Nucleus Nucleus 2015
21-26 June 2015 Catania

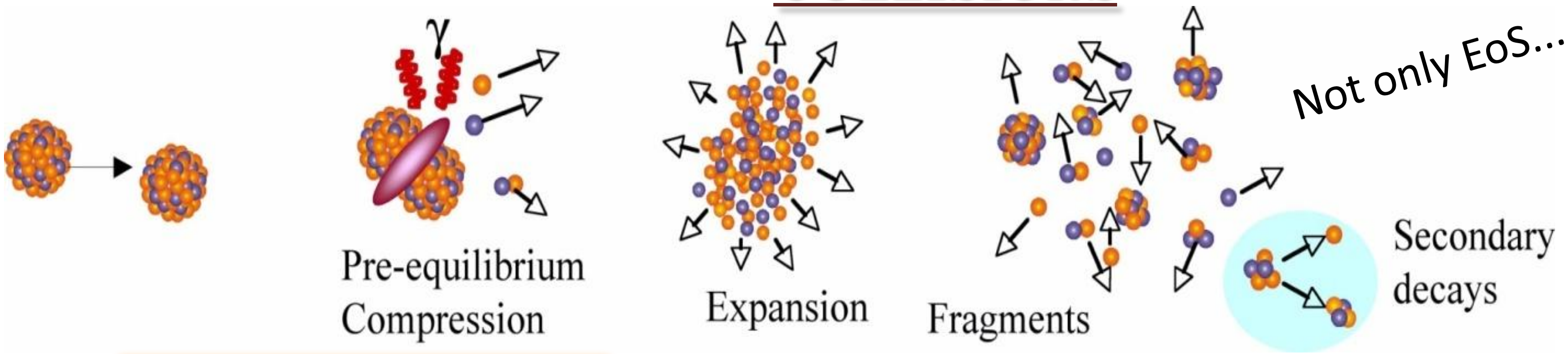
Lucia QUATTROCCHI[1,2]

1-Università degli Studi di Messina
2- INFN- Gruppo Collegato di Messina

STUDY OF TWO AND MULTI PARTICLE CORRELATIONS IN $^{12}C+^{24}Mg$ AND $^{12}C+^{208}Pb$ REACTIONS AT E=35AMeV

PHYSICS CASES

TWO AND MULTI PARTICLE CORRELATIONS IN HEAVY ION COLLISIONS



Not only EoS...

Nuclear Dynamics

- Femtoscopy: space -time probes of light particle emitting source
- Nuclear Equation of State

Secondary decays,unbound states,spectroscopy tools

Invariant Mass Spectroscopy

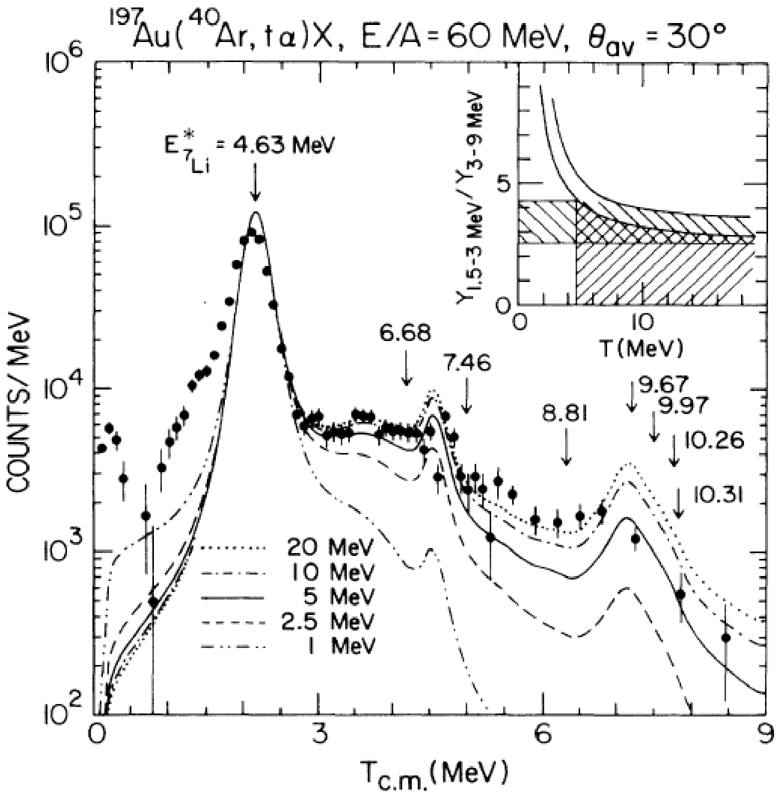
- Reconstruct unbound states from correlation of two and multi particle decay
- Spin of states, branching ratio for simultaneus and sequential decay
- clusters, boson condensates, new states....

Correlations: interconnections between nuclear dynamics and spectroscopy

PHYSICS CASES

"emission temperature"

^{7}Li->t-α



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

THERMAL MODEL

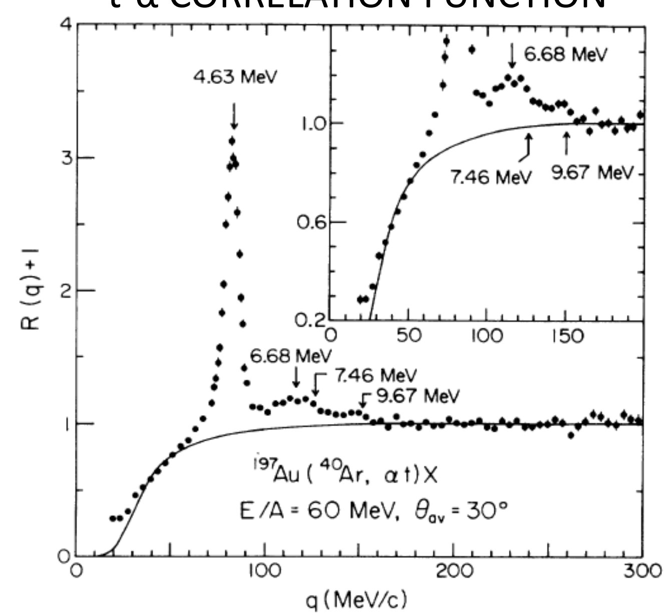
Relative populations used to determine temperature

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

Correlation function depend on some of spectroscopic properties (if no collective motion G. Verde, P. Danielewicz et al. Physics B653 (2007))

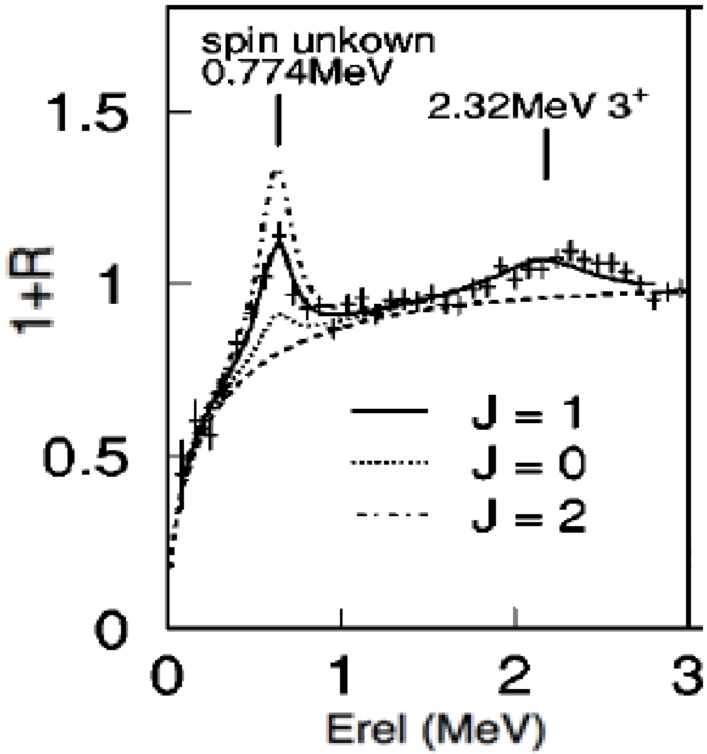
$$1 + R(E_{rel}) = \frac{Y_{corr}(E_{star})}{Y_{uncorr}(E_{star})} \propto \sum_i (2J_i + 1) \left[\frac{\Gamma_i / 2}{(E - E_i)^2 + \Gamma_i^2 / 4} \right];$$

