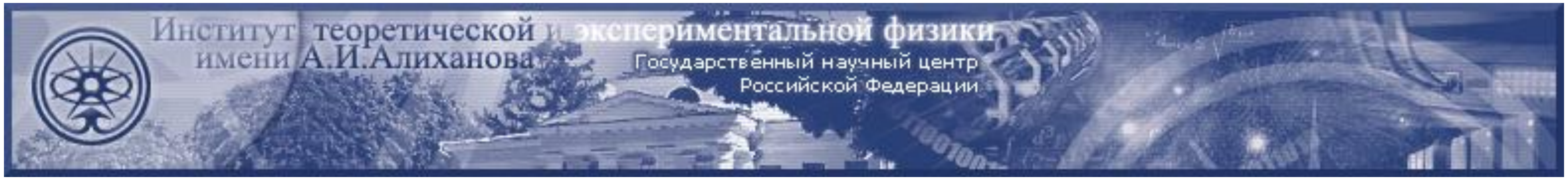

High Energy Protons from C-12 Fragmentation

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Introduction and motivation

Experiment FRAGM

$^{12}C + Be \rightarrow f + X$

^{12}C fragments at 3.5^0: p, d, t, ^3He, ^4He, ^6He, ^8He,…C

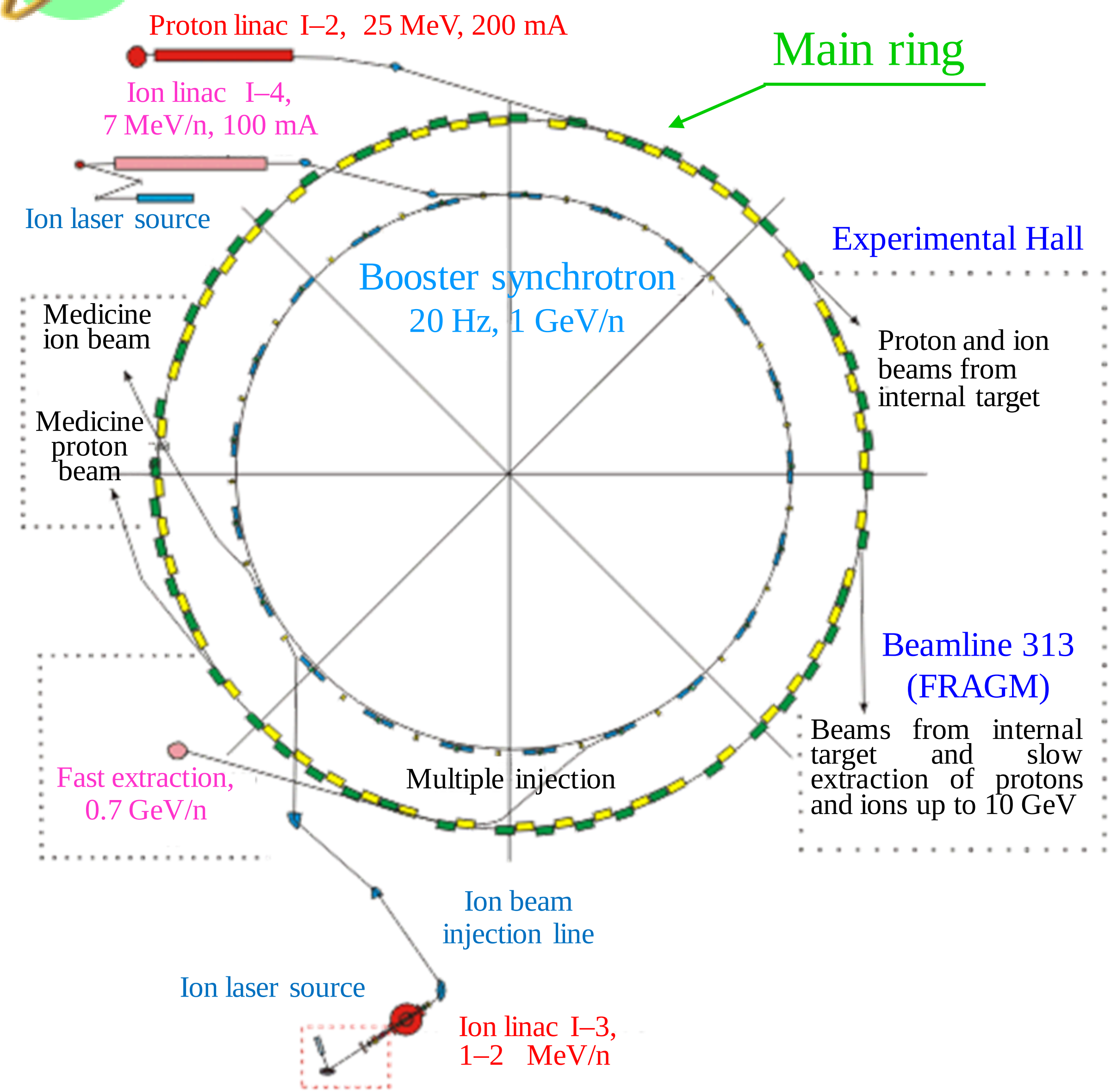
^{12}C kinetic energies: $T_0 = 0.2 - 3.2$ GeV/nucleon

Here we focus mostly on: protons with momentum higher than momentum per nucleon of the projectile

Motivation:

- ✓ origin of high momentum (cumulative) particles in interactions with nuclei is still an open question
- ✓ there is a lot of data in pA,nA,πA,… interactions (A.M.Baldin, V.S.Stavinsky, G.A.Leksin and others) and only a few in ion-ion collisions

