Light nuclei formation in FRIGA

Light nuclei formation in FRIGA

- A clusterisation approach…
- An application: the hypernucleus production.
- How are influenced the (hyper-)isotope yields and phase space distributions by:
  - the clusterisation time,
  - the cluster binding energy,
  - the ingredients (EOS, in-medium properties) of the transport model.
- Spectator versus fireball cluster formation: cold-static versus hot-sequential clustering

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 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** = 2010-2017 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** = 2010-2017 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 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** = 2010-2017 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 **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** = 2010-2017 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.

GSI HELMHOLTZ ASSOCIATION

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.**

HELMHOLTZ ASSOCIATION

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

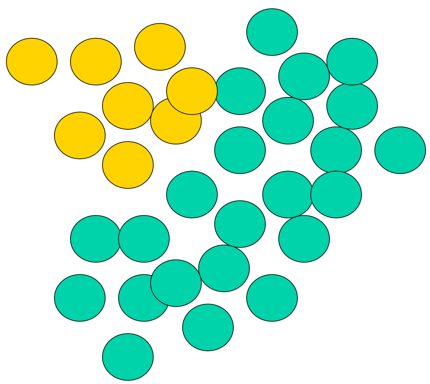
If we want to identify fragments early, one has to use momentum space info as well as coordinate space info.

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.



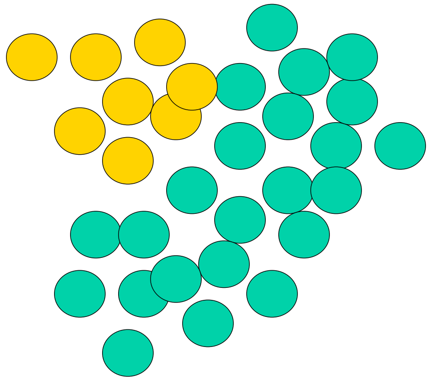
$$E=E^{1}_{kin}+E^{2}_{kin}+V^{1}+V^{2}$$

FRIGA: a clusterisation approach…

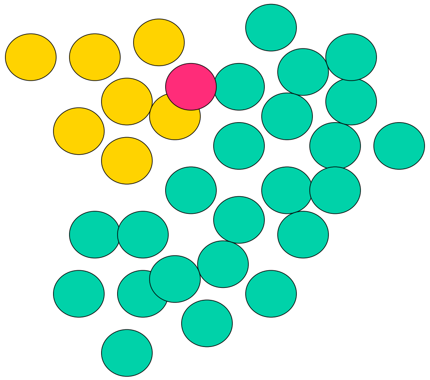
Steps:

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



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



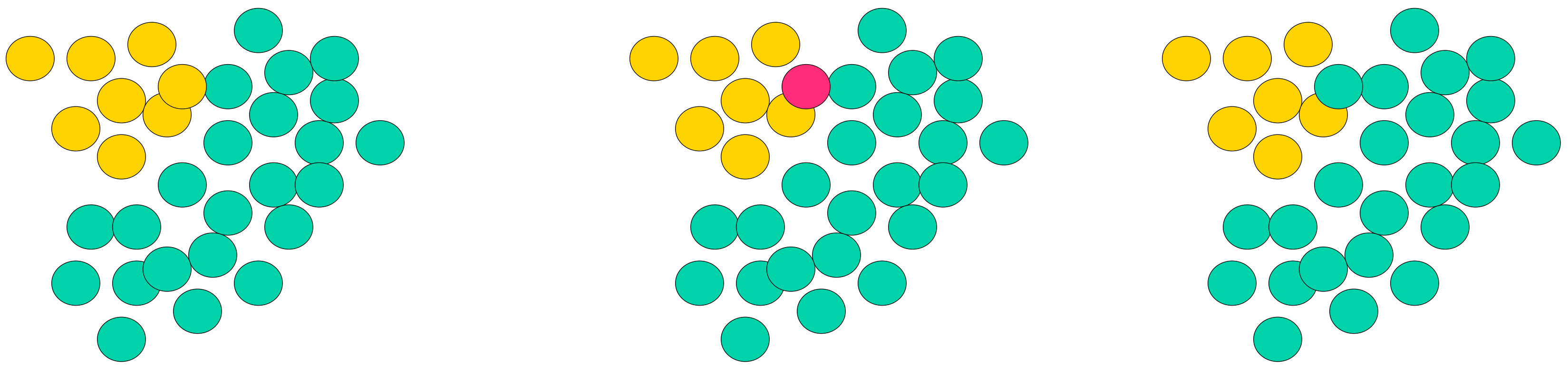
FRIGA: a clusterisation approach…

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



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

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

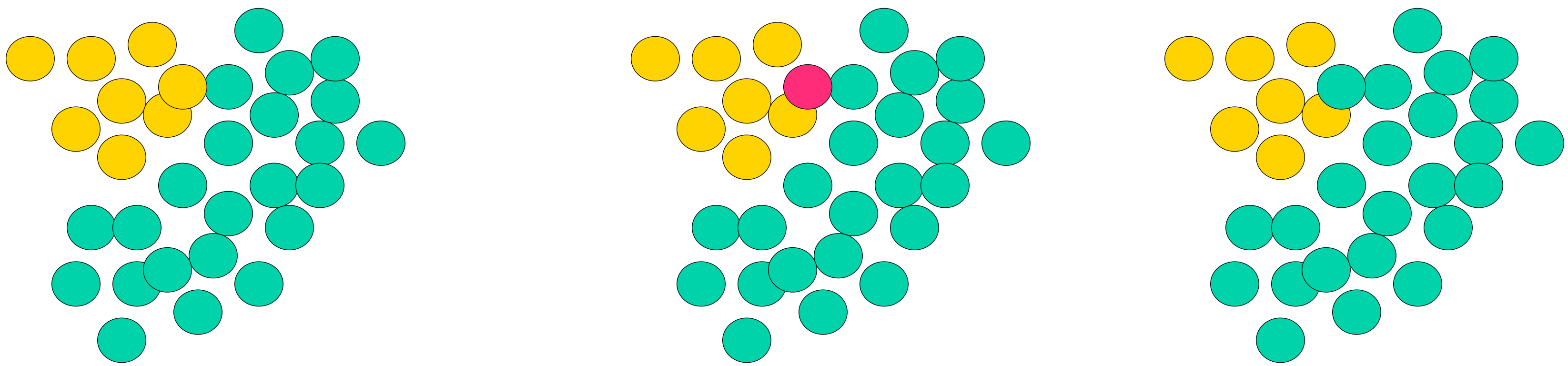
FRIGA: a clusterisation approach…

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



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

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

If $E' < E$ take the new configuration

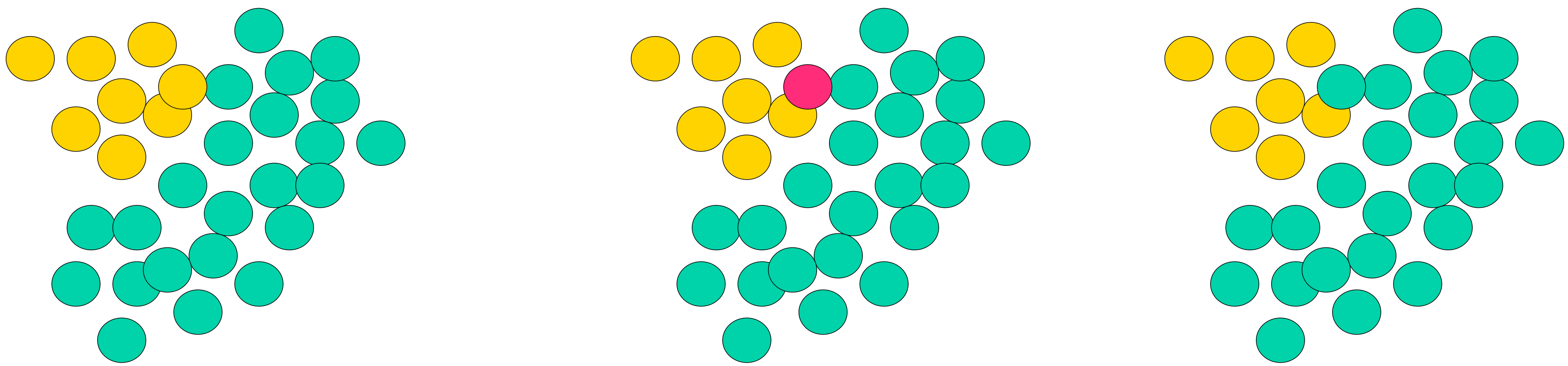
FRIGA: a clusterisation approach…

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

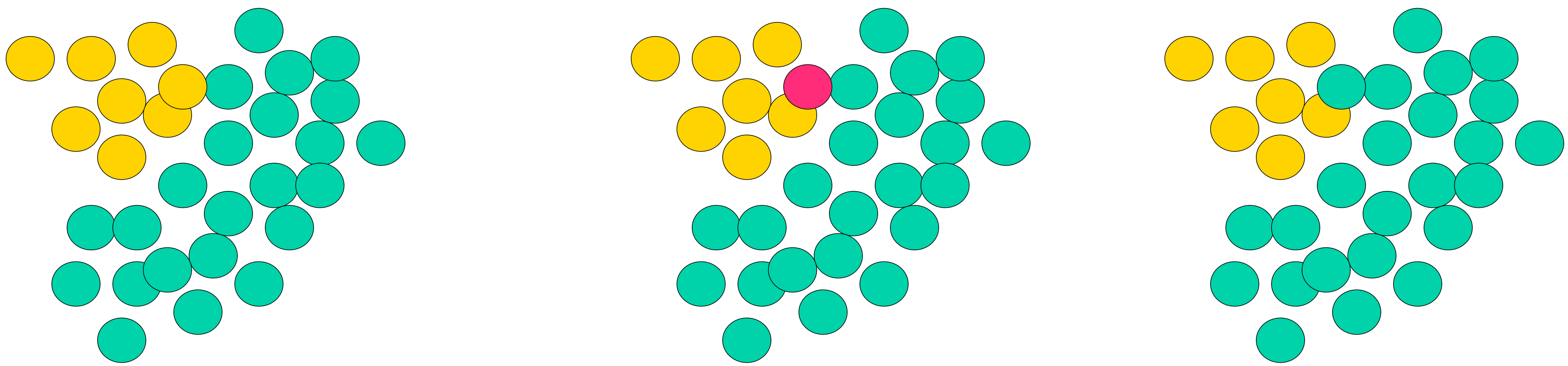
FRIGA: a clusterisation approach…

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)

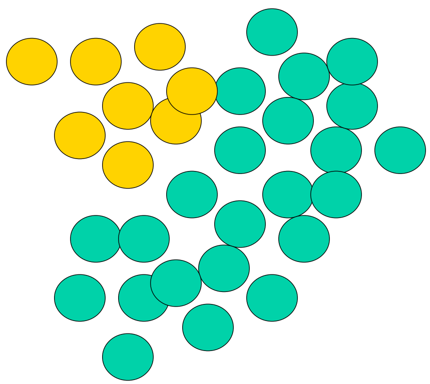
FRIGA: a clusterisation approach…

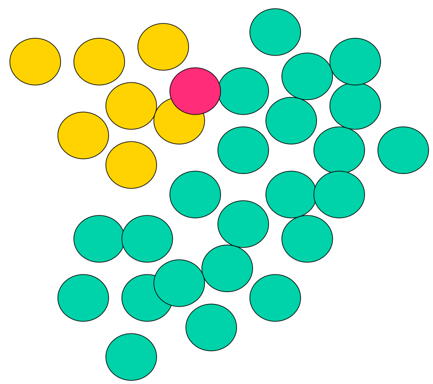
Steps:

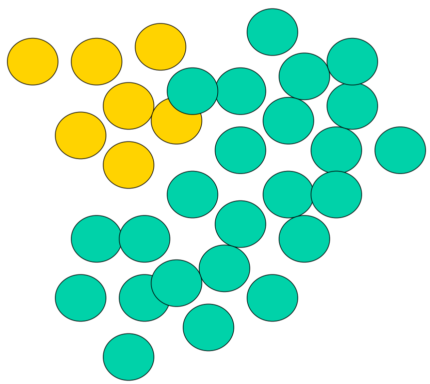
1) Pre-select good «candidates» for fragments according to proximity criteria: coordinate and momentum space coalescence = Minimum Spanning Tree (**MST**) procedure.

2) Take randomly 1 nucleon out of one fragment

3) Add it randomly to another fragment







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

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

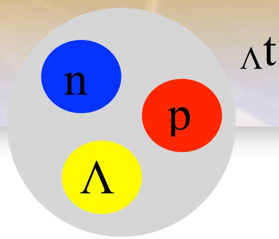
If $E' < E$ take the new configuration

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

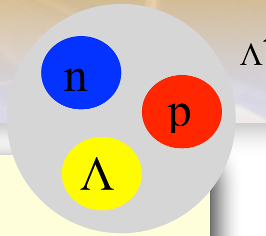
Repeat this procedure very many times… (Metropolis procedure)

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

FRIGA: a clusterisation approach…

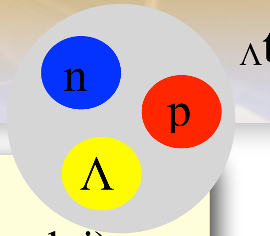


FRIGA: a clusterisation approach…



Ingredients of the binding energy of the clusters :

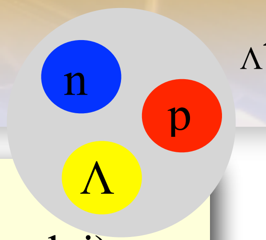
FRIGA: a clusterisation approach…



Ingredients of the binding energy of the clusters :

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

FRIGA: a clusterisation approach…

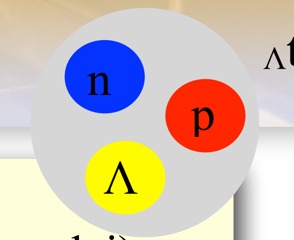


Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN. For 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…



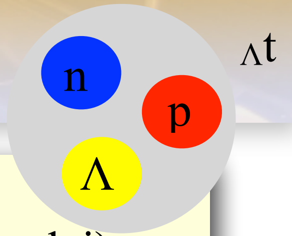
Ingredients of the binding energy of the clusters :

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

② Surface effect correction: Yukawa term. And optionally:

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

FRIGA: a clusterisation approach…



Ingredients of the binding energy of the clusters :

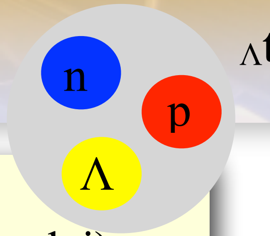
① Volume component: mean field (Skyrme, dominant), for NN. For NΛ(hypernuclei), we consider the strange quark as inert as a first approach ⇒ U(NΛ) = 2/3.U(NN)

② Surface effect correction: Yukawa term. And optionally:

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

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. For NΛ(hypernuclei), we consider the strange quark as inert as a first approach ⇒ $U(N\Lambda) = 2/3.U(NN)$

② Surface effect correction: Yukawa term. And optionally:

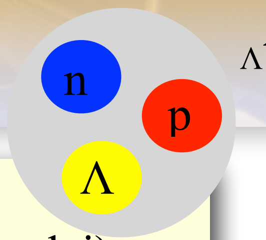
③ Asymmetry energy (potential part): $23.3\ \text{MeV}.(\langle\rho'_B\rangle)^{\gamma_{ASY}}.[(\langle\rho'_n\rangle - \langle\rho'_p\rangle)/\langle\rho'_B\rangle]^2$

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

⑤ Secondary decay: GEMINI.

GSI HELMHOLTZ ASSOCIATION

FRIGA: a clusterisation approach…



Ingredients of the binding energy of the clusters :

① Volume component: mean field (Skyrme, dominant), for NN. For 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:

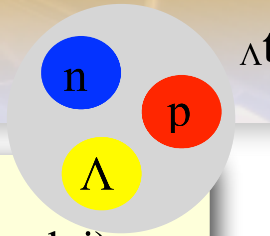
③ Asymmetry energy (potential part): $23.3\ \mathrm{MeV}.(<\rho'_B>)^{\gamma_{ASY}}.[(<\rho'_n>-<\rho'_p>)/<\rho'_B>]^2$

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

⑤ Secondary decay: GEMINI.

⑥ 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. For NΛ(hypernuclei), we consider the strange quark as inert as a first approach ⇒ $U(N\Lambda) = 2/3.U(NN)$

② Surface effect correction: Yukawa term. And optionally:

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

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

⑤ Secondary decay: GEMINI.

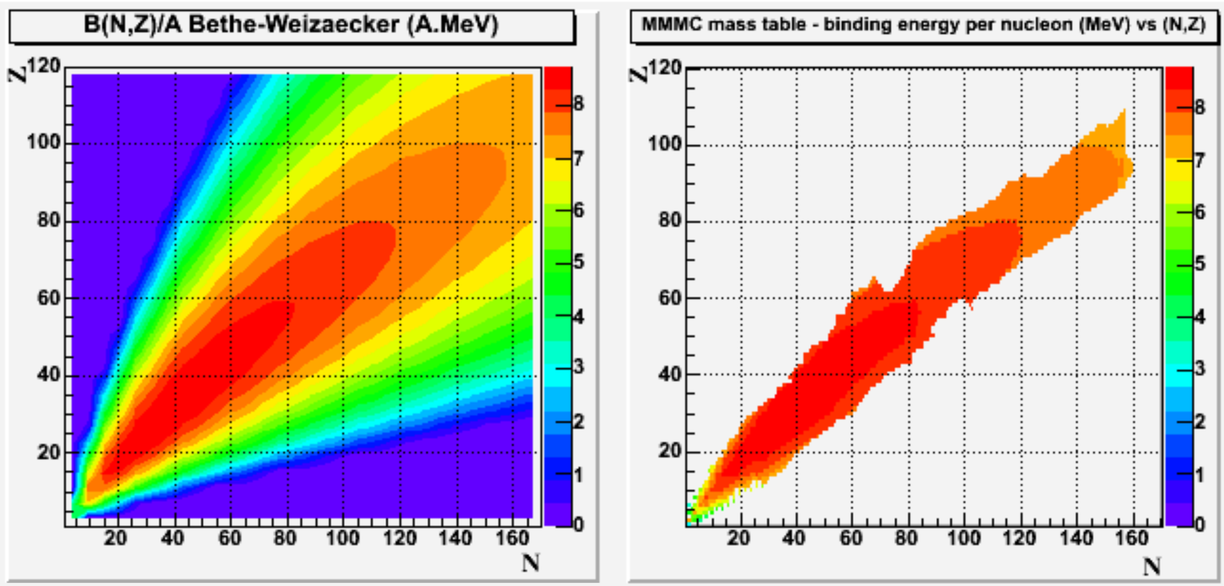
⑥ Rejection of « non-existing » isotopes and hyper-clusters.

➲ Remarks:

- The clusterisation has to happen quite early (passing time) such as to produce hypernuclei.
- Λ yields and phase space distribution 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 «shell» binding energy will be the difference in binding energy between experimental measurements (hypernuclei included) and the Bethe-Weizäcker formula (without pairing).

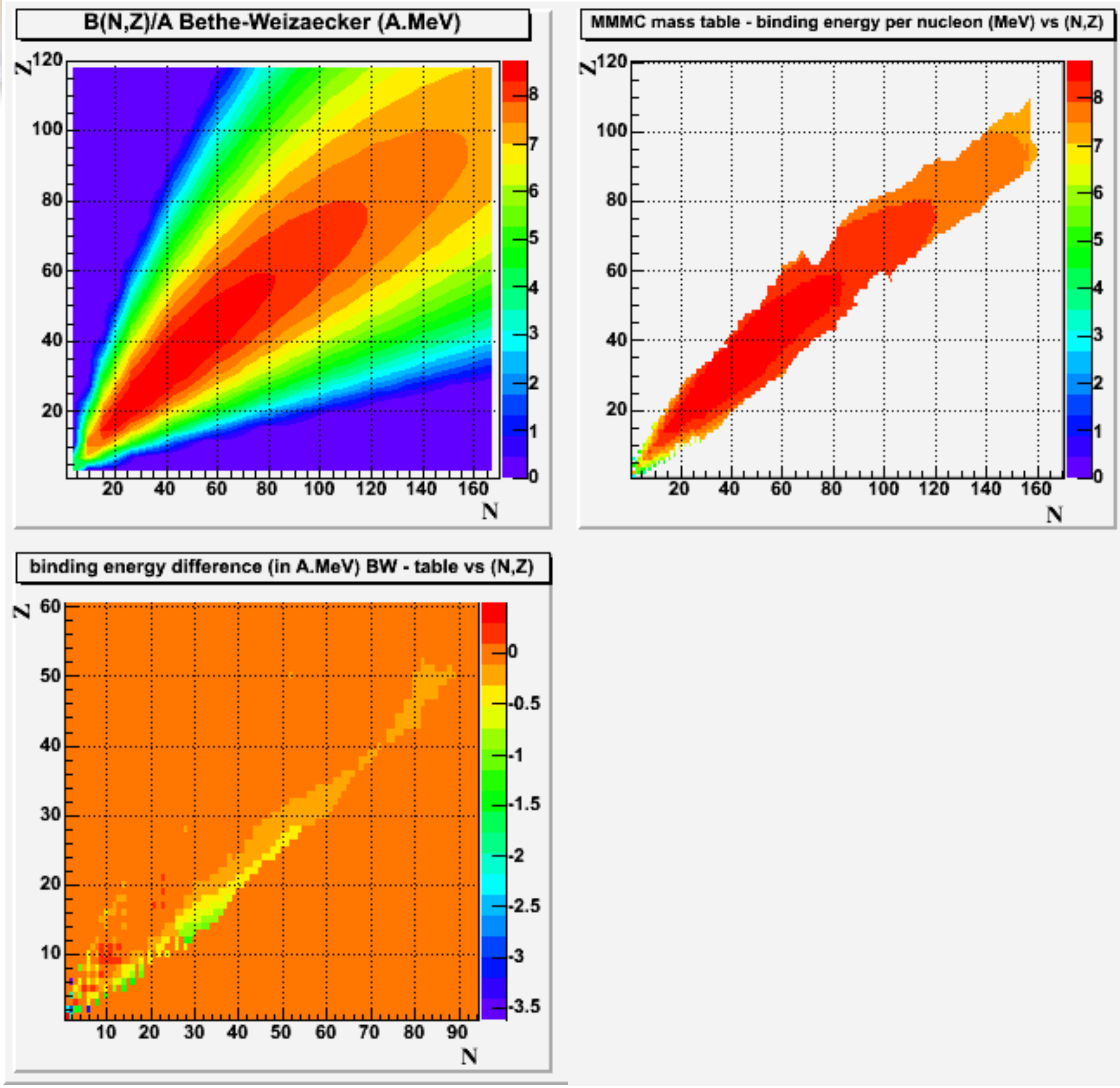


More detailed structure corrections to apply

☞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 «shell» binding energy will be the difference in binding energy between experimental measurements (hypernuclei included) and the Bethe-Weizäcker formula (without pairing).

