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Comparison of the Measured Invariant Cross Sections with Model Predictions for Production at Zero Angle of Secondary Light Nuclei in CC-collisions at Beam Energy 20.5 GeV/n on the Accelerator U-70

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M.Yu. Bogolyubsky, A.A. Volkov, D.K. Elumahov, A.A. Ivanilov, A.Yu. Kalinin, A.N. Krinitsyn, V.I. Kryshkin, N.V. Kulagin, D.I. Patalakha, K.A. Romanishin, V.V. Skvortsov, V.V. Talov, L.K. Turchanovich

Introduction

Recently U-70 provided ^{12}C beam. It opens new possibilities in study CA-scattering.

The aim of this experiment is to measure production at angle 0 charged particles and nuclear fragments. For this the combined spectrometer for 2ry particles is used consisting of beam line no. 22 and detectors of the modified setup FODS (with varying beam line rigidity from 7 to 70 GeV).

1. Proposal of the experiment : M.Yu. Bogolyubsky at al., Preprint IHEP, 2013—11, OEF

2. Simulation (Geant4) for beam-line 22: M.Yu.Bogolyubsky, «Selection and Transportation of Light High-energy Nuclei by Beamline 22 of the U-70 Accelerator: The Monte Carlo Simulation», Instruments and Experimental Techniques, 2014, vol. 57, pp. 519-530

3. 1st results demonstrated that the experiment is successfully launched: M.Yu. Bogolyubsky et al. «Forward Particle Production in Proton-Nucleus Interactions at momenta 25 and 50 GeV/c and Proton-Nucleus Interactions at Energy 25 GeV/n», Phisics of Atomoc Nuclei, 2017, Vol. 80., No. 3, pp. 455-460.

Presentation of the 1st data on particles and nuclei yields:

4. *M.Yu. Bogolyubsky at al., XXIII International Baldin Seminar, 19-24 Sept, 2016, Dubma, Book of abstracts. p. 35.*
5. *M.Yu. Bogolyubsky at al., XXIII International Baldin Seminar, 19-24 Sept. 2016, Dubna, Book of abstracts, p. 48.*
6. *M.Yu .Bogolyubsky at al. , The 3rd International Conference on Particle Physics and Astrophysics, 2-6 Oct., Moscow; Journal of Physics: Conference Series , 9 Apr. 2018, pp 97-101, http://iopscience.iop.org/issue/1742-6596/934/1.*

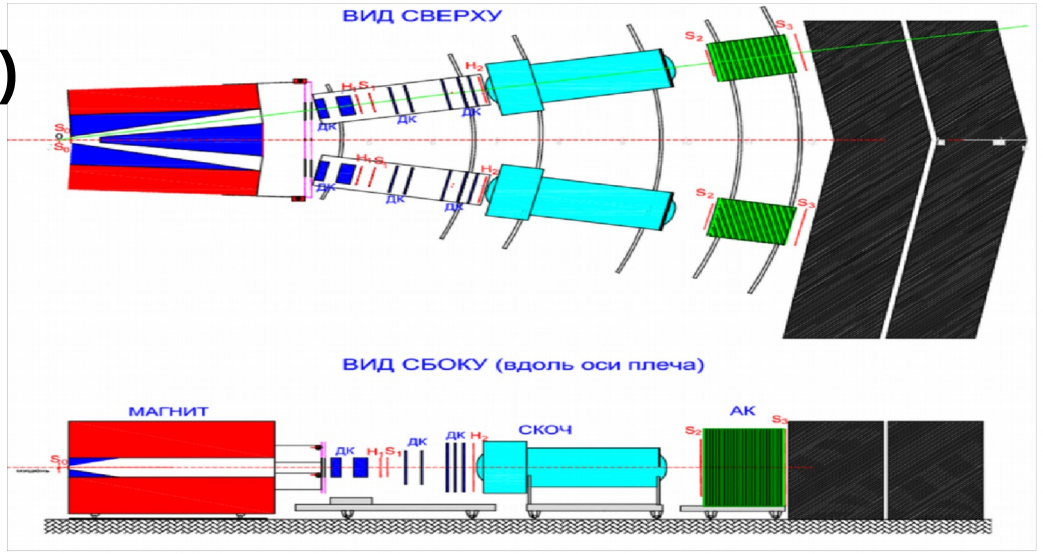
Introduction (continue)

In this work we transfer from yields of particles to invariant cross section. This is more usefull for comparison with predictions of the theoretical models. Such transfer was made on the base detailed simulation for passing of particles and nuclei through used combined spectrometer to define acceptance in framework of Geant4 (version 10.4.p02).

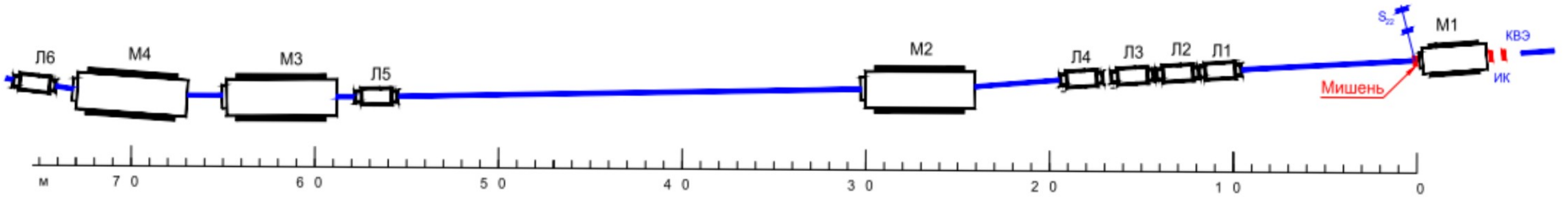
The experiment setup

a)

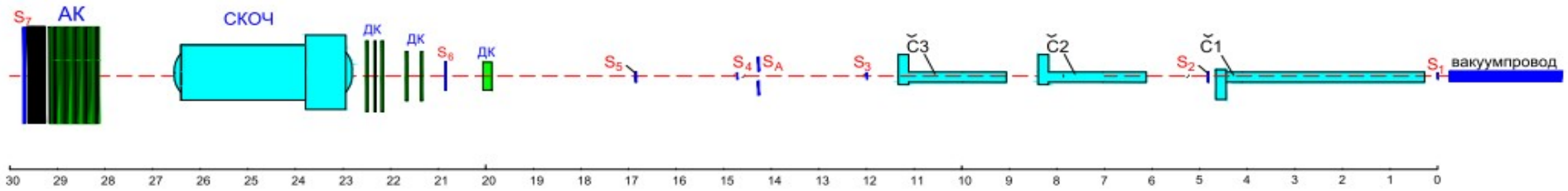
b)



c)



d)



S_i-scintillator counters, $\check{C}_i$- Cherenkov counters, SCOCH – RICH detector, hadron calorimeter, DT – drift tubes, DC – drift chambers.

The main experiment parameters

Beam: ^{12}C, 20 A GeV.

Beam extraction:

- Stochastic slow extraction (10^9 per spill)
- Extraction with bent crystal (10^7 per spill)

Targets: Carbon, Lead (~1.8 cm length) and empty target.

Total length of the setup ~120m.

Angular acceptance: ~6 mrad.

Theory and Models

UrQMD (ver. 3.4, used for primary interaction) model based on the Ultrarelativistic Quantum Molecular Dynamics.

FTFP-BERT-EMV (used for primary interaction and/or transport code) is built from several components like AA model Fritiof handling the formation of initial strings and following them fragmentation into hadrons according to the Lund model in the framework of Bertini cascades, de-excitation of the remnant nucleus in the precompaund part and CPU oprimization of electromagnetics.

QGSP-FTFP-BERT-EMV (used for primary interaction and/or transport code) additionally to previous includes hA quark gluon string precompound model.

Quark Cluster model (QCM, used for interpretation of data in kinematically forbidden region) — The model considers the nucleus as consisting of clusters with n-nucleons (3n-quarks), n = 1,2,3 .., A.V. Efremov et al., Phys.Atom.Nucl. 57, 932 (1994).

Models QGSP-FTFP-BERT-EMV and UrQMD allow one to describe the production of particles and nuclei in kinematically forbidden regions.

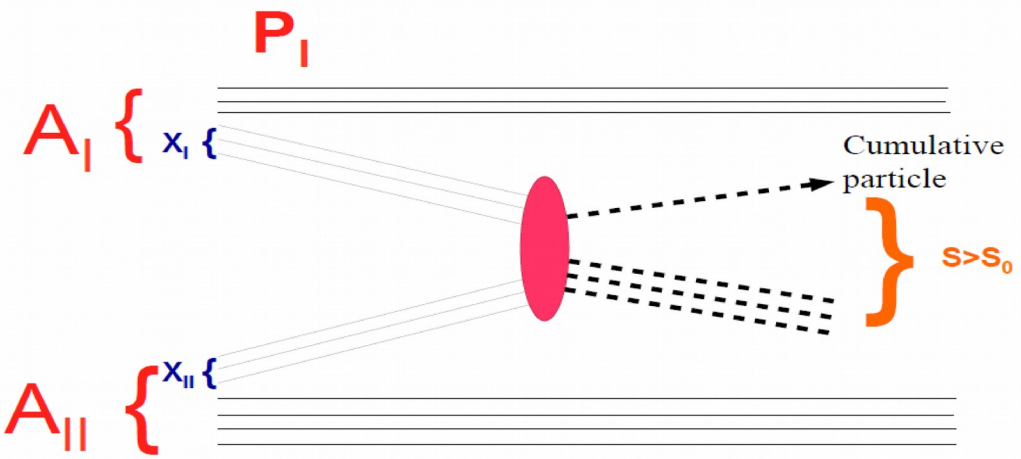
Theory and models:

Stavinsky process and S_{min} variable

S_{min} — minimal squared energy of colliding constituents to produce observed particle

