Strangeness Production at COSY

September 07, 2015 | Florian Hauenstein | HYP2015, Sendai, Japan

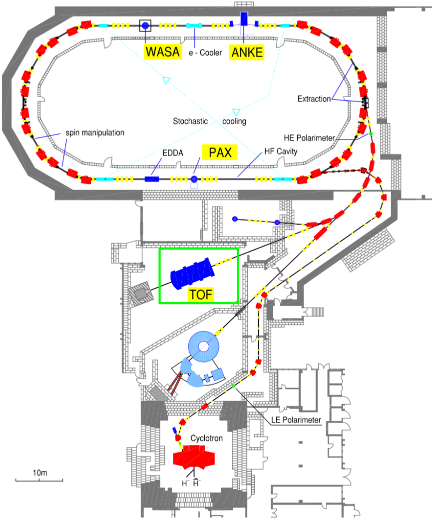
Physics Program at COSY

Non-perturbative QCD in the up, down and strange sector

- Structure of hadrons
  - nucleons
  - hyperons
  - mesons
- Dynamics and interactions
  - nucleon-nucleon (NN)
  - nucleon-hyperon (NY)
  - nucleon-meson
  - meson-nucleus, in medium effects
- Symmetries and symmetry breaking
  - chiral symmetry
  - isospin and charge symmetry in reactions
  - discrete symmetries in meson decays

COSY Facility

COoler SYnchroton



- Circumference: 184 m
- Beam momentum: 0.3 GeV/c - 3.7 GeV/c
- Stochastic and electron cooling
- (Un-)Polarized proton and deuteron beams

COSY-TOF: Physics Program

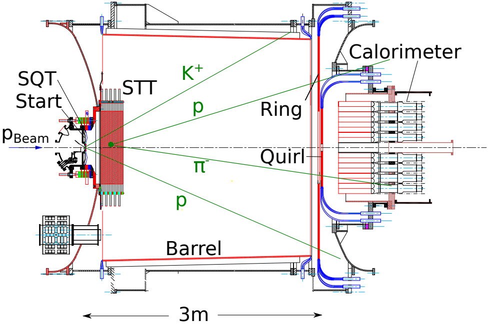
- Meson production in pp collisions
- Study of $pp \to pp\gamma$
- Exclusive hyperon production in $pN \to NKY$ with polarized and unpolarized beams
  - production mechanism of associated strangeness
  - NY interaction through final state interaction (FSI)
  - $N\Lambda - N\Sigma$ coupled channel effect
  - nucleon excited states (N^* resonances)
  - polarization observables

Recent studies:

- $\vec{p}p \to pK\Lambda$ at $p_{\mathrm{beam}} = 2.7\,\mathrm{GeV}/c$ with $\approx 78\,\%$ polarization
- $\vec{p}p \to pK\Lambda$ at $p_{\mathrm{beam}} = 2.95\,\mathrm{GeV}/c$ with $\approx 88\,\%$ polarization
- $pn \to NK\Lambda$ at $p_{\mathrm{beam}} = 2.95\,\mathrm{GeV}/c$

COSY-TOF Detector

Time Of Flight



Features:

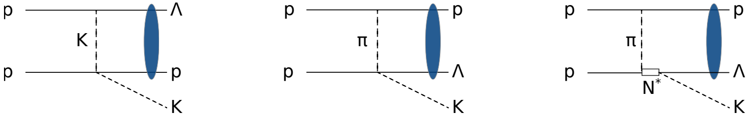
- Full phase space coverage
- Clear signature for $pK\Lambda \to pK\,\{p\pi\}$ (2 primary and 2 secondary tracks)
- Primary and delayed hyperon decay vertex ($c\tau(\Lambda) = 7.89\,\text{cm}$)

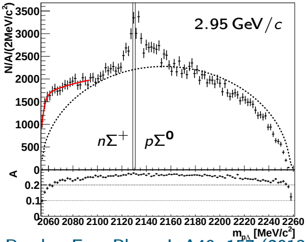
Latest Measurements of $\vec{p}p \to pK\Lambda$:

- $2.95\,\text{GeV}/c$ with $(61.0 \pm 1.7)\,\%$ polarization $\to$ 42,000 events
- $2.95\,\text{GeV}/c$ with $(87.5 \pm 2.0)\,\%$ polarization $\to \sim$ 132,000 events
- $2.70\,\text{GeV}/c$ with $(77.9 \pm 1.2)\,\%$ polarization $\to \sim$ 220,000 events

