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The Production of η Mesons in the d+p→^{3}He+η Reaction at the ANKE Spectrometer

Seminar Kernstruktur-, Elementarteilchen- und Astrophysik

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Institut für Kernphysik

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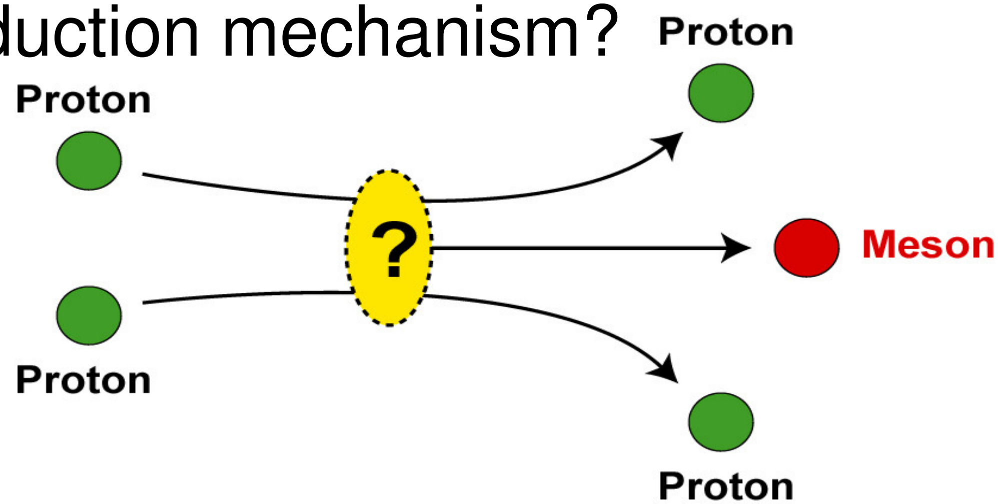
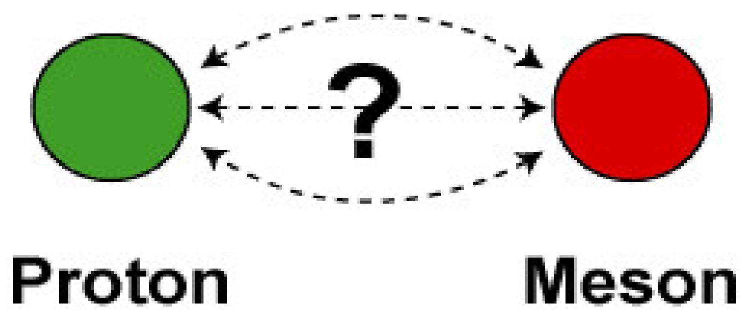
Why Meson Production Close to Threshold?

- What is the production mechanism?

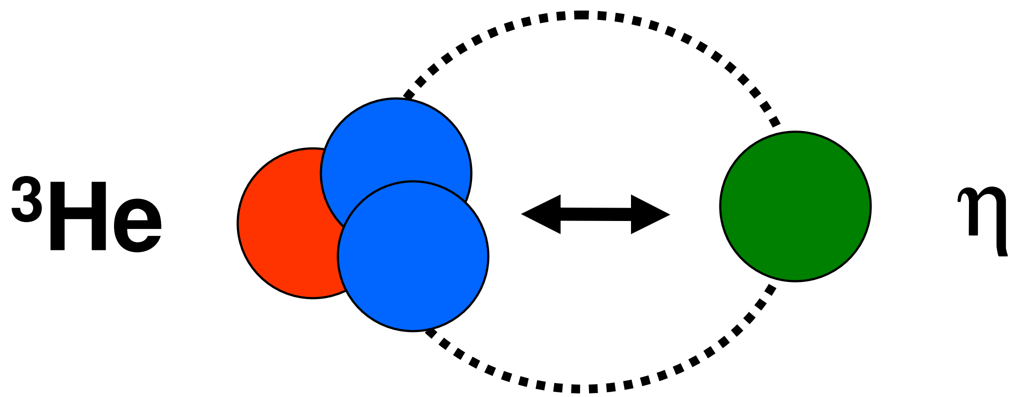


- Interaction between mesons and nucleons, nuclei or other mesons?



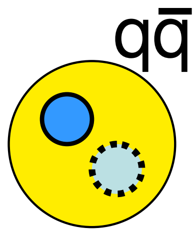
Why Meson Production Close to Threshold?

- Do bound meson-nucleus systems exist?

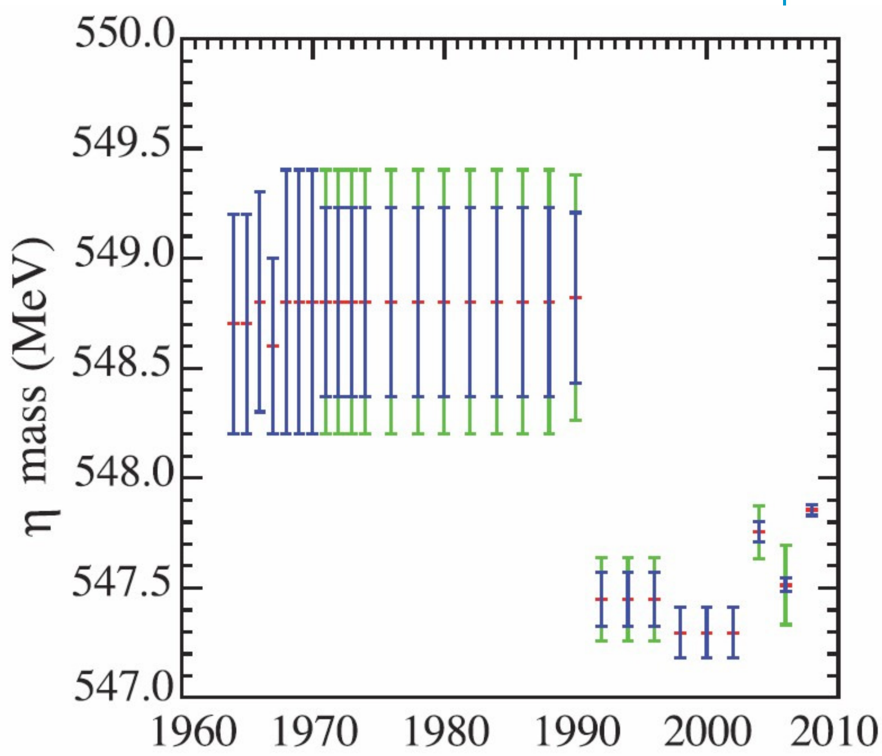


- Investigation of symmetries and conservation laws
- Determination of „techincal data“ of elementary particles
  - Mass, life time, ...

The η Meson



- Mass: m_η = 547.853 MeV/c^2
- Life time: t ~ $5 \cdot 10^{-19}$ s
- Width: ΔE = 1.30 keV
- Quark content: mixed state



$$
\begin{aligned}
|\eta\rangle &= |\eta_8\rangle \cdot \cos\theta_{PS} - |\eta_1\rangle \cdot \sin\theta_{PS} \\
&= \left(\frac{1}{\sqrt{6}}\left|u\bar{u} + d\bar{d} - 2s\bar{s}\right\rangle\right) \cdot \cos\theta_{PS} - \left(\frac{1}{\sqrt{3}}\left|u\bar{u} + d\bar{d} + s\bar{s}\right\rangle\right) \cdot \sin\theta_{PS} \\
&\approx 30\%\left|u\bar{u}\right\rangle + 30\%\left|d\bar{d}\right\rangle + 40\%\left|s\bar{s}\right\rangle
\end{aligned}
$$

The η Meson

Decays:

$\eta \rightarrow \pi\pi$: Forbidden (violates parity/angular momenta)

$\eta \rightarrow \pi\pi\pi$: Forbidden (violates G-parity)

Dominant decays:

$\eta \rightarrow \gamma\gamma$: ~39%

$\eta \rightarrow \pi\pi\pi$: ~55% ! (see above)

$\eta \rightarrow \gamma\pi\pi$: ~5%

η Meson:

Well suited for investigation of **rare decays** and verification of **conservation laws**

Study of Meson – Nucleus Interaction

How can we investigate the interaction of very short living mesons with nuclear matter?

Trick:

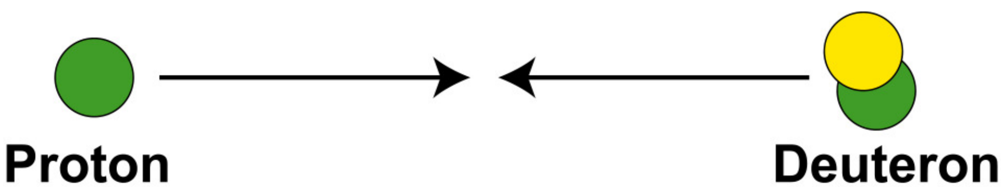
Create the short-living meson together with the nucleus of interest!

$\longrightarrow$

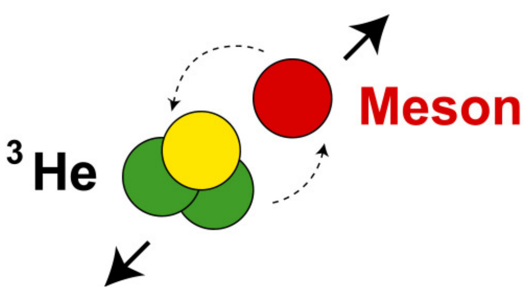
Maximum interaction time between meson + nucleus!

Near-Threshold Meson Production

before:



after:



Reaction threshold:

- Just enough energy to allow for the reaction
- Meson + nucleus have maximum interaction time!

