Reconstructing Hyperons with the $\overline{\text{P}}$ANDA Detector at FAIR

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on behalf of the $\overline{\text{P}}$ANDA collaboration

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Motivation

What is special about strangeness production?

- Light quark (u, d) production
  - Highly non-perturbative
  - Hadrons as relevant degrees of freedom
- Strangeness production
  - Scale: $m_s \approx 100\text{MeV} \sim \Lambda_{\text{QCD}} \approx 200\text{MeV}$
  - Relevant degrees of freedom unclear
- Heavier quark (c, b) production
  - Quarks and gluons relevant
  - Perturbative QCD applicable

Hyperon production $\bar{p}p \to \bar{Y}Y$

Models based on the quark-gluon picture[1] and on the hadron picture[2].

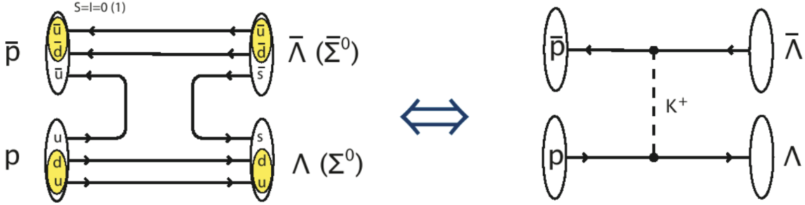


Figure: $\bar{p}p \to \bar{\Lambda}\Lambda$ in quark-gluon picture (left) and in Hadron picture (right).

Different models give different predictions of e.g.

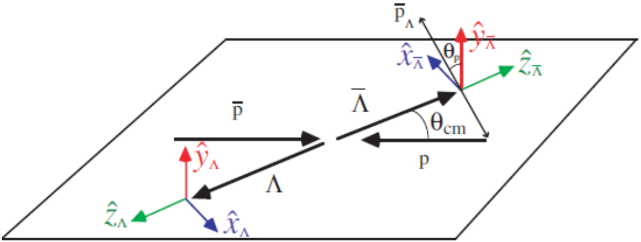
- angular distributions
- the correlation of the spin of the antihyperon-hyperon

[1] PLB 179 (1986); PLB 165 (1985) 187; NPA 468 (1985) 669

[2] PRC 31 (1985) 1857; PLB 179 (1986); PLB 214 (1988) 317

Hyperons: Spin observables in $\bar{p}p \to \bar{Y}Y$

Spin observables can be used to test theoretical models



Polarisation in $\bar{p}p \to \bar{Y}Y$

- 3 polarisations for spin-$\frac{1}{2}$ hyperons: P_x, P_y, P_z
- $P_x = P_z = 0$ due to strong production
- $P_y = P_{\bar{y}}$ due to rotational invariance

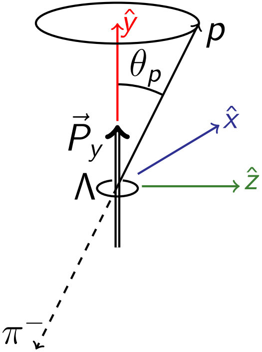
Hyperons: Spin observables in $\bar{p}p \to \bar{Y}Y$

The $\Lambda \to p\pi^-$ decay

- Ground state hyperons decay via the weak interaction
- Parity violating decay $\to$ asymmetry in angular distributions

