13th Collaboration Meeting of the BM@N Experiment at NICA

Analysis of Λ-hyperon production in carbon-nucleus run

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JOINT INSTITUTE FOR NUCLEAR RESEARCH

Physical motivation BM@N experiment

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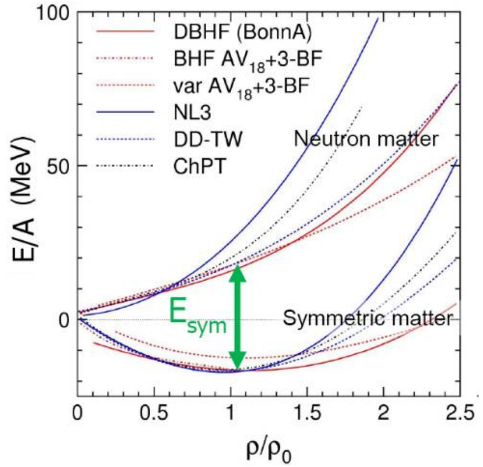
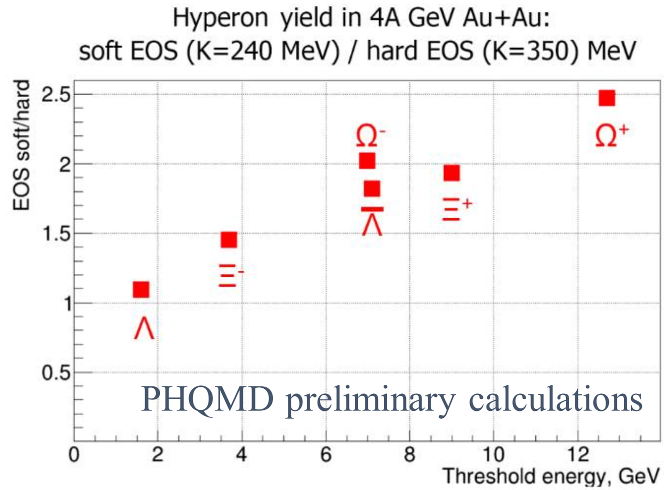
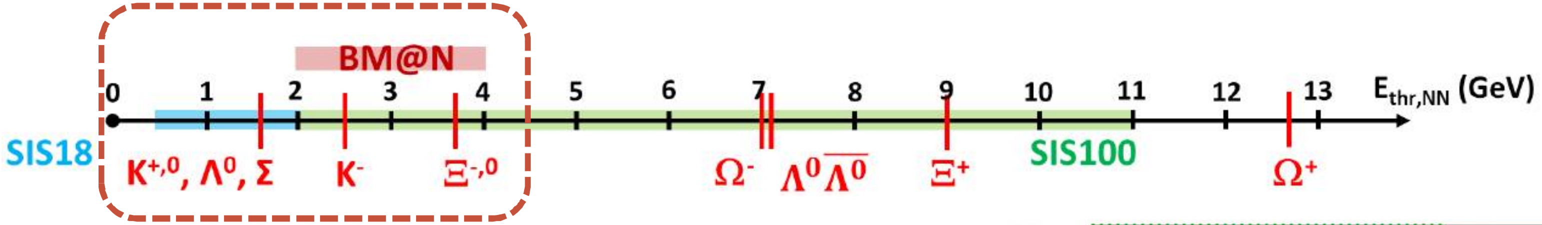
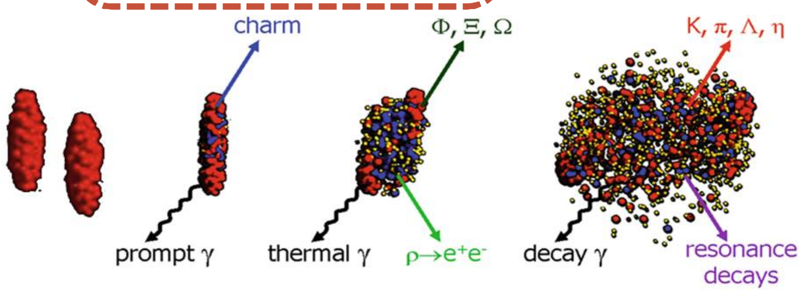


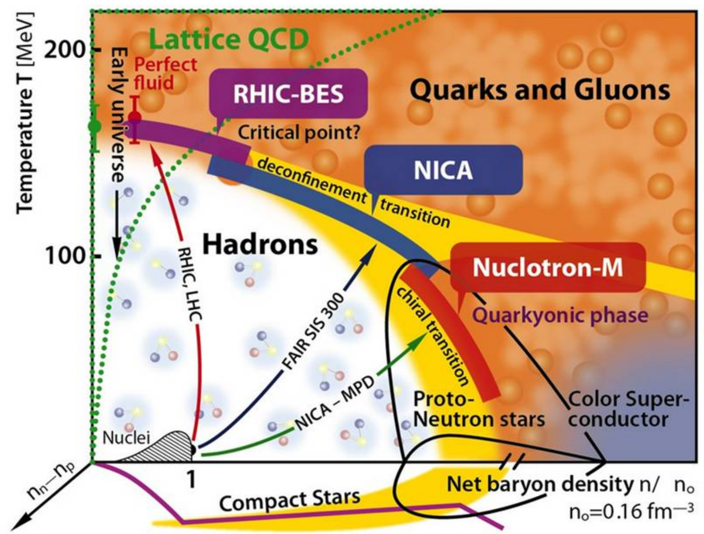


EoS study for symmetric matter at $\rho/\rho_0 = 3 - 5$, $\rho_0 = 0.16 fm^{-1}$:

- Elliptical flow of protons, mesons and hyperons;
- Sub-threshold production of strange mesons and hyperons extract nuclear;
- Incompressibility (K_{mn}) from the modeled data;







EoS: The relation between density, pressure, temperature, energy and isospin asymmetry:

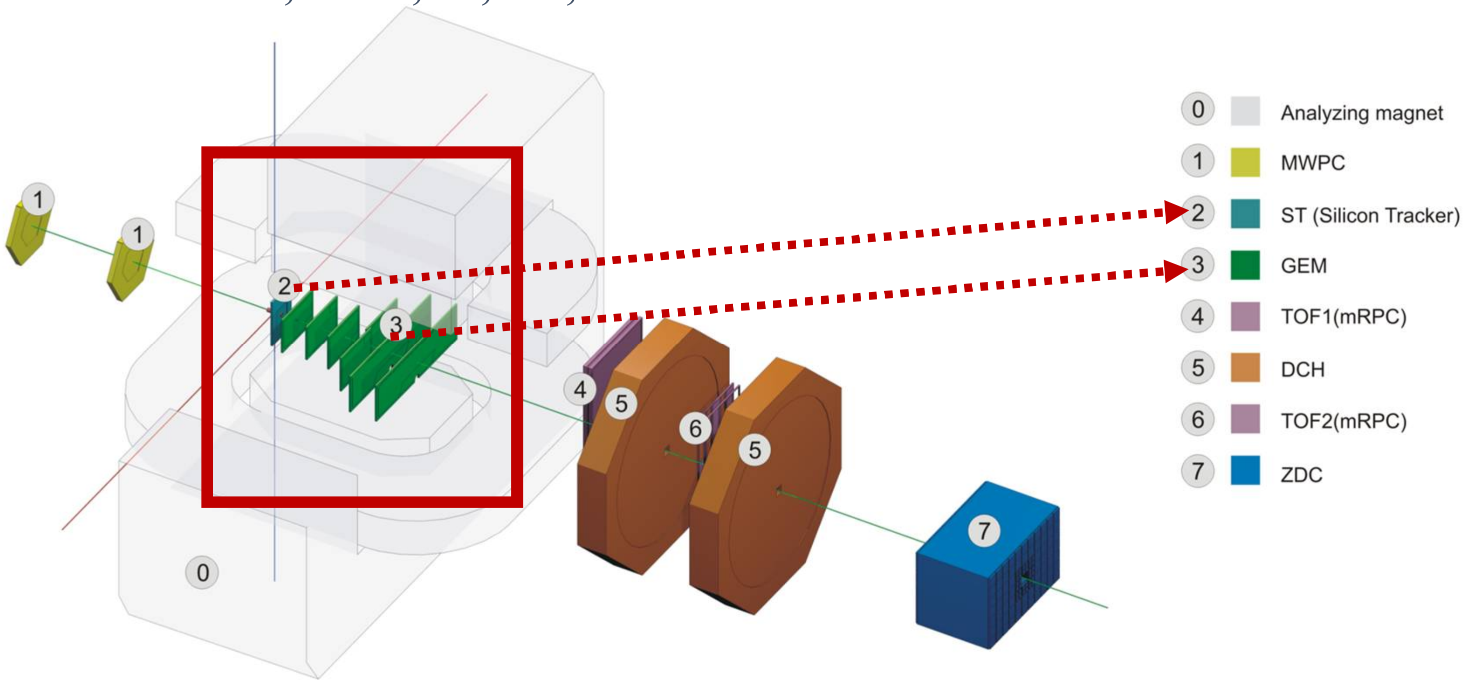
$$E_A(\rho,\delta) = E_A(\rho,0) + E_A(\rho)\,\delta^2$$
$$\delta = (\rho_n - \rho_\rho)/\rho$$

Incompressibility of the nucleus: $K_{mn} = 9\rho^2 \frac{\partial^2}{\partial \rho^2}(E/A)|_{\rho=\rho_0}$

Setup scheme

$C + A \rightarrow X$, A : C, Al, Cu, Pb

Energy beam = 4.0 AGeV, 4.5 AGeV



Central tracker:

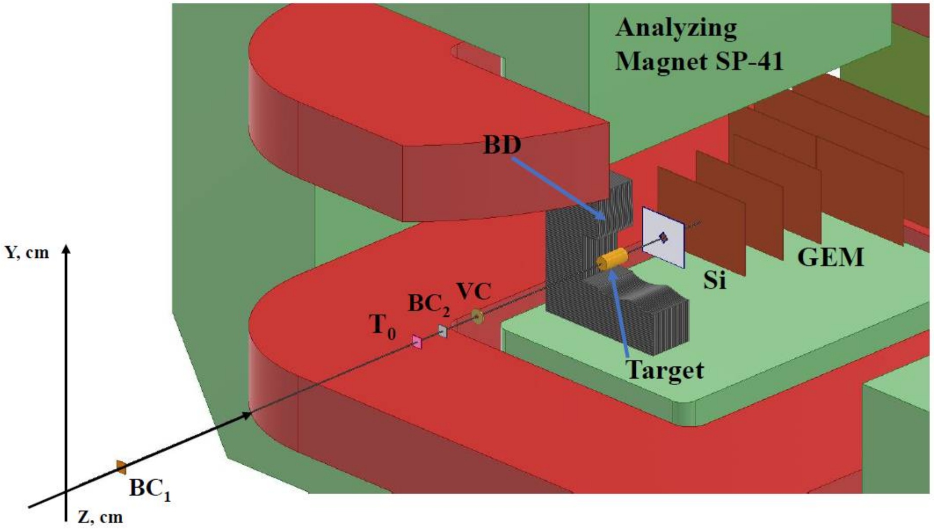
- One plane of a forward Si detector;
- 6 GEM stations:
  - 5 GEM detectors (66x41 cm^2);
  - 2 GEM detectors (163x45 cm^2);

