



Study of the ^{12}C Hoyle state produced by fragmentation

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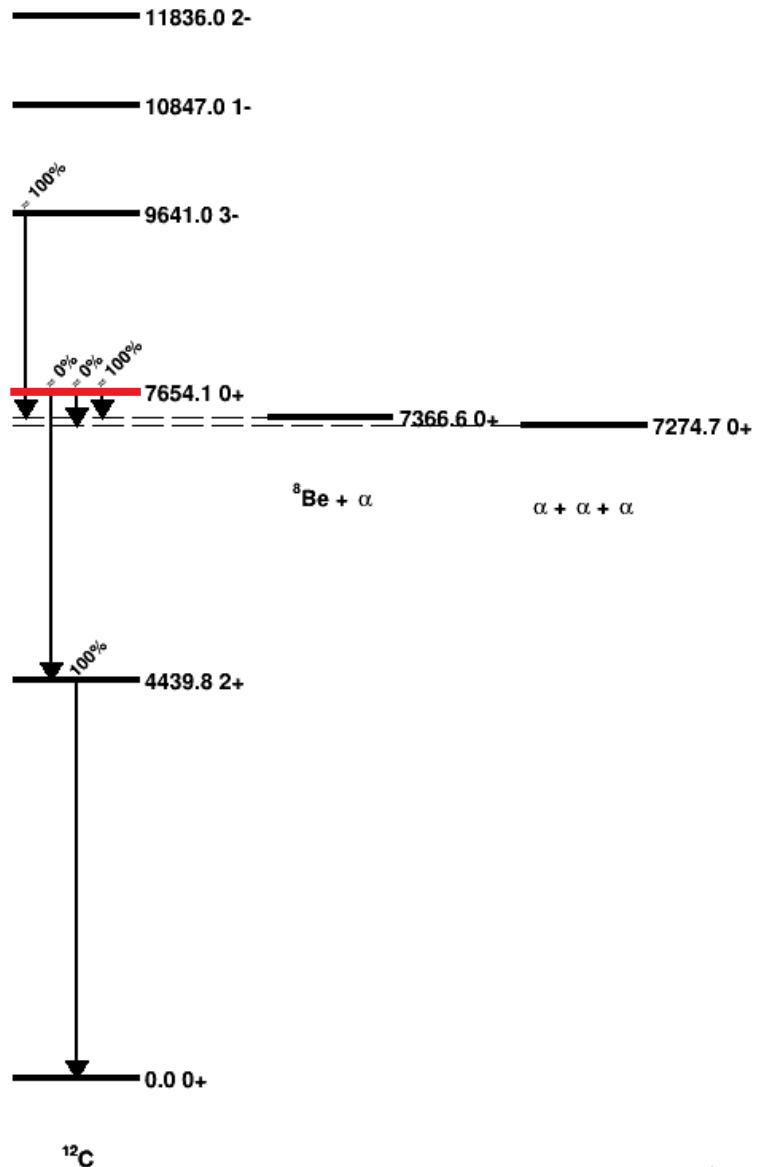
International Workshop on Multi-facets of EOS and Clustering, 2021



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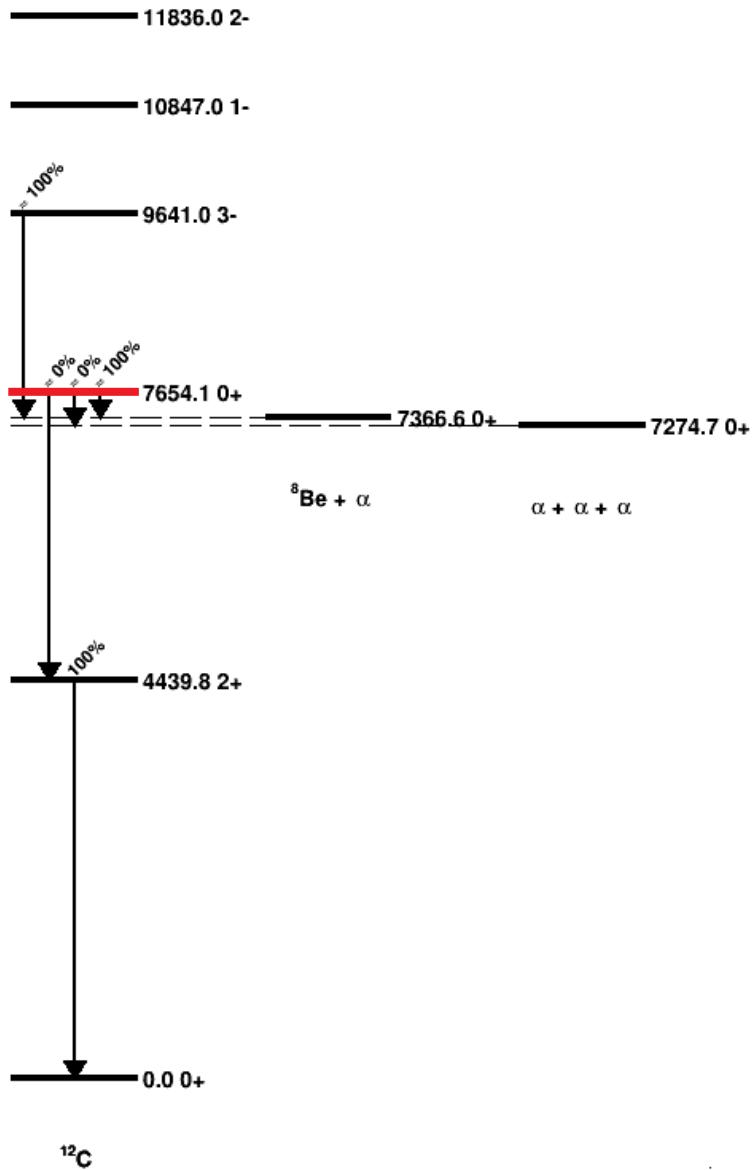


The Hoyle state in ^{12}C



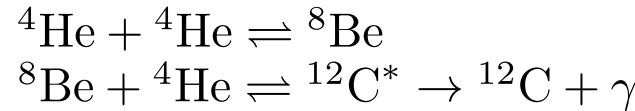
^{12}C level scheme

The Hoyle state in ^{12}C



Astrophysical interest :

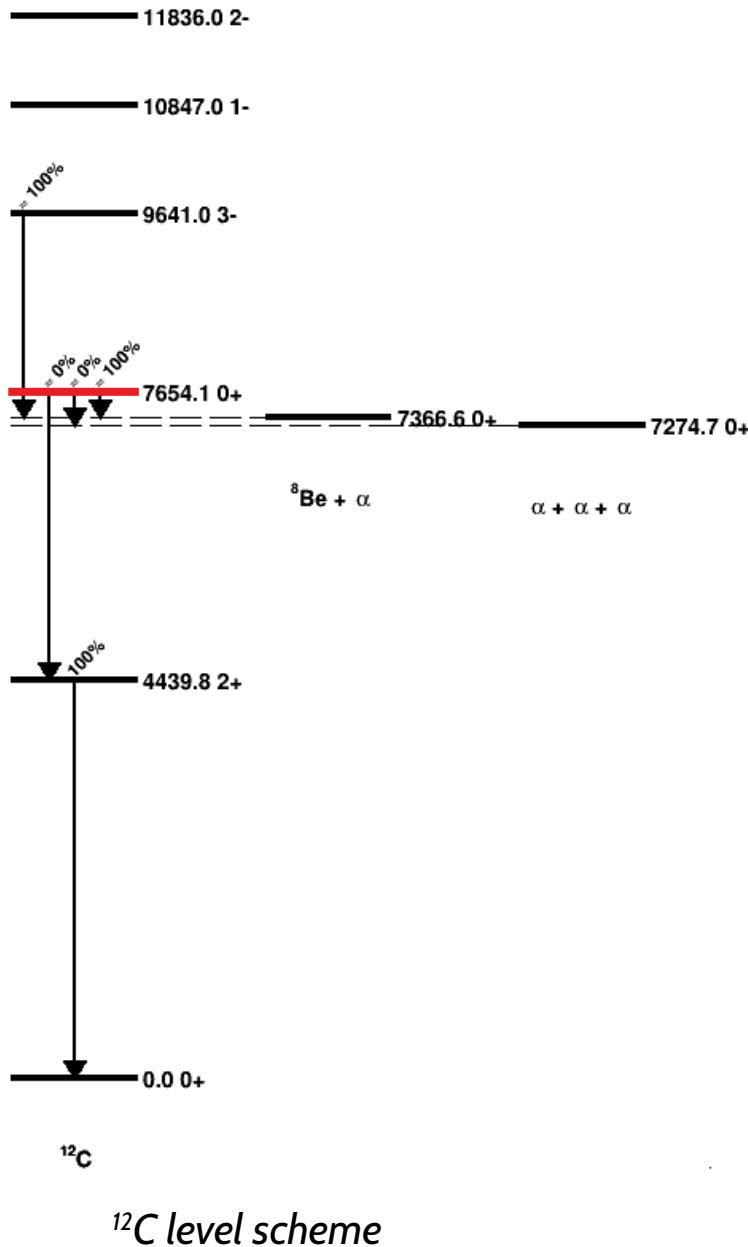
Triple- α process forming stable ^{12}C



The presence of Hoyle state boosts the capture process by $\sim 10^8$, explaining the observed abundance of stable ^{12}C in the universe

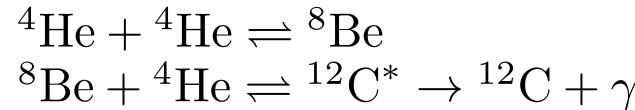
F. Hoyle, *The Astro. J. Supp. Series 1* (1954), 121

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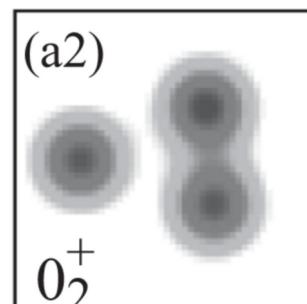


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Nuclear structure interest :

Several models describing a well developed cluster structure : ACM, THSR wave-function, AMD, etc ...



