Summary on the relevant energies for space radiation protection: the case of the next ^{16}O measurements

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XV FOOT Collaboration Meeting, Trento, 11 - 13 Dec. 2023

Introduction

During the FOOT Coll. Meeting on June 2023 some discussion has started about the relevant energies for measurements of interest for Space Radioprotection.

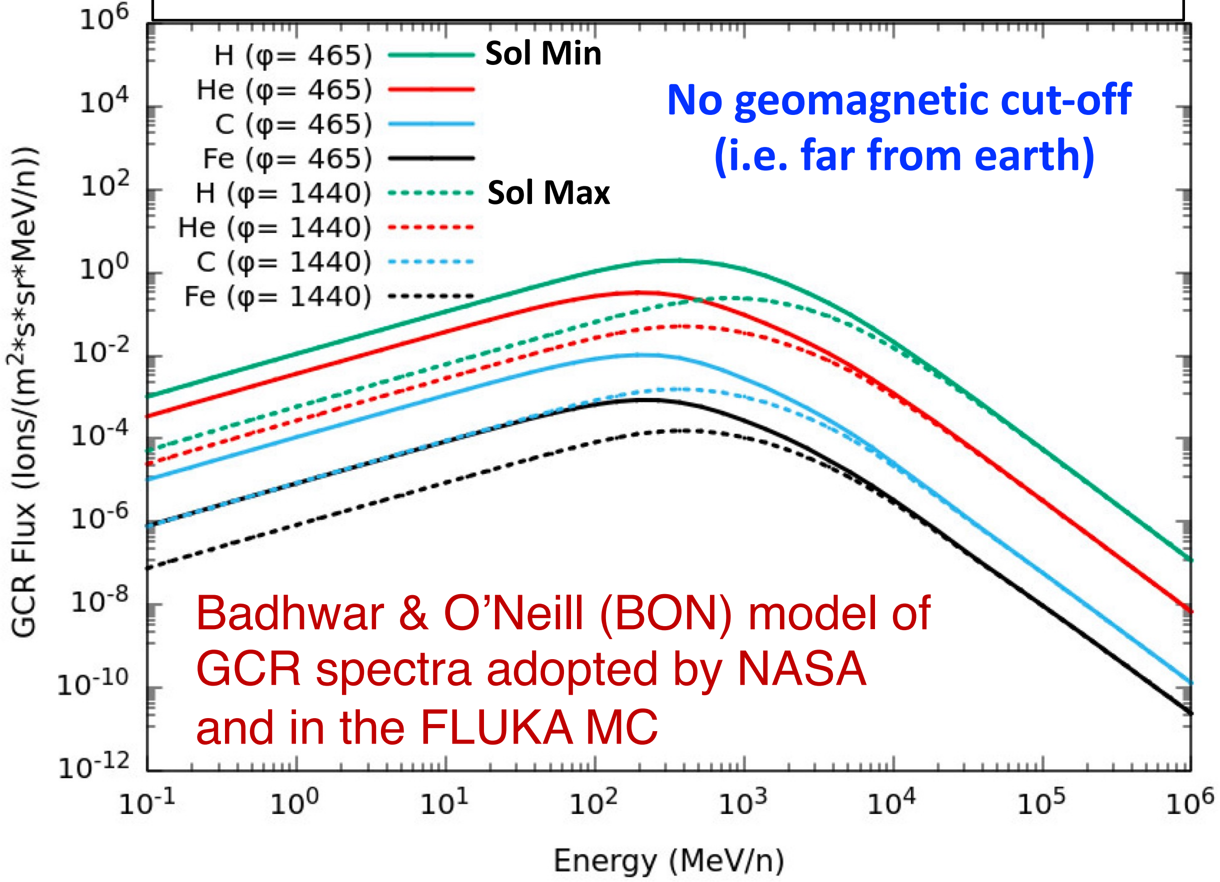
In September, during the Physics Meeting, we tried to clarify a few aspects and propose some discussion about the future programme of FOOT in this topic:

https://agenda.infn.it/event/37490/contributions/209898/attachments/109868/156241/SpaceRadioprotection_20230913.pdf

Given the news of the approval of the MOFFIITS (MAECI) project, we would like to start a more in-depth discussion.

The galactic cosmic ray spectrum

A few Z spectra for 2 values of solar modulation potential representing typical solar max and solar min conditions



In GCR you can find all nuclei from H to Fe (and also something beyond Fe)
Above a few GeV/nucleon all energy spectra exhibit a power law behaviour $\sim E^{-\gamma}$, where $\gamma \sim 2.7$ (somewhat depending on nuclear species)

The energy region below 1 GeV/u is strongly affected by:

- Solar Modulation (in the whole solar system)

  Moving **from solar min to solar max**:
  - increase in peak energy
  - decrease of flux intensities for E<1GeV/u:

  Up to ¾ of the total GCRs flux is lost!

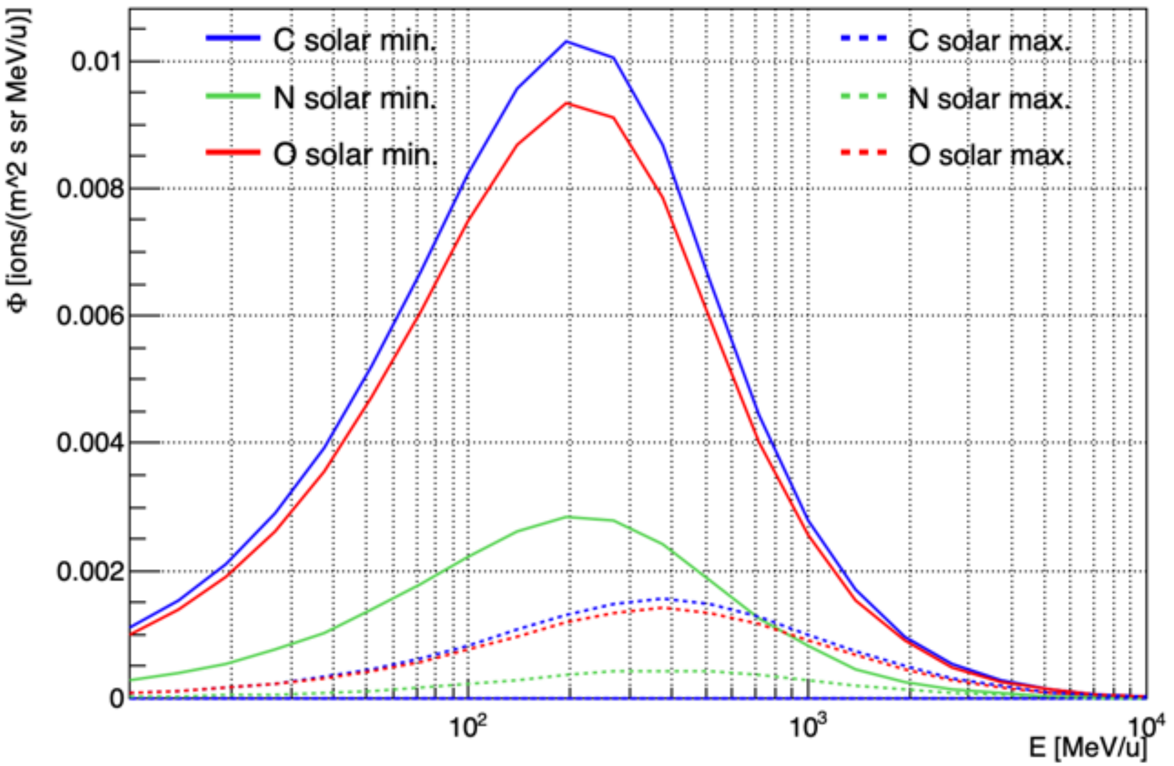
- Earth Magnetic field (coordinate dependent) relevant for all missions in Low Earth Orbit, e.g. on the International Space Station

Example for C,N,O spectra

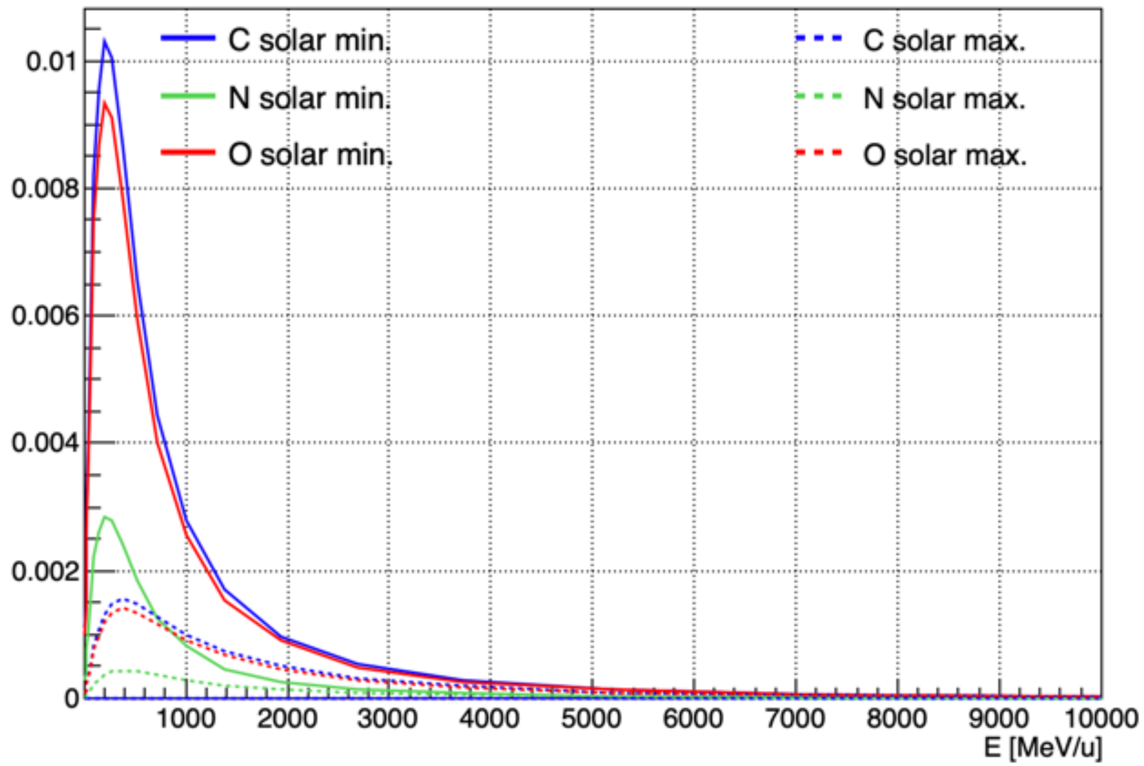
Badhwar & O'Neill (BON) model of GCR spectra adopted by NASA and in the FLUKA MC

No geomagnetic cut-off
(i.e. far from earth)

Lin-Log scale



Lin-Lin scale



Notice for example that peak energy for C,O moves from ~300 MeV/u at solar min to ~500 MeV/u at solar max

It is also evident that, from the point of view of radiation protection, solar max is a safer condition with respect to solar min as far as GCR are concerned, but… probability of Solar Particle Events (SPE) is higher during solar maximum.

Which are the relevant energies and ion measurements for Space Radioprotection?

There are 2 completely different, but complementary, evaluations to be carried out:

- The radiation damage directly produced by primary GCR. This can be of relevance for Extra Vehicular Activity or for activity on the surface of the Moon or Mars. Both these activities are of limited time duration

- The radiation damage produced by primary GCR and their secondaries produced in the shielding of the spacecraft. This is usually considered the most crucial contribution for long duration space travels

Composite GCR contribution and Exposure limits for astronauts

Expected effective dose (total body) for a typical mission to Mars of 650 days (Ramos et al 2023 Int J Mol Sci)

Solar Min

Al Thickness (g/cm^2)	Equivalent Dose (mSv)
0	986.7
0.3	904.5
1	812.1
2	770.4
5	729.0
10	681.6
20	708.5

Solar Max

Al Thickness (g/cm^2)	Equivalent Dose (mSv)
0	240.9
0.3	249.2
1	279.5
2	319.6
5	254.1
10	227.6
20	266.4

Limits for the whole career

ESA/RSA: 1 Sv
NASA: 0.6 Sv (!)
JAXA: 0.5-1 Sv
age- and sex-dependent

This is one of the main reasons why there are efforts to try to go back on the Moon at the end of 2024 and to go to Mars in 2035: **Solar Max!!!**

Courtesy of F. Ballarini (Pv)

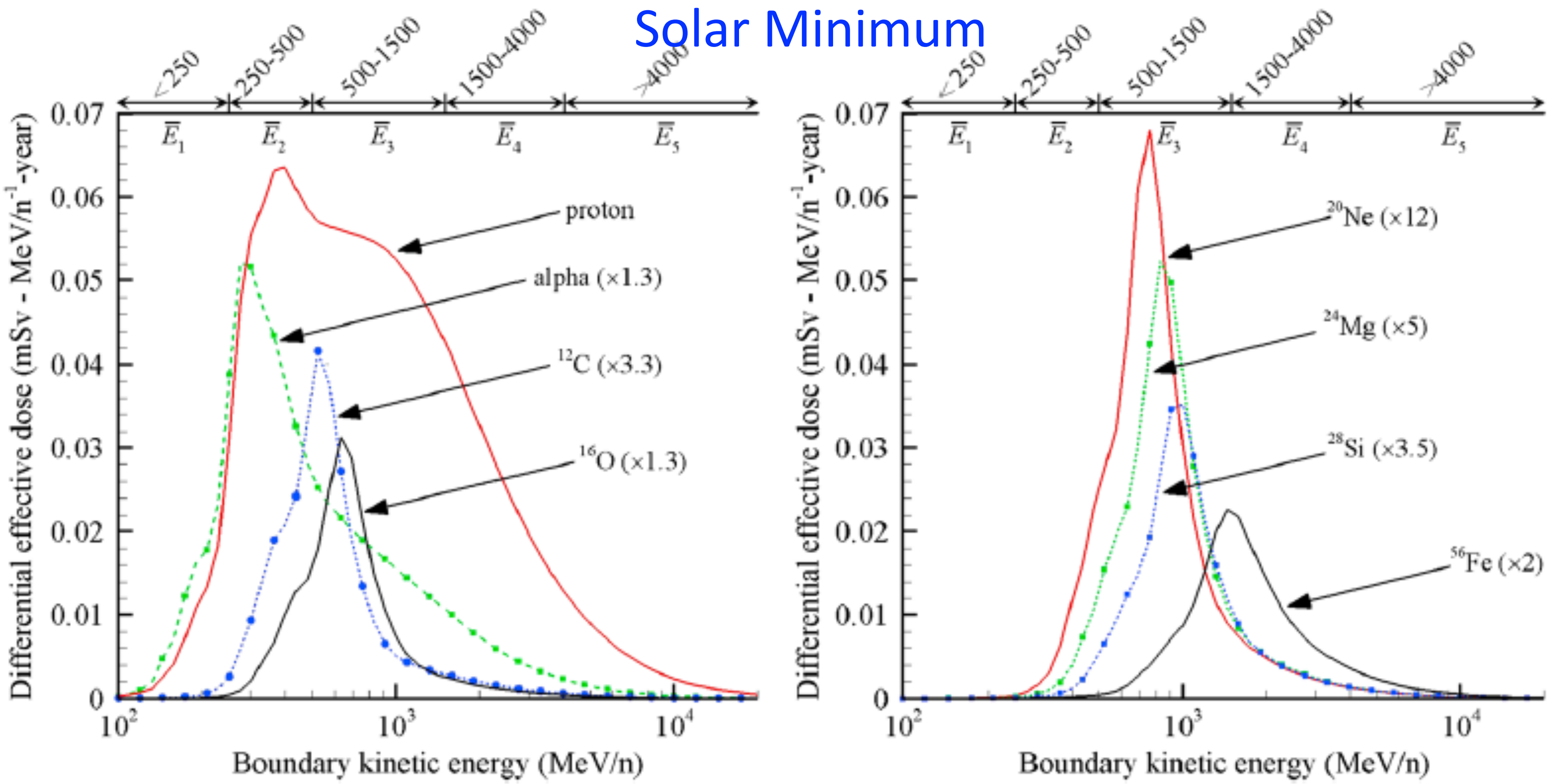
Space Weather (2014) 12, 217–224,
doi:10.1002/2013SW001025.

