A new approach to detect hypernuclei in the phase space distributions generated by microscopic transport models

by A. Le Fèvre[1], Y. Leifels[1], J. Aichelin[2], Ch. Hartnack[2]
E. Bratkovskaya[3], V. Kireyev[4]

[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

[2]SUBATECH, UMR 6457, Ecole des Mines de Nantes - IN2P3/CNRS - Université de Nantes, France

[3]FIAS, Frankfurt University, Germany

[4]JINR, Dubna, Russia

A new approach to detect hypernuclei in the phase space distributions generated by microscopic transport models

by A. Le Fèvre[1], Y. Leifels[1], J. Aichelin[2], Ch. Hartnack[2]
E. Bratkovskaya[3], V. Kireyev[4]

[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

[2]SUBATECH, UMR 6457, Ecole des Mines de Nantes - IN2P3/CNRS - Université de Nantes, France

[3]FIAS, Frankfurt University, Germany

[4]JINR, Dubna, Russia

- A clusterisation approach…
- An application: the hypernucleus production.
- How are influenced the hypernucleus yields and phase space distributions by:
  - the clusterisation time,
  - the cluster binding energy,
  - the ingredients (EOS, in-medium properties) of the transport model.

GSI HELMHOLTZ | ASSOCIATION

Already existing approaches

Already existing approaches

- Statistical hadronisation models: *A. Andronic at al., PLB 697 (2011) 203* —> sudden hadronisation of a chemical freeze-out @ ultra-relativistic energies

Already existing approaches

- Statistical hadronisation models: *A. Andronic at al., PLB 697 (2011) 203* —> sudden hadronisation of a chemical freeze-out @ ultra-relativistic energies
- Coordinate and momentum space coalescence:
  - Simple coalescence, 1970-1980's:
    - *A.K. Kerman and M.S. Weiss, PRC 8 (1973) 408410*
    - *F. Asai et al., PLB 145 (1984) 17*
    - *H. Bando et al., NPA 501 (1989) 90*
  - Transport models + phase-space coalescence :
    - *T. Gaitanos et al., PLB 675 (2009) 297* <-> coalescence factor
    - *V. Topor and S. Das Gupta, PRC 81 (2010) 054911* <-> temperature

Already existing approaches

- Statistical hadronisation models: *A. Andronic at al., PLB 697 (2011) 203* —> sudden hadronisation of a chemical freeze-out @ ultra-relativistic energies
- Coordinate and momentum space coalescence:
  - Simple coalescence, 1970-1980's:
    - *A.K. Kerman and M.S. Weiss, PRC 8 (1973) 408410*
    - *F. Asai et al., PLB 145 (1984) 17*
    - *H. Bando et al., NPA 501 (1989) 90*
  - Transport models + phase-space coalescence :
    - *T. Gaitanos et al., PLB 675 (2009) 297* <-> coalescence factor
    - *V. Topor and S. Das Gupta, PRC 81 (2010) 054911*
      <-> temperature
- Dynamical-statistical hybrid approach: *Botvina et al., PRC 88 (2013) 054605, & PLB 742 (2015) 7* -> Fermi break-up of the excited spectators.
  <-> spectator excitation energy.

Already existing approaches

- Statistical hadronisation models: *A. Andronic at al., PLB 697 (2011) 203* —> sudden hadronisation of a chemical freeze-out @ ultra-relativistic energies
- Coordinate and momentum space coalescence:
  - Simple coalescence, 1970-1980's:
    - *A.K. Kerman and M.S. Weiss, PRC 8 (1973) 408410*
    - *F. Asai et al., PLB 145 (1984) 17*
    - *H. Bando et al., NPA 501 (1989) 90*
  - Transport models + phase-space coalescence :
    - *T. Gaitanos et al., PLB 675 (2009) 297* <-> coalescence factor
    - *V. Topor and S. Das Gupta, PRC 81 (2010) 054911* <-> temperature
- Dynamical-statistical hybrid approach: *Botvina et al., PRC 88 (2013) 054605, & PLB 742 (2015) 7* -> Fermi break-up of the excited spectators. <-> spectator excitation energy.
- Problematic:
  - Predicted hypernuclei yields differ by orders of magnitude.
  - Still very scarce experimental data available -> Difficult to constraint the models.

FRIGA: a clusterisation approach…

Fragment **R**ecognition **I**n **G**eneral **A**pplications

Frigg / Friga, spinning the clouds

Friga (Frigg), goddess of harmonious weddings and alliances, setting order in the chaos, in the old Germanic mythology.

FRIGA: a clusterisation approach…

Fragment Recognition In General Applications

* Simulated Annealing Procedure: *PLB301:328,1993*; later called SACA (Simulated Annealing Clusterisation Algorithm) with:

Frigg / Friga, spinning the clouds

Friga (Frigg), goddess of harmonious weddings and alliances, setting order in the chaos, in the old Germanic mythology.

FRIGA: a clusterisation approach…

Fragment Recognition In General Applications

* Simulated Annealing Procedure: *PLB301:328,1993*; later called SACA (Simulated Annealing Clusterisation Algorithm) with:
* *P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390*

Frigg / Friga, spinning the clouds

Friga (Frigg), goddess of harmonious weddings and alliances, setting order in the chaos, in the old Germanic mythology.

FRIGA: a clusterisation approach…

Fragment **R**ecognition **I**n **G**eneral **A**pplications

* Simulated Annealing Procedure: *PLB301:328,1993*; later called SACA (Simulated Annealing Clusterisation Algorithm) with:
* *P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390*
* **FRIGA** = 2010-2015 development version: A. Le Fèvre et al., *Journal of Physics: Conference Series* 668 (2016) 012021.
  a *more complete publication in progress.*

Frigg / Friga, spinning the clouds

Friga (Frigg), goddess of harmonious weddings and alliances, setting order in the chaos, in the old Germanic mythology.

FRIGA: a clusterisation approach…

Fragment **R**ecognition **I**n **G**eneral **A**pplications

- * Simulated Annealing Procedure: *PLB301:328,1993*; later called SACA (Simulated Annealing Clusterisation Algorithm) with:
- * *P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390*
- * **FRIGA** = 2010-2015 development version: A. Le Fèvre et al., *Journal of Physics: Conference Series* 668 (2016) 012021.
  a *more complete publication in progress.*
- * So far applied with various transport models: BQMD, IQMD, pHSD.

Frigg / Friga, spinning the clouds

Friga (Frigg), goddess of harmonious weddings and alliances, setting order in the chaos, in the old Germanic mythology.

FRIGA: a clusterisation approach…

Fragment **R**ecognition **I**n **G**eneral **A**pplications

* Simulated Annealing Procedure: *PLB301:328,1993*; later called SACA (Simulated Annealing Clusterisation Algorithm) with:
* *P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390*
* **FRIGA** = 2010-2015 development version: A. Le Fèvre et al., *Journal of Physics: Conference Series* 668 (2016) 012021.
  a *more complete publication in progress.*
* So far applied with various transport models: BQMD, IQMD, pHSD.
* Applicable from the Fermi energy domain (50 A.MeV, multi-fragmentation) up to (ultra-)relativistic energies (spectator - participant decay).

Frigg / Friga, spinning the clouds

Friga (Frigg), goddess of harmonious weddings and alliances, setting order in the chaos, in the old Germanic mythology.

FRIGA: a clusterisation approach…

Fragment Recognition In General Applications

* Simulated Annealing Procedure: *PLB301:328,1993*; later called SACA (Simulated Annealing Clusterisation Algorithm) with:
* *P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390*
* **FRIGA** = 2010-2015 development version: A. Le Fèvre et al., *Journal of Physics: Conference Series* 668 (2016) 012021.
  a *more complete publication in progress.*
* So far applied with various transport models: BQMD, IQMD, pHSD.
* Applicable from the Fermi energy domain (50 A.MeV, multi-fragmentation) up to (ultra-)relativistic energies (spectator - participant decay).
* Prediction of (light and heavy) (hyper)isotope yields and full phase space distribution.

Frigg / Friga, spinning the clouds

Friga (Frigg), goddess of harmonious weddings and alliances, setting order in the chaos, in the old Germanic mythology.

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

Motivations

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

Motivations

- The major difficulty that are facing transport models is the formation of clusters. For this reason, this aspect is often oversimplified, when not omitted.

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

Motivations

- The major difficulty that are facing transport models is the formation of clusters. For this reason, this aspect is often oversimplified, when not omitted.
- Having the clusters correctly formed is as important as the transport and creation of their constituents in the curse of the collisions.

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

Motivations

- The major difficulty that are facing transport models is the formation of clusters. For this reason, this aspect is often oversimplified, when not omitted.
- Having the clusters correctly formed is as important as the transport and creation of their constituents in the curse of the collisions.

➡ Because, apart from emitted elementary particles, they carry the only information that the experimental instruments can measure.

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

Motivations

- The major difficulty that are facing transport models is the formation of clusters. For this reason, this aspect is often oversimplified, when not omitted.
- Having the clusters correctly formed is as important as the transport and creation of their constituents in the curse of the collisions.
- ➡ Because, apart from emitted elementary particles, they carry the only information that the experimental instruments can measure.
- 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

Simulated Annealing Clusterization Algorithm (SACA): The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Simulated Annealing Clusterization Algorithm (SACA):
The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Simulated Annealing Clusterization Algorithm (SACA): The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Idea by Dorso et al. (Phys.Lett.B301:328,1993) :

Simulated Annealing Clusterization Algorithm (SACA):
The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Idea by Dorso et al. (Phys.Lett.B301:328,1993) :
a) Take the positions and momenta of all nucleons at time t.

Simulated Annealing Clusterization Algorithm (SACA):
The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Idea by Dorso et al. (Phys.Lett.B301:328,1993) :
a) Take the positions and momenta of all nucleons at time t.
b) Combine them in all possible ways into fragments or leave them as single nucleons.

Simulated Annealing Clusterization Algorithm (SACA): The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Idea by Dorso et al. (Phys.Lett.B301:328,1993) :

a) Take the positions and momenta of all nucleons at time t.

b) Combine them in all possible ways into fragments or leave them as single nucleons.

c) Neglect the interaction among clusters.

Simulated Annealing Clusterization Algorithm (SACA):
The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Idea by Dorso et al. (Phys.Lett.B301:328,1993) :

a) Take the positions and momenta of all nucleons at time t.

b) Combine them in all possible ways into fragments or leave them as single nucleons.

c) Neglect the interaction among clusters.

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

Simulated Annealing Clusterization Algorithm (SACA):
The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Idea by Dorso et al. (Phys.Lett.B301:328,1993) :
a) Take the positions and momenta of all nucleons at time t.
b) Combine them in all possible ways into fragments or leave them as single nucleons.
c) Neglect the interaction among clusters.
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.

Simulated Annealing Clusterization Algorithm (SACA): The principles

If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

Idea by Dorso et al. (Phys.Lett.B301:328,1993) :

a) Take the positions and momenta of all nucleons at time t.

b) Combine them in all possible ways into fragments or leave them as single nucleons.

c) Neglect the interaction among clusters.

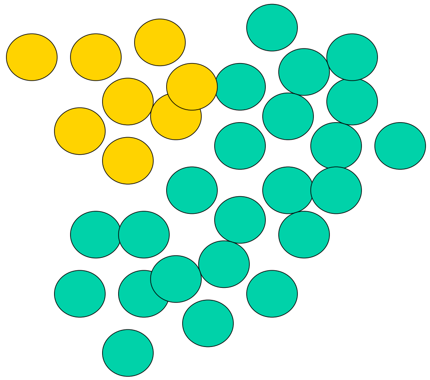
d) **Choose that configuration which has the highest binding energy.**

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.

FRIGA: a clusterisation approach…

Steps:

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



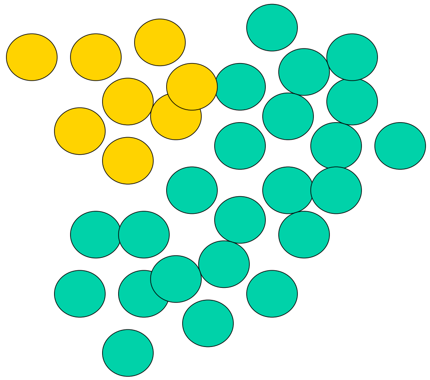
$$E=E^1_{kin}+E^2_{kin}+V^1+V^2$$

FRIGA: a clusterisation approach…

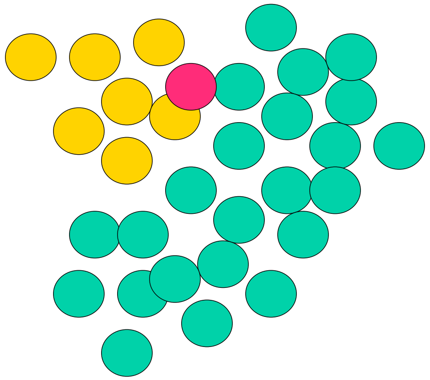
Steps:

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

2) Take randomly 1 nucleon out of one fragment



$E = E^1_{kin} + E^2_{kin} + V^1 + V^2$



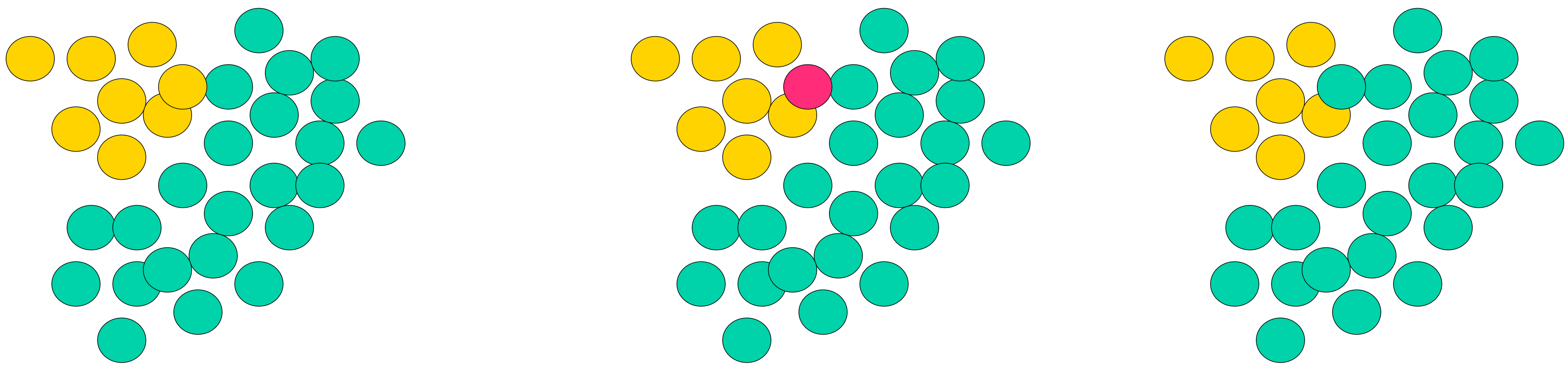
FRIGA: a clusterisation approach…

Steps:

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

2) Take randomly 1 nucleon out of one fragment

3) Add it randomly to another fragment



$E = E^1_{kin} + E^2_{kin} + V^1 + V^2$

$E' = E^{1'}_{kin} + E^{2'}_{kin} + V^{1'} + V^{2'}$

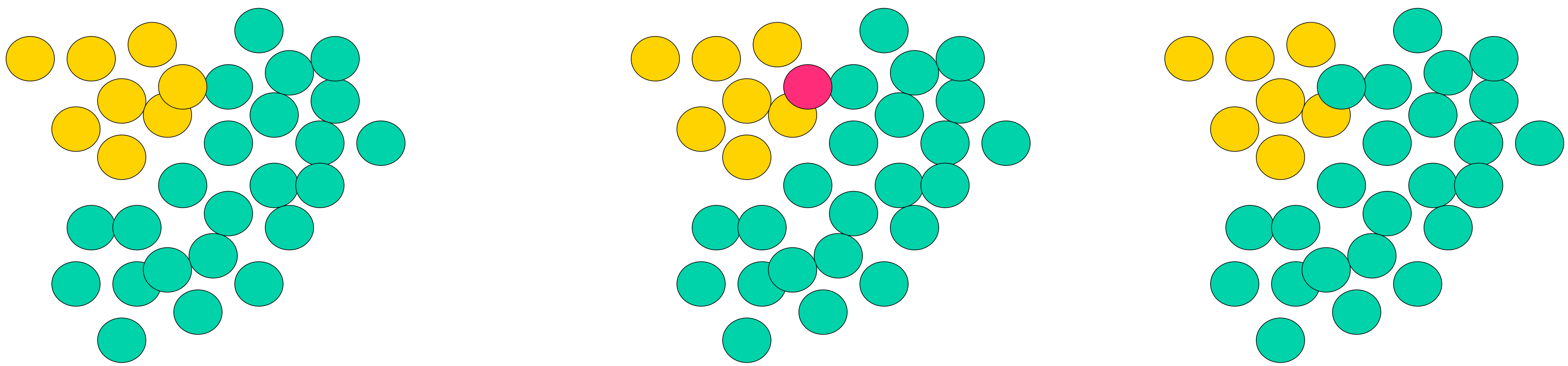
FRIGA: a clusterisation approach…

Steps:

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

2) Take randomly 1 nucleon out of one fragment

3) Add it randomly to another fragment



$E = E^{1}_{kin} + E^{2}_{kin} + V^{1} + V^{2}$

$E' = E^{1'}_{kin} + E^{2'}_{kin} + V^{1'} + V^{2'}$

<u>If $E' < E$</u> take the new configuration

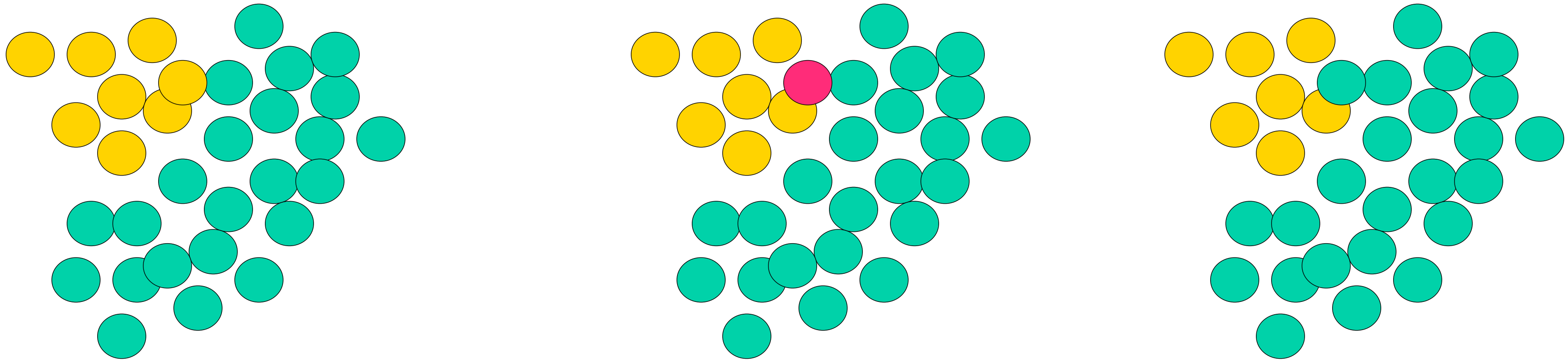
FRIGA: a clusterisation approach…

Steps:

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

2) Take randomly 1 nucleon out of one fragment

3) Add it randomly to another fragment



$E = E^{1}_{kin} + E^{2}_{kin} + V^{1} + V^{2}$

$E' = E^{1'}_{kin} + E^{2'}_{kin} + V^{1'} + V^{2'}$

If $E' < E$ take the new configuration

If $E' > E$ take the old with a probability depending on $E'-E$

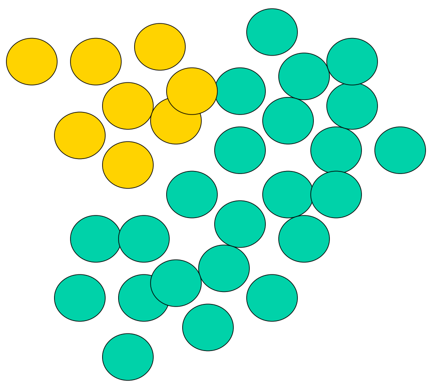
FRIGA: a clusterisation approach…

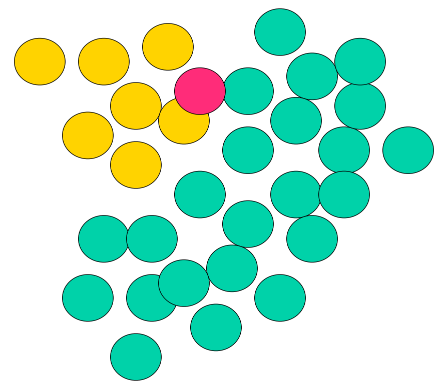
Steps:

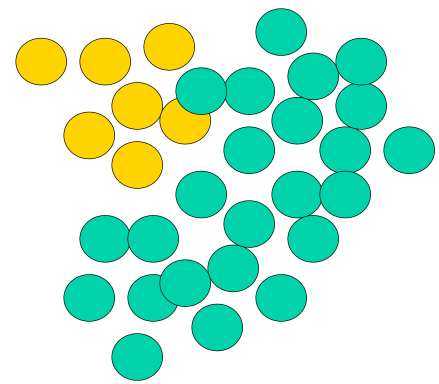
1) Pre-select good «candidates» for fragments according to proximity criteria: coordinate and momentum space coalescence = Minimum Spanning Tree (**MST**) procedure.

2) Take randomly 1 nucleon out of one fragment

3) Add it randomly to another fragment







$E = E^{1}_{kin} + E^{2}_{kin} + V^{1} + V^{2}$

$E' = E^{1'}_{kin} + E^{2'}_{kin} + V^{1'} + V^{2'}$

If $E' < E$ take the new configuration

If $E' > E$ take the old with a probability depending on $E'-E$

Repeat this procedure very many times… (Metropolis procedure)

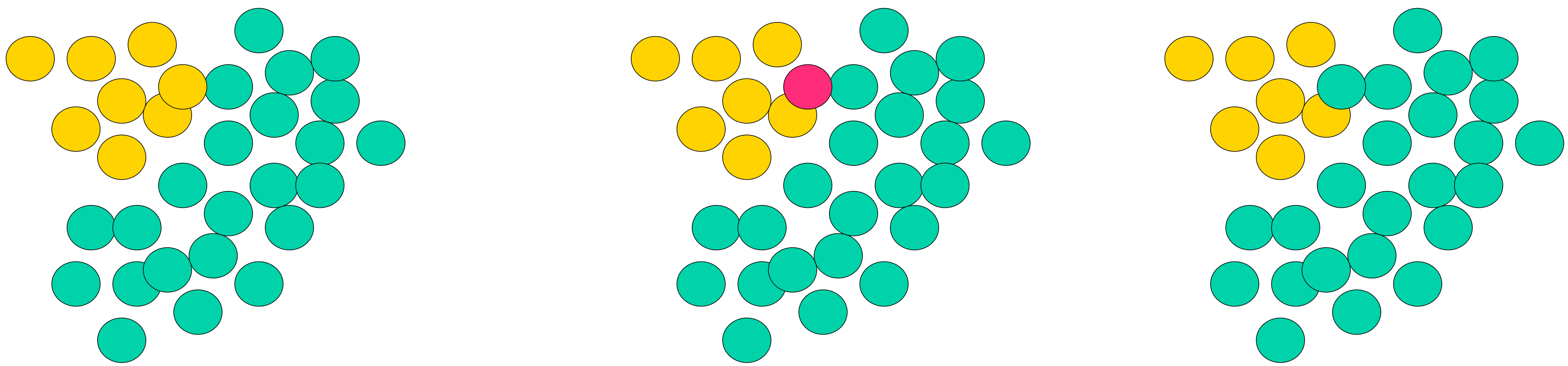
FRIGA: a clusterisation approach…

Steps:

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

2) Take randomly 1 nucleon out of one fragment

3) Add it randomly to another fragment



$E = E^1_{kin} + E^2_{kin} + V^1 + V^2$

$E' = E^{1'}_{kin} + E^{2'}_{kin} + V^{1'} + V^{2'}$

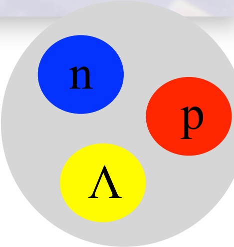
If $E' < E$ take the new configuration

If $E' > E$ take the old with a probability depending on E'-E

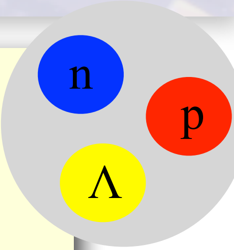
Repeat this procedure very many times… (Metropolis procedure)

It leads automatically to **the most bound configuration**.

FRIGA: a clusterisation approach…



FRIGA: a clusterisation approach…

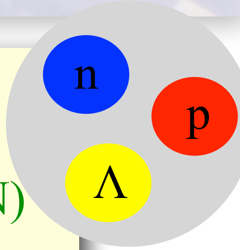


Ingredients of the binding energy of the clusters :

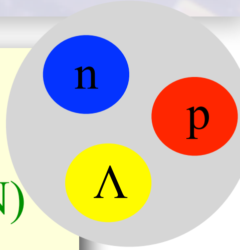
FRIGA: a clusterisation approach…

Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei).
We consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)



FRIGA: a clusterisation approach…

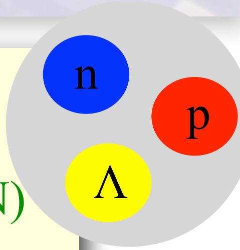


Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei).
We consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)

② Surface effect correction: Yukawa term. And optionally:

FRIGA: a clusterisation approach…



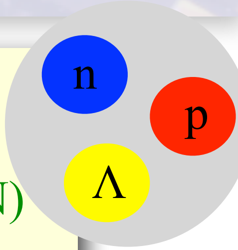
Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei).
We consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)

② Surface effect correction: Yukawa term. And optionally:

③ Asymmetry energy : $23.3\ \text{MeV}.(\langle\rho'_B\rangle)^{(\gamma_{ASY}-1)}.(\langle\rho'_n\rangle-\langle\rho'_p\rangle)^2/\langle\rho'_B\rangle$

FRIGA: a clusterisation approach…



Ingredients of the binding energy of the clusters :

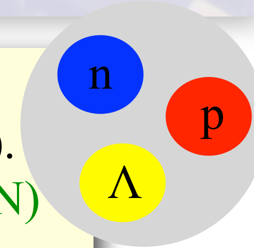
① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei).
We consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)

② Surface effect correction: Yukawa term. And optionally:

③ Asymmetry energy : $23.3\ \text{MeV}.(\langle\rho'_B\rangle)^{(\gamma_{ASY}-1)}.(\langle\rho'_n\rangle-\langle\rho'_p\rangle)^2/\langle\rho'_B\rangle$

④ Extra « structure » energy $(N,Z,\rho) = B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$

FRIGA: a clusterisation approach…



Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei).
We consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)

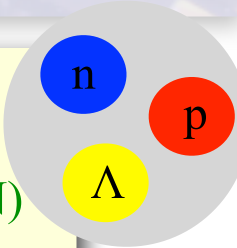
② Surface effect correction: Yukawa term. And optionally:

③ Asymmetry energy : $23.3\ \mathrm{MeV}.(\langle\rho'_B\rangle)^{(\gamma_{ASY}-1)}.(\langle\rho'_n\rangle-\langle\rho'_p\rangle)^2/\langle\rho'_B\rangle$

④ Extra « structure » energy $(N,Z,\rho) = B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$

⑤ ^{3}He+n recombination.