ITEP accelerator complex TWAC



TWAC= TeraWatt Accumulator Complex

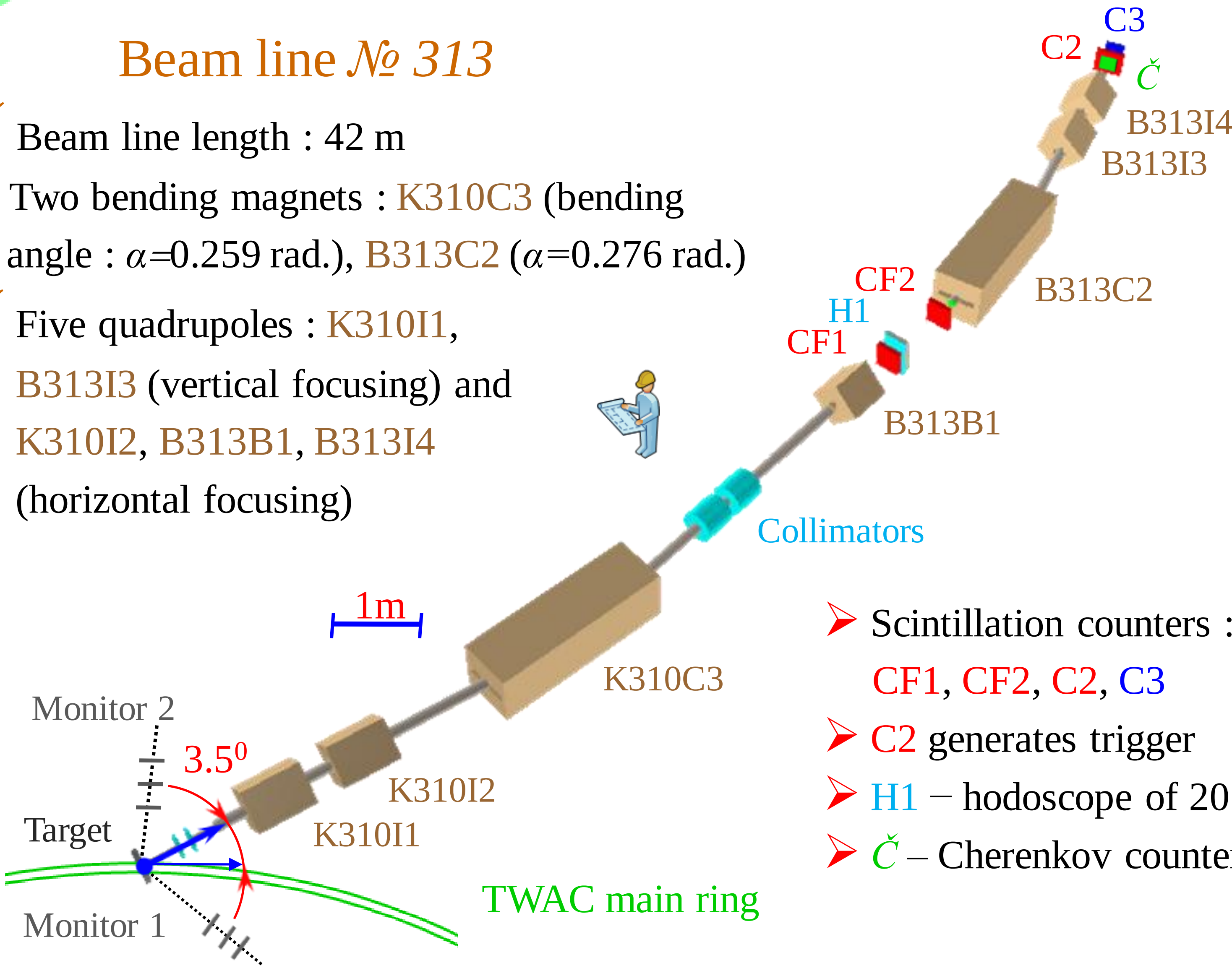
TWAC current parameters

- ✓ 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

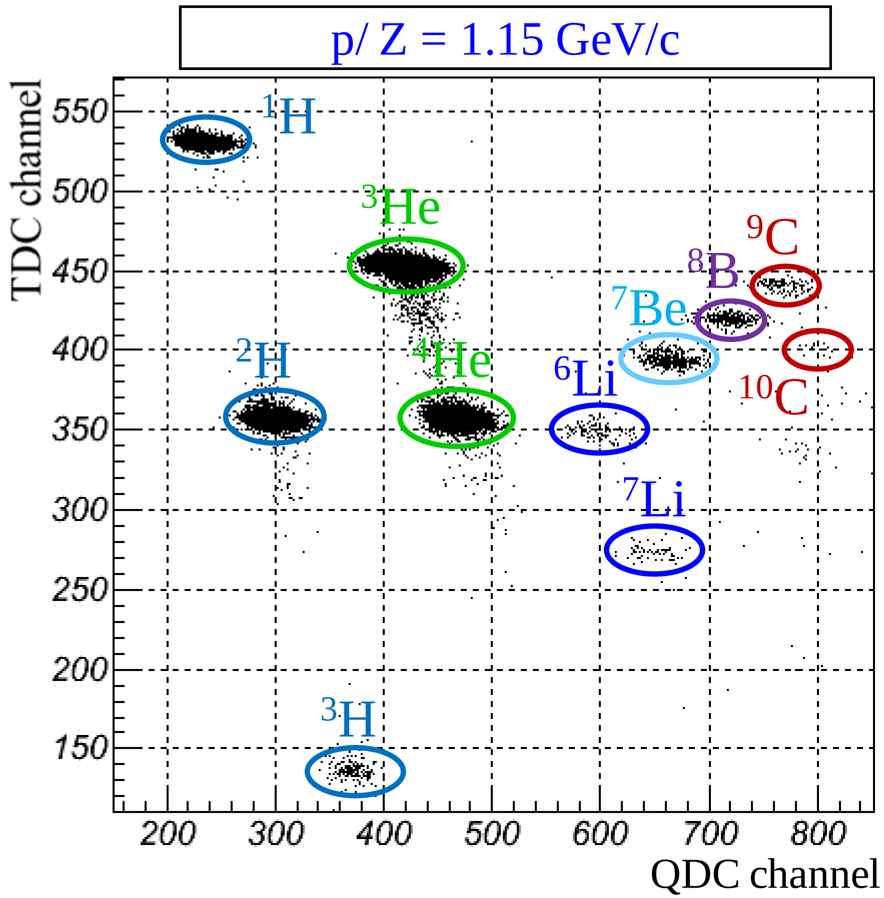
Beam line *№ 313*

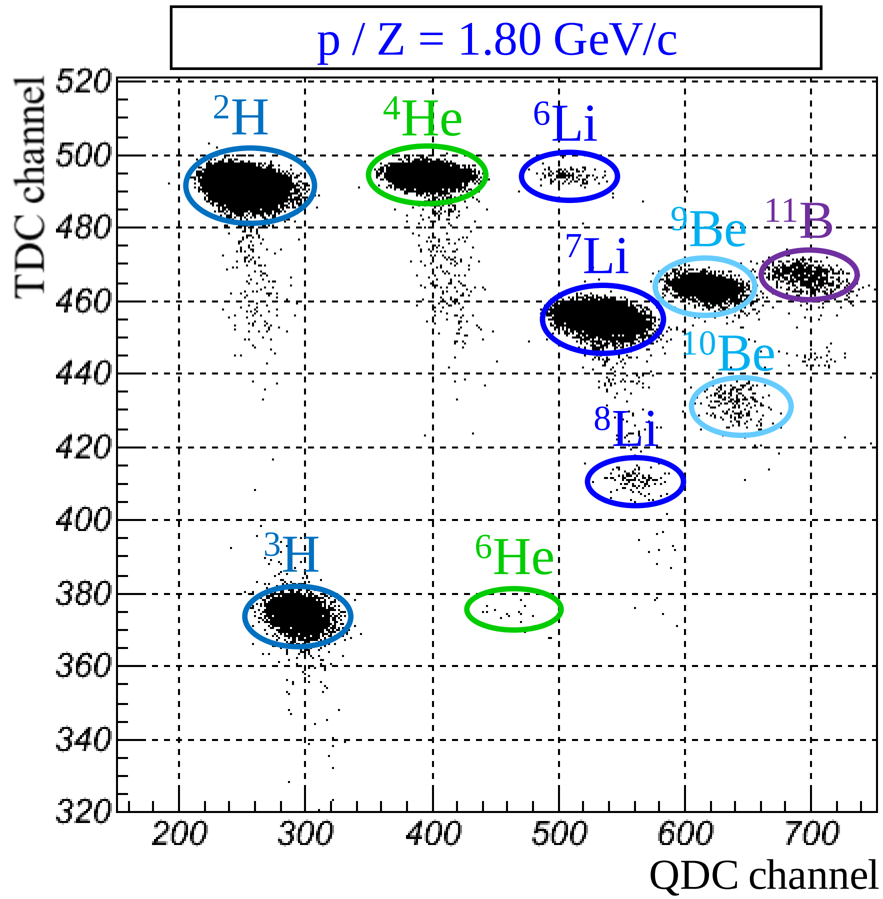
- ✓ Beam line length : 42 m
- ✓ Two bending magnets : K310C3 (bending angle : α=0.259 rad.), B313C2 (α=0.276 rad.)
- ✓ Five quadrupoles : K310I1, B313I3 (vertical focusing) and K310I2, B313B1, B313I4 (horizontal focusing)



- ➢ Scintillation counters : CF1, CF2, C2, C3
- ➢ C2 generates trigger
- ➢ H1 – hodoscope of 20 elements
- ➢ Č – Cherenkov counter