GCR environmental models I: Sensitivity analysis for GCR environments

Tony C. Slaba[1] and Steve R. Blattnig[1]

dose contribution from GCR on the basis of BON spectra (2010 update)

Solar Minimum



Differential effective dose rate as a function of incident kinetic energy behind 20 g/cm2 of Aluminium exposed to solar minimum conditions described by BON2010 model. Results for specific ions have been scaled to improve plot clarity.

GCR spectrum 90% effective dose > 500 MeV/n, Z=1 and 2 are the most effective

E_1: < 250 MeV/n
E_2: 250-500 MeV/n
E_3: 500-1500 MeV/n
E_4: 1500-4000 MeV/n
E_5: > 4000MeV/n

Solar Minimum	$\bar{E}_1$	$\bar{E}_2$	$\bar{E}_3$	$\bar{E}_4$	$\bar{E}_5$	Total
$Z = 1$	1.2	5.4	18.2	18.4	14.8	58.1
$Z = 2$	1.2	2.2	4.1	2.9	1.7	12.2
$Z = 3\text{-}10$	0.0	3.3	3.8	1.3	0.8	9.1
$Z = 11\text{-}20$	0.0	0.2	6.6	2.0	1.1	10.0
$Z = 21\text{-}28$	0.0	0.0	4.7	3.8	2.1	10.6
Totals	2.5	11.1	37.4	28.4	20.5	100.0

$E_3 + E_4 + E_5 = 86\%$ $E_4 + E_5 = 49\%$

Relative contribution (×100) of GCR boundary energy and charge groups to effective dose with **20 g/cm²** aluminium shielding. A value of 0.0 indicates that the relative contribution is less than 0.1%.

For **40 g/cm²**: $E_3 + E_4 + E_5 = 91\%$ $E_4 + E_5 = 57\%$

The 2020 paper by J. Norbury et al.

Are Further Cross Section Measurements Necessary for Space Radiation Protection or Ion Therapy Applications? Helium Projectiles

Front. Phys. 8:565954.
doi: 10.3389/fphy.2020.565954

John W. Norbury[1], Giuseppe Battistoni[2], Judith Besuglow[3,4], Luca Bocchini[5], Daria Boscolo[6], Alexander Botvina[7], Martha Clowdsley[1], Wouter de Wet[8], Marco Durante[6,9], Martina Giraudo[5], Thomas Haberer[10], Lawrence Heilbronn[11], Felix Horst[6], Michael Krämer[6], Chiara La Tessa[12,13], Francesca Luoni[6,9], Andrea Mairani[10], Silvia Muraro[2], Ryan B. Norman[1], Vincenzo Patera[14], Giovanni Santin[15,16], Christoph Schuy[6], Lembit Sihver[17,18], Tony C. Slaba[1], Nikolai Sobolevsky[7], Albana Topi[6], Uli Weber[6], Charles M. Werneth[1] and Cary Zeitlin[19]*

Here the role of FOOT has been emphasized

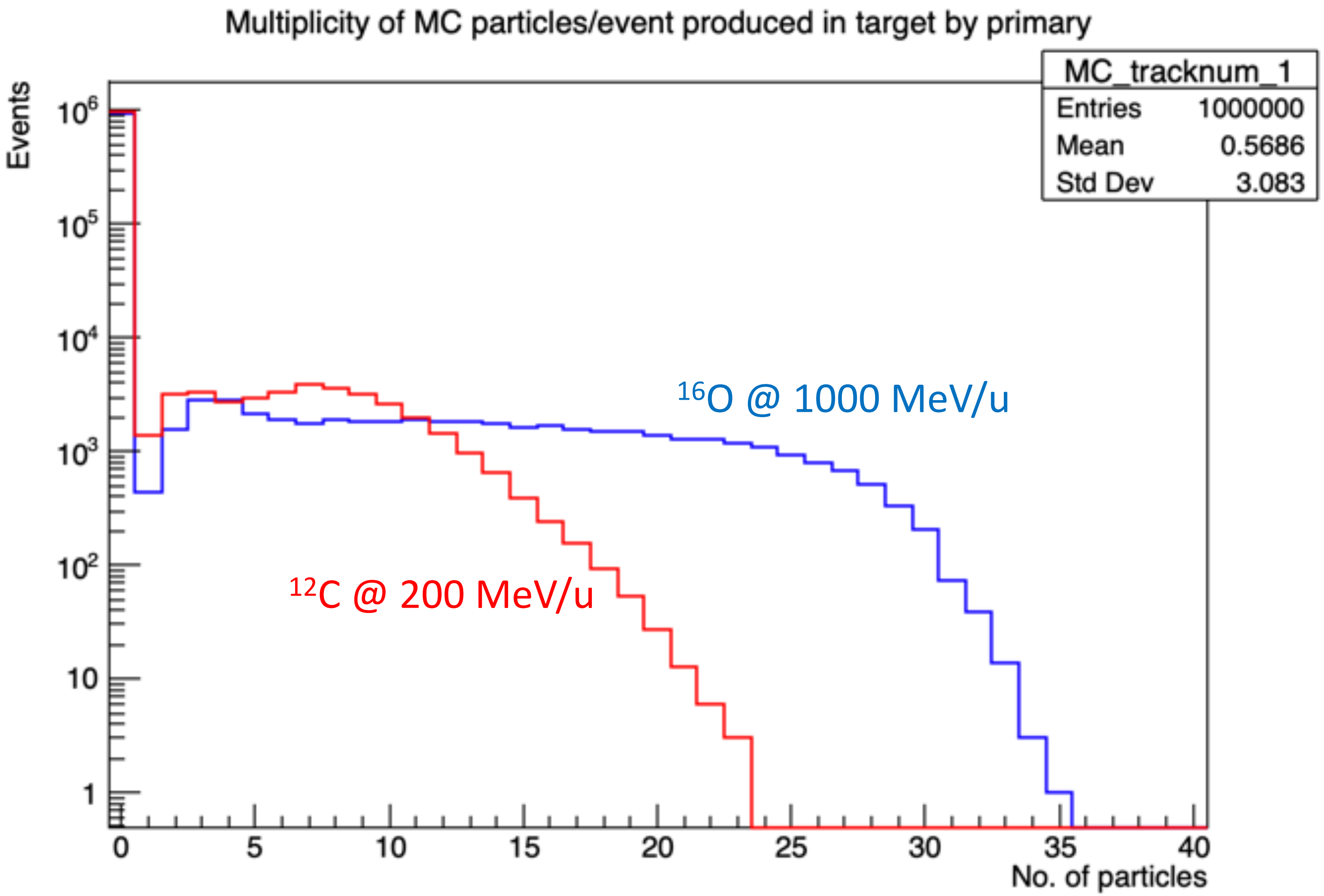
Main remarks and suggestions from this paper

- He data below 3 GeV/n reveals significant problems and defects: almost no high quality double differential data for helium projectiles over the entire energy region
- No double differential cross section data exist for light ion fragment production from O projectiles above the pion threshold (>290 MeV/n).
- Energies > 500 MeV/u have to be considered in any case, better if up to 1500 MeV/u.
- Most important targets: H, C, O, Ca, Al, [Fe] (secondary production in shielding is important)
- Priority has to be given to the double differential cross sections for the production of light fragments

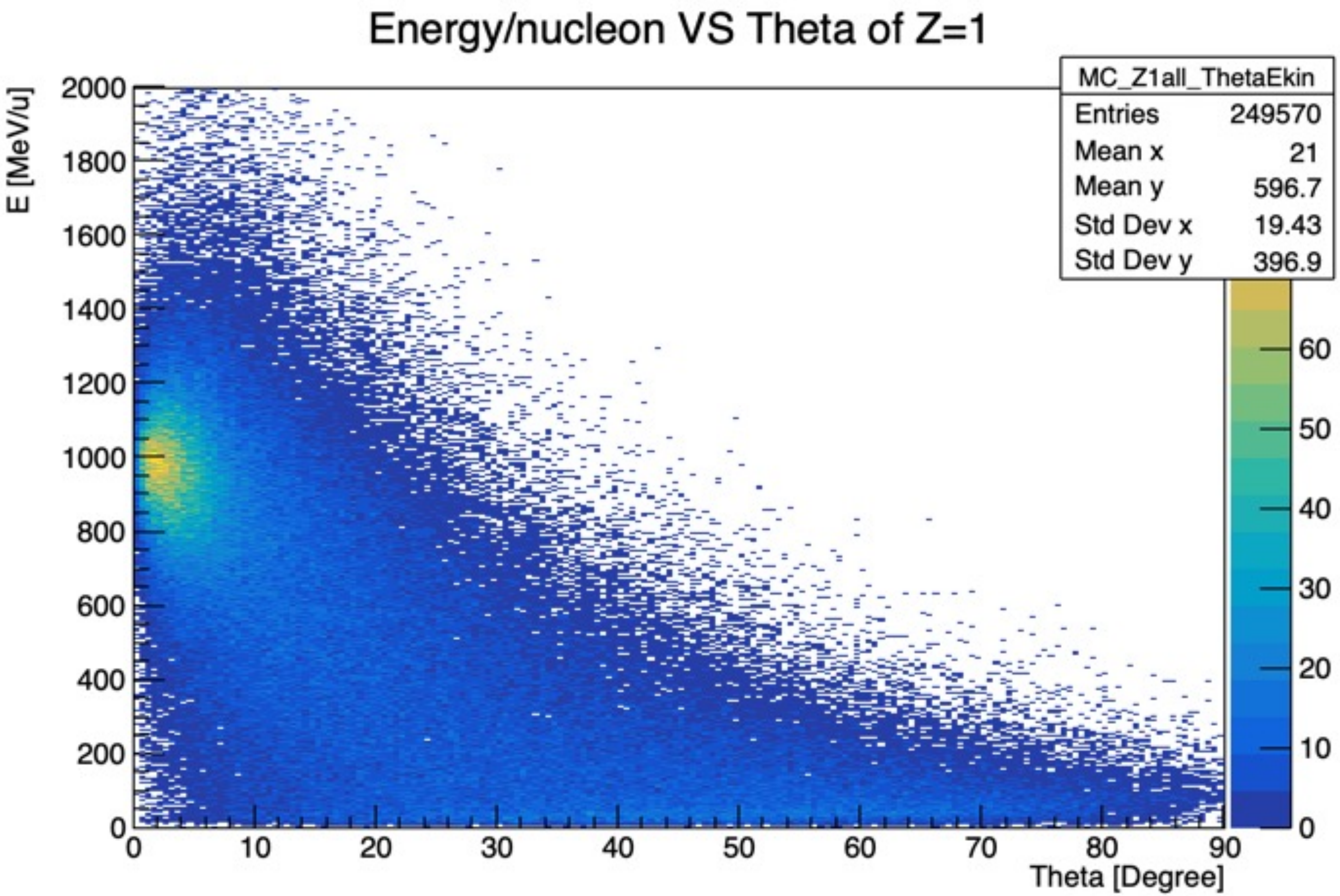
Preliminary study
in view of the GSI 2025 data taking
^{16}O @ 1 GeV/u

With the approval of the MOFFIITS project, we will have the opportunity to take data with oxygen to the GSI.
In the project it is proposed to use ^{16}O at 400-700 MeV/u, but we know from M. Durante that in Cave A is possible to get 1 GeV/u. (*Even up to 1.9 GeV/u, but there are doubts on radioprotection issues, private communication*).
So we started looking at what happens for ^{16}O at 700 MeV/u and 1 GeV/u on carbon target

