Searching for signals of Bose-Einstein condensation in the decay of hot nuclear systems

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Cluster formation at low densities

Heavy Ion Collisions ⟶ access extreme (T, ρ) of nuclear system

(Very) low ρ :

- Correlations are expected to become important ⟶ non-homogeneous nuclear matter
↓
fragmentation

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↓
fragmentation

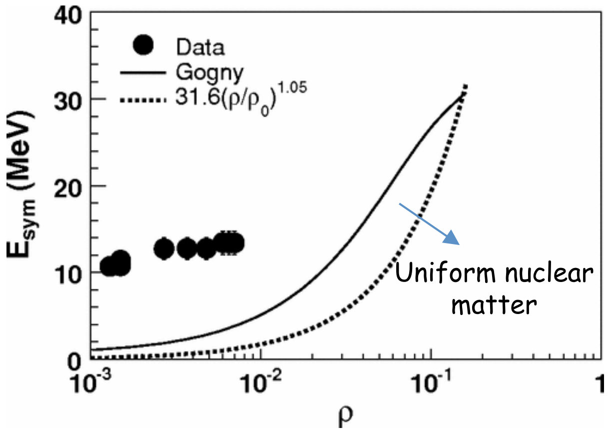
- Even lower ρ : few body - correlations remain important
(system minimizes its E by forming light clusters)

↓

Clusters formation

Correlations
In-medium modification of cluster properties
Mean-field effects

C. Horowitz et al., Nucl. Phys. A 776 (2006) 55
E. O'Connor et al., PRC 75 (2007) 055803
S. Typel et al., PRC 81 (2010) 015803
G. Ropke et al., PRC 88 (2013) 024609
....

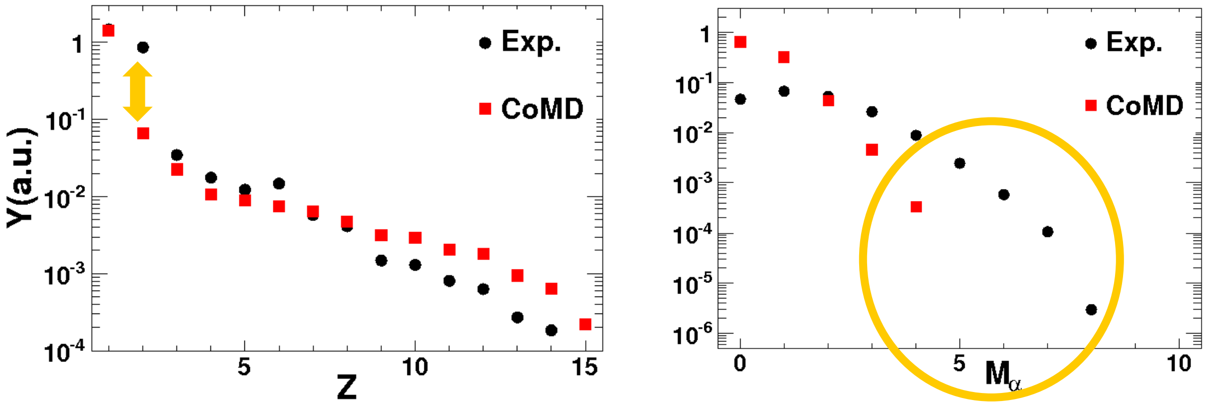


S. Kowalski et al., PRC 75 (2007) 014601

The occurrence of clusters changes E_{sym} because cluster correlations depend on N/Z

Cluster formation at low densities

Cluster formation : α production is underestimated



What is the role of bosons in nuclei (and nuclear matter)?

α-cluster structure of light nuclei (^{12}C Hoyle state) A. Raduta et al., PLB 705 (2011) 65; Manfredi et al., PRC 85 (2012) 037603

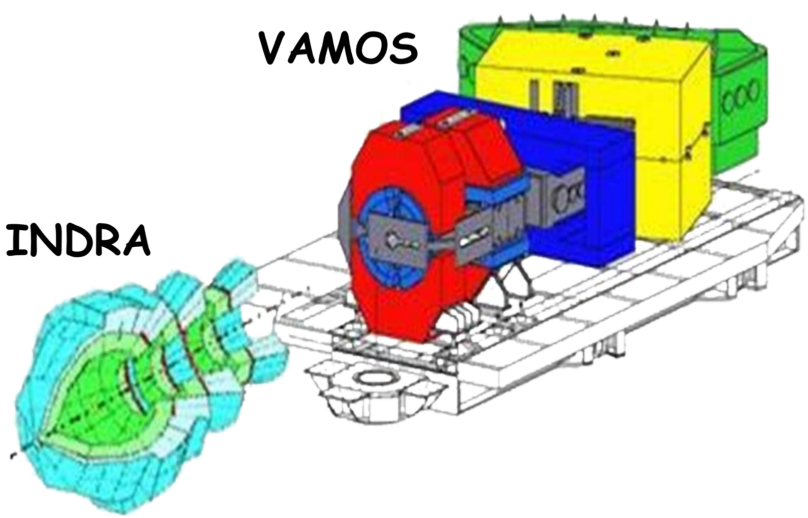
Preformed α particle in nuclei Scarpacci et al., PRC 82 (2010) 031301

Cluster structure of N=Z nuclei M. Freer , Rep. Prog. Phys. 70 (2007) 2149

Do and when bosonic properties dominate over fermionic properties?

The experiment

Goal: Study the isotopic composition of quasi-projectiles (QP) in $^{40,48}Ca+^{40,48}Ca$ @35MeV/A



VAMOS

Large acceptance
High resolution
} Projectile-like fragment - PLF (Z, A, E_k, $\vec{p}$)

INDRA

High granularity
High E resolution
Z (A) identification
} Light Charged Particles - LCP (Z, A, E_k, $\vec{p}$)

⇨ Event-by-event reconstruction of the decaying QP

QP reconstruction :

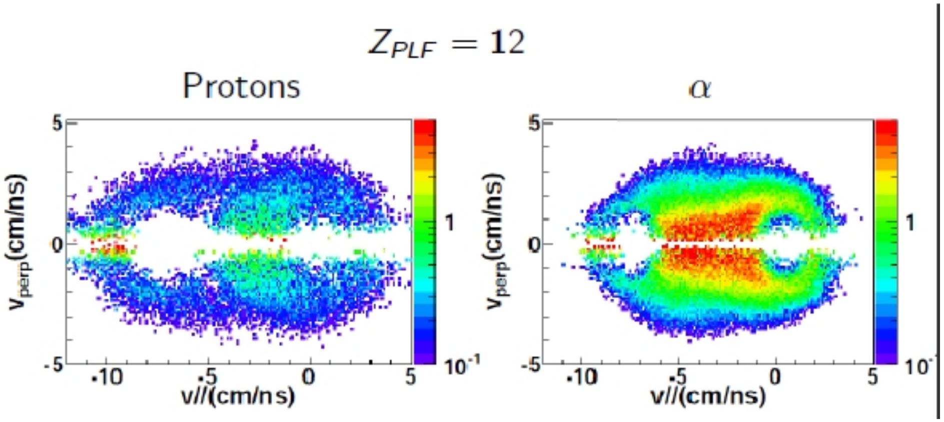
PLF + CP belonging to QP

(based on v/v_{PLF} criteria)

J. Steckmeyer et al., Nucl. Phys. A 686 (2001) 537

→ Z_{QP}, A_{QP}, E_{QP}*

(from calorimetry)



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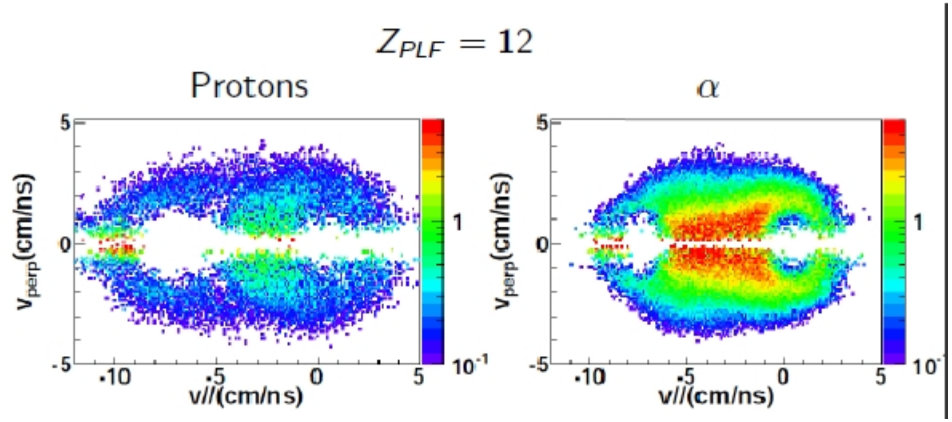


<u>Event selection</u> : $^{34-46}$Ca QP events

<u>Event selection</u> : isotropic emission events

to have a certain degree of equilibration

↓

$$Q_{shape} = \frac{\Sigma (p_z^i)^2}{\Sigma (p_{perp}^i)^2}$$

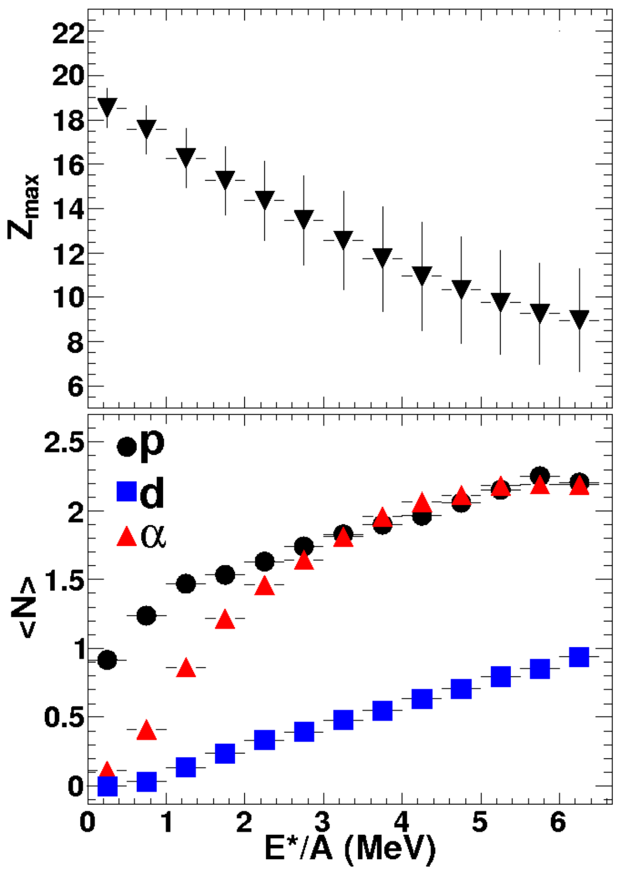
$$-0.3 < \log Q_{shape} < 0.3$$

The influence of these selections was monitored all along the analysis

Event characteristics

Z of the biggest fragment :

