Pionic fusion experiments at subthreshold energies

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Outline

- Motivation
- Some theoretical aspects
- Experimental setup
- Candidate selection
- Preliminary results
- Conclusion

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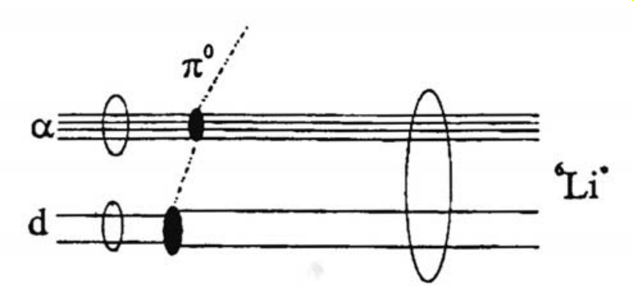
Motivation

$A + B \longrightarrow C + \pi$



• **Absolute threshold energy for pion production in free Nucleon-Nucleon interaction :**
280 (290) MeV

• **Coherent threshold energy for pion production in Nucleus-Nucleus interaction :**
<< 280 AMeV !!

A highly coherent reaction mechanism is required.

Our aim is
the study of a coherent process of several nucleons and clusters within a nuclear system.

We measure the exclusive final state defined by the isospin conservation

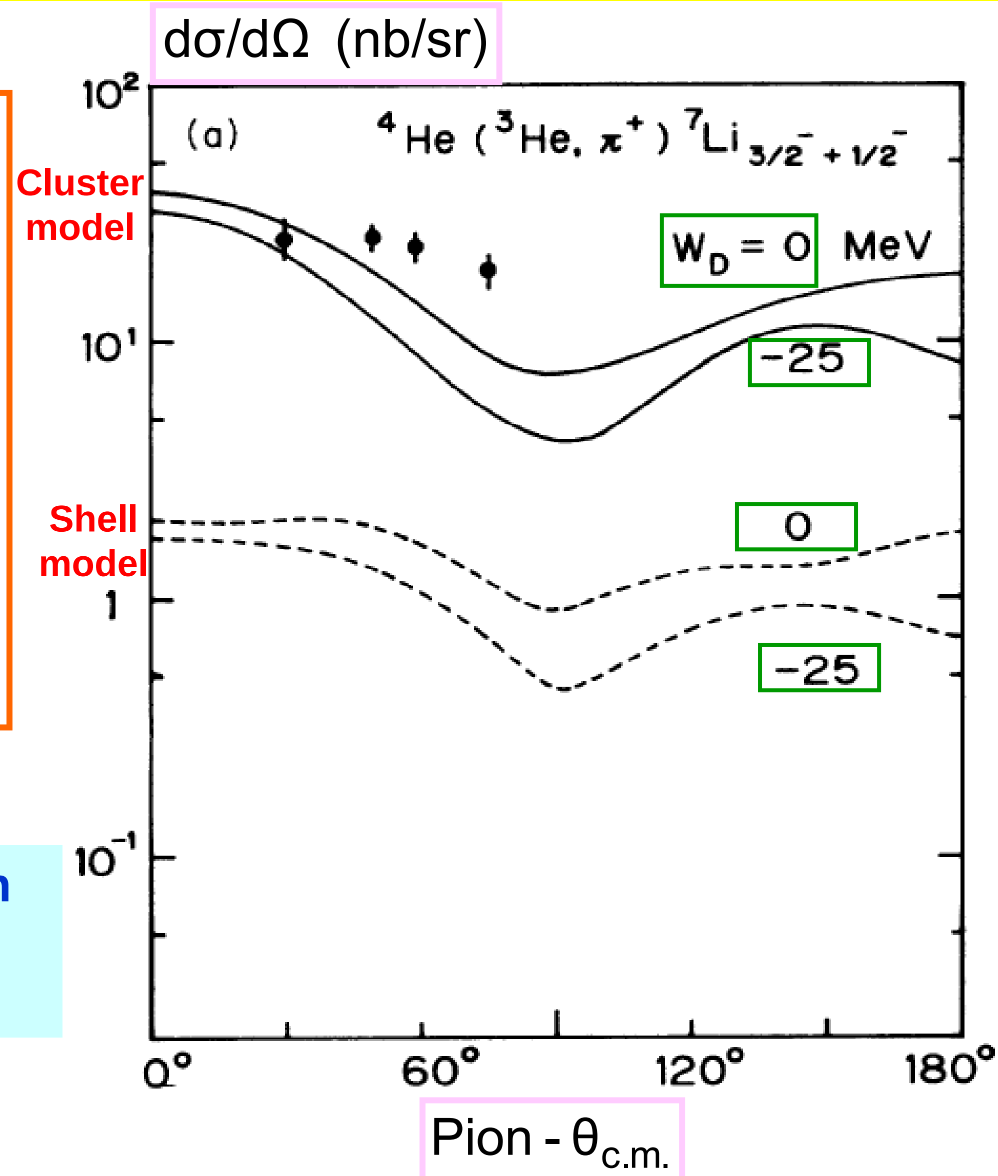
Theoretical calculations

Magnitude:
- Shell model cross section is10-100 times lower than cluster model
- The influence of **Local imaginary potential**

Shape:
- Forward-backward asymmetry but no data available for the full angular range
- The influence of **Local imaginary potential**

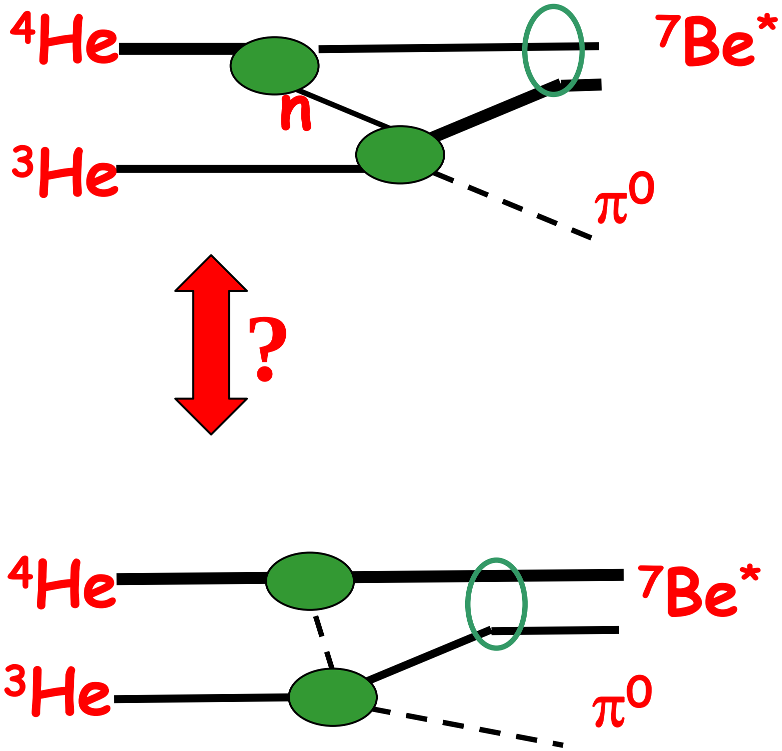
Cluster model underestimates existing data:
Rate of two-body interactions (Δ excitation)?

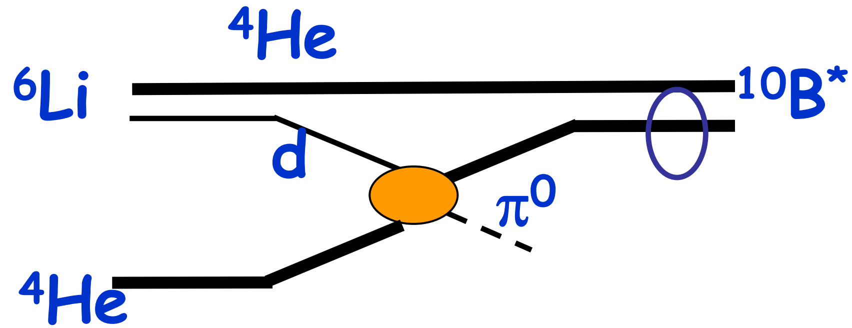
inter-cluster (^3H – ^4He) relative motion absorbs large momentum transfer to fused system ^7Li



Kajino, Toki, Kubo, PRC 35 (87) 1370
L. Bimbot et al.,PL B 14 (82) 311

Systematic study of cluster structures



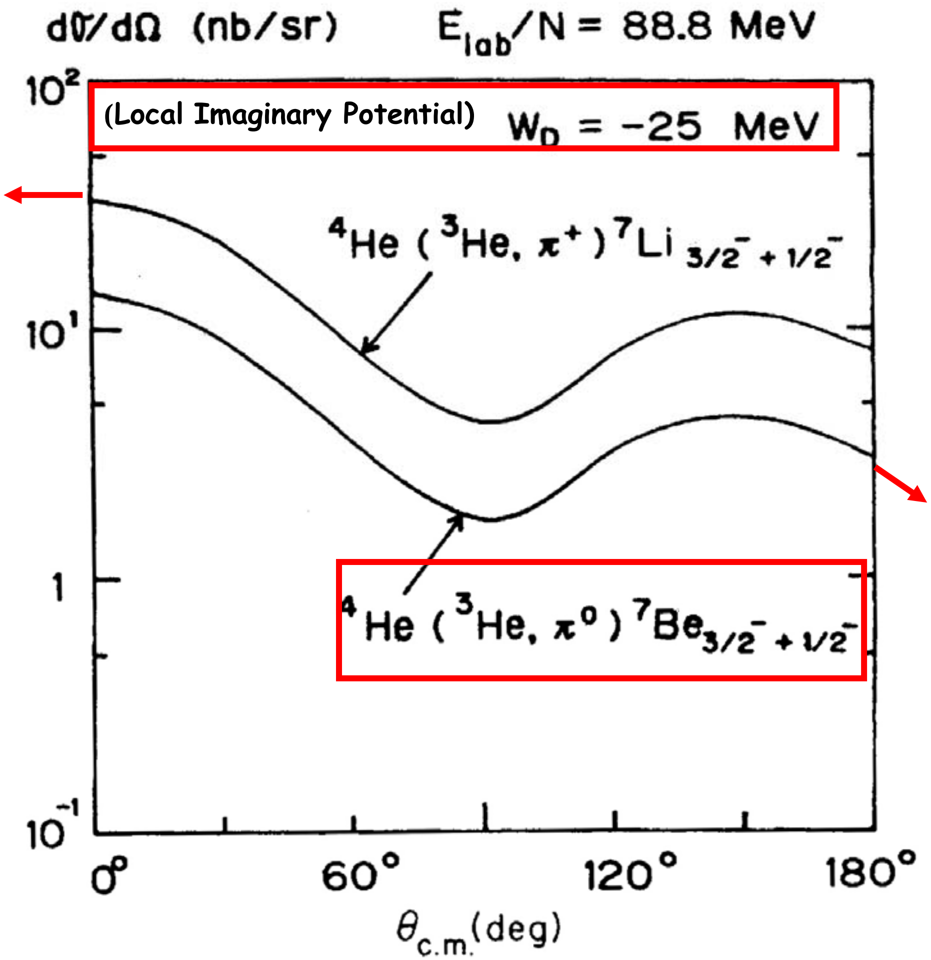


Experimental data required to determine the reaction mechanism

Cross-section and angular distribution

Predictions of Cluster model for π^0 fusion to ^{7}Be

Prediction of pion angular distribution for $^4He(^3He,\pi^+)^7Li$ reaction.
(scarce data available)



Prediction of pion angular distribution for $^4He(^3He,\pi^0)^7Be$ reaction.
(no data available)

Measurement of full angular distribution is needed.