➜ $\Delta B_{shell}(N,Z,\rho_0)$.

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

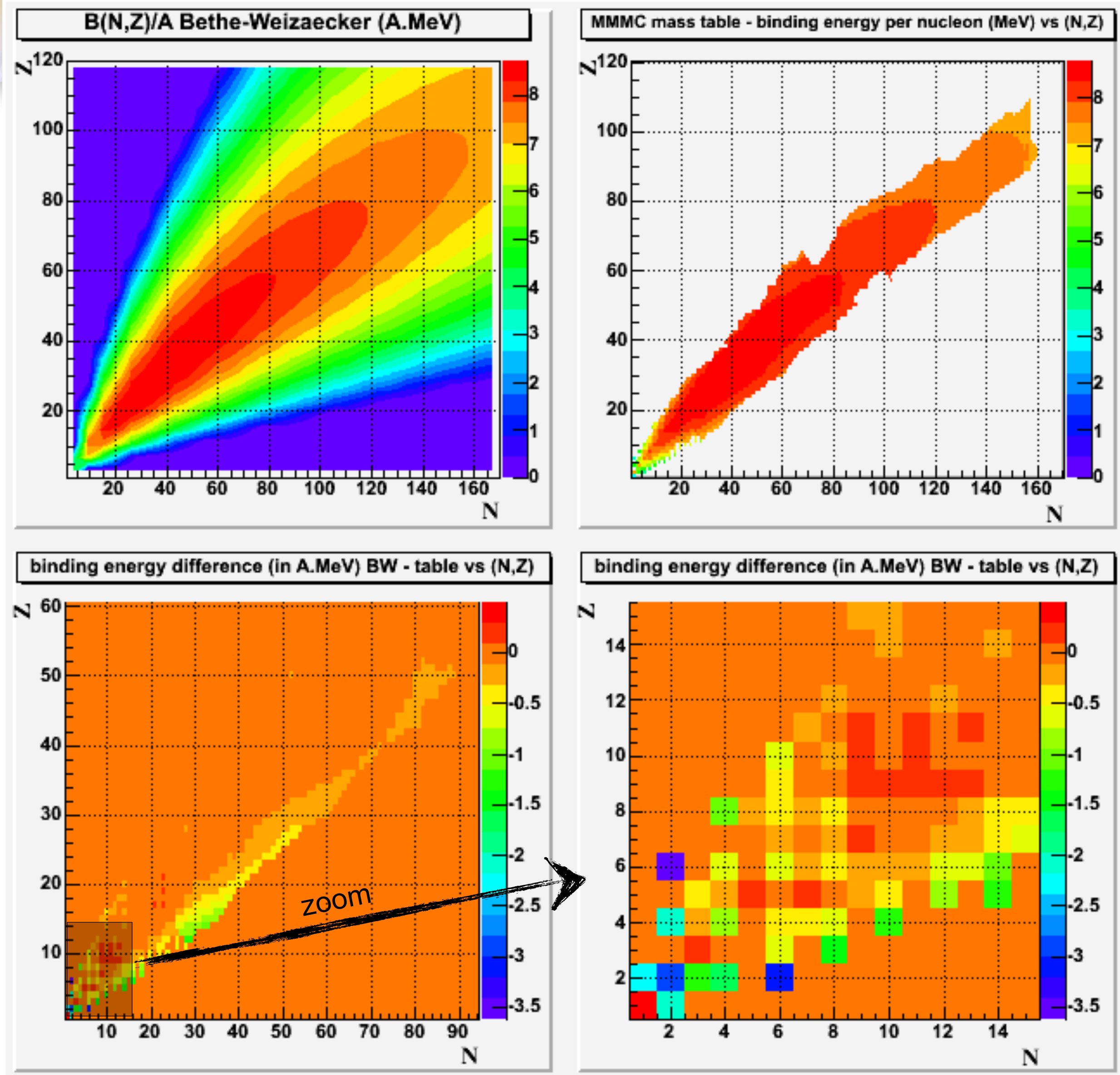


More detailed structure corrections to apply

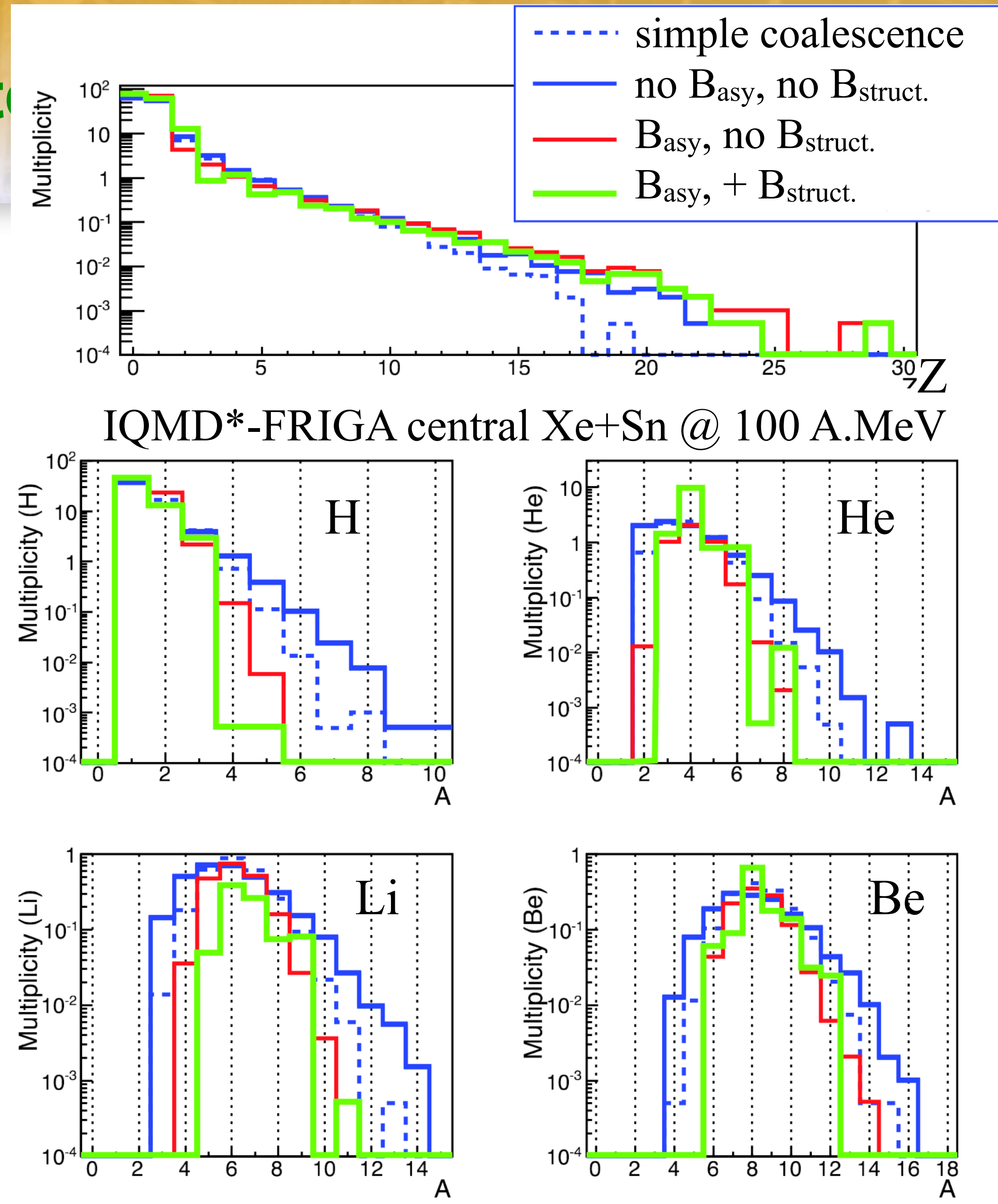
☞In order to account for all major structure effects which make the binding energy deviate from the liquid drop model, for each nucleus (N,Z), what we call «shell» binding energy will be the difference in binding energy between experimental measurements (hypernuclei included) and the Bethe-Weizäcker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

➜ $\Delta B_{shell}(N,Z,\rho_0)$.

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



FRIGA: a clust

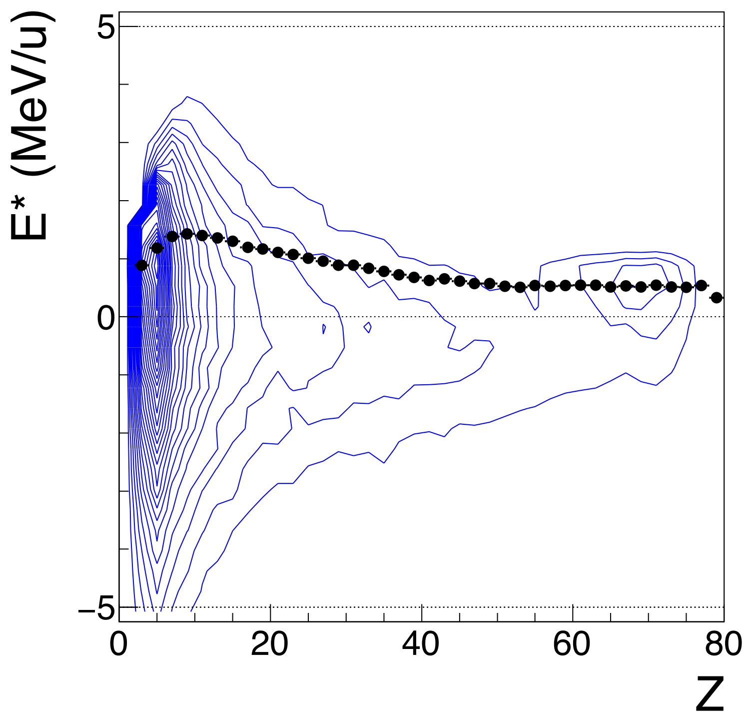


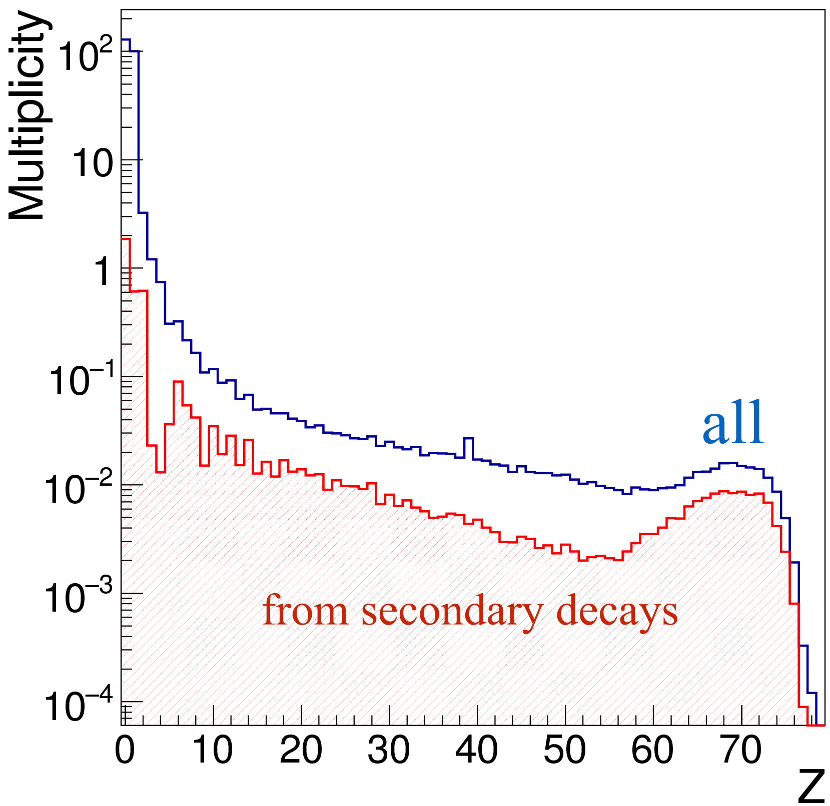
*: Ch.Hartnack et al., Eur. Phys. J. A 1(1998) 151.

Influence of the secondary decays on light isotope yields

An example: Au+Au @ 600 A.MeV (min. bias), b<6 fm (passing time = 2 t_{pass})
from BQMD*+FRIGA

Primary cluster excitation energy

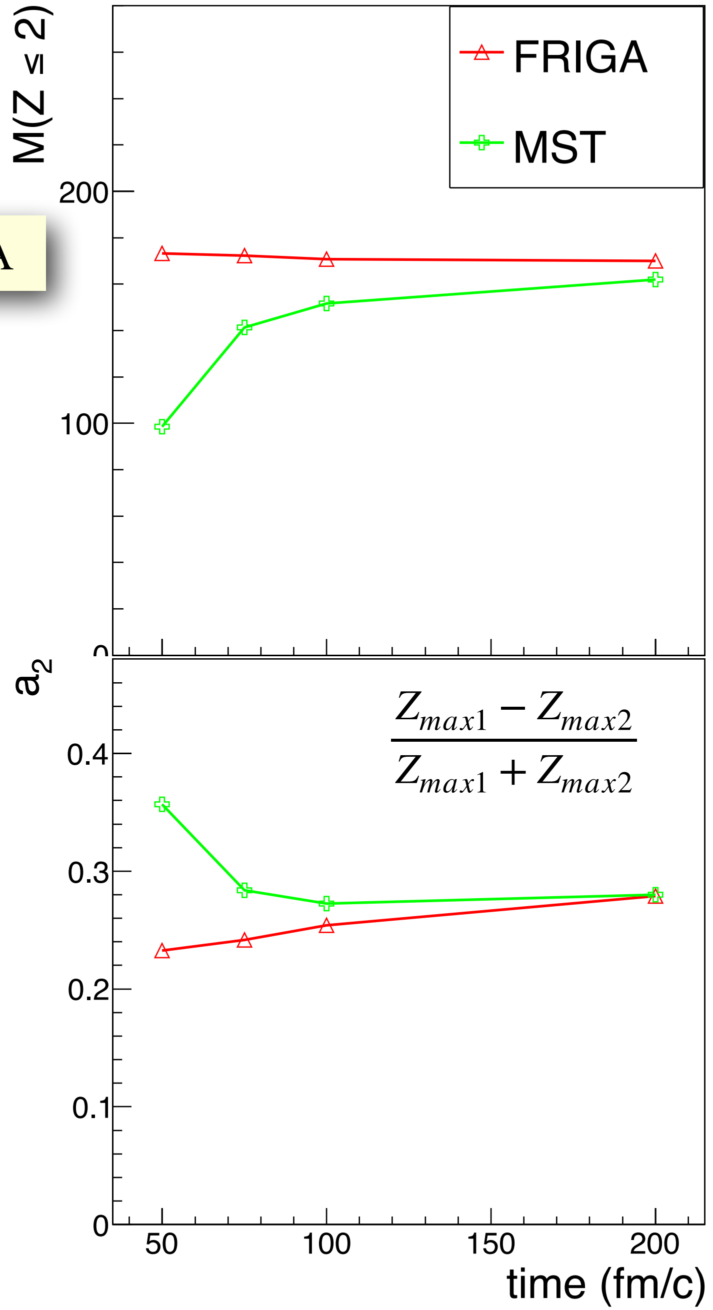




*: J. Aichelin. Phys. Reports 202, 233 (1991).

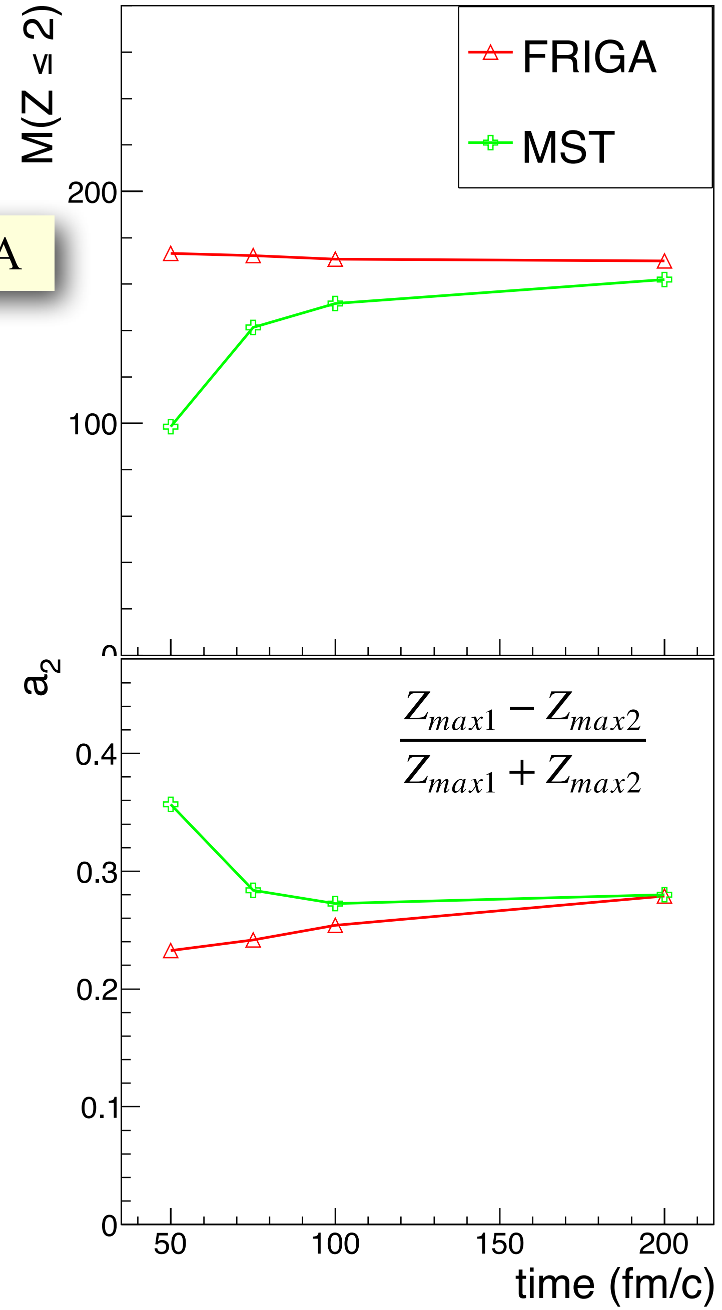
FRIGA versus coalescence (Minimum Spanning Tree)

Au+Au @ 600 A.MeV, b<6 fm from BQMD*+FRIGA



FRIGA versus coalescence (Minimum Spanning Tree)

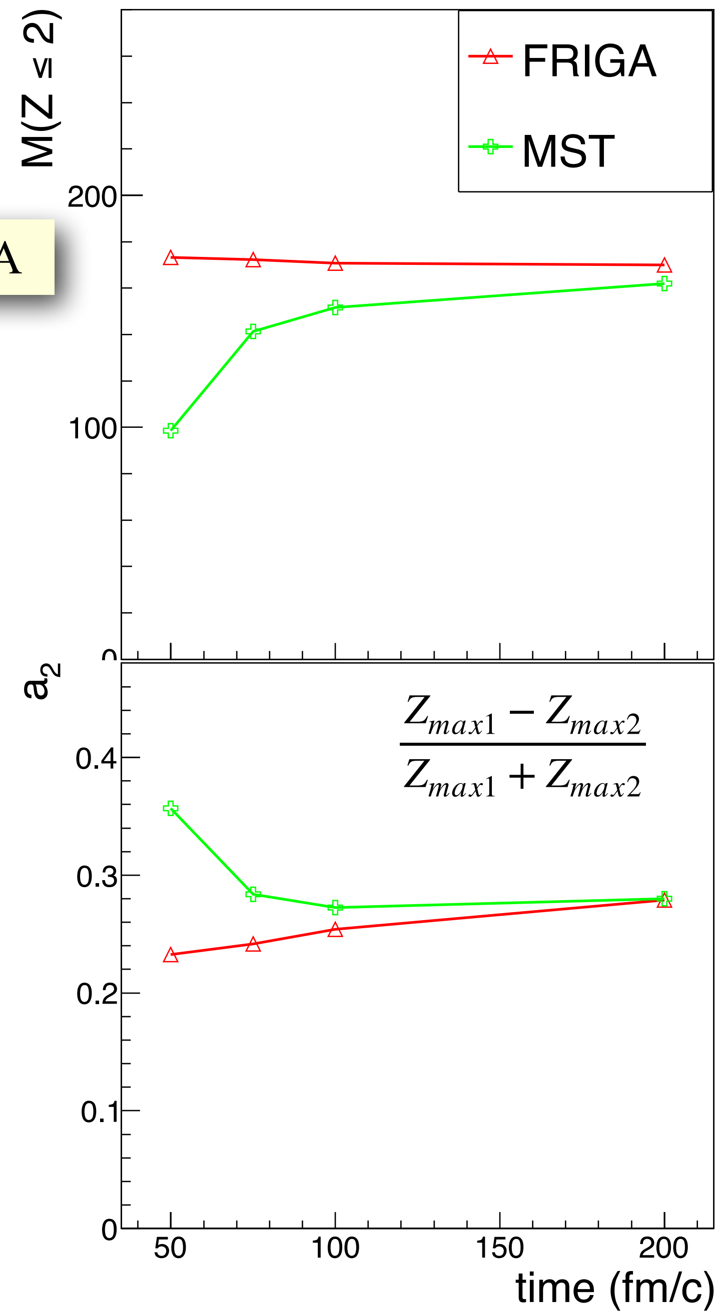
Au+Au @ 600 A.MeV, b<6 fm from BQMD*+FRIGA



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

FRIGA versus coalescence (Minimum Spanning Tree)

Au+Au @ 600 A.MeV, b<6 fm from BQMD*+FRIGA



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.

