14th Collaboration Meeting of the BM@N Experiment at NICA

Production of Λ hyperons in 4.0 and 4.5 AGeV carbon-nucleus interactions at the Nuclotron

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VB LHEP, JINR, Dubna

BM@N
Baryonic Matter at Nuclotron

JOINT INSTITUTE
FOR NUCLEAR RESEARCH

Setup scheme

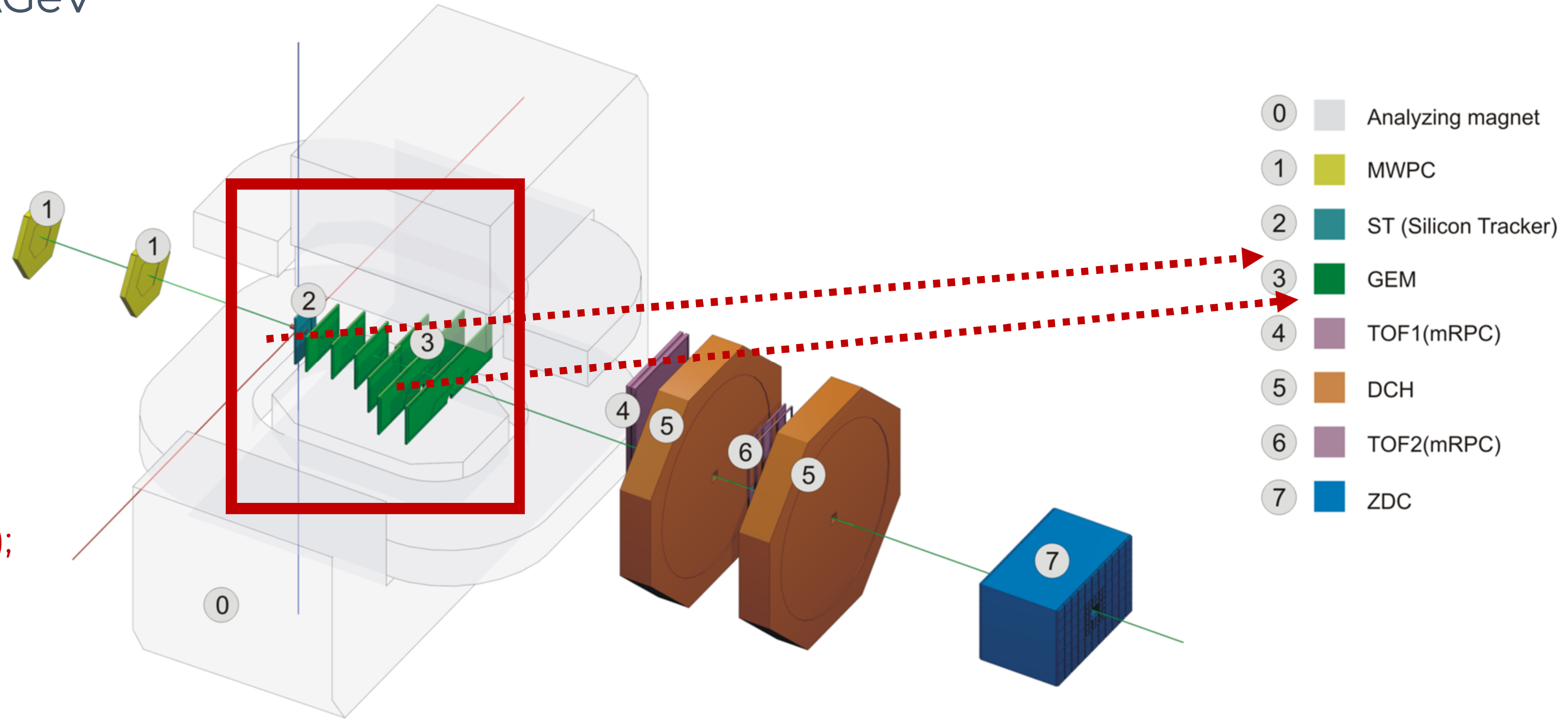
C + A → X , A : C, Al, Cu, Pb

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);

Triggers: BD, BC_1, BC_2, T_0, VETO



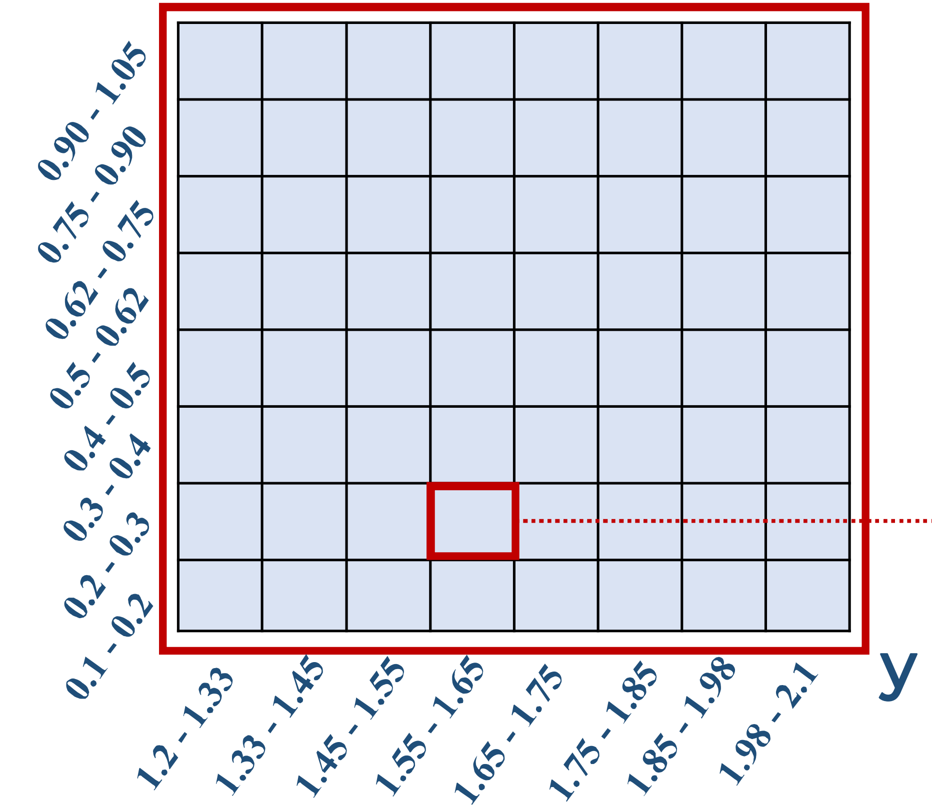
Gas Electron Multiplier (GEM) system:
To measure momenta of a charged particle;

Event reconstruction in GEM in C+A interaction;

Acceptance evaluation procedure (DCM - QGSM)

Kinematic measuring range (4, 4.5 AGeV):

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



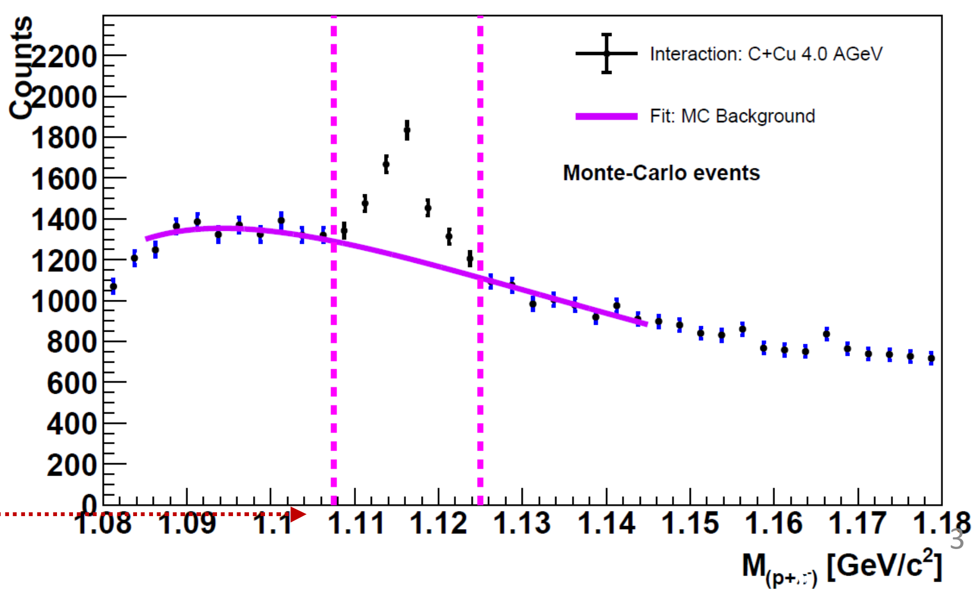
1 Divide the kinematic measuring range by y, p_T into (8×8) cells in the MC simulation.

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

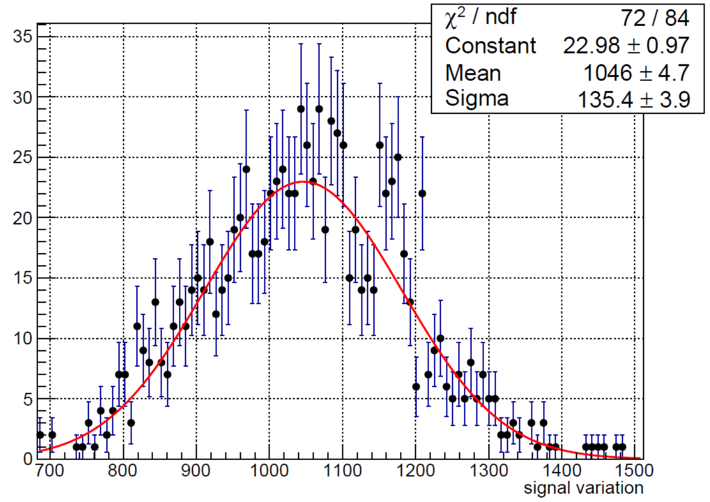
3 In each cells the invariant mass distribution fit with

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

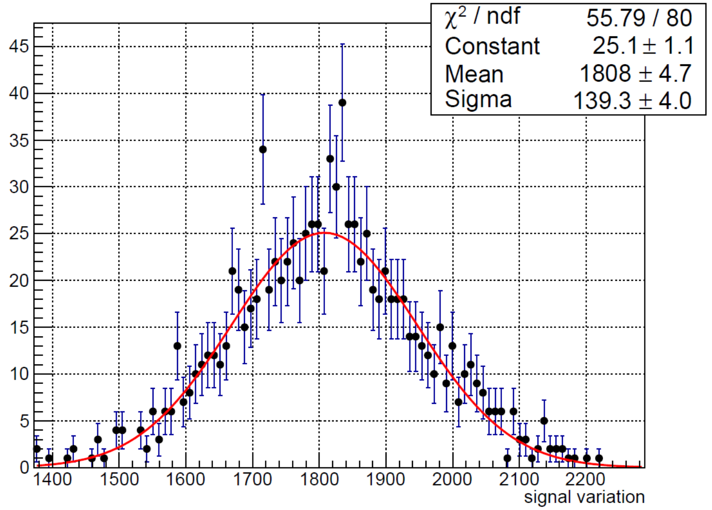
N, A, B are free parameters,
$M_0 = 1.078$ ГэВ/c^2 is the threshold limit, $\mathbf{m}$ is the mass value.



Evaluation of the precision of the acceptance



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



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

Pseudo-experiment

Gaussing smearing.

The **“new”** histogram was fit an the new signal was evaluated.

1000 times

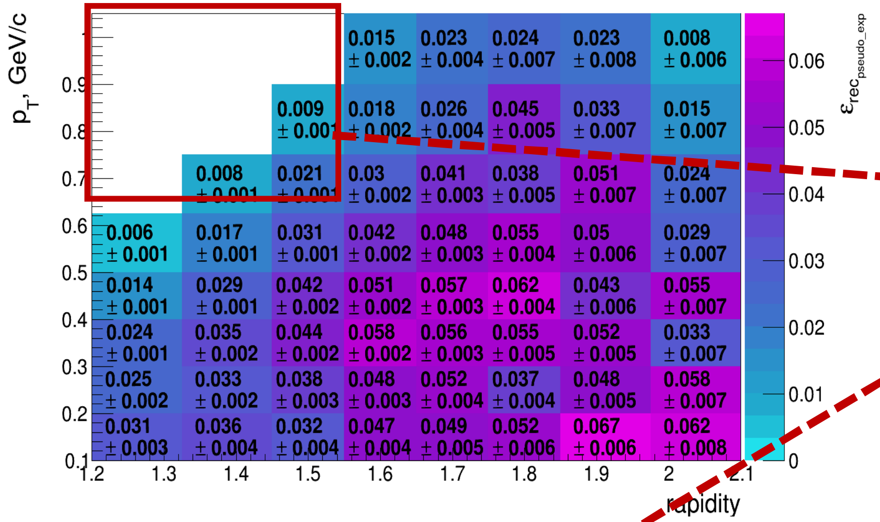
Procedure was repeated.

