High precision η meson mass determination at ANKE-COSY

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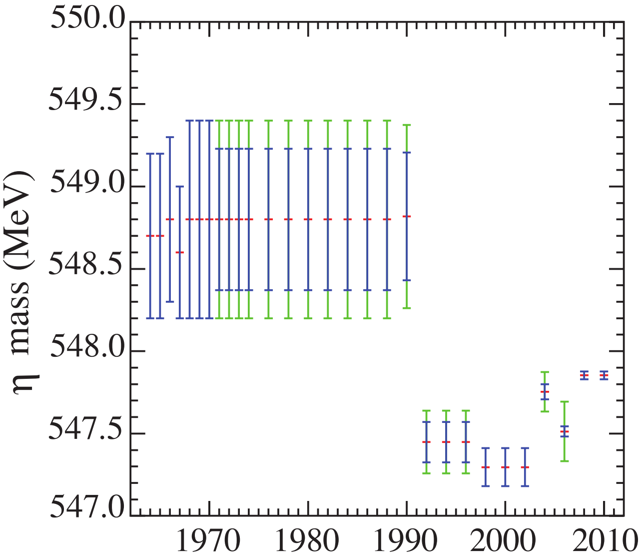
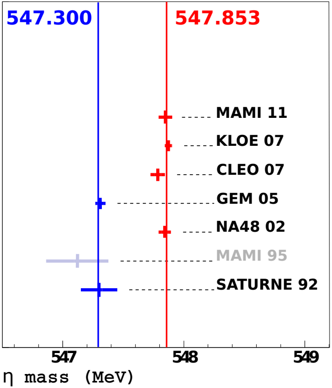
Motivation

History of the **PDG** value of the η meson mass



Motivation

Current situation on the η meson mass



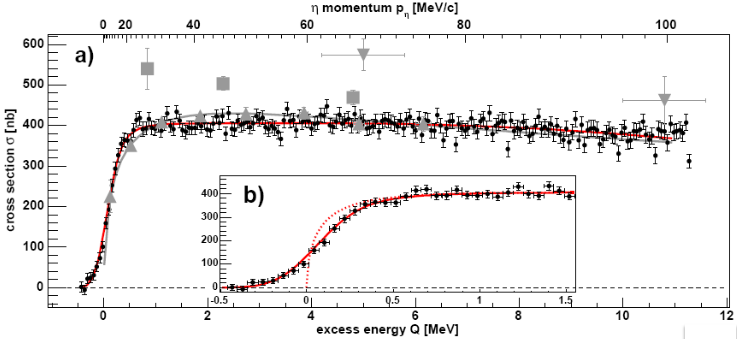
Results of the η mass experiments with uncertainties below 60 keV/c^2

Experimental Facility	Mass [MeV/c^2]	Measuring Method
SPES-SATURNE	547.300	dp $\rightarrow$ ^{3}He η
NA48-SPS	547.843	decay products
GEM-COSY	547.311	pd $\rightarrow$ ^{3}He η
CLEO-CESR	547.785	decay products
KLOE-DAΦNE	547.873	decay products
CB-MAMI	547.851	photoproduction

Current PDG η mass value: (547.853 ± 0.024) MeV/c^2

Motiviation - "Reasons for disagreement"

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

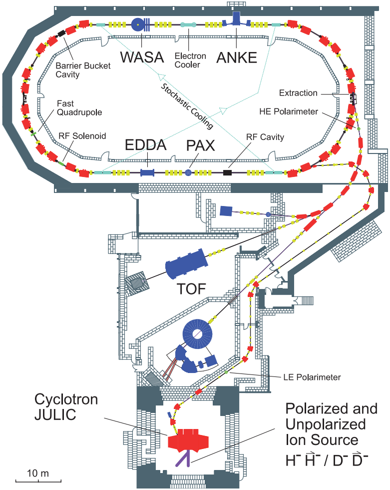


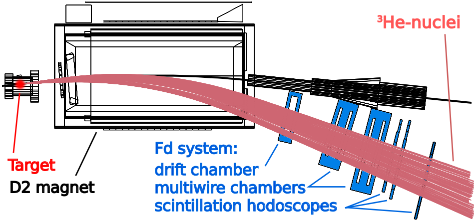
Ideas/Speculation:

- Previous measurements shown strong η^3He FSI
- Coupling of $\eta^3\text{He} \leftrightarrow \pi^+\pi^{-3}\text{He}$ can disturb the multipion background near the η position
  $\rightarrow$ Wrong identification of the central η mass

Determination of the η mass with a two-body reaction

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





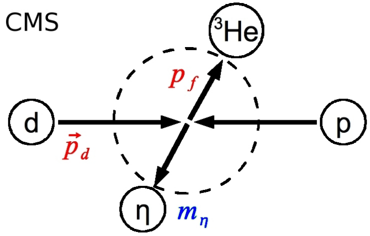
- Internal fixed target experiment with a cluster-jet target
- ^{3}He nuclei detected in the forward-system
- Full geometrical acceptance for dp $\rightarrow$ ^{3}He η up to 20 MeV excess energy

Determination of the η mass with a two-body reaction

Kinematics

Two-body reaction:

$$\boxed{dp \to {}^3\text{He}\,\eta}$$



- Final state momentum of ^{3}He and η

$$p_f = \frac{\sqrt{(s - \{m_{^3\text{He}} + m_\eta\}^2) \cdot (s - \{m_{^3\text{He}} - m_\eta\}^2)}}{2\sqrt{s}}$$

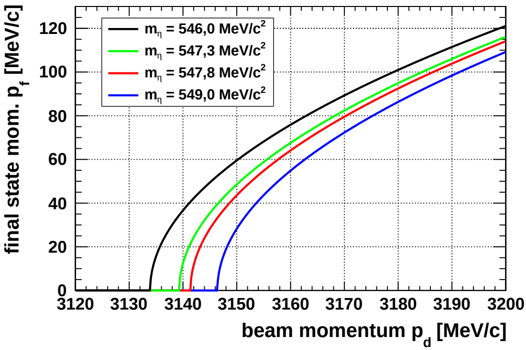
- CM-energy depends only on the beam momentum $\vec{p_d}$

$$\sqrt{s} = |P_d + P_p| = \sqrt{2m_p\sqrt{{m_d}^2 + \vec{p_d}^2} + {m_d}^2 + {m_p}^2}$$

Determination of the η mass with a two-body reaction

Kinematics

Dependency: $p_f = p_f(p_d, m_\eta)$



Needed accuracy: $\frac{\Delta p_d}{p_d} < 10^{-4}$

Near threshold:

Final state momentum is very sensitive to the η mass!

