Precision measurement of the η meson mass at COSY-ANKE

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Outline

Introduction

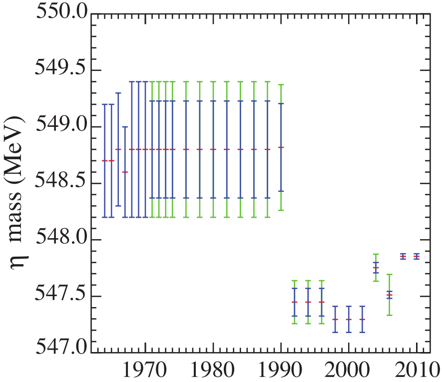
Measuring method at COSY-ANKE using the reaction $dp \to {}^3\mathrm{He}\,\eta$

Beam momentum determination

Final state momentum determination

COSY-ANKE η mass result

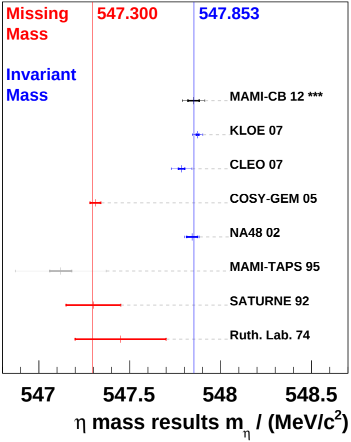
History of the PDG value of the η meson mass



Publicaton date	PDG values of the η mass (MeV/c^2)
until 1990	548.800 ± 0.600
1992	547.450 ± 0.190
1997	547.300 ± 0.120
2003	547.750 ± 0.120
2006	547.510 ± 0.180
2008	547.853 ± 0.024

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

Current situation of the η meson mass

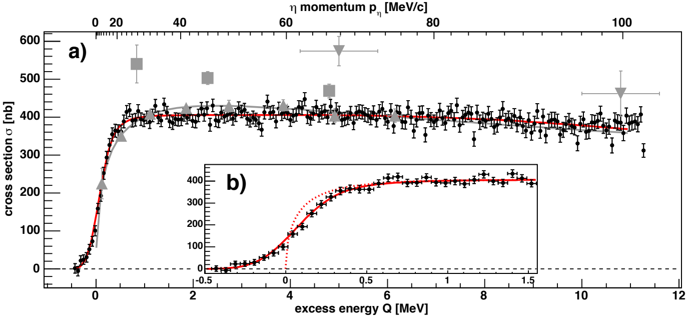


Experimental Facility	Measuring Method	η mass (MeV/c^2)
MAMI-CB ***	Photoprod.	547.851
DAFNE-KLOE	Invariant Mass	547.874
CESR-CLEO	Invariant Mass	547.785
COSY-GEM	**MM: $pd \to {}^3\mathrm{He}\,\eta$**	**547.311**
CERN-NA48	Invariant Mass	547.843
MAMI-TAPS	Photoprod.	547.120
SATURNE	**MM: $dp \to {}^3\mathrm{He}\,\eta$**	**547.300**
Ruth. Lab.	Missing Mass	547.450

Precision: $\boxed{\Delta m_\eta < 50\,\mathrm{keV/c^2}}$

Different measuring methods result in different η mass values

"Reason for disagreement: Reaction $dp \to {}^3\mathrm{He}\,\eta$"

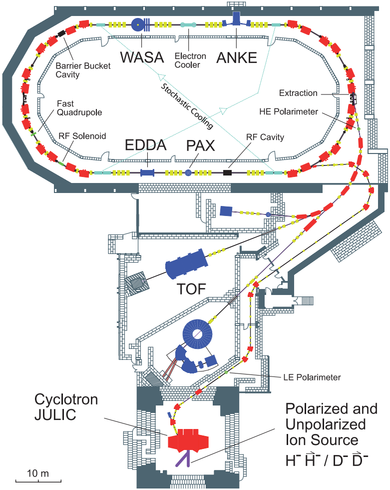


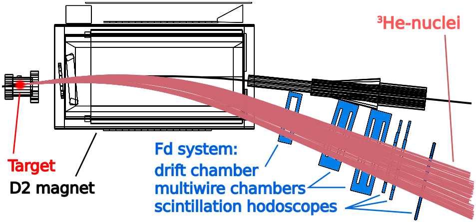
Ideas / Speculations:

- Strong ${}^3\mathrm{He}\,\eta$ FSI $\to$ Indication for a $\eta\,{}^3$He quasi-bound state
- Coupling of ${}^3\mathrm{He}\,\eta \leftrightarrow {}^3\mathrm{He}\,\pi\pi$ can disturb the multipion background near the η position $\to$ Wrong identification of the η mass

Determination of the η mass at COSY-ANKE

The $dp \to {}^3\mathrm{He}\,\eta$ reaction at COSY-ANKE





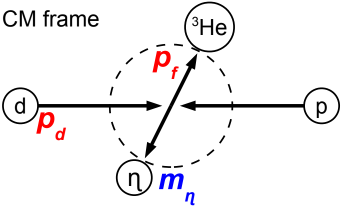
- ANKE: internal fixed target experiment with a cluster-jet target
- ^{3}He nuclei are detected in the forward-system
- Full geometrical acceptance for the reaction $dp \to {}^3\mathrm{He}\,\eta$ for excess energies below 20 MeV

Determination of the η mass at COSY-ANKE

Kinematics

Two-body reaction:

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



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

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

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

$$p_f = \frac{\sqrt{\left[s - (m_{^3\mathrm{He}} + m_\eta)^2\right] \cdot \left[s - (m_{^3\mathrm{He}} - m_\eta)^2\right]}}{2\sqrt{s}}$$

Determination of the η mass at COSY-ANKE

Method and Objective

Dependence: $\boxed{p_f = p_f(p_d, m_\eta)}$

Near threshold:

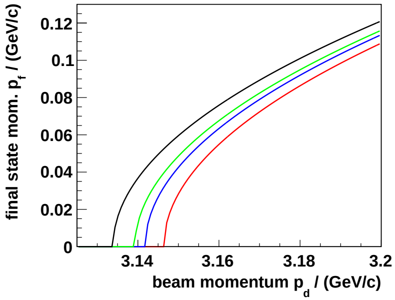
Final state momentum is very sensitive to the η mass!