Light charged particle multiplicties :



Similar to previous works

E. Bonnet et al., Nucl. Phys. A 816 (2009) 1 and refs therein

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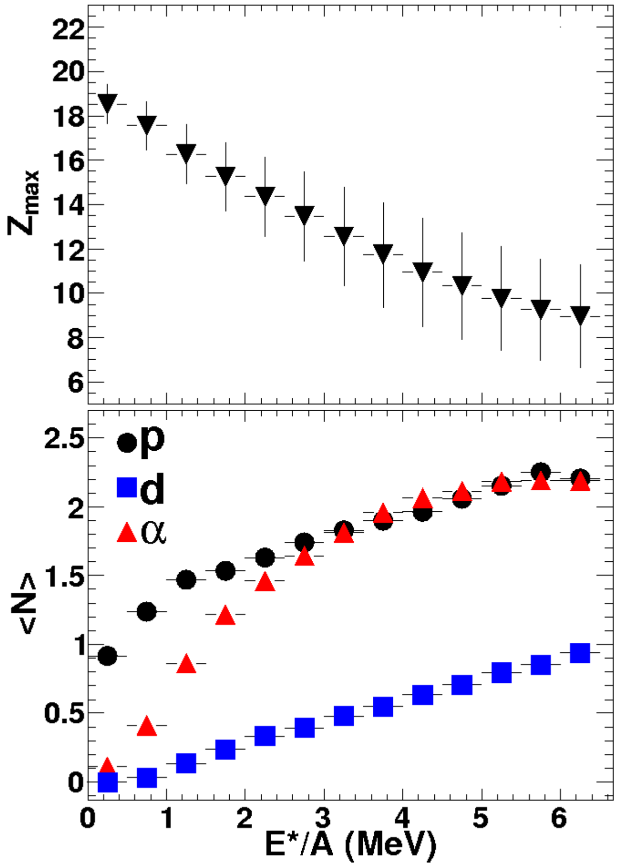
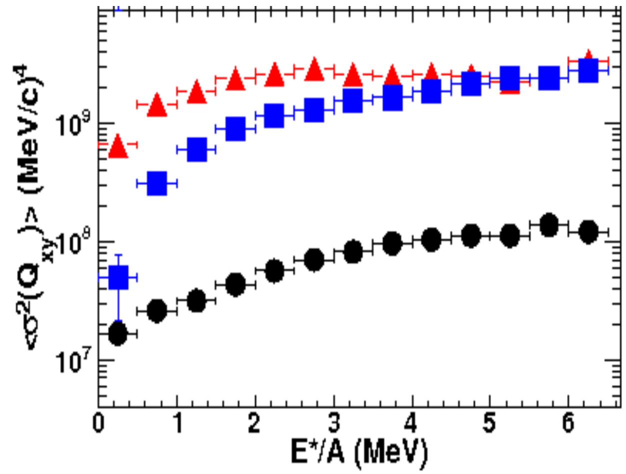


Similar to previous works

E. Bonnet et al., Nucl. Phys. A 816 (2009) 1 and refs therein

Quadrupole momentum fluctuations :

$Q_{xy} = p_x^2 - p_y^2$



Within a classical picture:

different QP T at the emission of each particle-type

S. Wuenschel et al., Nucl. Phys. A 843 (2010) 1

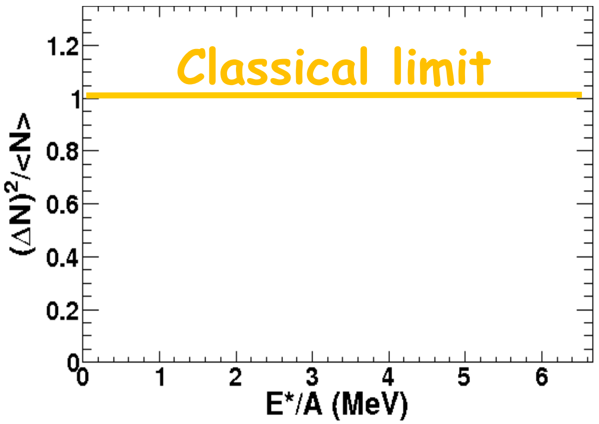
↓

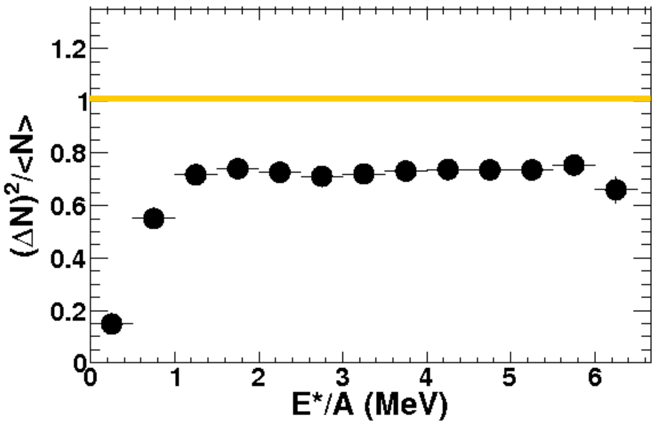
different time scale of different particle-type emission

G. Verde et al., EPJA 30 (2006) 81
R. Ghetti et al., PRL 91 (2003) 092701
D. Gourio et al., EPJA 7 (2000) 245

Particle multiplicity fluctuations

Fermions

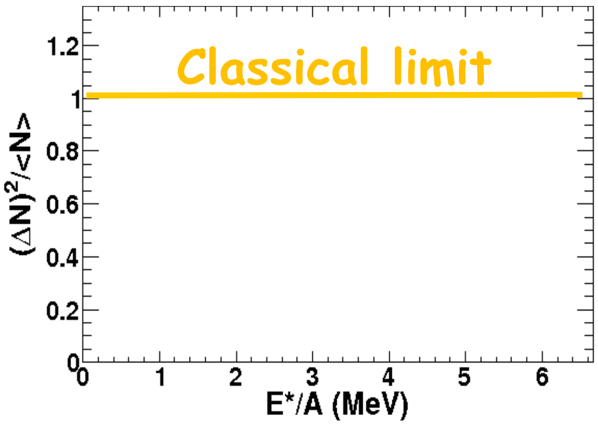


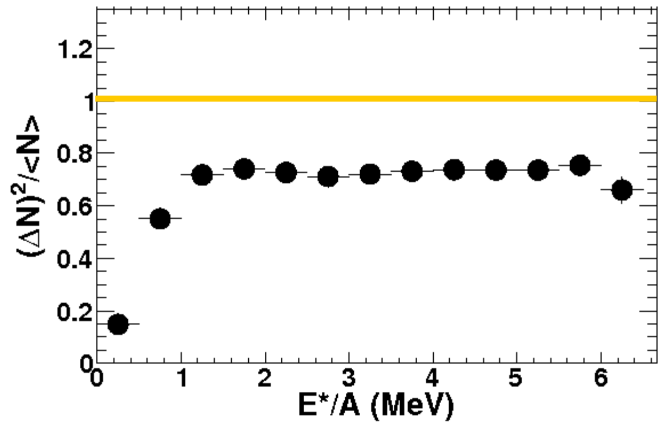


FERMI quenching

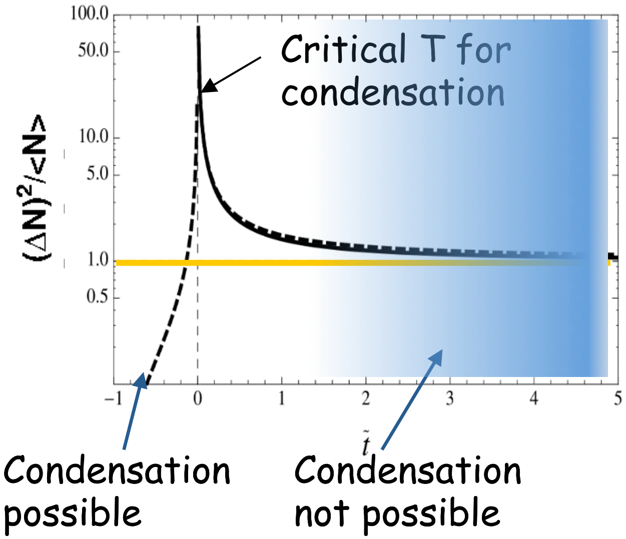
Particle multiplicity fluctuations

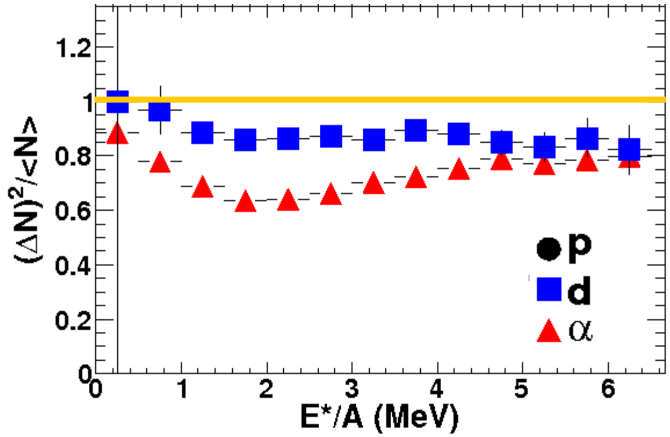
Fermions





Bosons





Particle multiplicity fluctuations

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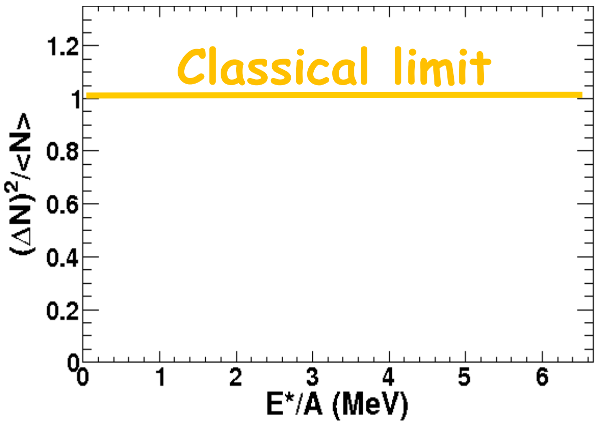

