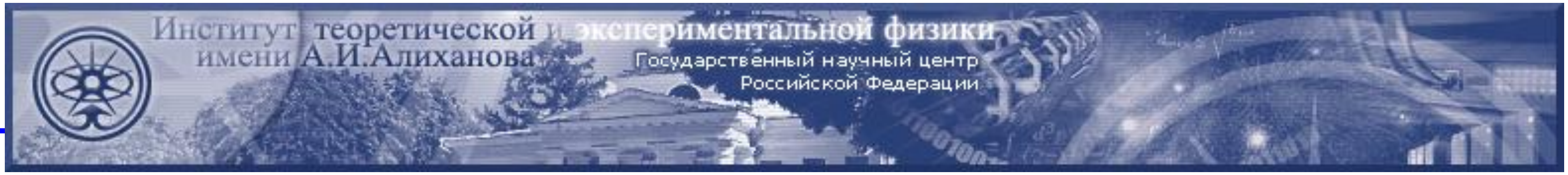

^{12}C fragmentation at 0.3-2.0 GeV/n: test of ion-ion interaction models

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Introduction and motivation

Experiment FRAGM at ITEP TWAC (Moscow)

$^{12}C + Be \rightarrow f + X$ (inverse kinematics)

fragments: p, d, t, ^{3}He, ^{4}He, ^{6}He, ^{8}He,…,C

^{12}C kinetic energies: T_0 = 0.2 – 3.2 GeV/nucleon

fragment angle: 3.5° with respect to ^{12}C direction

different targets: Al, Cu, Ta for ^{12}C beam of 0.3 GeV/n

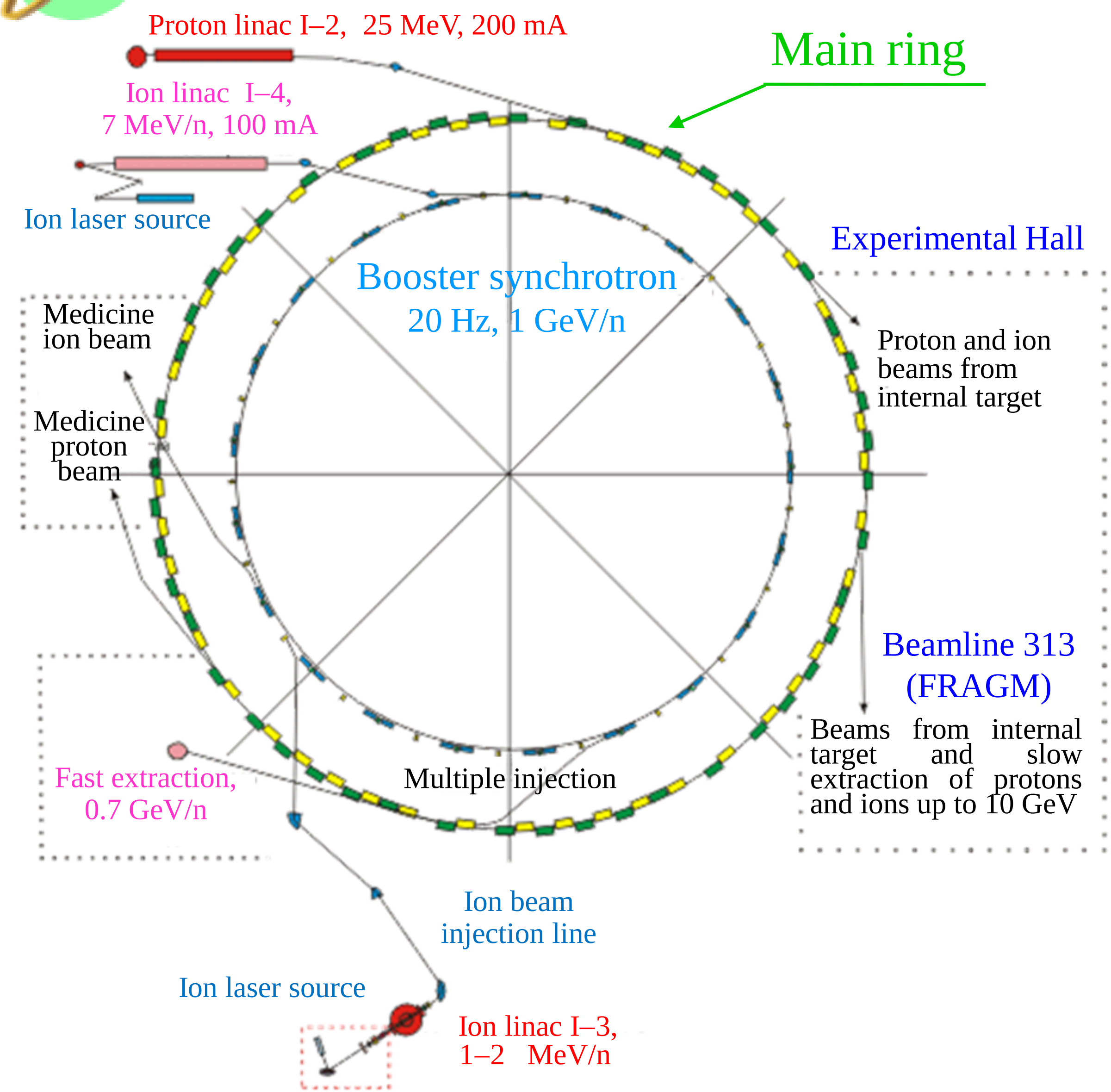
another projectile; ^{56}Fe of 0,2 GeV/n and Be target

sensitivity: up to 6 orders of the cross section magnitude

Here we focus mostly on proton fragments

- cumulative protons (with velocity higher than that of the projectile) provide information on localized dense objects (fluctuons) in the projectile nucleus
- there is lack of data on cumulative particle production in ion-ion collisions
- test of different models of nucleus-nucleus interactions in a wide kinematic region from deep cumulative to midrapidity region

