A new approach to detect hypernuclei and isotopes in the QMD phase space distribution at relativistic energies

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Motivations

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- Making clusters is not an easy task, because it involves, in a complex environment:
  - the fundamental nuclear properties,
  - quantum effects,
  - and variable timescales.

Simulated Annealing Clusterization Algorithm (SACA): The principles

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d) Choose that configuration which has the highest binding energy.

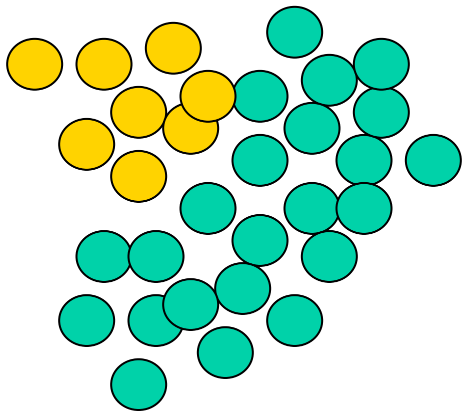
Simulations show: Clusters chosen that way at early times are the pre-fragments of the final state clusters, because fragments are not a random collection of nucleons at the end but initial-final state correlations.

SACA: How does this work?

Simulated Annealing Procedure: PLB301:328,1993; later called SACA.

2 steps:

1) Pre-select good «candidates» for fragments according to proximity criteria: real space coalescence = Minimum Spanning Tree (MST) procedure.



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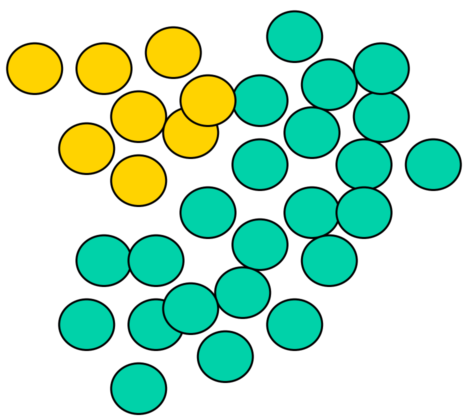

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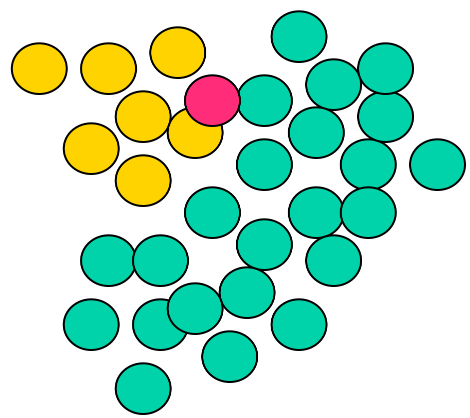

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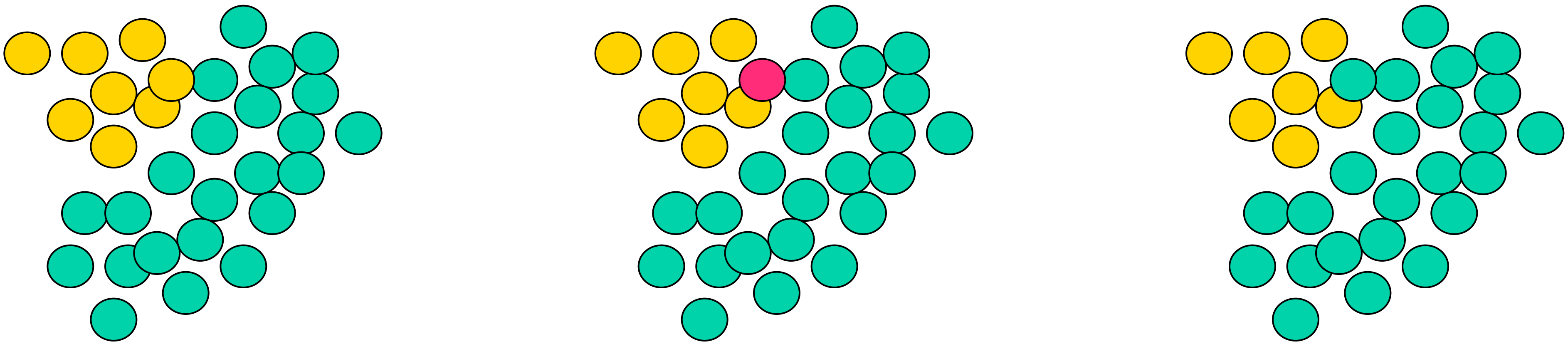

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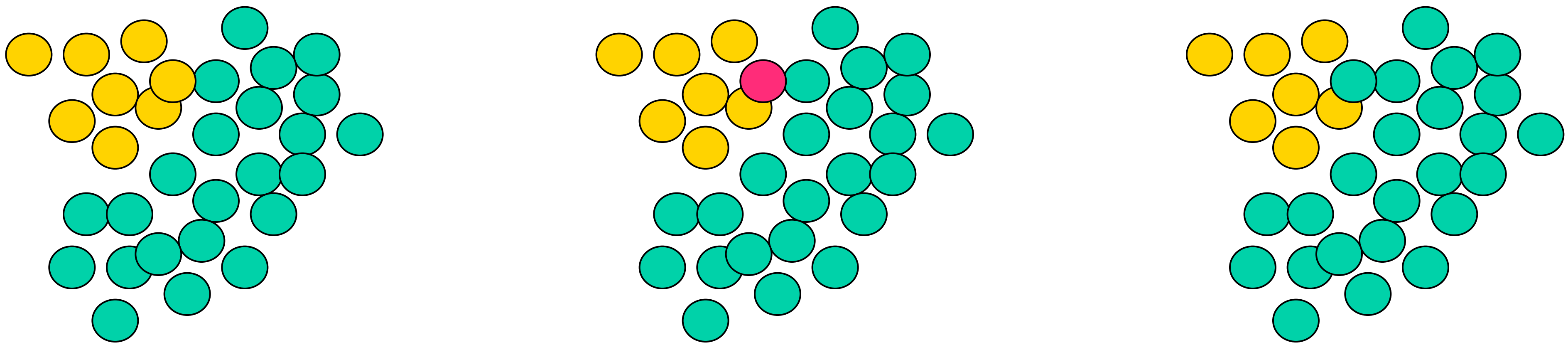

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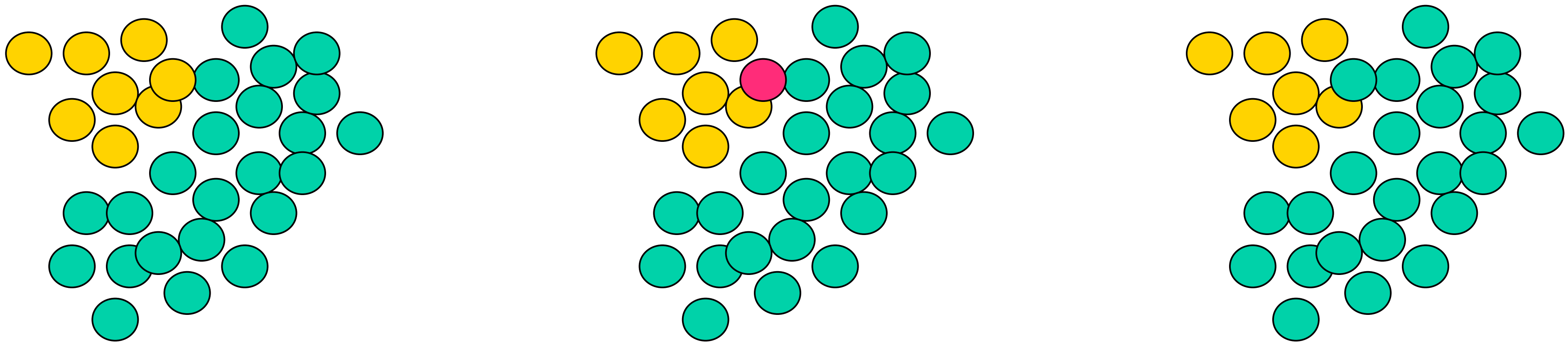

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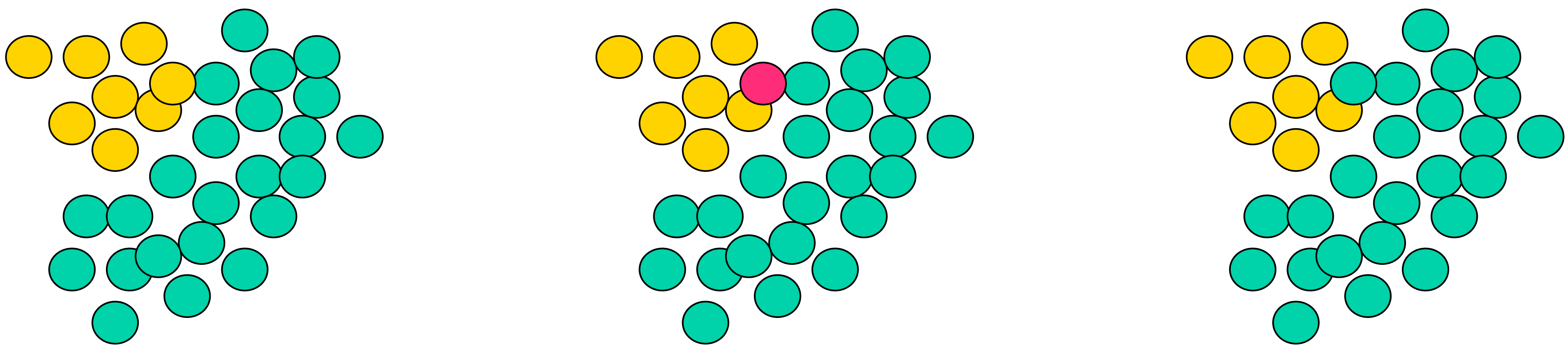

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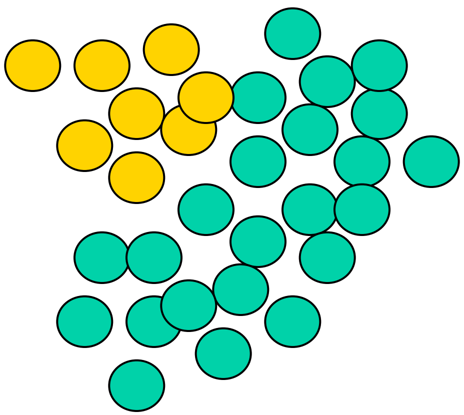

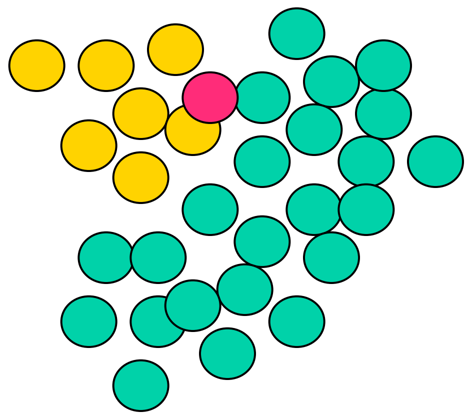

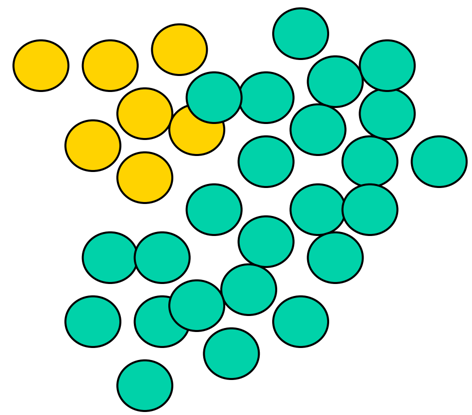

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It leads automatically to the most bound configuration.

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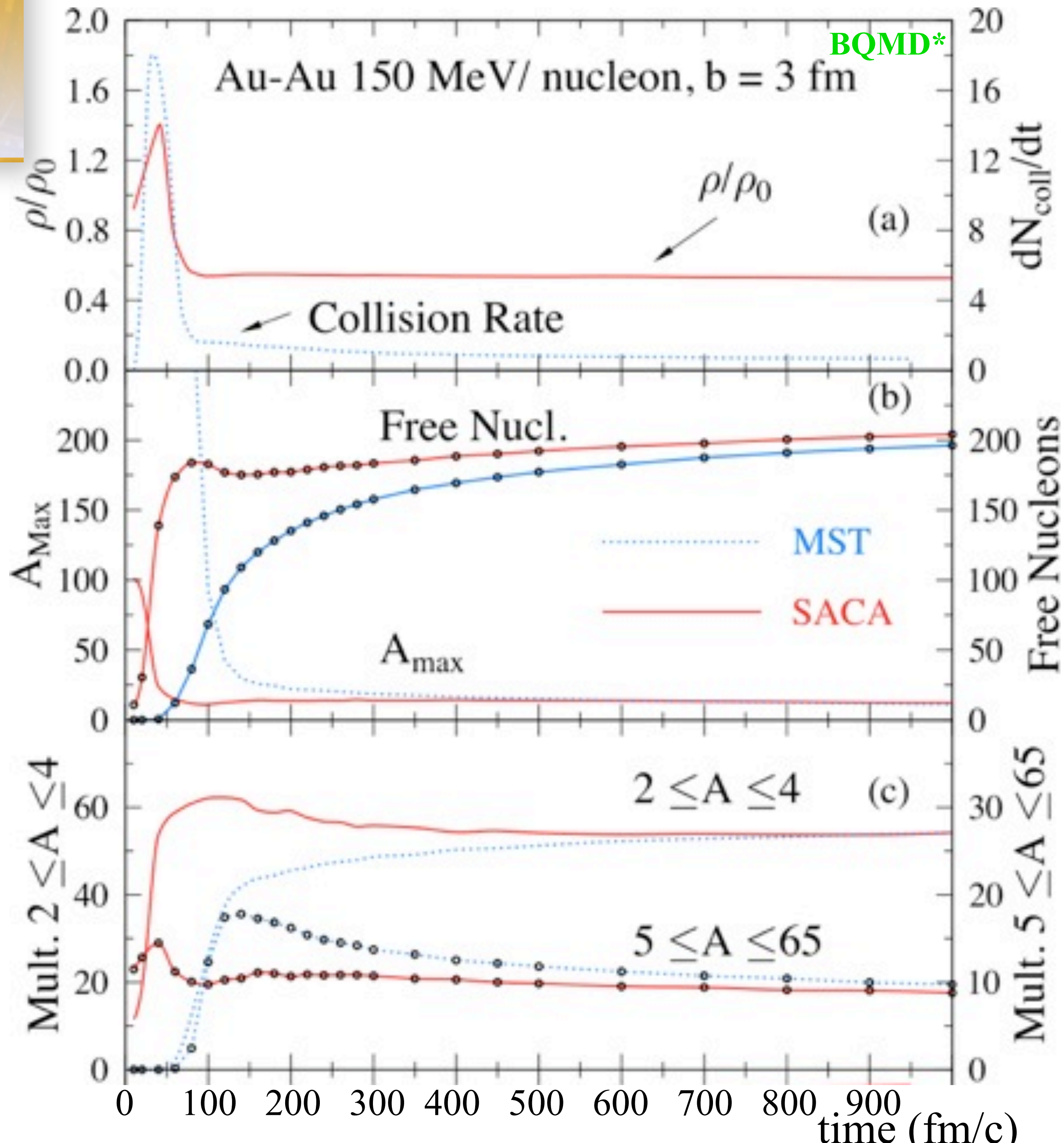

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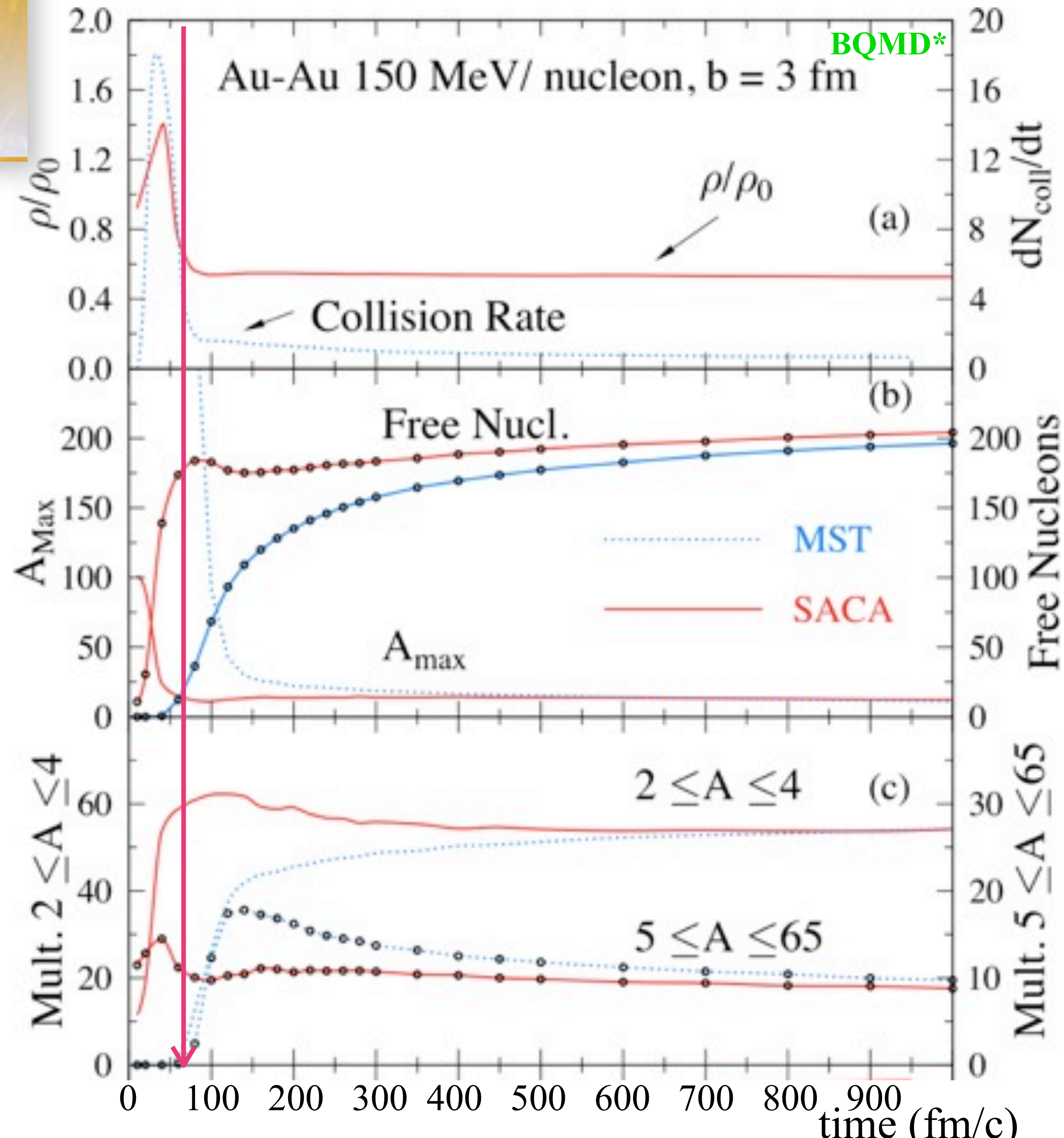

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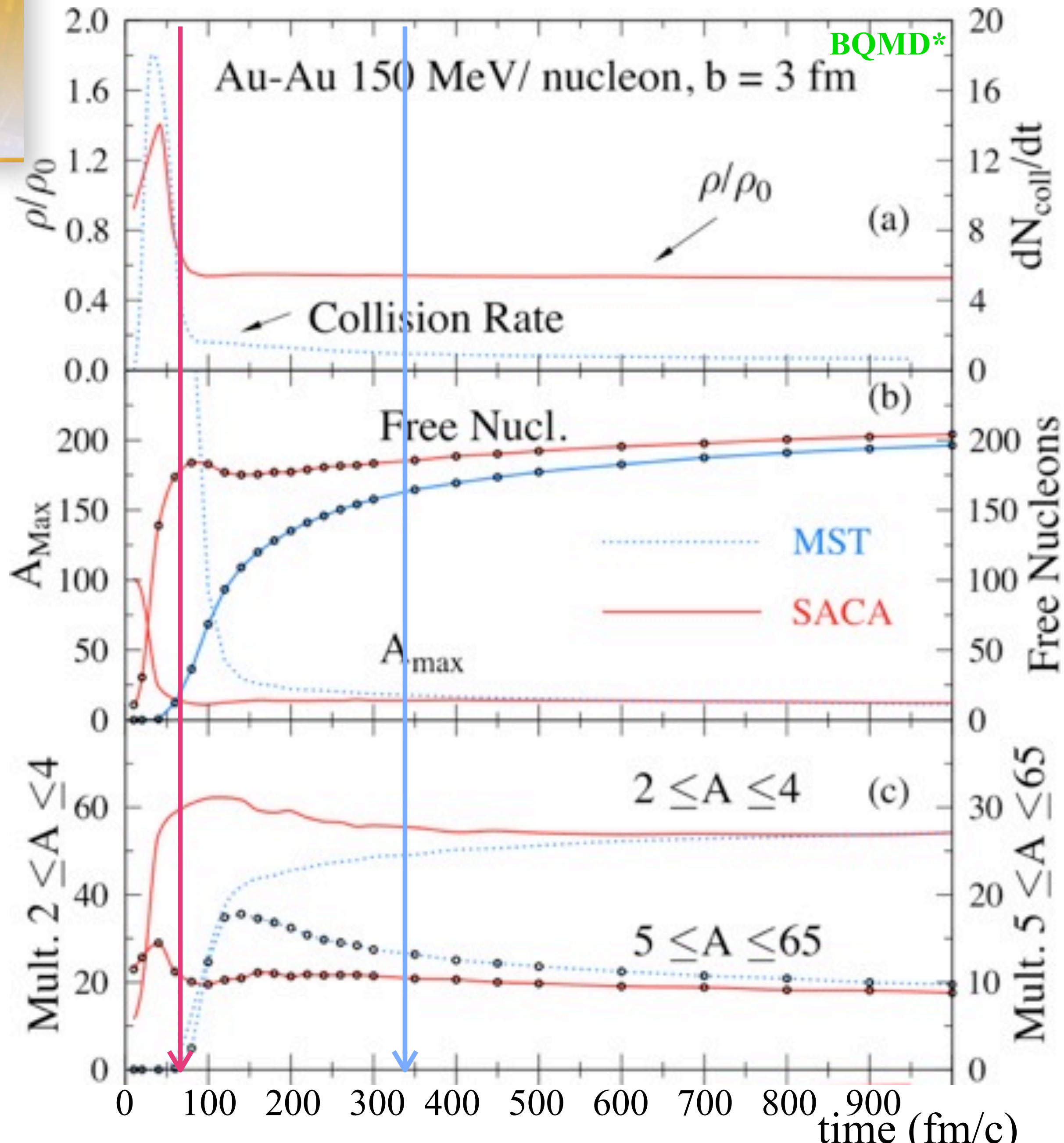

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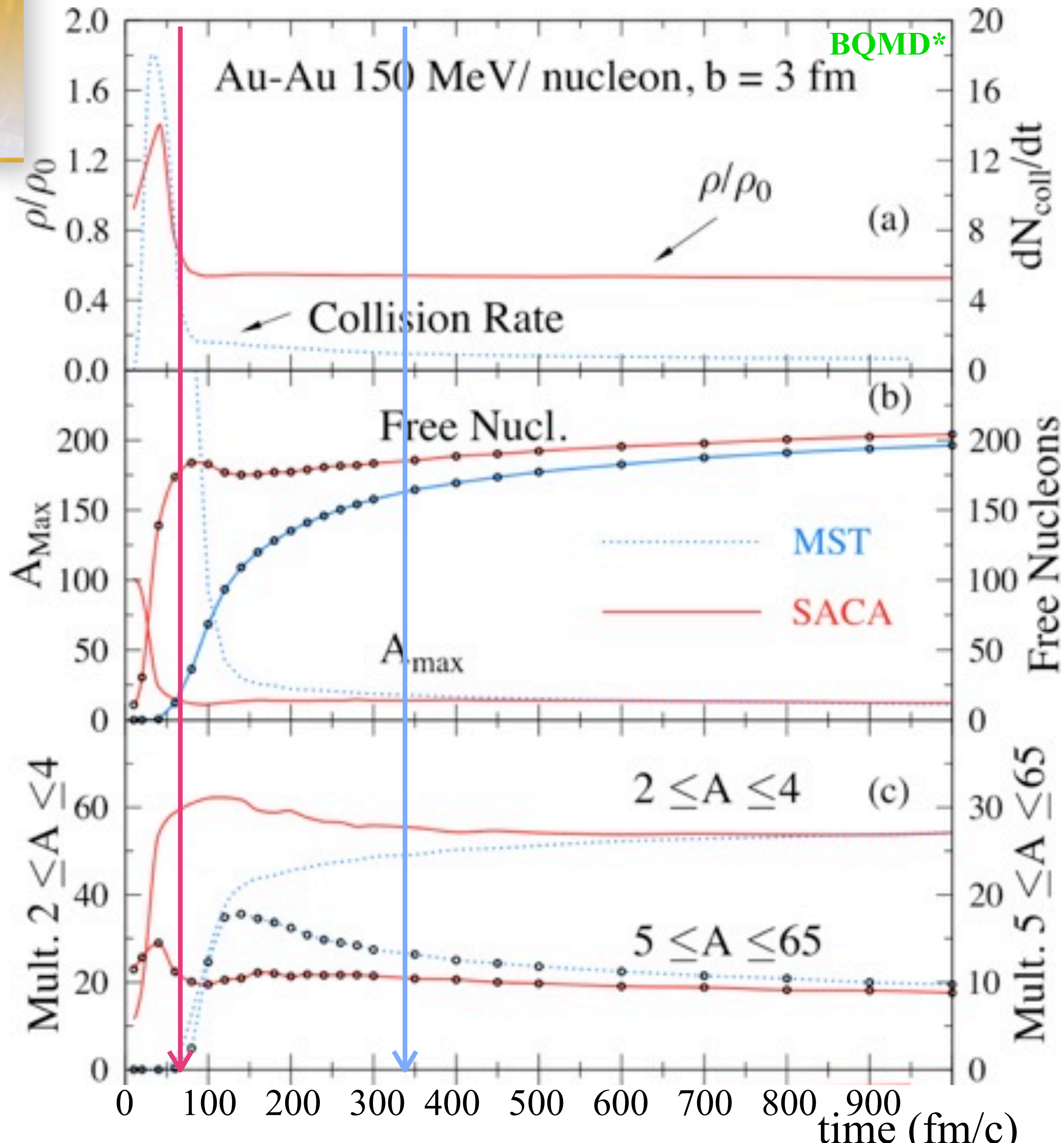