Multiplicity of secondaries produced by **1 GeV/u** ^{16}**O** on **C target**



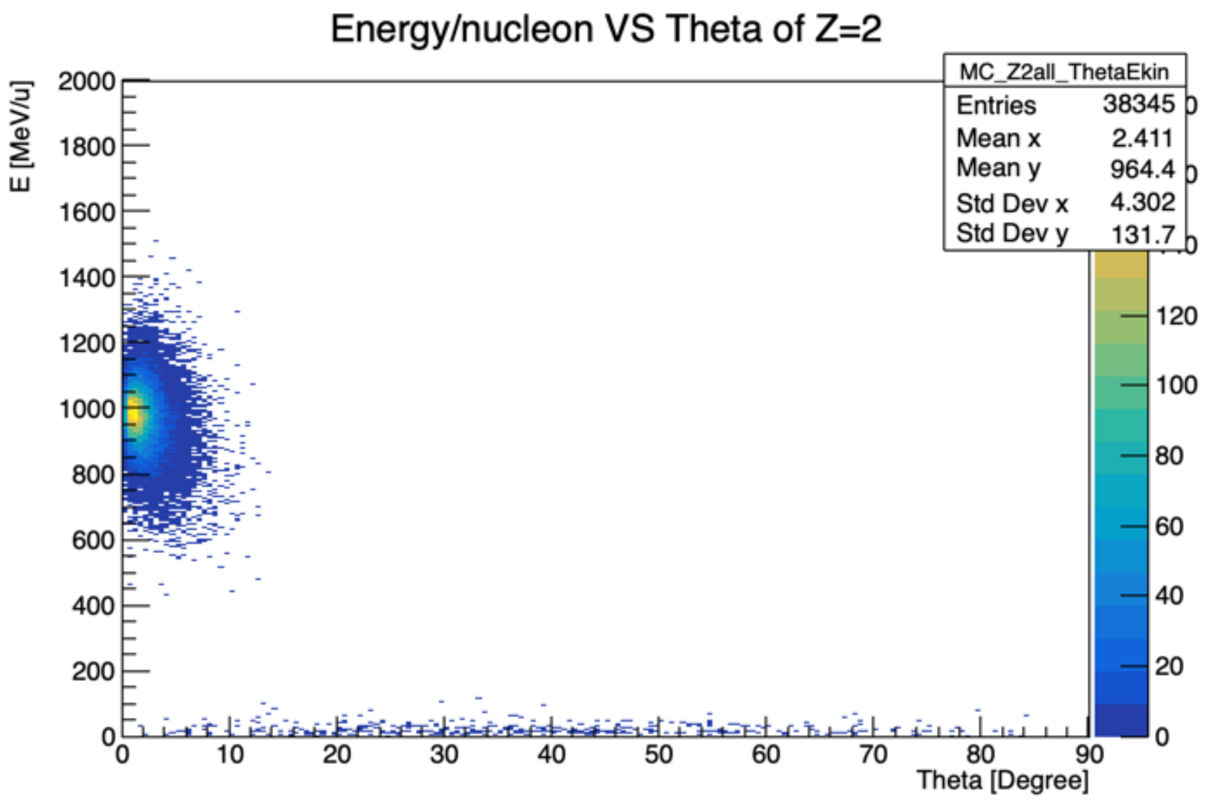
E_{kin} VS Theta - Z=1

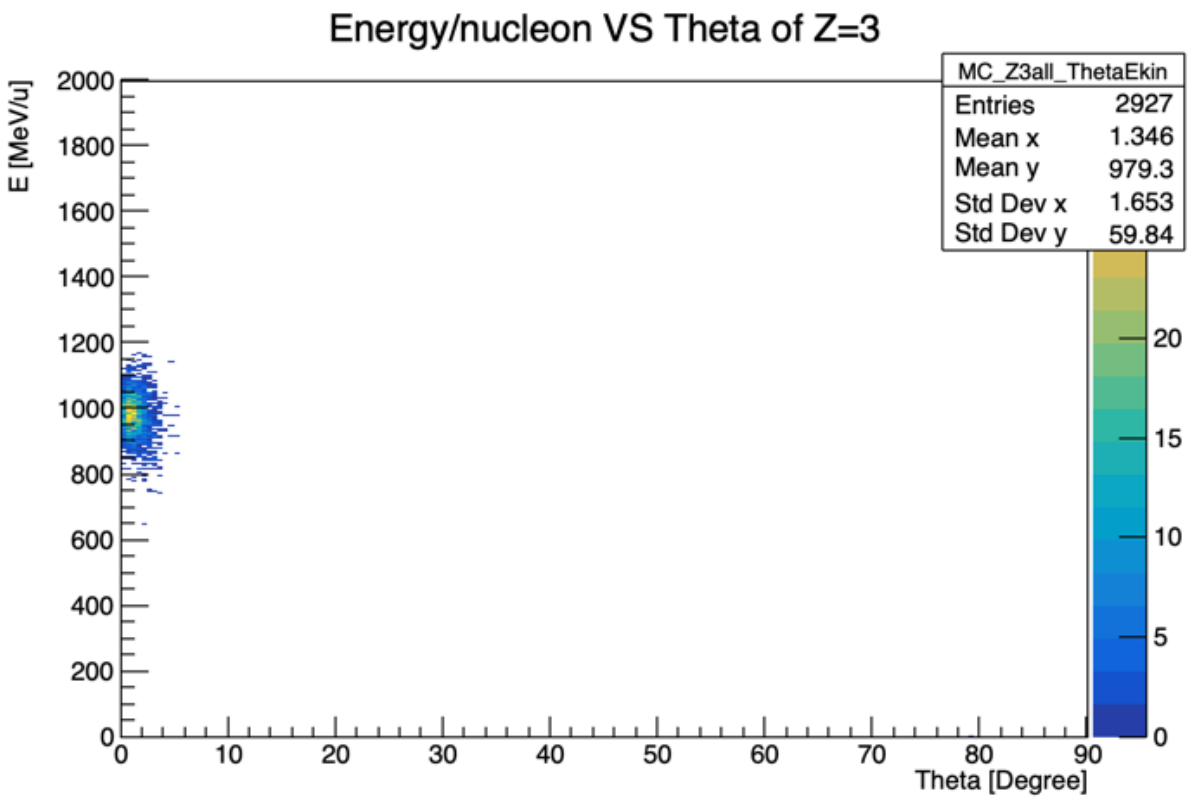


The forward protons:
E ~ 1 GeV
Within the detector geometrical acceptance

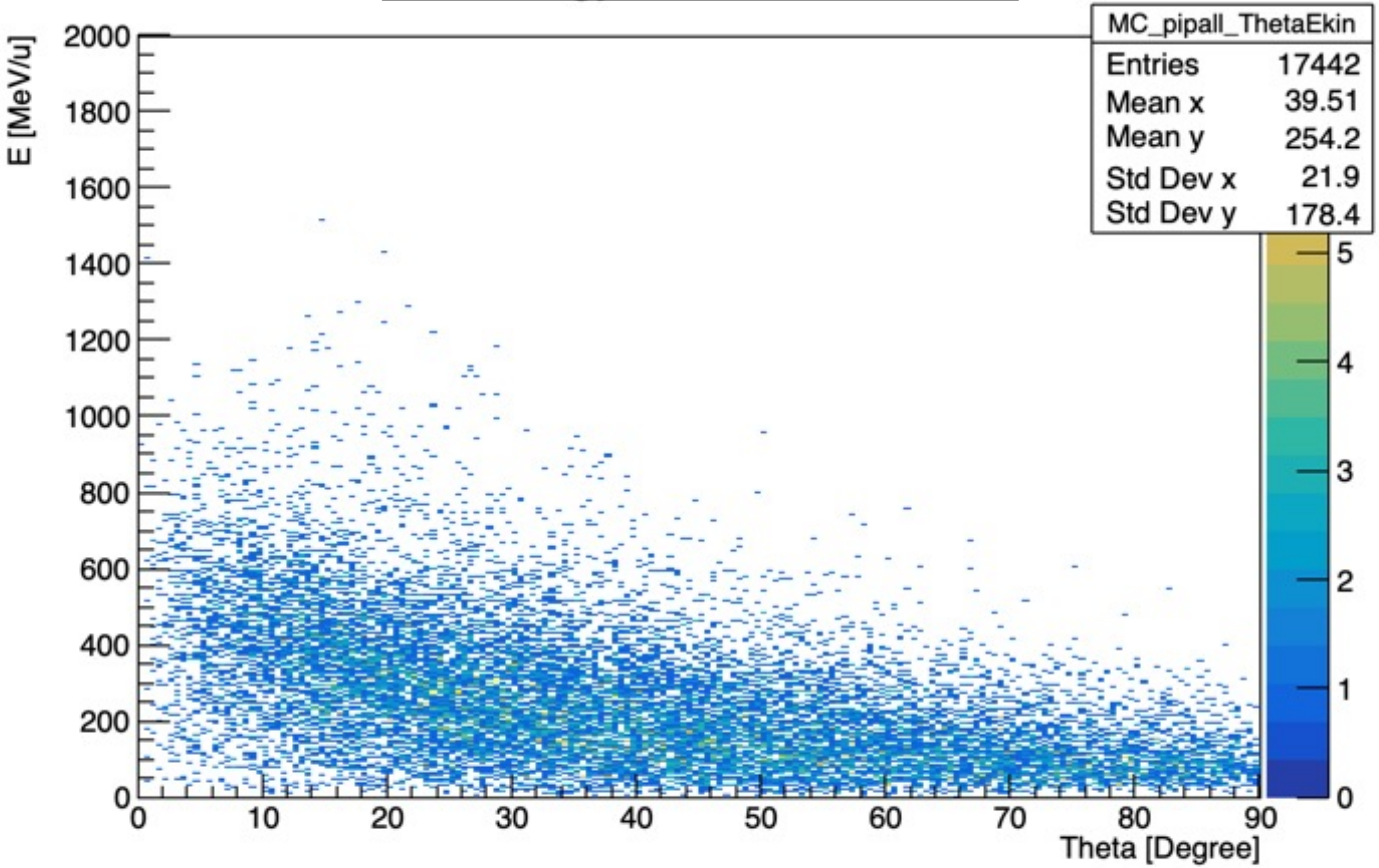
E_{kin} VS Theta - Z=2

E_{kin} VS Theta - Z=3

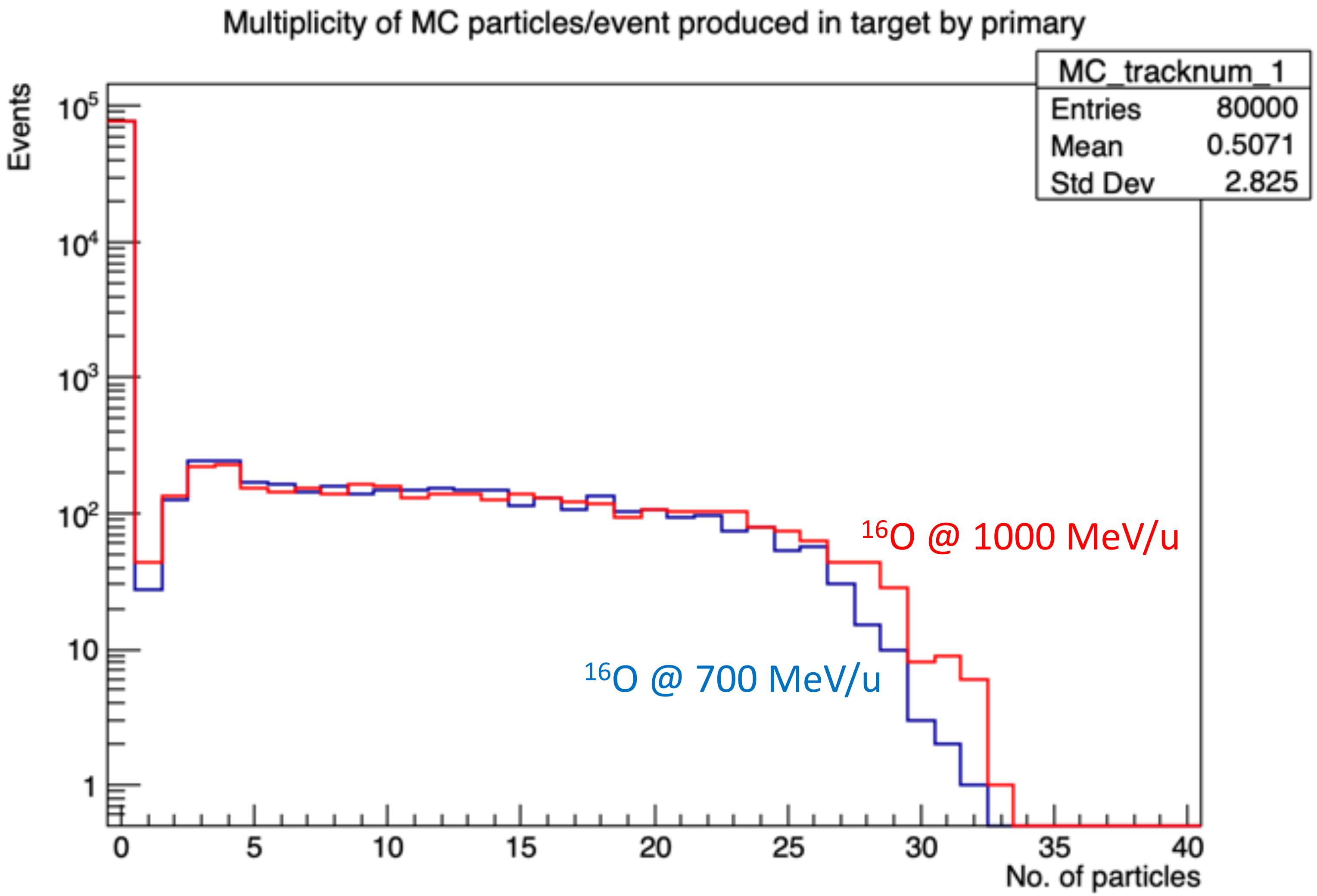


