Associated Strangeness Production in the $\vec{p}p \to pK^{+}\Lambda$ Reaction Measured by COSY-TOF

July 20, 2016 | Florian Hauenstein | Seminar at Jefferson Lab, Virginia, USA

Outline

- Introduction
- COSY-TOF Detector
- Data Analysis
- Results
  - Dalitz Plot
  - $p\Lambda$ Scattering Length
  - Λ Polarization
  - Spin Transfer Coefficient D_{NN}
- Summary and Outlook

Production and Decay of Λ-Hyperons

Production in $pp \to pK\Lambda$ or $\gamma p \to K\Lambda$

Strangeness is conserved in strong interaction

$\to$ Creation of an $s\bar{s}$ pair $\Rightarrow$ Production of Λ and Kaon

$\to$ Associate strangeness production

Λ-Decay

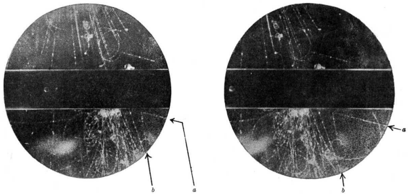


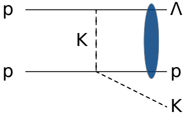
Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

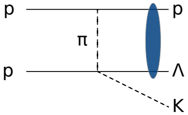
Decay: $\Lambda \to p\pi^-$

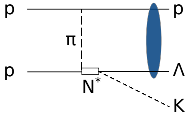
- Weak decay in $p\pi^-$ (64%) and $n\pi^0$ (36%)
- Life time $2.63 \cdot 10^{-10}\,\mathrm{s}$
- Separated decay and production vertex ($c\tau = 7.89\,\mathrm{cm}$)

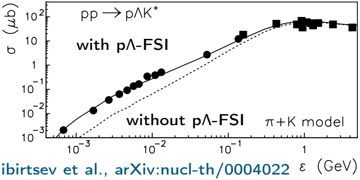
Physics of $\vec{p}p \to pK\Lambda$

- Investigation of production mechanism of associated strangeness close to threshold
  - Which kind of meson-exchange (no perturbative QCD)
  - Role of N^* resonances ($S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$)
  - Dalitz plot and polarization observables e.g. Λ polarization or spin transfer coefficient D_{NN}







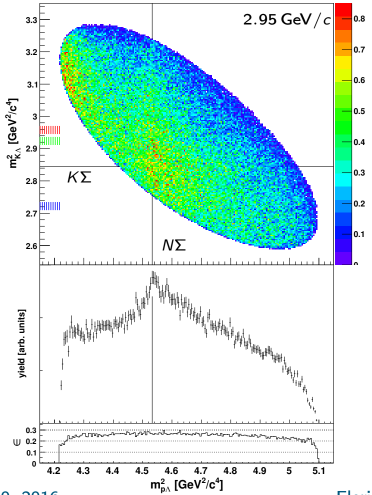


Sibirtsev et al., arXiv:nucl-th/0004022

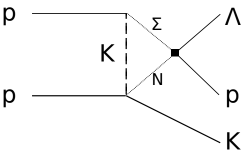
- $p\Lambda$ final state interaction (FSI)
  - Connection to $p\Lambda$ interaction
  - Extraction of parameter S-wave scattering length a

Dalitz Plot for $pp \to pK\Lambda$

see S. Jowzaee et al., Eur. Phys. J. A52, 7 (2016)

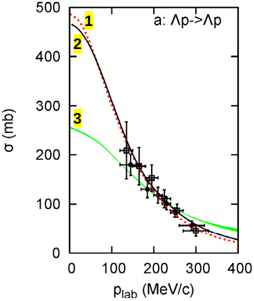


- Clear enhancement at low $m_{p\Lambda}$ masses from final state interaction
- Full phase space coverage
- $p\Lambda - N\Sigma$ coupled channel enhancement (cusp effect)



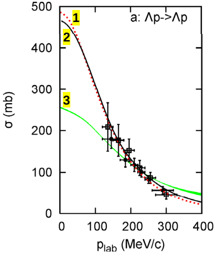
The $N\Lambda$ Interaction

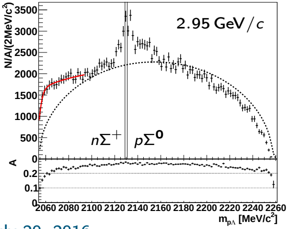
- Limits of SU(3) flavor symmetry in the correlation between $N\Lambda$ and NN interactions
- Poor data base on $p\Lambda$ elastic scattering (no data for pure spin singlet/triplet states as well as $n\Lambda$)
- No discrimination between different theoretical calculations



- Understanding of interaction important for
  - Hyperons in neutron stars
  - Hypernuclei (Nuclei with hyperons e.g. $^3\mathrm{H}_\Lambda$)
- Strength of the interaction is given by the scattering length *a*

Determination of $p\Lambda$ Scattering Length a





- Extraction from $p\Lambda \rightarrow p\Lambda$ scattering
  - Total cross section for $k = p/\hbar \rightarrow 0$ is

$$\lim_{k \to 0} \sigma_{\mathrm{tot}} = 4\pi a^2$$

  - S-wave scattering for $k \rightarrow 0$ ($l_{p\Lambda} = 0$)
  - Model dependent determination with effective range approximation

- Model independent extraction of scattering length from the shape of the $p\Lambda$-FSI for specific spin states

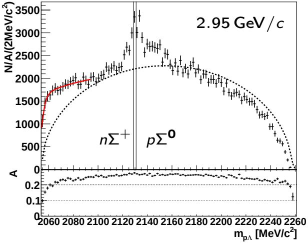
Gasparyan et al., Phys. Rev. C69, 034006 (2004)

  - Dispersion relation approach
  - Known theoretical precision (0.3 fm)

Determination of $p\Lambda$ Scattering Length

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

- Integral representation of a in terms of differential cross section
- Parametrization: $\frac{\mathrm{d}\sigma}{\mathrm{d}m_{p\Lambda}} = PS \cdot \exp\left[C_0 + \frac{C_1}{m_{p\Lambda}^2 - C_2}\right]$
- $a(C_1, C_2) = -\frac{1}{2} C_1 \sqrt{\left(\frac{m_0^2}{m_p m_\Lambda}\right) \cdot \frac{(m_{\max}^2 - m_0^2)}{(m_{\max}^2 - C_2)\cdot(m_0^2 - C_2)^3}}\,\hbar c$
- Spin resolved determination via suitable polarization observable



