STUDYING THE DECAY OF ^{46}TI*: ENTRANCE CHANNEL AND/OR α-STRUCTURE EFFECTS?

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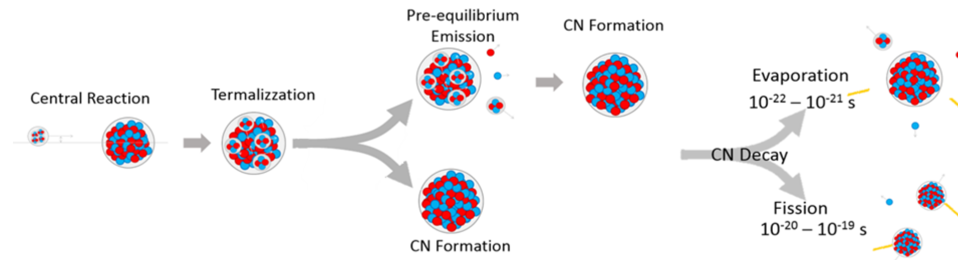
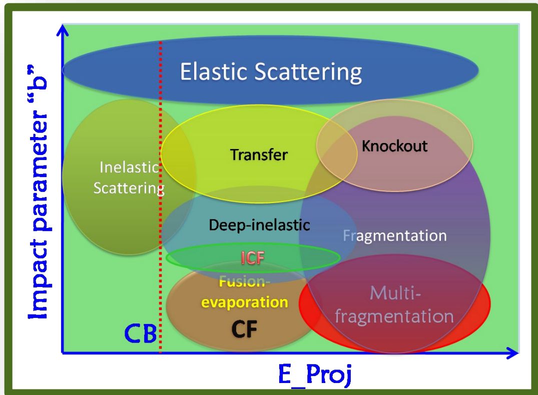
OUTLINE

- Fusion reaction between light/medium nuclei: fast & thermal emission competition, structure effects, clustering
- The $^{46}Ti^*$ formed through different entrance channels
- Simulations, geometrical filters and data selections
- Experimental Results & comparison to model predictions
- Conclusions

Reaction Mechanisms

$$E_p > B_C \Rightarrow \sigma_{reaz} = \sum_{\ell} \sigma_{reaz}(\ell) = \frac{\pi}{k^2}\sum_{0}^{\infty}(2\ell+1)T_\ell$$



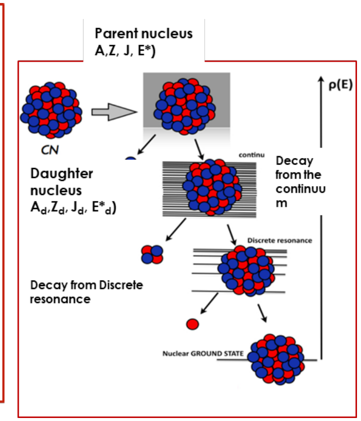


EXP: highly exclusive detection **NUCL-EX collaboration campaign**:

- **STATistical properties of LIGHT nuclei from Fus-Evap.**
- **ACLUST-ACLUST2: Study of the competition between fast and thermal emission from a hot source**

GARFIELD+RCo @ LNL

- low multiplicity events & high detection coverage
- high energy and angular resolution
- complete event Reconstruction
- global control on the decay mechanism



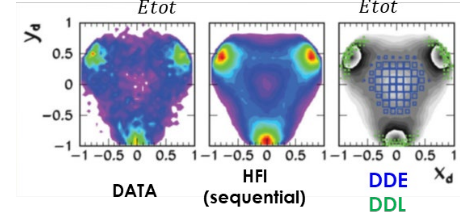
- **Hot light nuclei** (E*~3 A.MeV) → produced in **multi-fragmentation** in a wide range of N/Z → **TRACING BACK** → access to the **symmetry energy term** in the NEOS
- **Limiting Temperature**
- only access **to Level densities** above the **thresholds for particle decay** via evaporation reactions (**compound nucleus decay theory)** → decreasing of **NLD** as a function of increasing **N-Z**
- mainly **inclusive experiments** → **lack of complete studies** on the evaporation from light nuclei especially in the mass region **A~20**
- Some **excited states** of different nuclei in this mass region are known to present **pronounced clustered structures**

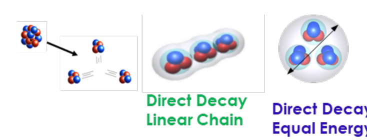
Hoyle State in $^{12}C + ^{12}C$ reaction

L. Morelli et al. J.Phys.G 43(2016) 045110

Energy DALITZ Plot

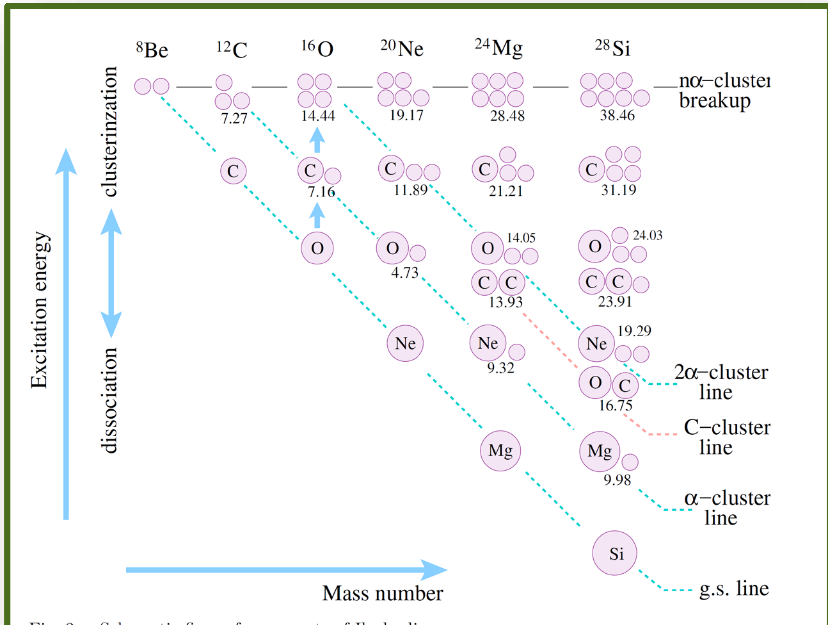
$$X = \frac{\sqrt{3}(Ei - Ej)}{Etot} \qquad Y = \frac{2Ek - Ei - Ej}{Etot}$$



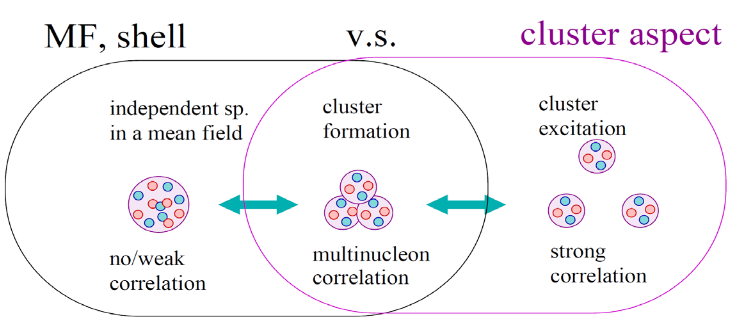


- **Medium light nuclei** → studying the competition between **fast** and **thermal emission** from a **hot source**→ **pre-equilibrium processes** → **cluster emission**→ **link to structure effects or dynamical formation?**

Studying Nuclear clustering



Y. Kanada-En'yo, International School of Physics "Enrico Fermi", course 201 (Nuclear Physics with Stable and Radioactive Beams), 14-19 July 2017



Light Nuclei

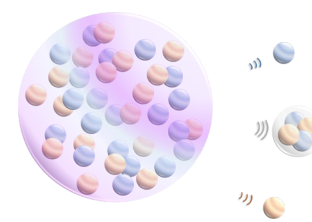
Coexistence of cluster and mean-fields aspects:

connection between cluster emission and nuclear structure.

Medium Mass Nuclei

Clustering effects on reaction dynamics can be **observed.** Are they due to **cluster pre-formation either in the colliding partners or in the CN*** or do they derive by a **dynamical formation**.

Analizying the competition of **CF** with **fast processes →** Thermal vs pre-equilibrium particles emission



Studying the competition between evaporation (surface) and fast (volume) emission of LCP.

- Y. Kanada-En'yo et al., Prog.Theo.Exp.Phys. 01A202 (2012).
- P.E. Hodgson, E. Běták, Phys. Rep. 374 (2003) 1-89.

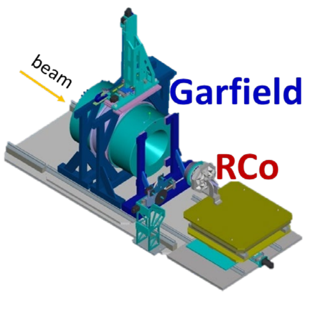
The $^{46}Ti^*$ formed through different entrance channels

Entrance channel	$E_{beam, lab}$		$\theta_{grazing}$	CN	η	σ_{fus}	E*	Lcrit (Bass)	Lab. Vel.	E.R. Distrib. θ_{lab}
Beam + Target	MeV	MeV/u	deg			mb	MeV	hbar	cm/ns	deg
$^{16}O + ^{30}Si$	128	8	8,8	^{46}Ti	0,304	1070	98,4	37.3	1,37	0 – 30
$^{16}O + ^{30}Si$	111	7	10,1	^{46}Ti	0,304	1081	88,0	35.4	1,28	0 – 30
$^{18}O + ^{28}Si$	126	7	9,0	^{46}Ti	0,217	1110	98,5	37.7	1,44	0 – 28
$^{19}F + ^{27}Al$	133	7	8,9	^{46}Ti	0,174	1100	103,5	38.3	1,52	0 – 28

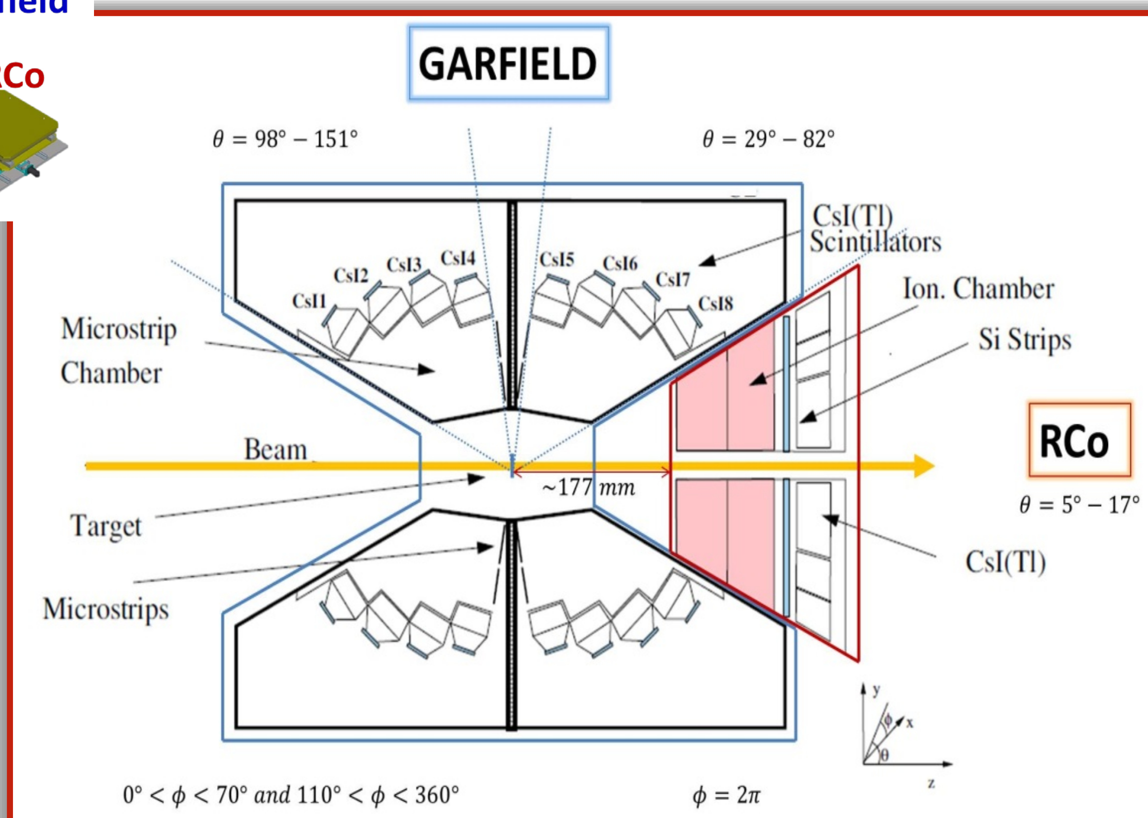
same beam velocity ⇒ same pre-equilibrium component

same CN Excitation Energy ⇒ same statistical component

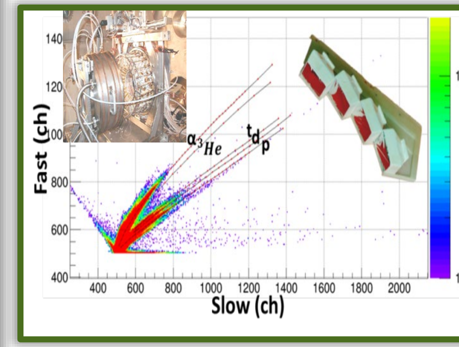
The Experimental Set-up



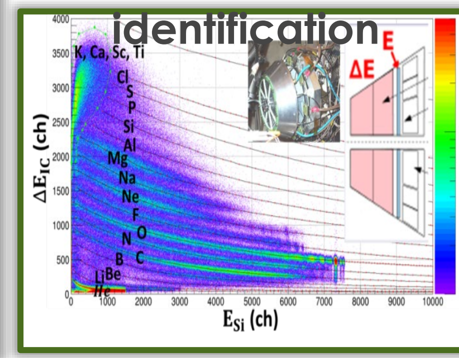
GARFIELD + RCo



LCP identification



RESIDUE identification



- F. Gramegna et al., Proc. of IEEE Nucl.Symp., 2004, Roma, Italy, 0-7803-8701-5/04/.
- M. Bruno et al. Eur. Phys. J. A (2013) 49: 128

Selection of CENTRAL EVENTS ⇨ Evaporation Residue is detected in coincidence with Light Particles

^{46}Ti* & Model Simulations

Effects of Structure of Interacting Nuclei & Reaction Dynamics

8 MeV/n ^{16}O+^{30}Si
7 MeV/n ^{16}O+^{30}Si
7 MeV/n ^{18}O+^{28}Si
7 MeV/n ^{19}F+^{27}Al

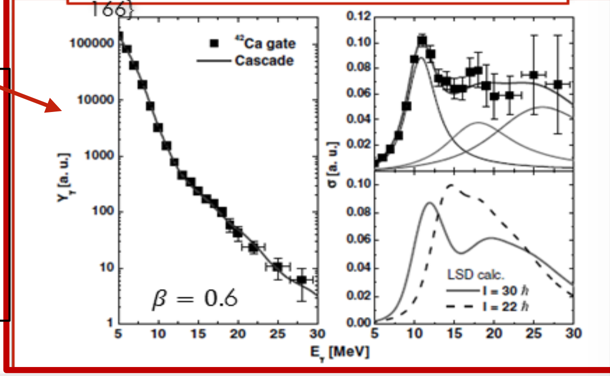
^{46}Ti*

DECAY

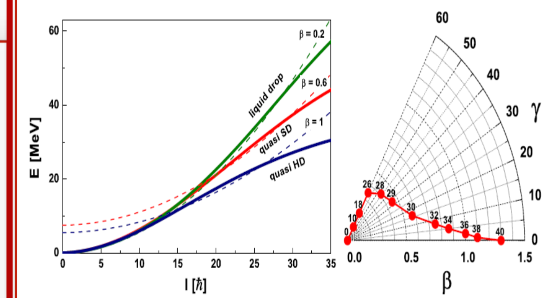
DEFORMED NUCLEUS

Cacarizo

{A. Maj et al., Eur.Phys.J. A 20 (2004) 165-166}



{M. Brekiesz et al., Nucl.Phys A 788 (2007) 224c-230c}



LSD

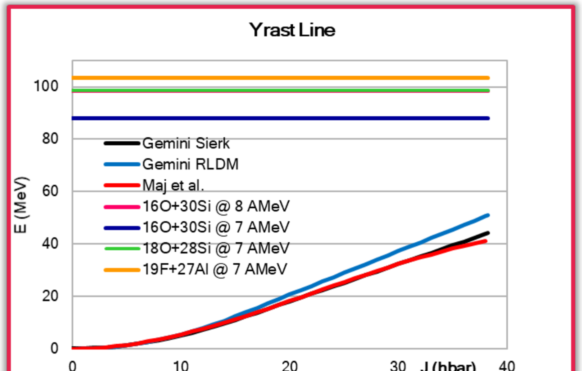
Figure 2. Left: the yrast lines used in the calculations (solid lines) and the rigid body yrast lines with different deformation parameters (dotted lines). Right: the evolution of the equilibrium shape of ^{46}Ti as a function of spin predicted by the LSD model.

GEMINI++ (R. J. Charity, Phys Rev C82 (2010) 014610.)

Simulate the **decay of hot nuclei** formed in fusion/quasi-fusion reaction.

- **Standalone** → a good selection of central events can be performed; different code parameters can be set.

β	δ_1	δ_2	Shape
0.2		*RLDM* parameters	
0.6	**4.6 × 10^{-4}**	**1.0 × 10^{-7}**	***Quasi – SUPERDEFORMED***
1.0	1.1 × 10^{-3}	1.0 × 10^{-7}	*Quasi – HYPERDEFORMED*



1. Macroscopic Rotational Energy

$$E_{Yrast}(J) = \begin{cases} E_{Sierk}(J) \text{ if } J < J^* \\ E_{Sierk}(J) + (J - J^*)E_{Sierk}(J^*) \text{ if } J > J^* \end{cases}, J^* = 0.319A$$

2. Transmission coefficients

$$T_l(\epsilon) = \frac{T_l^{R_0-\delta r}(\epsilon) + T_l^{R_0}(\epsilon) + T_l^{R_0+\delta r}(\epsilon)}{3}, \delta r = w\sqrt{T}$$

a) w=0.0 G00, b) w=1.0 G10, c) w=1.1 G11

3. Level density

$$\rho_B(E_B^*) \propto 2\sqrt{aE_B^*}$$

$$a = \frac{A}{k_\infty - (k_\infty - k_0)exp\left(-\frac{\kappa}{k_\infty - k_0}\frac{U}{A}\right)}$$

$$\kappa(A) = 0.000517exp(0.0345A)$$

Antisymmetrized Molecular Dynamics {A. Ono, Phys. Rev. C59, 853 (1999)}

- describes the cluster structure of the interacting particles.
- takes into account the particle-particle correlations.

