Λ hyperon yields in carbon-nucleus interactions

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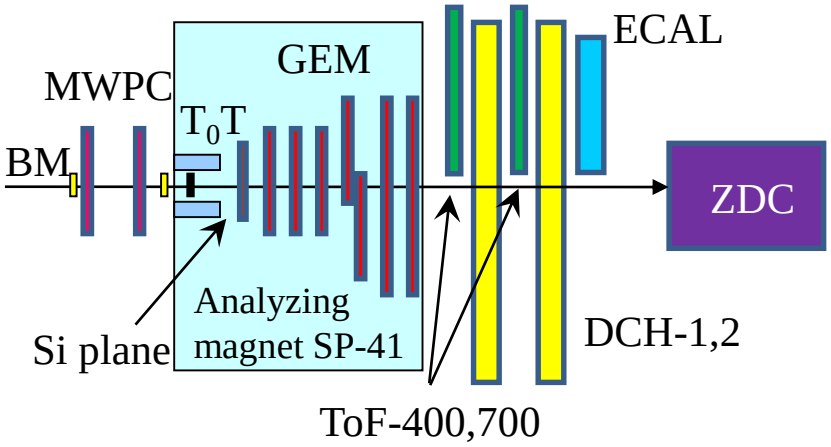
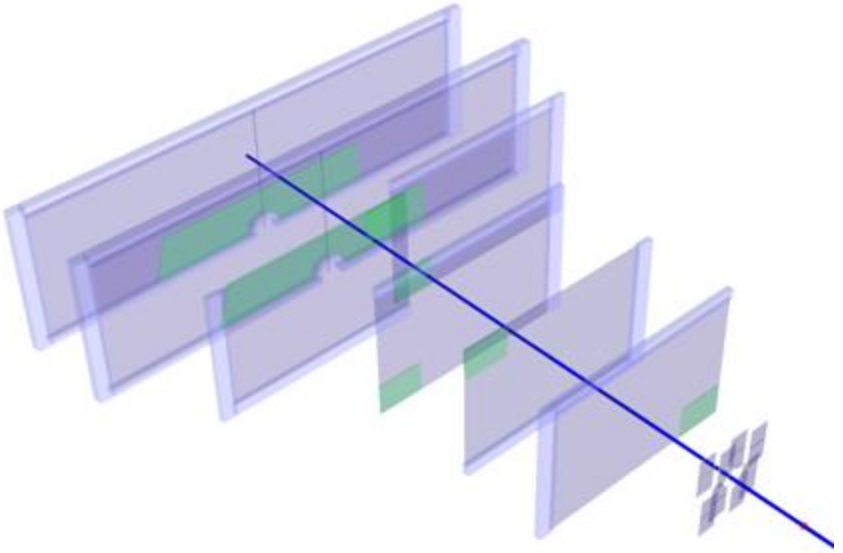
Outline

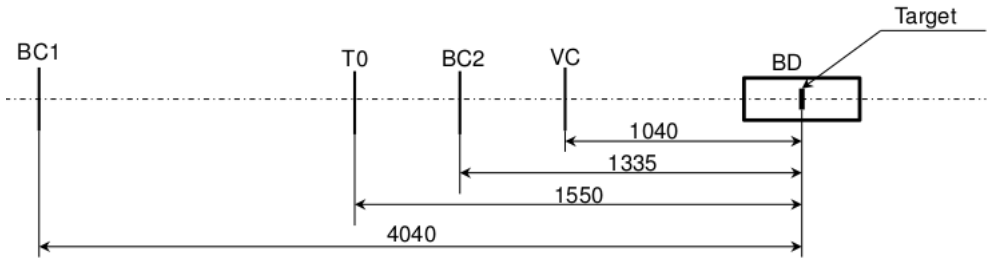
1. Run with carbon beam (March 2017)
   - ✓ BM@N detector set-up
2. Data analysis ($C+C$, $C+Al$, $C+Cu$, $C+Pb$ at 4A GeV and 4.5A GeV)
   - ✓ Selection criteria
   - ✓ Reconstructed signal of Λ (dN/dy & dN/p_T spectra)
   - ✓ Data – MC agreement: multiplicity, momentum spectra
   - ✓ Decomposition of Λ reconstruction efficiency
   - ✓ Cross section and yields of Λ
   - ✓ Reconstructed p_T spectra of Λ and extracted temperature
   - ✓ Systematic errors
3. Summary

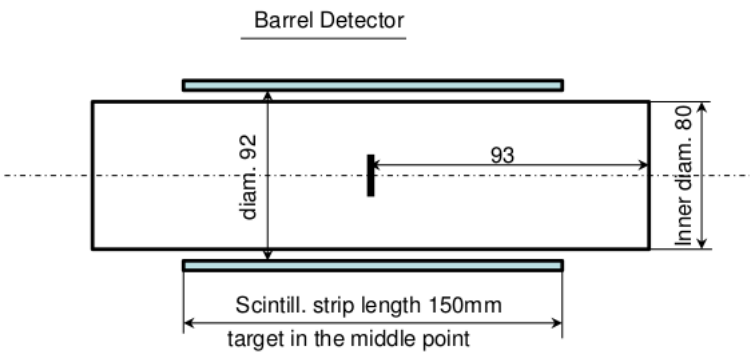
BM@N set-up in carbon run





Central tracker in carbon run.





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

Event selection criteria

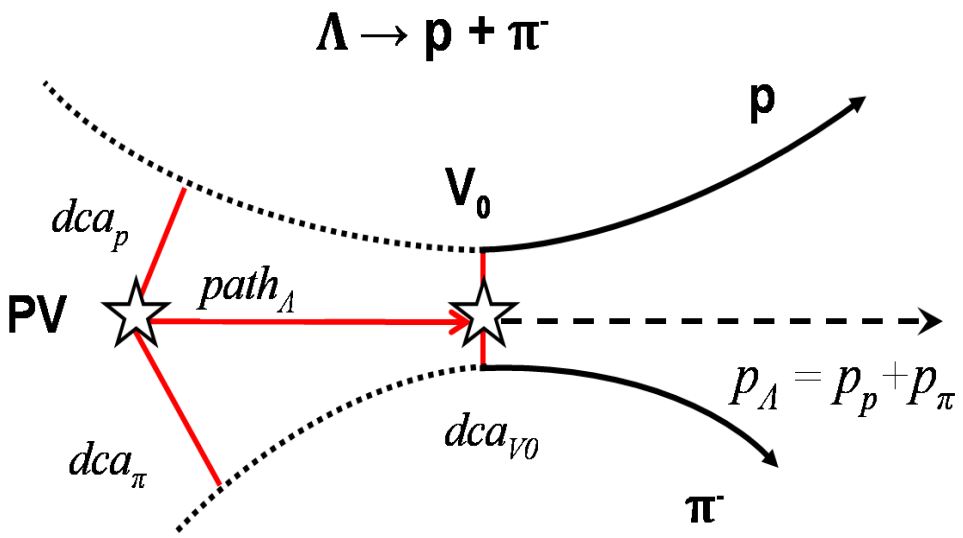
- ✓ Number of tracks in selected events: pos>=1, neg>=1;
- ✓ Beam halo, pile-up suppression within the readout time window: number of signals in the start detector: T0=1, number of signals in the beam counter: BC2=1, number of signals in the veto counter around the beam: Veto=0;
- ✓ Trigger condition in the barrel multiplicity detector: number of signals BD>=2 or BD>=3 (run dependent).

Selection	4AGeV	4.5AGeV
T0==1	+	+
BC2==1	+	+
VETO==0	+	+
C	0.64	0.53
Al	0.74	0.58
Cu	0.78	0.62
Pb	-	0.68

Table. Number of triggered events, beam fluxes and integrated luminosities collected in the carbon beam of 4.5A GeV (4A GeV).

Interactions (target thickness)	Number of triggers / 10^6	Integrated beam flux / 10^7	Integrated luminosity / 10^{30} cm^{-2}
C+C (9mm)	2.75(4.57)	4.53(6.99)	4.52(7.16)
C+Al (12mm)	3.23(5.35)	4.53(4.41)	3.27(3.11)
C+Cu (5mm)	3.76(5.31)	5.22(4.57)	2.22(1.98)
C+Pb (9.9mm)	2.36	2.62	0.86

Λ hyperon selection criteria



Event topology:

- ✓ PV – primary vertex
- ✓ V_0 – vertex of hyperon decay
- ✓ *dca* – distance of the closest approach
- ✓ *path* – decay length

- ✓ Number of hits in 1 Si + 6 GEM per track > 3
- ✓ Momentum range of positive tracks: 0.5 $< p_{pos} <$ 4.5 GeV/*c*
- ✓ Momentum range of negative tracks: 0.1 $< p_{neg} <$ 2.5 GeV/*c*
- ✓ Distance of minimum approach of *V0* tracks: *dca*< 1 cm
- ✓ Distance between *V0* and primary vertex: *path* > 2.5 cm

Signal of Λ in *C+C, C+Al, C+Cu, C+Pb* interactions

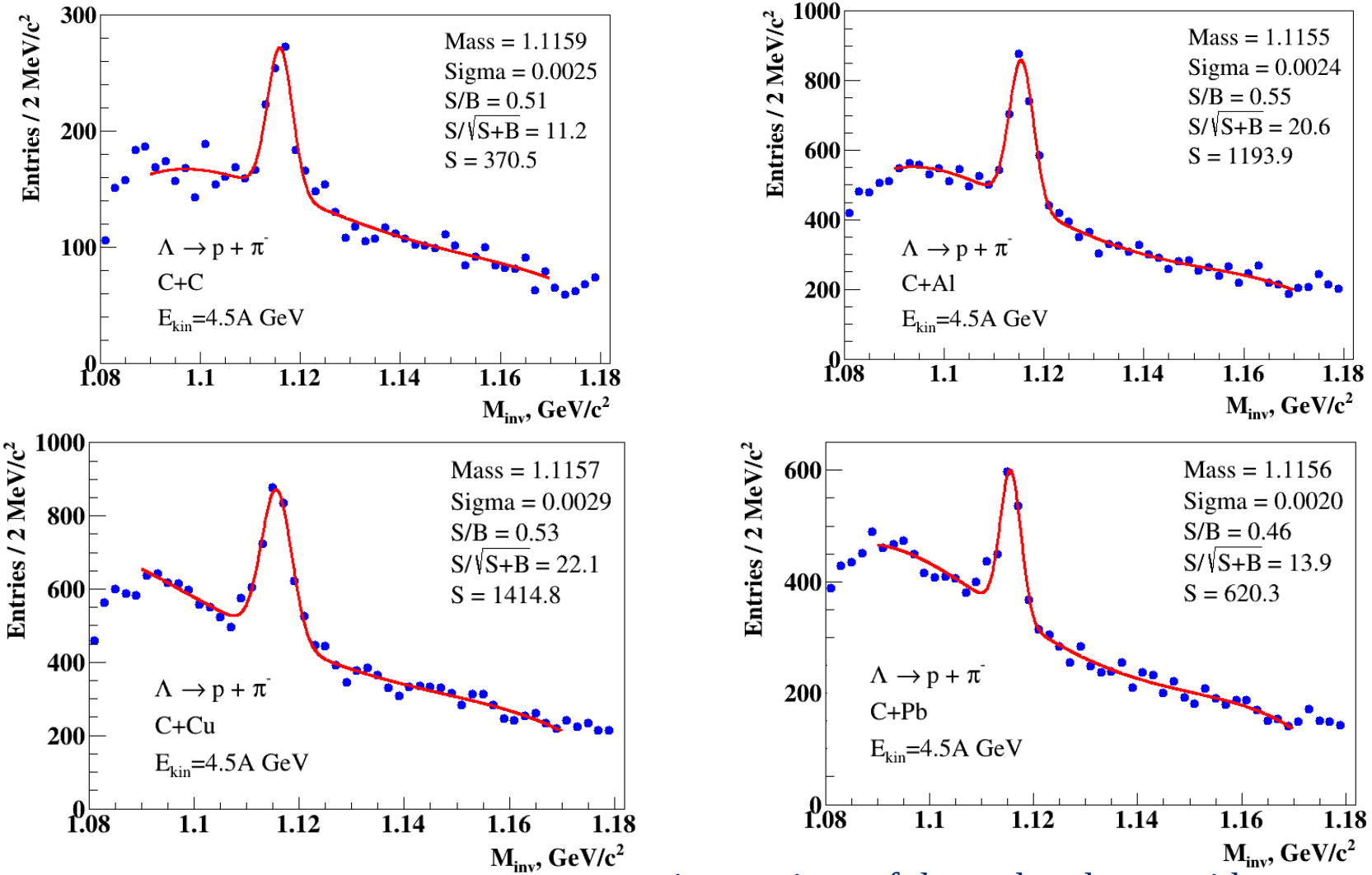
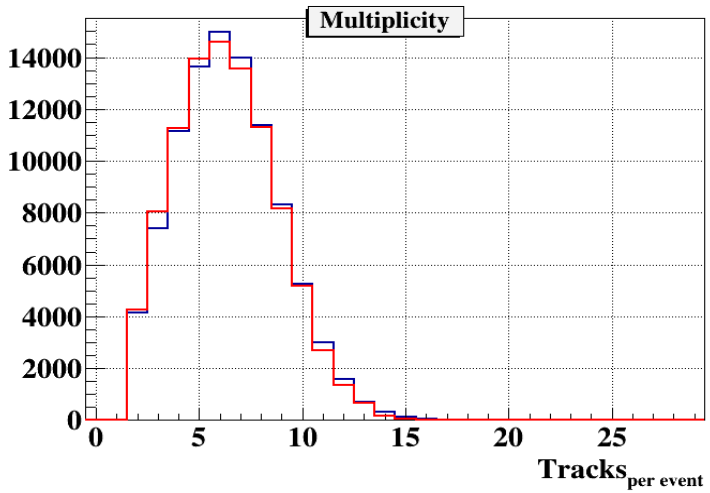
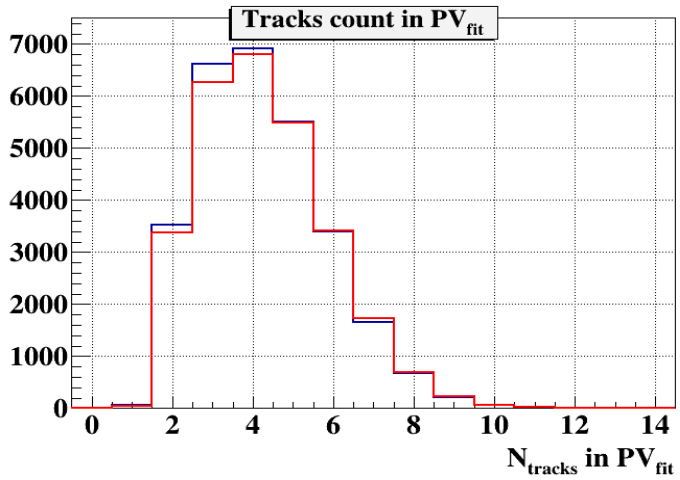
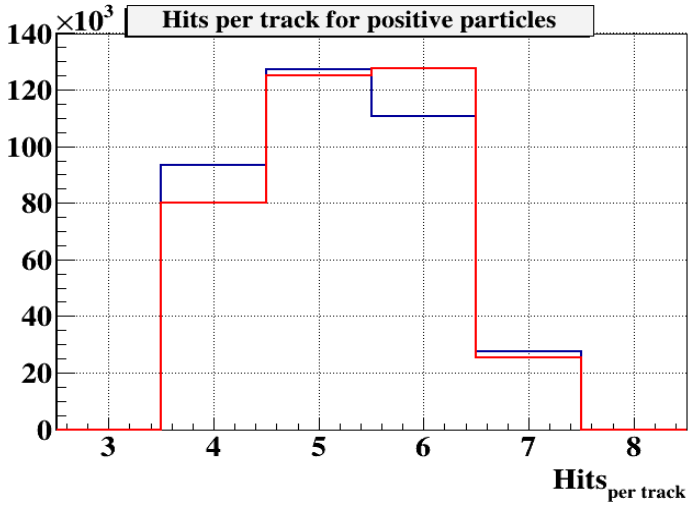


