FIRST MEASUREMENT WITH TROJAN HORSE METHOD USING RADIOACTIVE ION BEAM

$^{18}F + p \rightarrow {}^{15}O + \alpha$ @ CRIB

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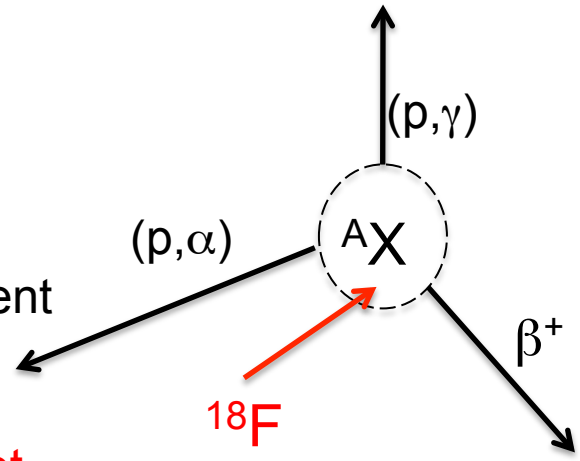
Summary

- Astrophysical motivations & State of Art
- Indirect measurement by Trojan Horse Method
- Experimental set-up → new apparatus for RIB application
- Data Analysis and preliminary results

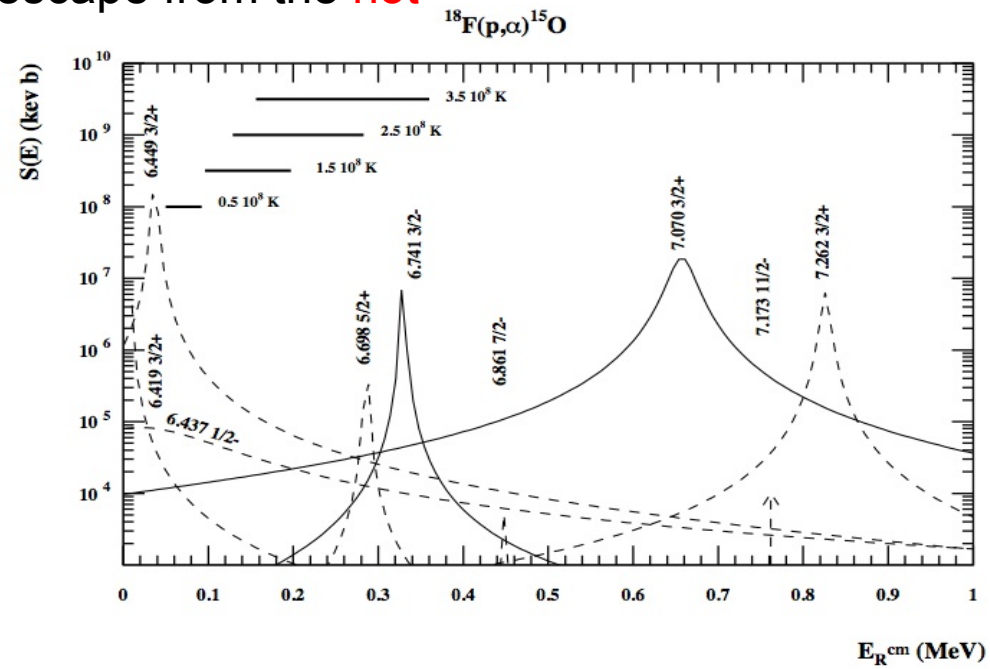
Astrophysical motivations

- Gamma-ray emission of energy 511keV from novae is dominated by the positron annihilation following the β^+ decay of unstable nuclei
- ^{18}F is especially important because
  - It is produced relatively abundantly
  - Its lifetime of ~158 min is well matched to the timescale for nova ejecta to become transparent to γ -ray emission
- The $^{18}F(p,\alpha)^{15}O$ reaction influence the ^{15}O production considered as a key isotope for the escape from the hot-CNO cycle to the rp-process



$^{18}F(p,\alpha)^{15}O$

S(E) dominated by several resonances of ^{19}Ne



State of Art

Many experiments performed using 18F beam @

ARGONNE - ATLAS
LLN
ORNL
TRIUMF
GANIL- SPIRAL
RIKEN – CRIB
TAMU

Direct measurements → thick target method

Indirect measurement → (d,p) (d,n) stripping reaction

Most recent references:

D. J. Mountford et al PHYSICAL REVIEW C 85, 022801(R) (2012)
"Resonances in 19Ne with relevance to the astrophysically important 18F(*p,α)15O reaction."*

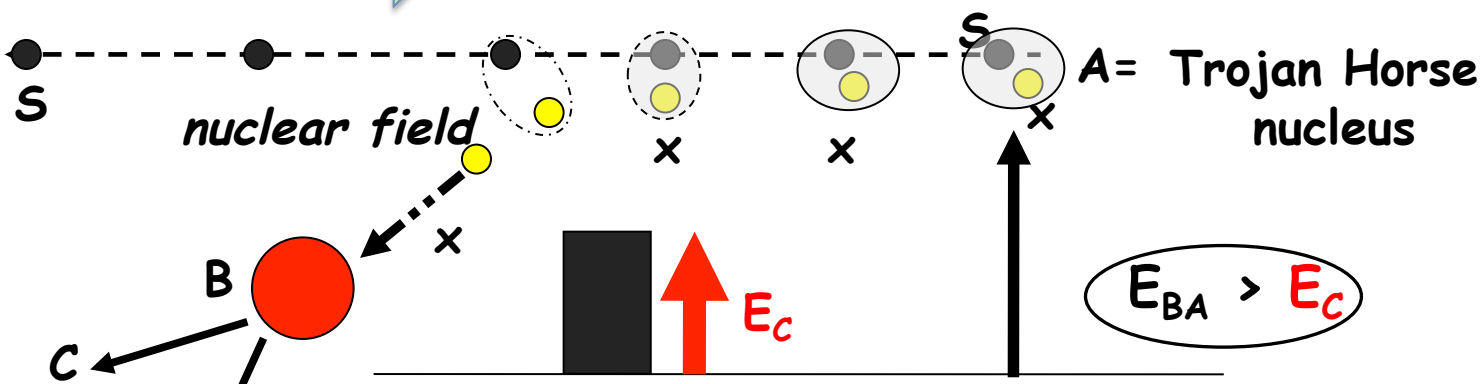
A. S. Adekola et al. PHYSICAL REVIEW C 83, 052801(R) (2011)
"First proton-transfer study of 18F + *p resonances relevant for novae"*

C. E. Beer et al. PHYSICAL REVIEW C 83, 042801(R) (2011)
"Direct measurement of the 18F(*p,α)15O reaction at nova temperatures"*

New measurement @ CRIB by using the Trojan Horse Method

A (x+s) + B → C + D + S

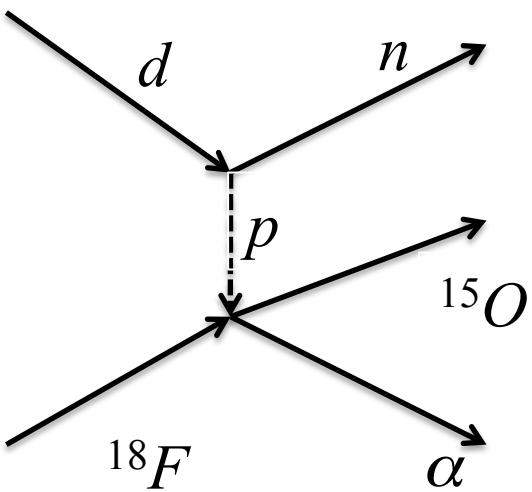
B + x → C + D



$E_{Bx} = E_{CD} - Q^{2Body}$ (pcp)

E_{BA}= A-B relative energy

E_C= A-B Coulomb Barrier

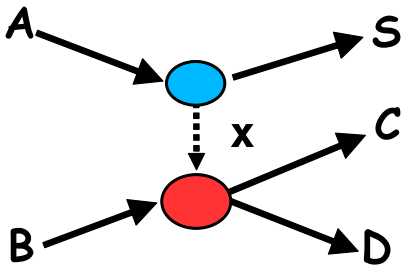


$$^{18}F + d \rightarrow {}^{15}O + \alpha + n$$

$$^{18}F + p \rightarrow {}^{15}O + \alpha$$

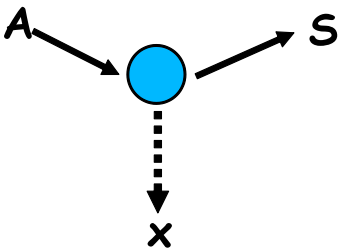
TURNING THE IDEA INTO PRACTICE

Assuming the QF mechanism is dominant the process can be represented in Feynman diagrams



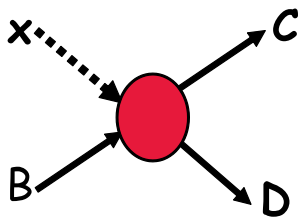
Three body reaction

=



Virtual decay

+



Virtual reaction

Half off-shell

(astrophysical process)

In PWIA:

$$\frac{d^3\sigma}{d\Omega_C\, d\Omega_D\, dE_C} = KF \cdot |\Phi(P_s)|^2 \times \frac{d\sigma^N}{d\Omega}$$

Measured

at high energy

Calculated

e.g.

