α clustering analysis with nuclear emulsion films

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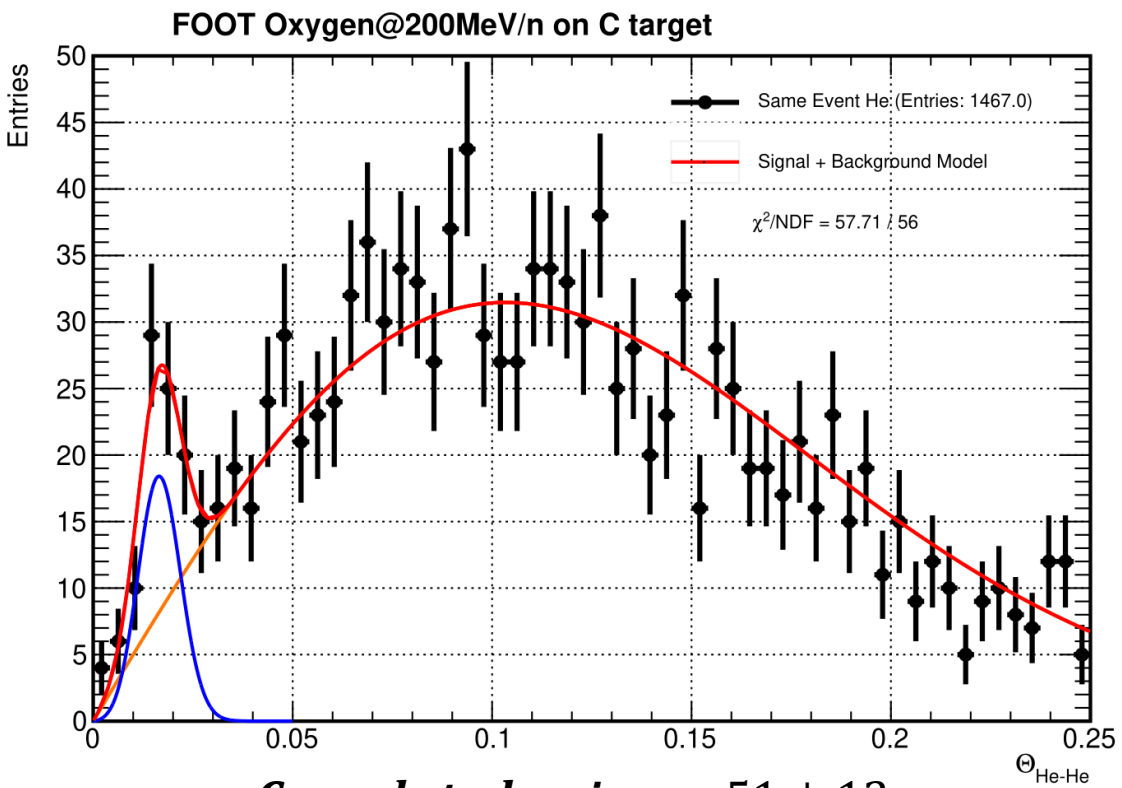
DAMON Meeting, 27 January 2026, Hotel Lungomare, Jr Hotels Oriente, Bari

Outline

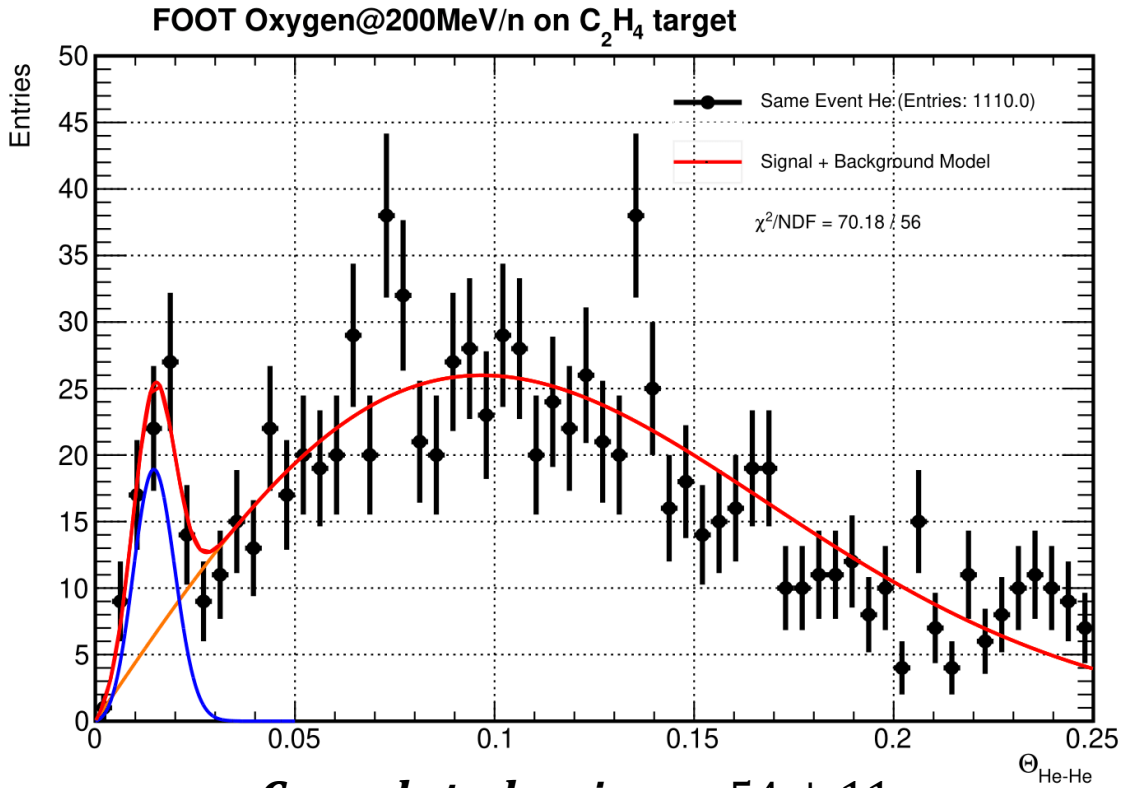
- Updates on α clustering analysis of 2019 GSI data
  - Geant4 simulation of Section 1 of the Emulsion Cloud Chamber (ECC)
  - Comparisons between DATA, FLUKA and Geant4 (200 MeV/n ^{16}O on carbon and polyethyelene)
  - Estimates of $^{8}Be_{g.s.}$ production cross section
- Comparisons with existing ^{12}C measurements in the literature
- Conclusions

Correlated Helium Pairs in 2019 GSI Data

- Relative angles between pairs of He tracks are evaluated and the background is estimated via combinations of uncorrelated tracks from different events
- To take into account the uncertainty from the measurement of the charge, a minimum probability $p(Z{=}2){=}5\%$ was used



$$\boldsymbol{Correlated\ pairs} = 51 \pm 12$$



$$\boldsymbol{Correlated\ pairs} = 54 \pm 11$$

$^{8}Be_{g.s.}$ production cross sections (2019 GSI)

- The fit results were used to evaluate the production cross section: $\sigma^{\mathbf{^8Be_{g.s.}}} = \frac{N^{\,^8Be_{g.s.}}}{\bar{N}_B \cdot \rho \cdot d \cdot \frac{N_A}{A} \cdot \varepsilon_{reco}}, \overline{N_B} = N_B - N_B^{EMU}$

Carbon Target

$$\varepsilon_{reco} = \frac{N^{RMC}_{^8Be_{g.s.}}}{N^{MCTrue}_{^8Be_{g.s.}}} = 52\% \pm 2\%$$

From **FOOT MAECI-MOFFITS Meeting**

$$\sigma^{\mathbf{^8Be_{g.s.}}}(C_{nat}) = 22 \pm 6 \pm 2\ mb$$

MC Tool	Physics List	Result (mb)	Data / MC
FLUKA	/	40 ± 1	$53\ \% \pm 15\ \%$
Geant4	INCL++	59 ± 3	$37\ \% \pm 12\ \%$
Geant4	BIC	52 ± 3	$41\ \% \pm 13\ \%$
Geant4	QMD	64 ± 3	$34\ \% \pm 11\ \%$

Polyethylene Target

$$\varepsilon_{reco} = \frac{N^{RMC}_{^8Be_{g.s.}}}{N^{MCTrue}_{^8Be_{g.s.}}} = 60\% \pm 2\%$$

$$\sigma^{\mathbf{^8Be_{g.s.}}}(C_2H_4) = 48 \pm 11 \pm 4\ mb$$

MC Tool	Physics List	Result (mb)	Data / MC
FLUKA	/	122 ± 2	$39\ \% \pm 10\ \%$
Geant4	INCL++	192 ± 9	$25\ \% \pm 7\ \%$
Geant4	BIC	192 ± 8	$25\ \% \pm 7\ \%$
Geant4	QMD	186 ± 8	$26\ \% \pm 8\ \%$

