Analysis of nuclear clustering at intermediate energies with the FOOT experiment

FOOT Collaboration Meeting
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Author: Alice Caglioni

Introduction to nuclear clustering

Nucleons interactions (attractive nuclear forces) → Spatial correlation between nucleons → Formation of cluster structures

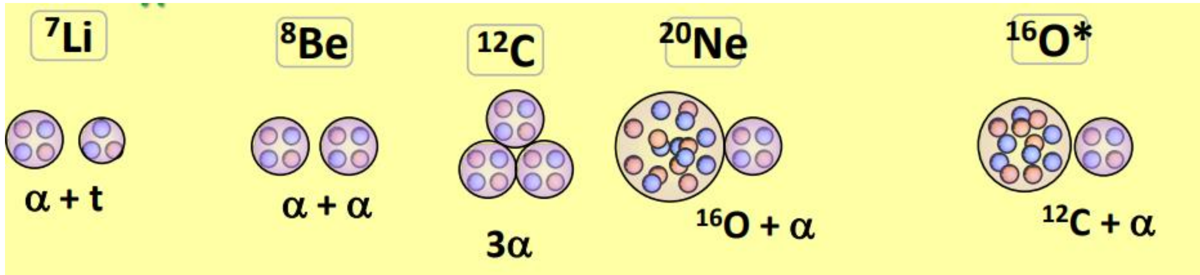


Fig. 1: Typical cluster structures known in the stable nuclei.

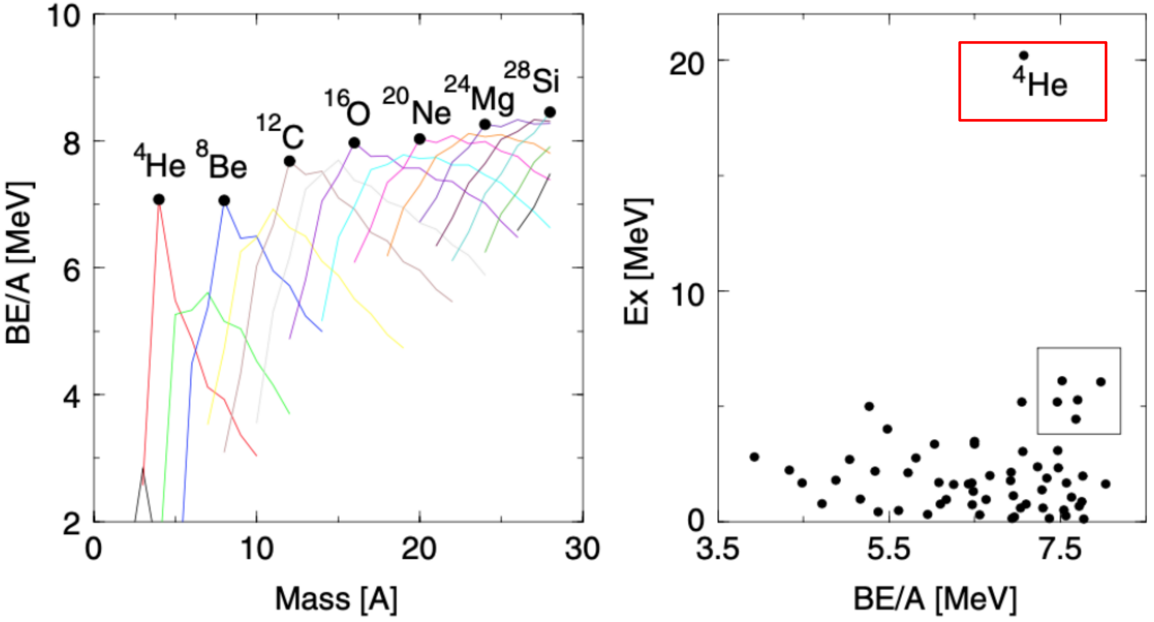
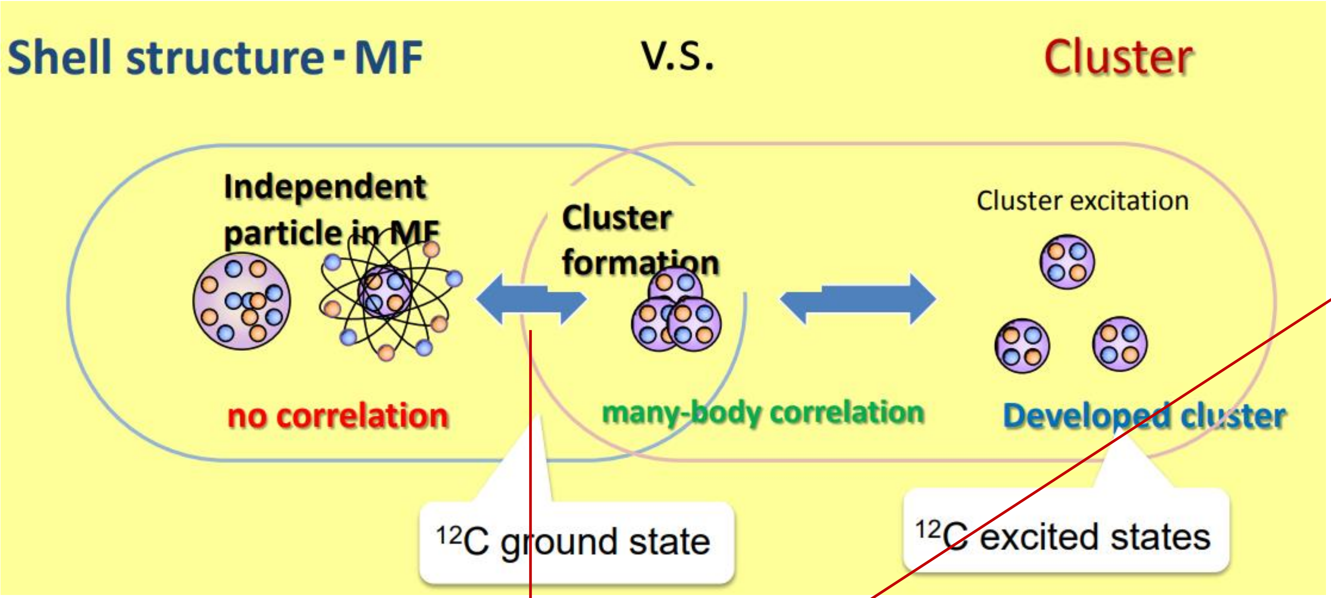


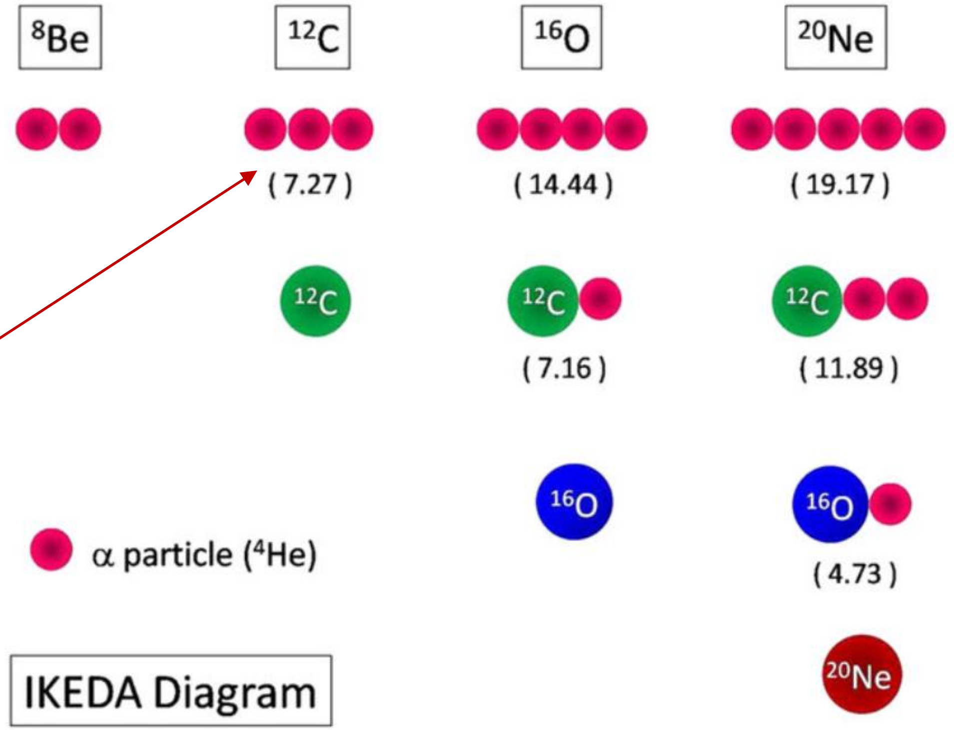
Fig. 2: (Left) Binding energy per nucleon of light nuclear systems up to A = 28. (Right) Excitation energy of first excited states plotted versus binding energy per nucleon for nuclei up to A = 20.

