and vertex position, Sys2 – X, Y vertex distribution, Sys3 – method of K⁺ background subtraction (linear fit instead of “mixed event” method), Sys4 – data based BD trigger vs all BD+FD data.



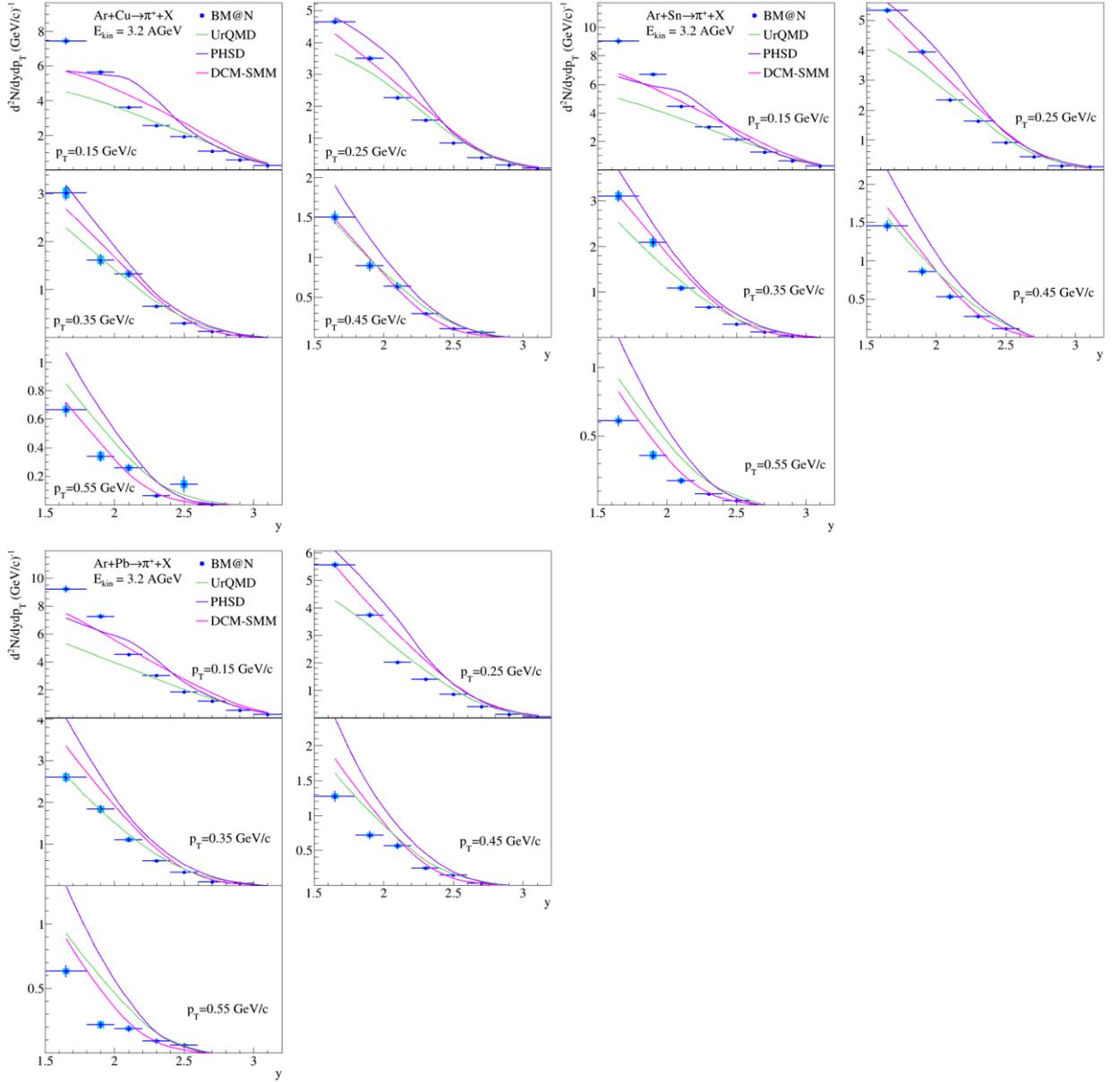


Fig. 15a. Reconstructed rapidity y spectra of π^+ measured in bins of p_T in minimum bias $Ar+C$, $Ar+Al$, $Ar+Cu$, $Ar+Sn$, $Ar+Pb$ interactions at 3.2 AGeV argon beam energy. The error bars represent the statistical errors, the boxes show the systematic errors. Predictions of the DCM-SMM, UrQMD and PHSD models are shown as rose, green and magenta lines.