ITEP accelerator complex TWAC



TWAC= TeraWatt Accumulator Complex

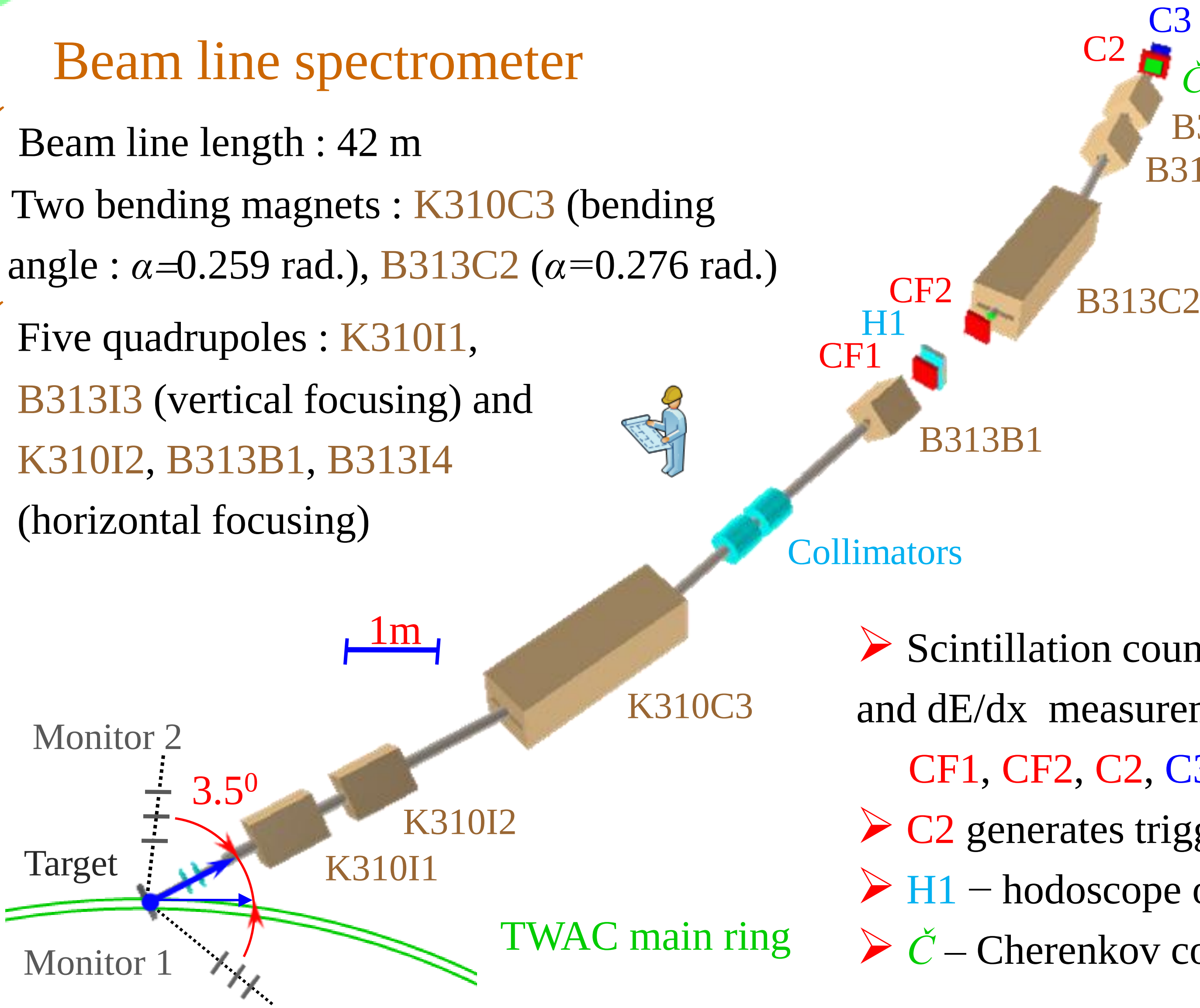
TWAC current parameters

- ✓ Proton acceleration :
  50 – 10000 MeV
- ✓ Ion acceleration :
  up to 4 GeV/nucleon
- ✓ Ion accumulation :
  up to 700 MeV/nucleon
- ✓ Accelerating ions :
  up to ^{56}Fe
- ✓ Typical intensity :
  10^{11} nucleons / s

Experiment FRAGM

Beam line spectrometer

- ✓ Beam line length : 42 m
- ✓ Two bending magnets : K310C3 (bending angle : α=0.259 rad.), B313C2 (α=0.276 rad.)
- ✓ Five quadrupoles : K310I1, B313I3 (vertical focusing) and K310I2, B313B1, B313I4 (horizontal focusing)



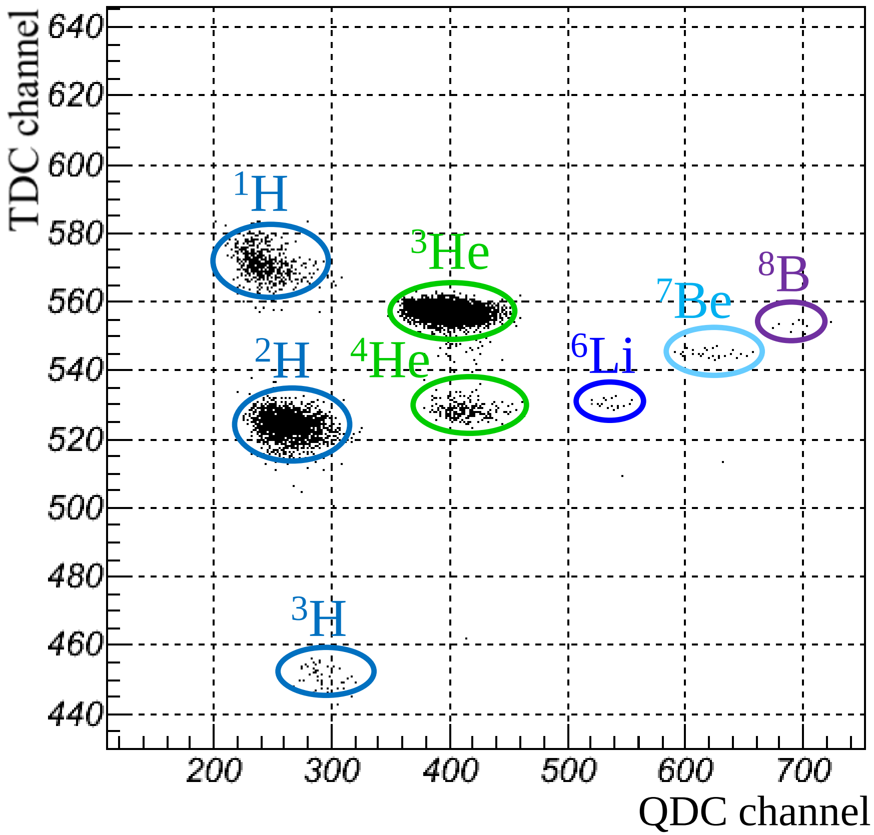
Max. rigidity 6 GeV/c

- Scintillation counters for TOF and dE/dx measurement: CF1, CF2, C2, C3
- C2 generates trigger
- H1 − hodoscope of 20 elements
- Č – Cherenkov counter

