Cumulative to evaporation ratio in ^{12}C fragmentation into protons

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Motivation for nuclear fragmentation study

1. **Measurement of nuclear composition of secondary beams at ITEP heavy ion accelerator**

2. **Precise measurement of high energy fragment spectra for:**

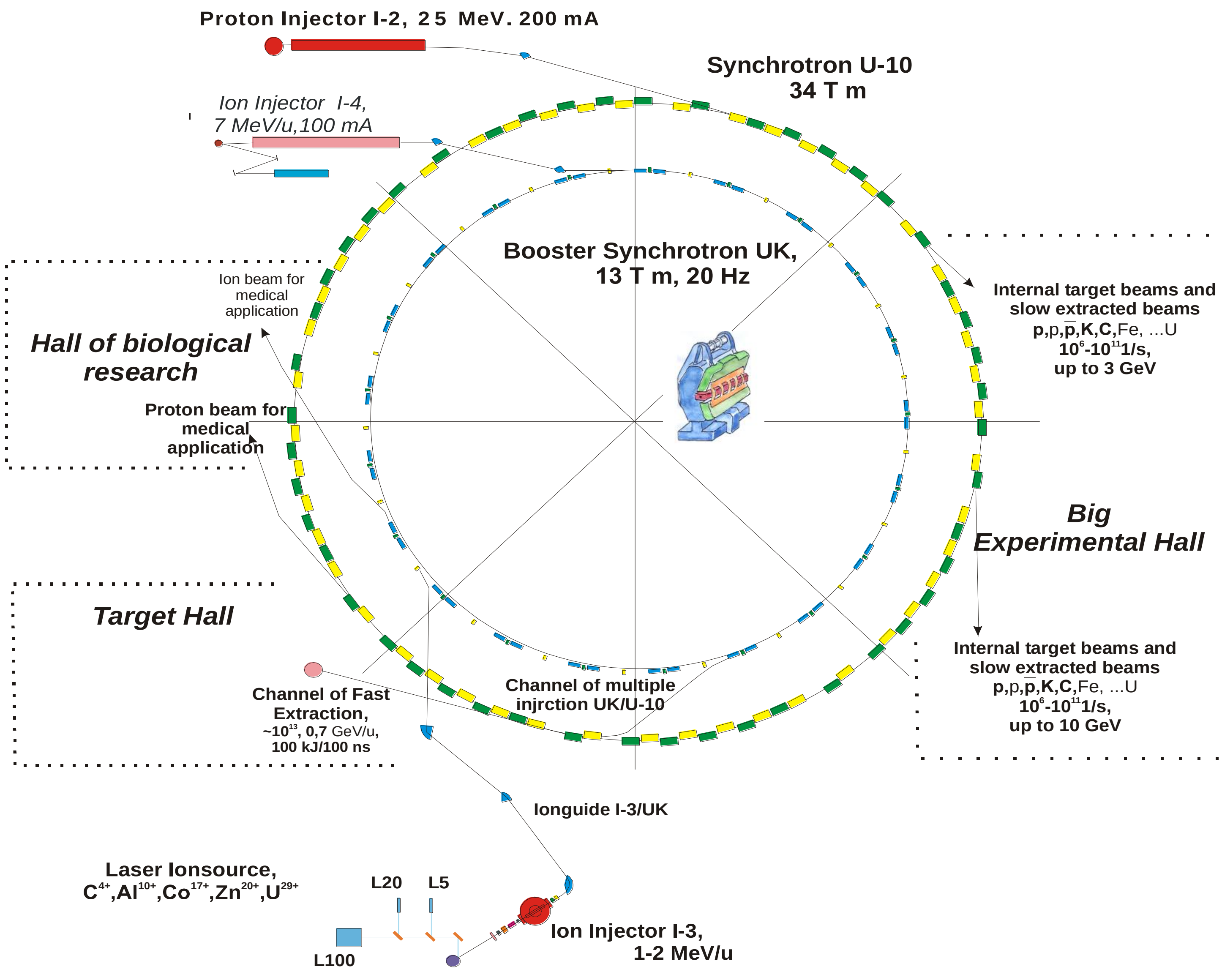
   a) study of cumulative effect in fragment production in the heavy ion collisions,

   b) test of theoretical models in the unstudied region of high momentum.

3. **Processes with proton-fragment are main base for understanding of production mechanisms of heavier fragments**

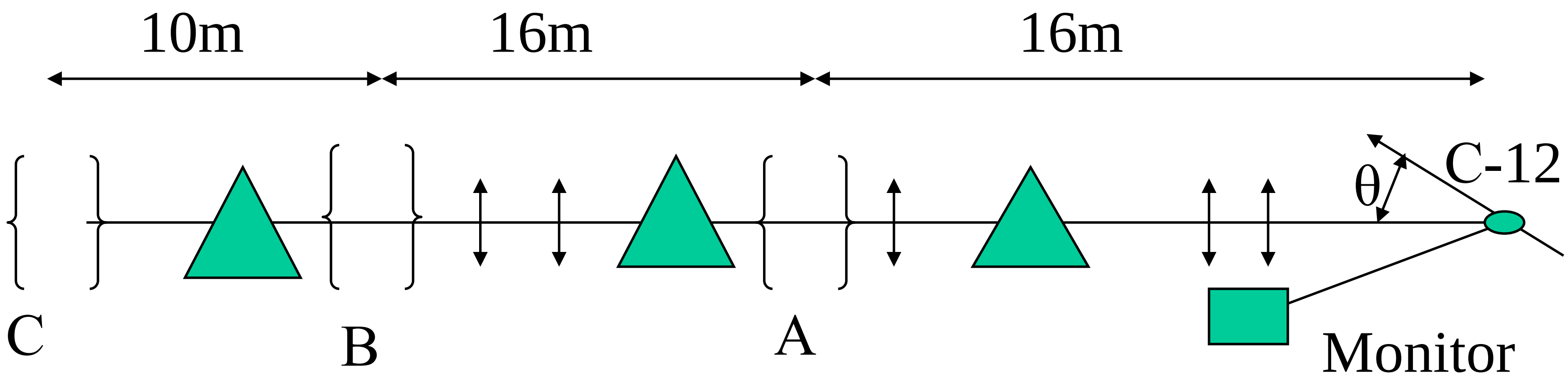
4. **Ion fragmentation data are also needed as input to transport codes for radiotherapy with heavy ions, for shielding calculation for long duration space missions and for radioactive ion beams design**