[M. Freer. *Reports on Progress in Physics*, 70(12):2149, (nov 2007)]

Introduction to nuclear clustering



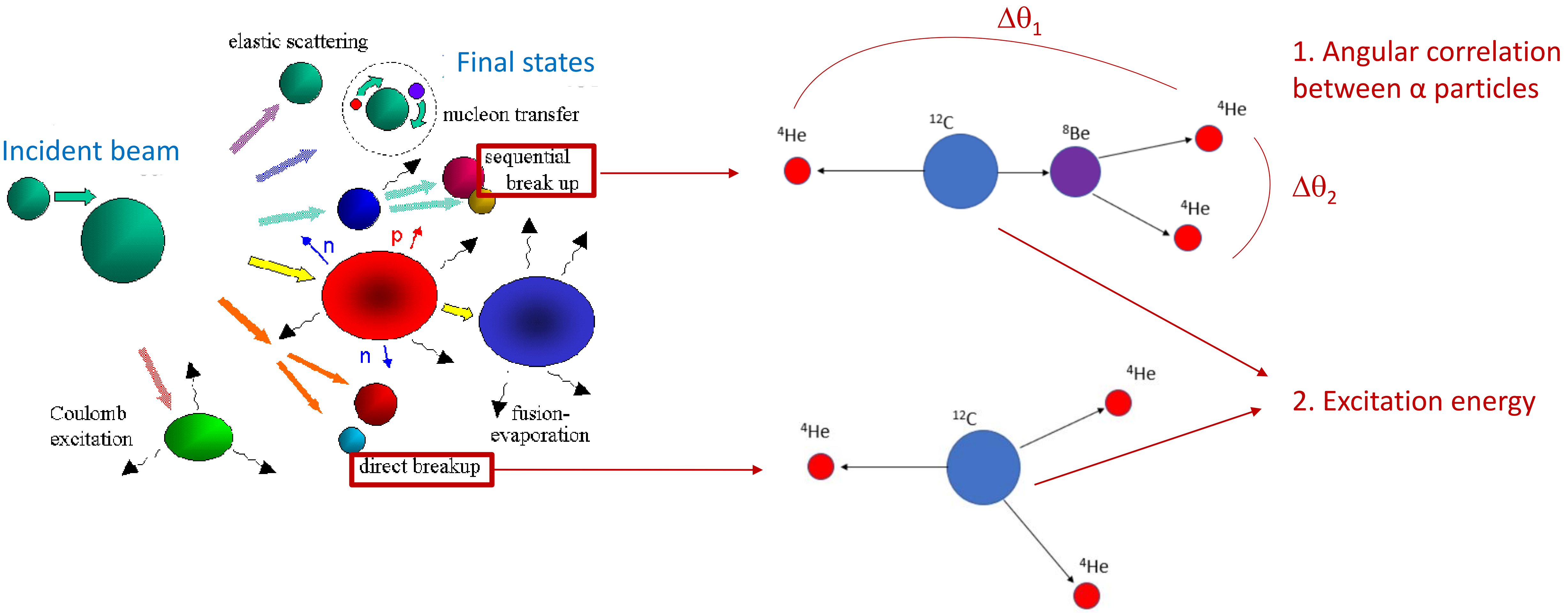
Threshold rule



[K. Ikeda, et al. *Progress of Theoretical Physics Supplement*, E68:464–475, 07 (1968)]

Fig. 3: The so-called 'Ikeda' diagram showing how above particle-breakup thresholds, the structure of light α-conjugate nuclei can be thought of as comprised of α clusters.

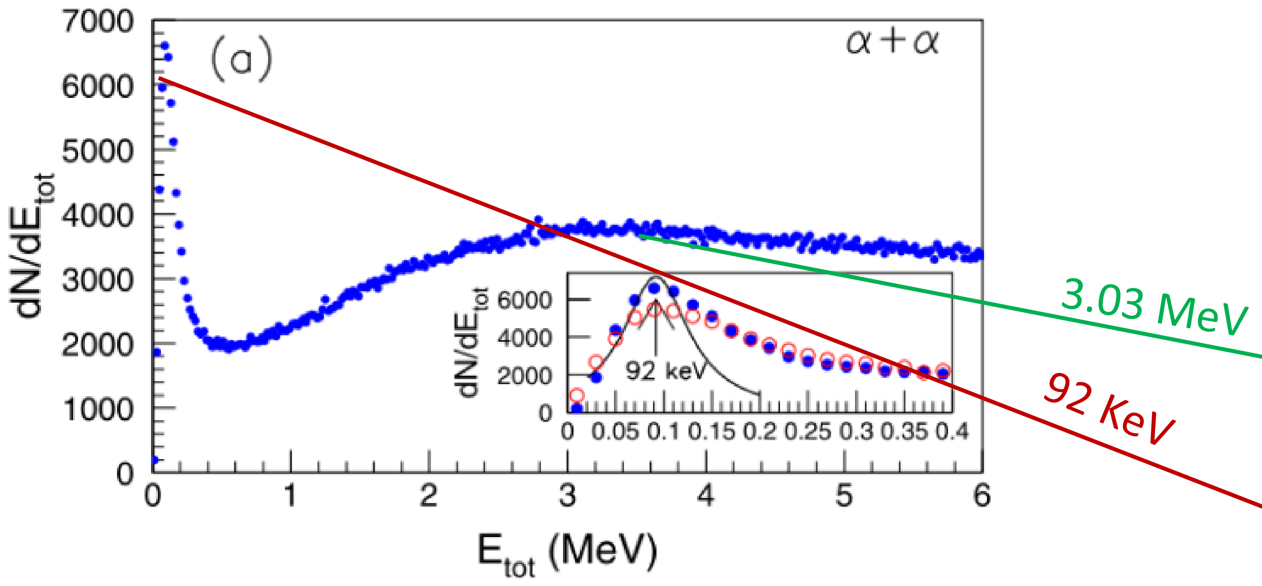
Techniques for the study of clusters in nuclei



Experimentally Observed Clusters in α-Particle Nuclei at low energies in literature

Excitation energy: ^{8}Be → Yields of correlated **2α** emissions

^{40}Ca + ^{12}C at **25 MeV/u**



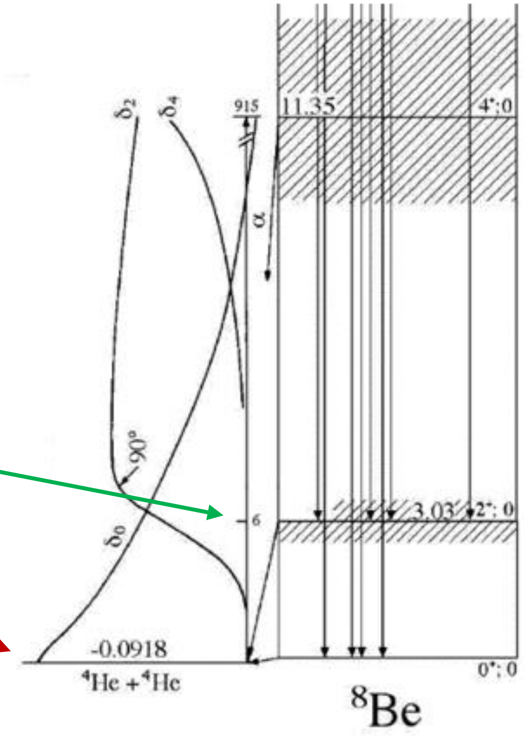


Fig. 4: Yields of correlated α − α emissions out of quasi-projectile expressed as a function of total kinetic energy. The inset corresponds to zooms on the 8Beg.s. peak.

[Ad.R. Raduta, et al. *Physics Letters B*, 705(1):65–70, (2011)].

Experimentally Observed Clusters in α-Particle Nuclei at low energies in literature

Excitation energy: ^{12}C → Yields of correlated **3α** emissions

^{40}Ca + ^{12}C at **25 MeV/u**

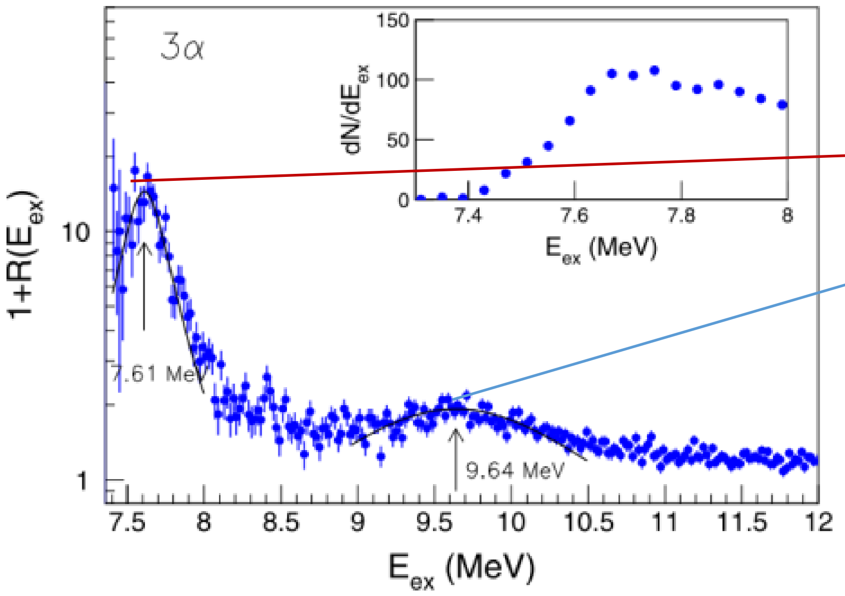


Fig. 5: 3α correlation function as a function of excitation energy.