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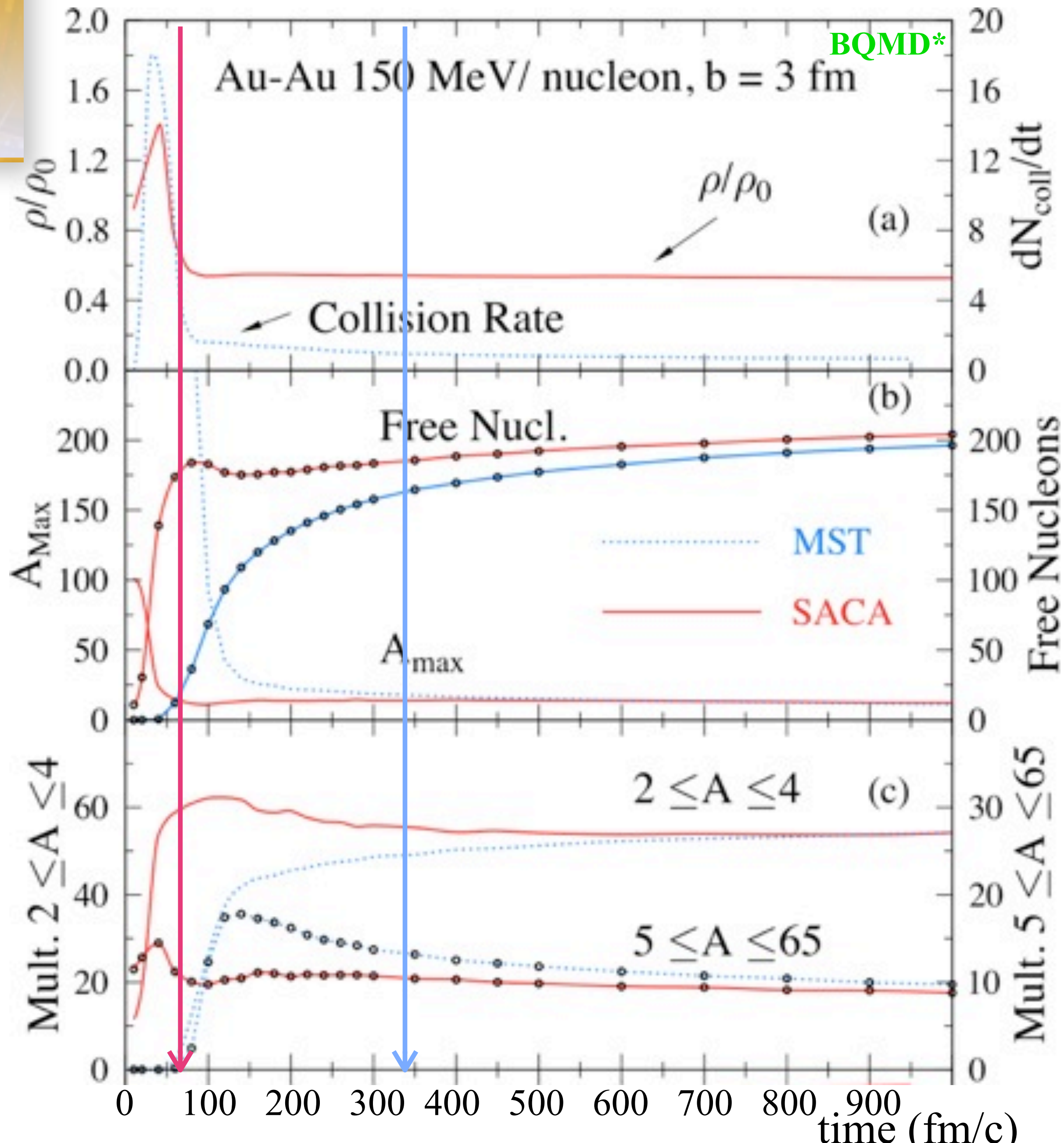

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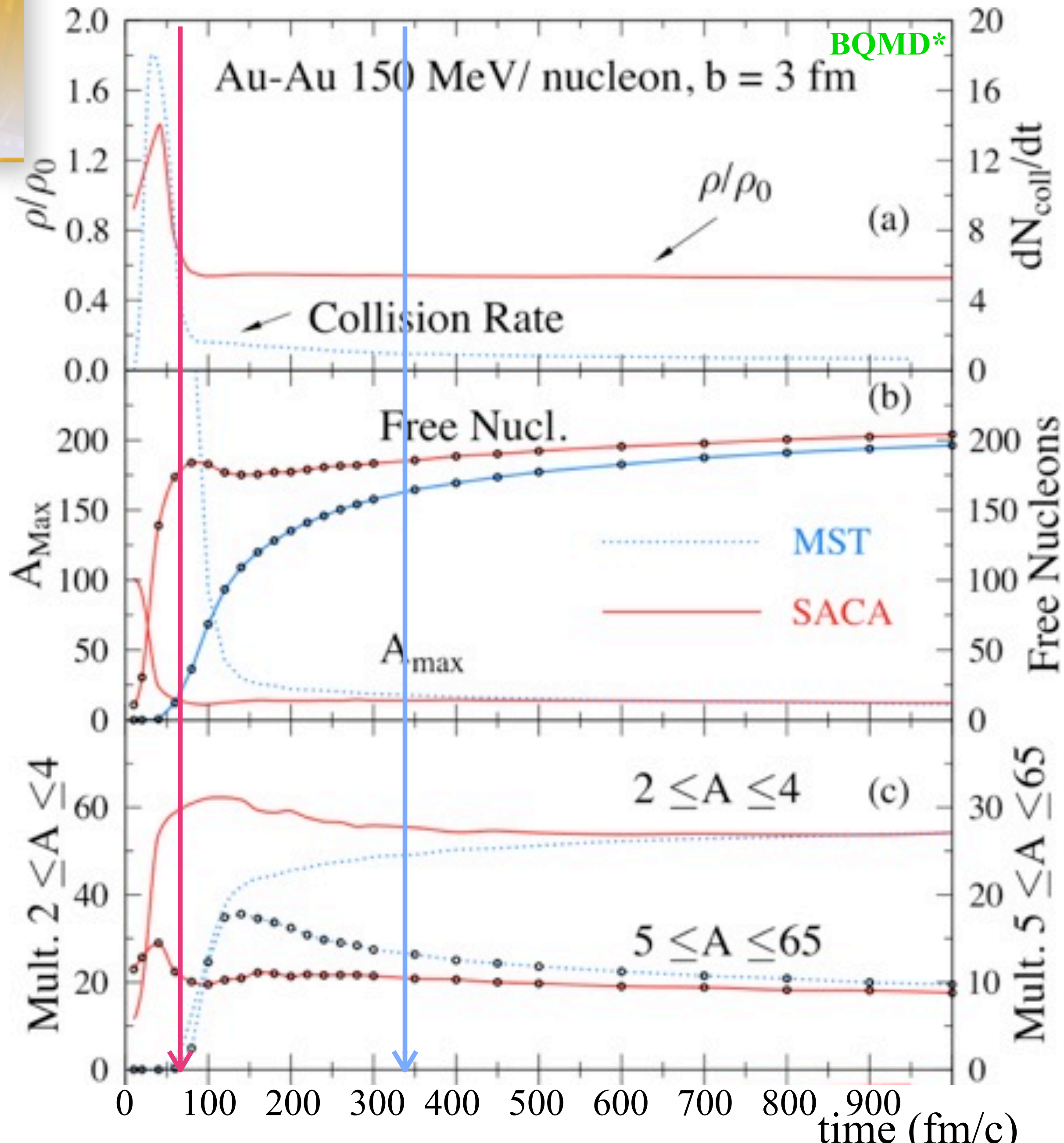
▸ Advantage of SACA : the fragment partitions can reflect the early dynamical conditions (Coulomb, density, flow details, strangeness...).



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Toward the isotope yields... IQMD + new SACA

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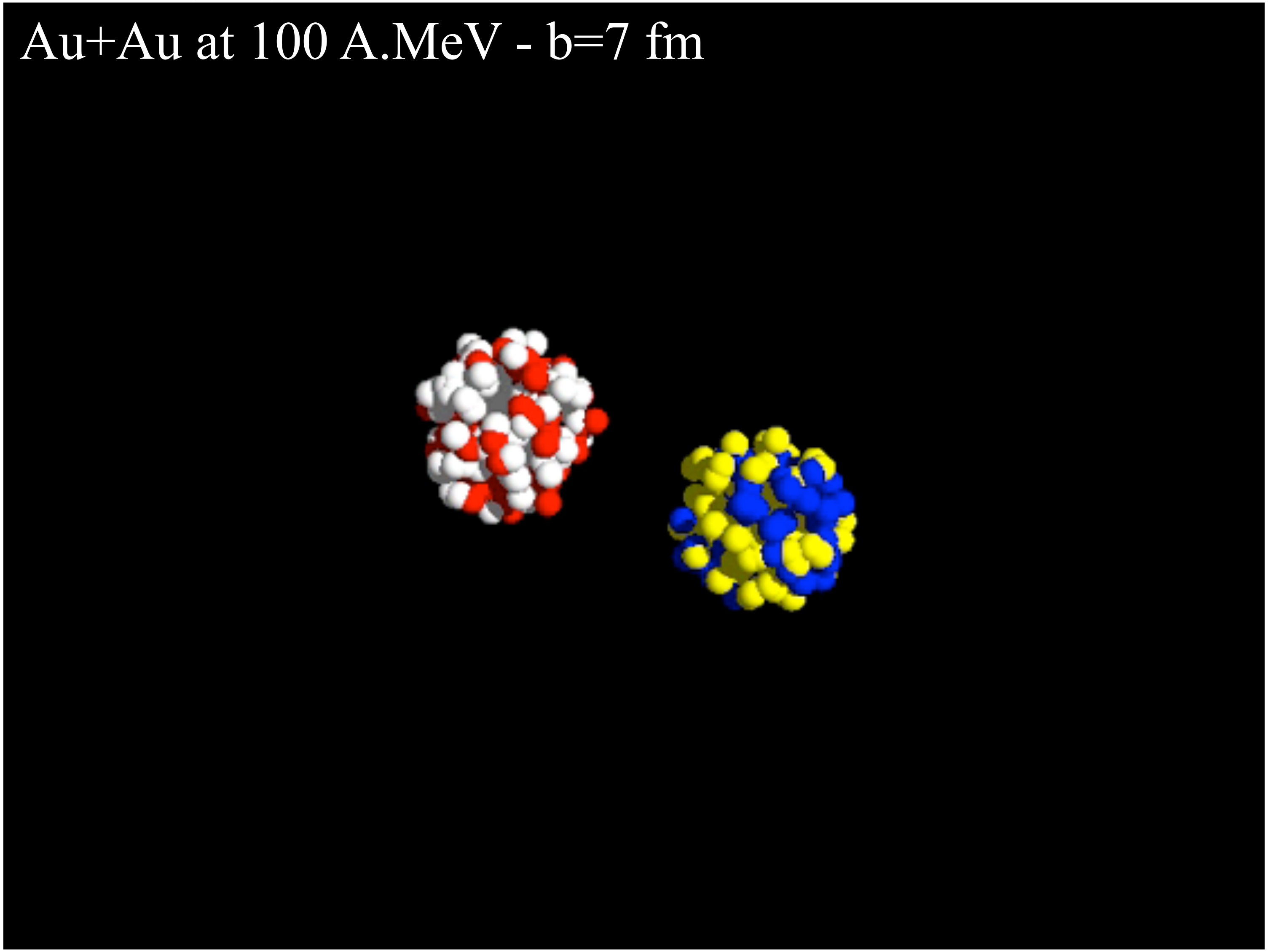

An example of complex system accurately measured

Large Z range of measured isotopes,
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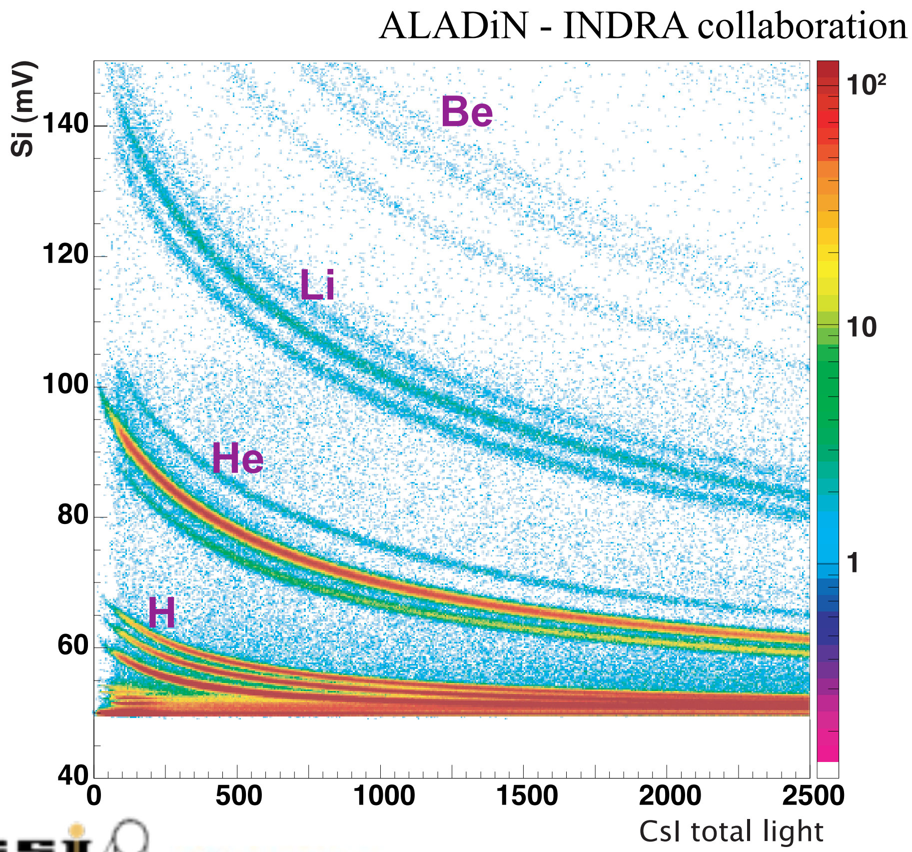

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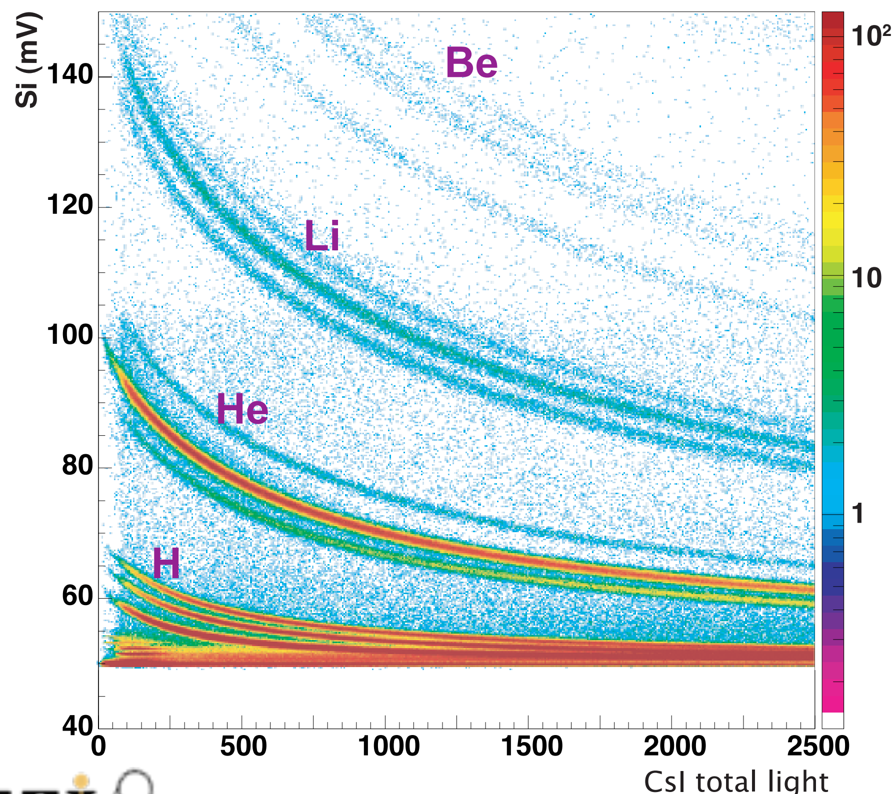
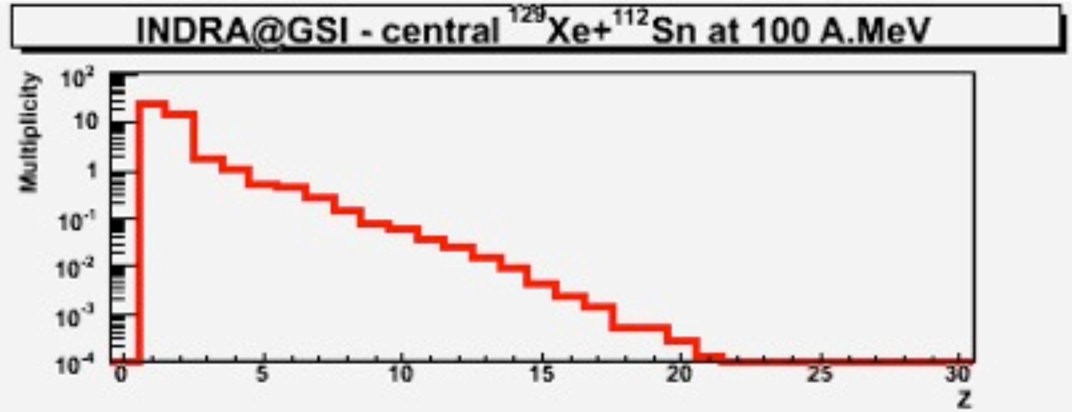
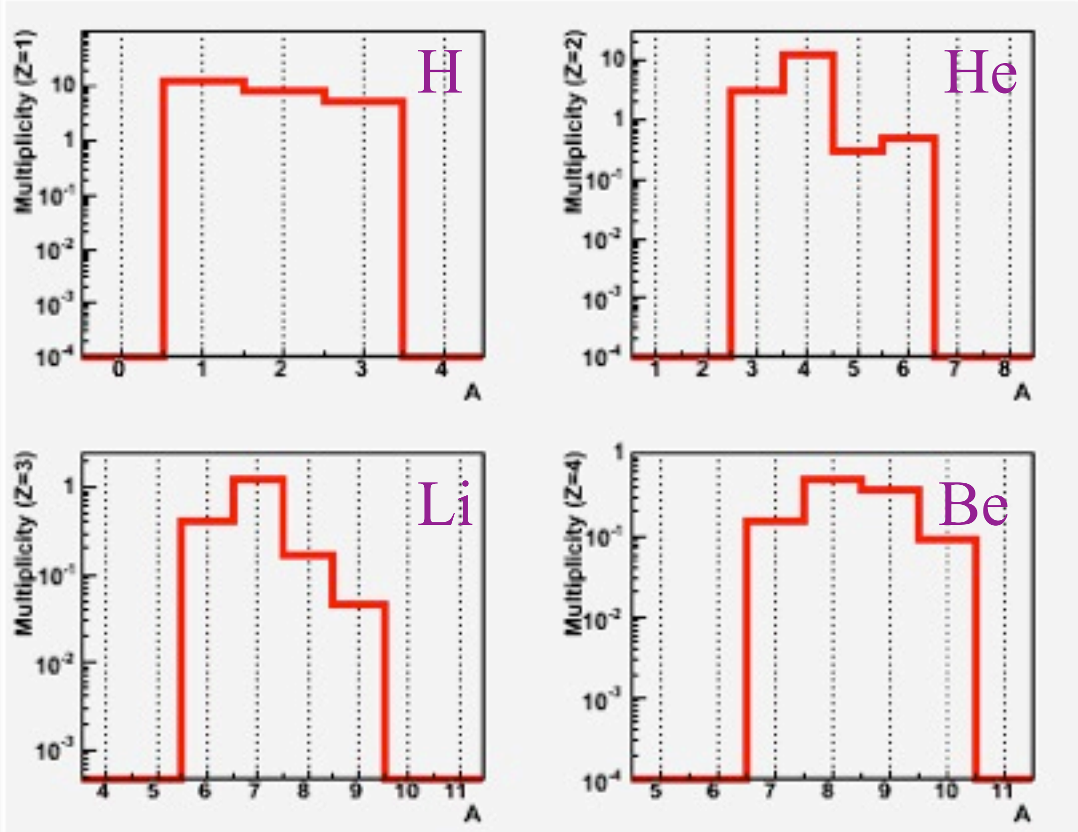
ALADiN - INDRA collaboration







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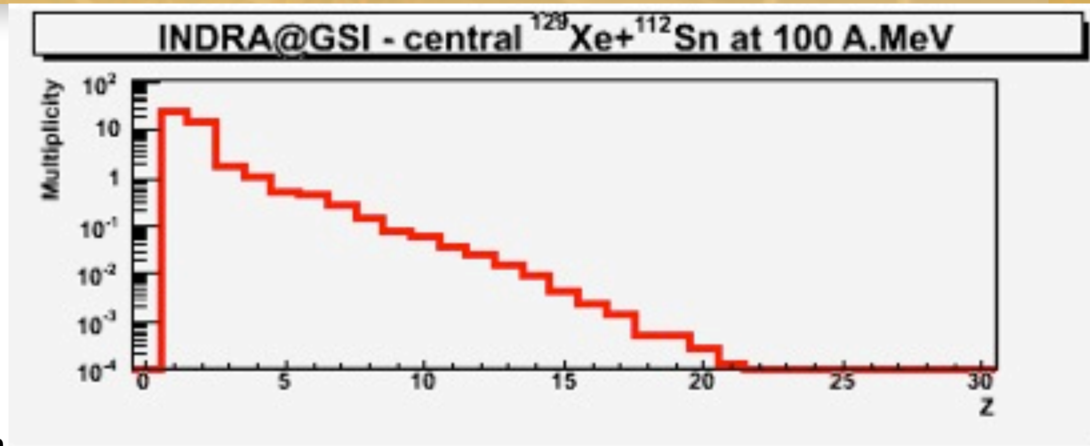

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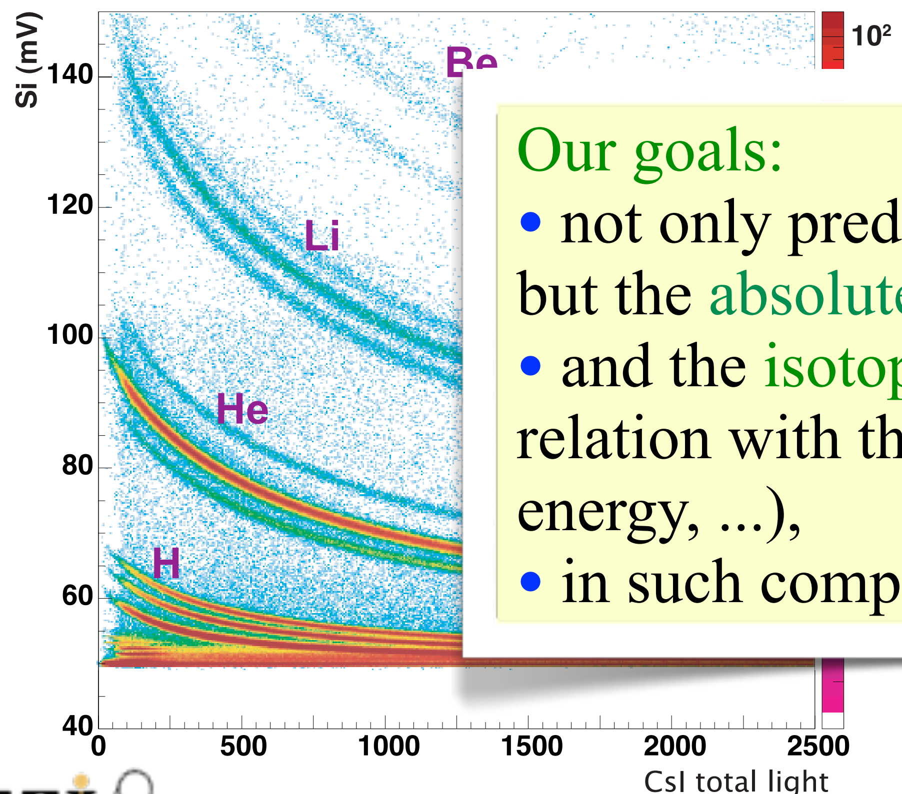
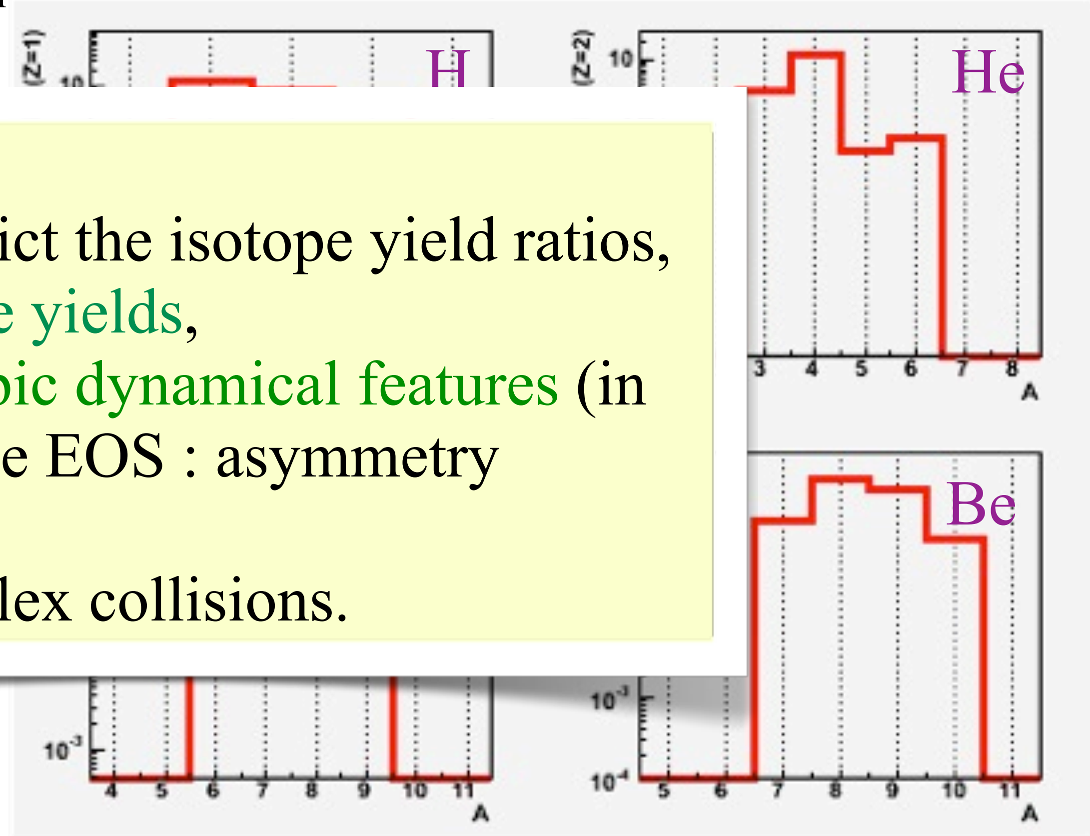




Our goals:

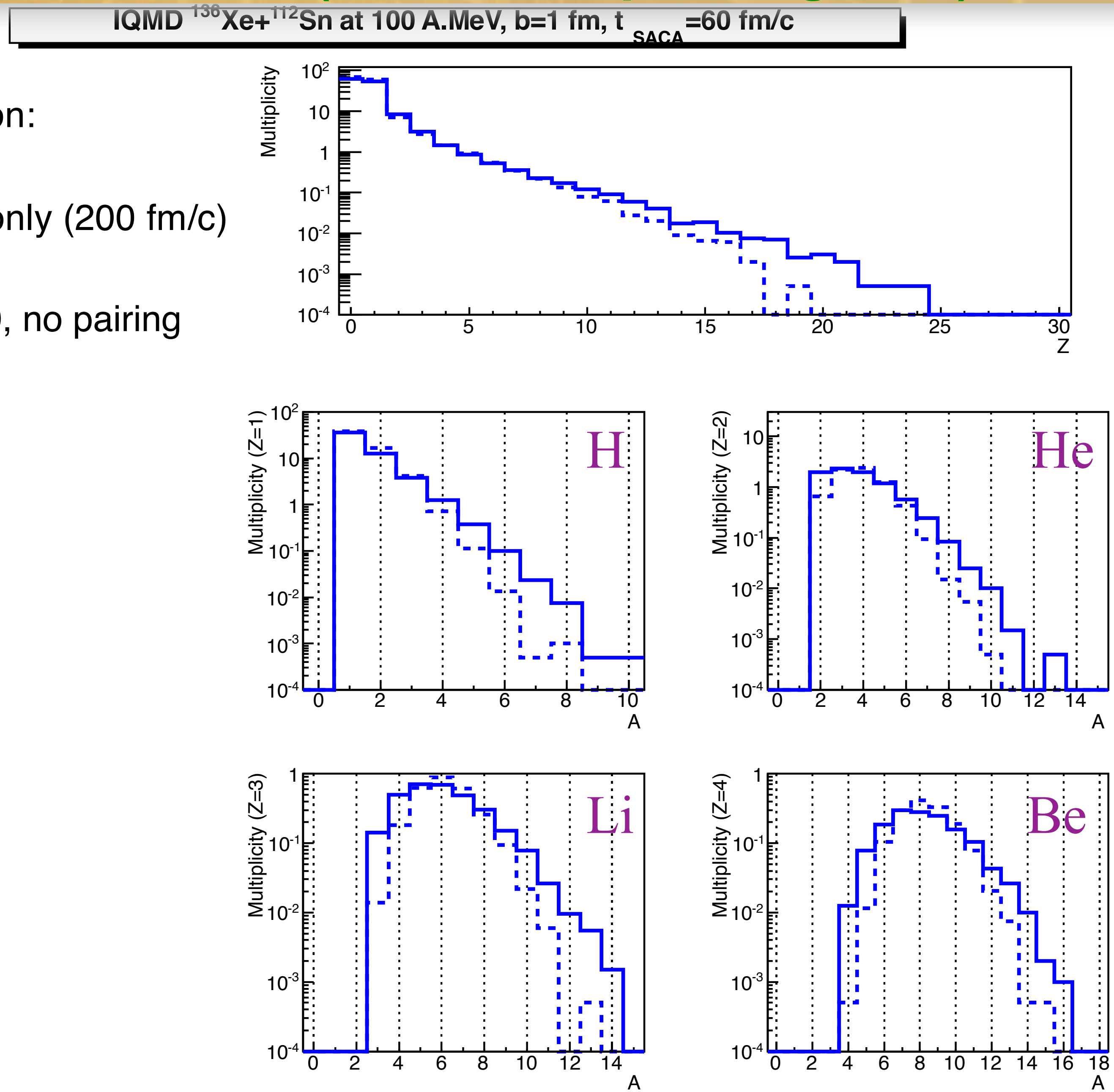
- not only predict the isotope yield ratios, but the absolute yields,
- and the isotopic dynamical features (in relation with the EOS : asymmetry energy, ...),
- in such complex collisions.