Fig. *Λ→pπ⁻* signal reconstructed in interactions of the carbon beam with targets: *C, Al, Cu, Pb*.

Comparison of experimental data and MC







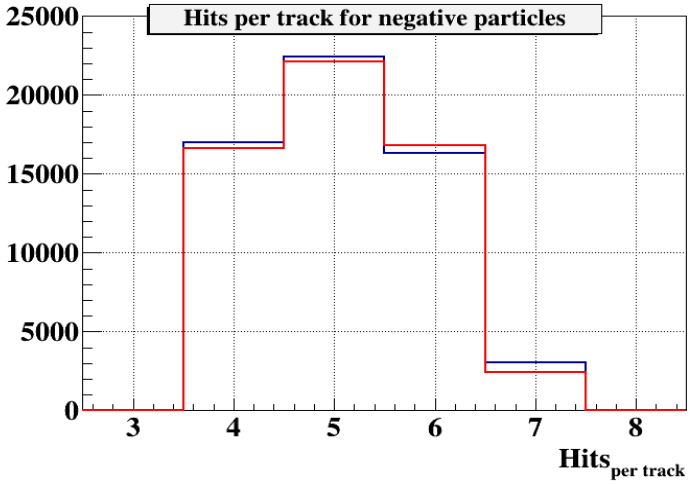
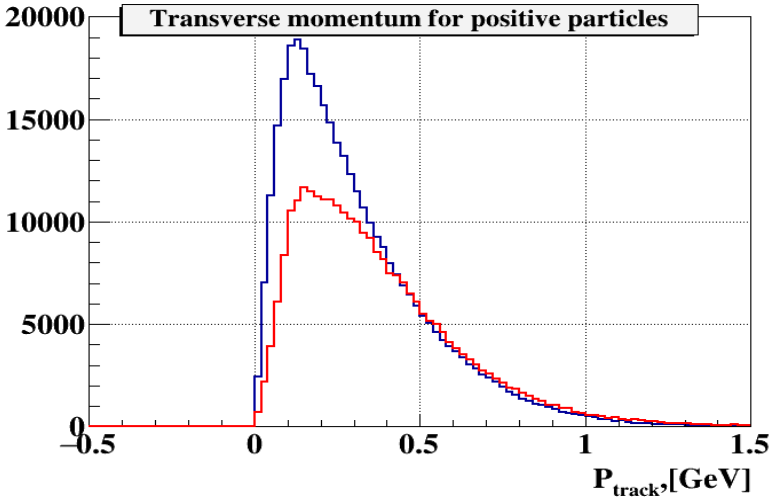
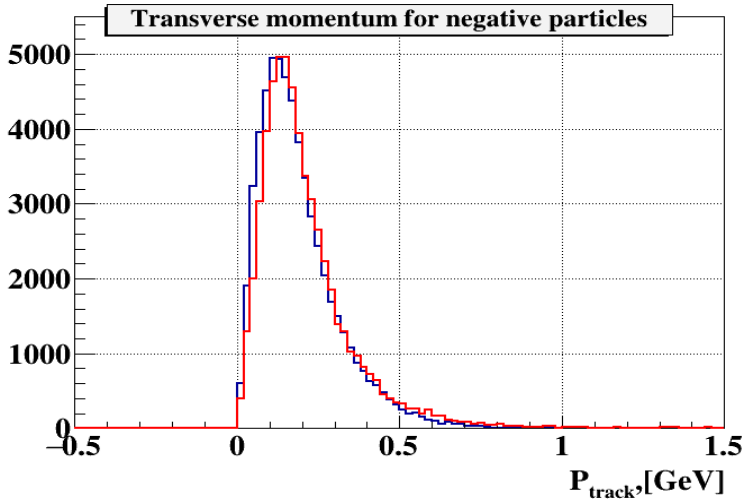


Fig. Comparison of experimental distributions (red lines) and MC (DCM-QGSM) (blue curves) in *C+Cu* interaction: track multiplicity per event; number of tracks reconstructed in the primary vertex; number of hits per positive particle reconstructed in 1 Si + 6 GEM detectors; number of hits per negative particle.

Comparison of experimental data and MC





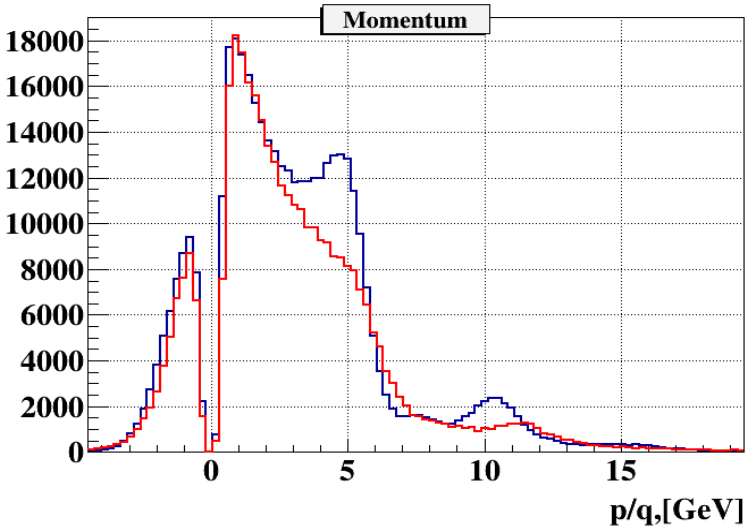


Fig. Comparison of experimental data (red curves) and MC (DCM-QGSM) simulation (blue curves) in *C+Cu* interaction: transverse momentum of positive particles; transverse momentum of negative particles; total momentum of negative ($p/q<0$) and positive particles ($p/q>0$).

Decomposition of efficiency

Table. Decomposition of Λ reconstruction efficiency.

Reconstruction efficiency	$\varepsilon_{rec} = \varepsilon_{acc} \cdot \varepsilon_{emb} \cdot \varepsilon_{cuts}$
Λ geometrical acceptance in GEM detectors	$\varepsilon_{acc} = N_{acc}(y,p_T) / N_{gen}(y,p_T)$
Efficiency of reconstruction of embedded Λ	$\varepsilon_{emb} = N_{emb}(y,p_T) / N_{acc}(y,p_T)$
Efficiency of Λ selection: kinematical and spatial cuts	$\varepsilon_{cuts} = N_{rec}(y,p_T) / N_{emb}(y,p_T)$

Efficiency in *C+Cu* interaction

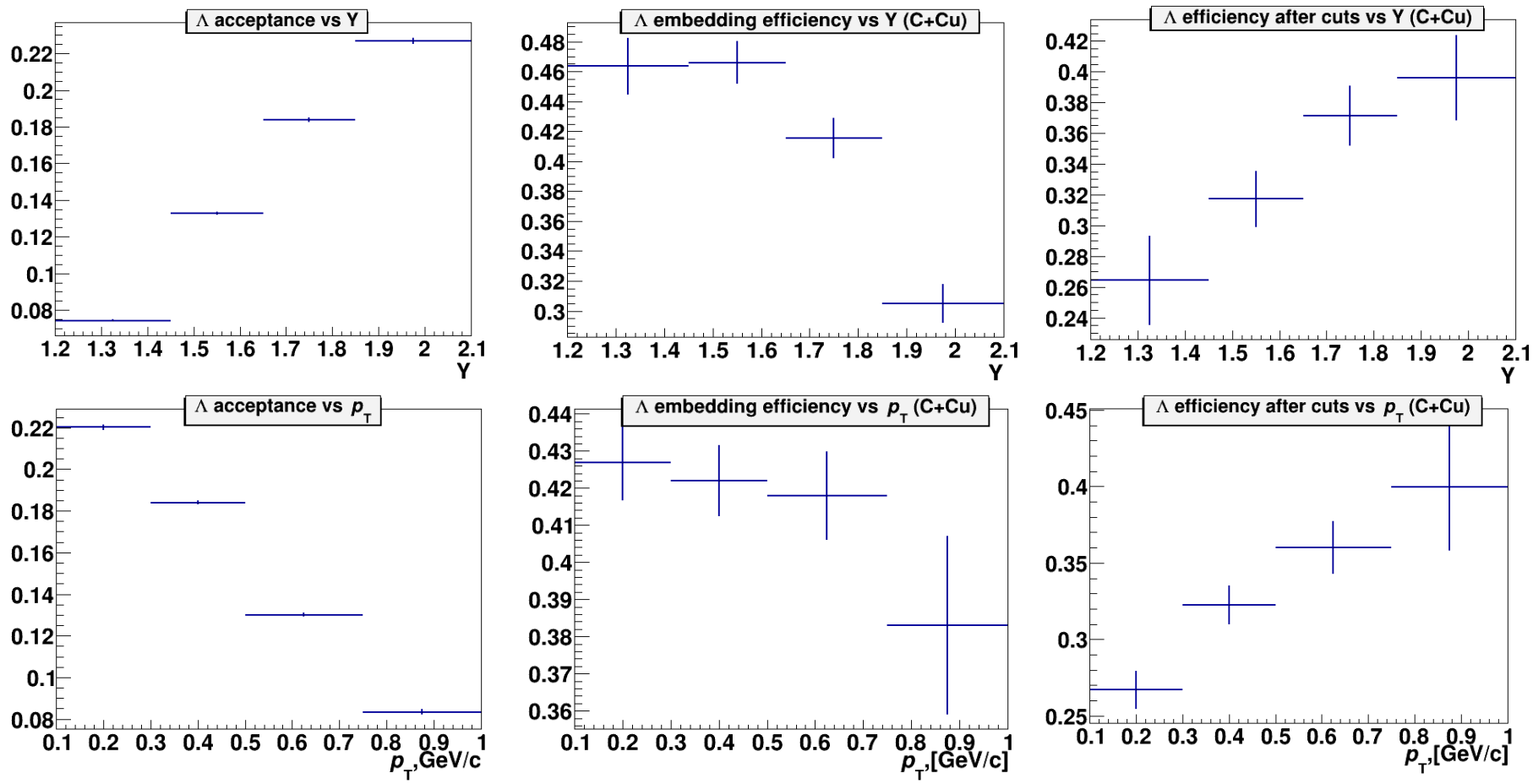


Fig. Λ geometrical acceptance (ε_{acc}); efficiency of reconstruction of embedded Λ (ε_{emb}); efficiency of kinematical and spatial cuts applied for Λ reconstruction (ε_{cuts}) as functions of rapidity y (top plots) and p_T (bottom plots). Results are shown for *C+Cu* interaction.

