Pre-equilibrium particles emission to study Clustering in nuclei

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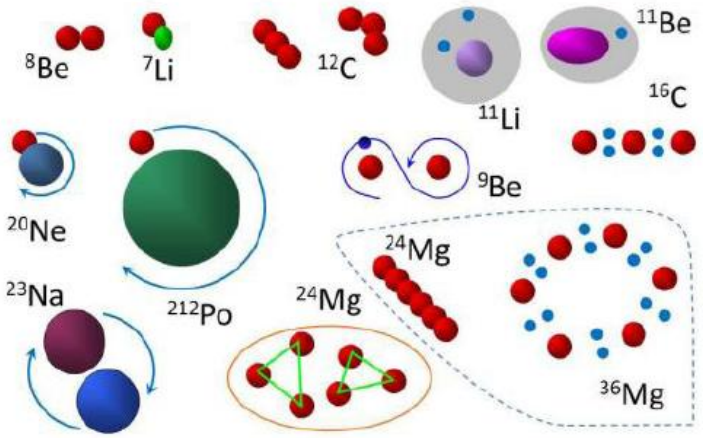
INFN Sezione di Padova
on behalf of Nucl-Ex collaboration

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

May 17 – 19, 2016 GANIL, Caen, France

Nuclear Clustering

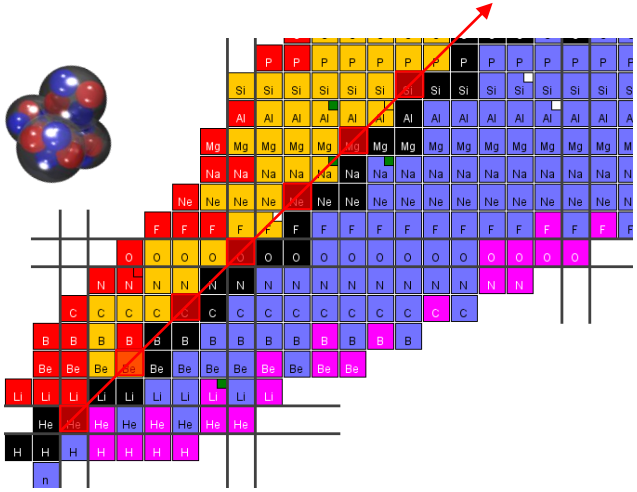
'Clustering reactions' are a good tool to study the interplay between ***nuclear structure*** and ***reaction dynamics***



W.N. Catford J. Phys. Conf. Series 436, 012095

α-particle is the most likely cluster structure observed in N=Z nuclei at E* close to the α-decay threshold

Different other **types** of clustering have been experimentally investigated



Interest in nuclear clustering renewed due to the study of **exotic weakly-bound nuclei**

In **light nuclei** at drip-lines, clustering might be the preferred structural mode

P.E. Hodgson, E. Běták, Phys. Rep. 374 (2003) 1-89
W. Von Oertzen et al. Phys. Rep. 432 (2006) 43
M. Freer et al. , Rep. Progr. Phys. 70 (2007) 2149

Nuclear Clustering

Pre-formation

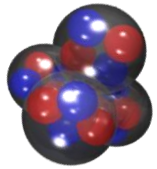
↓

α- cluster are pre-formed inside nuclear matter

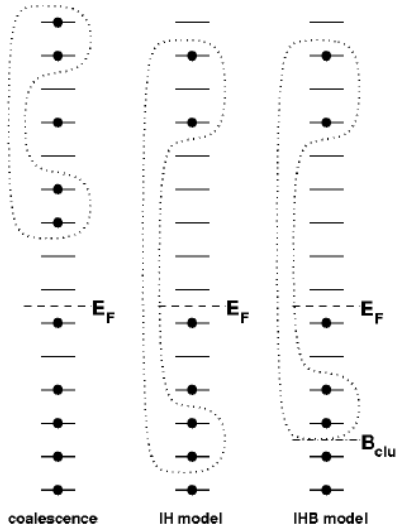
Dynamical formation
Coalescence

↓

Clusters are formed in a course of a reaction



- Different phenomena of clustering effects can be related to either their **structural presence** (pre-formation) or to their **dynamical formation** .
- Links between **Cluster Emission** and its connection with nuclear structure and dynamics have been evidenced in light-mass nuclei .



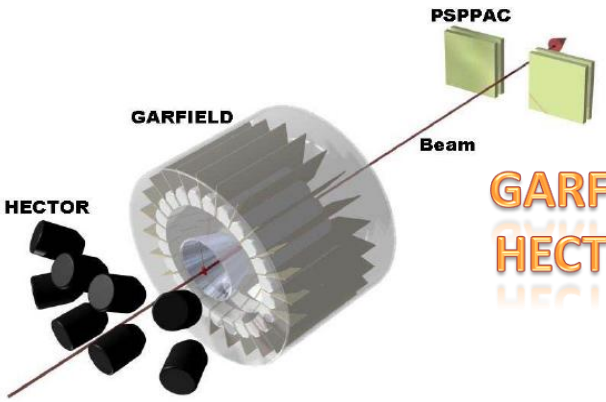
Studying **Medium Mass systems** through reaction dynamics
→ **Pre-Equilibrium particles emission**

Studying th competition between evaporation (surface) and fast (volume) emission of LCP and clusters

Different Pre-equilibrium Models

E. Běták EPJ Web of Conf. 21 (2012) 09004

Previous Experimental results: $^{16}O + ^{116}Sn$ @ 130, 250 MeV (8, 16 AMeV)



GARFIELD FW + HECTOR + PPAC

Light Charged Particles & **High Energy γ-rays**
in coincidence with
Evaporation Residues

Moving Source Fit

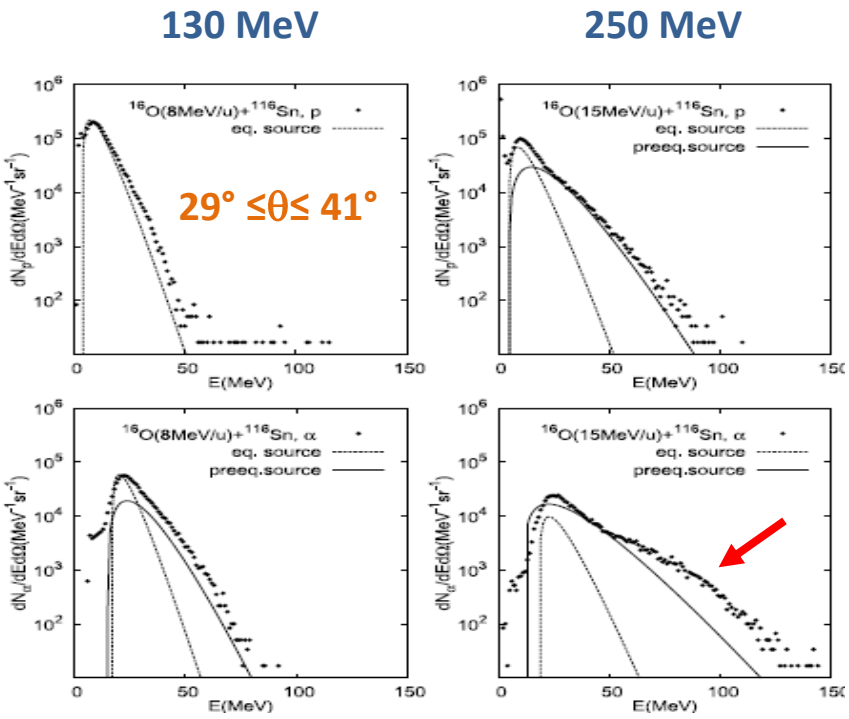


Table 3. Moving source fit parameters for the reaction $^{16}O+^{116}Sn$ at 8.1 and 15.6 AMeV.

E(AMeV)	LCP	$\frac{N_2}{N_1}$	E_{C1}(MeV)	T_1(MeV)	E_{C2}(MeV)	T_2(MeV)	$\frac{v_2}{v_{CN}}$
8.1	p	0.0	2.77 ± 0.46	3.02 ± 0.16	-	-	-
8.1	α	0.21	11.0 ± 1.50	3.20 ± 0.35	12.4 ± 1.70	3.80 ± 0.75	3.83
15.6	p	0.30	3.16 ± 0.44	3.55 ± 0.47	4.49 ± 1.53	4.68 ± 0.83	5.49
15.6	α	1.30	12.3 ± 0.20	4.38 ± 0.28	12.2 ± 0.90	7.10 ± 0.60	2.85

A. Corsi et al., PLB 679 (2009) 197

Moscow Pre-equilibrium Model: statistical + pre-equilibrium emission

Evaporative (statistical) emission:

Statistical decay of a Compound Nucleus is analyzed using **modified PACE2** Monte Carlo code , with level density parametrization [**A.V. Ignatyuk et al. Sov. J.Nucl. Phys. 29 (1979) 450**] , decay competition probability (n, p, α, γ or fission), kinetic energy of emitted particles, binding energy, transmission coefficients, angular momentum.

- Insertion of **non-equilibrium** stage in the fusion reaction
- All the process probabilities are calculated within the Hauser-Feshbach model

Pre-equilibrium emission:

The Relaxation process in the nuclear system after fusion reaction is described by the **Hybrid exciton model** based on Griffin model [**J.J.Griffin PRL 17 (1966) 478, M. Blann PRL 27 (1971) 337**].

The state of nuclear system produced in the collision is determined by the **exciton number** $n_o = p_o + h_o$ where p is the number of valence particles over the Fermi energy and h the number of holes located under the Fermi energy, and by excitation energy **E***.

- The **exciton number** n_o can be determined from the empirical trend [**N.Cindro et al. Phys. Rev. Lett. 66 (1991) 868; E. Běták Fizika B12 (2003) 11**]

Model Parameters:

$n_0 = p_0 + h_0$	Number of excitons
K-> $\|M\|^2 = KA^{-3}e^{-1}$	100 – 800 MeV^3
$g = 6a/p^2$	Level density parameter

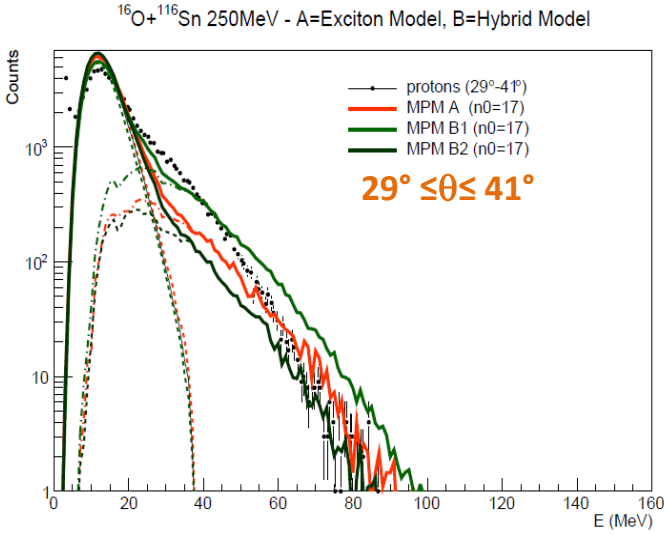
O.V. Fotina et al. Int. Journ. Mod. Phys. E19 (2010) 1134
D.O. Eremenko et al. Phys Atom. Nucl. 65 (2002) 18
O.V. Fotina et al. Phys. Atom. Nucl. 73 (2010) 1317

Comparison with *Moscow Pre-equilibrium Model*

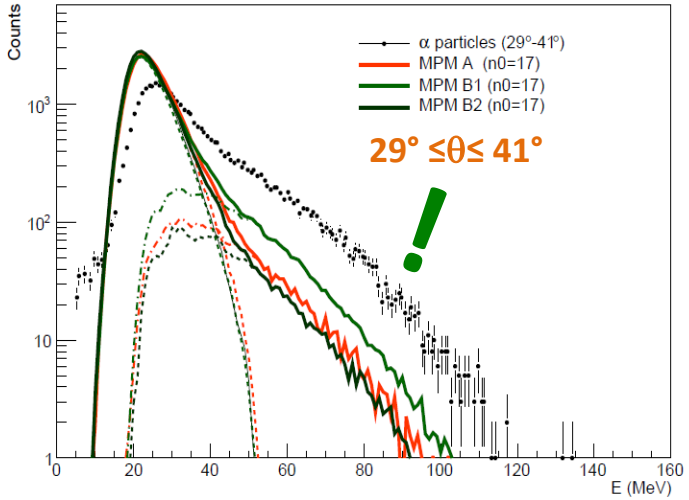
$^{16}O + ^{116}Sn$ @ 250 MeV

$n_0 = 17$ (16p +1h)

Protons



α-particles



B1 $\beta = 1.8$, $pf_{CN} = 0.5$

B2 $\beta = -1$, $pf_{CN} = 0.95$

Different simulations with different **Pre-equilibrium particles Angular Distributions**:

Caso A : based on ***Exciton Model*** -> Angular Distribution from optical model

Caso B : based on ***Hybrid Exciton Model*** -> $q(n, \Omega, t)$ with Ω direction of fast particle

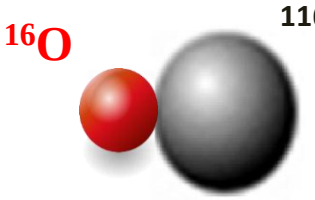
β nuclear finite size effect

Adding α-clusters structure effect to the model

Clustering:

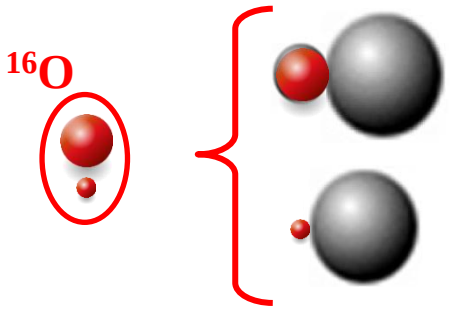
Pre-formation probability of cluster in the **projectile** and **exciton energies** for cluster/light ion induced reactions

→ 2 possible starting configurations are considered in ^{16}O nucleus



n_O=16p+0(1)h

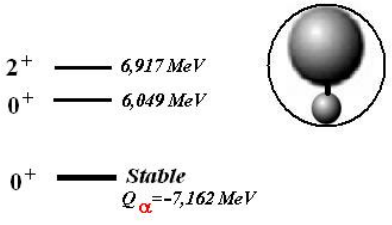
100 - N(%)