FRIGA: a clusterisation approach…



Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei).
We consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)

② Surface effect correction: Yukawa term. And optionally:

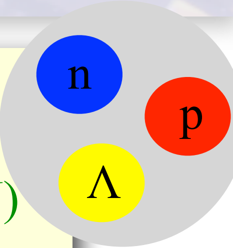
③ Asymmetry energy : $23.3\ \text{MeV}.(\langle\rho'_B\rangle)^{(\gamma_{ASY}-1)}.(\langle\rho'_n\rangle-\langle\rho'_p\rangle)^2/\langle\rho'_B\rangle$

④ Extra « structure » energy $(N,Z,\rho) = B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$

⑤ ^3He+n recombination.

⑥ Secondary decay: GEMINI.

FRIGA: a clusterisation approach…



Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei).
We consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)

② Surface effect correction: Yukawa term. And optionally:

③ Asymmetry energy : $23.3\ \mathrm{MeV}.(<\rho'_B>)^{(\gamma_{ASY}-1)}.(<\rho'_n>-<\rho'_p>)^2/<\rho'_B>$

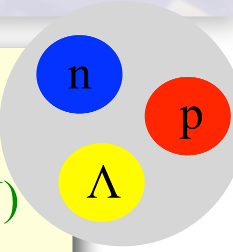
④ Extra « structure » energy (N,Z,ρ) = $B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$

⑤ ^{3}He+n recombination.

⑥ Secondary decay: GEMINI.

⑦ Rejection of « non-existing » isotopes and hyper-clusters.

FRIGA: a clusterisation approach…



Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei).
We consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)

② Surface effect correction: Yukawa term. And optionally:

③ Asymmetry energy : 23.3 MeV.$(<\rho'_B>)^{(\gamma_{ASY}-1)}.(<\rho'_n>-<\rho'_p>)^2/<\rho'_B>$

~~④ Extra « structure » energy (N,Z,ρ) = $B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$~~

~~⑤ ^{3}He+n recombination.~~

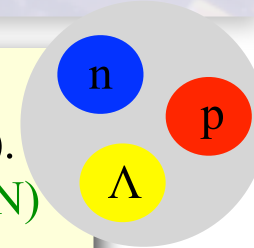
~~⑥ Secondary decay: GEMINI.~~

Not used here

⑦ Rejection of « non-existing » isotopes and hyper-clusters.

FRIGA: a clusterisation approach…

Ingredients of the binding energy of the clusters :



① Volume component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei).
We consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)

② Surface effect correction: Yukawa term. And optionally:

③ Asymmetry energy : 23.3 MeV.$(\langle\rho'_B\rangle)^{(\gamma_{ASY}-1)}.(\langle\rho'_n\rangle-\langle\rho'_p\rangle)^2/\langle\rho'_B\rangle$

~~④ Extra « structure » energy (N,Z,ρ) = $B_{MF}(\rho).((B_{exp}-B_{BW})/(B_{BW}-B_{Coul}-B_{asy}))(\rho_0)$~~

~~⑤ ^{3}He+n recombination.~~

Not used here

~~⑥ Secondary decay: GEMINI.~~

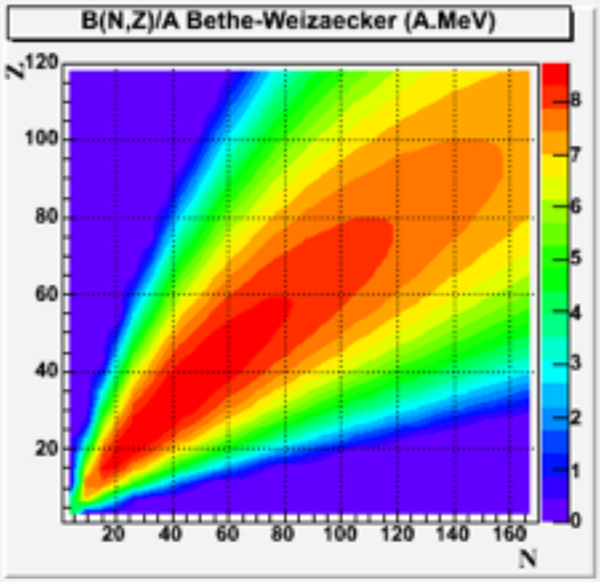
⑦ Rejection of « non-existing » isotopes and hyper-clusters.

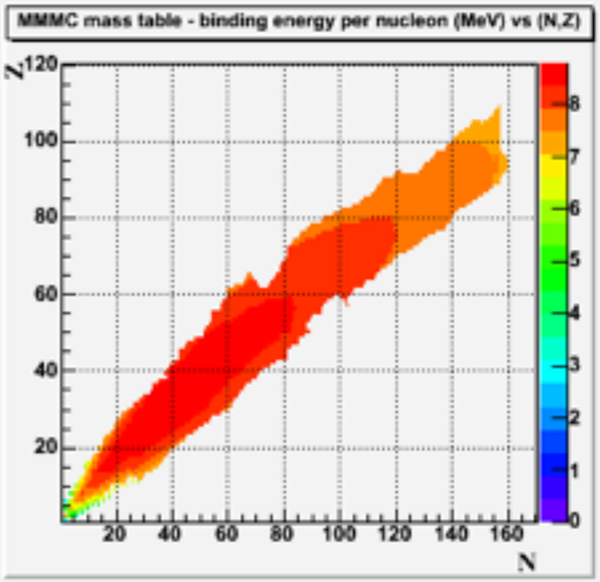
Remarks:

- The clusterisation has to happen quite early (passing time) such as to produce hypernuclei.
- Λ yields and phase space repartition as regard to the hadronic matter has to be realistic ⇒ influence of the EOS, in medium-properties, etc. of the transport model.

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 (hypernuclei included) and the Bethe-Weizäcker formula (without pairing).



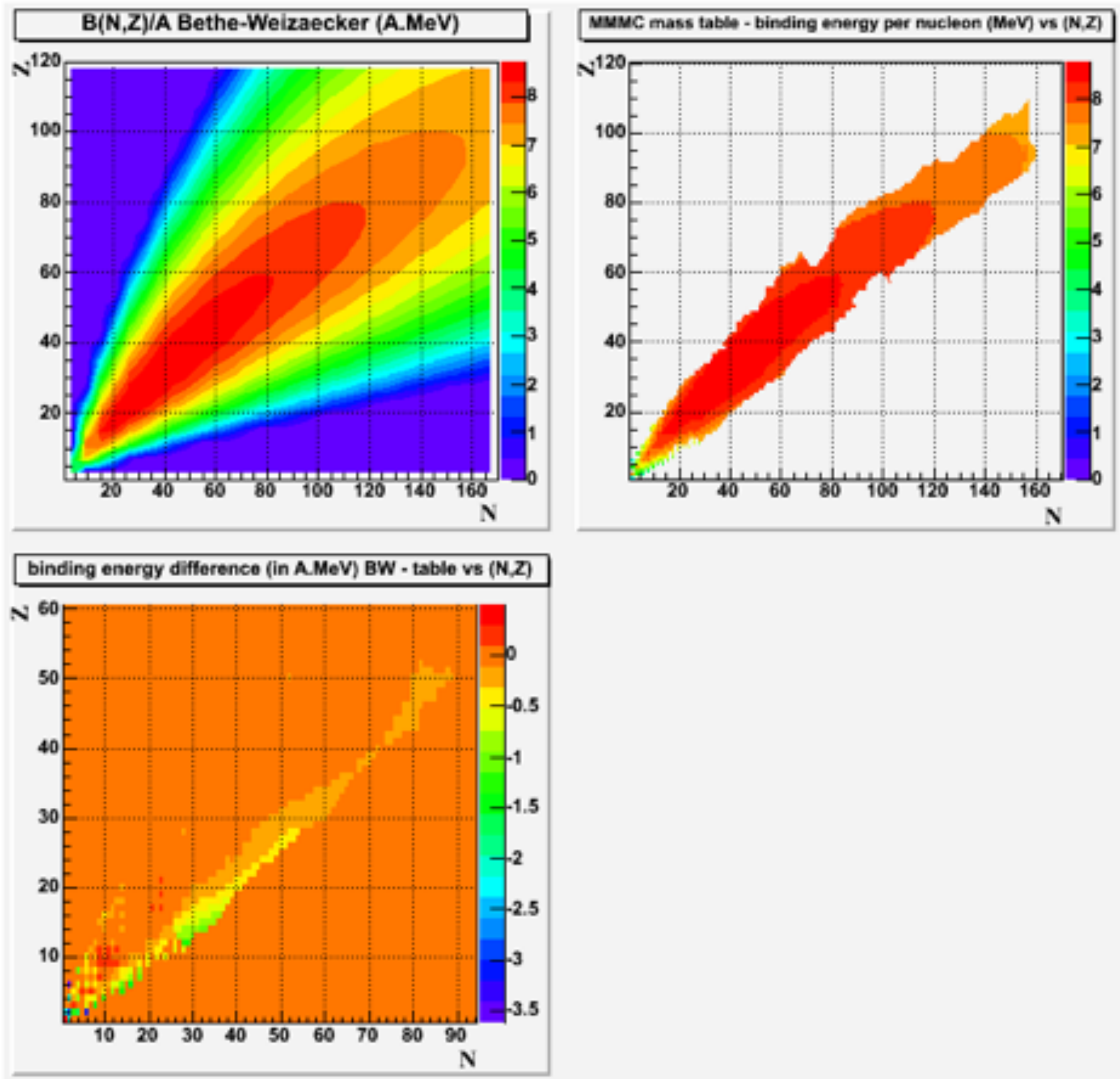


More detailed structure corrections to apply

☞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 (hypernuclei included) and the Bethe-Weizäcker formula (without pairing).

➜ $\Delta B_{pairing}(N,Z,\rho_0)$.

Strategy adopted in FRIGA: whatever the cluster density ρ, $\Delta B_{pairing}(N,Z,\rho)$ is determined from the assumption of a fixed proportion $\Delta B_{pairing}/B_{surf.+vol.}$

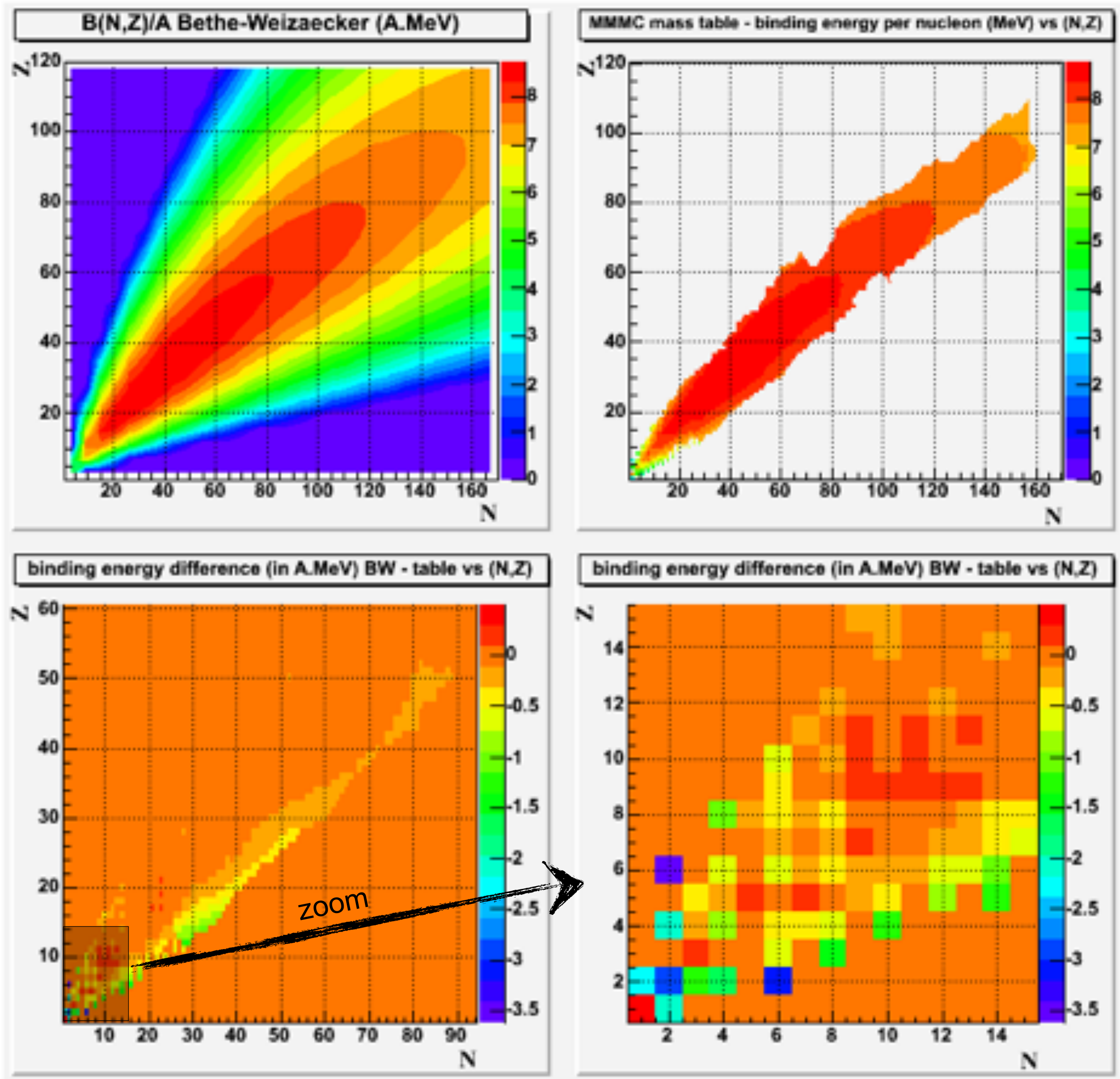


More detailed structure corrections to apply

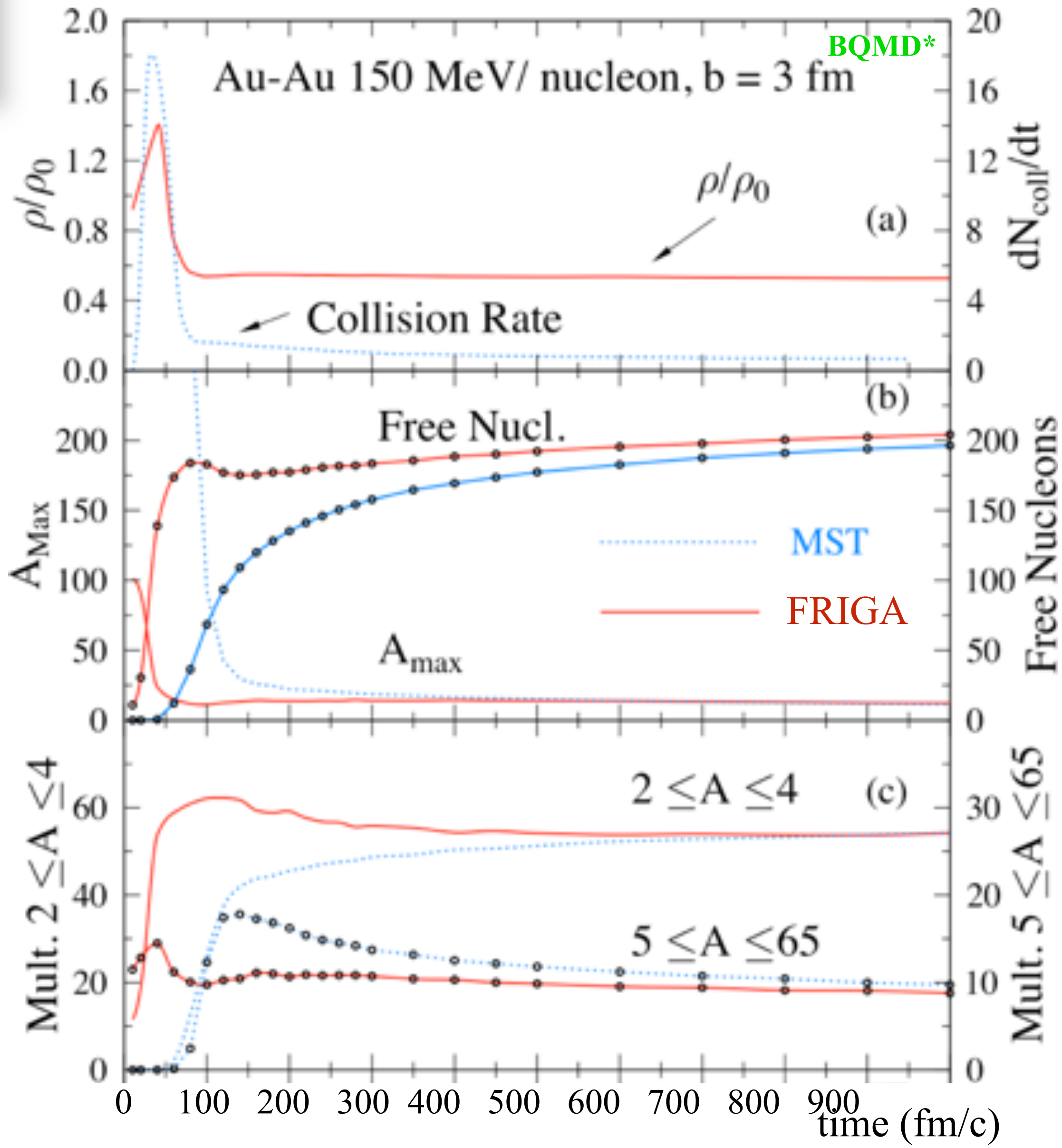
☞In order to account for all major structure effects which make the binding energy deviate from the liquid drop model, for each nucleus (N,Z), what we call «pairing» binding energy will be the difference in binding energy between experimental measurements (hypernuclei included) and the Bethe-Weizäcker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

➜ $\Delta B_{pairing}(N,Z,\rho_0)$.

Strategy adopted in FRIGA: whatever the cluster density ρ, $\Delta B_{pairing}(N,Z,\rho)$ is determined from the assumption of a fixed proportion $\Delta B_{pairing}/B_{surf.+vol.}$

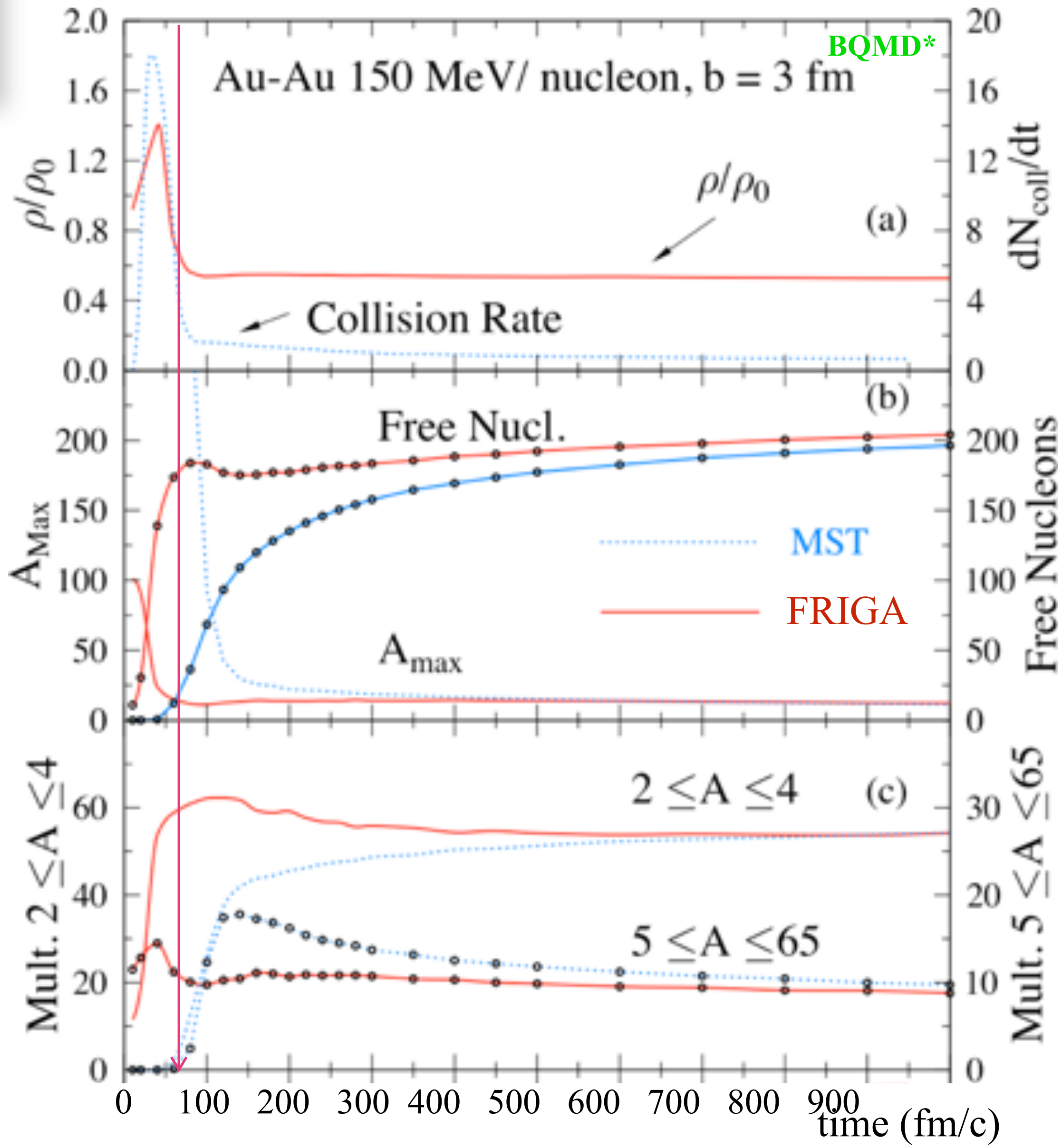


FRIGA versus coalescence (Minimum Spanning Tree)



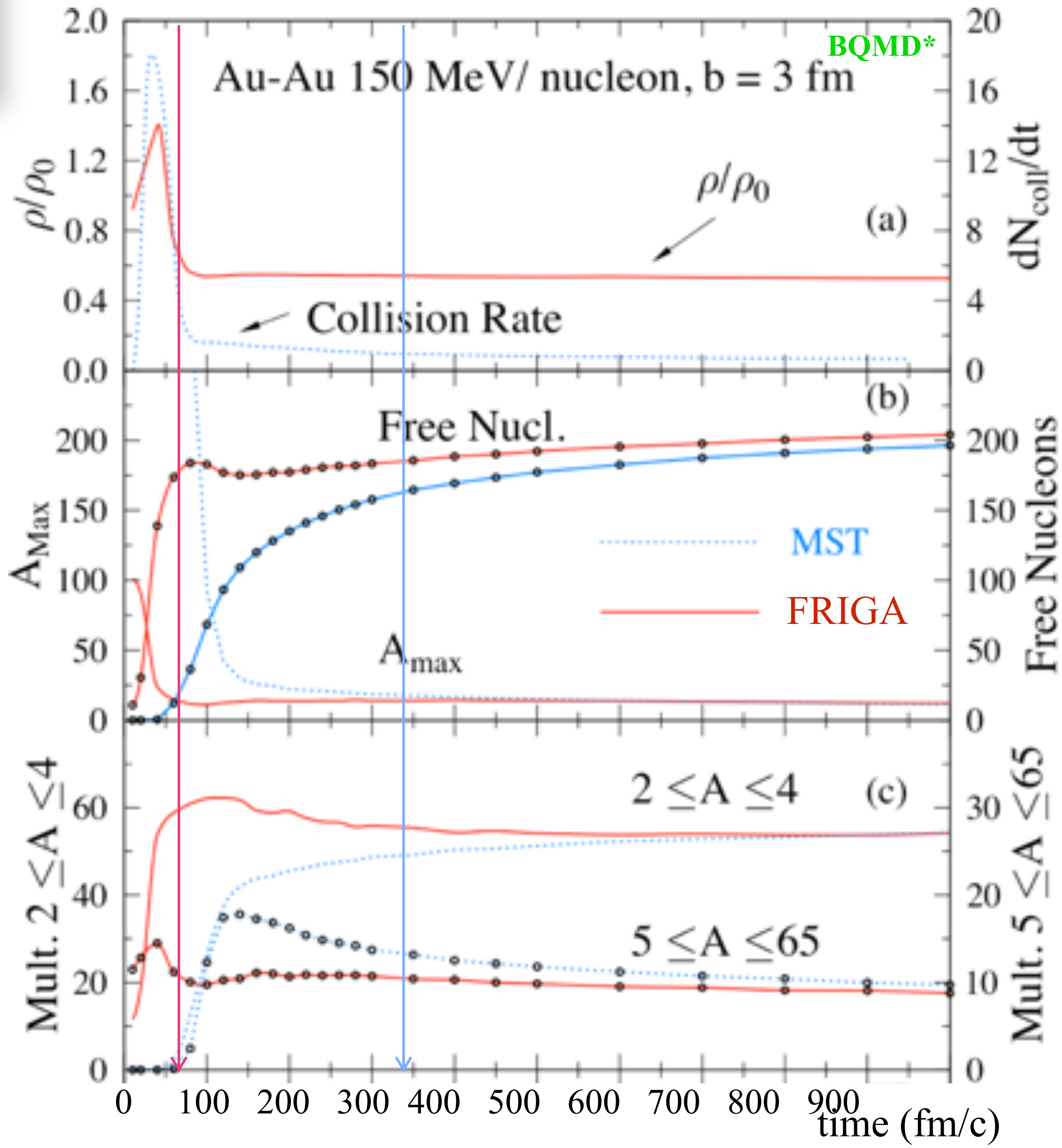
* P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

FRIGA versus coalescence (Minimum Spanning Tree)



* P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

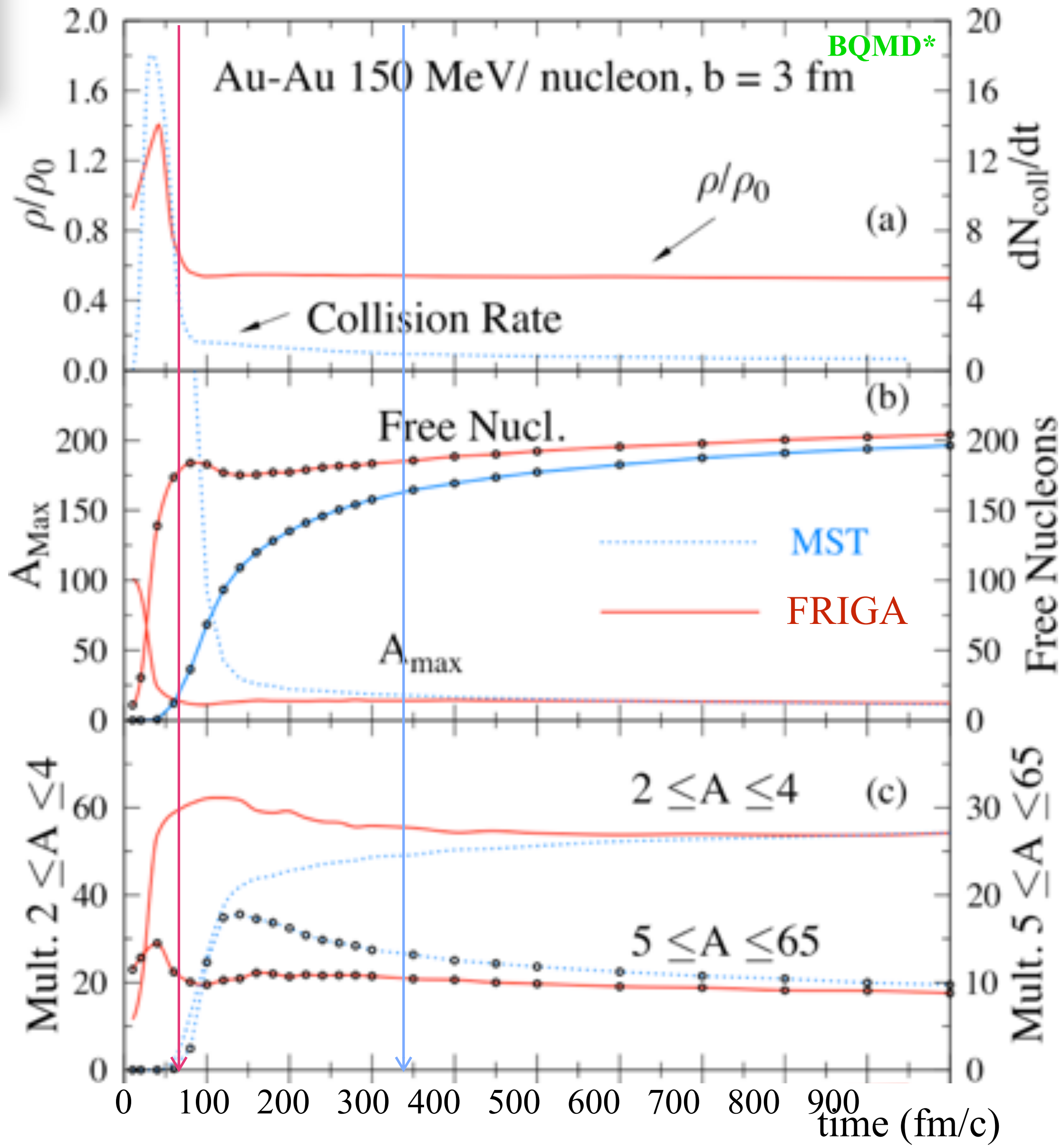
FRIGA versus coalescence (Minimum Spanning Tree)



* P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

FRIGA versus coalescence (Minimum Spanning Tree)

Unlike FRIGA, MST is not able to describe the early formation of fragments.