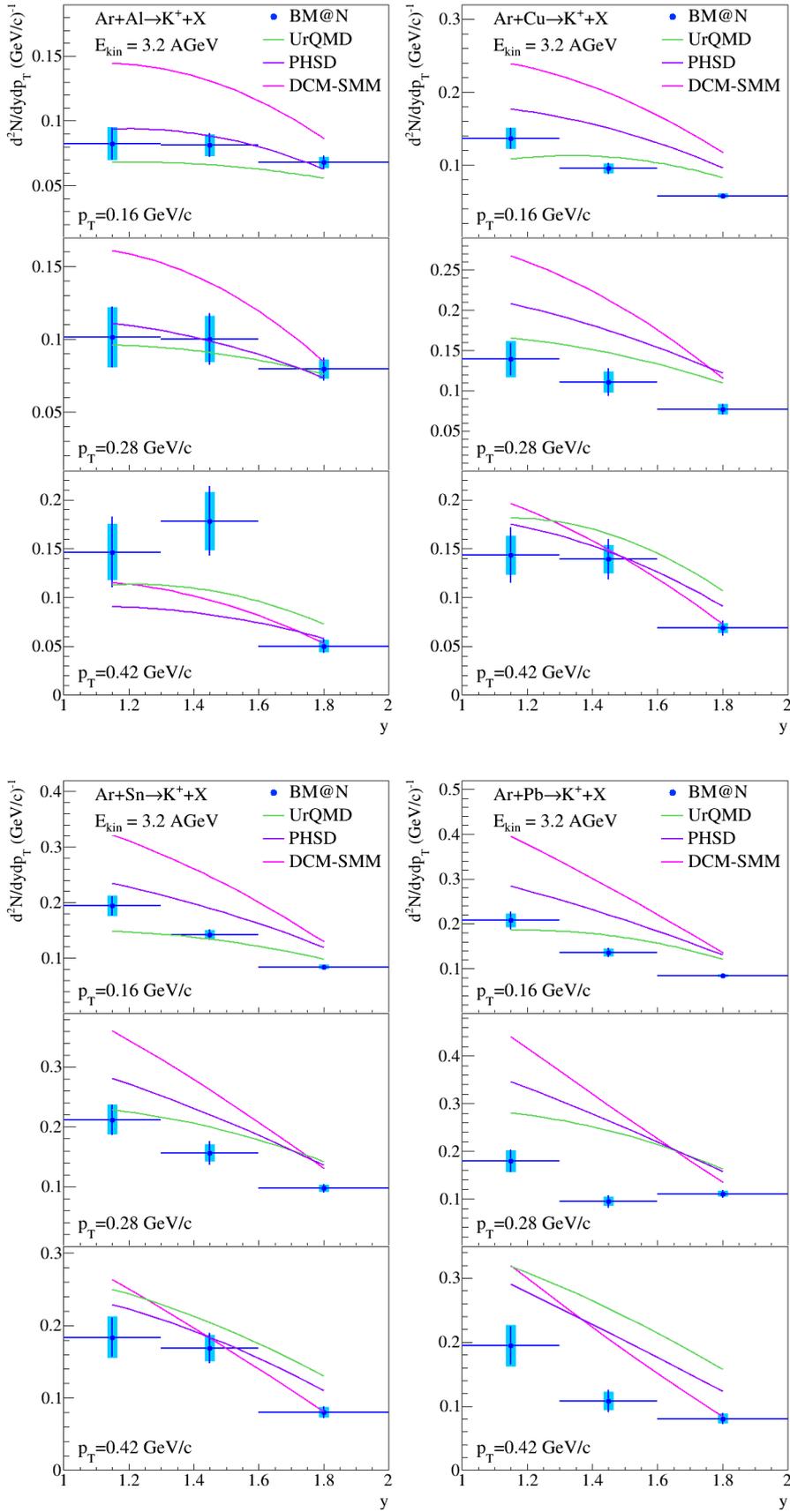
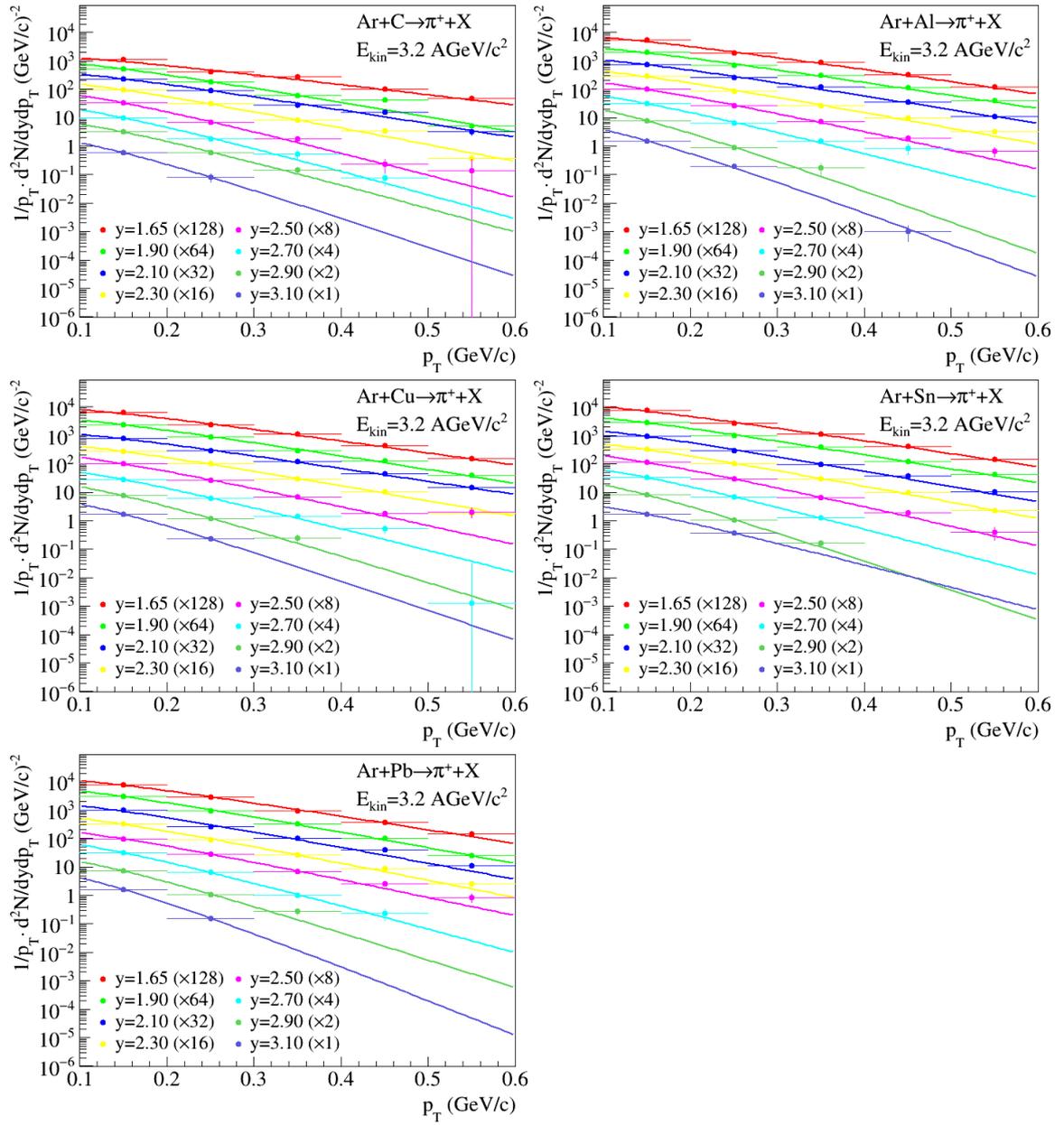