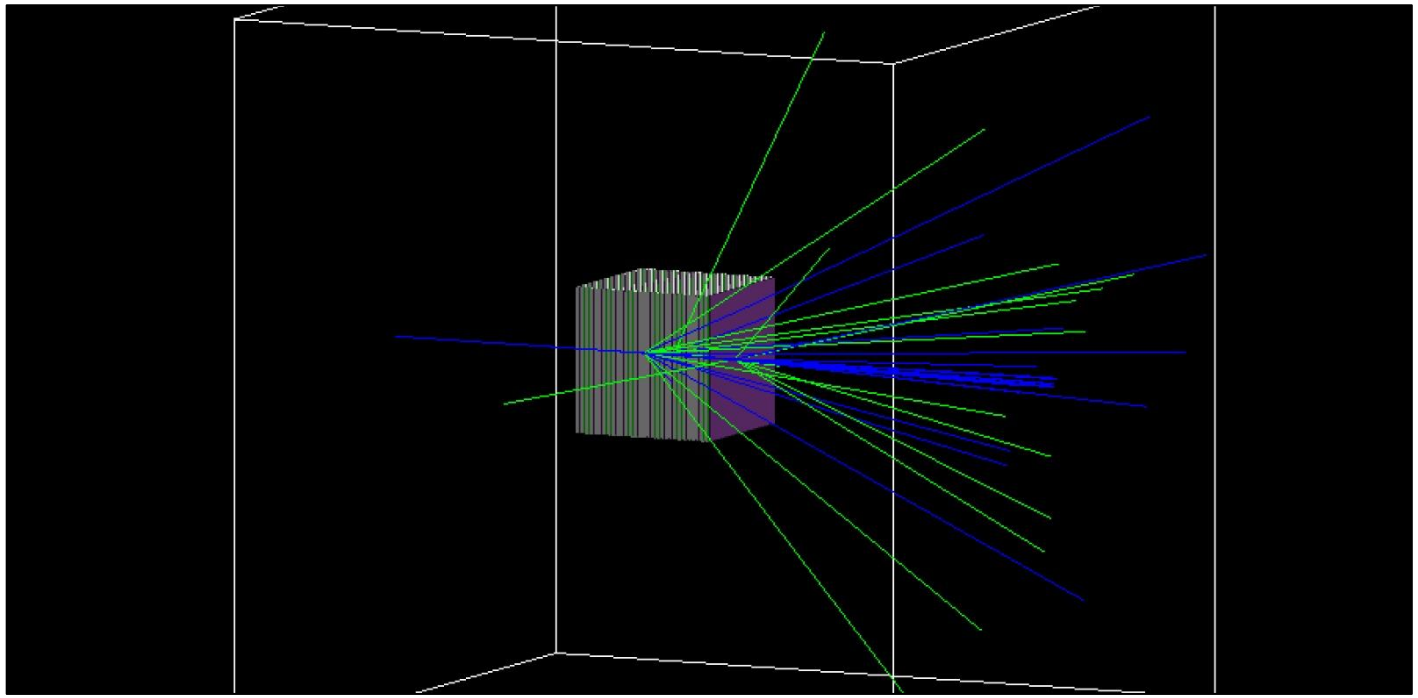
Updated Geant4 Simulation

- The geometry of the Geant4 simulation was updated from a single target layer to the full first section of the emulsion detectors (to reflect that in FLUKA)

- A total of 400k oxygen ions were simulated at 200 MeV/n for both the carbon targets and polyethylene targets

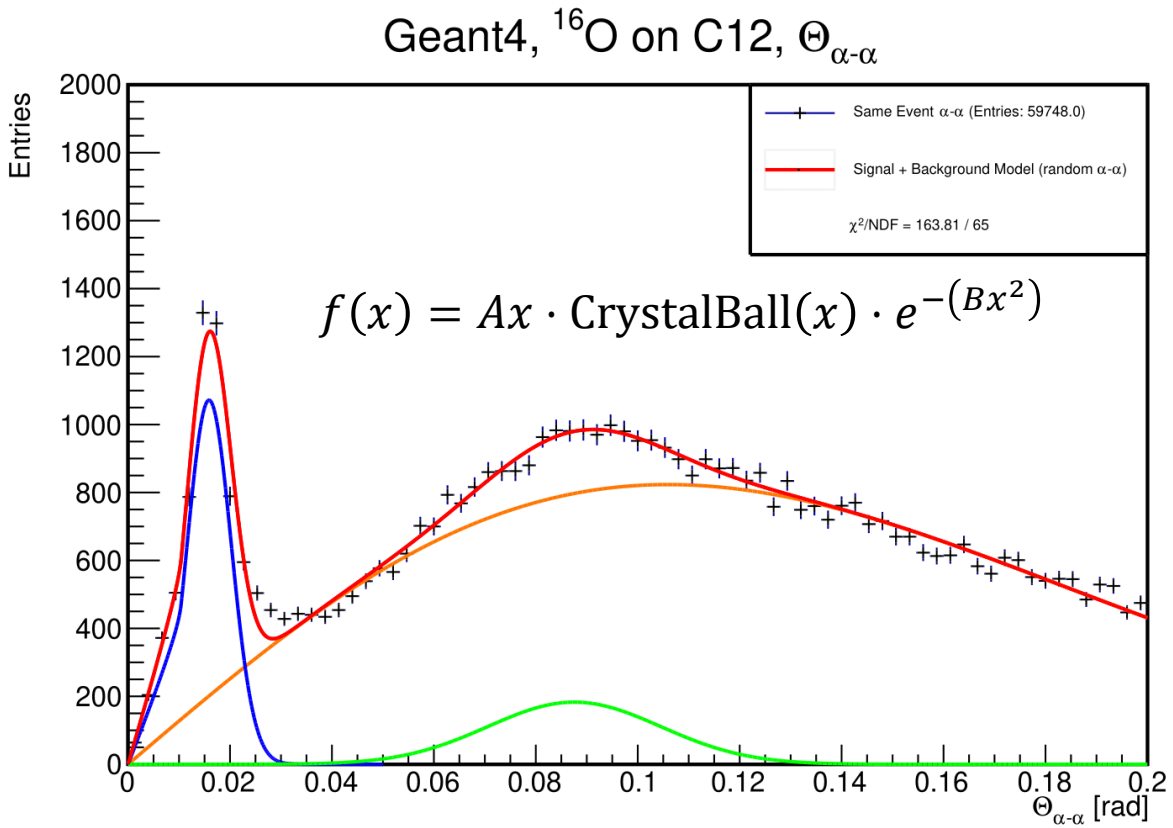
New Selection Cuts

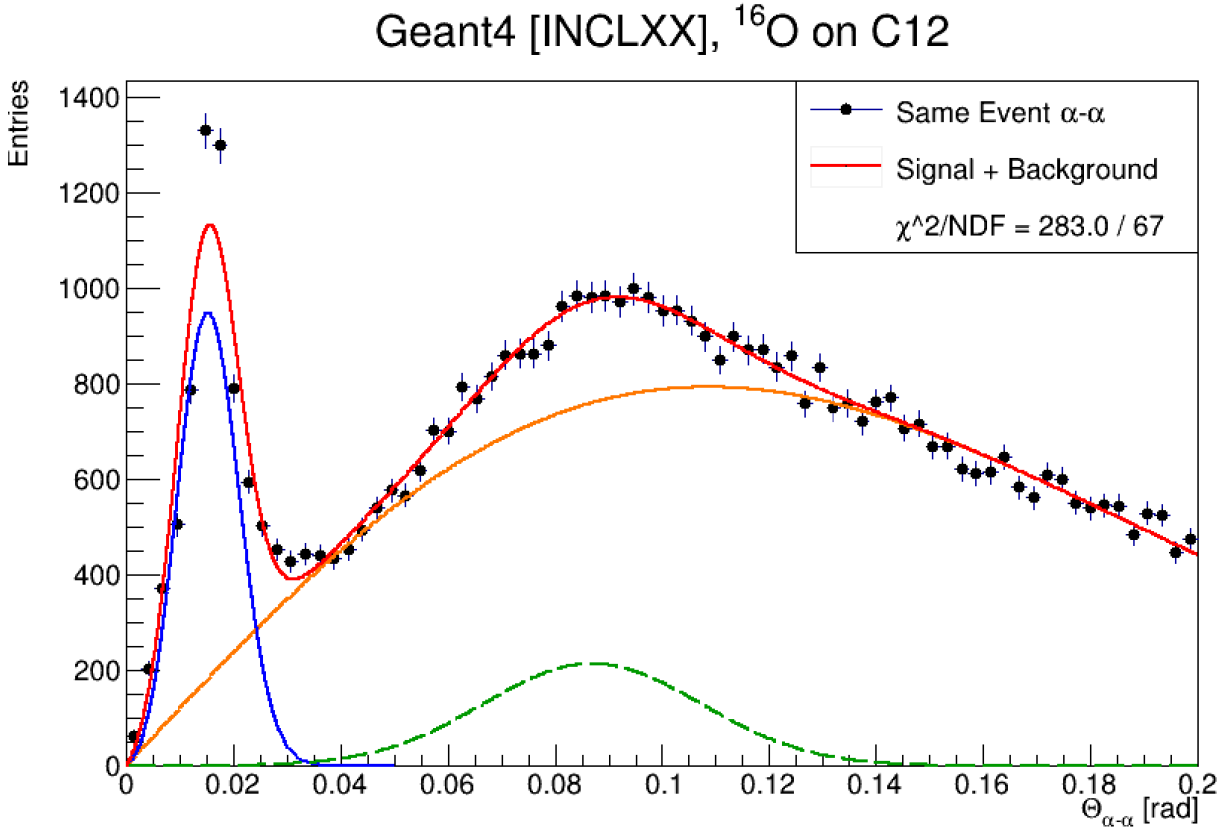
1. Only using true alpha particles (used to be helium particles)
2. No cut on reaching Section 2
3. Minimal cut on momentum (greater than 100 MeV/c)
4. Cut on the maximum angle w.r.t. beam axis ($\theta < 1$)