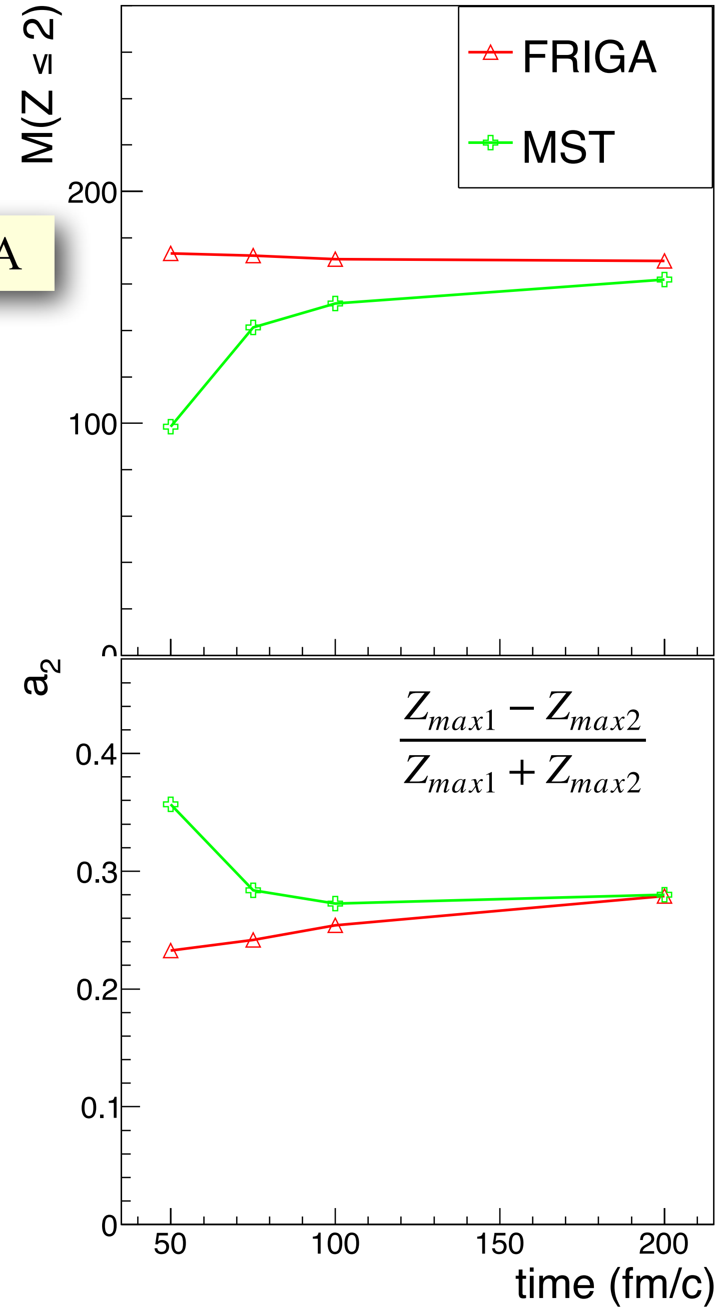
FRIGA versus coalescence (Minimum Spanning Tree)

Au+Au @ 600 A.MeV, b<6 fm from BQMD*+FRIGA

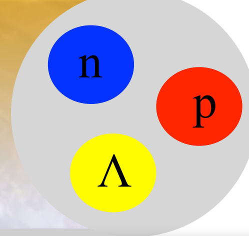
Unlike FRIGA, MST is not able to describe the early formation of fragments.

➡ 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.



Clusterisation time influence on hypernuclei (phase space and yields)



$_{\Lambda}t$

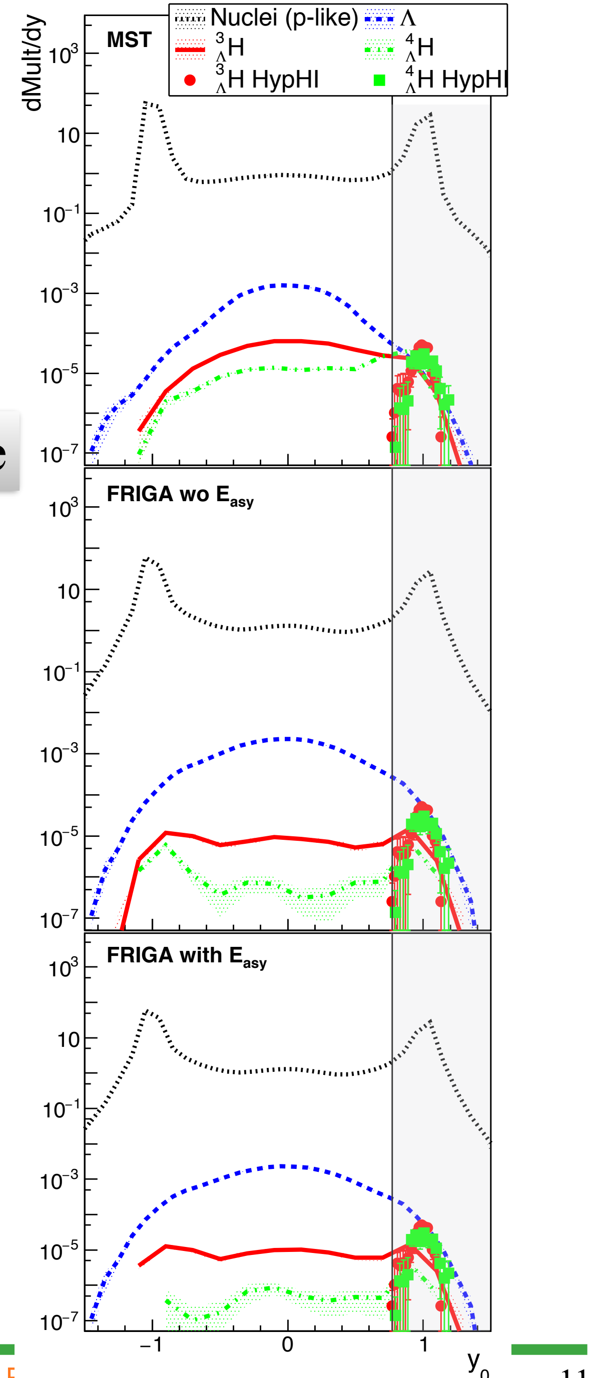
An example: HypHI experiment, $^{6}Li+^{12}C$ @ 2A GeV (SIS), b=6 fm (passing time = 4.4 fm/c) from IQMD+FRIGA

2 x passing time

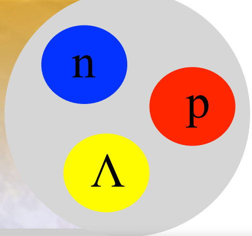
HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129–13:

$R=Y(_{\Lambda}^{3}H)/Y(_{\Lambda}^{4}H)=1.4 \pm 0.8$

IQMD-FRIGA :
without Easy: R=2.7 ± 0.5
with Easy: R=4.6 ± 1.1



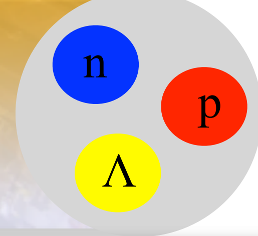
Clusterisation time influence on hypernuclei (phase space and yields)



$_{\Lambda}t$

An example: HypHI experiment, $^{6}Li+^{12}C$ @ 2A GeV (SIS), b=6 fm (passing time = 4.4 fm/c) from IQMD+FRIGA

Clusterisation time influence on hypernuclei (phase space and yields)



$_{\Lambda}t$

An example: HypHI experiment, $^{6}Li+^{12}C$ @ 2A GeV (SIS), b=6 fm (passing time = 4.4 fm/c) from IQMD+FRIGA

4 x passing time

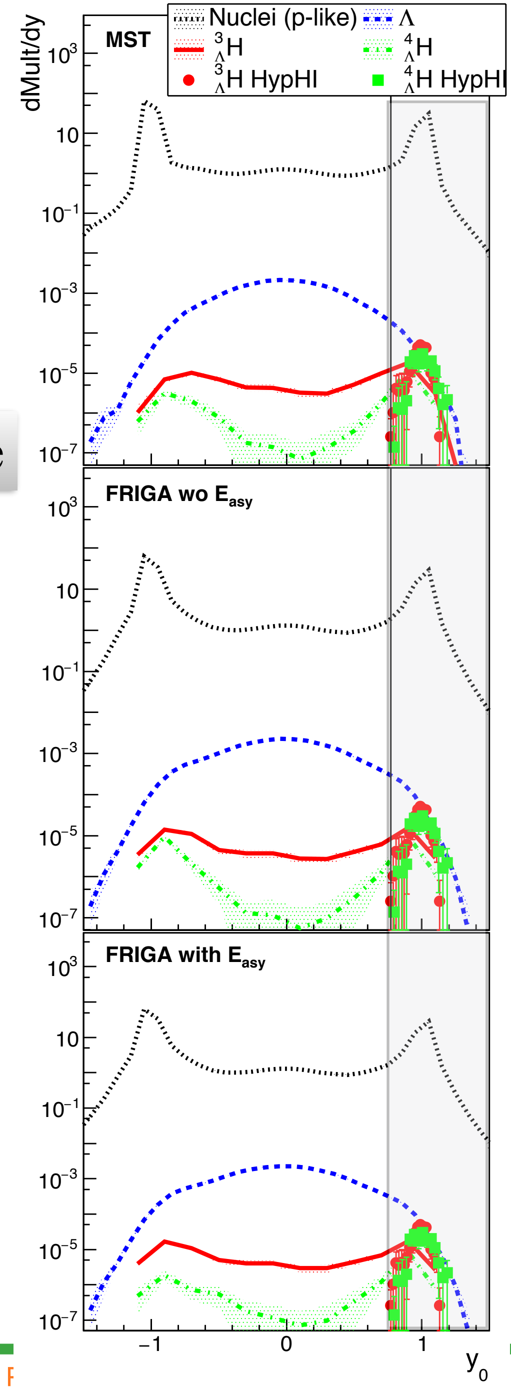
Remarks:

- At mid-rapidity (fireball), the instantaneous hyper-light cluster yields are strongly changing up to at least 4 times the passings
- In the spectator region, they are stabilising faster

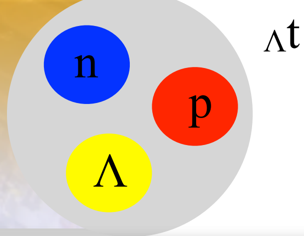
HyPHI experiment @ GSI
Ch. Rappold et al.,
PLB 747 (2015) 129–13:

$R=Y(_{\Lambda}^{3}H)/Y(_{\Lambda}^{4}H)=1.4 \pm 0.8$

IQMD-FRIGA :
without Easy: $R=2.0 \pm 0.4$
with Easy: $R=2.5 \pm 0.5$



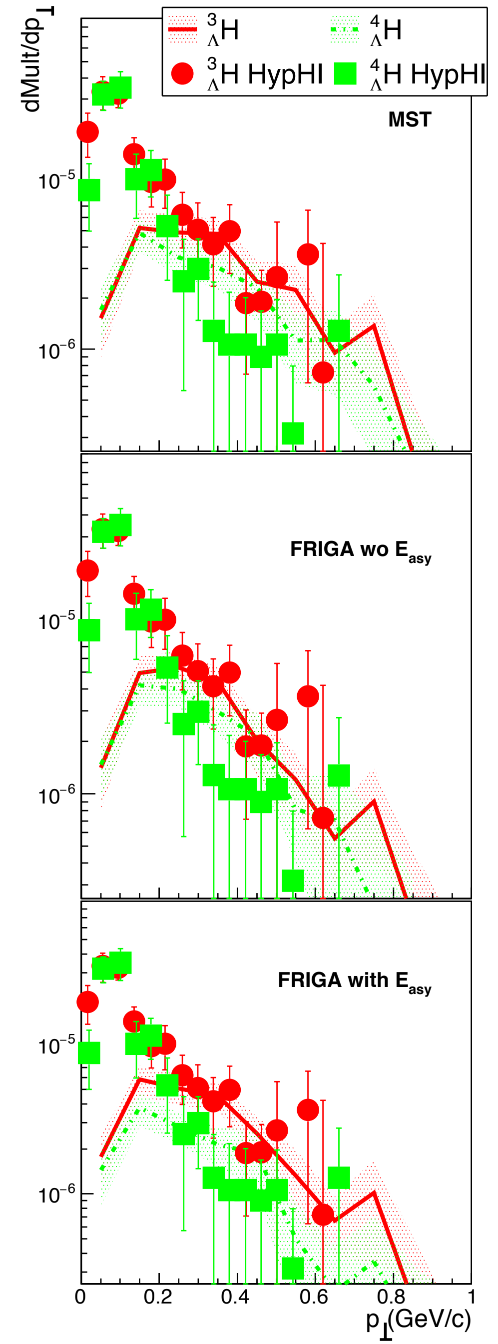
Clusterisation time influence on hypernuclei (phase space and yields)



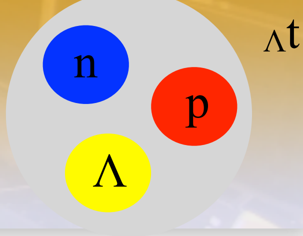
An example: HypHI experiment, $^{6}Li+^{12}C$ @ 2A GeV (SIS), b=6 fm (passing time = 4.4 fm/c) from IQMD+FRIGA

➲ Remarks:

- Yields and transverse momentum distributions are well reproduced
- Except at very low p_t where predicted Lambdas are not numerous enough to induce large hyper-cluster yields.

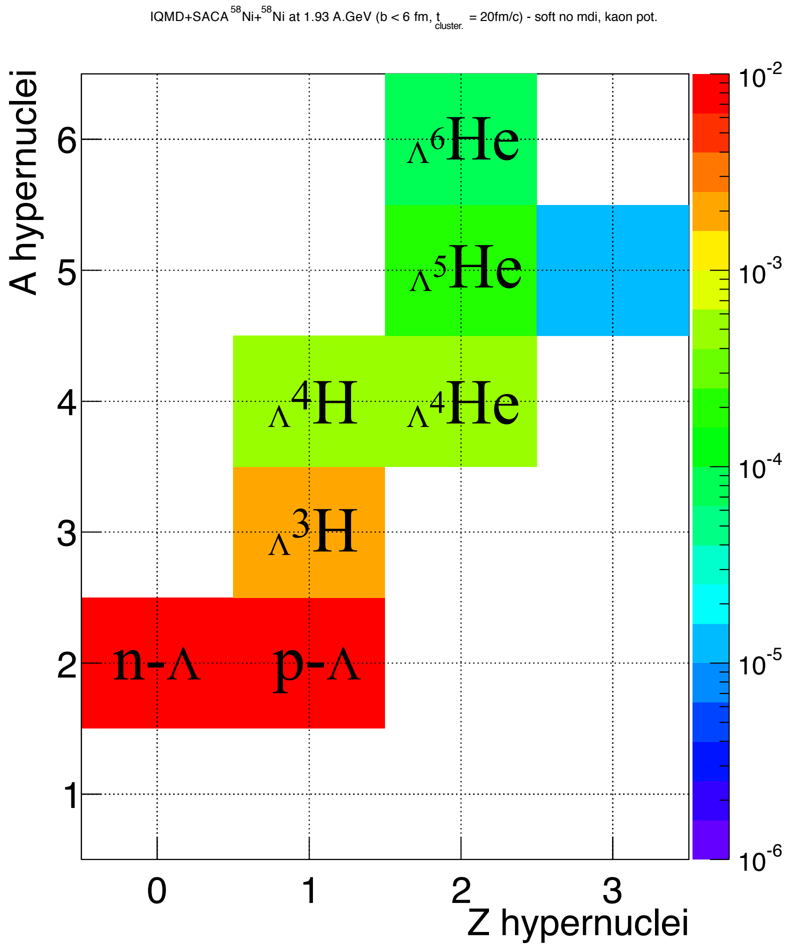


EOS, in medium-properties and hypernuclei yields



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



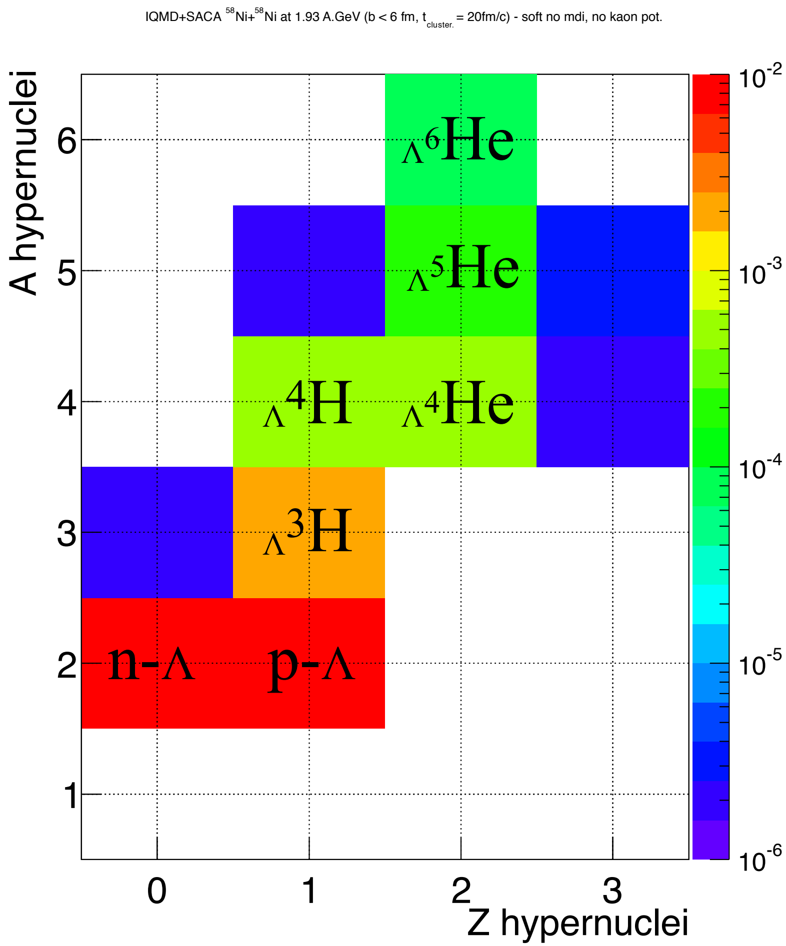
Soft EOS
no m.d.i.
with Kaon pot.