→

Need of an accelerator with high energy resolution

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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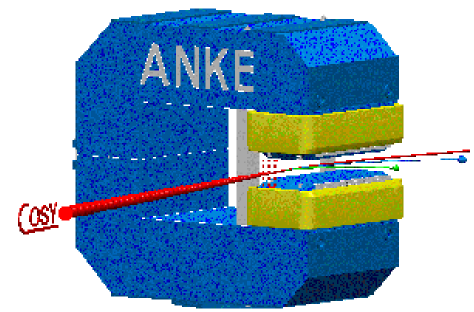
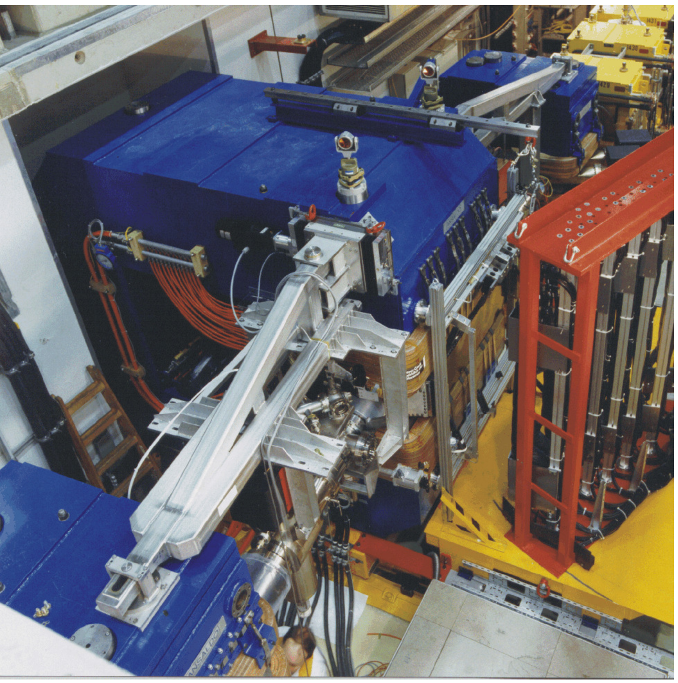
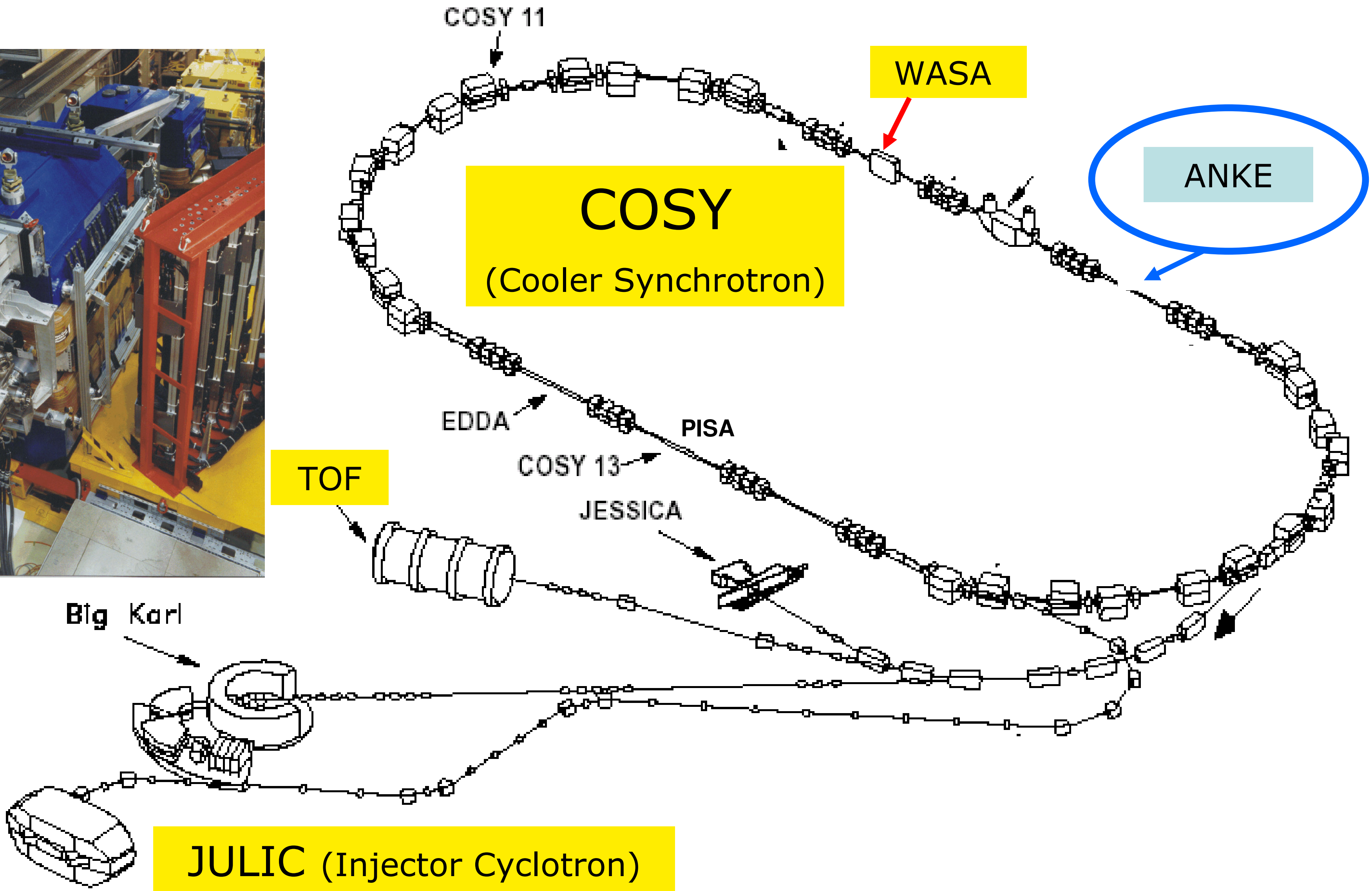
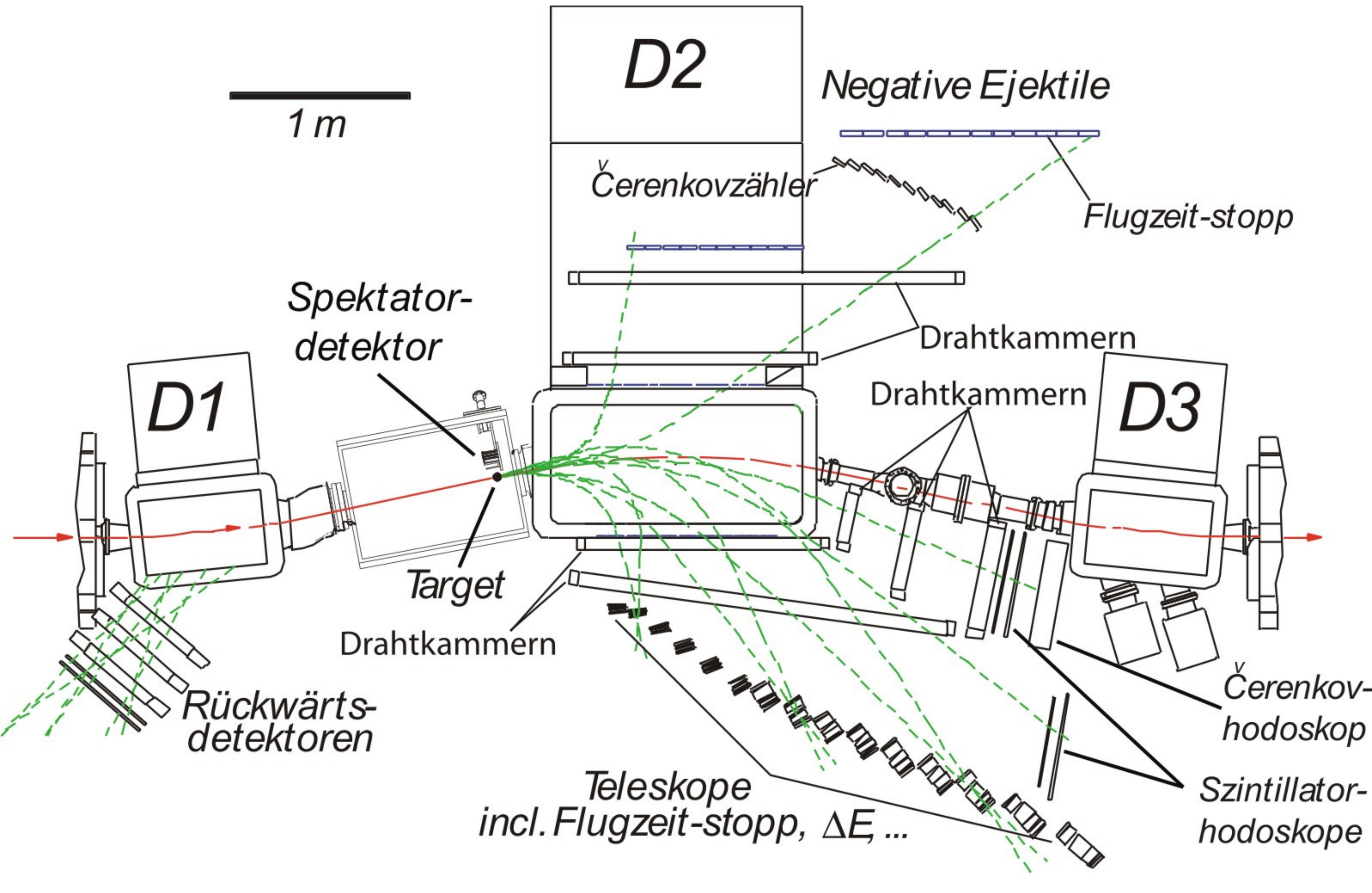
The ANKE-Facility








D2
1 m
Negative Ejektile
Čerenkovzähler
Flugzeit-stopp
Spektator-
detektor
Drahtkammern
Drahtkammern
D1
D3
Target
Drahtkammern
Rückwärts-
detektoren
Čerenkov-
hodoskop
Teleskope
incl. Flugzeit-stopp, ΔE, ...
Szintillator-
hodoskope

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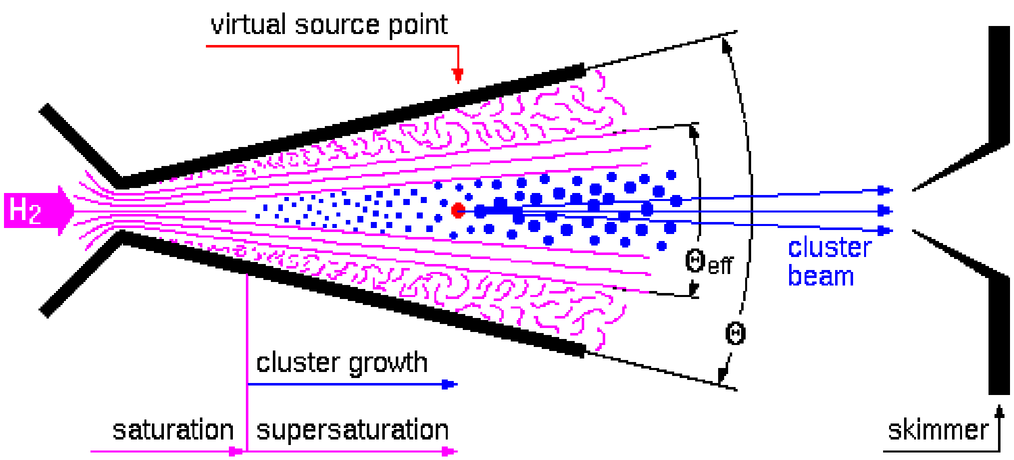
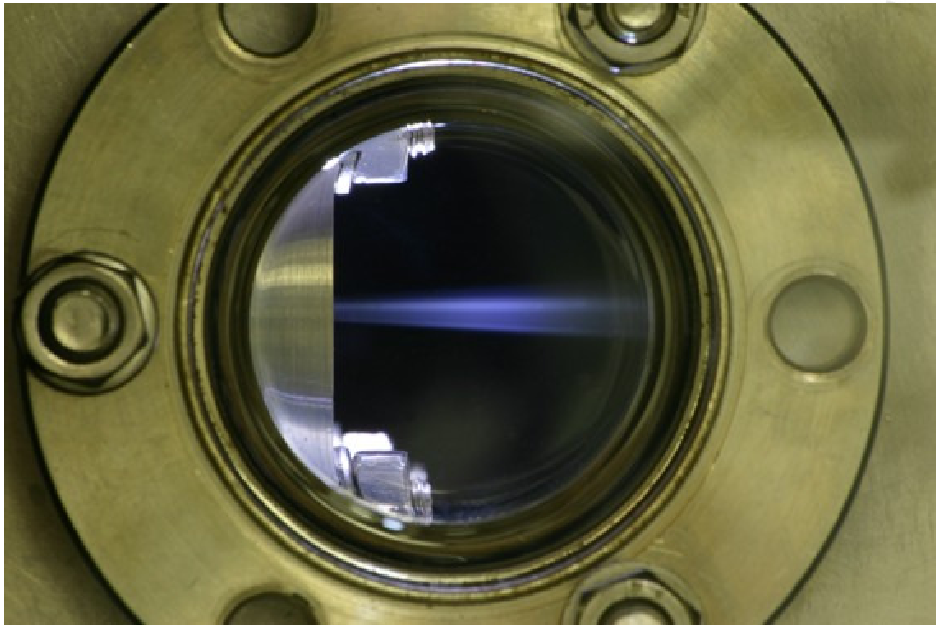
Cluster-Jet-Target

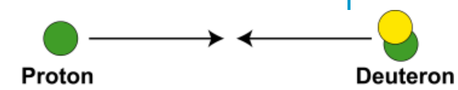
- Expansion of compressed, pre-cooled gases through fine Laval-type nozzles (e.g. H_2, 20 K, 18 bar)

  → Production of supersonic cluster-jets

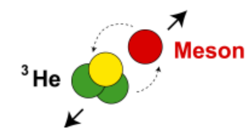




Cluster: nm - µm depends on operational parameters



Meson Production at Threshold



Production threshold:

- Minimum accelerator energy to allow for a certain reaction

  E.g.: $d+p \rightarrow {}^3He+\eta$ possible above $E_{deuteron}$= 1.781 GeV

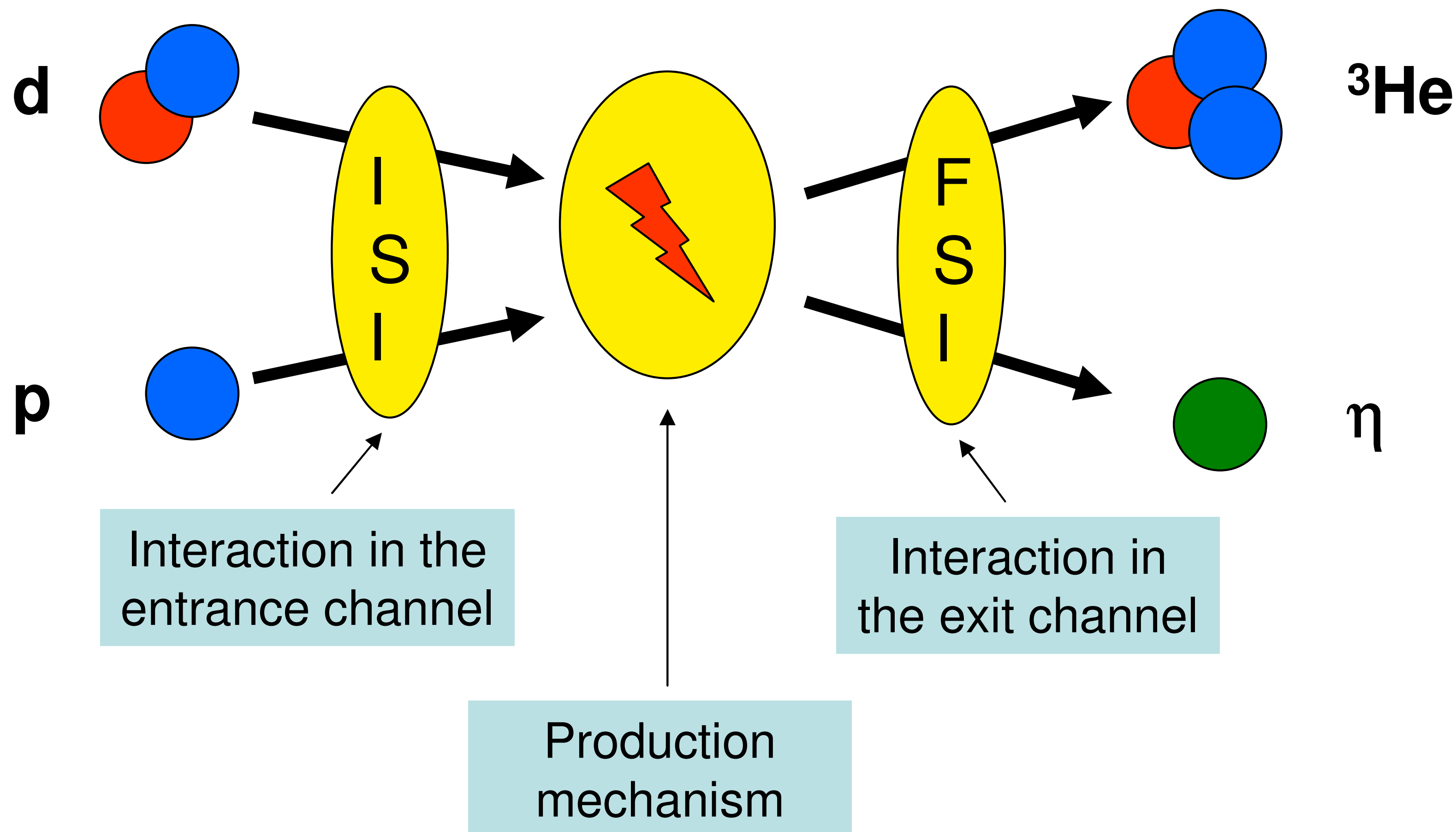
- At $E=E_{thresh.}$ the complete energy (in the CMS) is transformed into mass energy

  → Kinetic energie in the CMS = 0

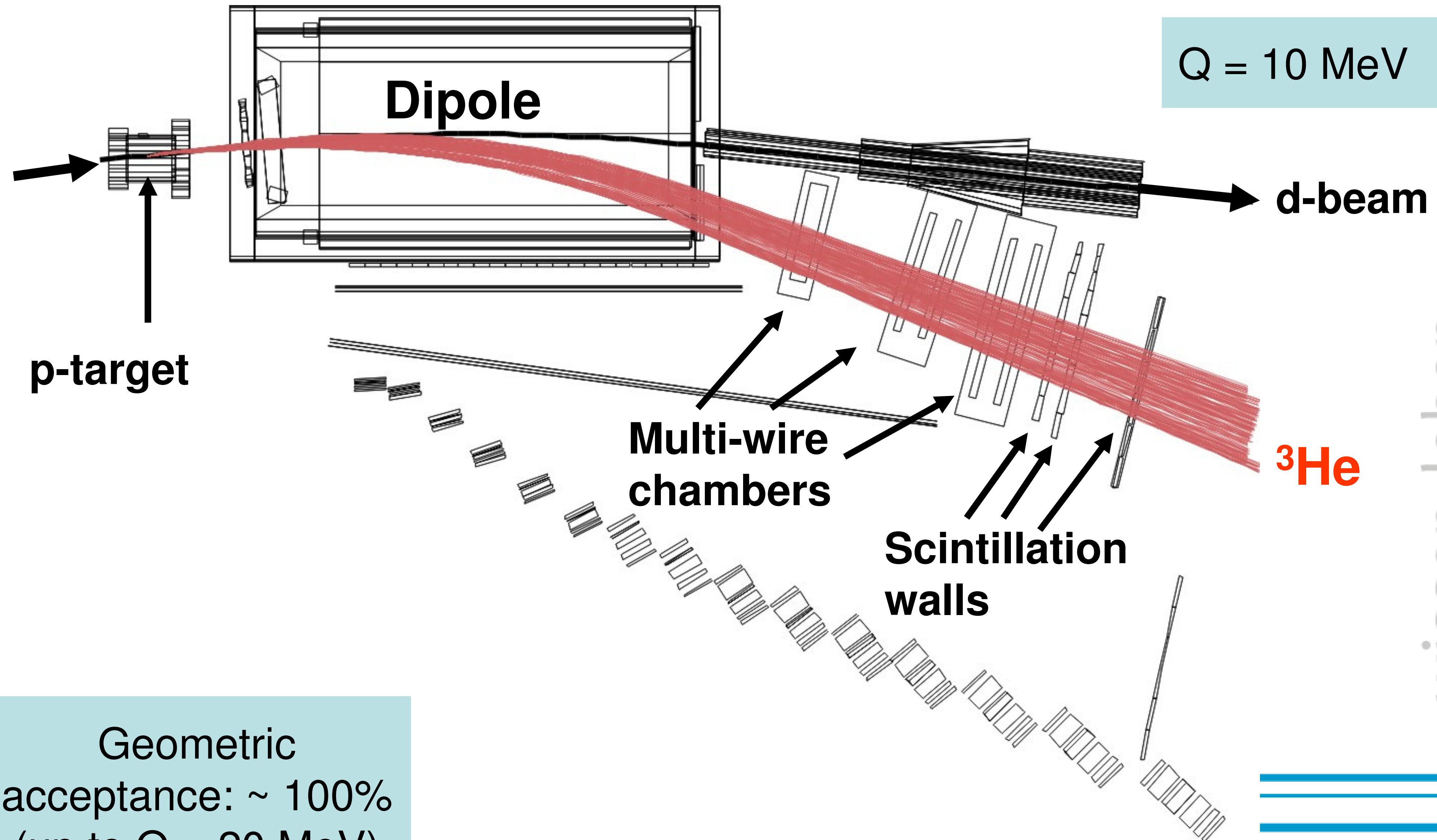
  → Maximum interaction time of the ejectiles

  → Maximum effect of final state interactions

The Reaction d+p → $^3He+\eta$



Identification of ^{3}He Nuclei at ANKE



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

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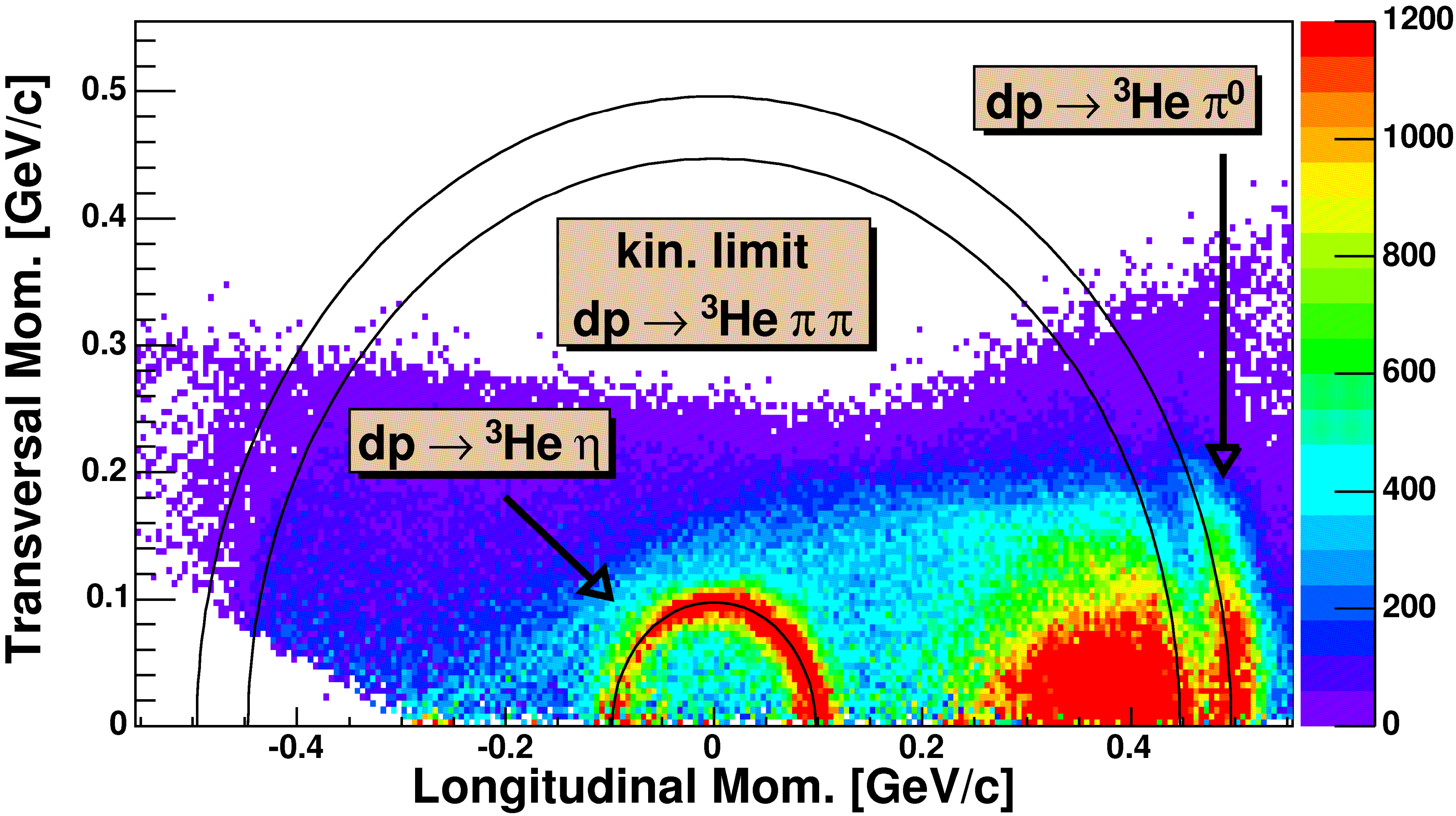
Identification of the Reactions: d+p → ^{3}He+X

„Momentum rabbit“



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

- 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
  $\tau \sim 5 \times 10^{-19}$ s

Question: How can we identify the production of η-mesons?