V.S. Stavinsky JINR Rapid Communications N18-86, p.5 (1986)

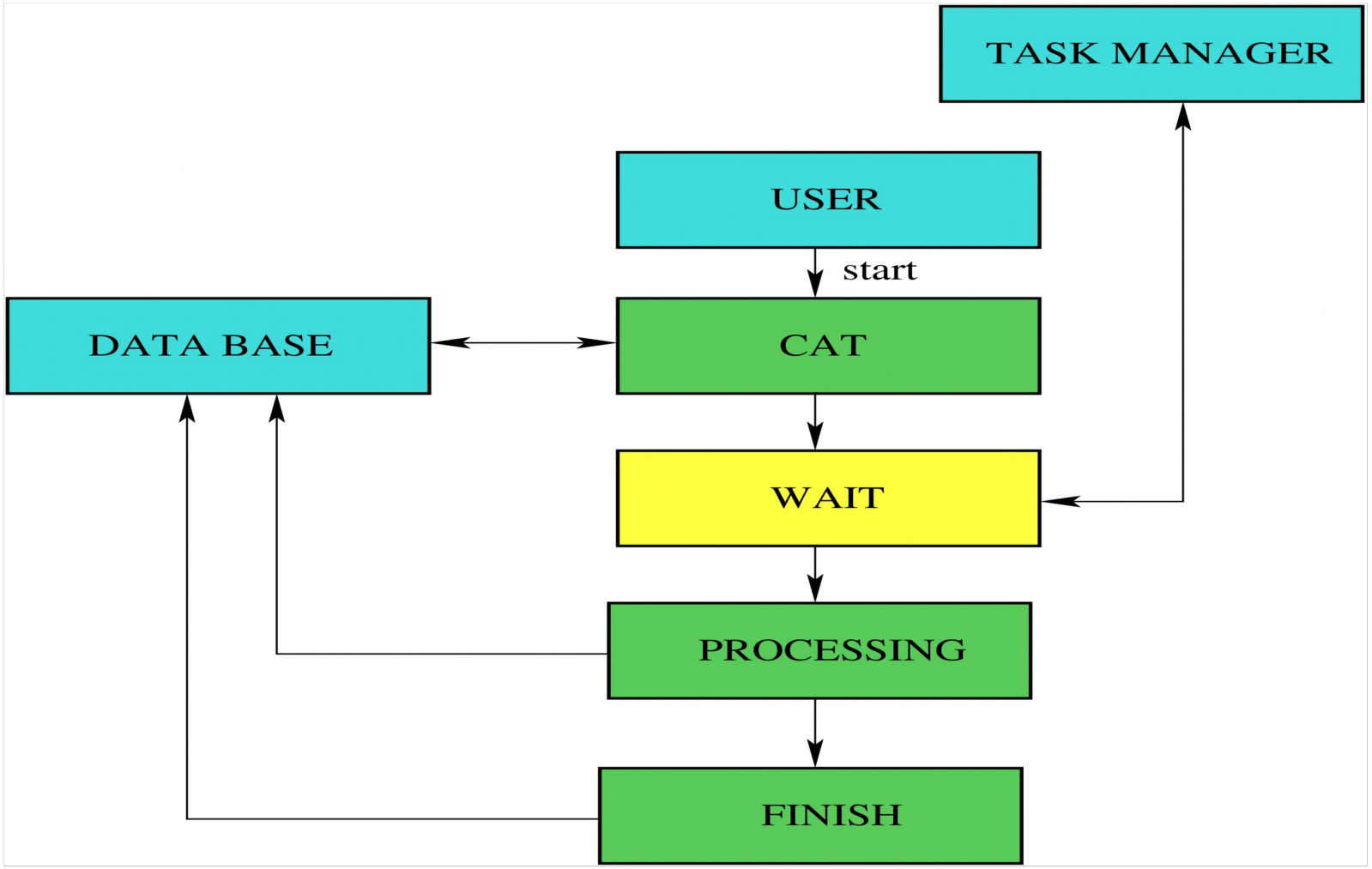
In cumulative processes $(X_I \cdot M_I) + (X_{II} \cdot M_{II}) \rightarrow m_c + [X_I \cdot M_I + X_{II} \cdot M_{II} + m_2]$



***Baldin-Stavinsky formula* for invariant cross section on the base of S_{min}:**
A.A. Baldin*, Physics of Atomic Nuclei (ЯФ), *V.56, 3 (1993) p.174.

Determination acceptance dΩ and attenuation coefficients Ka (beam line 22), Kf (FODS setup) by Monte-Carlo simulation in Geant4 v. 10.02.p02

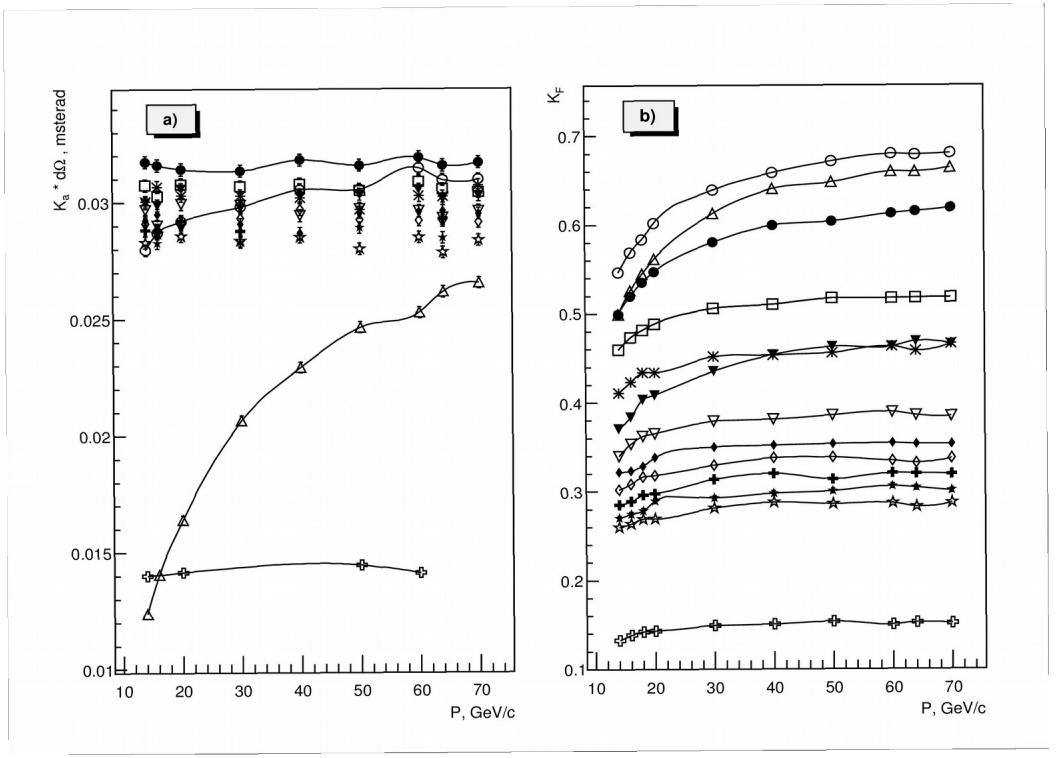
Organization of mass calculations on computer cluster IHEP, up to 3000 parallel jobs



Determination acceptance dΩ and attenuation coefficients Ka (beam-line 22), Kf (FODS setup) with Monte-Carlo sumulation in Geant4

Simulation process for dΩ-definition:

N events with one particle of each type (pi, K, proton, antiproton, d, t, He, Li, Be, B, carbon ..) were generated with uniform distrib. in target, with uniform ditribution through fixed solid angle $d\Omega_0$ and momentum interval (P_1, P_2). Solid angle $d\Omega_0$ overlaps the angle capture of particles in beam lin22 and P_2-P_1=8 σ, where σ is momentum beam line resolution. Then number of particles of every type n_1, n_2, n_3 .. was counted at the end of beam line 22 with sort them into two clases: a) produced in primary interaction, b) produced in 2ry processes at flight inside of the beam line.