SACA versus coalescence (Minimum Spanning Tree)

SACA version:

MST only (200 fm/c)

E_{asy}=0, no pairing



SACA versus coalescence (Minimum Spanning Tree)

IQMD ^{136}Xe+^{112}Sn at 100 A.MeV, b=1 fm, t_{SACA}=60 fm/c

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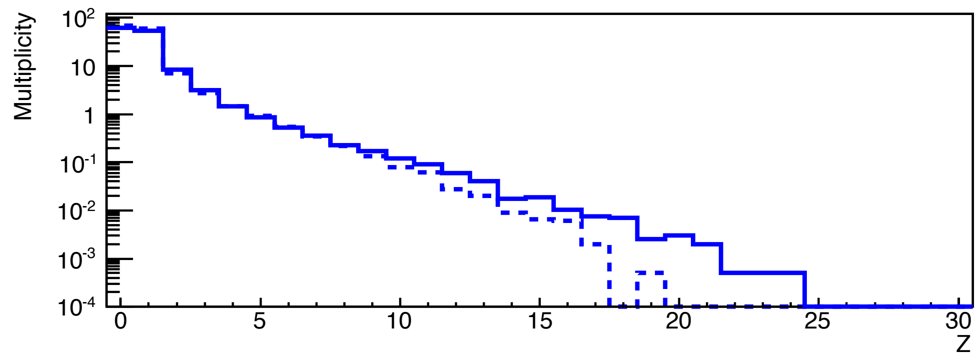
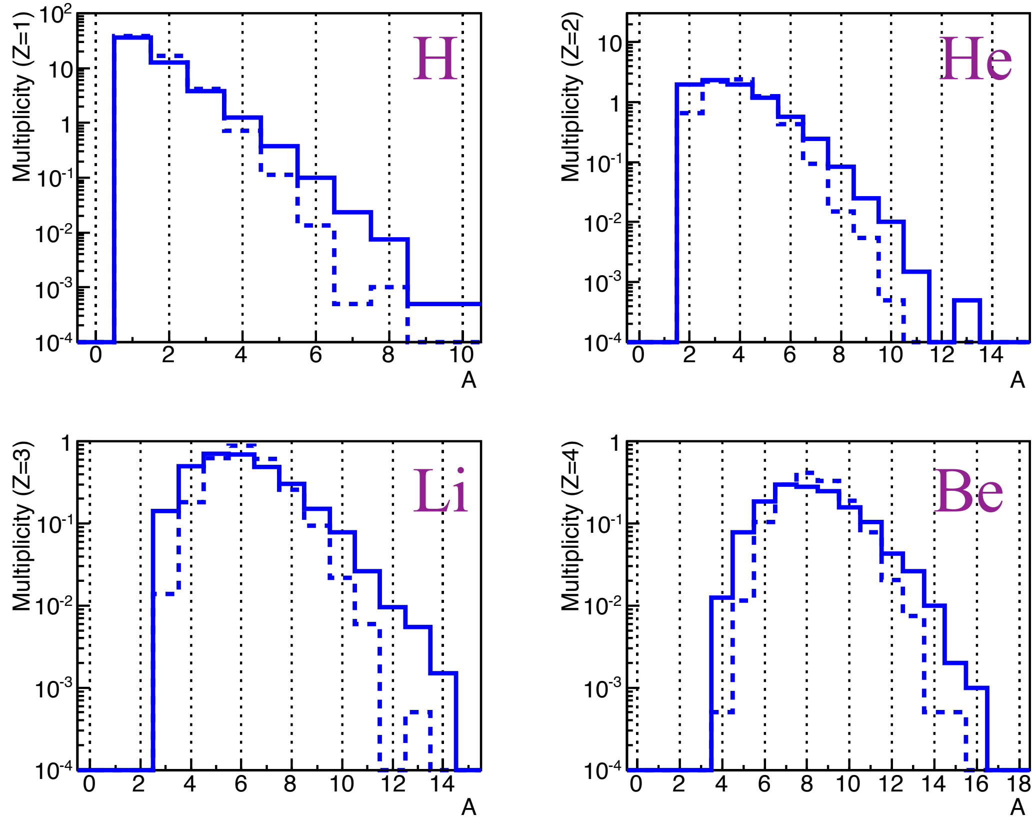


At this stage, SACA contains as ingredients of the potential making the binding energy of the clusters :

① volume component:
mean field (Skyrme, dominant)

② correction of surface effects:
Yukawa

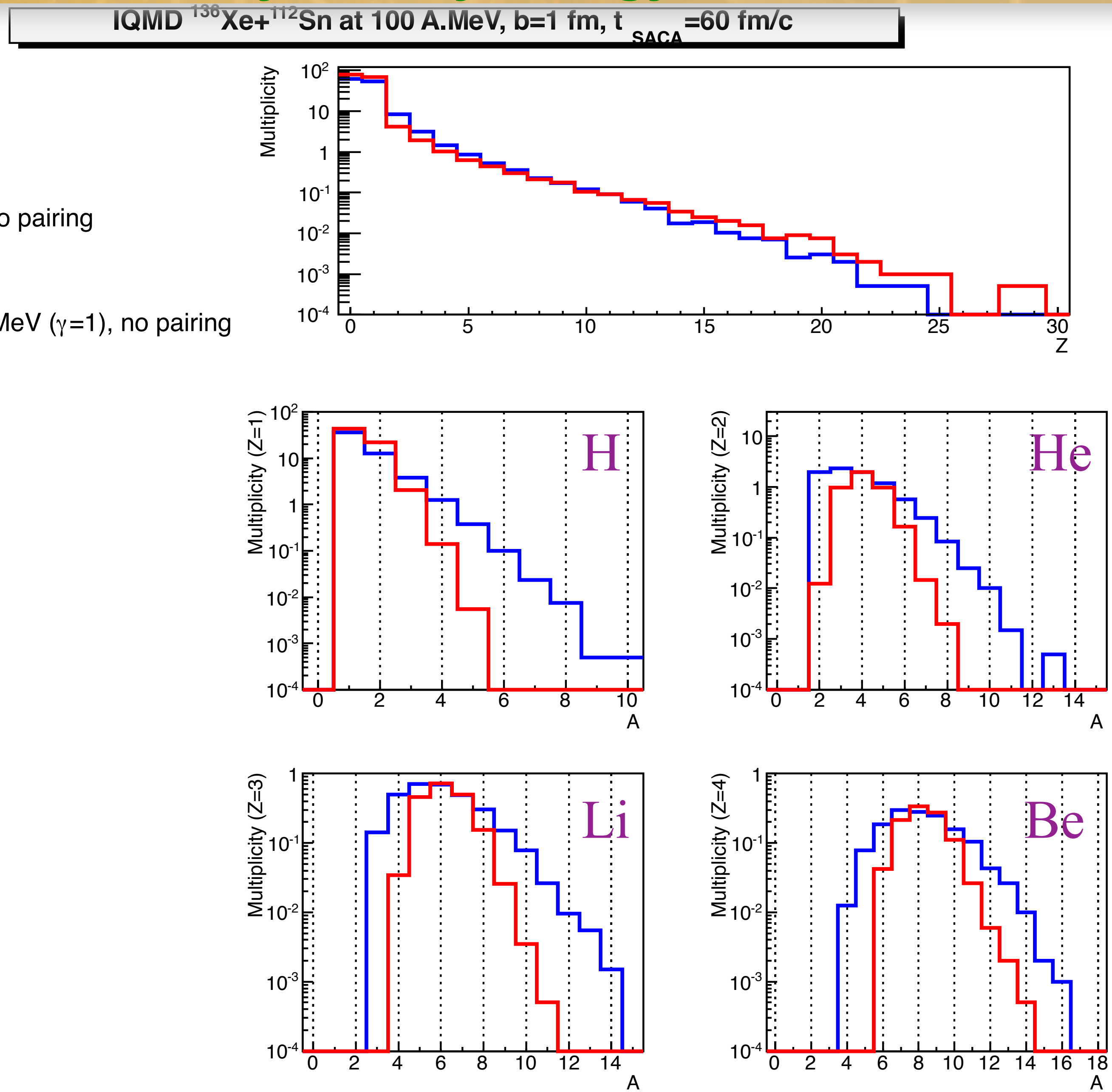


SACA with asymmetry energy

SACA version:

— E_{asy}=0, no pairing

— E_{asy}=32 MeV (γ=1), no pairing



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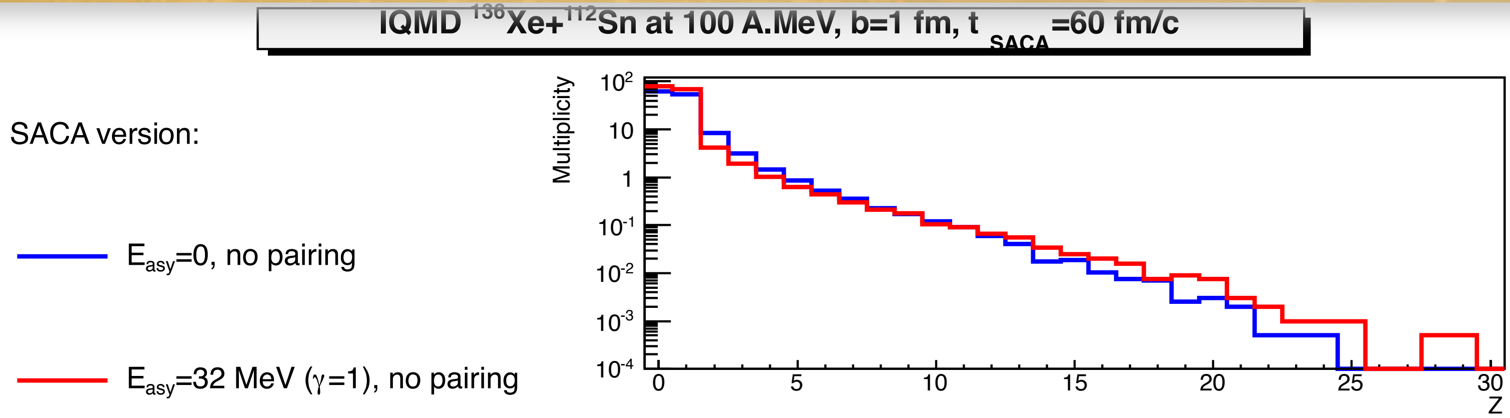
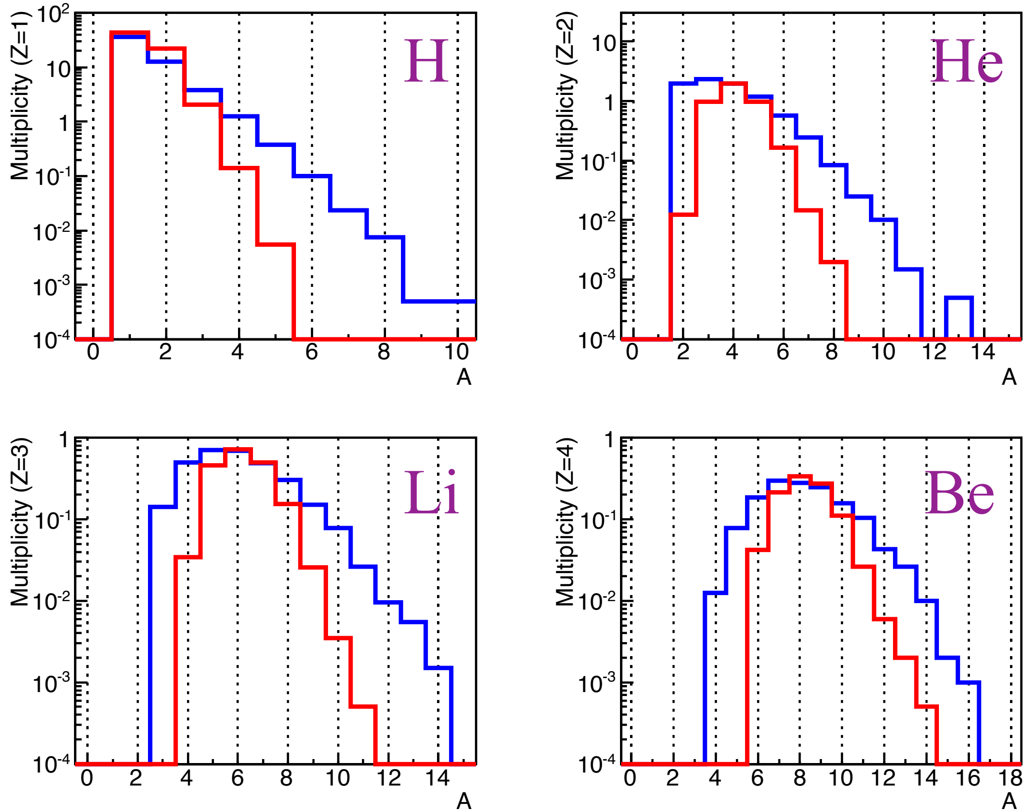


Here,
in IQMD and SACA, we adopt the following asymmetry energy parametrisation:

$$E_{asy}=E_0.(\langle\rho_B\rangle/\rho_0)^{(\gamma-1)}.(\langle\rho_n\rangle-\langle\rho_p\rangle)/\langle\rho_B\rangle$$

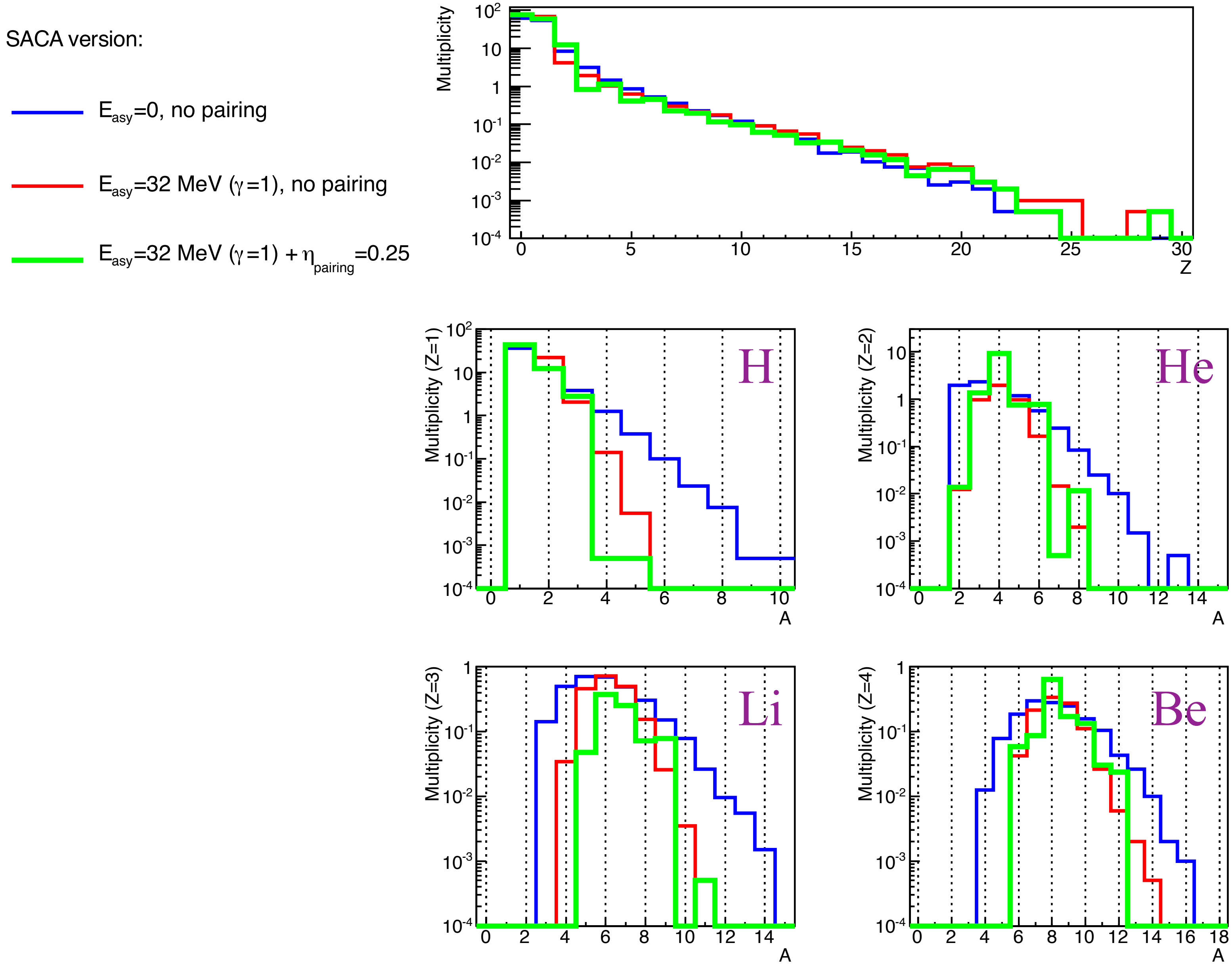
with E_0=32 MeV, γ=1 («stiff»)

- ➡ Z and A yields not strongly modified
- ➡ Isotope yields shrink onto the N=Z line
- ➡ Still not fully realistic: shell, odd-even effects (pairing) still absent.

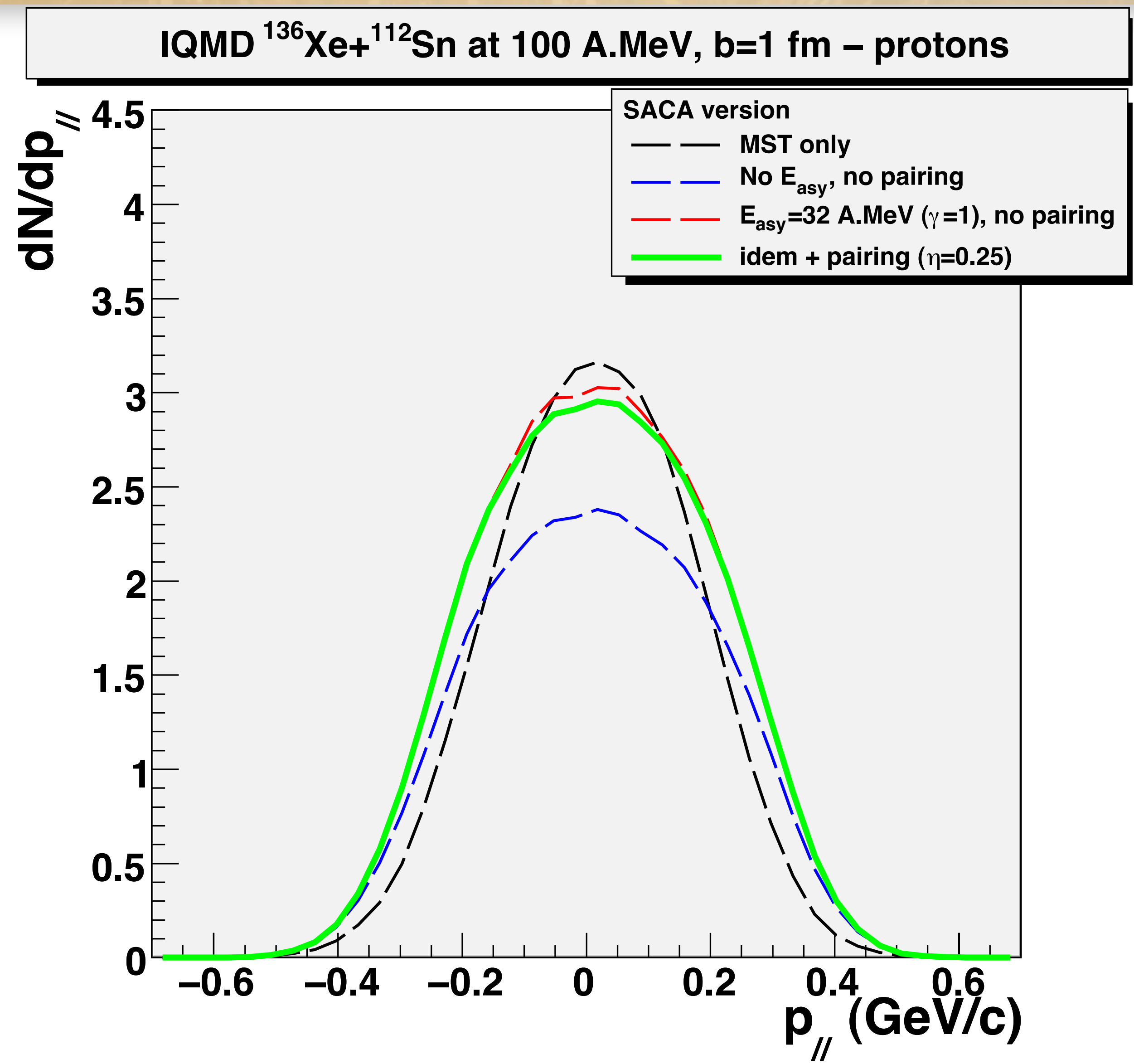


SACA with asymmetry energy and pairing

INDRA@GSI - central ^{129}Xe+^{112}Sn at 100 A.MeV



How the dynamical patterns of isotopes are affected



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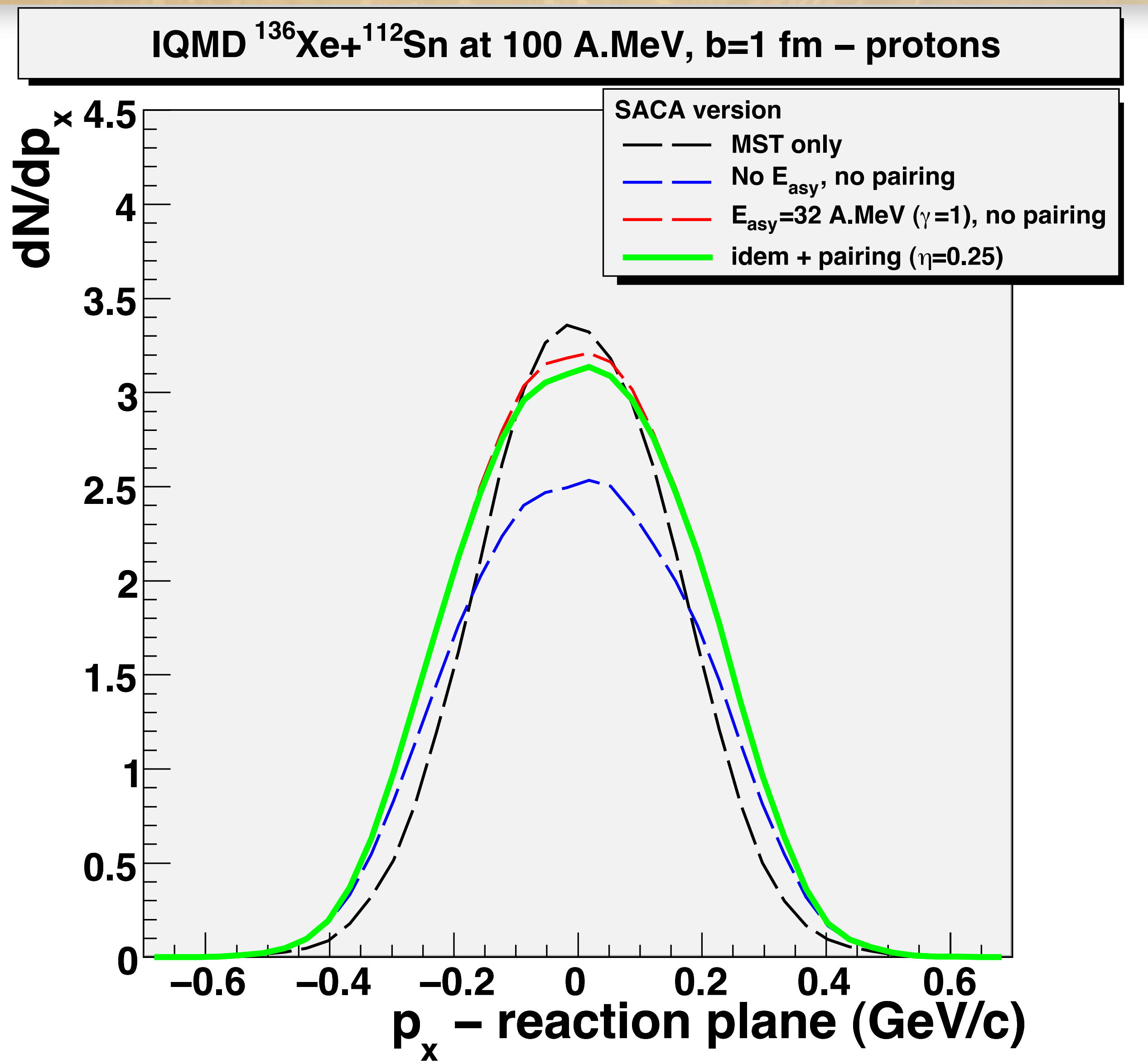