Pionic fusion experiments at KVI

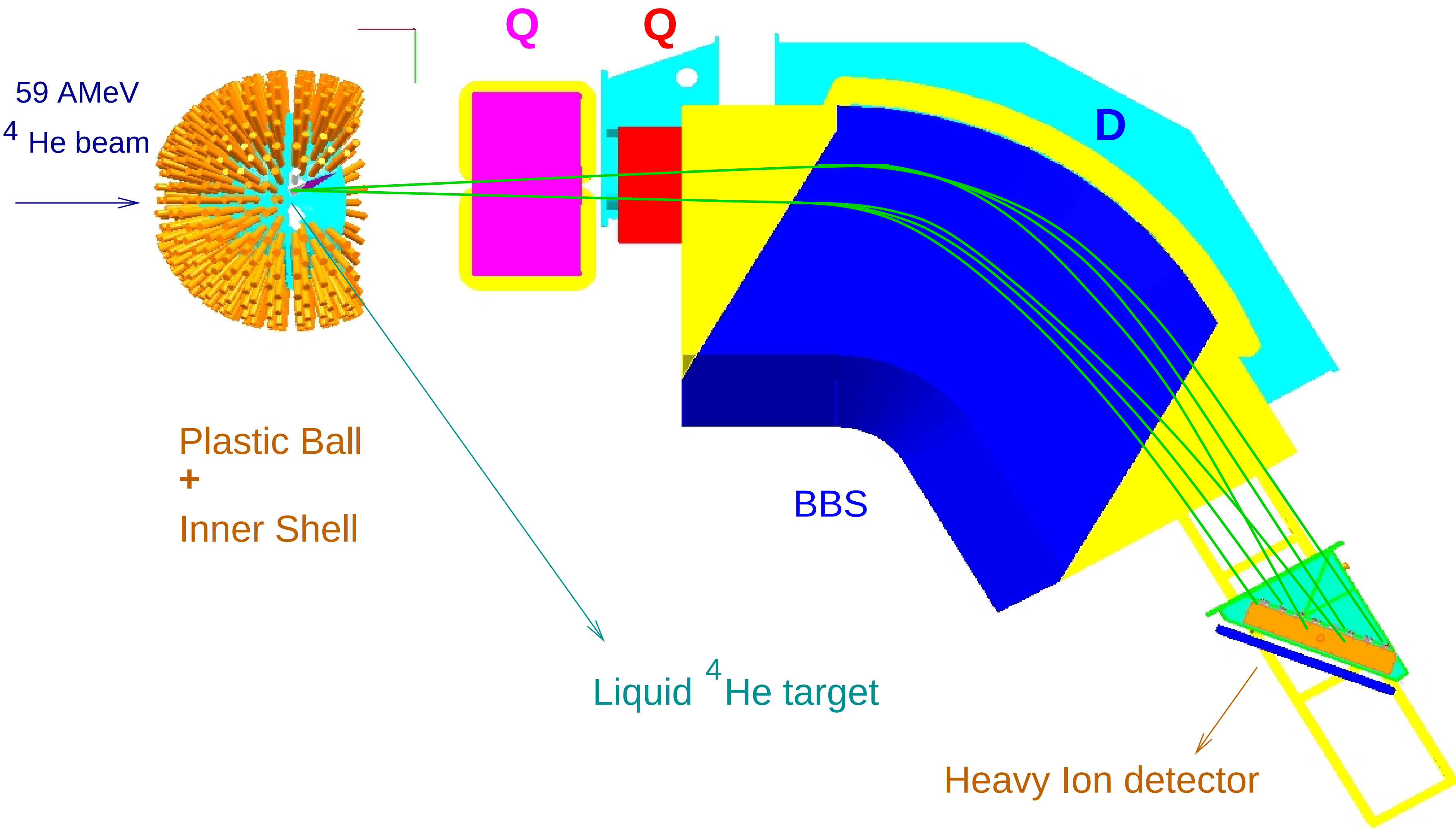
$$^{3}\text{He} + {}^{4}\text{He} \rightarrow {}^{7}\text{Be} + \pi^{0}$$

- 11 MeV above the coherent threshold
  (Liquid ^{4}He target)

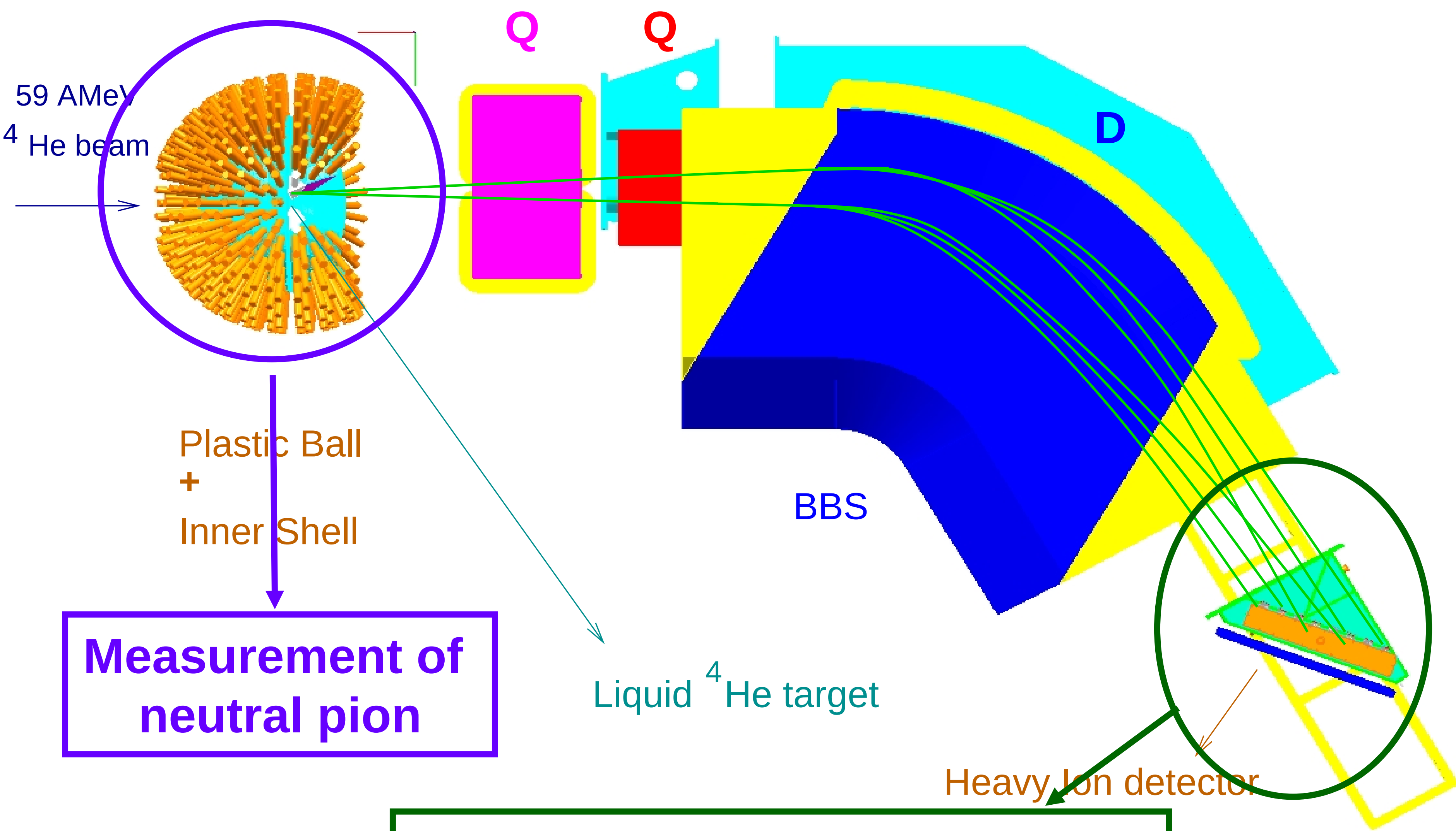
$$^{4}\text{He} + {}^{6}\text{Li} \rightarrow {}^{10}\text{B} + \pi^{0}$$

