FUSTIPEN

French-U.S. Theory Institute for Physics with Exotic Nuclei

Dynamical cluster formation and correlations in heavy-ion collisions, within transport models and in experiments

Ganil 17-19 May

Study of two and multi particle correlations in $^{12}C+^{24}Mg$ collisions at 35 AMeV

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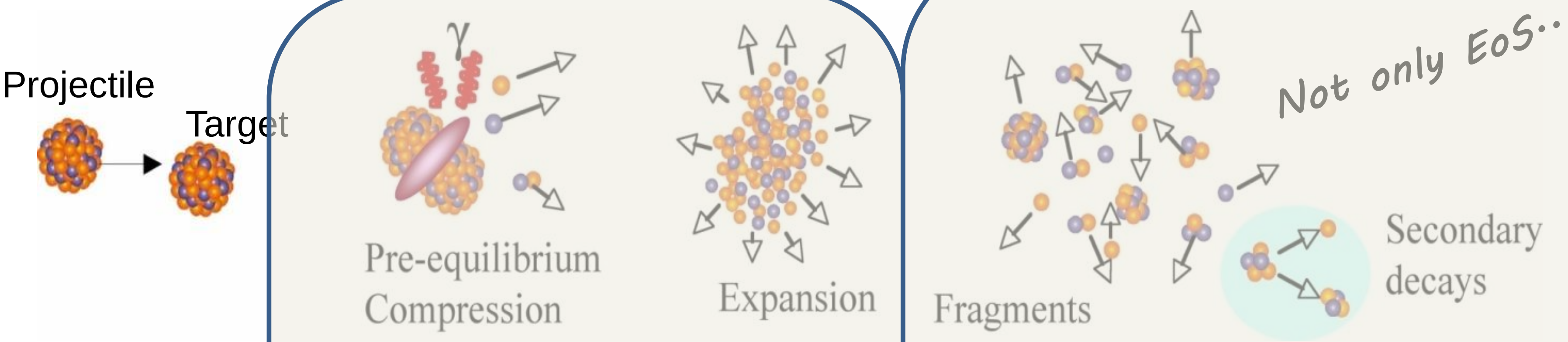
Two and multi particle correlation in Heavy Ion Collisions



Not only EoS...

Correlation techniques

Nuclear Dynamics

✓Femtoscopy: space-time properties of light particle emitting source

✓Nuclear Equation of State

Spectroscopy tools

✓Reconstruct of unbound states from correlation of two and multi particle decay

✓Spin of states, branching ratio for simultaneus and sequential decay

✓Clusters, boson condensates, new states....

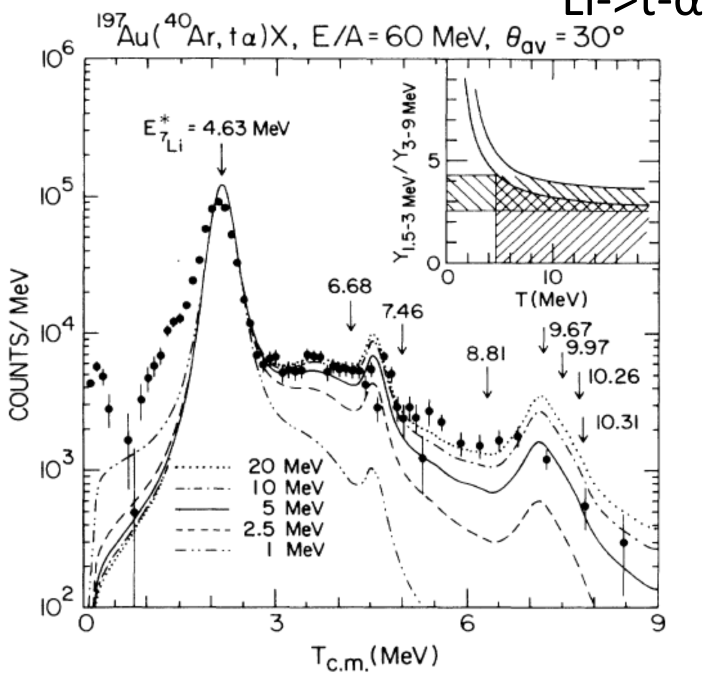
Correlation measurements as probe for spectroscopy and dynamics

Dynamics vs Spectroscopy

DYNAMICS

Emission temperature

^{7}Li->t-α



Pochodzalla et al., Phys.Rev.C.35.1695.1987

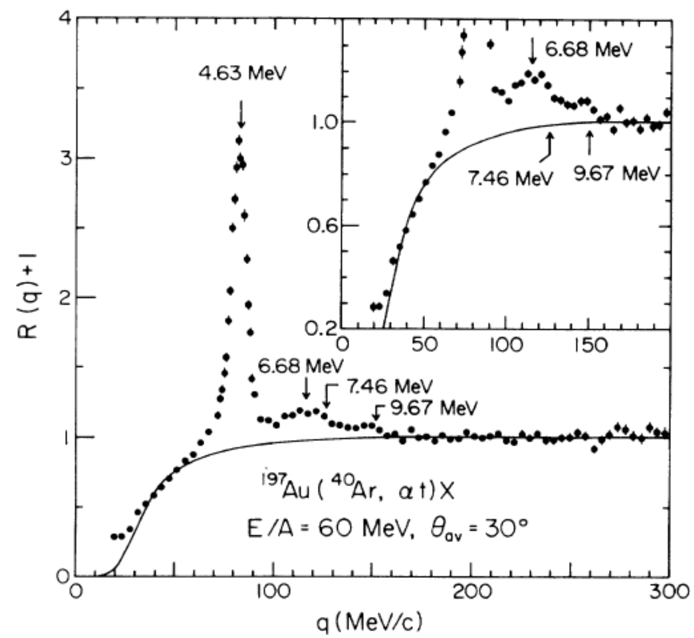
Thermal Model

Excited states population used to determine temperature

$$Y_{corr}(E_{rel}) = \frac{N}{\pi} e^{-E/T} \sum_i (2J_i+1)\left[\frac{\Gamma_i/2}{(E-E_i)^2+\Gamma_i^2/4}\right];$$

Spectroscopic properties

t-α CORRELATION FUNCTION



Correlation function depend on some of spectroscopic properties

(*if no collective motion* G. Verde, P. Danielewicz et al. Physics B653 (2007))

$$1+R(E_{rel}) = \frac{Y_{corr}(E_{star})}{Y_{uncorr}(E_{star})} \propto \sum_i (2J_i+1)\left[\frac{\Gamma_i/2}{(E-E_i)^2+\Gamma_i^2/4}\right];$$

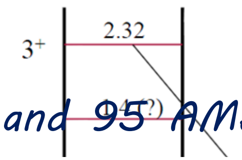
Spectroscopy tools from resonances decay

Correlations in 4π detectors

Study of 3 body decay :branching ratio- direct vs sequential

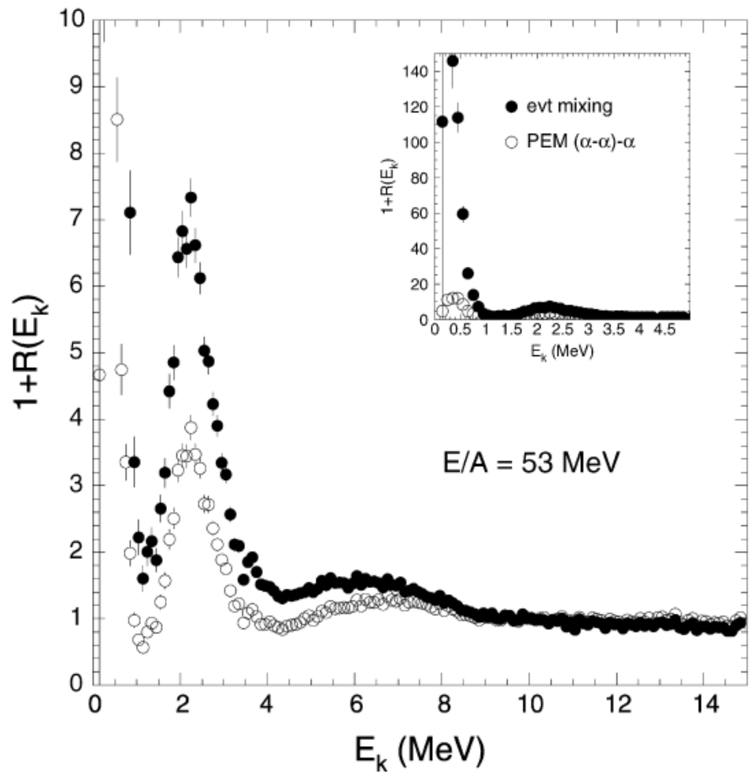
Xe+Au ... central collisions (LASSA data)

States of $^{8}B \rightarrow p+^{7}Be$



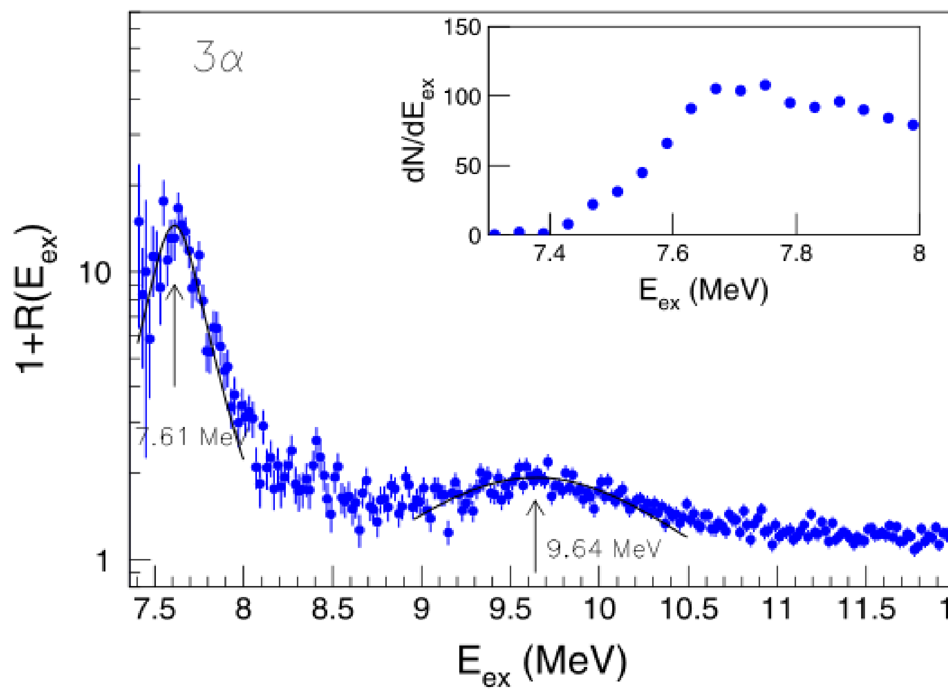
$^{12}C \rightarrow 3\alpha$

$^{12}C+^{24}Mg$ E=53 and 95 AMeV with INDRA



F. Grenier et al., Nucl. Phys. A811, 233 (2008).

$^{40}Ca+^{12}C$ E=25 AMeV with CHIMERA



Raduta et al., Phys. Lett. B 705, 65 (2011)

"CORRELATION" experiment with CHIMERA at LNS

MAIN GOALS:

$^{12}C + ^{24}Mg$ @ 35 AMeV

$^{12}C + ^{208}Pb$ @ 35 AMeV

➢ Nuclear dynamics

- ✓ Space-time evolution of emitting source;
- ✓ Density and emission temperature ;

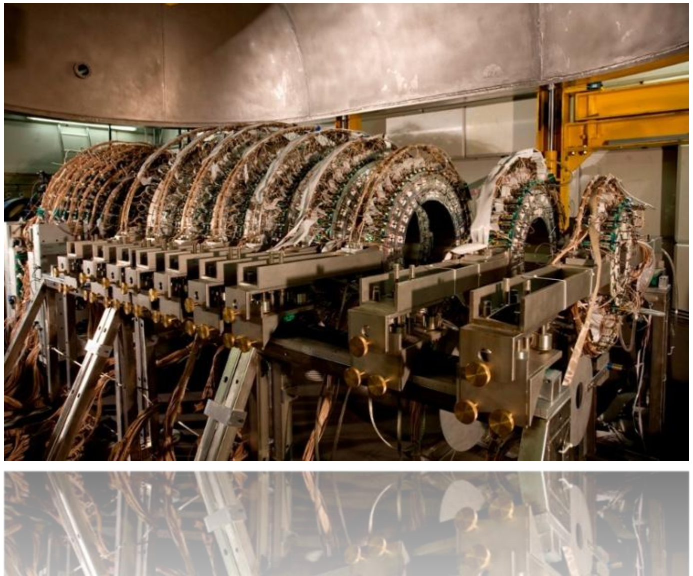
➢ Invariant Mass Spectroscopy

- ✓ Resonances decay of light nuclei;
- ✓ Clustering in nuclei and nuclear matter;
- ✓ Effects of medium and reaction process on the decay of resonance (in-medium structure)