ITEP Accelerator Facility:
TeraWatt Accelerator Complex (TWAC)



APK is indebted to N.N. Alexeev for providing her with this slide

Experimental set up



-- thin foil Be-target

-- bending magnet

-- quadrupole

Scintillation counters

A 3(TOF+dE/dx) + H(20x10)

B 2(TOF+dE/dx)

Trigger = 1A x 1B

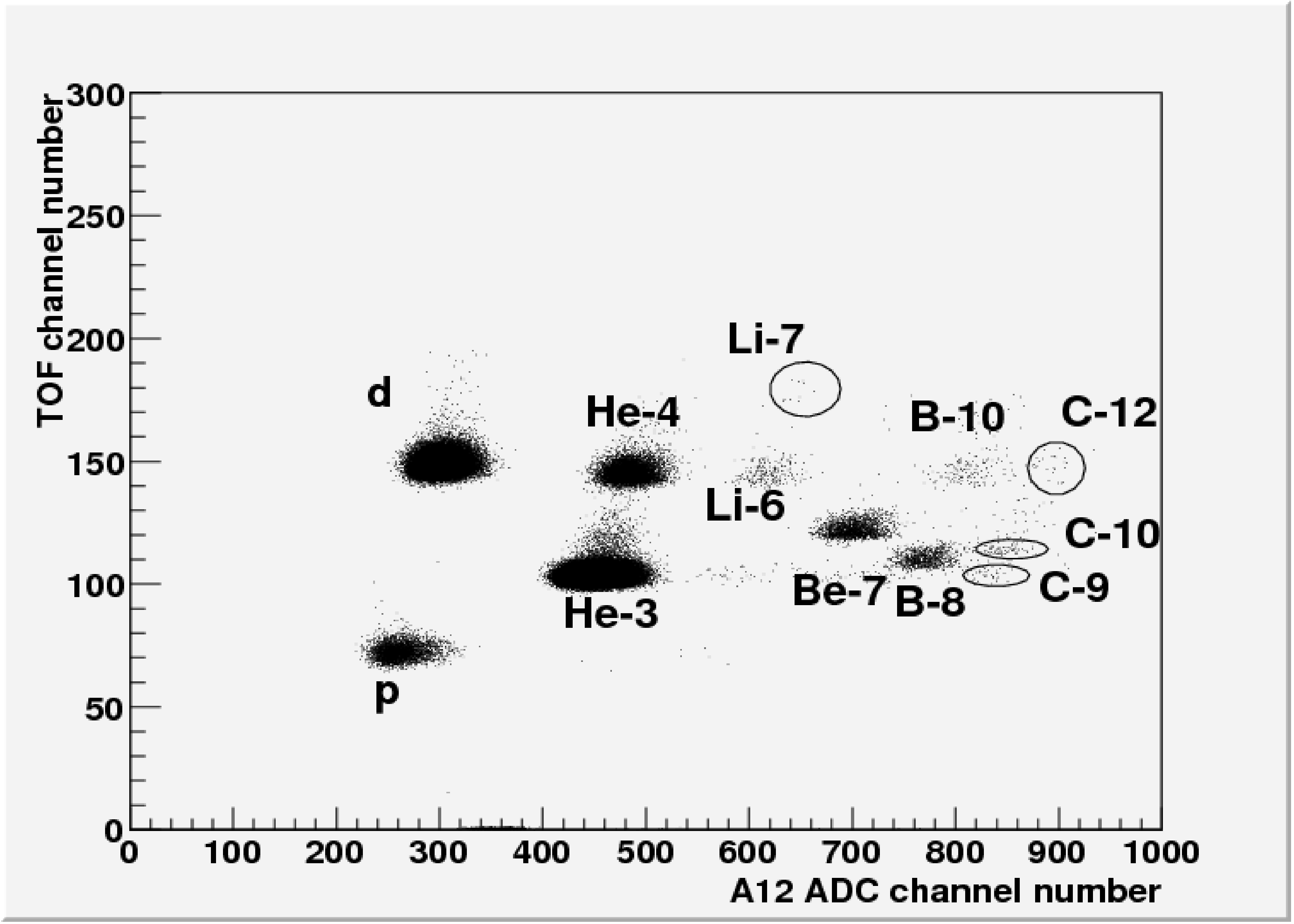
C 14(TOF) 0.6x2.0 mxm

^{12}C + Be → p (d, t, ^{3}He, ^{4}He, ^{6}He, ^{8}He,…) + X, θ = 3.5^{O}

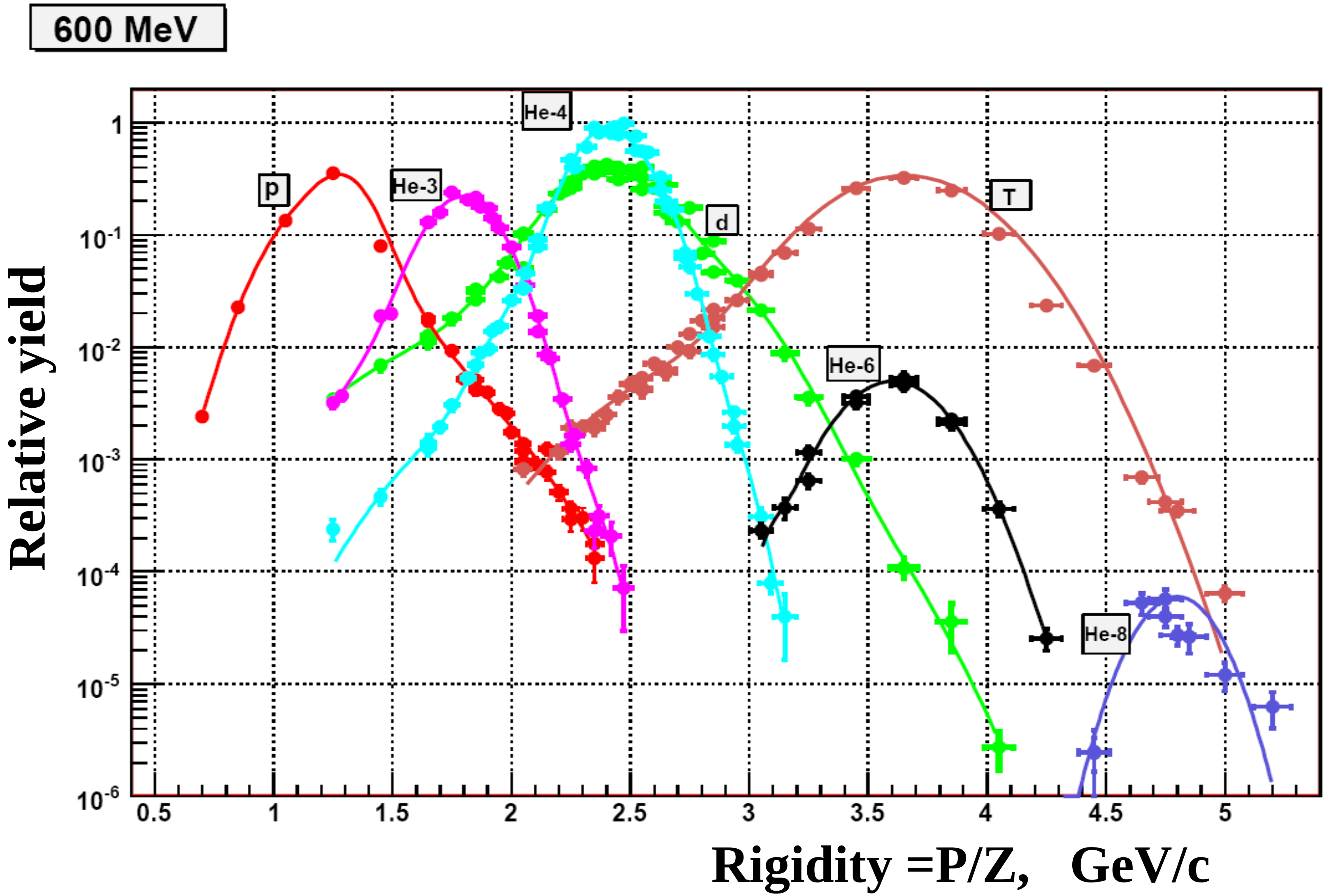
T_0 = 0.2, 0.3, 0.6 and 3.2 GeV/nucleon

(p_0 = 0.67, 0.81, 1.22, 4.03 GeV/c/nucleon)

Beam channel rigidity P/Z=1.8 GeV/c/Z (T_0=600 MeV)