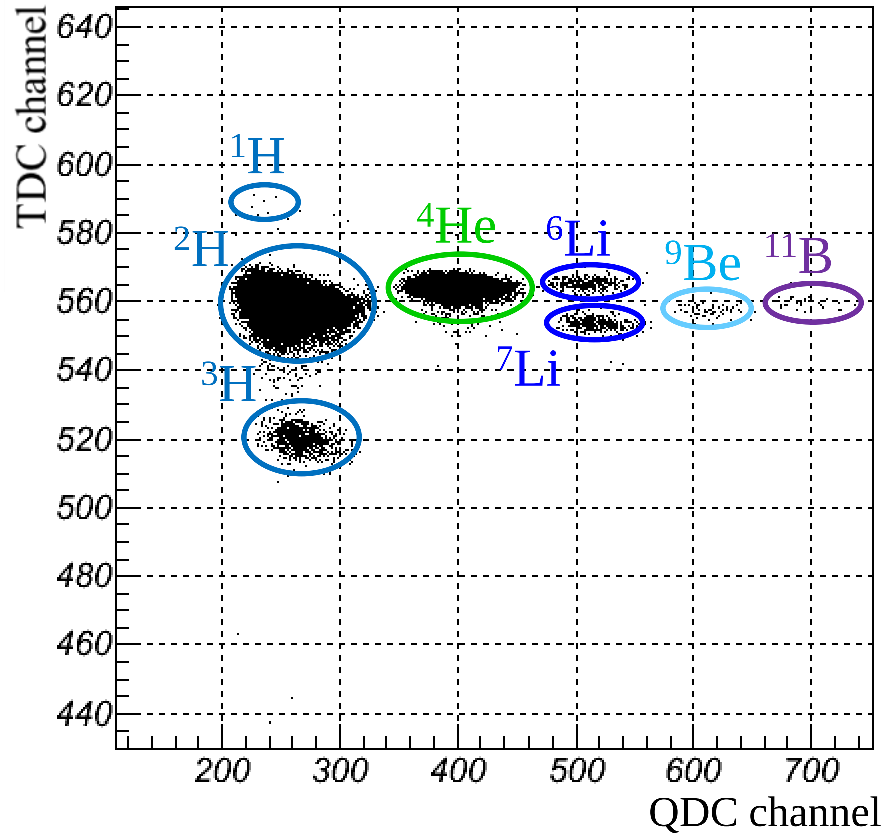
Fragment production in FRAGM

C – Be collisions at 0.95 GeV/nucleon

P beamline / Z = 2.5 GeV/c

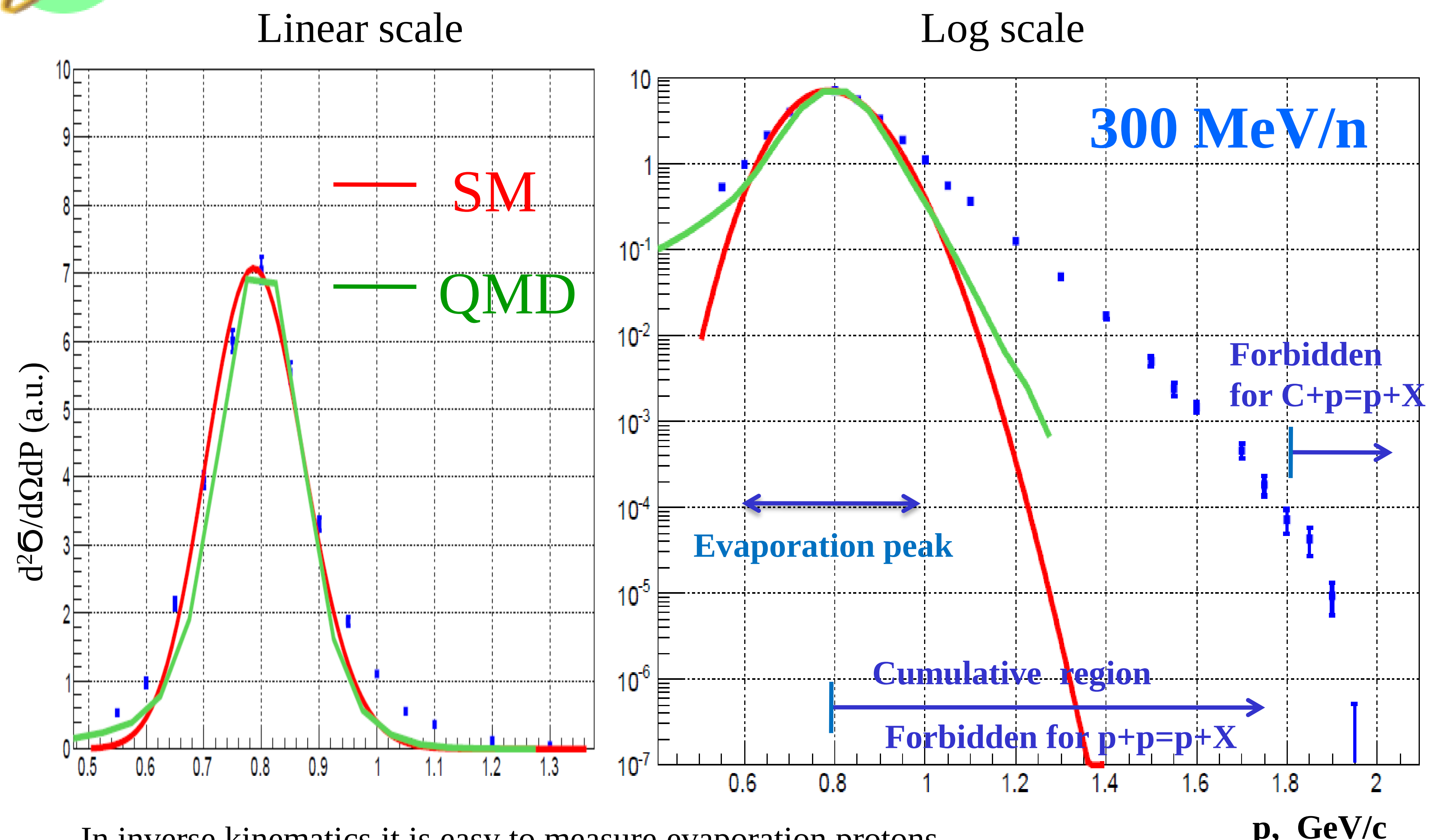


P beamline / Z = 3.5 GeV/c



- ✓ Regions of the different fragments are well separated and can be clearly selected

Proton momentum spectrum



In inverse kinematics it is easy to measure evaporation protons even with zero momentum in projectile rest frame to normalize cumulative protons

Theoretical interpretation

- Nature of **cumulative protons** is under discussion up to now.

  Within appropriate models they can come from :

  - **highly excited nuclear pre-fragments**
  - **intranuclear multiple scattering**
  - fluctuations of nuclear matter density
  - short-range correlations (SRC) of nucleons
  - **multiquark clusters**

- We estimated probabilities of the multiquark clusters in nucleus using approache by A.V.Efremov, A.B.Kaidalov et al. (Phys.At.Nucl. 57,874(1994)) in the framework of quark–gluon string model (QGSM) and
- Tested predictions of few models of ion-ion interactions for yield of cumulative protons

Cumulative protons from multiquark clusters

Production of cumulative protons is considered as fragmentation into protons of clusters consisting of 3k quarks (k=1: (3q) – nucleon, k=2: (6q) – two - nucleon cluster, k=3: (9q) – three - nucleon cluster); w_k is the probability to find k -nucleon cluster in ^{12}C; $x = p / p_0$, where $p(p_0)$ – proton (projectile) momentum per nucleon

$$Ed^3\sigma/d^3p(x,p_t^2) = C'(w_1 g(x,p_t^2) + w_2 b_2(x,p_t^2) + w_3 b_3(x,p_t^2))$$

A.V. Efremov,
A.B. Kaidalov,
G. I. Lykasov,
N. V. Slavin

$$g(x,p_t^2) = G\exp(-0.5\,(1-x-\Delta)^2/\sigma_x^2)\exp(-0.5\,p_t^2/\sigma_p^2)$$

$$b_2(x,p_t^2) = B_2\,(x/2)^3\,(1-x/2)^3\exp(-\alpha_1 p_t^2),\quad b_2(x,p_t^2)=0 \text{ at } x>2$$

$$b_3(x,p_t^2) = B_3\,(x/3)^3\,(1-x/3)^6\exp(-\alpha_2 p_t^2),\quad b_3(x,p_t^2)=0 \text{ at } x>3$$

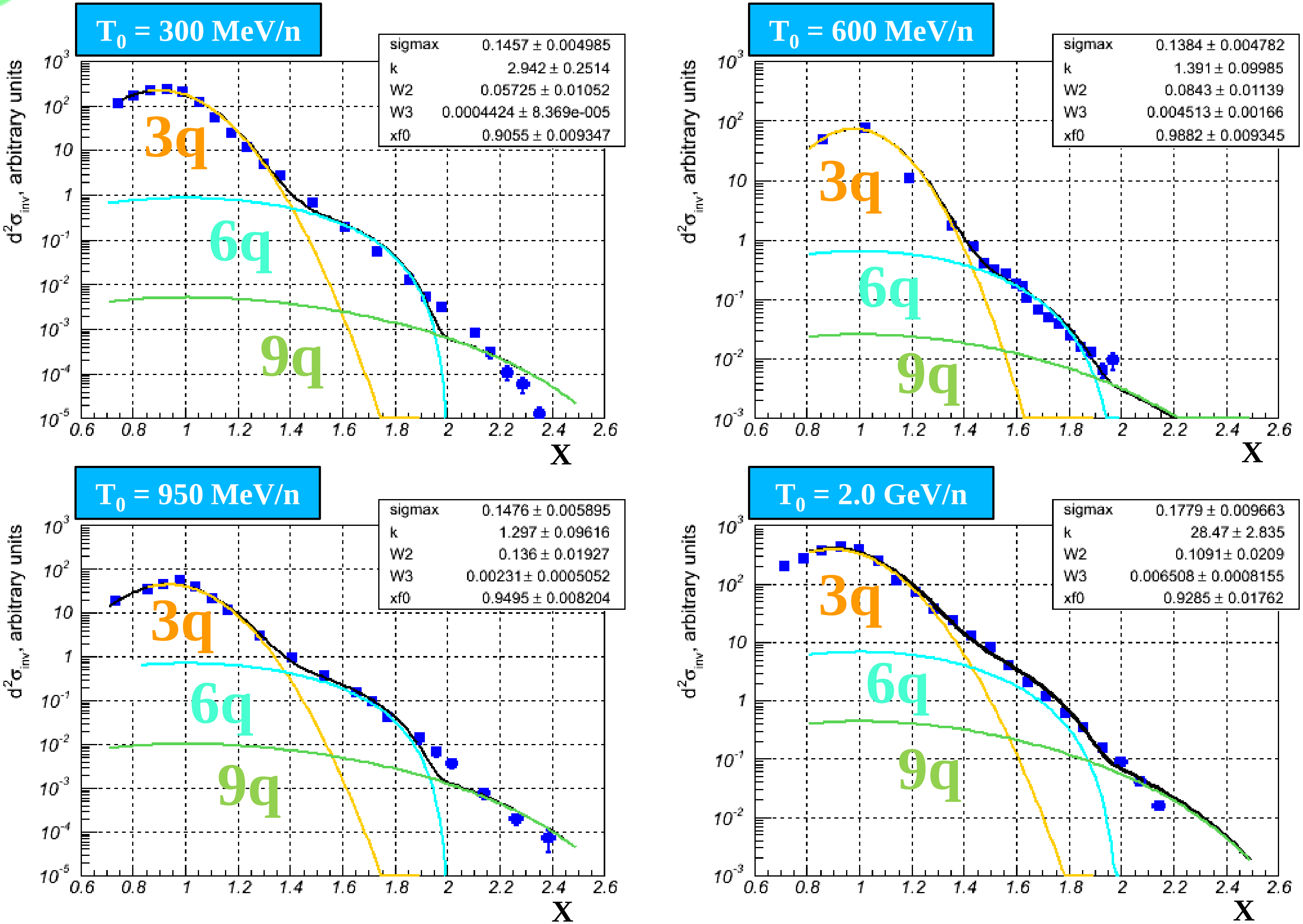
where g, b_2, b_3 are known fragmentation functions (QGSM).
G, B_2 and B_3 are known normalization constants.
Transverse parameters α_1 and α_2 from Phys.Rev. C 28 (1983) 1224

