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Investigation of the ^{3}He-η system in deuteron-proton collisions at COSY-ANKE

YITP Workshop on Hadron in Nucleus

31st October - 2nd November, 2013

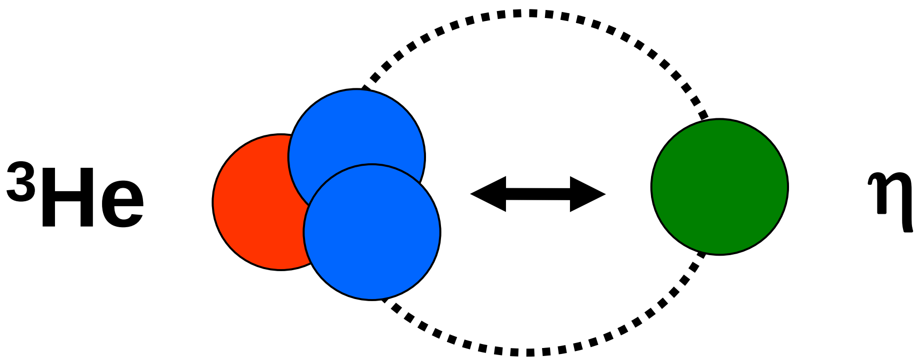
Institut für Kernphysik

wissen.leben
WWU Münster

Alfons Khoukaz

Why η-Meson Production Close to Threshold?

- Do bound meson-nucleus systems exist?



- ANKE: $\overset{(\rightarrow)}{d}+p \rightarrow {}^{3}He+\eta$
- 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, …

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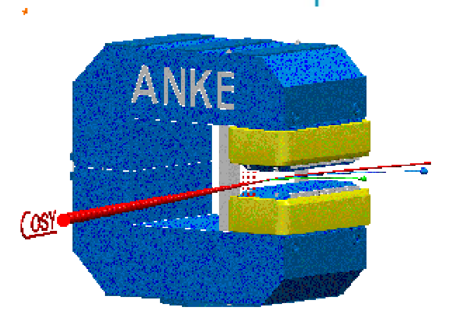
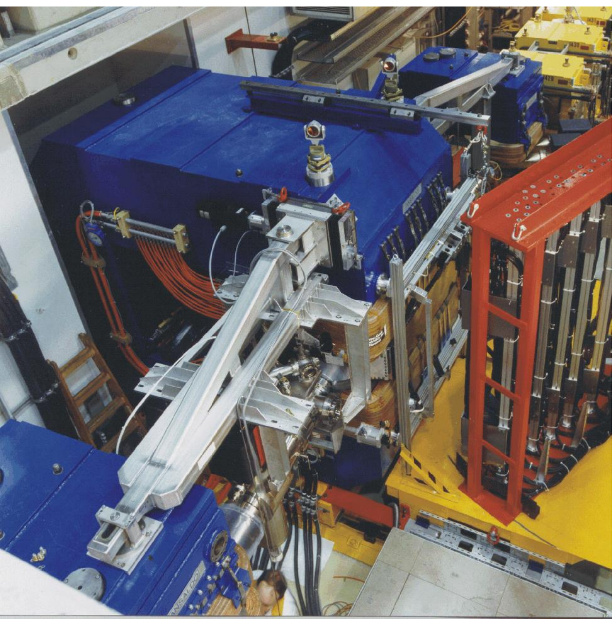
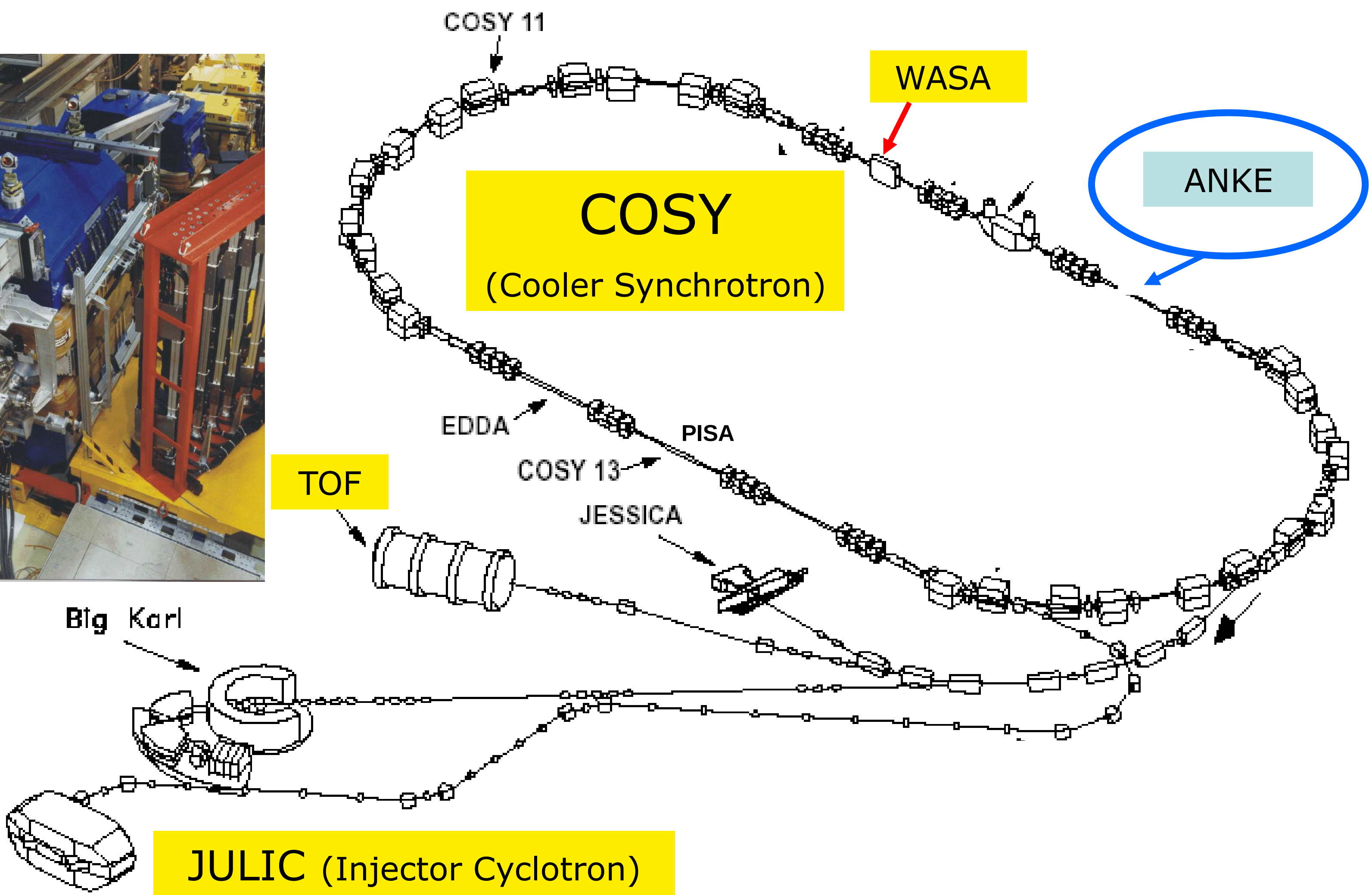
The ANKE-Facility