Geant4 Predictions: a closer look

- The distribution of the opening angles between pairs of α particles shows both a peak at small angles (due to ${}^{8}Be_{g.s.}$) and a secondary peak at around 0.9 rad
- The usual fit function does not perform as well, especially close to the ${}^{8}Be_{g.s.}$ peak (< 20 mrad)

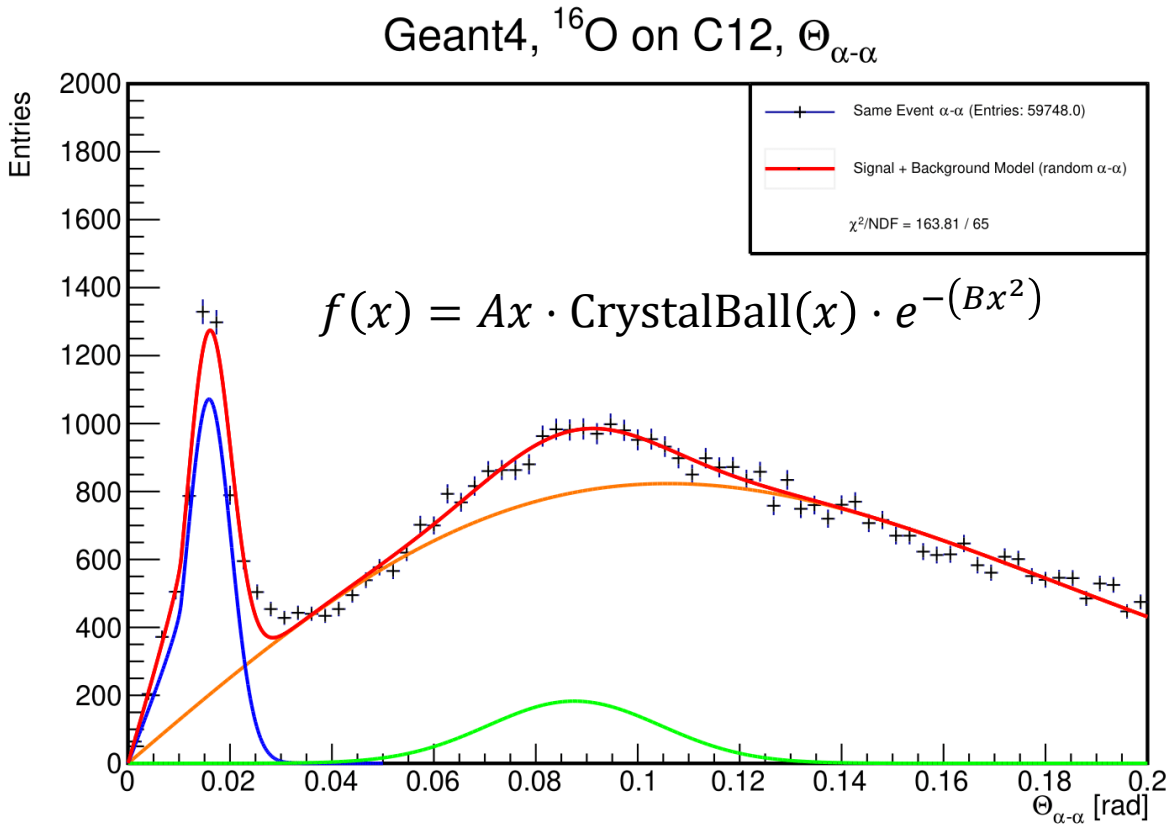


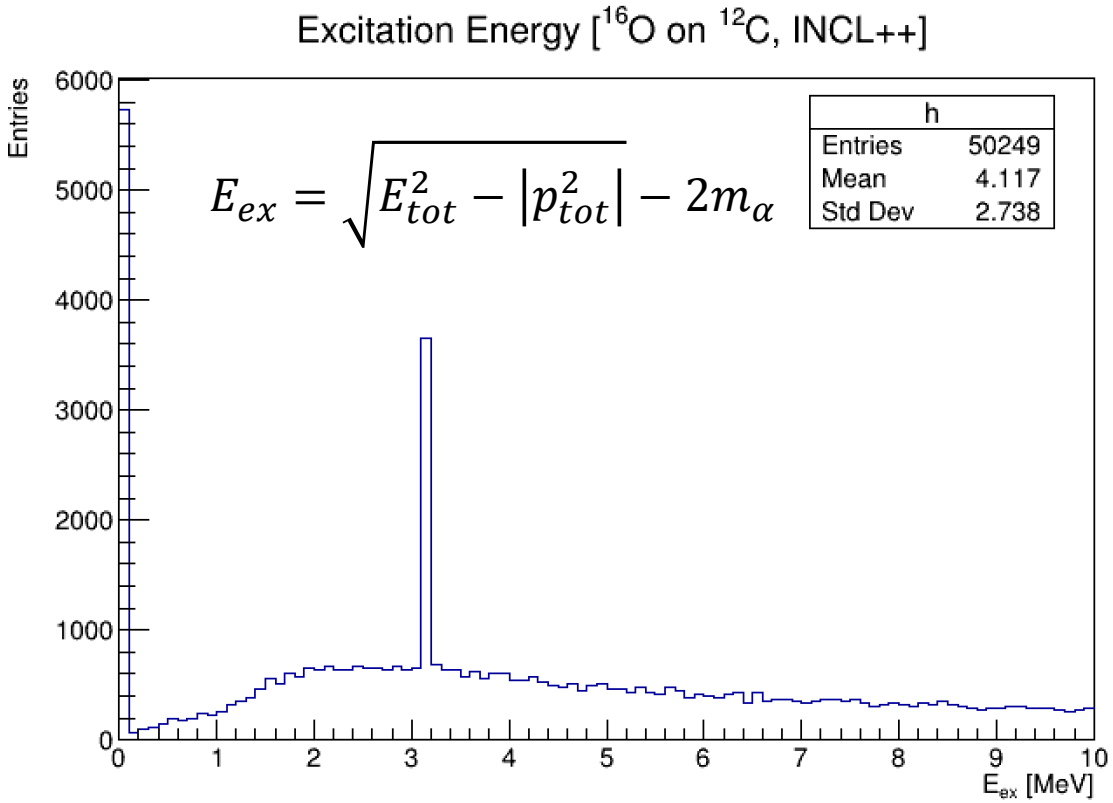


Geant4 Predictions: a closer look

- The distribution of the opening angles between pairs of α particles shows both a peak at small angles (due to ${}^{8}Be_{g.s.}$) and a secondary peak at around 0.9 rad

- The excitation energy spectrum shows that the secondary peak corresponds to ~ 3.1 MeV (maybe due to the first excited state of ${}^{8}Be$)