$$G = 1/(2\cdot\sigma_x\cdot\sqrt{2\pi})\cdot 1/(2\cdot\sigma_p^2),\ \sigma_p = \sigma_x\cdot m_p\cdot p_0/E_0,$$

$$\int\int B_i\cdot b_i(x,p_t^2)\,dx\,dp_t^2 = i/2,\ i=2,3$$

Fitted variables are: C', $W_2 = w_2/w_1$, $W_3 = w_3/w_1$, Δ, σ_x

x spectra at different energies



Probabilities of quark clusters

T_0, GeV/n	w_1 (3q)	w_2 (6q)	w_3 (9q)
0.3	0.95	0.05(1)	0.0005(1)
0.6	0.919	0.077(10)	0.004(2)
0.95	0.879	0.119(17)	0.002(1)
2.0	0.896	0.098(18)	0.006(1)
Quark cluster probabilities (theor.)	0.847	0.125 0.06	0.026
^{12}C (e,e') at J – LAB (E = 4.4 GeV)	–	0.19(4)	.006(2)

We used fitting procedure to get w_2 and w_3

M. Sato *et al (1986)*

V.Burov *et al* (1977), pions, fluctuon

K.S. Egiyan *et al (2006)*

- **For the first time the quantitative estimation on few nucleon clusters in nuclei was obtained from fragmentation data**
- **Wider range on x and wider projectile energy range are desirable**

Test of four models of ion-ion interactions

- QMD – Quantum Molecular Dynamics (Geant4 package).
- BC – Binary Cascade model (Geant4 package).
- LAQGSM – Los Alamos Quark Gluon String Model by courtesy of Stepan Mashnik (LA-UR-11-018**87)**
- SHIELD-HIT code with MSDM (Multi Stage Dynamic Model) by courtesy of Nikolay Sobolevsky (www.inr.ru/shield).

100M of simulated interactions are needed to have a reasonable comparison with our data. It is a serious computational problem.