[Ad.R. Raduta, et al. *Physics Letters B,* 705(1):65–70, (2011)].

^{12}C + ^{12}C at **95 MeV**

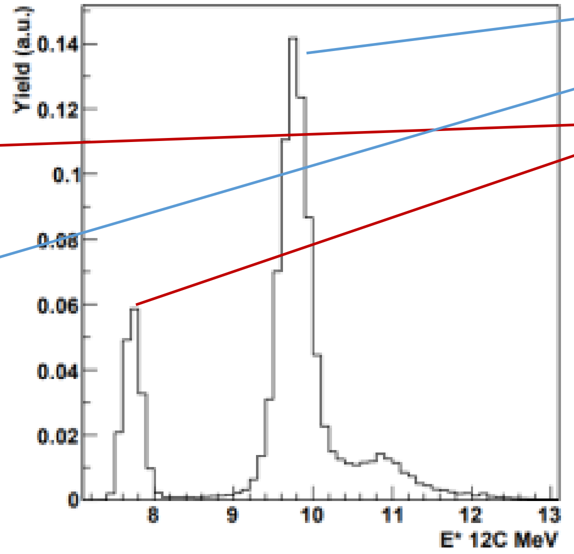
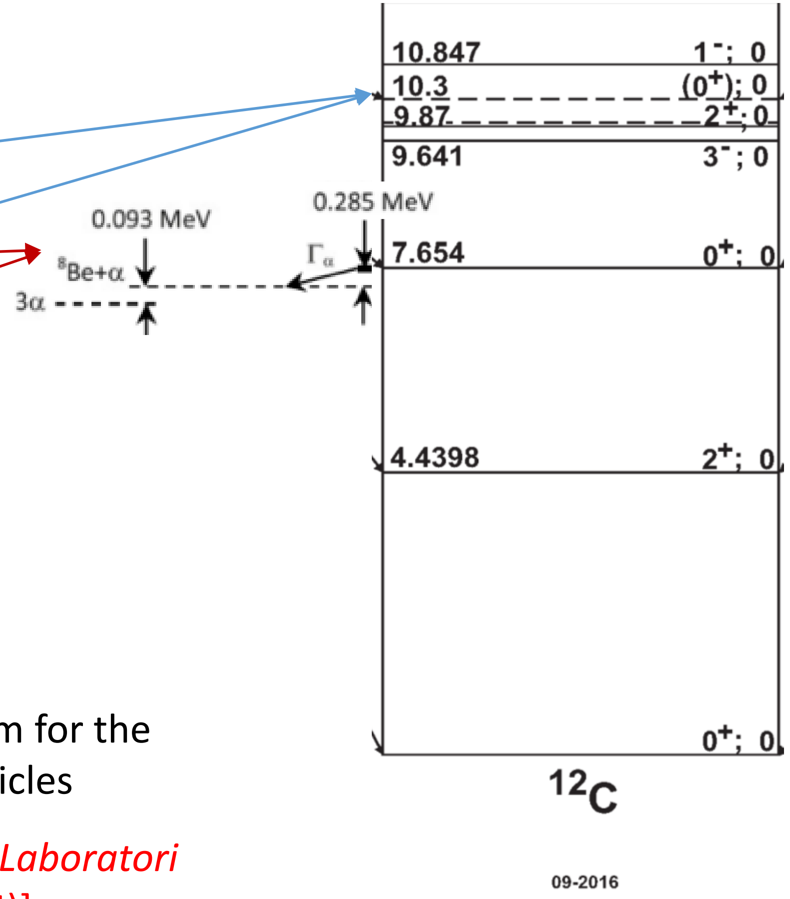
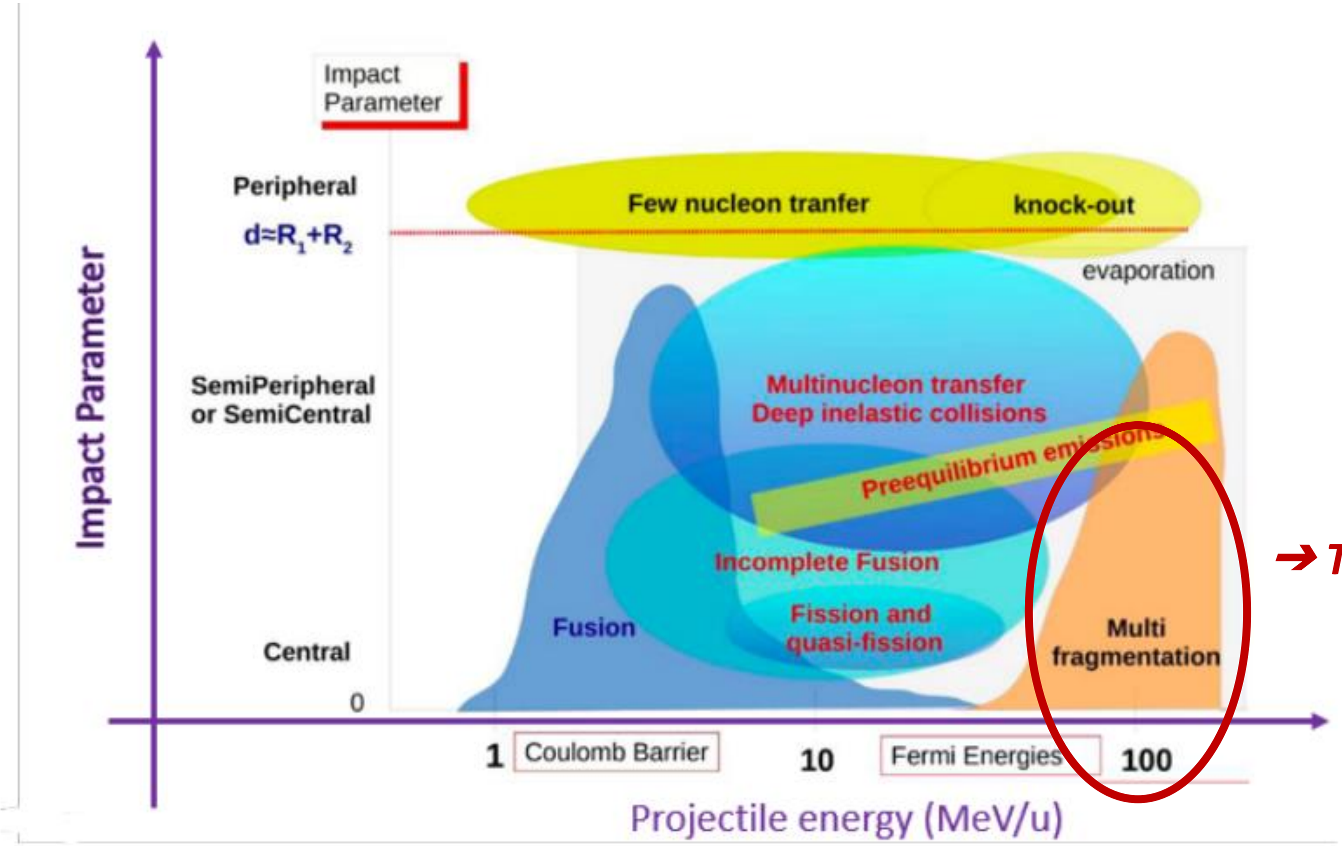


Fig.6: Excitation energy spectrum for the breakup of ^{12}C into three α-particles

[L. Morelli, et al. *Annual Report Laboratori Nazionali di Legnaro INFN* (2014)].



Experimentally Observed Clusters in α-Particle Nuclei at **intermediate energies**



[G. De Lellis, et al. *Nuclear Physics A*, 853(1):124–134, (2011)]

➔ ***The FOOT experiment***

- ECC — ^{12}C at 400 MeV/u HIMAC
- Electronic Spectrometer

Performed analyses

Aim: exploring the possibility to analyze α clustering phenomenology through the FOOT experiment by quantifying α correlation arising from the 2 decay channels of ^{12}C.

$^{12}C(\alpha, 2\alpha)$ $^{12}C(\alpha, {}^{8}Be)$

MC Simulation:

- $^{12}C + {}^{12}C$ at **200 MeV/u** with the full FOOT experimental setup;
- Campaign: **12C_C_200_2023v2**;
- **5.000.000** simulated primaries.

MC Truth

Reconstruction:

- **7** points for reconstruction;
- **5.000.000** reconstructed events.

