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Ion production in the ^{12}C + ^{7}Be interactions at GeV energies



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Motivations and purposes

- **FRAGM detector was optimized to measure yields of nuclear fragments produced at ion–ion interactions** and operated at accelerating–storage complex TWAC at ITEP (Moscow) until 2012

- **Experimental setup permits us to detect ^{12}C fragments** (p, d, ^{3}He, ^{6}Li …) **with high kinetic energy** at T_0 = 0.2 - 3.0 GeV/nucleon

- **Report is based on the results obtained for reaction** : $^{12}C + {}^{9}Be \rightarrow f + X$, where f – proton or nuclear fragment detected at small angle (~ 3.5 ^{0}) **at T_0 = 0.95 and 2.0 GeV/nucleon**

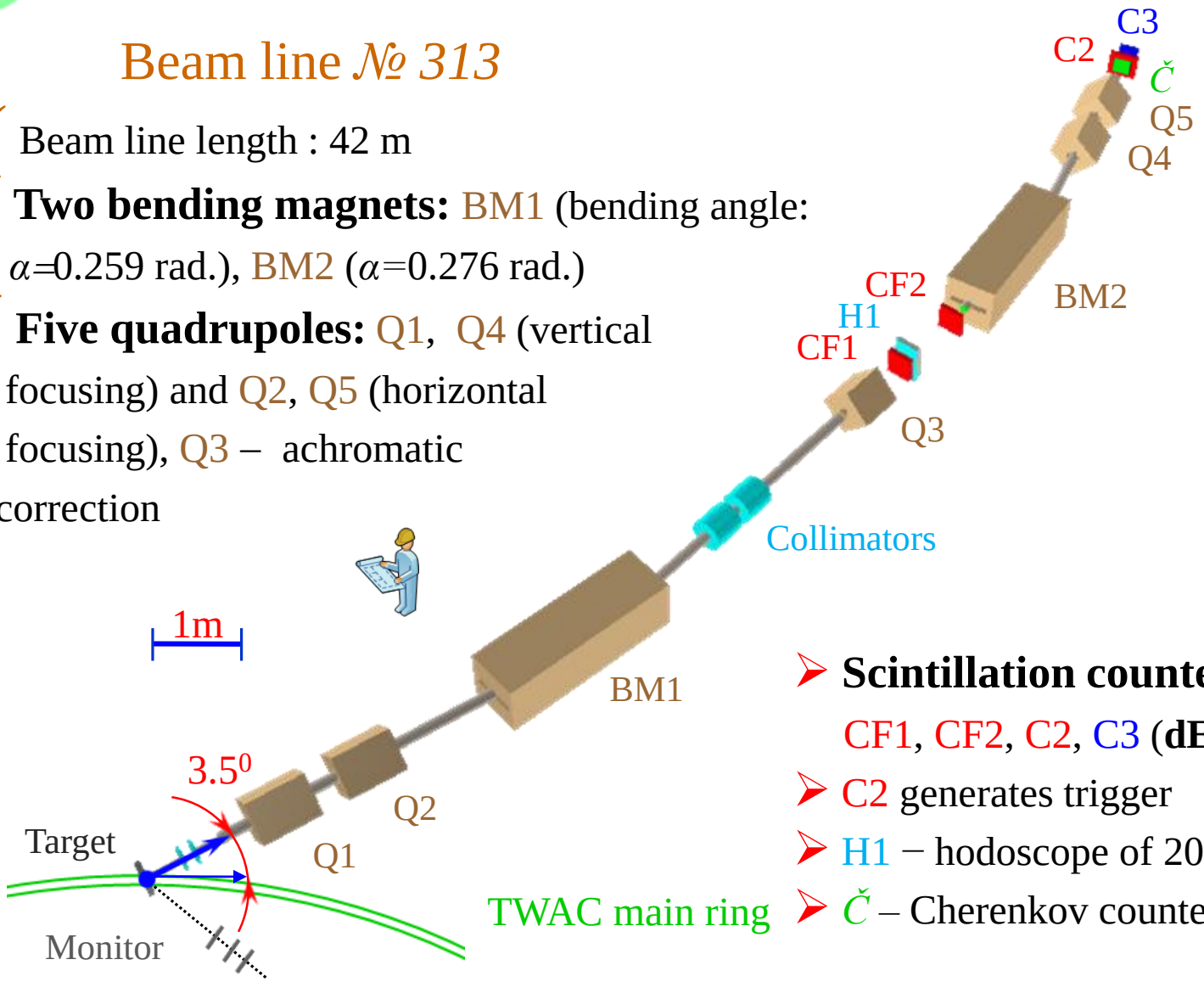
- **Measurement** of the differential cross sections for fragments:
  - ✓ **allows to test of different models of ion–ion interactions** covering both evaporation and cumulative regions
  - ✓ gives a possibility to calculate physical parameters of nuclear structure used in the theoretical models, such as thermodynamical (thermal) and coalescence models

- Current study is also important as input to transport codes

Experiment FRAGM

Beam line *№ 313*

- ✓ Beam line length : 42 m
- ✓ **Two bending magnets:** BM1 (bending angle: α=0.259 rad.), BM2 (α=0.276 rad.)
- ✓ **Five quadrupoles:** Q1, Q4 (vertical focusing) and Q2, Q5 (horizontal focusing), Q3 – achromatic correction