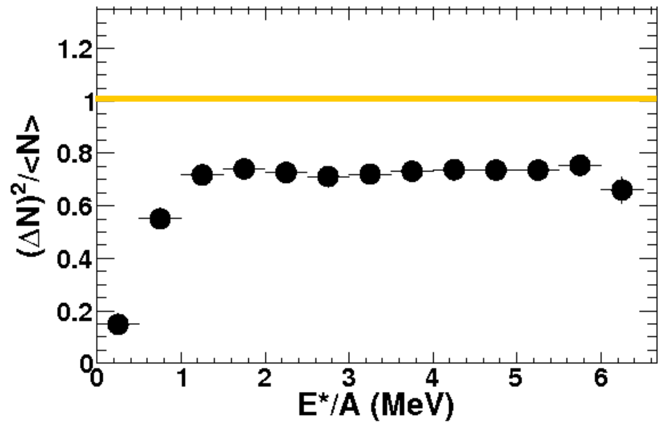

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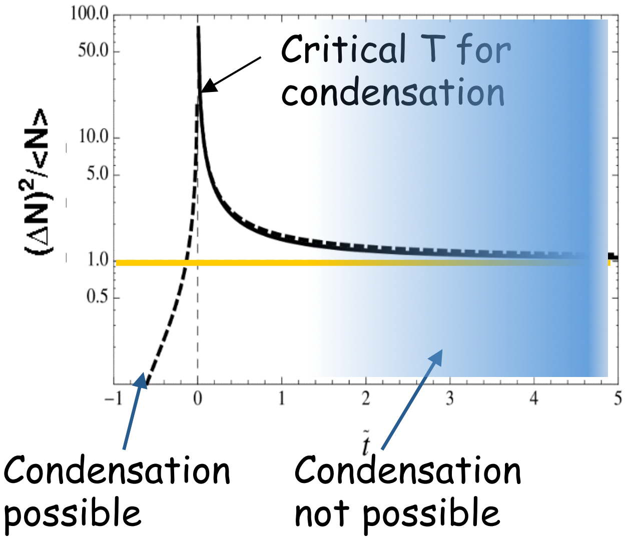
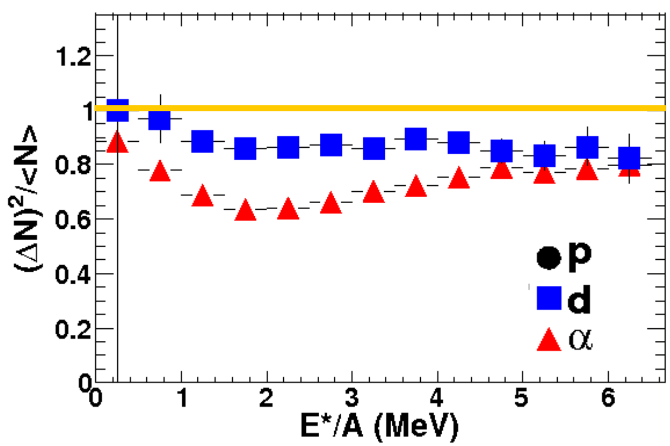
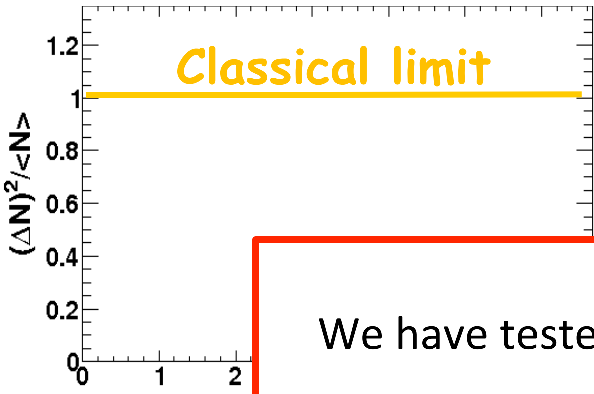


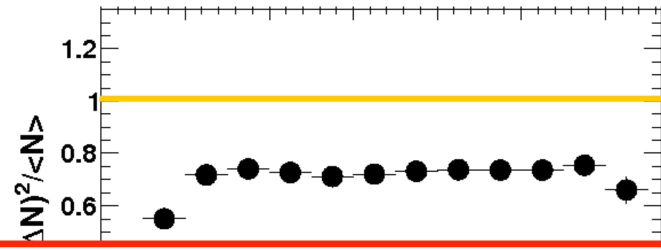


- ✓ The quantum nature of p, d, α **MUST** be accounted for
- ✓ Bosons experience conditions compatible with a possible condensation

Particle multiplicity fluctuations

Fermions





We have tested that:

the observed trends are **NOT compatible** with a standard **statistical** emission

Observables compared to GEMINI predictions(however dynamics is missing)

✓ The quantum
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MUST be
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nce condi-
ons compa-
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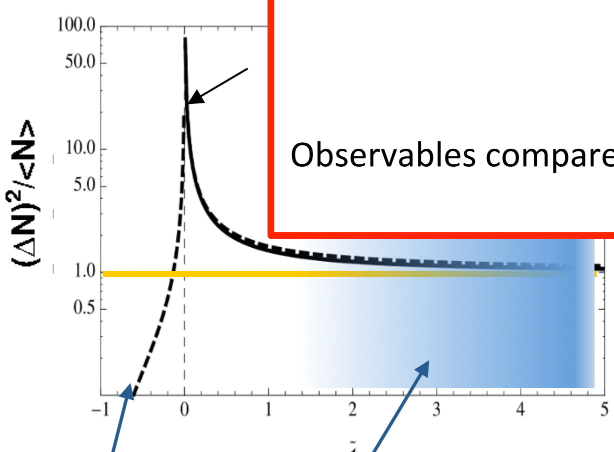
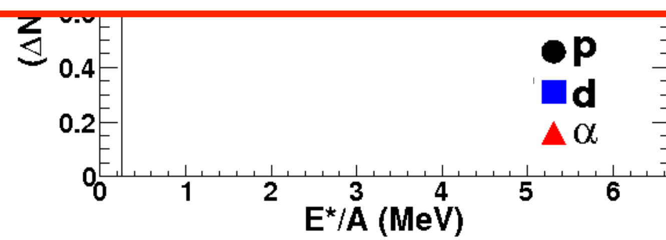
ossible con-
densation





Ideally: selection of α-conjugate and d-conjugate QP → A_{QP} = 40 events

- Mixing events with different number of bosons may wash out BEC signals
- Need statistics

A_{QP} = 36, 40, 44 for a-based analysis

$34 \leq A_{QP} \leq 46$ for d-based analysis

$38 \leq A_{QP} \leq 42$ for p-based analysis

Results consistent to those obtained with A_{QP} = 40 events within the error bars

Method: quantum fluctuation analysis technique

H. Zheng et al., Nucl. Phys. A 892 (2012) 43; PLB 696 (2011) 178;
PRC 86 (2012) 027602

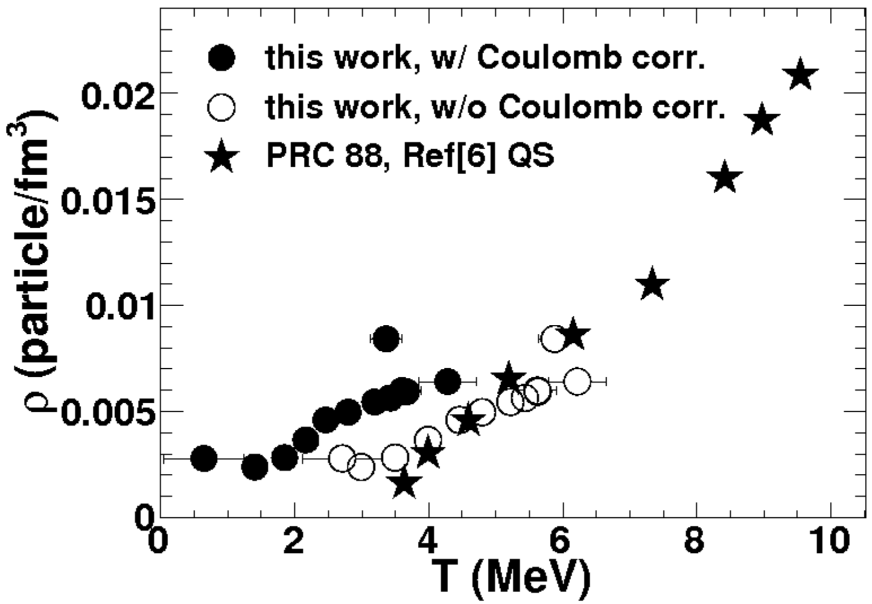
Ingredients :

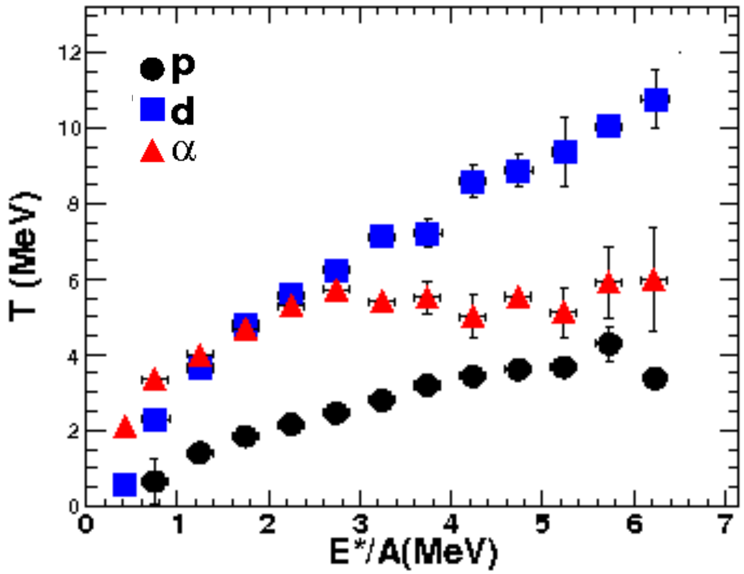
- Fermions follow the Fermi statistics and bosons the Bose statistics
- Coulomb repulsion is accounted for
- dilute system

$$\rightarrow \begin{cases} \langle N \rangle_i = f_1\,(T_i, \rho_i, \mu_i) \\ (\Delta N_i)^2/\langle N \rangle_i = f_2\,(T_i, \rho_i, \mu_i) \\ \sigma^2(Q_{xy})_i = f_3\,(T_i, \rho_i, \mu_i) \end{cases}$$

➡ (T_i, ρ_i) for each particle species i from experimental data

T : temperature
ρ : mean partial density
μ : chemical potential





- $(T,\rho)_p$ agreement with (T,ρ) from coalescence approach in a quantum-statistical framework including medium effects for similar experimental conditions

S. Kowalski et al. PRC 75 (2007) 014601;
L. Qin et al., PRL 108 (2012) 172701;
G. Ropke et al, PRC 88 (2013) 024609
H. Zheng et al., J of Phys G 41 (2014) 055109