*: 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



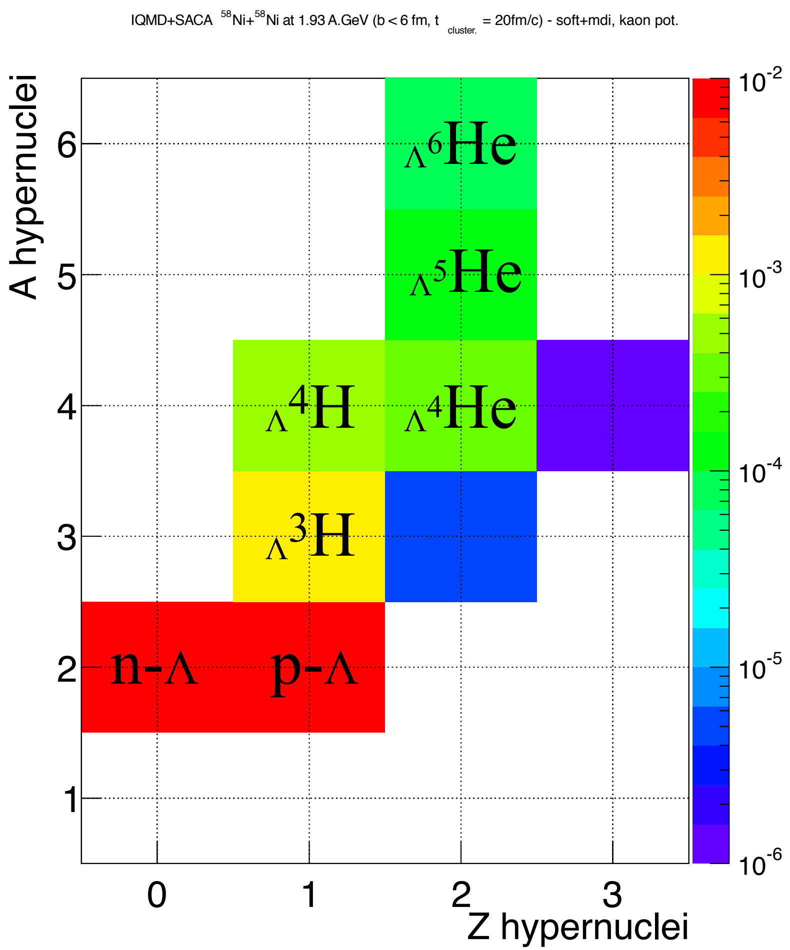
Soft EOS
no m.d.i.
no Kaon pot.

*: 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



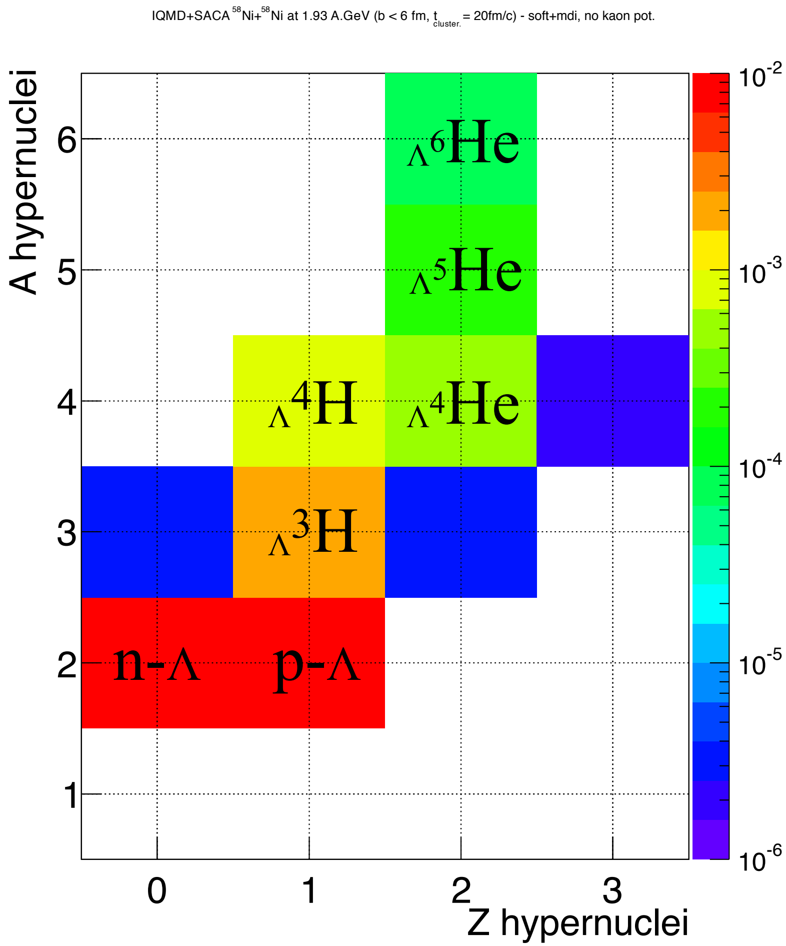
Soft EOS
with m.d.i.
with Kaon pot.

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

EOS, in medium-properties and hypernuclei yields

FOPI system

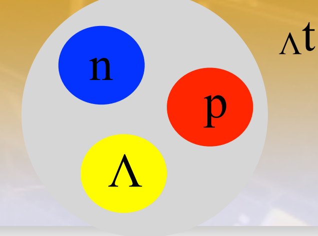
IQMD*+FRIGA
$^{58}Ni+^{58}Ni$ @1.91A.GeV
b < 6 fm
($t_{passing}$=8.7 fm/c)
$t_{cluster.}$=20 fm/c



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



FOPI system

IQMD*+FRIGA

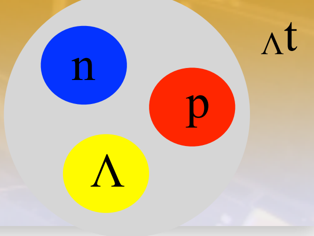
^{58}Ni+^{58}Ni @1.91A.GeV

b < 6 fm

(t = 2.3 t_{pass})

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

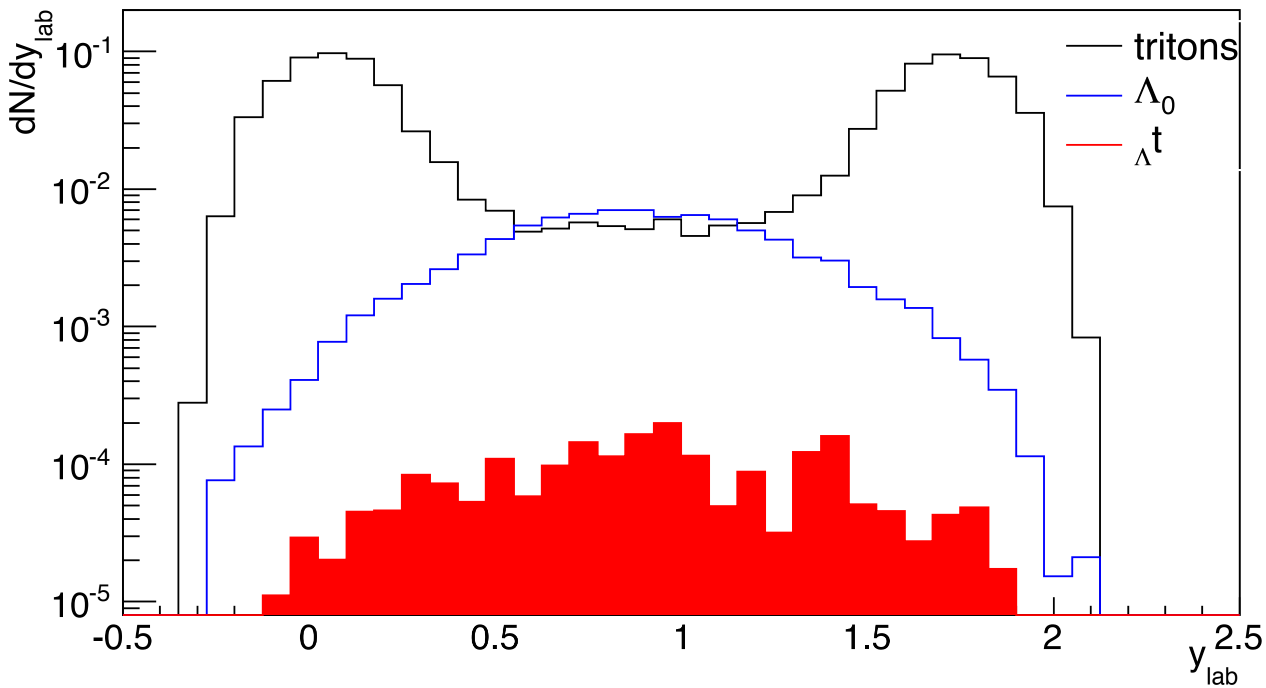
EOS, in medium-properties and hypernuclei yields



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.

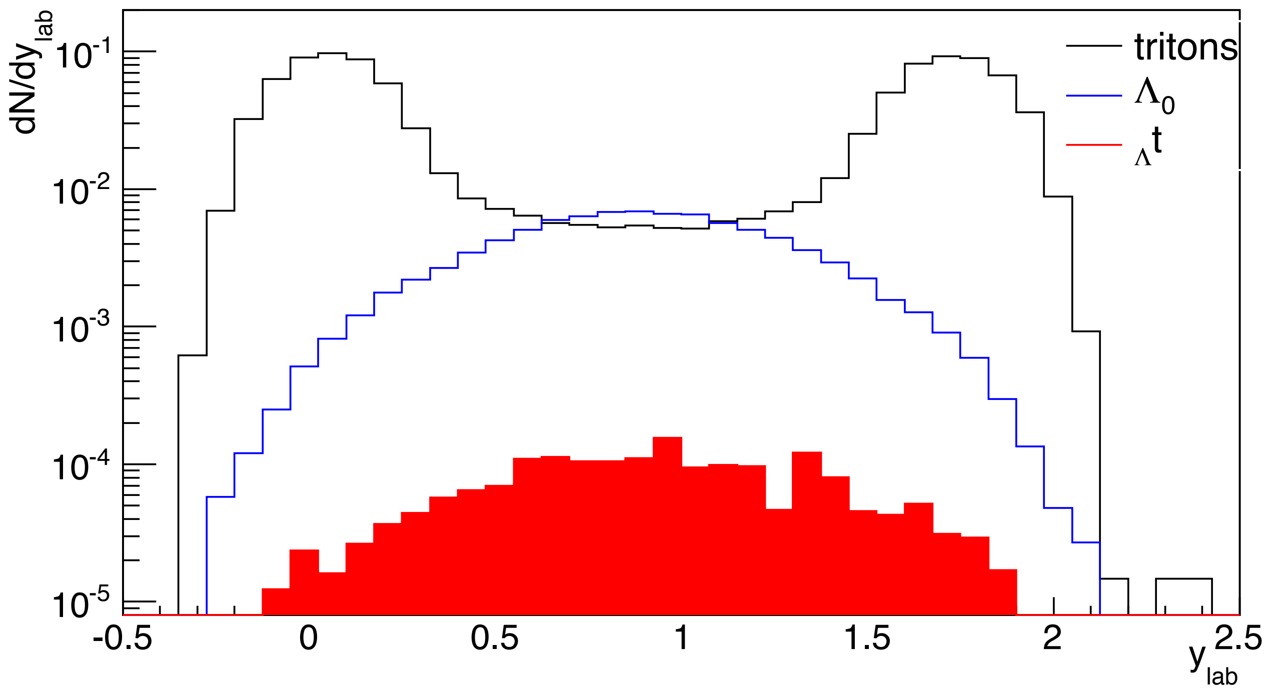
EOS, in medium-properties and hypernuclei yields

$_{\Lambda}t$

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.

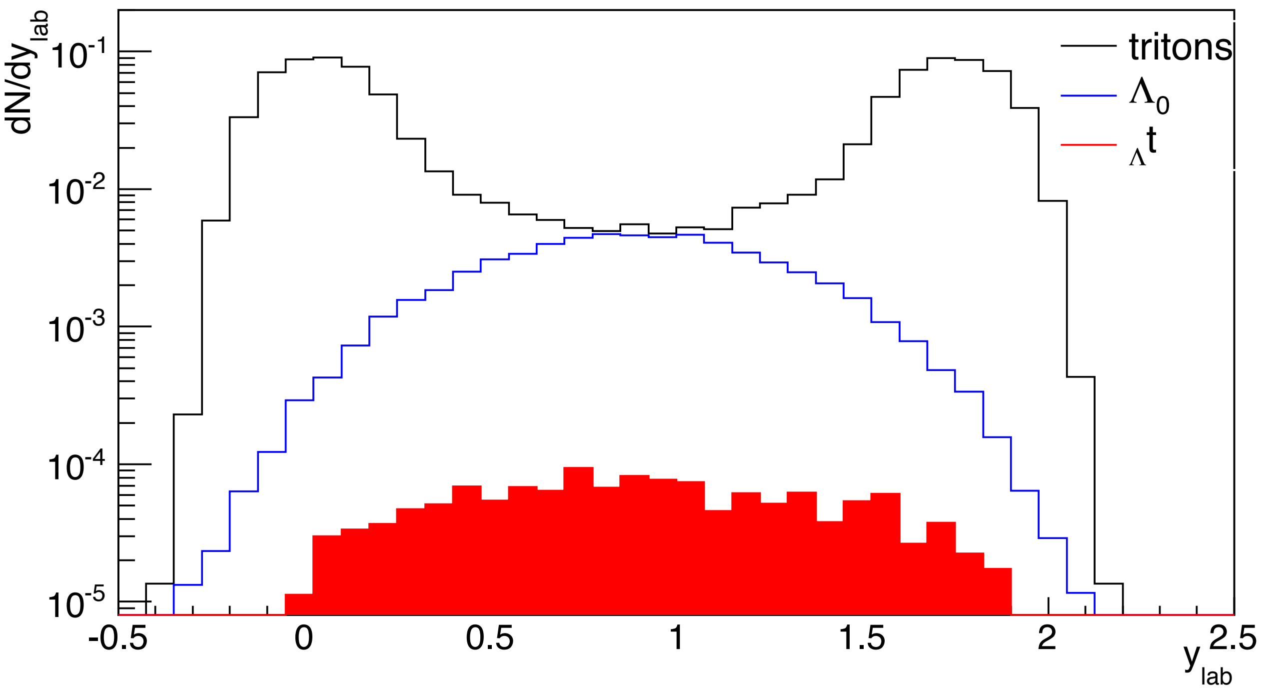
EOS, in medium-properties and hypernuclei yields

$_{\Lambda}t$

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.

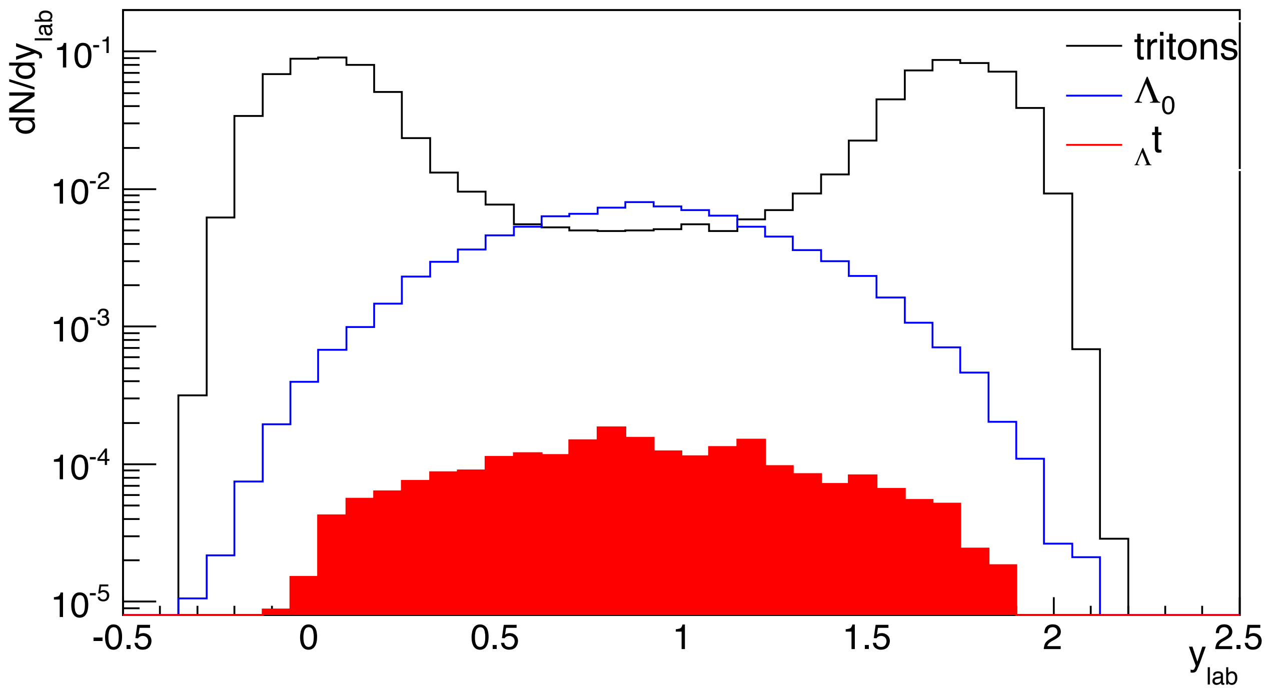


*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

FOPI system

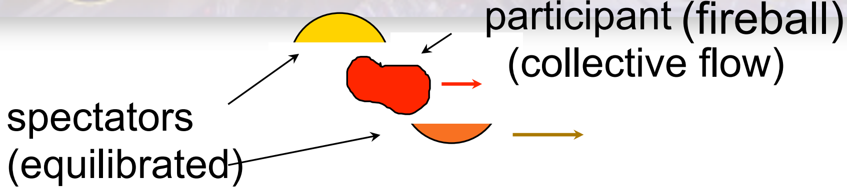
IQMD*+FRIGA
$^{58}Ni+^{58}Ni$ @1.91A.GeV
b < 6 fm
($t = 2.3\ t_{pass}$)

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



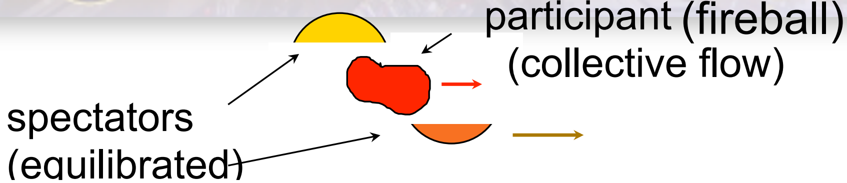
*: Ch.Hartnack et al.,Eur. Phys. J. A 1(1998) 151.