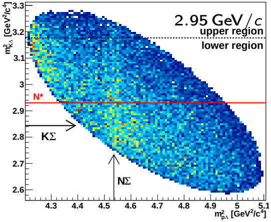
- COSY-TOF measurement at 2.95 GeV/c (42,000 events)

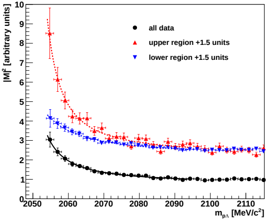
  M. Roeder et al., Eur. Phys. J. A49, 157 (2013)

- 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

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

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

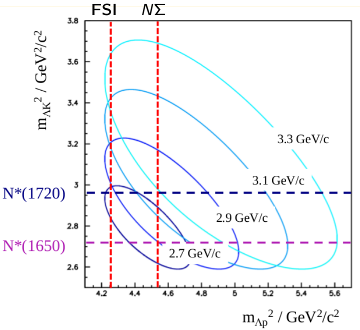


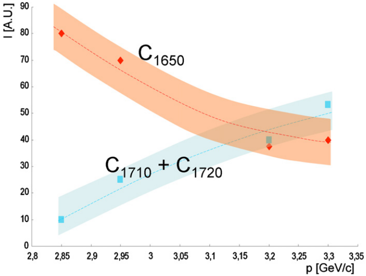


- $a_{\text{eff}} = (-1.25 \pm 0.08_{\text{stat.}} \pm 0.3_{\text{theo.}})$ fm (full data)
- $a_{\text{eff}} = (-2.06 \pm 0.16_{\text{stat.}} \pm 0.3_{\text{theo.}})$ fm (upper region)
- $a_{\text{eff}} = (-0.86 \pm 0.06_{\text{stat.}} \pm 0.3_{\text{theo.}})$ fm (lower region)

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

Dalitz Plot Dependence on Beam Momentum





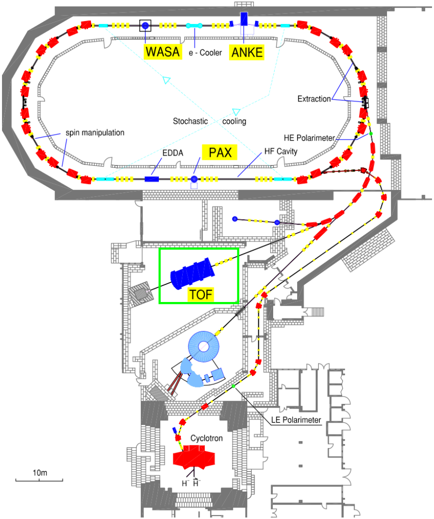
COSY-TOF Coll., Phys. Lett. B688, 142 (2010)

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

⇒ Comparison of results from the COSY-TOF measurements at 2.7 GeV/c and 2.95 GeV/c beam momentum

COSY Facility

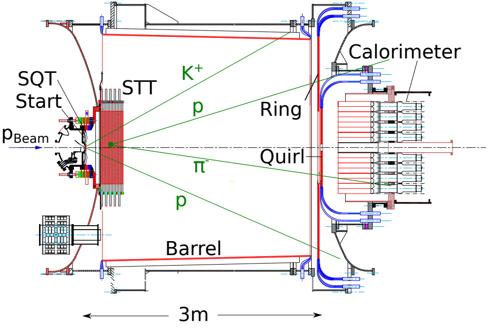
COoler SYnchroton



- 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 Detector

Time Of Flight



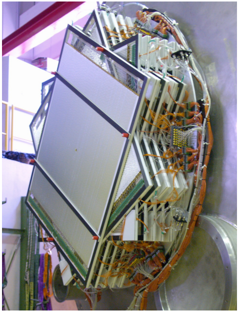
Features:

- 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 ($c\tau(\Lambda) = 7.89\,\text{cm}$)

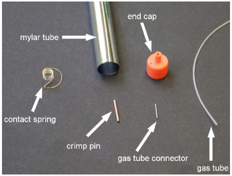
Measurements of $\vec{p}p \to pK\Lambda$:

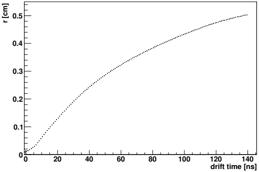
- $2.95\,\text{GeV}/c$ with $(61.0 \pm 1.7)\,\%$ polarization → 42,000 events
- $2.95\,\text{GeV}/c$ with $(87.5 \pm 2.0)\,\%$ polarization → 132,000 events
- $2.70\,\text{GeV}/c$ with $(77.9 \pm 1.2)\,\%$ polarization → 220,000 events

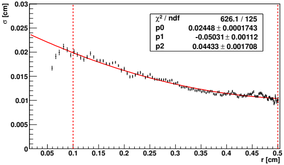
Straw-Tube-Tracker (STT)



- 2704 straw tubes ($l = 1\,\mathrm{m}$, $d = 1\,\mathrm{cm}$) arranged in 13 double layers
- $\mathrm{Ar} : \mathrm{CO}_2$ gas mixture with ratio 8 : 2 at 1.2 bar overpressure
- Drift time information used for track to wire distance
- Obtained averaged spatial resolution $\sigma = (137 \pm 9)\,\mu\mathrm{m}$



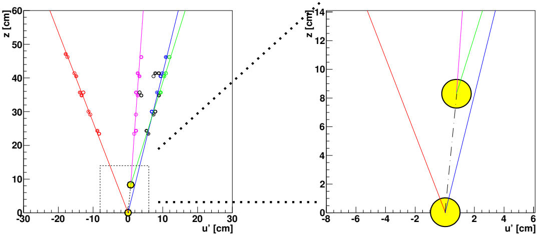


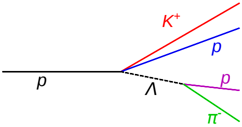


Event Reconstruction

Steps for $pp \rightarrow pK\Lambda$ reconstruction

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

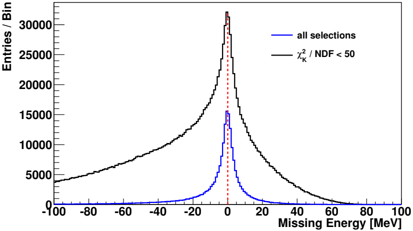




Event Selection at 2.7 GeV/c

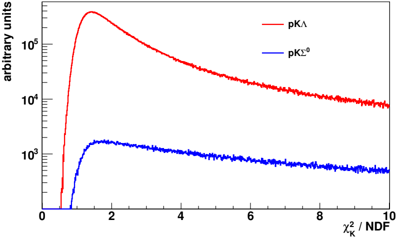
Selection criteria

- $\chi^2_{\mathrm{kin.fit}}/\mathrm{NDF} < 5$
- Λ decay length $> 3\,\mathrm{cm}$
- $\measuredangle(\Lambda, \mathrm{decayproton}) > 2^\circ$
- Similar for 2.95 GeV/c

