Simulation studies for the GSI 2026 campaign

G. Battistoni, S. Muraro

Introduction

In 2023 some discussion has started about the relevant energies for measurements of interest for Space Radioprotection.

In September 2023, during the Physics Meeting, we have 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

With the approval of the MOFFIITS (MAECI) project, we started a more in-depth discussion during the FOOT Coll. Meeting Dicember 2023:

https://agenda.infn.it/event/37748/contributions/217807/attachments/114212/163813/SpaceRadProt_GMeetTrento23_new.pdf

In early 2024 we agreed to take data at GSI in 2025 with ^{16}O @ 500 MeV/u. A preliminary study has been presented at the Foot Coll. Meeting June 2024 :

https://agenda.infn.it/event/40055/contributions/233765/attachments/122534/179381/MCupdate.pdf

We discovered on that occasion that it would not be possible to go to the GSI in 2025.

We are now going to prepare a request to bio-PAC for 2026.

In this presentation we try to give useful elements to decide which energy and configuration of the electronic set-up can be reasonably proposed.

Deadline for 2026 GSI Bio-PAC

Beamtime applications

Period for Proposal Submission:
Bio-PAC <http://www.gsi.de/bio-pac>: mid-January to mid-March 2025

Outline

- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

FLUKA MC updates

https://www.fluka.org

For all recent simulation we started to use the last release of FLUKA: 2024.1.2

Now also available on the linux upgraded machines of tier1 at the path:

/opt/exp_software/foot/fluprogfor2024.1.2

Release notes available at: http://www.fluka.org/fluka.php?id=release_notes&mm2=3

For a while we shall also maintain the older version 2021.2.9:

/opt/exp_software/foot/fluprogfor2021.2.9

However, interested people are strongly recommended to use the new version

FLUKA MC updates

https://www.fluka.org

All about the physics models of the code and the new developments can be found in a very recent (*63 pages!!!*) open access paper:

EPJ Nuclear Sci. Technol. **10**, 16 (2024)
© F. Ballarini et al., Published by EDP Sciences, 2024
https://doi.org/10.1051/epjn/2024015

EPJ Nuclear Sciences & Technologies

Available online at:
https://www.epj-n.org

Status and advances of Monte Carlo codes for particle transport simulation, edited by Andrea Zoia, Cheikh Diop and Cyrille de Saint Jean

REGULAR ARTICLE **OPEN ACCESS**

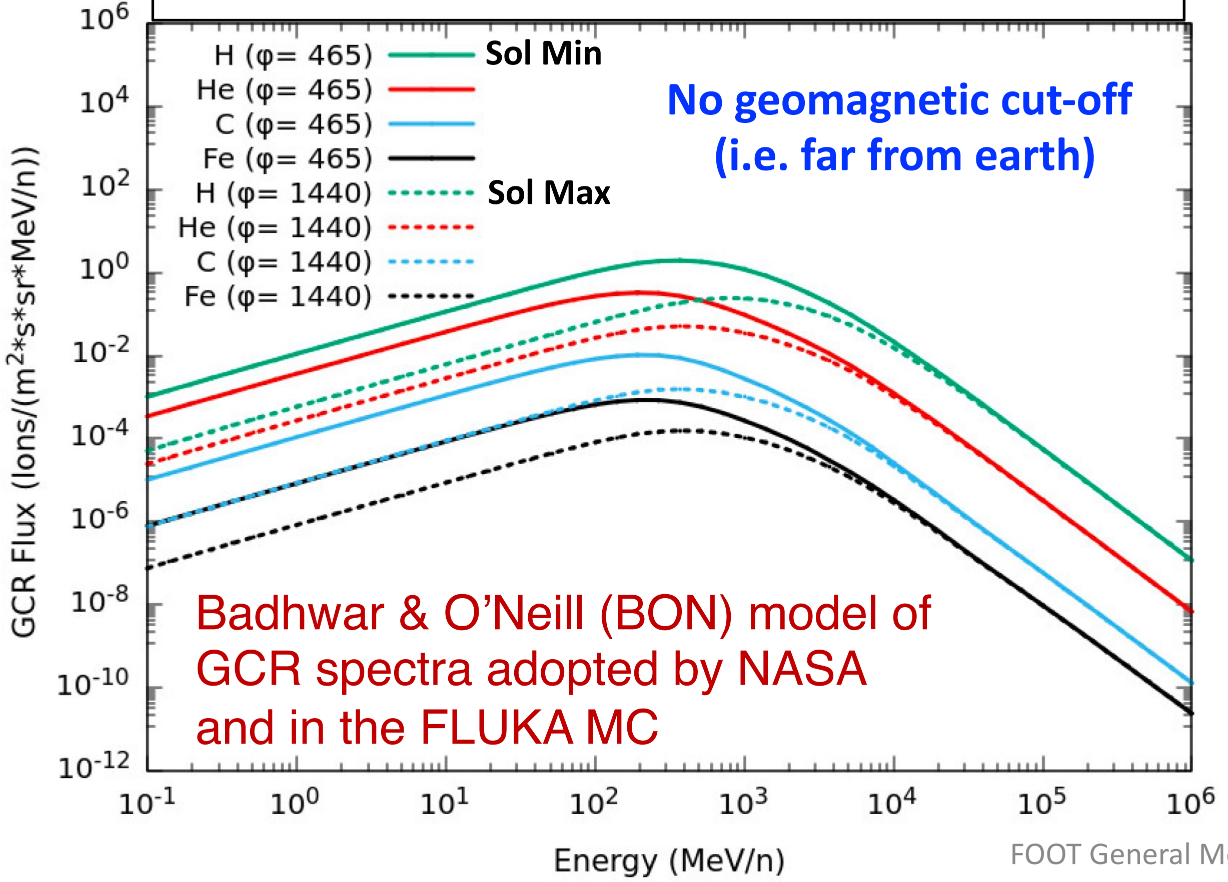
The FLUKA code: Overview and new developments

Outline

- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

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!

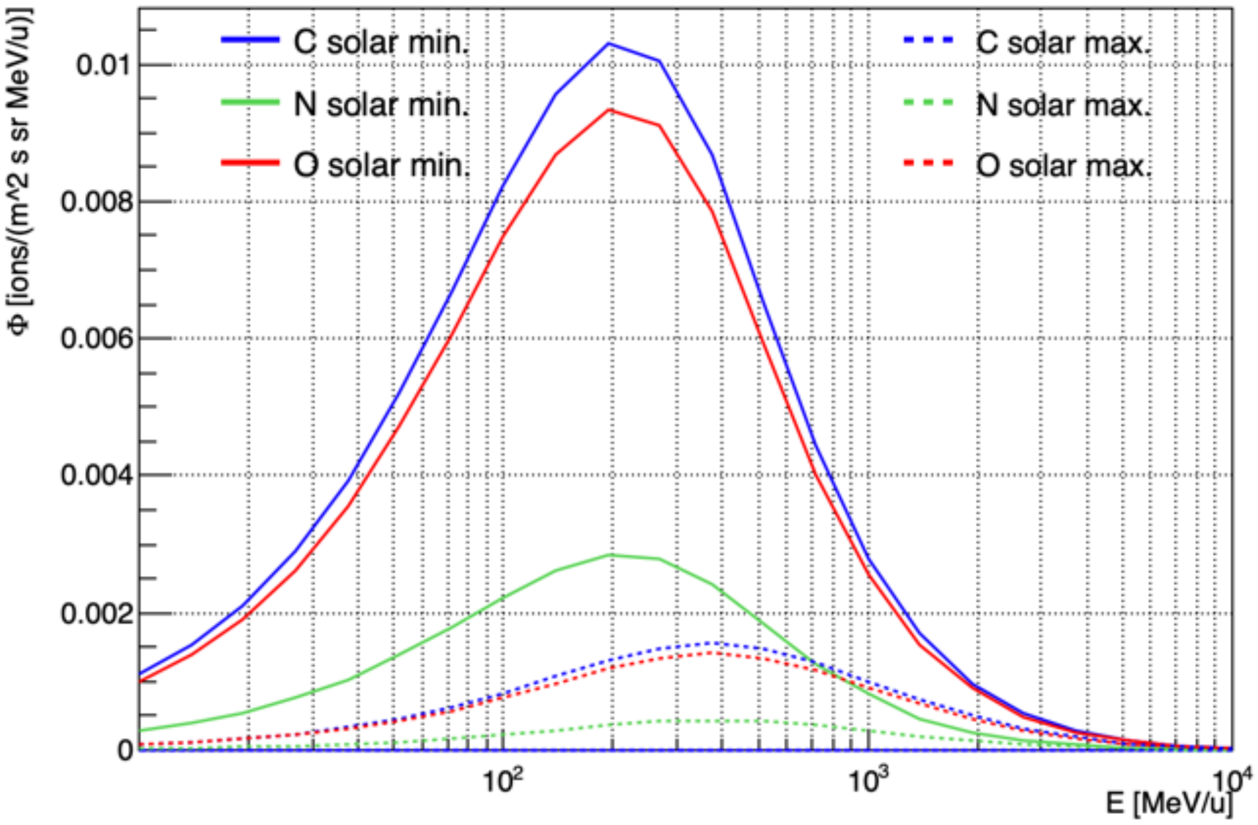
- Earth Magnetic field (coordinate dependent, relevant for all missions in Low Earth Orbit, e.g. on the International Space Station)

Example for C,N,O spectra

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

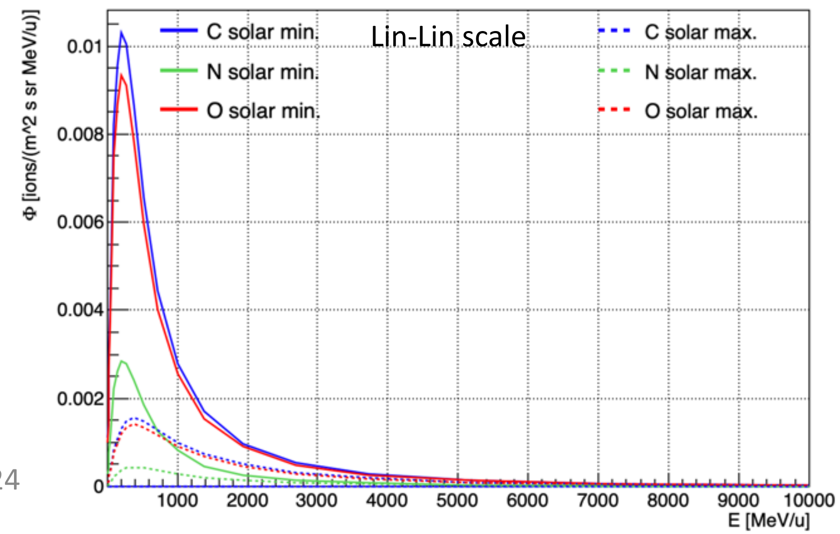
No geomagnetic cut-off (i.e. far from earth)

Lin-Log scale



The peak energy for C,O moves from ~200 MeV/u at solar min to ~400 MeV/u at solar max.

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



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 GCRs and their secondaries produced in the shielding of the spacecraft. This is usually considered the most crucial contribution for long duration space travels

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

Dose contribution from GCR

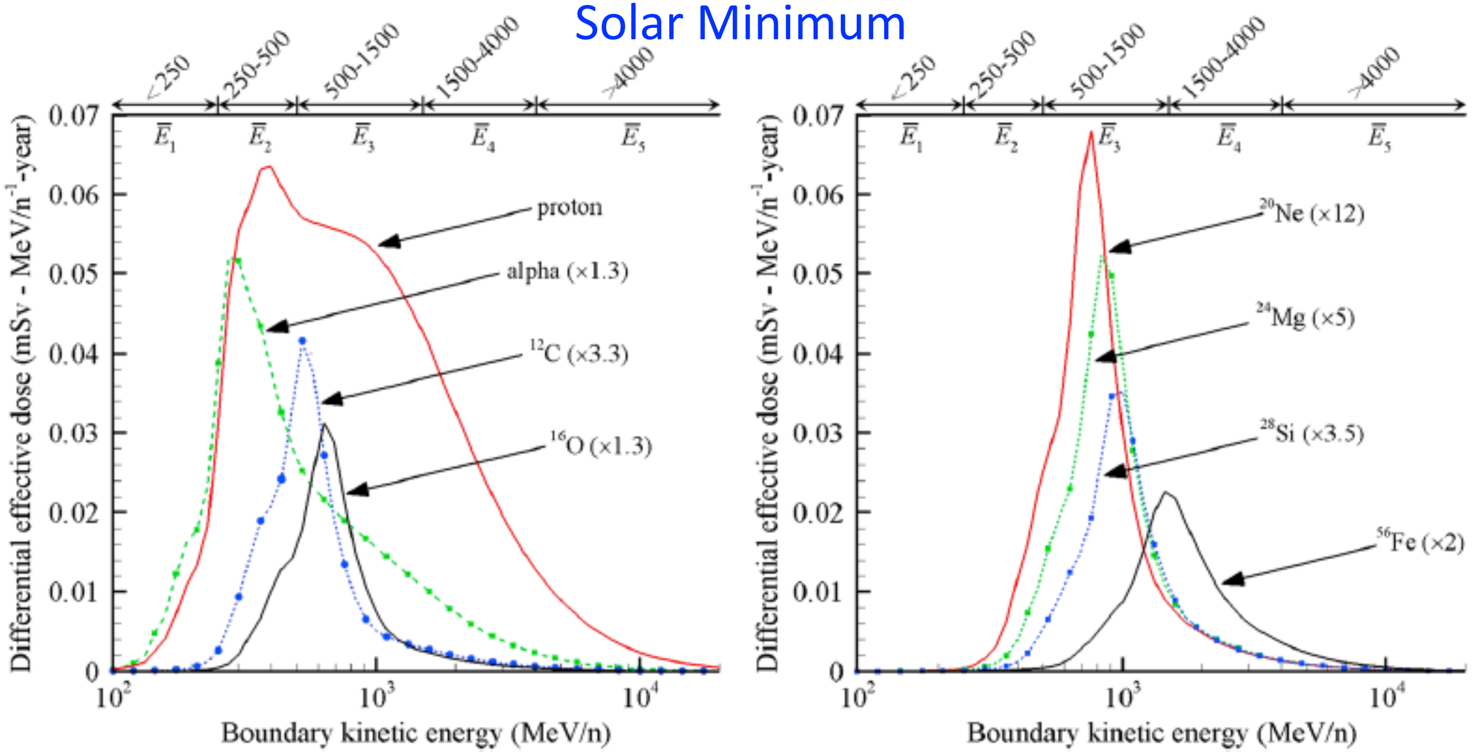
on the basis of BON spectra (2010 update)

GCR environmental models I: Sensitivity analysis for GCR environments

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

[1]NASA Langley Research Center, Hampton, Virginia, USA

Solar Minimum



Differential effective dose rate as a function of incident kinetic energy behind 20 g/cm^2 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

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

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 = $ 3-10	0.0	3.3	3.8	1.3	0.8	9.1
$Z = $ 11-20	0.0	0.2	6.6	2.0	1.1	10.0
$Z = $ 21-28	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

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**: $E_3 + E_4 + E_5 = 91\%$ $E_4 + E_5 = 57\%$

Outline

- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

The 2020 paper by J. Norbury et al.