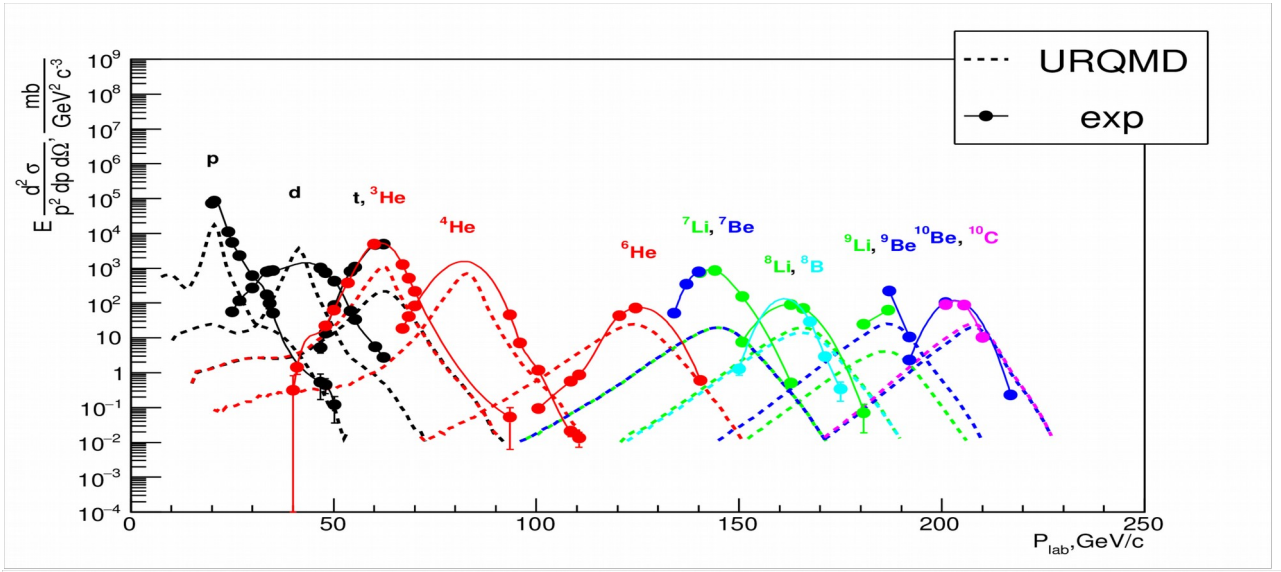


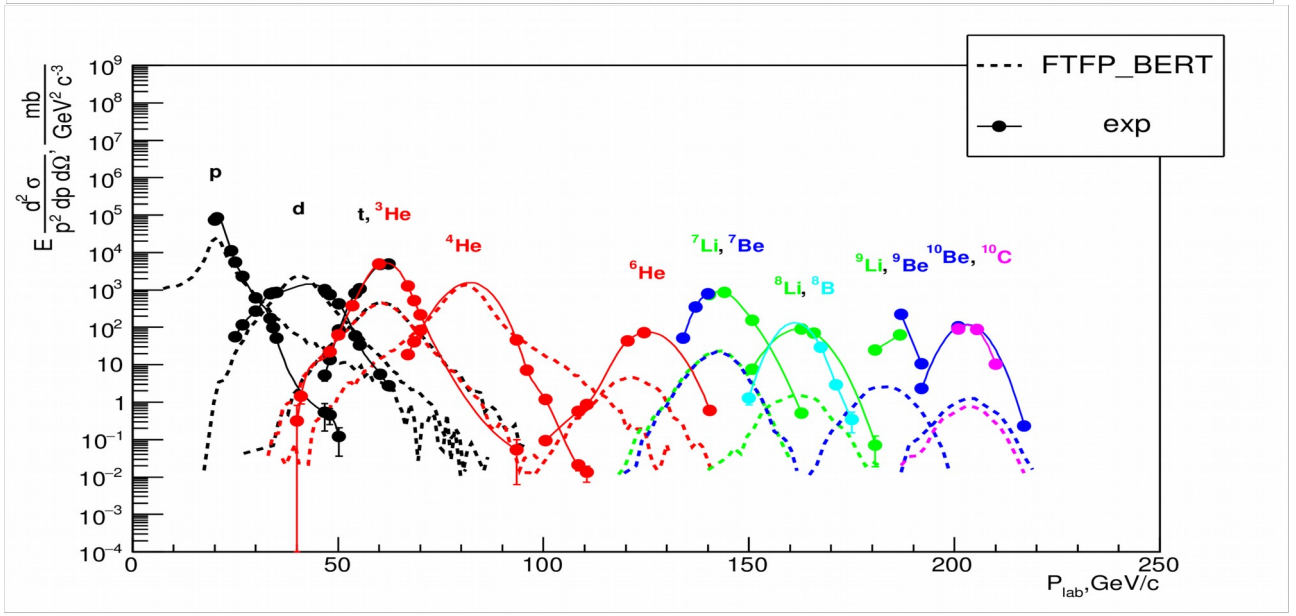
The dependences: a) - Ka *dΩ and b) — Kf in CC interactions on beam-line rigidity P for positive particles and nuclear fragments, transport code is - QGSP-FTFP-BERT-EMV, notations: white points - π+ mesons, white triangles - K+ mesons, black points - protons, white squares - deuterons, black triangle (inverted) - Triton and He3, the six-pointed star - He4, white triangle (inverted) - He6, black diamond - Li6, white diamond - Li7, black cross - Li8, white cross - Li9, black five-pointed star - B10, light five-pointed star - C12, solid lines - spline between computed points, a) - contains for simplicity splines only for protons, π+, K+ mesons and Li9.

Light nuclei: Invariant cross-section Finv(P) with UrQMD and QGSP_FTFP_BERT model calculations

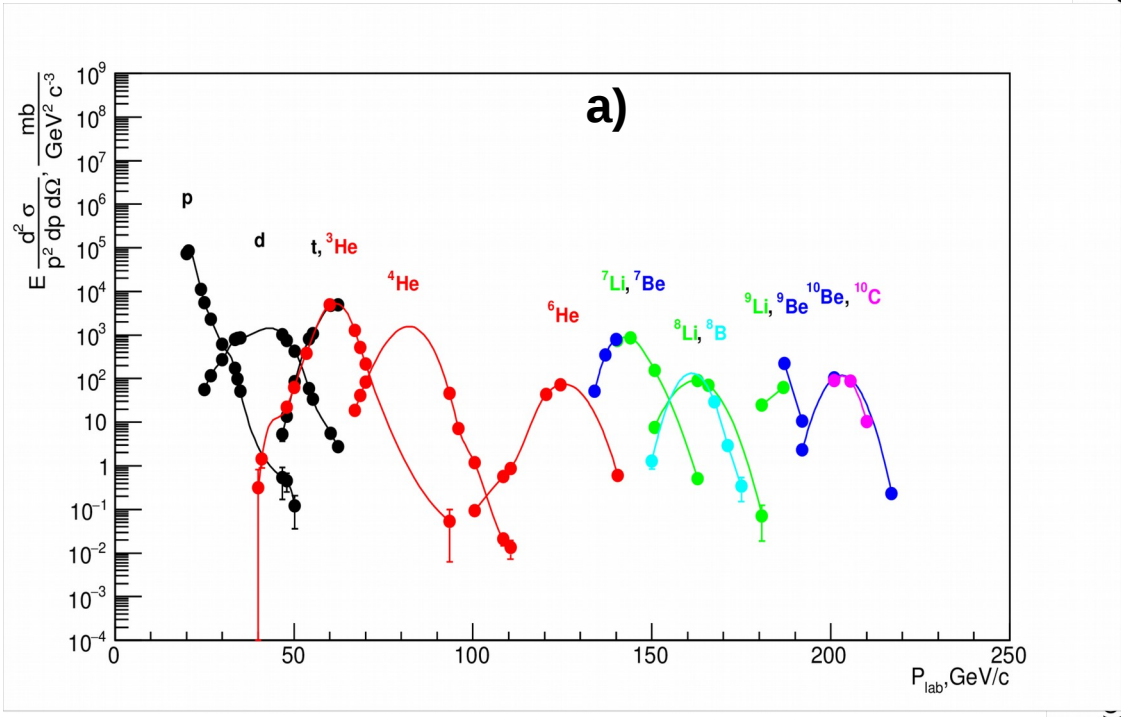
C target

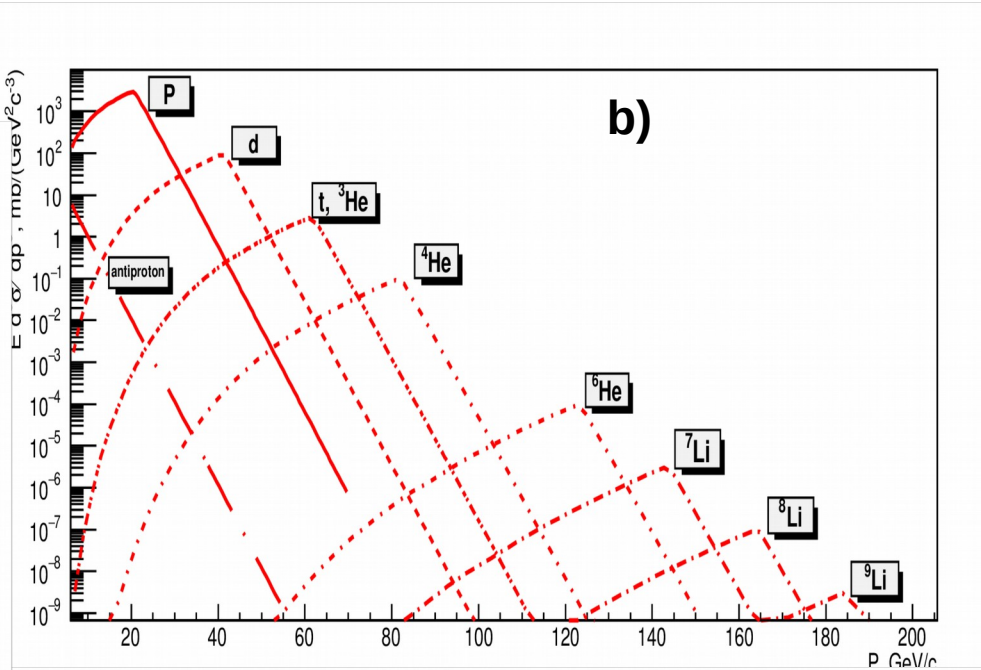
Figures show for each fragment essential population in cumulative region
P>20.5*A GeV/c

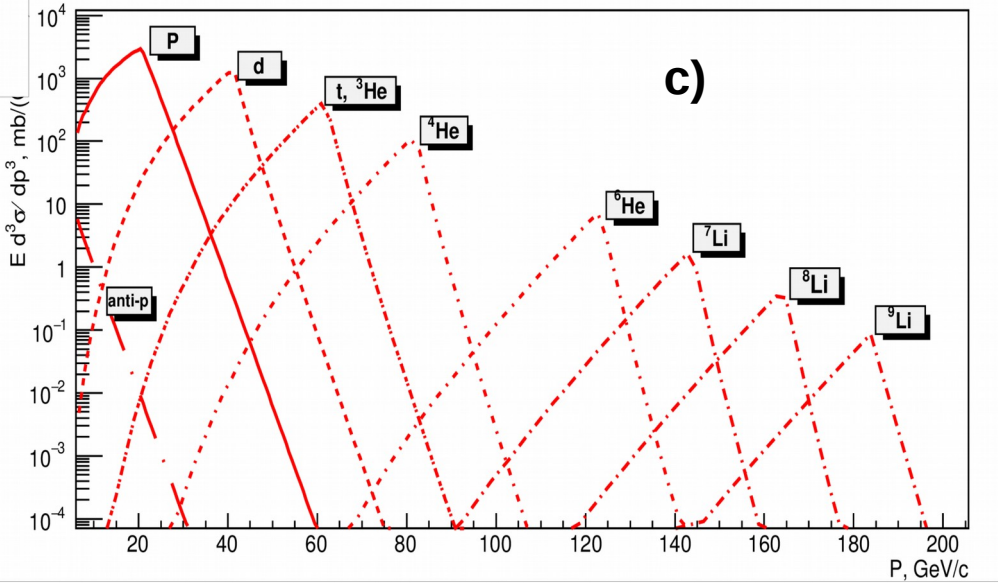




Light nuclei: Invariant cross-section Finv(P) on C-target (a — experiment)
in comparison with Baldin-Stavinsky formula (b — standard, c - modified)