$$I(\theta_p) = \frac{1}{4\pi}(1 + \alpha P_y \cos\theta_p)$$

$\alpha = 0.64$ - decay asymmetry parameter



Hyperons: Existing data on $\bar{p}p \to \bar{Y}Y$

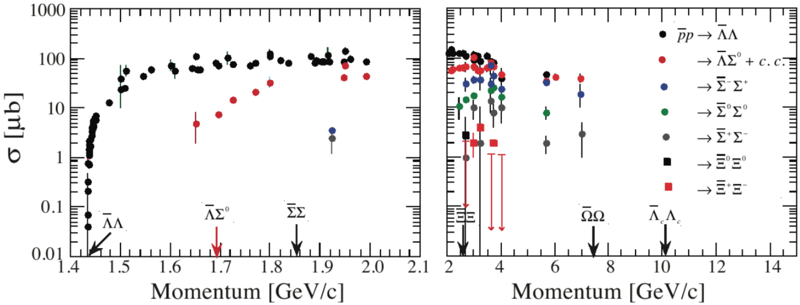


Figure: Cross section of $\bar{p}p \to \bar{Y}Y$ reactions

- Most data on $\bar{p}p \to \bar{\Lambda}\Lambda$ from PS185 @ LEAR
- Few data on multistrange production
- Only bubble chamber measurement of $(\bar{\Xi}\Xi)$
- No data on $\bar{\Omega}\Omega$ or $\bar{\Lambda}_c\Lambda_c$

Hyperons: Existing data on $\overline{p}p \rightarrow \overline{Y}Y$

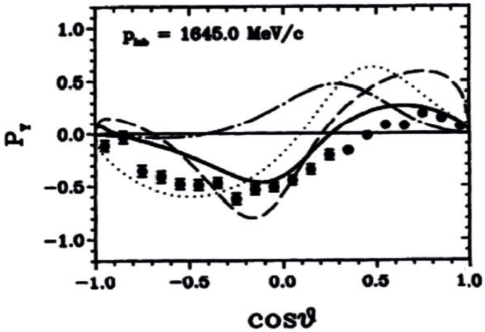
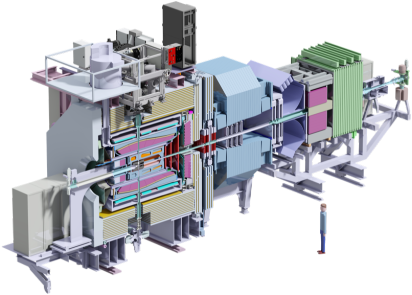


Figure: Polarisation P_y prediction from quark-gluon (dotted) and hadron exchange picture (solid and dashed)

Neither models describe the data perfectly[3]

[3] Figure from Phys. Rep. 368 (2002) 119.

$\overline{\text{P}}$ANDA - antiProton ANnihilation at DArmstadt



- Target- and forward spectrometer provide a near 4π coverage
- $\overline{p}$ beam momentum of 1.5 - 15 GeV/c
- Unpolarized beam and target
- High resolution measurement and PID
- HESR day-1 luminosity $\mathcal{L} \sim 10^{31}\text{cm}^{-2}\text{s}^{-1}$

Accessible hyperons at $\overline{\text{P}}$ANDA

Efficiencies simulated using a simplified MC framework[4][5]

- Cross section of $\bar{p}p \to \bar{\Lambda}\Lambda, \bar{\Lambda}\Sigma^0$ known near threshold
- Only theoretical prediction of $\bar{\Omega}\Omega$ and $\bar{\Lambda}_c\Lambda_c$ cross sections

Momentum (GeV/c)	Reaction	σ (μb)	Efficiency (%)	Rate at $10^{31}\text{cm}^{-2}\text{s}^{-1}$
1.64	$\bar{p}p \to \bar{\Lambda}\Lambda$	64	11	29s^{-1}
4	$\bar{p}p \to \bar{\Lambda}\Sigma^0$	~ 40	31	30s^{-1}
4	$\bar{p}p \to \bar{\Xi}^+\Xi^-$	≈ 2	≈ 20	1.5s^{-1}
12	$\bar{p}p \to \bar{\Omega}^+\Omega^-$	≈ 0.002	≈ 30	$\approx 4\text{h}^{-1}$
12	$\bar{p}p \to \bar{\Lambda}_c^-\Lambda_c^+$	≈ 0.1	≈ 35	$\approx 2\text{day}^{-1}$

