Measurement of the Hoyle State Radius using single and double excitation inelastic scattering

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- ***Hoyle state ^{12}C (0_2^+) :***

  Resonant state of ^{12}C at 7.65MeV excitation energy.
  Slightly above the 3α threshold (~ 0.285keV).
  Explains the abundance of ^{12}C by considering
  the 3α process (α + α → ^8Be & ^8Be + α → ^{12}C + ɣ).

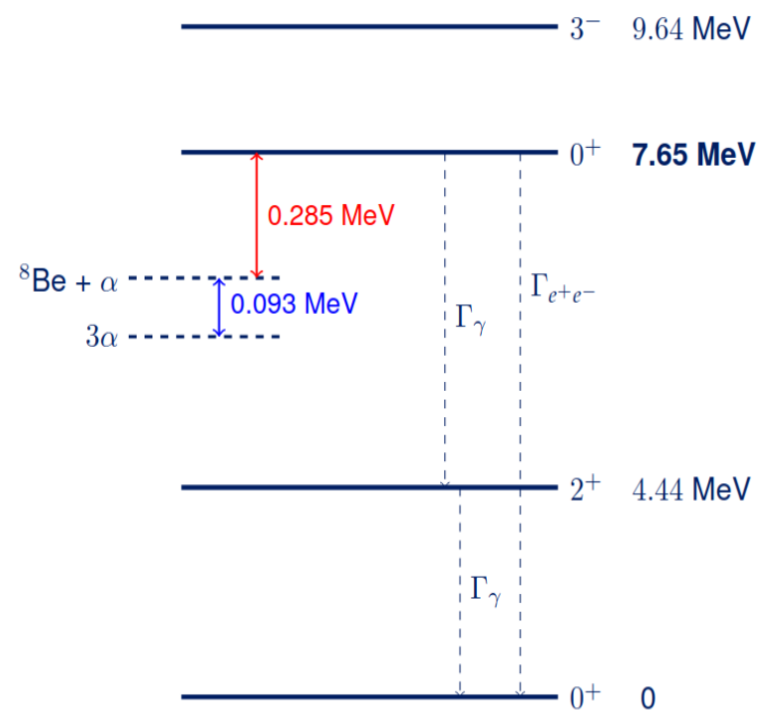
- ***Hoyle state Decay :***

➔Sequential Decay : Multi-step decay process
($^{12}C^*$ → ^8Be + α & ^8Be → α + α).

➔Direct Decay : Directly to 3α bypassing the ^8Be intermediate state ($^{12}C^*$ → α + α + α)

➔ɣ- emission : Transition to 4.44 MeV and then to the ground state.

➔e^+ - e^- production : direct decay to the ground state.



- ***Spatial Configuration :***

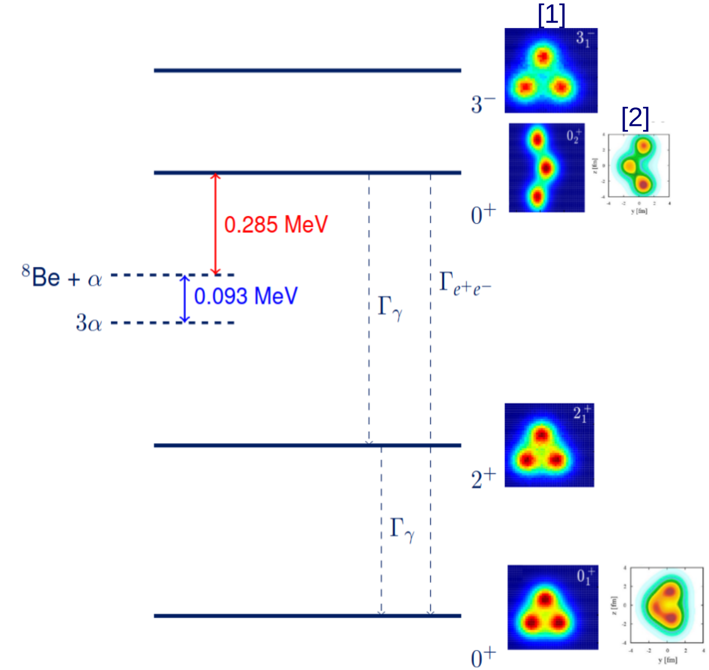
Nuclear Lattice EFT [1]:

- Compact structure for the ground state.
- Obtuse triangle for the Hoyle state.

