Skobeltsyn Institute of Nuclear Physics

Lomonosov Moscow State University

Review of the results of the space experiment NUCLEON

A. Panov, on behalf of the NUCLEON collaboration:
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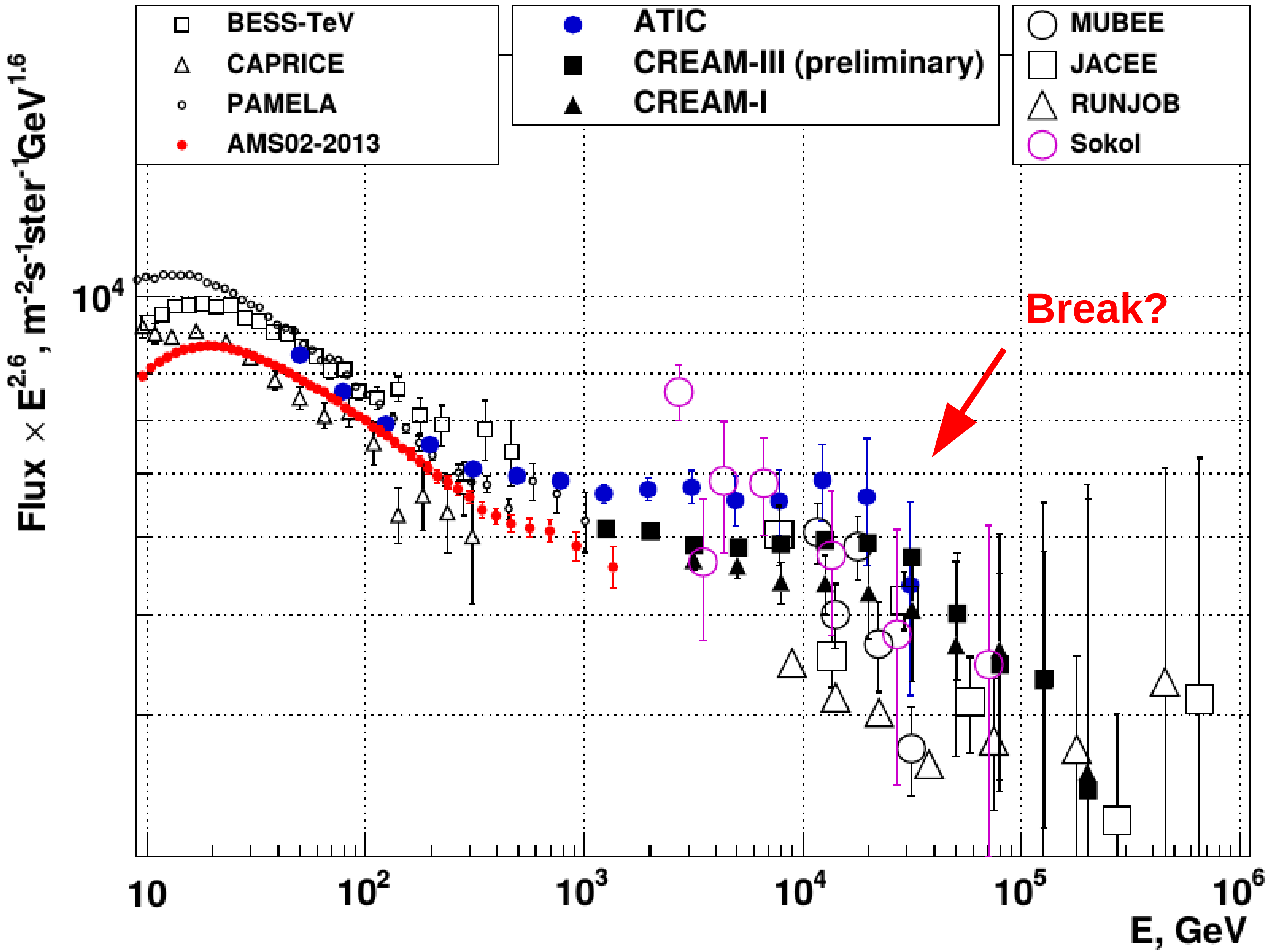
WASDHA2018

Approaching the knee area.

Problems in cosmic-ray spectra at energies 10 TeV - 1PeV per particle.

An example: proton spectra before NUCLEON.



The objectives of NUCLEON space experiment

Priority: experimental study of cosmic ray spectra in the energy range from a few TeV - 1 PeV per particle with elemental charge resolution.

Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow,

Joint Institute for Nuclear Research, Dubna, Russia

National Research Nuclear University “MEPhI”, Moscow

SDB Automatika, Ekaterinburg, Russia

ROSKOSMOS, Russia

JSC SRC "Progress"

Russian Academy of Sciences

NUCLEON mission

NUCLEON apparatus is placed on board of the RESURS-P regular satellite as an additional payload.

Lanched December 28, 2014.

The spacecraft orbit is a Sun-synchronous one with inclination 97.276° and an average altitude of 475 km.

Vessel:

Weight ~360 kg

Power consumption ~160 W

Telemetry ~10 GB/day

The NUCLEON detector on board of the satellite RESURS-P N2.

IMPORTANT FEATURE OF THE EXPERIMENT:

Two different methods of measuring of the energy of particles are implemented in the NUCLEON experiment:

1. The kinematic method KLEM

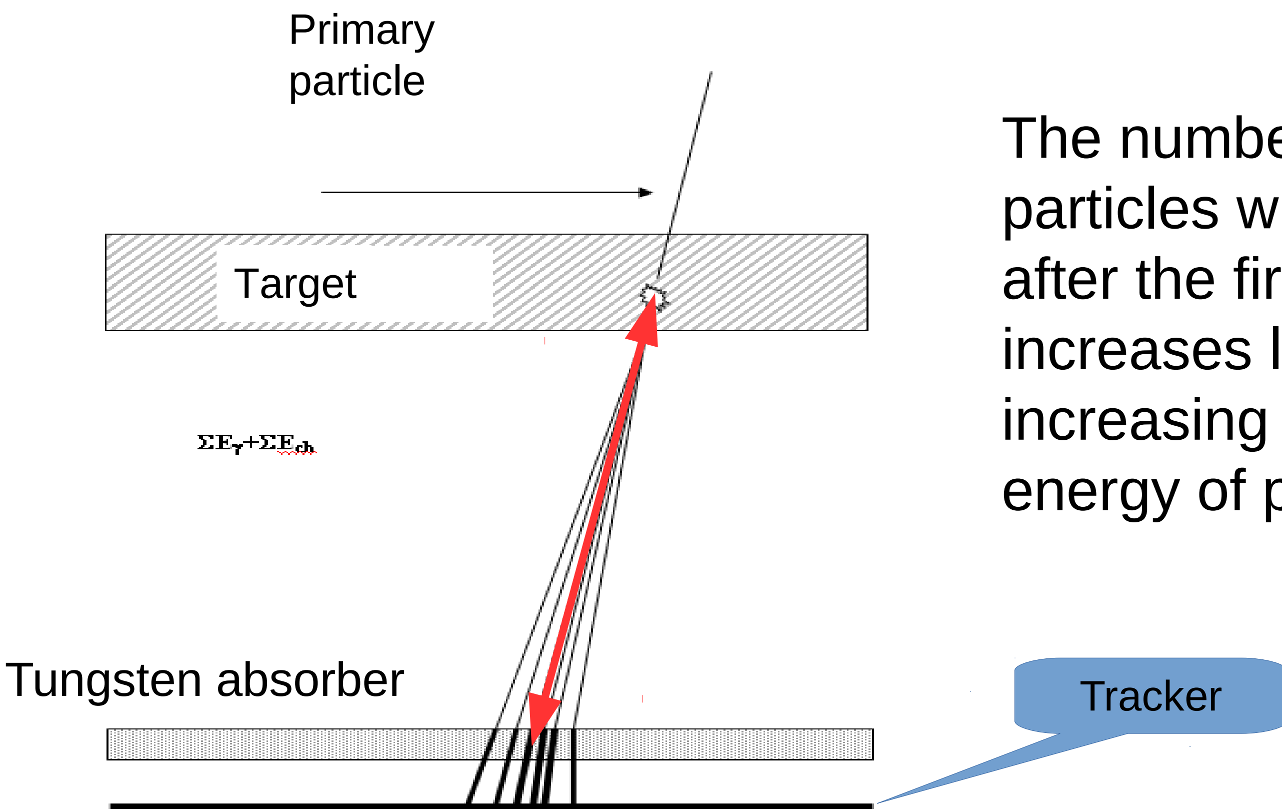
   (Kinematic Lightweight Energy Meter)

   -for the first time (main)

2. The calorimetric method

   -usual and well studied

The kinematic method KLEM + calorimeter

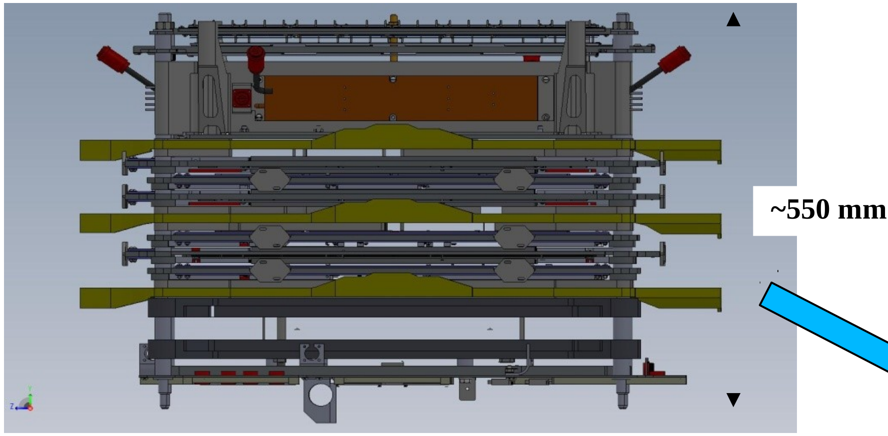


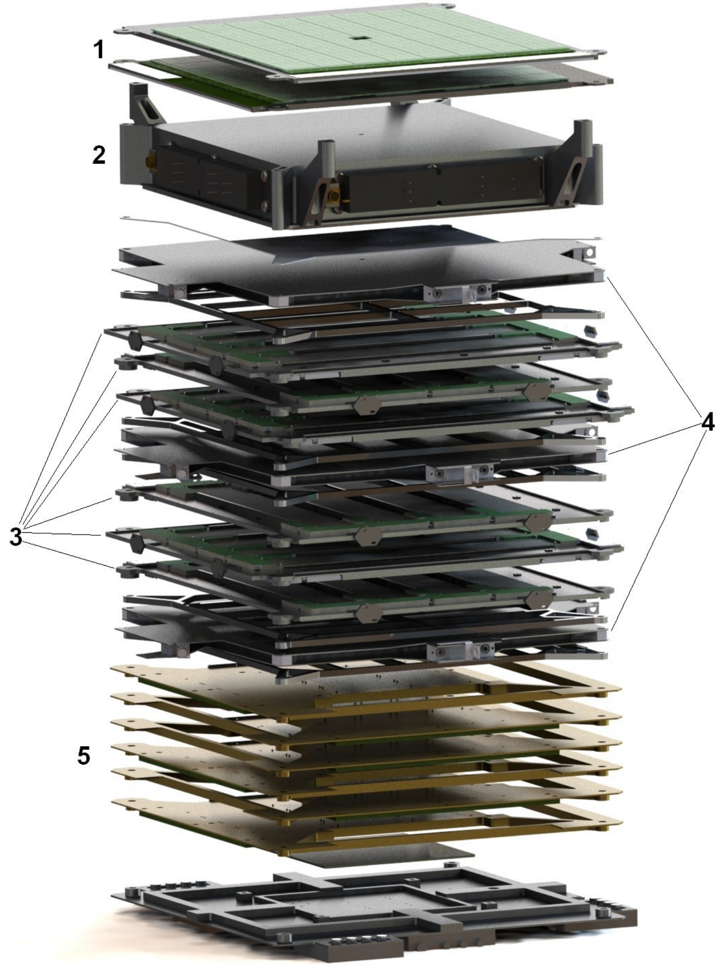
The number of secondary particles with high pseudorapidity after the first interaction increases logarithmically along increasing of the primary energy of particle

The energies are reconstructed by S-parameter -

$$S=\Sigma(I_i * \ln^2(2H/x_i))$$

The NUCLEON apparatus





(1) System of charge measurements – four planes of pad silicon detectors (1.5×1.5 cm^2);

(2) Carbon target of 0.25 proton interaction lengths;