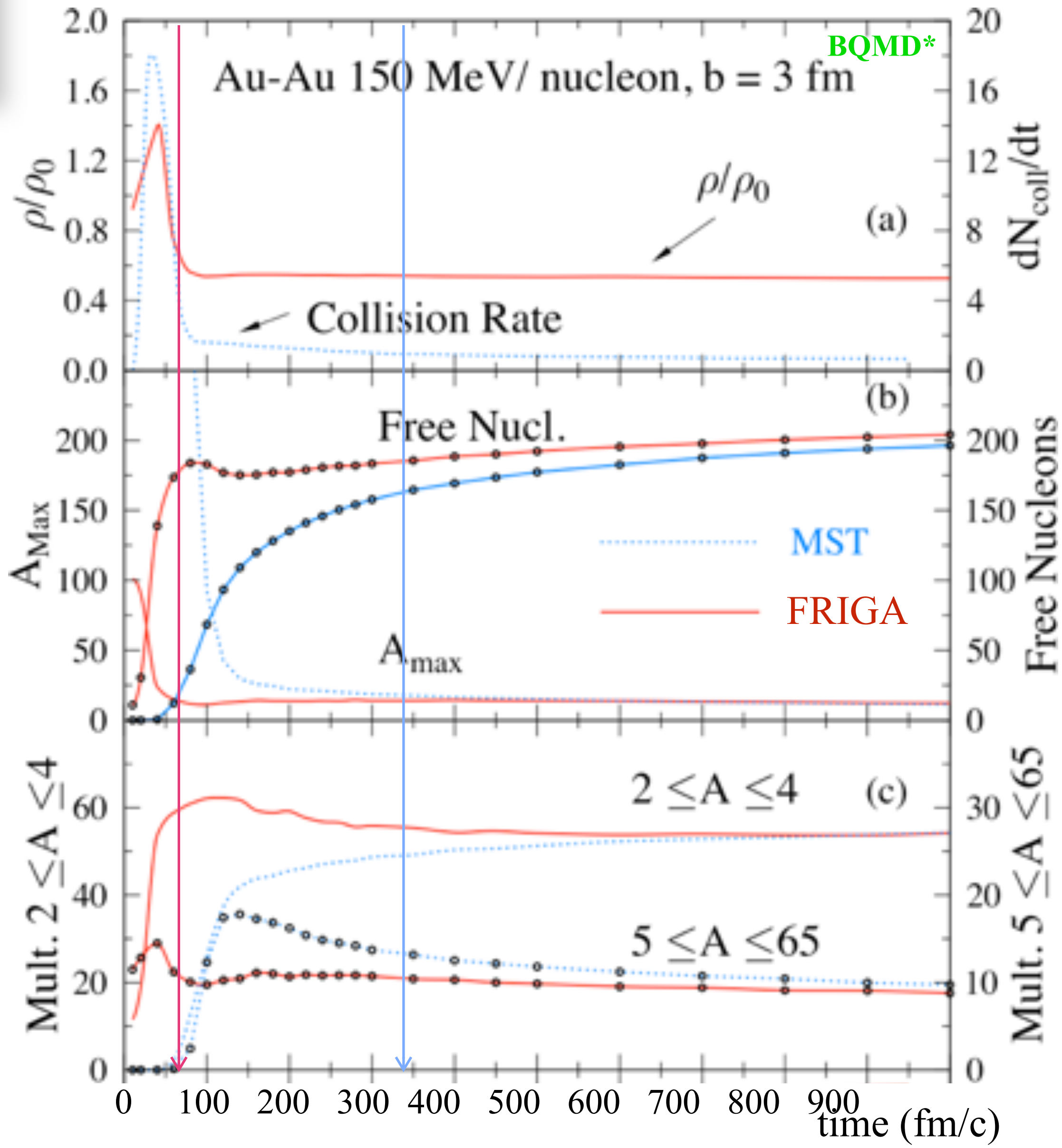


* P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

FRIGA versus coalescence (Minimum Spanning Tree)

Unlike FRIGA, MST is not able to describe the early formation of fragments.

➡ With MST, one has to consider necessarily later times (typically 200-400 fm/c), where the dynamical conditions are no longer the same.



* P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

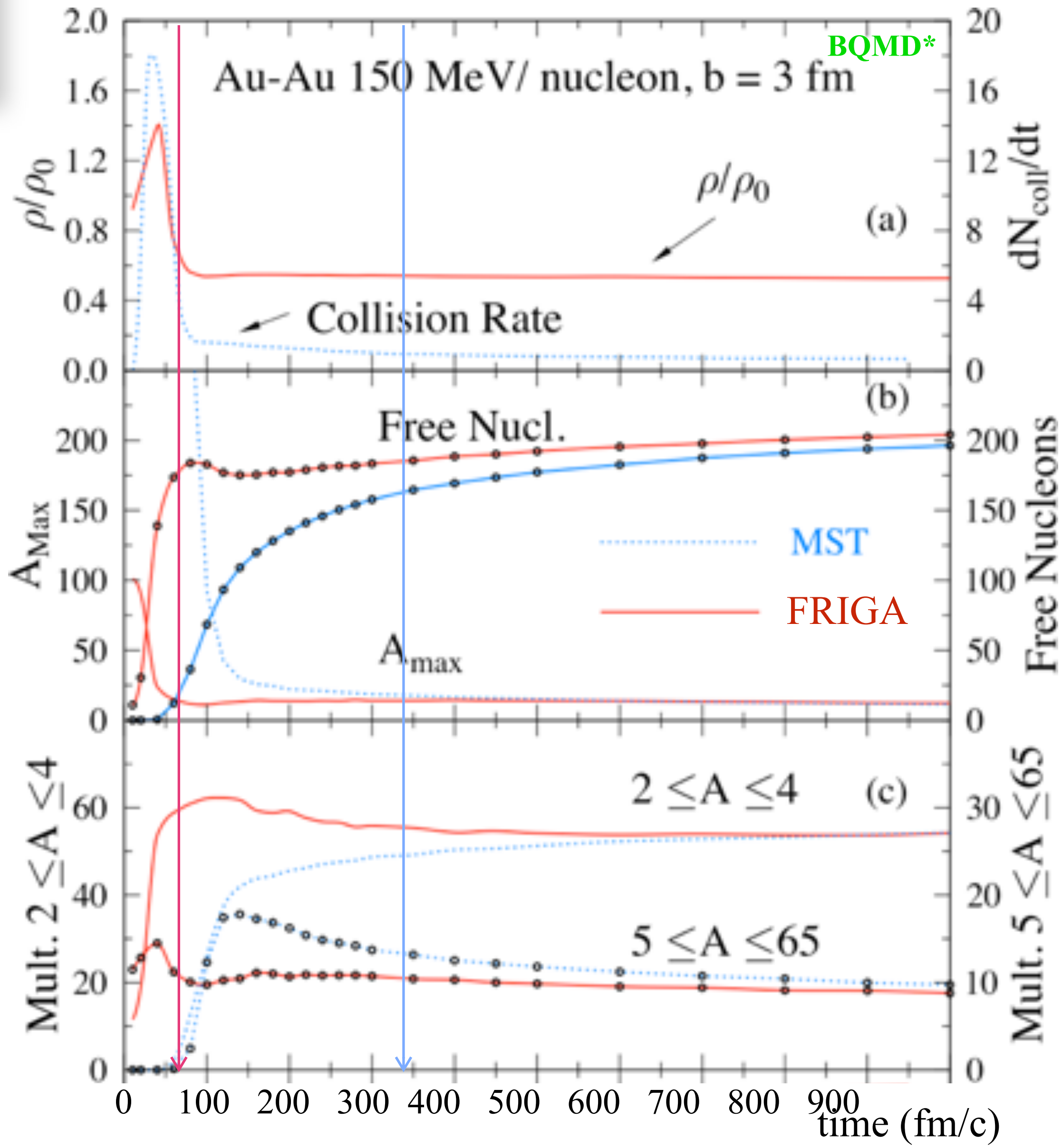
GSI HELMHOLTZ ASSOCIATION

FRIGA versus coalescence (Minimum Spanning Tree)

Unlike FRIGA, MST is not able to describe the early formation of fragments.

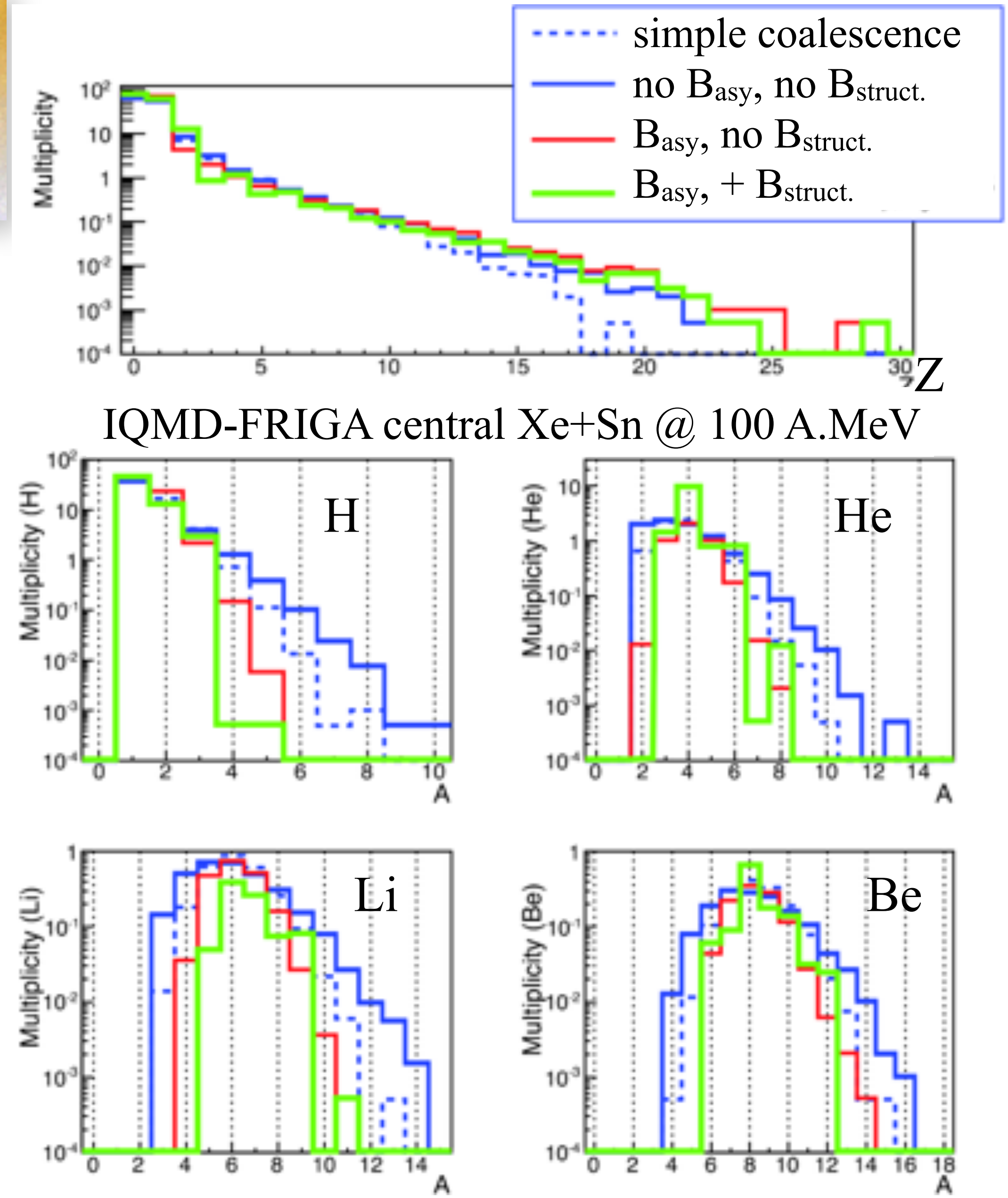
➡ With MST, one has to consider necessarily later times (typically 200-400 fm/c), where the dynamical conditions are no longer the same.

▸ Advantage of FRIGA : the fragment partitions can reflect the early dynamical conditions (Coulomb, density, flow details, strangeness…), which is particularly important for the hypernucleus formation.



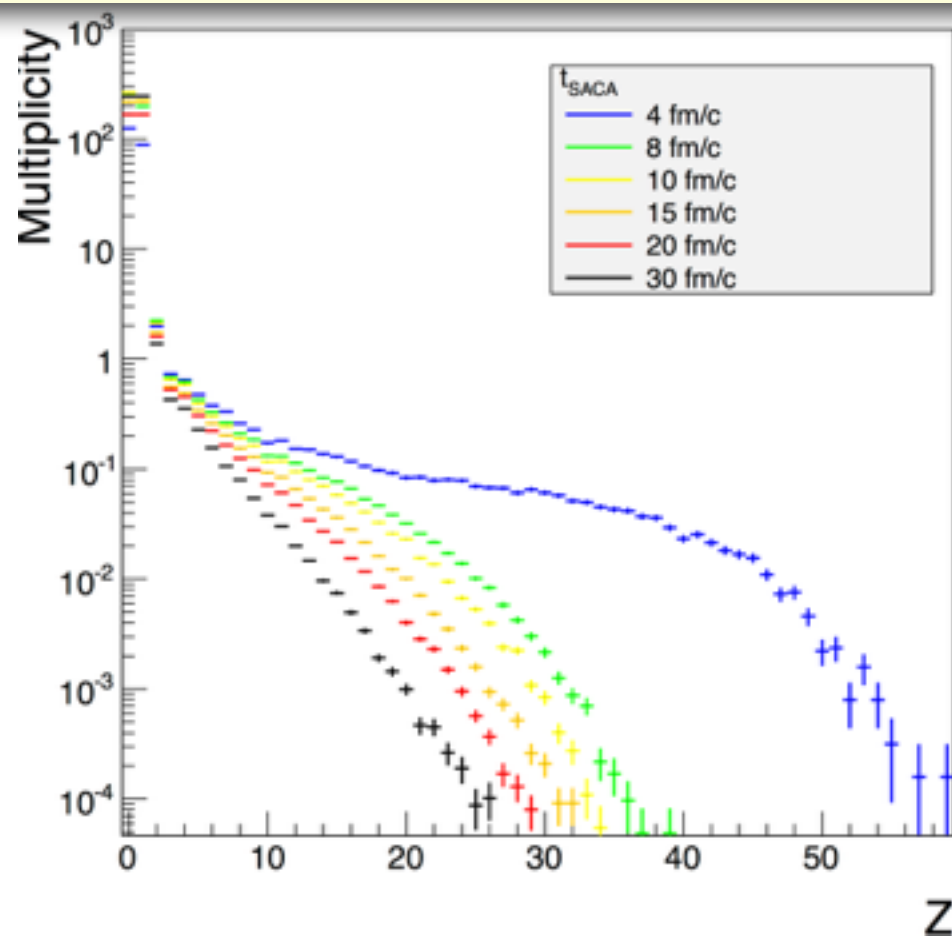
* P.B. Gossiaux, R. Puri, Ch. Hartnack, J. Aichelin, Nuclear Physics A 619 (1997) 379-390

FRIGA: a clusterisation approach…



Clusterisation time influence on hypernuclei (phase space and yields)

An example: Au+Au @ 11.45 A.GeV (AGS), b=6 fm (passing time = 7.5 fm/c)
from PHSD*+FRIGA



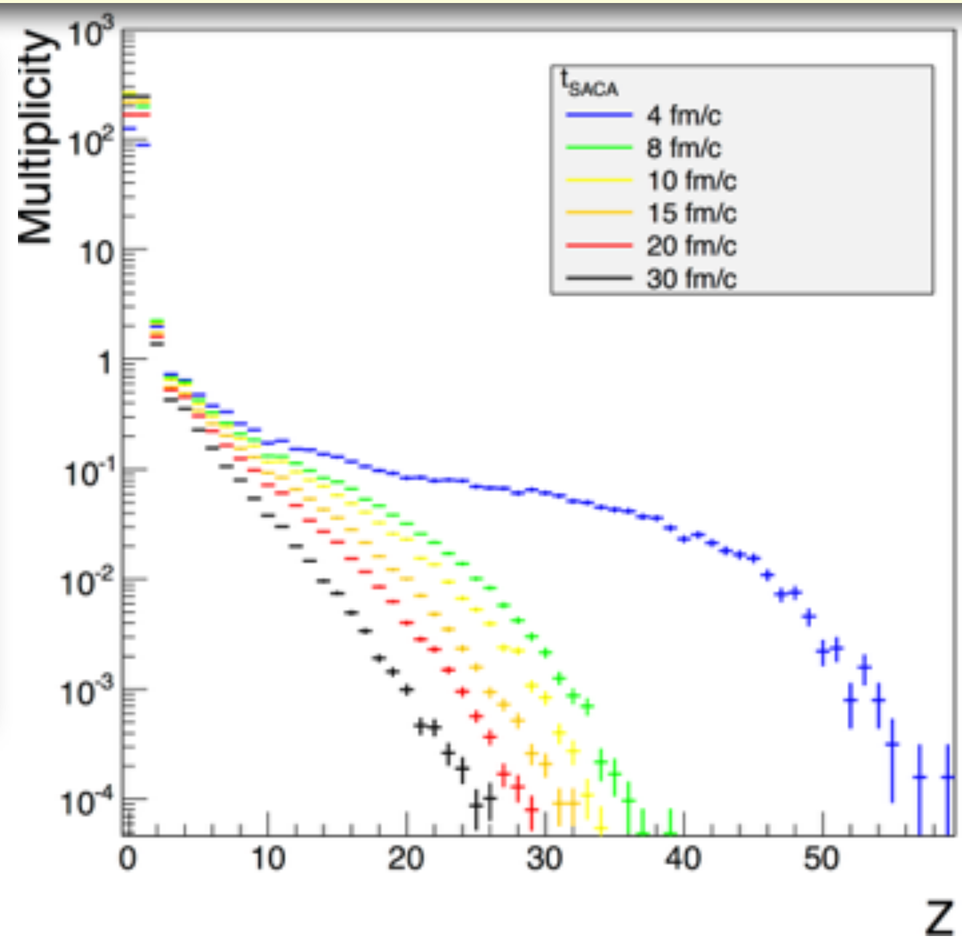
*: W. Cassing, E.L. Bratkovskaya, Nucl. Phys. A 831 (2009) 2.

Clusterisation time influence on hypernuclei (phase space and yields)

An example: Au+Au @ 11.45 A.GeV (AGS), b=6 fm (passing time = 7.5 fm/c)
from PHSD*+FRIGA

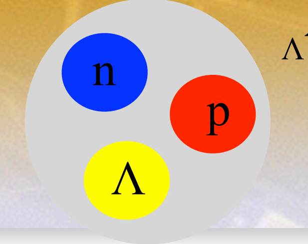
Remarks:

- At the passing time, the partitions are stabilising,
- Apart from a tendency of the size of the biggest fragments to decrease over time due to the artificial evaporation of the spectators, inherent to the present version of PHSD (improvements under construction).



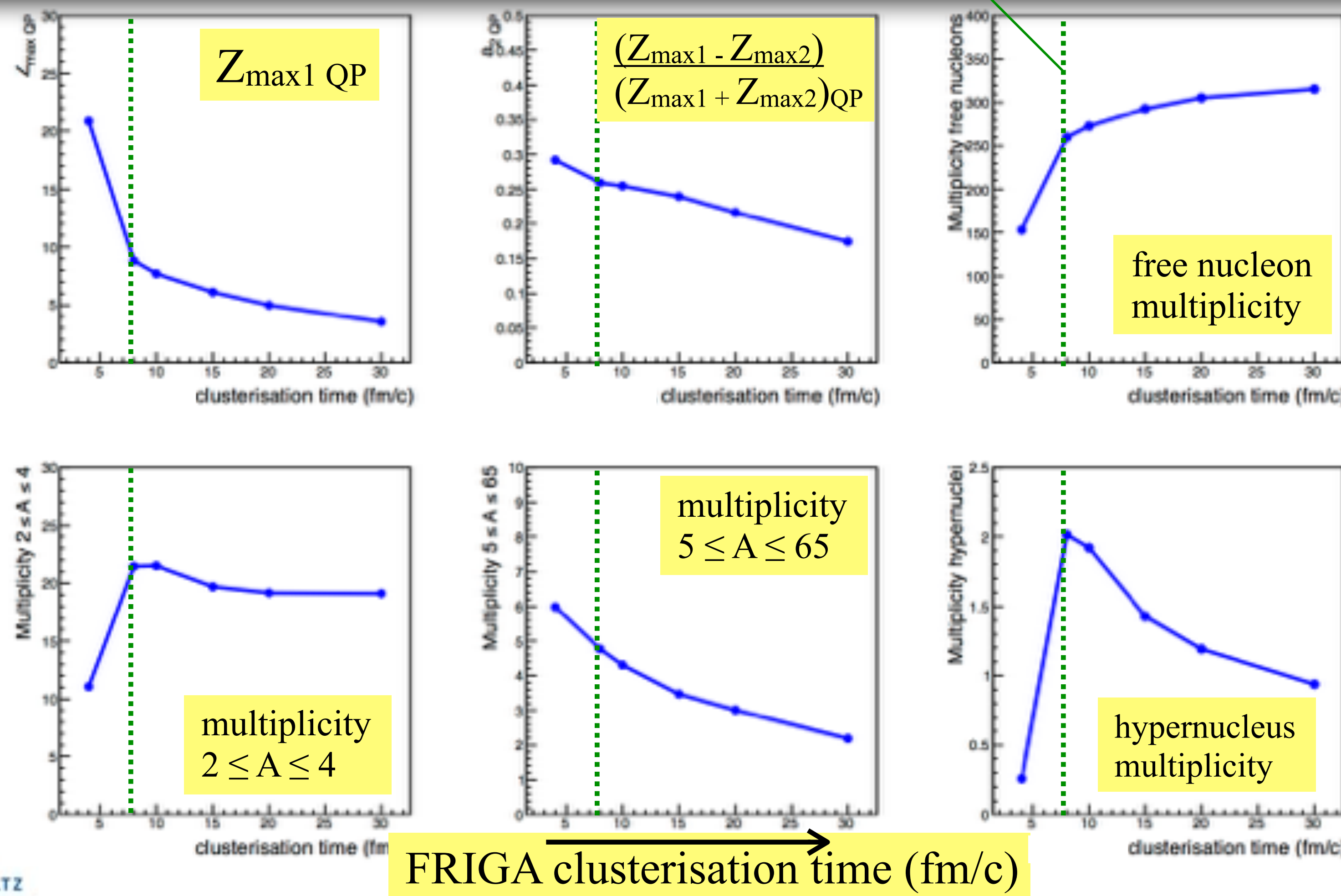
*: W. Cassing, E.L. Bratkovskaya, Nucl. Phys. A 831 (2009) 2.

