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Measurements on the ^{3}He+η system at ANKE

International Symposium on Mesic Nuclei

June 16th, 2010

Institut für Kernphysik

Alfons Khoukaz

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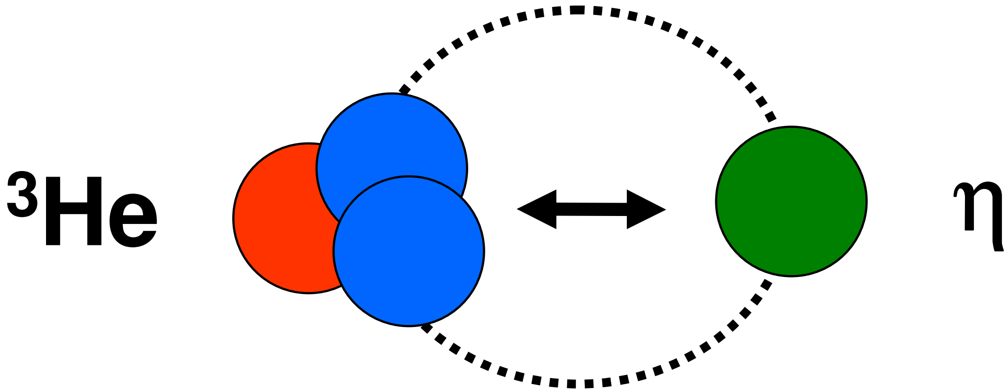
Why η-Meson Production Close to Threshold?

- Do bound meson-nucleus systems exist?



- Investigation of symmetries and conservation laws
- Determination of „techincal data“ of elementary particles
  - Mass, life time, ...

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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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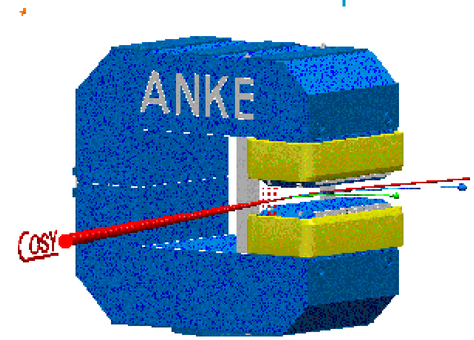
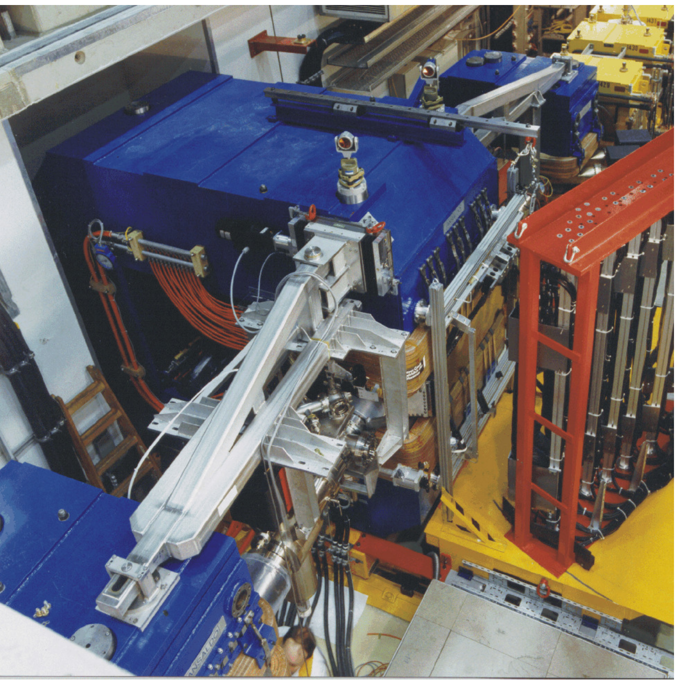
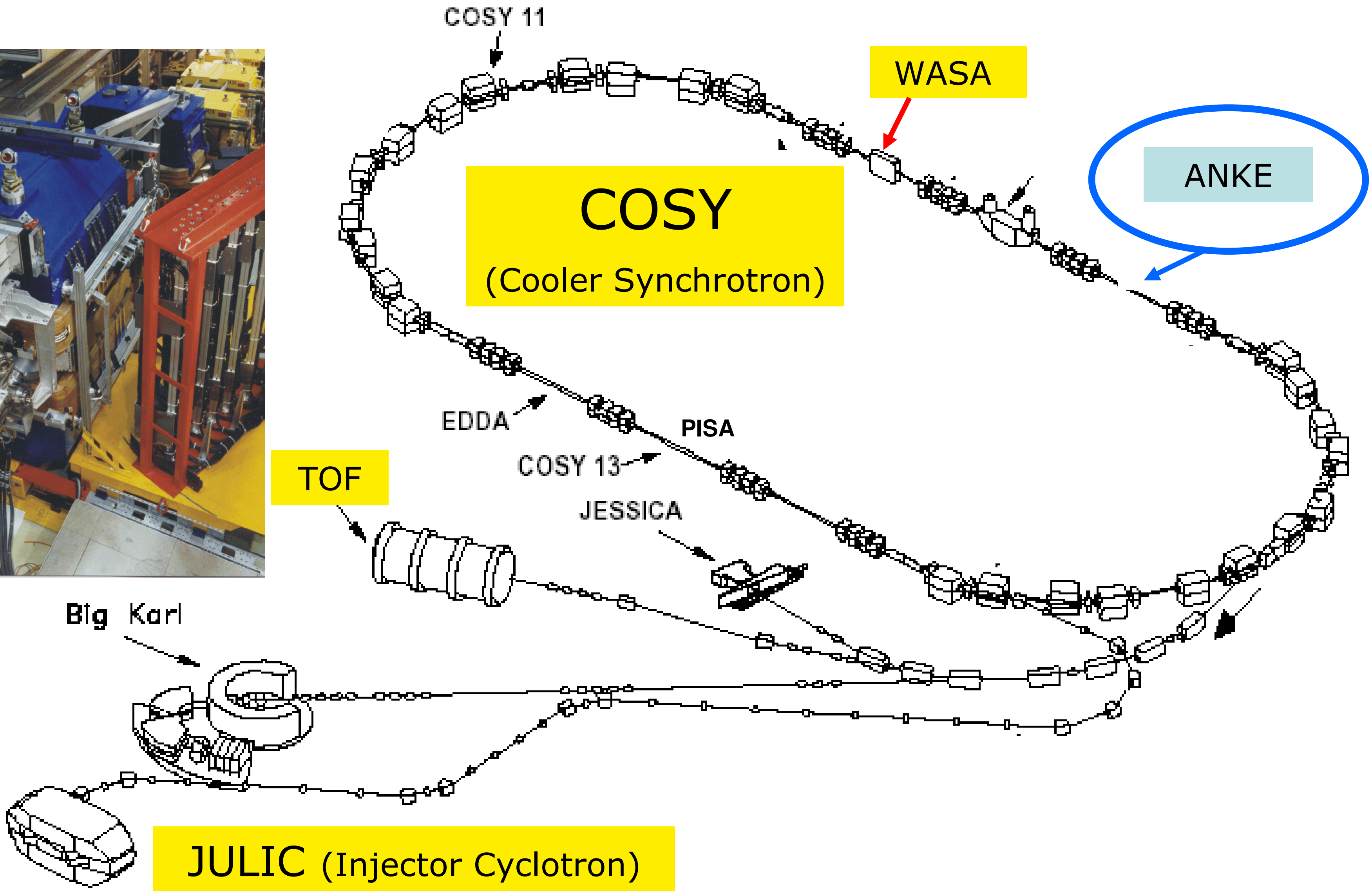
The ANKE-Facility