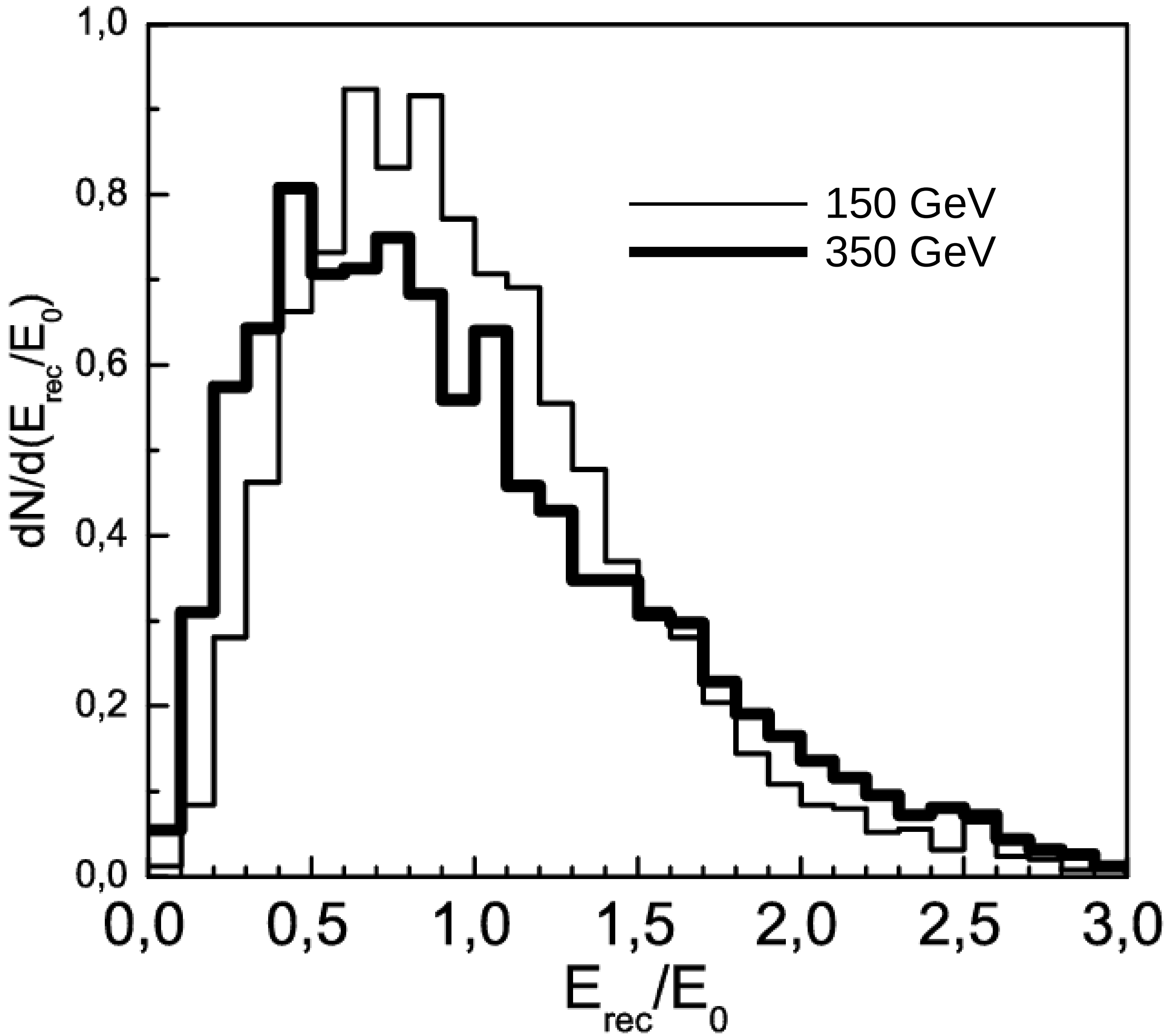
(3) KLEM tracker – six planes of microstrip silicon detectors (0.4mm step) with tungsten between them (~2mm each, ~3 X-lengths summary).
Active square 500*500 mm^2.
KLEM geometrical factor 0.24m^2sr.

(4) Trigger system – tree double sntillator planes;

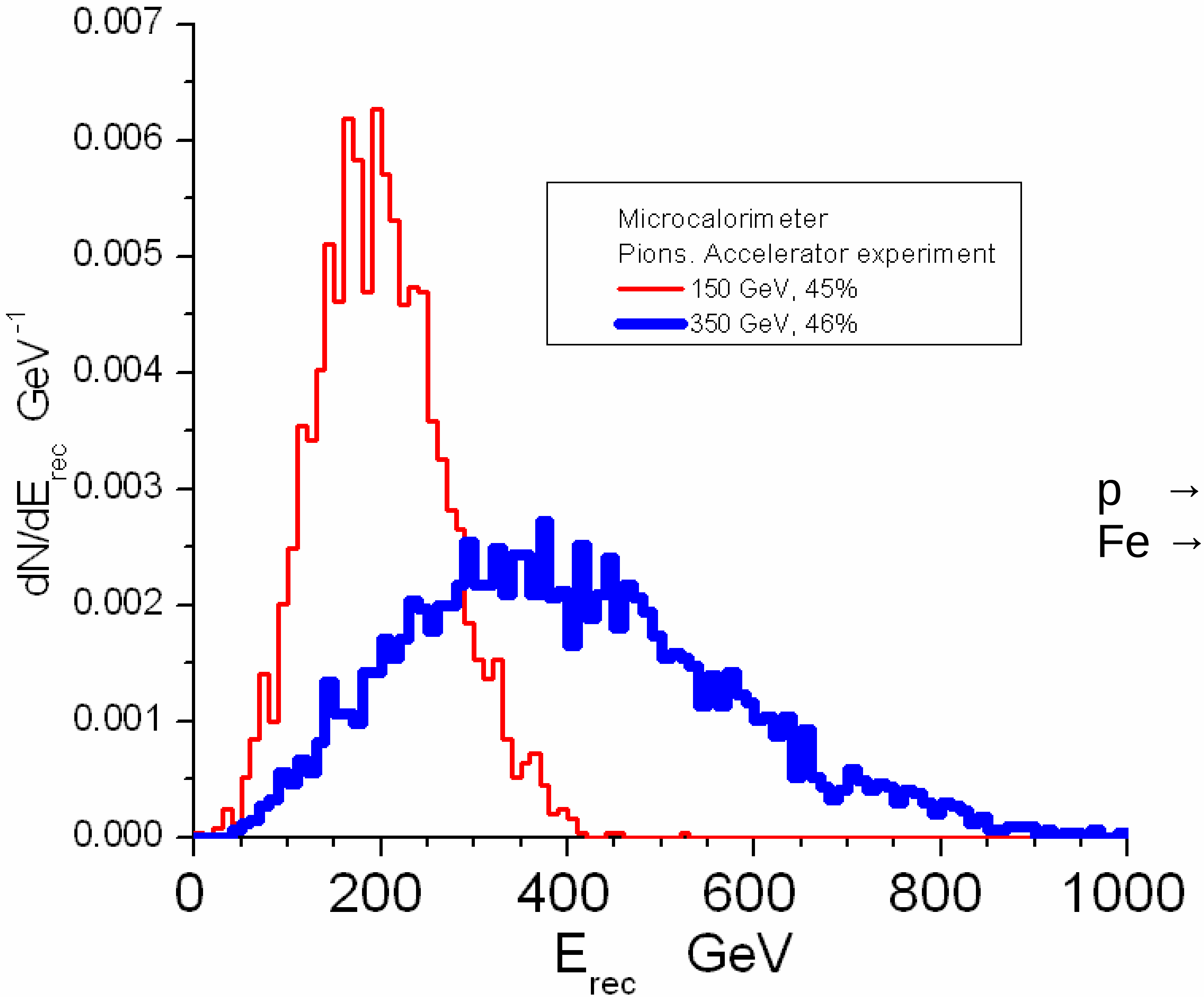
(5) Ionization calorimeter (IC) – six planes of tungsten absorber (~8mm each, ~12 X-lengths summary) with silicon strip detectors (1mm step).
Active square 250*250mm^2.
IC geometrical fact 0.06m^2sr

10604 independent electronic channels in total

KLEM, CERN test for π^-, resolution ~60%



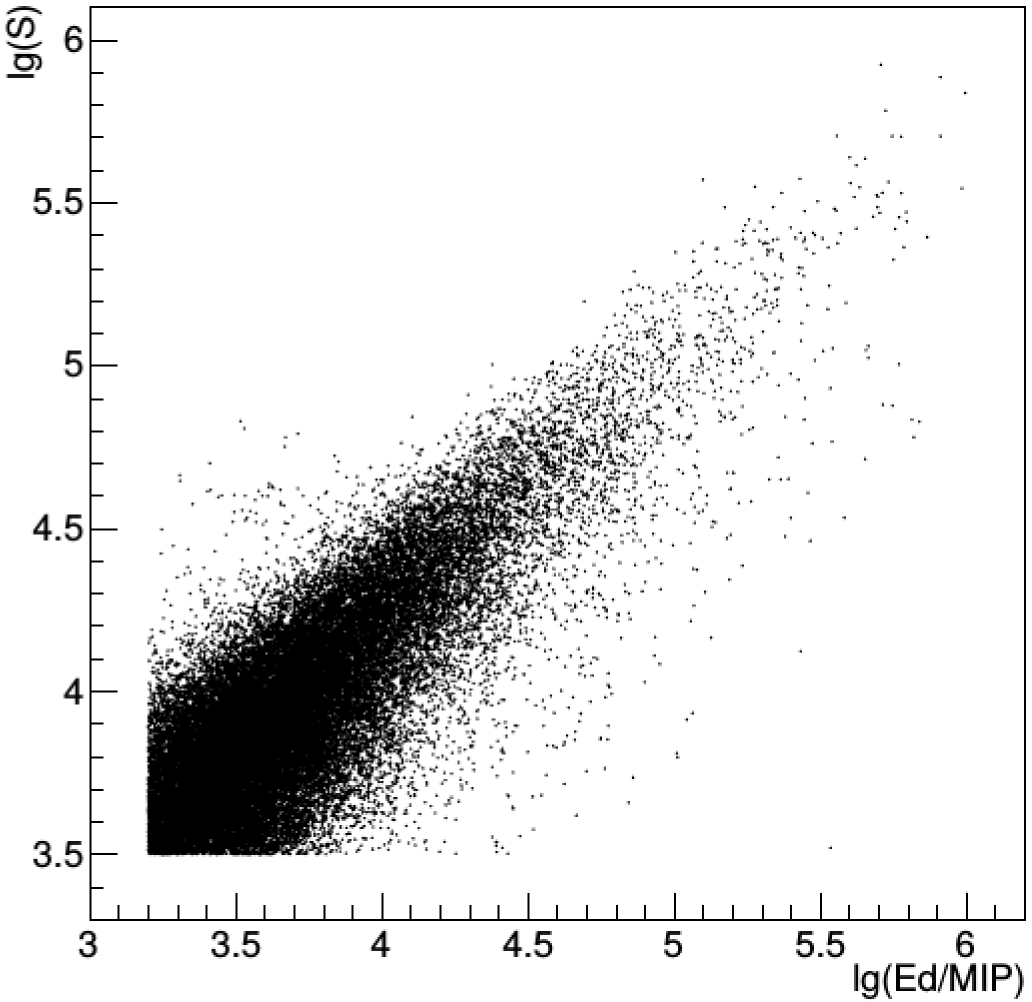
Calorimeter, CERN test for π^-, resolution ~45%



p → ~45%
Fe → ~35%

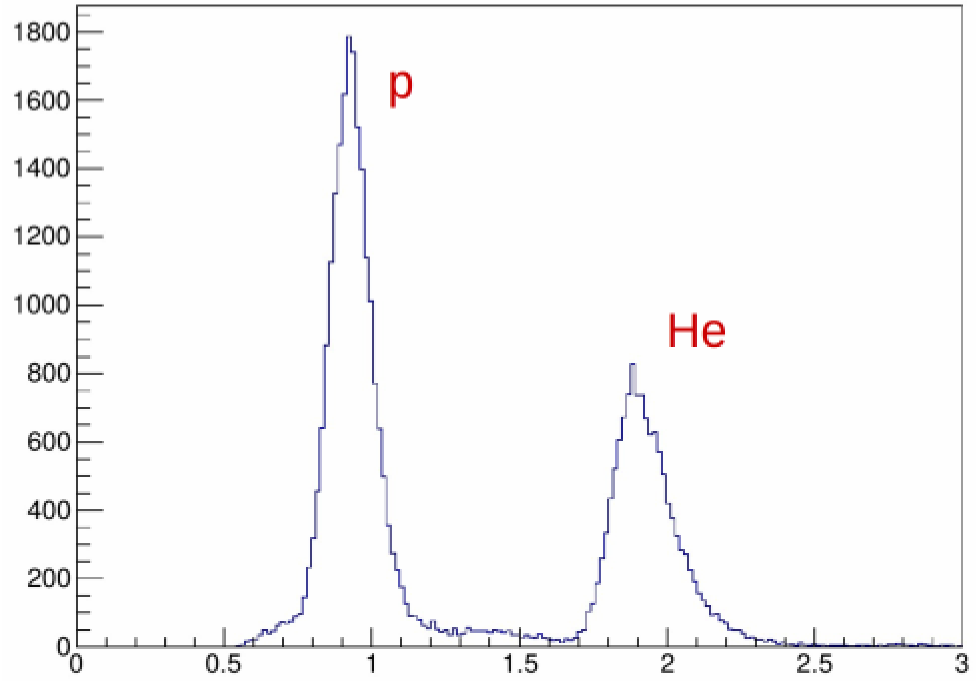
Model-independent evidence that the KLEM method may be used to measure energy of particles