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

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]

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

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

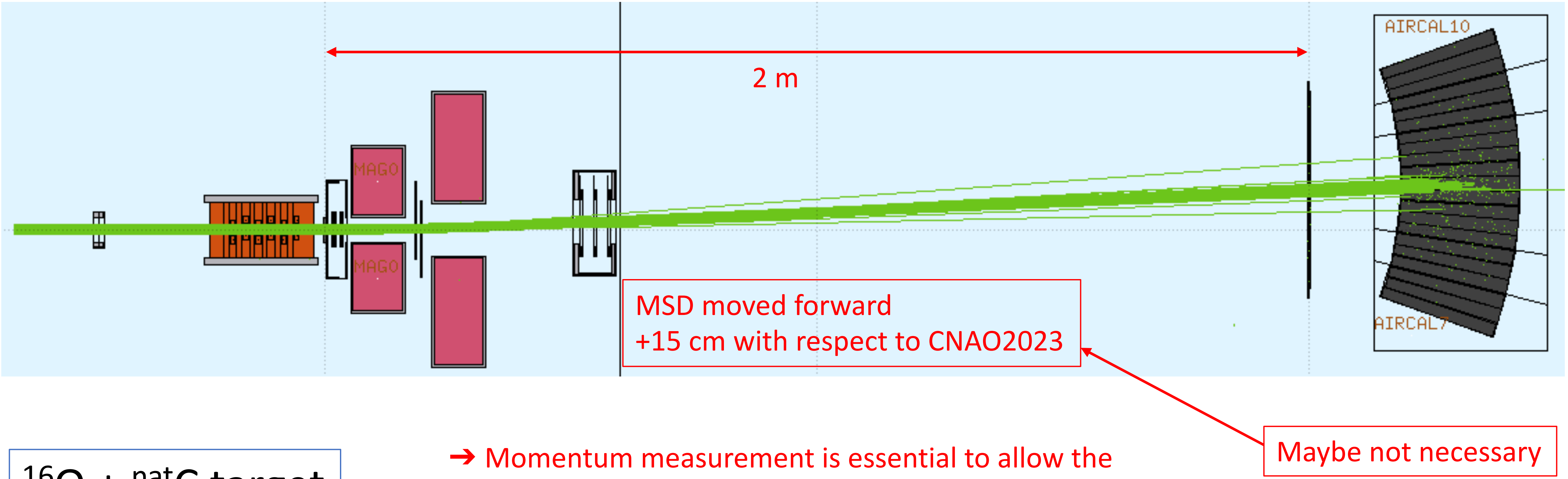
- No double differential cross section data exist for light ion fragment production from O projectiles above the pion threshold (>280 MeV/n).
- Energies > 500 MeV/u have to be considered in any case, better if up to 1500 MeV/u.
- Most important targets: H, C, O, Ca, Al, [Fe] (secondary production in shielding is important)
- Priority has to be given to the double differential cross sections for the production of **light fragments**

Outline

- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

Campaign GSI25PS_MC

Cloned from CNAO23PS_MC with few differences



^{16}O + ^{nat}C target

➔ Momentum measurement is essential to allow the measurement of differential cross sections dσ/dE

Available MC Productions

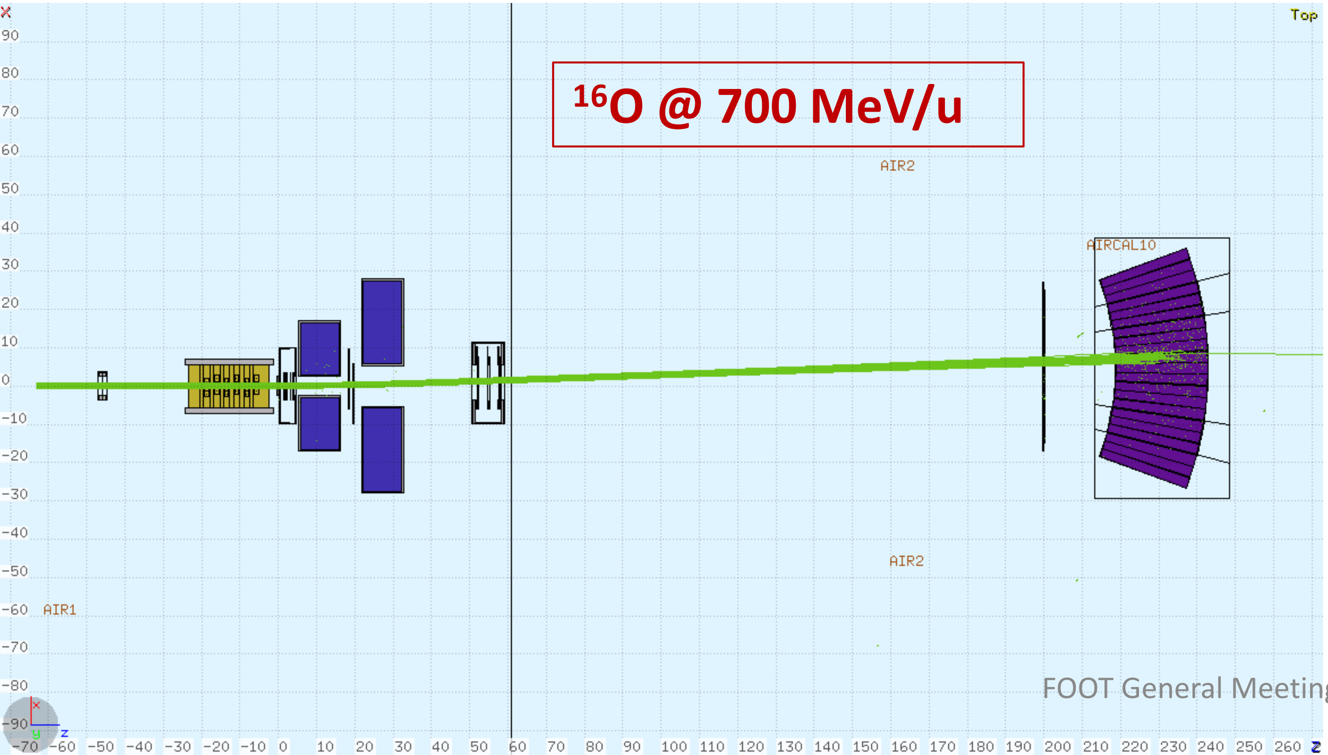
Due to these considerations, we started to compare the results for three energies:

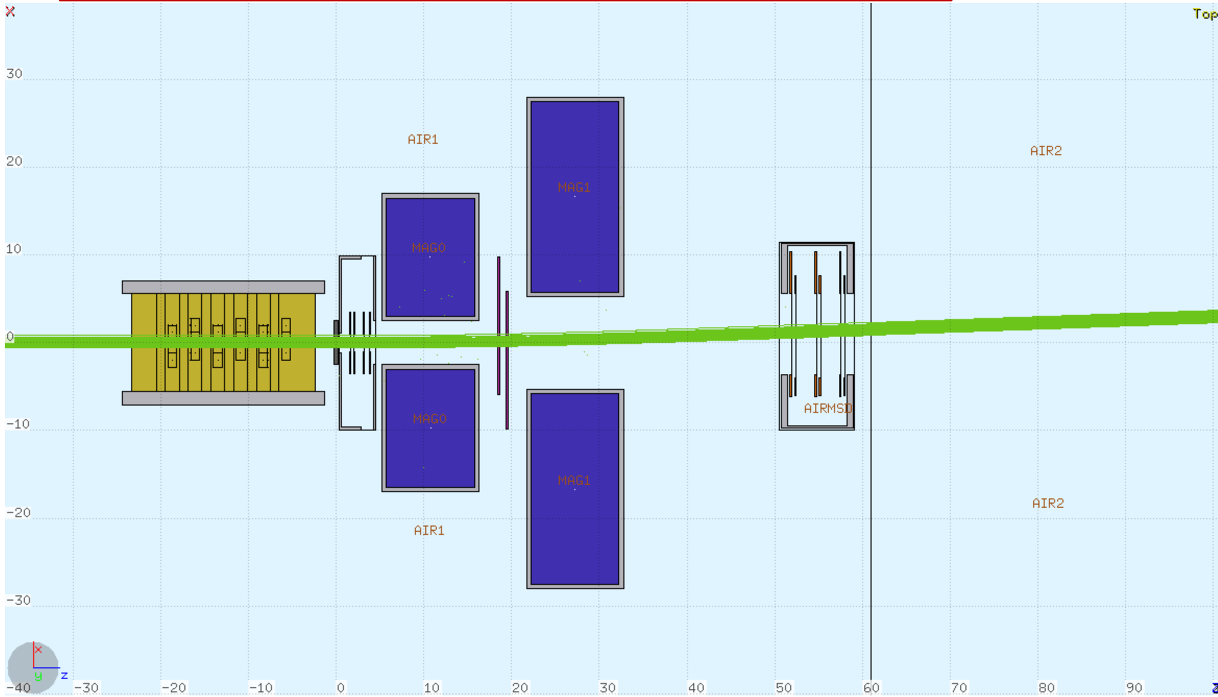
Marco Durante told us that the maximum energy used in Cave A was 1 GeV/u

^{16}O @ 500 MeV/u; 700 MeV/u; 1 GeV/u

^{nat}C target

10^6 events available for each run





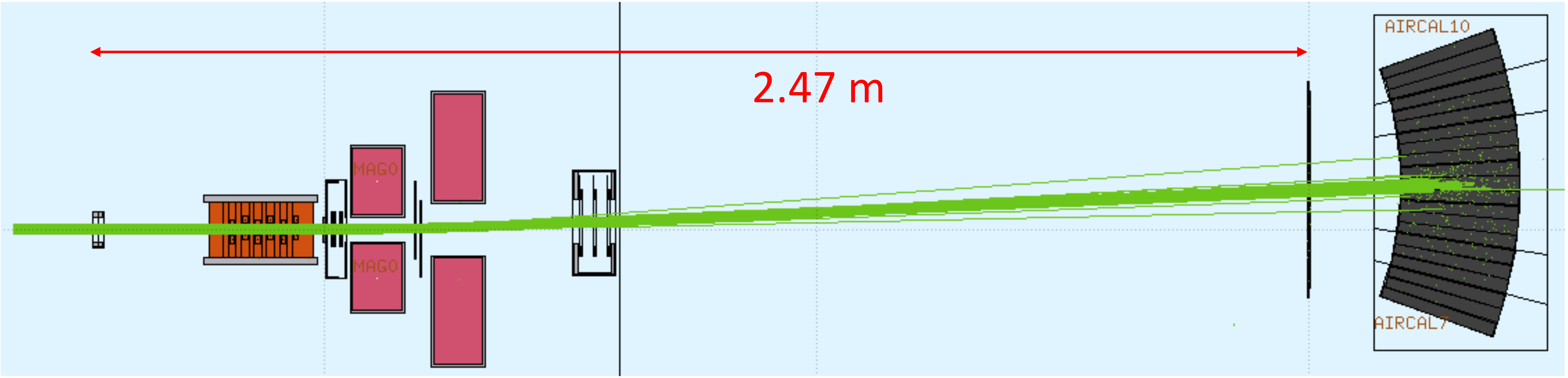
Shoe Genfit reconstruction

Outline

- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

Overall size of GSI2025 detector hypothesis

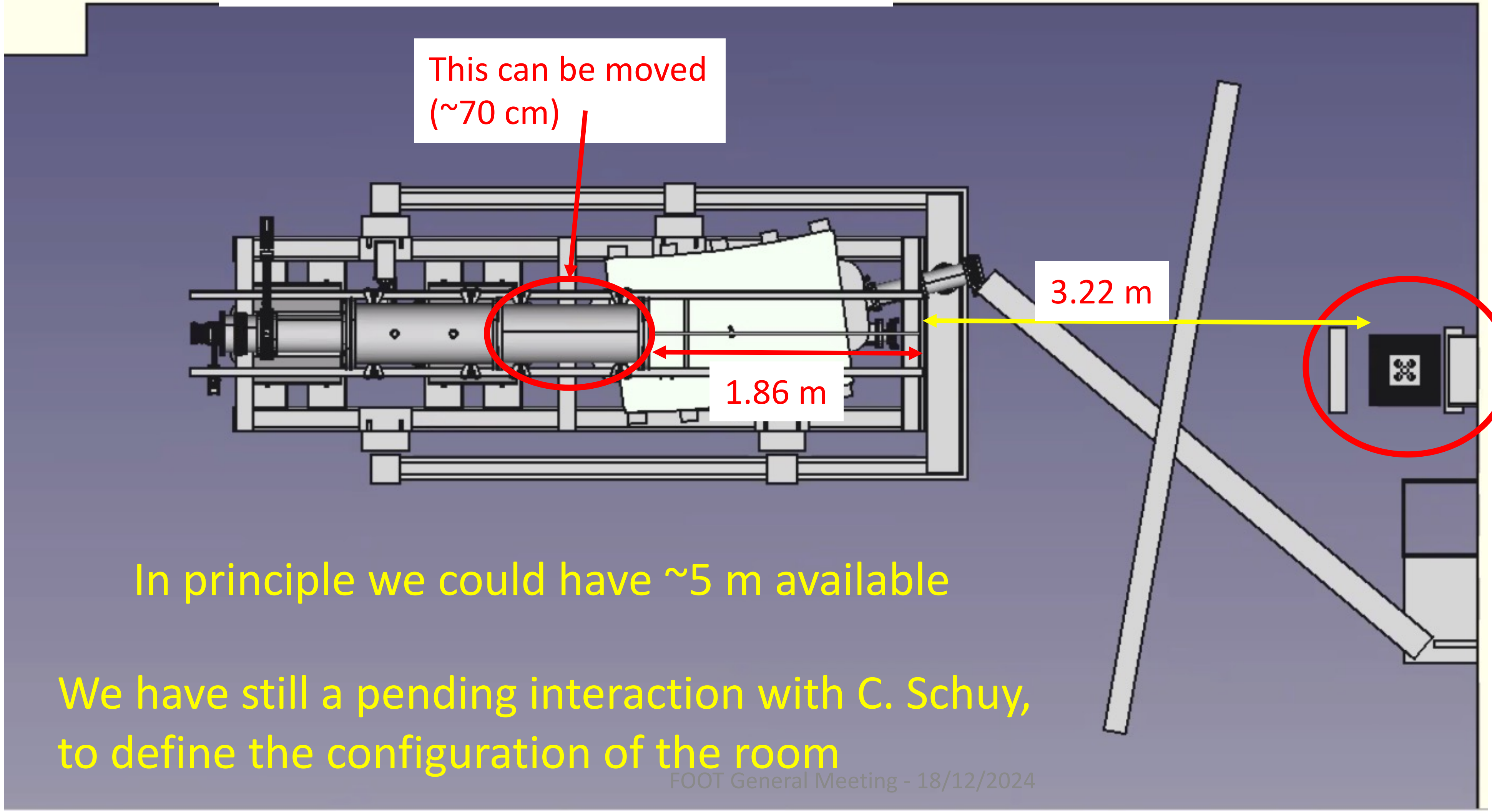
For “high” energies it’s important to have a large distance between target and TW.



Calo would need
2 m of total space

Is there enough room in Cave A?

From a meeting with C. Schuy on June 20th

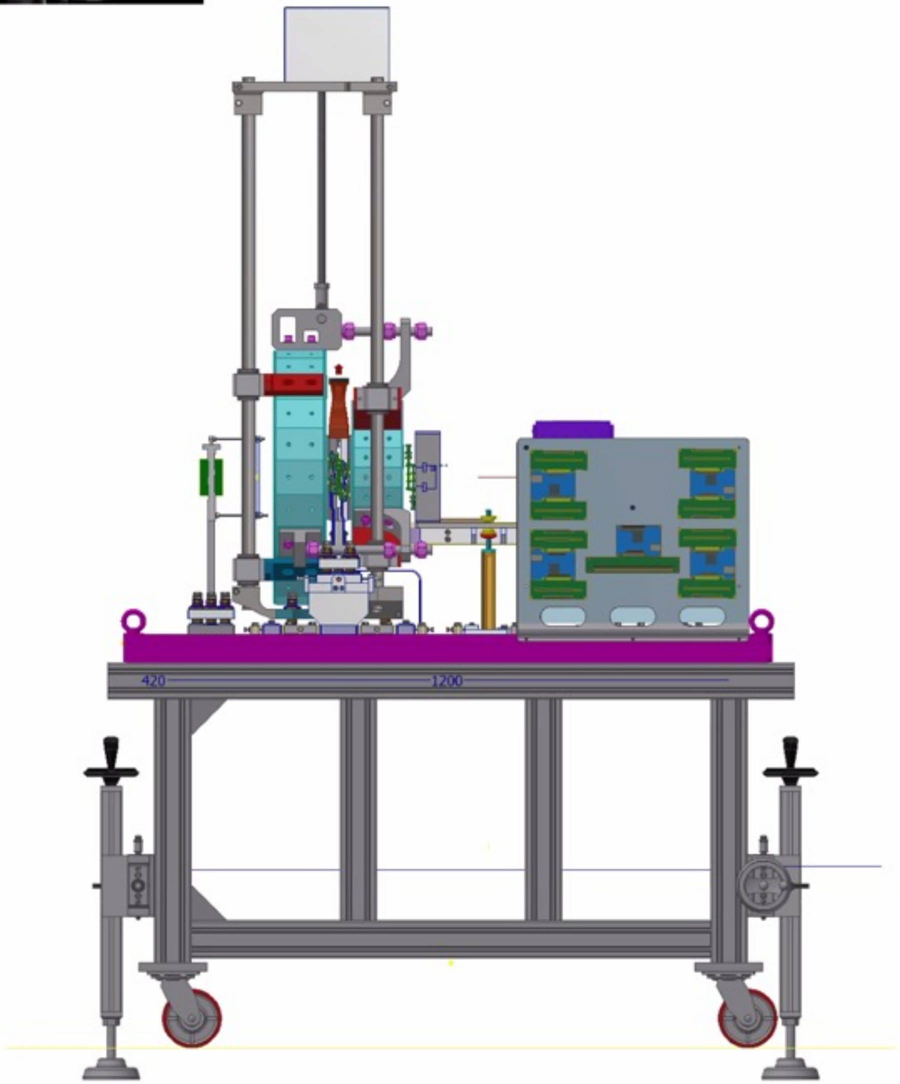


In principle we could have ~5 m available

We have still a pending interaction with C. Schuy, to define the configuration of the room