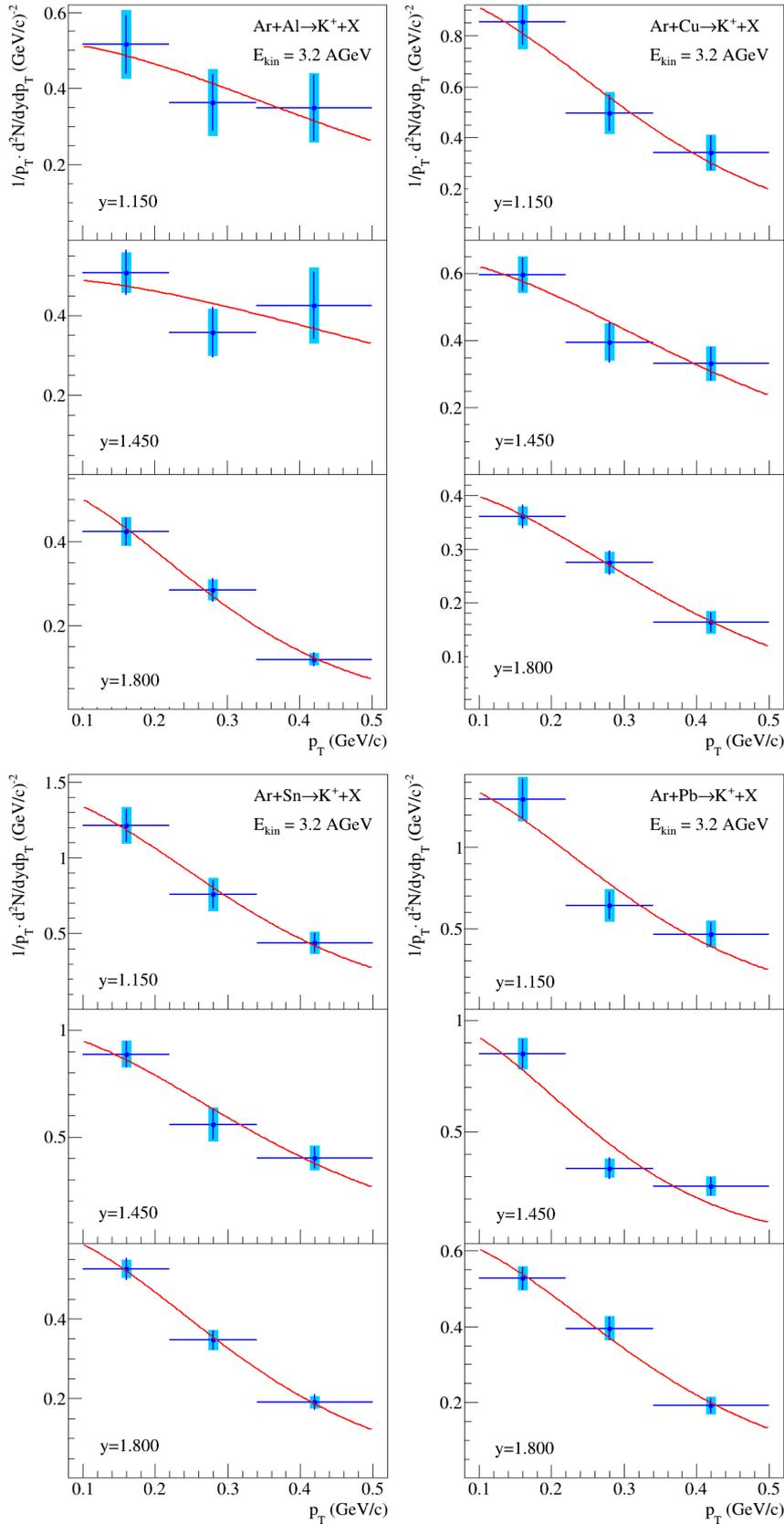