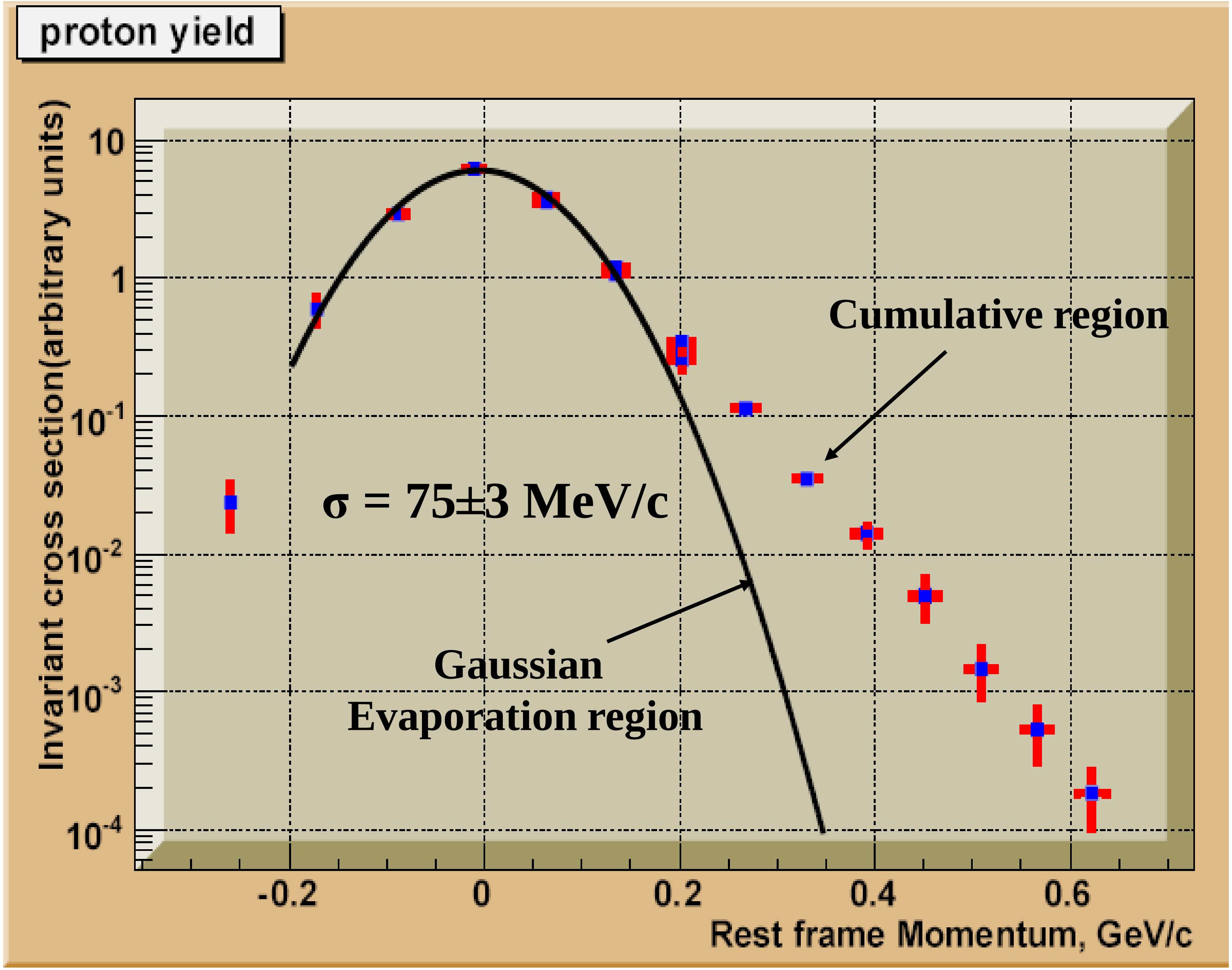


Relative yield, $d^2\sigma/d\Omega(dp/p)$, of H and He isotopes at 3.5^0 from ^{12}C fragmentation on Be target



Proton parallel momentum distribution in ^{12}C rest frame

Fit with Gaussian from -0.2 to 0.2 GeV/c.



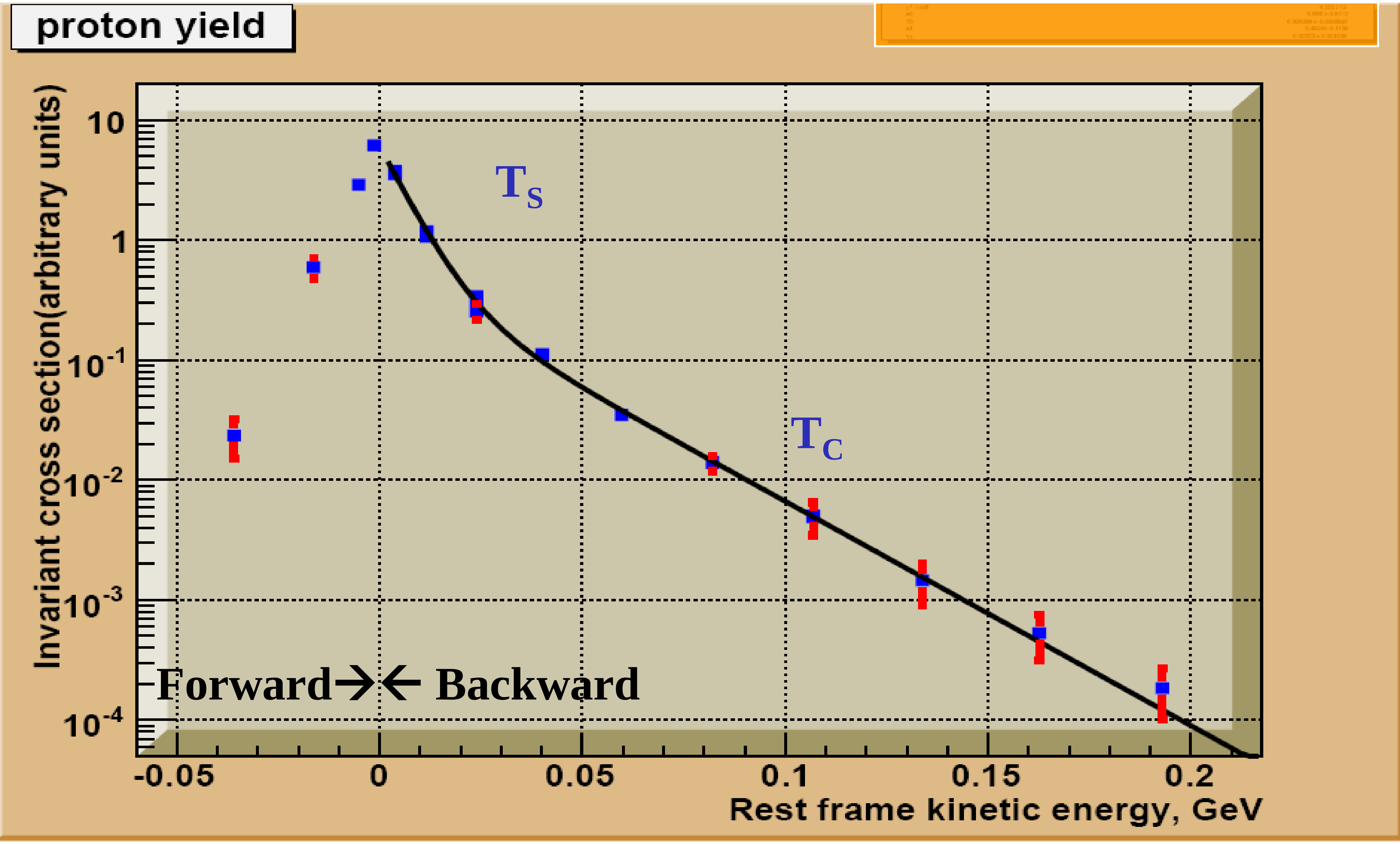
Parameters of momentum spectra in evaporation region