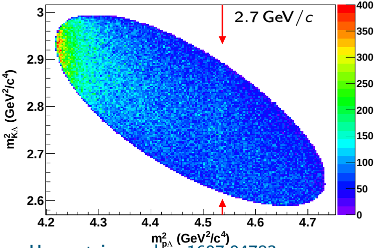


Monte Carlo simulations

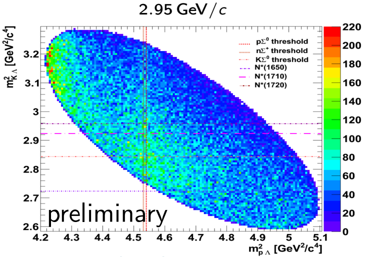
- Low background from other reactions ($pp \to pK\Sigma^0 < 1\,\%$)
- Reconstruction efficiency $\sim 15\,\%$ ($20\,\%$ for 2.95 GeV/c)



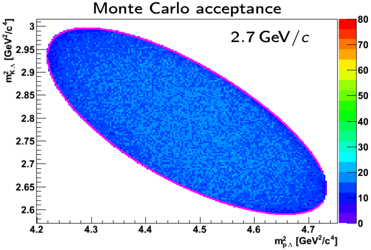
$\vec{p}p \to pK\Lambda$ Dalitz Plot



Hauenstein, nucl-ex:1607.04783



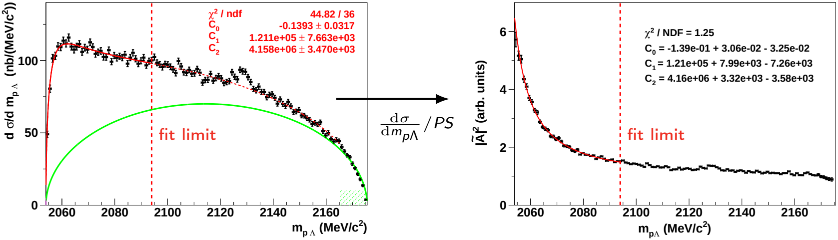
Jowzaee, PhD Thesis, 2014



- 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 at 2.7 GeV/c

Hauenstein et al., nucl-ex:1607.04783, submitted to PRL



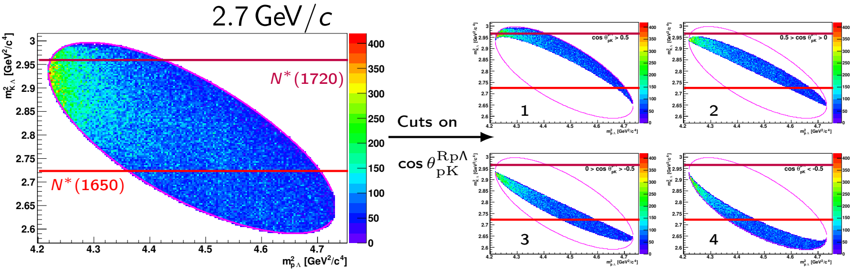
- Parametrization:

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

- $a_{\mathrm{eff}} = (-1.38^{+0.04}_{-0.05}{}_{\text{stat.}} \pm 0.22_{\text{syst.}} \pm 0.3_{\text{theo.}})$ fm
- 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)

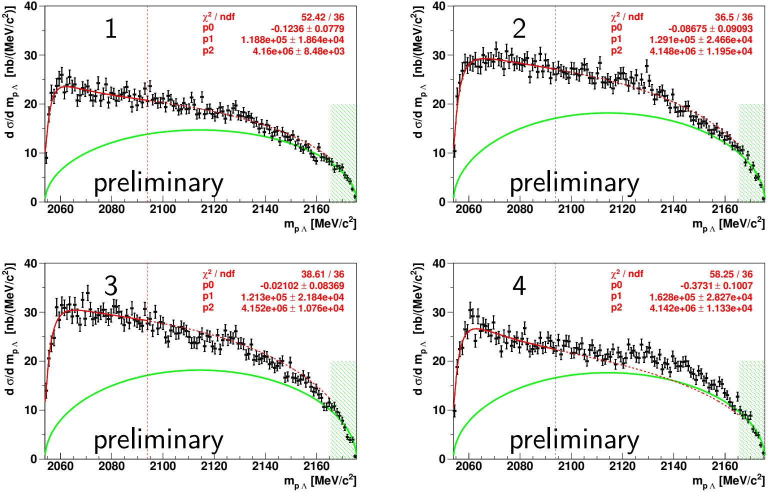
Systematic Error from N^* Resonances (1)

Dalitz plot slices



- Dalitz plot sliced by cuts on helicity angle ($\cos\theta^{\mathrm{Rp}\Lambda}_{\mathrm{pK}}$)
  → same $m_{p\Lambda}$ phase space acceptance but different N^* fraction
- Determination of effective scattering length for each slice
  → Access to systematic error from N^*s in the $K\Lambda$ channel

Systematic Error from N^* Resonances (2)



Systematic Error from N^* Resonances (3)

$\cos\theta_{pK}^{Rp\Lambda}$ range	a_{eff} [fm]
1) $\cos\theta_{pK}^{Rp\Lambda} > 0.5$	$-1.51^{+0.09}_{-0.10}$
2) $0 < \cos\theta_{pK}^{Rp\Lambda} < 0.5$	$-1.33^{+0.08}_{-0.08}$
3) $-0.5 < \cos\theta_{pK}^{Rp\Lambda} < 0$	$-1.43^{+0.08}_{-0.10}$
4) $\cos\theta_{pK}^{Rp\Lambda} < -0.5$	$-1.33^{+0.06}_{-0.07}$
full range	$-1.38^{+0.04}_{-0.05}$

- Systematic error from N^*s is about 0.1 fm
- Systematic error about factor ten weaker than for 2.95 GeV/c (1 fm)
- Assume similar error for spin triplet scattering length