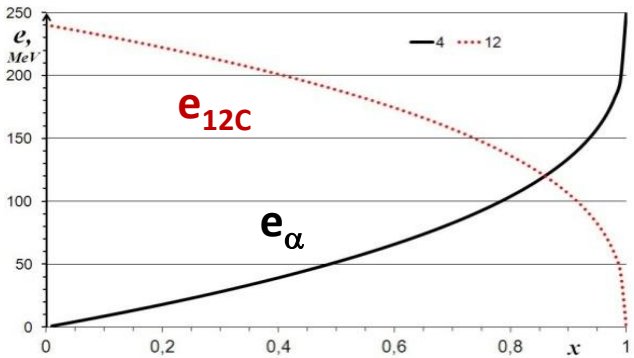


n_C=12p+0(1)h

n_α=4p+0(1)h

N(%) = ??





$$e = E(1-(1-x)^{1/(n-1)}).$$

e – clusters energy
x – random number

PHYSICAL REVIEW C, VOLUME 62, 034604

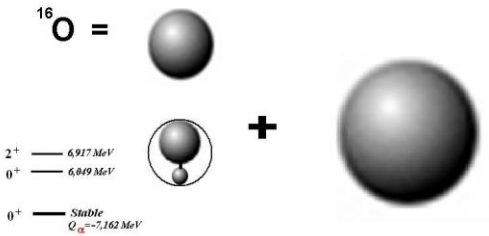
Precompound Monte-Carlo model for cluster induced reactions

M. Blann[1] and M. B. Chadwick[2]

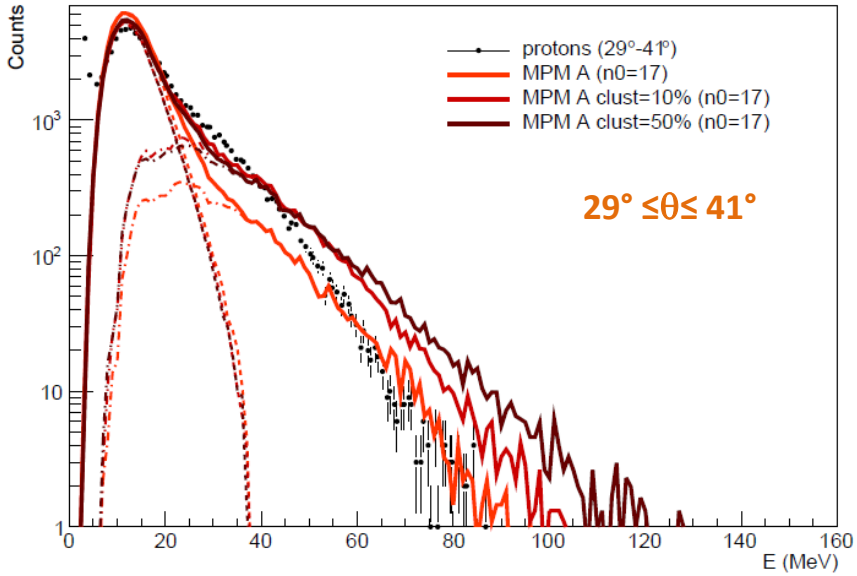
Comparison with *Moscow Pre-equilibrium Model* : projectile **Clustering**

$^{16}O + ^{116}Sn$ @ 250 MeV

- Exp
- No α-clustering in ^{16}O
- 10% α-clustering in ^{16}O
- 50% α-clustering in ^{16}O

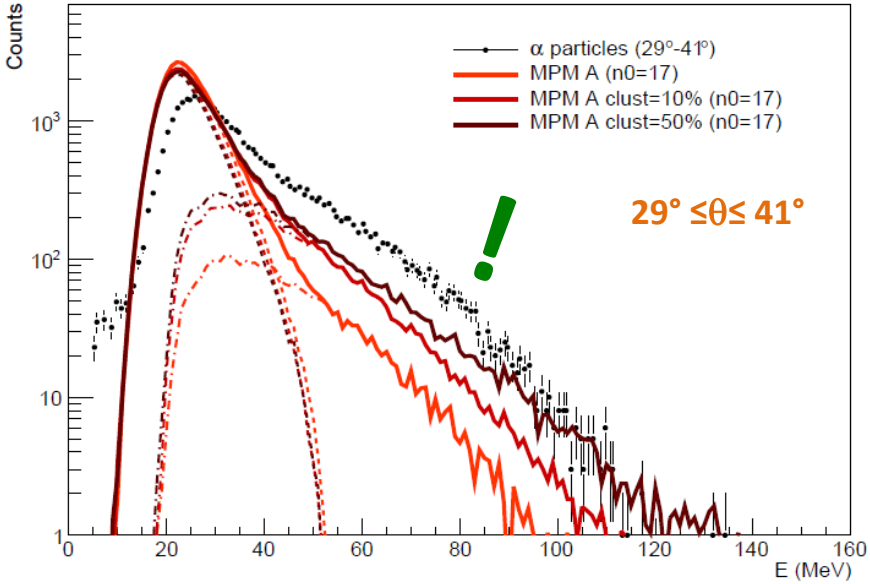


Protons



Protons : No α–clustering

α-particles

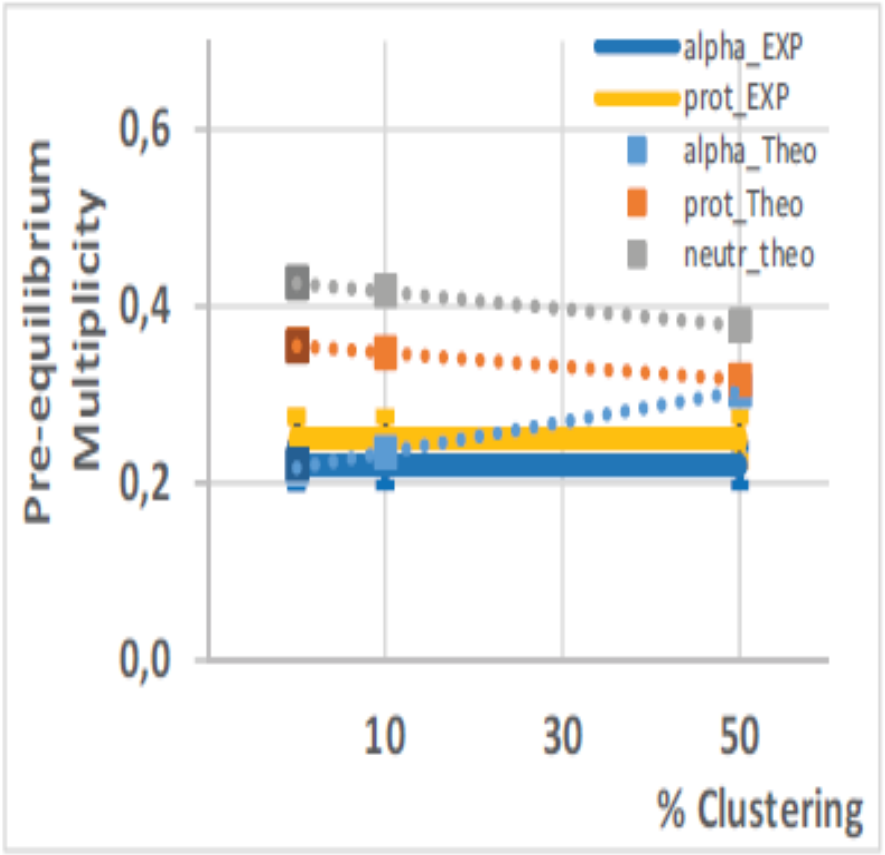


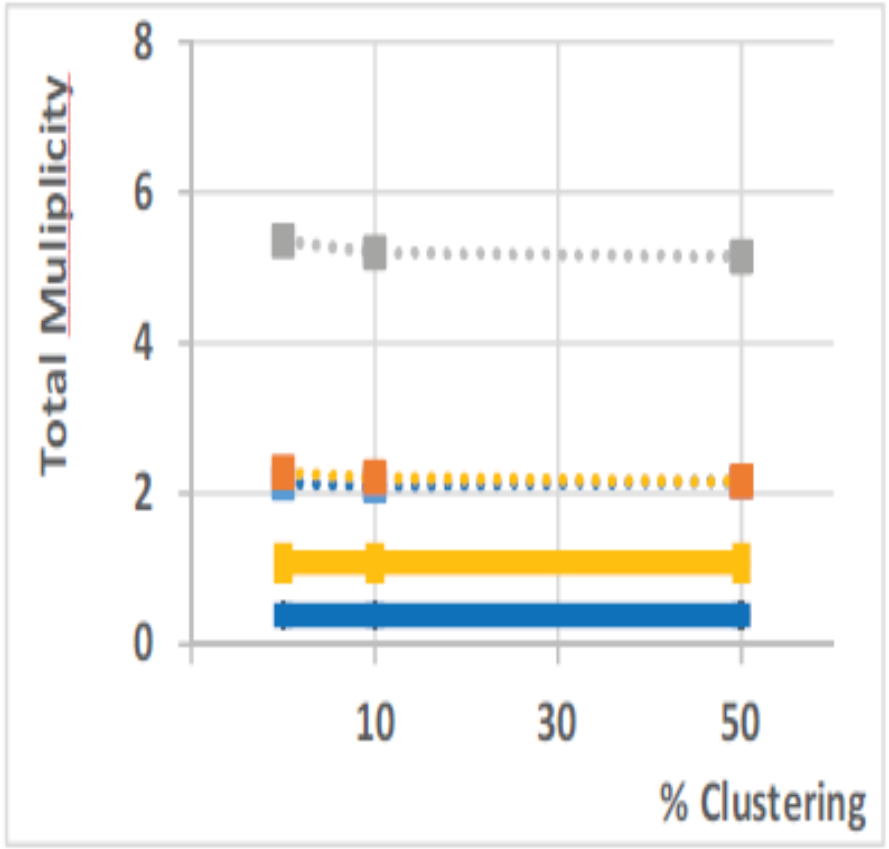
α-particles : not completely described by 50% α–clustering , but it is going in the right direction..

Comparison with *Moscow Pre-equilibrium Model* : projectile **Clustering**

$^{16}O + ^{116}Sn$ @ 250 MeV

Multiplicities





$[M^{\alpha}_{pre}/M^{\alpha}_{tot}]_{exp}$ ~ **0.5** ⟺ $[M^{\alpha}_{pre}/M^{\alpha}_{tot}]_{theo}$ ~ **0.1**

- To study possible effects of **α-cluster structure** in the **projectile** :

  → comparing light charged particles emitted in **two fusion reactions** with different N/Z projectiles

  → studing **pre-equilibrium particles emission**

$^{16}O + ^{65}Cu$ E_b = 256 MeV (16 MeV/u)

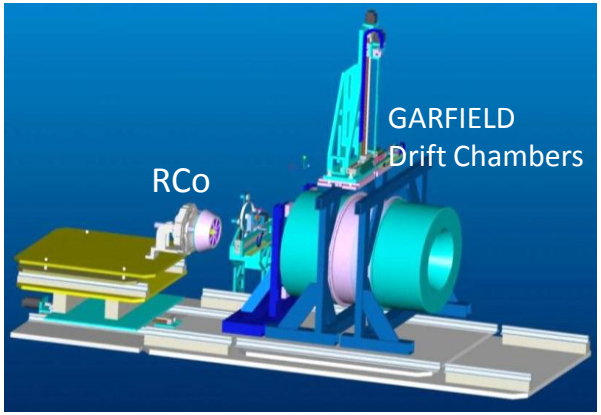
$^{19}F + ^{62}Ni$ E_b = 304 MeV (16 MeV/u)

CN $^{81}Rb^*$ $E^*(^{16}O)$ = 209 MeV

$E^*(^{19}F)$ = 240 MeV

- Two systems with the **same projectile velocity** -> **Pre-equilibrium emission** depends mainly on the projectile energy per nucleon

J. Cabrera et al., Phys rev C68(2003) 034613



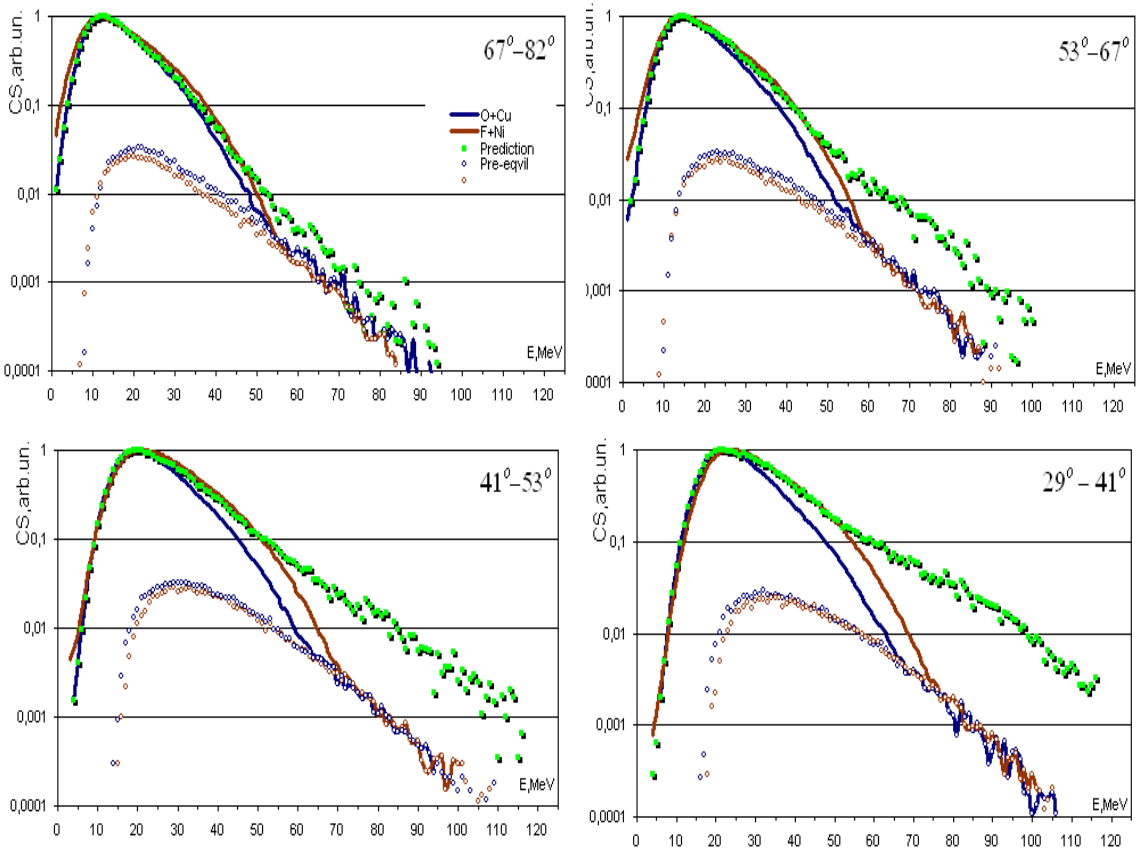
M. Bruno et al., EPJ A 49 (2013) 128

- **Set-up**: **GARFIELD** 4π apparatus at Legnaro National Laboratory for Fragments and Light Charged Particles identification with **Ring Counter (Rco)** at forward angles fully equiped with digital electronics