T_0, GeV/n	P_0, GeV/c/n	P_{t0}^2, $(GeV/c)^2$	σ, GeV
0.2	0.67	.0016	.077(2)
0.3	0.81	.0024	.072(2)
0.6	1.22	.0055	.077(4)
1.05	1.75	.0	.063(4)
2.10	2.88	.0	.067(5)
3.2	4.03	.06	-

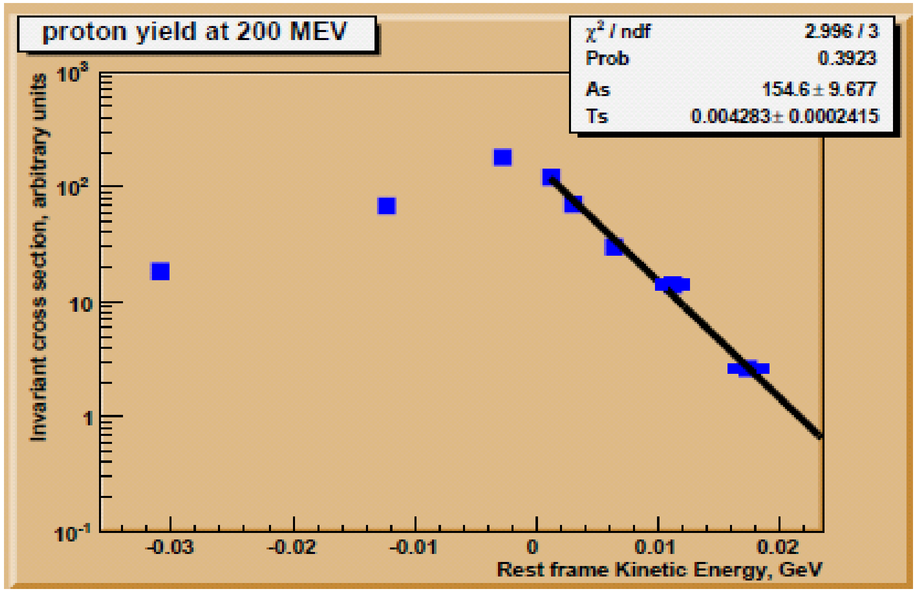
σ is the same at 0.2, 0.3 and 0.6 GeV as expected in statistical model
σ is higher at 3.2 GeV as here we are not at evaporation region
σ tends to be a bit larger than values from D. Greiner et al PRL, 35 (1975) 152 (note: syst.errors not taken into account)

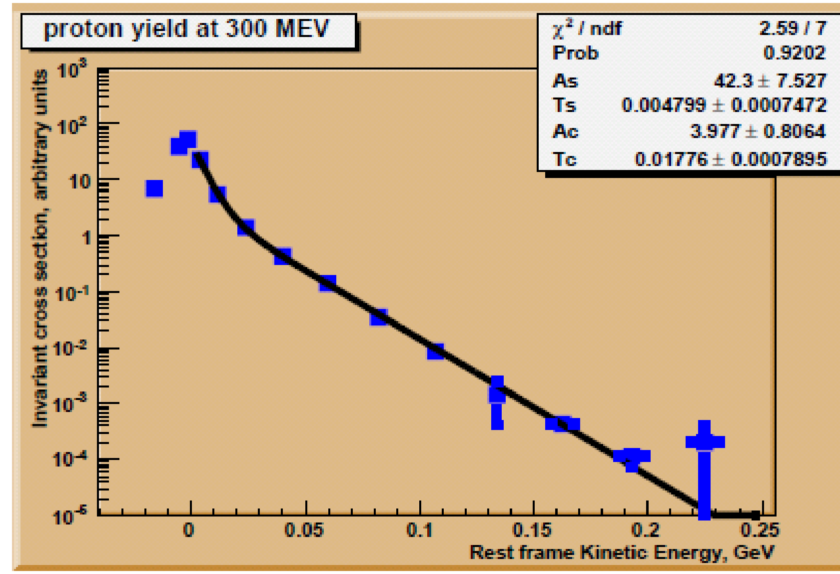
Temperatures from slope parameters.