Typel Phys. Conf. Ser. 420.012078;

CHIMERA Charged Heavy Ion Mass and Energy Resolving Array

Granularity	1192 moduli Si (300μm) +CsI(Tl)
Geometry	RINGS: 688 modules 100-350cm SFERA: 504 modules 40 cm
Angular coverage	RINGS: 1°< θ < 30° SPHERE: 30°<θ<176°, 94% 4π



Angular range used

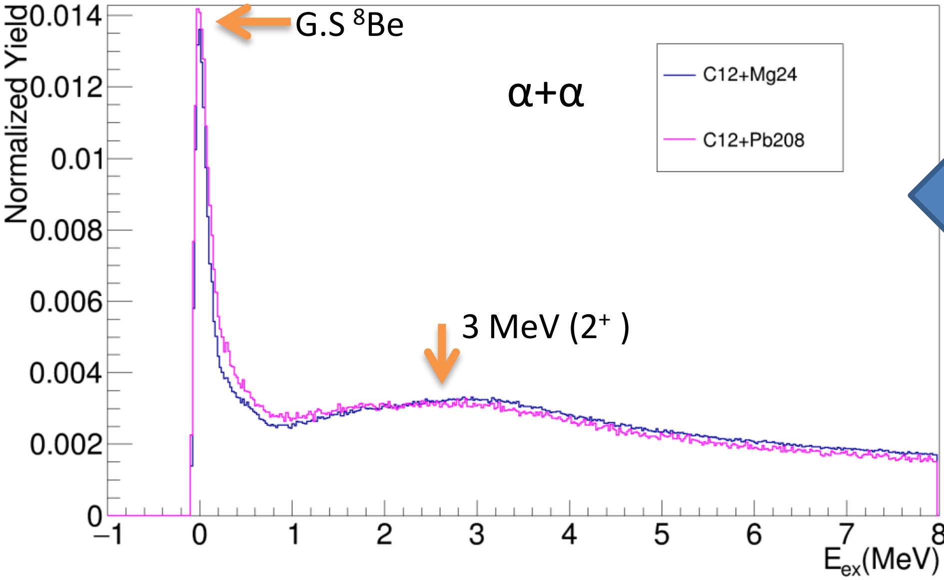
0°<θ<30° QP decay in semi-pheripheral collisions

Particles identification:

Up to Z=8 with dE-E and PSD in CsI(Tl);

Two particle correlations with CHIMERA

$^{8}Be \rightarrow \alpha + \alpha$



States of ^{8}Be

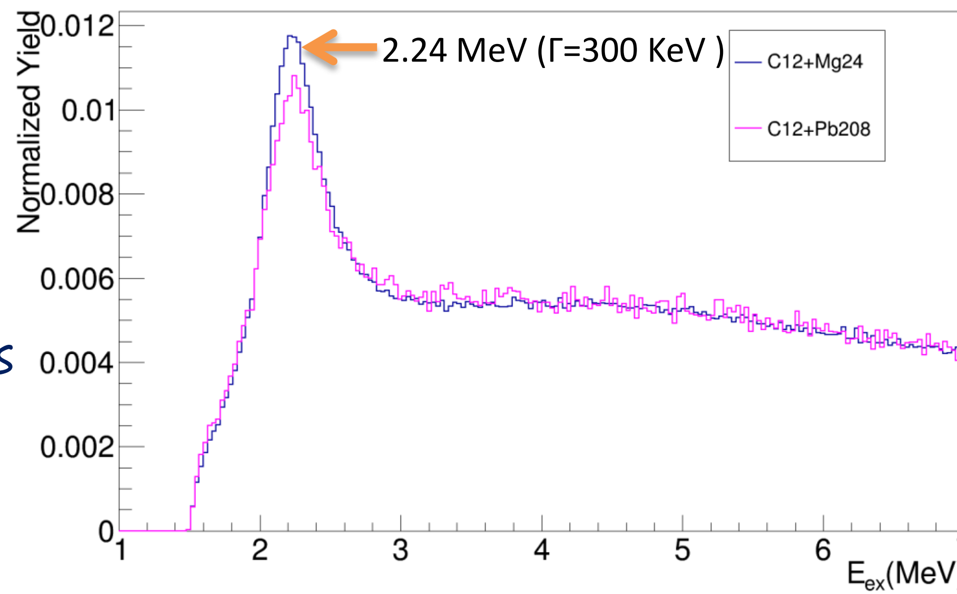
G.S. E_{rel} (total energy in CM)=92 keV

2^{+} $E_{excitation}$ (E_{rel} +Q_{value}) = 3 MeV

$^{6}Li \rightarrow d + \alpha$

States of ^{6}Li

3^{+} $E_{excitation}$ = 2.19 MeV Γ=24 KeV



Good quality of particle calibrations

Good angular resolution

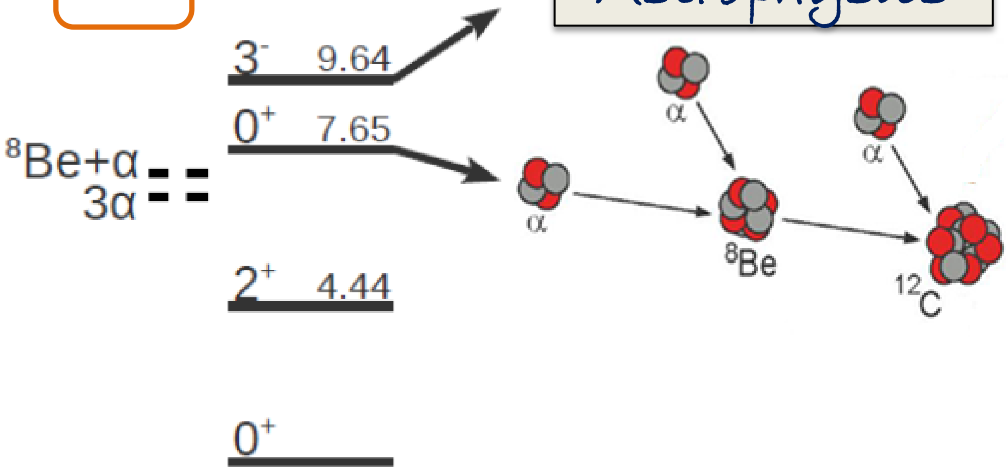
Three- and two-particle correlations: sequential vs direct

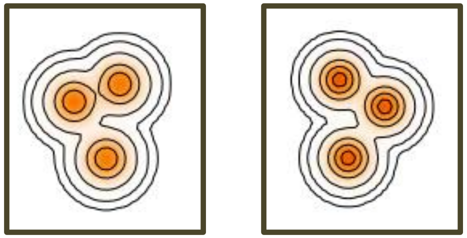
Exploring nuclear structure (sequential and direct decay resonance decay widths)
in dissipative heavy-ion collisions

^{12}C

Astrophysics

Cluster Structure





Decay width fully Sequential observed

Itoh, PRC 113 (2014) 102501

Rana PRC 88 (2013) 021601

M. Freer et al., PRC 49 (1994) R1751

Inelastic Scattering

....Evidence of Direct decay mechanisms

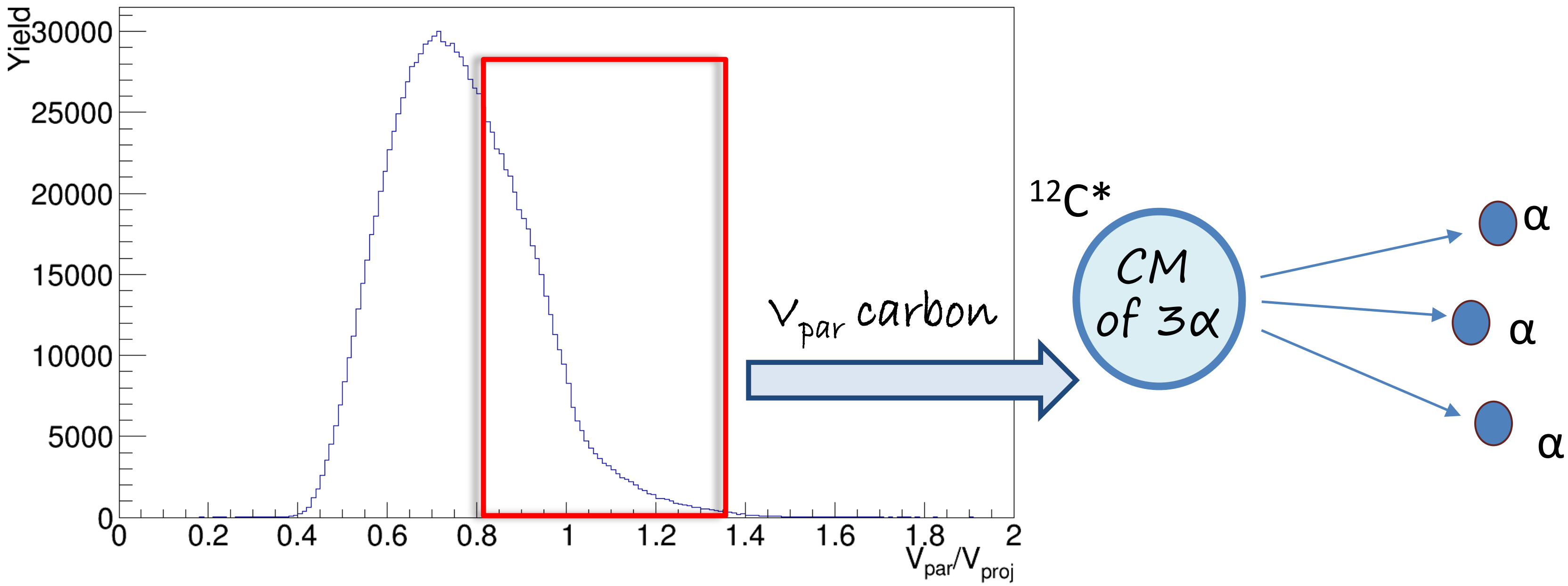
Raduta et al. ,Phys. Lett. B 705, 65 (2011)

F. Grenier et al., Nucl. Phys. A811, 233 (2008)

Heavy Ion Collisions

Events Selection

Criteria to select events (excitation and decay of quasi-projectile)



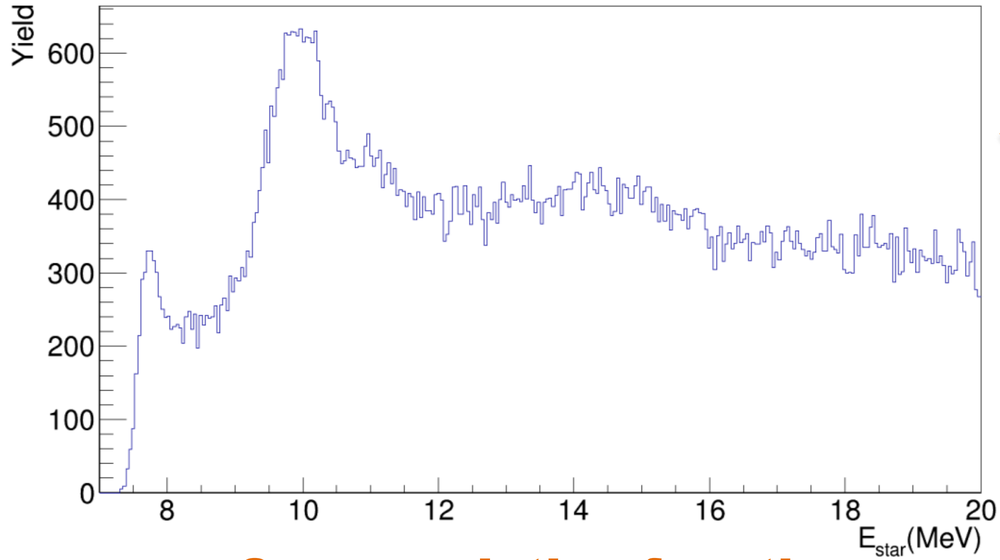
SELECTION: $$\frac{V_{par}}{V_{proj}} > 0.8 \quad (V_{proj} = 7.99\,cm/ns)$$