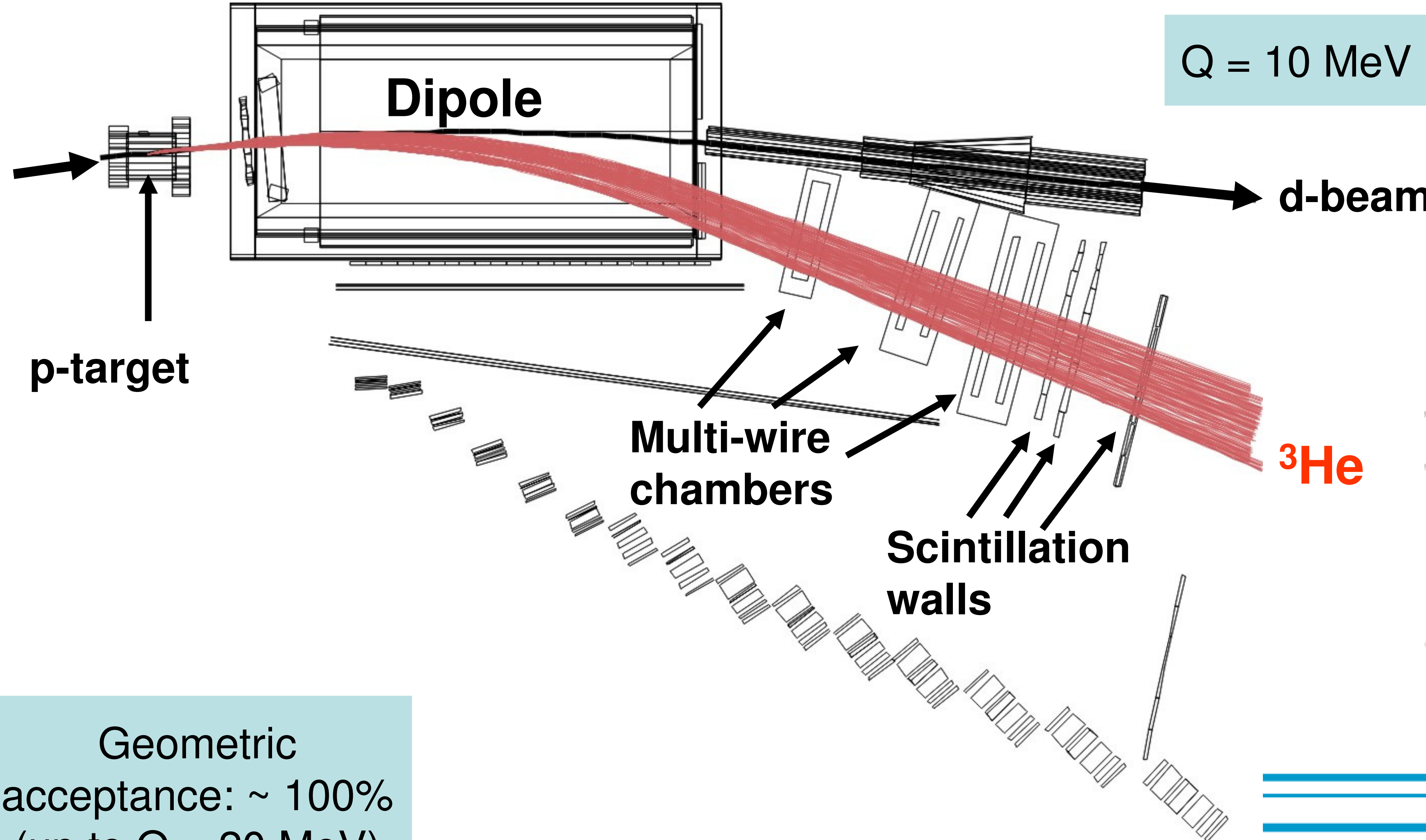






Identification of ^{3}He Nuclei at ANKE

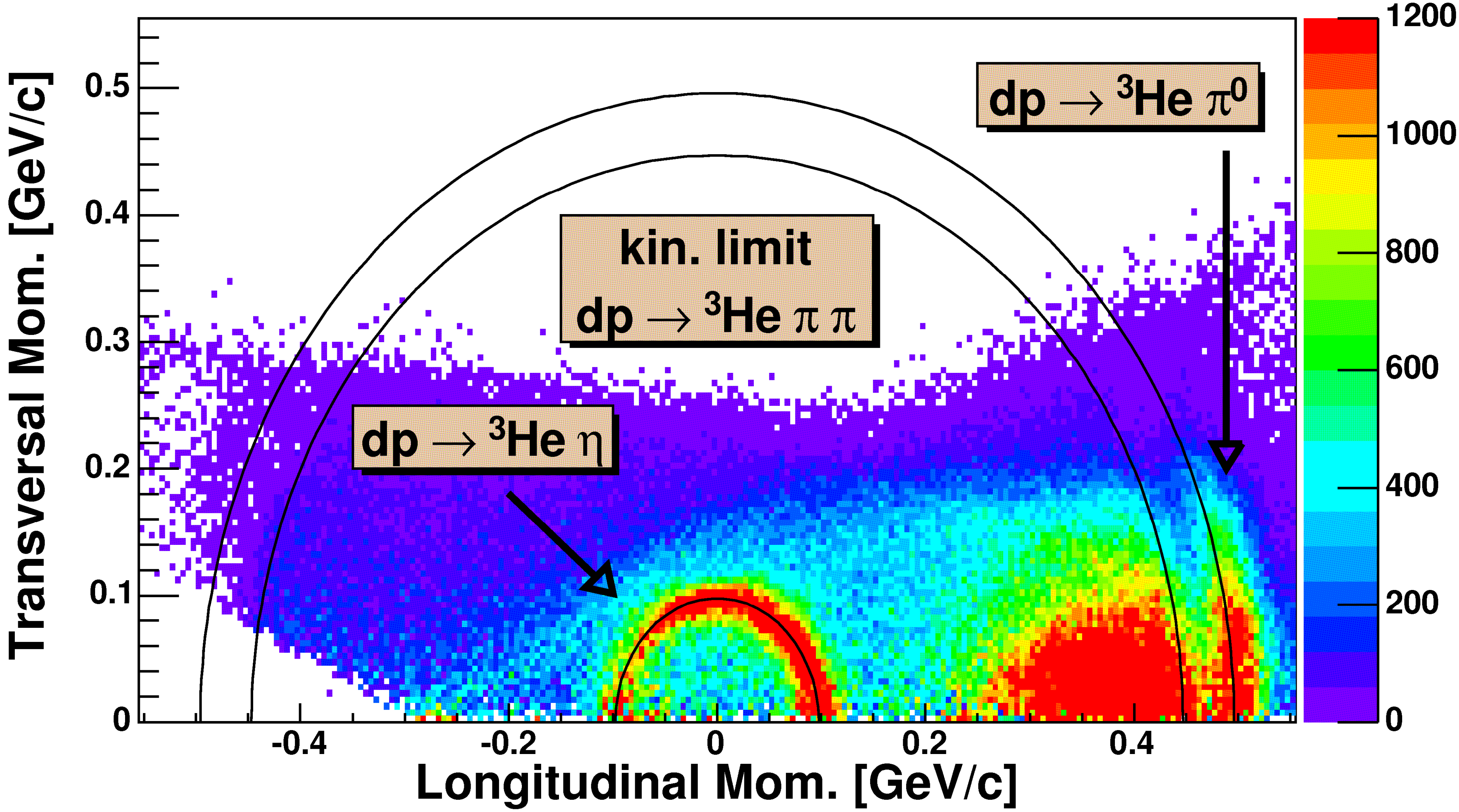
Q = 10 MeV



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

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

„Momentum rabbit“



Identification of the Reactions: $d+p \rightarrow {}^3He+X$

- 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

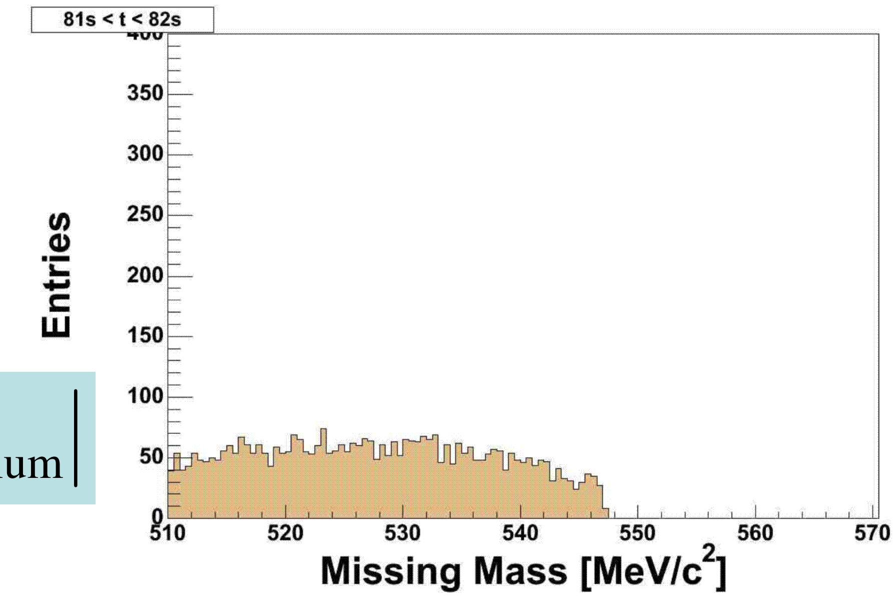
Identification of the Reactions: d+p → ^{3}He+X

Missing-mass analysis: Use four-momenta $P=(E,p_x,p_y,p_z)$

$$P_{Deuteron} + P_{Proton} = P_{Helium} + P_X$$

$$P_X = P_{Deuteron} + P_{Proton} - P_{Helium}$$

$$m_X = |P_X| = |P_{Deuteron} + P_{Proton} - P_{Helium}|$$



m_X: Invariant mass of the not detected system (one of more particles)

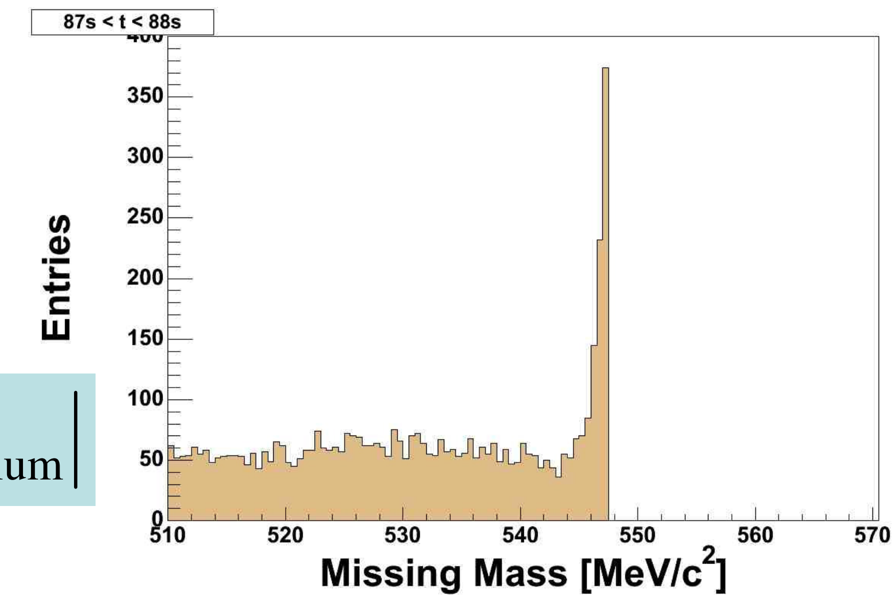
Identification of the Reactions: d+p → ^{3}He+X

Missing-mass analysis: Use four-momenta $P=(E,p_x,p_y,p_z)$

$$P_{\mathrm{Deuteron}} + P_{\mathrm{Proton}} = P_{\mathrm{Helium}} + P_X$$

$$P_X = P_{\mathrm{Deuteron}} + P_{\mathrm{Proton}} - P_{\mathrm{Helium}}$$

$$m_X = \left|P_X\right| = \left|P_{\mathrm{Deuteron}} + P_{\mathrm{Proton}} - P_{\mathrm{Helium}}\right|$$



m_X: Invariant mass of the not detected system (one of more particles)

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.