Fig. 15b. Reconstructed rapidity y spectra of K^+ measured in bins of p_T in minimum bias Ar+Al, Ar+Cu, Ar+Sn, Ar+Pb interactions at 3.2 AGeV argon beam energy. The error bars represent the statistical errors, the boxes show the systematic errors. Predictions of the DCM-SMM, UrQMD and PHSD models are shown as rose, green and magenta lines.



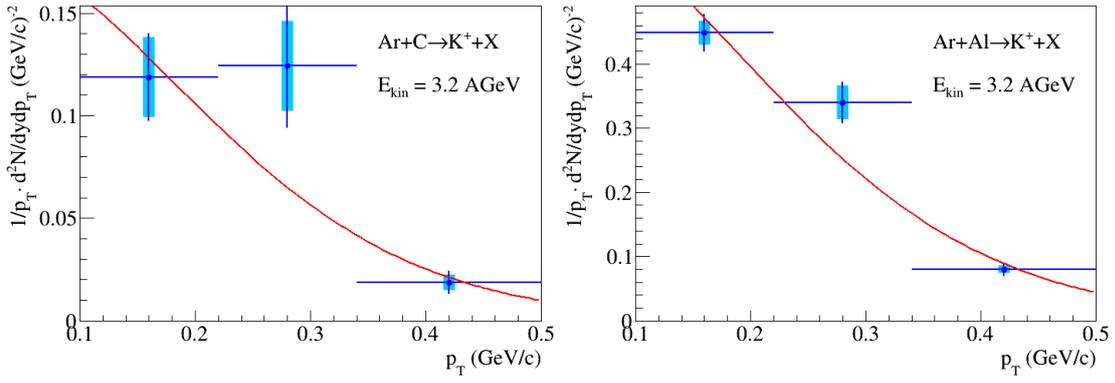
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Fig.16a. Reconstructed invariant transverse momentum p_T spectra of π^+ measured in bins of rapidity in minimum bias $Ar+C$, $Ar+Al$, $Ar+Cu$, $Ar+Sn$, $Ar+Pb$ interactions at 3.2 AGeV argon beam energy. Results of the fit described in the text are shown as colored lines.