The goal:

- Accuracy of the η-mass: $\Delta m_\eta < 50\ \text{keV}/\text{c}^2$
- Final state momentum of the ^{3}He-nuclei: p_f $\Delta p_f = 400\ \text{keV}/\text{c}$
- Beam momentum: p_d $\Delta p_d = 300\ \text{keV}/\text{c}$

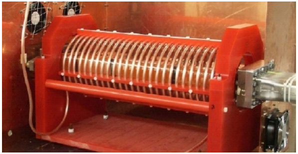
Beam momentum determination p_d

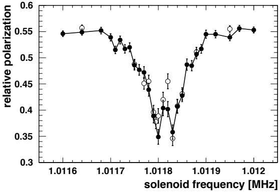
Beam momentum determination

Method

Artificial spin resonance

- Induced by a horizontal magnetic rf-field
- Depolarization of a vertically polarized deuteron beam



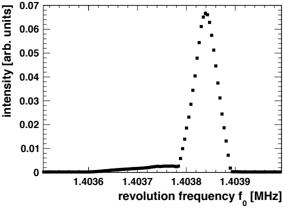


Resonance condition:

$$f_r = (1 + \gamma G_d)\, f_0$$

$$\gamma = \frac{1}{G_d}\left(\frac{f_r}{f_0} - 1\right)$$

$$p_d = m_d \sqrt{\gamma^2 - 1}$$



f_r - resonance frequency
f_0 - revolution frequency
G_d - gyromagnetic anomaly

Beam momentum determination

$$p_d = (3146.41 \pm 0.05_{\text{stat.}} \pm 0.17_{\text{sys.}})\ \text{MeV/c}$$

$$\frac{\Delta p_d}{p_d} < 6 \cdot 10^{-5}$$

- Uncertainty of 170 keV/c is dominated by the systematic variation of the spin resonance frequency
- Spin resonance frequency f_r: Systematic uncertainty of $\pm$15 Hz dominated by the variation of the orbit length
- Method and results published in *Phys. Rev. ST Accel. Beams 13 (2010) 022803*

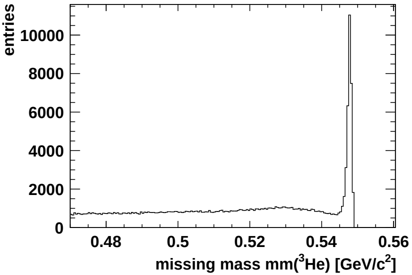
Final state momentum determination p_f

Final state momentum determination

Classical calibration:

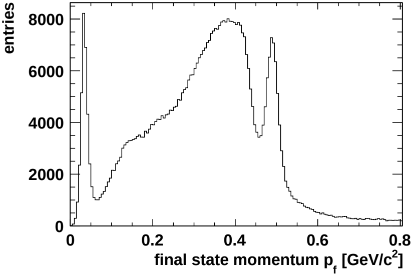
Reactions used to calibrate ANKE:

- *dp* → *dp* elastic with
  – fast forward scattered d detected
  – with both particles detected
- *dp* → *ppn* charge-exchange scattering with two p detected
- *dp* → ^{3}He π^0 with ^{3}He nucleus detected



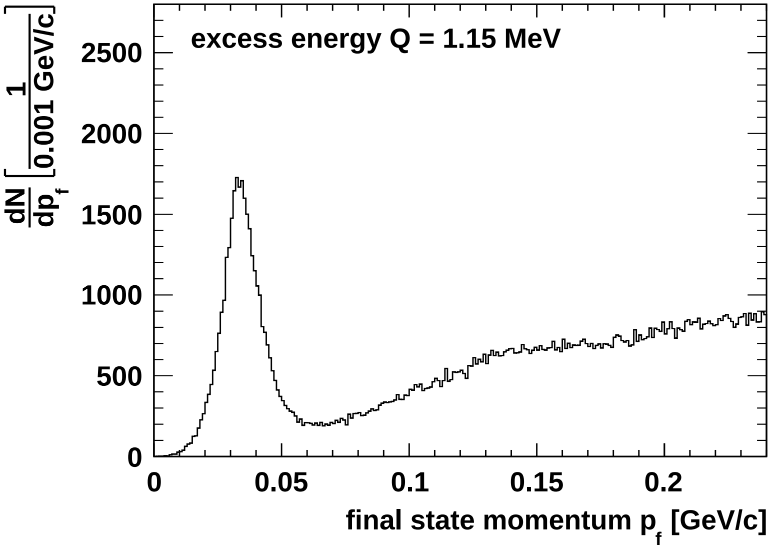
Identification of dp → ^{3}He η

- Background: dp elastic and deuteron break-up
- Suppressed by energy loss and TOF cut on the ^{3}He nuclei



Final state momentum determination

The ^{3}He η signal



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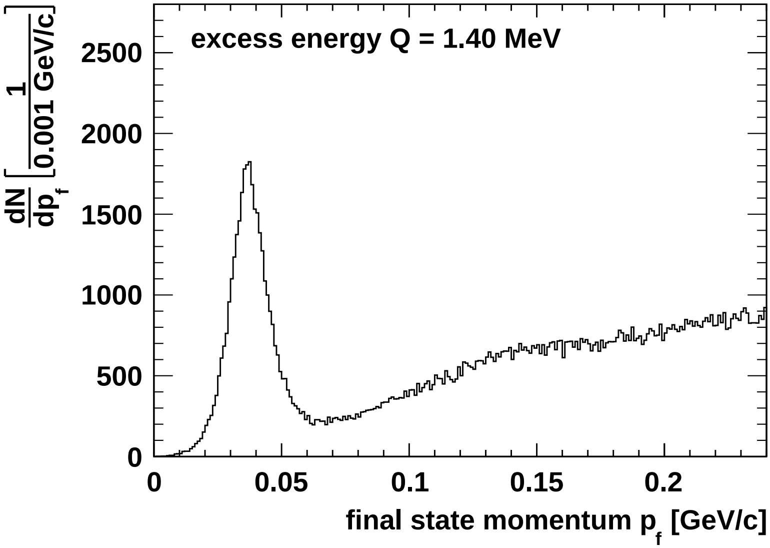

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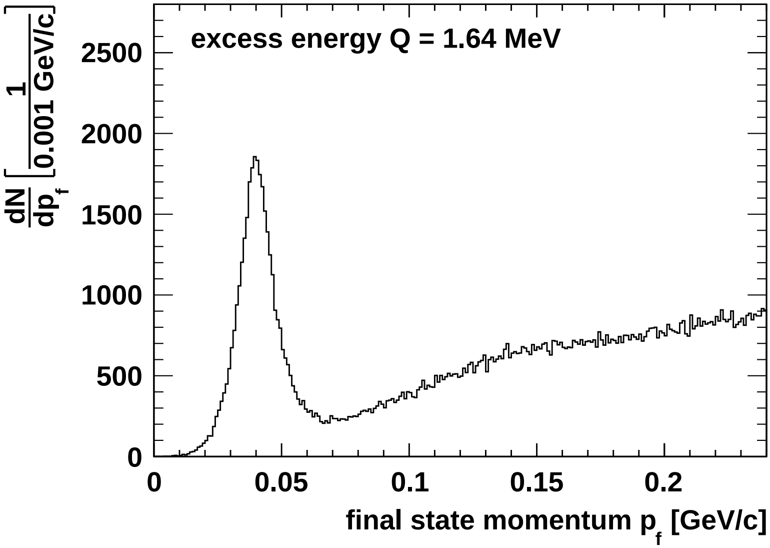