Monte Carlo SM [2] :

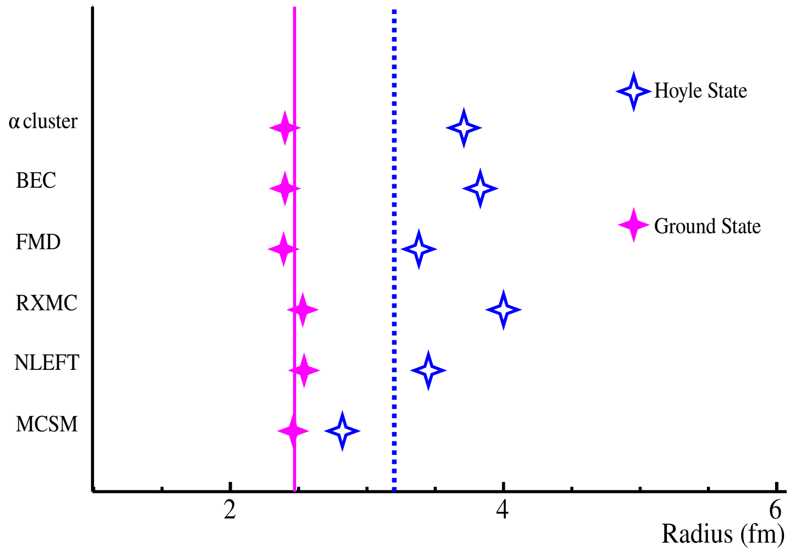
- Superposition of independent particles and α clusters for the ground state.
- Compact 3α structure for the Hoyle state.

➔ No **consensus** on the Hoyle state **spatial configuration**.



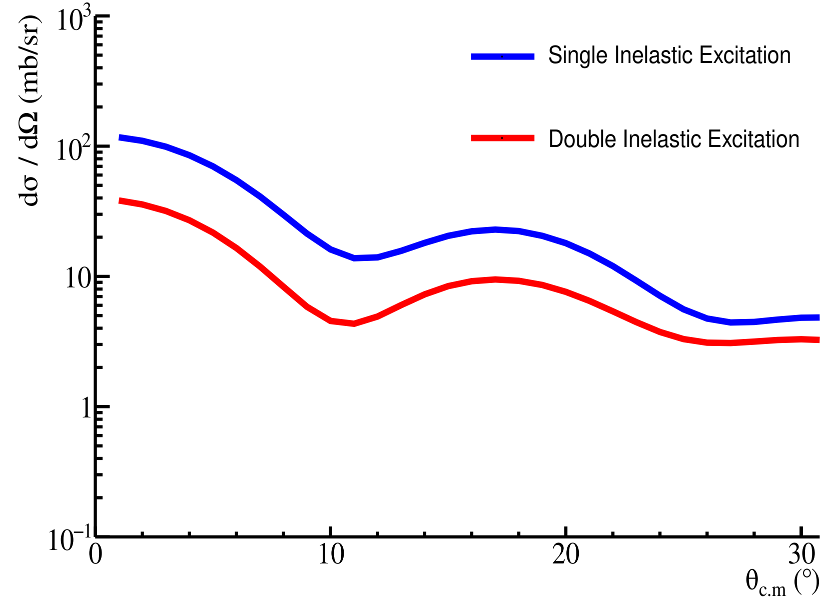
- ***Matter Radius :***

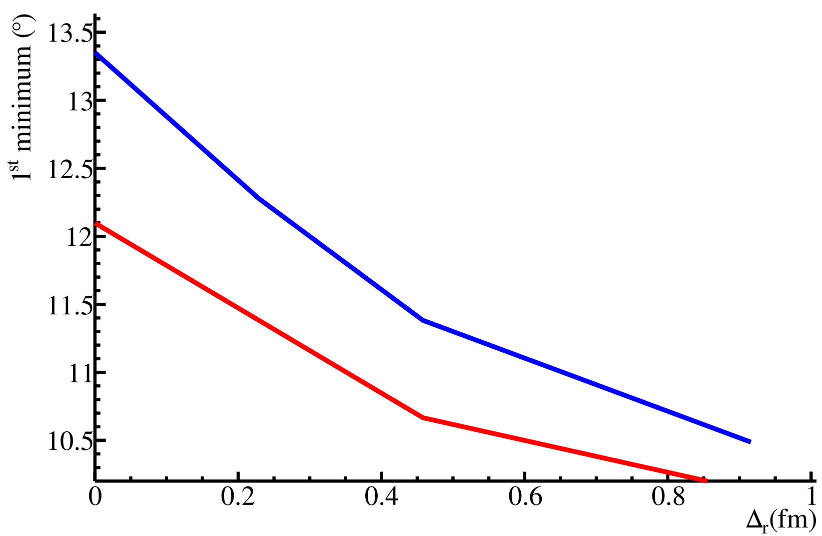
All the theoretical frameworks predict the Hoyle State to be larger than the ground state.
Different models predict different Hoyle state radius values from 2.82 fm to 4 fm.