Example of fragment selection at 0.3 GeV/nucleon

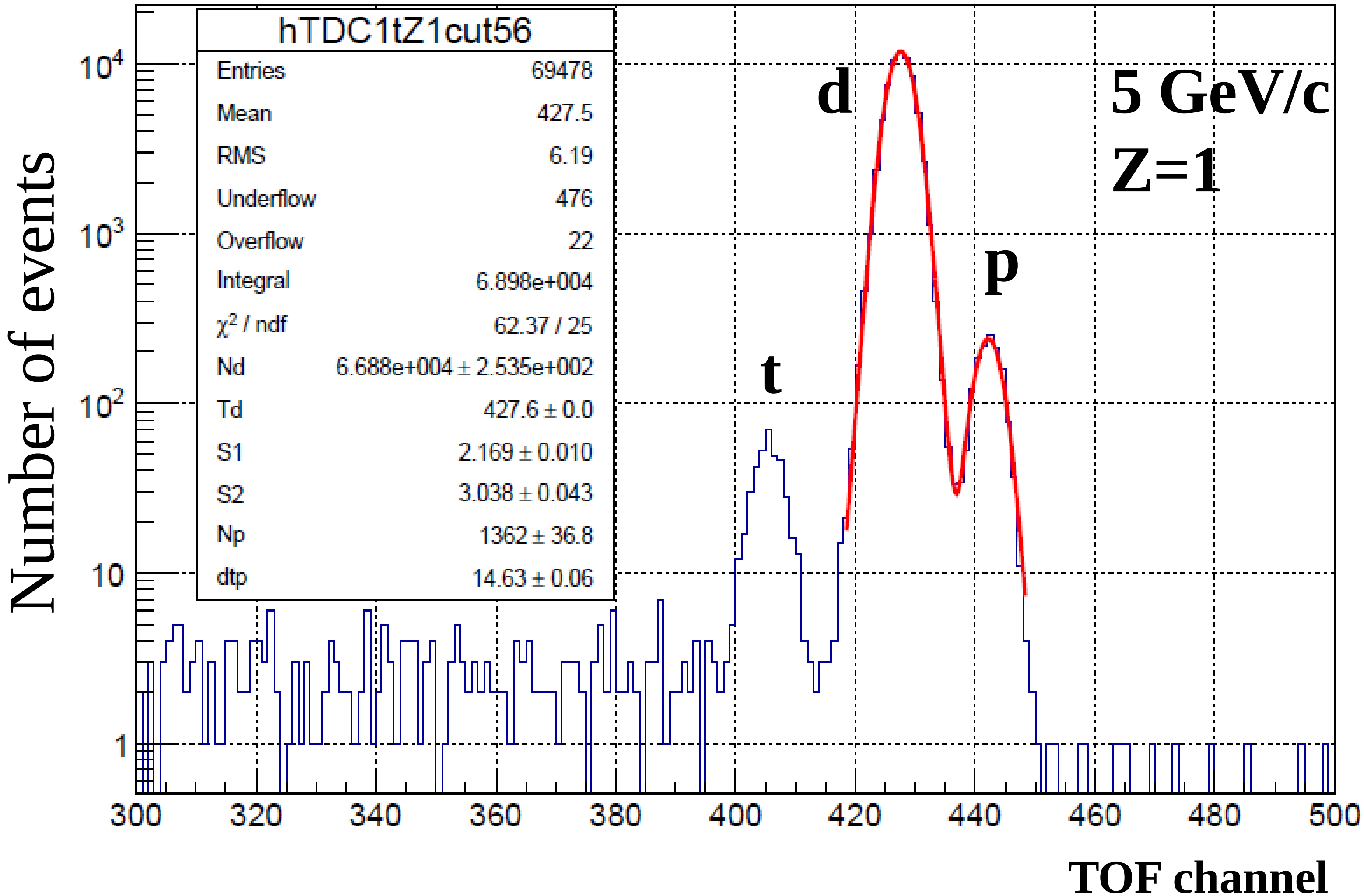




- ✓ QDC (from CF1) vs TOF between CF1 and C2
- ✓ Regions of the different fragments are well separated and can be clearly selectet
- ✓ TOF is a function of Z/A, so it gives a mark for clear fragment identification