Confirmed by comparison with model prediction

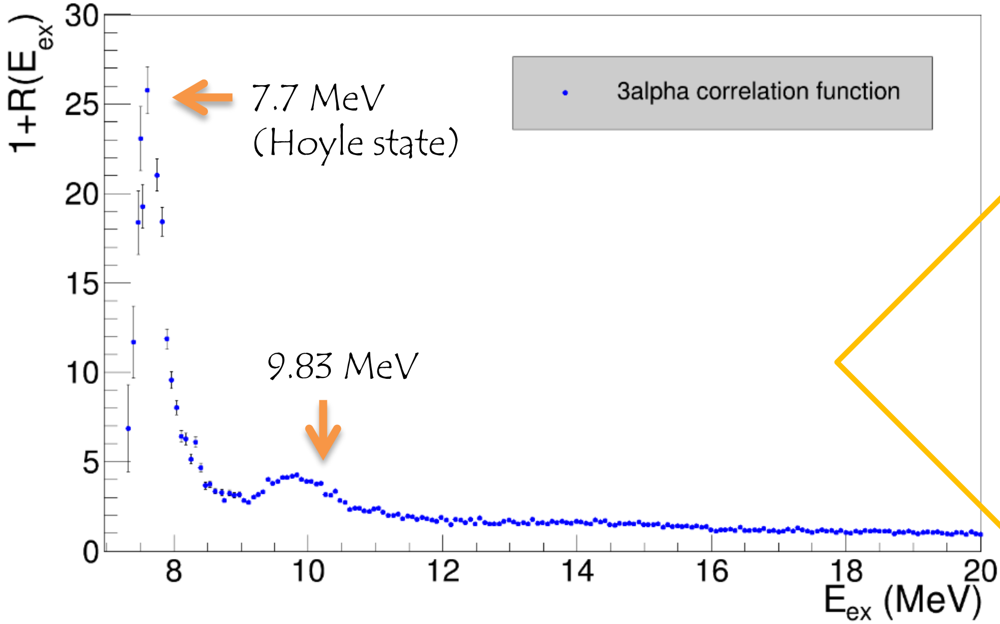
D. Lacroix et al. ,Phys. Rev. C69 054604

3α Correlations in $^{12}C+^{24}Mg$

Yield of correlated 3α



3α correlation function



$^{12}C \rightarrow 3\alpha$

Correlation function:

$$1 + R(E_{star}) = \frac{Y_{corr}(E_{star})}{Y_{uncorr}(E_{star})}$$

$$E_{star} = E_{tot} - Q$$

3α threshold=7.27MeV

product of single particle yield

States of ^{12}C

0^+ E_{star} = 7.654 MeV Γ=8.5 eV

3^- E_{star} = 9.641 MeV Γ=34 keV

2_2^+ E_{star} = 10.03 MeV Γ=800 KeV MeV

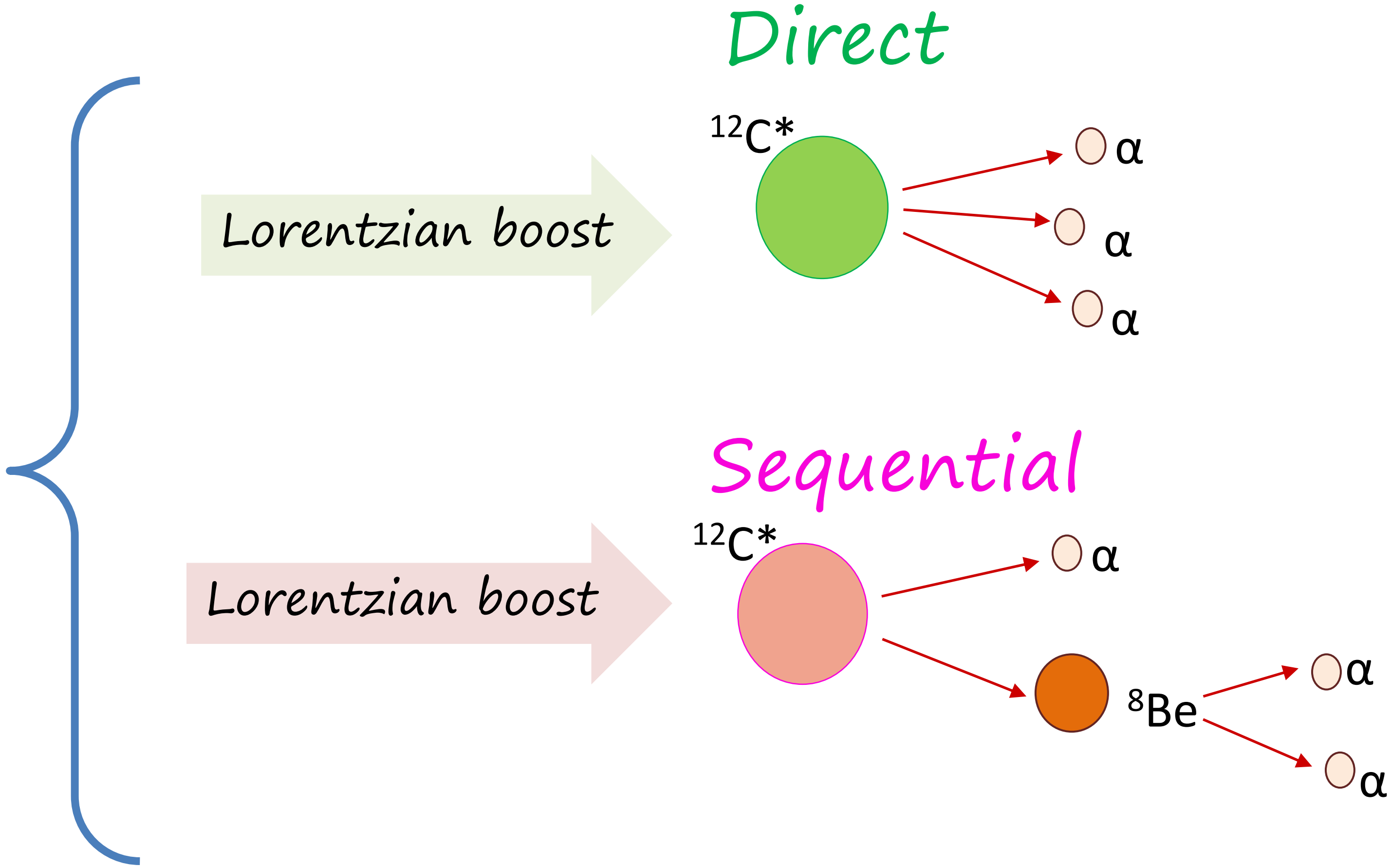
0_3^+ E_{star} = 10.3 MeV Γ=3 MeV

Montecarlo Simulations

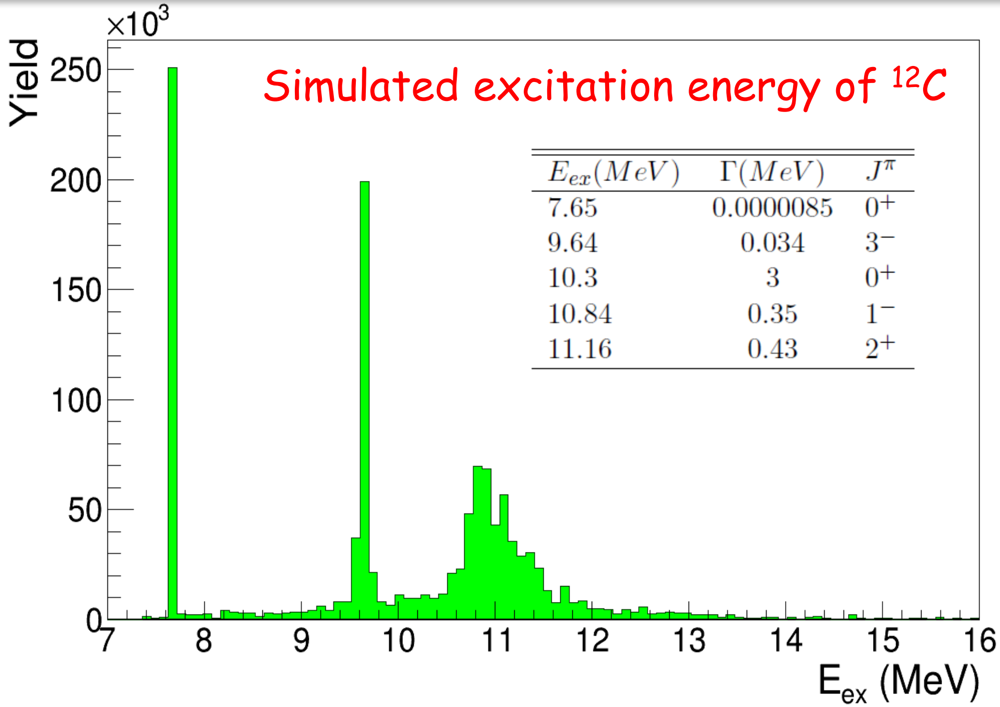
Genbod Monte Carlo events generator

D. Lacroix et al. ,Phys. Rev. C69 054604

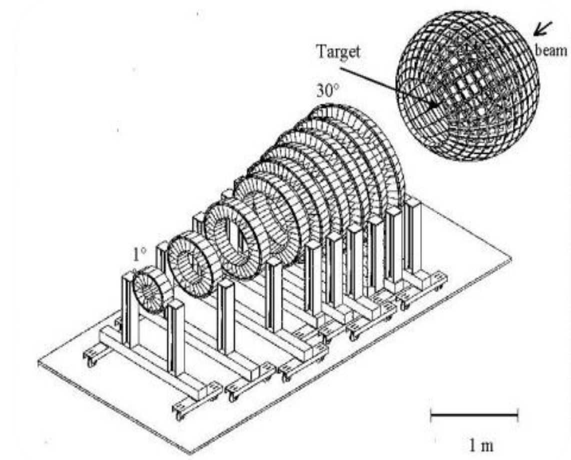
HIPSE



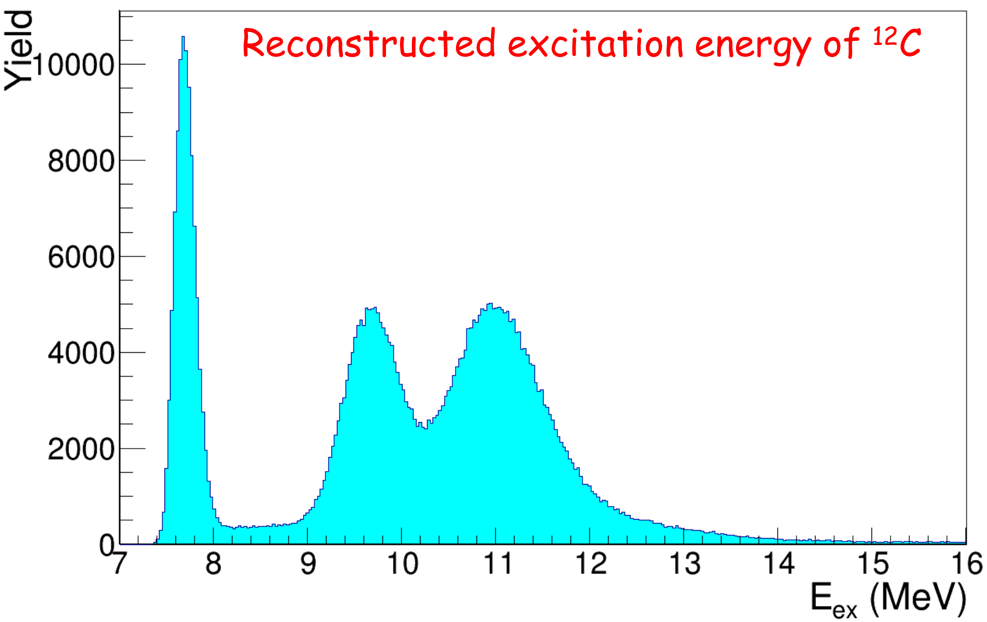
Detection simulations with CHIMERA apparatus