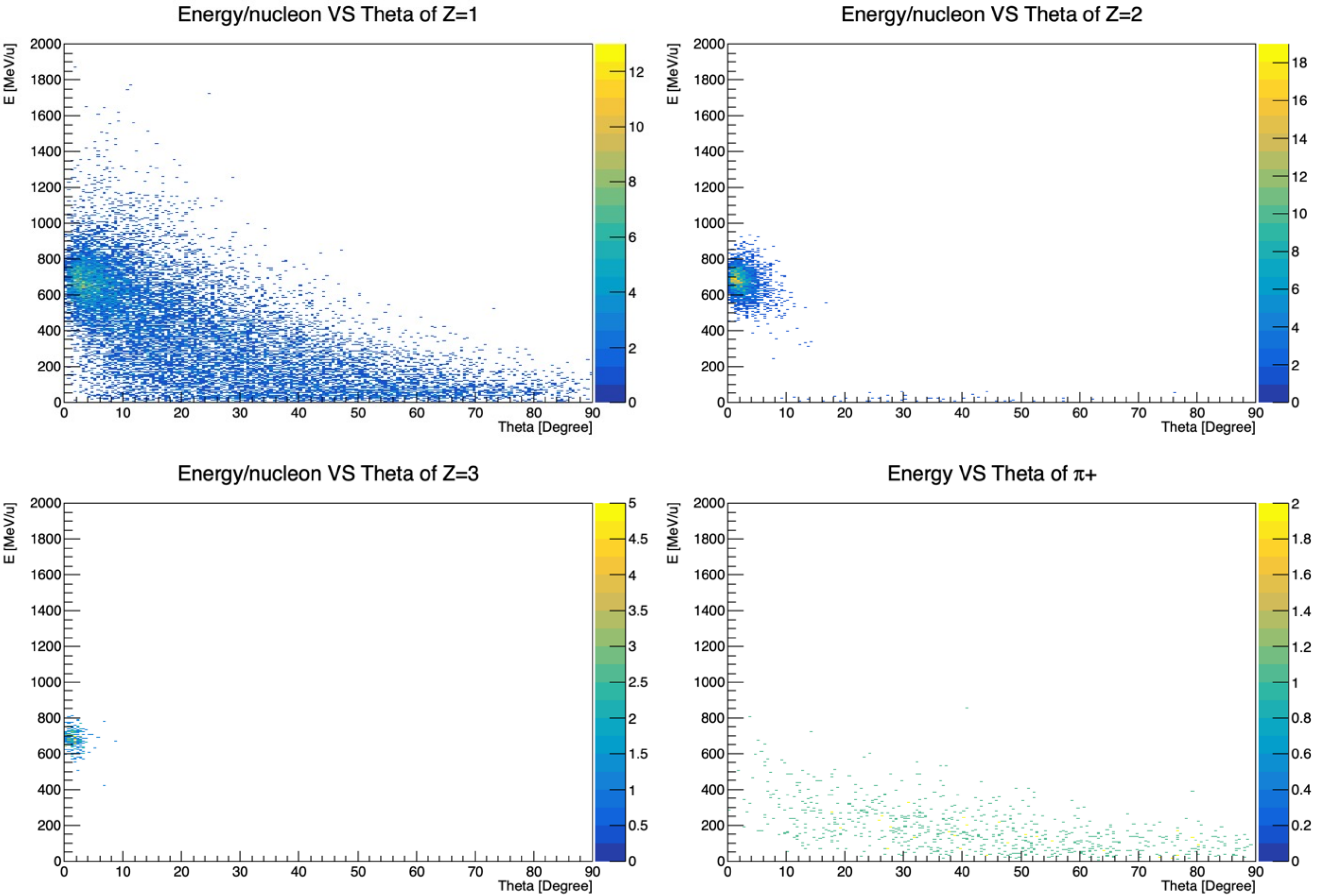


E_{kin} VS Theta - π^+



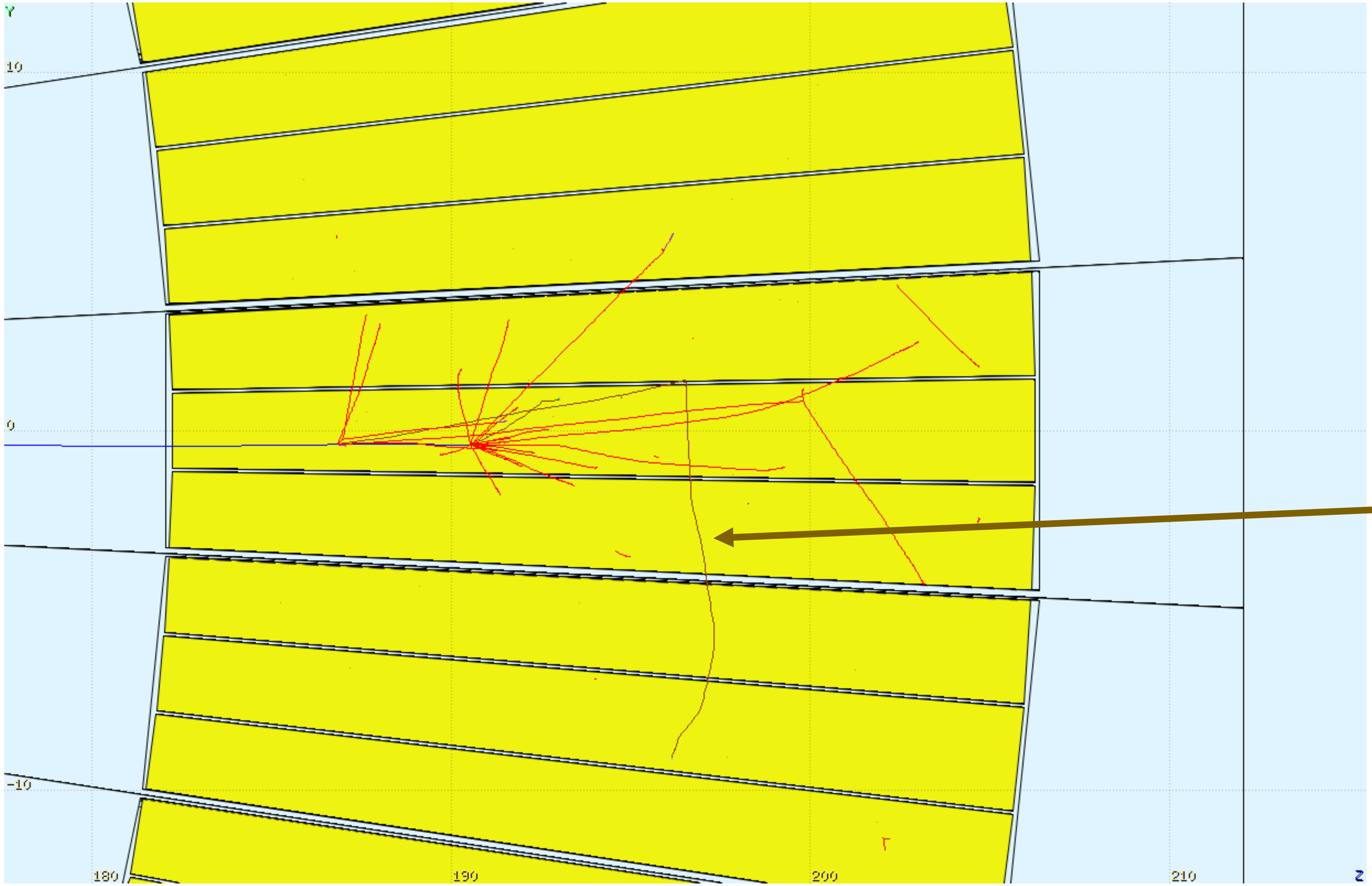
Multiplicity of secondaries produced by **700 MeV/u** and **1 GeV/u ^{16}O** on **C target**





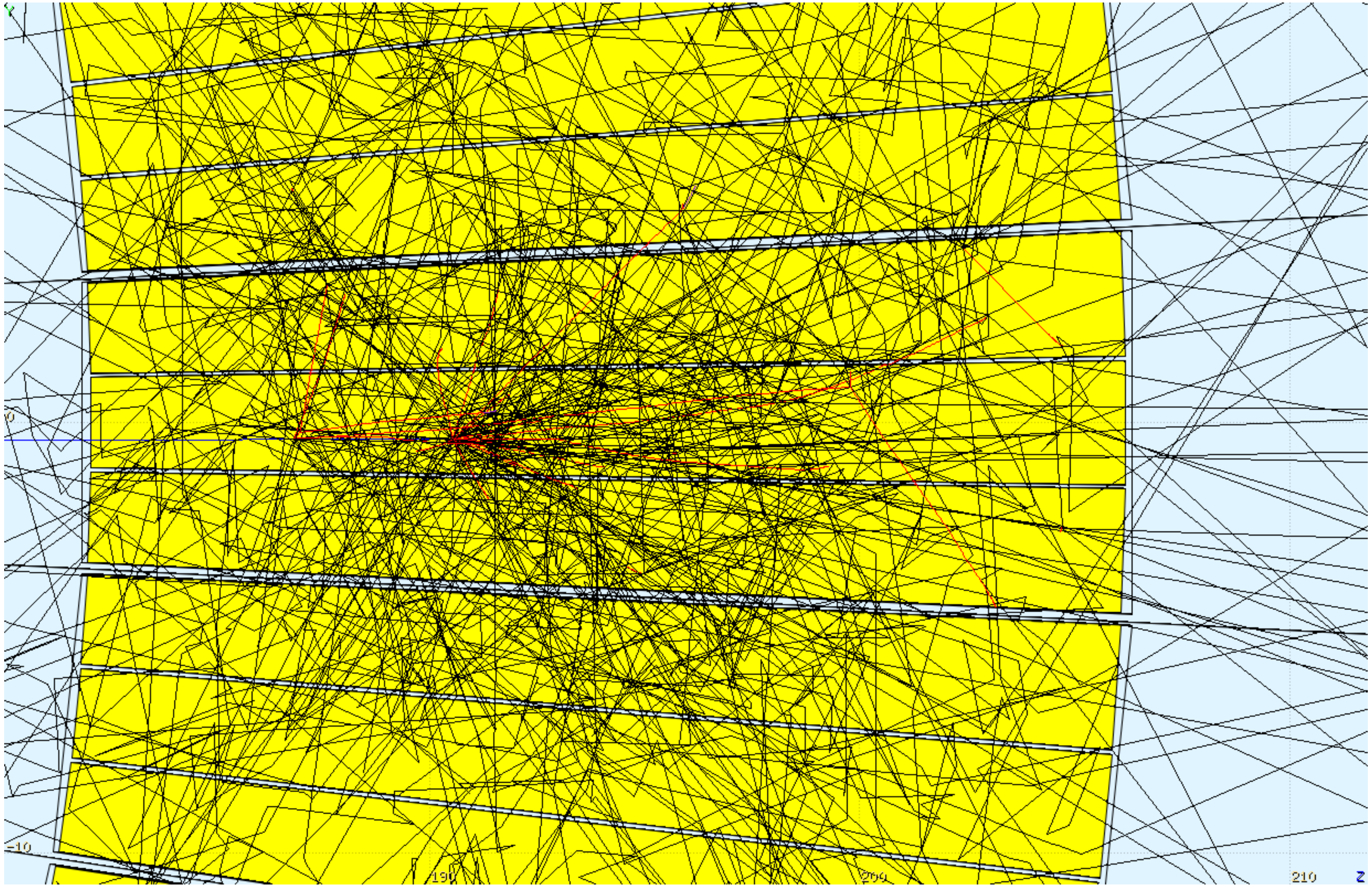
Energy/nucleon VS Theta of Z=1
Energy/nucleon VS Theta of Z=2
Energy/nucleon VS Theta of Z=3
Energy VS Theta of π+
E [MeV/u]
Theta [Degree]

