Westfälische Wilhelms-Universität Münster

Investigation of the ^{3}He-η system with polarized beams at ANKE

II International Symposium on Mesic Nuclei

September 22-25, 2013

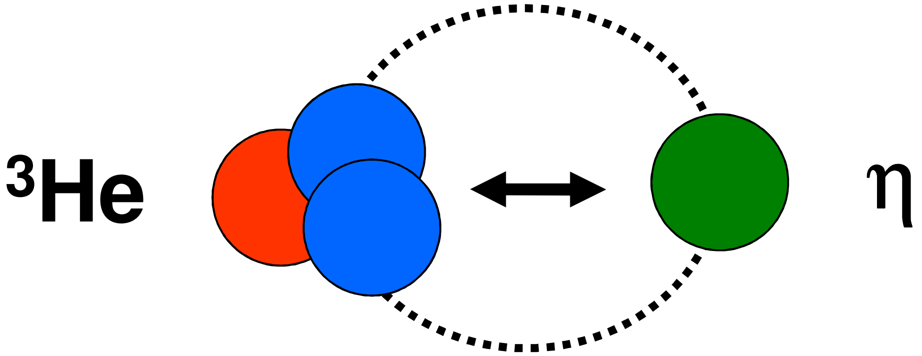
Institut für Kernphysik

Alfons Khoukaz

wissen.leben
WWU Münster

Why η-Meson Production Close to Threshold?

- Do bound meson-nucleus systems exist?



- ANKE: $\overset{(\rightarrow)}{d}+p \rightarrow {}^3He+\eta$
- Excitation function close to threshold → FSI
- Polarized beam → Test of FSI hypothesis, role of spins

The COSY-Accelerator at Jülich

COSY (Cooler Synchrotron)

Energy range
- 0.045 – 2.8 GeV (p)
- 0.023 – 2.3 GeV (d)
  (momentum 3.7 GeV/c)

Beam cooling
- Electron cooling
- Stochastic cooling

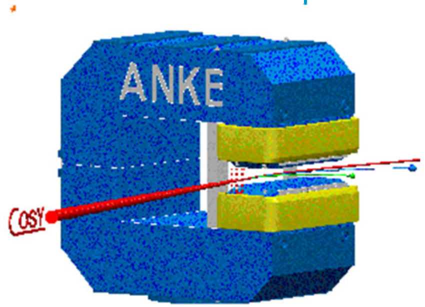
Polarisation
- p, d beams & targets

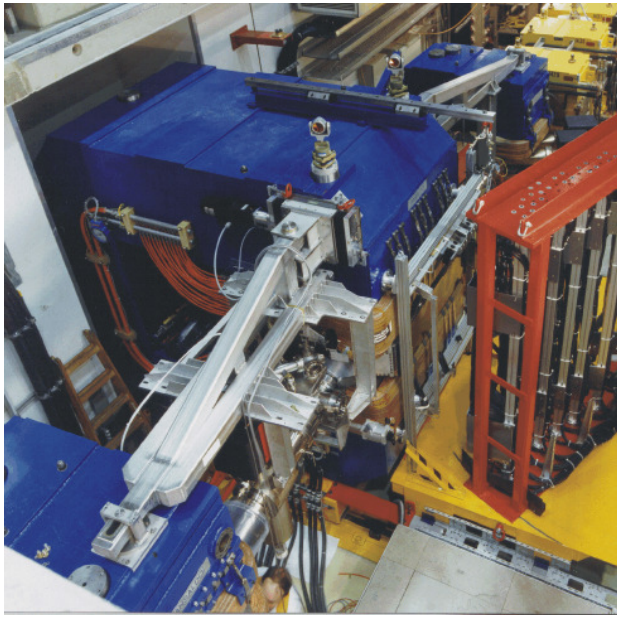
Beams
- internal, external

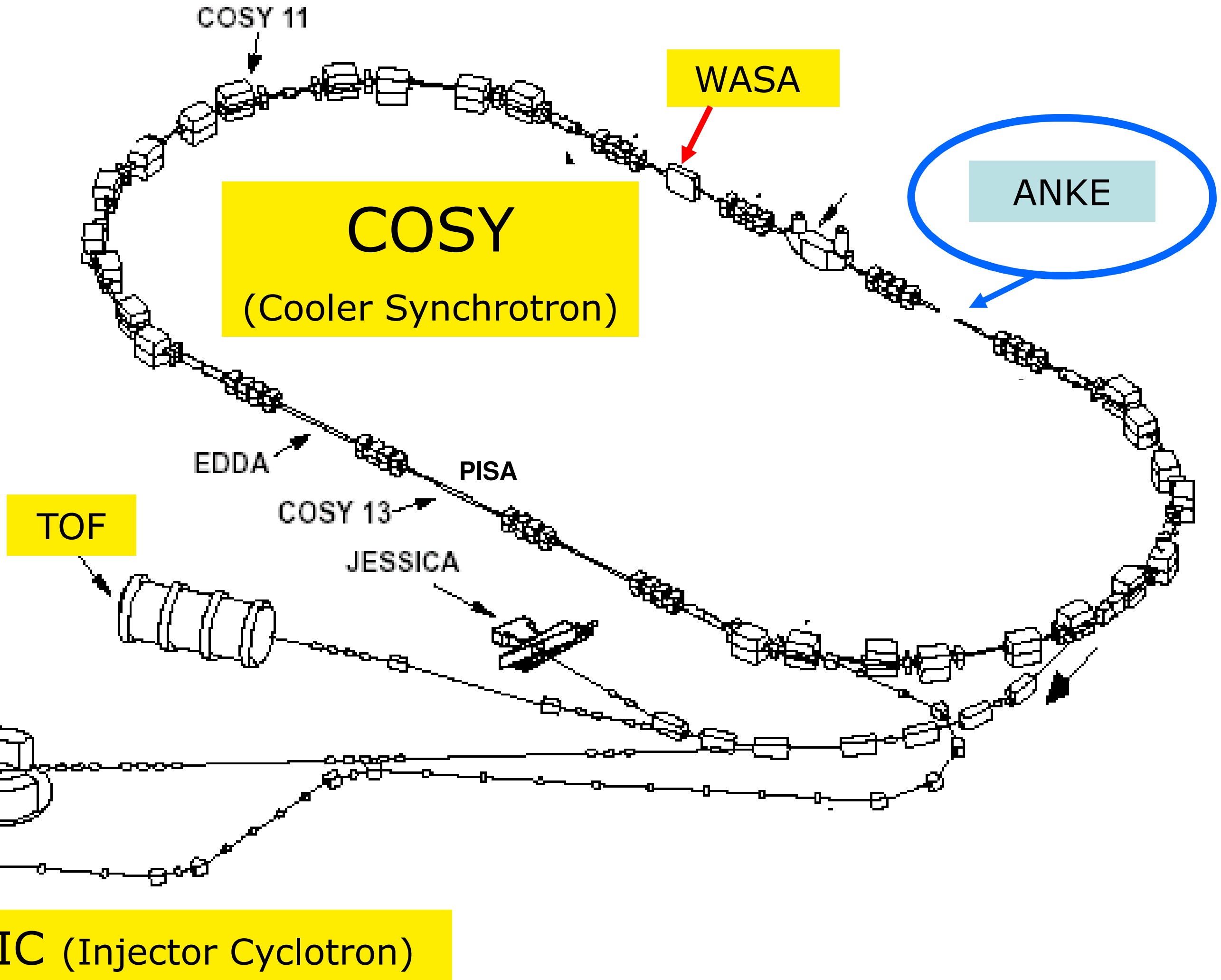
Experiments, Detectors
- ANKE, TOF, WASA, …