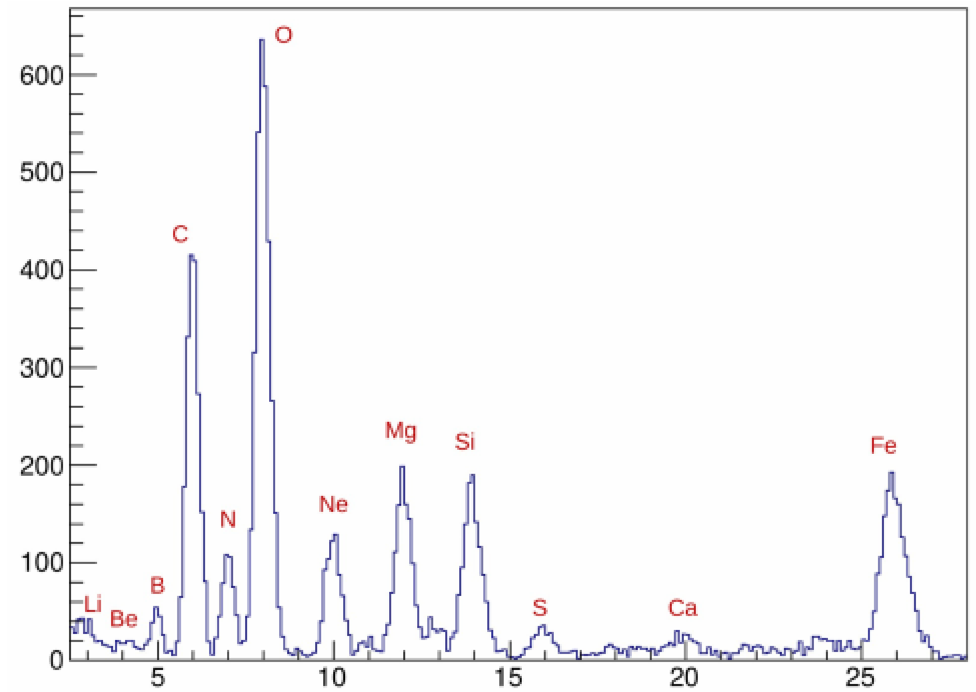
Correlation of the calorimeter energy deposit (Ed)
and KLEM
parameter (S)
~90%



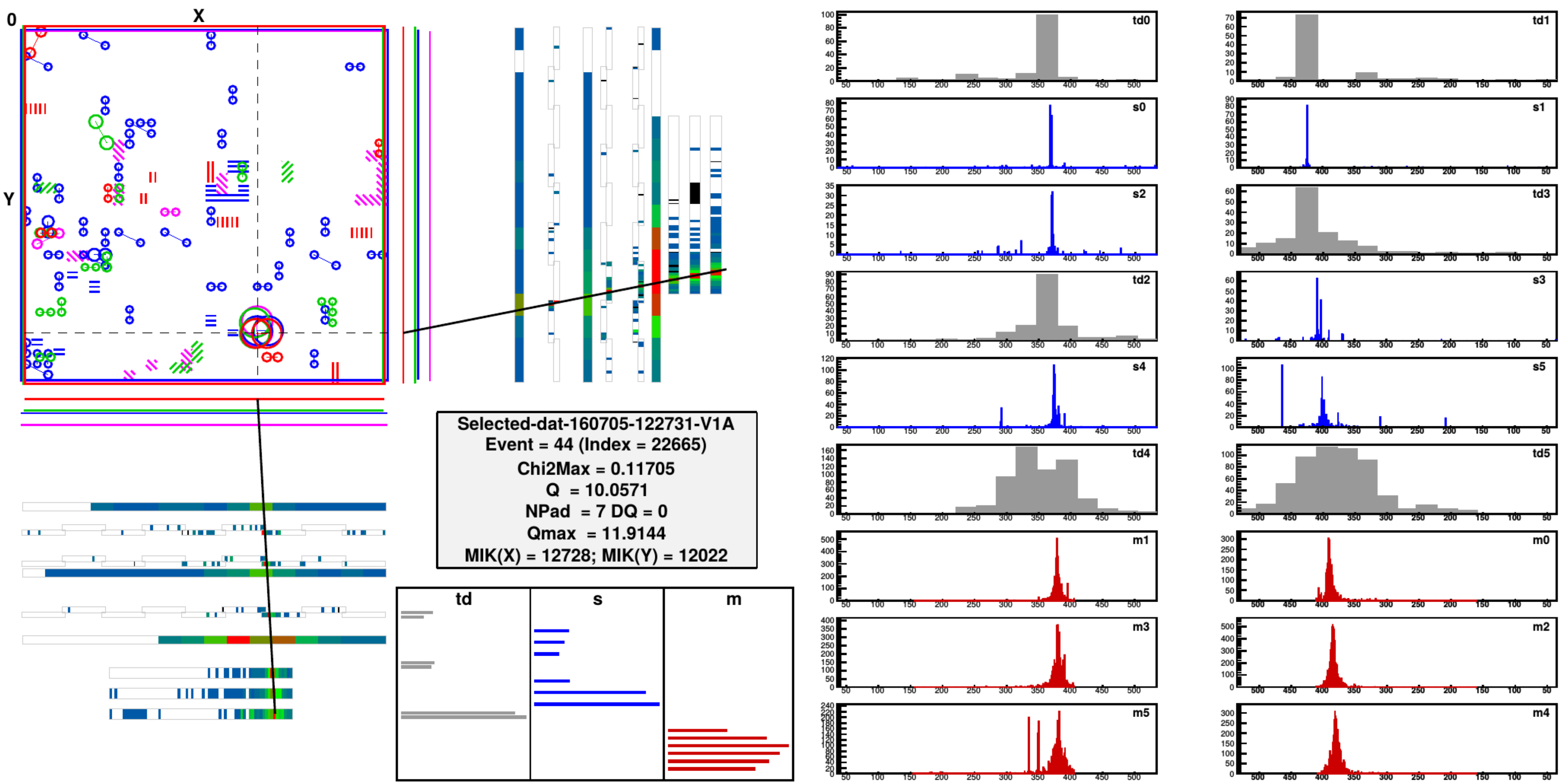
This correlation is a model-independent result

Charge resolution of four silicon planes detector ~0.2 charge units

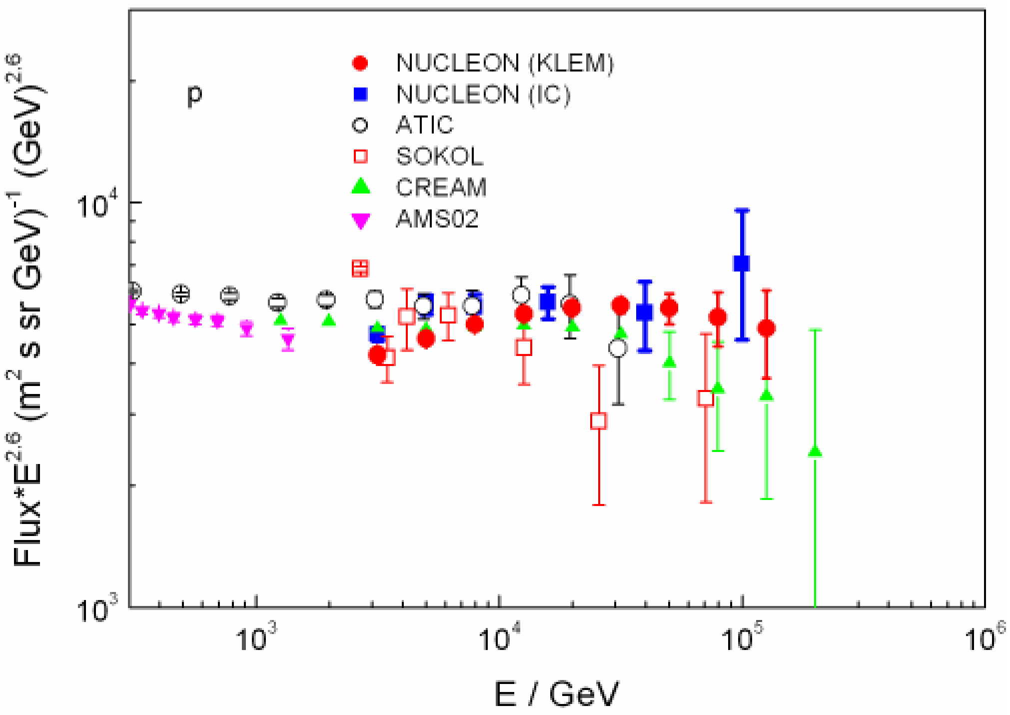


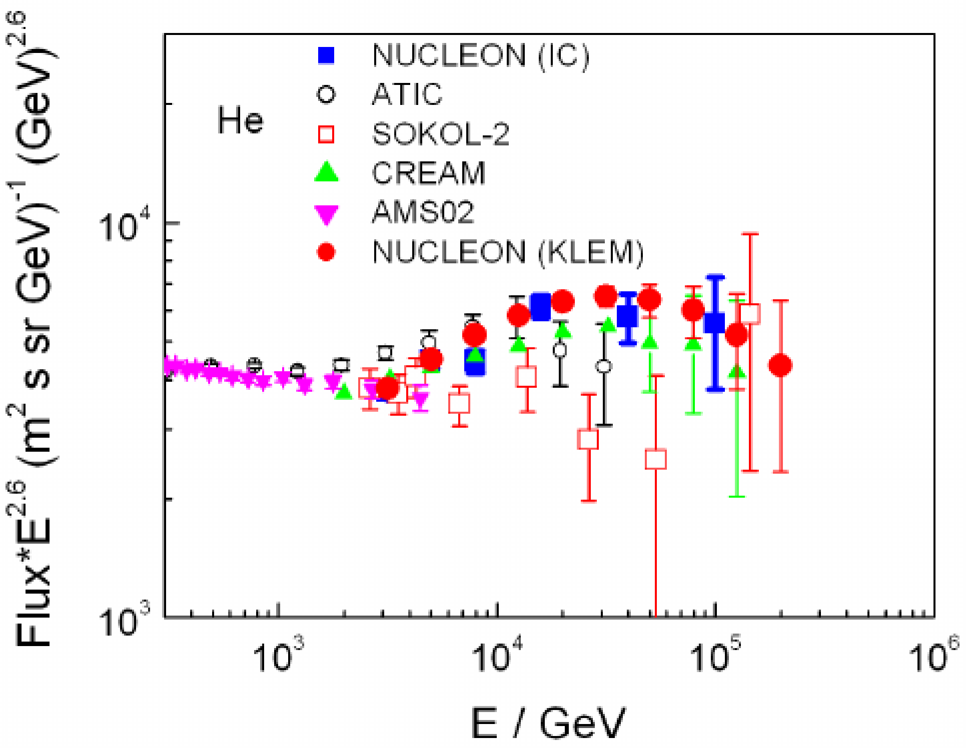


An example of an event «portrait»