Montecarlo

Deduced

Need direct data for normalization

$(E_{Bx} = E_{CD} - Q^{2body})$

"Plus" of the TH methods

1) Typical QF process cross sections (mbarn/sr) though measuring astrophysical ones

2) The TH cross sections is the purely NUCLEAR one: no Coulomb barrier effects

3) No electron screening effects: an INDEPENDENT piece of information can be obtained on the electron screening potential Ue by comparison to direct data

4) Can be extended to use QFR for studying NEUTRON induced reactions (VNM Virtual Neutron Method)

"Minus" of the TH methods

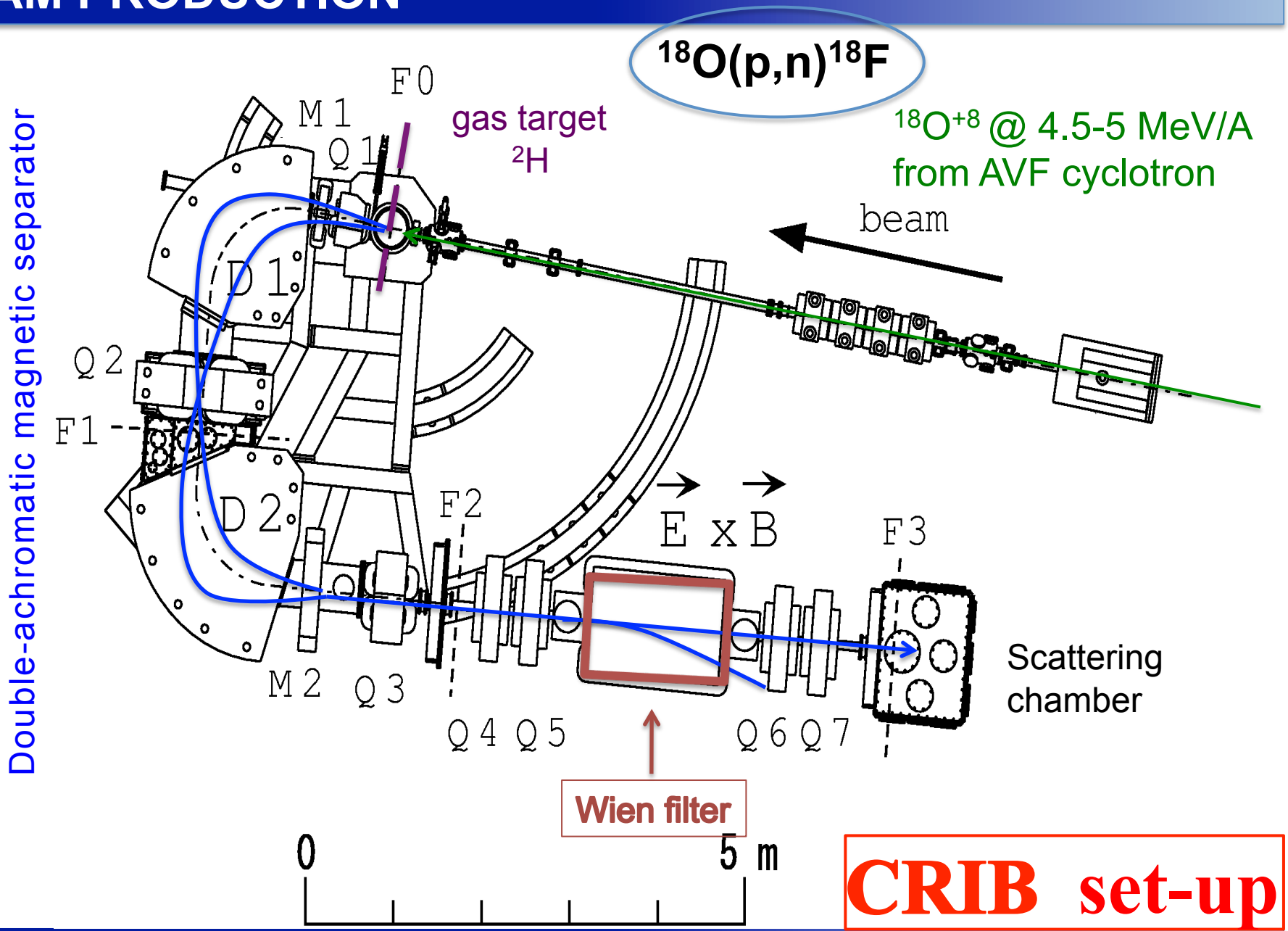
1) Competition between QF and other reaction mechanisms: identification of the convenient kinematical conditions may need more than one experiment run

2) Some dependence on theoretical models

3) Need of direct data at higher energies for normalization

S. C. et al., ApJ 457 (1996) 855

BEAM PRODUCTION



CRIB set-up

^{18}F beam development

Year	BTU type	Prod. Target type	Peak intensity
2006	Beam dev	Room temp.	~10^5
2007	Thick target experiment	Liquid N cooled	$5x10^5$
2008	Trojan Horse experiment	Liquid N cooled	> 10^6

Primary beam: $^{18}O^{8+}$, 4.5-5 MeVA

Production target: H_2

Production reaction: $^{18}O(p,n)^{18}F$

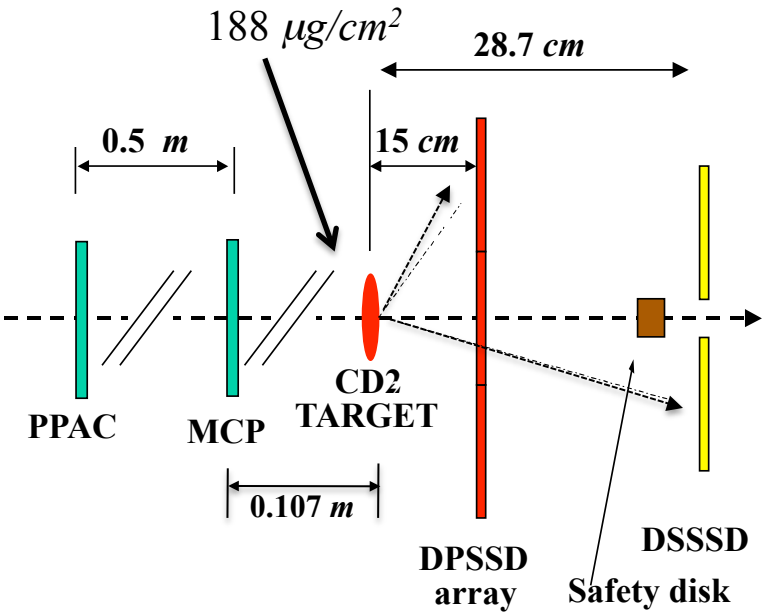
BEAM PURITY > 98%

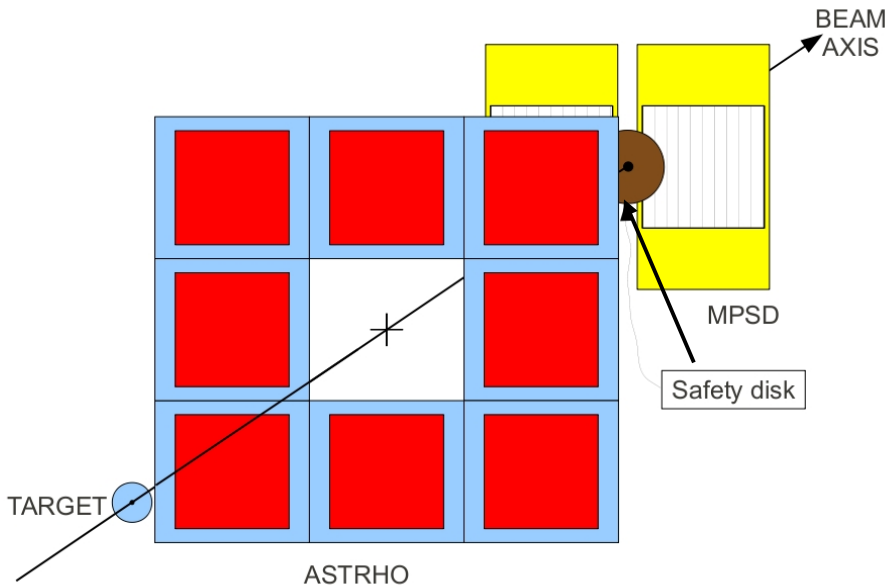
E_{beam} = 48.7 MeV

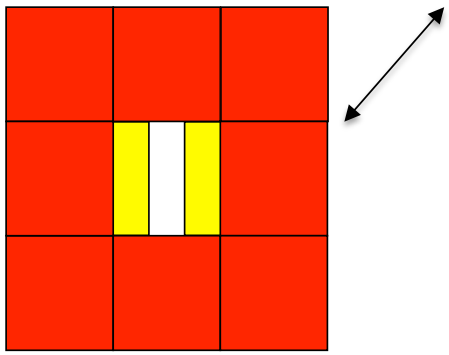
σ = 0.8 MeV

EXPERIMENTAL SETUP

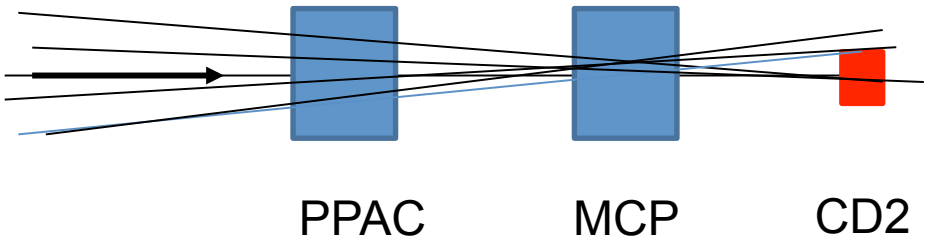
(other than CRIB.....)