Westfälische Wilhelms-Universität Münster

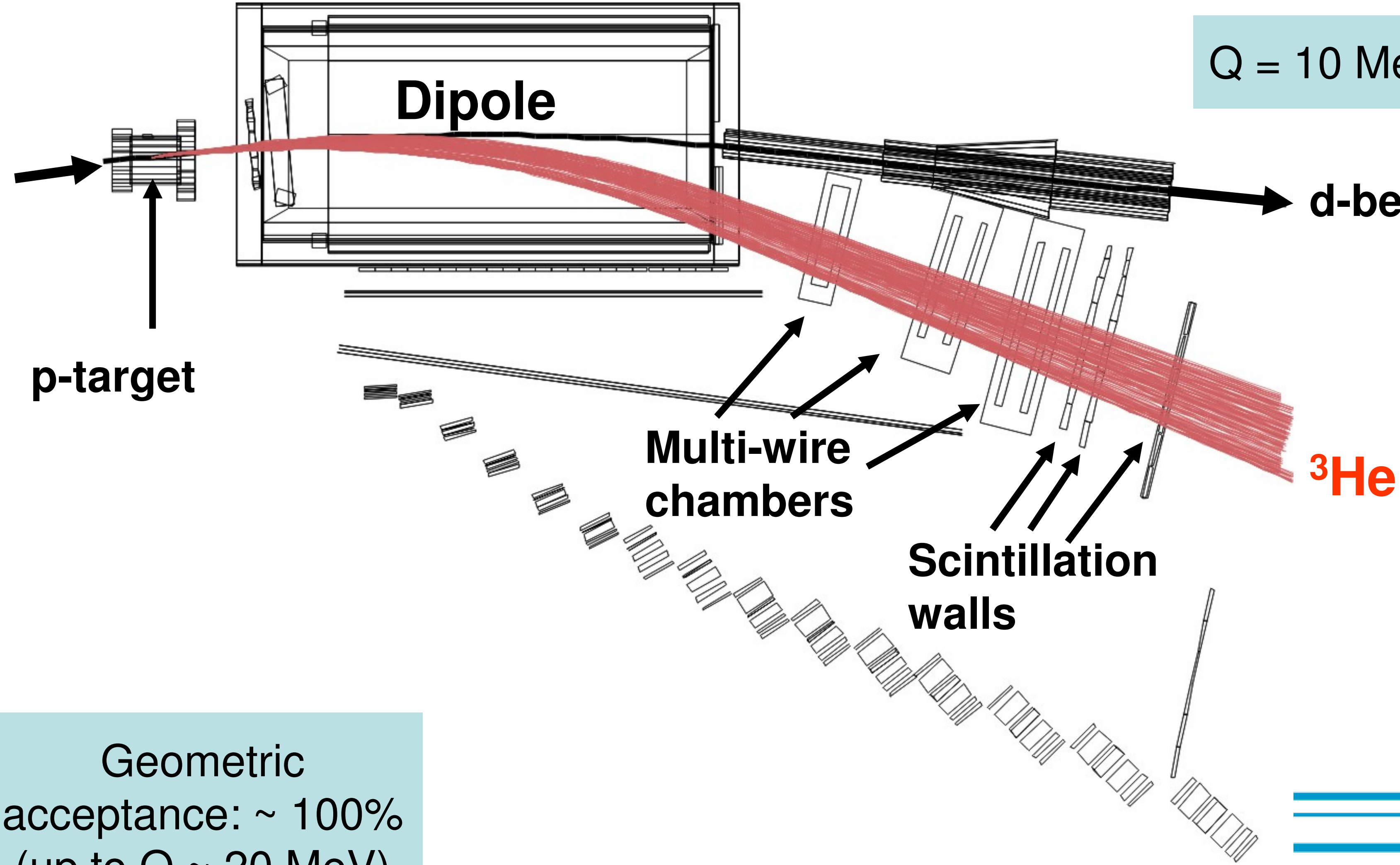
The ANKE-Facility







Identification of ^{3}He Nuclei at ANKE



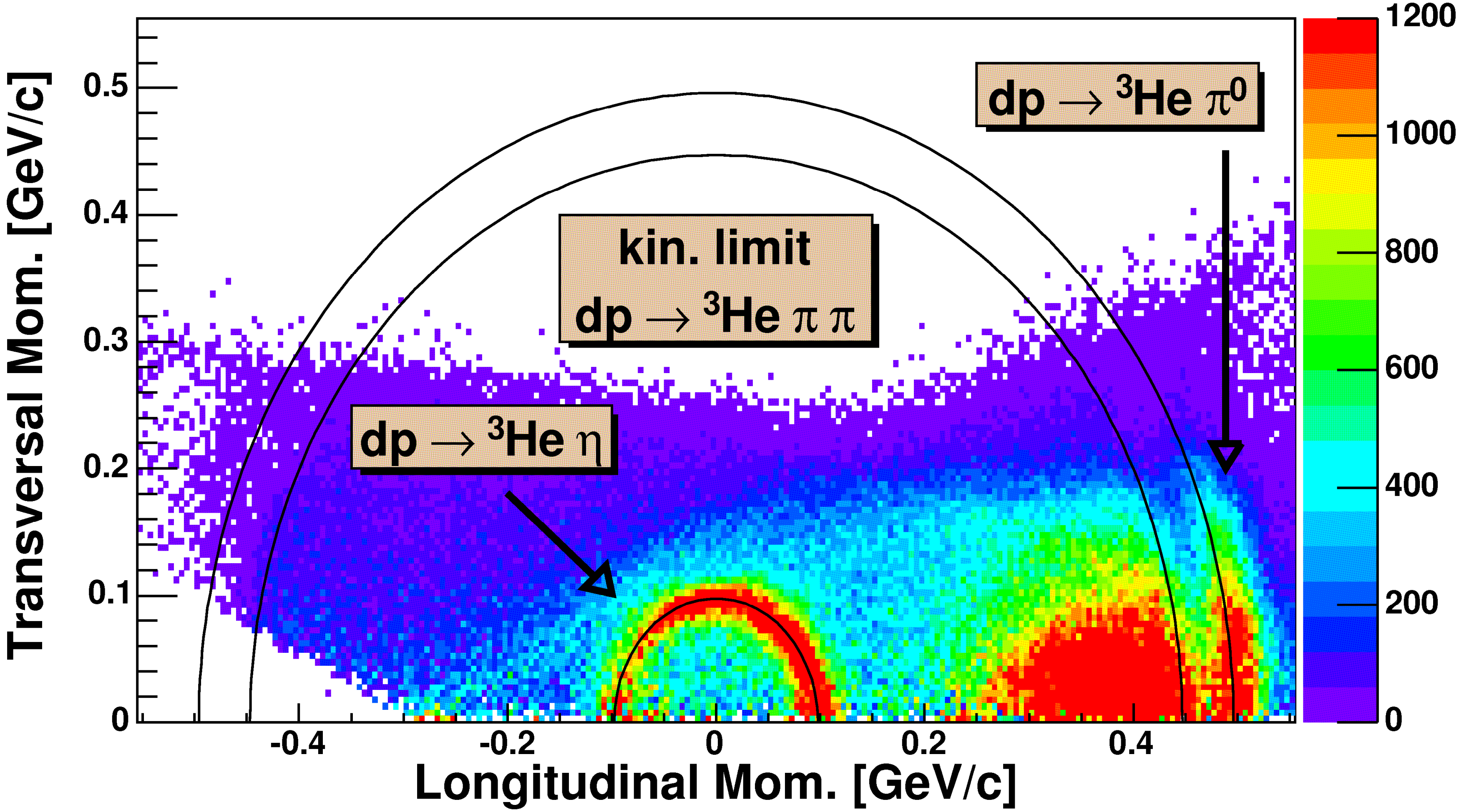
Q = 10 MeV

Geometric acceptance: ~ 100% (up to Q ~ 20 MeV)

Westfälische Wilhelms-Universität Münster

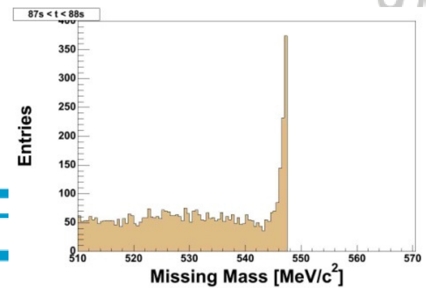
Identification of the Reactions: d+p → ^{3}He+X

„Momentum rabbit“



Identification of the Reactions: d+p → ^{3}He+X

- Energies and momenta of the incoming particles (d,p) known
  - Deuteron (mass = m_d):
    energy + momentum: Adjustable by the accelerator
  - Proton (mass = m_p):
    target particle at rest, momentum = 0
- Energy of the ^{3}He nucleus measurable by detectors