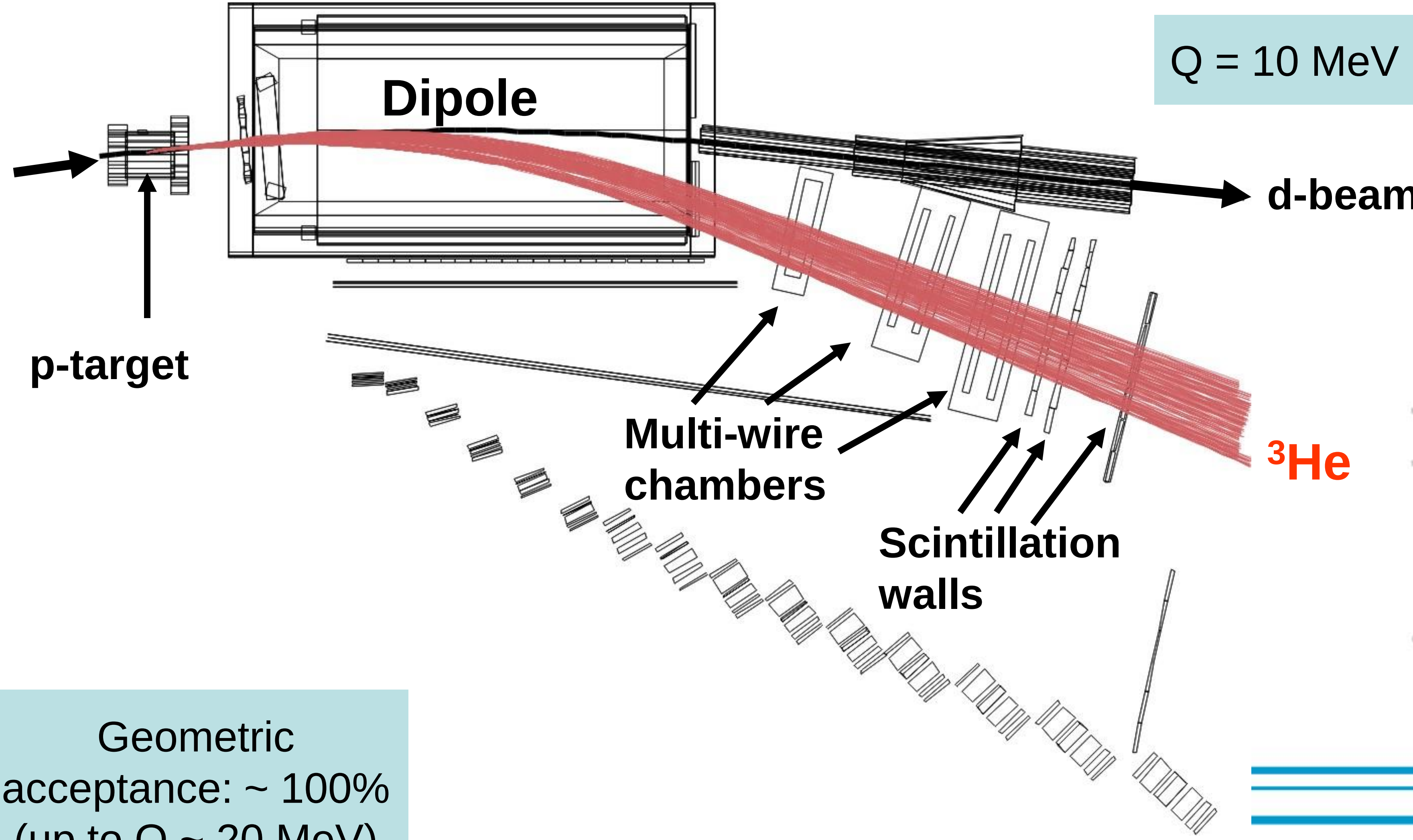






Identification of ^{3}He Nuclei at ANKE

Q = 10 MeV



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

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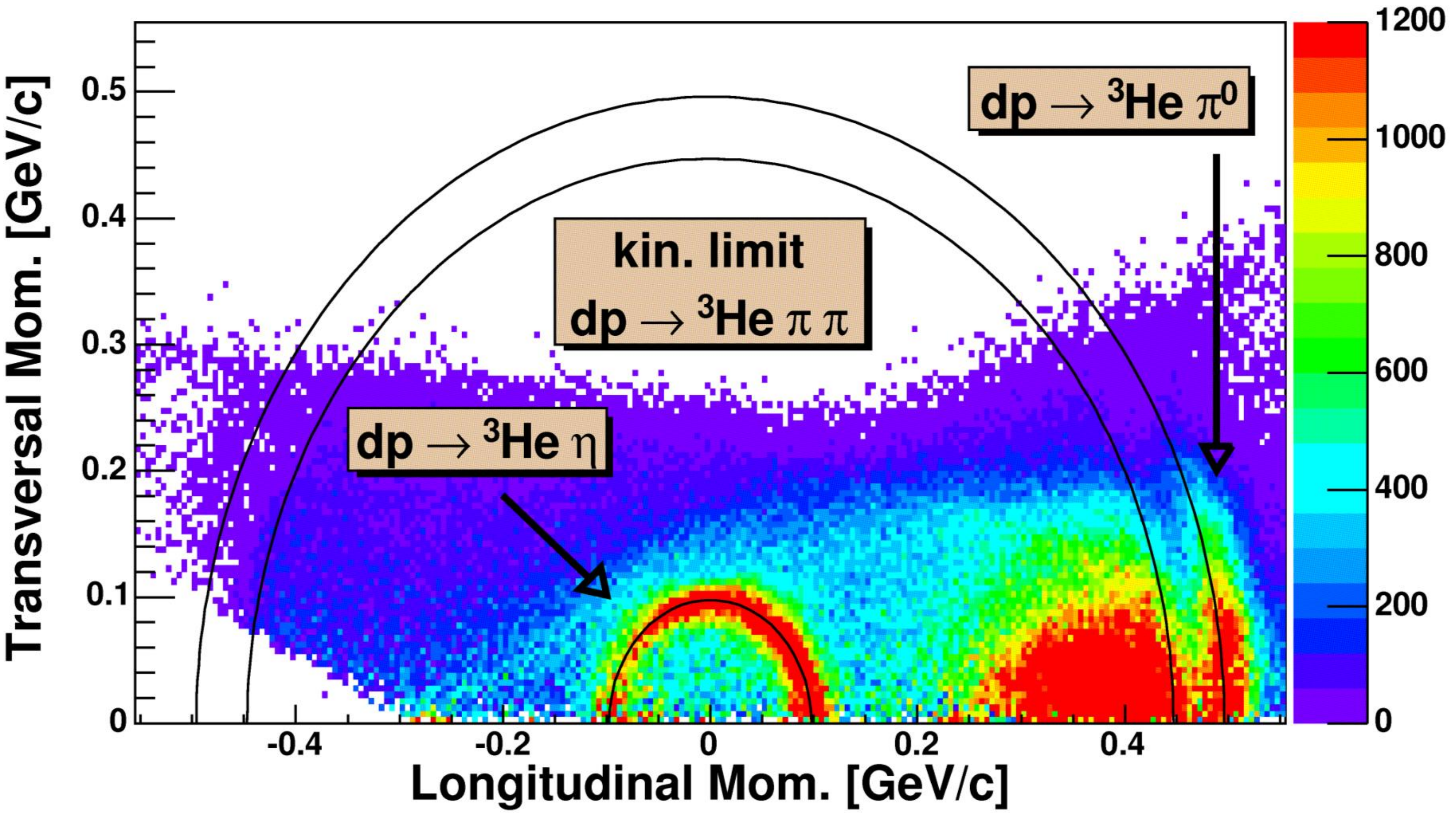
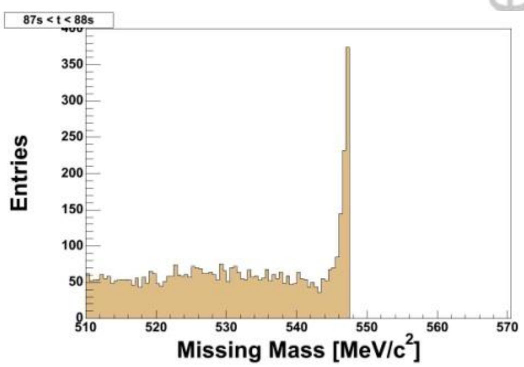
Identification of the Reactions: d+p → ³He+X