[4] Sophie Grape, Ph. D. Thesis, Uppsala University 2009

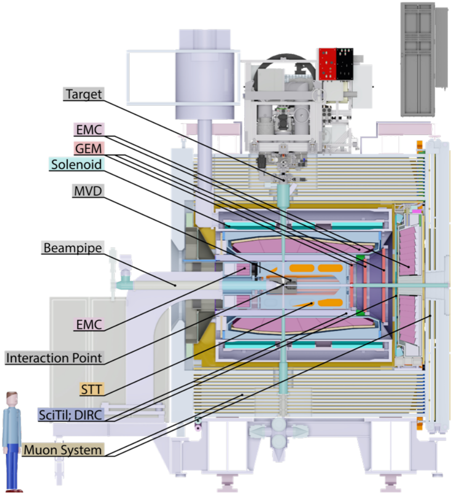
[5] Erik Thomé, Ph. D. Thesis, Uppsala University 2012

$\overline{\text{P}}$ANDA target spectrometer

Detect particles with $\theta \geq 10°$,
$0 \leq \phi < 360°$

Charged track reconstruction

- Micro Vertex Detector (MVD)
- Straw Tube Tracker (STT)
- Gas Electron Multiplier (GEM)



$\overline{\text{P}}$ANDA target spectrometer tracking scheme

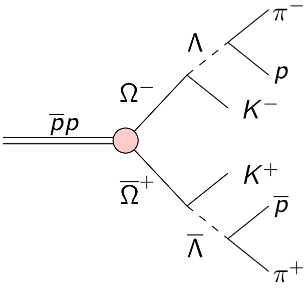
- Clusterization
  - Bunch correlated hits
  - Extrapolate to different detectors
- Initial guess of trajectory
  - No energy loss
  - Solenoid $\vec{B}$-field in beam direction

  $\rightarrow$ Helix trajectory.
- Kalman filter
  - Inhomogeneity in $\vec{B}$-field
  - Energy loss
  - Detector material

  $\rightarrow$ Realistic trajectory.

$\overline{\text{P}}$ANDA target spectrometer tracking scheme

- Different requirements:
  - Detectors/detector groups
  - Topologies
  - Online/offline
- Dedicated pattern recognition and tracking algorithms for $\overline{\text{P}}$ANDA under development



Hyperon decay characteristics

! Ground state hyperons decay weakly $\rightarrow$ displaced vertices

! Many hyperons decay to Λ

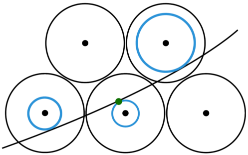
- $\bar{p}p \rightarrow \overline{\Omega}\Omega$: In $\sim 30\%$ of events, ≥ 1 tracks only leave hits in STT

The $\overline{\text{P}}$ANDA Straw Tube Tracker

STT specifications	
Total straws	4636
Axial layers	15-19
Stereo layers	8
Stereo angle	$\pm$ 2.9 deg

Isochrone radius

Radial distance from track to wire



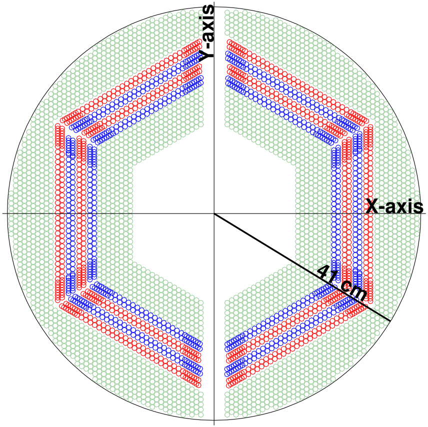


Figure: Cross sectional view of STT
Green - parallel straw
Red, blue - skewed straw

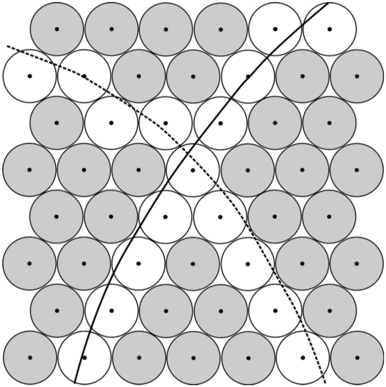
Tracking algorithm dedicated for STT

Track reconstruction algorithm using only STT.
(J. Schumann, Forschungszentrum Jülich)