- η-meson: Not directly detectable at ANKE
  → Identification of the reaction via the missing mass analysis



Two-Particle Final State: Phase Space

Assumption:

- Two-particle reaction a+b → c+d without initial and final state interactions („ISI“ and „FSI“):
- Scattering (and production) amplitude f = const.

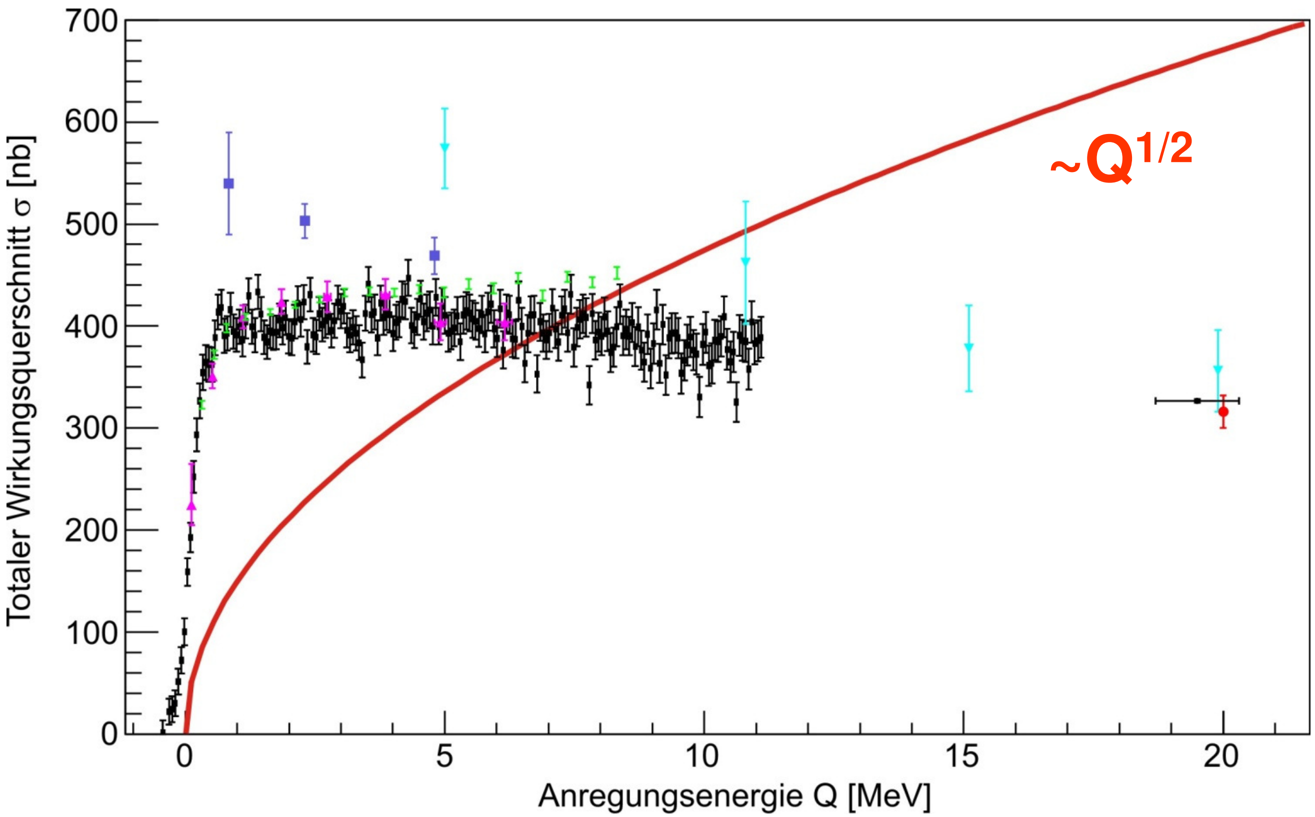
→ Increase of the cross section according to phase space expectations

$$\frac{d\sigma(\vartheta)}{d\Omega} = \frac{p_f}{p_i}\left|f_s\right|^2 \propto p_f \propto \sqrt{Q}$$

p_i / p_f: Momenta of in- and outgoing particles in the CMS

Q: Q-value = Sum of kinetic energies im CMS

Results for the Reaction d+p → ^{3}He+η



But:

- Strong deviation from phase space expectation!
- Most probably not caused by higher partial waves

The Reaction d+p → ^{3}He+η

- Extreme increase of the total cross section close to the production threshold
- Increase of the cross sections within ΔQ < 1 MeV
  → strong energy dependence at threshold
- After that total cross sections remain almost constant
  → Additional effect beside pure phase space

<u>Explanation:</u> Strong final state interaction (FSI) between ^{3}He nucleus and η-meson

Scattering Theory and Final State Interaction

Description of the cross section including FSI:

$$\frac{d\sigma(\vartheta)}{d\Omega} = \frac{p_f}{p_i} \left| f_s \right|^2 = \frac{p_f}{p_i} \cdot \frac{\left| f_{\text{prod}} \right|^2}{\left| 1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2 \right|^2}$$

Assumption:

- Energy dependence of the production amplitude f_{Prod} is negligible close to threshold: $f_{Prod} \sim$ const.
- Initial State Interaction (ISI) also: ISI = const.

Scattering Theory and Final State Interaction

- The scattering length can deliver informationen about possible bound states
- Conditions for bound η^3He state:
  - Existence of a pole in the complex p_f plane

$$f_s = \frac{f_{\text{prod}}}{1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r \cdot p_f^2}$$

$$a \equiv a_r + i a_i$$

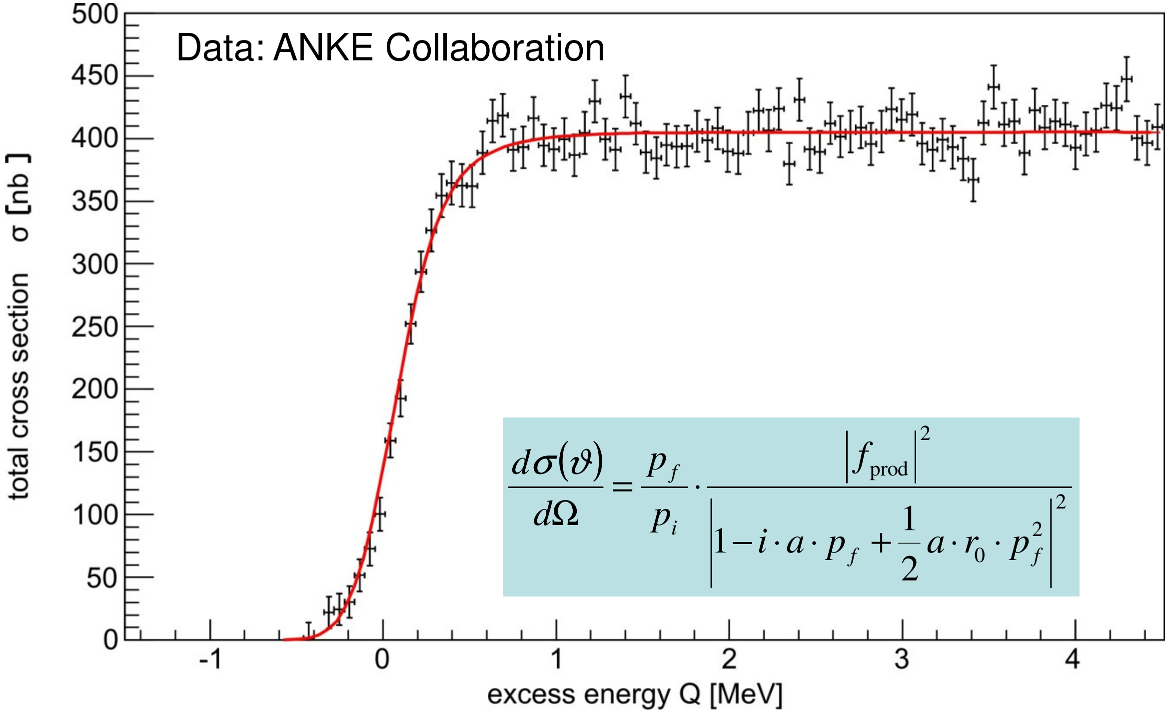
$$r \equiv r_r + i r_i$$

  - As well as

$$a_r < 0, \qquad a_i > 0, \qquad R = \frac{|a_i|}{|a_r|} < 1$$

The Reaction $d+p \rightarrow {}^3He+\eta$

Fit to data very close to threshold: Only s-wave



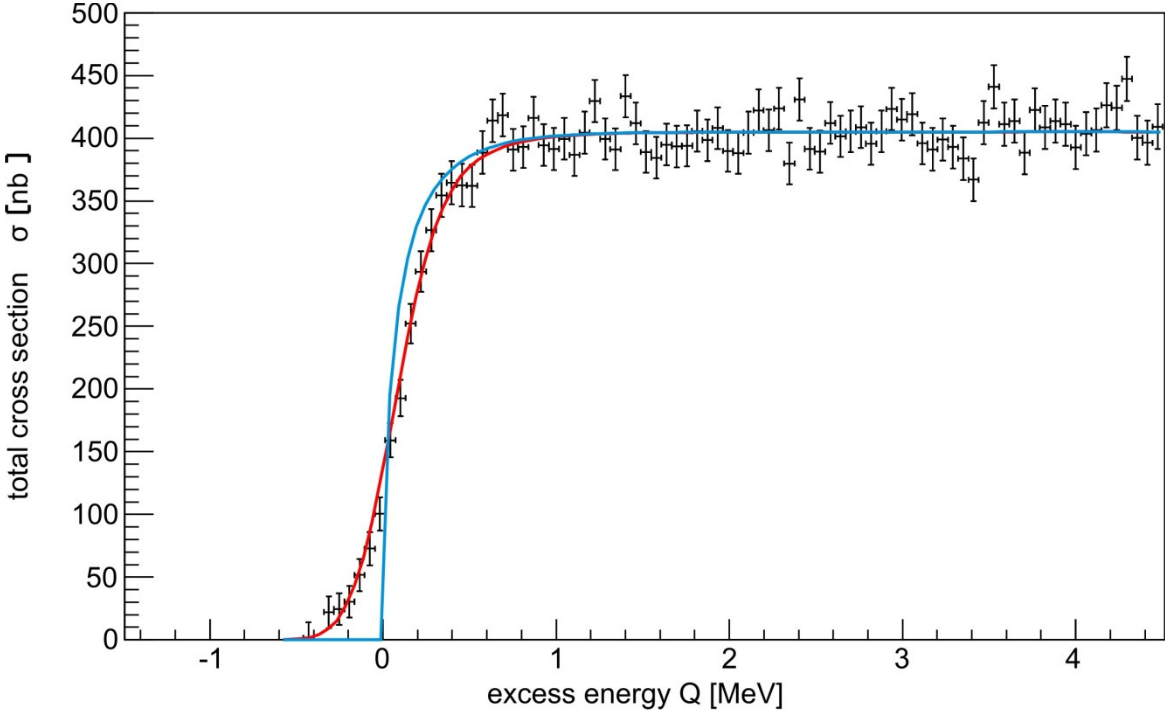