AMD calculated densities for the 2nd 0⁺ state (Hoyle state)

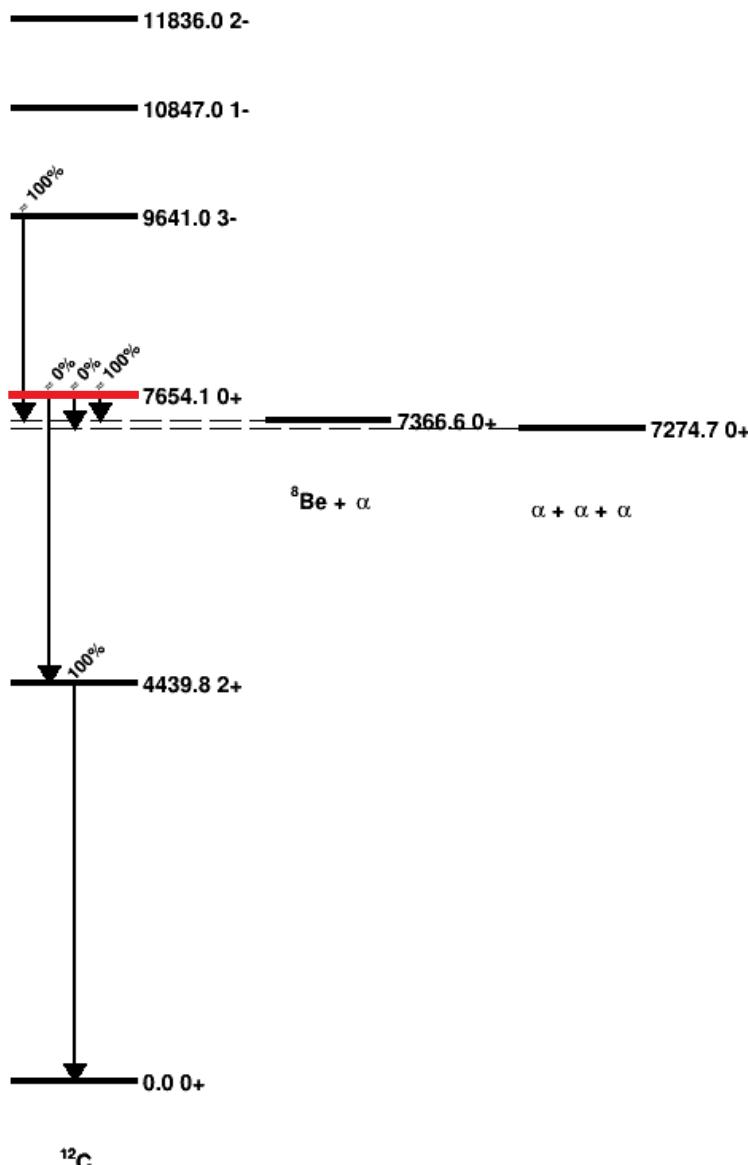
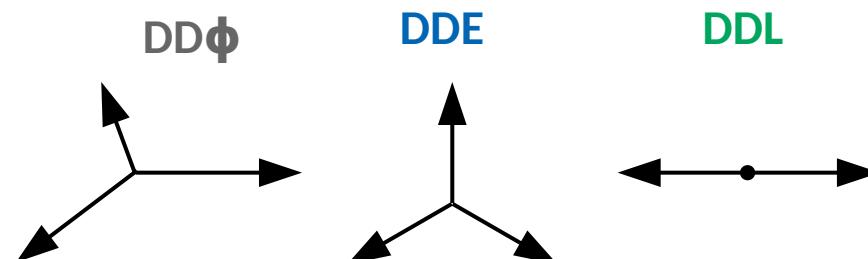
Y. Kanada En'yo, *Progr. Th. Phys.* **142** (2007), 655

Motivations

Decay channels :

Sequential $^{12}C^* \rightarrow ^8Be + \alpha \rightarrow 3\alpha$

Direct $^{12}C^* \rightarrow 3\alpha$



^{12}C level scheme

Motivations

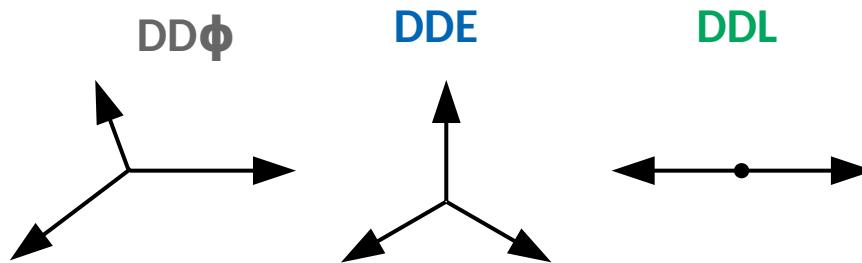
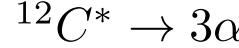


Decay channels :

Sequential



Direct



D. Dell'Aquila :

- Transfert reaction
- Direct decay : <0,043 % (DDΦ)

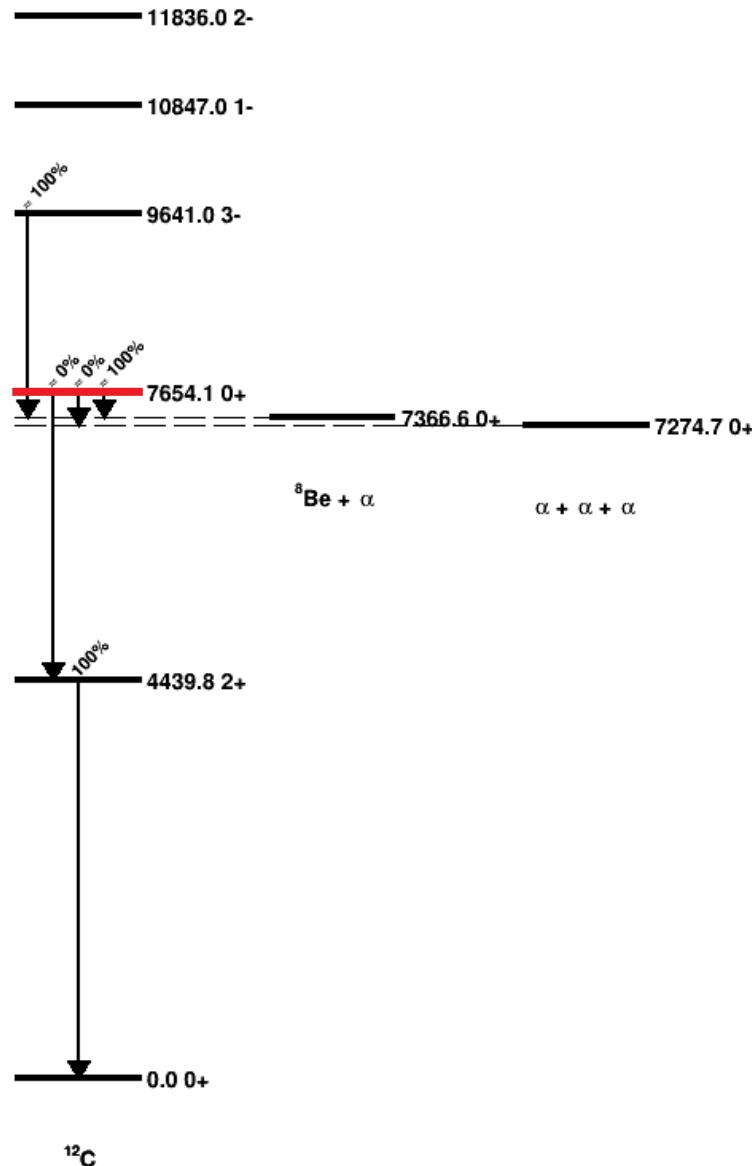
D. Dell'Aquila, PRL, 119 (2017) 132501

Ad. Raduta :

- Fragmentation reaction
- Direct decay : (17±8) % (7,5 % DDE + 9,5 % DDL)