Efficiency in *C+Cu* interaction

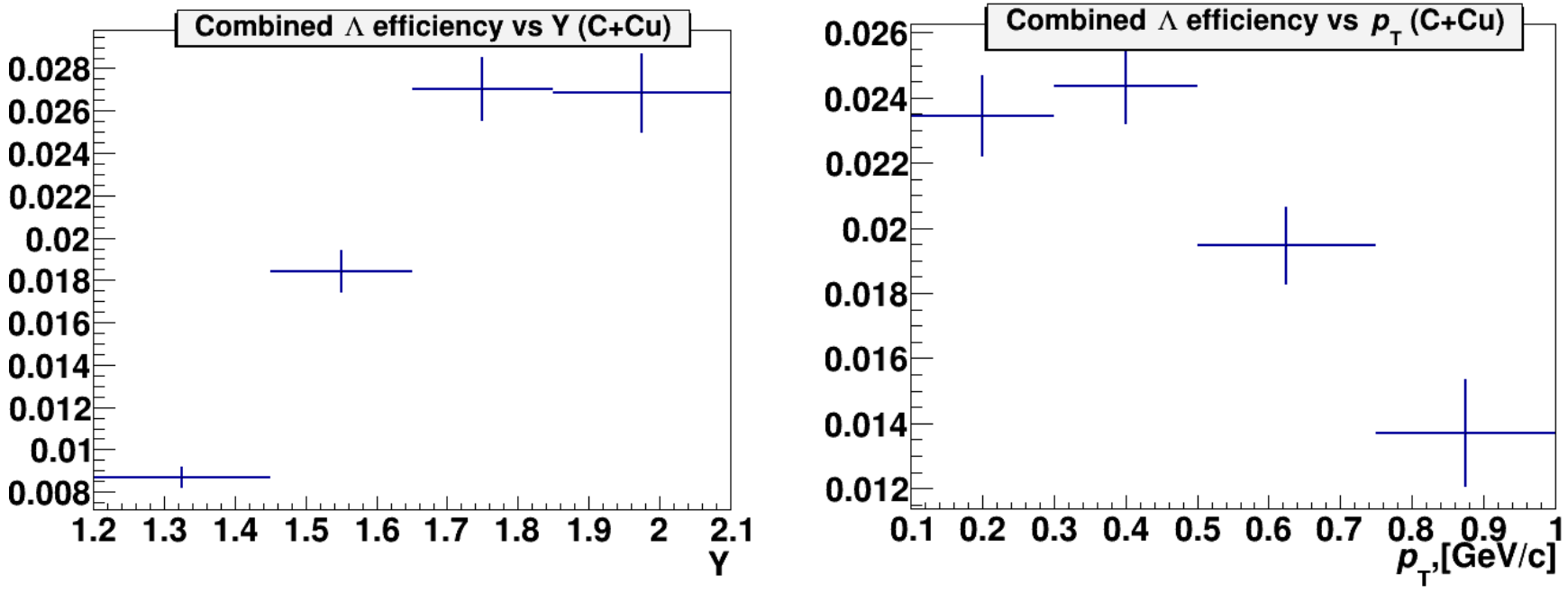


Fig. Combined Λ efficiency as functions of rapidity y (left plot) and p_T (right plot).

Cross section and yields of Λ hyperon

The cross section σ_Λ and yield Y_Λ of Λ hyperon production in $C+C$, $C+Al$, $C+Cu$, $C+Pb$ interactions are calculated in bins of y and p_T according to the formulae:

$$\sigma_\Lambda(y,p_T)=N_{rec}^{\Lambda}(y,p_T) / (\varepsilon_{rec}(y,p_T)\cdot\varepsilon_{trig}\cdot L); \qquad Y_\Lambda(y,p_T) = \sigma_\Lambda(y,p_T) / \sigma_{inel}$$

where L is the luminosity,
N_{rec}^{Λ}–the number of reconstructed Λ hyperons,
ε_{rec}–the combined efficiency of the Λ hyperon reconstruction,
ε_{trig}–the trigger efficiency,
σ_{inel}– the cross section for minimum bias inelastic $C+A$ interactions.

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

The cross sections for inelastic $C+Al$, $C+Cu$,$C+Pb$ interactions are taken from the predictions of the DCM-QGSM 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.

Yields of Λ hyperons in 4A GeV C+A (updated)

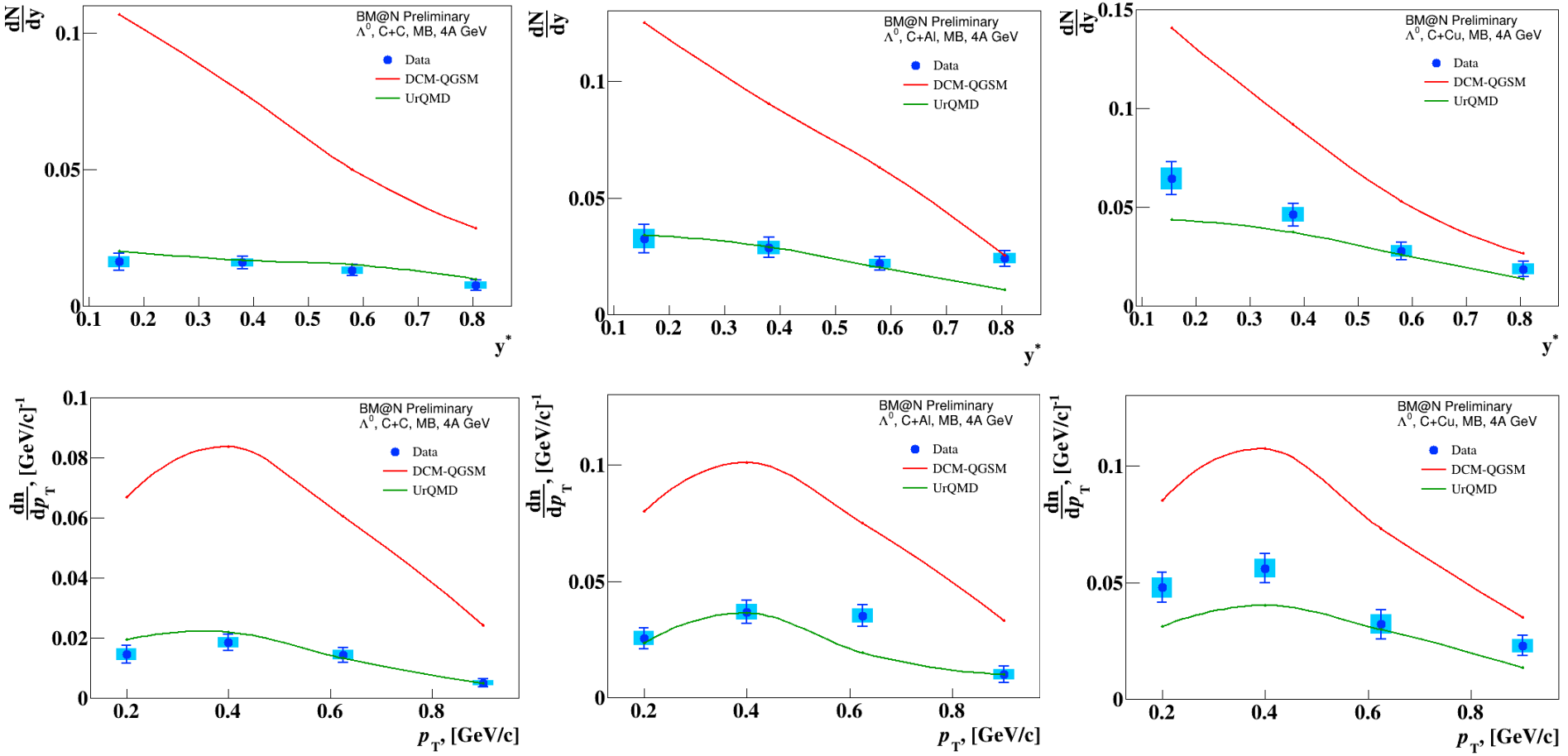
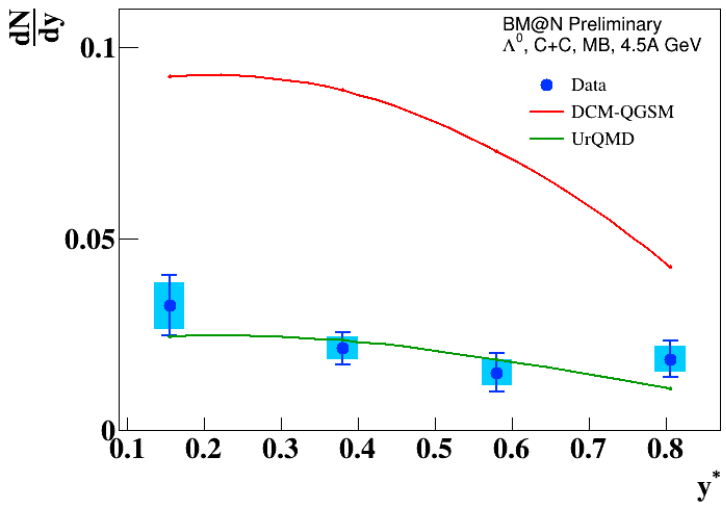
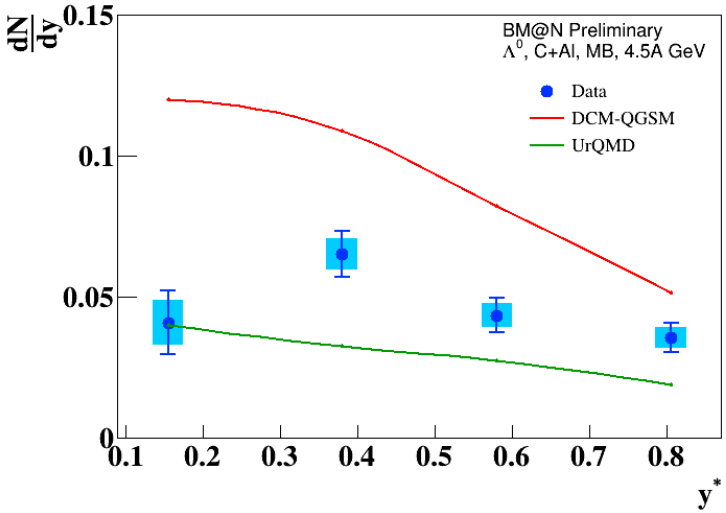
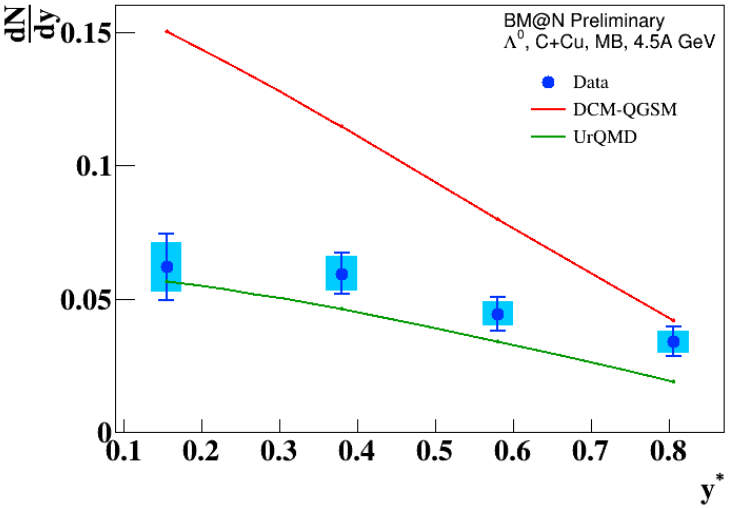


Fig. Reconstructed yields of *Λ* hyperons in minimum bias *C+C, C+Al, C+Cu* interactions vs rapidity *y* and transverse momentum p_T for 4A GeV.

Yields of Λ hyperons in 4.5A GeV C+A







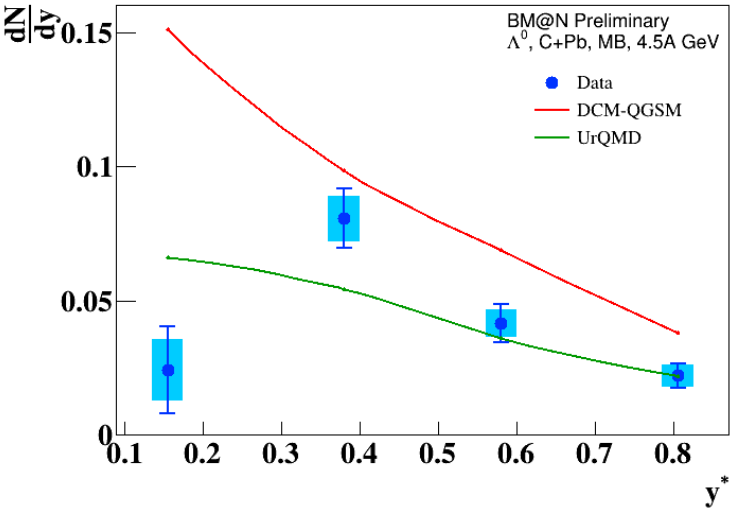
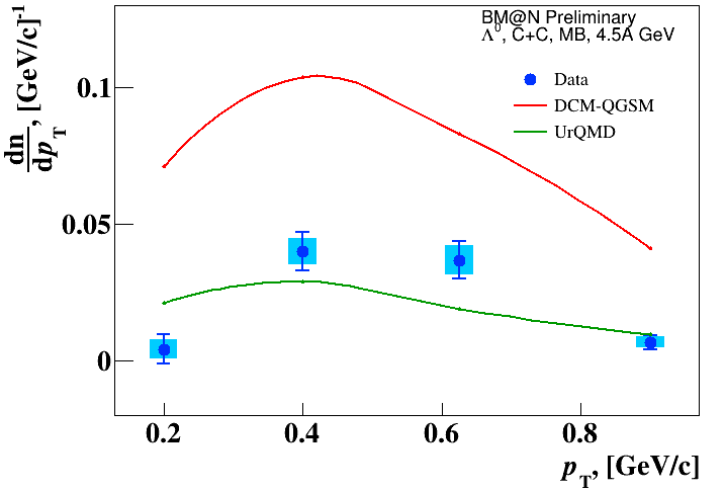
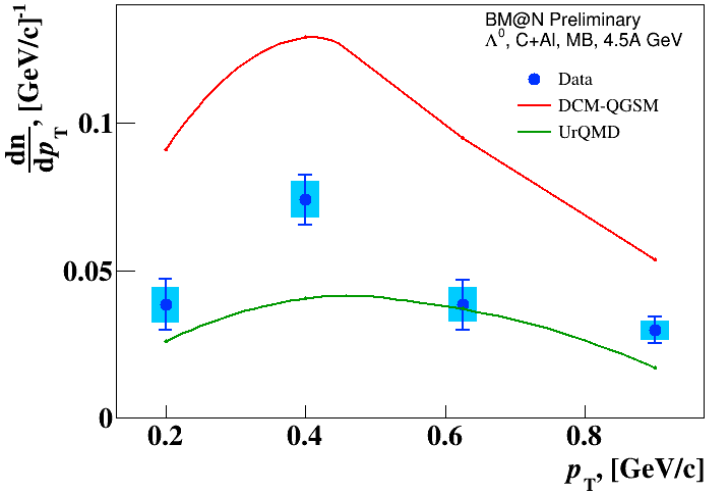
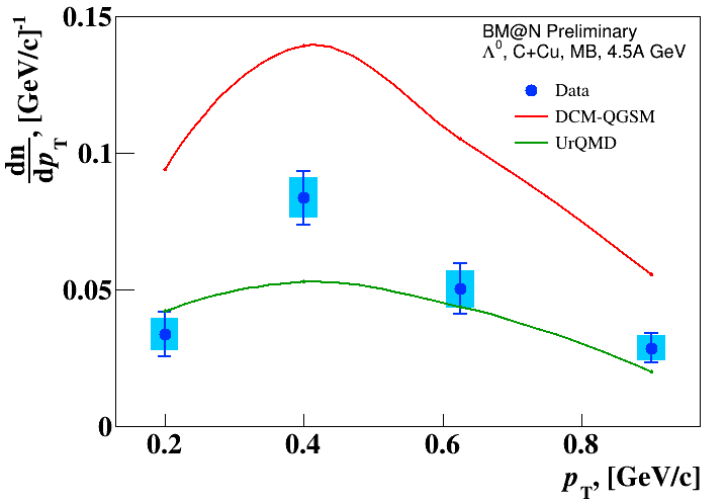


Fig. Reconstructed yields of *Λ* hyperons in minimum bias *C+C, C+Al, C+Cu, C+Pb* interactions vs rapidity *y* for 4.5A GeV.