$E_{ex}(MeV)$	$\Gamma(MeV)$	J^{π}
7.65	0.0000085	0^+
9.64	0.034	3^-
10.3	3	0^+
10.84	0.35	1^-
11.16	0.43	2^+



Simulated data have been filter to the geometry and response of CHIMERA apparatus



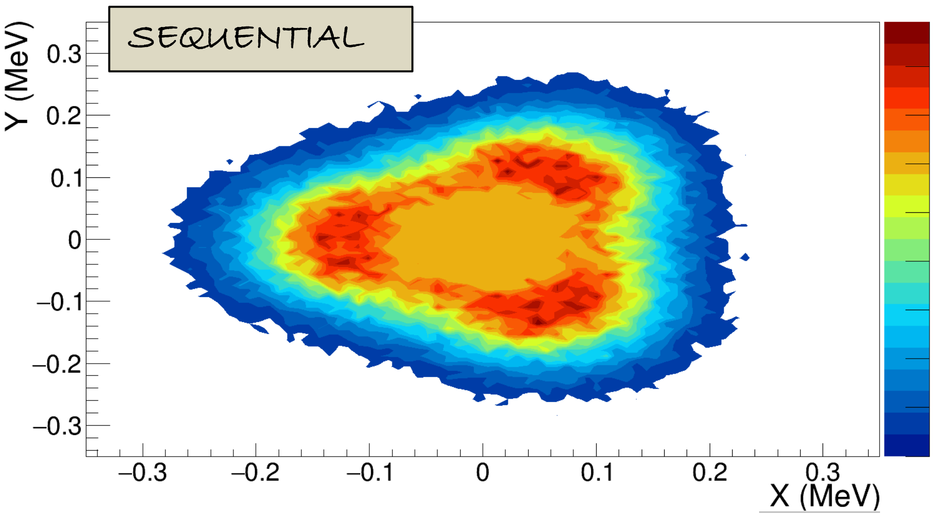
Hoyle State: Dalitz Plots

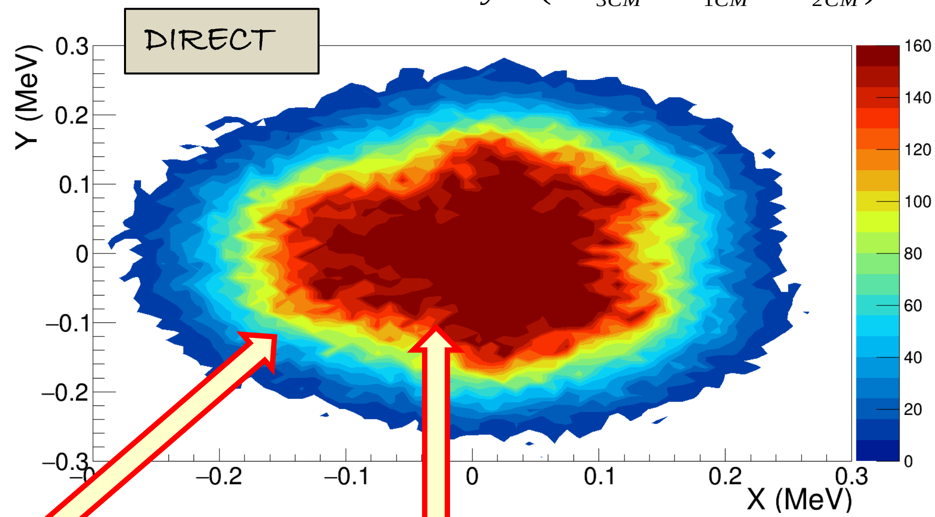
SIMULATED DATA

Dalitz parameter

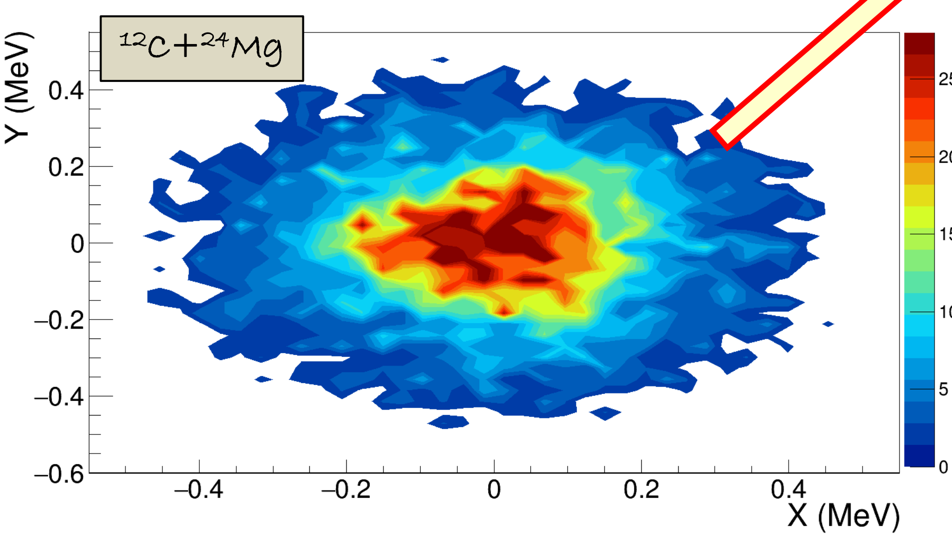
$$x = \sqrt{3}(E_{1CM} - E_{2CM})/3$$

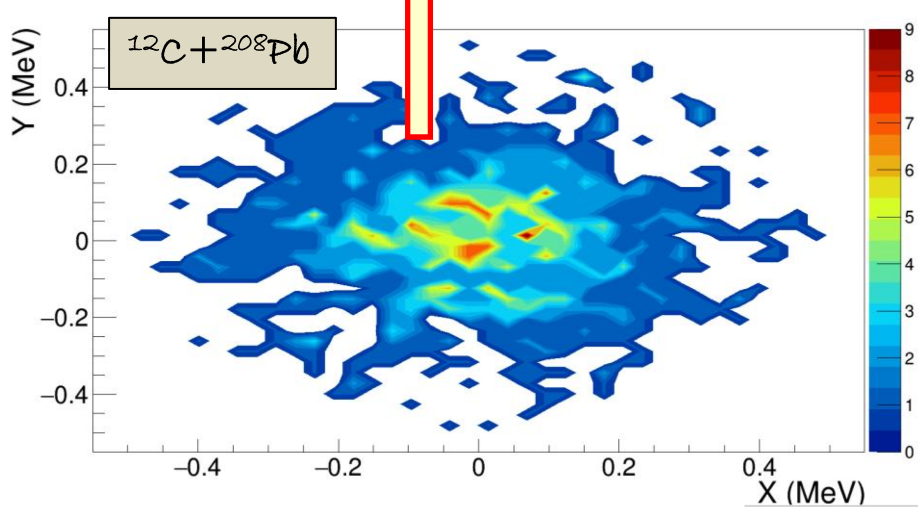
$$y = (2E_{3CM} - E_{1CM} - E_{2CM})/3$$





EXPERIMENTAL RESULTS





Hoyle State: Symmetric Dalitz Plots

Dalitz parameter

$x = \sqrt{3}(\varepsilon_i - \varepsilon_k)$

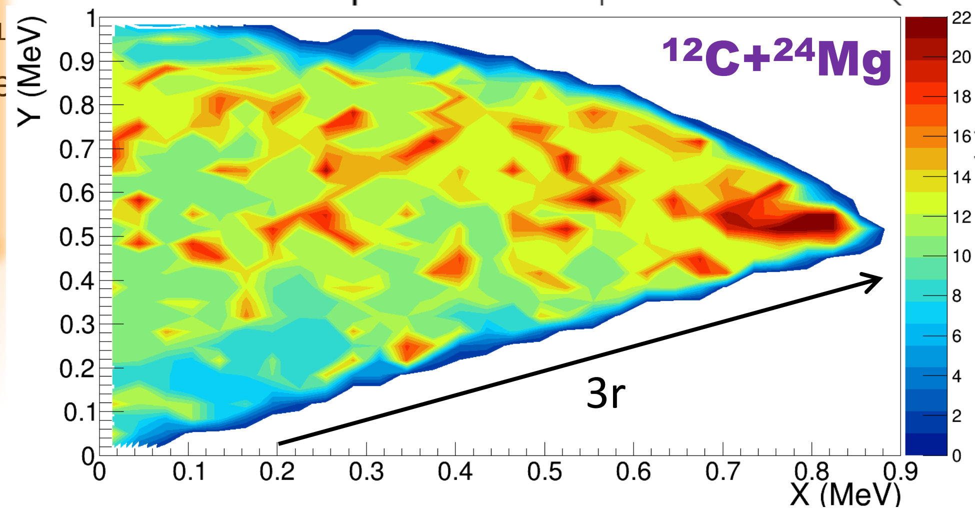
$\varepsilon_{i,j,k} = E_{i,j,k} / (E_i + E_j + E_k)$

Exhibits a more uniform distribution that does not allow us to exclude any of the two decay mechanisms

Radial parameter

$$(3r)^2 = 3(\varepsilon_j - \varepsilon_k)^2 + (2\varepsilon_i - \varepsilon_j - \varepsilon_k)^2$$

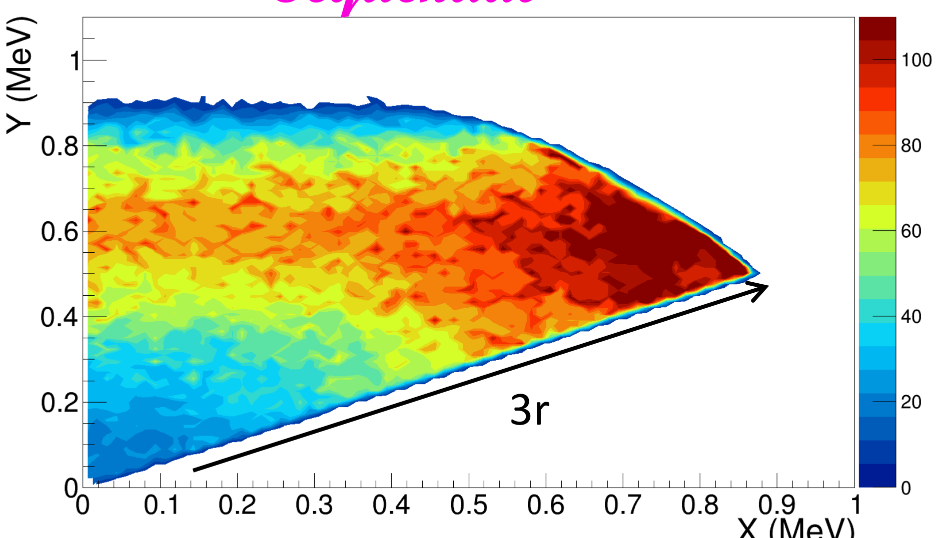
EXPERIMENTAL RESULTS



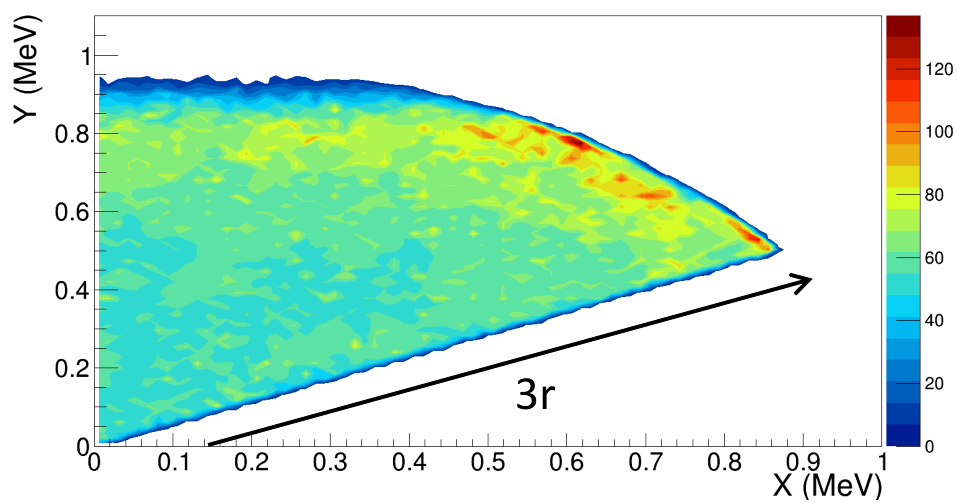
Itoh et al., PRL 113, 102501 (2014)