Moscow Pre-equilibrium Model: plus **Clustering**

Predictions ….. $^{16}O + ^{65}Cu$ $^{19}F + ^{62}Ni$

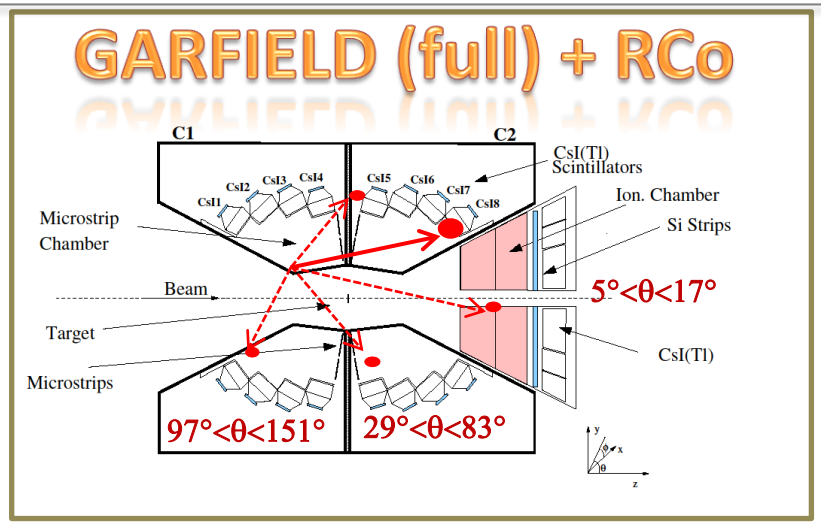
α-particles



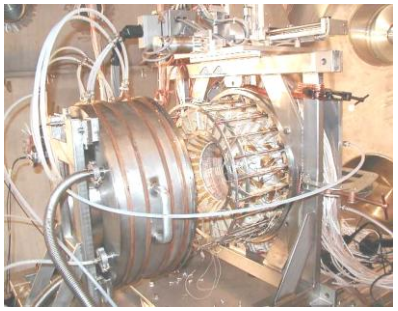
- Evaporative : small differences
- Pre-equilbrium: same
- **50% α-clustering in ^{16}O:**
  high energy tail increase

If any differences
-> **clusterizartion of ^{16}O projectile**

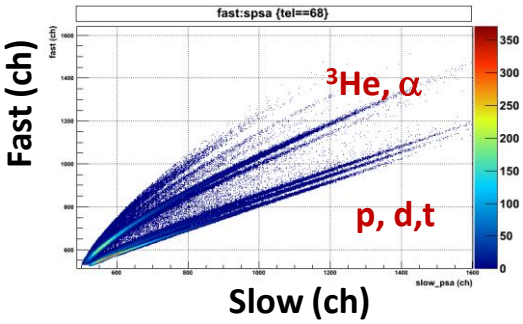
Experimental set-up: GARFIELD + RCo



GARFIELD

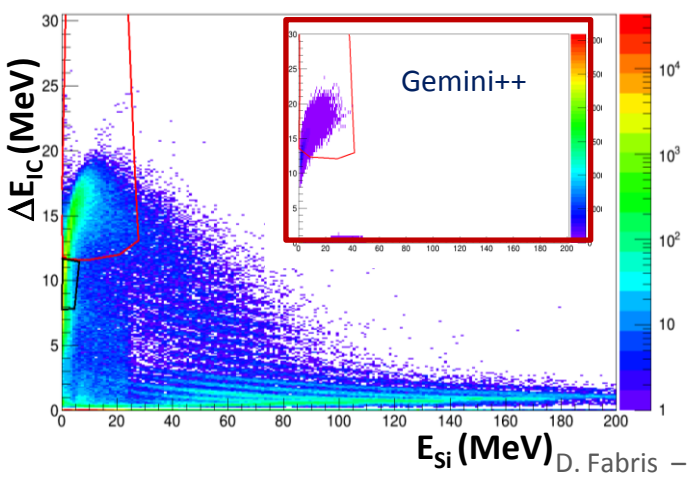


- Two Drift Chambers
- Double stage **ΔE-E:**
  μStrip Gas Counter + CsI(Tl)
- Z identification
- A identification (1≤A≤3)
  (in total **180+180** for the 2 chambers)

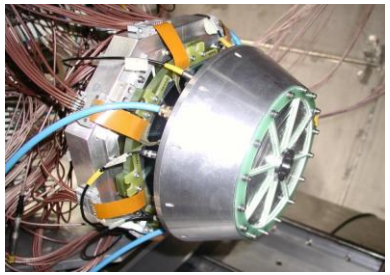


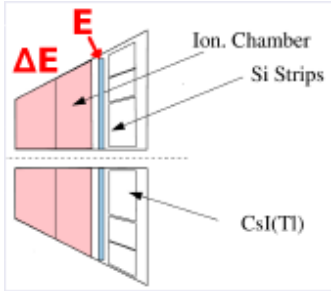
PSA CsI GARFIELD

Evaporation Residues identified in **RCo** IC-Si : $\Delta\theta = 8.6° \div 17°$



RCo

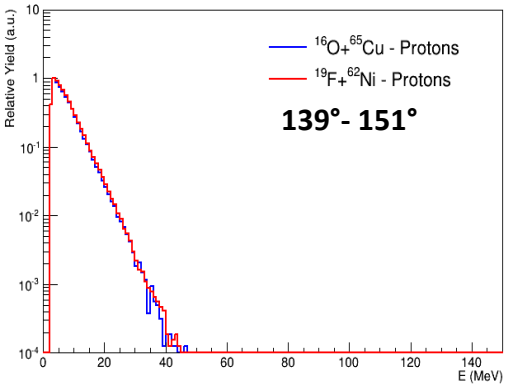


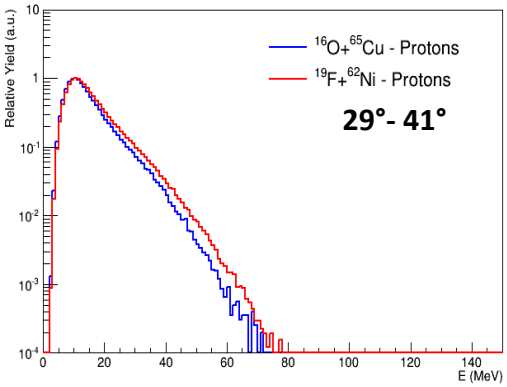


- Three stage telescope:
  IC + Si Strip + CsI(Tl).
- Z, A identification

Experimental spectra in Lab

Protons

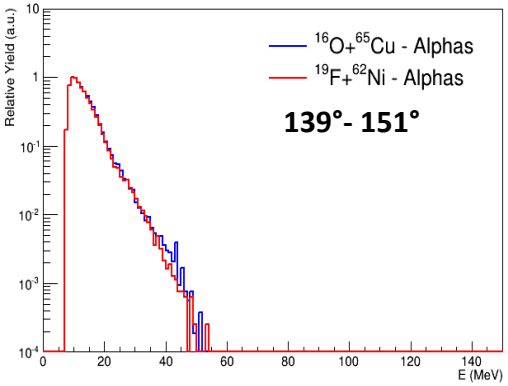


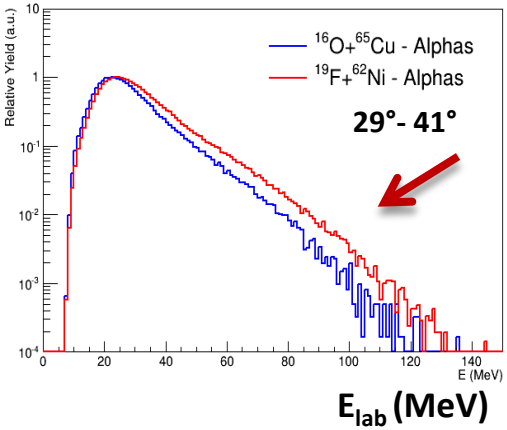


$^{16}O + ^{65}Cu$

$^{19}F + ^{62}Ni$

α-particles

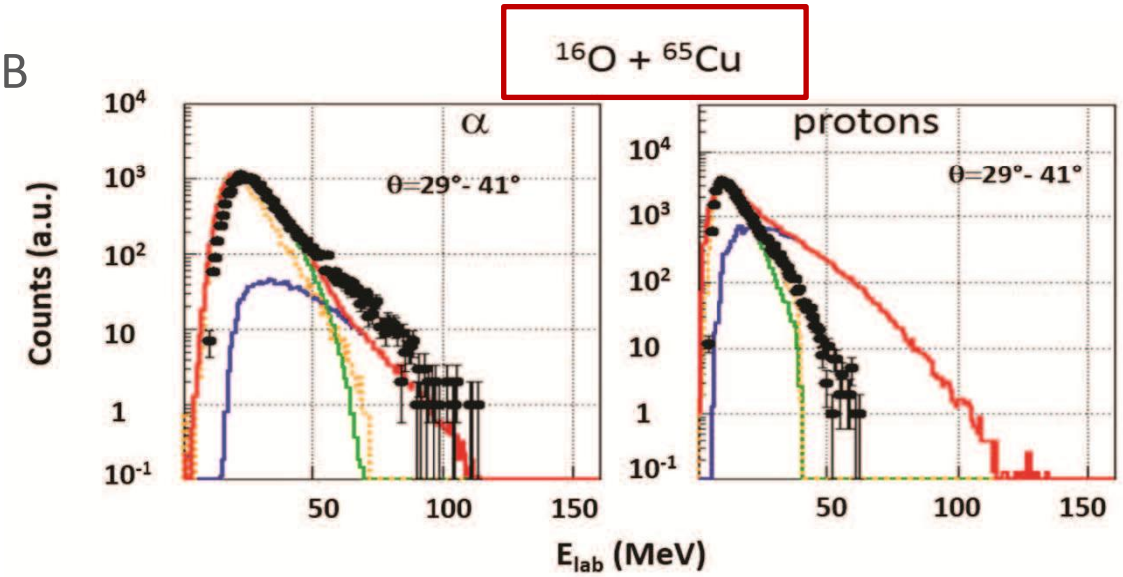




Larger Pre-equilibrium contribution from **^{19}F induced reaction α-spectra** with respect to **^{16}O**

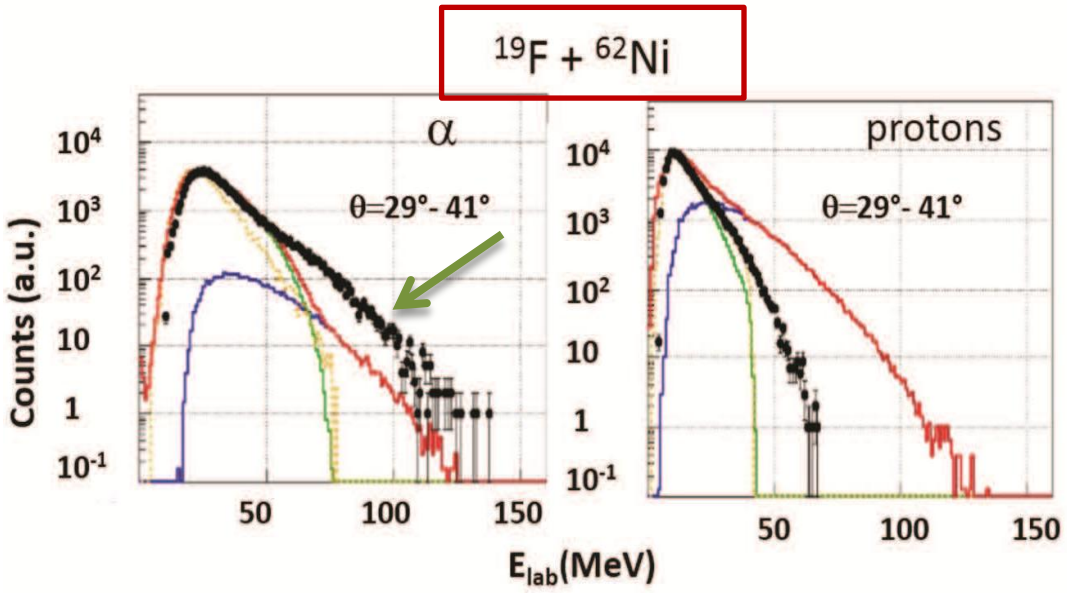
Comparison with *Moscow Pre-equilibrium Model* : NO clustering

Case B



$n_0 = 17(16p + 1h)$

- Exp
- Total
- Pre-eq
- Evap
- PACE



$n_0 = 20(19p + 1h)$

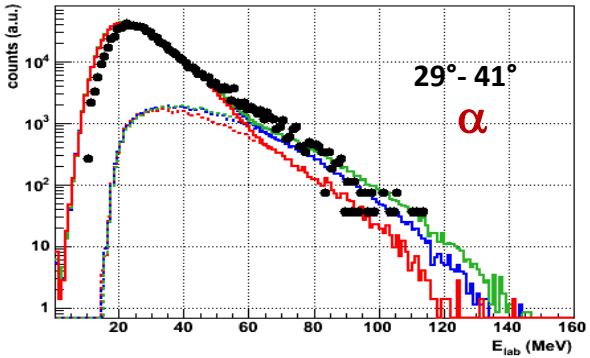
But…..