HIPSE {D. Lacroix, et al., Phys. Rev. C69, 054604 (2004)}

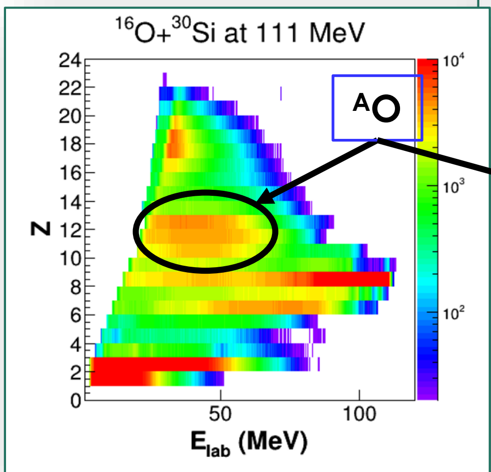
- describes nuclear collisions of heavy-ions in the intermediate energy range.
- Based on sudden approximation.

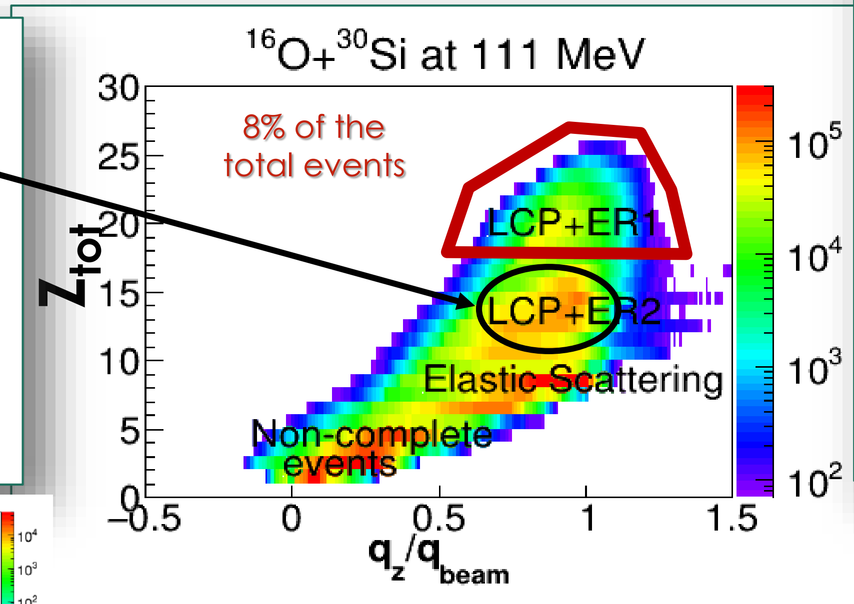
GEMINI++ as Afterburner (after a dynamical code) to **produce secondary particles distributions** from primary fragments → to be compared with exp data.

Events Selection

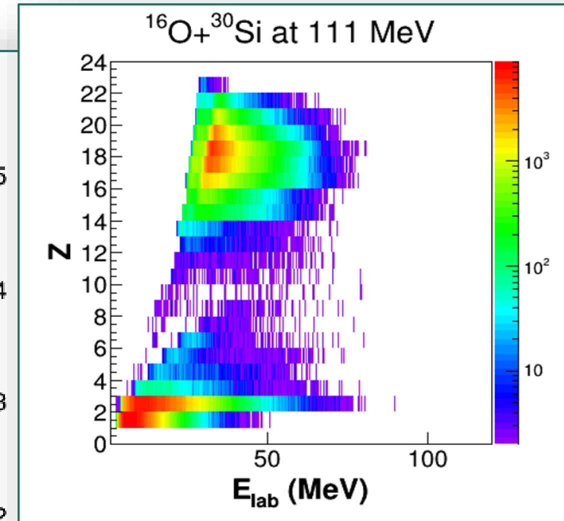
Correlation between the **longitudinal momentum** and the **total detected charge**

Z vs E_{lab}





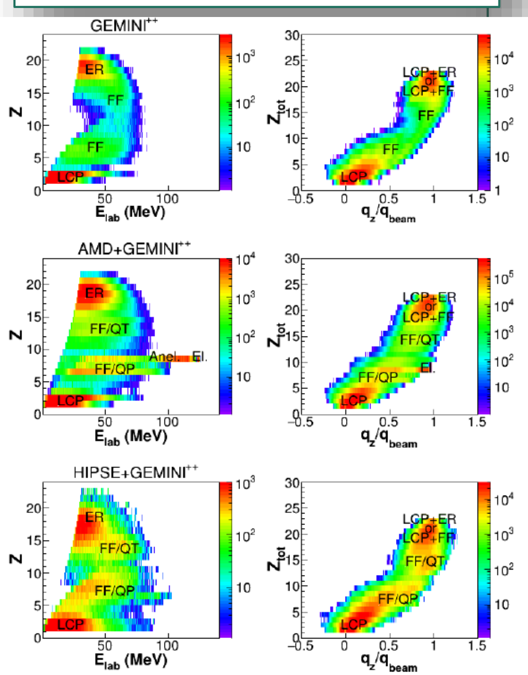
Z vs E_{lab}



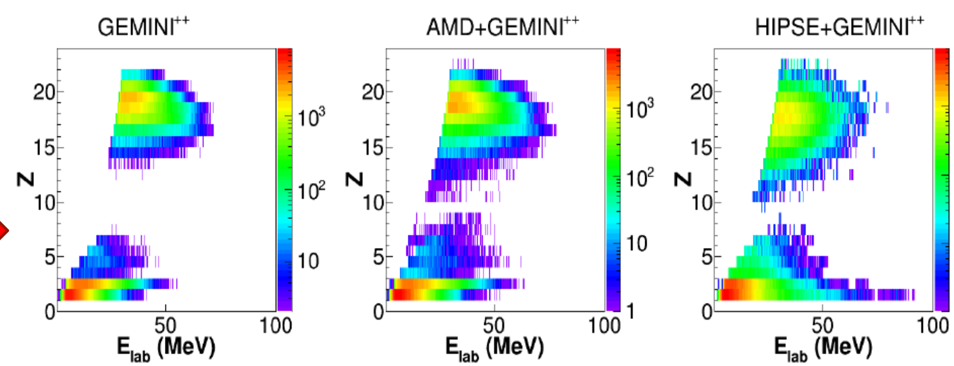
More restrictive: selecting almost complete events

- **Z_{tot} > 18 (>82%)**
- **q_z/q_{beam}<1.2**

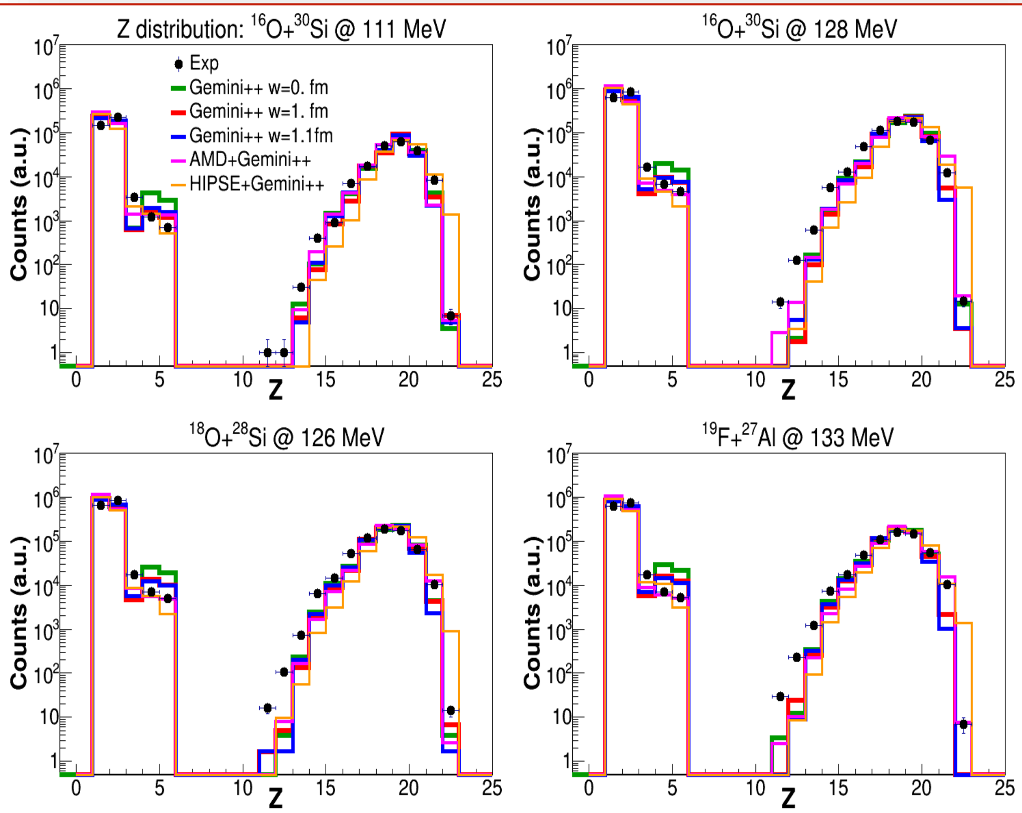
To cut **contamination events** we need to ask at least **Z_{tot}>16=O+O**



Same cuts on simulations !!!!!



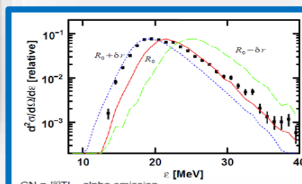
Results: $Z_{tot}=Z_p+Z_t=22$
Complete events - **Z-distribution**



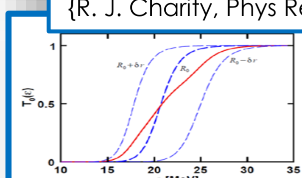
TOTAL CHARGE DETECTED
Only neutrons missing

$\frac{\#_{Evts\ Z_{tot}=22}}{\#_{Tot\ Evts}}$	^{16}O+^{30}Si 111 MeV	^{16}O+^{30}Si 128 MeV	^{18}O+^{28}Si 126MeV	^{19}F+^{27}Al 133 MeV
Experimental	0.3%	0.3%	0.4%	0.6%
GEMINI^{++} w=0.0 fm	3.4%	3.6%	3.9%	3.9%
GEMINI^{++} w=1.0 fm	4.0%	4.1%	4.5%	4.3%
GEMINI^{++} w=1.1 fm	3.8%	3.9%	4.4%	4.3%
AMD+GEMINI^{++}	2.5%	2.8%	3.4%	3.3%
HIPSE+GEMINI^{++}	2.8%	2.9%	3.2%	2.7%

- Exp
- Gemini++ w=0. fm → **Unique barrier G00**
- Gemini++ w=1. fm → **Deformation 2:1 G10**
- Gemini++ w=1.1fm → **Deformation 2.2:1 G11**
- AMD+Gemini++
- HIPSE+Gemini++



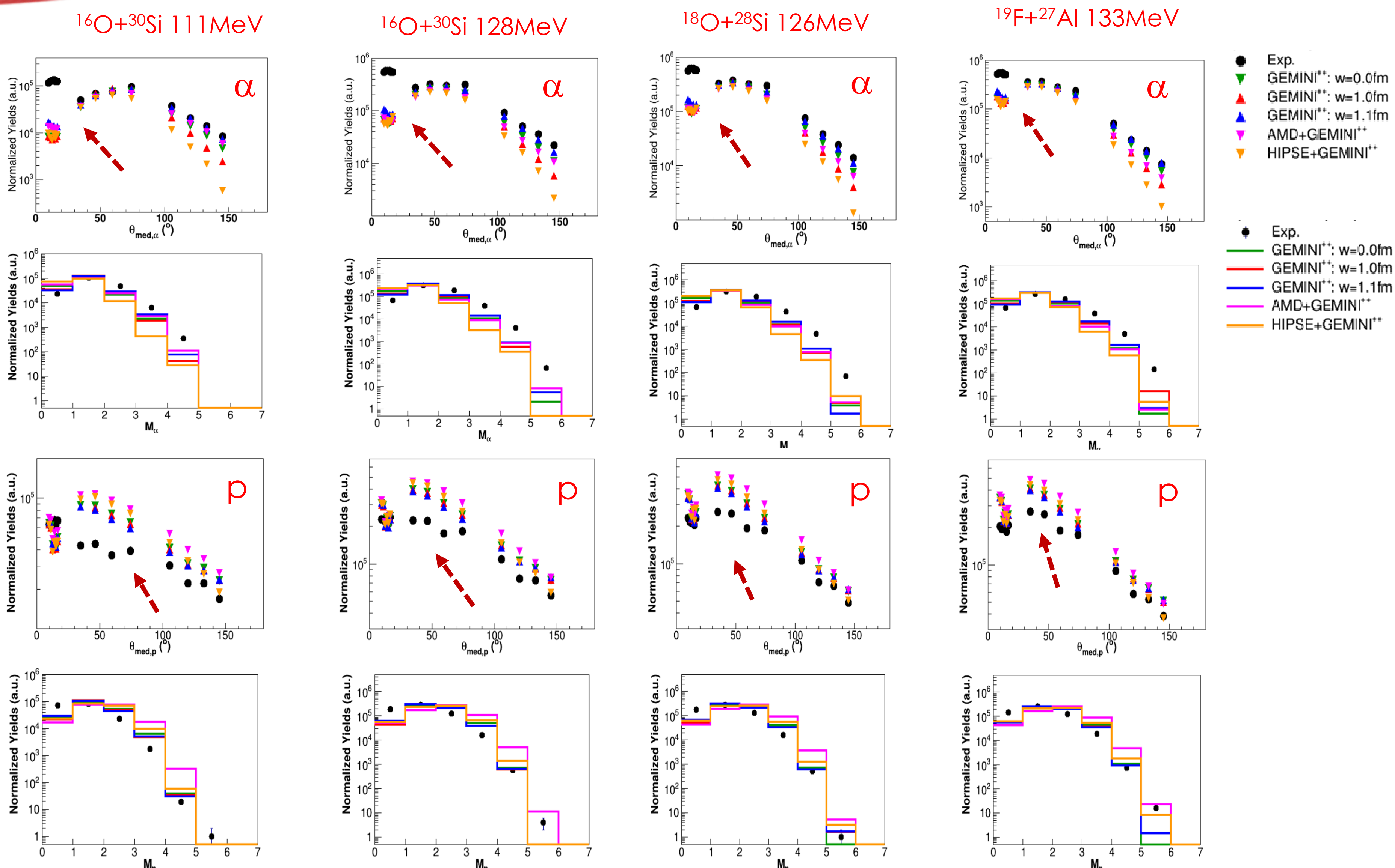
{R. J. Charity, Phys Rev C 82 (2010) 014610}



$$T_l(\epsilon)=\frac{T_l^{R_0-\delta r}(\epsilon)+T_l^{R_0}(\epsilon)+T_l^{R_0+\delta r}(\epsilon)}{3}, \delta r = w\sqrt{T}$$