„Momentum rabbit“



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

- 4-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



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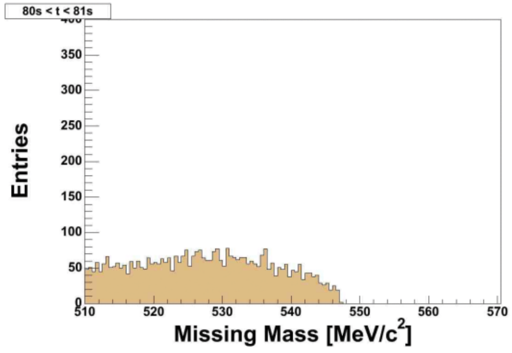

Two-Particle Final State: Phase Space

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

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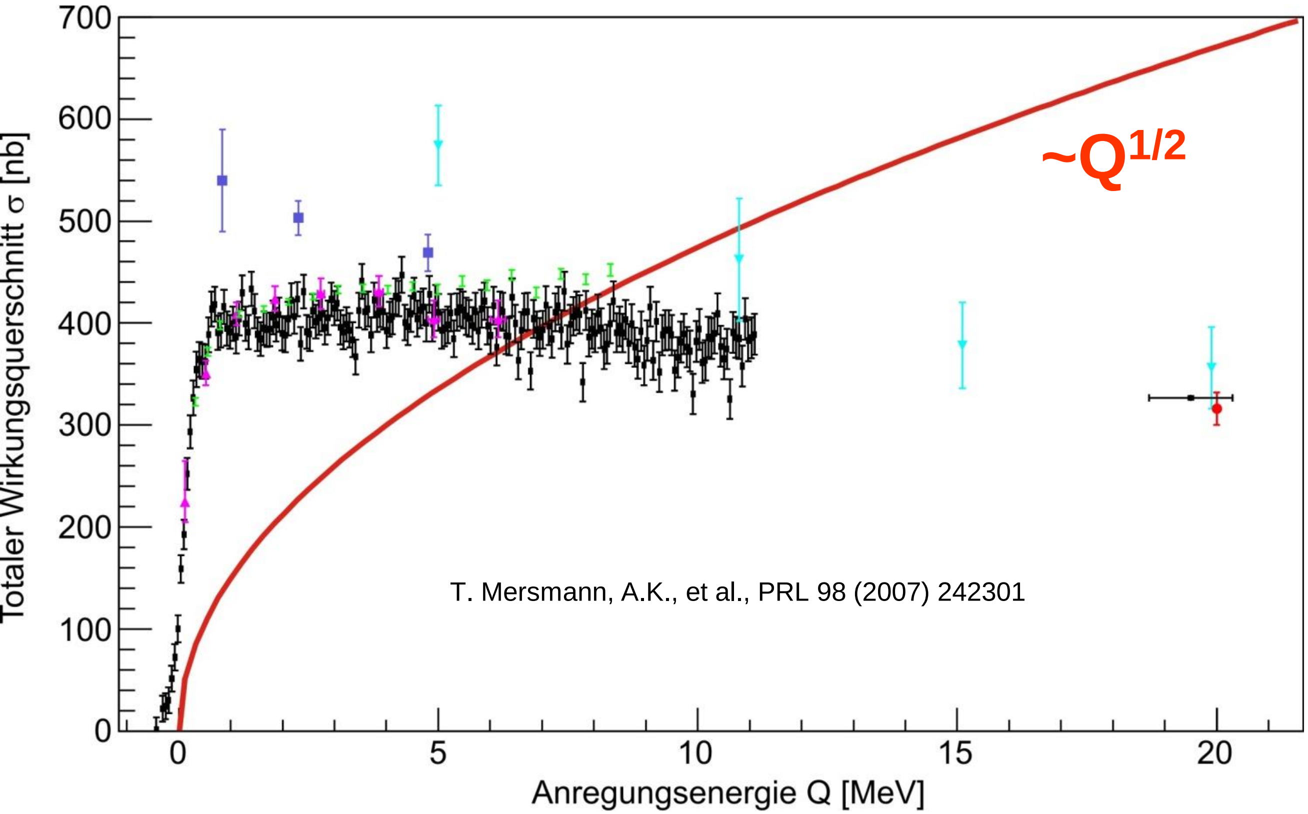
Results for the Reaction d+p → ^{3}He+η



- 195 data points from ANKE close to threshold
- 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

Explanation: 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:

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

Assumption:

- Energy dependence of the production amplitude f_{Prod} is negligible close to threshold: f_{Prod} ~ 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