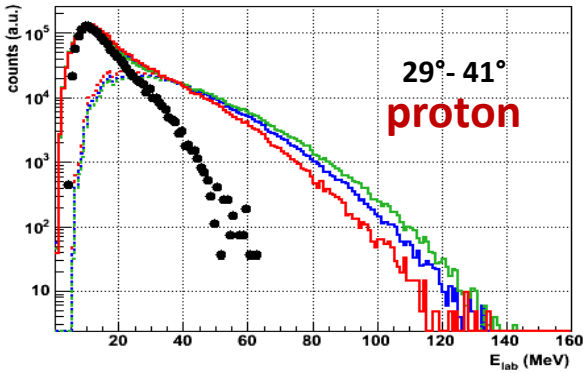
$^{16}O \rightarrow ^{12}C + \alpha$ (7.16 MeV)

$^{19}F \rightarrow ^{15}N + \alpha$ (4.01 MeV)

Comparison with *Moscow Pre-equilibrium Model:* changing exciton number n_o

$^{16}O + {}^{62}Cu$





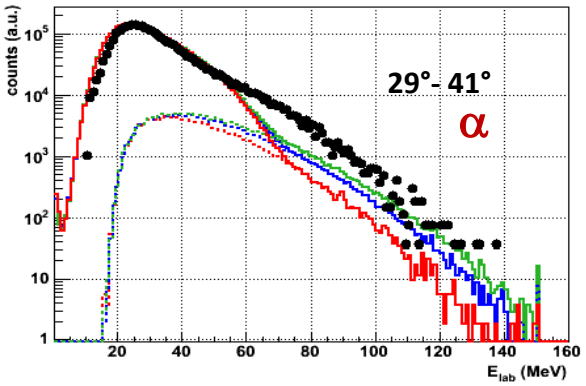
- Exp

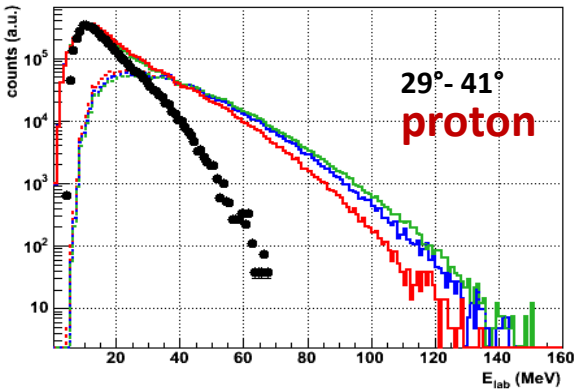
$n_0 = 17$ — Total ----- Pre-eq

$n_0 = 15$ — Total ----- Pre-eq

$n_0 = 14$ — Total ----- Pre-eq

$^{19}F + {}^{61}Ni$





- Exp

$n_0 = 20$ — Total ----- Pre-eq

$n_0 = 18$ — Total ----- Pre-eq

$n_0 = 17$ — Total ----- Pre-eq

Theoretical Models

Statistical Model

- **GEMINI ++ code** - most used Statistical Model in heavy ion collisions to simulate the decay of hot nuclei

  ✓ *Standalone* when a good selection of central events can be performed

  ✓ *Afterburner (after a dynamical code)* to produce secondary particles distributions from primary fragments -> to be compared with experimental data

  R. J. Charity, Phys Rev C 82 (2010) 014610

Dynamical Models

- **Stochastic Mean Field (SMF)** - **Twingo** code, based on SMF model, has been used to generate primary fragments distributions.

  M. Colonna et al. NPA 642 (1998) 449

- **Antisymmetrized Molecular Dynamics (AMD)** - Clustering effects are better described, but not still optimized for Low Energies.

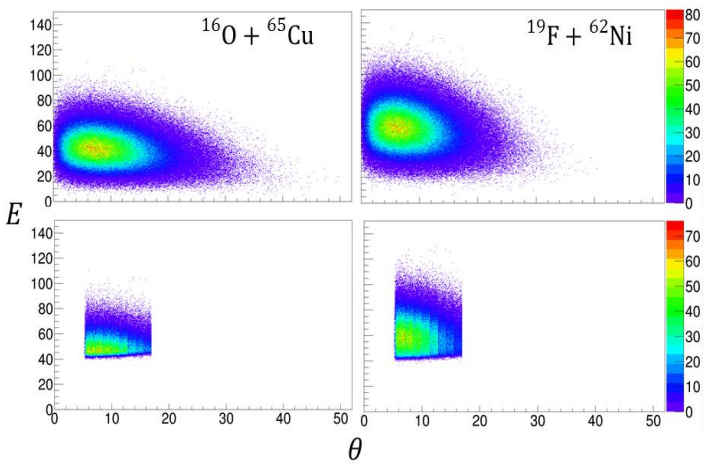
  A. Ono, PRC 59 (1999) 853

GEMINI++ : Effect of the **Experimental filter** on the two systems

$^{16}O + {}^{65}Cu$

$^{19}F + {}^{62}Ni$

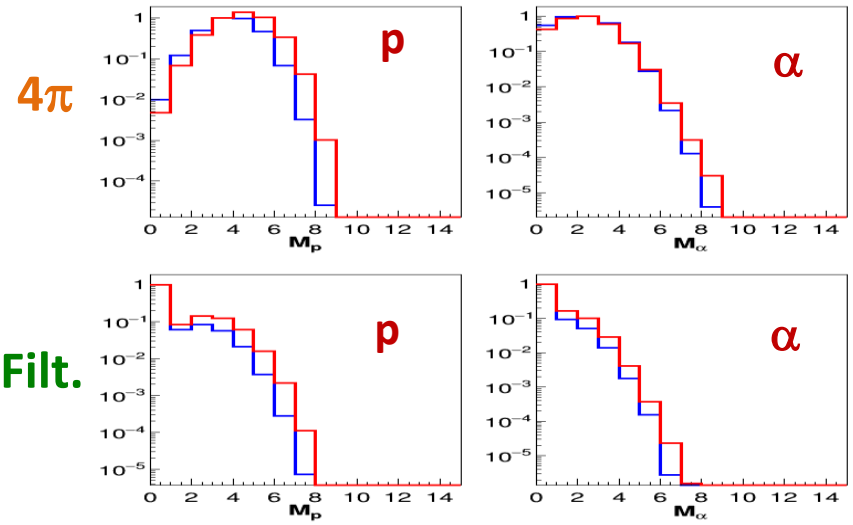
Evaporation Residues
E vs. θ Distributions



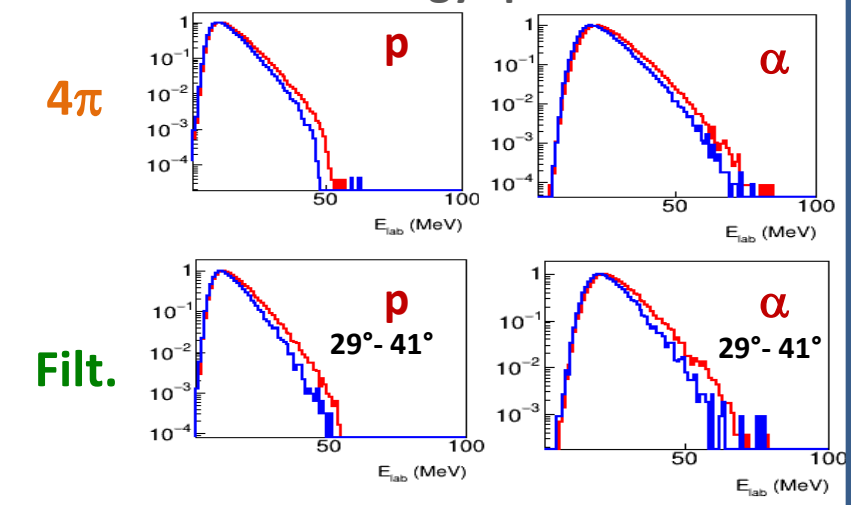
4π

Filtered

Particle Multiplicity



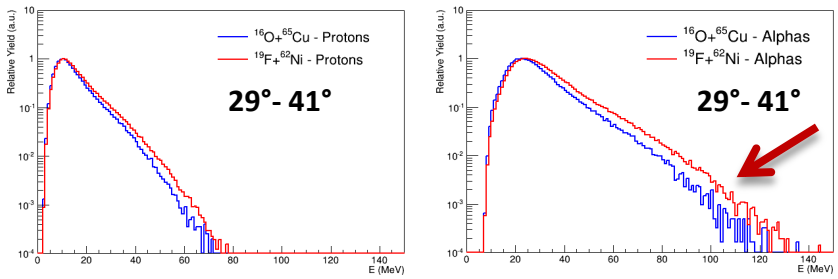
Energy spectra



Experimental Energy spectra

Protons

α-particles

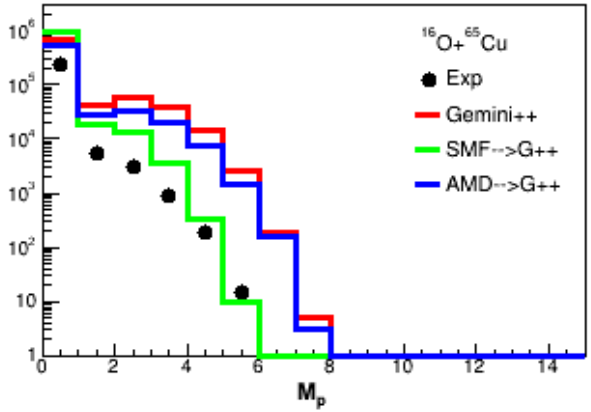


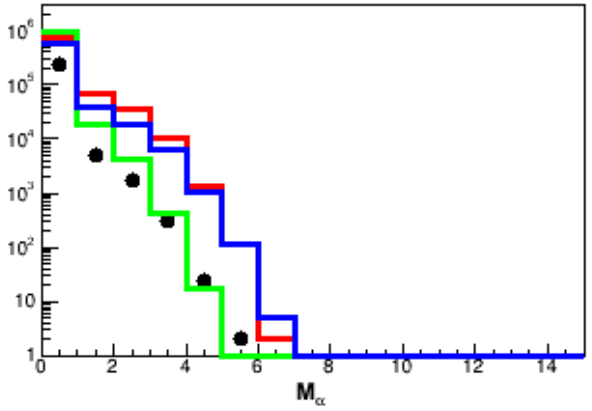
Comparison with different Models: LCP Multiplicities coinc. *Residues*

Protons

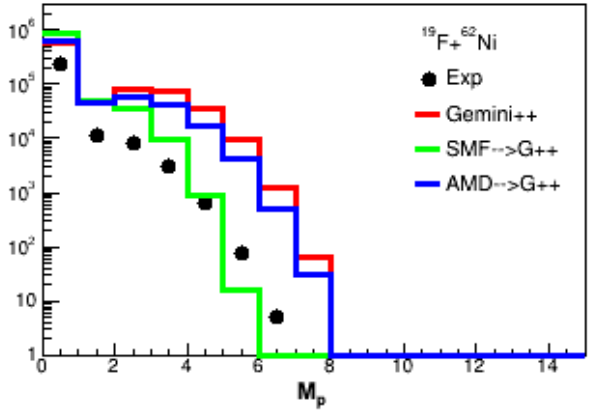
α-particles

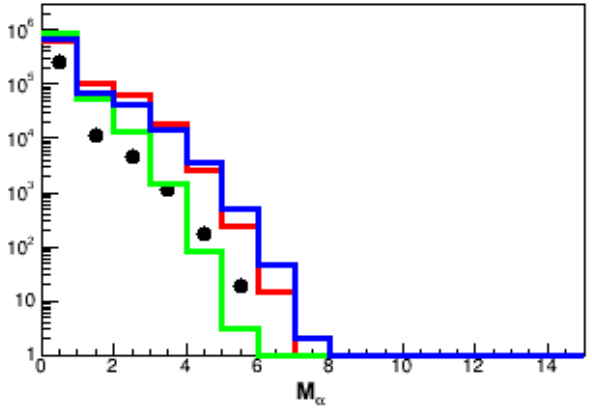
$^{16}O+^{65}Cu$





$^{19}F+^{62}Ni$

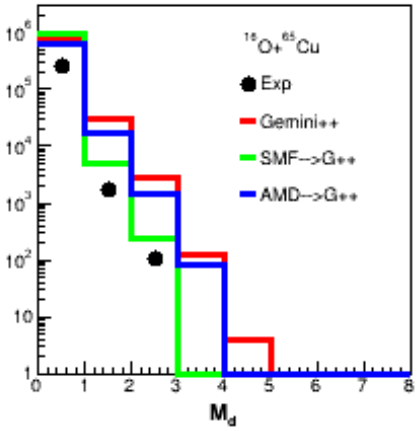


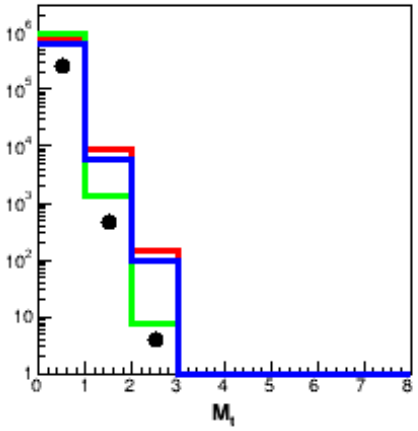


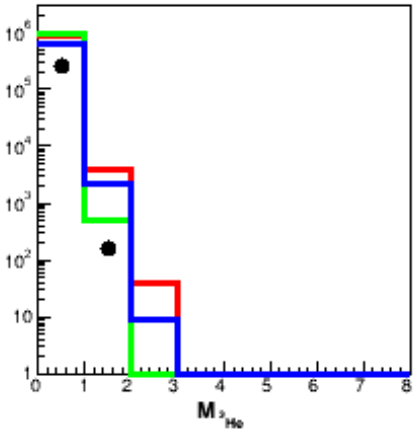
Comparison with different Models: LCP Multiplicities coinc. *Residues*