➔ No **consensus** on the Hoyle state **radius** from the theoretical point view

[1] : S. Shen, Nature Com. 14, 2777
[2] : T. Otsuka et al., Nature Com. 13, 2234





- ***How can we measure the Hoyle state radius ?***

- ***Theoretical Calculations :***

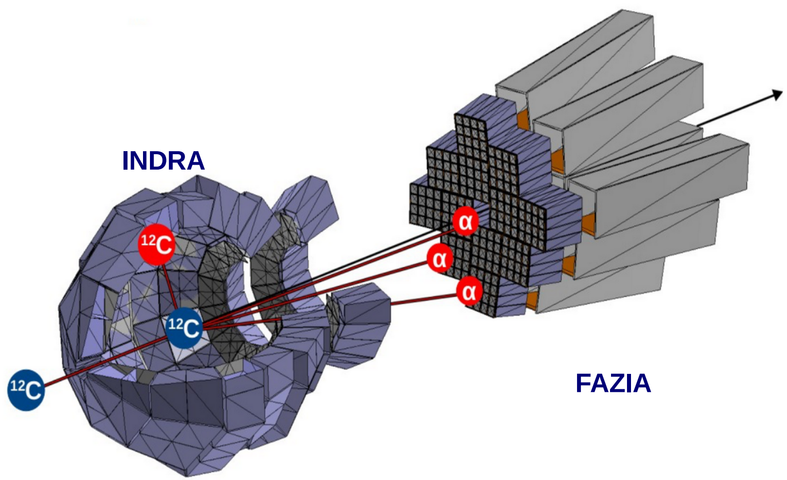
  Coupled channel calculations performed for $^{12}C + ^{12}C$ at 100 MeV.

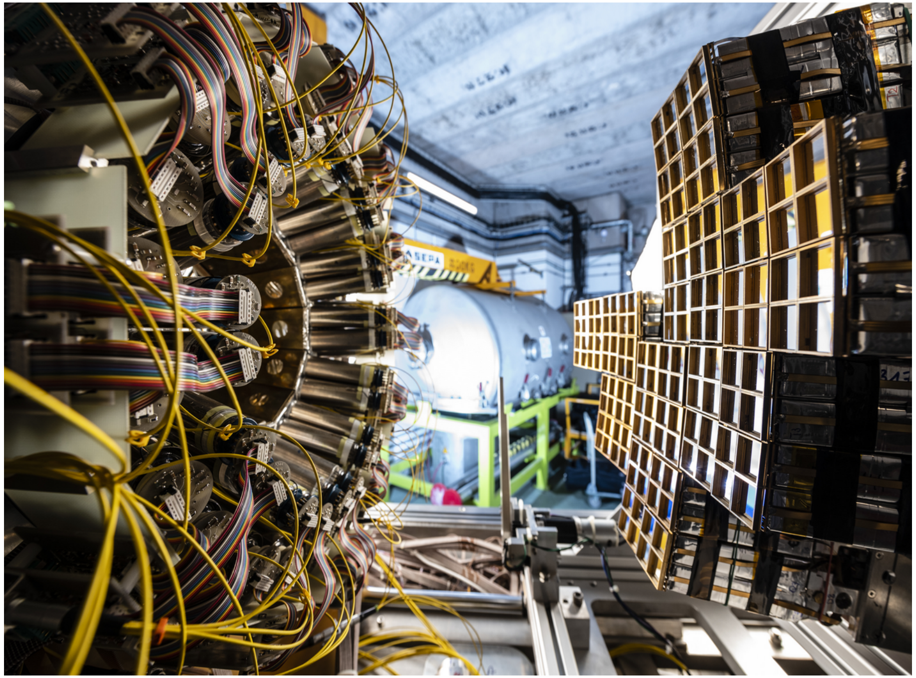
  Single- and Double-excitation inelastic scattering of the Hoyle state computed with CHUCK3 code by varying the difference between the ground and Hoyle states radii Δ_r = 0 - 0,92fm.

- ***Observable sensitivity to the Hoyle state radius :***

  The position of the first and second minima decreases with Δr increasing.

→ **Single- and Double- excitation inelastic cross sections** show a **sensitivity** to the Hoyle state radius.





➢ <u>***How can we measure these cross sections ?***</u>

- ***Experimental Framework :***
  A ^{12}C target was irradiated with a ^{12}C beam at an energy of 8.81 MeV/A at GANIL in April 2025.
  The diffused ^{12}C or three α particles resulting from the decay of the projectile-like are detected using the FAZIA detector placed at 2° to 13.6°.

  - <u>Procces 1</u> : ^{12}C is diffused without decaying into 3α.
  - <u>Process 2 :</u> $^{12*}C$ decays into 3α.

- ***FAZIA :***
  12 blocks consisting of 16 three stages telescopes (2x2 cm²)
  - Si1 (300 µm), Si2 (500 µm) and CsI (10 cm)

  Allows for the use of multiple identification methods :
  - PSA (Pulse Shape Analysis)
  - ΔE – E method

- ***Pulse Shape Analysis:***

Ions with different charge or mass exhibit different energy loss profiles.

Use the shape of the signal collected to identify charge Z and mass A.