Spin Triplet $p\Lambda$ Scattering Length

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

- $\{p\Lambda\}$ in S-wave $\Rightarrow$ $\{p\Lambda\}$ in spin triplet configuration only for odd kaon partial waves
- Kaon angular distribution flat → Use analyzing power A_y^K from kaon asymmetry
- A_y^K sensitive to interferences of kaon partial waves
- Expand in associated Legendre Polynomials $P_l^1(\cos\theta)$

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

- For $A_y^K(\cos\theta = 0) = -\alpha$ only spin triplet scattering contributes
- Determination of a_t from

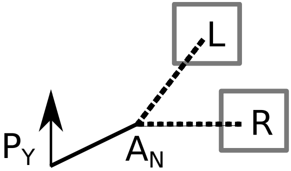
$$|\alpha(m_{p\Lambda})| \cdot \left|\tilde{A}(FSI)_{\mathrm{eff}}(m_{p\Lambda})\right|^2 = \exp\left[C_0 + \frac{C_1}{m_{p\Lambda}^2 - C_2}\right] = |b_1(m_{p\Lambda})|$$

Analyzing Power - Determination Principle

see also F. Hauenstein et al., Nucl. Inst. Meth. A817, 42 (2016)

Angular distribution with beam polarization P_Y:

$$I(\vartheta^*, \phi) = I_0(\vartheta^*) \cdot (1 + A_N(\vartheta^*) P_Y \cos\phi)$$



ϑ^*: cm scattering angle

ϕ: azimuthal angle

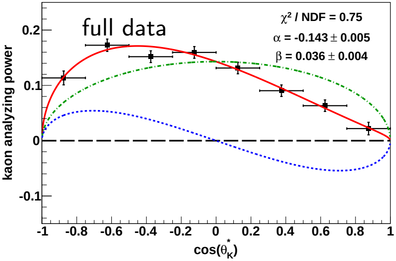
- Formula:

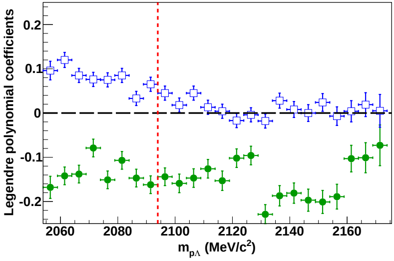
$$A_N(\vartheta^*) = \frac{2}{P_Y} \cdot \epsilon_A(\vartheta^*) = \frac{2}{P_Y} \cdot \frac{(N_L^{\uparrow}(\vartheta^*)+N_R^{\downarrow}(\vartheta^*))-(N_R^{\uparrow}(\vartheta^*)+N_L^{\downarrow}(\vartheta^*))}{N_L^{\uparrow}(\vartheta^*)+N_R^{\downarrow}(\vartheta^*)+(N_R^{\uparrow}(\vartheta^*)+N_L^{\downarrow}(\vartheta^*)}$$

- Beam polarization P_Y
- $N_{L,R}^{\uparrow\downarrow}$ countrates left or right with polarization directions

Analyzing Power at 2.7 GeV/c

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

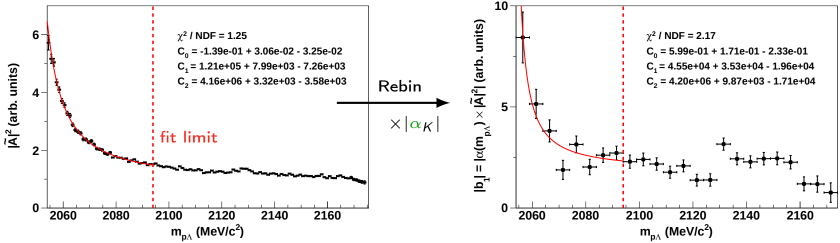




- Reasonable fit of analyzing power by $A_y^K = \alpha P_1^1 + \beta P_2^1$
- β decreases for higher $m_{p\Lambda}$ masses (expected due to lower kaon momentum)
- α non zero for low $m_{p\Lambda}$ mass $\rightarrow$ extraction of spin triplet scattering length possible

Spin Triplet Scattering Length a_t

Hauenstein et al., nucl-ex:1607.04783, submitted to PRL



- Fit limit and parametrization as for effective scattering length
- Value and statistical errors determined with bootstrapping
- $a_\mathrm{t} = (-2.55^{+0.72}_{-1.39}{}_{\mathrm{stat.}} \pm 0.6_{\mathrm{syst.}} \pm 0.3_{\mathrm{theo.}})\,\mathrm{fm}$
- First direct model-independent determination of a_t

Comparison with Theory and Other Measurements

	a_t(fm)	stat.(fm)	sys.(fm)	theo.(fm)
COSY-TOF	-2.55	$^{+0.72}_{-1.39}$	±0.6	±0.3
$pp \to K^+ + (\Lambda p)$ [1]	-1.56	$^{+0.19}_{-0.22}$		±0.4
$p\Lambda$ scattering [2]	-1.6	$^{+1.1}_{-0.8}$		
$K^- d \to \pi^- p\Lambda$ [3]	-2.0	±0.5		
χEFT NLO (500)	-1.61			
χEFT NLO (700)	-1.48			
Jülich 04 model	-1.66			
Nijmegen NSC97f	-1.75			

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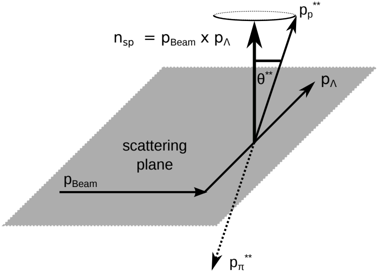
[1] Combined fit of inclusive data and elastic data with constraint from $K^- d \to \pi^- p\Lambda$; Budzanowski et al., Phys. Lett. B687, 31 (2010)

[2] Alexander et al., Phys. Rev. 173, 1452 (1968)

[3] Tan, Phys. Rev. Lett. 23, 395 (1969)

Λ Polarization - Determination Principle

see also F. Hauenstein et al., Nucl. Inst. Meth. A817, 42 (2016)