Gas Electron Multiplier (GEM) system:
To measure momenta of a charged particle;

Event reconstruction in GEM in C+A interaction;

Triggers: BD, BC_1, BC_2, T_0, VETO

Event selection criteria



1 Number of tracks in selected events:
positive>=1, negative>=1

2 Number of signals in the start detector: T_0=1

3 Number of signals in the beam counter:
BC_2=1

4 Number of signals in the veto counter around the beam: Veto=0

5 Trigger condition in the barrel detector: number of signals BD>=2 or BD>=3 (run dependent)

Trigger efficiency

The trigger efficiency was evaluated by a convolution of the **GEANT simulation** of the trigger BD detector response to DCM-QGSM events with reconstructed Λ hyperons and the GEANT simulation of delta electrons.

$$\varepsilon_{trig} = N_{sim_{\Lambda}}(BD \geq n)/N_{sim_{all\Lambda}}$$

The systematic errors in **Table 1** cover:

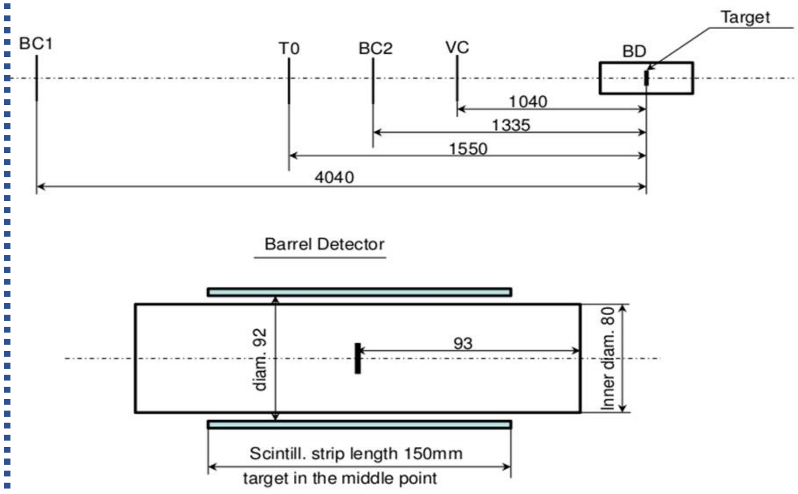
1) Contribution of delta electrons;
2) The spread of the trigger efficiencies calculated for different y and p_T bins of the reconstructed Λ-hyperons;
3) Change in the trigger efficiency after correction of the simulated track multiplicity in agreement with the experimental data.

Table 1. Trigger efficiency ε_{trig}

4 AGeV	C	Al	Cu	Pb
ε_{trig}(BD≥2)	0.80±0.02	-	-	-
ε_{trig}(BD≥3)	-	0.87±0.02	0.92±0.02	0.95±0.02

4.5 AGeV	C	Al	Cu	Pb
ε_{trig}(BD≥2)	0.80±0.02	-	-	-
ε_{trig}(BD≥3)	-	0.83±0.02	0.91±0.02	0.94±0.02

ε_{trig} is used for evaluation of production cross section;



Schematic view and positions of the beam counters, barrel detector and target

Monte - Carlo tuning

1 | Gem's Efficiency(next slide, example C+C);

2 | Track hits residual corrections*;

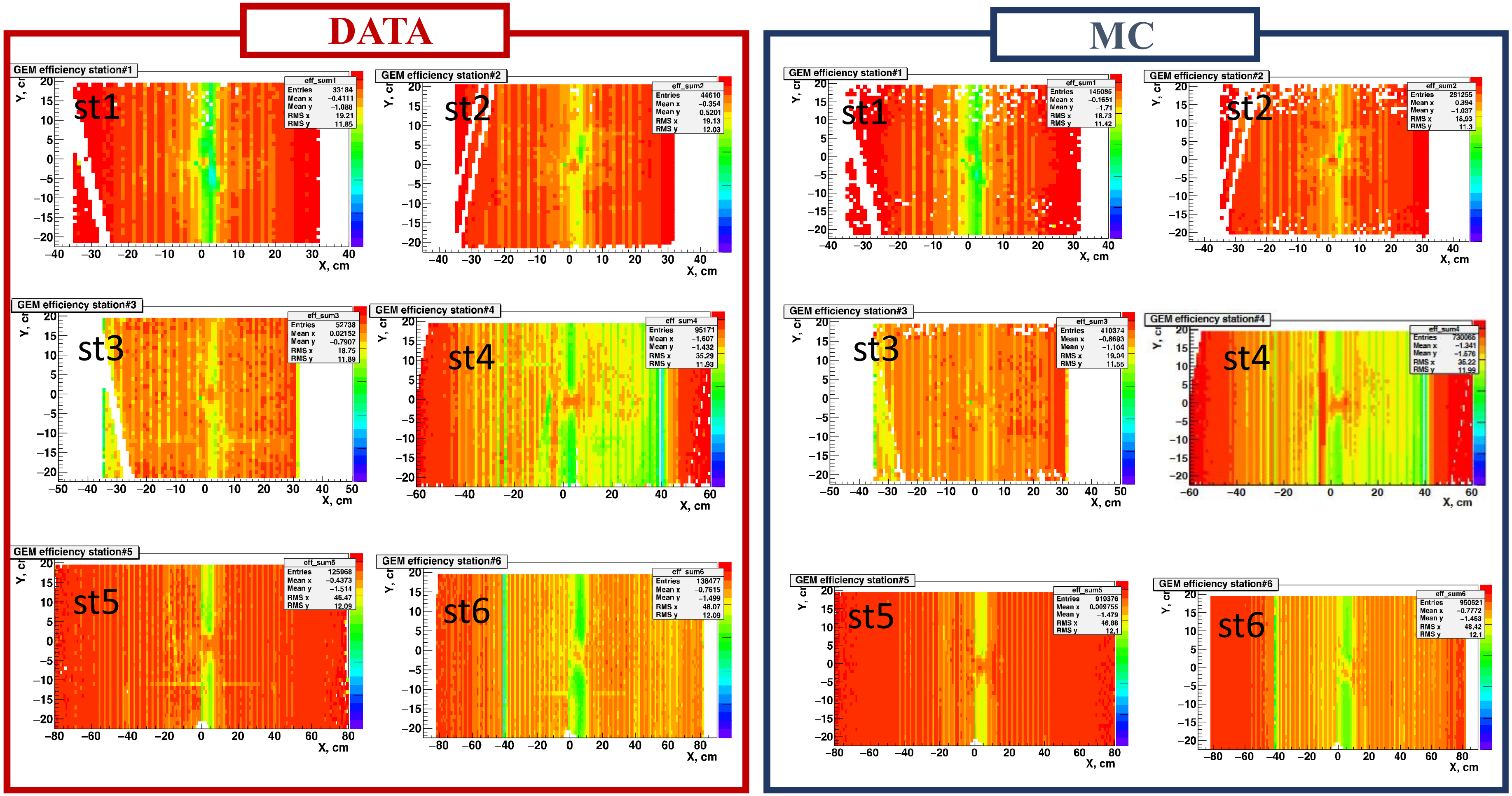
3 | Track hit position error corrections;

4 | Residuals width vs. momentum corrections;

Yury Stepanenko

*K. A. Alishina, Yu. Yu. Stepanenko, A.Y Khukhaeva" Gem residuals corrections in monte-carlo simulation for the run 6 at the BM@N experiment", PEPAN letters – volume 19, part 5, 2022

GEM efficiencies comparison Data/MC (4.0GeV C+C) after applying effs to MC

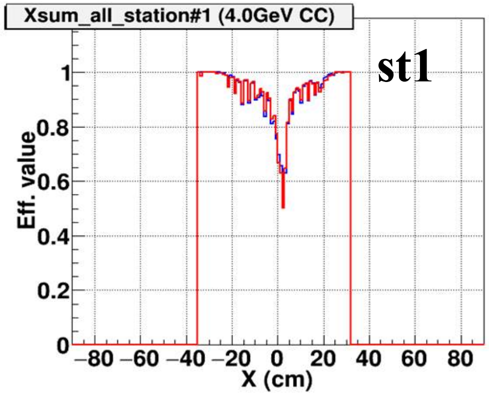


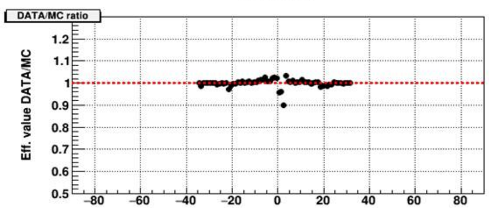
For each GEM station they were estimated using the following approach:

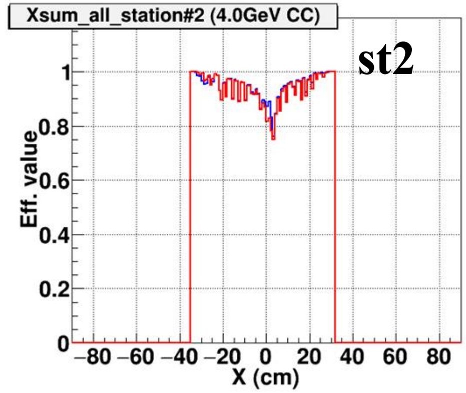
1. Select good quality tracks with the number of hits per track (excluding the station under study) not less than N;
2. Check that track crosses the detector area, if yes, add one track to the denominator;
3. If there is a hit in the detector, which belongs to the track, add one track to the numerator;
4. **GEM** efficiency = sum of tracks in numerator / sum of tracks in denominator.