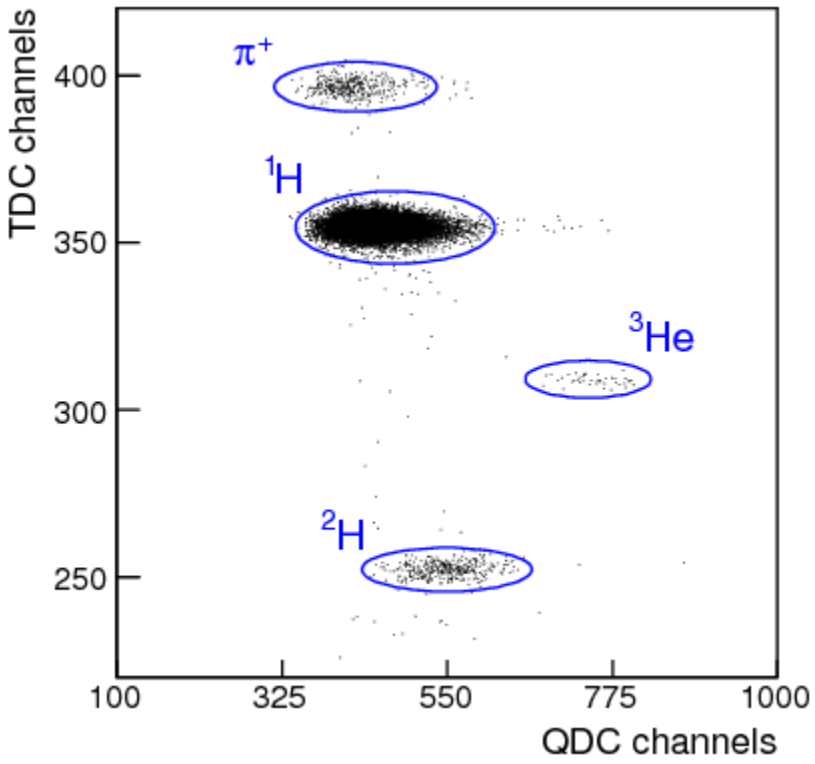
- ➢ **Scintillation counters:** CF1, CF2, C2, C3 (**dE/dx, TOF**)
- ➢ C2 generates trigger
- ➢ H1 – hodoscope of 20 elements
- ➢ Č – Cherenkov counter