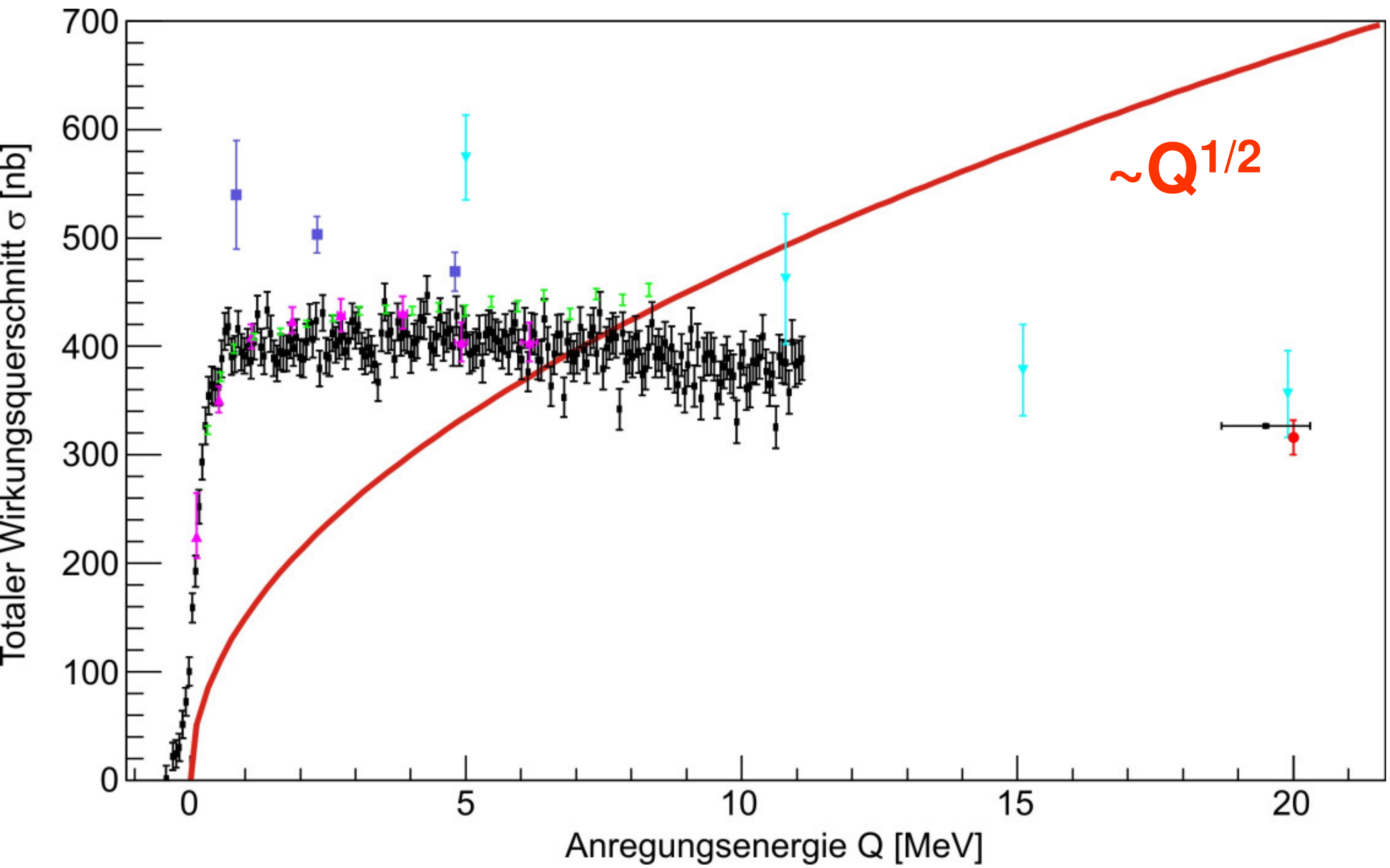
→ Increase of the cross section according to phase space expectations

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

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

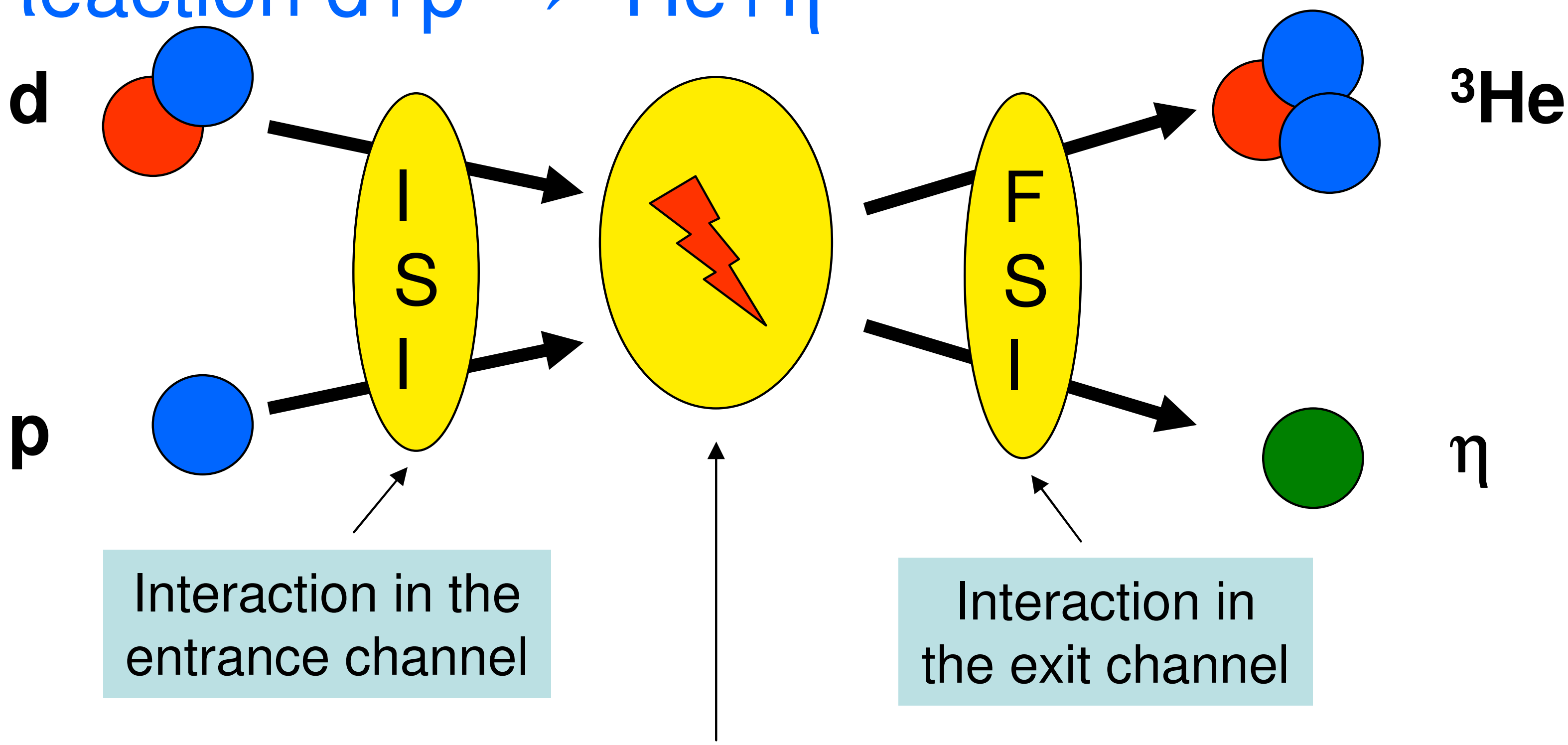
→ strong energy dependence at threshold

- After that total cross sections remain almost constant

→ Additional effect beside pure phase space

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

The Reaction d+p → ^{3}He+η



Ansatz:

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

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} ~ 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