α particles selection → Angular separation analysis → Excitation energy analysis

In this presentation, for the first time, we attempt to use reconstructed tracks by SHOE (Genfit) using a full magnetic setup

α particles selection

MC Truth

- Particle generated from a primary;
- Particle forward directed (initial momentum>0);
- Production region: TGT;
- Detection region: TW;
- Angular acceptance: 10°;
- Initial Kinetic energy > 50 [MeV/u];
- Charge = 2;
- Baryonic number = 4;

Reconstruction

- Detection region: TW;
- Reconstruction charge from TW = 2;
- Reconstructed mass in range 3.2 ÷ 4.3 GeV/c^2;

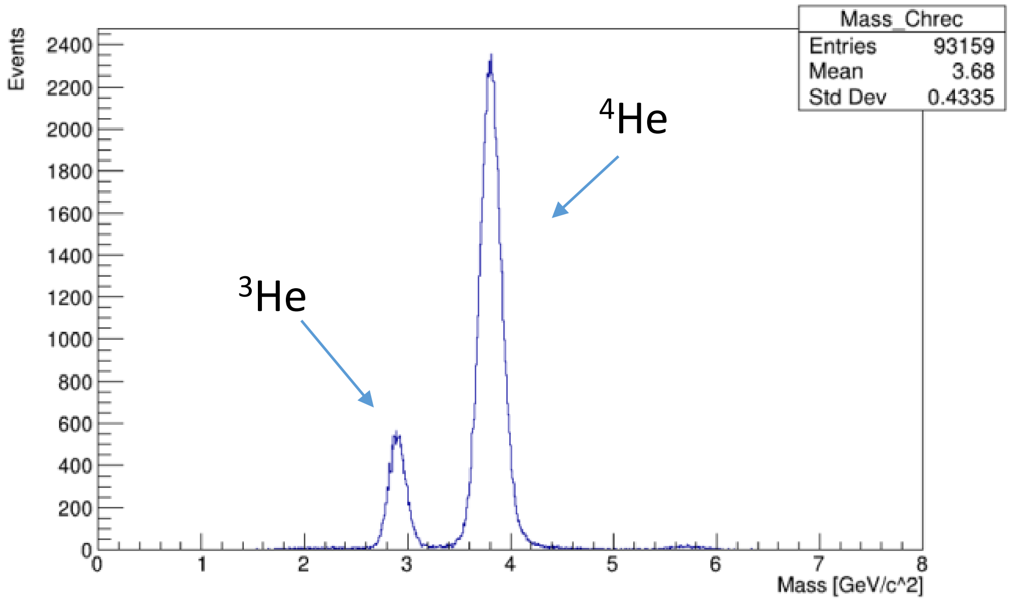
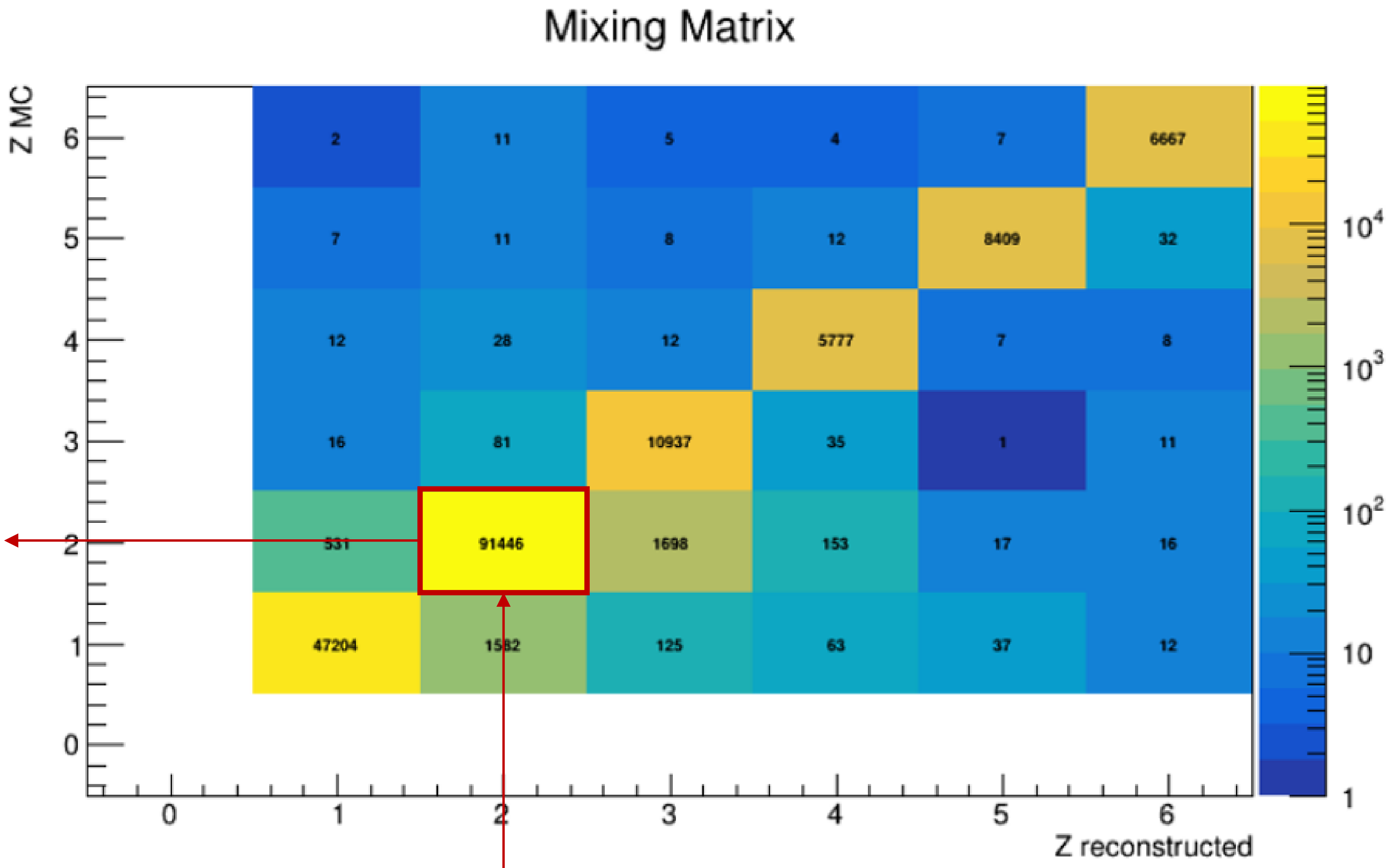


Fig. 7: Reconstructed mass distribution of reconstructed particles with the reconstructed charge Z_{rec} = 2 generated on target that arrive on TW.

α particles selection

from the GetMcMainTrackId();

98.16%



from the GetTwChargeZ();

Fig. 8: Correlation between the charge reconstructed by the TW and the MC charge.

Angular Separation Analysis

MC Truth

$$p_k = \sqrt{P^2_{x_k} + P^2_{y_k} + P^2_{z_k}};$$

$$\Delta\Theta = \arccos\left(\frac{P_{x_i}P_{x_j} + P_{y_i}P_{y_j} + P_{z_i}P_{z_j}}{p_i p_j}\right)$$

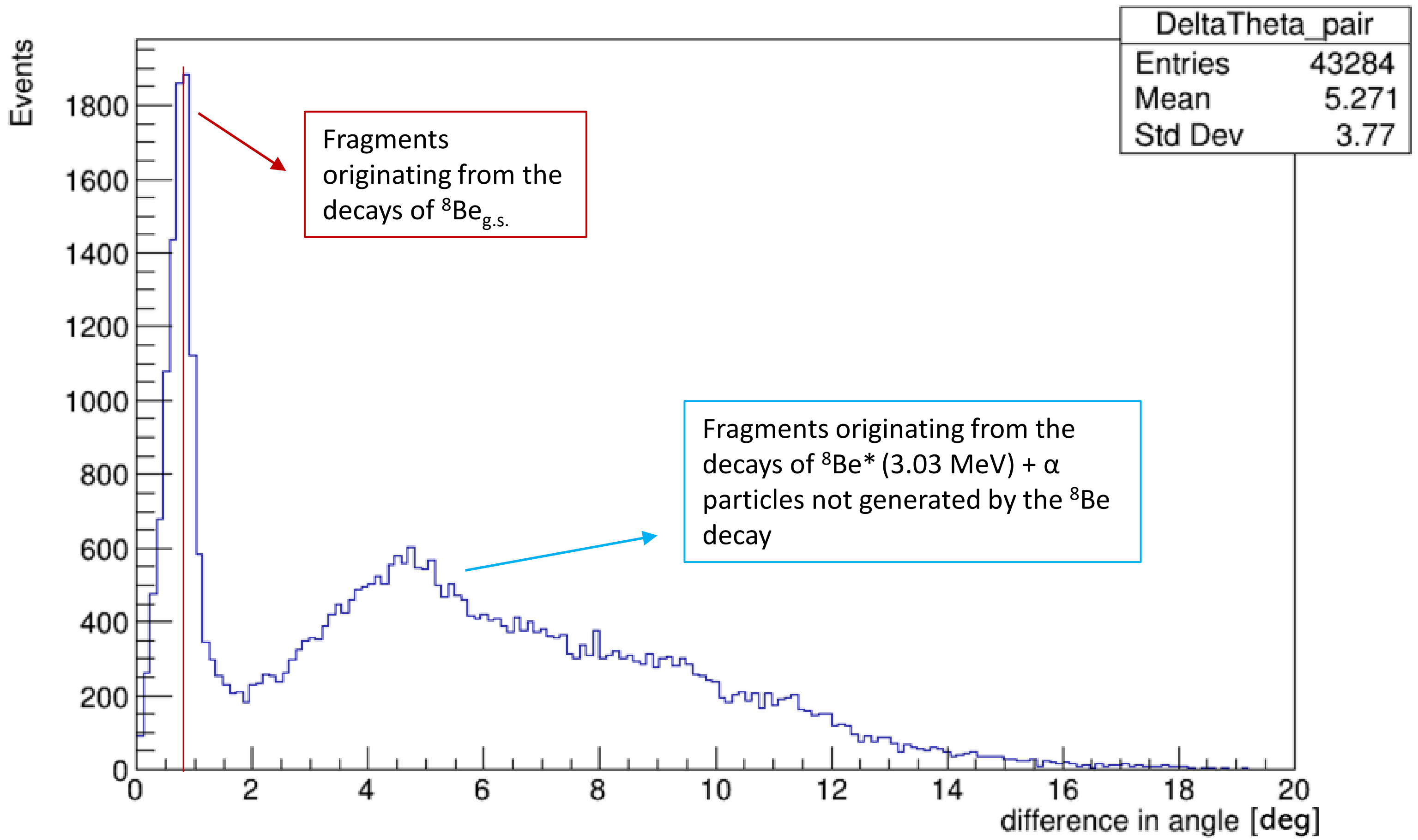


Fig. 9: Opening angle between pairs of MC simulated α particles **out of target** from events producing two and three α particles together