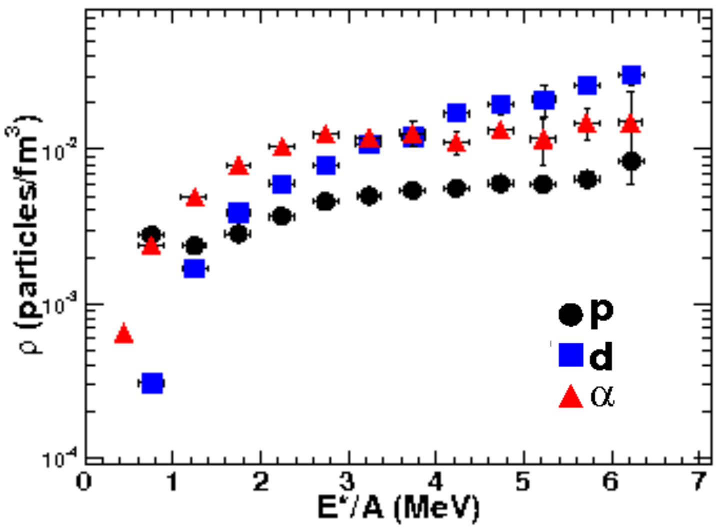
- Influence of Coulomb correction studied

Spread in T : different ordering in emission time observed via particle interferometry
(classical picture)

In agreement with previous works

G. Verde et al., EPJA 30 (2006) 81
R. Ghetti et al., PRL 91 (2003) 092701
D. Gourio et al., EPJA 7 (2000) 245

Density vs E*



- ✓ ρ increases as E* increases :
  - E* <2-3 MeV : emission from the surface (ρ surface < ρ bulk)
  - E* >3 MeV bulk multifragmentation (coexistence of LP and fragments)

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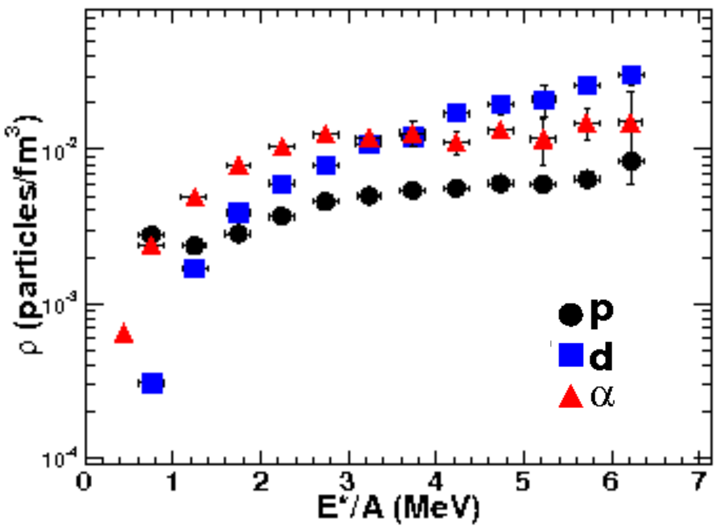

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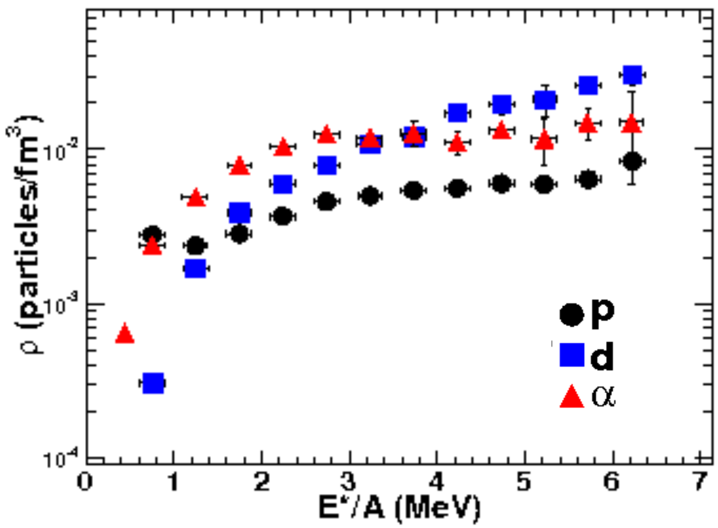
✓ $\rho_{fermions} < \rho_{bosons}$ **up to 4 times (E*>1MeV)**

$v_i = \langle N \rangle_i / \rho \quad R_i^3$

Mean distance between fermions **60%** higher than mean distance between bosons

Density vs E*



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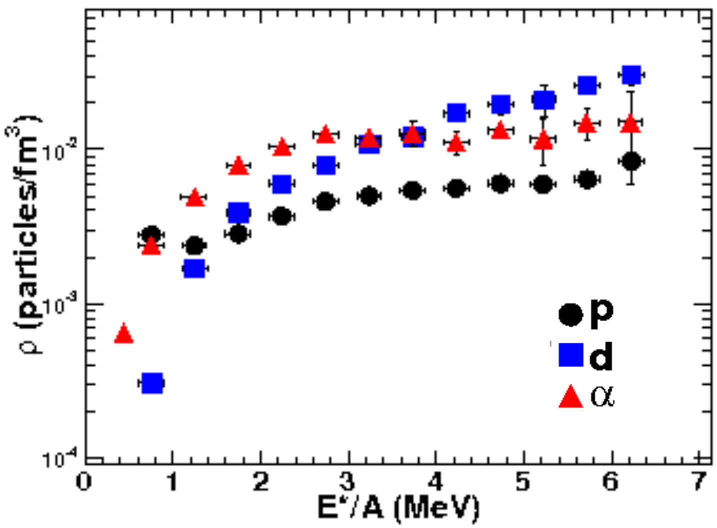
Interpretation :

- Reduction of fermionic component where the bosonic one is present
- Appearance of BEC?
  - $\varepsilon_{bosons} > \varepsilon_{fermions}$
  - T_C ~ few MeV
  - ...

Density vs E*



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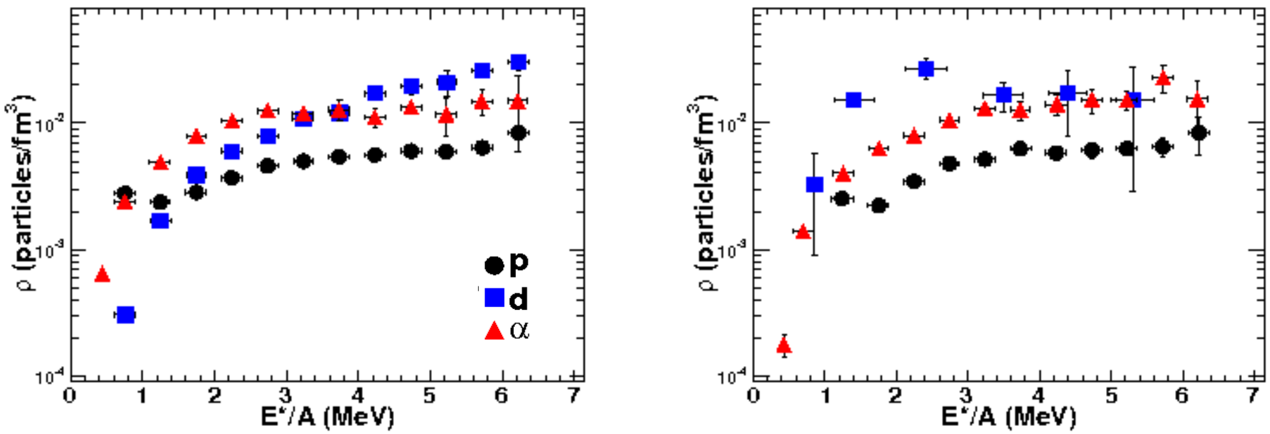
Mean distance between fermions **60%** higher than mean distance between bosons

These events are a **mixture** of bosons and fermions

Density vs E* for "purely" α (d,p)-like events

Selection of events dominated by emission of bosons or fermions : "**pure**" events

Mixture | Pure



- ✓ $\rho_{\alpha\ pure} = \rho_{d\ pure}$ (E*>2MeV)
- ✓ $\rho_{fermions\ pure} < \rho_{bosons\ pure}$

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Selection of events dominated by emission of bosons or fermions : "**pure**" events

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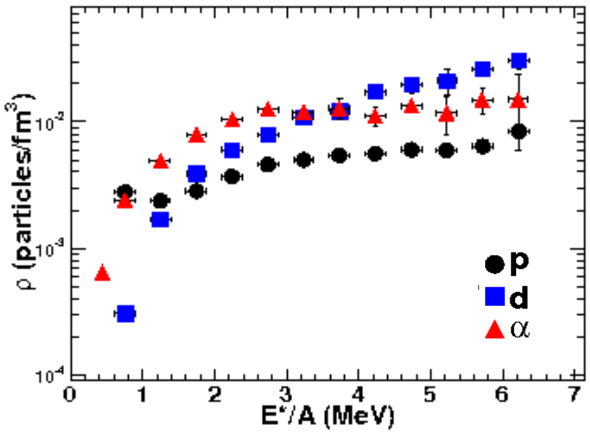
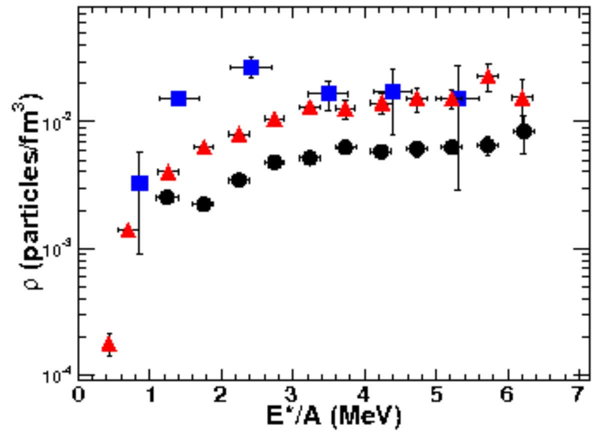


Pure



- ✓ $\rho_{\text{ i pure}} = \rho_{\text{ i mixture}}$
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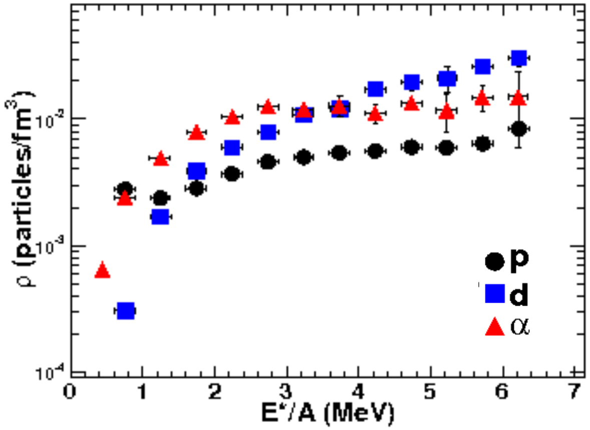