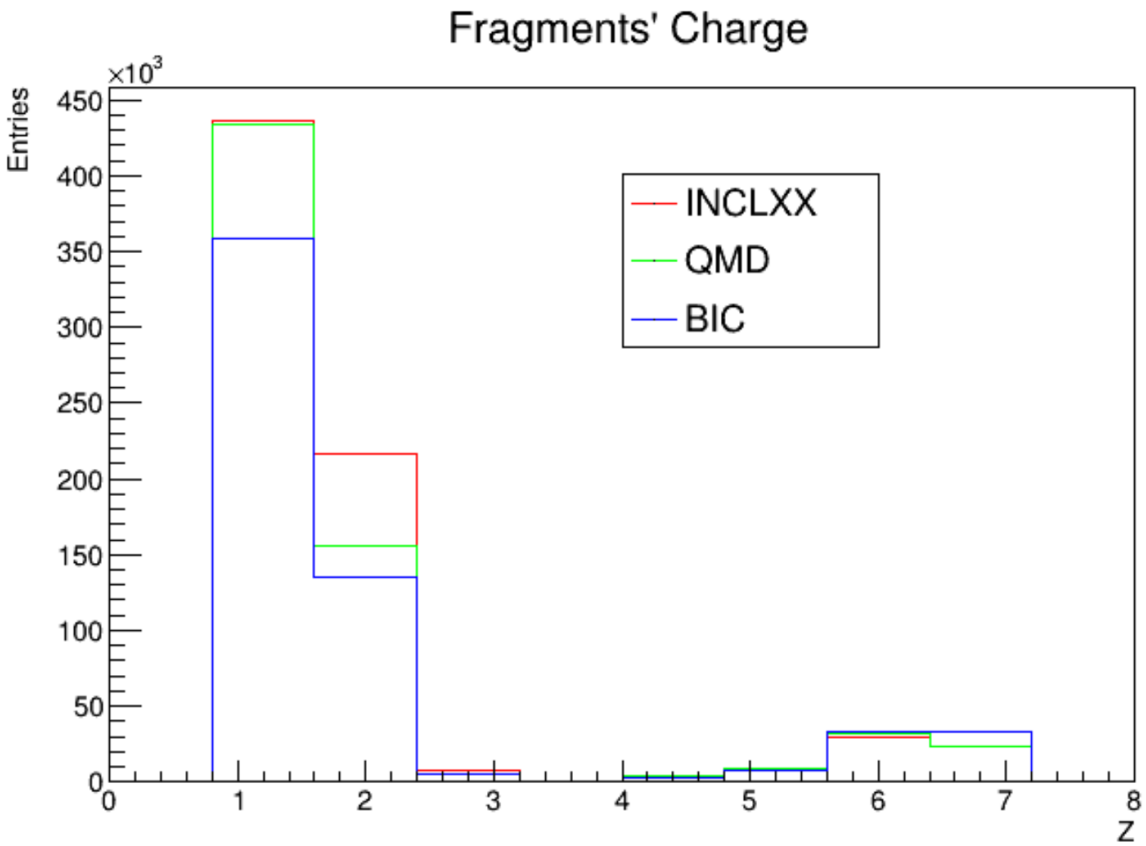


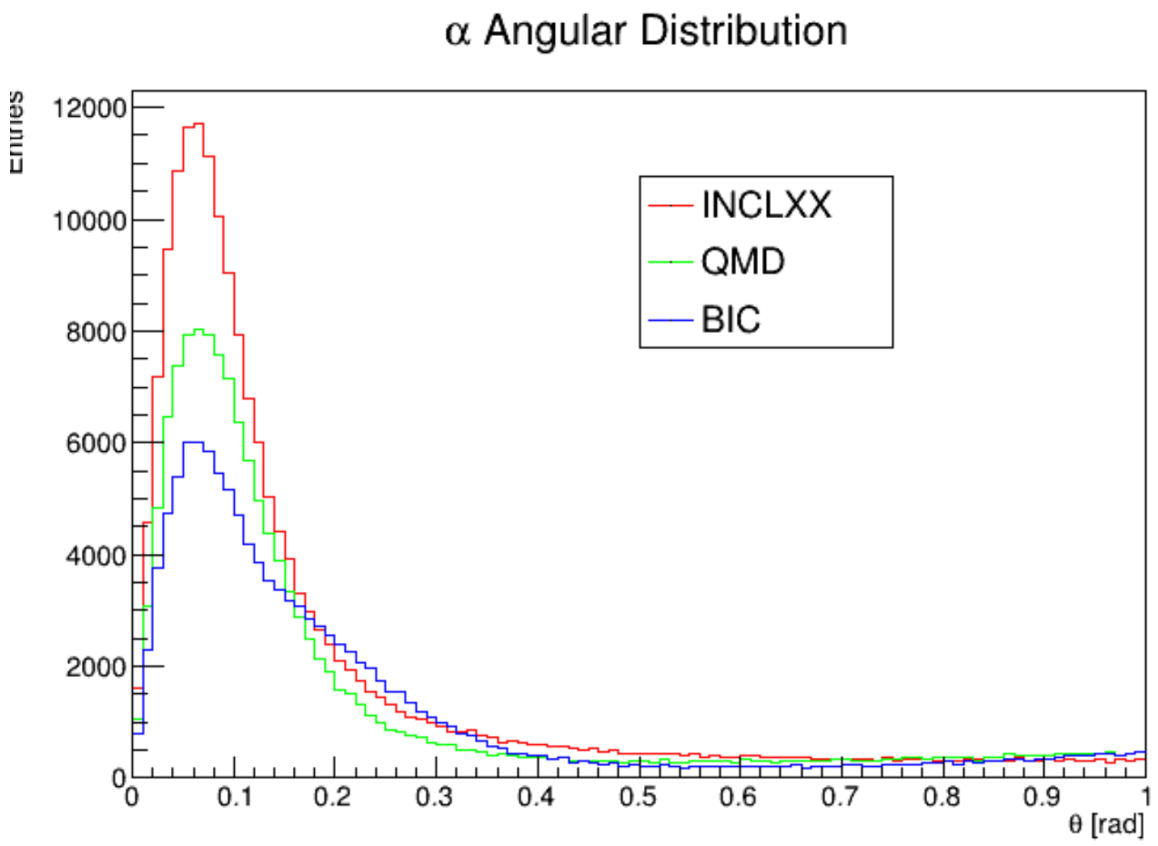


Model Dependence: Helium Fragments

- Geant4 simulations were performed with three physics lists: Liège Intranuclear Cascade++ (INCLXX), Quantum Molecular Dynamics (QMD) and Binary Ion Cascade (BIC)

- Among them, INCLXX predicts the largest amount of helium fragments, followed by QMD and BIC