Modification of Baldin-Stavinsky formula:

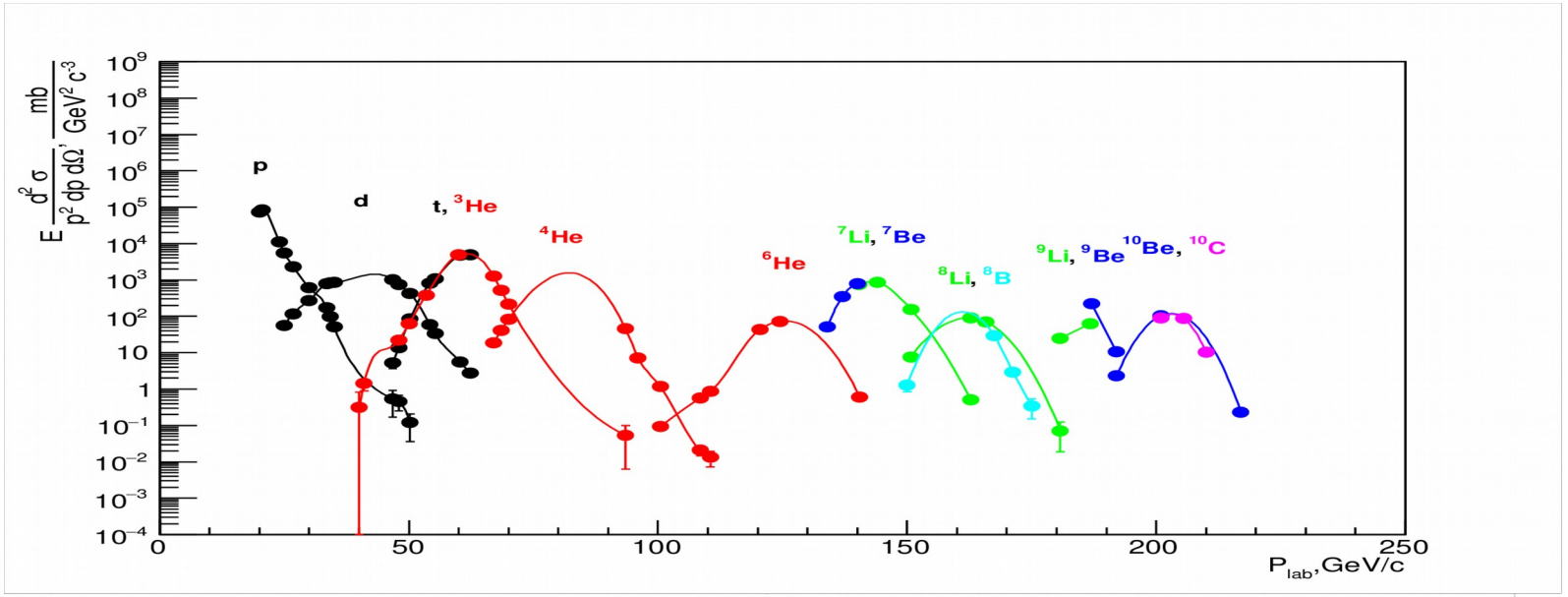
Smin → Smin - ((Mf-Mp)*a)2 ,**

where a ~ 0.91

Light nuclei: Comparison CC-data of this exp. (top) with CC-data at 2.1 GeV/n (down)

from: Anderson at al., Phys. Rev. C, V. 28, No 3, p.1224

C target



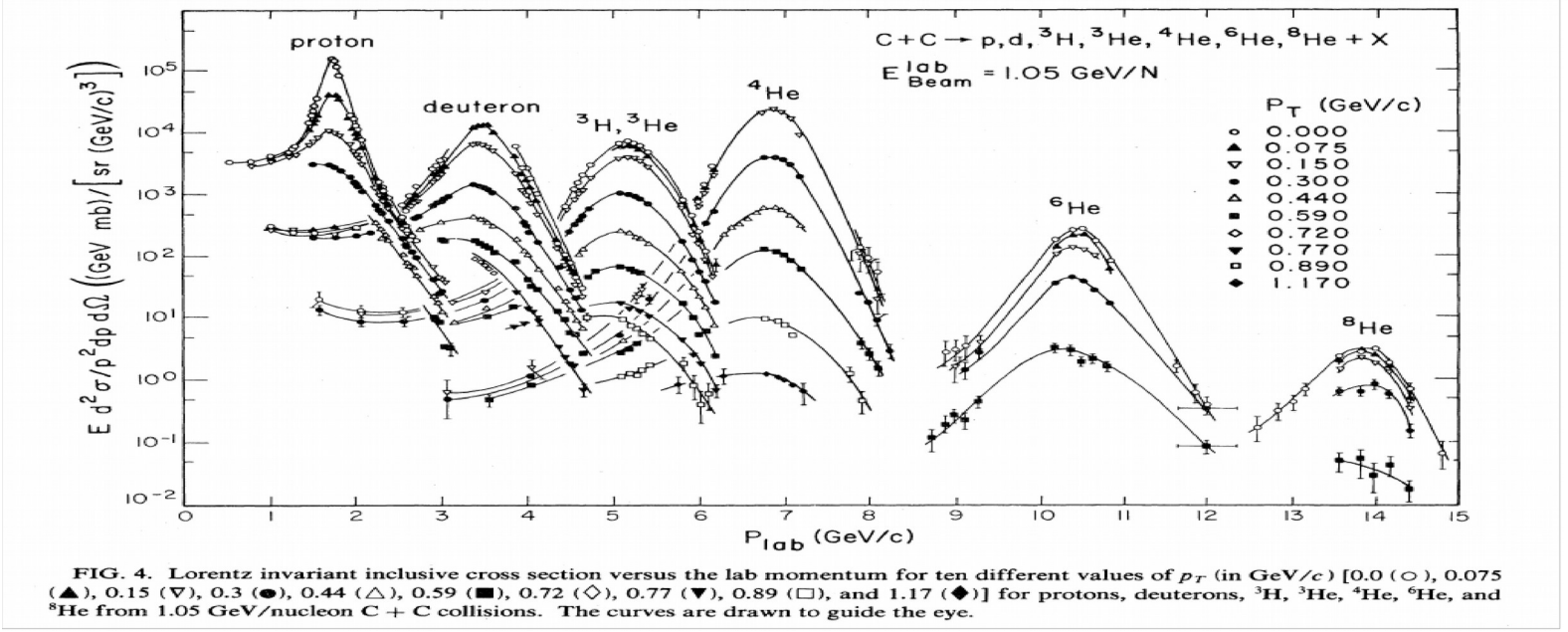
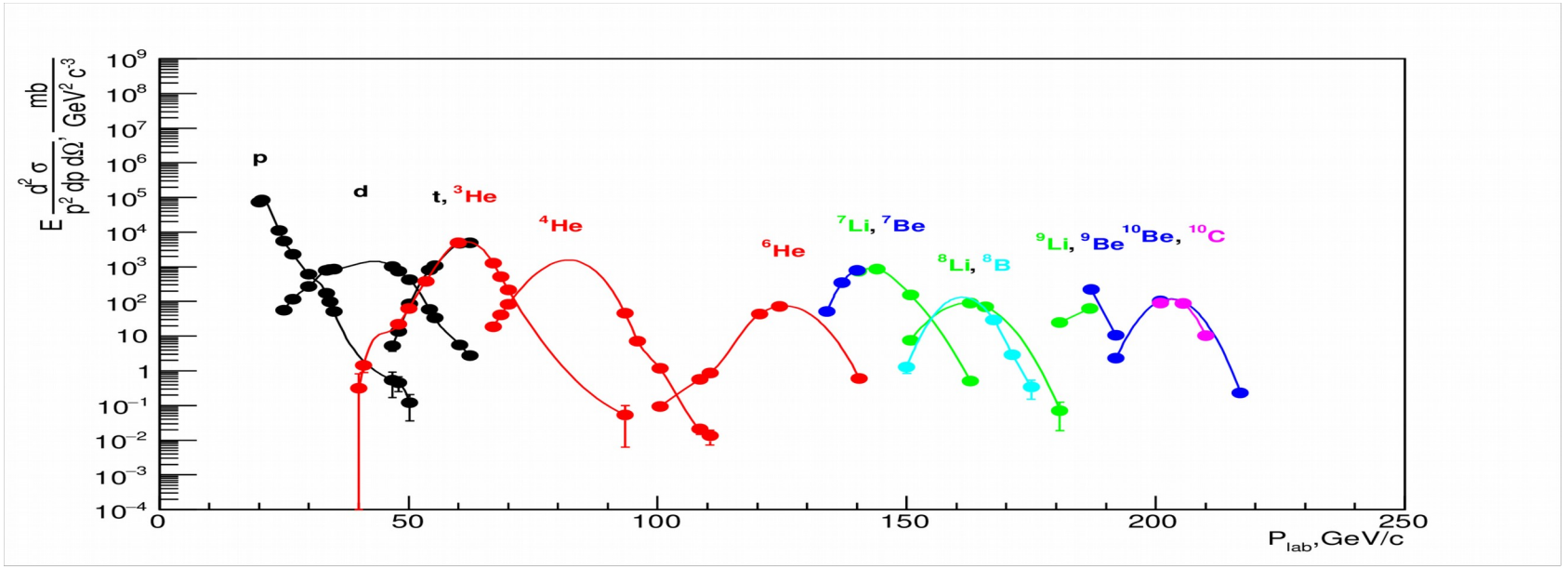


FIG. 4. Lorentz invariant inclusive cross section versus the lab momentum for ten different values of p_T (in GeV/c) [0.0 (○), 0.075 (▲), 0.15 (▽), 0.3 (●), 0.44 (△), 0.59 (■), 0.72 (◇), 0.77 (▼), 0.89 (□), and 1.17 (◆)] for protons, deuterons, ^{3}H, ^{3}He, ^{4}He, ^{6}He, and ^{8}He from 1.05 GeV/nucleon C + C collisions. The curves are drawn to guide the eye.