Some successful applications in the spectator regime

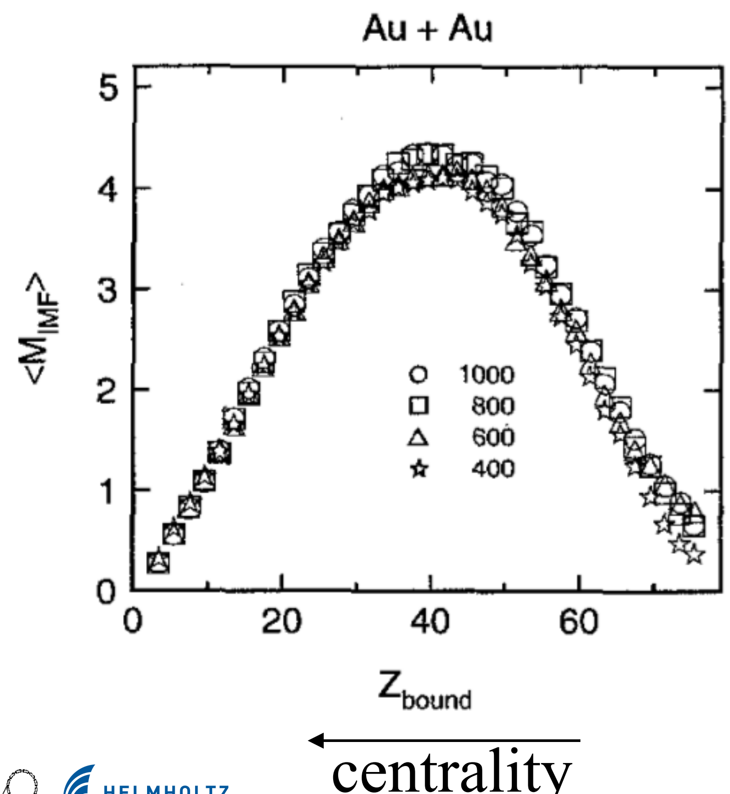


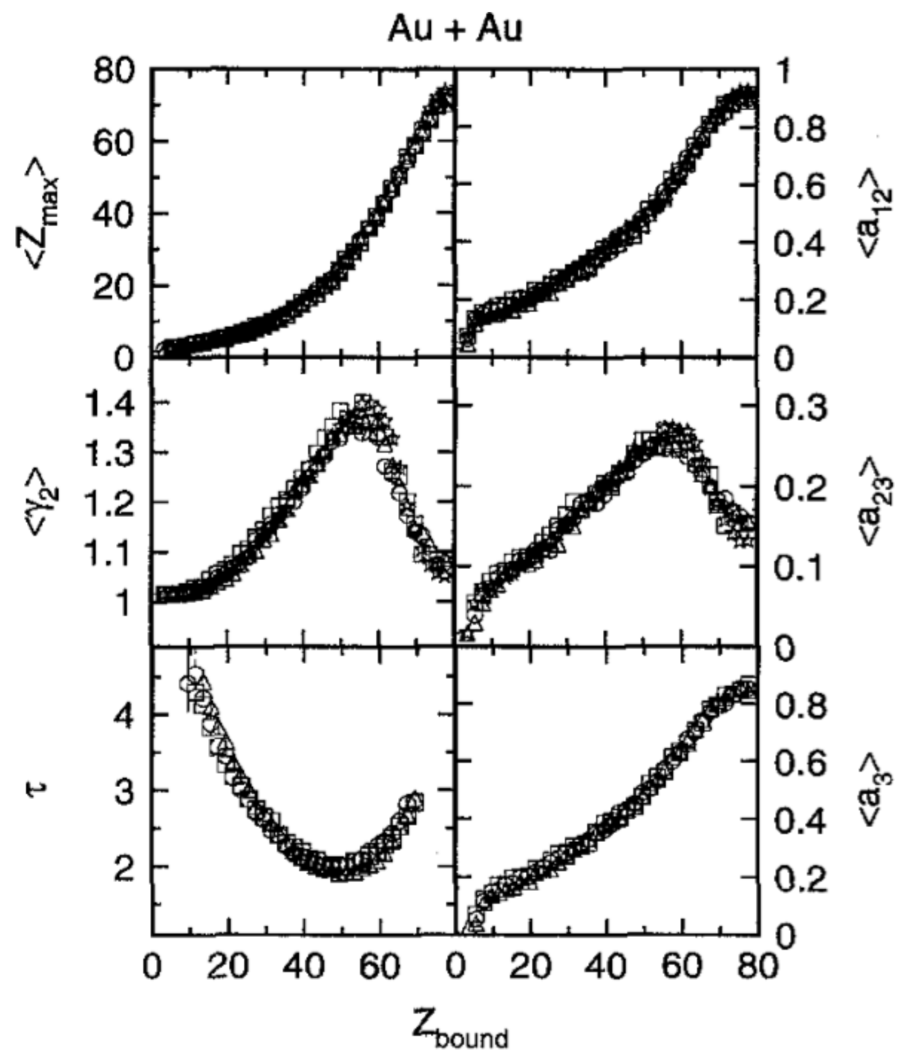
centrality

Some successful applications in the spectator regime

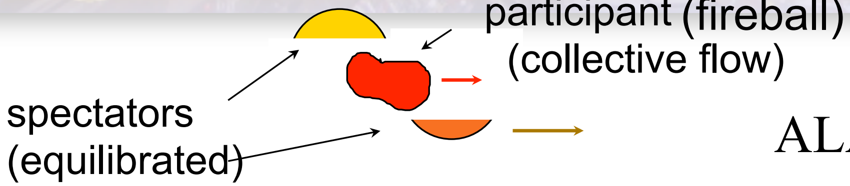


A. Schüttauf et al. / Nuclear Physics A 607 (1996) 457–486

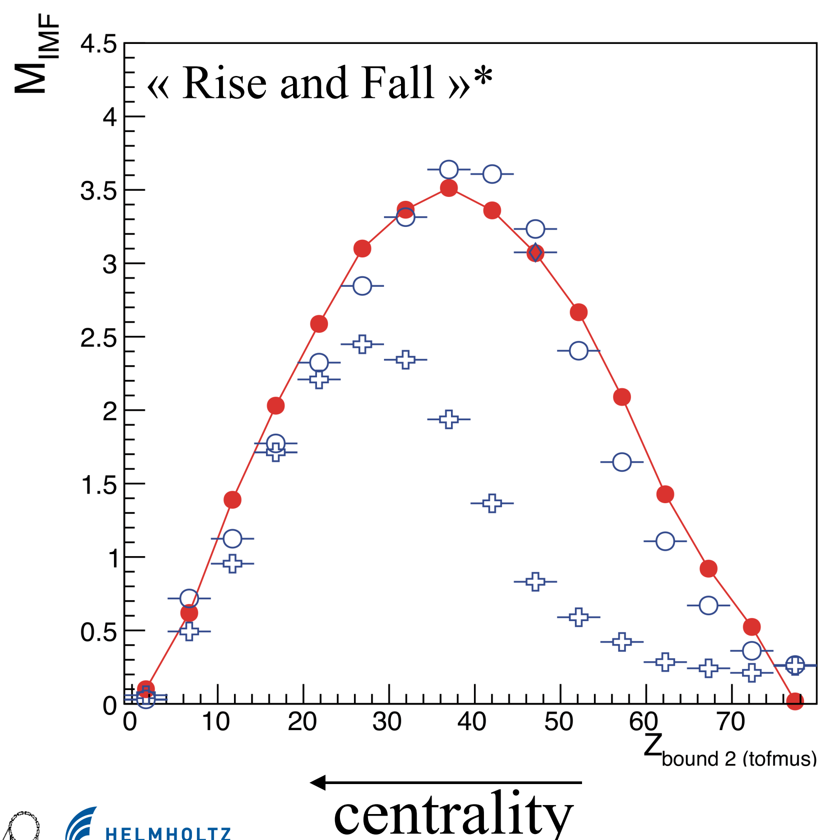


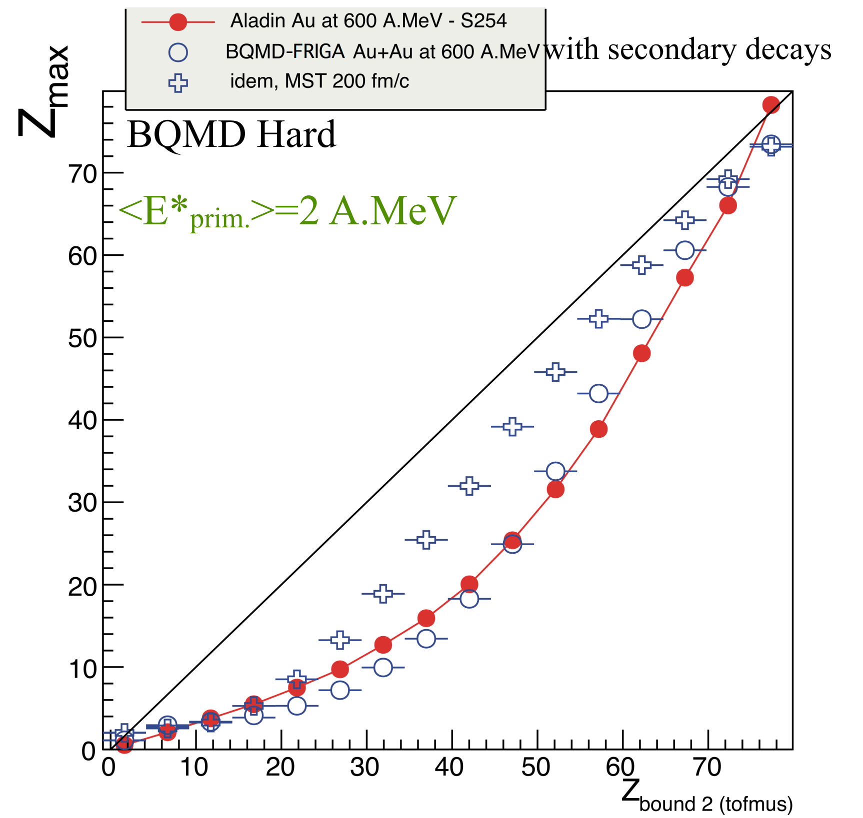


Some successful applications in the spectator regime

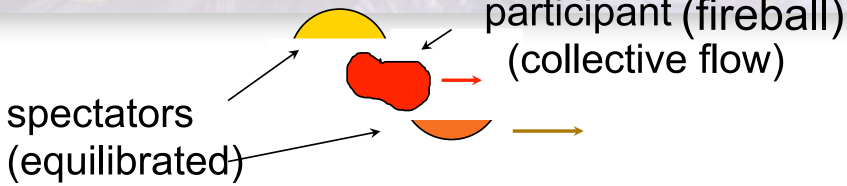


ALADiN Au+Au @ 600 A.MeV (S254 exp., 2003)





Another world: the fireball regime



Central

Au+Au:

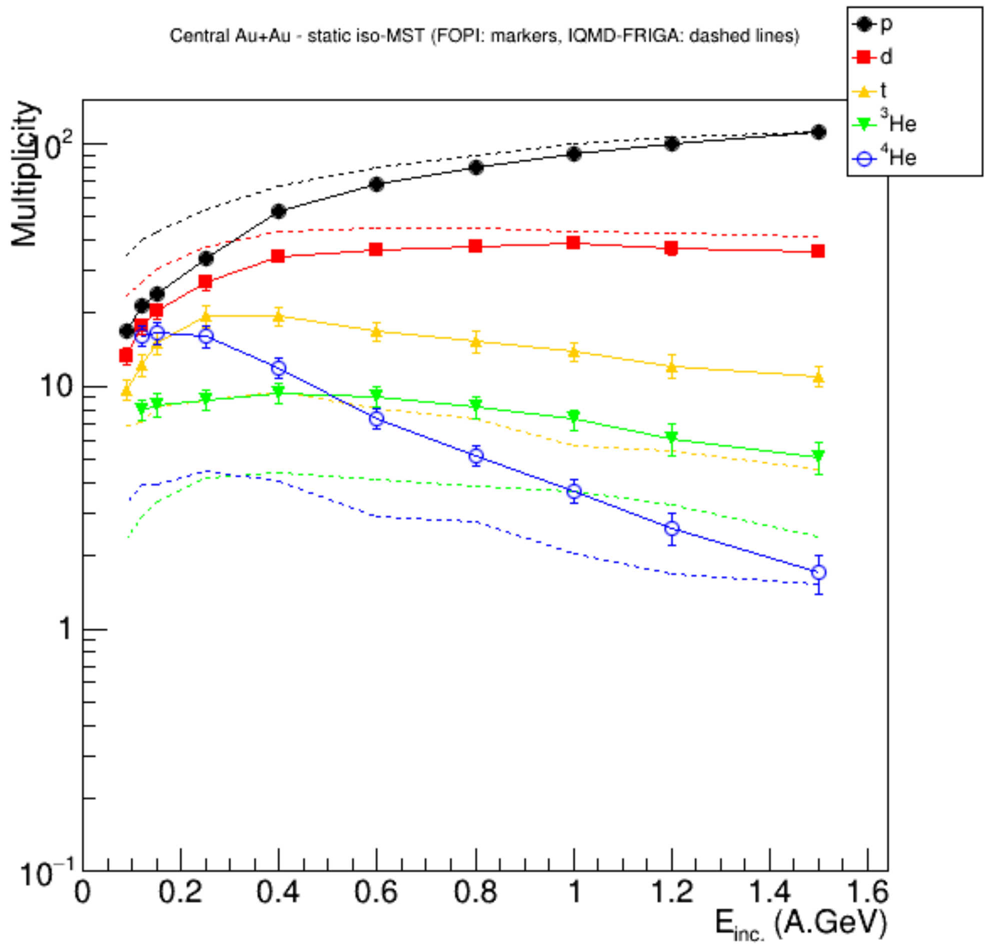
IQMD-FRIGA (dashed lines)

vs

FOPI data (markers)*

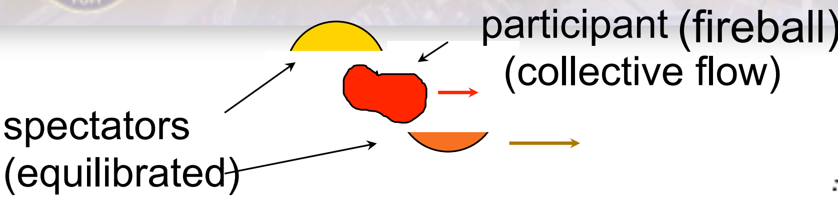
MST

(200 fm/c)



*: *W. Reisdorf at al., FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427*

Another world: the fireball regime



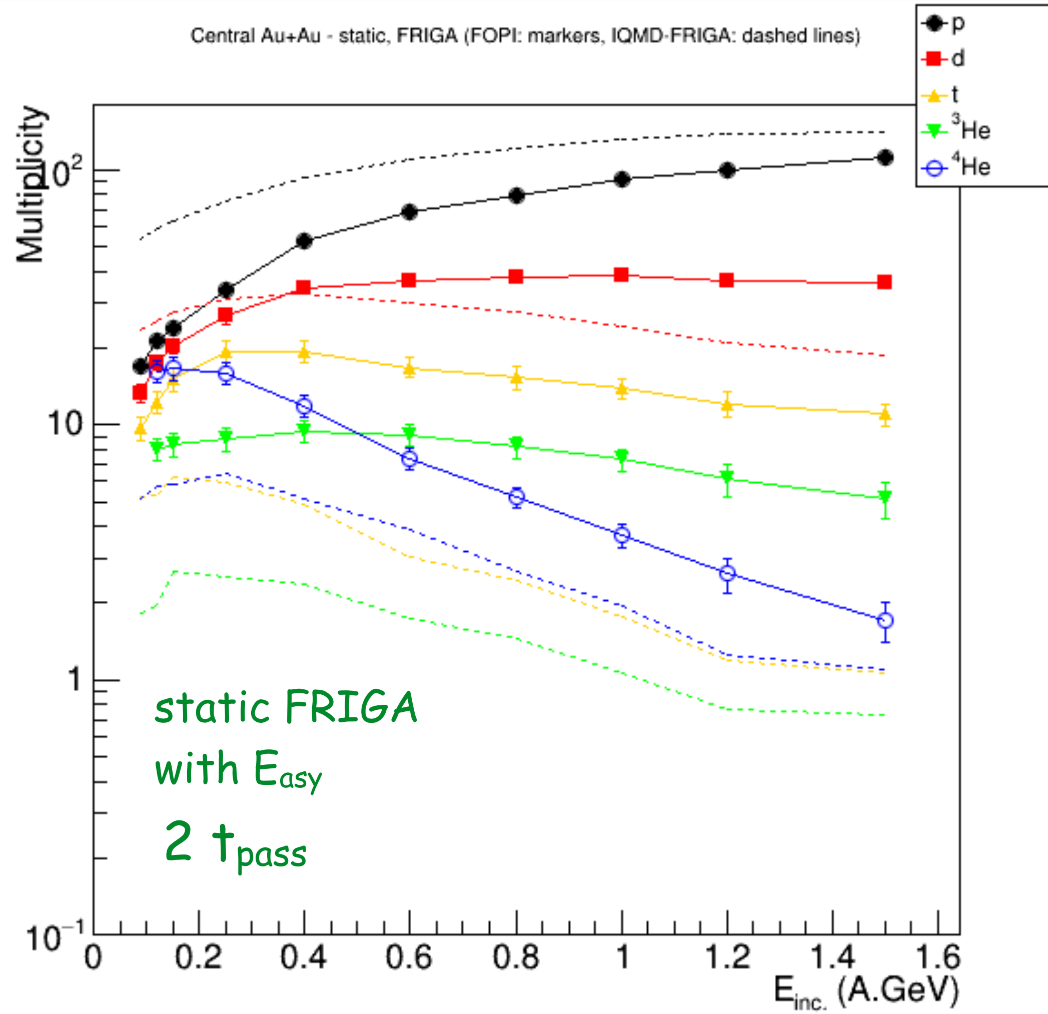
Central

Au+Au:

IQMD-FRIGA (dashed lines)

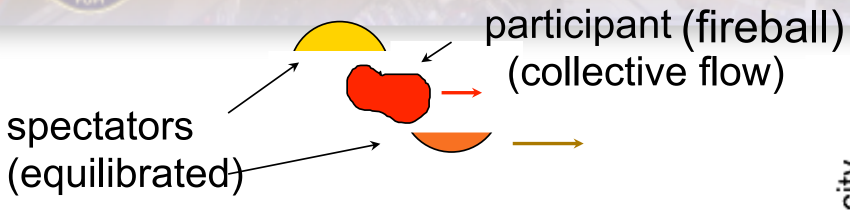
vs

FOPI data (markers)*



*: *W. Reisdorf at al., FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427*

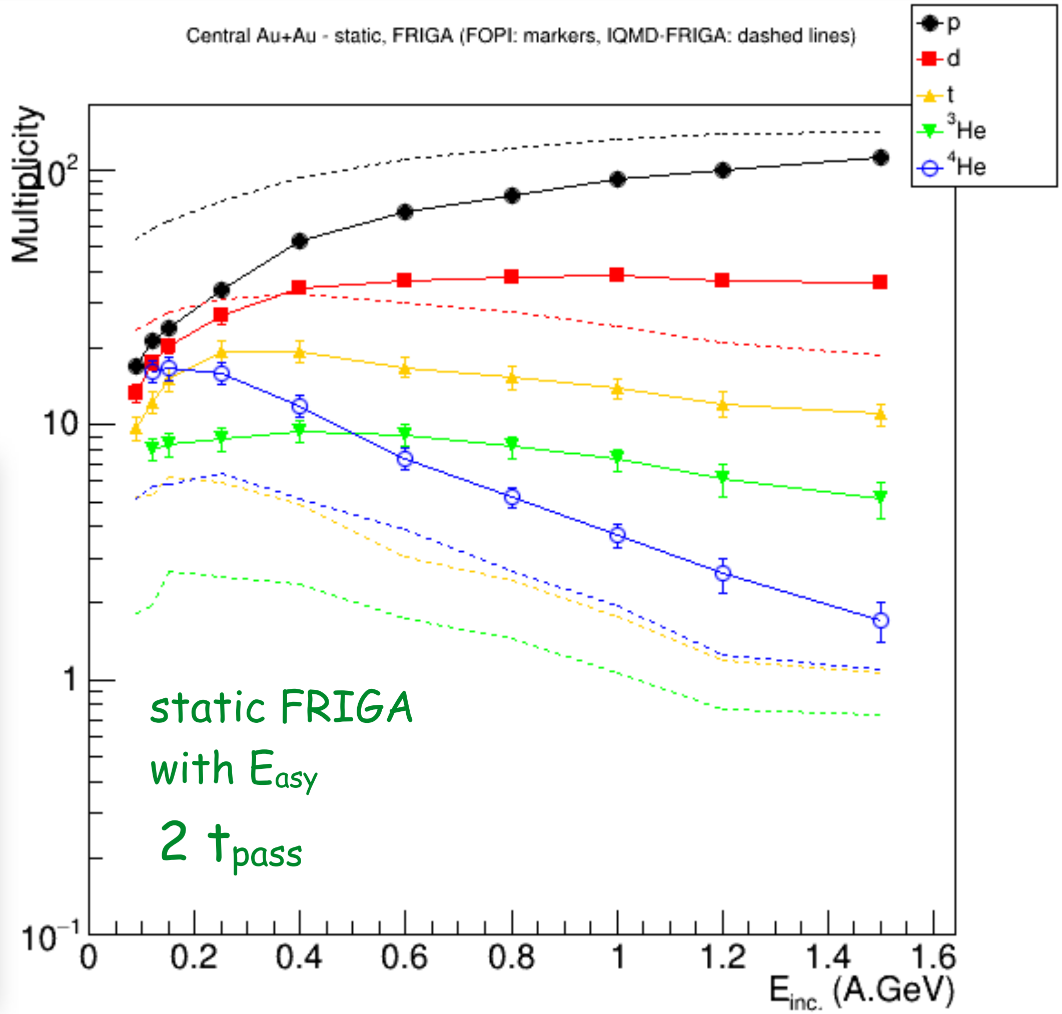
Another world: the fireball regime



Central
Au+Au:
IQMD-FRIGA (dashed lines)
vs
FOPI data (markers)*

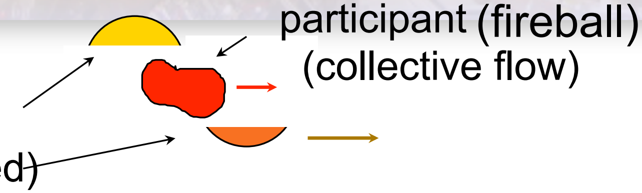
➲ In central collisions, the static/ instantaneous FRIGA strategy (including asymmetry and structure binding energies) does not provides accurate light isotope yields at large incident energies.

➲ Reversely, the static MST coalescence approach fails at these lowest energies, and is more reliable so far (but not the final word) at the highest energies.