Clusterisation time influence on hypernuclei (phase space and yields)



An example: Au+Au @ 11.45 A.GeV, b=6 fm (passing time = 7.5 fm/c) from PHSD+FRIGA

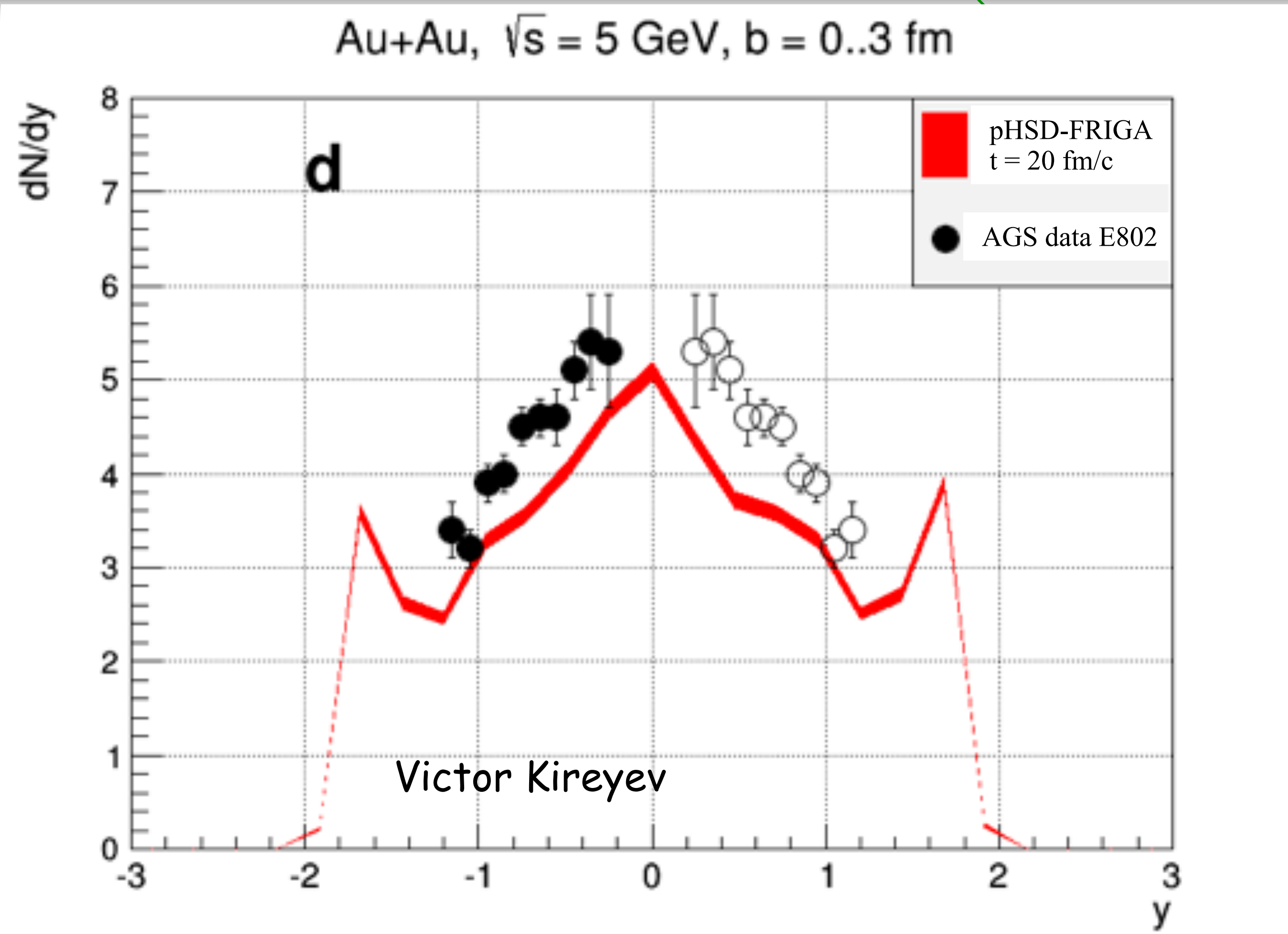
AGS system



Clusterisation time influence on hypernuclei (phase space and yields)

An example: Au+Au @ 11.45 A.GeV, b=6 fm (passing time = 7.5 fm/c) from PHSD+FRIGA

AGS system

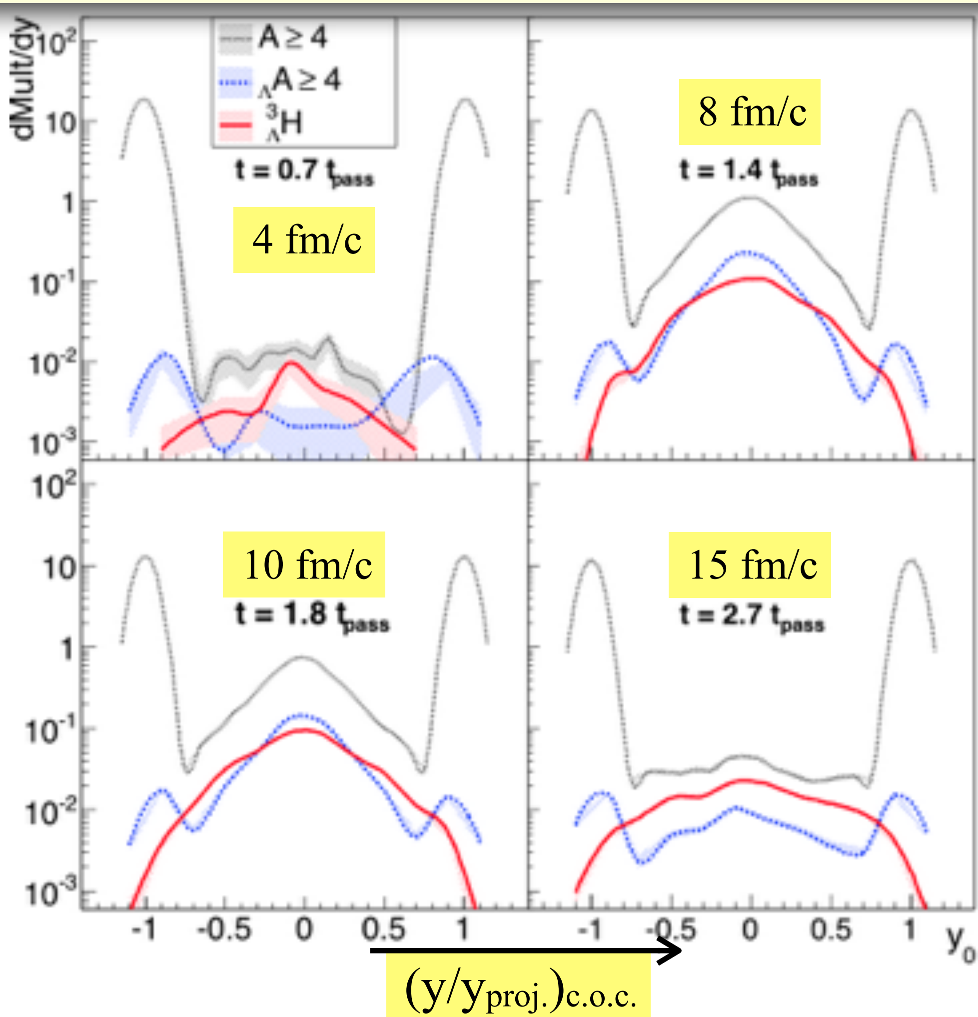


Clusterisation time influence on hypernuclei (phase space and yields)

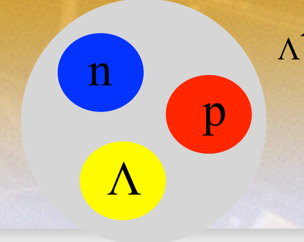
An example: Au+Au @ 11.45 A.GeV, b=6 fm (passing time = 7.5 fm/c) from HSD+FRIGA

AGS system

heavy (A>3) hypernuclei and hypertritons



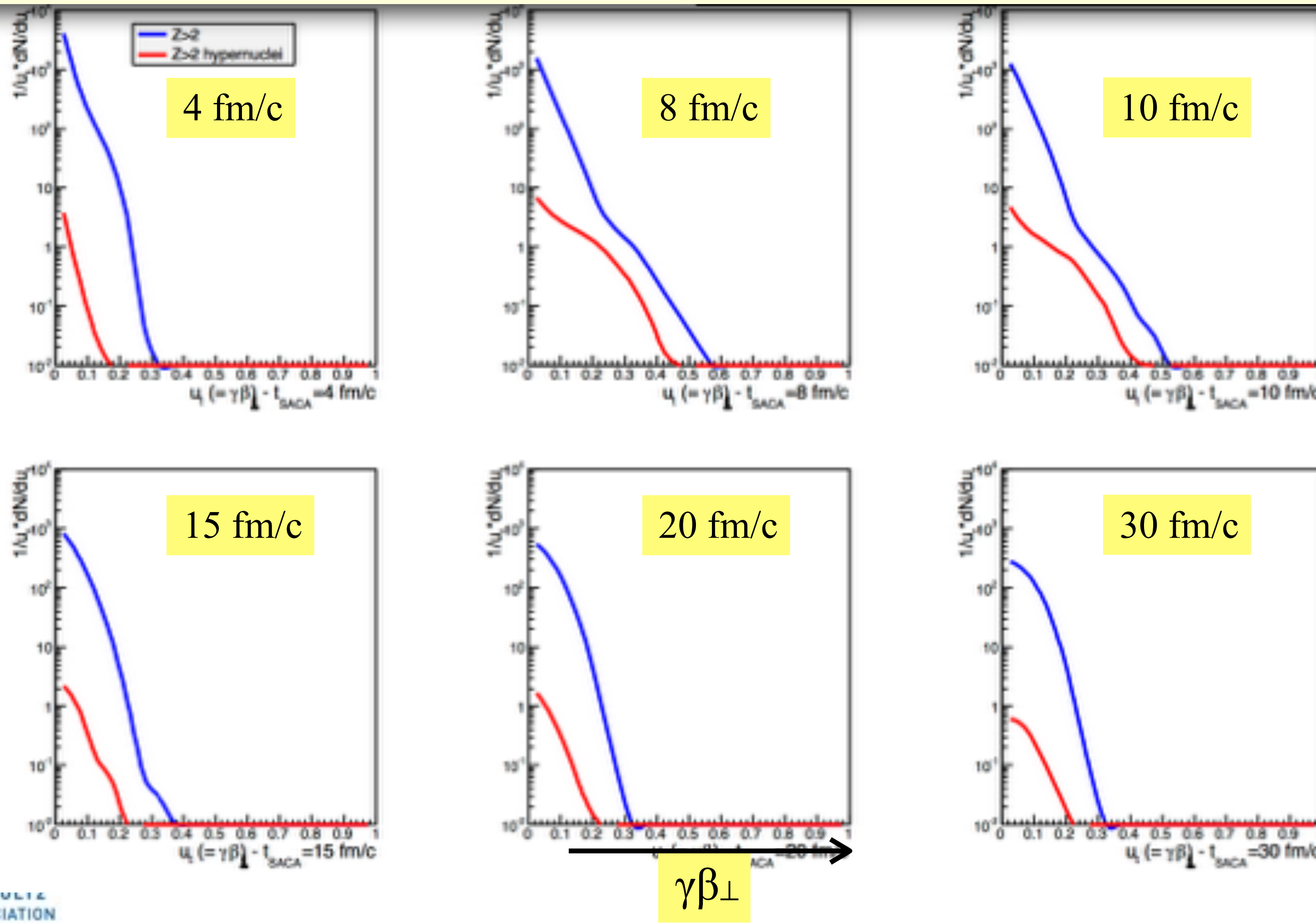
Clusterisation time influence on hypernuclei (phase space and yields)



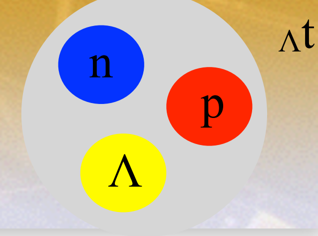
An example: Au+Au @ 11.45 A.GeV, b=6 fm (passing time = 7.5 fm/c) from HSD+FRIGA

AGS system

heavy (Z>2) hypernuclei

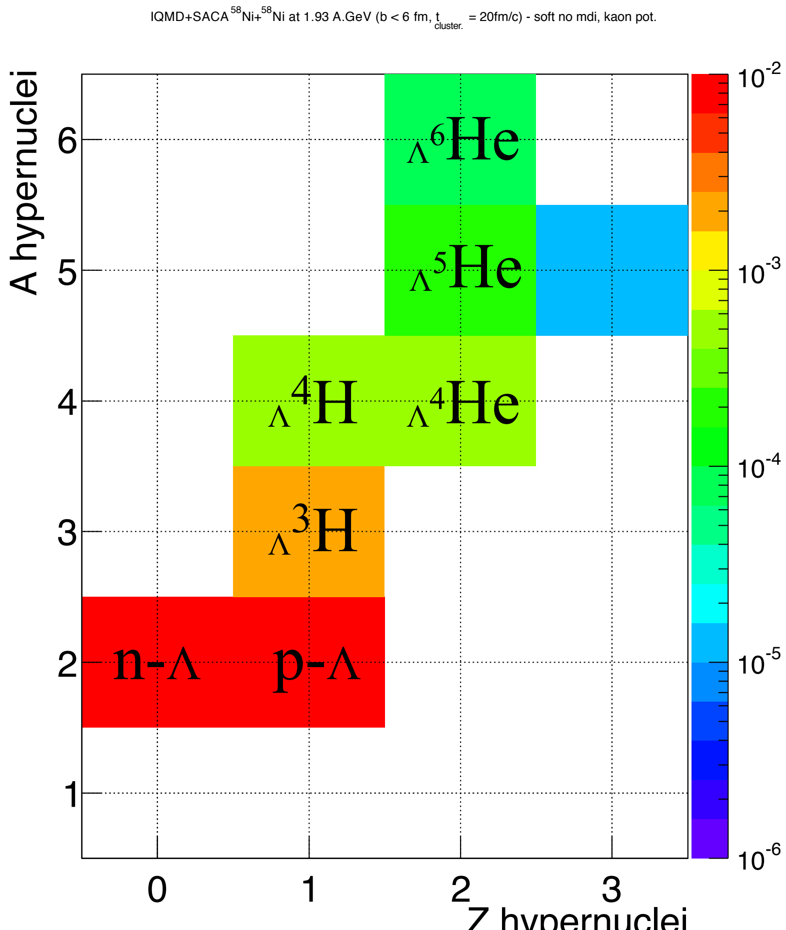


EOS, in medium-properties and hypernuclei yields



FOPI system

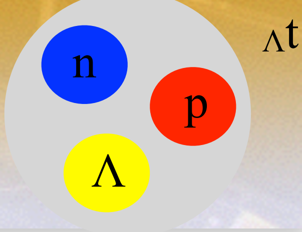
IQMD*+FRIGA
$^{58}Ni+^{58}Ni$ @1.91A.GeV
b < 6 fm
($t_{passing}$=8.7 fm/c)
$t_{cluster.}$=20 fm/c



Soft EOS
no m.d.i.
with Kaon pot.

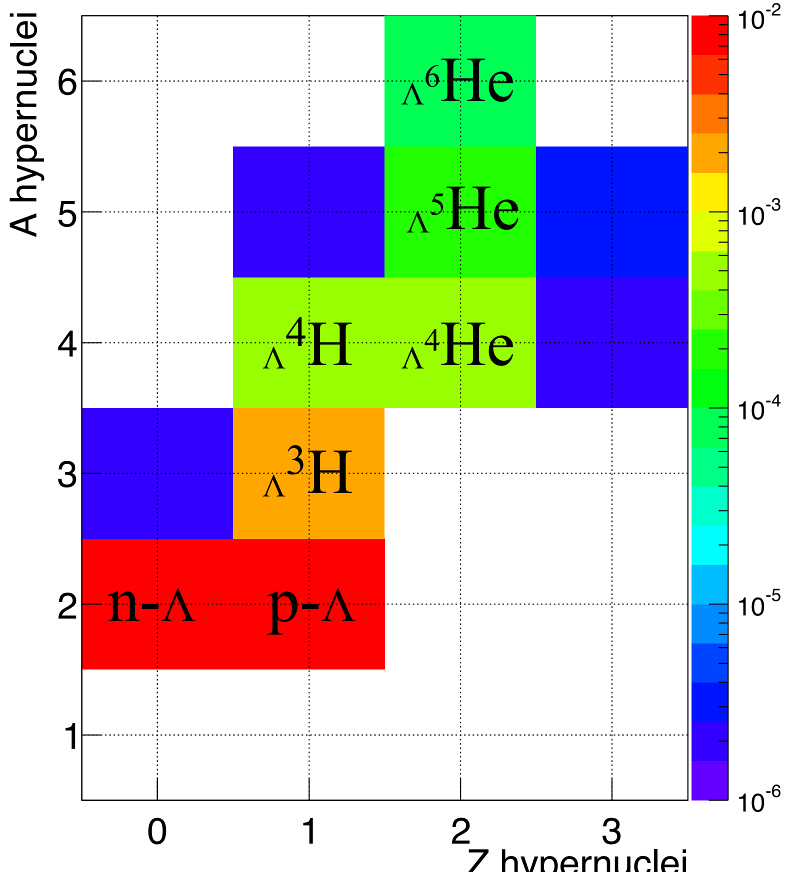
*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

EOS, in medium-properties and hypernuclei yields



FOPI system

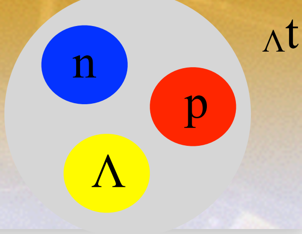
IQMD*+FRIGA
$^{58}Ni+^{58}Ni$ @1.91A.GeV
b < 6 fm
($t_{passing}$=8.7 fm/c)
$t_{cluster.}$=20 fm/c



Soft EOS
no m.d.i.
no Kaon pot. .

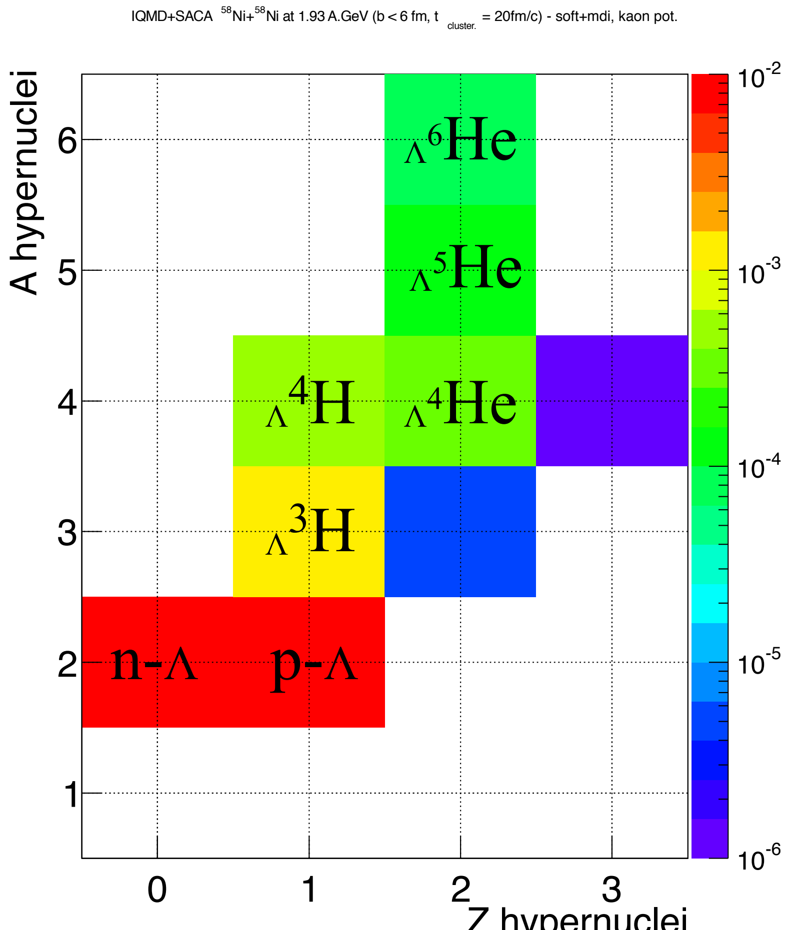
*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

EOS, in medium-properties and hypernuclei yields



FOPI system

IQMD*+FRIGA
^{58}Ni+^{58}Ni @1.91A.GeV
b < 6 fm
($t_{passing}$=8.7 fm/c)
$t_{cluster.}$=20 fm/c



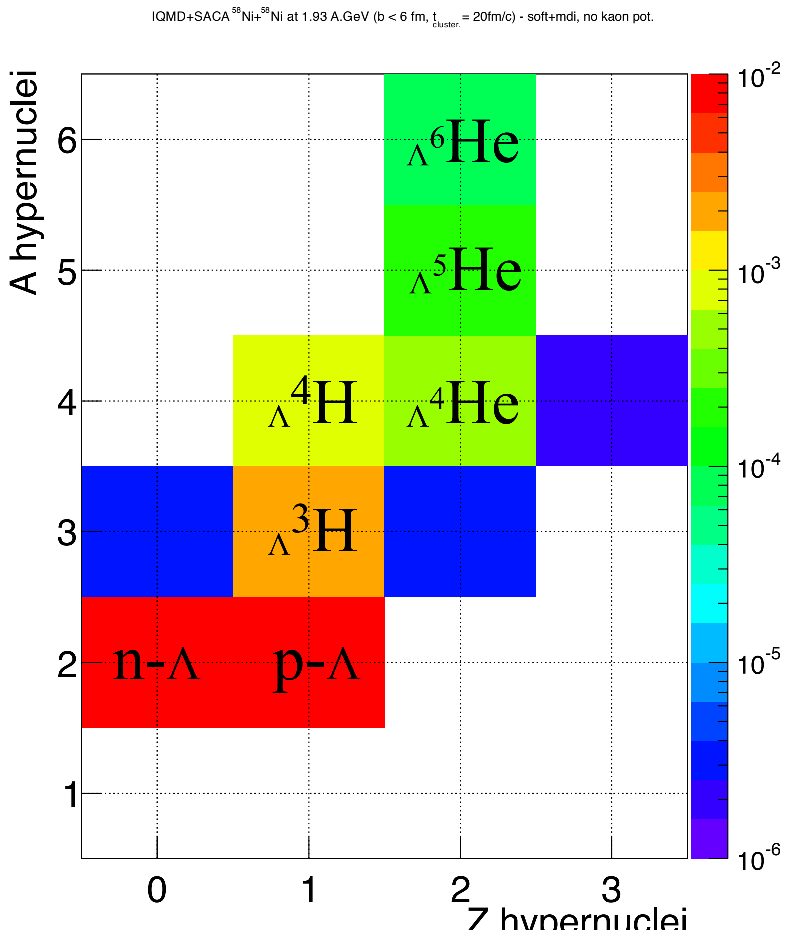
Soft EOS
with m.d.i.
with Kaon pot.

*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

EOS, in medium-properties and hypernuclei yields

FOPI system

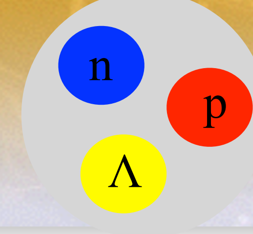
IQMD*+FRIGA
$^{58}Ni+^{58}Ni$ @1.91A.GeV
b < 6 fm
($t_{passing}$=8.7 fm/c)
$t_{cluster.}$=20 fm/c



Soft EOS
with m.d.i.
no Kaon pot. .

*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

EOS, in medium-properties and hypernuclei yields



$_{\Lambda}t$

FOPI system

IQMD*+FRIGA

^{58}Ni+^{58}Ni @1.91A.GeV

b < 6 fm

(t = 2.3 t_{pass})

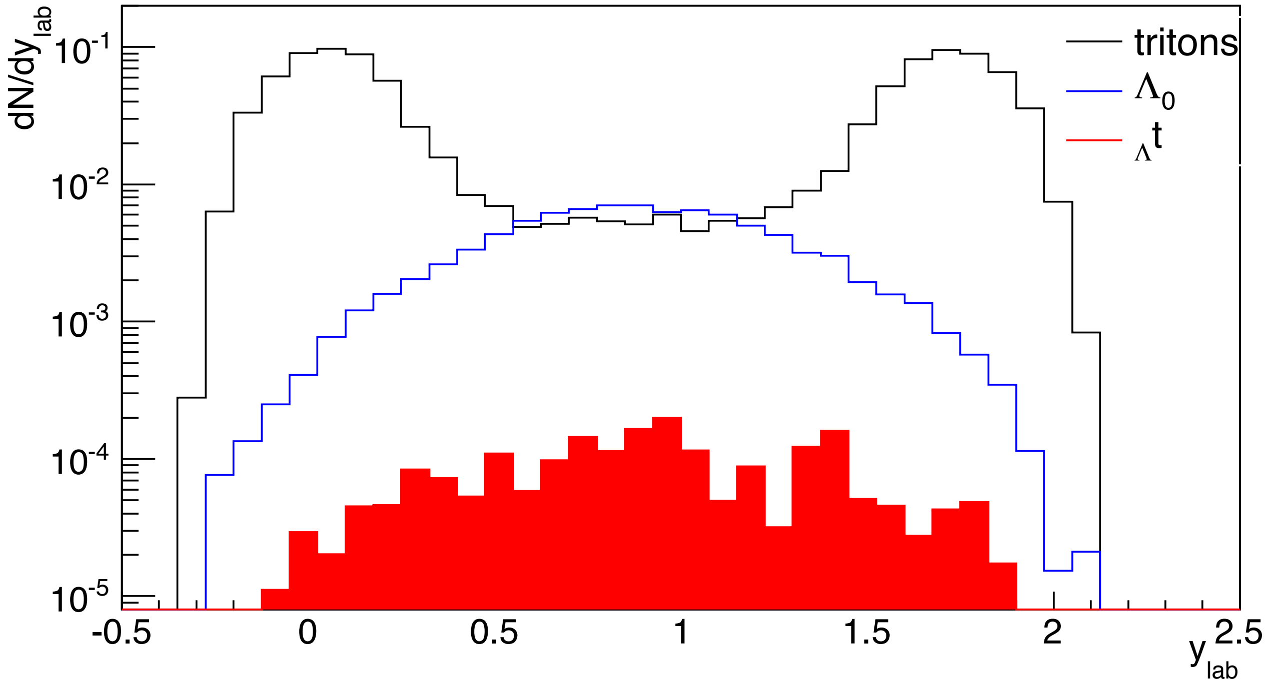
*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

EOS, in medium-properties and hypernuclei yields

FOPI system

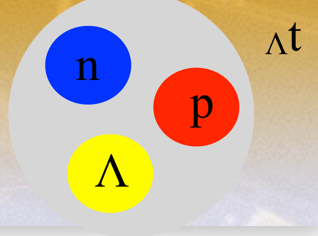
IQMD*+FRIGA
$^{58}Ni + ^{58}Ni$ @1.91A.GeV
b < 6 fm
(t = 2.3 t_{pass})

Soft EOS, no m.d.i., with Kaon pot.