Light nuclei: Top — Fin(P) on C-targ, this exp., Down - non-invariant cross section at CBe-collisions at 0.95 GeV/n from:

B.M. Abramov et al., Physics of Atomic Nuclei, 2018, V 81, No 3, p330.



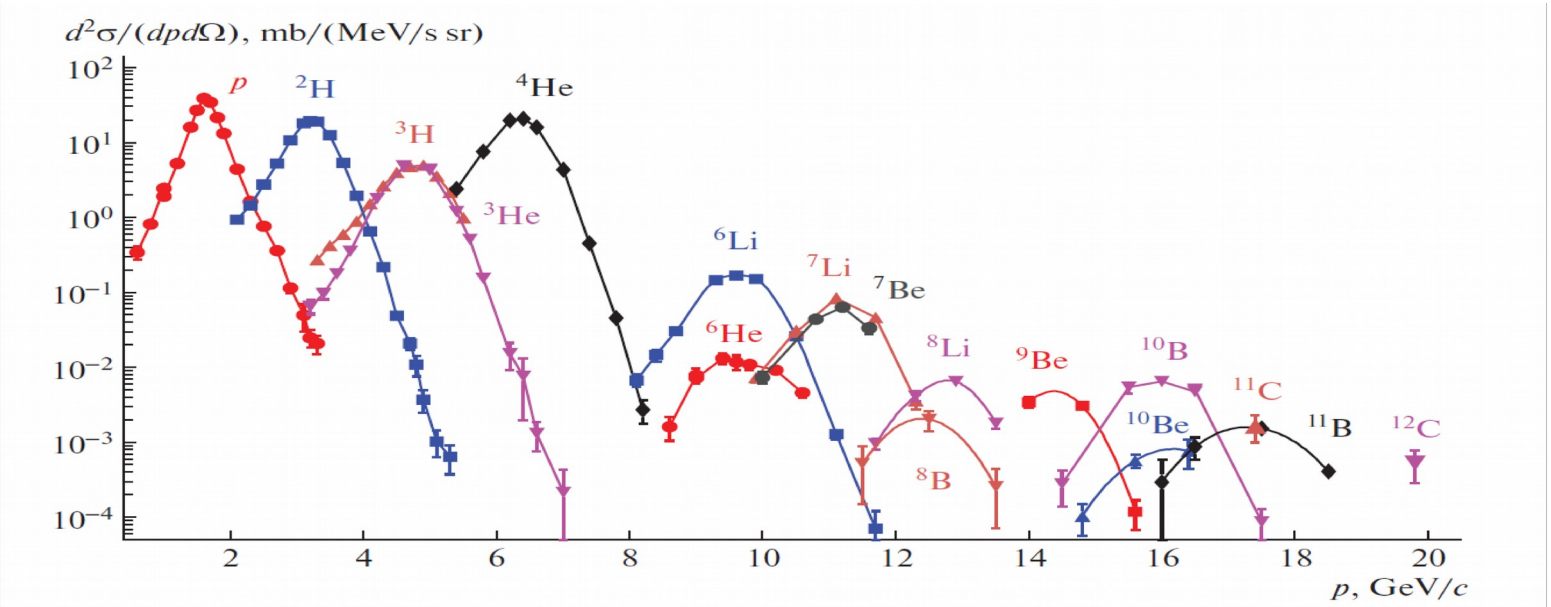


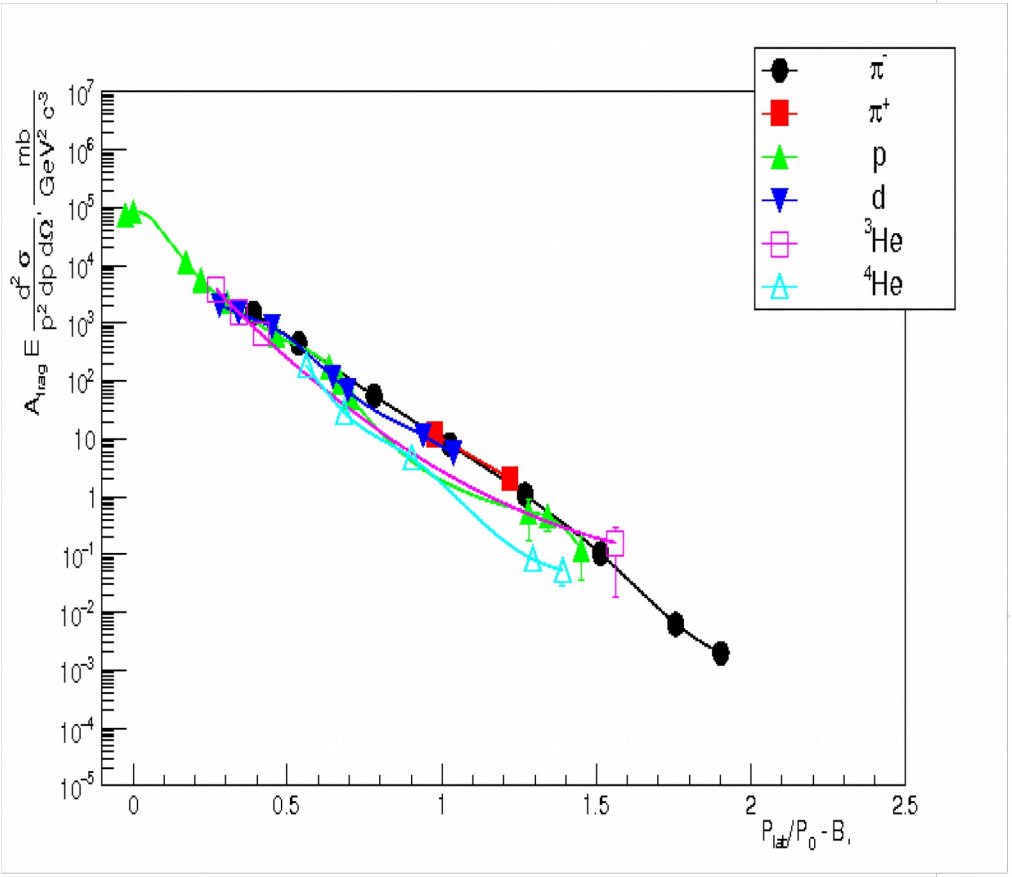
Fig. 2. Differential cross sections for the yield of fragments versus the laboratory momentum.

Cross-section profile form universality on argument P/P0-B,

where B - barionic number of observed particle

Comparison of this exp. (left) with back production in pPb-collisioms at beam momentum at 8.9 GeV/c (right)

from review: A.V. Efremov, Physics of Particles and Nuclei (ЭЧАЯ), 1982, т. 13, вып. 3, с. 613.



