Nuclear Clustering with FOOT:

search for the exclusive fragmentation channels $^{12}C \rightarrow 3\ ^{4}He$ and $^{16}O \rightarrow 4\ ^{4}He$

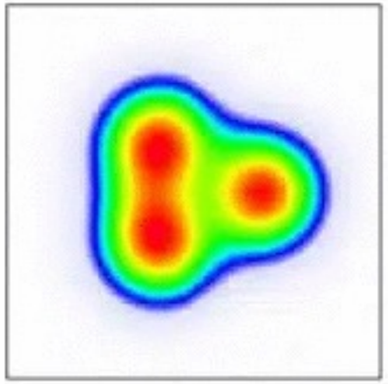
FOOT Collaboration Meeting

November 2021

Cross Sections Measurements with FOOT

- So far our collaboration has been focusing on the measurement of inclusive cross sections, such as $^{16}O + C \rightarrow p + X$, $^{12}C + H \rightarrow {}^{4}He + X$, etc.
- There are other important measurements to be performed, and these concern exclusive channels
- In particular, when dealing with projectiles (and targets) like ^{16}O and ^{12}C there exist important fragmentation channels with multiple ^{4}He in the final state
- This is related to a phenomenology known in literature as "Nuclear Clustering"

Nuclear Clustering



- There is a tendency of nucleons in a nucleus to form permanent or transient substructures
- The likelihood of clustering depends on binding energy
- Of all possible clusters, the α-particle is the most likely because of its high simmetry and binding energy
- α-clustering is suggested by calculations considering how the stability of an infinite gas of nucleons depends on its density
- Cluster formation becomes more and more energetically favoured as the nuclear density decreases.
- This occurs near nuclear surface, as confermed by shell model calculations. Light nuclei are essentially all surface
- To some extent, even-even light nuclei ($A \geq 8$) may be thought as α-particles bound together

The first literature

- A first seminal work on this subject dates back to 1938:

L. R. Hafstad & E. Teller, **"The Alpha-Particle Model of the Nucleus"**, PHYSICAL REVIEW Vol. 54 (1938) p. 681*:*

"...nuclei which contain 2n neutrons and 2n protons, can therefore be considered as consisting of n α–particles, saturated nuclei.

The name saturated nucleus refers to the fact that the α-particles are the saturated subunits in nuclear structure.

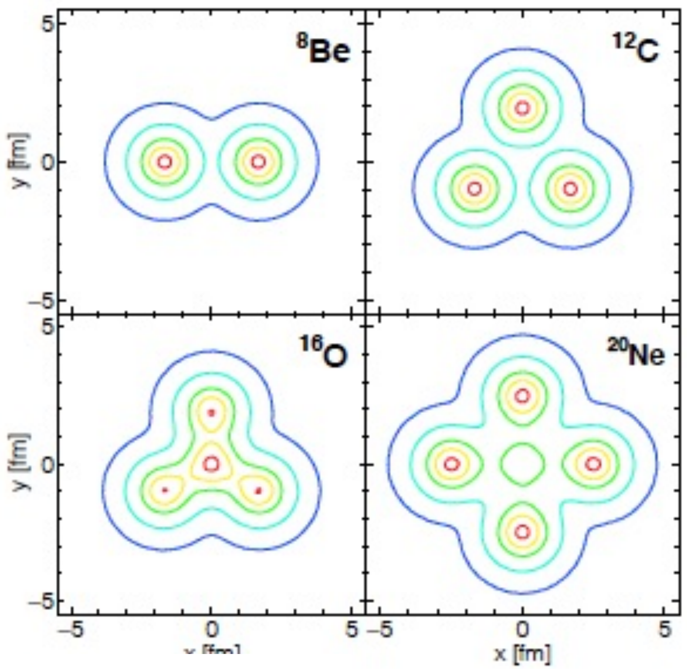
In fact, these nuclei are analogous to the rare gases: and other saturated shells in molecular physics.

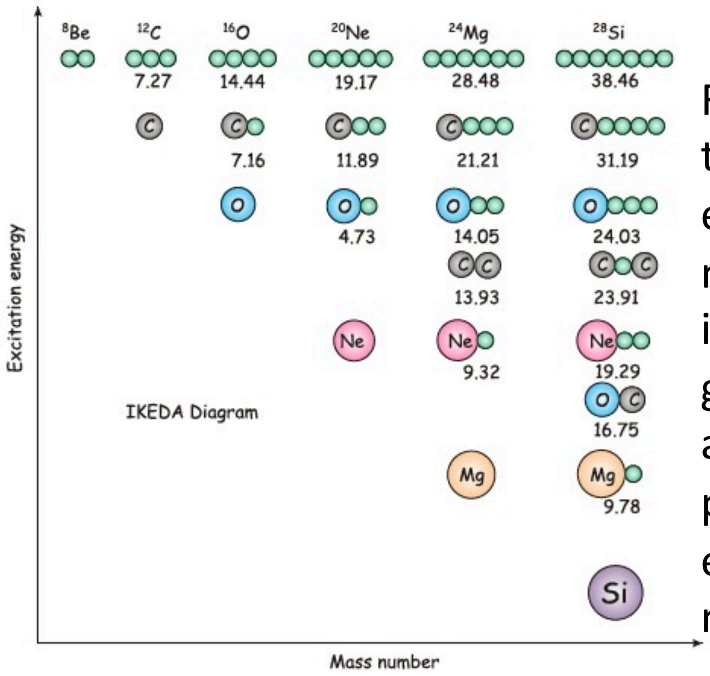
They have, at least for light nuclei, a comparatively high binding energy, a high frequency of occurrence in nature, and no angular or magnetic momentum…"

Modern Literature (Theory)

- There exist many studies in which nuclear physicists seem to have successes in obtaining correct quantitative predictions from phenomenological nuclear models. Many reviews from M. Freer and others. For example:
  - M. Freer & A.C. Merchant, "Developments in the study of nuclear clustering in light even–even nuclei", J. Phys. G: Nucl. Part. Phys. 23 (1997) 261–323.
  - M. Freer, "The clustered nucleus—cluster structures in stable and unstable nuclei", Rep. Prog. Phys. 70 (2007) 2149–2210

  and reference therein





Reversing the channel, this mechanism is essential for the nucleosynthesis of carbon in helium-burning red giant stars, and predicts an amount of carbon production in a stellar environment which matches observations.

Modern Literature (Experiment)

- The existence of preferential fragmentation channels like $^{12}C \rightarrow 3\ ^{4}He$ and $^{16}O \rightarrow 4\ ^{4}He$ is well experimentally established, mainly for E/A > 1 GeV/nucleon

For example:

1) V. V. Belaga et al.(1995) Coherent dissociation $^{12}C \rightarrow 3\ \alpha$ in lead-enriched emulsion at 4.5 GeV/c per nucleon, Physics of Atomic Nuclei 58, 1905–1910.

2) N. P. Andreeva et al.(1996) Coherent dissociation $^{16}O \rightarrow 4\ \alpha$ in photoemulsion at an incident moment of 4.5 GeV/c per nucleon, Physics of Atomic Nuclei 58, 1905–1910.