Yields of Λ hyperons in 4.5A GeV C+A







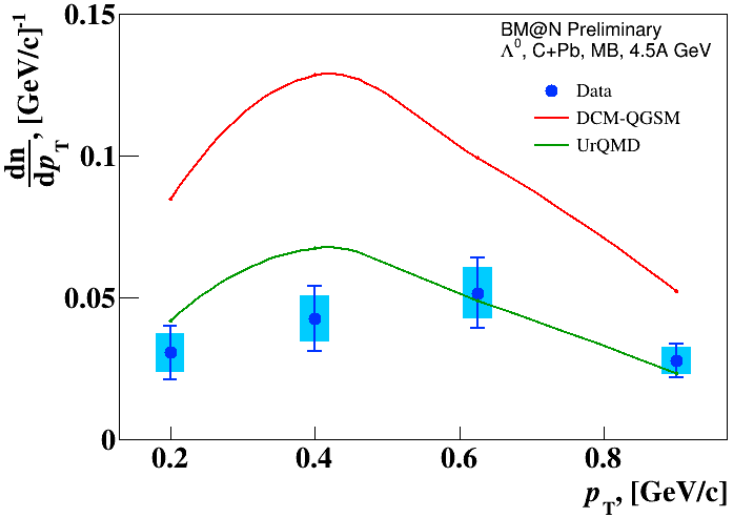
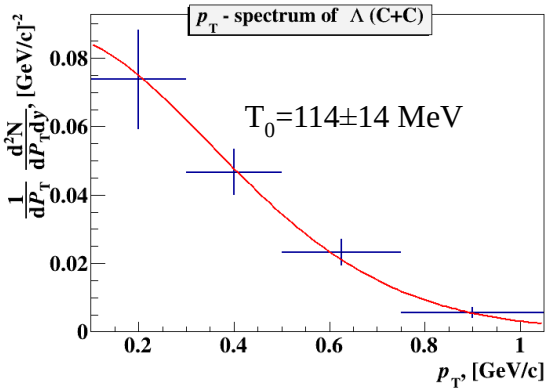


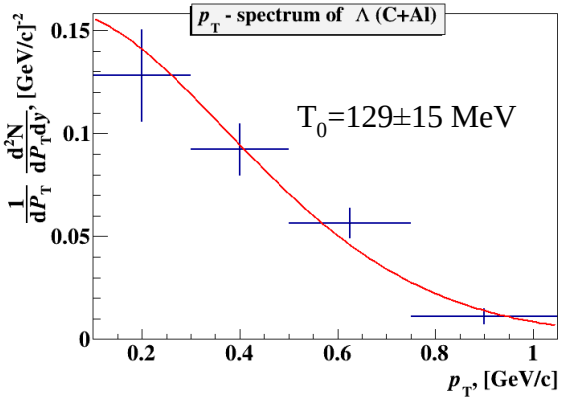
Fig. Reconstructed yields of *Λ* hyperons in minimum bias *C+C, C+Al, C+Cu, C+Pb* interactions vs transverse momentum p_T for 4.5A GeV.

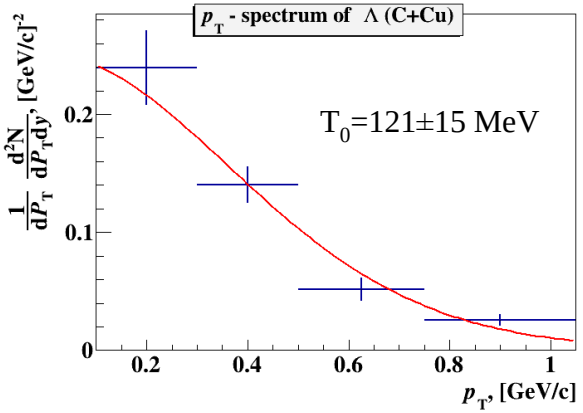
p_T spectra of Λ and T_0 slope in 4A GeV C+A (updated)

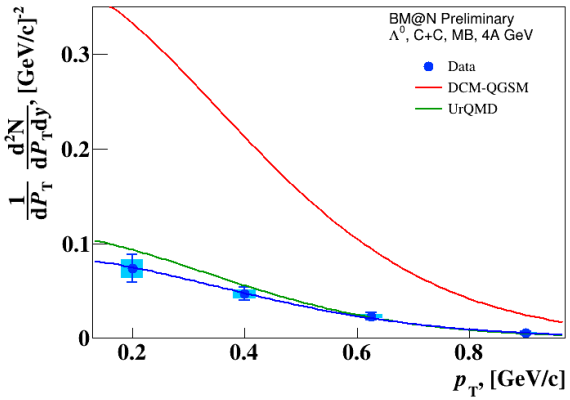
Table. Temperature parameter extracted from the fit of the p_T spectra.

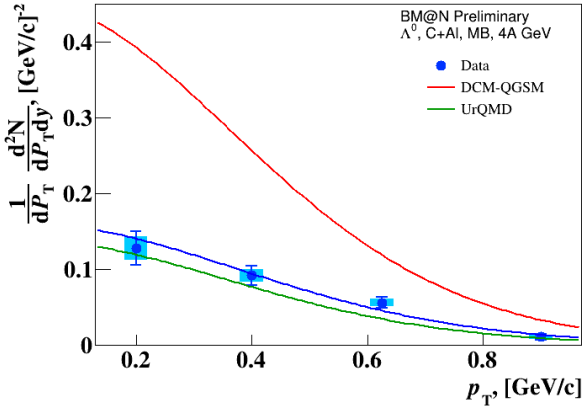
	T_0, MeV (*C+C*)	T_0, MeV (*C+Al*)	T_0, MeV (*C+Cu*)
Experiment	114 ± 14 ± 9	129 ± 15 ± 10	121 ± 15 ± 10
DCM-QGSM	115	122	121
UrQMD	100	118	124

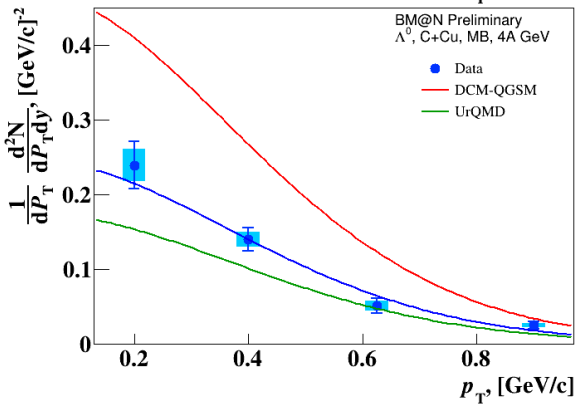










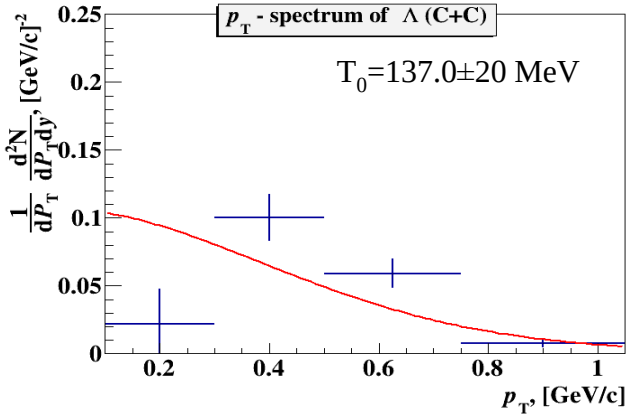


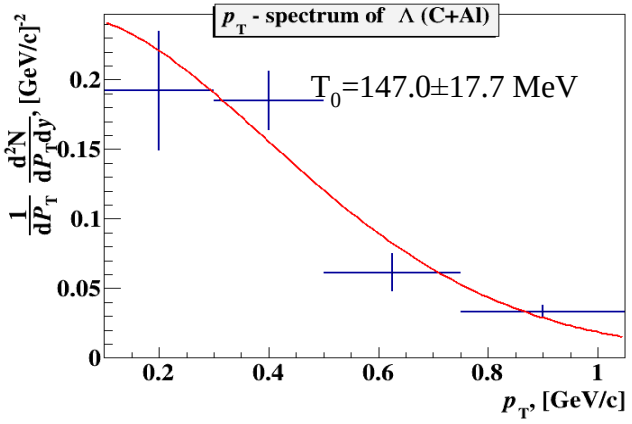
Fit of invariant p_T spectra of Λ yields in C+C, C+Al, C+Cu minimum bias interactions by function:
1/pT·d2N/dpTdy = A·exp(-(mT-mΛ)/T), mT=√(mΛ2+pT2)

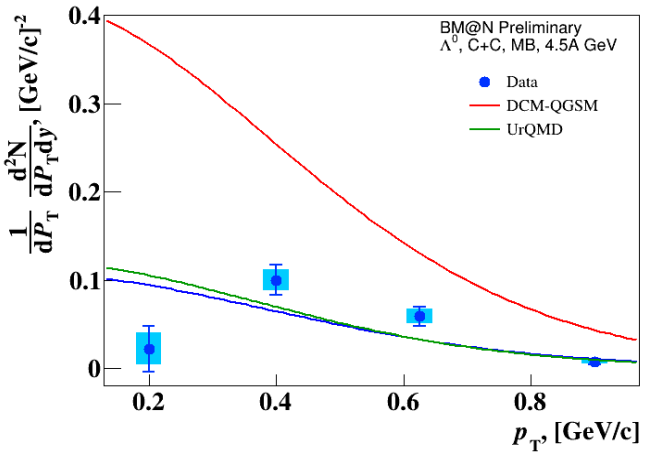
p_T spectra of Λ and T_0 slope in 4.5 AGeV C+A

Table. Temperature parameter extracted from the fit of the p_T spectra.

	T_0, MeV (*C+C*)	T_0, MeV (*C+Al*)
Experiment	137 ± 20 ± 15	147± 18 ± 9
DCM-QGSM	140	142
UrQMD	125	150







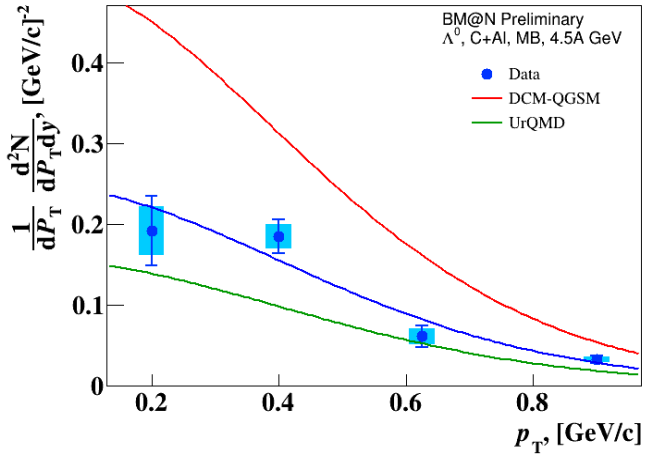


Fig. Thermal fit results with the inverse slope parameter T_0: data and predictions of models for 4.5A GeV.

p_T spectra of Λ and T_0 slope in 4.5 AGeV C+A

Table. Temperature parameter extracted from the fit of the p_T spectra.