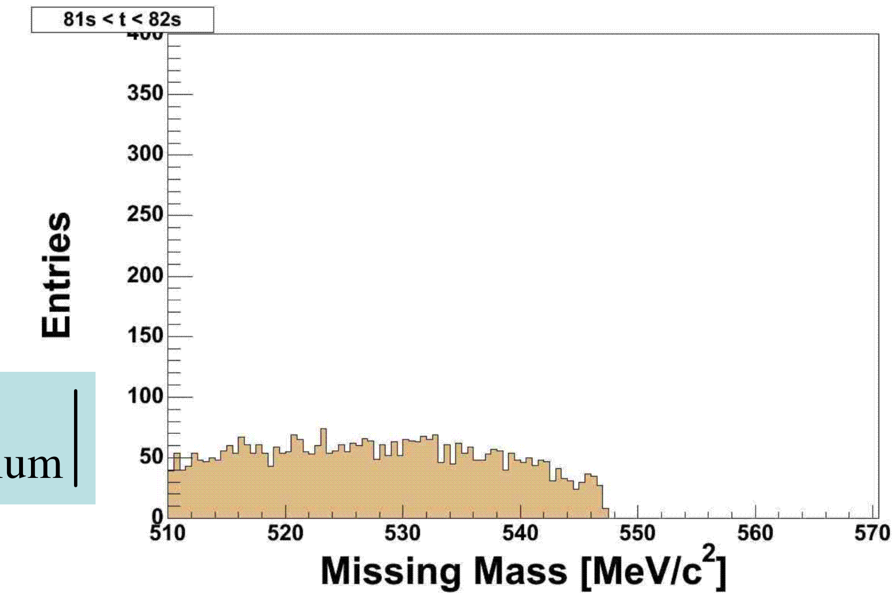
Identification of the Reactions: d+p → ^{3}He+X

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 $P=(E,p_x,p_y,p_z)$

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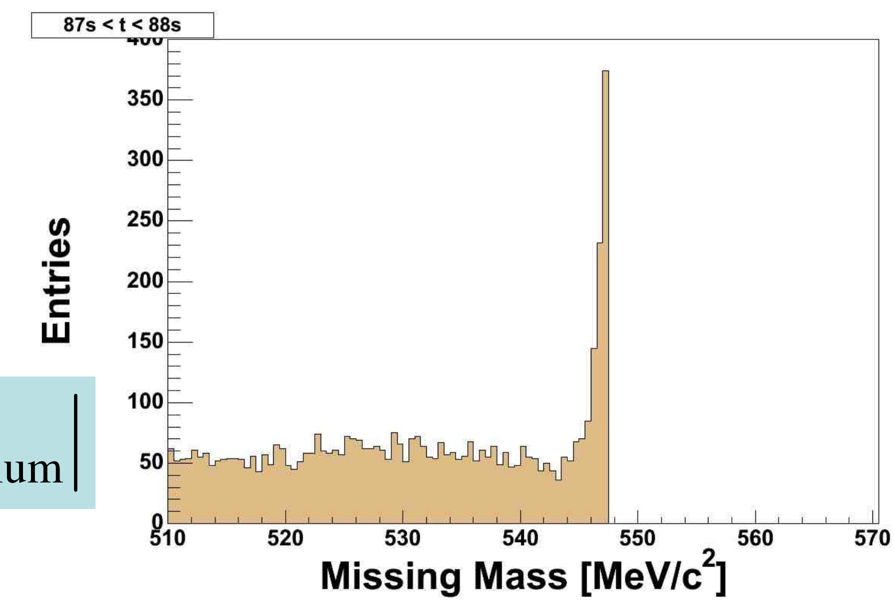

m_X: Invariant mass of the not detected system
(one of more particles)

Typical Analysis Procedure

- Measurement at different energies close to threshold
- Identification of the η-meson production via missing-mass analysis
- Determination of angular distributions
- Normalization using reference reactions (e.g. dp elast. scattering)
- Determination of differential und total cross sections ($d\sigma/d\Omega$, σ_{total})

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

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

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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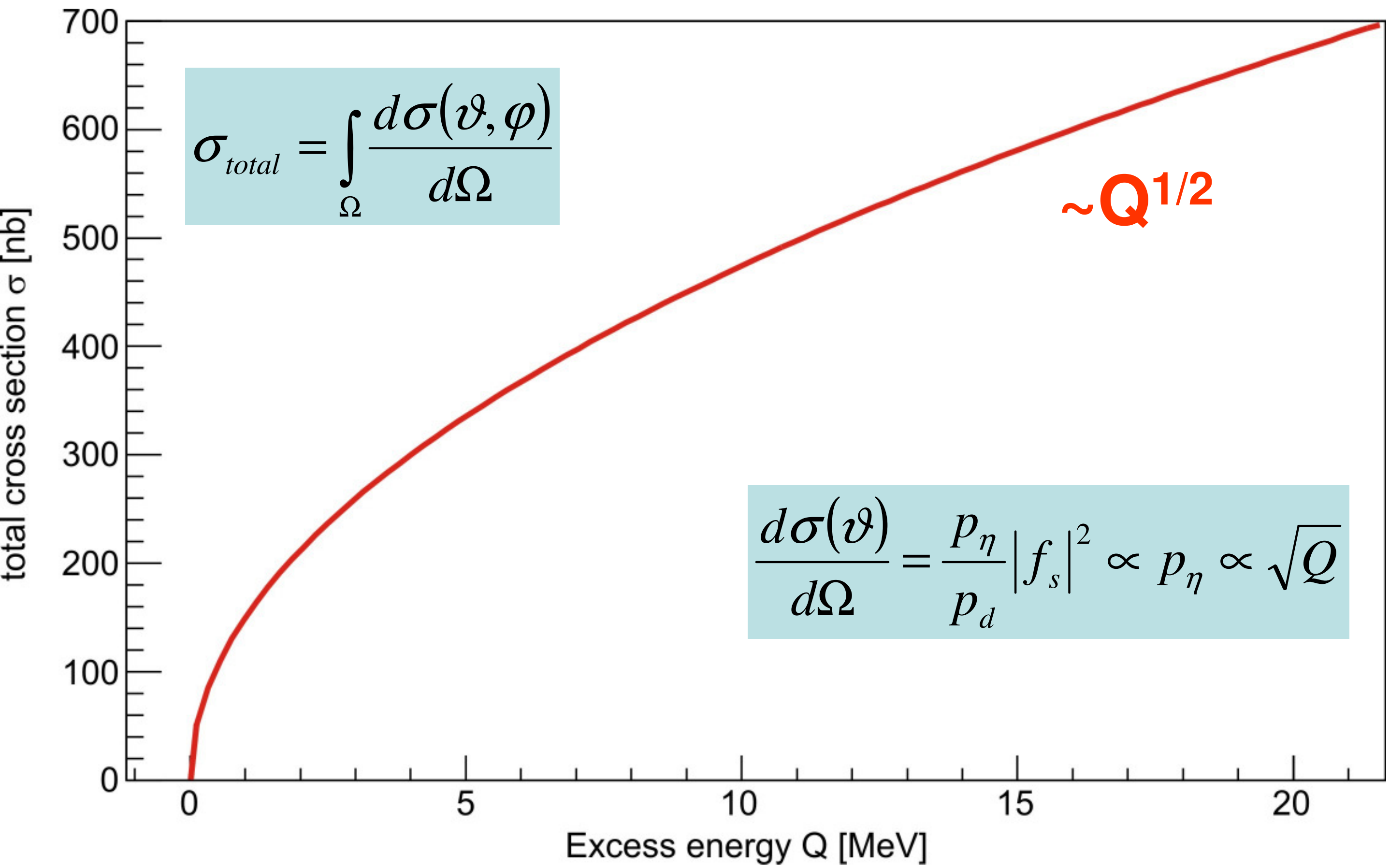
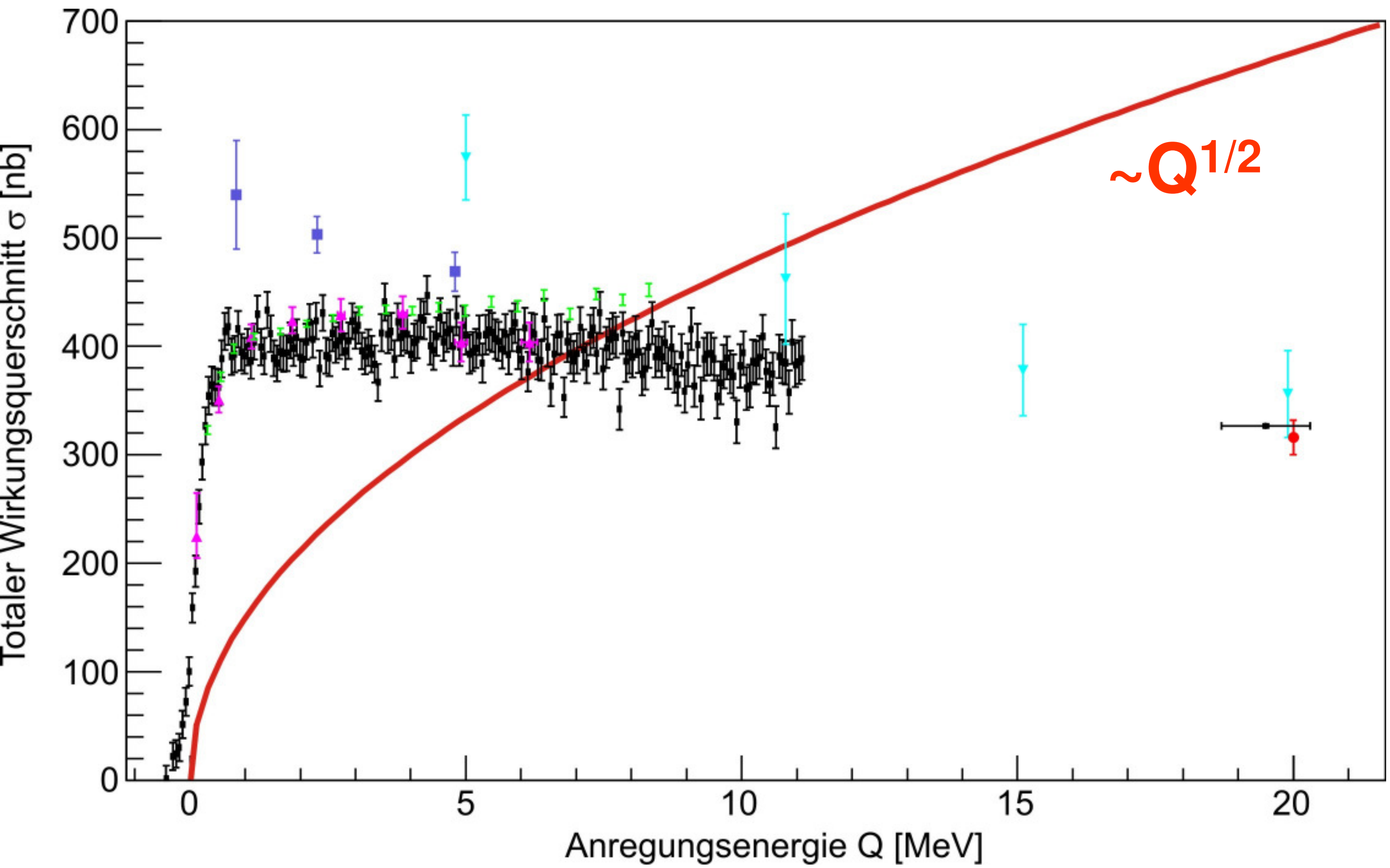
Two-Particle Final State: Phase Space



Expectation for $d+p \rightarrow {}^3He+\eta$:

- Increase $\sim Q^{1/2}$ close to threshold
- Deviations at higher energies possible (higher partial waves)

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 $\Delta Q < 1$ 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

Question:

- How can we quantify the strength of the final state interaction (FSI)?
- Is this FSI between the meson and the nucleus strong enough to form a bound state?