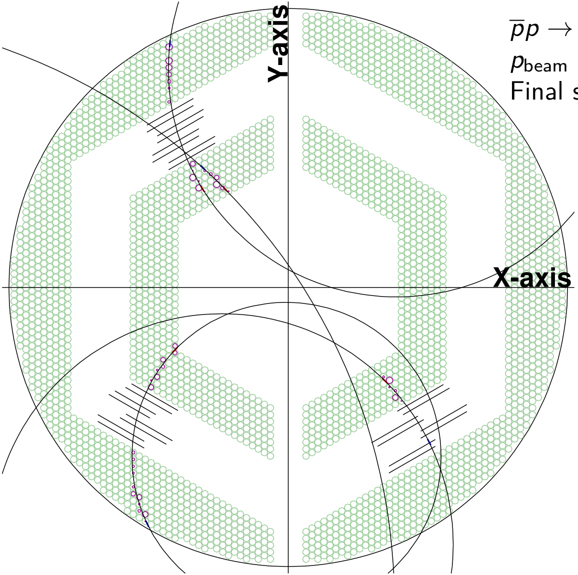
1. Cluster hits in parallel straws into tracklets (neighboring relations)
2. Refined circle fit using isochrones
3. Assign skewed straw hits to track

Output: circle for each track in *xy*-plane

Must include skewed straws to reconstruct p_z

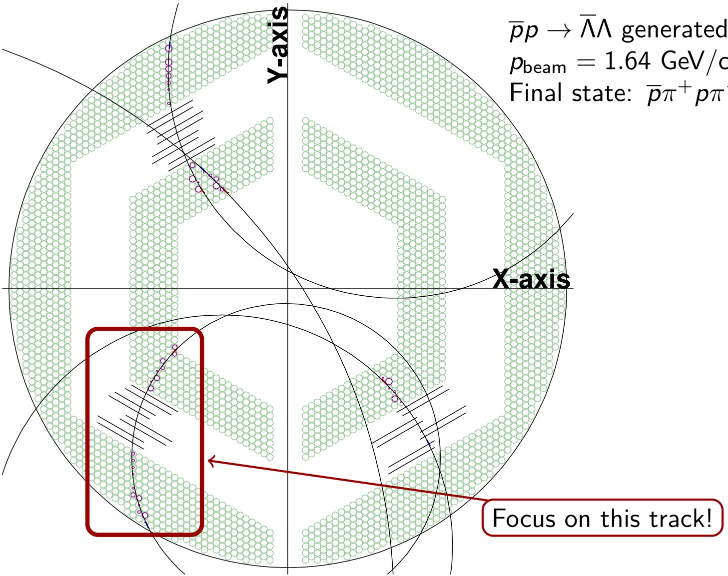


Longitudinal position from skewed straws



$\overline{p}p \rightarrow \overline{\Lambda}\Lambda$ generated at
$p_{\text{beam}} = 1.64$ GeV/c
Final state: $\overline{p}\pi^{+}p\pi^{-}$

Longitudinal position from skewed straws



$\bar{p}p \to \bar{\Lambda}\Lambda$ generated at
$p_{\text{beam}} = 1.64$ GeV/c
Final state: $\bar{p}\pi^+ p\pi^-$

Longitudinal position from skewed straws

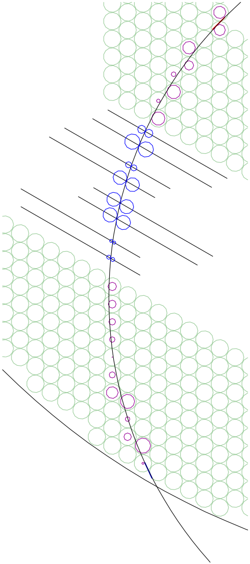
The method:

1. Extract isochrone radius in skewed straw
2. Center of isochrone gives $z-$position
3. Generate all possible isochrone positions
4. Calculate (z, ϕ)

Ambiguity: Each straw gives two possible (z, ϕ)

Solve ambiguity

Use Hough transform or combinatoric method to reject fake positions



Method 1: Hough transform

Find geometric shapes in images.

- Helix trajectory $\rightarrow$ straight line in $z - \phi$ space
- Line parameters in xy-plane, slope k and intercept m
  - $y(x) = kx + m$

Problem: The intercept parameter m unbound.