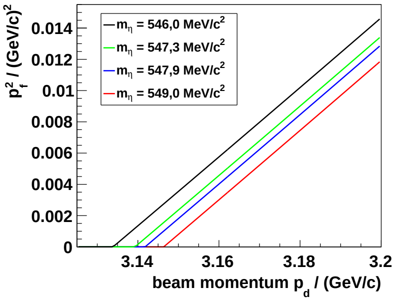
Objective of ANKE measurement:

- Precision comparable to recent results:

  $\boxed{\Delta m_\eta < 50\,\mathrm{keV/c^2}} \rightarrow \boxed{\frac{\Delta m_\eta}{m_\eta} \approx 10^{-4}}$

- Final state mom. p_f of the ^{3}He-nuclei: $\Delta p_f = 300$ keV/c
- Beam momentum p_d: $\Delta p_d = 300$ keV/c





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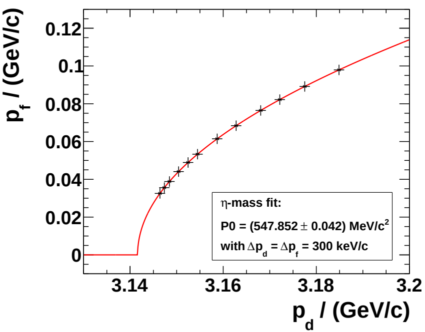
- Beam momentum p_d: $\Delta p_d = 300$ keV/c

η mass fit: $p_f = p_f(p_d, m_\eta)$



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

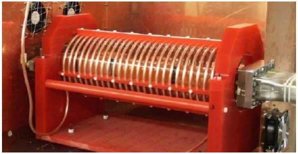
Beam momentum determination p_d

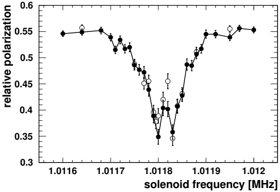
Beam momentum determination

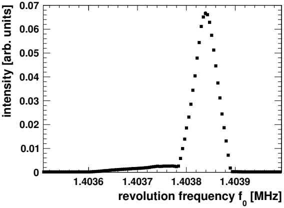
Spin resonance method

Resonant depolarization technique

- Depolarization of a vertically polarized deuteron beam with an artificial spin resonance
- Induced by a horizontal magnetic rf-field







Resonance condition:

$$\boxed{\begin{aligned} f_r &= (1+\gamma G_d)\, f_0 \\ \gamma &= \frac{1}{G_d}\left(\frac{f_r}{f_0}-1\right) \\ p_d &= m_d\sqrt{\gamma^2-1} \end{aligned}}$$

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

Beam momentum determination

$$\boxed{p_d = (3146.409 \pm 0.029_{\text{stat.}} \pm 0.095_{\text{sys.}})\ \text{MeV}/c}$$

$$\boxed{\frac{\Delta p_d}{p_d} \approx 3 \times 10^{-5}}$$

- Uncertainty of 95 keV/c is caused by systematic variations of the spin resonance frequency f_r
- A systematic f_r shift of ± 15 Hz is observed and originated by the variation of the orbit length in COSY
- Method and results have been published in *P. Goslawski et al., Phys. Rev. ST Accel. Beams 13 (2010) 022803*

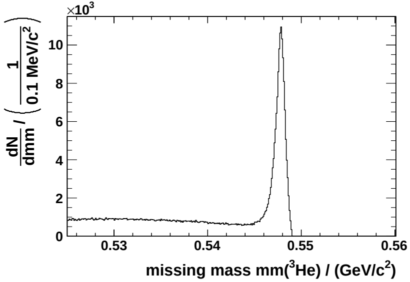
Final state momentum determination p_f

Final state momentum determination

Standard ANKE FD calibration:

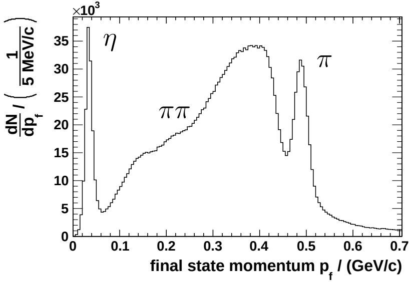
Reactions used:

- *dp* → *dp* elastic with
  - fast forward scattered d detected
  - both particles detected
- *dp* → *ppn* charge-exchange scattering with two p being detected
- *dp* → $^3\mathrm{He}\,\pi^0$ with ^{3}He nucleus being detected

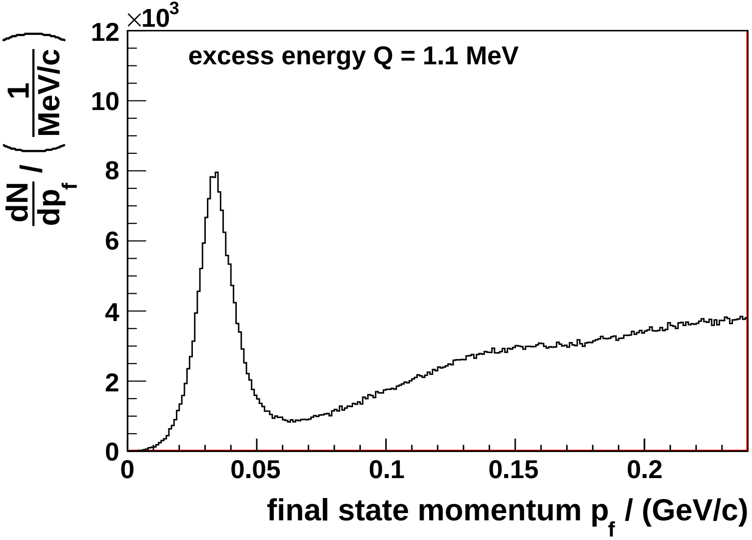


Identification of *dp* → $^3\mathrm{He}\,\eta$

- Background consisting of *d*, *p* from *dp* elastic and deuteron break-up
- Suppressed by energy loss and TOF cut on the ^{3}He nuclei