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

$$a \equiv a_r + i a_i$$

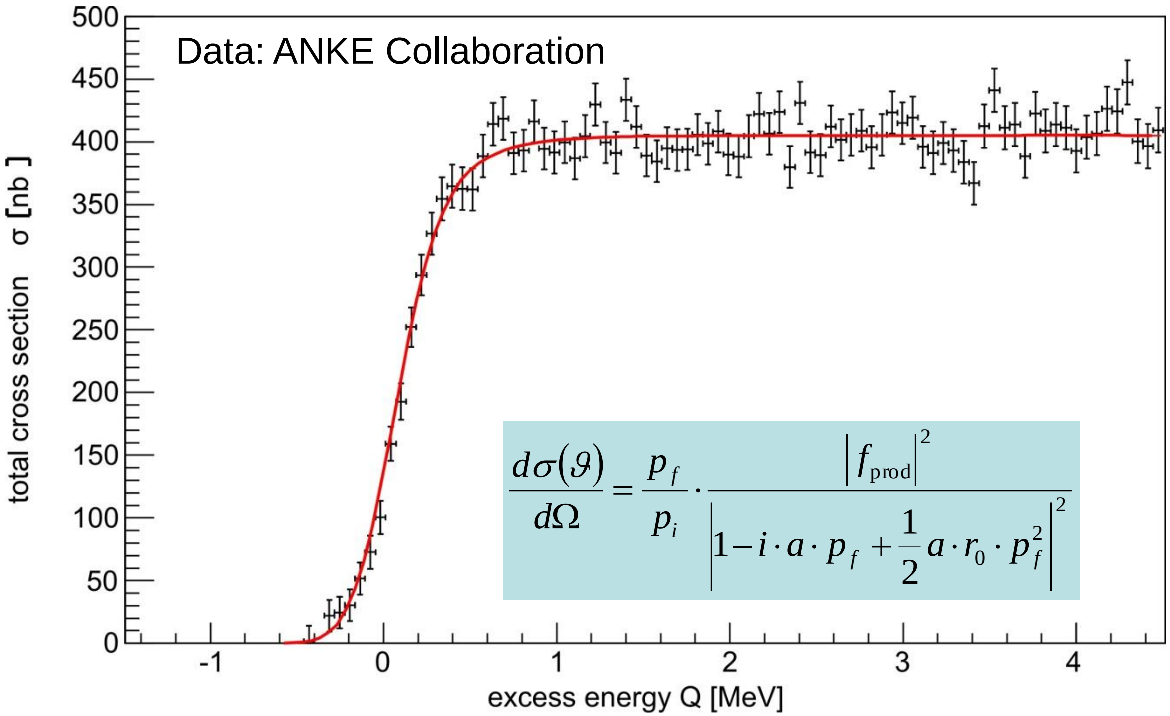
$$r \equiv r_r + i r_i$$

  - As well as

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

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

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



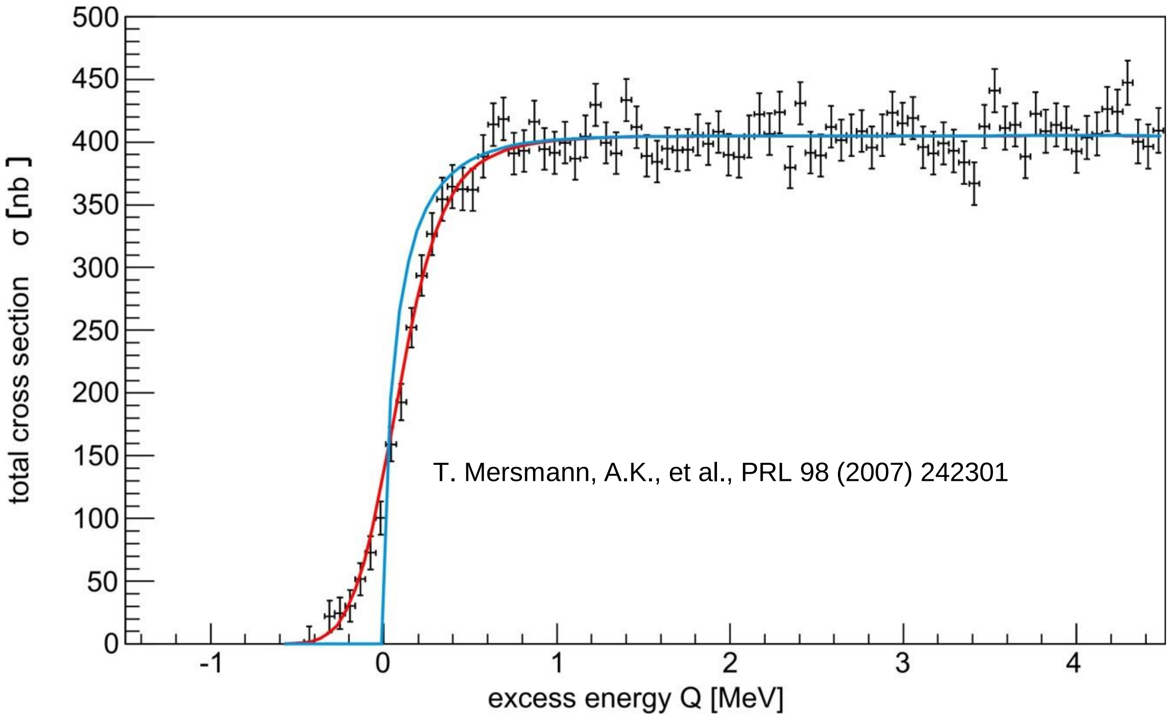
$$\frac{d\sigma(\vartheta)}{d\Omega} = \frac{p_f}{p_i} \cdot \frac{\left|f_{\text{prod}}\right|^2}{\left|1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2\right|^2}$$

Fit parameter:

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

The Reaction d+p → ^{3}He+η

Excitation function without accelerator beam smearing δp_{beam}:



Blue line:

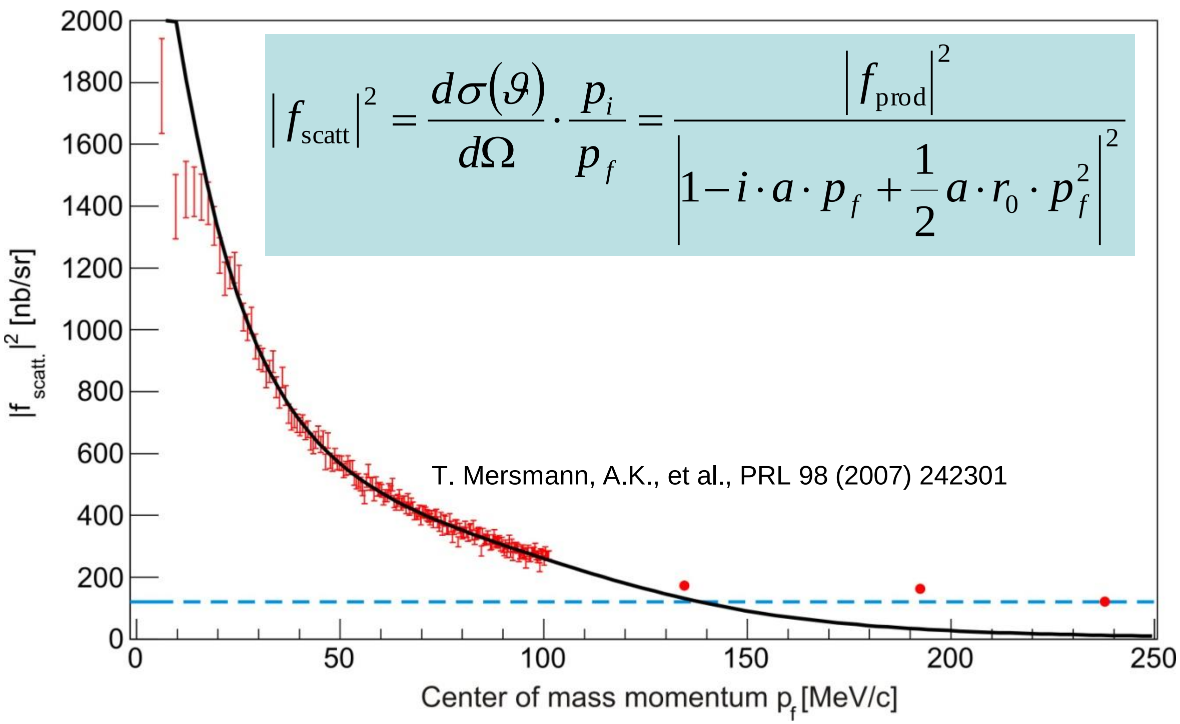
- Defolded shape, extracted from data (no accelerator beam smearing)

→

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

The d+p → ^{3}He+η Scattering Amplitude

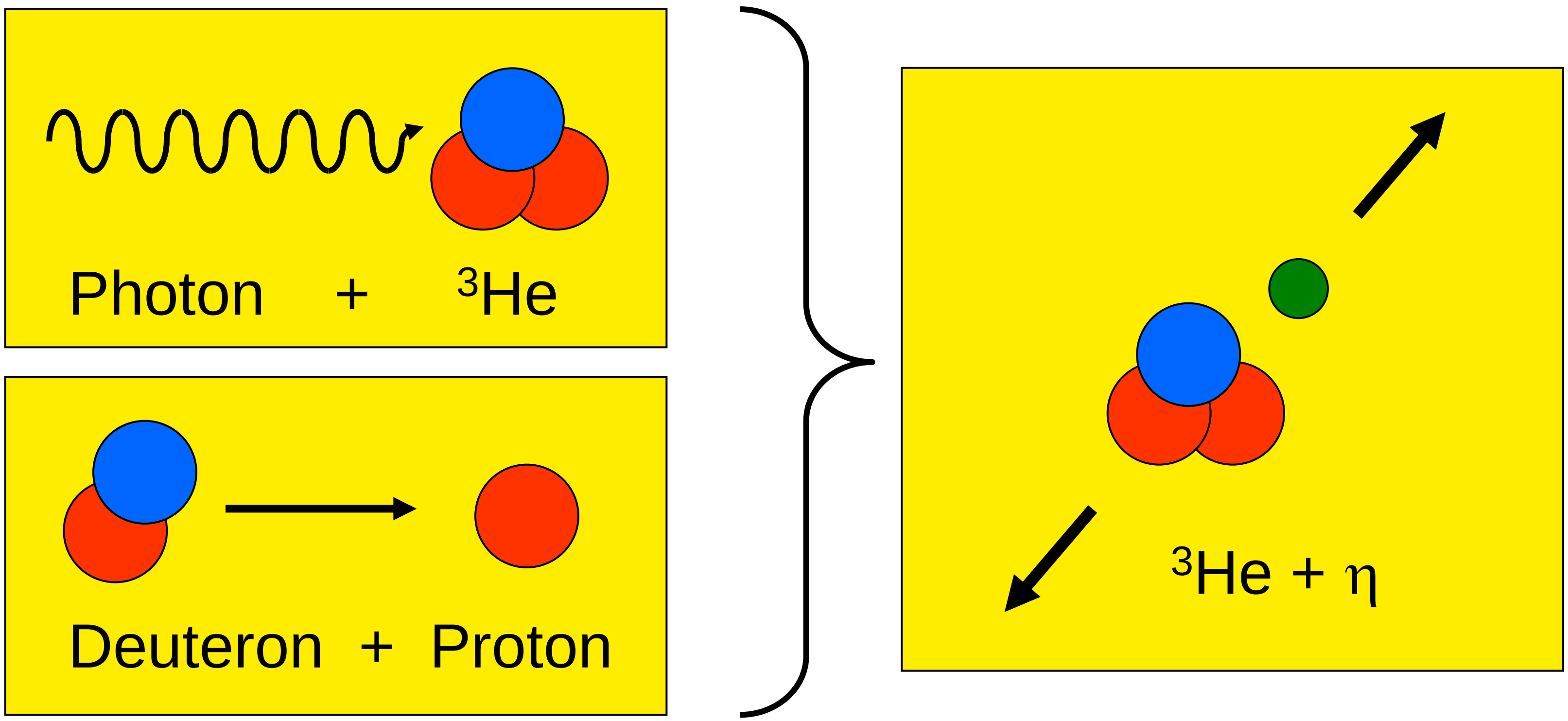
Extracted scattering amplitude (Q > 0 MeV)