Structure of ion-ion interactions model

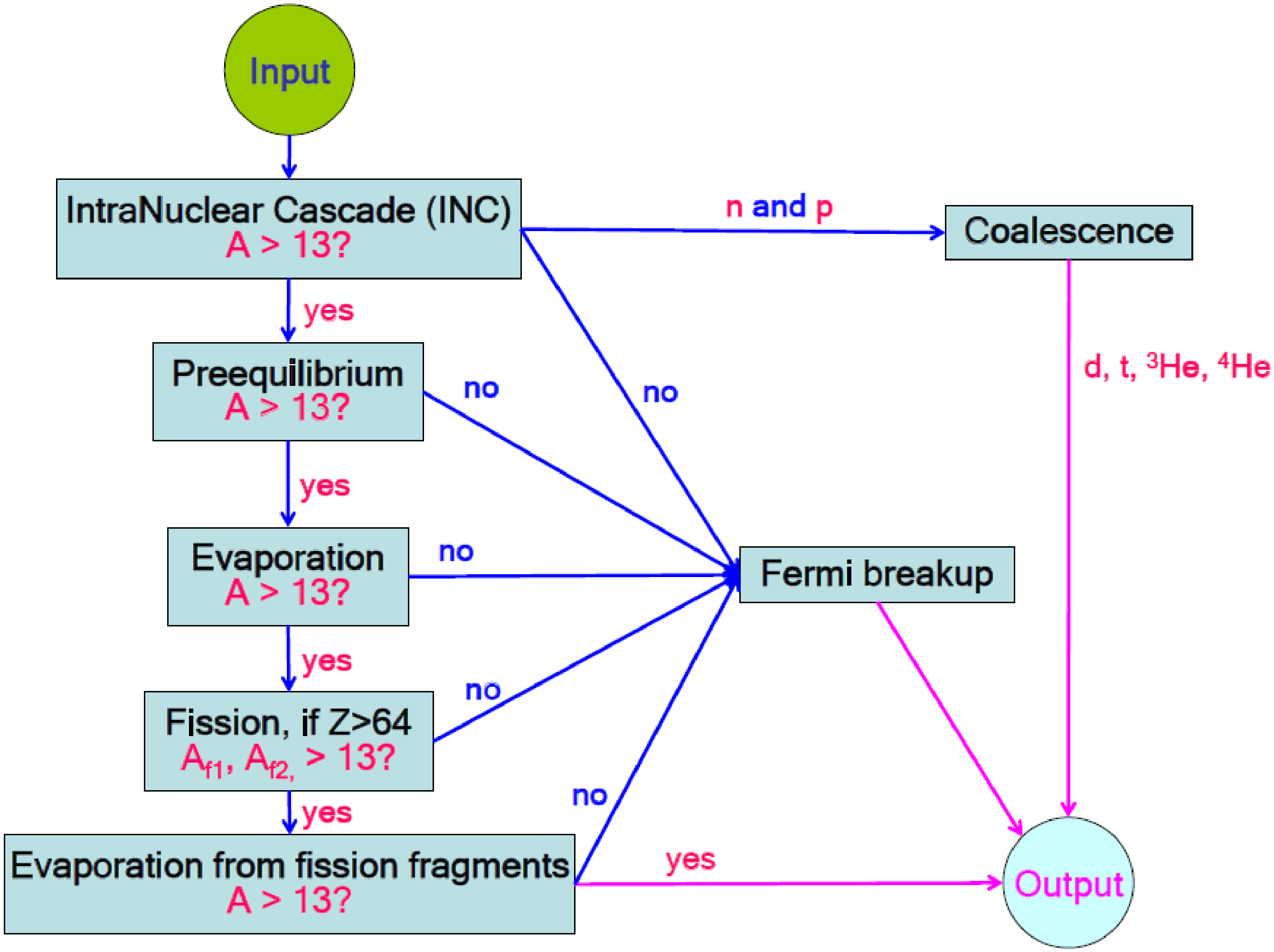
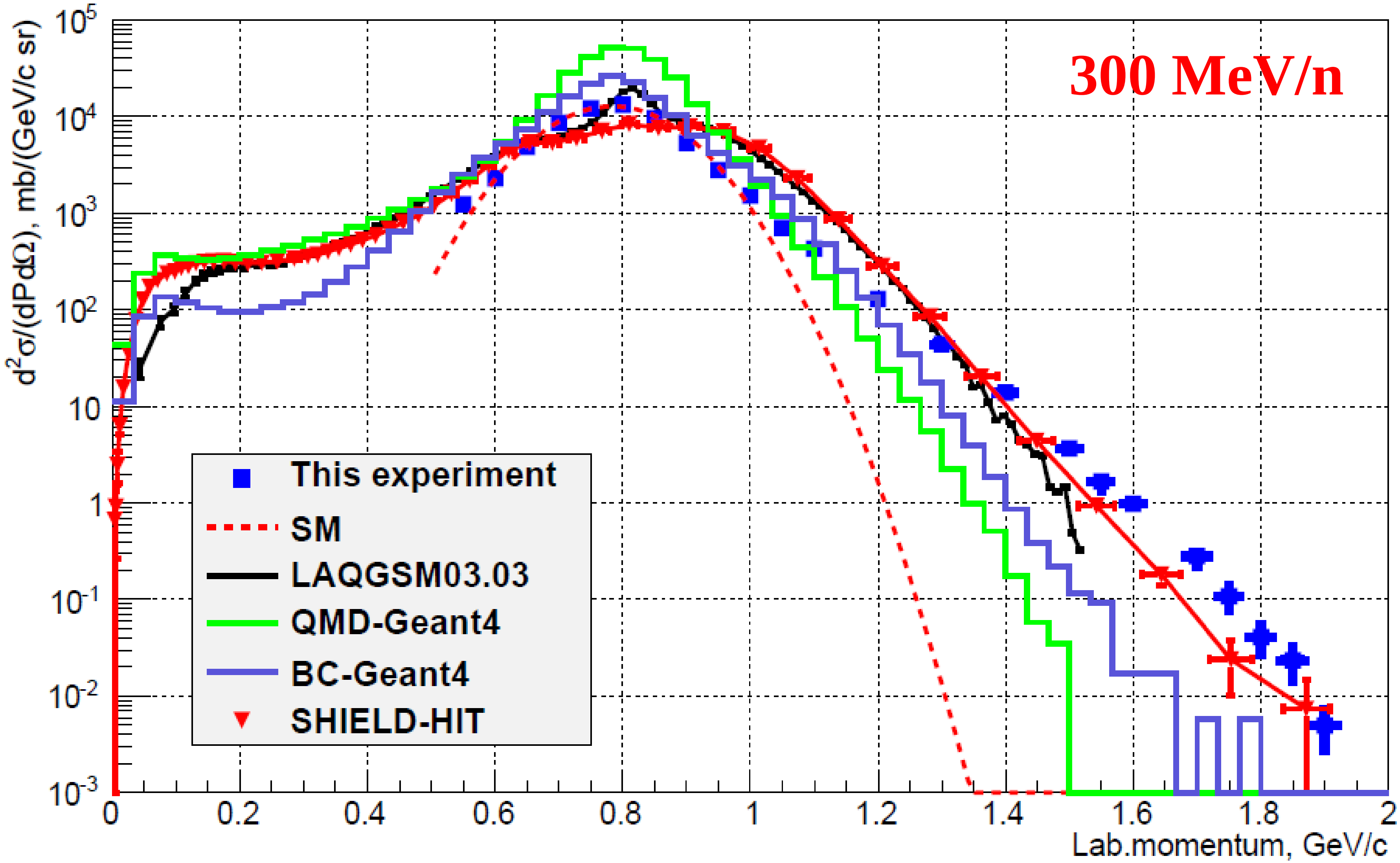
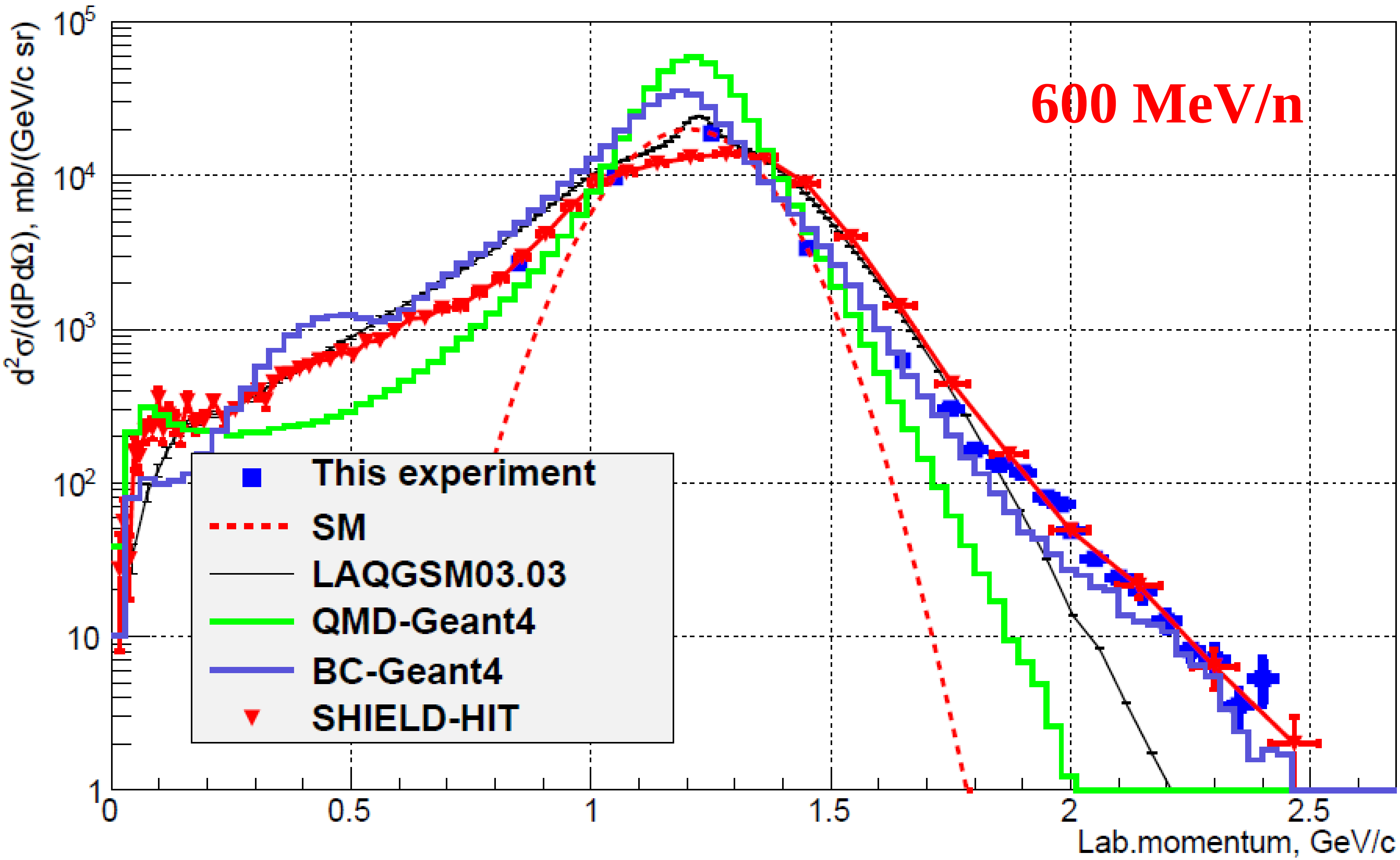


Figure 1: General scheme of nuclear reaction calculations by LAQGSM03.03.