The ^{3}He η signal



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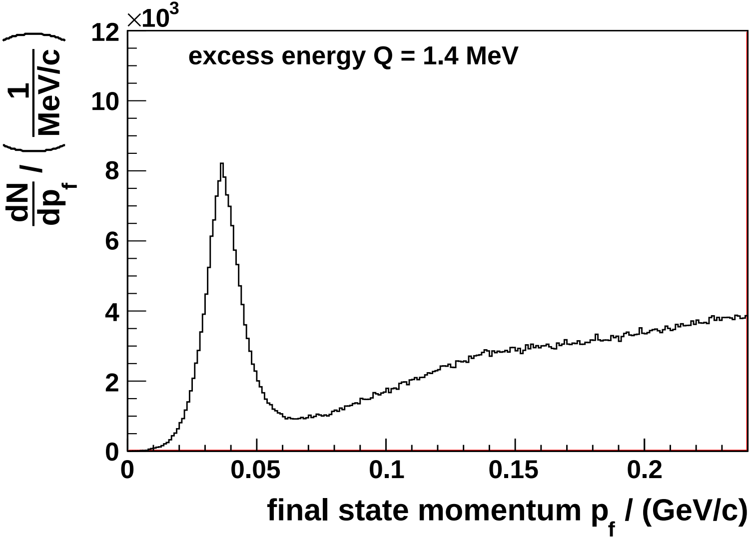

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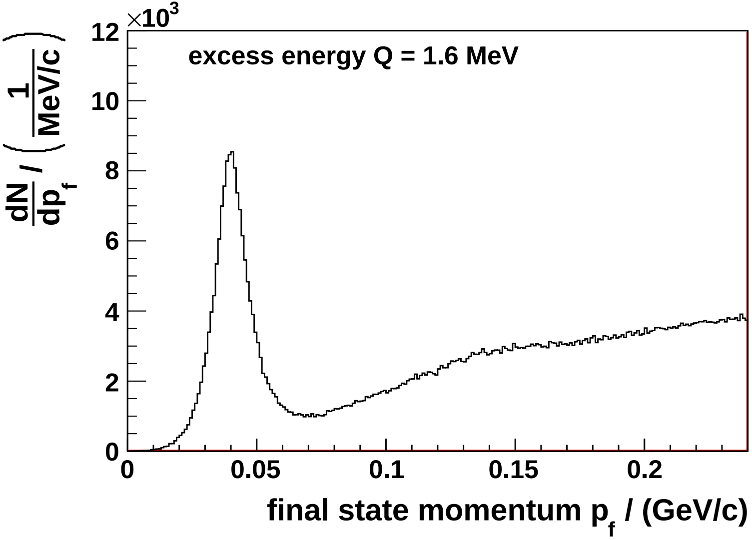

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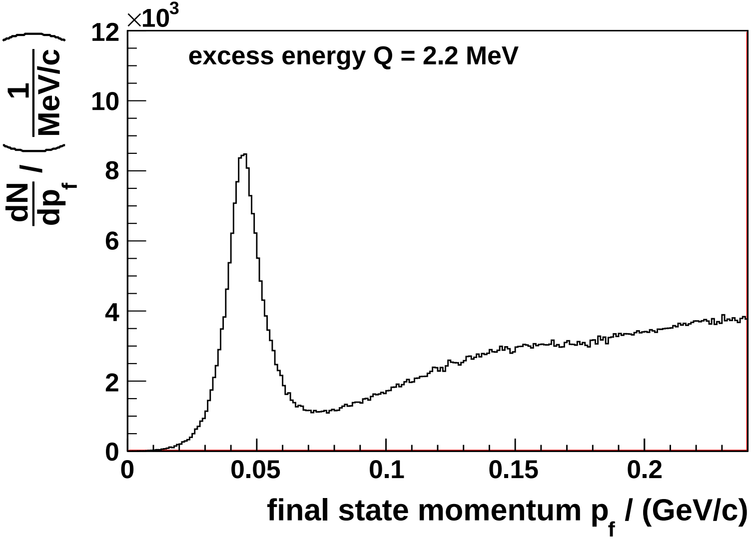

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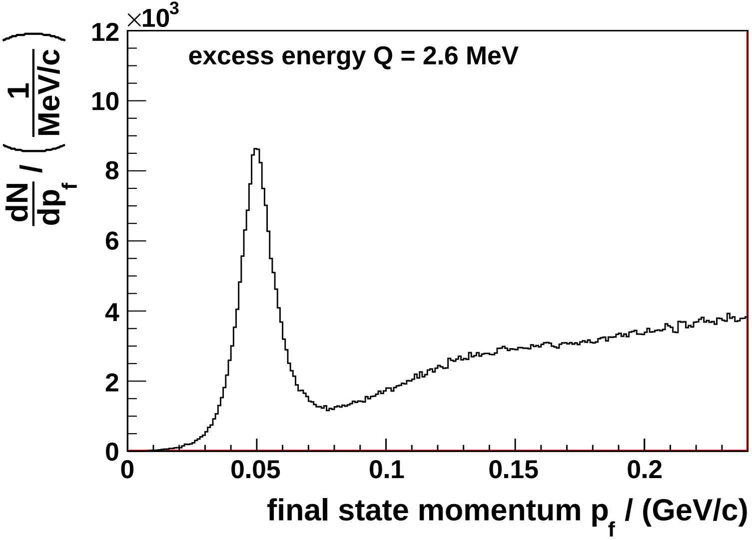

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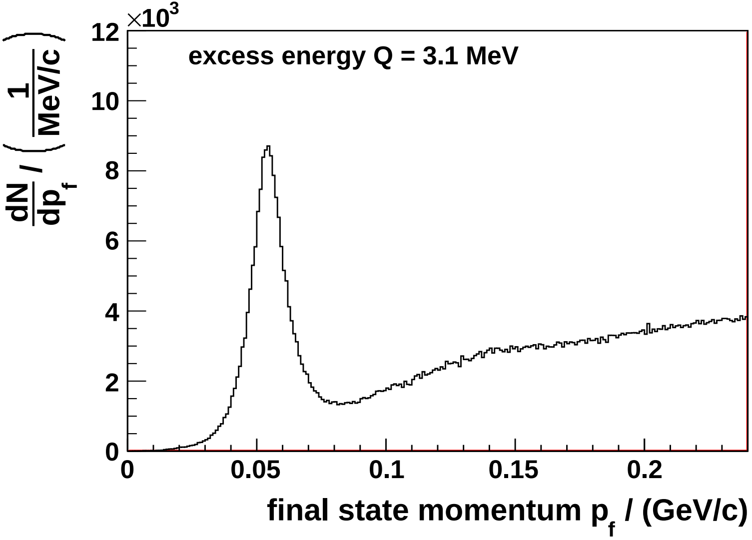