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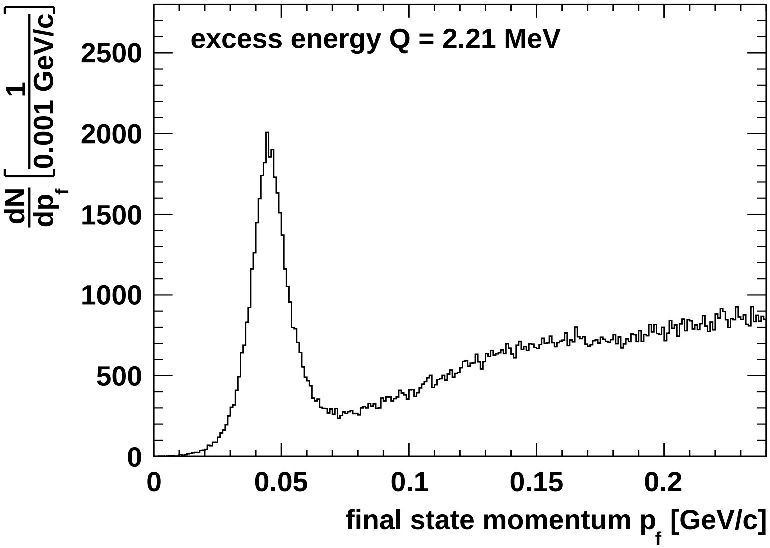

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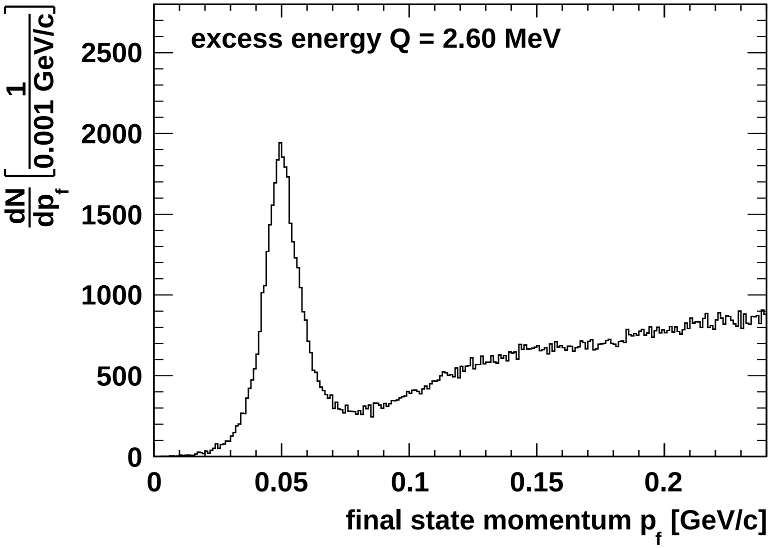

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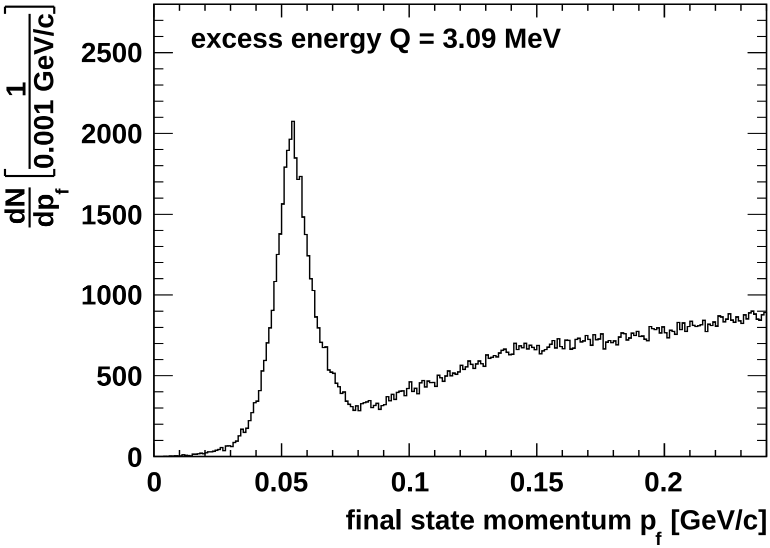
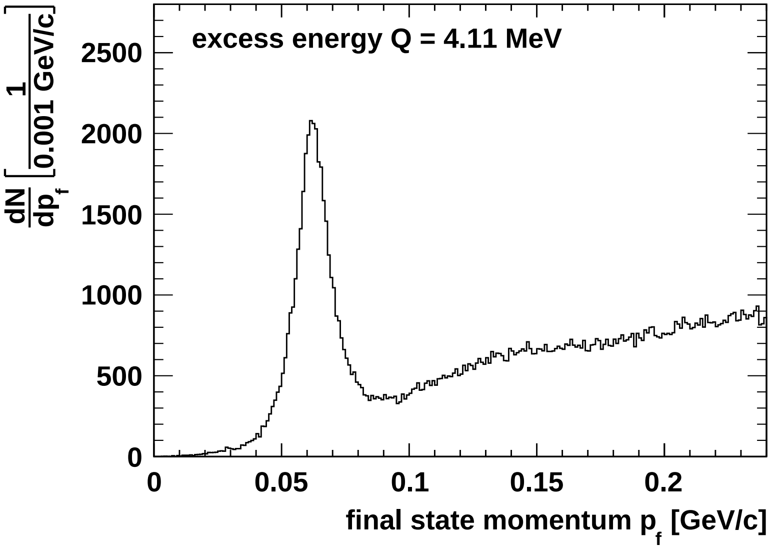
The ^{3}He η signal



Final state momentum determination

The ^{3}He η signal



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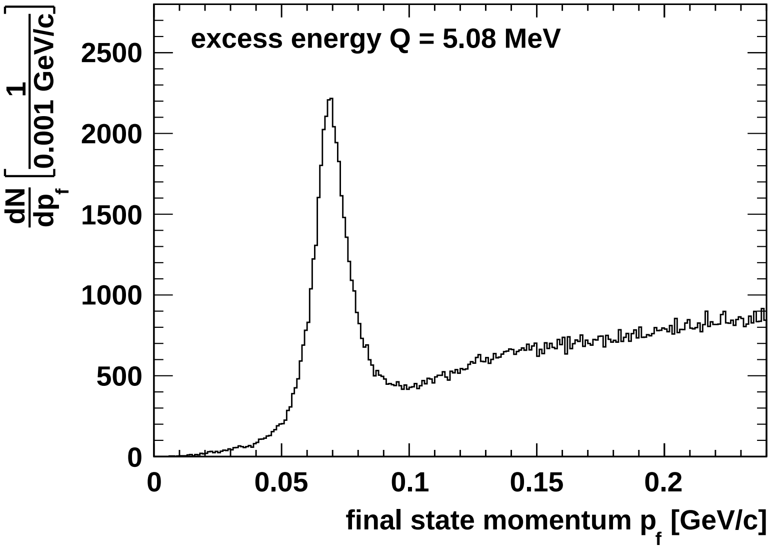