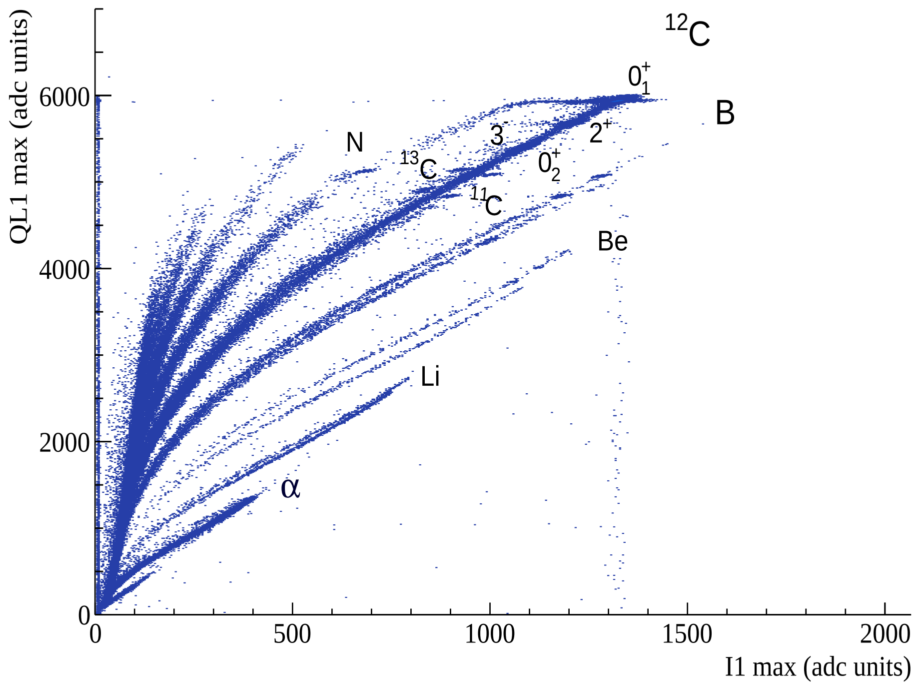
- ***Particles stopped in Si1 :***

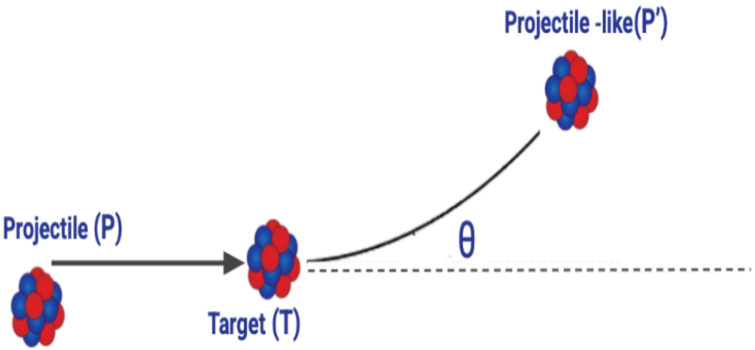
PSA : Correlation of the total collected charge (QL1 max proportional to the deposited energy) to the maximum current (Imax).

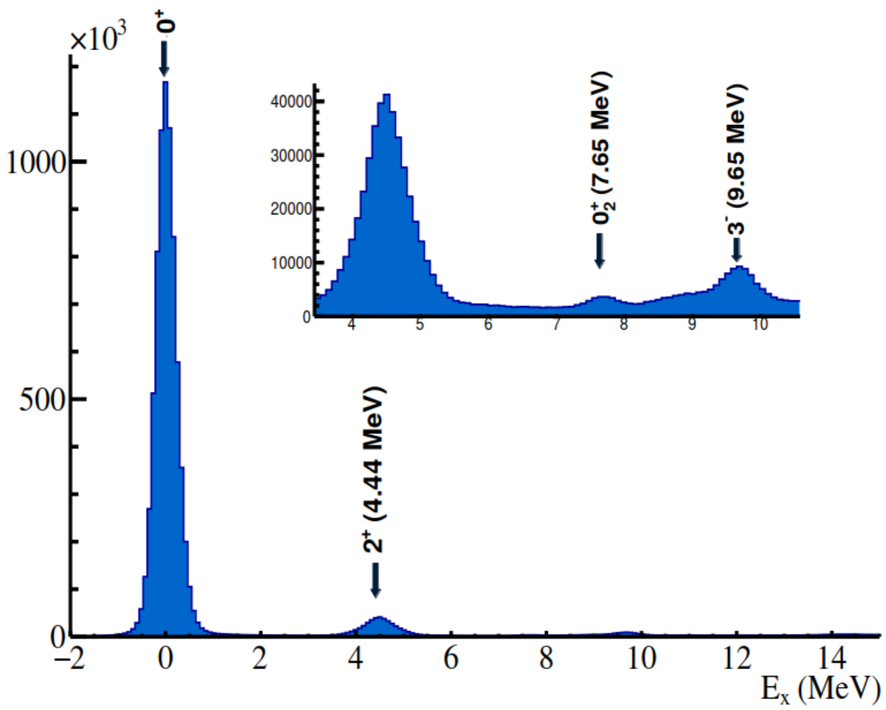
Each line corresponds to the different particles charge and mass.

- Charge identification up to Z ~ 9.
- Isotopic Identification up to Z ~ 6.

On the line corresponding to ^{12}C : We can also spot the elastic peak + some excited states (2^+, 0_2^+ , 3^-).