Fragment separation in FRAGM

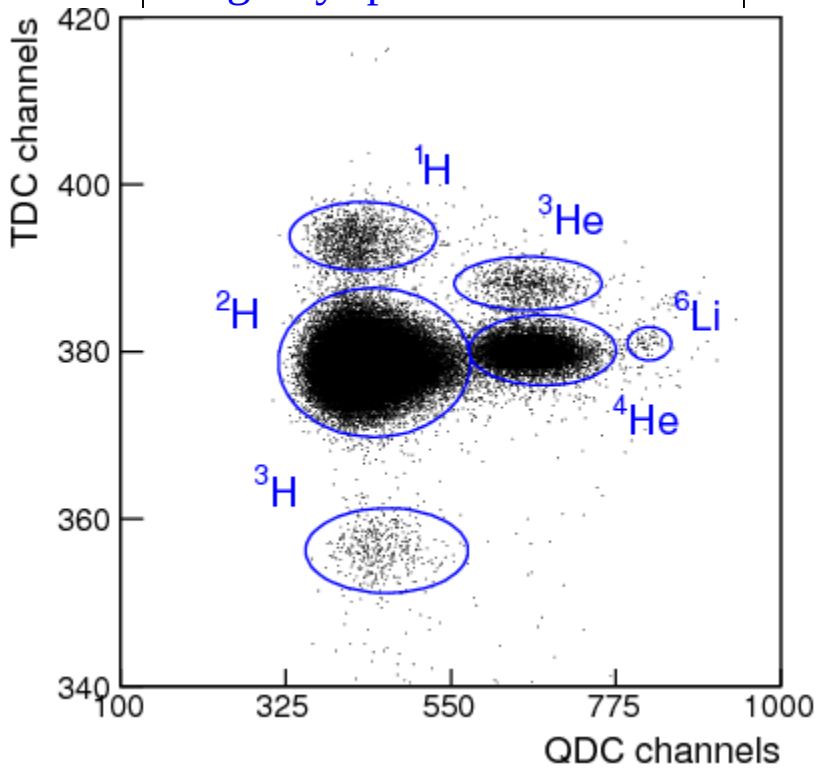
C – Be collisions at T_0 = 2.0 GeV/c

NEW

Rigidity=p / Z = 1.6 GeV/c



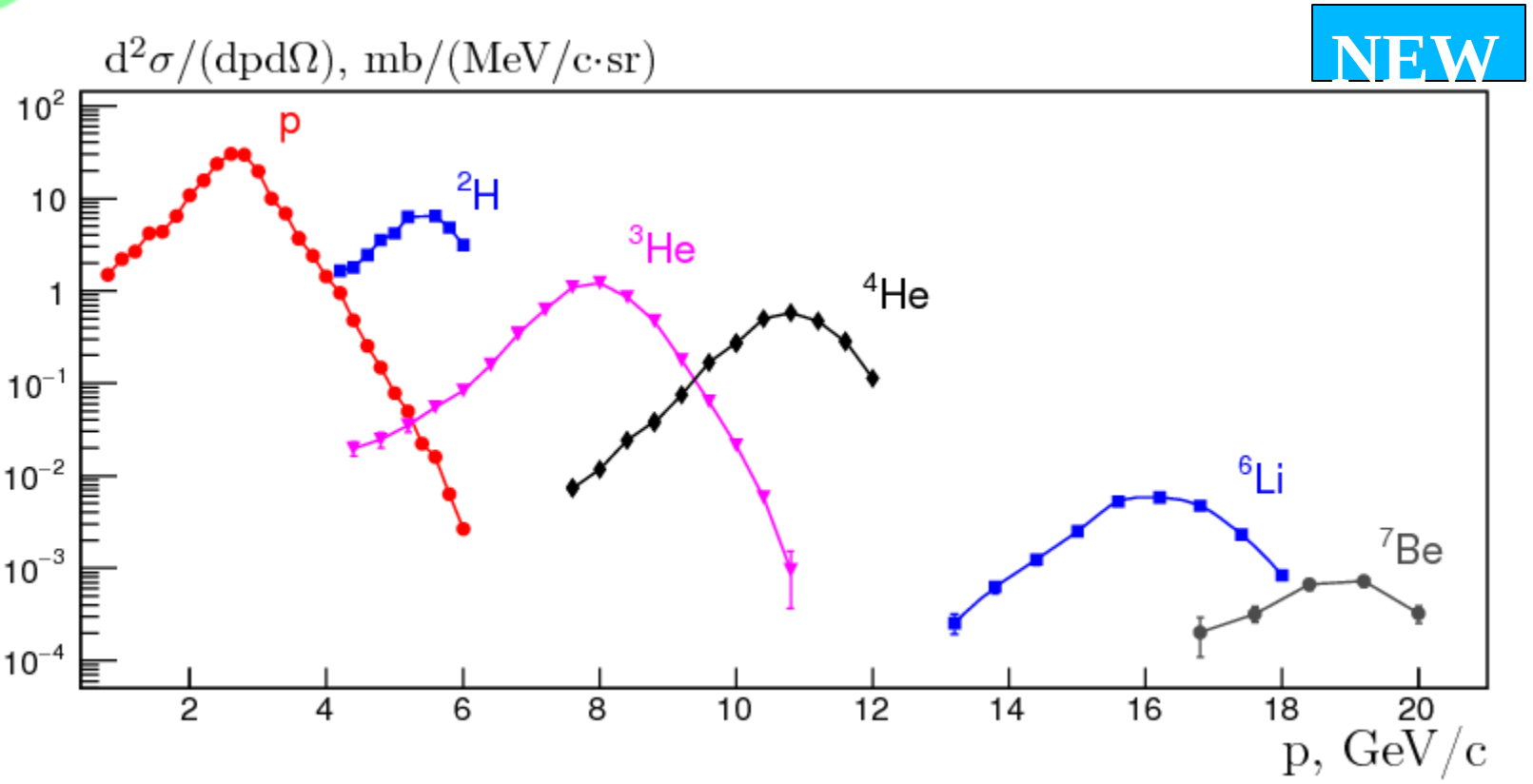
Rigidity=p / Z = 5.0 GeV/c



✓QDC (function of dE/dx and Z of fragment) (from CF1) vs TDC (TOF as a function of the atomic mass number of fragment between CF1 and C2)

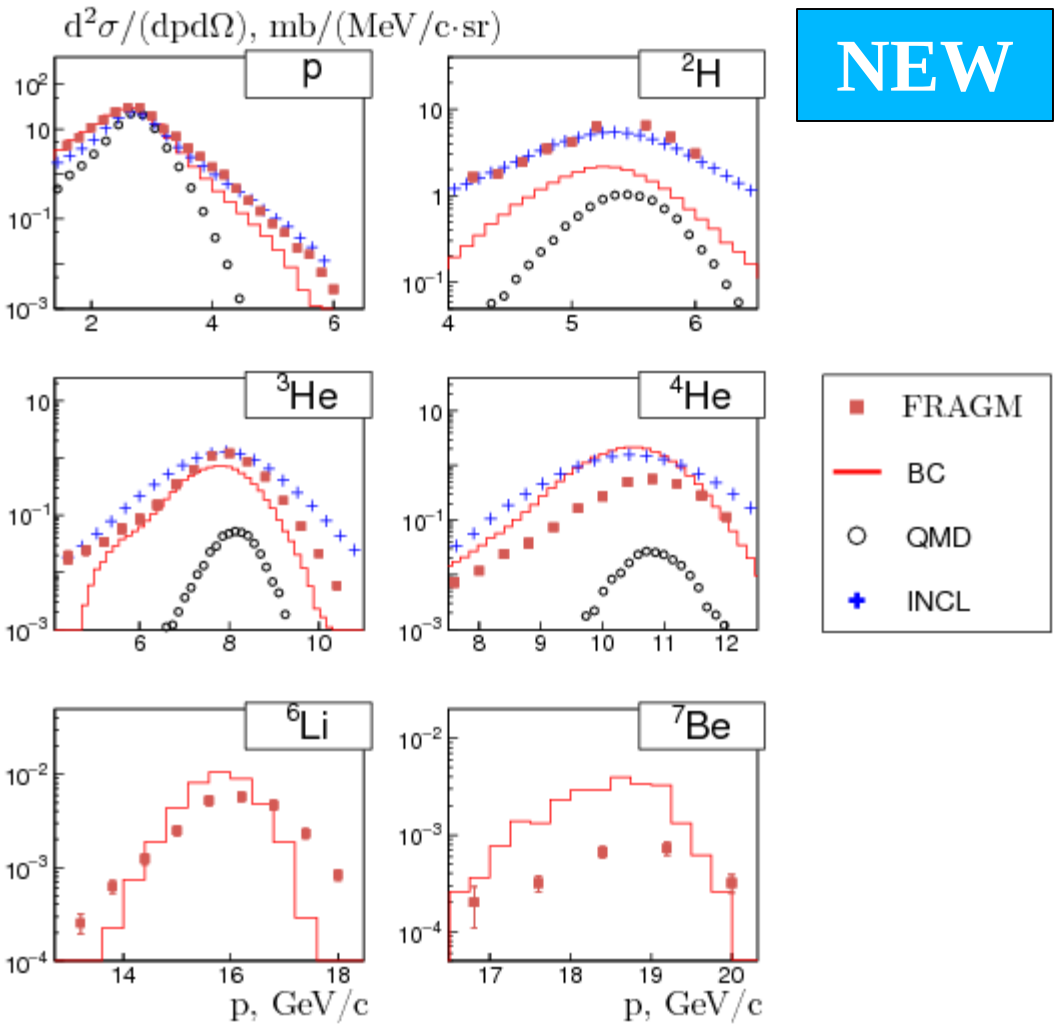
✓**Regions of different fragments are well separated**

Measured fragment momentum spectra at 2 GeV



- ✓ **Six fragments have been observed from proton to ^{7}Be**
- ✓ Spectra cover from one to four orders of magnitude
- ✓ Data are normalized to BC model prediction for protons at fragmentation maximum (with total cross section σ_{tot} = 859.78 mb)

Comparison : FRAGM data vs models at 2 GeV



NEW

- **For p both INCL++ and BC give rather good description of the experimental data, for deuterons BC looks worse than INCL++**
- The QMD model predicts much narrower fragmentation peaks for all fragments than observed in the experiment
- **Yields of fragments decrease with A grows and the accuracy of the prediction becomes worse**
- Only BC model has reasonable prediction of observed heavy fragments yields

RF kinetic energy spectra at 2.0 GeV/nucl.

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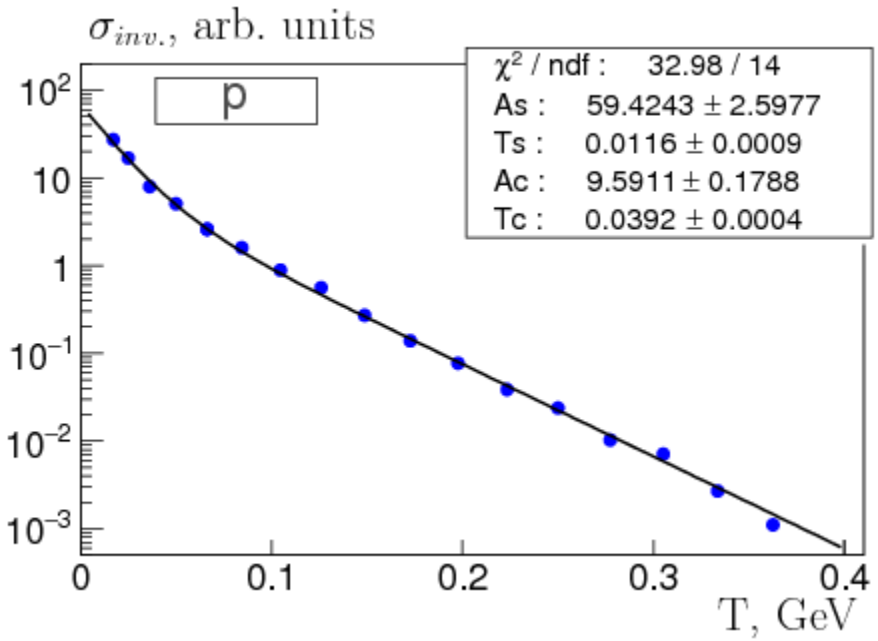

