α clustering analysis with nuclear emulsions

A. Alexandrov, V. Boccia, A. Di Crescenzo, G. De Lellis, G. Galati, A. Iuliano, A. Lauria, M.C. Montesi, V. Tioukov

Università di Napoli "Federico II", INFN Napoli
Università di Bari "Aldo Moro", INFN Bari

Napoli, XVI FOOT General Meeting, 26/06/2024

Outline

- Status of α clustering analysis with nuclear emulsions
- Effect of $p(Z=2)$ selection on $^{8}Be_{g.s.}$ production cross section
- Quick update on He multiplicity in clustered events
- Reduction of the statistical uncertainty on the reconstruction efficiency
- Next steps

Introduction

From last February Physics Meeting

- According to alpha clustering models, nuclei (in particular, self-conjugated ones) can be thought of as aggregates of transient clusters (α particles)

- Cluster structures can be investigated by probing preferential dissociation channels such as $^{12}C \rightarrow 3\alpha$, $^{16}O \rightarrow 4\alpha$
  - These tend to proceed through intermediate channels like $^{12}C \rightarrow {}^{8}Be + \alpha \rightarrow 3\ \alpha$

- α clustering has not been thoroughly explored in the energy regime accessed by FOOT

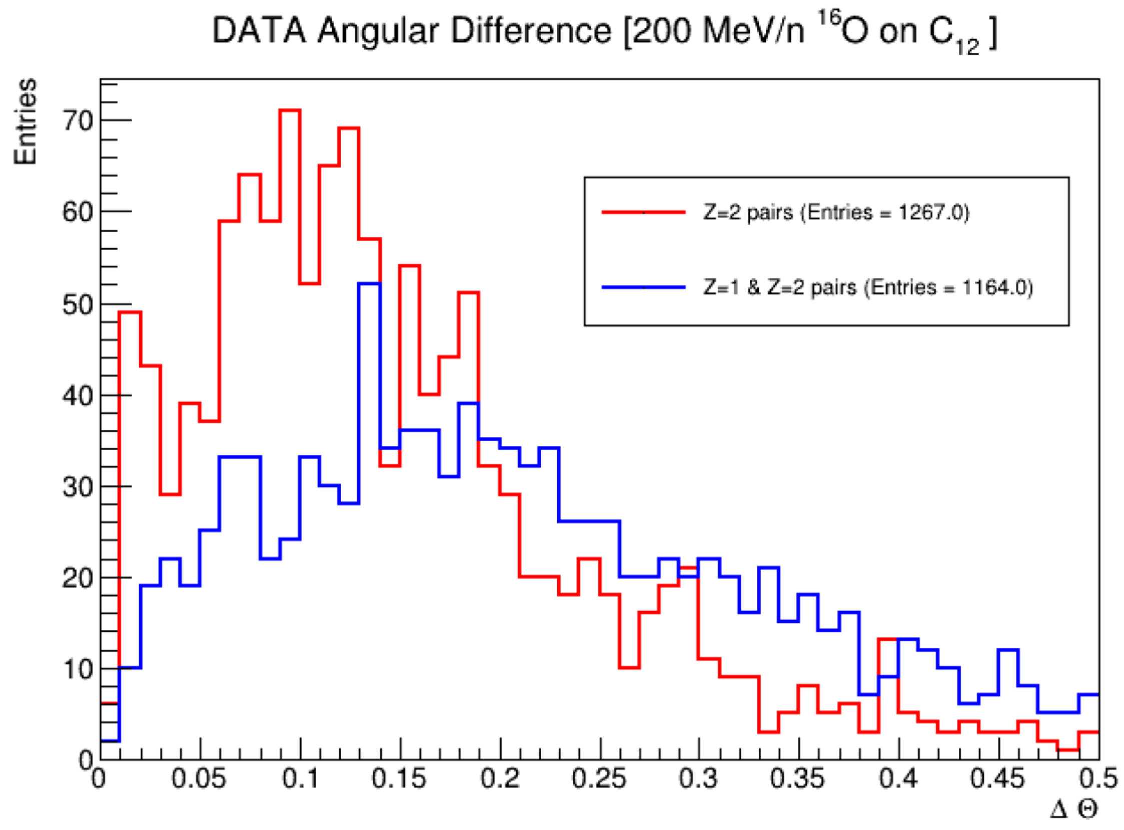
- We are currently analyzing 2019 emulsion data (^{16}O @ $200\ \mathrm{MeV/n}$ on carbon and polyethylene targets) in order to prove the existence of clusters at intermediate energies
  - The analysis focuses on finding correlated α particles couples that reveal the production of ^{8}Be in the fragmentation of the oxygen nucleus
  - No information about the momentum of these particles is being used at this time

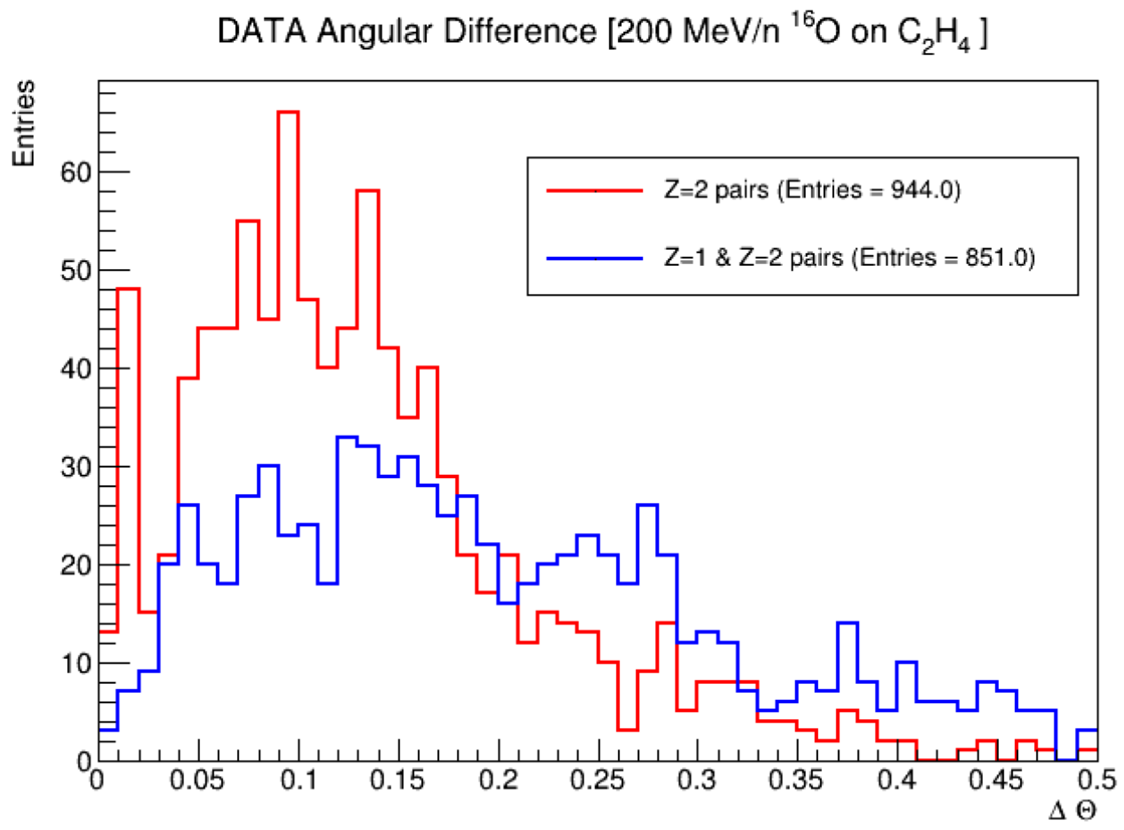
- A much more detailed introduction to α clustering can be found in the following presentations:
  - https://agenda.infn.it/event/37748/contributions/217798/attachments/114168/163750/Presentazione%20GM%20Alice.pdf
  - https://agenda.infn.it/event/35352/contributions/201149/attachments/106123/149798/AlphaClustering.pdf
  - https://agenda.infn.it/event/30579/contributions/168437/attachments/91804/124825/Clustering_may2022.pdf

From XV FOOT General Meeting

Opening angle distributions (DATA)

- The plots show the difference between the angles of couples of Z=2 tracks per reconstructed event with at least 2 Z=2 tracks
- The background is estimated with the comparison of the angular differences between Z=1 and Z=2 tracks

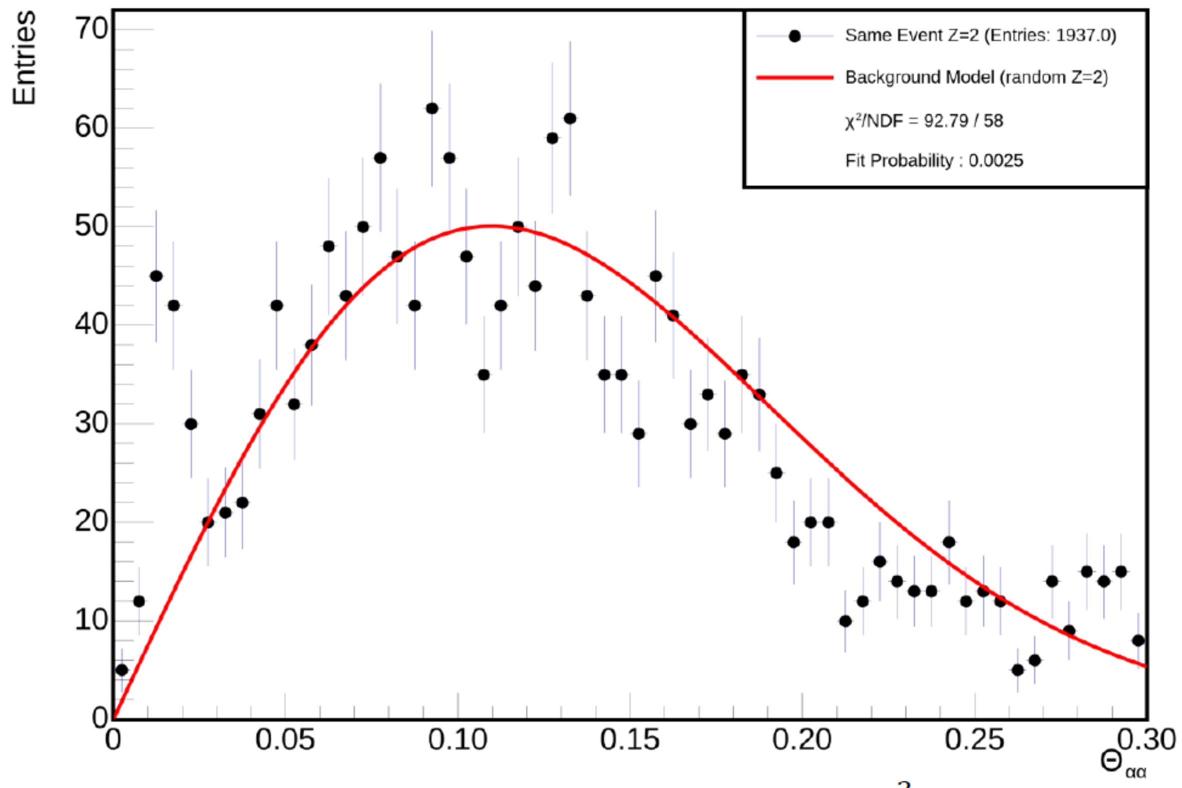




Background Evaluation in DATA (1)

- Fitted the combined background distribution (random Z=2 couples) with a smooth function in DATA
- The estimated number of background events can be evaluated as the integral of the fit function
- The fit results on the combined distributions were compared to the fits performed separately on GSI1 and GSI2