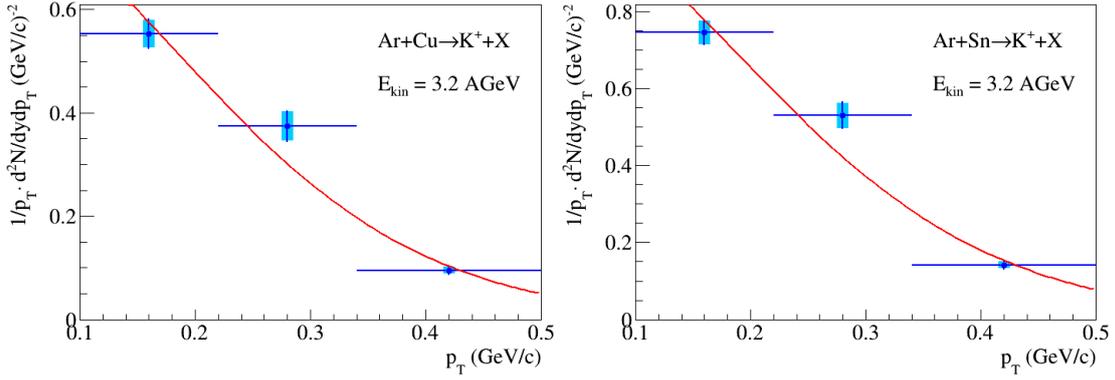


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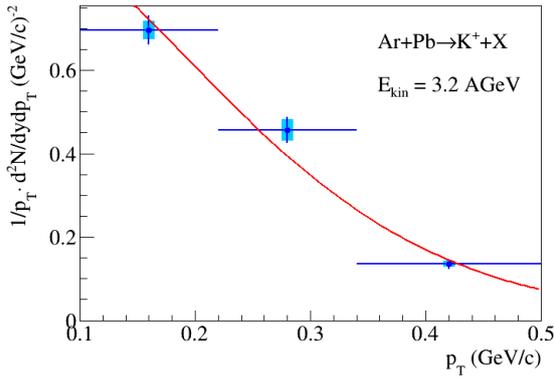
314 Fig.16b. Reconstructed invariant transverse momentum p_T spectra of K^+ in minimum bias
 315 Ar+Al, Ar+Cu, Ar+Sn, Ar+Pb interactions at 3.2 AGeV argon beam energy. The error bars
 316 represent the statistical errors, the boxes show the systematic errors. Results of the fit described
 317 in the text are shown as lines.