Physics of $\vec{p}p \to pK\Lambda$

- Described by meson exchange models (no perturbative QCD)
  - Which kind of meson exchange
  - Role of N^* resonances





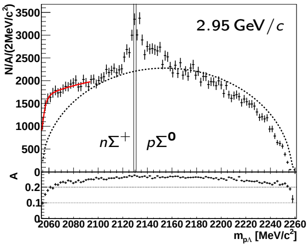
M. Roeder, Eur. Phys. J. A49, 157 (2013)

- $p\Lambda - N\Sigma$ coupled channel (cusp) effect
- $p\Lambda$ final state interaction (FSI)
- Connection to $p\Lambda$ interaction
  $\to$ Parameter: scattering length a
  $$\lim_{k\to 0} \sigma_{p\Lambda\to p\Lambda} = 4\pi a^2$$

Determination of $p\Lambda$ Scattering Length

Method from A. Gasparyan et al., Phys. Rev. C69, 034006 (2004)

- Extraction of $p\Lambda$ scattering length a from the shape of the final state interaction (FSI)
- No further theoretical assumption necessary
- Known theoretical precision (0.3 fm)
- Spin resolved measurement via suitable polarization observable

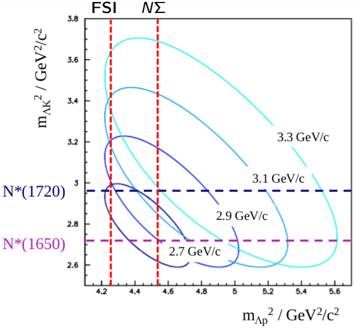


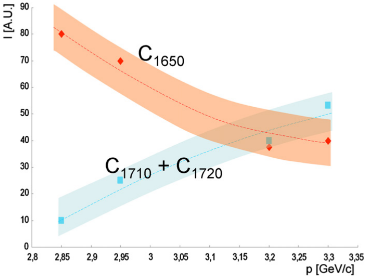
- COSY-TOF measurement at 2.95 GeV/c (42,000 events)

  M. Roeder et al., Eur. Phys. J. A49, 157 (2013)

- Effective scattering length $a_{\text{eff}} = (-1.25 \pm 0.08_{\text{stat.}} \pm 0.3_{\text{theo.}})$ fm
- Large systematic error (1 fm) due to kinematical reflection of N^* resonance

Dalitz Plot Dependence on Beam Momentum



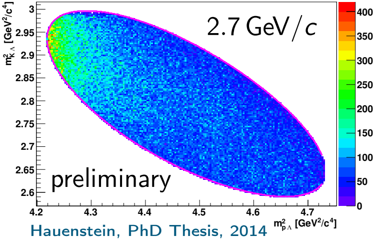


COSY-TOF Coll., Phys. Lett. B688, 142 (2010)

- Contributions of N^* change with beam momenta
- Expected smaller systematic effect on FSI for 2.7 GeV/c?

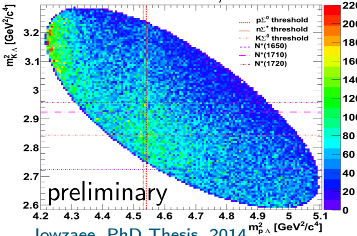
$\Rightarrow$ Comparison of results from the recent data at 2.7 GeV/c ($\sim$ 132,000 events) and 2.95 GeV/c ($\sim$ 220,000 events)

$\vec{p}p \rightarrow pK\Lambda$ Dalitz Plot



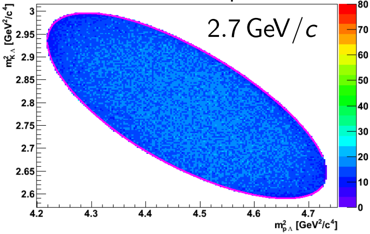
Hauenstein, PhD Thesis, 2014

2.95 GeV/c



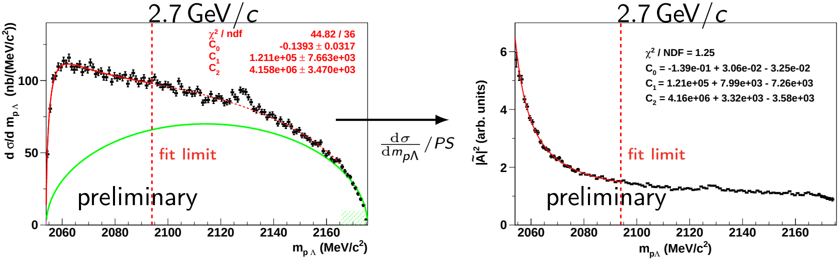
Jowzaee, PhD Thesis, 2014

Monte Carlo acceptance



- Full phase space acceptance
- Reconstruction efficiency relatively flat
- Strong $p\Lambda$ final state interaction for both data sets
- More substructures for 2.95 GeV/c