Results: $Z_{tot}=Z_p+Z_t=22$

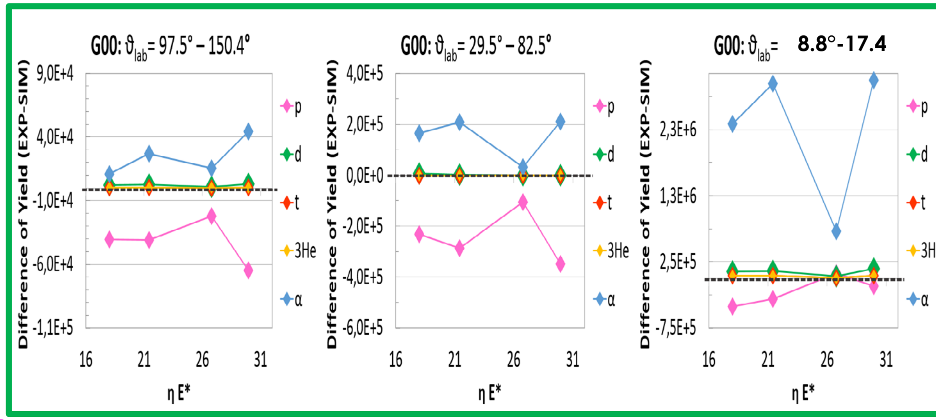
Ang. Distributions & Multiplicities

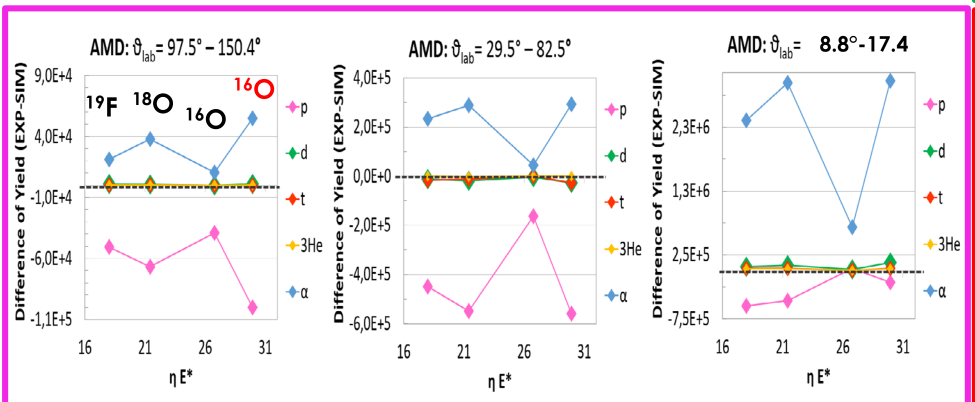


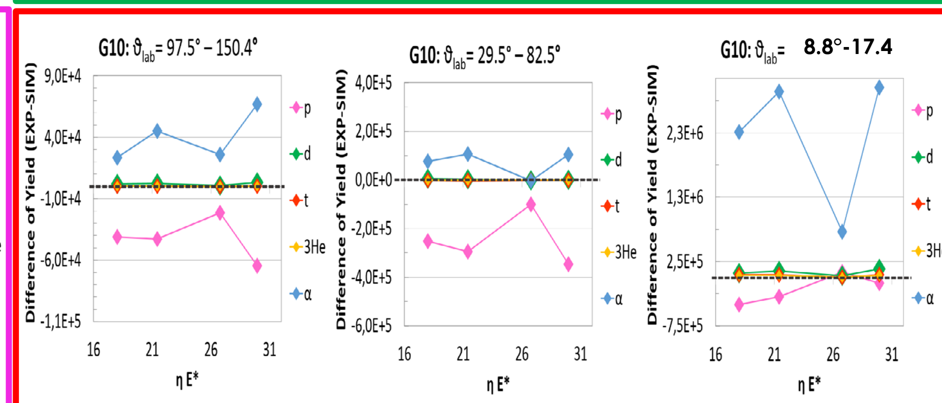
Results: $Z_{tot}=Z_p+Z_t=22$

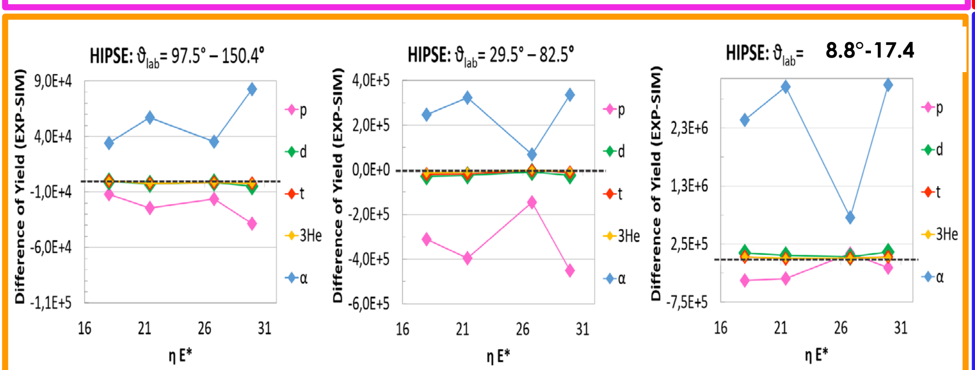
Ang. Distributions Differences

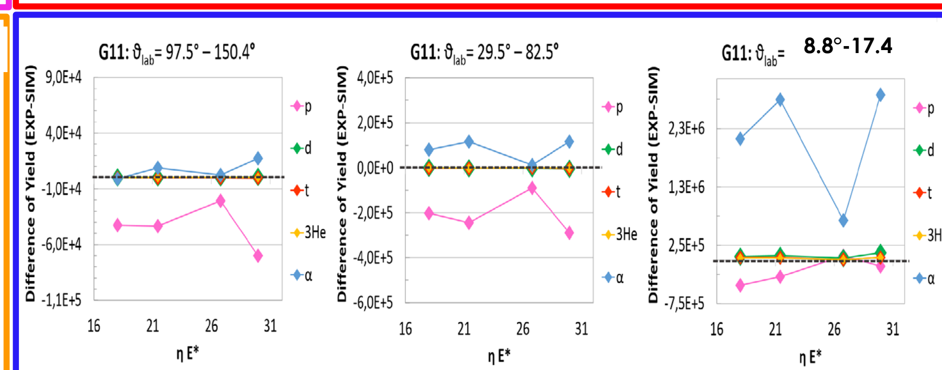
Reaction	E*(MeV)	η	ηE*
$^{16}O+^{30}Si$ 111 MeV	88	0,304	26,78
$^{16}O+^{30}Si$ 128 MeV	98.4	0,304	29,95
$^{18}O+^{28}Si$ 126MeV	98.5	0,217	21,41
$^{19}F+^{27}Al$ 133MeV	103.5	0,174	18,00









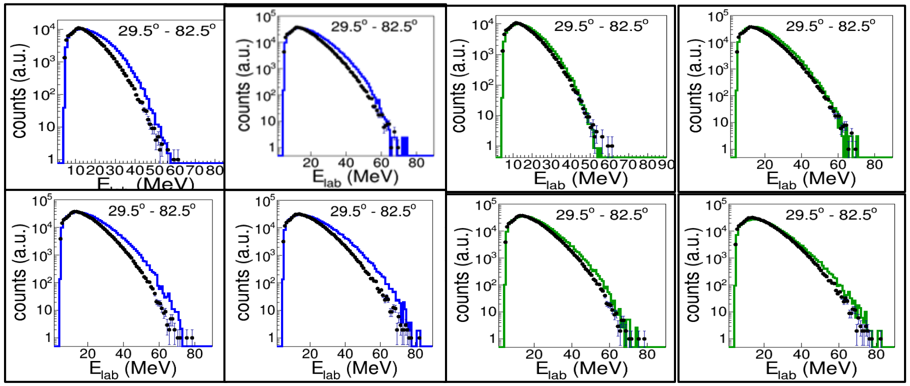


Results: $Z_{tot}=Z_p+Z_t=22$

Decay channel competition – Energy spectra

G11 **Ztot=22** **G00**

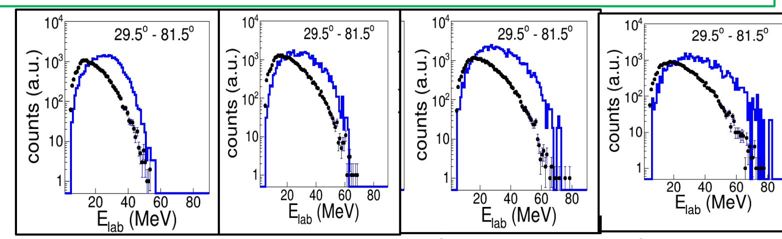
^{16}O - 7MeV/n | ^{16}O - 8MeV/n | ^{16}O - 7MeV/n | ^{16}O - 8MeV/n



^{18}O - 7MeV/n | ^{19}F - 7MeV/n | ^{18}O - 7MeV/n | ^{19}F - 7MeV/n

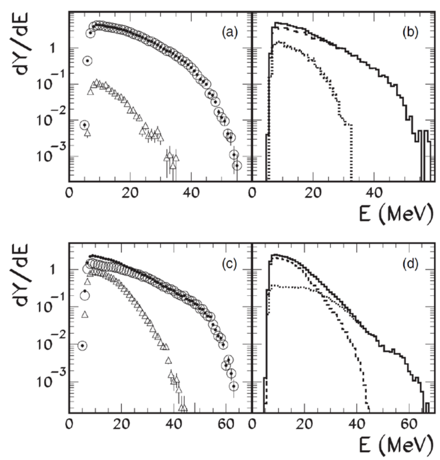
Different spectral shapes can derive from **different decay chains contributions**: either **more n-emission** or **different priority** in particle emission: This is even more evident in **more exclusive channels**

G11
Ztot=22
Z_{ER}=20



^{16}O - 7MeV/n | ^{16}O - 8MeV/n | ^{18}O - 7MeV/n | ^{19}F - 7MeV/n

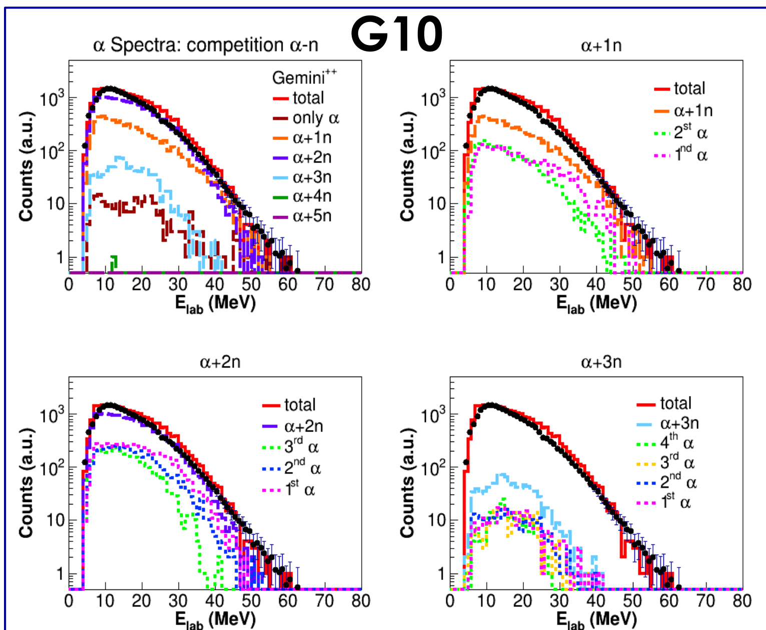
From: **L. Morelli et al. J. Phys. G: Nucl. Part. Phys. 41(2014)075107**



^{A}C
C+3α decay channel vs C+2H +2α decay channel: **exp (left) vs HFℓ *(right)***

^{A}O
O+2α decay channel vs O+2α+2H decay channel : **exp (left) vs HFℓ *(right)***

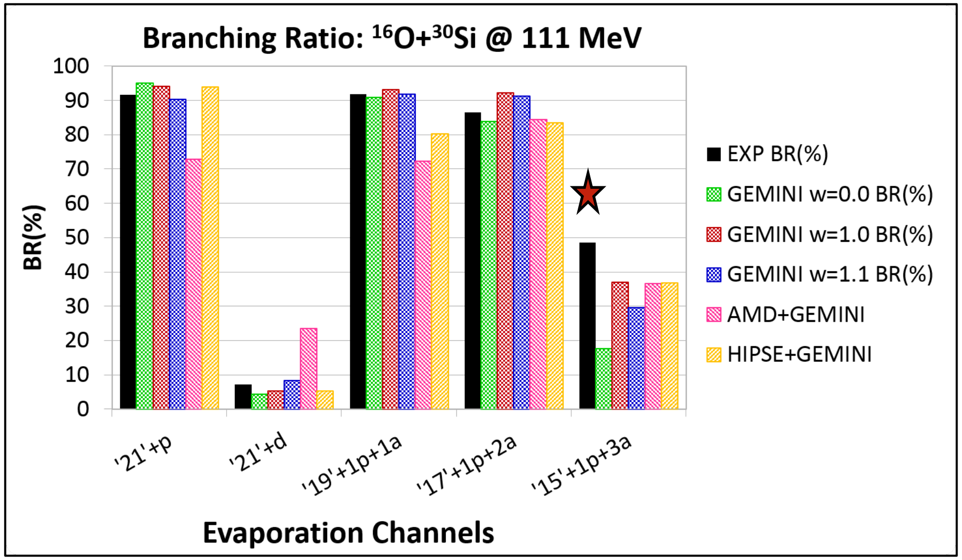
^{16}O - 8MeV/n

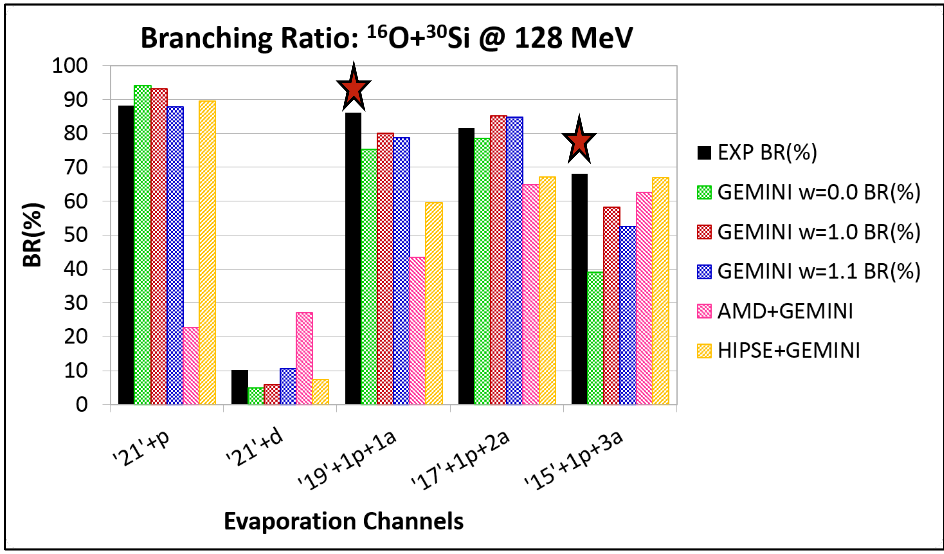


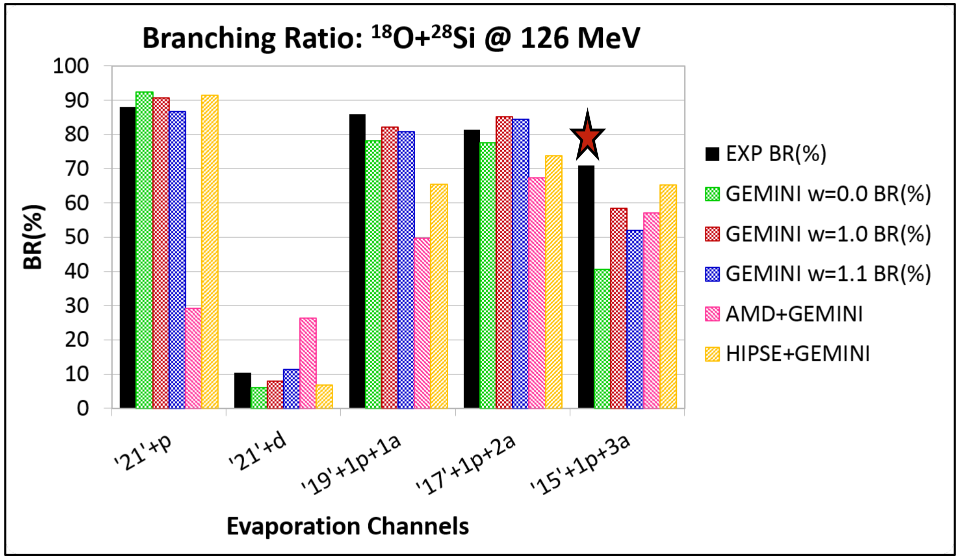
Gemini^{++}: comparison to exp data from 4π simulation including n-emission