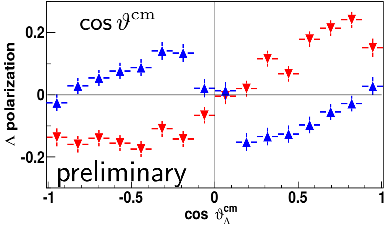


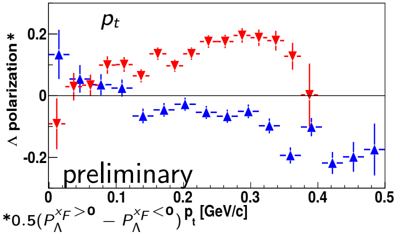
- Λ polarization along $\vec{n}_{\text{sp}}$ axis
- Measurement via self analyzing Λ decay
- Distribution of decay protons: $I = I_0\,(1 + \alpha P_\Lambda \cos\theta^{**})$
- $\alpha = 0.642 \pm 0.013$ (weak asymmetry parameter)
- $A =$ same hemisphere $\vec{n}_{\text{sp}}$
- $B =$ opposite hemisphere $\vec{n}_{\text{sp}}$

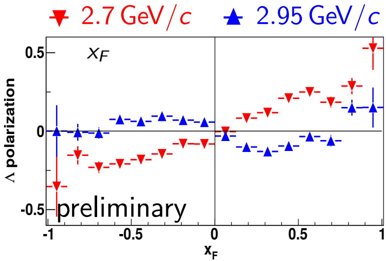
$$P_\Lambda = \frac{2}{\alpha}\frac{N^A - N^B}{N^A + N^B}$$

Member of the Helmholtz-Association

Results for the Λ Polarization



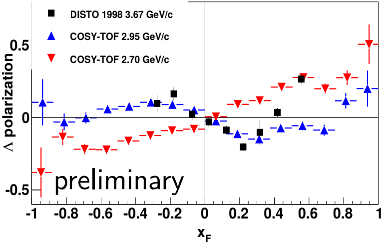


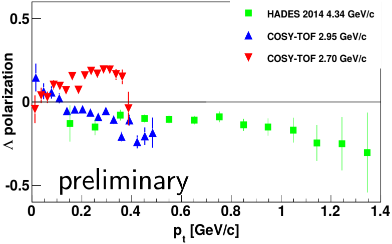


- Expected point symmetry at $\cos\vartheta^* = 0$ and $x_F = 0$
- Λ polarization changes sign
- No explanation available

Λ Polarization Comparison

Similar Energy Regime



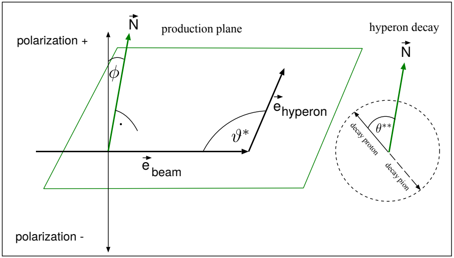


- DISTO ($pp \to pK\Lambda$, Nucl. Phys. A639, 1 (1998)) and HADES ($p + Nb \to \Lambda X$, Eur. Phys. J. A50, 81 (2014)) cover large part of the phase space
- Compatible results with the COSY-TOF data at 2.95 GeV/c
- Λ polarization probably independent of target material

Λ Spin Transfer Coefficient D_{NN}

see also F. Hauenstein et al., Nucl. Inst. Meth. A817, 42 (2016)

$$I = I_0 \cdot (1 + A_N P_B \cos\phi + \alpha P_\Lambda \cos\theta^{**} + D_{NN} \alpha P_B \cos\phi \cos\theta^{**})$$

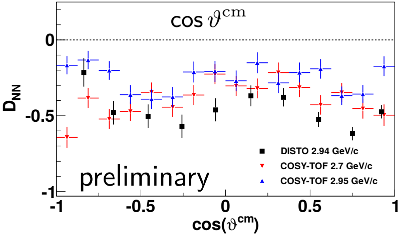


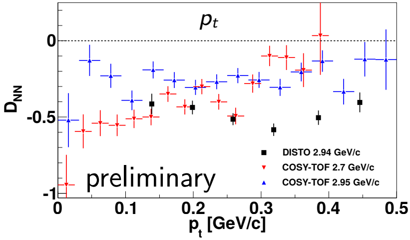
$$D_{NN} = \frac{4}{\alpha P_B} \cdot \epsilon_D$$

$$\epsilon_D = \frac{N_{\text{same}} - N_{\text{op}}}{N_{\text{same}} + N_{\text{op}}}$$

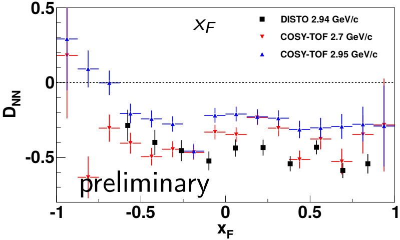
- 8 countrates depending on beam spin (↑↓), ϕ angle (LR) and hemisphere in Λ decay (AB)
- $N_{\text{same}} = N_L^{A\uparrow} + N_R^{B\uparrow} + N_R^{A\downarrow} + N_L^{B\downarrow}$ (P_Λ & P_B same direction)
- $N_{\text{op}} = N_L^{A\downarrow} + N_R^{B\downarrow} + N_R^{A\uparrow} + N_L^{B\uparrow}$ (P_Λ & P_B opposite direction)

Results for D_{NN}





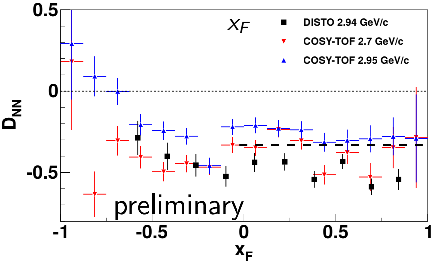
DISTO, Nucl. Phys. A691, 329c (2001)

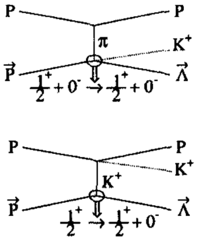


- Both data sets similar behavior
- Results compatible with DISTO

D_{NN} Theoretical Explanation

see also M. Maggiora, Nucl. Phys. A691, 329 (2001)





- $x_F \rightarrow -1$: Λ from unpolarized target proton → $D_{NN} = 0$
- $x_F \rightarrow 1$: Λ stems from polarized beam proton
- Pion exchange → no spin-flip at Λ-vertex → $D_{NN} = +1$
- Kaon exchange → spin-flip at Λ-vertex → $D_{NN} = -1$
- Data exhibits combination of both exchanges
- Missing contributions from vector mesons like K^*?