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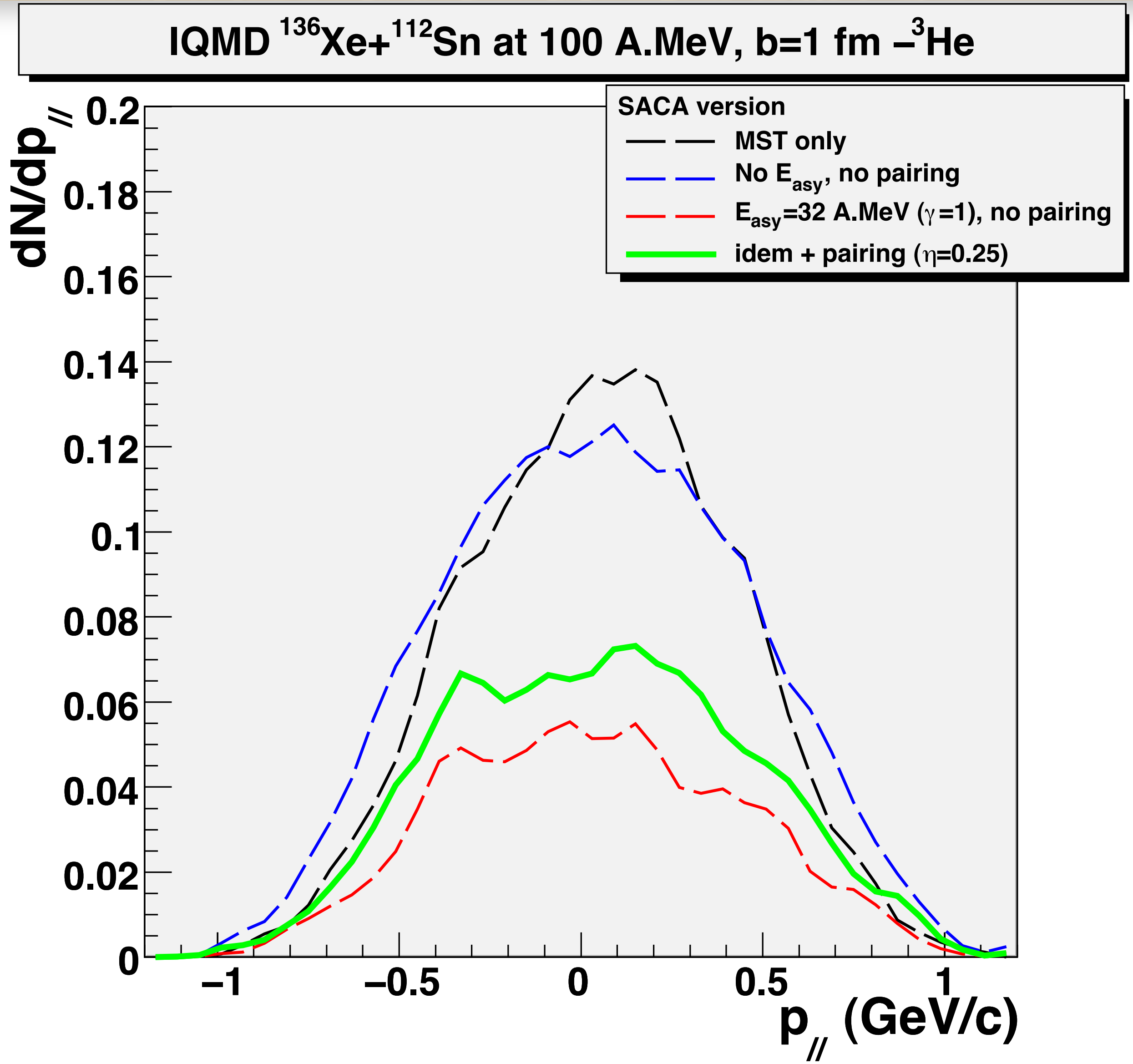

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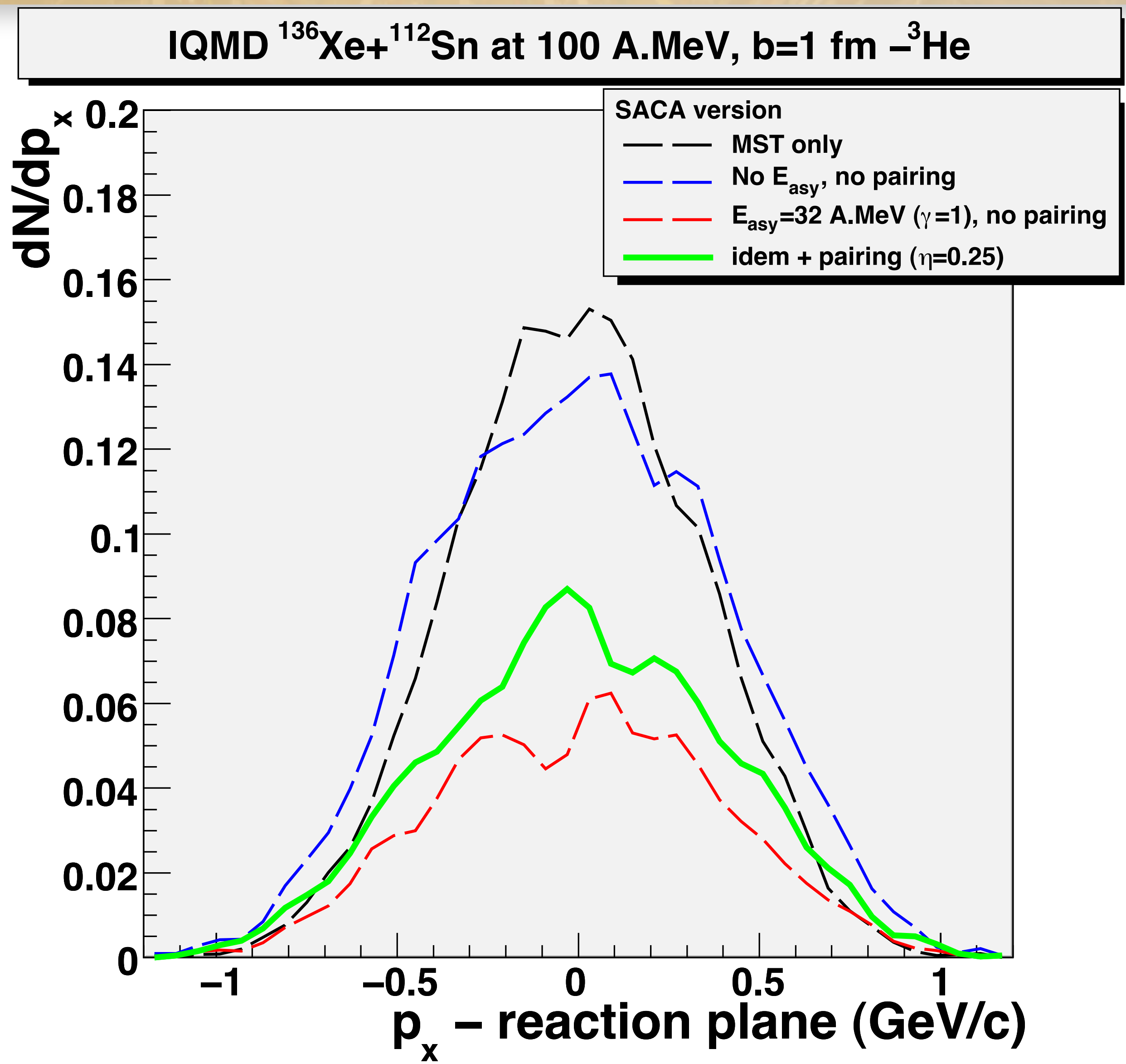

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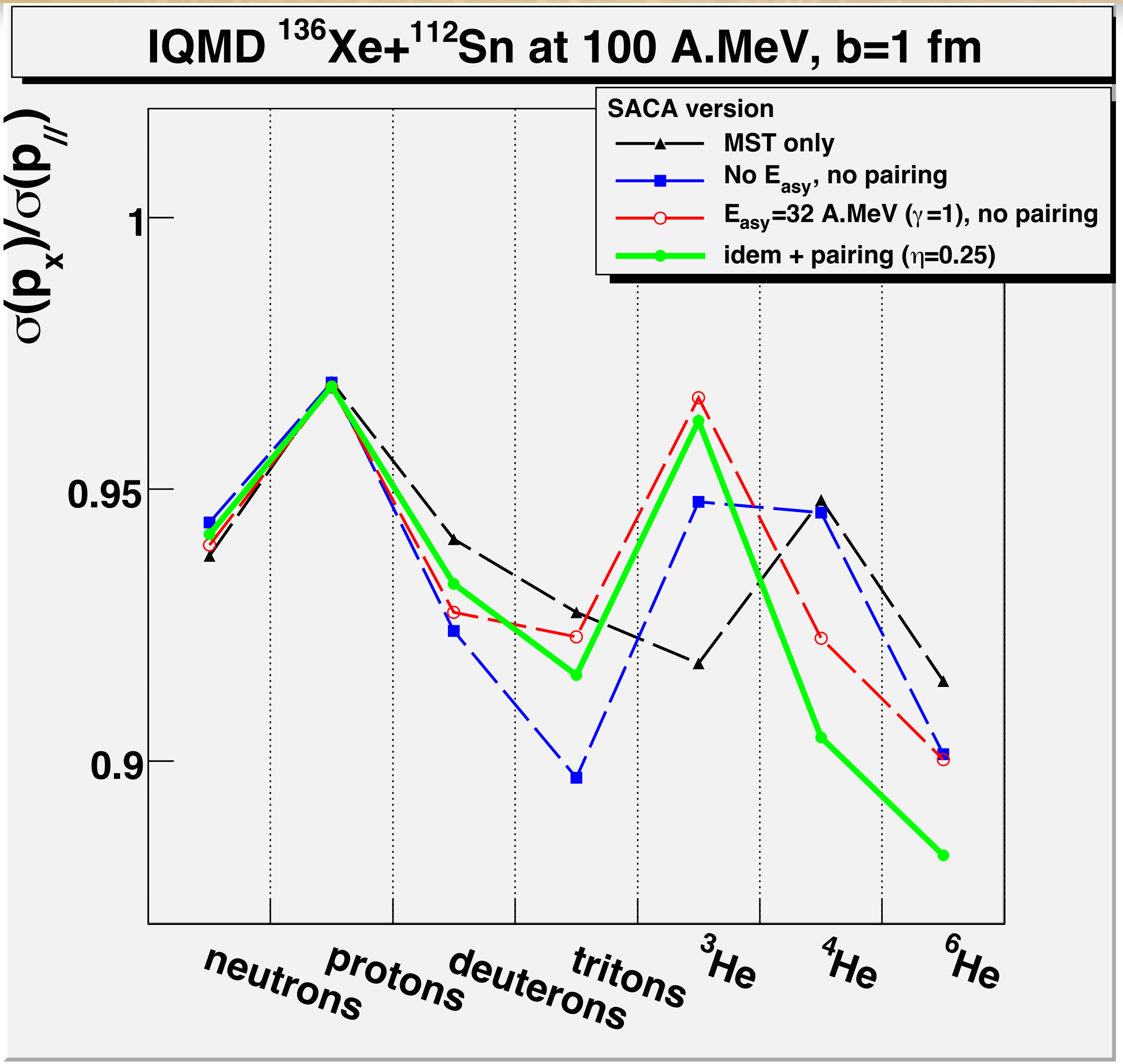

Excitation energy of the primary fragments

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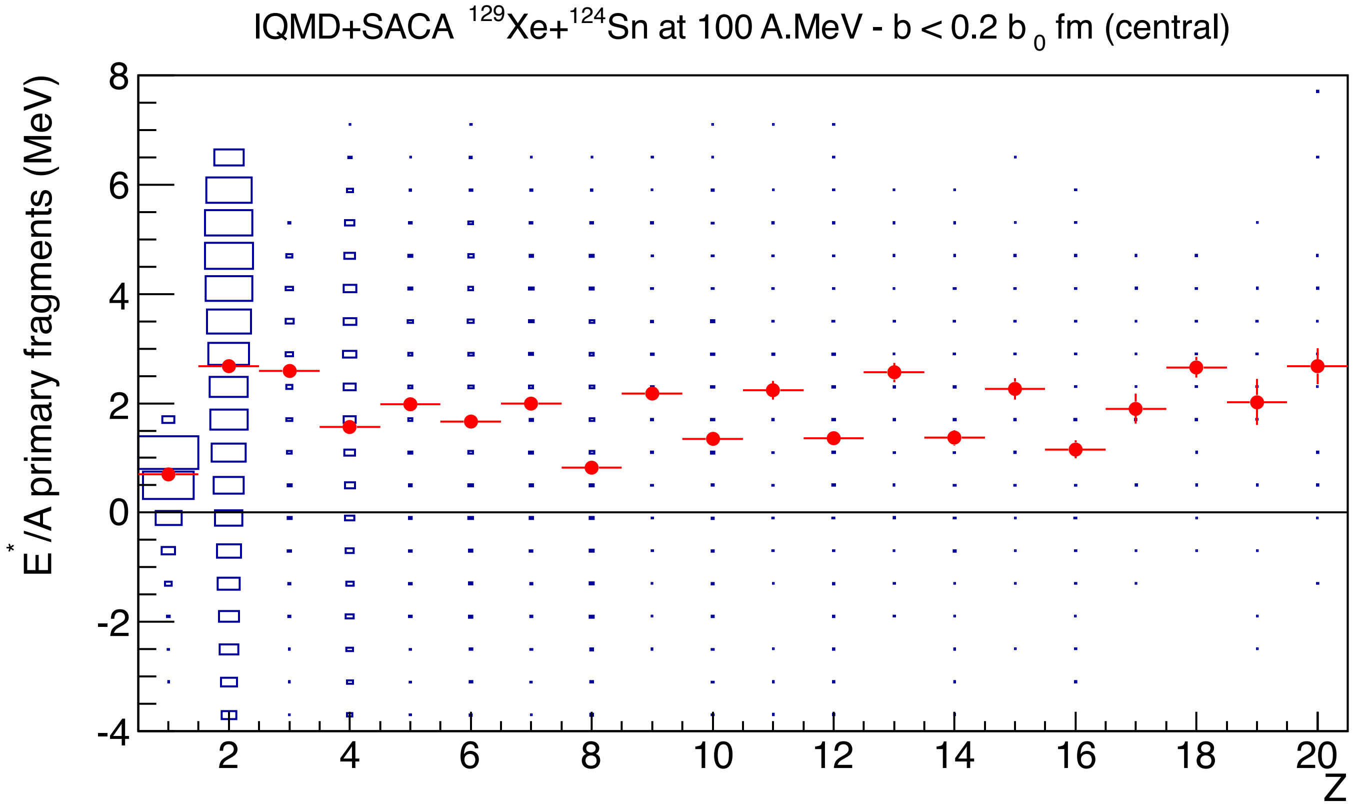

On Average, 2 A.MeV of excitation energy. Corresponds to findings of S. Hudan et al. (INDRA collaboration), PRC 67, 064613 (2003).
=> secondary decay (GEMINI) justified here.

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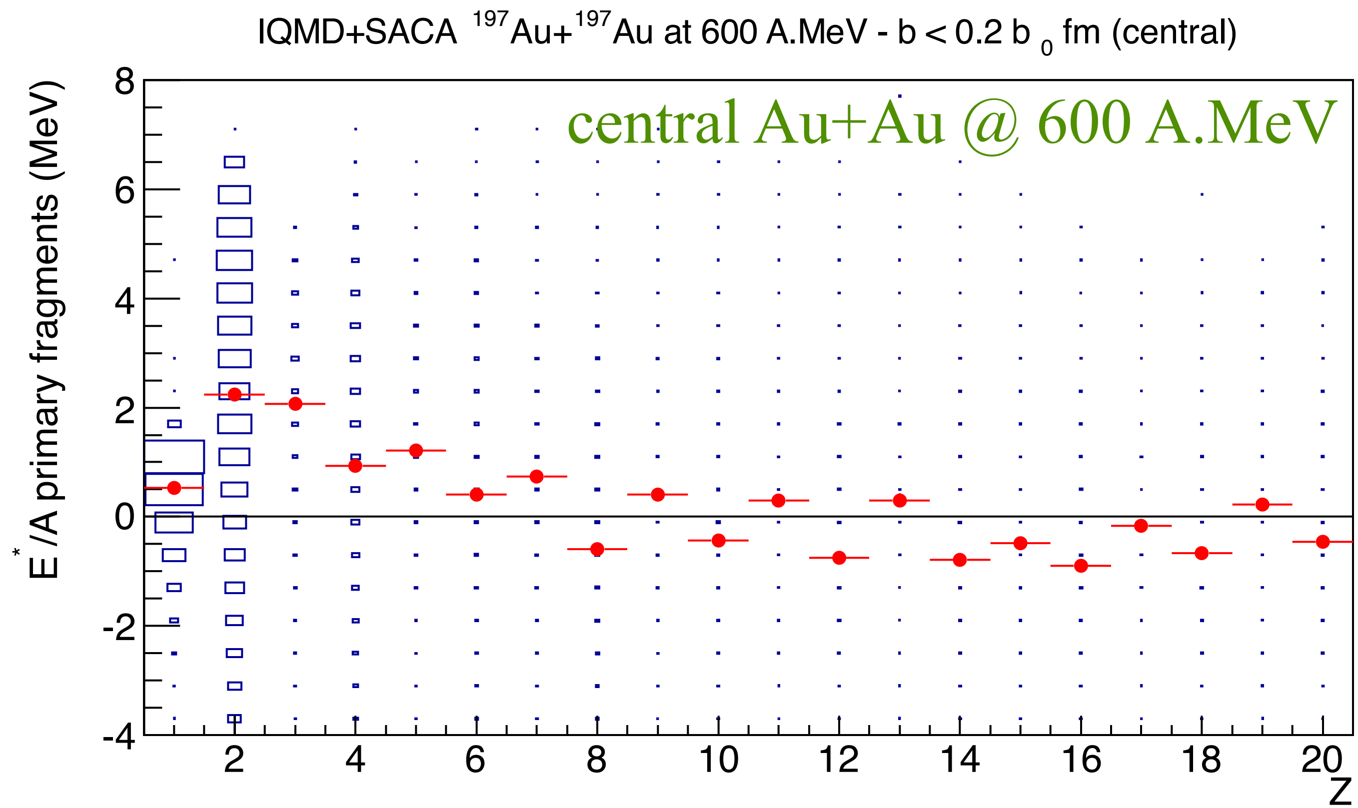

At relativistic energies, in the participant-spectator regime, heavy primary clusters are produced colder on average.

What can we learn from the isotope yields regarding the asymmetry energy?

Mean radius of primary clusters

IQMD+SACA

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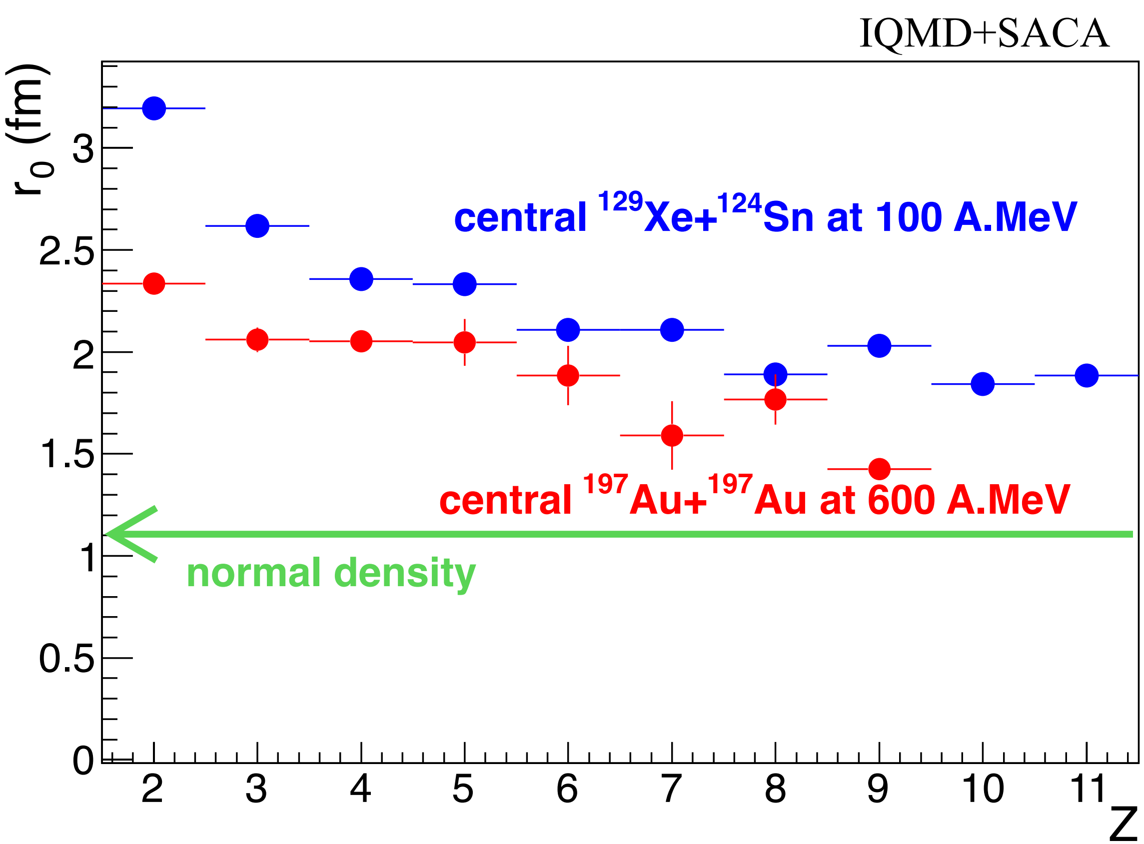

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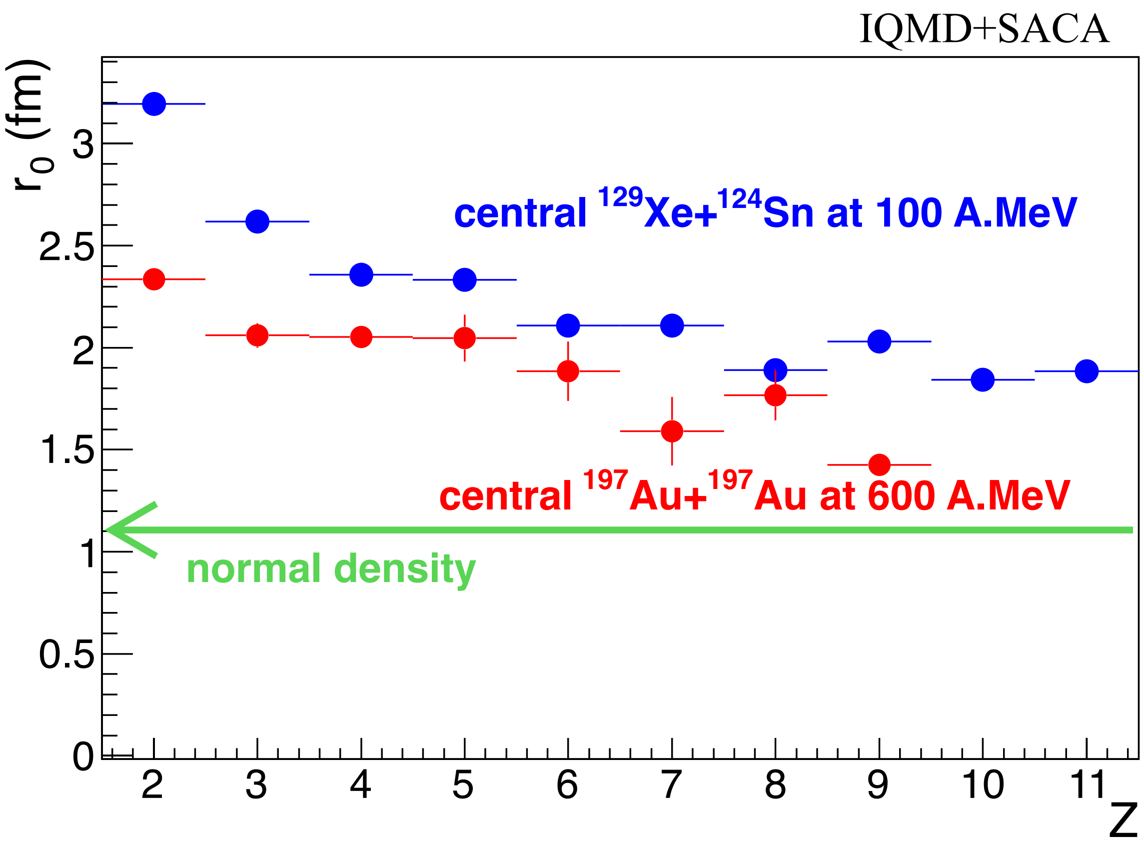

Though the medium is dense at this early stage, the dense clusters are disfavoured, because they would correspond to nucleons flowing against each other, hence with too high relative momenta to make a cluster.

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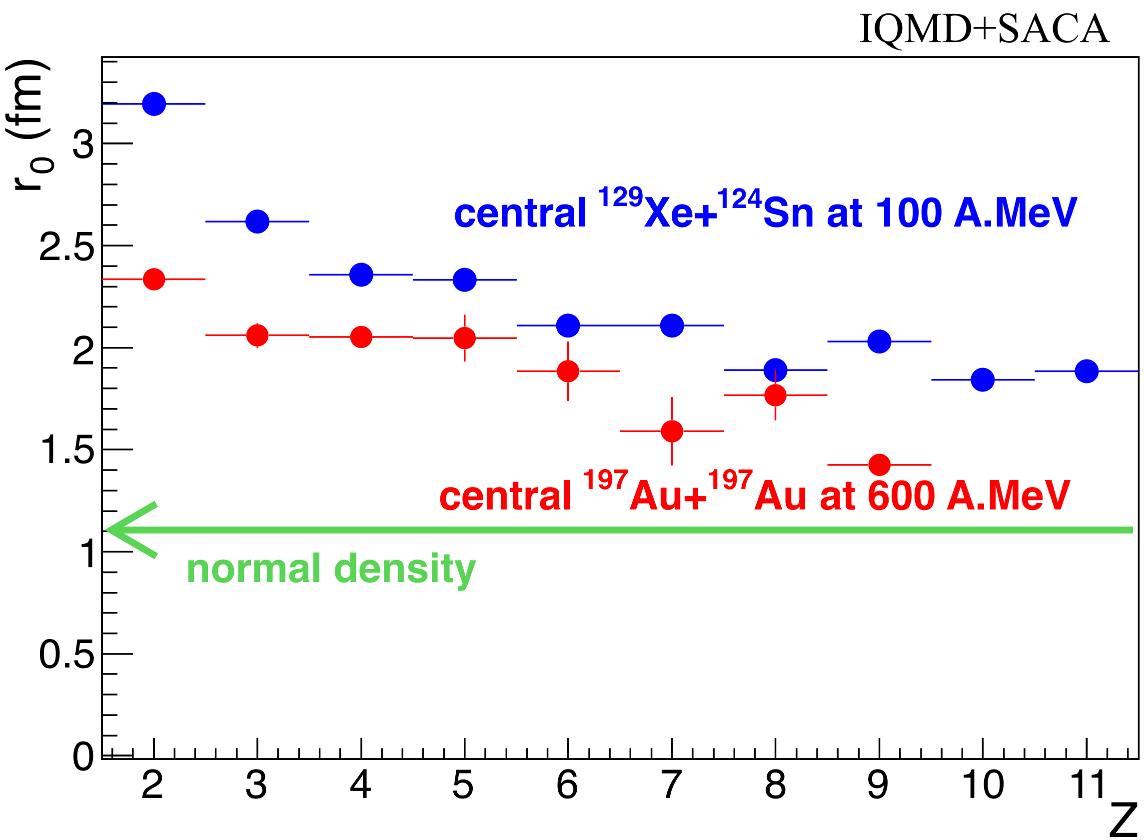

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=> The isotope yields can only inform on the low density dependence on the asymmetry energy.