Effective $p\Lambda$ Scattering Length



- Parametrization: $\frac{\mathrm{d}\sigma}{\mathrm{d}m_{p\Lambda}} = PS \cdot \left|\tilde{A}(FSI)\right|^2 = PS \cdot \exp\left[C_0 + \frac{C_1}{m_{p\Lambda}^2 - C_2}\right]$
- $a_{\mathrm{eff}} = (-1.38^{+0.04}_{-0.05}{}_{\text{stat.}} \pm 0.12_{\text{syst.}} \pm 0.3_{\text{theo.}})$ fm (preliminary)
- Compatible with the result at 2.95 GeV/c ($a_{\mathrm{eff}} = (-1.25 \pm 0.08_{\text{stat.}} \pm 0.3_{\text{theo.}})$ fm)
- Systematic error mainly due to influence of N^* resonances $\rightarrow$ but weaker than for 2.95 GeV/c (1 fm)

Spin Triplet $p\Lambda$ Scattering Length

see Appendix B in Gasparyan et al., Phys. Rev. C69, 034006 (2004)

- $\{p\Lambda\}$ in S-wave and kaon in P-wave $\Rightarrow$ $\{p\Lambda\}$ in spin triplet configuration due to parity and angular momentum conservation
- Kaon analyzing power A_y^K sensitive to kaon P-wave contribution

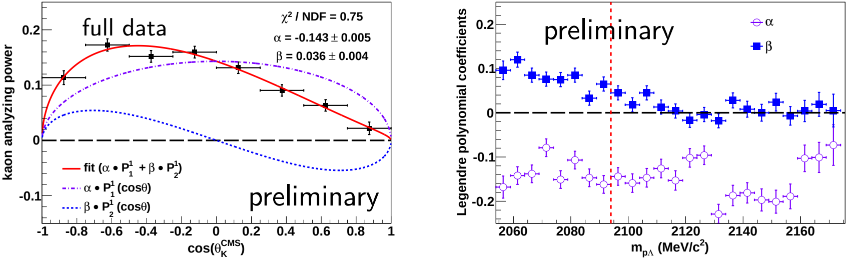
$$A_y^K(X, m_{p\Lambda}) \approx \alpha(m_{p\Lambda})P_1^1(X) + \beta(m_{p\Lambda})P_2^1(X)$$

- Kaon P-wave contribution proportional to $A_y^K(\cos\theta = 0) = -\alpha$
  $\rightarrow$ α gives relative contribution of spin triplet scattering
  $\rightarrow$ Measurement of α dependence on $m_{p\Lambda}$ to determine spin triplet scattering length using the formula

$$|A(FSI)_{\mathrm{t}}(m_{p\Lambda})|^2 = -\alpha(m_{p\Lambda}) \cdot \left|\tilde{A}(FSI)_{\mathrm{eff}}(m_{p\Lambda})\right|^2$$

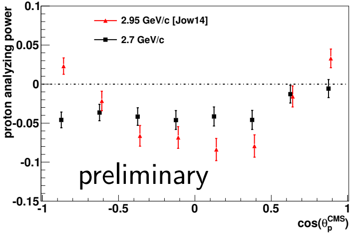
Kaon Analyzing Power at 2.7 GeV/c

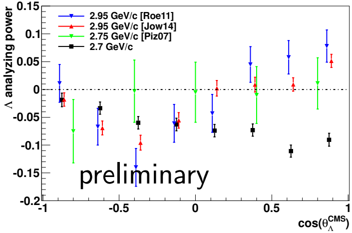
Fit with associated Legendre polynomials and dependence on $m_{p\Lambda}$

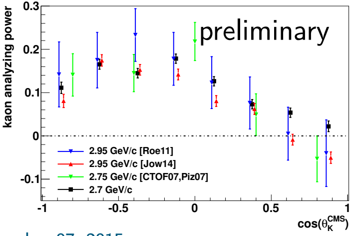


- Reasonable fit of analyzing power by $A_y^K = \alpha P_1^1 + \beta P_2^1$
- β decreases for higher $m_{p\Lambda}$ masses (expected due to lower kaon momentum)
- α non zero for low $m_{p\Lambda}$ mass $\rightarrow$ extraction of spin triplet scattering length possible $\rightarrow$ publication in preparation