*: W. Reisdorf at al., FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427

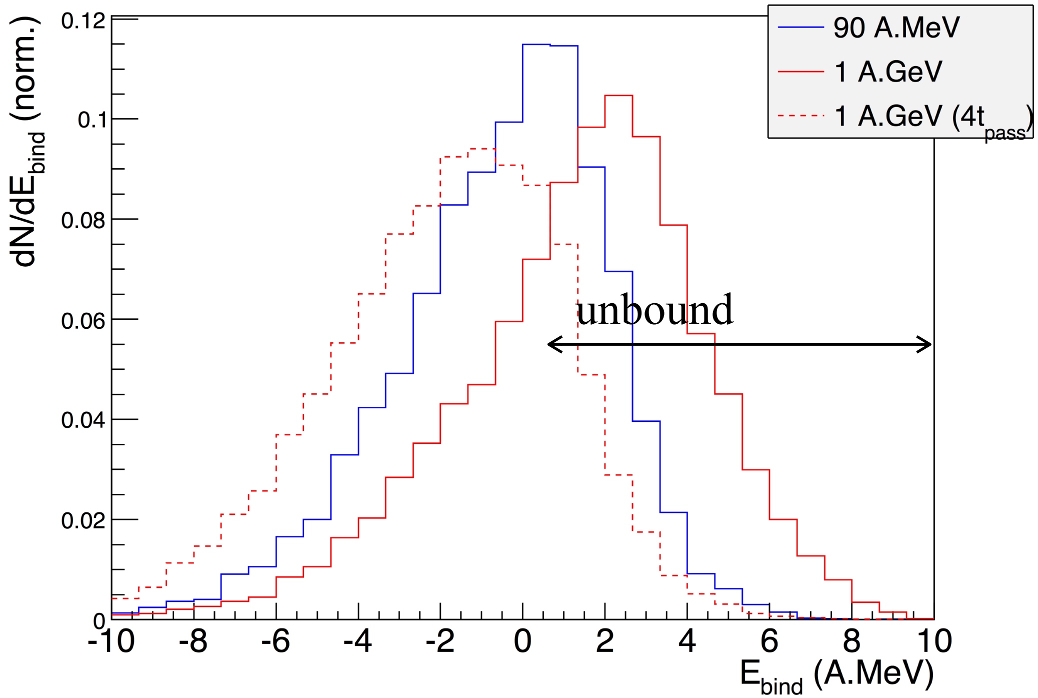
Still to be worked on: the fireball regime



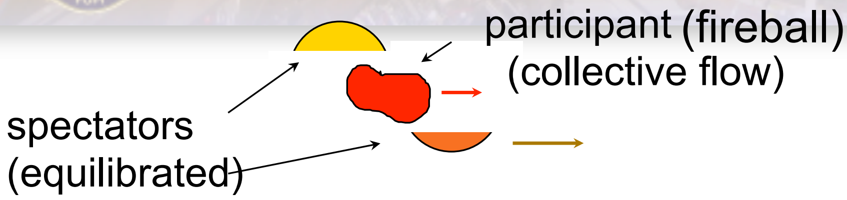
Central
Au+Au:
IQMD-FRIGA

B_{asy} on
B_{struct} on

Binding energy of early (2 t_{pass}) tritons from coalescence (MST)



Still to be worked on: the fireball regime



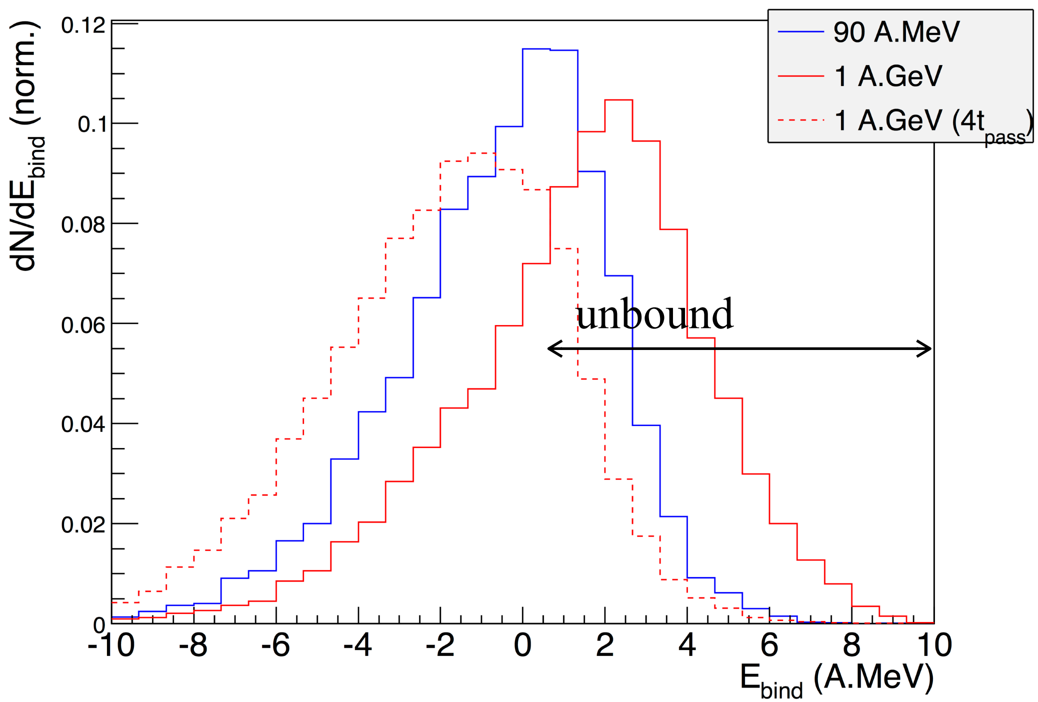
Central
Au+Au:
IQMD-FRIGA

In the contrary of the rather cool central source of intermediate energies (and spectator),

in the hot fireball, early pre-fragments are mostly hot and unbound.

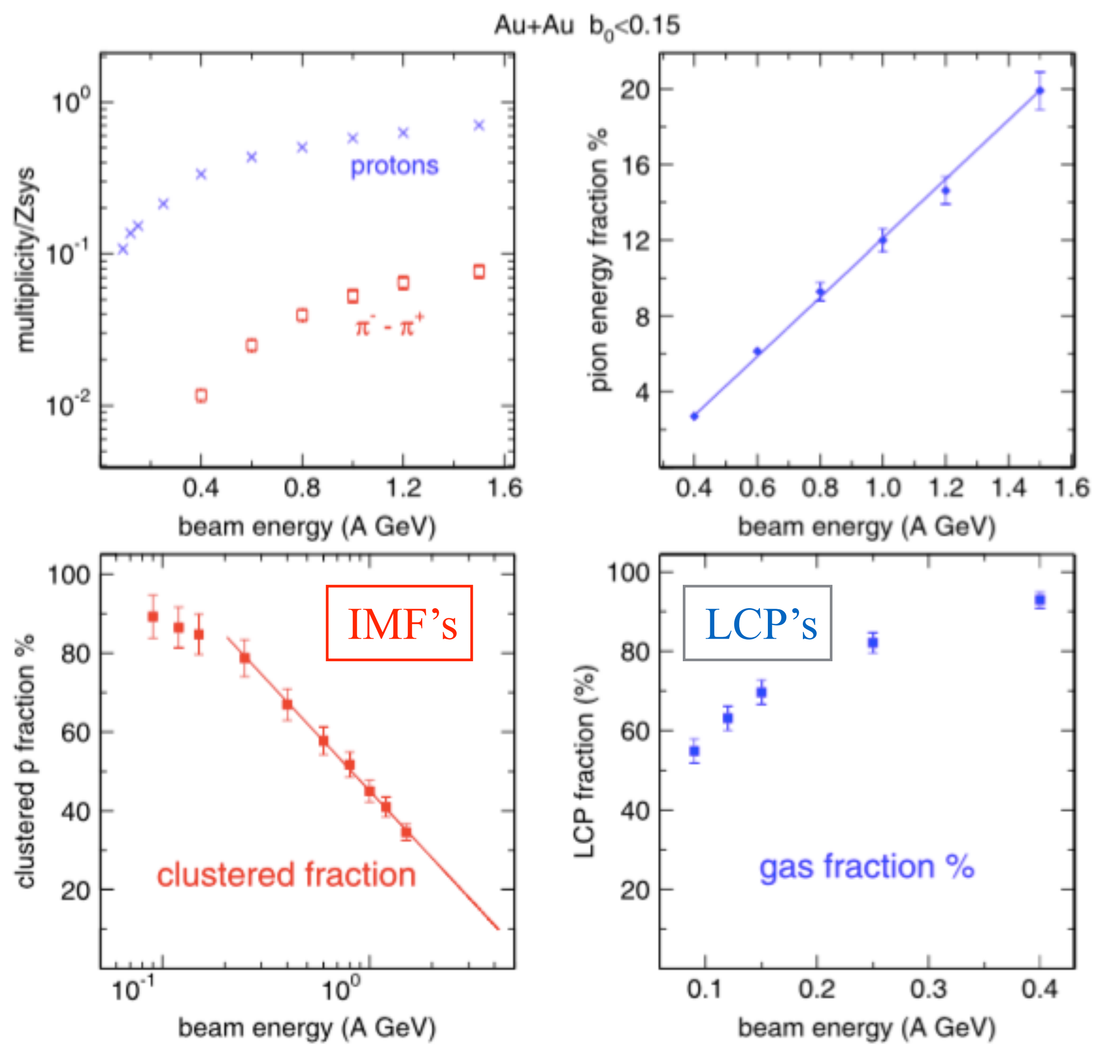
➲ Invalidity of FRIGA as an early « afterburner » in the fireball regime. Better alternative: follow the process of cluster formation up to a relatively longer time.

Binding energy of early (2 t_{pass}) tritons from coalescence (MST)



The fireball regime: a high degree of clusterisation

FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427



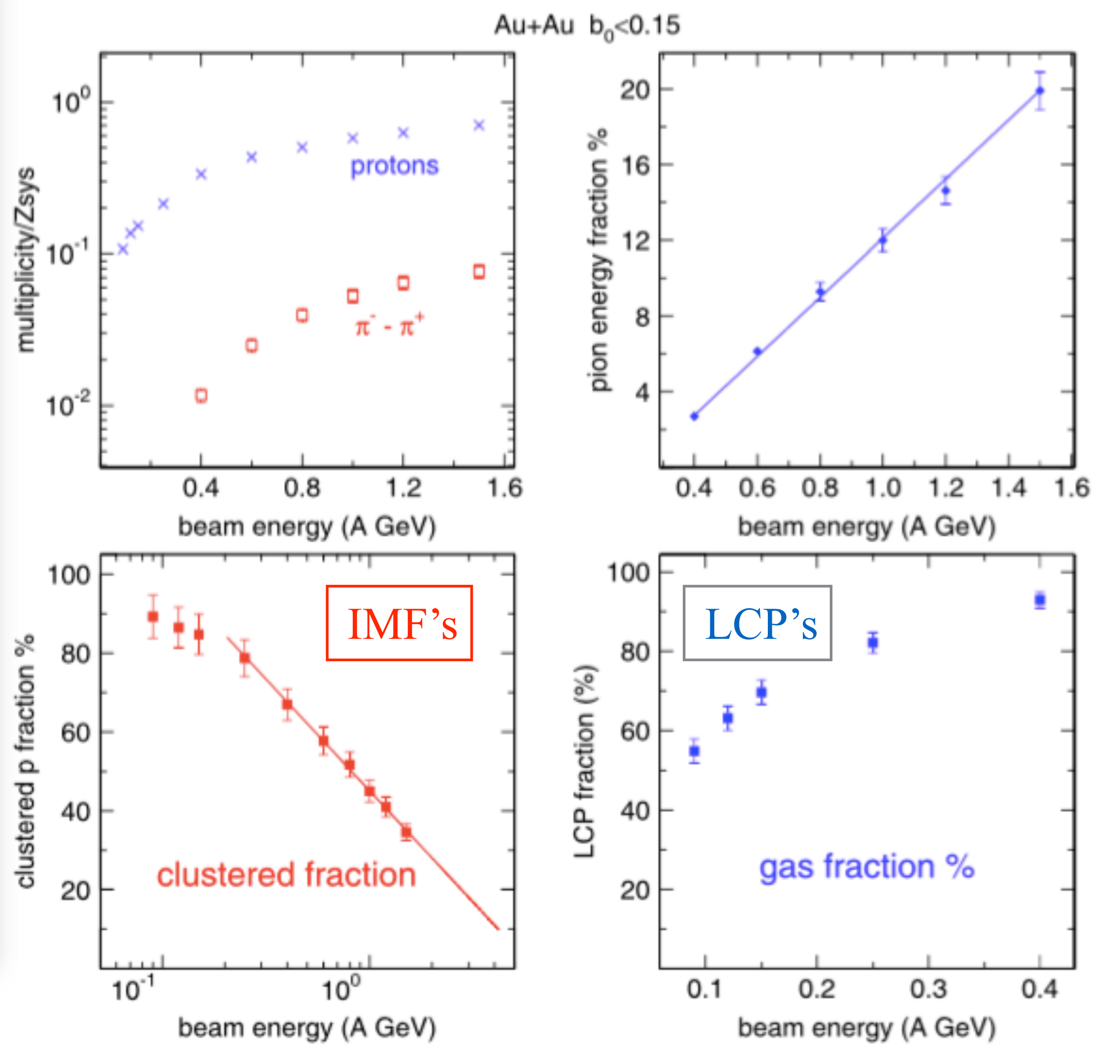
The fireball regime: a high degree of clusterisation

Extrapolation -> clustered fraction >10% up to 4A GeV. Persistence of a significant probability to clusterize at freeze-out up to an available energy per nucleon more than two orders of magnitude higher than typical nucleonic binding energies

➲ Signal of local cooling accompanying the fireball expansion

➲ Strong constraint on the associated entropy.

FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427



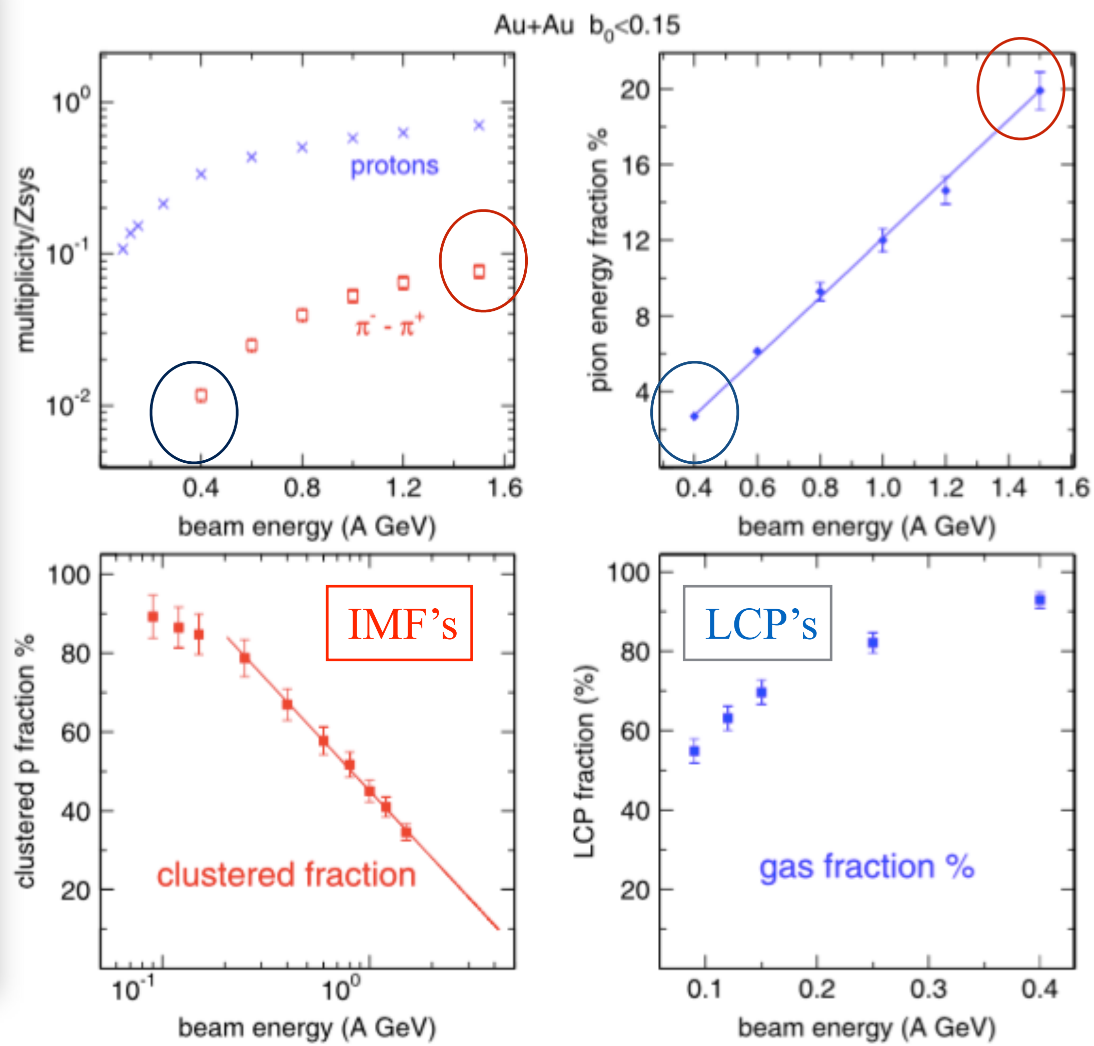
The fireball regime: a high degree of clusterisation

Pions in a large system:

At low energy: perturbative, low incidence on the dynamics and available N/Z.

At high energy: non-perturbative, modify the available N/Z (1.49->1.26 : 8 protons converted into neutrons), and modify the dynamics (carry 20% of the total energy)

FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427



The fireball regime: a high degree of clusterisation

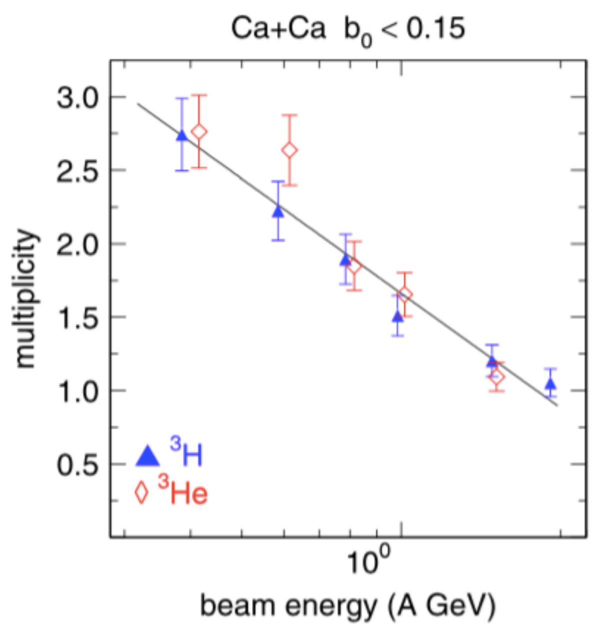


Fig. 42. ^{3}He and ^{3}H multiplicities in central ^{40}Ca + ^{40}Ca collisions as function of the incident beam energy. The straight line is a common fit linearly decreasing with the logarithm of the energy.

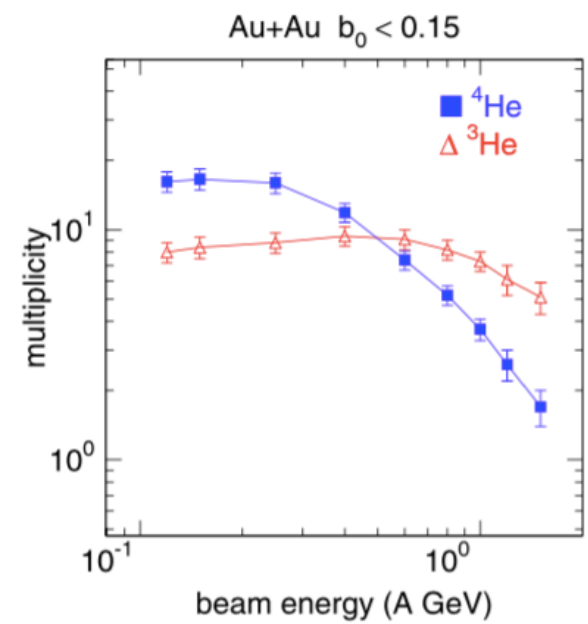


Fig. 43. ^{3}He and ^{4}He multiplicities in central Au + Au collisions as function of the incident beam energy. The 'crossing' energy is 0.5*A* GeV.

The fireball regime: a high degree of clusterisation

Small symmetric system:

➲ The available N/Z for cluster stay unchanged up to high energies.

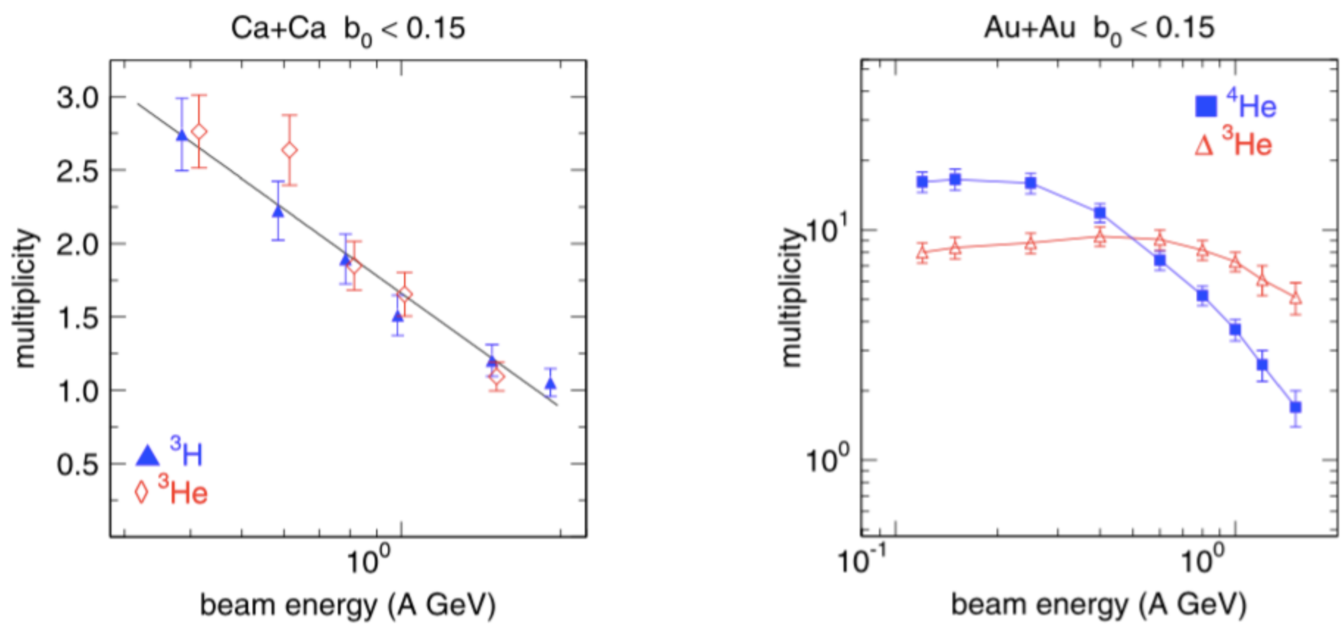


Fig. 42. ^{3}He and ^{3}H multiplicities in central ^{40}Ca + ^{40}Ca collisions as function of the incident beam energy. The straight line is a common fit linearly decreasing with the logarithm of the energy.