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

$$a \equiv a_r + i a_i$$

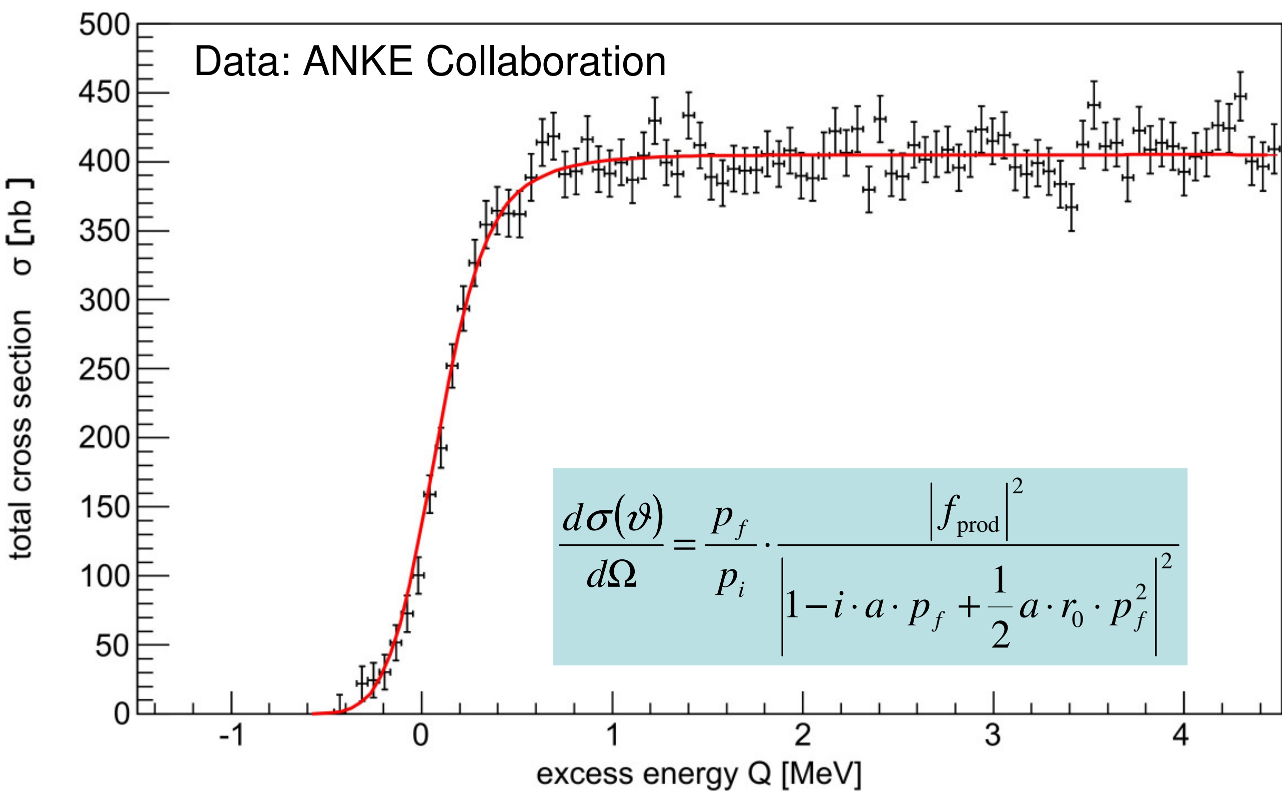
$$r \equiv r_r + i r_i$$

  - As well as

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

The Reaction d+p → ^{3}He+η

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



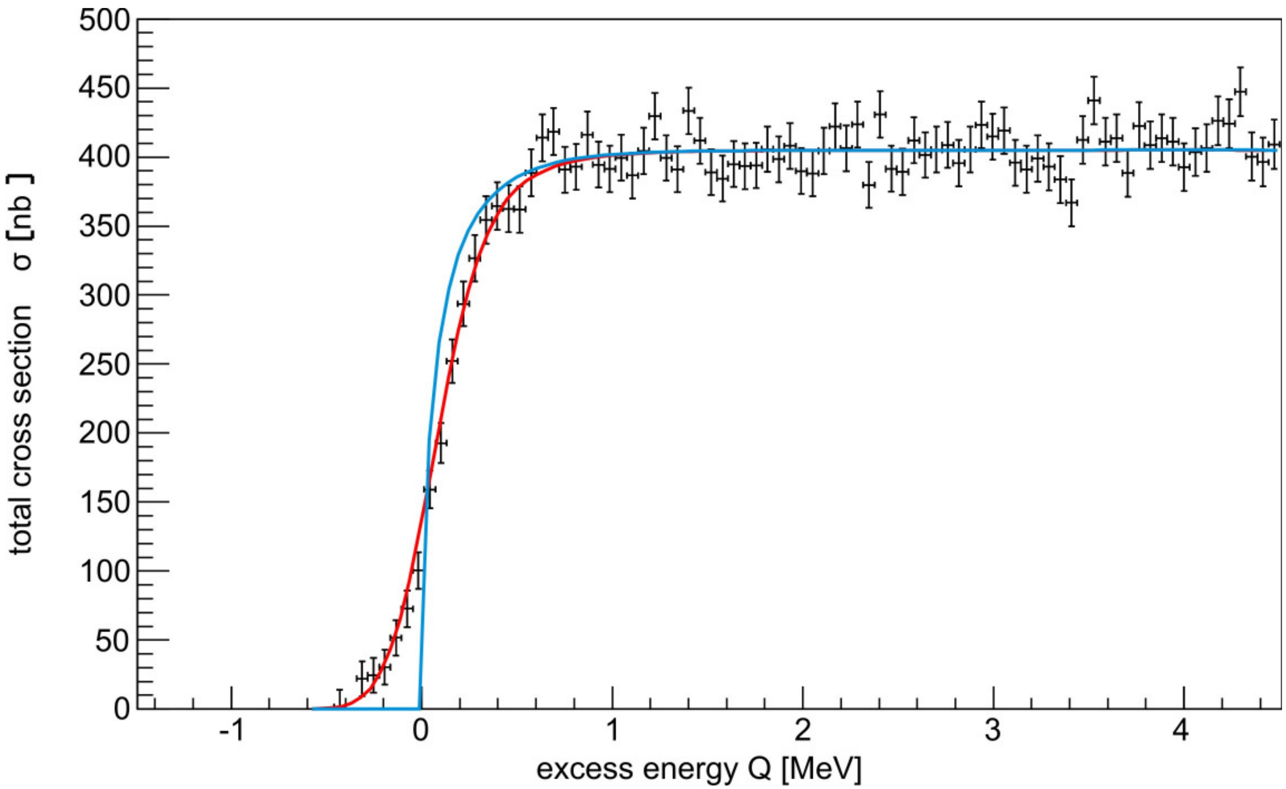
$$\frac{d\sigma(\vartheta)}{d\Omega} = \frac{p_f}{p_i} \cdot \frac{|f_{\text{prod}}|^2}{\left|1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2\right|^2}$$

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 → ^{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 $\Delta Q < 0.5$ MeV above threshold

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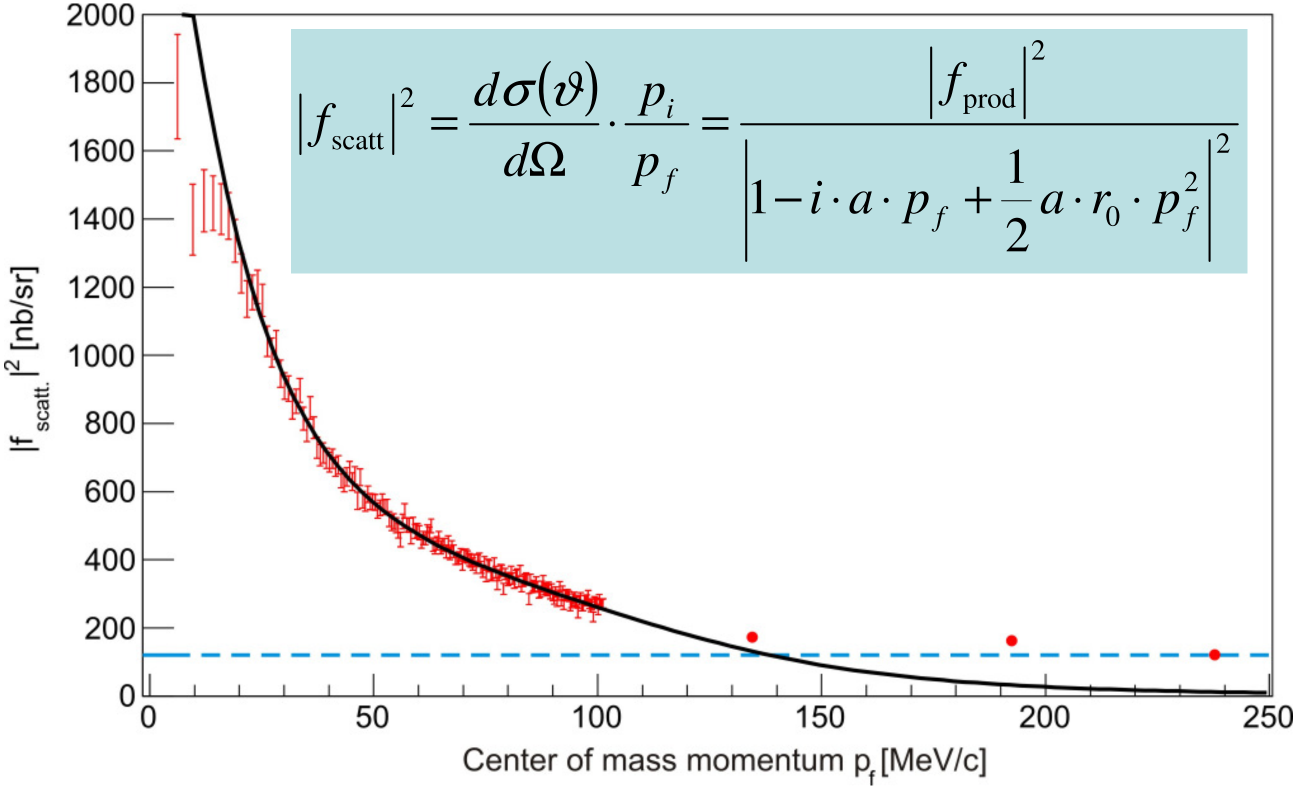
The d+p → ^{3}He+η Scattering Amplitude

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^{3}He system

η–³He Scattering Length

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

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

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

Result:

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

Notice: Determination of $|a_r|$!