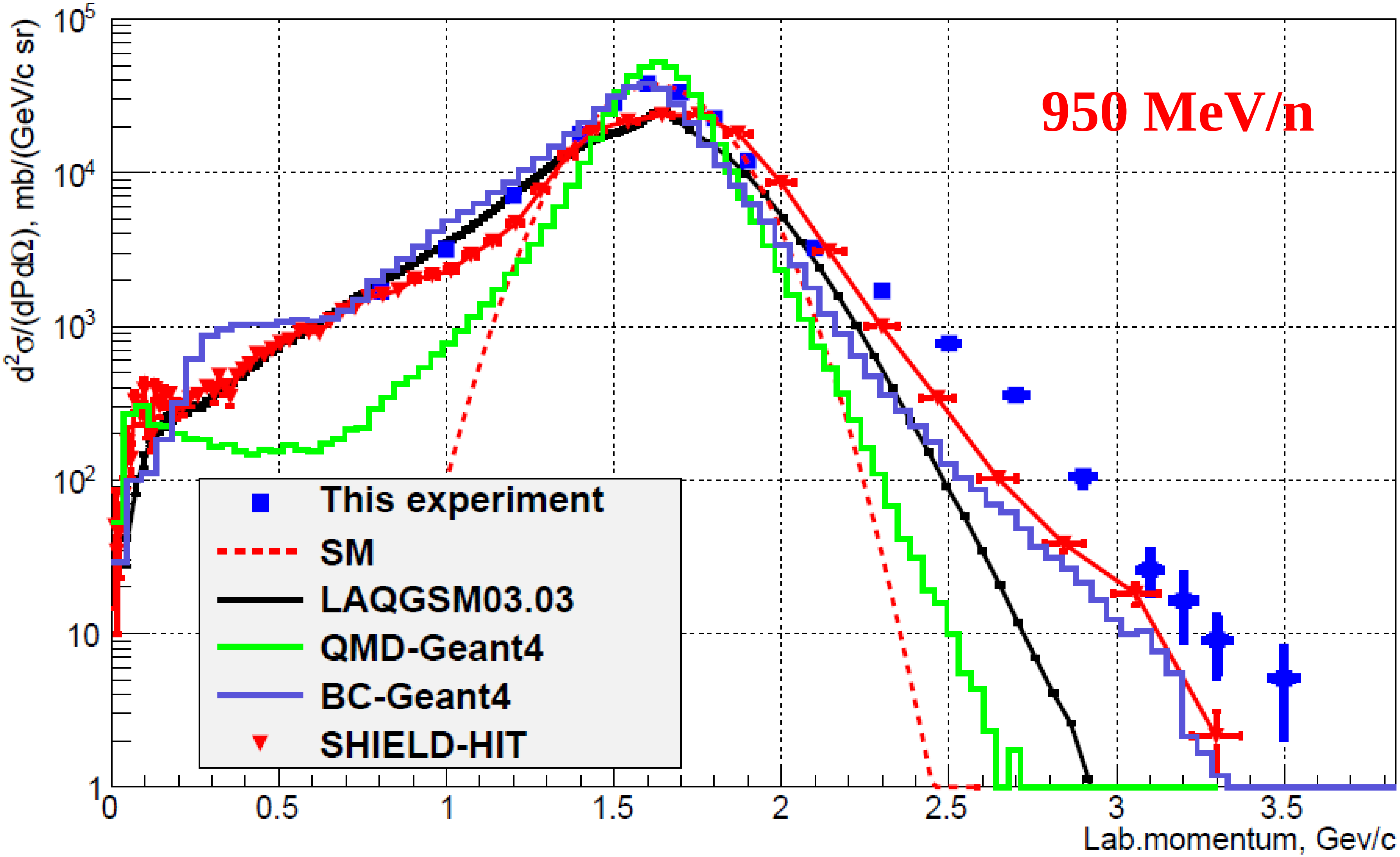
Protons from C+Be→p+X at 3.5^0



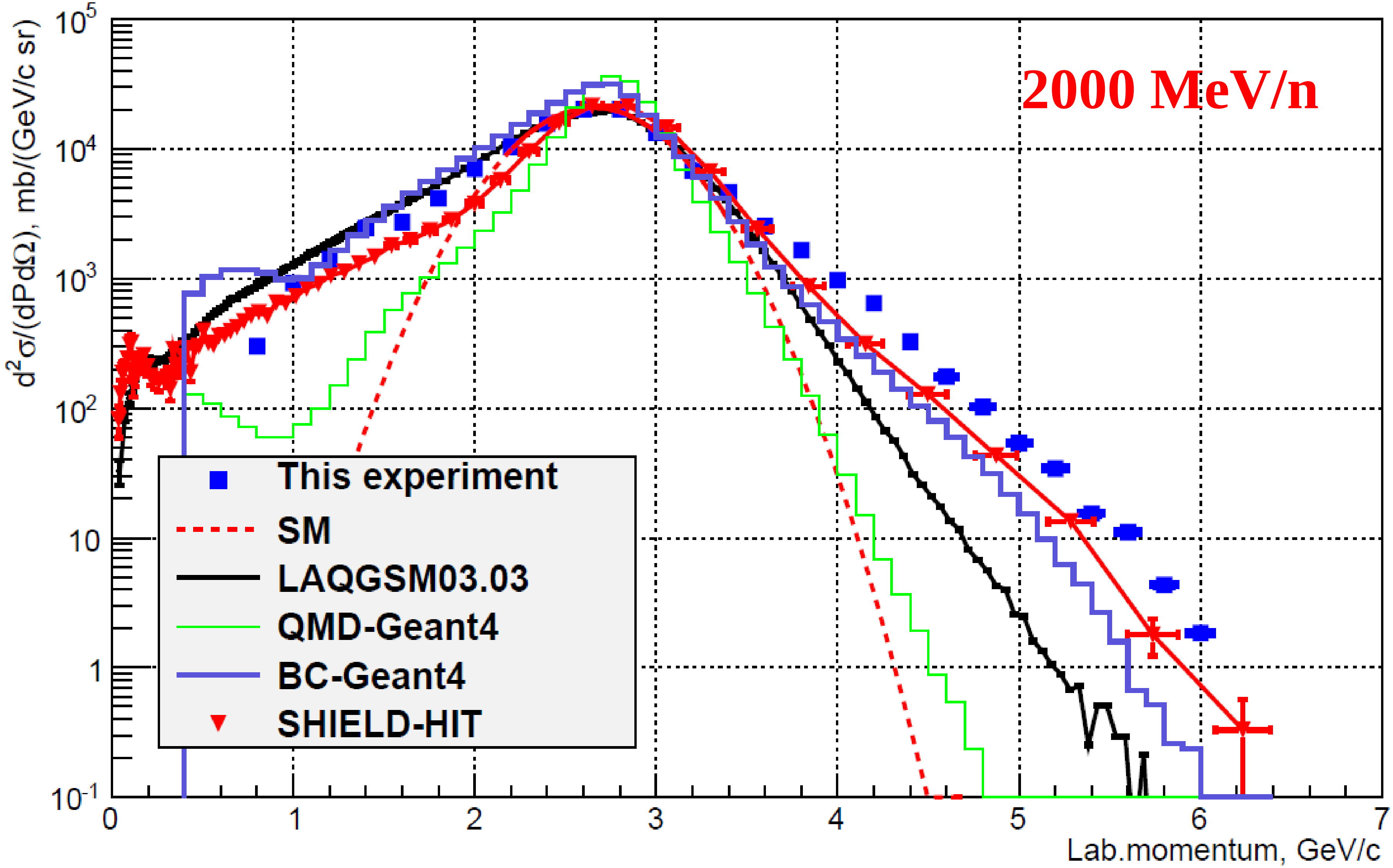
Protons from C+Be→p+X at 3.5^{0}



Protons from C+Be→p+X at 3.5^0



Protons from C+Be→p+X at 3.5^0



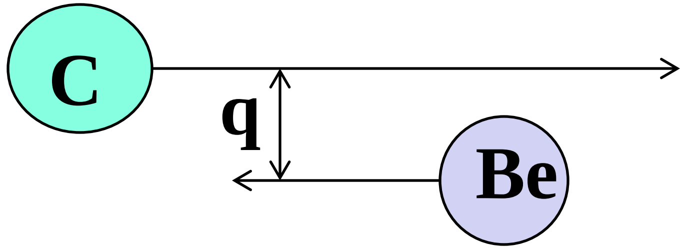
r.m.s. (MeV/c) of fragmentation peak near maximum.

T	Exp.	BC	QMD	LAQGSM	SHIELD
300	91±5	81	75	113*	130*
600	130±7	126	100	172*	243*
950	165±12	147	121	217*	270
2000	352±38	270	207	384	337

