laboratoire commun CEA/DRF CNRS/IN2P3

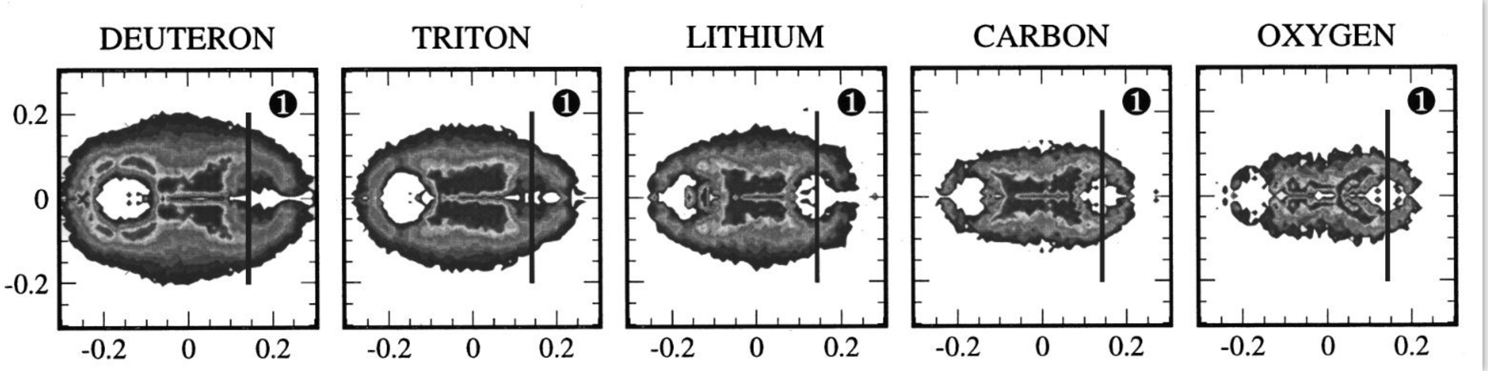
Tom GÉNARD

Supervised by Abdelouahad CHBIHI
INDRA-FAZIA Collaboration

DYNAMICS OF CLUSTER PRODUCTION IN HEAVY ION COLLISIONS

Cluster production in the mid-velocity region

Collisions of heavy ions at intermediate energy cannot be completely described using statistical fragmentation
→ Especially the large quantity of light nuclei (deutons, tritons, helium-3) produced in the mid-velocity region



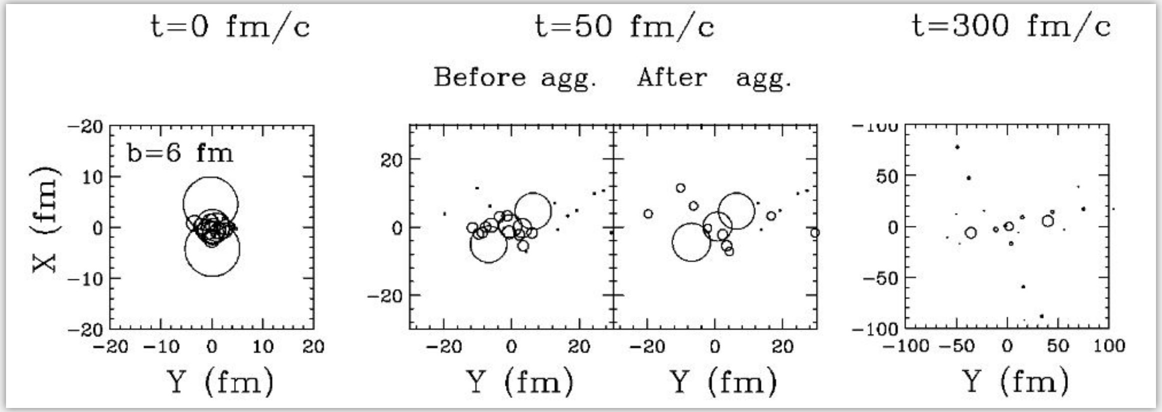
J. Łukasik, Phys. Rev. C 55, 1906 (1997)

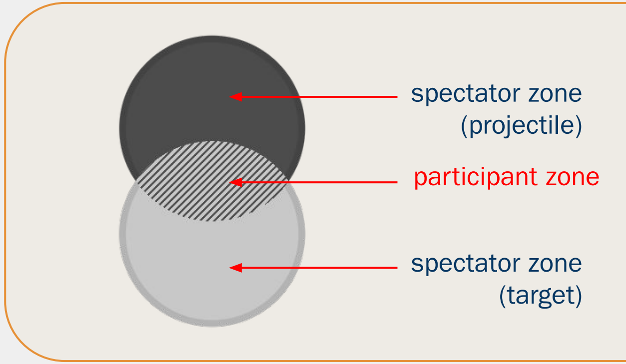
The introduction of dynamically formed **clusters** has improved the reproduction capabilities of various models. The formation process of these clusters is closely linked to the equation of state of nuclear matter

→ An experimental study of the characteristics of these nuclei will probe the effects of the EoS in a hot, compressed, dynamical nuclear medium

→ Participant-spectator model

Lacroix et al. - PRC 69.054604 (2004)





→ High incident energy, heavy ion collisions (above Fermi energy)

→ Participant zone defined as the overlap volume between the projectile and the target during the collision

Compression of the participant zone

According to Lacroix et al., high maximum nucleon density can be reached during the collision

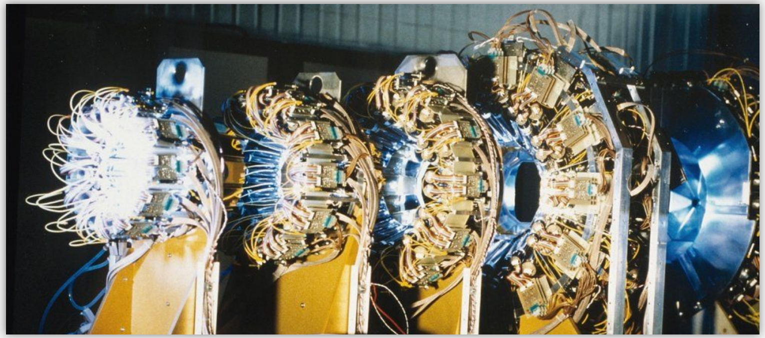
→ The clusters formed from this zone carry information about this high density origin

→ In this study, the participant zone will be extracted using an angular cut between 70° and 110° angles, relative to the beam axis (in CM frame)

The detector : the INDRA multidetector array

→ 4π detector → high completeness of the reaction (90% of the space covered)
→ Angular and energy data allows reconstruction of the reaction
→ Identification of charges and fragment masses up to Z = 6 for INDRA (up to Z = 50 for charge identification)

For more info, see talks of C. Ciampi and Q. Fable



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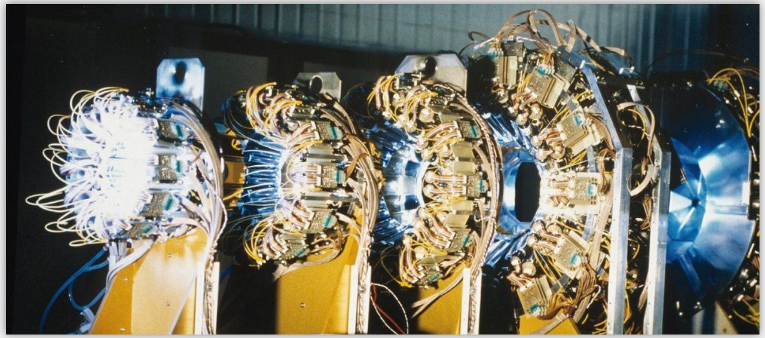

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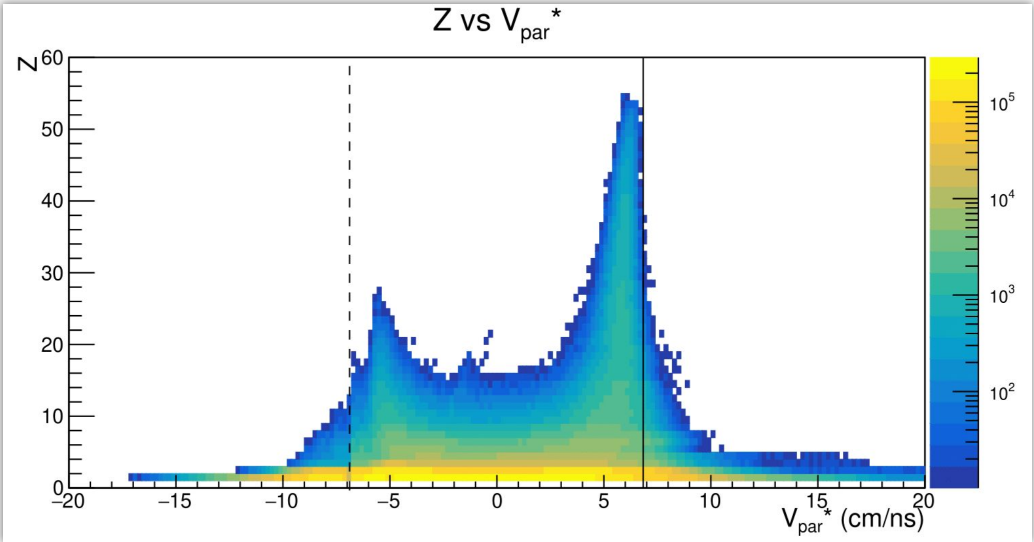
$^{129}Xe + ^{124}Sn$ @ 100 A MeV (INDRA data)