Fig. 43. ^{3}He and ^{4}He multiplicities in central Au + Au collisions as function of the incident beam energy. The 'crossing' energy is 0.5*A* GeV.

The fireball regime: a high degree of clusterisation

Small symmetric system:

➲ The available N/Z for cluster stay unchanged up to high energies.

412 FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427

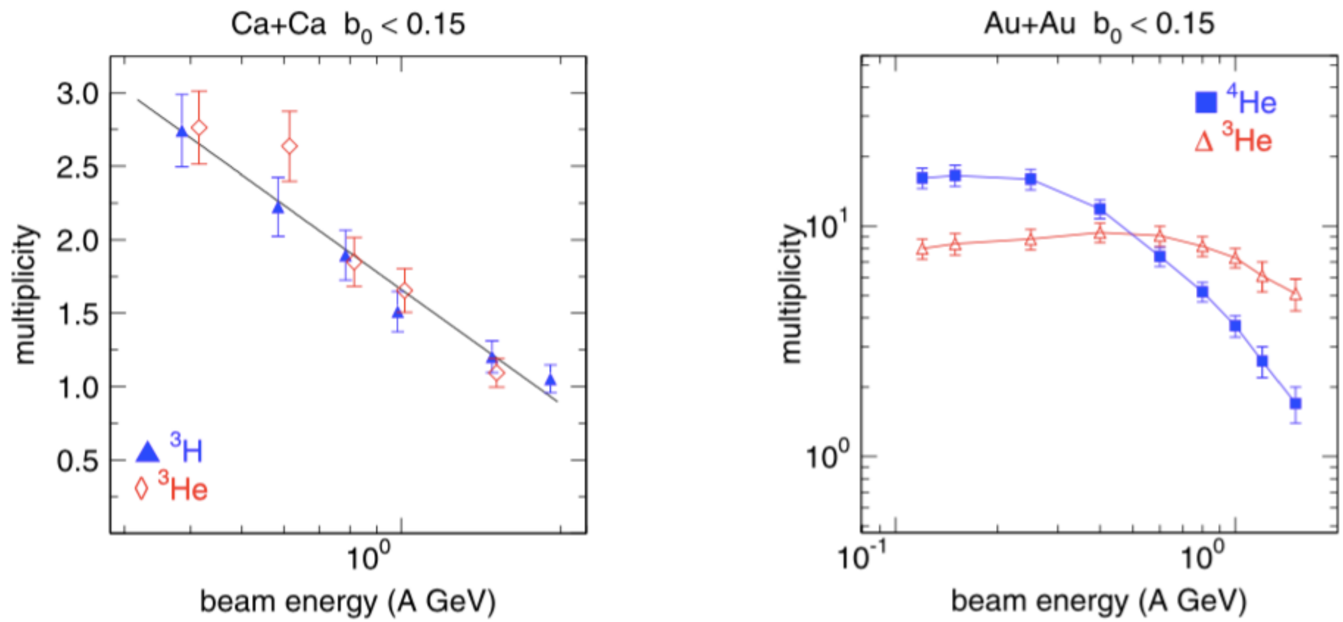


Fig. 42. ^{3}He and ^{3}H multiplicities in central ^{40}Ca + ^{40}Ca collisions as function of the incident beam energy. The straight line is a common fit linearly decreasing with the logarithm of the energy.

Fig. 43. ^{3}He and ^{4}He multiplicities in central Au + Au collisions as function of the incident beam energy. The 'crossing' energy is 0.5*A* GeV.

A simple perturbative coalescence model cannot explain this behavior.

GSI HELMHOLTZ ASSOCIATION

The fireball regime: droplet formation?

FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427 417

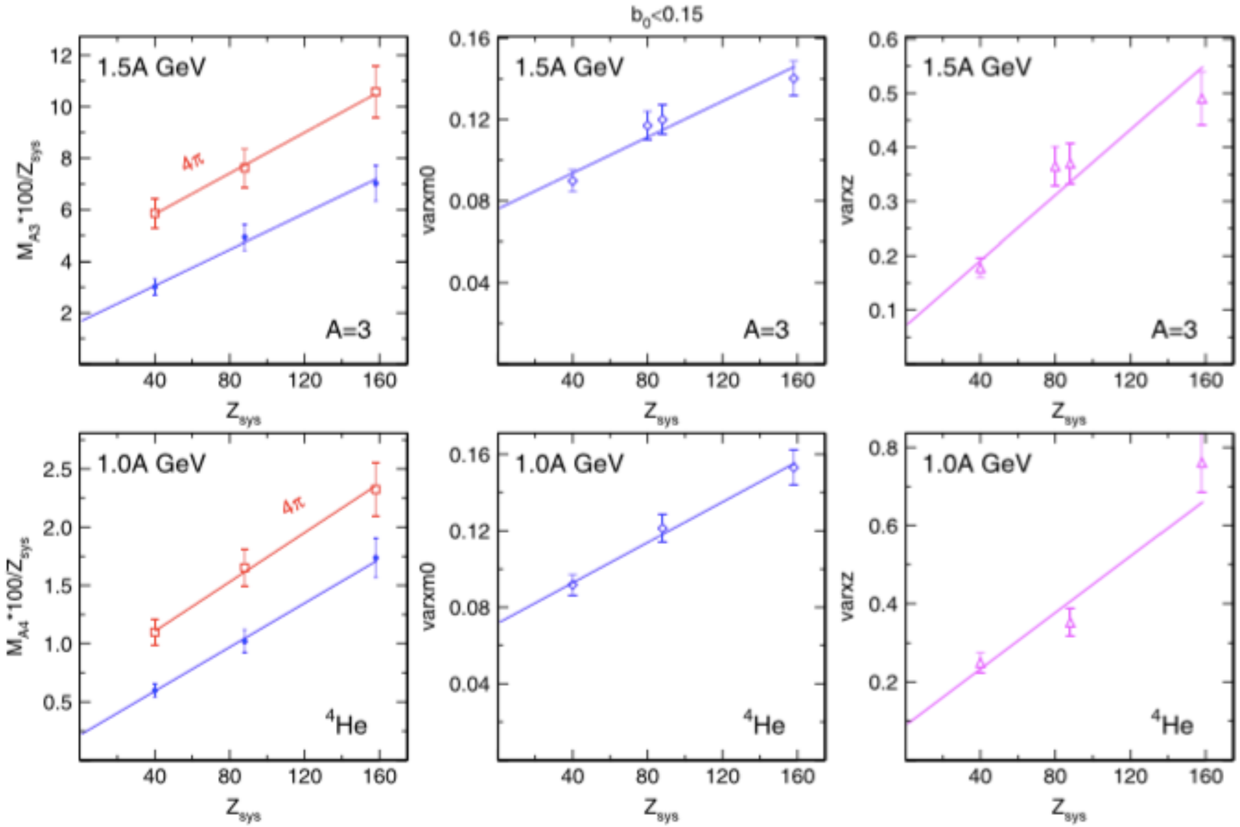


Fig. 48. System size dependences of symmetric central collisions at incident beam energies of 1.0*A* GeV (lower panels, ^{4}He fragments) and 1.5*A* GeV (upper panels, average of ^{3}He and ^{3}H fragments). All straight lines are linear fits. Left panels: multiplicities (reduced to 100 protons). The data marked 4π with open square symbols are 4π integrated, while the closed symbols represent midrapidity yields (constrained to $|y_{z0}| < 0.5$). Middle panels: variance *varxm0* of the scaled constrained transverse rapidity distributions (dn/dy_{xm0}). Right panels: stopping *varxz*.

The fireball regime: droplet formation?

An interpretation:

Increased stopping (right panels) <-> increased compression.

Increasing constrained transverse rapidity variances varxm0 (middle panels) <-> increasing radial flow developed thereafter in the expansion phase coupled to increased cooling

('droplet formation')

FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427 417

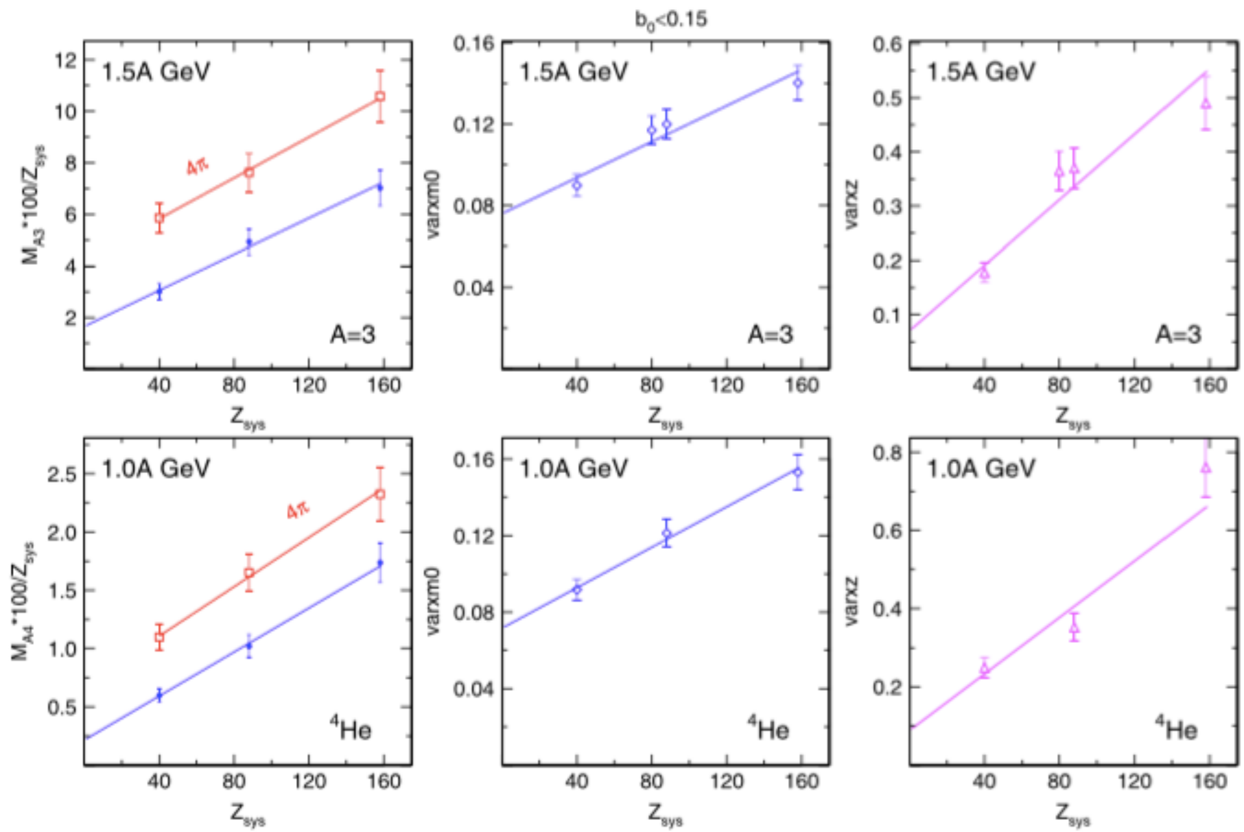


Fig. 48. System size dependences of symmetric central collisions at incident beam energies of 1.0*A* GeV (lower panels, ^{4}He fragments) and 1.5*A* GeV (upper panels, average of ^{3}He and ^{3}H fragments). All straight lines are linear fits. Left panels: multiplicities (reduced to 100 protons). The data marked 4π with open square symbols are 4π integrated, while the closed symbols represent midrapidity yields (constrained to $|y_{z0}| < 0.5$). Middle panels: variance *varxm0* of the scaled constrained transverse rapidity distributions (dn/dy_{xm0}). Right panels: stopping *varxz*.

A new non-static approach: « sequential » FRIGA

- **Start from a first time step of the collision (typically when the 2 nuclei start to collide):**

Pre-detect a partition of clusters with FRIGA/MST

- **At each subsequent time step of the collision (typically every fm/c):**

1) Let survive clusters of the previous time step that have not suffered from any collision and that have not been approached (at coalescence proximity) by an external hadron in the meanwhile.
2) Otherwise set all its constituents as free
3) Process with MST/FRIGA free hadrons only.

- **Follow the process until the cluster partition has stabilised**

A new non-static approach: « sequential » FRIGA

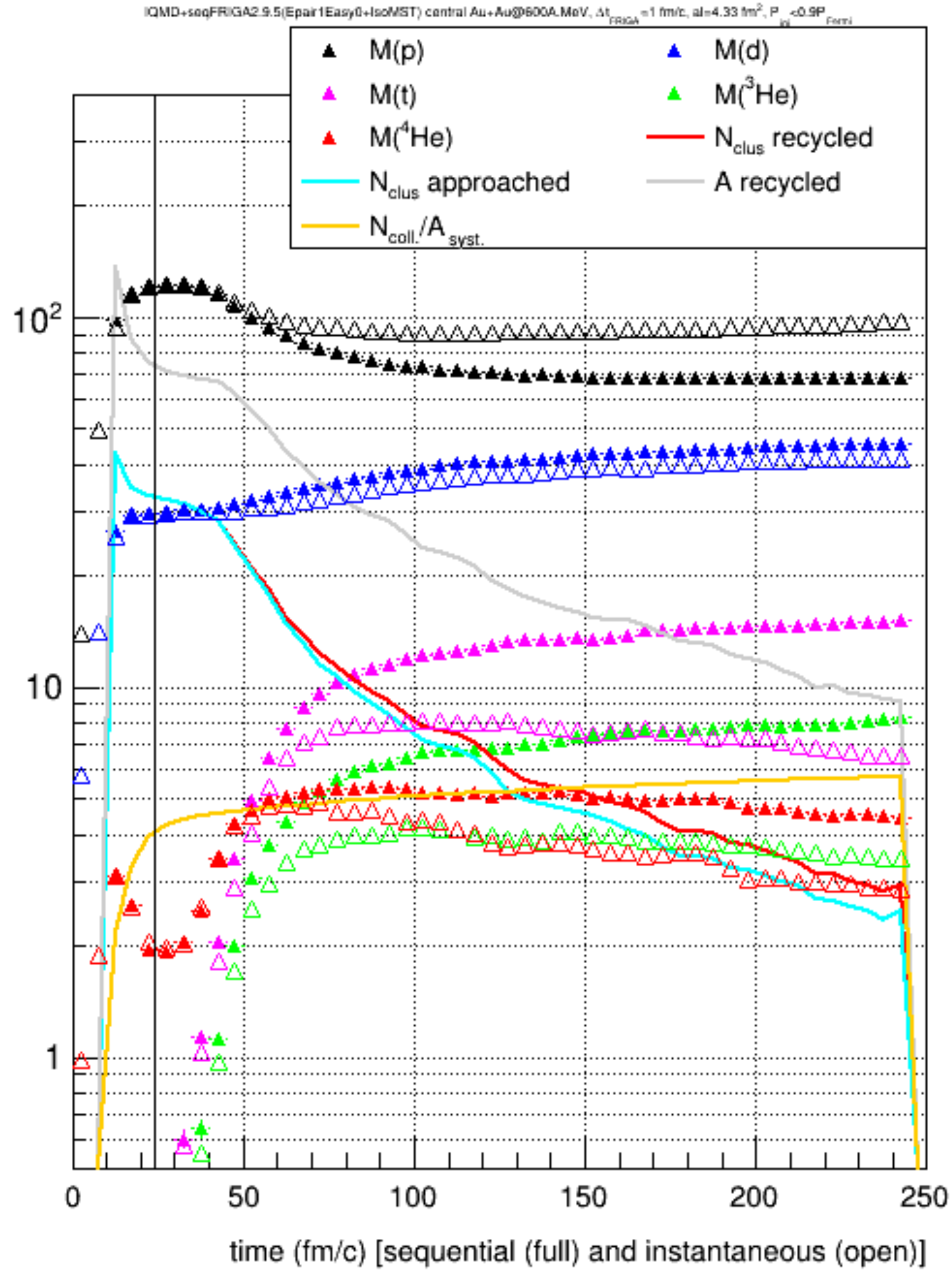
Central

IQMD Au+Au 600A MeV:

sequential FRIGA

versus

static FRIGA



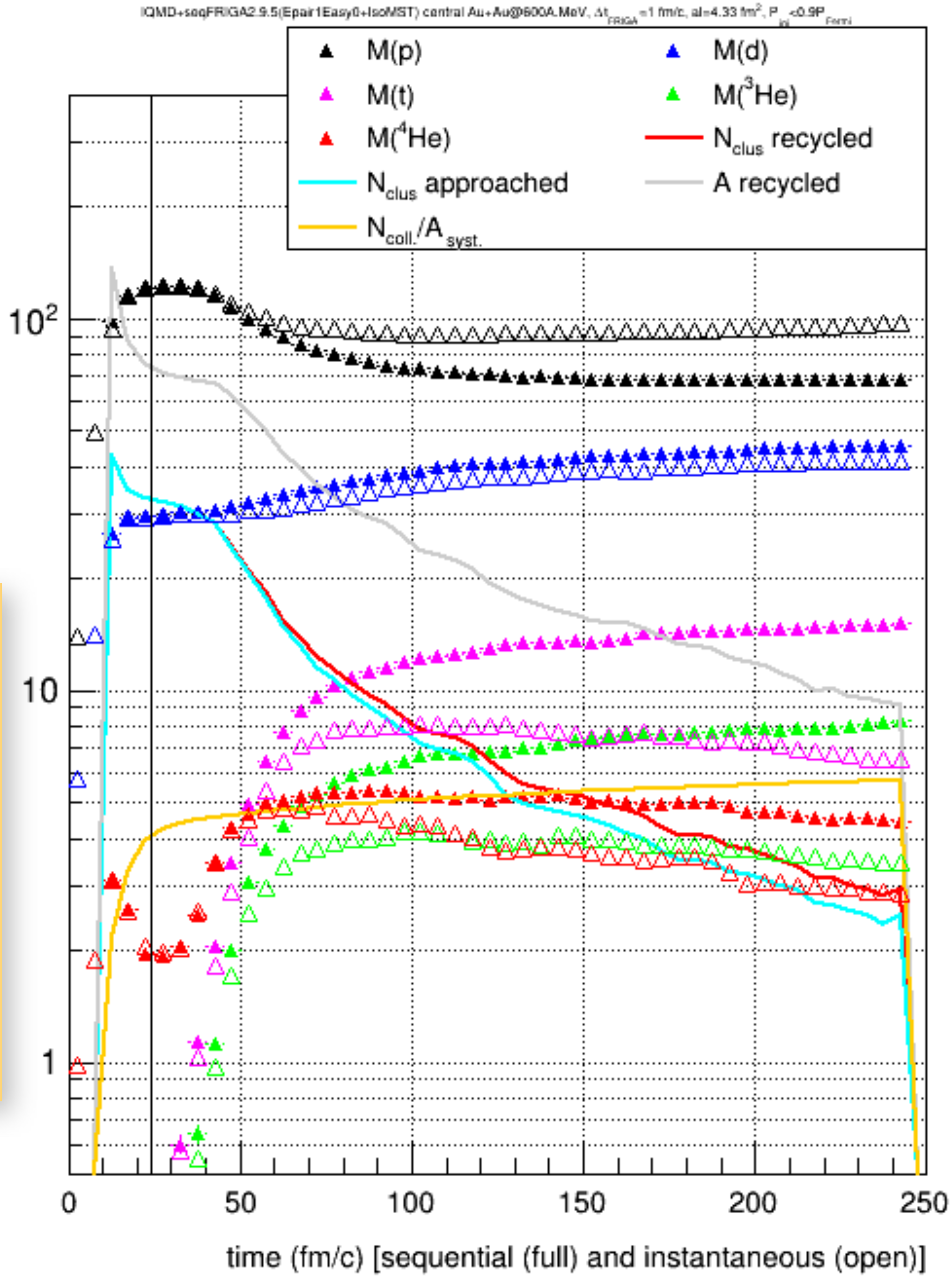
*: W. Reisdorf at al., FOPI

A new non-static approach: « sequential » FRIGA

Central
IQMD Au+Au 600A MeV:
sequential FRIGA
versus
static FRIGA

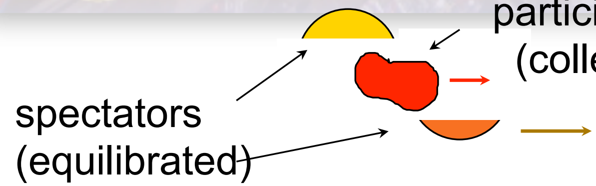
➲ Sequential strategy: light cluster yields grow over <u>a long period of time</u>, during the expansion of the fireball

➲ Reversely, with the <u>static</u> approach, the yields saturate earlier, at lower values.