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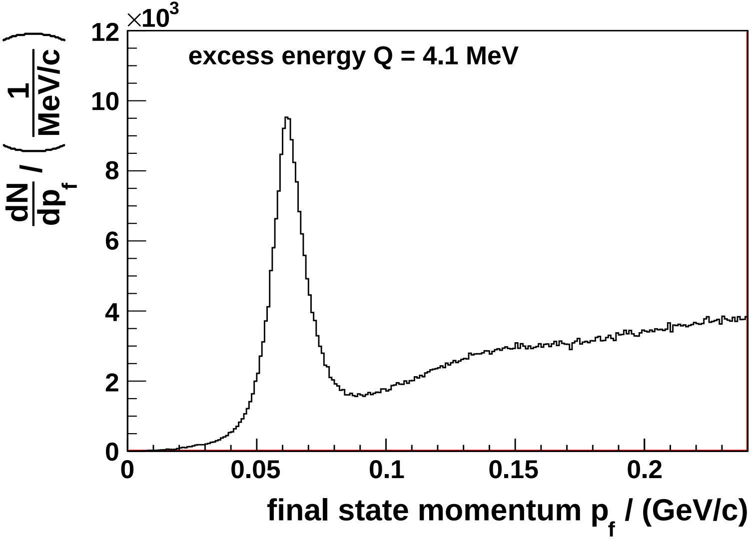

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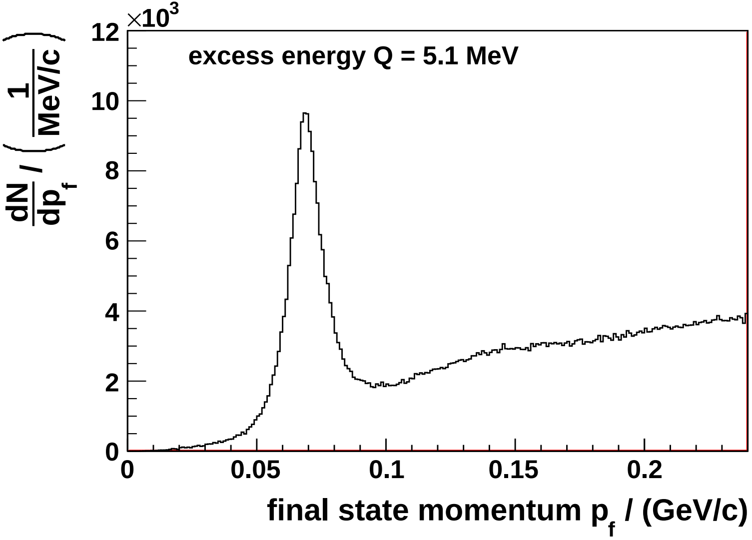

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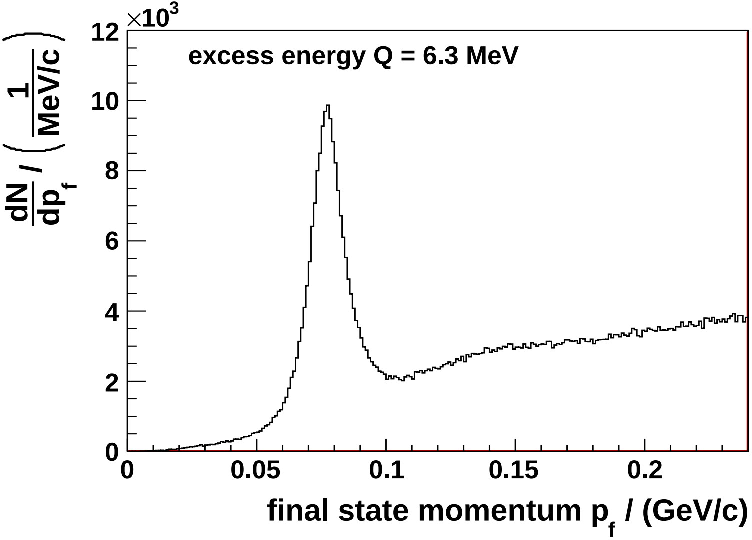

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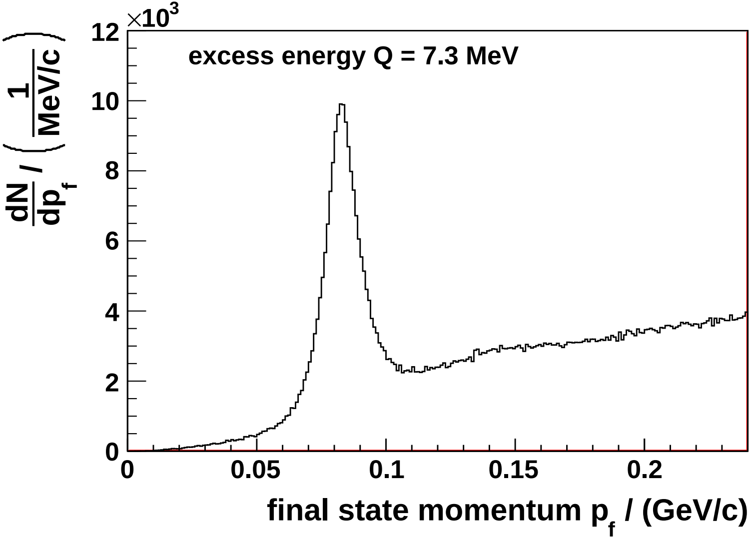

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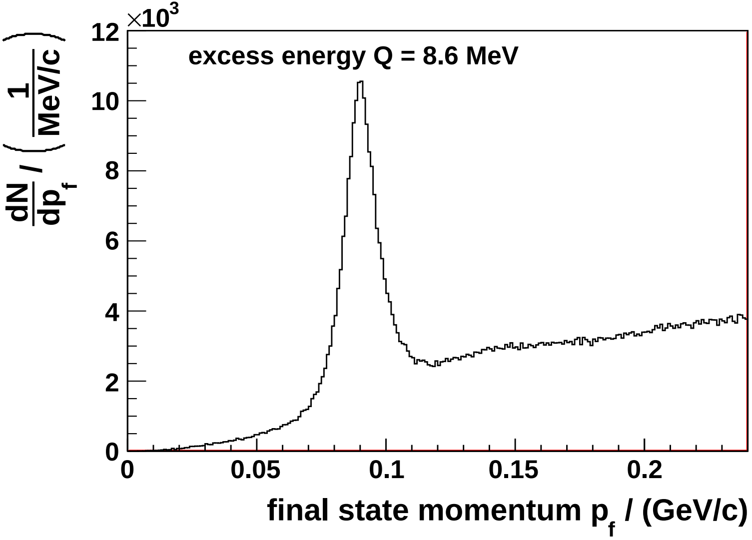