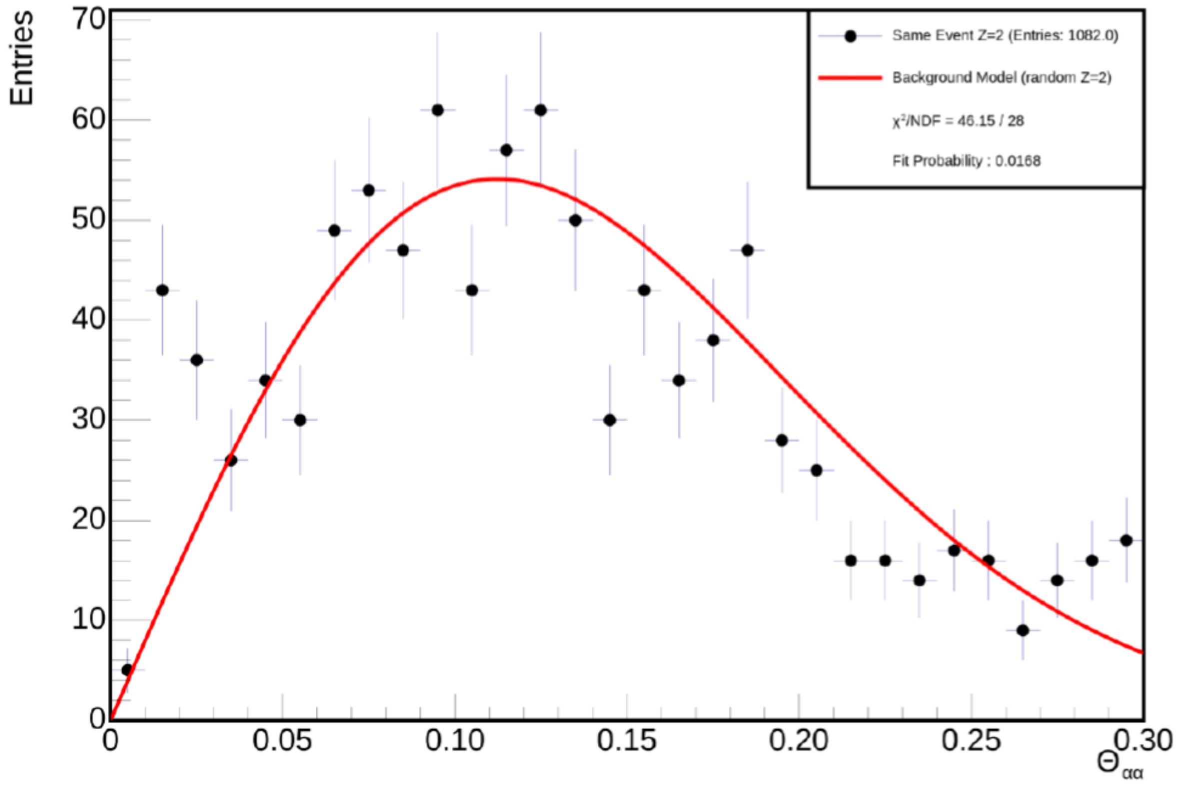
DATA Combined $\Theta_{\alpha\alpha}$ Distributions



$$Fit\ Function: f(x) = Axe^{-Bx^2}$$

$$A = 752 \pm 27, B = 41.5 \pm 1.2$$

DATA (GSI1) $\Theta_{\alpha\alpha}$ Distributions

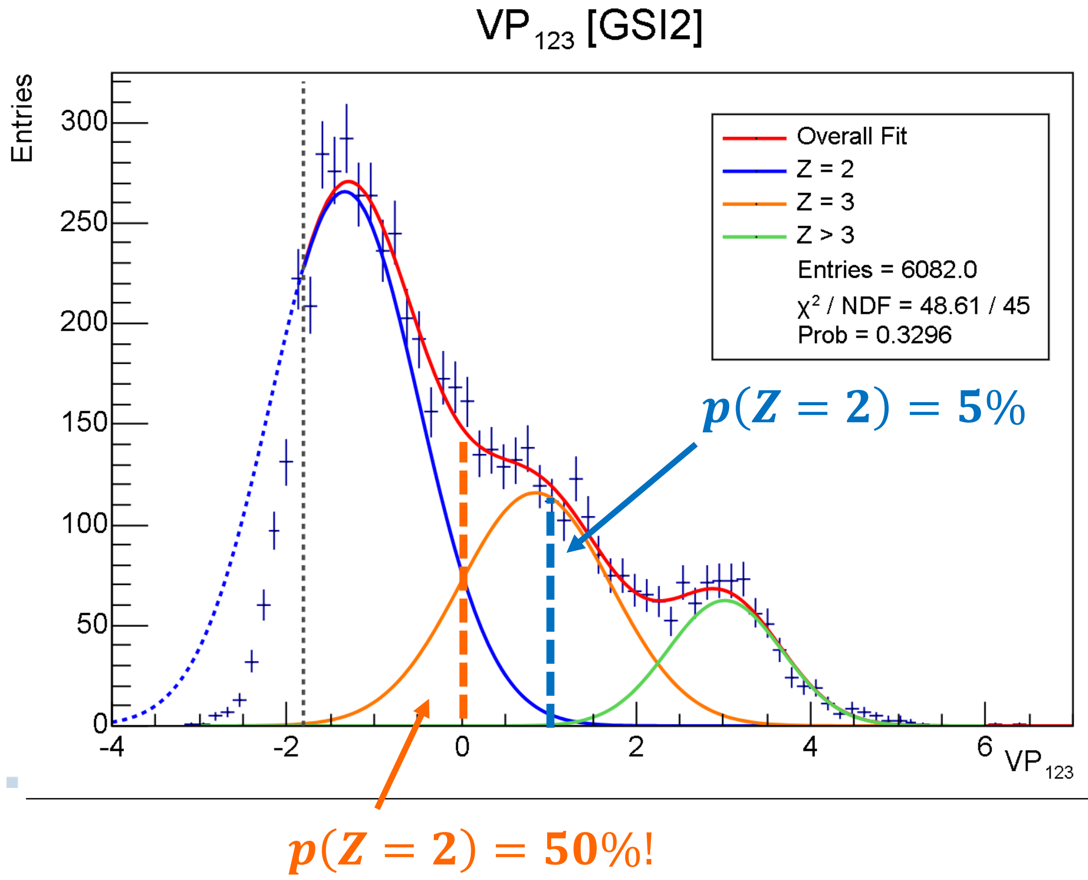


$$Estimated\ Background: 24 \pm 1$$

$$A = 848 \pm 36, B = 39.7 \pm 1.6$$

Z=2 Identification via Principal Component Analysis

- Most of the $Z \geq 2$ tracks are identified by using the VP_{123} distribution, combining the information of all the thermal treatments (R1, R2, R3)
  - Each track is assigned a charge through a probabilistic approach based on the shape of the fitted Gaussians
- While this approach is correct on a «global» level, there is a significant fraction of tracks for which the charge assignment is ambiguous (overlap between Gaussians)



Two main consequences:

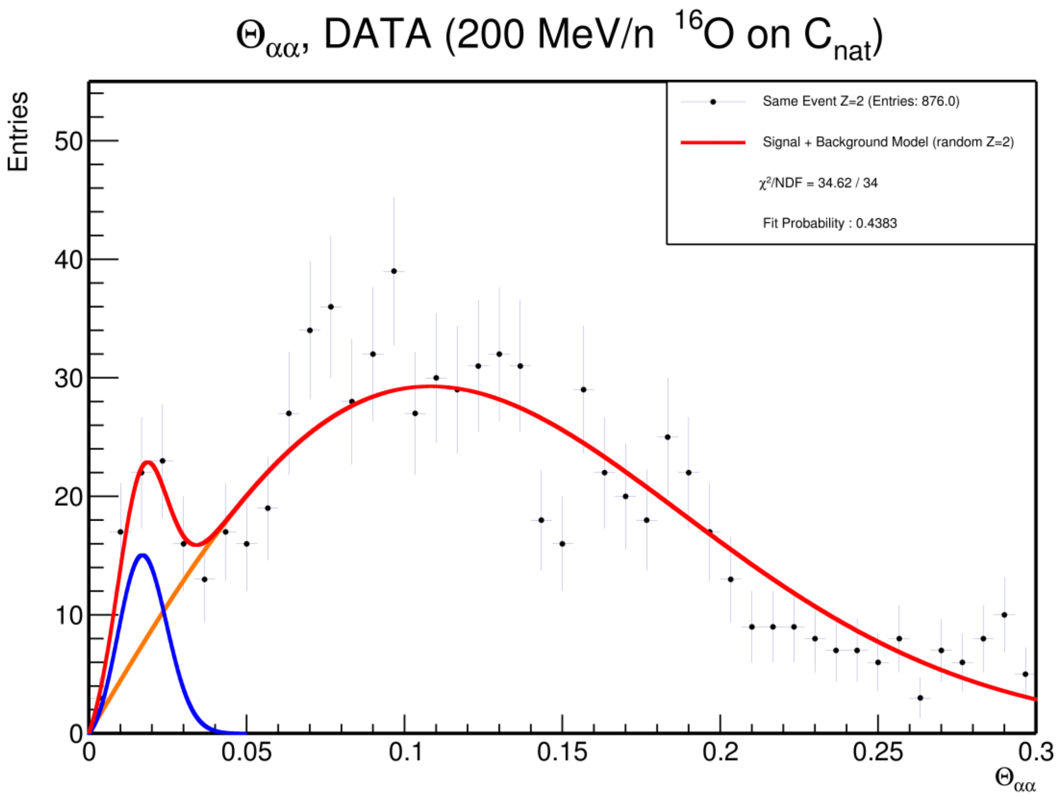
1. $Z_{true} = 2$ misclassified as $Z = 3$ are discarded
2. $Z_{true} = 3$ mislassified as $Z = 2$ contribute to the final background estimate

No expected correlation peak at small angles between true $Z_{true} = 2$ and $Z_{true} = 3$
→ consider all tracks that have $\boldsymbol{p(Z = 2) \geq X\%}$

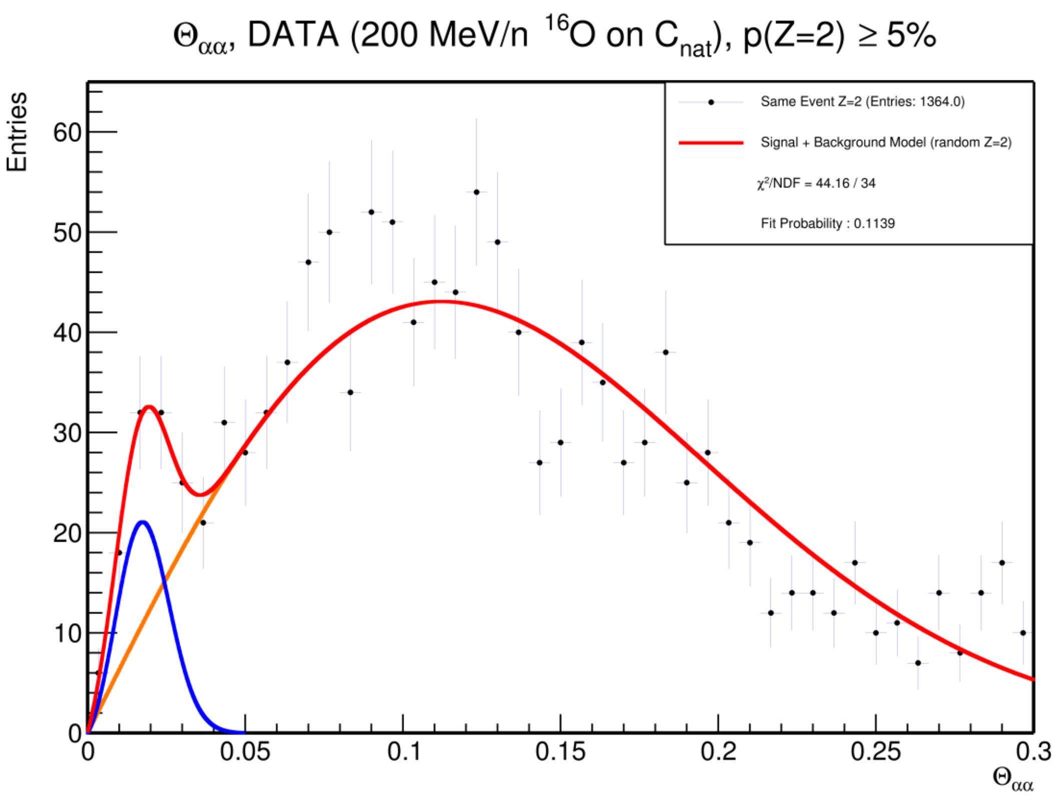
In the following analysis, $X = 5$ (~ 2σ of the Z=2 Gaussian)

Correlation Peak Comparisons: 200 MeV/n $^{16}\boldsymbol{O}$ on $\boldsymbol{C_{nat}}$

- In order to obtain the final estimate, a fit including both the signal and background model was used
    - The shape of the background contribution («B» parameter) was fixed
- After background subtraction, the correlation peak is more populated → efficiency improvement!