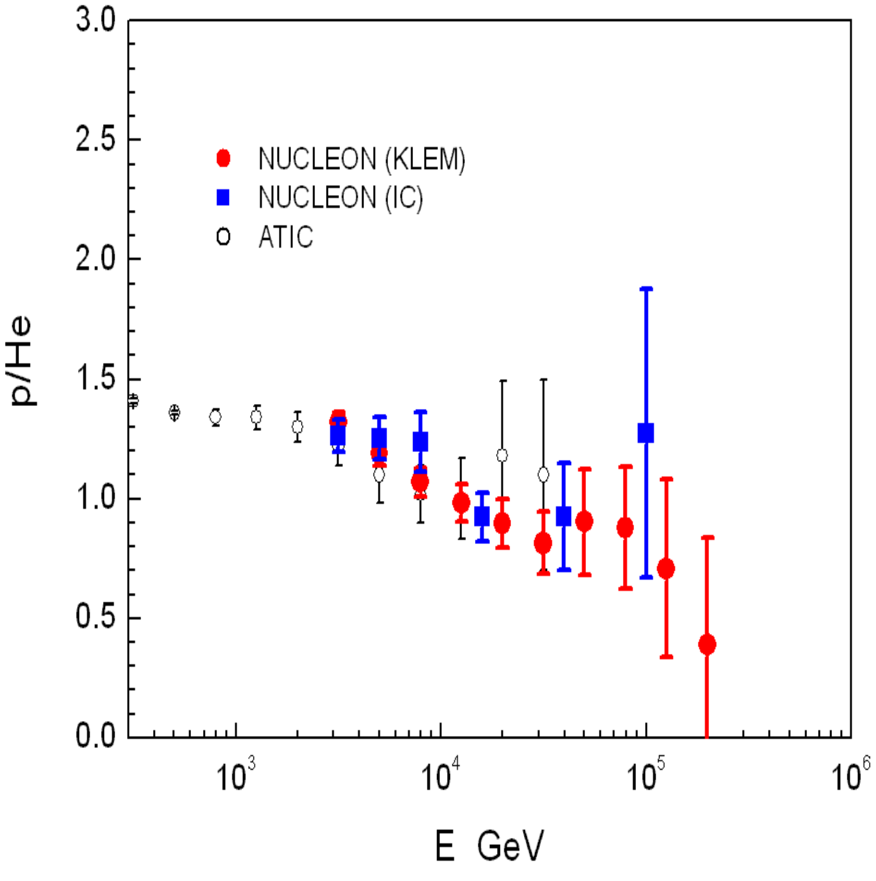


Protons and Helium

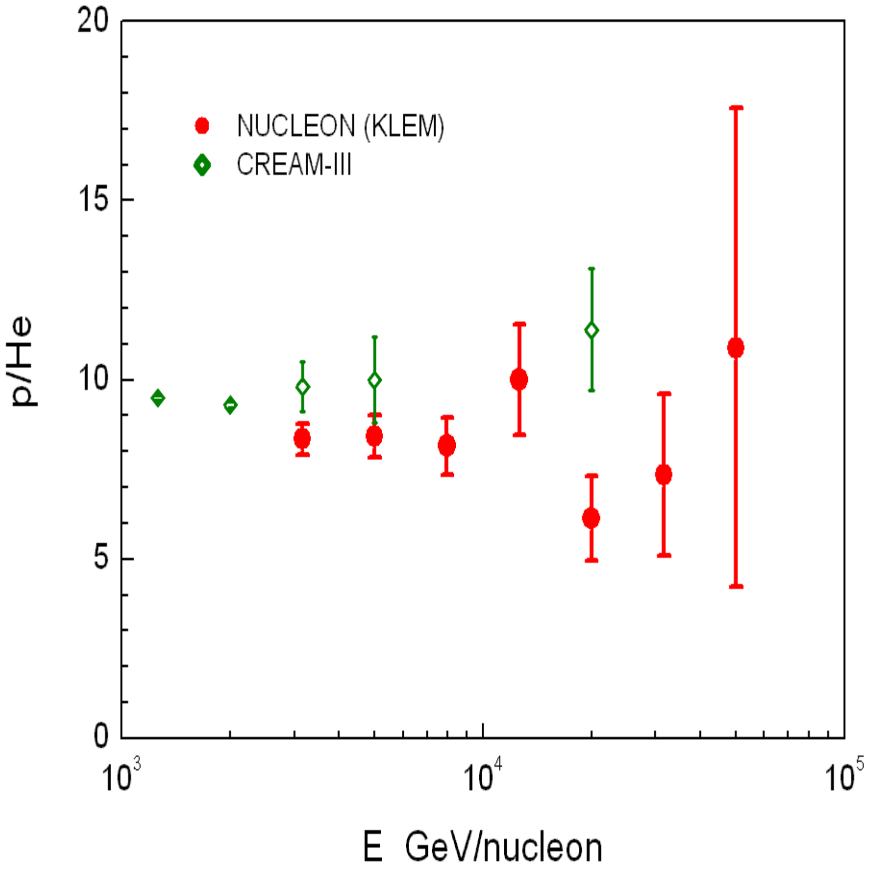




p/He ratio

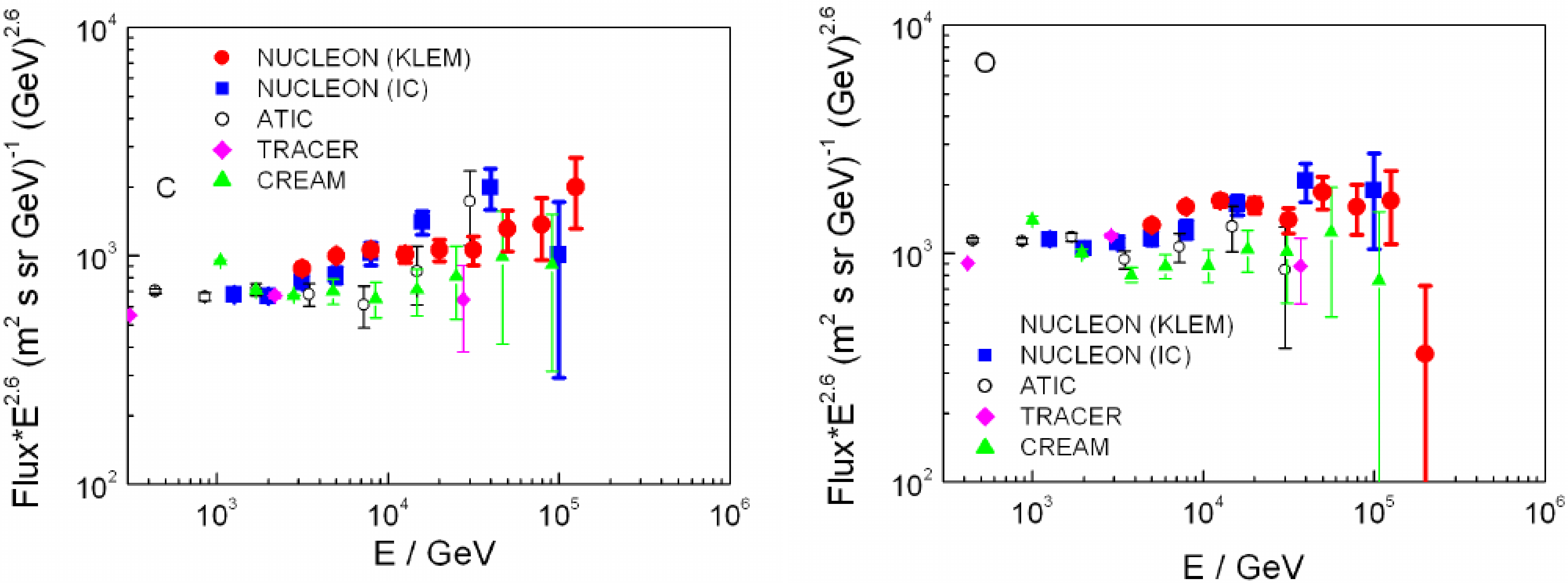


NUCLEON (KLEM)
NUCLEON (IC)
ATIC
p/He
E GeV

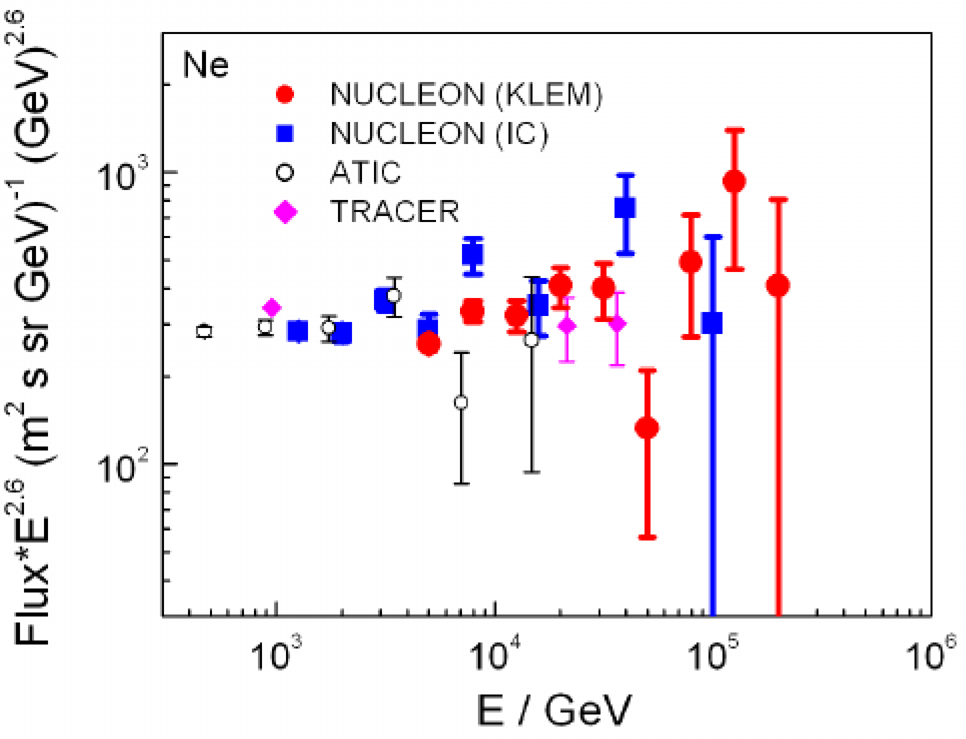


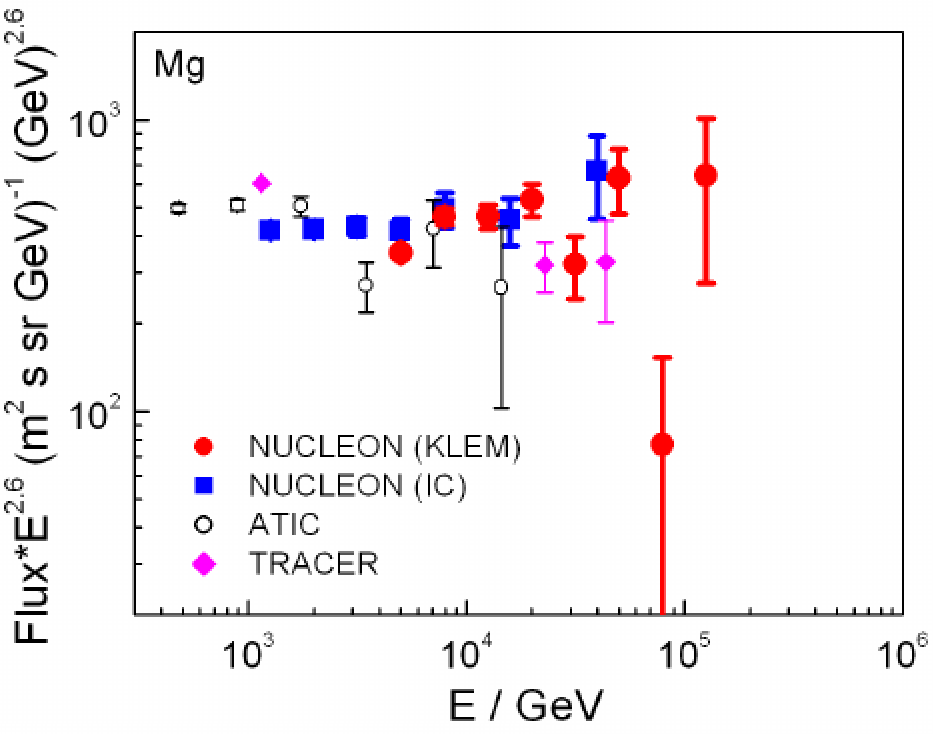
NUCLEON (KLEM)
CREAM-III
p/He
E GeV/nucleon

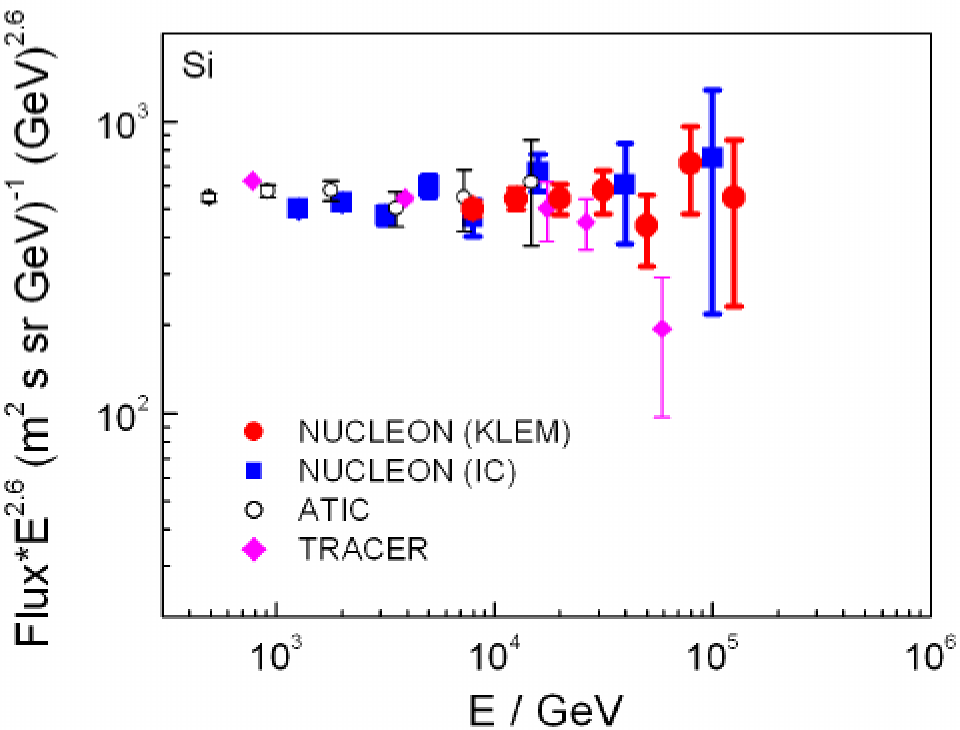
Carbon and Oxygen: hard (γ≈2.4) above ~3 TeV