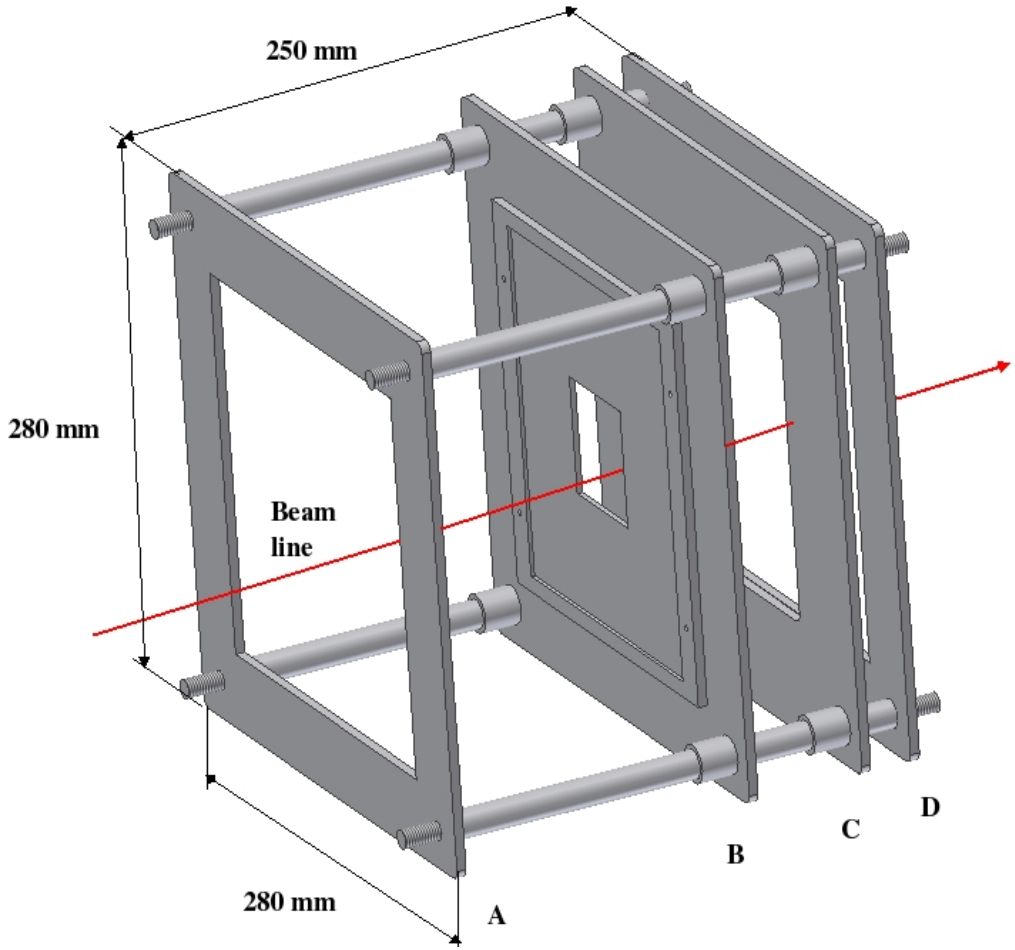
Beam @PPAC
$2.4 \cdot 10^6$ pps
48.7 ± 0.8 MeV

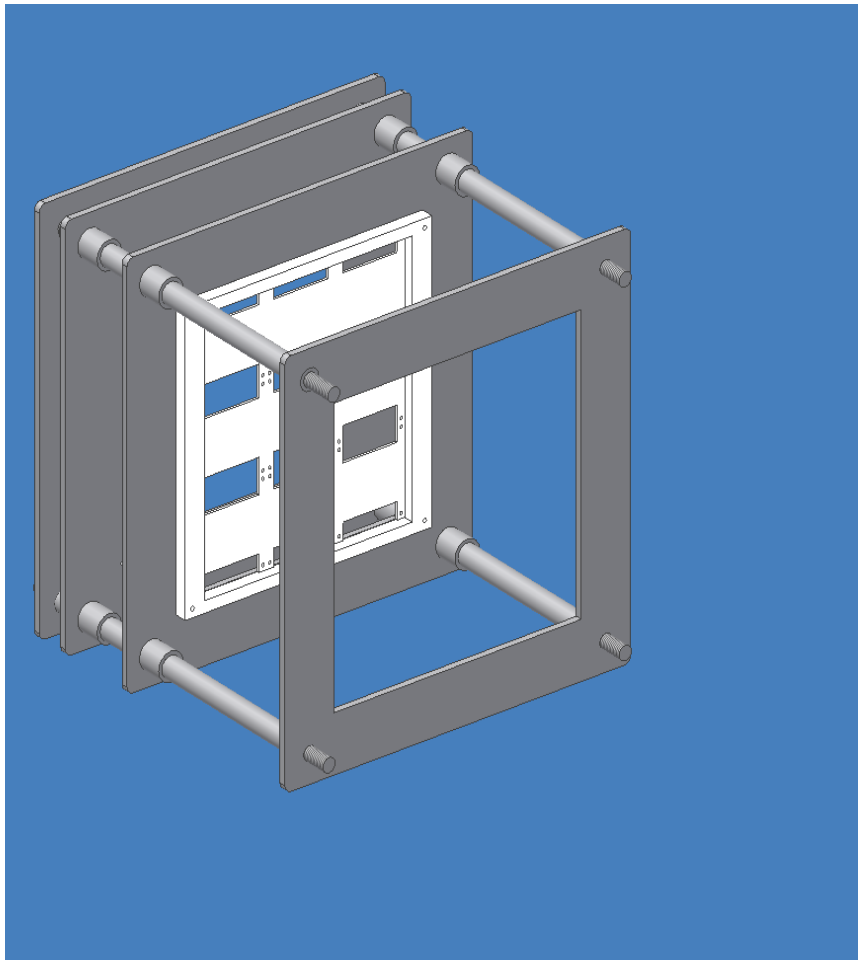


Beam track reconstruction event by event

ASTRHO:
Array of Silicons for TRojan HOrse

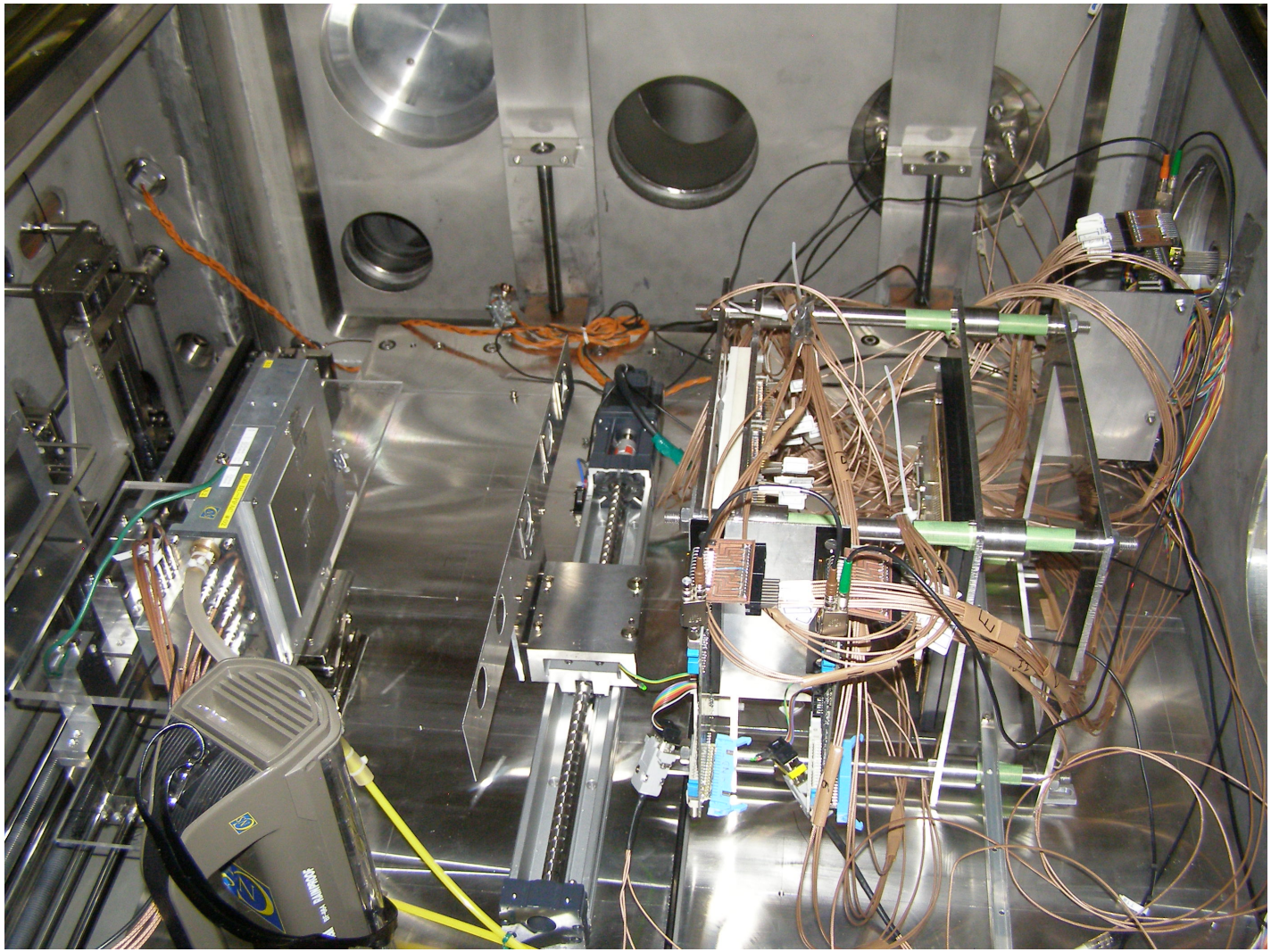
EXPERIMENTAL SETUP





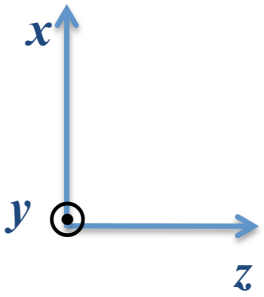
In order to allow for the optimization of the two experiments ASTRHO and the DSSSD were hosted in a mechanical system that allowed for easy movement of the detector holder plates