*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

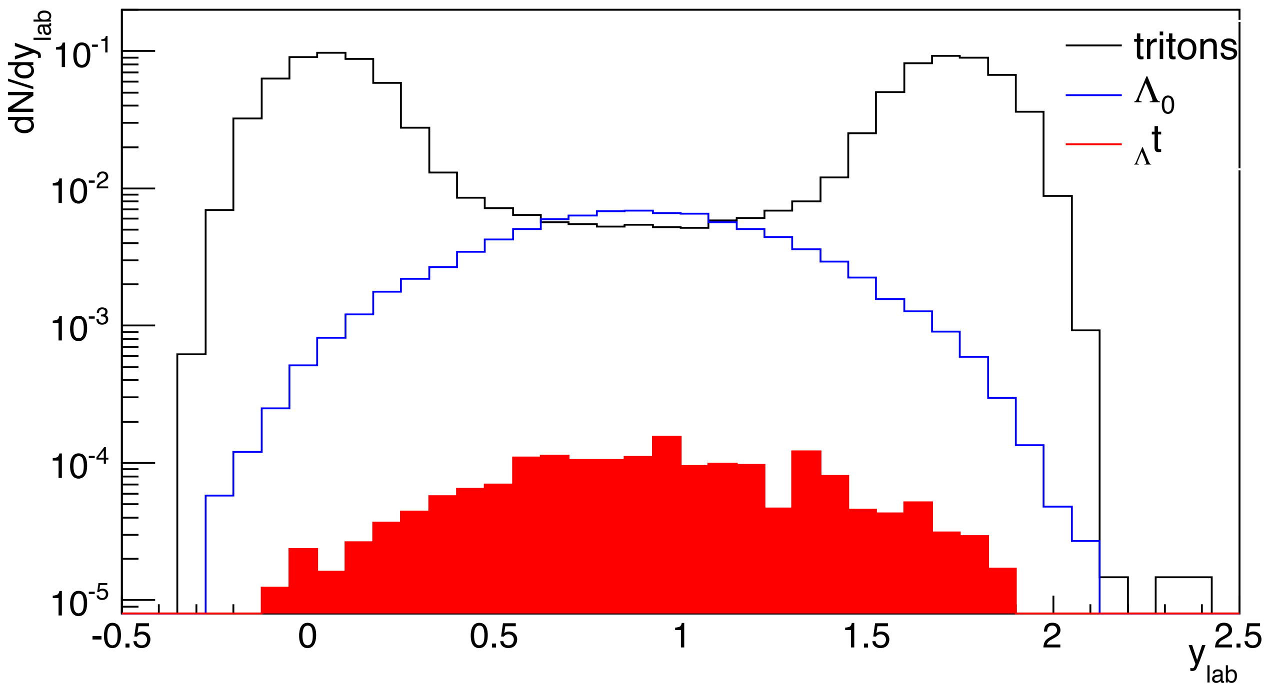
EOS, in medium-properties and hypernuclei yields



FOPI system

IQMD*+FRIGA
$^{58}Ni+^{58}Ni$ @1.91A.GeV
b < 6 fm
(t = 2.3 t_{pass})

Soft EOS, no m.d.i., no Kaon pot.



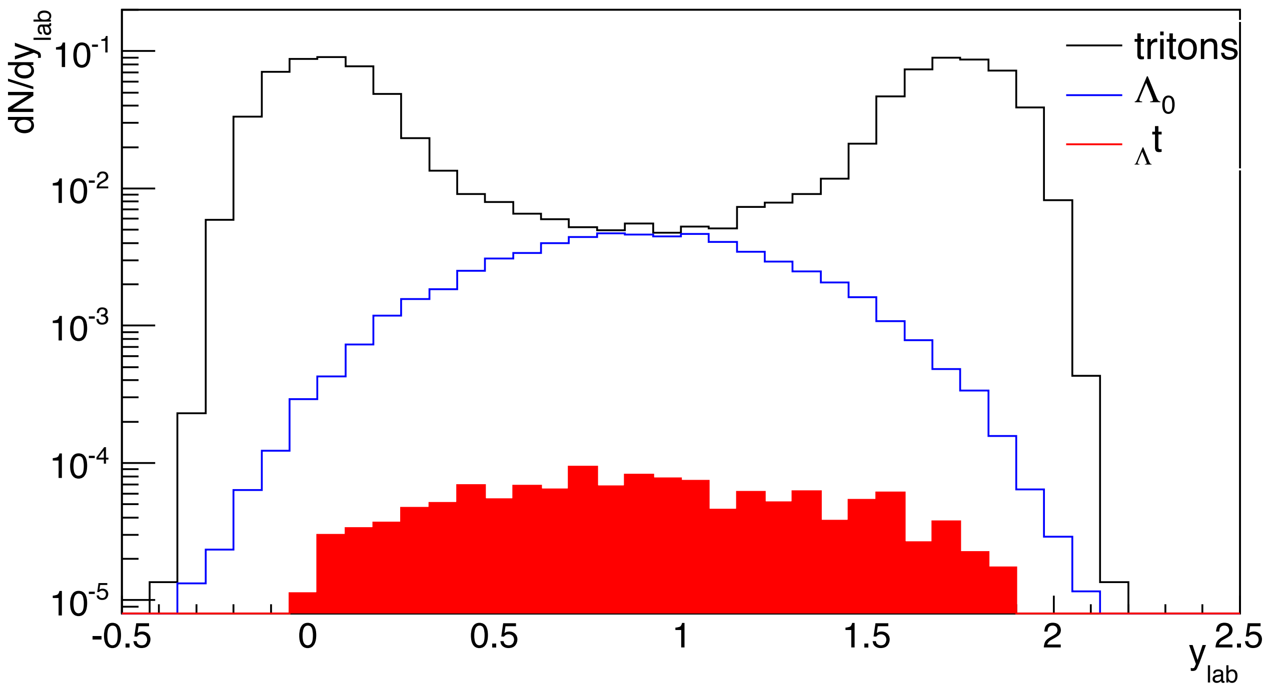
*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

EOS, in medium-properties and hypernuclei yields

FOPI system

IQMD*+FRIGA
$^{58}Ni+^{58}Ni$ @1.91A.GeV
b < 6 fm
(t = 2.3 t_{pass})

Soft EOS, no m.d.i., with Kaon pot.



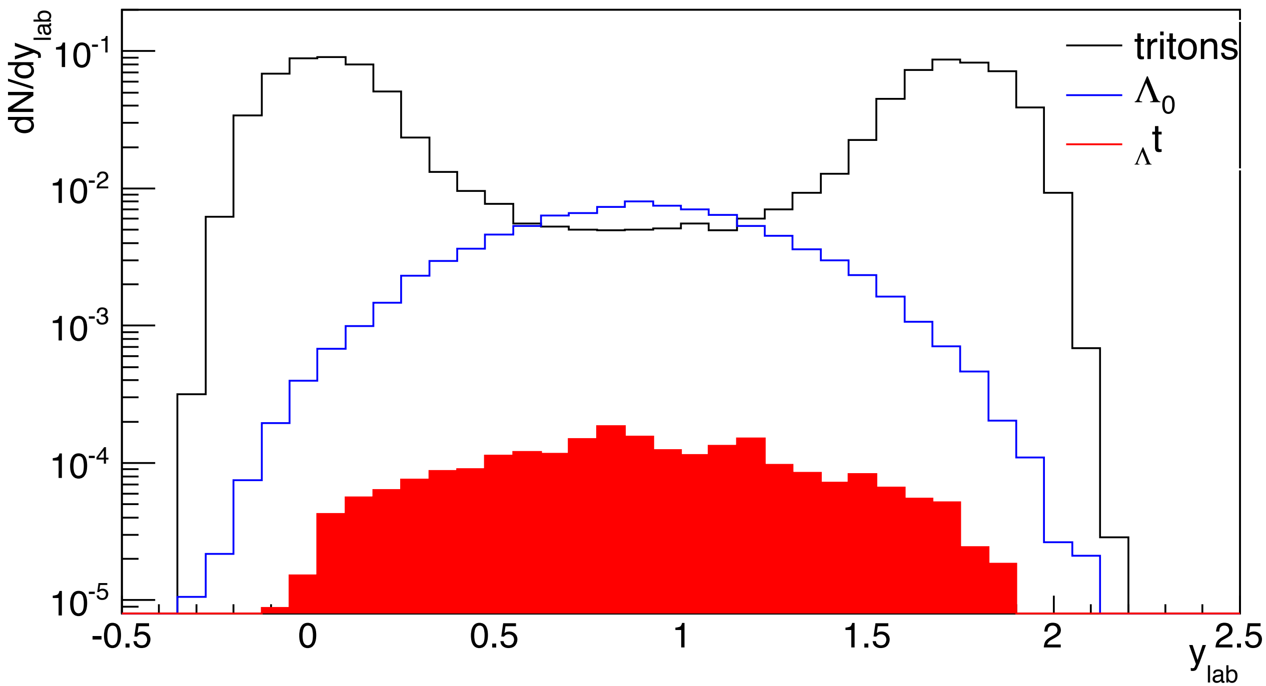
*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

EOS, in medium-properties and hypernuclei yields

FOPI system

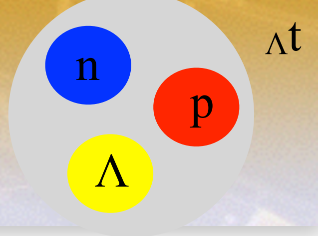
IQMD*+FRIGA
$^{58}Ni + ^{58}Ni$ @1.91A.GeV
b < 6 fm
(t = 2.3 t_{pass})

Soft EOS, no m.d.i., no Kaon pot.



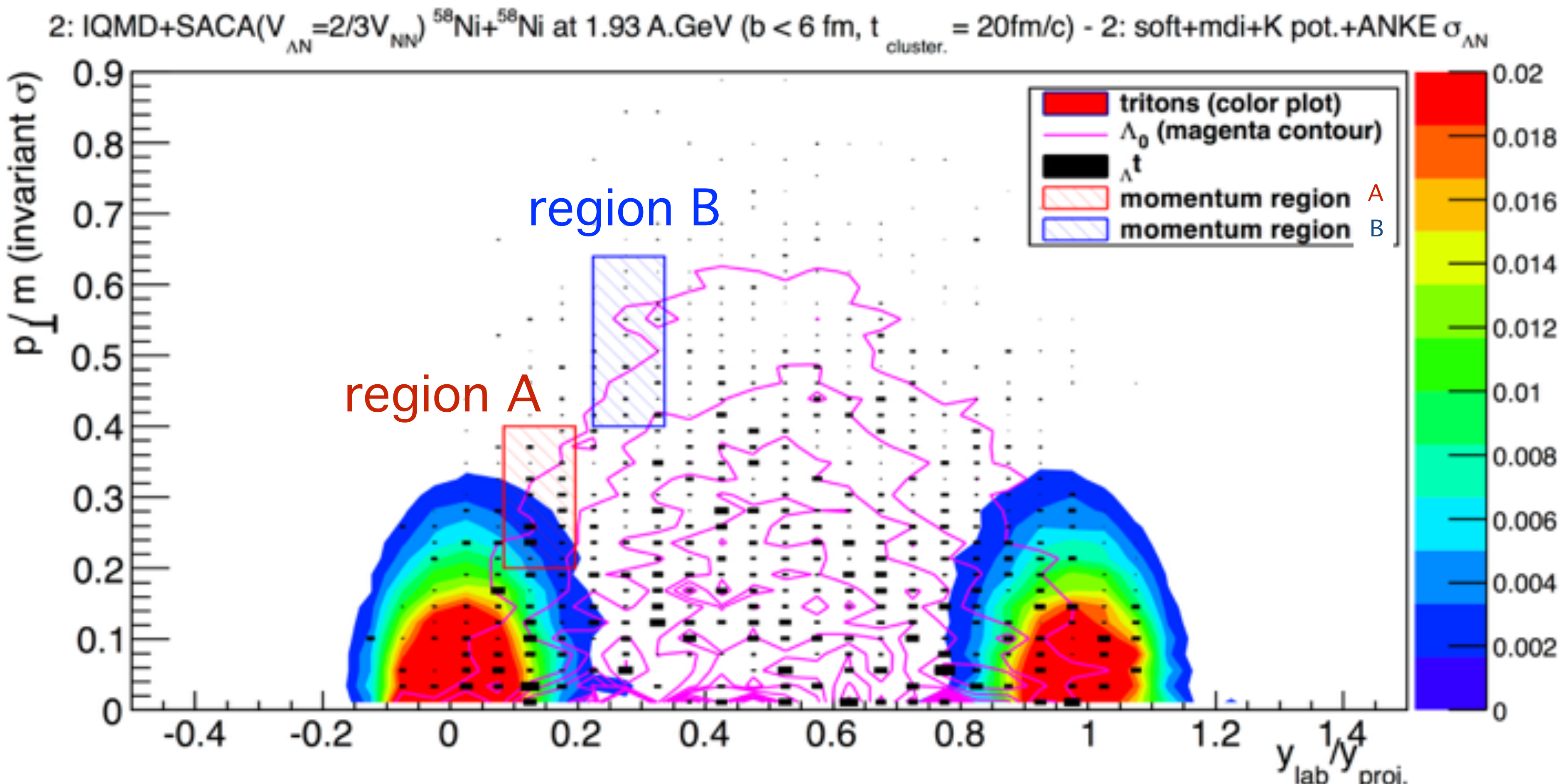
*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

EOS, in medium-properties, V(ΛN) and hypernuclei yields



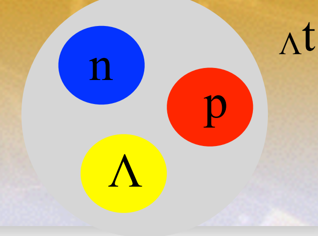
IQMD*+FRIGA, $^{58}Ni+^{58}Ni$ @1.93A.GeV, b < 6 fm, t = 2.3 t_{pass}

FOPI system



*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

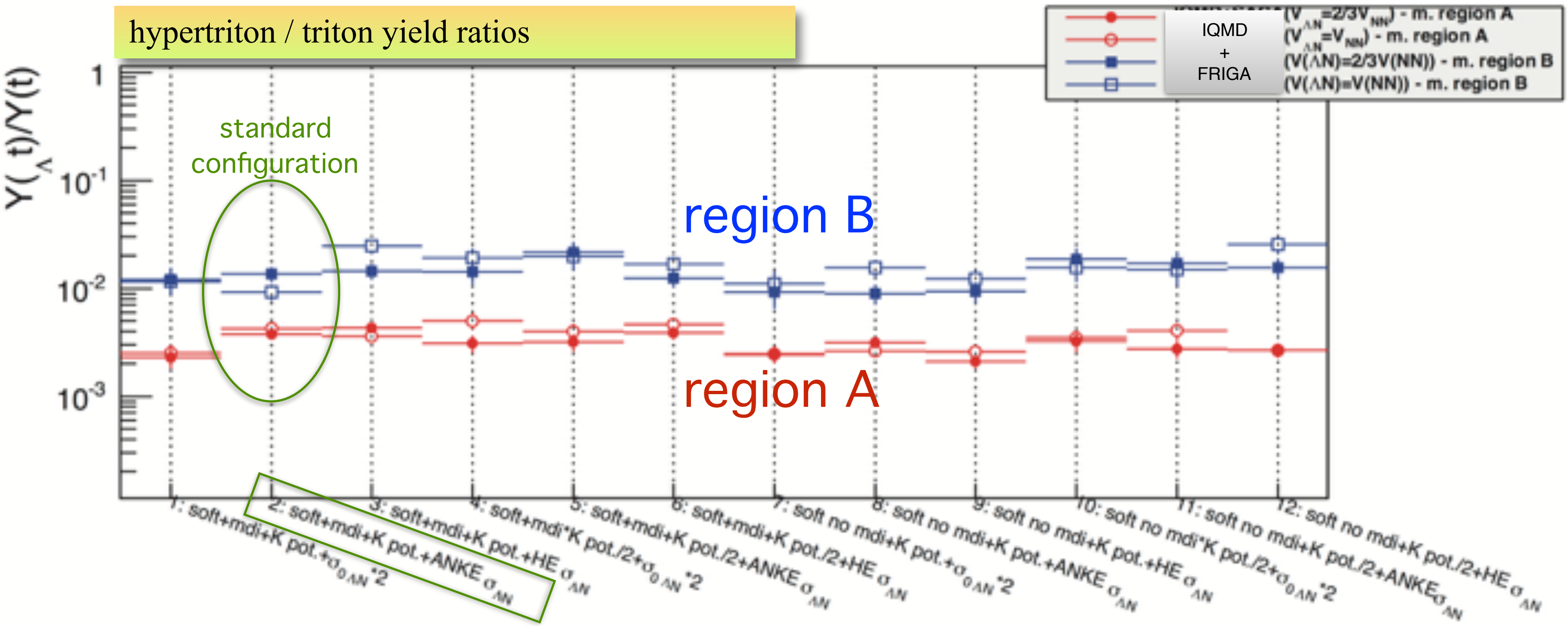
EOS, in medium-properties, V(ΛN) and hypernuclei yields



IQMD*+FRIGA, $^{58}Ni+^{58}Ni$ @1.93A.GeV, b < 6 fm, t = 2.3 t_{pass}

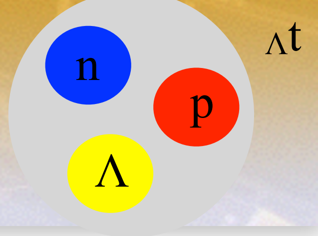
FOPI system

hypertriton / triton yield ratios



*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

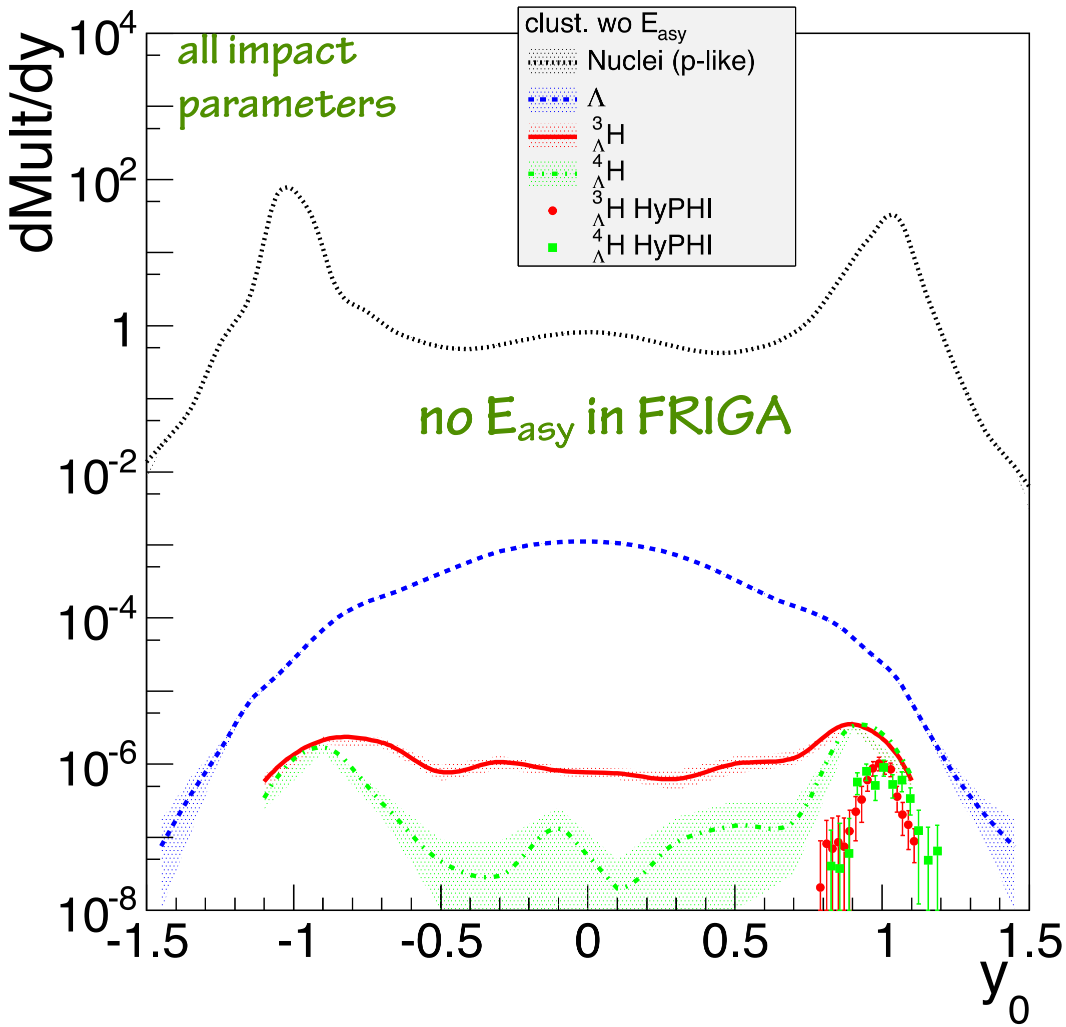
Asymmetry energy and hypernuclei yields



HyPHI system

IQMD*+FRIGA
$^6Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

$R=Y(_\Lambda{}^3H)/Y(_\Lambda{}^4H)$



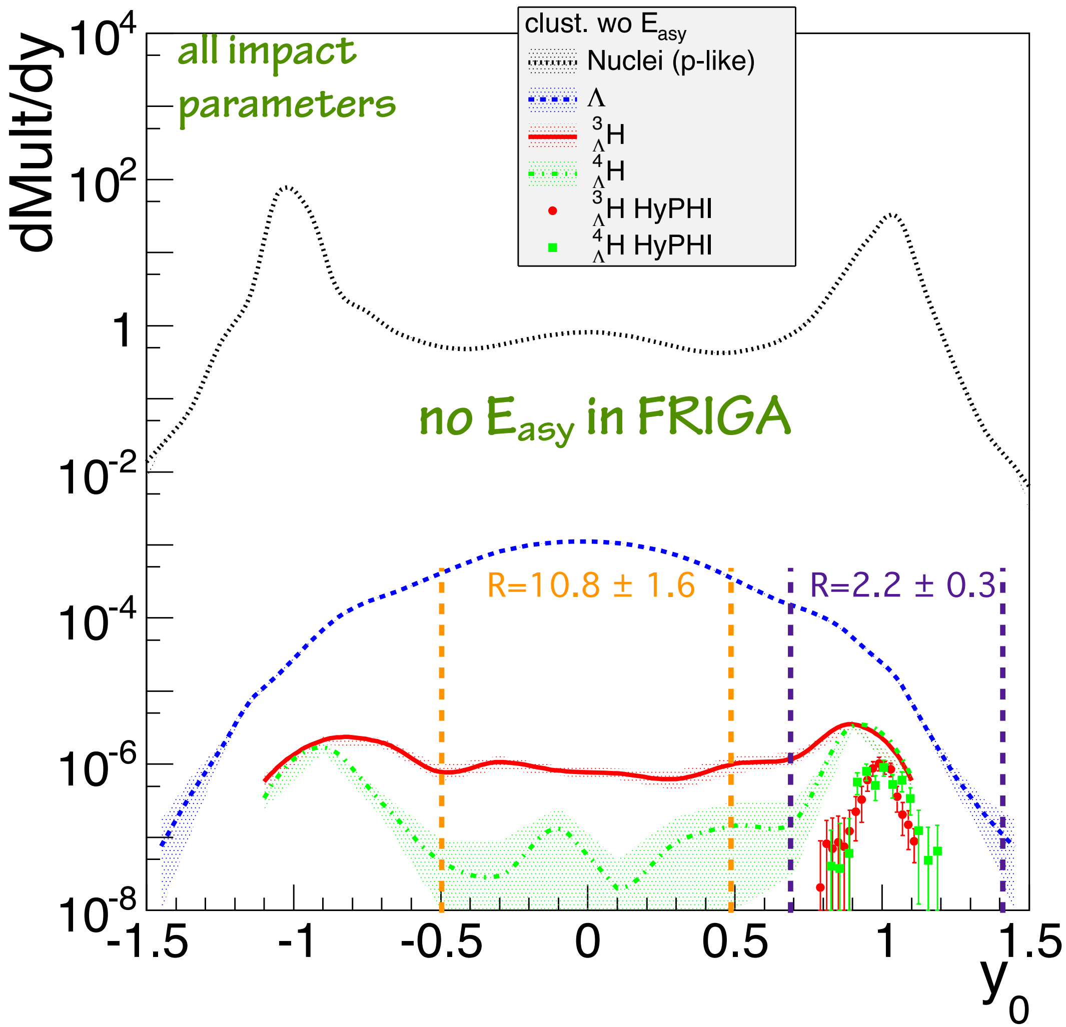
*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

Asymmetry energy and hypernuclei yields

HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

$R=Y(_{\Lambda}^{3}H)/Y(_{\Lambda}^{4}H)$



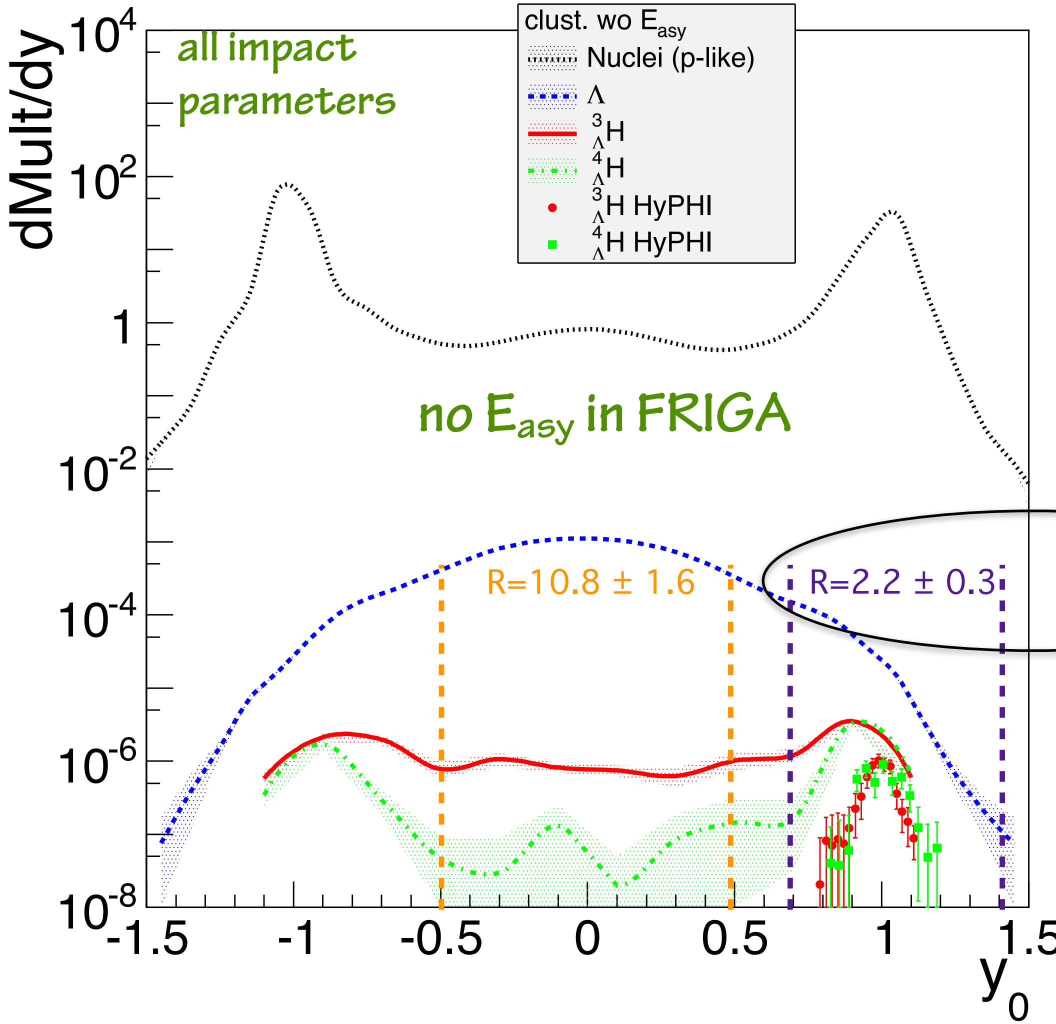
*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

Asymmetry energy and hypernuclei yields

HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

$R=Y({}_{\Lambda}^{3}H)/Y({}_{\Lambda}^{4}H)$



HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129–13:

