The search for a quasi-bound η^3He state in dp collisions with COSY-ANKE

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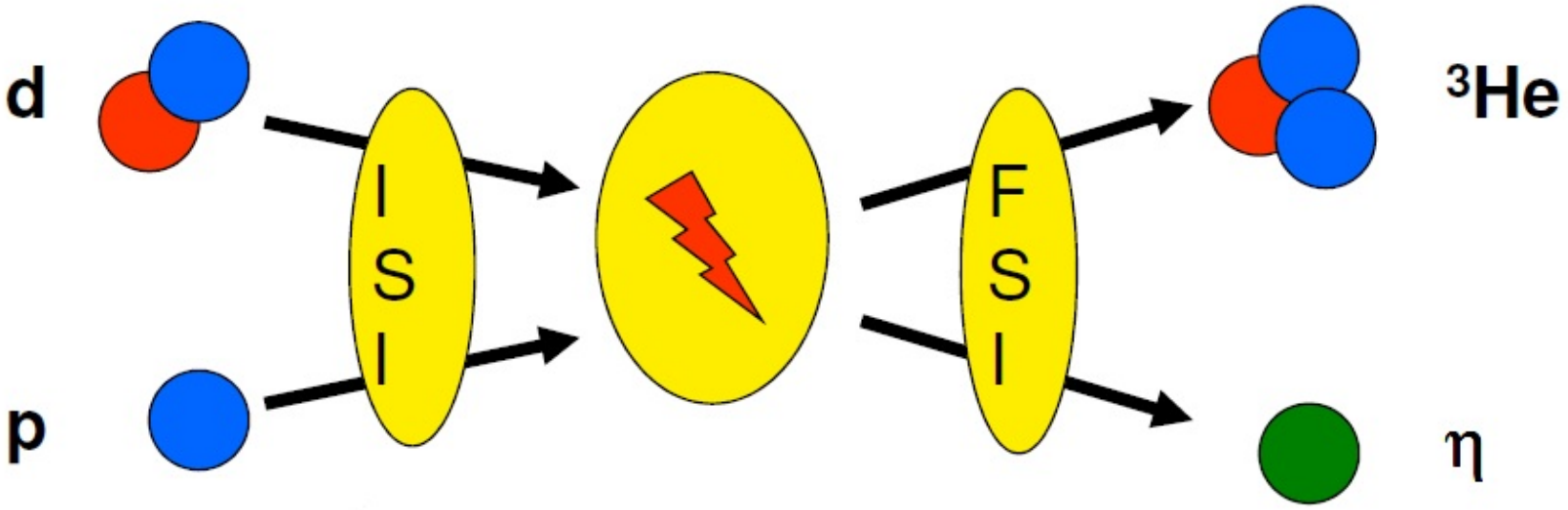
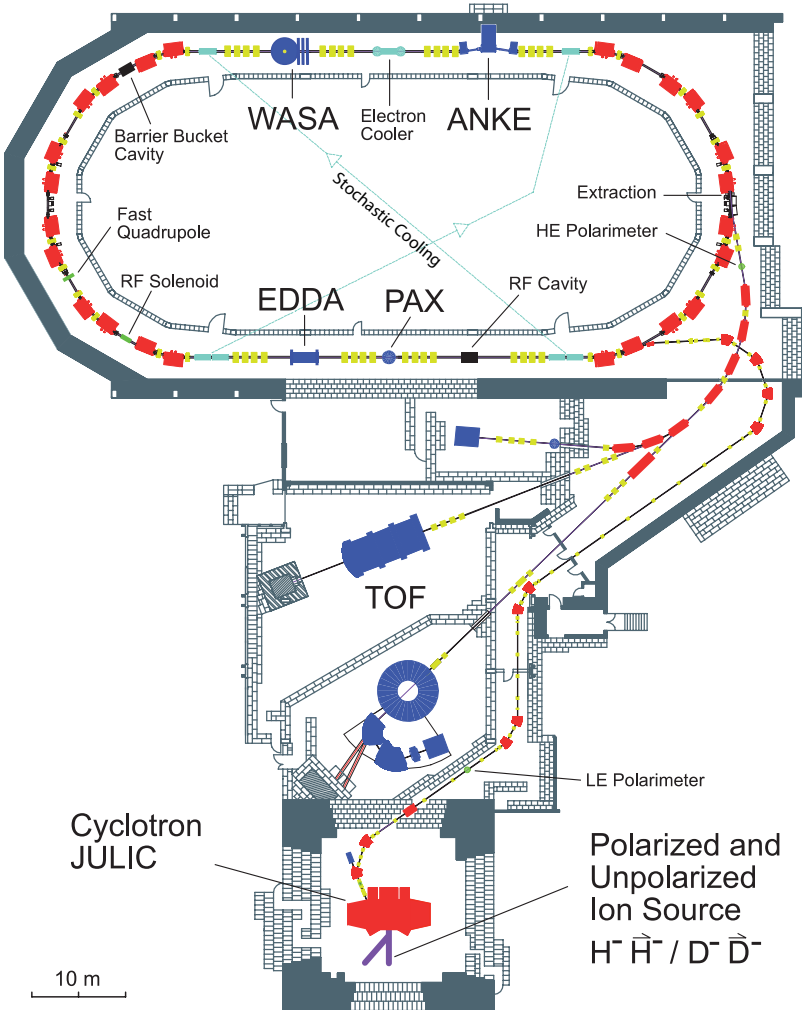
Motivation

- Search for a quasi-bound state of a meson-nucleon system



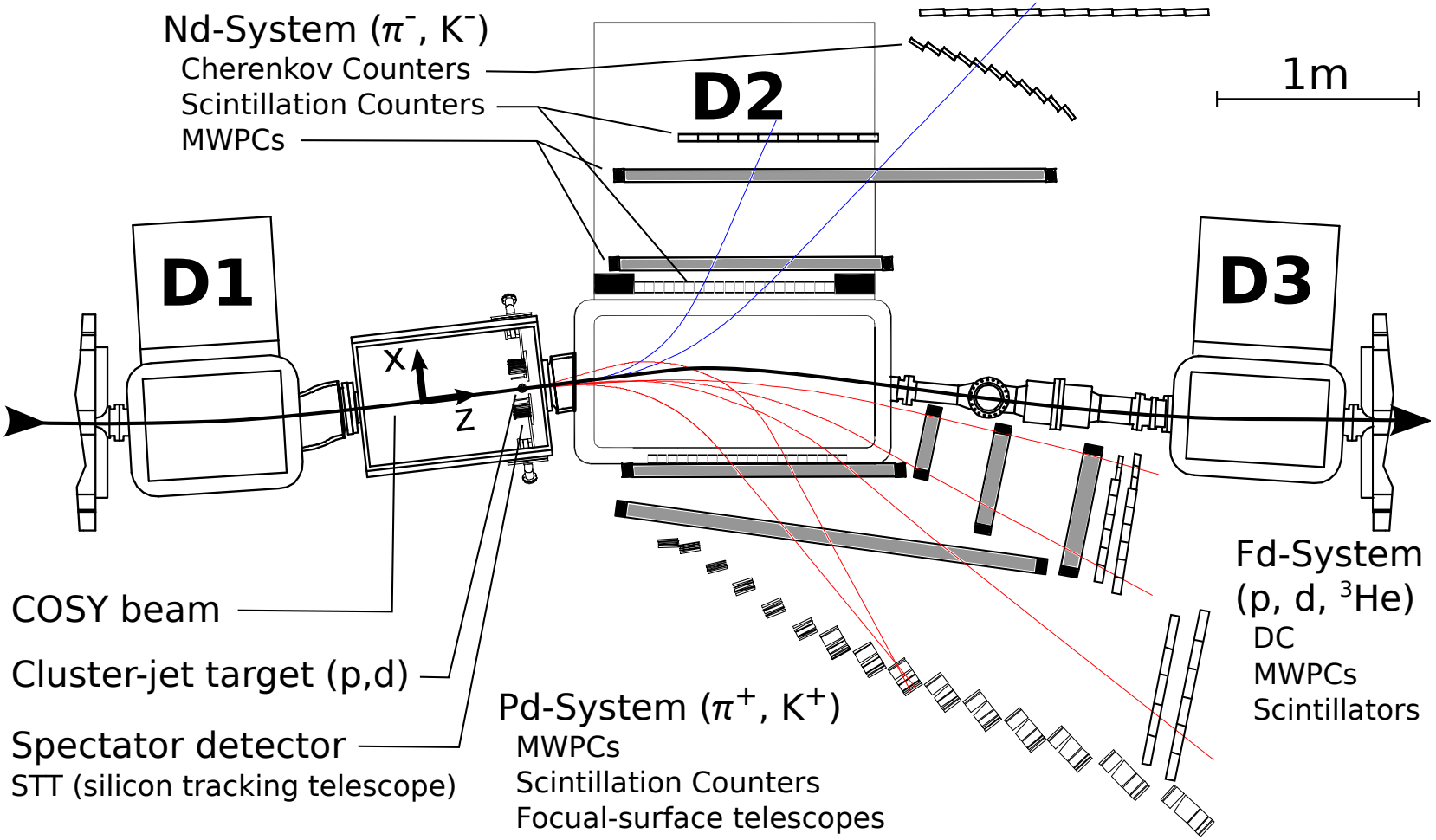
- Possible candidate with ANKE: $dp(\vec{d}p) \to {}^3\mathrm{He}\,\eta$
- Excitation close to threshold reveals hints towards strong final state interaction
- Polarised measurments allows investigation of spin-dependent non-FSI effects