1 event: ^{16}O @ 1000 MeV/u in BGO, charged trackes only

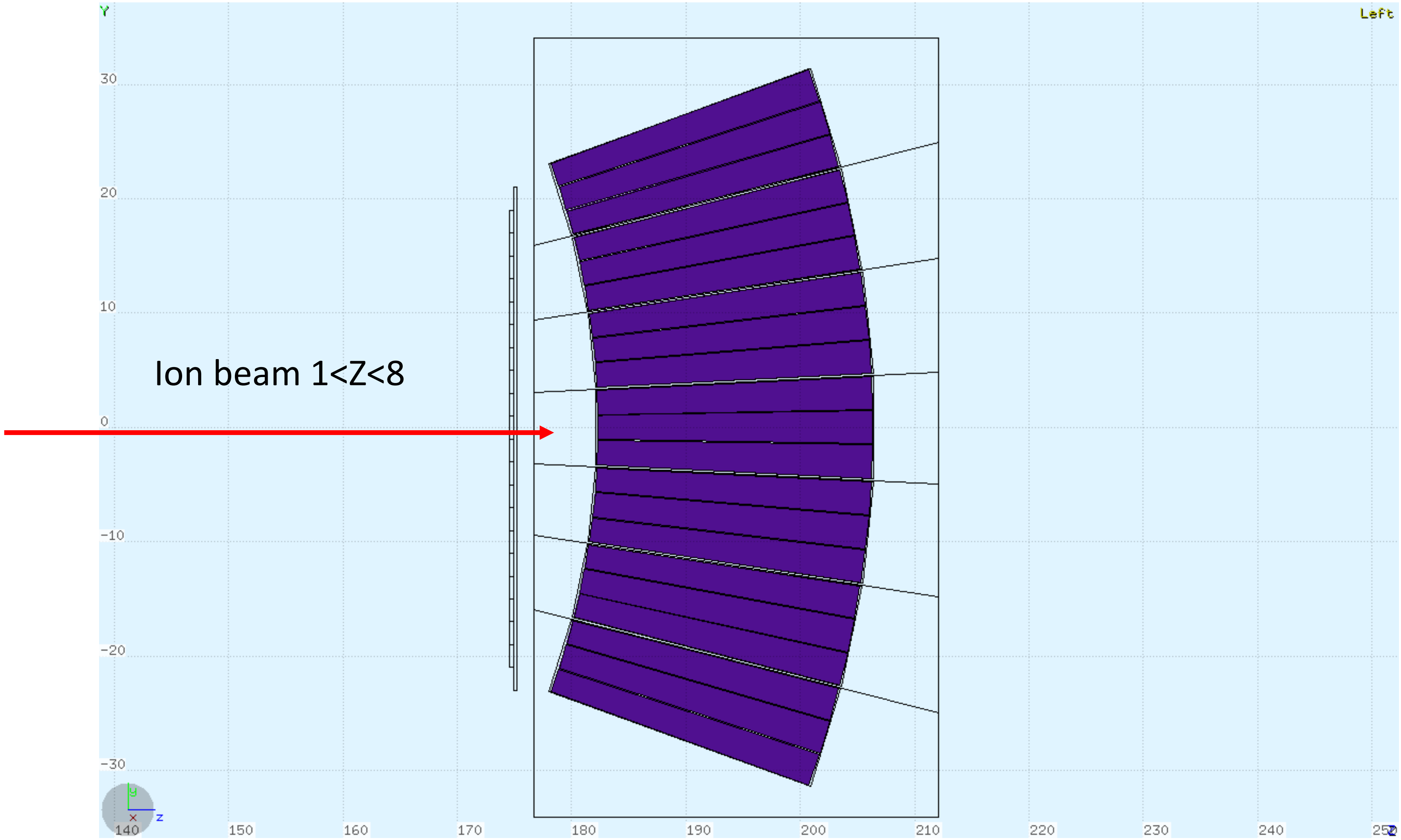


In brown a **π**

The same event with neutrons…



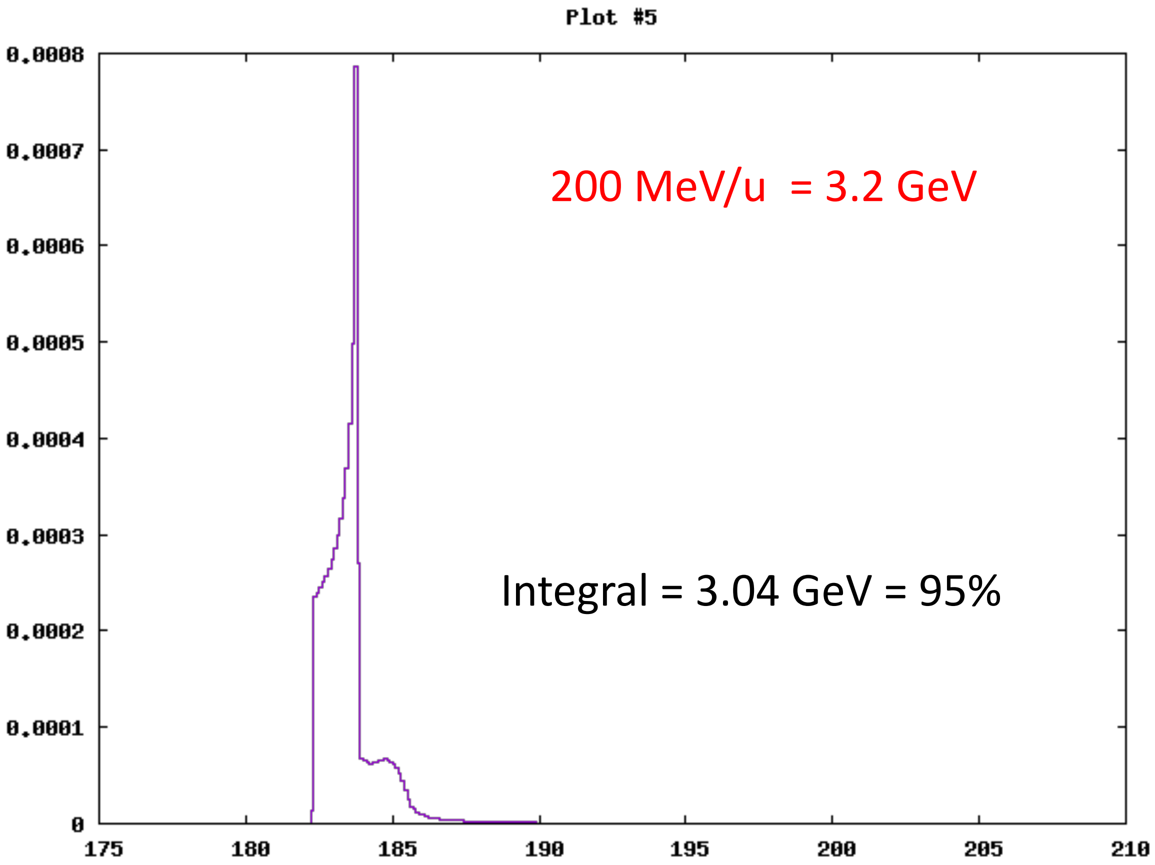
Calorimeter response: 1 GeV/u VS 0.2 GeV/u



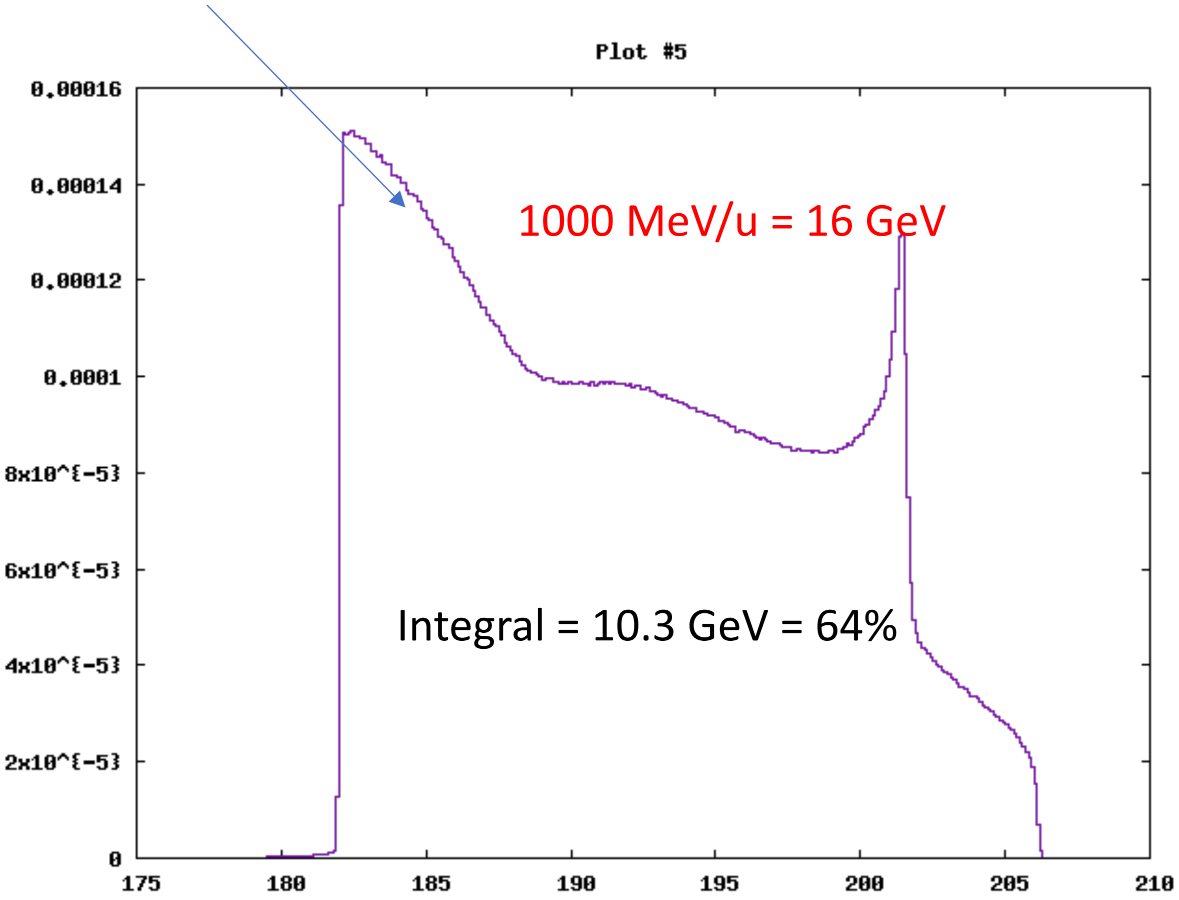
Scoring:

Energy deposition vs z
in the whole BGO calo

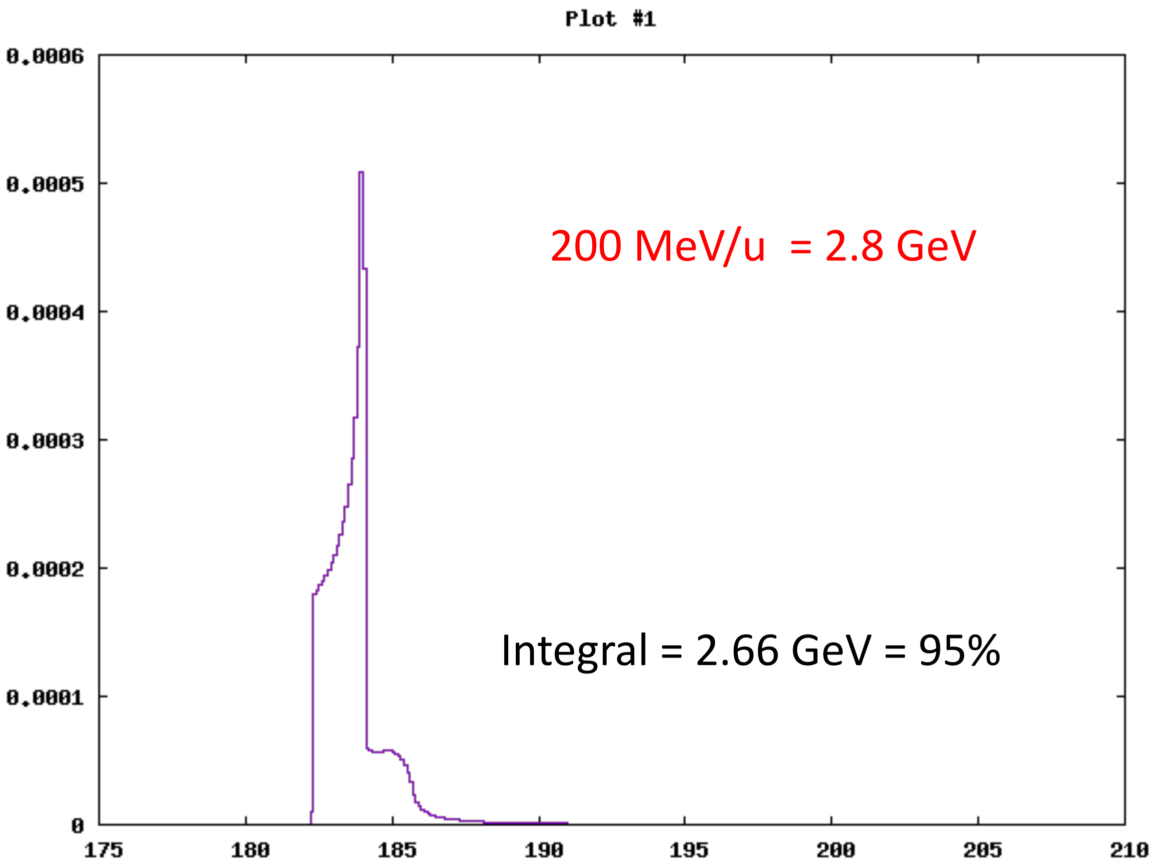
^{16}O (Z=8)



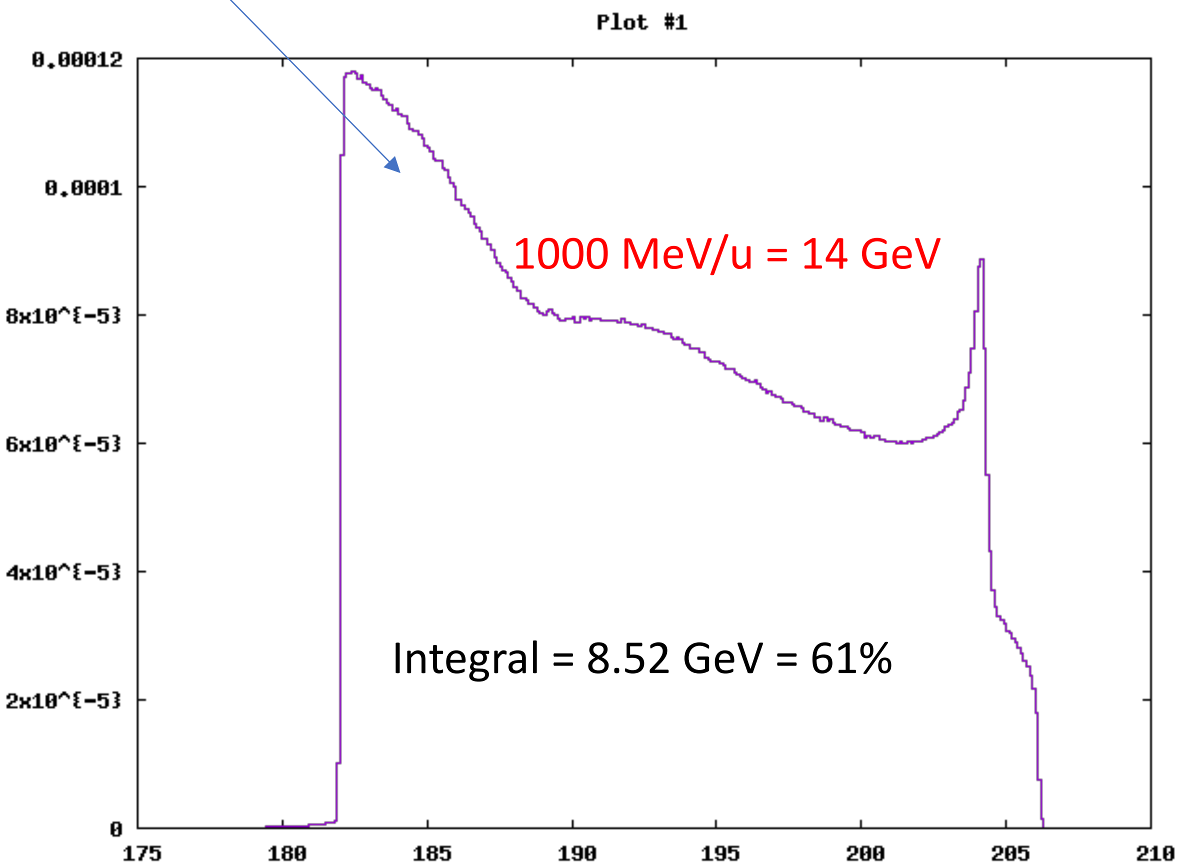
Hadronic showering regime



^{14}N (Z=7)