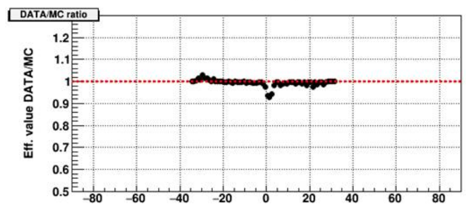
1D GEM efficiency comparison between the experimental data and MC (4.0GeV C+C)

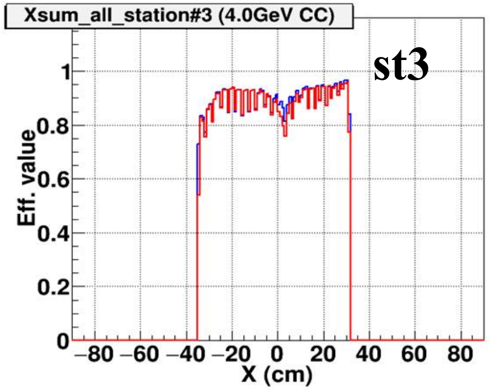
Data–red line, MC–blue line;

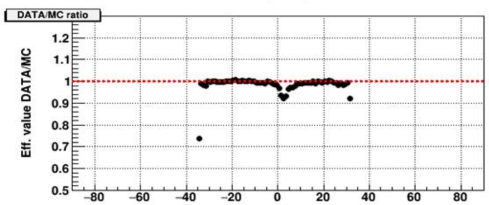


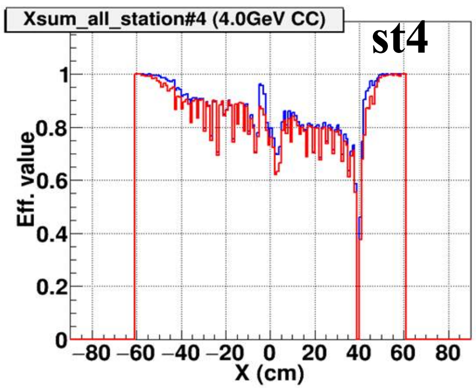


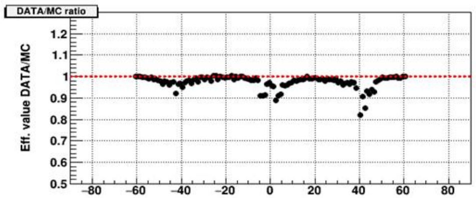


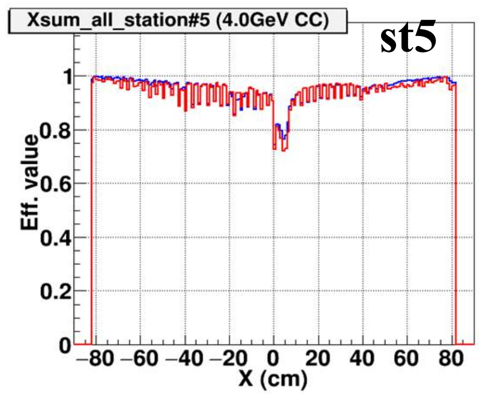


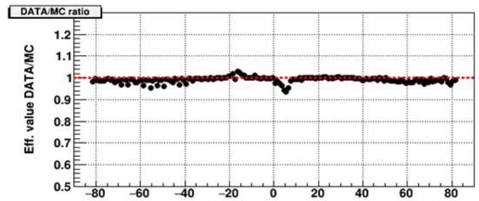


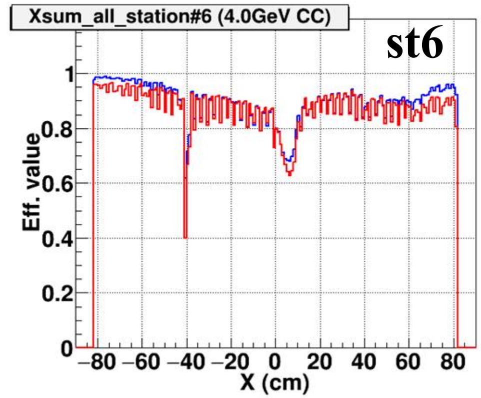


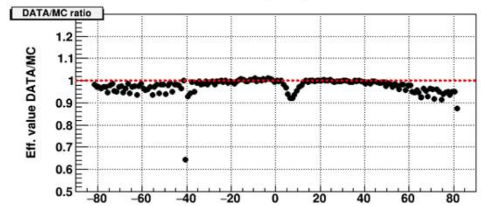


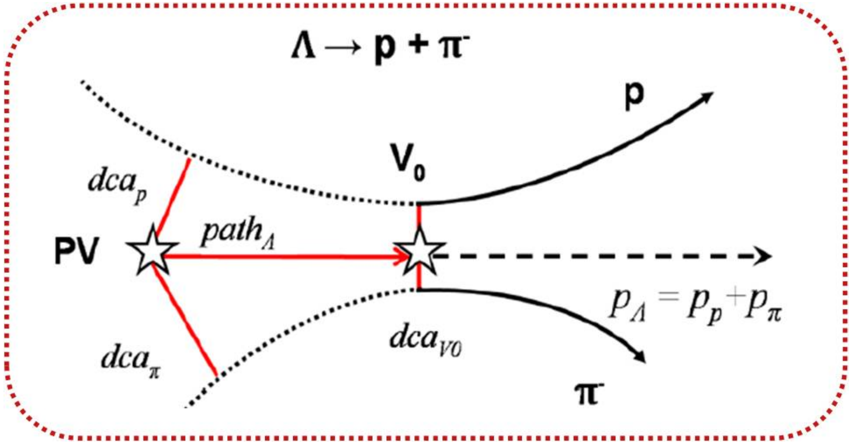












Event topology:

PV – primary vertex

V0 – vertex of hyperon decay

dca – distance of the closest approach

path – decay length

Criteria for the selection of Λ - hyperons :

1 Each track has at least 4 of the 6 hits in (Si+GEM);

2 p_{pos} < 3.9(4.4) GeV/c for a beam energy of 4 (4.5) AGeV;

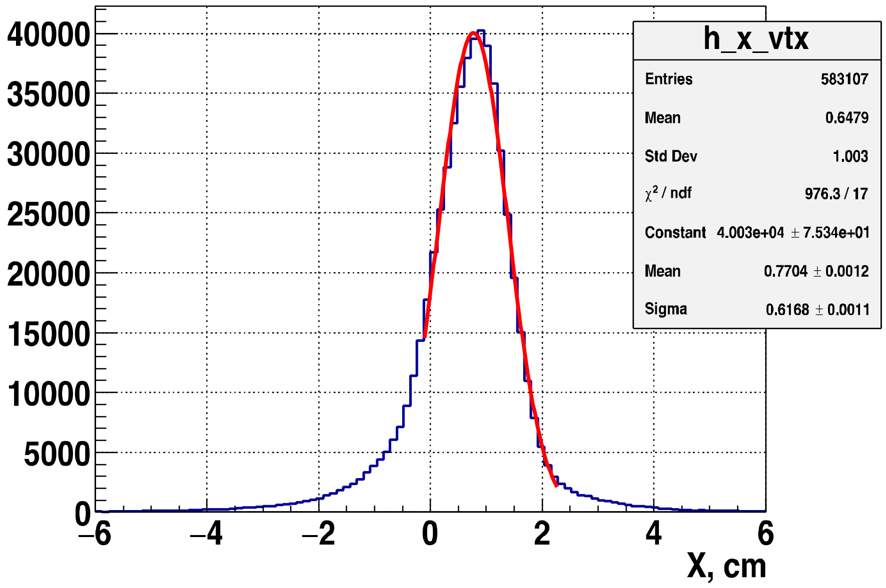
3 p_{neg} > 0.3 GeV/c;

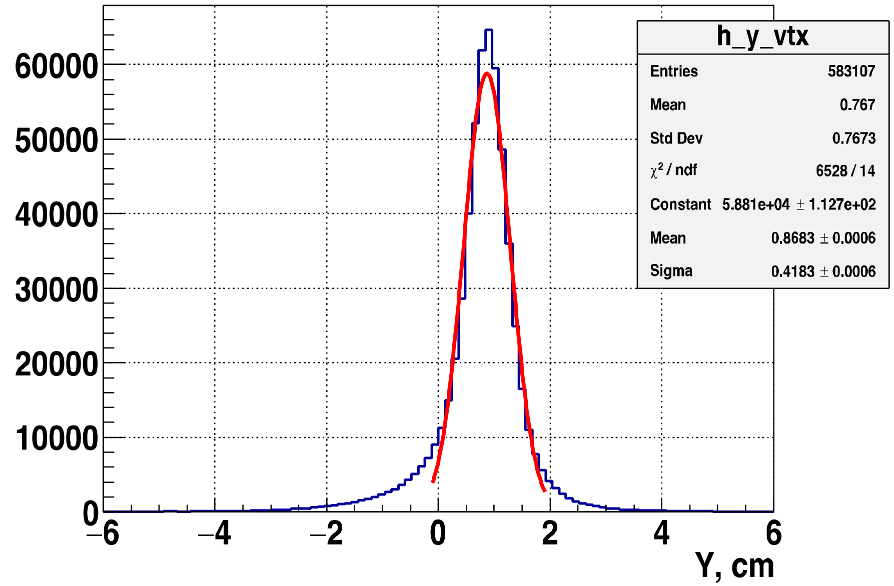
4 dca < 1 cm;

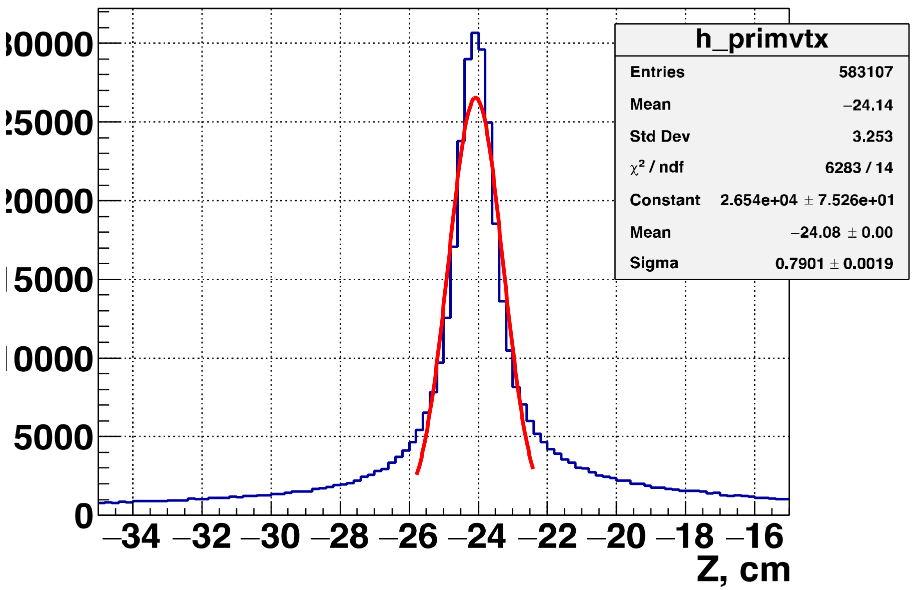
5 Distance between the decay vertex V_0 and the primary vertex: path > 2.5 cm;

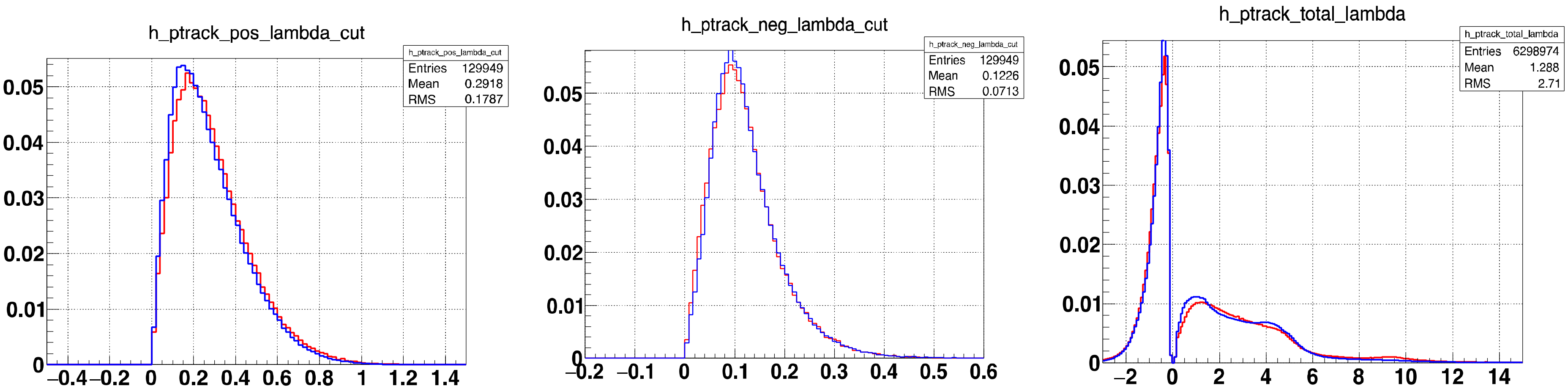
K. A. Alishina, Yu. Yu. Stepanenko, "Study of Λ–hyperon production in collisions of heavy ions with solid targets in the BM@N experiment" volume 21, part 4, 2024