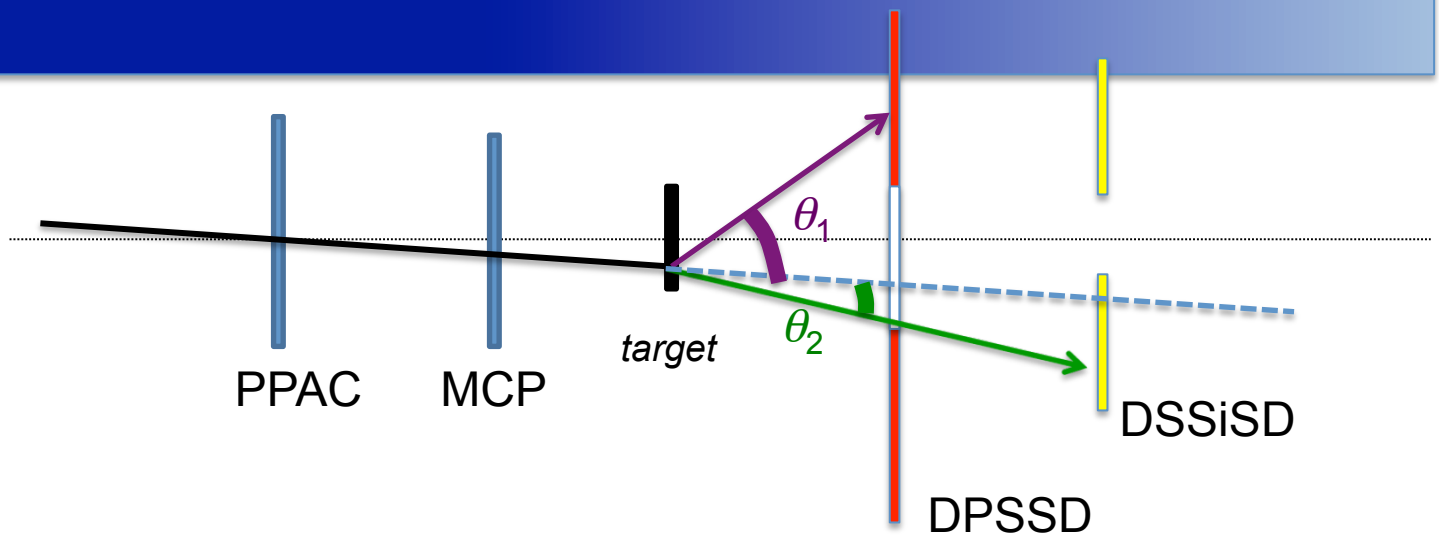
EXPERIMENTAL SETUP



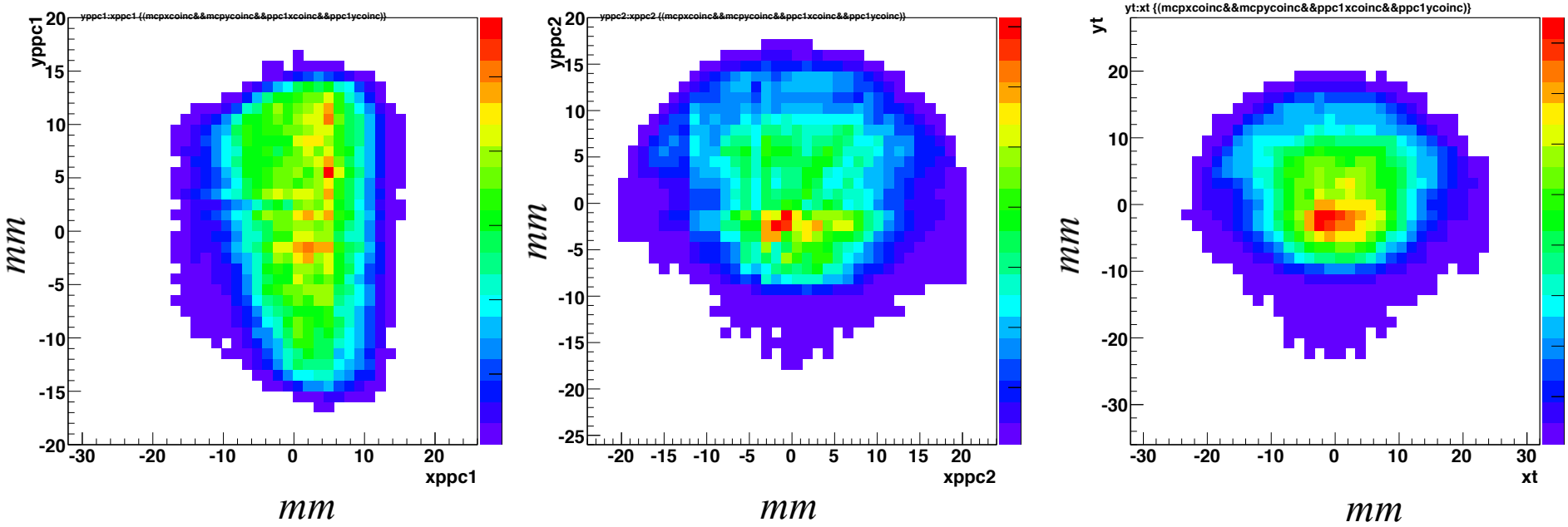
How ASTRHO looks like in reality
(before PPAC explosion...)

BEAM TRACKER



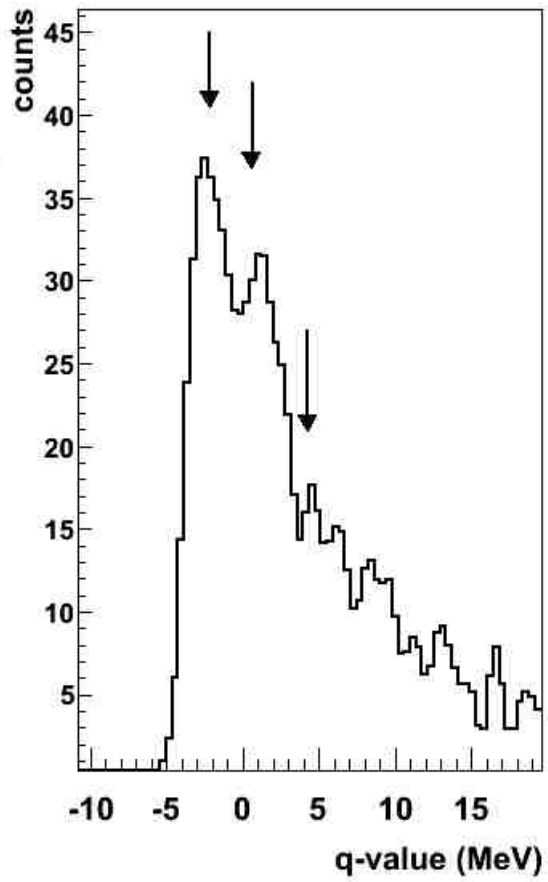


Beam track reconstruction event by event

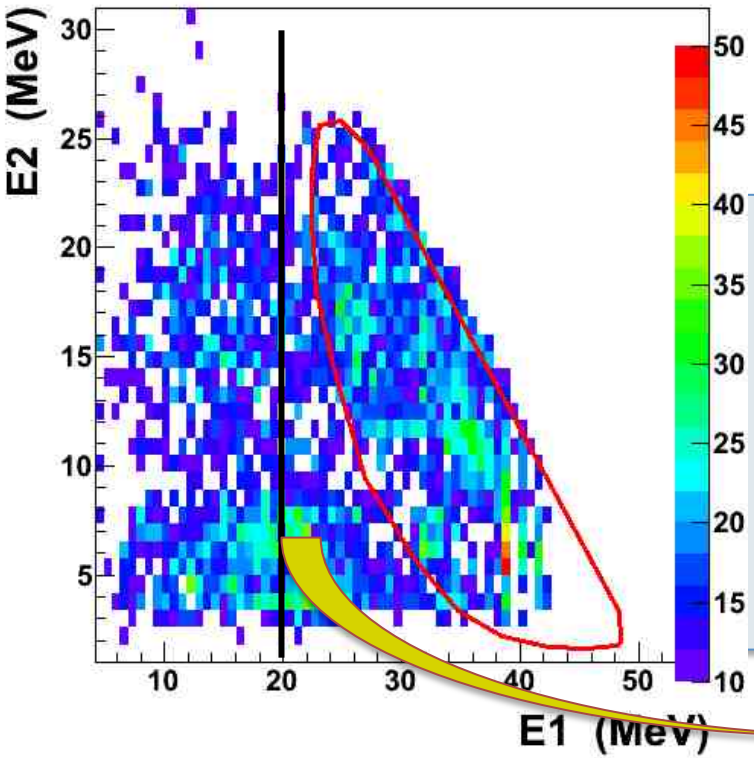


Q-VALUE SPECTRUM

$^{18}F+d \rightarrow {}^{15}N+\alpha+p$ @ $q = 4.194$ MeV
$^{18}F+d \rightarrow {}^{15}O+\alpha+n$ @ $q = 0.658$ MeV
$^{18}F+d \rightarrow {}^{18}O+p+p$ @ $q = 0.213$ MeV
$^{18}F+d \rightarrow {}^{18}F+p+n$ @ $q = -2.225$ MeV