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

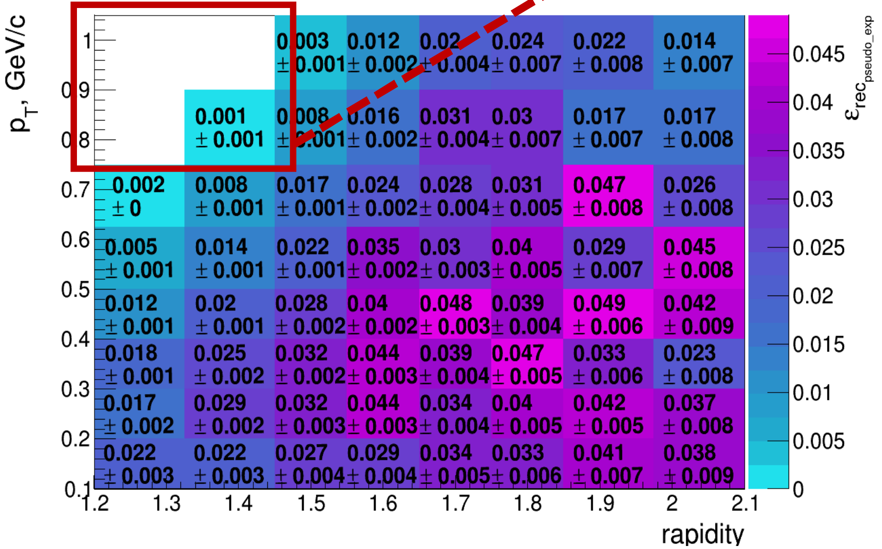
Each event is weighted with $\boldsymbol{\varepsilon_i} = < N^{\Lambda}_{recMC} >_i / N^{\Lambda}_{gen_i}$ is evaluated number of $\boldsymbol{\Lambda}$, $N^{\Lambda}_{gen_i}$ is the number of $\boldsymbol{\Lambda}$ generated; $\Delta\boldsymbol{\varepsilon}_i = \sigma_{N^{\Lambda}_{recMC\,i}} / N^{\Lambda}_{gen_i}$ 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+Cu, Ekin= 4 AGeV



Extrapolation to low acceptance (y, p_T) cells

$$\varepsilon_i < (0.0007, 0.001)$$

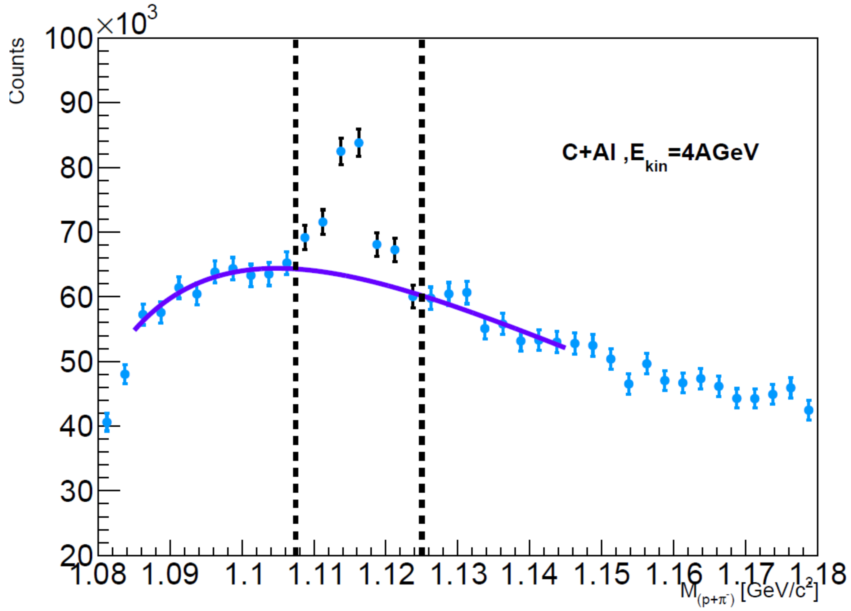
Extrapolation steps:

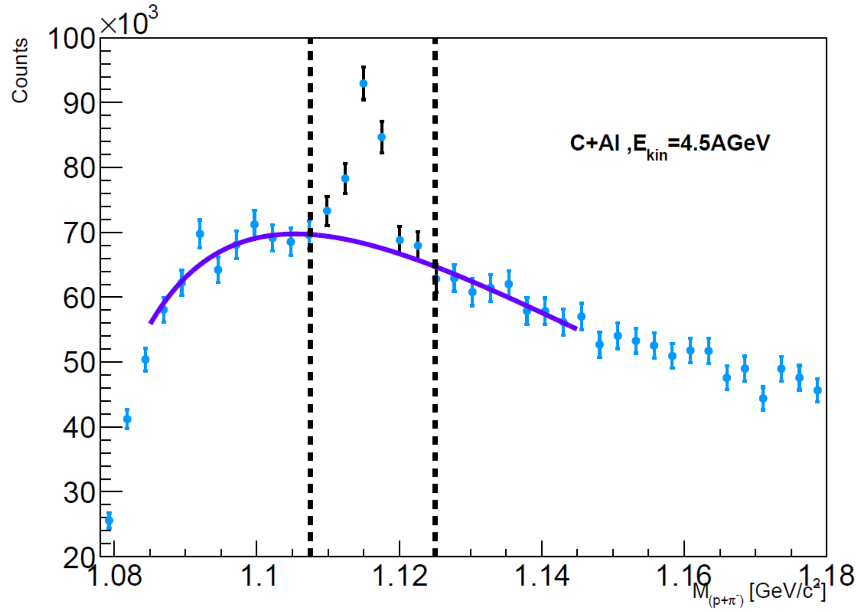
1 Extrapolation based on the DCM – QGSM model;

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 acceptance range;

Mass distribution of the Λ (BM@N DATA)





Procedure in DATA C+A → X

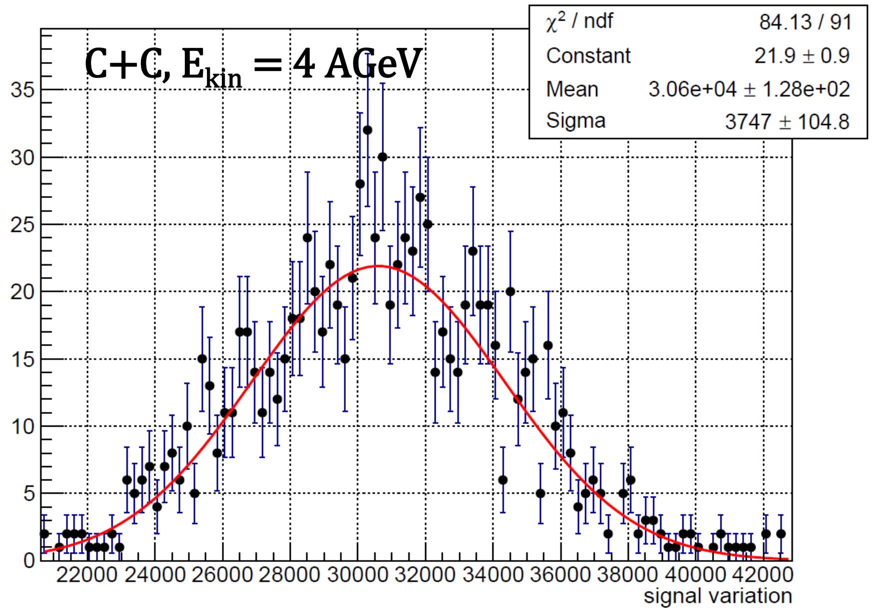
1) Split (y, pT) area in small cells for MC/DATA (8x8);
2) To each event assigned the weight ε_{acc_i};
3) Sum the cells by $\sum_{ij} y_{ij}$ and by $\sum_{ij} pT_{ij}$

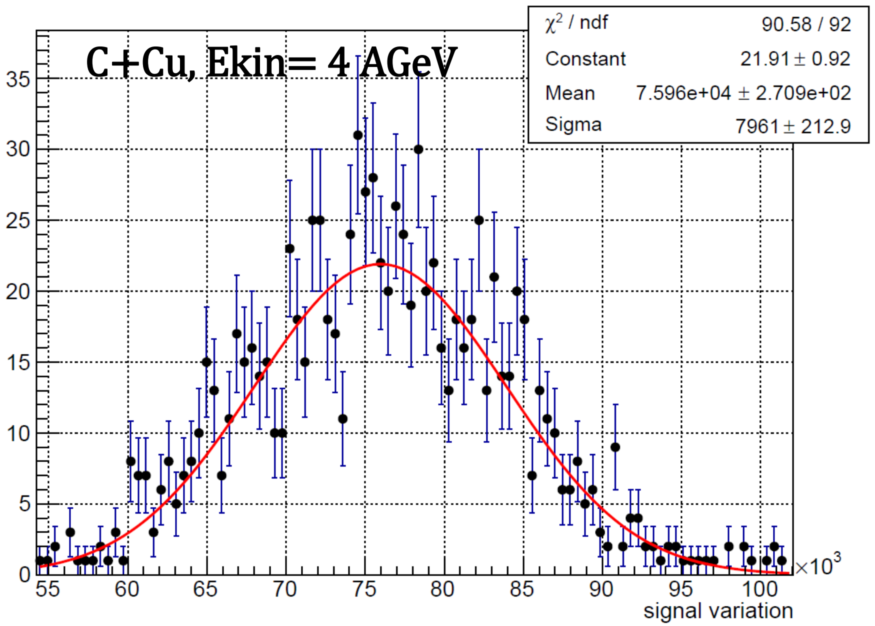
$0.1 < p_T < 1.05$
and
$1.2 < y_{lab} < 2.1$

Signal = hist – Background in 1075 - 1250 MeV/c²;

The violet lines represent the result of the fit by the sum of the threshold and exponential functions;

Uncertainties from signal variation (BM@N DATA)





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

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

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

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

Cross sections $\sigma_\Lambda(y/p_T)$ of the Λ and yields (BM@N)

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

$$\sigma_\Lambda(p_T) = \underbrace{[\textstyle\sum_y N_{rec}^\Lambda(y,p_T)/\varepsilon_{rec}(y,p_T)]}_{\text{weighted signal}}/[\varepsilon_{trig}\cdot\varepsilon_{pileup}\cdot L]$$

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

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

L is the luminosity, $\boldsymbol{N_{rec}^\Lambda}$ is the number of recontacted Λ-hyperons,

$\boldsymbol{\varepsilon_{rec}}$ is the combined efficiency of the Λ - hyperon reconstruction,

$\boldsymbol{\varepsilon_{trig}}$ is the trigger efficiency, $\boldsymbol{\varepsilon_{pileup}}$ is the suppression factors of reconstructed events.

$\boldsymbol{\sigma_{inel}}$ is the cross section for minimum bias inelastic C+A interactions(DCM-QGSM model).

Yield RESULTS (Preliminary)

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 (BM@N acceptance)				
C + C	4.0	0.023 ± 0.003 ± 0.005	4.5	0.027 ± 0.005 ± 0.006
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		-		0.033 ± 0.010 ± 0.010

Systematic evaluation: Cut variation

An approach in the estimation of systematic uncertainties related to the variation of selection criteria for events with Λ-hyperons.

The selection criteria based only on two parameters **path, dca.**

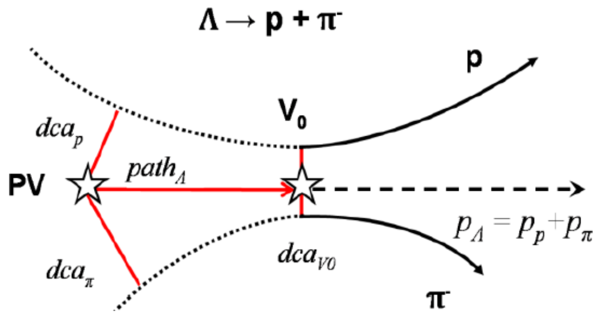
Nominal values:

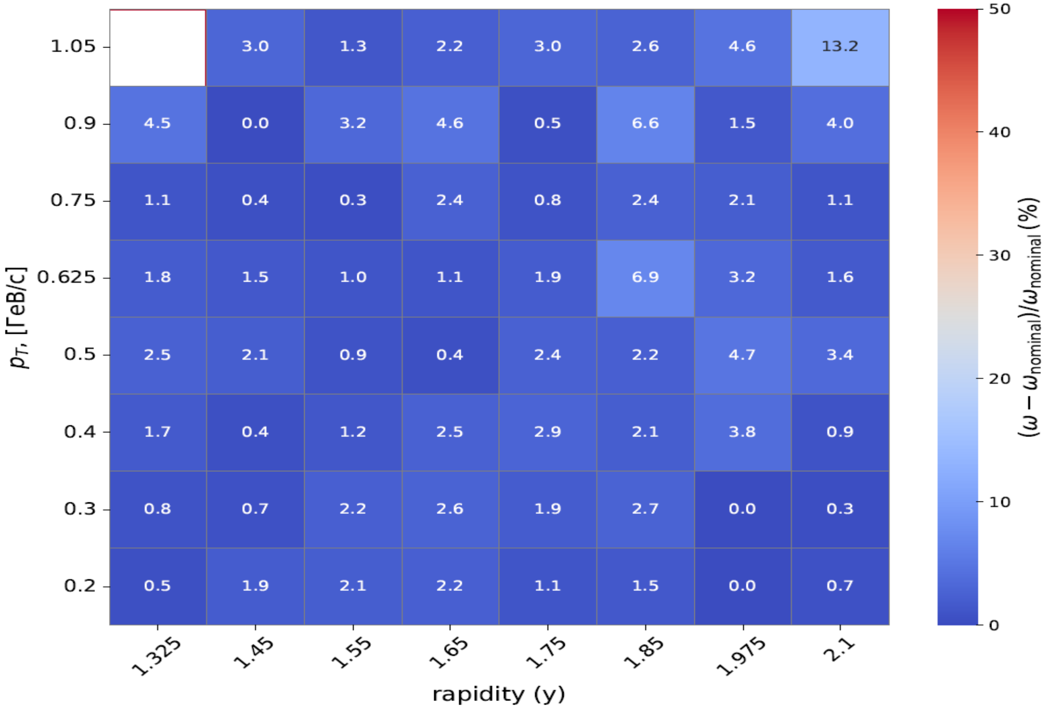
1 | **path** > 2.5 cm

2 | **dca** < 1 cm

±10%

Variation of nominal values





Event topology:

PV – primary vertex

V0 – vertex of hyperon decay

dca – distance of the closest approach

path – decay length

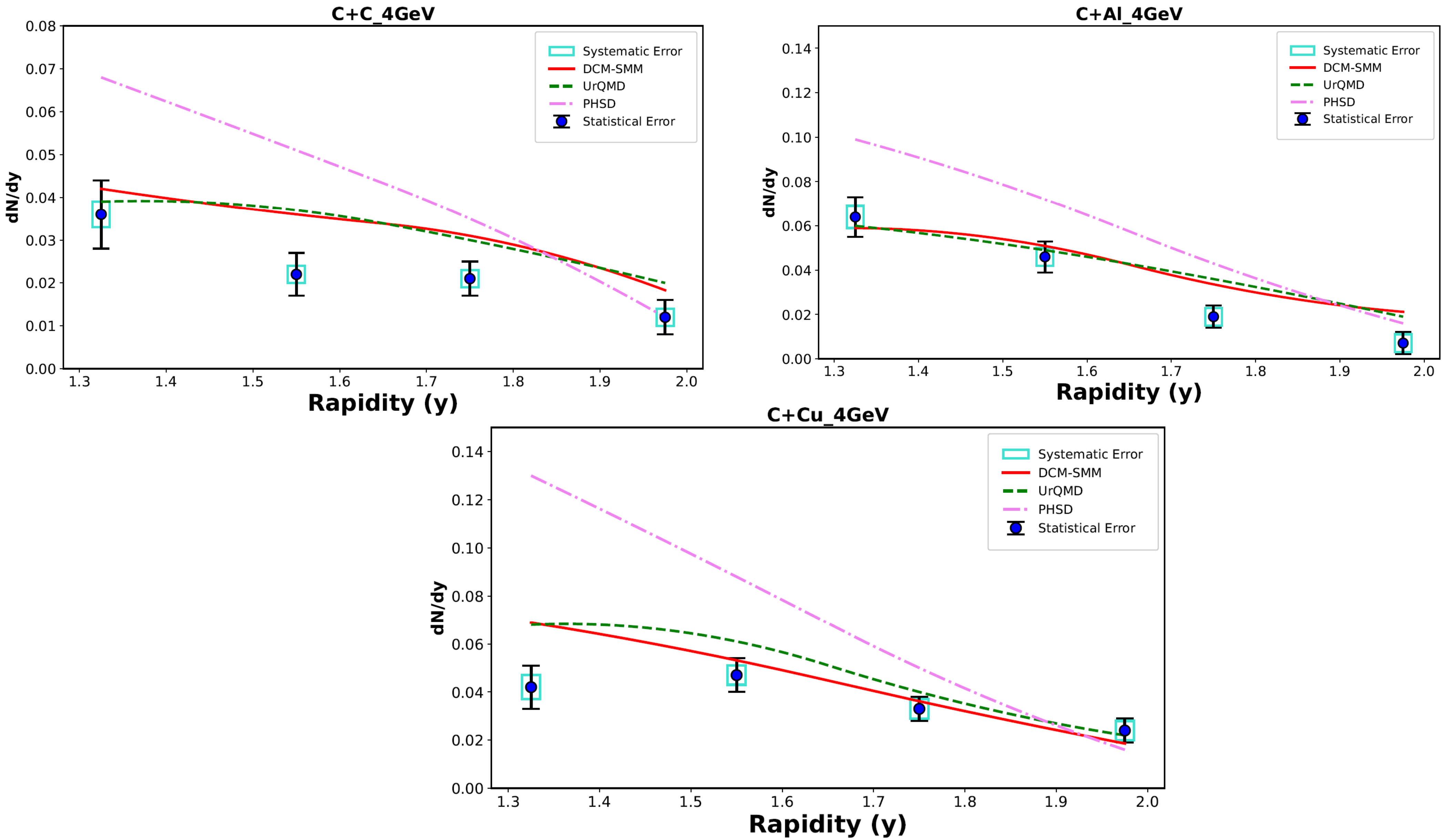
Calculation of systematic uncertainties yields of the $\boldsymbol{\Lambda}$

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

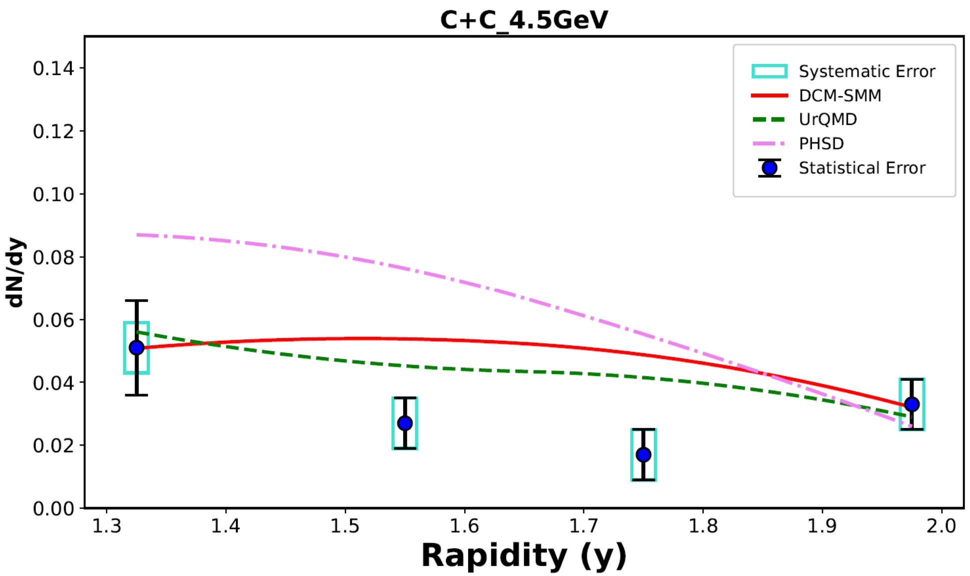
2 $\boldsymbol{\Delta Y_{\Lambda_{sys_{cut\_var}}} = 0.004}$ – from the variation of the $\boldsymbol{\Lambda}$-hyperon selection criteria;

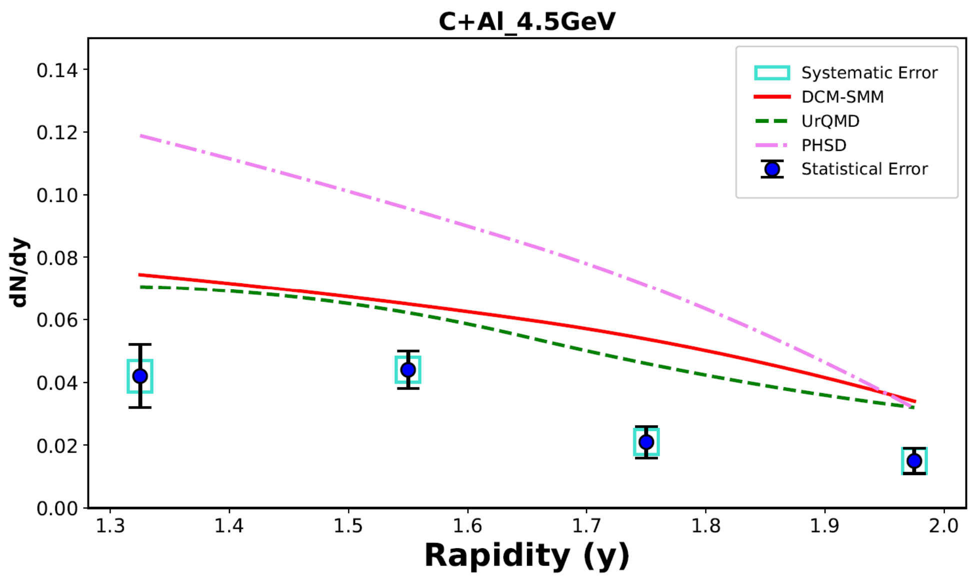
3 $\Delta Y_{\Lambda_{sys}} = \sqrt{\Delta Y_{\Lambda_{sys\_pseudo\_exp}}{}^2 + \Delta Y_{\Lambda_{sys_{cut\_var}}}{}^2}$ – total systematic uncertainty;

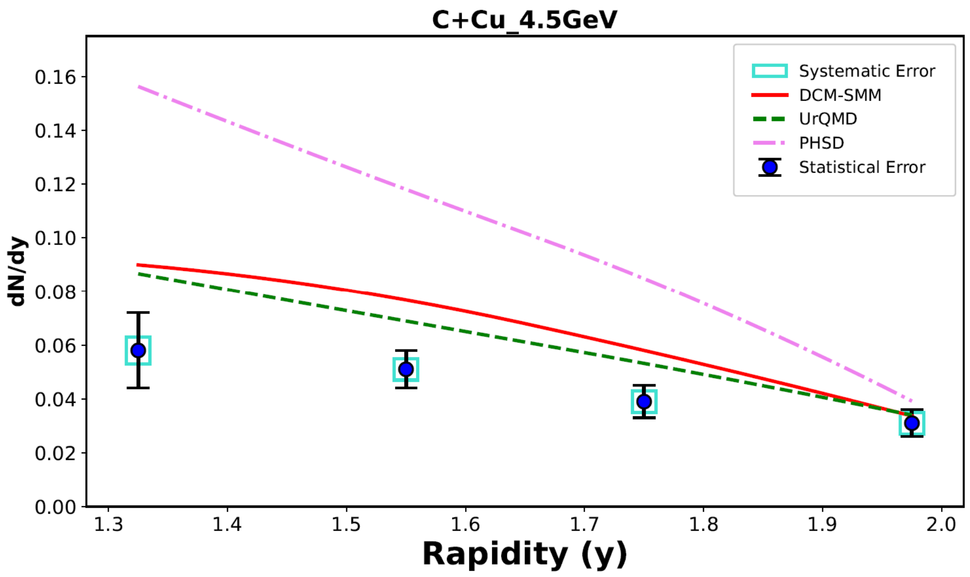
Rapidity (y) spectra of Λ hyperons vs models predictions (Preliminary)

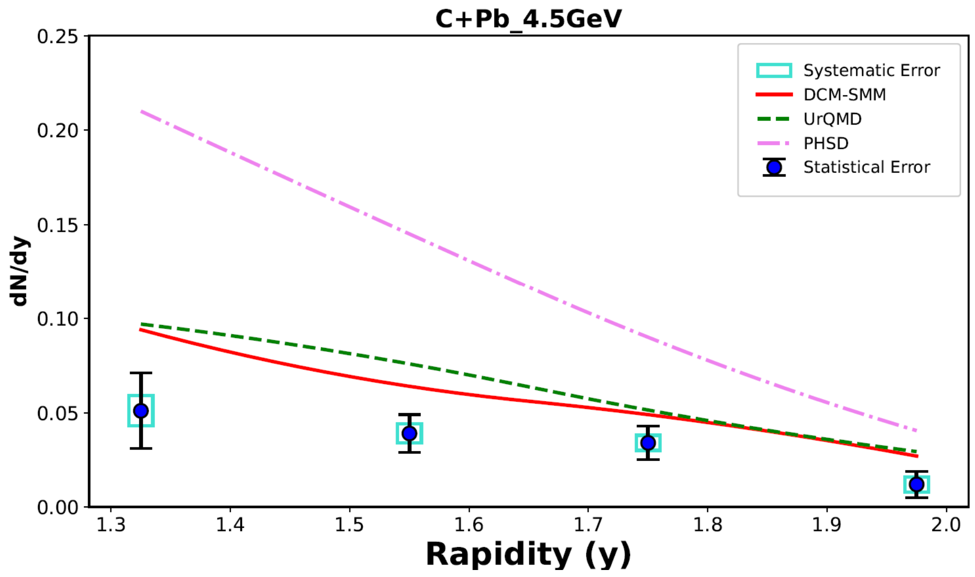


Rapidity (y) spectra of Λ hyperons vs models predictions (Preliminary)