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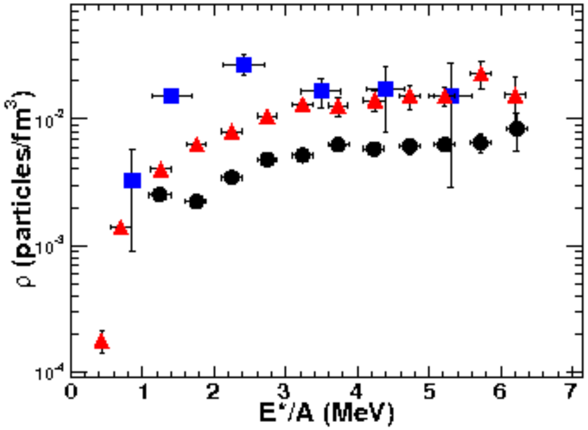

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$\rho_{fermions} < \rho_{bosons}$ independently of the presence of fermions in the event

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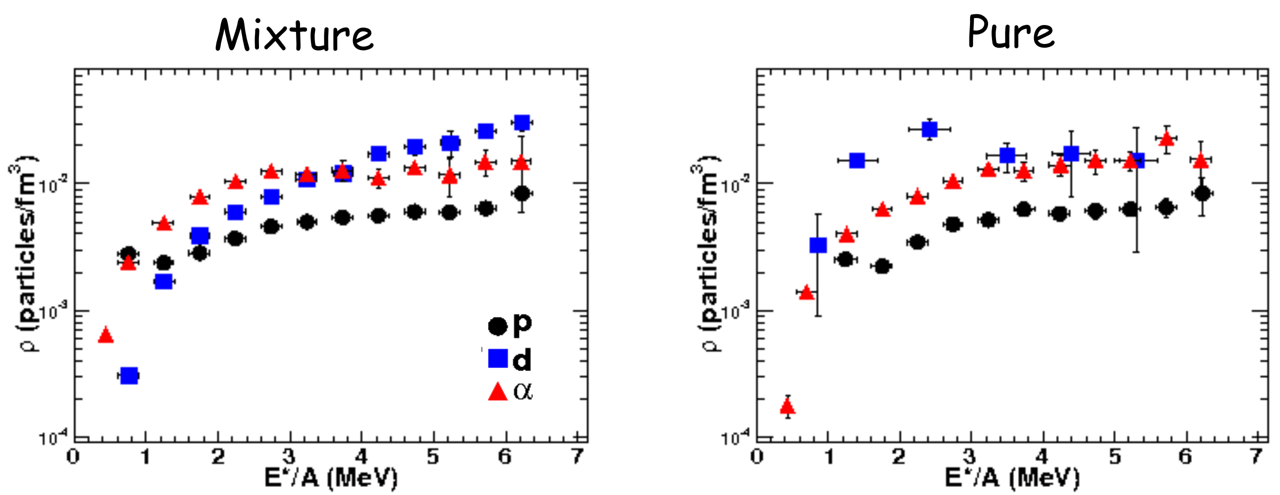

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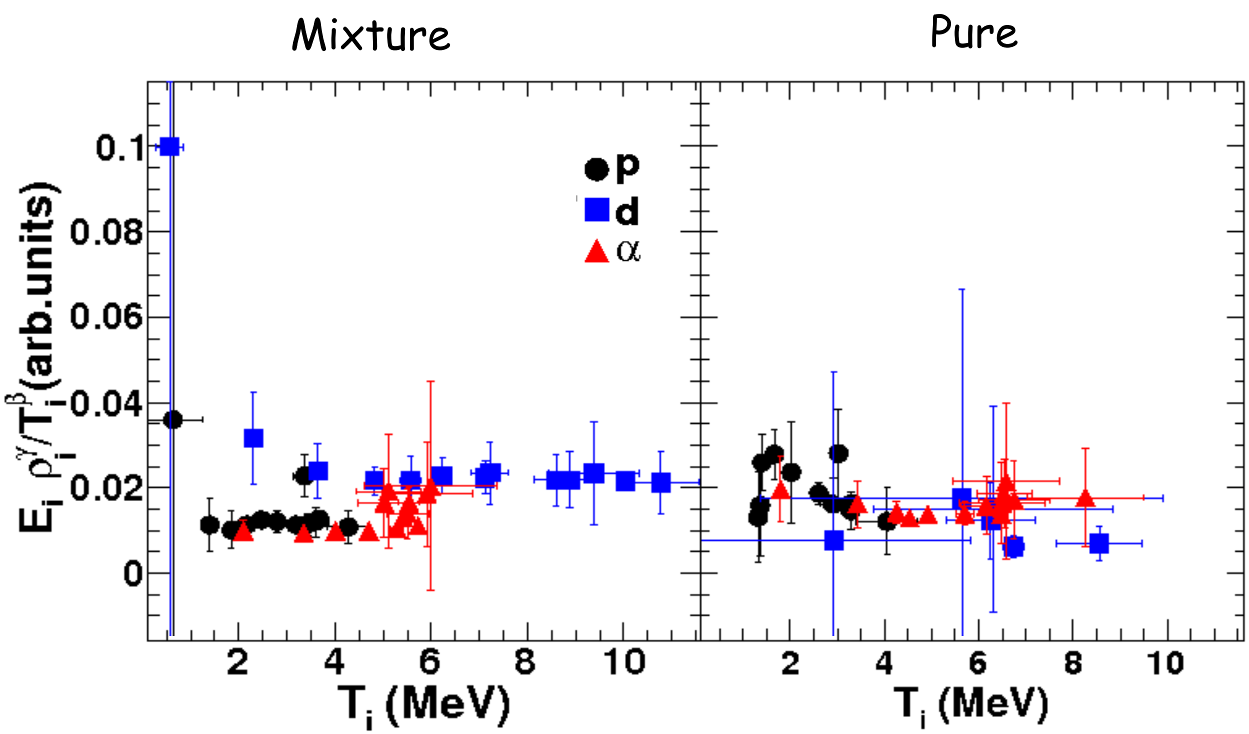
Possible BEC **persisting** in presence of fermions

$E_i = A_i E^*/A_{QP}$

Ideal Fermi gas : $E_i \quad T_i^2/\rho_i^{2/3}$

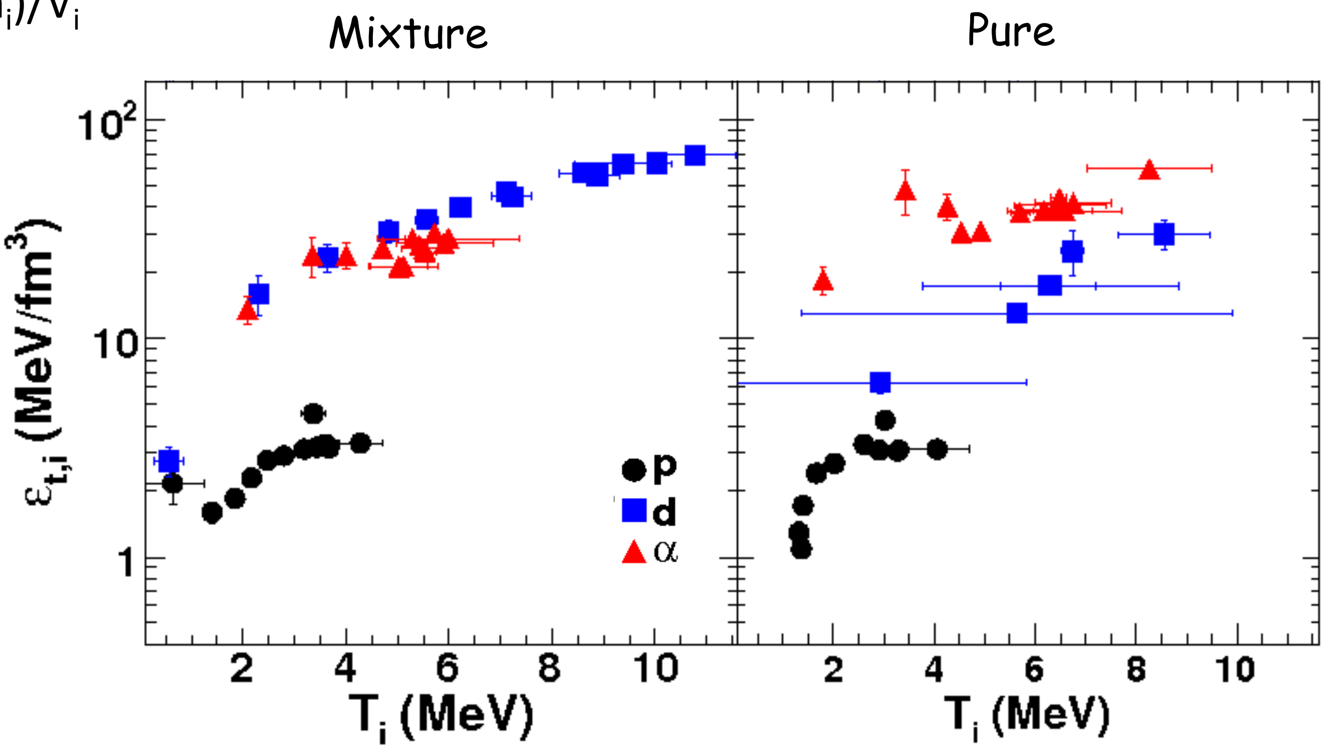
Ideal Bose gas : $E_i \quad T_i^{5/2}/\rho_i$