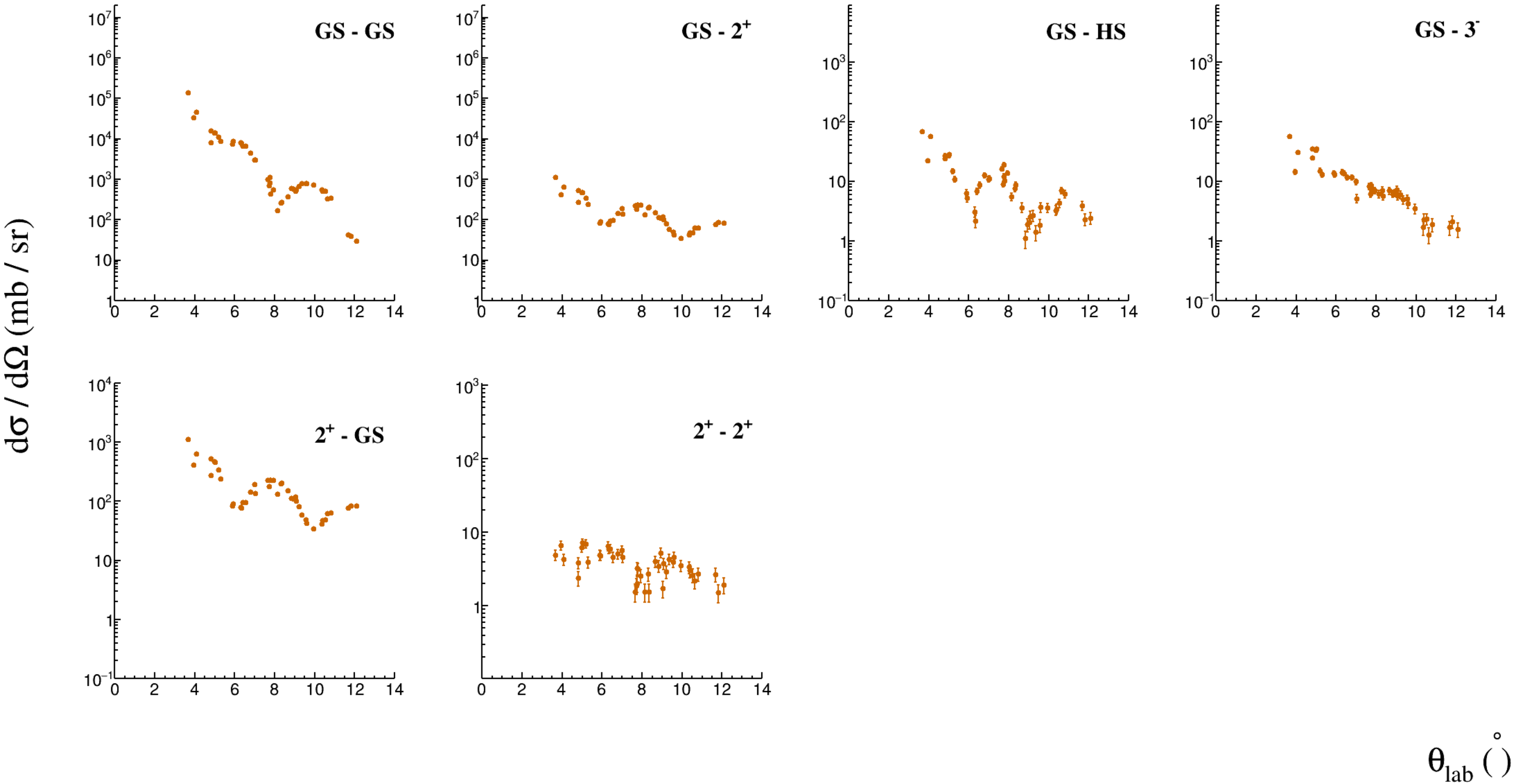
- ***Direct missing mass :***

  Non decaying projectile-like ^{12}C are directly detected in the first stage Si1.

  Using 2-body kinematics, we reconstruct the dissipated energy.

- Probe projectile-like excited states **below** the particle emission threshold.

- Cross sections of multiple inelastic channels are extracted and evaluated to compare with theoretical models.



GS - GS
GS - 2$^+$
GS - HS
GS - 3$^-$
2$^+$ - GS
2$^+$ - 2$^+$
dσ / dΩ (mb / sr)
θ_{lab} (°)

➢ ***What if the projectile-like decays ?***

- ***Invariant mass :***

Employ the invariant mass method on the detected 3α to extract the projectile-like propreties.

➔ **Projectile-like** excitation energy can be extracted.