Analyzing Power of Final State Particles

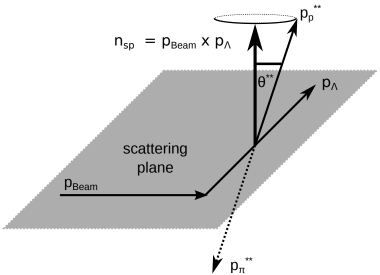






- Proton and kaon analyzing power: Same behavior for different momenta
- Λ analyzing power: for $\cos(\theta_\Lambda^{CMS} > 0)$ different behavior

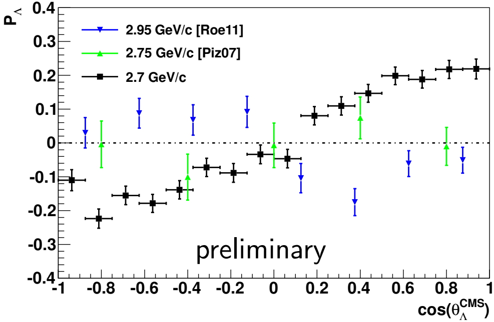
Λ Polarization
Determination Principle



- Λ polarization along n_{sp} axis
- Measurement via self analyzing Λ decay
- Distribution of decay protons: $I = I_0(1 + \alpha P_\Lambda \cos\theta^{**})$
- $\alpha = 0.642 \pm 0.013$ (weak asymmetry parameter)
- Determination by "weighted sum method" [D. Besset et al., Nucl. Instr. Meth. 166, 515 (1979)]

$$P_\Lambda = \frac{1}{\alpha} \frac{\sum_{i=0}^{N} \cos(\theta_i^{**})}{\sum_{i=0}^{N} \cos^2(\theta_i^{**})}$$

Results for the Λ Polarization



[Roe11]
M. Roeder, PhD Thesis, University Bochum, 2012

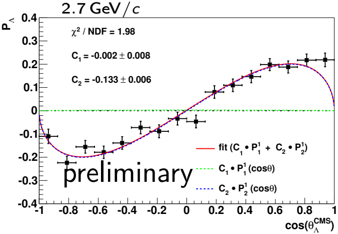
[Piz07]
C. Pizzolotto, PhD Thesis, University Erlangen, 2007

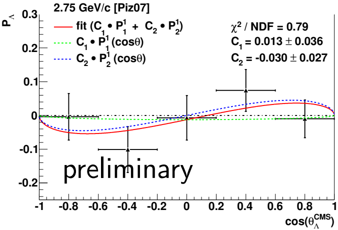
2.7 GeV/c
Hauenstein, PhD Thesis, University Erlangen, 2014

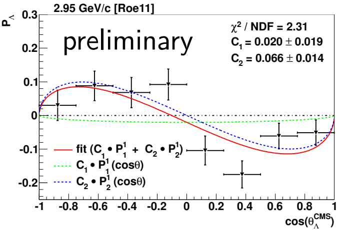
- Λ polarization changes sign
- Further study by fitting of associated Legendre polynomials to available COSY-TOF data

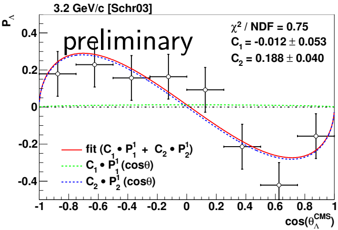
Λ Polarization

Associated Legendre Polynomials Fits



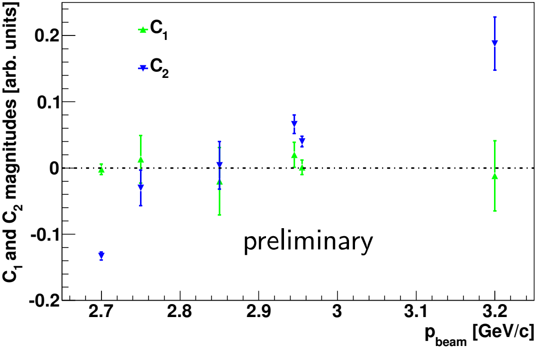






Λ Polarization

Associated Legendre Polynomials Contributions



- As expected C_1 compatible with zero for all beam momenta
- C_2 strong variation with beam momentum. Linear increase?
- No theoretical calculations available