A. Raduta, PLB, 705 (2011) 65–70

Motivations

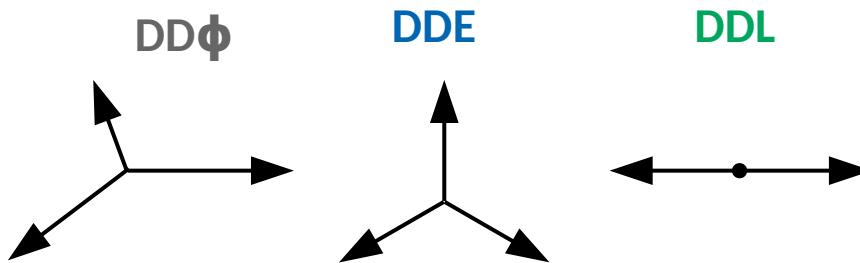
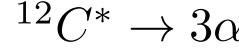


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2 different conclusions

Experimental device

Experiment :

FAZIACOR, Catania (Italy), 2017

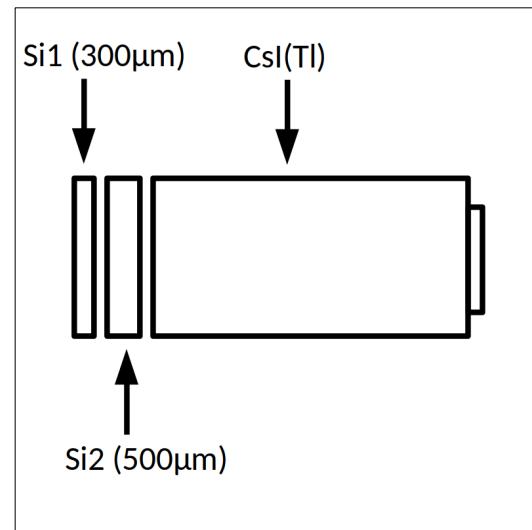
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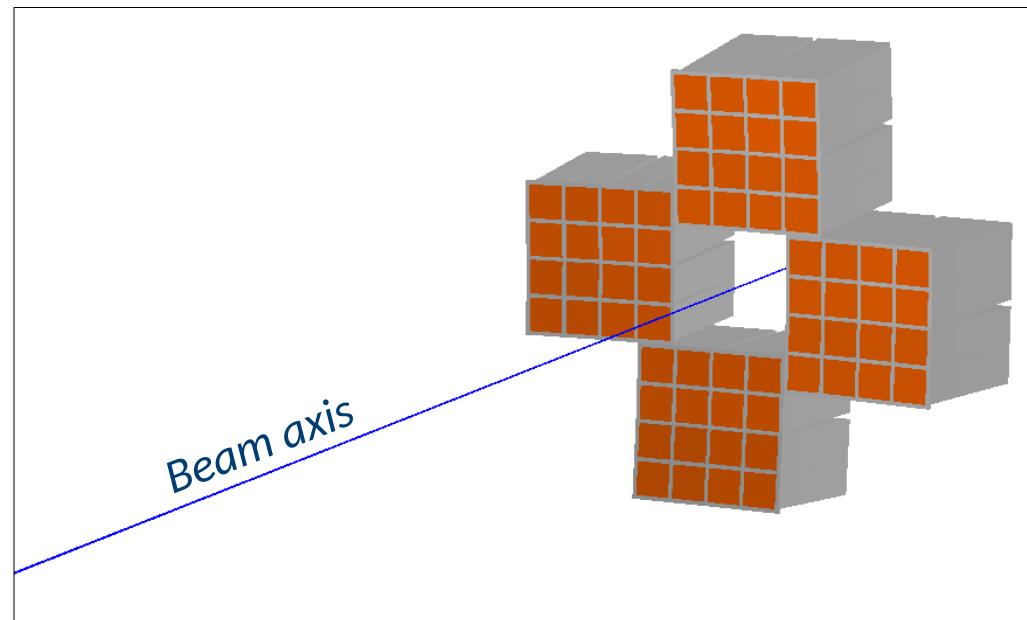
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Device :

- 4 blocks
- 4 quartets/blocks (total 16)
- 4 telescopes/quartet (total 64)
- Angular coverage : $2^\circ - 8^\circ$



Scheme of a FAZIA telescope



Performances :

- Isotopical identification to $Z \sim 25$ with $\Delta E-E$ et PSA methods
- High granularity
- High energy range

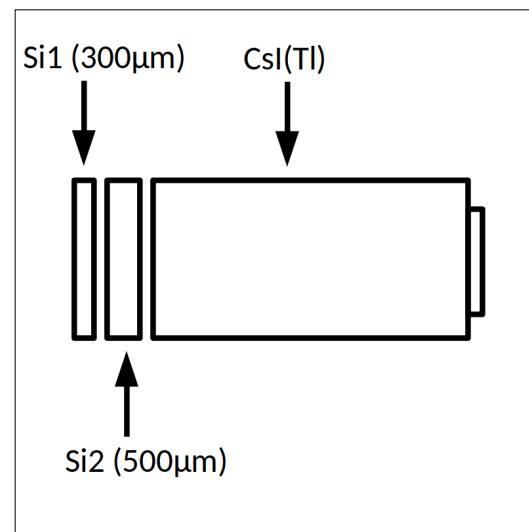
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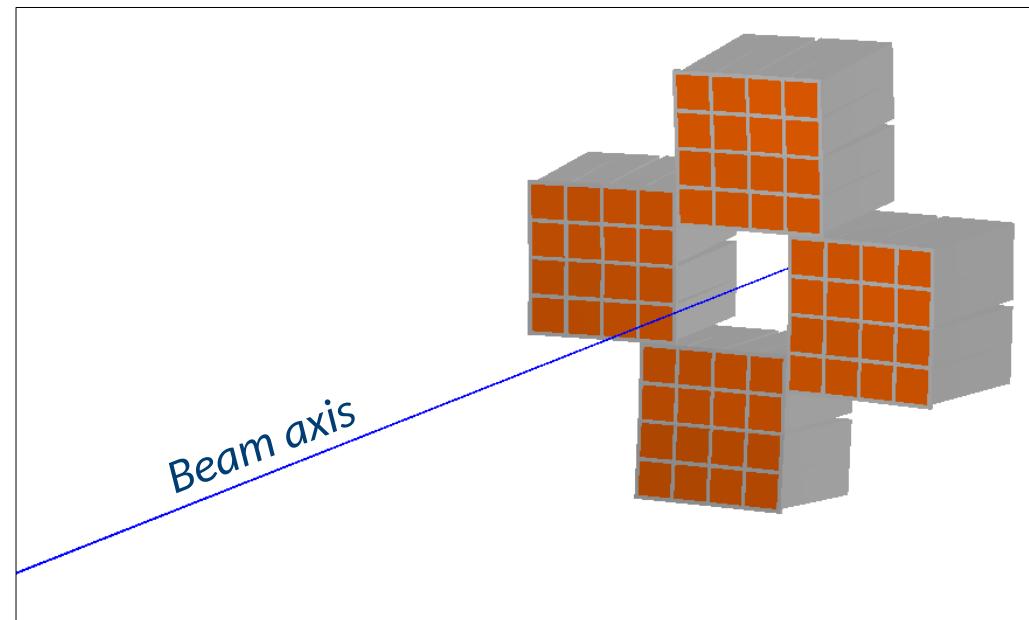
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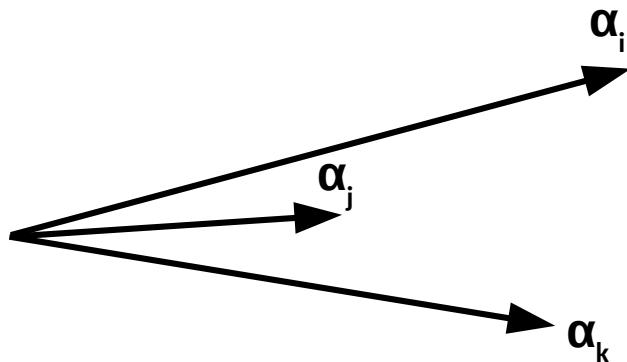
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Available systems :

- $^{32}\text{S} + ^{12}\text{C}$ @ 50 MeV/nucleon
- $^{32}\text{S} + ^{12}\text{C}$ @ 25 MeV/nucleon
- $^{20}\text{Ne} + ^{12}\text{C}$ @ 50 MeV/nucleon
- $^{20}\text{Ne} + ^{12}\text{C}$ @ 25 MeV/nucleon