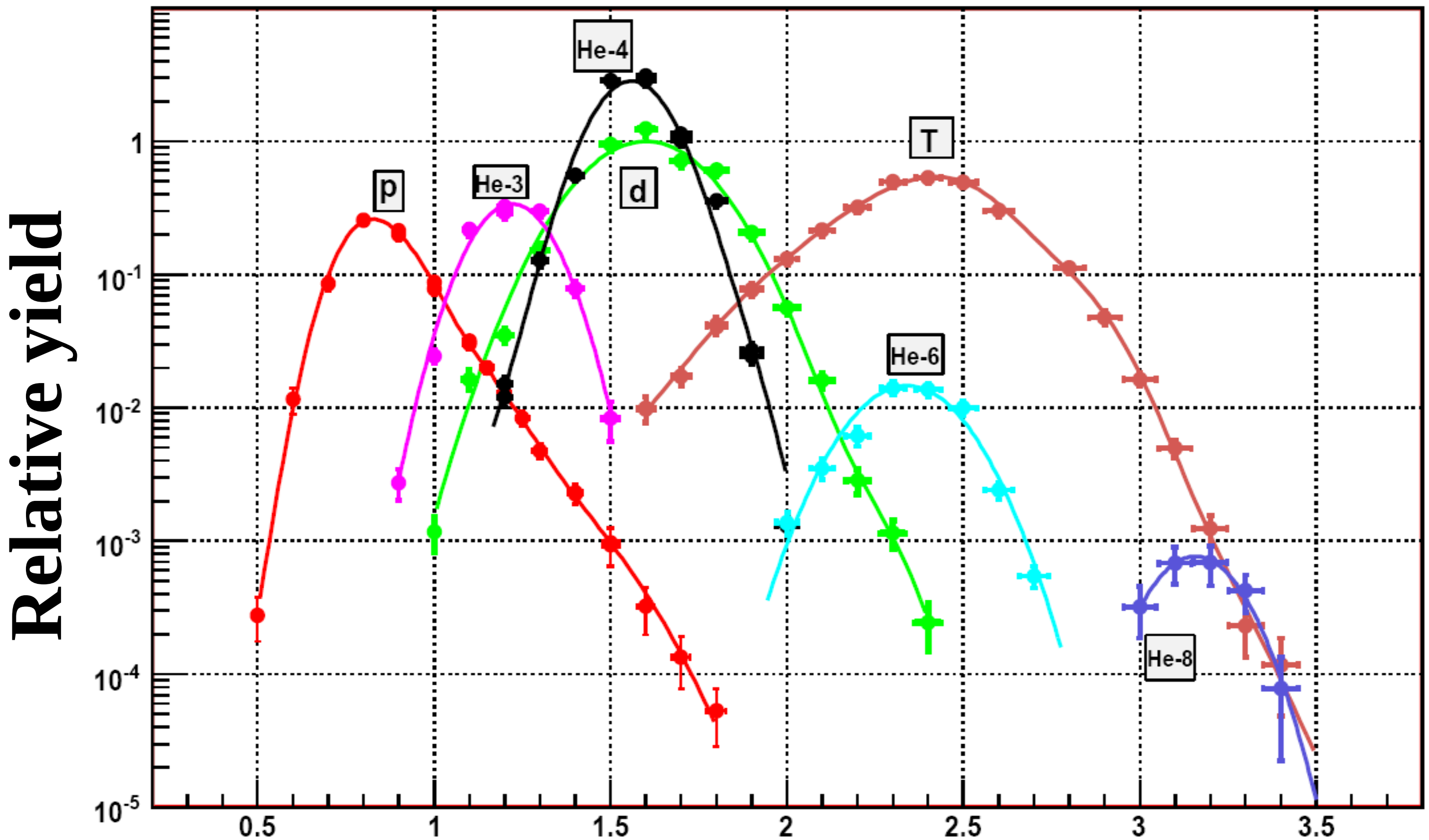
Proton selection at high energy

C – Be collisions at 2.0 GeV/nucleon



Relative yields of H and He isotopes

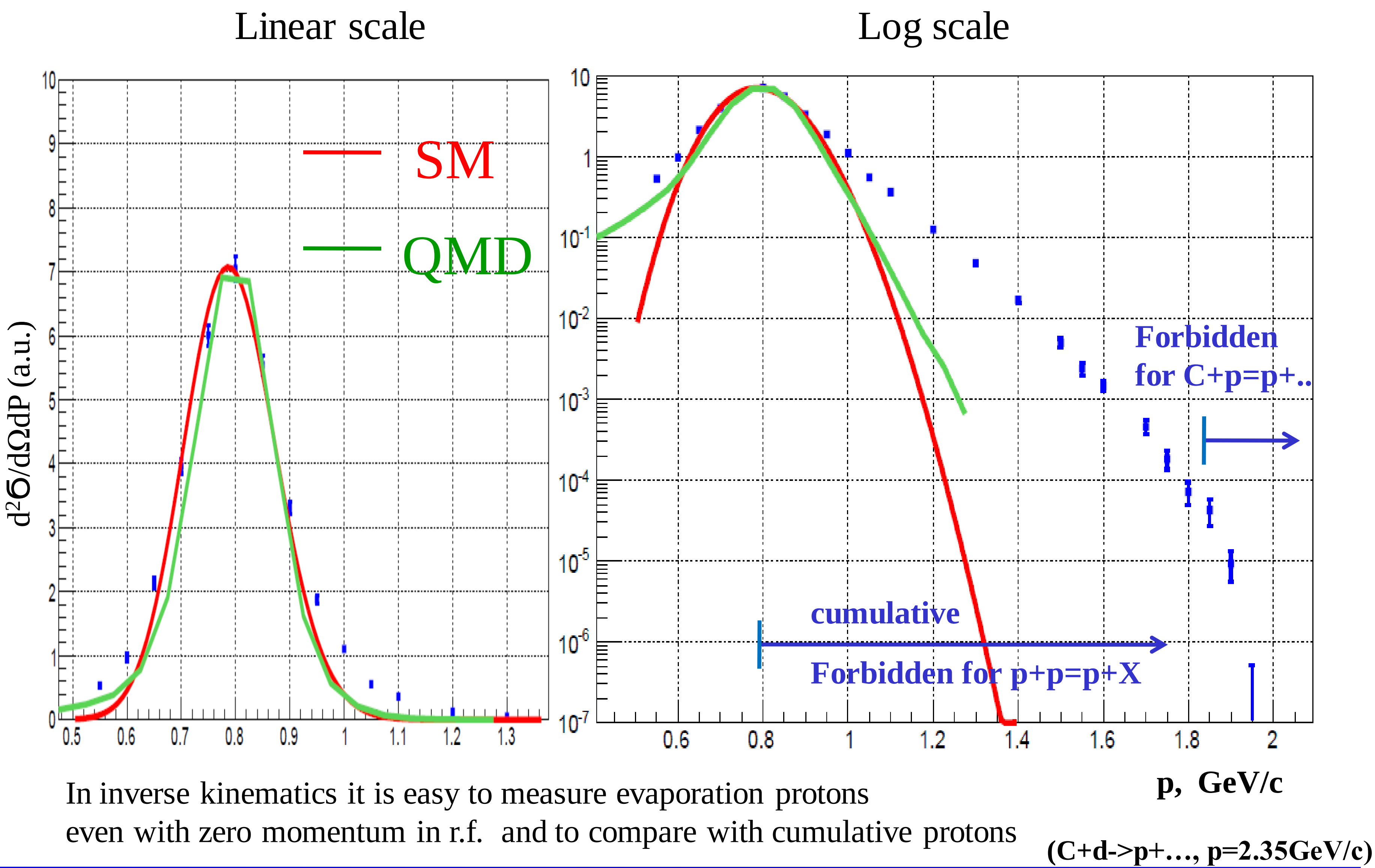
C – Be collisions at 0.3 GeV/nucleon



Proton spectrum has non-Gaussian right tail

Z is a fragment charge

Proton momentum spectrum at 300 MeV/n



In inverse kinematics it is easy to measure evaporation protons even with zero momentum in r.f. and to compare with cumulative protons