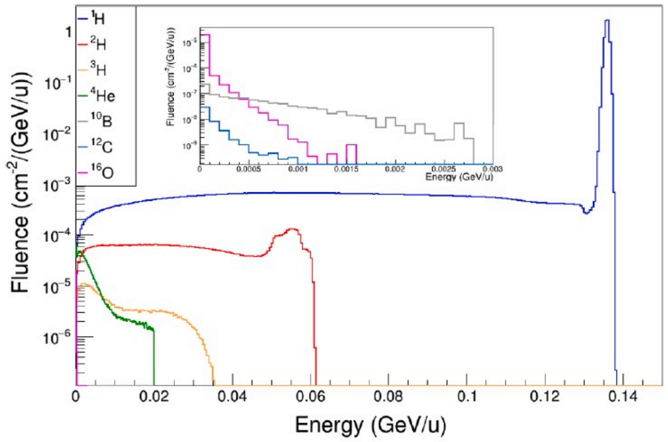
- There are also investigations at very low energy

See for instance the experiment performed at iThemba concerning $^{12}C+x \rightarrow {}^{8}Be + {}^{4}He$ described in C. Mancini, PhD Thesis, Univ. Roma 3, 2015

- What happens at intermediate energies? (FOOT energies)

Why we are interested

- Just beyond Z=1 fragments, ^{4}He nuclei, in both projectile and target fragmentation, turn out to be the most relevant Z>1 particles from the point of view of radiobiological effectiveness. See studies performed in the MoVE-IT INFN Call of CSN5



Fluence of target fragments induced by 150 MeV protons in water at z = 2.5 cm. (A. Embriaco et al, PMB 80 (2020) 342)

- The capability of correctly reproducing the experimental rate of $^{12}C \rightarrow 3\ ^{4}He$ and $^{16}O \rightarrow 4\ ^{4}He$ is important to qualify nuclear models and MC codes
- Beyond applications, the investigation of the mechanisms underlying these fragmentation channels is of interest for nuclear physics

Nuclear Physics: intermediate channels in clustering

- Exp. Data at low energy, in our language close to Bragg Peak, show that actually the $^{12}C \rightarrow 3\ ^{4}He$ fragmentation channel can go through a 2 step process:

$$^{12}C \rightarrow {}^{8}Be + {}^{4}He$$

$$\hookrightarrow {}^{4}He + {}^{4}He$$

- This may be expected, since a 2-body channel has more phase space available with respect to a 3-body one.

WARNING! $t_{1/2}(^{8}Be) = 6.7\times10^{-17}s$: <u>not directly detectable</u>

Here are the Interesting Questions

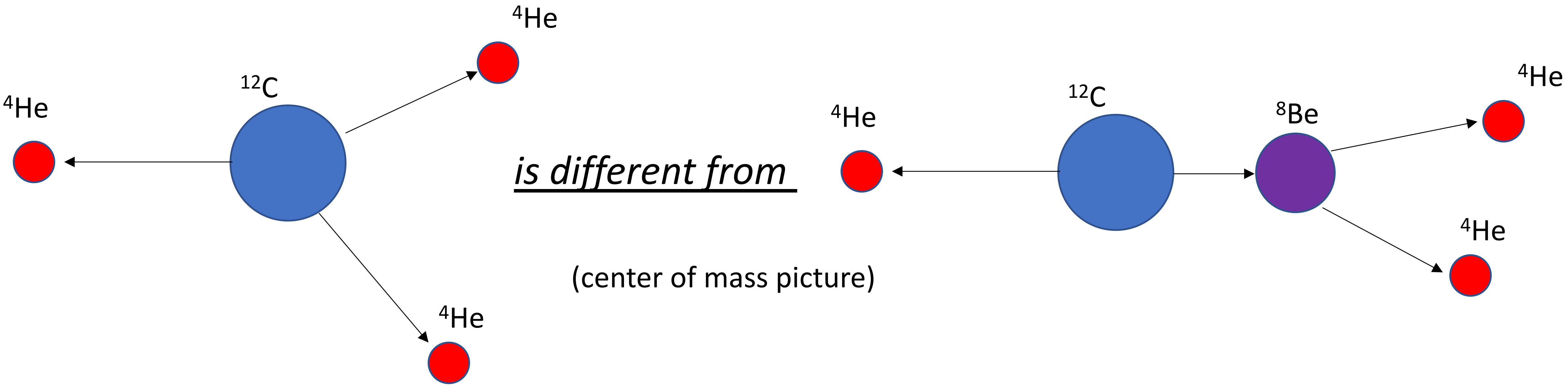
- Does the $^{12}C \rightarrow {}^{8}Be + {}^{4}He \rightarrow 3\ {}^{4}He$ process occur also at intermediate energies? (200 MeV/u?)
- If yes, what is its fraction with respect to the direct $^{12}C \rightarrow 3\ {}^{4}He$ channel?
- How does this scale with energy?
- What about $^{16}O \rightarrow 4\ {}^{4}He$? Does this fragmentation proceed through $^{16}O \rightarrow 2\ {}^{8}Be$? How does this compete with $^{16}O \rightarrow {}^{8}Be + 2\ {}^{4}He$ or the direct $^{16}O \rightarrow 4\ {}^{4}He$? How does this scale with energy?

There are some data at higher energies: analysis of early exposures of lead enriched NTE to relativistic ^{12}C nuclei revealed that the fraction of 3α events containing ^{8}Be is 40% *[D.A. Artemenkov et al., Few-Body Syst (2017) 58]*

Apparently there are no data at the FOOT energies

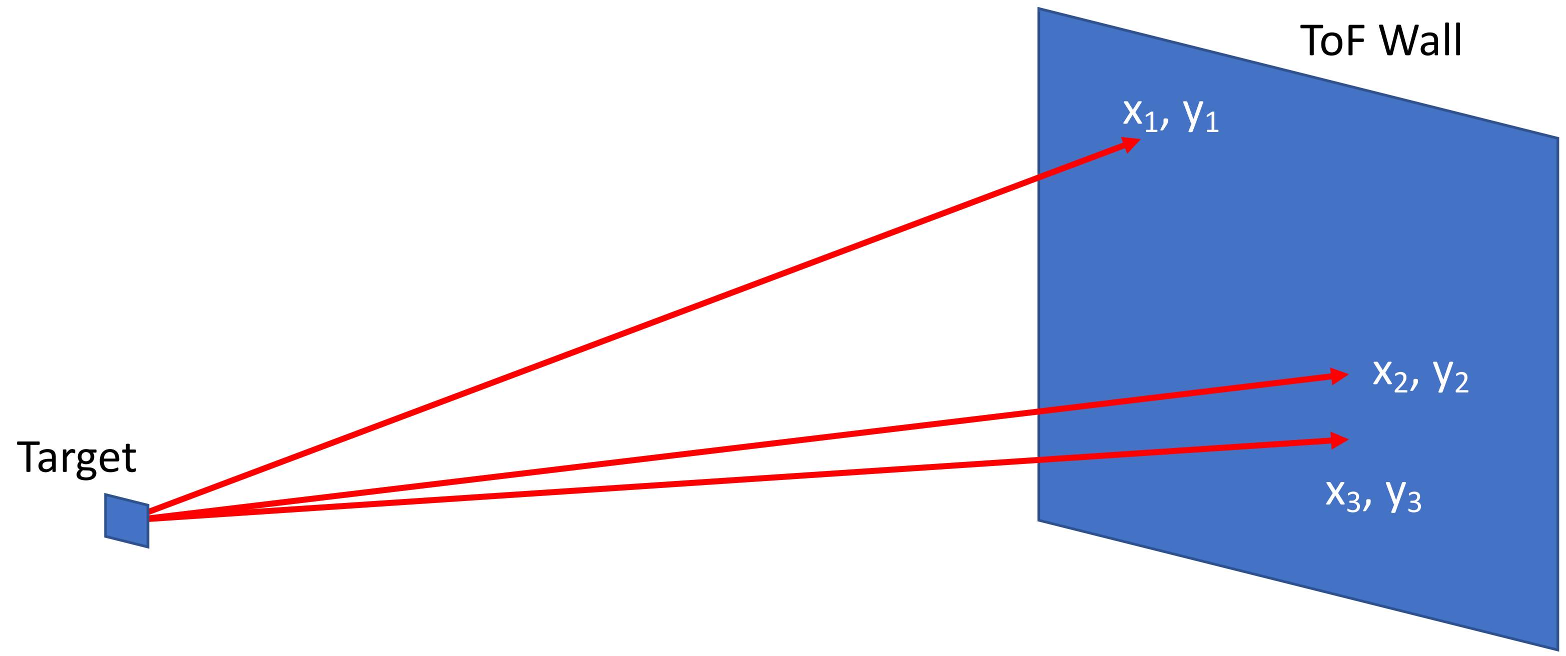
How can we detect these channels in FOOT?