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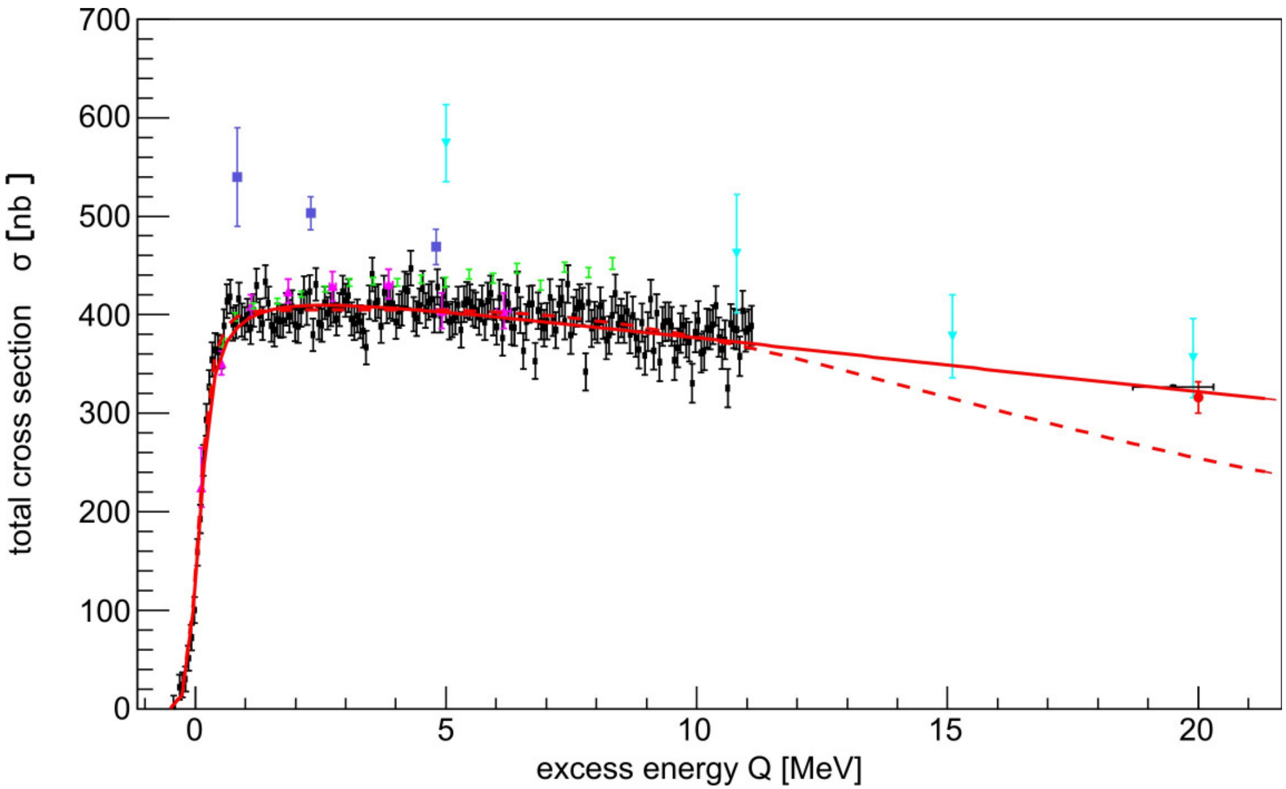
The Reaction d+p → ^{3}He+η

Fit to the near-threshold ANKE data:



Fit to 0-11 MeV: ·········

Fit to 0-20 MeV: ———

→

- Shape of the fit curve depends sligthly on the fit range
- Reason:
  E.g. contributions from higher partial waves

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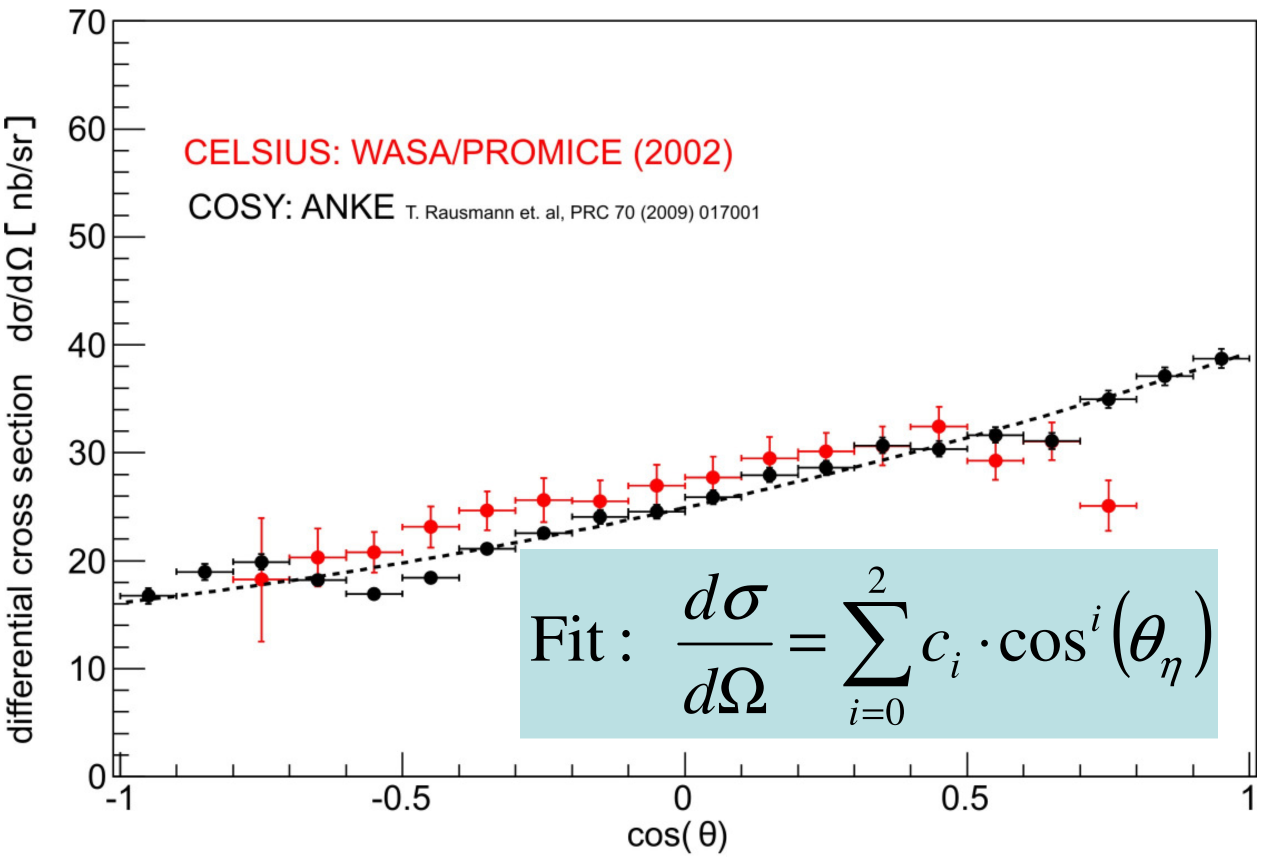
Differential Cross Sections

Angular distributions of η-mesons at Q = 20 MeV:



$$\text{Fit}: \quad \frac{d\sigma}{d\Omega} = \sum_{i=0}^{2} c_i \cdot \cos^i(\theta_\eta)$$

Data up to Q ~ 2 MeV:

- s-wave:
  (dσ/dΩ)(θ)=const.