$^{12}\text{C}^*$ reconstructions

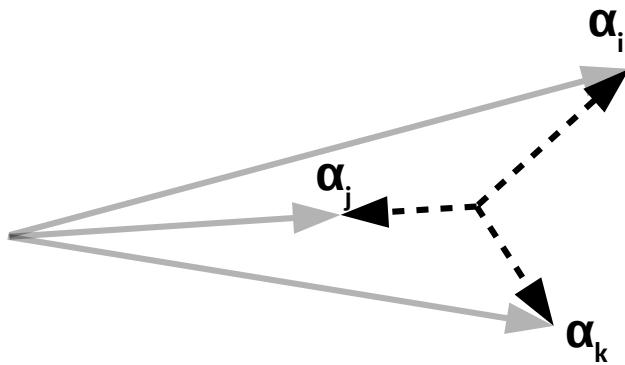
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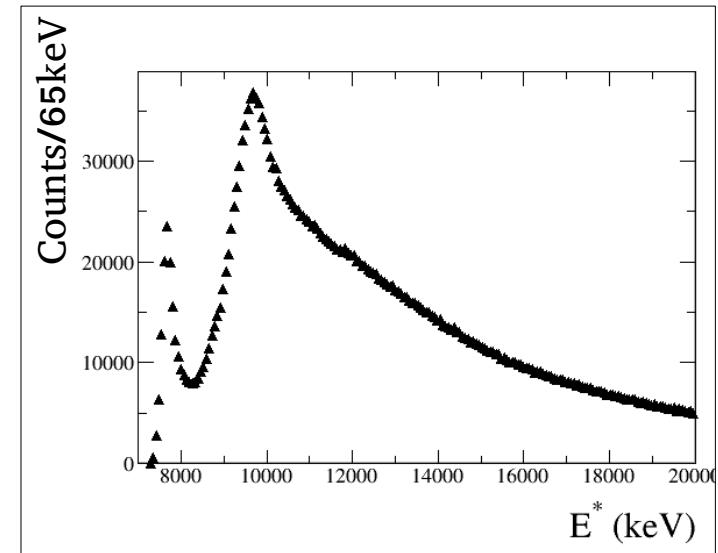
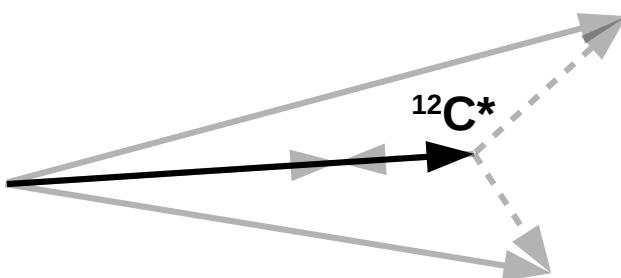
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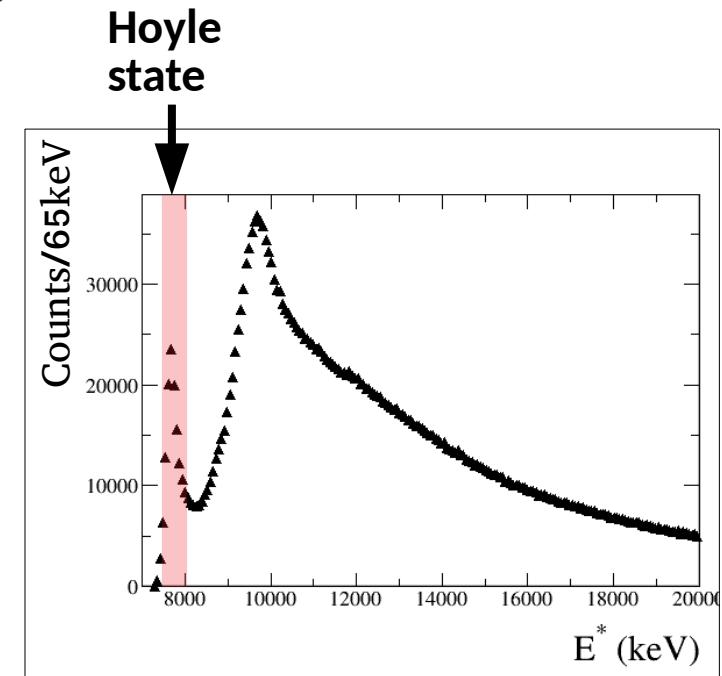
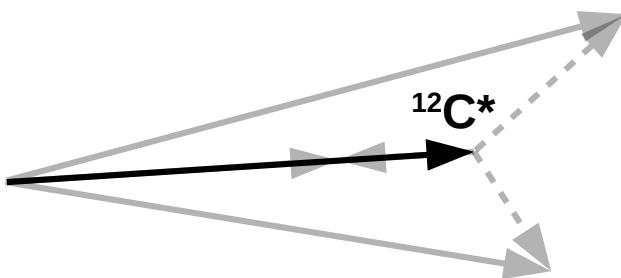


- $^{12}\text{C}^*$'s properties : excitation and kinetic energies
- 2 peaks : 7,65MeV (0⁺ Hoyle state) ; 9,5-10MeV (several excited states leading to a 3- α decay)

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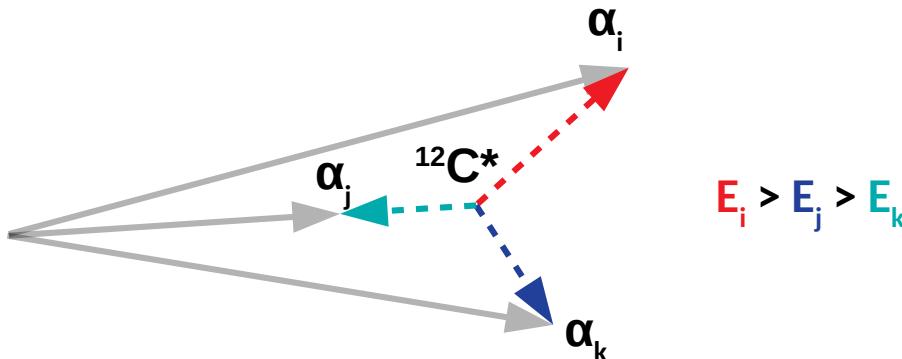


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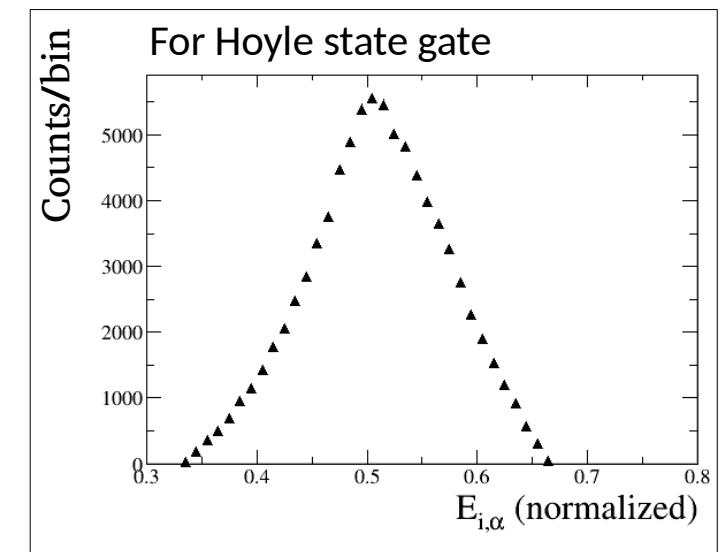
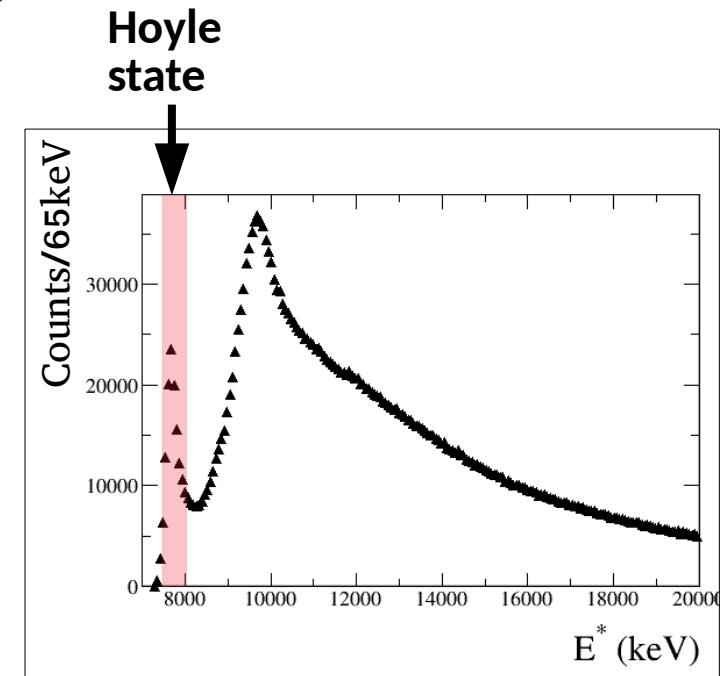
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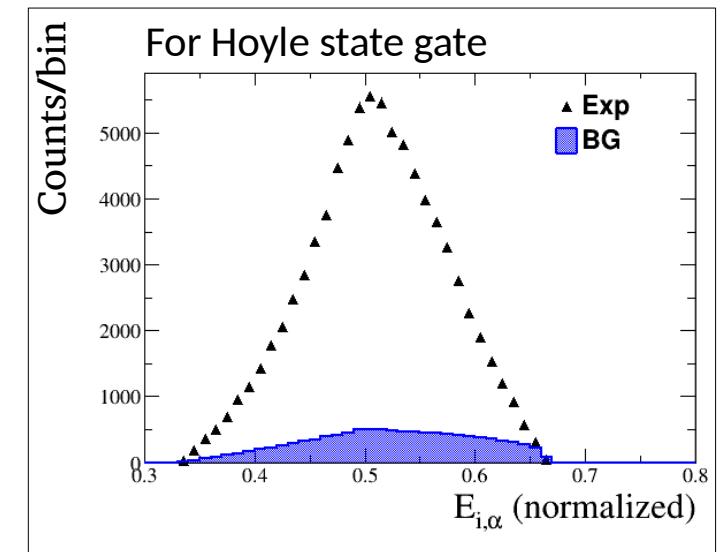
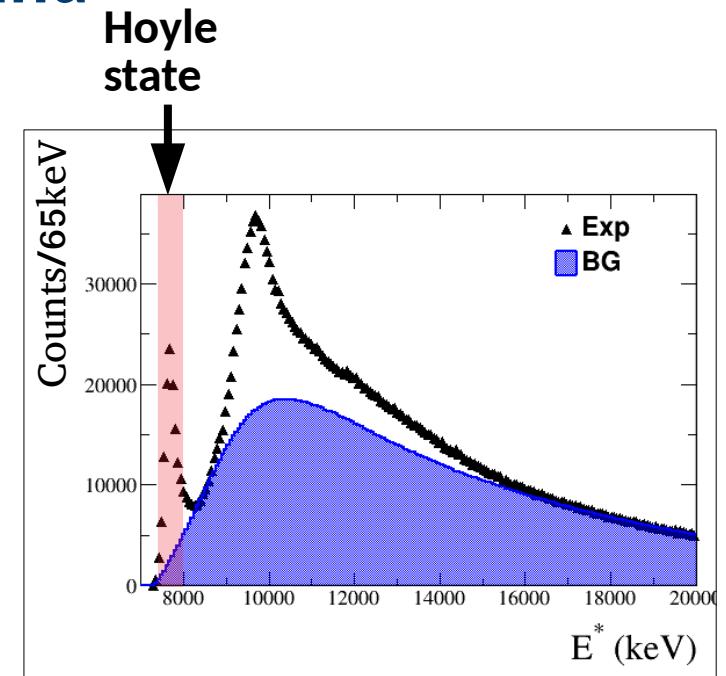
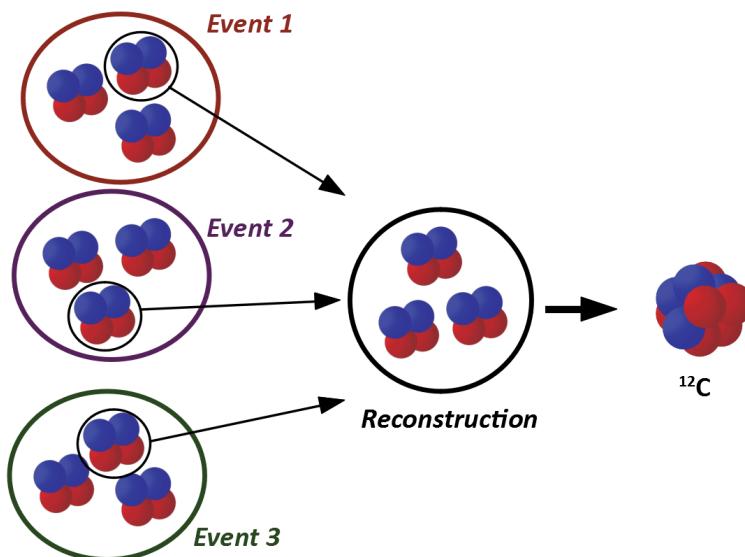
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- Discrimination observable : E_i (highest α energy)