COoler SYnchrotron - COSY



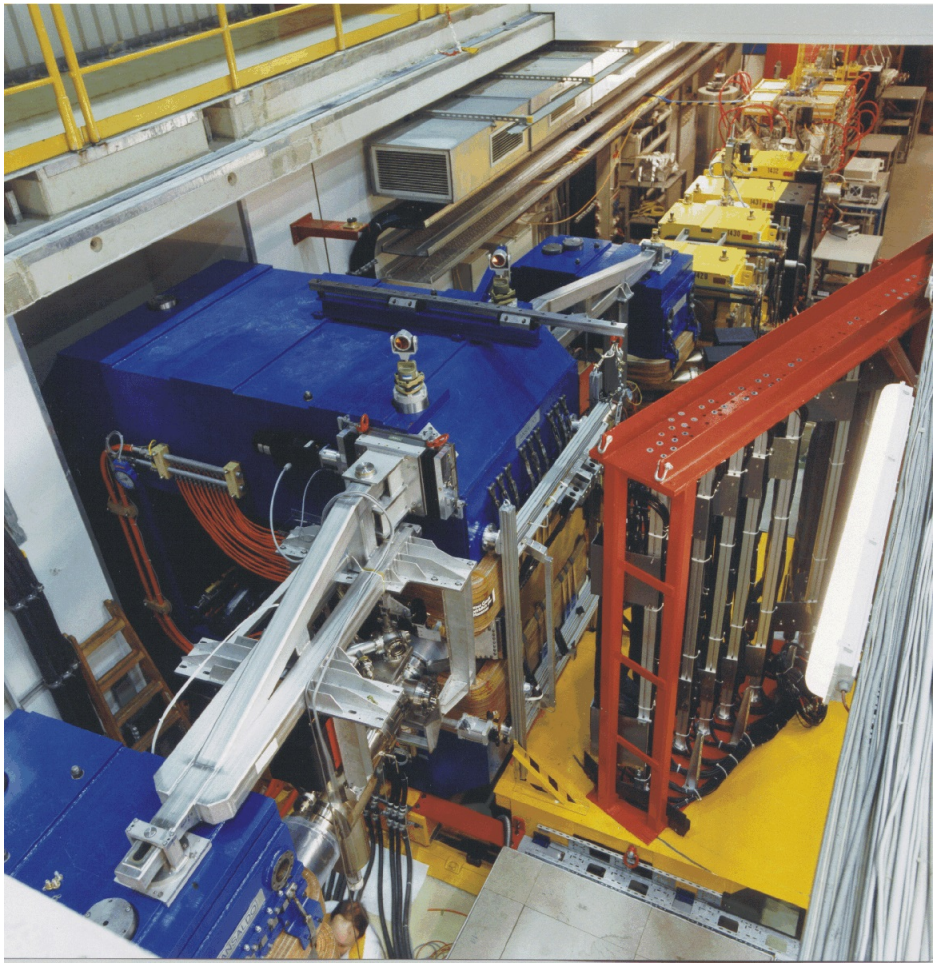
- Unpolarised source: $\approx 10^{10}$ particles in the ring
- Polarised source: $\approx 10^{9}$ particles in the ring
- Frequency: > 1 MHz

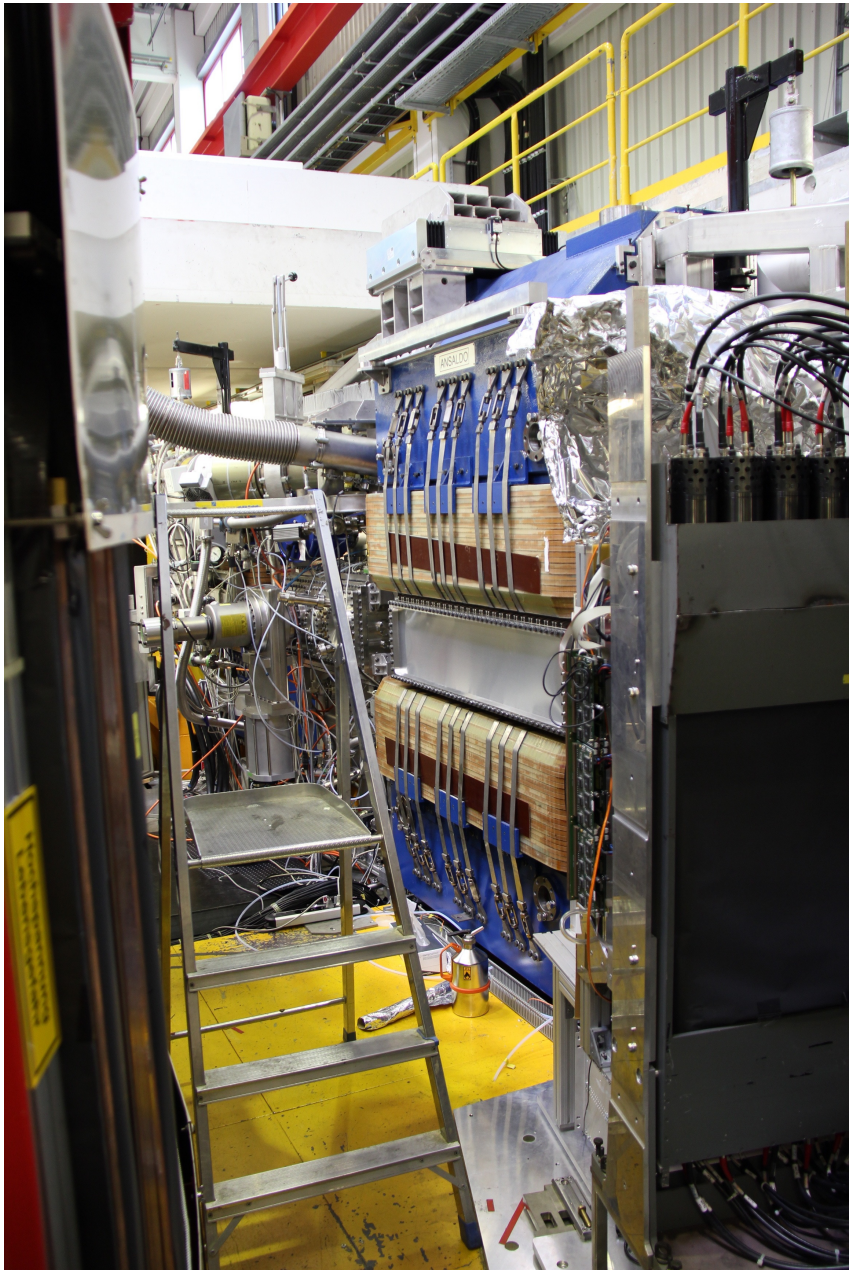
ANKE detection system



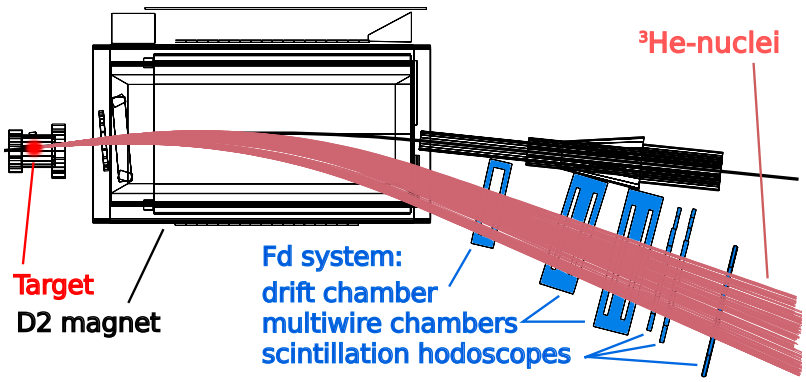
$$\vec{F}_L = q(\vec{v} \times \vec{B})$$

