Search for η bound states in nuclei

Hartmut Machner
(FZ Jülich & University Duisburg-Essen)
GEM collaboration

Outline

- Why are η-mesic nuclei interesting?
- Search via production experiments
- Search via Two Body Final State Interaction (FSI)
    - $p+d \rightarrow \eta + {}^3He$
    - tensor pol. $d+d \rightarrow \eta + \alpha$
    - $p+{}^6Li \rightarrow \eta + {}^7Be$

Heuristic approach

Heuristic approach

- A rather large s-wave η-nucleon scattering length lead to the idea of bound η-nucleus systems.

Heuristic approach

- A rather large s-wave η-nucleon scattering length lead to the idea of bound η-nucleus systems.
- This would be a strong bound system, contrary to pionic atoms (Coulomb bound).

Heuristic approach

- A rather large s-wave η-nucleon scattering length lead to the idea of bound η-nucleus systems.
- This would be a strong bound system, contrary to pionic atoms (Coulomb bound).
- How to observe?

Heuristic approach

- A rather large s-wave η-nucleon scattering length lead to the idea of bound η-nucleus systems.
- This would be a strong bound system, contrary to pionic atoms (Coulomb bound).
- How to observe?
- Recoil free transfer reactions like in hyper-nuclei and in pionic atoms cases.

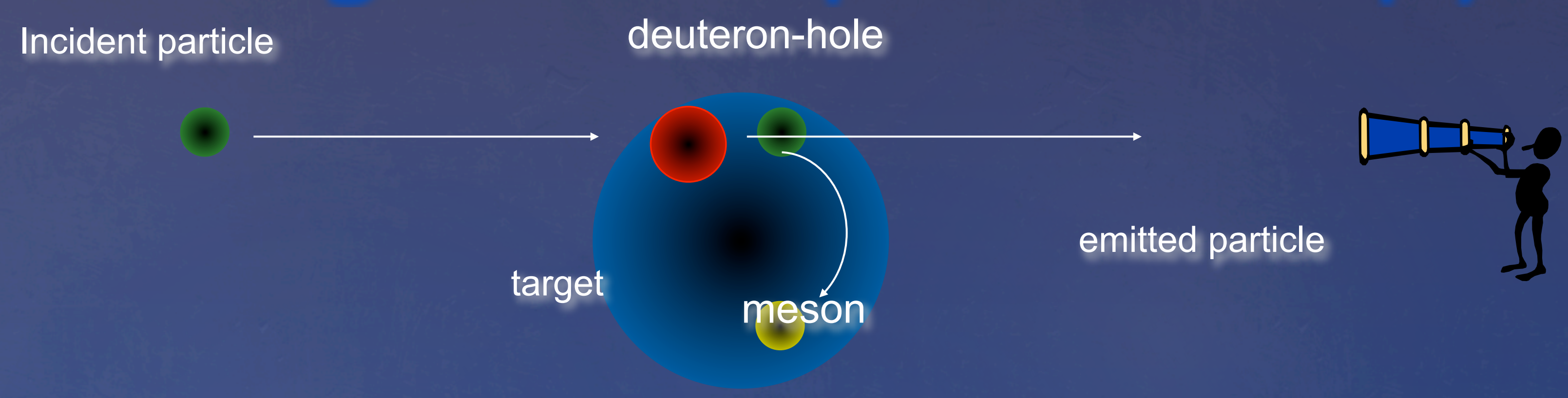
Heuristic approach

- A rather large s-wave η-nucleon scattering length lead to the idea of bound η-nucleus systems.
- This would be a strong bound system, contrary to pionic atoms (Coulomb bound).
- How to observe?
- Recoil free transfer reactions like in hyper-nuclei and in pionic atoms cases.
- Nuclear projectiles:
  - d+A®^{3}He+[(A-1)⊗η]:
    - Break up protons have same magnetic rigidity as ^{3}He’s. ☹
    - Large cross section. ☺
  - p+A®^{3}He+[(A-2)⊗η]:
    - Magnetic rigidity of beam particles differ by a factor of two from ^{3}He’s. ☺
    - Small cross section. ☹

Missing mass spectroscopy

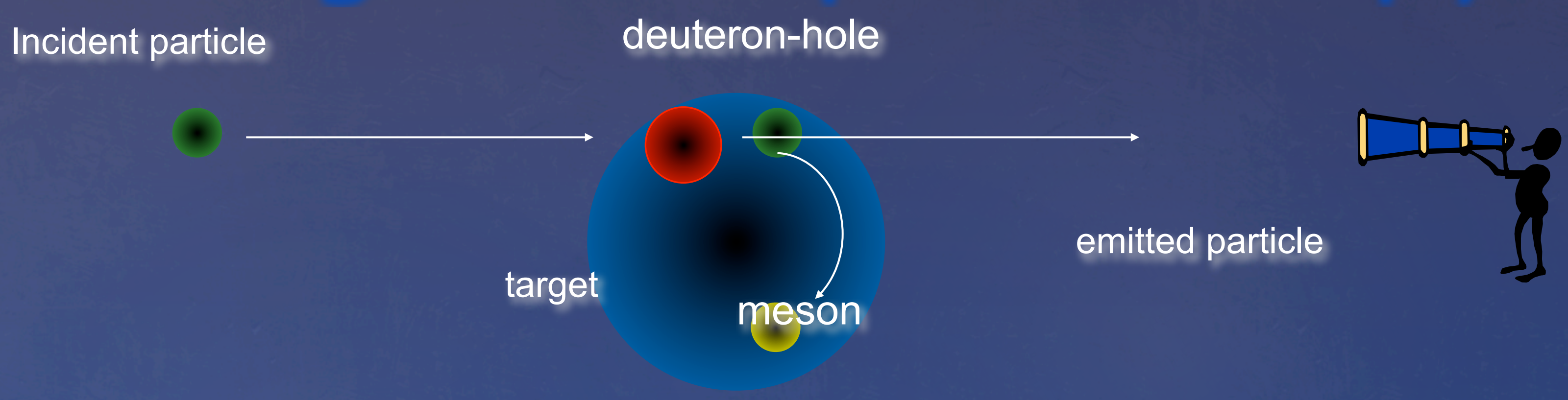
Missing mass spectroscopy

Missing mass spectroscopy

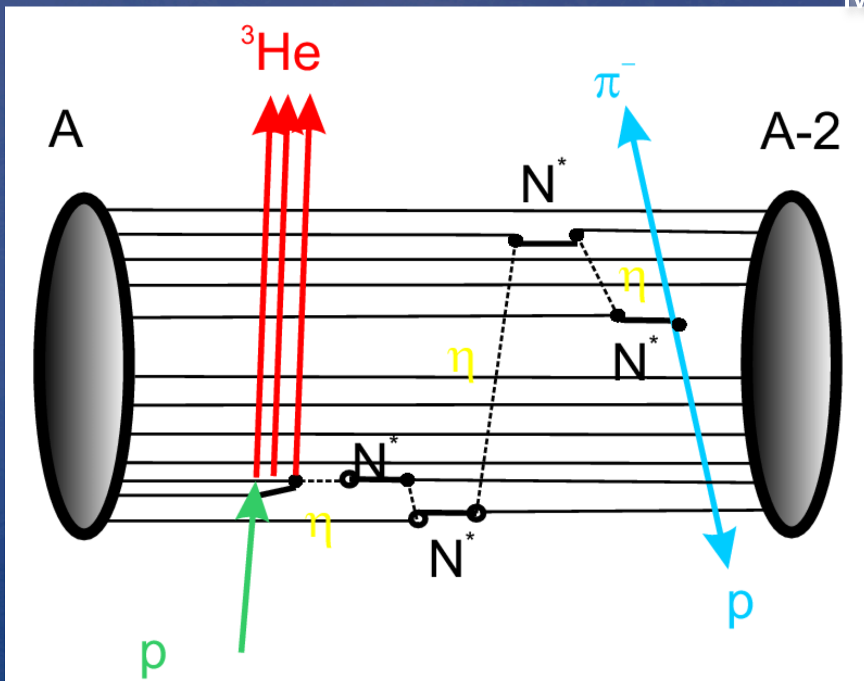


Momentum transfers for η-mesic nuclei formation

Missing mass spectroscopy

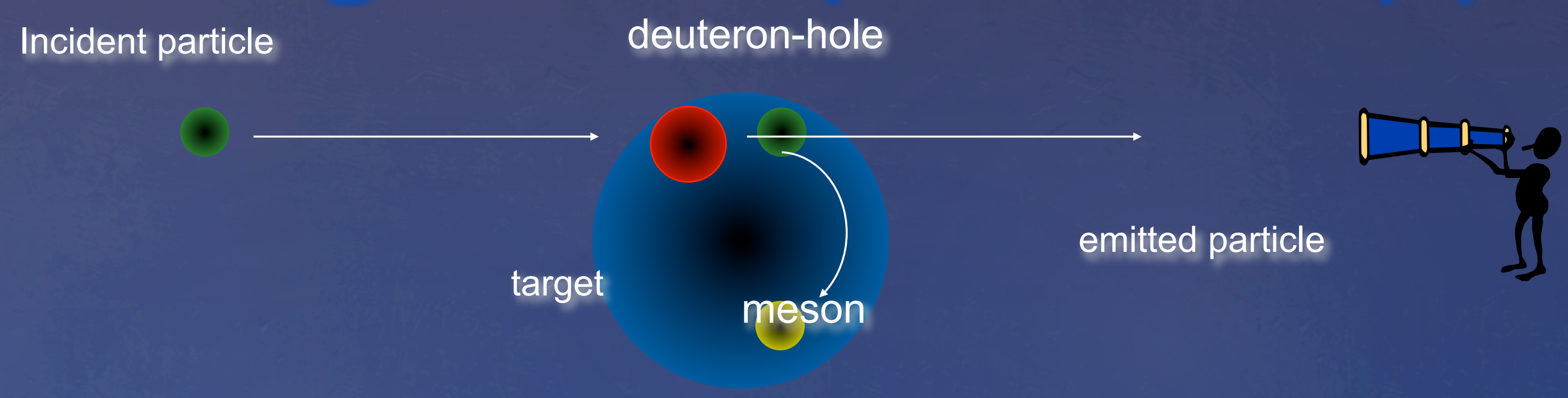


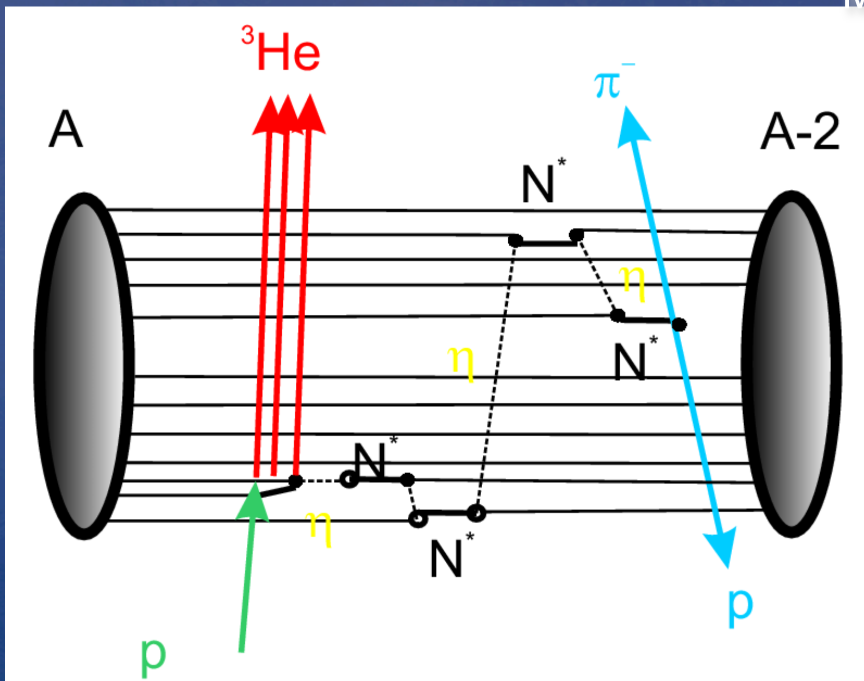
Momentum transfers for η-mesic nuclei formation



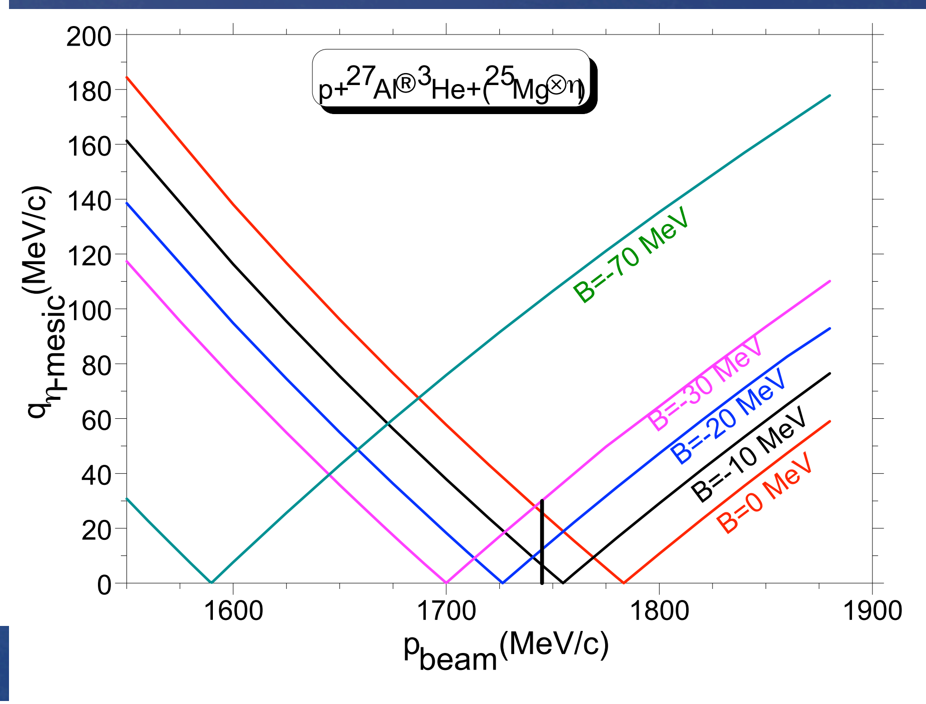
10 Williamsburg [redacted]

Missing mass spectroscopy

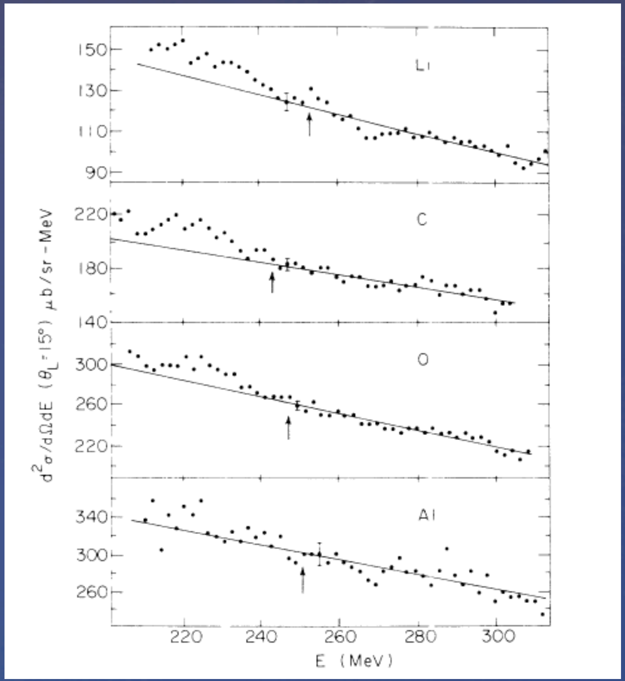




Momentum transfers for η-mesic nuclei formation



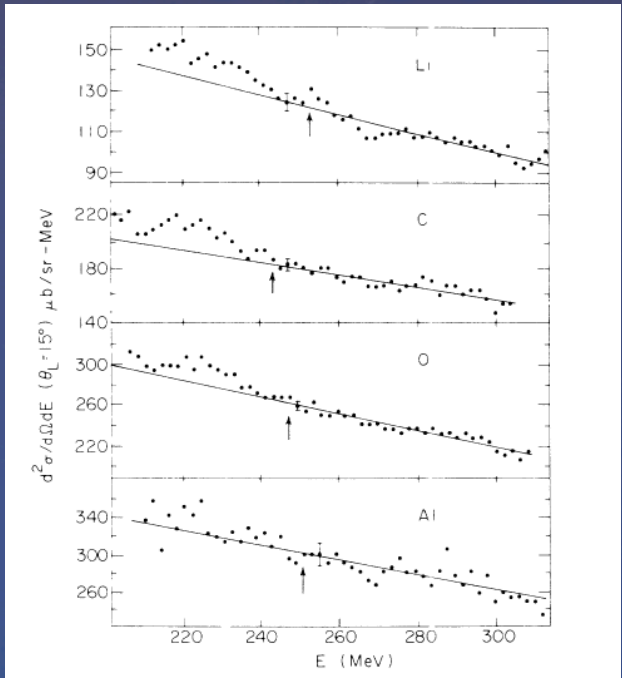
Previous searches



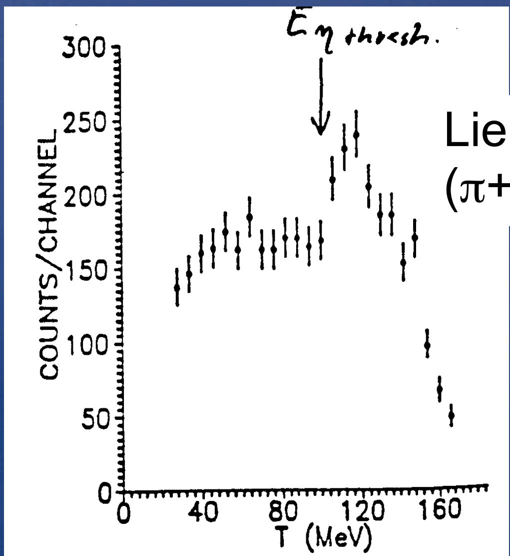
Chrien et al. PRL
- q=200 MeV/c
- inclusive

H.M.