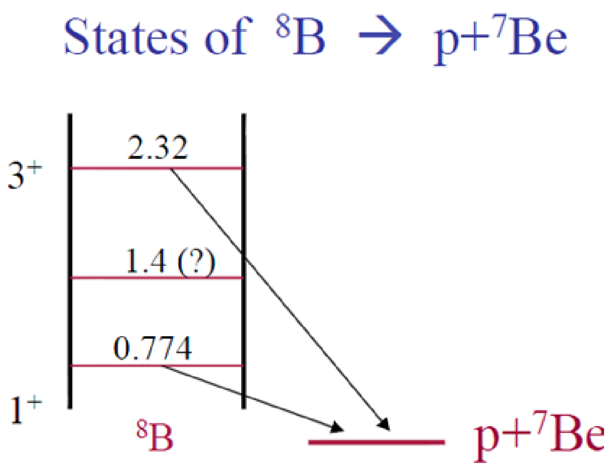
t-α CORRELATION FUNCTION



Spin determination

Xe+Au E=50 AMeV
central collisions
(LASSA data)





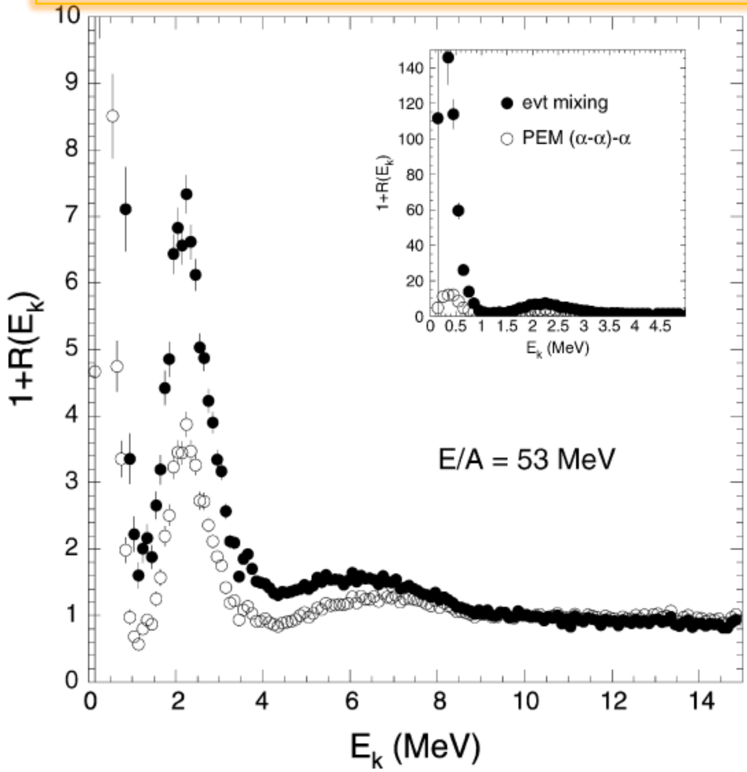
W.P. Tan et al. Phys. Rev. C69, 061304 and PhD thesis MSU

Multi particles correlations in same experiment

Study of 3body decays: branching ratios- direct vs sequential

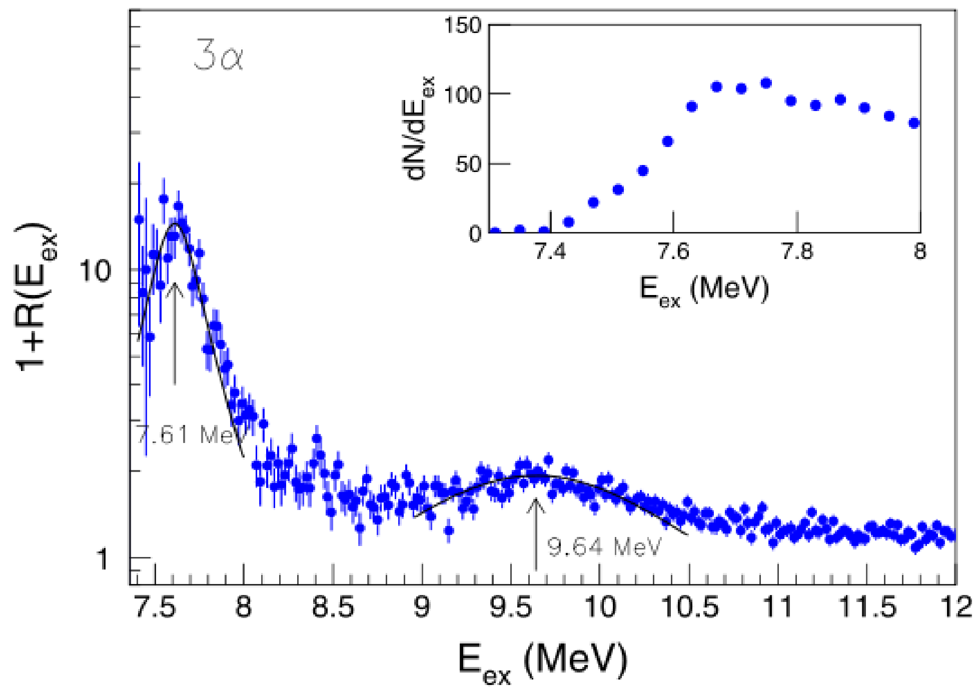
$^{12}C \rightarrow 3\alpha$

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

Resonances decay to study dynamics/ mechanism and to probes some spectrocopic properties

"CORRELATION" EXPERIMENT AT LNS WITH CHIMERA

feasibility of multi particle correlation analyses with CHIMERA

→ $^{12}C + ^{24}Mg$ 35 AMeV

→ $^{12}C + ^{208}Pb$ 35 AMeV

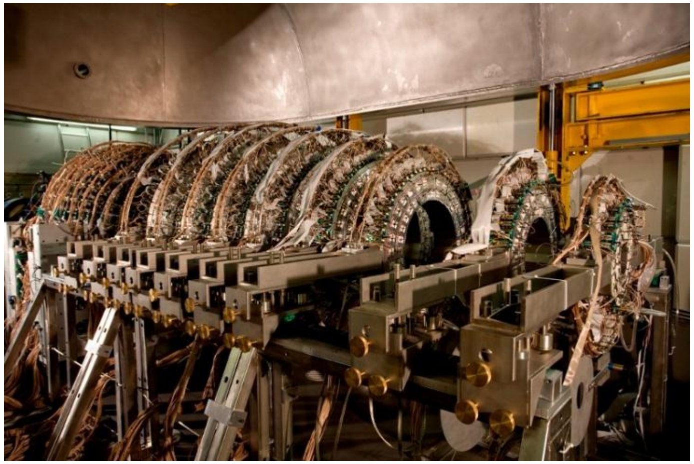
MAIN GOALS

- **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:

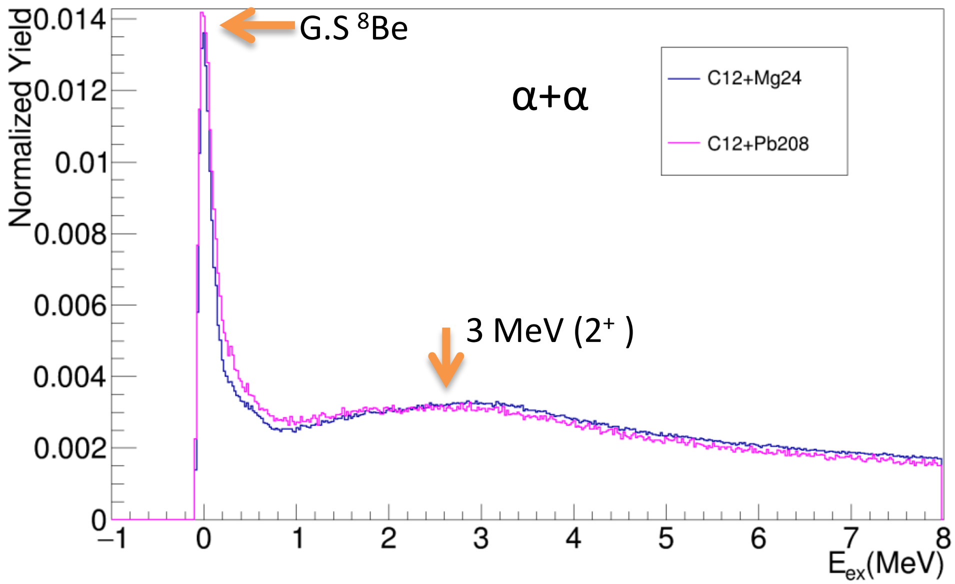
0°<θ<30° QP decay in semi-pheripheral collisions