Estimated Signal = 35 ± 9

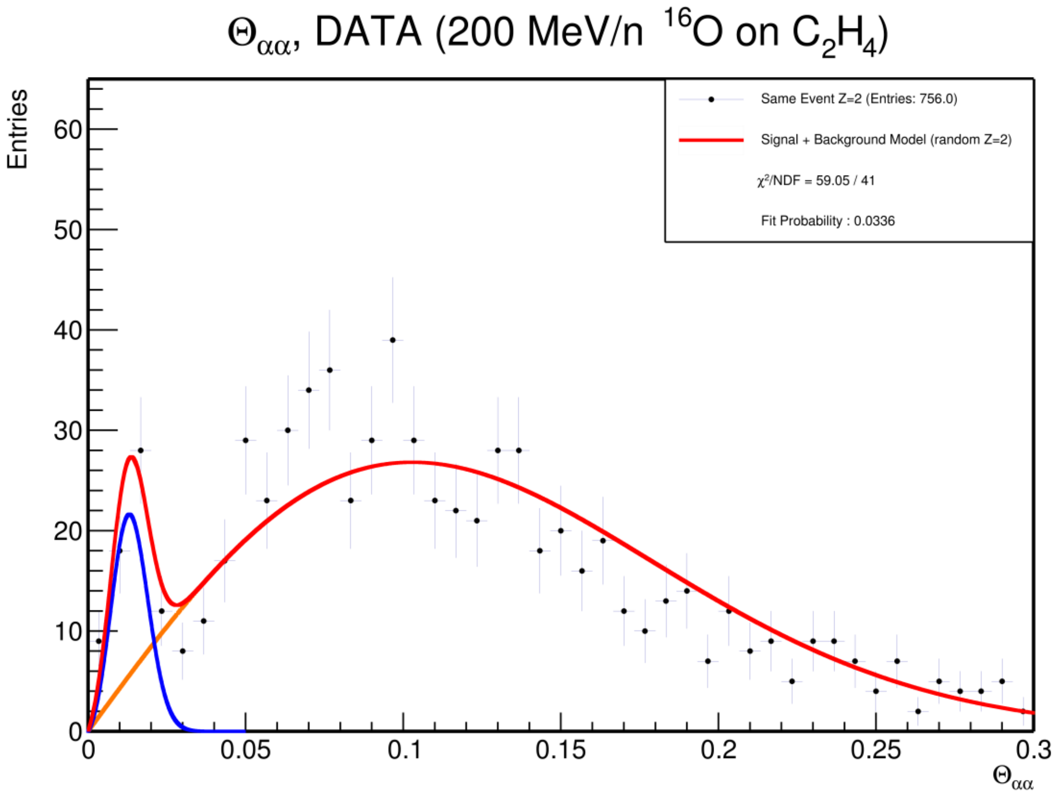


Estimated Signal = 50 ± 11

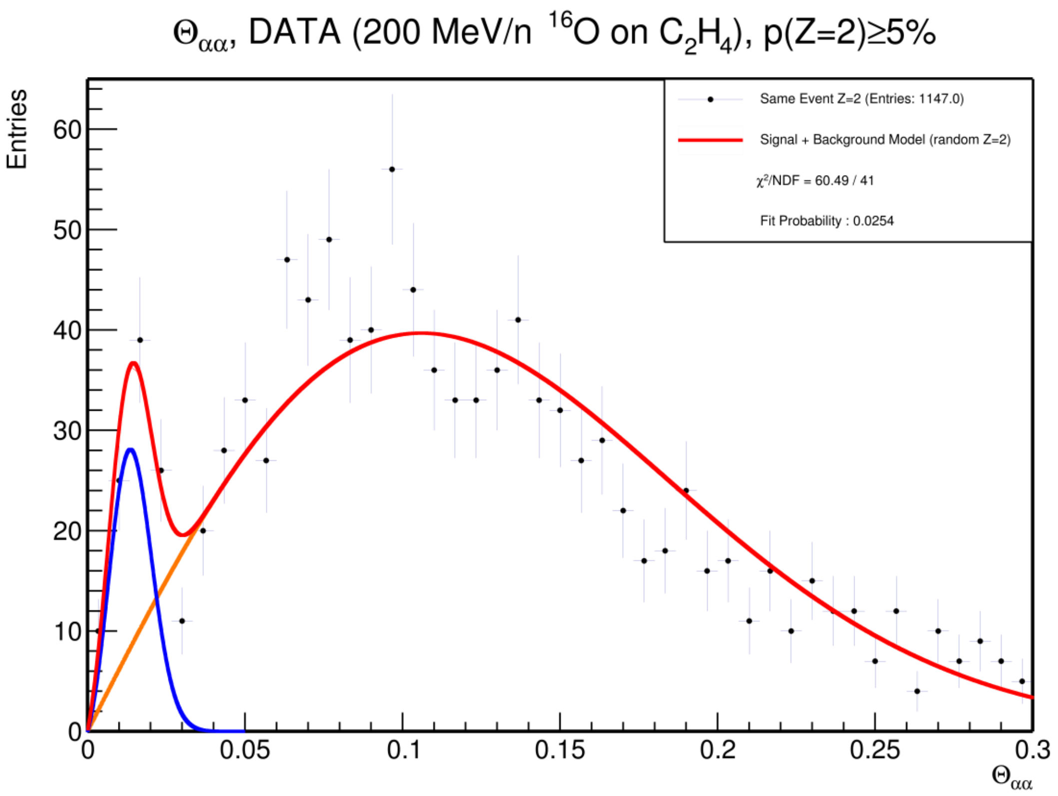
Fit Function: $g(x) = N_1 x e^{-Bx^2} + N_2 x e^{-(x-C)^2/D^2}$

Correlation Peak Comparisons: 200 MeV/n ^{16}O on C_2H_4

- In order to obtain the final estimate, a fit including both the signal and background model was used
  - The shape of the background contribution («B» parameter) was fixed
- After background subtraction, the correlation peak is more populated → efficiency improvement!



Estimated Signal = 44 ± 9

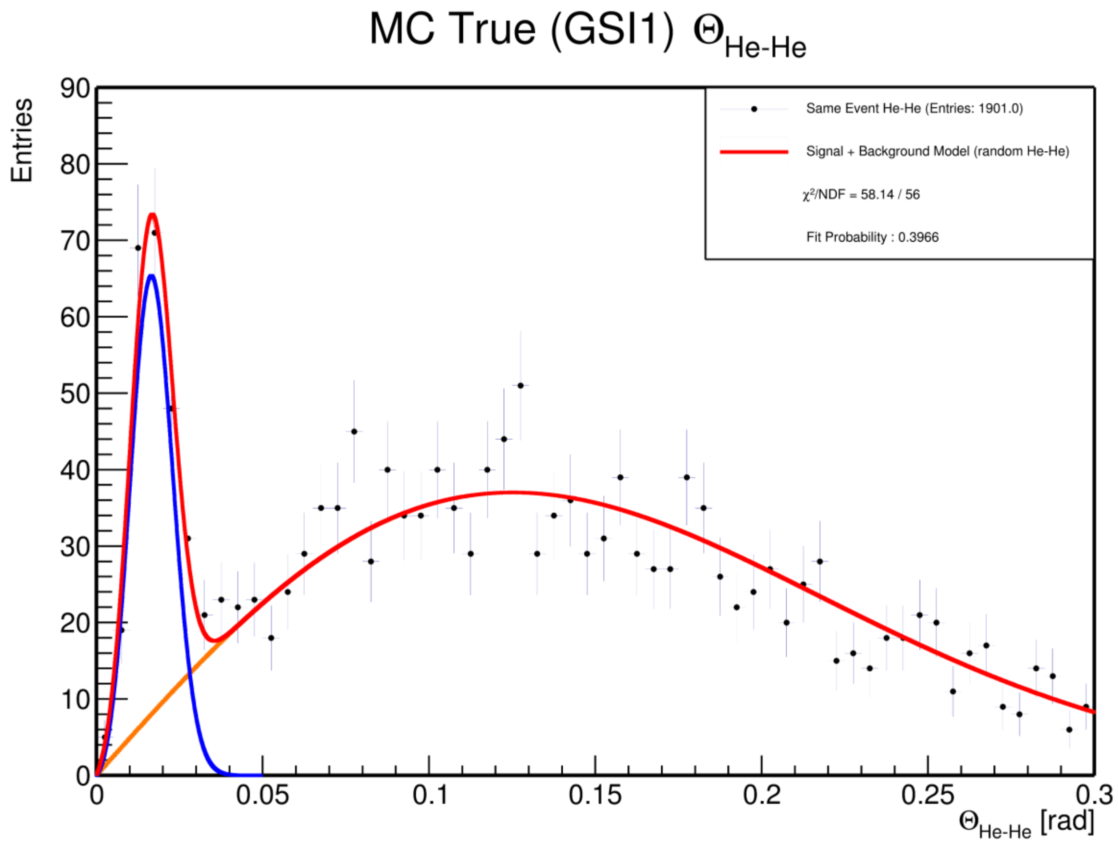


Estimated Signal = 61 ± 11

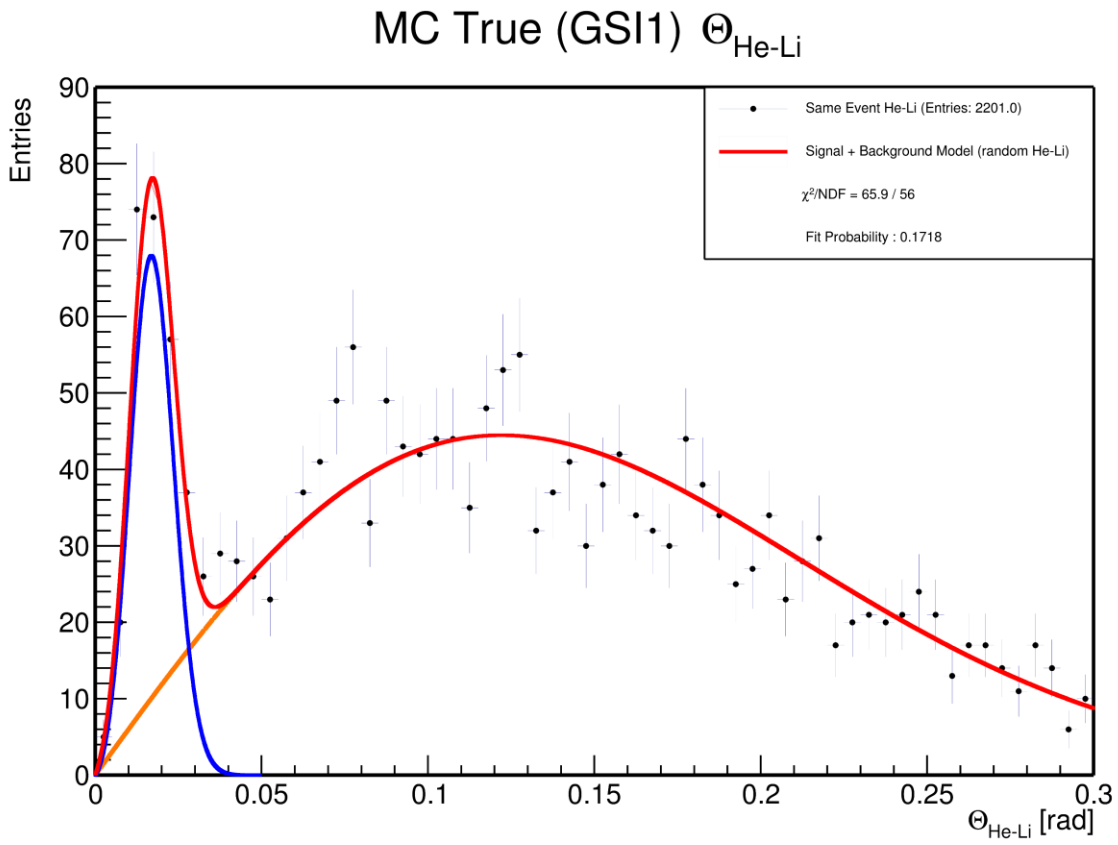
Fit Function: $g(x) = N_1 x e^{-Bx^2} + N_2 x e^{-(x-C)^2/D^2}$

Correlation Peak with He-Li (MC True)

- The clustering analysis was repeated in MC True after the inclusion of **all the available** He-Li pairs
- In this case, the increase in the background only partially compensates the additional pairs
- As a result, an increase in the signal can be observed (smaller than the counting error!)



Estimated signal (He pairs) = 183 ±14

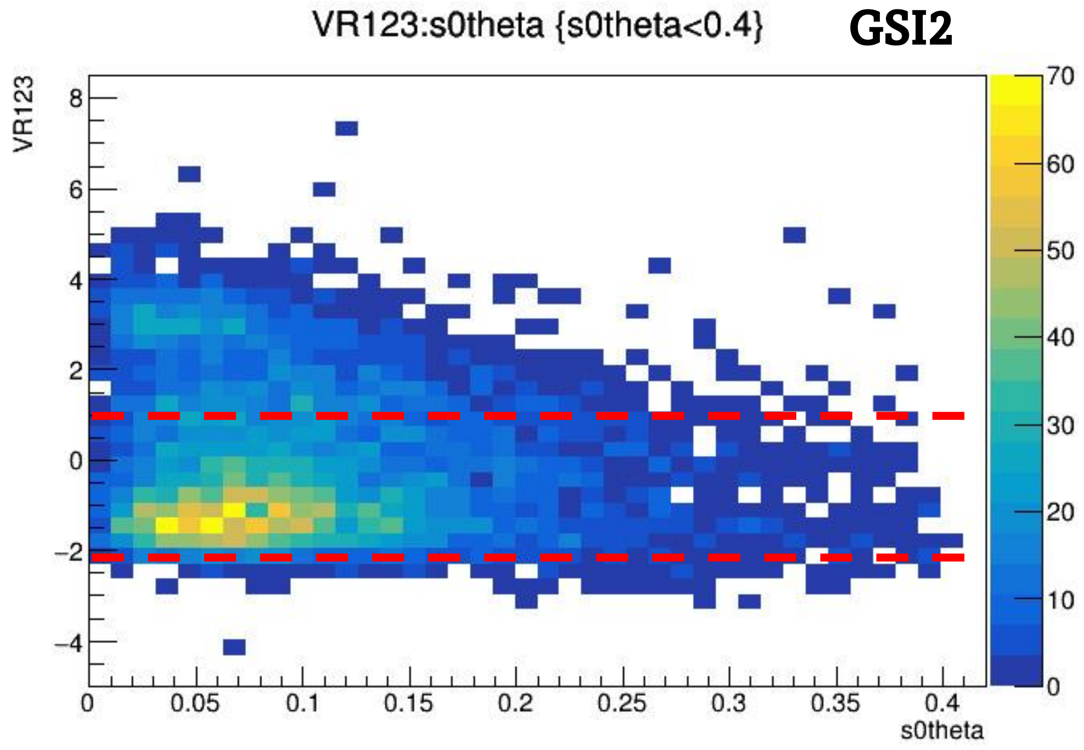


Estimated signal (He pairs) = 193 ±15

GSI1 = 200 MeV/n $^{16}\boldsymbol{O}$ on $\boldsymbol{C_{nat}}$, Fit Function: $g(x) = N_1 x e^{-Bx^2} + N_2 x e^{-(x-C)^2/D^2}$