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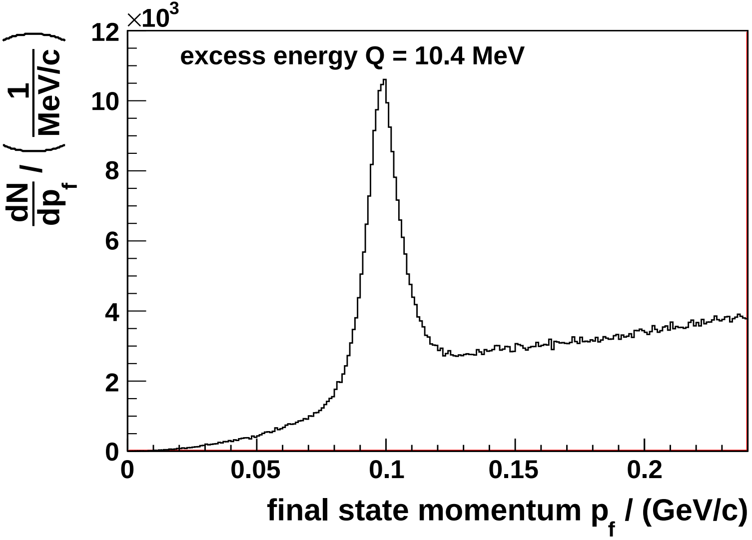
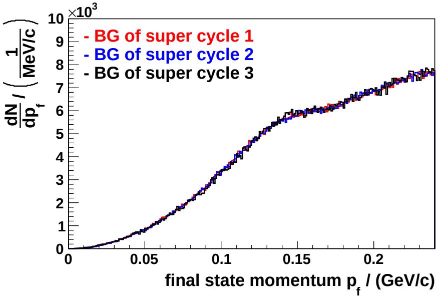
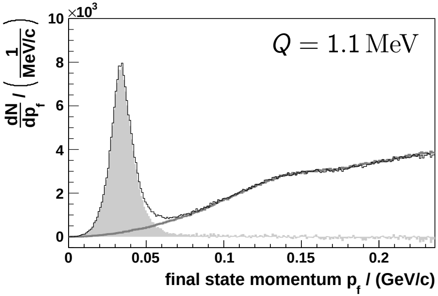


Background description using subthreshold data

- Subthreshold data at $Q \approx -5\,\mathrm{MeV}$ were analyzed as if they were taken above threshold: $\vec{p}^{LS} = \frac{p_{beam}}{p_{beam,\,sub.}} \cdot \vec{p}^{LS}_{sub.}$
- Reconstructed momenta are linearly scaled with beam momentum
- Pure ${}^{3}\mathrm{He}\,\eta$ signal after background subtraction

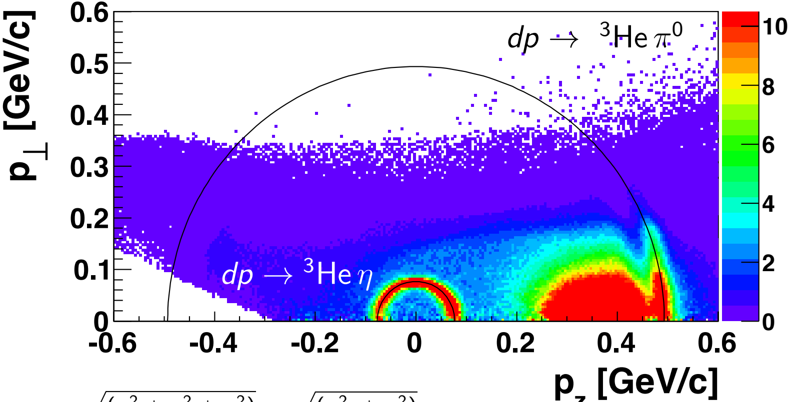




Identification of the reaction $dp \to {}^3\mathrm{He}\,\eta$

The momentum ellipse

Excess energy $Q = 6.3\,\mathrm{MeV}$



$$p_f = \sqrt{(p_x^2 + p_y^2 + p_z^2)} = \sqrt{(p_\perp^2 + p_z^2)}$$

with $p_\perp = \sqrt{p_x^2 + p_y^2}$

Verification of calibration using two-body reaction

Kinematics of two-body reaction

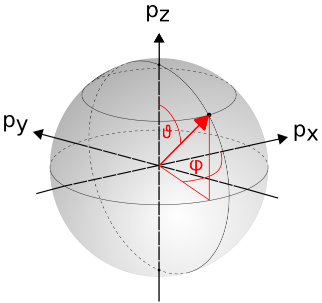
- Perfect symmetric momentum sphere in p_x, p_y, p_z with radius

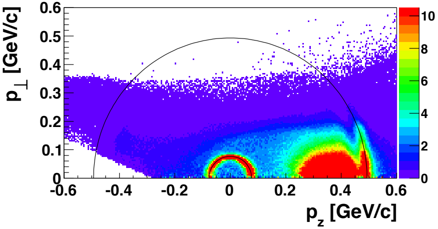
$$p_f = \sqrt{p_x^2 + p_y^2 + p_z^2}$$

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

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

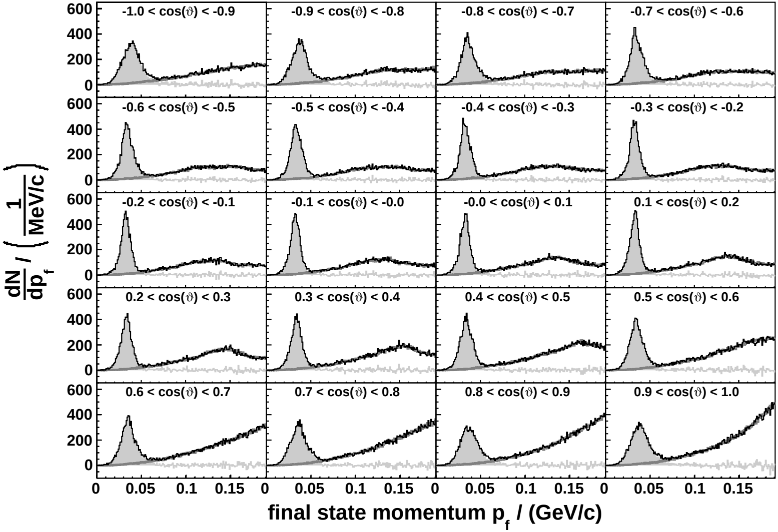
- Therefore full geometrical acceptance is needed $\rightarrow$ ANKE