- 10 MeV above the coherent threshold

Experimental setup



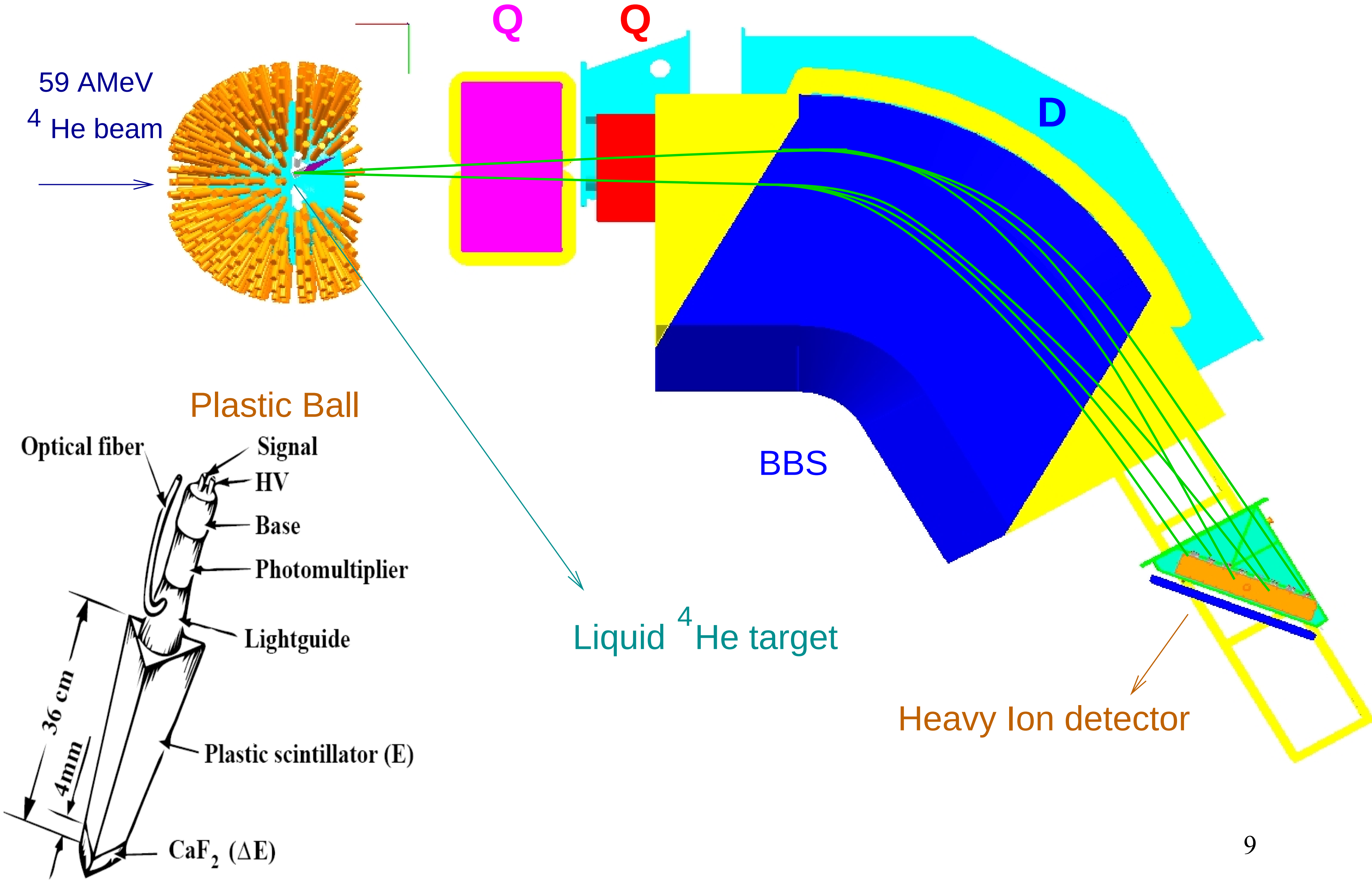
Experimental setup



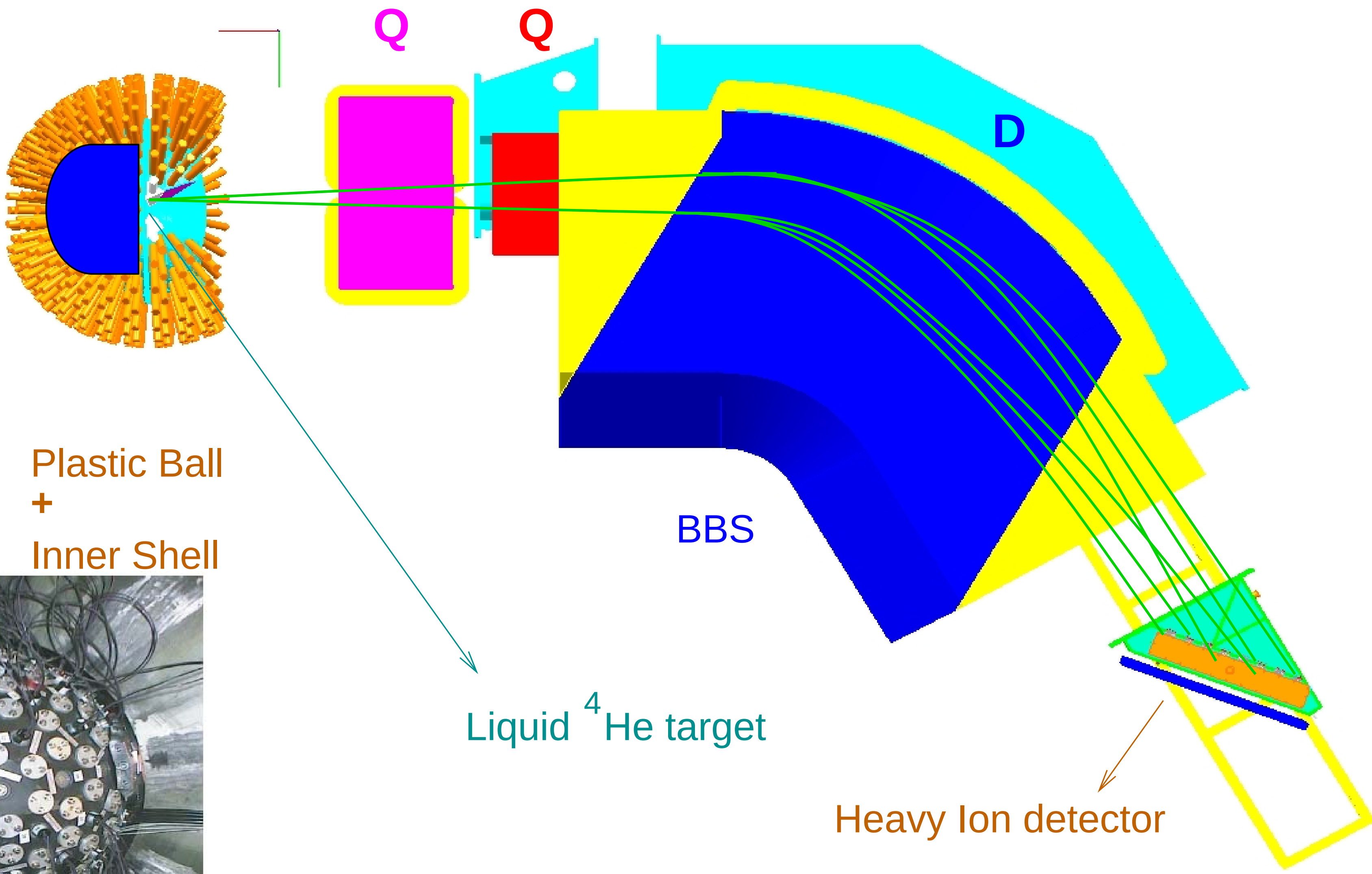
Measurement of neutral pion

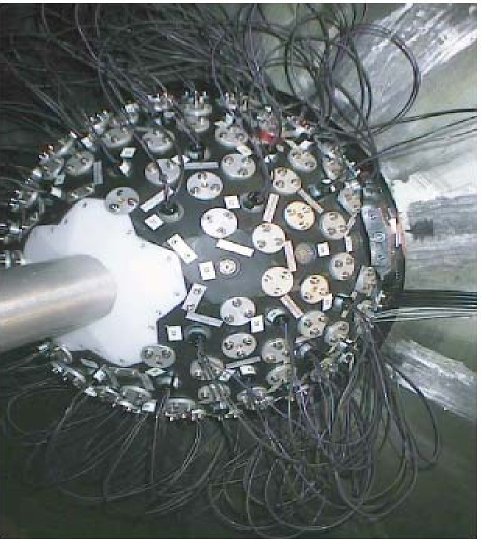
Measurement of fusion product

Experimental setup

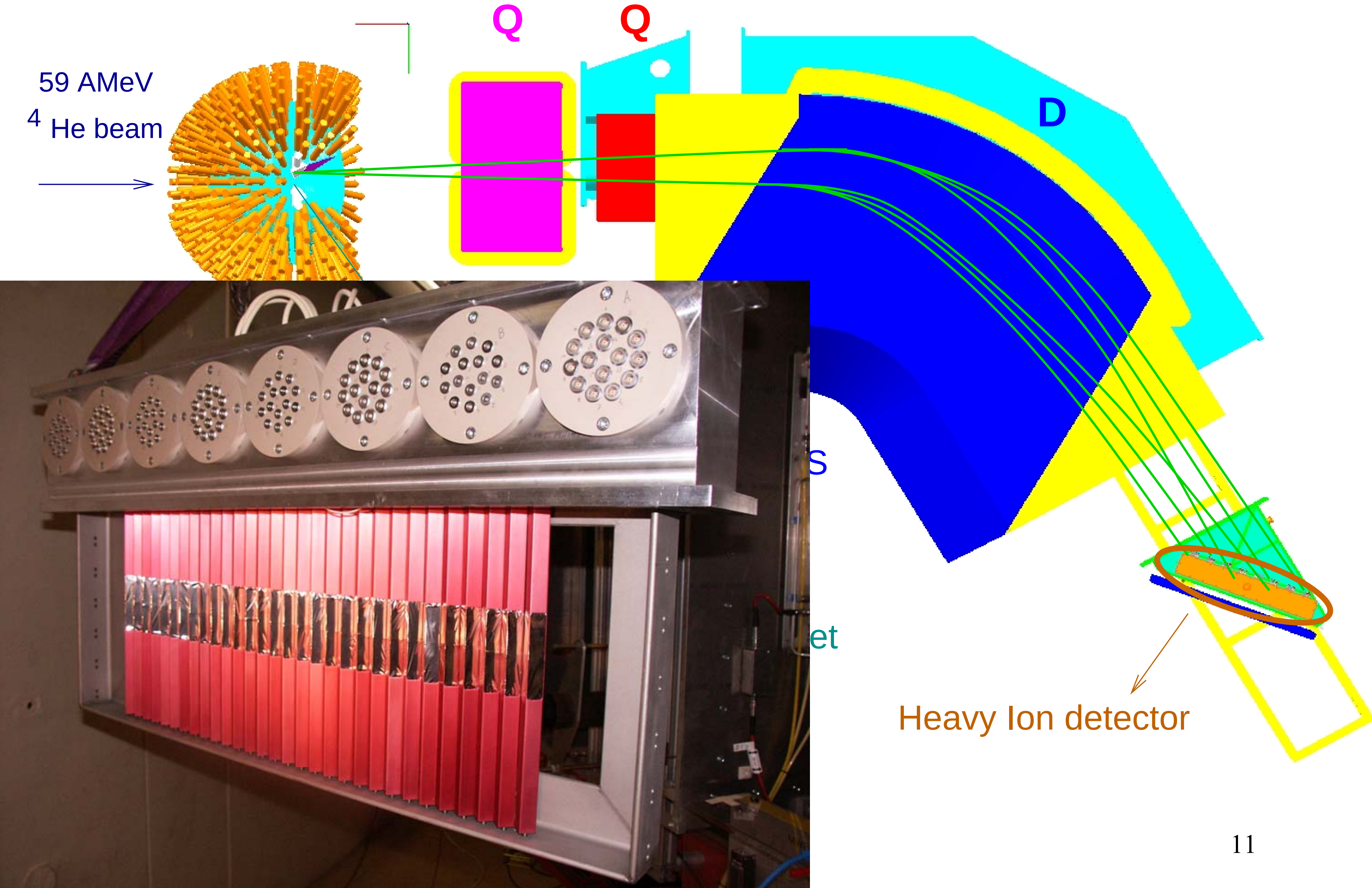


Experimental setup

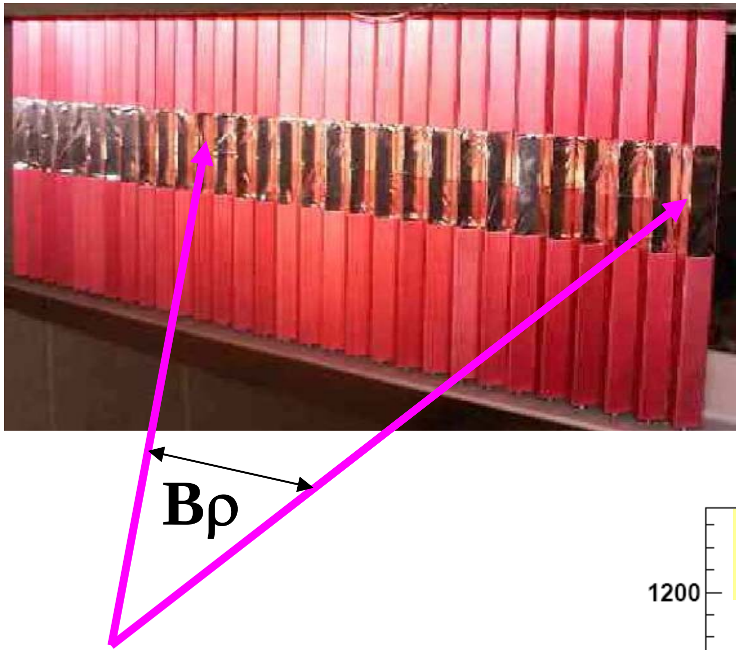




Experimental setup



momentum acceptance of fusion products



60 phoswich detectors

100 μm plastic/CsI 1.3X4 cm^2

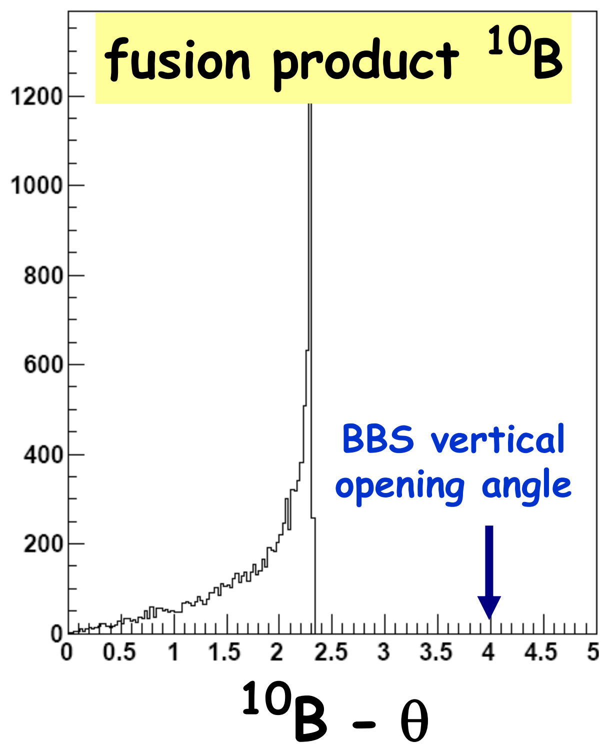
fusion products of 10 – 30 A MeV

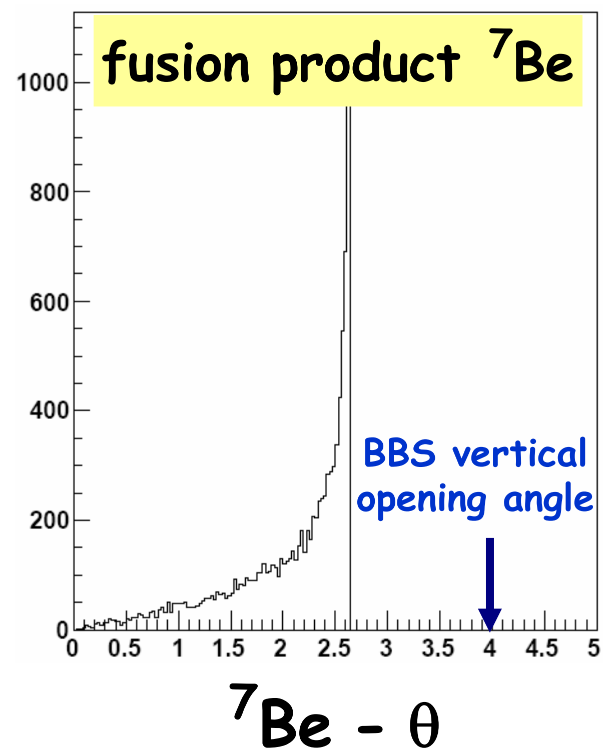
82% coverage of momentum distribution

Momentum resolution :