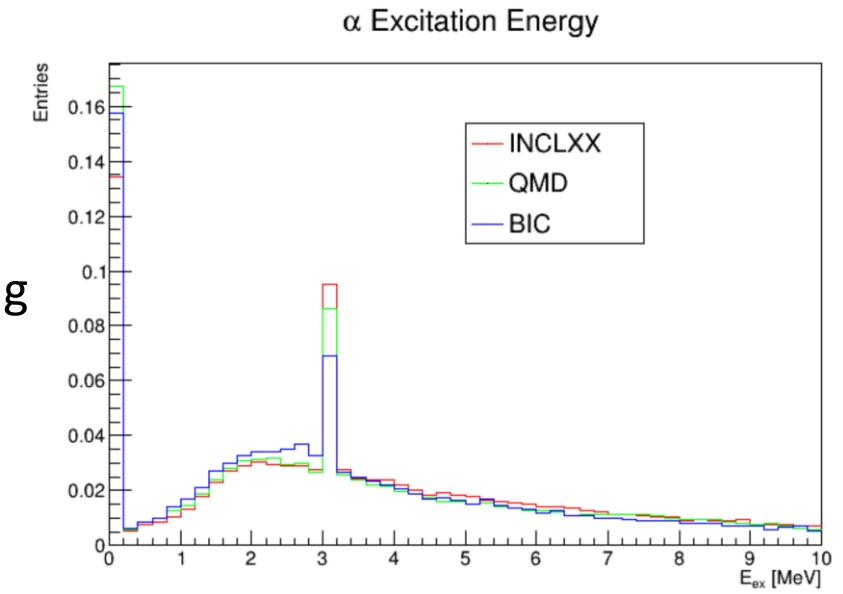


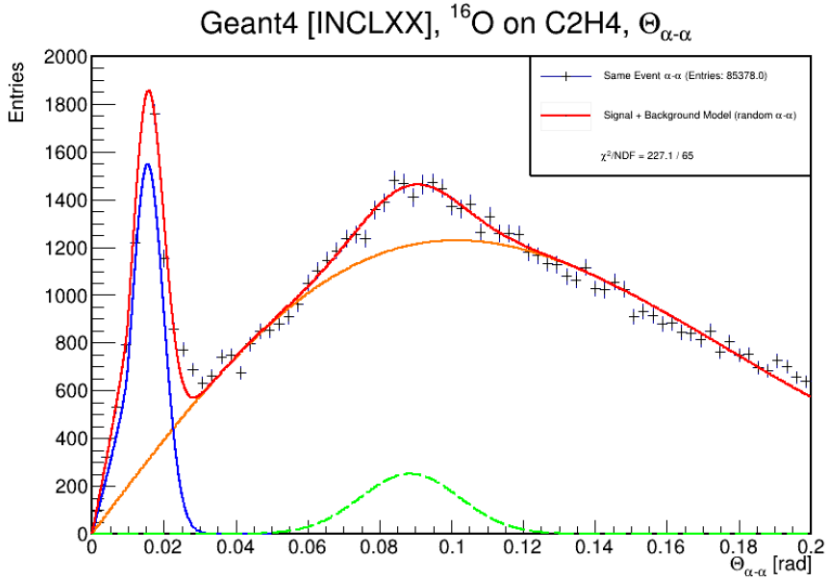


$200\ MeV/n\ ^{16}O$ on C_2H_4

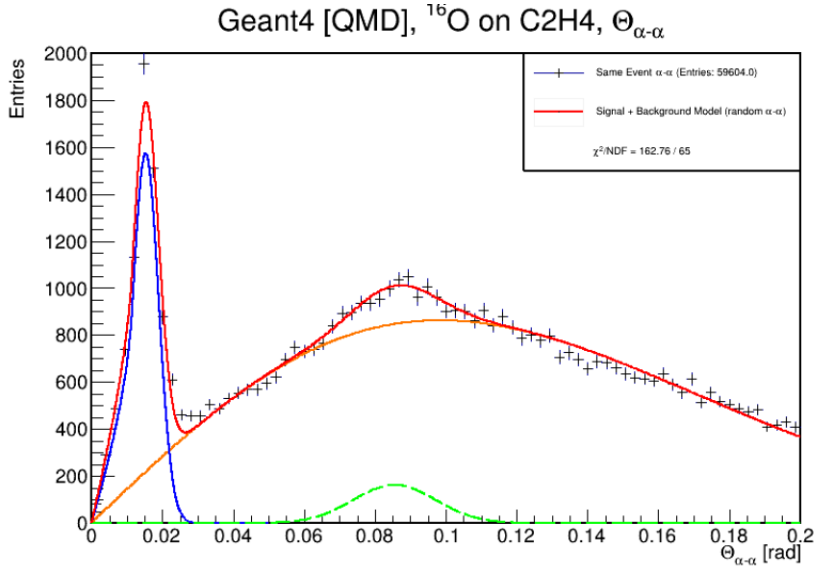
Model Dependence: ^{8}Be Production

- For each simulation, alpha particles coming from fragmentation events were recorded to calculate the opening angles
- The fraction of events in the secondary peak varies significantly depending on the interaction model
- The predicted cross section values are significantly larger than the measured ones

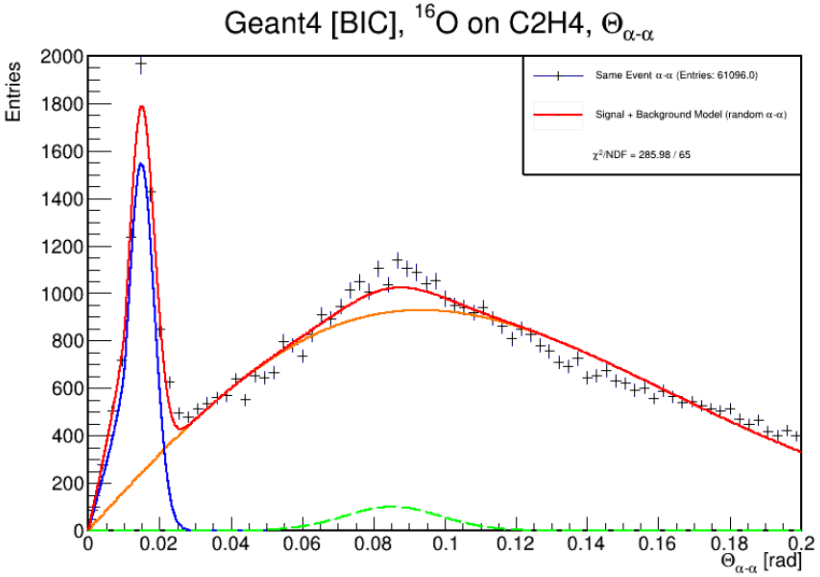




$$\sigma\,^{8}Be_{g.s.} = \frac{N\,^{8}Be_{g.s.}}{\bar{N}_B \cdot \rho \cdot d \cdot \frac{N_A}{A}} = 178 \pm 2\ mb$$