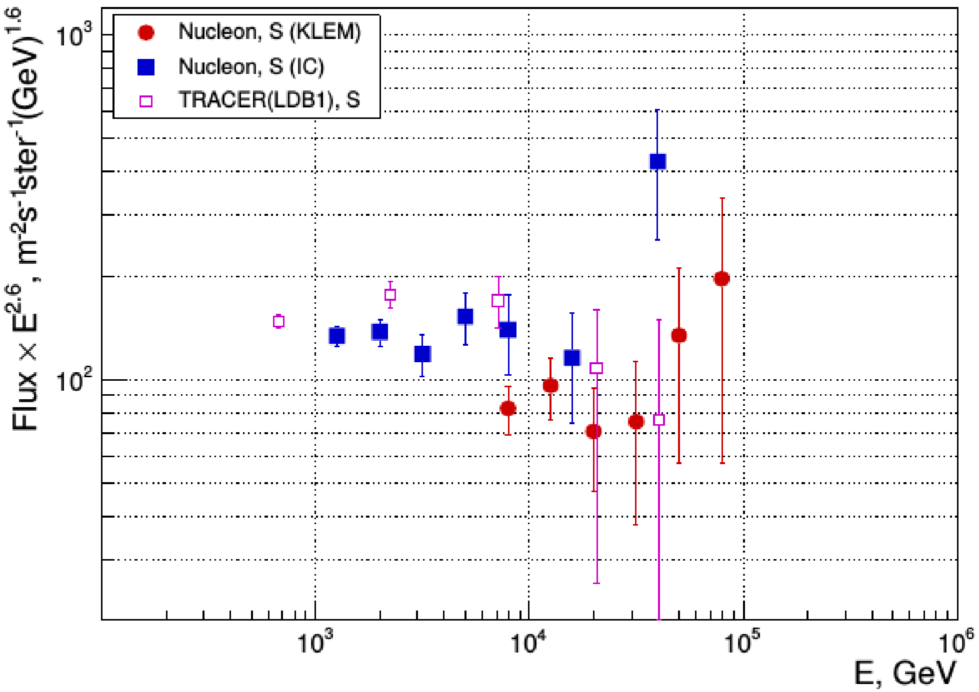
Ne-Mg-Si

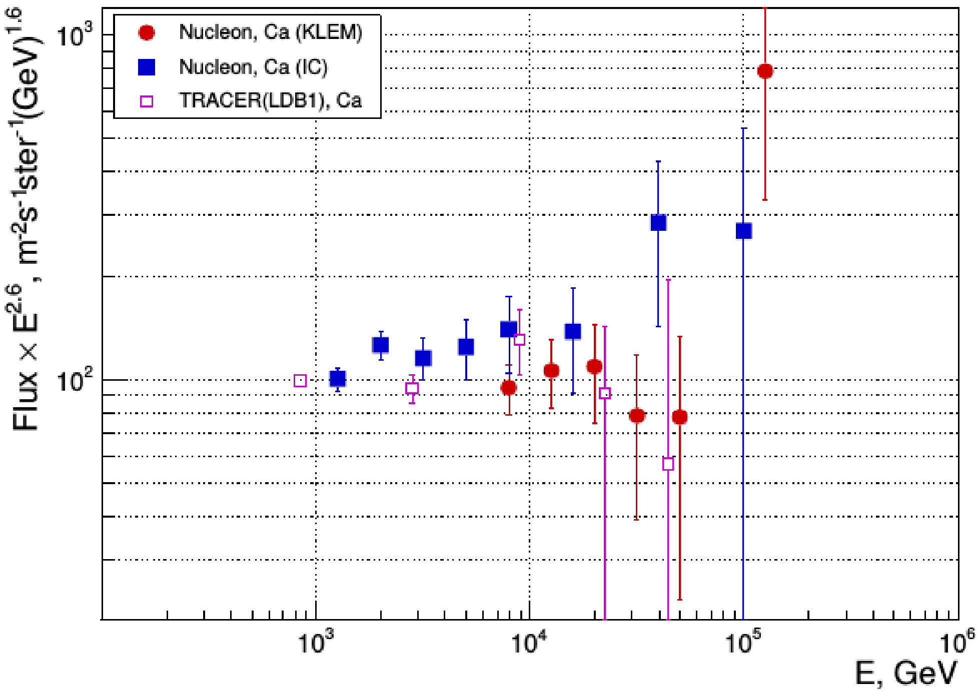

Ne
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
TRACER
Flux*E$^{2.6}$ (m^2 s sr GeV)$^{-1}$ (GeV)$^{2.6}$
E / GeV


Mg
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
TRACER
Flux*E$^{2.6}$ (m^2 s sr GeV)$^{-1}$ (GeV)$^{2.6}$
E / GeV

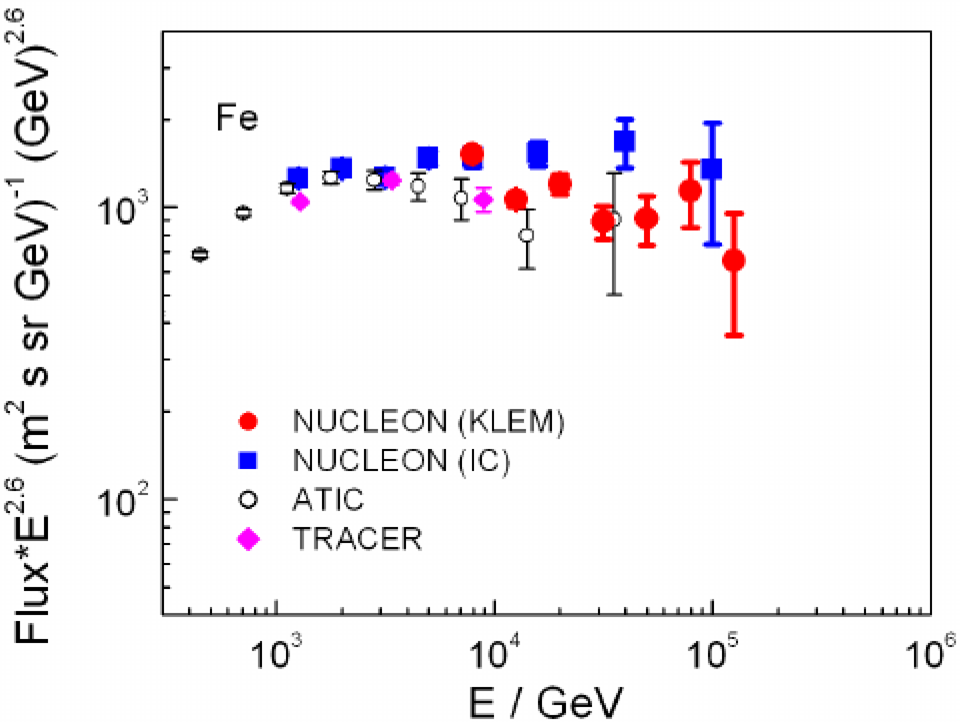

Si
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
TRACER
Flux*E$^{2.6}$ (m^2 s sr GeV)$^{-1}$ (GeV)$^{2.6}$
E / GeV

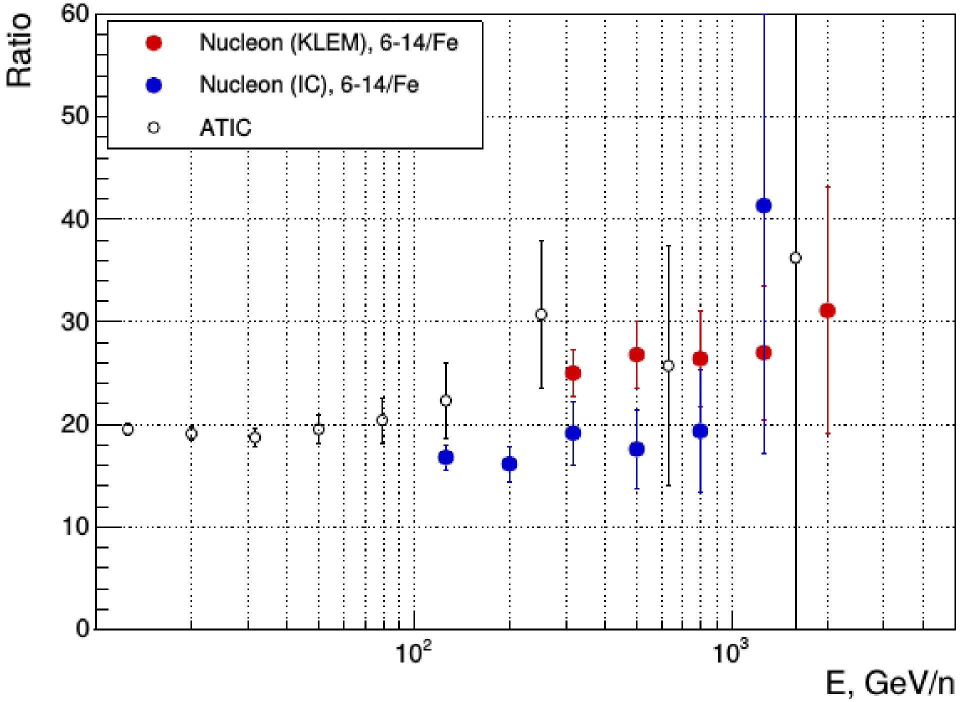
S and Ca - hints of complicated behavior, more statistics are needed



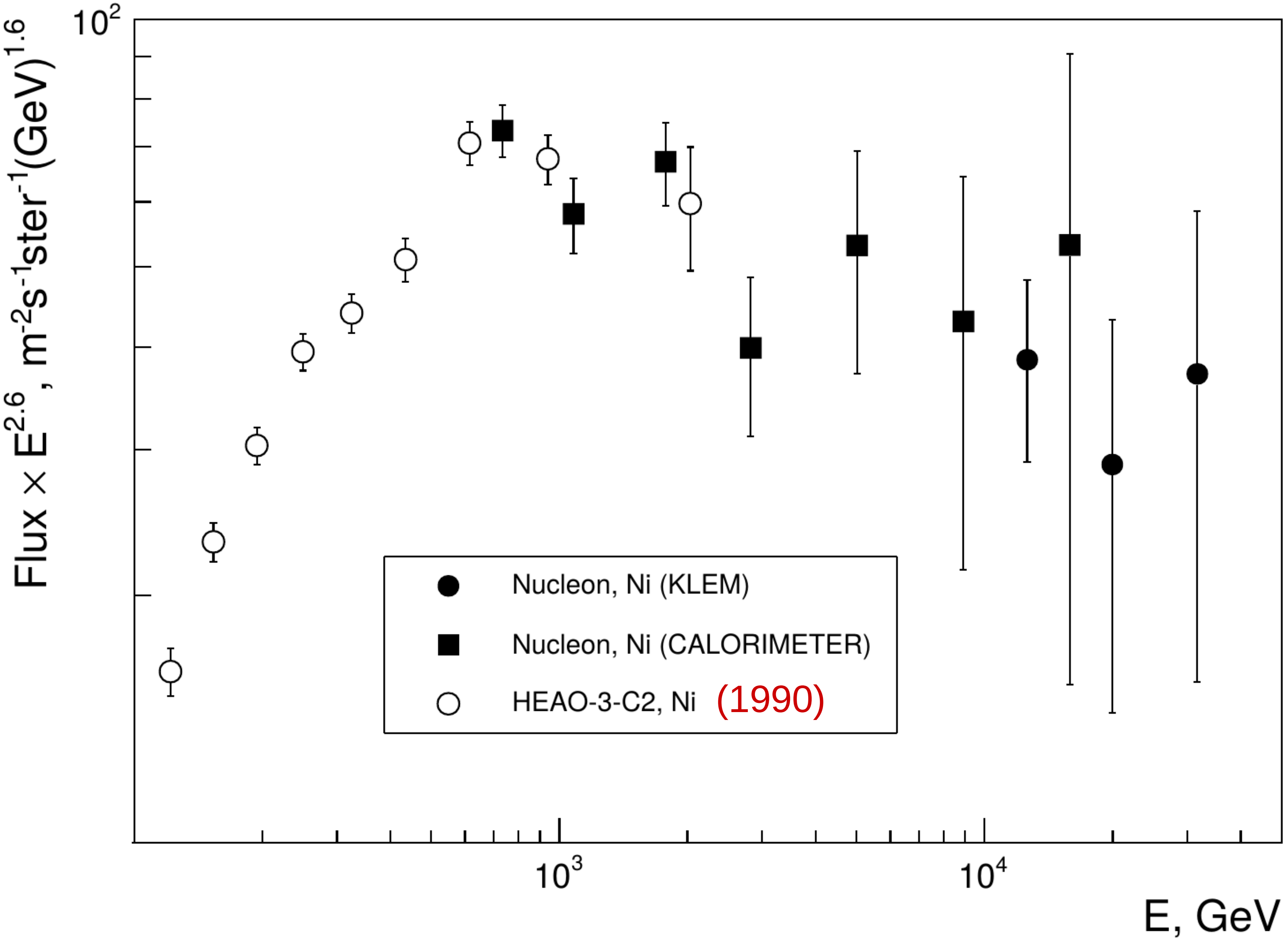


Iron spectrum ($\gamma \approx 2.6$) -
softer, than the spectra of other heavy nuclei?
(Z = 6-14)