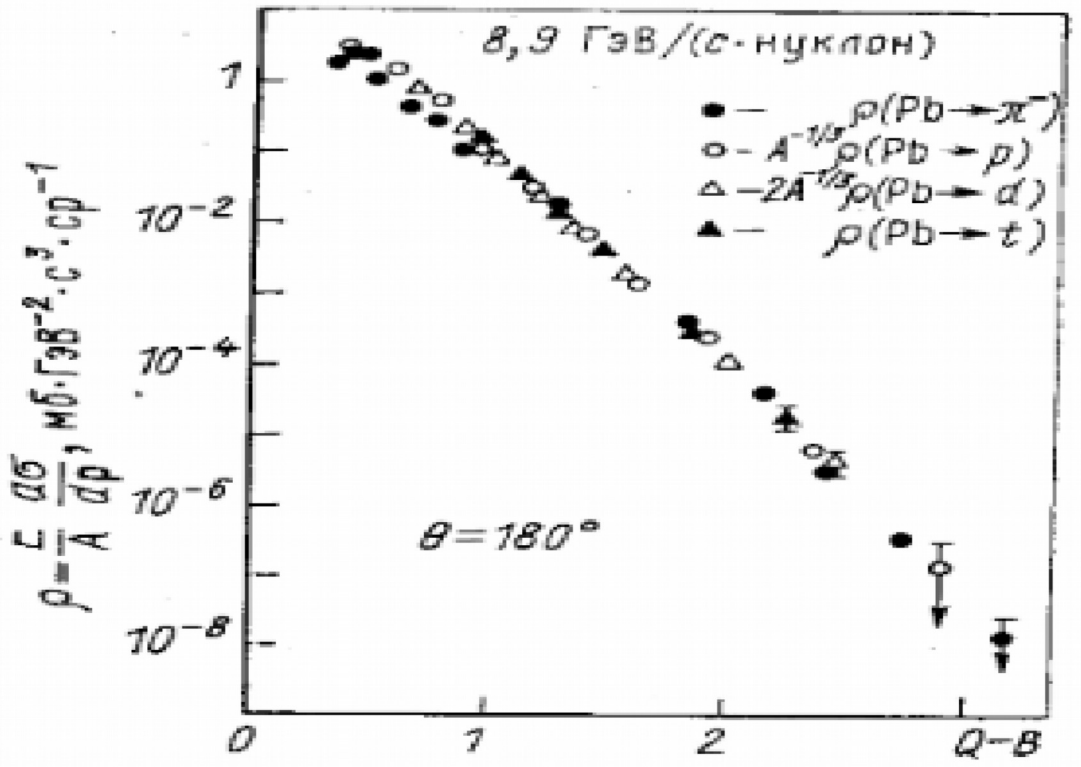
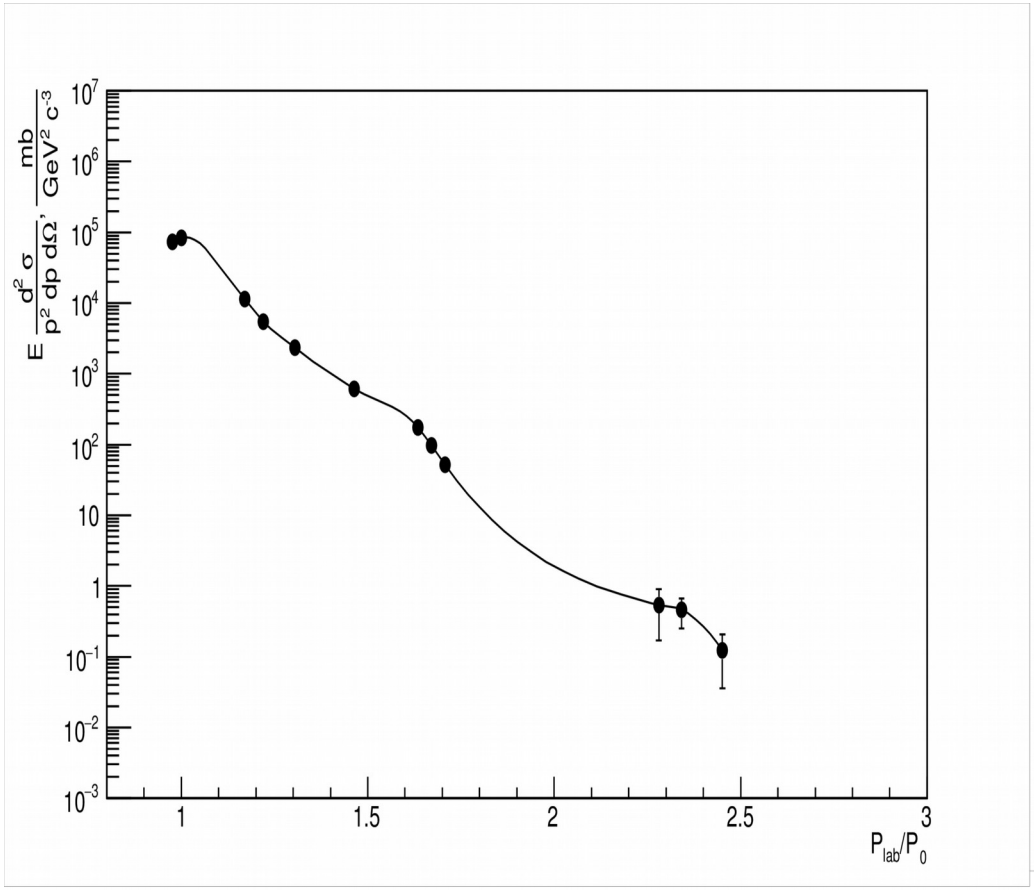


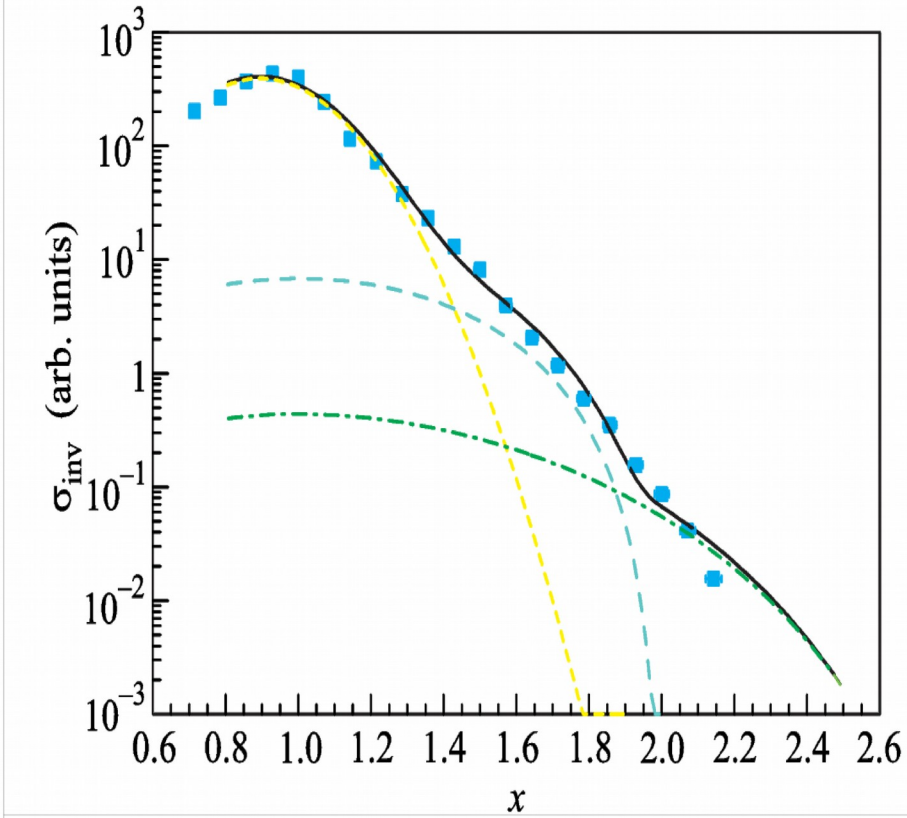
Рис. 3. Универсальность формы спектра кумулятивного процесса; *B*-барионное число кумулятивной частицы

Protons: Invariant cross-section as function x=P/Po

from point of view quark cluster model **(A.V. Efremov et al., Phys.Atom.Nucl. 97, 932 (1994)).**

Left - this exp., Right — CBe-data at 0.6 GeV/n from:
B.M. Abramov et al., JETP Lett, V97, 5 (2013), p. 509.





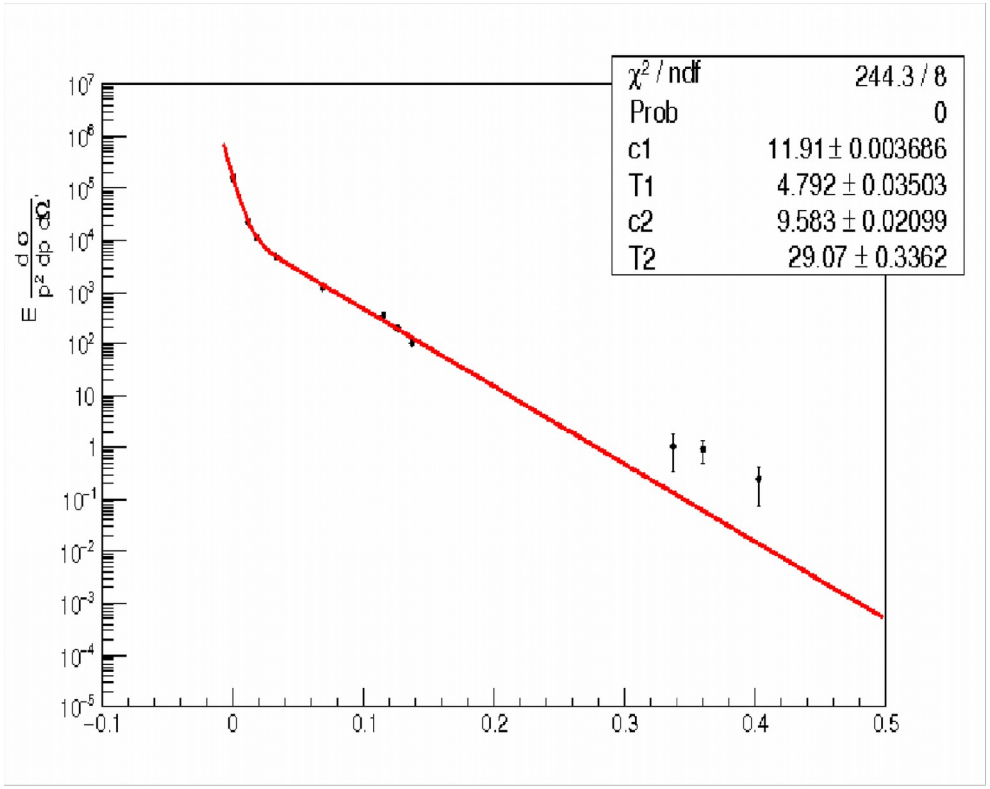
Wave-like profile of Finv(x) reflects
the multicluster structure of nucleus.