Summary

- High statistics measurement with full phase space acceptance of the $\vec{p}p \rightarrow pK\Lambda$ reaction at 2.7 GeV/c and 2.95 GeV/c
- Dalitz plot
  - Strong $p\Lambda$ final state interaction
  - Strength of enhancement at $N\Sigma$ threshold (cusp effect) varies with beam momentum
- Scattering length at 2.7 GeV/c
  - $a_{\mathrm{eff}} = (-1.38^{+0.04}_{-0.05}{}_{\mathrm{stat.}} \pm 0.12_{\mathrm{syst.}} \pm 0.3_{\mathrm{theo.}})$ fm (preliminary)
  - Kaon analyzing power: α not vanishing for low $m_{p\Lambda}$ masses
  - First model independent determination of a_t possible
- Λ analyzing power
  - Deviation for different beam momenta for $\cos\theta_{\Lambda}^{\mathrm{CMS}} > 0$
- Λ polarization
  - Strong variation with beam momentum
  - Fit with Legendre polynomials $\rightarrow$ Solely described by P_2^1

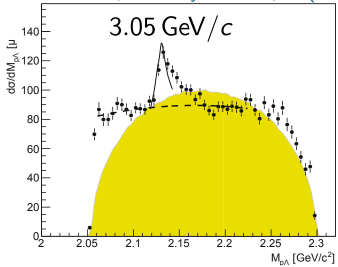
Outlook

- Detailed study of the $N\Sigma$ cusp effect at $2.95\,\mathrm{GeV}/c$
- Combined Partial Wave Analysis of $pp \to pK\Lambda$ at different beam momenta including data from DISTO and HADES/FOPI
- Publication of spin triplet scattering length a_t from $p\Lambda$ final state interaction (September - October)
- Publication of polarization observables (P_Λ, A_y, D_{NN})
  $\to$ Method paper submitted to NIM (arXiv:1508.04908)

Backup Slides

$p\Lambda - N\Sigma$ Cusp

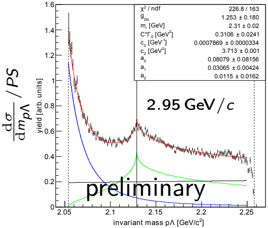
COSY-TOF Coll., Eur. Phys. J. A49, 41 (2013)



- Cusp described by Flatté distribution
- Angular distributions in cusp region point to S-wave in $K - p\Sigma$ and subsequent $\Lambda - p$

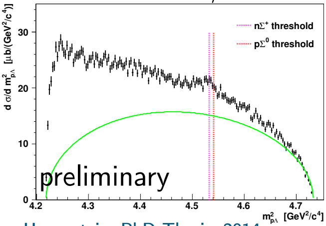
- In preparation: Study of cusp at 2.95 GeV/c
- Reasonable description of spectrum by FSI + cusp(Flatté) + N^* reflections
- Further theoretical description necessary

Jowzaee, EPJA, in preparation



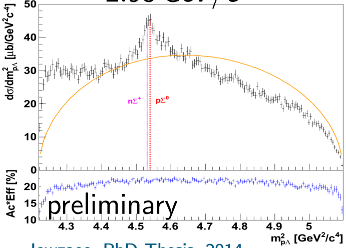
Dalitz Plot Projections on $m_{p\Lambda}$

2.7 GeV/*c*



Hauenstein, PhD Thesis, 2014

2.95 GeV/*c*



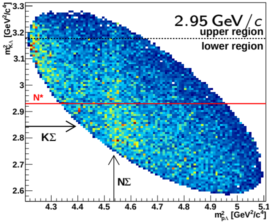
Jowzaee, PhD Thesis, 2014

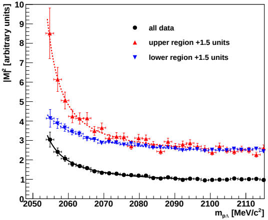
- Green: Scaled phase space distribution
- Small enhancement at $N\Sigma$ threshold

- Brown: Scaled phase space distribution
- Large enhancement at $N\Sigma$ threshold compared to 2.7 GeV/*c*

Effective $p\Lambda$ Scattering Length for $m_{K\Lambda}$ Regions

see M. Roeder et al., Eur. Phys. J. A49, 157 (2013)