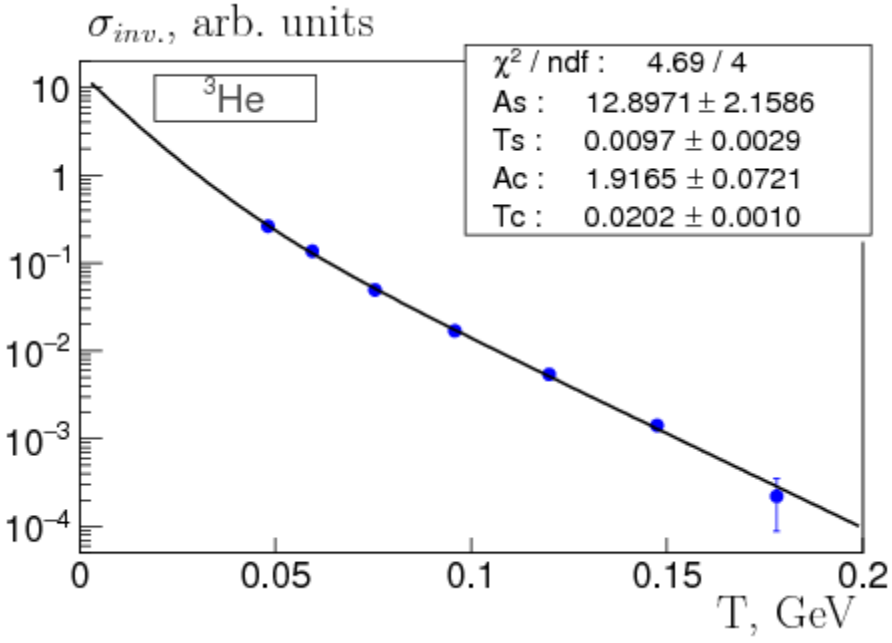

- **Kinetic energy spectra can be described by a sum of two exponents** with slope parameters T_S (which describes fragmentation peak) and T_C (high momentum part)
- **High momentum** (cumulative) **component is typical for light fragments**

RF kinetic energy spectra at 950 MeV/nucl.

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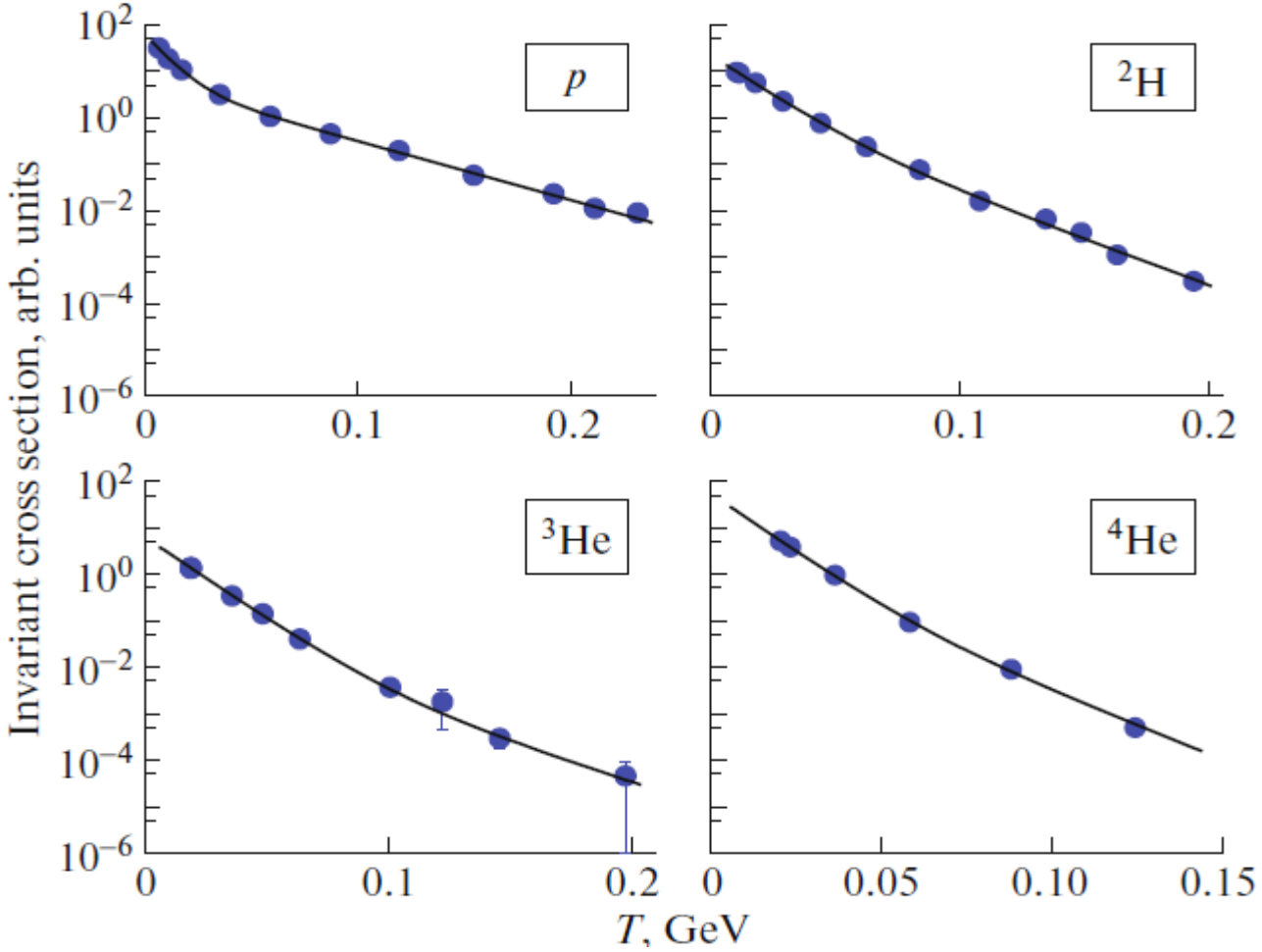
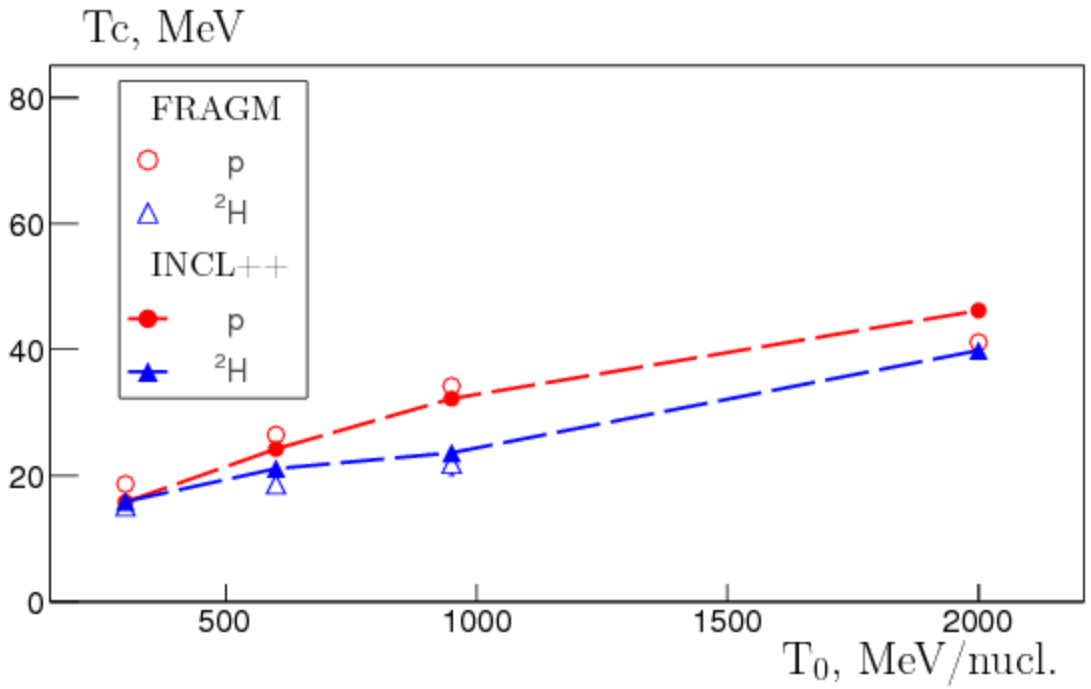