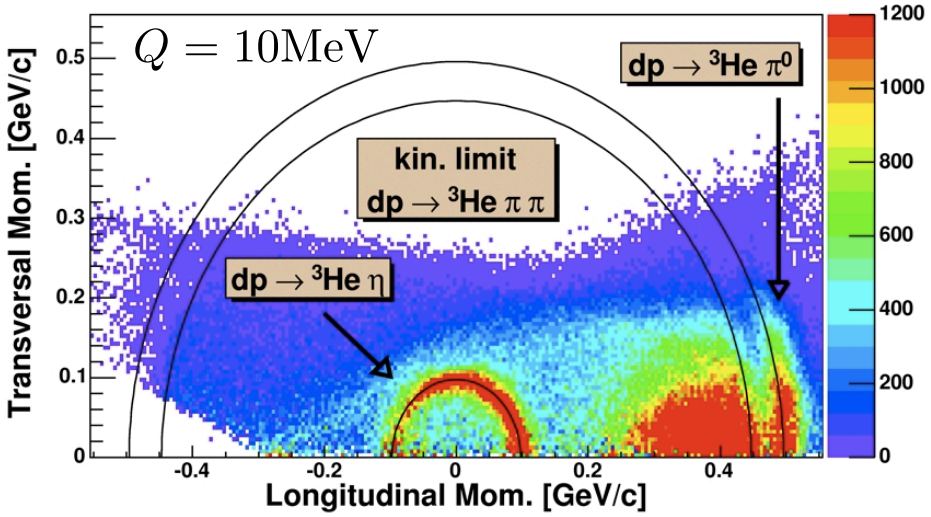
ANKE experiment





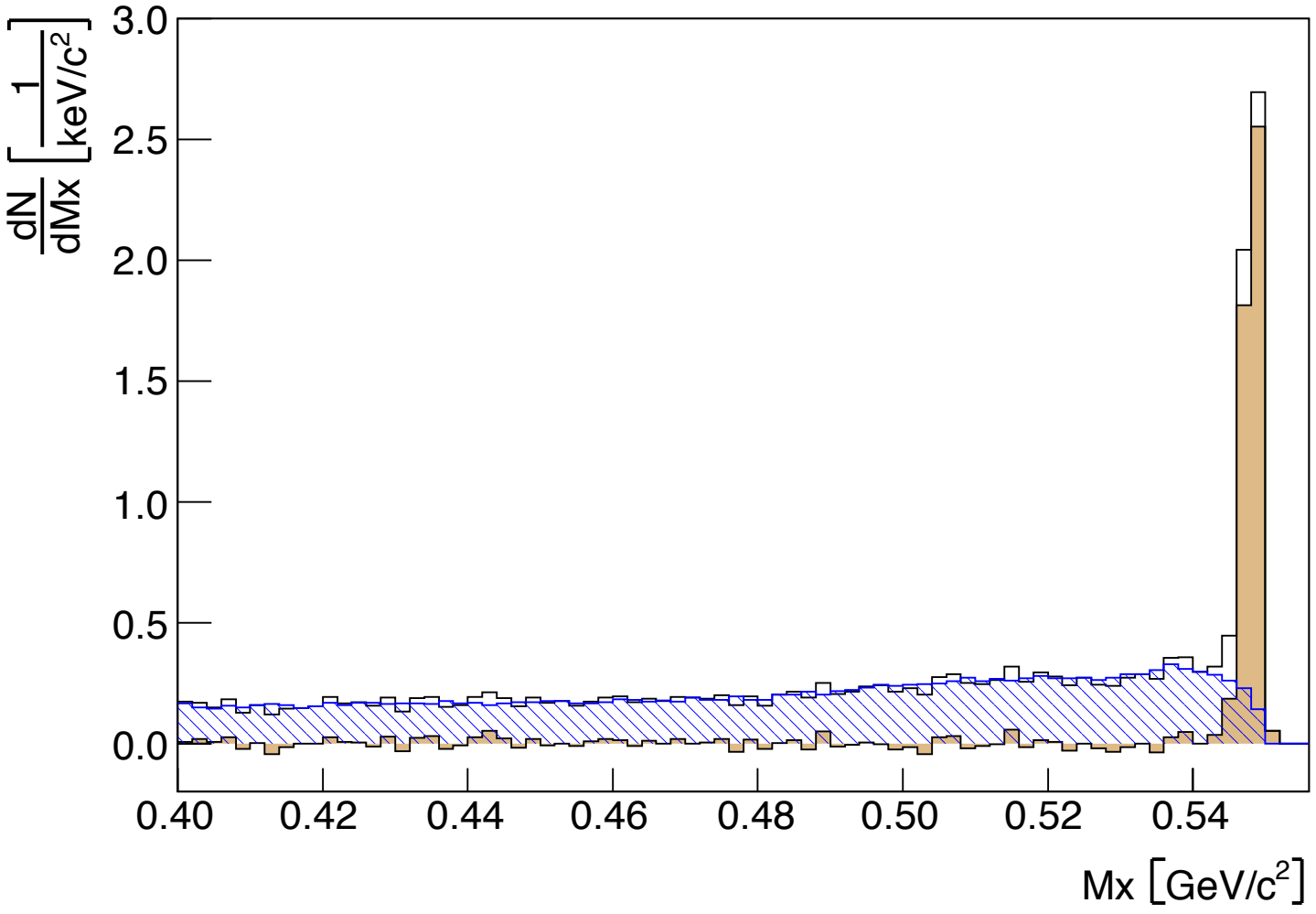
Measuring dp $\rightarrow$ ^{3}He η at ANKE at COSY





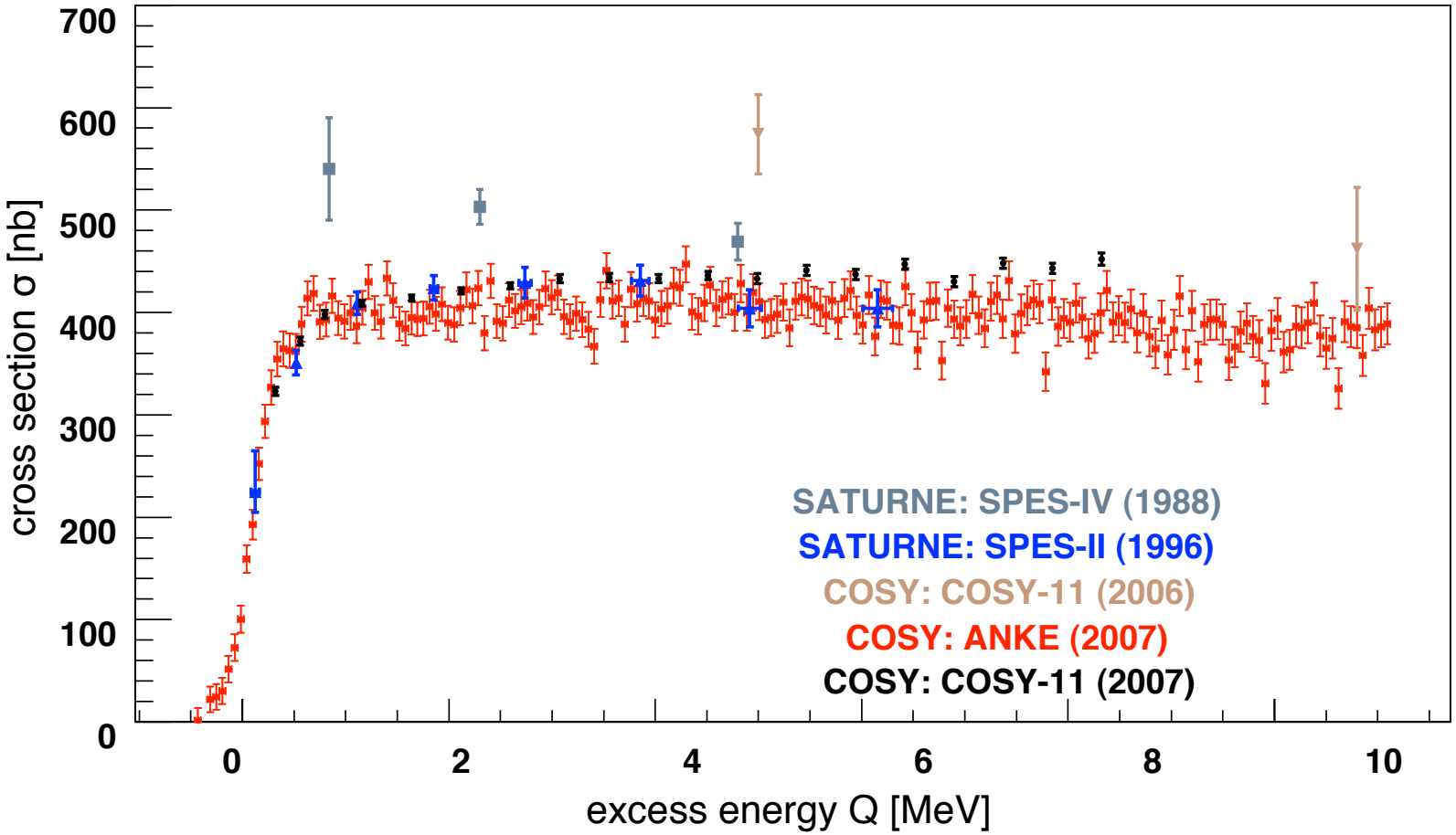
- ^{3}He nuclei detected in forward detection system, η reconstructed through missing mass technique
- Full geometrical acceptance for dp $\rightarrow$ ^{3}He η up to 20 MeV excess energy
- Continuously ramped beam from $Q = -5$ MeV to $Q = 11$ MeV

Extracting events of dp $\rightarrow$ ^{3}He η



- Subthreshold data describe background perfectly
- Clean η signal remains after subtraction

Unpolarised total cross section of dp $\rightarrow$ ^{3}He η



- 198 data points over 10 MeV in Q
- Cross section rises to plateau within < 1 MeV

^{3}Heη final state interaction

Description of the differential cross section

- Differential cross section of a two-body reaction:

$$\frac{p_i}{p_f} \cdot \frac{d\sigma}{d\Omega} = |f|^2 = |f_B \cdot FSI|^2 = |f_B|^2 \cdot |FSI|^2$$

- Effective range approximation:

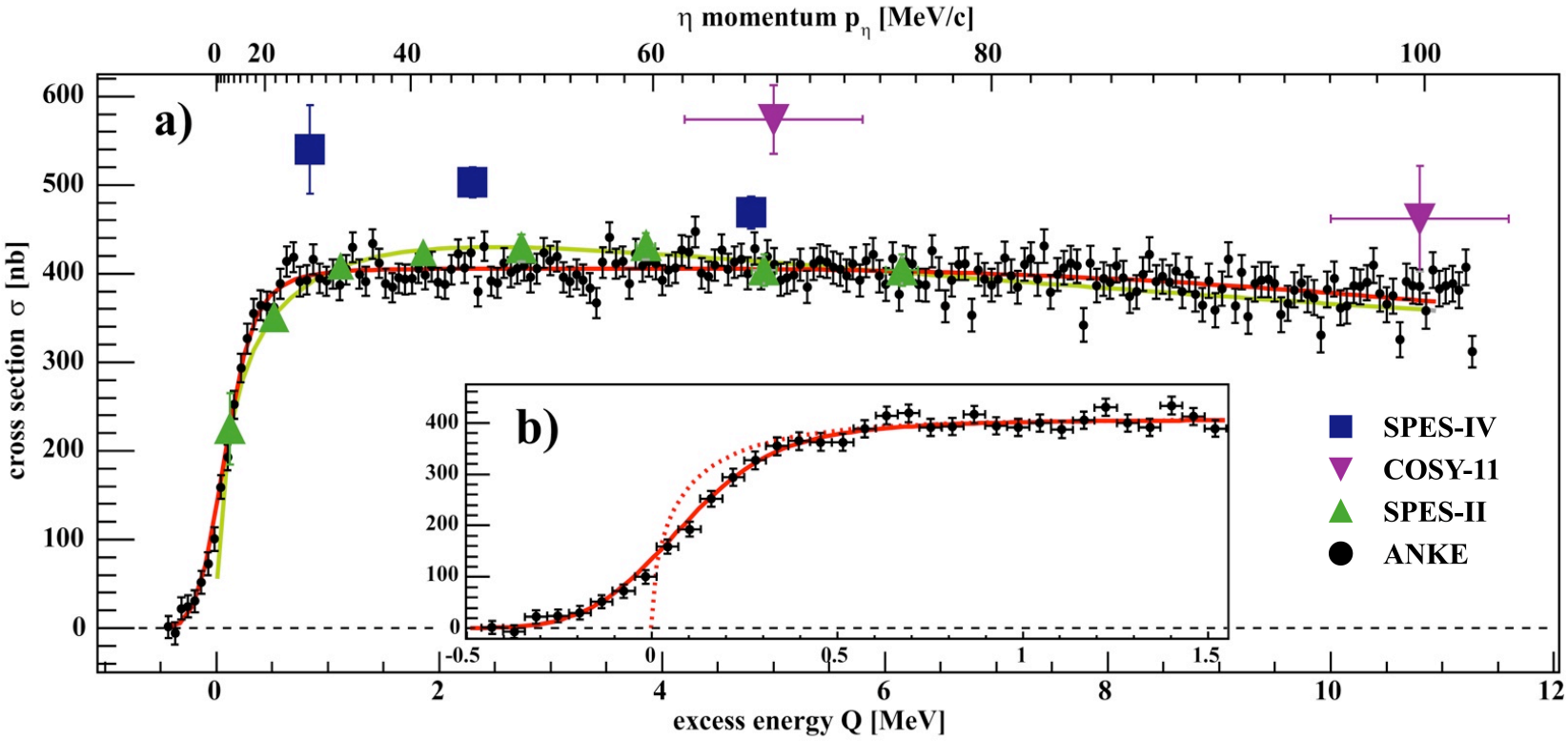
$$FSI = \frac{1}{1 + i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2}$$