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

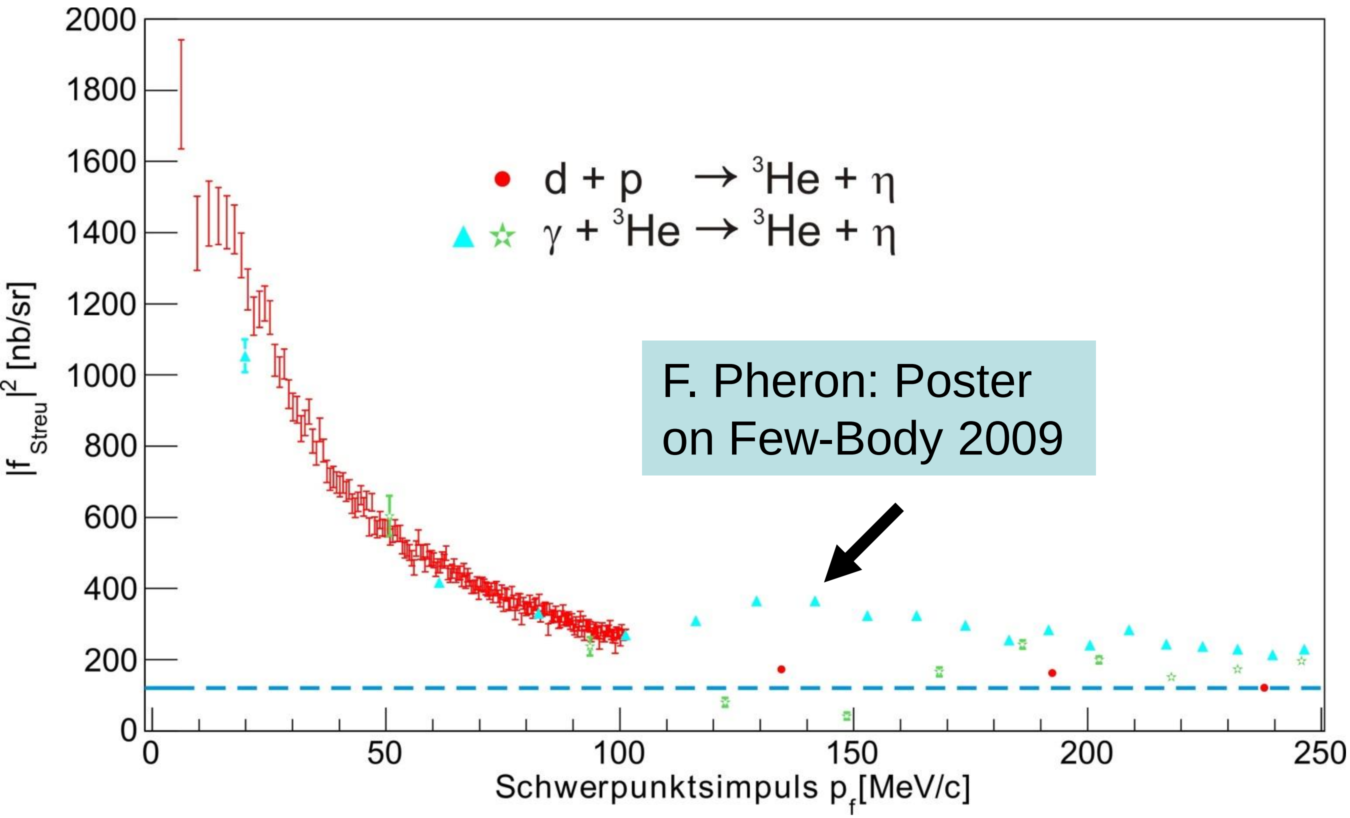
→ strong FSI in η^3He system

Compare: dp- and γ^3He-Scattering



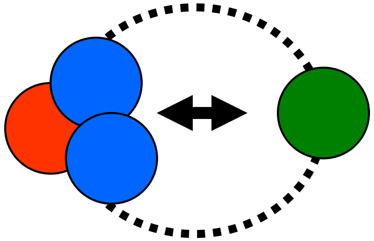
- Different initial states and production mechanism, but same final state

Compare: dp- and γ^3He-Scattering



- Scattering amplitudes show similar energy dependence

- Strong hint for a strong FSI between He-nuclei and η-mesons



η–^{3}He Scattering Length

Fit to data delivers information about the complex η–^{3}He 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:

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

T. Mersmann, A.K., et al., PRL 98 (2007) 242301

Notice: Determination of $|a_r|$!

η–³He-Interaction: Determination of Pols

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

$$FSI = \frac{1}{1 - i\cdot a\cdot p_f + \frac{1}{2}a\cdot r_0\cdot p_f^2} \quad \longleftrightarrow \quad FSI = \frac{1}{\left(1-{p_f}/{p_1}\right)\cdot\left(1-{p_f}/{p_2}\right)}$$

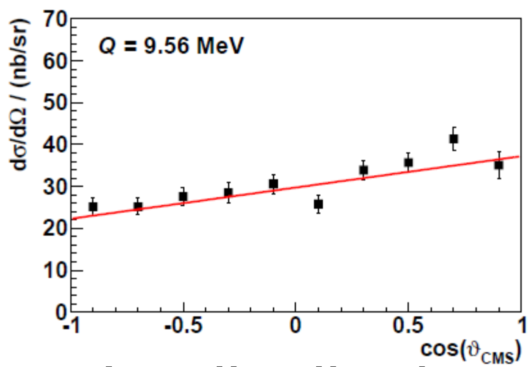
$$a = -i\cdot\frac{p_1+p_2}{p_1\cdot p_2} \qquad r_0 = +\frac{2\cdot i}{p_1+p_2}$$