1 + 2 + 3



CUTS:

- Event multiplicity = 2
- $|T_2 - T_1| \cong 0$
- E1 > 20 MeV

EVENT SELECTION

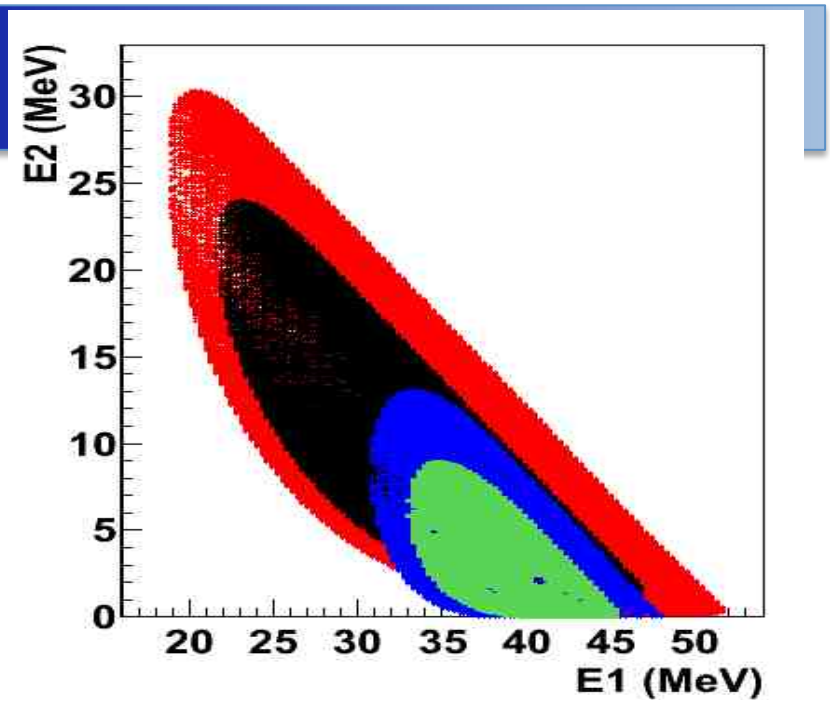
Red : $^{18}F + d \rightarrow {}^{15}N + \alpha + p$

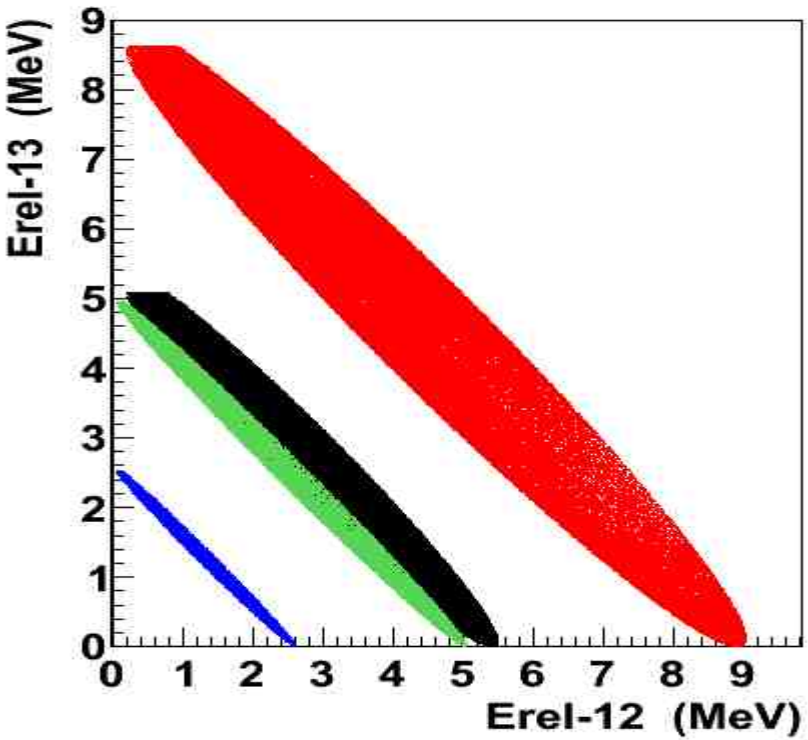
Black: $^{18}F + d \rightarrow {}^{15}O + \alpha + n$

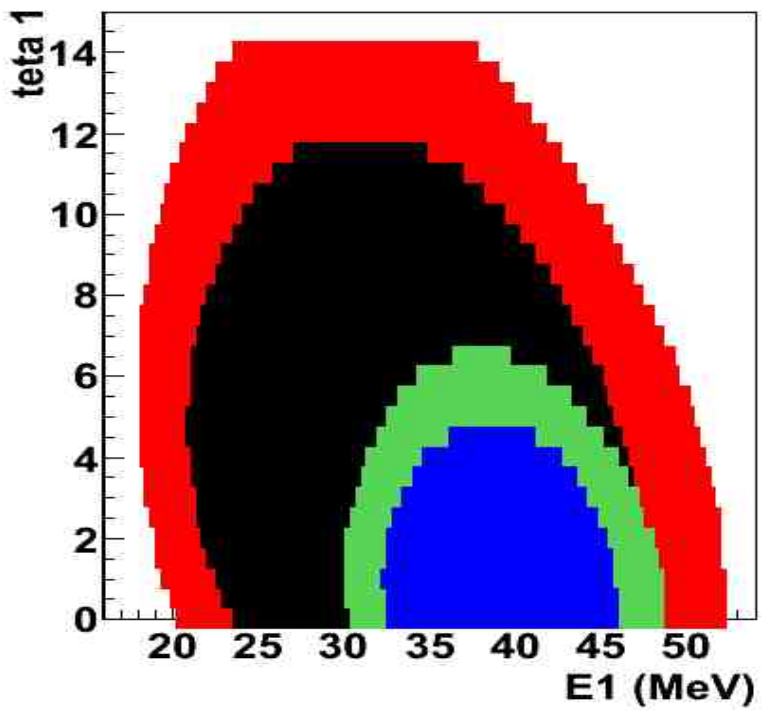
Blue: $^{18}F + d \rightarrow {}^{18}F + p + n$

Green: $^{18}F + d \rightarrow {}^{18}O + p + p$

"1"+"2"+"3"





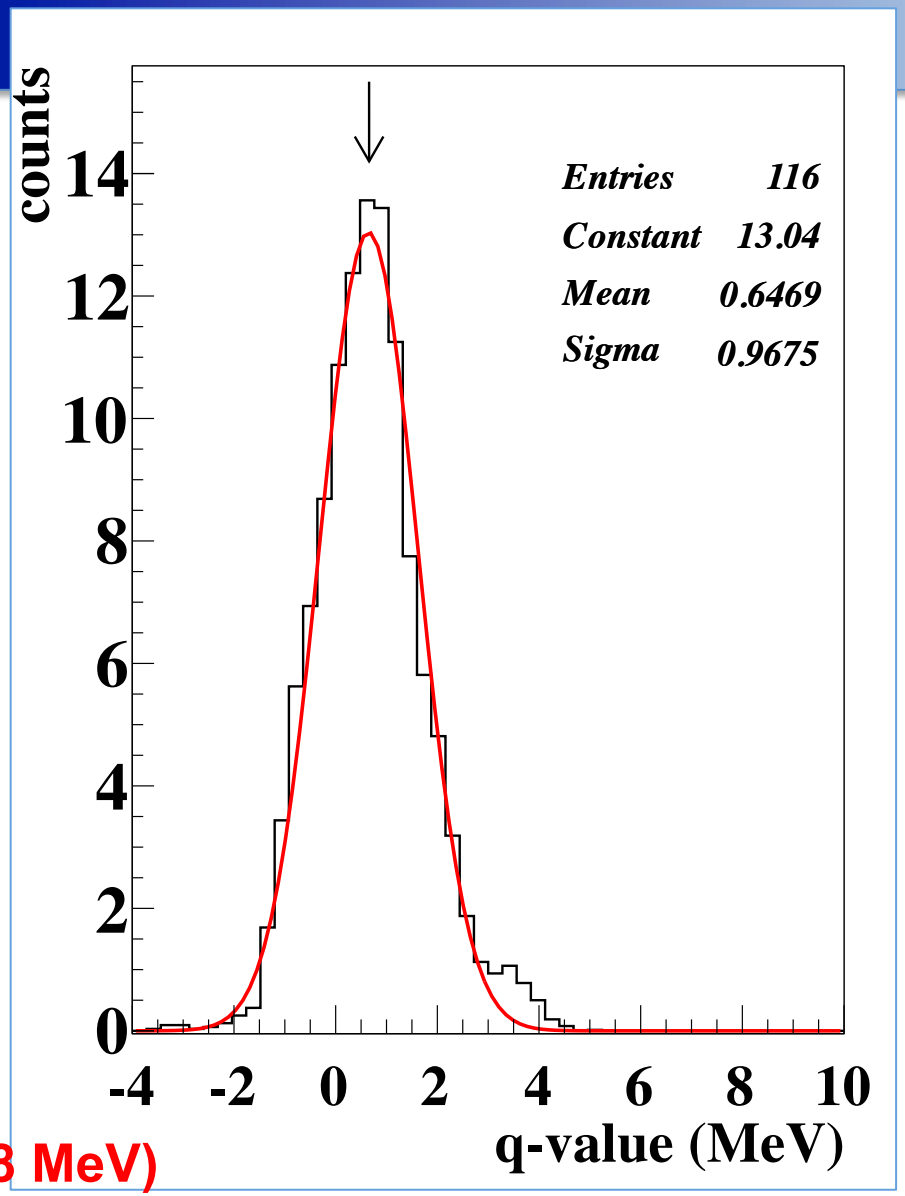


Q-VALUE SPECTRUM

CUTS:

- Event multiplicity = 2
- $|T_2 - T_1| \cong 0$
- E1 > 20 MeV

- Correlation E_{13} - E_{12}
- Correlation E_1 - θ_1

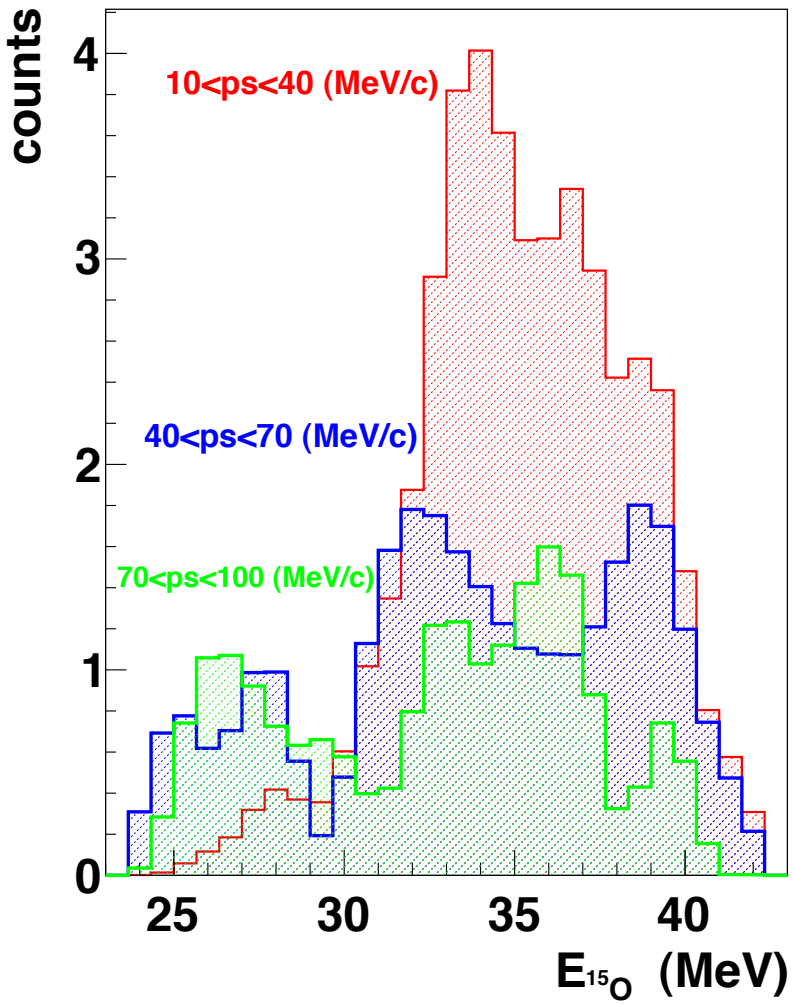


GOOD AGREEMENT with

- ❑ **q-value expected position (0.658 MeV)**
- ❑ **and beam profile (exp. Sigma 0.8 MeV)**

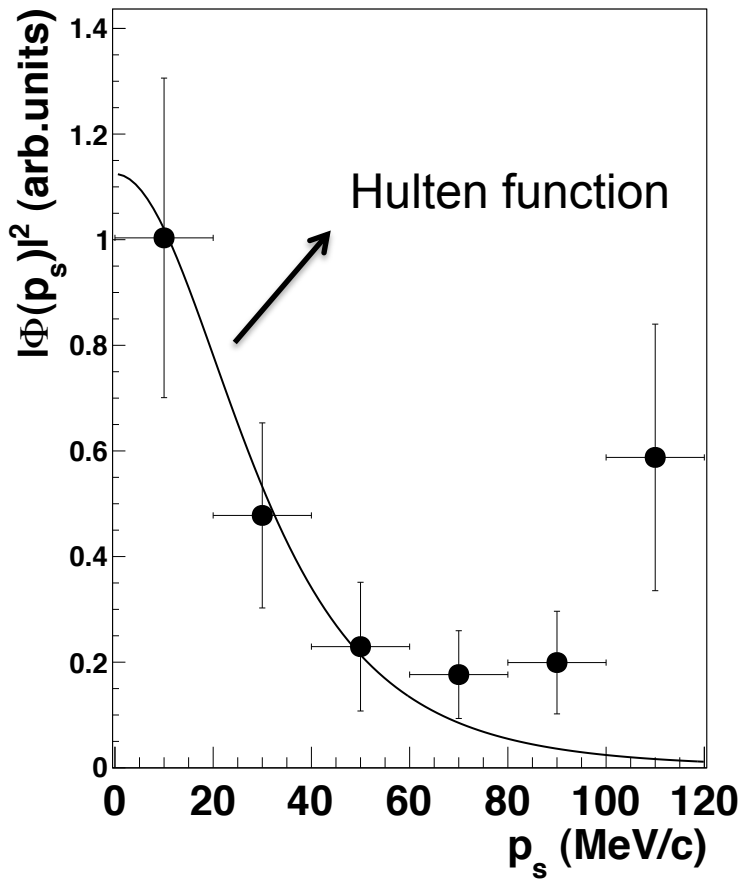
HINTS FOR QF MECHANISM

Minumum of p_s



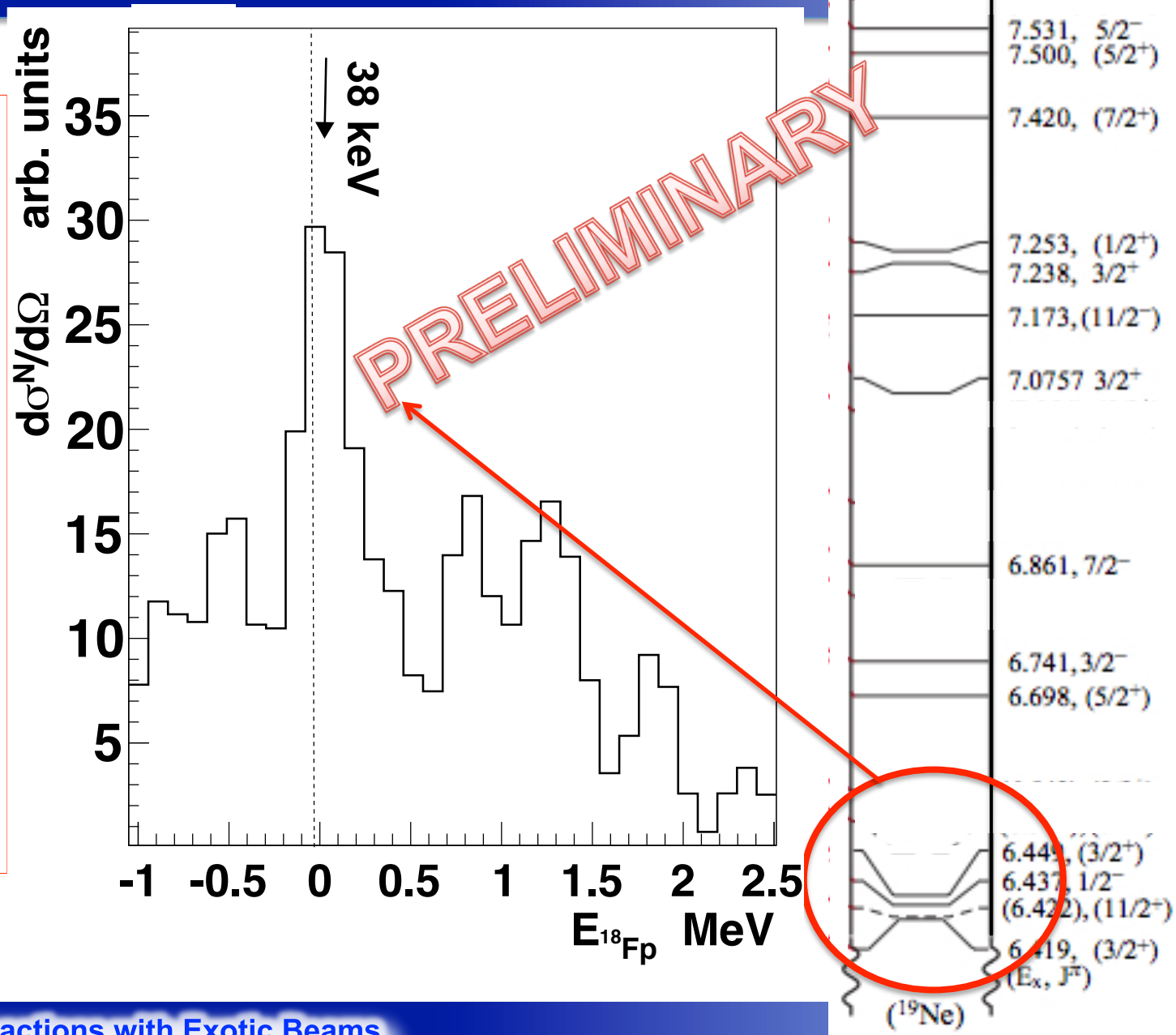
If the quasi-free mechanism is predominant

$$\frac{d^3\sigma}{d\Omega_{^{15}O}\, d\Omega_\alpha\, dE_\alpha} \propto KF\left|\Phi(p_s)\right|^2 \cdot \frac{d\sigma}{d\Omega}^{N}$$