X, Y, Z distributions of the experimental primary vertex



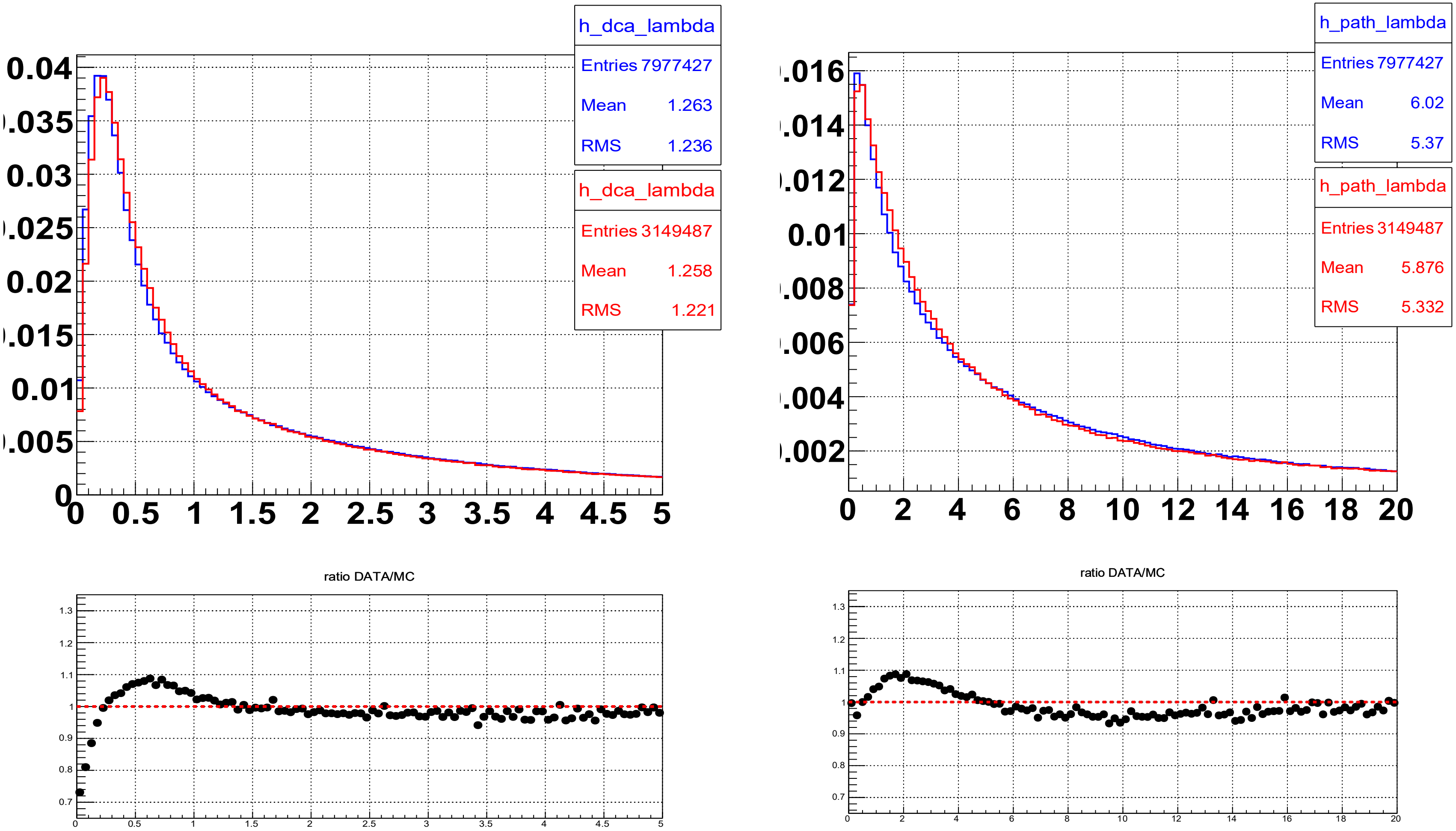






C+Cu interactions at **4.0 AGeV** carbon beam energy: transverse momentum of positive particles (left); transverse momentum of negative particles (center); total momentum of negative (*p/q*<0) and positive particles (*p/q*>0) (right). **Blue line** - MC, **red line** - data.

Data and Monte-Carlo comparison



Distance of the closest approach of *V0* decay tracks (*dca*), distance between the primary vertex and *V0* (path). Ratio of the data/MC presented on bottom pictures. Cuts were applied as follow: dca<1.0, path>2.5. Reaction *C+Cu*, energy **4.0** GeV

Physical analysis steps

1. The experiment accumulated data, but the statistics from the reconstructed selected Λ candidates are not very rich. (N_{data}~5.9×10^5).

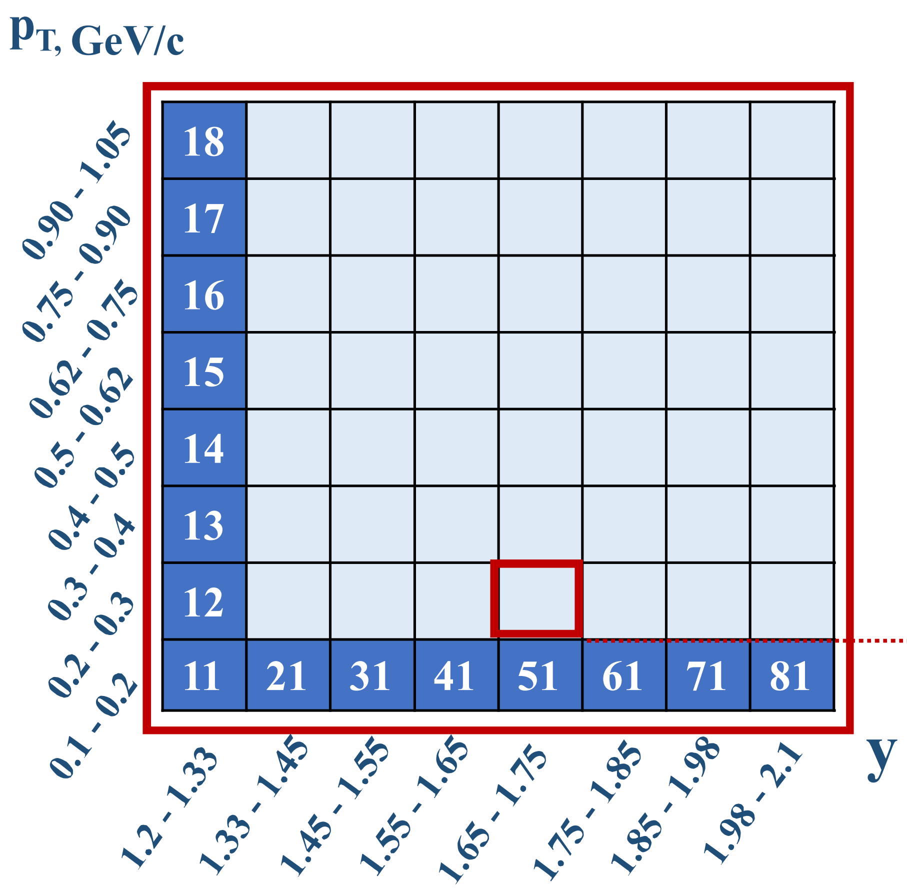
2. The high statistic MC data set was generated: (N_{MC} ~3.8×10^7). MC were tuned to data and acceptance was evaluated in (y, p_T) cells with high pression.

3. Each event was weighted with the acceptance for each cell.

4. 1D distributions in y or p_T were evaluated as the projections of 2D distributions to the corresponding kinematic variable.

Kinematic measuring range (4, 4.5 AGeV):

$0.1 < p_T < 1.05$ GeV/c
$1.2 < y_{lab} < 2.1$



1 Divide the kinematic measuring range by y, p_T into (8×8) cells in the MC simulation.

2 To get the number of events generated by the MC.

In each cells the invariant mass distribution fit with

3

$$f_{bg} = N \cdot (m - M_0)^A \cdot e^{-B \cdot (m - M_0)}$$

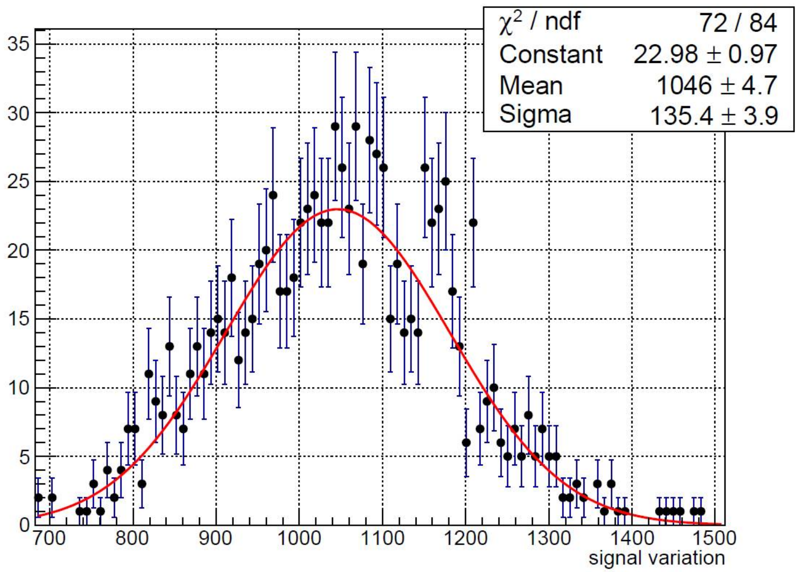
N, A, B are free parameters,
$M_0 = 1.078$ ГэВ/c^2 is the threshold limit, m is the mass value.

Pseudo-experiment

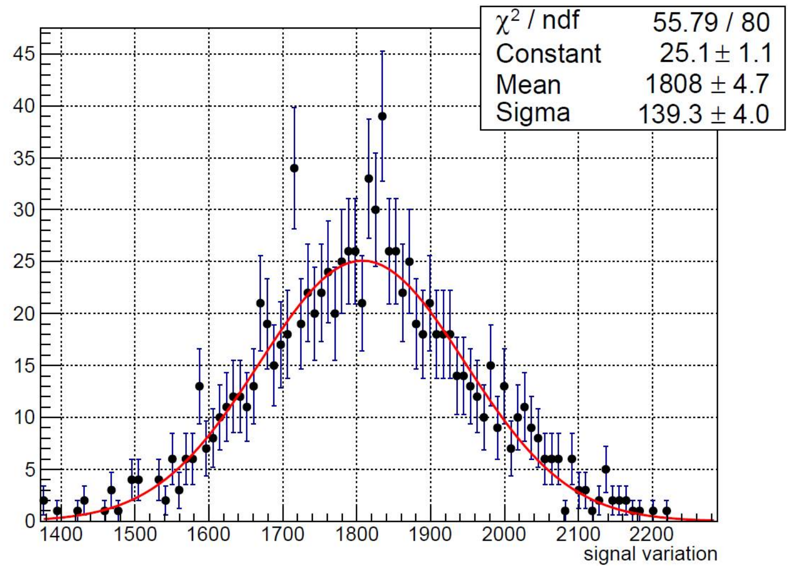
In each bin the bin content was modified by gaussian distribution with the widths equal to the bin error.