*: W. Reisdorf at al., FOPI

A new non-static approach: « sequential » FRIGA



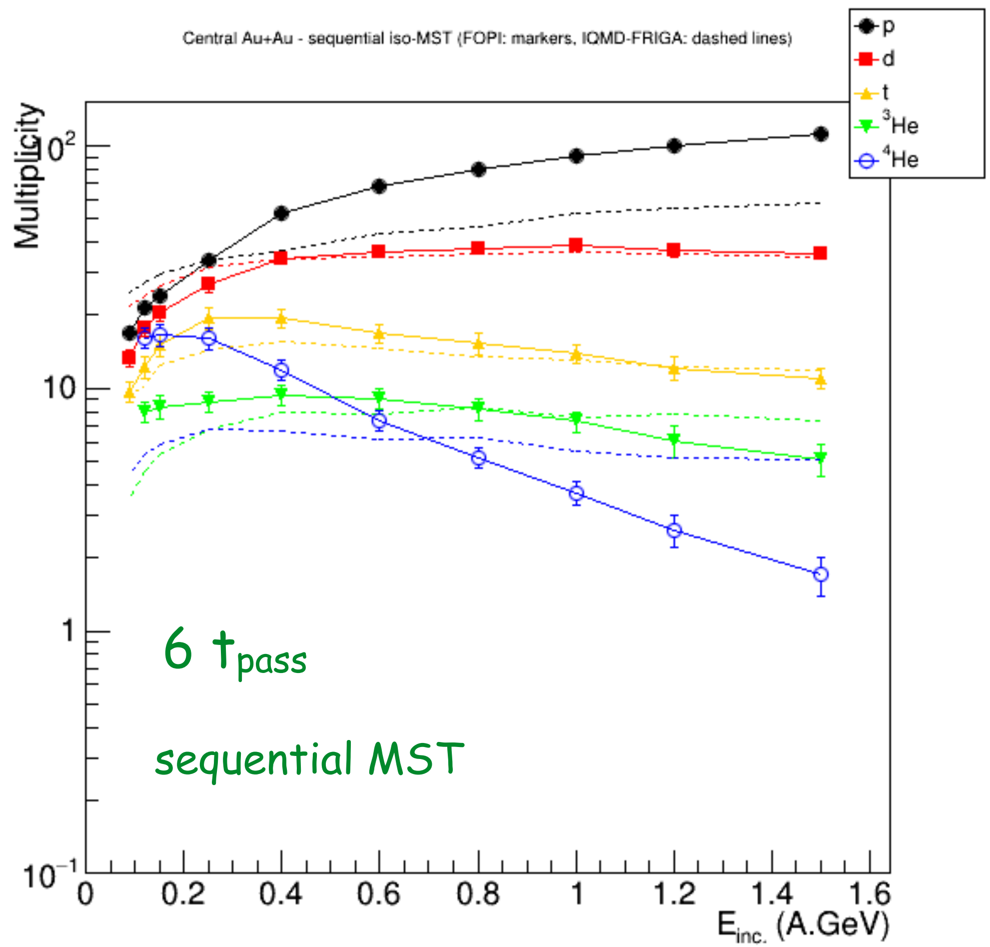
Central

Au+Au:

IQMD-FRIGA (dashed lines)

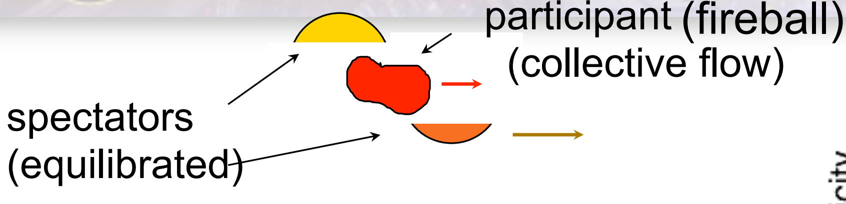
vs

FOPI data (markers)*

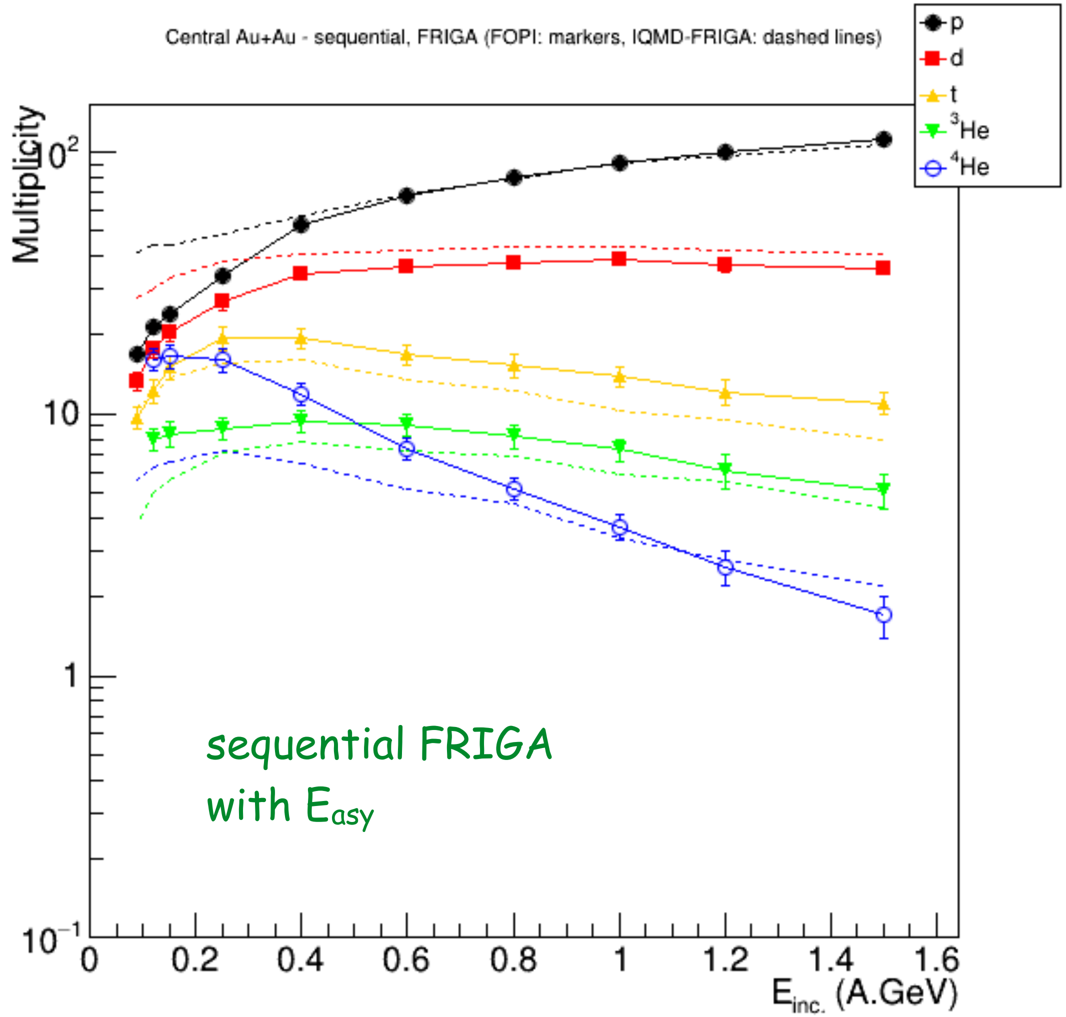


*: *W. Reisdorf at al., FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427*

A new non-static approach: « sequential » FRIGA

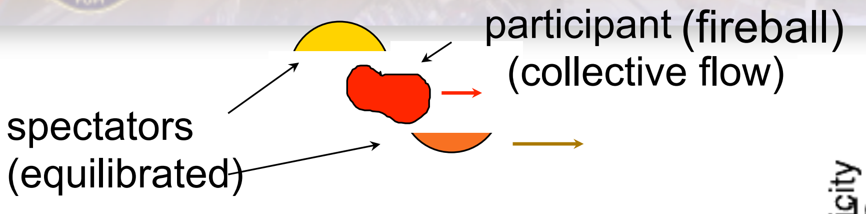


Central
Au+Au:
IQMD-FRIGA (dashed lines)
vs
FOPI data (markers)*



*: *W. Reisdorf at al., FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427*

A new non-static approach: « sequential » FRIGA



Central

Au+Au:

IQMD-FRIGA (dashed lines)

vs

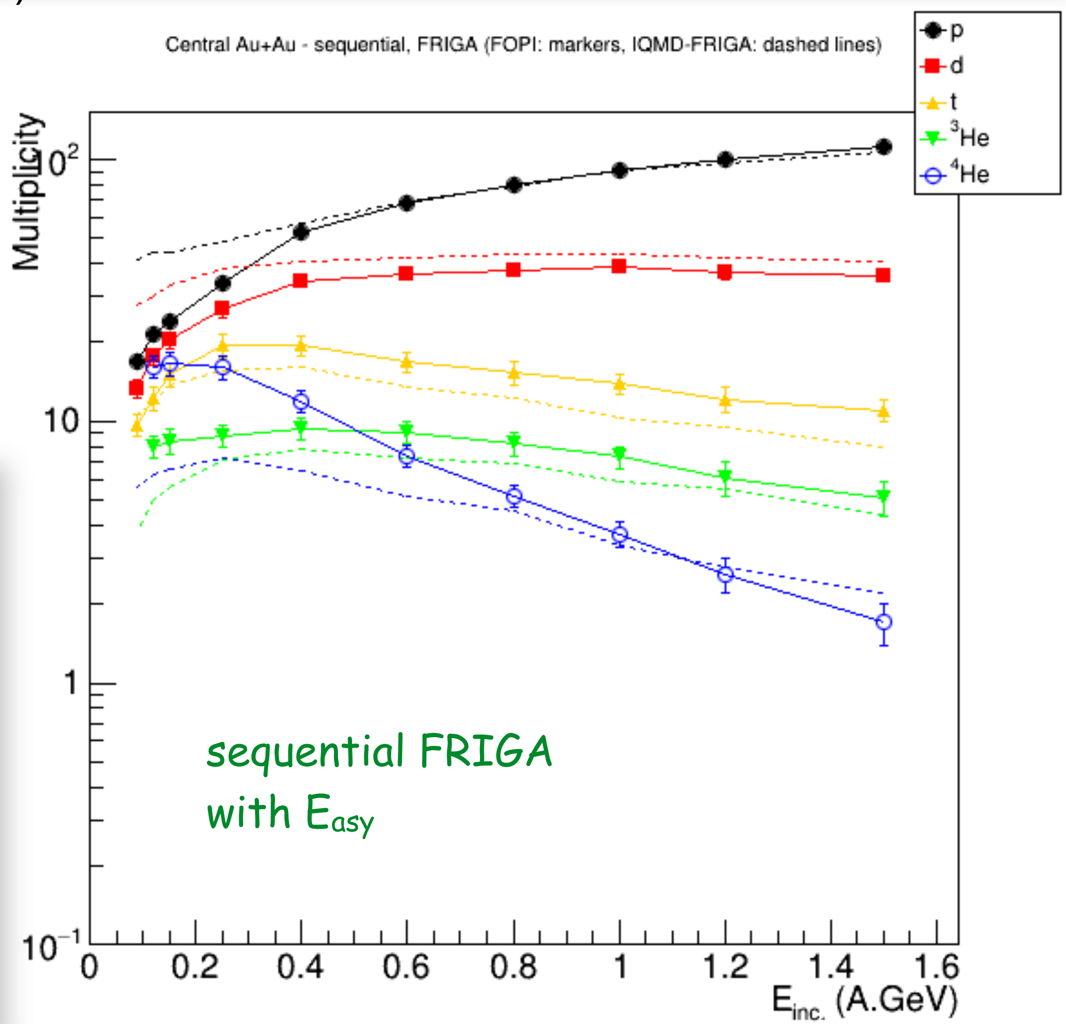
FOPI data (markers)*

➲ Sequential strategy: exhibit light cluster yields in much better agreement with experimental data

➲ The FRIGA approach remains better than the simple coalescence method.

➲ Still discrepancies at the lowest incident energies: d yields too large, 4He yields too small.

➲ Extra coalescence channels with unusually large cross-sections to implement: d+d->4He, n+3He->4He



*: W. Reisdorf at al., FOPI Collaboration / Nuclear Physics A 848 (2010) 366–427

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.

❖ The secondary decays and structure effects should not be neglected.

❖ Whereas the early clustering with FRIGA gives good results in the spectator / intermediate energy regime, the fireball regime needs a relatively longer time to pre-form clusters (droplets?).

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.

❖ The secondary decays and structure effects should not be neglected.

❖ Whereas the early clustering with FRIGA gives good results in the spectator / intermediate energy regime, the fireball regime needs a relatively longer time to pre-form clusters (droplets?).

New developments:

❖ Sequential/Hot clustering: allow clustering to be done all along the expansion phase coupled to increased cooling.

❖ Promising description of light cluster yields in the fireball regime at SIS energies.

❖ Still some refinements to implement

- ❖ regarding alpha particles
- ❖ so far, or clusters do not interact as state of their own with the rest of the system during the dynamical development; necessary?

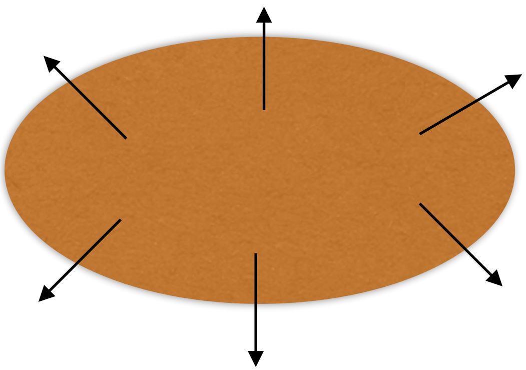
❖ For doing this: compulsory in transport models: a stable nuclear matter + enough fluctuations.

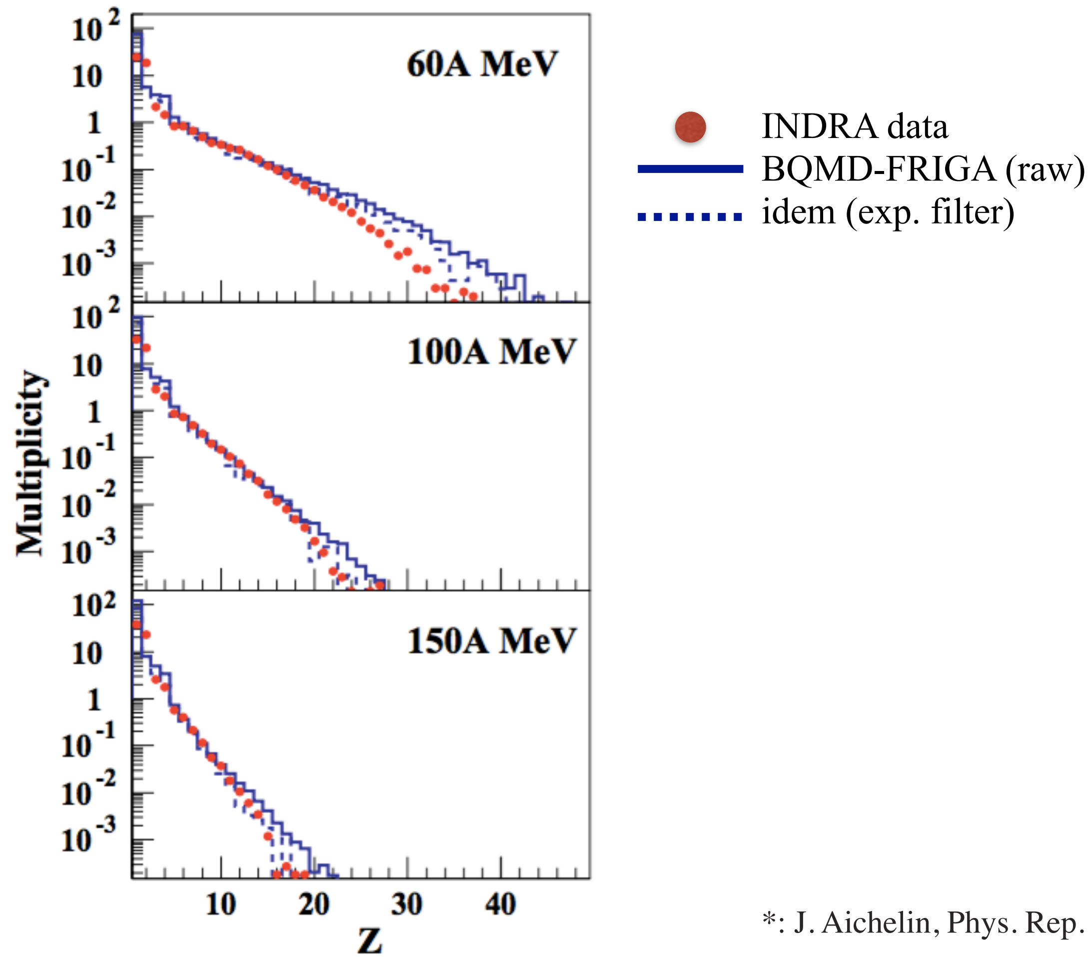
❖ The fragment formation in the fireball at SIS energies (overclustering) = opening a field of understanding of clustering in ultra-relativistic energies.

Some successful applications at intermediate energies

INDRA systems K. Zbiri et al., PHYSICAL REVIEW C **75**, 034612 (2007)

BQMD*+FRIGA
central **Au+Au**
($t = 2\ t_{pass}$)





*: J. Aichelin, Phys. Rep. **202**, 233 (1991).

Some successful applications at intermediate energies

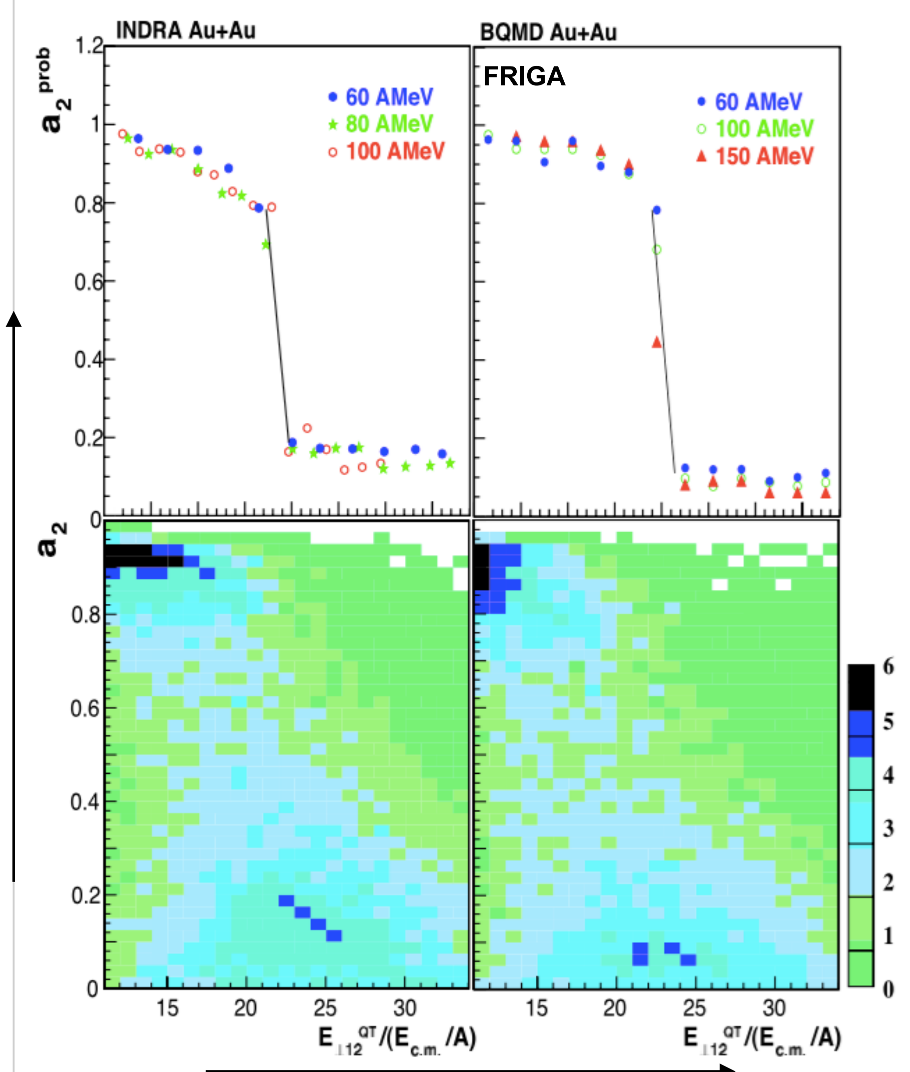
INDRA systems
A. Le Fèvre and J. Aichelin - PRL 100, 042701 (2008)

BQMD*+FRIGA
Au+Au
(t = 2 t_{pass})

=> Bimodality** =
a mechanical instability
(critical phenomenon)

fragment size asymmetry
$a_2 = (Z_1 - Z_2)/(Z_1 + Z_2)$

=> sufficient fluctuations
necessary in transport models



centrality

*: J. Aichelin, Phys. Rep. **202**, 233 (1991).
**: also found in Xe+Sn system in
M. Pichon et al,
INDRA, ALADIN Coll. / Nuclear Physics A 779 (2006) 267–296