Protons: Invariant cross-section on Tkin (in atilab. system)

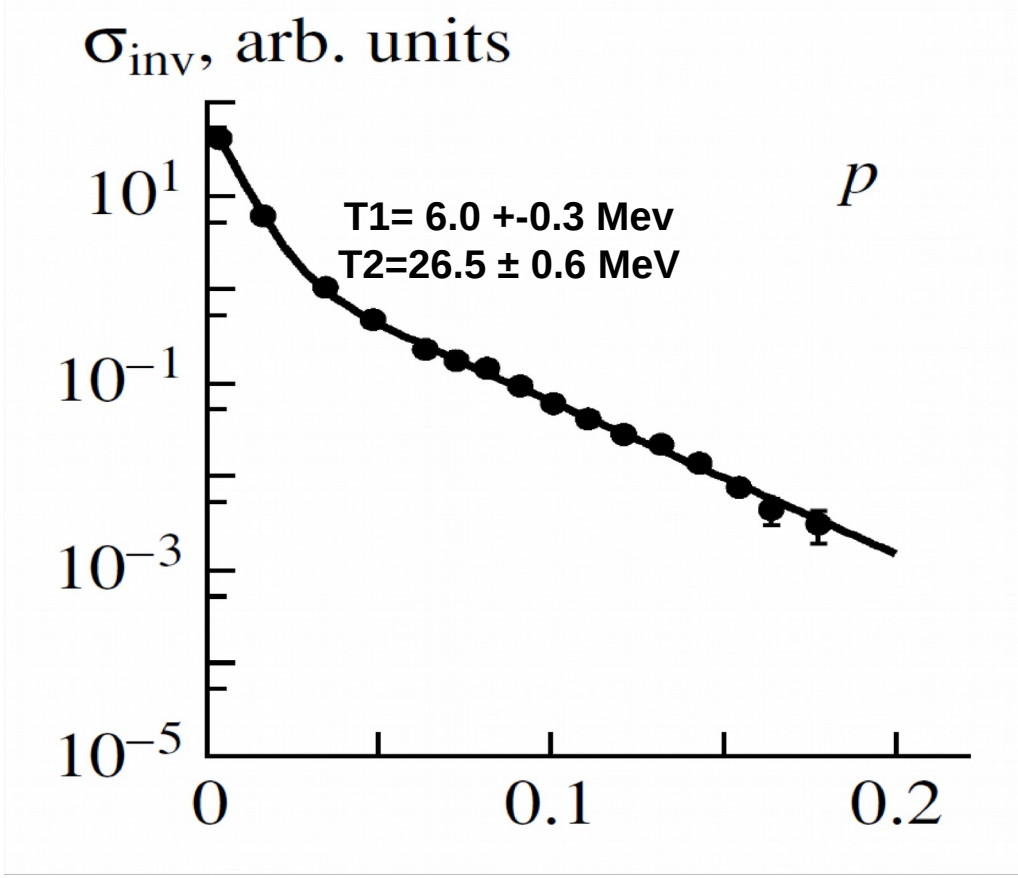
Measurements temperature of eavaporation (T1 MeV) and cumulative regions (T2 MeV)
Fit of data by sum of two exponents: f = c1*exp(-Tkin/T1) + c2*exp(-Tkin/T2)

Left — CC-data, this exp., Right — CBe-data at 0.6 GeV/n from:
B.M. Abramov et al., Physics of Atomic Nuclei, 2016, V79, No 5, p. 700.

arb. units



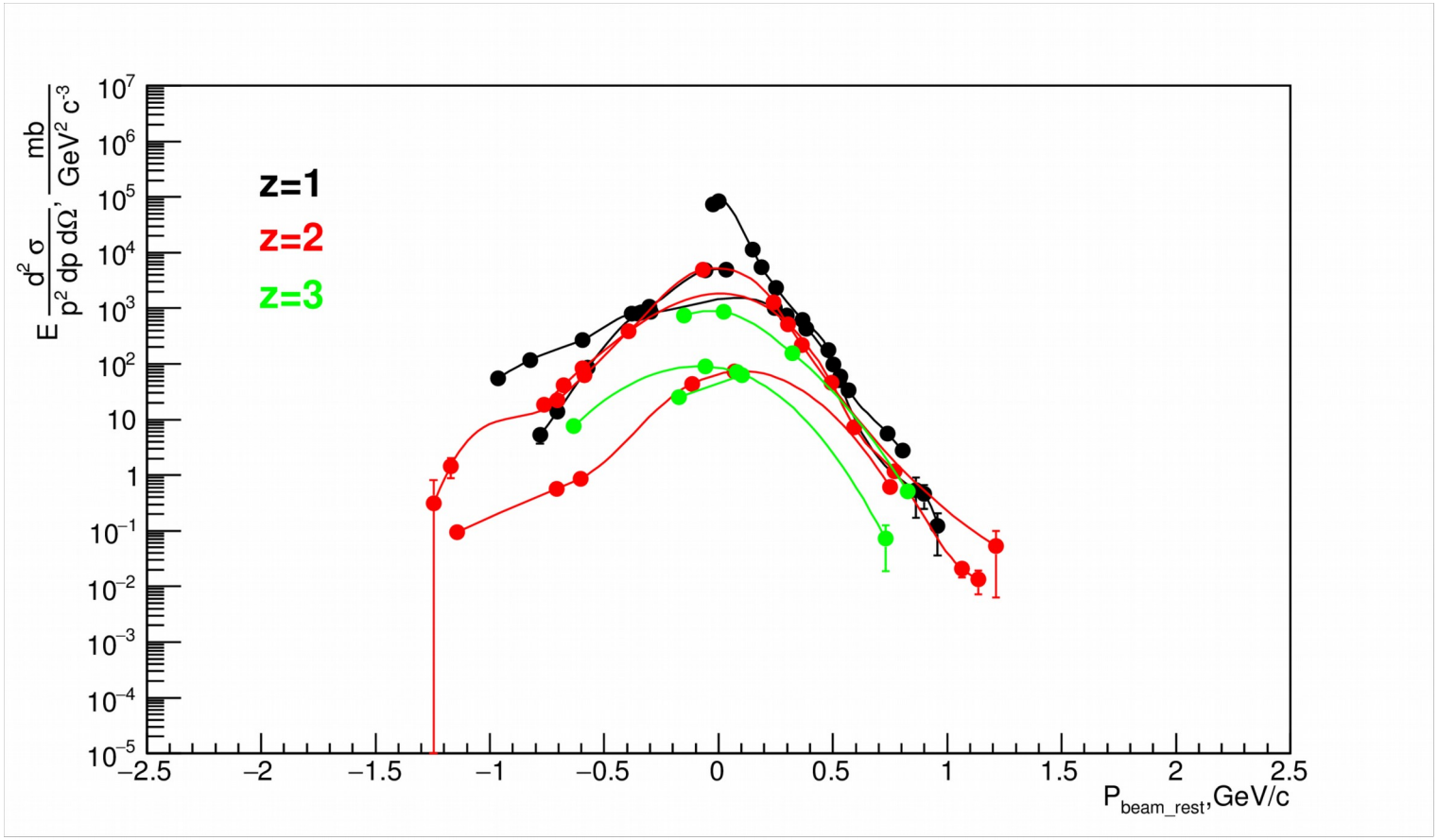
Tkin,GeV



Tkin,GeV

Light nuclei: Invariant cross section on momentum P in antilab. system.

C — target



Gauss approximation of Finv cross-section in antilab-system

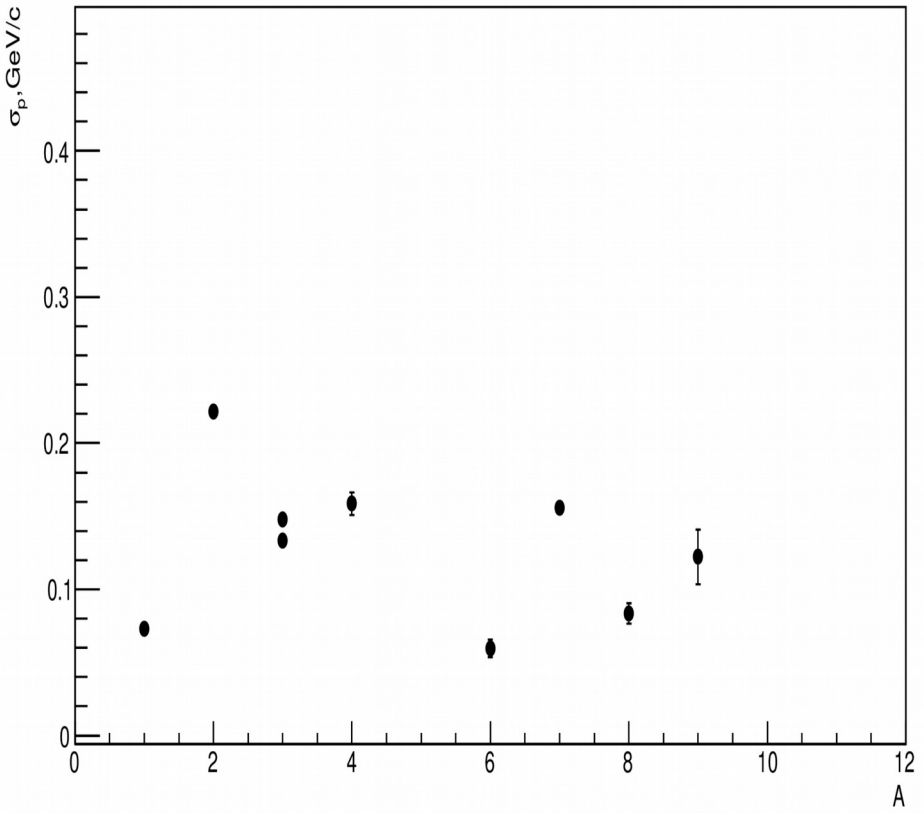
$$\sigma_p = P_F * \sqrt{A_f(A_p - A_f)/(5*(A_p - 1))} \qquad (1)$$

where PF - Fermi momentum, Ap and Af related to beam and observed fragment

Goldhaber A., Phys. Lett, B53 (1974) p.306 - statistical model

Left — CC-data, this exp.; Right — CBe-data at 0.3 Gev/n from:

B.M. Abramov et al., Talk on XXIV International Baldin Seminar, Dubna, 17-22 Sept. 2018