- Alternative description with poles:

$$FSI = \frac{1}{\left(1 - \frac{p_f}{p_1}\right) \cdot \left(1 - \frac{p_f}{p_2}\right)}$$

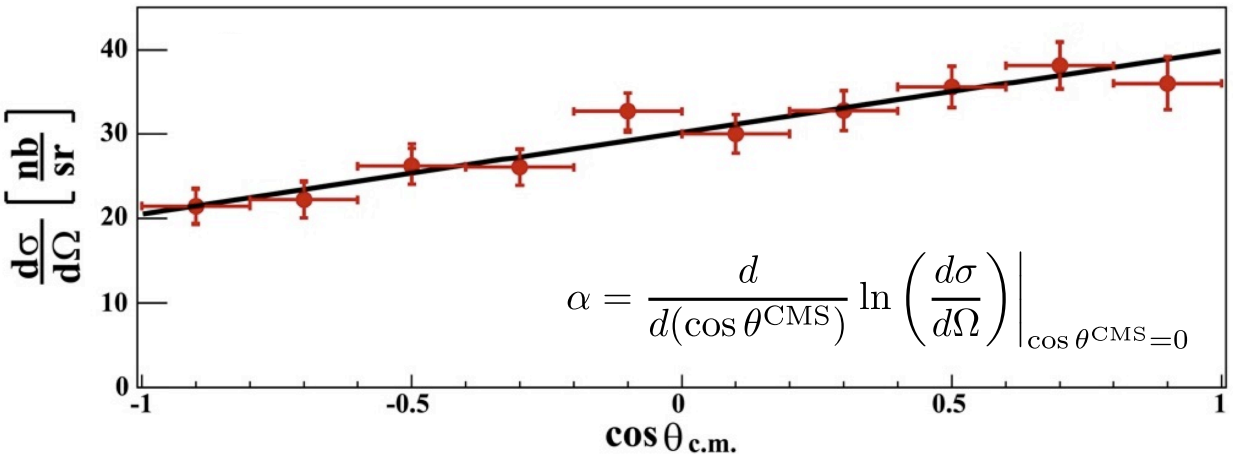
with $a = -i \cdot \frac{p_1 + p_2}{p_1 \cdot p_2}$ and $r_0 = +\frac{2 \cdot i}{p_1 + p_2}$

^{3}Heη final state interaction: unpolarized data



- Very good description for the whole energy range
- Pole close to threshold ($|Q_0| \approx 0.4\,\mathrm{MeV}$) might be an indication for a quasi-bound state

Description by s- and p-wave

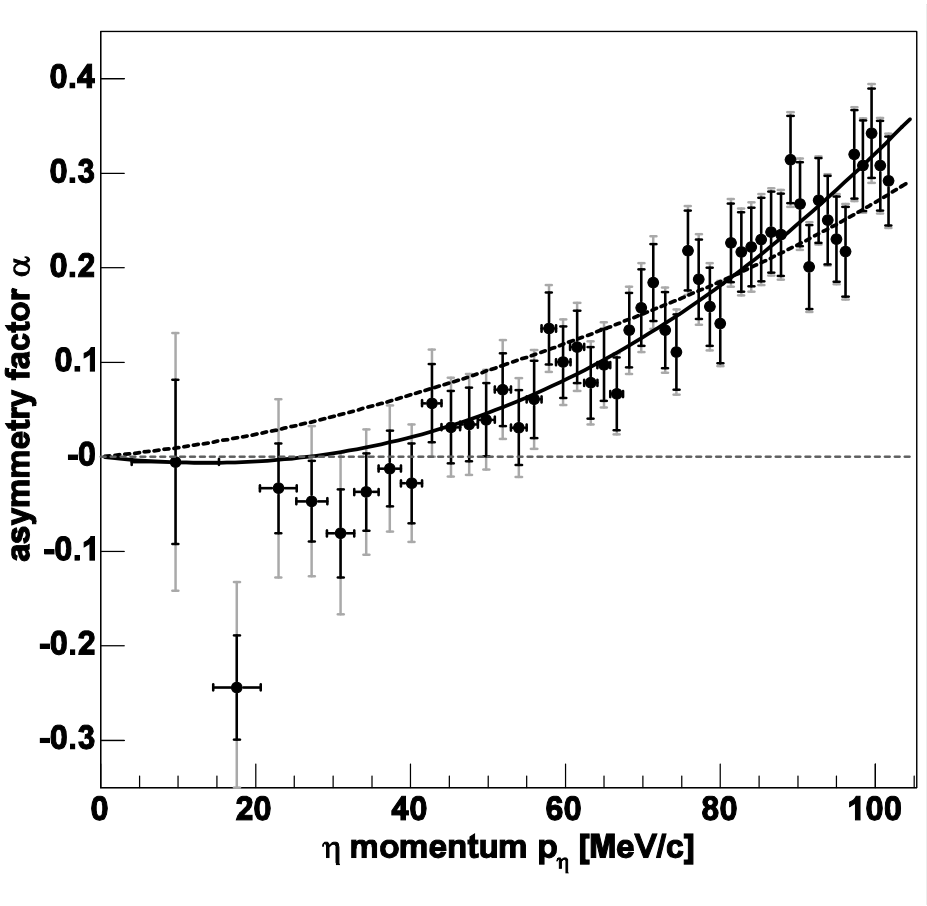


- Differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{p_f}{p_i} \cdot |f|^2 = \frac{p_f}{p_i} \cdot \left(|f_s|^2 + p_f^2 |f_p|^2 + 2p_f \Re(f_s^* \cdot f_p)\cos\theta\right)$$

- Hence in α: $\alpha = 2p_f \frac{\Re(f_s^* \cdot f_p)}{|f_s|^2 + p_\eta^2 |f_p|^2}$

Energy dependence of the asymmetry factor



- Contributions from higher partial waves already for $p_\eta < 60\frac{\text{MeV}}{\text{c}}$ $\quad (Q < 4\text{MeV})$
- Strong variation of phase between s- and p-wave

$\rightarrow$ Also expected from quasi-bound state

(C. Wilkin et al., PLB 654, 2007)

Why polarised measurements?

Additional information for FSI ansatz needed

- Test for further contributions besides FSI
- Investigate production amplitude very close to threshold, η^3He in relative s-wave

Alternative description of the η^3He s-wave production amplitude:

$$f = \bar{u}_{^3\mathrm{He}} \hat{p}_\mathrm{p} \cdot \left(A \vec{\varepsilon}_\mathrm{d} + iB \vec{\varepsilon}_\mathrm{d} \times \vec{\sigma} \right) u_\mathrm{p}$$

(Shown in J.-F. Germond & C. Wilkin, J. Phys. G 14, 181 (1988))

$$\frac{d\sigma}{d\Omega} = \frac{1}{3} \frac{p_f}{p_i} \left[|A|^2 + 2 \cdot |B|^2 \right]$$

with A, B as the two s-wave amplitudes of the ^{3}Heη system

Why polarised measurements?

Assumption 1 Cross sections only differ from phase space because of FSI
$\Rightarrow A, B$ show same energy dependence

Assumption 2 Cross sections depend on spin dependent production amplitudes (no FSI effect)
$\Rightarrow A, B$ might show different energy dependence

How to separate $|A|^2$ and $|B|^2$?

$\Rightarrow$ Tensor analysing power T_{20}:

$$T_{20}(p_f) = \sqrt{2}\frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2}$$

Why polarised measurements?

Assumption: $|A|^2$ and $|B|^2$ only depend on FSI

$$|A|^2 = |A_0|^2 \cdot \mathrm{FSI}(p_f)$$
$$|B|^2 = |B_0|^2 \cdot \mathrm{FSI}(p_f)$$

$$\Rightarrow T_{20}(p_f) = \sqrt{2} \cdot \frac{|B_0|^2 - |A_0|^2}{|A_0|^2 + 2|B_0|^2} \cdot \frac{\mathrm{FSI}(p_f)}{\mathrm{FSI}(p_f)} = const.$$

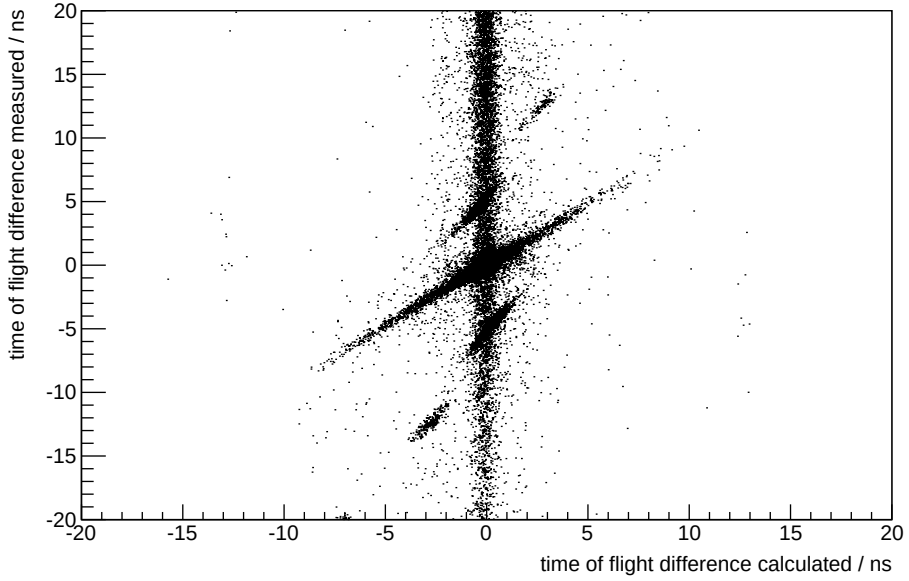
Measure T_{20} via ratio of polarised/unpolarised cross sections