Variables for physics analysis

(Projectile) + (Target) → $P_{forward}$ + all

T_0 = Tproj. (GeV/nucleon), $p_0 = p_{proj.}$(GeV/c/nucleon),

p – outgoing proton momentum

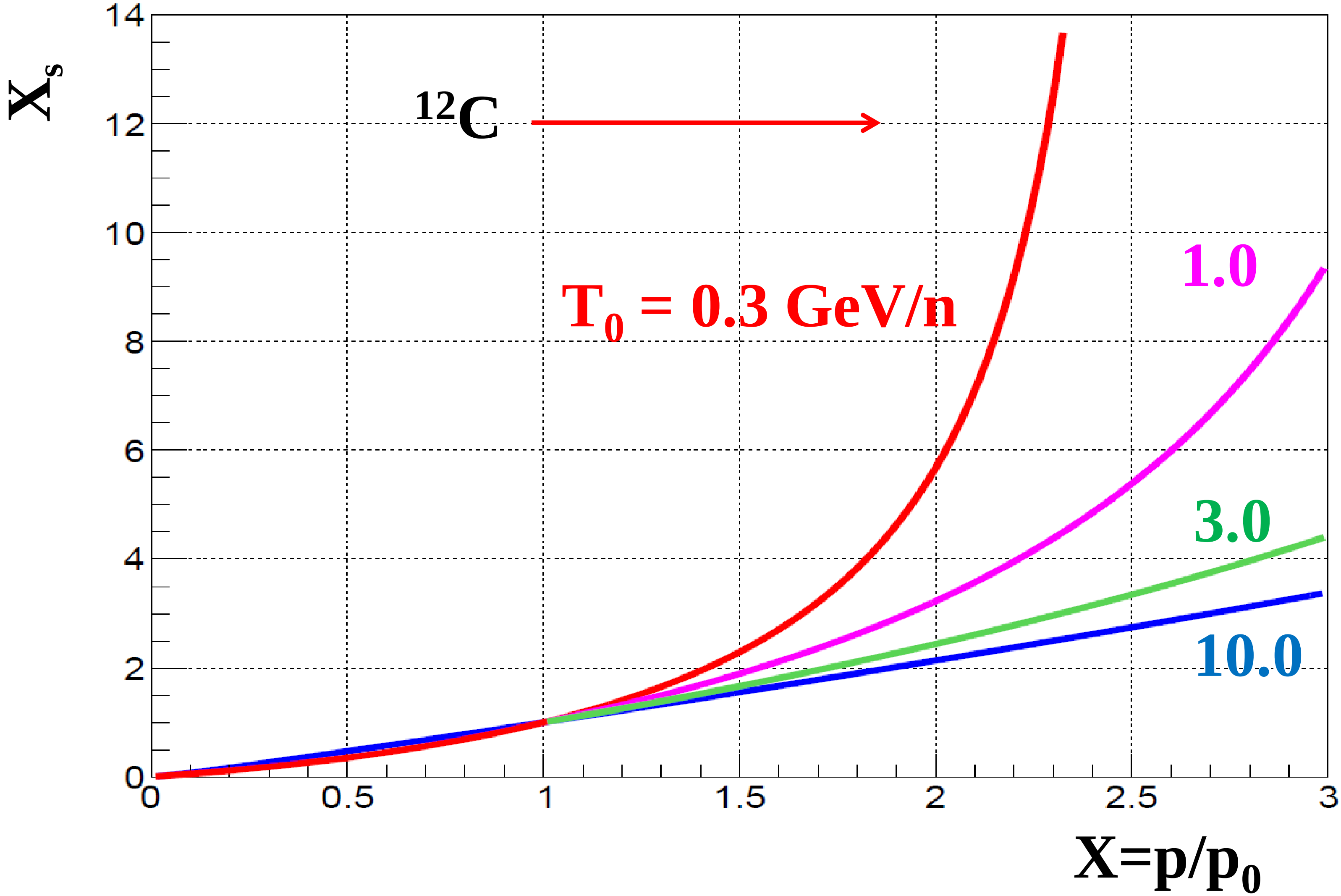
$X = p/p_0$, where p_0 is projectile momentum per nucleon and it is also maximal proton momentum for collisions of free nucleons

$X_{lf} = (E+p)/(E_0+p_0)$ – relativistic invariant light front variable, for our energy range the difference between X and X_{lf} is 3% – 15%

X_s – introduced by V.S.Stavinsky(JINR) – ($X_s{*}M_N$ – min. projectile mass that can produce proton with given momentum, it is obtained from energy-momentum conservation $(X_s{*}p_0 + M_N - p)^2 = (X_s{*}M_N)^2$ for free nucleon target

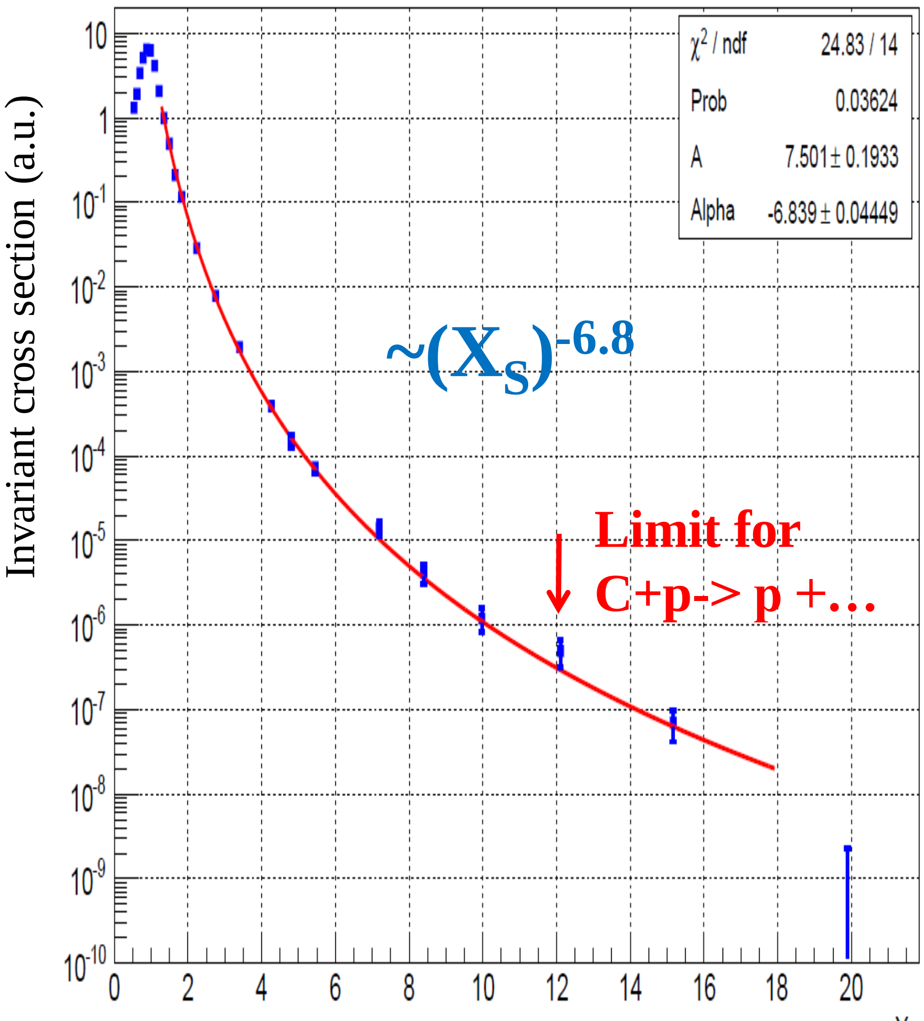
$X = X_{lf} = X_s$ at high energy but at our energy region →