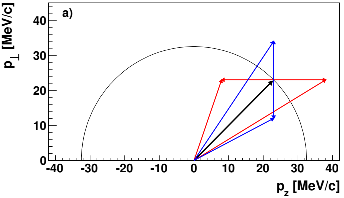
Angular dependence of p_f

$p_f = p_f(\cos\vartheta)$ for $Q = 1.1\,\mathrm{MeV}$



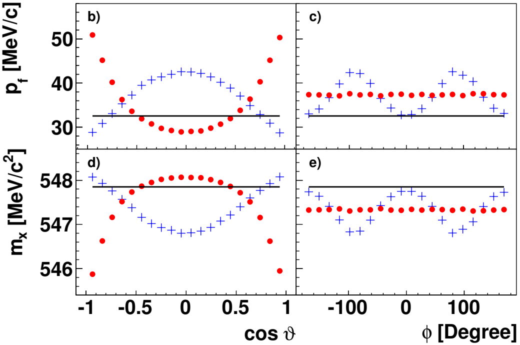
Influence of (p_x, p_y, p_z) momentum resolution on p_f

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



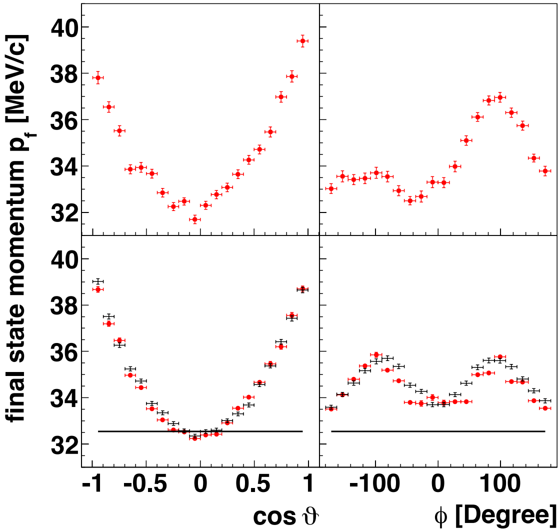
$\cos\vartheta = -1$ $\cos\vartheta = 0$ $\cos\vartheta = 1$

$(0, 0, \sigma_{p_z})$ $(\sigma_{p_x}, \sigma_{p_y}, 0)$



- Final state momentum and missing mass depend on $\cos\vartheta$ and ϕ

Improvement of calibration and determination of momentum spreads



$p_f = p_f(\cos\vartheta)$ and $p_f = p_f(\phi)$ for:

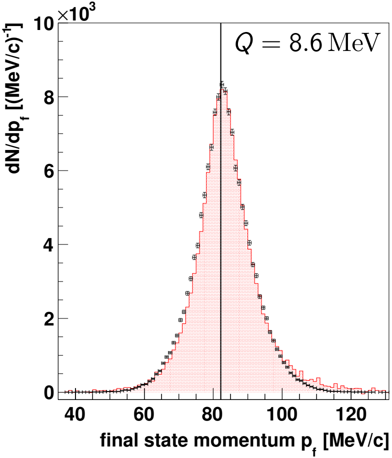
1.) Standard ANKE calibration

2.) Calibration improved using kinematics of two body reaction

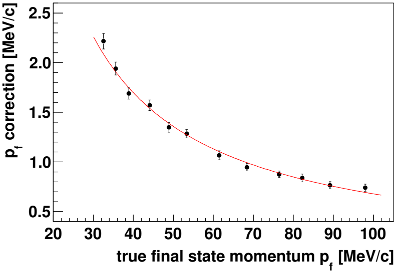
Extracted momentum spreads $(\sigma_{p_x}, \sigma_{p_y}, \sigma_{p_z}) = (2.8, 7.9, 16.4)\,\mathrm{MeV/c}$

with uncertainties of $(\Delta\sigma_{p_x}, \Delta\sigma_{p_y}, \Delta\sigma_{p_z}) = (0.2, 0.2, 0.1)\,\mathrm{MeV/c}$

Final state momentum determination



12 final state momenta in the range of $p_f = 30 - 100\,\mathrm{MeV/c}$
with uncertainties $\Delta p_f < 80\,\mathrm{keV/c}$

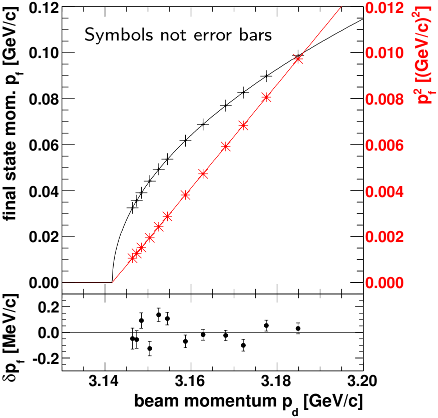


- Difference of $2.22 - 0.7\,\mathrm{MeV/c}$ from true value: p_f correction $\sim 1/p_f$
- Errors arise from uncertainties of resolution $(\Delta\sigma_{p_x}, \Delta\sigma_{p_y}, \Delta\sigma_{p_z})$
- Without p_f correction $150\,\mathrm{keV/c^2}$ lower η mass value

$\rightarrow$ Same effect occurs for missing mass distributions

COSY-ANKE η mass result

Excess energy Q MeV	Beam momentum p_d MeV/c	Final-state momentum p_f MeV/c
1.1	3146.41(3)	32.46(8)
1.4	3147.35(3)	35.56(7)
1.6	3148.45(3)	39.00(6)
2.1	3150.42(3)	44.09(6)
2.6	3152.45(3)	49.25(5)
3.1	3154.49(3)	53.66(5)
4.1	3158.71(3)	61.70(5)
5.1	3162.78(3)	68.77(4)
6.3	3168.05(3)	76.92(4)
7.3	3172.15(3)	82.64(5)
8.6	3177.51(3)	89.81(4)
10.4	3184.87(3)	98.64(4)