Above Q ~ 2 MeV:

- s+p-waves:
  linear + quadratic term in cos(θ)
  (interference possible)

η–³He-Interaction: Determination of Pols

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

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

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

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

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

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

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

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

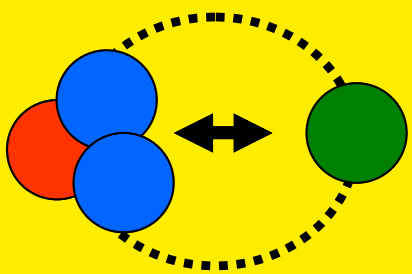
- Pole close to the reaction threshold

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

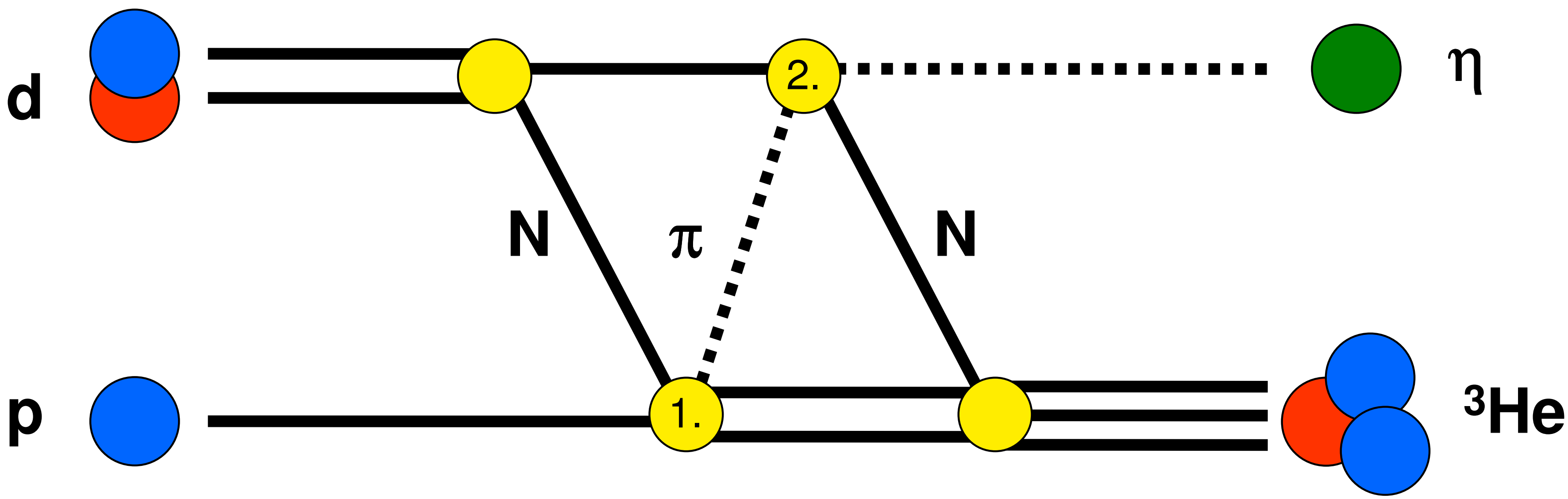
- Position of the near-threshold pole (and scattering length) stable, i.e. nearly independend of fit range
- Large real part of scattering length and $|a_r|>a_i$

→ indication for the existence of a bound state

(strong interaction!)

^{3}He  η

Production Mechanism: Two-Step-Model

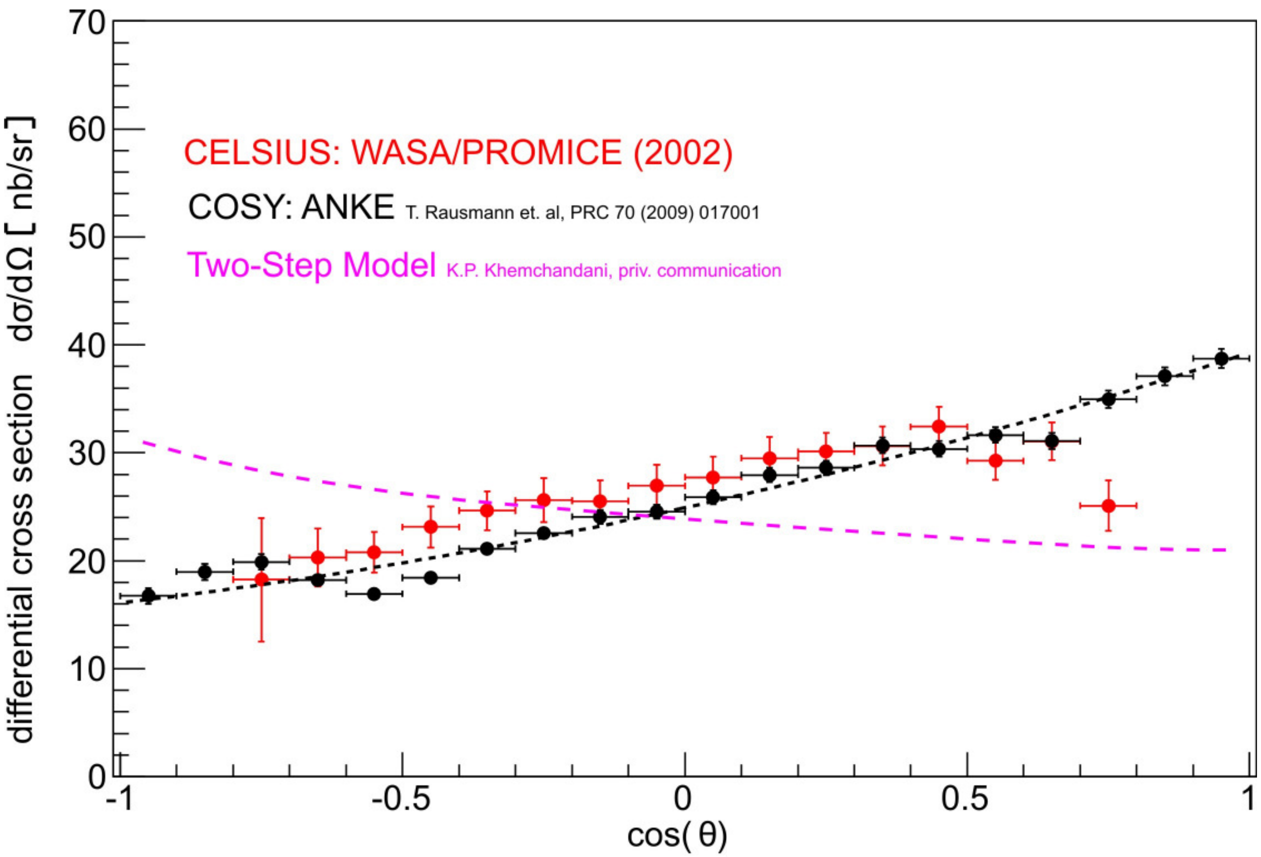


1. $p+p \rightarrow d+\pi^+$	or	1. $p+n \rightarrow d+\pi^0$
2. $\pi^+ + n \rightarrow \eta + p$	or	2. $\pi^0 + p \rightarrow \eta + p$

Use known cross sections for complete process

Prediction of the Two-Step-Model

Angular distributions of η-mesons at Q = 20 MeV:



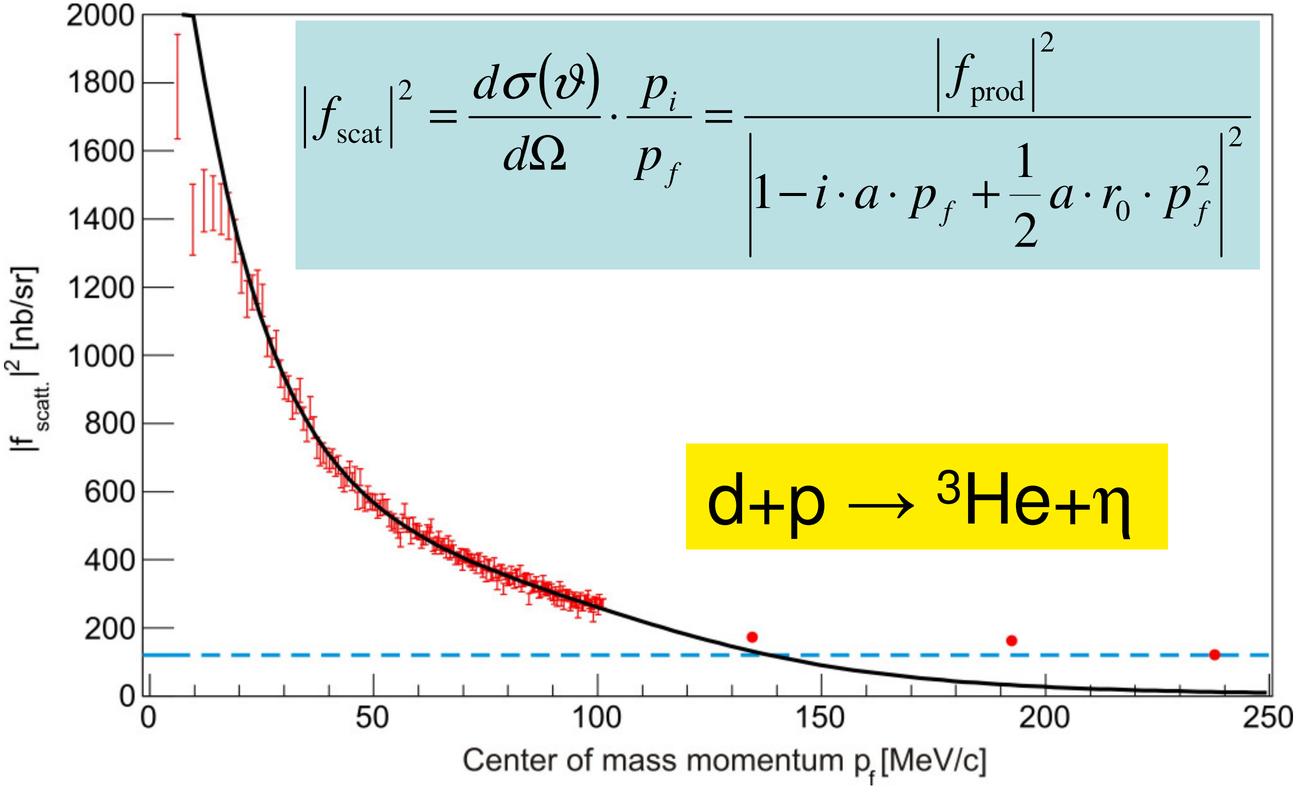
- Two-step-model predicts a different emission of the ejectiles
- Obviously the two-step-model is not sufficient to explain the data