- ***Indirect missing mass :***

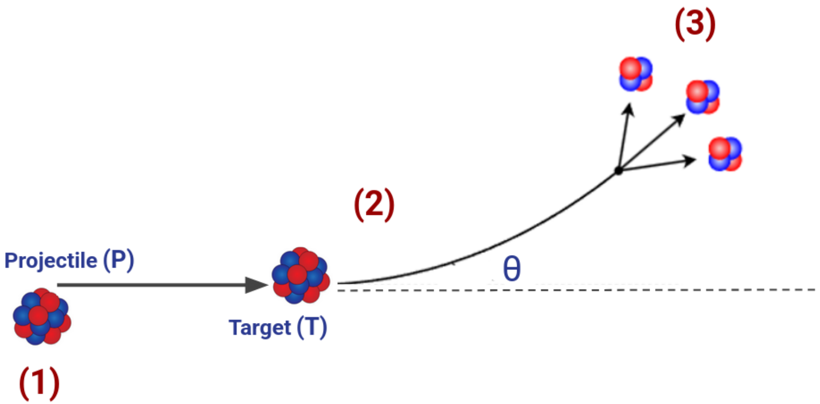
Apply the missing mass technique on the reconstructed $^{12}C^*$ to determine the excitation energy of the target-like.

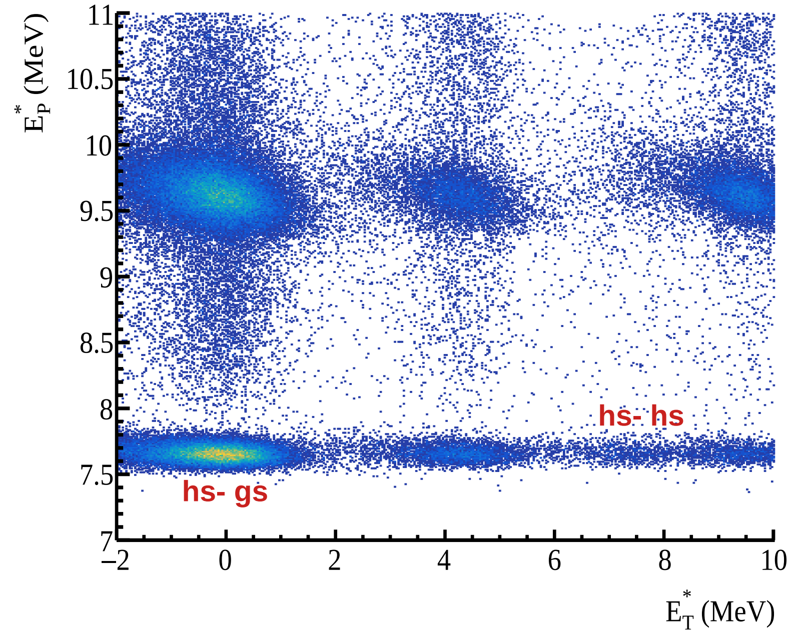
➔ **Target-like** excitation energy can be extracted.