Particles identification:

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

TWO PARTICLE CORRELATION WITH CHIMERA

$^{8}Be \rightarrow 2\alpha$



^{8}Be states

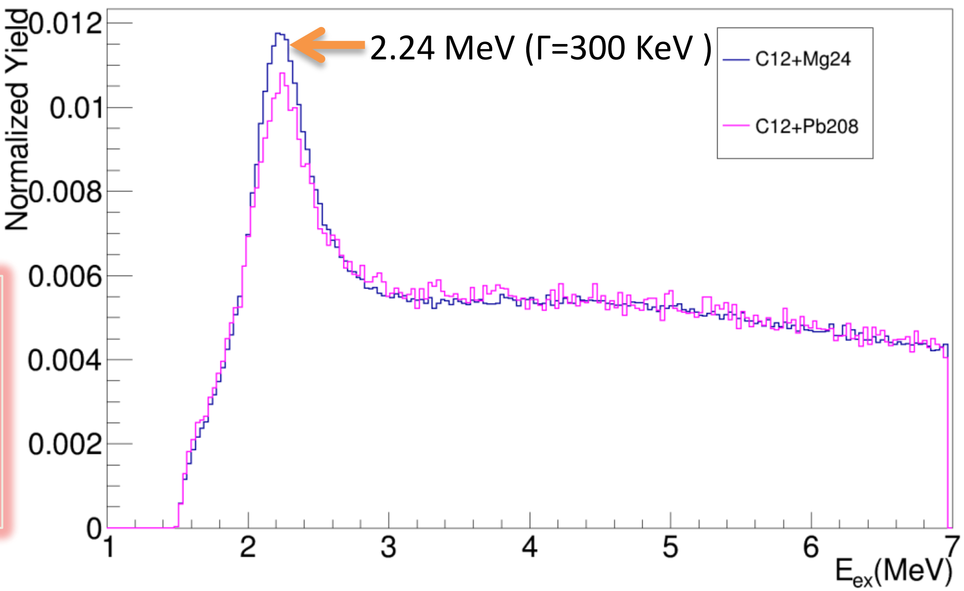
G.S. E_{rel} (total energy in CM)=92 keV

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

^{6}Li states

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

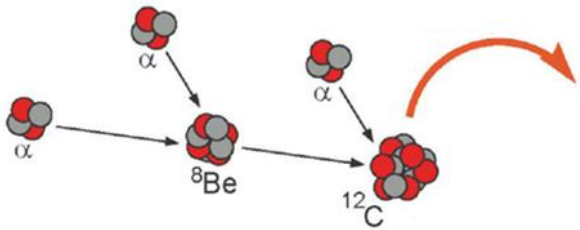
$^{6}Li \rightarrow d+\alpha$

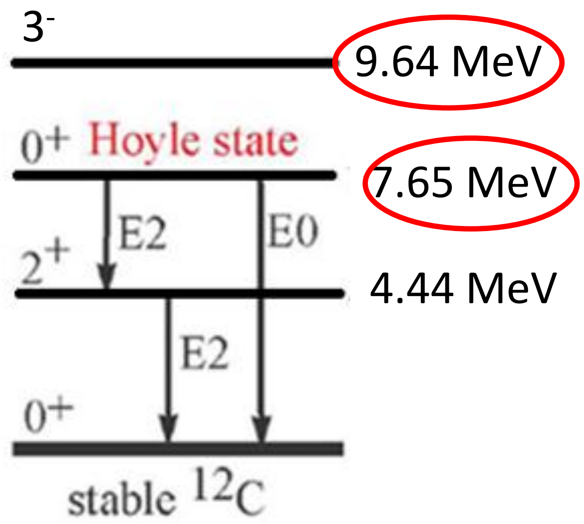


Good quality of particle calibrations
Good angular resolution

Study of dynamics-thermal properties
+
Mechanisms of resonances decay
($^{12}C \rightarrow 3\alpha$, $^{10}B \rightarrow \alpha+\alpha+d$ and many others..)

EXCITED STATES IN ^{12}C





- **Nucleosyntesis**
- **Nuclear structure and reactions**

Intriguing discrepancies in sequential vs direct observed in different experiments!

✓M. Freer et al., PRC 49 (1994) R1751: upper limit 4% for direct 3-alpha decay ^{12}C+^{12}C 54 MeV (inel. scatt.)

✓ T.K. Rana et al., PRC 88 021601 (2013) : 0.3 ± 0.1% for DDE (alpha condensation) and 0.01±0.03% for DDL (linear alpha chain) inel. scatt. α (60 MeV) + ^{12}C

✓ Raduta et al. ,Phys. Lett. B 705, 65 (2011) : 7.5 ± 4.0% for DDE and 9.5±4.0 % for DDL in quasi proj. fragmentation ^{40}C+^{12}C 25AMeV

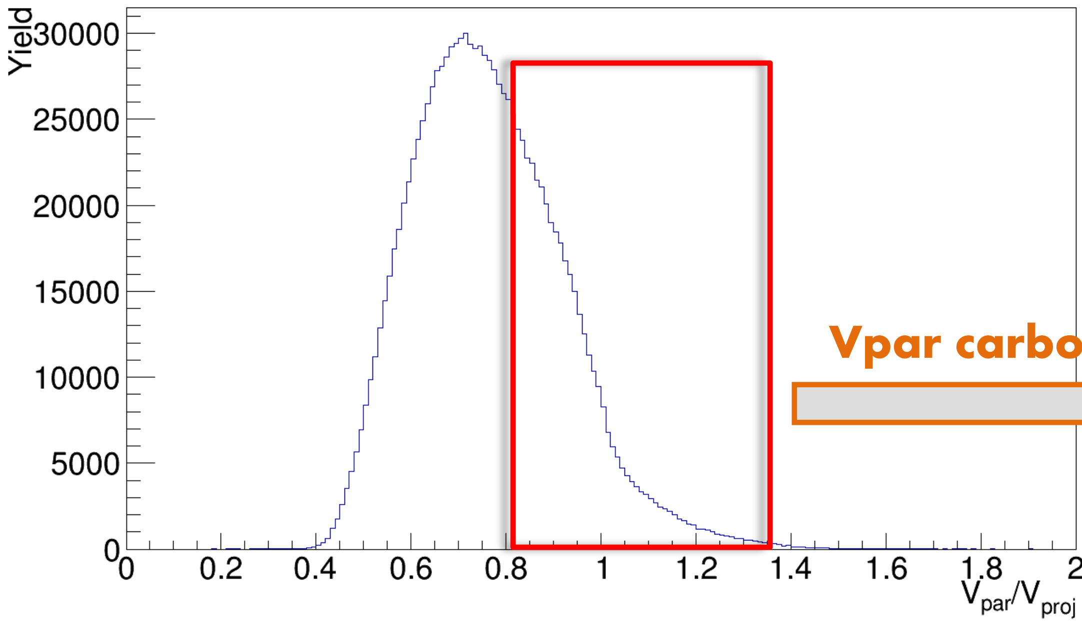
✓ Manfredi J. et al., PRC 85 037603 (2012): upper limit 0.45% for DDE transfer reactions from ^{10}C at E= 10.7 AMeV;