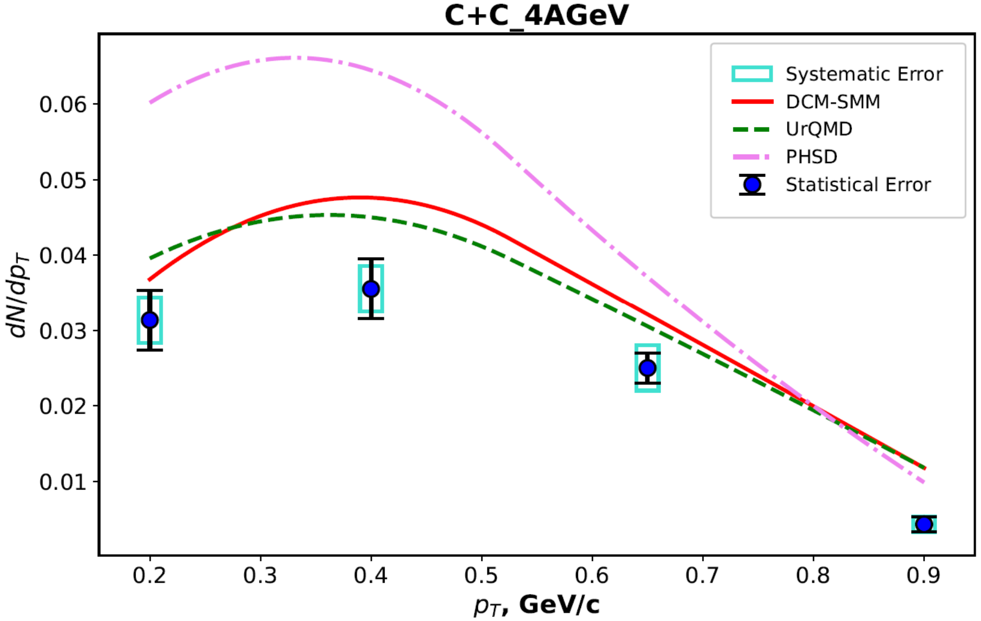


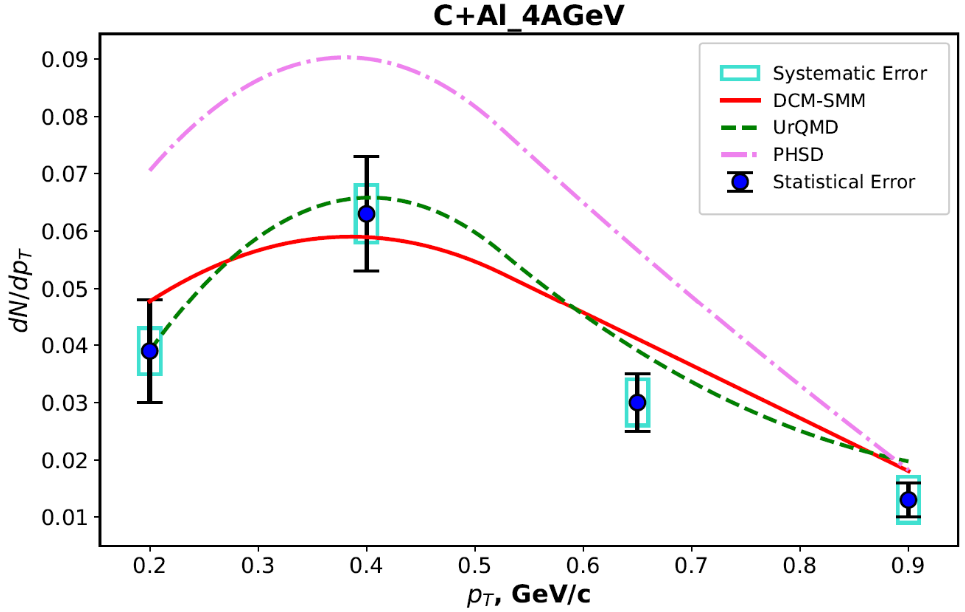


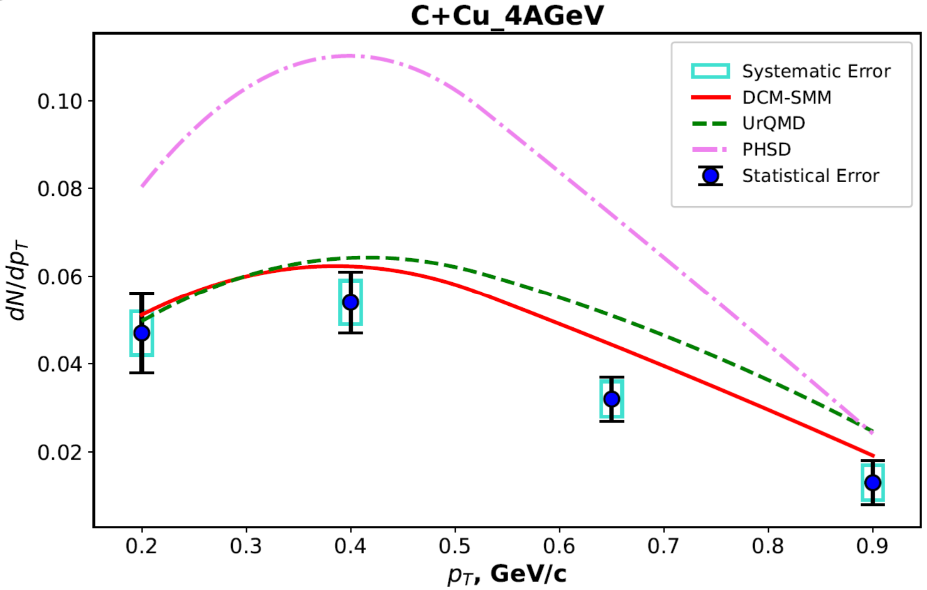




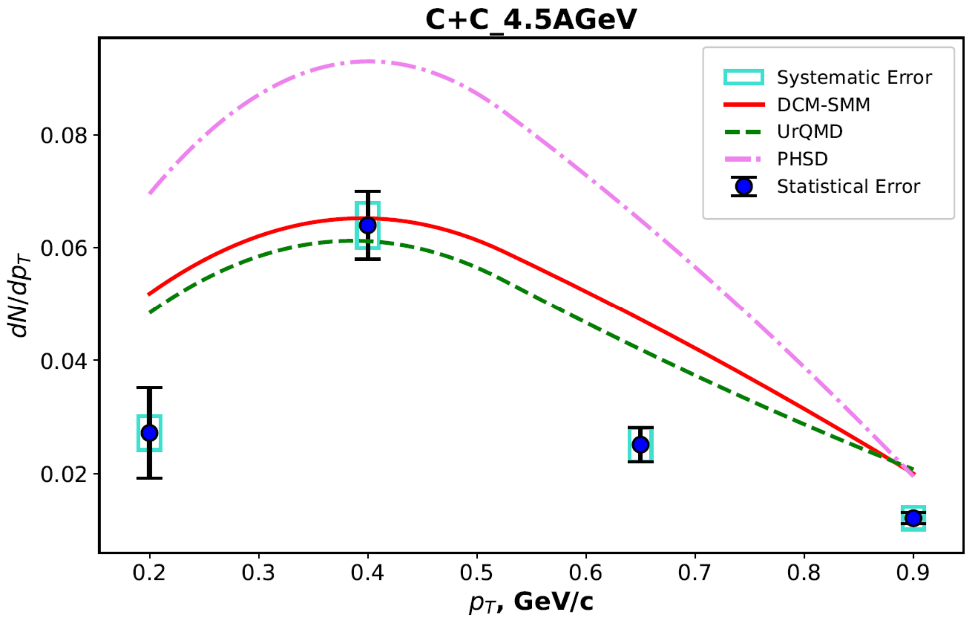
p_T spectra of Λ hyperons vs models predictions (Preliminary)

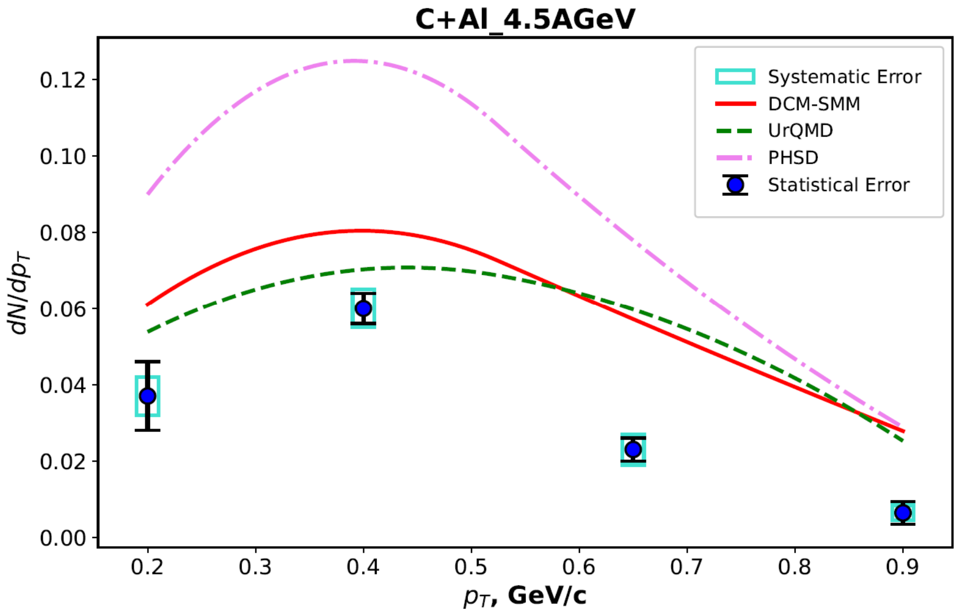


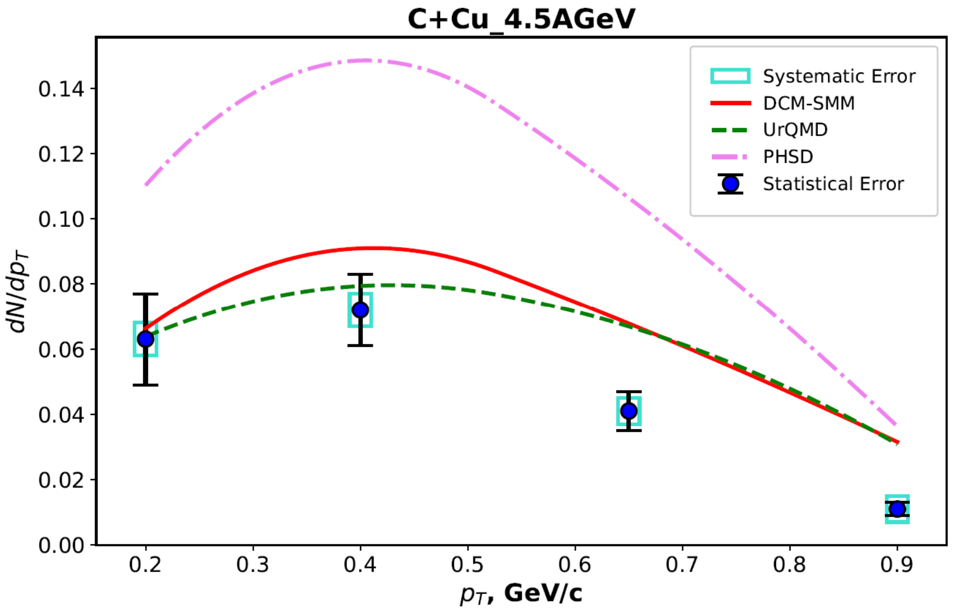


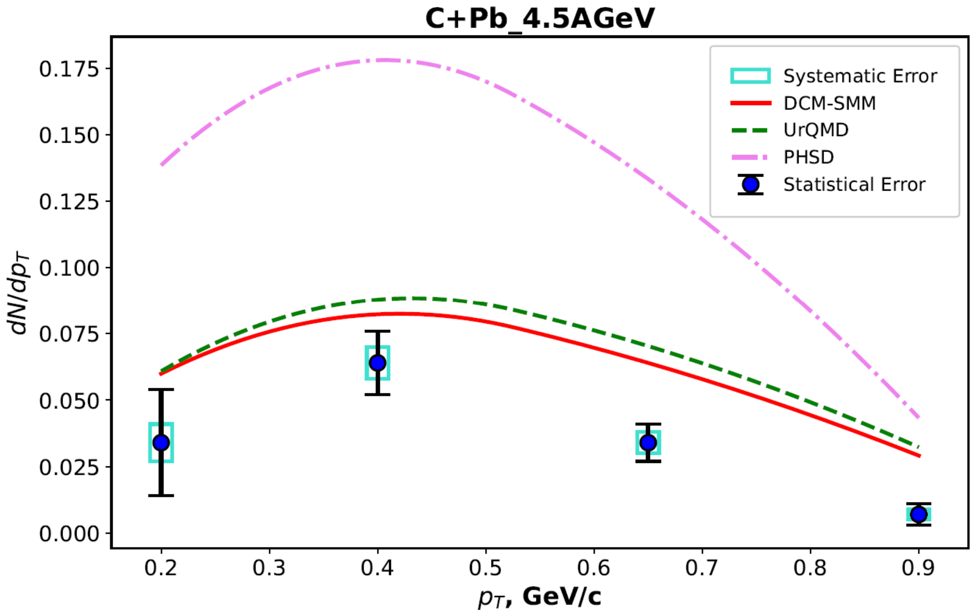


p_T spectra of Λ hyperons vs models predictions(Preliminary)