Status of the Analysis (as of last Physics Meeting)

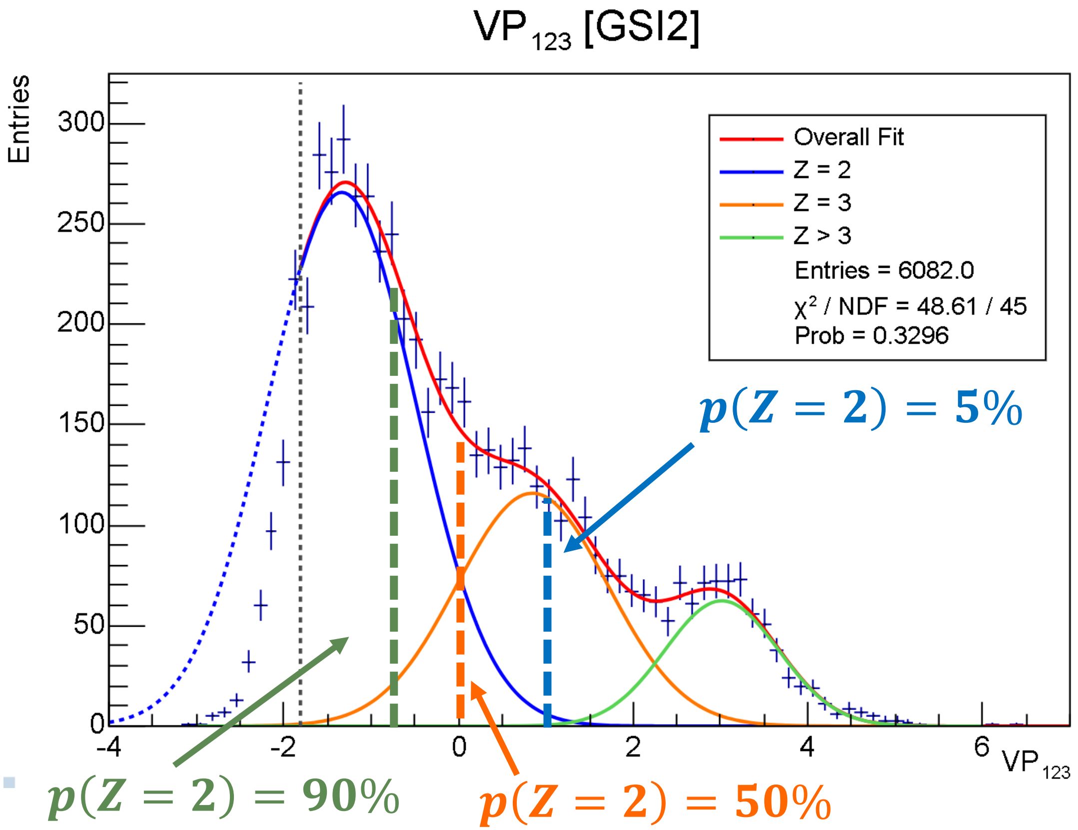
- If the Li contamination estimates from True MC could be applied to DATA then an increase of ~ 6% would be expected with the inclusion of all He-Li pairs
- The actual increase observed in DATA is around 30/35%!
- However, the expected contamination in DATA is still being studied
  - The relative abundancies of He, Li in DATA do not match those in MC
  - The selection of tracks in DATA cannot be easily translated to MC because it is linked to volume variables which are not simulated
  - An approximate selection would neglect correlations between volume variables and angles/energies of the fragments



The dependance on the angle is mild in the region of interest → approximate selection using a flat cut (this talk)

Emulating the p(Z=2) cut in Reconstructed MC (RMC)

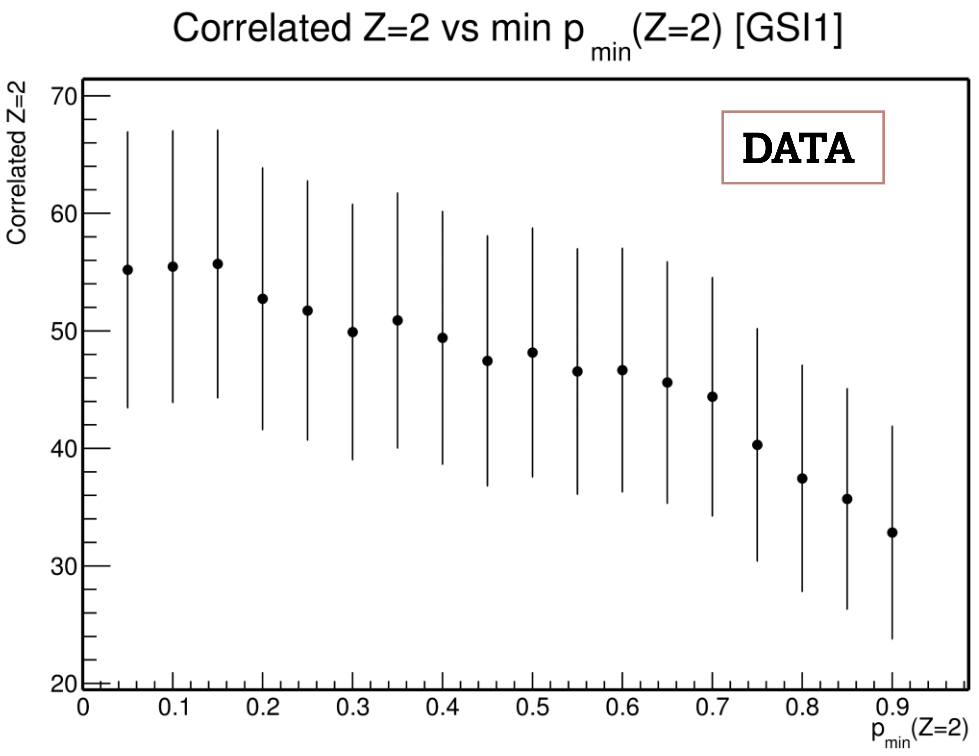
- To emulate the new track selection in RMC, the following steps were taken
  - Fix a minimum probability p_{min}^{Z2}
  - In DATA, look for angular correlations between track pairs satisfying $p(Z=2) \geq p_{min}^{Z2}$
  - In Reconstructed MC, randomly assign a fake volume variable to each track and perform the same selection as in DATA (flat cut)
  - Evaluate the reconstruction efficiency
  - Repeat all previous steps for different values of p_{min}^{Z2} (from 5% to 90% in this analysis)

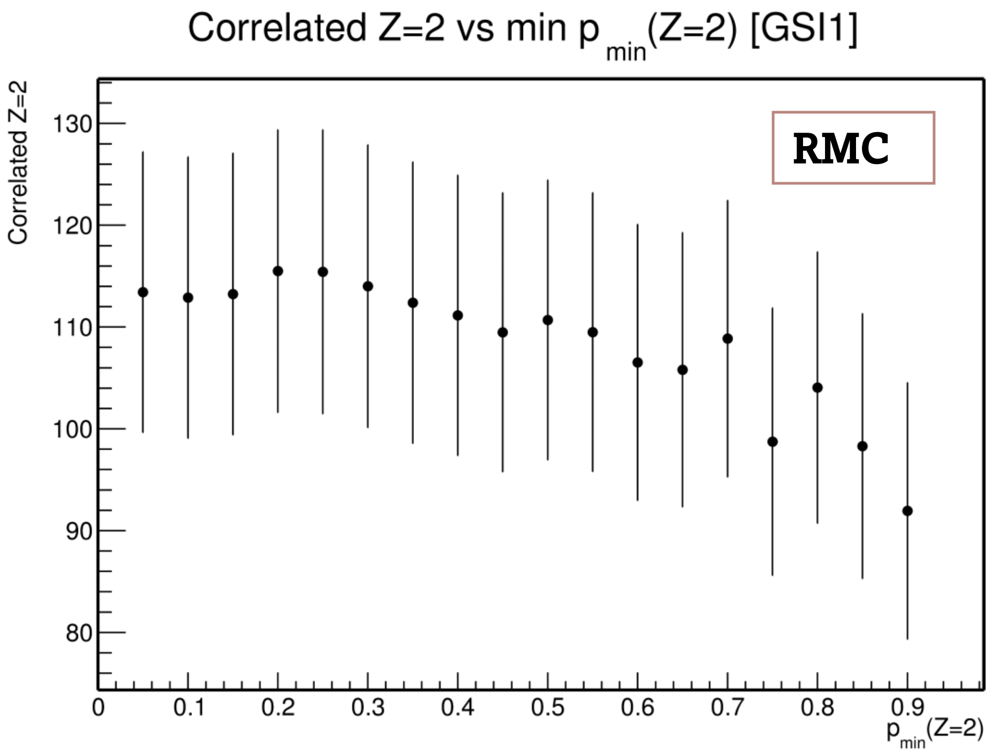


p_{min}^{Z2}	He Fraction	Li Fraction
0.9	79%	3%
0.05	99%	57%

Results in GSI1 (Carbon)

- The clustering analysis was repeated in RMC and DATA for different values of p_{min}^{Z2}
- Each point in RMC is the average between 3 different random seeds
- As expected, more stringent cuts on p_{min}^{Z2} lead to a lower efficiency
- The loss of efficiency is linked to $(probability\ of\ losing\ an\ He)^2$ which can be derived from the VP123 Gaussians integrals





GSI1 = 200 MeV/n ^{16}O on C_{nat}

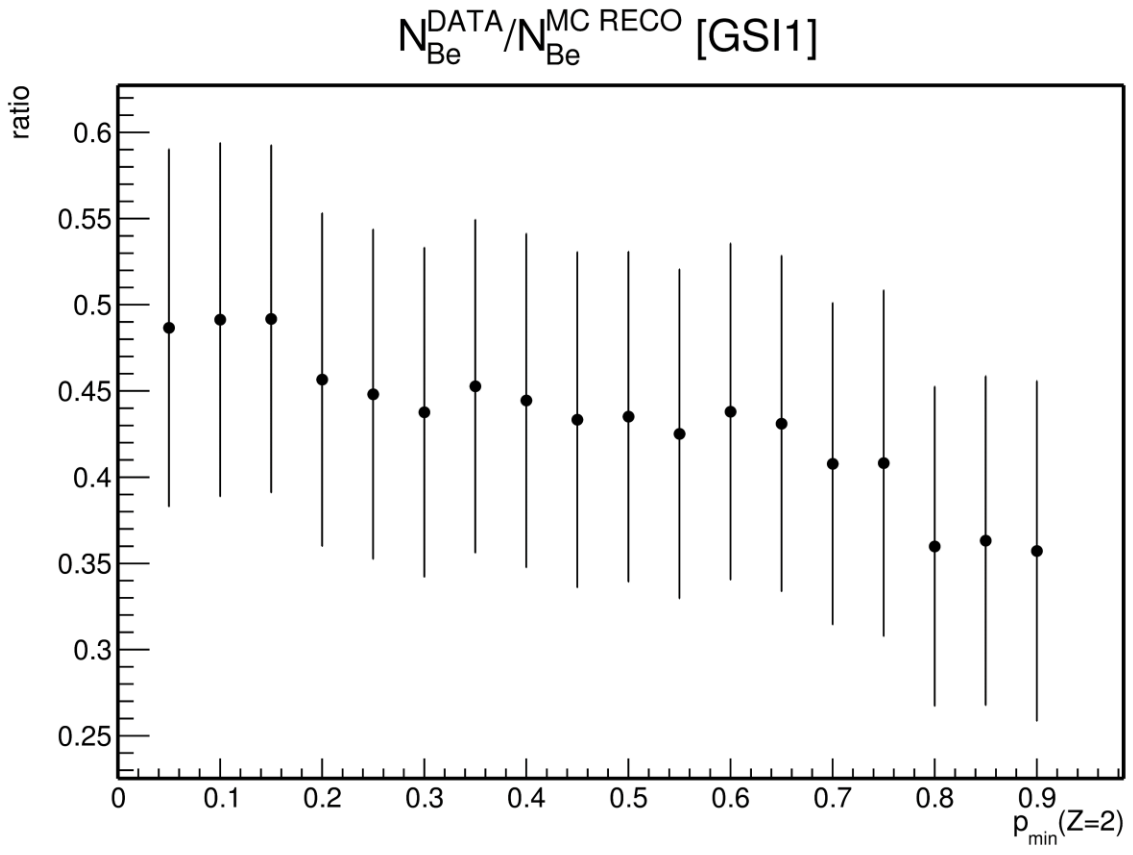
Influence on the Cross Section (GSI1)