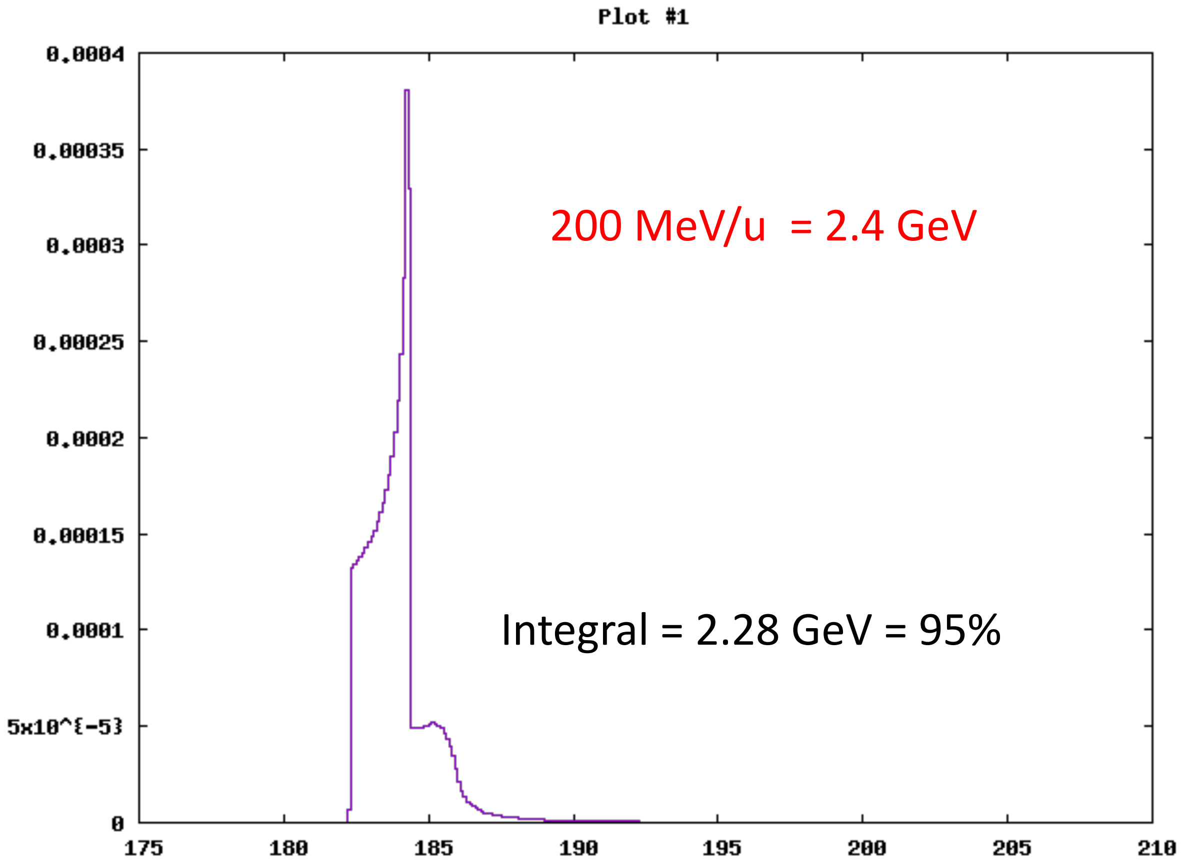


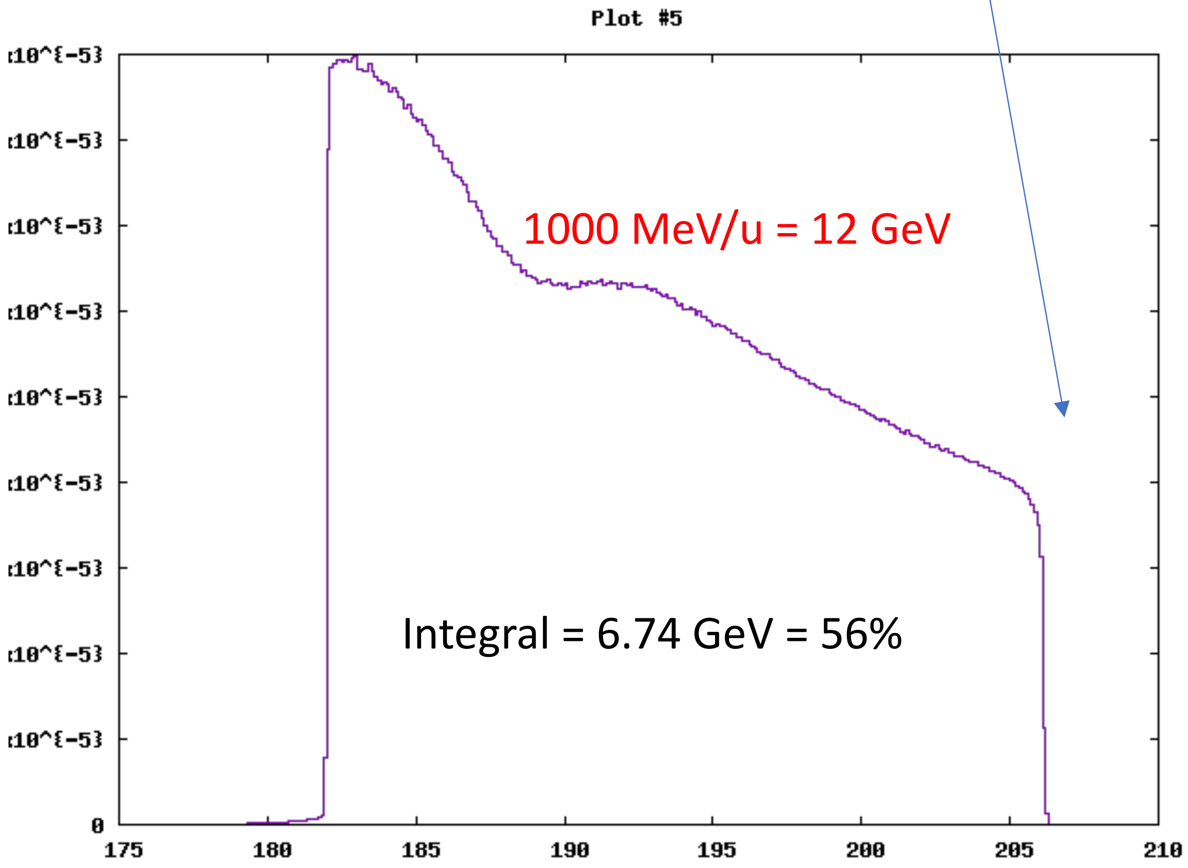
Hadronic showering regime



^{12}C (Z=6)

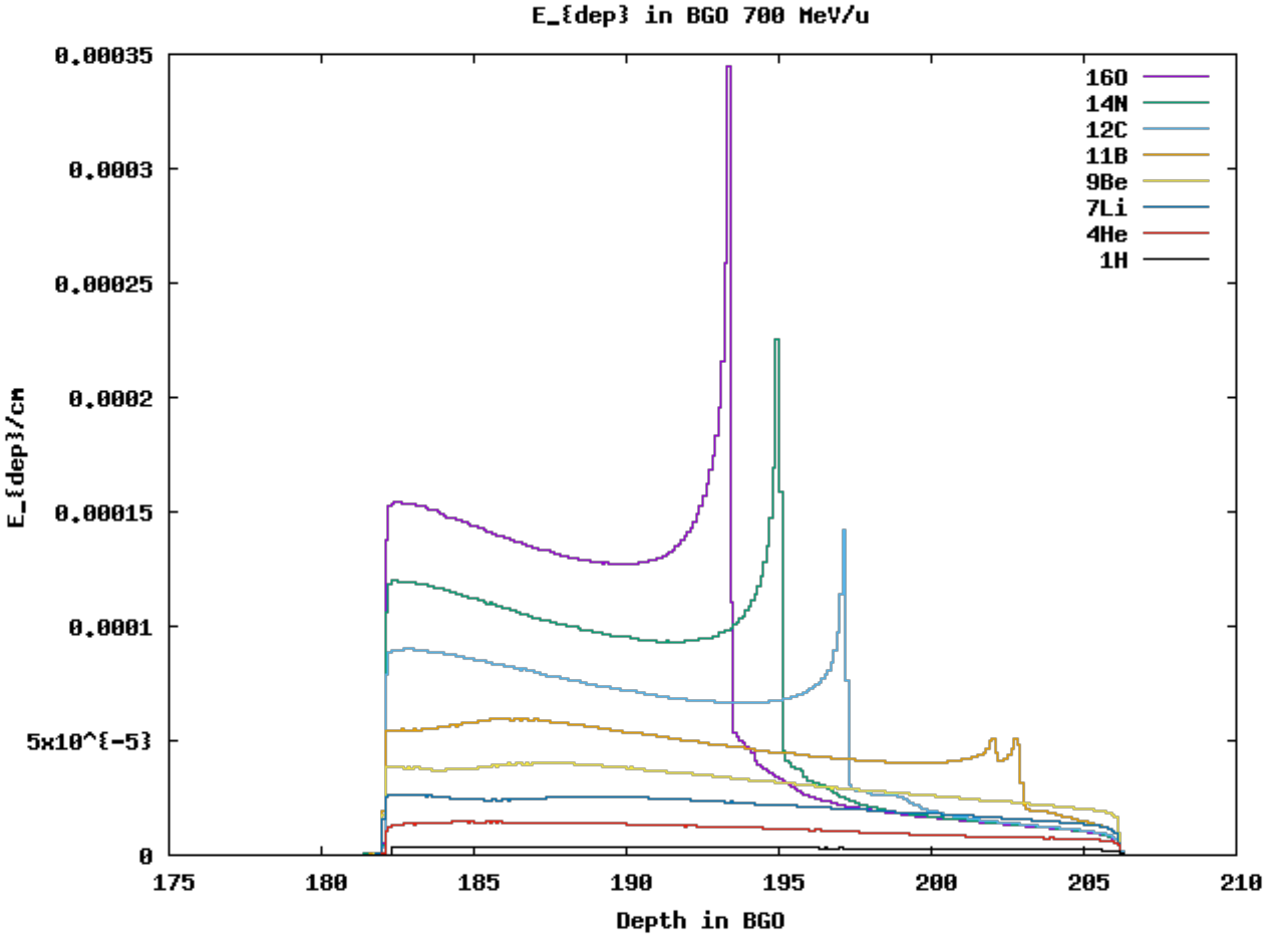
Bragg peak oustide the calo

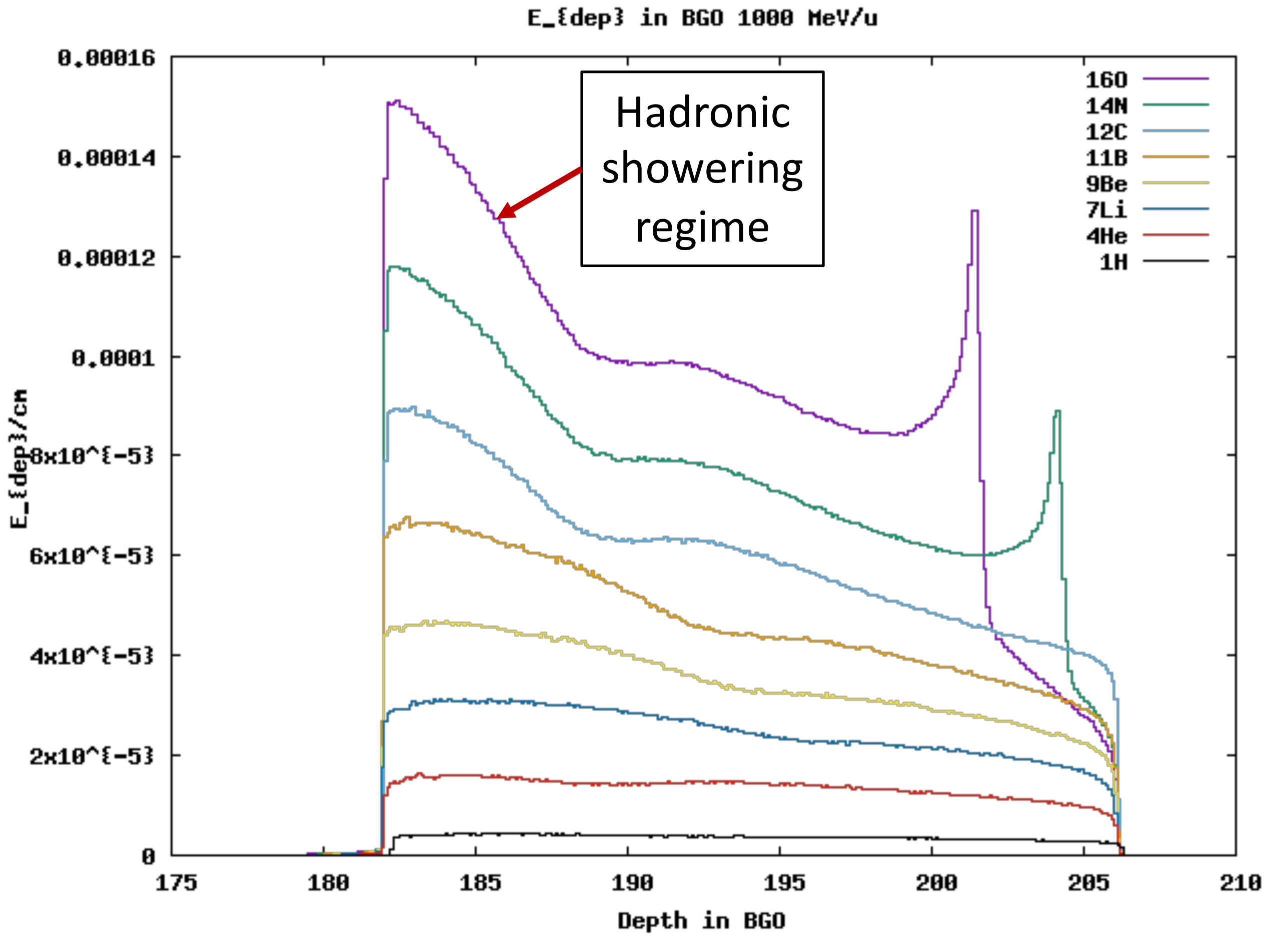




At this energy all ions with Z<7 are not contained within the depth of our BGO crystals: the lower is Z, the lower is the fraction of energy deposited in the calorimeter