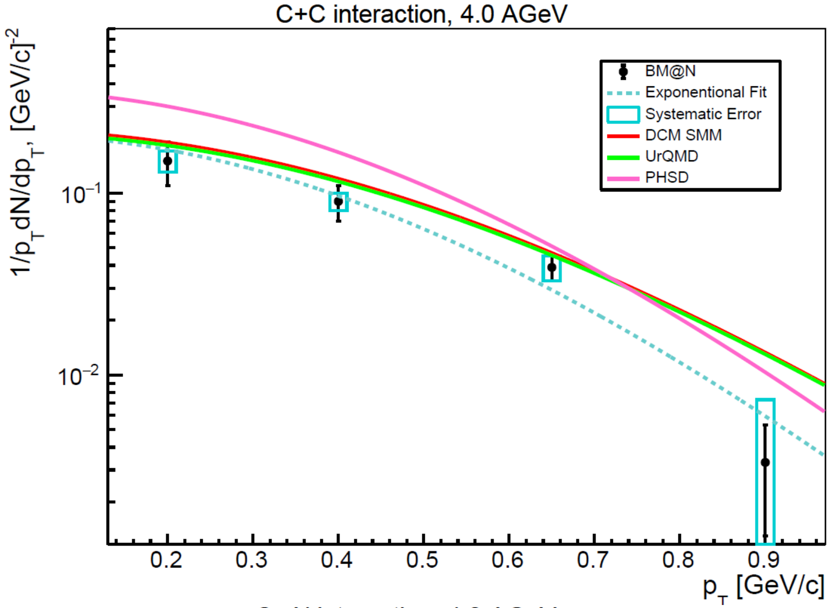








Invariant pT spectra of Λ hyperons vs models predictions (Preliminary)



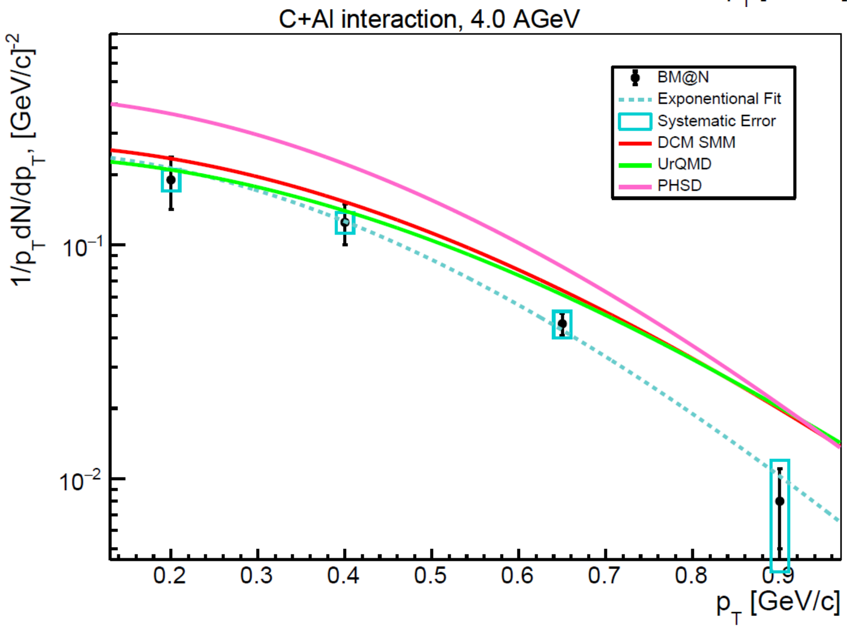
The measured spectra of the Λ yields in p_T are parameterized by the formula:

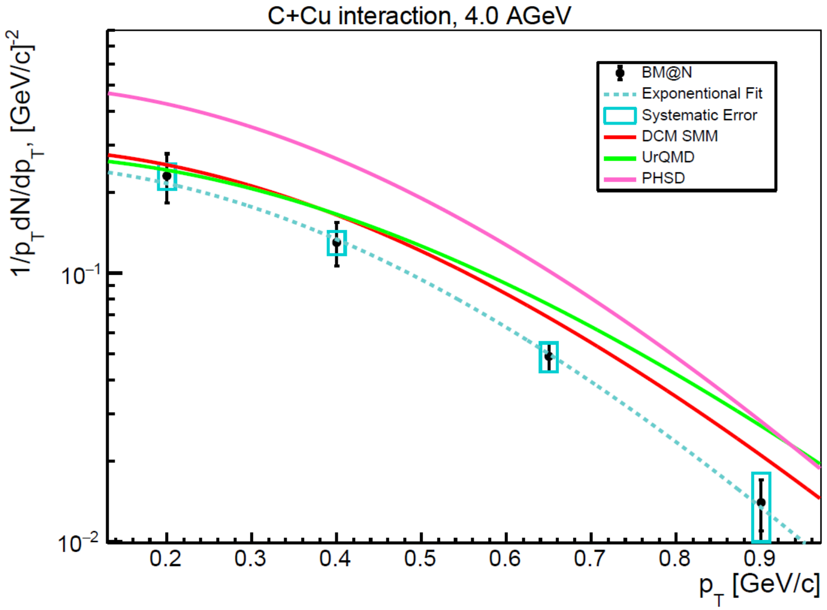
$$1/p_T\, d^2N/dp_T dy = N \cdot \exp(-(m_T - m_\Lambda)/T_0)$$

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

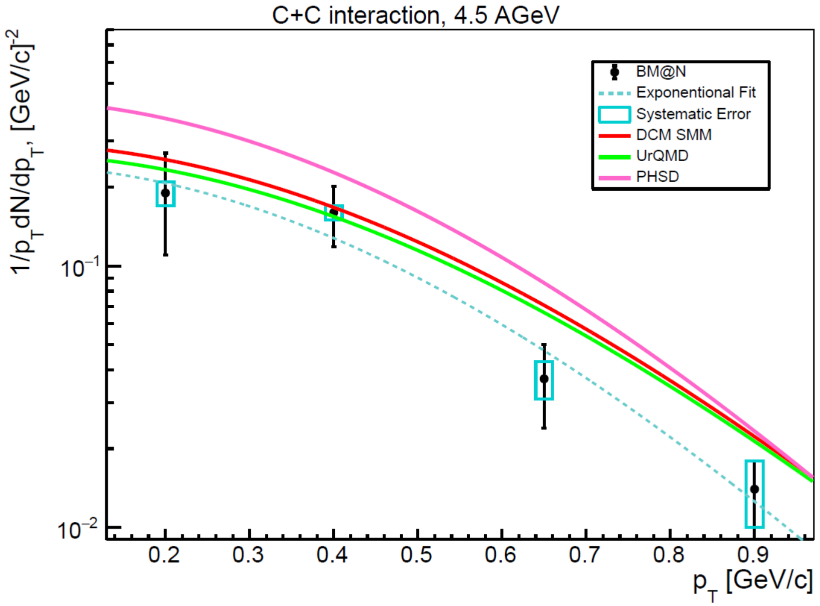
The **N** normalization,

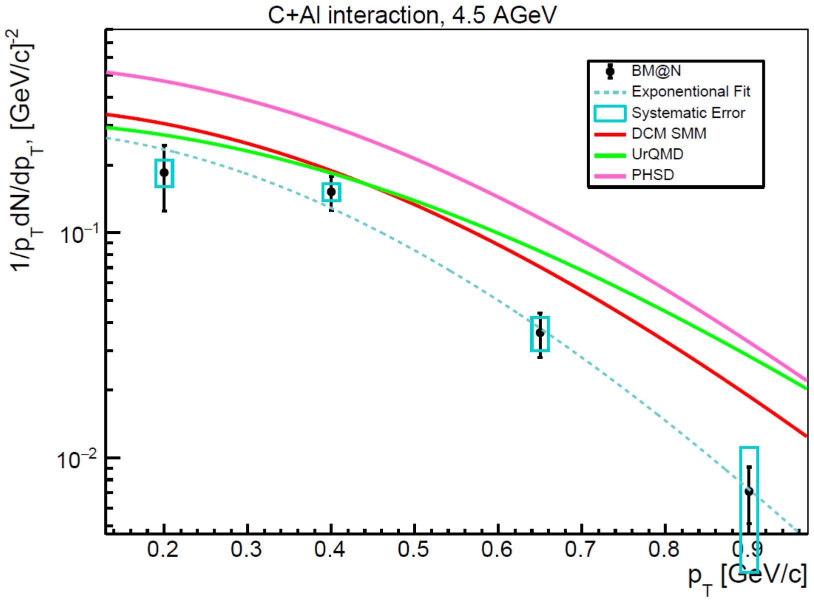
The inverse slope parameter T_0 are free parameters of the fit;

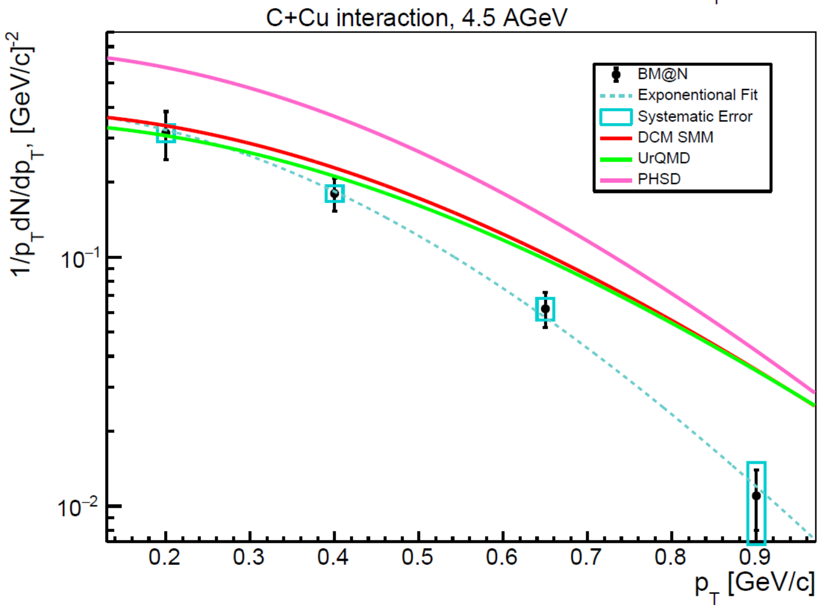


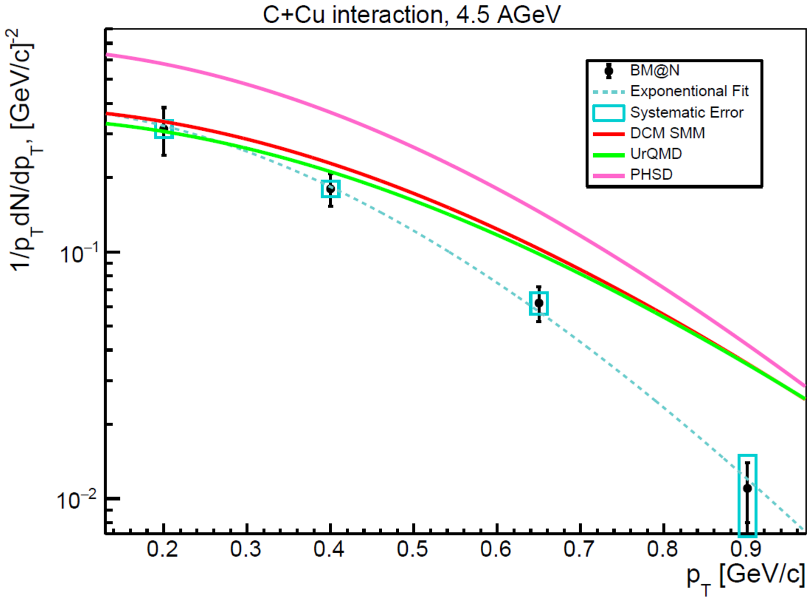


Invariant p_T spectra of Λ hyperons vs models predictions (Preliminary)









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	89 ± 9 ± 17	99 ± 10 ± 16	108 ± 11 ± 14	Low statistic
DCM - SMM	109 ± 1	117 ±3	117 ± 3	123 ± 4
UrQMD	114 ± 7	128 ± 7	137± 6	135 ± 8
PHSD	89 ± 3	105 ± 3	111 ± 7	102 ± 4

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	107 ± 17 ± 17	86 ± 8 ± 17	91 ± 8 ± 15	99 ± 17 ± 20
DCM - SMM	118 ± 2	126 ± 4	129 ± 2	130 ± 1
UrQMD	125 ± 4	132 ± 7	138 ± 8	143 ± 6
PHSD	109 ± 5	113 ± 5	115 ± 5	113 ± 5

Extrapolation in full kinematic range

DCM-SMM
and
URQMD

The extrapolation factor was calculated as the arithmetic average of the two models