- The 2 step process changes the kinematics:



→ the 2 ^{4}He from the ^{8}Be fragmentation are very correlated (closer in angle)

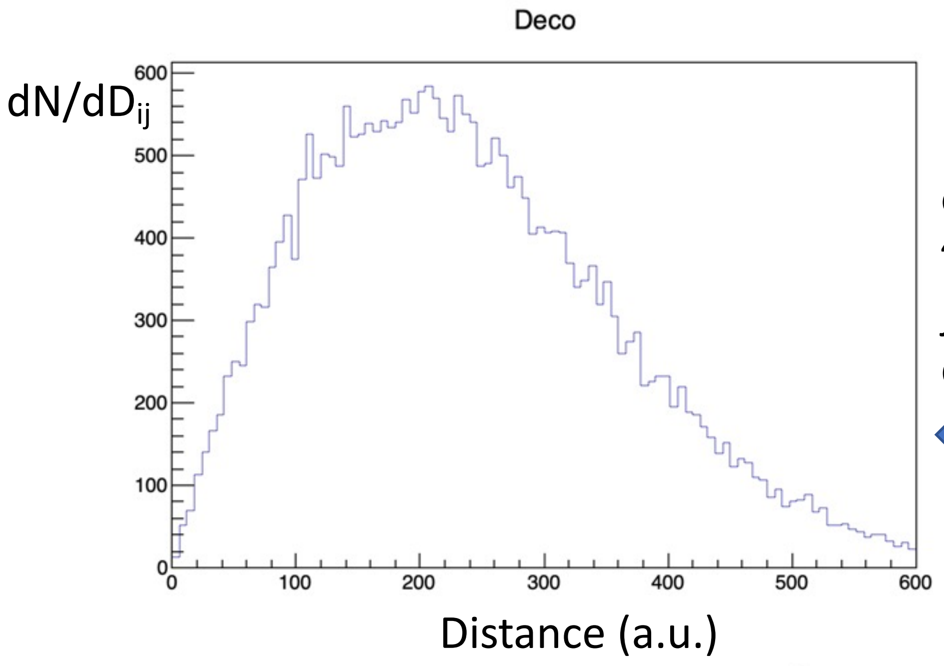
How can we detect these channels in FOOT?



- We can identify events with 3 ^{4}He arriving at TW, and determine their x,y coordinates projecting tracks reconstructed from VTX and/or MSD (with ^{12}C projectiles, even without A reconstruction, if you get 3 Z=2 particles they are surely ^{4}He)
- Then we can study the distribution of the relative distances between each pair of (x,y) coordinates building the so called "Decoherence Curve" *(same method used in Cosmic Ray physics to study the correlation of muons inside an Extensive Air Shower)*

A toy model (and no detector):

Just a simple statistical Phase Space generator

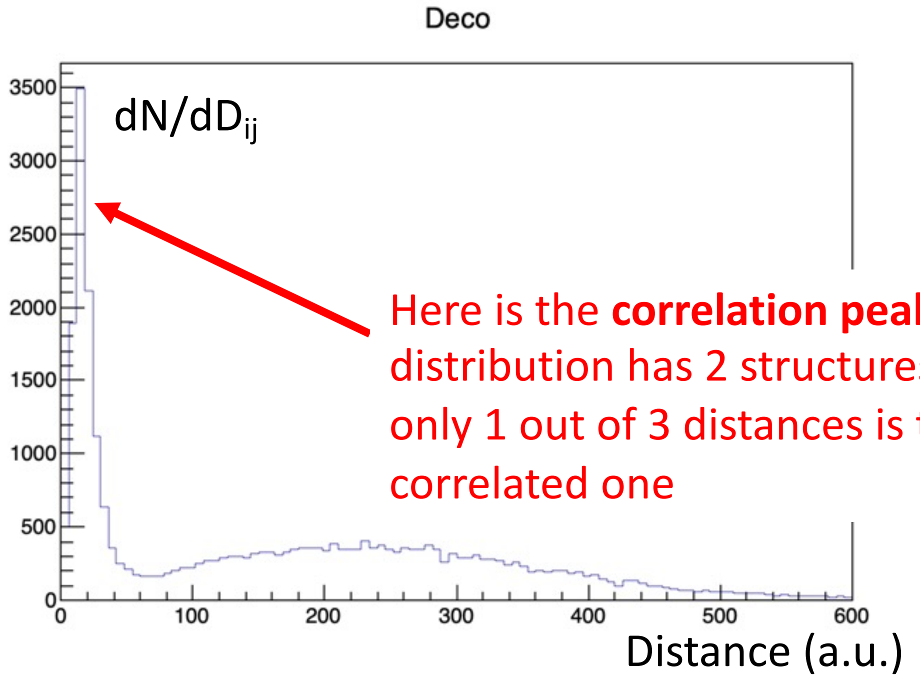


Distribution between pairs of coordinates in $^{12}C \rightarrow 3\ ^{4}He$, all generated using just a pure phase space distribution

$$Distance_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$$

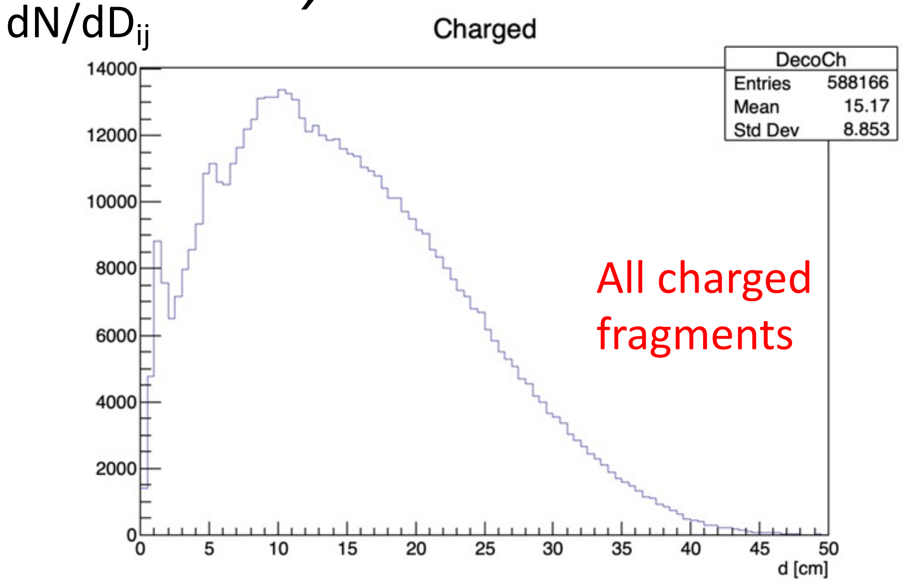
$$N_{Distances} = n\frac{(n-1)}{2}; n = no. of\ particles\ in\ the\ event$$