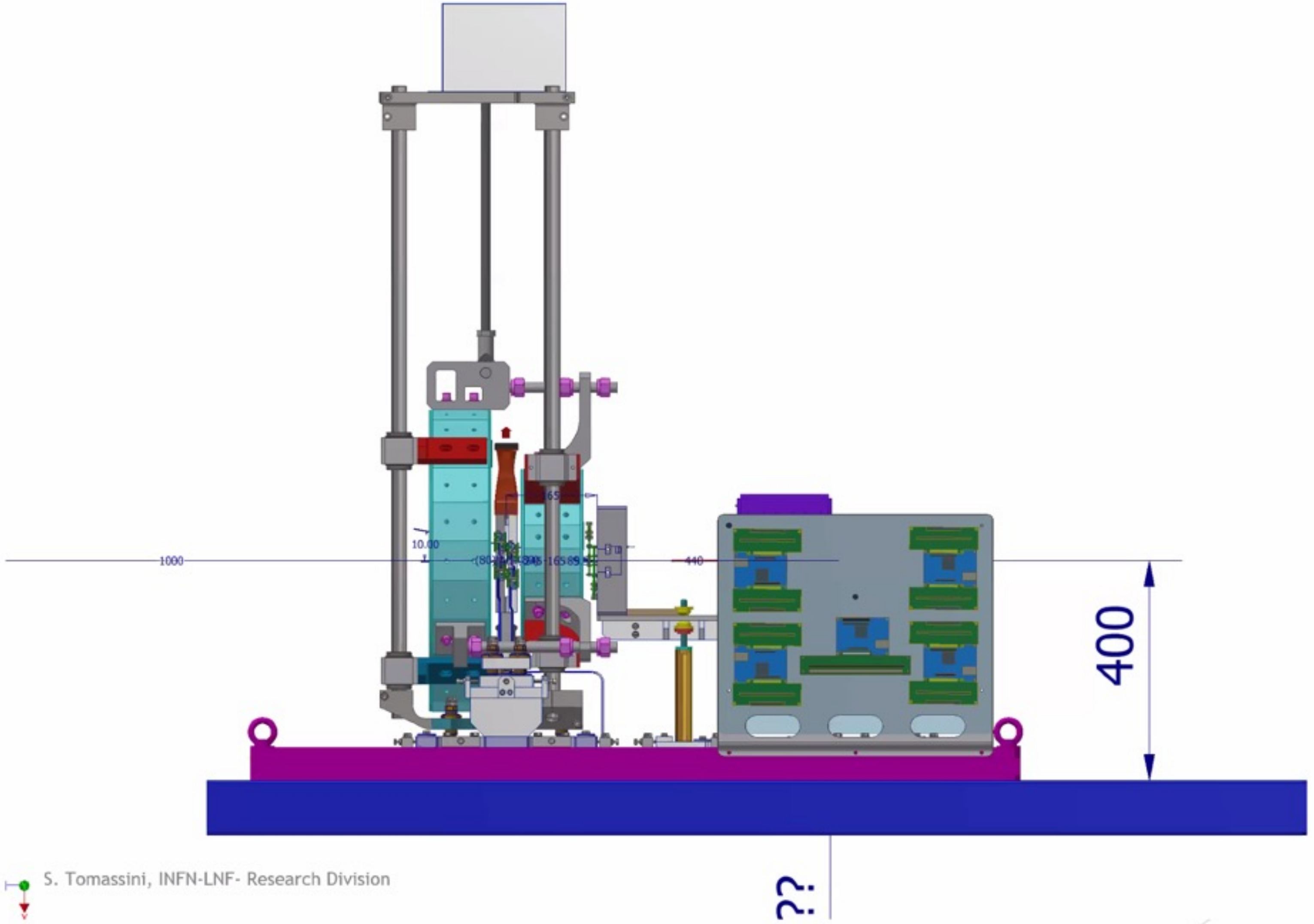
Layout @ CNAO

From a Zoom meeting with S. Tomassini on 22 March 2023

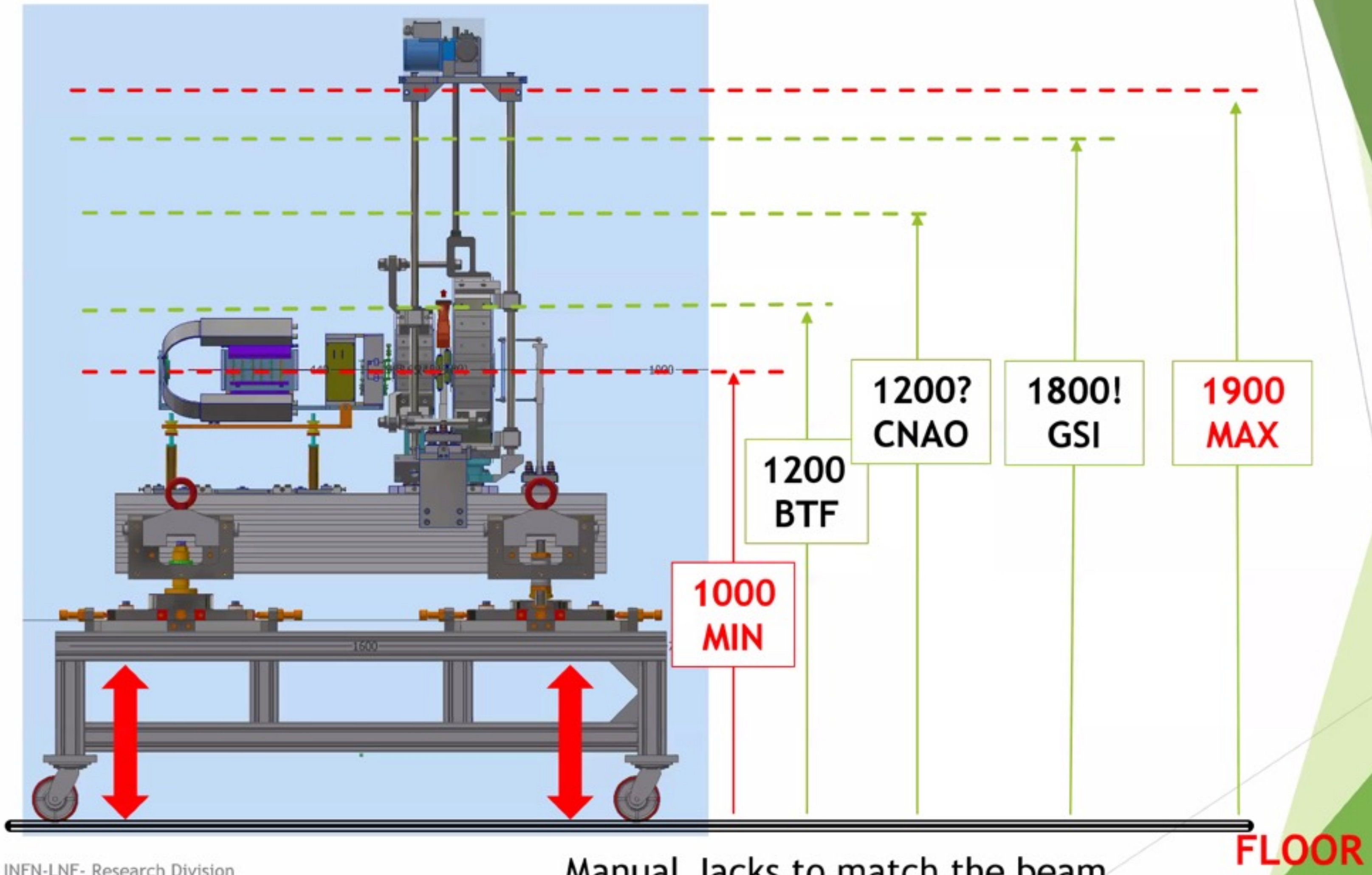


S. Tomassini, INFN-LNF- Research

Layout @ GSI



BEAM LINE: *FLOOR HEIGHT*



S. Tomassini, INFN-LNF- Research Division

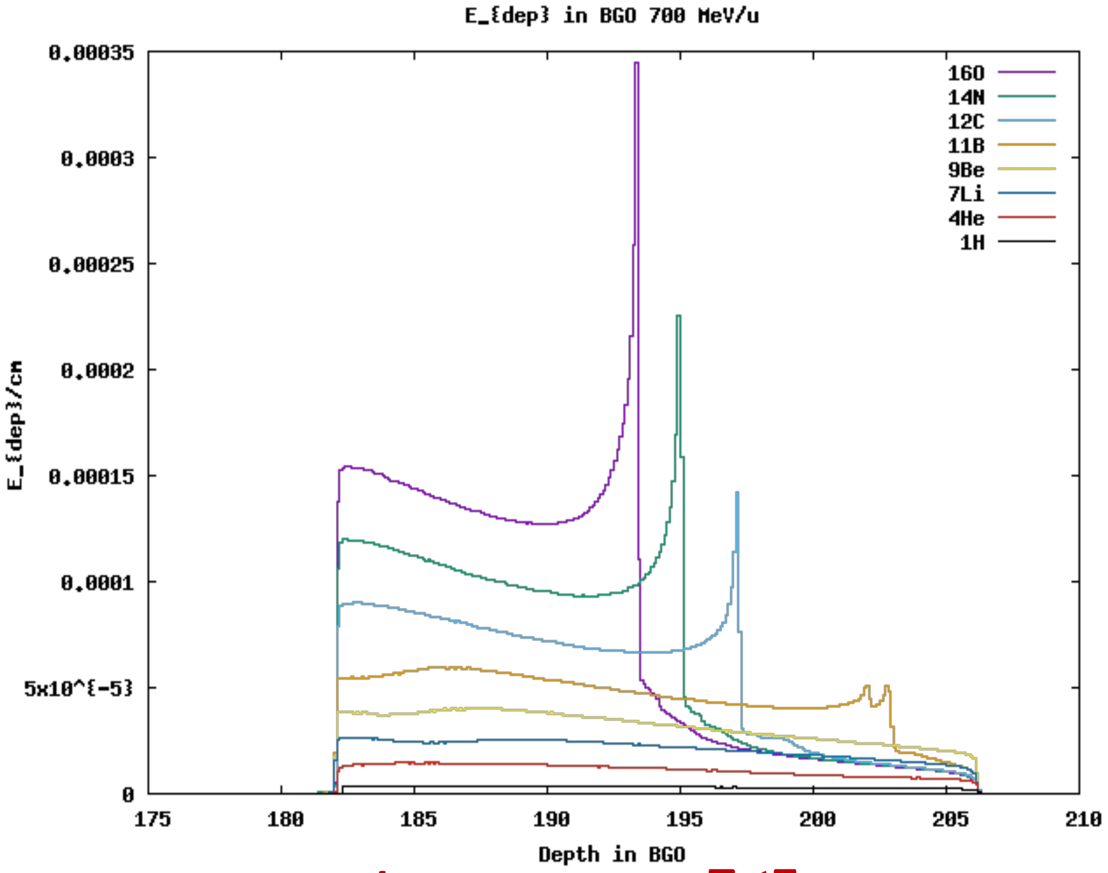
Manual Jacks to match the beam height in different sites

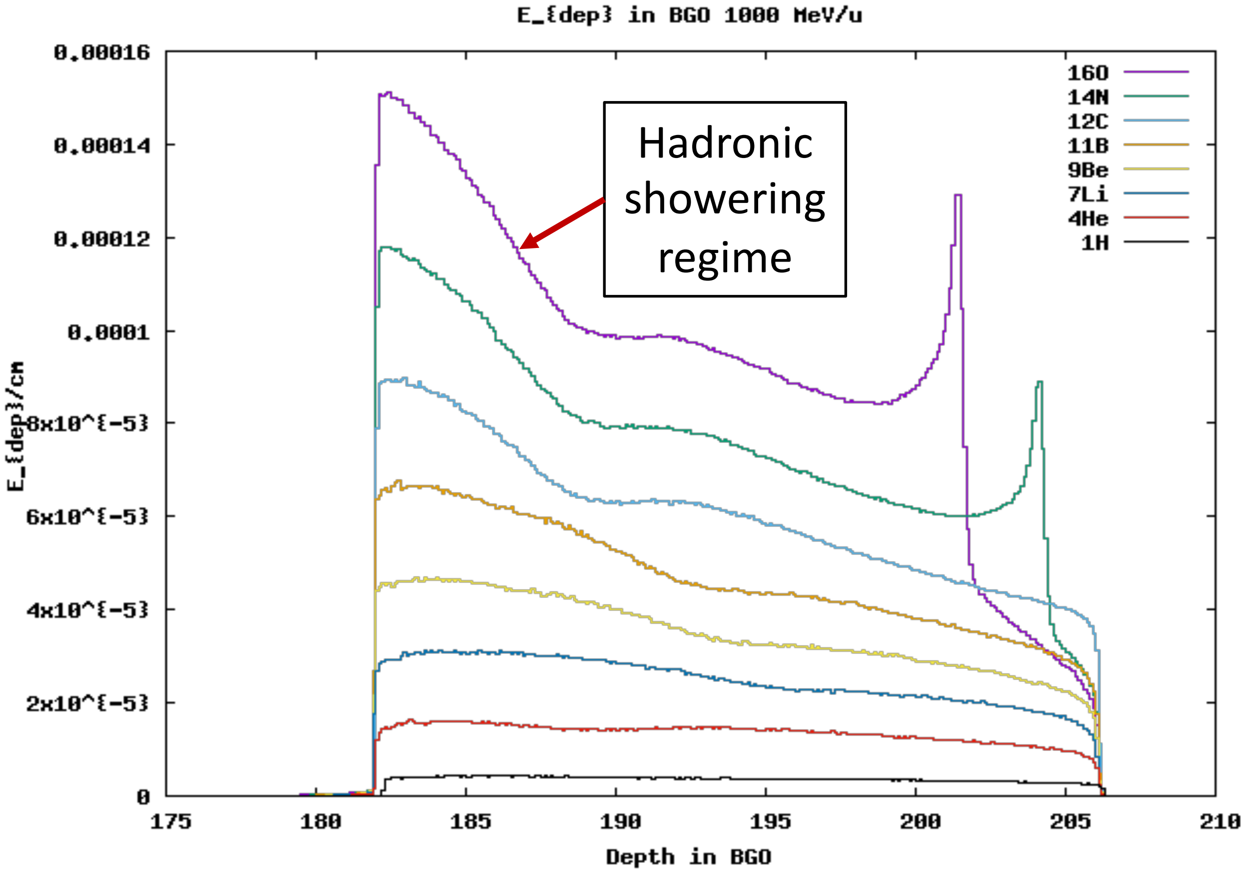
Outline

- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

Calorimeter response:
700 MeV/u and 1 GeV/u

MC truth





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

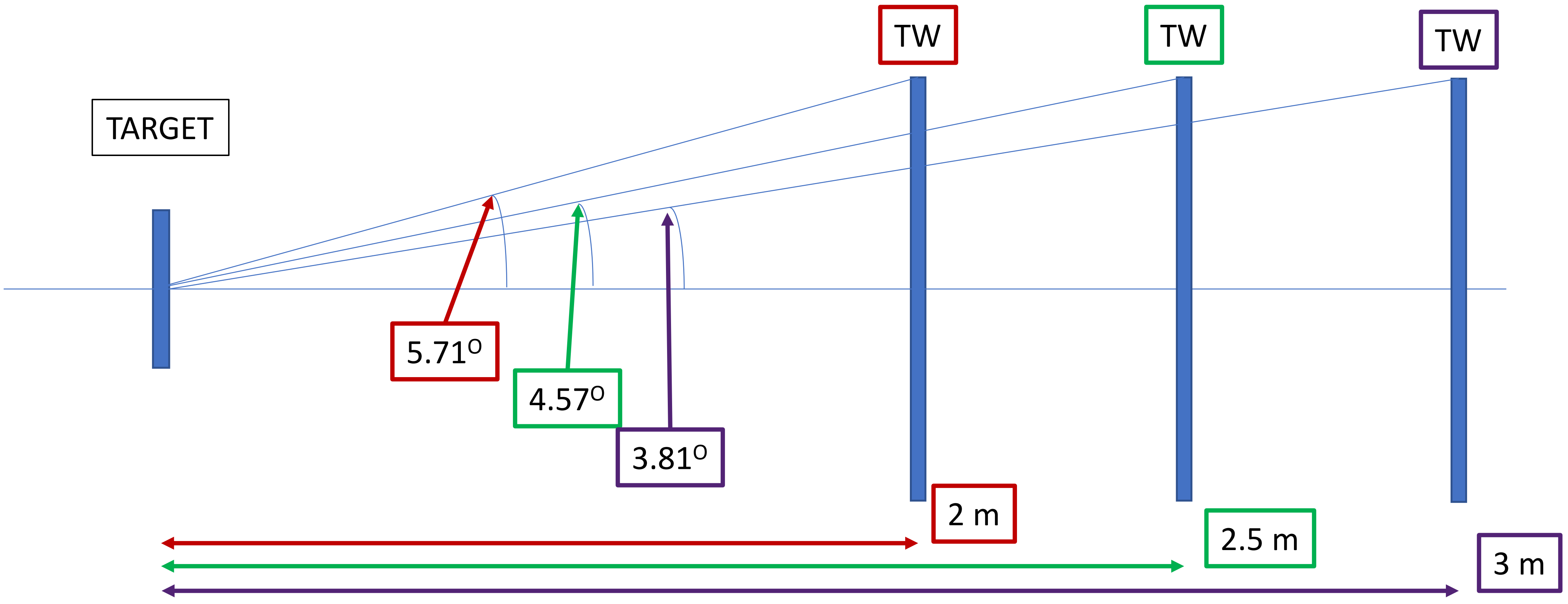
@1 GeV/u all ions with Z<7 are not contained within the depth of our BGO crystals