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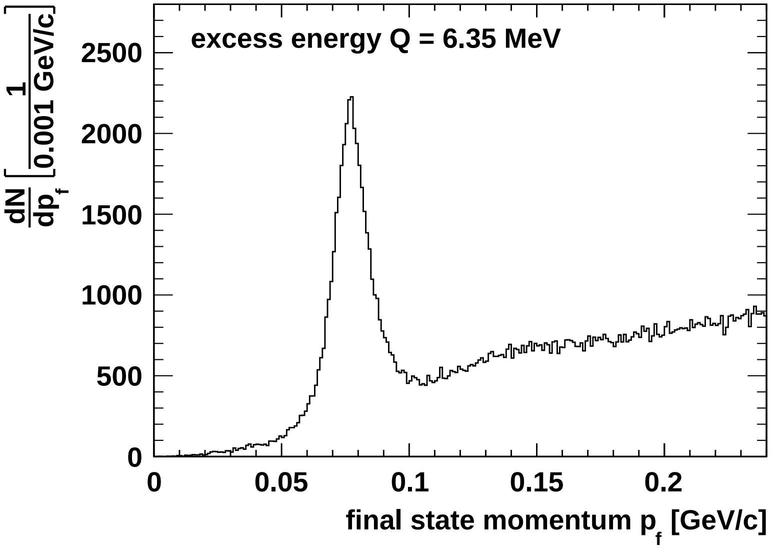
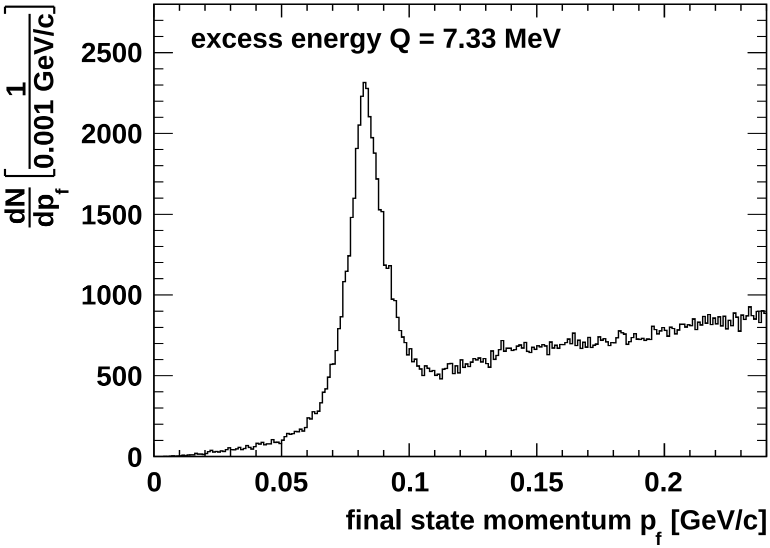


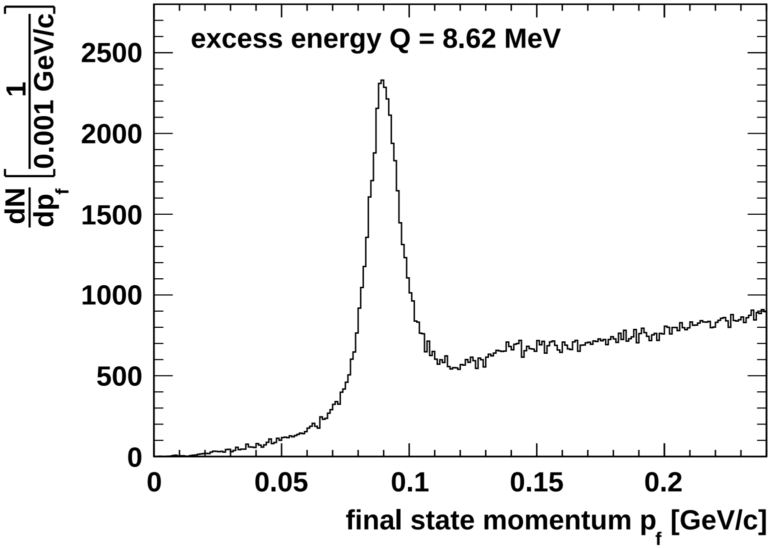
Final state momentum determination

The ^{3}He η signal



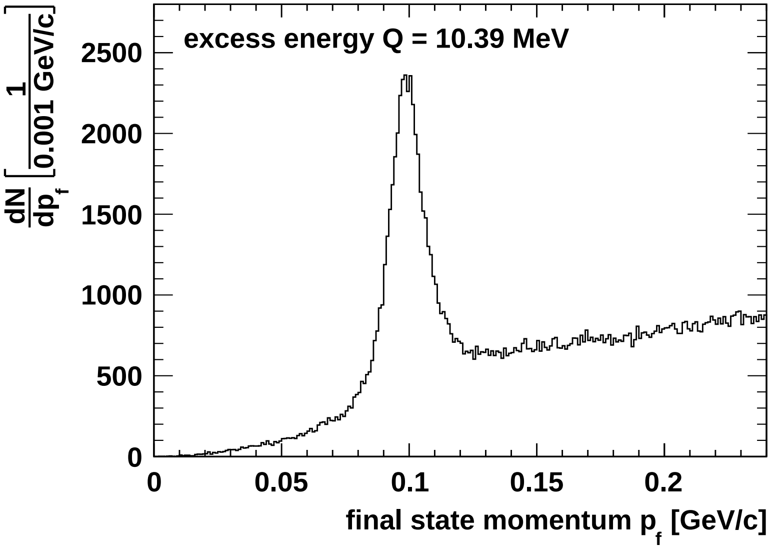
Final state momentum determination

The ^{3}He η signal



Final state momentum determination

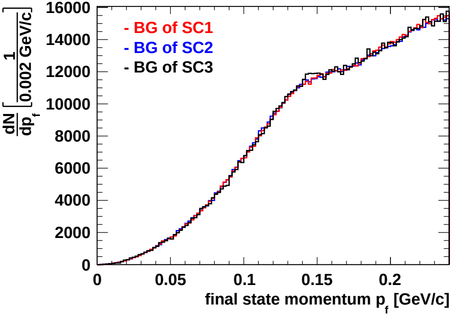
The $^3He\,\eta$ signal

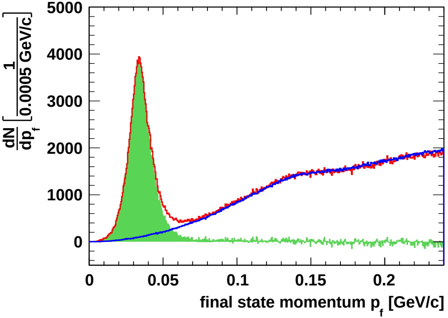


Final state momentum determination

Background description using subthreshold data

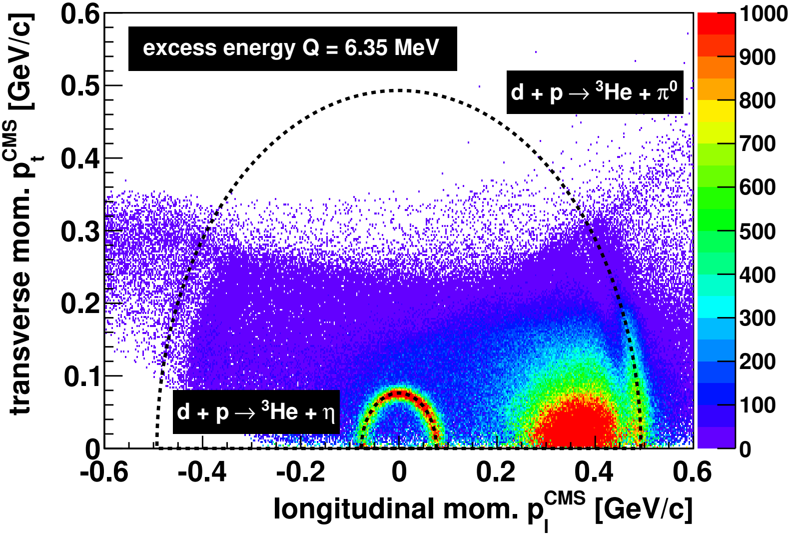
- Subthreshold data were analyzed as if they were taken above threshold: $\vec{p}^{LS} = \frac{p_{beam}}{p^{sub.}_{beam}} \cdot \vec{p}^{LS}_{sub.}$
- Pure ^{3}He η signal after background subtraction