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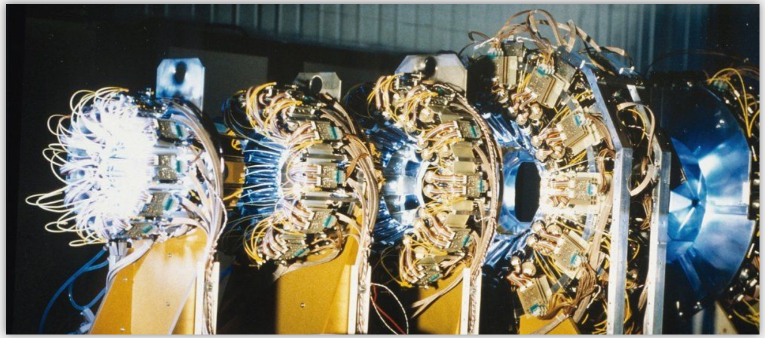

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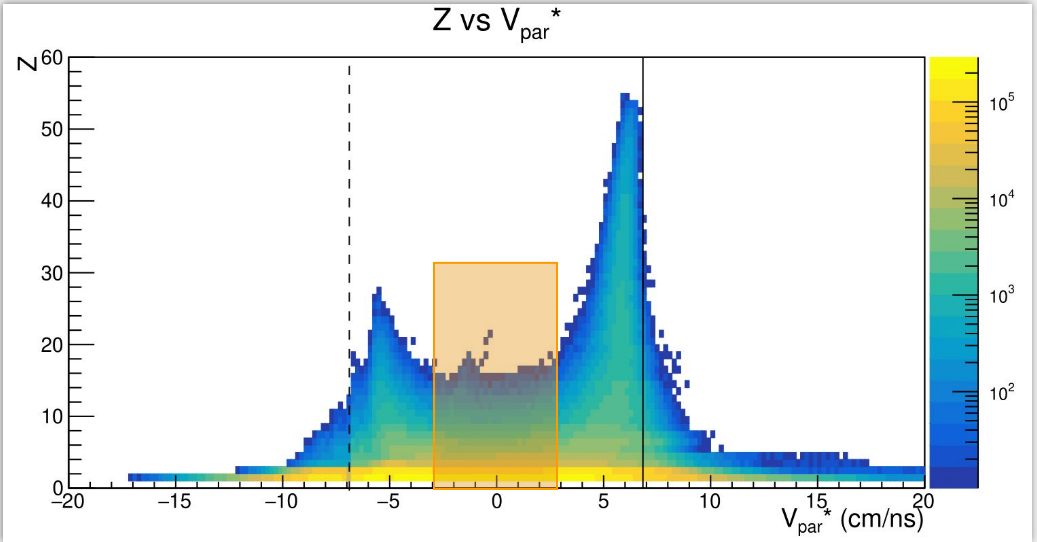


Mid-velocity products are mostly light particles
→ Deconvolution between spectator and participant contributions is complicated
→ We can only choose a limited sample of the mid-velocity region

→ **In this study, we will look at the static and dynamic properties of nuclei emitted by the participant zone**

INDRA dataset used for the analysis :

Neutron richness (isospin) effects : 4 systems

@ 100 A MeV
→ $^{124,129}Xe + ^{112,124}Sn$ → Composition of the participant zone

Incident energy effects : 6 systems

$^{129}Xe + ^{124}Sn$
→ @ 150 A MeV
→ @ 100 A MeV
→ @ 80 A MeV
→ @ 65 A MeV
$^{136}Xe + ^{124}Sn$
→ @ 45 A MeV
→ @ 32 A MeV

→ Effects of compression on the kinematics of the clusters emitted by the participant area

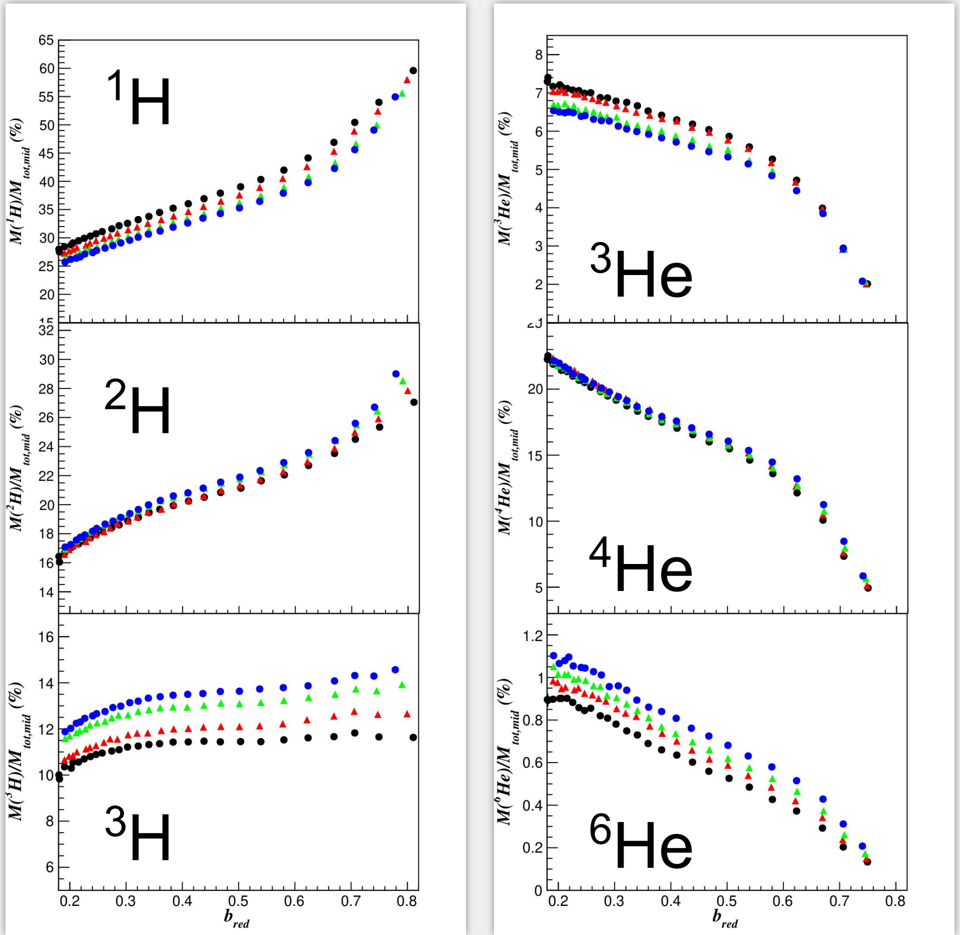
Composition of the participant zone

$^{124,129}Xe + ^{112,124}Sn$ @ 100 A MeV
($70° < \theta_{CM} < 110°$)

- ● 124Xe + 112Sn (N/Z = 1.269)
- △ 129Xe + 112Sn (N/Z = 1.317)
- ▲ 124Xe + 124Sn (N/Z = 1.385)
- ○ 129Xe + 124Sn (N/Z = 1.433)

Multiplicity is normalized by the total multiplicity in our selection

Evolution of the shape of the distribution depending on the nature of the particle
→ Production of free protons is the highest among the other LCP
→ The shape of the particle multiplicity distributions changes completely, from an increase with impact parameter for p, d and only slightly for tritons to an inversion of shape for clusters Z = 2



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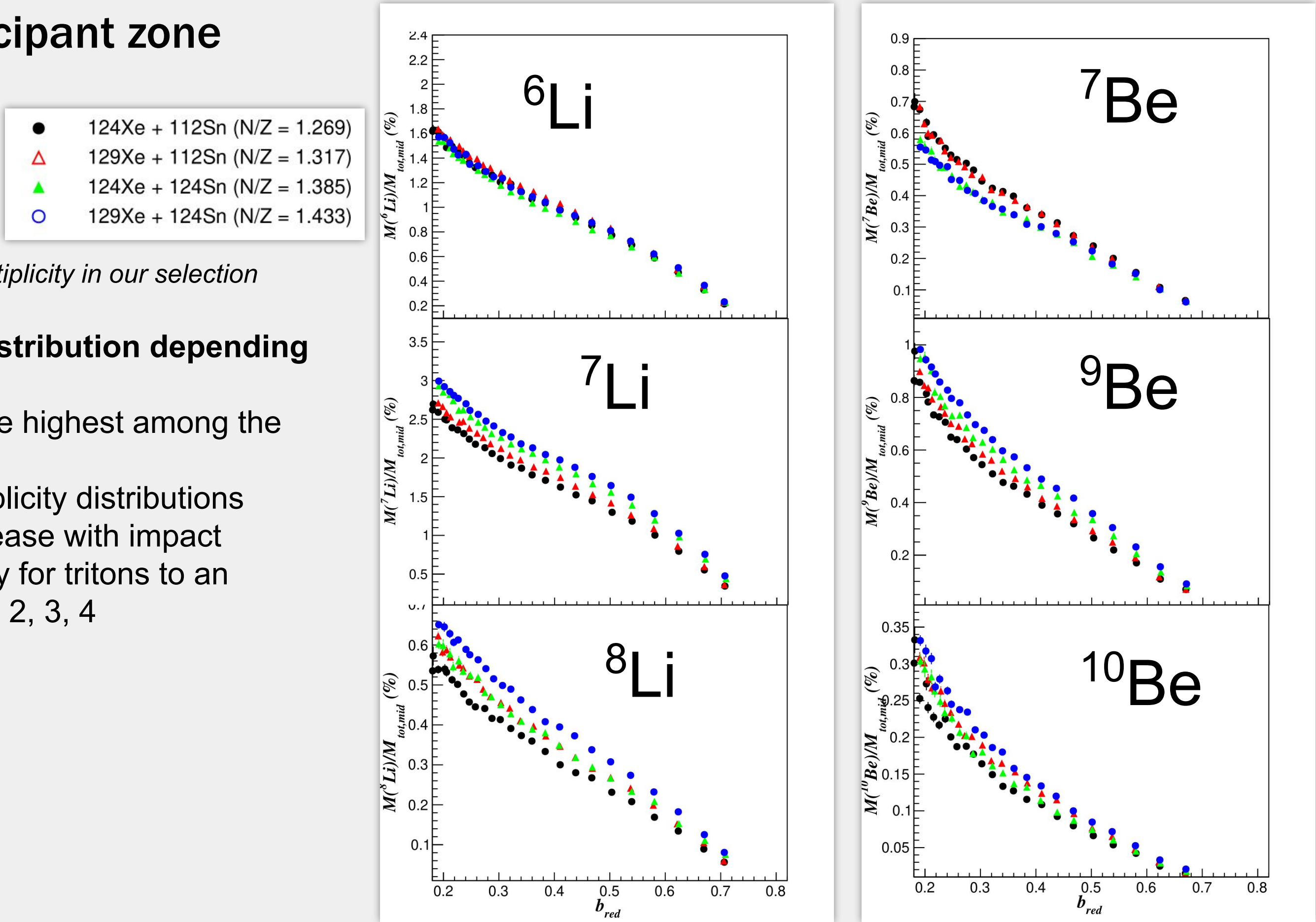