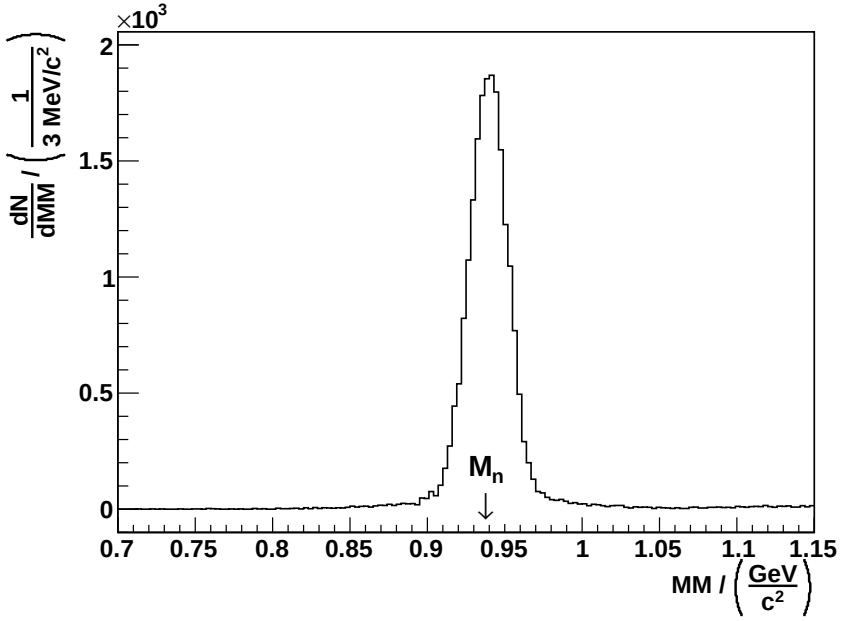
$$\frac{d\sigma^{\uparrow}}{dt}(\theta,\varphi)/\frac{d\sigma^{0}}{dt}(\theta) = 1 + \sqrt{3} p_z i T_{11}(\theta)\cos\varphi$$
$$-\frac{1}{2\sqrt{2}} p_{zz} T_{20}(\theta) - \frac{\sqrt{3}}{2} p_{zz} T_{22}(\theta)\cos 2\varphi$$

Determining p_{zz}

Investigate reaction $d + p \to \{pp\}_s + n$ with known analysing powers ($E_{pp} \leq 3\,\mathrm{MeV}$)

$$\frac{d\sigma^{\uparrow}}{dt}(\theta,\varphi)/\frac{d\sigma^{0}}{dt}(\theta) = 1 + \sqrt{3}p_z iT_{11}(\theta)\cos\varphi$$
$$-\frac{1}{2\sqrt{2}}p_{zz}\,T_{20}(\theta) - \frac{\sqrt{3}}{2}p_{zz}\,T_{22}(\theta)\cos 2\varphi$$





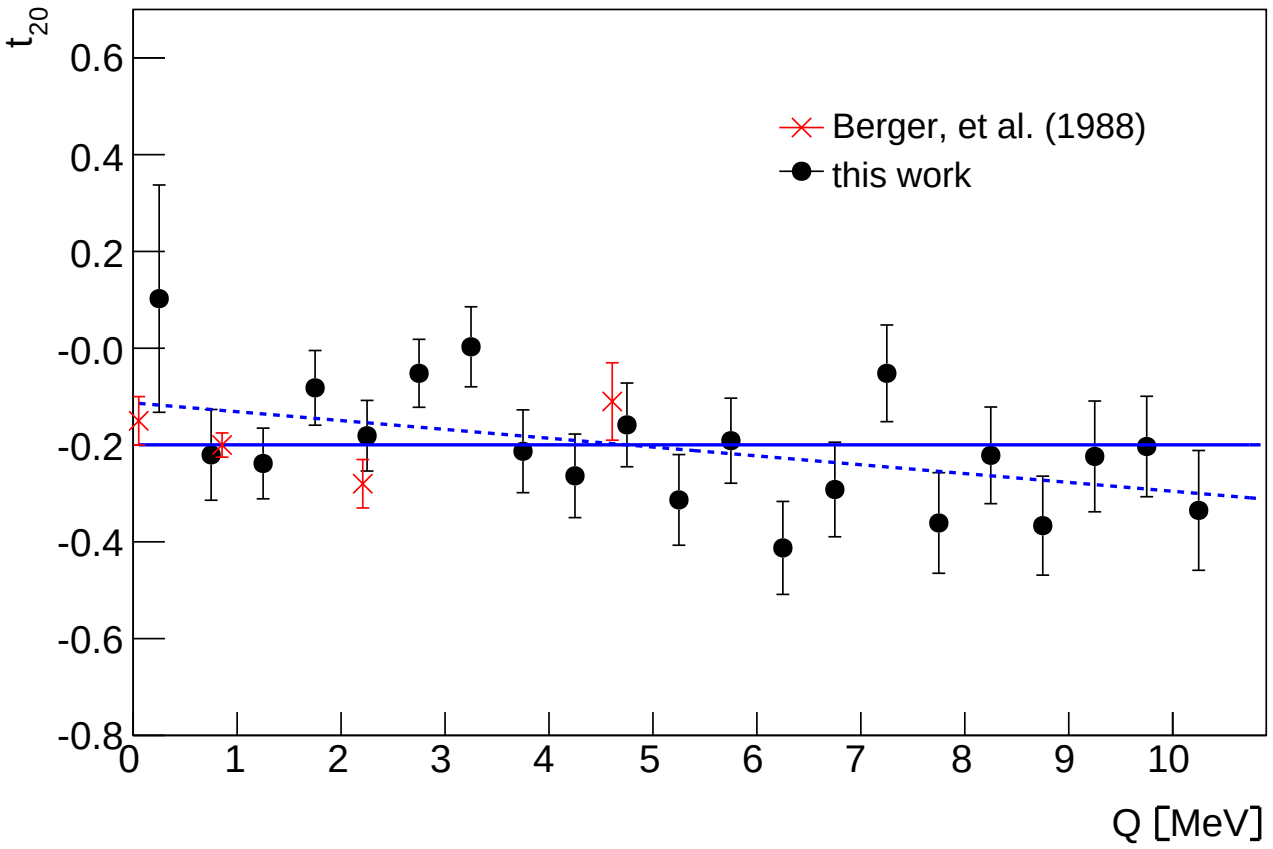
Polarisation numbers

Mode	p_z^{ideal}	p_{zz}^{ideal}	p_z^{LEP}	p_{zz}^{ANKE}
1	$+1/3$	-1	$+0.244 \pm 0.032$	-0.62 ± 0.05
2	-1	$+1$	-0.707 ± 0.026	$+0.67 \pm 0.05$
3	$+1$	$+1$	$+0.601 \pm 0.027$	$+0.22 \pm 0.05$:(

- Mode 3 obviously not working properly
- One or more hyperfine transitions not operating as desired

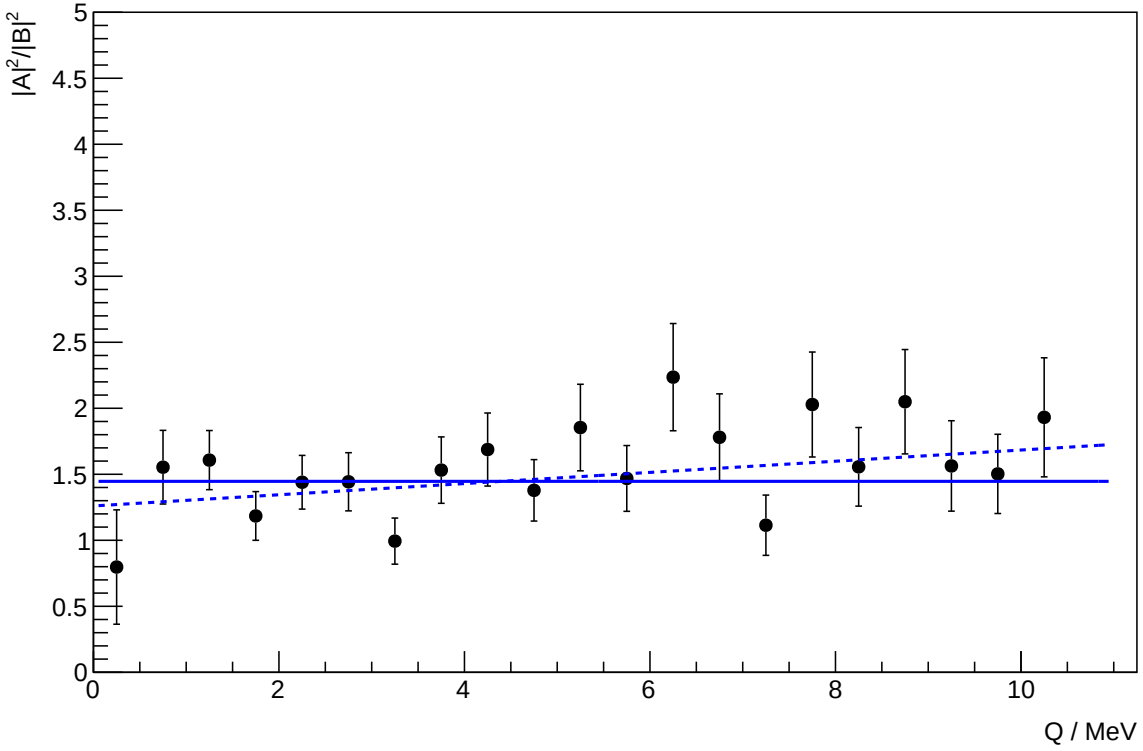
$\rightarrow$ Only modes 1 and 2 used for rest of analysis

T_{20}



- Data on T_{20} consistent with Berger, et al.
- T_{20} constant close to threshold