Uncorrelated background

Event mixing background method :

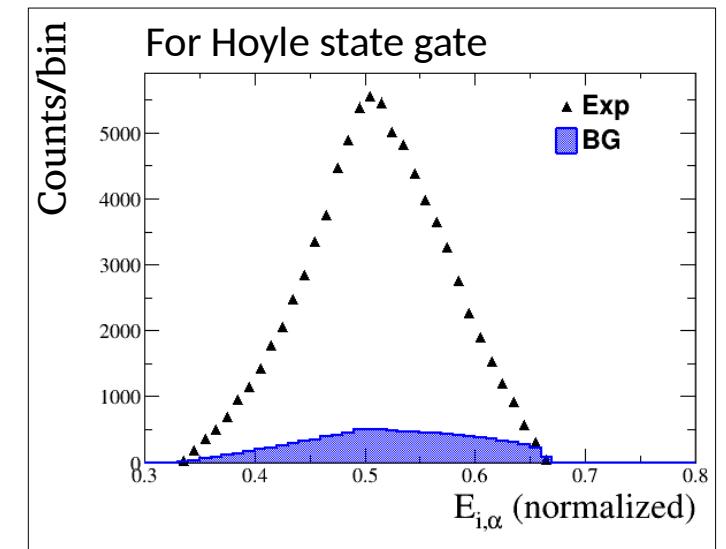
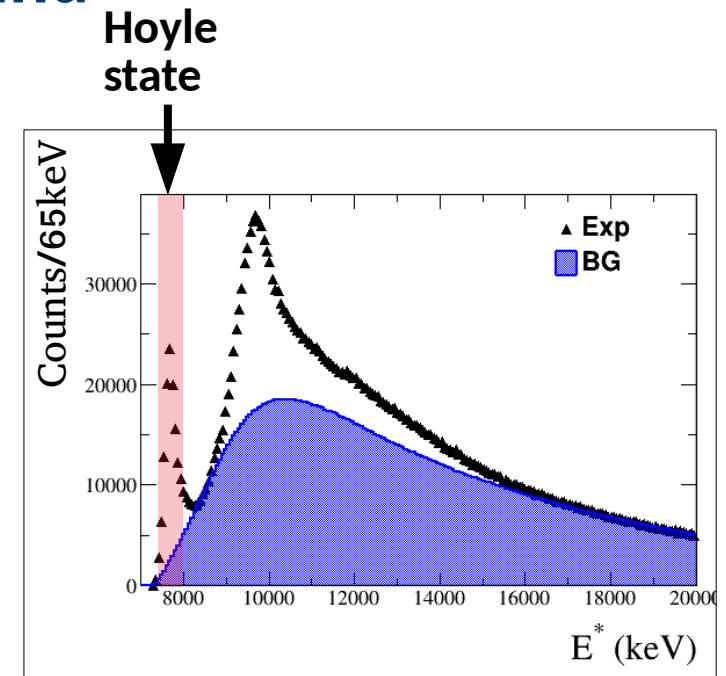
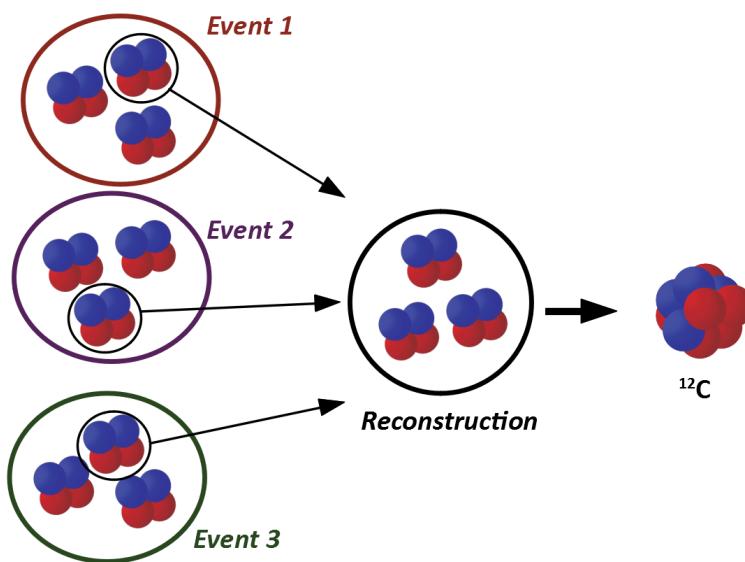
- 3 independant events combinaison
- 3 α particle combinaison (1 from each event)
- Calculation of $^{12}\text{C}^*$'s properties (E^* , E_{kin} , ...)
- Normalization : ratio between integrals on a range without resonances (18-20MeV)



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Possible contamination in the gate from other excited states