→

open questions to theory

Further Evidences for a Strong FSI

Idea: Compare production amplitudes of different reactions with same final state

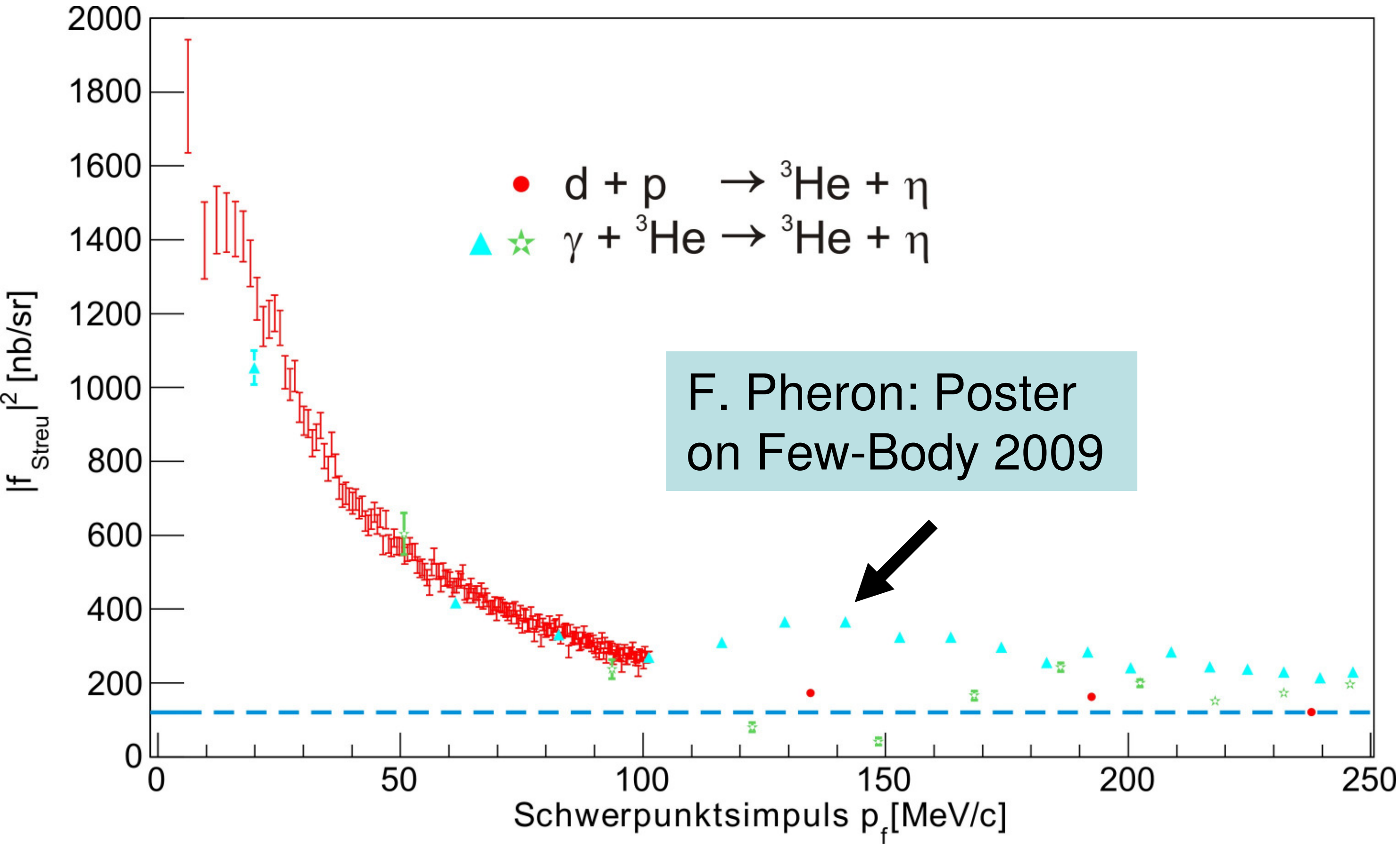


$$|f_{\text{scat}}|^2 = \frac{d\sigma(\vartheta)}{d\Omega} \cdot \frac{p_i}{p_f} = \frac{|f_{\text{prod}}|^2}{\left|1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2\right|^2}$$

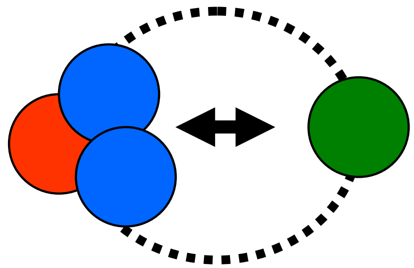
Remember:

- $|f_{prod}|$ = const. for relevant energy range
- energy dependence of ISI neglected
- $|f_{scat}|$: energy dependence according to FSI

Compare: dp- and γ^3He-Scattering



- Scattering amplitudes show similar energy dependence
- Strong hint for a strong FSI between He-nuclei and η-mesons



So we have…

- Observation of an extremely large scattering length $a_{He\eta}$

$$a = \left[\pm\left(10.7 \pm 0.8^{+0.1}_{-0.5}\right) + i\left(1.5 \pm 2.6^{+1.0}_{-0.9}\right)\right] \mathrm{fm}$$

- Scattering amplitude has a pole very close to threshold

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

- Similar behaviour in case of photoproduction

The η–^{3}He final state is a good candidate for a bound meson-nucleus system

Next Steps...

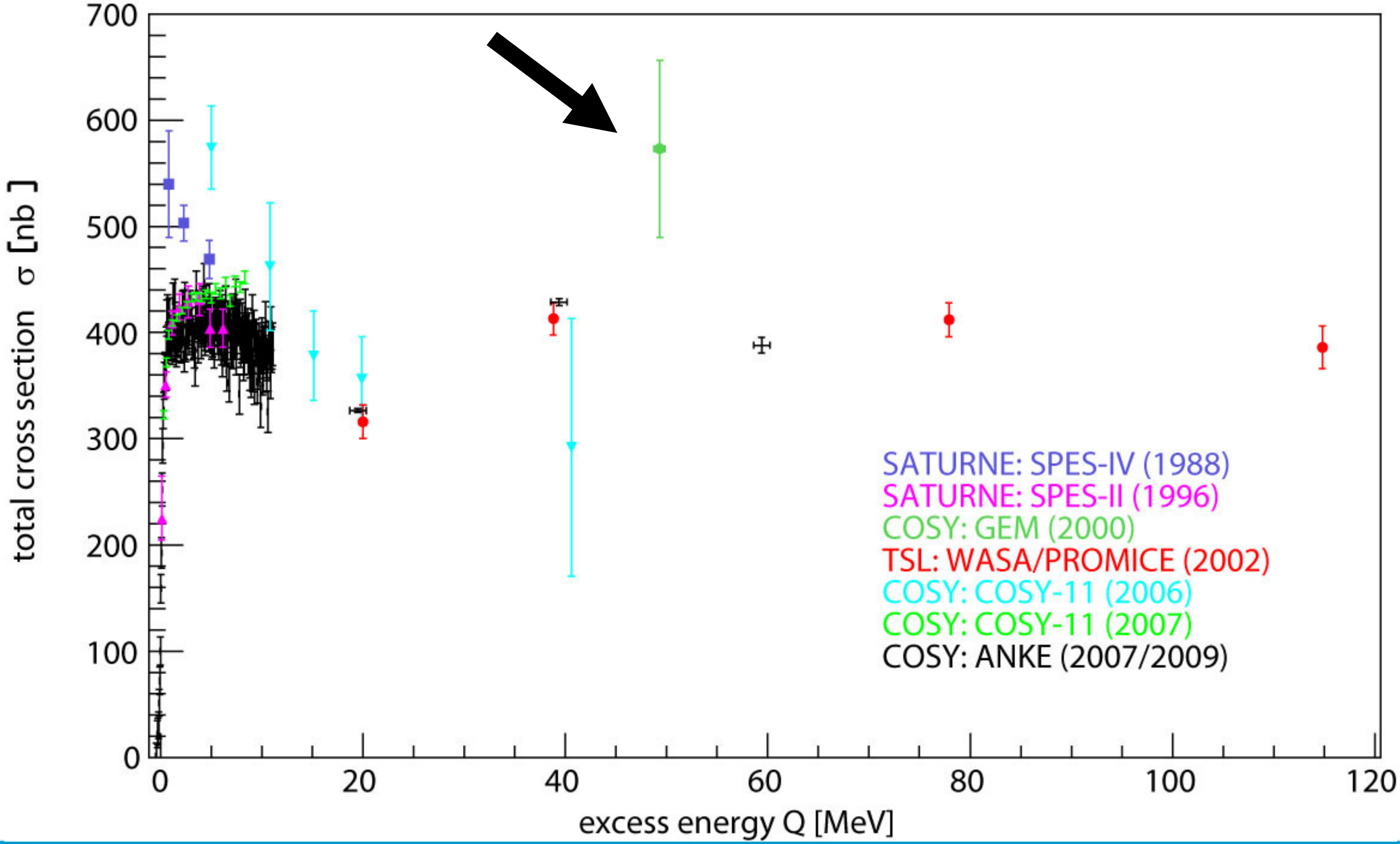
- Measurement of $d+p \rightarrow {}^3He+\eta$ with polarized beam and/or target
  - Informationen about contributing partial waves
  - Determination of the sign of the scattering length $a_{He\eta}$

- Measurement of $d+n \rightarrow {}^3H+\eta$ (by $d+d \rightarrow {}^3H+\eta+p_{spec}$)
  - Informationen about isospin/charge invariance of the FSI
  - Determination of the scattering amplitude

- Measurement of $d+p \rightarrow {}^3He+\eta$ at fixed excess energies
  - Is the „GEM-Peak“ real?
  - How do the total and differential cross sections develop?