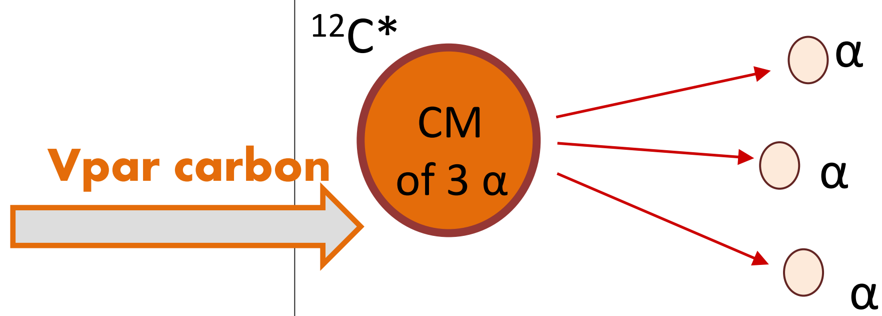
✓ Itoh et al., PRL 113, 102501 (2014): upper limit 0.08 % for DDE

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

Events Selection

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





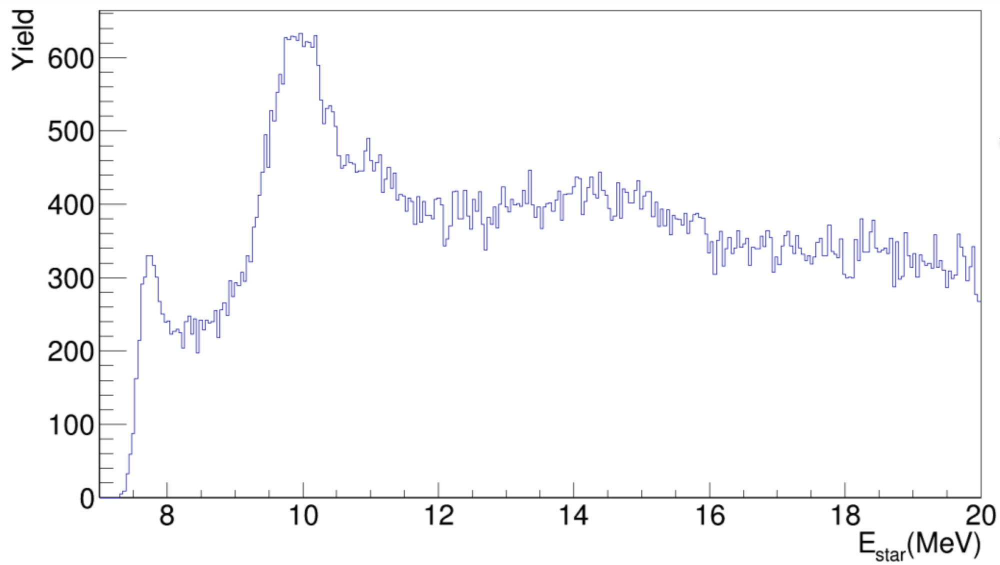
SELECTION: $$\frac{V_{par}}{V_{proj}} > 0.8 \qquad V_{proj} = 7.99\, cm/ns$$

Confirmed by comparison with model prediction

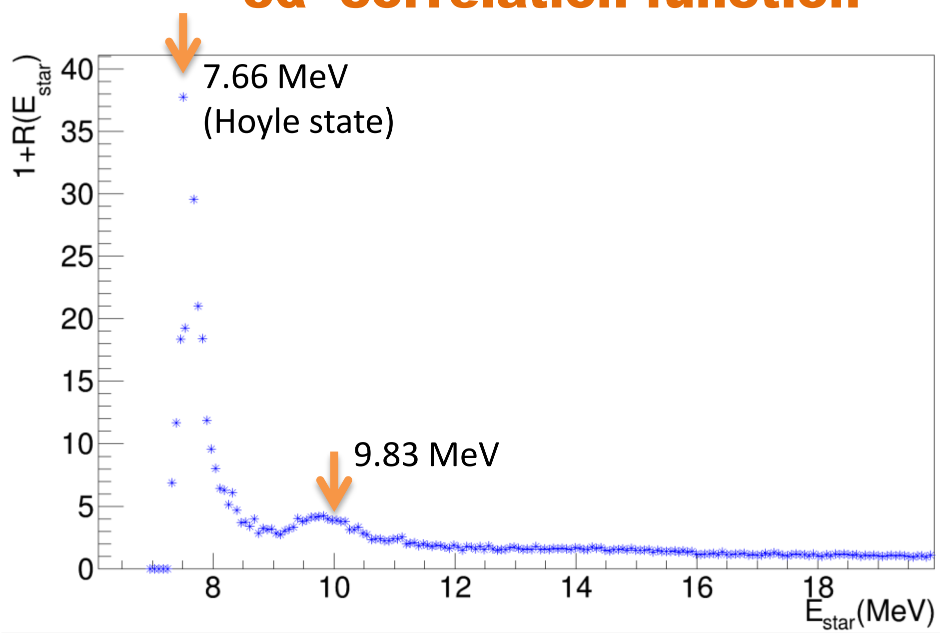
D. Lacroix et al. ,Phys. Rev. C69 054604