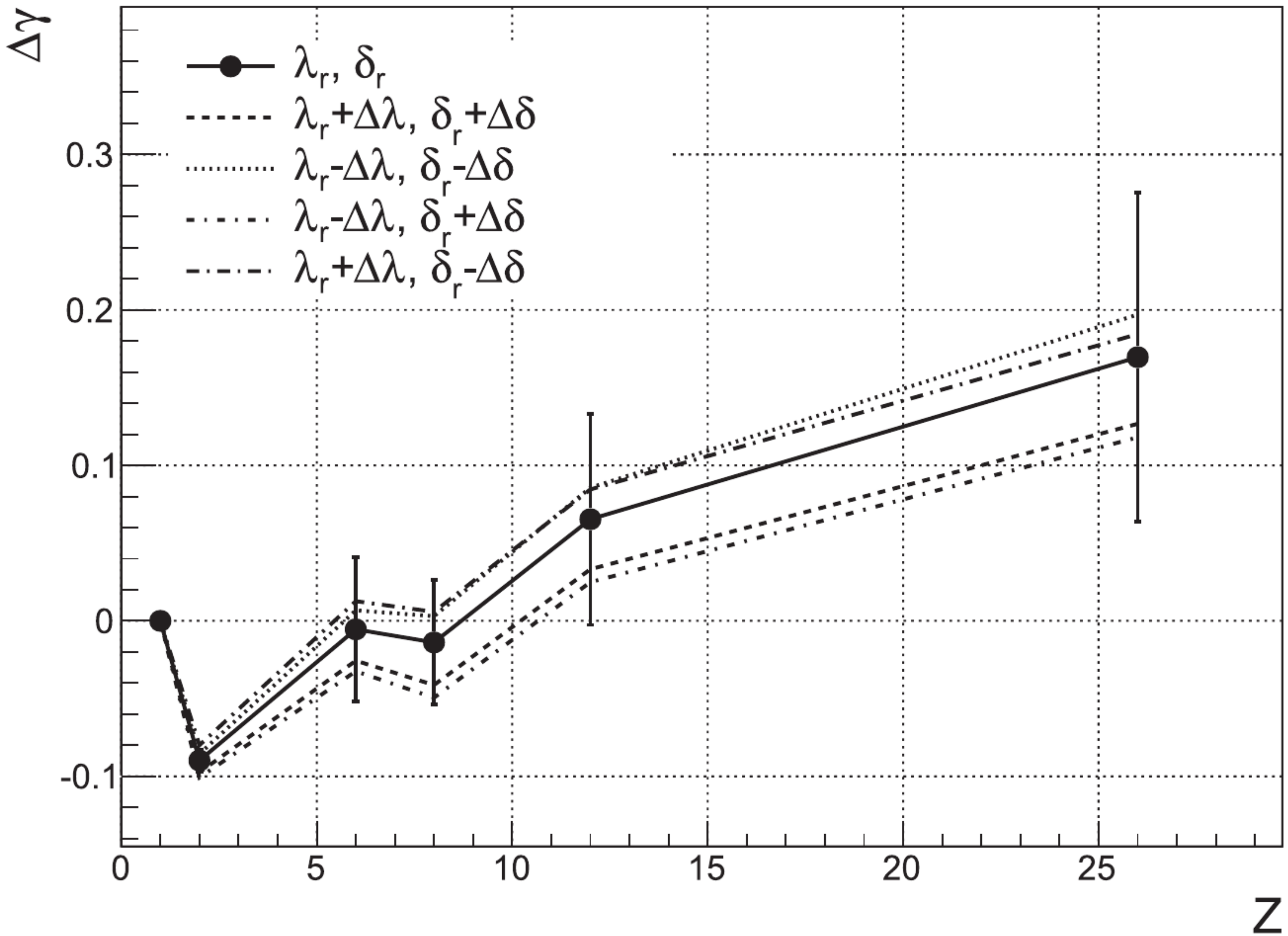


Nickel (Z=28) spectrum. $\gamma = 2.83 \pm 0.09$

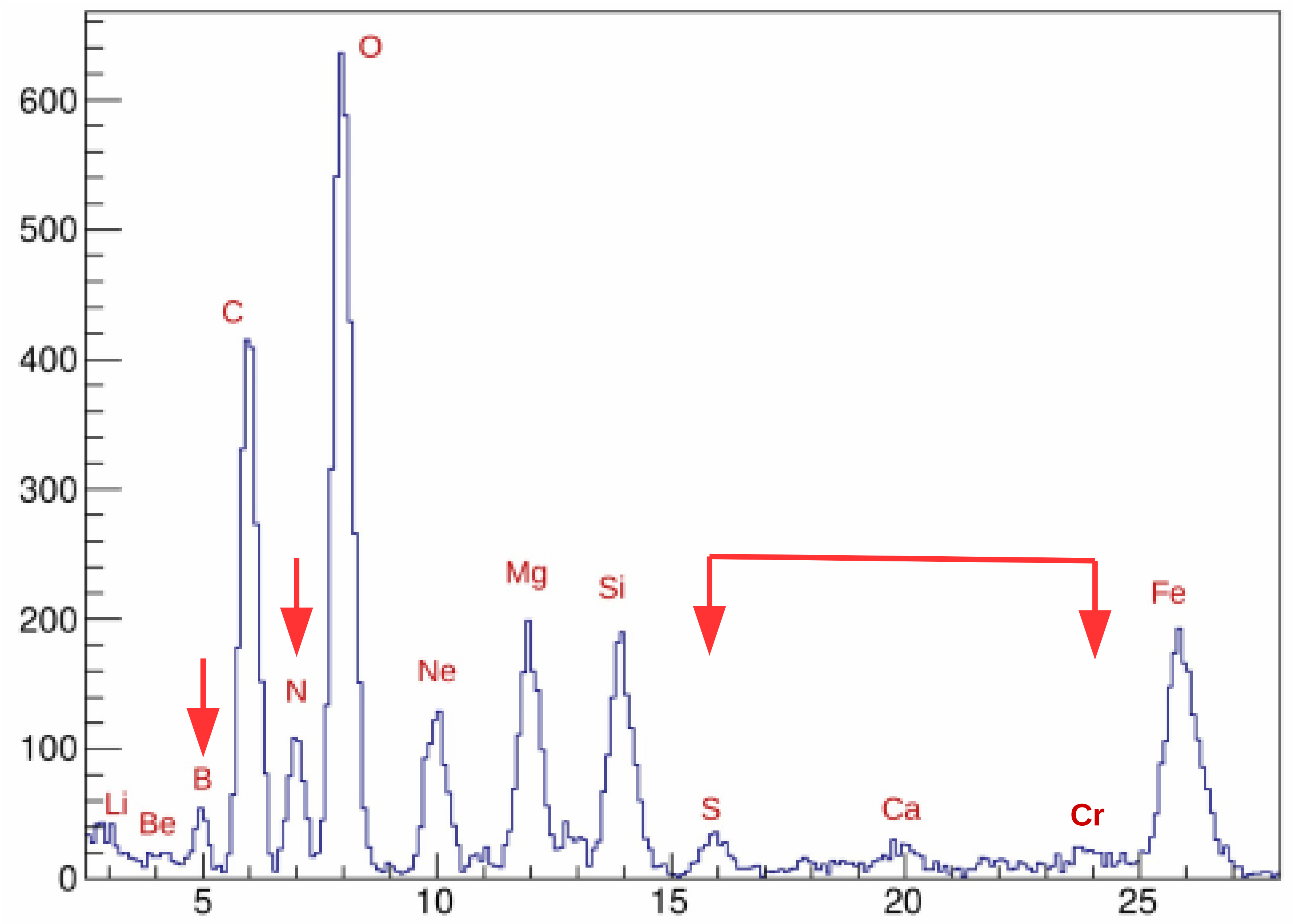


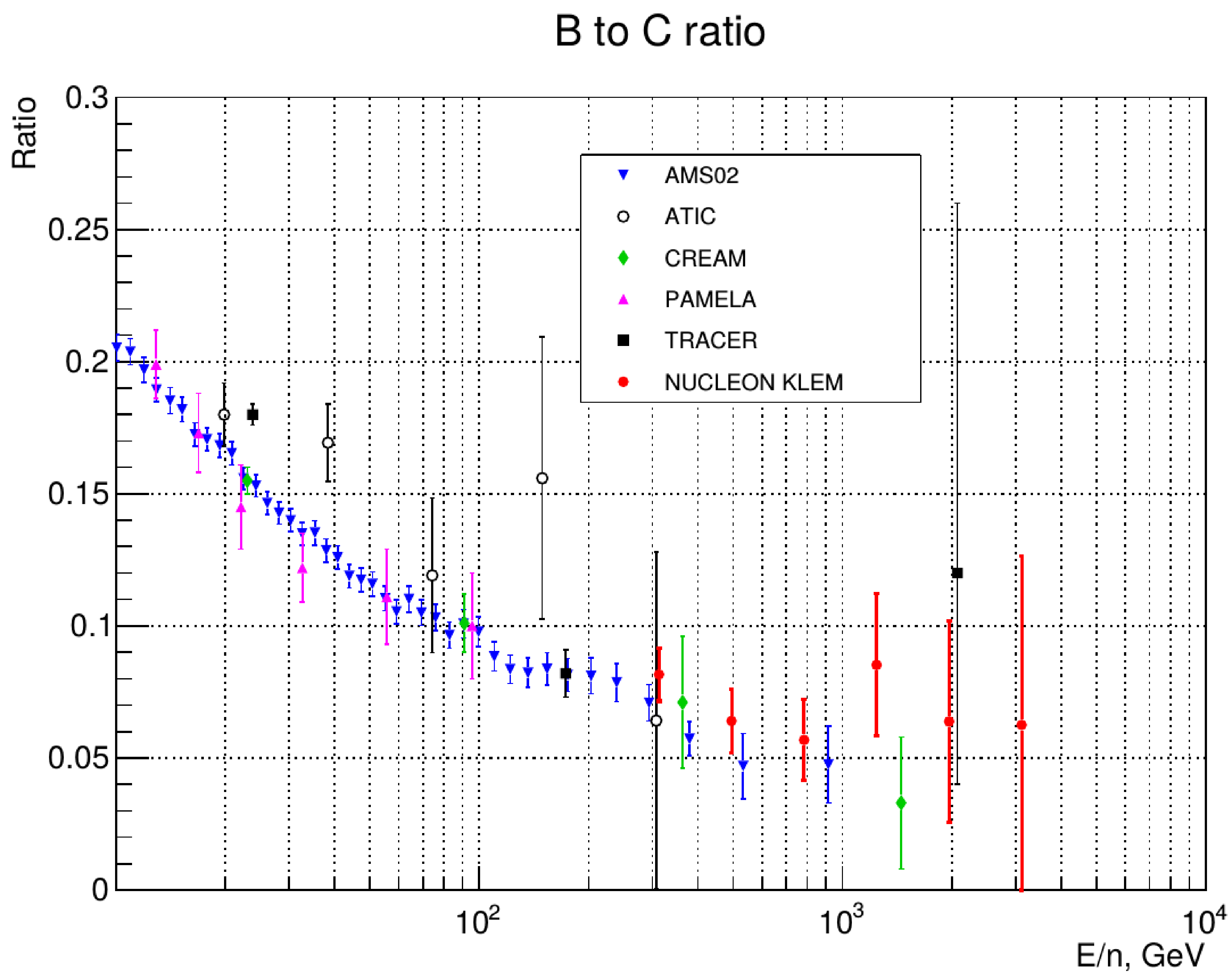
ATIC: the spectra of nuclei in source are softer for higher charges

The Astrophysical Journal, V.837, 77 (2017)