Ansatz:

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

Scattering Theory and Final State Interaction

„Effective-Range-Approximation“:

- Description of the FSI amplitude by scattering length *a* and the effective range *r* (Landau, Schwinger,Bethge)

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

$$a \equiv a_r + i a_i$$

$$r \equiv r_r + i r_i$$

- Special case: *a* = 0

→ no interaction

$$\sigma_{WW} = \lim_{p \to 0} 4\pi |f|^2 = 4\pi \cdot a^2$$

→ phase space behaviour, $\sigma \sim p_f \sim (Q)^{1/2}$

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

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

$$a \equiv a_r + i a_i$$

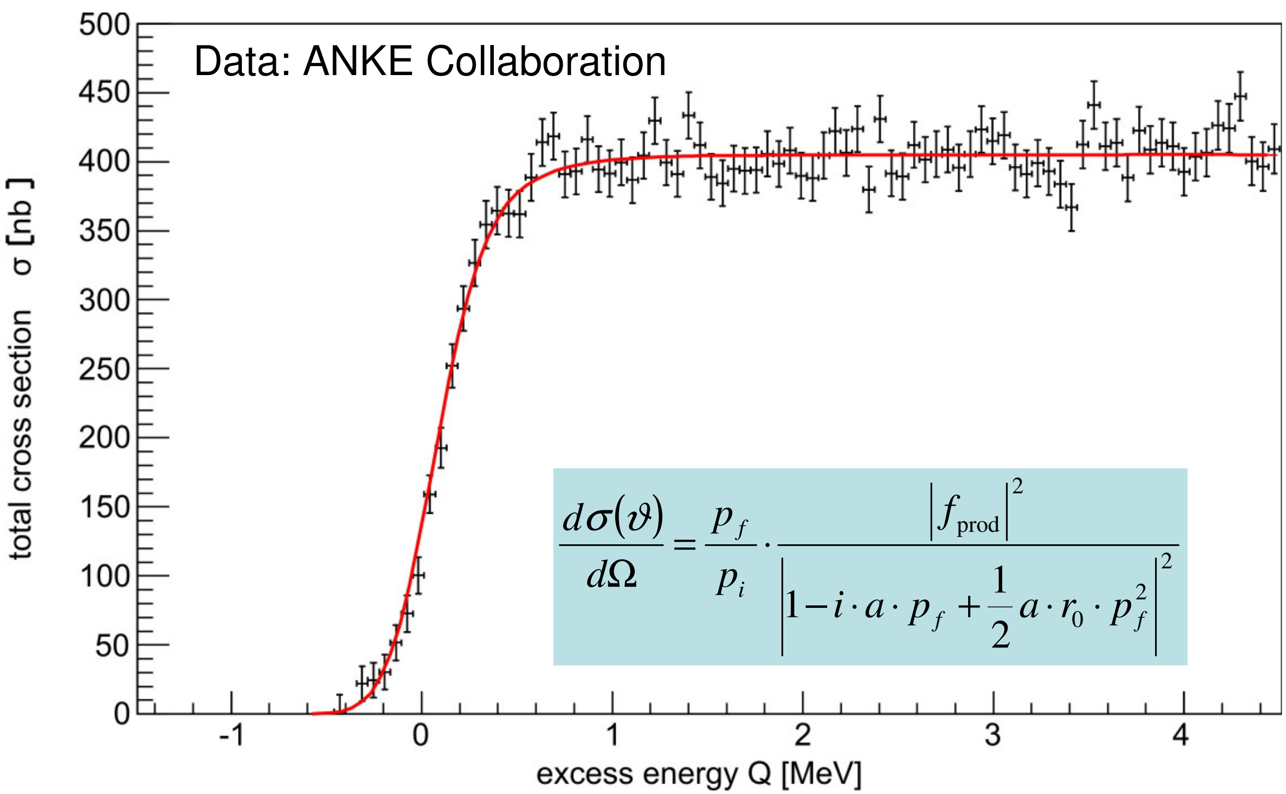
$$r \equiv r_r + i r_i$$

  - As well as

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

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

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



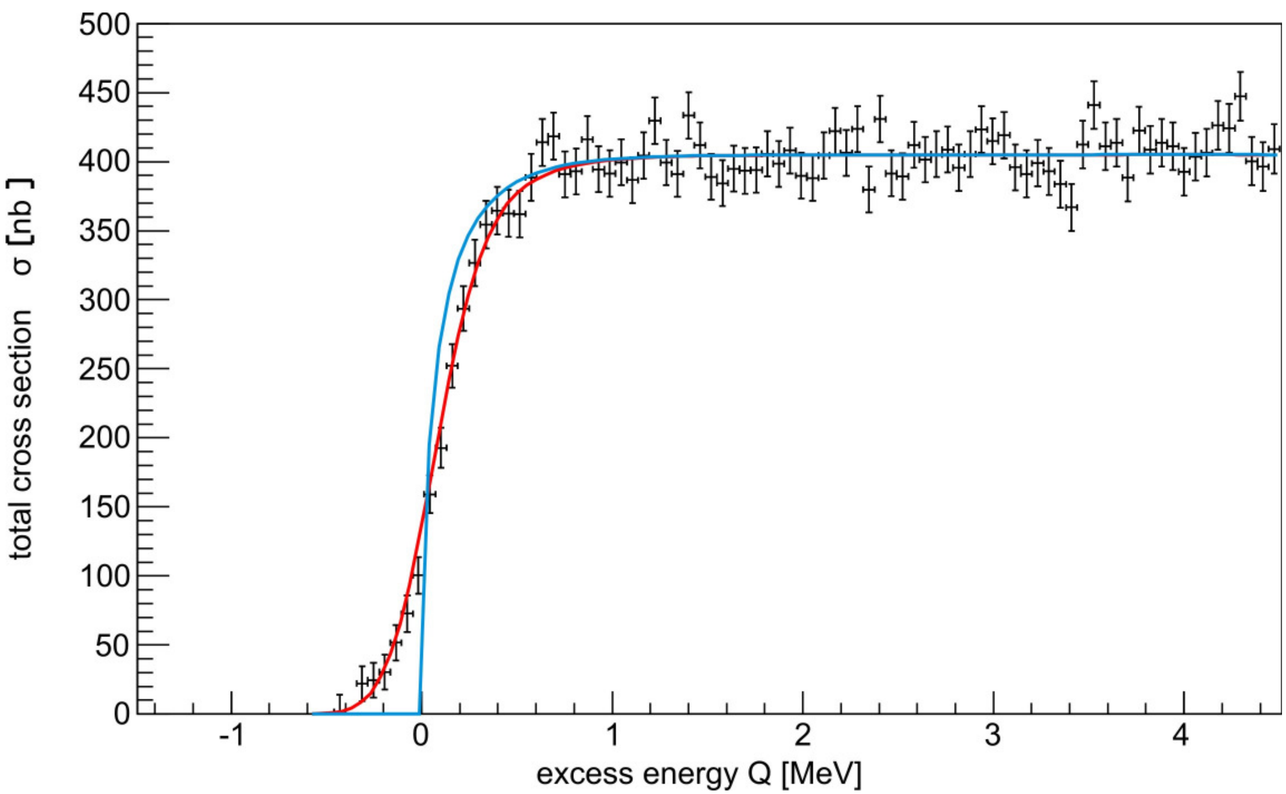
$$\frac{d\sigma(\vartheta)}{d\Omega} = \frac{p_f}{p_i} \cdot \frac{\left|f_{\text{prod}}\right|^2}{\left|1 - i \cdot a \cdot p_f + \frac{1}{2} a \cdot r_0 \cdot p_f^2\right|^2}$$

Fit parameter:

- Complex scattering length $a = a_r + ia_i$
- 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:

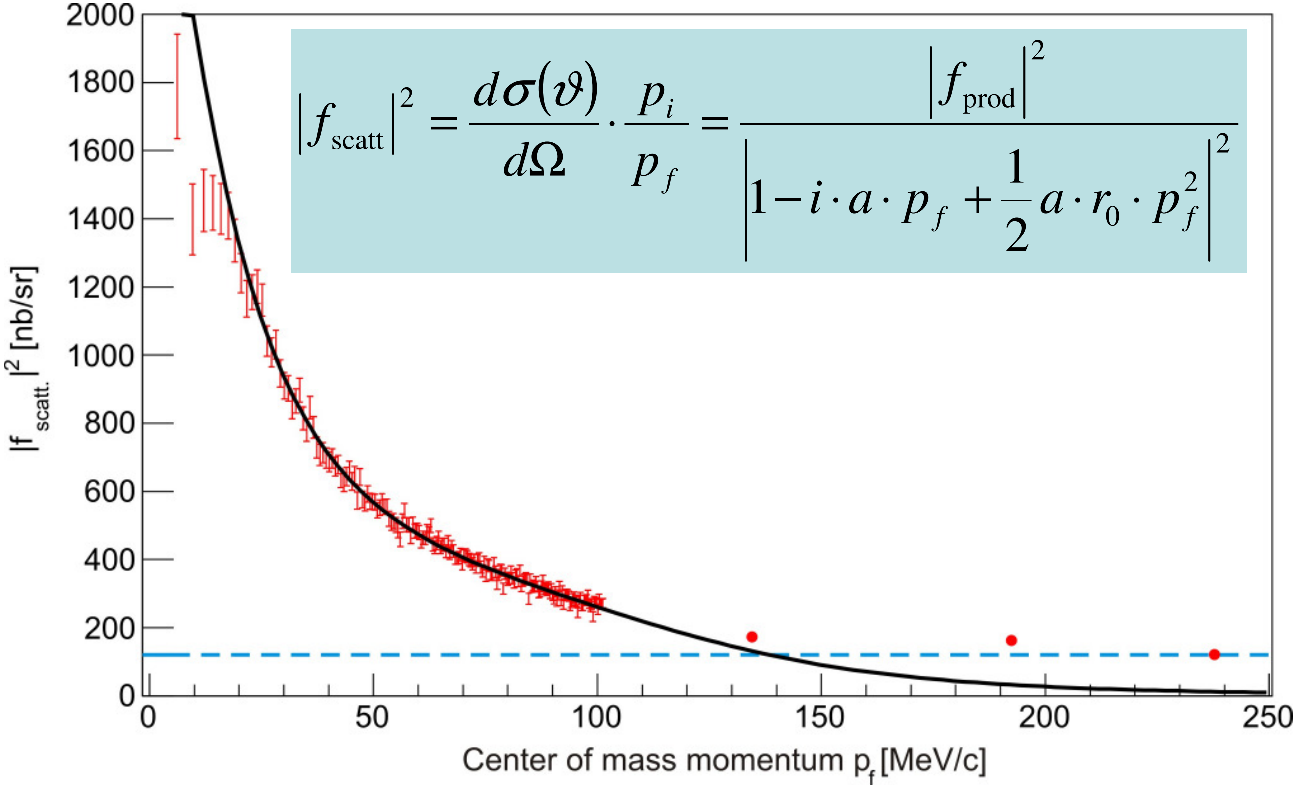
- Defolded shape, extracted from data (no accelerator beam smearing)

→

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

The d+p → ^{3}He+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^{3}He system

η–^{3}He Scattering Length

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

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

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

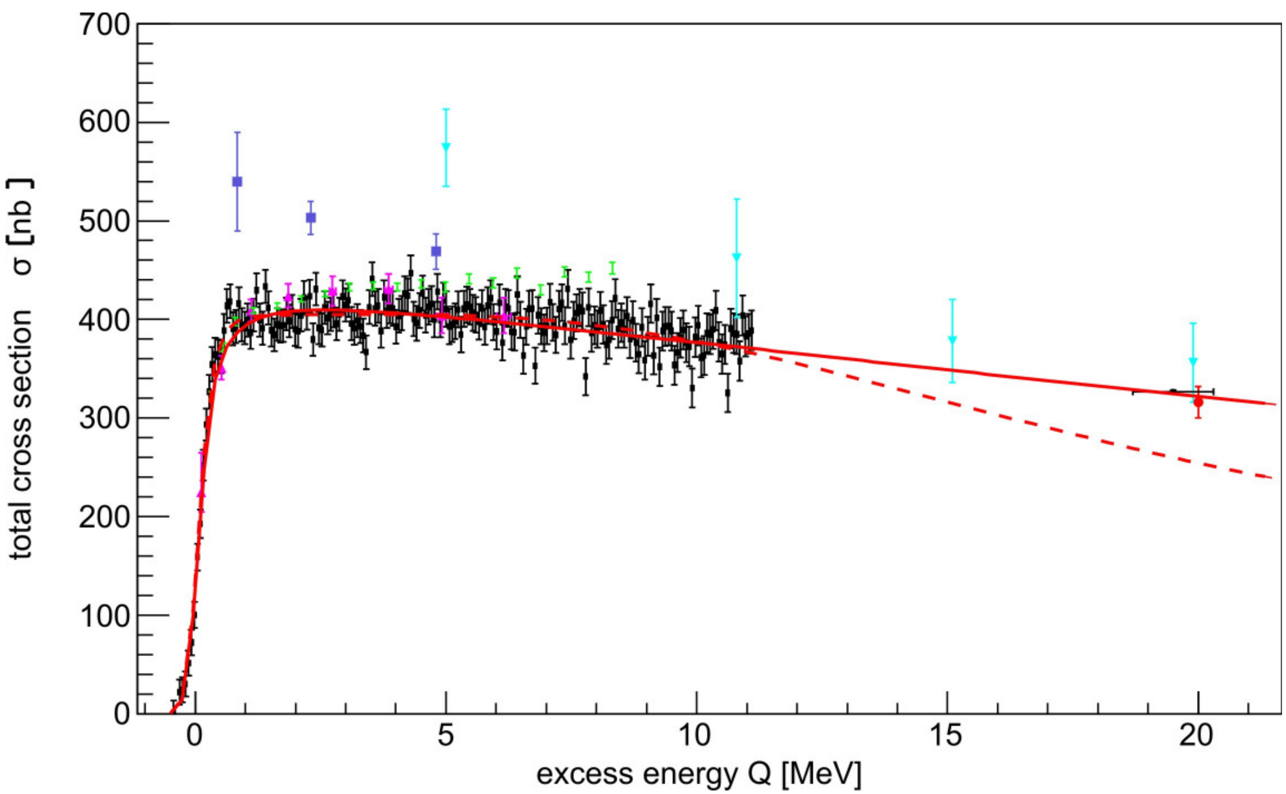
Result:

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

Notice: Determination of $|a_r|$!