The lower is Z, the lower is the fraction of energy deposited in the calorimeter

Outline

- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

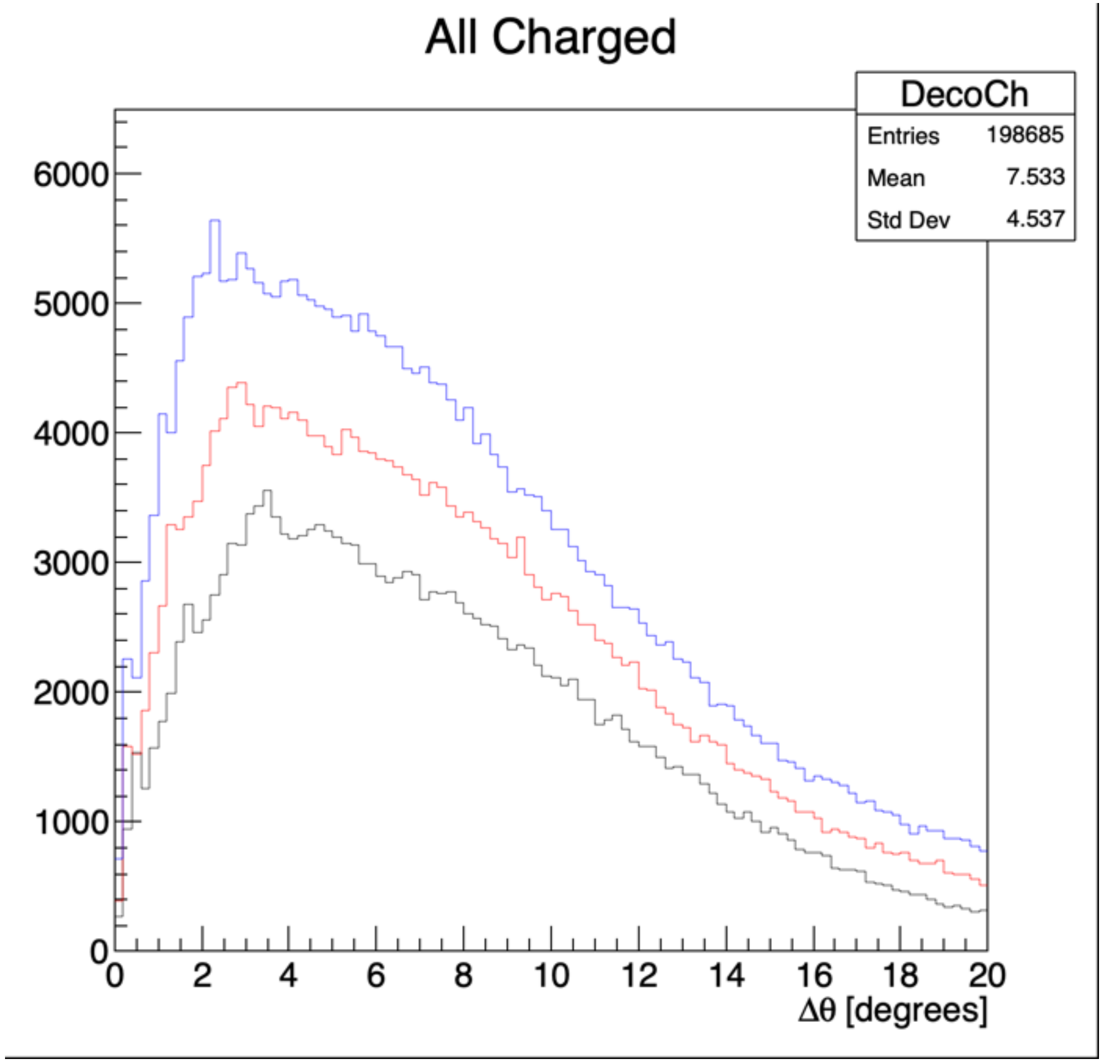
TW geometrical acceptance



We have seen how important p, He and light fragments are for radiation protection in space.
We know that they are the most widely distributed fragments.
<u>By increasing the TW distance, the angular acceptance decreases.</u>
<u>We shall see later the dependence of mass resolution on this distance.</u>

Angular Separation of tracks

secondaries arriving at the TW depth



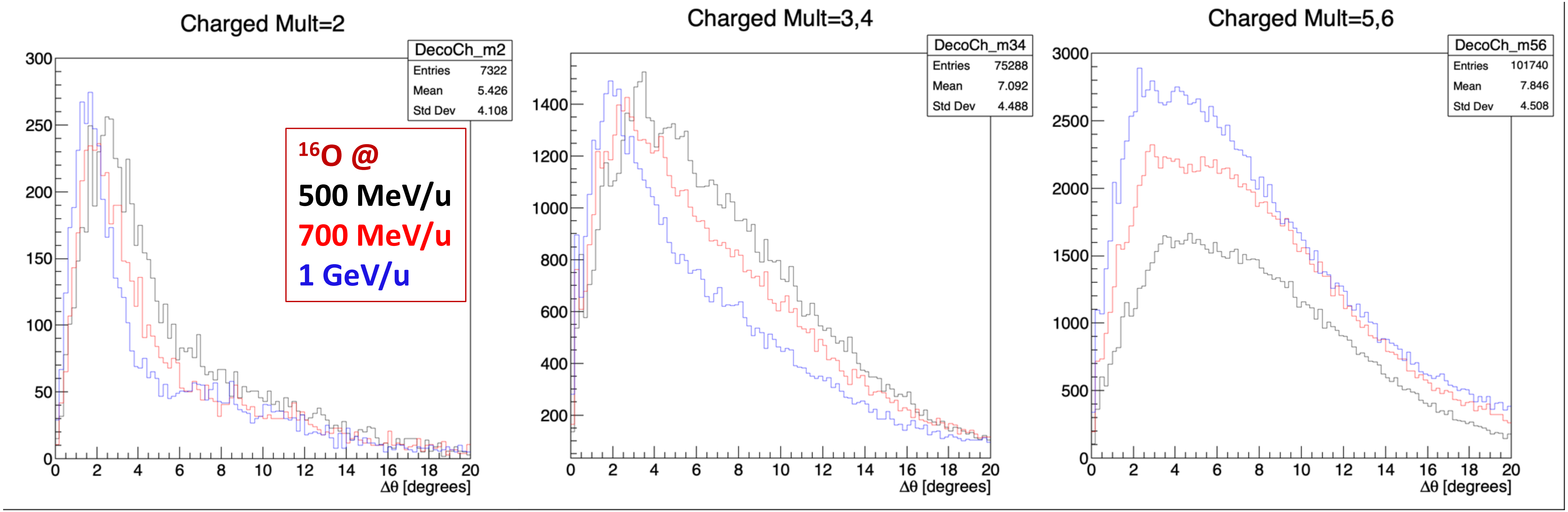
^{16}O @
500 MeV/u
700 MeV/u
1 GeV/u

MC truth

Most events can be completely contained

Angular separation of tracks VS multiplicity

particles arriving at the TW

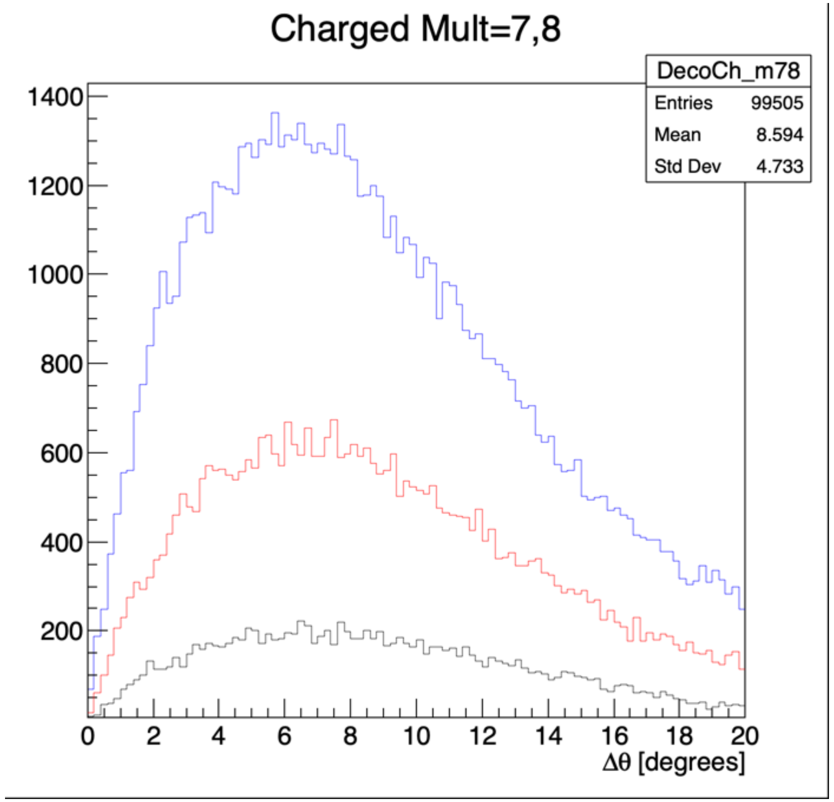


The greater the multiplicity, the greater the separation of tracks.

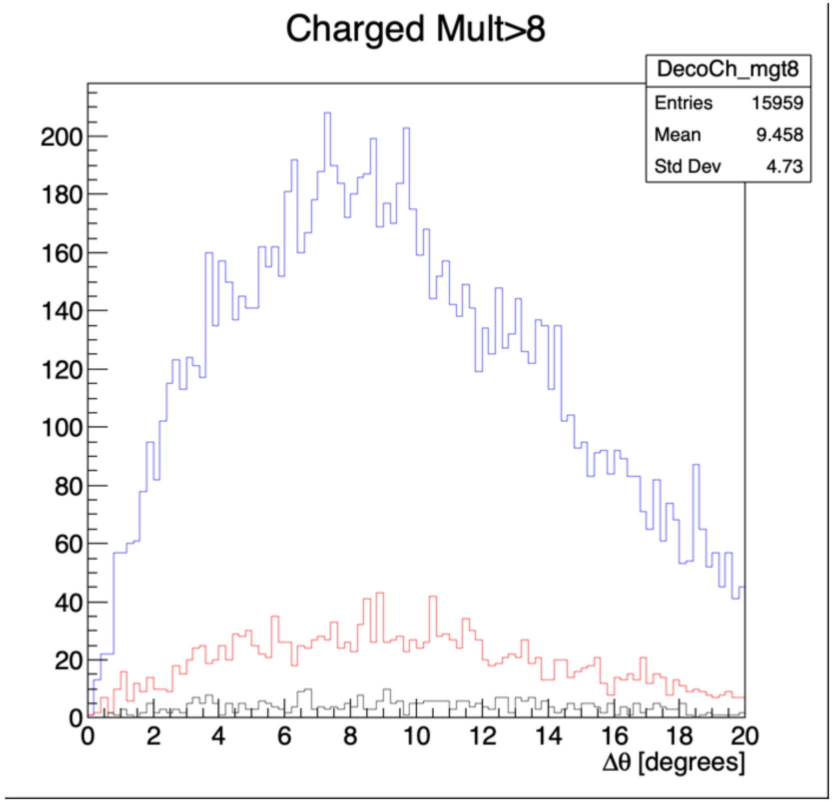
Increasing the primary energy, the number of events with more than 5 tracks grows more and more

Angular separation of tracks VS multiplicity

particles arriving at the TW



^{16}O @
500 MeV/u
700 MeV/u
1 GeV/u



At least up to multiplicity = 8 , events are almost completely contained in the TW acceptance,

BUT… the number of events with high track multiplicity becomes important.

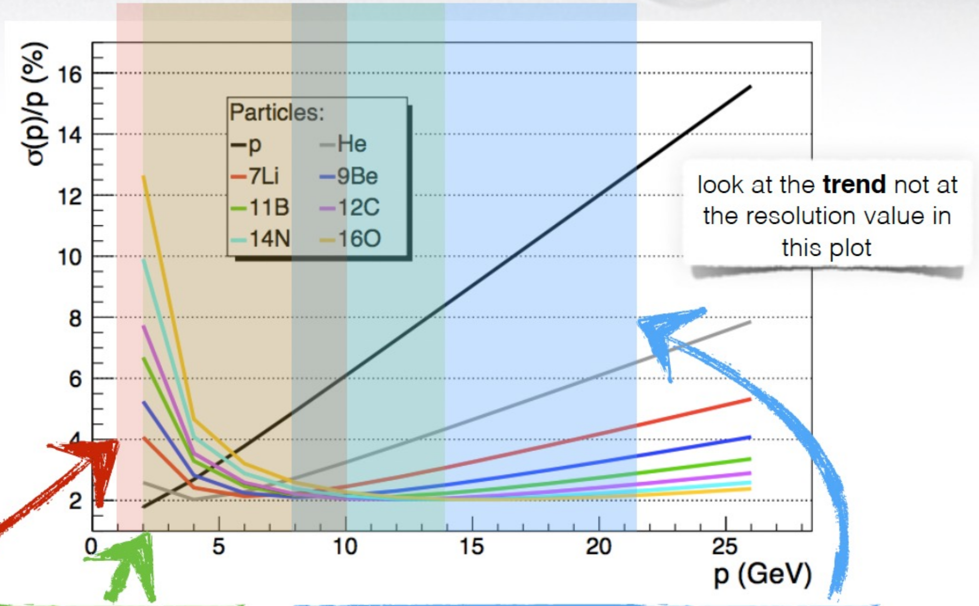
→ The new high granularity TW could be useful.