Angular Separation Analysis

Reconstruction efficiency:

$$Eff = \frac{Number\ of\ reconstructed\ \alpha\ particles}{Number\ of\ MC\ \alpha\ particles} = 67.2\%$$

Reconstruction

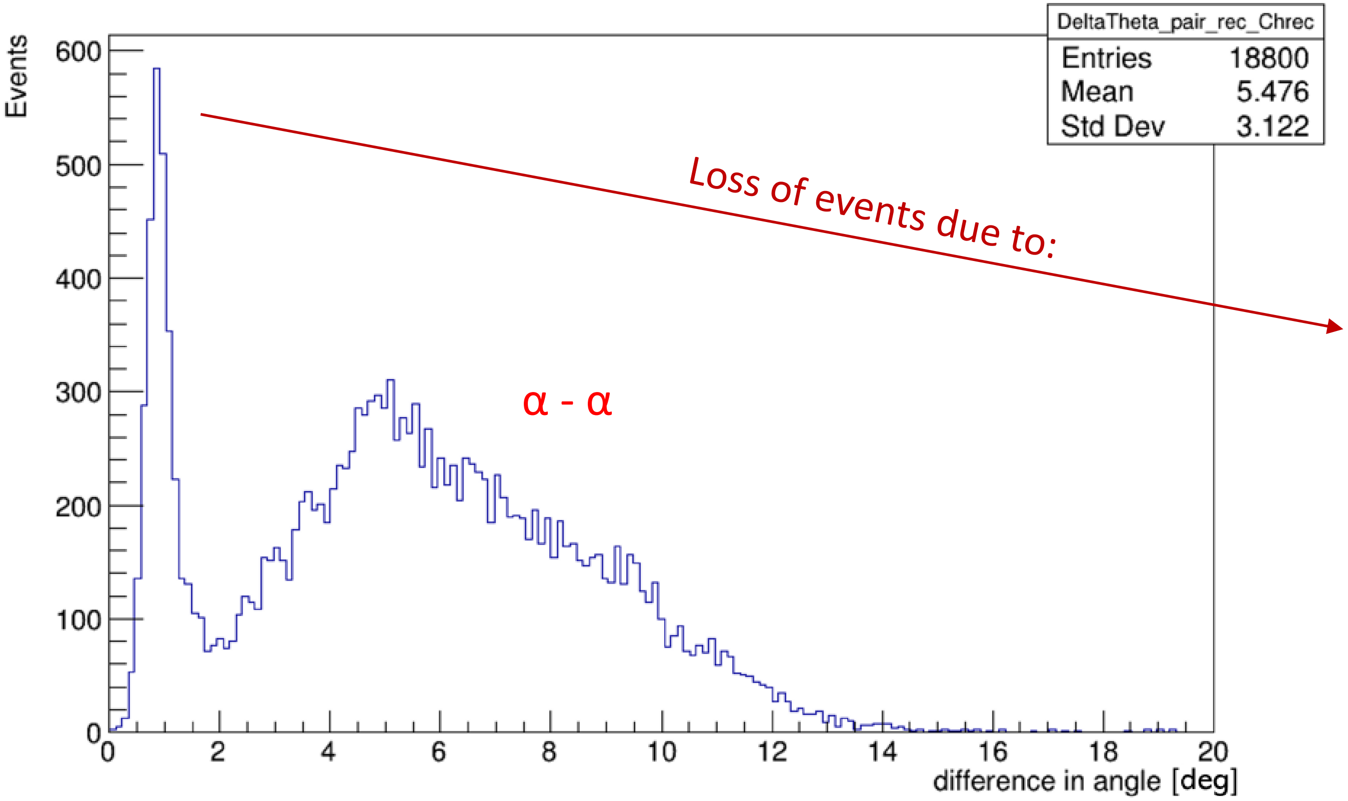


Fig. 10: Opening angle between **pairs of reconstructed α particles at TW** from events producing two and three α particles together.

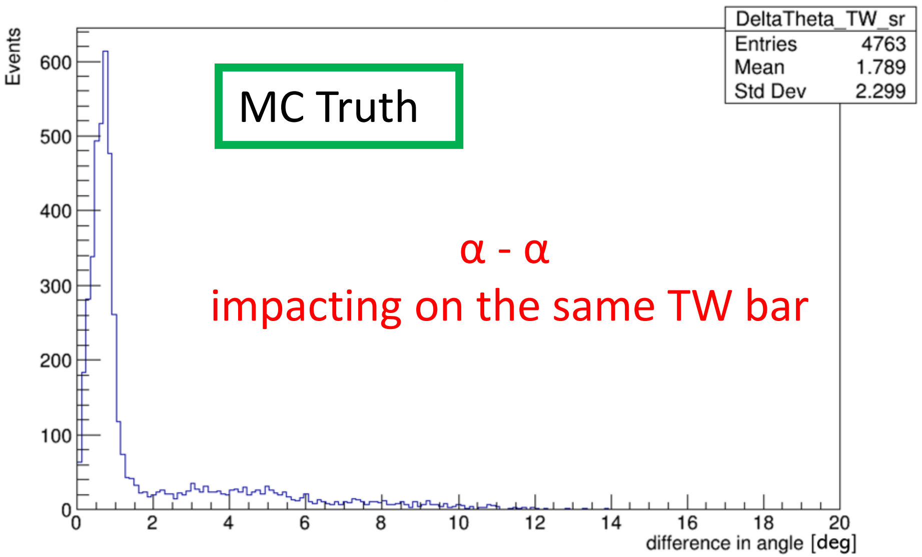
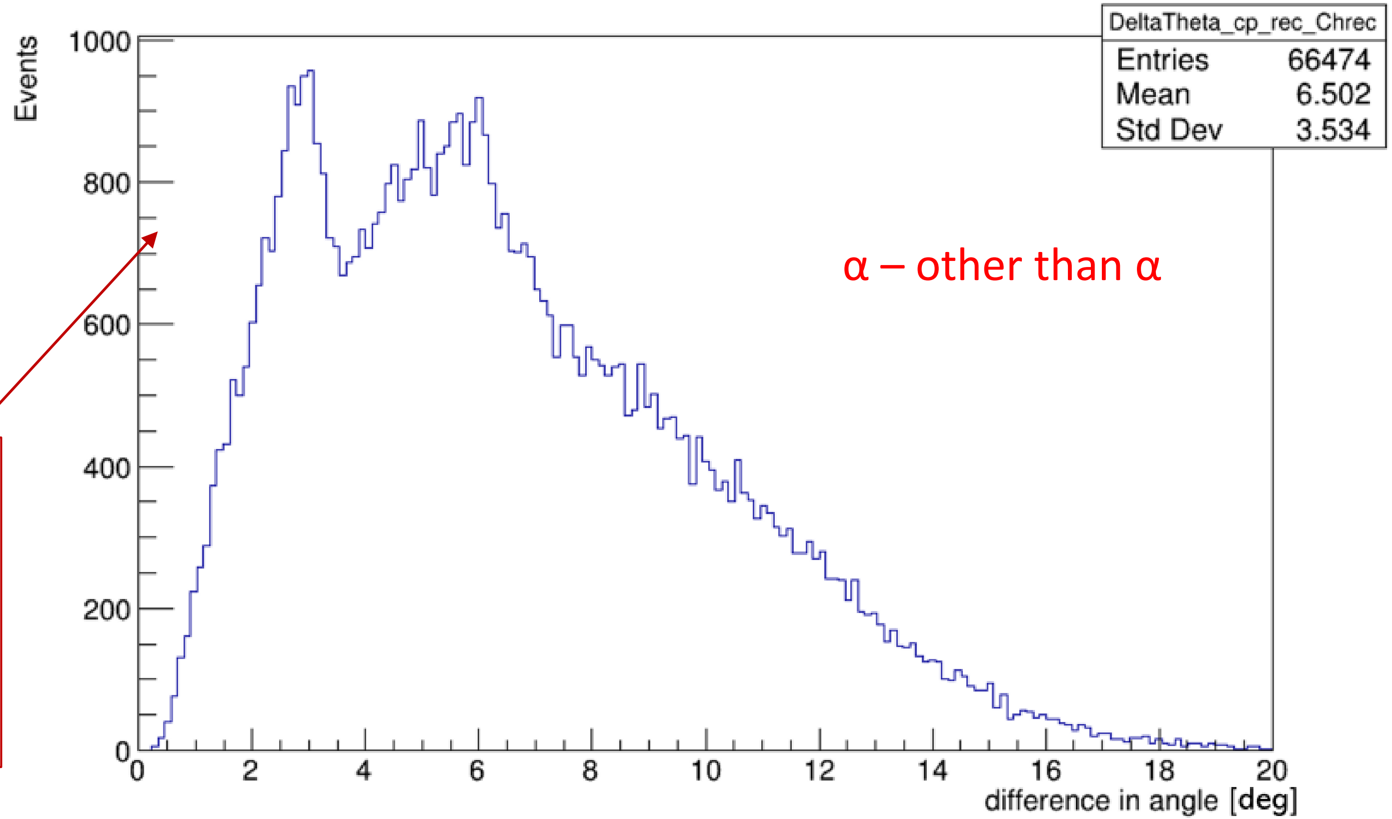


Fig. 11: Opening angle between pairs of MC α particles at TW **impacting on the same TW bar** from events producing two and three α particles together.