Asymmetry energy influence versus system energy

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W. Reisdorf and the FOPI Collaboration

Nuclear Physics A 848 (2010) 366–427

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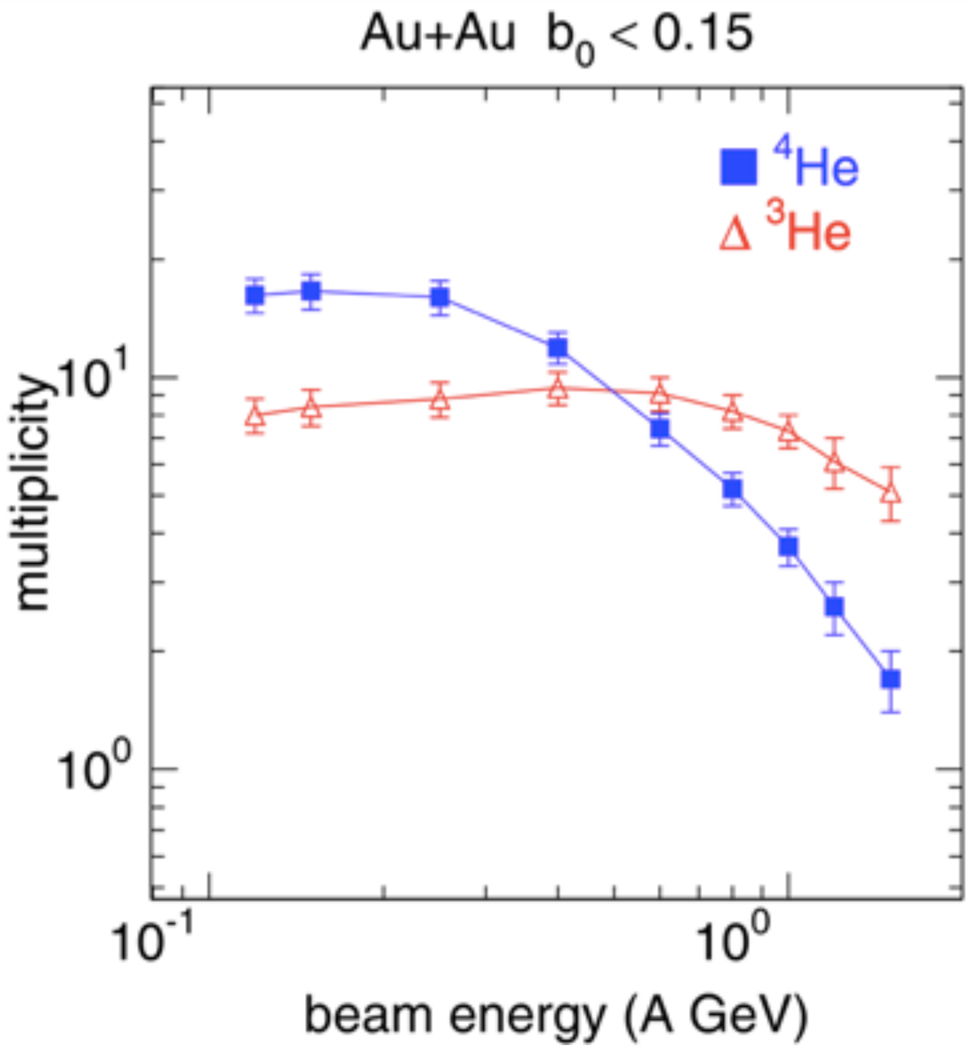

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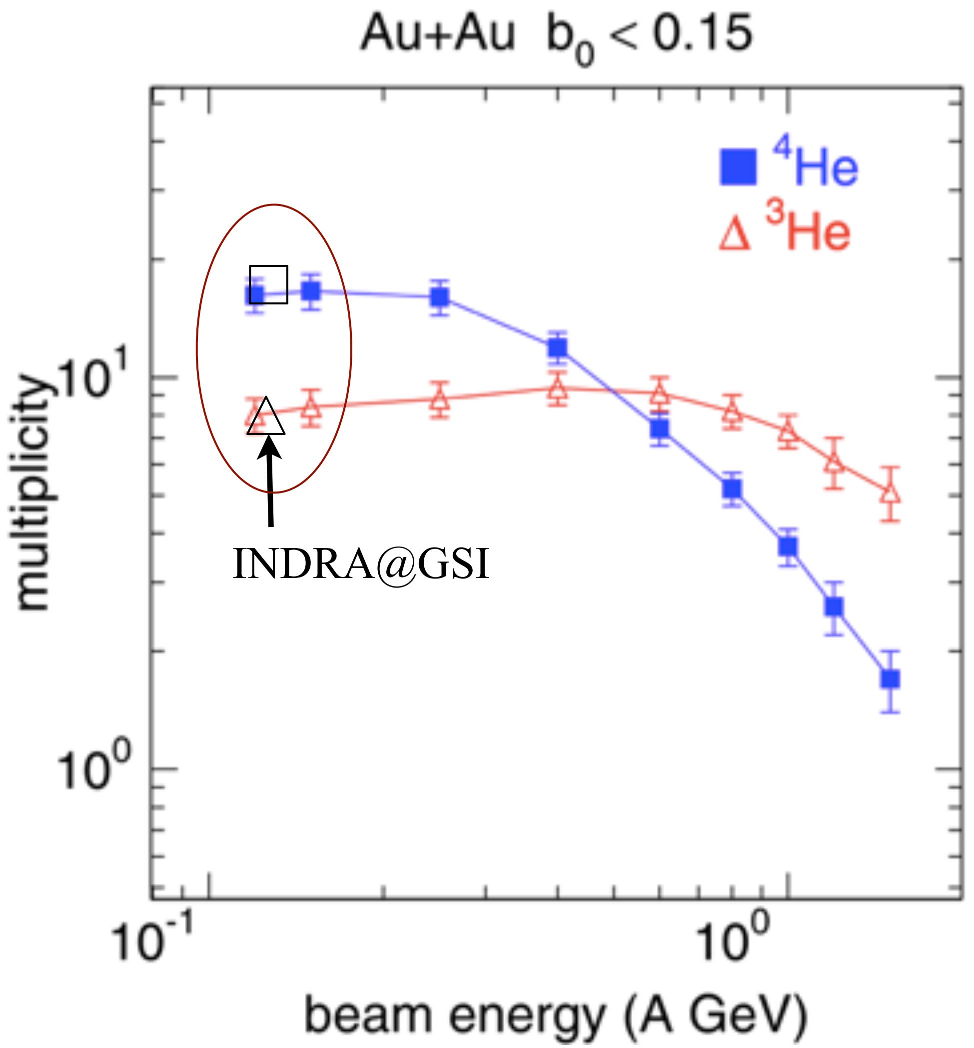

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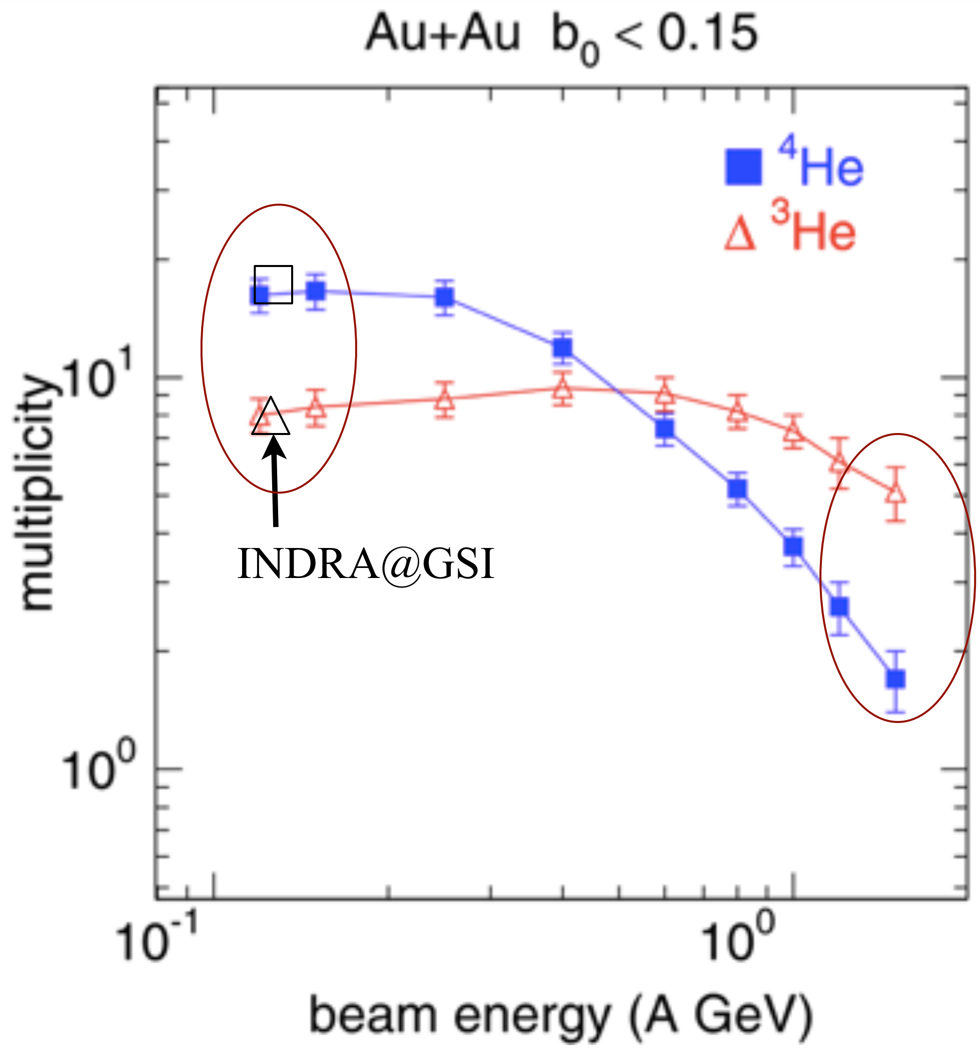

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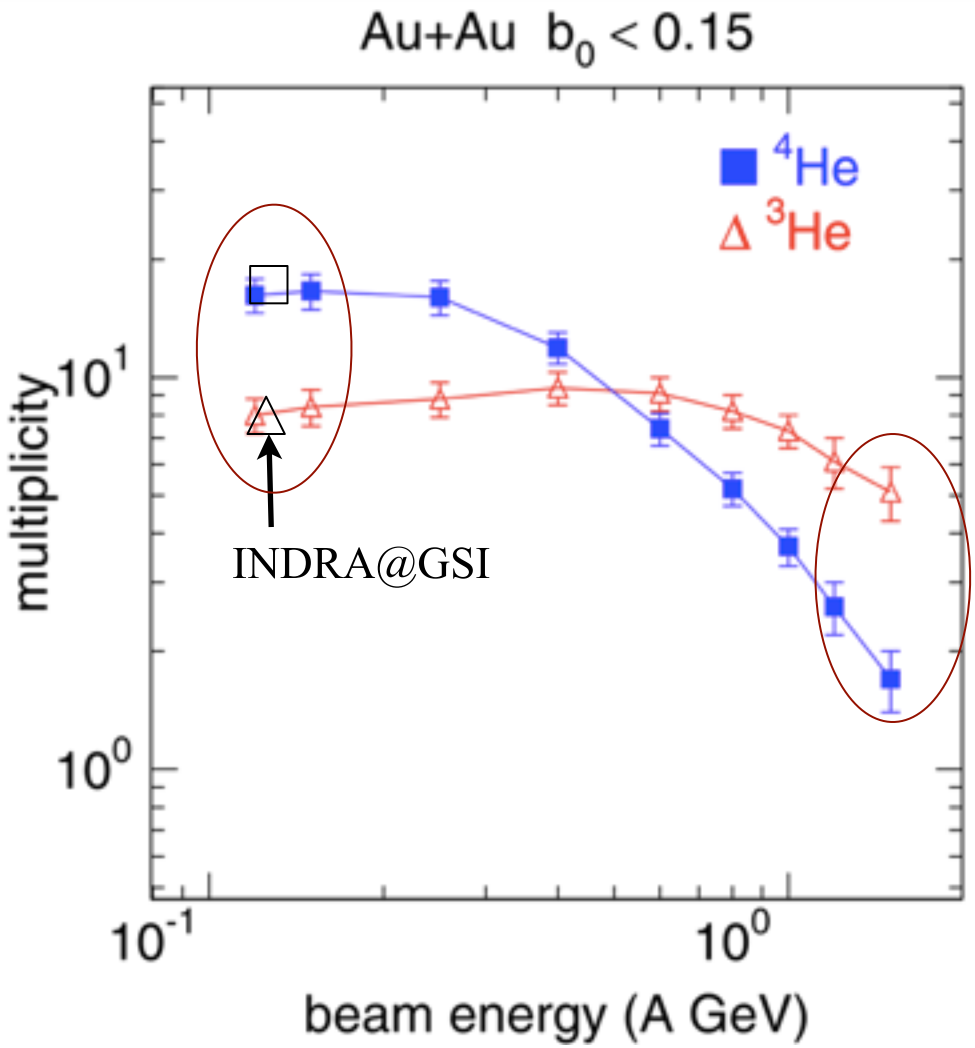
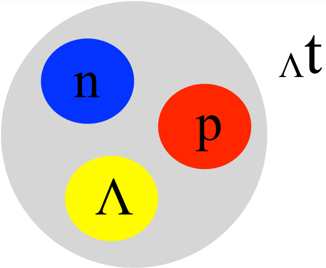
=> At high energy, the asymmetry energy effect on clusters seems to vanish. Timescale effect? Non-linear dependence on the density?



Another application of SACA : hypernuclei production



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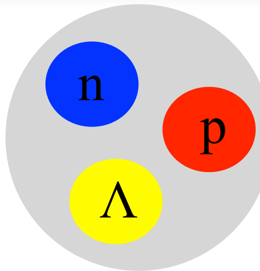
A hypernucleus is a nucleus which contains at least one hyperon (Λ(ud**s**), ...) in addition to nucleons.



$_\Lambda t$

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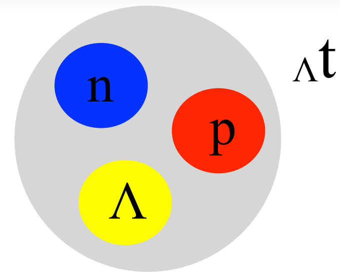

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Extending SACA for clusterising hadrons with hyperons (lambdas,...) for making hypernuclei is straightforward:

- one replaces $V_{n\text{-}p}$ by $V_{\Lambda\text{-}p}$ and $V_{n\text{-}n}$ by $V_{\Lambda\text{-}n}$
- and applies with these modifications the SACA algorithm.

If in a final fragment there is a lambda, a hypernucleus should be created.
As a first approach, we have adopted $V_{\Lambda\text{-}N} = 2/3\ V_{n\text{-}N}$; further refinements are possible.

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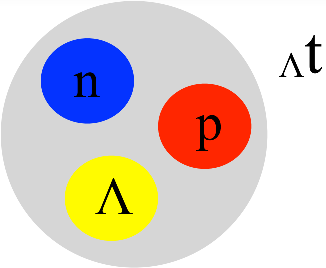

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Many ways of producing lambdas: $K\,N \rightarrow \Lambda\,\pi$, $\pi^+ n \rightarrow \Lambda\,K^+$, $\pi^- p \rightarrow \Lambda\,K_0$, $p\,p \rightarrow \Lambda\,X$
$\Rightarrow$ influence of the EOS, in medium-properties, etc.

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at
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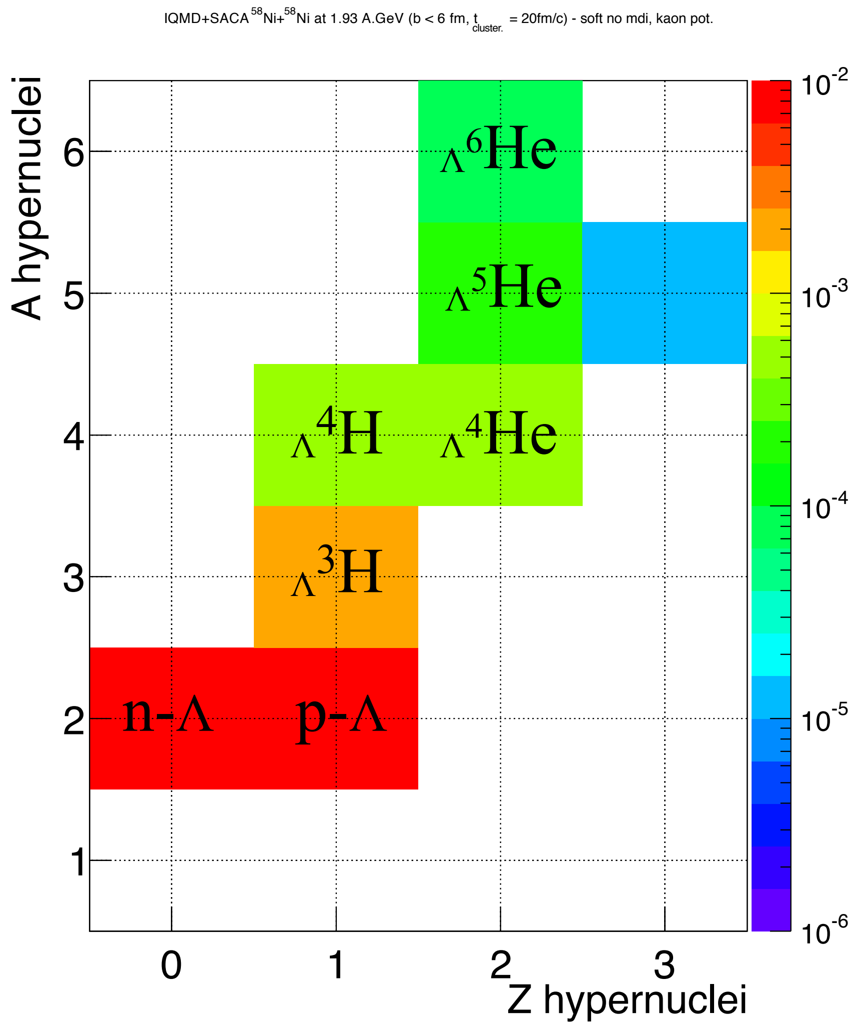
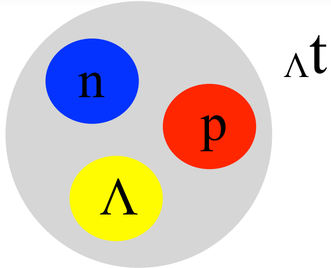
(b < 6 fm) -
$t_{cluster.}$=20 fm/c





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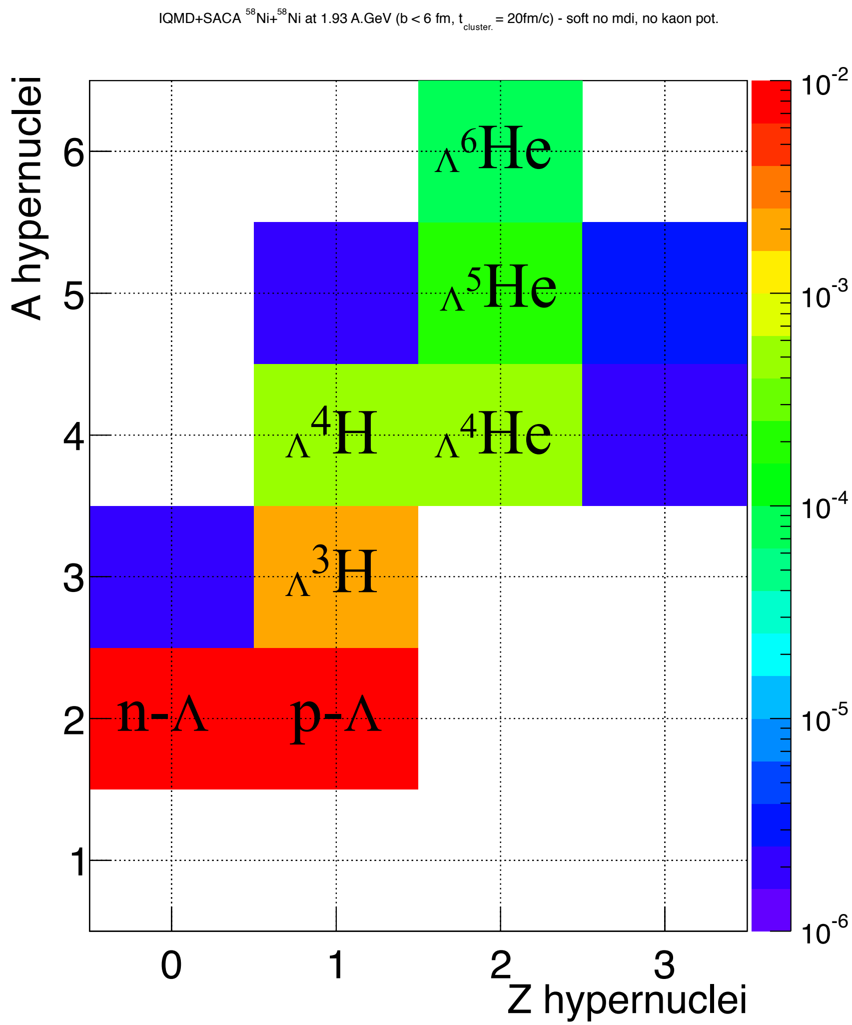

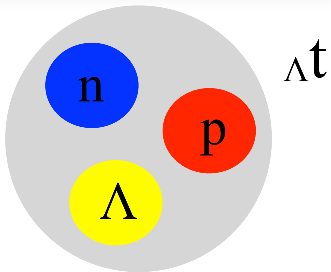

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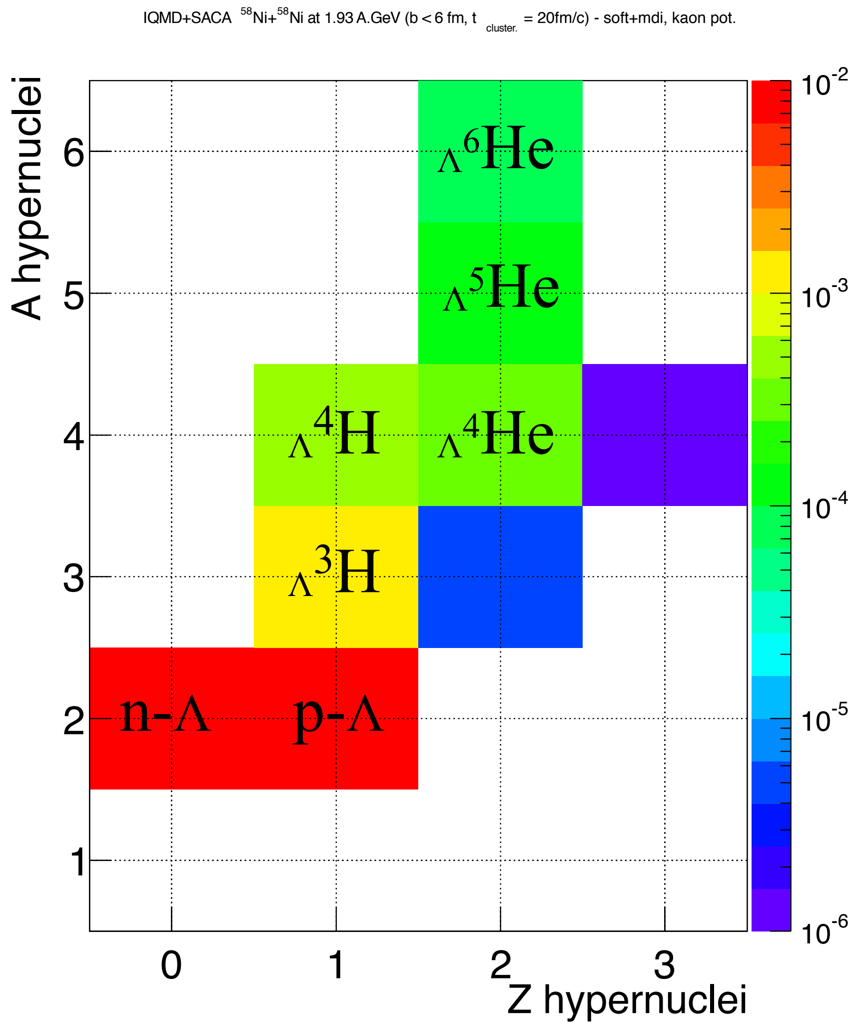

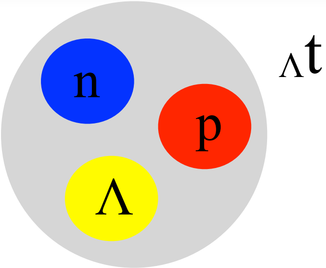

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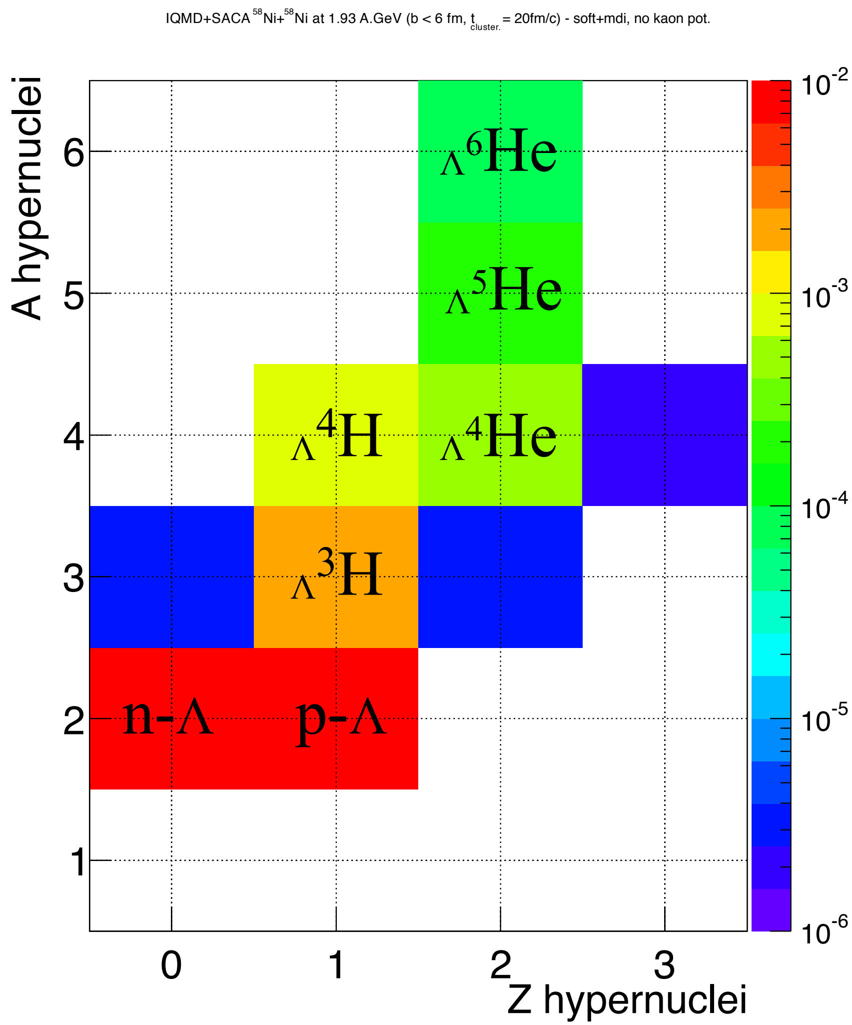