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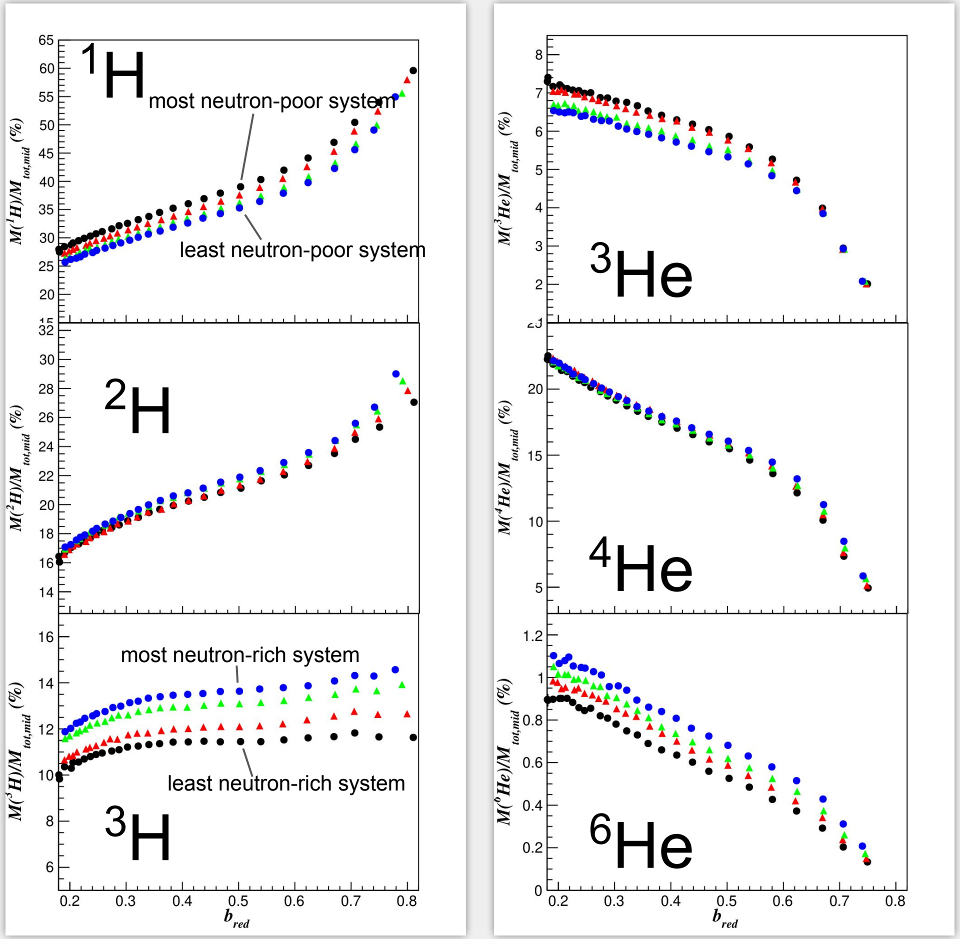
Ordering of the production distributions depending on the N/Z ratio of the system

→ Neutron-rich nuclei production is favored for neutron-rich systems

→ Neutron-poor nuclei production is favored for neutron-poor systems



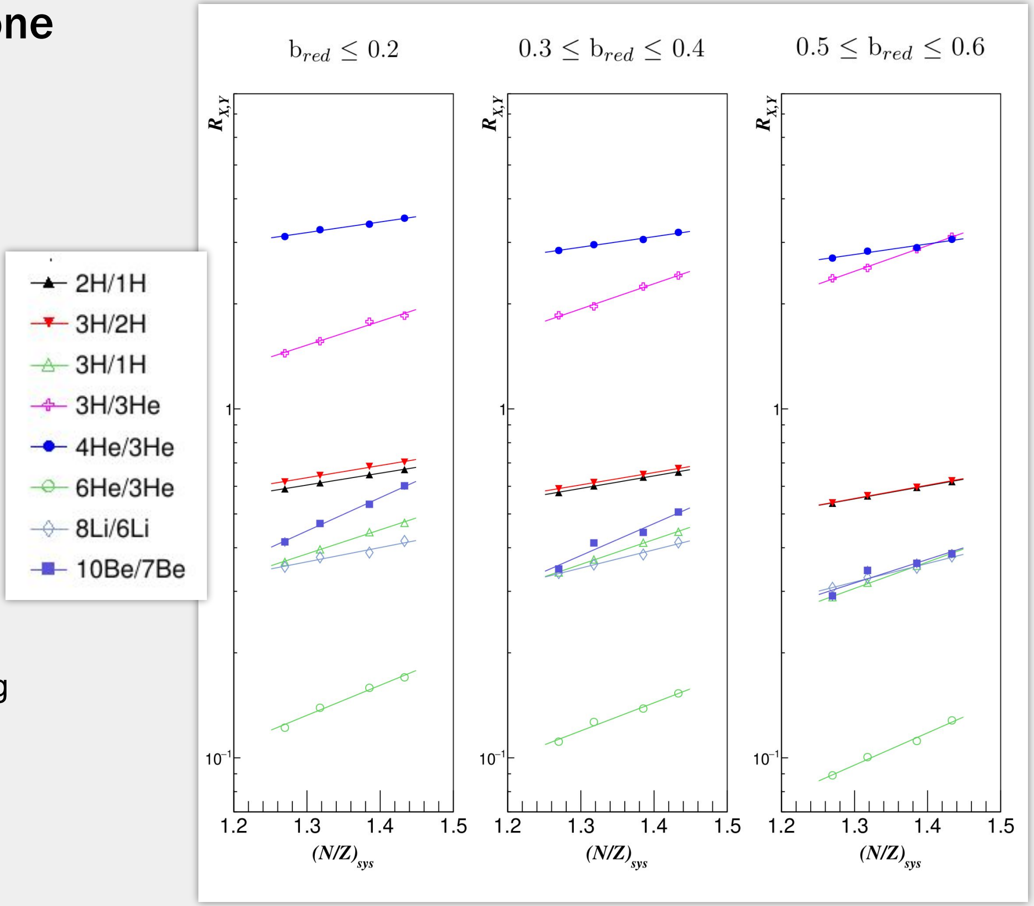
Isotopic yield ratios in the participant zone

^{124,129}Xe + ^{112,124}Sn @ 100 A MeV
($70° < \theta_{CM} < 110°$)

Three centrality selections ($b_{red} = b/b_{max}$) :
- central ($b_{red} \leq 0.2$)
- semi-peripheral ($0.3 \leq b_{red} \leq 0.4$)
- peripheral ($0.5 \leq b_{red} \leq 0.6$)

Previously seen scaling between yield ratios and $(N/Z)_{sys}$ is found for all centrality selections
→ Absolute values changes, with a lower production of light isotopes compared to heavy isotopes for higher impact parameters

Chemical equilibration is observed for all presented impact parameters
→ Shift of the slope parameter of the exponential scaling indicates a dependence of neutron-richness sensitivity with centrality



Isotopic yield ratios in the participant zone

^{124,129}Xe + ^{112,124}Sn @ 100 A MeV

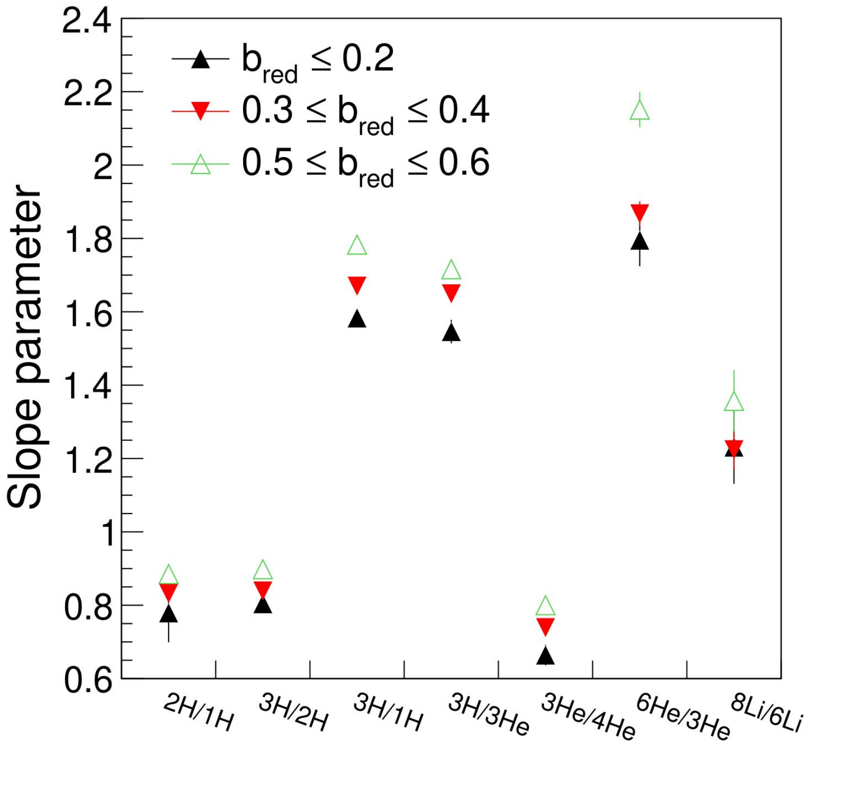
(70° < θ_{CM} < 110°)