Angular Separation Analysis

Reconstruction



No angular correlations between particles are visible at angle of 0.6°.

Fig. 12: Opening angle on TW between reconstructed α and particles other than ^4He.

Excitation energy Analysis: ^{8}Be → ^{12}C(α, ^{8}Be)

MC Truth

$$^{8Be}E_{ex} = \sqrt{(E_{kin_i} + E_{kin_j} + 2m_\alpha)^2 - (\bar{p}_i + \bar{p}_j)^2} - 2m_\alpha$$

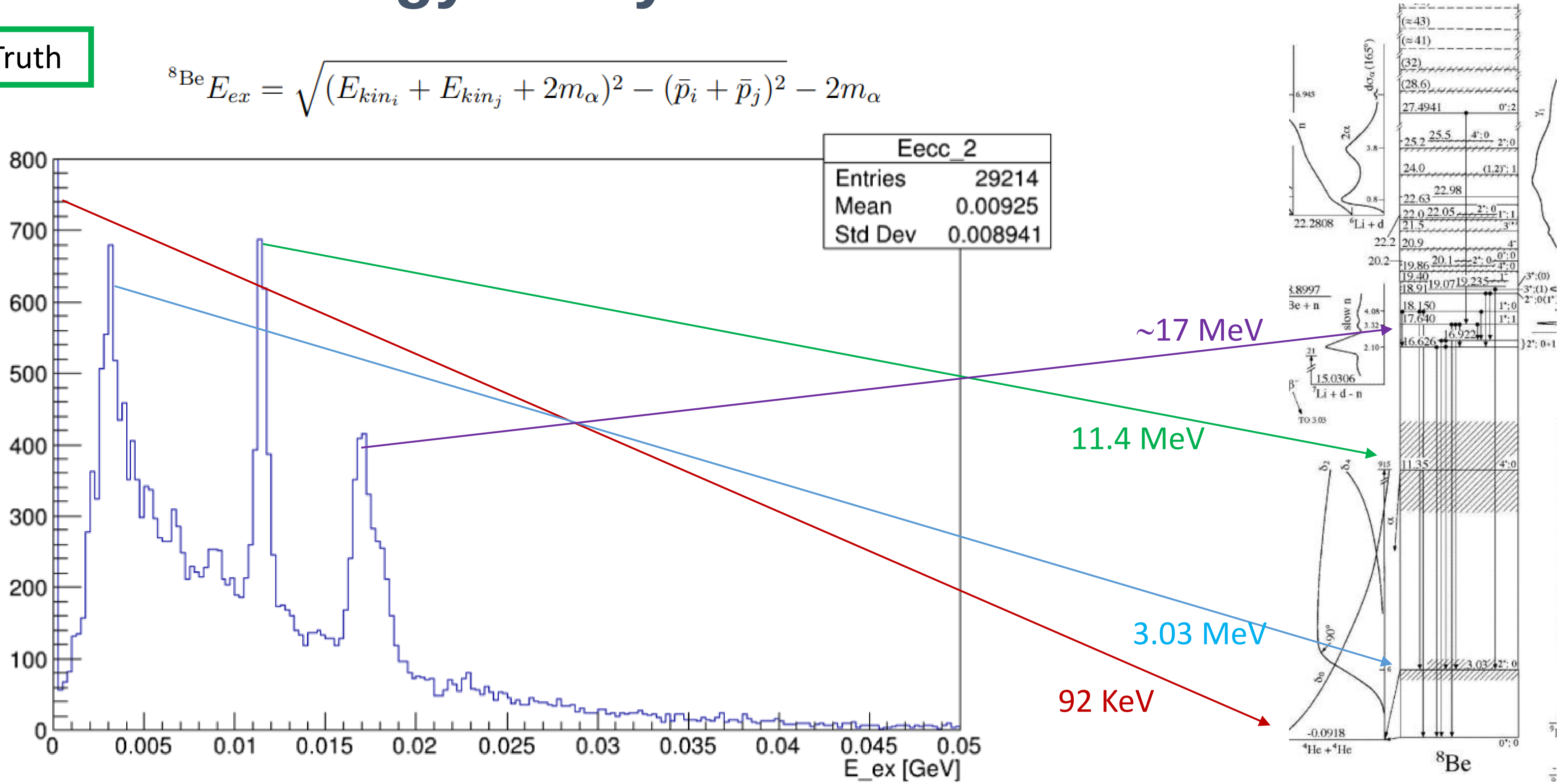


Fig. 13: Excitation energy spectrum for the breakup of 8Be intermediate stage of ^{12}C into two α particles from MC α particles analysis.

Excitation energy Analysis: ^{8}Be

$^{12}C(\alpha, {}^8Be)$

MC Truth

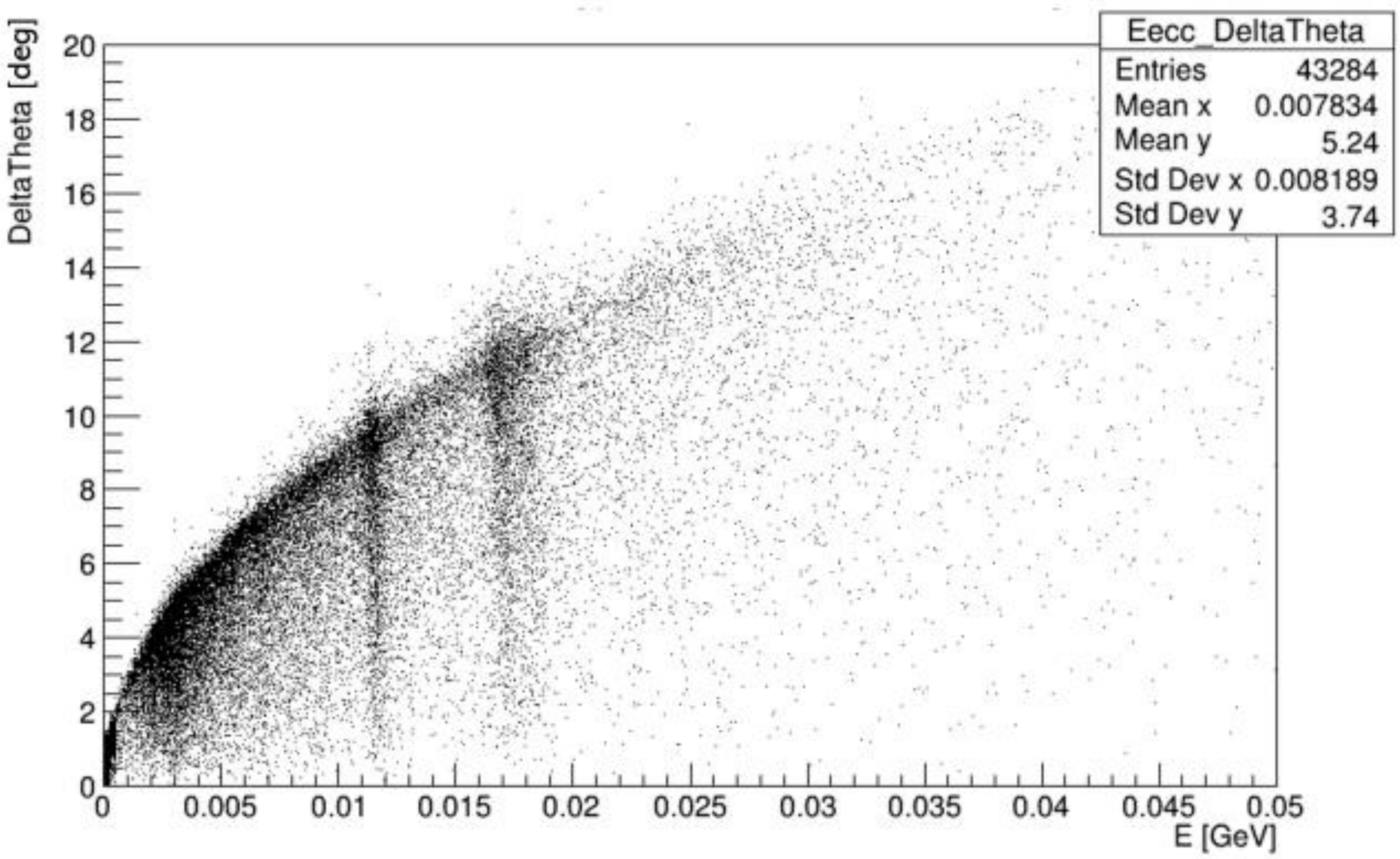


Fig. 14: Excitation energy spectrum of the breakup of 8Be intermediate stage of ^{12}C into 2 α particles VS the opening angular distribution between α particles in the MC Truth analysis.