Summary

- High resolution 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
- Determination of $p\Lambda$ scattering length from $p\Lambda$-FSI at 2.7 GeV/c (Hauenstein et al., nucl-ex:1607.04783)
  - Compatible result for effective $p\Lambda$ scattering length with previous TOF result at 2.95 GeV/c
  - Systematic error from N^* resonances factor ten weaker
  - First direct measurement of spin triplet $p\Lambda$ scattering length $\rightarrow a_{\mathrm{t}} = (-2.55^{+0.72}_{-1.39}{}_{\mathrm{stat.}} \pm 0.6_{\mathrm{syst.}} \pm 0.3_{\mathrm{theo.}})$ fm
- Λ polarization
  - Changes sign from 2.7 GeV/c to 2.95 GeV/c
  - Results at 2.95 GeV/c compatible to DISTO and HADES results
- Spin transfer coefficient D_{NN}
  - Results for both momenta similar and compatible with DISTO
  - Combination of kaon and pion exchange in the production?

Outlook

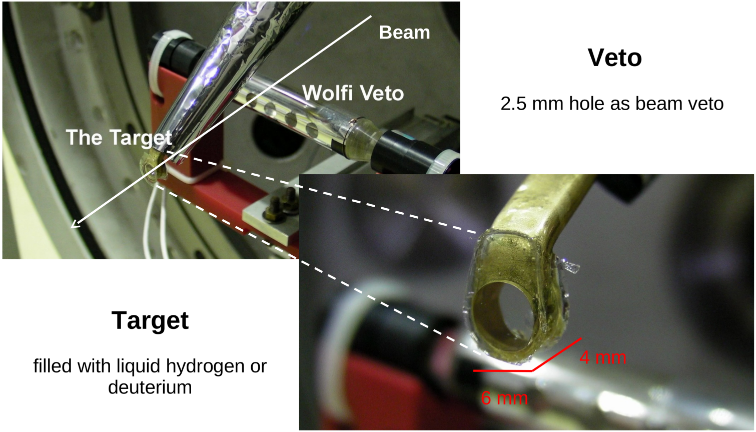
- Partial wave analysis of the data under way
- Need: Theoretical description for the behavior of the Λ polarization
- Publishing of the results for the polarization observables soon

Backup Slides

Overview of Considered Systematic Errors

Error	a_{eff}	a_t
Fit limit	negligible	negligible
Wrong beam polarization	negligible	negligible
Improper acceptance correction	0.2 fm	0.2 fm
Influence of N^*s	0.1 fm	0.1 fm
Binning of $m_{p\Lambda}$	0.02 fm	0.56 fm
Total	0.22 fm	0.6 fm

COSY-TOF Target



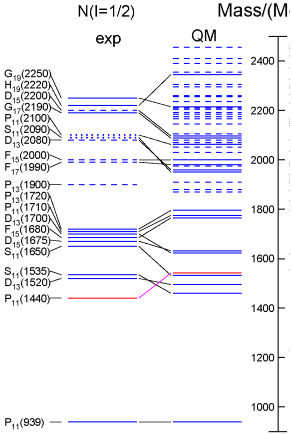
Veto

2.5 mm hole as beam veto

Target

filled with liquid hydrogen or deuterium

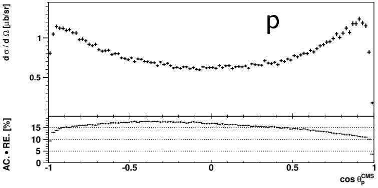
N^* Resonances

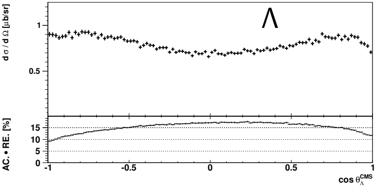


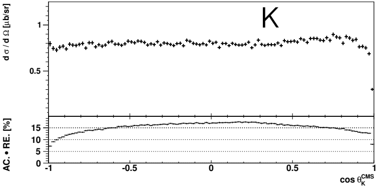
coupling of N^* to hyperons little known

Baryon	Status	Mass	Width	ΛK	ΣK
S_{11}	****	1645-1670	145-185	3-11	?
D_{15}	****	1670-1680	130-165	<1	?
F_{15}	****	1680-1690	120-140	?	?
D_{13}	***	1650-1750	50-150	<3	?
P_{11}	***	1680-1740	50-250	5-25	?
P_{13}	****	1700-1750	150-300	1-15	?
P_{33}	***	1550-1700	250-450	-	?
D_{33}	****	1670-1750	200-400	-	?

CMS Distributions for 2.7 GeV/c



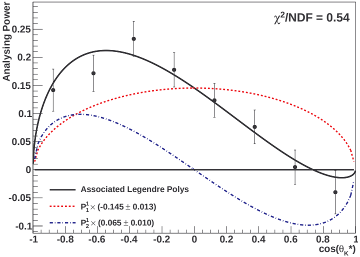


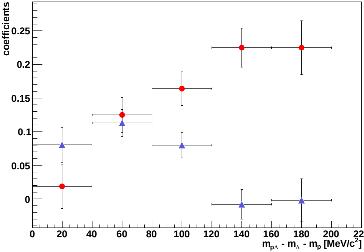


- Distributions almost symmetric
- Small deviations at boarders due to acceptance correction

Measurement of α at 2.95 GeV/c

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

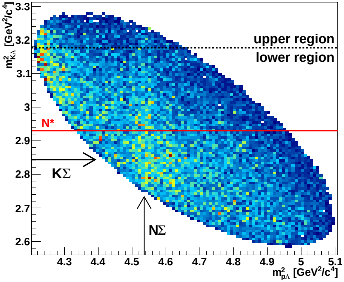


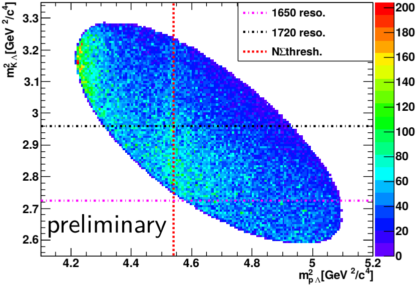


- Unexpected: α is $< 11\,\%$ (3σ) for low invariant mass → no sufficient precision for extraction of spin triplet $p\Lambda$ scattering length
- β behavior reasonable (high $p\Lambda$ mass → low momentum kaons)