BARE NUCLEUS CROSS SECTION

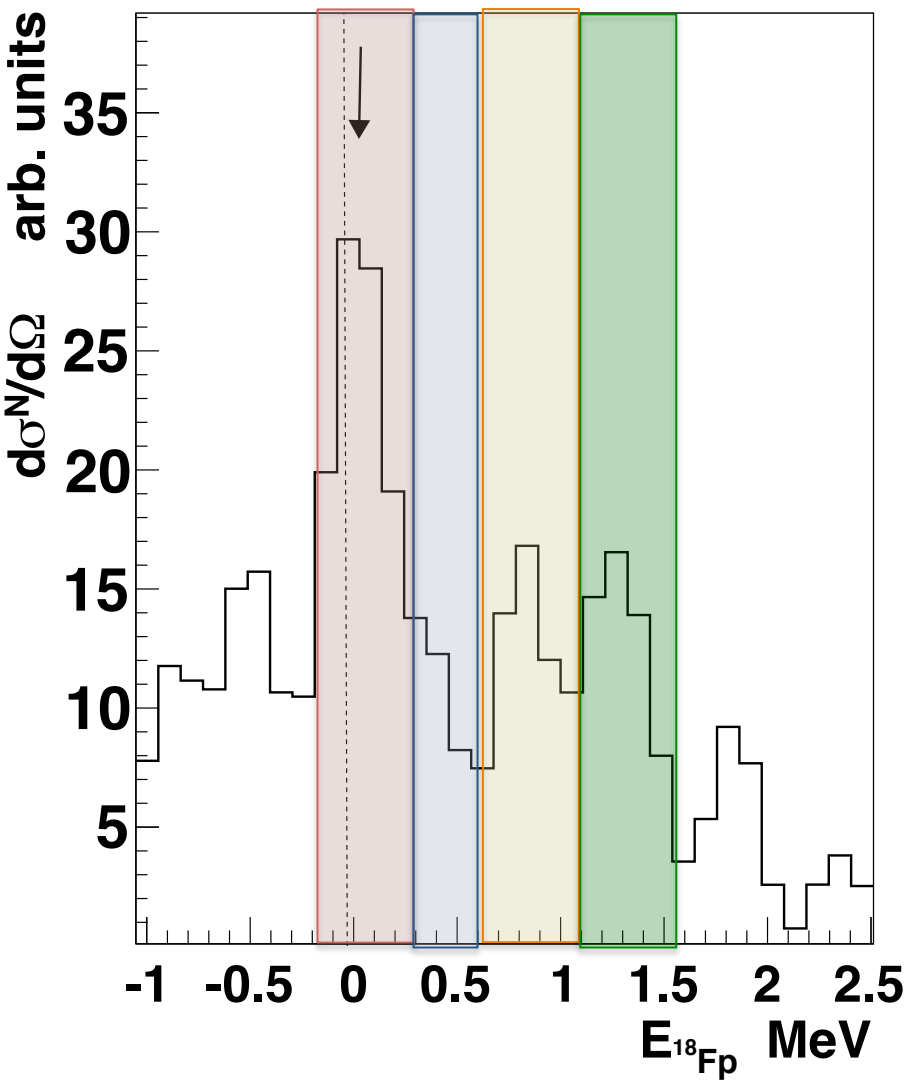
FIRST TROJAN HORSE experiment with RIB !!!

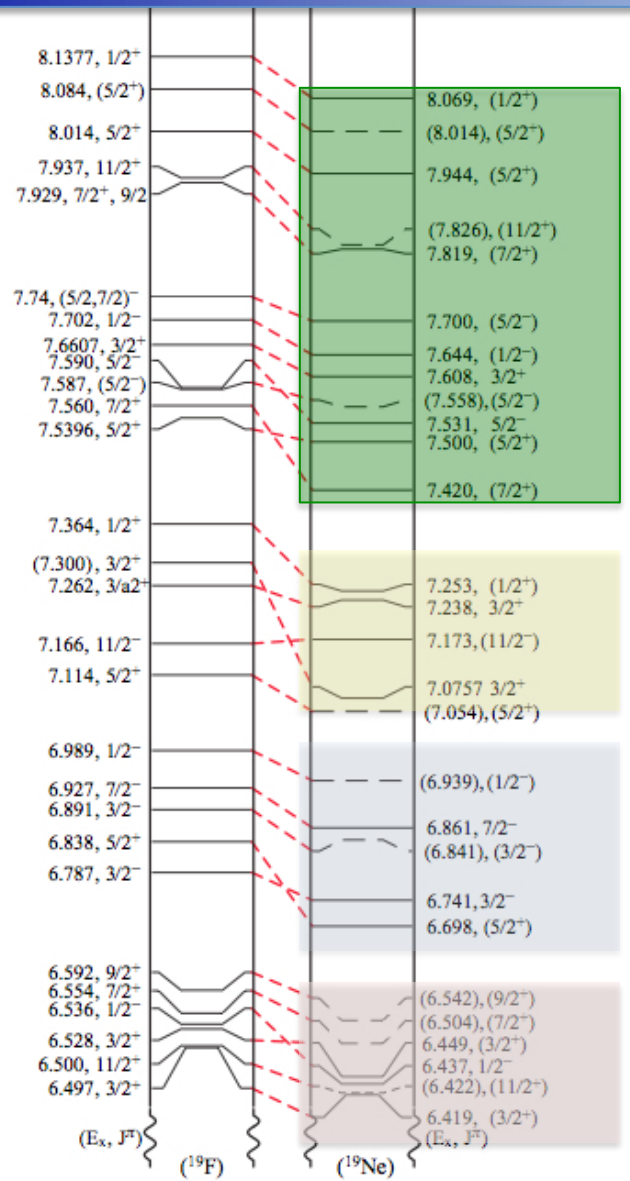


Conclusions and Perspective

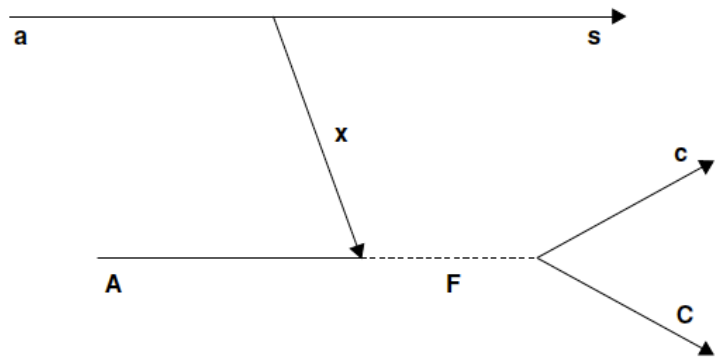
- THM was successfully applied to radioactive ion beam induced reaction
- the beam is tracked event by event and the kinematical variables were consequently rencostructed
- the preliminary results showed the possibility to study the cross section of the 18F(p,a)15O reaction and extract complementary information on S(E) factor → (work in progress)
- Increase statistic and confirm the results with a second experimental run
- Possibility to measure the 18F(n,a)15N reaction

BARE NUCLEUS CROSS SECTION





Trojan Horse for Resonance Reactions



HALF OFF-SHELL

$$\frac{d^2\sigma^{TH}}{d\Omega_{\hat{k}_{sF}}\, dE_{cC}} = \frac{1}{2\pi}\,\frac{\Gamma_{cC}(E_{cC})}{(E_{cC}-E_{R_{cC}})^2+\frac{1}{4}\Gamma^2(E_{cC})} \times \frac{d\sigma_{(a+A\to s+F)}}{d\Omega_{\hat{k}_{sF}}},$$

ON-SHELL

$$\sigma^R_{(x+A\to c+C)} = \frac{\pi}{k^2_{xA}}\,\frac{\hat{J}_F}{\hat{J}_A\,\hat{J}_a}\,\frac{\Gamma_{cC}(E_{cC})\,\Gamma_{xA}(E_{xA})}{(E_{cC}-E_{R_{cC}})^2+\frac{1}{4}\Gamma^2_{cC}(E_{cC})}.$$

$$\Gamma_{xA}(E_{xA}) = 2\,P_{l_i}(E_{xA},\, r_0)\,\gamma^2_{xA}$$

PENETRABILITY

$$\sigma^R_{(x+A\to c+C)} = \frac{d^2\sigma^{TH}}{d\Omega_{\hat{k}_{sF}}\, dE_{cC}}\,\frac{\Gamma_{xA}(E_{xA})}{\frac{d\sigma_{(a+A\to s+F)}}{d\Omega_{\hat{k}_{sF}}}}\,\frac{2\pi^2}{k^2_{xA}}\,\frac{\hat{J}_F}{\hat{J}_A\,\hat{J}_x},$$

Indipendent from **spectroscopic** factor value

THE ASTROPHYSICAL JOURNAL, 708:796–811, 2010 January 1

Collaborators

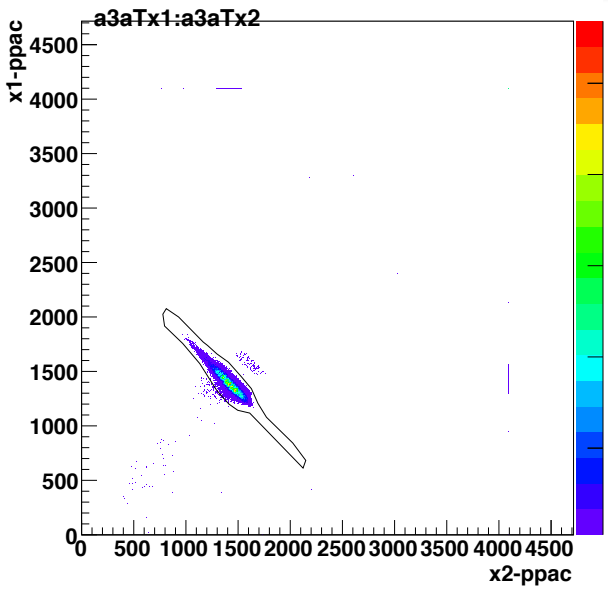
M. Gulino, G. G. Rapisarda, L. Lamia, M. L. Sergi, C. Spitaleri