- $a_{\text{eff}} = (-1.25 \pm 0.08_{\text{stat.}} \pm 0.3_{\text{theo.}})$ fm (full data)
- $a_{\text{eff}} = (-2.06 \pm 0.16_{\text{stat.}} \pm 0.3_{\text{theo.}})$ fm (upper region)
- $a_{\text{eff}} = (-0.86 \pm 0.06_{\text{stat.}} \pm 0.3_{\text{theo.}})$ fm (lower region)

- Strong influence of N^* resonances
- Error in the order of 1 fm

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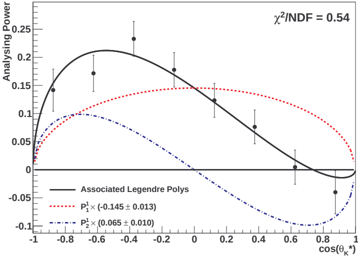
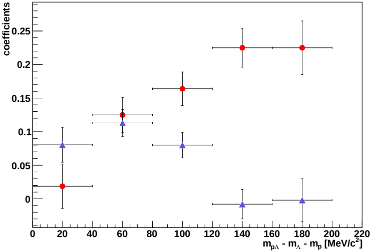
FORSCHUNGSZENTRUM

α Measurement at 2.95 GeV/c

see M. Roeder et al., Eur. Phys. J. A49, 157 (2013)



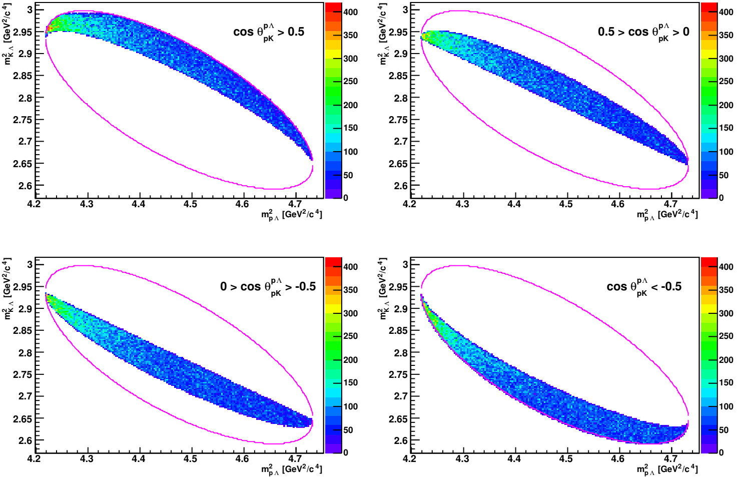


- Unexpected: α is $< 11\,\%$ (3σ) for low invariant mass $\rightarrow$ no sufficient precision for extraction of spin triplet $p\Lambda$ scattering length
- β behavior reasonable

$\rightarrow$ Work in progress: Analysis of additional measurement at 2.95 GeV/c to reduce statistical error

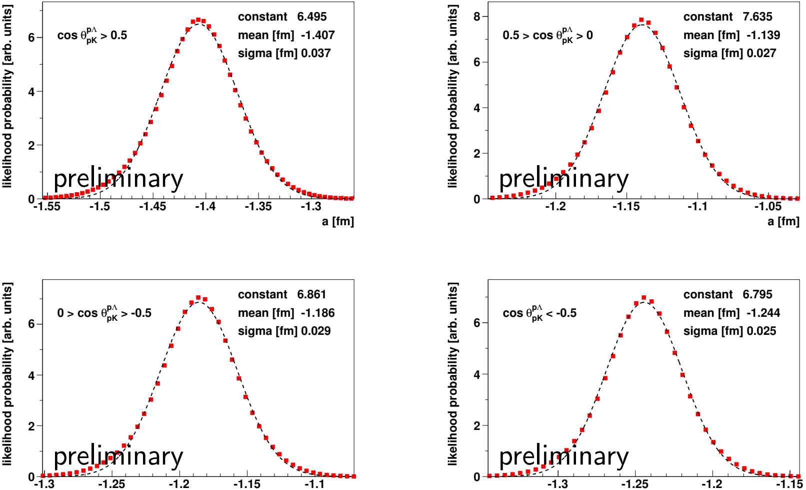
Results from the Measurement at 2.7 GeV/c