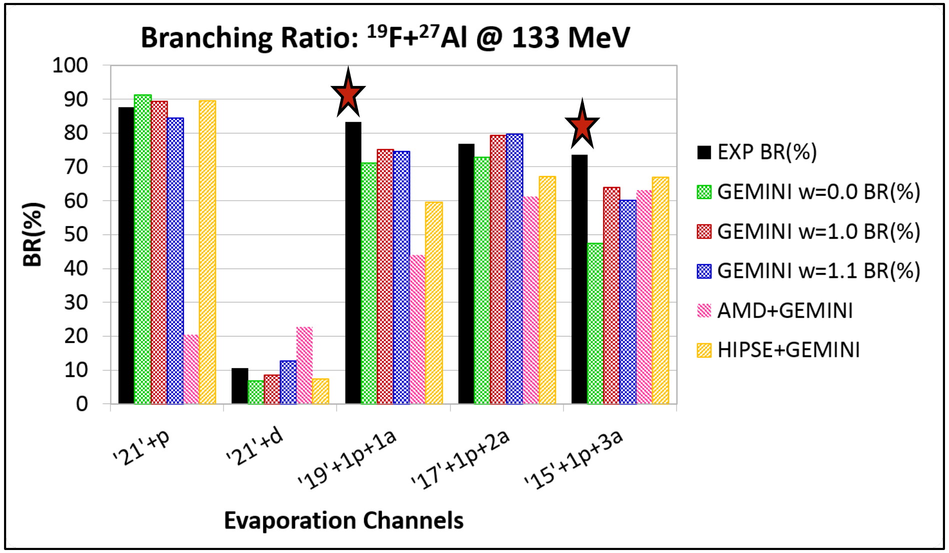
Results: $Z_{tot}=22$

Odd Z_{ER} - Branching Ratios



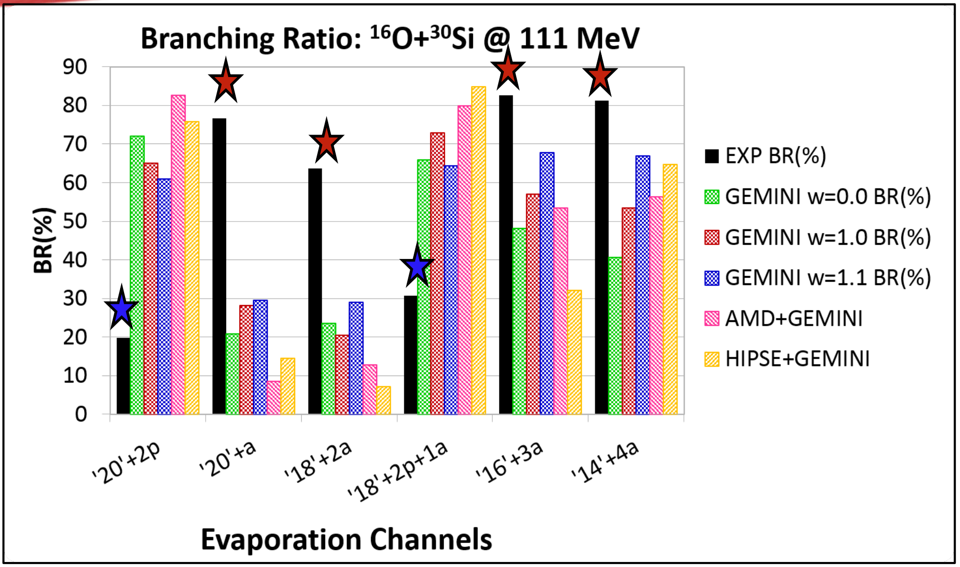


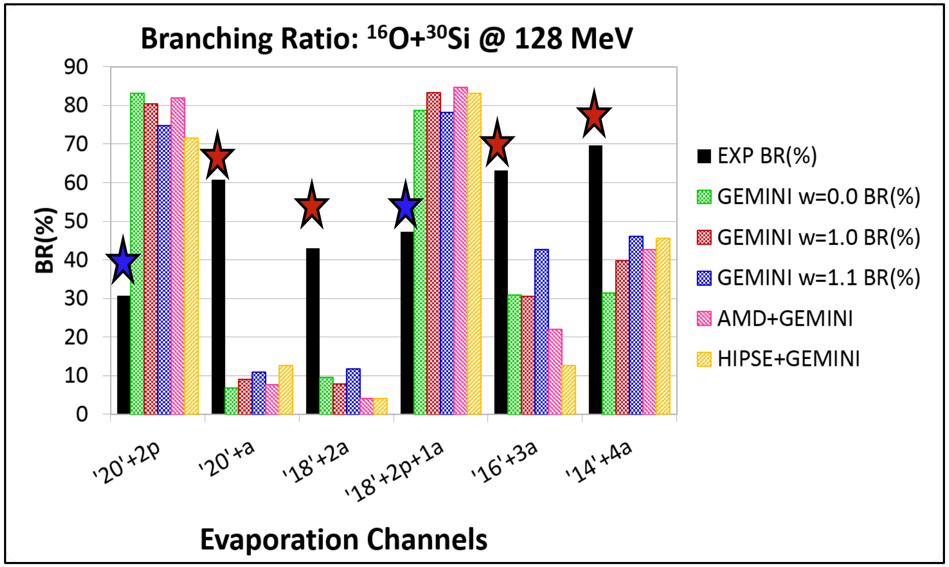


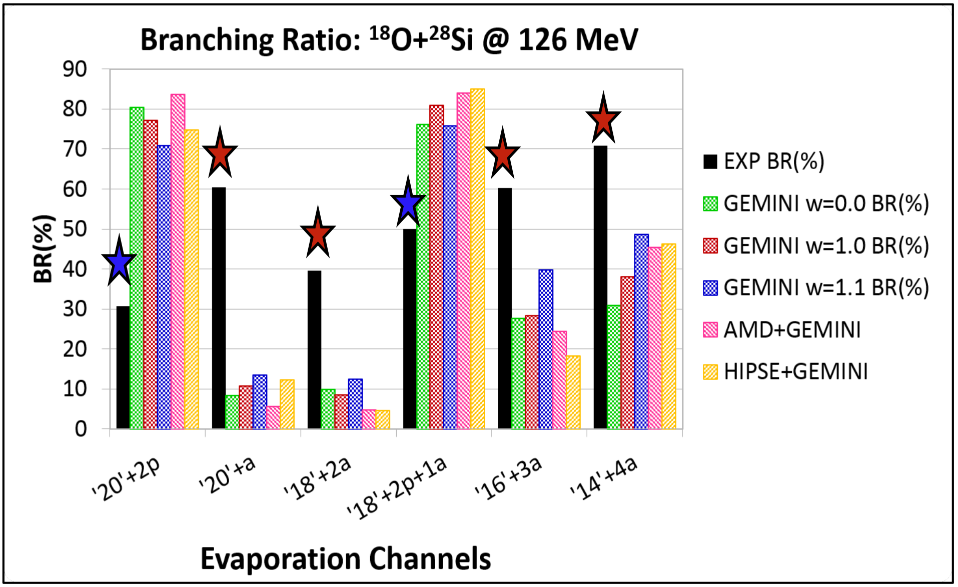


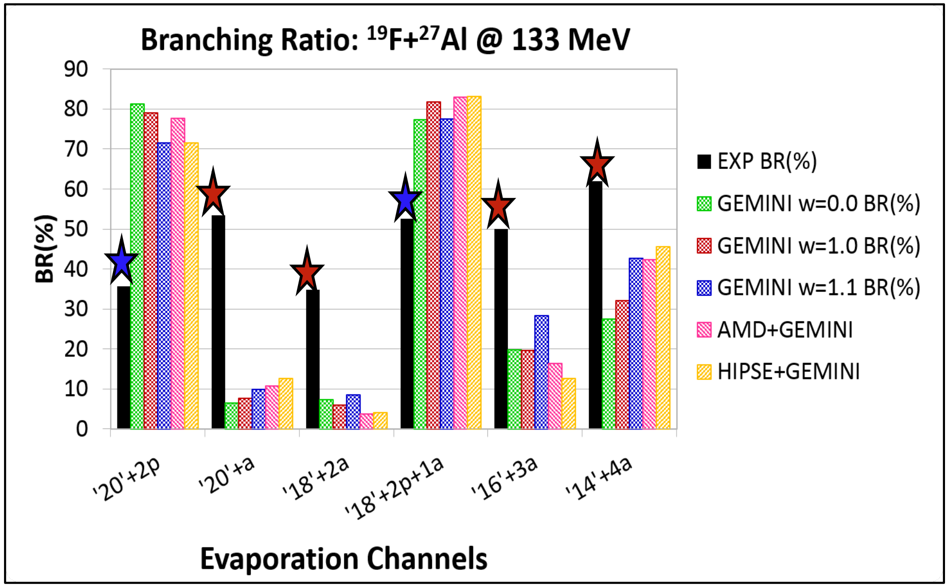
Results: Z_{tot}=22

Even Z_{ER}- Branching Ratios





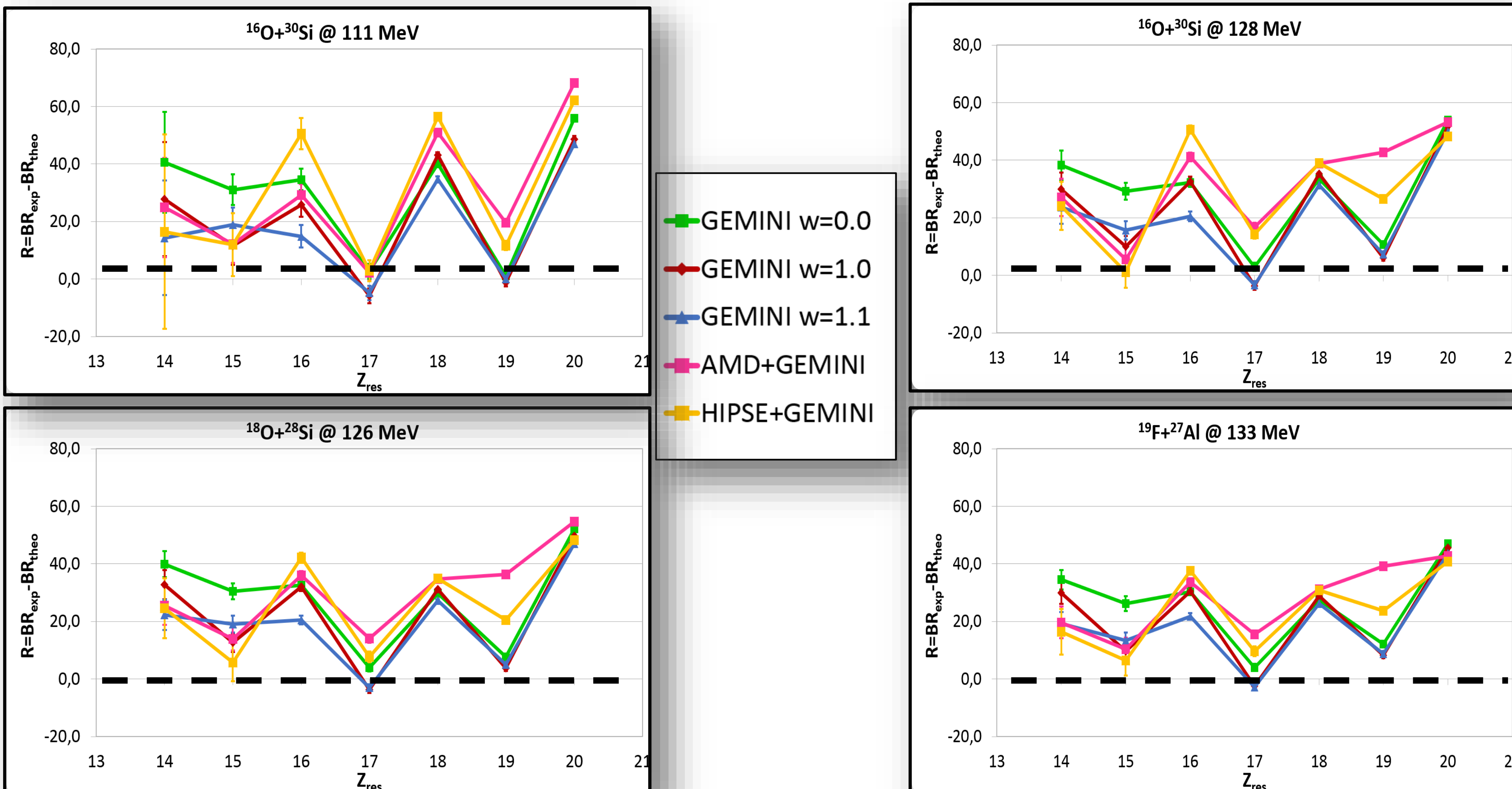




Results: $Z_{tot}=22$

Branching Ratios: differences with Models

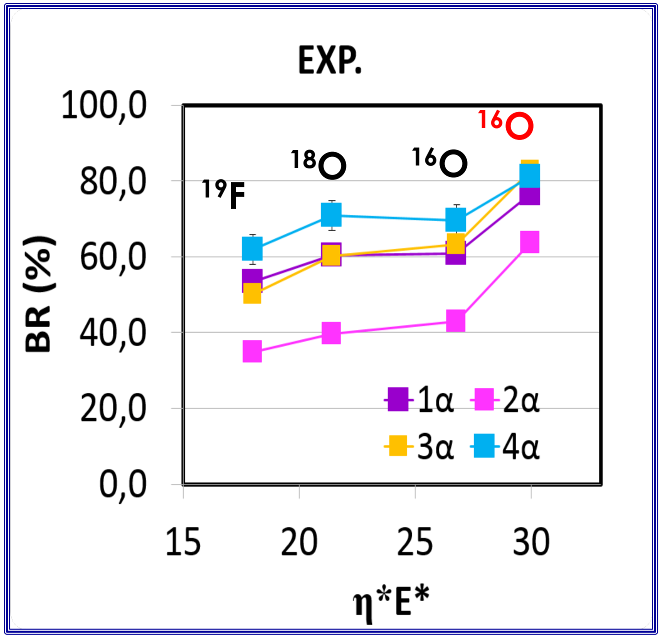
$$R = \frac{Y_{exp}(Z; n_z\alpha)}{Y_{exp}(Z)} - \frac{Y_{theo}(Z; n_z\alpha)}{Y_{theo}(Z)}$$

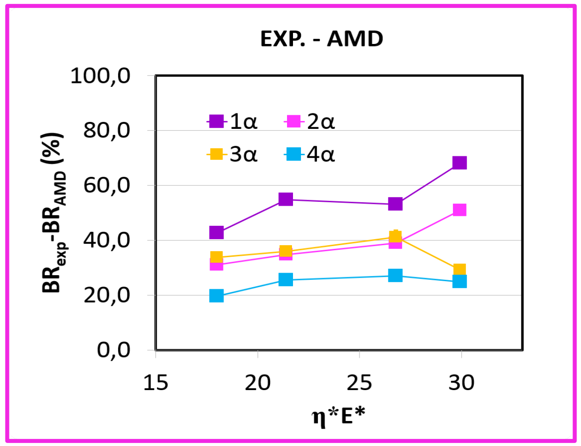


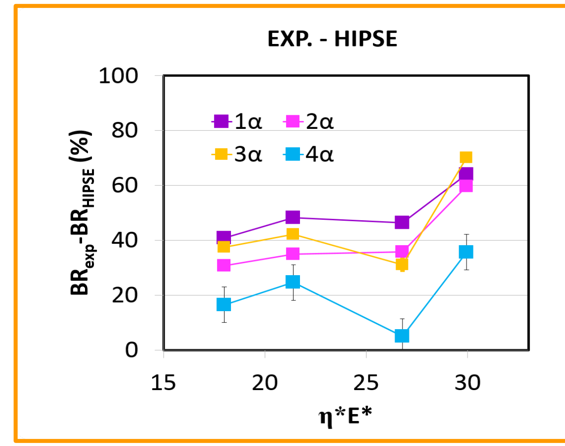
Results: Z_{tot}=22

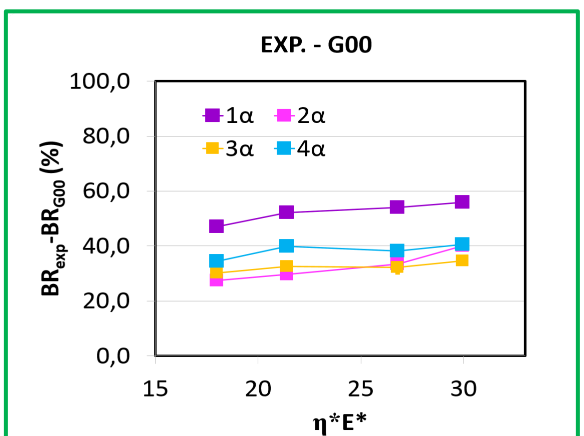
Branching Ratios

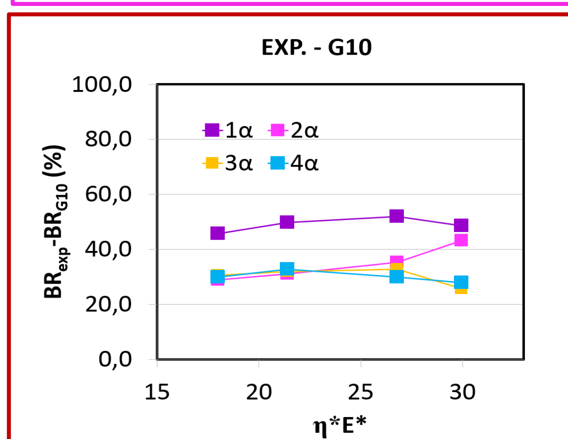
Reaction	η	E*	η/E*	η*E*
$^{16}O+^{30}Si$@111MeV	0,30	88	0,0035	26,78
$^{16}O+^{30}Si$@128MeV	0,30	98,4	0,0031	29,95
$^{18}O+^{28}Si$@126MeV	0,22	98,5	0,0022	21,41
$^{19}F+^{27}Al$@133MeV	0,17	103,5	0,0017	18,00