The "new" histogram was fit an the new signal was evaluated.

Procedure was repeated 1000 times and the signal variation are presented in a bottom histogram.



$1.2 < y_{lab} < 1.33,\ 0.1 < p_T < 0.2$



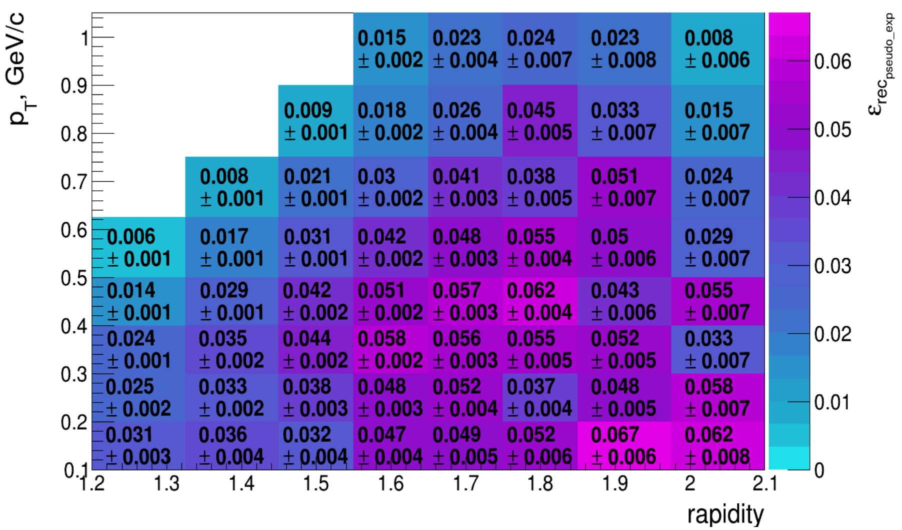
$1.33 < y_{lab} < 1.45,\ 0.2 < p_T < 0.3$

Red Line – Fit function Gauss($< N^{\Lambda}_{rec_{MC}} >, \sigma_{N^{\Lambda}_{rec_{MC}}}$)

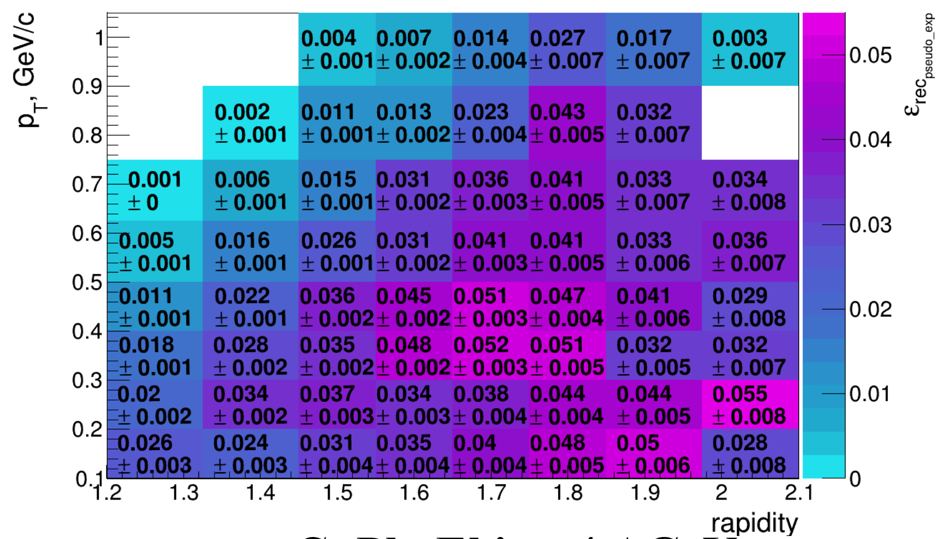
4 **Each event is weighted with $\varepsilon_i = < N^{\Lambda}_{rec_{MC}} >_i / N^{\Lambda}_{gen_i}$ is evaluated number of Λ, $N^{\Lambda}_{gen_i}$ is the number of Λ generated; $\Delta\varepsilon_i = \sigma_{N^{\Lambda}_{rec_{MC_i}}} / N^{\Lambda}_{gen_i}$ is evaluated error.**

Spectrometer acceptance ($\varepsilon_i \pm \Delta\varepsilon_i$) for Λ in (y, p_T)cells

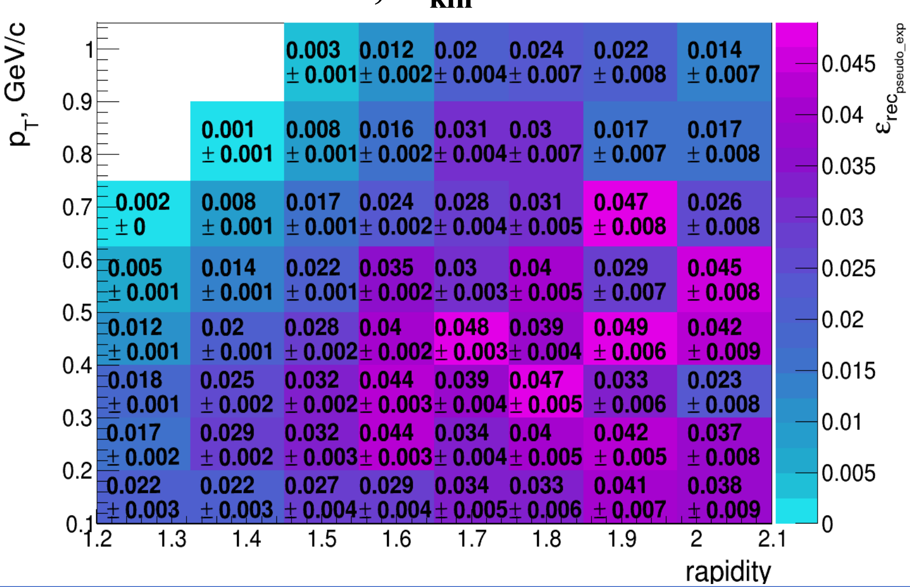
C+C, E_{kin} = 4 AGeV



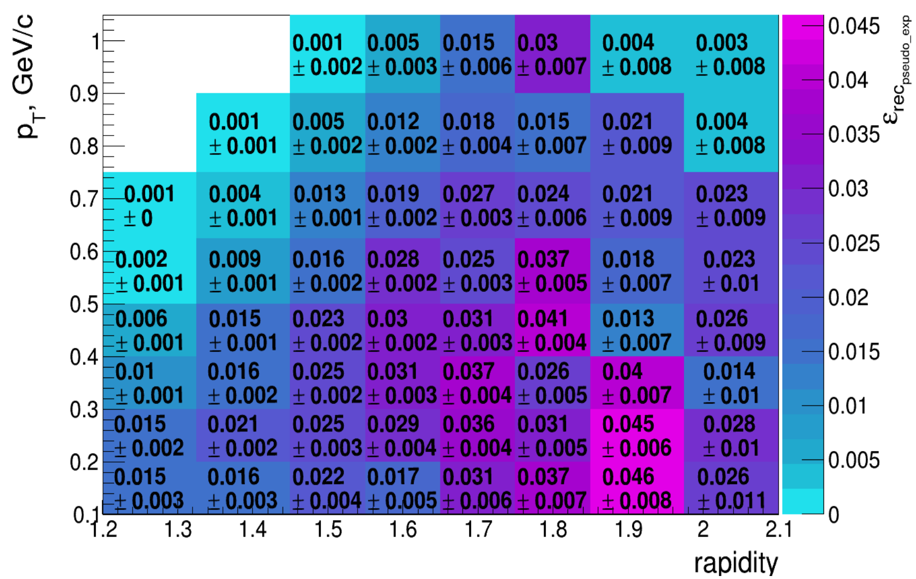
C+Al, E_{kin}= 4 AGeV



C+Cu, E_{kin}= 4 AGeV

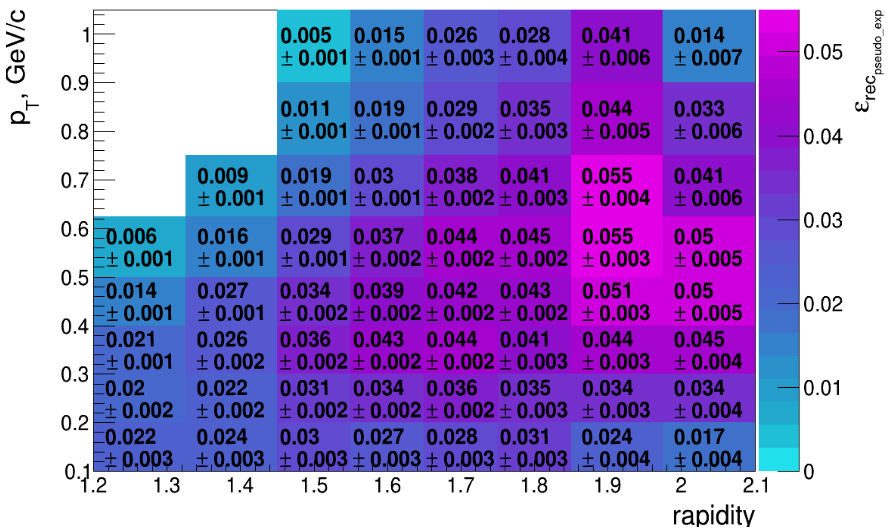


C+Pb, Ekin= 4 AGeV

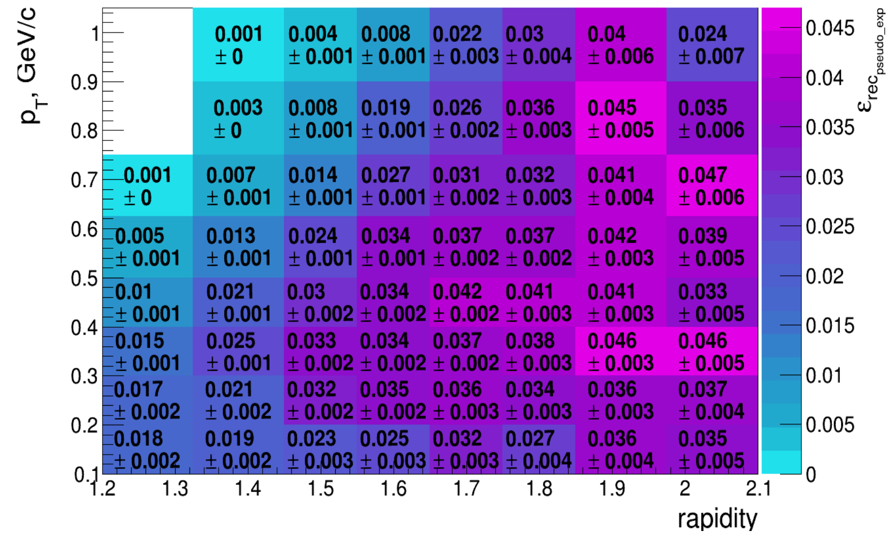


Spectrometer acceptance ($\varepsilon_i \pm \Delta\varepsilon_i$) for Λ in (y, p_T) cells