3α Correlation 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

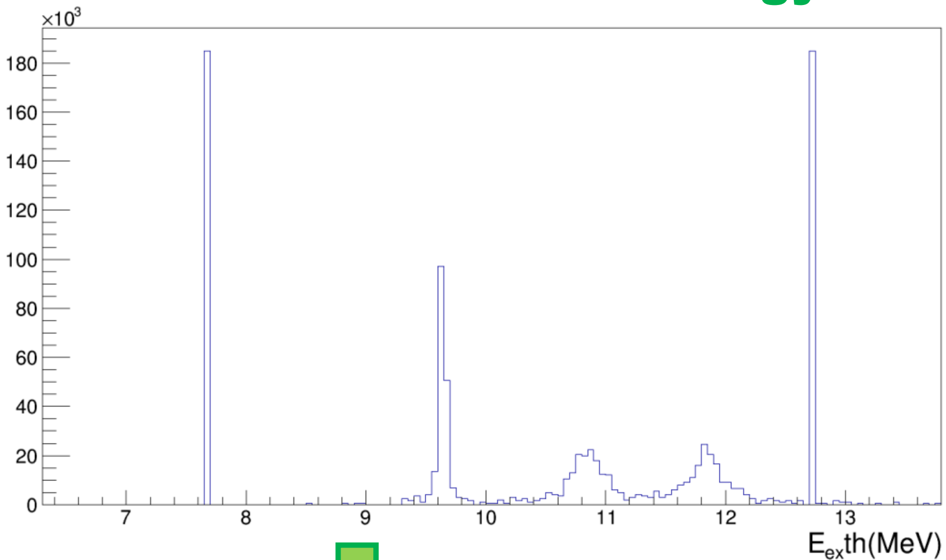
3^- E_{star} = 9.641 MeV Γ=34 keV

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

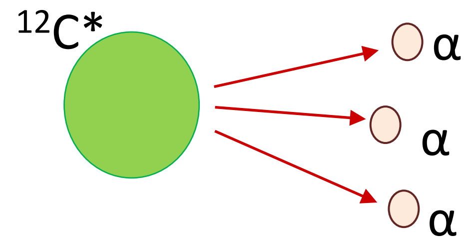
0_3^+ E_{star} = 10.3 MeV Γ=3 MeV

Montecarlo Simulations

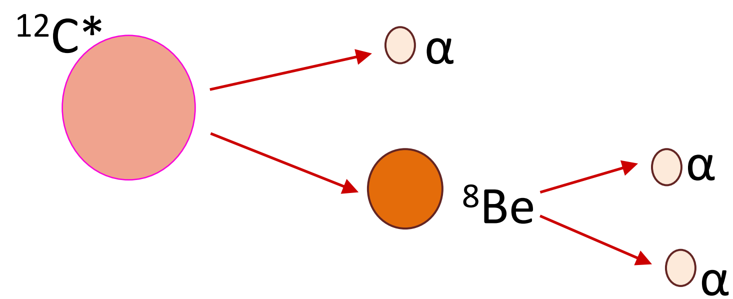
Simulated excitation energy of ^{12}C

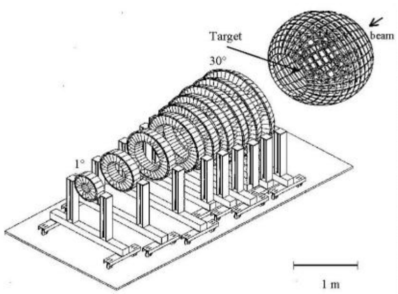


Direct



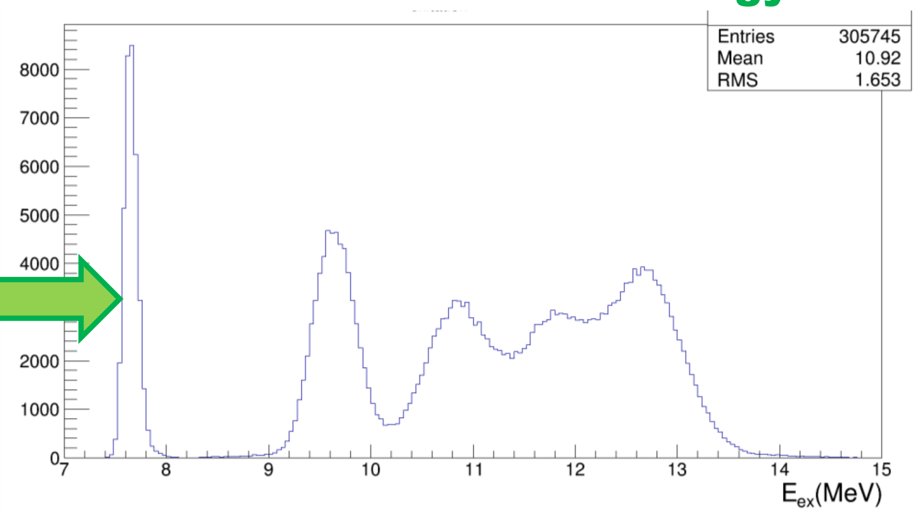
Sequential





Simulated data passed through a filter that take into account all physical and geometrical features of CHIMERA detector

Reconstructed exitation energy of ^{12}C



HOYLE STATE: DALITZ PLOTS

PRELIMINARY

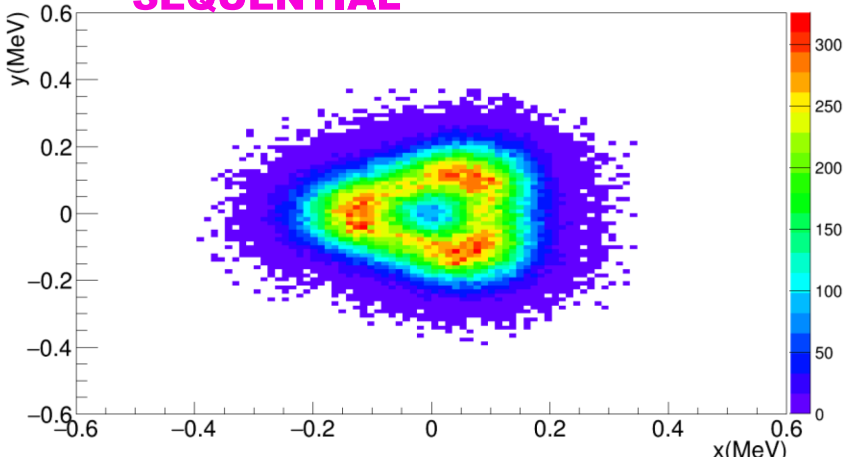
Dalitz parameter

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

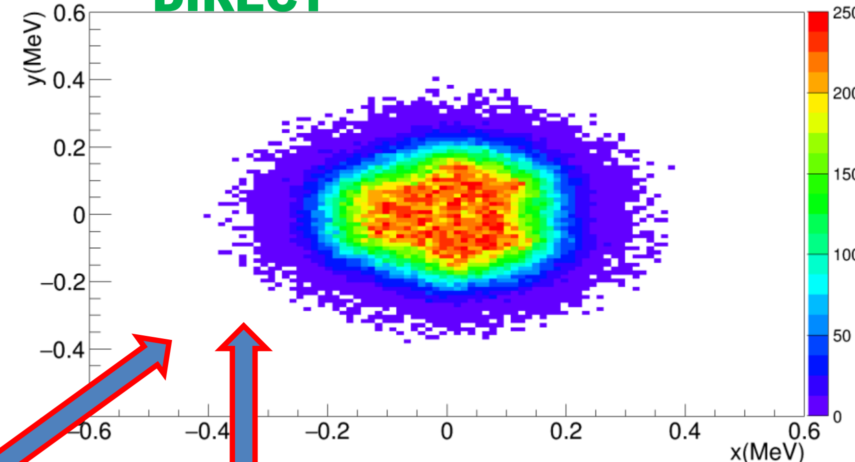
$$y = \sqrt{3}(E_{1CM} - E_{2CM})/2$$

SIMULATED DATA

SEQUENTIAL

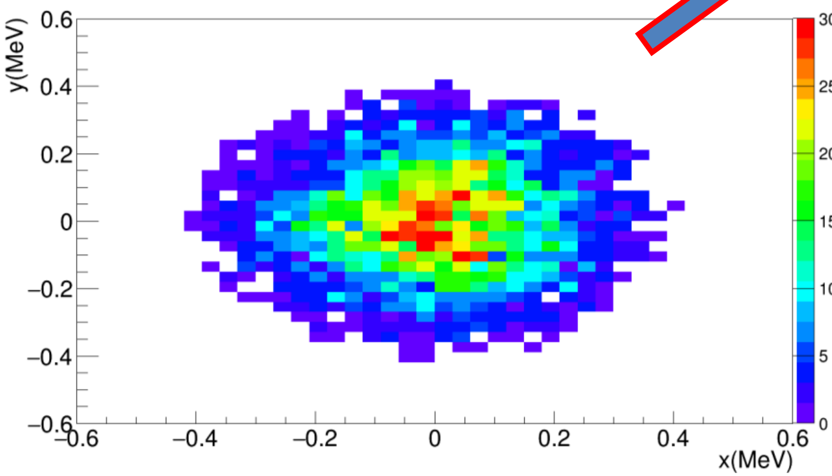


DIRECT

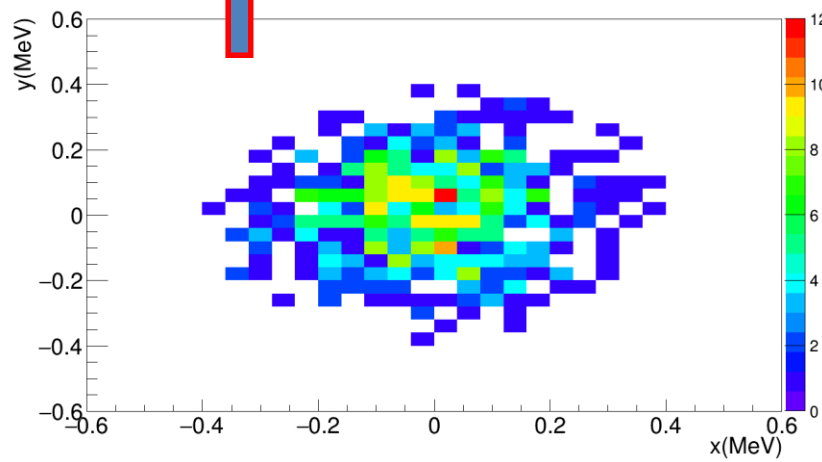


EXPERIMENTAL DATA!