A shift of the slope parameter is observed

→ For (almost) all yield ratios, the slope increases with the impact parameter

→ **Neutron-rich nuclei production in collisions of higher impact parameter is more sensitive to $(N/Z)_{sys}$**

The participant zone at high impact parameter is made up of more surface nucleons of the projectile and target



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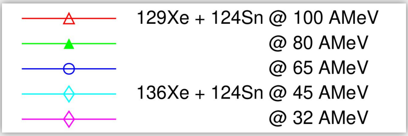
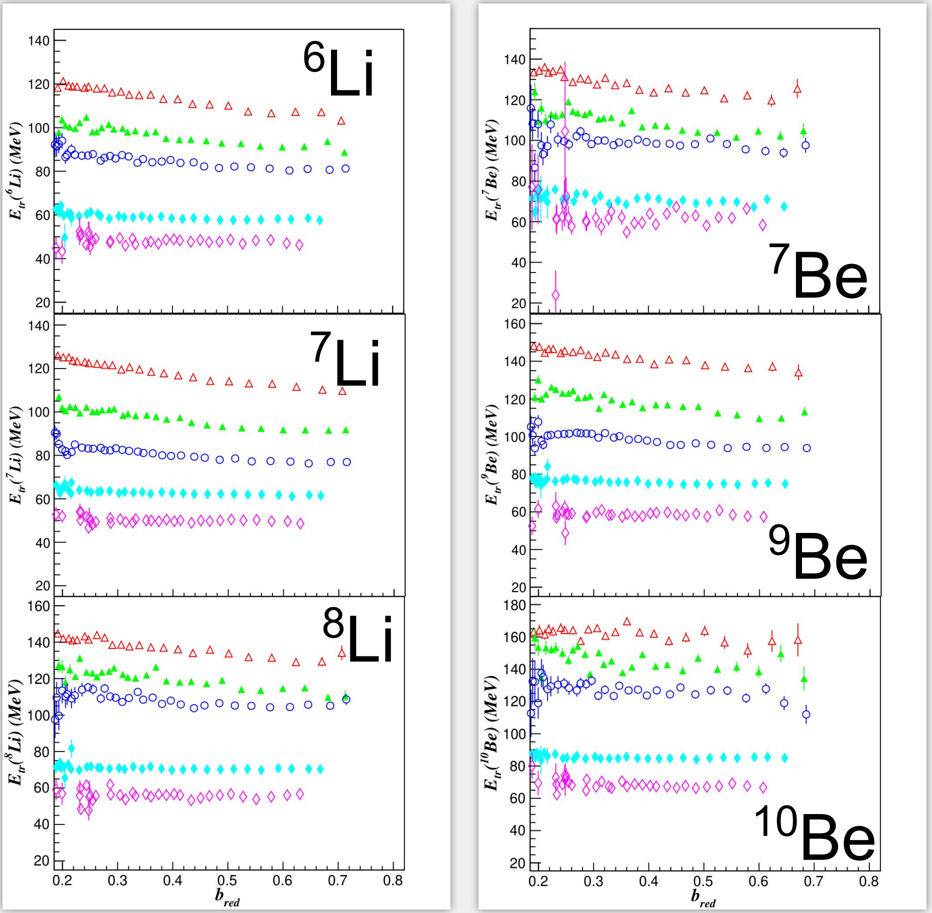
Transverse energy comparison

^{129}Xe + ^{124}Sn @ 100,80,65 A MeV
^{136}Xe + ^{124}Sn @ 45,32 A MeV
(70° < θ_{CM} < 110°)

$$E_{tr,i} = E_i sin^2(\theta_i)$$





Mean transverse energy depends (almost) linearly with the impact parameter
→ For higher mass nuclei, it becomes independent of the size of the participant zone

A constant order hierarchy is found for all nuclei, with the highest incident energy system producing the most energetic particles

Transverse energy comparison

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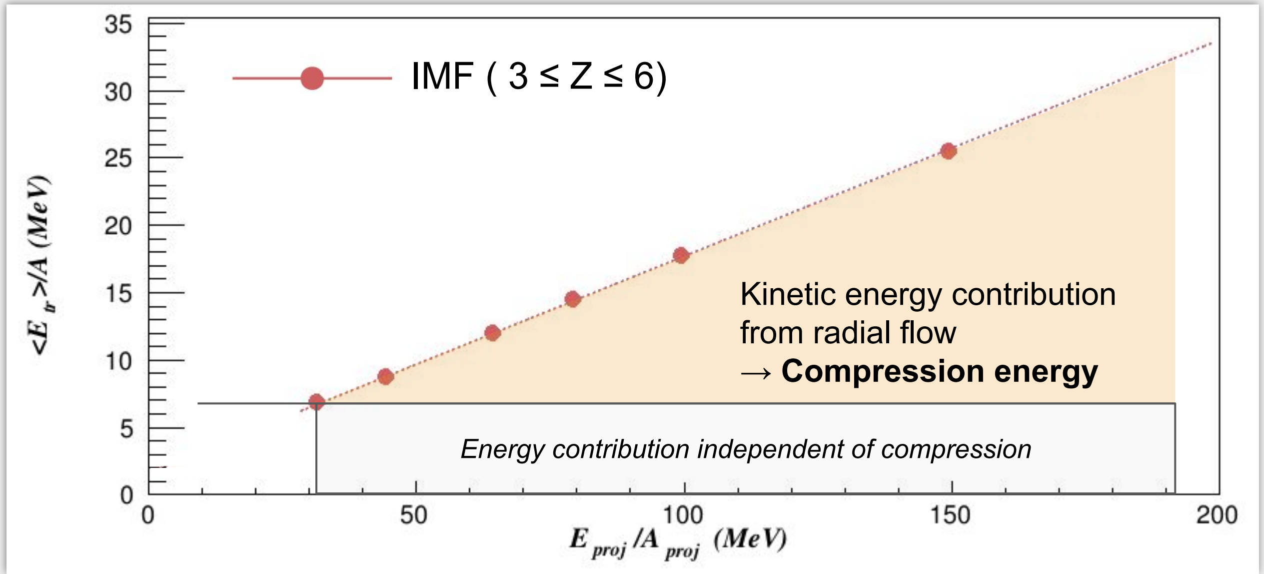


→ **Linearity observed between mean transverse energy per nucleon and incident energy per nucleon**
We can extract the compression energy, under the hypothesis than no other contribution depend on the density, and that we can set a constraint transverse energy threshold to collision where no compression is assumed

Maximum density calculations : hypotheses

Compression energy hypothesis

Above an energy threshold e_{th}, the kinetic energy contribution dependant on the density is the compression energy

$$e_{tr}(\rho) = e_{tr}(\rho = \rho_0) + e_{comp}(\rho)$$

Incompressibility of nuclear matter

Second order term of the EoS-NM

$$e_{comp} = \frac{K_\infty}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2$$

Size factor

Normalised number of nucleons present in the participant zone

$$\left(\frac{A(b_{red})}{A_0}\right)^\alpha$$

$K_\infty \simeq 240$ MeV

$\alpha \simeq 1/3$

$A_0 \simeq 240$

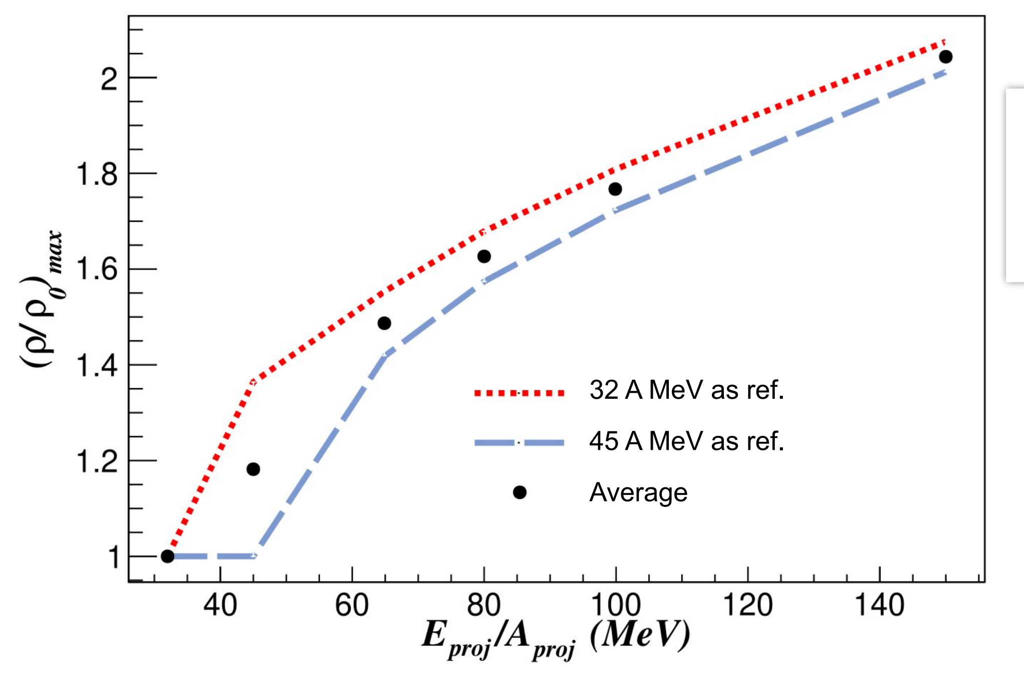
$$\frac{\rho}{\rho_0} = 1 + \sqrt{18\frac{(e_{tr} - e_{tr,th})}{K_\infty}}\left(\frac{A(b_{red})}{A_0}\right)^\alpha$$

Density derived from kinetic energy

Comparison of the Xe+Sn system between several energies

$^{129}Xe + ^{124}Sn$ @ 150,100,80,65 A MeV
$^{136}Xe + ^{124}Sn$ @ 45,32 A MeV

→ Densities calculated for central collisions (IMF, $b_{red} \approx 0.2$)