SIMULATED DATA

Sequential

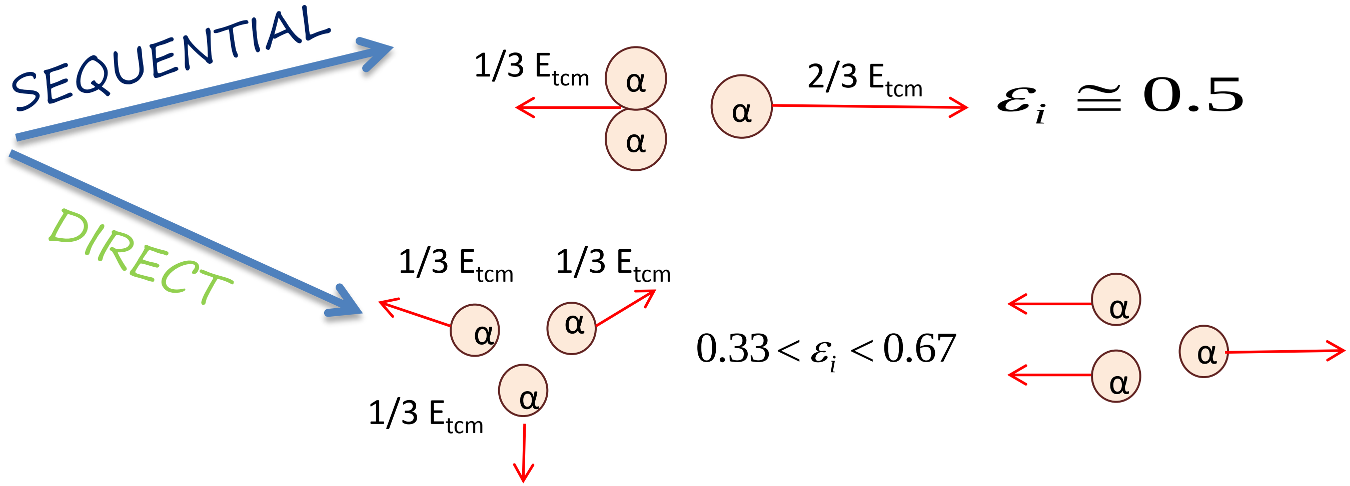


Direct



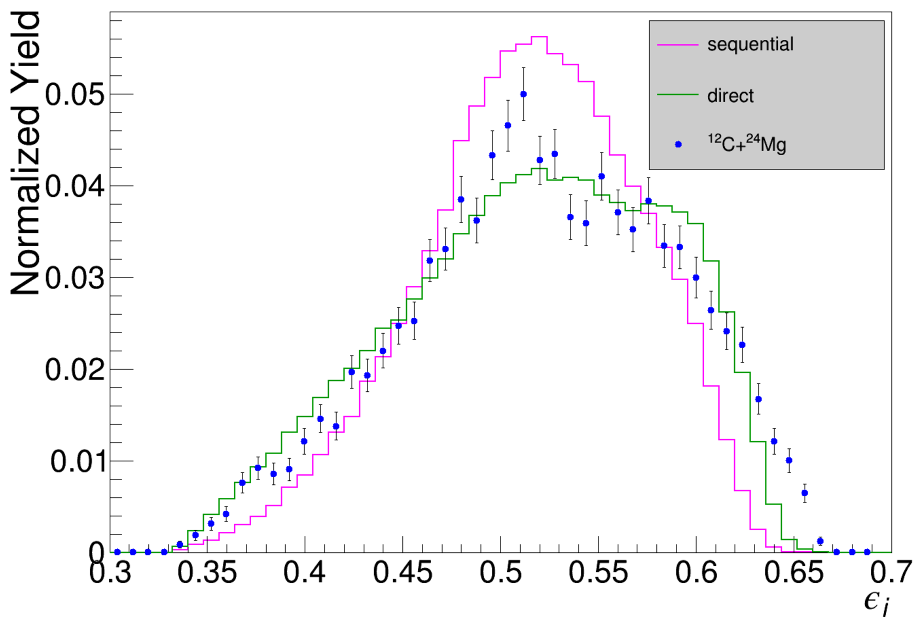
Hoyle State sequential vs direct: ε_i distribution