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



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



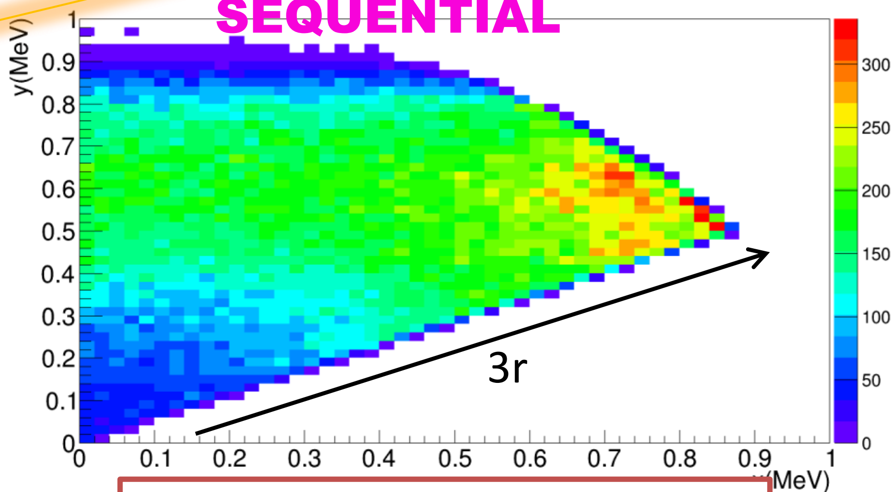
HOYLE STATE: SYMMETRIC DALITZ PLOTS

PRELIMINARY

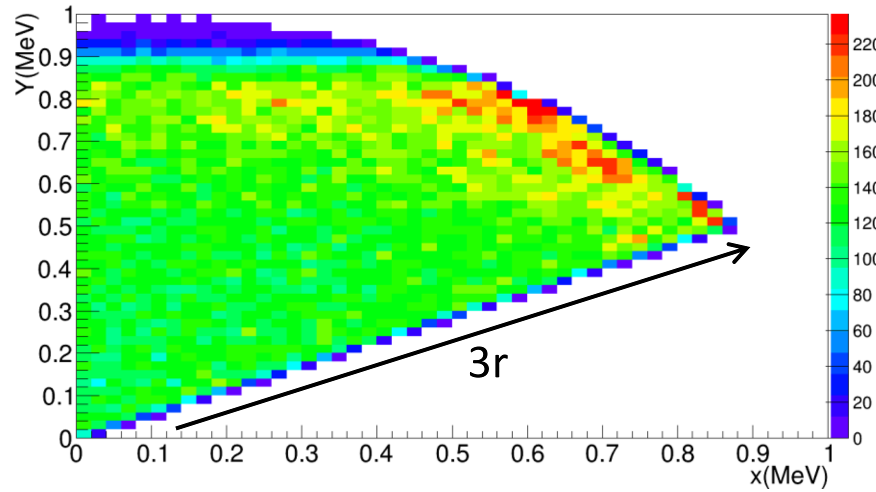
SIMULATED DATA

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

SEQUENTIAL

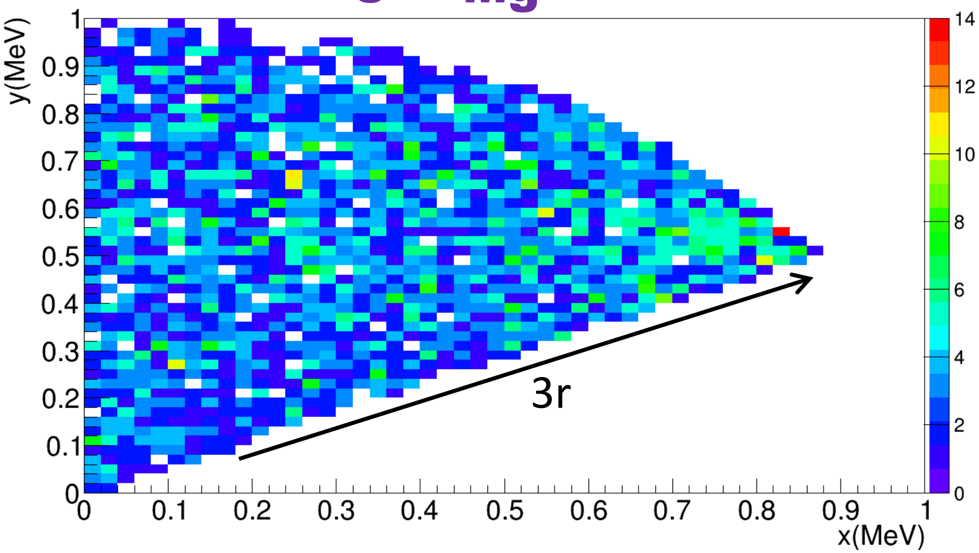


DIRECT



EXPERIMENTAL DATA!

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



$$x = \sqrt{3}(\varepsilon_j - \varepsilon_k)$$
$$y = 2\varepsilon_i - \varepsilon_j - \varepsilon_k$$
$$(\varepsilon_i > \varepsilon_j > \varepsilon_k)$$

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

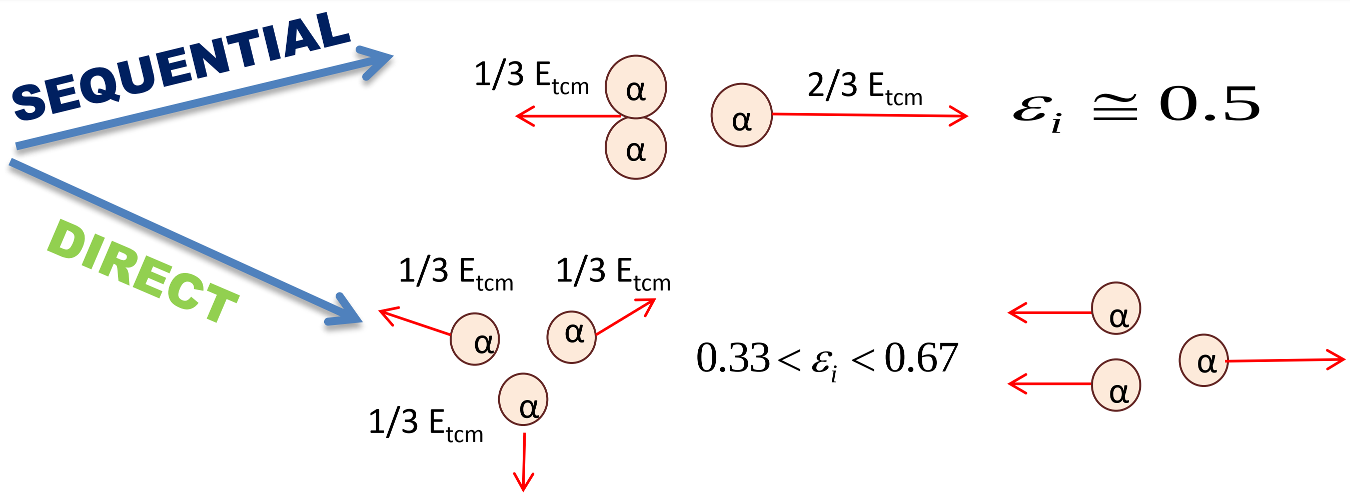
Particles energies in $^{12}C^*$ frame normalized to the total energy of 3α decay

Radial parameter

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

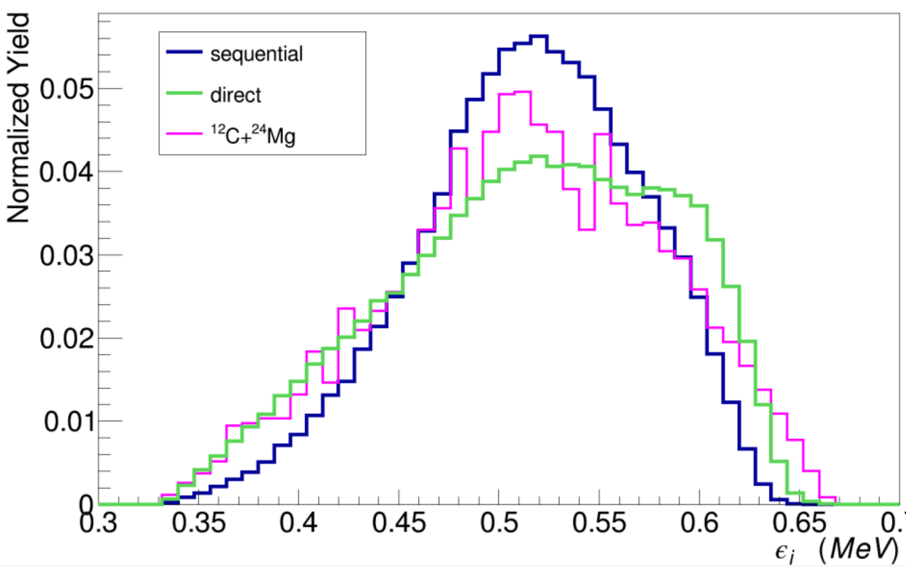
Hoyle state sequential vs direct: ε_i distribution