→ Additional measurement at 2.95 GeV/c to reduce statistical error

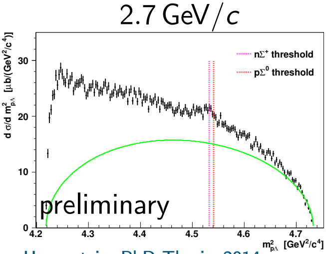
Dalitz Plot for Measurements at 2.95 GeV/c



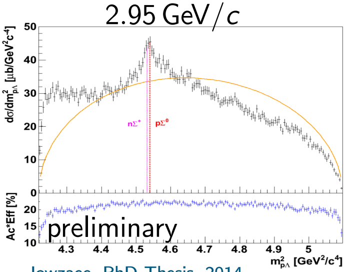


- Left: Published in M. Roeder et al., Eur. Phys. J. A49, 157 (2013)
- Right (preliminary): S. Jowzaee, PhD Thesis, Jagiellonian University Crakow (2014)
- Enhancement at $p\Lambda$-FSI and $N\Sigma$ threshold (cusp effect)

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



Hauenstein, PhD Thesis, 2014



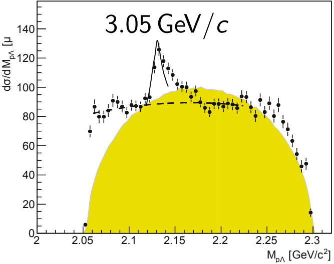
Jowzaee, PhD Thesis, 2014

- 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

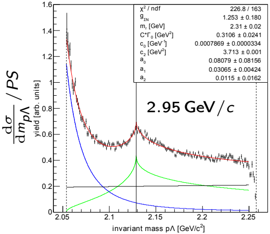
$p\Lambda - N\Sigma$ Cusp

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 $\Lambda - p$

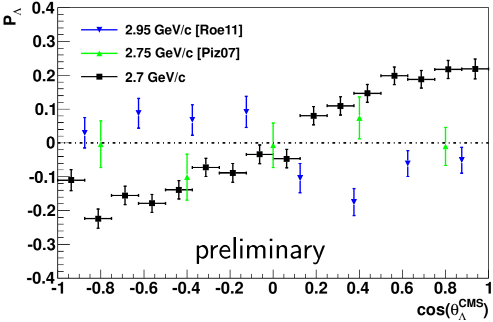
- Study of cusp at 2.95 GeV/c (Jowzaee et al., EPJA 52, 7 (2016))
- Reasonable description of spectrum by FSI + cusp(Flatté) + N^* reflections
- Further theoretical description necessary



Self Analyzing Λ Decay

- Quantum numbers of particles in the decay $\Lambda \rightarrow p\pi^-$ $J^P(\Lambda) = \frac{1}{2}^+$, $J^P(p) = \frac{1}{2}^+$ and $J^{\pi^-}(\Lambda) = 0^- \rightarrow \Delta I = 0, 1 \rightarrow$ S-wave or P-wave in the decay system
- Decay proton distribution $I = I_0(1 + \alpha P_\Lambda \cos(\theta_p^{**}))$
- Asymmetry parameter $\alpha = \frac{2\Re(a_s^* a_p)}{|a_s|^2 + |a_p|^2}$
- a_s and a_p S-wave and P-wave amplitudes
- If parity conservation holds in decay no S-wave possible $\rightarrow a_s = 0 \rightarrow \alpha = 0 \rightarrow$ no measurement of P_Λ
- Parity violation in weak decay $\rightarrow \alpha \neq 0$

Results for the Λ Polarization



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

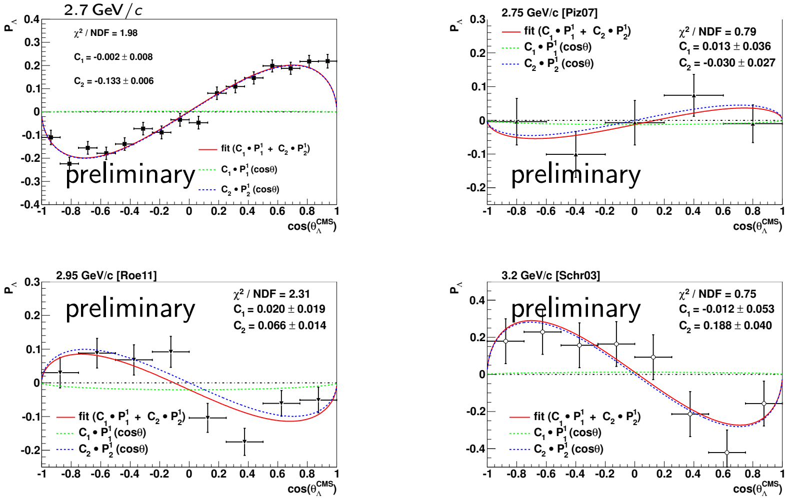
[Piz07]
C. Pizzolotto, PhD Thesis,
University Erlangen, 2007

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

- Λ polarization changes sign
- Expected point symmetry at $\cos\vartheta^* = 0$
- Further study by fitting of associated Legendre polynomials

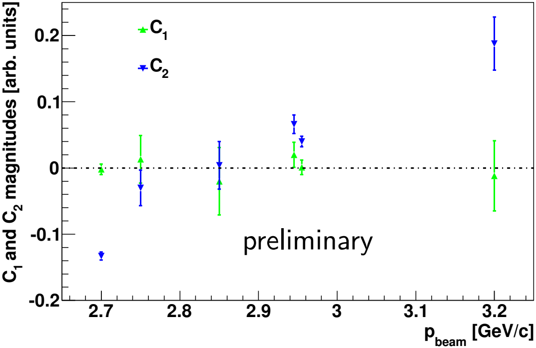
Λ Polarization

Associated Legendre Polynomials Fits



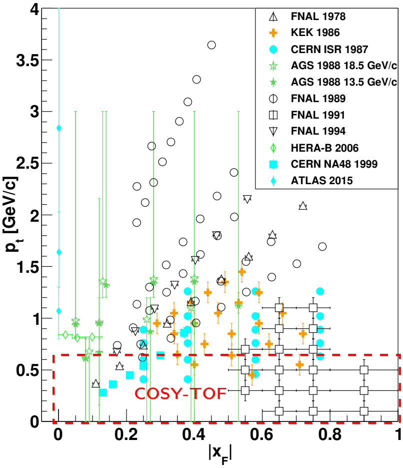
Λ Polarization

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

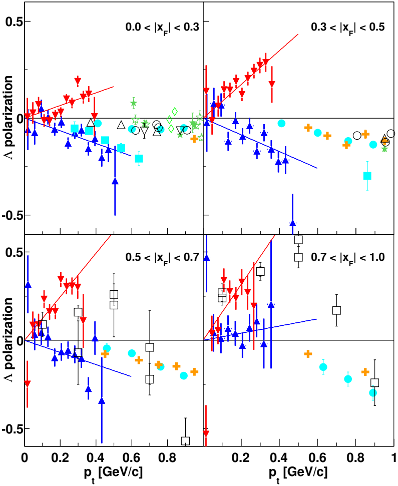
Λ Polarization High Energy Data Sets



- Measurements with very limited kinematic regions
- Different target materials
- Reactions from inclusive to exclusive Λ production