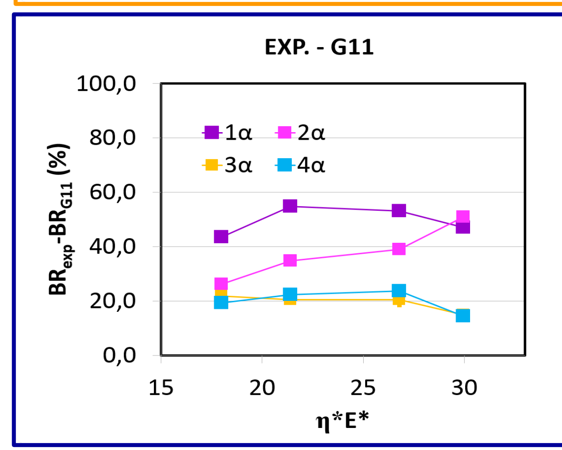






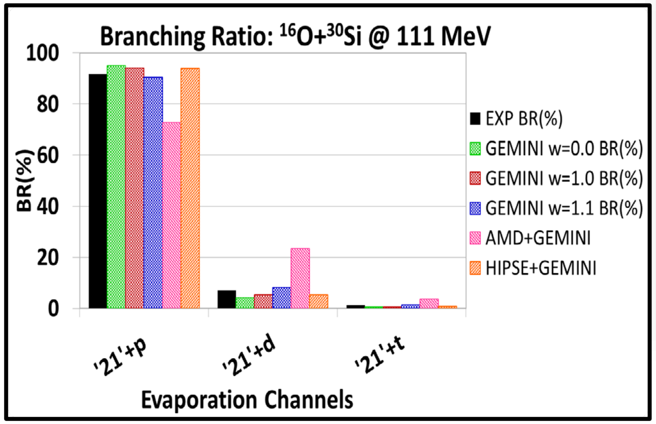


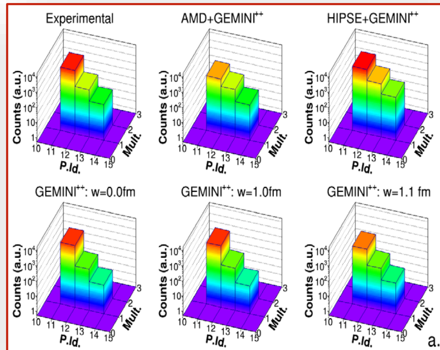


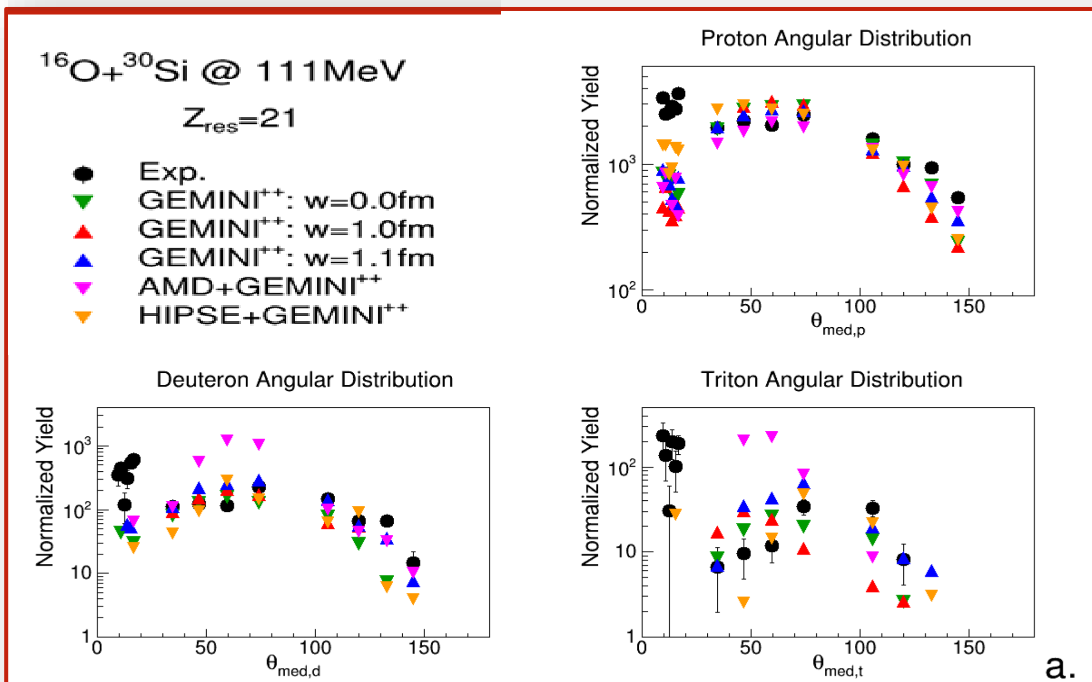


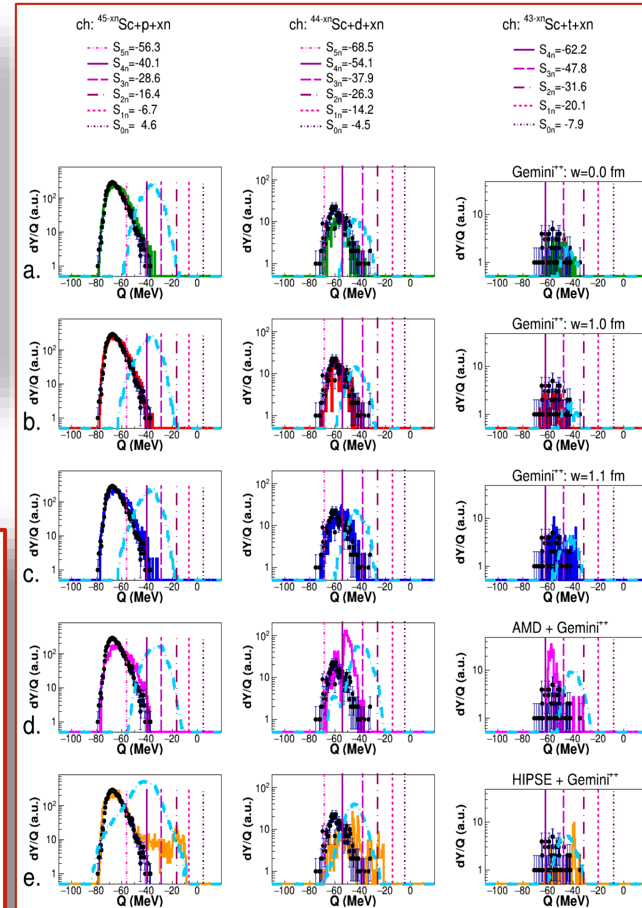
Results: Z_{tot}=22

Z_{ER}=21 - $^{16}O+^{30}Si$@111MeV









G00

G10

G11

AMD

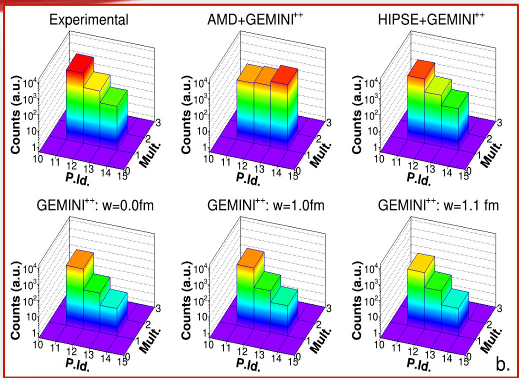
HIPSE

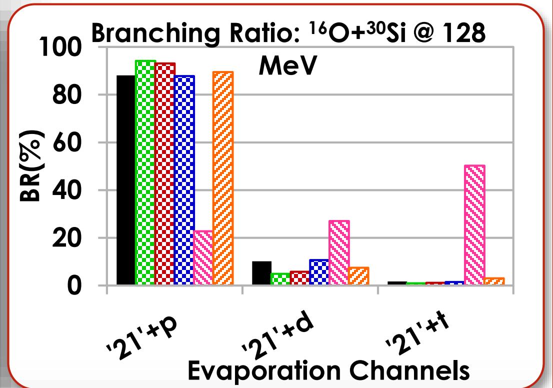
"Missing" Q-value

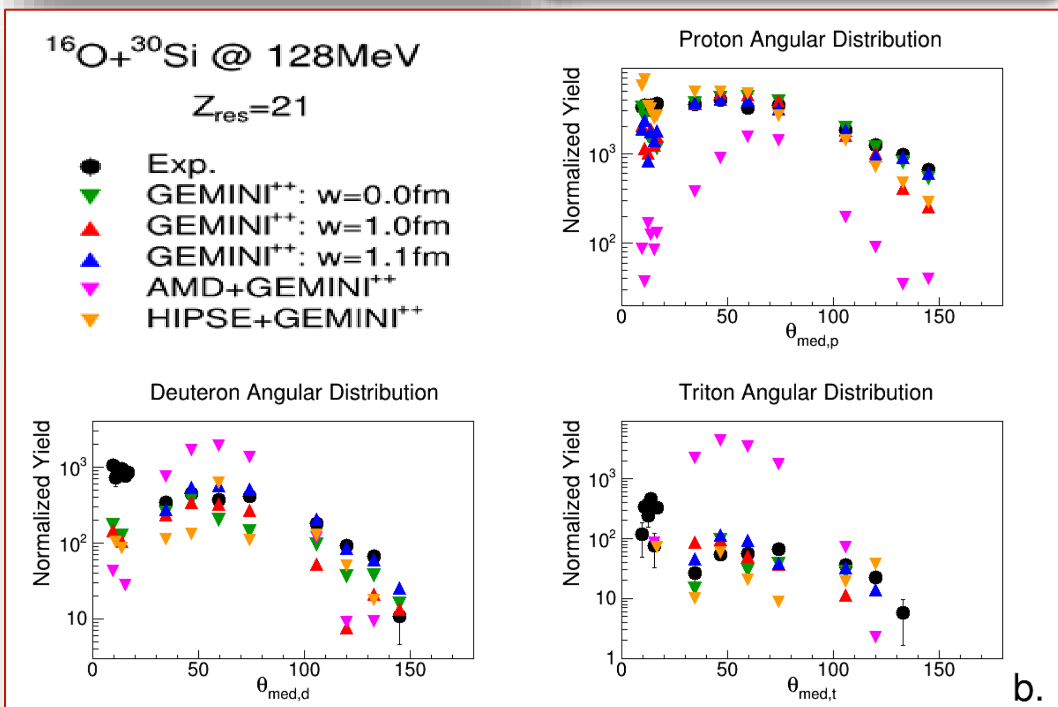
- ^{42}Sc + p + 3n, followed by ^{43}Sc + p + 2n & ^{41}Sc + p + 4n;
- ^{41}Sc + d + 3n followed by ^{42}Sc + d + 2n;
- ^{41}Sc + t + 2n.

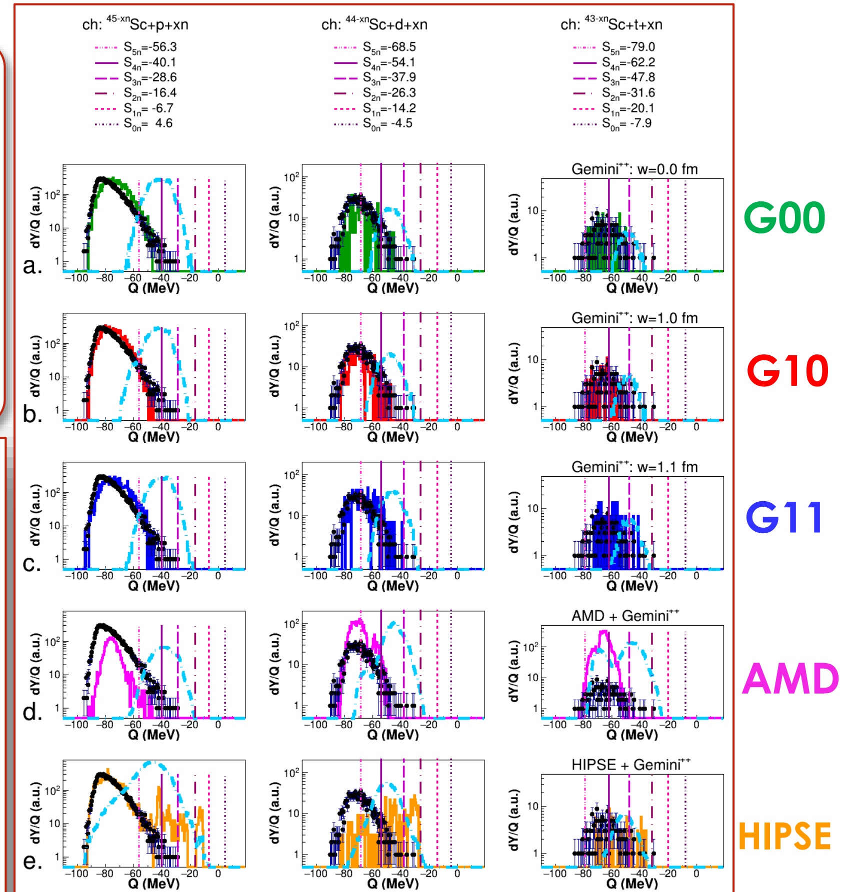
Results: Z_{tot}=22

Z_{ER}=21 - $^{16}O+^{30}Si$@128 MeV







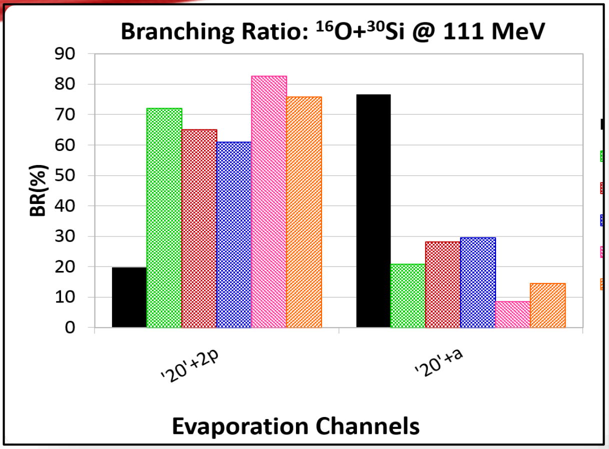


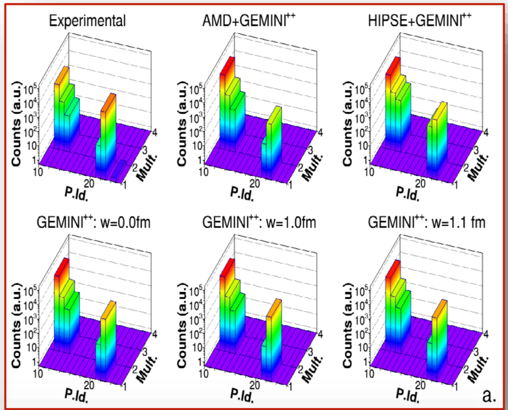
"Missing" Q-value

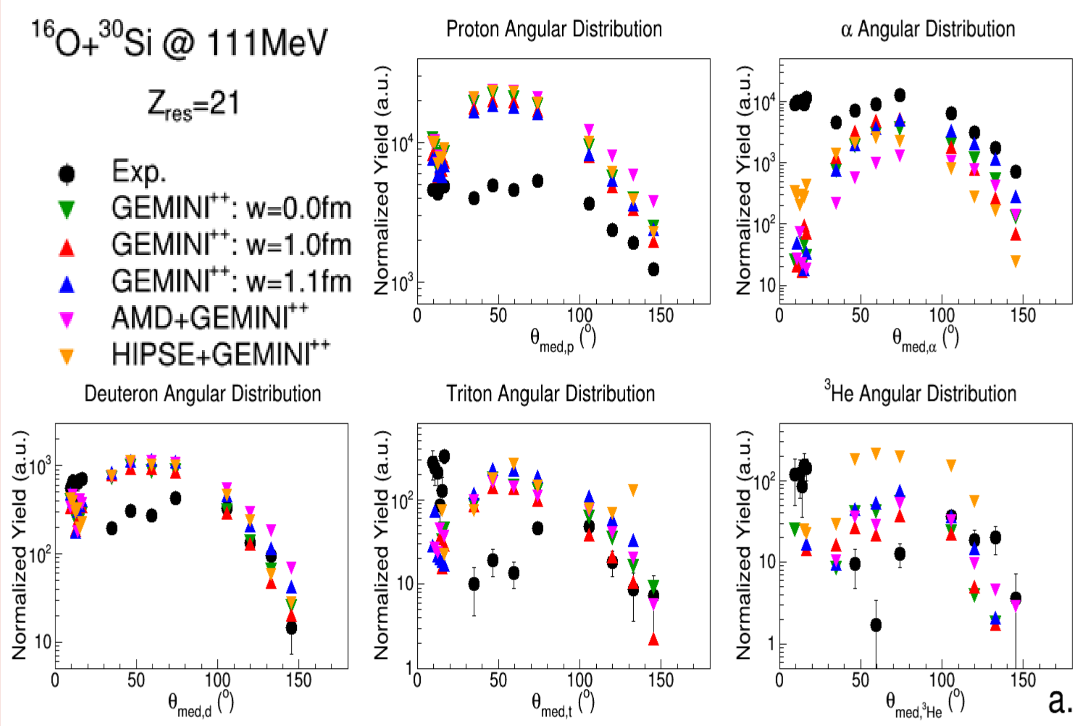
- **^{42}Sc + p + 3n** & **^{41}Sc + p + 4n** followed by smaller yields **^{43}Sc + p + 2n** & **^{41}Sc + p + 5n**;
- **^{41}Sc + d + 3n** followed by **^{42}Sc + d + 2n** & **^{40}Sc + d + 4n** ;
- **^{41}Sc + t + 2n** & **^{40}Sc + t + 3n**