$$\sigma\,^{8}Be_{g.s.} = 155 \pm 2\ mb$$

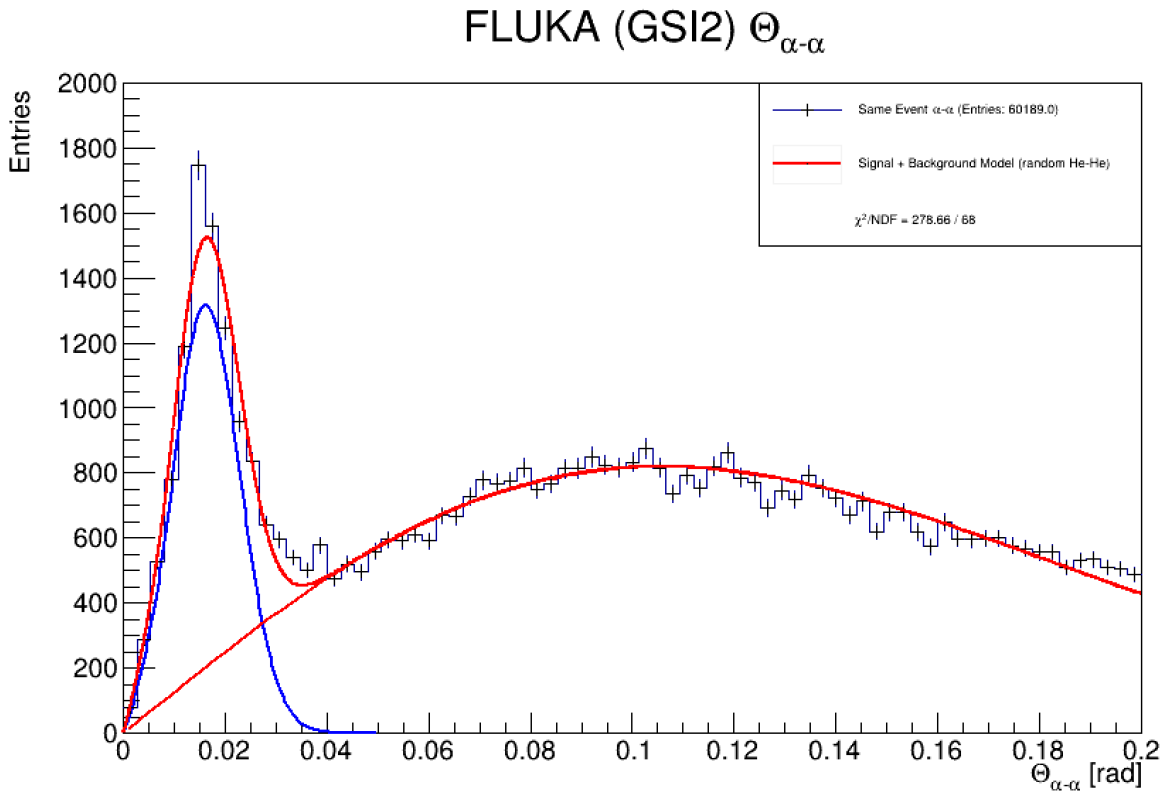


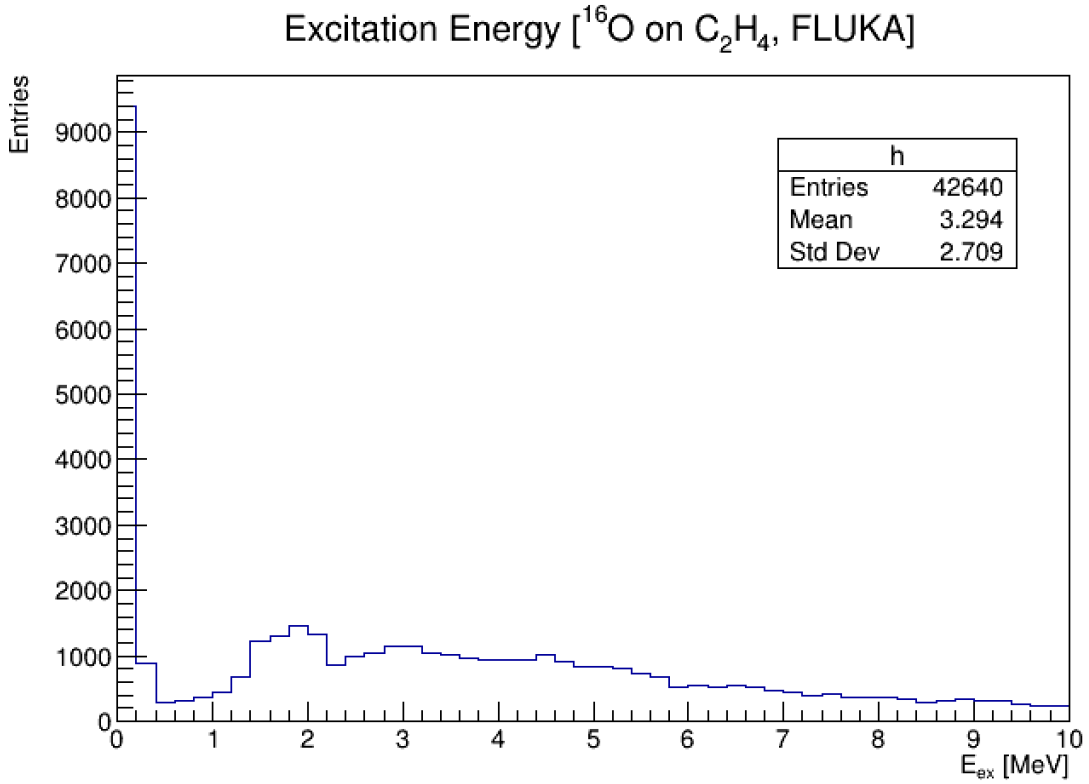
$$\sigma\,^{8}Be_{g.s.} = 152 \pm 2\ mb$$

Updated FLUKA Predictions

- The estimate from FLUKA has been re-calculated with more stringent selection cuts:
  - Only including true α particles and without the request that tracks reach the second section of the ECC
  - At this time, an indirect cut requiring that each fragment exits the target layer is still applied

- The excitation energy distribution lacks the peak at around 3 MeV: to be understood





$$\sigma\,^{8}Be_{g.s.}(\text{FLUKA}) = 155 \pm 2\ mb$$

$^{8}Be_{g.s.}$ production cross sections (2019 GSI)

- The fit results were used to evaluate the production cross section: $\sigma^{\mathbf{^8Be_{g.s.}}} = \frac{N_{^8Be_{g.s.}}}{\bar{N}_B \cdot \rho \cdot d \cdot \frac{N_A}{A} \cdot \varepsilon_{reco}}, \overline{N_B} = N_B - N_B^{EMU}$

Carbon Target

$$\varepsilon_{reco} = \frac{N^{RMC}_{^8Be_{g.s.}}}{N^{MCTrue}_{^8Be_{g.s.}}} = 44\% \pm 1\%$$

$$\sigma_{\mathbf{^8Be_{g.s.}}}(C_{nat}) = 25 \pm 6 \pm 2\ mb$$

MC Tool	Physics List	Result (mb)	Data / MC
FLUKA	/	47 ± 1	$53\ \% \pm 15\ \%$
Geant4	INCL++	48 ± 1	$52\ \% \pm 14\ \%$
Geant4	BIC	43 ± 1	$57\ \% \pm 16\ \%$
Geant4	QMD	48 ± 1	$53\ \% \pm 14\ \%$

Polyethylene Target

$$\varepsilon_{reco} = \frac{N^{RMC}_{^8Be_{g.s.}}}{N^{MCTrue}_{^8Be_{g.s.}}} = 45\% \pm 1\%$$

$$\sigma_{\mathbf{^8Be_{g.s.}}}(C_2H_4) = 64 \pm 15 \pm 6\ mb$$

MC Tool	Physics List	Result (mb)	Data / MC
FLUKA	/	155 ± 2	$41\ \% \pm 10\ \%$
Geant4	INCL++	178 ± 2	$36\ \% \pm 10\ \%$
Geant4	BIC	156 ± 2	$41\ \% \pm 11\ \%$
Geant4	QMD	152 ± 2	$42\ \% \pm 11\ \%$

Comparisons with Available Literature

- The ratio between the measured cross sections and the MC predictions ranges around $\sim 40\%$ to $\sim 50\%$
- At least one other paper studying the formation of ^{8}Be from ^{16}O has been published (Eur. Phys. J. A **11**, 285–296 (2001)); however, an explicit value of the production cross section has not been reported (moreover the energy of the primary oxygen ions was equal to 3.25 GeV/n)
- Unlike ^{16}O, there are works that published the ^{8}Be production cross section from ^{12}C at energies similar to ours (roughly 200 to 400 MeV/n)
- Therefore, the following papers were considered:

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NUCLEAR PHYSICS A
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Measurement of the fragmentation of Carbon nuclei used in hadron-therapy

G. De Lellis [a,b,*], S. Buontempo [b], F. Di Capua [b], A. Di Crescenzo [a,b], P. Migliozzi [b], Y. Petukhov [a,1], C. Pistillo [a,2], A. Russo [b], P. Strolin [a,b], V. Tioukov [b], M. Durante [c,d], Y. Furusawa [e], T. Toshito [e], N. Yasuda [f], A. Ariga [g,2], N. Naganawa [g]

PHYSICAL REVIEW C **78**, 067602 (2008)

Measurements of projectile-like ^{8}Be and ^{9}B production in 200–400 MeV/nucleon ^{12}C on water

T. Toshito,[1,2] K. Kodama,[3] L. Sihver,[4] K. Yusa,[5] M. Ozaki,[6] K. Amako,[2] S. Kameoka,[2] K. Murakami,[2] T. Sasaki,[2] S. Aoki,[7] T. Ban,[8] T. Fukuda,[8] H. Kubota,[8] N. Naganawa,[8] T. Nakamura,[8] T. Nakano,[8] M. Natsume,[8] K. Niwa,[8] S. Takahashi,[8] J. Yoshida,[8] H. Yoshida,[9] M. Kanazawa,[10] N. Kanematsu,[10] M. Komori,[10] S. Sato,[10] M. Asai,[11] T. Koi,[11] C. Fukushima,[12] S. Ogawa,[12] M. Shibasaki,[12] and H. Shibuya[12]

Previous Alpha Clustering Measurement with ECC (1)

- The previous alpha clustering measurement by our group was performed in 2011
- The ECC consisted of 73 units containing three emulsions interleaved with lexan plates
  - Two different thermal treatments were applied (R1, R2)
- The detector was exposed to 400 MeV/n Carbon ions with an estimated flux of 1.000 ions/cm^2
- A total of 2394 carbon interactions were reconstructed
- These interactions were used to measure the charge-changing cross section ($\Delta z = 1$ up to $\Delta z = 4$)
- The ^{8}Be production cross section was also measured

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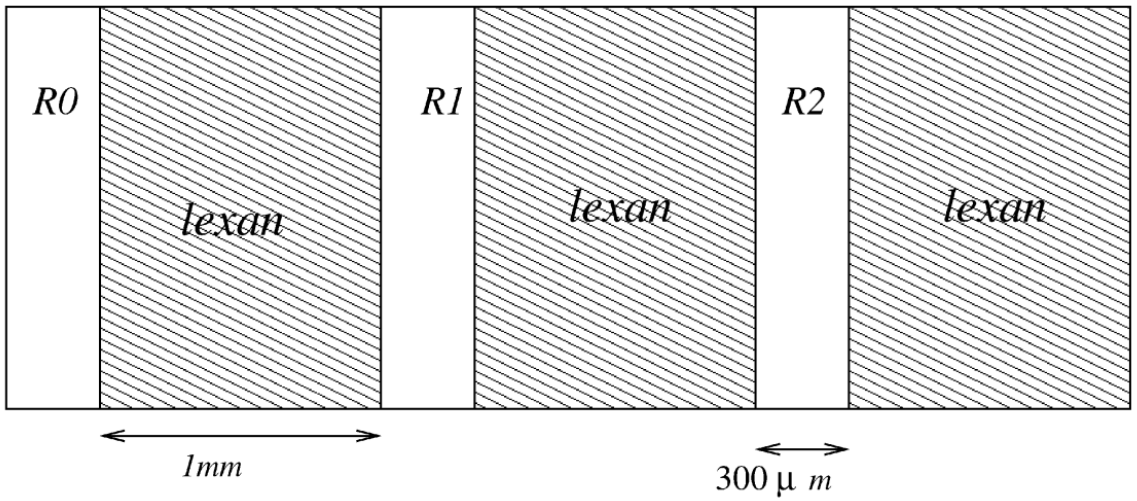
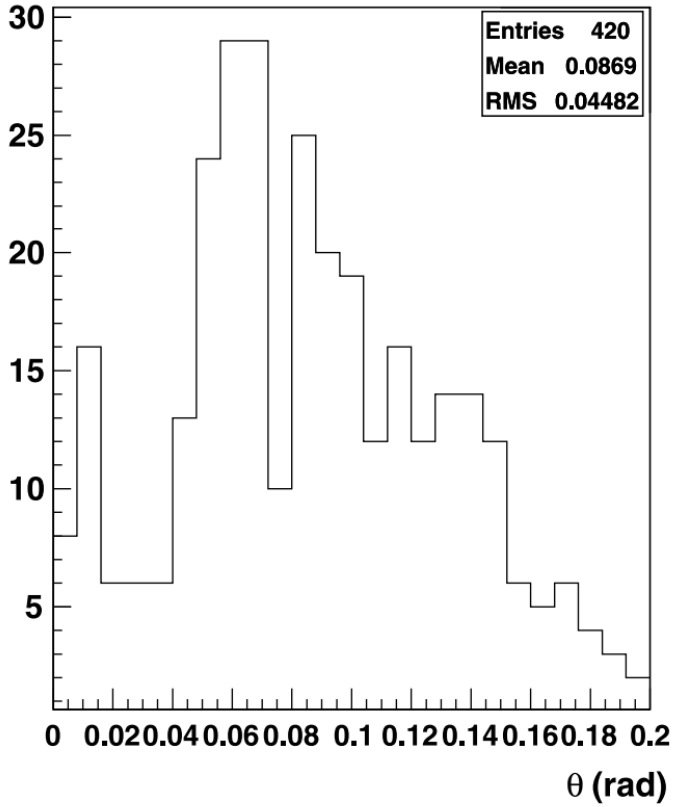