Hesse normal form

$$r = x\cos\theta + y\sin\theta$$

$$y = \left(-\frac{\cos\theta}{\sin\theta}\right)x + \left(\frac{r}{\sin\theta}\right)$$

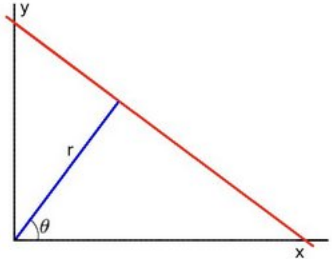
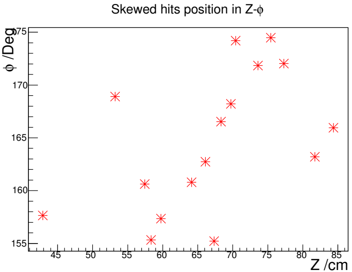


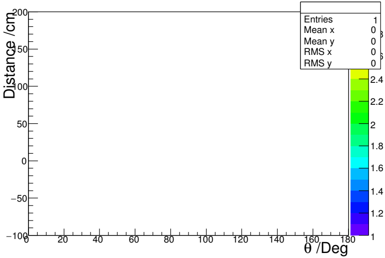
Figure: Blue line perpendicular to red line and crosses the origin

Method 1: Hough transform

The method:

1. Isochrone centers in $z - \phi$ space

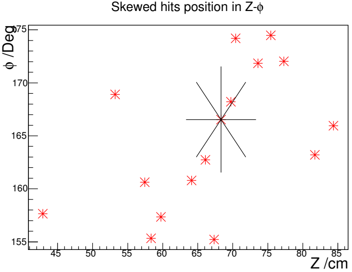


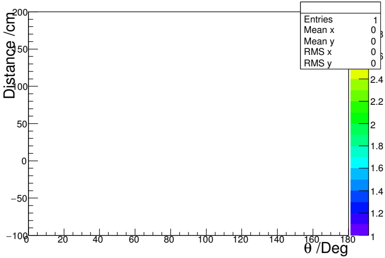


Method 1: Hough transform

The method:

1. Isochrone centers in $z - \phi$ space
2. Generate set of all lines

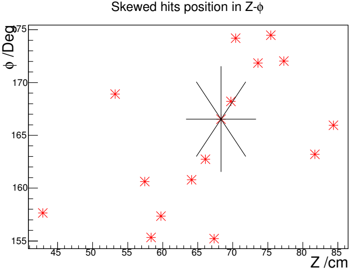


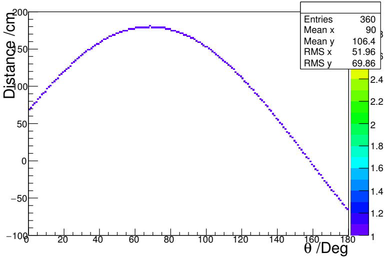


Method 1: Hough transform

The method:

1. Isochrone centers in $z - \phi$ space
2. Generate set of all lines
3. Parameters $\rightarrow$ accumulator space

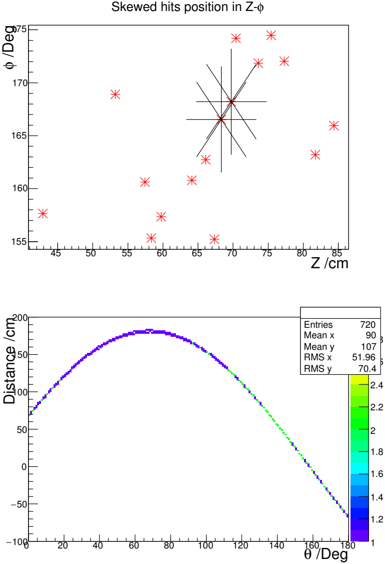




Method 1: Hough transform

The method:

1. Isochrone centers in $z - \phi$ space
2. Generate set of all lines
3. Parameters $\rightarrow$ accumulator space
4. Repeat for all points