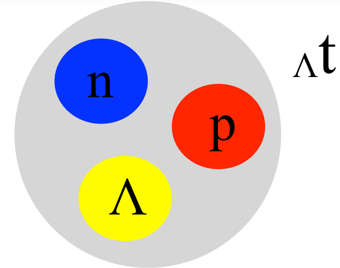

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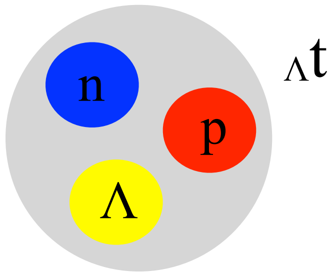
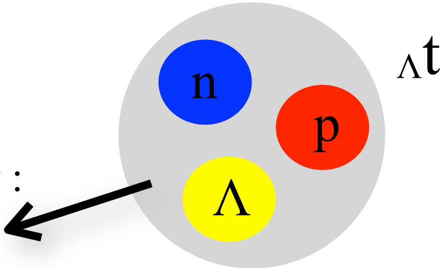
Strong phase space constraints



Strong phase space constraints

detected decay :

$^{3}He + \pi^{-}$



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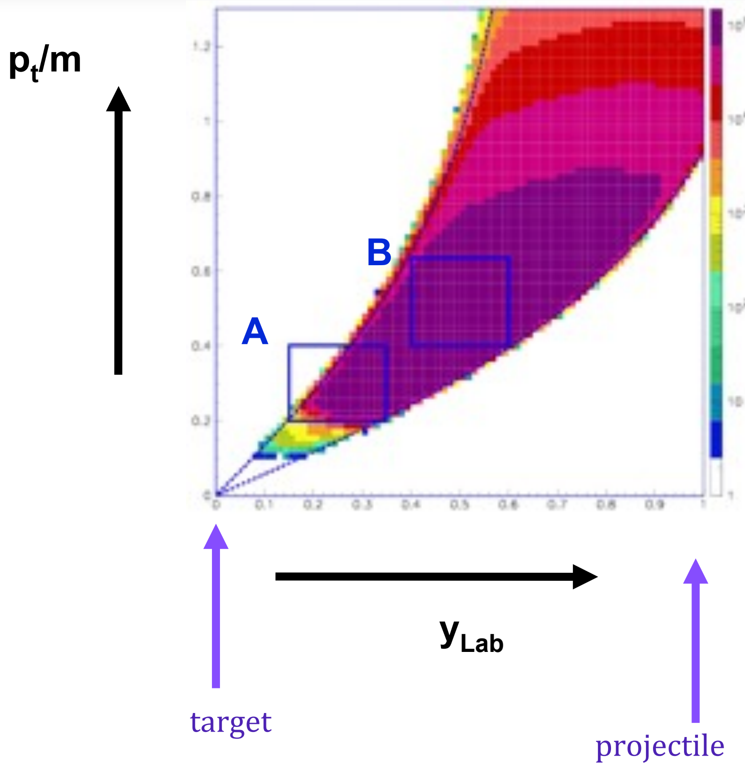
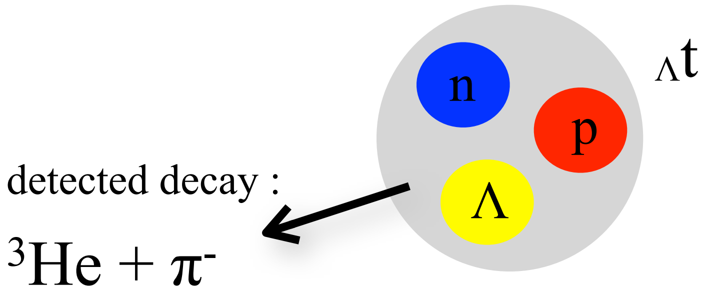
FOPI Coll.
Y. Zhang, Heidelberg





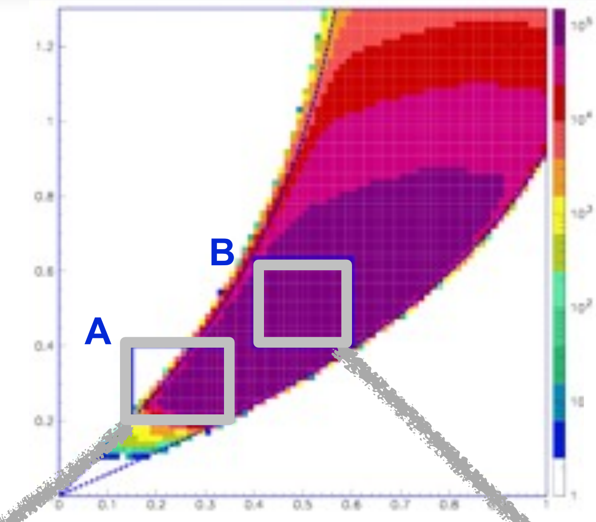
Ni+Ni @ 1.91 A.GeV

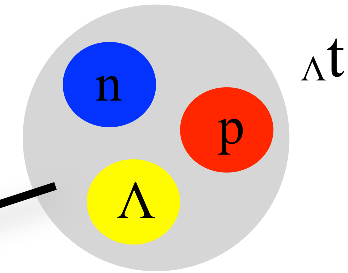
Preliminary

Strong phase space constraints

FOPI Coll.
Y. Zhang, Heidelberg

Excess over combinatorial background only in region A





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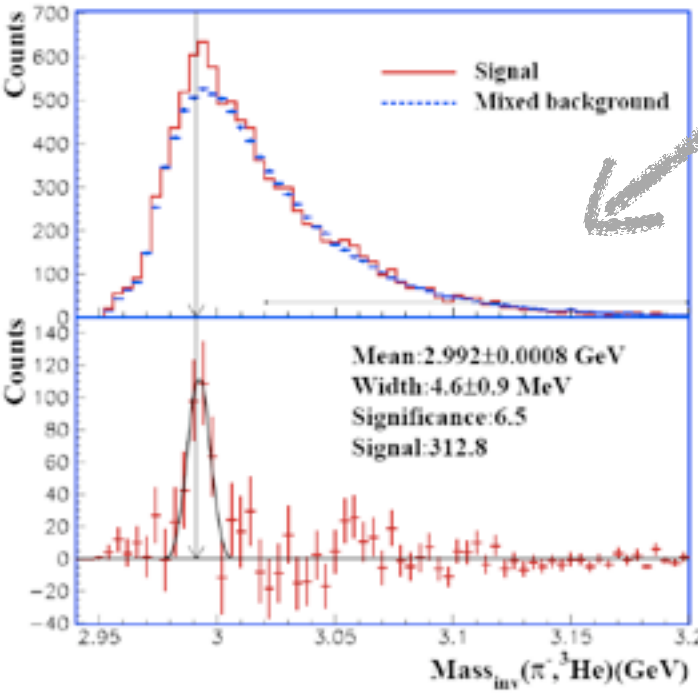

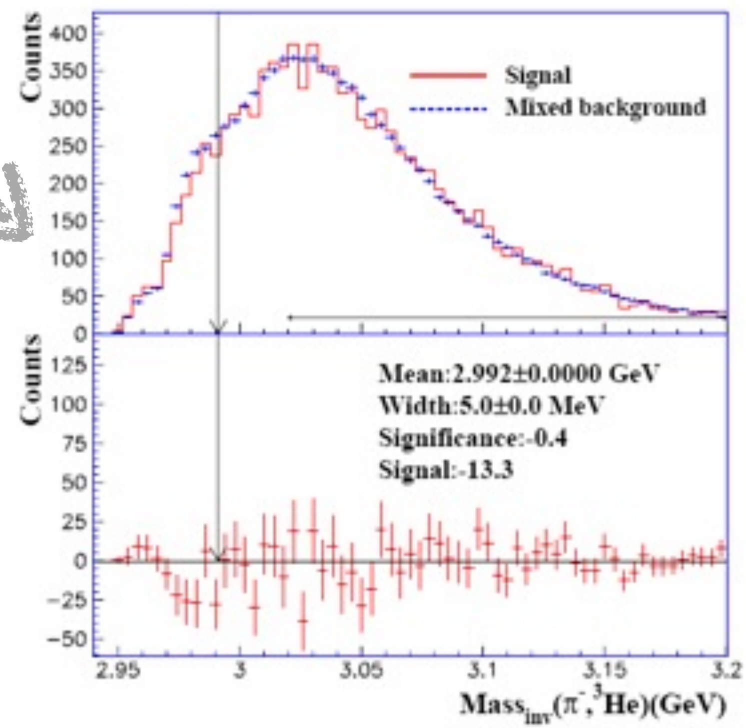

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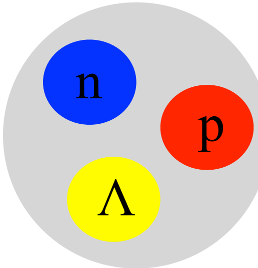

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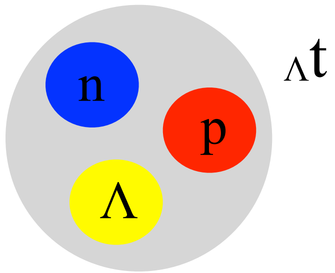

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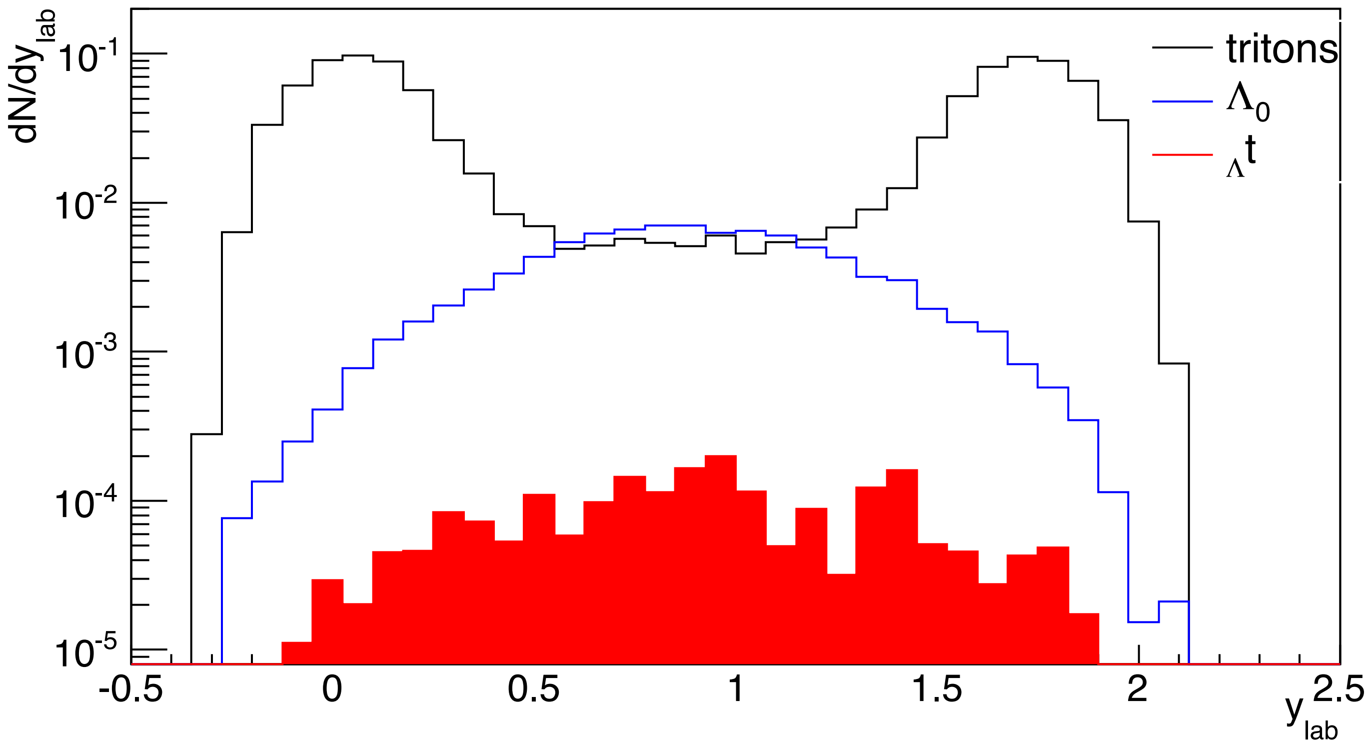

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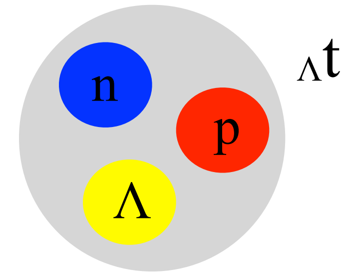

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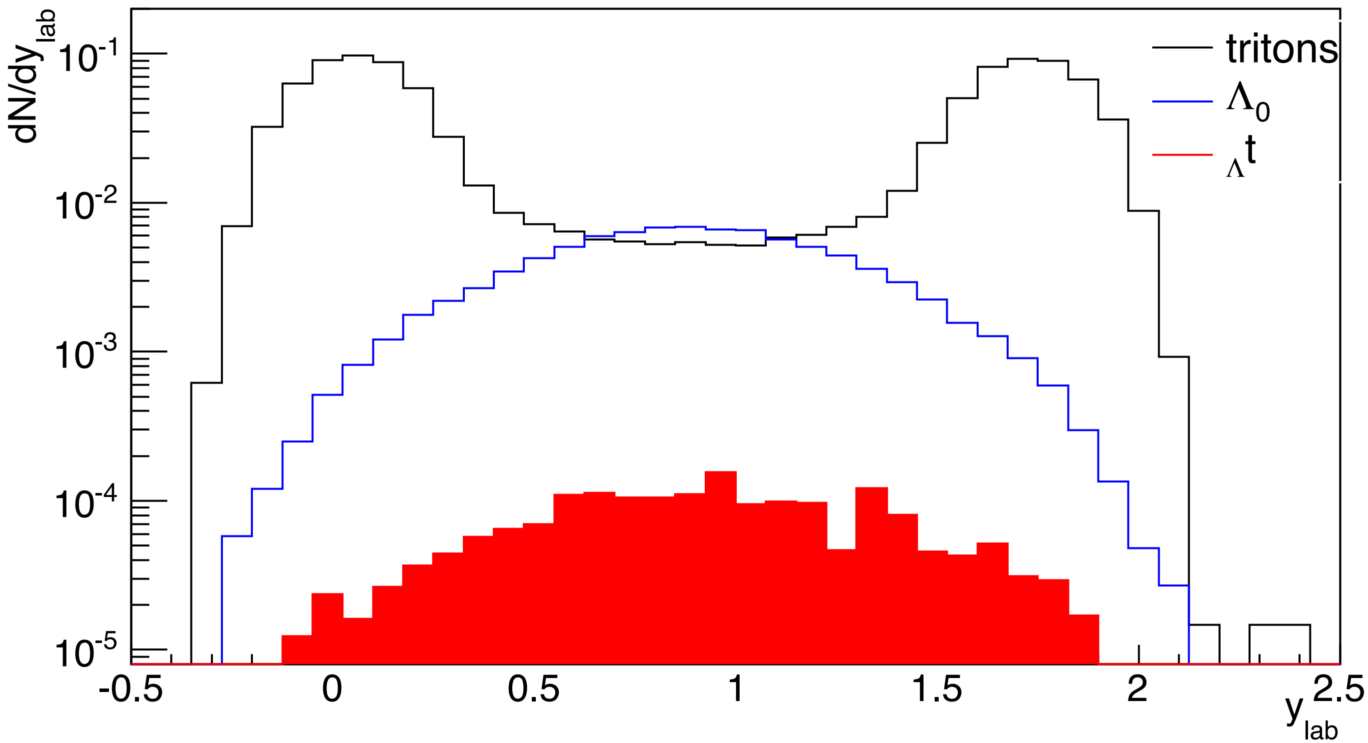

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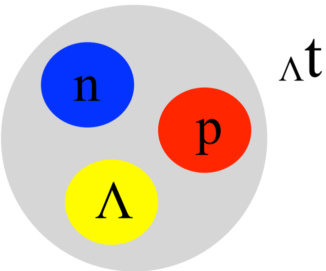

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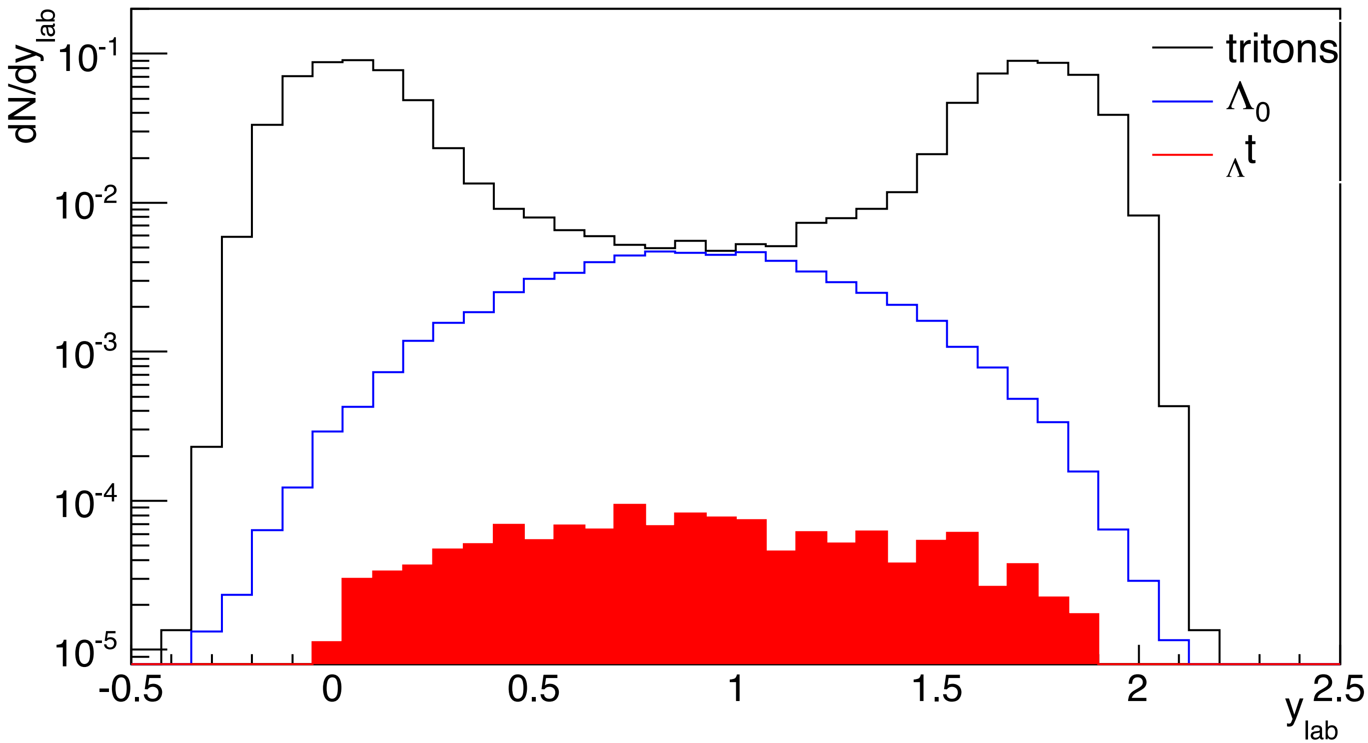

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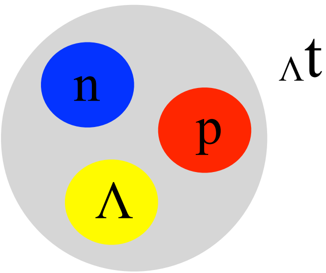

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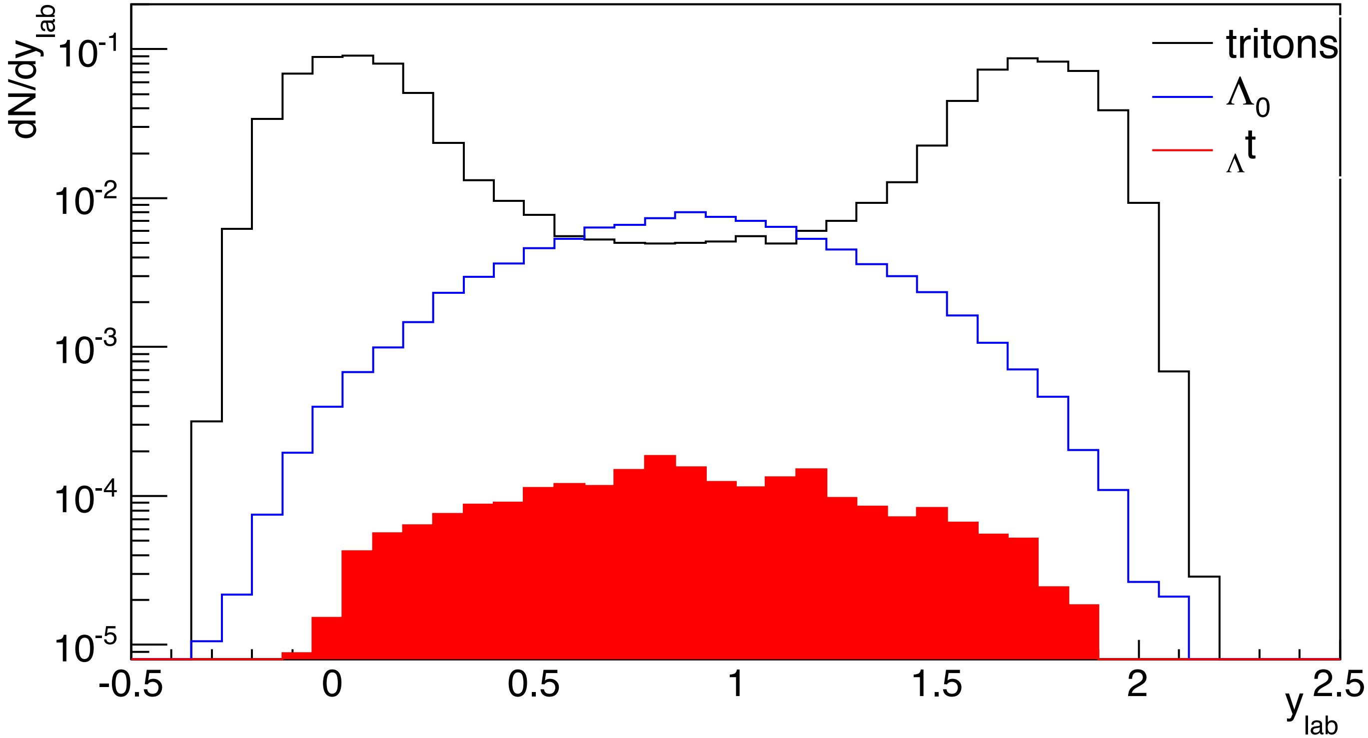

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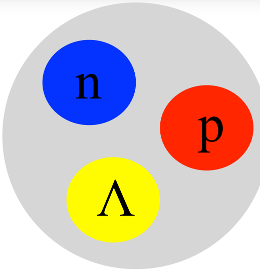

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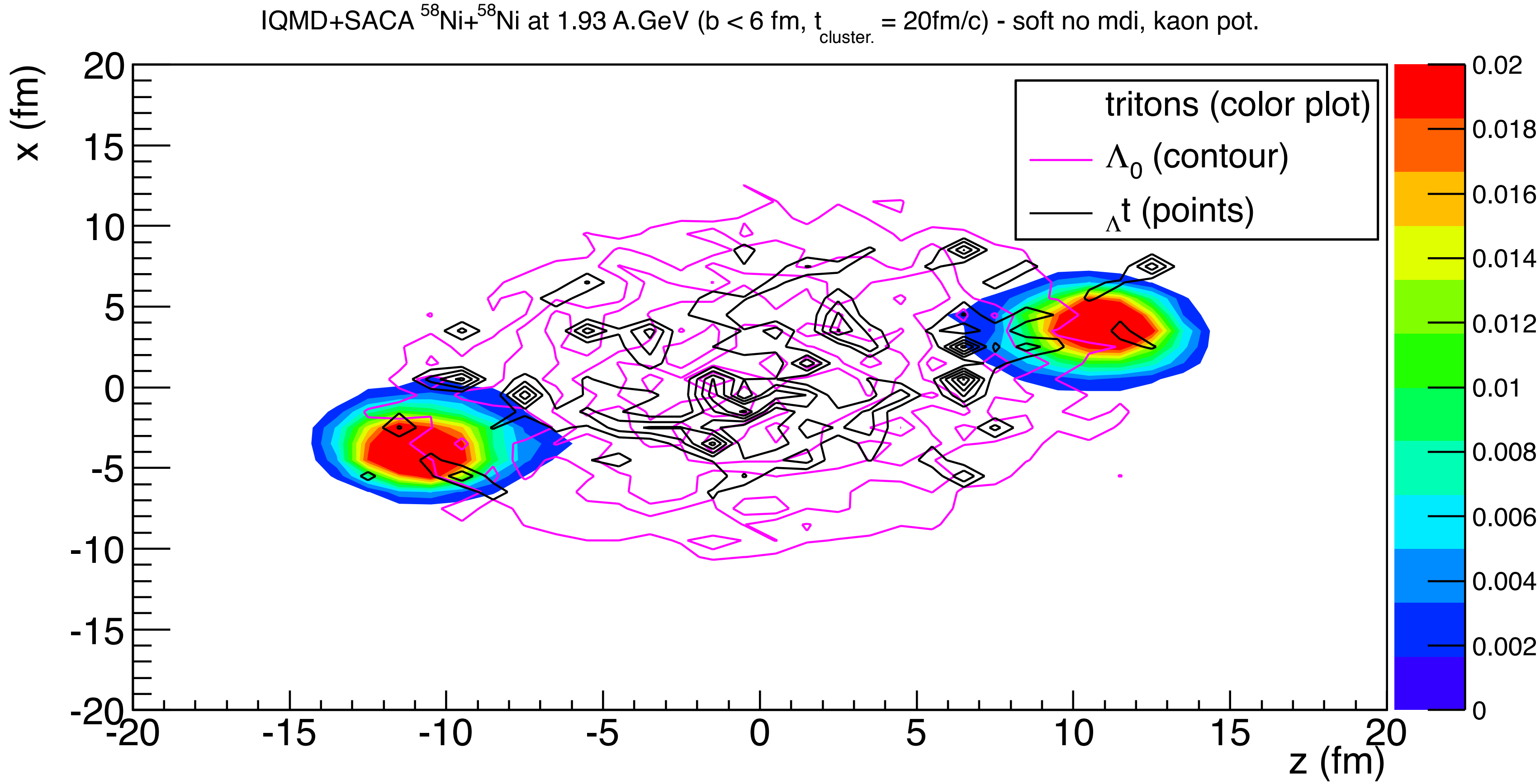