➢ High momentum (cumulative) component is typical for light fragments up to ^{4}He

T_C as function of kinetic energy spectra T_0

- ✓ **Slope T_C rises with increase of kinetic energy of incident nucleus**
- ✓ **INCL++ predicts well energy dependence for T_C** for p and d.
- ✓ T_C at 2 GeV is compatible with the result at 3.6 GeV/n for $^{12}C^{12}C$-interactions from Sov. J. Nucl. Phys. 43, 780 (1986)



Conclusions

✓ **Fragment yields for the reaction $^{12}C + Be \rightarrow f + X$ were measured at ion incident energies T_0 = 0.95 and 2.0 GeV/nucleon** with a magnetic spectrometer in the FRAGM experiment at accelerating–storage complex TWAC at ITEP (Moscow).

✓ Fragments from protons to carbon isotopes were identified by the correlation measurement TOF–ionization losses in scintillation detectors

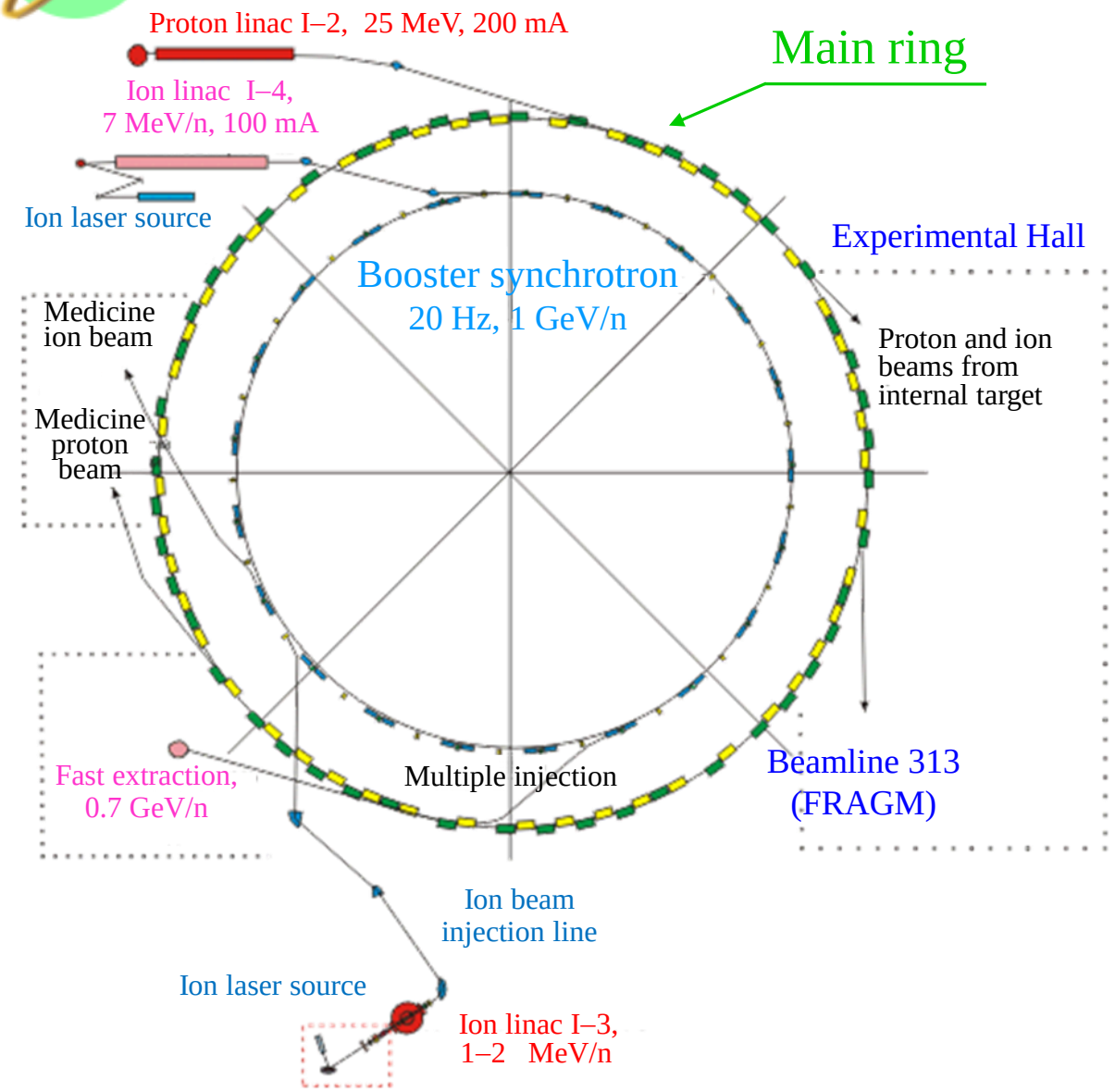
✓ **Fragment momentum spectra were measured/compared with predictions of four models**; best description is obtained with the INCL++