$$\frac{d\sigma(\vartheta)}{d\Omega} = \frac{p_f}{p_i} \cdot \frac{\left|f_{\mathrm{prod}}\right|^2}{\left|1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2\right|^2}$$

Fit parameter:

- Complex scattering length $a=a_r+ia_i$
- Complex effective range $r=r_r+ir_i$
- Finite momentum width δp_{beam} of the accelerator beam

The Reaction $d+p \rightarrow {}^3He+\eta$

Excitation function without accelerator beam smearing δp_{beam}:



Blue line:

- Defolded shape, extracted from data (no accelerator beam smearing)

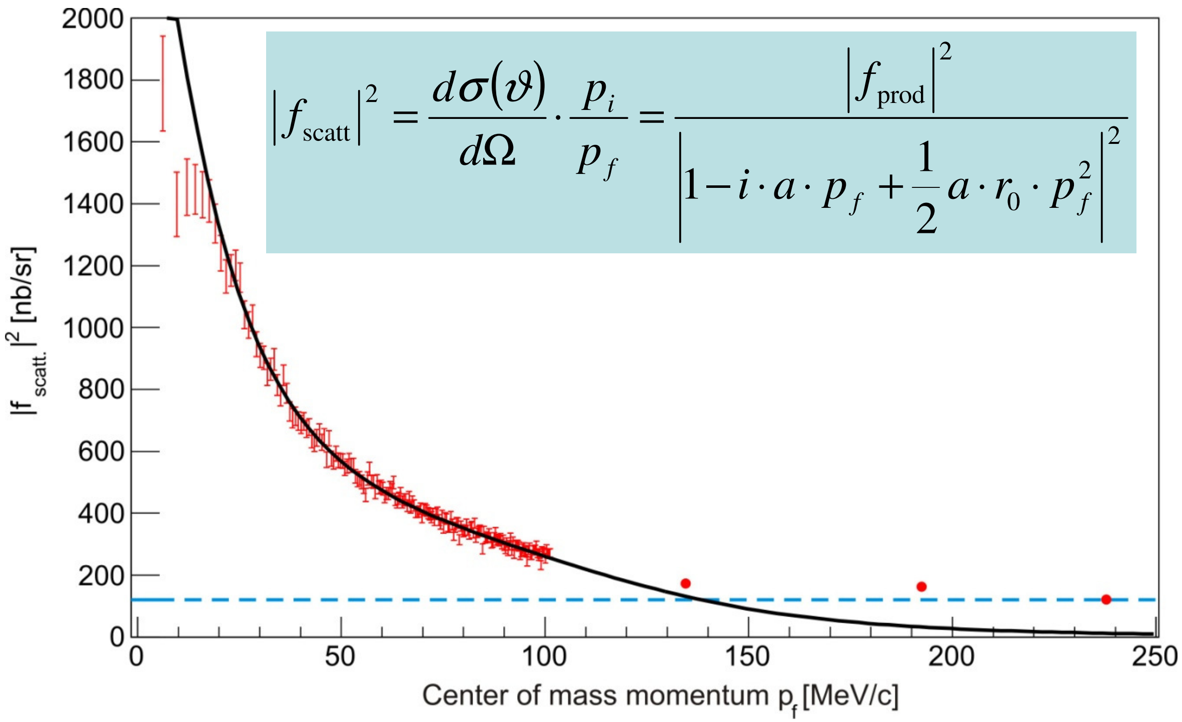
$\rightarrow$

- Total cross section reaches maximum already ΔQ<0.5 MeV above threshold

WESTFÄLISCHE
WILHELMS-UNIVERSITÄT
MÜNSTER

The d+p → ³He+η Scattering Amplitude

Extracted scattering amplitude (Q > 0 MeV)



$$|f_{\text{scatt}}|^2 = \frac{d\sigma(\vartheta)}{d\Omega} \cdot \frac{p_i}{p_f} = \frac{|f_{\text{prod}}|^2}{\left|1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2\right|^2}$$

- Scattering amplitude decreases rapidly with increasing final state momentum p_f
- Scattering amplitude almost constant at high energies

→ strong FSI in η^3He system

η–³He Scattering Length

Fit to data delivers information about the complex η–³He scattering length:

$$\left(\frac{d\sigma(\vartheta)}{d\Omega}\right)\cdot\frac{p_i}{p_f}=\left|f_{\text{scat}}\right|^2=\left|f_{\text{prod}}\cdot FSI\right|^2=\left|f_{\text{prod}}\right|^2\cdot\left|FSI\right|^2$$

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

Result:

$$a=\left[\pm\left(10.7\pm0.8^{+0.1}_{-0.5}\right)+i\left(1.5\pm2.6^{+1.0}_{-0.9}\right)\right]\text{fm}$$

Notice: Determination of $|a_r|$!