Dalitz Plot Slices

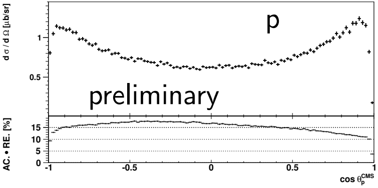


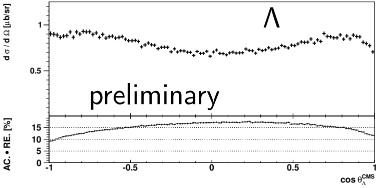
Effective $p\Lambda$ Scattering Length for Dalitz Plot Slices

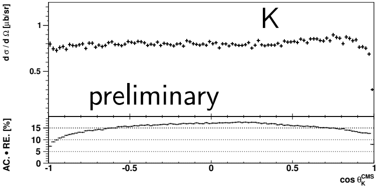
Likelihood Distributions



CMS Distributions for $2.7\,\mathrm{GeV}/c$







- Distributions almost symmetric
- Small deviations at boarders due to acceptance correction

Formulas for Scattering Length Extraction

- Parametrization of $p\Lambda$ invariant mass spectrum

$$\frac{\mathrm{d}\sigma}{\mathrm{d}m_{p\Lambda}} = PS \cdot |A_{\mathrm{FSI}}(m_{p\Lambda})|^2 = PS \cdot \exp\left[C_0 + \frac{C_1}{m_{p\Lambda}^2 - C_2}\right]. \quad (1)$$

- a dependence on C_1 and C_2

$$a_t(C_1, C_2) = -\frac{\hbar c}{2} C_1 \times \sqrt{\left(\frac{m_0^2}{m_p m_\Lambda}\right) \frac{(m_{\mathrm{max}}^2 - m_0^2)}{(m_{\mathrm{max}}^2 - C_2)(m_0^2 - C_2)^3}}$$

with $m_0 = m_p + m_\Lambda$ and $m_{\mathrm{max}} = m_0 + 40\,\mathrm{MeV}/c^2$

- Spin Triplet Amplitude

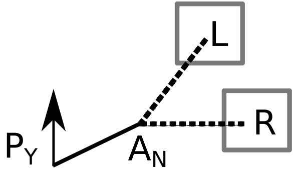
$$|A_{\mathrm{t}}(m_{p\Lambda})|^2 = -\alpha \cdot \left|\tilde{A}_{\mathrm{eff}}(m_{p\Lambda})\right|^2$$

Analyzing Power

Determination Principle

Angular distribution for particles with polarization P_Y:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{pol.}} = \left(\frac{d\sigma}{d\Omega}\right)_0 \cdot (1 + A_N P_N) = \left(\frac{d\sigma}{d\Omega}\right)_0 \cdot (1 + A_N P_Y \cos\phi)$$

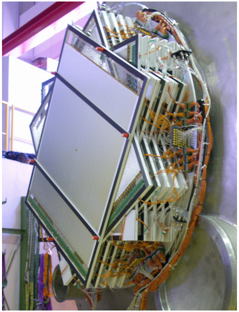


$$A_N(\cos\theta^{\mathrm{CMS}}) = \frac{\epsilon_{LR}(\cos\theta^{\mathrm{CMS}}, \phi)}{\cos(\phi)\cdot p_B}$$

- Azimuthal left-right asymmetry
  $$\epsilon_{LR}(\cos\theta^{\mathrm{CMS}}, \phi) = \frac{L(\theta_p^{\mathrm{CMS}},\phi) - R(\theta_p^{\mathrm{CMS}},\phi)}{L(\theta_p^{\mathrm{CMS}},\phi) + R(\theta_p^{\mathrm{CMS}},\phi)}$$
- Count rates
  $L(\theta_p^{\mathrm{CMS}}, \phi)) = \sqrt{N^+(\phi)\cdot N^-(\phi+\pi)}$ and
  $R(\theta_p^{\mathrm{CMS}}, \phi) = \sqrt{N^+(\phi+\pi)\cdot N^-(\phi)}$
- Beam polarization p_B

Experimental Setup

Straw Tube Tracker (STT)

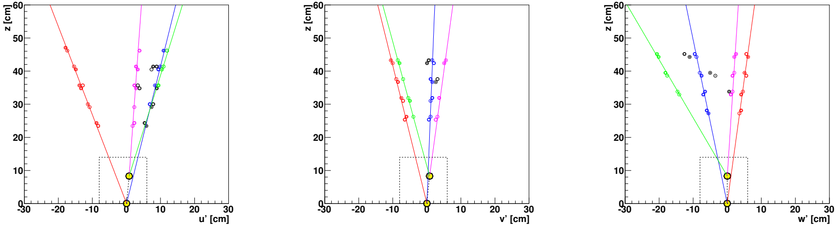


- 2704 straw tubes ($l = 1\,\mathrm{m}$, $d = 1\,\mathrm{cm}$) arranged in 13 double layers
- Every double layer is shifted by 60° angle to the other for 3D track reconstruction
- $\mathrm{Ar} : \mathrm{CO_2}$ gas mixture with ratio 8 : 2 at 1.2 bar overpressure
- Drift time information used for track to wire distance
- Obtained averaged spatial resolution $\sigma = (137 \pm 9)\,\mu\mathrm{m}$