The Reaction d+p → ^{3}He+η

Fit to the near-threshold ANKE data:



Fit to 0-11 MeV: (dotted line)

Fit to 0-20 MeV: (solid line)

→

- Shape of the fit curve depends sligthly on the fit range

- Reason:
  E.g. contributions from higher partial waves

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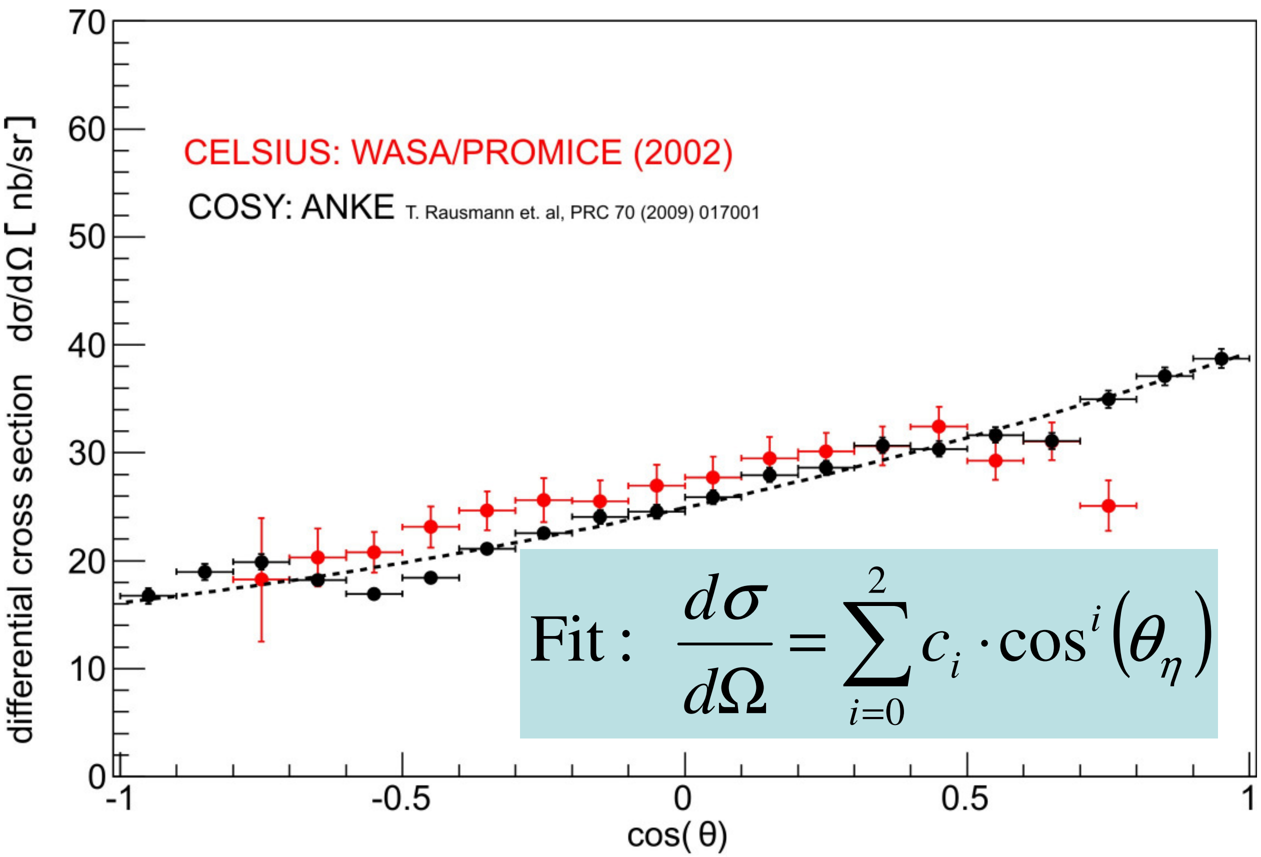
Differential Cross Sections

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



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

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

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

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

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

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

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

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

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

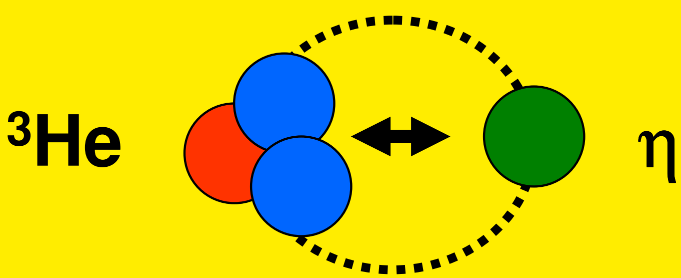
- Pole close to the reaction threshold

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

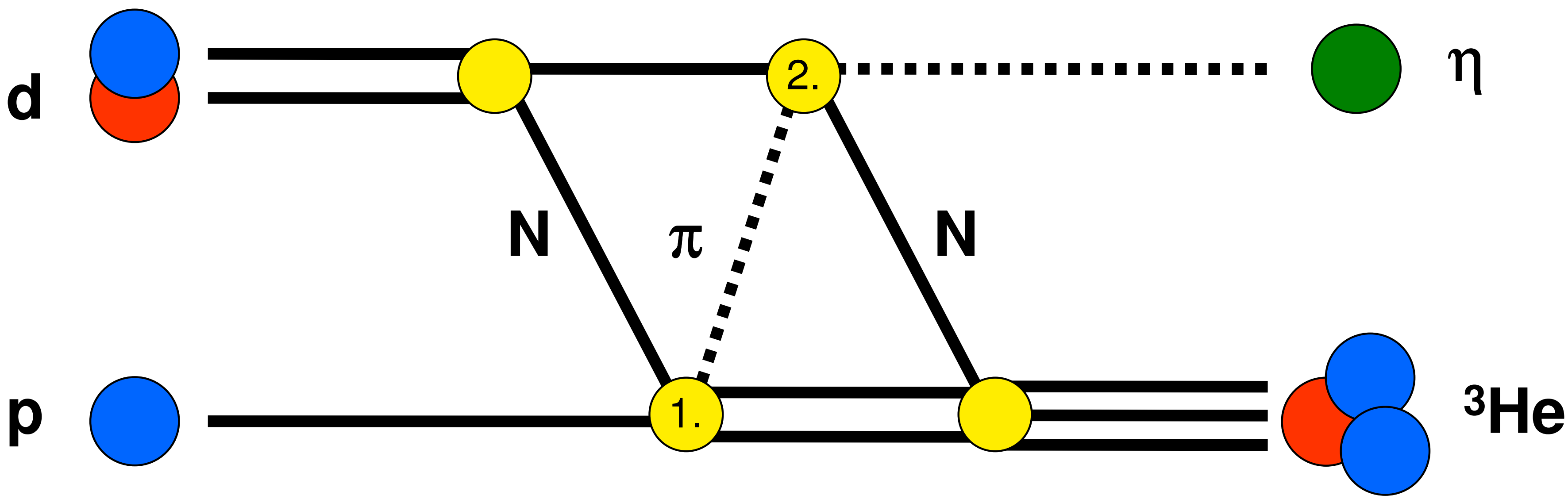
- Position of the near-threshold pole (and scattering length) stable, i.e. nearly independend of fit range
- Large real part of scattering length and $|a_r| > a_i$

→ indication for the existence of a bound state

(strong interaction!)



Production Mechanism: Two-Step-Model

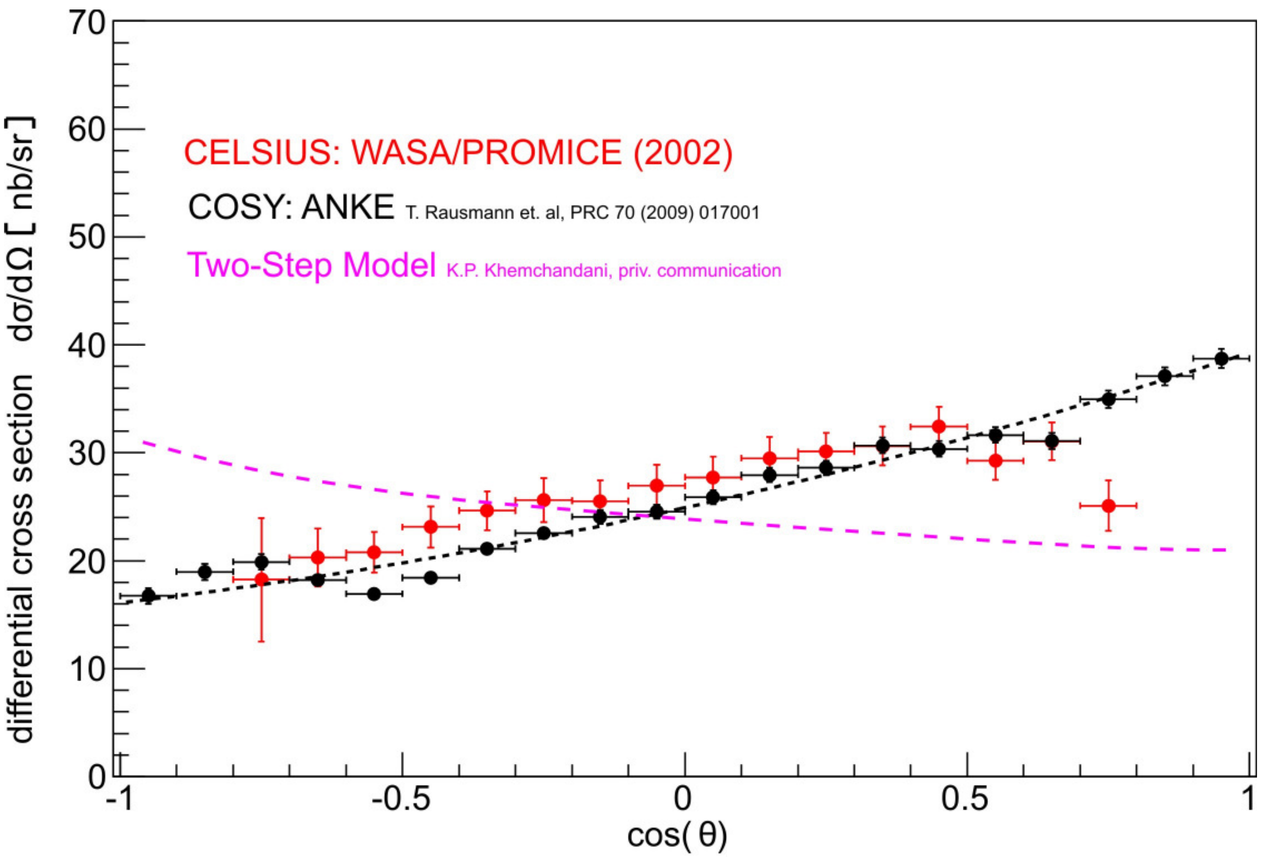


1. $p+p \rightarrow d+\pi^+$	or	1. $p+n \rightarrow d+\pi^0$
2. $\pi^+ +n \rightarrow \eta+p$	or	2. $\pi^0+p \rightarrow \eta+p$