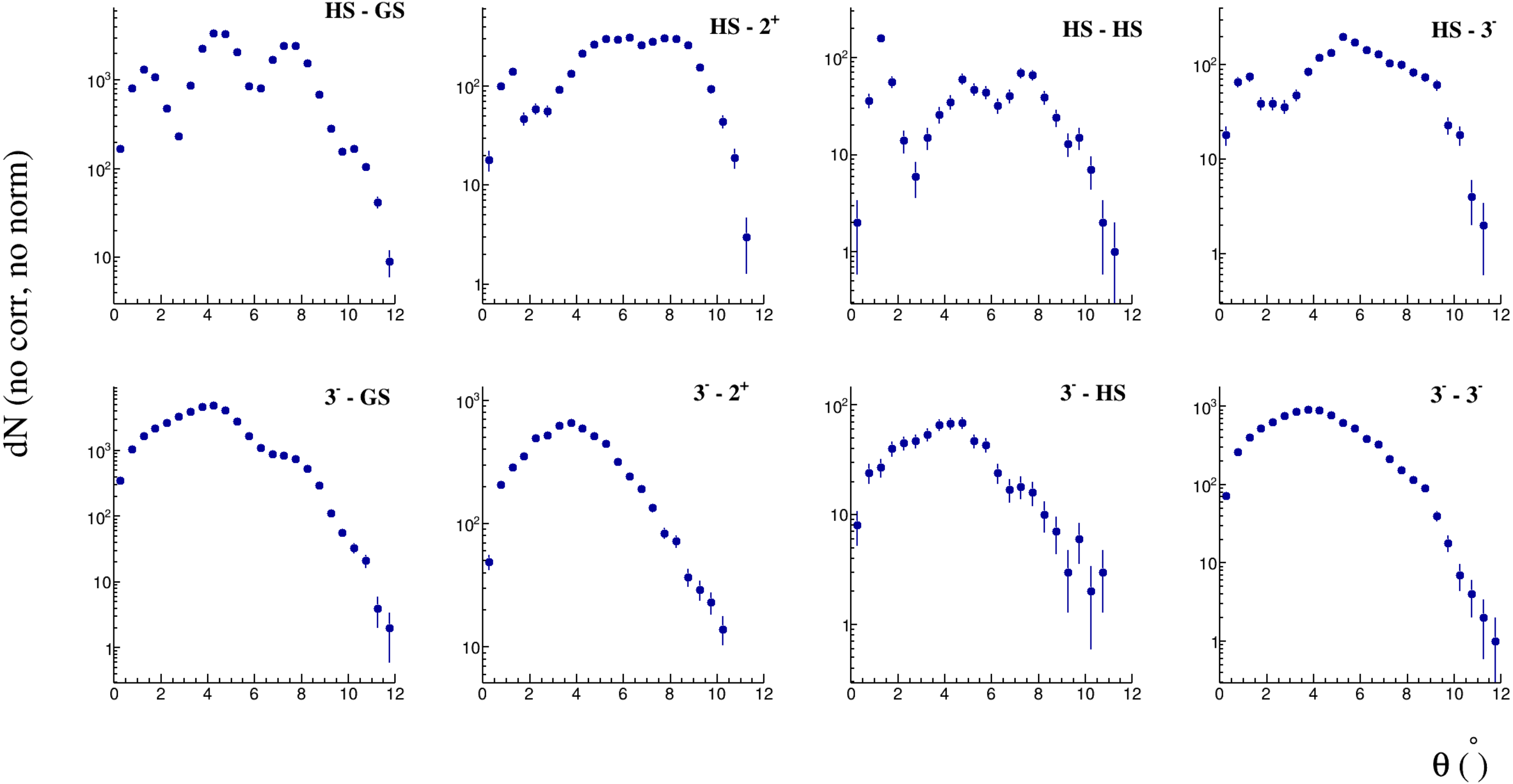
- ***Projectile-Target Channels :***

Multiple channels such as the HS - GS ,
HS – HS, 3^- - GS, 3^- - GS …,

➔ Extract the angular distribution corresponding to each (Projectile-like – Target-like) reaction channel.







dN (no corr, no norm)
HS - GS
HS - 2+
HS - HS
HS - 3-
3- - GS
3- - 2+
3- - HS
3- - 3-
θ (°)

- ***Experimental Output :***

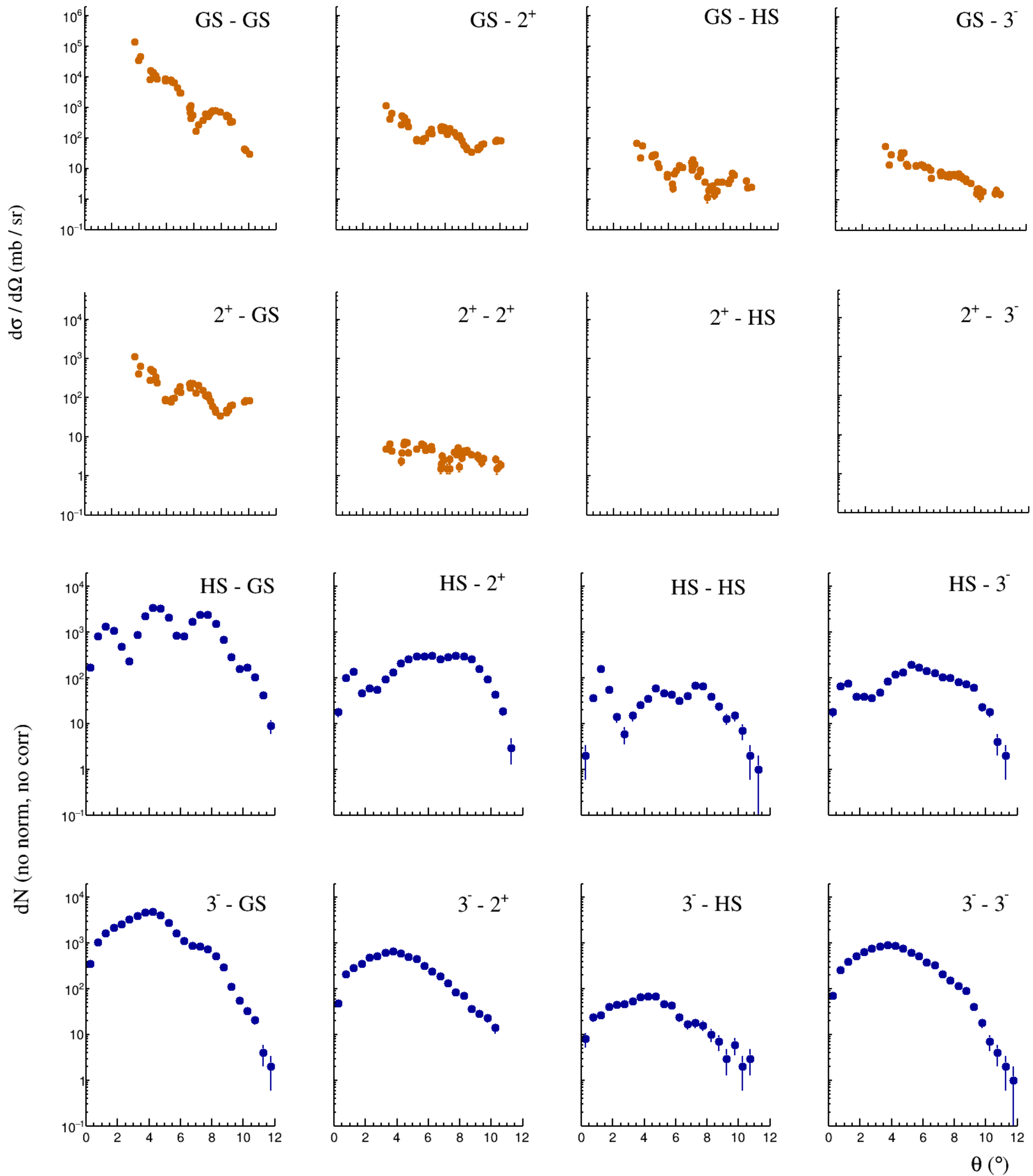
➔ Angular distribution for (almost) all combination of projectile and target excitation.