Final state momentum determination

The momentum locus



Final state momentum determination

Verify and improve calibration

Using a two body reaction to verify the calibration

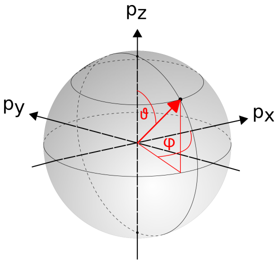
- Perfect symmetric momentum sphere in p_x, p_y, p_z with radius

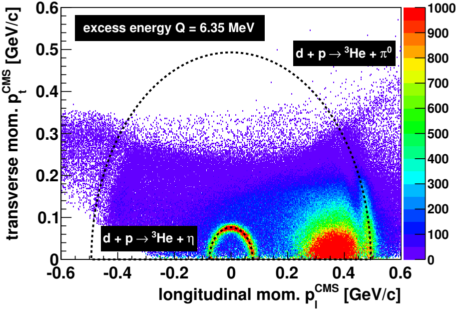
$$p_f = \sqrt{p_x^2 + p_y^2 + p_z^2}$$

- Deviations of symmetric shape $\rightarrow$ improve calibration
- Study $\cos\vartheta$ and ϕ dependency of the final state momentum

$$p_f = p_f(\cos\vartheta) \text{ and } p_f = p_f(\phi)$$

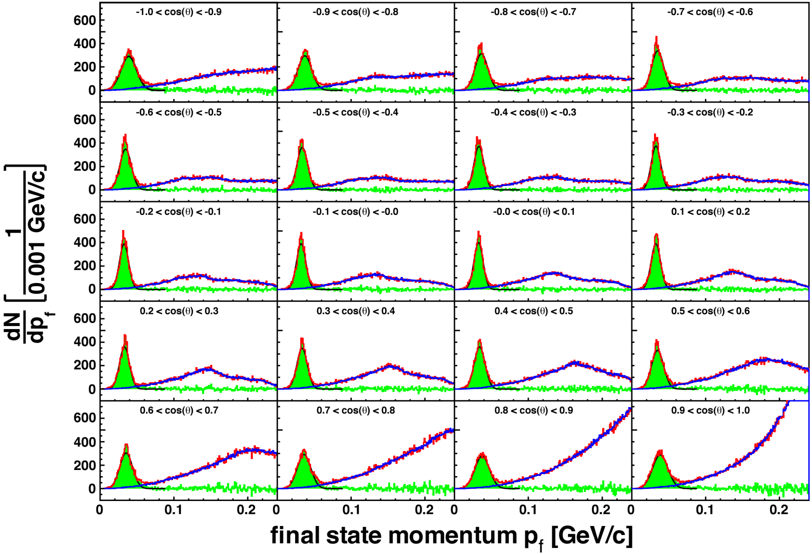
- Therefore full geometrical acceptance is needed





Final state momentum determination

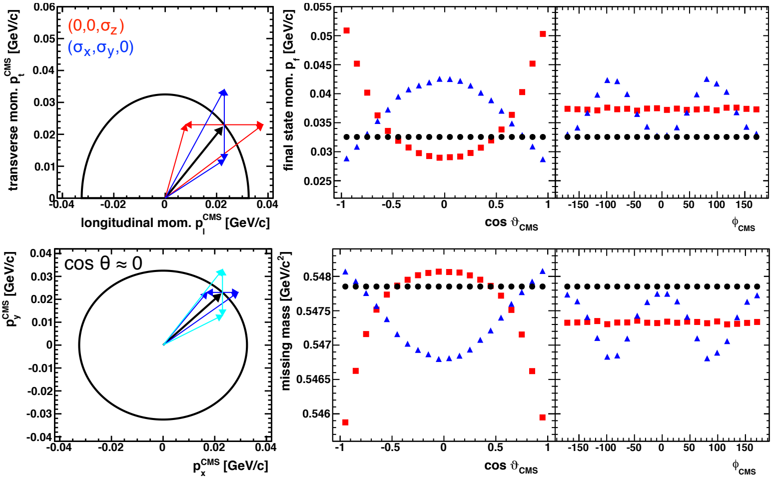
Angular dependence of the $^3\text{He}\,\eta$ final state momentum $p_f = p_f(\cos\vartheta)$ at an excess energy of $Q = 1.2$ MeV



Final state momentum determination

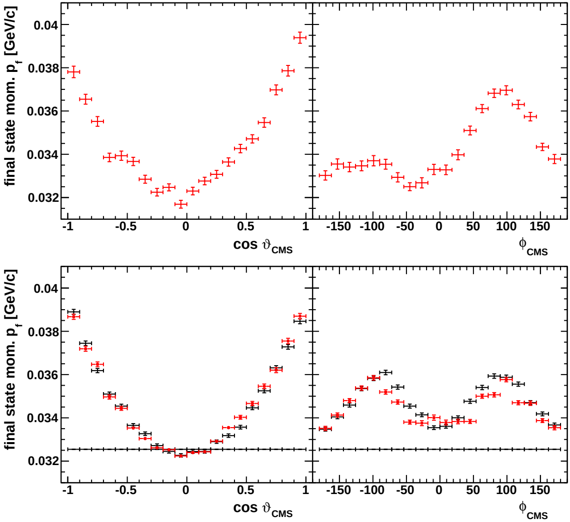
Influence of different momentum resolutions for p_x, p_y, p_z on p_f

Mom. are gaussian distributed with $(\sigma_{p_x}, \sigma_{p_y}, \sigma_{p_z}) = (10, 20, 30)\,\mathrm{MeV/c}$



Final state momentum determination

Improve calibration and extract resolution parameters



$p_f = p_f(\cos\vartheta)$ and

$p_f = p_f(\phi)$ for:

Classical calibration

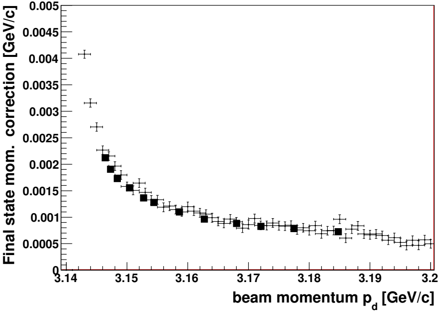
Calibraton improved using two body reaction