Previous searches

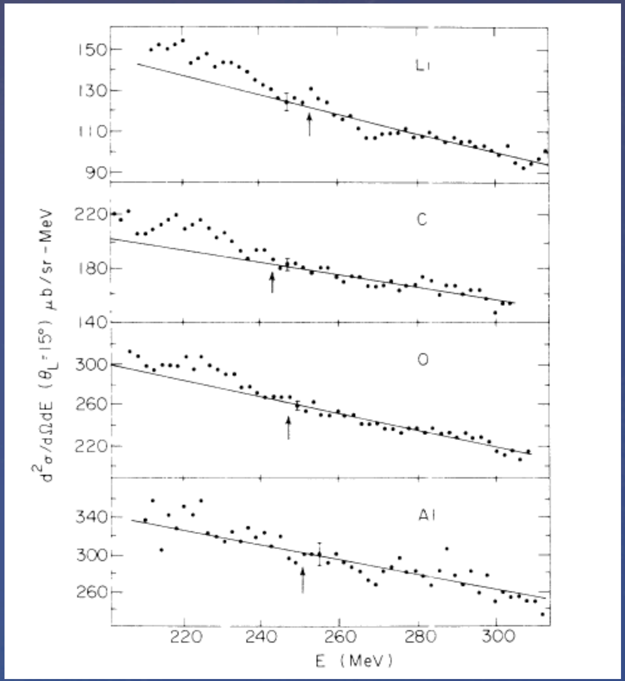


Chrien et al. PRL
- q=200 MeV/c
- inclusive

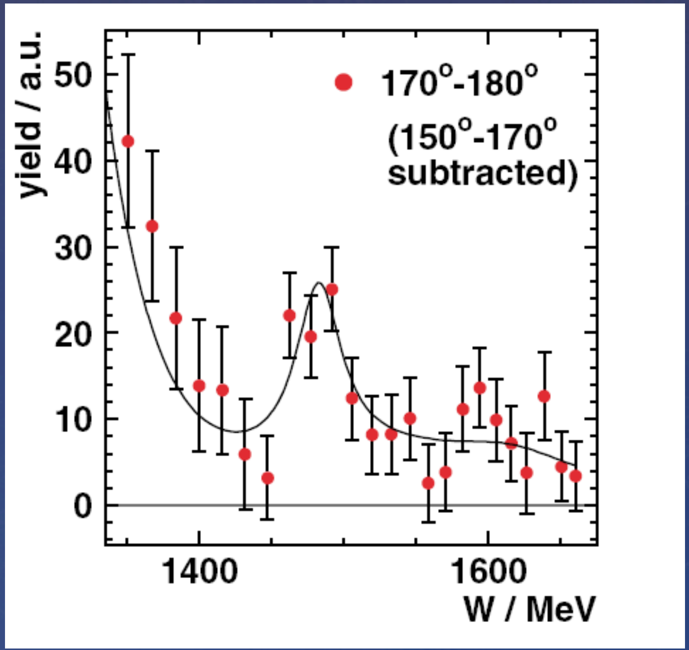


Lieb et al.
(π+,p)

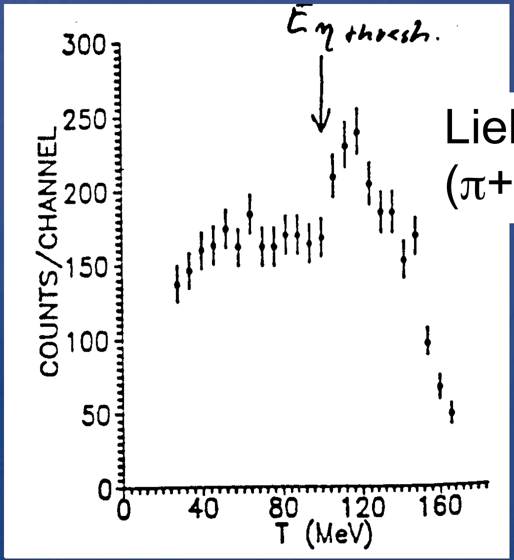
Previous searches



Chrien et al. PRL
• q=200 MeV/c
• inclusive



Pfeiffer et al. PRL: $\gamma+^3He\rightarrow\pi^0+p+X$, 3.5$\sigma$

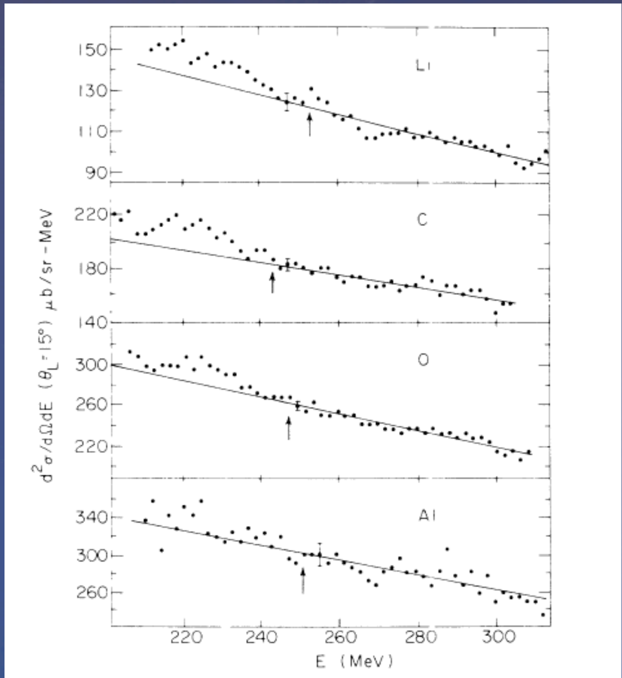


Lieb et al.
(π+,p)

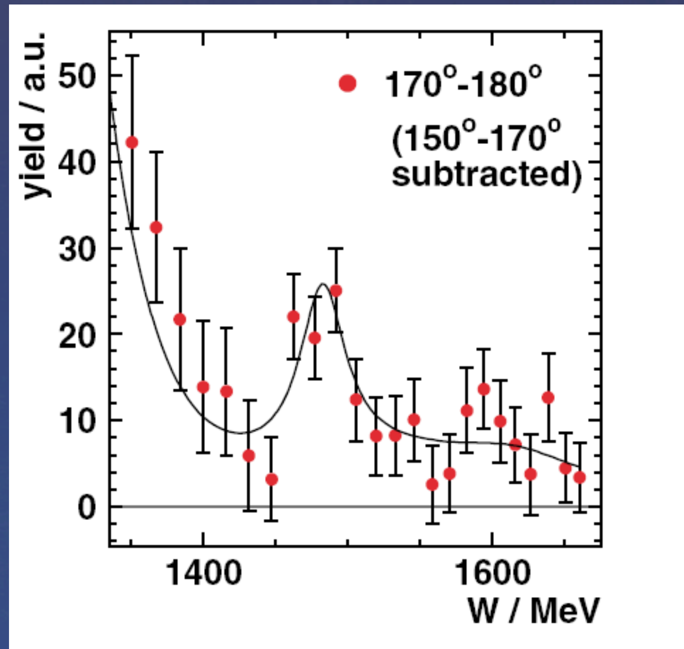
H.M.

piątek, 18 czerwca 2010

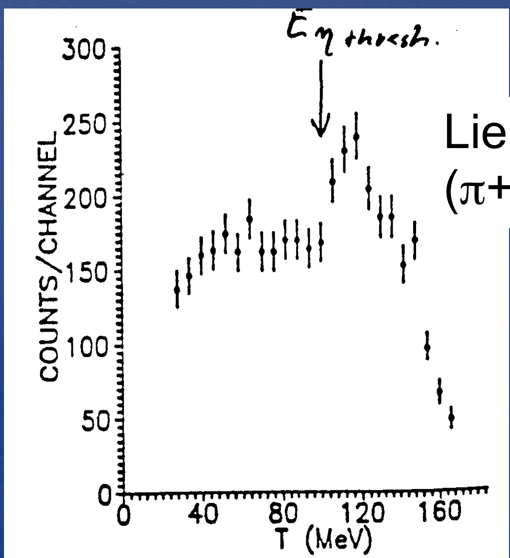
Previous searches



Chrien et al. PRL
- q=200 MeV/c
- inclusive



Pfeiffer et al. PRL: $\gamma+{}^3He \rightarrow \pi^0+p+X$, 3.5$\sigma$



Lieb et al.
(π+,p)

Sokol et al.: $\gamma+{}^{12}C \rightarrow \pi^+ + n + X$; Both ejectiles are anti-correlated;

$\langle E_\pi \rangle$=300 MeV, $\langle E_n \rangle$=100 MeV

H.M.

Reactions

step I:

$$p + {}^{27}Al \longrightarrow {}^{3}He + {}^{25}Mg \otimes \eta$$

step II:

$$\eta + n \text{ ® } N^{0*}(1535) \text{ ® } \eta + n$$

$$\text{® } \pi^{-} + p$$

^{3}He in BIG KARL, carries the full beam momentum

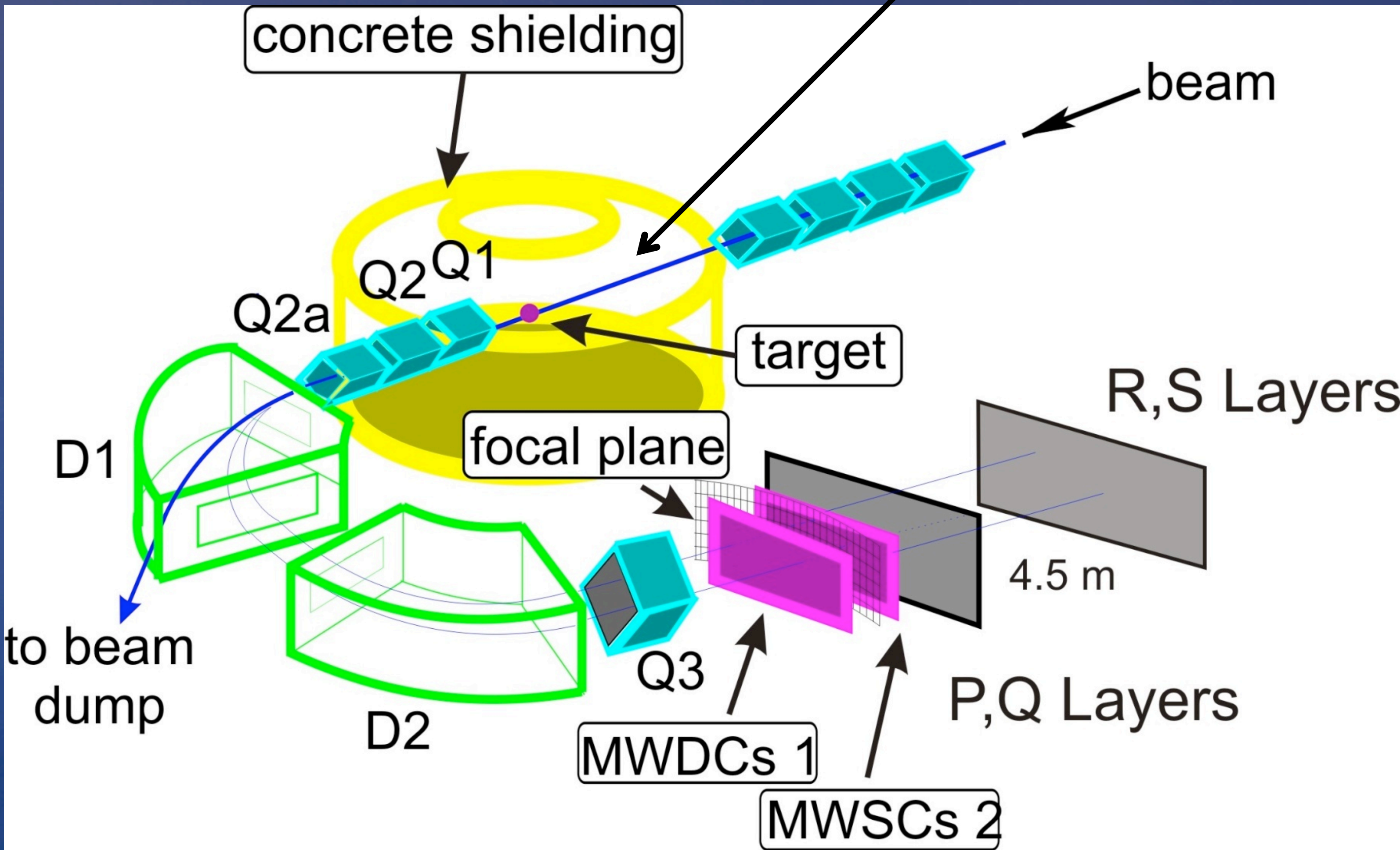
π-p almost back to back in ENSTAR

3-fold coincidence + 3 more constraints!