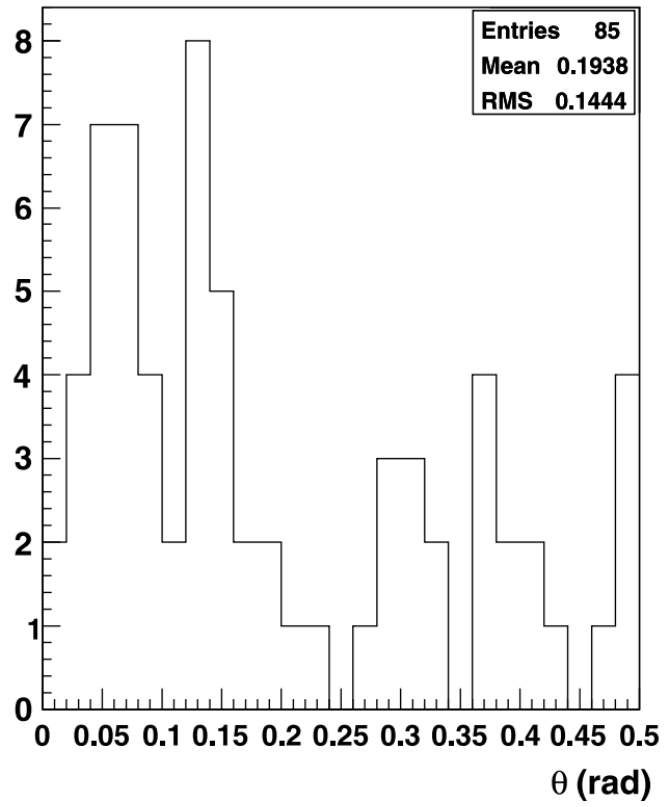
From
XV FOOT Collaboration Meeting

Previous Alpha Clustering Measurement with ECC (2)

- The study of the opening angles between pairs of Helium tracks enabled to find a correlation peak below 20 mrad
- By subtracting the background estimated with the opening angle distribution of H-Helium pairs, an excess of 25 ± 5 events was recorded

Opening angle between He-He pairs





Opening angle between H-He pairs

From XV FOOT Collaboration Meeting

^{12}C on Lexan: Geant4 predictions

- 3×10^6 primary carbon ions at the average energy of 313 ± 29 MeV/n were simulated impinging on a single 1 mm thick lexan target (G4_POLYCARBONATE)

- Both the total and partial charge changing cross sections were evaluated using the following selection cuts:
  - At least one carbon ion fragment with $p \geq 100\ MeV/c$ and $\theta < 1$

- $\sigma(\Delta Z = n) \rightarrow$ partial charge changing cross section considering all the events where the maximum fragment charge is equal to $Z_{MAX} = 6 - \Delta Z$

Geant4 (INCL++)

Charge Changing Cross Section

$$\sigma_{CC}(^{12}C \rightarrow \text{Lexan}) = 18700 \pm 160 \text{ mb}$$

Partial Changing Cross Sections

$$\sigma(\Delta Z = 1) = 1780 \pm 50 \text{ mb}$$

$$\sigma(\Delta Z = 2) = 650 \pm 30 \text{ mb}$$

$$\sigma(\Delta Z = 3) = 950 \pm 30 \text{ mb}$$

$$\sigma(\Delta Z = 4) = 13080 \pm 130 \text{ mb}$$

Published Data

Charge Changing Cross Section

$$\sigma_{tot} = (18420 \pm 380_{stat} \pm 1840_{sys}) \text{ mbarn}$$

Partial Changing Cross Sections

$$\sigma(\Delta z = 1) = (2510 \pm 140_{stat} \pm 250_{sys}) \text{ mbarn}$$

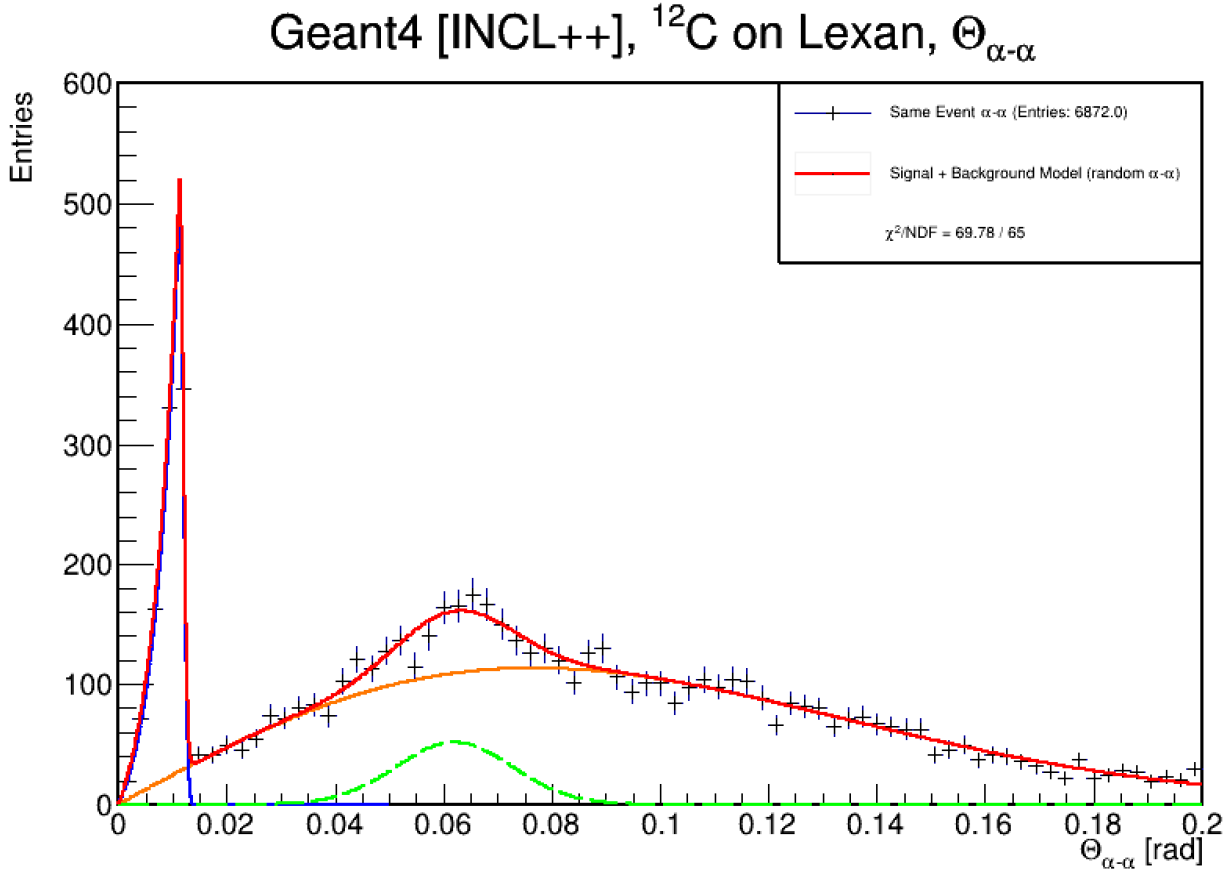
$$\sigma(\Delta z = 2) = (1170 \pm 90_{stat} \pm 120_{sys}) \text{ mbarn}$$

$$\sigma(\Delta z = 3) = (1460 \pm 105_{stat} \pm 150_{sys}) \text{ mbarn}$$

$$\sigma(\Delta z = 4) = (7510 \pm 240_{stat} \pm 750_{sys}) \text{ mbarn}$$

^{12}C on Lexan: $^{8}Be_{g.s.}$ production

- Opening angles were evaluated among α particles satisfying $p \geq 100\ MeV/c$ and $\theta < 1$
- The introduction of an asymmetric peak and a secondary Gaussian peak improved the fit quality