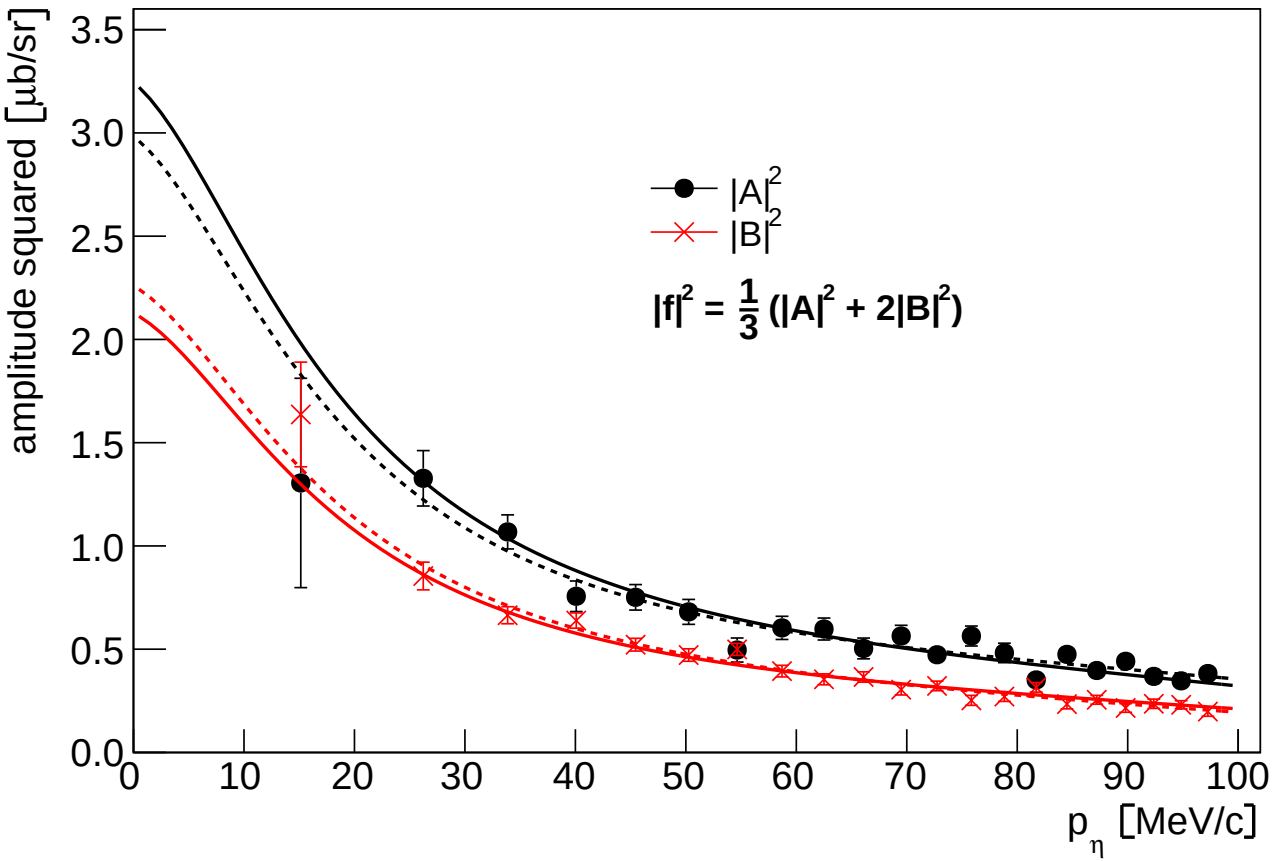
$|A|^2/|B|^2$



- Extract amplitude ratio $|A|^2/|B|^2$ from T_{20}

$$\frac{|A|^2}{|B|^2} = \frac{\sqrt{2} - 2T_{20}}{T_{20} + \sqrt{2}}$$

Individual squared amplitudes $|A|^2, |B|^2$



- Effect of slope (dashed lines) is small compared to the variation of the squared production amplitude

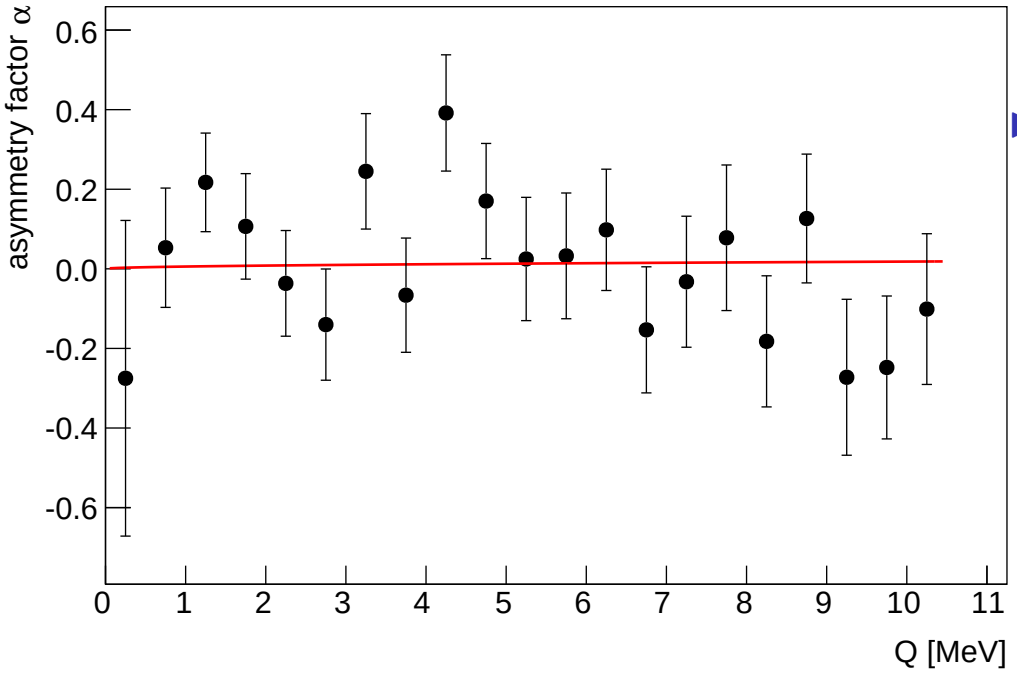
→ Compatible with strong final state interaction

T_{20} (angular dependence)

- T_{20} in collinear kinematics sensitive to interference of s- and p-wave

$$\sqrt{2}IT_{20} = 2(|B|^2 - |A|^2) + (|D|^2 - |C|^2)p_\eta^2(3\cos^2\theta_\eta - 1) \pm 4p_\eta \cos\theta_\eta \Re(B^* D - A^* C)$$

(C. Wilkin et al., PLB 654, 2007)



- Increasing asymmetry with Q would be expected due to rapid phase variation of s- and p-wave (see unpolarised data)

Possible implications of small asymmetry

A, B might contain contributions from higher partial waves

$$\begin{aligned} A &= A_0 \left[\mathrm{FSI}(p_\eta) + \alpha p_\eta \cos\theta + \beta p_\eta^2 (3\cos^2\theta - 1)/2 \right] \\ B &= B_0 \left[\mathrm{FSI}(p_\eta) + \alpha p_\eta \cos\theta + \beta p_\eta^2 (3\cos^2\theta - 1)/2 \right] \end{aligned}$$

- FSI factor only influences s-wave term
- A proportional to B in terms of p_η and θ

$\rightarrow$ T_{20} independent on both variables

- Linearity in $\cos\theta$ could arise from cancelation of s-d-interference and square of p-waves

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Summary

- Reaction $\vec{\mathrm{d}} + \mathrm{p} \rightarrow {}^3\mathrm{He} + \eta$ studied in energy range $Q = -5\,\mathrm{MeV}$ to $10\,\mathrm{MeV}$ relative to η-threshold
- Tensor polarisation determined with $d + p \rightarrow \{pp\}_s + n$ reaction
- Amplitudes $|A|^2, |B|^2$ show strong energy dependence compared to possible spin dependent contributions
- Rapid energy variation of $|f|^2$ close to threshold was found to be dominated by strong FSI

$\rightarrow$ Negligible effect from spin-dependent contributions

- Weak angular dependence of T_{20} leads to deeper insight into A, B

Thank you for your attention

Additional Slides

Production amplitude

- Two independent η s-wave amplitudes (close to threshold)
- Possible dp spin combinations: $S = \frac{3}{2}, \frac{1}{2}$
- Couples with orbital angular momentum of dp: $L_{dp} = 1$
  $\Rightarrow \quad J = \frac{1}{2}^{-}$
- Alternative production amplitude used for analogous π^0 production
  $f = \bar{u}_{^3\mathrm{He}} \hat{p}_\mathrm{p} \cdot (A\vec{\varepsilon}_\mathrm{d} + iB\vec{\varepsilon}_\mathrm{d} \times \vec{\sigma})\, u_\mathrm{p}$