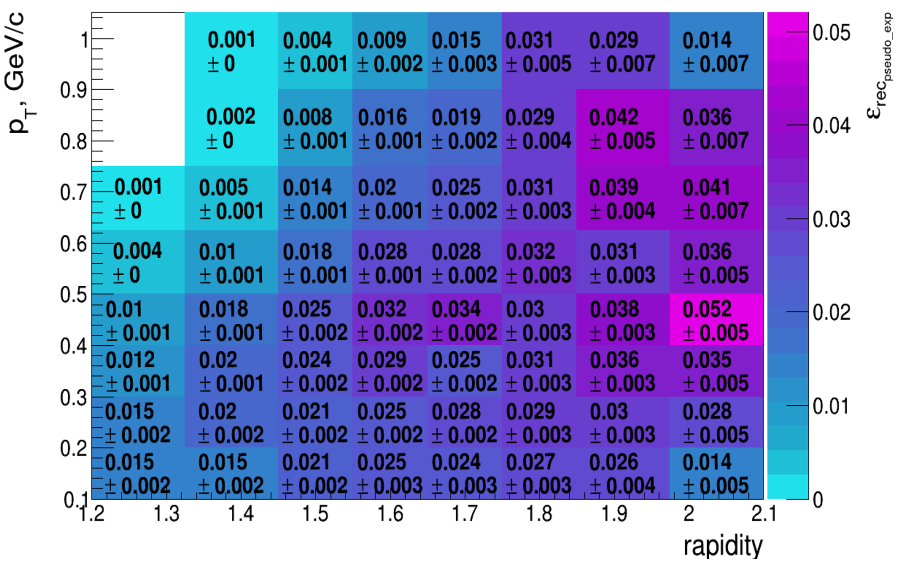
C+C, E_{kin} = 4.5 AGeV



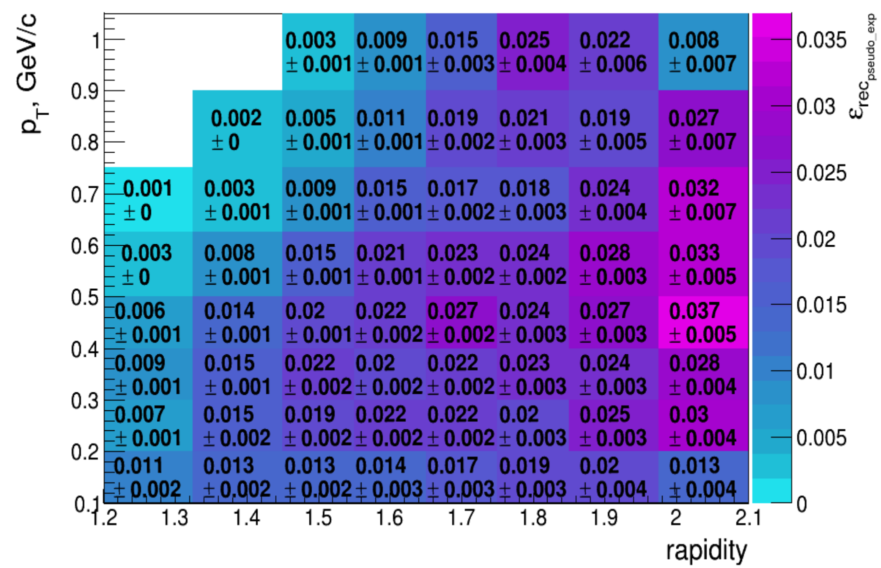
C+Al, Ekin= 4.5 AGeV



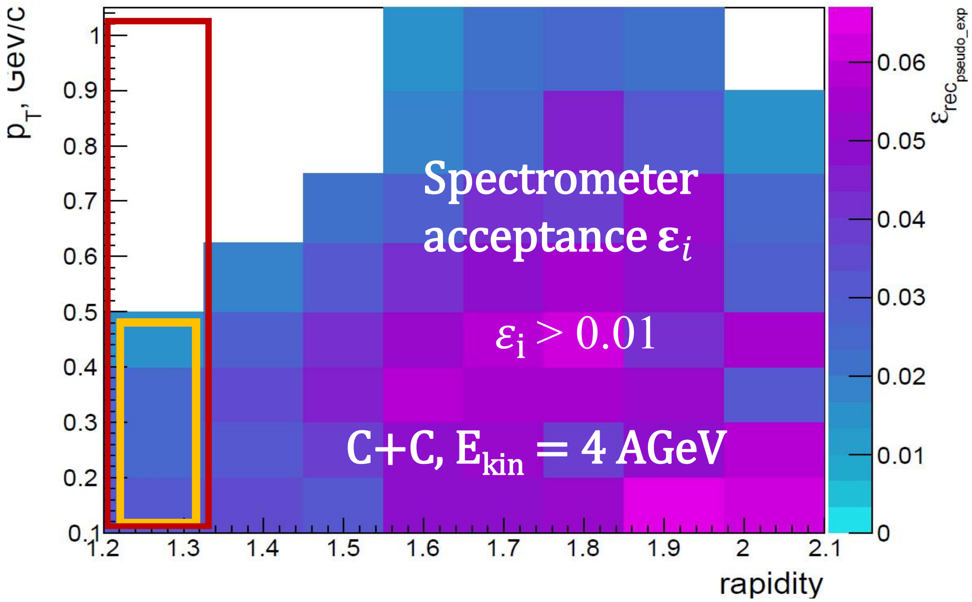
C+Cu, Ekin= 4.5 AGeV

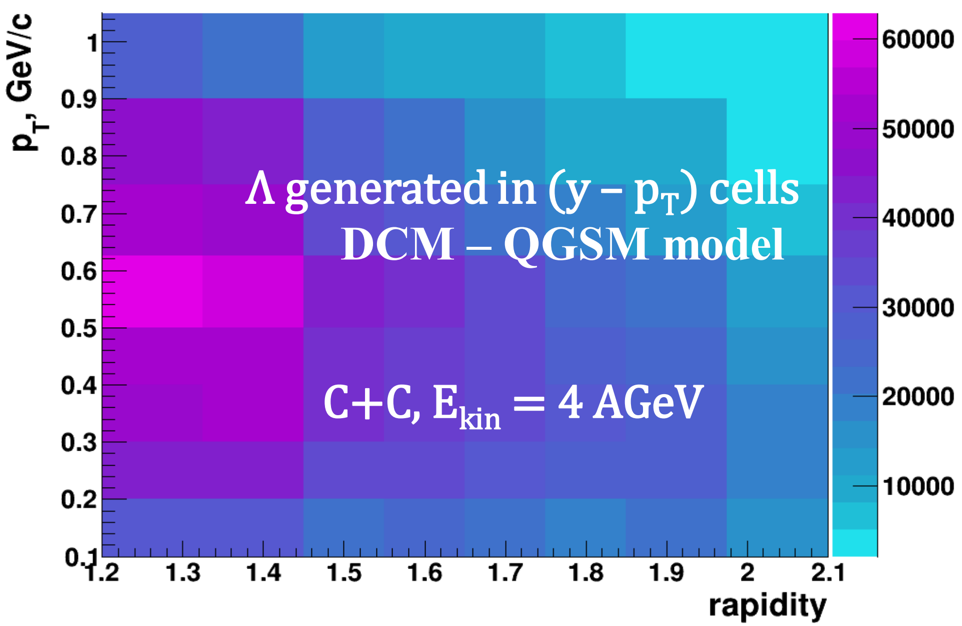


C+Pb, Ekin= 4.5 AGeV



Extrapolation to low acceptance (y, p_T) cells

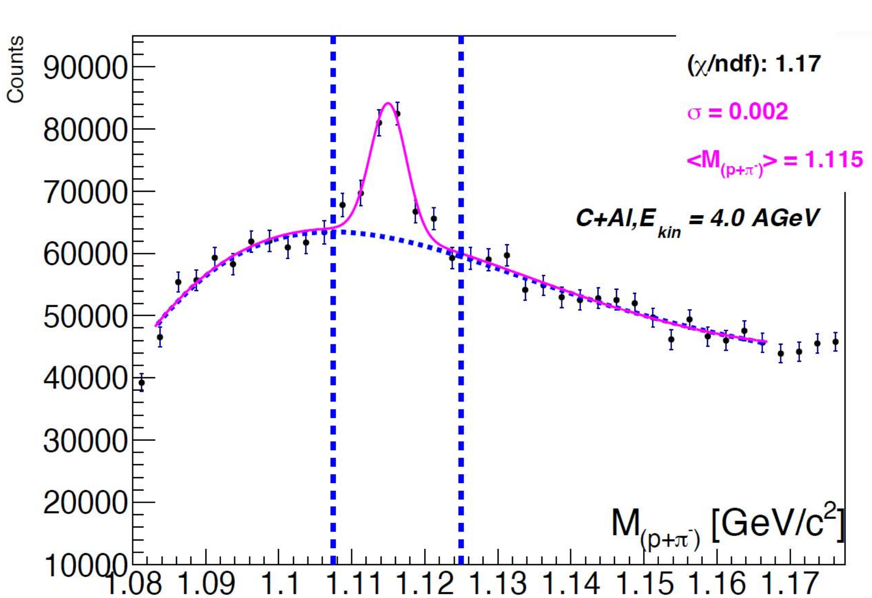


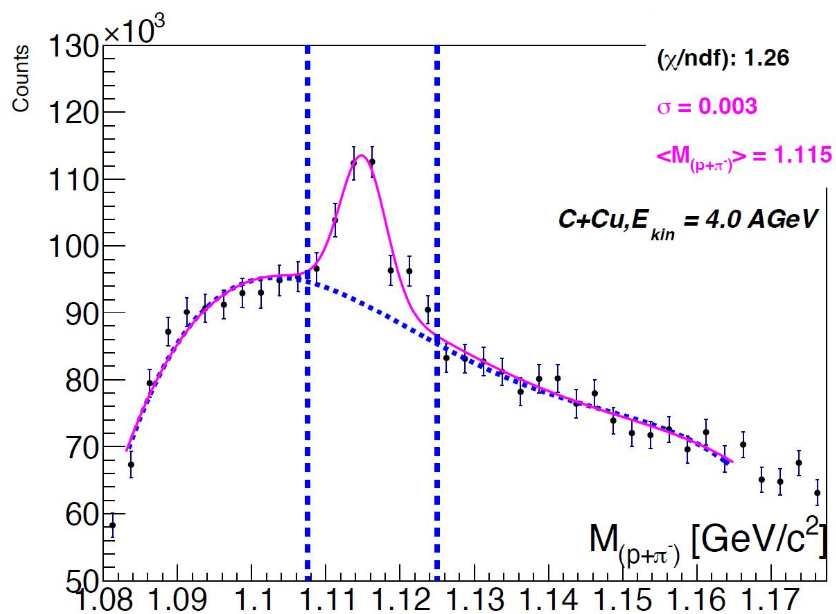


Extrapolation steps:

1. Extrapolation based on the DCM – QGSM model;
2. Extrapolation factor is calculated $f_{extr} = N_{all}/N_{con}$, N_{all} – sum of all generated events; N_{con} – sum of generated events in cells with high acceptance;
3. f_{extr} - is used for evaluation of production cross section in full kinematic range;

Mass distribution of the Λ (BM@N DATA)





Procedure in DATA C+A → X

1) Split (y, pT) area in small cells for MC/DATA (8x8);
2) **To each event assigned the weight ε_i;**
3) Sum the cells by $\sum_{ij} y_{ij}$ and by $\sum_{ij} pT_{ij}$

$0.1 < p_T < 1.05$
and
$1.2 < y_{lab} < 2.1$

- Λ signal width ~ 2.0 - 4 MeV;
- **Signal** = hist – Background in **1107.5 - 1125** MeV/c^2;

The suppression factors

- The suppression factors of reconstructed events ε_{pileup} due to selection **criteria 2** applied to eliminate beam halo and pile-up events in interactions of the 4.0 and 4.5 AGeV carbon beam with the C, Al, Cu, Pb targets.