Ambiguity on the threshold energy

→ Density calculated with both 32 and 45 A MeV transverse energy as thresholds, the average will be the "true" calculated density

$$\frac{\rho}{\rho_0} = 1 + \sqrt{18\frac{(e_{tr} - e_{tr,th})}{K_\infty}} \left(\frac{A(b_{red})}{A_0}\right)^\alpha$$

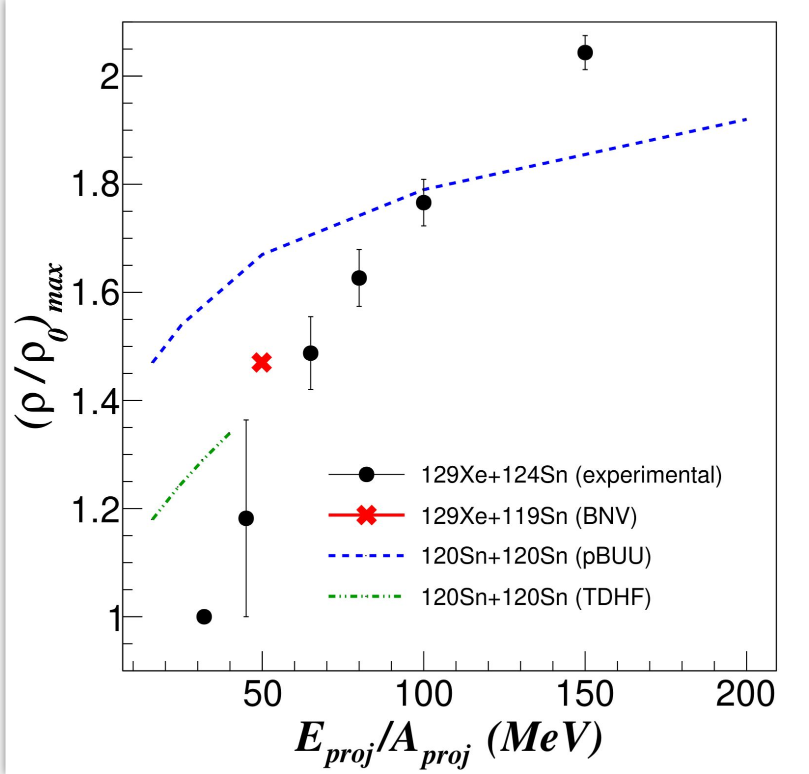
→ Average maximum density varies between $1.2\rho_0$ for 45 A MeV of incident energy, to $2.1\rho_0$ for 150 A MeV

→ The relation between the density and incident energy follows a square-root scale law

Comparison of our calculated density with transport model results

Calculated maximum densities are comparable to transport model predictions

→ Value calculated for 65 A MeV is comparable to the result of the BNV calculations
→ Value calculated for 100 A MeV is similar to the pBUU prediction
→ Low incident energy difference discrepancy can be explained by our use of the participant-spectator model, while large errors are due to threshold energy uncertainties



BNV : Le Fèvre - Thesis (1997)
pBUU, TDHF : Stone et al. Phys. Rev. C 96, 014612 (2017)

Conclusions

→ **Characterization of the participant zone**

→ **Cluster multiplicities**

- The relationship between production ratio and impact parameter depends on the mass of the particle
    - Very light particles are favored in peripheral collisions, and heavier particles in central collisions
- Production hierarchy for light particles based on the N/Z ratio of the whole system
- Scaling between the isotopic yield ratio and the N/Z ratio of the system

→ Chemical equilibration of the projectile and target contributions in the participant zone
→ Neutron-richness sensitivity depends on the impact parameter

→ **Study of the kinematics of the particles emitted by the midvelocity region**

- The relation between transverse kinetic energy and incident energy are indicators of compression effects
- The extracted densities vary from $1.2\rho_0$ to $2.1\rho_0$, respectively for incident energies of 45 and 150 MeV, and for the Xe+Sn system

→ Calculated densities are comparable to transport model calculations, for equivalent systems

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→ Calculated densities are comparable to transport model calculations, for equivalent systems

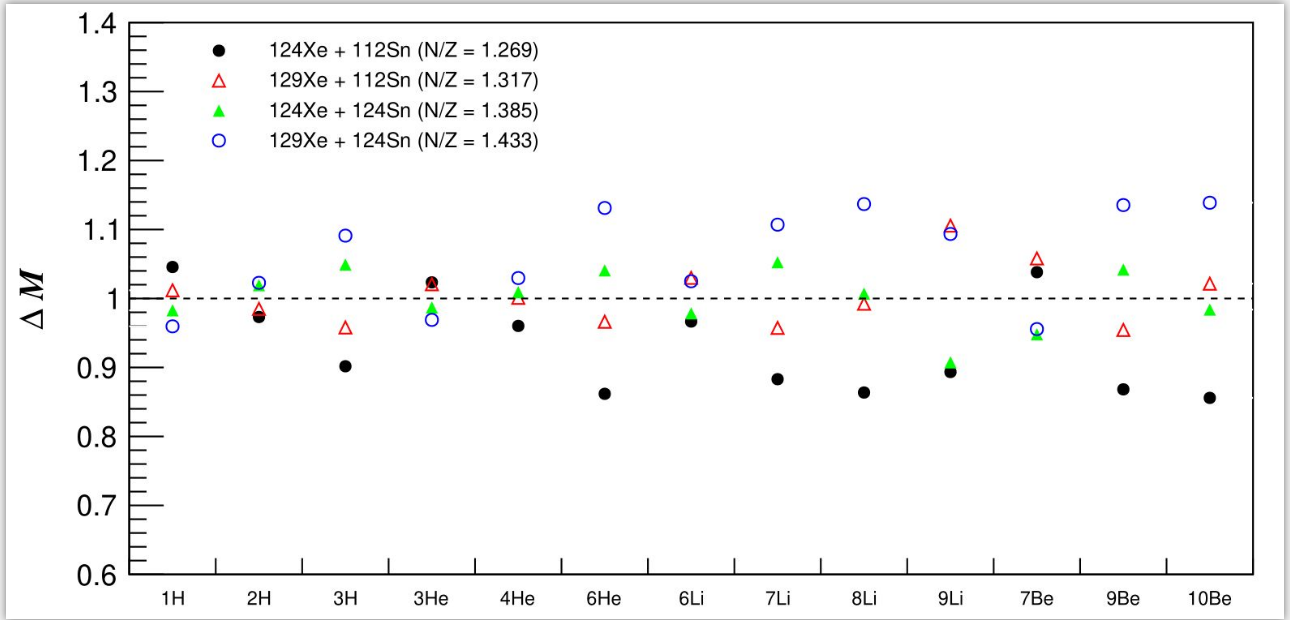
→ How clusters are formed ?

Thank you for your attention

BACKUP SLIDES

Composition of the participant zone

124,129Xe + 112,124Sn @ 100 A MeV
(70° < θ_{CM} < 110°)



Isotopic yield ratios $R_{X,Y}$

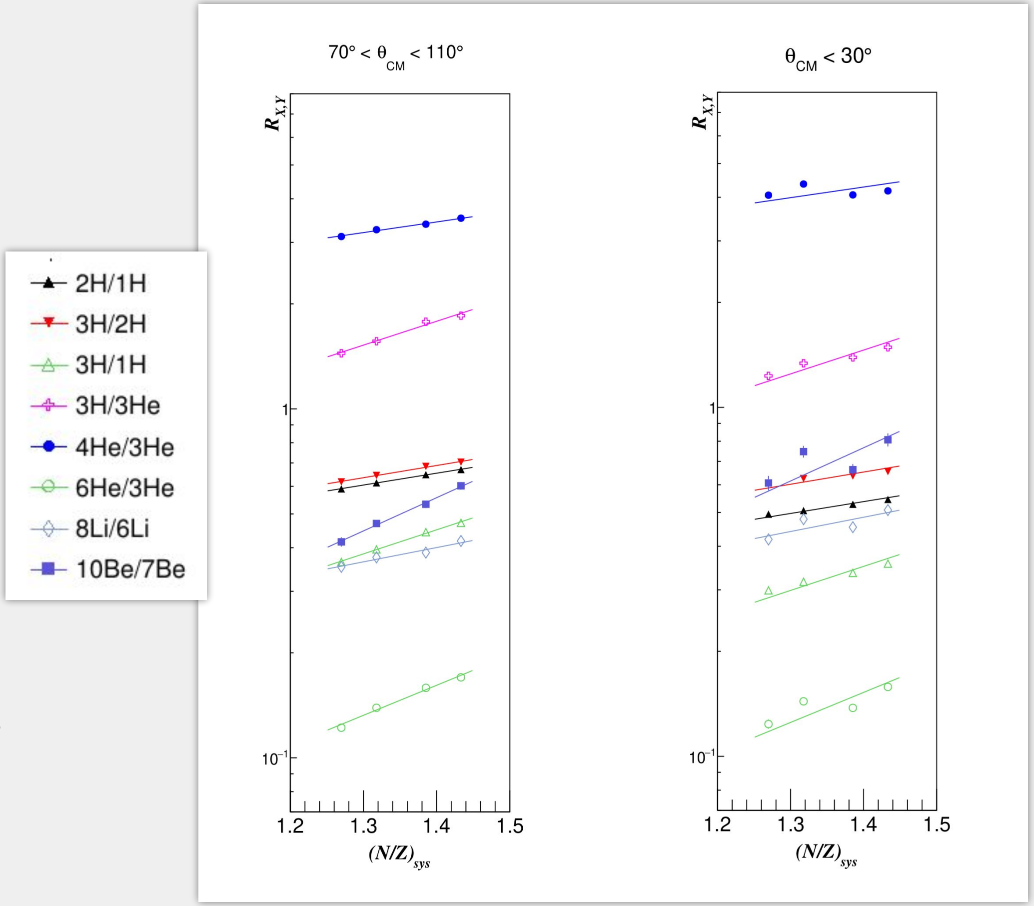
124,129Xe + 112,124Sn @ 100 A MeV
Central collisions ($b_{red} \leq 0.2$)