R=1.4 ± 0.8

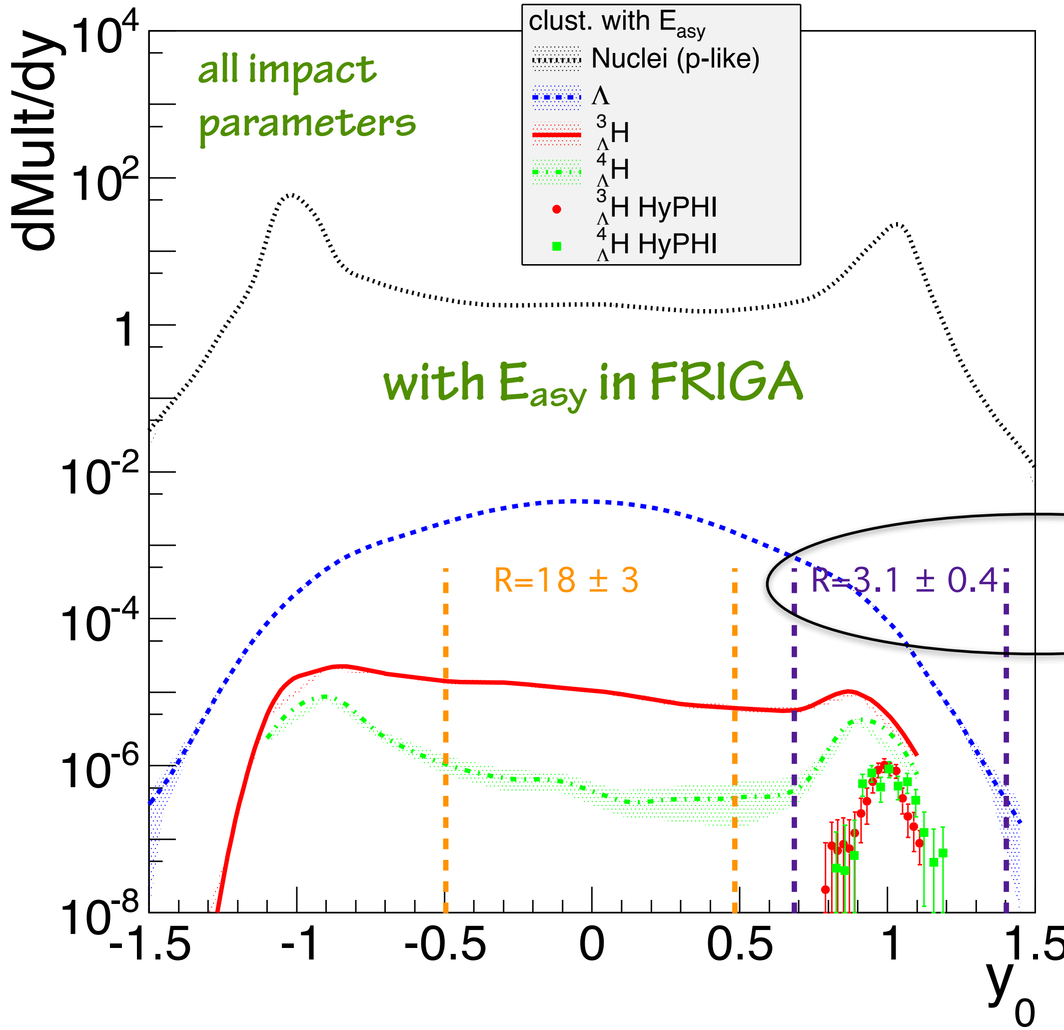
*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

Asymmetry energy and hypernuclei yields

HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

$R=Y({}_{\Lambda}^{3}H)/Y({}_{\Lambda}^{4}H)$



HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129–13:

R=1.4 ± 0.8

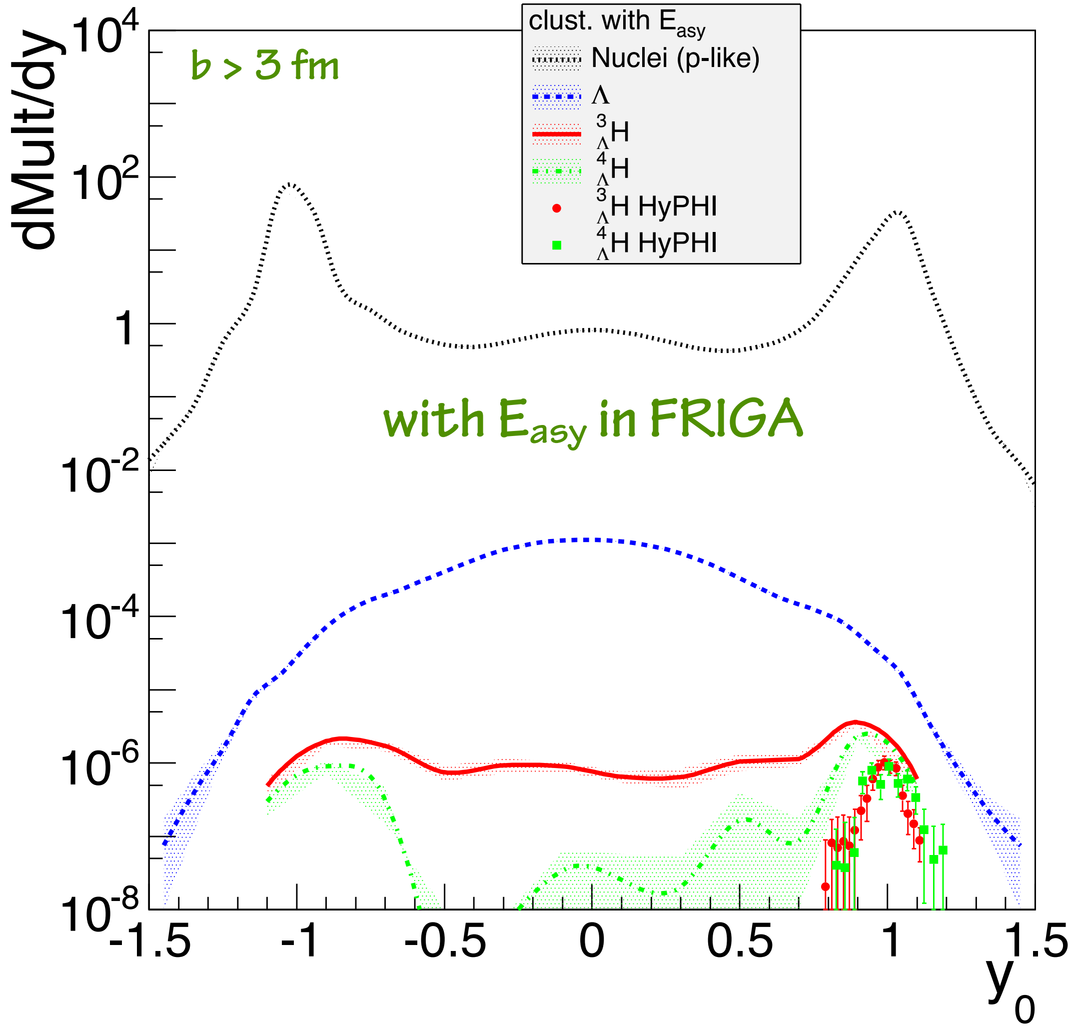
*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

Asymmetry energy and hypernuclei yields

HyPHI system

IQMD*+FRIGA
^{6}Li+^{12}C @ 2A.GeV
(t = 2 t_{pass})

$R = Y({}_\Lambda{}^3H)/Y({}_\Lambda{}^4H)$



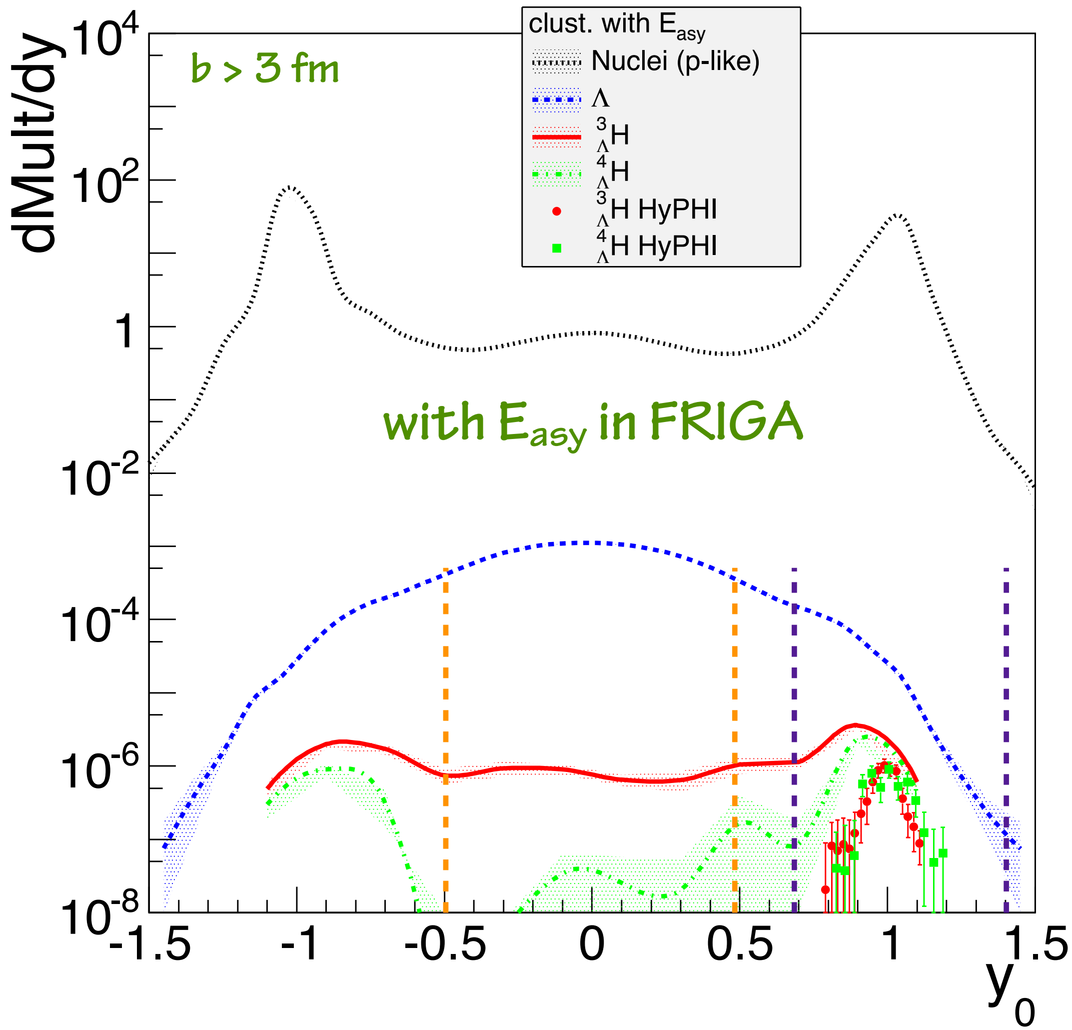
*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

Asymmetry energy and hypernuclei yields

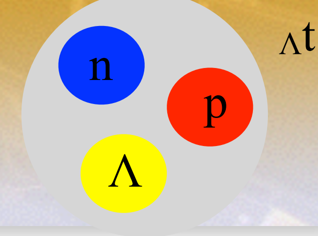
HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

$R=Y({}_{\Lambda}^{3}H)/Y({}_{\Lambda}^{4}H)$



*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

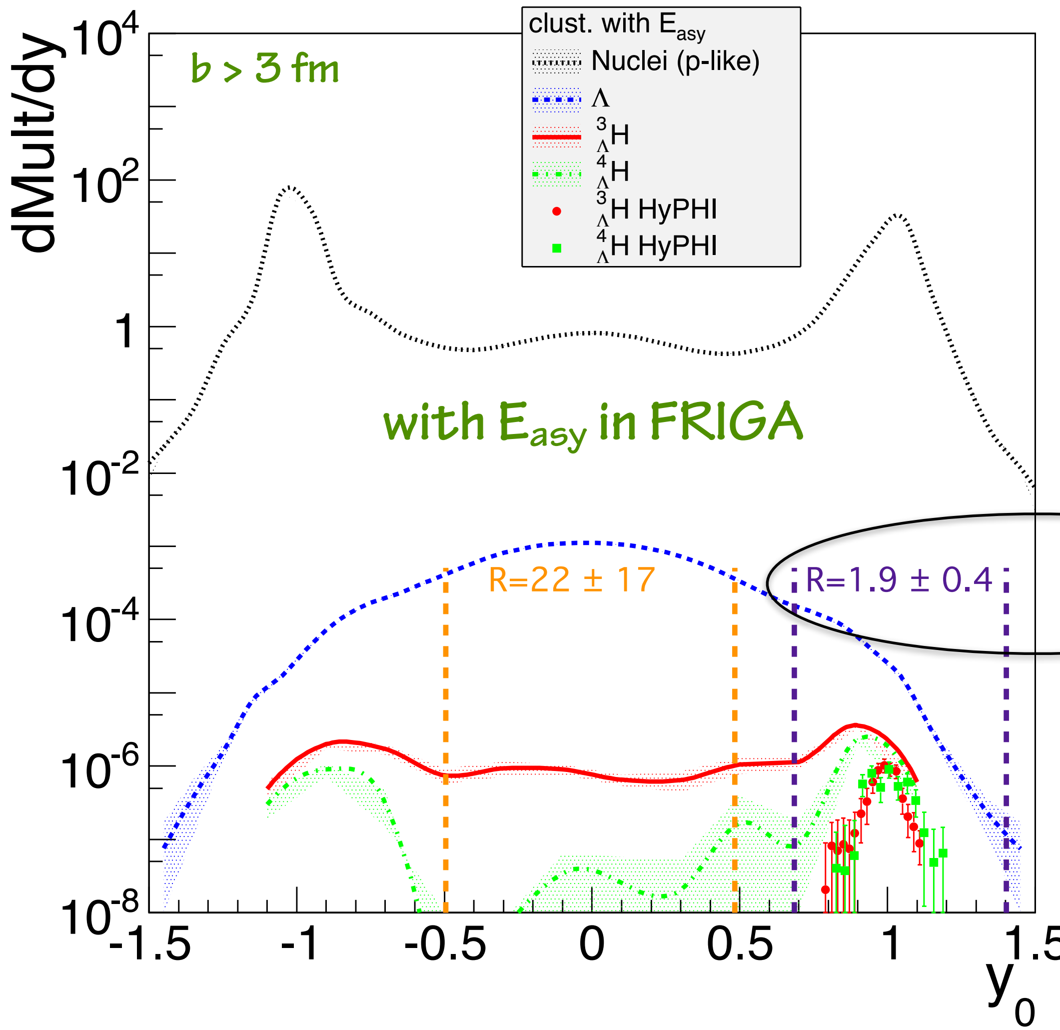


Asymmetry energy and hypernuclei yields

HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

$R=Y({}_{\Lambda}^{3}H)/Y({}_{\Lambda}^{4}H)$



HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129–13:

R=1.4 ± 0.8

*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

Asymmetry energy and hypernuclei yields

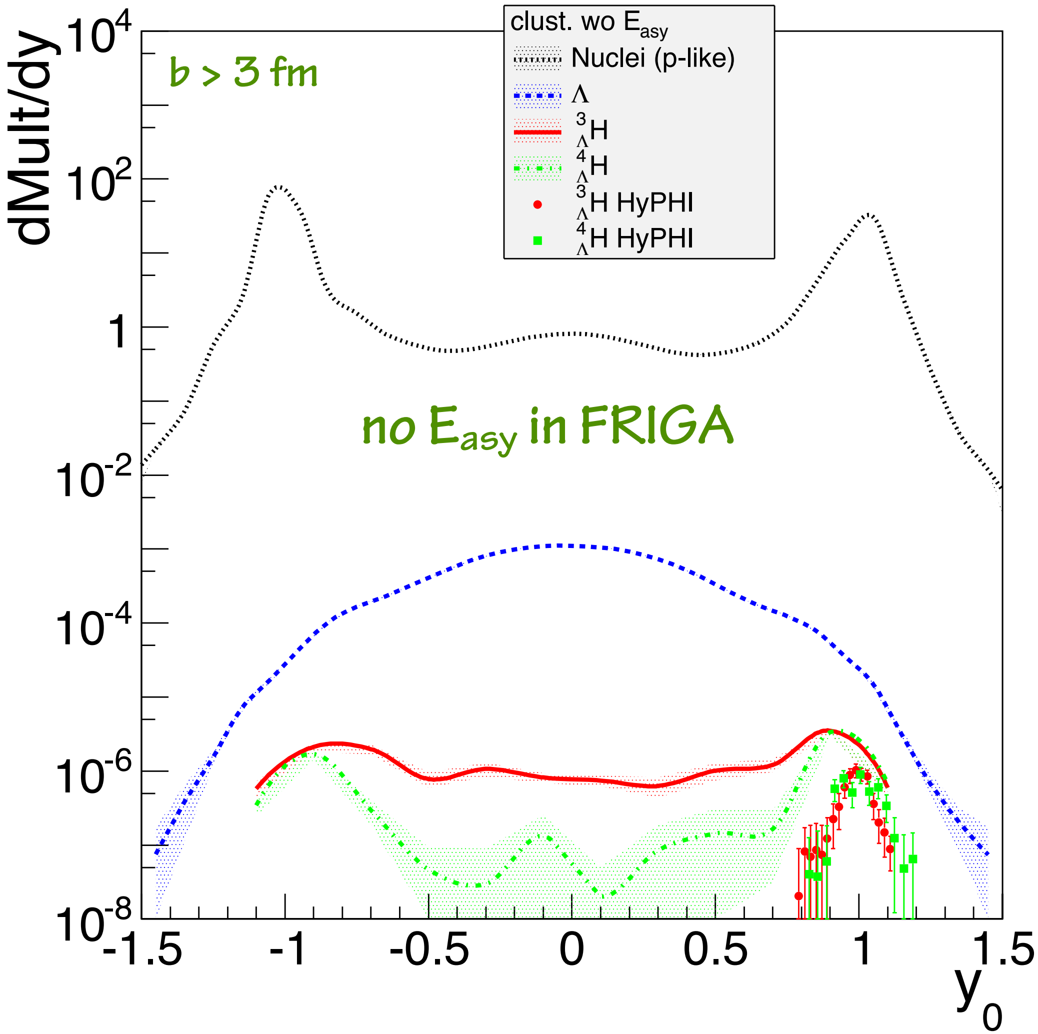
HyPHI system

IQMD*+FRIGA

$^{6}Li+^{12}C$ @ 2A.GeV

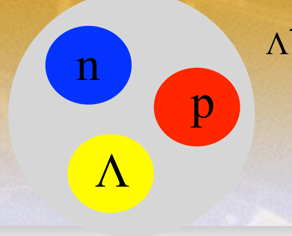
($t = 2\ t_{pass}$)

$R=Y({}_{\Lambda}{}^{3}H)/Y({}_{\Lambda}{}^{4}H)$



*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

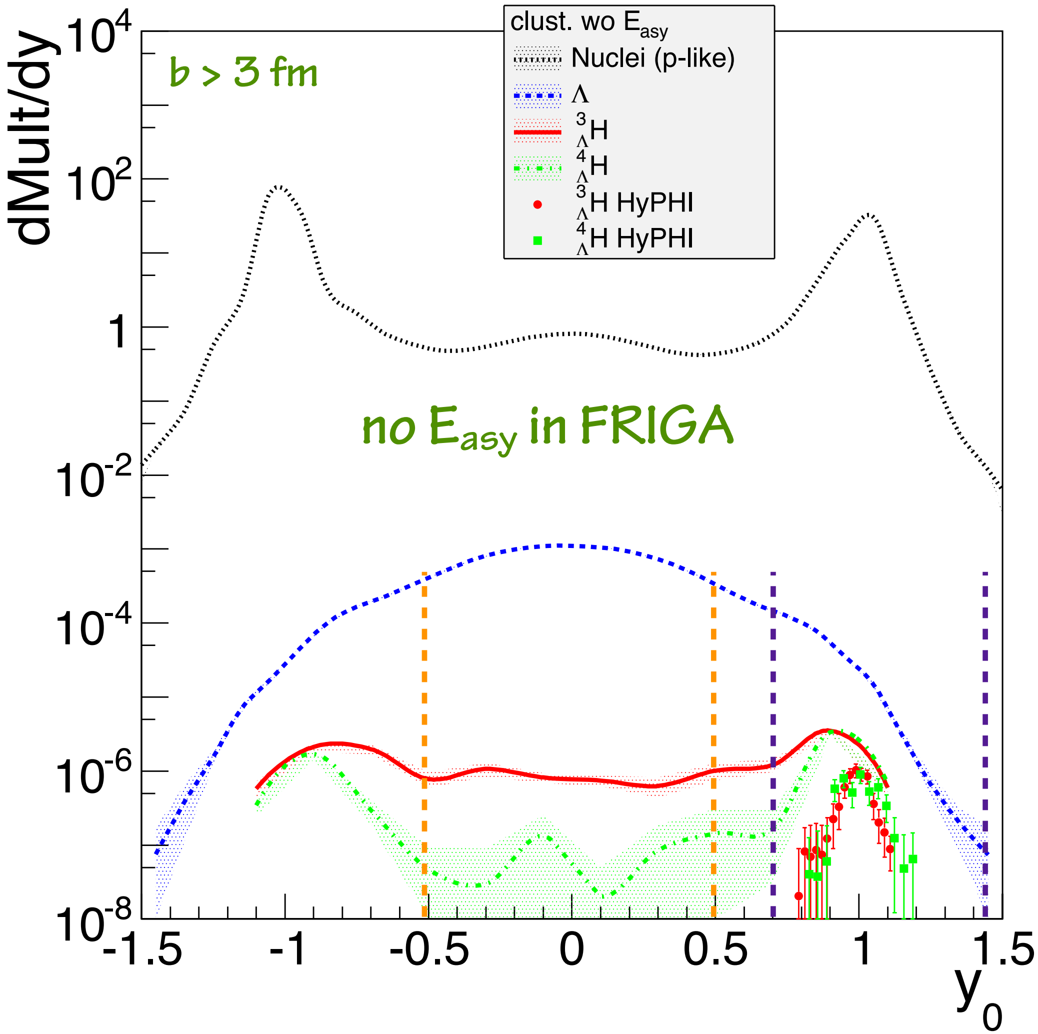
Asymmetry energy and hypernuclei yields



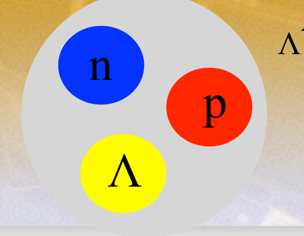
HyPHI system

IQMD*+FRIGA
$^6Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

$R=Y(_\Lambda{}^3H)/Y(_\Lambda{}^4H)$



*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

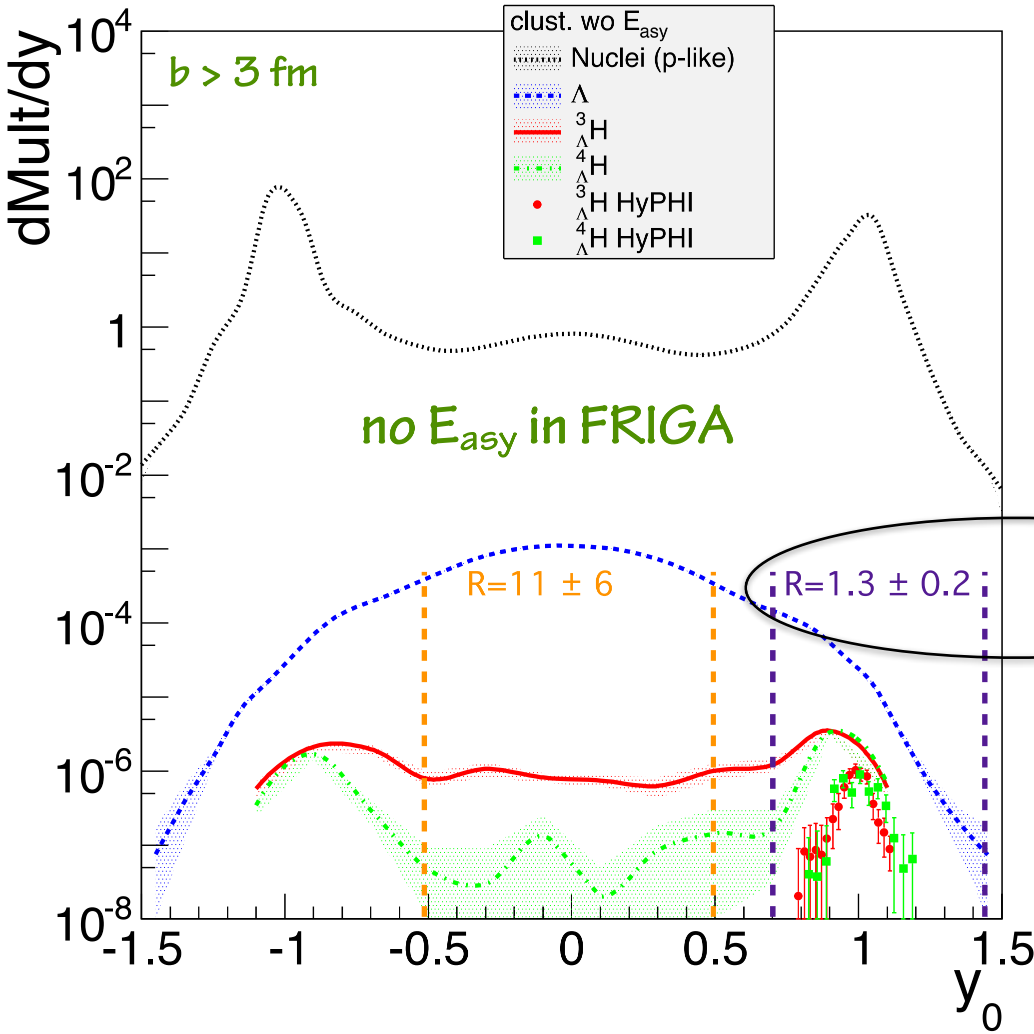


Asymmetry energy and hypernuclei yields

HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

$R=Y({}_{\Lambda}^{3}H)/Y({}_{\Lambda}^{4}H)$

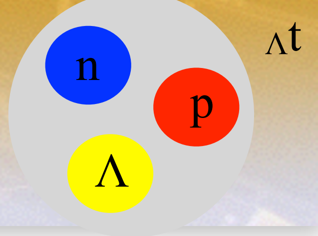


HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129–13:

R=1.4 ± 0.8

*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

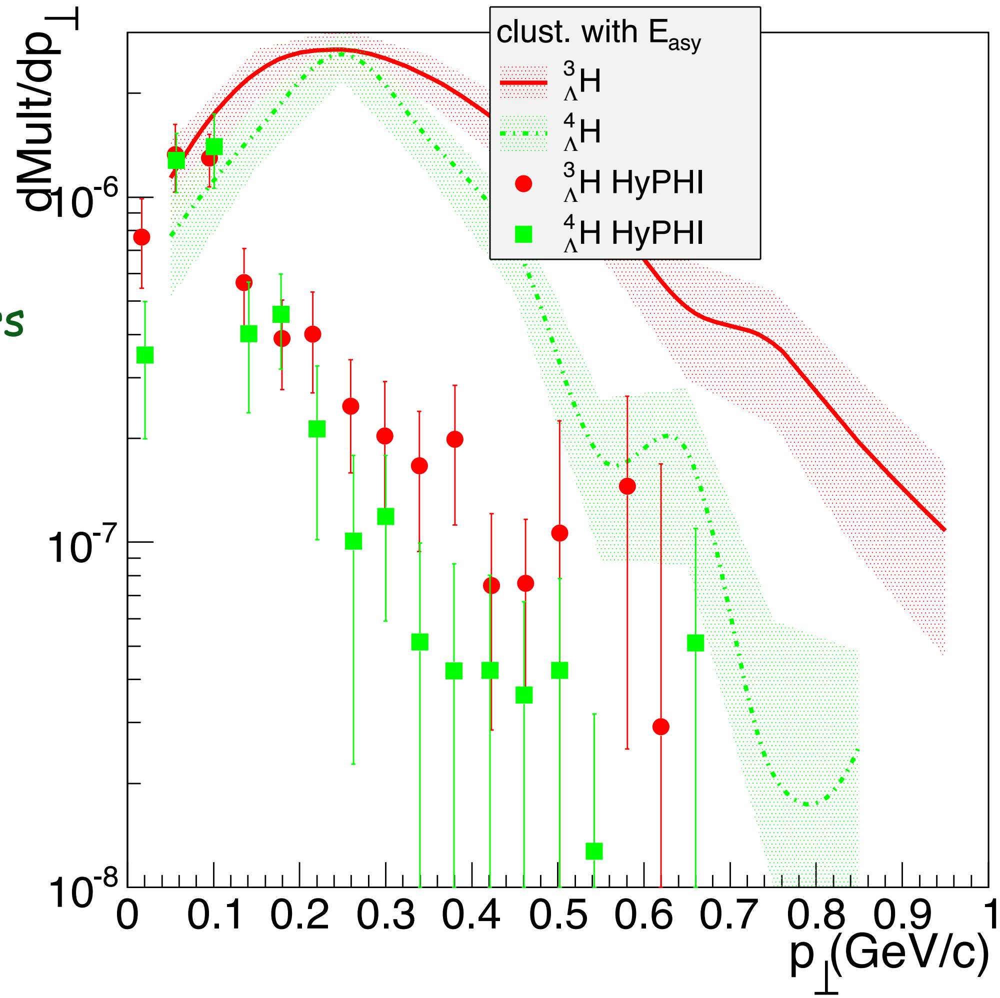
Asymmetry energy and hypernuclei yields



HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

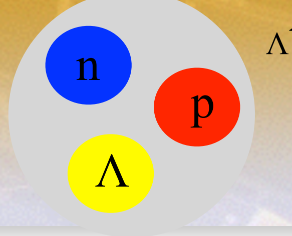
all impact parameters
$y_0 > 0.9$



HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129–13

*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

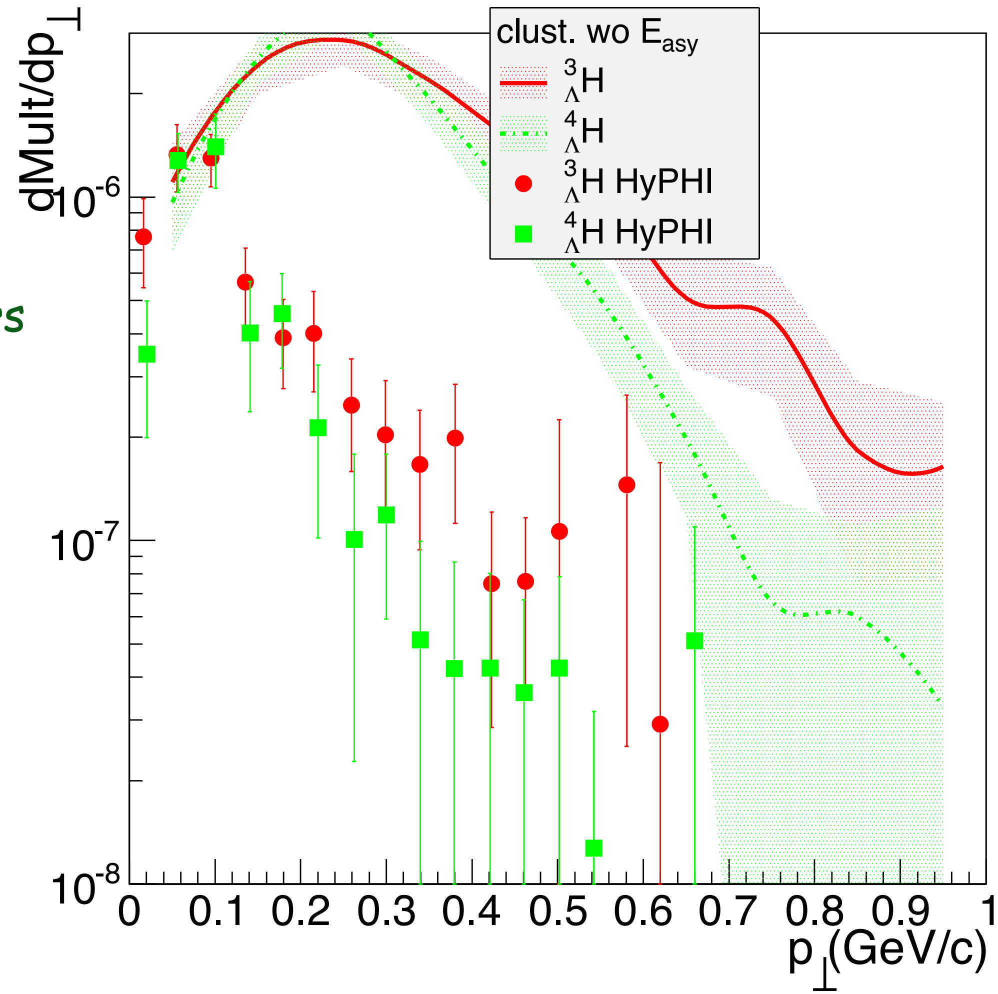
Asymmetry energy and hypernuclei yields



HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
(t = 2 t_{pass})

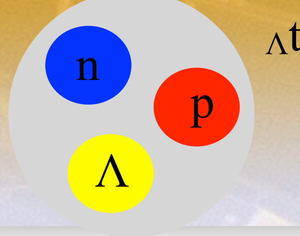
all impact parameters
$y_0 > 0.9$



HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129-13

*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

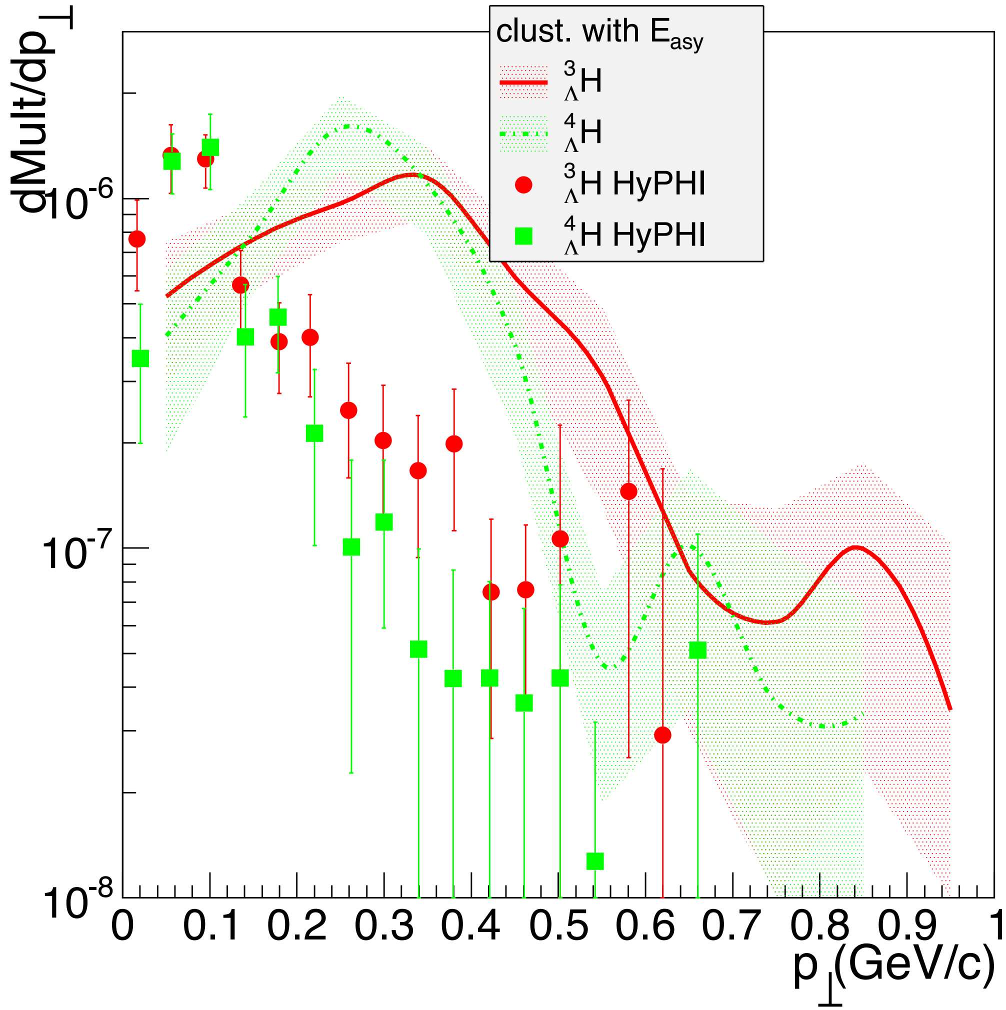
Asymmetry energy and hypernuclei yields



HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

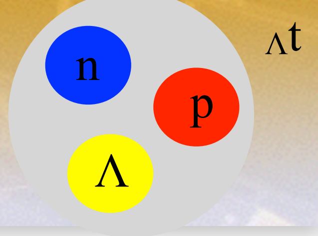
b > 3 fm
y_0 > 0.9



HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129–13

*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

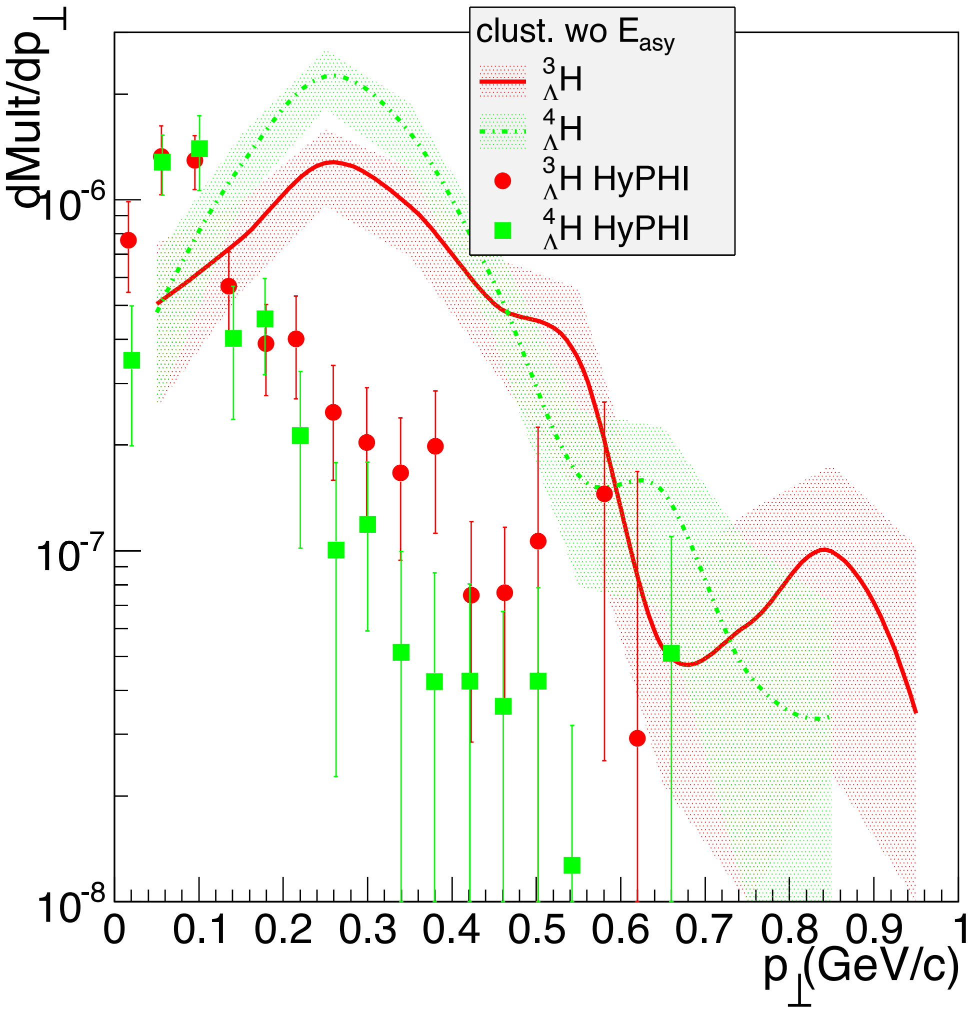
Asymmetry energy and hypernuclei yields



HyPHI system

IQMD*+FRIGA
$^{6}Li+^{12}C$ @ 2A.GeV
($t = 2\ t_{pass}$)

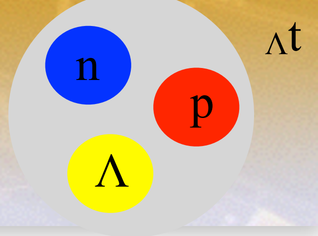
b > 3 fm
$y_0 > 0.9$



HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129-13

*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

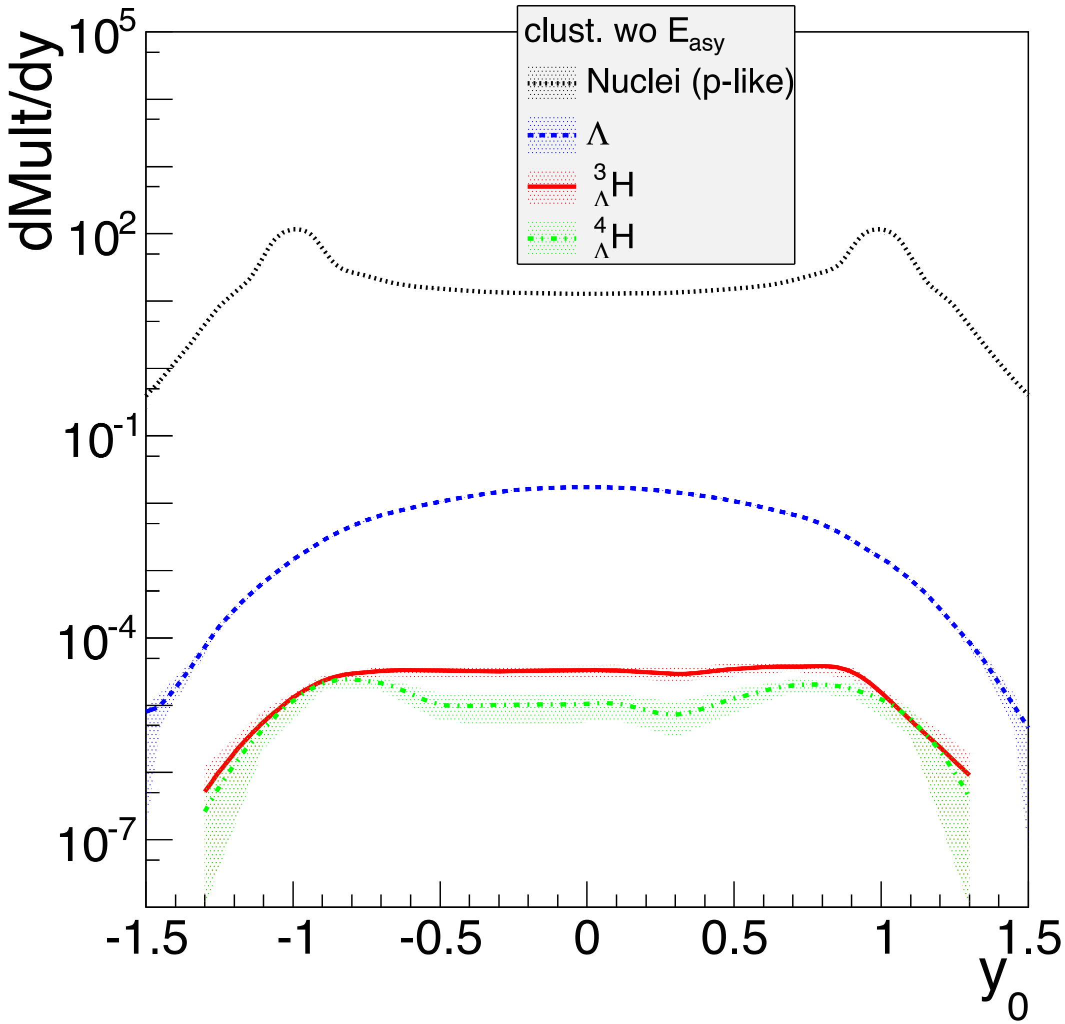
Hypernuclei with HADES ?



HADES system

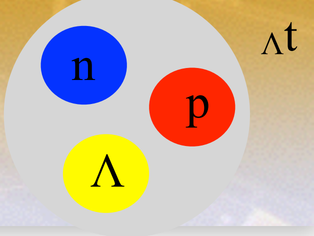
IQMD*+FRIGA
^{40}Ar+KCl @ 1.757A.GeV
(t = 2 t_{pass})

minimum bias



*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

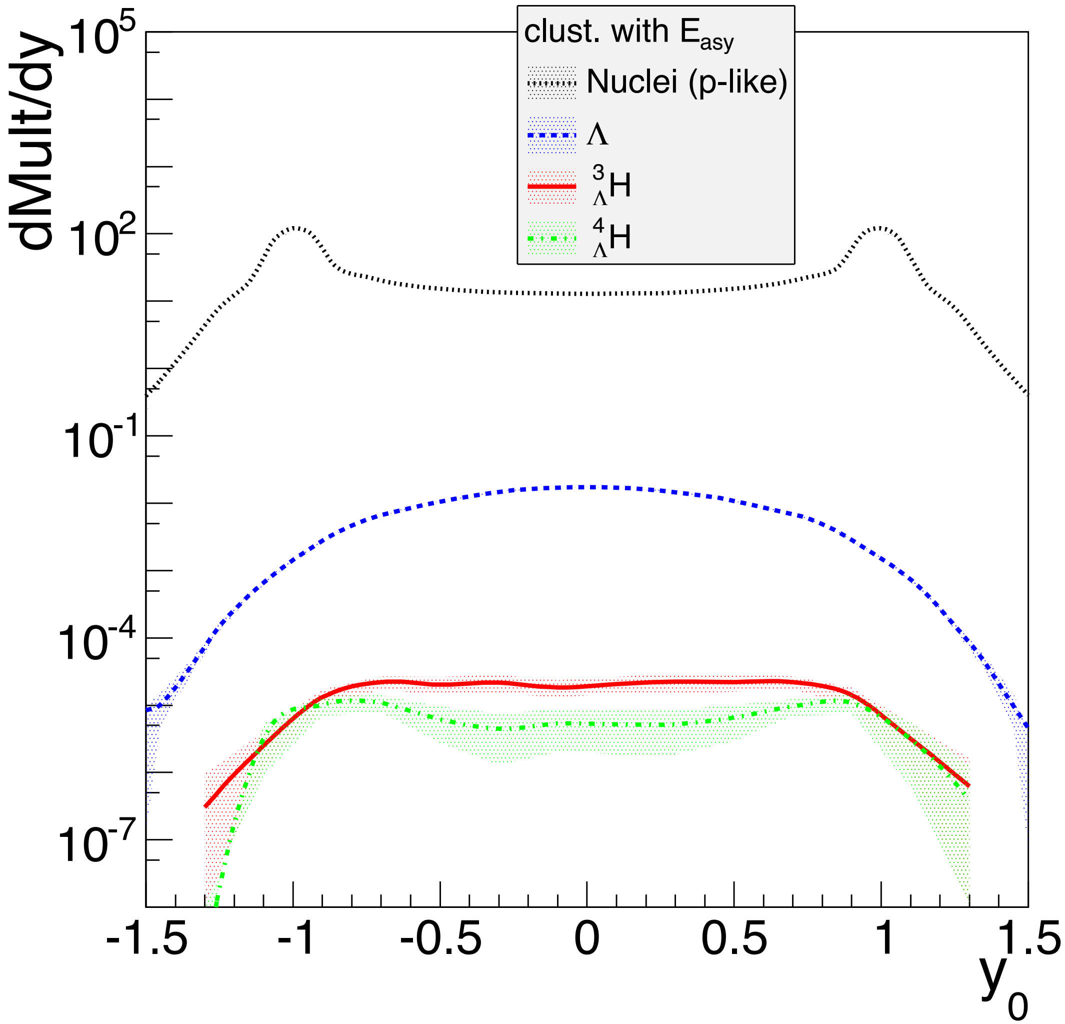
Hypernuclei with HADES ?



HADES system

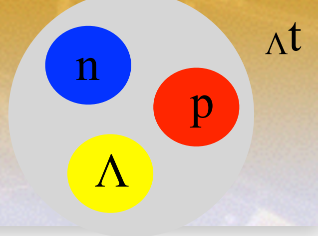
IQMD*+FRIGA
^{40}Ar+KCl @ 1.757A.GeV
($t = 2\ t_{pass}$)

minimum bias



*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

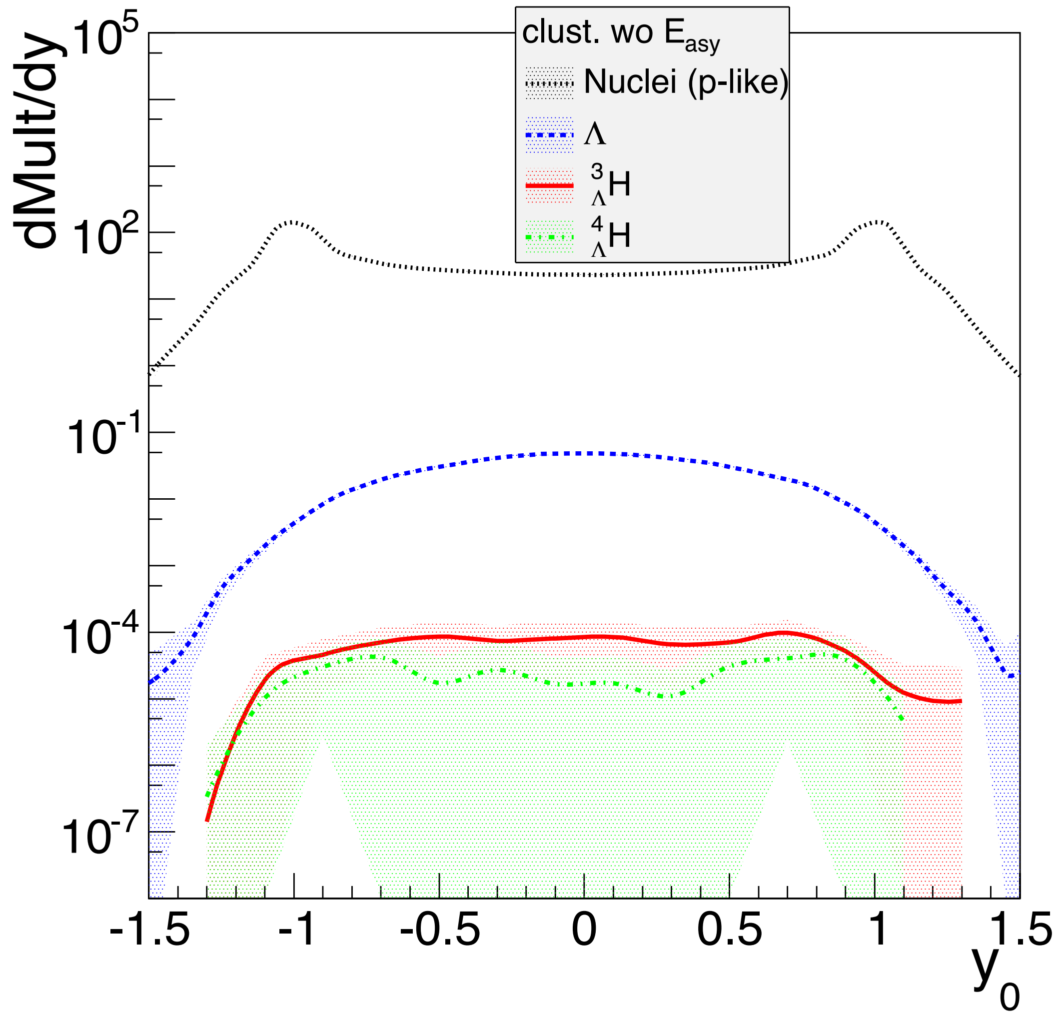
Hypernuclei with FOPI ?



FOPI system

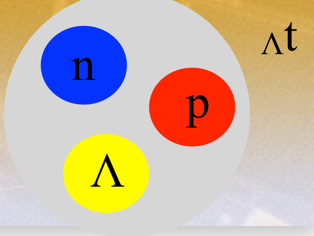
IQMD*+FRIGA
$^{56}Ni+^{56}Ni$ @ 1.93 A.GeV
($t = 2\ t_{pass}$)

minimum bias



*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

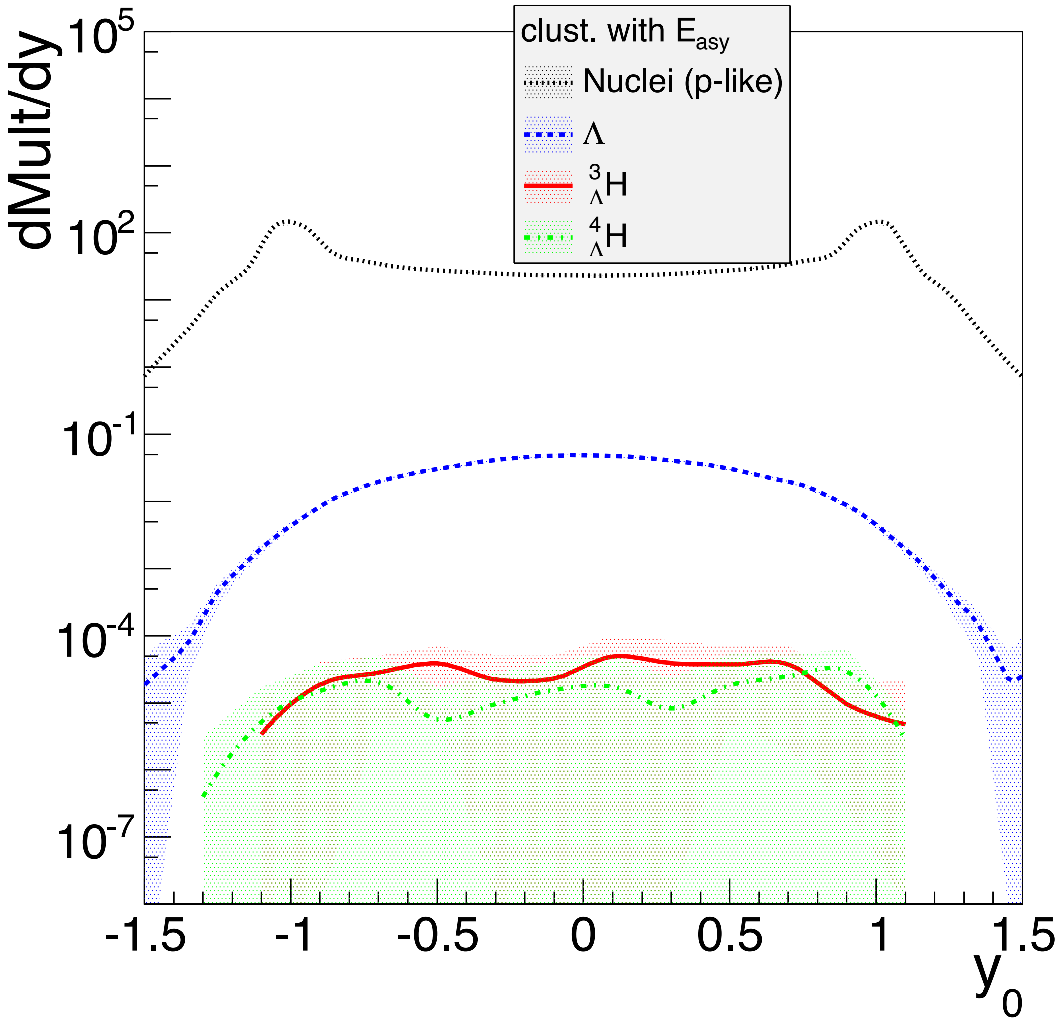
Hypernuclei with FOPI ?