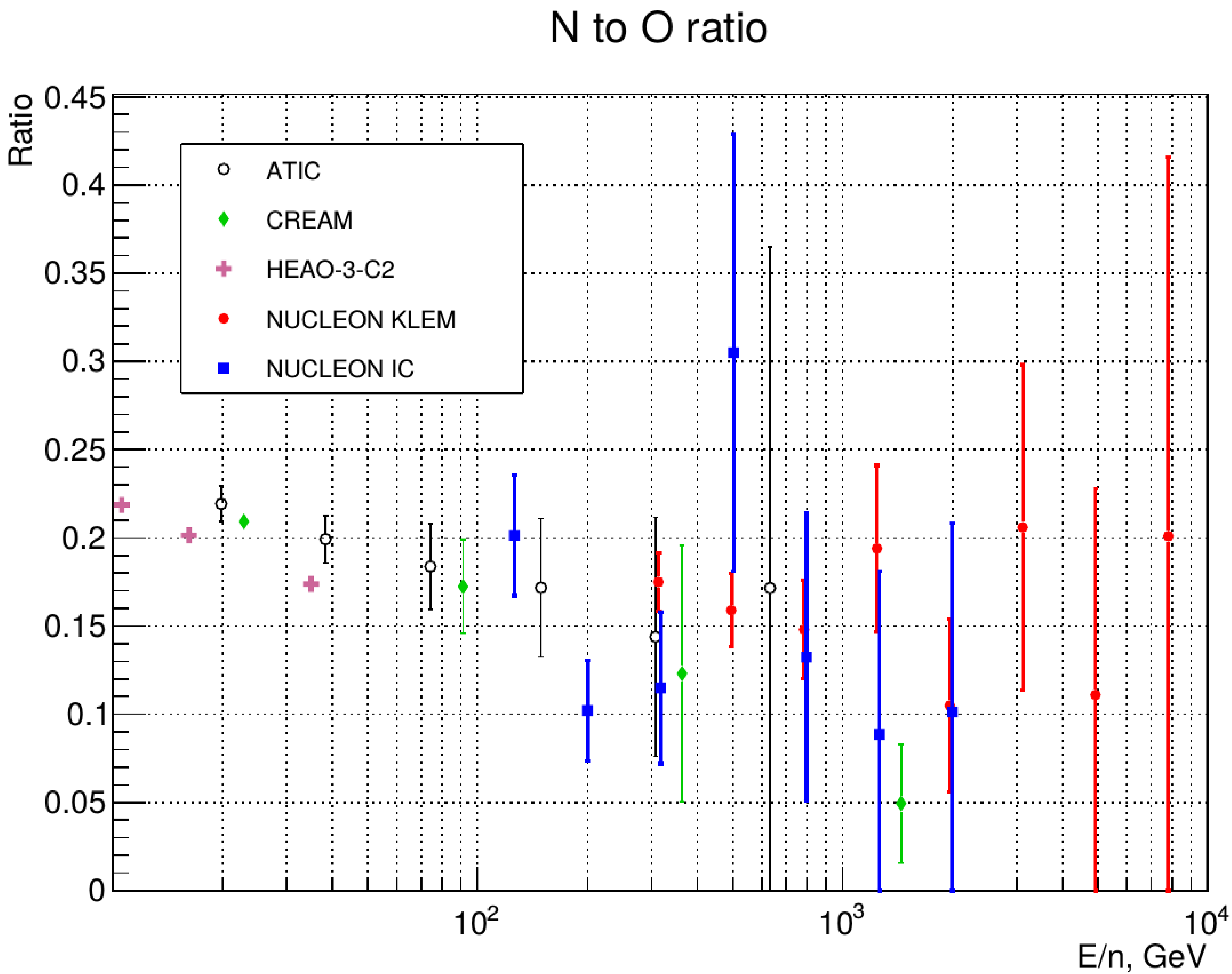


Spectra of secondary nuclei

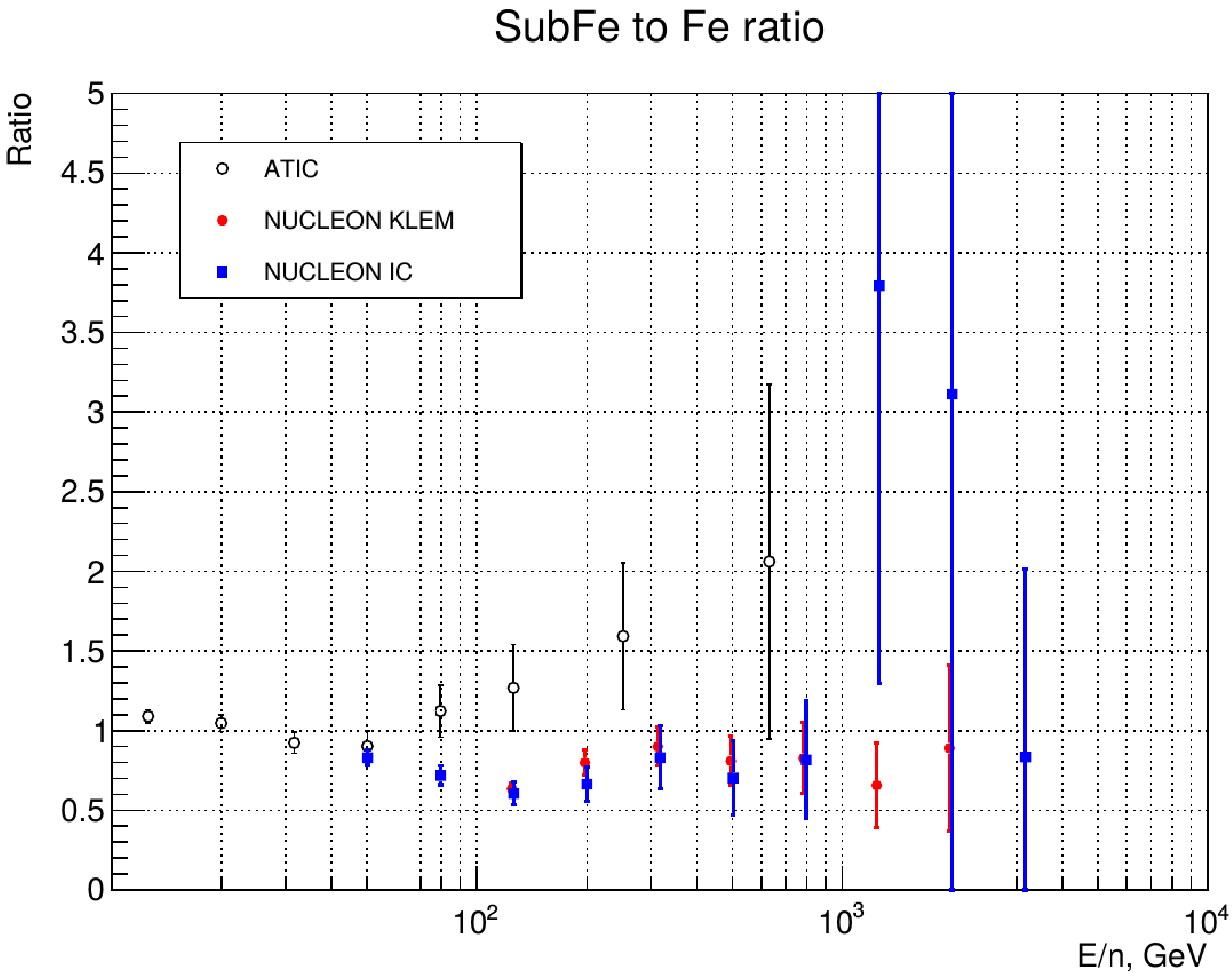




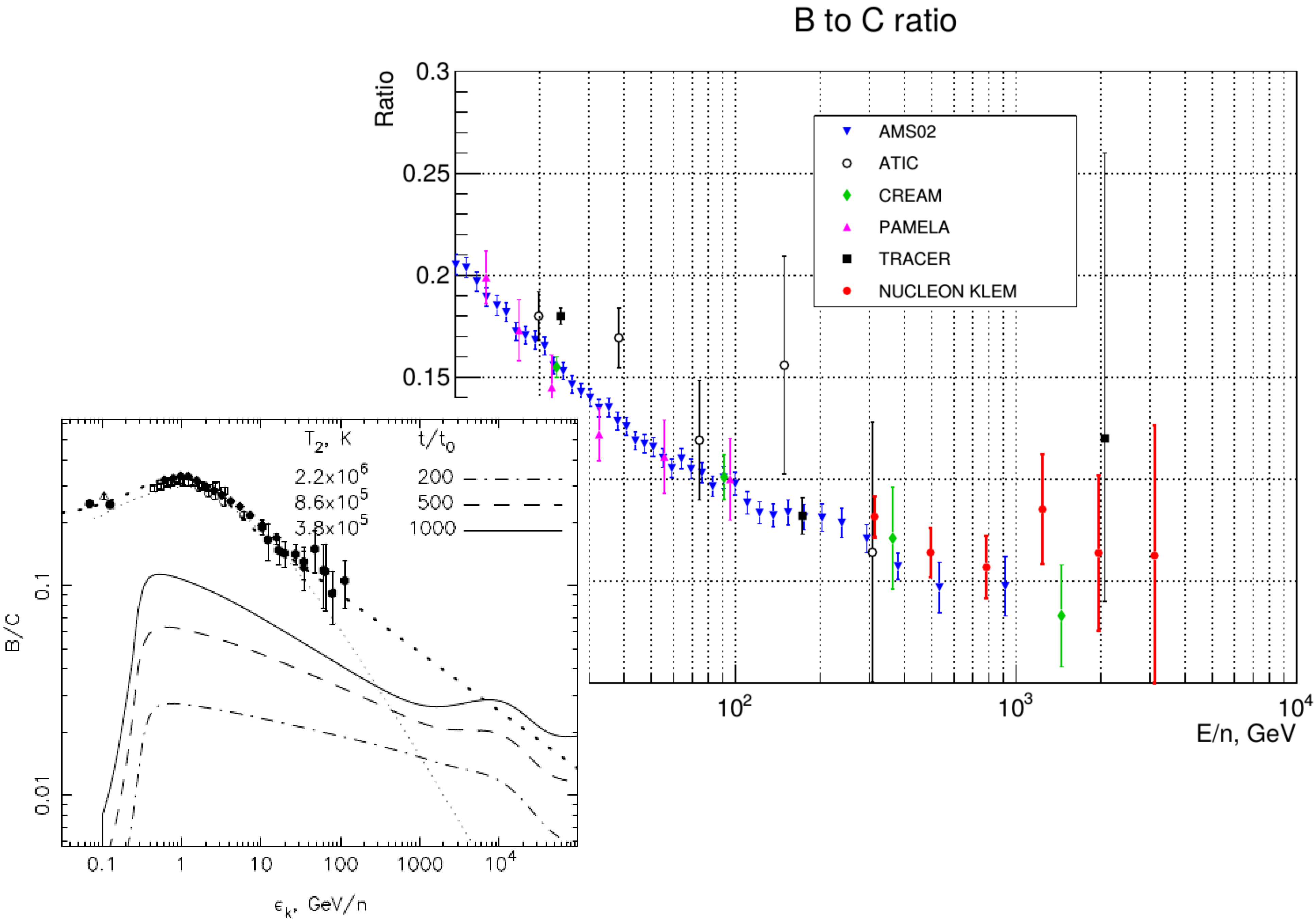
B to C ratio
Ratio
0.3
0.25
0.2
0.15
0.1
0.05
0
10^2
10^3
10^4
E/n, GeV
AMS02
ATIC
CREAM
PAMELA
TRACER
NUCLEON KLEM



N to O ratio
Ratio
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
ATIC
CREAM
HEAO-3-C2
NUCLEON KLEM
NUCLEON IC
10^2
10^3
10^4
E/n, GeV



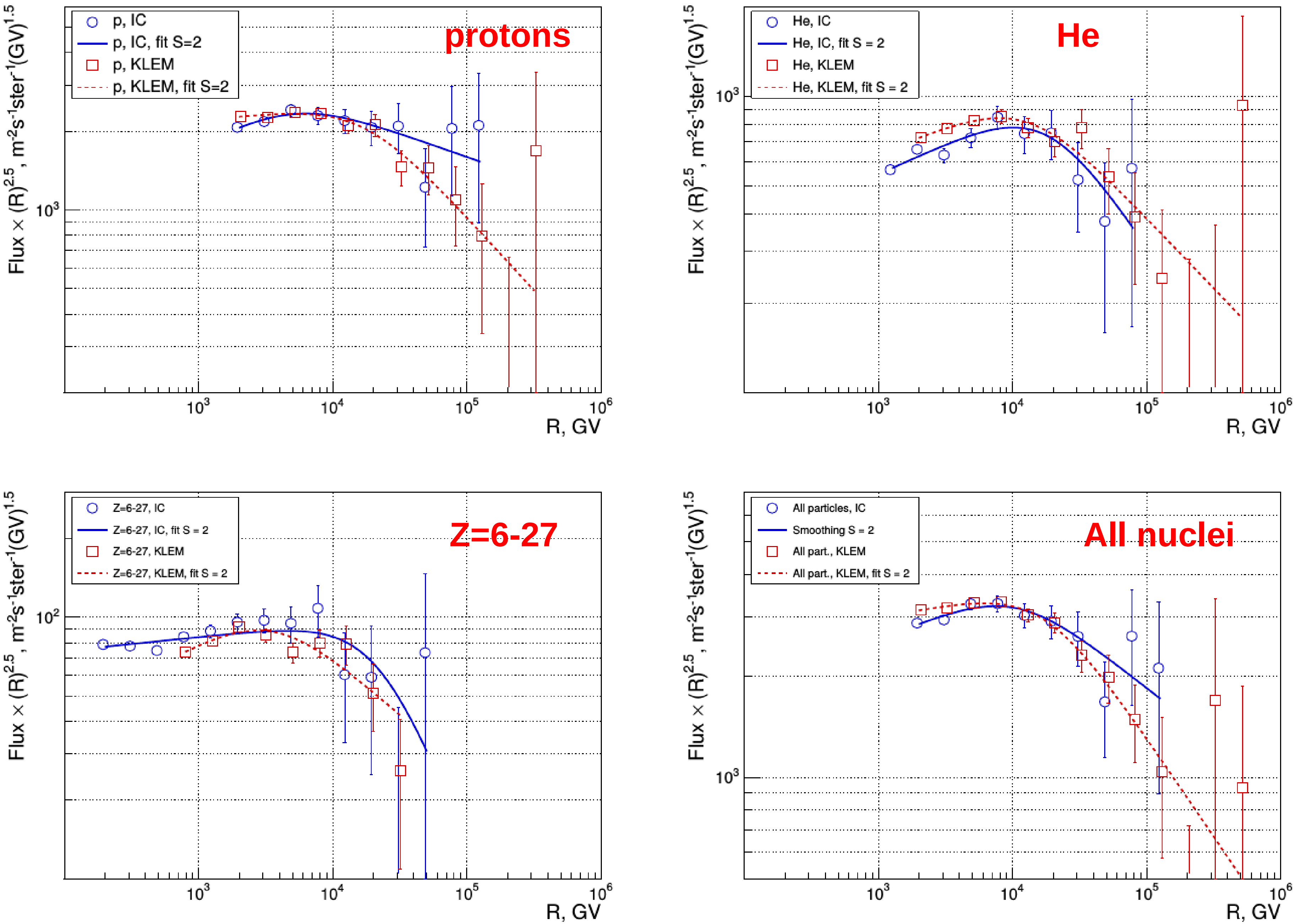
SubFe to Fe ratio
Ratio
ATIC
NUCLEON KLEM
NUCLEON IC
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
10^2
10^3
10^4
E/n, GeV



E. G. Berezhko, L. T. Ksenofontov, V. S. Ptuskin, V. N. Zirakashvili, H. J. Voelk. Astron.Astrophys. 410 (2003) 189-198 (arXiv:astro-ph/0308199v1).