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

$$\boxed{m_\eta = (547.873 \pm 0.005)\,\mathrm{MeV/c^2}}$$

$\chi^2/NDF = 1.28$

$$\boxed{p_d^{\mathrm{thr.}} = (3141.688 \pm 0.021)\,\mathrm{MeV/c}}$$

threshold momentum

Systematic uncertainties

Sources of systematic uncertainties

Source	Variation	Δm_η (keV/c^2)
Absolute beam momentum	95 keV/c	23
Experimental settings		2
m_η assumed in simulations	20 keV/c^2	< 2
$\Delta E \times \beta^2$ cut	$6\sigma \to 2\sigma$	5
Flight length cut	$3\sigma \to 2\sigma$	1
p_f correction parameters	$4\sigma \to 2\sigma$	12
Total systematic uncertainty		**27**

Systematic errors are mainly given by the determination of the absolute value of the beam momentum and the p_f correction parameters

Additional cross check of systematics:

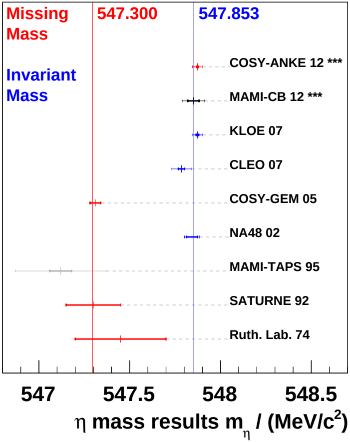
- η mass fit for each supercycle
- Small deviation of 7 keV/c^2

Supercycle	m_η (MeV/c^2)
1	547.870
2	547.877
1+2	547.873

COSY-ANKE result of the η meson mass

$$\boxed{m_\eta = (547.873 \pm 0.005_{\text{stat.}} \pm 0.027_{\text{sys.}})\ \text{MeV}/c^2}$$

- Submitted, accepted and published soon in *Physical Review D*
- Comparable and competitive in accuracy with best measurements
- In agreement with results of invariant mass experiments
- No influence of $dp \to {}^3\text{He}\,\eta$ on mass
- Probably that COSY-ANKE & KLOE results will shift PDG value



Thank you for your attention

Additional Slides

Determination of the η mass at COSY-ANKE

Cycle timing structure

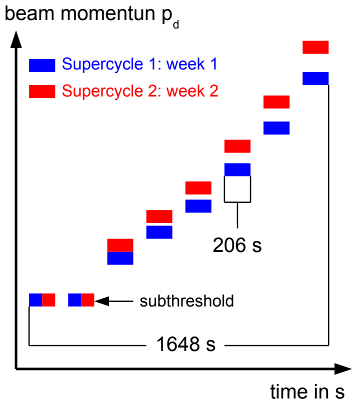
Measurement of (p_d, p_f) data set

- 12 fixed beam momenta divided alternately into two supercycles
- Each SC covers an excess energy range of $Q \approx 1 - 11\,\mathrm{MeV}$
- Data below η production threshold for background description

p_f: Five days of data taking for each setting (ANKE, unpol. beam)

p_d: Beam momentum measurement before and after data taking (EDDA, rf-solenoid, pol. beam)

Supercycle (SC) with 7 different beam energies



Beam momentum determination

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

Source	$\Delta f_r / f_r$
Resonance frequency accuracy from depolarization spectra	9.0×10^{-6}
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}

Determination of the η mass at COSY-ANKE

Method and Objective

Dependence: $\boxed{p_f = p_f(p_d, m_\eta)}$

Near threshold:

Final state momentum is very sensitive to the η mass!

Objective of ANKE measurement:

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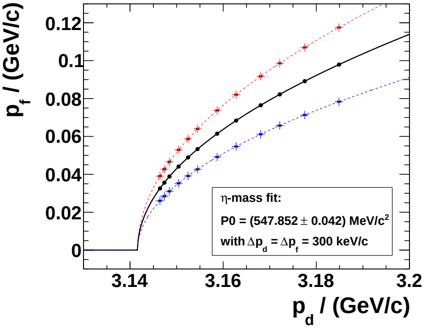
  $\boxed{\Delta m_\eta < 50\,\mathrm{keV/c^2}} \rightarrow \boxed{\frac{\Delta m_\eta}{m_\eta} \approx 10^{-4}}$

- Final state mom. p_f of the ^{3}He-nuclei: $\Delta p_f = 300$ keV/c
- Beam momentum p_d: $\Delta p_d = 300$ keV/c

η mass fit: $p_f = S \cdot p_f(p_d, m_\eta)$



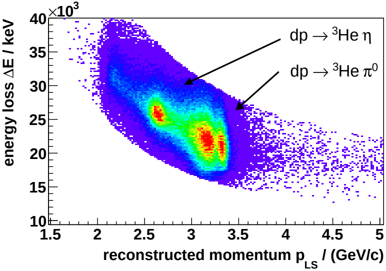
- Scaling in p_f because of small inaccuracies in distance between vertex and wire chambers

Final state momentum determination

Identification of the reaction $dp \to {}^3\mathrm{He}\,\eta$: Background suppression

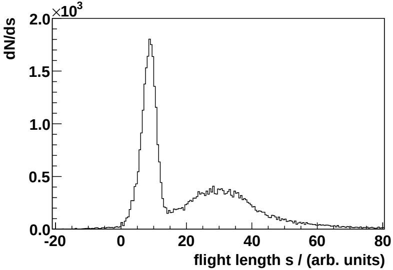
Cut on energy loss ΔE

- 3 layers of scintillation counters
- Energy loss according to Bethe-Bloch: $\Delta E \sim z^2/\beta^2$
- Energy loss of ^{3}He nuclei higher than for p and d
- Cut on $\Delta E \times \beta^2$