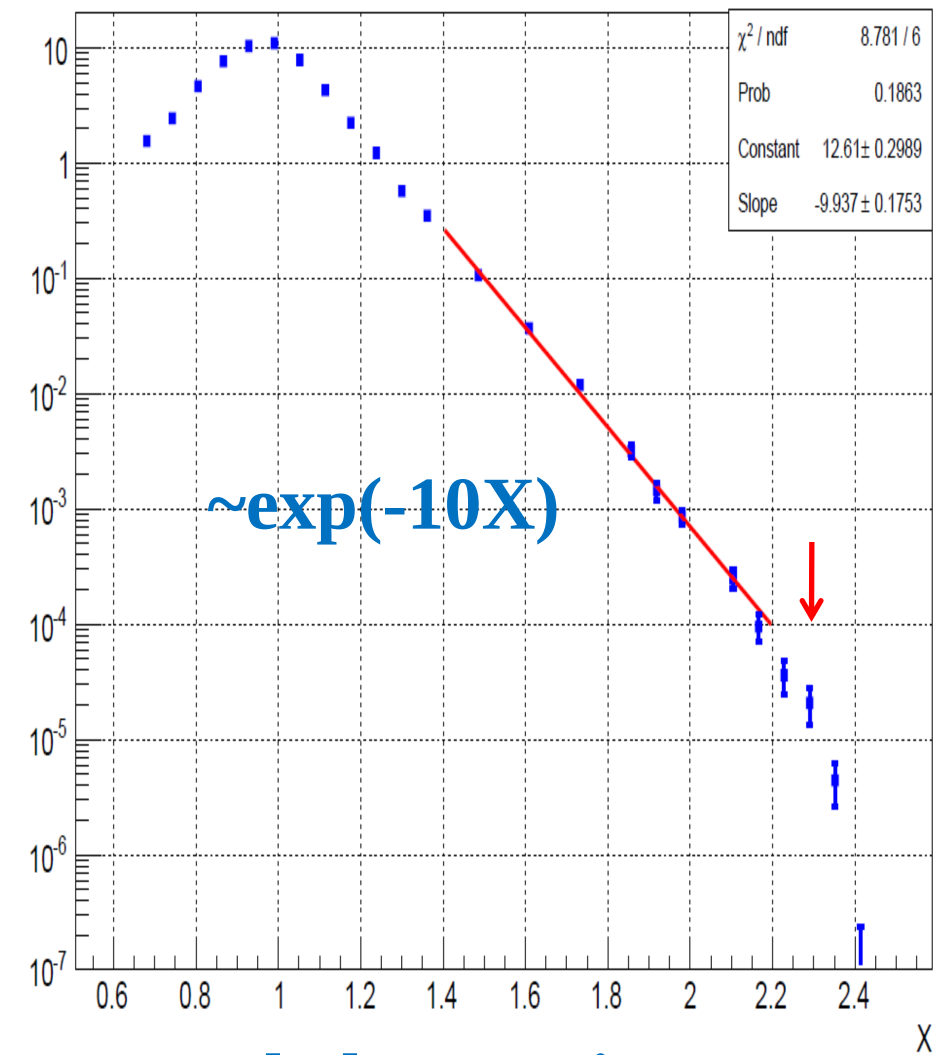
X_s vs X for different energies



For 0.3 GeV/n X=2.3 --> X_S = 12

Comparison of X_s and X-spectra at 300 MeV/n





Our data cover 8 orders in Xs and almost 7 in X

Theoretical interpretation

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

  Within appropriate models they can come from :

  - highly excited nuclear pre-fragments (FLUKA,RQMD)
  - intranuclear multiple scattering (V.Kopeliovich)
  - fluctuations of nuclear matter density (Blokhintsev)
  - short-range correlations (SRC) of nucleons (Frankfurt, Strikman)
  - **multiquark clusters** (Burov, Lukyanov, Titov(1984);
    Efremov, Kaidalov, Lykasov, Slavin(1994))

- We tried to estimate the probabilities of the existence in nucleus of the multiquark clusters using approaches by Efremov and Kaidalov in the framework of quark–gluon string model (QGSM)