Summary of experimental results

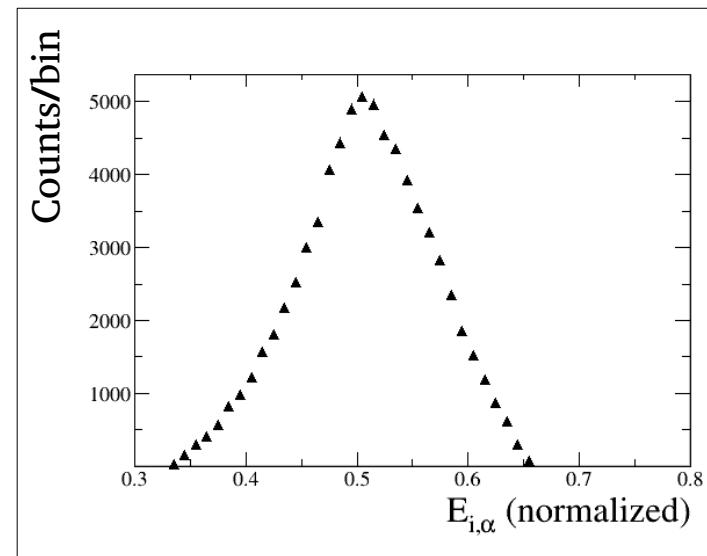
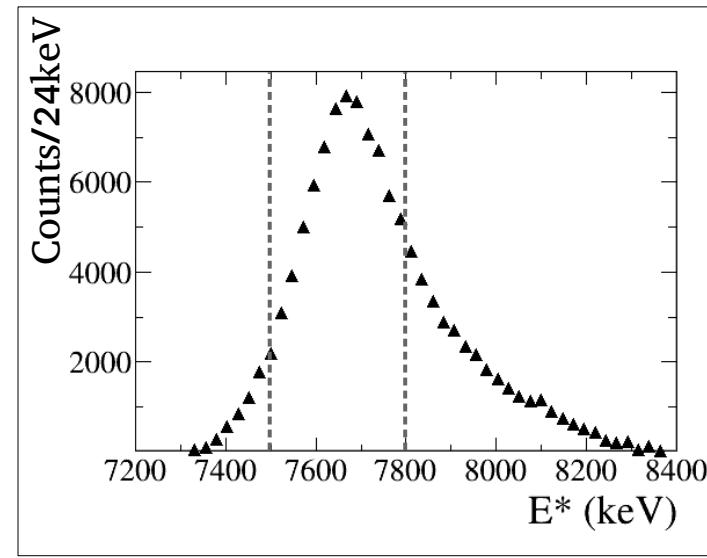
Coincidence reconstructions of $^{12}\text{C}^*$

Event mixing background estimation

Background subtraction

Correlated reconstructions : ~79k in Hoyle gate

Choose of a discrimination observable : E_i



Simulations

Simulated events :

- Kinematic properties of $^{12}\text{C}^*$ similar to the experimental data (E_{kin} , θ) by a weight applied to each simulated event :

$$w(E_{\text{kin}}, \theta) = \frac{Y_{\text{exp}}(E_{\text{kin}}, \theta)}{Y_{\text{sim}}(E_{\text{kin}}, \theta)}$$

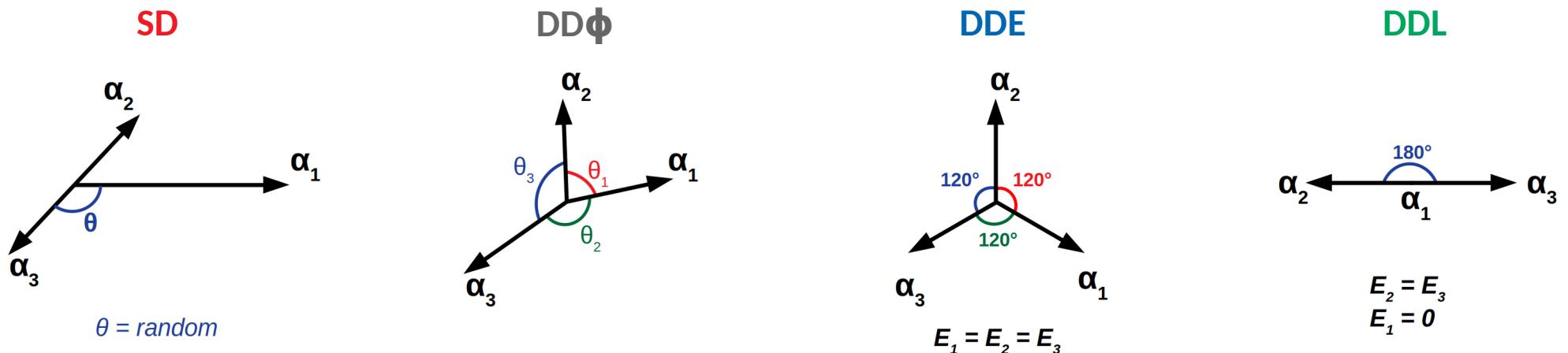
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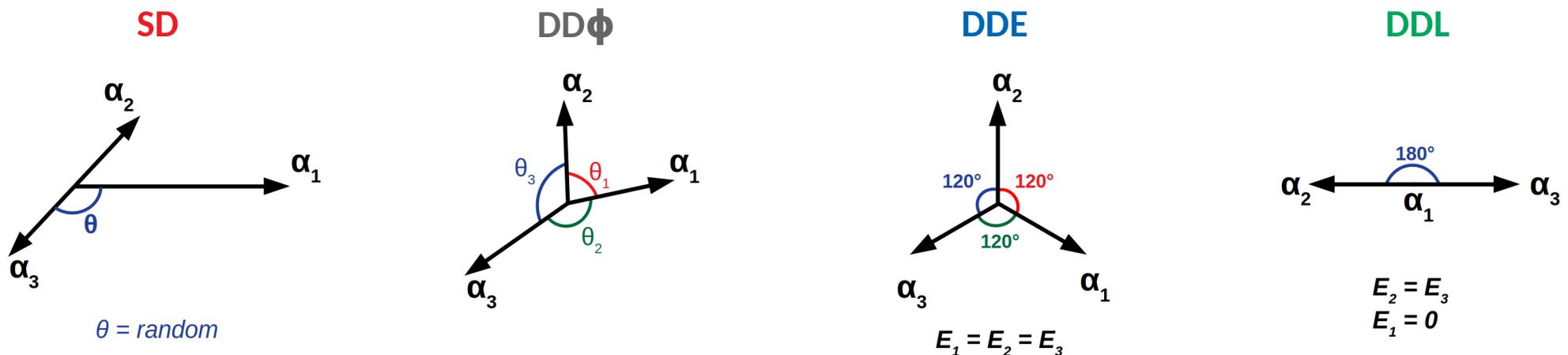
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Angular resolution :

- Experimental filter : detector geometry ; identification thresholds ; pile-up

KaliVeda, <http://indra.in2p3.fr/kaliveda/>

Energy resolution

Fluctuation on energy lost in each detection stage :

- Parametric formula :

$$\Delta E = \text{gaus}(0, \sigma(E))$$
$$\sigma(E) = a\sqrt{E} + b$$

- 5 parameters : a_{Si} ; b_{Si1} ; b_{Si2} ; a_{CsI} ; b_{CsI}

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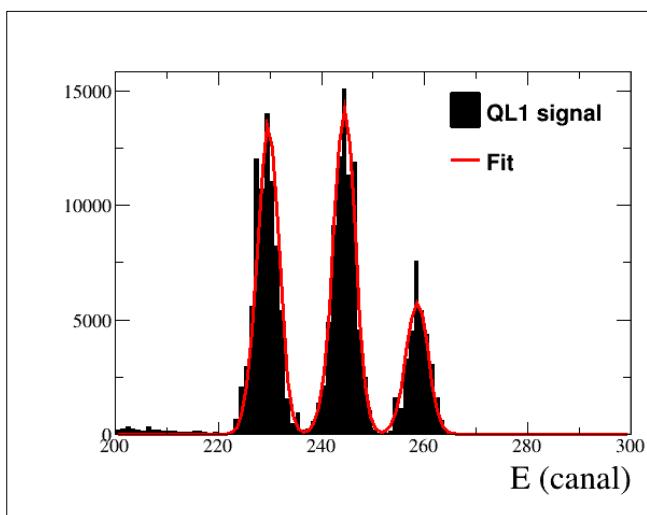
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Optimal parameters :