- The reconstruction efficiency can be evaluated for each value of p_{min}^{Z2}
- Assuming that the expected signal (True MC) remains the same, the quantity of interest for the evaluation of the cross section is the ratio $N_{^8Be_{g.s}}^{DATA}/N_{^8Be_{g.s.}}^{RMC}$

$$\sigma^{\,^8\boldsymbol{Be}_{g.s.}} = \frac{N_{Be}}{N_B \cdot \rho \cdot d \cdot \frac{N_A}{A} \cdot \varepsilon_{reco}} = \kappa \cdot \frac{N_{^8Be_{g.s.}}^{DATA}}{N_{^8Be_{g.s.}}^{RMC}}$$

$$\varepsilon_{reco} = \frac{N_{^8Be_{g.s.}}^{RMC}}{N_{^8Be_{g.s.}}^{MCTrue}}$$

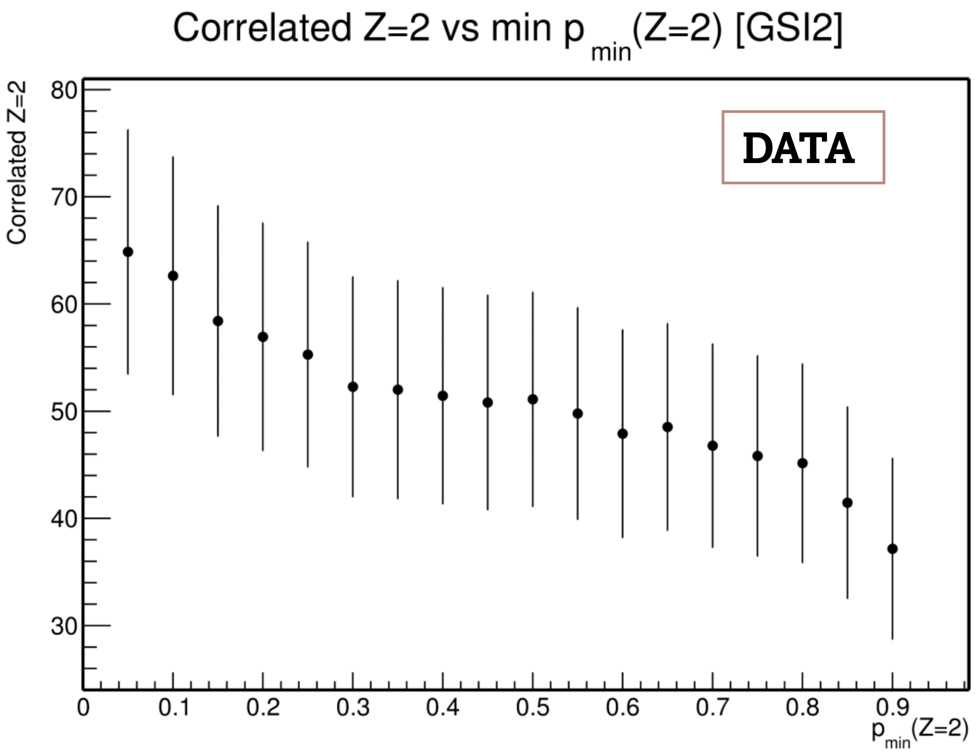
- The plot is the «best case scenario» because **only the statistical error coming from $N_{^8Be_{g.s.}}^{DATA}$ was taken into account**
- Because of the limited statistics, the choice of p_{min}^{Z2} does not significantly change the final result

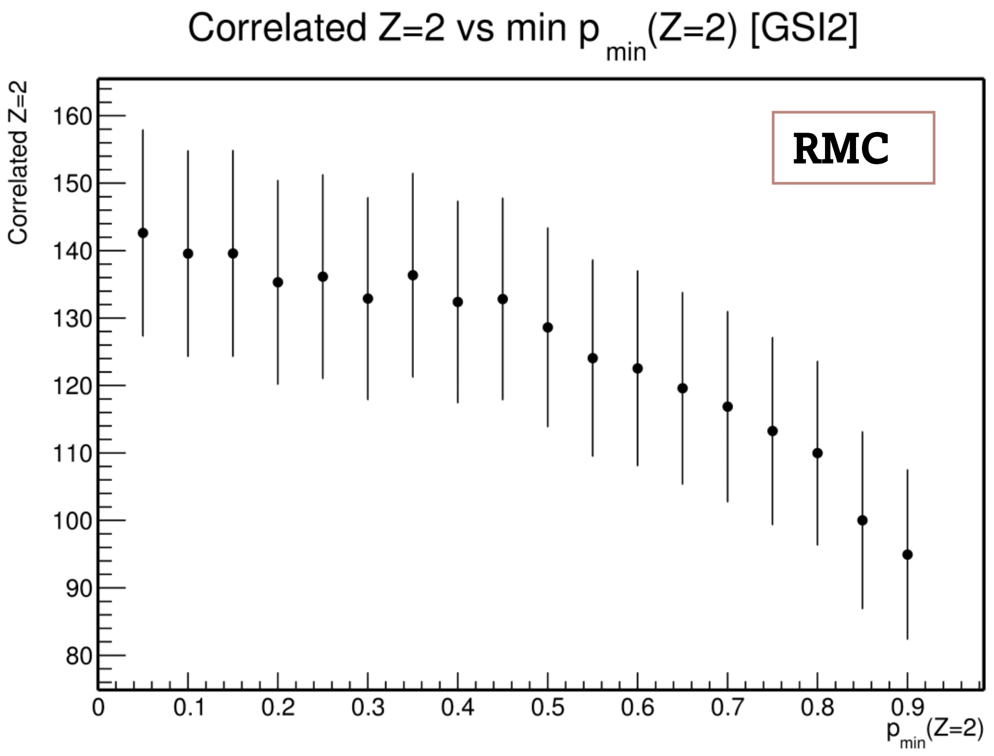


GSI1 = 200 MeV/n $^{16}\boldsymbol{O}$ on $\boldsymbol{C}_{nat}$

Results in GSI2 (C2H4)

- The clustering analysis was repeated in RMC and DATA for different values of p_{min}^{Z2}
- Each point in RMC is the average between 3 different random seeds
- As expected, more stringent cuts on p_{min}^{Z2} lead to a lower efficiency
- The loss of efficiency is linked to $(probability\ of\ losing\ an\ He)^2$ which can be derived from the VP123 Gaussians integrals





GSI1 = 200 MeV/n ^{16}O on C_{nat}

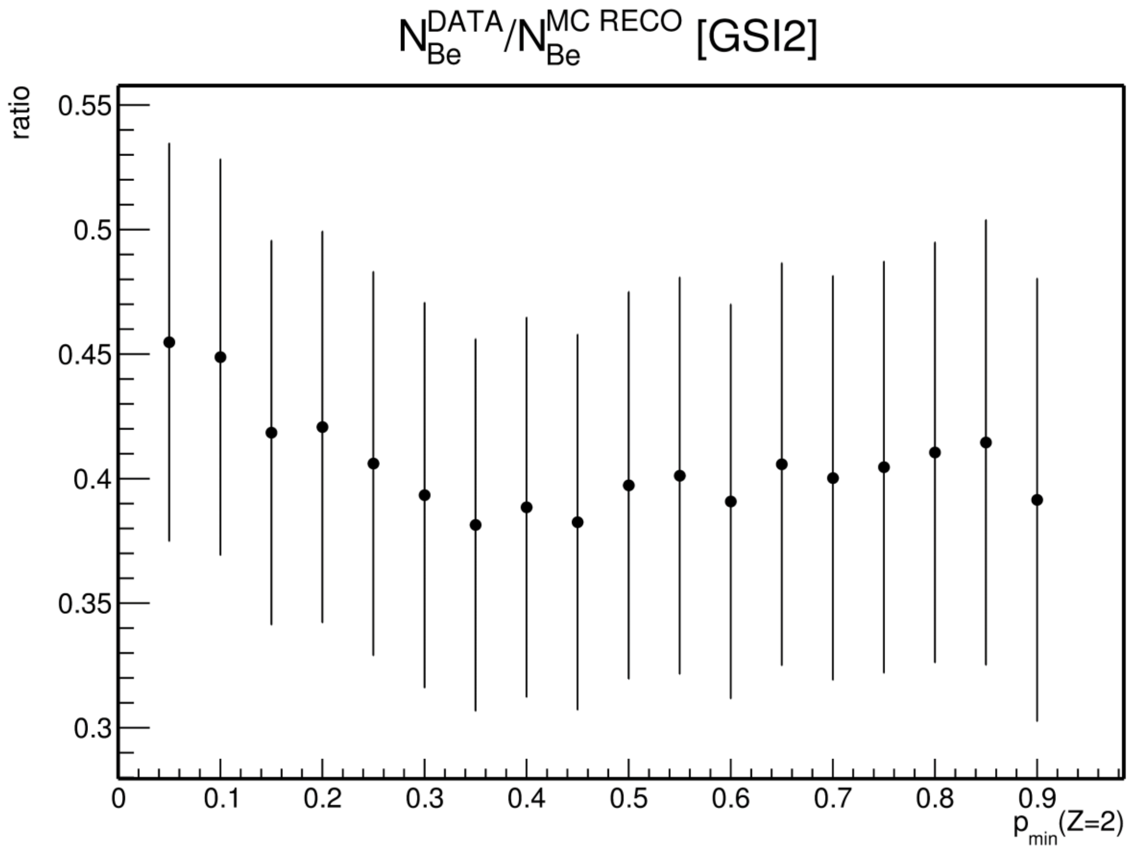
Influence on the Cross Section (GSI2)

- The reconstruction efficiency can be evaluated for each value of p_{min}^{Z2}
- Assuming that the expected signal (True MC) remains the same, the quantity of interest for the evaluation of the cross section is the ratio $N_{^8Be_{g.s}}^{DATA}/N_{^8Be_{g.s.}}^{RMC}$

$$\sigma^{\,\mathbf{^8Be_{g.s.}}} = \frac{N_{Be}}{N_B \cdot \rho \cdot d \cdot \frac{N_A}{A} \cdot \varepsilon_{reco}} = \kappa \cdot \frac{N_{^8Be_{g.s.}}^{DATA}}{N_{^8Be_{g.s.}}^{RMC}}$$

$$\varepsilon_{reco} = \frac{N_{^8Be_{g.s.}}^{RMC}}{N_{^8Be_{g.s.}}^{MCTrue}}$$

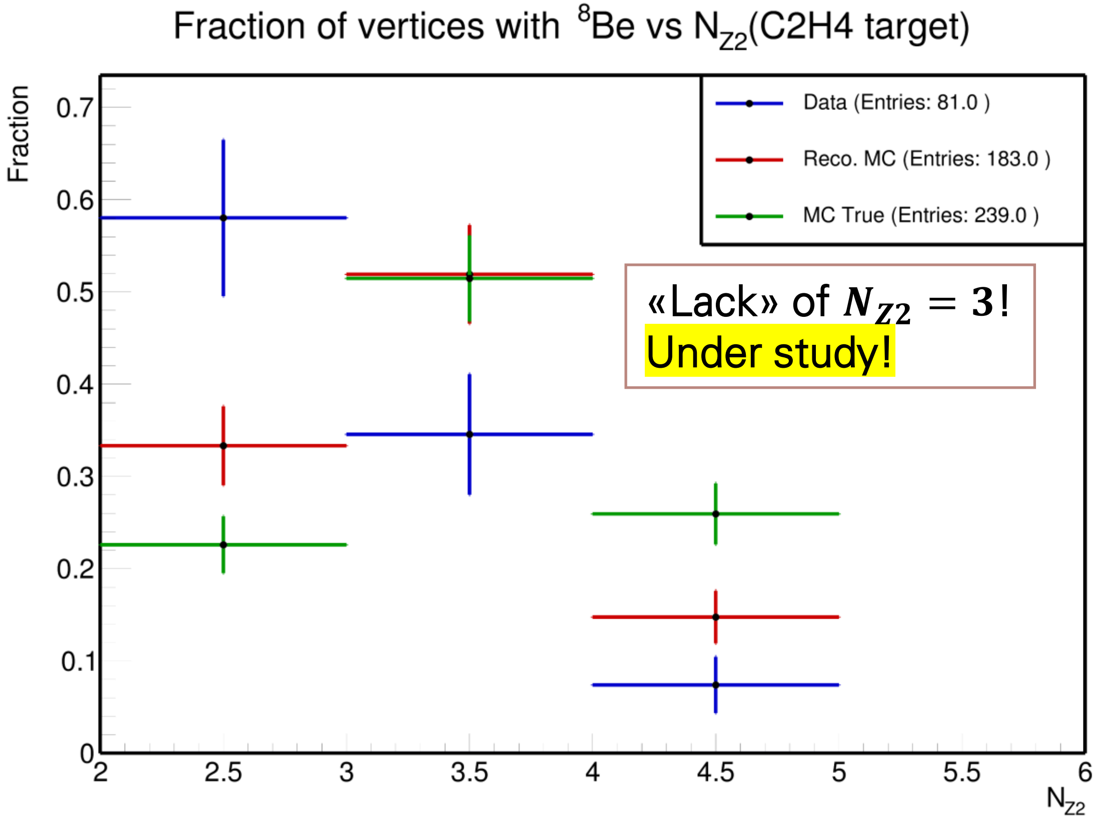
- The plot is the «best case scenario» because **only the statistical error coming from $\boldsymbol{N_{^8Be_{g.s.}}^{DATA}}$ was taken into account**
- Because of the limited statistics, the choice of p_{min}^{Z2} does not significantly change the final result