$\bar{u}_{^3\mathrm{He}}$:Spinors of the particles

$\vec{\varepsilon}_\mathrm{d}$:Polarisation vector of the deuteron

$\hat{p}_\mathrm{p}$:Direction of momentum

$\vec{\sigma}$:Pauli matrix

^{3}Heη final state interaction

- Fit to the data for $Q < 11$MeV

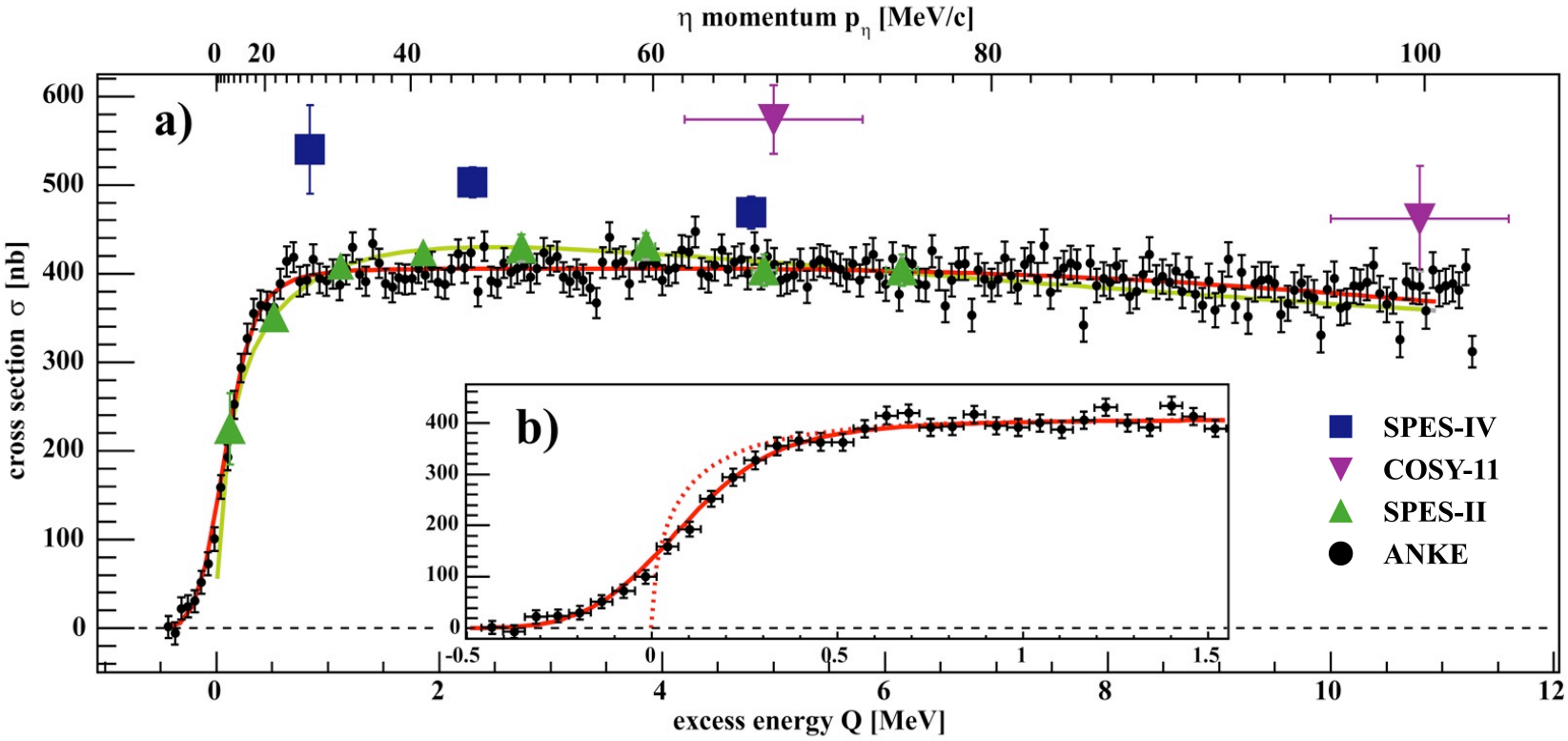
$$p_1 = \left[\left(-5 \pm 7^{+2}_{-1}\right) \pm i \cdot (19 \pm 2 \pm 1)\right] \frac{\text{MeV}}{\text{c}}$$
$$p_2 = \left[(106 \pm 5) \pm i \cdot \left(76 \pm 13^{+1}_{-2}\right)\right] \frac{\text{MeV}}{\text{c}}$$

- Pole of the production amplitude:

$$\begin{aligned} Q_0 &= \frac{p_1^2}{2 \cdot m_{\text{red}}} \\ &= [(-0.30 \pm 0.15 \pm 0.04) \pm i \cdot (0.21 \pm 0.29 \pm 0.06)]\,\text{MeV} \\ |Q_0| &\approx 0.4 \end{aligned}$$

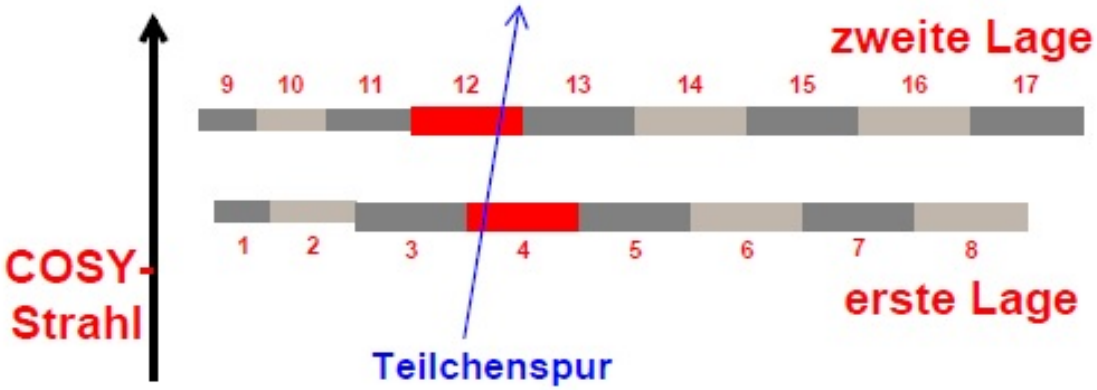
- Pole close to threshold expected from a quasi-bound state

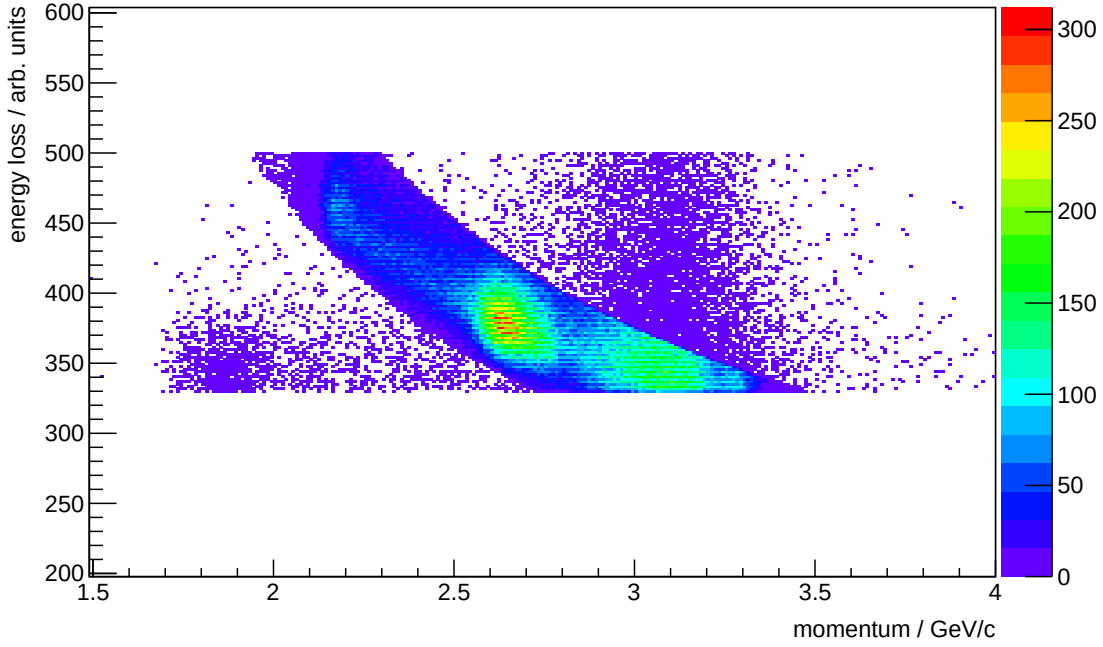
^{3}Heη final state interaction



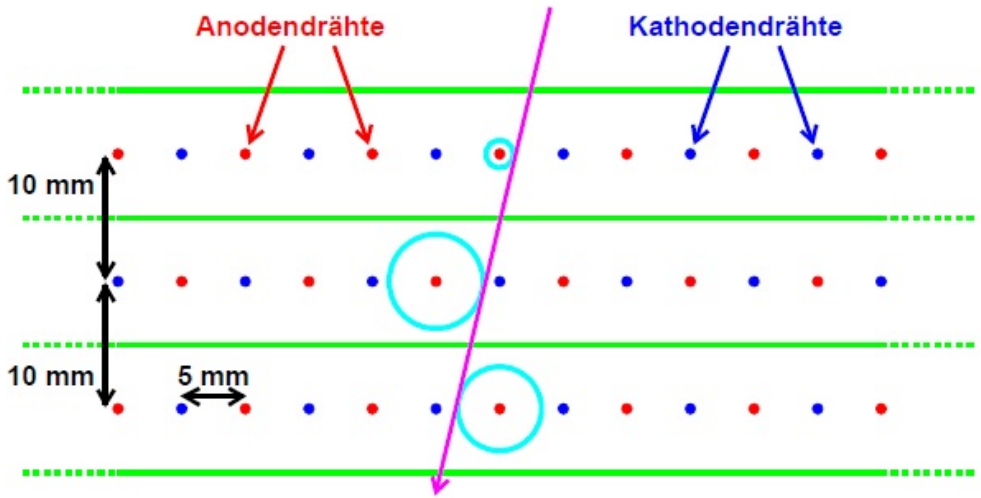
- Very good description for the whole energy range
- Unexpected large scattering length:
  $a_{^3\mathrm{He}\eta} = \left[\pm\left(10.7 \pm 0.8^{+0.1}_{-0.5}\right) + i \cdot \left(1.5 \pm 2.6^{-0.3}_{+1.0}\right)\right]$ fm