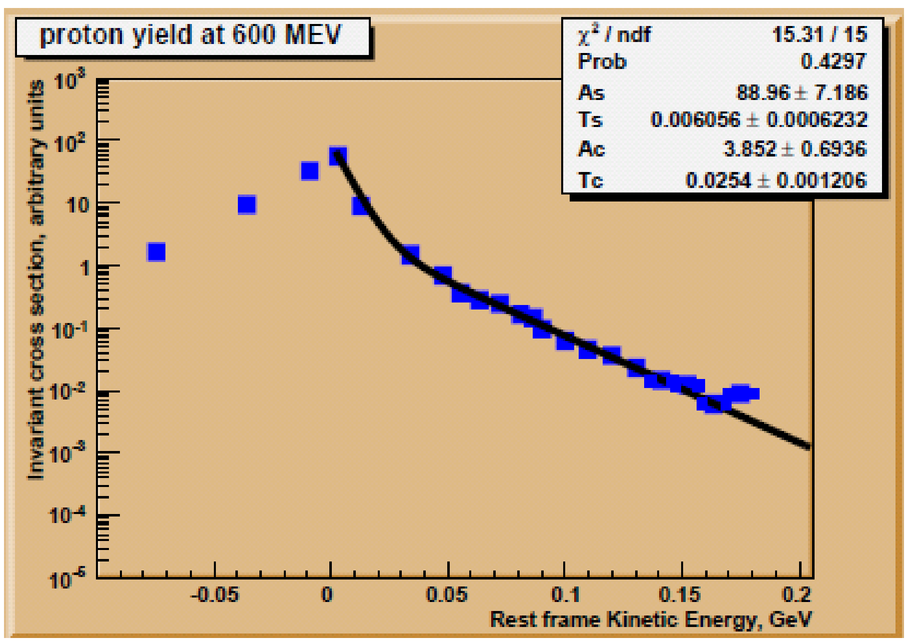
$$Ed^3\sigma/d^3p \sim A_S \exp(-T/T_s) + A_C \exp(-T/T_c)$$