η–[3]He-Interaction: Determination of Pols

$$\left(\frac{d\sigma(\vartheta)}{d\Omega}\right)\cdot\frac{p_i}{p_f} = \left|f_{\text{scatt}}\right|^2 = \left|f_{\text{prod}}\cdot FSI\right|^2 = \left|f_{\text{prod}}\right|^2\cdot\left|FSI\right|^2$$

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

↔

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

$$a = -i\cdot\frac{p_1+p_2}{p_1\cdot p_2}$$

$$r_0 = +\frac{2\cdot i}{p_1+p_2}$$

↔

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

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

η–^{3}He-Interaction: Determination of Pols

- Pole close to the reaction threshold

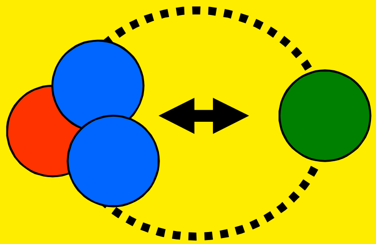
$$|Q_0| = \left| \frac{p_1^2}{2 \cdot m_{red}} \right| = 0.37\,\text{MeV}$$

- Position of the near-threshold pole (and scattering length) stable, i.e. nearly independend of fit range
- Large real part of scattering length and $|a_r| > a_i$

→ indication for the existence of a bound state

(strong interaction!)

^{3}He



η

Polarized Measurements

Production amplitude for $dp \rightarrow {}^3He + \eta\ (\pi^0)$:

$$f_B = \bar{u}_\tau \vec{p}_p \cdot (A\vec{\varepsilon}_d + iB\vec{\varepsilon}_d \times \vec{\sigma}) u_p$$

see: C. Kerboul et al., Phys. Lett. B 181, 28 (1986)

Determination of the energy dependence of the amplitudes A and B by measurement of:

$$\frac{d\sigma}{d\Omega} = \frac{1}{3}\frac{p_\eta}{p_p}\left[|A|^2 + 2|B|^2\right] \qquad T_{20} = \sqrt{2}\left[\frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2}\right]$$

$$|A|^2 = \frac{p_p}{p_\eta}(1 - \sqrt{2}T_{20})\frac{d\sigma}{d\Omega} \qquad |B|^2 = \frac{p_p}{p_\eta}(1 + \frac{1}{\sqrt{2}}T_{20})\frac{d\sigma}{d\Omega}$$

$$T_{20} = \frac{2\cdot\sqrt{2}}{p_{zz}} \cdot \frac{d\sigma_0/d\Omega(\vartheta) - d\sigma_\uparrow/d\Omega(\vartheta)}{d\sigma_0/d\Omega(\vartheta)} \qquad \vartheta = 0^0 or 180^0$$

Polarized Measurements

Assumption: $\vec{d}p \rightarrow {}^3He + \eta$

- Negligible effect of ISI
- Energy dependence of $|f|^2$ only given by FSI
  - → Shape of excitation function independent of spins
  - → Same energy dependence of amplitudes $|A|^2$ and $|B|^2$

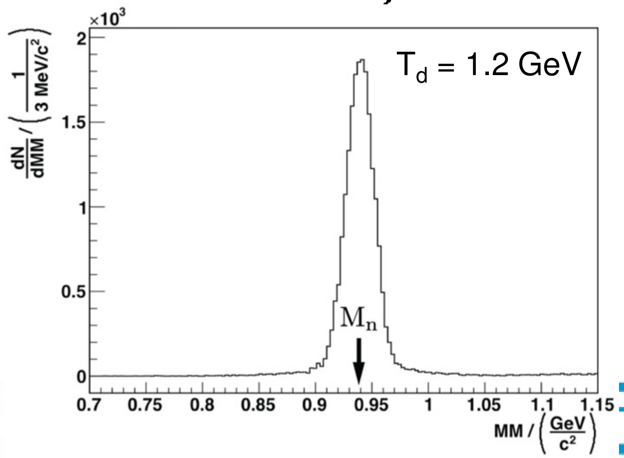
$$|A|^2 = |A_0|^2 \cdot FSI(p_\eta)$$
$$|B|^2 = |B_0|^2 \cdot FSI(p_\eta)$$

$$\Rightarrow \quad T_{20} = \sqrt{2}\left[\frac{|B_0|^2 - |A_0|^2}{|A_0|^2 + 2|B_0|^2}\right] \cdot \frac{FSI(p_\eta)}{FSI(p_\eta)} = \text{const.}$$

- Measure T_{20} as function of the excess energy

The Reaction $\vec{d}+p \rightarrow {}^3He+\eta$ at ANKE

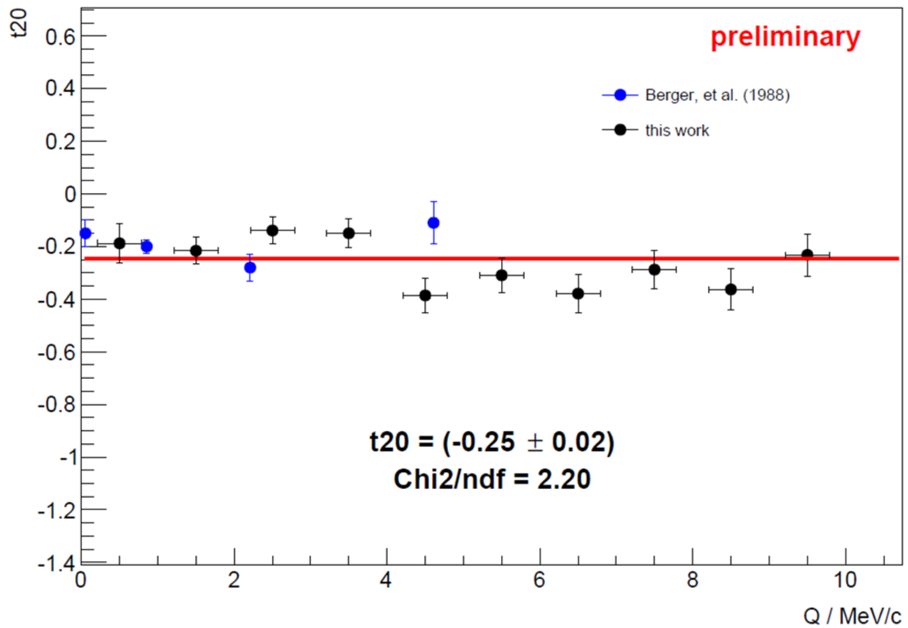
- Alternating injection of unpolarized and tensor polarized deuterons in COSY
- Ramped COSY beam: Q = -5 MeV ... +10 MeV (300 s)
- Full geometrical acceptance of ANKE for $d+p \rightarrow {}^3He+\eta$
- Determination of p_{zz} by, e.g., $d+p \rightarrow (pp)+n$ (analyzing powers known)



$$\frac{d\sigma_\uparrow}{dt}(q,\varphi) \Big/ \frac{d\sigma_0}{dt}(q,\varphi) = 1+\sqrt{3}p_z i t_{11}(\vartheta)\cos(\varphi) - \frac{1}{2\sqrt{2}} p_{zz} t_{20}(\vartheta) - \frac{\sqrt{3}}{2} p_{zz} t_{22}(\vartheta)\cos(2\varphi)$$