ε_i : *highest normalized energy among those of the 3α particles*

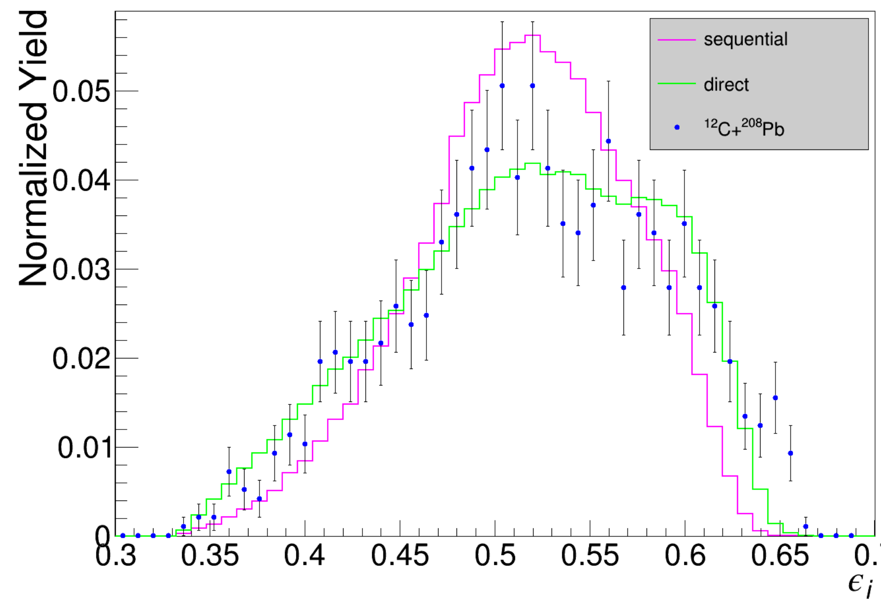


ε_i Distributions

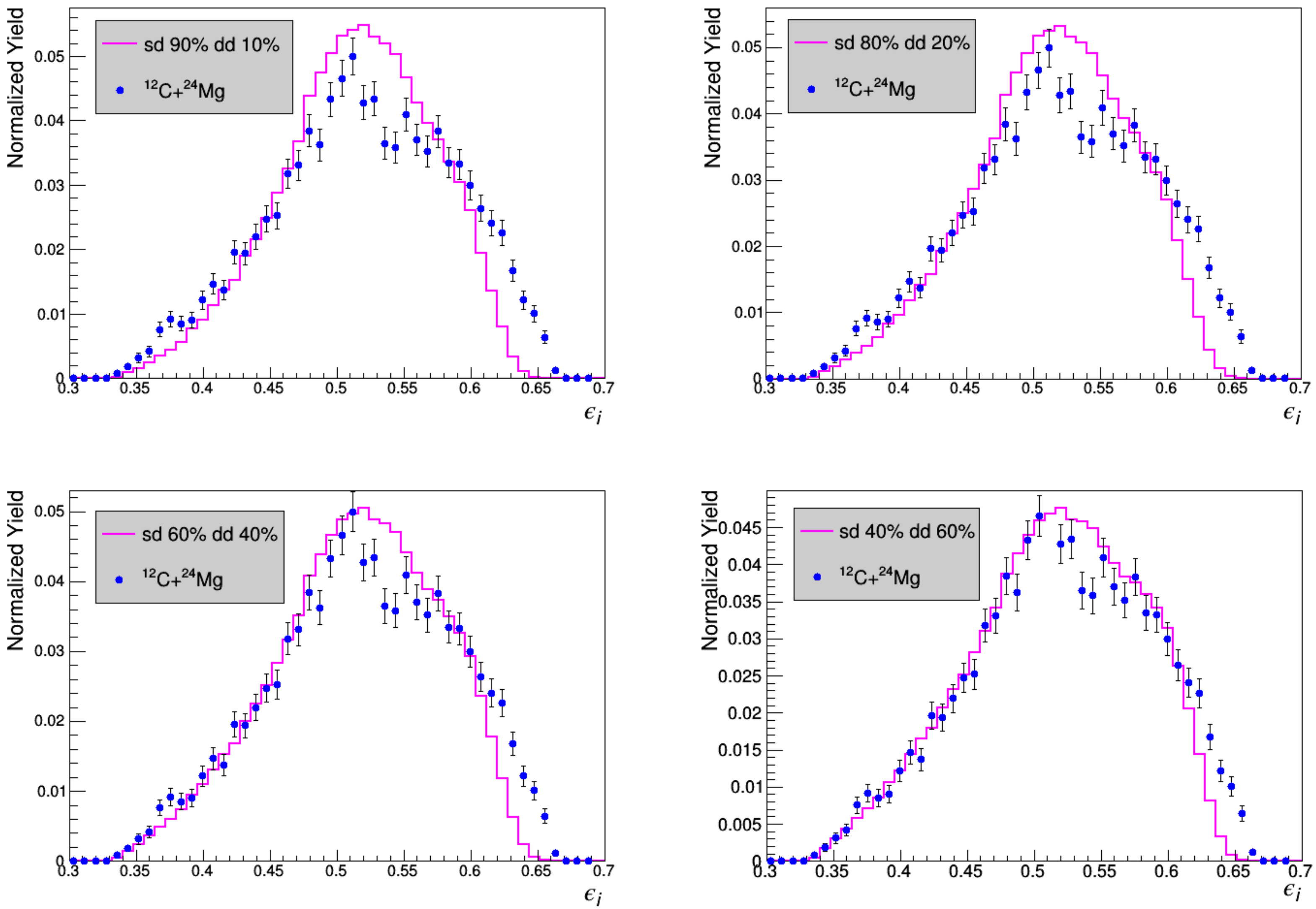
$^{12}C+^{24}Mg$



$^{12}C+^{208}Pb$



Sequential vs direct: fit of ε_i distribution



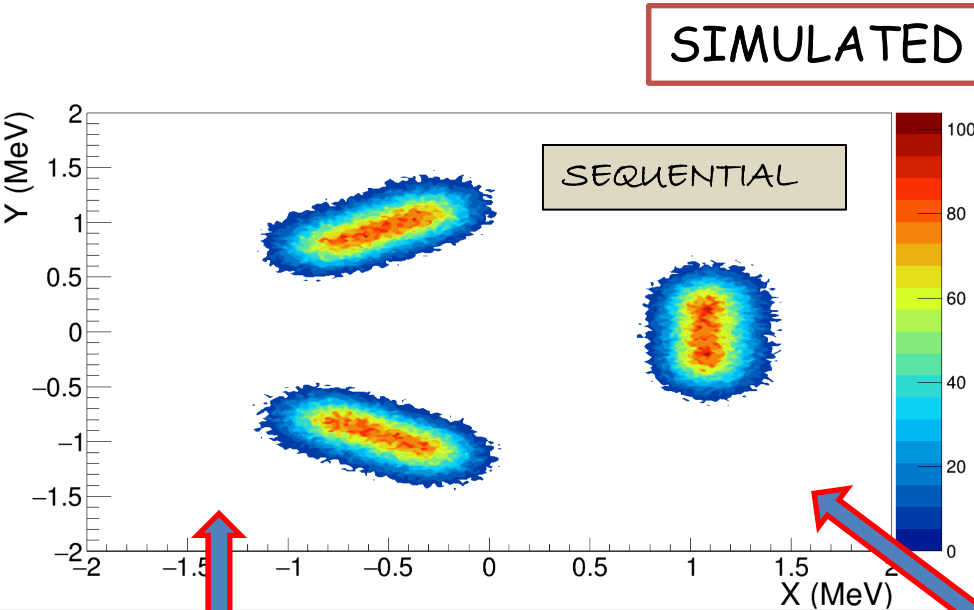
20 % < Direct Contribution < 60%

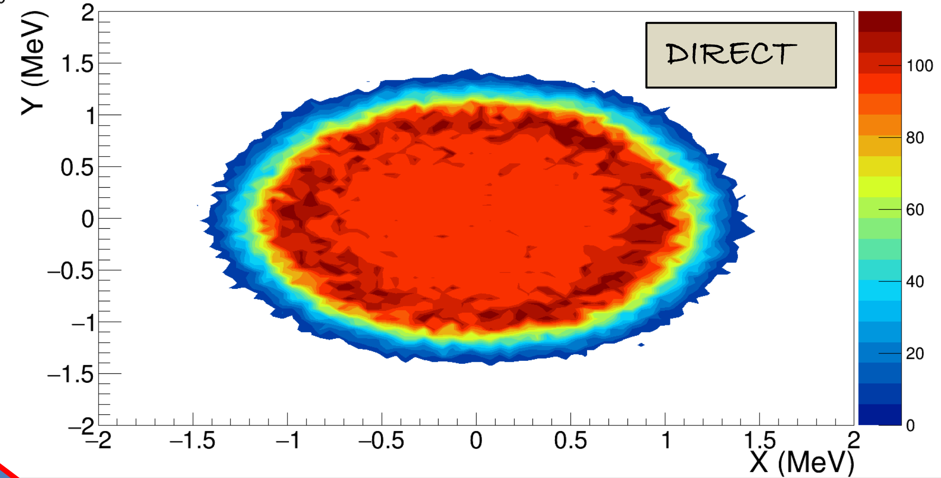
^{12}C state at E*=9.64: Dalitz Plots

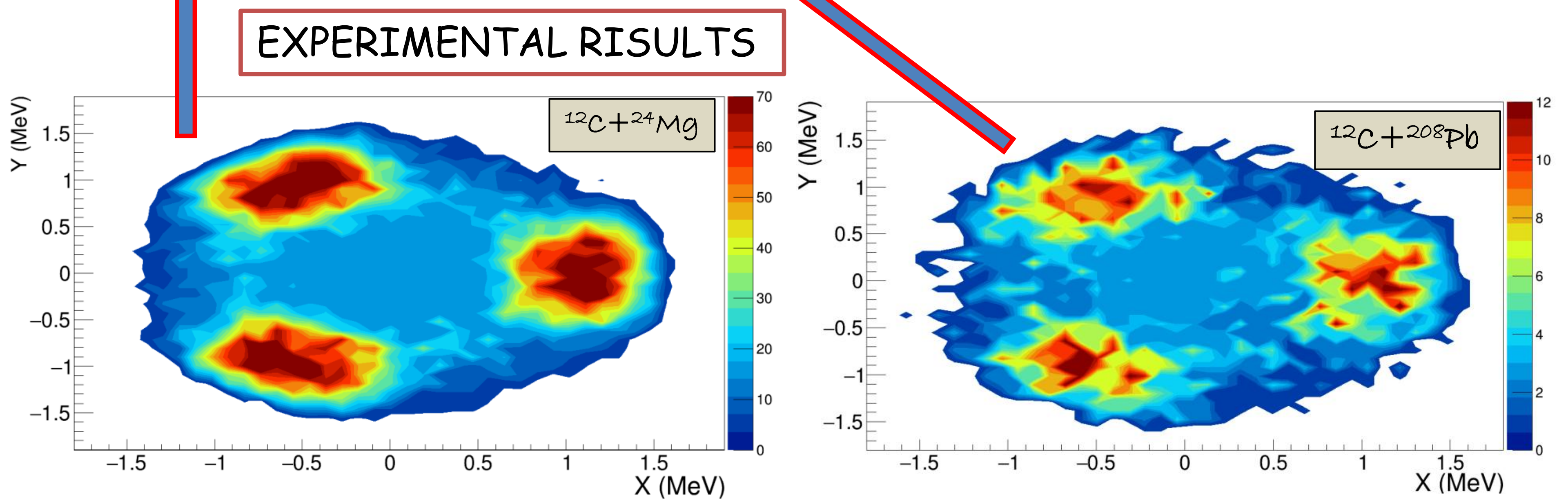
Dalitz parameters

$$x = (2E_{3CM} - E_{1CM} - E_{2CM})/2$$

$$y = \sqrt{3}(E_{1CM} - E_{2CM})/2$$





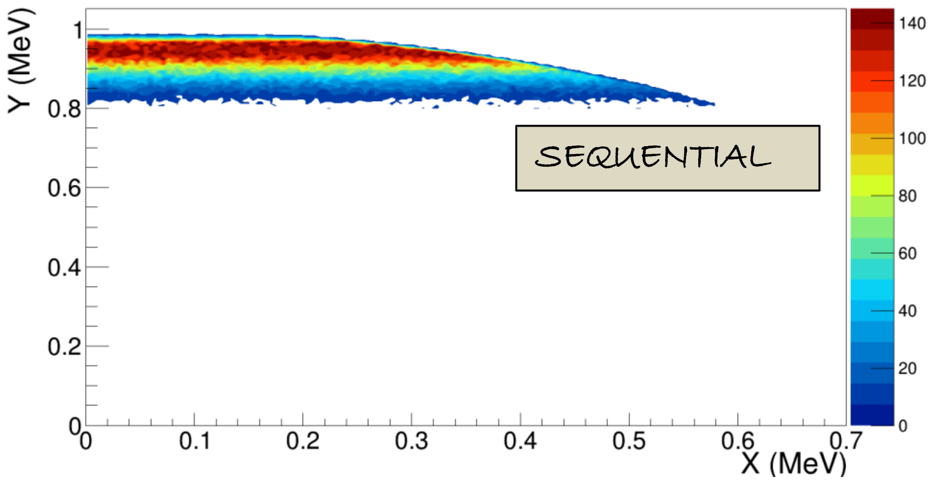


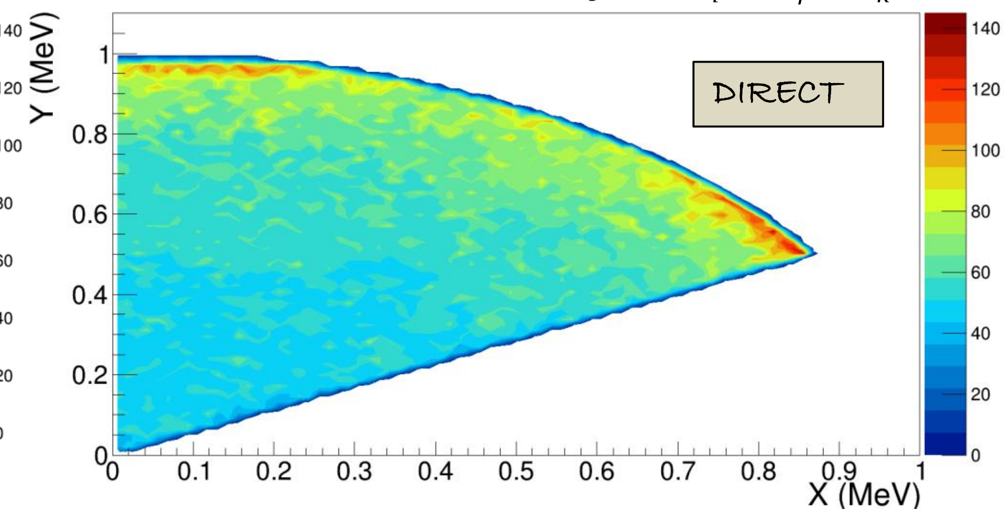
^{12}C states at E*=9.64: Symmetric Dalitz Plots

SIMULATED DATA

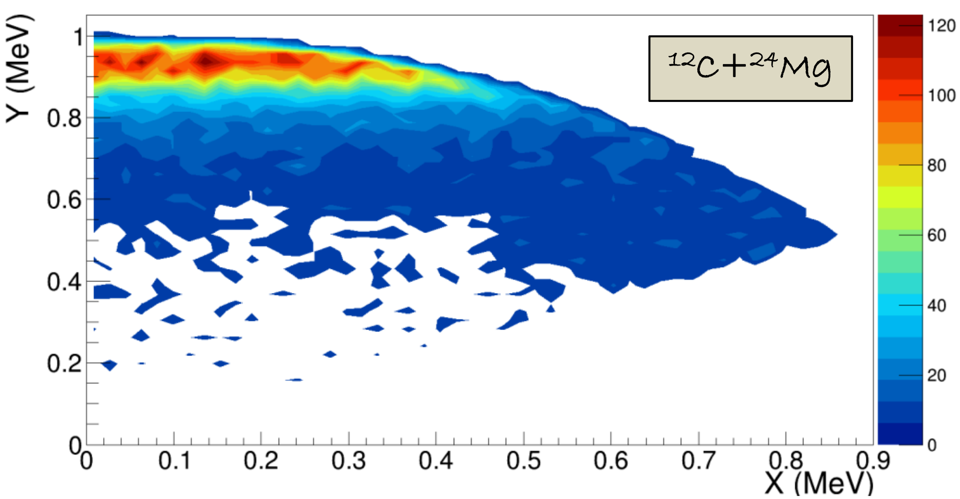
$$x = \sqrt{3}(\varepsilon_j - \varepsilon_k)$$

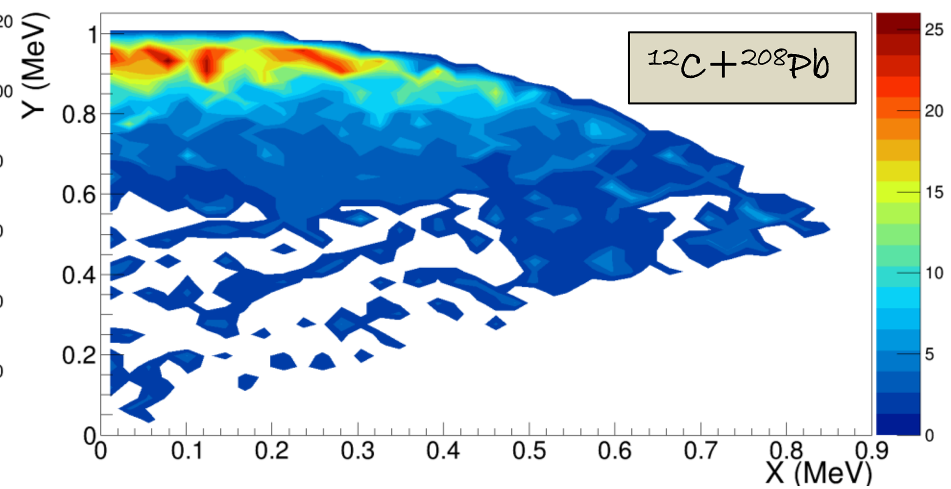
$$y = 2\varepsilon_i - \varepsilon_j - \varepsilon_k$$