Two angular selections :

- transverse (between 70 and 110° in CM frame)
- frontwards (below 30° in CM frame)

<u>Transverse</u> :
→ All isotopic yield ratios follows an exponential scaling with the N/Z of the system, $(N/Z)_{sys}$

<u>Frontwards</u> :
→ Staggering effect noticeable for all yield ratios



Scaling between yield ratios and $(N/Z)_{sys}$ implies chemical equilibration
→ Full mixing of projectile and target contributions in the mid-velocity region (participant zone)

Transverse energy comparison

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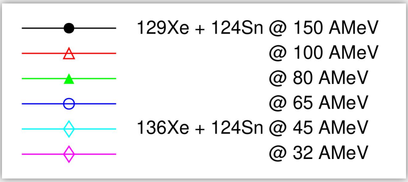
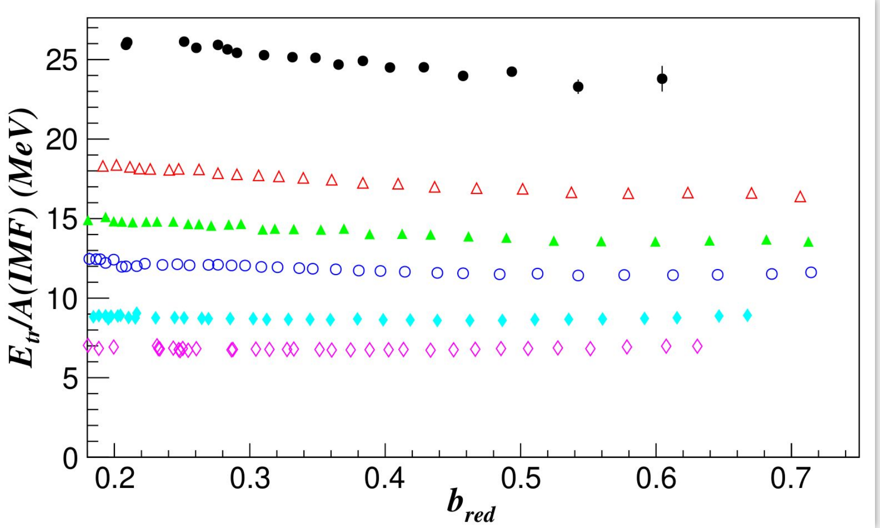
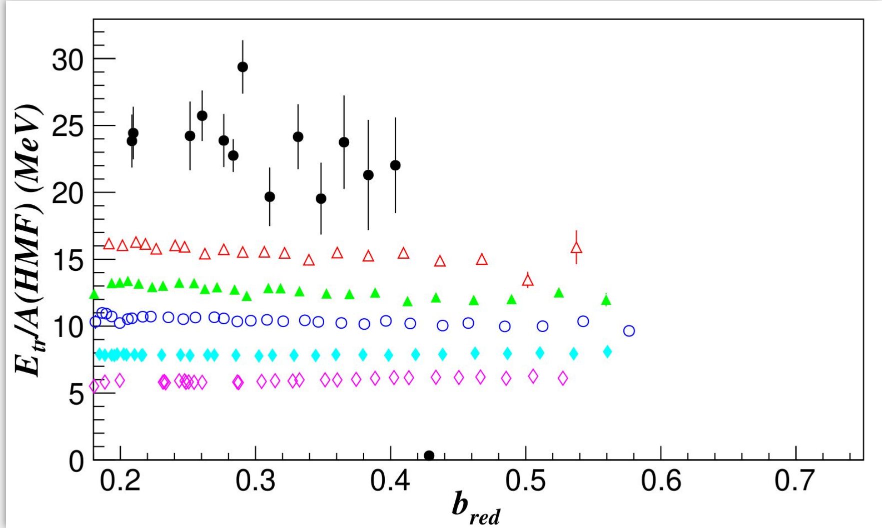


Intermediate Mass Fragments (IMF)
3 ≤ Z ≤ 6



Heavy Mass Fragments (HMF)
Z > 6



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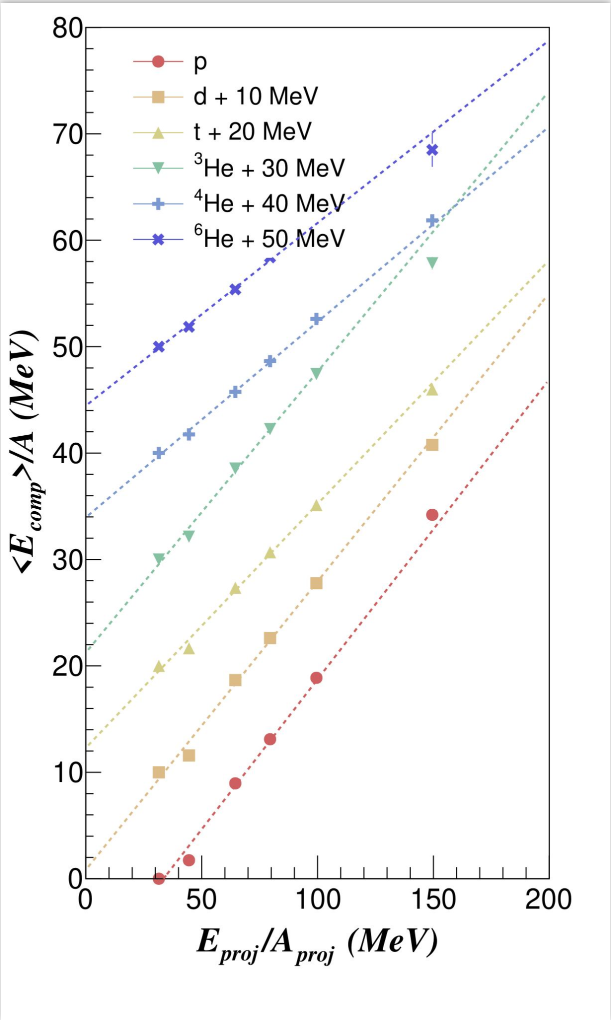
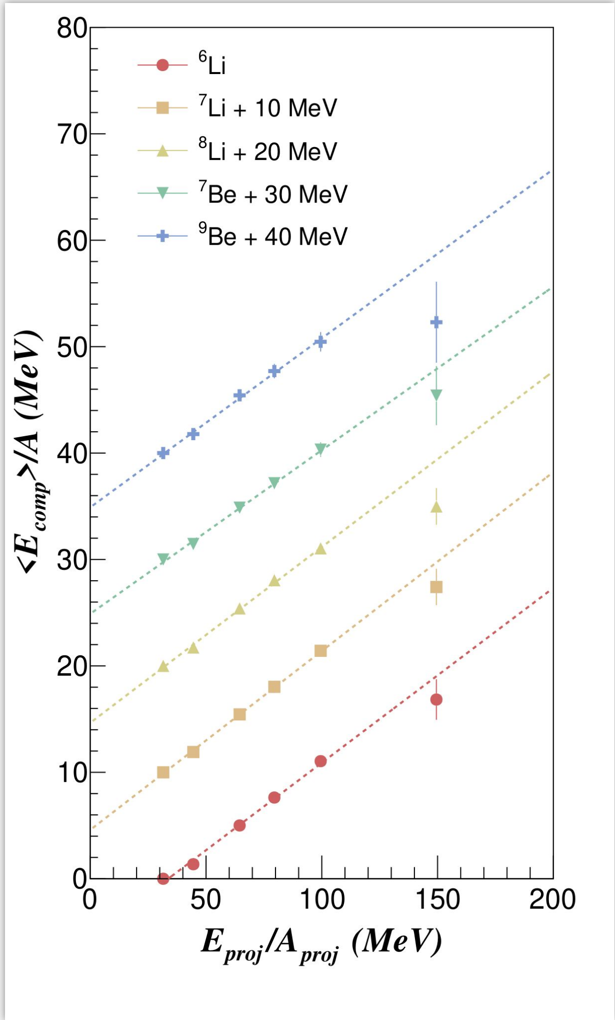
(70° < θCM < 110°)