Big Karl &

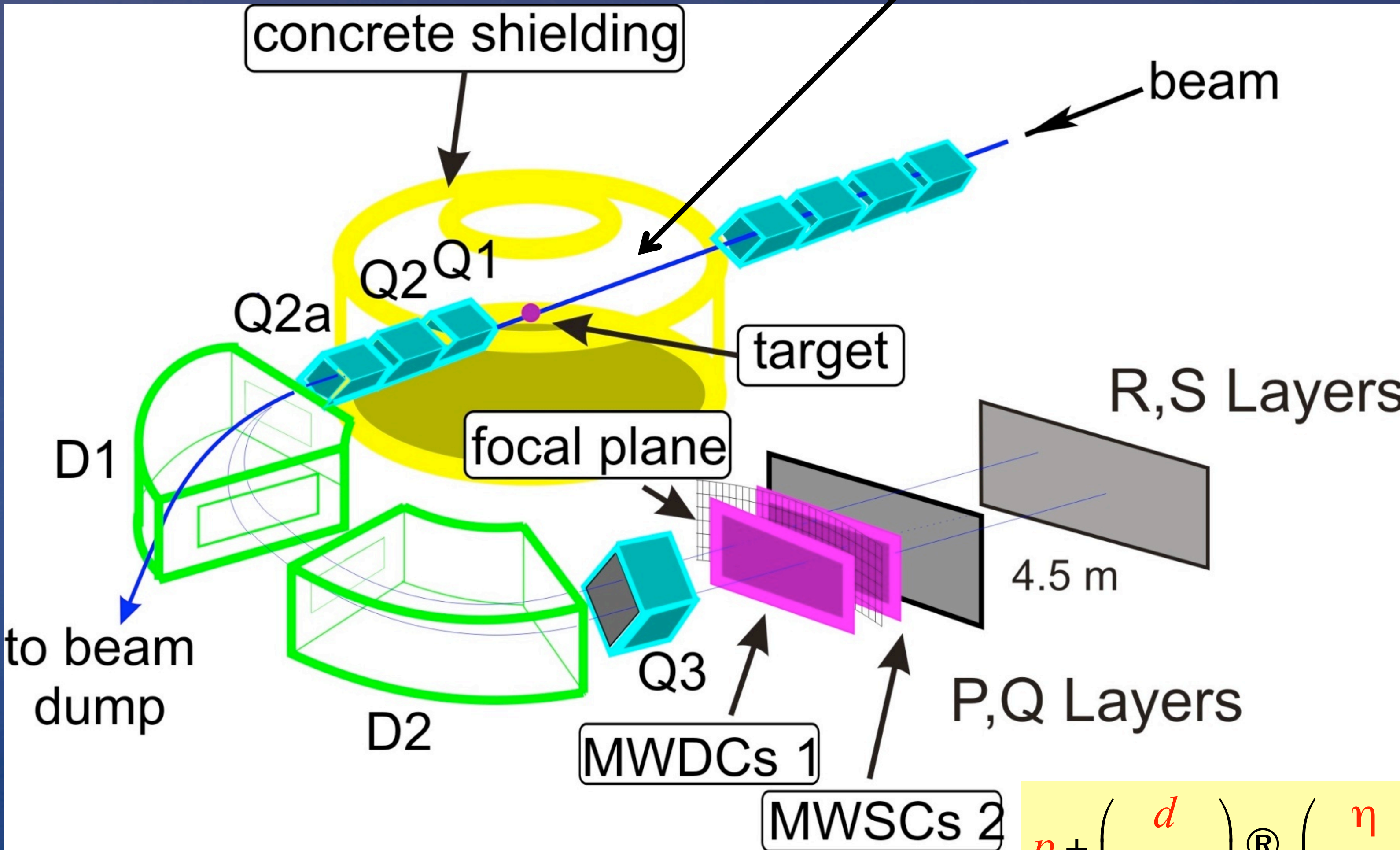
ENSTAR

Big Karl & ENSTAR



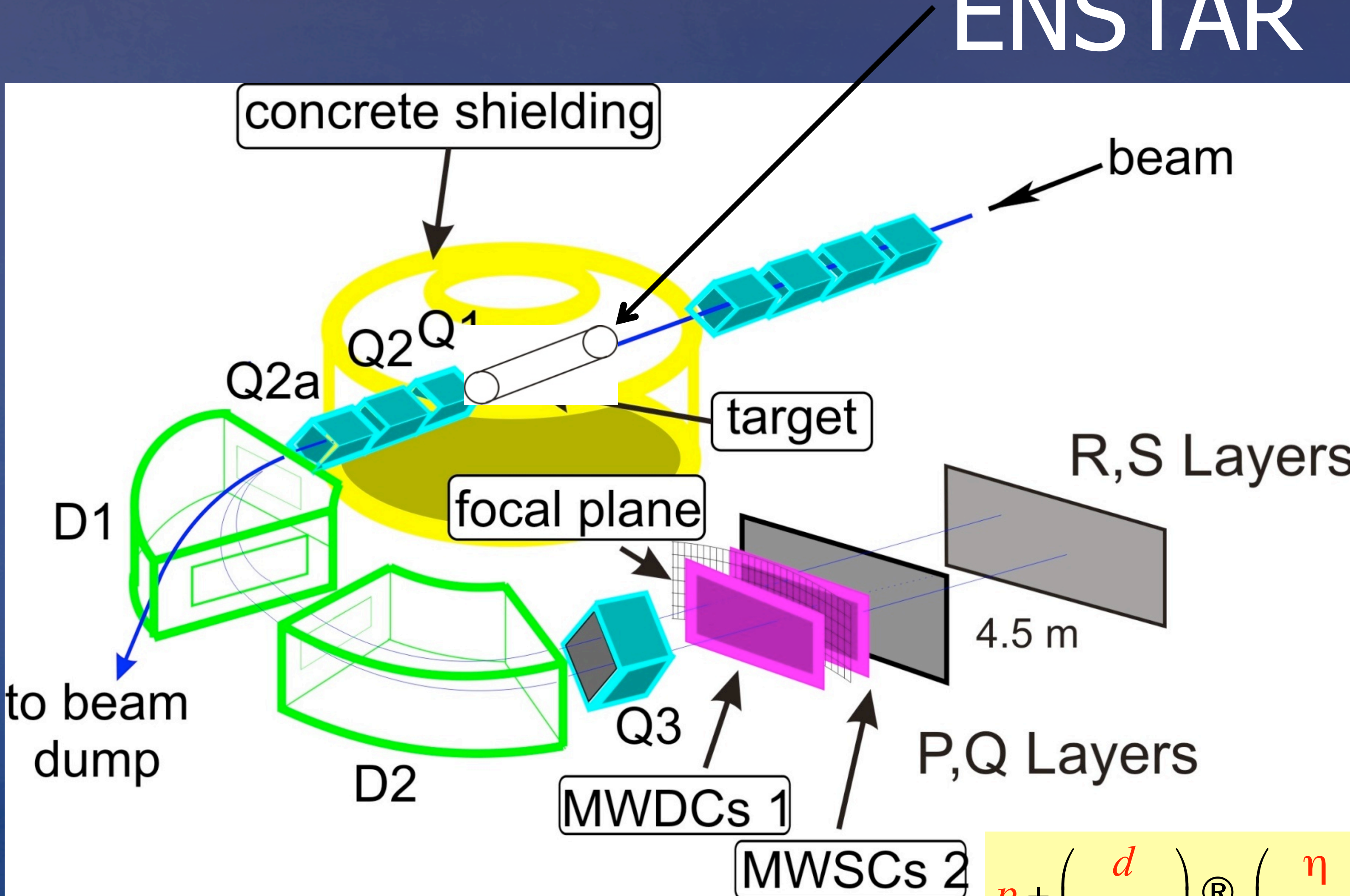
Big Karl &

ENSTAR



$$p + \begin{pmatrix} d \\ A-2 \end{pmatrix} \circledR \begin{pmatrix} \eta \\ A-2 \end{pmatrix} + {}^{3}He$$

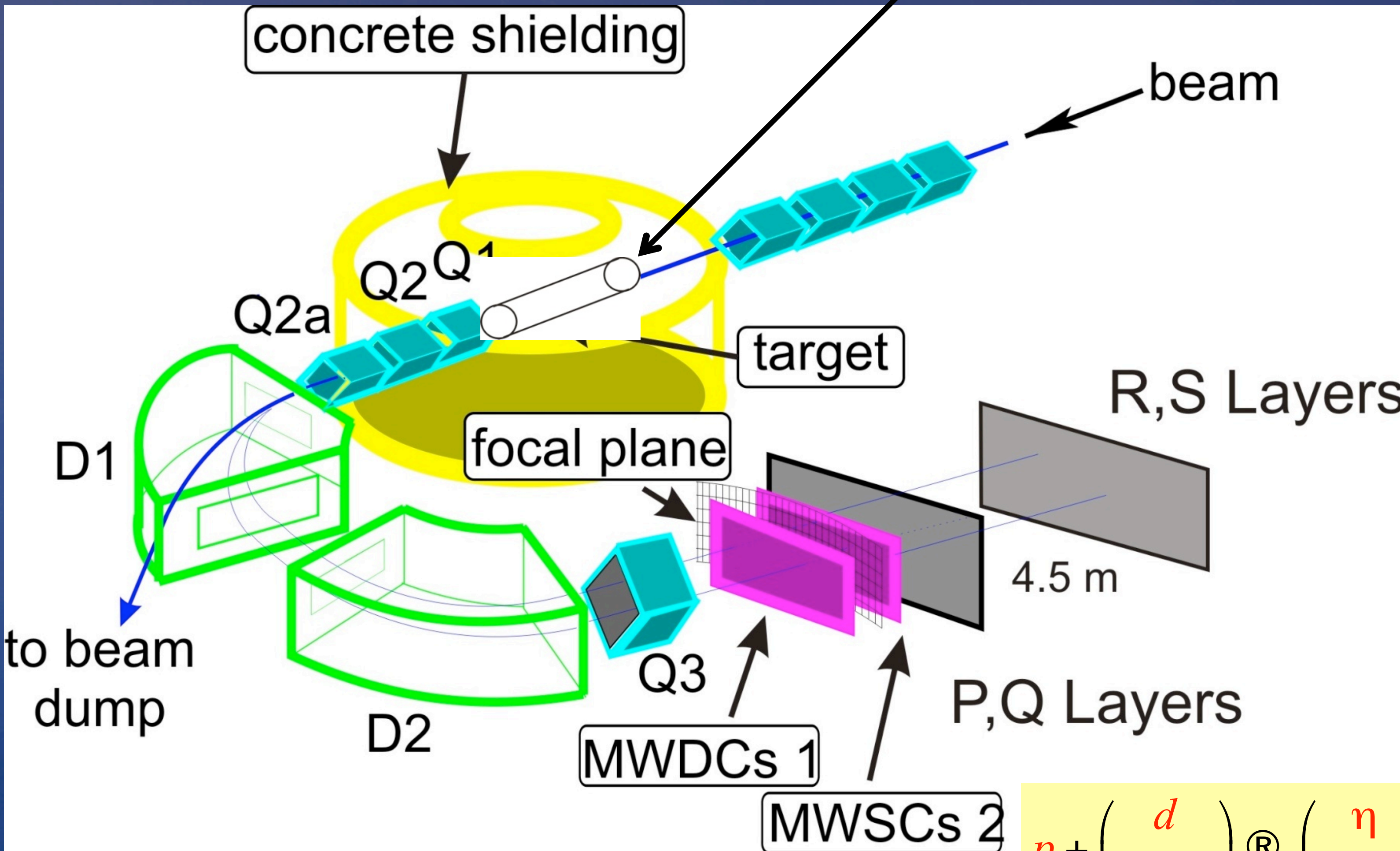
Big Karl & ENSTAR



$$p + \begin{pmatrix} d \\ A-2 \end{pmatrix} \text{®} \begin{pmatrix} \eta \\ A-2 \end{pmatrix} + {}^{3}He$$

$$\eta + N \rightarrow N^{*}(1535) \leftrightarrow \begin{cases} \pi^{-} + p \\ \pi^{0} + n \\ \pi^{0} + p \\ \pi^{+} + n \end{cases}$$

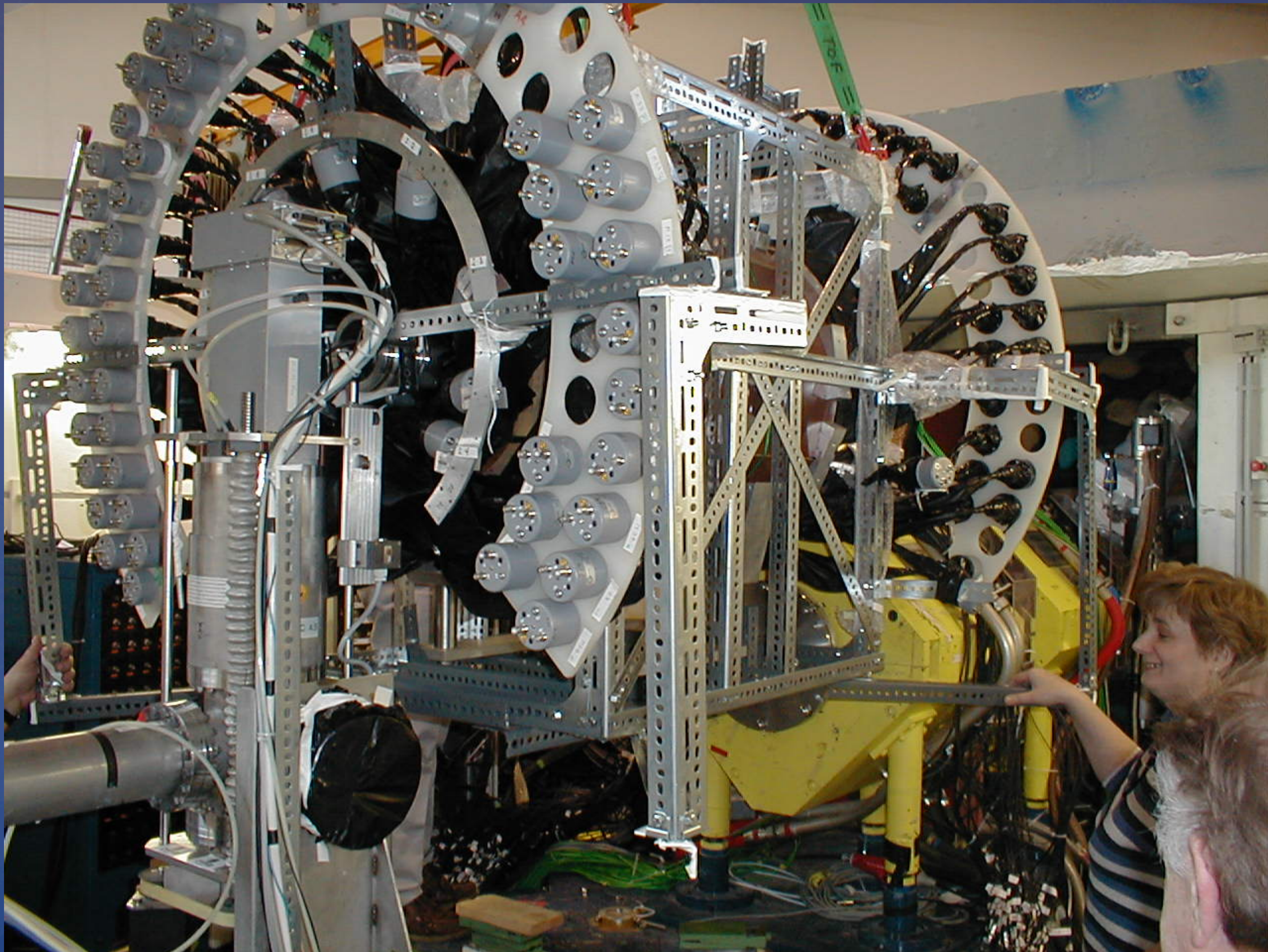
Big Karl & ENSTAR



$$p + \begin{pmatrix} d \\ A-2 \end{pmatrix} \text{®} \begin{pmatrix} \eta \\ A-2 \end{pmatrix} + {}^{3}He$$

ENSTAR detector

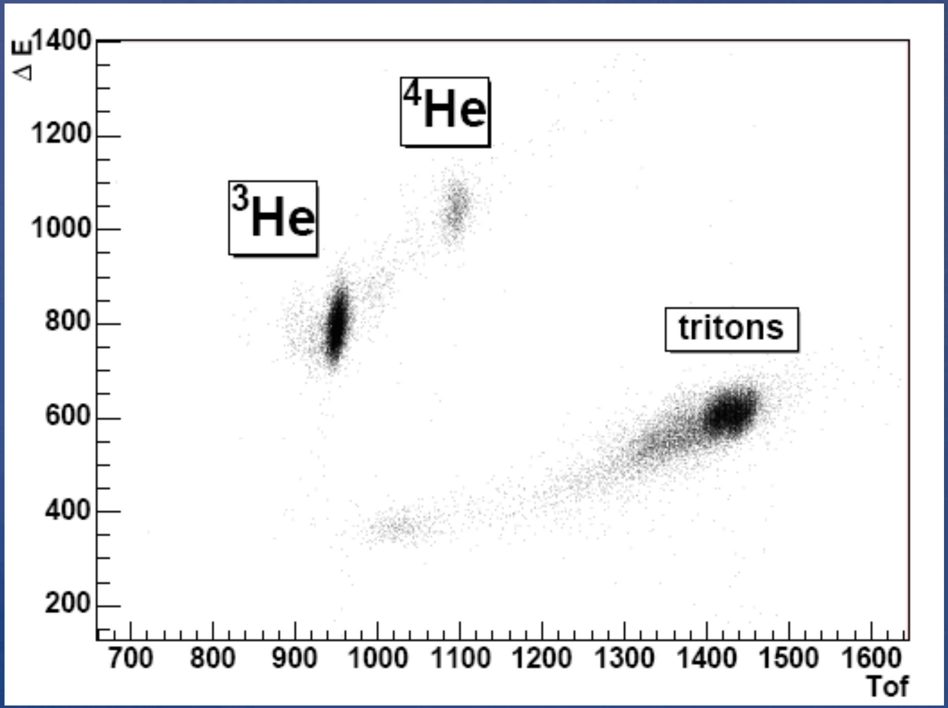
ENSTAR detector

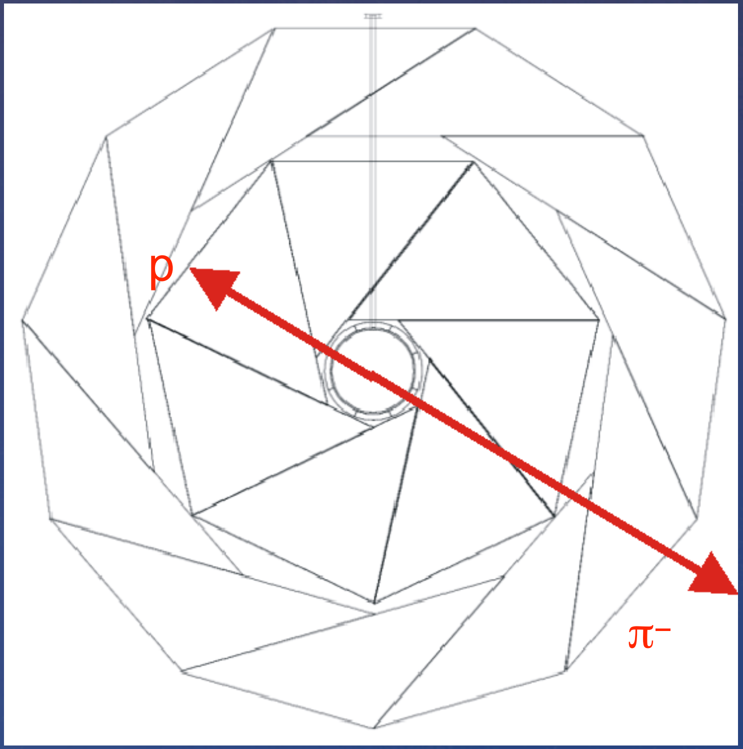


Proton + Aluminium target

Particle identification with BK focal plane detectors

(high threshold cuts light particles)