	T_0, MeV (*C+Cu*)	T_0, MeV (*C+Pb*)
Experiment	149 ± 18 ± 12	188 ± 38 ±26
DCM-QGSM	141	145
UrQMD	131	136

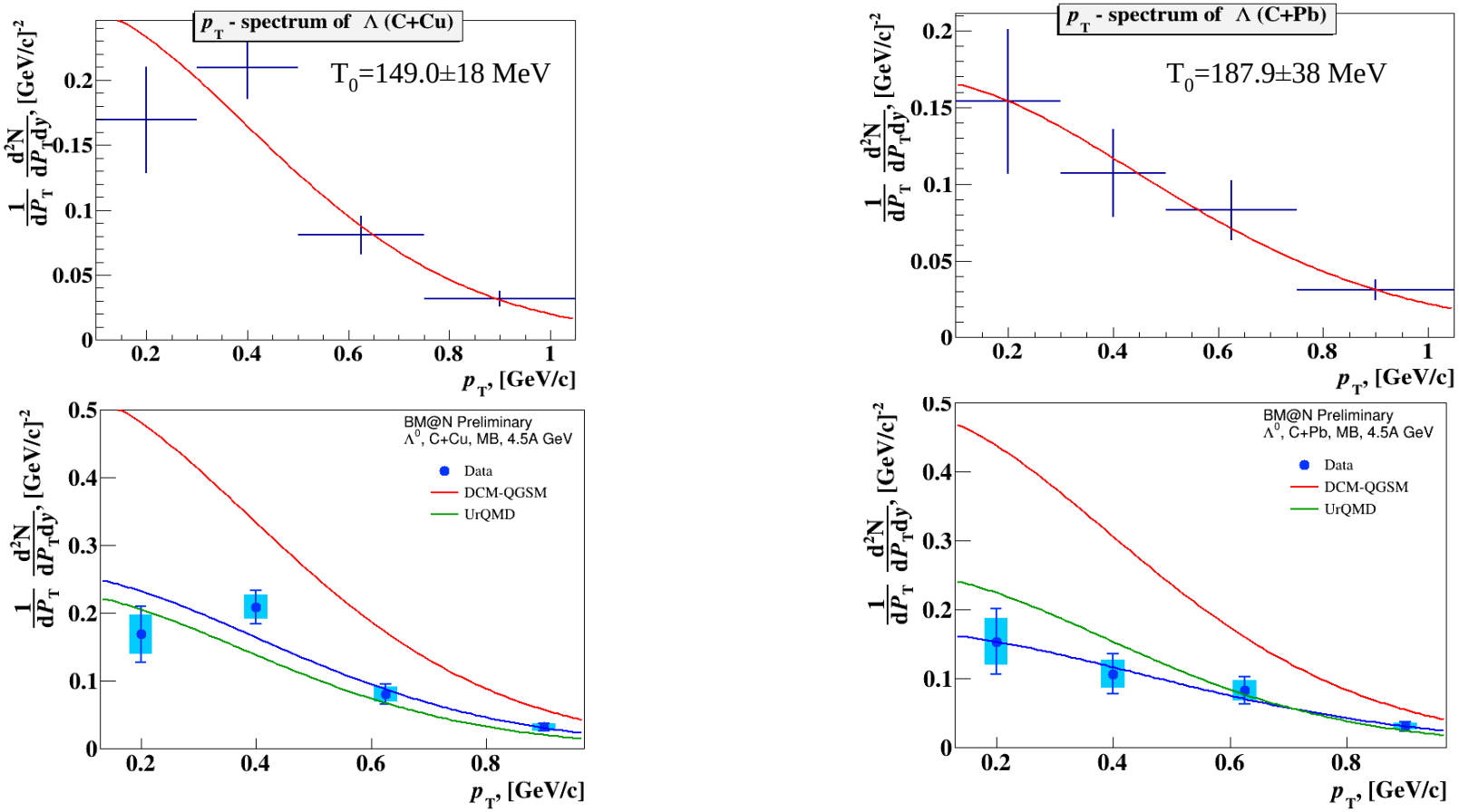


Fig. Thermal fit results with the inverse slope parameter T_0: data and predictions of models for 4.5A GeV.

Systematic errors

Table. Total systematic uncertainty of the yield for 4A GeV.

Target Interval	y			Target Interval	p_T		
	C, sys%	***Al***, sys%	***Cu***, sys%		***C***, sys%	***Al***, sys%	***Cu***, sys%
1.2-1.45	**13.5**	**13.3**	**10.0**	**0.1-0.3**	**17.4**	**12.6**	**8.6**
1.45-1.65	**11.1**	**11.0**	**9.4**	**0.3-0.55**	**11.6**	**11.1**	**8.5**
1.65-1.85	**13.5**	**11.0**	**14.2**	**0.55-0.8**	**12.4**	**9.6**	**17.0**
1.85-2.1	**23.7**	**12.5**	**13.5**	**0.8-1.05**	**21.3**	**26.8**	**15.4**

Table. Total systematic uncertainty of the yield for 4.5A GeV.

Target Interval	y				Target Interval	p_T			
	C, sys%	***Al***, sys%	***Cu***, sys%	***Pb***, sys%		***C***, sys%	***Al***, sys%	***Cu***, sys%	***Pb***, sys%
1.2-1.45	**18.7**	**19.2**	**17.8**	**47.8**	**0.1-0.3**	**55.0**	**15.7**	**16.5**	**22.2**
1.45-1.65	**13.6**	**8.7**	**9.9**	**10.4**	**0.3-0.55**	**12.1**	**7.6**	**8.5**	**19.6**
1.65-1.85	**22.8**	**10.1**	**10.5**	**12.6**	**0.55-0.8**	**14.5**	**11.0**	**14.4**	**17.9**
1.85-2.1	**18.3**	**10.3**	**11.3**	**18.8**	**0.8-1.05**	**29.9**	**12.9**	**14.8**	**16.2**

Measured kinimatic range:

* Uncertainty of background under Lambda signal: √(0.5*bkg)

+ Uncertainty of background fit by Legandre(4) - Legandre(3)

* Uncertainty of reconstruction efficiency (embeding+cuts) evaluated for different data runs

* Uncertainty of trigger efficiency (2%)

Full kinematic range:

* Extrapolation uncertainty to full kin. range (UrQMD;DCM-QGSM)

* Uncertainty of C+A inelastic cross section

Yields and cross sections for 4A GeV C+A (updated)

Table. Extrapolation factors to the full kinematic range, yields and cross sections.

	C	*Al*	*Cu*
DCM-QGSM URQMD extrapolation factors	6574/2474 1827/639	10539/3413 3248/1056	15817/3545 5509/1360
Yields in the measured kin range $0.1<p_T<1.05$ GeV/c, $1.2<y_{lab}<2.1$	0.0118±0.0011±0.0009	0.0243±0.0020±0.0016	0.0362±0.0027±0.0021
Yields in the full kinematic range N part DCM-QGSM	0.0327±0.0030±0.0024 9	0.0750±0.062±0.042 13.4	0.154±0.011±0.009 23
Λ cross section in min. bias interactions, mb	27.1 ± 2.5 (stat) ± 2.0 (sys)	94.5 ± 8.0 (stat) ± 6.1 (sys)	276 ± 20 (stat) ± 16 (sys)

Yields and cross sections for 4.5A GeV C+A

Table. Extrapolation factors to the full kinematic range, yields and cross sections.

	C	*Al*	*Cu*	*Pb*
DCM-QGSM URQMD extrapolation factors	3866/1581 1104/433	5447/1968 1955/671	8208/2222 3381/876	12324/2107 6404/1016
Yields in the measured kin range $0.1<p_T<1.05$ GeV/c, $1.2<y_{lab}<2.1$	0.0202±0.0026 ±0.0020	0.0410±0.0037 ±0.0026	0.0446±0.0034 ±0.0031	0.0356±0.0047 ±0.0036
Yields in the full kinematic range N part DCM-QGSM	0.0504±0.0063 ±0.0049	0.116±0.010 ±0.007	0.169±0.013 ±0.012	0.216±0.028 ±0.022
Λ cross section in min. bias interactions, mb	41.8 ± 5.3 ± 4.0	147 ± 13.0 ± 9.0	302 ± 23 ± 20	665 ± 87 ± 64

Energy dependence of Λ yields in C+C interactions

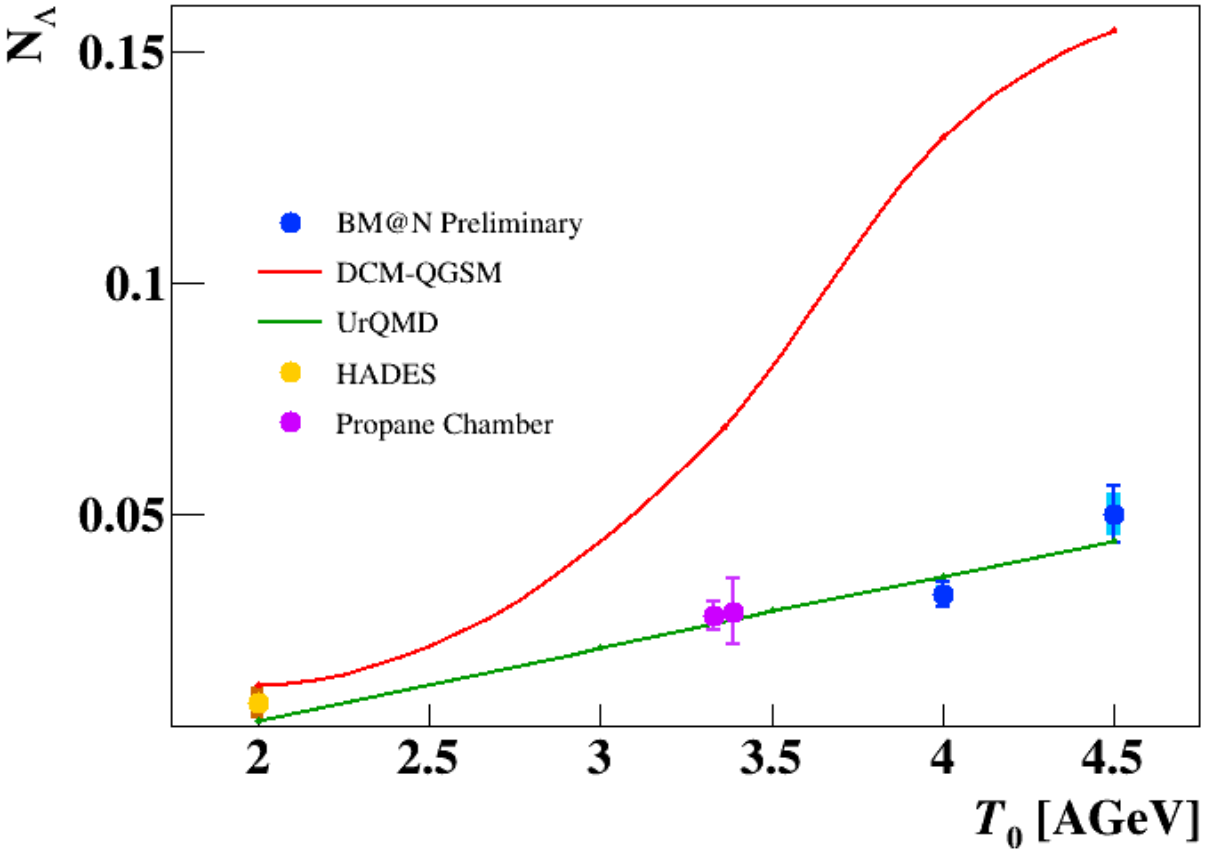


Fig. Energy dependence of *Λ* yields measured in different experiments. BM@N result is compared with data [*S.Arakelian et al., P1-83-354, JINR, Dubna; D.Armutlijsky et al., P1-85-220, JINR, Dubna; Kalliopi Kanaki, PhD "Study of Λ hyperon production"*]. The predictions of the DCM-QGSM and UrQMD models are shown.

Summary

1. Production of Λ hyperons in interactions of the 4A GeV and 4.5A GeV kinetic energy carbon beam with *C*, *Al*, *Cu*, *Pb* targets was studied with the BM@N detector at the Nuclotron.
2. The analysis procedure has been presented and described.
3. Results on Λ hyperon yields have been obtained and compared with model predictions and data available.
4. Analysis Note to be realized in a week.

Thank you for attention!

Backup

Results review

Table. Comparison between Λ yields and cross sections for 4A GeV.

	C	*Al*	*Cu*
Yields in the measured kin range (current)	0.0129±0.0011±0.0007	0.0243±0.0020±0.0014	0.0362±0.0027±0.0018
Yields in the full kinematic range (current)	0.0327±0.0028±0.0018	0.0759±0.062±0.044	0.154±0.011±0.008
Λ cross section, MB, mb (current)	27.1 ± 2.5 ± 1.6	94.5 ± 8.0 ± 5.3	276 ± 20 ± 14
Yields in the measured kin range (previous)	0.0214±0.0023±0.0024	0.0431±0.0034±0.0035	0.0561±0.0039±0.0047
Yields in the full kinematic range (previous)	0.0589±0.0063±0.0065	0.133±0.010±0.011	0.239±0.017±0.020
Λ cross section, MB, mb (previous)	48.9 ± 5.2 ± 5.1	167 ± 13 ± 13	427 ± 30 ± 29

	T_0, MeV (*C+C*)	T_0, MeV (*C+Al*)	T_0, MeV (*C+Cu*)
Experiment (current)	114 ± 14 ± 9	129 ± 15 ± 10	121 ± 15 ± 10
DCM-QGSM (current)	115	122	121
UrQMD (current)	100	118	124
Experiment (previous)	98 ± 24 ± 25	157 ± 24 ± 12	160 ± 27 ± 21
DCM-QGSM (previous)	122	129	131
UrQMD (previous)	107	127	132

Table. Comparison between temperatures parameters for 4A GeV.