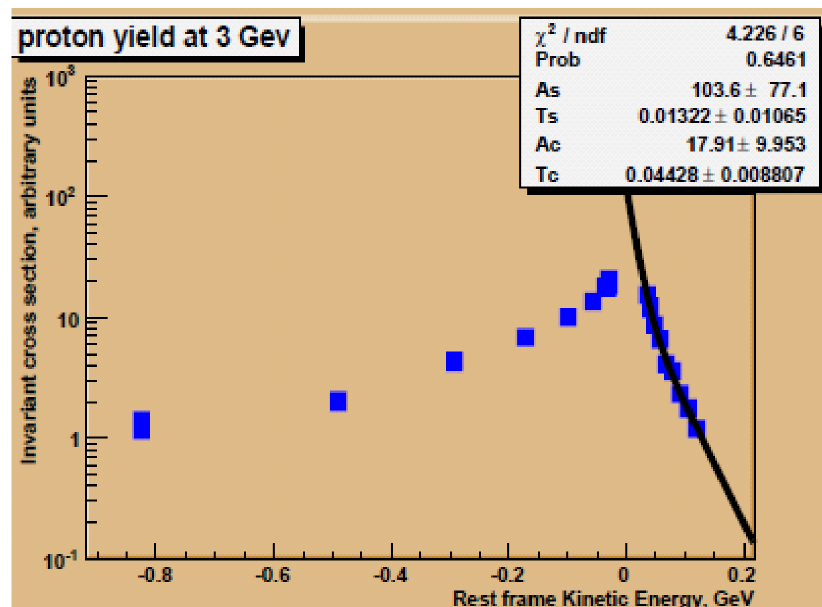


Proton kinetic energy distributions in ^{12}C rest frame

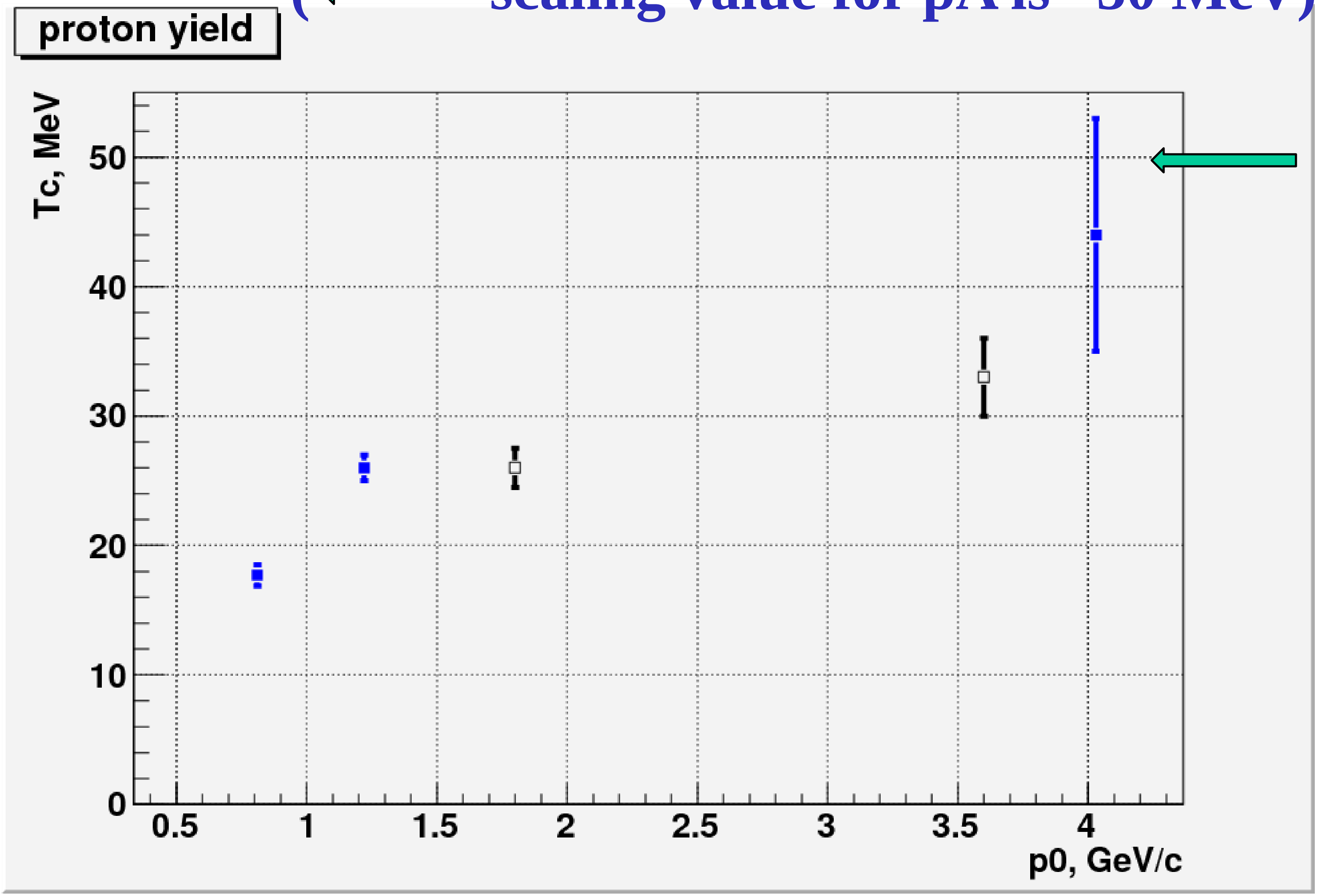








T_c as a function of ^{12}C momentum/nucleon
(⟵ scaling value for pA is ~50 MeV)



Parameters of kinetic energy spectra

$$Ed^3\sigma/d^3p \sim A_S\exp(-T/T_s) + A_C\exp(-T/T_c)$$

T_0, GeV/n	P_0, GeV/c/n	T_s, GeV	T_c, GeV
0.2	0.67	.0043(2)	-
0.3	0.81	.0048(7)	.018(1)
0.6	1.22	.0061(5)	.026(1)
1.0	1.70	.0060(5)	.026(1)
2.8	3.60	-	.033(3)
3.2	4.03	.013(11)	.044(9)

- T_s is in agreement with gaussian σ from momentum distribution and does not depend on initial energy
- T_c increases with energy being in agreement with values from T. Odeh et al. PRL 84 (2000)4557 and M.Anikina et al. YaF 45 (1986) 1217. This behaviour is similar to pA-interactions

Production of Cumulative particles

and Quark-Gluon String Model (KGSM)

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Phys. Atom. Nucl. 57 (1994) 932

Abstract

The production of cumulative particles in pA interaction was successfully considered in the framework of the KGSM. Assuming the existence of some coherent clusters in the nucleus and the asymptotic Regge behavior for their structure functions the distribution of quarks in the nucleus was derived and inclusive spectra of cumulative hadrons were analyzed.

Cumulative protons in Quark-Gluon String Model

Production of cumulative protons in fragmentation is considered as fragmentation into protons of clusters consisting of 3k valence quarks (k=1: (3q) - nucleon, k=2: 2(3q) – two-nucleon cluster, k=3: 3(3q) - three-nucleon cluster); ω_k is the probability to find k-nucleon cluster in ^{12}C nucleus

$$E \cdot d^3\sigma/d^3p(x,p_t^2) \sim G \cdot w_1 \cdot g(x,p_t^2) + w_2 \cdot B_2 \cdot b_2(x,p_t^2) + w_3 \cdot B_3 \cdot b_3(x,p_t^2), \quad (3)$$

$$g(x,p_t^2) = exp(-0.5 \cdot (1-\Delta-x)^2/\sigma_x^2) \cdot exp(-0.5 \cdot p_t^2/\sigma_p^2), \quad (4)$$

$$b_2(x,p_t^2) = (x/2)^3 \cdot (1-x/2)^3 \cdot exp(-\alpha_1 \cdot p_t^2) \quad (5)$$