Deuteron **Tritons** **3He**

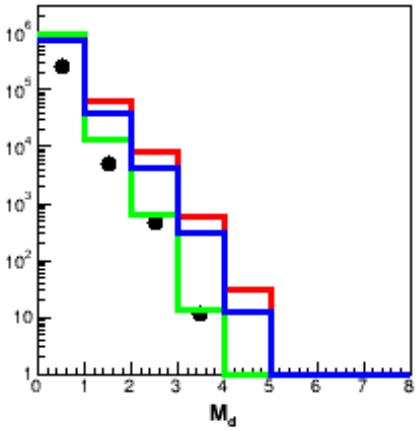
$^{16}O+^{65}Cu$

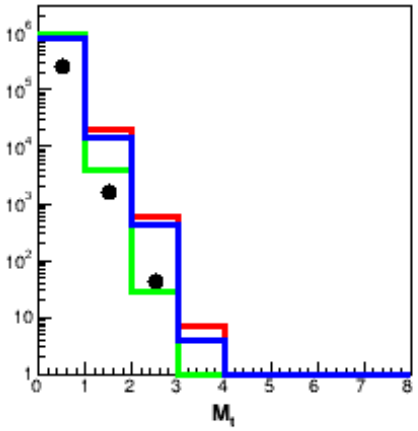


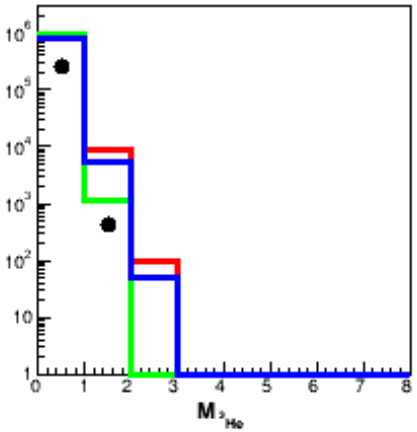




$^{19}F+^{62}Ni$





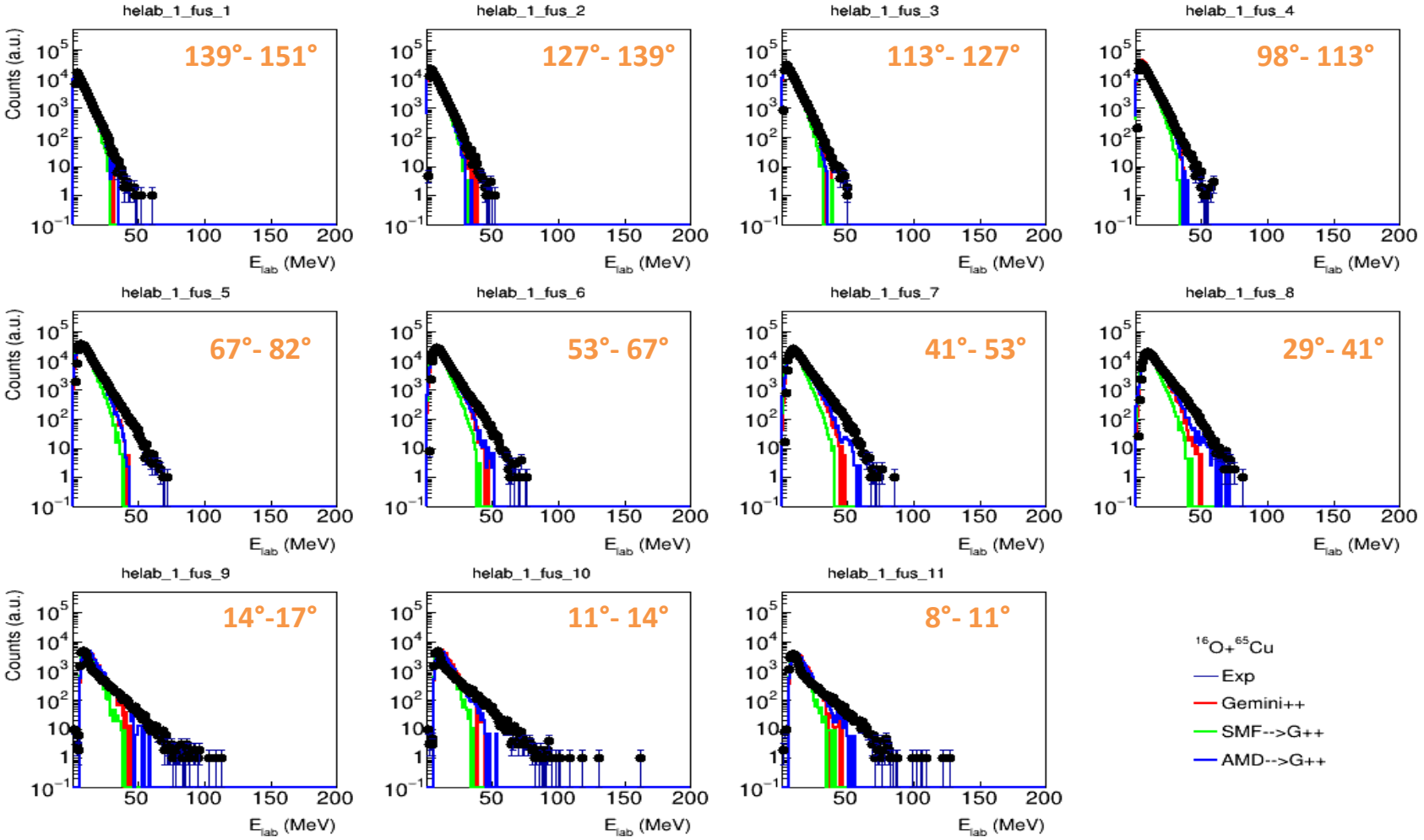


Comparison with different Models: Energy spectra in Lab

$^{16}O+^{65}Cu$

Protons

Coincidence with *Residues*

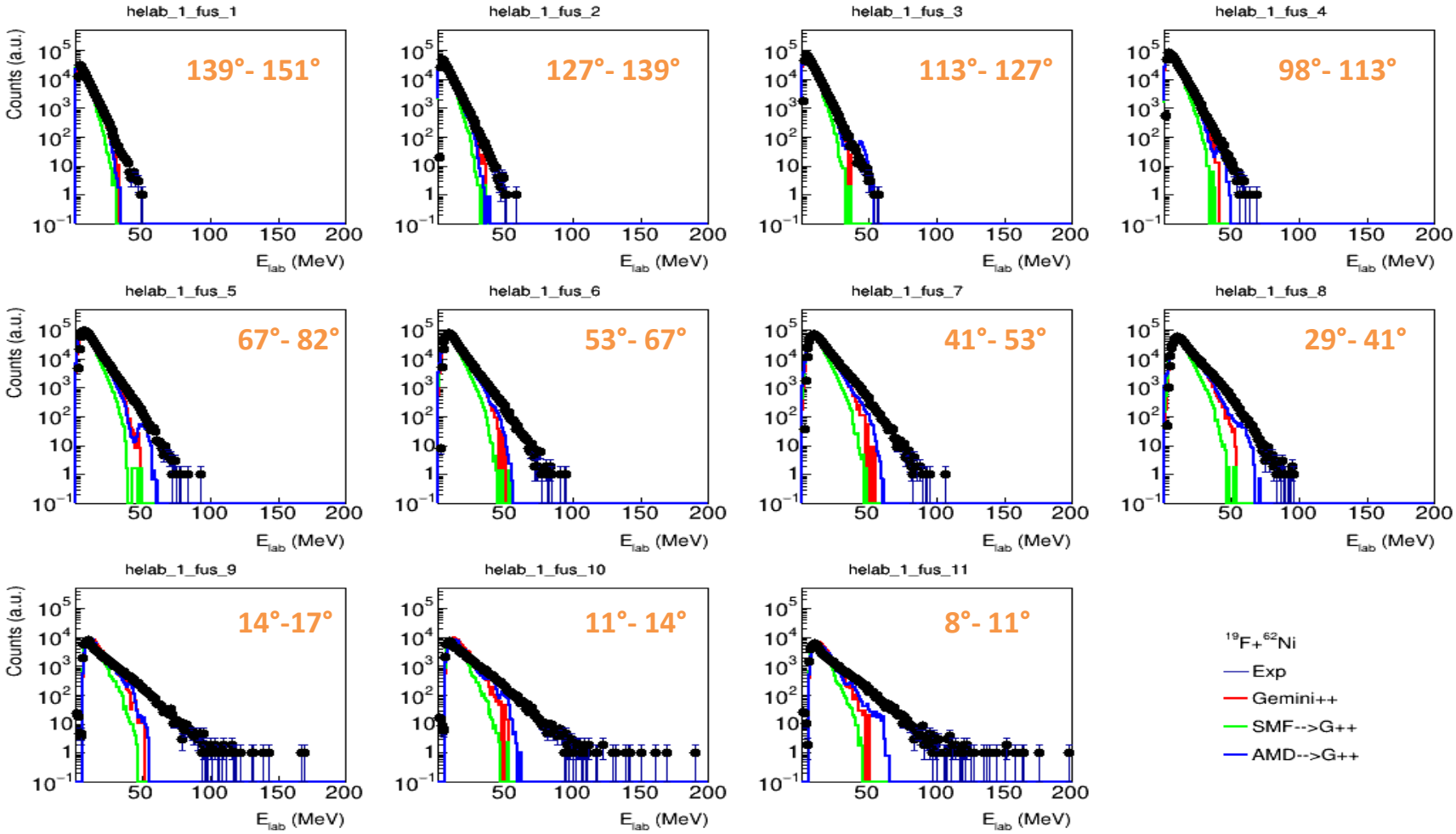


Comparison with different Models: Energy spectra in Lab

$^{19}F+^{62}Ni$

Protons

Coincidence with *Residues*

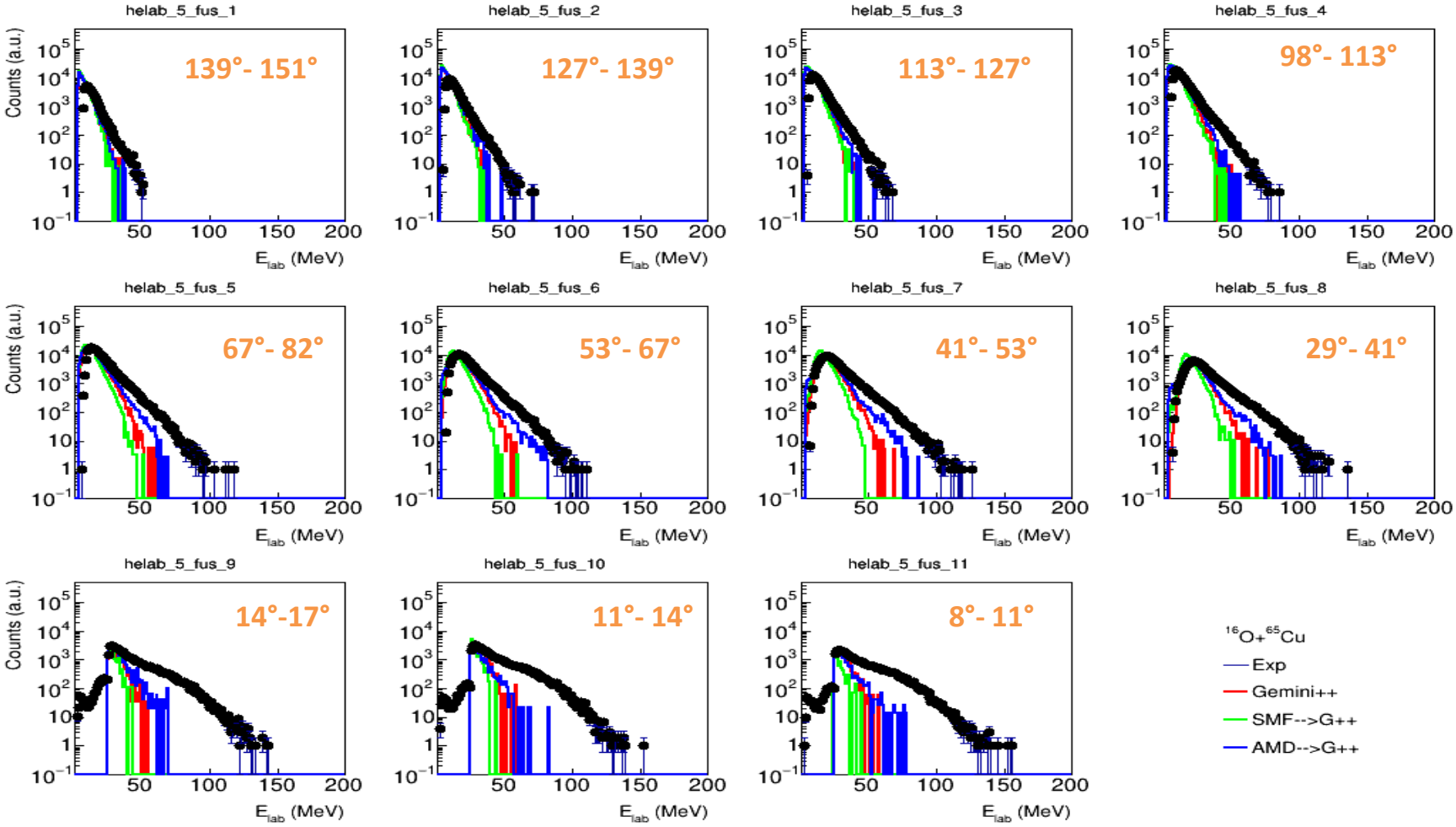


Comparison with different Models: Energy spectra in Lab

$^{16}O+^{65}Cu$

α-particles

Coincidence with *Residues*

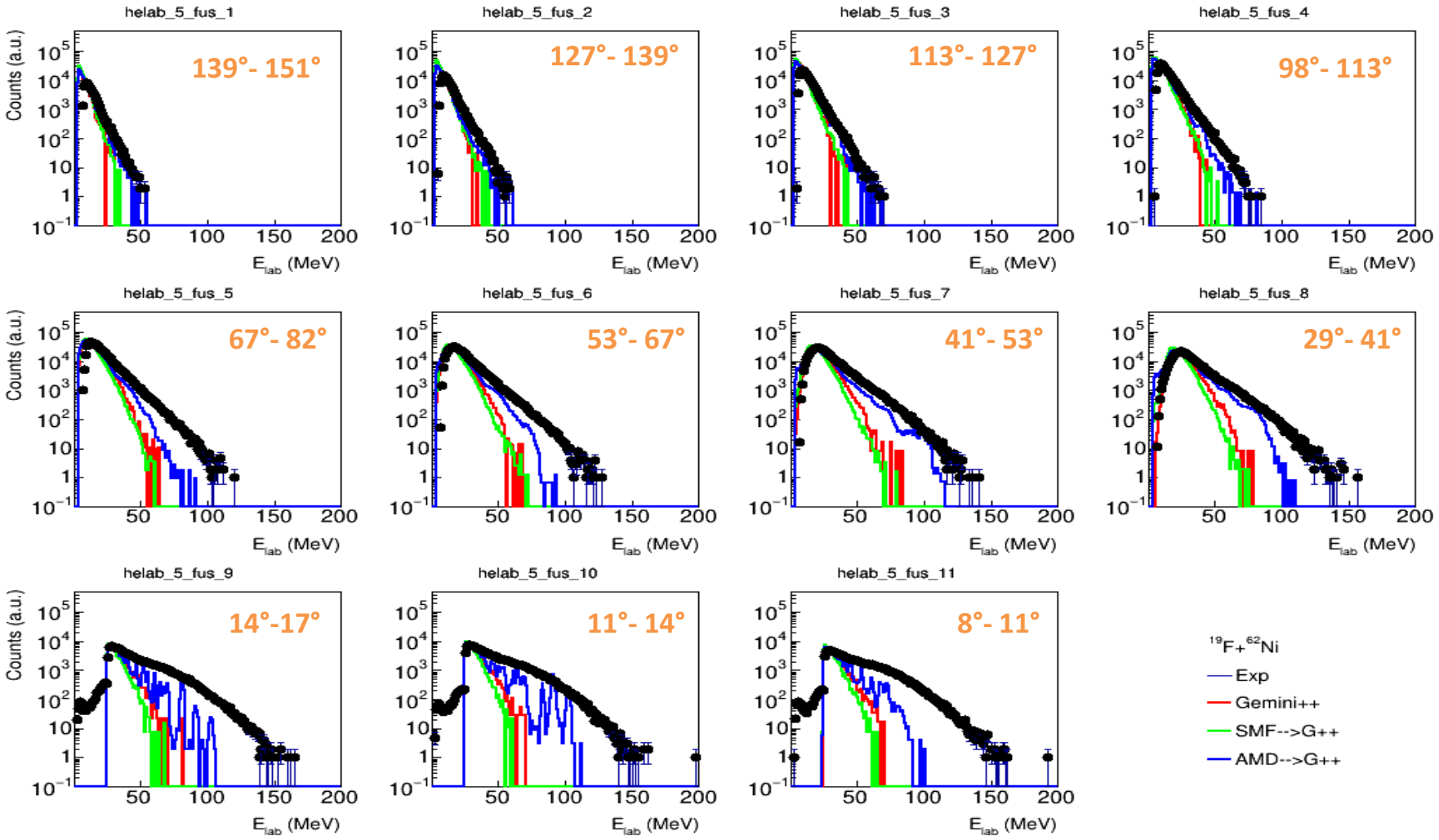


Comparison with different Models: Energy spectra in Lab

$^{19}F+^{62}Ni$

α-particles

Coincidence with *Residues*



Summary

- The **Pre-equilibrium particles emission** from the two ^{16}**O** + ^{65}**Cu** and ^{19}**F** + ^{62}**Ni** has been measured to get information on projectile clustering effects .