p_T spectra of Λ: MC predictions in 4A GeV C+A (upd

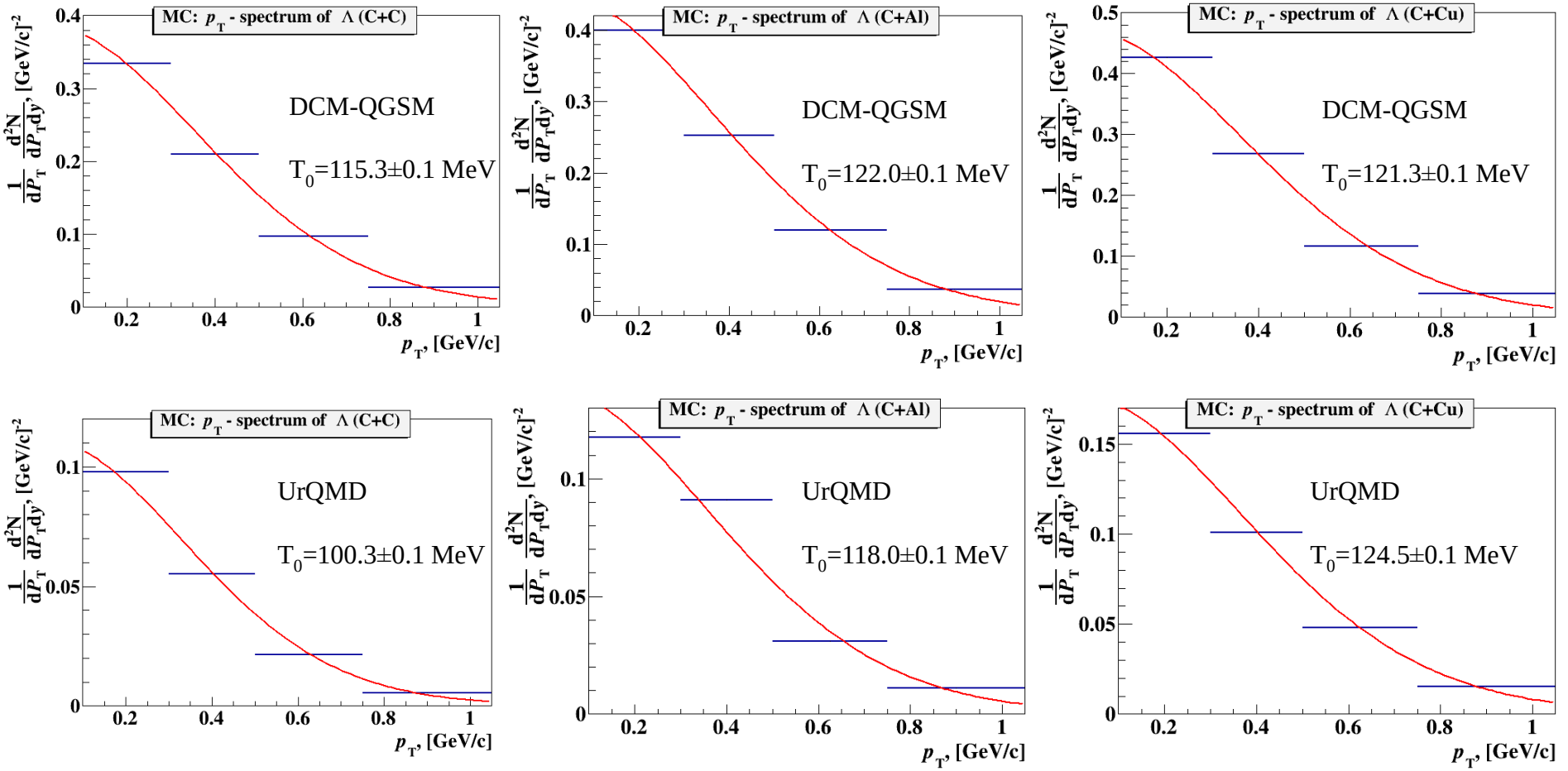
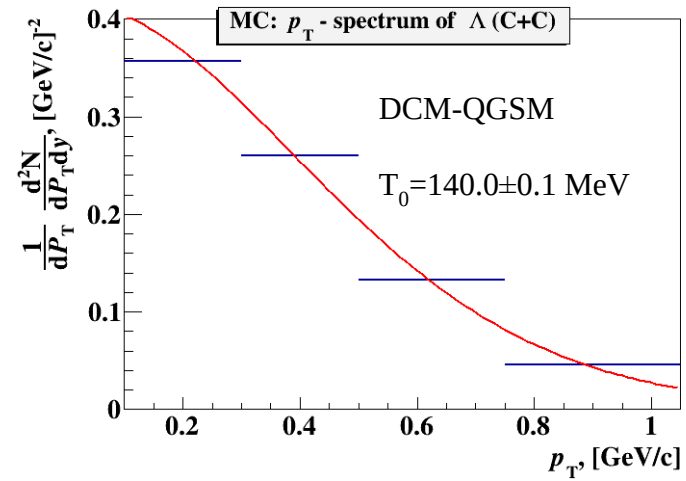
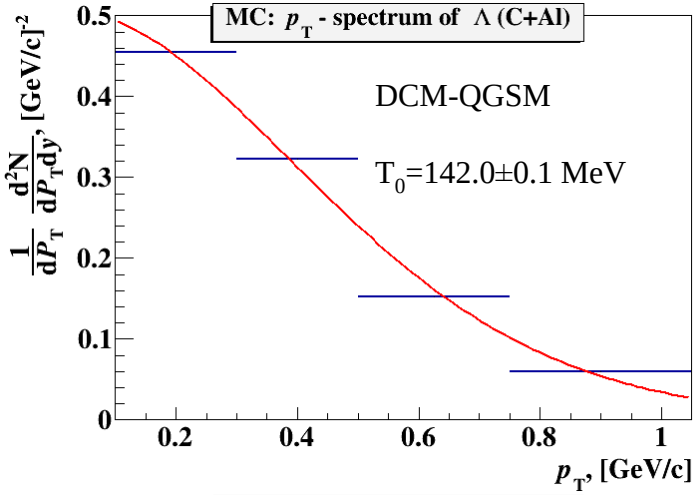
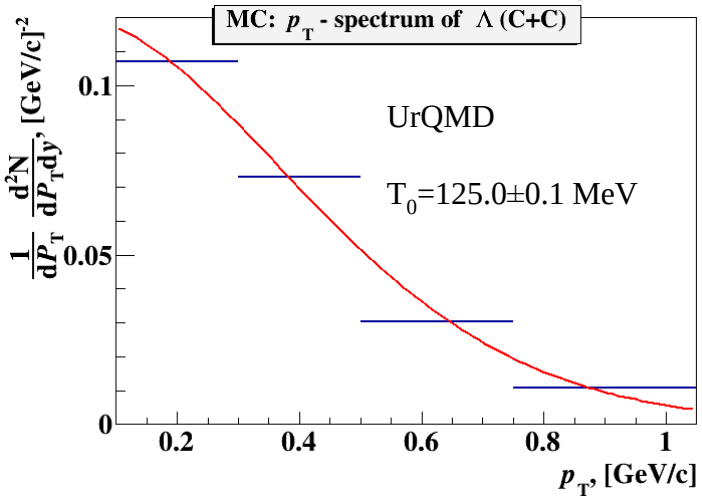


Fig. Fit of the DCM-QGSM and URQMD spectra. The inverse slope parameter T_0 is shown, extracted from the fit.

p_T spectra of Λ: MC predictions in 4.5A GeV C







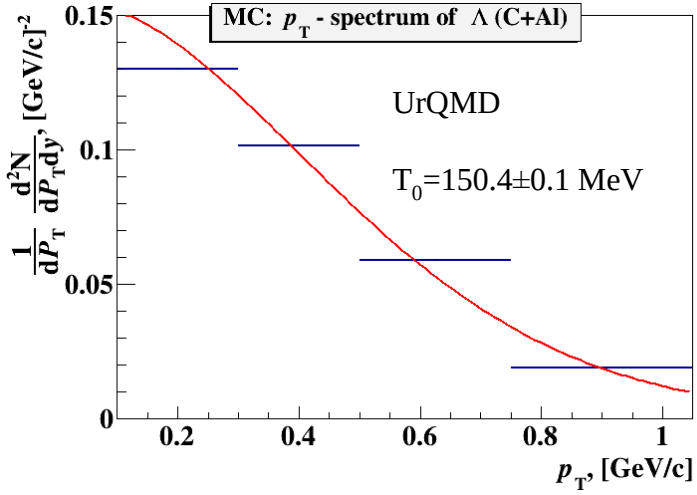
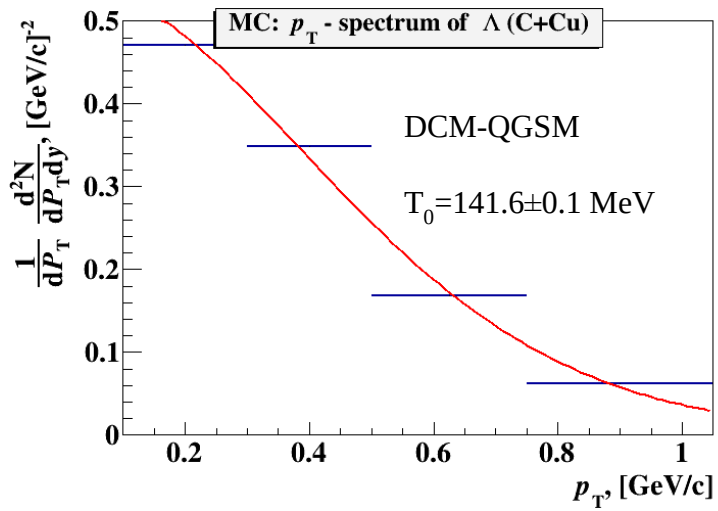
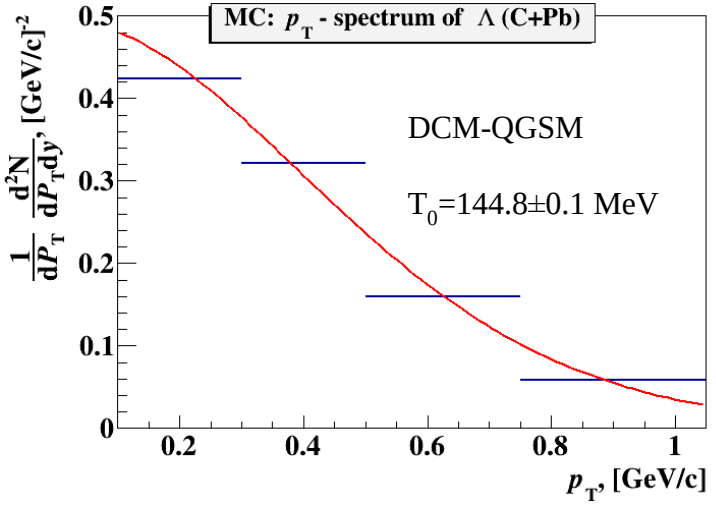
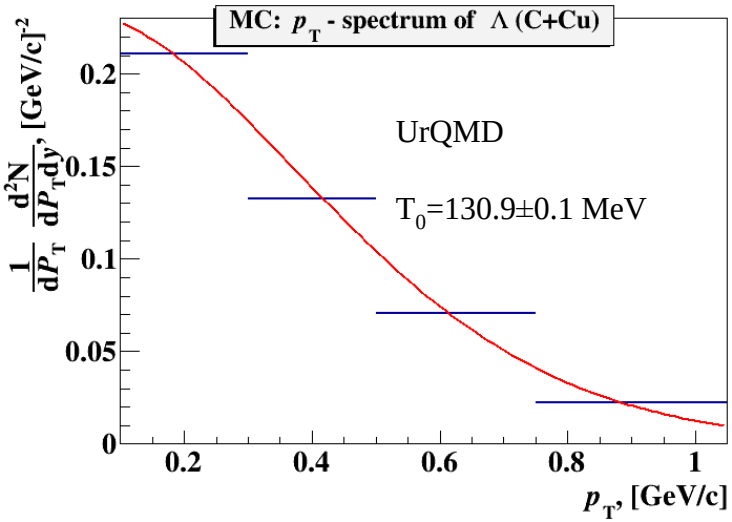


Fig. Fit of the DCM-QGSM and URQMD spectra. The inverse slope parameter T_0 is shown, extracted from the fit.

p_T spectra of Λ: MC predictions in 4.5A GeV C







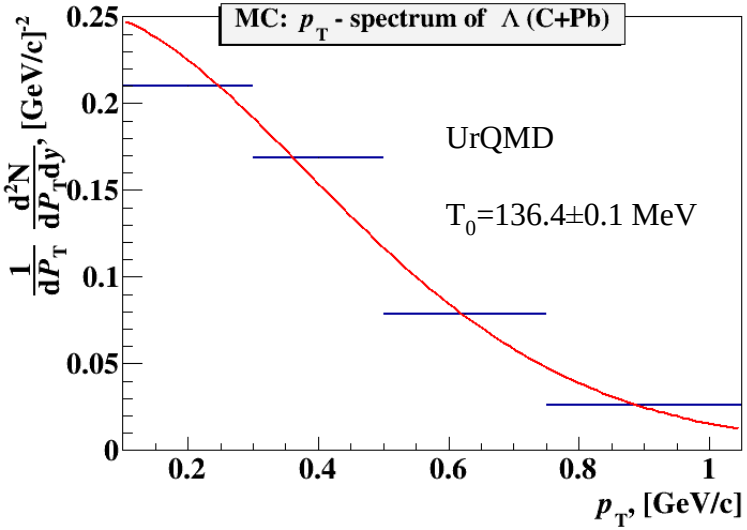


Fig. Fit of the DCM-QGSM and URQMD spectra. The inverse slope parameter T_0 is shown, extracted from the fit.

Triggers and impact parameters

Table. Trigger efficiency evaluated for events with reconstructed Λ hyperons in interactions of the carbon beam with *C*, *Al*, *Cu* targets. The systematic errors take into account the uncertainty due to the delta electron background. The last row shows the trigger efficiency averaged over the data samples with trigger conditions BD>=2 and BD>=3.