Use known cross sections for complete process

Prediction of the Two-Step-Model

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

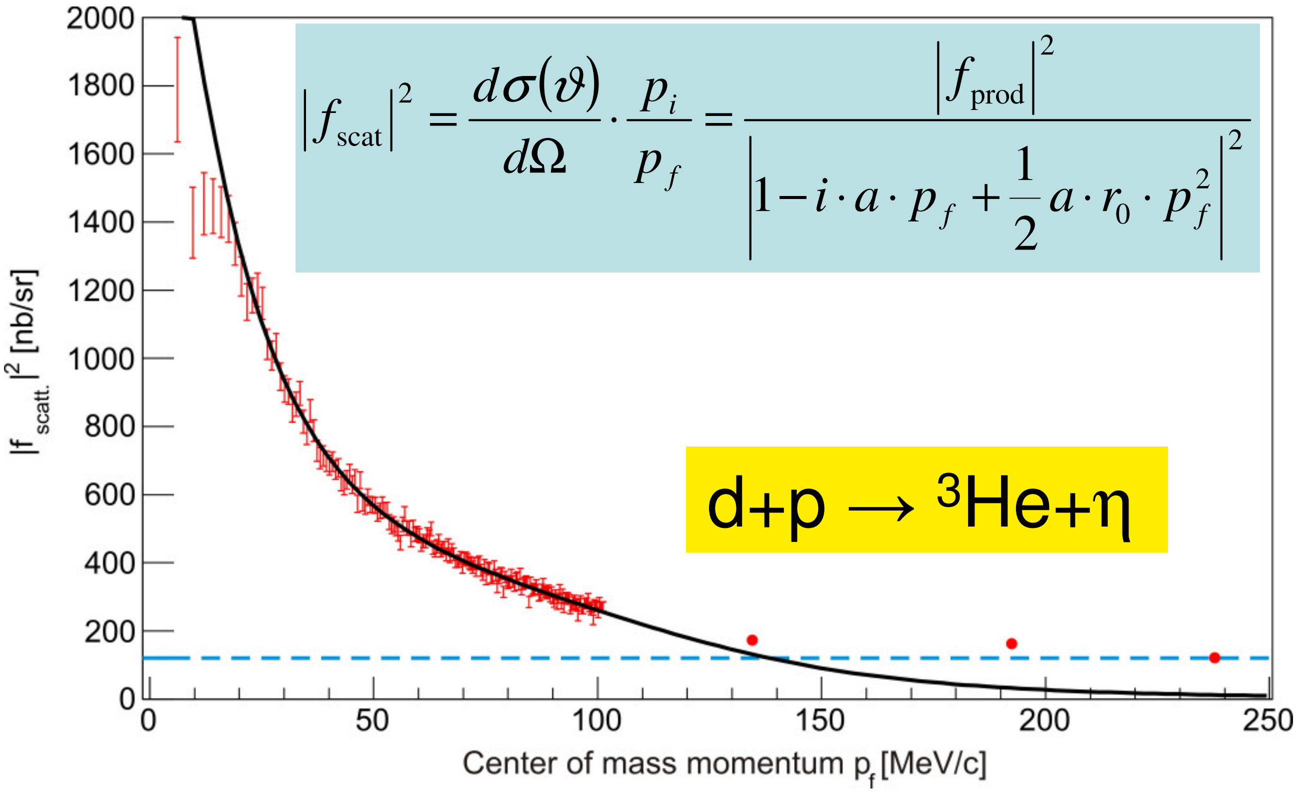


- Two-step-model predicts a different emission of the ejectiles
- Obviously the two-step-model is not sufficient to explain the data

→ open questions to theory

Further Evidences for a Strong FSI

<u>Idea:</u> Compare production amplitudes of different reactions with same final state

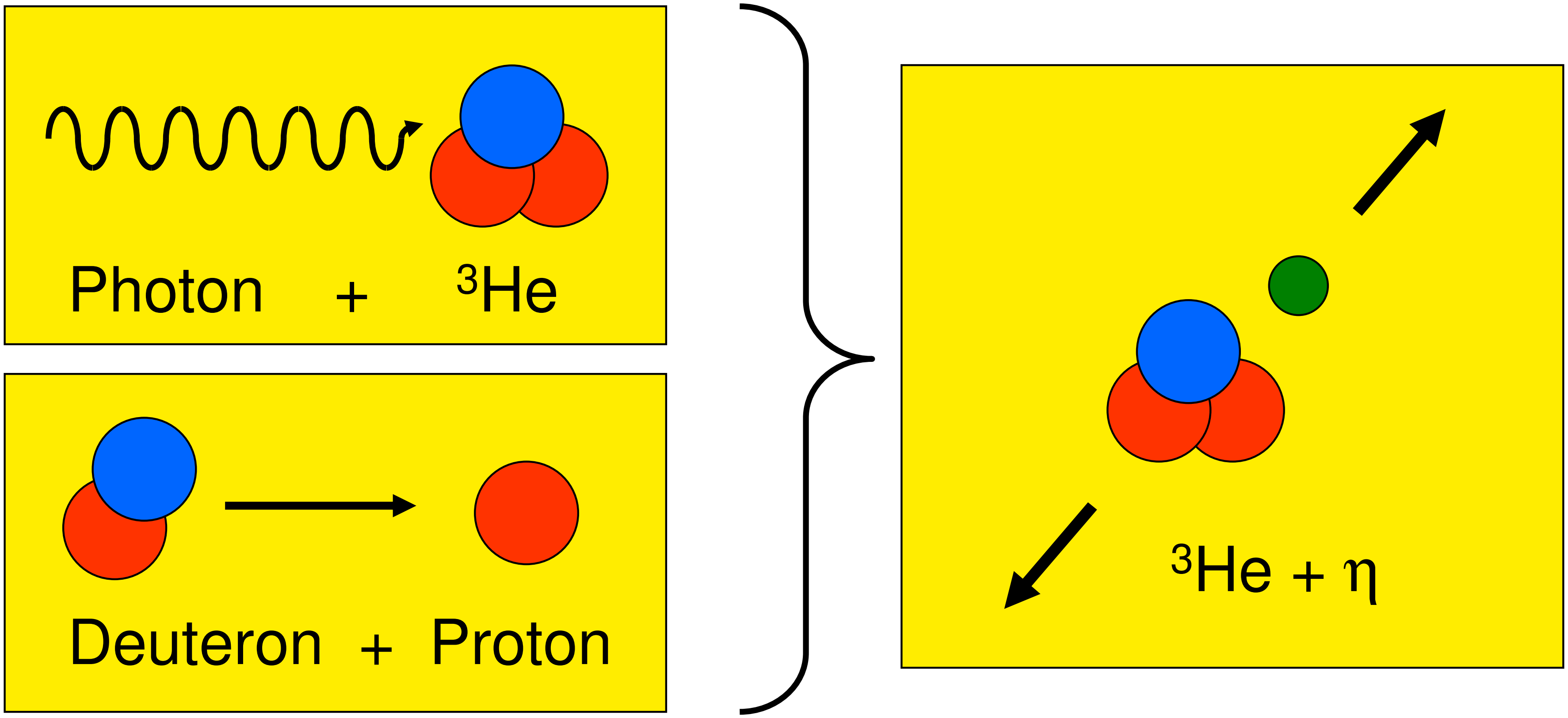


$$|f_{\text{scat}}|^2 = \frac{d\sigma(\vartheta)}{d\Omega}\cdot\frac{p_i}{p_f} = \frac{|f_{\text{prod}}|^2}{\left|1 - i\cdot a\cdot p_f + \frac{1}{2}a\cdot r_0\cdot p_f^2\right|^2}$$

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



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

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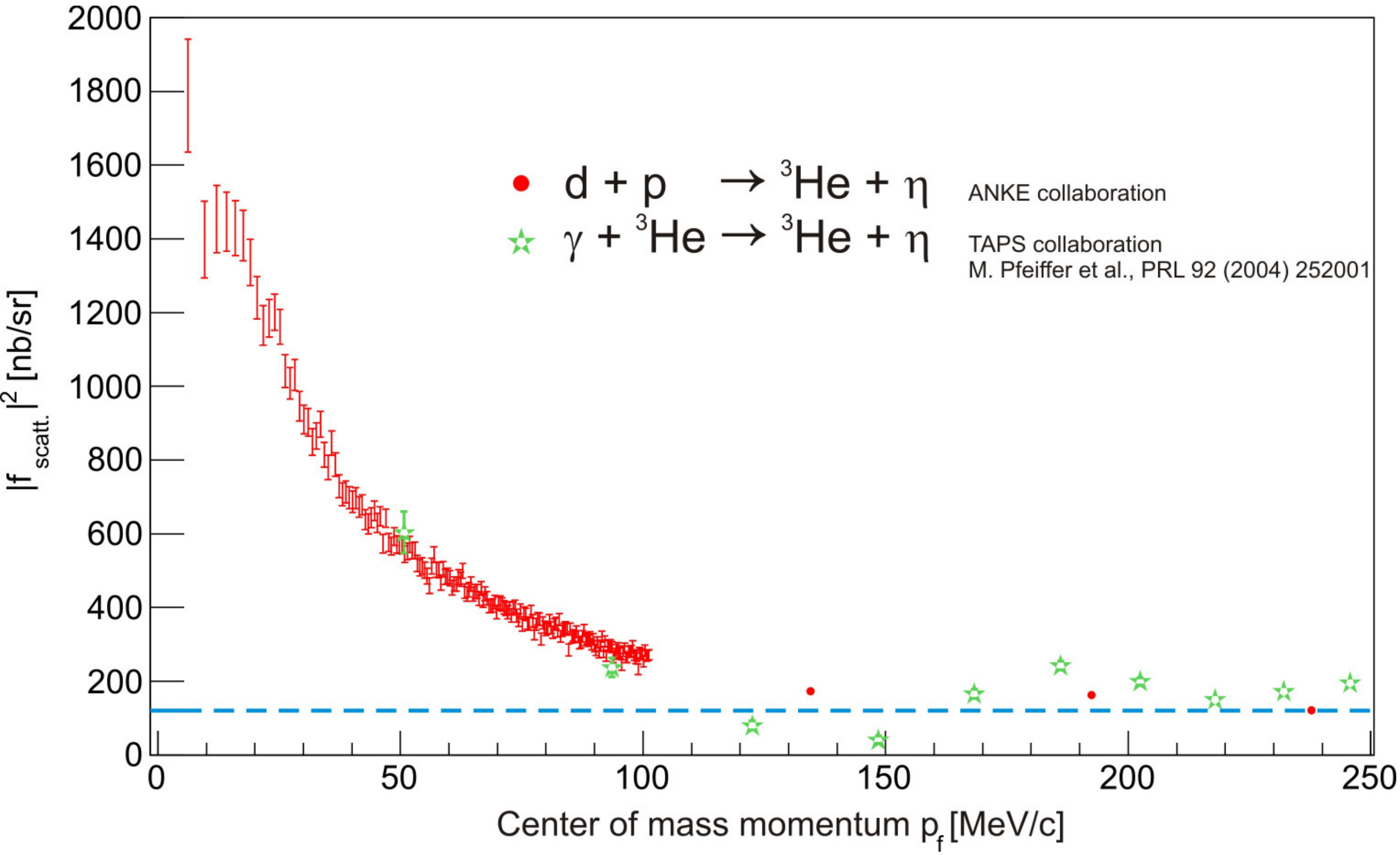
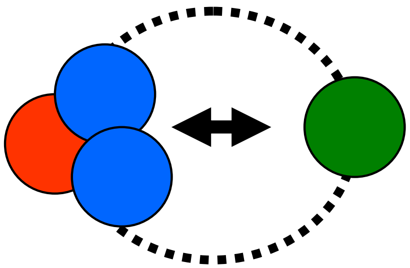
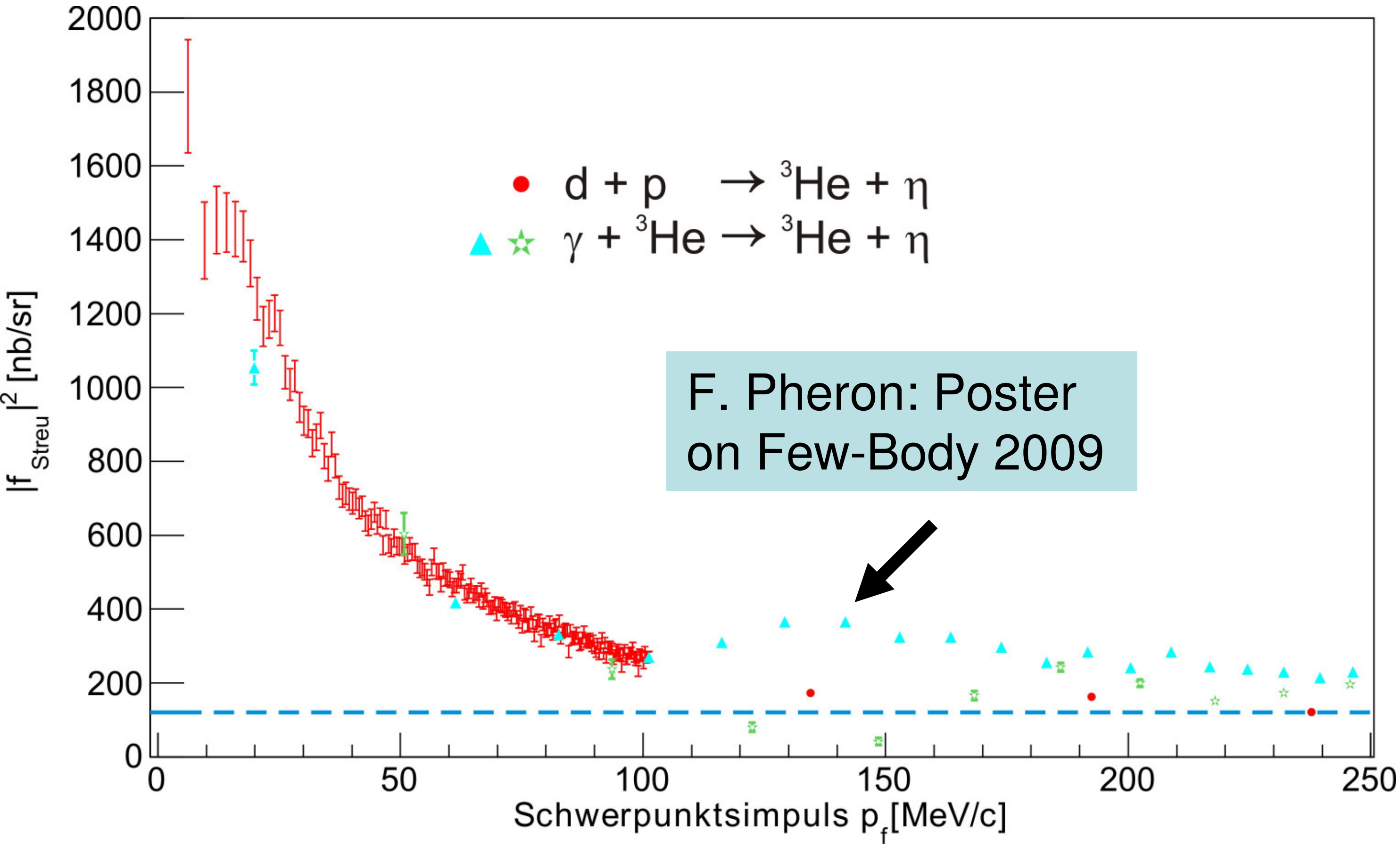
Compare: dp- and γ³He-Scattering