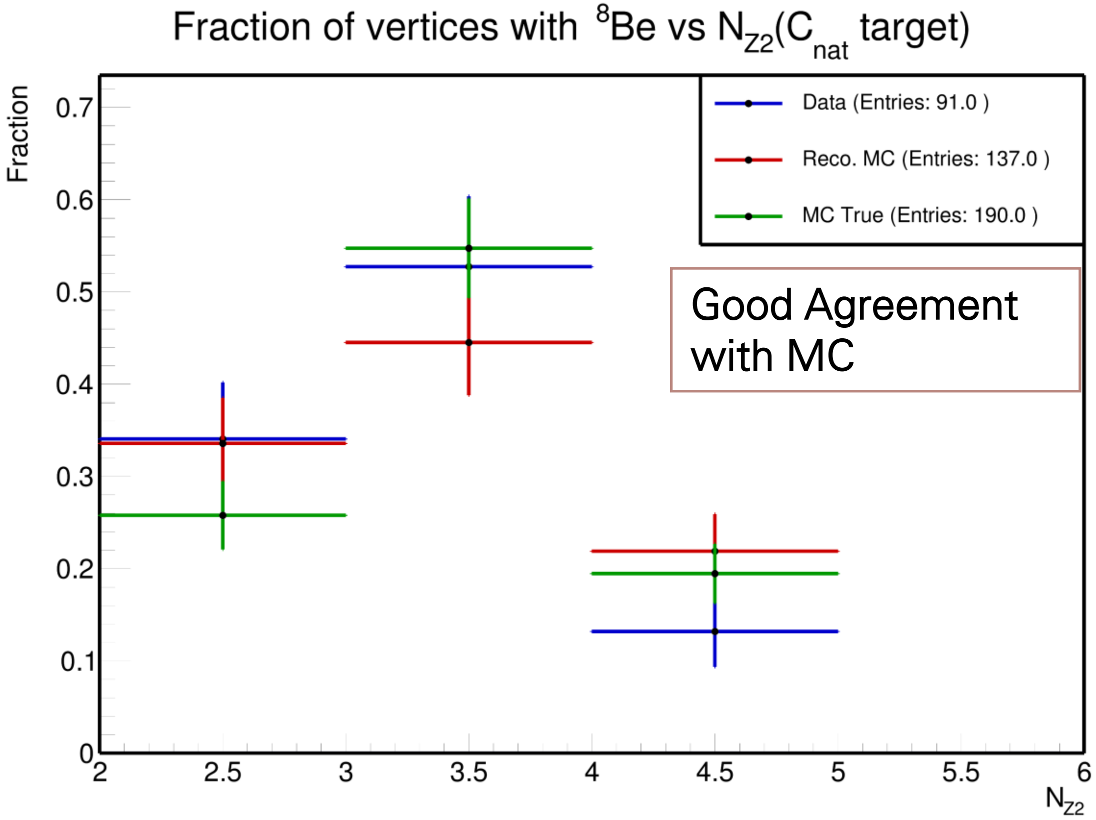


GSI2 = 200 MeV/n $\mathbf{^{16}O}$ on $\boldsymbol{C_2H_4}$

He Multiplicity Study

- The number of He was evaluated in DATA, Reconstructed MC and True MC in the events where at least one correlated pair was found
- No background subtraction used for these plots

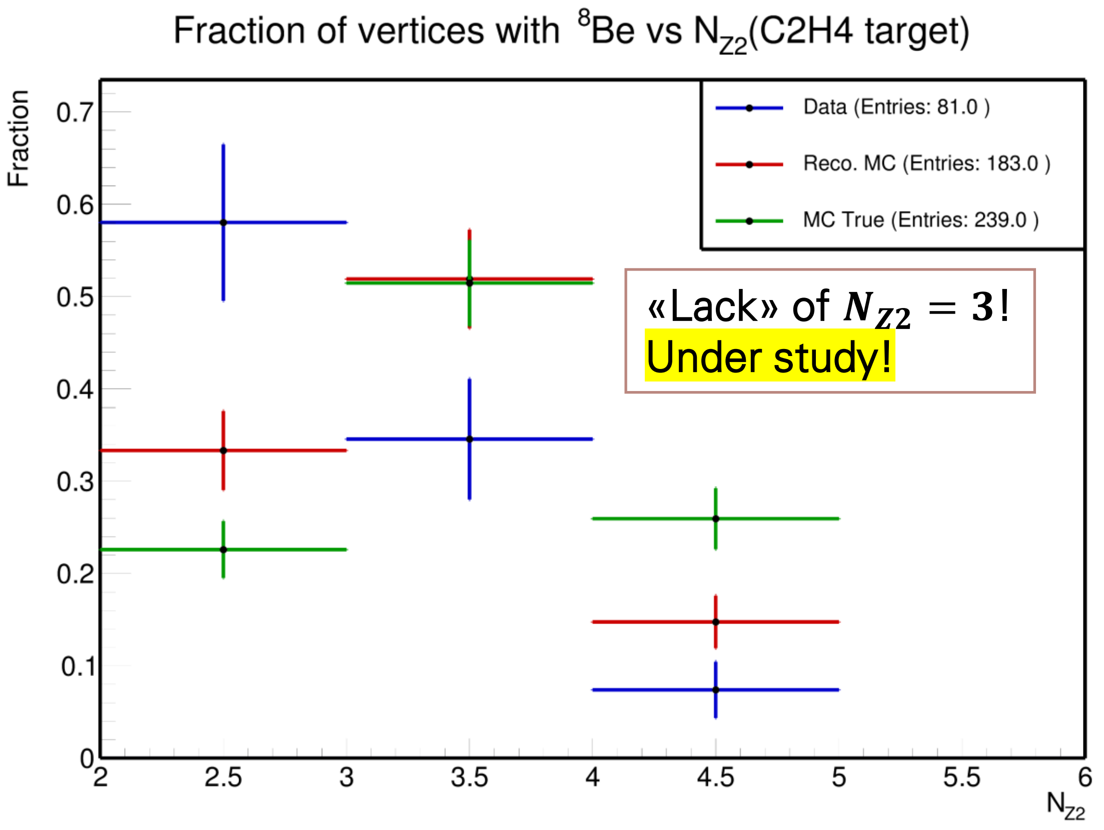


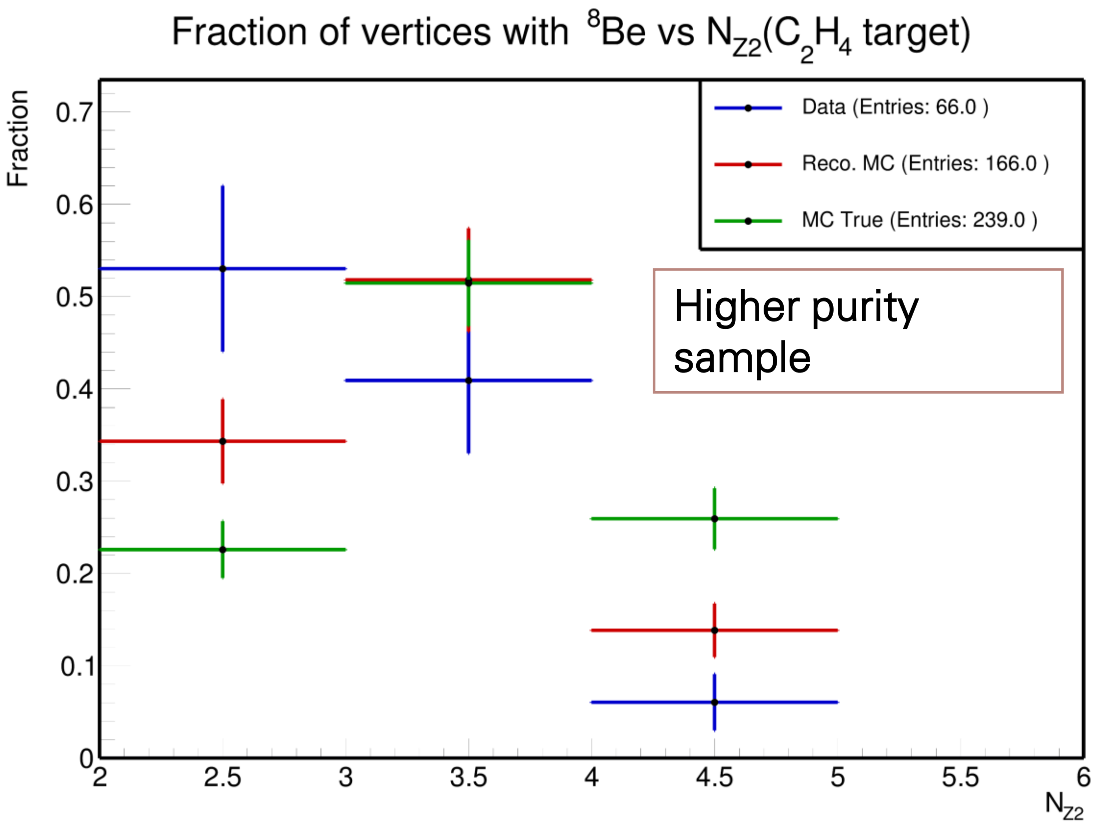


GSI1 = 200 MeV/n ^{16}O on C_{nat}, GSI2 = 200 MeV/n ^{16}O on C_2H_4

Update on He Multiplicity Study

- Because the final result on the cross section will not depend significantly on the choice of p_{min}^{Z2}, the multiplicity was studied again with $p_{min}^{Z2} = 50\%$ (higher purity sample)
- As can be seen from the plots below, the disagreement with MC becomes less clear





GSI1 = 200 MeV/n ^{16}O on C_{nat}, GSI2 = 200 MeV/n ^{16}O on C_2H_4

Reducing the statistical uncertainty on $\boldsymbol{\varepsilon_{reco}}$

- In order to reduce the statistical uncertainty on the reconstruction efficiency a ~4 times higher MC statistics has been used (around 80k events, divided into 4 batches)
- An in depth study of the systematic components will follow

CARBON TARGET

$$\varepsilon_{reco} = \frac{N^{RMC}_{^8Be_{g.s.}}}{N^{MCTrue}_{^8Be_{g.s.}}} = \frac{116 \pm 16}{183 \pm 14} = 63 \pm 14\%$$

$$\sigma_{\,^8\boldsymbol{Be}_{g.s.}}(C_{nat}) = 14 \pm 6\, mb$$

$$\varepsilon_{reco} = \frac{N^{RMC}_{^8Be_{g.s.}}}{N^{MCTrue}_{^8Be_{g.s.}}} = \\ = \frac{1}{4}\left(\frac{116 \pm 16}{183 \pm 14} + \frac{133 \pm 14}{191 \pm 17} + \frac{137 \pm 14}{178 \pm 16} + \frac{135 \pm 14}{194 \pm 17}\right) \\ = 70 \pm \mathbf{7}\%$$

$$\sigma_{\,^8\boldsymbol{Be}_{g.s.}}(C_{nat}) = 14 \pm 4\, mb$$

POLYETHYLENE TARGET

$$\varepsilon_{reco} = \frac{N^{RMC}_{^8Be_{g.s.}}}{N^{MCTrue}_{^8Be_{g.s.}}} = \frac{143 \pm 18}{208 \pm 17} = 69 \pm \mathbf{14}\%$$

$$\sigma_{\,^8\boldsymbol{Be}_{g.s.}}(C_2H_4) = 42 \pm 16\, mb$$

$$\varepsilon_{reco} = \frac{N^{RMC}_{^8Be_{g.s.}}}{N^{MCTrue}_{^8Be_{g.s.}}} = \\ = \frac{1}{4} \cdot \left(\frac{143 \pm 18}{208 \pm 17} + \frac{167 \pm 16}{245 \pm 19} + \frac{156 \pm 16}{239 \pm 19} + \frac{179 \pm 16}{242 \pm 19}\right) \\ = 69 \pm \mathbf{6}\%$$

$$\sigma_{\,^8\boldsymbol{Be}_{g.s.}}(C_2H_4) = 42 \pm 11\, mb$$

GSI1 = 200 MeV/n $^{16}\boldsymbol{O}$ on $\boldsymbol{C_{nat}}$, GSI2 = 200 MeV/n $^{16}\boldsymbol{O}$ on $\boldsymbol{C_2H_4}$