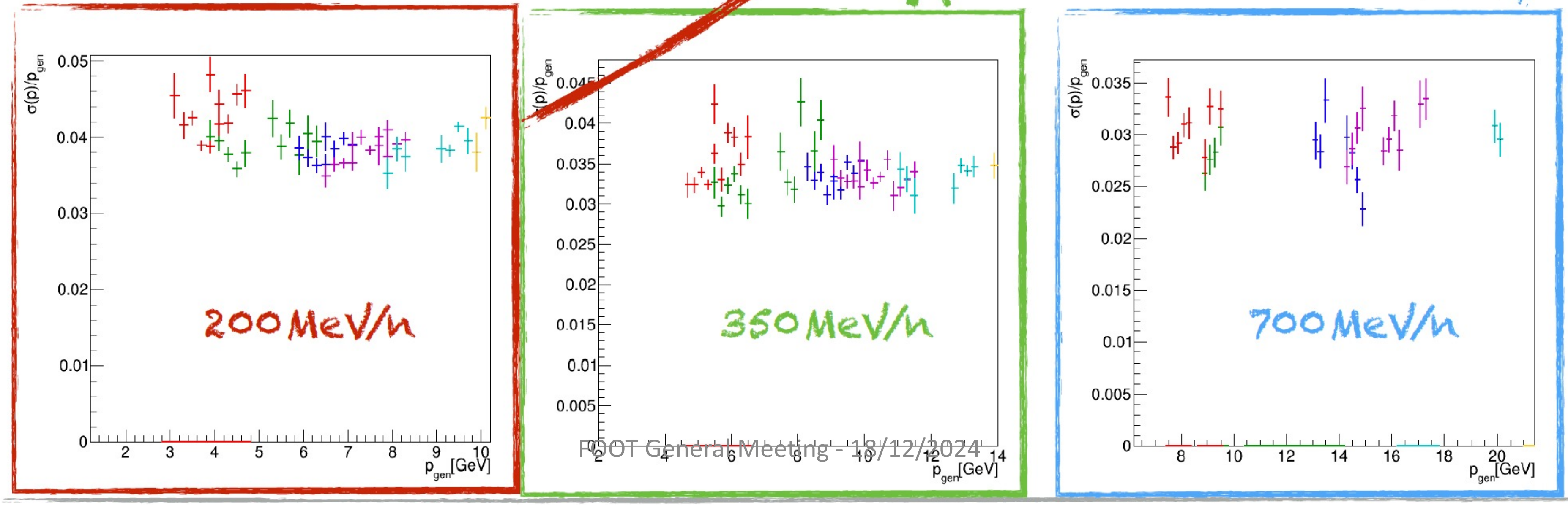
Outline

- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

From a study presented by M. Franchini at FOOT Meeting June 2018

- **At 200MeV/n**, all elements are in the "decreasing" part, dominated by ***MS contribution***;
  - **light elements** have *lower p*: MS contribution fall earlier;
  - **heavy-elements** have *higher p*: approaching minimum, MS not so high anymore;
- **At 700MeV/n**, all in region dominated by ***spatial resolution***;
  - **light elements** (steeper growth, lower-p minimum) have low p; still close to the minimum
  - **heavy elements** (grows slower, higher-p minimum) have higher p but still close to the minimum





Reconstruction criteria

Event Selection:

1. 1 Beam Monitor track
2. ≥ 1 reconstructed global track
3. $N_{tracks} = N_{TW\ points}$

Track Selection Cuts:

1. P-value > 0.02
2. 1 TW point
3. Reconstructed Vertex within target
4. Max(XY Fitted point – XY Meas. Point) in tracking det. < 0.015 cm

Warning:
dE/dx-Tof calibration not yet available at these energies and TW distance
→ *we rely upon MC-truth Z to define TW points*

Momentum resolution

Preliminary

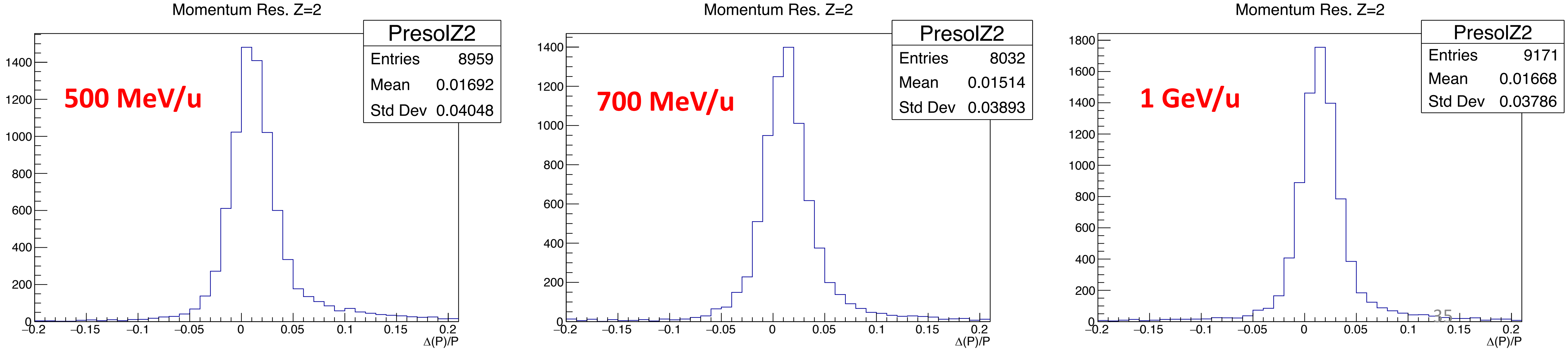
glbtrack->GetTgtMom() to obtain P from reconstructed track evaluated at production in target

$$\frac{\Delta P}{P} = \frac{(P_{rec} - P_{true})}{P_{true}}$$

Here Z = Z truth (MC)

ΔP/P (%)			
Z	**500 MeV/u**	**700 MeV/u**	**1 GeV/u**
1	4.7	4	3.7
2	4	3.8	3.7
3	4.1	4.8	4.5
4	4.6	6.3	5.5
5	4.2	4.3	4.5
6	4.6	4.6	4.5
7	3.4	3.3	3.1

Non-symmetric distributions. Notice the tails



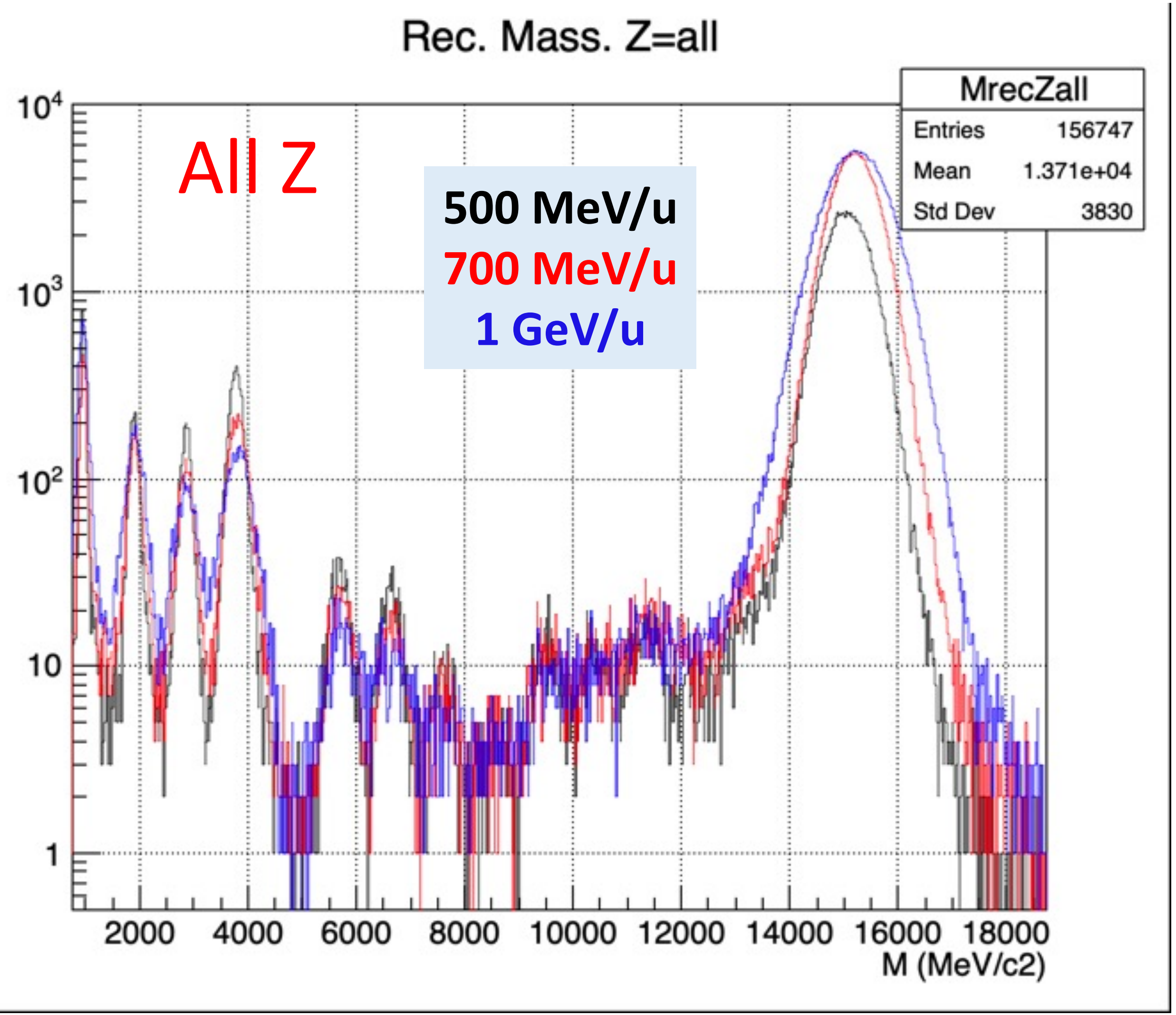
Outline

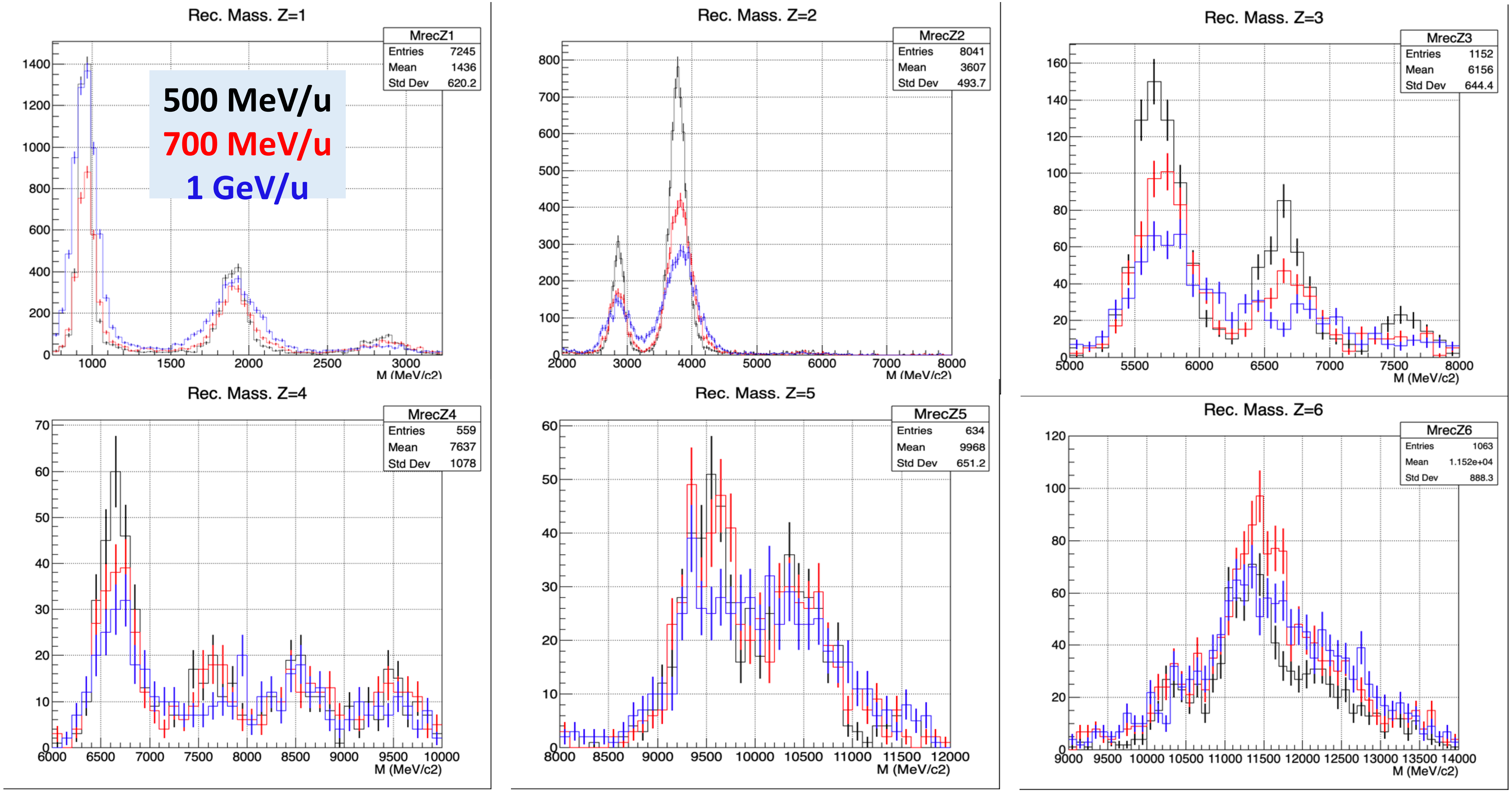
- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

Isotopic Mass-Id using P and ToF

glbtrack->GetTwTof() to obtain Tof resolution in MC from the parametrization of exp. data

$$M = \frac{P}{c\beta\gamma}$$

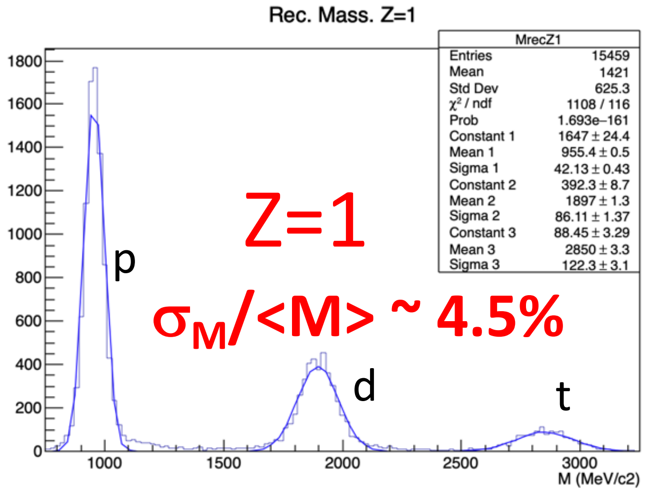


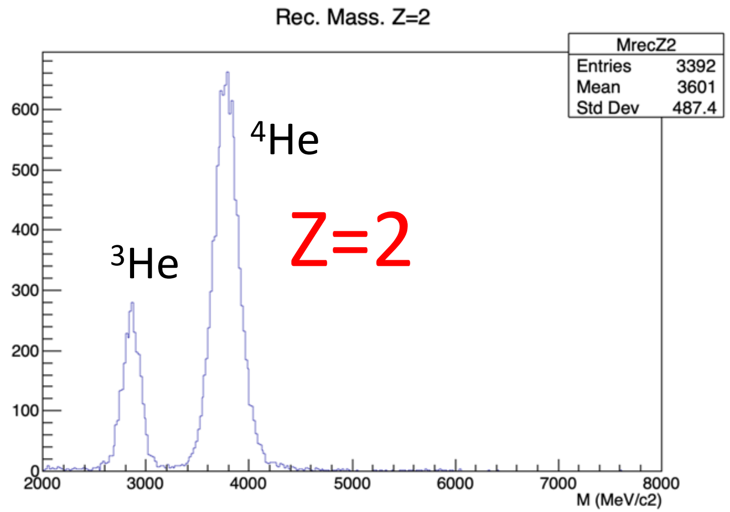


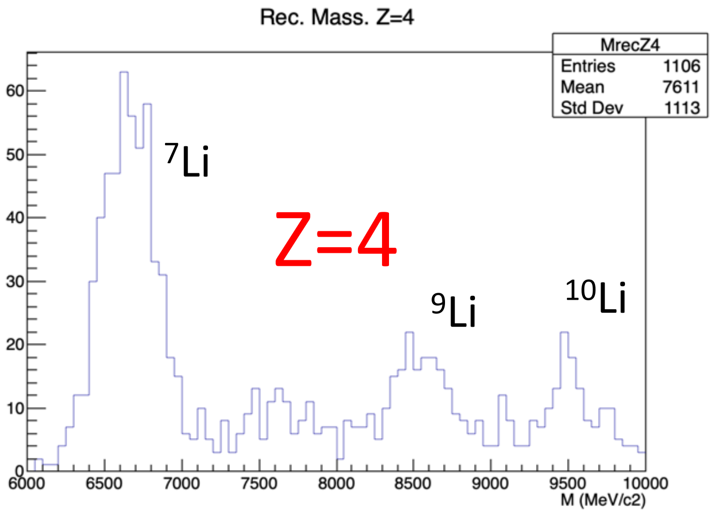
For Z>=4 the isotope cannot be distinguished.
We simulated 1 million events.
It is clear that **many more would be needed: 5 million at least? better 10 million? To be studied…**