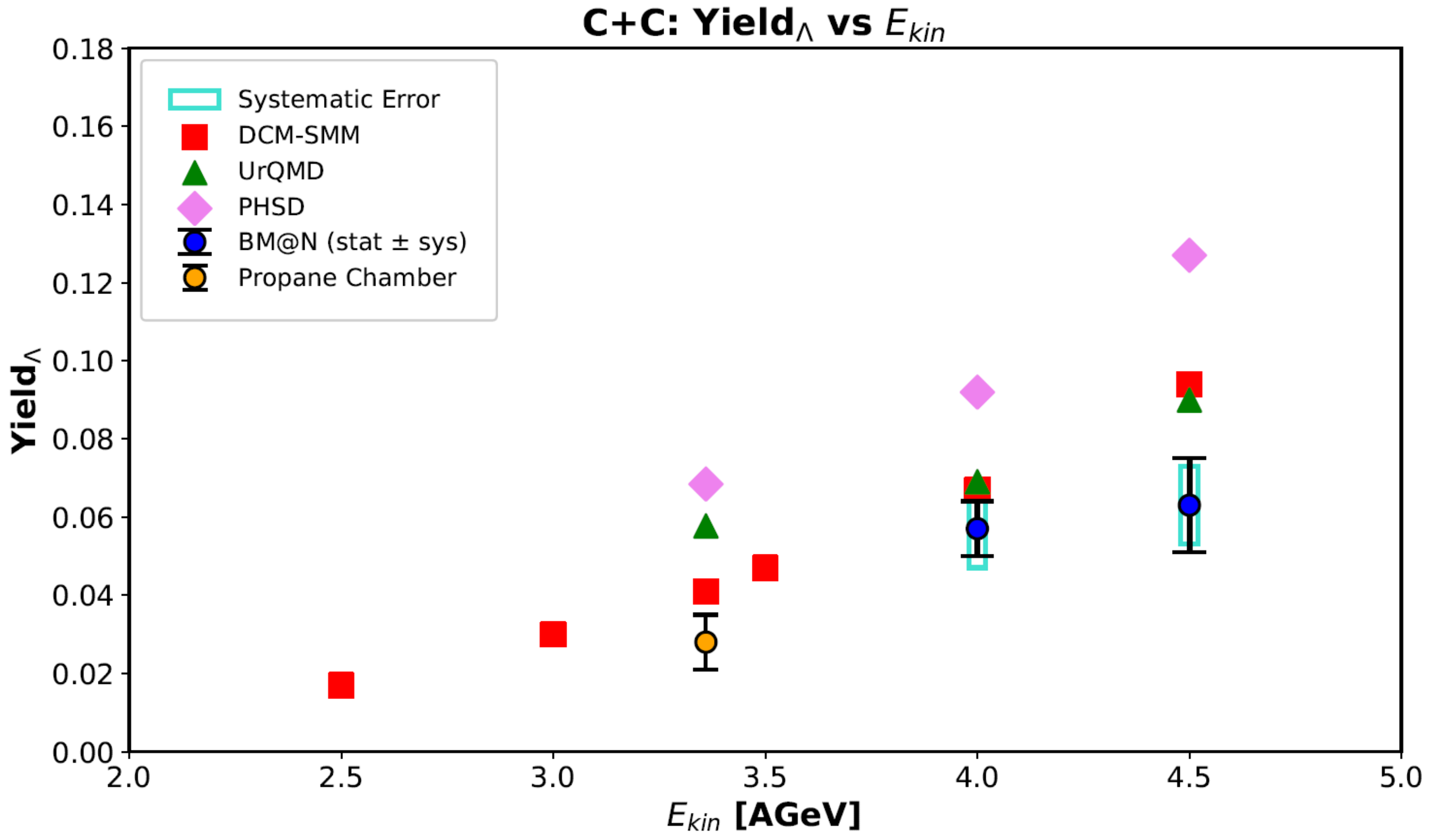
Measurement in BM@N acceptance

Yields of the Λ hyperon are multiplied by an extrapolation factor

Compare results

with other experiment and prediction model in full kinematic range

Energy dependence of Λ yields measured in C+C interactions



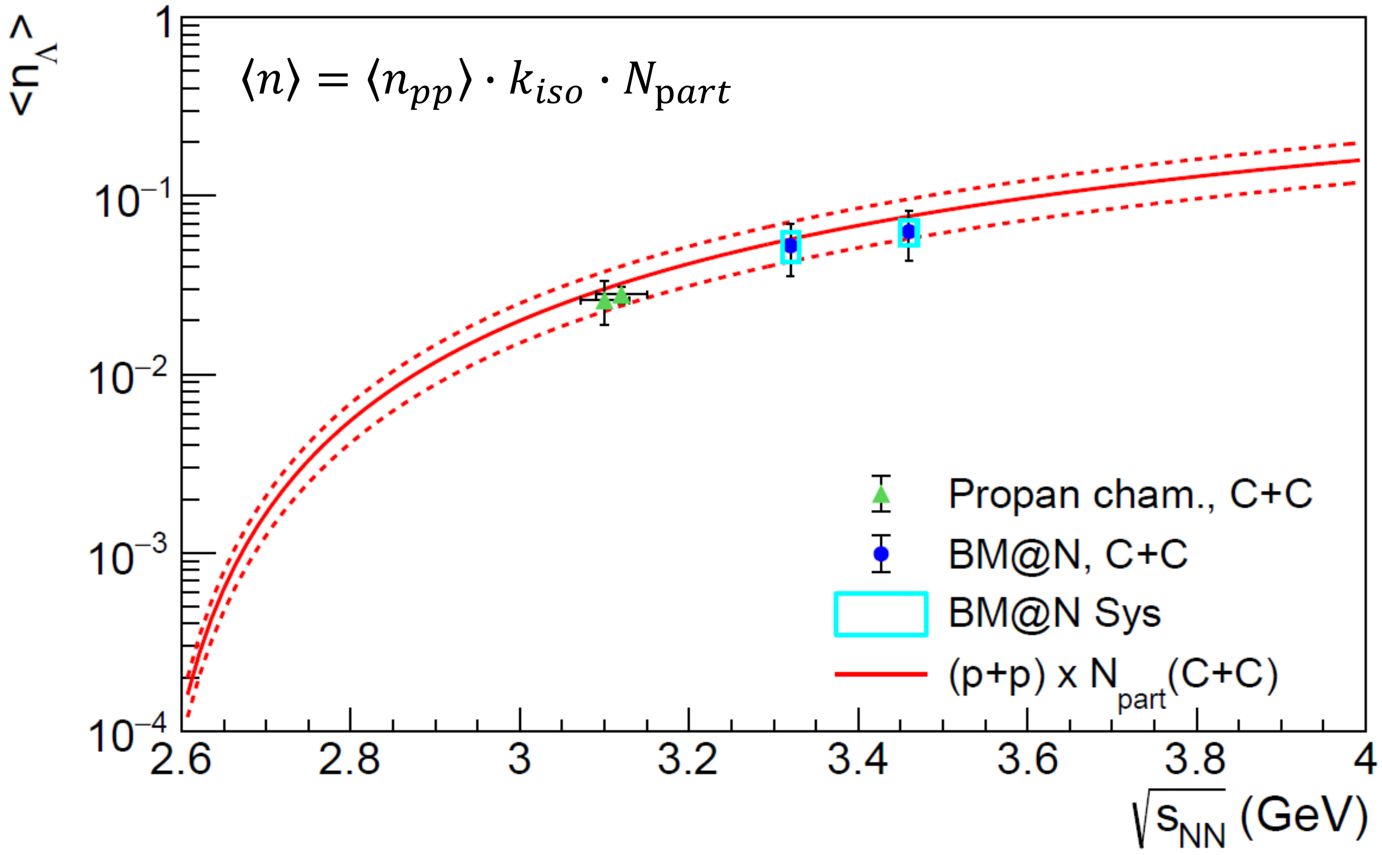
BM@N, 4 AGeV:
$(5.7\pm0.7\pm1.0)\cdot10^{-2}$

Propane Chamber, 3.36 AGeV:
$(2.89\pm0.72)\cdot10^{-2}$

The predictions of the **DCM-SMM**, UrQMD and PHSD models

HADES , 2 AGeV :
$0.0092\pm0.0012\pm^{0.0034}_{0.0017}$
unpublished data

Parameterisation for proton-proton collisions (pp) scaled to the C + C system



The parameterisation was based on the Lund-String-Model (LSM) from **[1]**:

$$\langle \mathbf{n} \rangle = \mathbf{a}(\mathbf{x}-\mathbf{1})^{\mathbf{b}}(\mathbf{x}^{-\mathbf{c}})$$

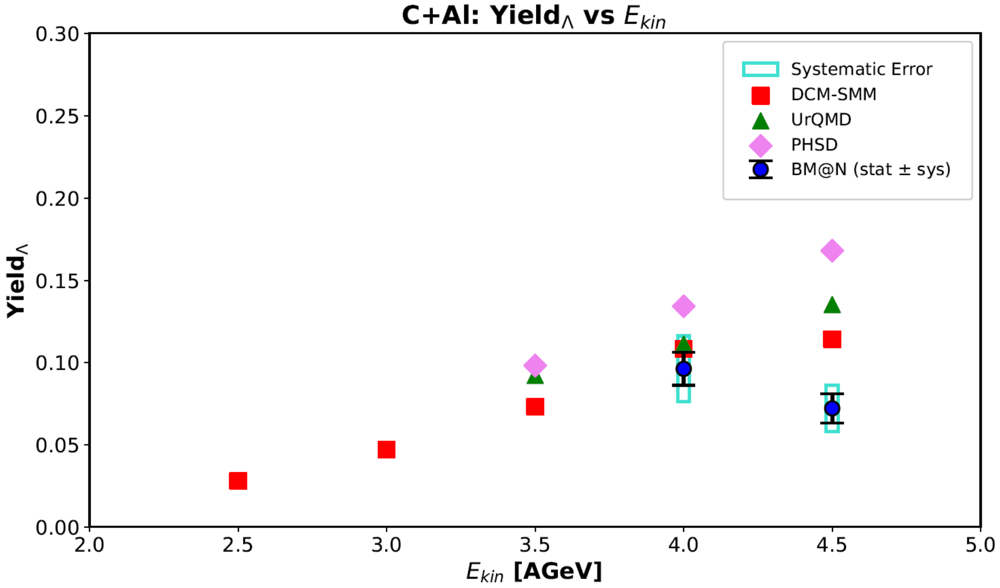
where $x = s/s_0$ is the square of the center-of-mass energy, s_0 is the square of the production threshold, and **a, b, c** are the fit parameters **[2]**.

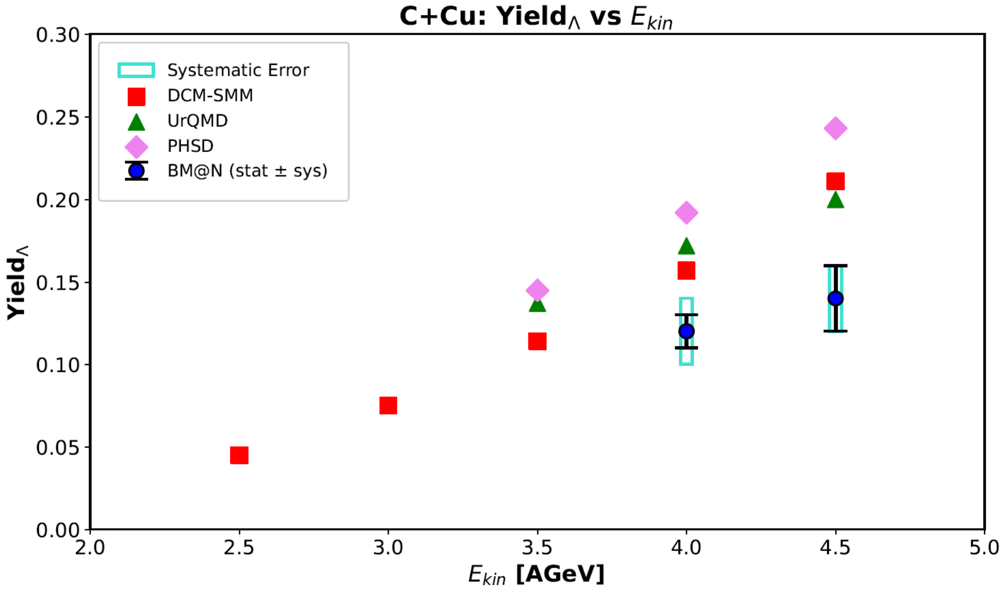
N_{part} = 9 (DCM – SMM);

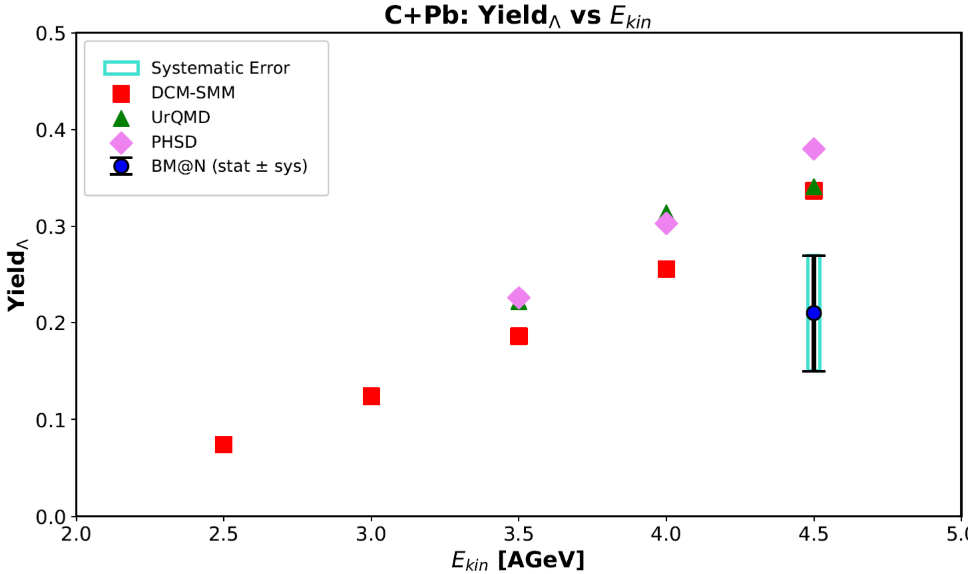
Dashed red lines indicate the uncertainties in the predicted excitation function (about 25%).