Different quantum behavior to the density profile

Energy density vs T

$\varepsilon_{t,i} = (E^*+m_i)/V_i$



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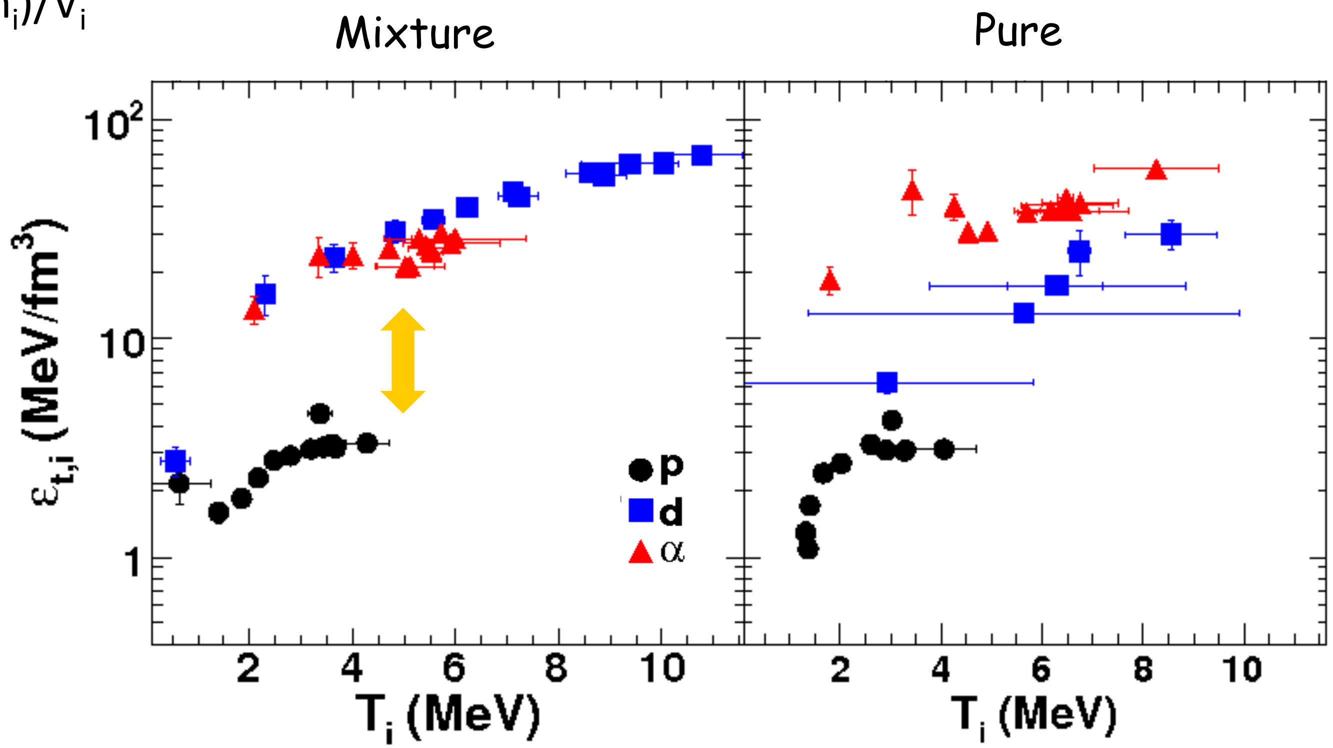
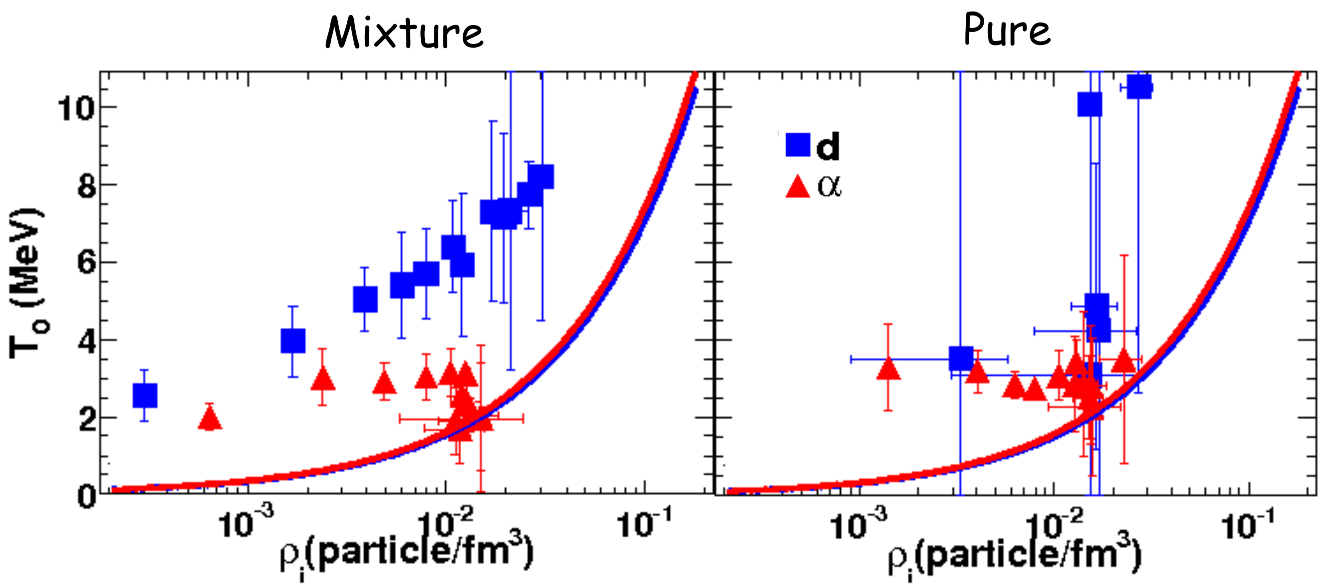


- ✓ $\varepsilon_{t,\alpha} = \varepsilon_{t,d}$ for mixture
- ✓ $\varepsilon_{t,fermions} < \varepsilon_{t,bosons}$ **up to 7 times**

Condensation temperature

$T_0 = f(E_i)$ for an ideal Bose gas

$E_i = A_i E^*/A_{QP}$



✓ **T_0 ~ few MeV** as theoretically predicted

H. Zheng et al.; PRC 88 (2013) 024607;
R. Smith et al., PRL 106 (2011) 250403

Condensation temperature

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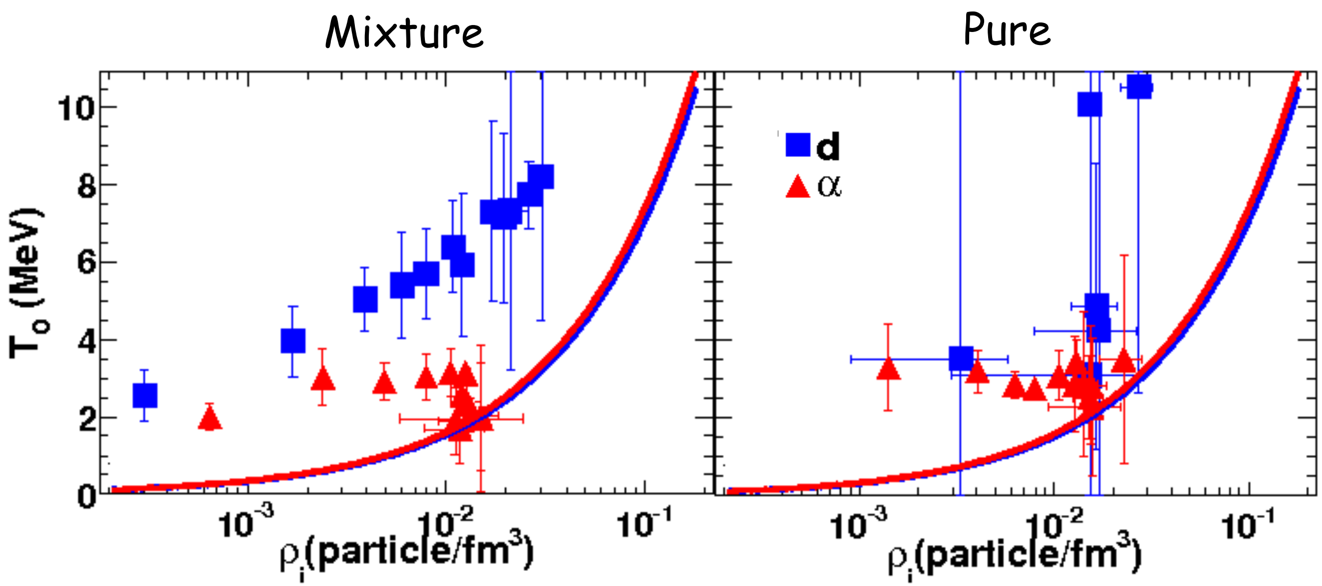

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- ✓ $T_0^{exp} > T_0^{ideal}$ due to Coulomb repulsion which enhances the condensation

  H. Zheng et al., Nucl. Phys. A; PLB 696 (2011) 178; PRC 86 (2012) 027602; PRC 88 (2013) 024607
  R. Smith et al., PRL 106 (2011) 250403
  K. Huang, Statistical Mechanics p286

Condensation temperature

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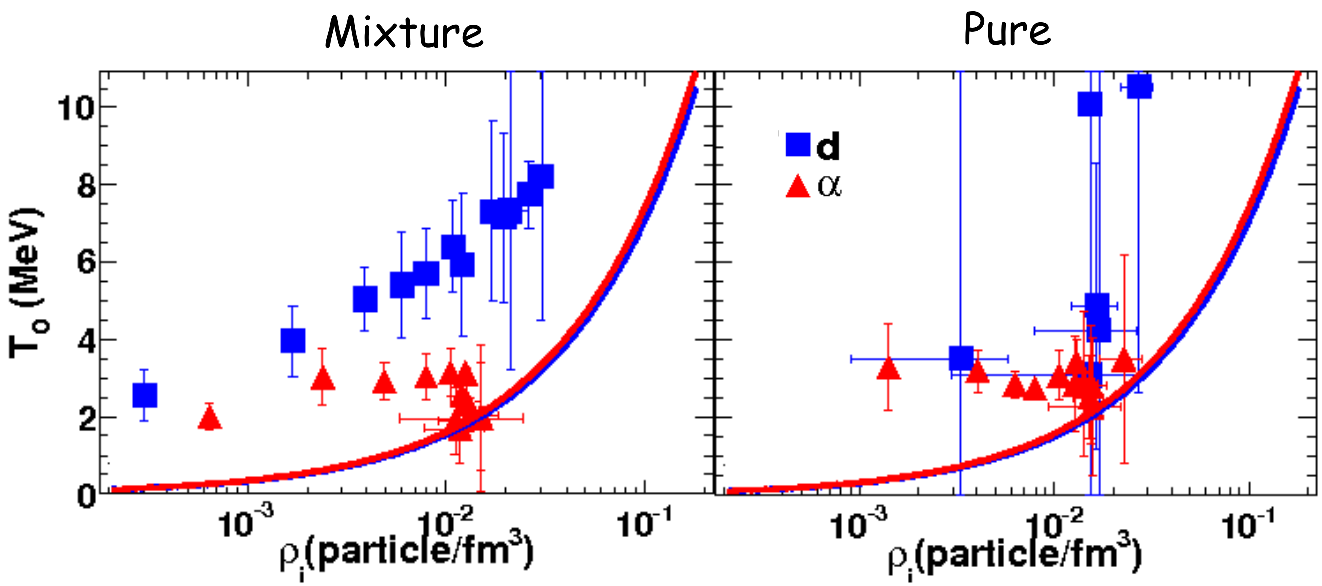

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- ✓ At higher ρ : $T_0 \to T_0^{ideal}$: increased contribution of nuclear force counterbalancing Coulomb repulsion — K. Huang, Statistical Mechanics (286)

…as ρ increases the attractive nuclear force becomes dominant, bosons overlap and dissolve in their constituent and the Pauli blocking becomes dominant

Conclusions …

Decay of **excited QP** systems produced in $^{40}Ca+^{40}Ca$ at 35MeV/A

- Detection system ⟶ reconstruction of A_{QP}, Z_{QP}, E^*_{QP} event by event

Technique : quantum fluctuation method

Results :

$\rho_{fermions} < \rho_{bosons}$

$\varepsilon_{t,fermions} < \varepsilon_{t,bosons}$

$T_0 \sim$ few MeV

The observed **signals** are **present** also **in** events where **mixture** of bosons and fermions are present (as observed in atomic traps)

⇒ Reduction of fermionic component where the bosonic one is present

Not reduced by boson-fermion interaction

Interpretation

Signals of Bose-Einstein condensation

Similar nature for processes occurring in quantum systems at the atomic and nuclear scales

What are the implications of these phenomena on α clustering and symmetry energy at low ρ?