A new universal cosmic-ray knee near the magnetic rigidity 10 TV

JETP Lett. V.108, No 1, P. 5 (2018) [arXiv:1805:07119]



Statistical significance of the 10 TV - knee: Monte Carlo method 10000 MC tests

S = 2 - smooth link
S = ∞ - point- like link.

nucl. group	$S=2$ percents(σ)	$S=\infty$ percents(σ)	single γ percents(σ)
1	2	3	4
IC			
p	99.31(2.70)	98.49(2.43)	53.17(0.73)
He	99.85(3.25)	99.45(2.78)	90.13(1.65)
$6 \div 27$	95.94(2.05)	97.93(2.31)	90.00(1.64)
All	99.97(3.62)	99.89(3.26)	91.07(1.70)
KLEM			
p	>99.99(3.9)	>99.99(3.9)	98.67(2.47)
He	>99.99(3.9)	>99.99(3.9)	99.59(2.93)
$6 \div 27$	>99.99(3.9)	>99.99(3.9)	>99.99(3.9)
All	>99.99(3.9)	>99.99(3.9)	>99.99(3.9)

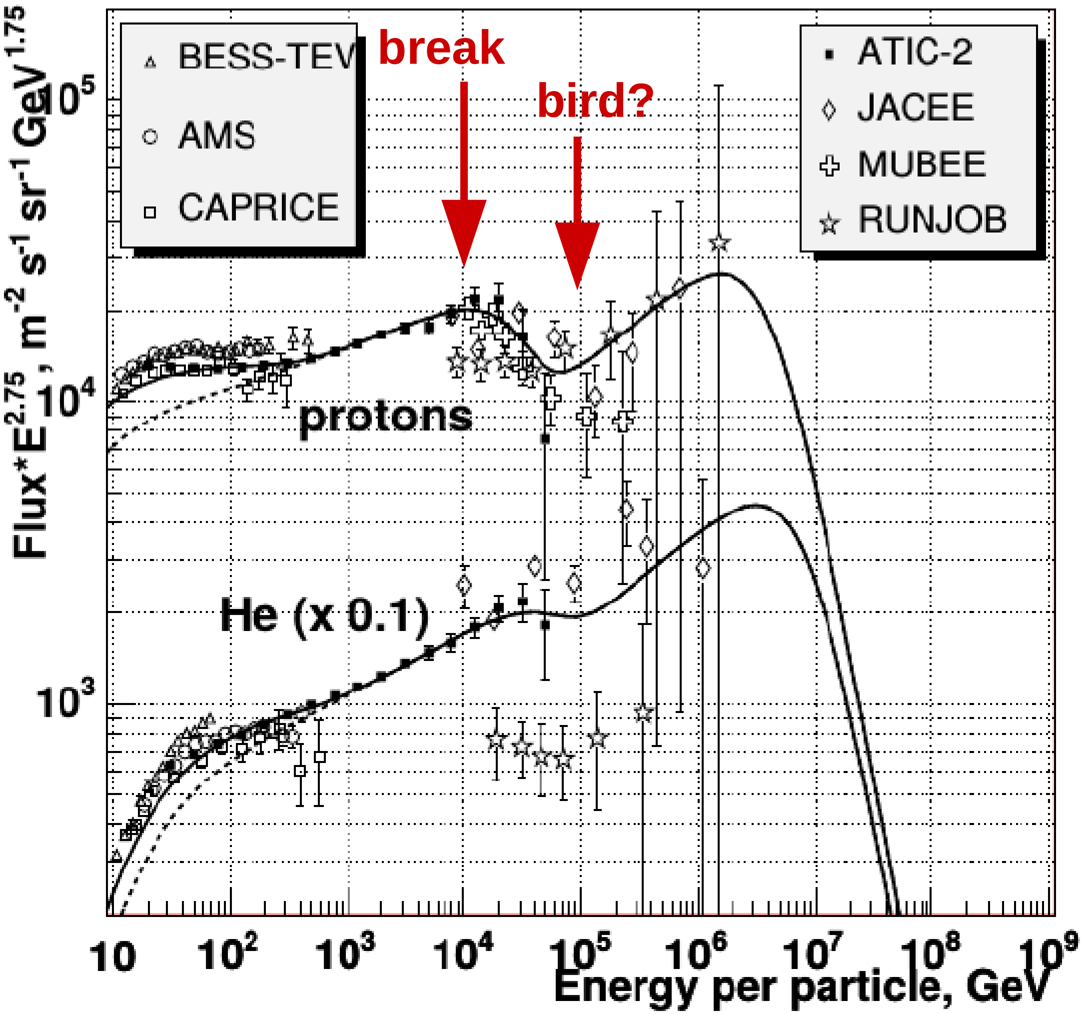
The simplest possible explanation of 10TV-knee:

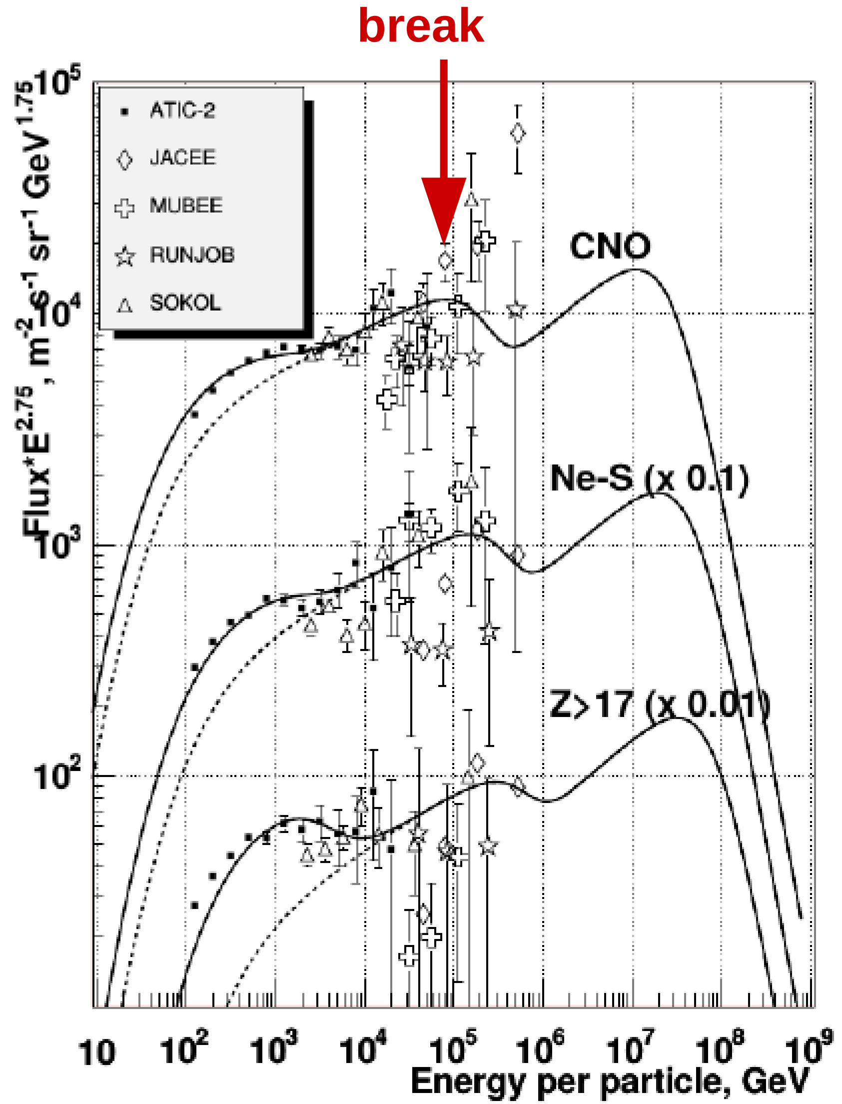
10TV is a limit of acceleration of some kind of CR source - a nearby one or generic.

Question:

How so soft spectra may be linked with the usual knee (3 PeV) region?

Zatsepin & Sokolskaya model predicts breaks
near R = 10 TV both
in spectra of protons and helium,
and in spectra of heavy nuclei





V.I. Zatsepin and N.V. Sokolskaya.
A&A, V.458, 2006, pp.1-5

Conclusions

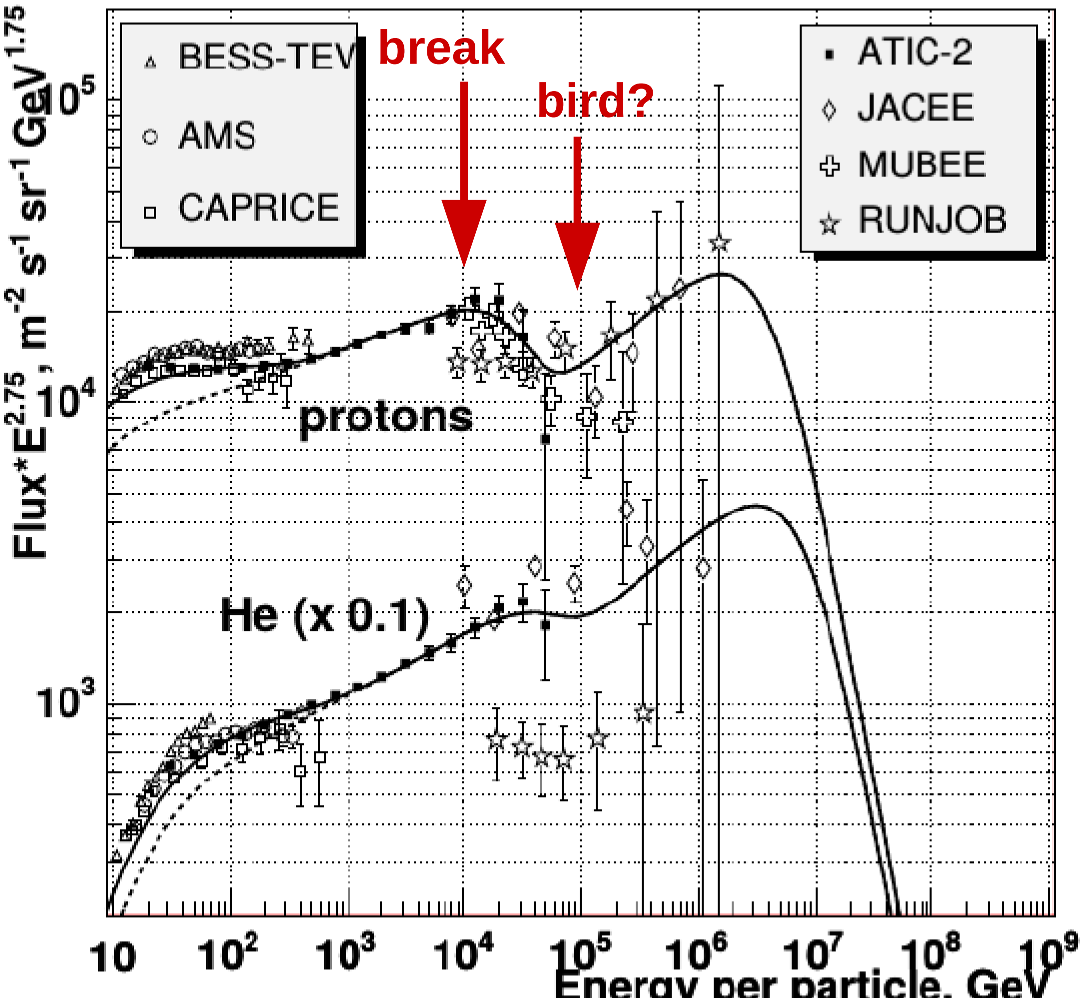
- **The preliminary analysis of the NUCLEON space experiment data gives indications of the existence of a number of features in the energy spectra of cosmic ray nuclei at energies from few TeV to ~100 TeV (per particle).**

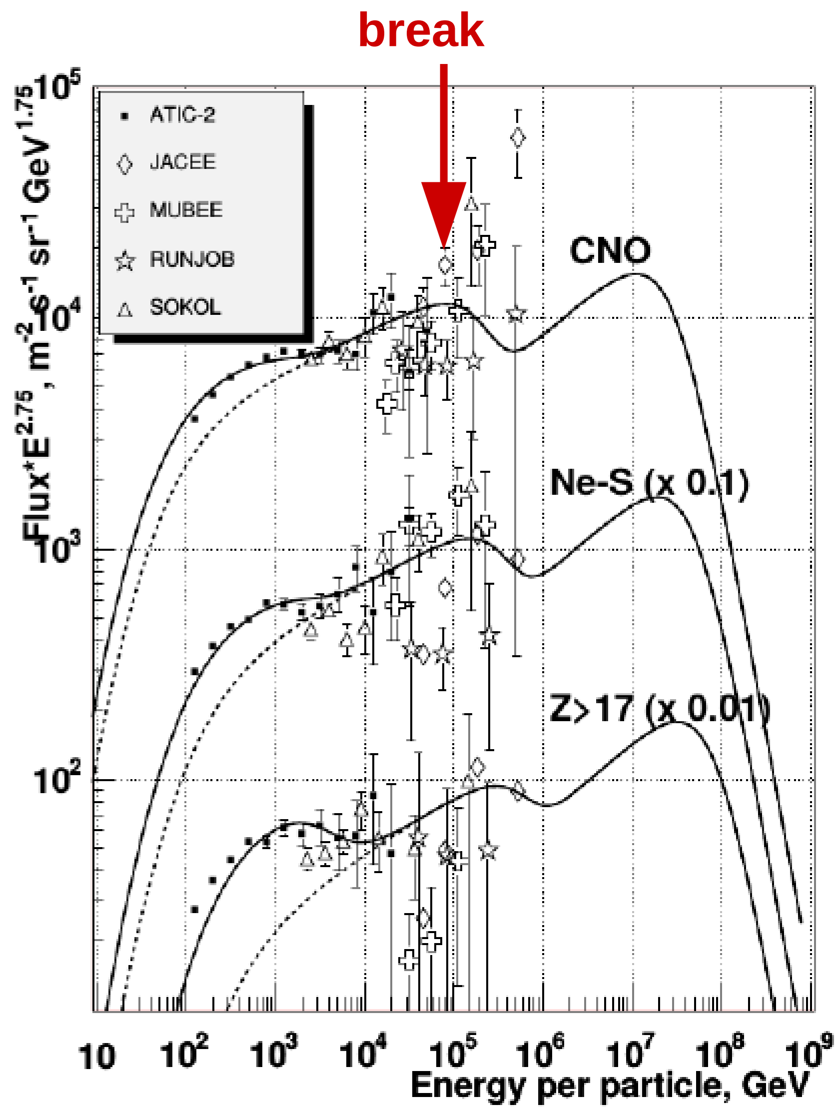
- **Secondary to primary ratios do not show decreasing at highest energies.**

- **A new universal cosmic-ray knee near 10 TV was observed with statistical significance more than 3.9 sigma.**


Thank you
for attention!

Zatsepin & Sokolskaya model predicts breaks near R = 10 TV both in spectra of protons and helium, and in spectra of heavy nuclei





V.I. Zatsepin and N.V. Sokolskaya.
A&A, V.458, 2006, pp.1-5

All particle spectrum