Mass reconstruction using P and ToF

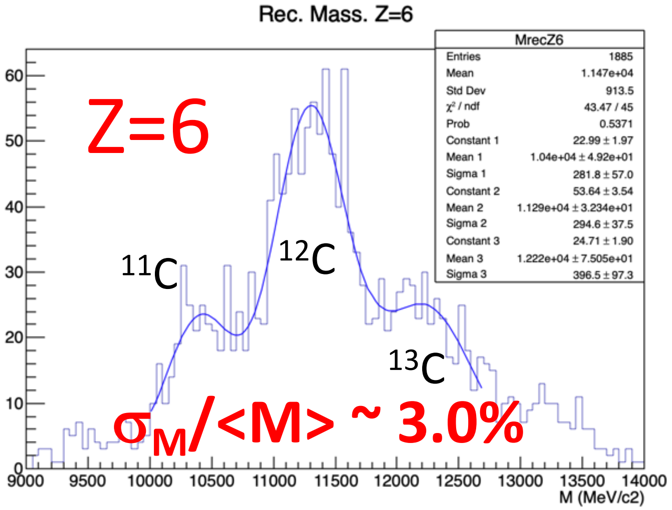
500 MeV/u

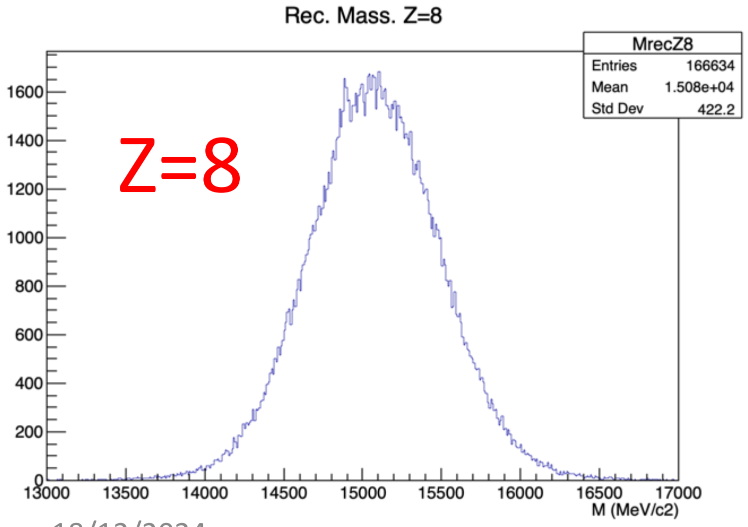






Z = Z truth (MC)



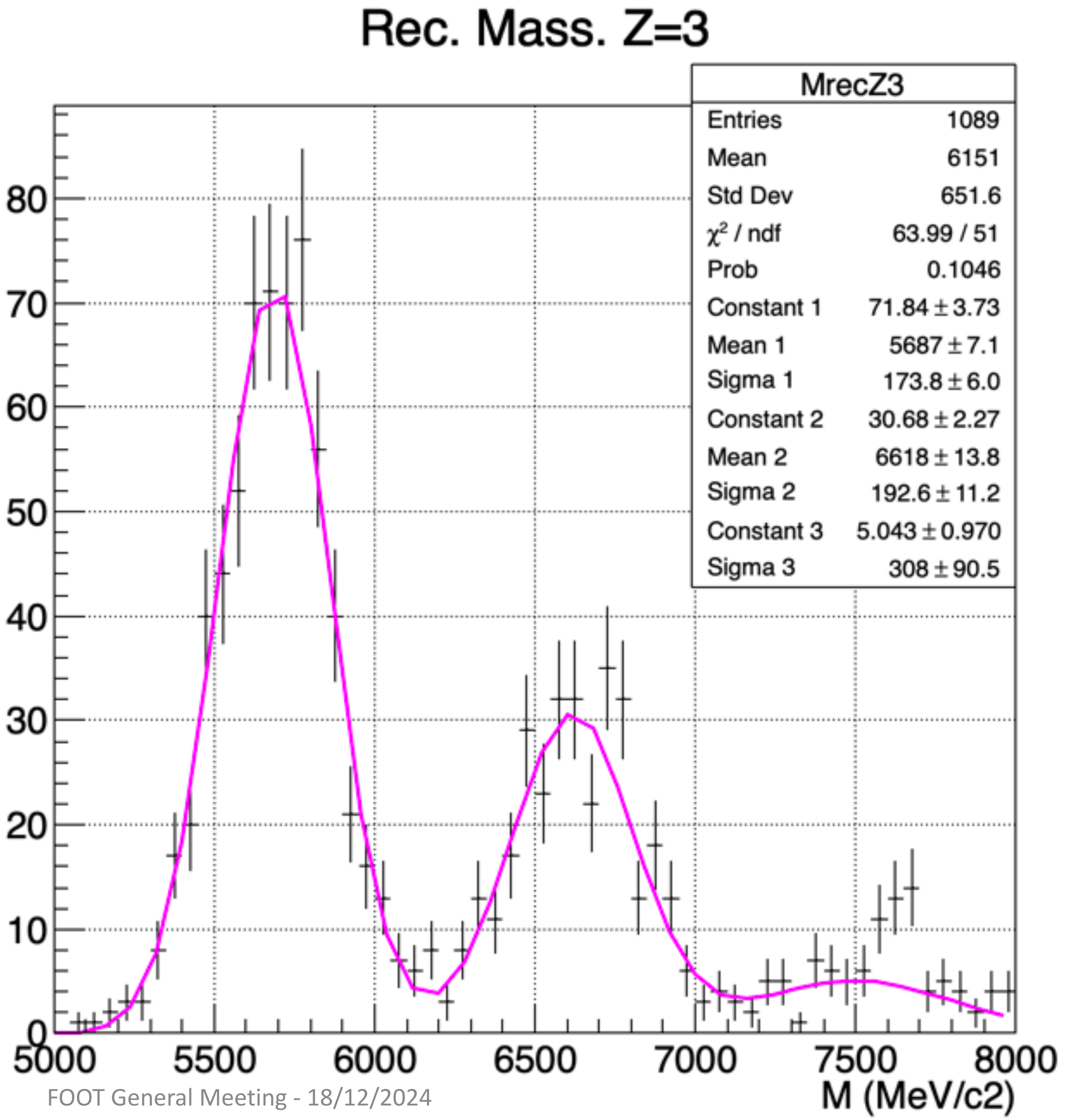


<M> in excess of ~1.5-2% for Z=1 and ~1% for Z = 6 with respect to true value

Isotope resolution (Z=3)

500 MeV/u

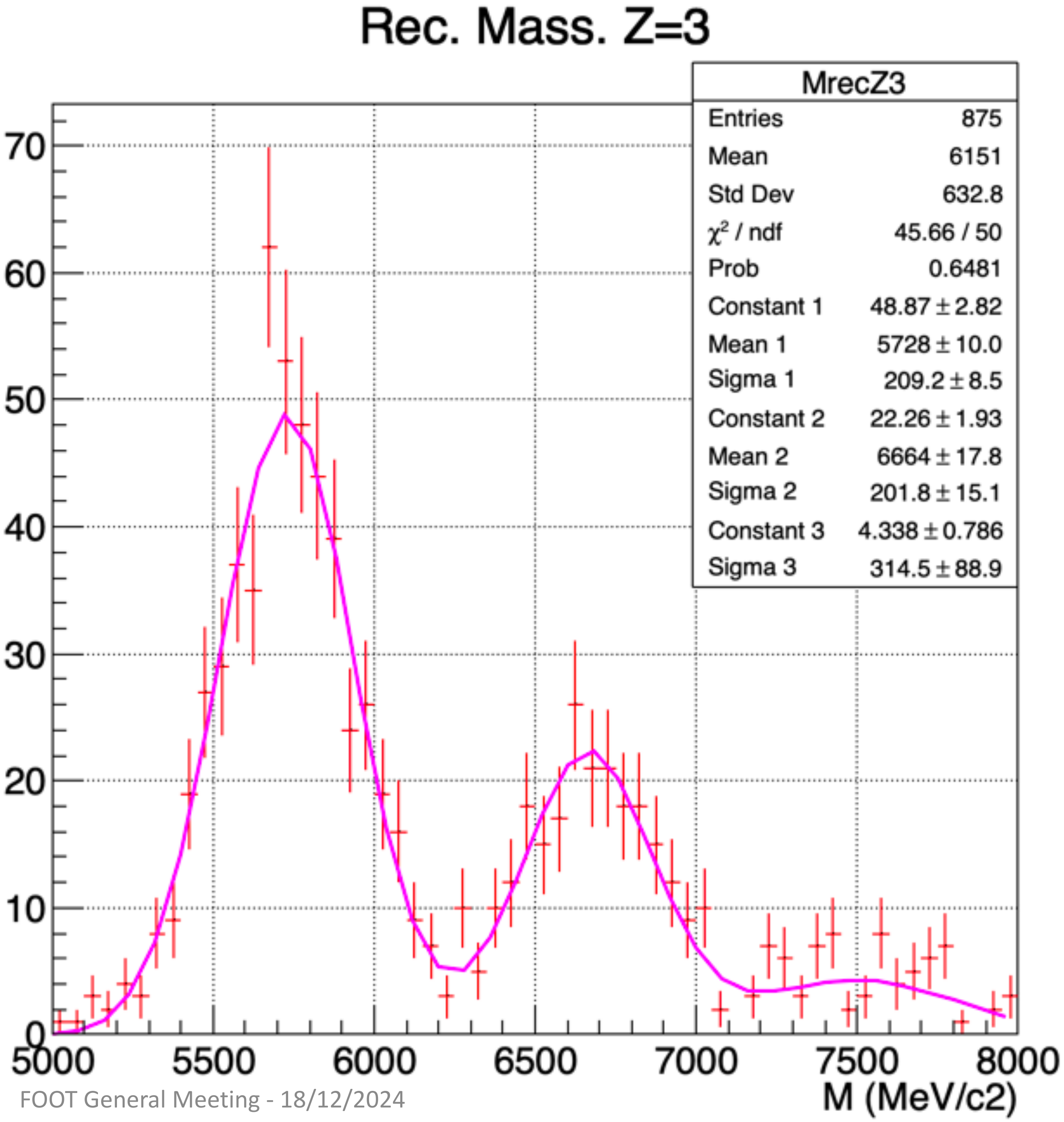
$\sigma_M/\langle M\rangle \sim 3.1\%$



Isotope resolution (Z=3)

700 MeV/u

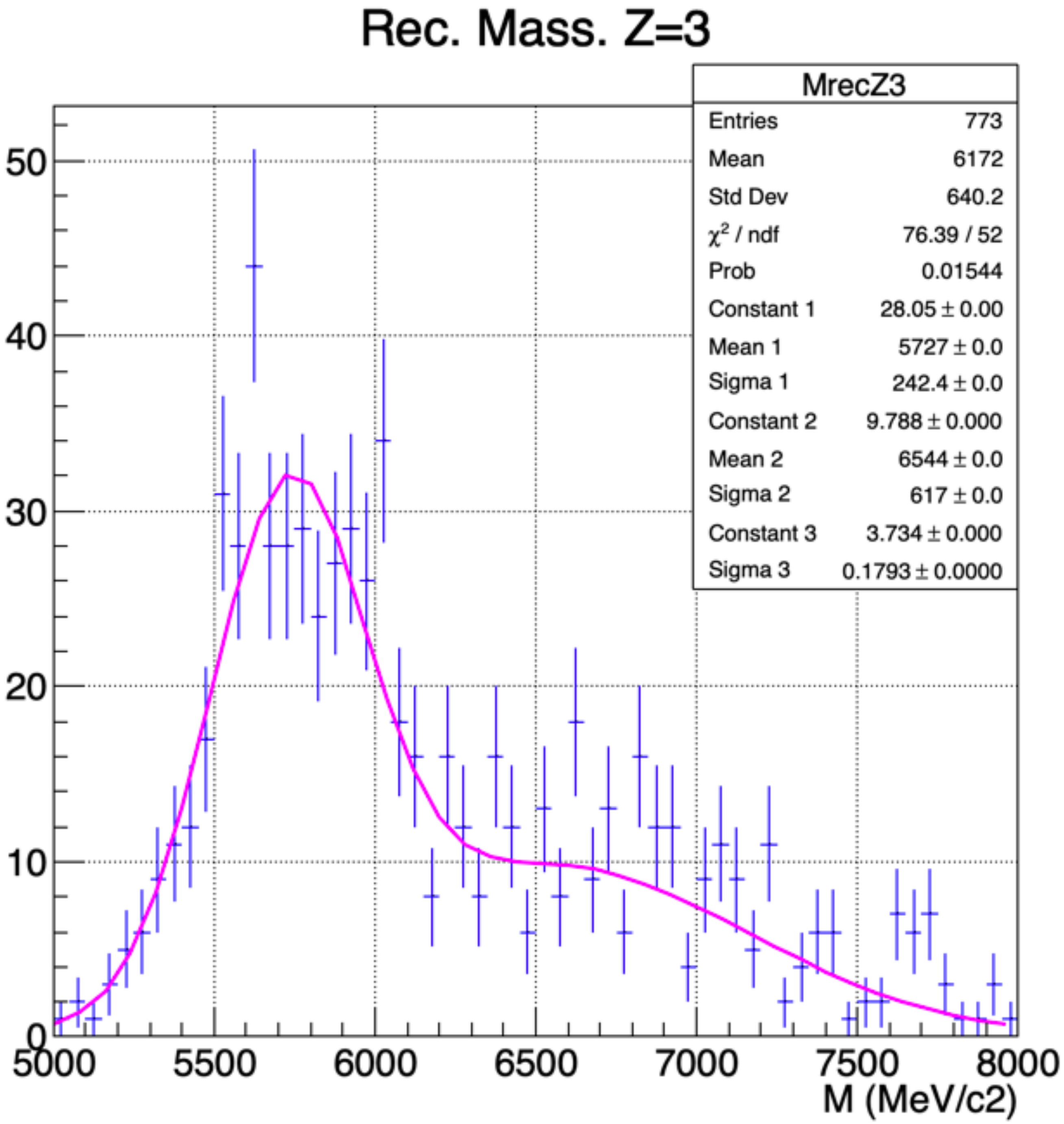
$\sigma_M/\langle M\rangle \sim 3.7\%$



Isotope resolution (Z=3)