0.66 ± 0.02 %/det. #

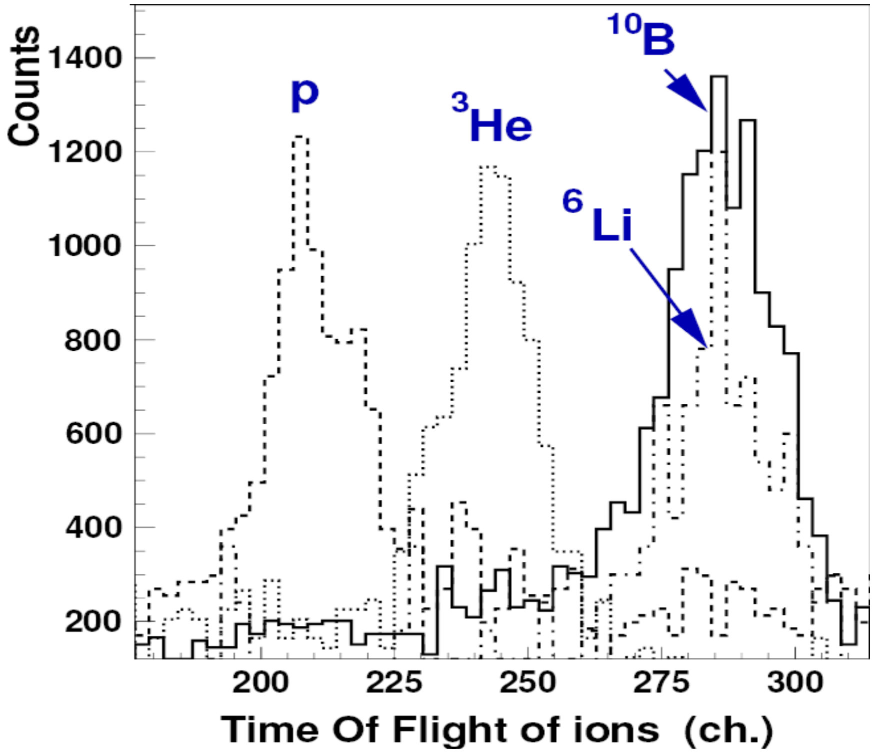
angle acceptance
of fusion products



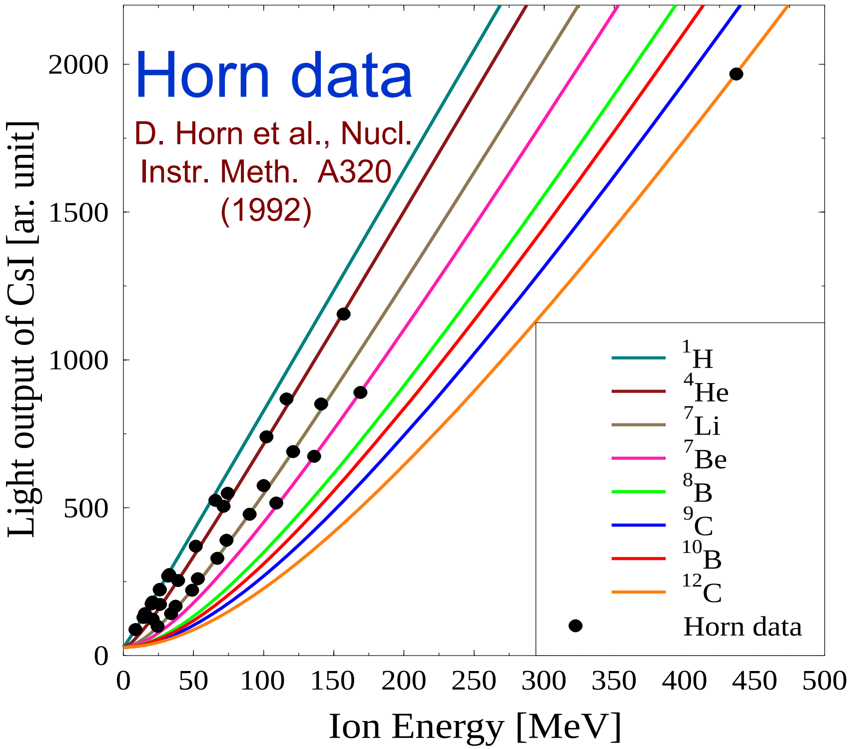


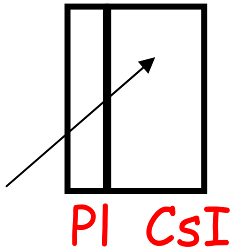
Particle identification in the fusion experimental data

TOF from photon-ion coincidence

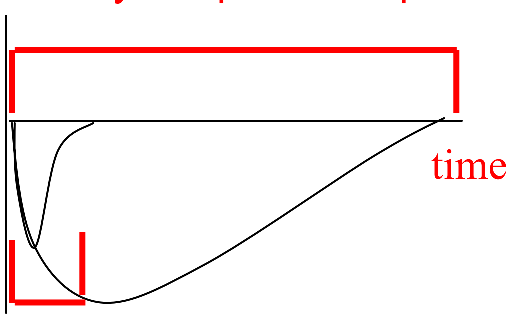


Quenching effects need to be considered



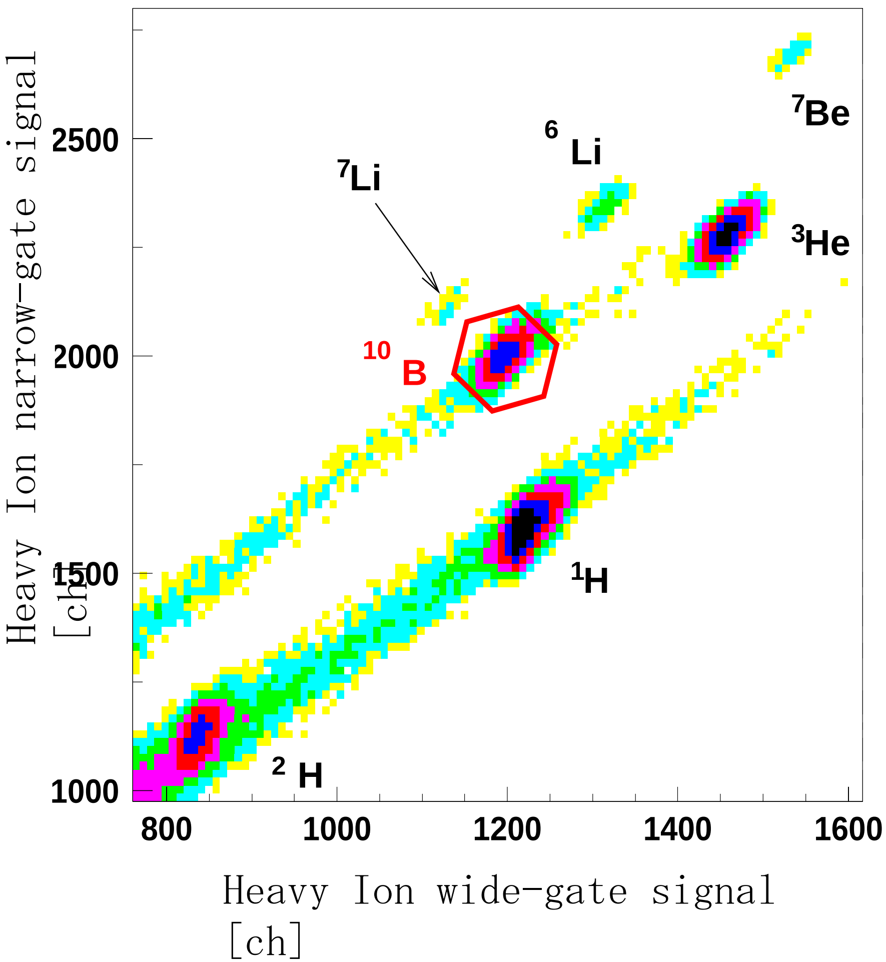


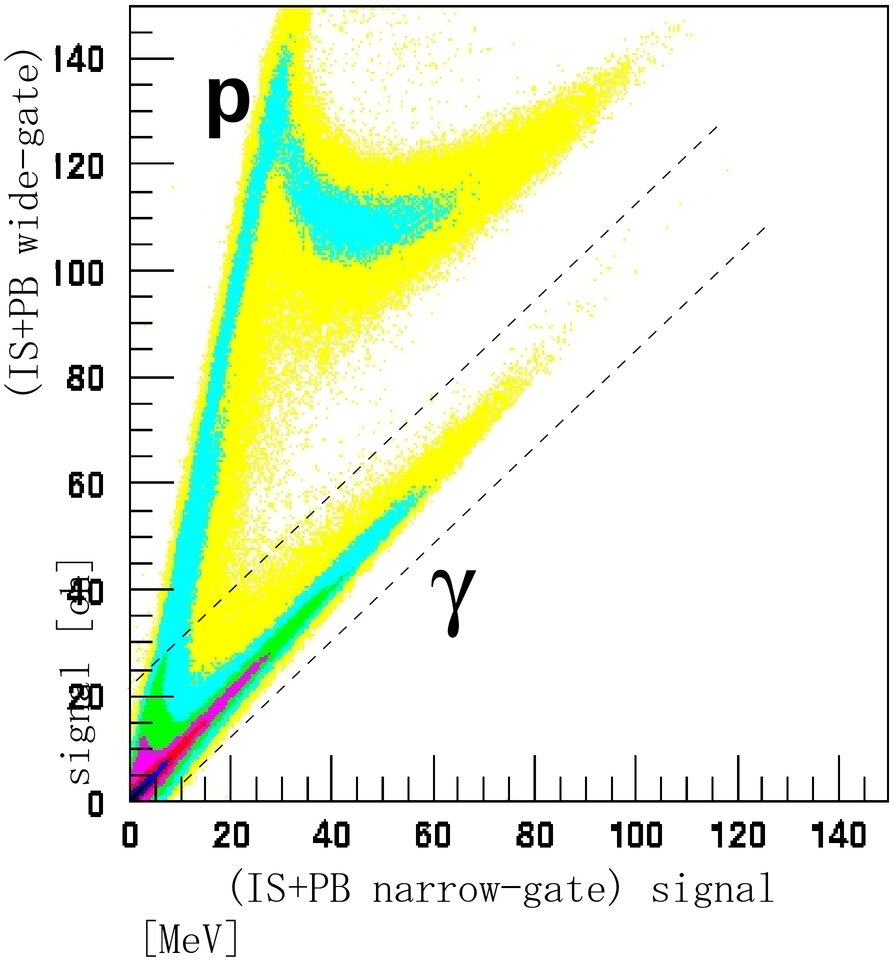
Heavy Ion pulse shape



$$L = a_1\left\{E - a_2 AZ^2 \ln\left|\frac{E + a_2 AZ^2}{a_2 AZ^2}\right|\right\}$$