Trigger / Target	*C*	*Al*	*Cu*	*Pb*
ε_{trig} (BD>=2)	0.906±0.010 0.870±0.020	0.955±0.010	0.904±0.01	
ε_{trig} (BD>=3)		0.923±0.020 0.890±0.020	0.883±0.02 0.930±0.02	0.950±0.02
ε_{trig} averaged		0.940±0.015	0.893±0.015	

Yields of Λ hyperons in 4A GeV C+A(previous)

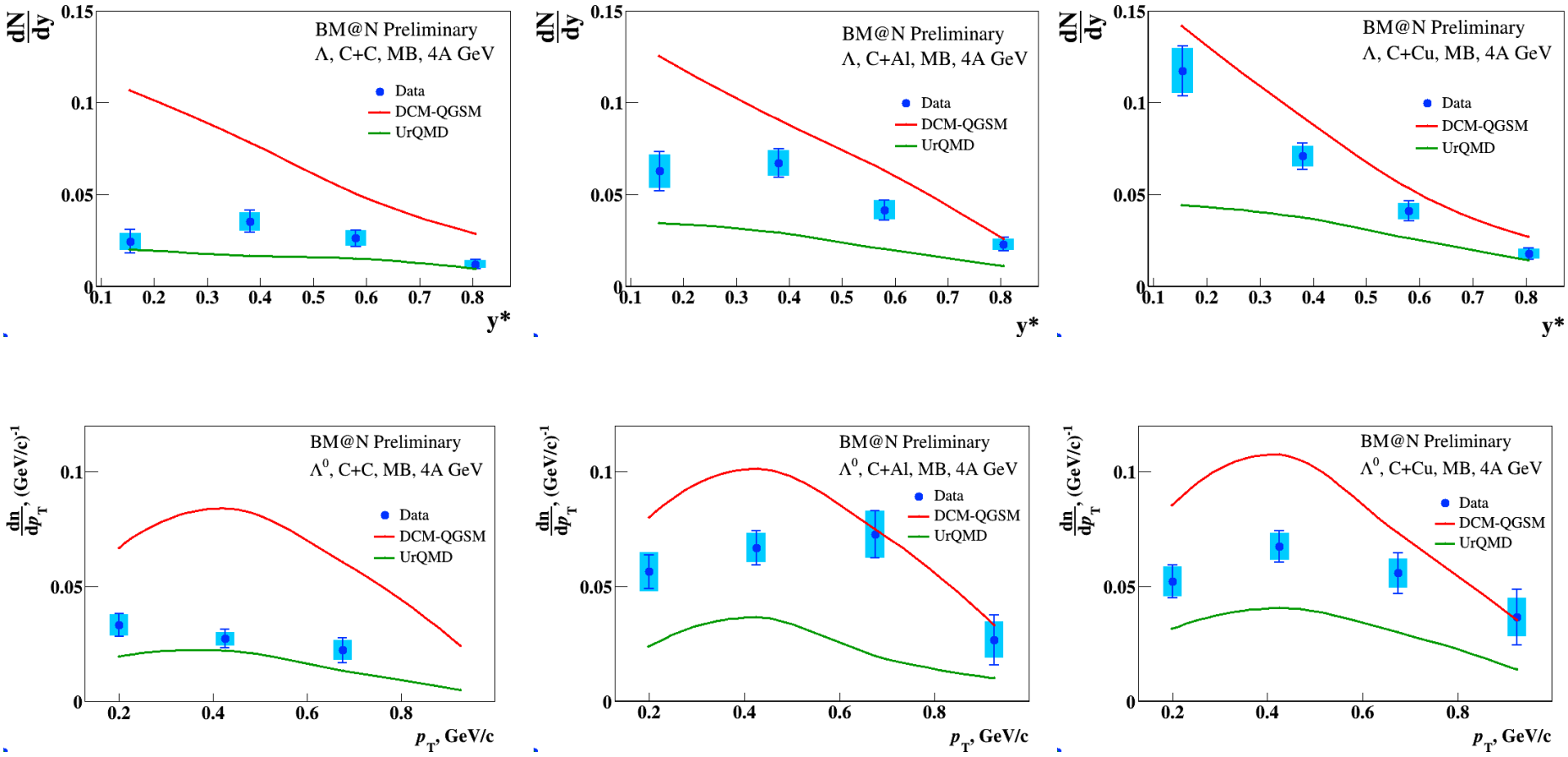


Fig. Reconstructed yields of *Λ* hyperons in minimum bias *C+C, C+Al, C+Cu* interactions vs rapidity *y* and transverse momentum p_T.

p_T spectra of Λ and T_0 slope in 4A GeV C+A(previous)

Table. Temperature parameter extracted from the fit of the p_T spectra.

	T_0, MeV (*C+C*)	T_0, MeV (*C+Al*)	T_0, MeV (*C+Cu*)
Experiment χ^2 /ndf	98 ± 24 ± 25 2.04/1	157 ± 24 ± 12 2.51/2	160 ± 27 ± 21 0.39/2
DCM-QGSM	122	129	131
UrQMD	107	127	132

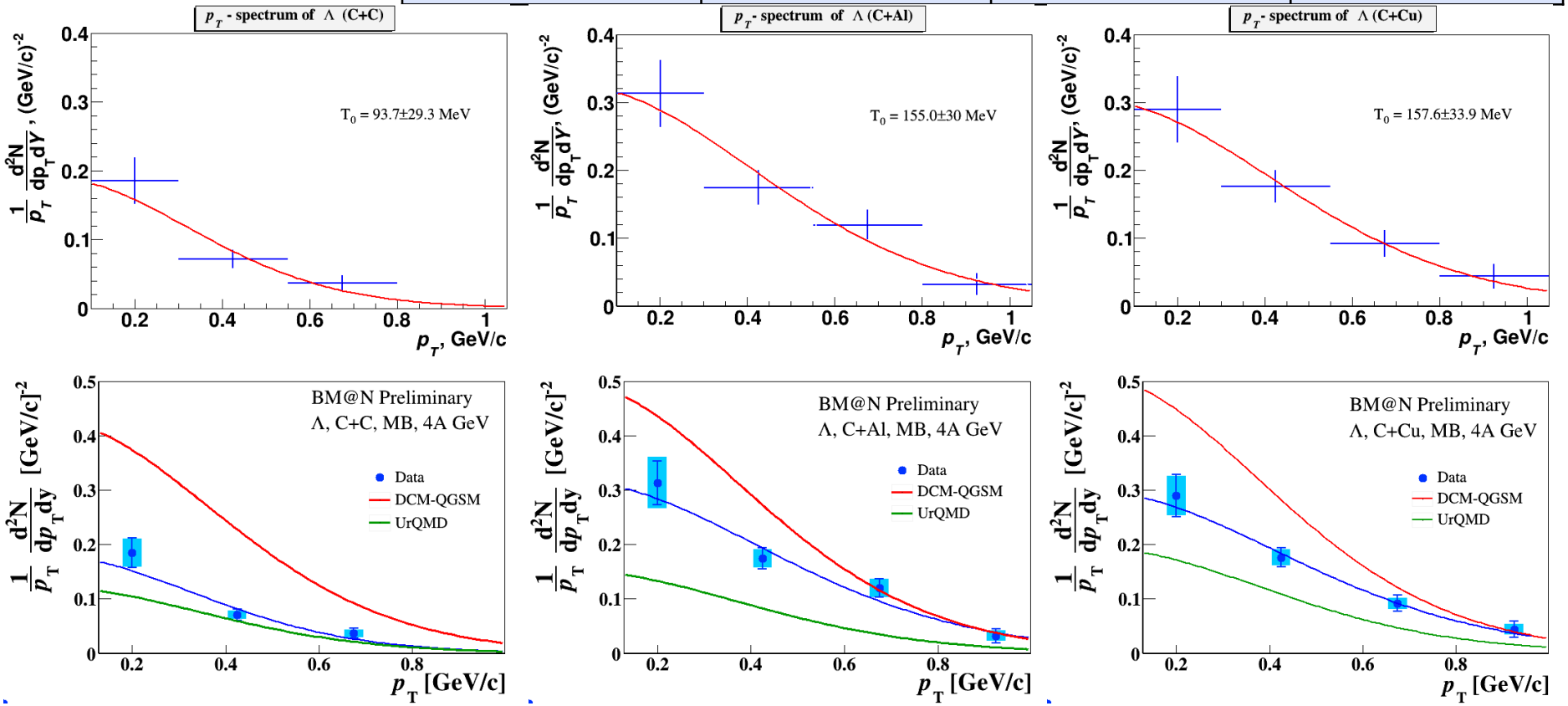


Fig. Thermal fit results with the inverse slope parameter T_0: data and predictions of models.

p_T spectra of Λ: MC predictions in 4A GeV C+A (previ

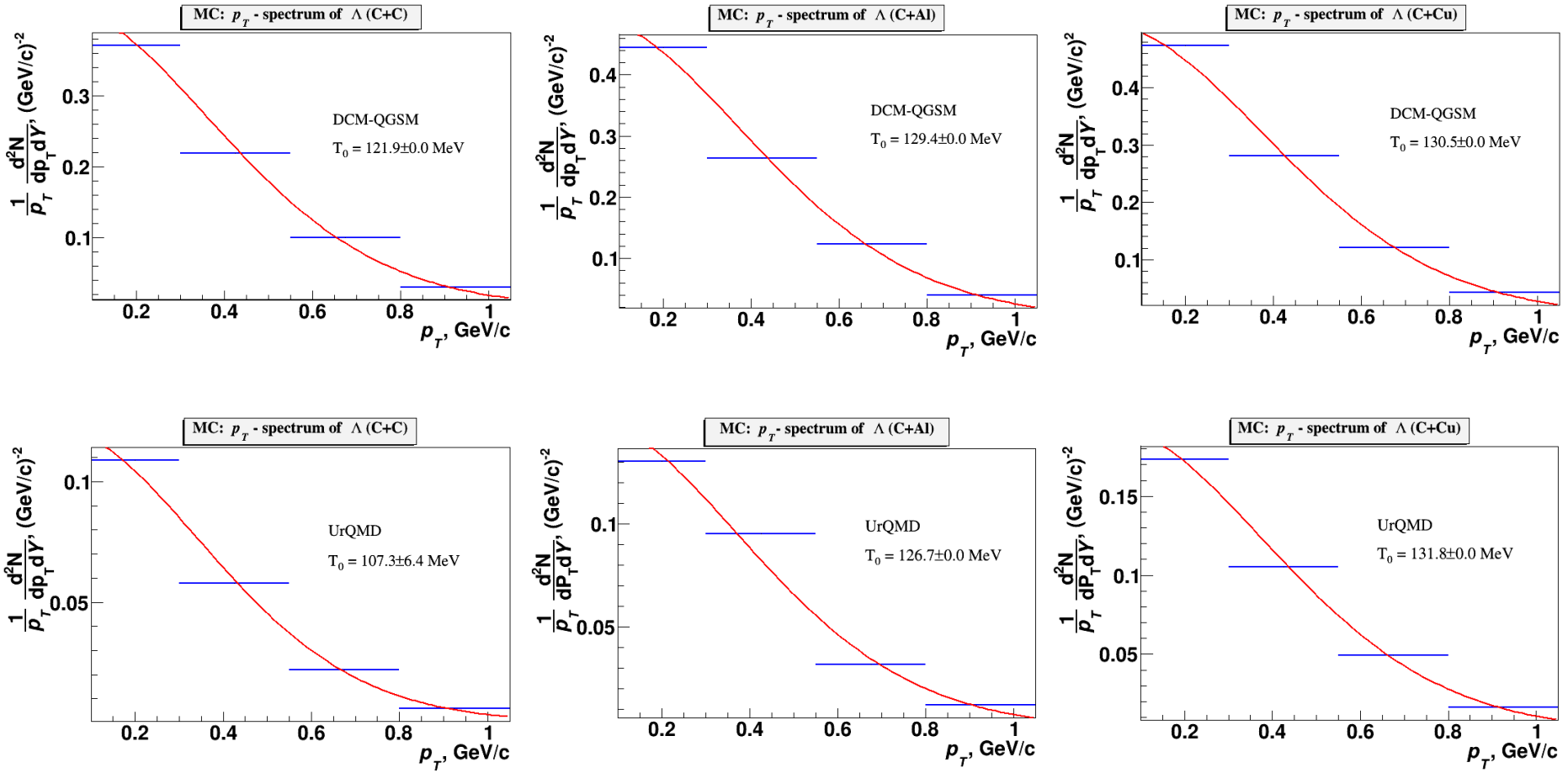


Fig. Fit of the DCM-QGSM and URQMD spectra. The inverse slope parameter T_0 is shown, extracted from the fit.

Yields and cross sections for 4A GeV C+A(previous)

Table. Extrapolation factors to the full kinematic range, yields and cross sections.

	C	*Al*	*Cu*
DCM-QGSM URQMD extrapolation factors	6574/2474 1827/639	10539/3413 3248/1056	15817/3545 5509/1360
Yields in the measured kin range $0.1<p_T<1.05$ GeV/c, $1.2<y_{lab}<2.1$	0.0214±0.0023±0.0024	0.0431±0.0034±0.0035	0.0561±0.0039±0.0047
Yields in the full kinematic range N part DCM-QGSM	0.0589±0.0063±0.0065 9	0.133±0.010±0.011 13.4	0.239±0.017±0.020 23
Λ cross section in min. bias interactions, mb	48.9 ± 5.2 ± 5.1	167 ± 13 ± 13	427 ± 30 ± 29

Energy dependence of Λ yields(previous)