1000 MeV/u

$\sigma_M/\langle M\rangle \sim 4.2\%$

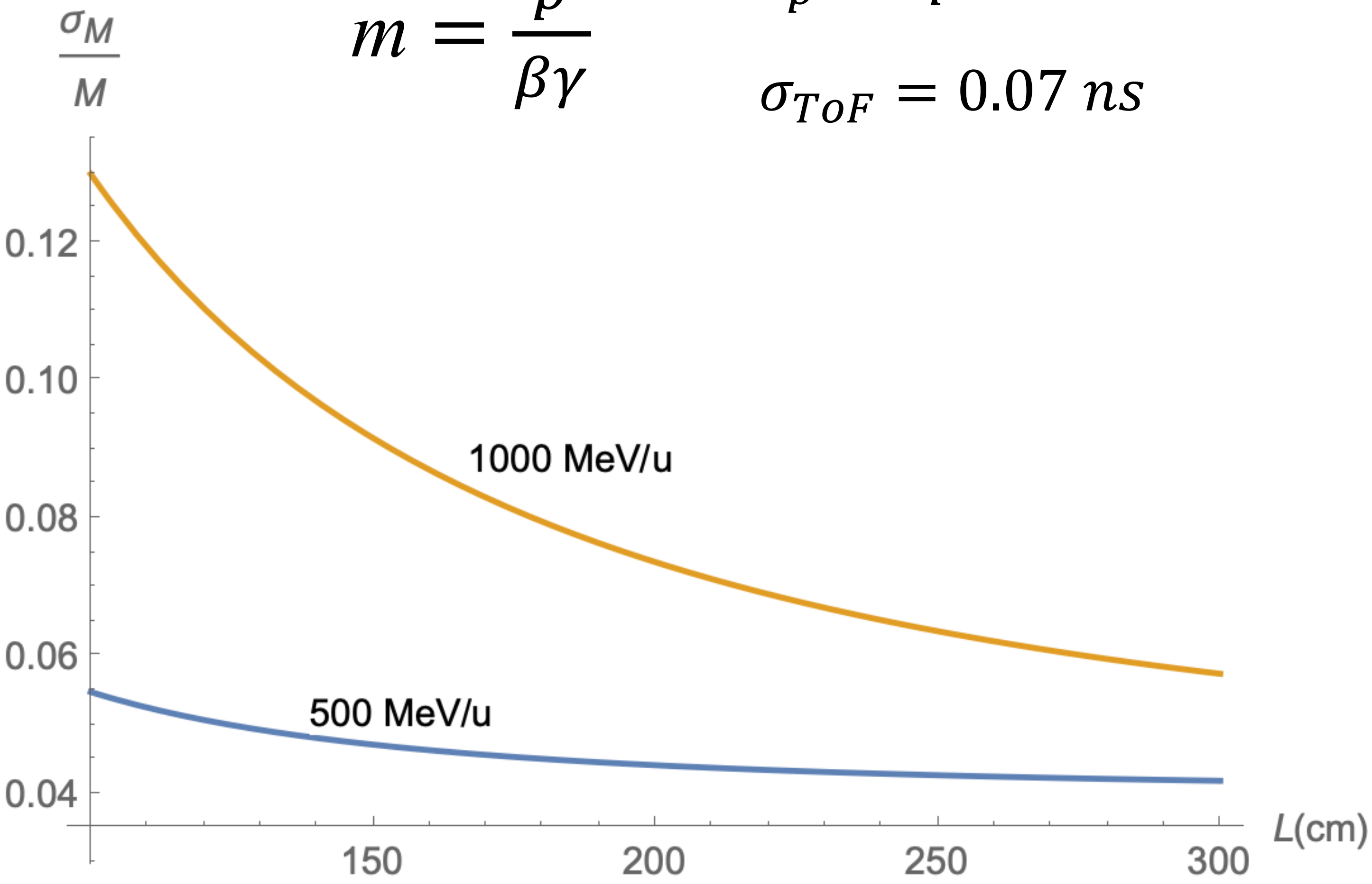


Error propagation on *m(p-ToF)*

$$m = \frac{p}{\beta\gamma}$$

$\sigma_p = kp \qquad k \sim 4\ \%$

$\sigma_{ToF} = 0.07\ ns$



$$\sigma_m^2 = \left(\frac{\partial m}{\partial p}\right)^2 \sigma_p^2 + \left(\frac{\partial m}{\partial \beta}\right)^2 \sigma_\beta^2$$

$$\sigma_m = \ p\sqrt{\frac{(1-\beta^2)}{\beta^2}k^2 + \frac{c^2\sigma_{ToF}^2}{(1-\beta^2)L^2}}$$

$$= \ p\sqrt{a(\beta) + b(\beta)\frac{\sigma_{ToF}^2}{L^2}}$$

$\frac{\sigma_m}{m}$ does not depend on m

We will not achieve a significant gain in mass resolution by increasing L above 2 m

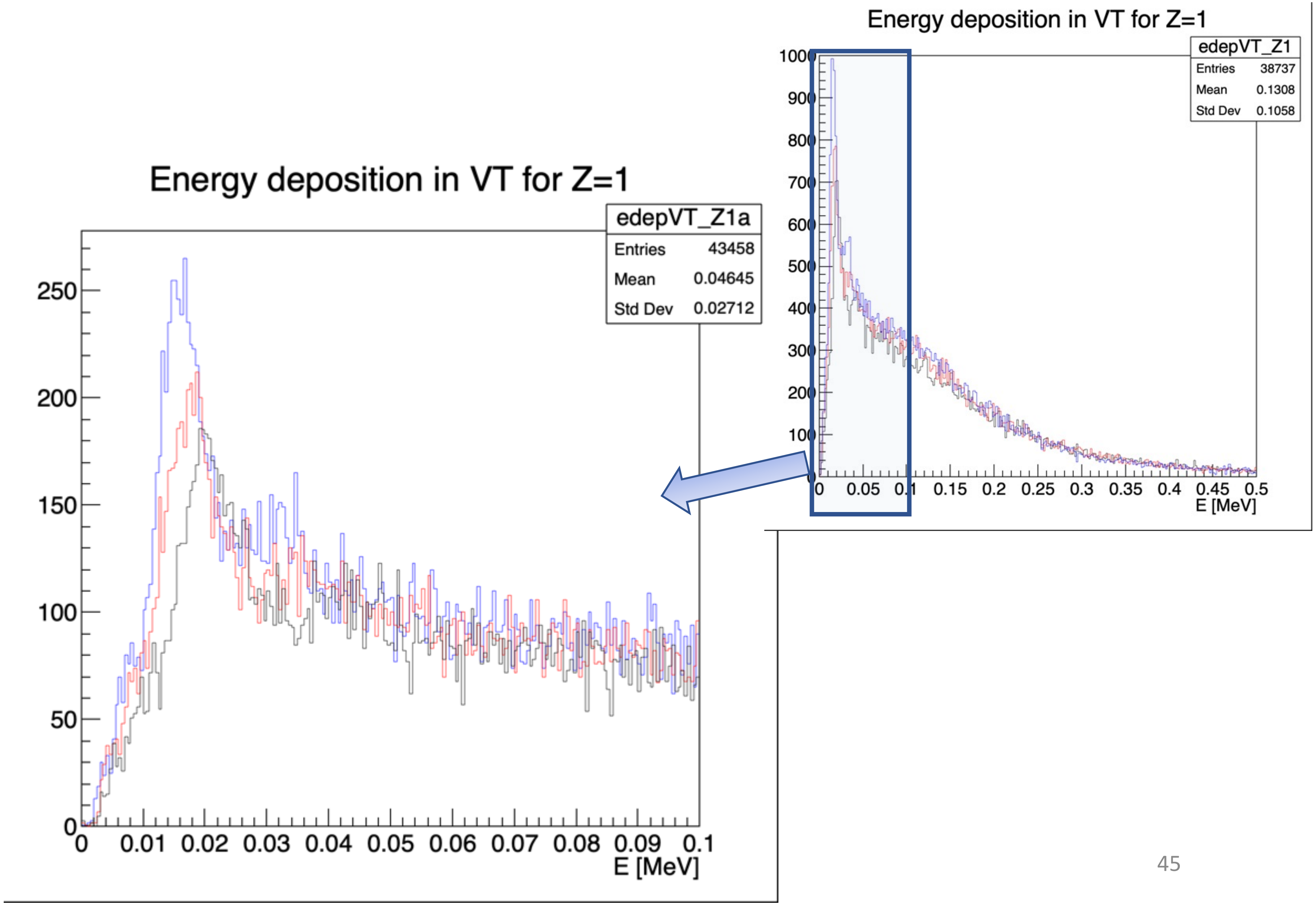
Outline

- An update on FLUKA MC
- The galactic cosmic ray spectrum
- The 2020 paper by J. Norbury et al.
- Proposed configurations: energies and set-up
- Cave A @ GSI and mechanical considerations
- Calorimeter response
- TW: distance, angular separation of tracks & multiplicity
- Momentum resolution
- Mass resolution
- Energy deposition in VTX

Energy deposition in VTX - 1

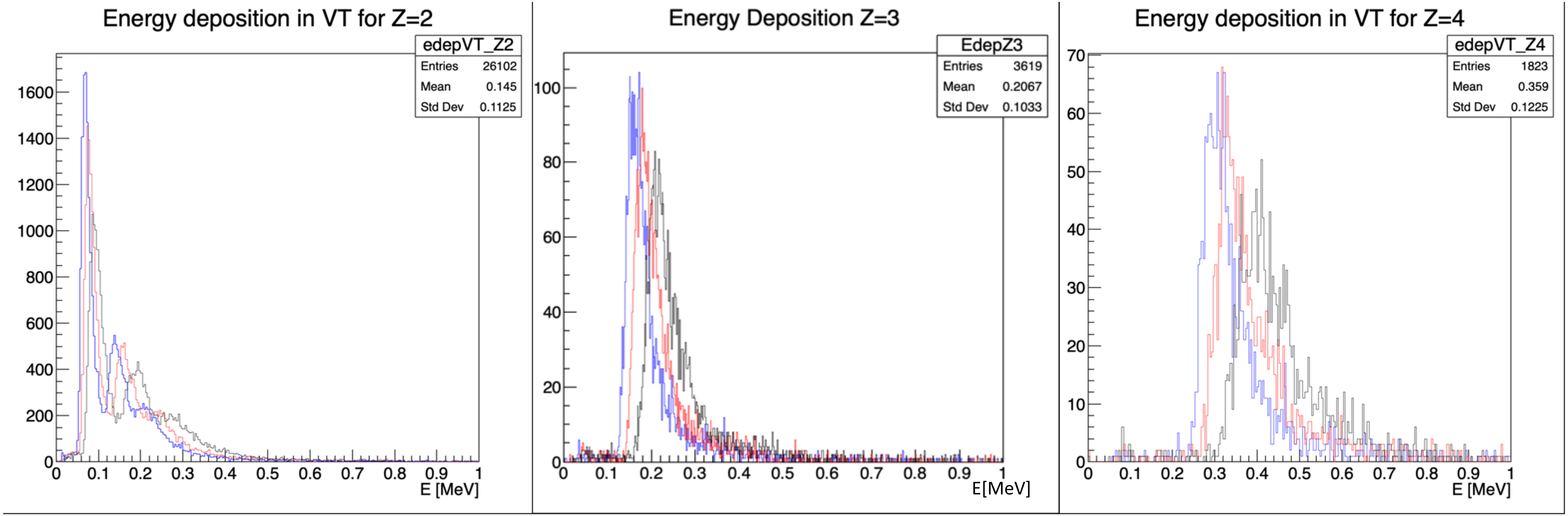
MC truth
No noise, no smearing.
All energies and all angles

Sum of energy deposition in the 4 layers. All events with at least 1 hit layer are included



500 MeV/u
700 MeV/u
1 GeV/u

Energy deposition in VTX - 2



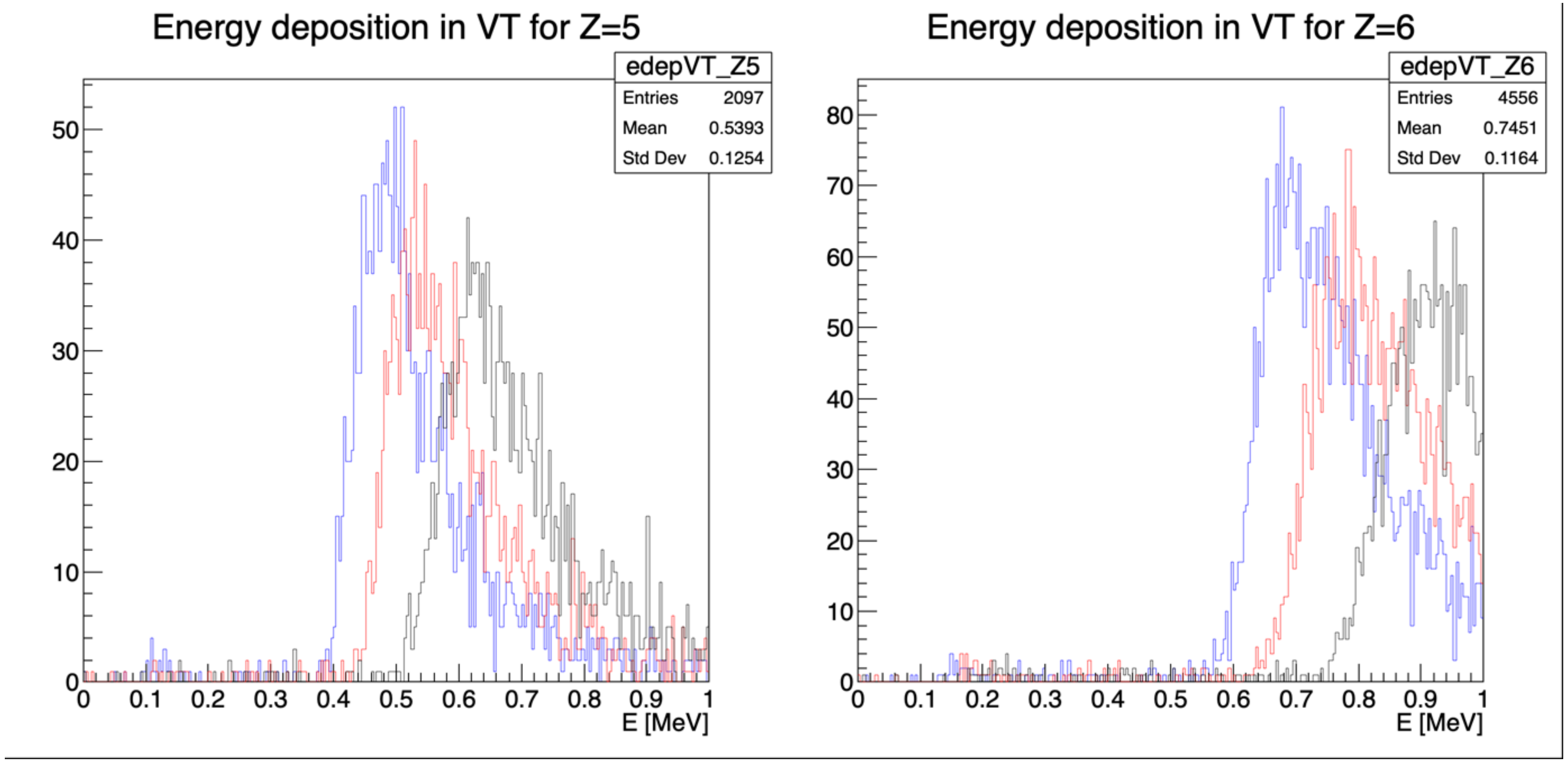
Increasing the energy, the signal in the tracking detectors and TW decreases.
Have we a detection threshold problem?

Sum of energy deposition in the 4 layers. All events with at least 1 hit layer are included

500 MeV/u
700 MeV/u
1 GeV/u

Energy deposition in VTX - 3

We saw yesterday morning during the talks about VTX (Giacomo Ubaldi and Luana Testa) that the m.i.p. are visible and that the cluster size is good



Sum of energy deposition in the 4 layers. All events with at least 1 hit layer are included

Work in progress

- Positioning of all detectors is still provisional:
  - we have to understand better the available space in cave A.
  - estimate optimal position along the beam axis for VTX, MSD and TW

- Studies:
  - Charge reconstruction using a correct calibration
  - Momentum resolution as a function of spacing between the different tracking detectors
  - Mass resolution from P-ToF combination
  - Angular separation of tracks & multiplicity
  - Energy deposition in tracking detectors

- Preliminary results are obtained in an optimistic approach:

in order to reduce CPU time and the size of the output file, the production of particles in the calorimeter has been switched off (too many neutrons)

Conclusions - 1

High energies (> 400 MeV/u)

Physics motivations to search for higher energies with C,N,O: galactic cosmic ray spectrum in view of space radioprotection needs

Main drawback: Above 500 MeV/u, Calorimeter starts to be not useful

Magnetic Spectrometer: fundamental to measure E in combination with ToF.
Without an estimate of mass, it is not possible to measure the kinetic energy of fragments.
➔ Necessary for double differential cross-sections

Conclusions - 2

To resolve the isotopic mass, we need at least 5 millions of "good" events.
But it’s a rough estimate. It’s to be carefully studied.

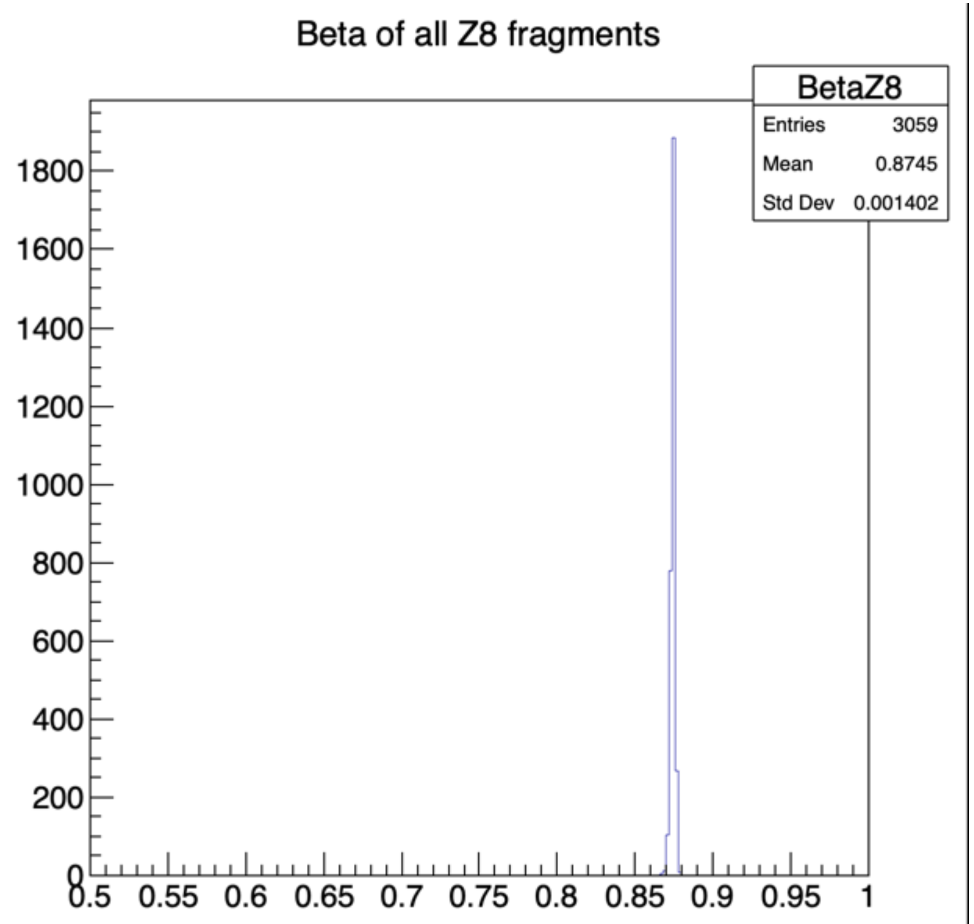
We have seen how important p, He and light fragments are for radiation protection in space.
We know that they are the most widely distributed fragments.
By increasing the TW distance, the angular acceptance decreases, and there is not much gain in mass resolution.