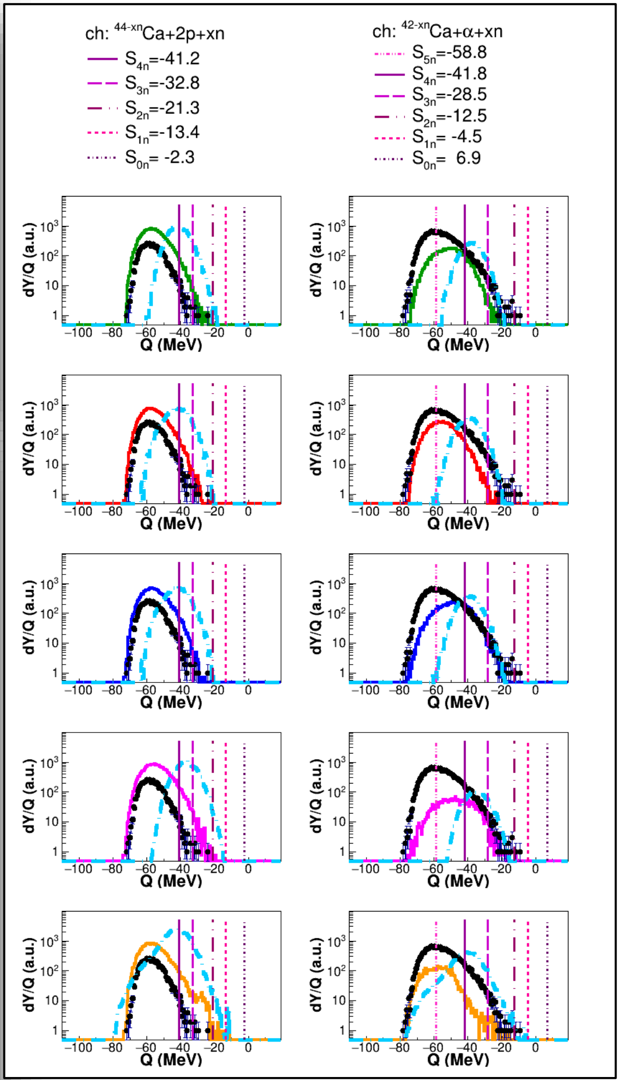
Results: $Z_{tot}=22$

$Z_{ER}=20$ - $^{16}O+^{30}Si$@111MeV









G00

G10

G11

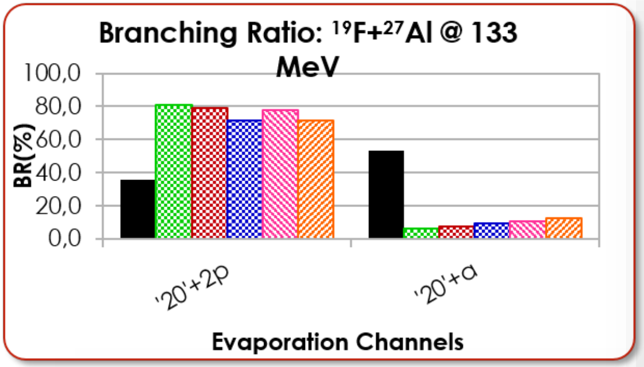
AMD

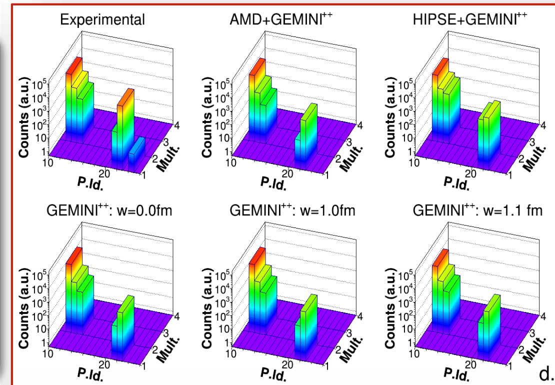
HIPSE

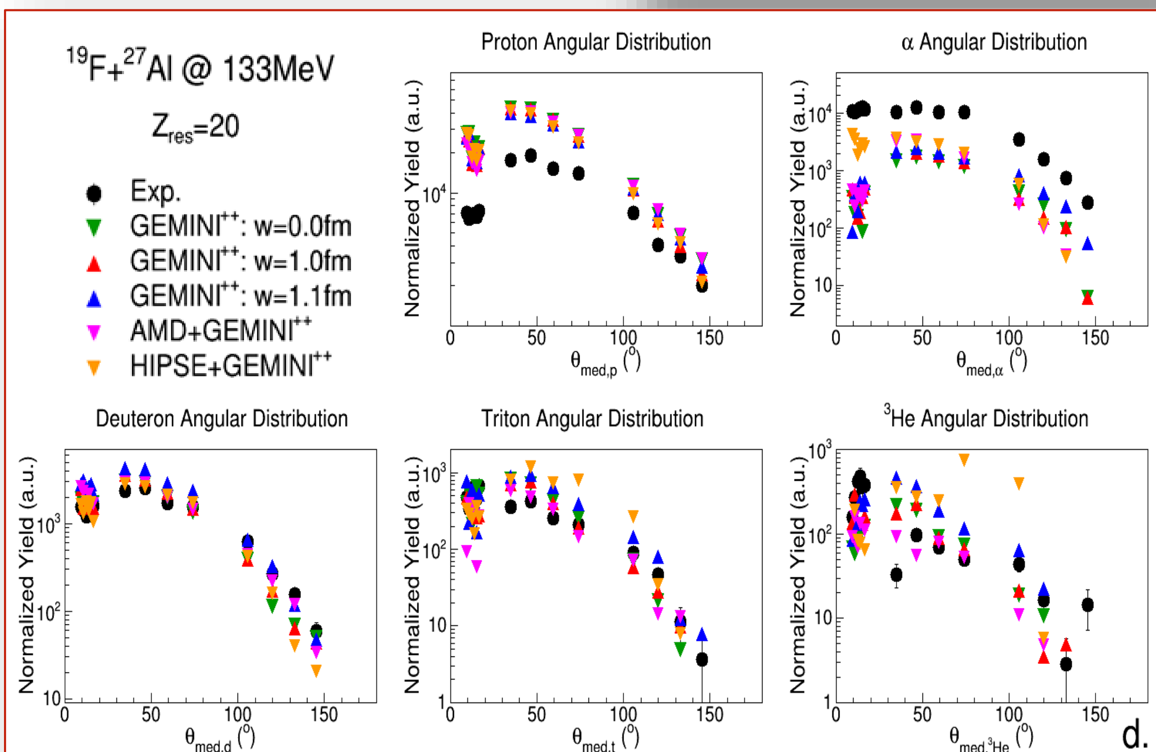
"Missing" Q-value

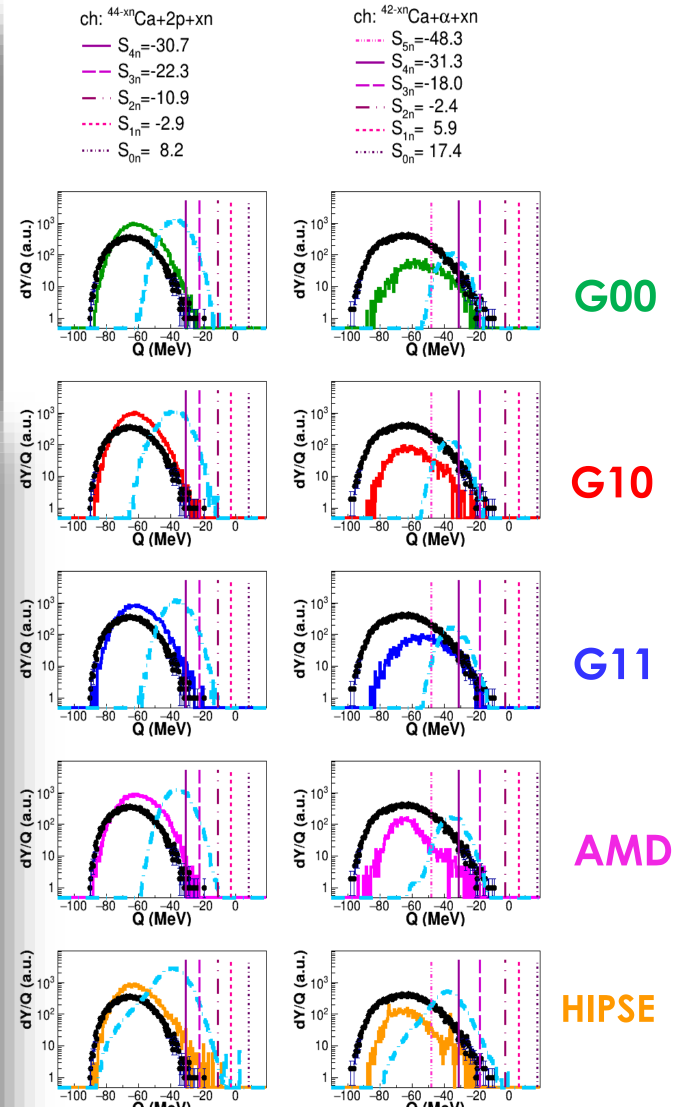
Results: Z_{tot}=22

Z_{ER}=20 – $^{19}F+^{27}Al$@133 MeV





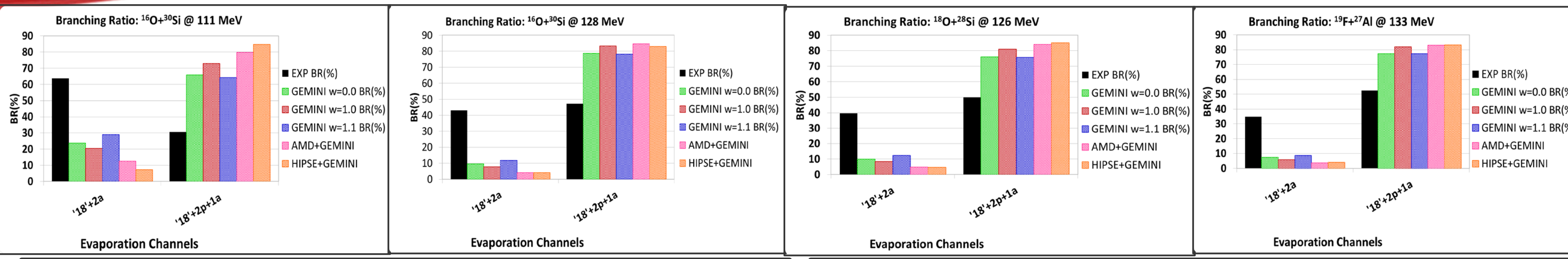


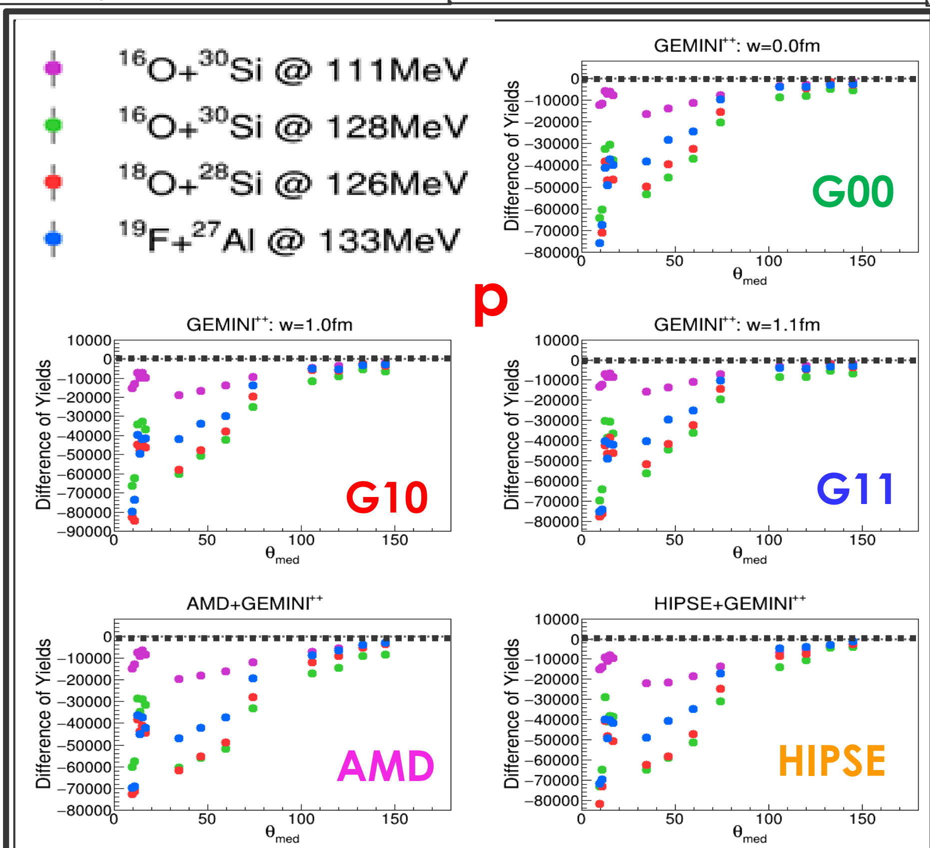


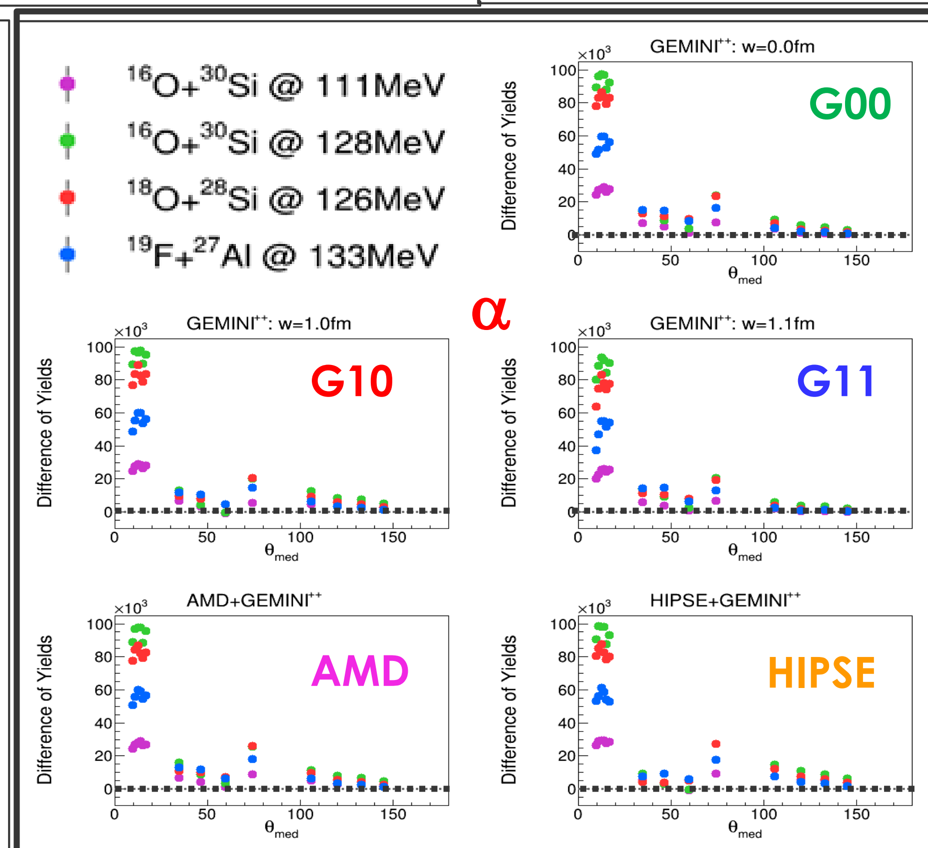
"Missing" Q-value

Results: $Z_{tot}=Z_p+Z_t=22$

$Z_{ER}=18$ – Difference in Ang. Distributions





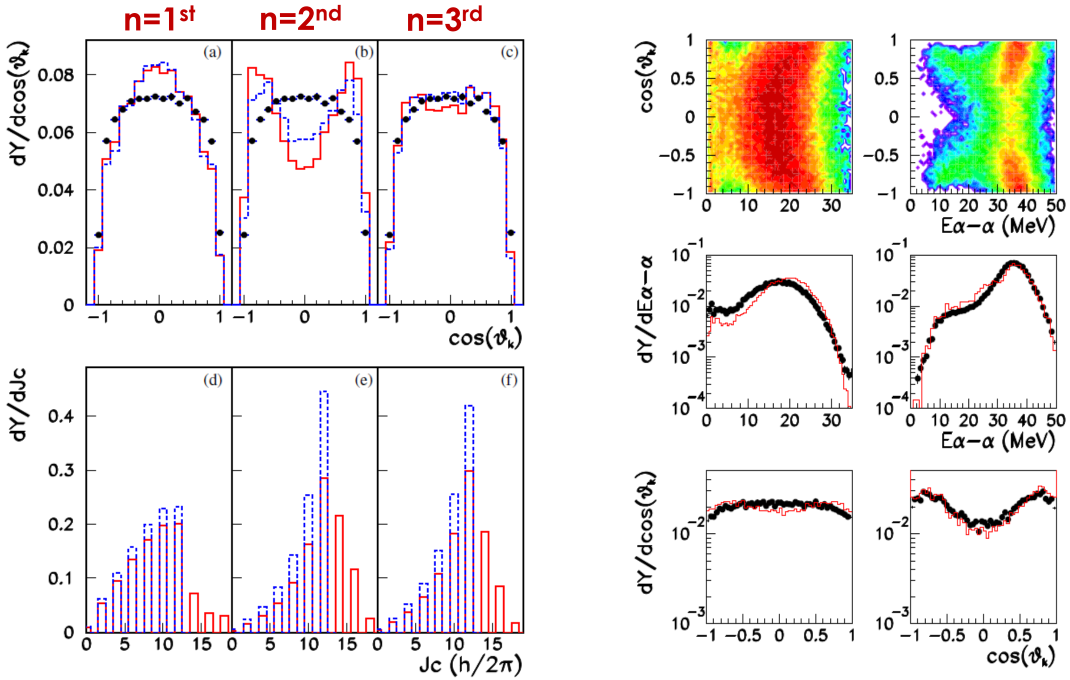


Results: Z_{tot}=22
Z_{ER}=18 – 2α correlations

L. Morelli – J. Phys. G Nucl. Part. Phys 41(2014)075108

$$E_{\alpha-\alpha} = \frac{\overrightarrow{k_{\alpha-\alpha}}^2}{2\mu}$$

$$cos(\theta_k) = \frac{\vec{k}_{residue} \cdot \vec{k}_{\alpha-\alpha}}{|\vec{k}_{residue}||\vec{k}_{\alpha-\alpha}|}$$



Shape of the cos(θ_k) distribution: **dependence on spin distribution involved in the process**, which depends on **the priority of neutron emission in the cascade**.

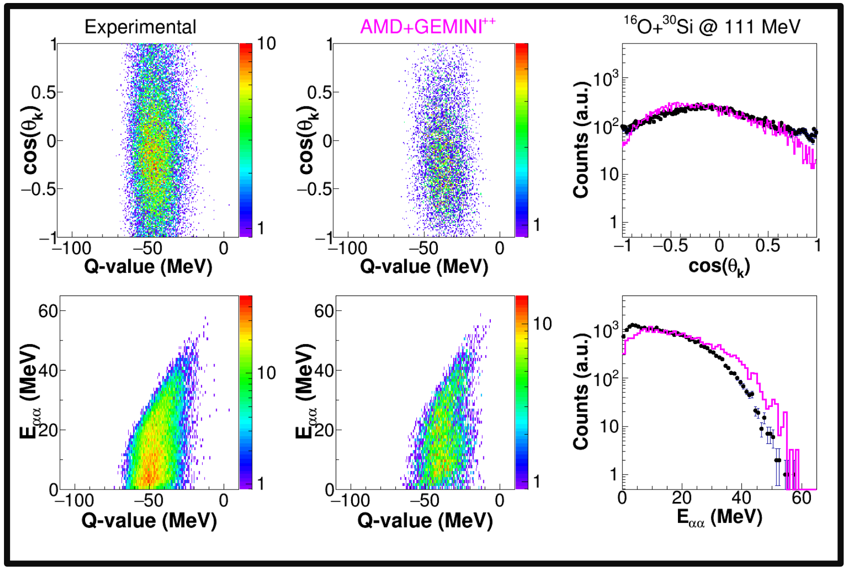
Example for the **$^{12}C+^{12}C$ at 95 MeV case.**

Blue and red distributions are obtained by **Hauser Feshbach model** developed for light nuclei (**HFℓ**) respectively with **J_{0max}=18 hbar (ΔJ=2)** and **J_{0max}=12 hbar (sharp cut off).**