✓ **Kinetic energy spectra in the rest frame were also measured** and parameterized with two slopes T_s and T_c; the experimental T_c is found to rise with energy being in agreement with INCL++ predictions for protons and deuterons.

✓ Results at 0.95 GeV were published in Phys. Atomic Nuclei

Thank You

TWAC – ITEP



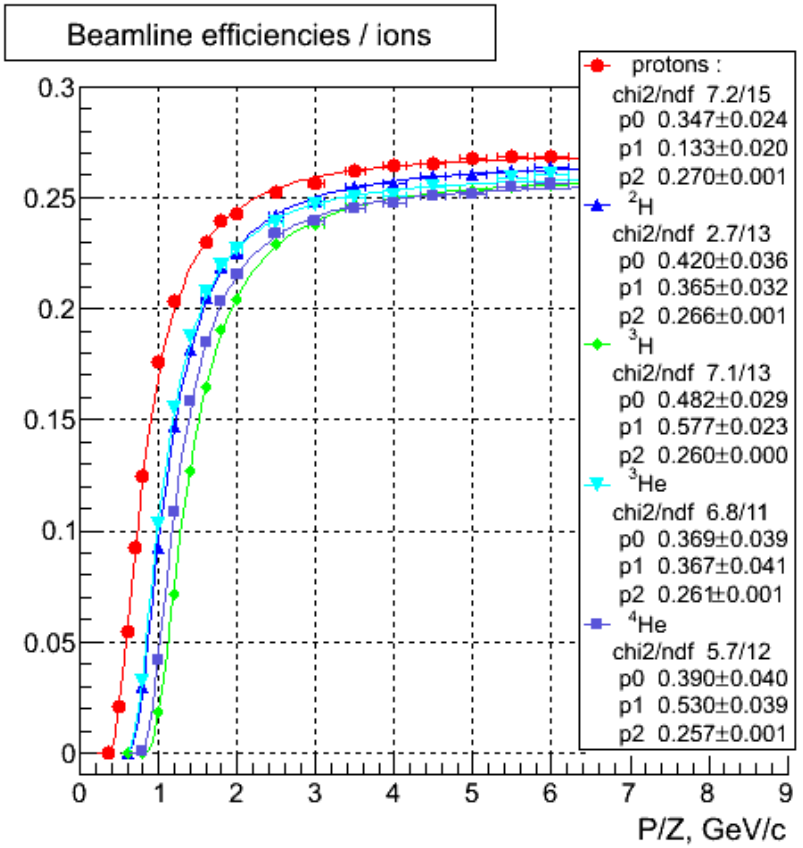
TWAC – TeraWatt Accumulator Complex

TWAC last 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
- ✓ As a result of the strong fire accident in 2012, TWAC was decommissioned. The restoration / modernization of the accelerating–storage complex is a priority task of ITEP

Beamline efficiencies for different ions

- Beamline has several construction features (beam pipe break ~ 3 m, stubs etc.); all counters are positioned on the beam. So, detection efficiency depends on beam momentum
- MC for FRAGM is performed with GEANT4 code (version 4.9.4)
- Protons and light ions (^{2}H, ^{3}H, ^{3}He, ^{4}He) at $0.6 < P/Z < 6$ GeV/c
- Values of the magnet currents are adjusted for different momenta



- Program transports particles in the magneto – optical channel taking into account multiple scattering effects, ionization losses and absorption in the detector materials.
- It is essential to take the efficiency into account for $P/Z < 2$ GeV/c

Ion – ion interaction models: brief overview

- Binary Cascade (BC, GEANT4 toolkit, G. Folger *et al.*, EPJA 21 (2004) 407) :
  - Useable when either projectile or target is ^{12}C or lighter
  - Novel approach of the intra-nuclear cascade is implemented
- Quantum Molecular Dynamics (QMD, GEANT4 toolkit)

  T. Koi *et al.*, AIP Conf. Proc. 896 (2007) 21:
  - Available for light and heavy ions
  - All nucleons are considered as participants and are propagated by means a phenomenological nucleon-nucleon potential
- Liege Intranuclear Cascade (INCL++, J. Dudouet *et al.*, PR **C**89 (2014) 054616) :
  - Model is implemented in the GEANT4 toolkit, projectiles lighter than A = 18
  - Combines best features of the BC and QMD models
- Los Alamos version of Quark Gluon String Model (LAQGSM03.03)

  LA-UR-11-01887, presented by S. Mashnik and K. Gudima
  - First stage is the internuclear time-dependent cascade developed initially at JINR
  - It was tested in a wide energy region till 1 TeV/nucleon and large number of ions

Relative fragment yields at 0.95 GeV/n

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Fragment	FRAGM	BC	QMD	INCL++	LAQGSM	[16]
$^{3}He/^{3}H$	1.07(8)	1.05(1)	0.72(1)	0.89(1)	1.34(2)	1.08(8)
$^{6}He/^{6}Li$	0.08(1)	0.39(1)	0.26(1)	0.30(1)	0.17(1)	0.08(1)
$^{7}Be/^{7}Li$	0.75(6)	0.96(1)	0.49(3)	0.76(2)	1.48(6)	0.76(5)
$^{8}B/^{8}Li$	0.30(9)	0.015(1)	0.20(5)	0.0003(1)*	1.74(2)*	0.66(5)
$^{10}Be/^{10}B$	0.11(3)	0.80(3)	0.44(1)*	0.16(1)*	0.17(1)*	0.17(2)
$^{11}C/^{11}B$	1.0(4)	0.94(6)	0.97(1)*	0.99(1)*	0.97(1)*	0.88(8)

* Ratios obtained in model calculations upon integration with respect to all angles.