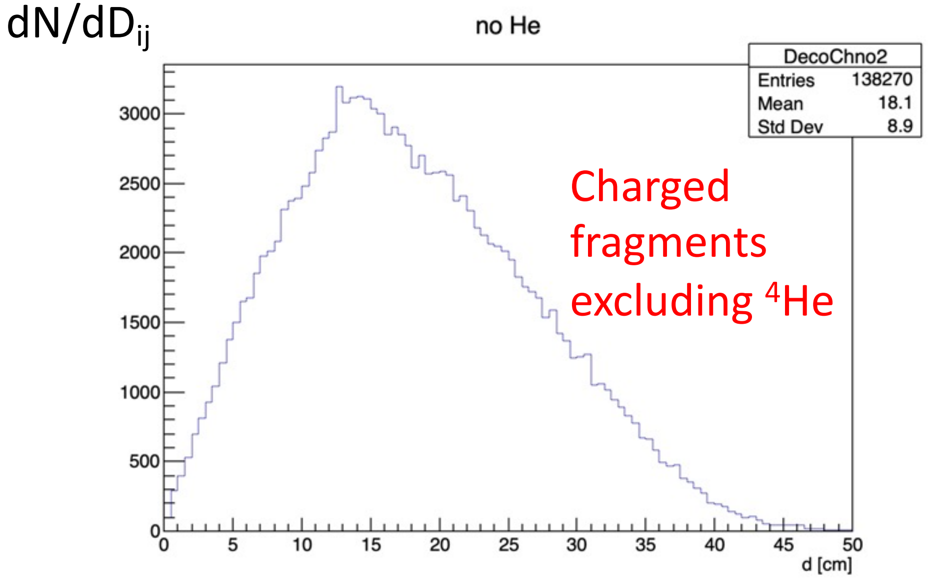
Distribution between pairs of coordinates in $^{12}C \rightarrow 3\ ^{4}He$, all generated using a 2 step 2-body decay sequence via ^{8}Be production



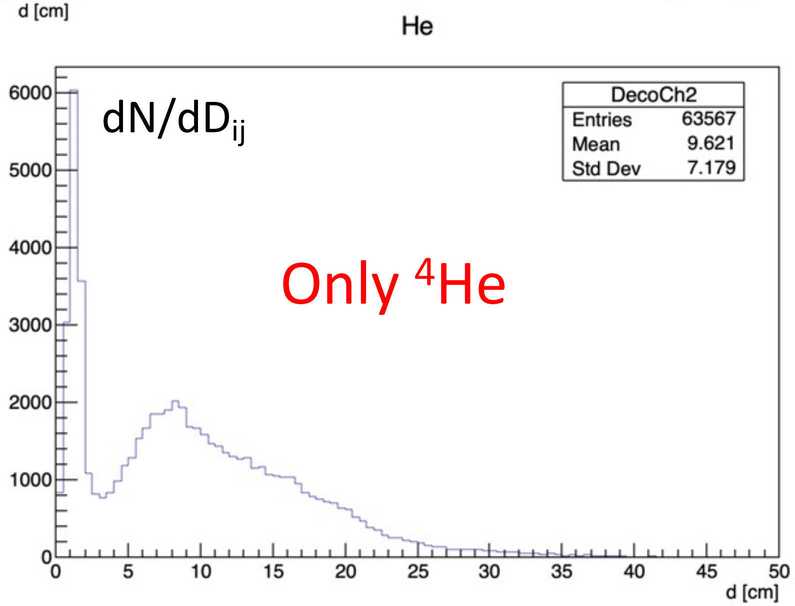
Here is the **correlation peak**. The distribution has 2 structures since only 1 out of 3 distances is the correlated one

What actually FLUKA predicts *(MC truth, no detector resolution)*





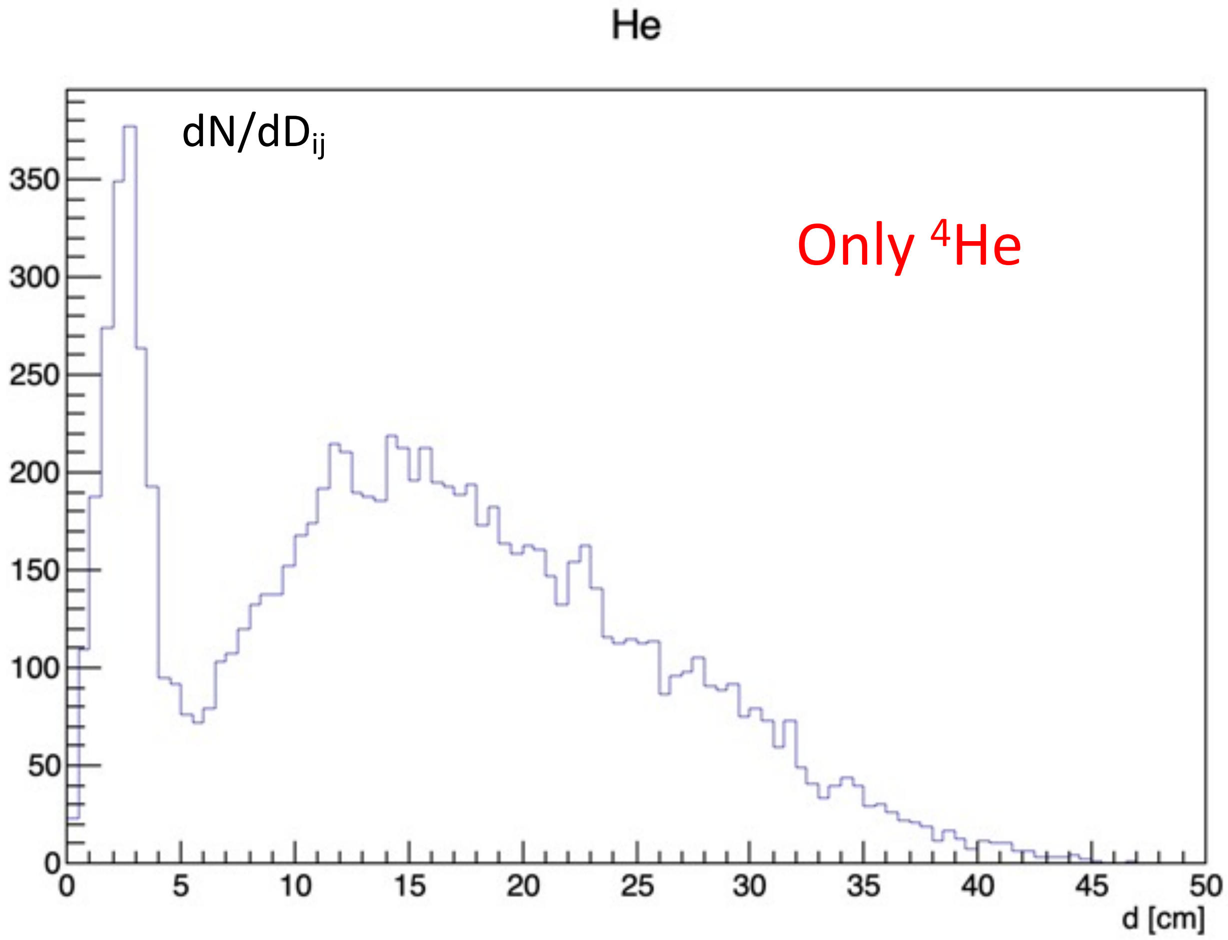
^{12}C + C @ 200 MeV/u



Notice: shape of distribution is now deformed by TW geometrical acceptance (which cuts a non negligible number of 4He fragments)

The same phenomenology is predicted by FLUKA for ^{16}O fragmentation

^{16}O + C @ 200 MeV/u GSI2021_MC campaign



At this stage we are not yet distinguishing the cases $^{16}O \rightarrow 2\ ^{8}Be$, $^{16}O \rightarrow\ ^{8}Be + 2\ ^{4}He$ or $^{16}O \rightarrow 4\ ^{4}He$

Comment:

The FLUKA models evidently assume that also at these intermediate energies, both ^{12}C and ^{16}O when fragmenting in the all ^{4}He channel, prevalently follow the 2 step chain involving ^{8}Be.