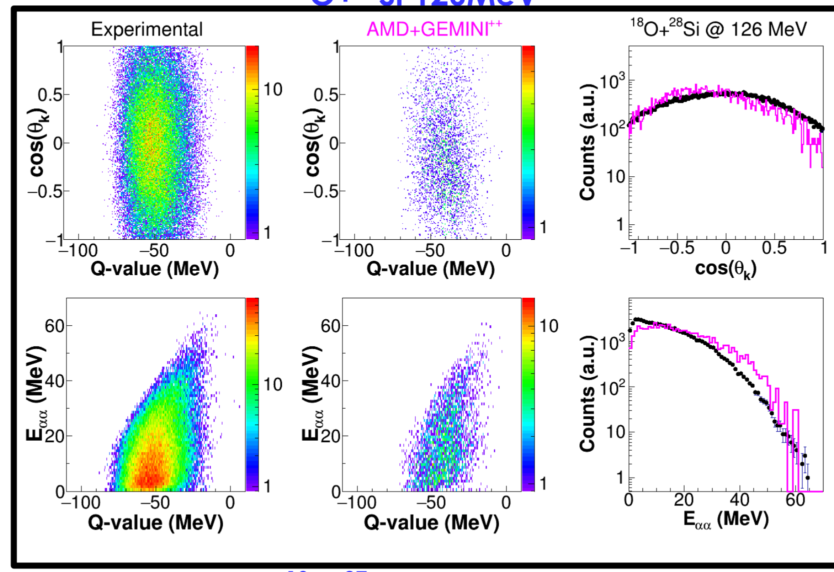
Results: Z_{tot}=22

Z_{ER}=18 – 2α correlations

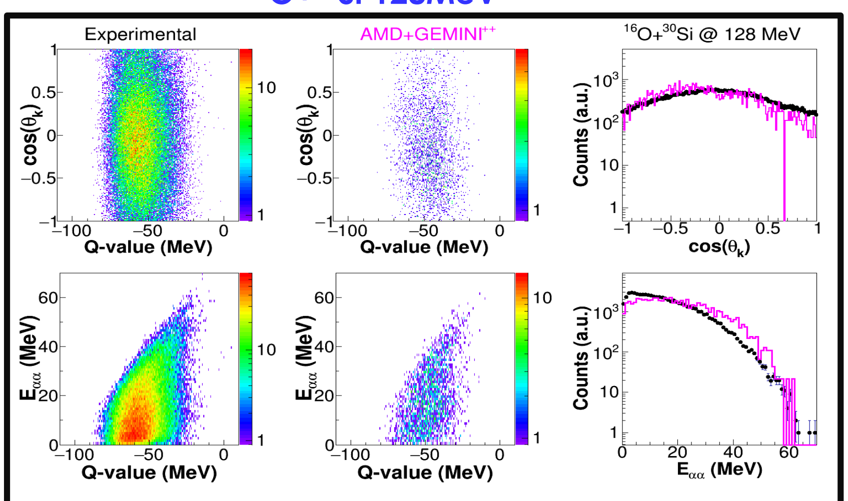
$^{16}O+^{30}Si$ 111MeV



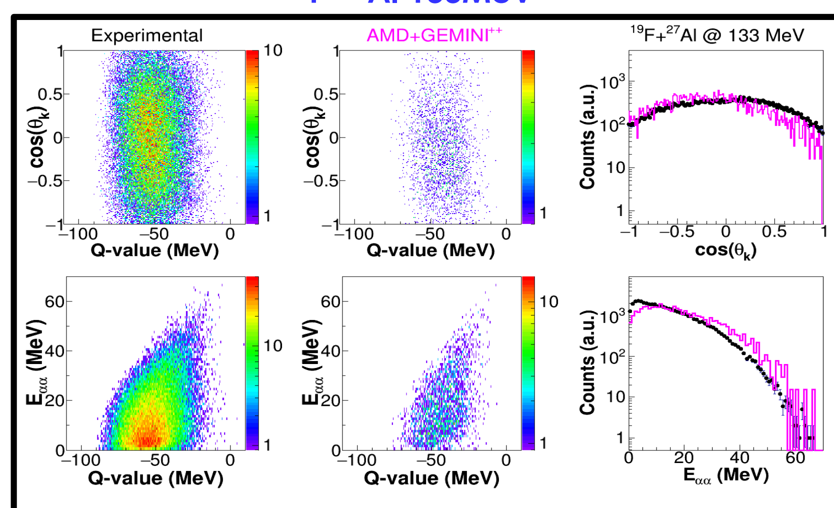
$^{18}O+^{28}Si$ 126MeV



$^{16}O+^{30}Si$ 128MeV



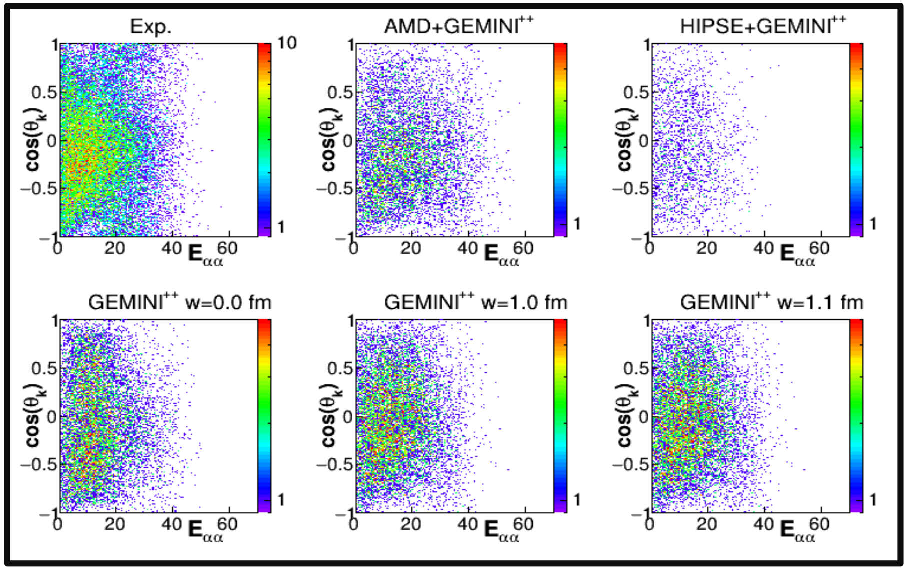
$^{19}F+^{27}Al$ 133MeV



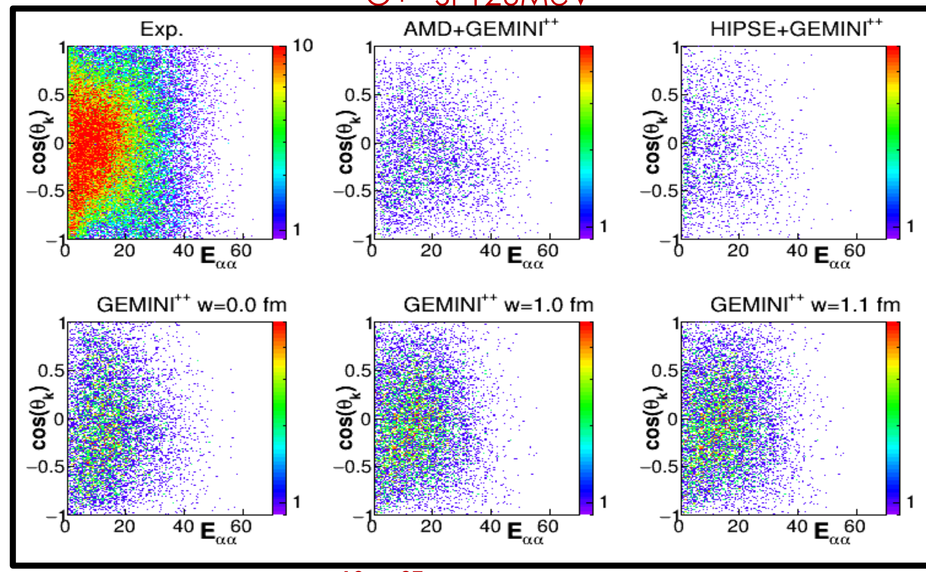
Results: Z_{tot}=22

Z_{ER}=18 – 2α correlations

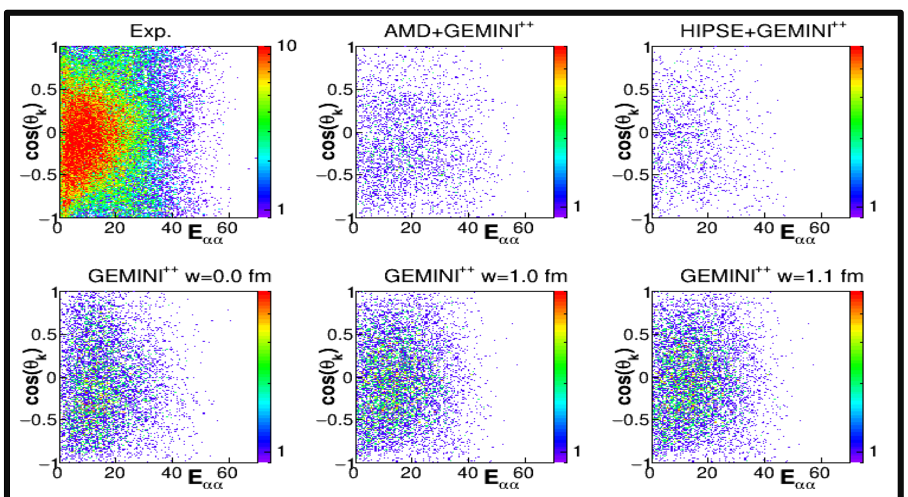
$^{16}O+^{30}Si$ 111MeV



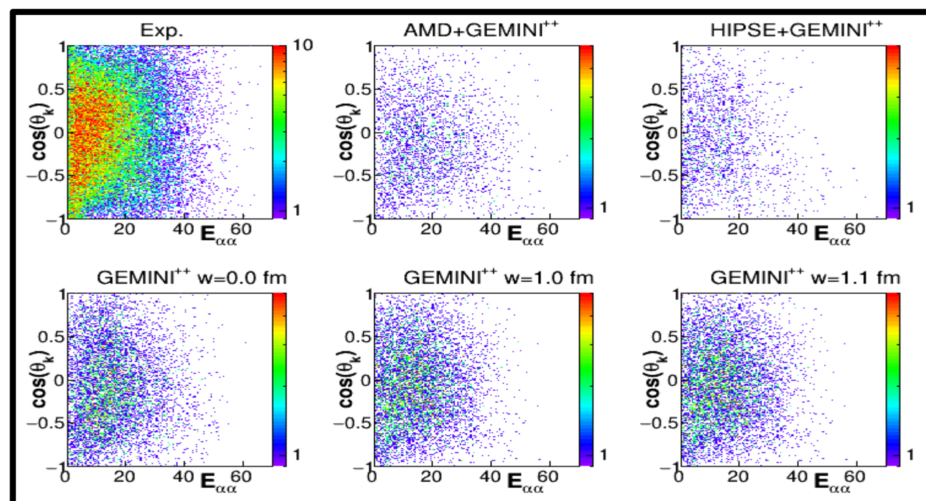
$^{18}O+^{28}Si$ 126MeV



$^{16}O+^{30}Si$ 128MeV

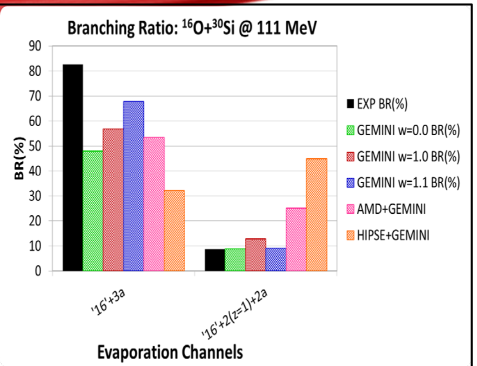


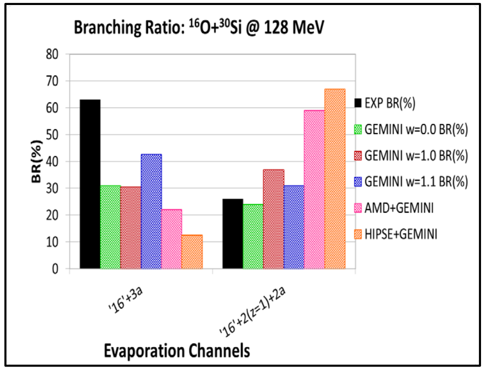
$^{19}F+^{27}Al$ 133MeV

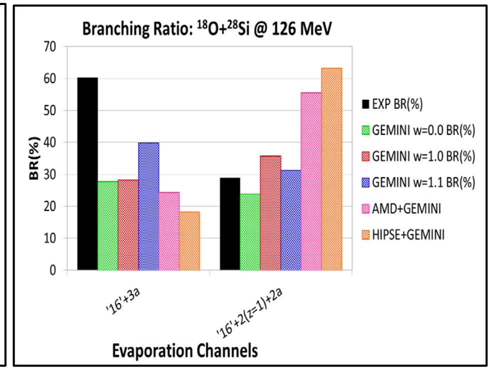


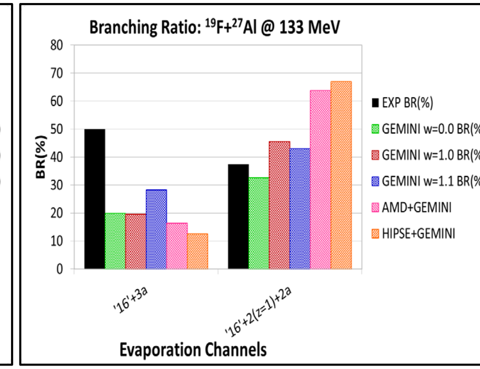
Results: Z_{tot}=22

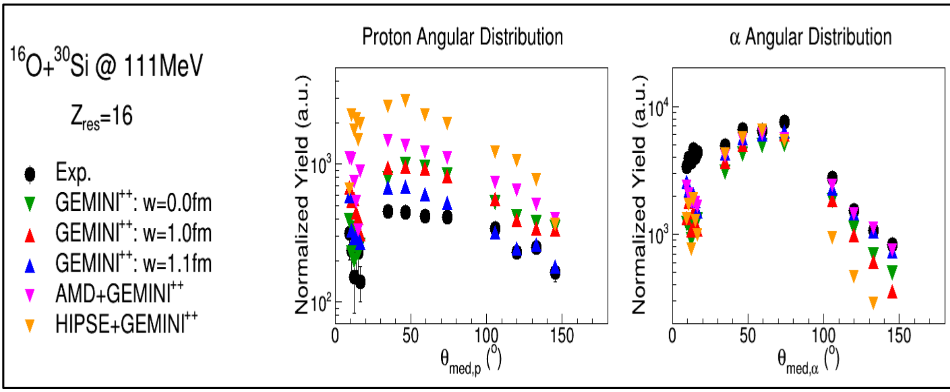
Z_{ER}=16 – 3α

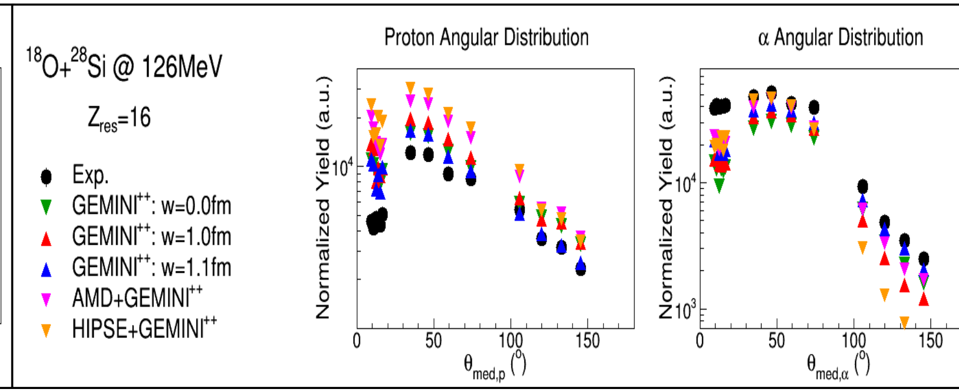


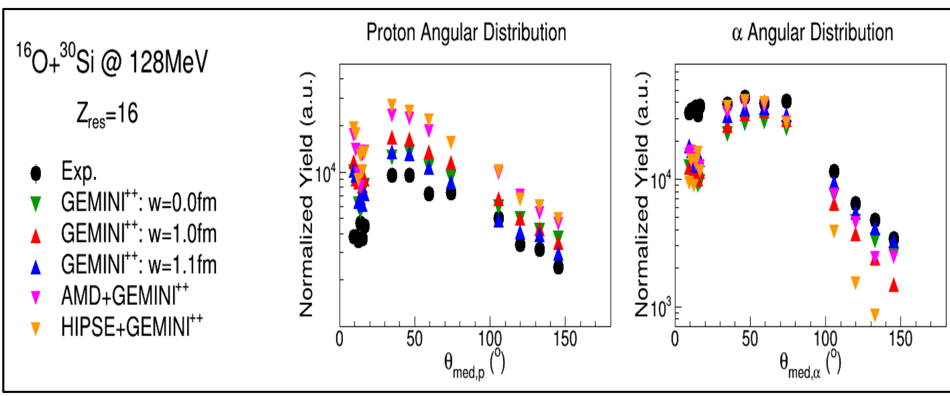


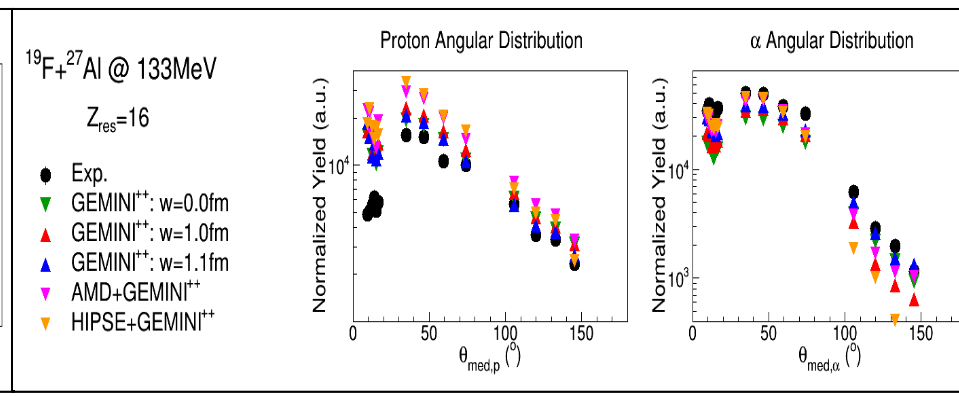








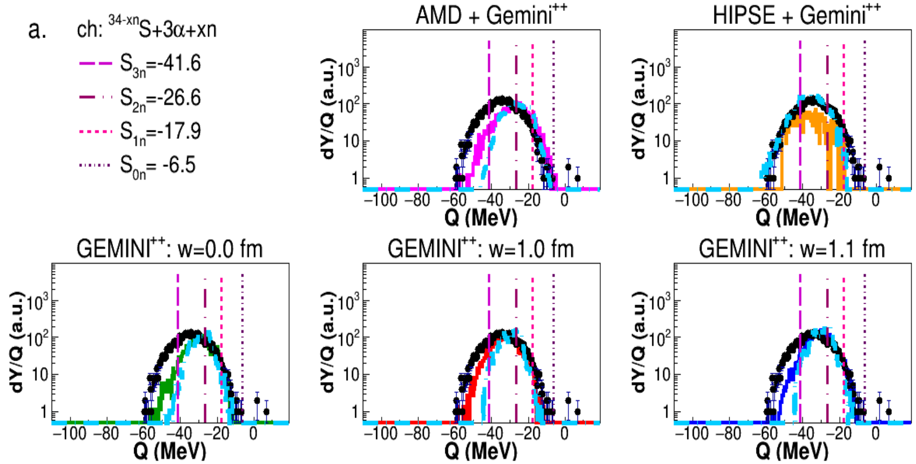




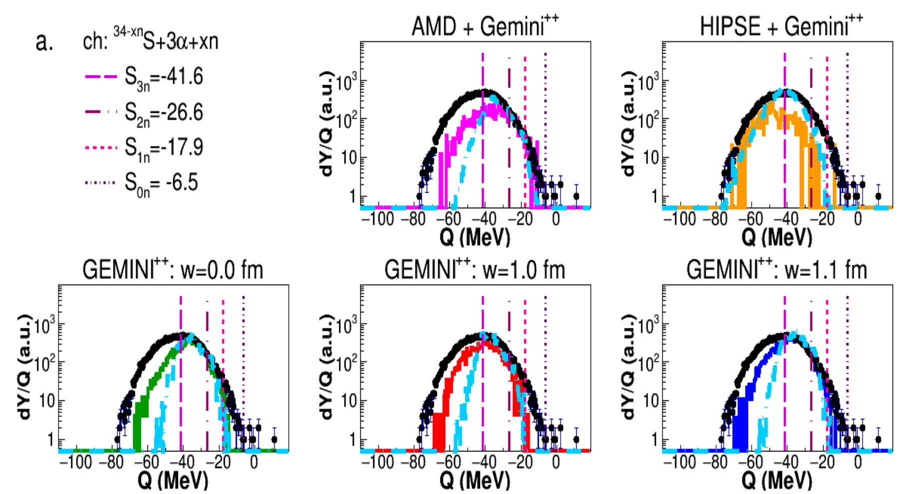
Results: $Z_{tot}=Z_p+Z_t=22$

$Z_{ER}=16$ – Q-values

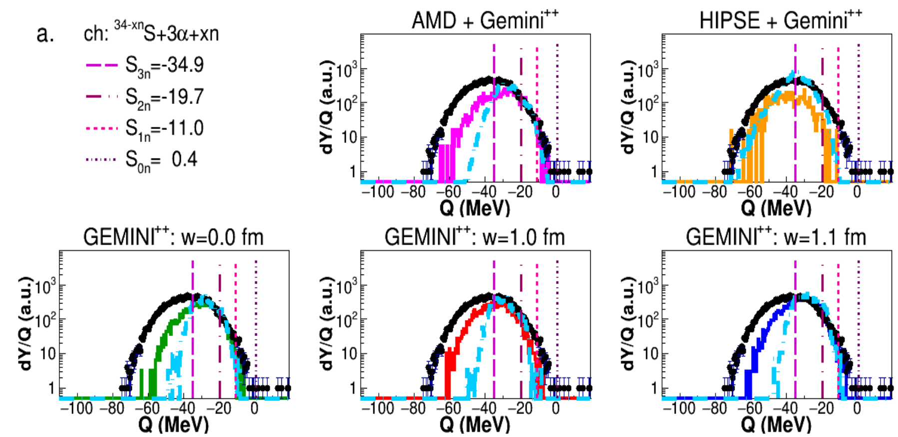
$^{16}O+^{30}Si$ 111MeV



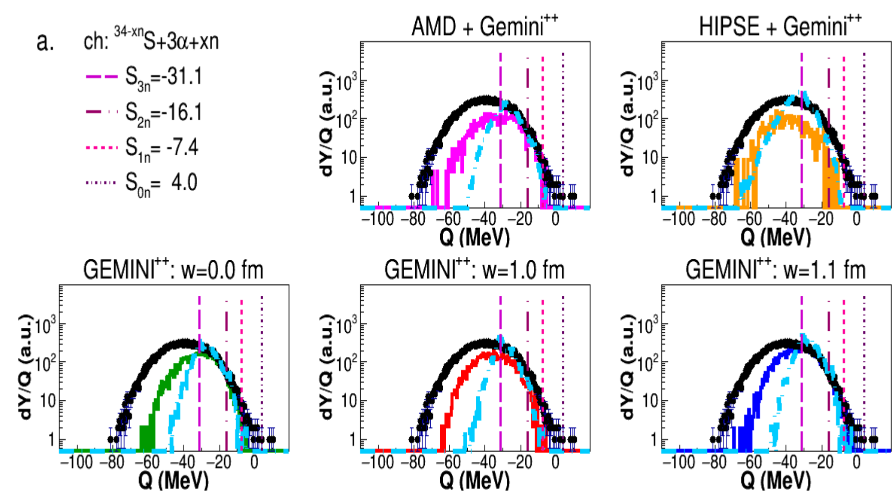
$^{16}O+^{30}Si$ 128MeV



$^{18}O+^{28}Si$ 126MeV



$^{19}F+^{27}Al$ 133MeV



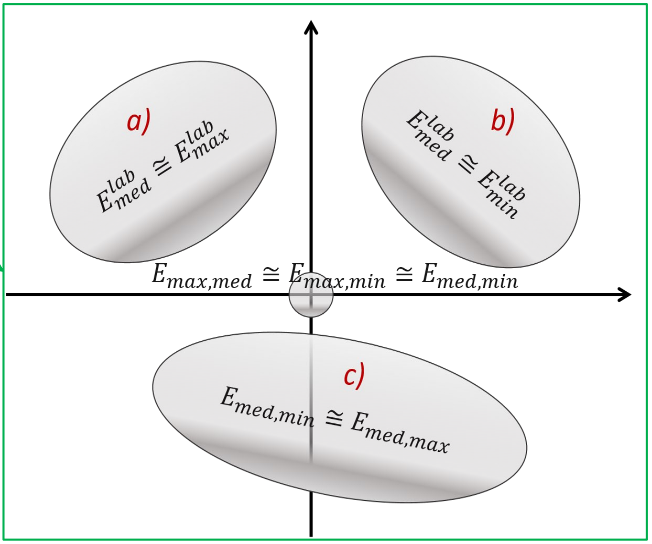
Results: Z_{tot}=22

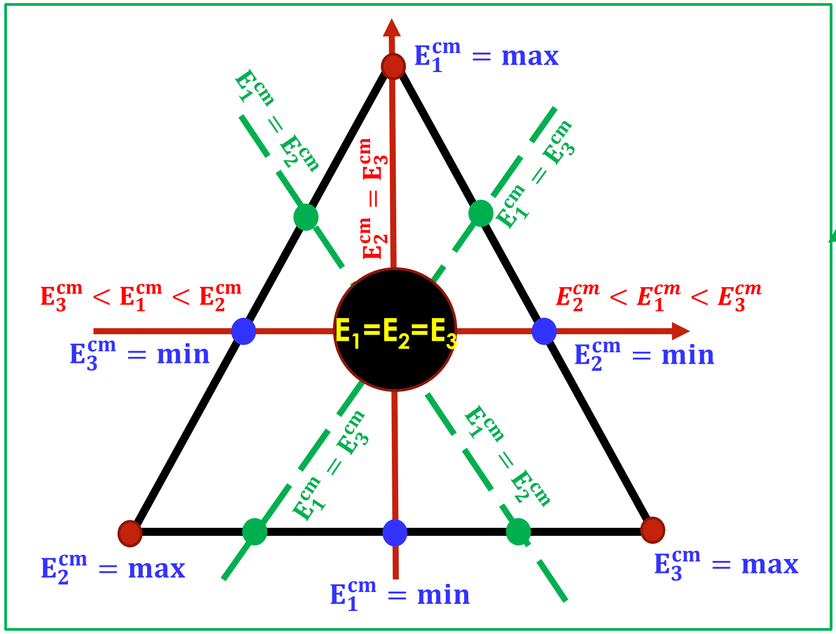
Z_{ER}=16 – 3α DALITZ PLOTS

DALITZ 1: relative energies

$$x_D = \sqrt{3}\frac{E_{max,med} - E_{med,min}}{2}$$

$$y_D = \frac{2E_{max,min} - E_{max,med} - E_{med,min}}{2}$$





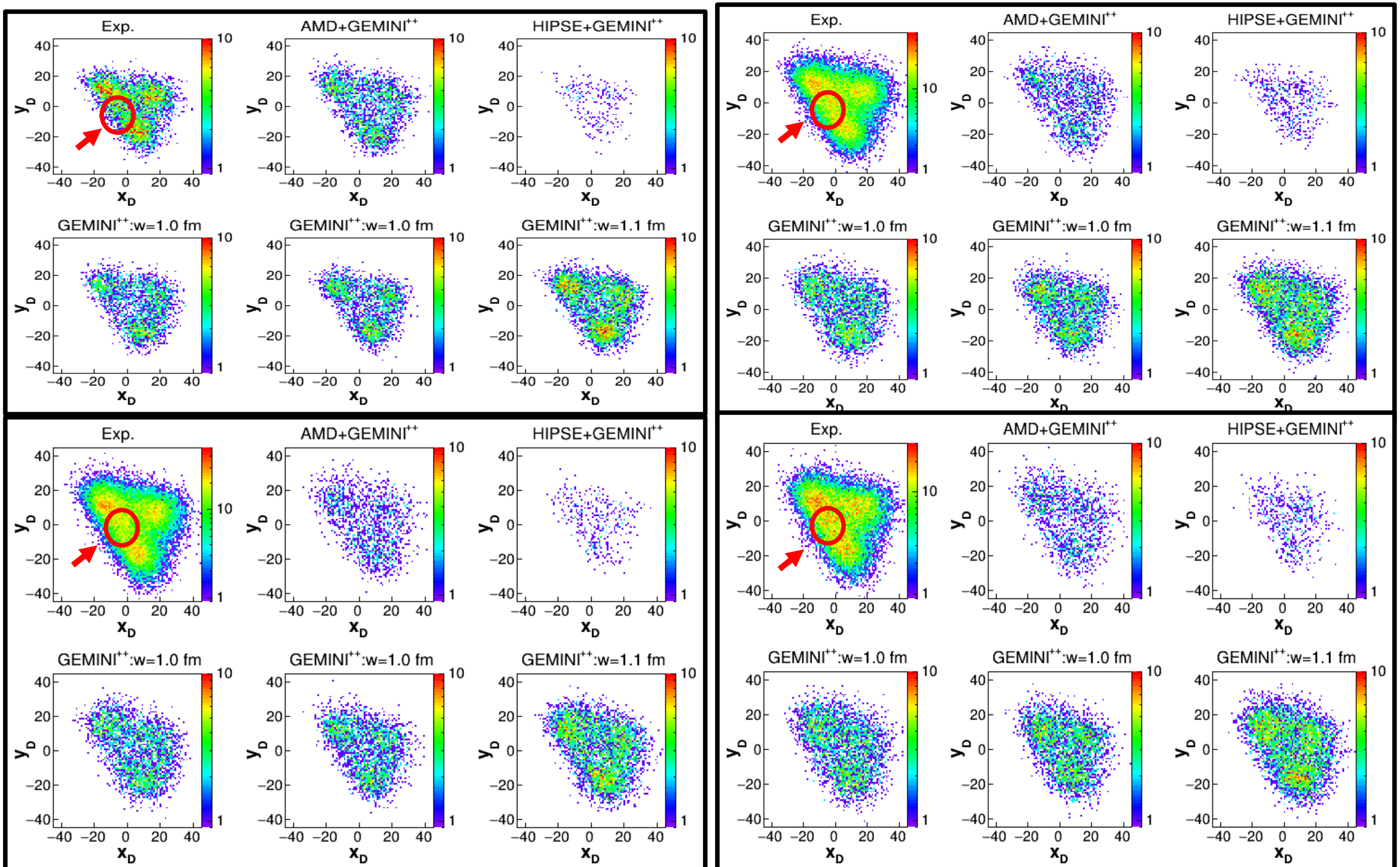
DALITZ 2: absolute cm energies

Starting from ordered $\mathbf{E}^{lab}$: $E_1^{lab}<E_2^{lab}<E_3^{lab}$

$$x_D = \sqrt{3}\frac{E_3^{cm} - E_2^{cm}}{2}$$

$$y_D = \frac{2E_1^{cm} - E_3^{cm} - E_2^{cm}}{2}$$

Results: Z_{tot}=22
Dalitz Plots 1→ Z_{ER}=16 & 3α



COMEX6

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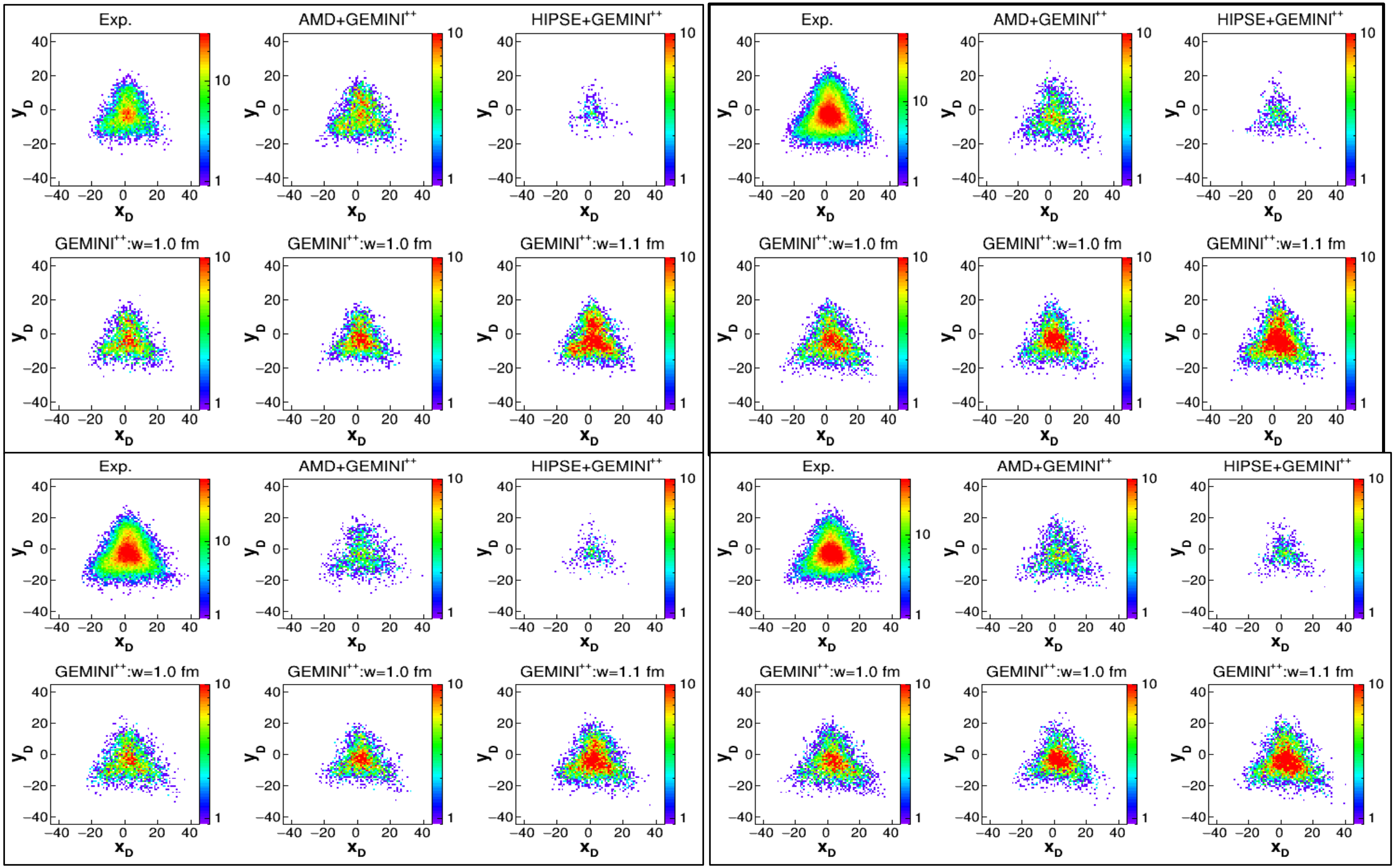
Laboratori Nazionali di Legnaro

Results: Z_{tot}=22
Dalitz Plots 2→ Z_{ER}=16 & 3α



Summary