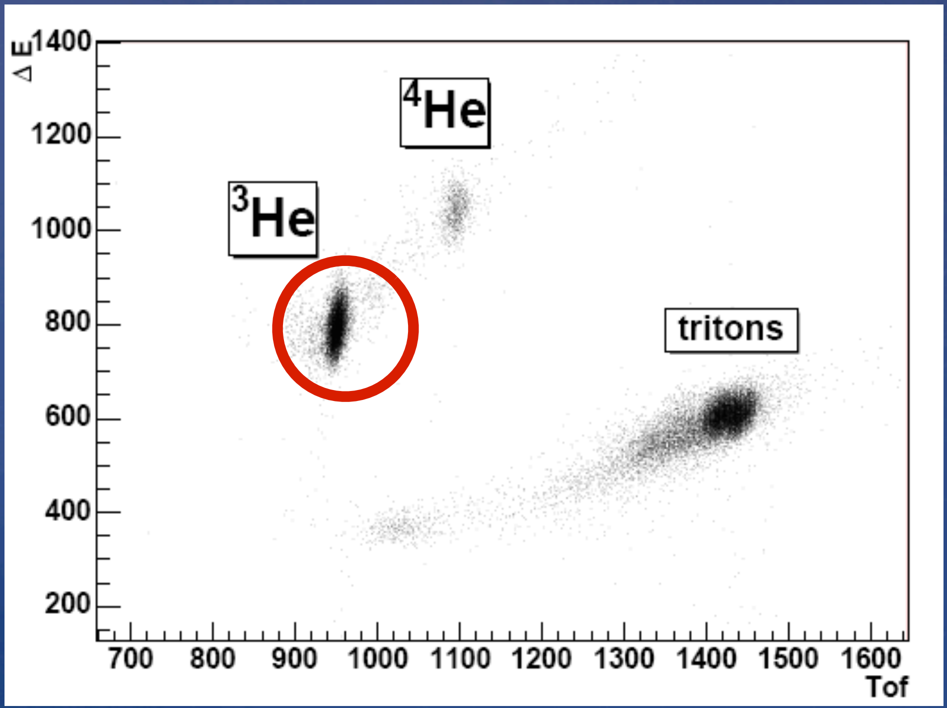


NIM A 596 (08) 31

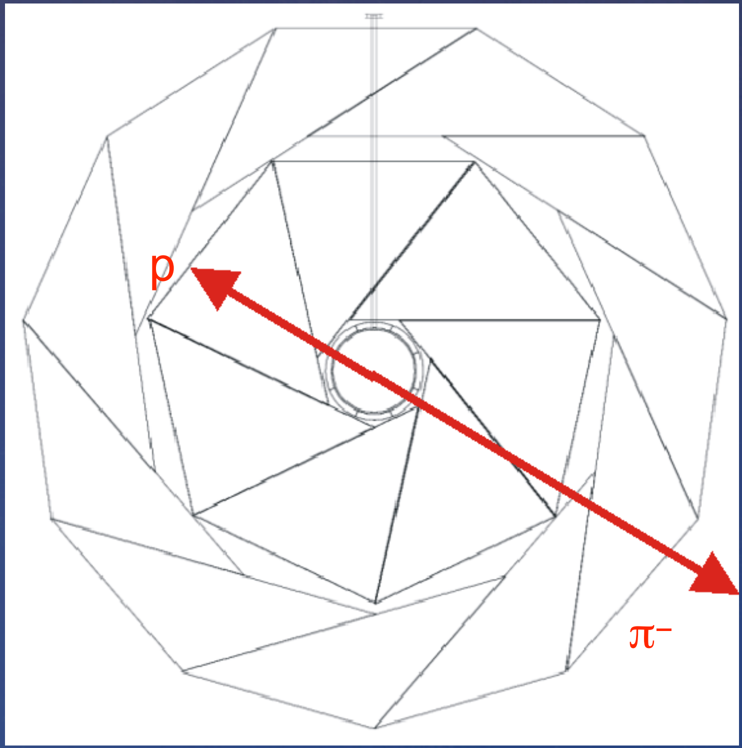
Proton + Aluminium target

Particle identification with BK focal plane detectors

(high threshold cuts light particles)



NIM A 596 (08) 31

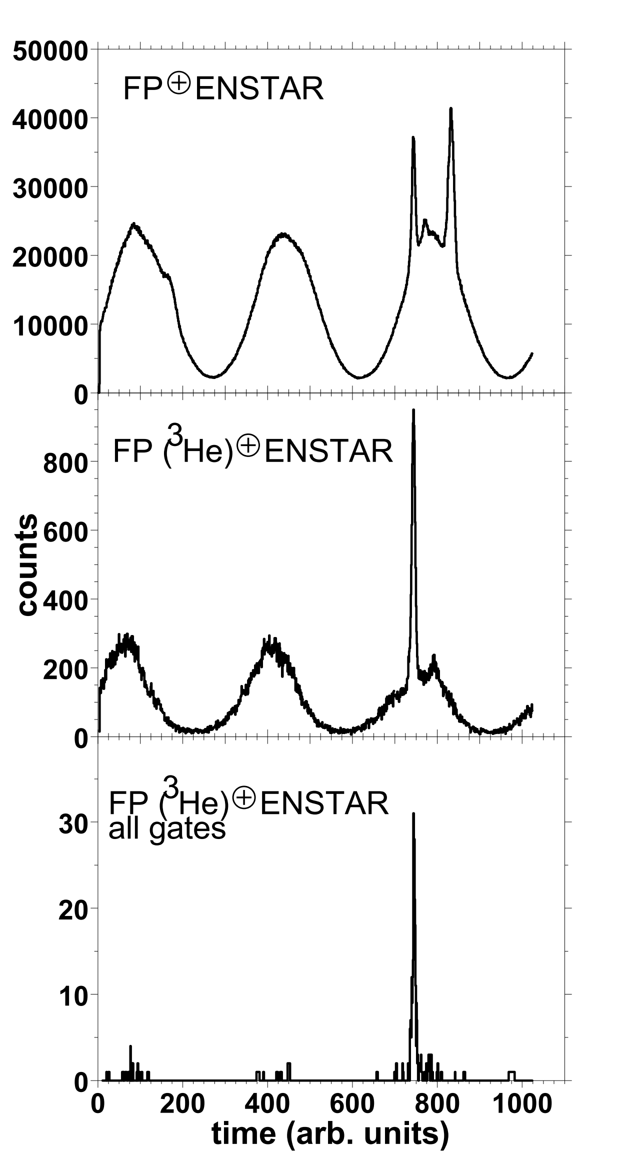


Event of interest:

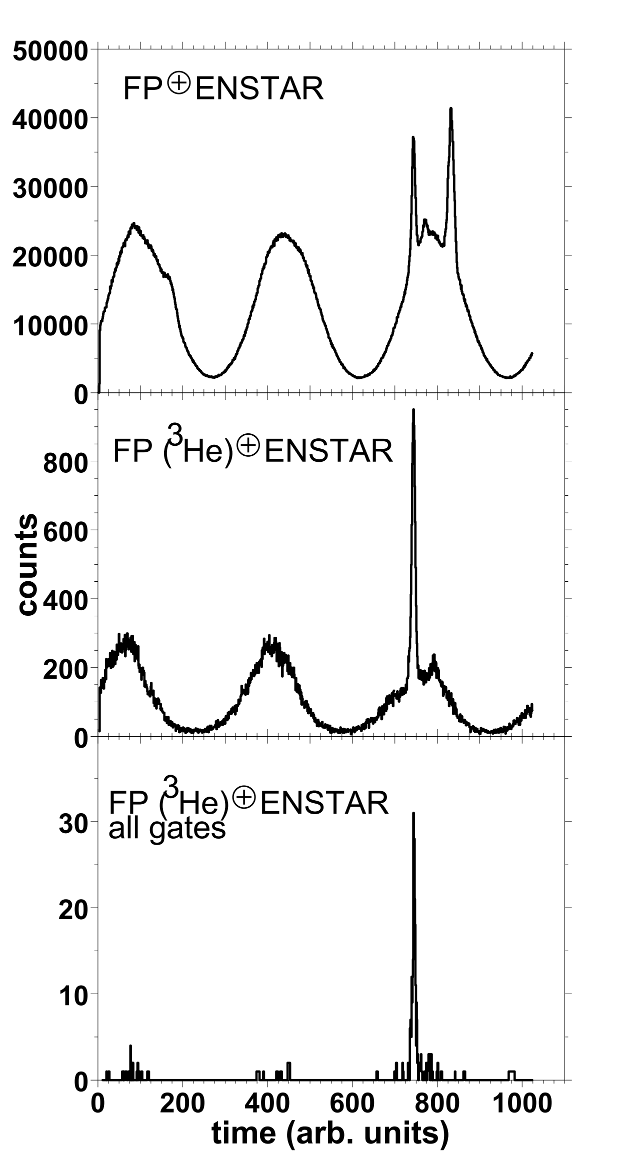
- Two correlated particles: 5+4=9 fold coincidence
- Pion leaves the detector: outer layer fires
- Proton stopped in the middle layer

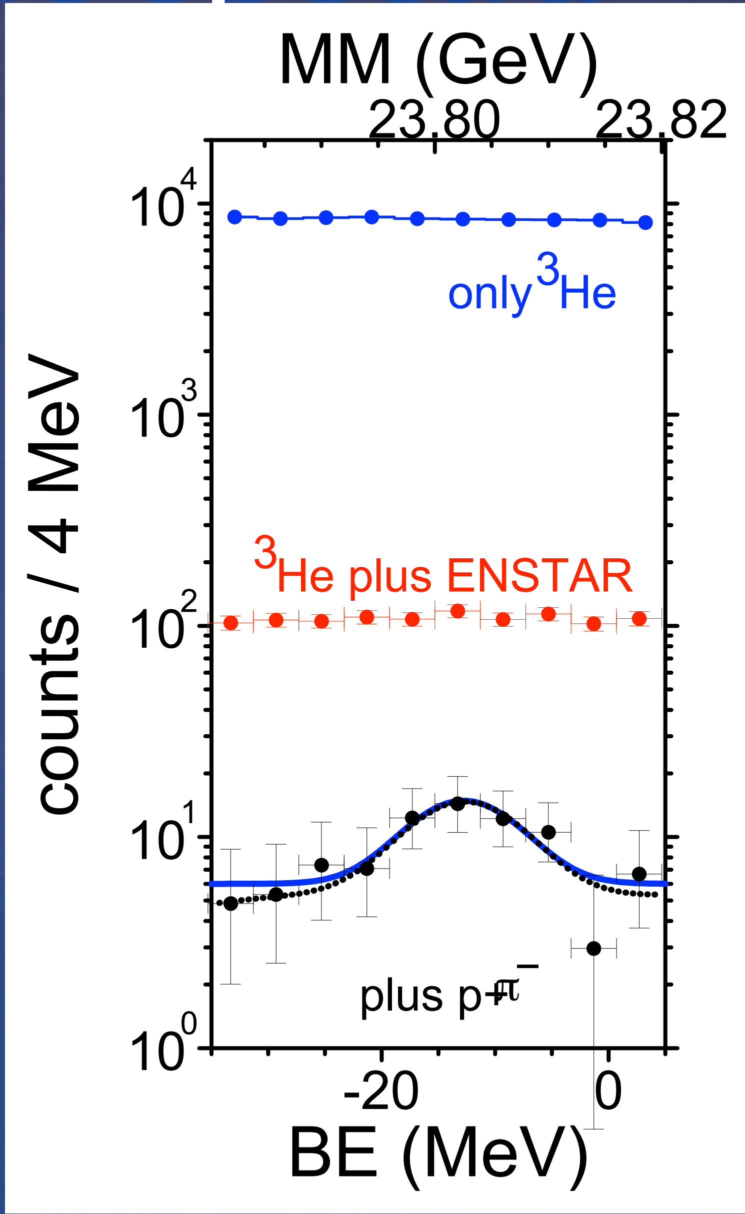
Time- and ^{3}He spectra

Time- and ^{3}He spectra

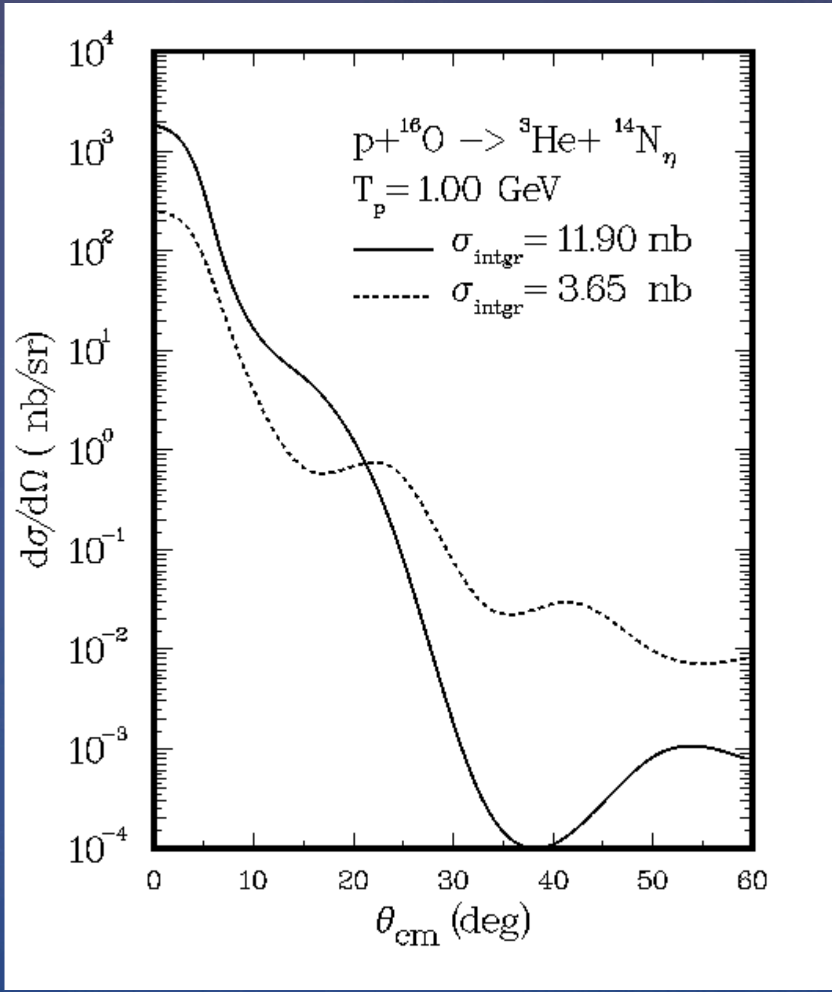


Time- and ^{3}He spectra





Cross section



expected: 5-22 nb

L.-C. Liu

σ(bump) = 50 pb

ε_{branch} = 1/3

$$\sigma_{exp.} = 152 \pm 54(\text{stat.}) \pm 21(\text{syst.})\ \text{pb}$$

Results

$BE_0 = 12.0 \pm 2.2$ MeV

FWHM $= 11.04 \pm 4.0$ MeV

Gaussian errors:

$(N - BG)/\sqrt{(BG + \sigma_{BG})} = 5.3\sigma$

Poisson errors:

$(N - BG)/\sqrt{(BG + \sigma_{BG})} = 4.9\sigma$

Likelihood $\sqrt{-2\Delta lnL} = 6.2\sigma$

PRC 70 (2009) 012201(R)

Results

$BE_0 = 12.0 \pm 2.2$ MeV

FWHM $= 11.04 \pm 4.0$ MeV

Gaussian errors:

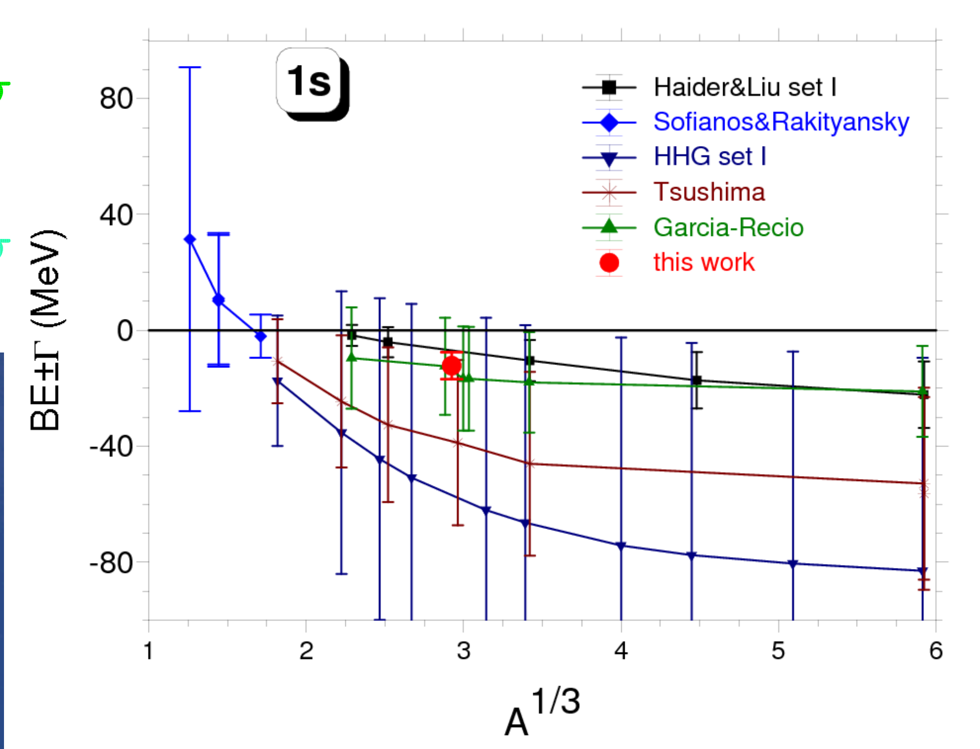
$(N - BG)/\sqrt{(BG + \sigma_{BG})} = 5.3\sigma$

Poisson errors:

$(N - BG)/\sqrt{(BG + \sigma_{BG})} = 4.9\sigma$

Likelihood $\sqrt{-2\Delta lnL} = 6.2\sigma$

PRC 70 (2009) 012201(R)



Results

$BE_0 = 12.0 \pm 2.2$ MeV

FWHM $= 11.04 \pm 4.0$ MeV

Gaussian errors:

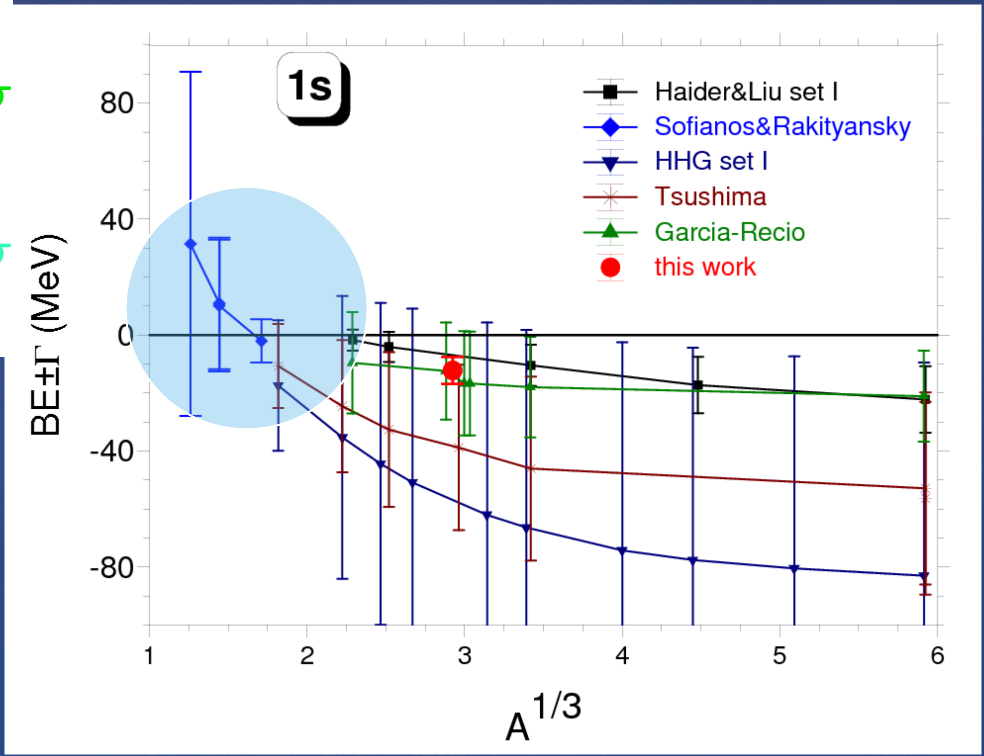
$(N - BG)/\sqrt{(BG + \sigma_{BG})} = 5.3\sigma$

Poisson errors:

$(N - BG)/\sqrt{(BG + \sigma_{BG})} = 4.9\sigma$

Likelihood $\sqrt{-2\Delta lnL} = 6.2\sigma$

PRC 70 (2009) 012201(R)



Two body final state interaction

$$\frac{p_i}{p_f}\left(\frac{d\sigma}{d\Omega}\right)=\left|f\right|^2=\left|f_B \times FSI\right|^2=\left|f_B\right|^2 \times \left|FSI\right|^2$$

Tacid assumption:

s-wave, and then $d\sigma/d\Omega=\sigma/4\pi$

$$FSI=\frac{1}{1-i\cdot a\cdot p_f+\frac{1}{2}a\cdot r_0\cdot p_f^2}$$

Quasi-bound requires:

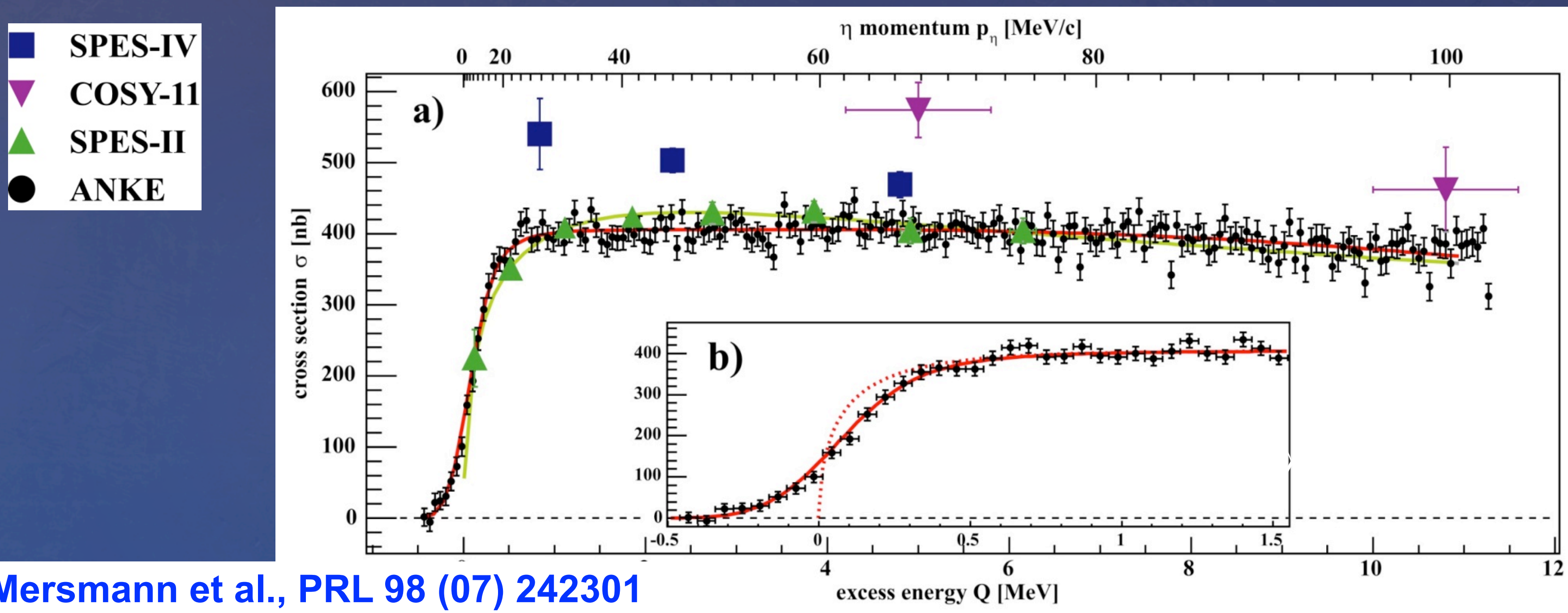
- $\mathrm{Im}(a_{\eta A}) > 0$ from unitarity
- $|\mathrm{Im}(a_{\eta A})| < |\mathrm{Re}(a_{\eta A})|$ to have a pole in the negative energy half plane
- $\mathrm{Re}(a_{\eta A}) < 0$ to have a bound state, but

$|FSI|^2 \propto 1/\mathrm{Re}(a_{\eta A})^2$

$|Q_0(\eta^3He)|<|Q_0(\eta^4He)|\ )|<|Q_0(\eta^7Be)|$

Otherwise: virtual (unphysical) state

Excitation function: $dp \to {}^3He\eta$



T. Mersmann et al., PRL 98 (07) 242301

$$a_{{}^3He\eta} = \left[\pm\left(10.7 \pm 0.8^{+0.1}_{-0.5}\right) + i \times \left(1.5 \pm 2.6^{+1.0}_{-0.9}\right)\right] \text{fm}$$

$$r_0 = \left[\left(1.9 \pm 0.1\right) + i \times \left(2.1 \pm 0.2^{+0.2}_{-0.0}\right)\right] \text{fm}$$

$$|Q_0| \approx 0.30 \text{ MeV}$$

GEM dd→αη

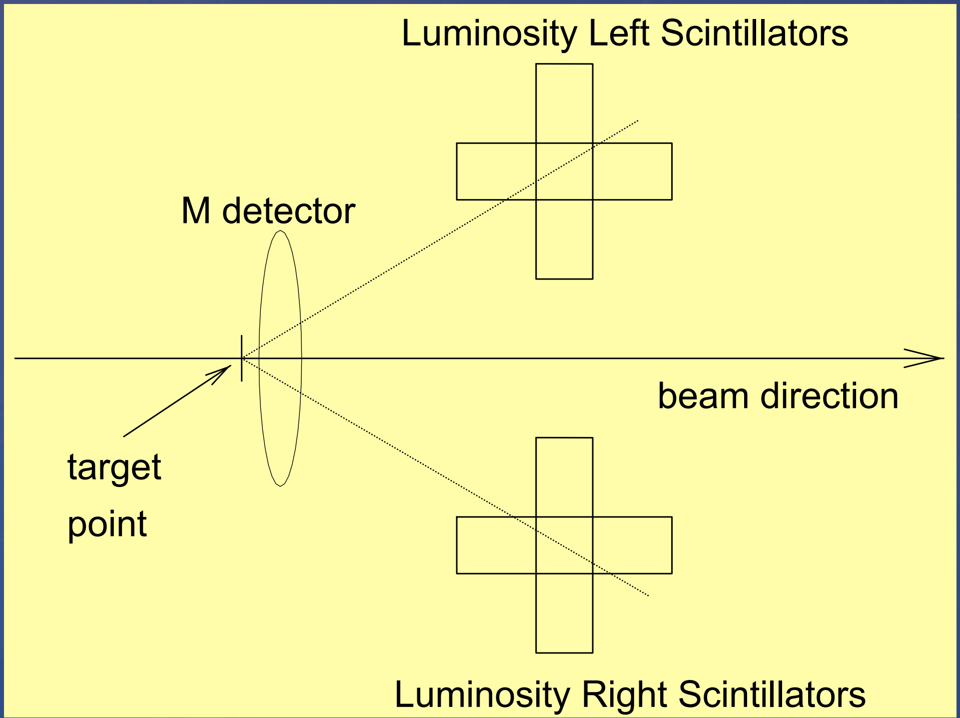
In order to extract s-wave production, tensor polarised deuteron beam

Target area:

GEM dd→αη

In order to extract s-wave production, tensor polarised deuteron beam

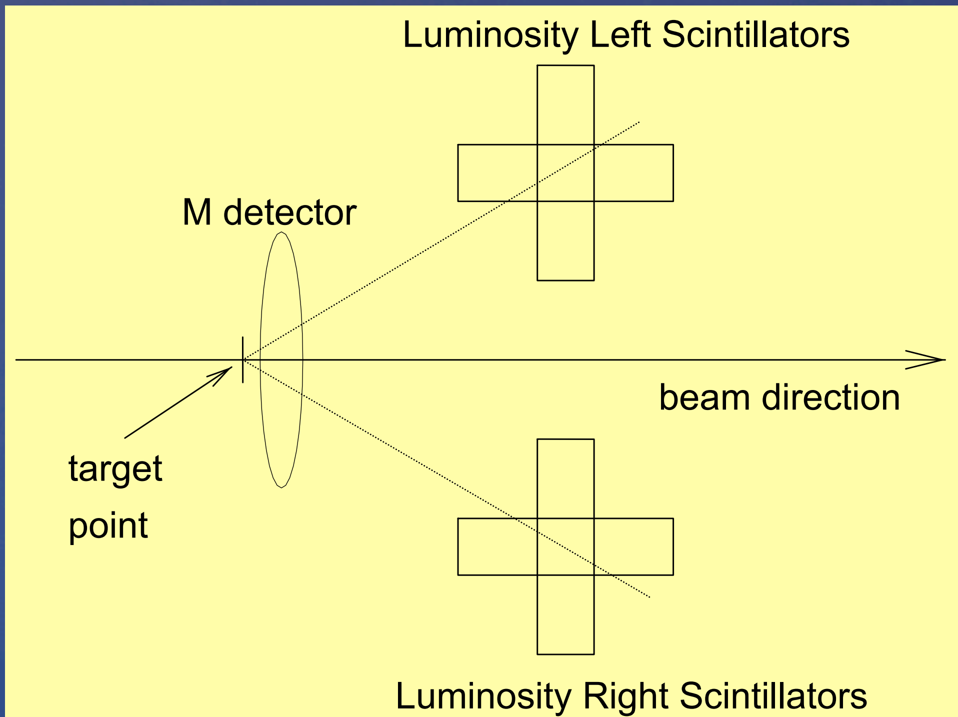
Target area:

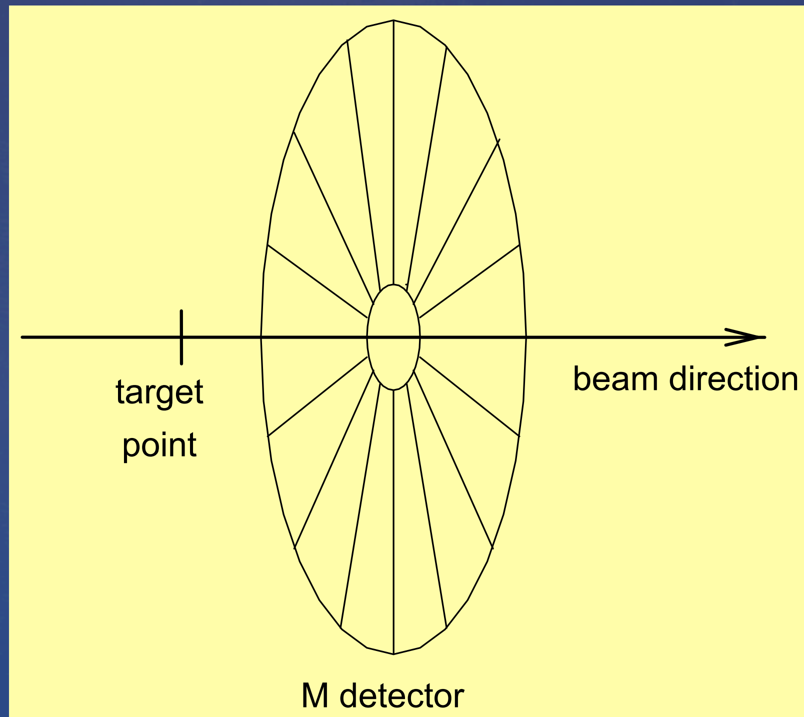


GEM dd→αη

In order to extract s-wave production, tensor polarised deuteron beam

Target area:





Raw data

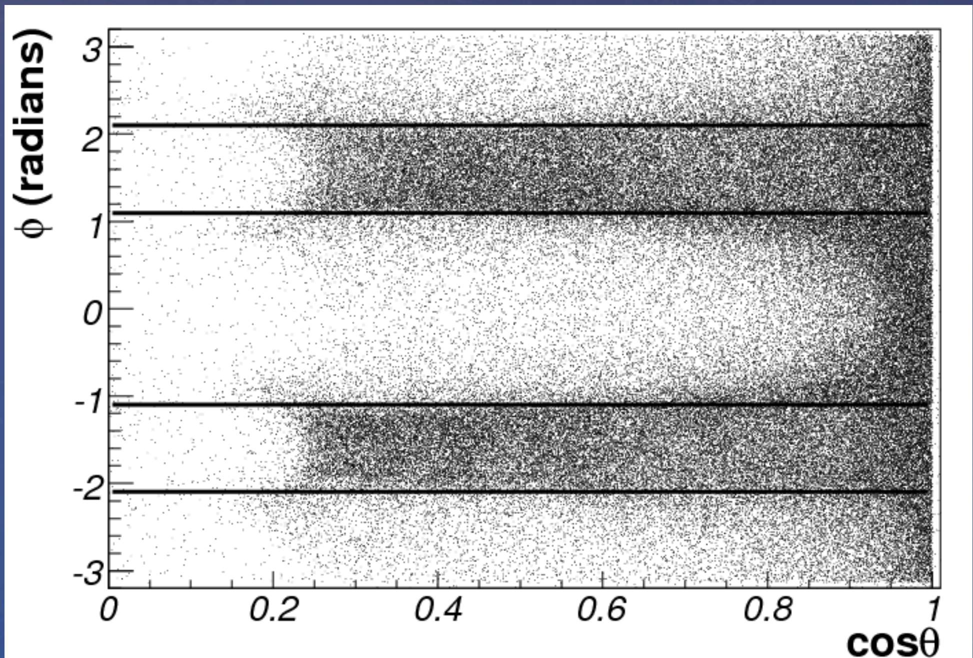
$(\pi+1)/2$

$(\pi-1)/2$

$-(\pi-1)/2$

$-(\pi+1)/2$

Raw data



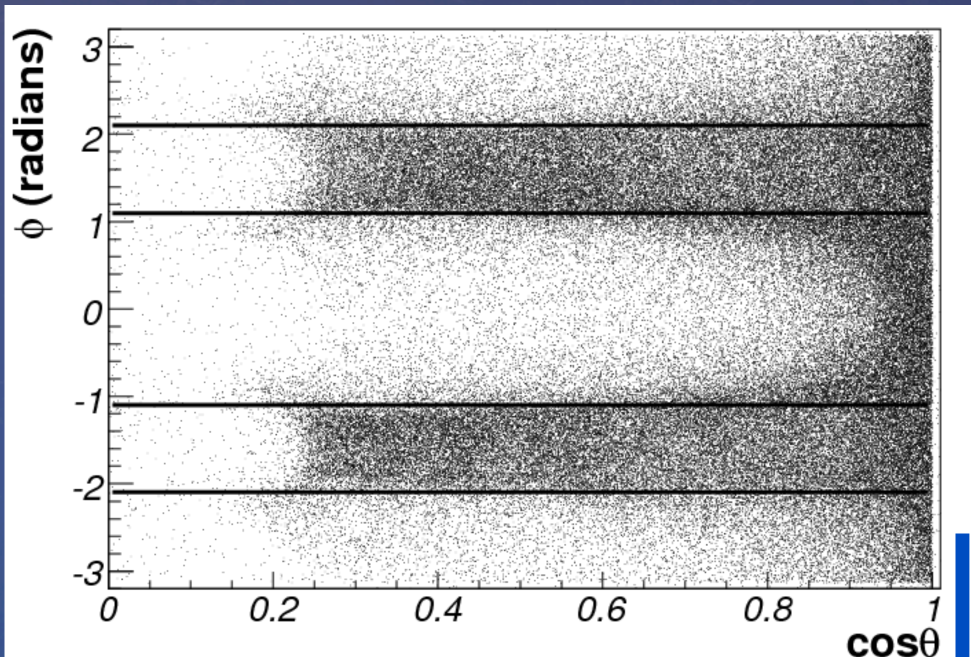
$(\pi+1)/2$

$(\pi-1)/2$

$-(\pi-1)/2$

$-(\pi+1)/2$

Raw data

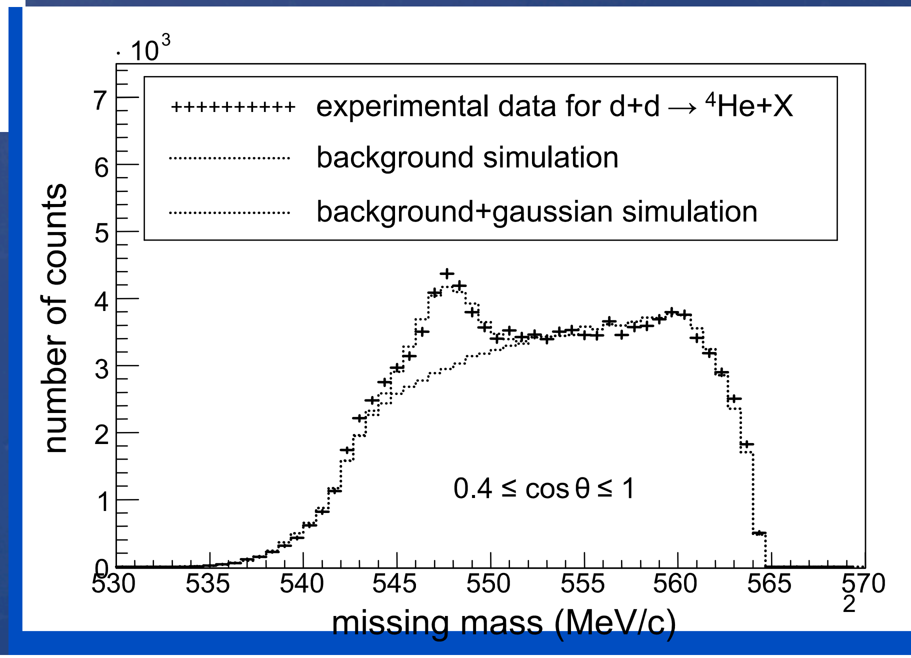


$(\pi+1)/2$

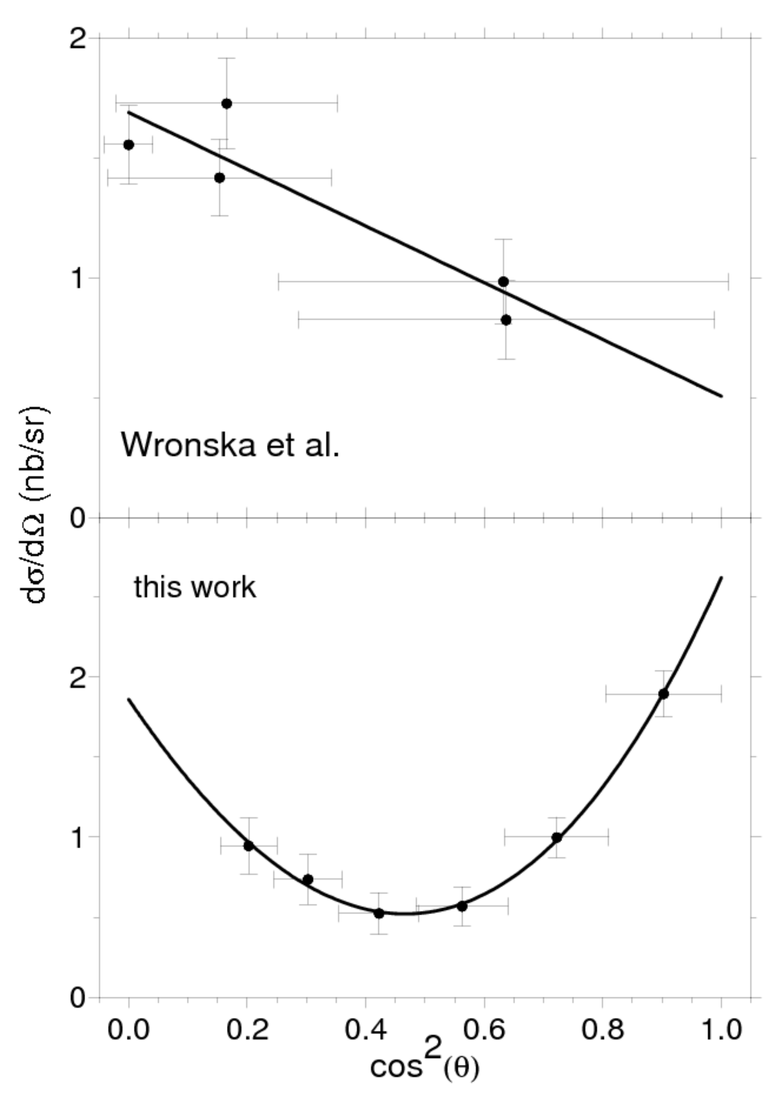
$(\pi-1)/2$

$-(\pi-1)/2$

$-(\pi+1)/2$



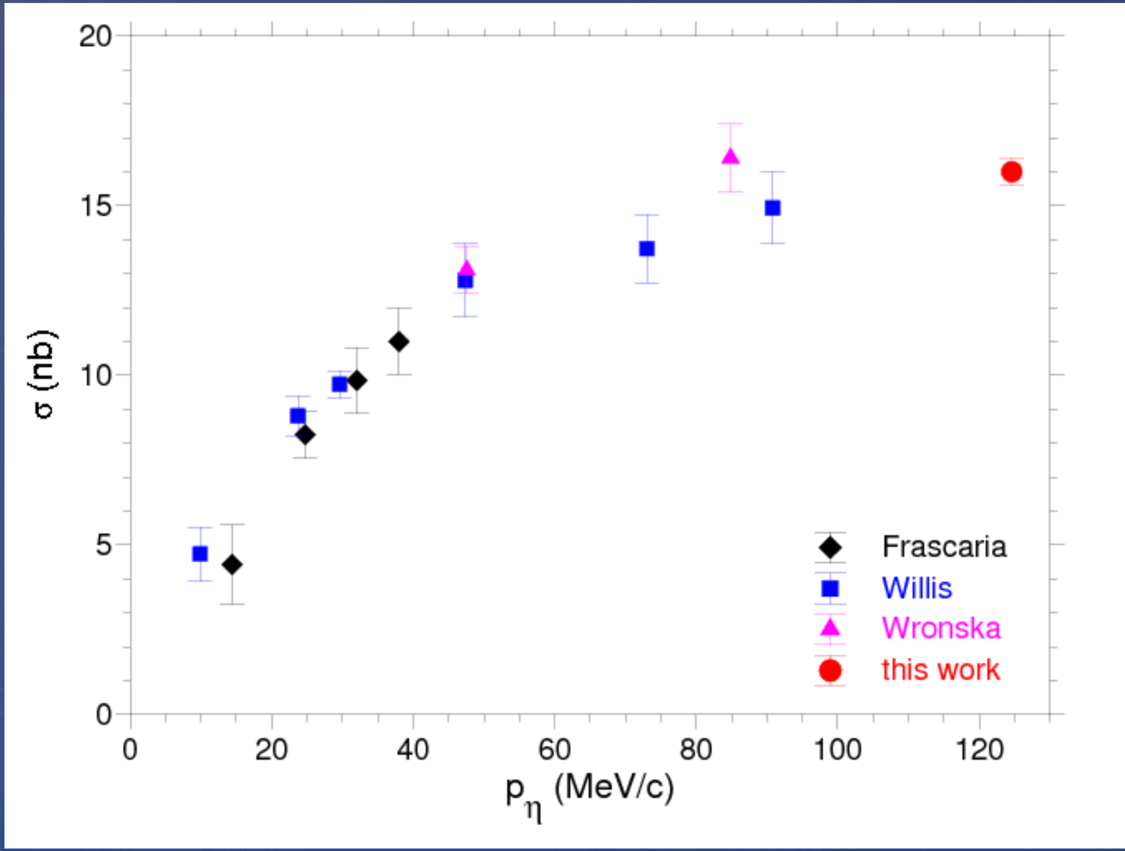
Unpolarised cross



Exp.	a_0	a_2	a_4
ANKE	1.30 ±0.18	-0.79 ±0.19	
GEM	1.27 ±0.03	-0.29 ±0.06	1.65 ±0.07

s, p and d-waves!

Excitation Function



Same momentum range as in p+d, but less data points. Cross section less than 5%!

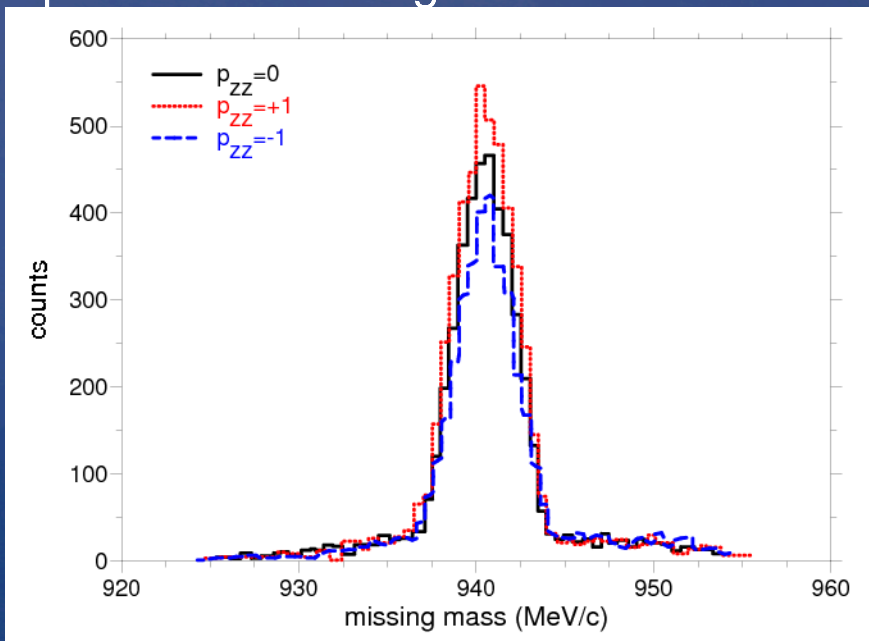
How to extract s-wave?