Event Reconstruction

Steps for $pp \to pK\Lambda$ reconstruction

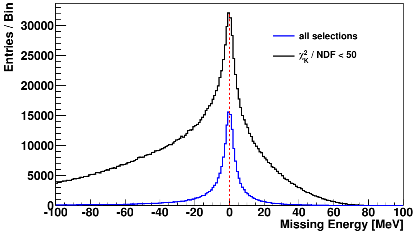
1. Track finding (Hough transformation) and fitting
2. Vertex finding and fitting
3. Geometric fit of $pp \to pK\Lambda$ event topology
4. Kinematic fit of $pp \to pK\Lambda$
   $\to$ Kinematically complete events
   $\to$ $p\Lambda$ mass resolution $\sigma = 1.1\,\mathrm{MeV}/c^2$



Event Selection

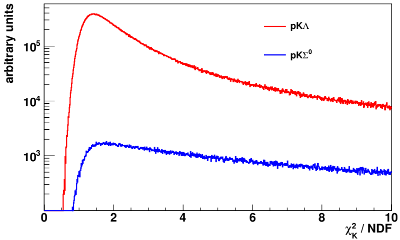
Selection criteria

- $\chi^2_{\mathrm{kin.fit}} < 5$
- Λ decay length $> 3\,\mathrm{cm}$
- $\measuredangle(\Lambda, \mathrm{decayproton}) > 2^\circ$



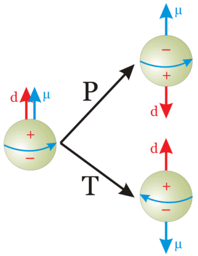
Monte Carlo simulations

- Low background from other reactions ($pp \to pK\Sigma^0 < 1\,\%$)
- Reconstruction efficiency $\sim 15\,\%$



Future of COSY

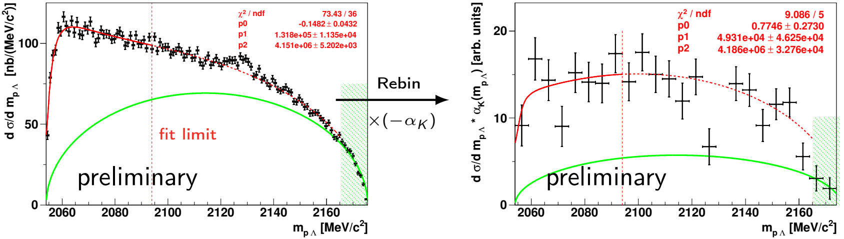
- Test facility for FAIR (Facility for Antiproton and Ion Research) at GSI in Darmstadt, Germany
  - Accelerator components → HESR at FAIR
  - Detector components → PANDA, CBM, ...
- Measurement of charged particle EDM (Electric Dipole Moment)



- EDMs are candidates to solve matter-antimatter asymmetry
- Measurement of proton and deuteron EDM with one dedicated ring → JEDI collaboration
- Precursor experiments with actual COSY ring

Spin Triplet Scattering Length a_t

Preliminary from Hauenstein, PhD Thesis, 2014



- Parametrization: $\frac{\mathrm{d}\sigma}{\mathrm{d}m_{p\Lambda}} = \mathit{Phasespace} \cdot \exp\left[p_0 + \frac{p_1}{m_{p\Lambda}^2 - p_2}\right]$
- $a_\mathrm{t} = (-1.31^{+0.32}_{-0.49}{}_\mathrm{stat.} \pm 0.3_\mathrm{theo.} \pm 0.16_\mathrm{syst.})\,\mathrm{fm}$ (very preliminary)
- First direct determination of a_t
- Comparison:
  - $a_\mathrm{t} = (-1.6^{+1.1}_{-0.8})\,\mathrm{fm}$ (Λp elastic scattering)
  - $a_\mathrm{t} = -1.54\,\mathrm{fm}$ (theoretical calculation [NPA 915, 24-58 (2013)])