$^{8}Be_{g.s.}$ Production Cross Section

Published Data

$$\sigma\left(^{8}\mathrm{Be}\right) = 190 \pm 40\ \mathrm{mbarn}$$

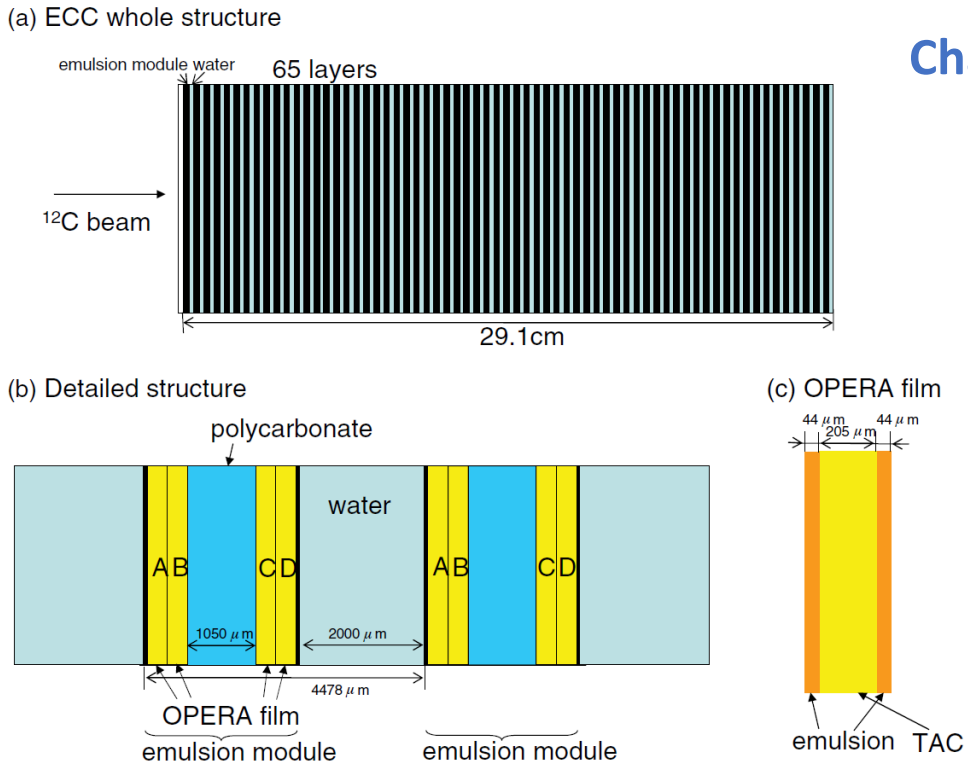
Geant4 (INCL++)

$$\sigma\,^{\mathbf{8}}\boldsymbol{Be_{g.s.}}\left(^{12}C \rightarrow \mathrm{Lexan}\right) = 960 \pm 40\ \mathrm{mb}$$

$$\mathbf{Ratio} = 20 \pm 5\ \%$$

Available Literature: ^{12}C on Water and Lexan

- In the second work considered for this comparison, an hybrid ECC containing both polycarbonate and solid water targets was used (PHYSICAL REVIEW C **75**, 054606 (2007))
- Primary particles were ^{12}C ions with energies ranging from 200 MeV/n to 400 MeV/n
- Total and partial charge changing cross section on water and polycarbonate were published (those related to ^{8}Be and ^{9}Be production in a separate work: PHYSICAL REVIEW C **78**, 067602 (2008)



Charge Changing Cross Section ^{12}C on Lexan

Our measurements	
E (MeV/nucleon)	σ_{tot} (mb)
364 ± 25	17682 ± 595
312 ± 27	16723 ± 648
255 ± 30	17225 ± 747

Charge Changing Cross Section ^{12}C on Water

Our measurements	
E (MeV/nucleon)	σ_{tot} (mb)
377 ± 12	1253 ± 45
352 ± 13	1202 ± 47
326 ± 13	1250 ± 51
299 ± 14	1183 ± 52
271 ± 15	1193 ± 56
241 ± 16	1241 ± 61
208 ± 17	1231 ± 64

Comparison to Geant4 predictions

- 3×10^6 primary carbon ions at the average energy of 312 ± 27 MeV/n were simulated impinging on a single 1 mm thick lexan target (G4_WATER)

- Both the total and partial charge changing cross sections were evaluated using the following selection cuts:
  - At least one carbon ion fragment with $p \geq 100\ MeV/c$ and $\theta < 1$

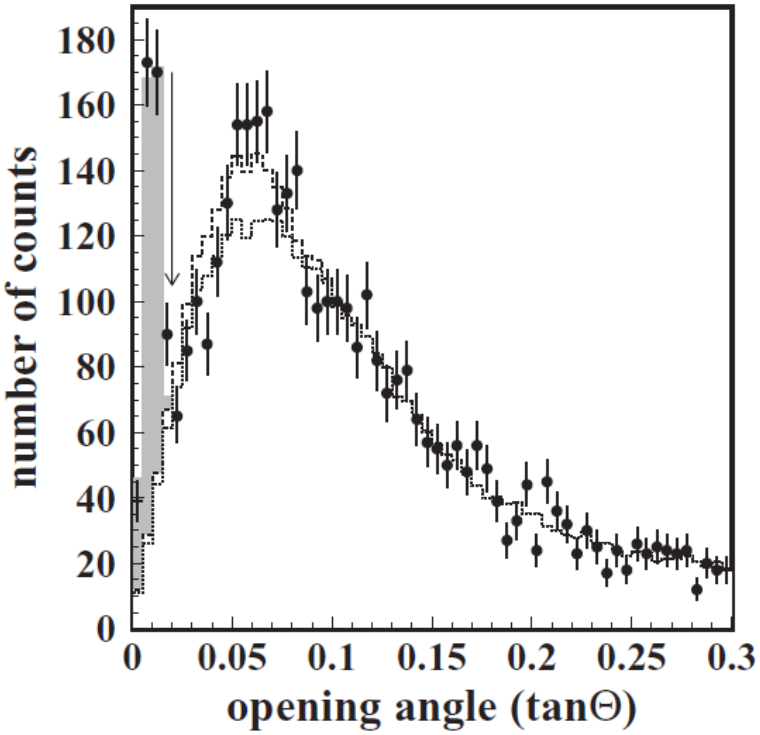


FIG. 2. Opening angle between two helium particles ($\Theta_{\alpha\alpha}$).

Geant4 (INCL++)

$$\sigma^{\mathbf{^8Be_{g.s.}}}\left(^{12}C \rightarrow \text{Water}\right) = 95 \pm 3\ \text{mb}$$

$$\textbf{Ratio} = 33 \pm 9\ \%$$

TABLE I. ^{8}Be production cross sections for ^{12}C beams in a water target.

Energy (MeV/nucleon)	$\sigma_{^8Be} + \sigma_{^9B}$ (mb) Our results	$\sigma_{^8Be}$ (mb)	
		Our results	Ref. [2]
364 ± 25	33^{+7}_{-6}	22^{+7}_{-6}	140
312 ± 27	42^{+8}_{-7}	31^{+8}_{-7}	159
255 ± 30	39^{+9}_{-8}	28^{+9}_{-8}	177

Conclusions

- Updates on α clustering analysis of 2019 GSI data
  - Geant4 simulations were updated by including Section 1 of the Emulsion Cloud Chamber (ECC) to represent the energy spectrum more faithfully
  - Slight improvement of event selection cuts (only alpha particles, no requirement to reach Section 2)
  - Difference in the distributions of the excitation energy (FLUKA, Geant4) currently being investigated

- Comparison of Geant4 to existing ^{12}C measurements in the literature
  - $^{8}Be_{g.s.}$ production cross sections were found to be consistently over estimated in the cases considered

Thank you!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Geant4 Predictions: a closer look

- By isolating only pairs on alphas with the excitation energy close to true (92 keV), the peak returns to be symmetric

- The peak in the excitation energy spectrum confirms that the second peak is due to the first excited state of ^{8}Be (at around 3 MeV)