Number of signals in the start detector: T_0=1

Table 2. ε_{pileup} suppression factors

Selection	4 AGeV	4.5 AGeV
T0==1	+	+
BC2==1	+	+
Veto==0	+	+
C	0.674±0.034	0.529±0.026
Al	0.740±0.037	0.618±0.031
Cu	0.779±0.039	0.621±0.031
Pb	0.784±0.039	0.686±0.034

Preliminary systematics evaluation:

$$\delta\varepsilon_{pileup_{SYS}} = \varepsilon_{pileup} \cdot \delta\varepsilon_{pileup};$$

where $\delta\varepsilon_{pileup} = 5\%$

- ε_{pileup} is used for evaluation of production cross section;

Cross sections $\sigma_\Lambda(y/p_T)$ of the Λ

The inclusive cross section $\boldsymbol{\sigma_\Lambda}$ and $\mathbf{Y_\Lambda}$ of Λ hyperon in C+A interactions are calculated in bins of (y - p_T) according to the formula:

weighted signal

$$\sigma_\Lambda(p_T) = [\textstyle\sum_y N^\Lambda_{rec}(y,p_T)/\varepsilon_{rec}(y,p_T)]/[\varepsilon_{trig}\cdot\varepsilon_{pileup}\cdot L]$$
$$\sigma_\Lambda(y) = [\textstyle\sum_{p_T} N^\Lambda_{rec}(y,p_T)/\varepsilon_{rec}(y,p_T)]/[\varepsilon_{trig}\cdot\varepsilon_{pileup}\cdot L]$$

L is the luminosity, N^Λ_{rec} is the number of recontacted Λ-hyperons,
ε_{rec} is the combined efficiency of the Λ - hyperon reconstruction,
ε_{trig} is the trigger efficiency, ε_{pileup} is the suppression factors of reconstructed events.

Table 3. Integrated **luminosities** collected in interactions of the carbon beam of 4.0 and 4.5AGeV with different targets.

Interactions, target thickness		Integrated luminosity/ 10^{30} cm^{-2}		Integrated luminosity/ 10^{30} cm^{-2}
C+C (9 mm)	4 AGeV	6.06	4.5 AGeV	4.69
C+Al (12 mm)		2.39		3.60
C+Cu (5 mm)		2.00		3.06
C+Pb (10 mm)		0.22		0.84

Yields of the Λ

The $\mathbf{Y_\Lambda}$ of Λ hyperon in C+A interactions are calculated in bins of (y - p_T) cells according to the formula:

$$Y_\Lambda(y - p_T) = \sigma_\Lambda(y - p_T)/\sigma_{inel}$$

σ_{inel} is the cross section for minimum bias inelastic C+A interactions(model).

The cross sections for inelastic C+Al, C+Cu, C+Pb interactions calculated by the formula (DCM-QGSM): $\sigma_{inel} = \pi R_0^2 (A_P^{1/3} + A_T^{1/3})^2$

R_0 = 1.2 fm is an effective nucleon radius, A_P and A_T are atomic numbers of the beam and target nucleus [1]. The **uncertainties** for C+Al, C+Cu, C+Pb inelastic cross sections are estimated by 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 [2].

Table 4. Inelastic cross sections σ_{inel} for carbon-nucleus interactions

Interaction	C+C	C+Al	C+Cu	C+Pb
Inelastic cross section, mb	830±50	1260±50	1790±50	3075±50

[1] Kalliopi Kanaki "Study of Λ hyperon production in C+C collisions at 2 AGeV beam energy with the HADES spectrometer".
[2] H.Angelov et al., P1-80-473, JINR, Dubna.

The results (Preliminary) of the integrated yields of the Λ

Target	Energy, AGeV	$Y_{\Lambda} \pm \Delta Y_{stat\Lambda} \pm \Delta Y_{\Lambda_{sys}}$	Energy, AGeV	$Y_{\Lambda} \pm \Delta Y_{stat\Lambda} \pm \Delta Y_{\Lambda_{sys}}$
$0.1 < p_T < 1.05$ and $1.2 < y_{lab} < 2.1$				
C + C	4.0	0.011 ± 0.001 ± 0.004	4.5	0.013 ± 0.002 ± 0.005
C + Al		0.032 ± 0.004 ± 0.006		0.025 ± 0.003 ± 0.005
C + Cu		0.030 ± 0.003 ± 0.005		0.037 ± 0.004 ± 0.006
C + Pb		0.039 ± 0.008 ± 0.009		0.033 ± 0.010 ± 0.010

Systematic evaluation: Cut variation

1 part

An approach in the estimation of systematic uncertainties related to the variation of selection criteria for events with Λ-hyperons.
The selection criteria considered are **path, dca.**

Nominal Analysis: dca < 1 cm, path > 2.5 cm;

Cut variation 1:
path > 2.25 cm, **fixed:** dca < 1 cm;
path > 2.75 cm,

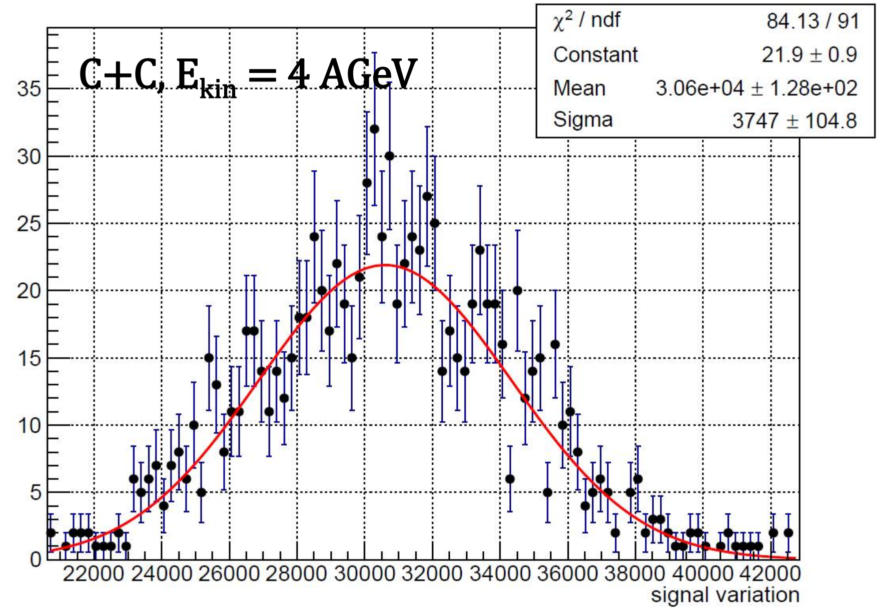
Cut variation 2:
dca < 0.9 cm,
dca < 1.1 cm, **fixed:** path > 2.5 cm;

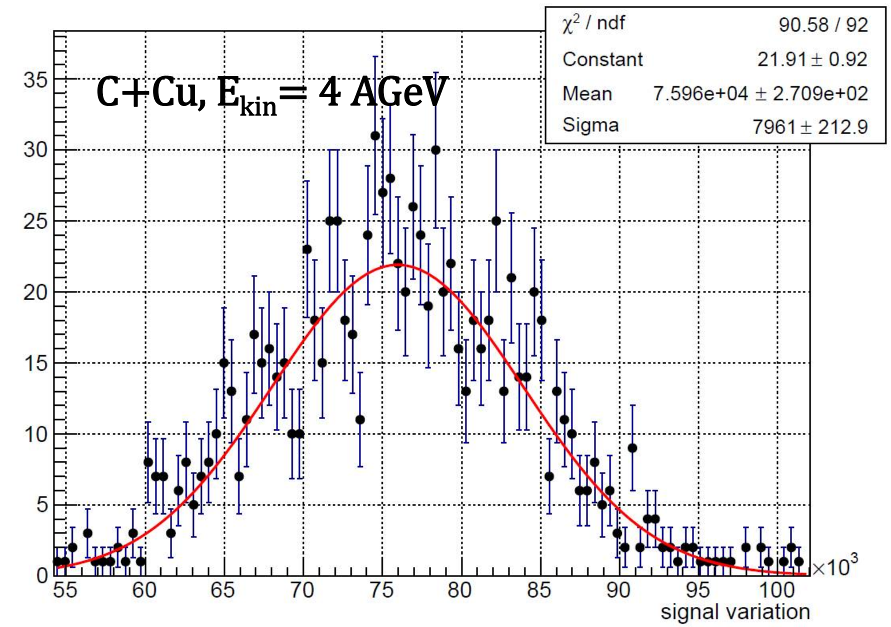
Combined systematic uncertainties

C+Cu, E_{kin} = 4.5 AGeV

dca	path	Yields (with cut variation)	Yields (nominal analysis)
Data statistic – II period			
Fixed: dca <1 cm	Path >2.25	0.043±0.004	0.035±0.009±0.007
	Path >2.75	0.042±0.004	
dca <0.9 cm	**Fixed:** Path >2.5	0.041±0.004	
dca <1.1 cm		0.042±0.004	
Data statistic – I period			
Fixed: dca <1 cm	Path >2.25	0.037±0.004	0.035±0.011±0.003
	Path >2.75	0.036±0.005	
dca <0.9 cm	**Fixed:** Path >2.5	0.038±0.004	
dca <1.1 cm		0.039±0.005	
Data statistic – (I + II) periods			
Fixed: dca <1 cm	Path >2.25	0.041±0.003	0.037±0.007±0.004
	Path >2.75	0.041±0.003	
dca <0.9 cm	**Fixed:** Path >2.5	0.041±0.003	
dca <1.1 cm		0.041±0.003	

Uncertainties from signal variation (BM@N DATA)





2 part

Red Line – Fit function

Gauss($< N^{\Lambda}_{rec_{DATA}} >, \sigma_{N^{\Lambda}_{rec_{DATA}}}$)