Dif.cross section (mb/GeV/c/sr) at P =2P_0

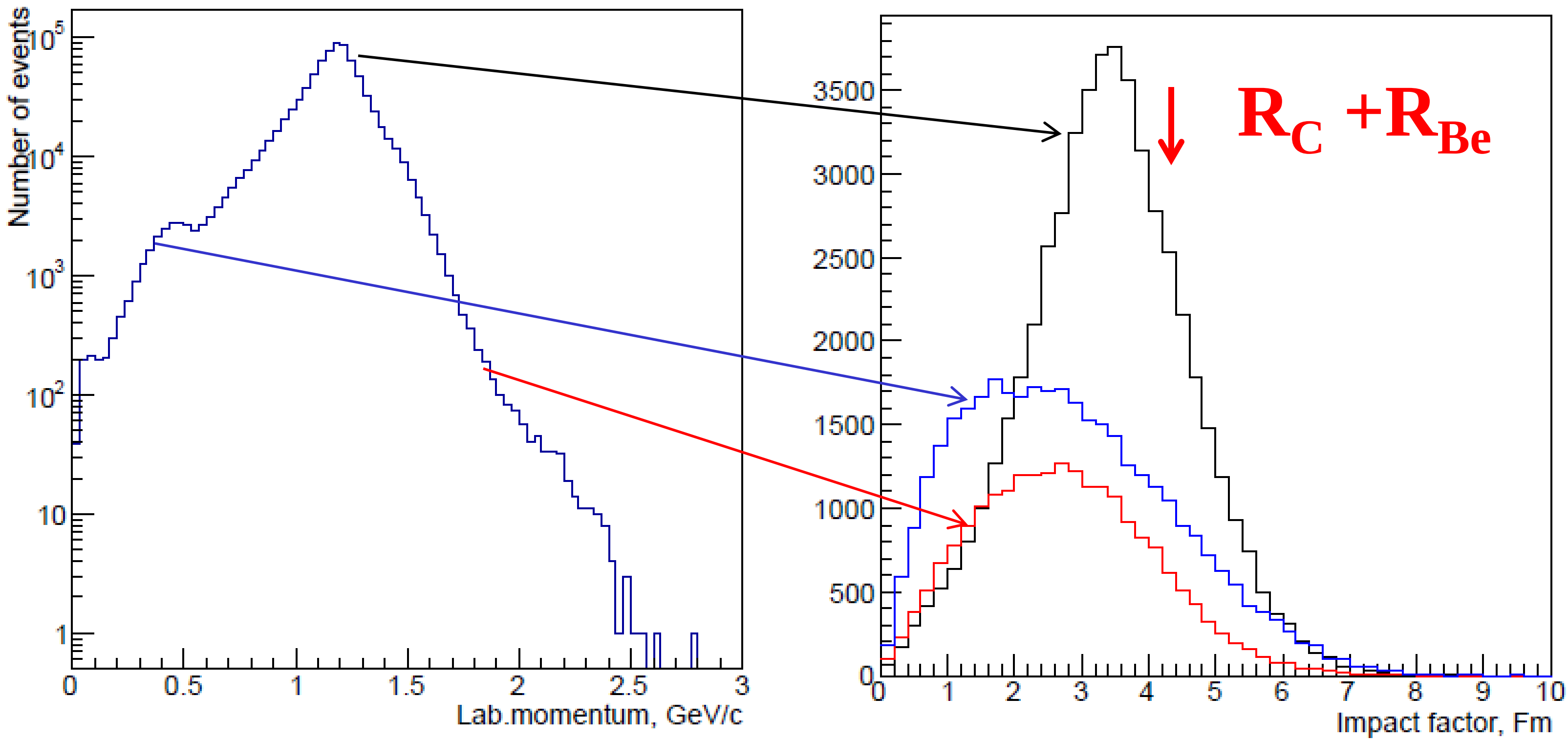
T	Exp.	BC	QMD	LAQGSM	SHIELD
300	1.7±0.2	.02	.003	.009	.44
600	5.3±0.7	1.8	.002	.11	3.8±1.3
950	29.2±3.1	1.2	.0065	.07	5.1±3.1
2000	24.3±1.6	4.2	.002	.29	9.9±2.8

Proton momentum spectrum vs impact factor in BC



q- impact factor

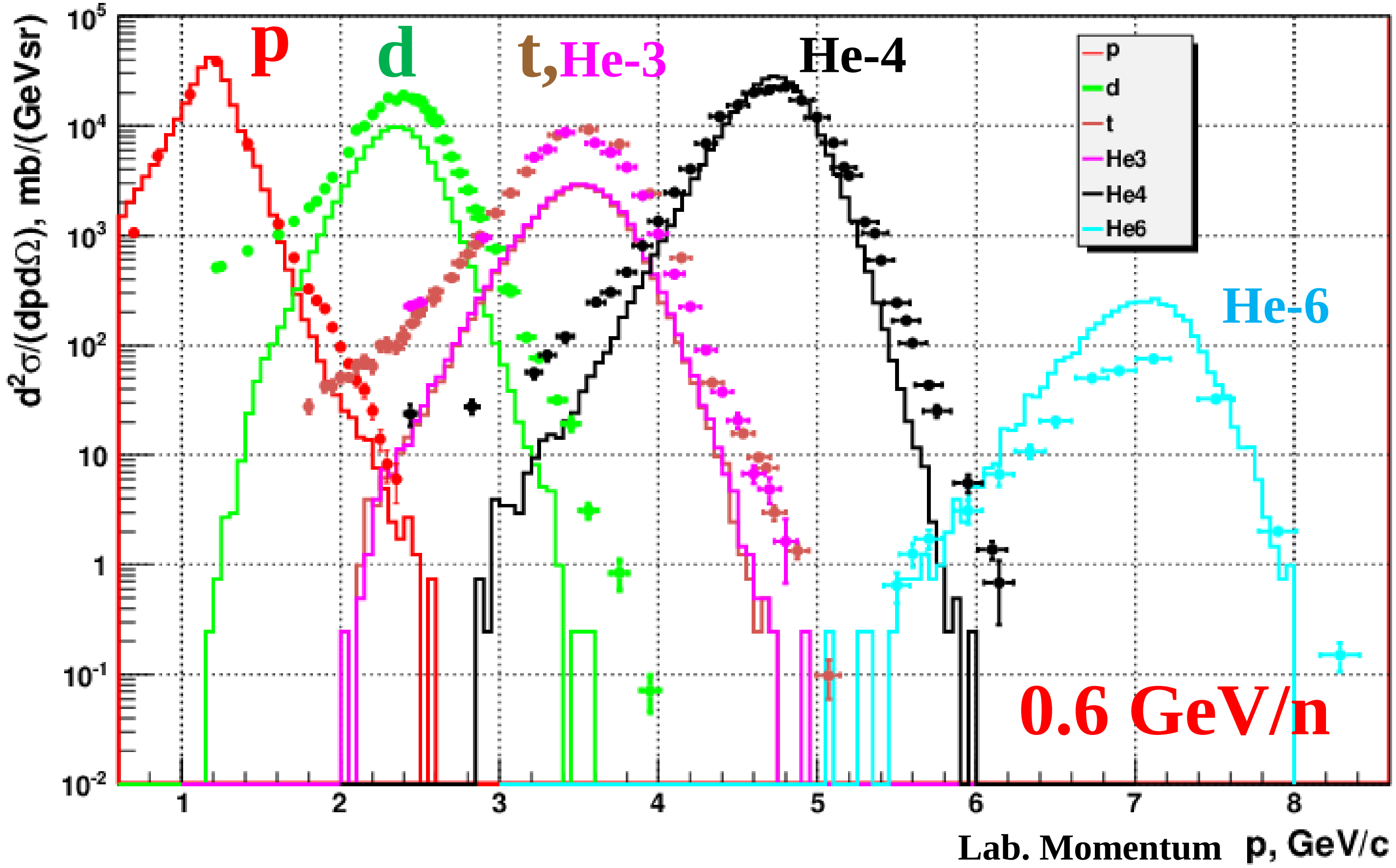
600 MeV/n



Protons at fragmentation maximum result from peripheral interactions, cumulative and mid-rapidity regions are more central.