ε_i : highest normalized energy among the decay of 3α particles

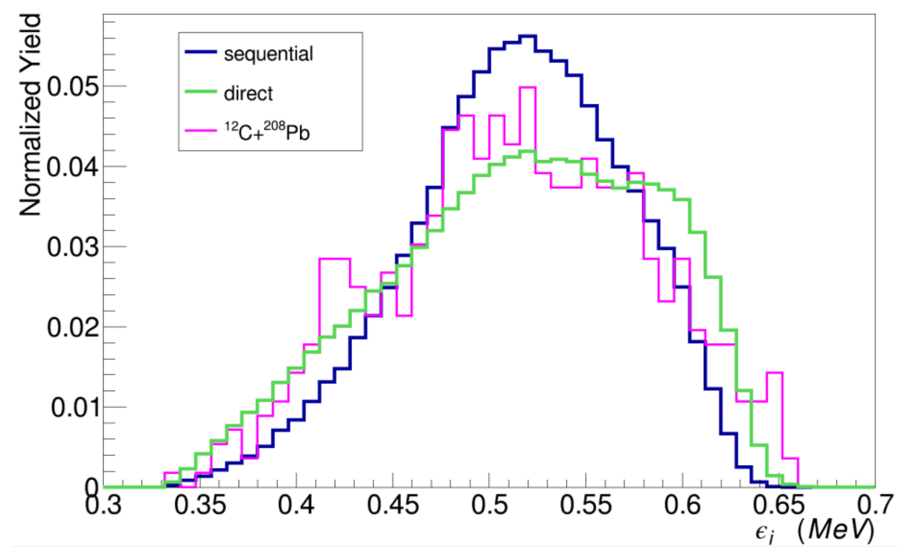


ε_i distribution

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



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



IMPORTANT COMPONENT OF DIRECT DECAY EMERGES !!!

(In agreement with Raduta et al. and Grenier et al.)

^{12}C STATE at E*=9.64: DALITZ PLOTS

PRELIMINARY

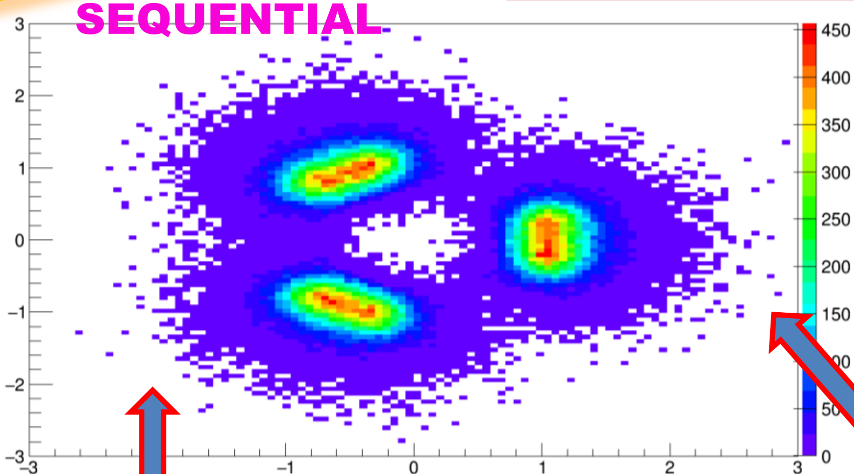
SIMULATED DATA

Dalitz parameters

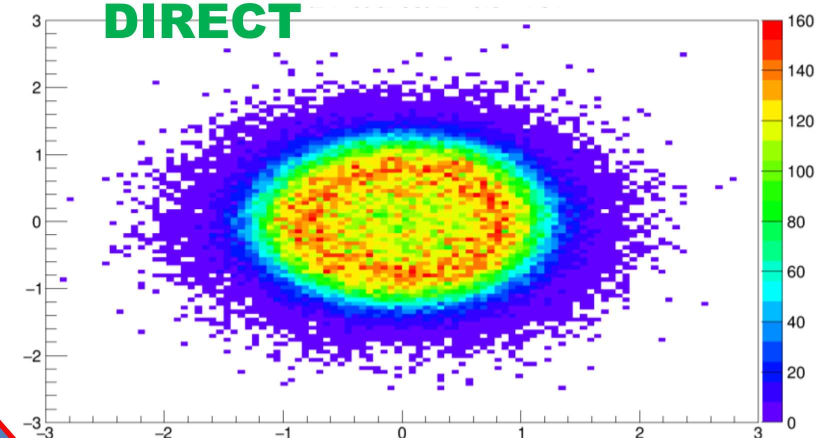
$$x = (2E_{3CM} - E_{1CM} - E_{2CM})/2$$

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

SEQUENTIAL

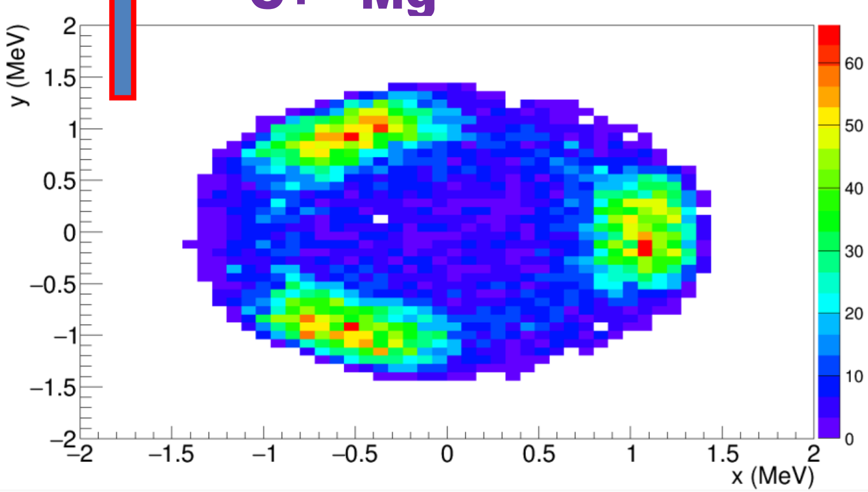


DIRECT

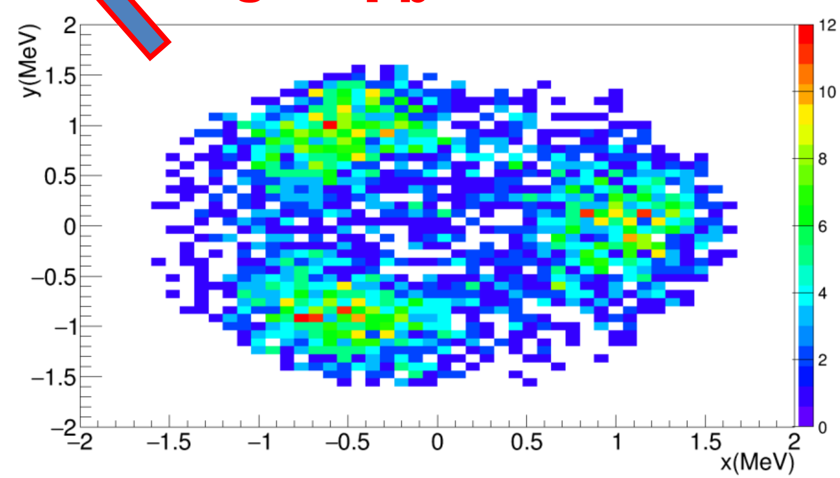


EXPERIMENTAL DATA!