FOPI system

IQMD*+FRIGA
$^{56}Ni+^{56}Ni$ @ 1.93 A.GeV
($t = 2\ t_{pass}$)

minimum bias



*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

Summary and perspectives

Summary and perspectives

Summary:

- Supplying FRIGA with a more precise description of nuclei binding energy at abnormal density allows promising, realistic predictions of absolute isotope yields, and hypernuclei.
- The clusterisation time has a strong influence on the heavy hypernucleus yields and momentum distributions.
- In comparison, the EOS, in medium-properties of the transport model (studied here) have a moderate influence.

Summary and perspectives

Summary:

❖ Supplying FRIGA with a more precise description of nuclei binding energy at abnormal density allows promising, realistic predictions of absolute isotope yields, and hypernuclei.

❖ The clusterisation time has a strong influence on the heavy hypernucleus yields and momentum distributions.

❖ In comparison, the EOS, in medium-properties of the transport model (studied here) have a moderate influence.

On-going developments:

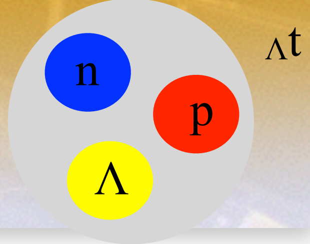
❖ After processing FRIGA, proceed the further decay of primary unstable hyper-isotopes which lifetime does not allow to detect them still bound,

❖ Dynamical clustering: allow clustering to be done at various time steps and to have the clusters interacting with the rest of the system during the dynamical development (no longer just an afterburner). Under development with E. Bratkovskaya and P. Moreau in PHSD.

Perspectives:

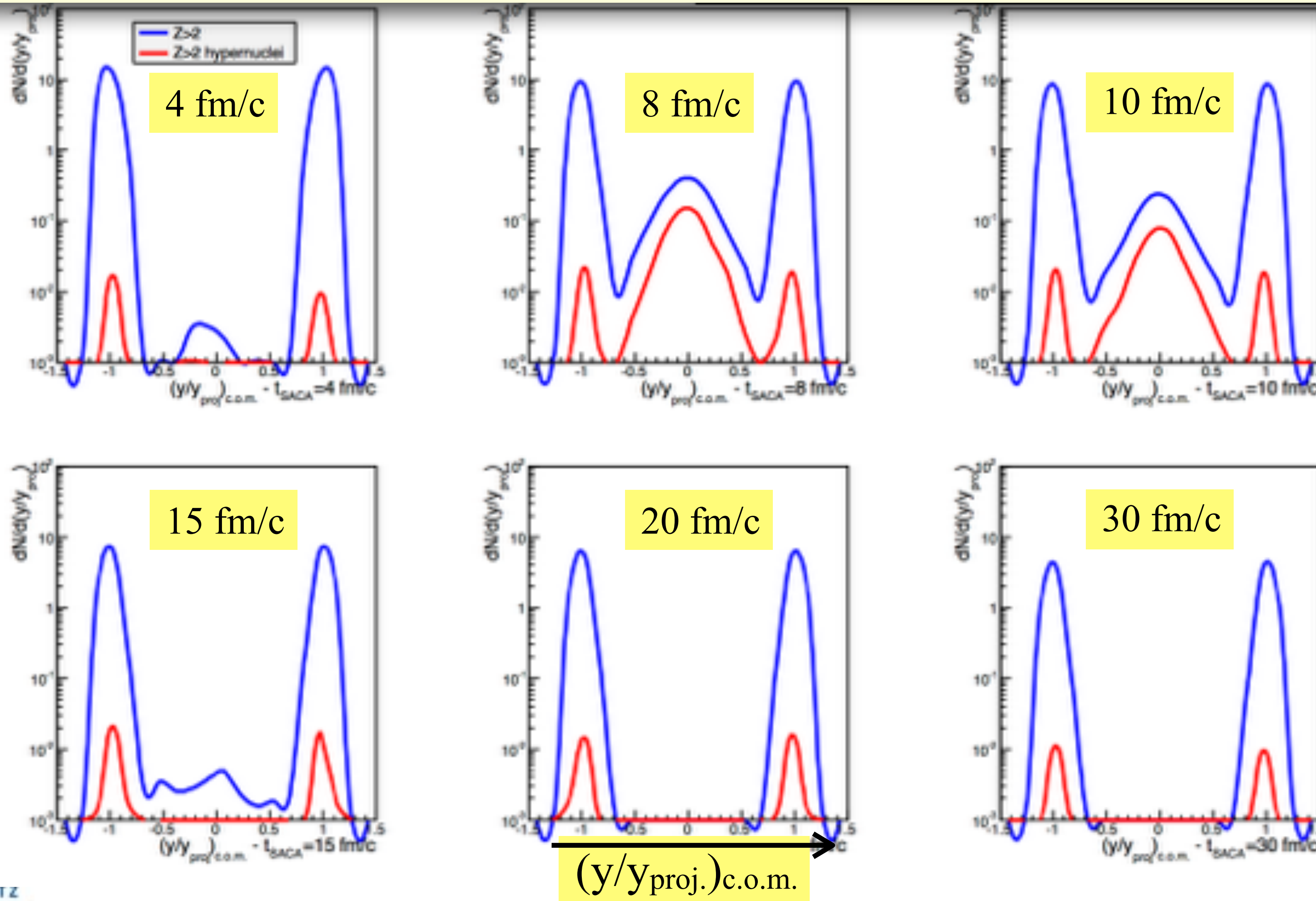
❖ An urgent need for accurate hypernucleus yield and dynamics measurements, with the largest possible acceptance, in the spectator and/or the participant phase space, for better constraining both transport and clustering models.

Clusterisation time influence on hypernuclei (phase space and yields)

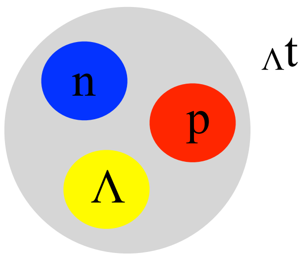


An example: Au+Au @ 11.45 A.GeV, b=6 fm (passing time = 7.5 fm/c) from HSD+FRIGA

heavy (Z>2) hypernuclei



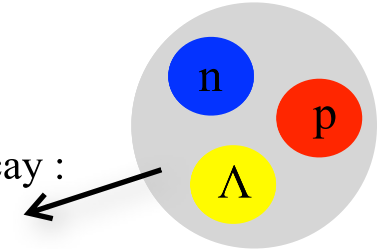
Strong phase space constraints ?



Strong phase space constraints ?

detected decay :

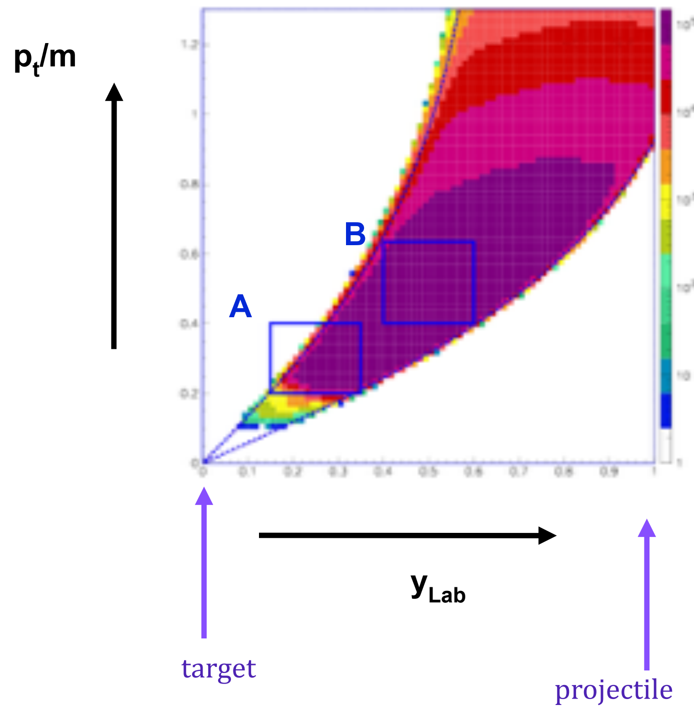
$^{3}He + \pi^{-}$



$_{\Lambda}t$

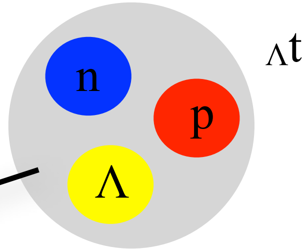
Strong phase space constraints ?

FOPI Coll.
Y. Zhang, Heidelberg



detected decay :

$^3He + \pi^-$



Ni+Ni @ 1.91 A.GeV

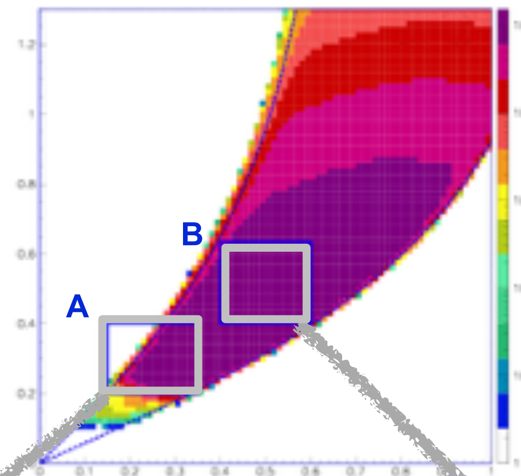
Preliminary

Strong phase space constraints ?

FOPI Coll.
Y. Zhang, Heidelberg

Excess over combinatorial background only in region A

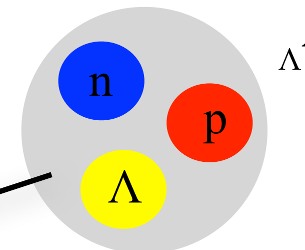
p_t/m



y_{Lab}

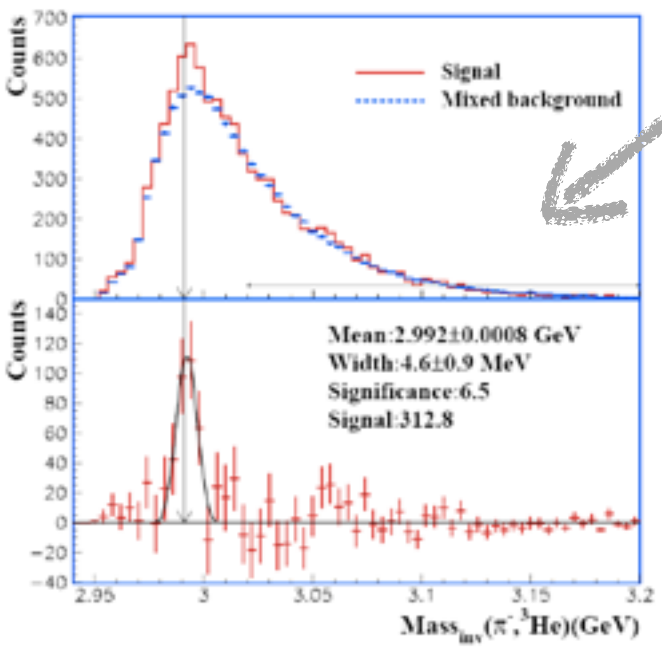
target

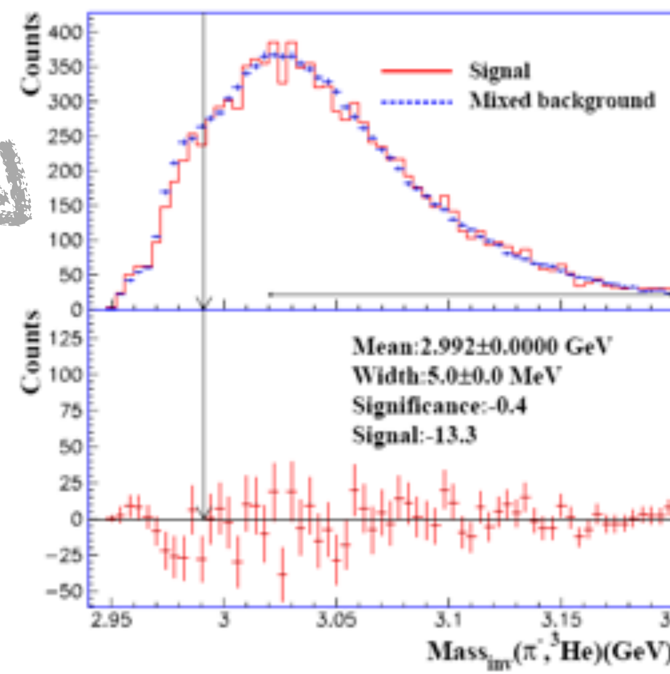
projectile



detected decay :

$^3He + \pi^-$





Ni+Ni @ 1.91 A.GeV

Preliminary

Influence of the EOS, in medium-properties of the transport model on the hypernuclei production

$_{\Lambda}t$

IQMD+FRIGA

^{58}Ni+^{58}Ni @1.91A.GeV

b < 6 fm

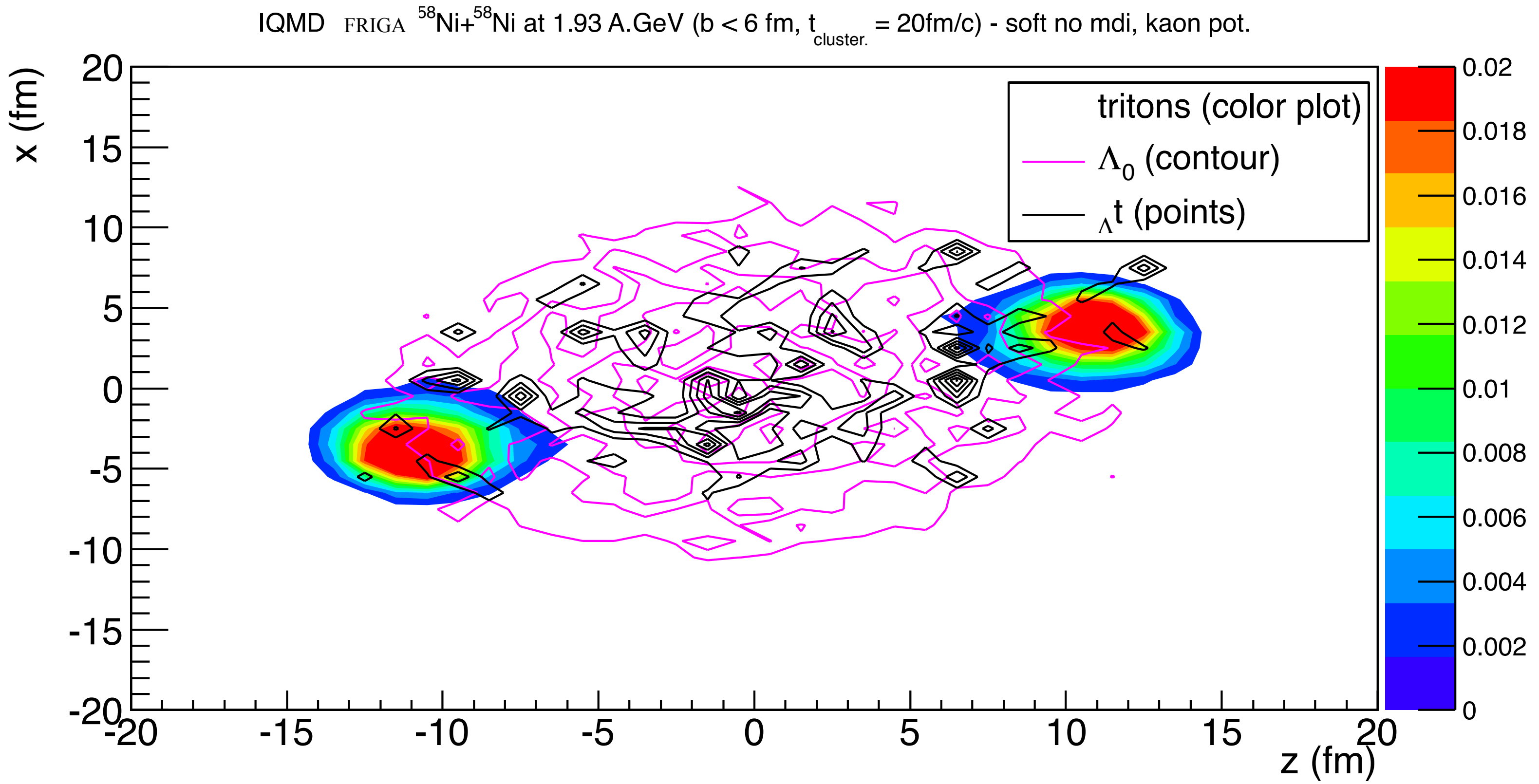
($t_{passing}$=8.7 fm/c)

$t_{cluster.}$=20 fm/c

FRIGA

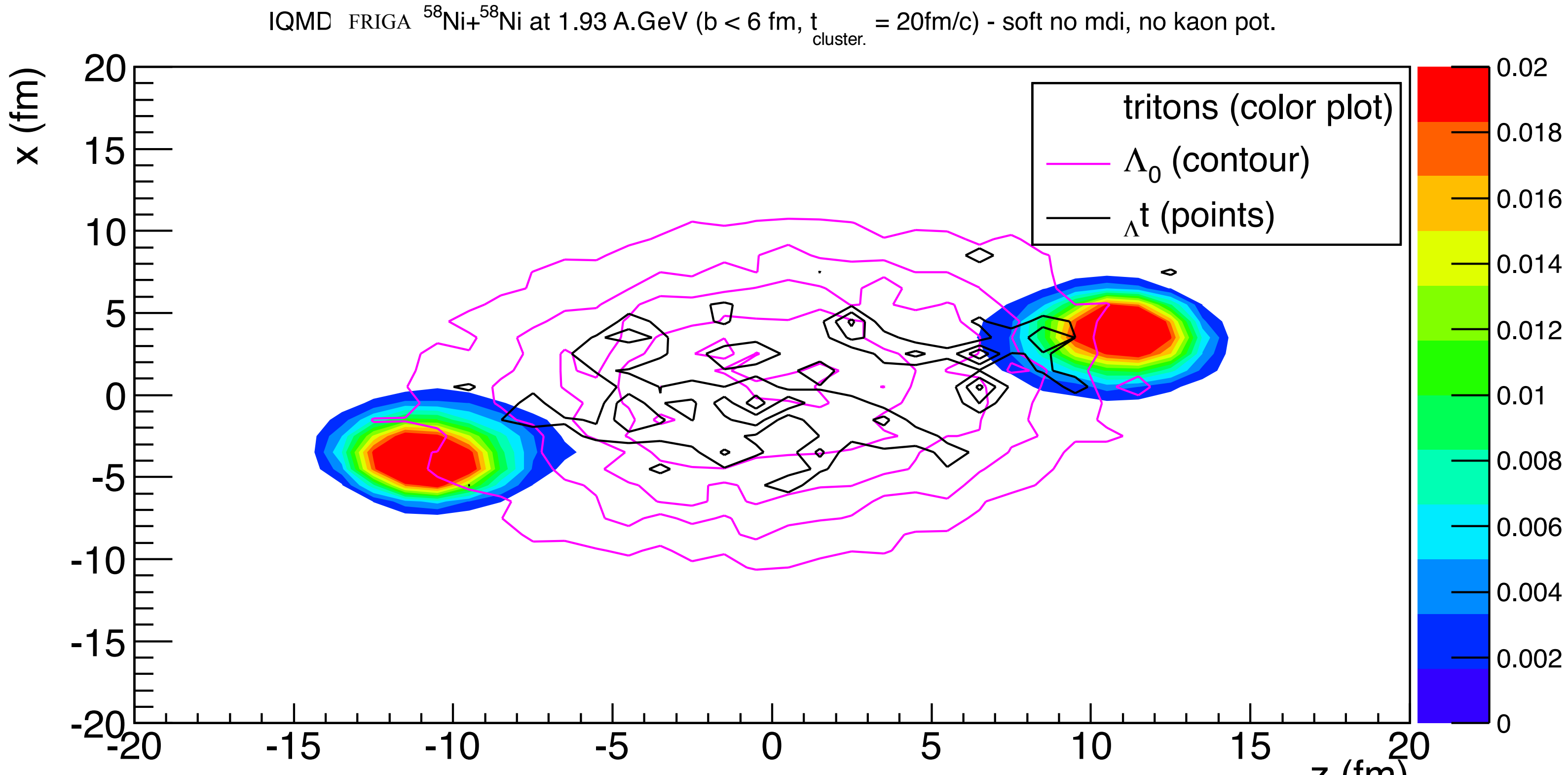
Influence of the EOS, in medium-properties of the transport model on the hypernuclei production

IQMD+FRIGA
^{58}Ni+^{58}Ni @1.91A.GeV
b < 6 fm
($t_{passing}$=8.7 fm/c)



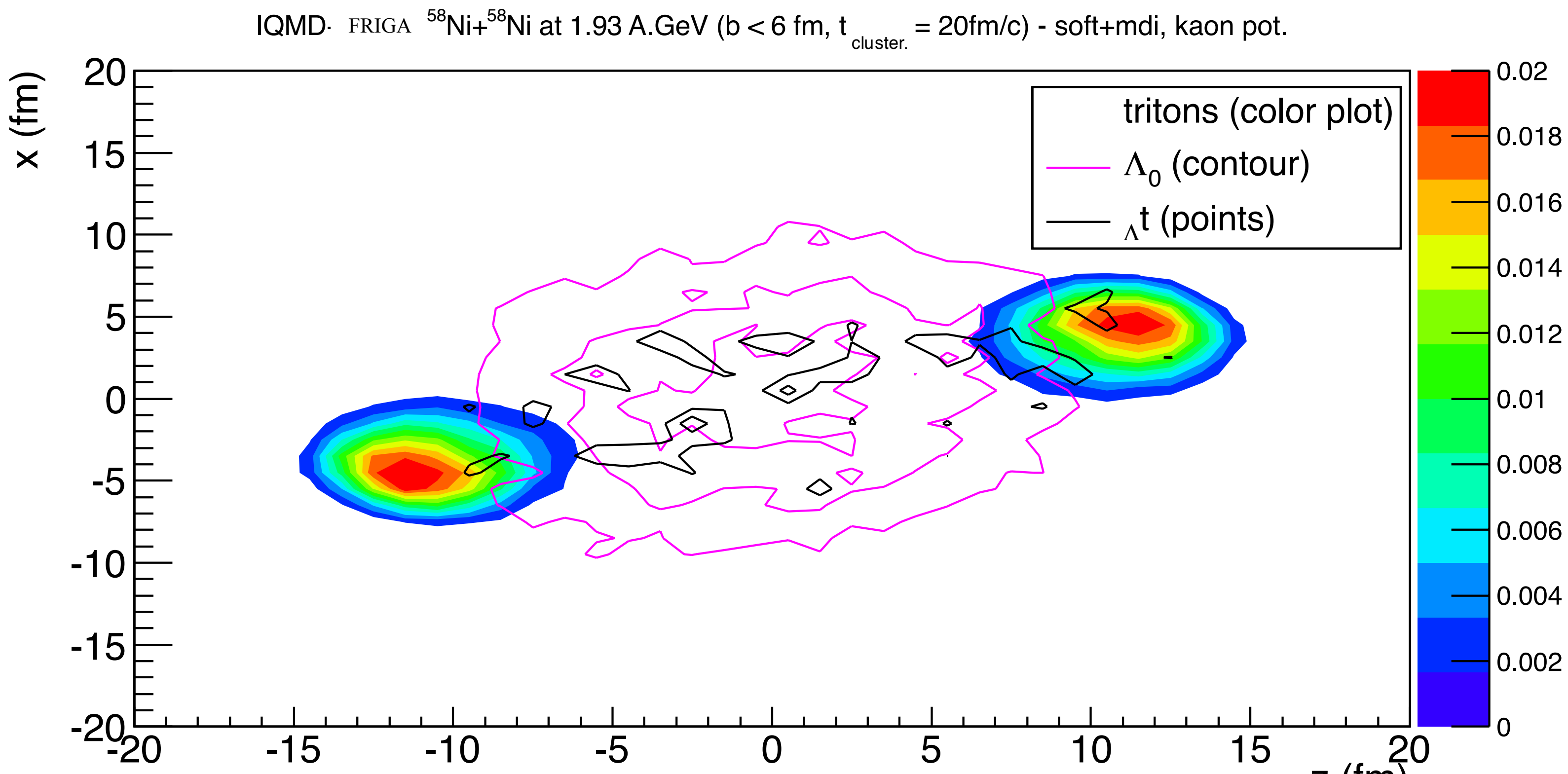
Influence of the EOS, in medium-properties of the transport model on the hypernuclei production

IQMD+FRIGA
$^{58}Ni+^{58}Ni$ @1.91A.GeV
b < 6 fm
($t_{passing}$=8.7 fm/c)



Influence of the EOS, in medium-properties of the transport model on the hypernuclei production

IQMD+FRIGA
$^{58}Ni + ^{58}Ni$ @1.91A.GeV
b < 6 fm
($t_{passing}$=8.7 fm/c)



Influence of the EOS, in medium-properties of the transport model on the hypernuclei production

IQMD+FRIGA
$^{58}Ni+^{58}Ni$ @1.91A.GeV
b < 6 fm
($t_{passing}$=8.7 fm/c)