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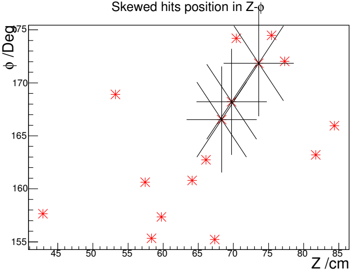
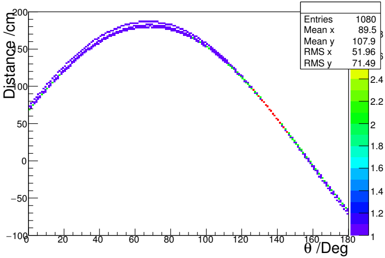


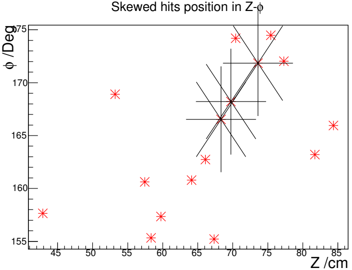


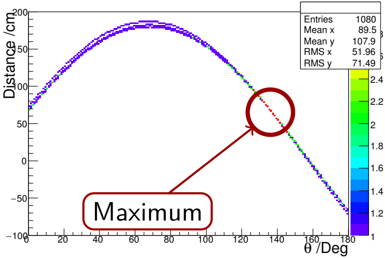
Method 1: Hough transform

The method:

1. Isochrone centers in $z - \phi$ space
2. Generate set of all lines
3. Parameters $\rightarrow$ accumulator space
4. Repeat for all points
5. Voting procedure $\rightarrow$ true line

True line found in maximum!





Method 1: Hough transform - our track

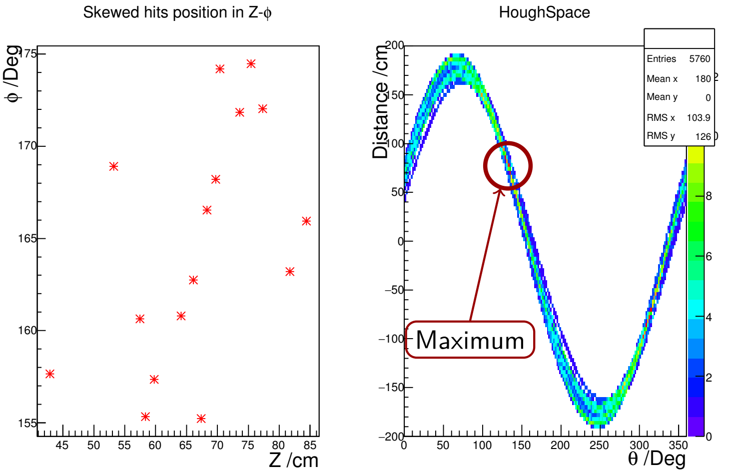


Figure: 360 lines generated for each data point in steps of 1° in θ

Method 1: Extracting helix angle

The method:

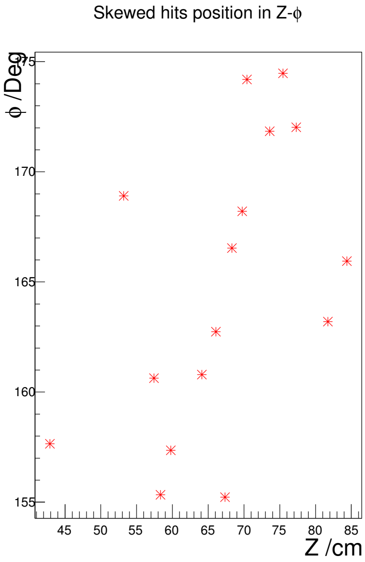
1. Calculate point of closest approach (POCA) from hits to true line
2. Accept hit with smallest POCA
3. Straight line fit with selected (z, ϕ) coordinates

Finish

The slope of the fitted line yields the helix angle. z_0 and p_z can now be extracted!