Extracted momentum resolution

$(\sigma_{p_x}, \sigma_{p_y}, \sigma_{p_z}) = (3.2, 7.8, 16.4)\,\mathrm{MeV/c}$

Final state momentum determination

Final state momentum correction



- Extracted p_f have to be corrected
- Differ by up to 2 MeV/c in the excess energy range 1-11 MeV

→ Same effect occurs at the missing mass (Difference of 0.3 MeV/c^2)

Final state momentum determination

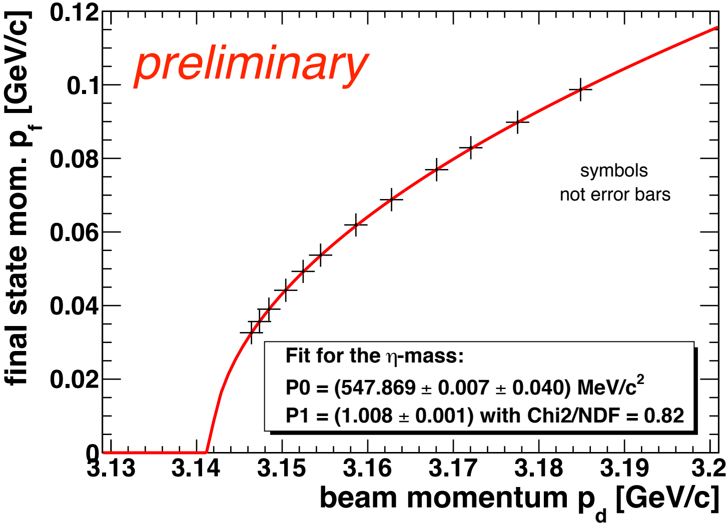
- 12 final state momenta in the range of $p_f = 30 - 100$ MeV/c
- Accuracy:

$$\boxed{\Delta p_f < 320 \text{ keV/c}}$$

- In progress: Uncertainties of correction function depending on the precision of the extracted resolution in p_x, p_y, p_z

High precision η mass determination

Preliminary "final" ANKE-COSY result of the η mass



High precision η mass determination

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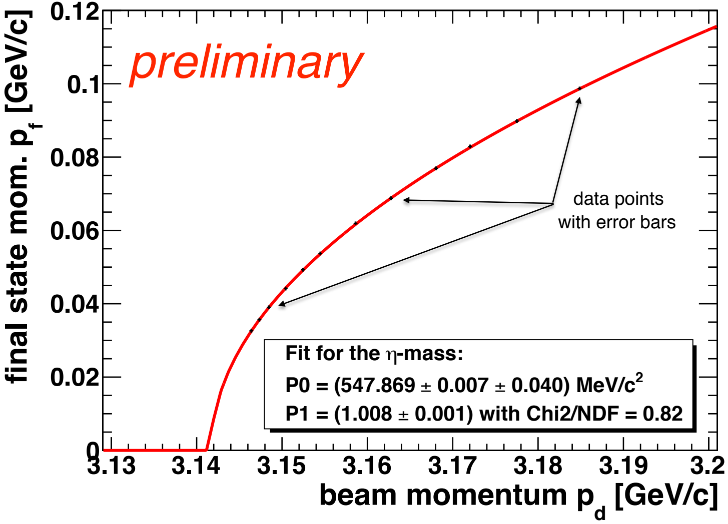


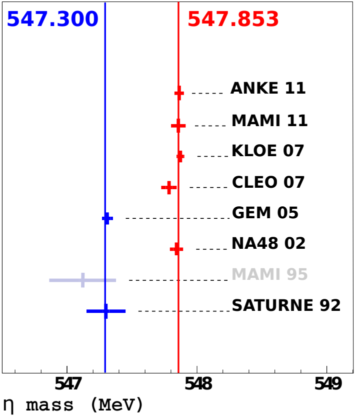
Preliminary ANKE-COSY result of the η mass

Summary

$$m_\eta = (547.869 \pm 0.007_{\text{stat.}} \pm 0.040_{\text{sys.}})\ \text{MeV}/c^2$$

ANKE η meson mass

- Competitive with best measurements
- In agreement with higher η meson mass measurements
- Challenges:
  $\rightarrow$ Beam momentum determination
  $\rightarrow$ Final state mom. extraction

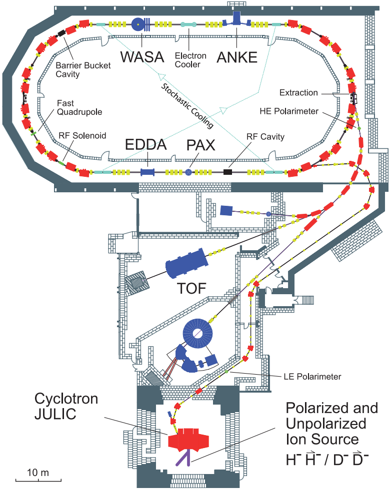


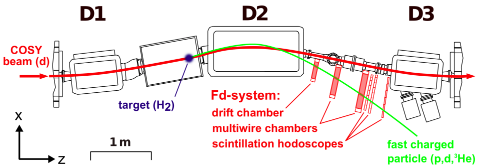
Thank you for your attention

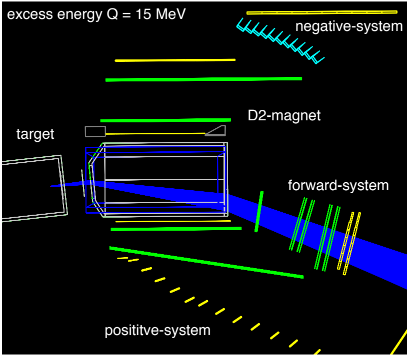
Additional Slides

ANKE at COSY

The reaction dp → ^{3}He η at ANKE







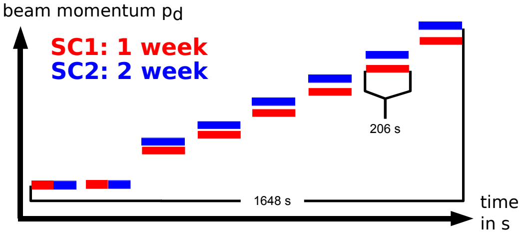
Determination of the η mass with a two-body reaction

Cycle timing structure

Measurement of (p_d, p_f)

- 12 fixed beam momenta divided into two supercycles (SC)
- Five days of data taking for every supercycle
- Data below η-production threshold for background description

Supercycle with 7 different beam energies



Beam momentum determination

Spin in a synchrotron - Thomas-BMT equation

Spin in a synchrotron

- Vertical polarized deuteron beam
- Magnetic moment and Spin: $\vec{\mu} = g \frac{q}{2m} \vec{S}$
- Spin in a magnetic field: $\frac{d\vec{S}}{dt} = g \frac{q}{2m} \vec{S} \times \vec{B}$

  $\rightarrow$ equation is defined in the rest frame of the particle
  $\rightarrow$ transform magnetic structure of synchrotron in rest frame of particle

- Thomas-BMT-equation:

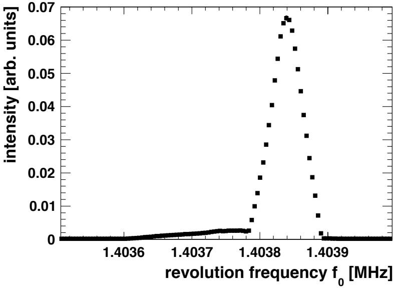
$$\frac{d\vec{S}}{dt} = \frac{e}{\gamma m} \vec{S} \times \left[(1 + G\gamma) \vec{B}_{\perp} + (1 + G) \vec{B}_{||} + \left(G\gamma + \frac{\gamma}{\gamma + 1} \right) \frac{\vec{E} \times \vec{v}}{c^2} \right]$$

Beam momentum determination

Revolution frequency f_0

Schottky Noise of the beam

- Origin: statistical distribution of the particles in the beam
- Current fluctuations induce a voltage signal at a beam pick-up
- Fourier transformation of the voltage signal delivers the frequency distribution around the harmonics of the revolution frequency



Mean revolution frequency:
Arithmetic mean of the frequencies

$$\bar{f}_0 = \frac{\sum_{i=1}^{m} f_i \cdot \bar{I}_i}{\sum_{i=1}^{m} \bar{I}_i}$$

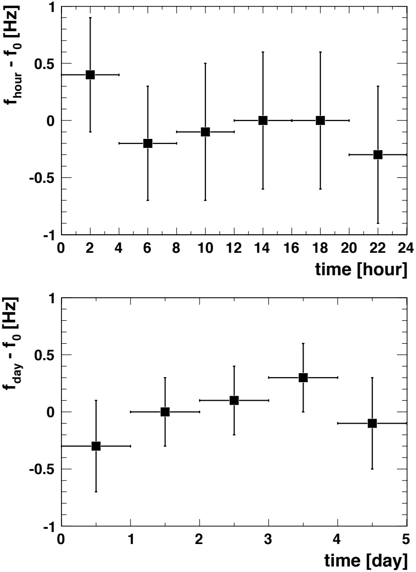
Beam momentum determination

Revolution frequency f_0

Stability of the revolution frequency ($f_0 \approx 1.4$ MHz)

- Over 1 day stable in the range of 1 Hz
- Over 5 days stable in the range of 1 Hz
- Stable before and after a COSY-breakdown

$\rightarrow$ Determination of the revolution frequency with a systematic uncertainty of $\Delta f_0 = \pm 6$ Hz



Beam momentum determination

Spin resonance frequency f_r

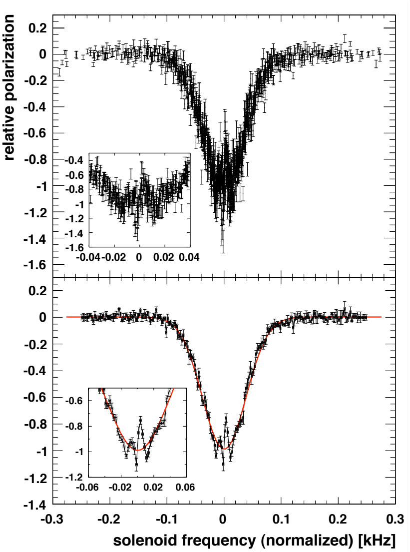
Normalized spin resonance spectrum

Top part:

- Describe every spin resonance spectrum by a gaussian
- Shift all spectra by the mean value of the gaussian
- Normalize the height of each measurement

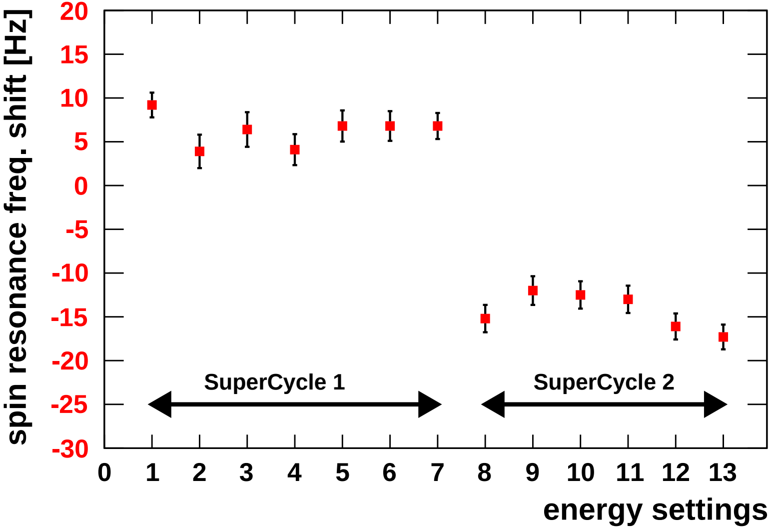
Bottom part:

- In addition bin x-axis



Beam momentum determination

Spin resonance frequency f_r



Beam momentum determination

Spin resonance frequency f_r and orbit length s

Origin of the shift of the spin resonance frequency

- Revolution frequency is stable → no shift
- Change of the orbit length s up to 3 mm

→ Spin resonance method allows an orbit length determination of below 0.3 mm at a circumference of COSY of 183.4 m

Orbit length s determination

$$\gamma = \frac{1}{G_d}\left(\frac{f_r}{f_0} - 1\right)$$

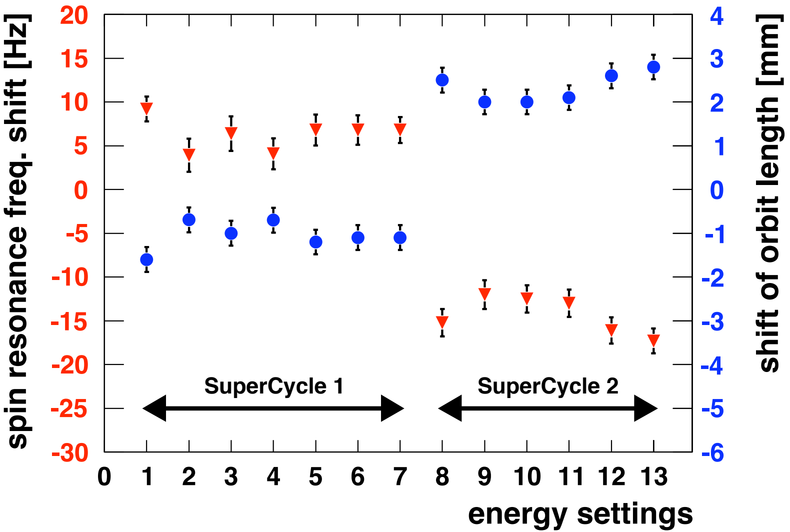
$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{1}{\sqrt{1 - s^2 \cdot f_0^2/c^2}}$$

$$s = c \cdot \left\{\frac{1}{f_0^2} - \left(\frac{G_d}{f_r - f_0}\right)^2\right\}^{\frac{1}{2}}$$

Accuracy of the orbit length determination: $\frac{\Delta s}{s} < 2 \cdot 10^{-6}$

Beam momentum determination

Spin resonance frequency f_r and orbit length s



Beam momentum determination

Accuracy and possible systematic shifts of the resonance frequency f_r

Table: Accuracy and possible systematic shifts of the resonance frequency f_r.

Source	$\Delta f_r / f_r$
Resonance frequency accuracy from depolarization spectra	1.5×10^{-5}
Spin tune shifts from longitudinal fields (field errors)	1.4×10^{-9}
Spin tune shifts from radial fields (field errors, vertical correctors)	6.0×10^{-9}
Spin tune shifts from radial fields (vertical orbit in quadrupoles)	4.1×10^{-8}

η^3He final state interaction
Is there a quasi bound state?