- Previous findings of **overproduction** of **Pre-equilibrium a-particles**, expecially in the ^{19}**F induced** reaction**,** has been **confirmed** also from the comparison with statistical predictions of the **GEMINI ++** code, filtered through a replica of the experimental set-up

- The **Moscow Pre-equilibrium** model resonably describes the **a** energy spectra, but overstimates the proton spectra. Model implementation are ongoing to include Clustering structure effects.

- The dynamical part of the reaction is under study using the **SMF Model** (Stochastic Mean Field) with GEMINI++ as *Afterburner* .

- Clustering effects are better described by the **AMD Model** (Antisymmetrized Molecular Dynamics) whc seems to agree better with the experimental data, even if it is not still optimized for Low Energies.

What next….

- **Complete the data analysis looking to more exclusive observables..**

- **Improve the comparison with theoretical models ...**

NUCL-EX collaboration

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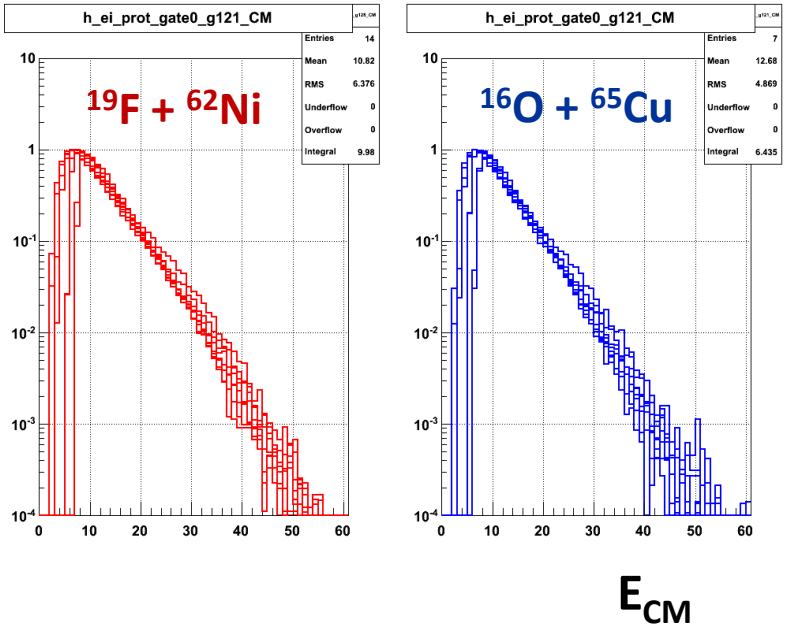
[1]INFN sezione di Padova, Padova, Italy
[2]Laboratori Nazionali di Legnaro, Legnaro (PD), Italy
[3]University of Nevsehir, Science and Art Faculty, Physics Department, Nevsehir, Turkey
[4]National Research Center "Kurchatov Institute", Moscow, Russia
[5]Dipartimento di Fisica, Universita' di Bologna and INFN sezione di Bologna, Bologna, Italy
[6]Dipartimento di Fisica, Universita' di Firenze and INFN sezione di Firenze, Firenze, Italy
[7]Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, Russia
[8] Dipartimento di Scienze Fisiche, Università di Napoli "Federico II", Napoli, Italy

Spares

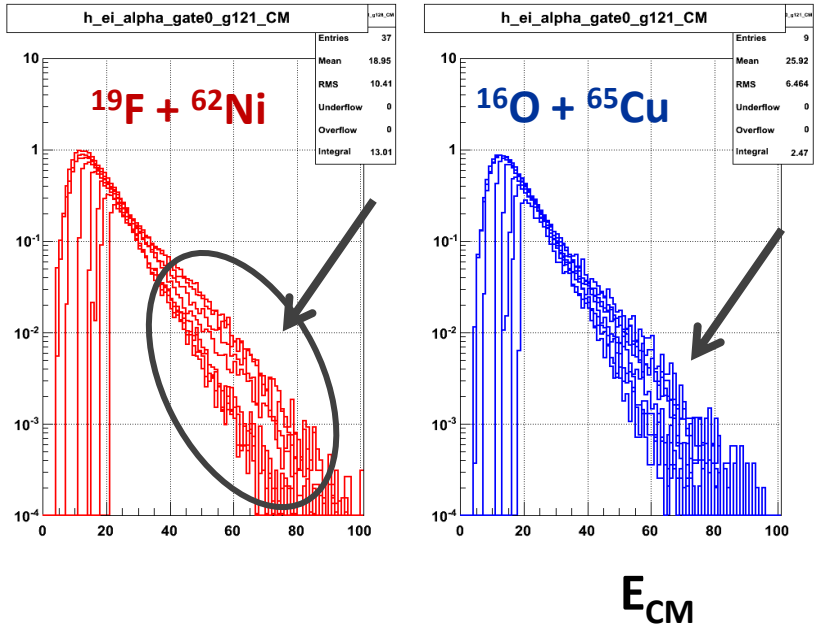
CM Spectra at **different angles**

Proton in CM



Very **small** pre-equilibrium contribution in proton spectra

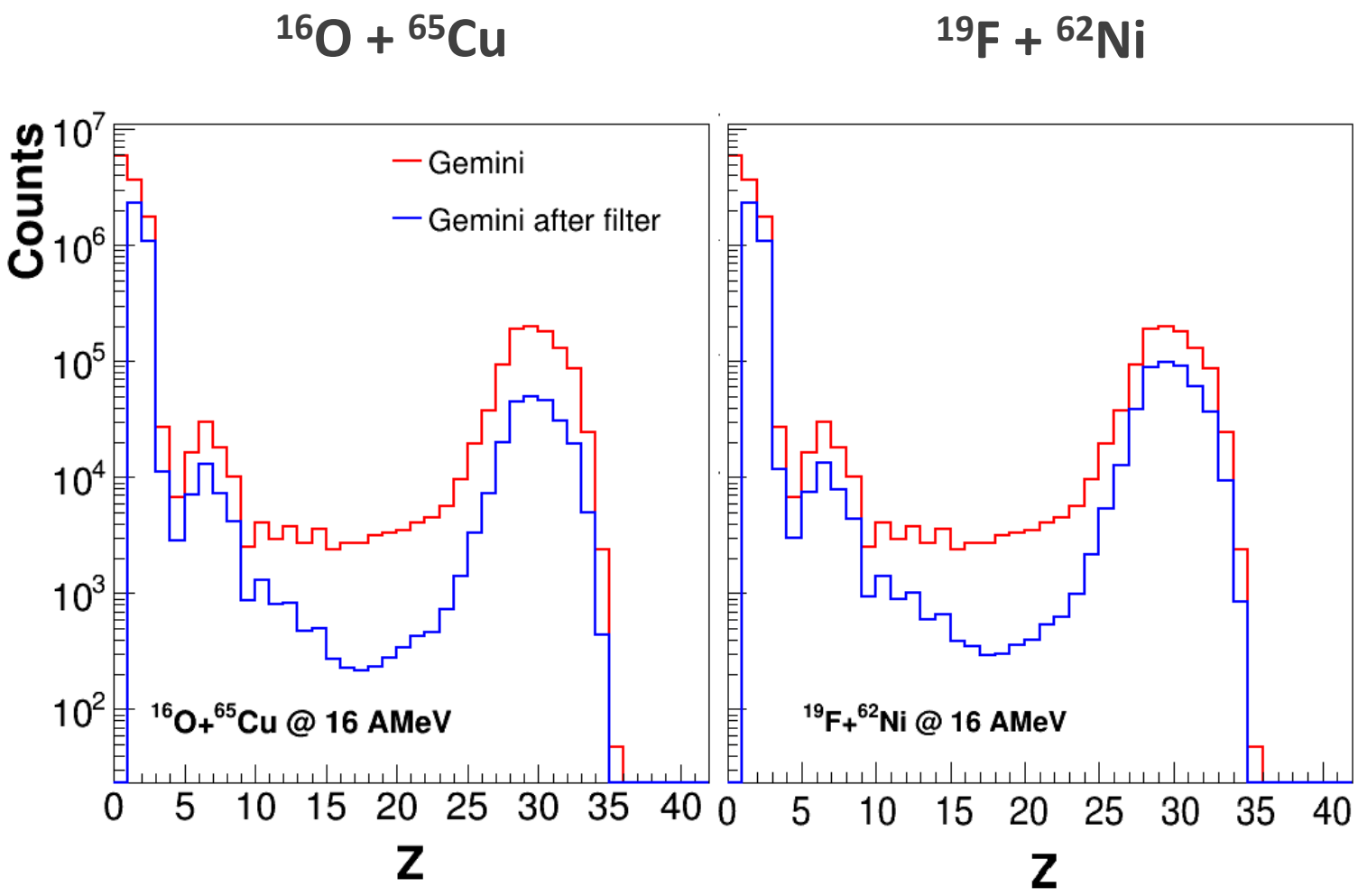
Alpha in CM



Larger pre-equilibrium contribution in **^{19}F induced reaction α-spectra** with respect to **^{16}O reaction**

G.A.R.F.I.E.L.D.
General ARray for Fragment Identification and Emitted Light particles in Dissipative collisions