- Observing the **decay** of ^{46}**Ti***, through the **quasi-complete events (Z_{tot}>18)** → a reasonable **reproduction** by model predictions of the **major part of global variables**
- nevertheless, **some differences** observed → crucial in the study of the **interplay** between the **two different reaction mechanisms**: **α-particles overproduction** observed at **forward angles,** which represents a **signature of the onset of fast emission** not reproduced by dynamical models.

- Looking in more details **complete events (Z_{tot}=22)**:
  - **BR** for **odd Z residues** are **well reproduced –** observed **differences in ang distrib**. & **energy spectra**
  - **BR** for **even Z residues** are quite **different** from **model predictions:**
    - ✓ **overproduction** of **multiple-α channels**, in which **pure α-particles (plus n)** are emitted.
    - ✓ **forward emission component** evident at variance with **p** which are correspondingly **depleted.**
  - **particle-particle correlations**, **selecting specific decay channels** (1α, 2α 3α .. **channels**) show some peculiarities in the experimental data:
    - ✓ especially at higher E* **larger exp dissipations** (**more n-evaporation expected**) in the **α-decay** channels;
    - ✓ Exp. peak at small relative energy correlations **(^{8}Be decay?)** in the **2α** channel
    - ✓ **equal energy** and **equal relative energy** of the **3α** → not accounted for by models both as **yields** and **shapes**.
  - Observed **experimental trends** vs. η**E*** of **different variables** → not reproduced by models → **possible extra (structure?) effects** in the dynamics of the reaction.

… and Perspectives

- ➢ Final consideration on obtained results are still **under discussion** due to the huge amount of data and findings → Dynamical models/phase to be better described → **discussion/collaboration ongoing**.
- ➢ Further **AMD simulations** are in progress with **different parameter sets (σ_{NN} – clustering etc.).**

COMEX6

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Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

M. Cicerchia – PhD work @UNIPD

NUCL-EX COLLABORATION

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THANK YOU