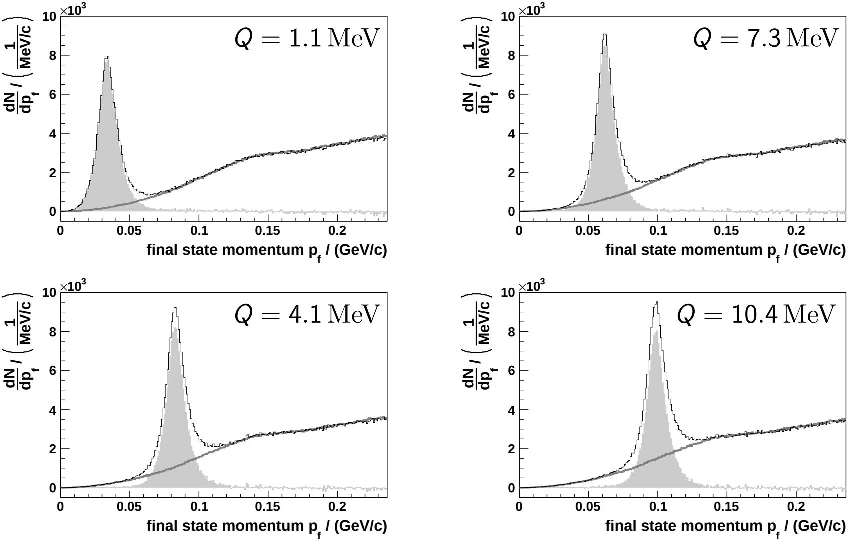


Cut on flight length s (TOF)

- Time difference Δt between 1. and 3. scintillation wall
- Flight length s: $s = \Delta t \times \beta = \Delta t \times p/E$
- Clear peak for ^{3}He nuclei

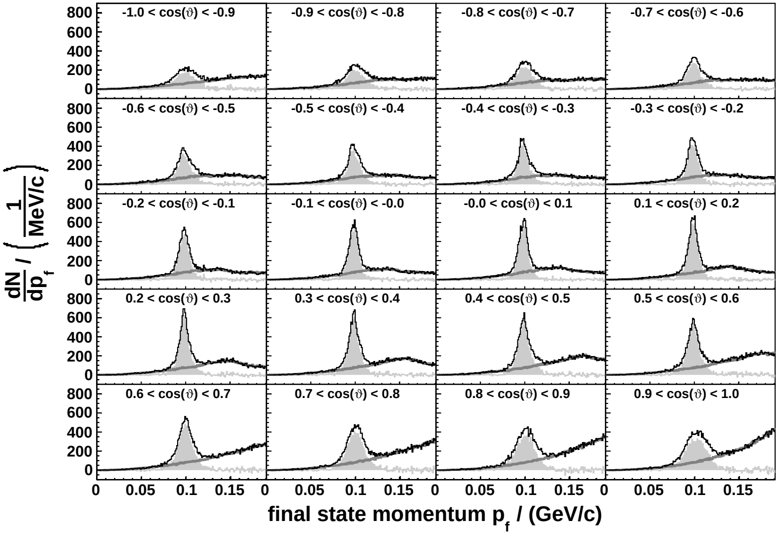


Background description using subthreshold data for different excess energies



Angular dependence of p_f

$p_f = p_f(\cos\vartheta)$ for $Q = 10.4\,\mathrm{MeV}$



Improvement of calibration/alignment - fine tuning

- p_z - magnetic field of D2

  Changes from $1.4172\,\mathrm{T} \rightarrow 1.4159\,\mathrm{T}$ $\Delta = 0.0013\,\mathrm{T}$

  Changes of below 0.1%

- p_x - deflection angle

  Changes from $5.816\,^\circ \rightarrow 5.792\,^\circ$ $\Delta = 0.024\,^\circ$

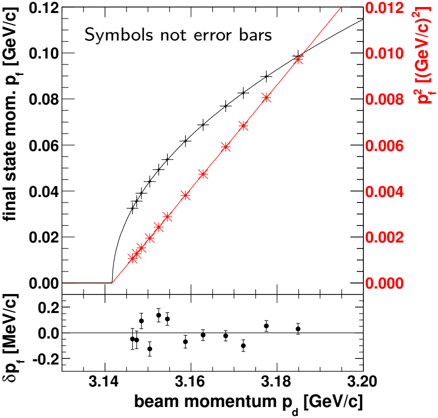
  Changes of below 0.4%

- p_y - y-position of the wire chambers

  Changes of $0.4\,\mathrm{mm}$

COSY-ANKE η mass result

Excess energy Q MeV	Beam momentum p_d MeV/c	Final-state momentum p_f MeV/c
1.1	3146.41(3)	32.46(8)
1.4	3147.35(3)	35.56(7)
1.6	3148.45(3)	39.00(6)
2.1	3150.42(3)	44.09(6)
2.6	3152.45(3)	49.25(5)
3.1	3154.49(3)	53.66(5)
4.1	3158.71(3)	61.70(5)
5.1	3162.78(3)	68.77(4)
6.3	3168.05(3)	76.92(4)
7.3	3172.15(3)	82.64(5)
8.6	3177.51(3)	89.81(4)
10.4	3184.87(3)	98.64(4)



Result: $p_f = S \cdot p_f(p_d, m_\eta)$

$$\boxed{m_\eta = (547.873 \pm 0.005)\,\mathrm{MeV/c^2}}$$

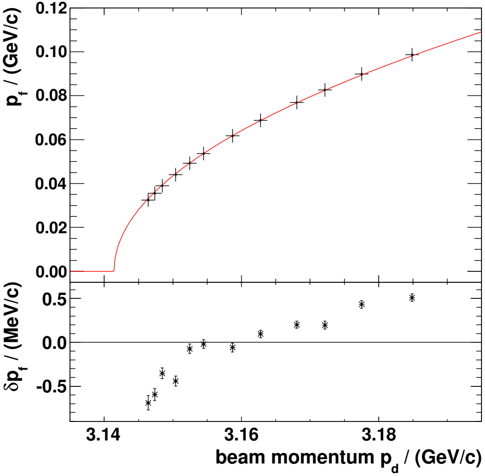
with $S = 1.008 \pm 0.001$

$\chi^2/NDF = 1.28$

$$\boxed{p_d^{\mathrm{thr.}} = (3141.688 \pm 0.021)\,\mathrm{MeV/c}}$$

threshold momentum

COSY-ANKE η mass result



Result without scaling factor: $p_f = p_f(p_d, m_\eta)$

$m_\eta = (547.809 \pm 0.003)$ MeV/c^2

$\chi^2/NDF \approx 25$

Residual plot shows systematic deviation of pure kinematics for the reconstructed p_f

Shift of 64 $\mathrm{keV}/\mathrm{c}^2$ in m_η compared to fit with scaling factor