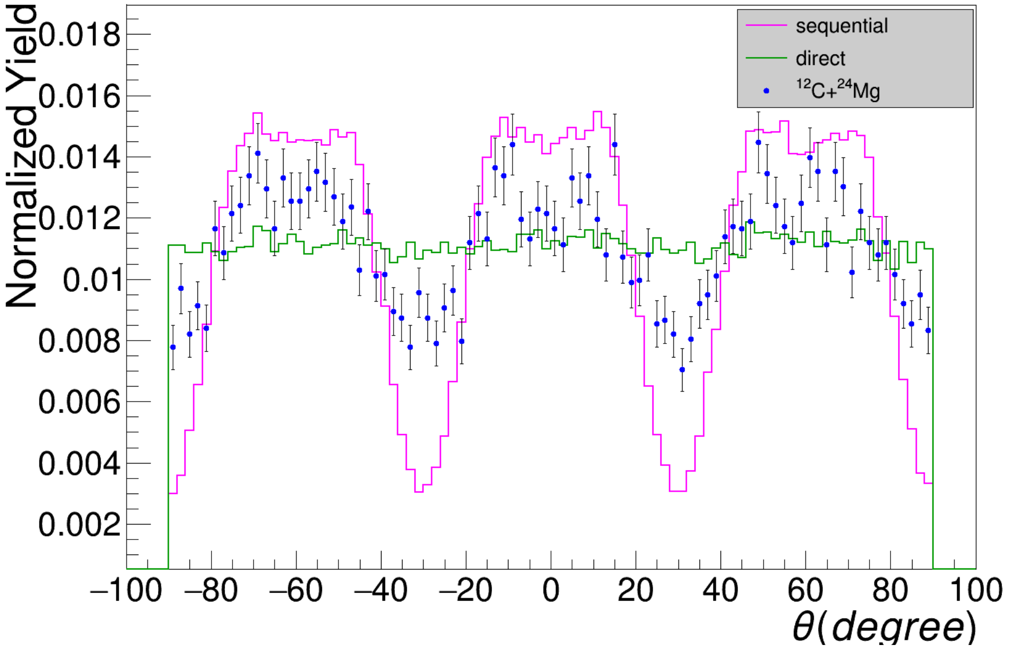


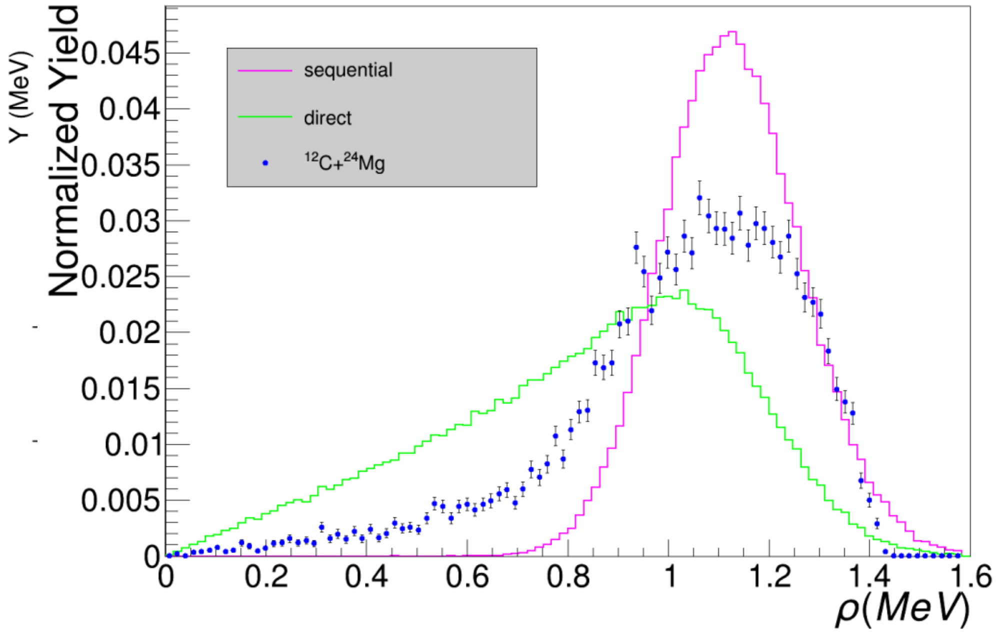
EXPERIMENTAL RISULTS



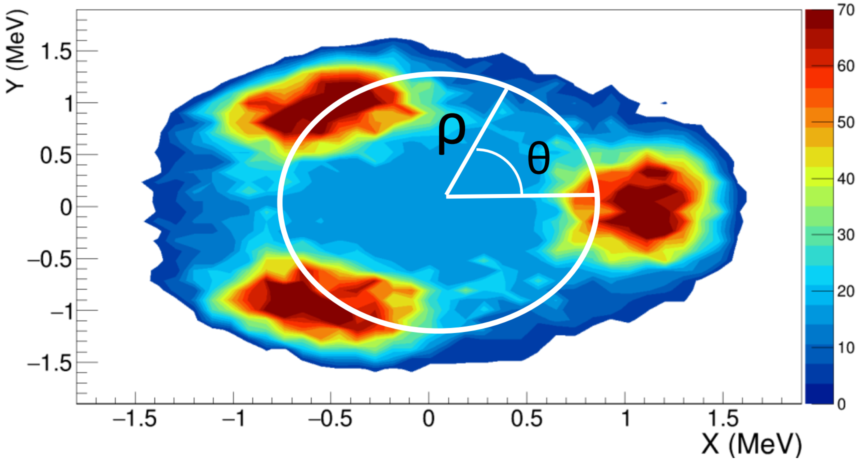


^{12}C state at E*=9.64 : Polar Dalitz correlation



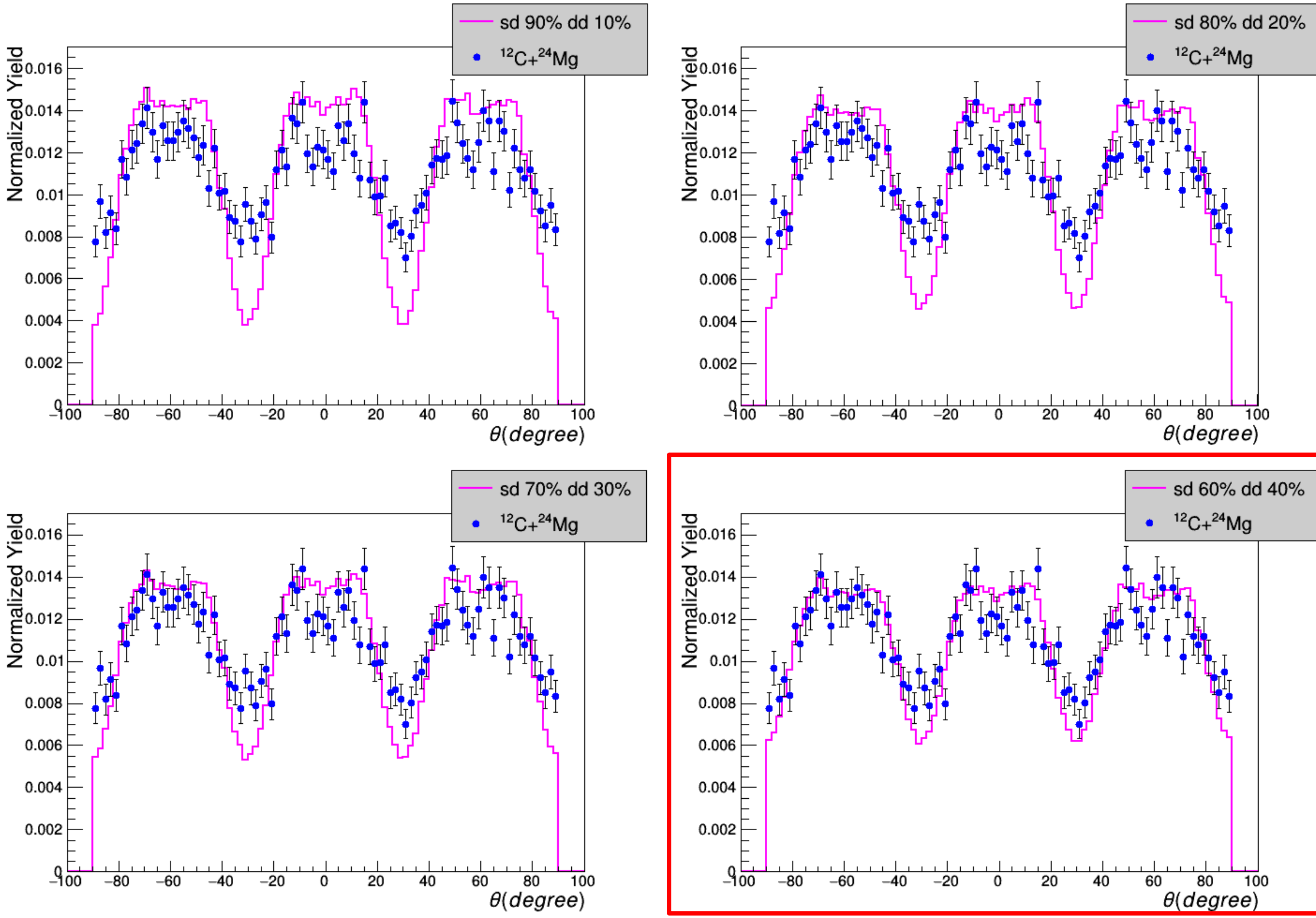


Change of coordinates X,Y-> θ, ρ



Entirely direct or sequential mechanisms are not able to explain experimental data

Fit of Polar Dalitz correlation plots



In- medium dynamics on the structure properties?

Direct contribution ~ 40%

Medium characterization: emission temperatures

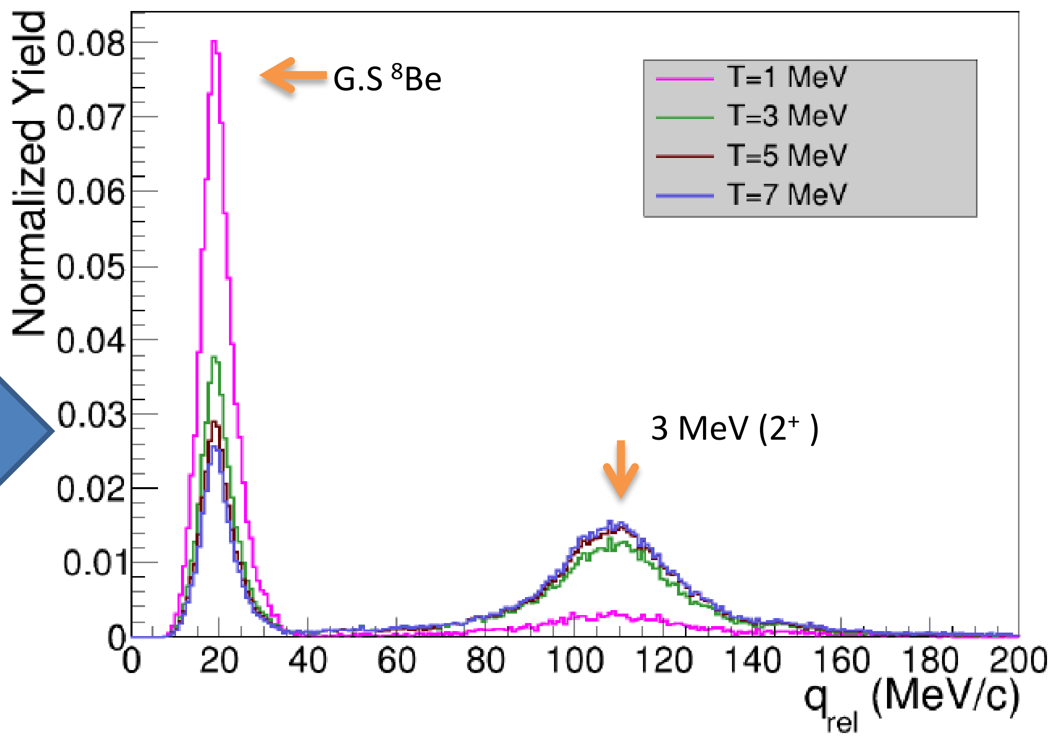
Thermal Model

The relative population of particle unstable states is strictly related to the temperature of the system

$$R_{ij} = \frac{Y_i}{Y_j} = \frac{(2J_i+1)}{(2J_j+1)} e^{-\Delta E/T}$$

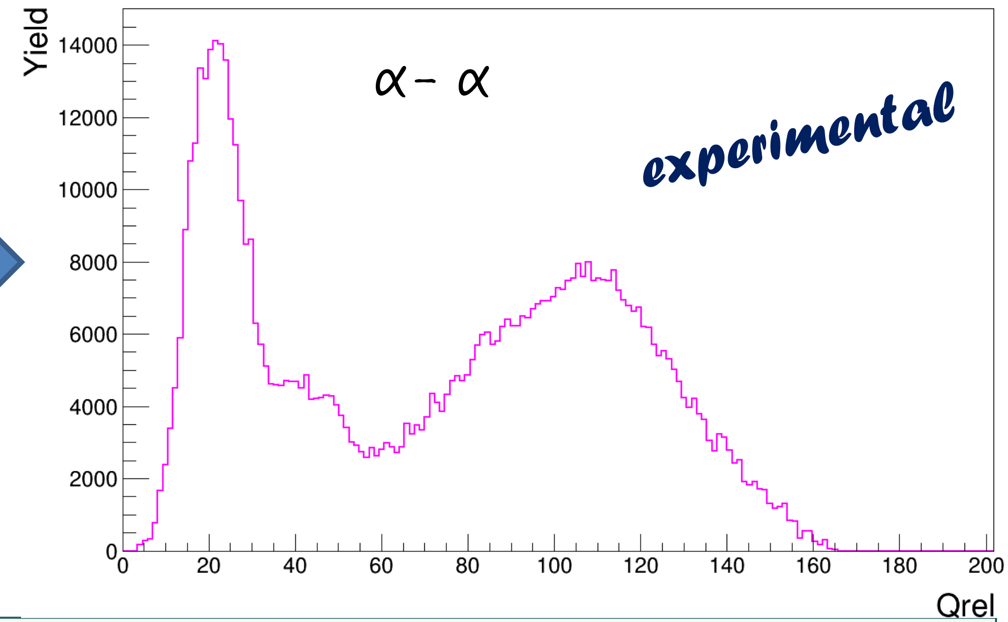
Simulated taking into account the temperature dependence of relative population of parent nucleus states