1. W. Cassing and E. L. Bratkovskaya, "Hadronic and electromagnetic probes of hot and dense nuclear matter," Phys. Rep. 308, 65 (1999).
2. V. Kolesnikov at al, A New Review of Excitation Functions of Hadron Production in pp Collisions in the NICA Energy Range, PEPAN Letters (2020), Vol. 17, №2, pp. 388 142-153.

Energy dependence of Λ yields measured in C+Al, C+Cu, C+Pb interactions

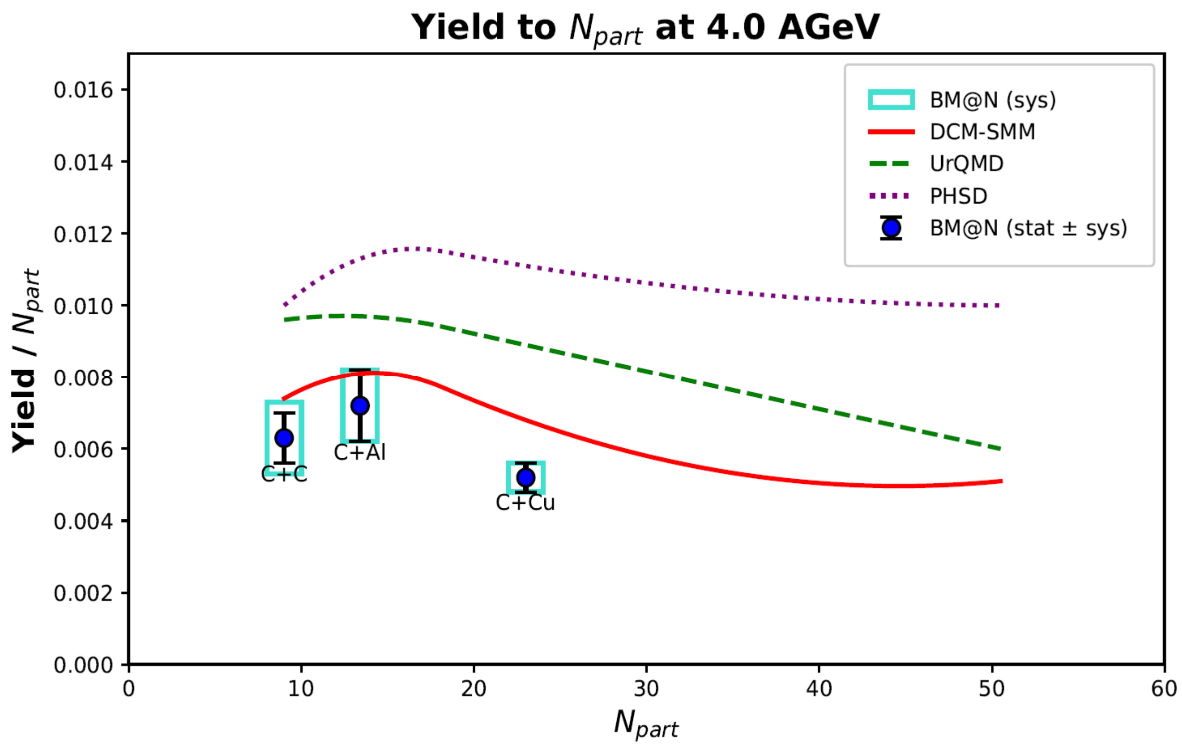


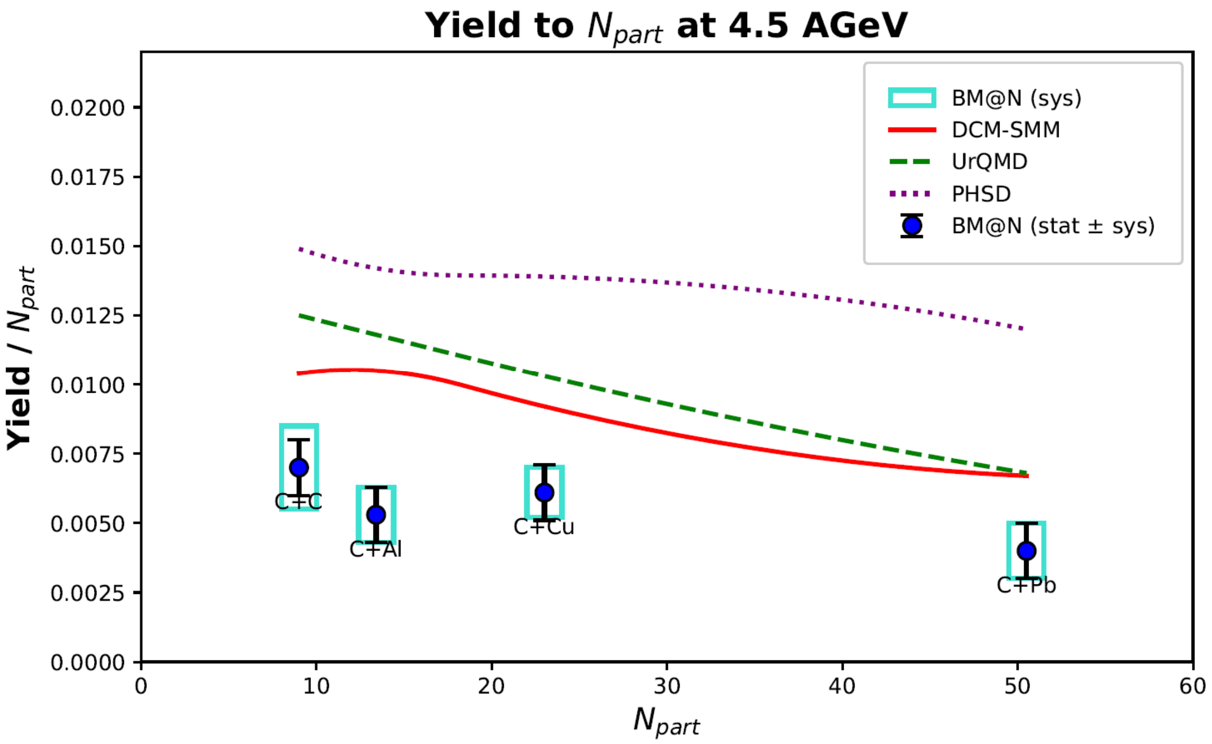




The predictions of the DCM-SMM, UrQMD and PHSD models

Ratios of the Λ hyperon yields to the number of nucleons-participants measured in BM@N carbon-nucleus interactions at 4.0 AGeV (left) and 4.5 AGeV (right)





The predictions of the **DCM-SMM**, UrQMD and **PHSD** models

Summary

Cross sections(σ_Λ), yields (Y_Λ), slope T_0 were measured and compare prediction model

24 ± 6 mb

The results of the Propane Chamber experiment at energy of **3.36 AGeV**

47 ± 6 mb

Cross sections for carbon-carbon collisions at **4 AGeV** in the full kinematic range were obtained(BM@N)

52 ± 10 mb

Cross sections for carbon-carbon collisions at **4.5 AGeV** in the full kinematic range were obtained (BM@N)

Summary

In the energy range 4 - 4.5 AGeV this difference is not significant and the temperature values are close within the error.

4 AGeV

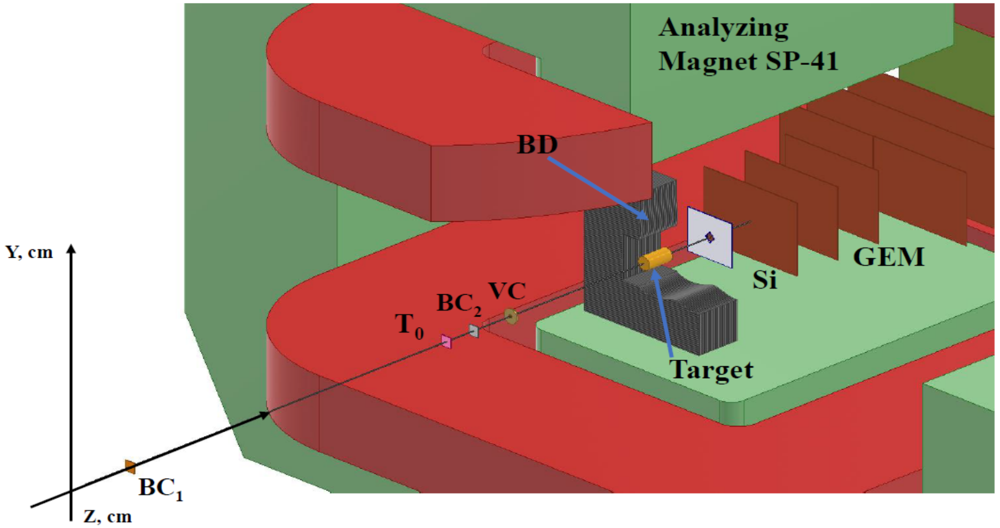
T_0 = **89 ± 9 ± 17** MeV (C+C interactions) to **108 ± 11 ± 14** MeV (C+Cu interactions)

4.5 AGeV

T_0 = **107 ± 15 ± 17** MeV (C+C interactions) to **99 ± 17 ± 20** MeV (C+Pb interactions)

BACK UP

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.

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

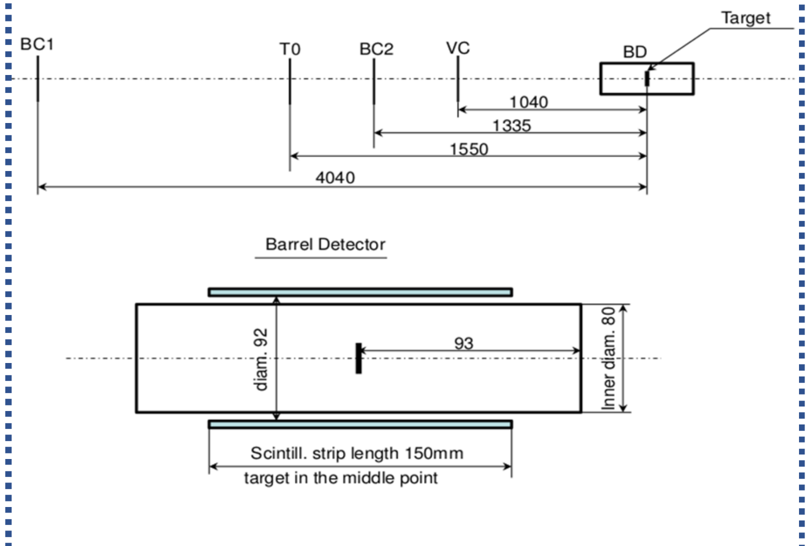
The systematic errors in Table 1 cover:

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

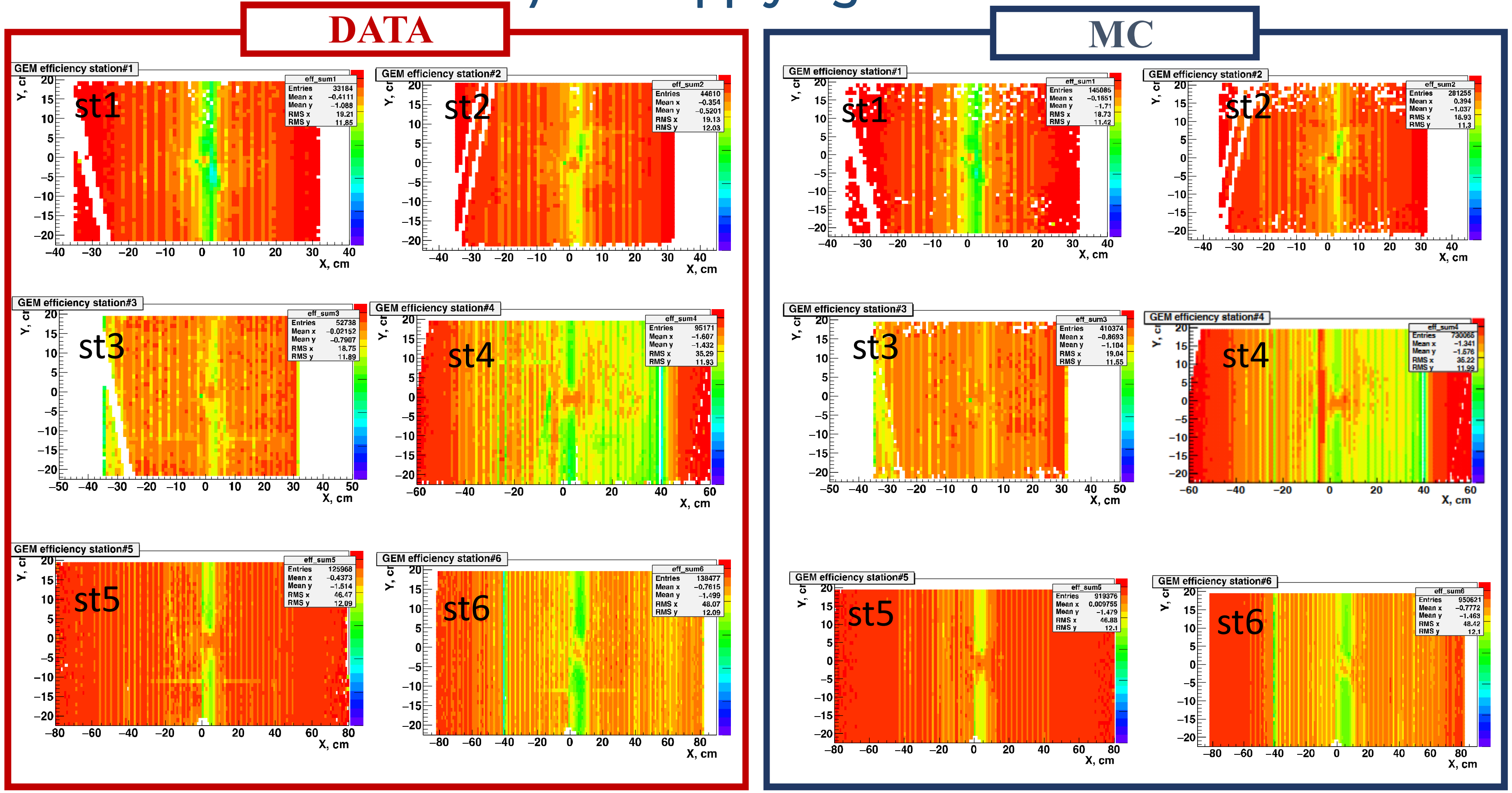
4.5 AGeV	C	Al	Cu	Pb
ε_{trig}(BD≥2)	0.80±0.02	-	-	-
ε_{trig}(BD≥3)	-	0.83±0.02	0.91±0.02	0.94±0.02