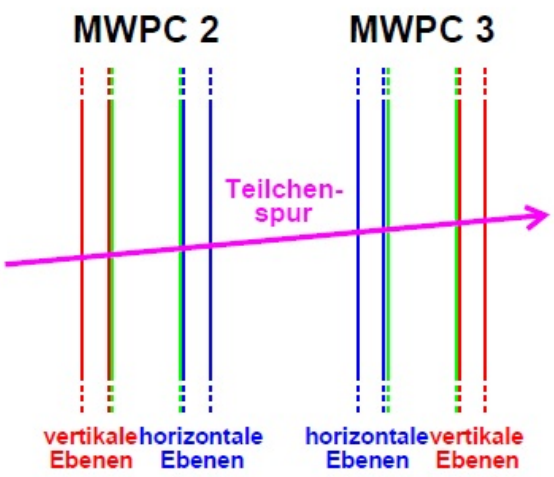
Scintillator hodoscope

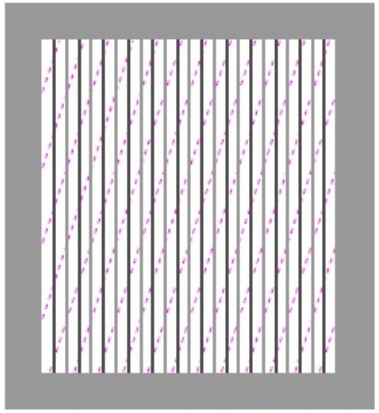




MultiWire Drift/Proportional Chambers



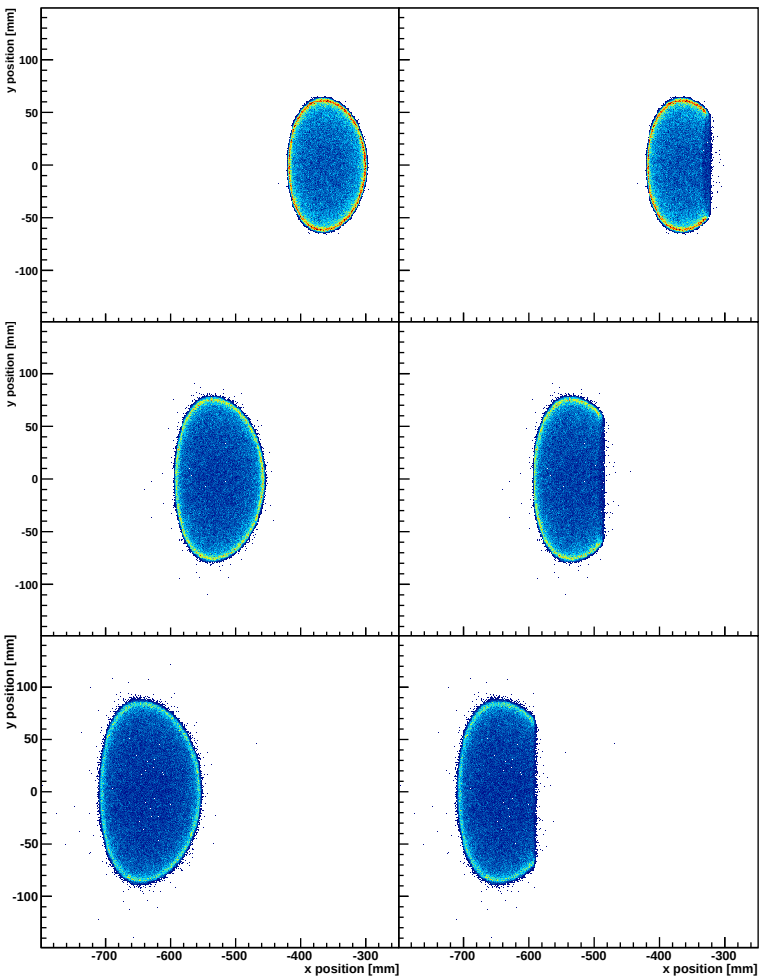


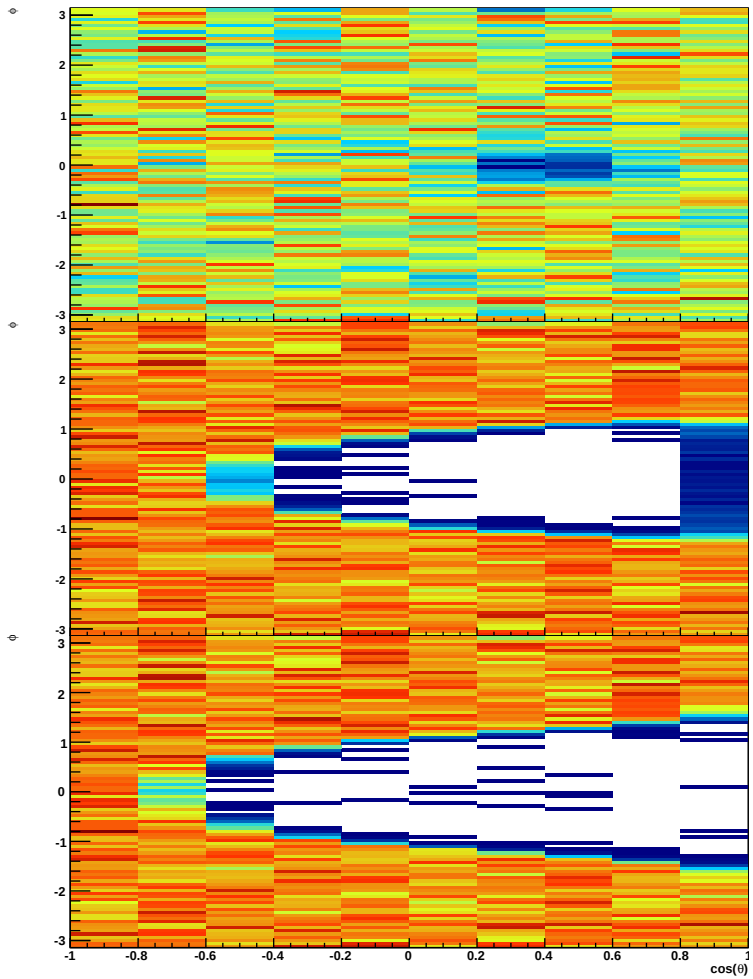


Schematische Aufsicht auf die vertikalen Draht- und Streifenebenen

- MWDC resolution $\approx 200\mu\mathrm{m}$
- MWPC resolution $\approx 1\mathrm{mm}$
- Precision of angle determination $\approx 0.2^\circ$
- Resulting momentum resolution $\lesssim 1\%$

Acceptance for $dp \to {}^3\mathrm{He}\,\eta$

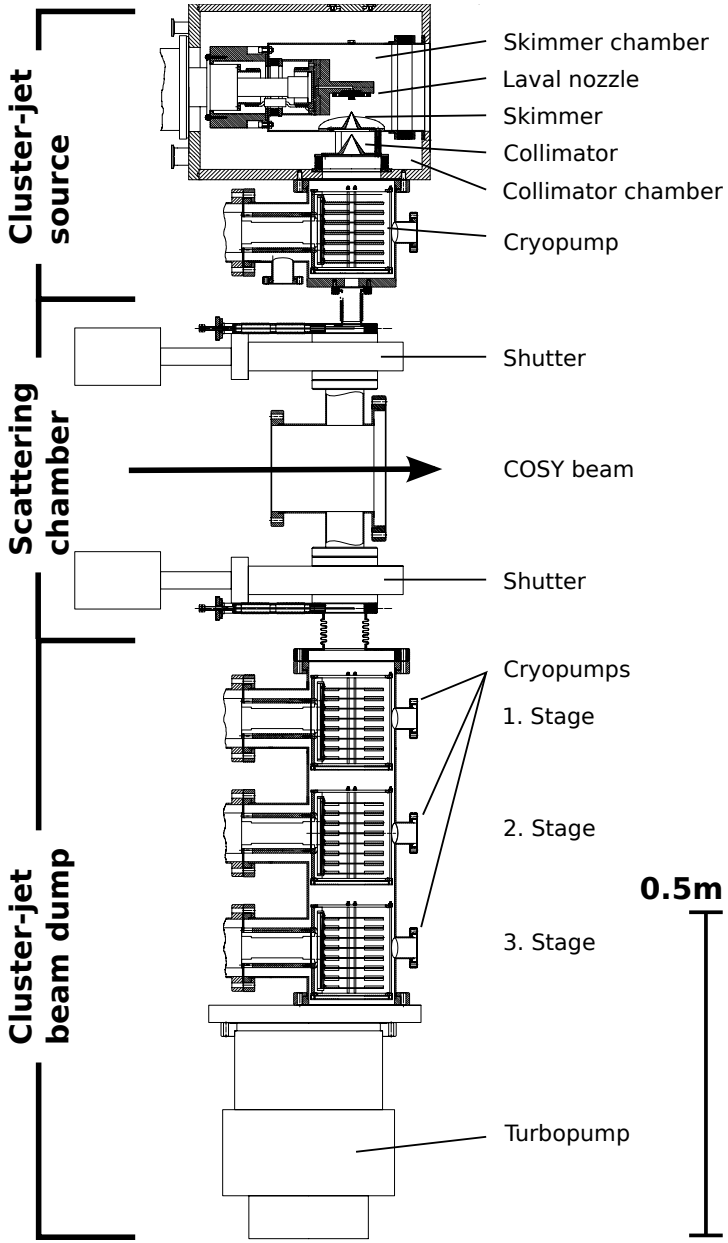


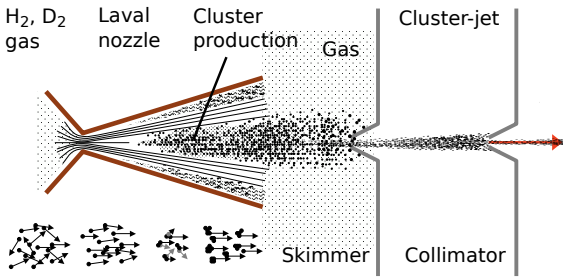


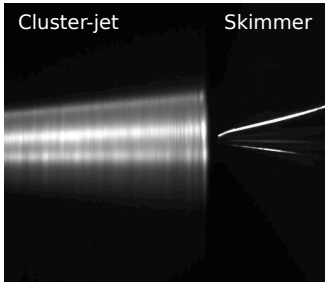
- Defective counter in third hodoscope layer

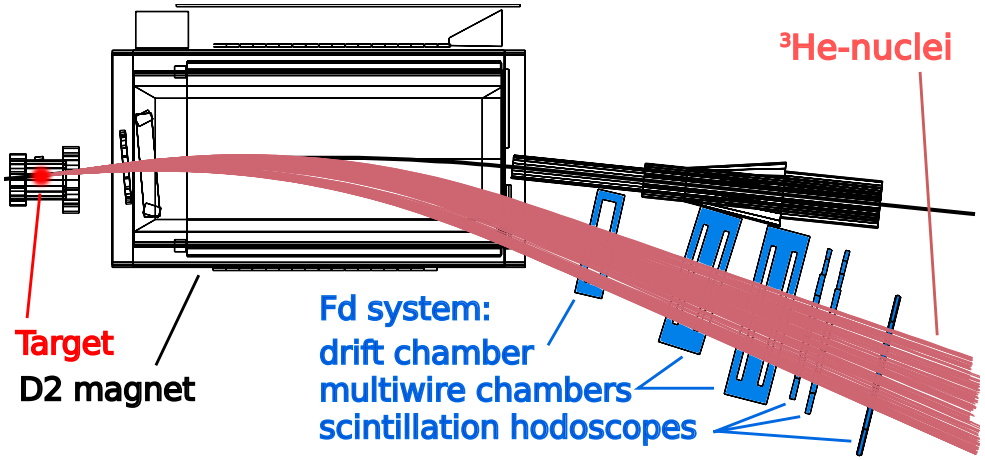
$\to$ Group data in 10 $\cos\theta$ and 4 ϕ bins, so that $\int \cos 2\phi \, \mathrm{d}\phi = 0$

Measuring dp $\rightarrow$ ^{3}He η at ANKE at COSY









- Full geometrical acceptance for dp $\rightarrow$ ^{3}He η up to 20 MeV excess energy