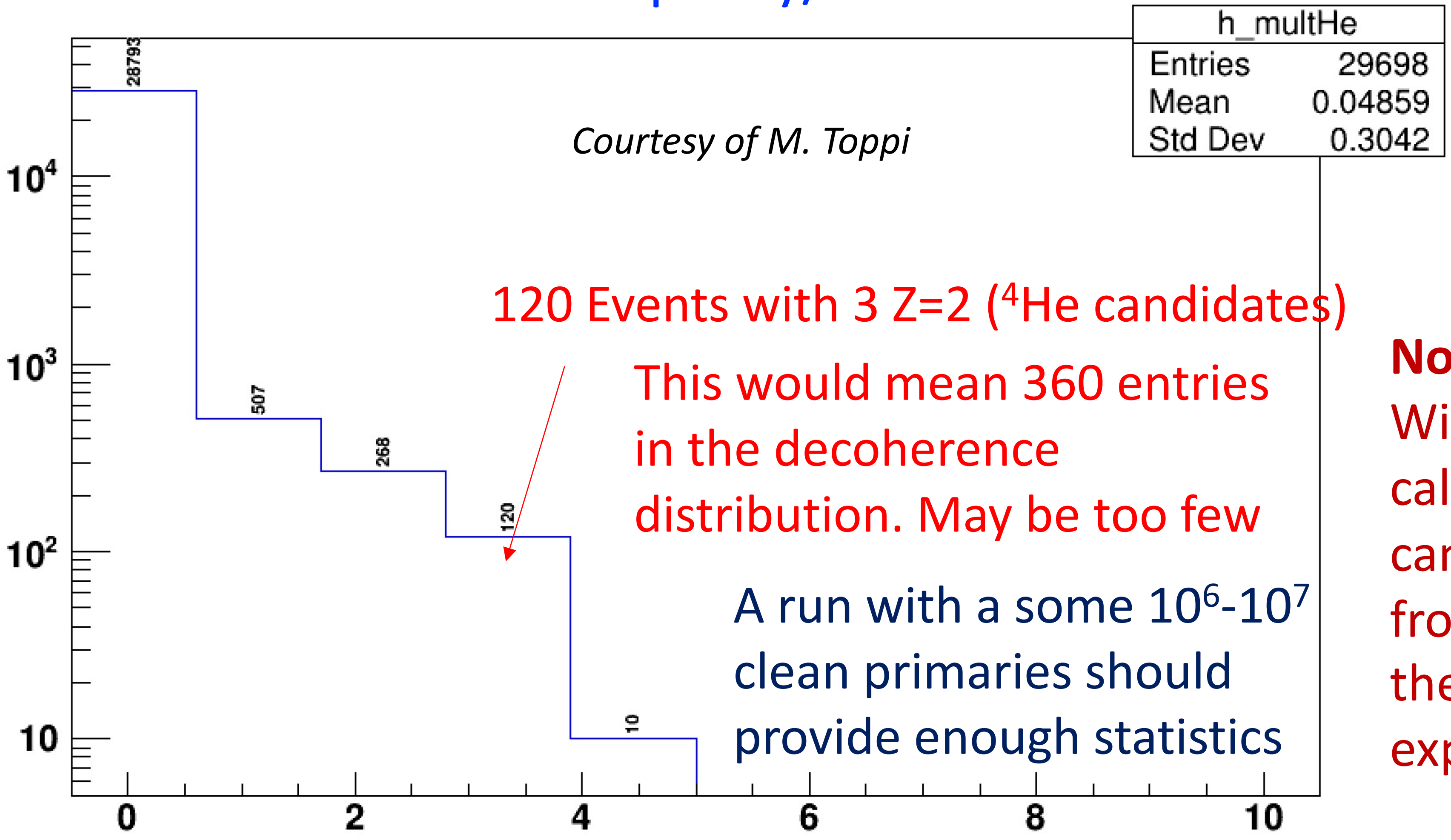
This is of course natural in terms of phase space considerations, however there is not yet experimental confirmation of this.

Alternatives Methods

- The same study can be performed using angular separation instead of distances at the TW (or other plane)
- Some day, when we shall have the full detector with magnetic analysis, the m_{ij} invariant masses can be reconstructed and Dalitz plot technique can be used.

FOOT exp data GSI 2019

Z=2 Multiplicity/event



Courtesy of M. Toppi

120 Events with 3 Z=2 (^{4}He candidates)

This would mean 360 entries in the decoherence distribution. May be too few

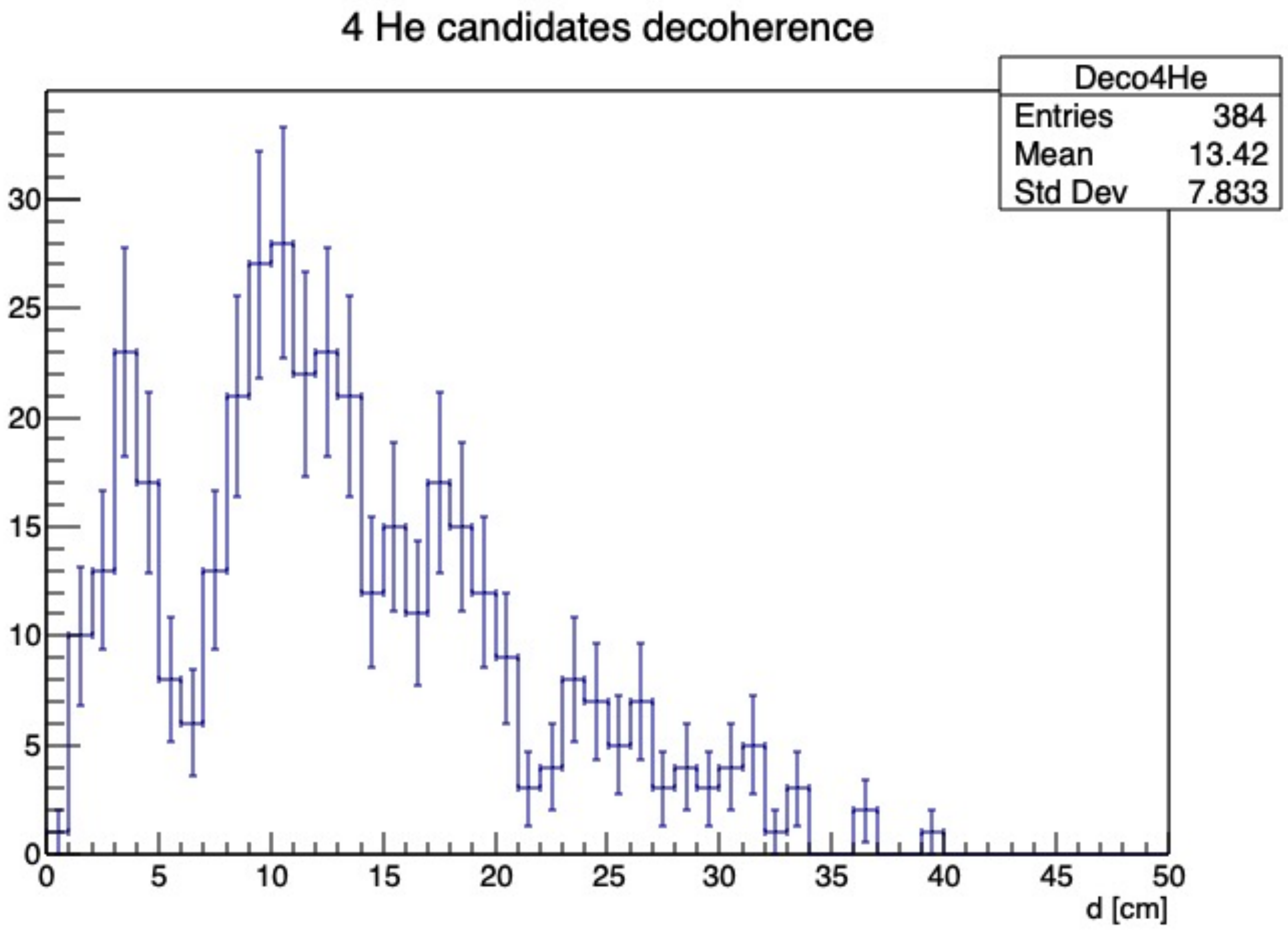
A run with a some 10^6-10^7 clean primaries should provide enough statistics

Notice:

Without calo (or with a single calo module in GSI2021), we cannot clearly separate ^{4}He from ^{3}He and ^{6}He. However their contamination is expected to be small

Can we get enough statistics?