η^3He final state interaction – quasi bound state?

η-mesic nucleus

Quasi-bound η-mesic nuclei

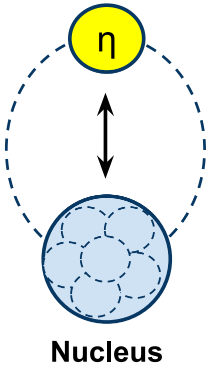
- Attractive S-wave ηN interaction

  R.S. Bhalerao and L.C. Liu, Phys. Rev. Lett. 54 (1985) 685

- Possible formation of η-nucleus bound states

  Q. Haider and L.C. Liu, Phys. Lett. B172 (1986) 257

  C. Wilkin, Phys. Rev. C47 (1993) 938



η-mesic nuclei program at COSY

- $A > 4$: GEM (η^6Li and η^{25}Mg)
- η^4He: ANKE, GEM, WASA
- η^3He: ANKE, COSY-11, GEM, WASA
- ηd & η^3H: Proposed measurements at ANKE

η^3He final state interaction – quasi bound state?

FSI - Final State Interaction

Two ways to investigate η-mesic nuclei

- Signal from such a state **below** the ηA production threshold
  (WASA-at-COSY, Talk of M. Skurzok, Sunday evening)
- Investigation of the excitation function **above** threshold;
  A pole close to threshold should influence the ηA production
  $\rightarrow$ described by a FSI ansatz

S-wave FSI ansatz for dp $\rightarrow$ ^{3}He η:

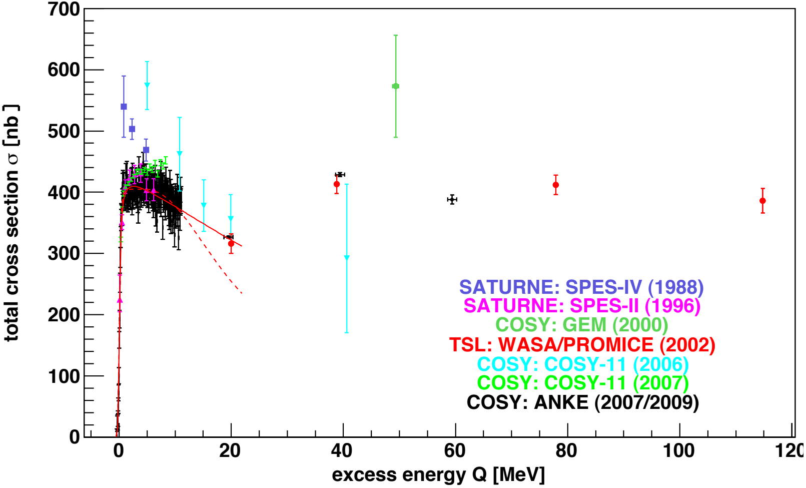
$$\frac{p_i}{p_f} \cdot \frac{d\sigma}{d\Omega} = |f|^2 = |f_{\text{prod.}} \cdot FSI|^2$$

- Classical description with a and r_0: $FSI = \frac{1}{1 - i \cdot a \cdot p_f + \frac{1}{2} \cdot a \cdot r_0 \cdot p_f^2}$
- Alternative description with poles: $FSI = \frac{1}{(1 - p_f/p_1)(1 - p_f/p_2)}$

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

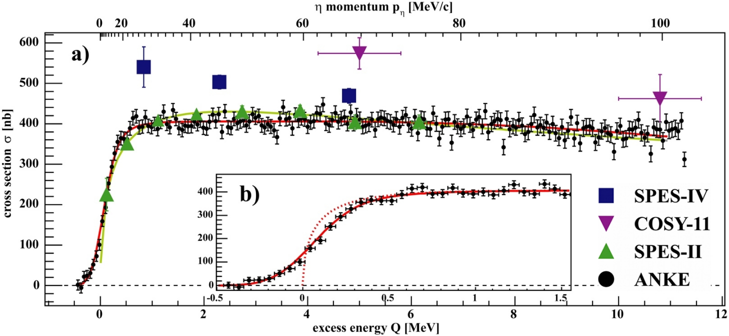
η^3He final state interaction – quasi bound state?

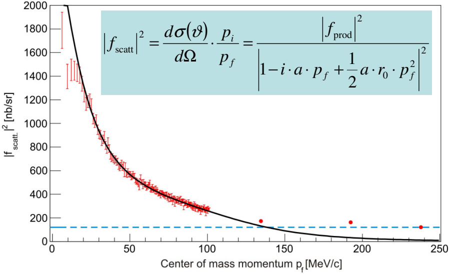
Total cross section of $dp \to {}^3He\,\eta$



T. Mersmann et al., Phys. Rev. Lett. 98 (2007) 242301; T. Rausmann et al., Phys. Rev. C80 (2009) 017001.

η^3He final state interaction – quasi bound state?

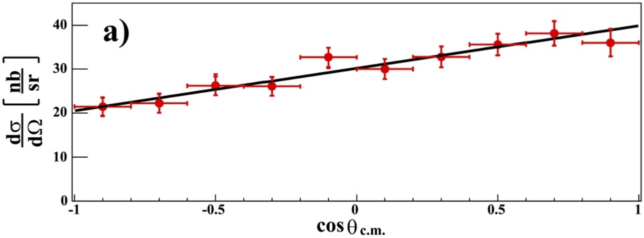


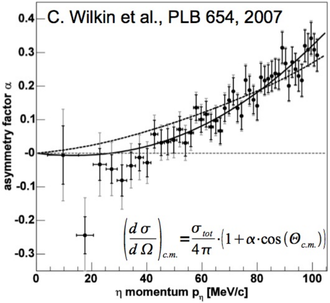


- Very good description of the whole energy range with FSI ansatz
- Momentum smearing of the COSY beam has to be taken into account

η^3He final state interaction – quasi bound state?

Angular distribution





Angular distribution

- Contributions from higher partial waves already at $Q = 4$ MeV
- Confirmed by COSY-11 measurements
- Behavior is expected from quasi-bound or virtual η^3He state

Status and results of the ANKE η^3He program

- Strong attractive FSI: large $|a|$ and small $|p_1|$
- Fit to the data for $Q < 11$ MeV:
  Pole of the scattering amplitude:

$$\boxed{Q_0 = p_1^2/2m_{\text{red}} = [(-0.30 \pm 0.15\ ) \pm i\,(0.21 \pm 0.29)]\,\text{MeV}}$$

  Scattering length:

$$\boxed{a(\eta^3\text{He}) = [\pm\,(10.7 \pm 0.8) + i\,(1.5 \pm 2.6)]\,\text{fm}}$$

  C. Wilkin, Phys. Rev. C47 (1993) 938: $a(\eta^3\text{He}) = (-2.31 + i2.57)$ fm

- **Indication for a quasi-bound or virtual state!**
  C. Wilkin et al., Phys. Lett. B654 (2007) 92-96;

Further investigations

- Polarized measurement: Verification of FSI
- Other ηN systems: ηd & η^3H