Relative yields of H and He isotopes: data vs BC

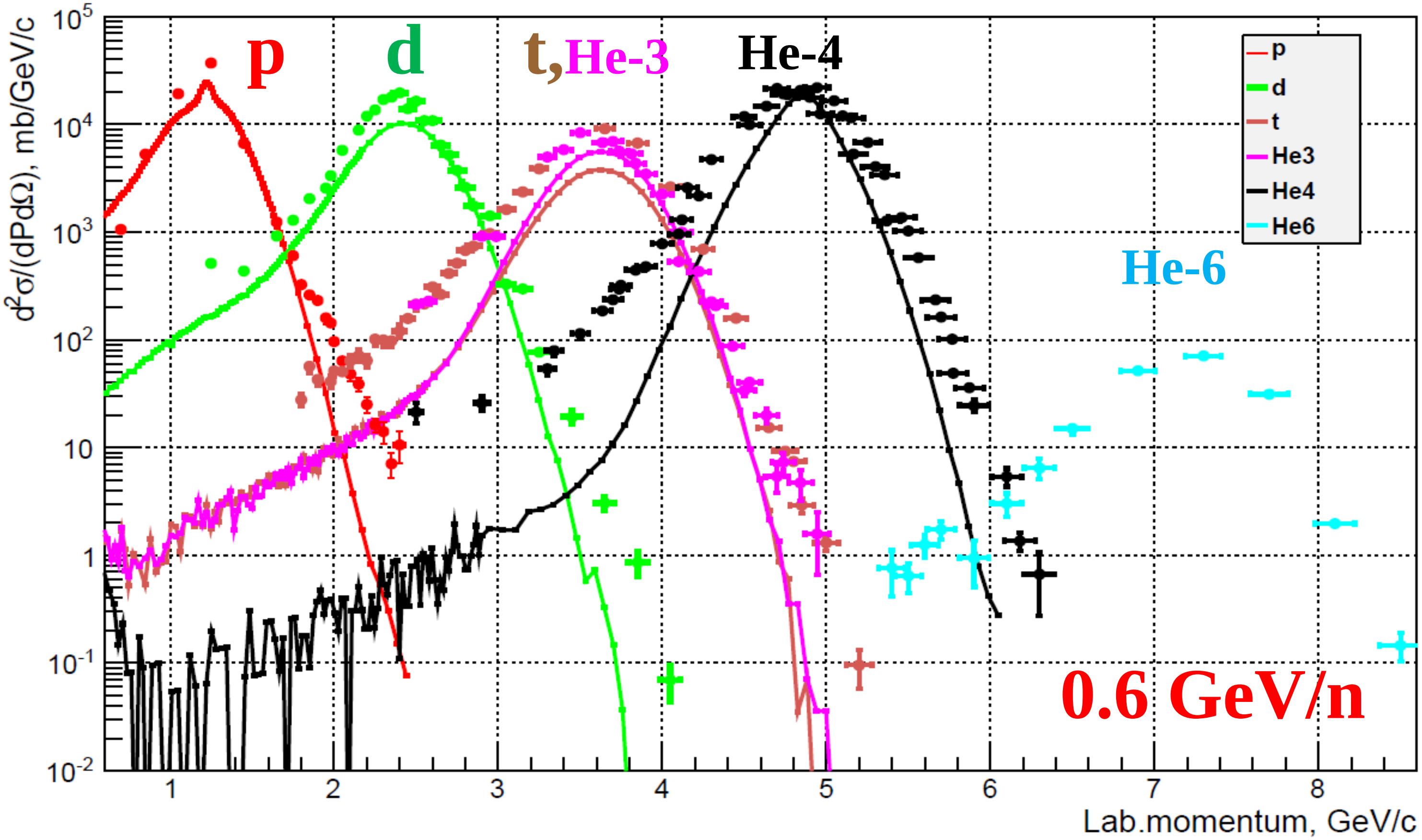
Data are normalized to BC for protons at fragmentation maximum,
Data – points, BC - histograms



- Shapes of fragmentation peaks near their maxima are well described by BC, cross section is predicted well for He-4, and less than 3 times lower for d, t and He-3.

Yields of H and He isotopes: data vs LAQGSM

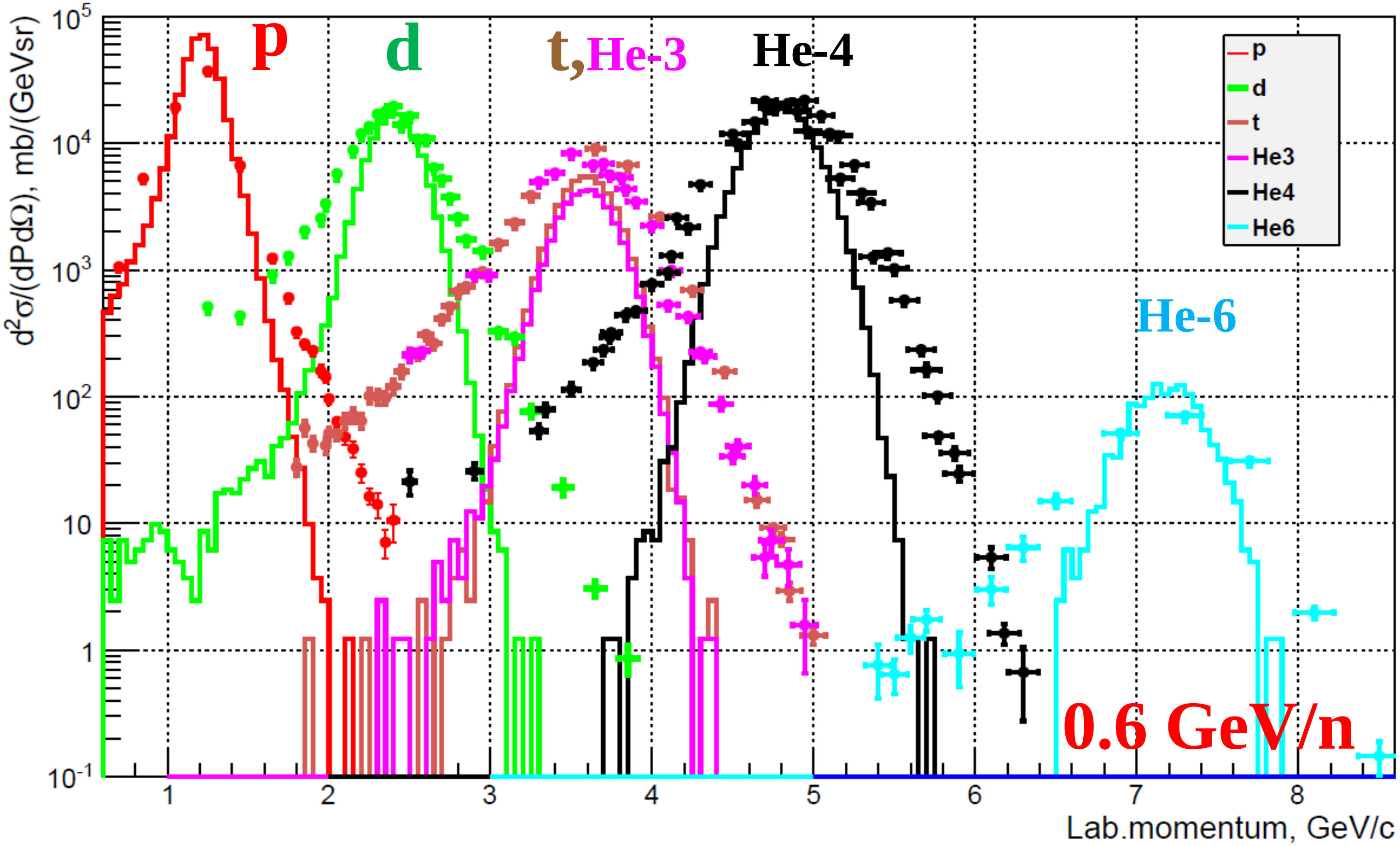
Data are normalized to BC for protons at fragmentation maximum,
Data – points, LAQGSM - lines



- Shapes of fragmentation peaks for p and d are reasonably described by LAQGSM, for t,He-3,He-4 peaks are narrower, cross sections at maxima are predicted well, mid-rapidity region for A>2 is underestimated.

Yields of H and He isotopes: data vs QMD

Data are normalized to BC for protons at fragmentation maximum,
Data – points, QMD - histograms



- Shapes of fragmentation peaks (apart from p) are too narrow, but cross sections at maxima are predicted well. Mid-rapidity region for A>1 is strongly underestimated.

Conclusion

- Proton momentum spectra from ^{12}C fragmentation have been analyzed in two approaches.
- 1) Multi-quark cluster model with fragmentation functions calculated in QGSM gives reasonable description of cumulative proton spectra in wide energy range. This analysis have been published in JETP Lett. 97 (2013) 439
- 2) Predictions of four models of ion-ion interactions (QMD, BC, LAQGSM, SHIELD-HIT) have been compared to the data. In the region of fragmentation peak all models give reasonable description of the data but in high momentum region they differ from each other up to few orders of magnitude. Best description of the data in this region gives SHIELD-HIT and BC. Production of H and He isotopes have been compared to the data.

Thank You