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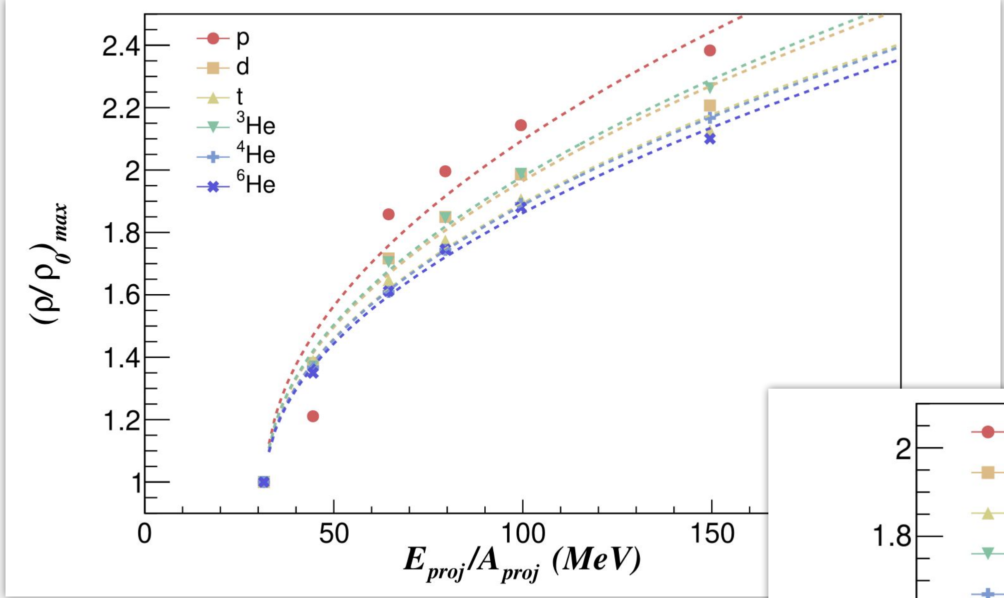
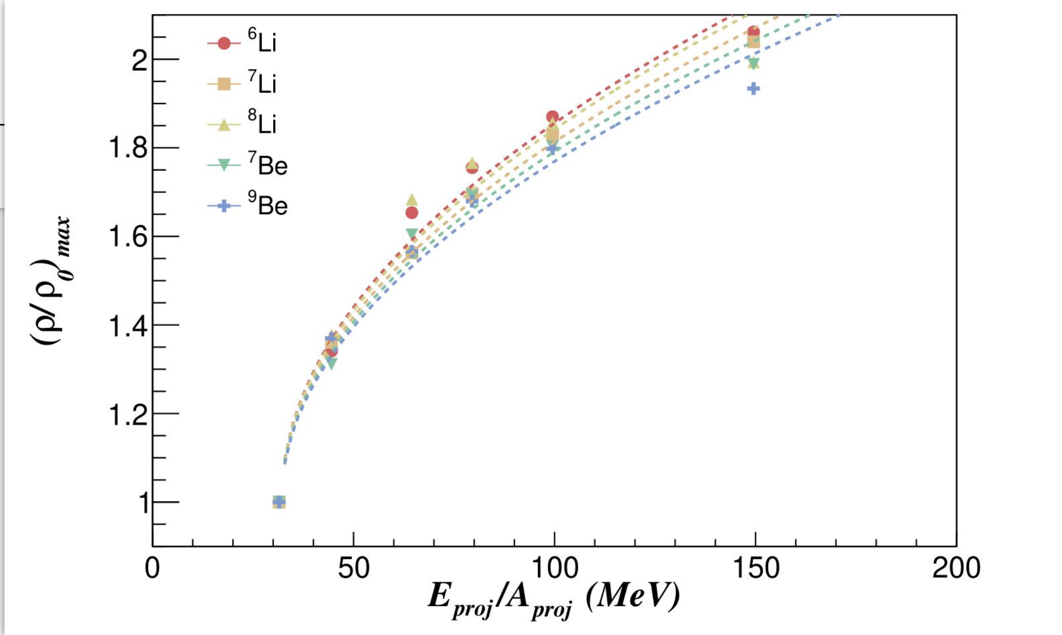




ELIE

D. Durand. Elie: an event generator for nuclear reactions, arXiv:0803.2159. (2008)

→ Event generator based on the participant-spectator model
→ Statistical model, without a full introduction of the equation of state (allows a first-order comparison with experimental data)
→ Filtered data, and particles selected using the same angular selection as the experimental analysis
→ Clusters formed randomly under high density conditions via coalescence

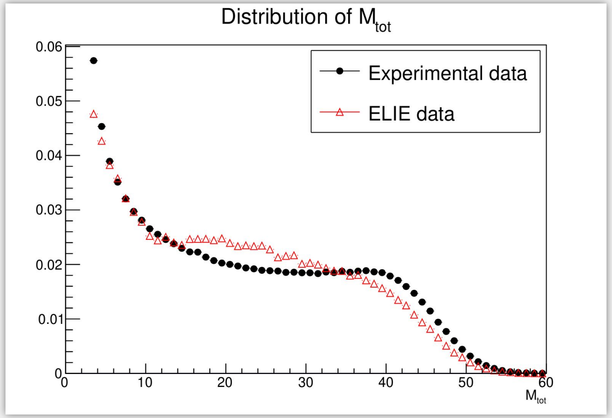
→ Calculation of state variables

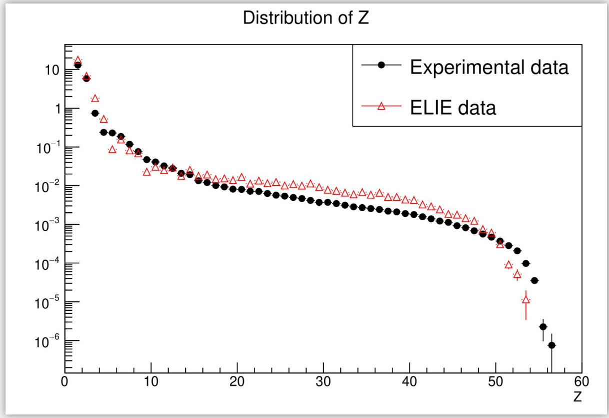
- Calculation of the maximum density in the participant zone during the collision from the compression energy (e_{comp}), derived from the CM energy, Coulomb and thermal kinetic energy contributions

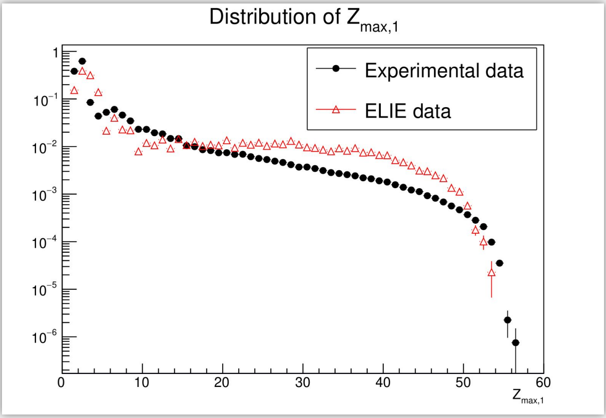
$$\frac{\rho}{\rho_0} = 1 + \sqrt{18\gamma \frac{(e^* - e_{th} - e_{coul})}{K_\infty} \left(\frac{A(b_{red})}{A_0}\right)^\alpha}$$

γ and α are parameters of the model

Comparison between experiment and ELIE

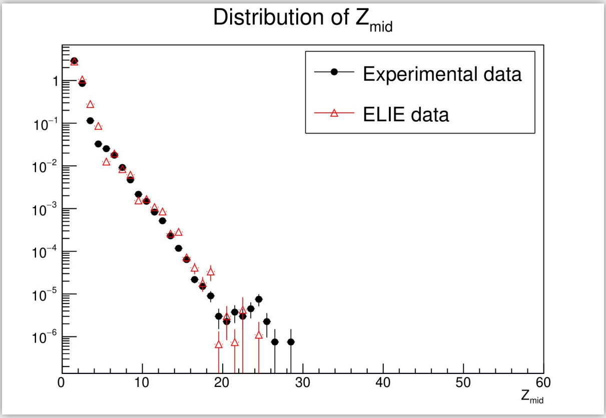






124Xe + 112Sn @ 100 A MeV

Angular selection →
(70° < θ_{CM} < 110°)



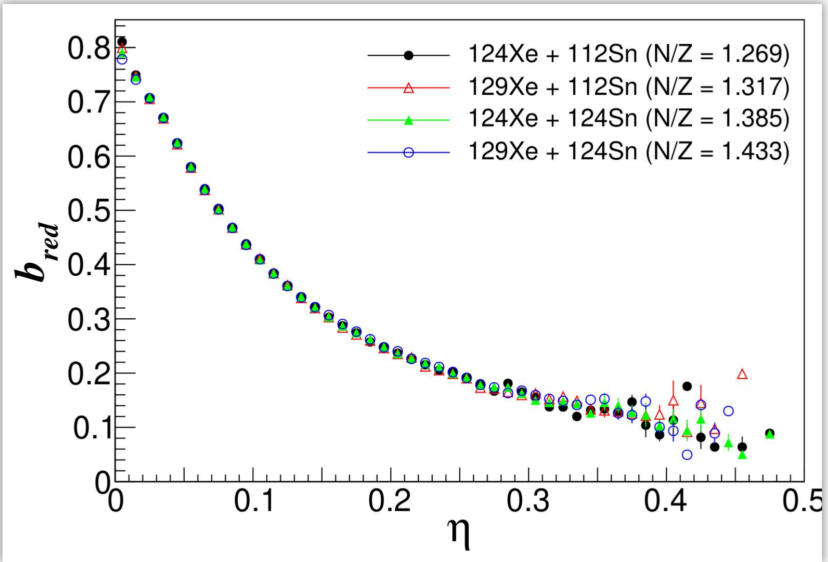
Impact parameter estimation

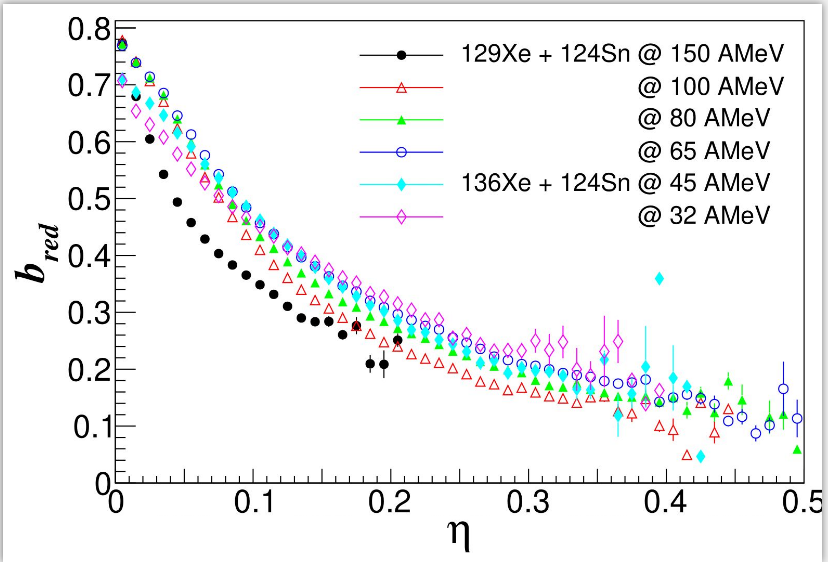
Reduced number of charges in our selected area

$$\eta = \sum_{70^\circ \geq \theta_{CM,i} \geq 110^\circ} \frac{Z_i}{Z_{proj} + Z_{targ}}$$