$0.1 < p_T < 1.05$

and

$1.2 < y_{lab} < 2.1$

$$\Delta\sigma_{\Lambda} = \sigma_{N^{\Lambda}_{rec_{DATA}}} / (\varepsilon_{trig} \times \varepsilon_{pileup} \times L)$$

$$\Delta Y_{stat\Lambda} = \Delta\,\sigma_{\Lambda} / \sigma_{inel}$$

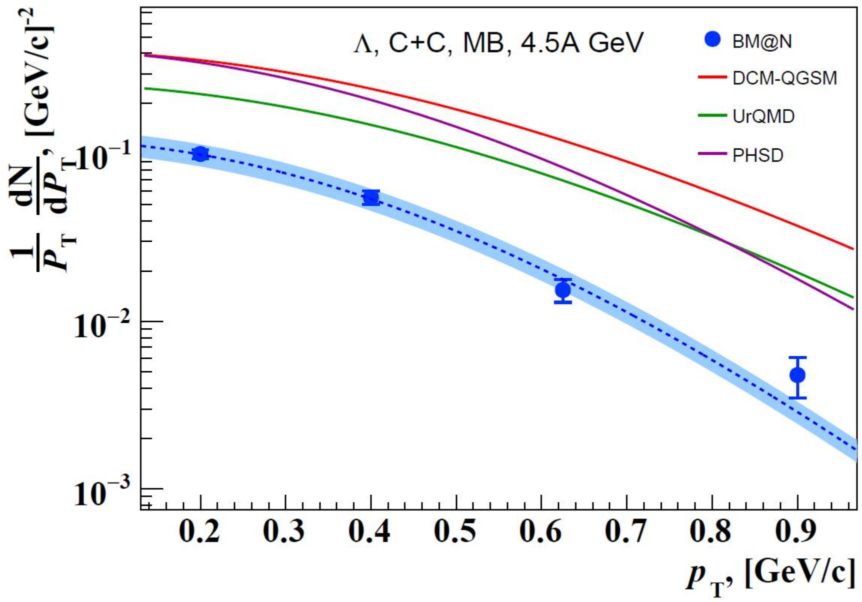
Calculation of systematic uncertainties yields of the Λ

1 $\Delta Y_{\Lambda_{sys\_pseudo\_exp}}{}^{2} = Y_{\Lambda}^{2}(\sigma_{N^{\Lambda}_{rec\,DATA}}{}^{2} / < N^{\Lambda}_{rec_{DATA}} >^{2} + \sigma_{N^{\Lambda}_{rec\,MC}}{}^{2} / < N^{\Lambda}_{rec_{MC}} >^{2});$

2 $\Delta Y_{\Lambda_{sys_{cut\_var}}} = 0.004$ – from the variation of the Λ-hyperon selection criteria;

3 $\Delta Y_{\Lambda_{sys}} = \sqrt{\Delta Y_{\Lambda_{sys\_pseudo\_exp}}{}^{2} + \Delta Y_{\Lambda_{sys_{cut\_var}}}{}^{2}}$ - total systematic uncertainty;

Invariant p_T spectra of Λ hyperons vs models predictions(Preliminary)



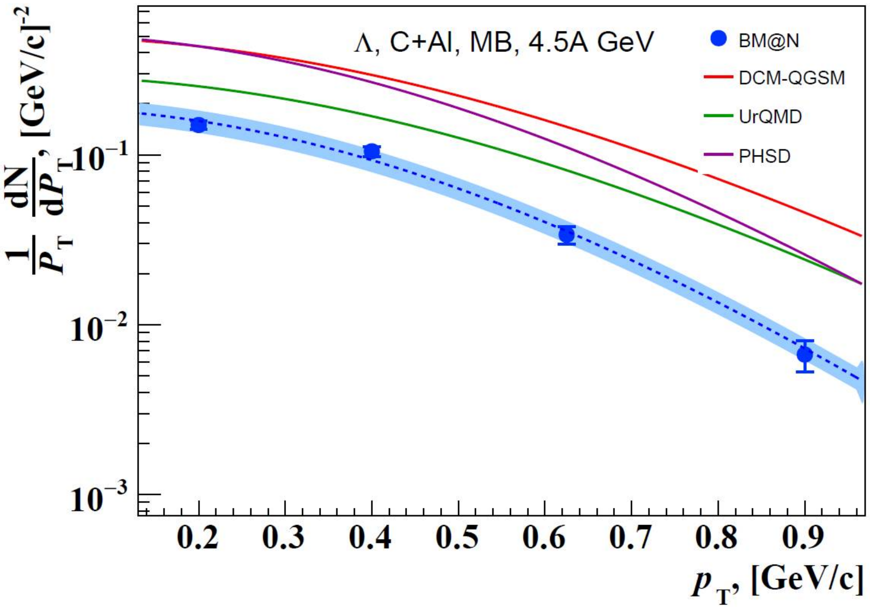
The measured spectra of the Λ yields in p_T are parameterized by the formula:

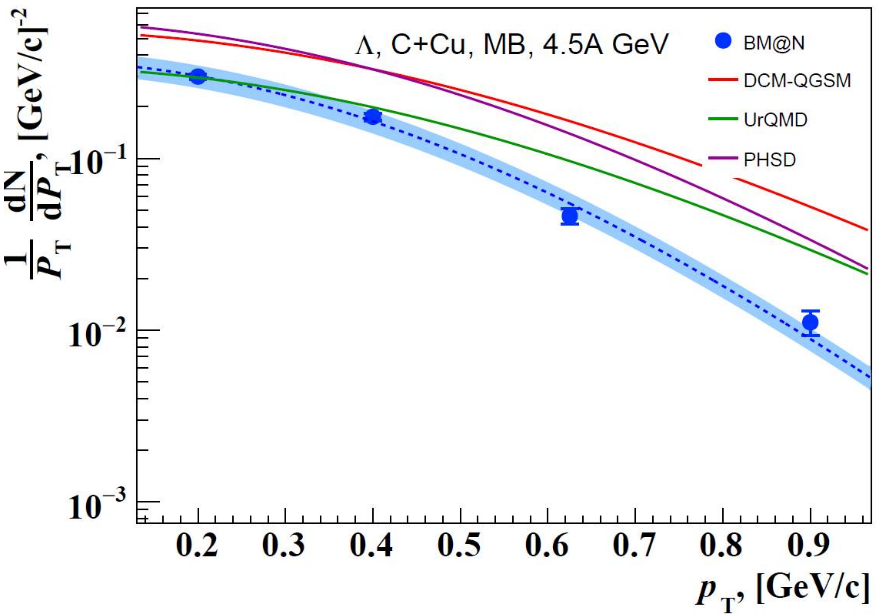
$$1/p_T\, d^2N/dp_T dy = N \cdot \exp(-(m_T - m_\Lambda)/T_0)$$

The transverse mass $m_T = \sqrt{m_\Lambda^2 + p_T^2}$,

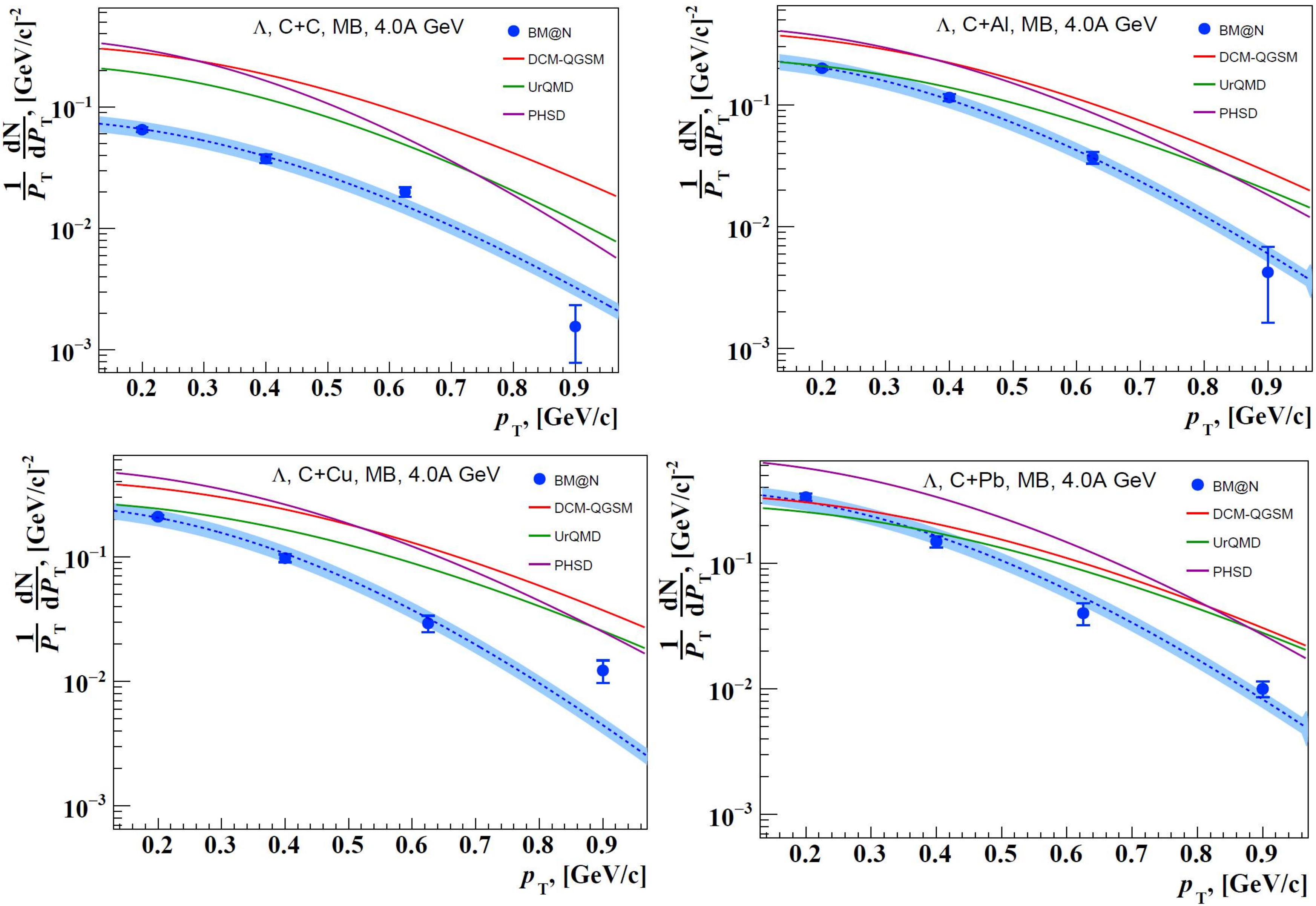
The **N** normalization,

The inverse slope parameter T_0 are free parameters of the fit;





Invariant p_T spectra of Λ hyperons vs models predictions(Preliminary)



SLOPE RESULTS (Preliminary)

4.0 AGeV	T_0, MeV, C+C	T_0, MeV, C+Al	T_0 MeV, C+Cu	T_0 MeV, C+Pb
BM@N	114±19±17	108±16±16	96±14±14	83±8±12
DCM - QGSM	126	120	133	130
UrQMD	107	128	133	136
PHSD	87	100	105	98

4.5 AGeV	T_0, MeV, C+C	T_0, MeV, C+Al	T_0, MeV, C+Cu	T_0, MeV, C+Pb
BM@N	116±24±17	115±7±17	101±3±15	Due to low statistics
DCM - QGSM	132	133	135	142
UrQMD	122	128	130	134
PHSD	101	106	109	108

Thank you for your attention