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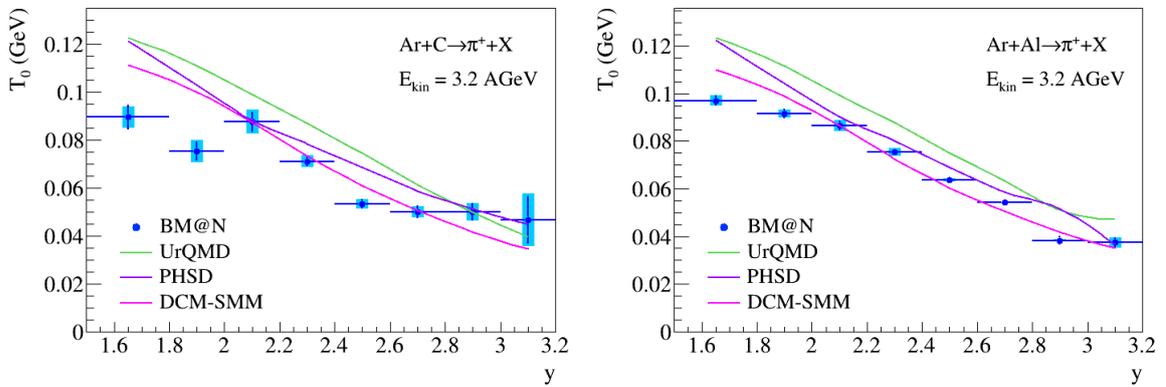
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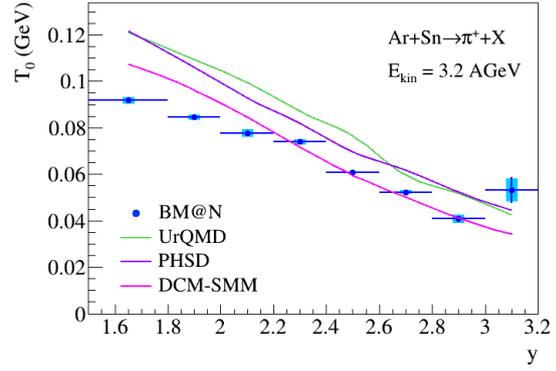
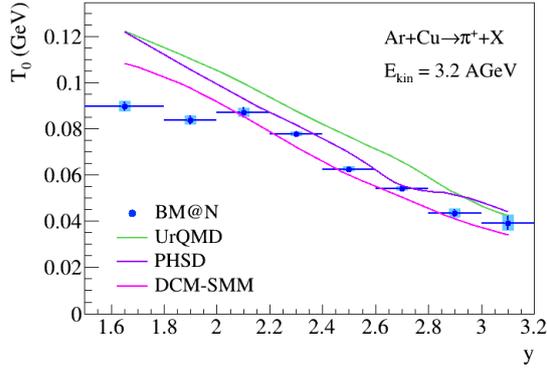
321

322 Fig.16c. Reconstructed invariant transverse momentum p_T spectra of K^+ in the measured
323 rapidity range in minimum bias A+C, Ar+Al, Ar+Cu, Ar+Sn, Ar+Pb interactions at 3.2 AGeV
324 argon beam energy. The error bars represent the statistical errors, the boxes show the systematic
325 errors. Results of the fit described in the text are shown as lines.