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

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

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

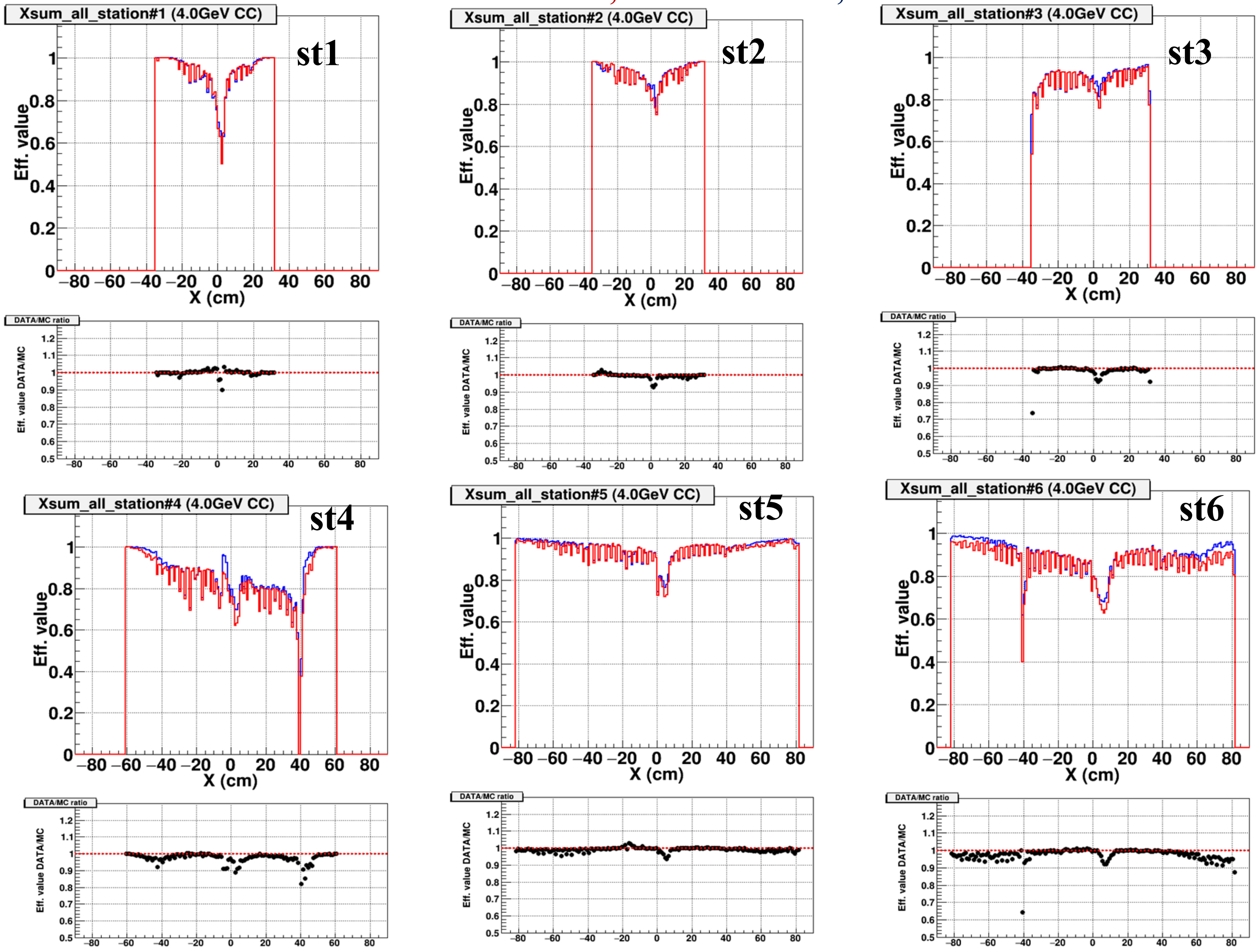


For each GEM station they were estimated using the following approach:

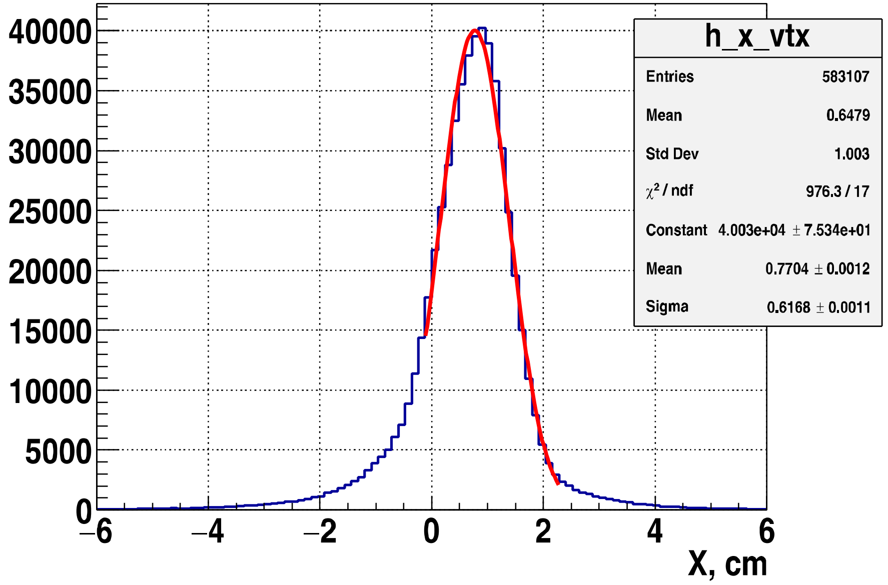
1. Select good quality tracks with the number of hits per track (excluding the station under study) not less than N;
2. Check that track crosses the detector area, if yes, add one track to the denominator;
3. If there is a hit in the detector, which belongs to the track, add one track to the numerator;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

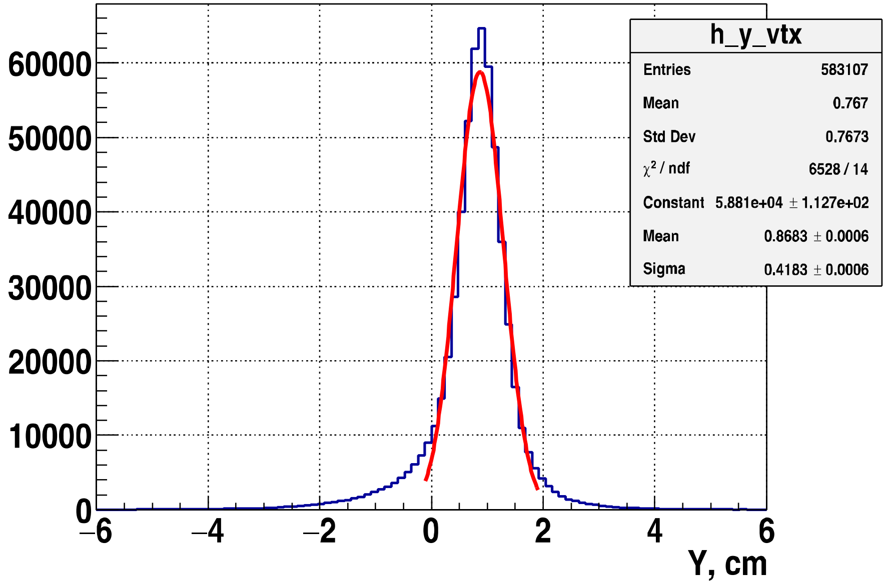
1D GEM efficiency comparison between the experimental data and MC (4.0GeV C+C)

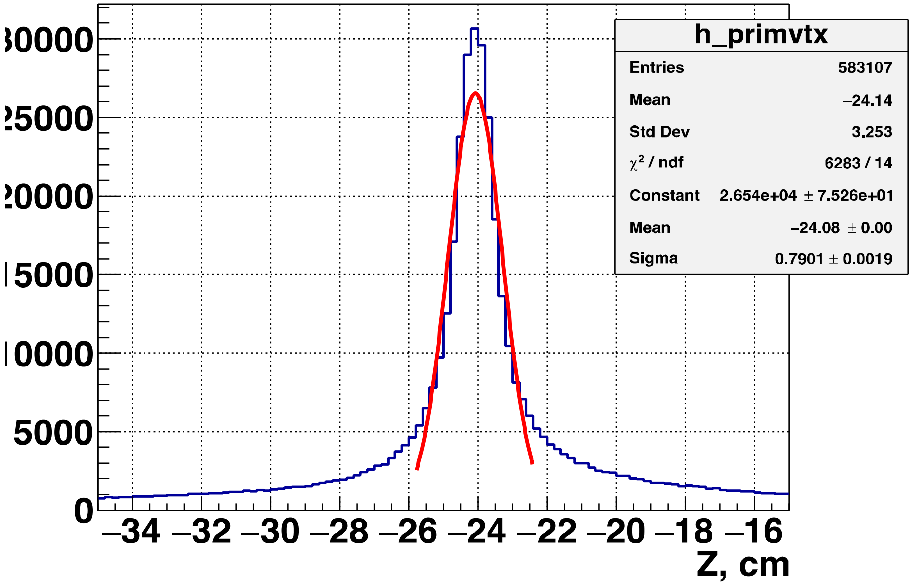
Data–red line, MC–blue line;



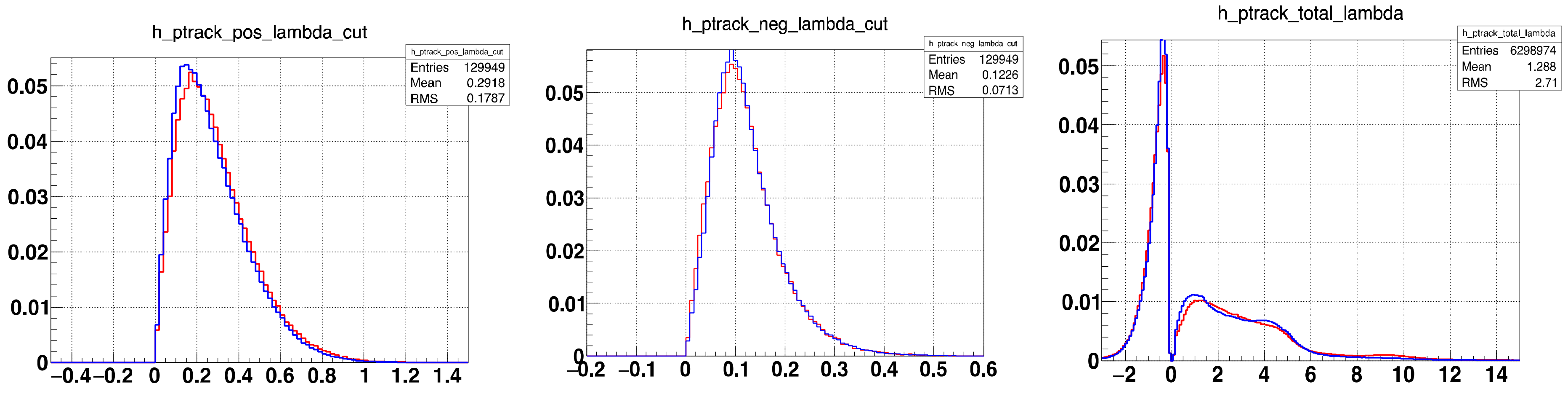
X, Y, Z distributions of the experimental primary vertex







Data and Monte - Carlo comparison



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.

The suppression factors

- The suppression factors of reconstructed events $\varepsilon_{\text{pileup}}$ 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. $\varepsilon_{\text{pileup}}$ 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:

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

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

L is the luminosity, $\boldsymbol{N^\Lambda_{rec}}$ is the number of recontacted Λ-hyperons,

$\boldsymbol{\varepsilon_{rec}}$ is the combined efficiency of the Λ - hyperon reconstruction,

$\boldsymbol{\varepsilon_{trig}}$ is the trigger efficiency, $\boldsymbol{\varepsilon_{pileup}}$ 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 $\boldsymbol{Y_\Lambda}$ of Λ hyperon in C+A interactions are calculated in bins of (y - pT) cells according to the formula:

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

$\boldsymbol{\sigma_{inel}}$ 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 $\boldsymbol{\sigma_{inel}}$ 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.