Alfons Khoukaz

Preliminary Results: $\vec{d}+p \to {}^3He+\eta$

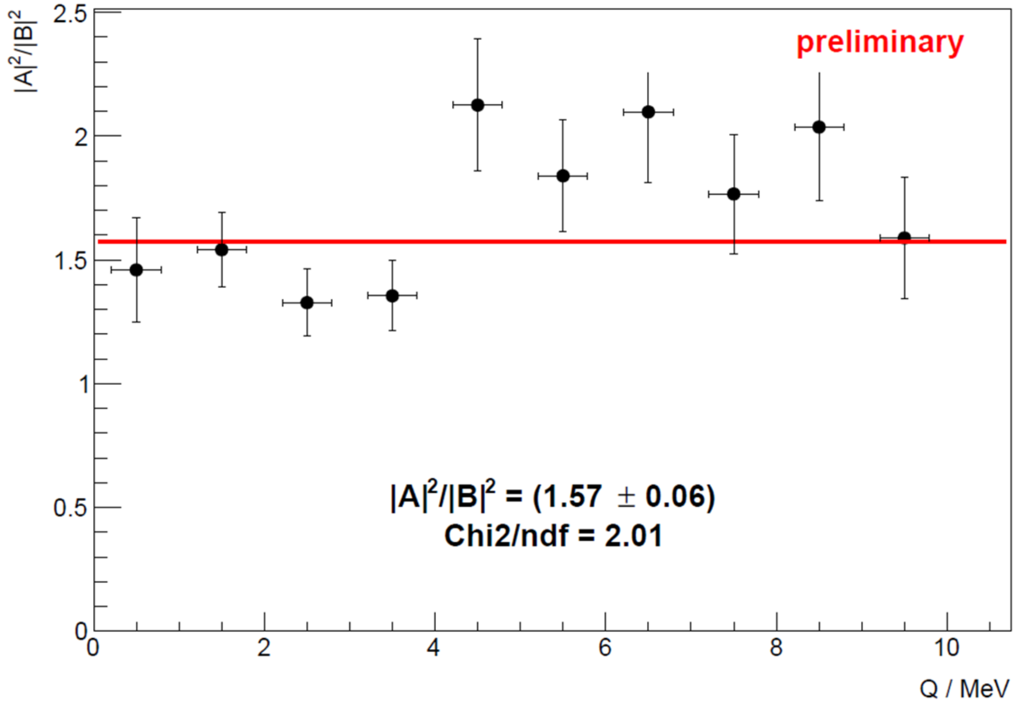


$$T_{20} = \frac{2\cdot\sqrt{2}}{p_{zz}} \cdot \frac{d\sigma_0/d\Omega(\vartheta) - d\sigma_\uparrow/d\Omega(\vartheta)}{d\sigma_0/d\Omega(\vartheta)}$$

- Data are consistent with T_{20} = const. close to threshold
- Extraction of $|A|^2/|B|^2$: $T_{20} = \sqrt{2}\left[\frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2}\right] \longrightarrow \frac{|A|^2}{|B|^2} = \frac{1-\sqrt{2}\cdot T_{20}}{1+T_{20}/\sqrt{2}}$

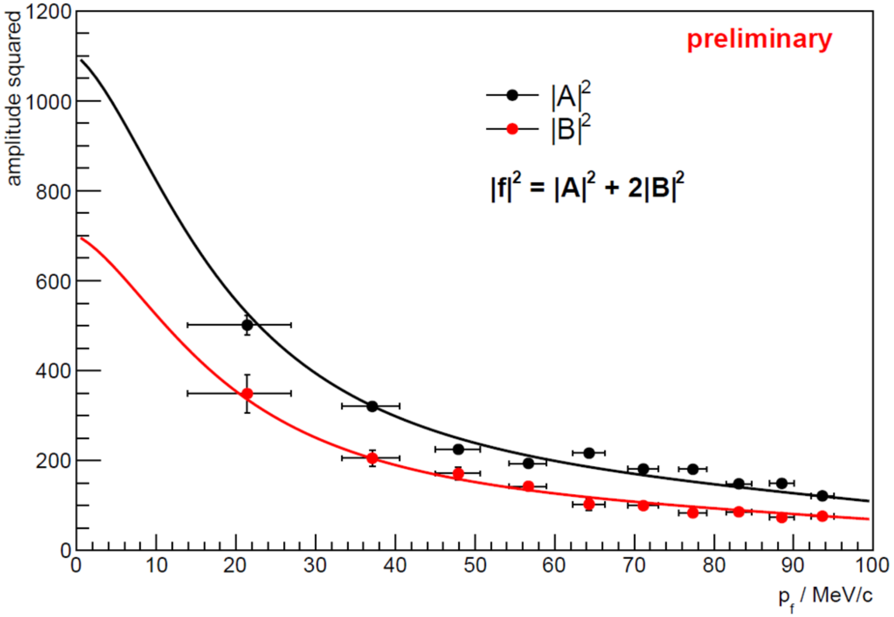
Preliminary Results: $\vec{d}+p \rightarrow {}^3He+\eta$

- Assumption: T_{20} = const. $\rightarrow$ $|A|^2/|B|^2$ = const.



Preliminary Results: $\vec{d}+p \rightarrow {}^3He+\eta$

- Energy dependence of $|f|^2$ known from „old“ unpolarized measurements
  - $\rightarrow |A|^2(p_f)$ and $|B|^2(p_f)$ can be calculated



$$\frac{d\sigma}{d\Omega} = \frac{1}{3}\frac{p_\eta}{p_p}\left[|A|^2 + 2|B|^2\right]$$