All ions in the Calorimeter:
700 MeV/u and 1 GeV/u

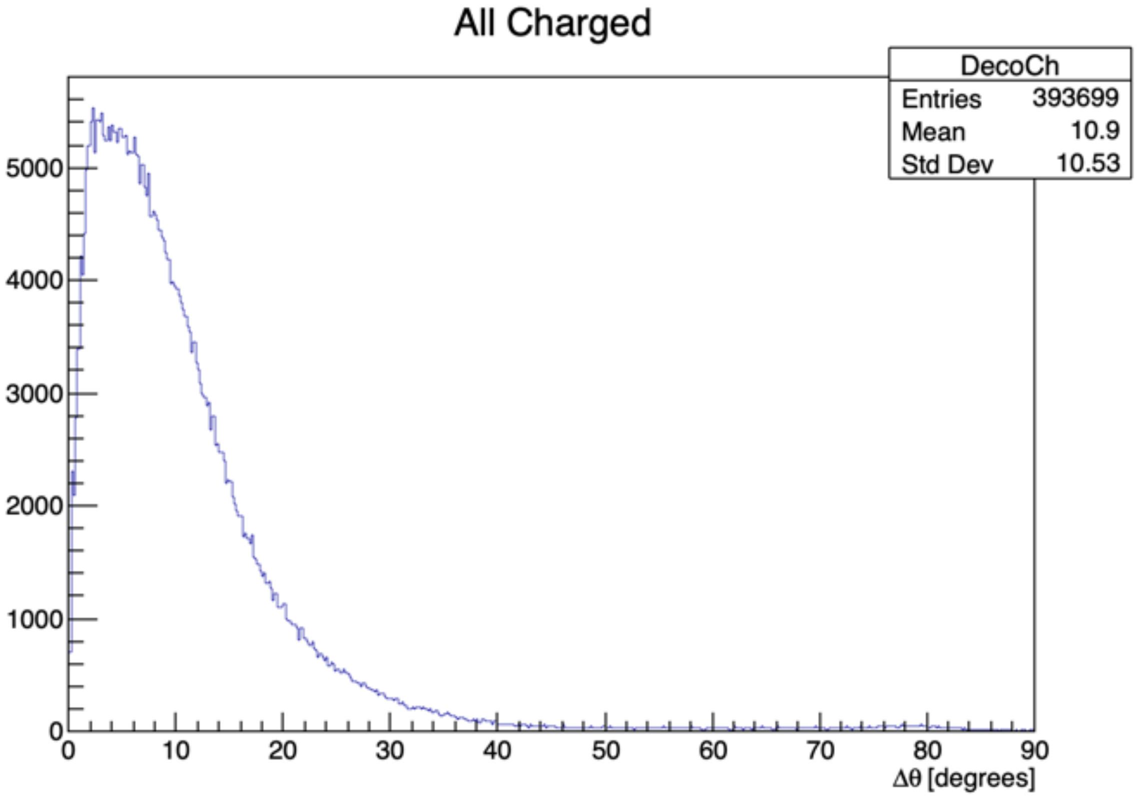




@700 MeV/u all ions with Z≤5 are not contained in our BGO crystals

Angular Separation of tracks

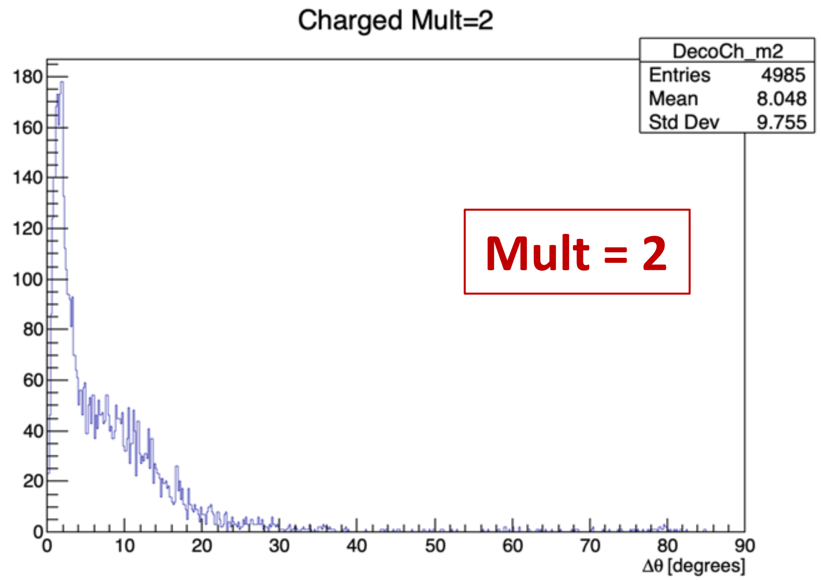
secondaries arriving at the TW depth (^{16}O @ 1 GeV/u)

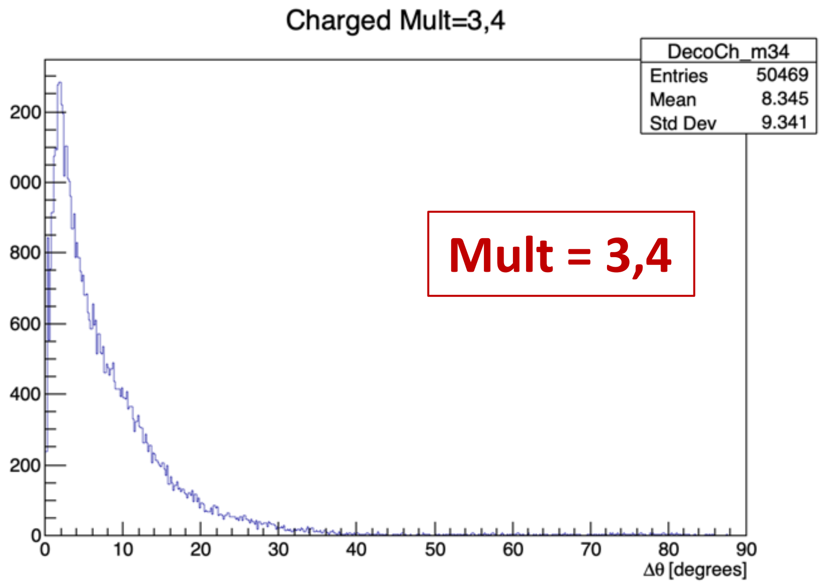


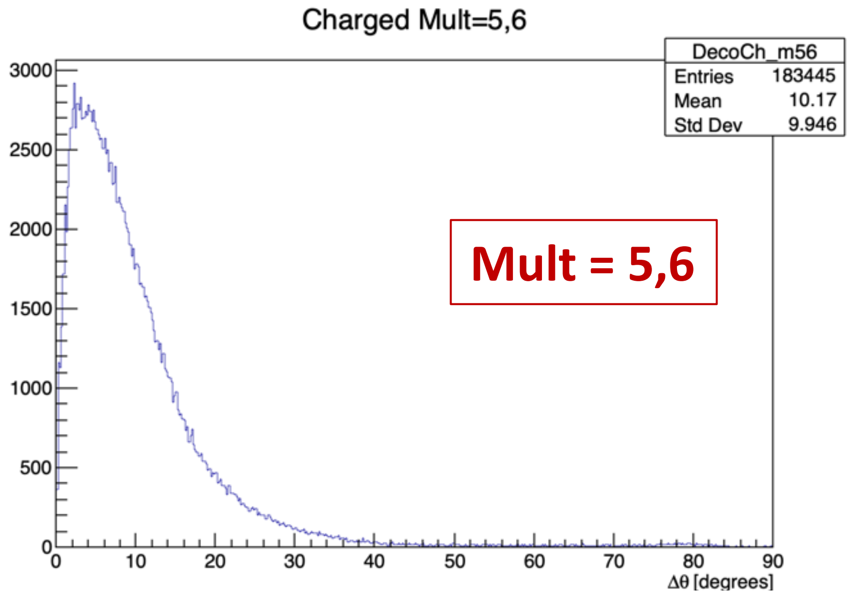
Most of events can be completely contained.

Angular separation of tracks VS multiplicity

particles arriving at the TW (^{16}O @ 1 GeV/u)

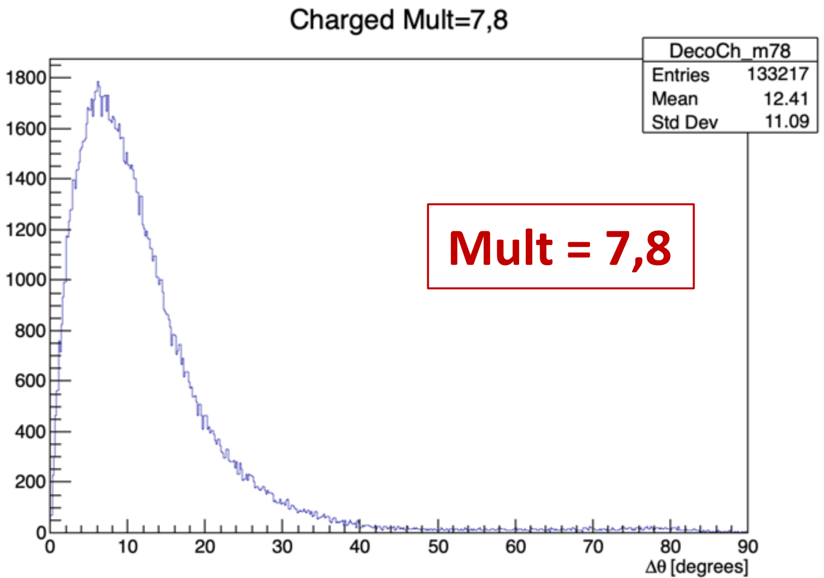


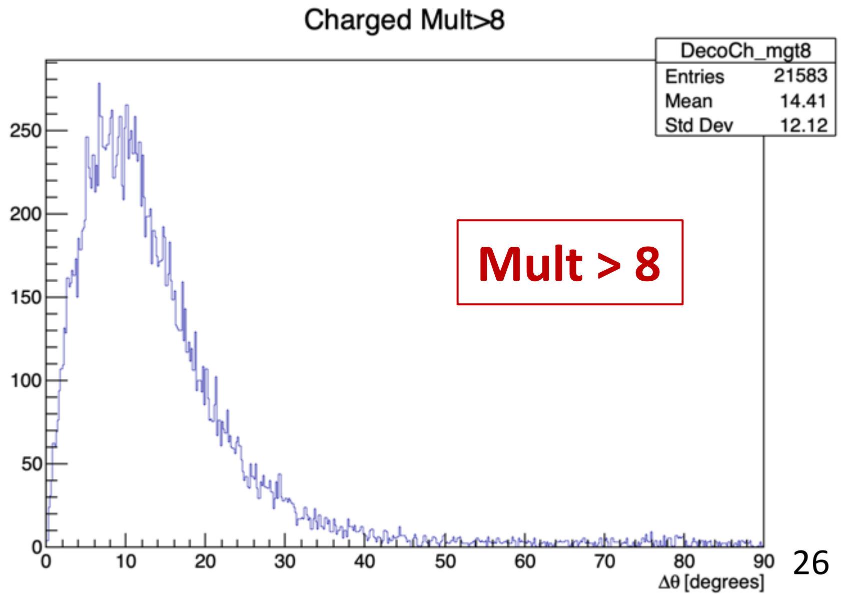




The greater the multiplicity, the greater the separation of tracks.

At 1 GeV/u, at least up to multiplicity = 8 , events are almost completely contained in the TW acceptance





Conclusions: 1

To acquire relevant measures for space radiation protection we must try to go to the highest energy that our detector allows us.

High energy causes a crisis in the calorimeter:
- energy is not contained for most of secondaries
- Hadronic showering regime (pion production)

It is not enough to remove the central crystals because the secondaries have high energy and are penetrating, so the calorimeter should probably be removed.
The isotopic identification (necessary to get the correct E_{kin}) has to be obtained from p-ToF.

Conclusions: 2

At higher energies, **β** higher (>0.8), ionization is lower => smaller signal.
Problem in TW for Z=1 (and maybe Z=2) which are the most important ions as far as dose is concerned.

It could be an advantage to use the TOFpRad TW that has a greater thickness: from 3 mm to 5 mm.

With a thicker TW, there would be a proportional increase of the number of secondary interactions on the TW and this would put the calorimeter even more in crisis.

Maybe a target-TW distance greater than 1.8 m (~CNAO2023) should be recommended.

Conclusions: 3

1. Can trackers resolve tracks that at high energy are less separated?

2. Which is the p resolution at these energies?

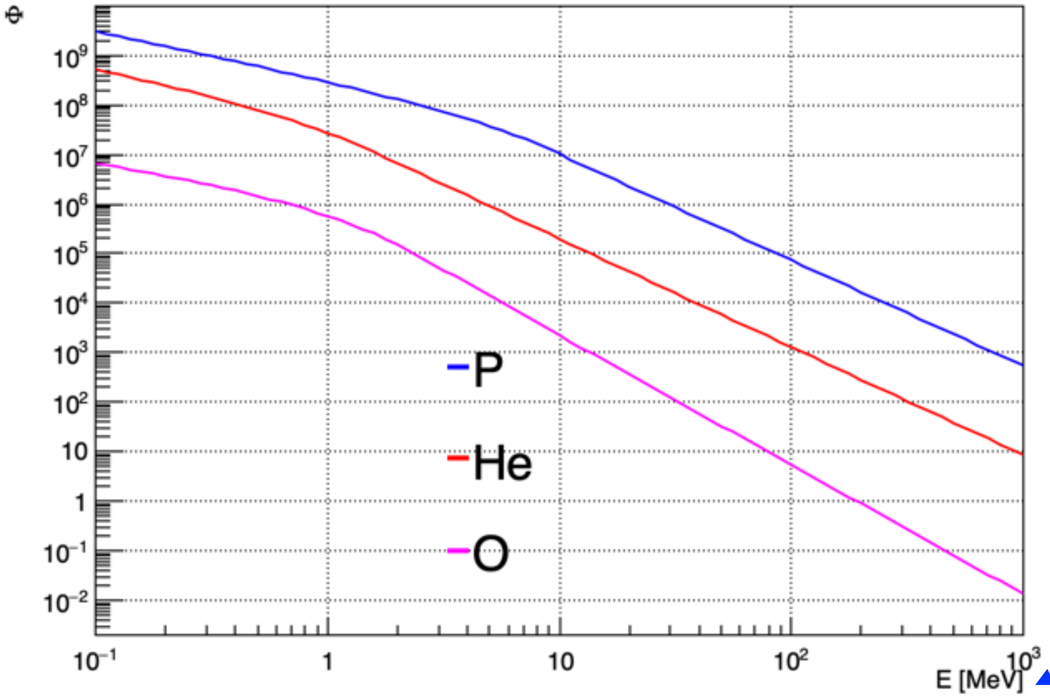
As we tried to say in Norbury et al., <u>measurements with the He </u>would be very important.
Unfortunately at the moment it is not easy to have the energy of our interest at the GSI (and in Europe).
On this topic we reserve to make a talk in the future.