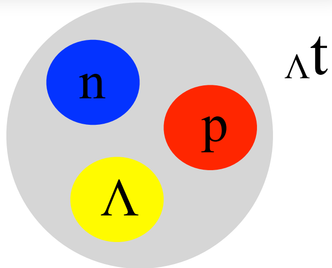

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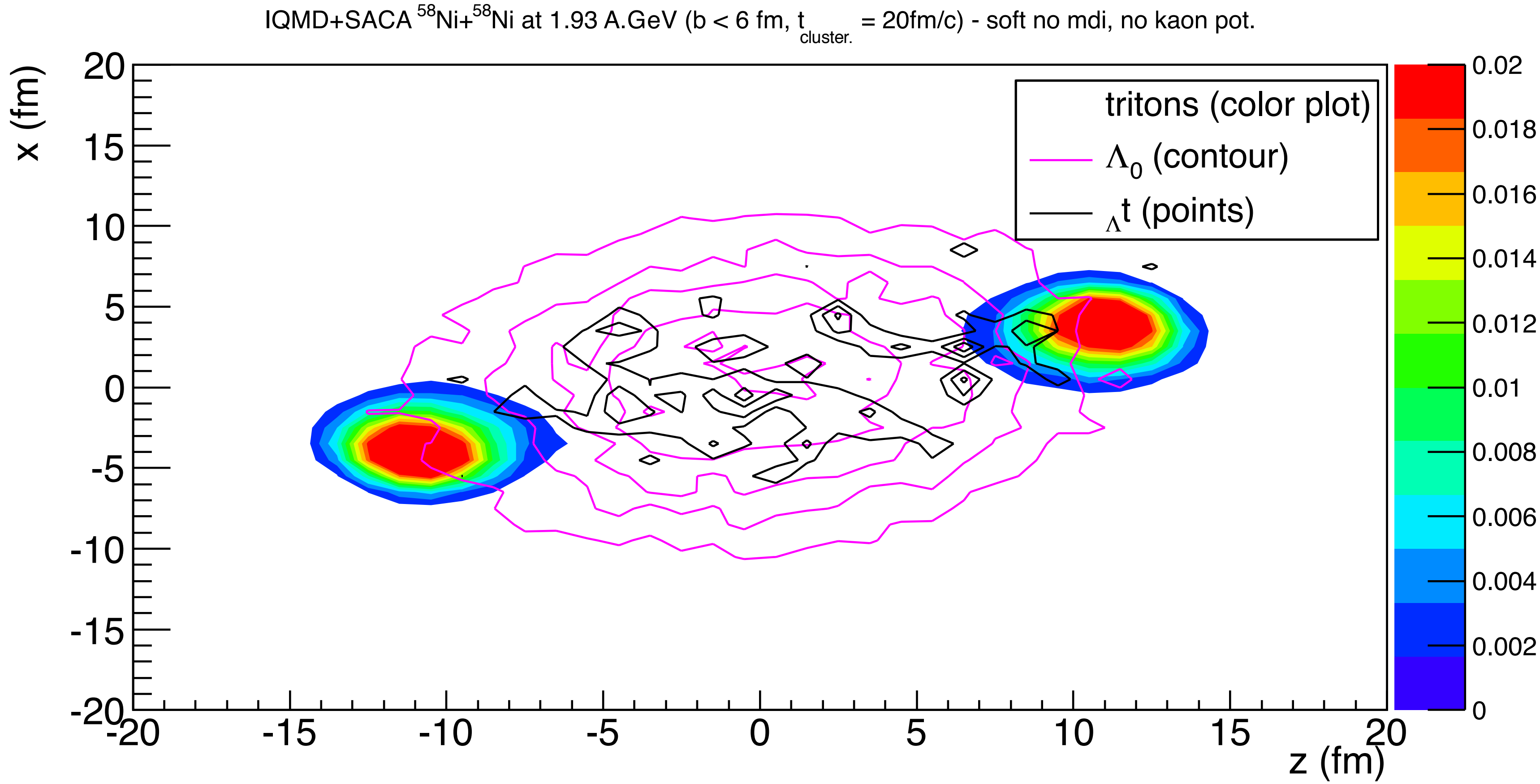

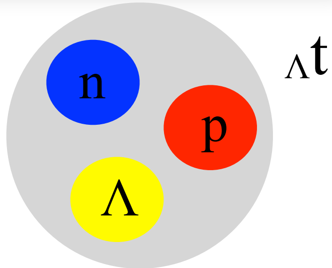

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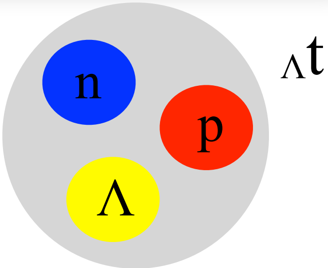

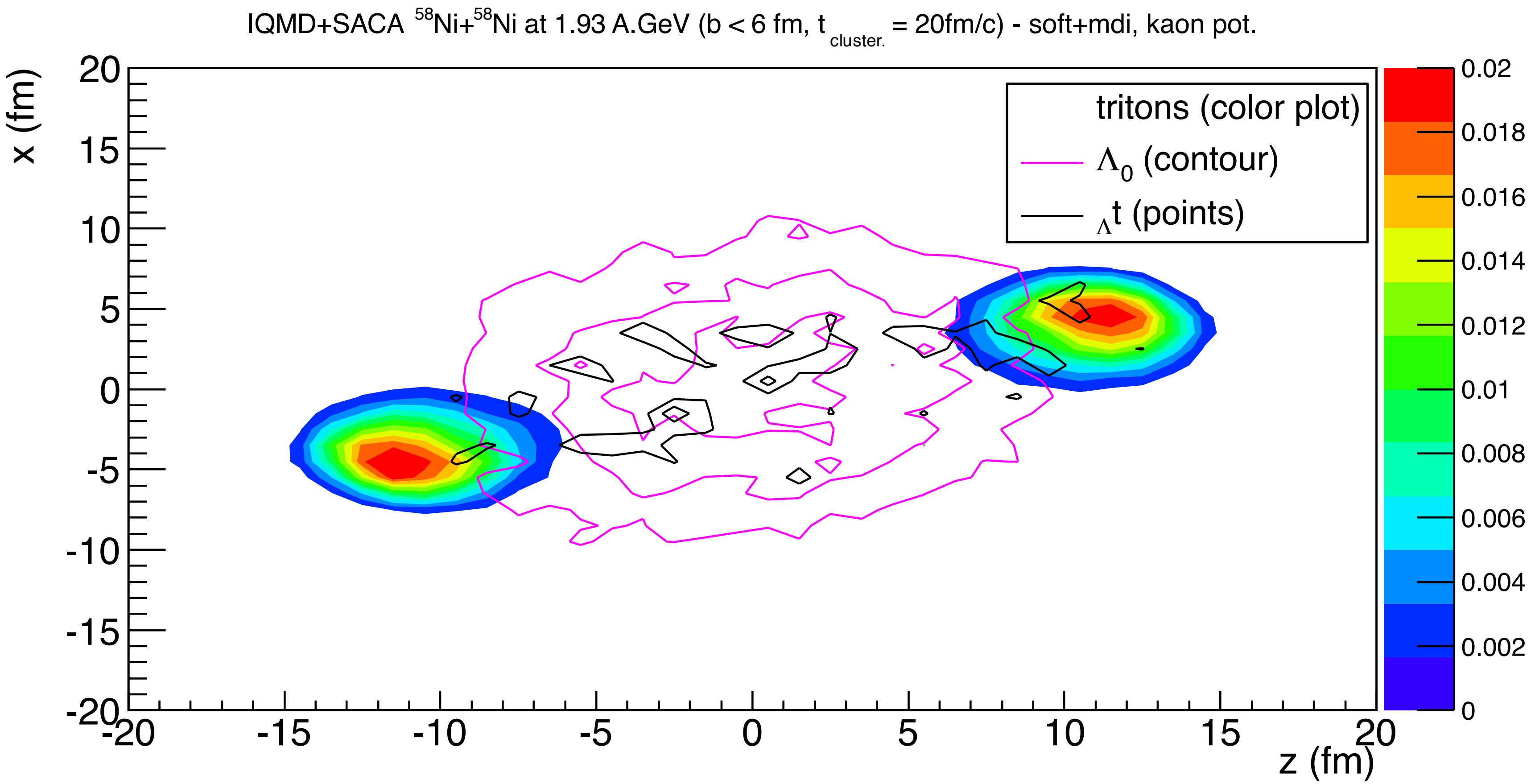

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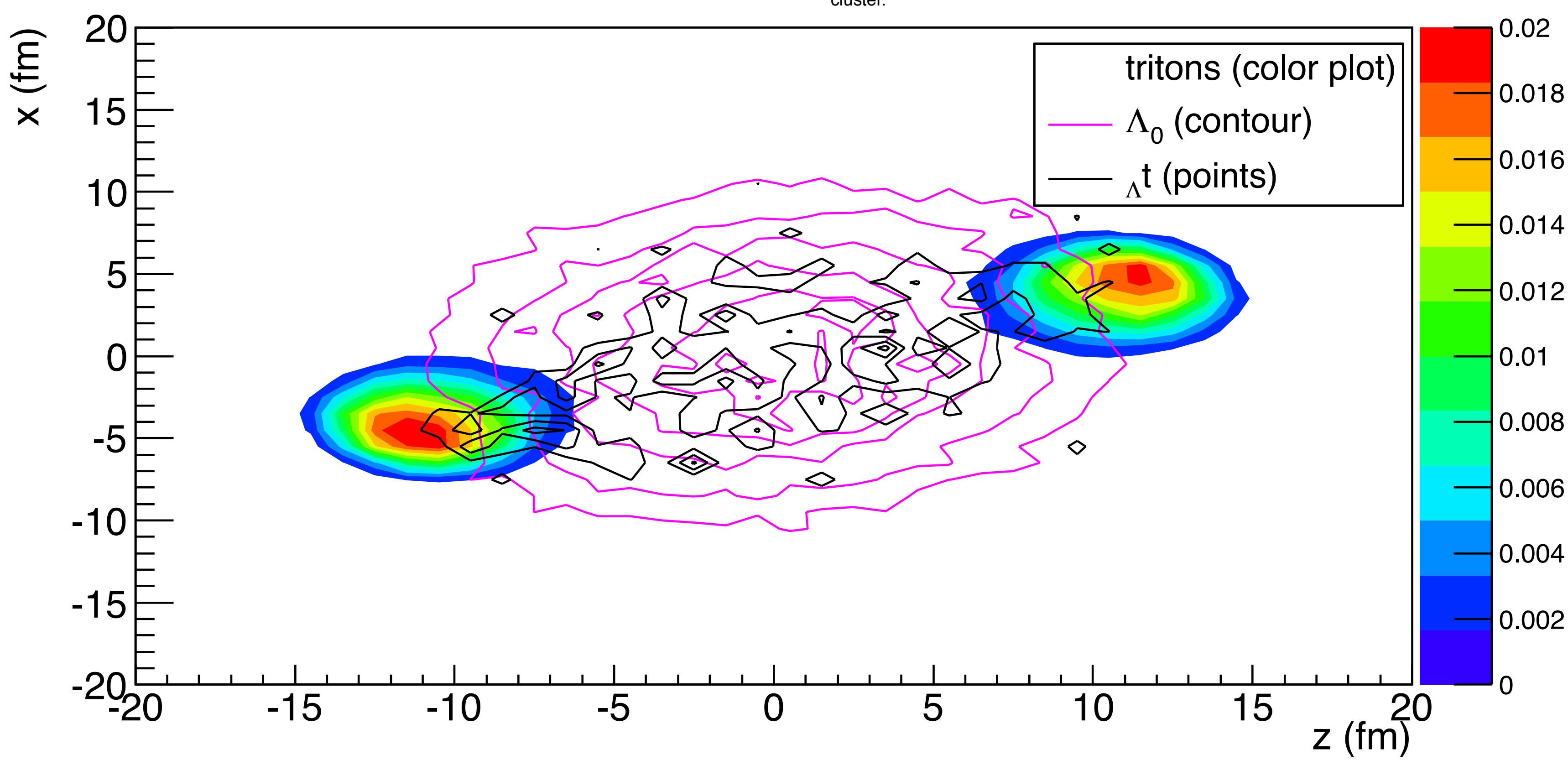

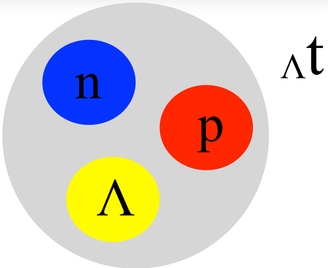

Summary and perspectives

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Further developments:

After processing SACA, proceed:

❖ further decay of primary unstable isotopes like ^{8}Be, ^{5}He, etc., which lifetime do not allow to detect them still bound in the detectors,

❖ allow early $^{3}\text{He} + n \rightarrow {}^{4}\text{He}$ according to its particularly high cross-section.

❖ secondary decay (evaporation code like GEMINI) of still excited clusters. Particularly relevant at intermediate energies (E_{beam} 100 A.MeV down to the Fermi regime)

❖ for hypernuclei formation, refine lambda-N potential in SACA or EOS/Kaon potential in IQMD in order to predict reasonnably the measured cross-sections, and momentum distributions, which are very constraining.

Density dependant pairing in SACA

Do the pairing and shell effect affect the primary fragments?

Probably yes, because:

- ✓ according to E. Khan et al., NPA 789 (2007) 94, pairing vanishes above $T \approx 0.5\Delta_{pairing}$

  $\Delta_{pairing}(\rho_0) = 12$ MeV/$\sqrt{A}$; $\Rightarrow \Delta B_{pairing}(^4He)$=12 MeV, $\Delta B_{pairing}(^3He)$=6.9 MeV.
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BUT, pairing effects have to vanish at high or low density.

➡ Need to apply a pairing correction factor depending on the cluster density.

E. Khan, M. Grasso and J. Margueron, in PRC 80 (2009) 044328 have derived the following function from the pairing potential $V_{pair} = V_0\{1-\eta[\rho(r)/\rho_0]\}\delta(\mathbf{r_1}-\mathbf{r_2})$ within the Hartree-Fock-Bogolioubov method:

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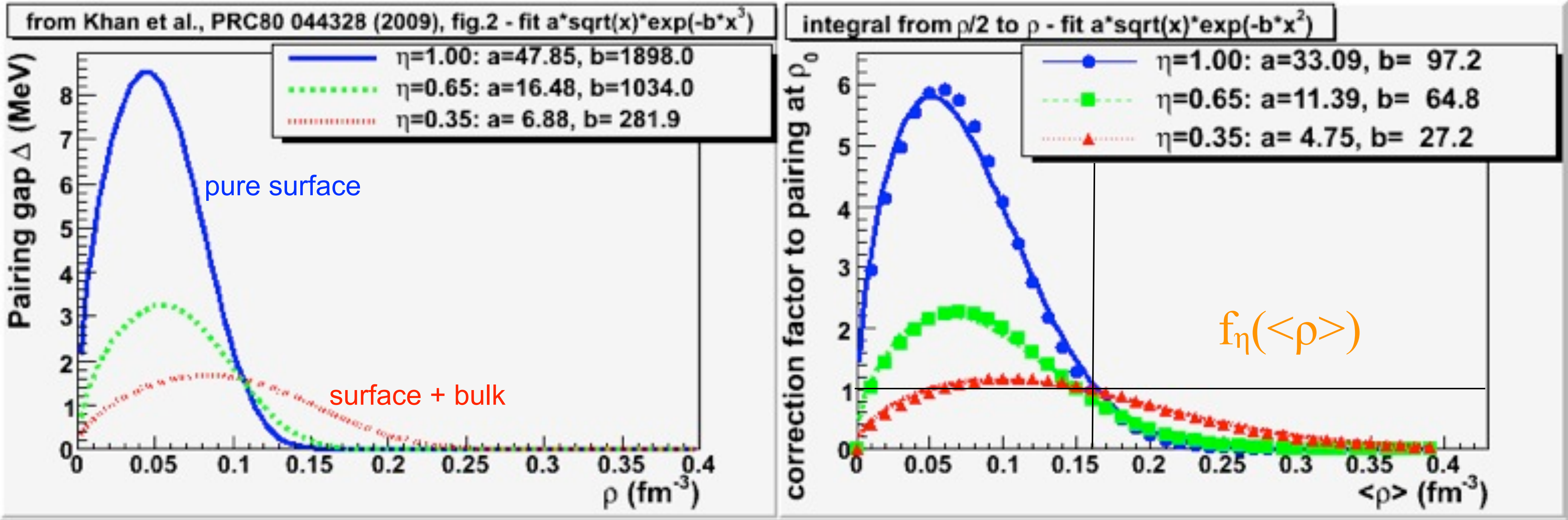

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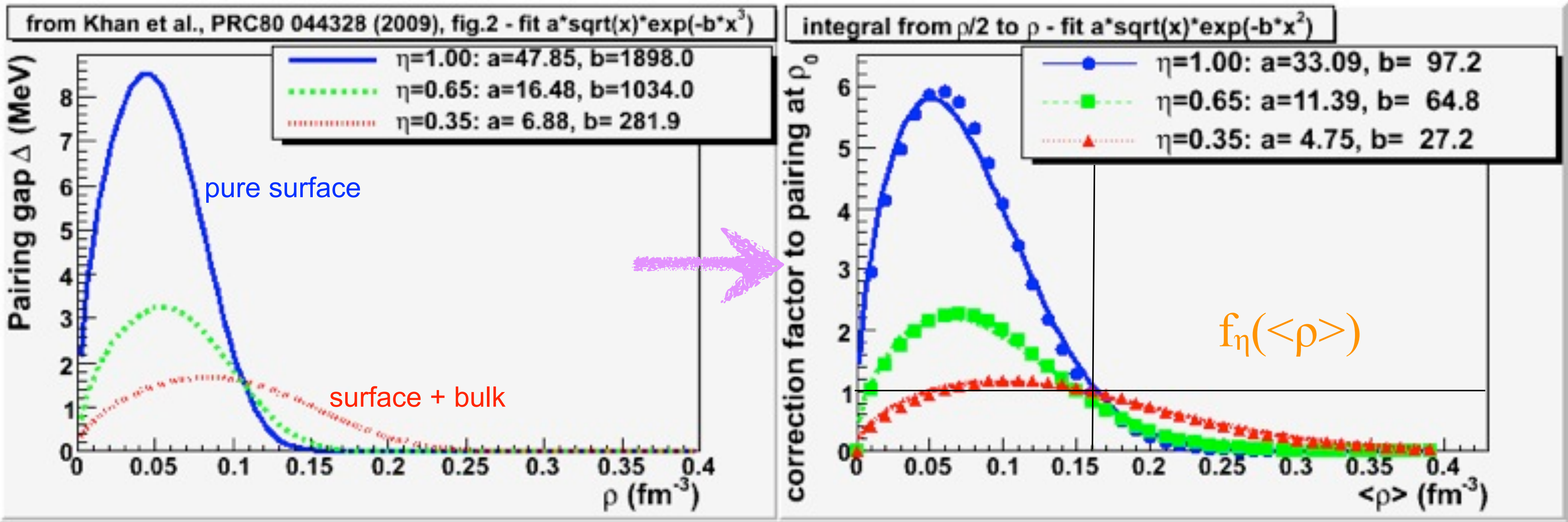


Density dependant pairing in SACA

Do the pairing and shell effect affect the primary fragments?

Probably yes, because:

✓ according to E. Khan et al., NPA 789 (2007) 94, pairing vanishes above $T \approx 0.5\Delta_{pairing}$

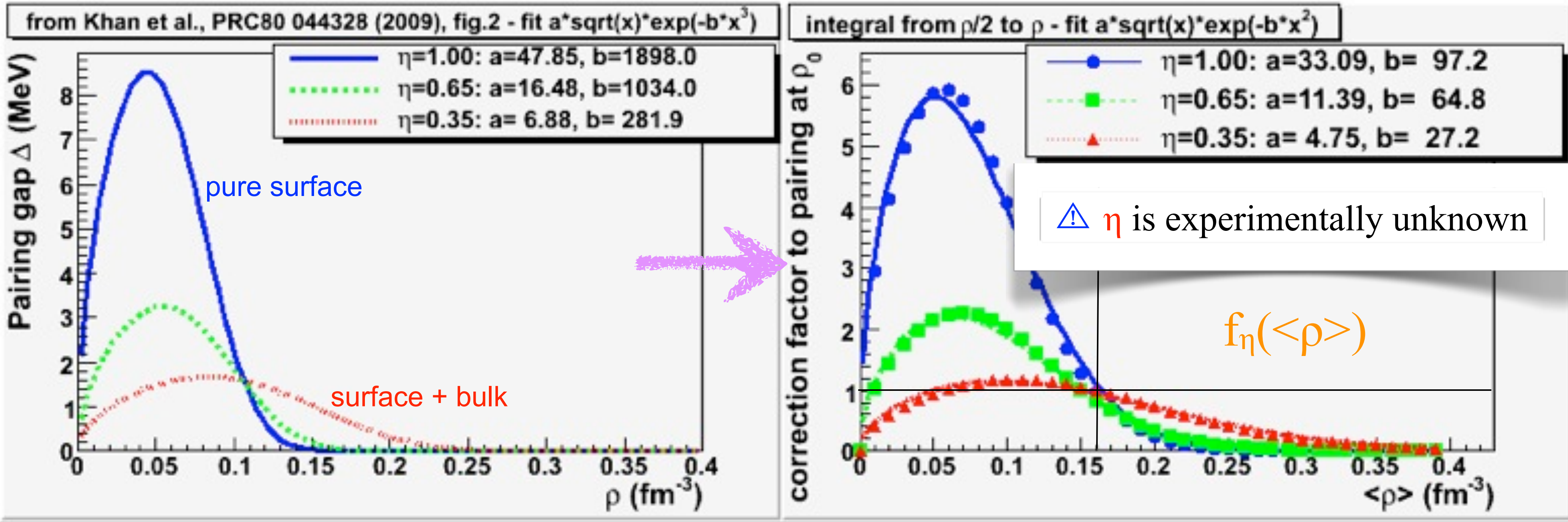
$\Delta_{pairing}(\rho_0) = 12$ MeV/$\sqrt{A}$; $\Rightarrow \Delta B_{pairing}(^4He)$=12 MeV, $\Delta B_{pairing}(^3He)$=6.9 MeV.

✓ in SACA, primary fragments are quite cold (T < 1-2 MeV)

BUT, pairing effects have to vanish at high or low density.

➡ Need to apply a pairing correction factor depending on the cluster density.

E. Khan, M. Grasso and J. Margueron, in PRC 80 (2009) 044328 have derived the following function from the pairing potential $V_{pair} = V_0\{1- \eta[\rho(r)/\rho_0]\}\delta(\mathbf{r_1}-\mathbf{r_2})$ within the Hartree-Fock-Bogolioubov method:



⚠ η is experimentally unknown

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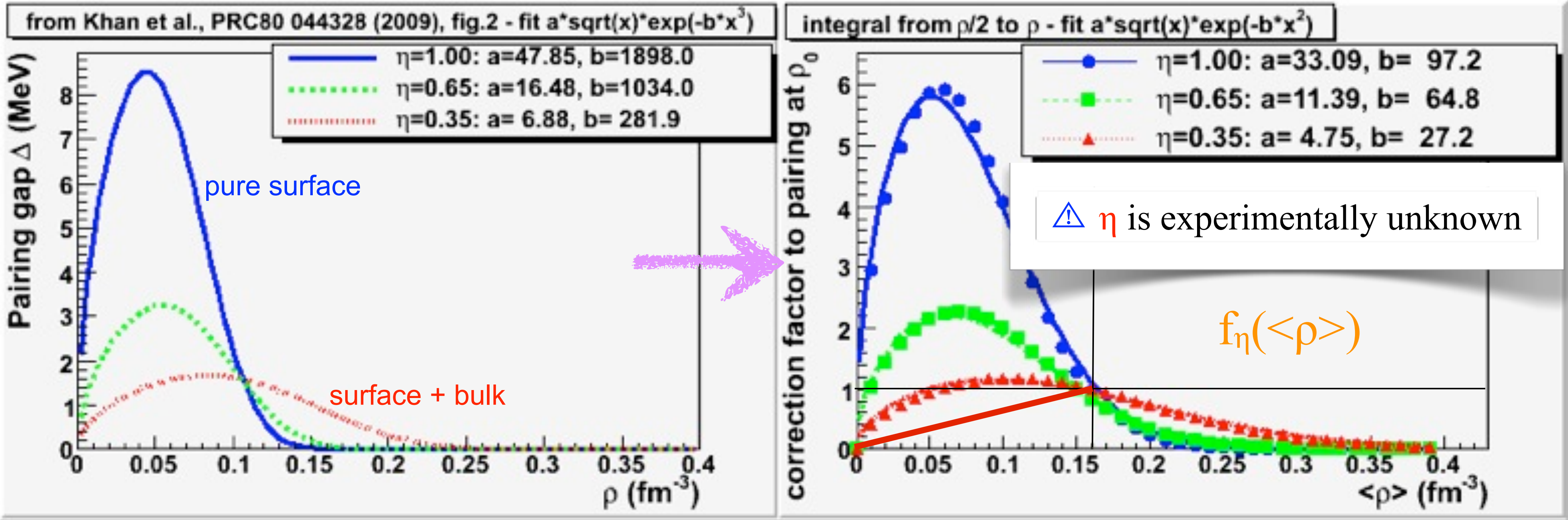
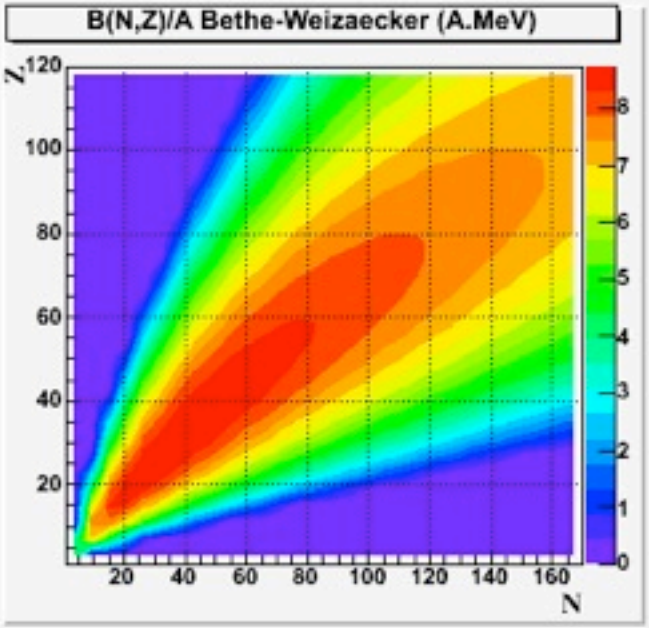
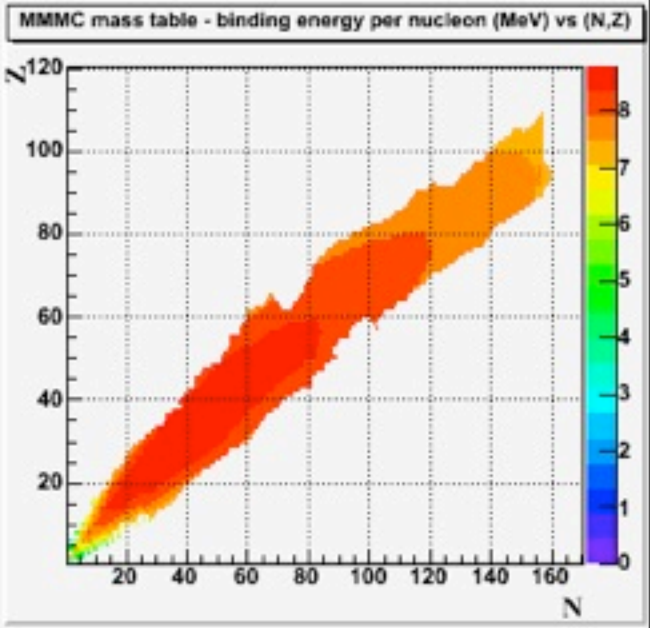


More detailed structure corrections to apply

☞In order to account for all major structure effects which make the binding energy deviate from the liquid drop model, for each nucleus (N,Z), what we call «pairing» binding energy will be the difference in binding energy between experimental measurements and the Bethe-Weizäcker formula (without pairing).