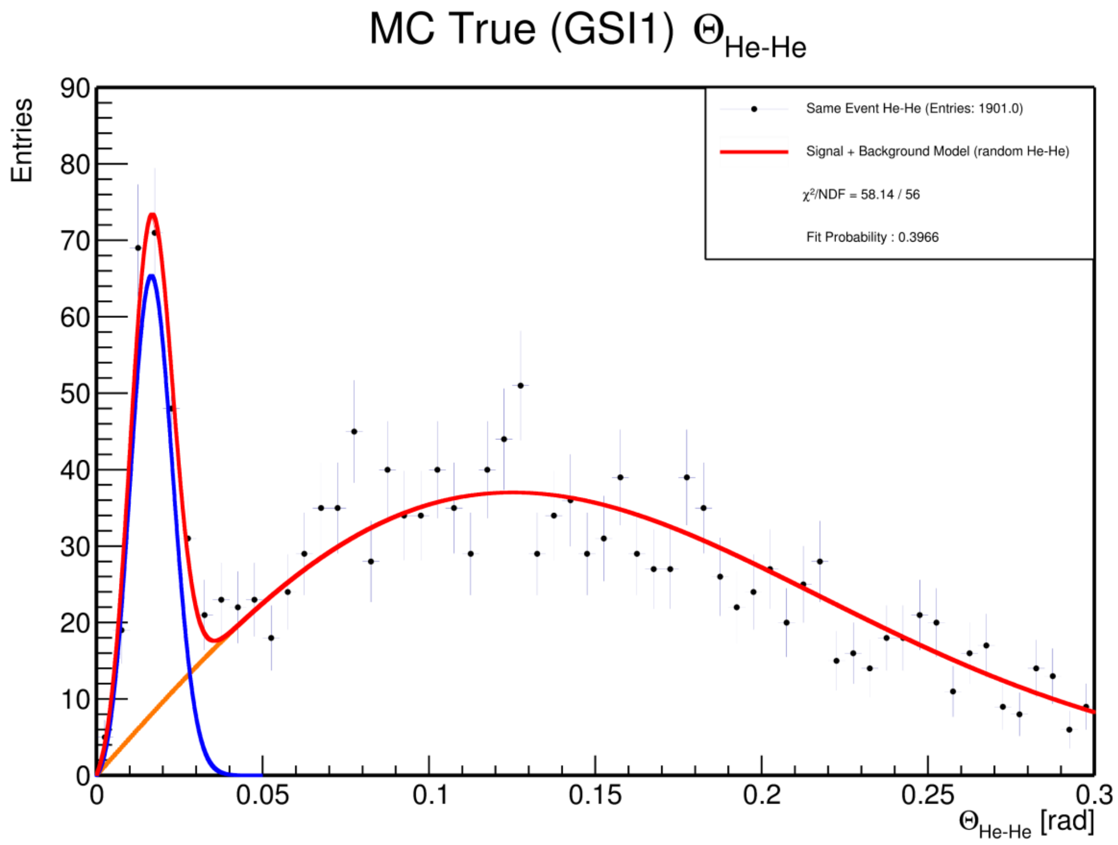
Conclusions

- The contamination of the correlation peak by the addition of He-Li pairs was studied in RMC with an approximated track selection to mimic DATA
  - The results show that the specific choice of p_{min}^{Z2} does not matter because of the limited statistics of our samples
- First comparisons of He multiplicity in clustered events between DATA and MC show a good agreement for GSI1
  - The disagreement for GSI2 becomes less severe when a higher purity sample is used
- Repeated the analysis with 4x higher MC statistics to reduce the statistical uncertainty on the final result
- Next: in-depth study of the systematic components of the error

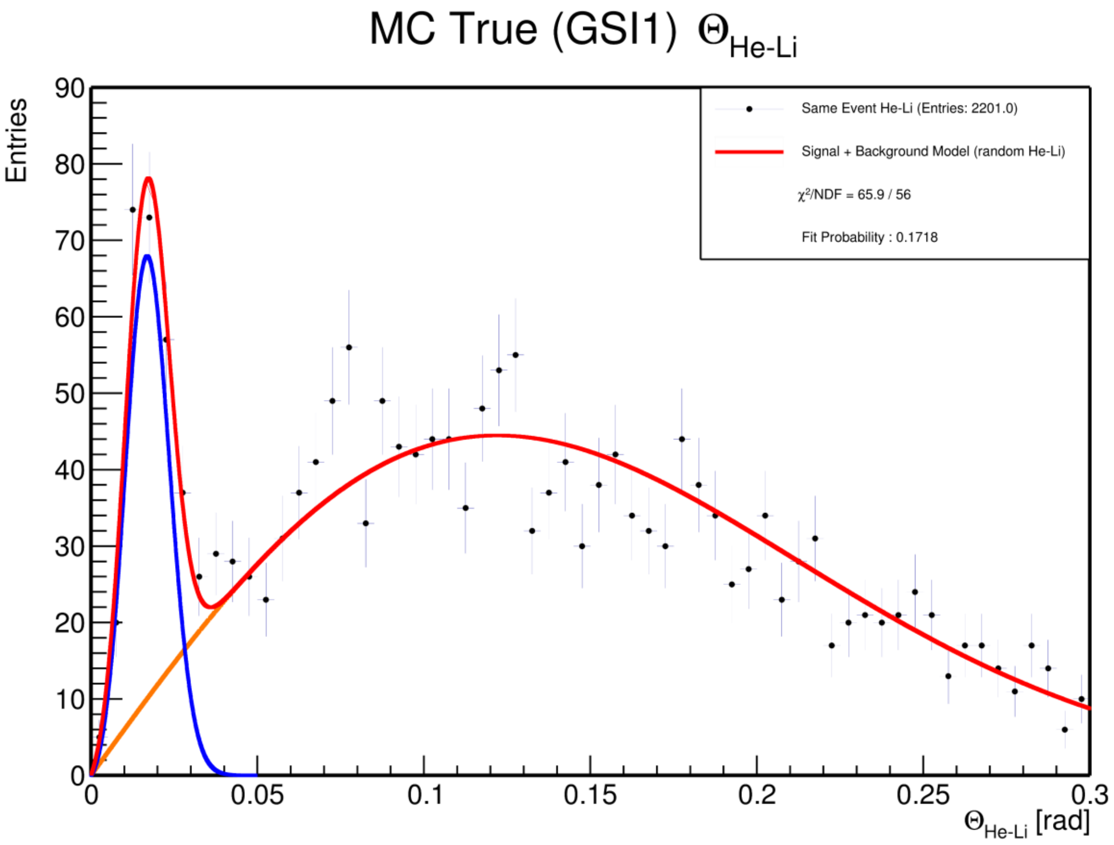
Thank You!

Correlation Peak with He-Li (MC True)

- The clustering analysis was repeated in MC True after the inclusion of **all the available** He-Li pairs
- In this case, the increase in the background only partially compensates the additional pairs
- As a result, an increase in the signal can be observed (smaller than the counting error!)



Estimated signal (He pairs) = 183 ±14

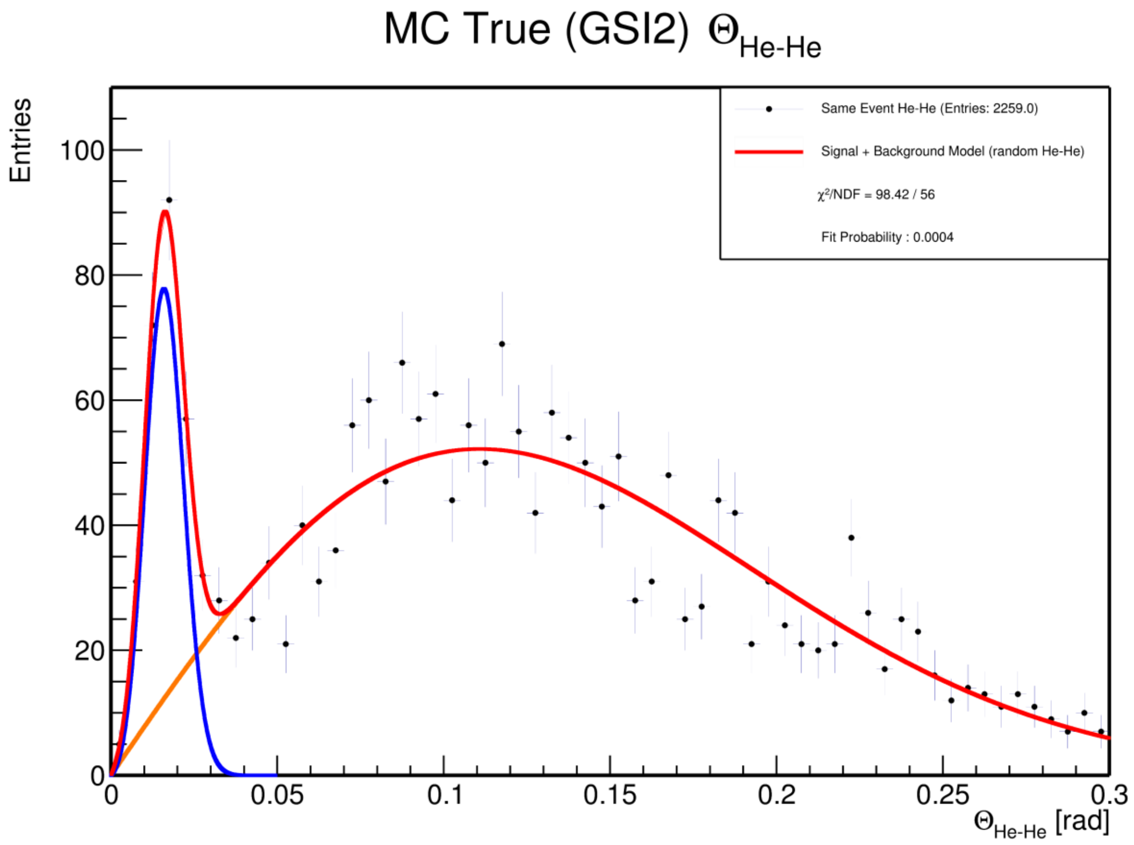


Estimated signal (He pairs) = 193 ±15

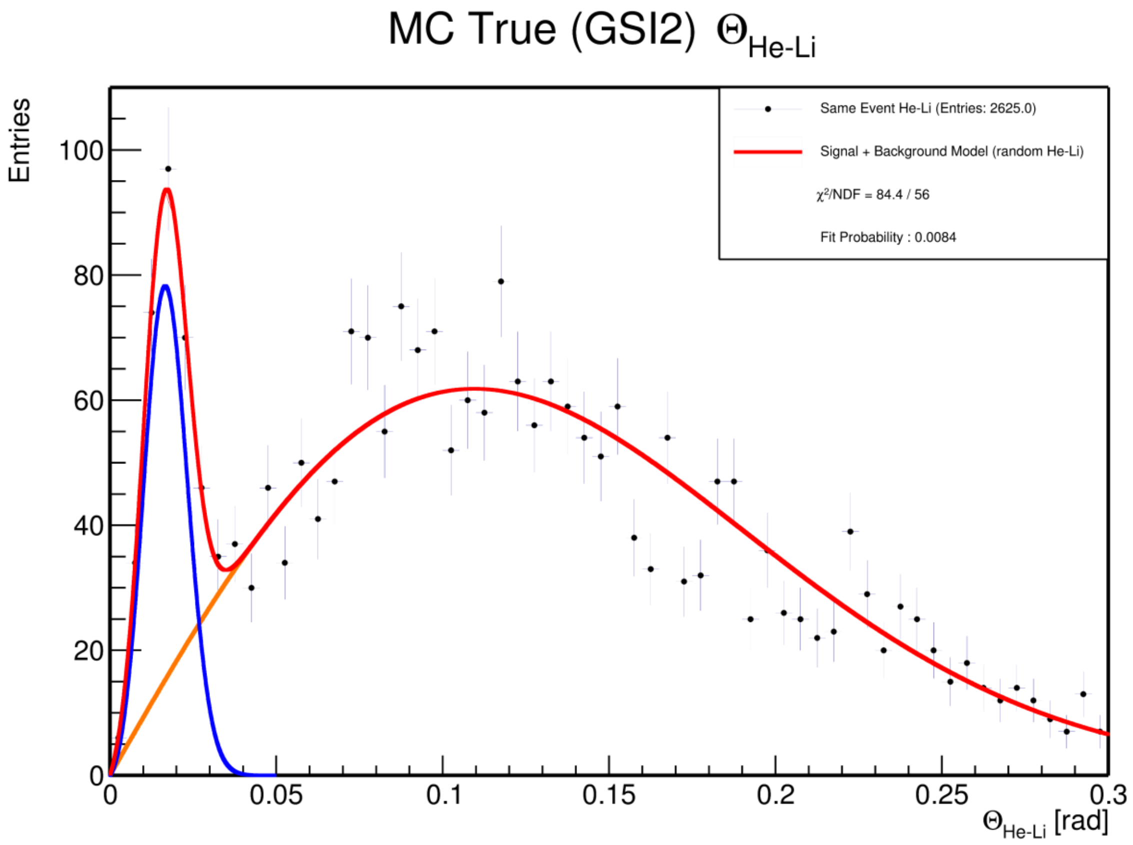
GSI1 = 200 MeV/n $^{16}\boldsymbol{O}$ on $\boldsymbol{C_{nat}}$, Fit Function: $g(x) = N_1 x e^{-Bx^2} + N_2 x e^{-(x-C)^2/D^2}$

Correlation Peak with He-Li (MC True)

- The clustering analysis was repeated in MC True after the inclusion of **all the available** He-Li pairs
- In this case, the increase in the background only partially compensates the additional pairs
- As a result, an increase in the signal can be observed (smaller than the counting error!)