GEMINI ++ : Total Z Distributions

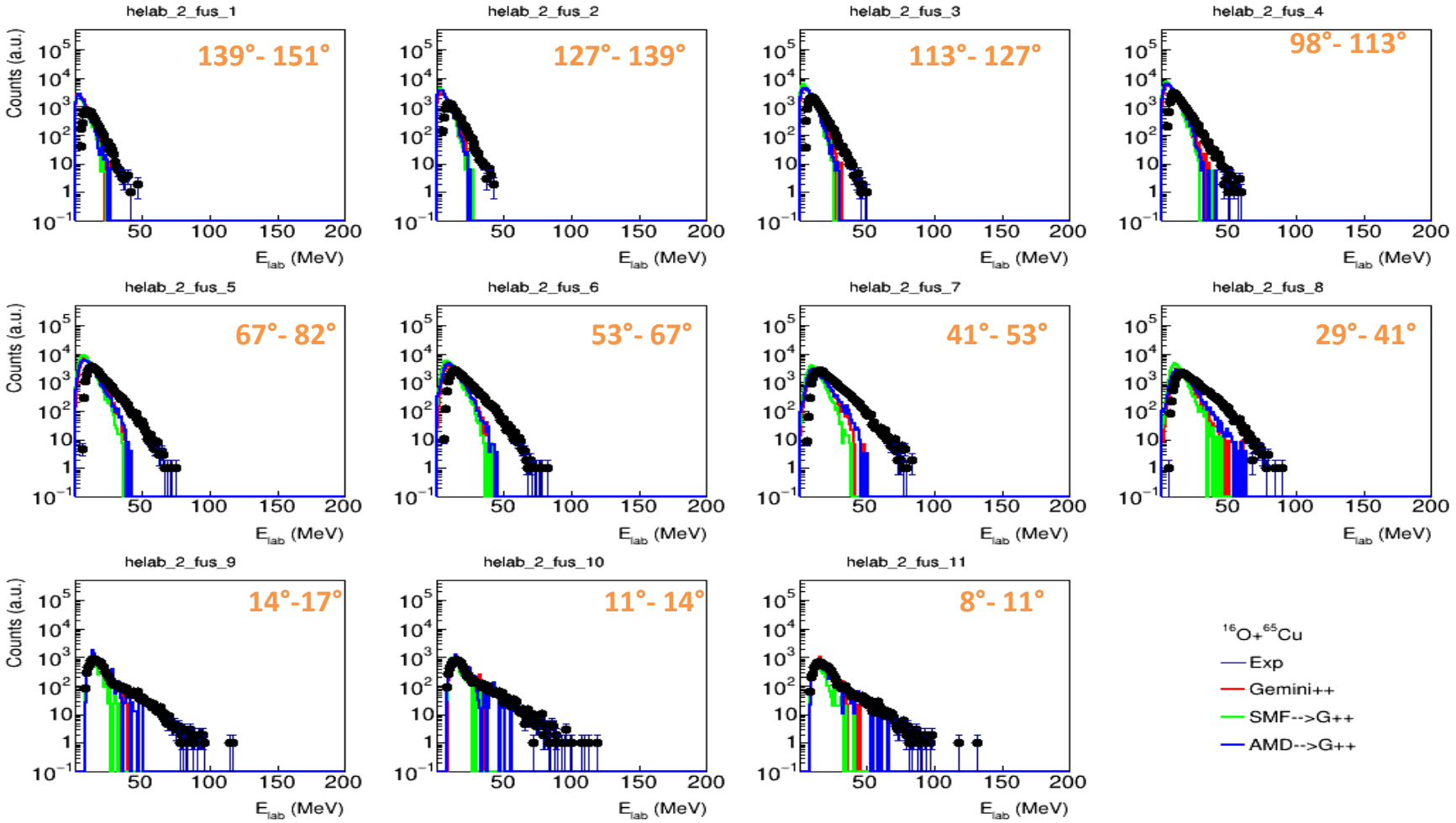


Comparison with different Models: Energy spectra in Lab

$^{16}O+^{65}Cu$

Deuterons

Coincidence with *Residues*

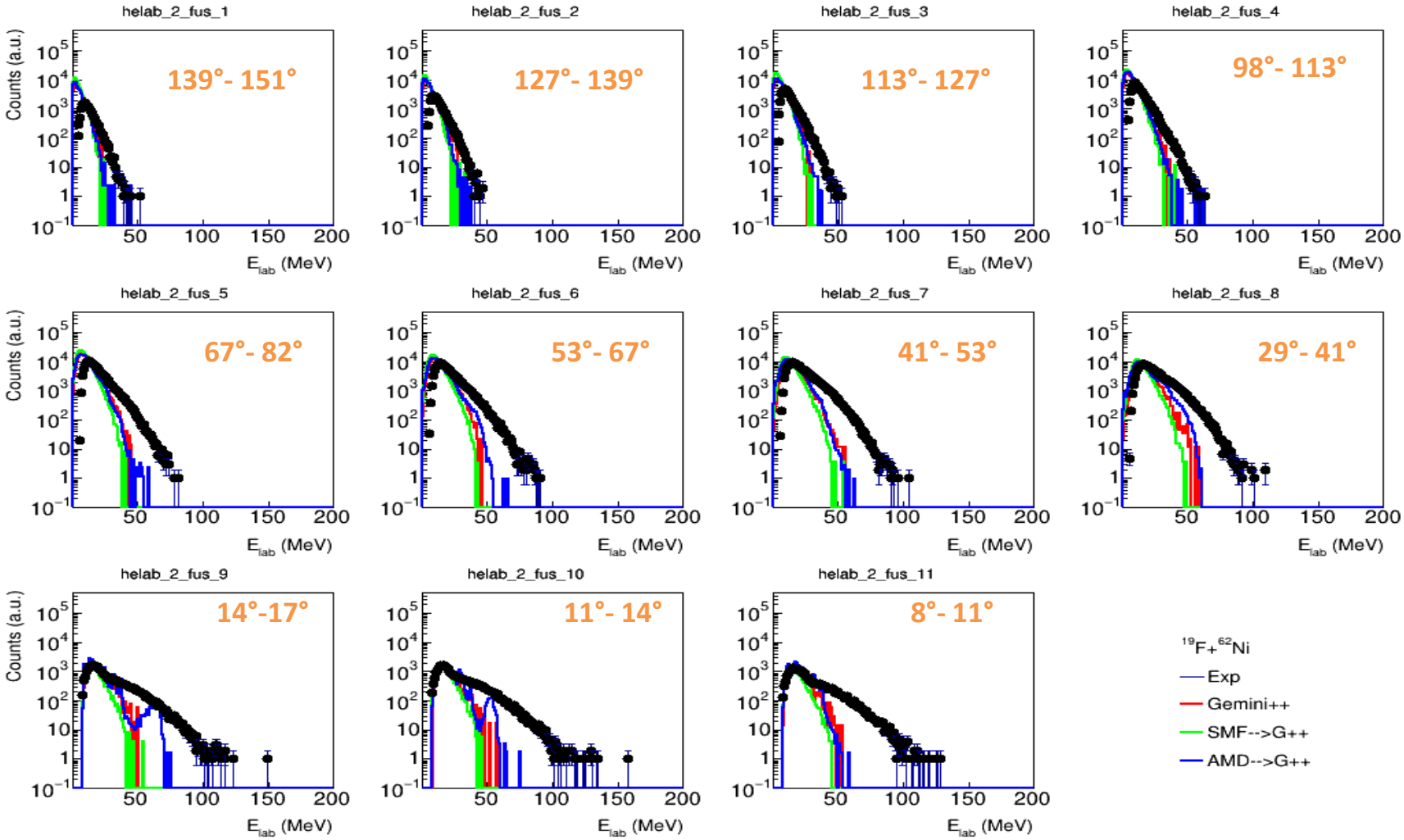


Comparison with different Models: Energy spectra in Lab

$^{19}F+^{62}Ni$

Deuterons

Coincidence with *Residues*

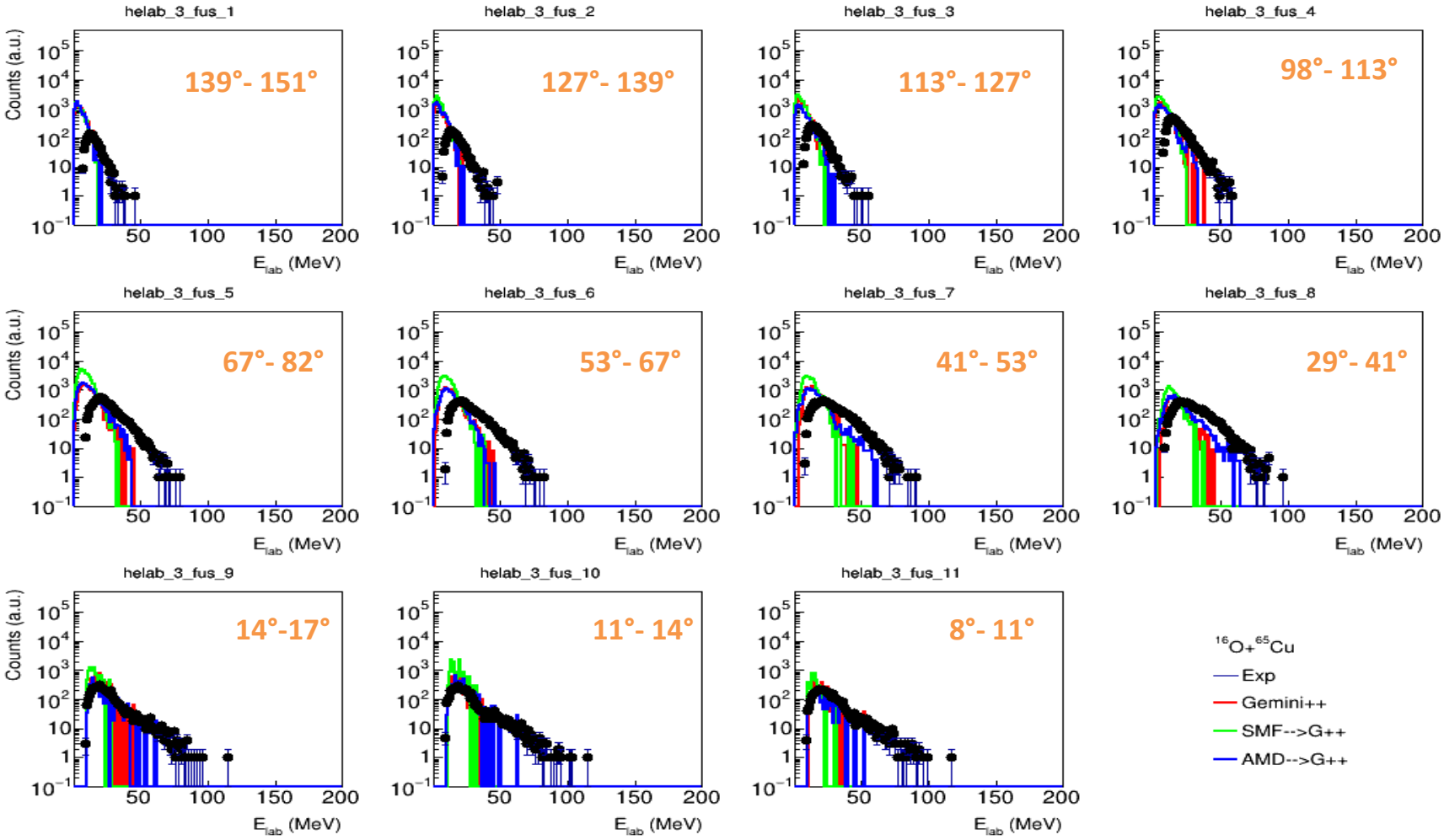


Comparison with different Models: Energy spectra in Lab

$^{16}O+^{65}Cu$

Tritons

Coincidence with *Residues*

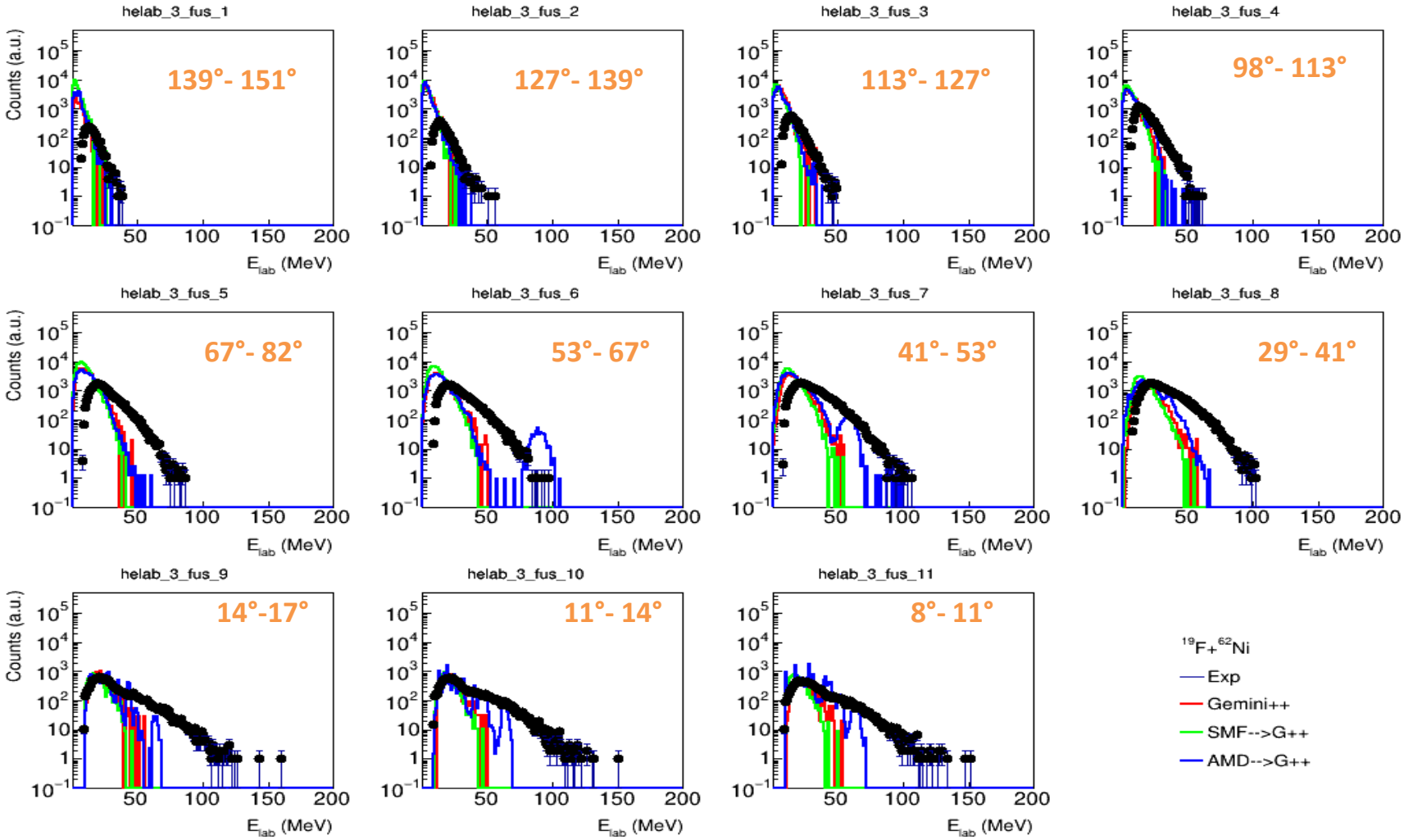


Comparison with different Models: Energy spectra in Lab

$^{19}F+^{62}Ni$

Tritons

Coincidence with *Residues*

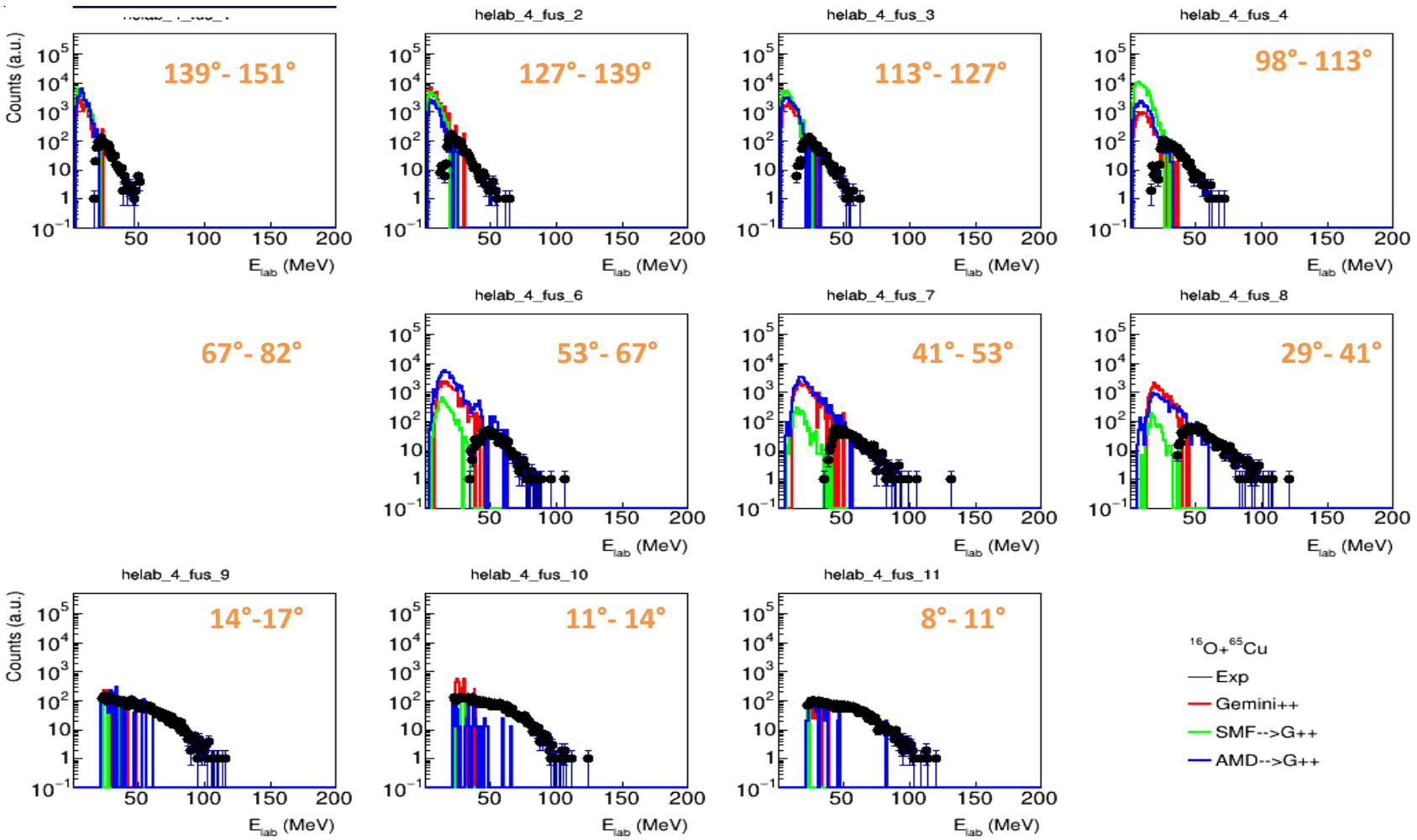


Comparison with different Models: Energy spectra in Lab

$^{16}O+^{65}Cu$

3He

Coincidence with *Residues*