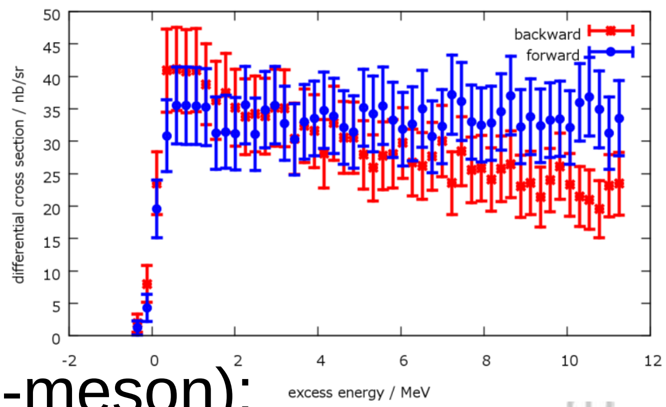
$$p_1 = \left[\left(-5\pm 7^{+2}_{-1}\right)\pm i\cdot\left(19\pm 2\pm 1\right)\right]\,\text{MeV/c}$$

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

Consideration of Higher Partial Waves: P-Waves

- Close to threshold: $d\sigma/d\Omega(\theta)$ = const. → pure s-wave
- Above a few MeV Q-value: Contributions ~cos(θ) visible
  → effect of p-wave





- Asymmetry in the angular distribution (η-meson):
  Slope at $\cos(\theta)=0$ for $d\sigma/d\Omega(\theta) = a+b\cdot \cos(\theta)$

$$\alpha = \frac{d}{d(\cos\theta_\eta)} \ln\left(\frac{d\sigma}{d\Omega}\right)\Bigg|_{\cos\theta_\eta=0}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{CM} = \frac{\sigma_{tot}}{4\pi}\cdot\left(1+\alpha\cdot\cos\theta_{CM}\right)$$

Consideration of Higher Partial Waves: P-Waves

- Assumption: Only s- and p-waves

  Production operator:

$$\hat{f} = A\vec{\varepsilon}\cdot\hat{p}_p + iB(\vec{\varepsilon}\times\vec{\sigma})\cdot\hat{p}_p + C\vec{\varepsilon}\cdot\vec{p}_\eta + iD(\vec{\varepsilon}\times\vec{\sigma})\cdot\vec{p}_\eta$$

A, B: s-wave amplitudes C, D: p-wave amplitudes

ε: polarisation vector of the deuteron

C. Wilkin, A.K., et al., PLB 654 (2007) 92

$$\frac{d\sigma}{d\Omega} = \frac{p_\eta}{p_p}\overline{|f|^2} = \frac{p_\eta}{3p_p} I$$

$$I = |A|^2 + 2|B|^2 + p_\eta^2|C|^2 + 2p_\eta^2|D|^2 + 2p_\eta \operatorname{Re}(A*C + 2B*D)\cos\theta_\eta$$

Consideration of Higher Partial Waves: P-Waves

- Resulting asymmetry factor:

$$\alpha = 2p_\eta \frac{\mathrm{Re}\left(A*C + 2B*D\right)}{|A|^2 + 2|B|^2 + p_\eta^2|C|^2 + 2p_\eta^2|D|^2}$$

Assumption:

- Same s-wave amplitudes: A = B = f_s
  energy dependence due to FSI
- Same p-wave amplitudes: C = D = const.

$$\alpha = 2p_\eta \frac{\mathrm{Re}\left(f_S^* C\right)}{|f_S|^2 + p_\eta^2|C|^2}$$

Consideration of Higher Partial Waves: P-Waves

- With the asymmetry factor

$$\alpha = 2 p_\eta \frac{\mathrm{Re}\left(f_S^* C\right)}{|f_S|^2 + p_\eta^2 |C|^2}$$

and the experimental data from ANKE

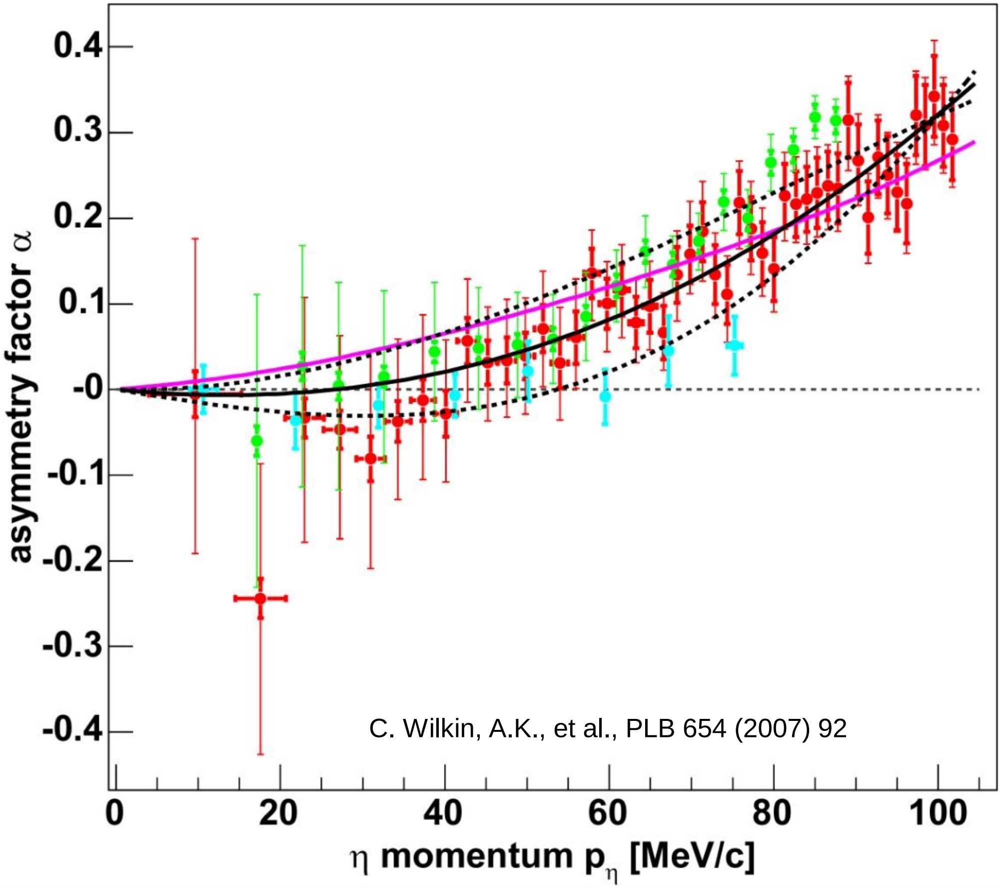
$$\alpha = \frac{d}{d(\cos\theta_\eta)} \ln\left(\frac{d\sigma}{d\Omega}\right)\Bigg|_{\cos\theta_\eta = 0}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{CM} = \frac{\sigma_{tot}}{4\pi} \cdot \left(1 + \alpha \cdot \cos\theta_{CM}\right)$$

it is possible to extract the amplitudes iteratively:

$$\sigma = 4\pi \frac{p_\eta}{p_p} \left[|f_s|^2 + p_\eta^2 |C|^2 \right]$$

Consideration of Higher Partial Waves: P-Waves



- Very good description of total and differential cross sections
- Position of the near-threshold pol nearly unaffected

  (same for second pol)
- Strong phase variation of s-wave

  Black: inclusion of phase variation

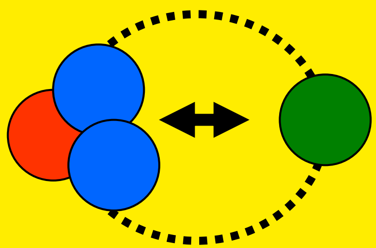
  Pink: no phase variation $|f_s|$

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

- Pole close to the reaction threshold
- Position of the near-threshold pole (and scattering length) stable, i.e. nearly independend of fit range
- Large real part of scattering length and $|a_r|>a_i$
- ANKE data indicate a rapid variation of the phase of the s-wave close to threshold

→ indication for the existence of a bound state

(strong interaction!)