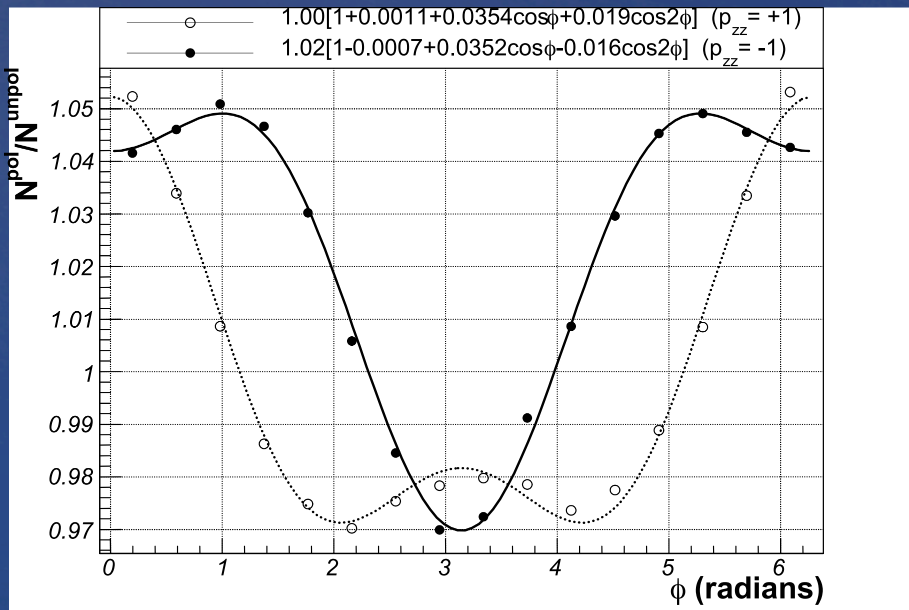
Polarised beam

At strictly 180 degree, there is only one analysing power, $A_{yy} = A_{xx}$ which was measured.

p_z		p_{zz}	
nominal	measured	nominal	measured
$-1/3$	-0.33 ± 0.02	-1	$-0.87 \pm 0.11 \pm 0.01$
$-1/3$	-0.32 ± 0.02	$+1$	$+0.91 \pm 0.14 \pm 0.01$

dp elastic scattering





$$\underbrace{\left(\frac{d\sigma}{d\Omega}(\theta,\phi)\right)_{\text{pol}} \Big/ \left(\frac{d\sigma}{d\Omega}(\theta)\right)_{\text{unpol}}}_{F} = \Big[1 + \frac{3}{2}\underbrace{A_y(\theta)p_z}_{H}\cos\phi$$

$$+\frac{1}{4}\underbrace{p_{zz}(A_{yy}(\theta)+A_{xx}(\theta))}_{G} + \frac{1}{4}\underbrace{p_{zz}(A_{yy}(\theta)-A_{xx}(\theta))}_{J}\cos 2\phi\Big]$$

Take the acceptance into account:

$$< \cos 2\phi >= \int_{(\pi-1)/2}^{(\pi+1)/2} \cos 2\phi \, d\phi = -0.84.$$

$$I = \int_{(\pi-1)/2}^{(\pi+1)/2} \left(\frac{d(\theta,\phi)}{d\Omega}\right)_{\text{pol}} d\phi = \left(\frac{d\sigma}{d\Omega}(\theta)\right)_{\text{unpol}} [1 + 0.46\, p_{zz} A_{xx}(\theta)]$$

Avoid to make use of unpolarised beam

$$\Delta = \frac{I^+ - I_1^-}{I^+ + I^-} = \frac{0.23\, A_{xx}\left(p_{zz}^+ - p_{zz}^-\right)}{1 + 0.23\, A_{xx}\left(p_{zz}^+ + p_{zz}^-\right)}.$$

$$A_{xx} = 2.44\,\Delta/(1 - 0.02\,\Delta)$$

is an even function on $cos(\theta)$

$$\mathcal{M} = A(\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \hat{p}_d + B(\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot [\hat{p}_d \times (\hat{p}_\eta \times \hat{p}_d)] (\hat{p}_\eta \cdot \hat{p}_d)$$
$$+C [(\vec{\epsilon}_1 \cdot \hat{p}_d) \vec{\epsilon}_2 \cdot (\hat{p}_\eta \times \hat{p}_d) + (\vec{\epsilon}_2 \cdot \hat{p}_d) \vec{\epsilon}_1 \cdot (\hat{p}_\eta \times \hat{p}_d)],$$

$$A(\theta) = A_0 + A_2 P_2(\cos\theta)$$

fit parameter	value
$\|A_0\|^2$	6.6 ± 1.7
$2Re(A_0^* A_2)$	-25.0 ± 9.5
$\|A_2\|^2$	48.4 ± 14.5
$\|B\|^2$	9.3 ± 5.1
$\|C\|^2$	0

Better fit than partial wave amplitudes (s, p, 2d waves), because less parameters (4 instead of 7)

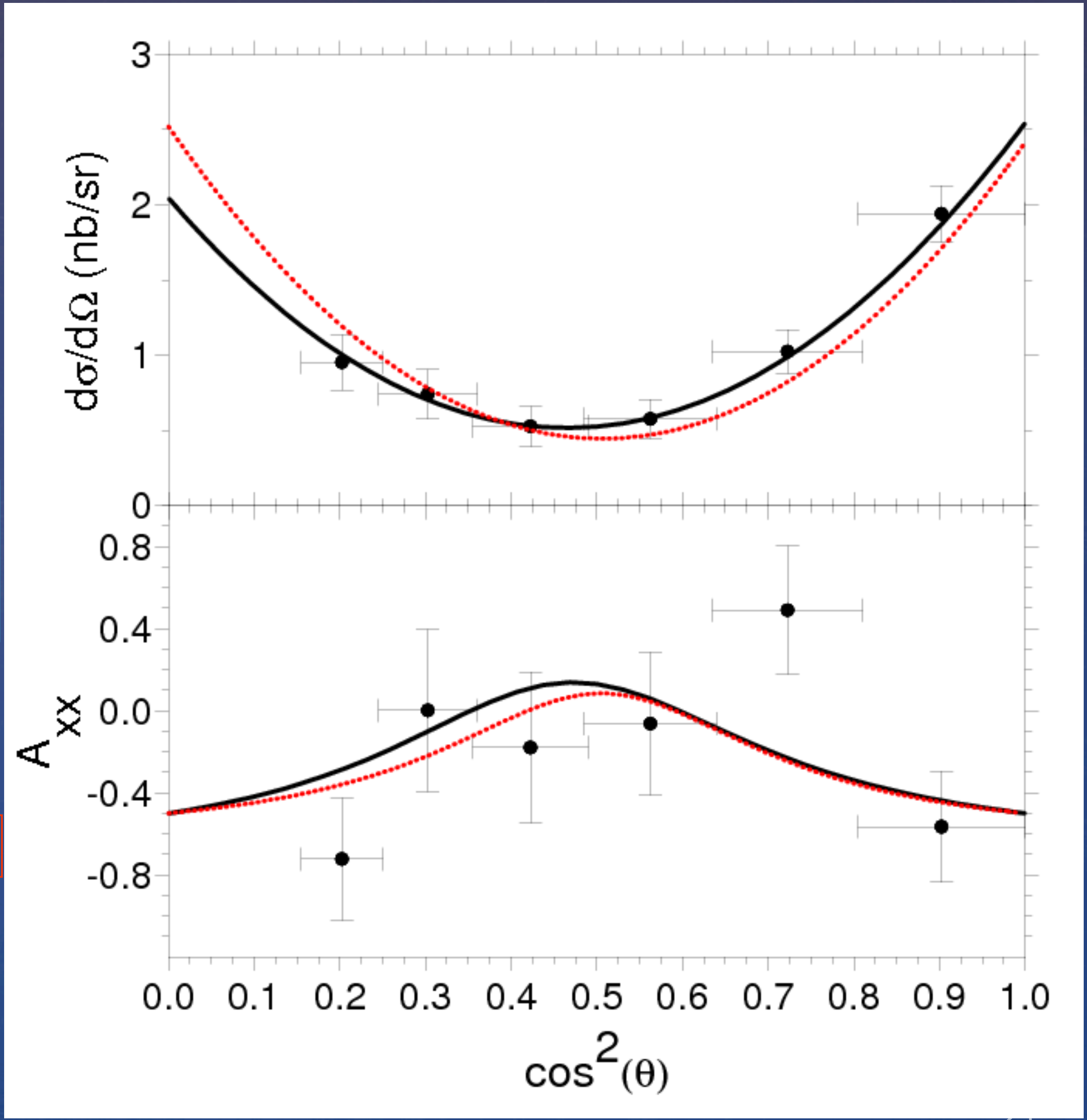
Angular dependence due to s-d interference

Final result

PWA ————

spin ampl. ------------

NP A 821 (2009) 193



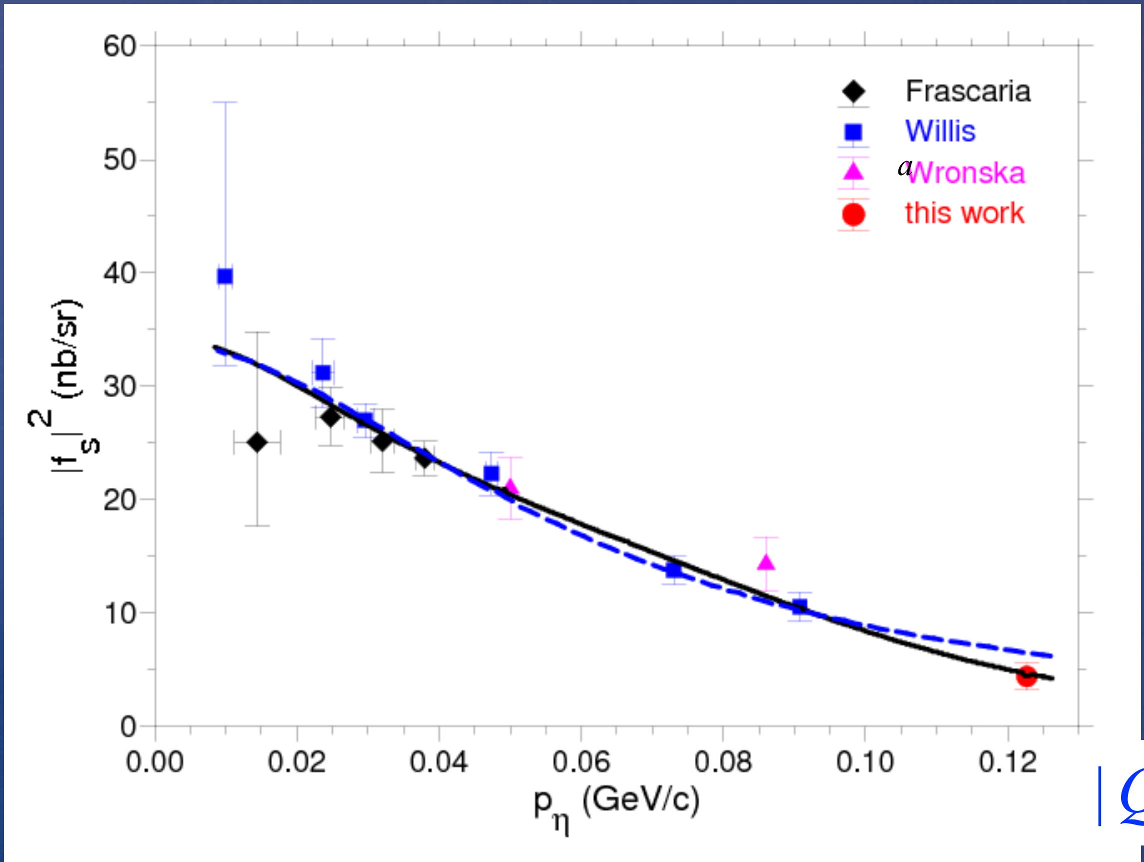
piątek, 18 czerwca 2010

Final result

$$\frac{d\sigma_s}{d\Omega} = \frac{p_\eta}{p_d}|f_s|^2 = \frac{2p_\eta}{3p_d}|A_0|^2 = \frac{1}{27}\frac{1}{4\pi}|a_0|^2$$

$$|f_s|^2 = 4.4 \pm 1.1 \text{ nb/sr}$$

spin ampl. (A_0) partial wave ampl. (a_0)

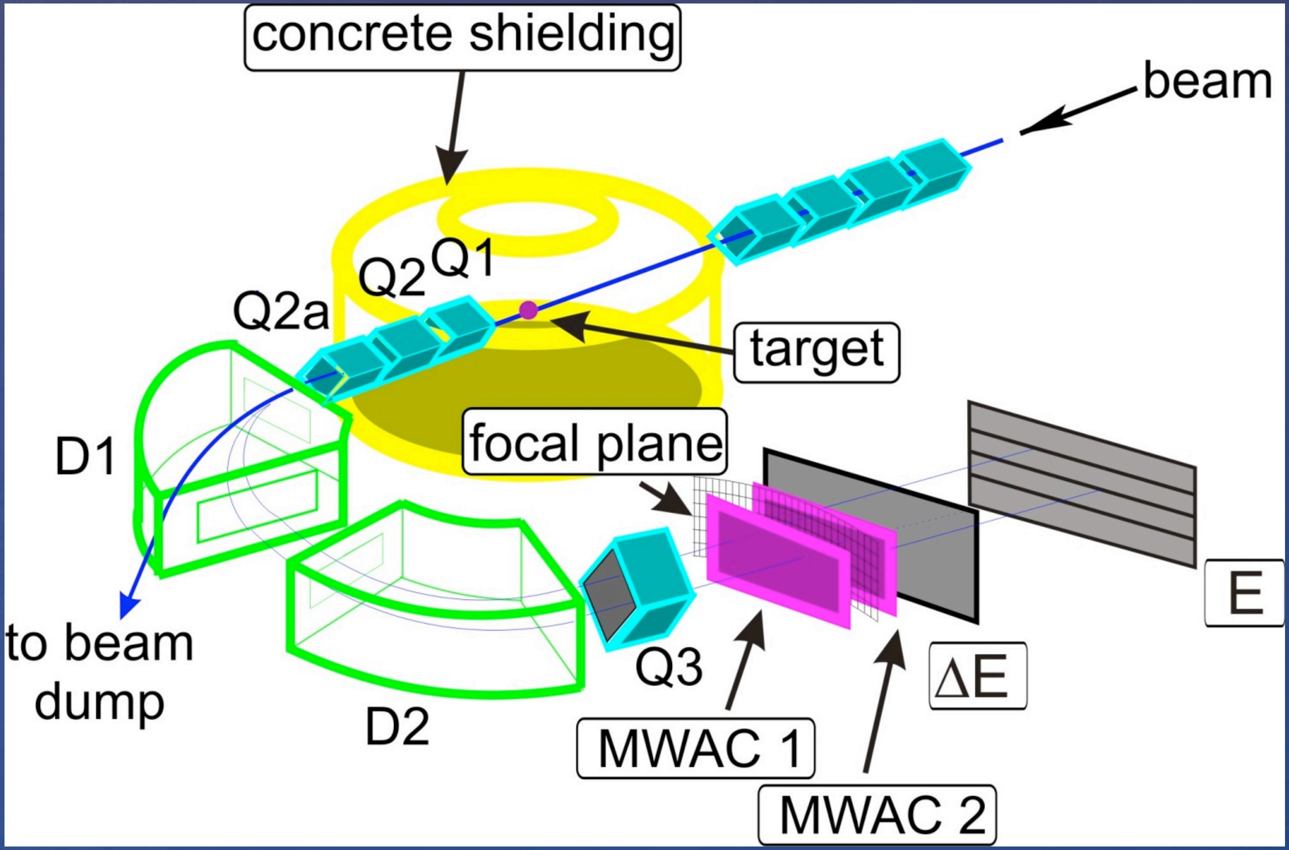


scatt. length (dashed)
effective range (solid)

$$|a_r| = 3.1 \pm 0.5 \text{ fm}$$
$$a_i = 0.0 \pm 0.5 \text{ fm}$$

$$|Q_0| \approx 4\text{MeV} > |Q_0(\eta\,{}^3\text{He})|$$

$p+^6Li \rightarrow \eta+^7Be$ 11 MeV above threshold

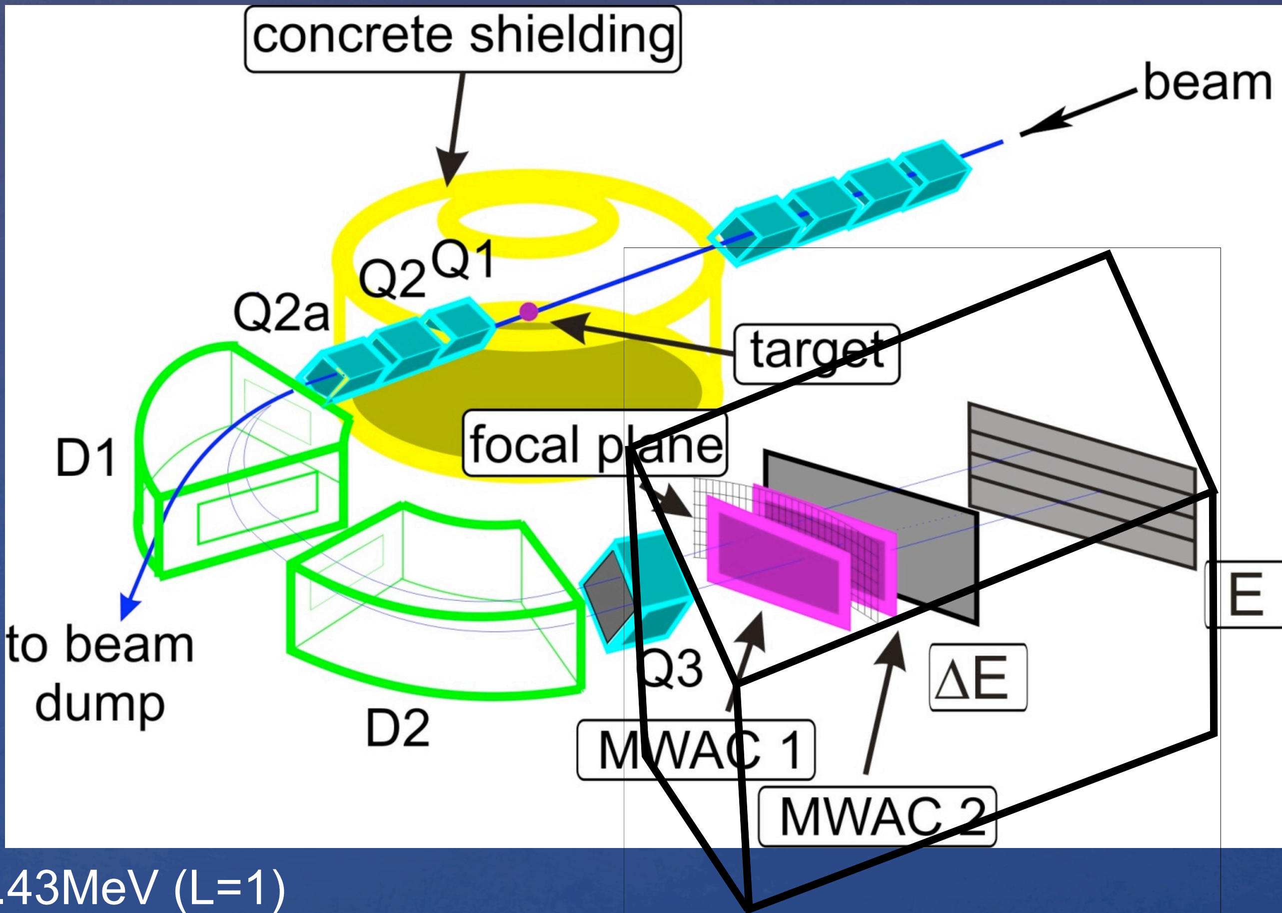


g.s.+0.43MeV (L=1)

previous exp. 4 states (L=1+L=3)