FOOT **Simulated data** GSI2021, ^{16}O+C @ 400MeV/u,
only the first 10^6 primaries (out of 5 millions)



Simple global tracking with straight extrapolation of VTX tracks to TW. Z obtained from GetTwChargeZ()

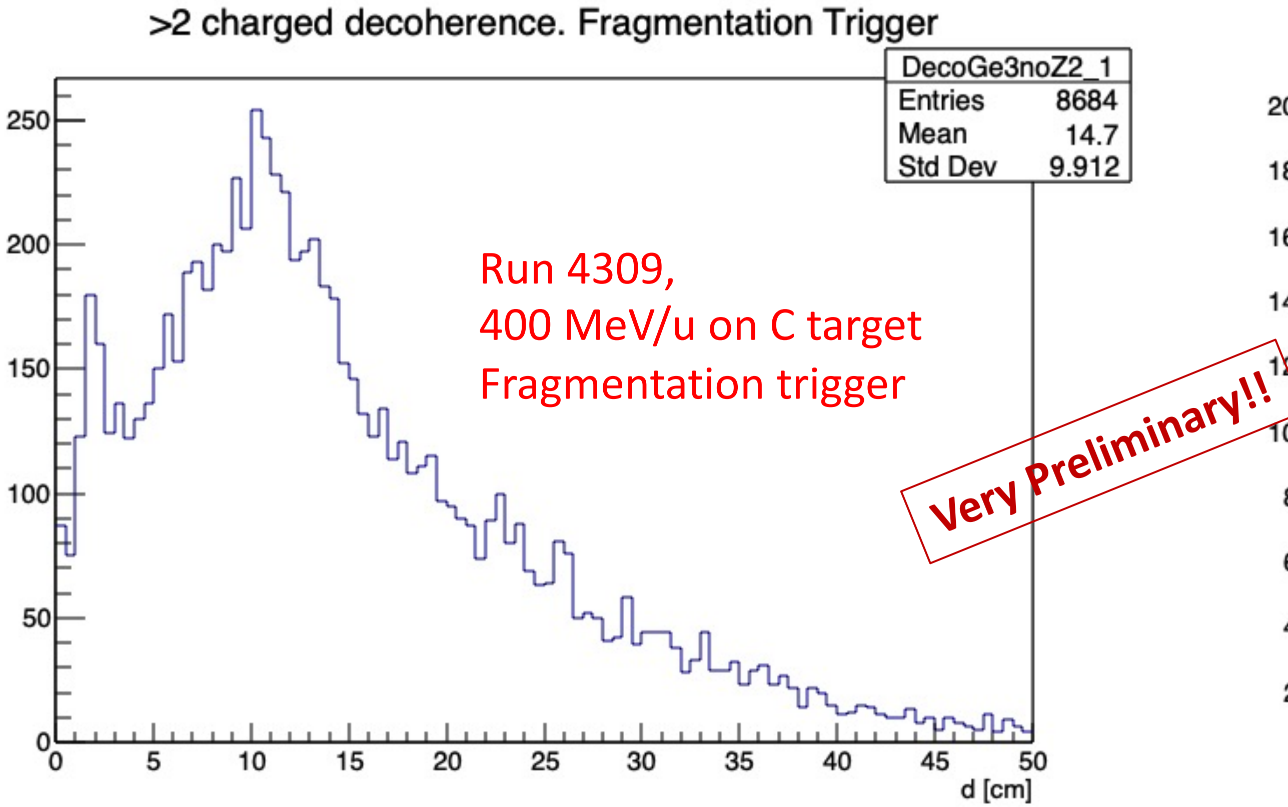
64 events with 4 Z=2 fragments on TW found (→384 pairs)
[330 ev (1980 pairs) in 5 10^6 prim]

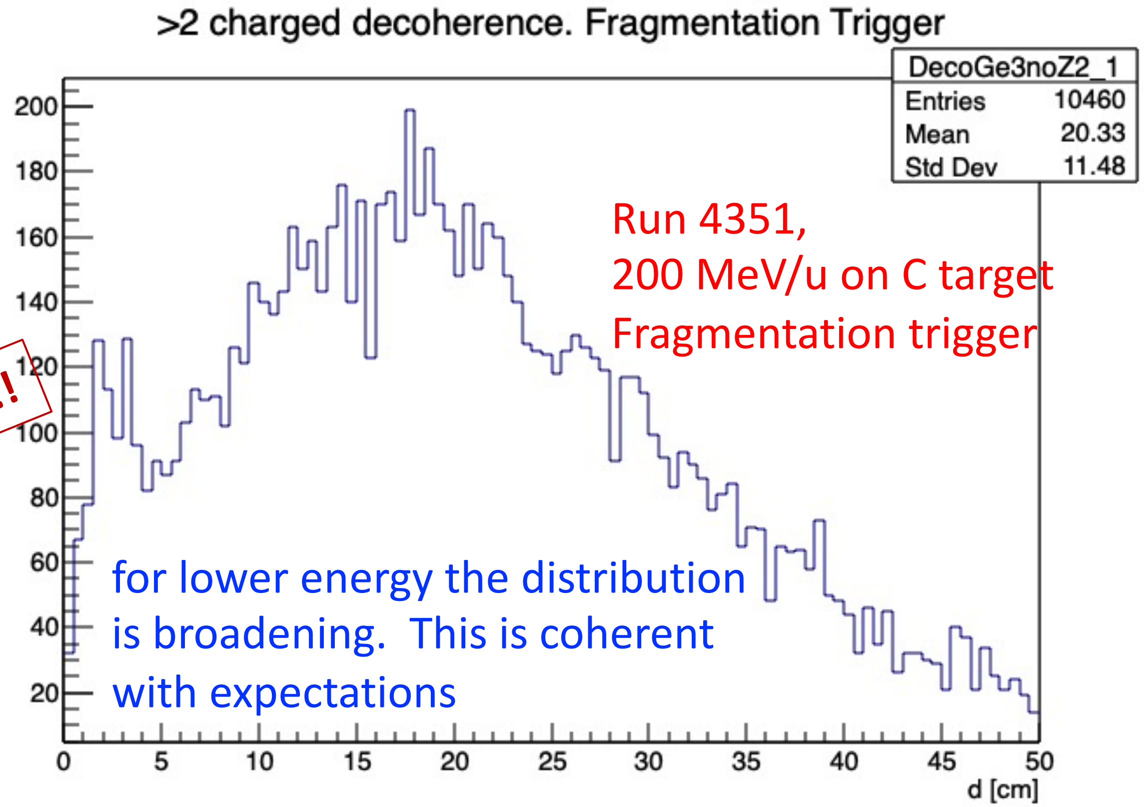
Enough (in principle, when you assume full efficiency!) to identify a correlation peak!