Particle identification in the fusion experimental data

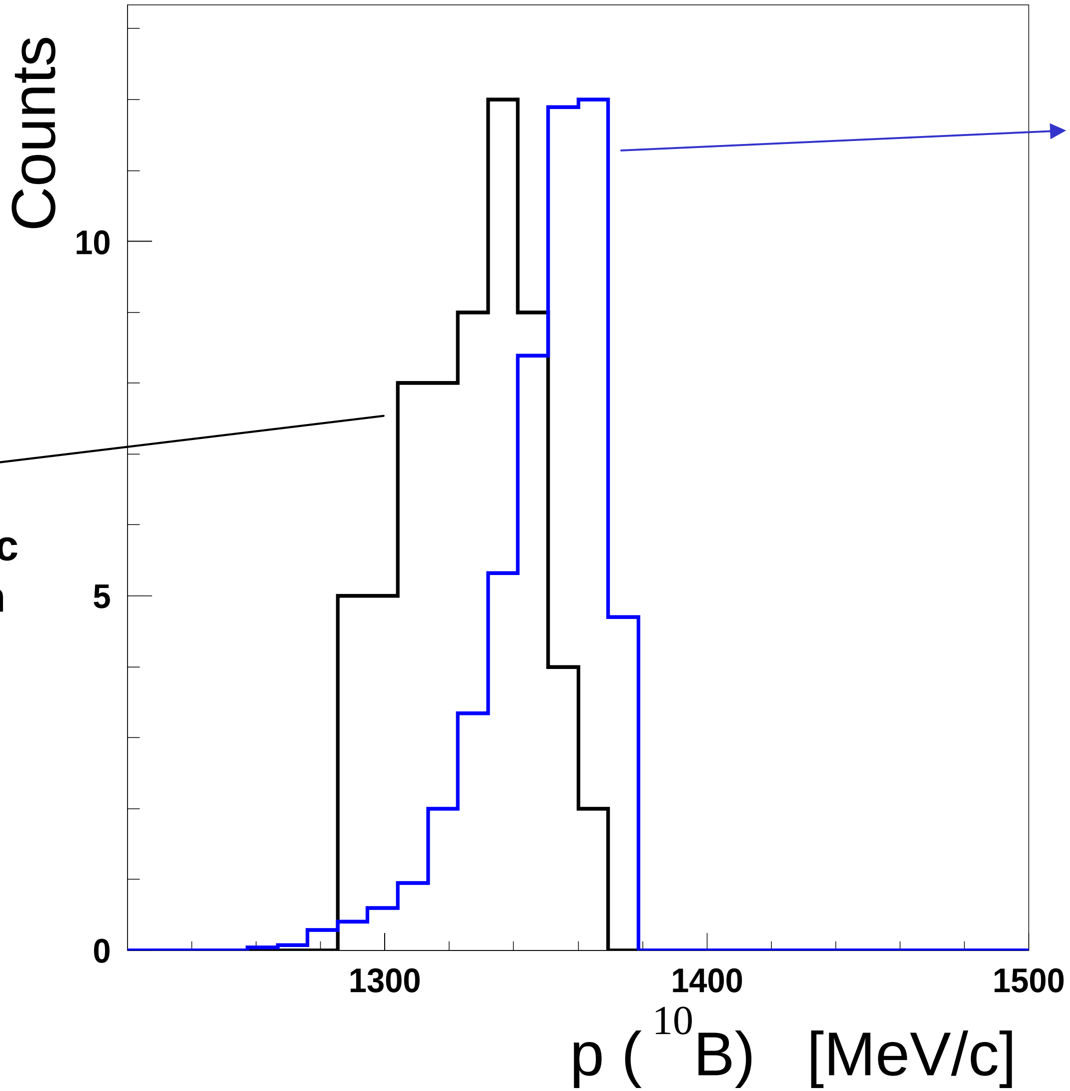




Boron identification from Heavy Ion pulse shape is consistent with time of flight, energy-loss and quenching

Photon identification from the Plastic Ball pulse shape

Momentum distribution of fusion product

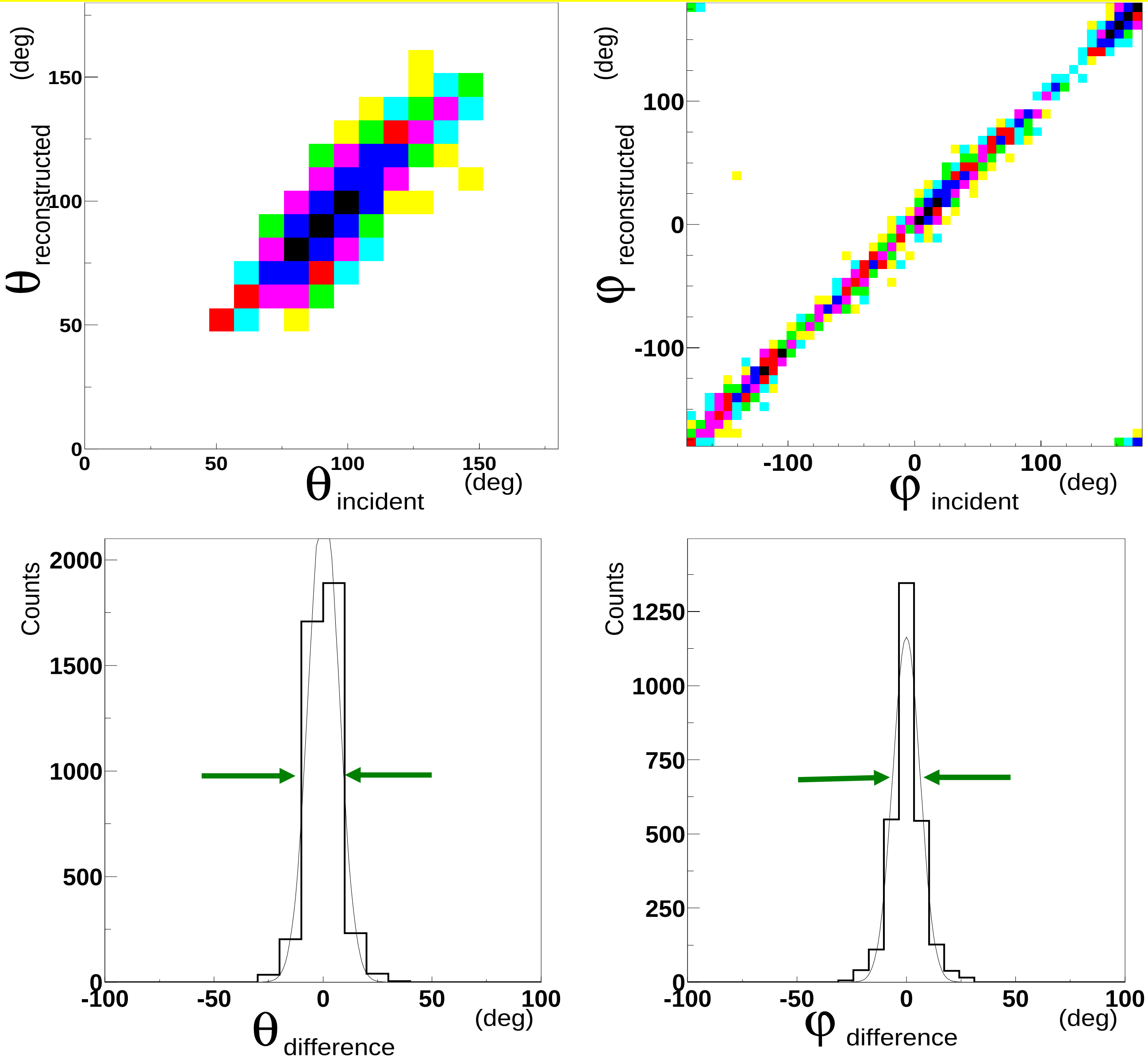


Simulation
Boron-momentum after the target

Data
using BBS magnetic field and Heavy Ion detector position

Data cover the same range as phase space simulation

Angle reconstruction of two-photons in the simulation



Ideal resolution: cluster centroid by energy weighting

Real resolution: angular spread of photon cluster

Two-photon opening angle

$$\cos\theta_{\gamma\gamma} = \sin\theta_{\gamma high}\sin\theta_{\gamma low}\cos\varphi_{\gamma high}\cos\varphi_{\gamma low} + \sin\theta_{\gamma high}\sin\theta_{\gamma low}\sin\varphi_{\gamma high}\sin\varphi_{\gamma low} + \cos\theta_{\gamma high}\cos\theta_{\gamma low}$$

$\theta_{\gamma\gamma}$: Two-photon opening angle

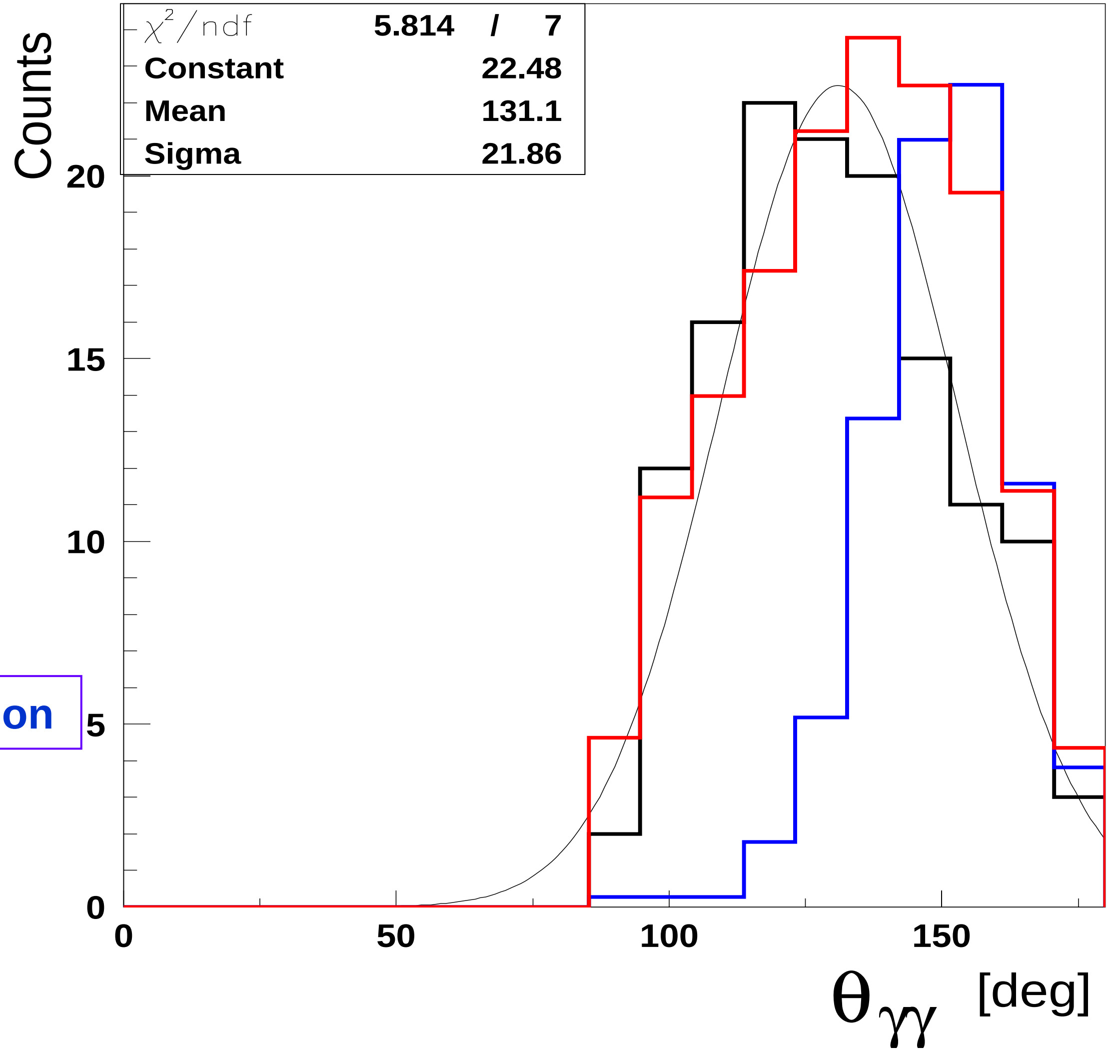
$\theta_{\gamma high\ (low)}$ and $\varphi_{\gamma high\ (low)}$: zenith and azimuth angles of photon with higher (lower) energy