Add comments from the 0.95 GeV paper

Fragment separation in FRAGM

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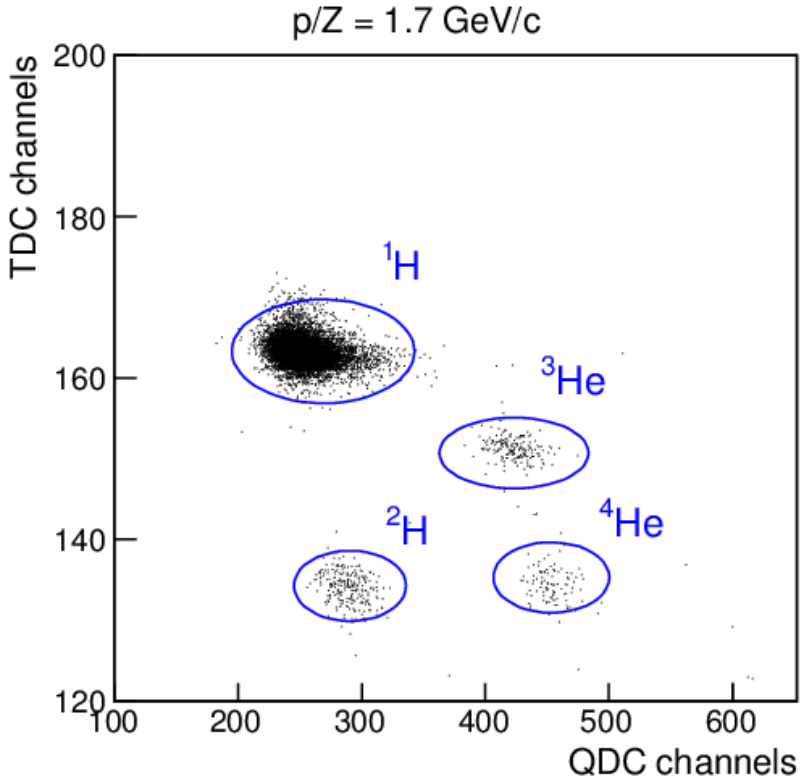
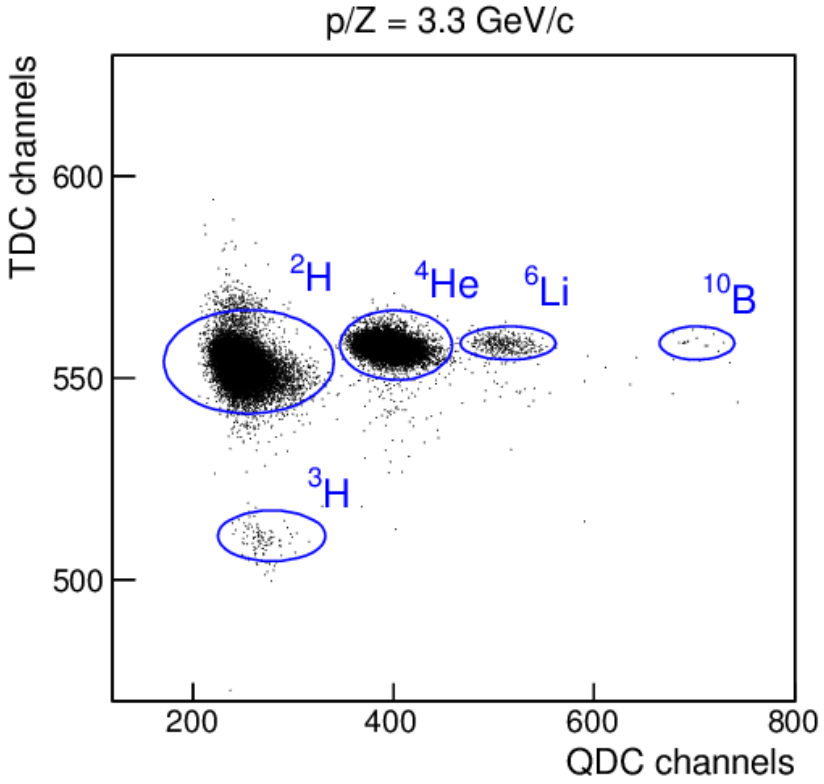
C – Be collisions at 0.95 GeV/nucleon





- ✓ **Regions of different fragments are well separated and can be clearly selected**
- ✓ Increase of the projectile momentum leads to smaller cross section for light fragment production at 3.5^{0}