Based on the total charge present in the angular selection
→ Allows us to use all events, without completude cuts

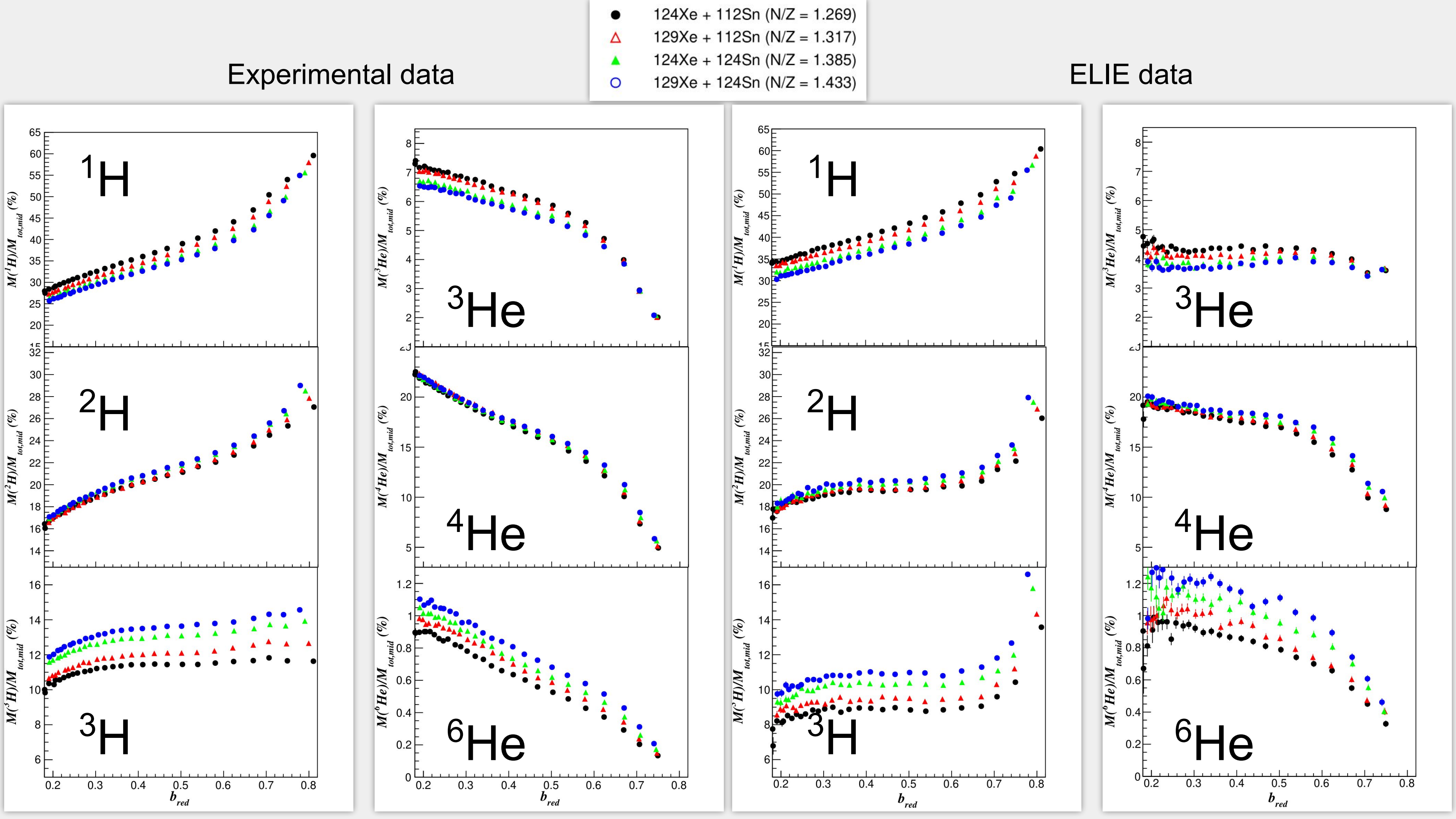
Using the ELIE model, we can associate, for each η, a mean impact parameter





Experimental data

ELIE data



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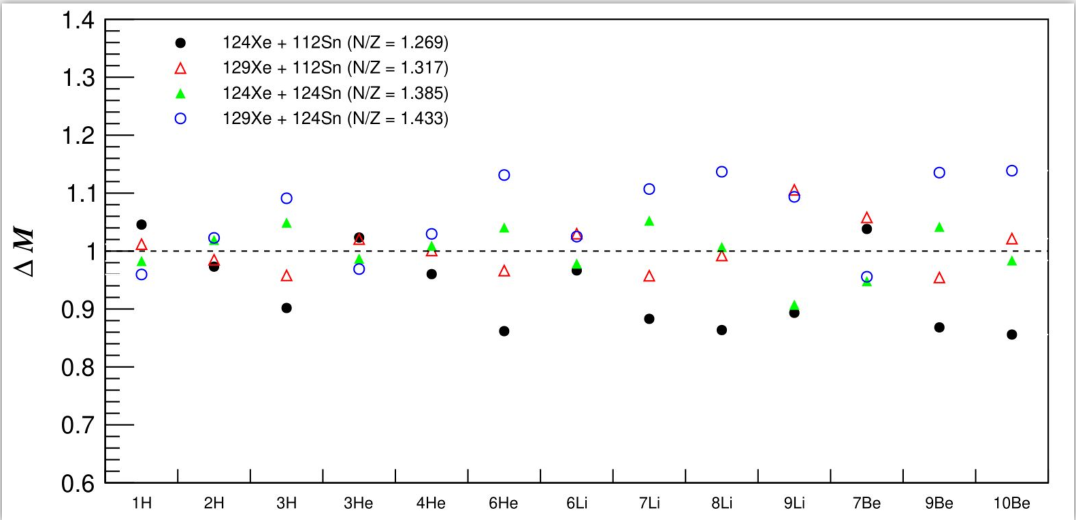

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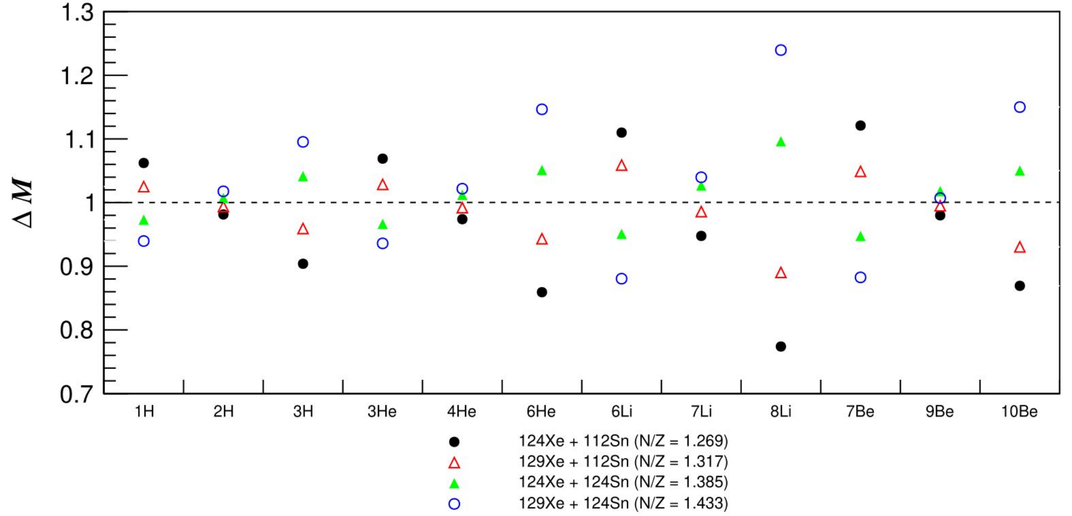

124Xe + 112Sn
@ 100 MeV.A

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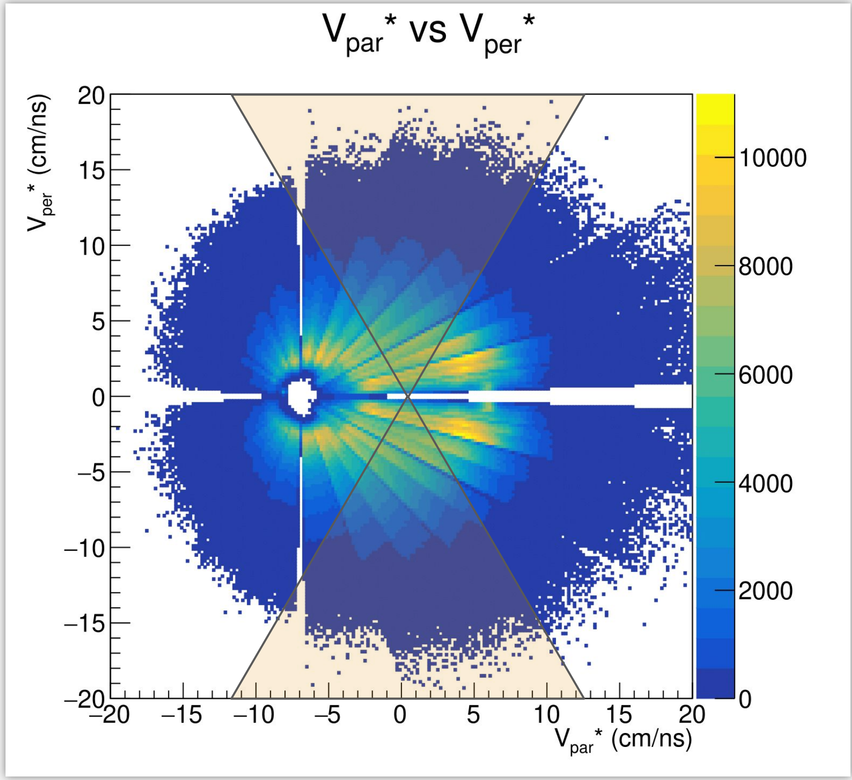

ELIE data