At high energy, the number of events with high track multiplicity becomes important.
The new high granularity TW could be useful.

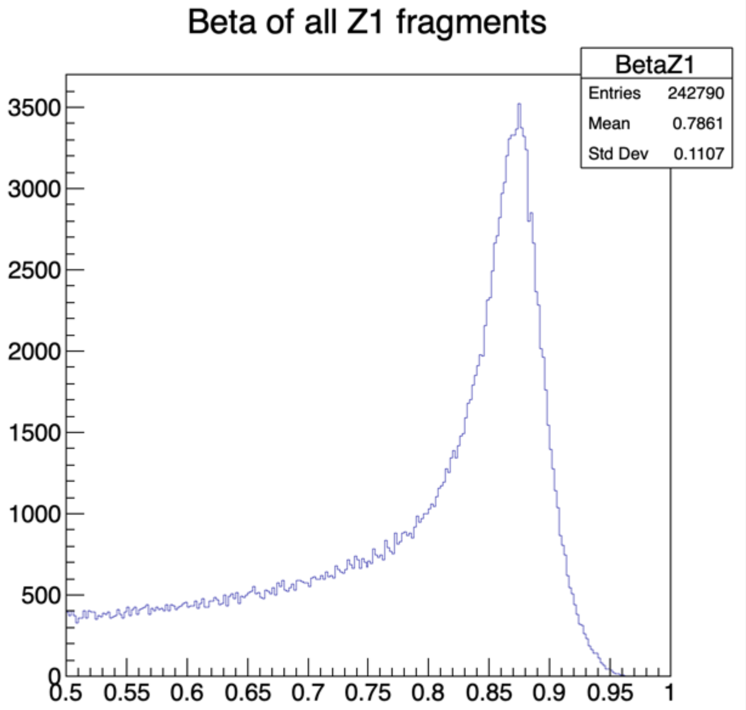
Increasing the energy, the signal in the tracking detectors and TW decreases.
The issue of the detection threshold must be carefully checked.

Thanks for your attention!

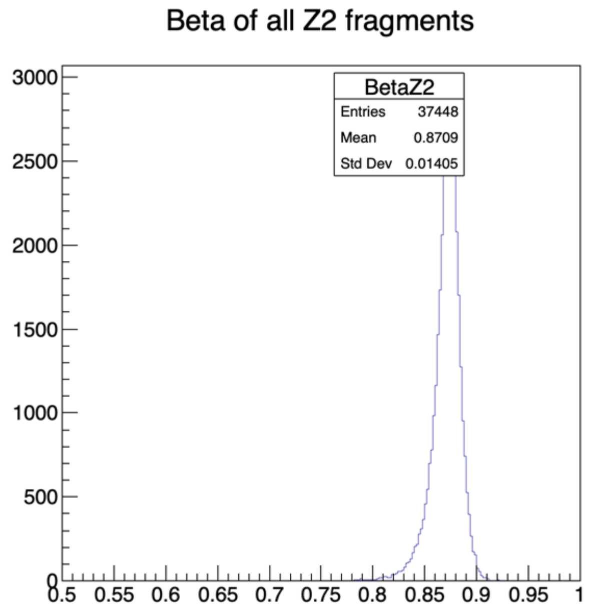
Beta @ 1 GeV/u



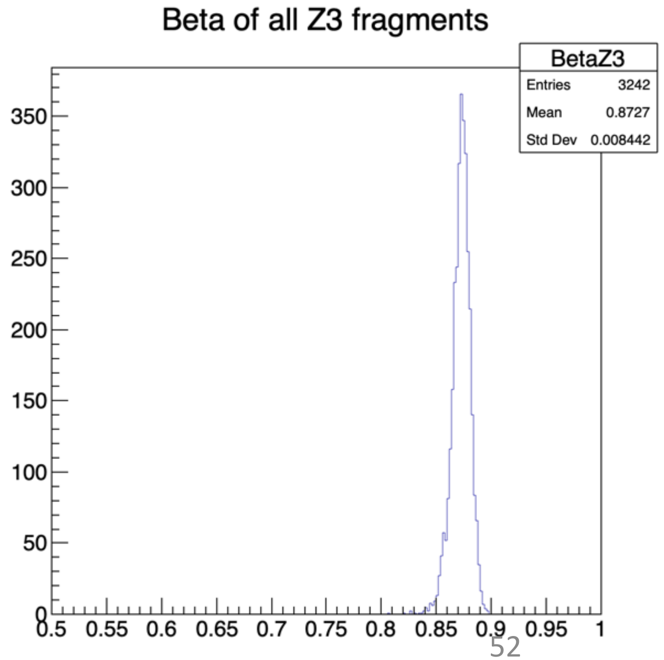
Beta of all Z8 fragments
BetaZ8
Entries 3059
Mean 0.8745
Std Dev 0.001402
1800
1600
1400
1200
1000
800
600
400
200
0
0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1



Beta of all Z1 fragments
BetaZ1
Entries 242790
Mean 0.7861
Std Dev 0.1107
3500
3000
2500
2000
1500
1000
500
0
0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1

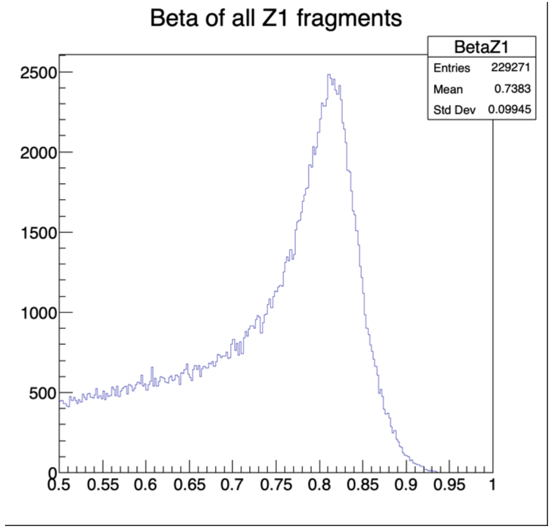


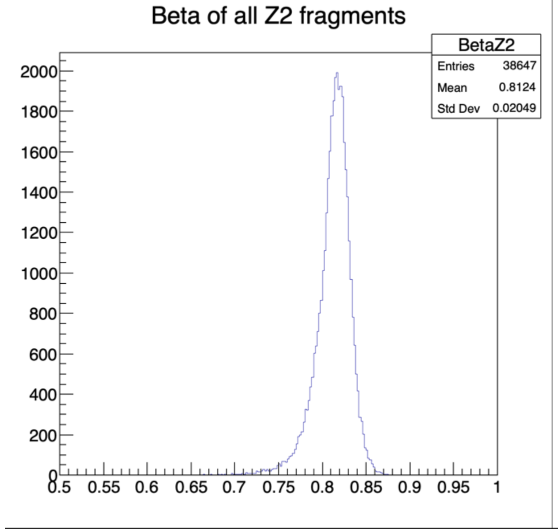
Beta of all Z2 fragments
BetaZ2
Entries 37448
Mean 0.8709
Std Dev 0.01405
3000
2500
2000
1500
1000
500
0
0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1

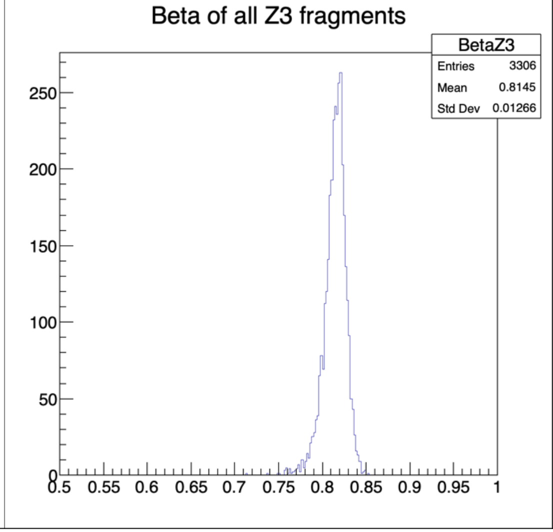


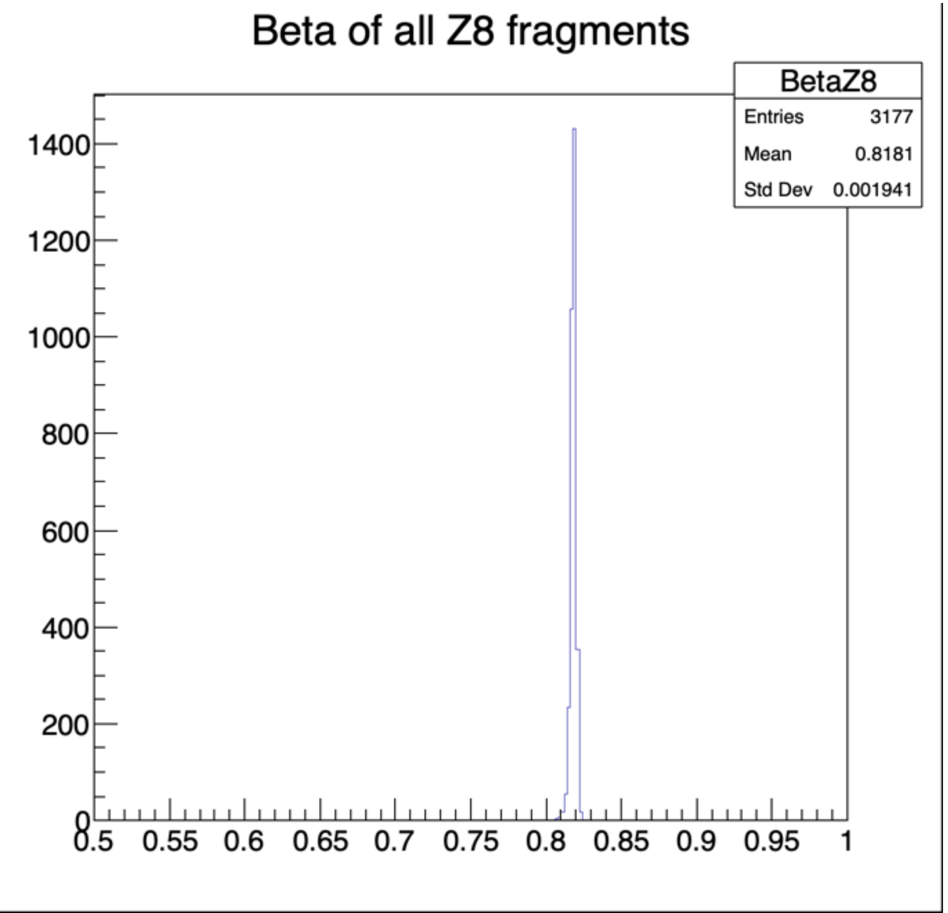
Beta of all Z3 fragments
BetaZ3
Entries 3242
Mean 0.8727
Std Dev 0.008442
350
300
250
200
150
100
50
0
0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1

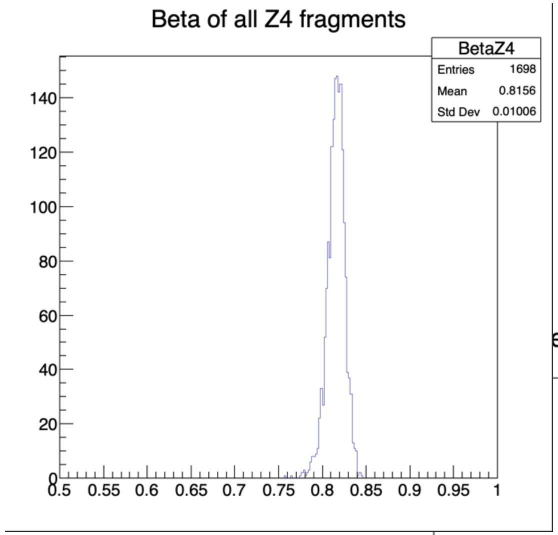
Beta @ 700 MeV/u

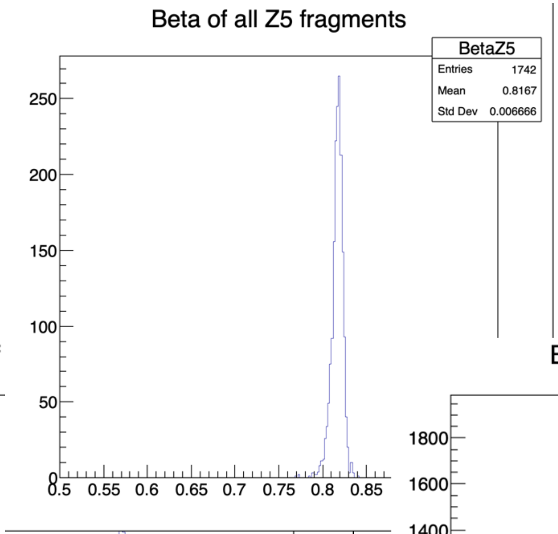


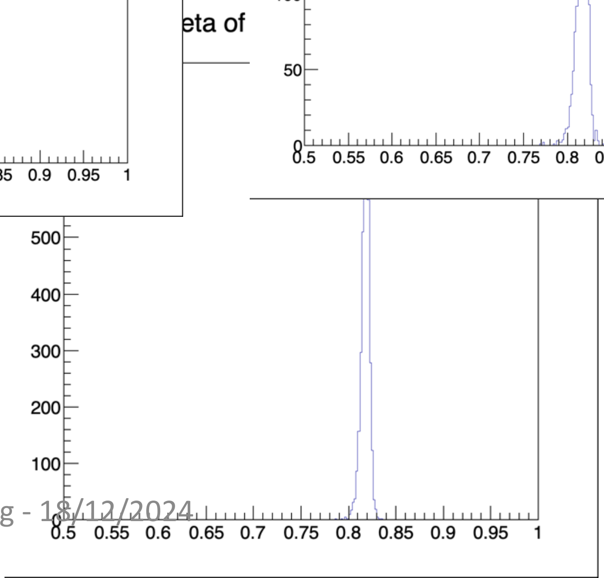


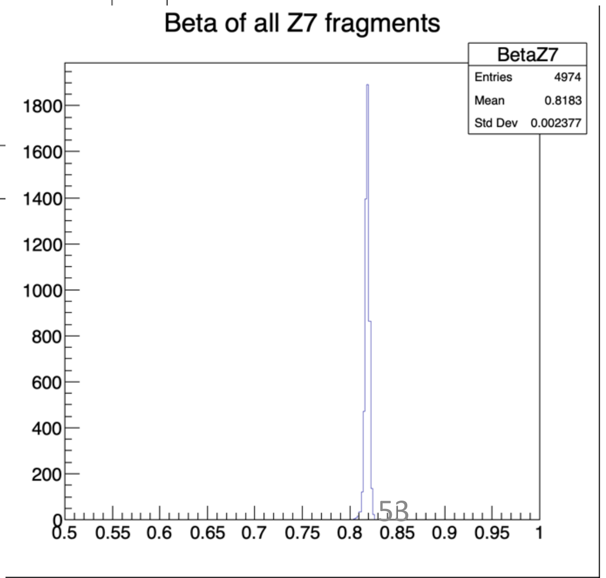












Beta @ 500 MeV/u