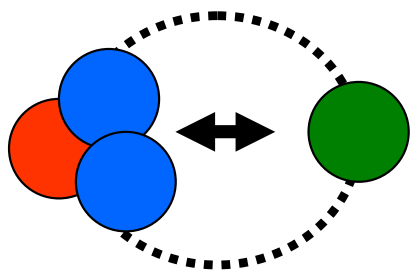
- Scattering amplitudes show similar energy dependence
- Strong hint for a strong FSI between He-nuclei and η-mesons



Compare: dp- and γ³He-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 $d+p \rightarrow {}^{3}He+\eta$ with polarized beam and/or target
  - Informationen about contributing partial waves
  - Determination of the sign of the scattering length $a_{He\eta}$
- Measurement of $d+n \rightarrow {}^{3}H+\eta$ (by $d+d \rightarrow {}^{3}H+\eta + p_{spec}$)
  - Informationen about isospin/charge invariance of the FSI
- Investigations with heavier nuclei: $d+d \rightarrow {}^{4}He+\eta$
  - Take data very close to threshold and compare with ${}^{3}He+\eta$
    Experimental challenge: $\sigma_{d+p \rightarrow 4He+\eta} / \sigma_{d+p \rightarrow 3He+\eta} \sim 1/30$

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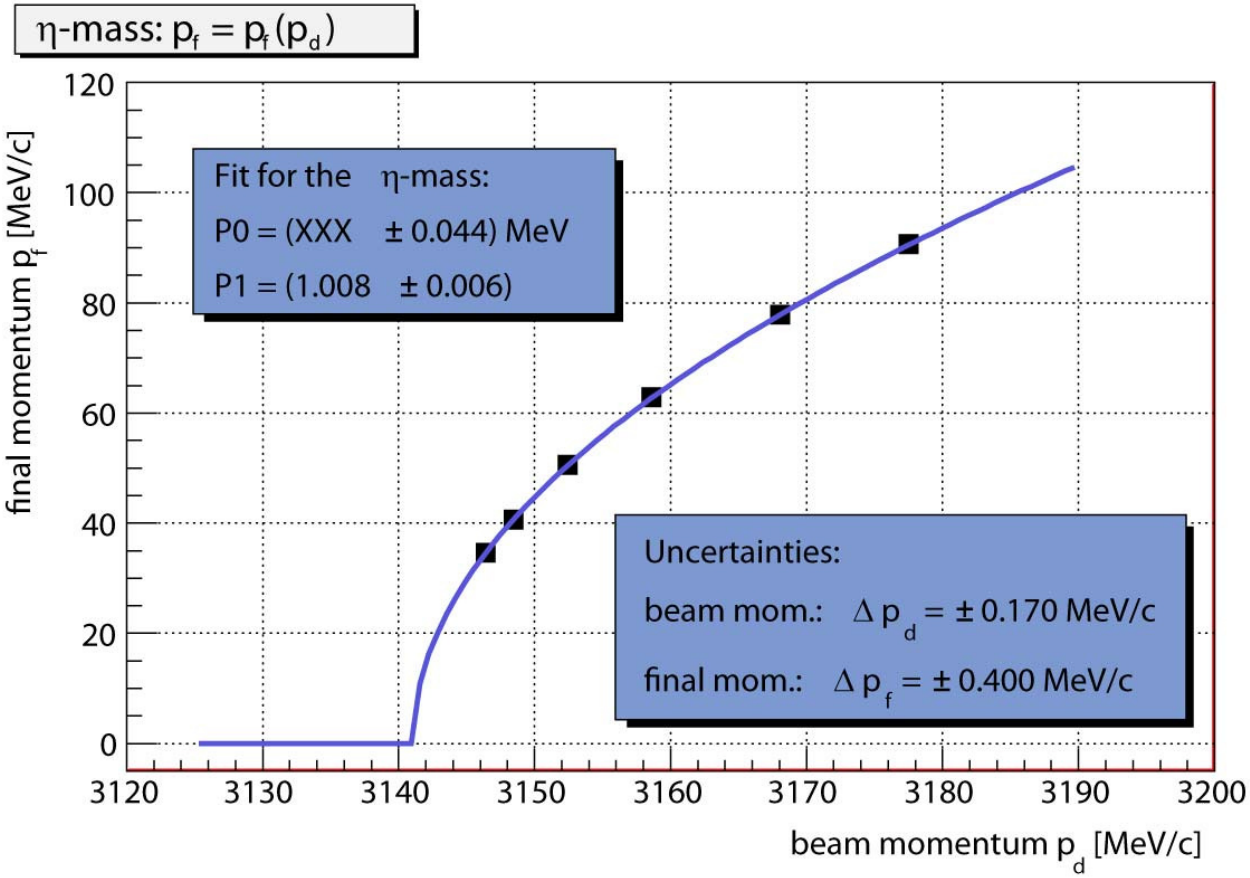
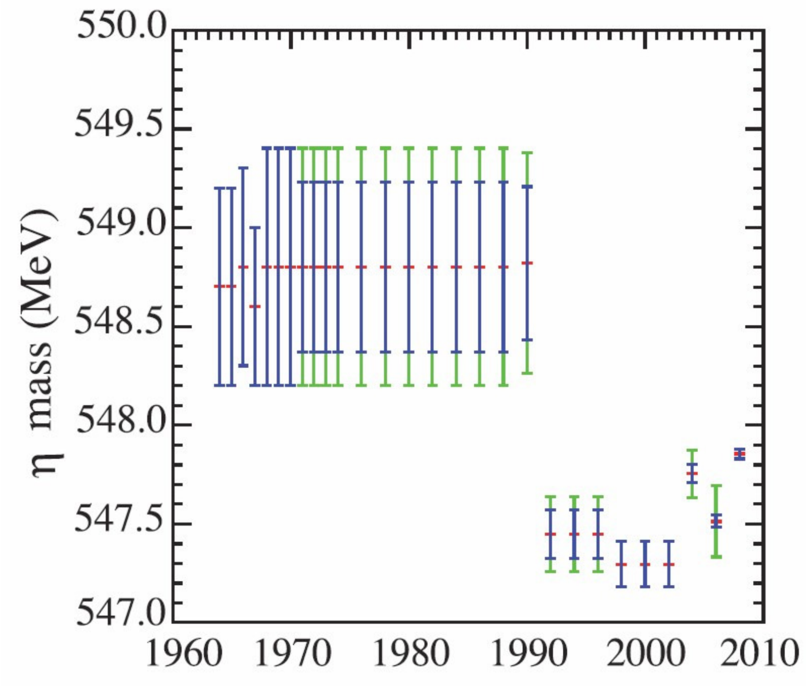
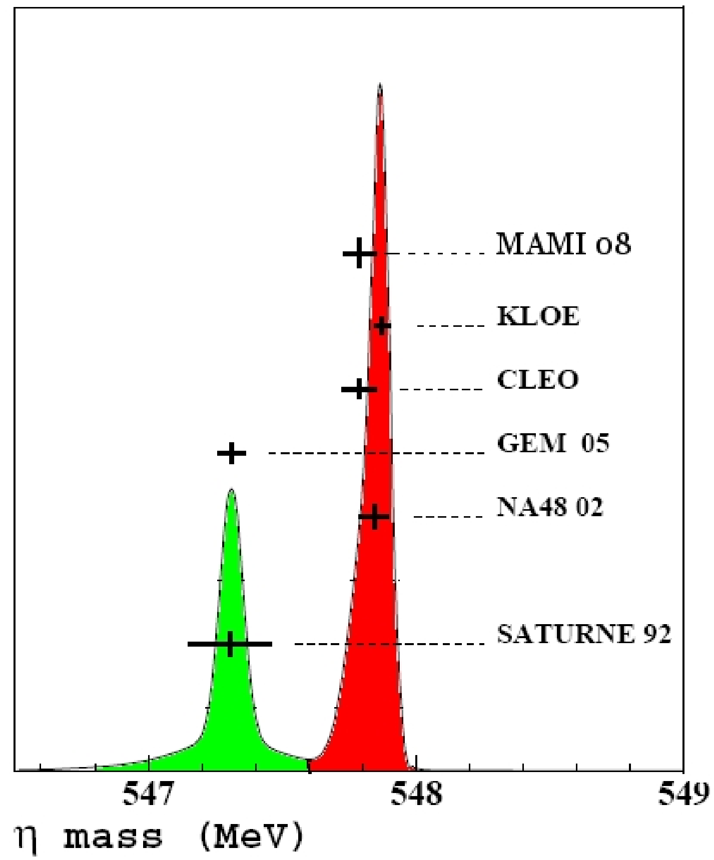
Mass of the η-Meson







Alfons Khoukaz

Summary

- Meson production close to the production threshold delivers a unique possibility to investigate the interaction of short living particles with nuclear matter or even other mesons
- 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)
- Photo-production data expose similar effects


Thank you very much....