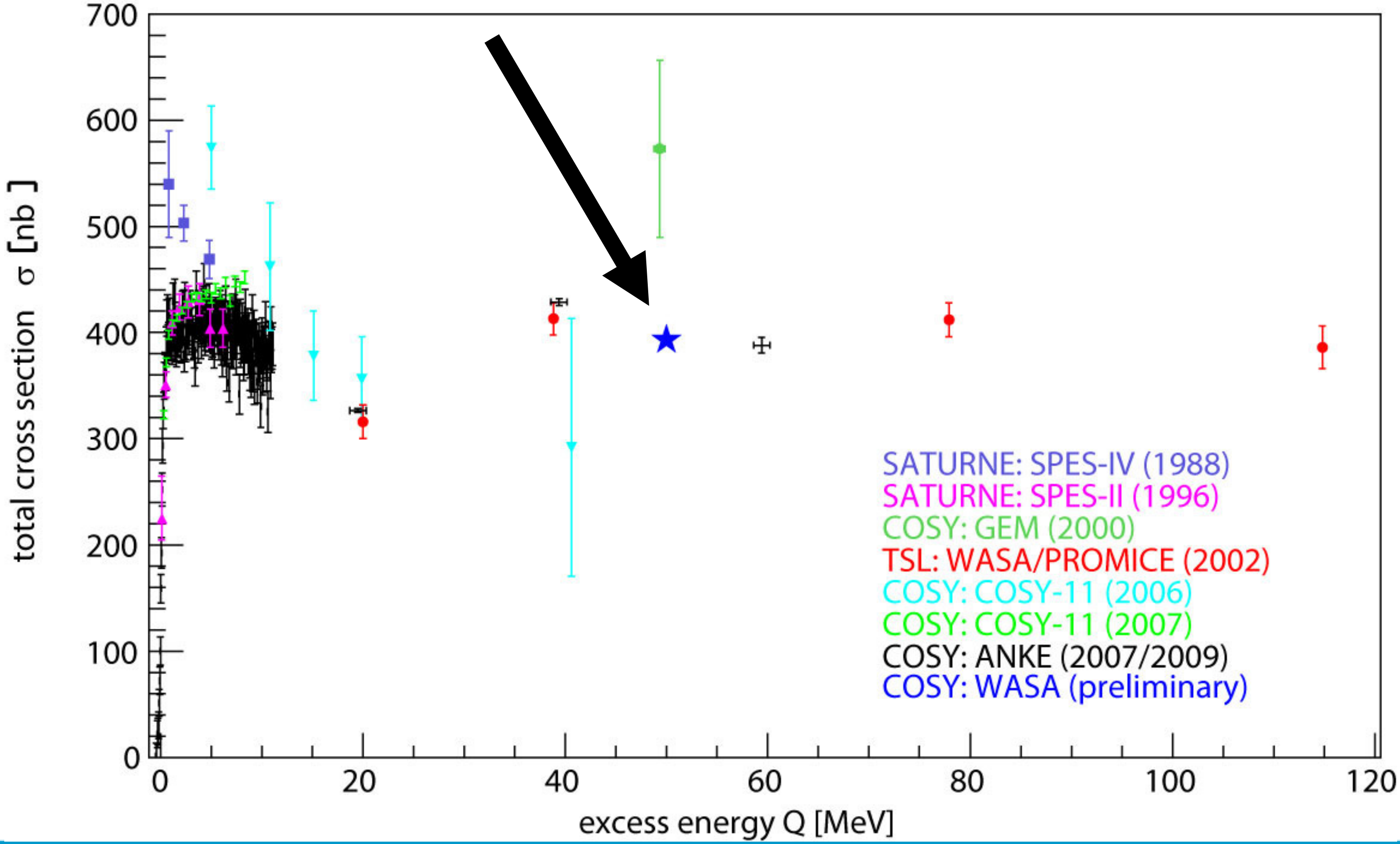
Investigations at Higher Excess Energies

- Is there a peak at Q = 50 MeV?



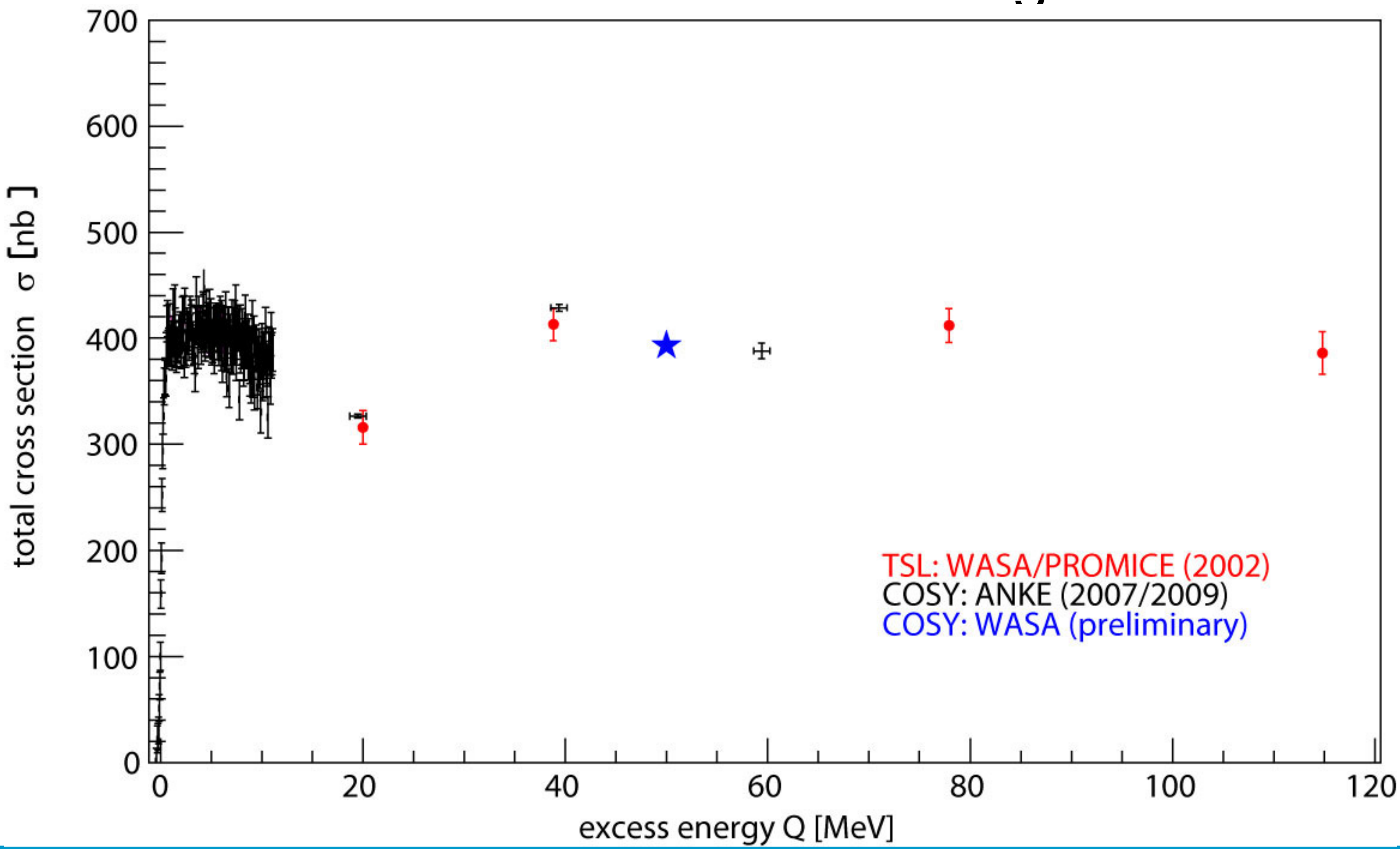
Investigations at Higher Excess Energies

- Most propably not! (Preliminary WASA-at-COSY data at Q = 50 MeV)



The ANKE and WASA Data Sets

- Consistent data set for further investigations



Summary

- The η-^{3}He system exposes an unexpected strong final state interaction
- The η-^{3}He system is a good candidate for a bound meson-nucleus state (strong interaction)
- There is need for further theoretical studies
  - on the extraction of FSI parameters from data
  - on the description of the production process: Two-Step Model etc.
- New data coming soon might support further theoretical investigation


Thank you very much....