Data

Simulation

Simulation using the real resolution of angle determination

Data agrees with realistic simulation



Two-photon invariant mass

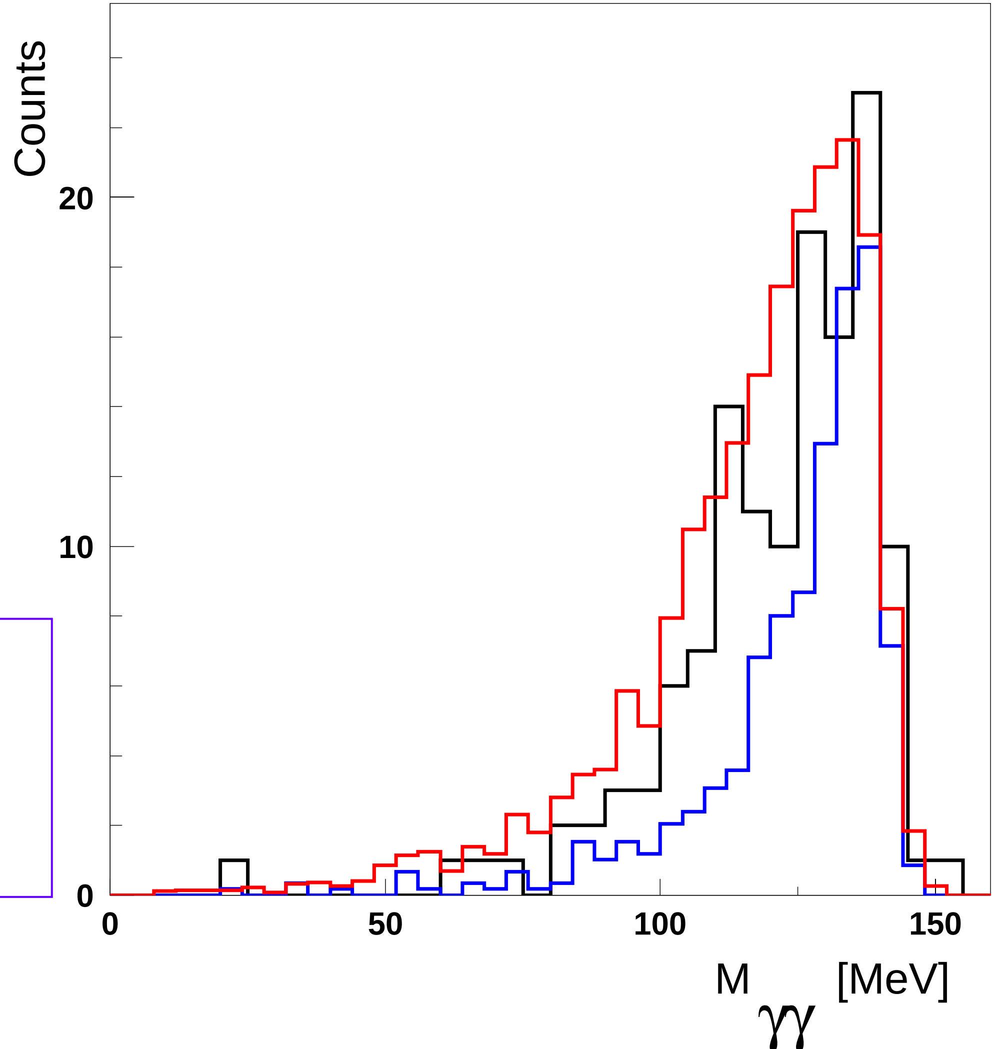
$$M_{\gamma\gamma} = \sqrt{2E_{\gamma high}E_{\gamma low}(1-\cos(\theta_{\gamma\gamma}))}$$

$\theta_{\gamma\gamma}$: Two photon opening angle, $E_{\gamma high\ (low)}$: higher (lower) photon energy

Data

Simulation

Simulation using the real resolution of angle determination

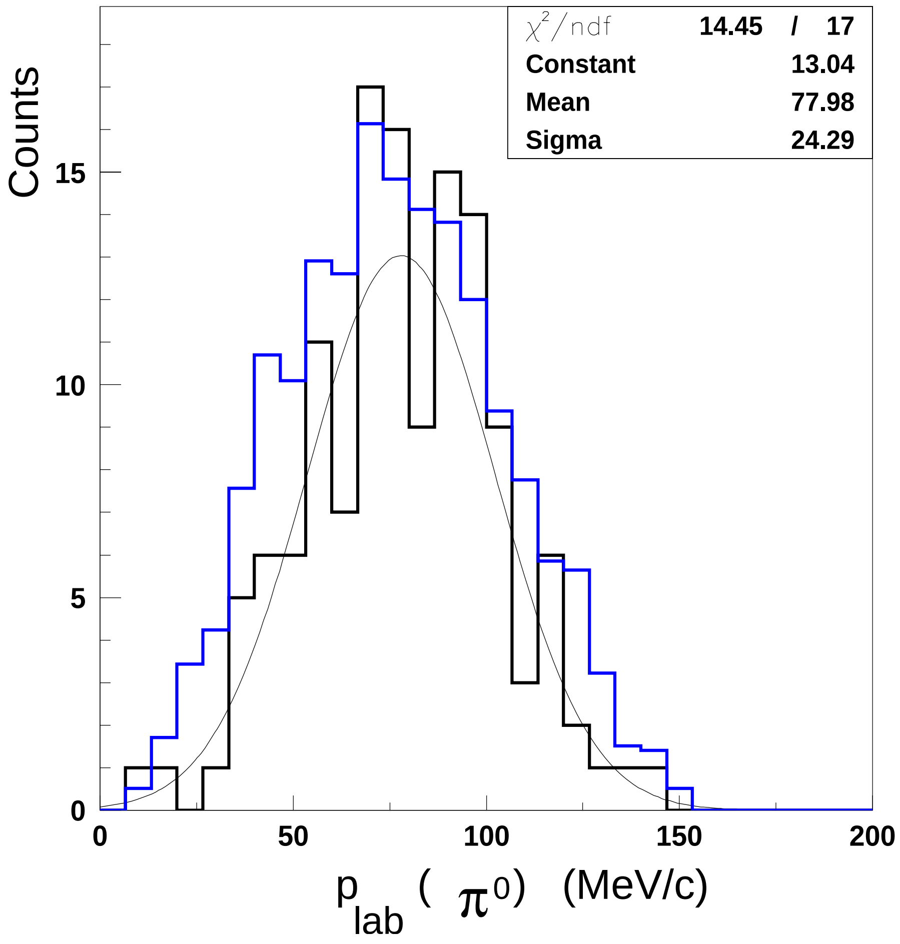


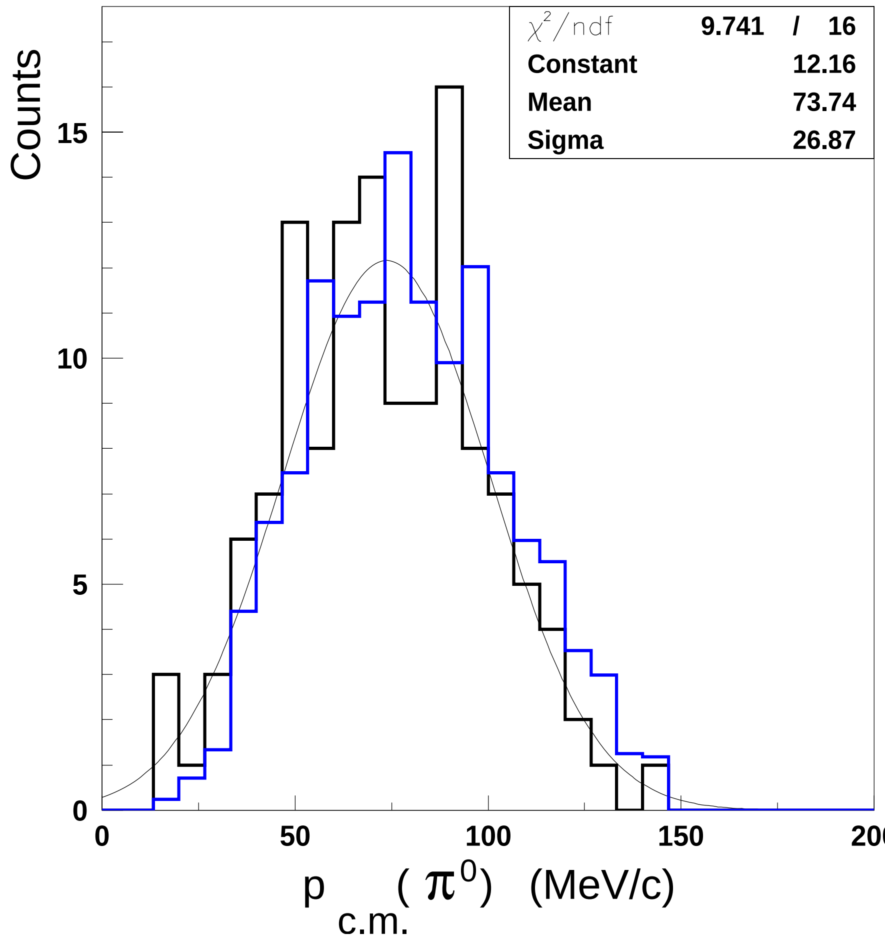
Simulated two-photon invariant mass using the real resolution of angle determination behaves similar to the result of data.

Pion-momentum distribution – Not normalized

Data

Simulation using the real resolution of angle determination





Good agreement between data and simulation using real resolution of opening angle distribution

Pion-angular distribution

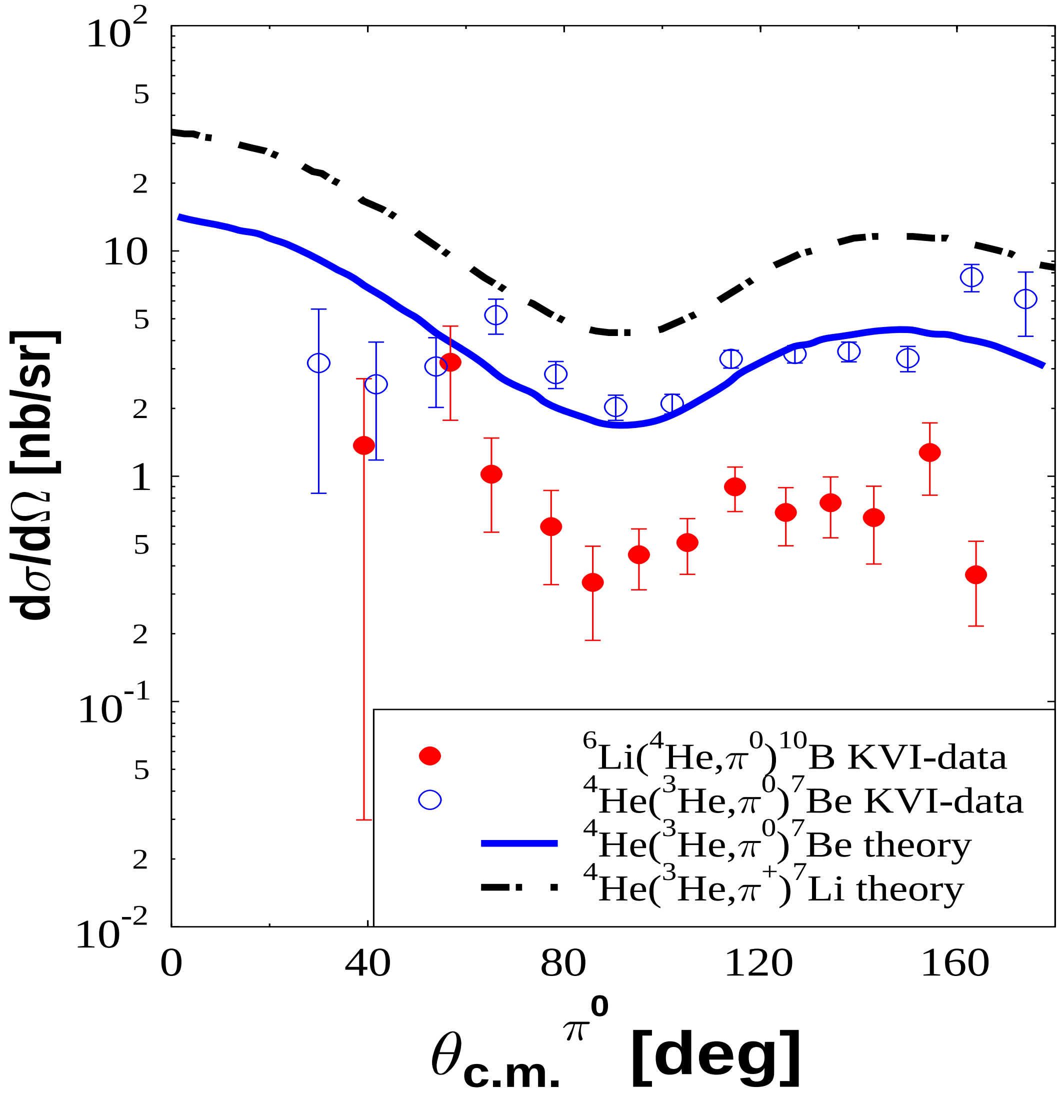
We observed:

- **Full angular distribution**
- **Magnitude of the cross section : consistent with clustering correlations**
- **Shape of the cross section: Double peak structure**

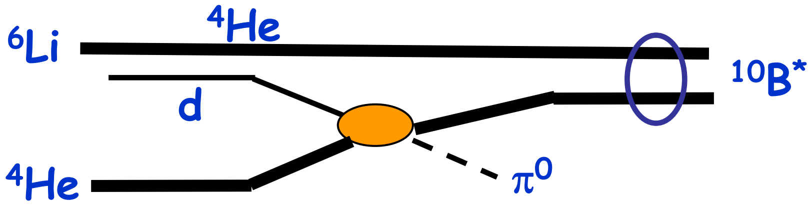
We further intend to study:

- **Local imaginary potential**
- **Two-body interactions**

Calculations need to be done for $^4He+^6Li \longrightarrow \pi^0+^{10}B$ reaction



Conclusion



- Pions have been produced at subthreshold energies in light ion collisions
- Tow pionic fusion experiments have been done at KVI
- Almost full angular distribution has been obtained
- The general behaviour of pionic fusion cross section is as predicted by the cluster model for lighter target-projectile combinations
- Theoretical analysis are ongoing to determine :

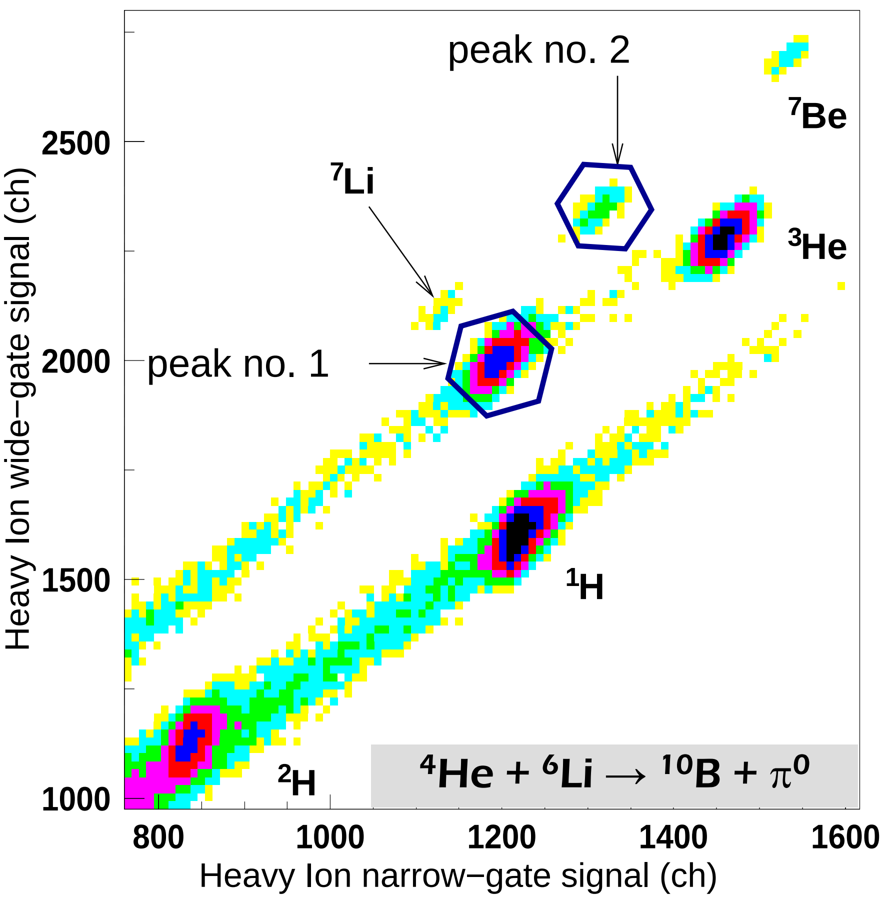
  Cluster potential
  Two-body interactions

Thanks to our collaborators

P. Dendooven, M. Eslami Kalantari, N. Kalantar, H. Mardanpur, J. Messchendorp, H. Moini A. Ramazani, S. Shende, E. Stephan

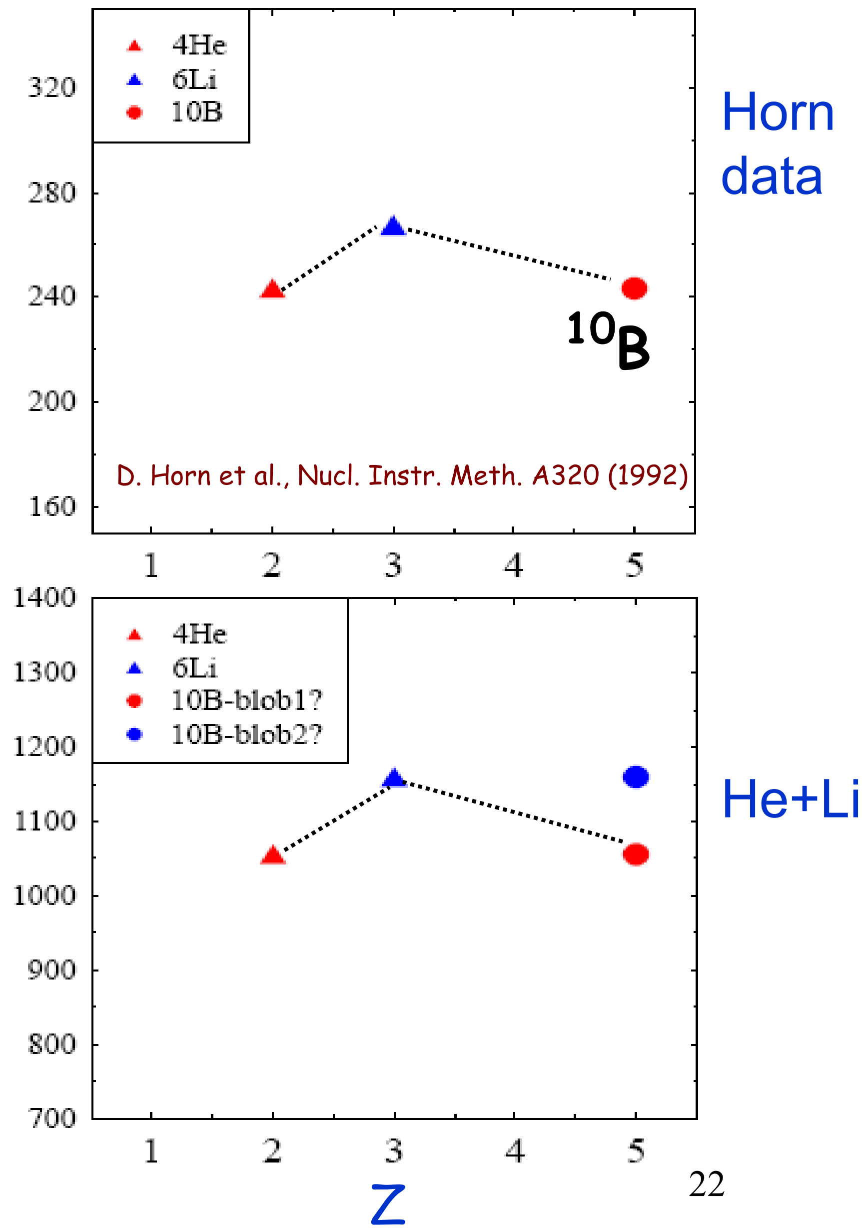
Particle identification in the fusion experimental data