Exp. data from GSI2021 campaign - 1

- Using the simple extrapolation of VTX tracks to TW introduced by CF (automatically performed by DecodeRaw from newgeom Branch, producing a sort of Global Tracks).
- VTX vertex cleaning is performed by checking the association with BM track.
- Unfortunately the assosciation to TW point is not yet efficient, and Z-id is not yet possible

Events with ≥ 3 tracks selected



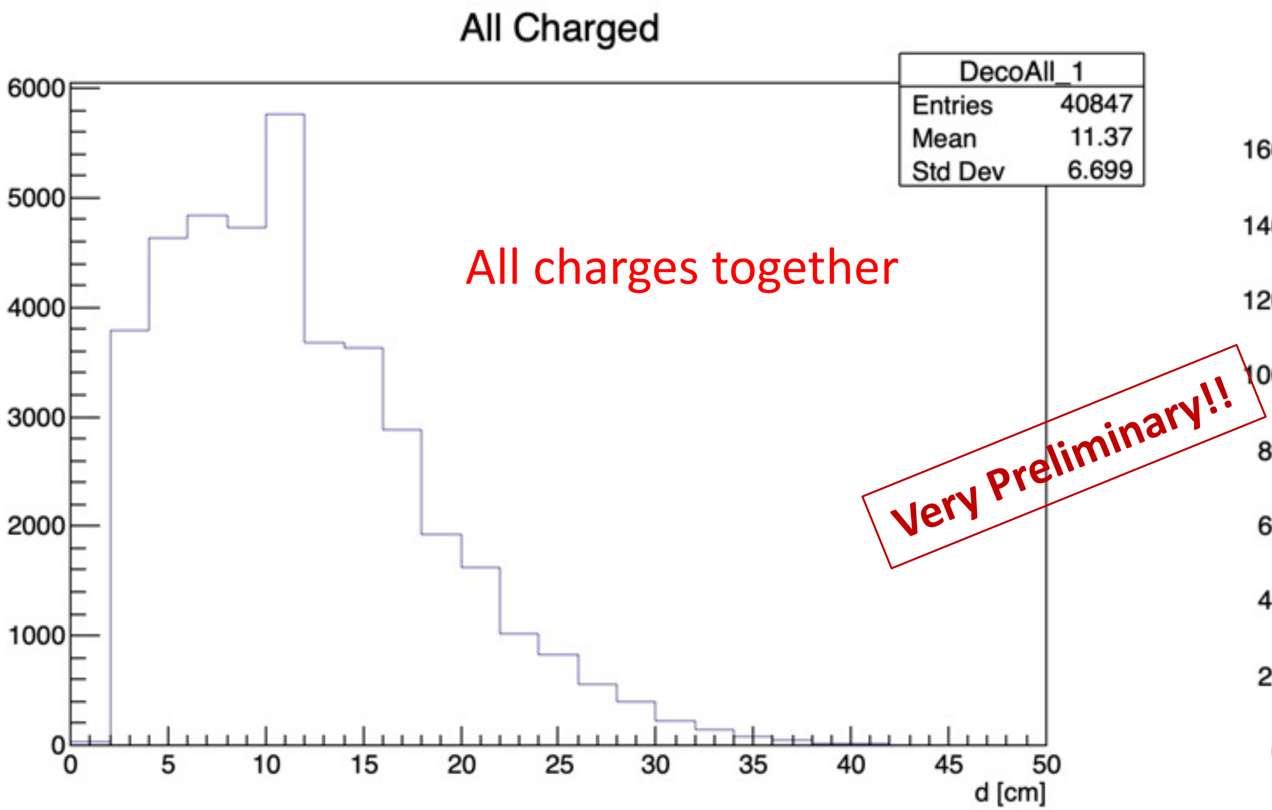


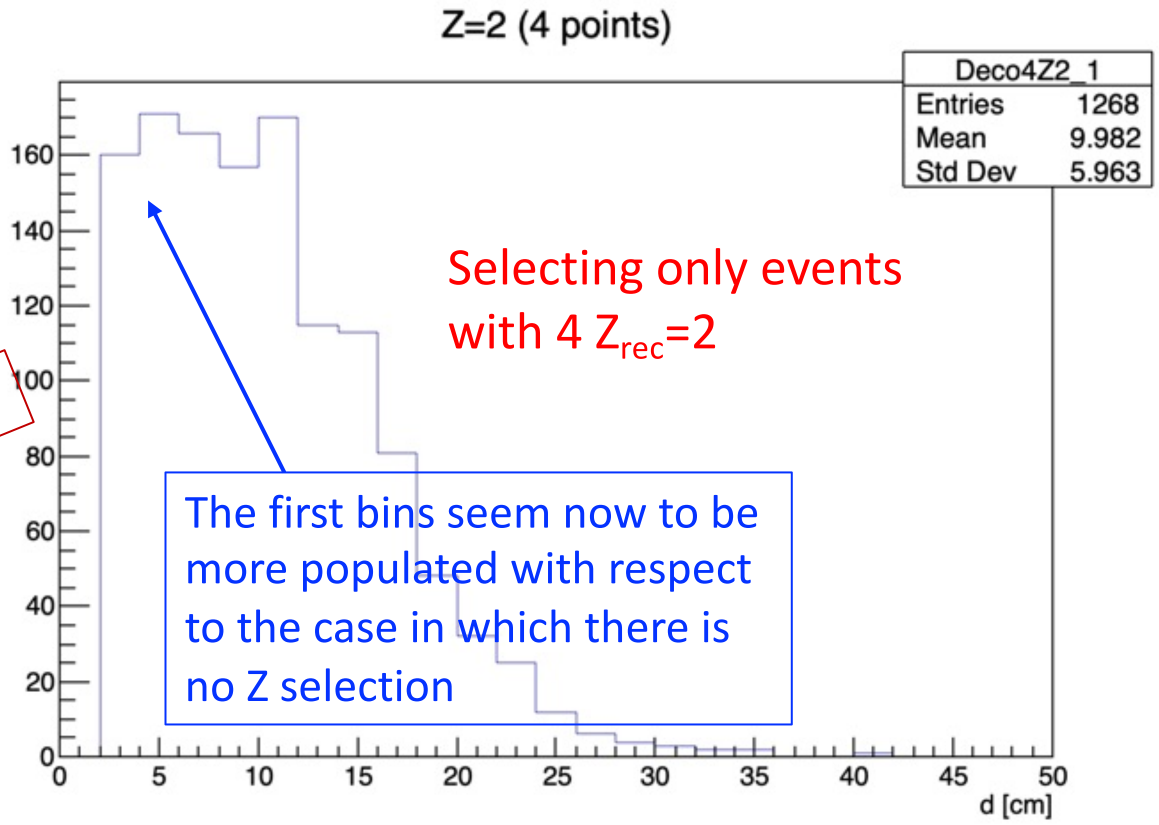
Intriguing… But wait, please don't get excited: there could be still artefacts, fakes, …

Exp. data from GSI2021 campaign - 2

- Z-id can be used with good efficiency on TW points, only at 400 MeV/u for the moment
- The spacing of TW point is however quantized at 2 cm level… Soace resolution is lost