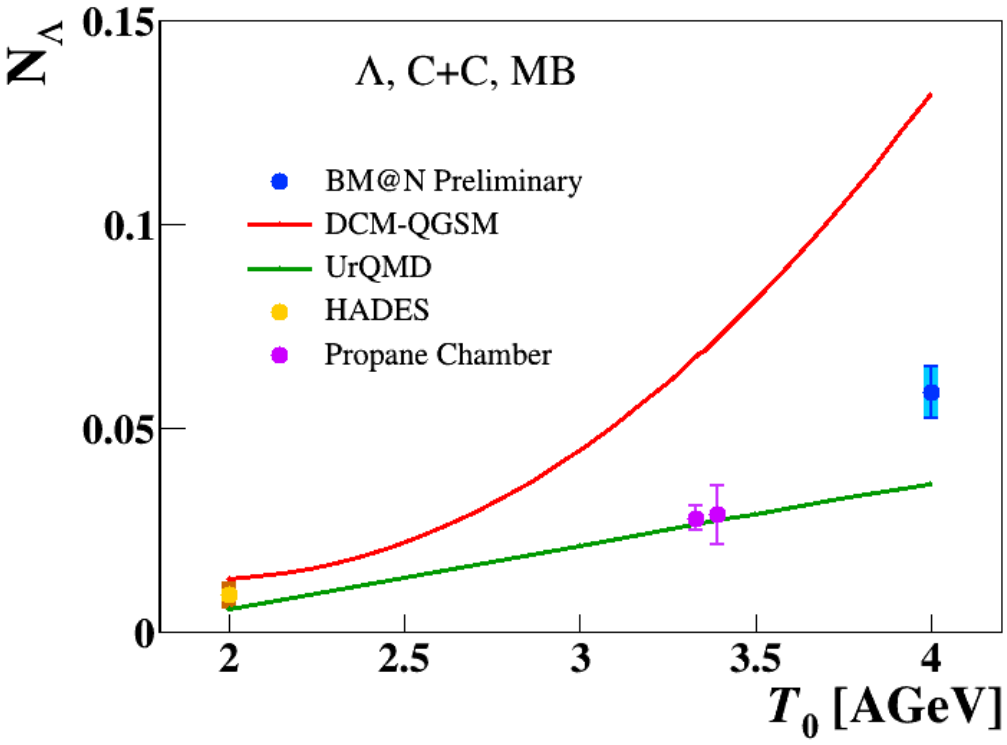
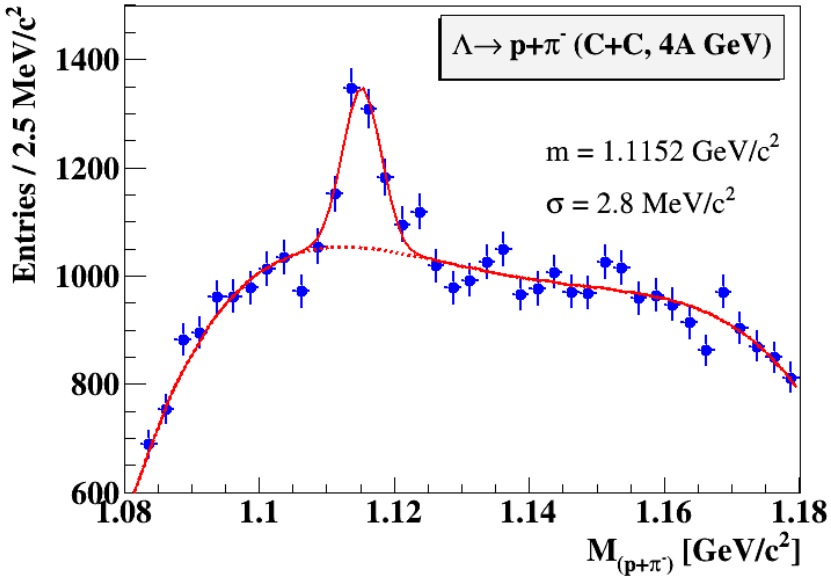
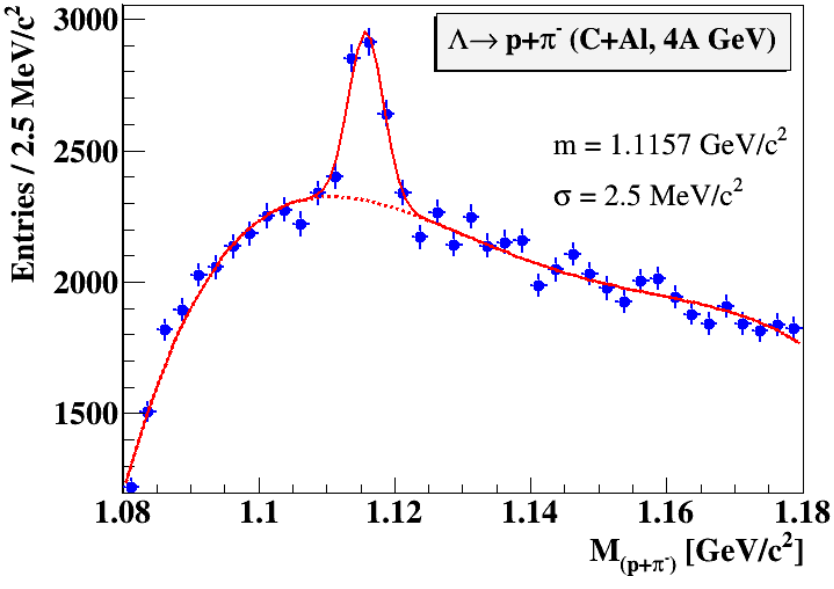


Fig. Energy dependence of *Λ* yields measured in different experiments. BM@N result is compared with data [*S.Arakelian et al., P1-83-354, JINR, Dubna; D.Armutlijsky et al., P1-85-220, JINR, Dubna; Kalliopi Kanaki, PhD "Study of Λ hyperon production"*]. The predictions of the DCM-QGSM and UrQMD models are shown.

Signal of Λ in *C+C, C+Al, C+Cu* interactions





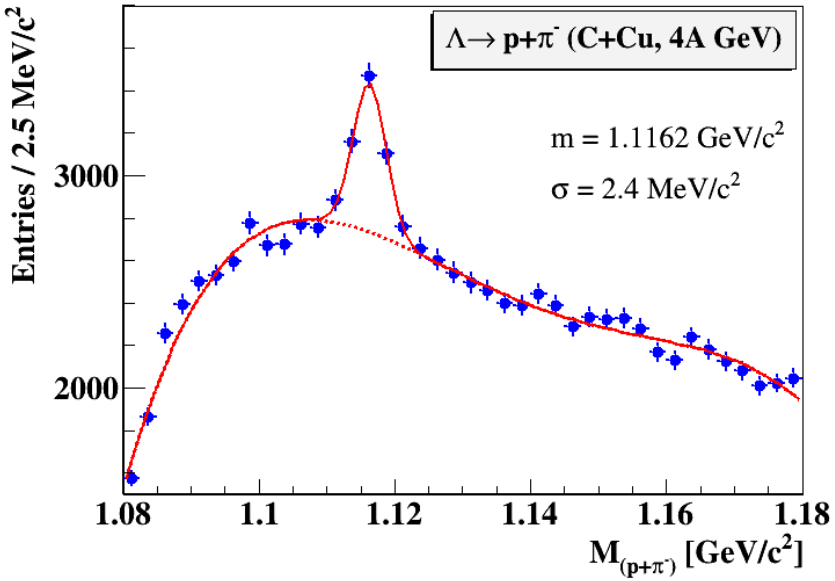
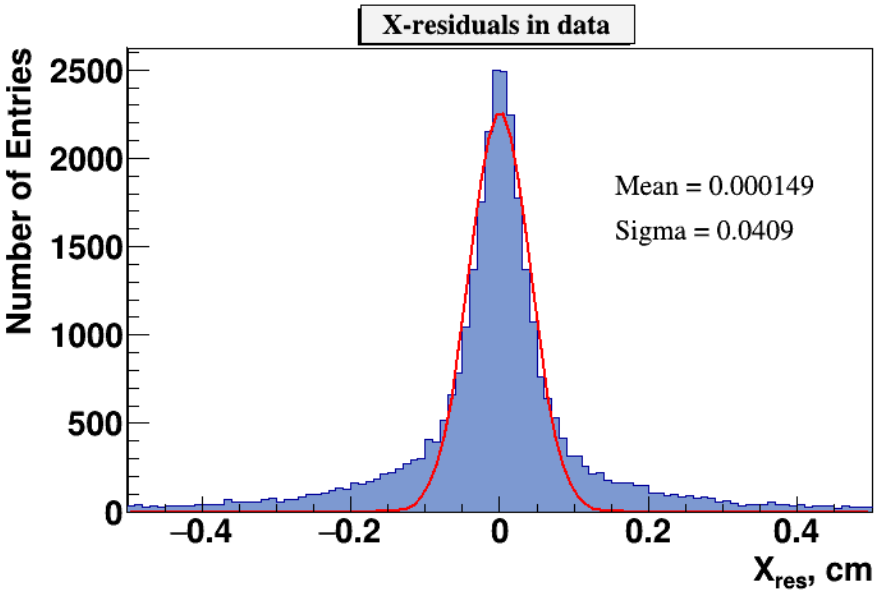


Fig. *Λ→pπ⁻* signal reconstructed in interactions of the carbon beam with targets: *C, Al, Cu*.

Residual distributions of GEM hits



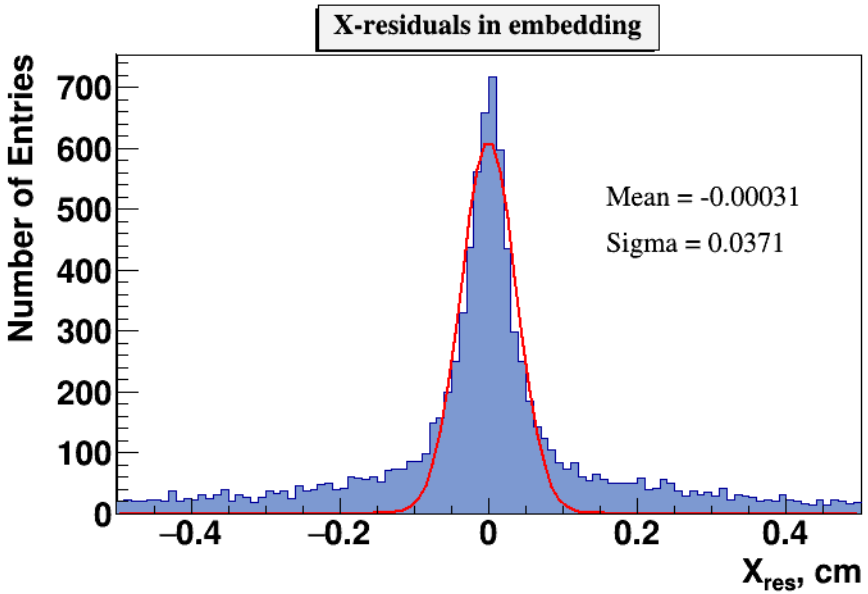


Fig. 12. Residual distributions of GEM hits with respect to reconstructed tracks: left) experimental data, right) reconstructed tracks of embedded Λ decay products.

The invariant mass spectrum

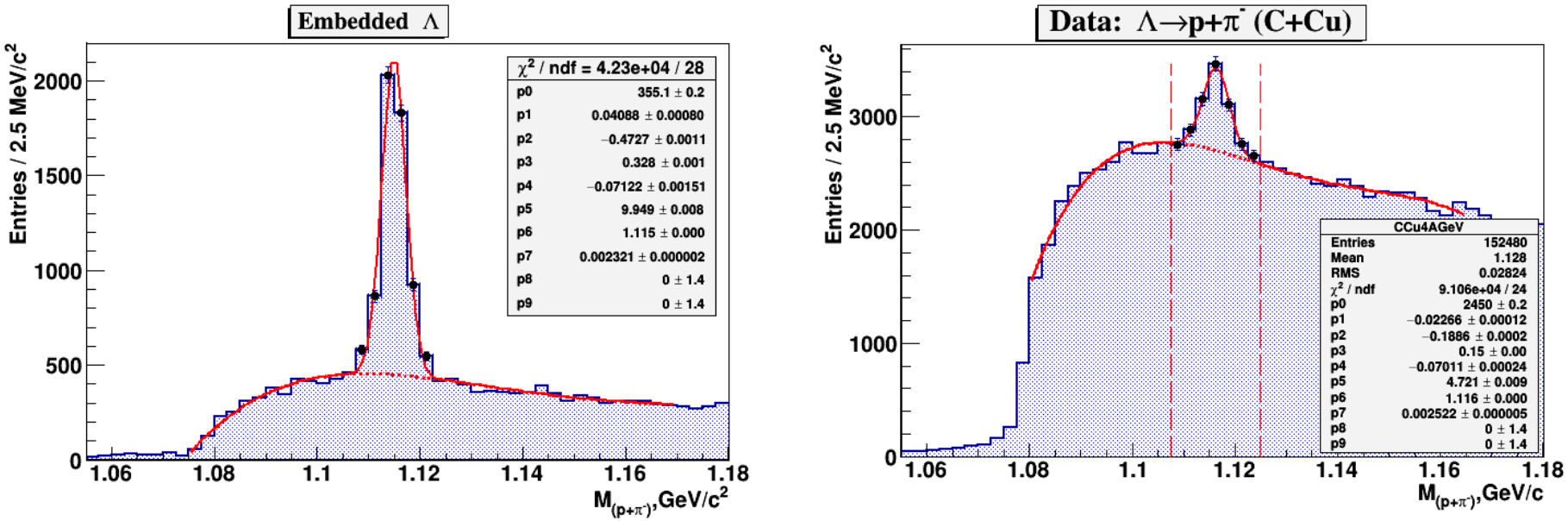


Fig. 13. The invariant mass spectrum of (p,π^-) pairs reconstructed in the experimental events of *C+Cu* interactions with embedded Λ hyperon decay products (left); The invariant mass spectrum of (p,π^-) pairs reconstructed in *C+Cu* interactions (right).

The Λ yields and production cross section

Interacting nucleus / reference	Beam momentum, kinetic energy (T_0)	Λ cross section, mb	Λ yield, $\cdot 10^{-2}$
He_4+Li_6	4.5 GeV/c (3.66A GeV)	5.9± 1.5	1.85 ± 0.5
$C+C$	4.2 GeV/c (3.36AGeV)	24 ± 4	
$C+C$, propane chamber	4.2 GeV/c (3.36A GeV)		2.8 ± 0.3
$p+p$	4.95 GeV/c (4.1 GeV)		2.3 ± 0.4
$C+C$, HADES	2A GeV	$8.7\pm1.1\pm^{3.2}_{1.6}$	$0.92\pm0.12\pm^{0.34}_{0.17}$
$Ar+KCl$, HADES	1.76AGeV		3.93±0.14±0.15
$Ar+KCl$, FOPI	1.93A GeV		3.9±0.14±0.08
$Ni+Ni$, FOPI, central 390 mb from 3.1 b	1.93A GeV		$0.137\pm0.005\pm^{0.009}_{0.025}$
$Ni+Cu$, EOS, full b<8.9 fm / central b<2.4 fm	2A GeV	112±24 / 20±3	
$Ar+KCl$, central b<2.4 fm	1.8A GeV	7.6±2.2	