Cumulative protons from multiquark clusters

Production of cumulative protons is considered as fragmentation into protons of clusters consisting of 3k valence 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; $x = p / p_0$

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

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

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

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

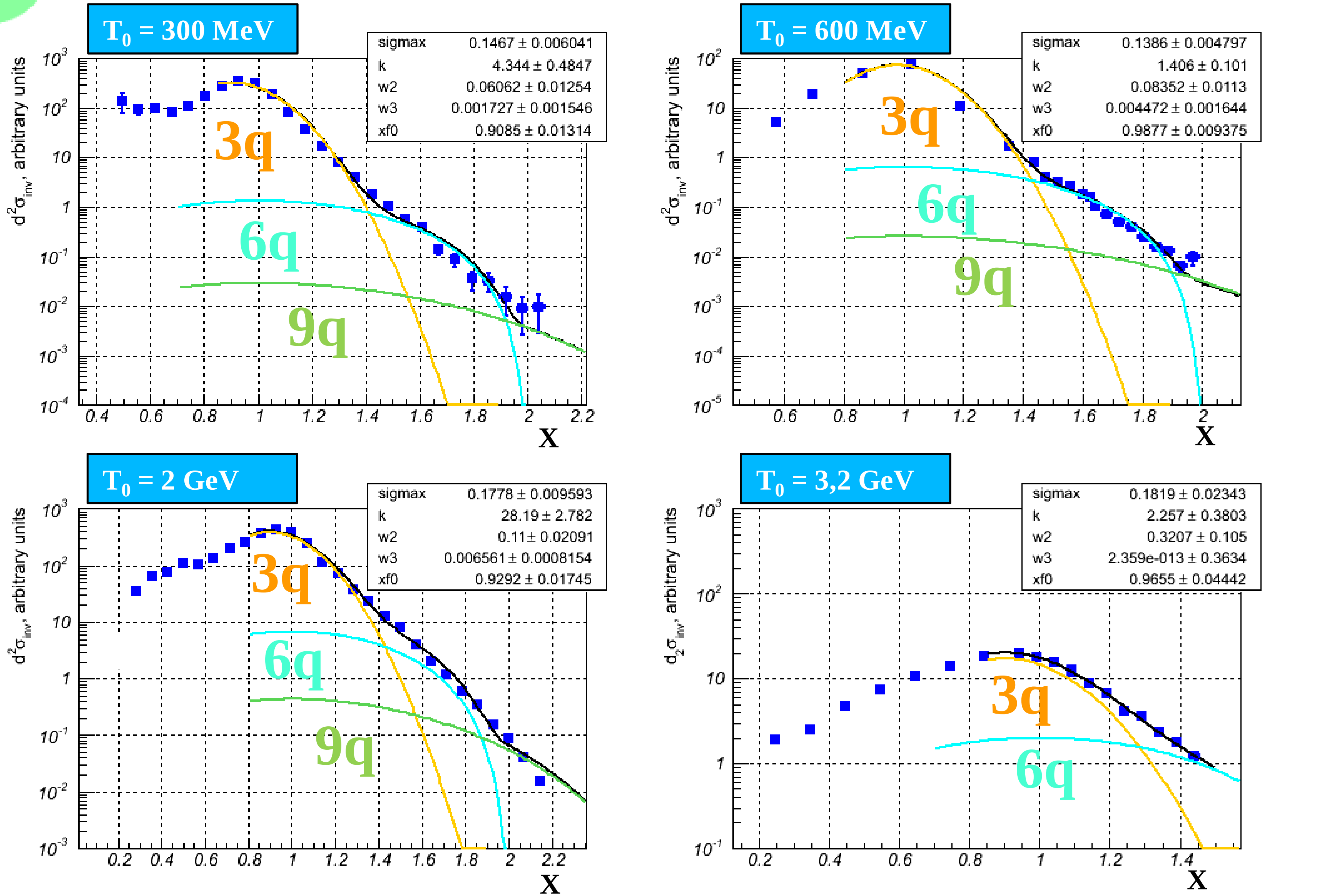
where g, b_2 , b_3 are known fragmentation functions (QGSM).
G, B_2 and B_3 are known normalization constants.
Transverse parameters α_1 and α_2 from Phys.Rev. C 28 (1983) 1224

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

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

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 existence

T_0, GeV/n	w_1 (3q)	w_2 (6q)	w_3 (9q)
0.3	0.95 0.94	0.05(1) 0.06(1)	0.002(1) 0.004(1)
0.6	0.915	0.08(1)	0.005(2)
2.0	0.894	0.10(2)	0.006(1)
3.2	0.76	0.24(8)	-
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)	0.006(2)

M. Sato *et al (1986)*
V.Burov et al(1977),pions, fluctuon
K.S. Egiyan *et al (2006)(SRC)*
H.J. Pirner , J. P. Vary(2011)(QCM)

- **Quantitative estimates on few nucleon clusters in nuclei could be obtained from fragmentation data**
- **Wider range on X and wider projectile energy range are desirable**

Conclusion

Proton yields from reaction $^{9}Be\ (^{12}C, p)\ X$ were measured at T_0 = 0.2 – 3.2 GeV/nucleon in projectile fragmentation region

- Proton momentum spectra are obtained in both evaporation and cumulative regions. Data cover seven orders of cross section magnitude.
- For the first time data were obtained in a region unreachable for nucleon-nucleus interactions.
- Cumulative number X spectra were analyzed in a multi quark cluster + quark gluon string model
- Probabilities of existence of 6q and 9q clusters in ^{12}C were estimated to be $w_6 \sim 10\%$ and $w_9 < 1\%$. Results for w_6 are in reasonable agreement with theoretical predictions and **J–LAB** measurements

Thank You