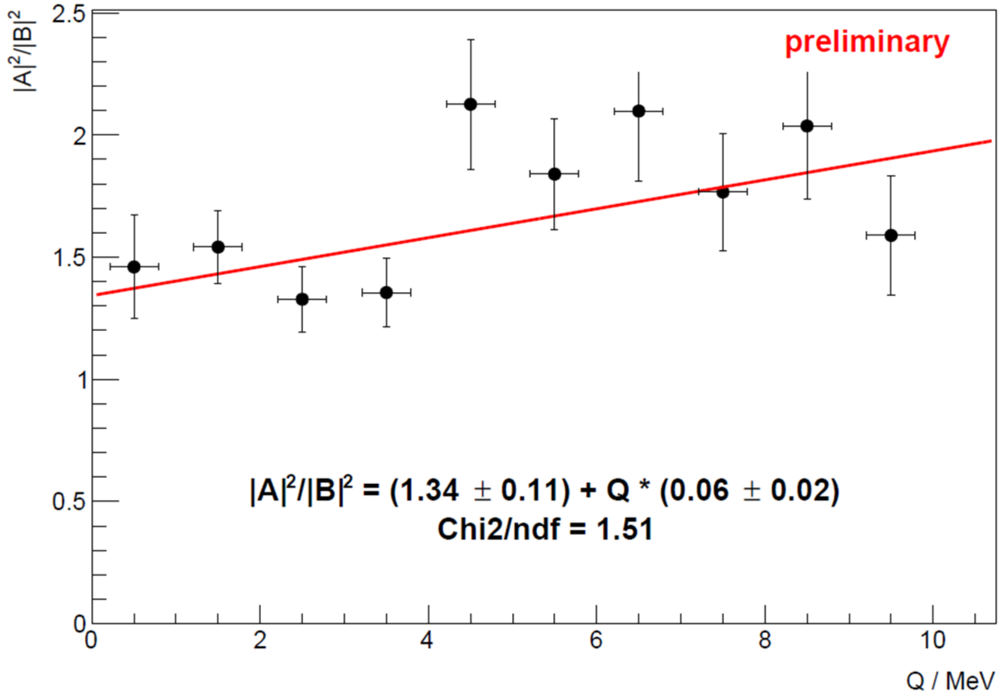
$$|A|^2 = \frac{p_p}{p_\eta}(1-\sqrt{2}T_{20})\frac{d\sigma}{d\Omega}$$

$$|B|^2 = \frac{p_p}{p_\eta}(1+\frac{1}{\sqrt{2}}T_{20})\frac{d\sigma}{d\Omega}$$

Preliminary Results: $\vec{d}$+p → ^{3}He+η

- Allow for an energy dependence of $|A|^2/|B|^2$:

→ Test: Different energy dependence of $|A|^2(p_f)$ and $|B|^2(p_f)$?



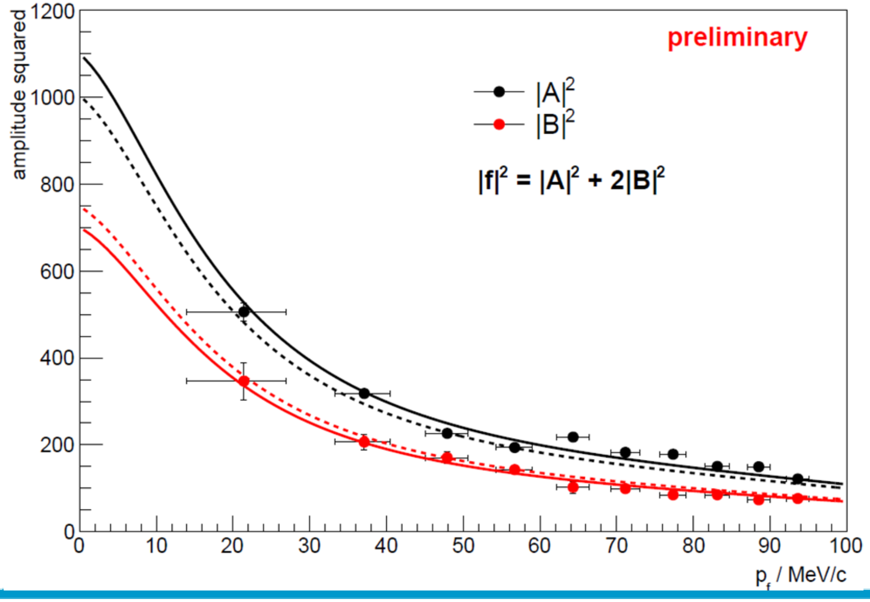
$$\frac{d\sigma}{d\Omega} = \frac{1}{3}\frac{p_\eta}{p_p}\left[|A|^2 + 2|B|^2\right]$$

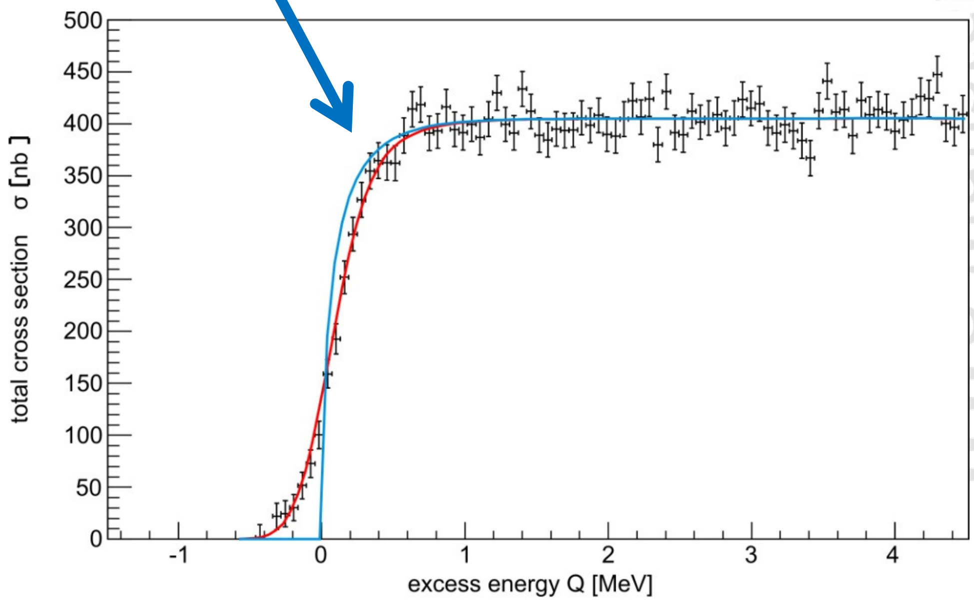
$$\frac{|A|^2}{|B|^2} = m \cdot Q + n$$

WESTFÄLISCHE
WILHELMS-UNIVERSITÄT
MÜNSTER

Preliminary Results: $\vec{d}$+p → ³He+η

- No significant different energy dependence of $|A|^2$ and $|B|^2$
- Remarkable excitation function of d+p → ³He+η still an indication for very strong FSI effect





Next Steps:

- Quantification of upper limits for non-FSI effect
- Evaluation of effect on pole position or scattering length

In parallel:

- Analysis of new data on $p+n \rightarrow d+\eta$ via $p+d \rightarrow d+\eta+p_{spec}$
- Comparison of results from
  - $p+n \rightarrow d+\eta$
  - $d+p \rightarrow {}^3He+\eta$
  - $d+d \rightarrow {}^4He+\eta$

Summary