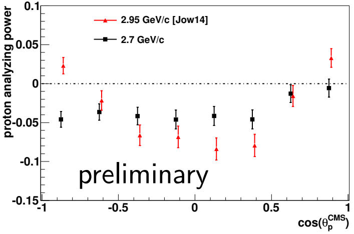
Λ Polarization Comparison High Energy Data

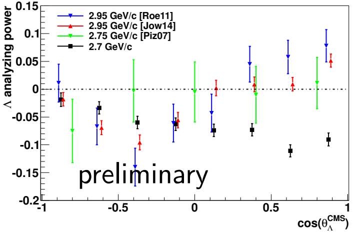
Limited x_f Regions

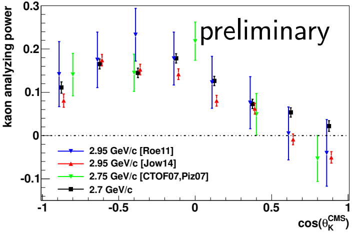


- Most data exhibit different behavior
- Common Feature: Linear increase of the polarization with p_t
- Increase of polarization with higher x_F

Analyzing Power of Final State Particles

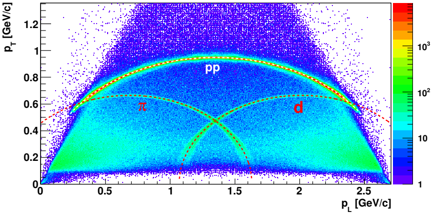


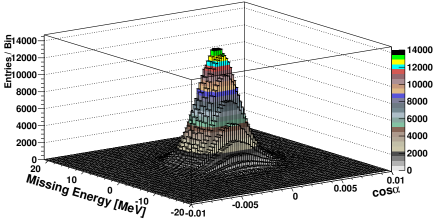


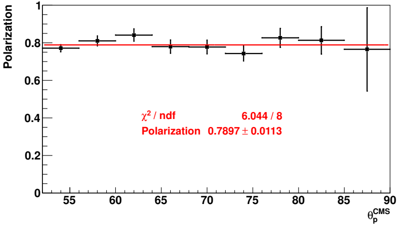


- Proton and kaon analyzing power: Similar behavior for different momenta
- Λ analyzing power: for $\cos(\theta_\Lambda^{CMS} > 0)$ different behavior

pp Elastics Event Selection and Beam Polarization Determination

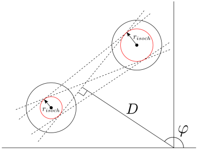


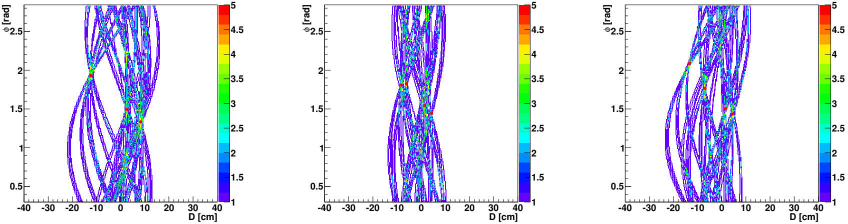


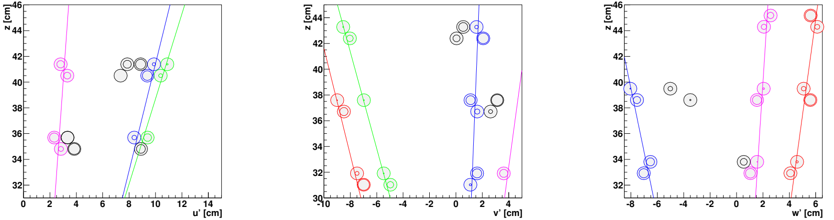


- Selection of elastics with circular cut on missing energy and coplanarity ($\cos\alpha$)
- Determination of polarization in bins of θ_p^{CMS} using analyzing power from SAID

Track Reconstruction with Hough Transformation





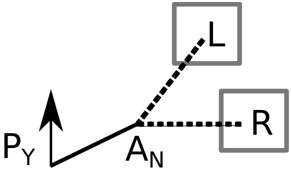


Analyzing Power - Determination Principle

see also F. Hauenstein et al., Nucl. Inst. Meth. A817, 42 (2016)

Angular distribution with beam polarization P_B:

$$I(\vartheta^*,\phi) = I_0(\vartheta^*)\cdot(1 + A_N(\vartheta^*)P_B\cos\phi)$$



ϑ^*: cm scattering angle
ϕ: Angle between polarization direction (Y) and normal on production plane (N)

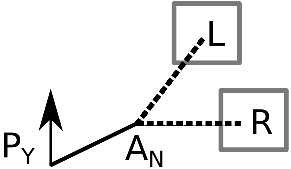
- Formula:
  $$A_N(\vartheta^*) = \frac{2}{P_B}\cdot\epsilon_A(\vartheta^*) = \frac{2}{P_B}\cdot\frac{(N_L^{\uparrow}(\vartheta^*)+N_R^{\downarrow}(\vartheta^*))-(N_R^{\uparrow}(\vartheta^*)+N_L^{\downarrow}(\vartheta^*))}{N_L^{\uparrow}(\vartheta^*)+N_R^{\downarrow}(\vartheta^*)+(N_R^{\uparrow}(\vartheta^*)+N_L^{\downarrow}(\vartheta^*)}$$
- Beam polarization P_B
- $N^{\uparrow\downarrow}_{L,R}$ countrates left or right with polarization directions

Analyzing Power

Determination Principle

Angular distribution for particles with polarization P_Y:

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



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

- 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_Y