Momentum spectra : T_0 = 0.95 GeV

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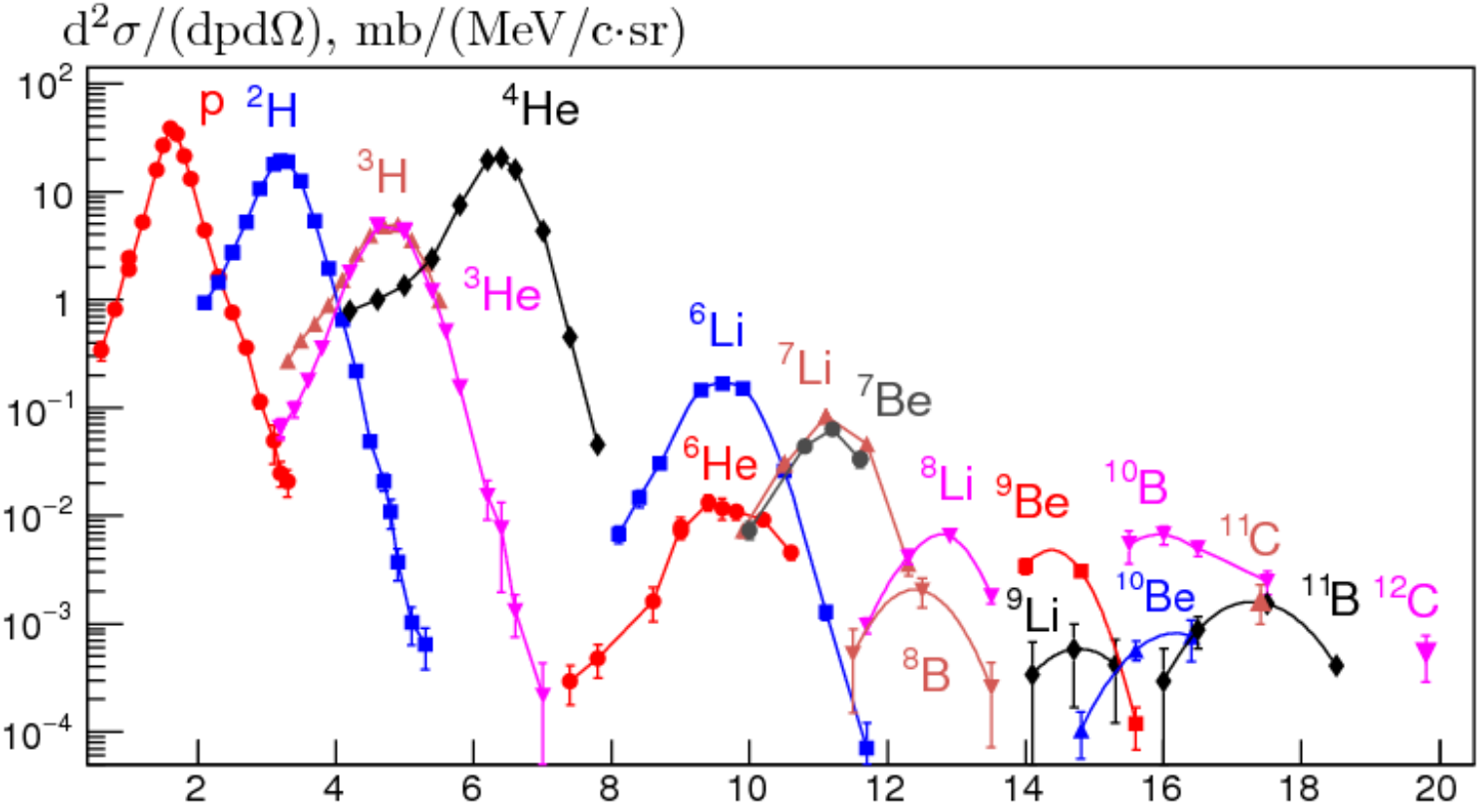

- **Momentum spectra cover 1-5 orders of magnitude**
- **18 different fragments were measured**

Fragment momentum spectra at 950 MeV/c

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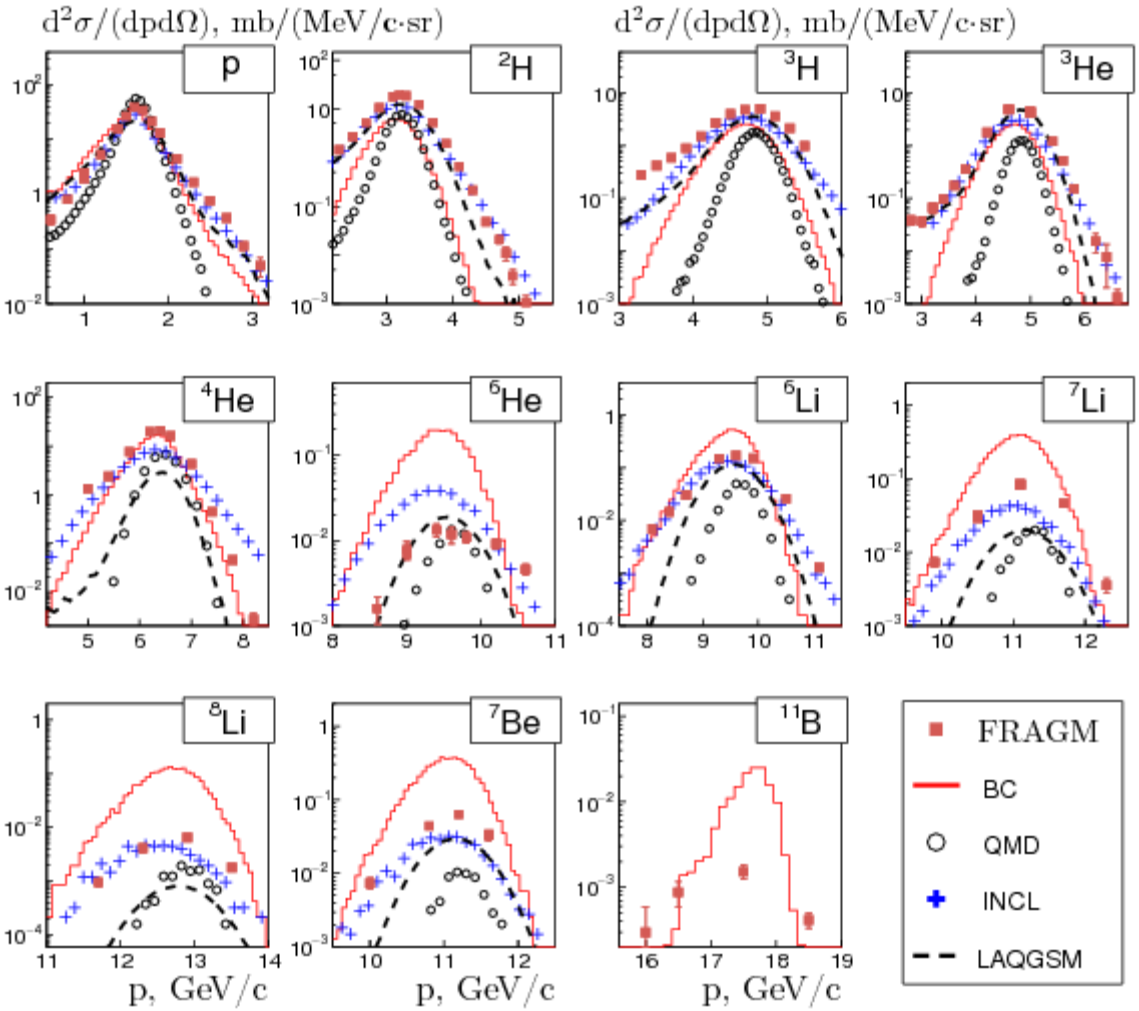
✓ Model INCL++ rather well reproduces the shape of fragmentation maxima at different T_0

✓ INCL++ predicts the cross section normalization better than all other models



Cross sections difference in models at 2 GeV