TOF : peaks 1 & 2 can be Boron



Use energy information:
Strong quenching effects

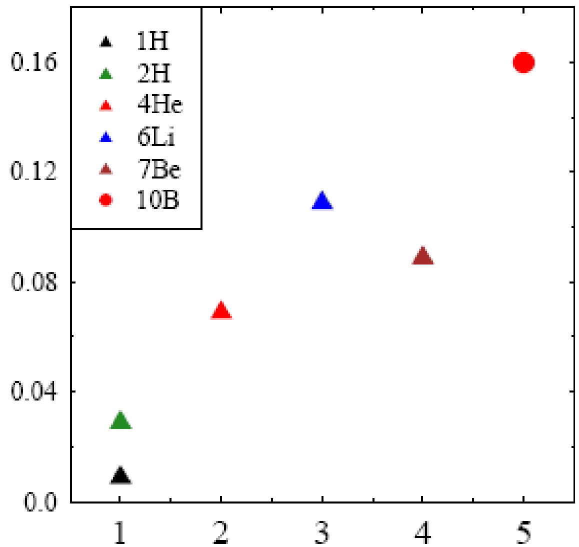
CsI Light output



Using Horn setup parameters for particle identification

Plastic Light output

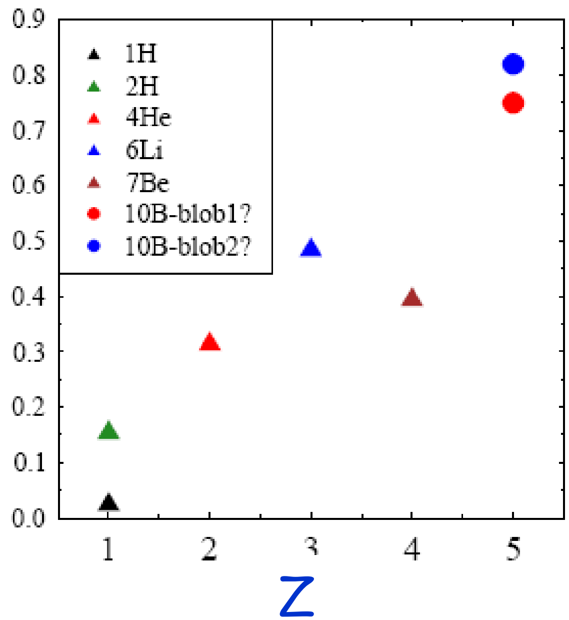
Horn



$$L_{pl} = a_0 + a_1(E_{pl} - a_2 A z^2 \ln(1 + \frac{E}{a_2 A z^2}))$$

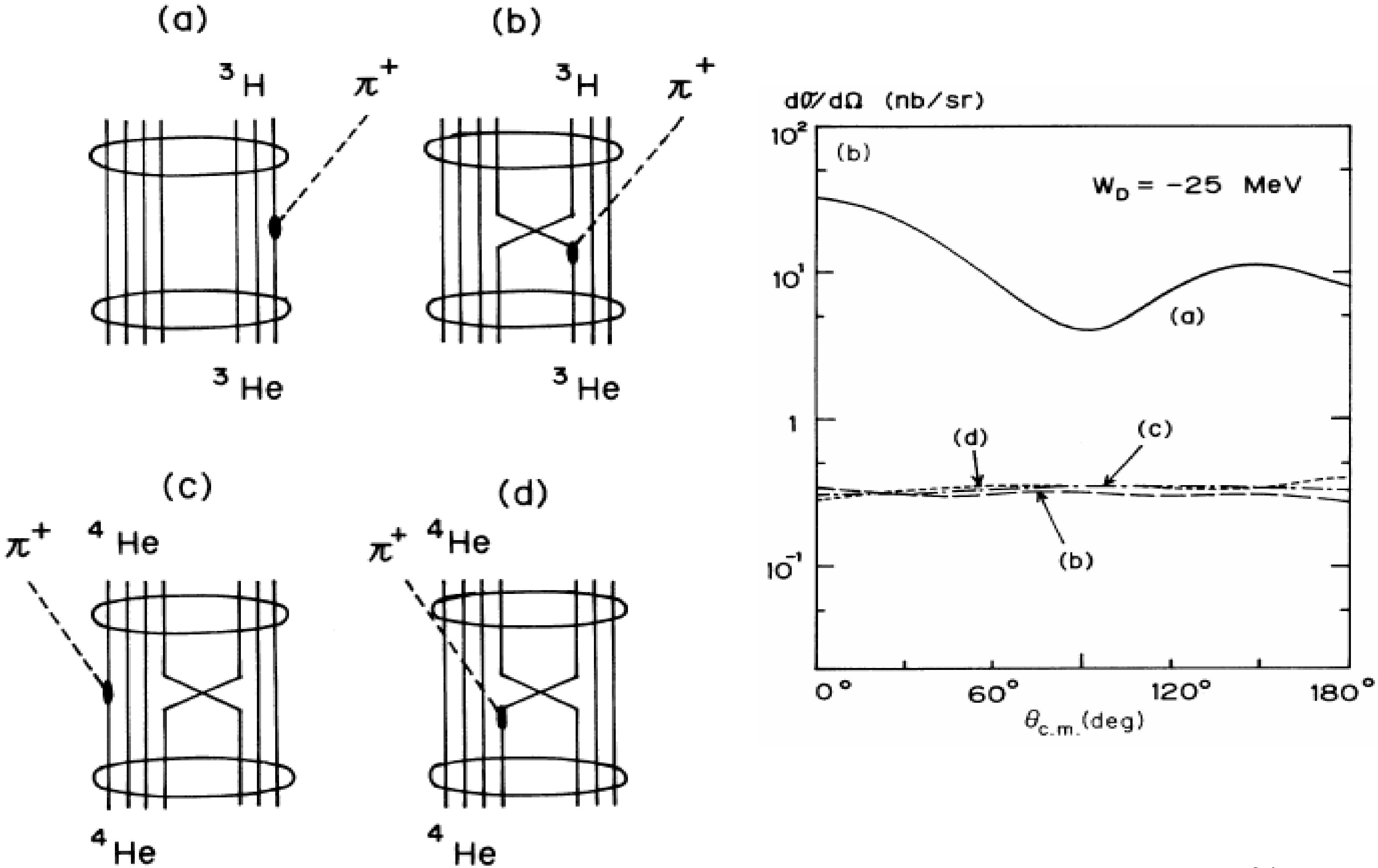
Horn setup parameters

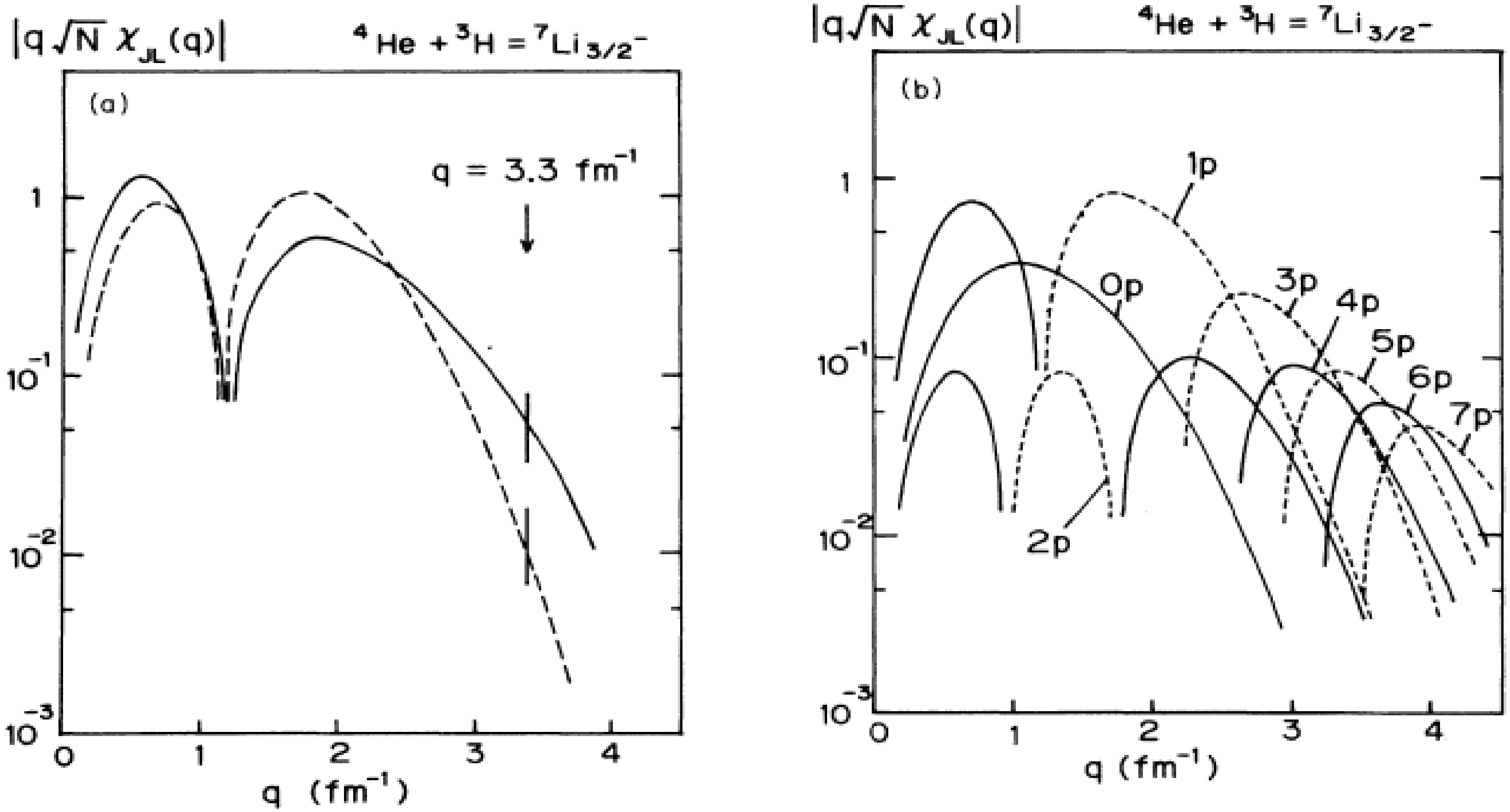
He+Li



$$L_{pl} = L_{wide} - L_{wide}\left(\frac{L_{CsI}}{L_{CsI} + L_{pl}}\right)_{Horn}$$

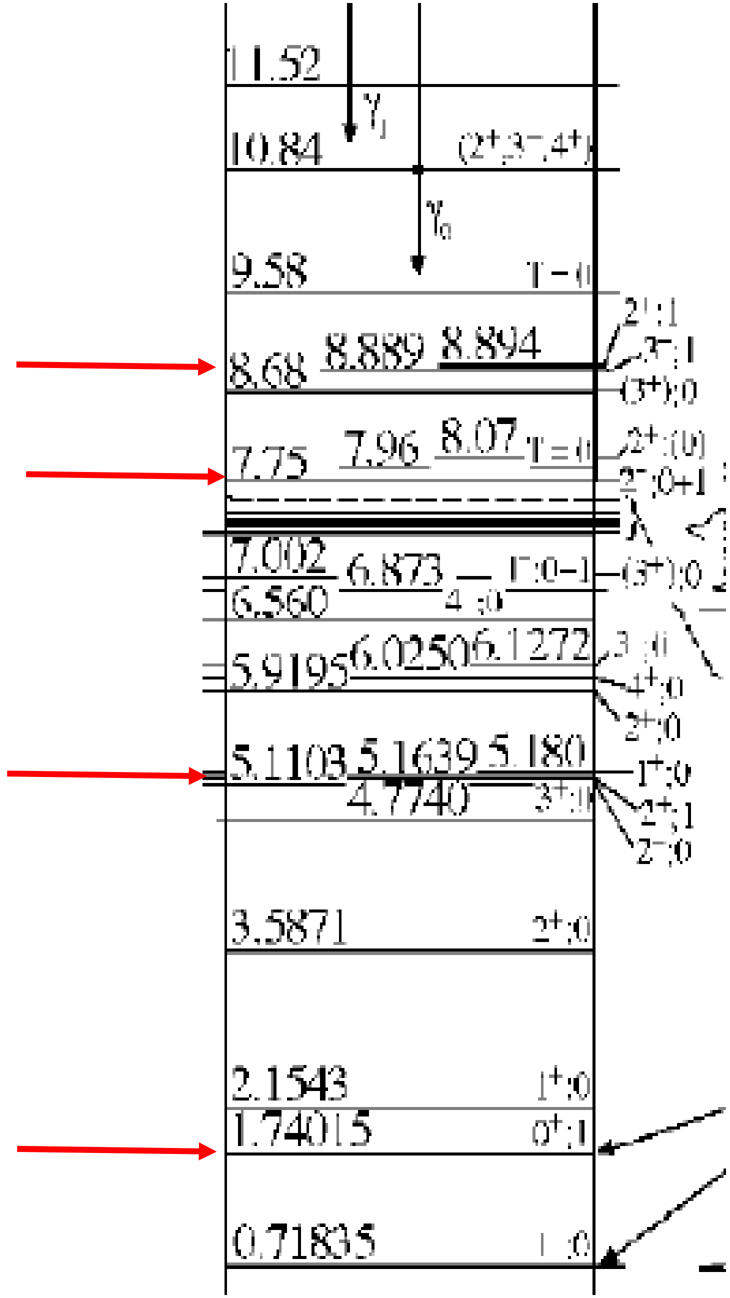
$^{4}He(^{3}He,\pi^{+})^{7}Li$



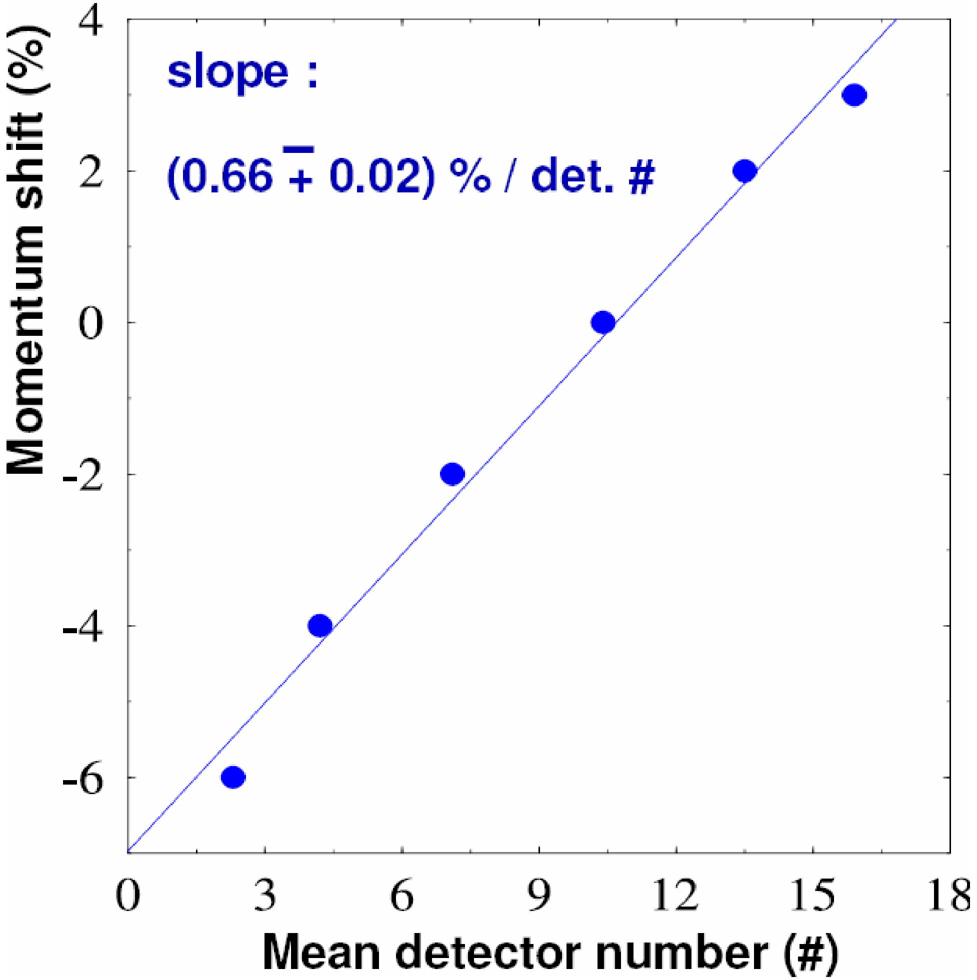


$$\langle \xi_\alpha \xi_\tau \mathbf{r} \,|\, JM \rangle = \left[\frac{4!3!}{7!} \right]^{1/2} A_{\alpha\tau} \{ [\phi_\alpha(\xi_\alpha)\phi_\tau^{(1/2)}(\xi_\tau) \otimes i^L Y^{(L)}(\hat{\mathbf{r}})]_M^{(J)} \chi_{JL}(r) \} \,,$$

$$\int [H_{\mathrm{RGM}}(\mathbf{r},\mathbf{r}') + iW_D(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}')]\chi_{JL}(\mathbf{r}')d\mathbf{r}' = E \int N_{\mathrm{RGM}}(\mathbf{r},\mathbf{r}')\chi_{JL}(\mathbf{r}')d\mathbf{r}'$$


11.52
10.84
(2+,3−,4+)
9.58
T=0
2+;1
8.68
8.889
8.894
(3+);0
7.75
7.96
8.07
T=0
2+;(0)
2−;0+1
7.002
6.873
(3+);0
6.560
5.9195
6.0250
6.1272
4+;0
2+;0
5.1103
5.1639
5.180
1+;0
4.7740
2+;1
2−;0
3.5871
2+;0
2.1543
1+;0
1.74015
0+;1
0.71835

HI detector commissioning



Systematic rigidity change of elastically scattered ions (C, Ne, O…)

Calibration of momentum-position achieved