Estimated signal (He pairs) = 208 ±17

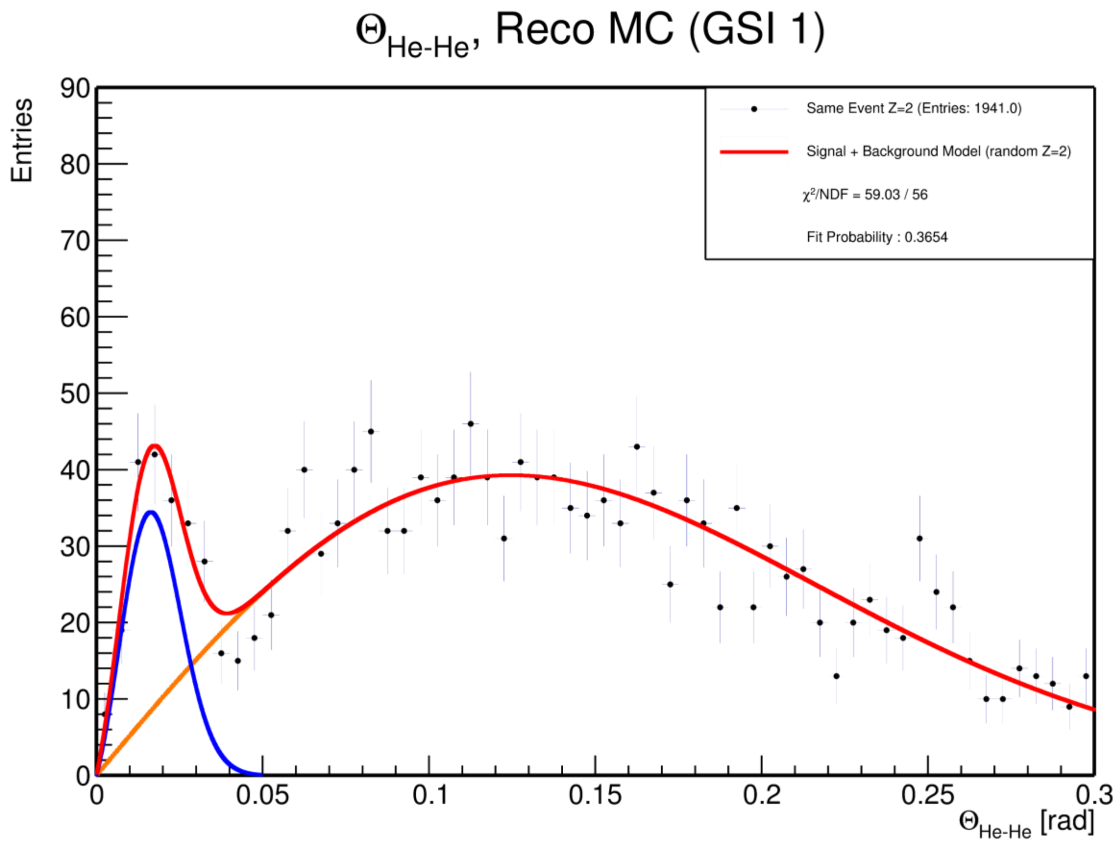


Estimated signal (He pairs) = 223 ±18

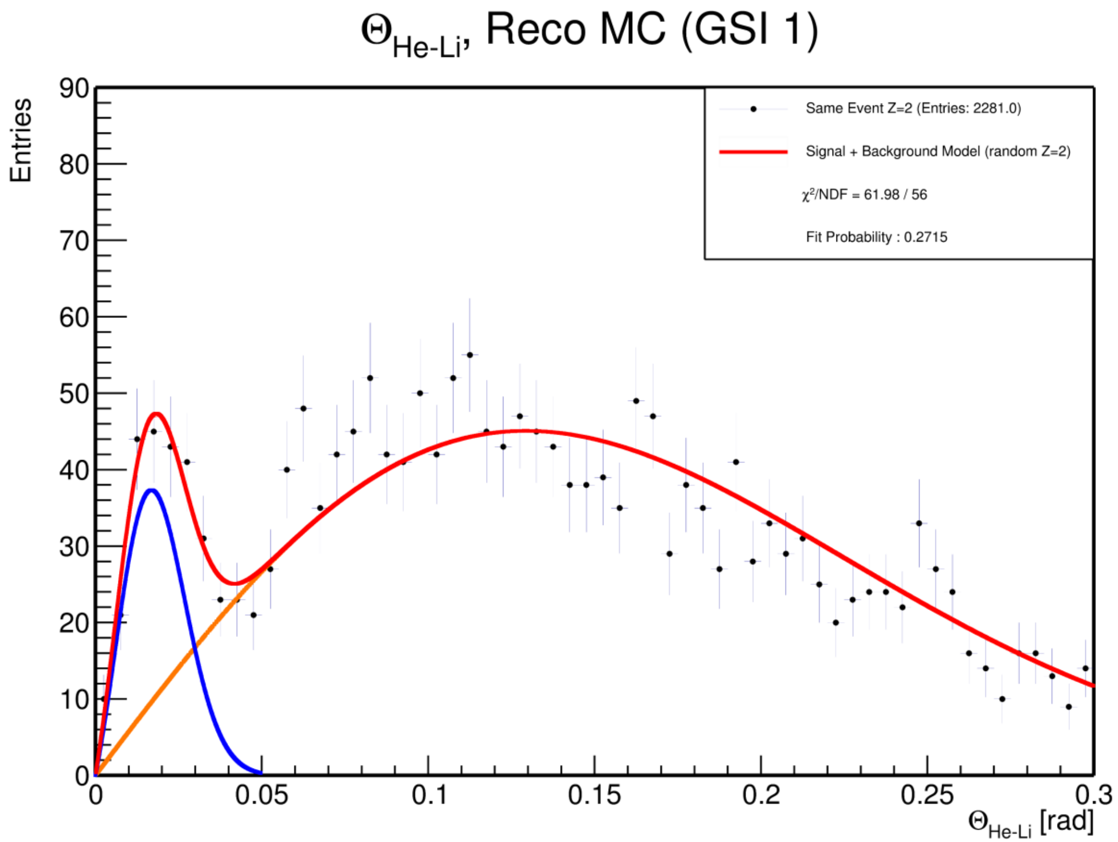
GSI2 = 200 MeV/n $^{16}\boldsymbol{O}$ on $\boldsymbol{C_2H_4}$, Fit Function: $g(x) = N_1 x e^{-Bx^2} + N_2 x e^{-(x-C)^2/D^2}$

Correlation Peak with He-Li (Reco MC)

- A similar approach (inclusion of **all the available** He-Li pairs) was followed in Reconstructed MC
- Once again, the increase in the background only partially compensates the additional pairs
- As a result, an increase in the signal can be observed (comparable to the counting error!)



Estimated signal (He pairs) = 116 ±16

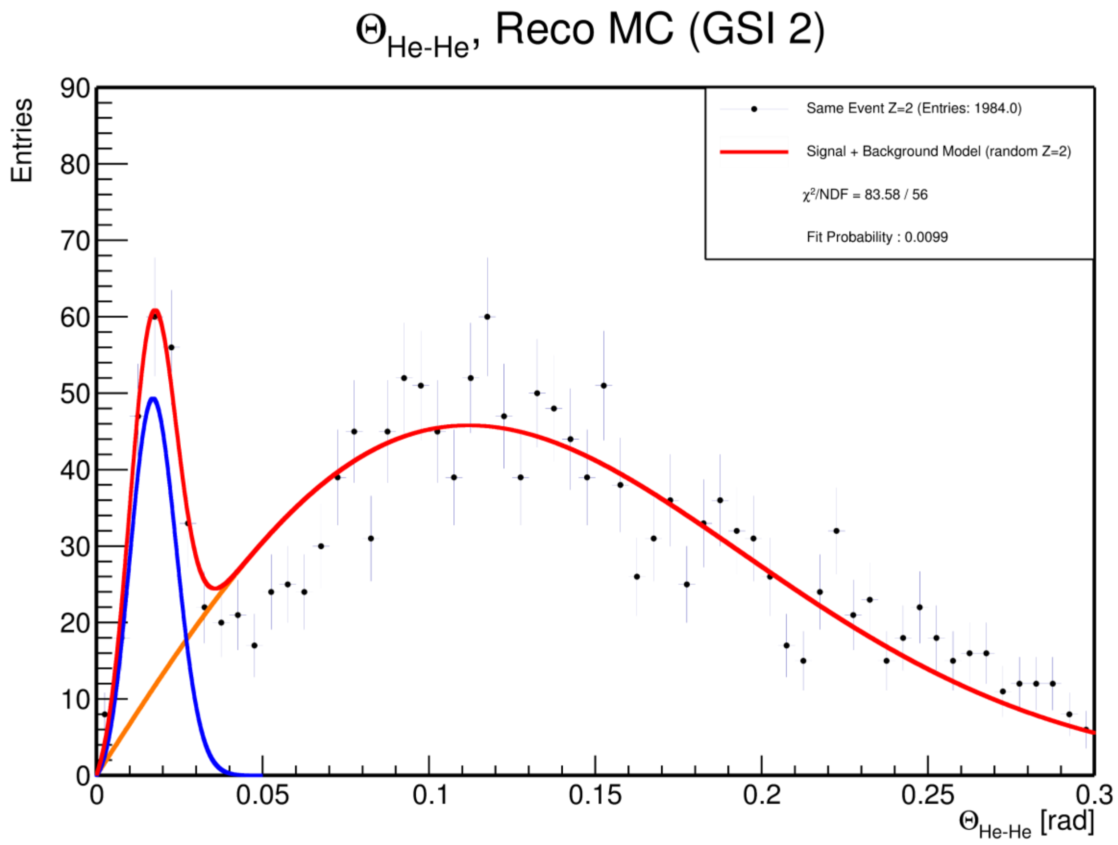


Estimated signal (He pairs) = 129 ±17

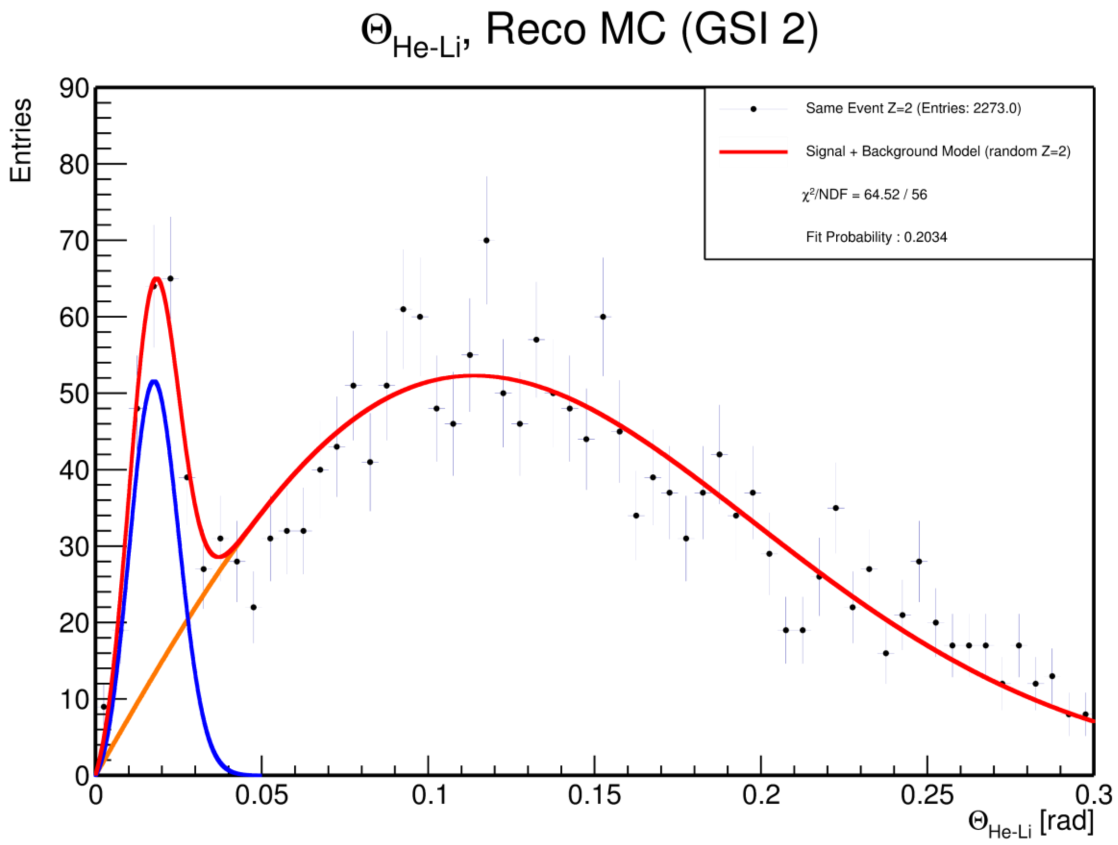
GSI1 = 200 MeV/n $^{16}\boldsymbol{O}$ on $\boldsymbol{C_{nat}}$, Fit Function: $g(x) = N_1 x e^{-Bx^2} + N_2 x e^{-(x-C)^2/D^2}$

Correlation Peak with He-Li (Reco MC)

- A similar approach (inclusion of **all the available** He-Li pairs) was followed in Reconstructed MC
- Once again, the increase in the background only partially compensates the additional pairs
- As a result, an increase in the signal can be observed (comparable to the counting error!)



Estimated signal (He pairs) = 143 ±18



Estimated signal (He pairs) = 153 ±19

GSI2 = 200 MeV/n $^{16}\boldsymbol{O}$ on $\boldsymbol{C_2H_4}$, Fit Function: $g(x) = N_1 x e^{-Bx^2} + N_2 x e^{-(x-C)^2/D^2}$