^{12}C+^{24}Mg



^{12}C+^{208}Pb



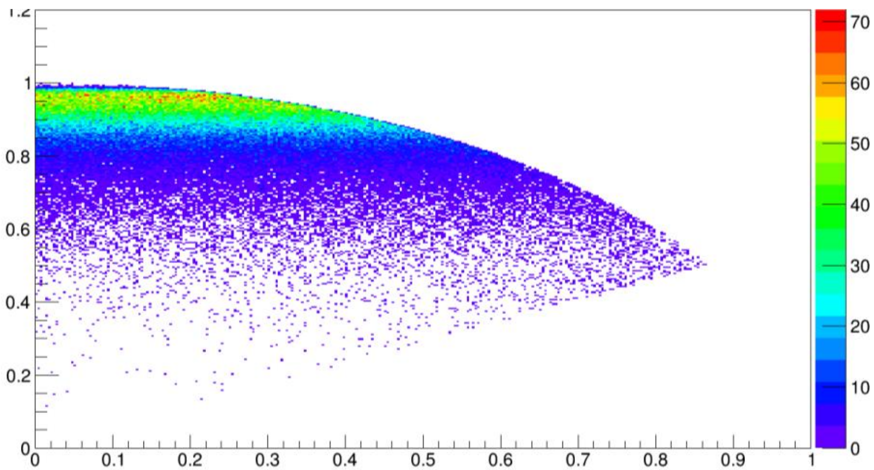
^{12}C STATE at E*=9.64: SYIMMETRIC DALITZ PLOTS

PRELIMINARY

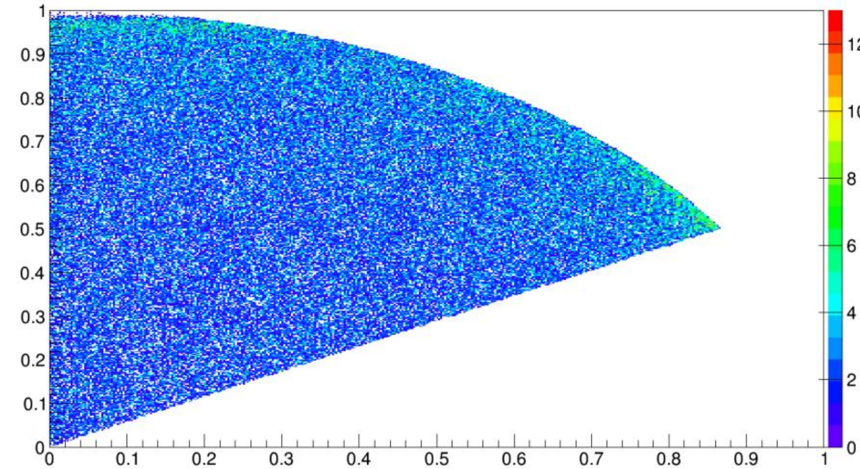
SIMULATED DATA

$$x = \sqrt{3}(\varepsilon_j - \varepsilon_k)$$
$$y = 2\varepsilon_i - \varepsilon_j - \varepsilon_k$$

SEQUENTIAL

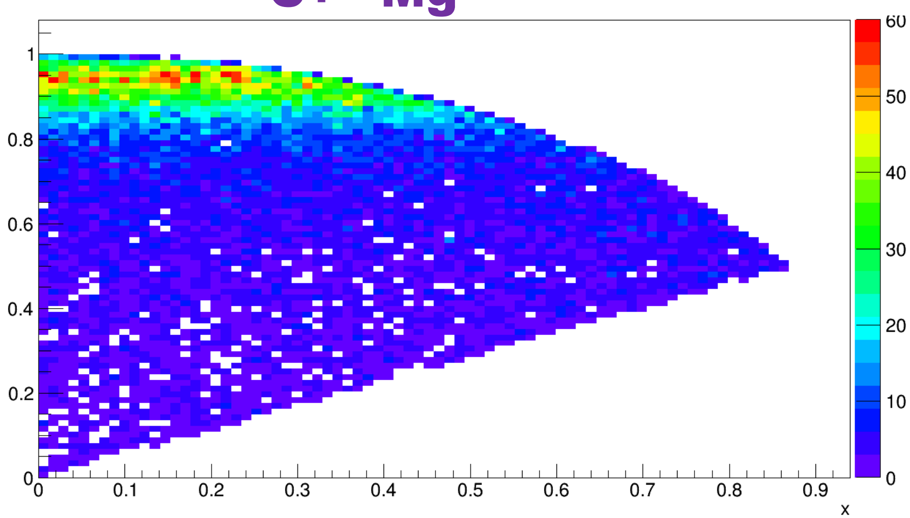


DIRECT

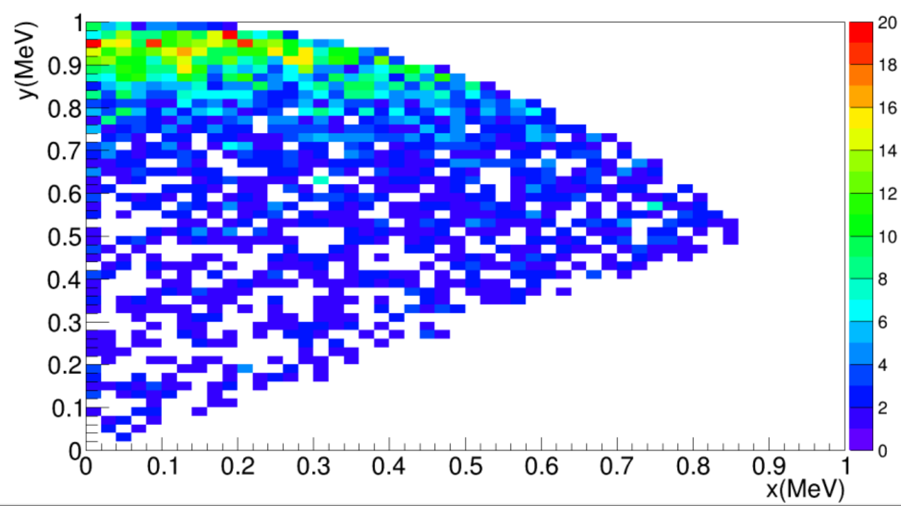


EXPERIMENTAL DATA!

^{12}C+^{24}Mg



^{12}C+^{208}Pb



CONCLUSIONS AND OUTLOOK

- ❑ Study of two- and three- particles correlations in dissipative QP decay: link to in-medium structure properties and reaction/dissipation mechanism → relavance to EoS;

- ❑ Emission temperature and structure properties, dynamics vs statistics → Thermal model?

- ❑ Focus on ^{12}C: a possible 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) PDC method under way;

- ❑ Coming up: Possible evidence of Bose-Einstein condensate (DDE) to be explored soon;

- ❑ Extend studies to resonances produced in other nuclei such as ^{9}B, ^{6}Be etc. (sequential/direct branching ratios, thermal models, etc.);

- ❑ In-medium and thermal effects in structure properties of observed states;

NEWCHIM 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. Trifirò[1,2], M. Trimarchi[1,2] G. Verde[3,4], M. Veselsky[12], M. Vigilante[8,11]

1) Università di Messina, Dip. di Fisica e Scienze della Terra, Messina, Italy
2) INFN, Gruppo Collegato di Messina, Messina Italy
3) INFN, Sezione di Catania, Catania Italy
4) IPN Orsay, Orsay, France
5) GANIL, CEA-IN2P-CNRS, Caen, France
6) Departamento de Fìsica Aplicada, Universitad de Huelva, Huelva, Spain
7) INFN, Laboratori Nazionali del Sud , Catania Italy
8) INFN, Sezione di Napoli, Napoli Italy
9) Università di Catania, Dip. di Fisica e Astronomia, Catania, Italy
10) Università Kore, Enna, Italy
11) Università di Napoli Federico II, Dipartimento di Fisica, Napoli, Italy
12)Slovak Academy of Sciences, Bratislava, Slovakia
13) Instituto de Física, Universidad Nacional Autónoma de México, Apartado Postal 20-364, México D. F. 01000, Mexico
[†]Deceased

Thank you
for your very kind attention!