Do these phenomena persist in lighter/heavier N=Z systems?

(candidate : $^{56-58}Ni+^{58}Ni$)

Do these phenomena persist in N>Z systems?

($^{48}Ca+^{48}Ca$…how to deal with non-detected neutrons)

Technique : particle-particle correlations for emission ρ estimation

A special thank to…

A. Bonasera, A. Chbihi, P. Napolitani, G. Verde, H. Zheng

the INDRA-VAMOS Collaboration

the ACEN group of CENBG

Thank you for your attention

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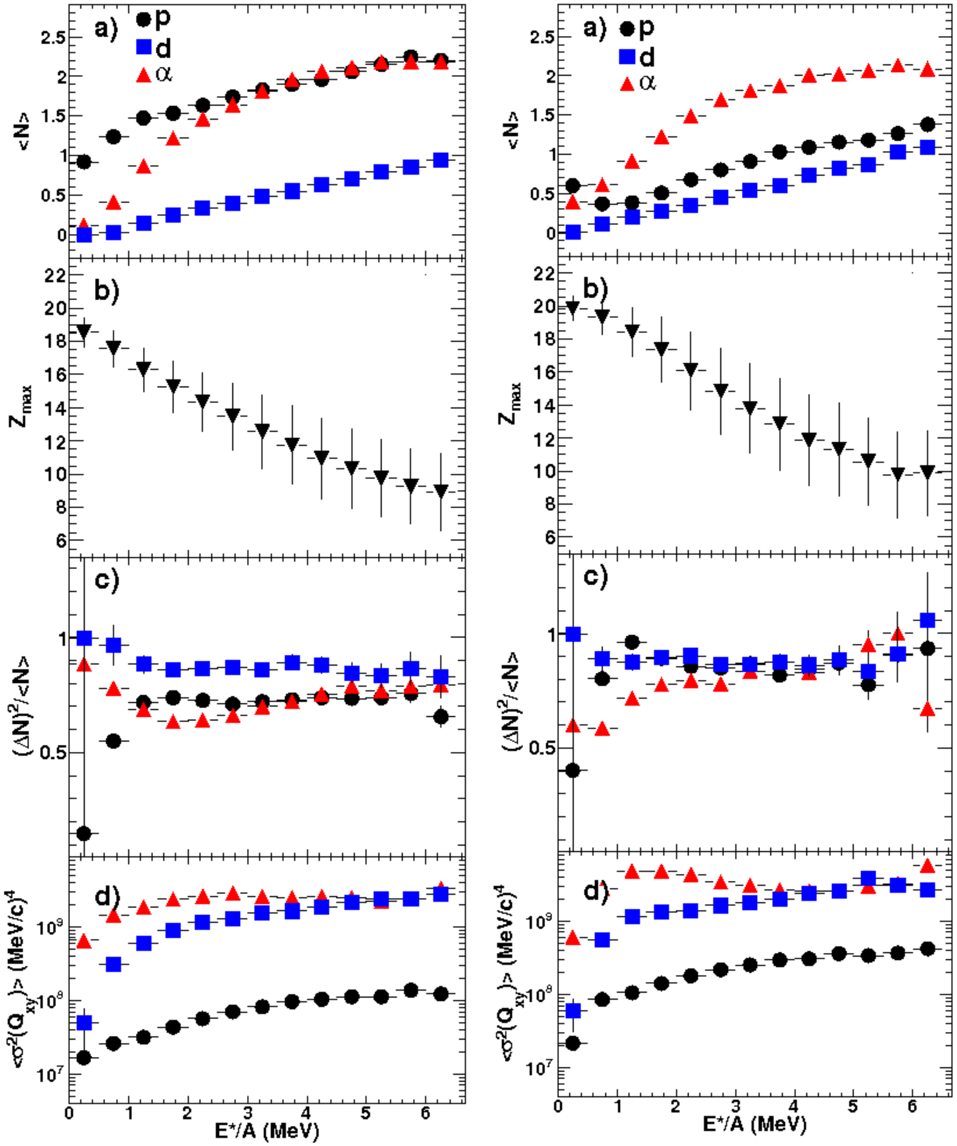
$^{40}Ca+^{40}Ca$ vs $^{48}Ca+^{48}Ca$



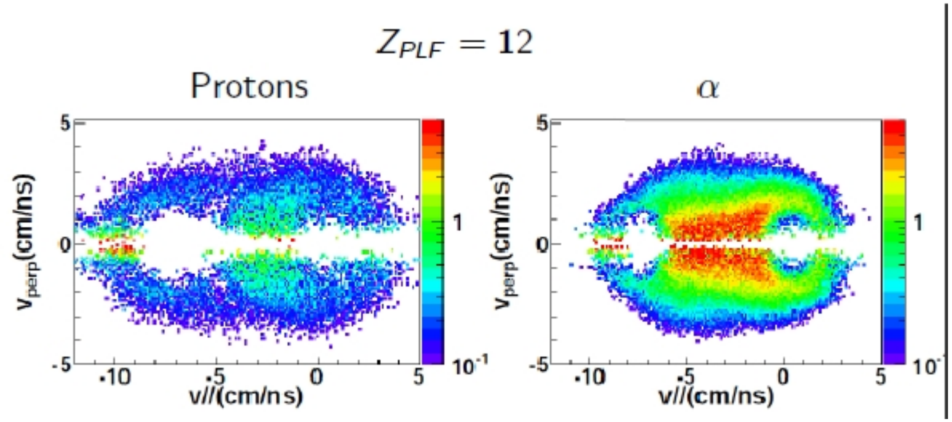
Event reconstruction and selection

QP reconstruction :

PLF + CP belonging to QP

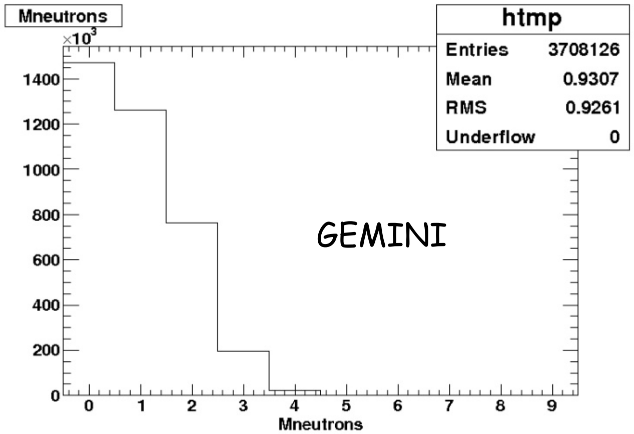
(based on v/v_{PLF} criteria)

J. Steckmeyer et al., Nucl. Phys. A 686 (2001) 537



→ Z_{QP}, A_{QP}, E_{QP}*
(from calorimetry)

Event selection : $^{34\text{-}46}$Ca QP events



Non-detected neutrons :

→ $<M_n><1$ for all E_{QP}*

α and p emissions are energetically favoured for $^{34\text{-}44}$Ca

Event selection

Event selection : isotropic emission events

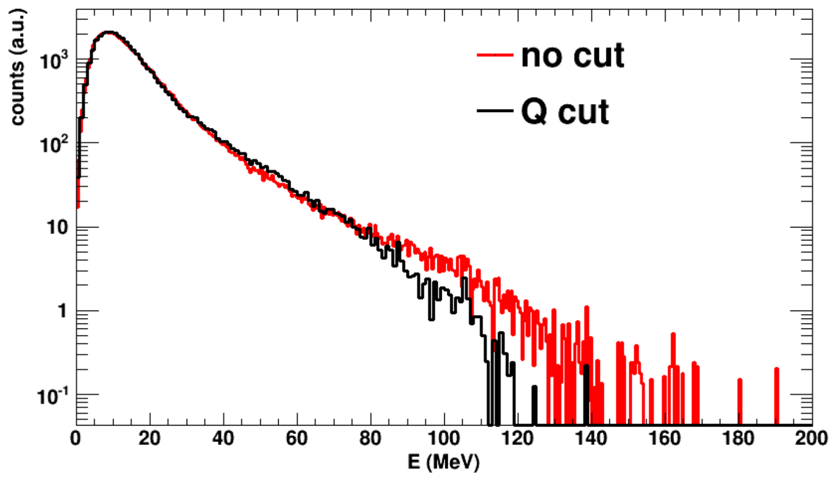
to have a certain degree of equilibration

↓

$$Q_{shape} = \frac{\Sigma (p_z^i)^2}{\Sigma (p_{perp}^i)^2}$$

$$-0.3 < \log Q_{shape} < 0.3$$

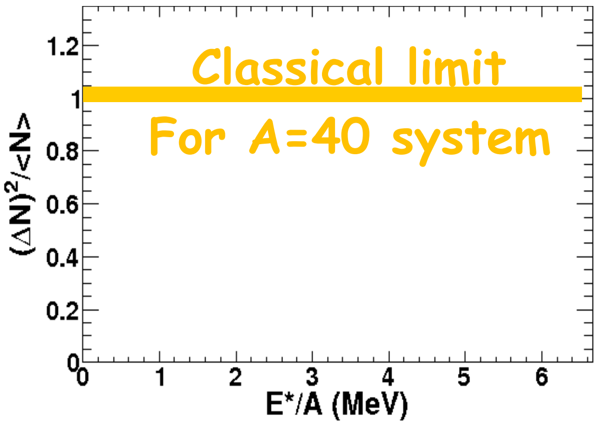
α particles (the most affected)