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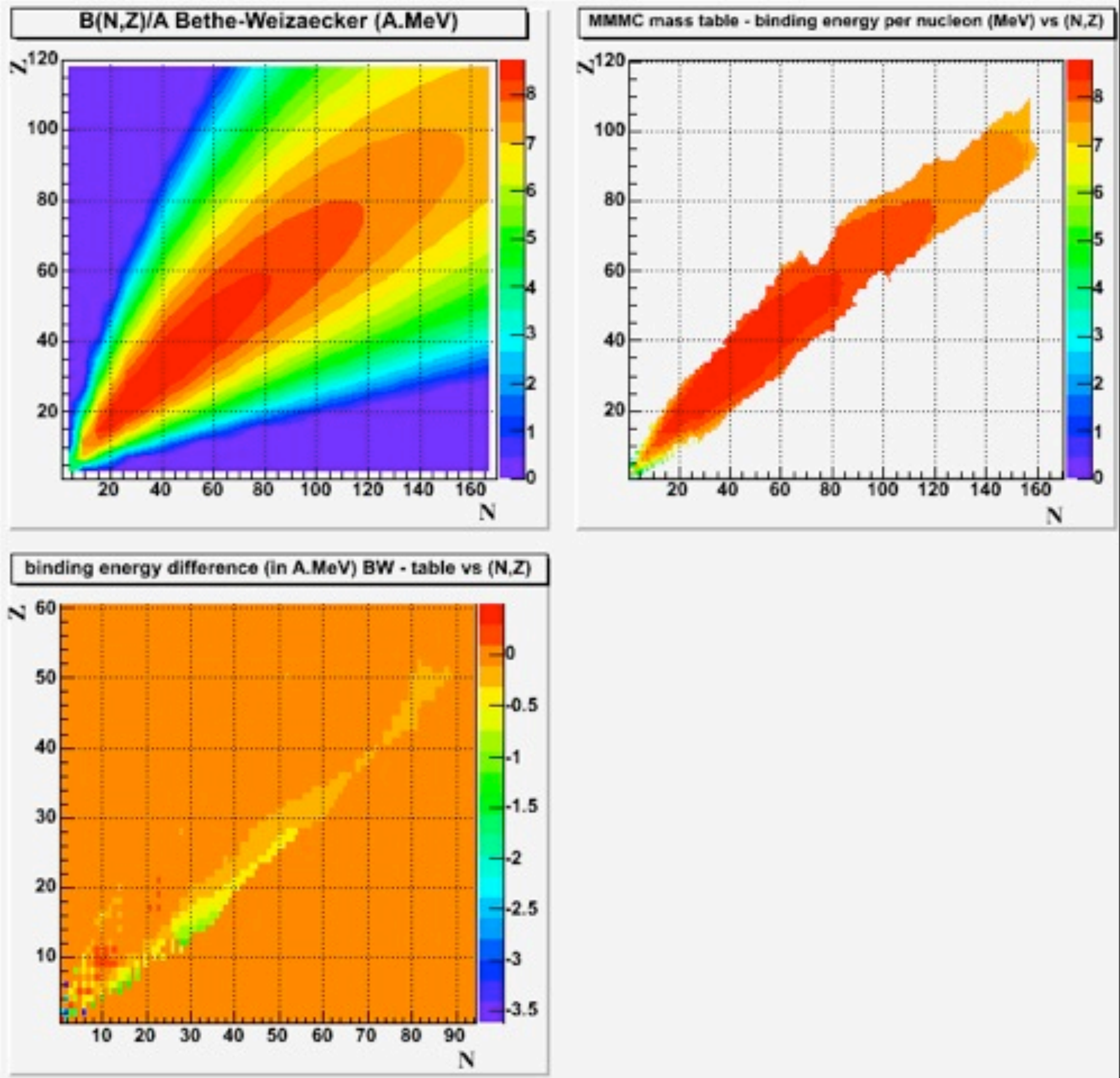
➜ $\Delta B_{pairing}(N,Z,\rho_0)$.

And for a cluster at mean baryonic density $<\rho_B>$, it will be

$\Delta B_{pairing}(N,Z,\rho_0) \times f_\eta(<\rho_B>)$



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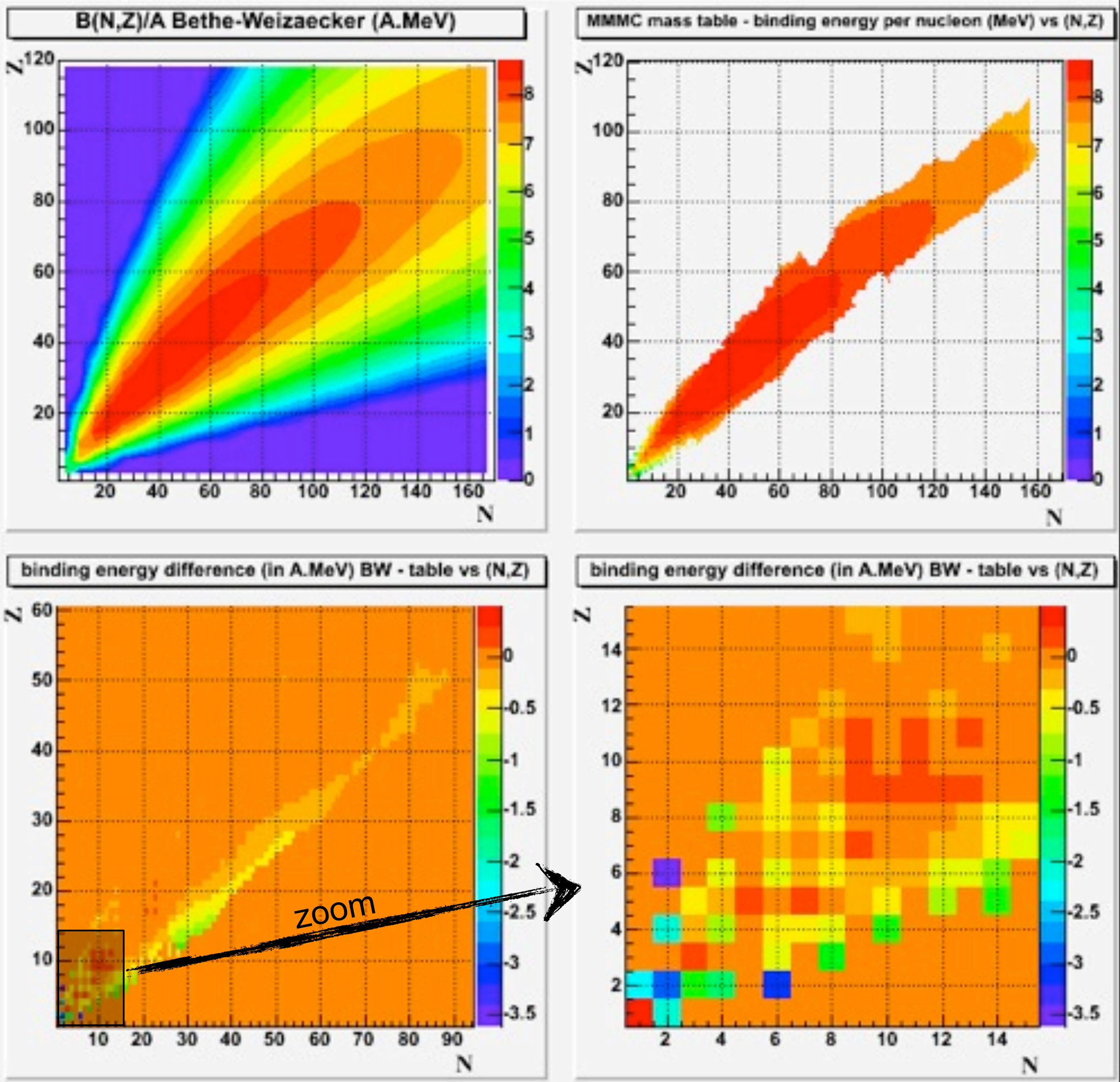
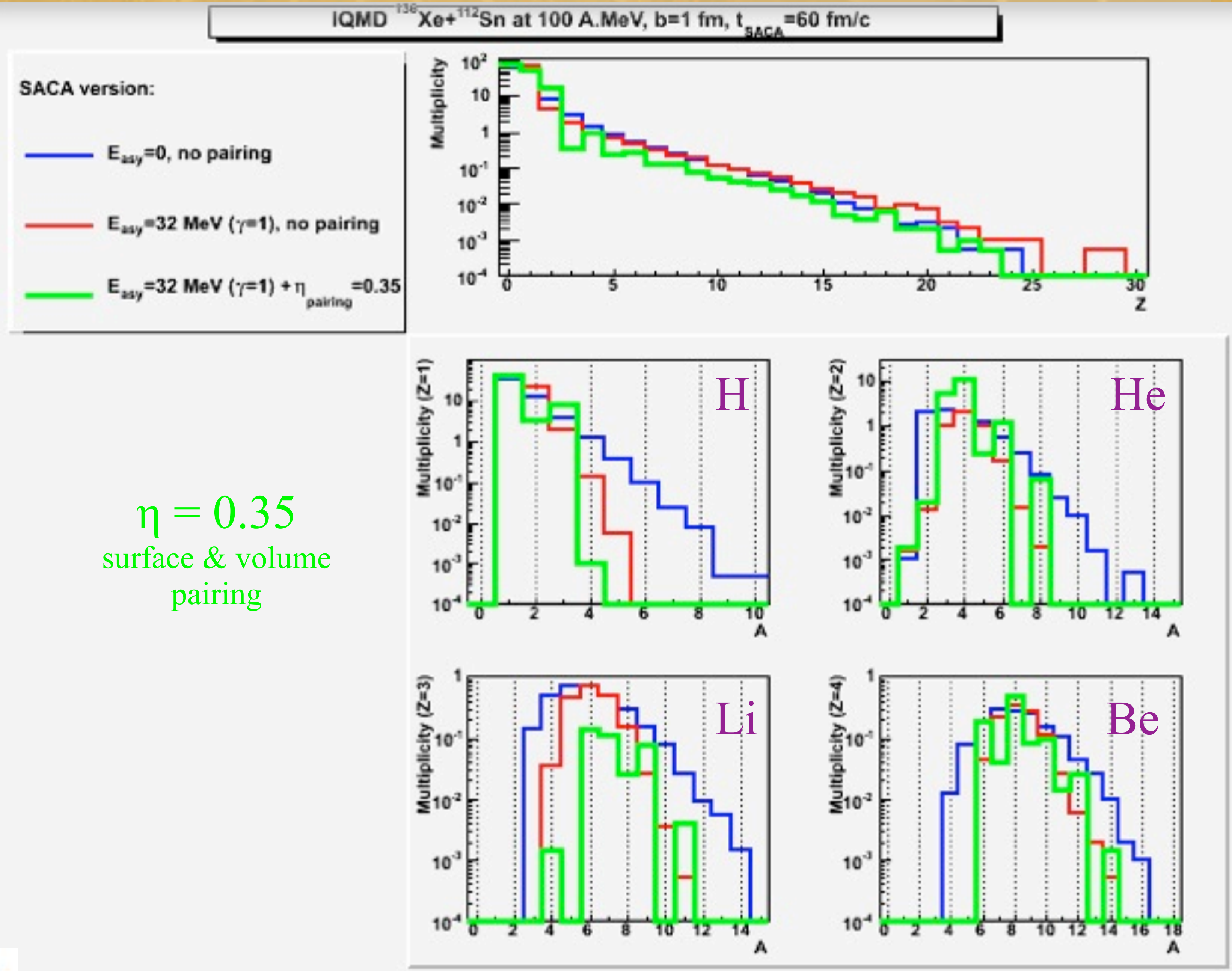
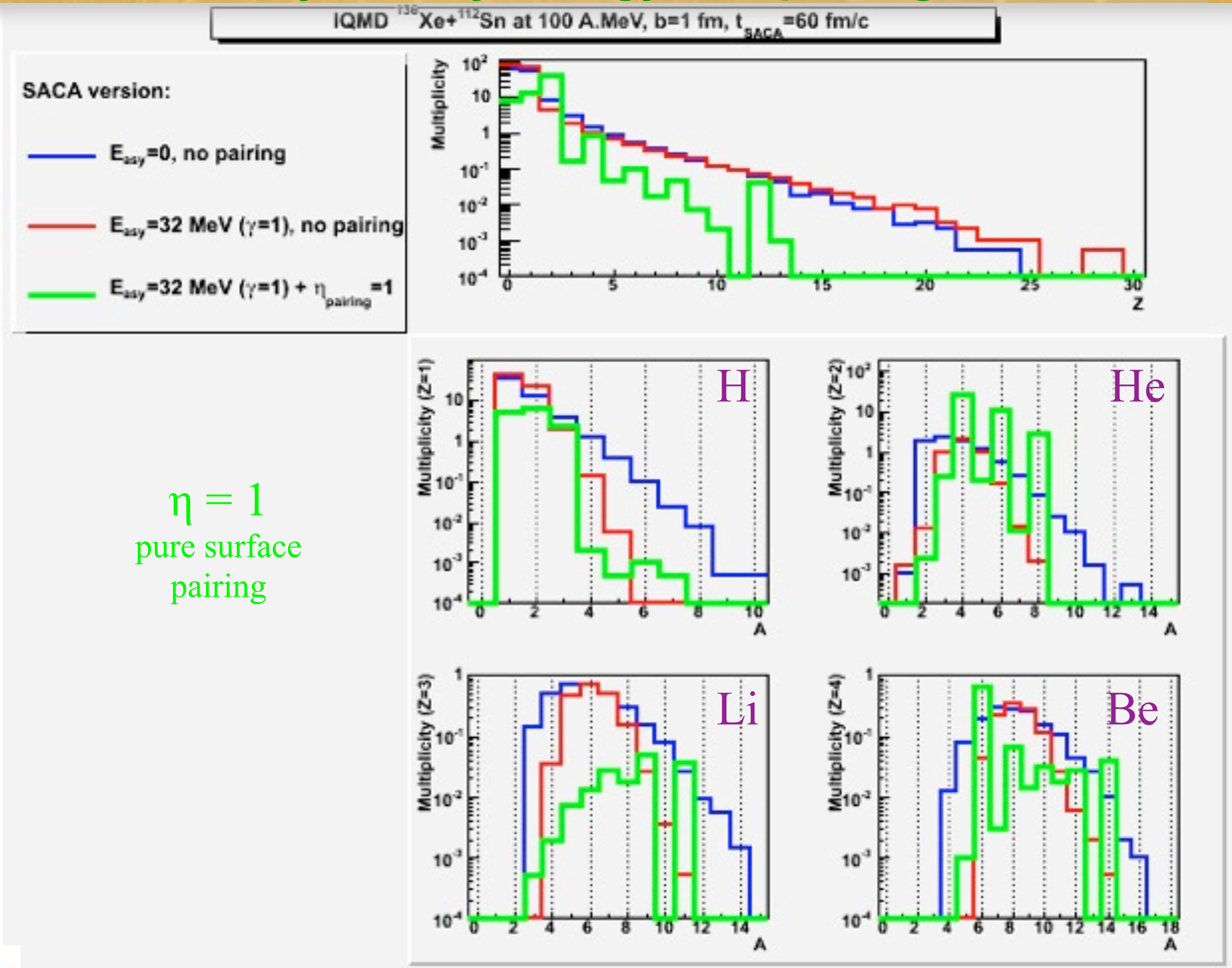


SACA with asymmetry energy and pairing



$\eta = 0.35$
surface & volume
pairing

SACA with asymmetry energy and pairing

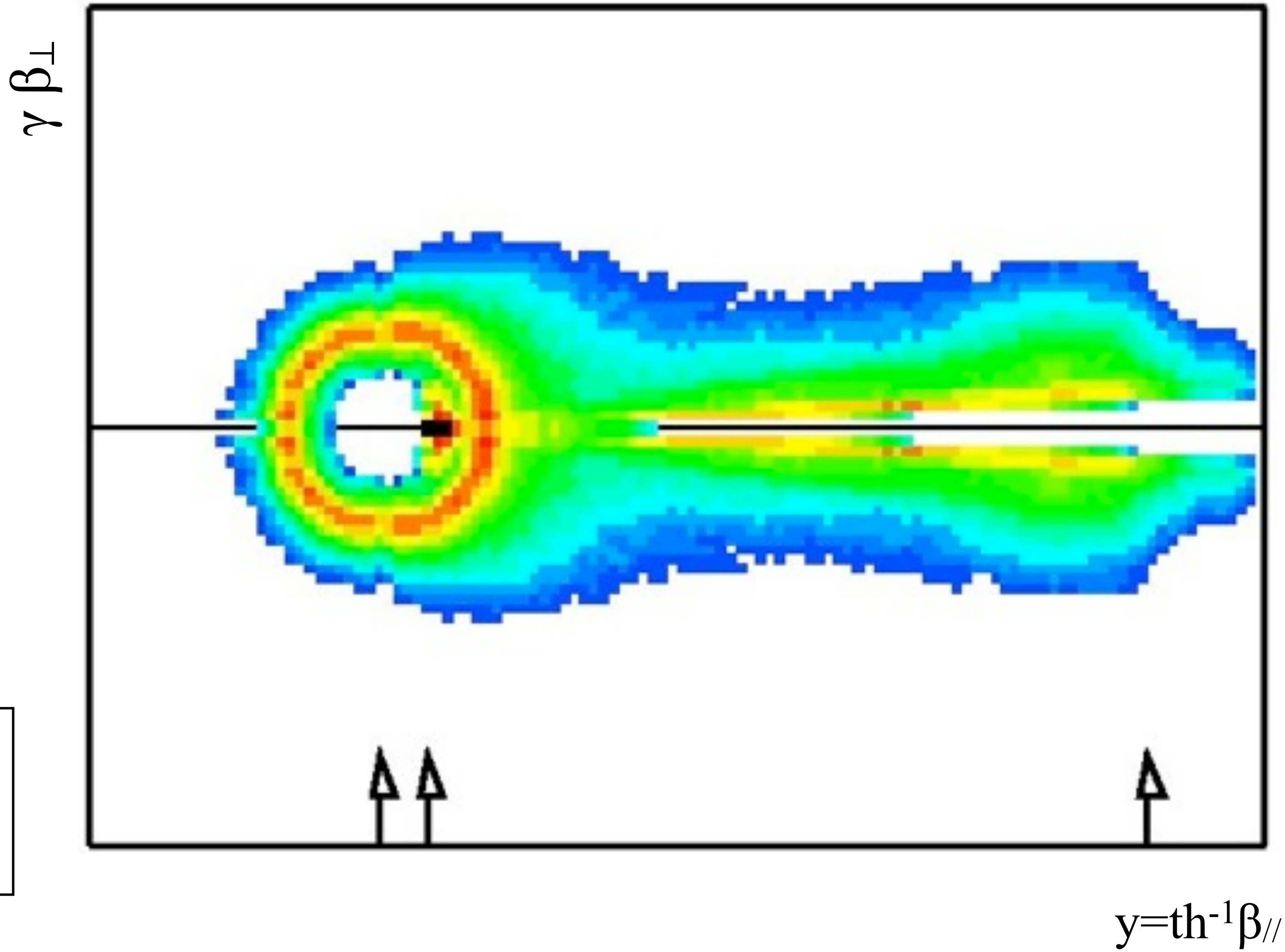


$\eta = 1$

pure surface pairing

Even in the spectator regime, we have to account correctly for isotope anisotropies

Illustration: alpha particles in C+Au at 300 A.MeV - peripheral collisions



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J. Lukasik
ALaDiN-INDRA Coll.

Even in the spectator regime, we have to account correctly for isotope anisotropies

Illustration: alpha particles in C+Au at 1 A.GeV - peripheral collisions

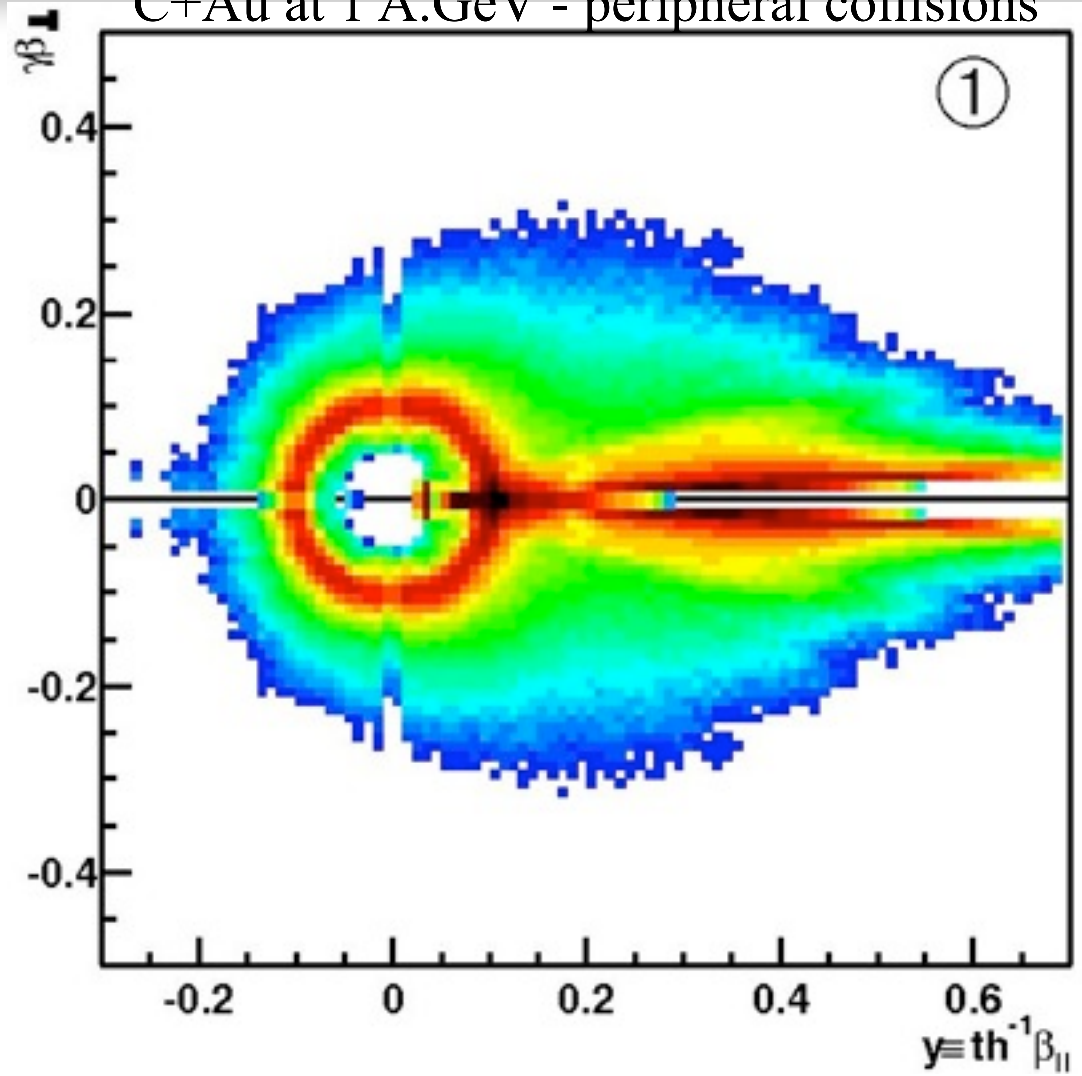

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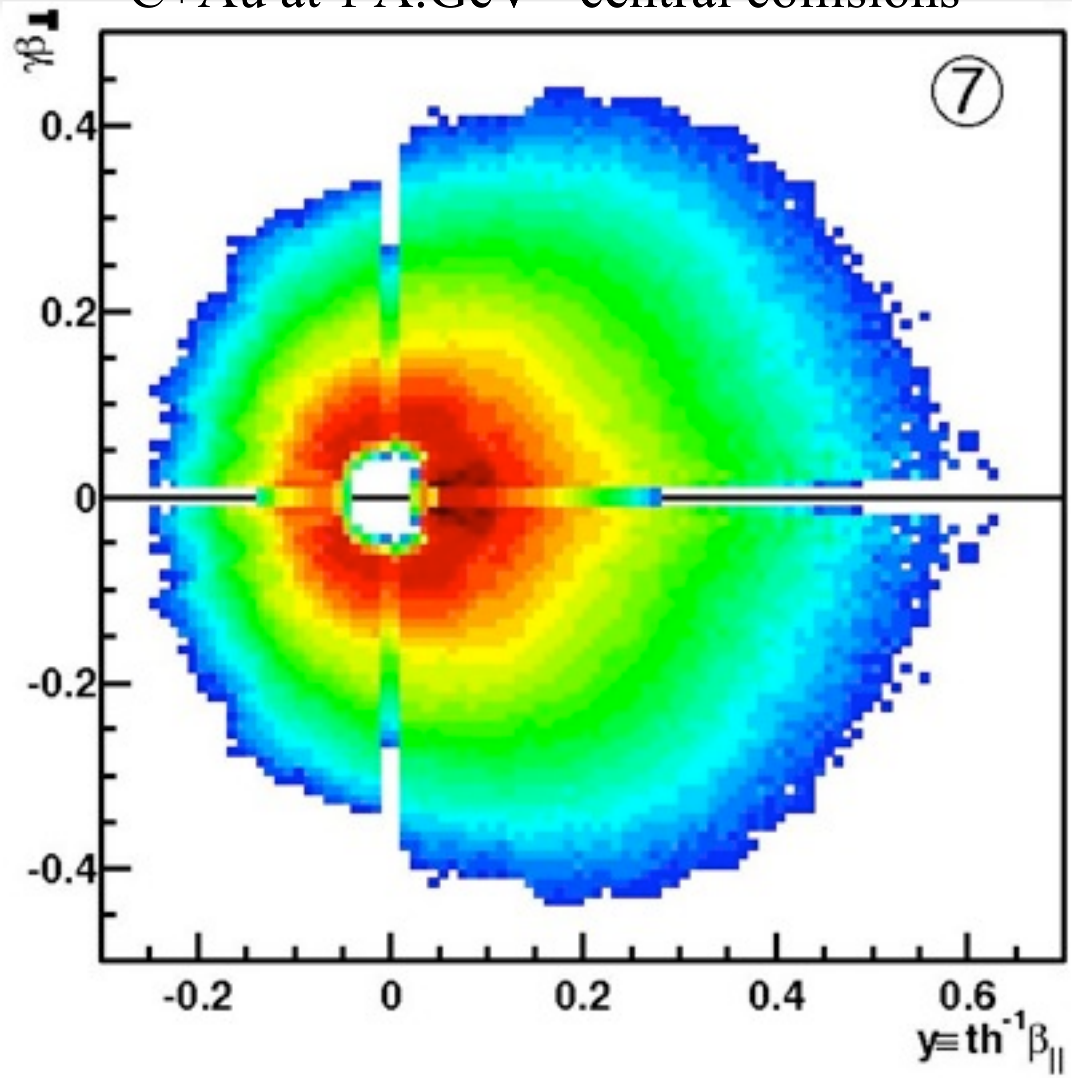
Illustration: alpha particles in C+Au at 1 A.GeV - central collisions



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