$p+^6Li \rightarrow \gamma\gamma+X$

$p + {}^6Li \rightarrow \eta + {}^7Be$ 11 MeV above threshold

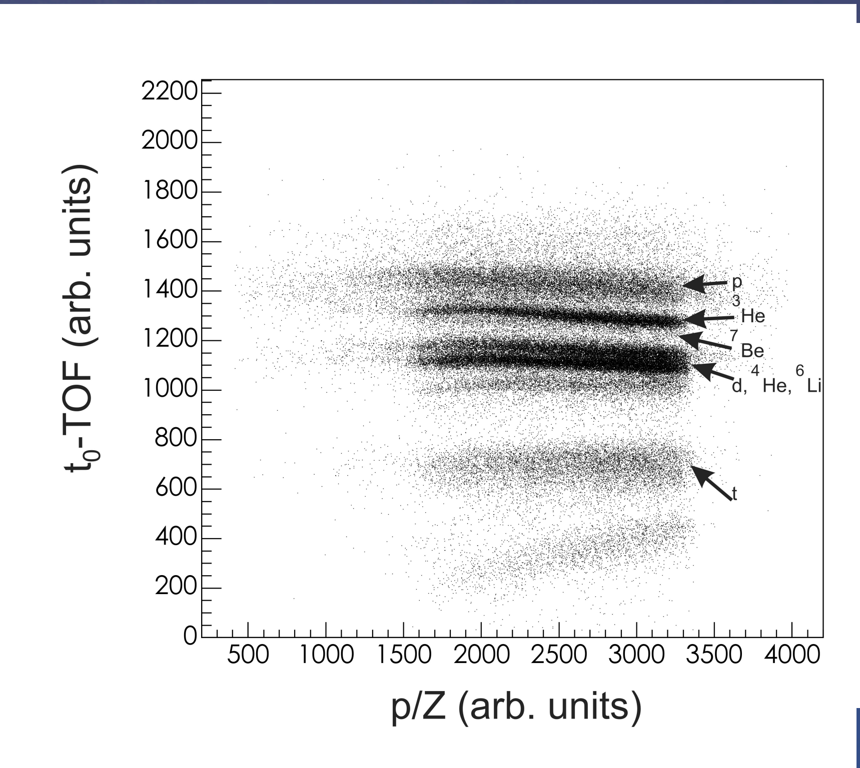


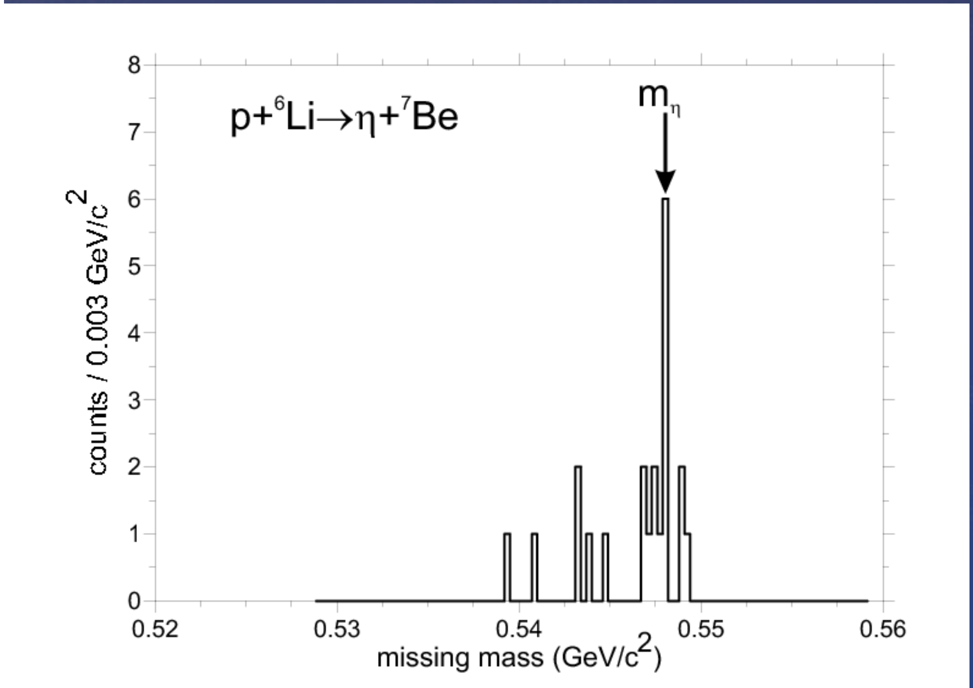
g.s.+0.43MeV (L=1)

previous exp. 4 states (L=1+L=3)

$p + {}^6Li \rightarrow \gamma\gamma + X$

Result





$$\frac{d\sigma}{d\Omega} = (0.69 \pm 0.20(\text{ stat.}) \pm 0.20(\text{ syst.}))\ \text{nb/sr.}$$

Subtraction of L=3 yield

Al Khalili et al.:

Upadhyay et al.: plus rescattering

Subtraction of L=3 yield

Al Khalili et al.:

$$\frac{d\sigma(p^6\text{Li} \text{ ® } \eta\, ^7\text{Be})}{d\Omega} = \text{C}|\, f(pd \text{ ® } \eta\, ^3\text{He})|^2 \sum_j \frac{2j+1}{2} \text{F}_j^{\,2}$$

Upadhyay et al.: plus
rescattering

Subtraction of L=3 yield

Al Khalili et al.:

$$\frac{d\sigma(p\,{}^{6}\mathrm{Li} \rightarrow \eta\,{}^{7}\mathrm{Be})}{d\Omega} = C\,|f(pd \rightarrow \eta\,{}^{3}\mathrm{He})|^{2} \sum_{j} \frac{2j+1}{2} F_{j}^{2}$$

C overlapp cluster wavefunctions

$f(pd \rightarrow \eta\,{}^{3}\mathrm{He})$ spin averaged amplitude

F_j form factor

Upadhyay et al.: plus rescattering

Subtraction of L=3 yield

Al Khalili et al.:

$$\frac{d\sigma(p^6\text{Li} \text{ ® } \eta\,^7\text{Be})}{d\Omega} = \text{C}\,|\,f(pd \text{ ® } \eta\,^3\text{He})\,|^2 \sum_j \frac{2j+1}{2}\text{F}_j^{\,2}$$

C overlapp cluster wavefunctions

$f(pd \text{ ® } \eta\,^3\text{He})$ spin averaged amplitude

F_j form factor

$$\frac{d\sigma(L=1)}{d\Omega} = \frac{d\sigma(exp.)}{d\Omega}\,\frac{\sum_{j=3/2,1/2} \frac{2j+1}{2}\text{F}_j^{\,2}}{\sum_{j=3/2,1/2,7/2,5/2} \frac{2j+1}{2}\text{F}_j^{\,2}}$$

Upadhyay et al.: plus
rescattering

Subtraction of L=3 yield

Al Khalili et al.:

$$\frac{d\sigma(p\,^6\text{Li} \text{ ® } \eta\,^7\text{Be})}{d\Omega} = \text{C}|\,f(pd \text{ ® } \eta\,^3\text{He})|^2 \sum_j \frac{2j+1}{2}\text{F}_j^{\,2}$$

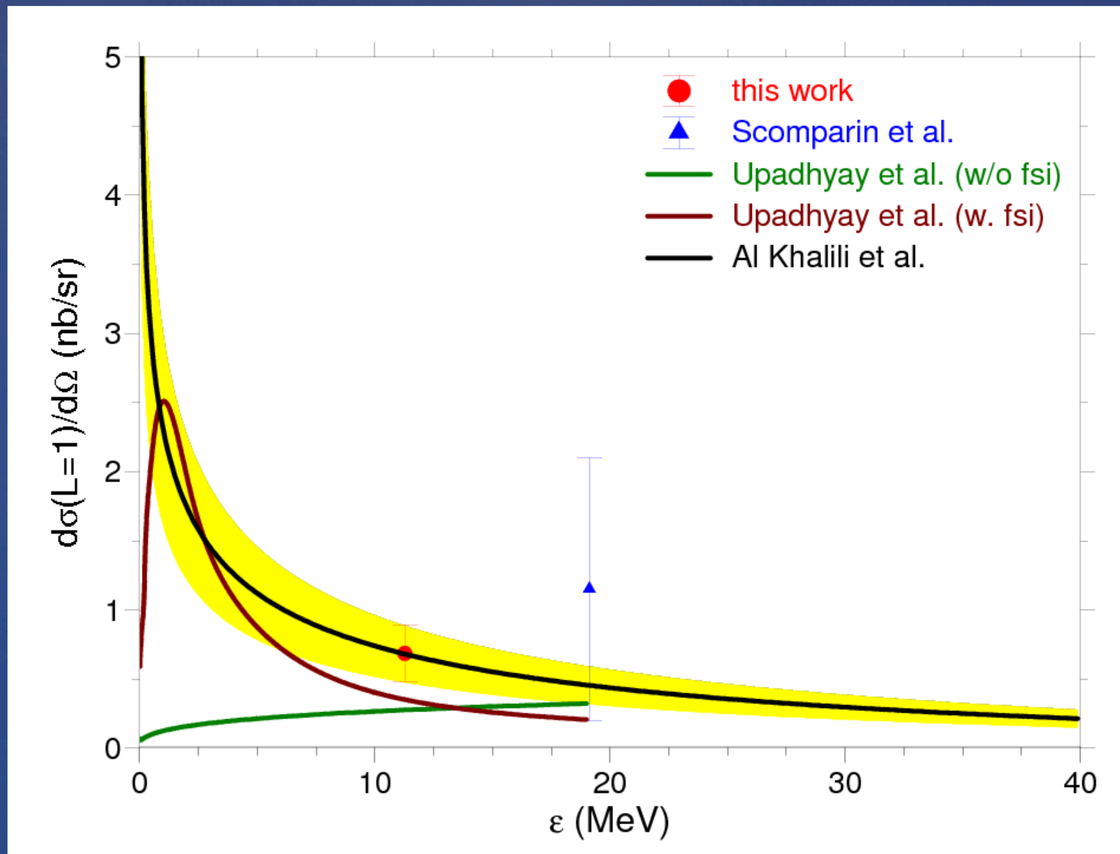
C overlapp cluster wavefunctions

$f(pd \text{ ® } \eta\,^3\text{He})$ spin averaged amplitude

F_j form factor

$$\frac{d\sigma(L=1)}{d\Omega} = \frac{d\sigma(exp.)}{d\Omega}\,\frac{\sum_{j=3/2,1/2} \frac{2j+1}{2}\text{F}_j^{\,2}}{\sum_{j=3/2,1/2,7/2,5/2} \frac{2j+1}{2}\text{F}_j^{\,2}}$$

Upadhyay et al.: plus rescattering



Summary:

- Search for η-mesic nuclei employing recoil free kinematics.
- We see an enhancement in the spectra after detecting 3 final particles: ^{3}He at small angles and $\pi^{-}+p$ back to back.
- $^{25}Mg \otimes \eta$ bound state: BE$\approx$ 13 MeV, FWHM$\approx$10 MeV
- 5σ effect
- We have measured angular distributions of cross sections and tensor analysing power for the reaction $dd \rightarrow \eta\alpha$ at 16.6 MeV above threshold
- s-wave strength could be extracted
- s-wave strength of other experiments (Willis et al., Wronska et al.) extracted
- FSI shows Im a $(\eta - \alpha)$ = 0.0(5) fm. This indicates a small absorption because the nucleons are strongly bound
- Not enough data for $\eta + {}^{7}Be$ to say something
- The η-nucleus levels in heavy nuclei thus might be fairly narrow.

The GEM Collaboration

M. Abdel-Bary[a], S. Abdel-Samad [a], A. Budzanowski [d], A. Chatterjee [i], J. Ernst [g], P. Hawranek [a,c], R. Jahn[e], V. Jha[i], S. Kailas[i], K. Kilian [a], Da. Kirilov[a,h], Di. Kirilov[h], S. Kliczewski [d], D. Kolev [f], M. Kravcikova [m], T. Kutsarova [e], M. Lesiak[a,c], J. Lieb [j], H. Machner [a], A. Magiera [c], G. Martinska [l], H. Nann [k], N. Piskinov[h], L. Pentchev [e], D. Protic [a], J. Ritman [a], P. von Rossen [a], B. J. Roy [i], P. Shukla[i], R. Siudak [d], I. Sitnik[h], M. Ulicny [a,l], R. Tsenov [f], J. Urban [l], G. Vankova[a,f], C. Wilkin[n], G. Wüstner[b]

a. Institut für Kernphysik, Forschungszentrum Jülich, Jülich, Germany
b. Zentrallabor für Elektronik, Forschungszentrum Jülich, Jülich, Germany
c. Institute of Physics, Jagellonian University, Krakow, Poland
d. Institute of Nuclear Physics, Pan, Krakow, Poland
e. Institute of Nuclear Physics and Nuclear Energy, Sofia, Bulgaria
f. Physics Faculty, University of Sofia, Sofia, Bulgaria
g. Institut für Strahlen- und Kernphysik der Universität Bonn, Bonn, Germany
h. LHE, JINR, Dubna, Russia
i. Nuclear Physics Division, BARC, Bombay, India
j. Physics Department, George Mason University, Fairfax, Virginia, USA
k. IUCF, Indiana University, Bloomington, Indiana, USA
l. P. J. Safarik University, Kosice, Slovakia
m. Technical University, Kosice, Kosice, Slovakia
n. Department of Physics & Astronomy, UCL, London, U.K.

Thank you for your attention

$$V = -\frac{4\pi}{2\mu_{\eta \mathrm{He}}}(V_R + iV_I)\rho(r), \tag{1}$$

$$\rho(r) = \frac{1}{(\sqrt{\pi}\alpha)^3}\, e^{-r^2/\alpha^2}, \qquad \alpha = \sqrt{\frac{2}{3}\,\langle r^2 \rangle} \tag{2}$$

$\mu_{\eta \mathrm{He}}$ is the reduced mass.

$$V_R + iV_I = 3a_{\eta N}\,\frac{\mu_{\eta \mathrm{He}}}{\mu_{\eta N}}\,. \tag{3}$$

$$q \cot \delta = \frac{1}{a} + \frac{1}{2} r_0 q^2 + \mathcal{O}(q^4)\,, \tag{4}$$