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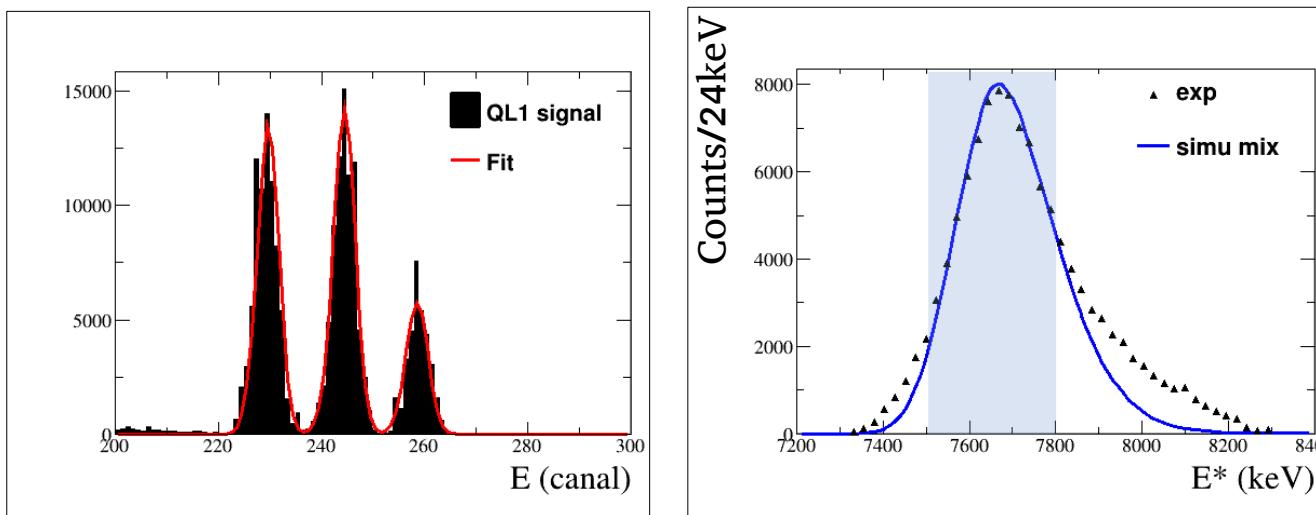
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- $b_{Si1} = 5 \cdot 10^{-2} \text{ MeV}$
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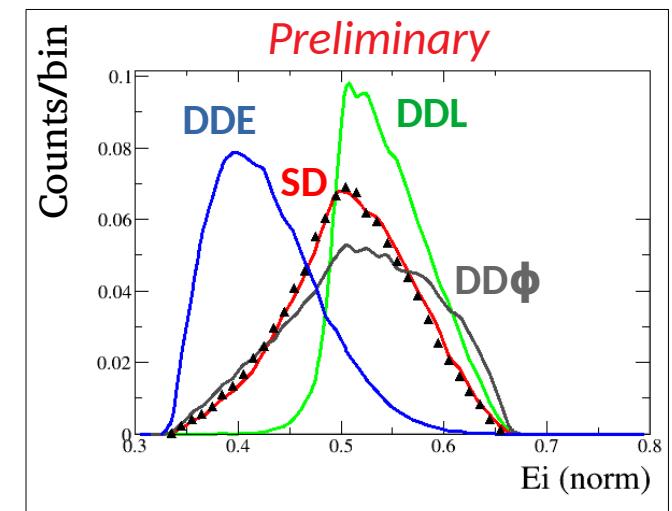
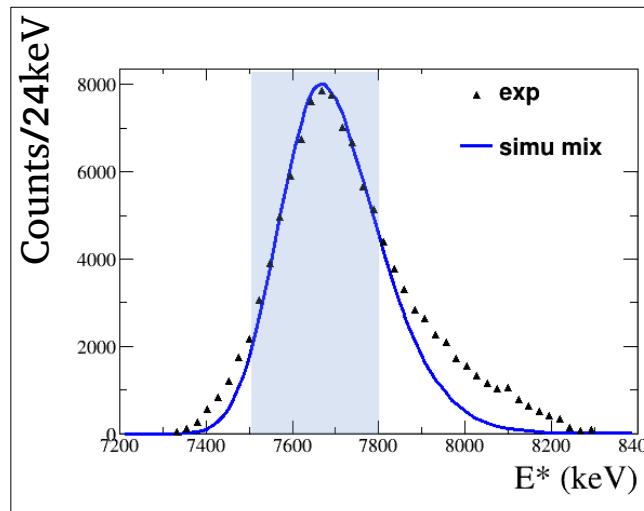
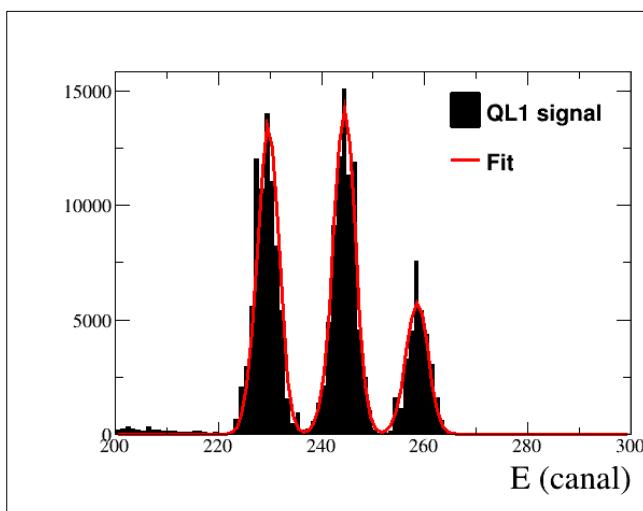
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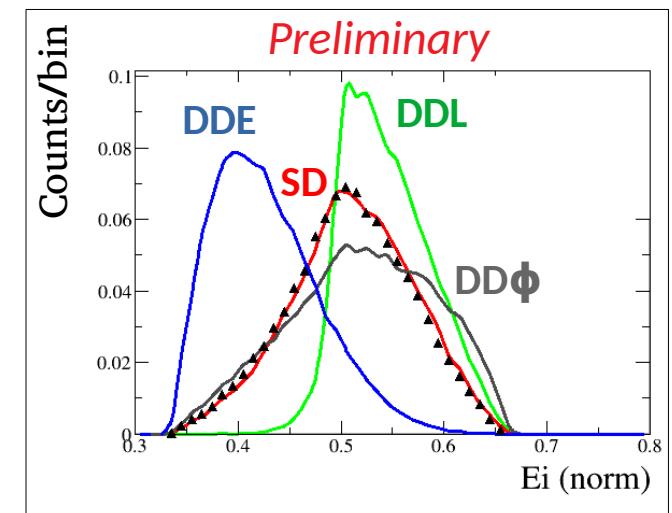
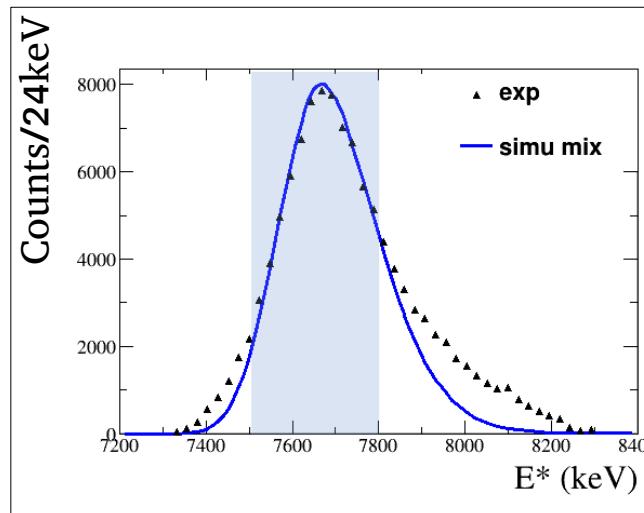
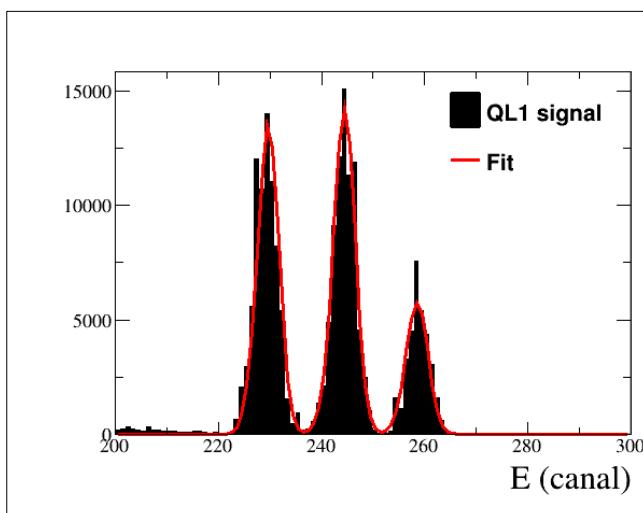
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!\\ Parameters uncertainties not yet evaluated



Branching ratio extraction (E_i fit)

Test distribution :

$$\begin{aligned} Y_{test}(E_i) = & R_{SD} \times Y_{SD}(E_i) \\ & + R_{DD\Phi} \times Y_{DD\Phi}(E_i) \\ & + R_{DDE} \times Y_{DDE}(E_i) \\ & + R_{DDL} \times Y_{DDL}(E_i) \end{aligned}$$

where R_{SD} , $R_{DD\Phi}$, R_{DDE} and R_{DDL} are the fitting parameters

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Fitting procedure :

χ^2 evaluated between test and experimental distributions

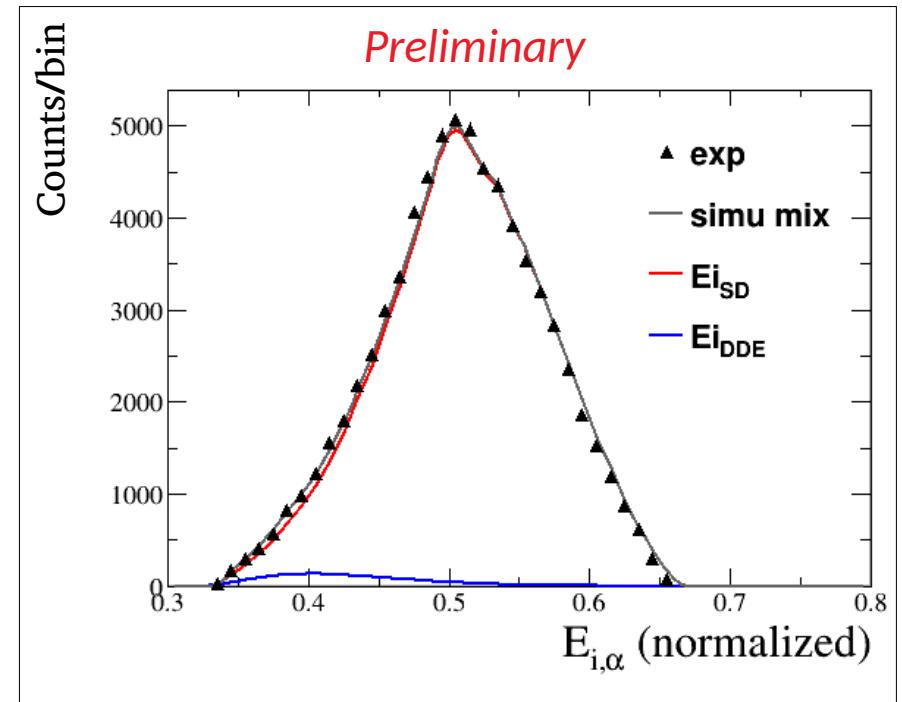
Exploration by « MINUIT » implemented in ROOT software