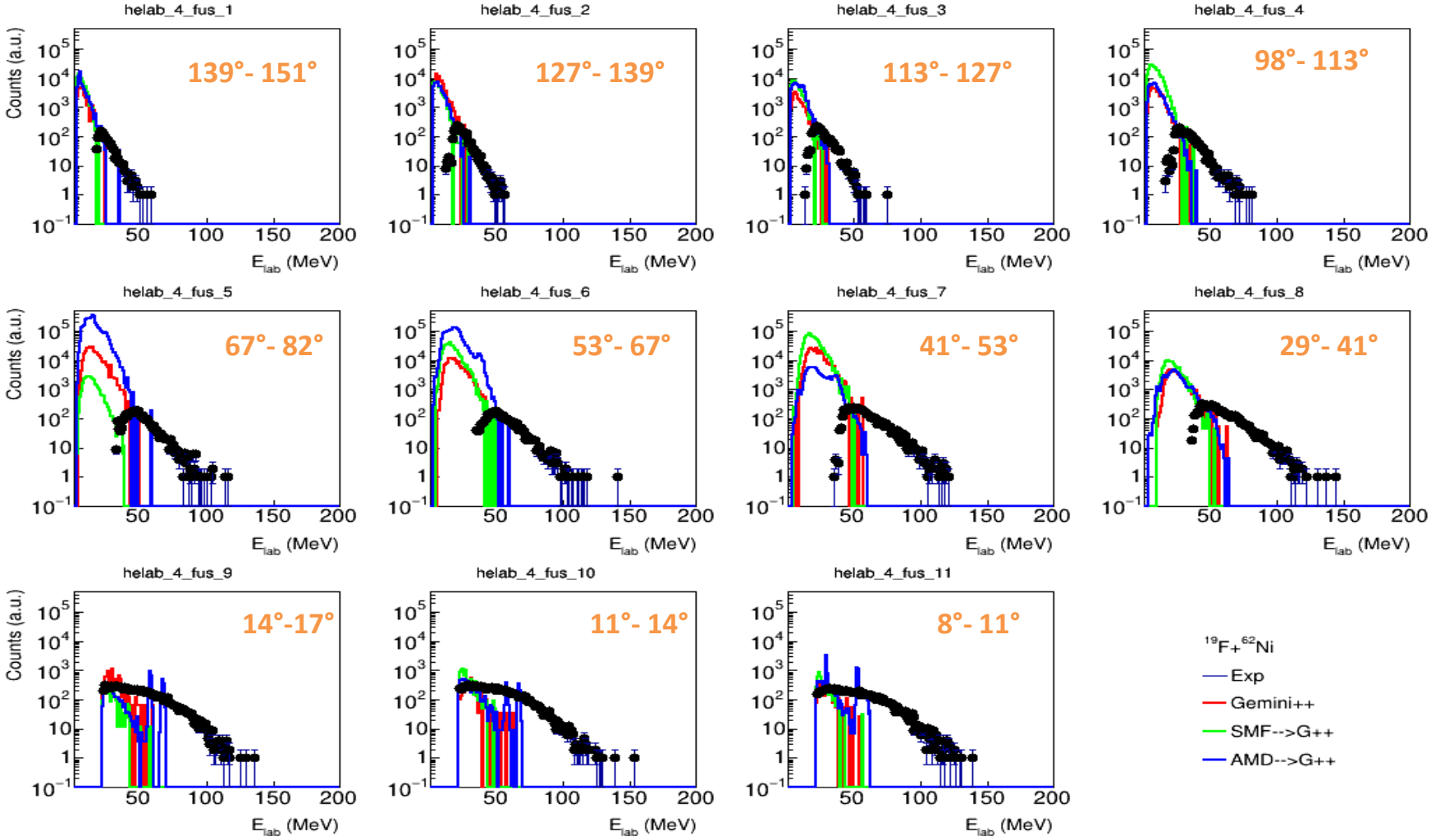


Comparison with different Models: Energy spectra in Lab

$^{19}F+^{62}Ni$

3He

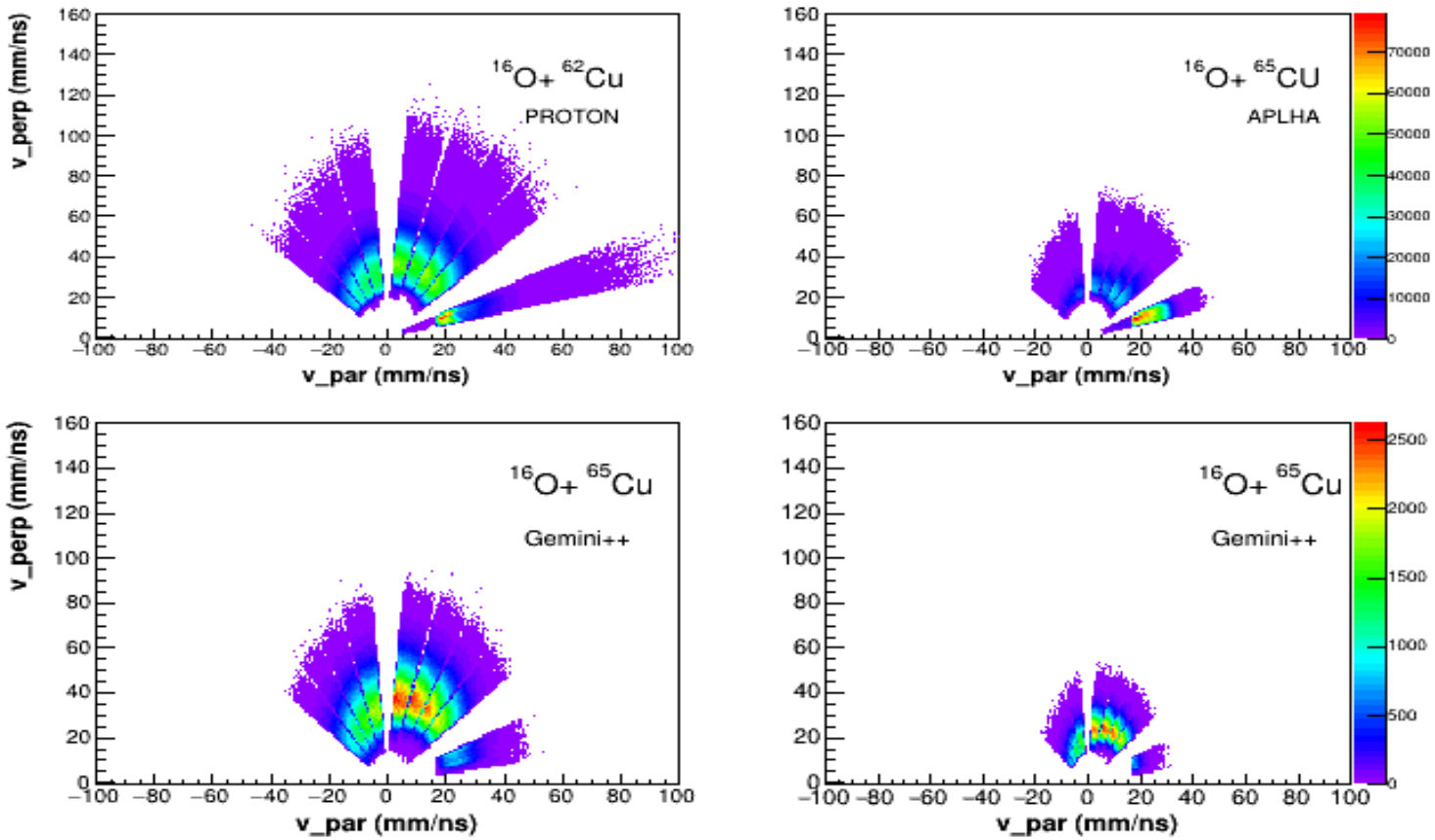
Coincidence with *Residues*



Comparison with filtered GEMINI ++ : $v_{\parallel}$ vs. $v_{\perp}$ in *Lab*

$^{16}O + {}^{65}Cu$

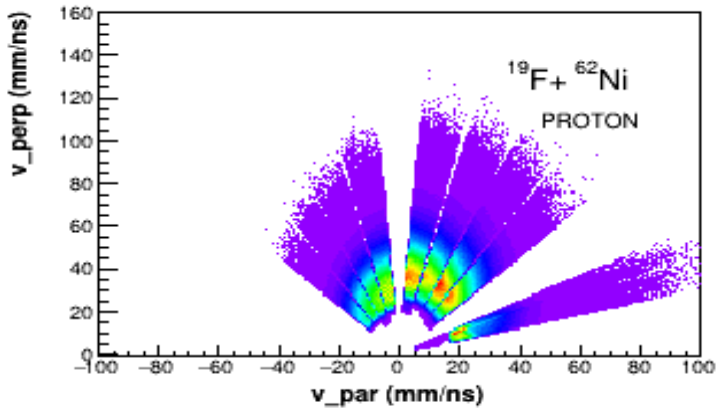
Coincidence with Resideus

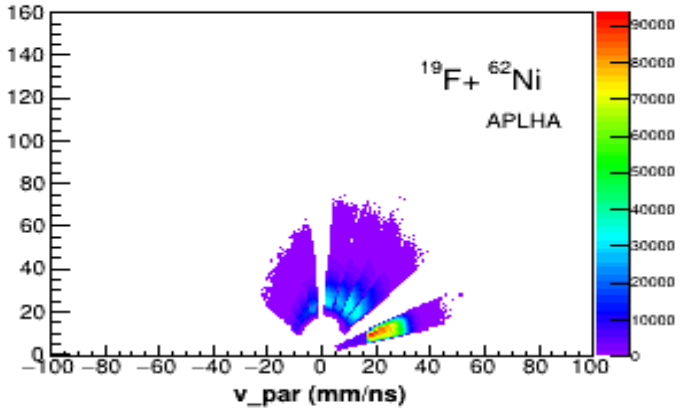


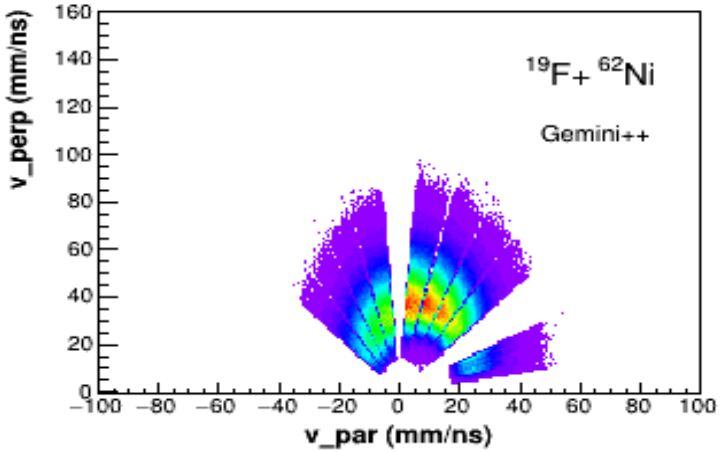
Comparison with filtered GEMINI ++ : $v_{\parallel}$ vs. $v_{\perp}$ in *Lab*

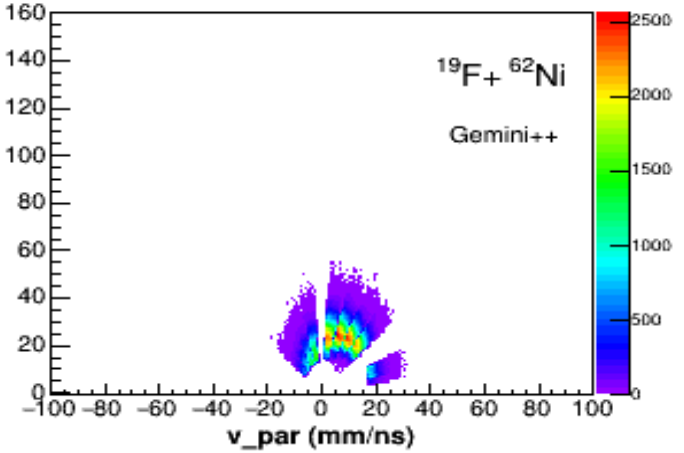
$^{19}F + {}^{62}Ni$

Coincidence with Resideus









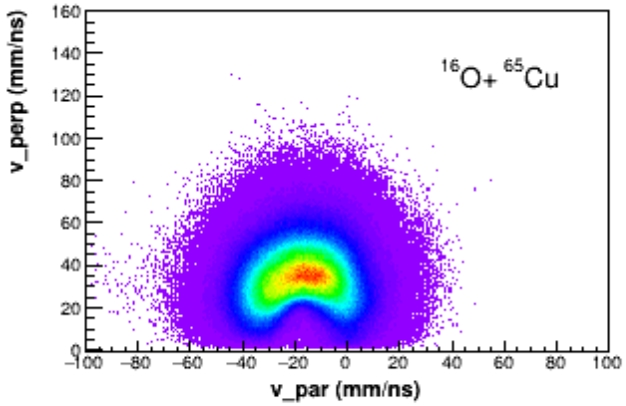
$v_{\parallel}$ vs. $v_{\perp}$ in *residue frame*

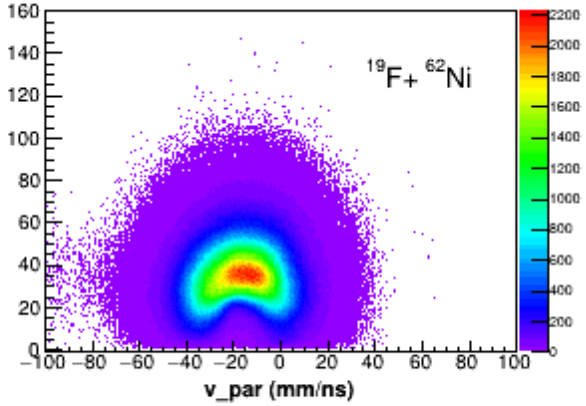
Exp

$^{16}O + ^{65}Cu$

$^{19}F + ^{62}Ni$

Protons





α-particles