Excitation energy Analysis: ^{8}Be → ^{12}C(α, ^{8}Be)

Reconstruction

Shift to the right

due to

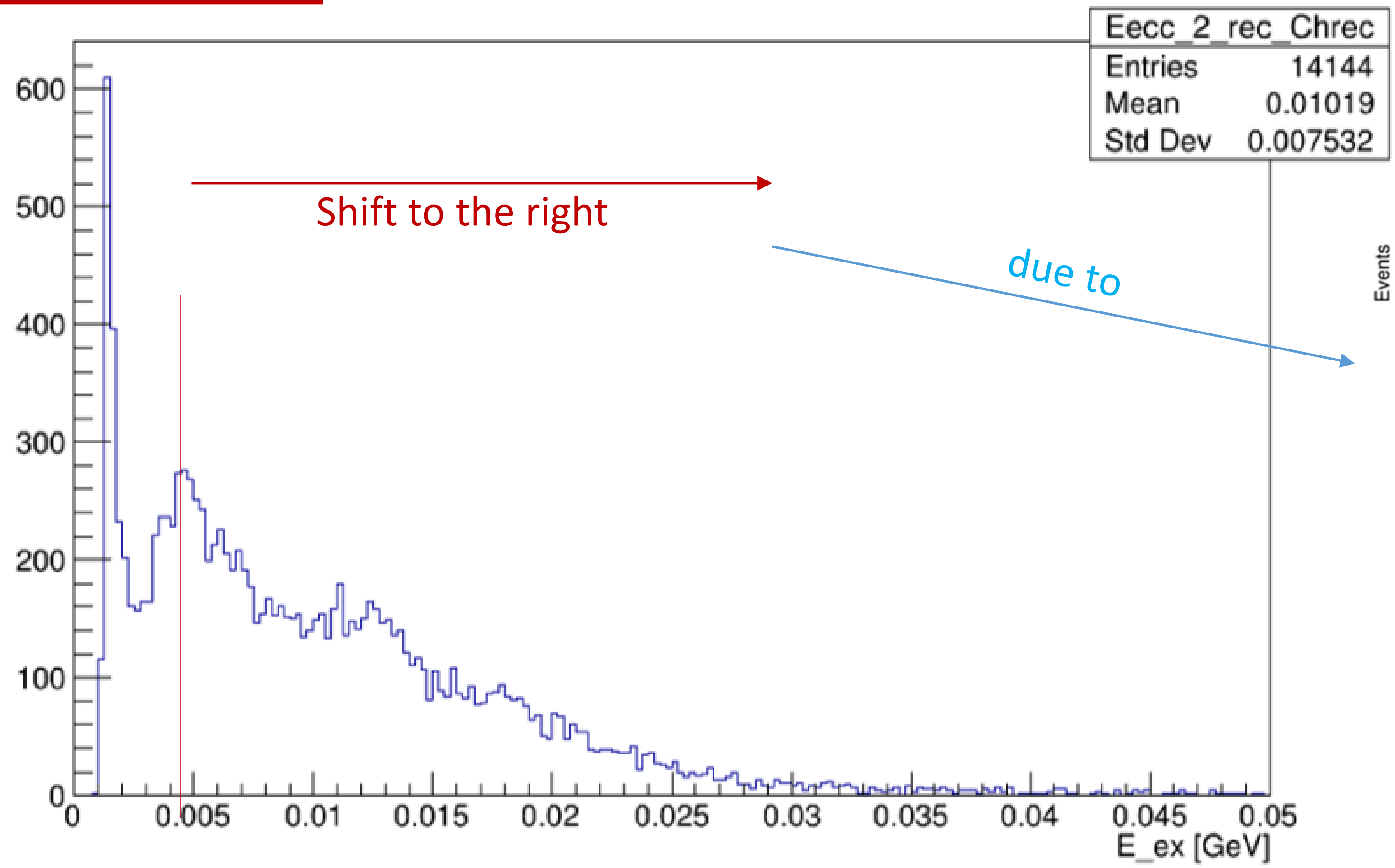


Fig. 15: Excitation energy spectrum for the breakup of ^{8}Be intermediate stage of ^{12}C into 2 α particles from reconstructed α particles analysis.

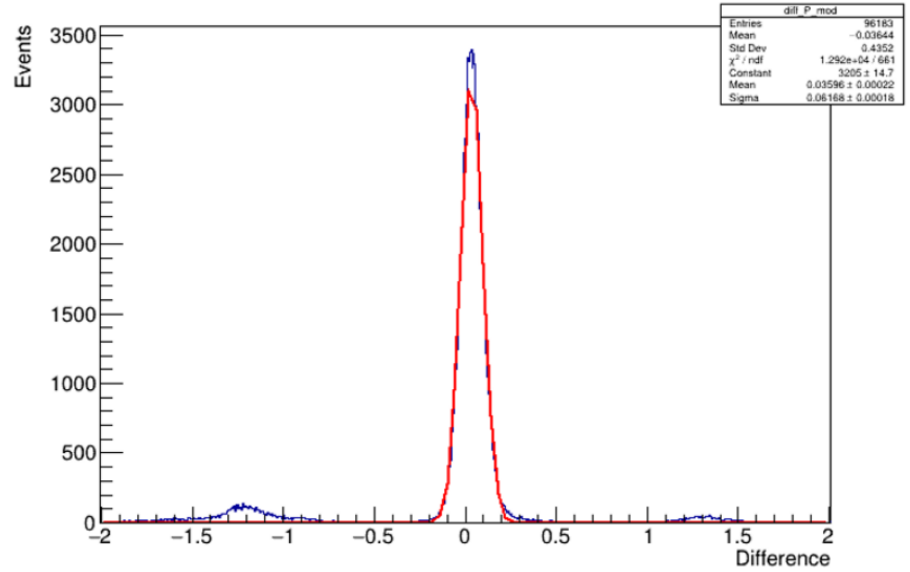


Fig. 16: Difference between the modulus of reconstructed and MC momenta. In red is reported the Gaussian distribution.

Excitation energy Analysis: ^{12}C → ^{12}C(α, 2α)

$$^{12\mathrm{C}}E_{ex} = \sqrt{(E_{kin_i} + E_{kin_j} + E_{kin_k} + 3m_\alpha)^2 - (p_i + p_j + p_k)^2} - 3m_\alpha$$

MC Truth

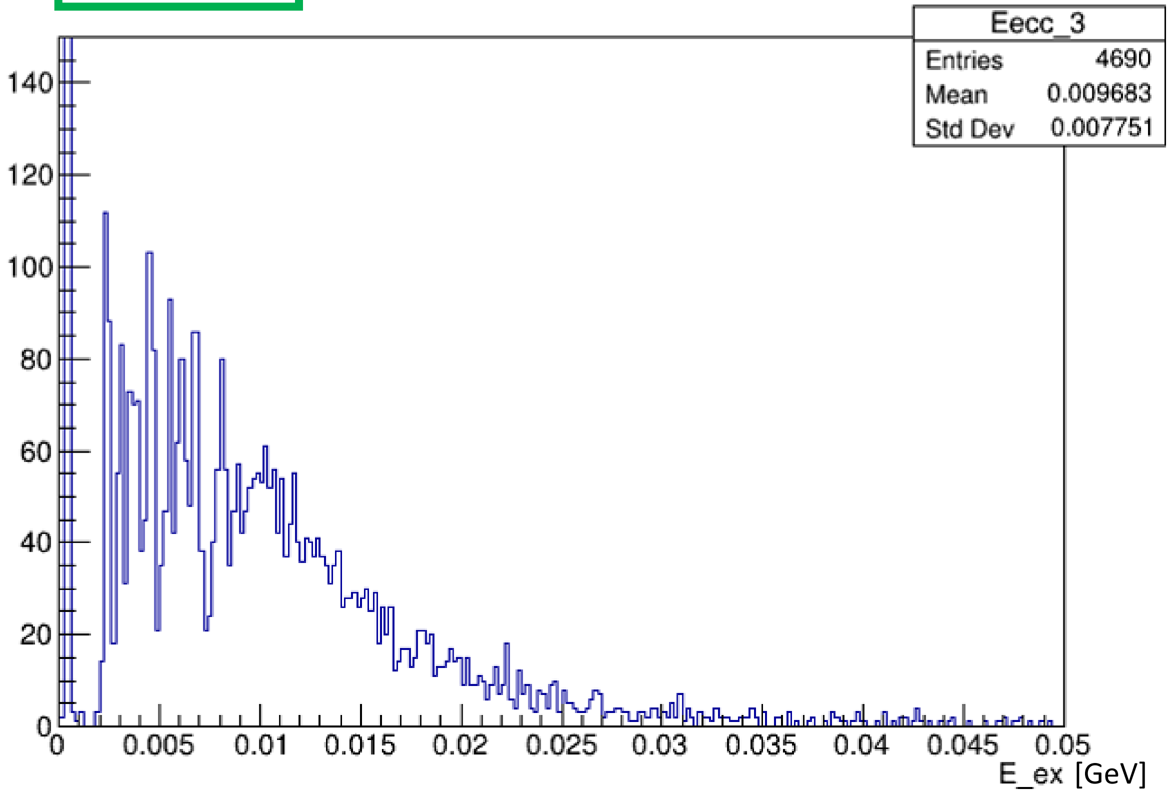


Fig. 17: Excitation energy spectrum for the breakup of ^{12}C into 3 α particles from MC Truth α particles analysis.