^{3}He  η

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

Polarized Measurements

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

Production amplitude for dp→^{3}He+η (π^0):

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

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 $|B|^2$

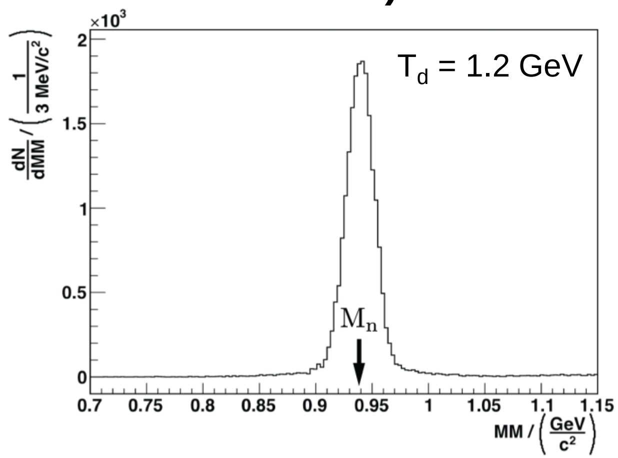
$$|A|^2 = |A_0|^2 \cdot FSI(p_\eta)$$
$$|B|^2 = |B_0|^2 \cdot FSI(p_\eta)$$

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

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

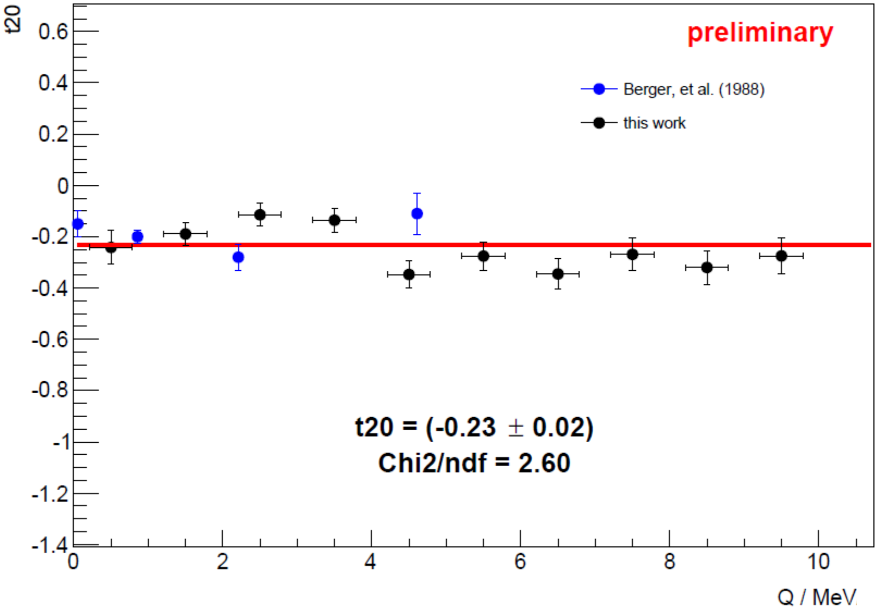
The Reaction $\vec{d}$+p → ^{3}He+η at ANKE

- 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 → ^{3}He+η
- Determination of p_{zz} by, e.g., d+p → (pp)+n (analyzing powers known)



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

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



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

M. Papenbrock, PhD thesis in preparation

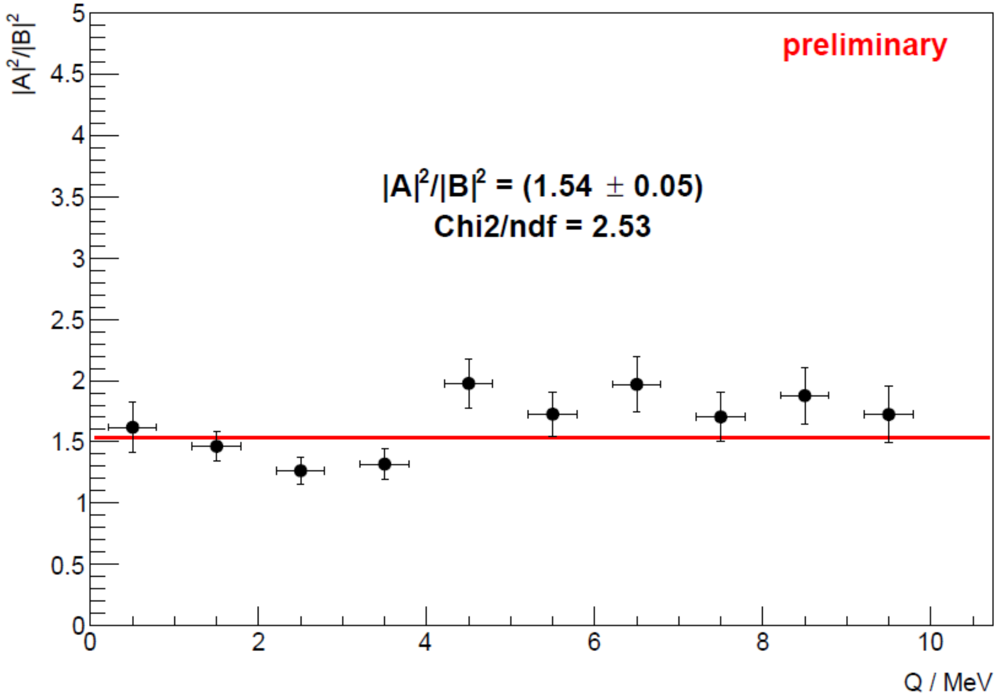
- Data indicate T_{20} = const. close to threshold
- $|T_{20}| \ll 1 \to |A|^2/|B|^2 = O(1)$
- S-Wave amplitudes $|A|^2$ and $|B|^2$ are of similar size

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

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

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

$$\rightarrow \quad \frac{|A|^2}{|B|^2} = \frac{1-\sqrt{2}\cdot T_{20}}{1+T_{20}/\sqrt{2}}$$



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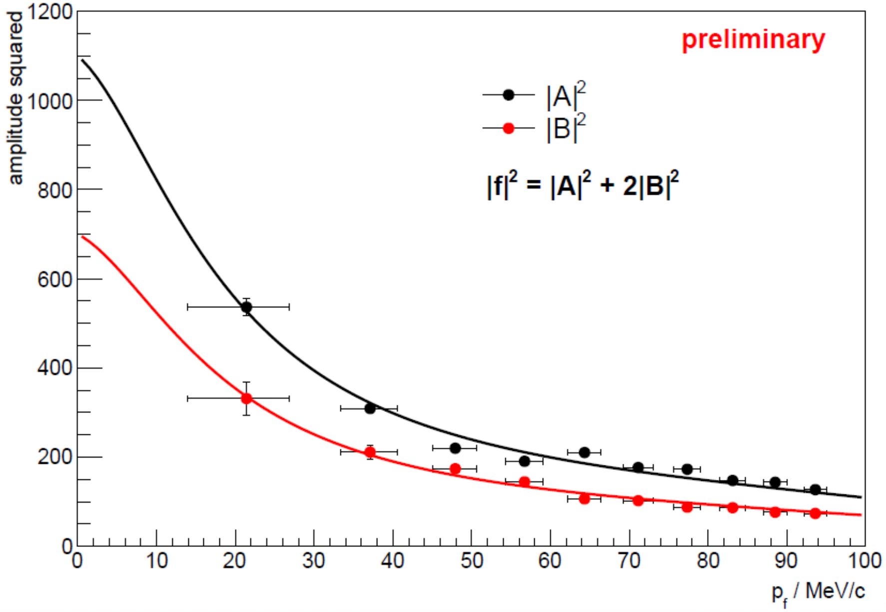
Preliminary Results: $\vec{d}+p \rightarrow {}^3He+\eta$