$^8Be \rightarrow 2\alpha$

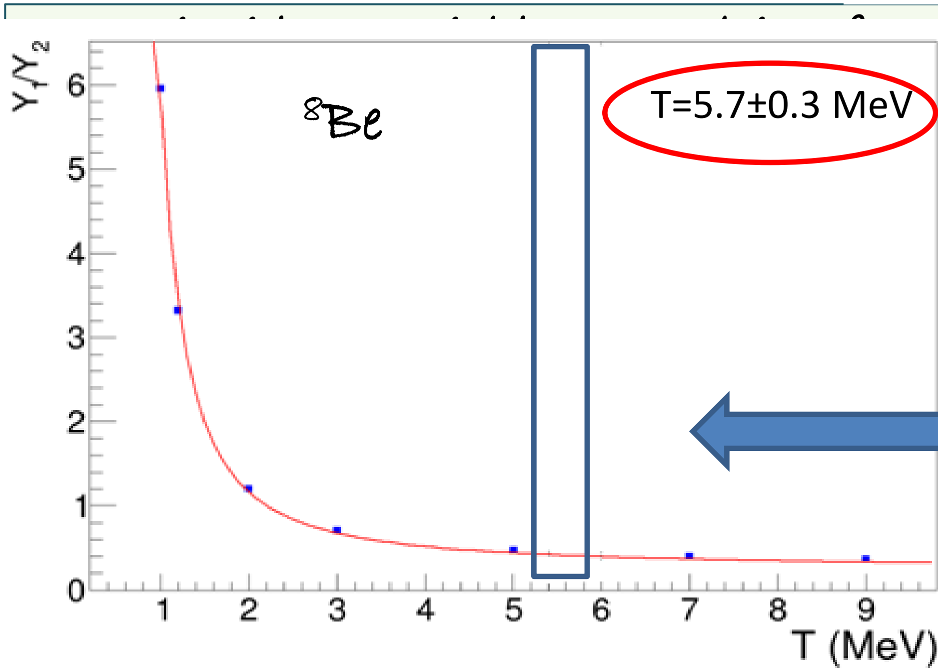


Medium characterization: emission temperatures (2)

Experimental α- α coincidence spectrum has been integrated over the range of energy dominated by corresponding resonances



… the decay of particles states is … given by:



Coulomb

$R_b(q)]$

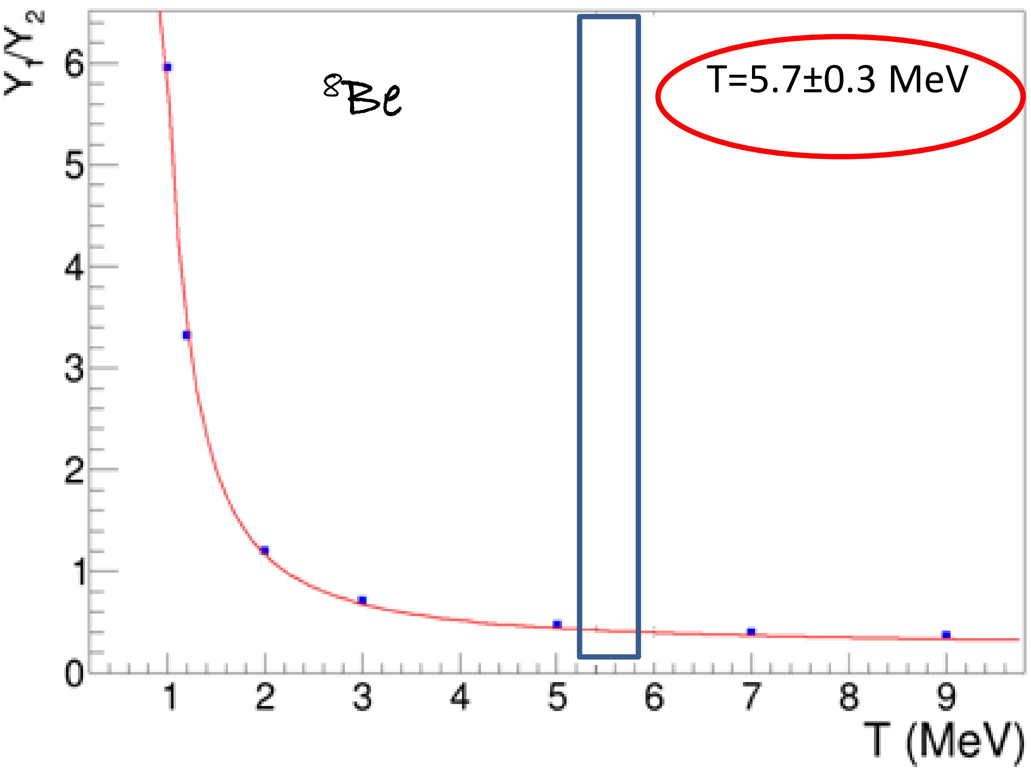
Background correlation Function

Range of experimental temperature values consistent with the assumption for the Coulomb background correlation function

$R_b(q)$ is varied within reasonable limits and the effect of final results have been calculated

In- medium dynamics on the structure properties?

Quasi- projectiles system represents a warm medium at temperature that may approach 5 MeV values!



Nuclear properties, reflected in measurements of resonances positions branching ratios, etc., could be modified by the medium where the decay of these unbound state occurs.

New experiments ……

<u>FAZIACOR</u>

$^{32}S+^{12}C$ and $^{36}S+^{12}C$ @ 25, 55 AMeV with FAZIA array

Spokespersons: G. Verde and D. Gruyer

Conclusions

Study of two- and three- particles correlations in dissipative QP decay

⇩

✓ ^{8}Be emission Temperature (Thermal model)

✓ Focus on ^{12}C: strong contribution of direct decay mechanism is present for all observed states (in agreement with Raduta et al. In $^{40}Ca+^{12}C$ with CHIMERA and Grenier et al. In $^{12}C+^{24}Mg$ with INDRA);

✓In- medium dynamics on the structure properties: effects of medium on structure properties of observed states???

✓ such direct decay could depend on complicate case of final state interactions within the 3α particle system produced by projectile fragmentation

Collaboration

L. Quattrocchi[1,2], L. Acosta[3,13], F. Amorini[7], A. Anzalone[7], L. Auditore[1,2], G. Cardella[3], A. Chbihi[5], E. De Filippo[3], Francalanza[7,9], G. Lanzalone[7,10], I. Lombardo[8,11], I. Martel[6], T. Minniti[9], S. Norella[1,2], A. Pagano[3], E.V. Pagano[7,9], M. Papa[3], S. Pirrone[3], G. Politi[3,9], F. Porto[7,9], F. Rizzo[7,9], E. Rosato[8,11†], P. Russotto[3], A. Trifiro[1,2], M. Trimarchi[1,2] G. Verde[3,4], M. Veselsky[12], M. Vigilante[8,11]

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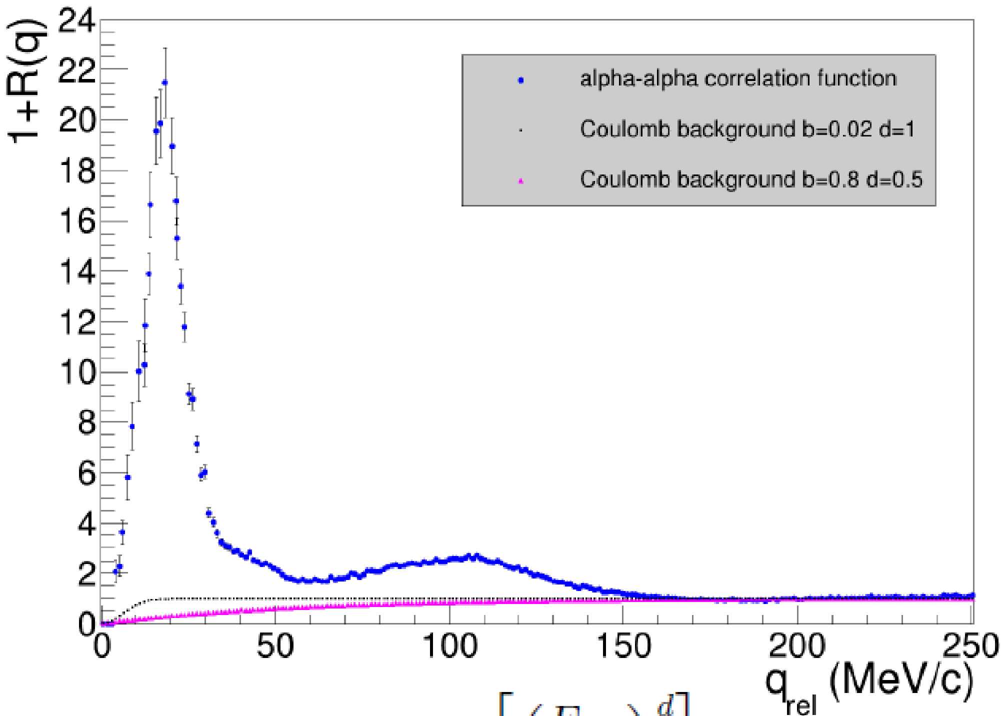
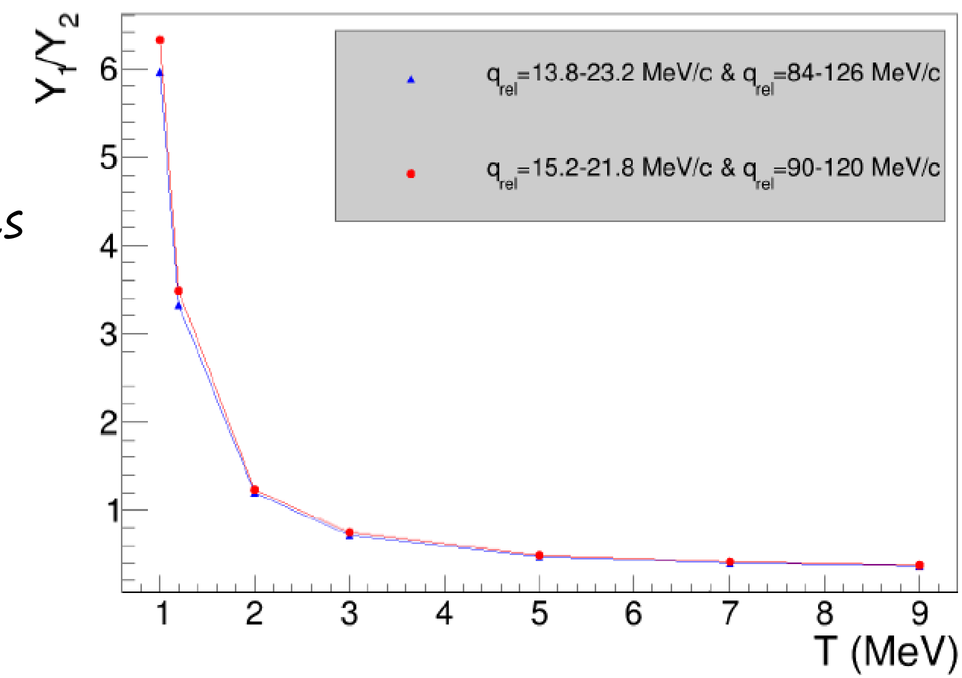
† Deceased



Using the two Coulomb background correlation functions, shown in Fig. 4.6, calculated yield ratio changes of less then 5% and the extracted temperature by about 0.6 MeV

the yield ratio Y1/Y2 is no more sensitive to the energy ranges chosen for integration.

$$1 + R(q) = 1 - exp\left[\left(\frac{E_{rel}}{b}\right)^d\right]$$



b and d are free parameters. This phenomenological function describes very well two-particle correlations which are not dominated by resonant interactions, but only by long-range Coulomb repulsion