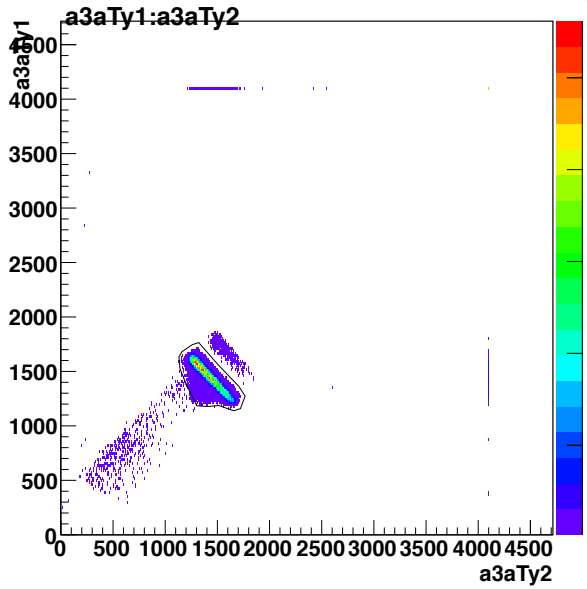
A. Coc, F. Hammache, N. de Sereville

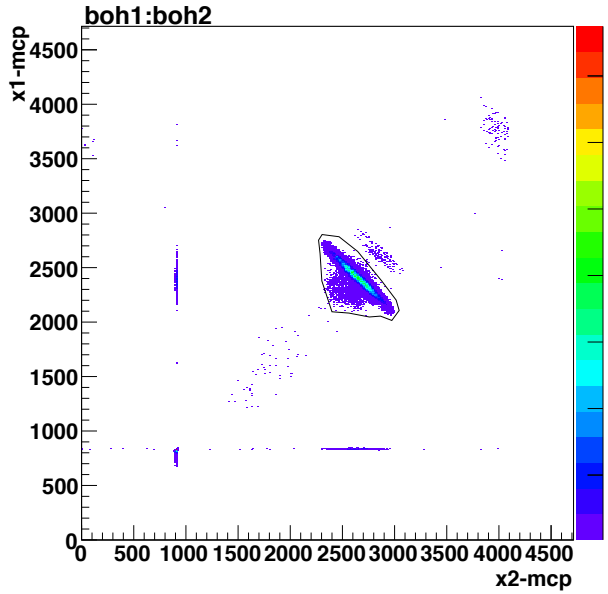
S. Kubono, H. Yamaguchi, S. Hayakawa, Y. Wakabayashi

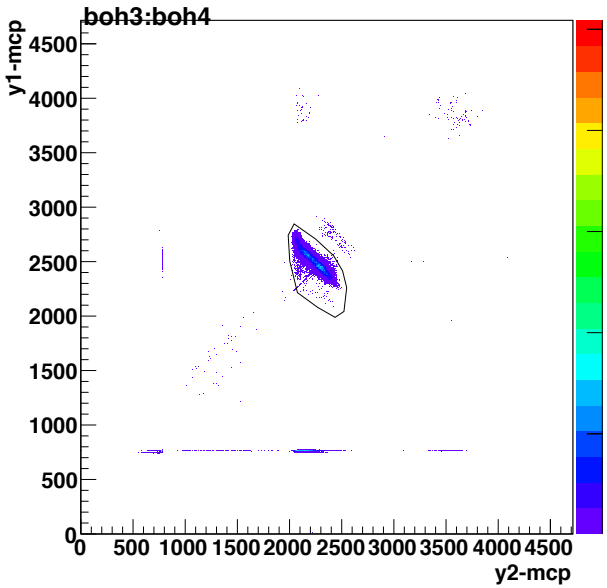
T. Komatsubara, N. Iwata, T. Teranishini

BEAM position on PPAC and MCP

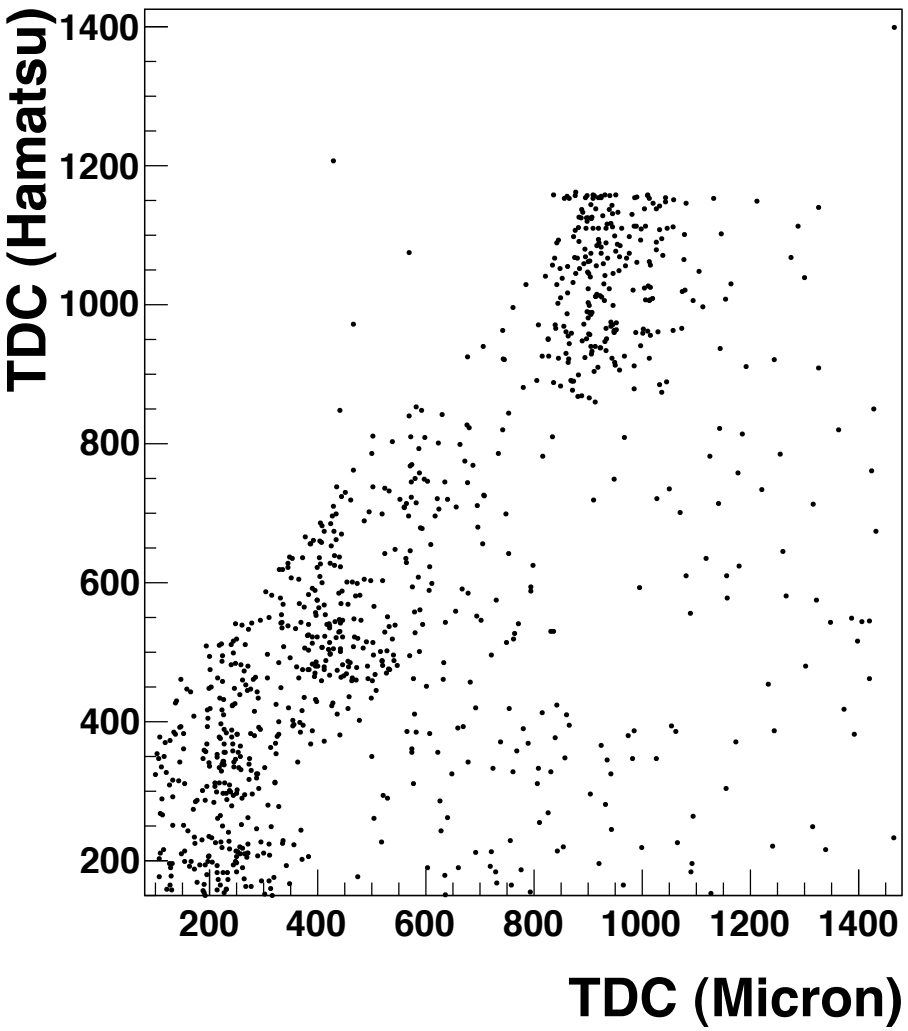


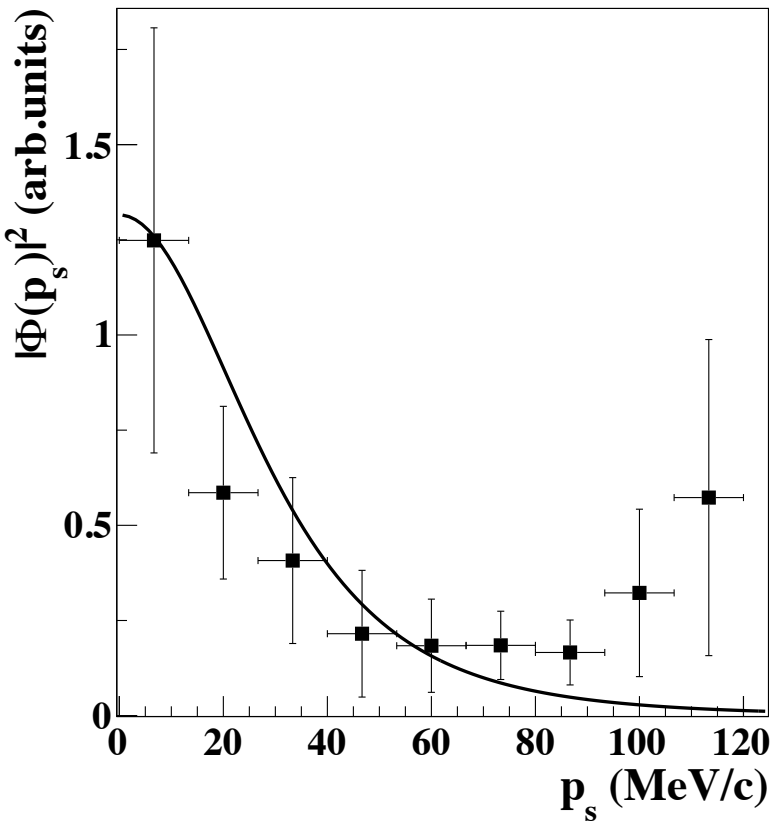






CUTS


TDC (Hamatsu)
1400
1200
1000
800
600
400
200
200
400
600
800
1000
1200
1400
TDC (Micron)


$|\Phi(p_s)|^2$ (arb.units)
1.5
1
0.5
0
0
20
40
60
80
100
120
p_s (MeV/c)