back up

Pro and Con of the Solar Maximum choice

From the point of view of radiation risk, Solar Max is taken as the preferred choice for Far From Earth missions. This is true from the point of view of dose from GCR

However, during Solar Max periods, the frequency of Solar Particle Events (SPE) is significantly higher



Example:
energy spectra from SPE of 20 Jan 2005

Mostly low energy protons

Warning: this is total kinetic energy

Countermeasurements to be taken by astronauts

A ~fast warning of SPE is possible: ~ 1 hour in advance

At present astronanuts can take shelter under their baggages in the cargo bay

Courtesy of F. Ballarini (Pv)

https://www.youtube.com/watch?v=70GrihLXmSs

Other possible countermeasurements against SPE and GCR

Beyond the choice of Solar Max periods as favourite period for travelling:

- Active (magnetic field) shielding *(research)*
- R&D to improve SPE forecasting and alert
- R&D to reduce travel time *(research on nuclear propulsion...)*
- Anti-oxydant rich diet
- Ibernation during travel *(research: it's not the science fiction cryogenic one…)*

About Solar Min periods: both on the Moon and Mars underground shelters have to be considered

In case of long periods in an orbiting station around the Moon, Solar Minimum is however an issue

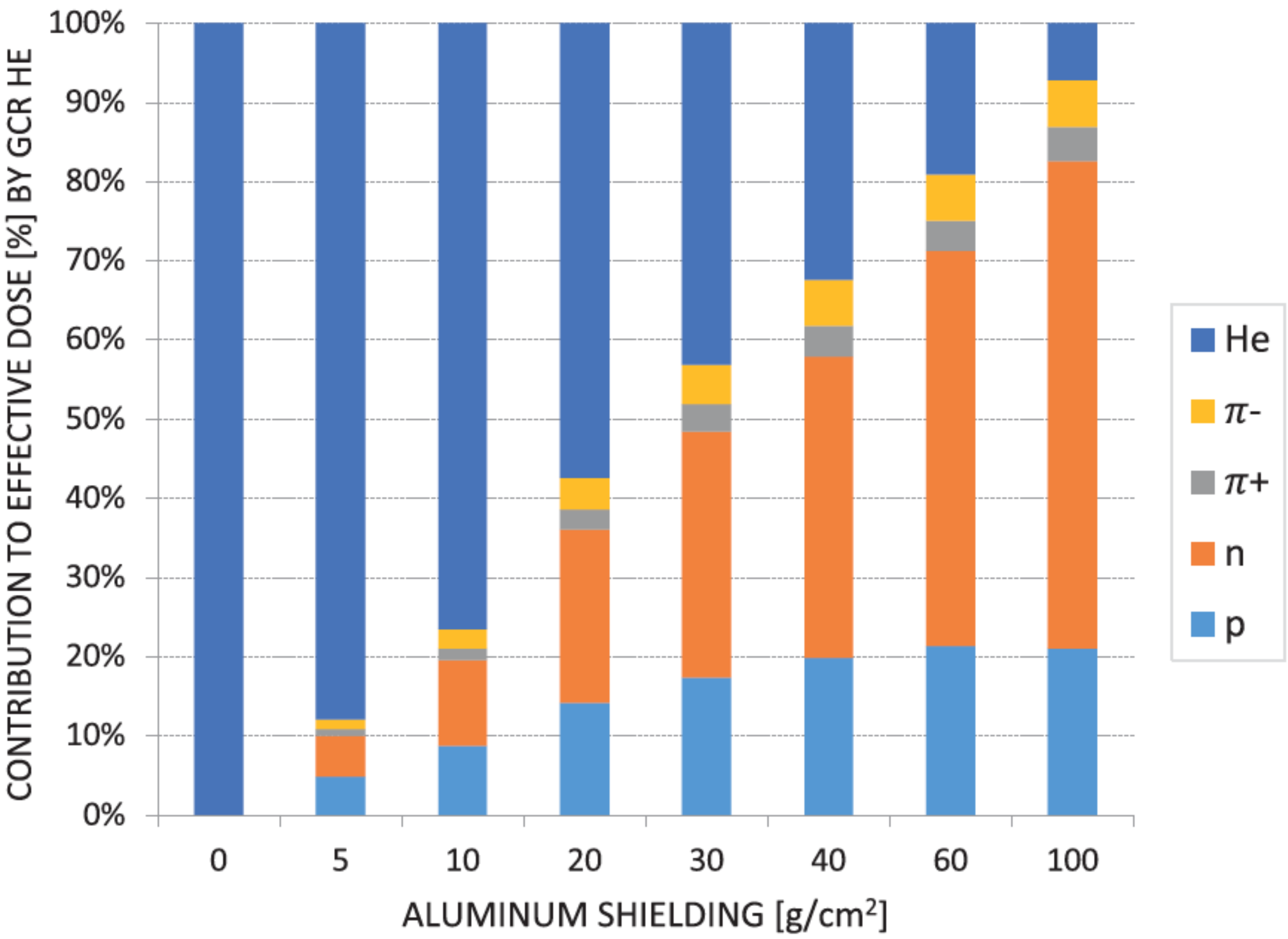
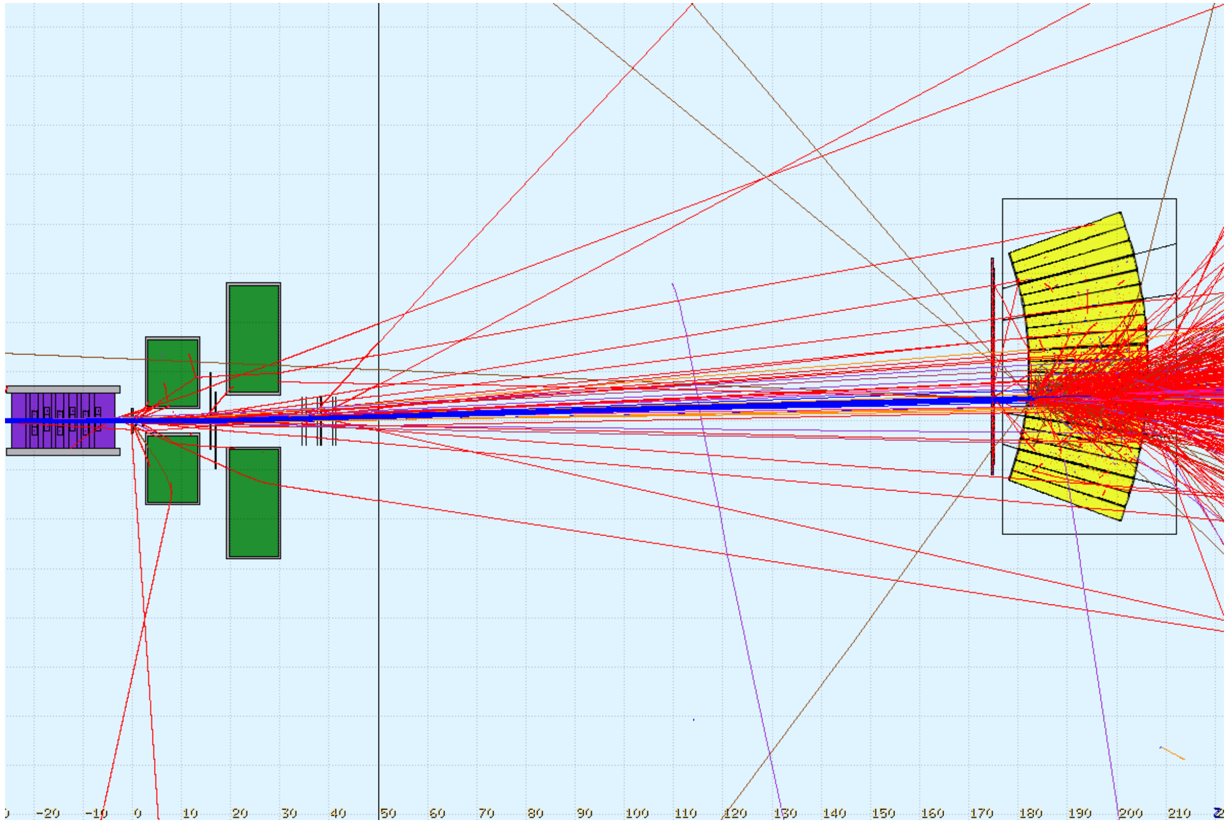
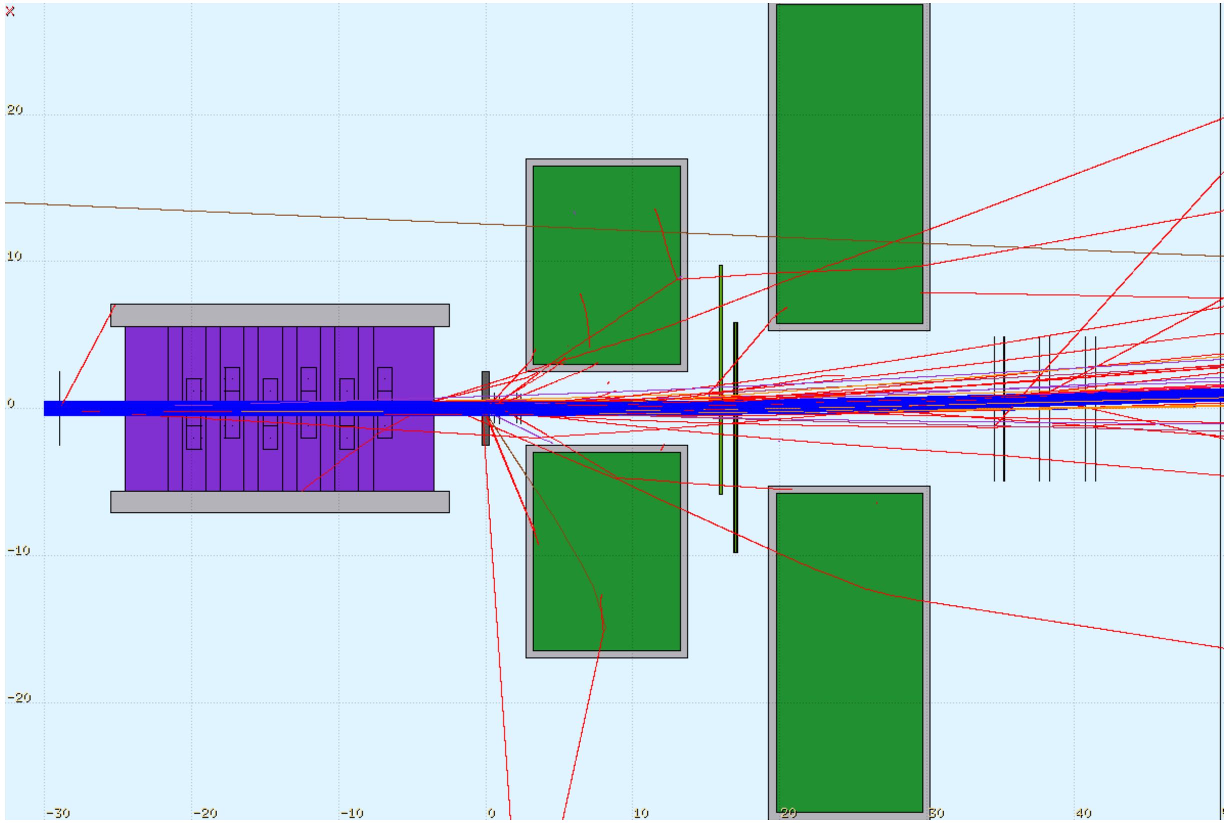
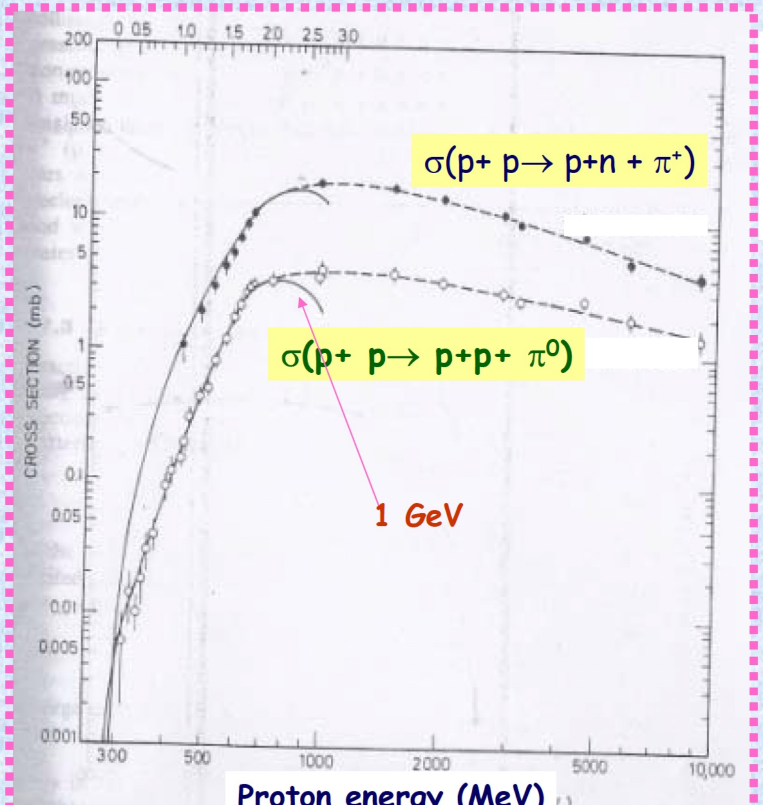


FIGURE 10 | Geant4 simulation of the percent contribution to the male effective dose of He GCR, showing in percentage the radiation component responsible for the GCR HE dose (either primary He or secondary particle generated by GCR He). Total male NASA effective dose has been calculated with ICRP Publication 123 fluence to dose conversion factors. 0 g/cm^2 refers to a free space scenario and applying the NASA quality factors.

Full MC simulation







Cross section for pion production