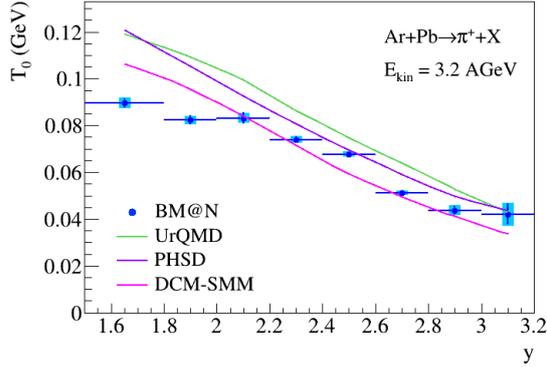
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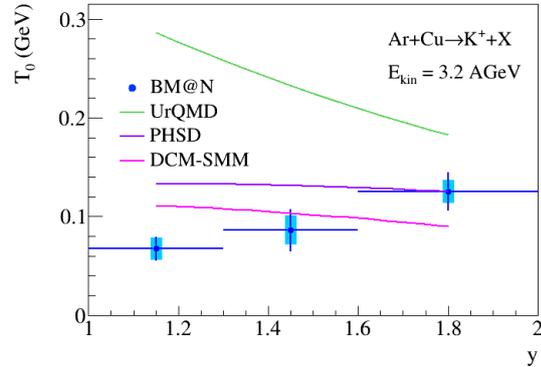
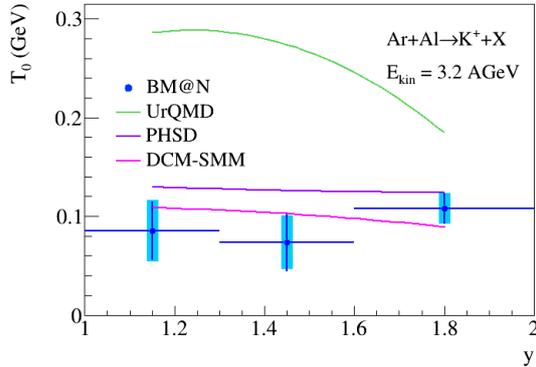


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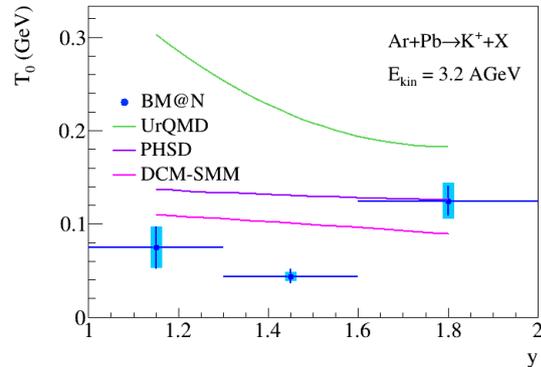
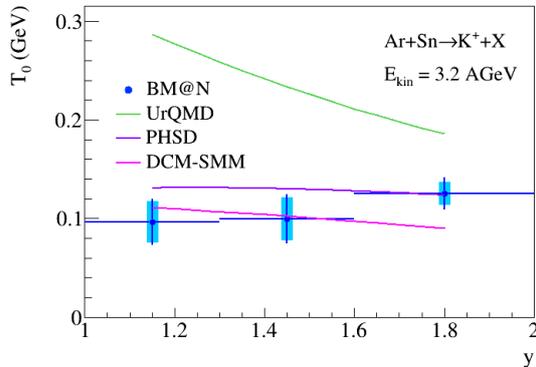


329

330 Fig17a. The y dependences of the inverse slope parameter T_0 of the π^+ invariant p_T spectra in
 331 $Ar+C$, $Ar+Al$, $Ar+Cu$, $Ar+Sn$, $Ar+Pb$ minimum bias interactions. The error bars represent the
 332 statistical errors, the boxes show the systematic errors. Predictions of the DCM-SMM, UrQMD
 333 and PHSD models are shown as rose, green and magenta lines.



334



335

336 Fig17b. The y dependences of the inverse slope parameter T_0 of the K^+ invariant p_T spectra in
 337 $Ar+Al$, $Ar+Cu$, $Ar+Sn$, $Ar+Pb$ minimum bias interactions. The error bars represent the statistical
 338 errors, the boxes show the systematic errors. Predictions of the DCM-SMM, UrQMD and PHSD
 339 models are shown as rose, green and magenta lines.