Run 4309, 400 MeV/u on C target, Fragmentation trigger

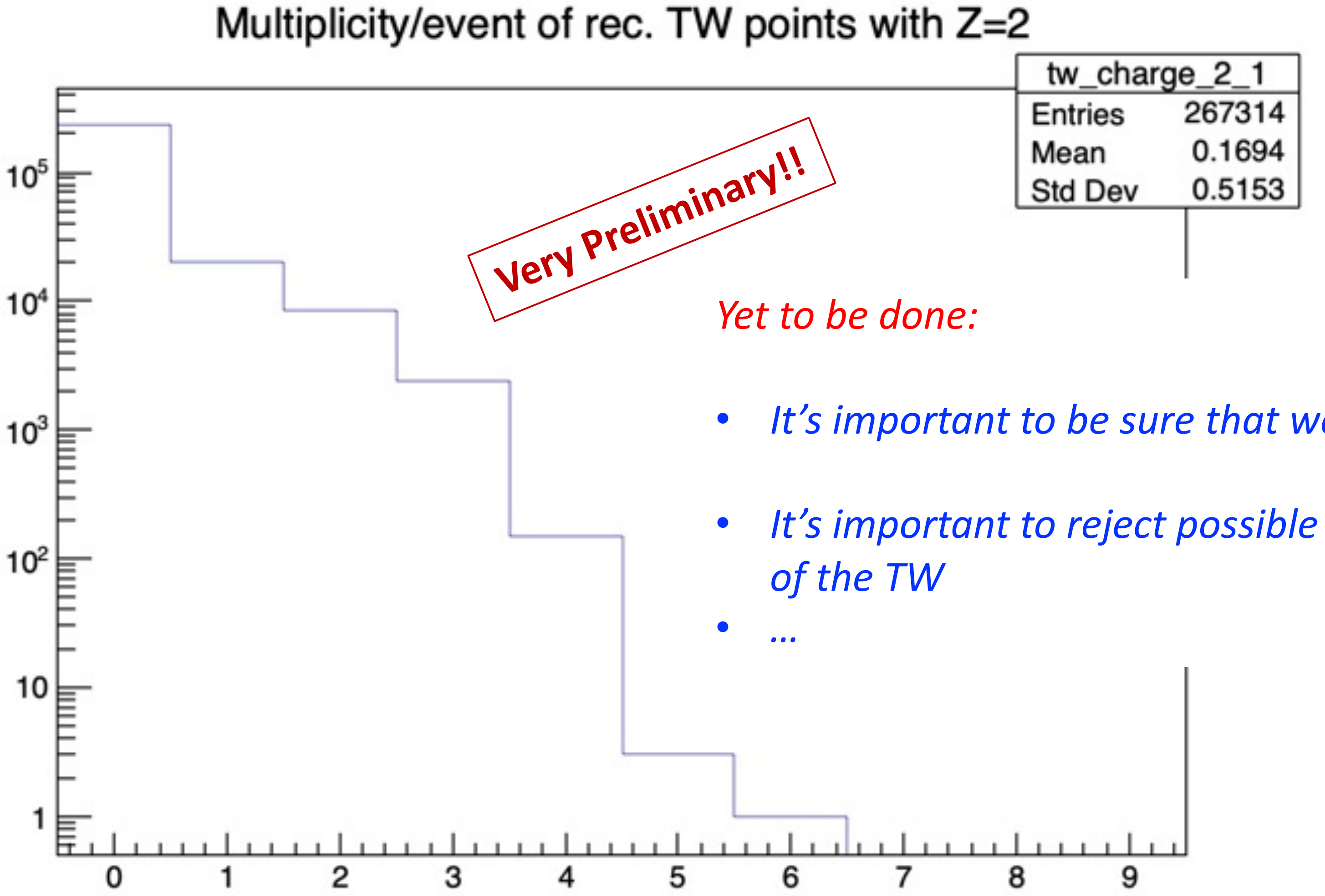




Intriguing again… but wait, many checks are still needed

Exp. data from GSI2021 campaign - 3

Run 4309, 400 MeV/u on C target, Fragmentation trigger



Yet to be done:

- *It's important to be sure that we have got rid of ghosts*
- *It's important to reject possible re-interactions upstream of the TW*
- *…*

Conclusions 1

- A new physics chapter for FOOT can be now considered: the measurement of inclusive cross sections is not the whole story
- The accurate measurement of some exclusive fragmentation channels of ^{12}C and ^{16}O is important and of interest for model benchmarking, nuclear physics and applications.
- The fragmentation channels into clusters of ^{4}He are of particular interest in the context of nuclear clustering phenomenology
- Rather simple kinematical analysis allows to identify intermediate channels involving the production of ^{8}Be. This is not relevant for applications but it's interesting for nuclear physics.
- FOOT is in principle able, without any additional detector or change in design, to identify and measure channels like $^{16}O \rightarrow {}^{12}C + {}^{4}He$, $^{16}O \rightarrow 4\ {}^{4}He$, $^{16}O \rightarrow {}^{8}Be + 2\ {}^{4}He \rightarrow 4\ {}^{4}He$, $^{16}O \rightarrow {}^{8}Be + {}^{8}Be \rightarrow 4\ {}^{4}He$
- A first look at recent data seems to confirm MC expectations *(but it's too early to get excited…)*

Conclusions 2: what we would like to do

- Perform a rigorous analysis on exp. data from GSI2021 campaign with ^{16}O (can GSI2019 data with ^{12}C be used?).
- Hoping for a larger data ^{12}C sample from a ~~CNAO2021~~ CNAO2022 campaign
- Study of acceptance, efficiencies, resolution effects, background and systematics
- Try to start answering to questions of slide #9
- Suggestion 1: also ECC data should be used for analysis. The issue can be the statistics
- Suggestion 2: beyond FLUKA model (stable at this level), it may be useful to check predictions of other models like those adopted in the most relevant physics lists of G4.

Can also the old FIRST data be recovedered and analyzed?

Conclusions 3: necessary technical steps

- At present VTX tracks are fundamental. MSD can help.
- We need to have a reliable Global Reconstruction with a correct coupling to Z-id
- It is fundamental to check the combination of BM and VTX to identify the good VTX vertex in noisy events
- Check for artefacts, ghosts, reinteractions, etc.
- The simple extrapolation of ”good” tracks to TW and association with TW points seems to be sufficient for the proposed analysis
- We need to assess which are the “good” runs in which synchronization is maintained for a long period

Some history of this work…

This idea was developed while working for the FOOTPRINT proposal in January 2021, by applying the concept "decoherence" distribution, derived from our old experience in cosmic ray physics (>20-30 years ago…).

This was done in the attempt to study the separation of neutrons from charged fragments in a FOOT-derived geometry.

At some point, we (GB, SM) noticed by chance the existence of peaks in the decoherence of simulated data, and we asked ourselves the reason of that… Was that a bug or something else?

Remember: no piece of work will eventually remain lost for ever!

Thank you for the attention

Work started by GB and SM; whole Milano group and AK from Pisa involved
Thanks to G. Traini, R. Zarrella for checking and fixing Z-id

Appendix 1

- The **Hoyle state** is an excited, spinless, resonant state of C-12. It is produced via the triple-alpha process, and was predicted to exist by Fred Hoyle in 1954. The existence of the 7.7 MeV resonance Hoyle state is essential for the nucleosynthesis of carbon in helium-burning red giant stars, and predicts an amount of carbon production in a stellar environment which matches observations. The existence of the Hoyle state has been confirmed experimentally, but its precise properties are still being investigated.
- The Hoyle state is populated when a He-4 nucleus fuses with a Be-8 nucleus in a high-temperature (10^8 K) environment with densely concentrated (10^5 g/cm^3) helium. This process must occur within 10^{-16} seconds as a consequence of the short half-life of ^{8}Be. The Hoyle state also is a short-lived resonance with a half-life of 2.4×10^{-16} seconds; it primarily decays back into its three constituent alpha particles, though 0.0413(11)% of decays occur by internal conversion into the ground state of ^{12}C.
- In 2011, an ab initio calculation of the low-lying states of C-12 found (in addition to the ground and excited spin-2 state) a resonance with all of the properties of the Hoyle state.

Appendix 2

^{8}Be:

Simbolo	^{8}Be
Protoni	4
Neutroni	4
Peso atomico	8,00530510(4)
Abbondanza isotopica	assente (elemento artificiale)
Proprietà fisiche	
Spin	0^{+}
Emivita	6.7×10^{-17} s
Decadimento	α
Prodotto di decadimento	^{4}He