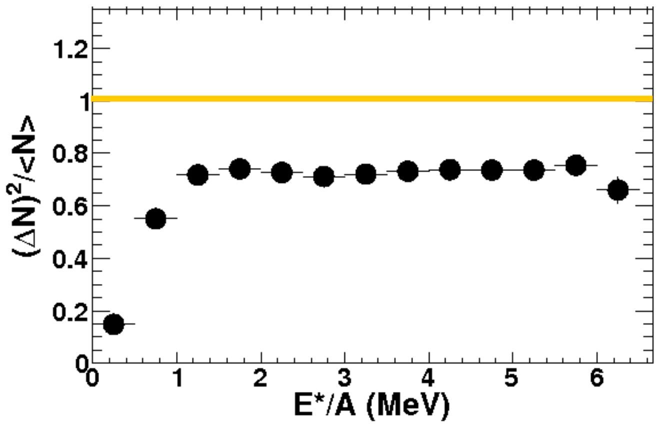


The influence of these selections was monitored all along the analysis

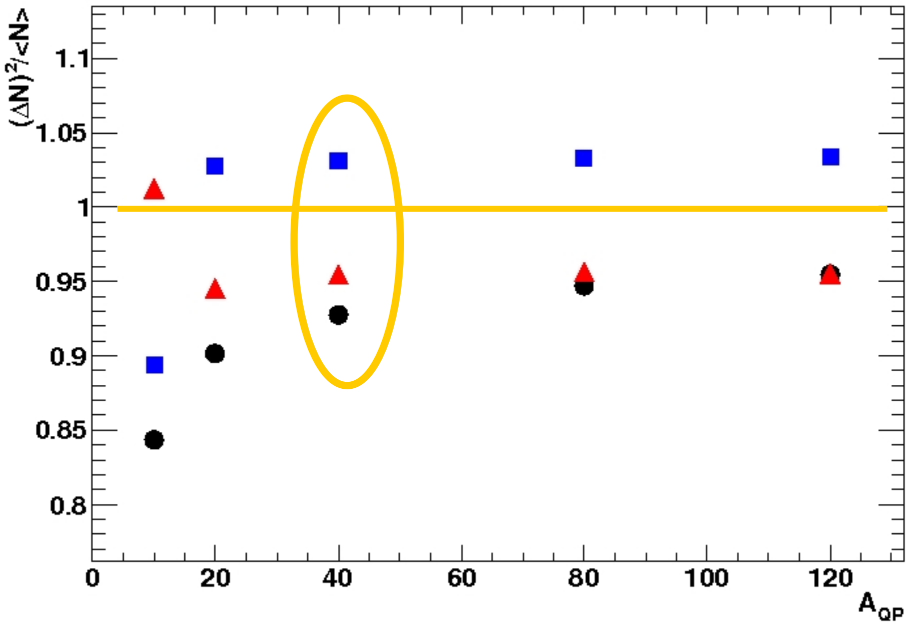
Particle multiplicity fluctuations

Fermions





FERMI quenching



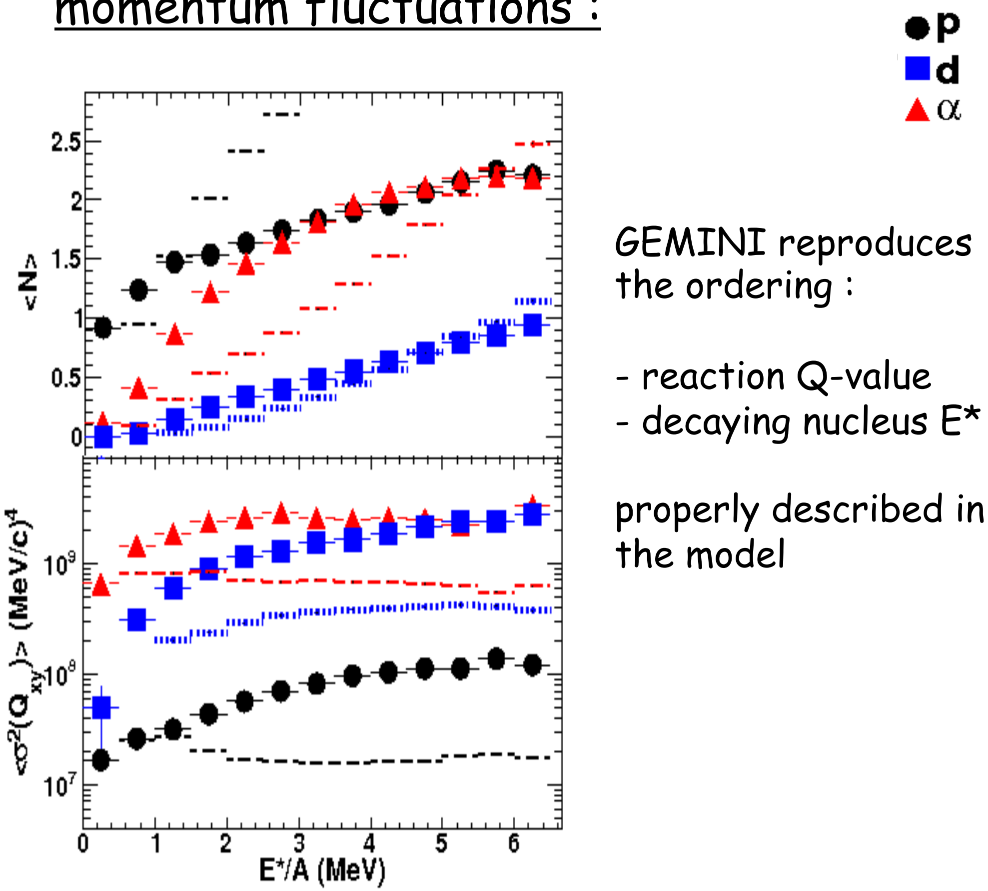
Simple MonteCarlo assuming a flat emission probability for particles up to Z=5

Comparison to statistical emission

GEMINI : typically reproduces observables from statistical decay at similar E*

R. Charity, PRC 82 (2010) 014610 and refs therein

Multiplicity & quadrupole momentum fluctuations :



GEMINI reproduces the ordering :

- reaction Q-value
- decaying nucleus E*

properly described in the model

Comparison to statistical emission

GEMINI : typically reproduces observables from statistical decay at similar E*

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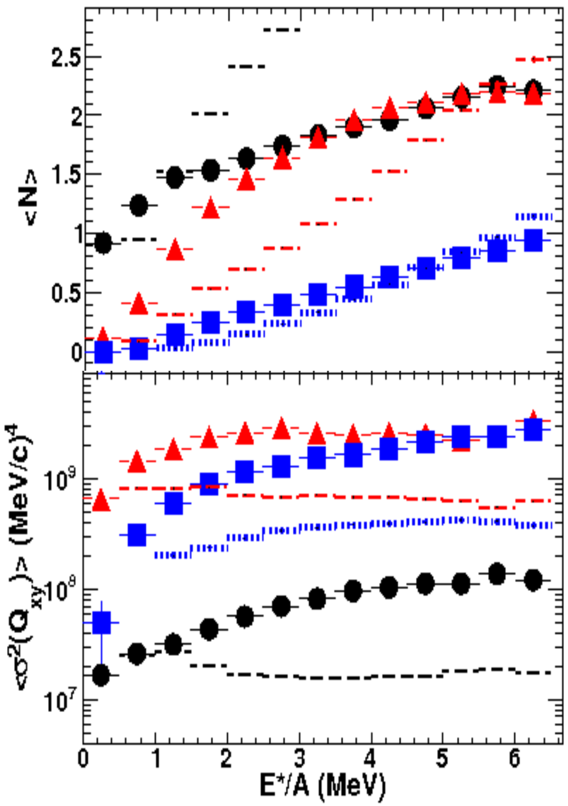

GEMINI reproduces the ordering :

- reaction Q-value
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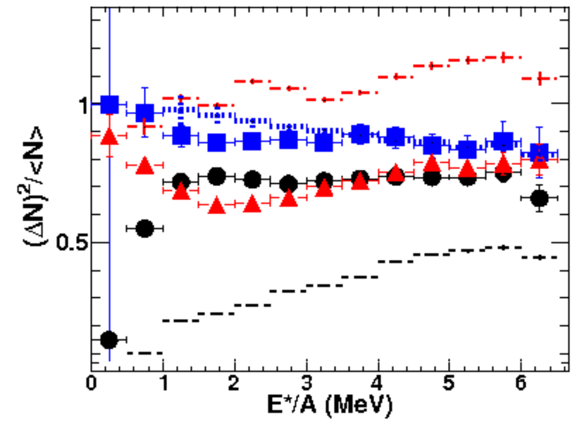
properly described in the model

Multiplicity fluctuations :



NOT reproduced :

quantum nature of particles neglected in the model

Not compatible with a standard statistical emission

Models accounting for bosonic nature of α and d are under development

S. Typel et al., PRC 81 (2010) 015803, and 89 (2014) 064321

H. Zheng et al.; PRC 88 (2013) 024607;

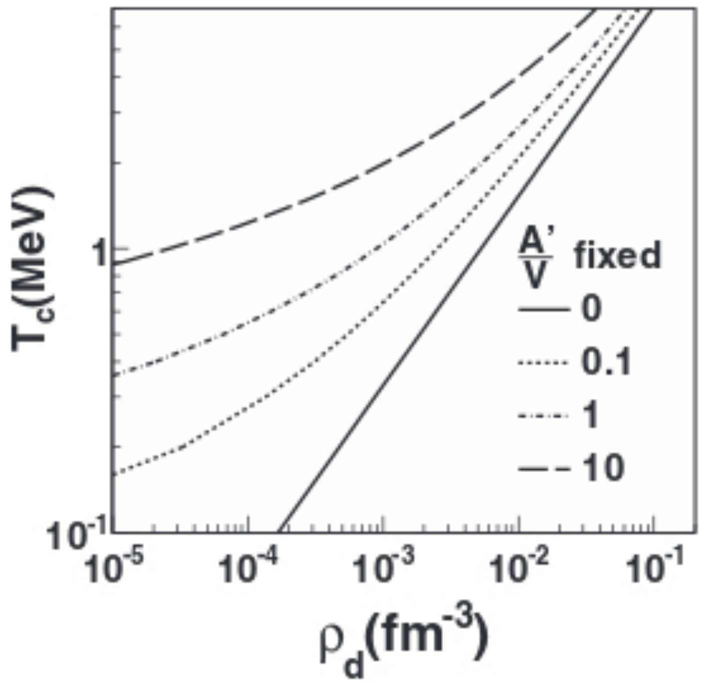


FIG. 2. Critical temperature versus density with fixed $\frac{A'}{V}$. We take d as an example.

The Coulomb interaction increases the condensation temperature