- Energy dependence of $|f|^2$ known from „old“ unpolarized measurements

  $\rightarrow |A|^2(p_f)$ and $|B|^2(p_f)$ can be calculated



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

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

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

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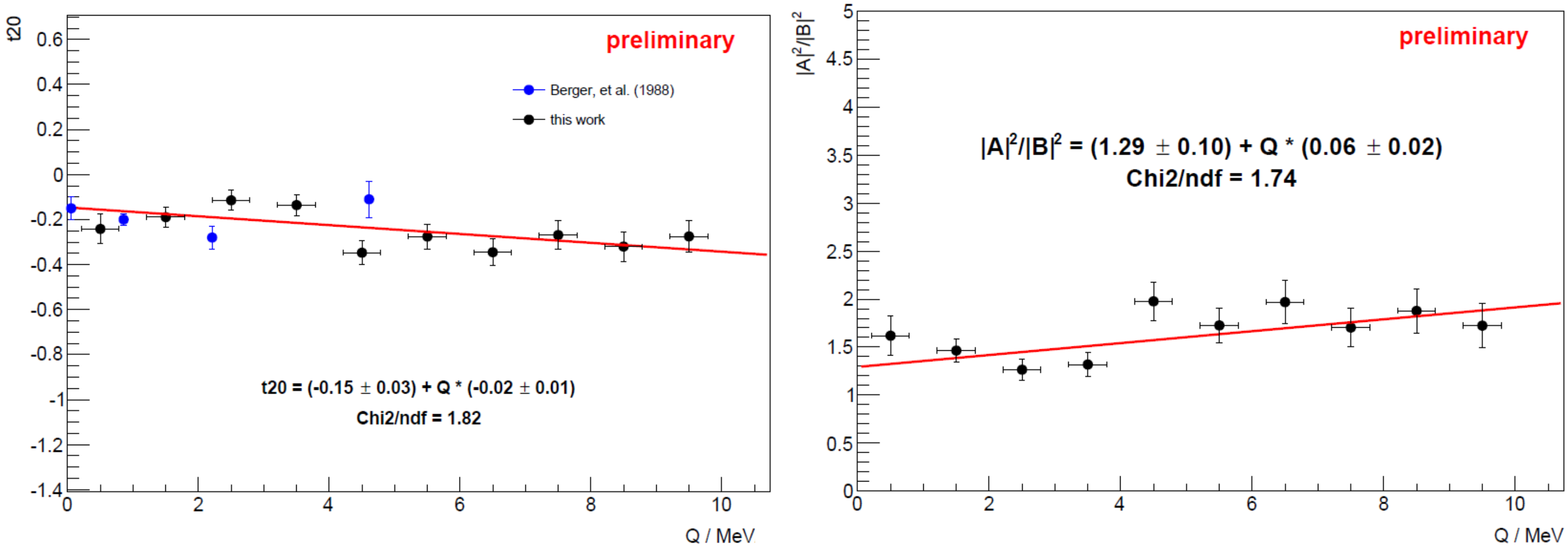
Preliminary Results: $\vec{d}+p \rightarrow {}^3He+\eta$

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

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



M. Papenbrock, PhD thesis in preparation

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

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

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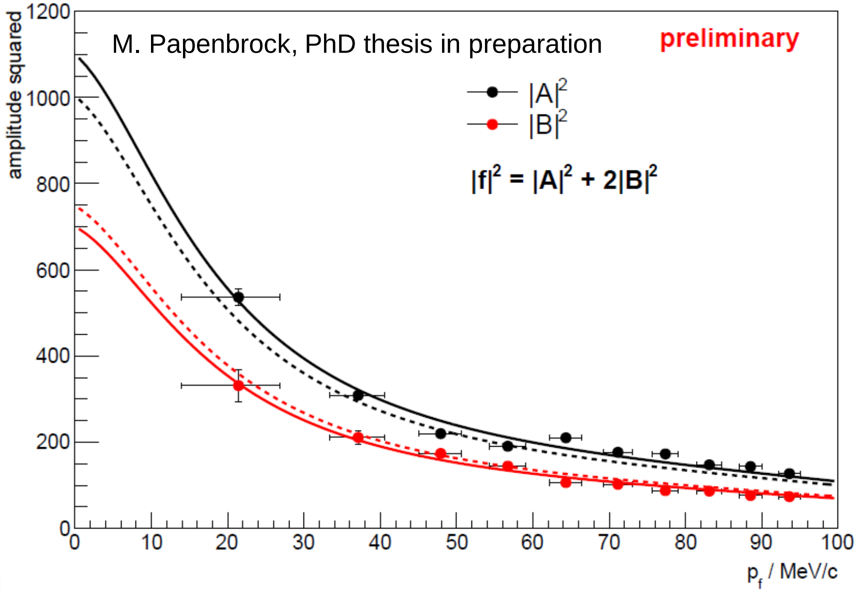
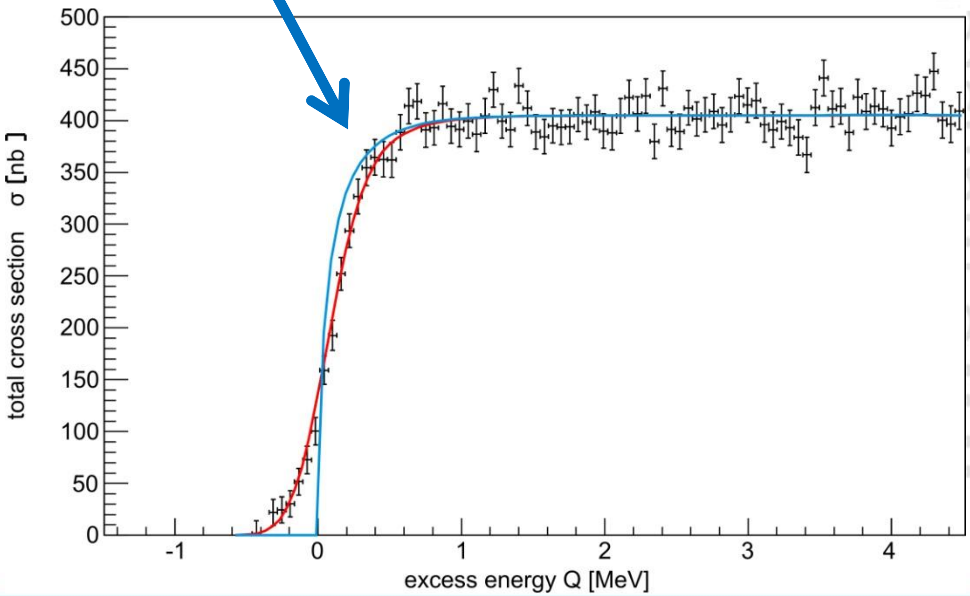
Preliminary Results: $\vec{d}+p \rightarrow {}^3He+\eta$

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





Next Steps:

- Finalize data analysis
- Quantification of T_{20} and $|A|^2/|B|^2$
- Esitmation (or upper limits) for non-FSI effect
- Evaluation of effect on pole position or scattering length

In parallel:

- Analysis of new ANKE 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

- The ANKE data on the η-^{3}He system exposes an unexpected strong final state interaction
- The energy dependence of σ_{total} and $d\sigma/d\Omega$ indicates a radip s-wave phase variation at threshold
- Preliminary tensor polarized data support the strong FSI interpretation
- The η-^{3}He system is a good candidate for a bound meson-nucleus state (strong interaction)
- New data the dη system will allow for further tests on the pole positions as function of the nucleus mass


Thank you very much....