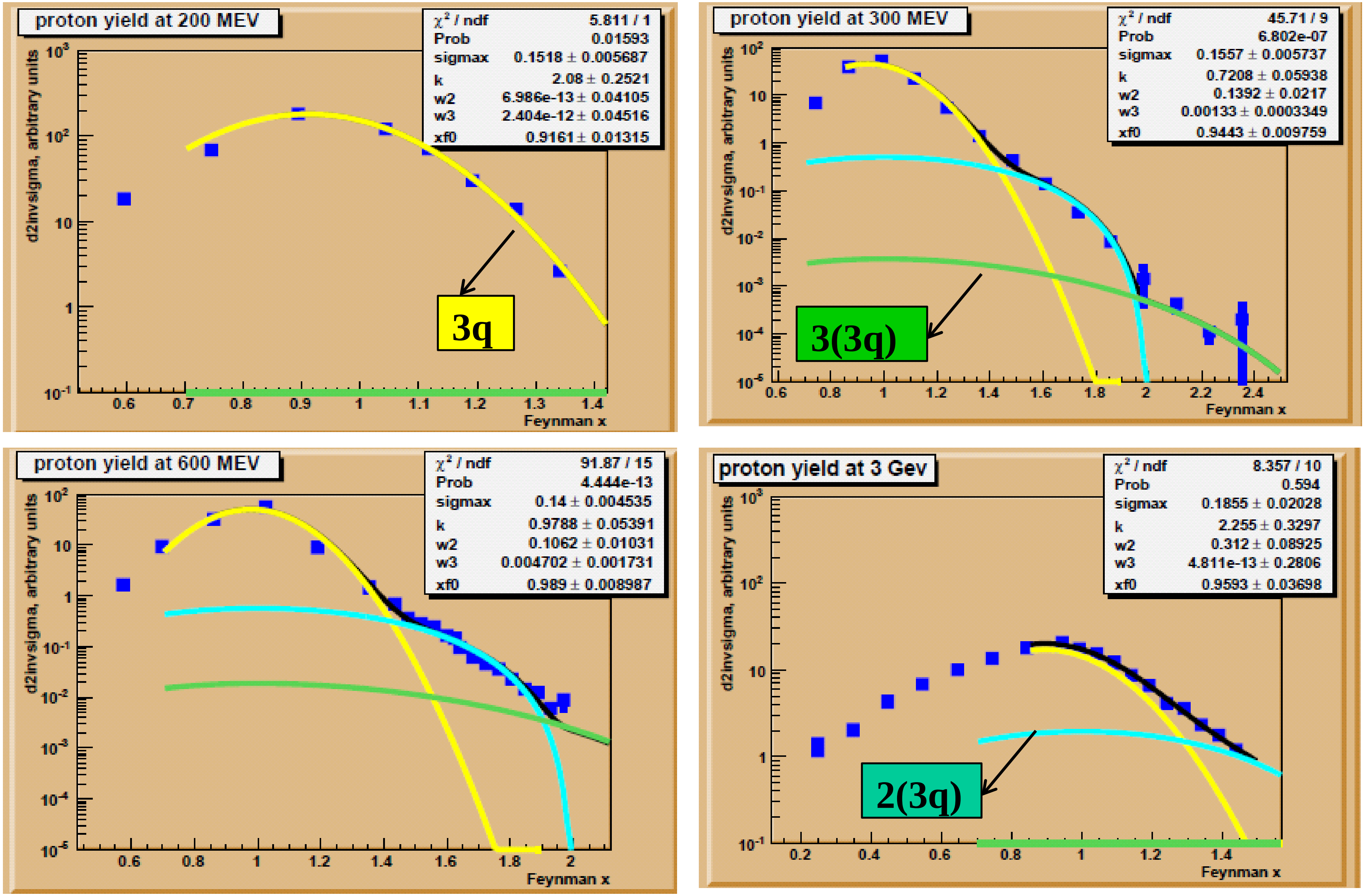
$$b_3(x,p_t^2) = (x/3)^3 \cdot (1-x/3)^6 \cdot exp(-\alpha_2 \cdot p_t^2) \quad (6)$$

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

$$\int\int B_i \cdot b_i(x,p_t^2) dx dp_t^2 = i/2, i = 2,3 \quad (7)$$

Fitted variables are: $W_2 = \omega_2/\omega_1$, $W_3 = \omega_3/\omega_1$, Δ, σ_x

Feynman-x ($x=p/p_0$) distributions at different energies



Parameters of Feynman-x spectra

T_0, GeV/n	P_0, GeV/c/n	x_{max}	<x>	σ_x	W_2	W_3
0.2	0.67	1.35	-	.152(6)	-	-
0.3	0.81	2.35	.086(6)	.156(6)	.14(2)	.0013(3)
0.6	1.22	2.0	.108(3)	.140(4)	.10(1)	.005(2)
1.05	1.75	1.7	.127(1)	-	-	-
2.8	3.60	2.1	.16(2)	-	-	-
3.2	4.03	1.45	.122(7)	.180(2)	.31(9)	-

- <x> increases with T_0 steeply (L.Anderson et al., PRC 28 (1983) 1224);
  σ_x does not depend on T_0 at low $T_{0;}$
  σ_X is higher at 3.2 GeV as here we are not at evaporation region
- W_2 and W_3 could be confronted with probabilities of two- and three-nucleon short-range correlations in ^{12}C(e,e') results, 0.19(4) and 0.005(2), respectively (Egiyan et al., PRL 96 (2006) 082501)

Conclusion

- **Proton spectra from reaction $^{9}Be(^{12}C, p)X$ were measured at initial energies T_0 = 0.2, 0.3, 0.6 and 3.2 GeV/nucleon. These spectra cover evaporation and cumulative regions.**
- **Momentum distributions in evaporation region are well described by gaussians with σ_p = 0.072 - 0.077 GeV/c**
- **In cumulative region T_C increases with energy from 18 to 44 MeV, similar to pA collisions. This means that nuclear scaling region is not reached yet.**
- **In the framework of QGSM we evaluated the probability of the 6- and 9-quark clusters existence in ^{12}C nucleus. They are ~ 10% and ~ 0.5%, respectively. These values can be compared with the recent result of CLAS on 2N and 3N SRC probabilities in nuclei. For ^{12}C they are (19±4)% and (0.5±0.2)%.**

Plans

At existing experimental setup and without principal changes in operation regime of our accelerator we might obtain data on the reaction $^{9}Be\ (^{12}C,\ p)X$ at 0.6, 0.9, 1.2 GeV/nucleon covering *x* up to 3. This would give more precise evidence for the existence of 2(3q) and 3(3q) clusters in ^{12}C nucleus.