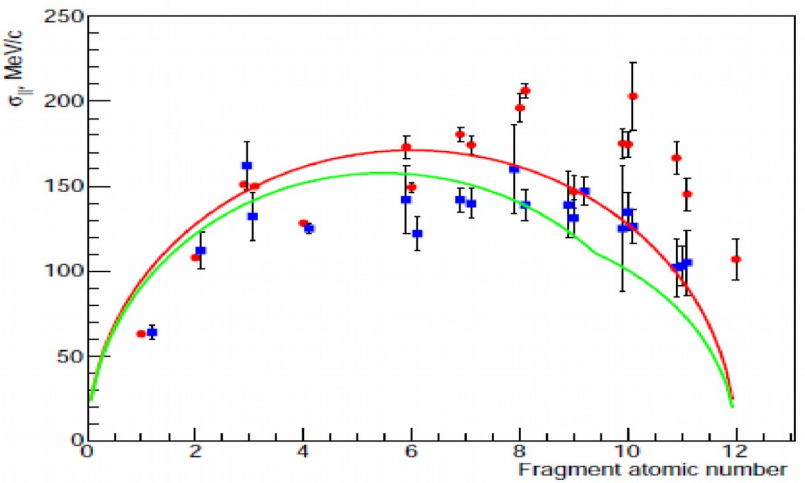


Figure 3. Gaussian parameter of the longitudinal momentum distribution $\sigma_{||}$ as a function of fragment atomic number. The red circles are the data of this experiment, the blue squares are data of [7] for 1 GeV/nucleon. The read line - parabolic law (1) with $\sigma_0 = 95.6$ MeV/c, green line - parametrization of [6].

Summary

The invariant cross sections of light nuclei fragments produced at zero angle in CC-interactions at energy 20 A GeV/c are presented.

Essential contrinution to cumulative region is seen for particles and nuclei.

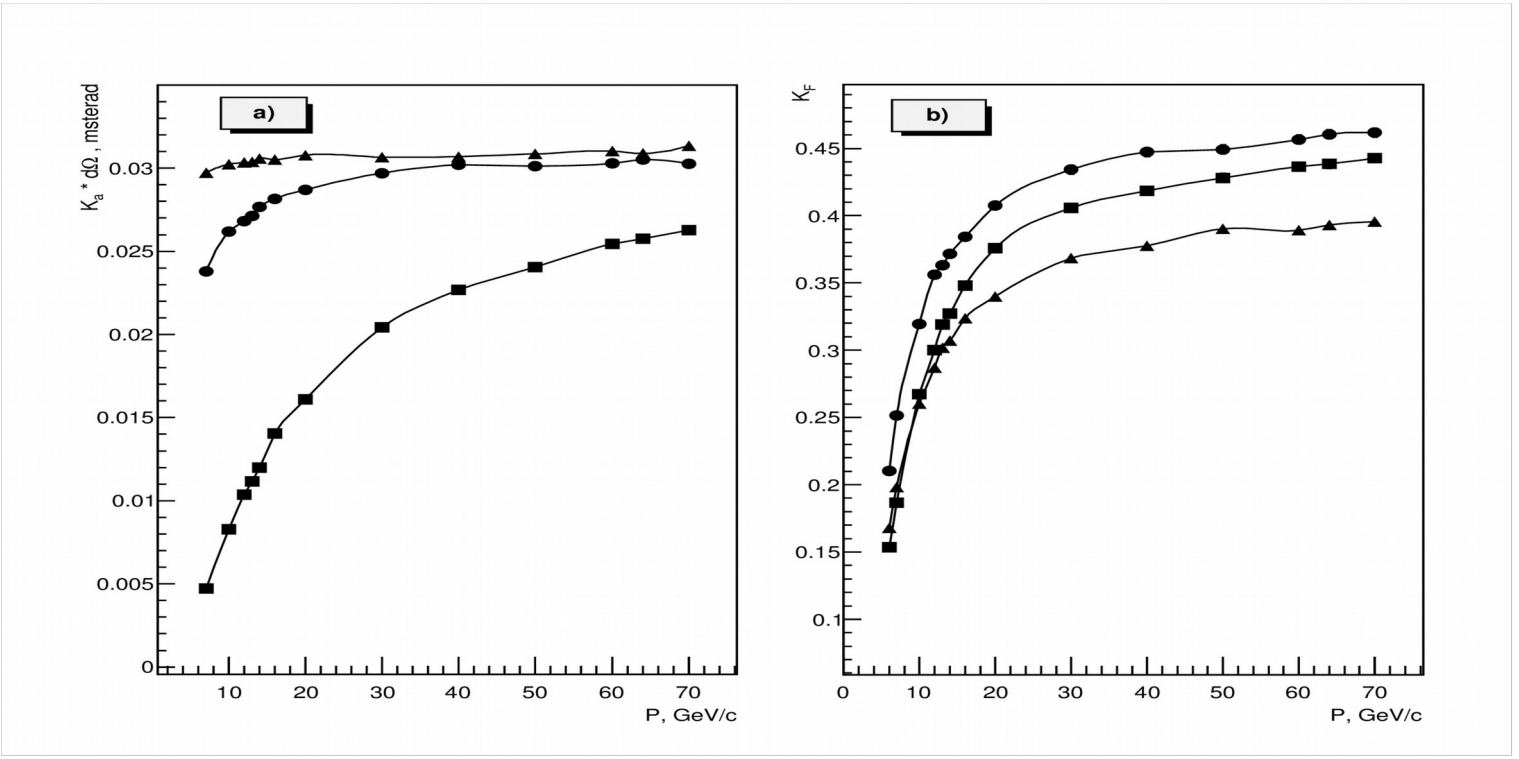
Temperatures of evaporation and cumulative regions are measured.

Comparison of presented results on invariant cross sections with models included in Genat4 QGSP-FTFP-BERT-EMV and also with model UrQMD are made.

Essential discripancy with Baldin-Stavinsky formula based on scailing variable S_{min} — minimal squared energy of colliding constituents to produce observed particle in framework of nuclear scaling hypothesis is observed. It may point out on need to subtract from scailing variable mass of inclusive particle and/or add new parameter in this formula, a variant of such modifications is offered.

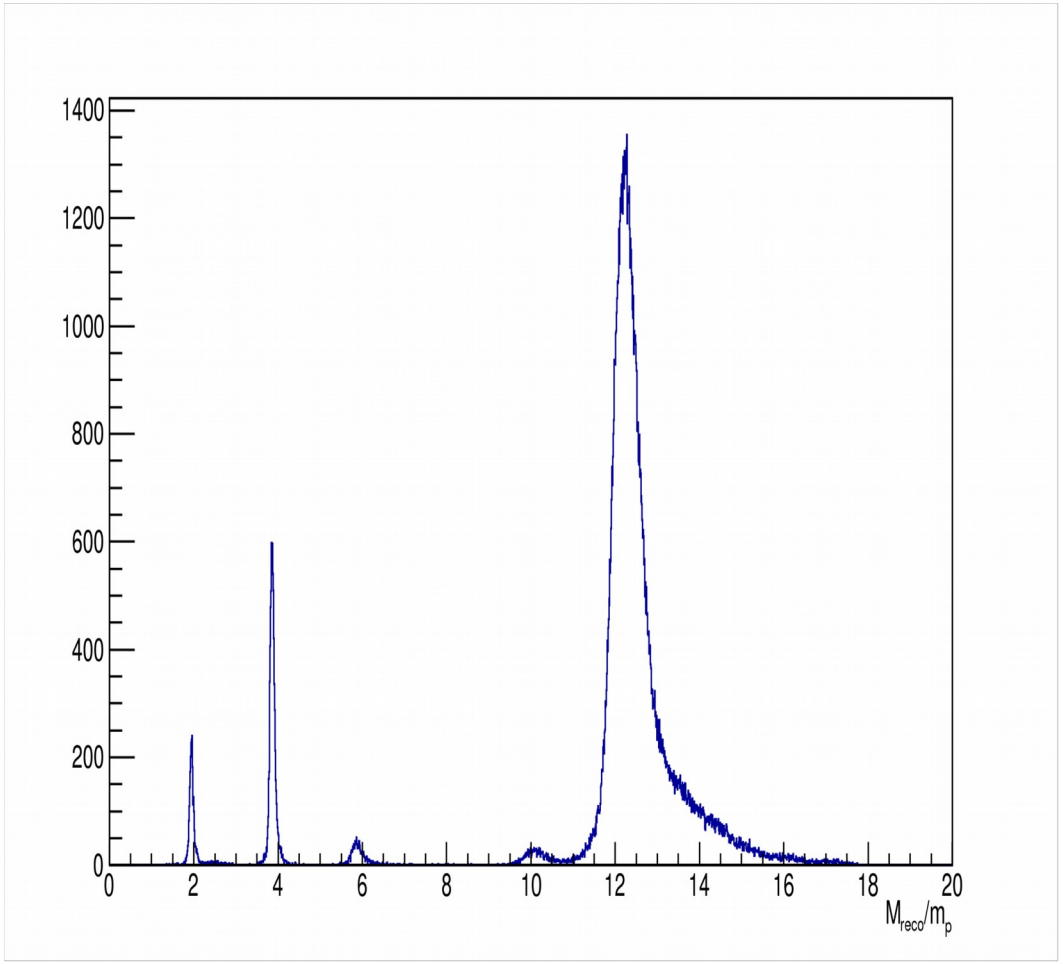
Back up

Determination acceptance dΩ and attenuation coefficients Ka (beam-line 22), Kf (FODS setup) by Monte-Carlo sumulation in Geant4 (continue)



The dependences: a) - Ka *dΩ and b) — Kf in CC interactions on beam-line rigidity P for positive particles and nuclear fragments, transport code is - QGSP-FTFP-BERT-EMV, notations: points - π- mesons, squares - K- mesons, triangles — antiprotons.,

Mass reconstruction in SCOCH



P=41 GeV/c, empty target
Beam extraction with bent crystal