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Fitting procedure :

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Fit results :

SD : 97,751 % DDE : 2,249 %

DD Φ : 0 % DDL : 0 %

Confidence interval

Uncertainty determination for the R_{DDE} parameter :

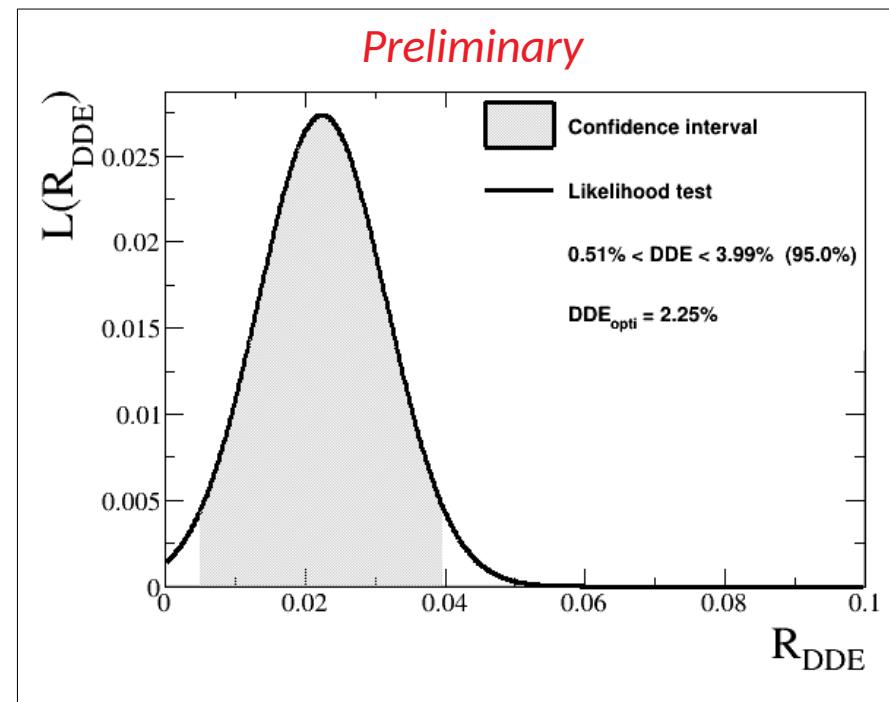
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- For each R_{DDE} value : likelihood probability

$$L(R_{DDE}) = \exp\left(\frac{-\chi^2(R_{DDE})}{N}\right)$$



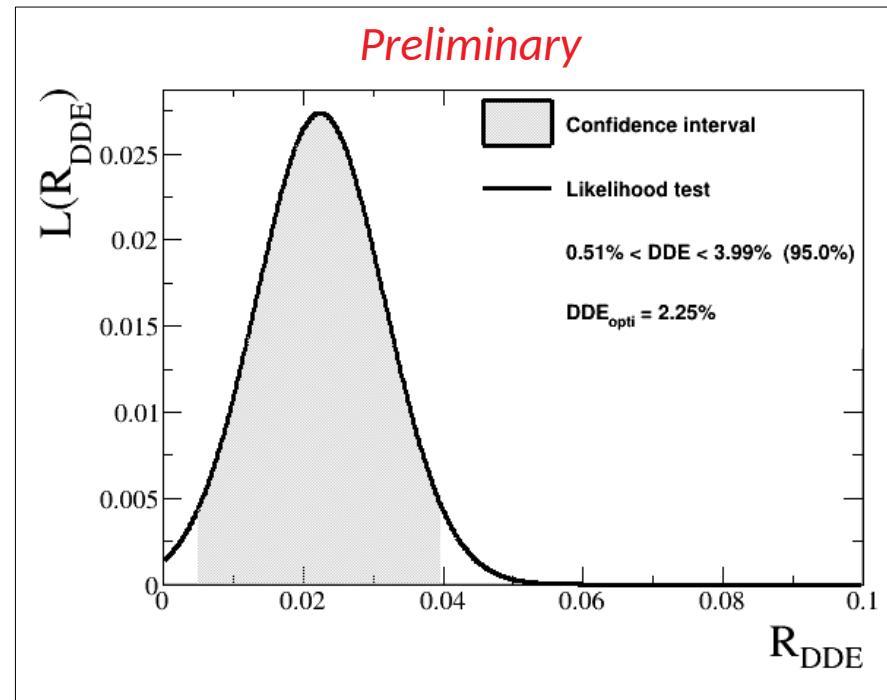
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- Confidence interval definition (95 %)



0,51 % < R_{DDE} < 3,99 % (C.L. 95 %)

Result to improve with the addition of resolution parameters uncertainties

Summary

- **$^{12}\text{C}^*$ reconstructions with $^{20}\text{Ne}+^{12}\text{C}$ data**

Triple- α correlations and $^{12}\text{C}^*$'s properties.

- **Background treatment**

Estimation of uncorrelated reconstructions : event mixing method. Hoyle state's statistics : 94k (16% BG).

- **Simulation of decay modes**

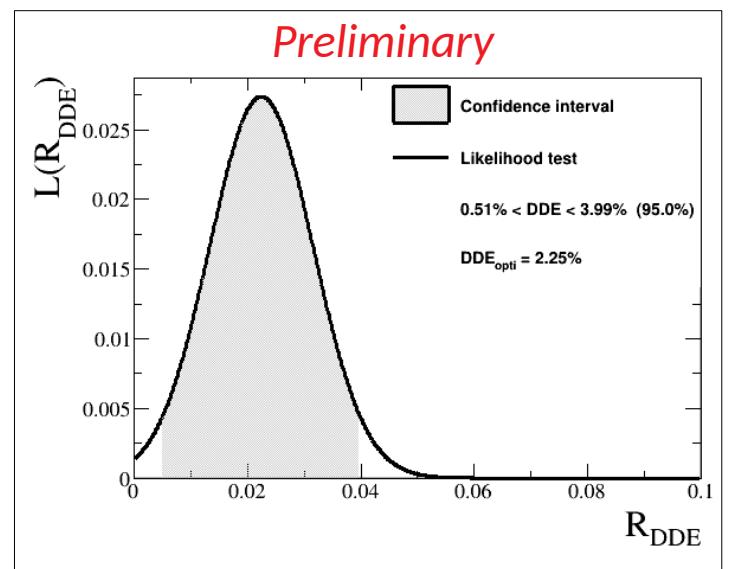
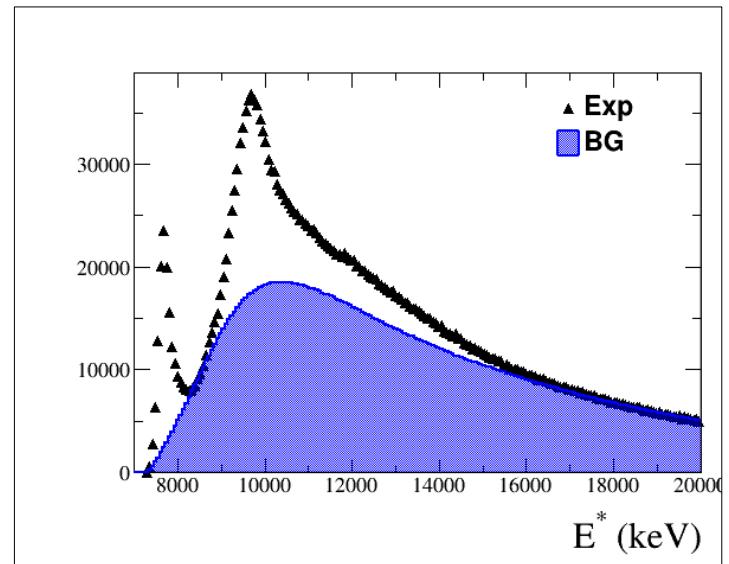
Event generation according to each mode. Add of angular and energy resolutions.

- **Branching ratio extraction**

Limits for the direct decay proportion by a fitting procedure : **0,51% < R_{DDE} < 3,99 %** (95 % C.L.).

- **Perspectives**

Add uncertainties to energy resolution parameters





Thank you

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