Reconstruction

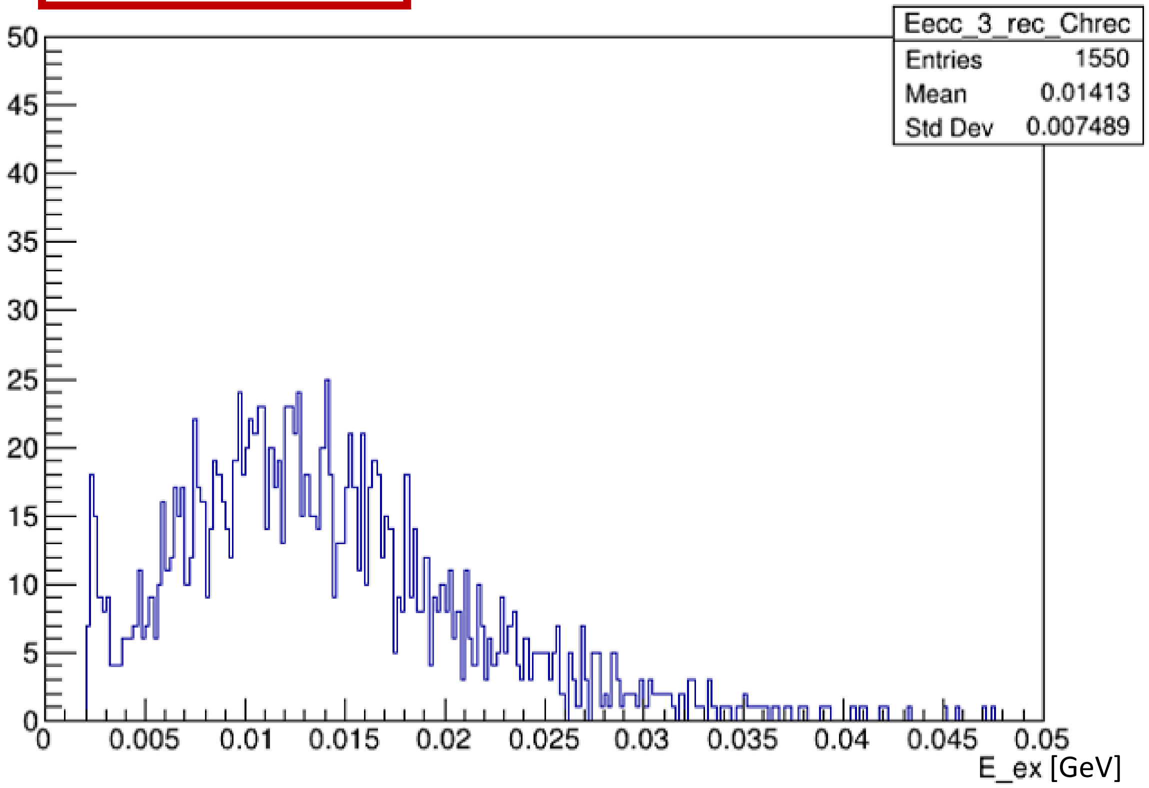


Fig. 18: Excitation energy spectrum for the breakup of ^{12}C into 3 α particles from Reconstruction α particles analysis.

Conclusions

- With reconstructed data, it can still observe the expected **angular correlations** between α particles. A minimum statistics of ~5 10^6 events have to be collected → Study of sequential decay.

- Possibility to investigate **excitation levels** from α particles detection in reconstructed events → Reconstruction energy calibration

Future Developments

- Future nucleus to be studied: ^{16}**O**

- Future experimental setup to be used: EEC

Backup Reconstruction efficiency

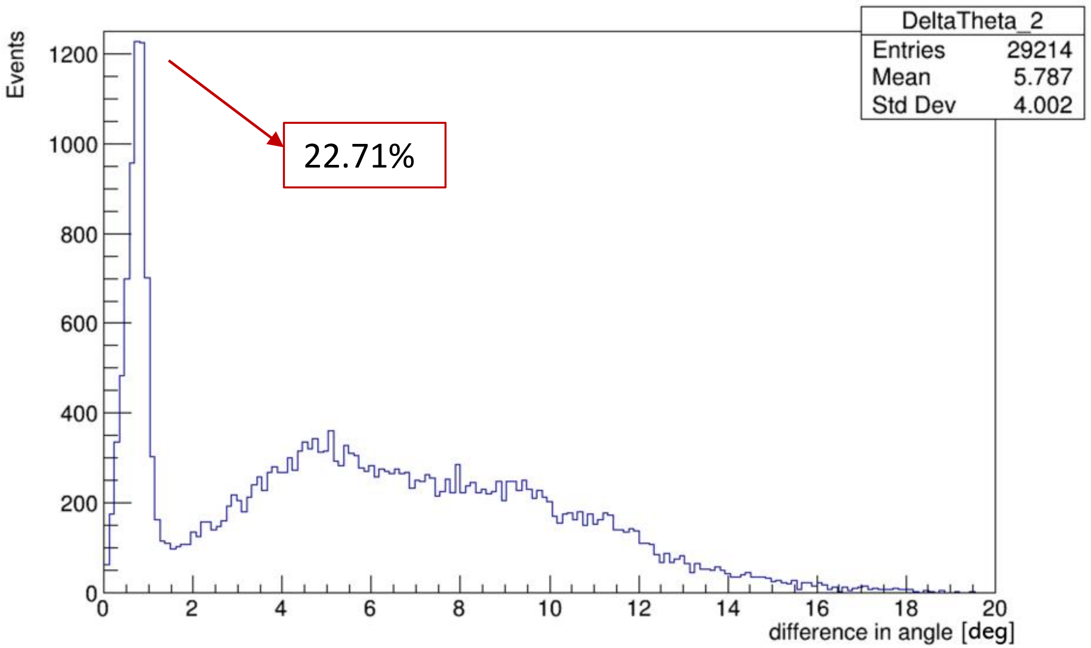
$$Eff_1 = \frac{No.\ of\ reconstructed\ \alpha\ from\ MC\ charge\ selection}{No.\ of\ MC\ \alpha\ particles} = 84.7\%$$

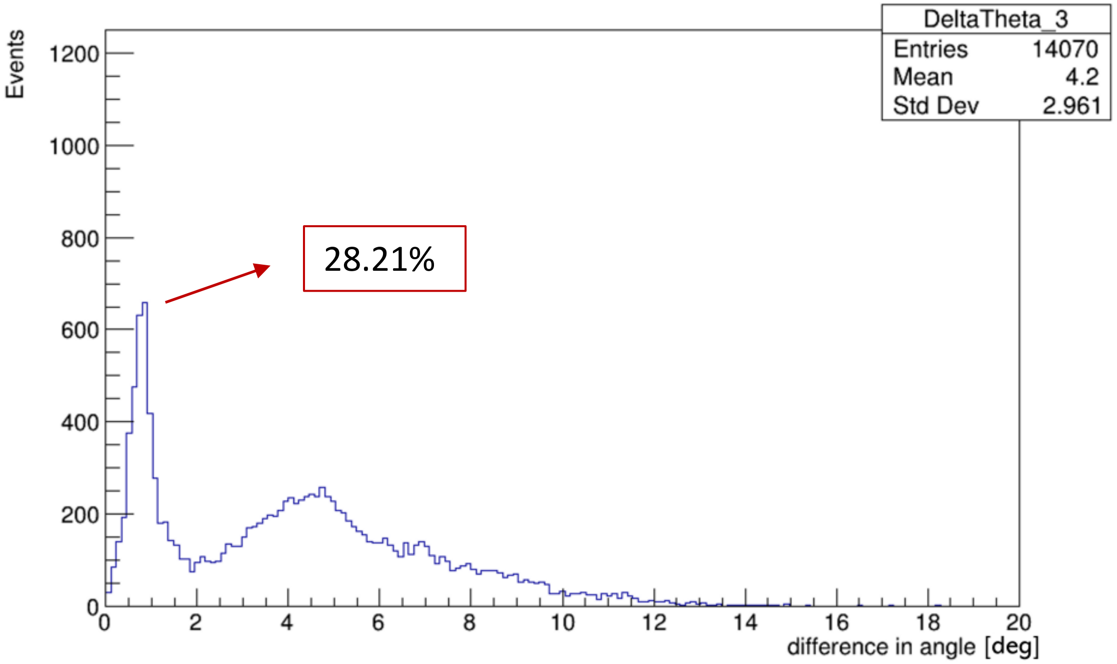
$$Eff_2 = \frac{No.\ of\ reconstructed\ \alpha\ from\ reco\ charge\ selection}{No.\ of\ MC\ \alpha\ particles} = 67.2\%$$

$$Eff_3 = \frac{No.\ of\ reconstructed\ \alpha\ from\ reco\ charge\ selection\ (No\ MC\ info)}{No.\ of\ MC\ \alpha\ particles} = 74.2\%$$

Backup Angular Separation Analysis

MC Truth





Opening angle between pairs of MC simulated α particles at target from events producing **2** (left) and **3** (right) α particles.

Backup Angular Separation Analysis

MC Truth