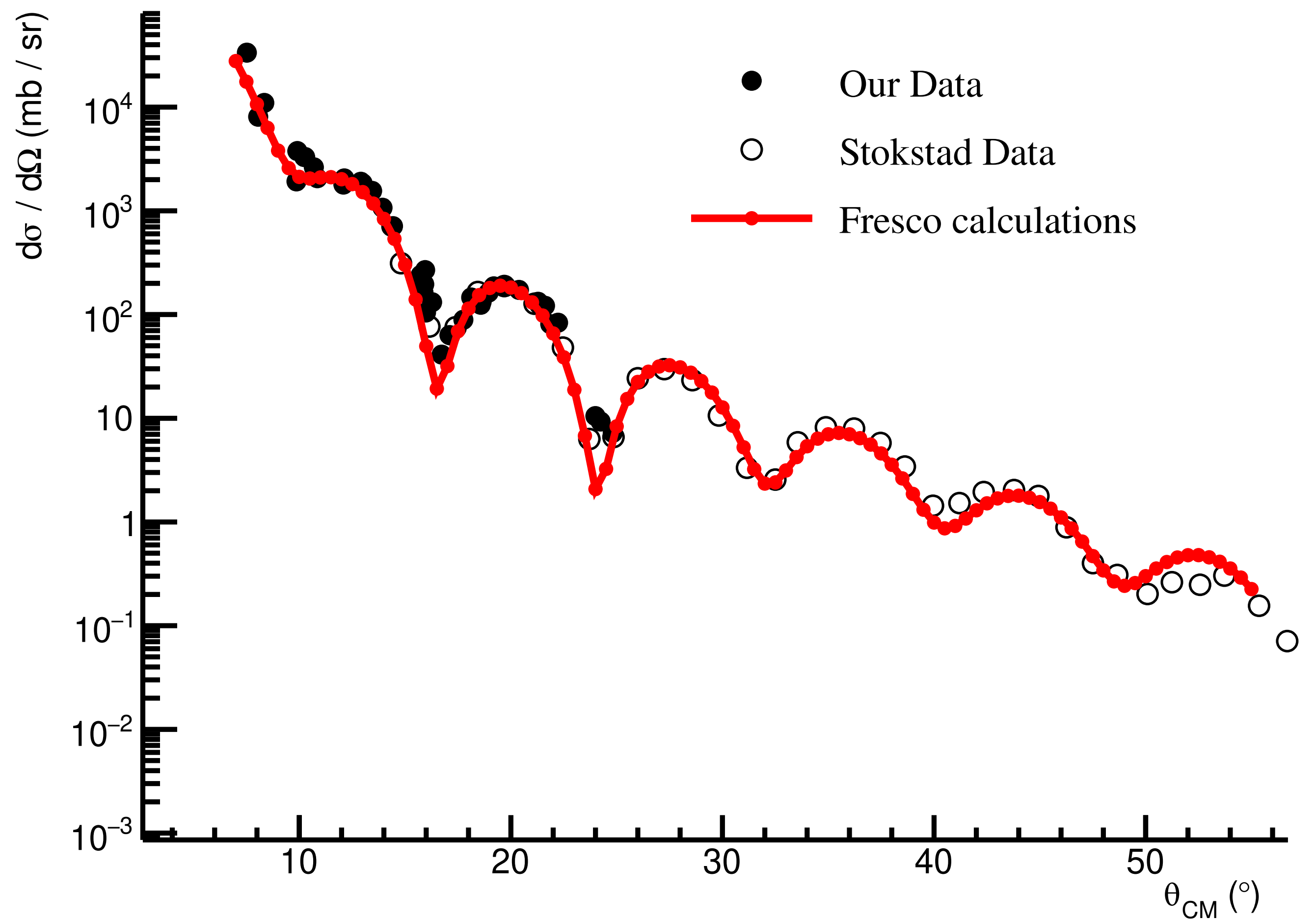
➔ ***2- - HS,*** *and* ***2- -*** 3^- angular distributions can be obtained soon.

- ***Next steps :***

➔ Efficiency correction and normalization for the indirect missing mass channels (blue).

➔ Theoretical calculations can be conducted using these angular ditributions as an input.





dσ / dΩ (mb / sr)
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10
20
30
40
50
θCM (°)
Our Data
Stokstad Data
Fresco calculations