Method 2: Combinatorics

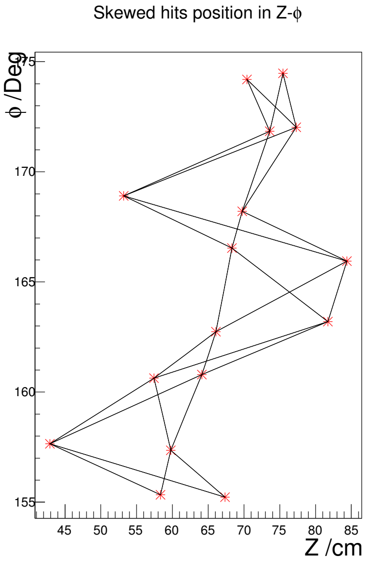
The method:



Method 2: Combinatorics

The method:

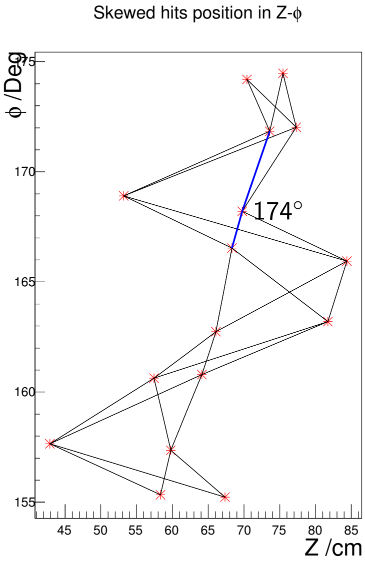
1. Calculate all lines between (z, ϕ) points in neighboring skewed straws



Method 2: Combinatorics

The method:

1. Calculate all lines between (z, ϕ) points in neighboring skewed straws
2. Calculate angle between all possible neighboring lines



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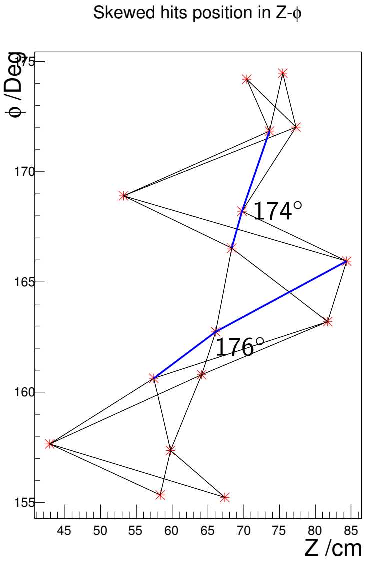

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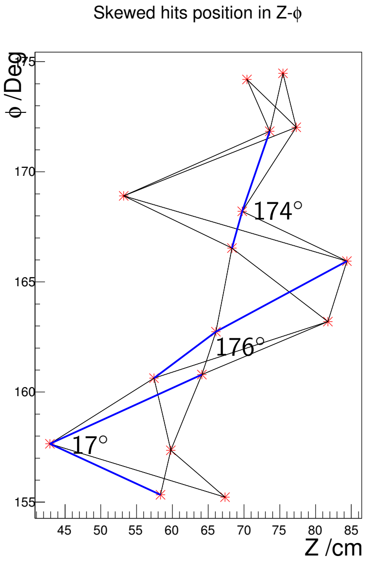
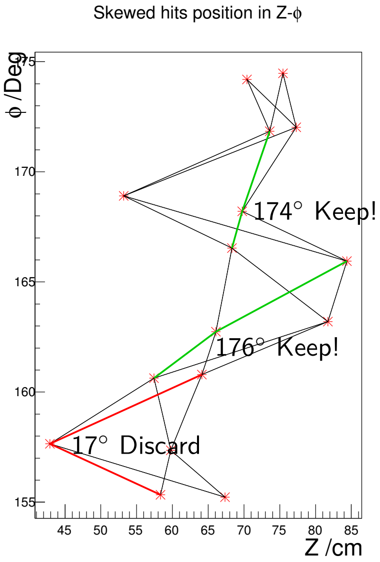


Method 2: Combinatorics

The method:

1. Calculate all lines between (z, ϕ) points in neighboring skewed straws
2. Calculate angle between all possible neighboring lines
3. Ignore paths where $\theta < 160^\circ$ $\rightarrow$ reduces number of combinations



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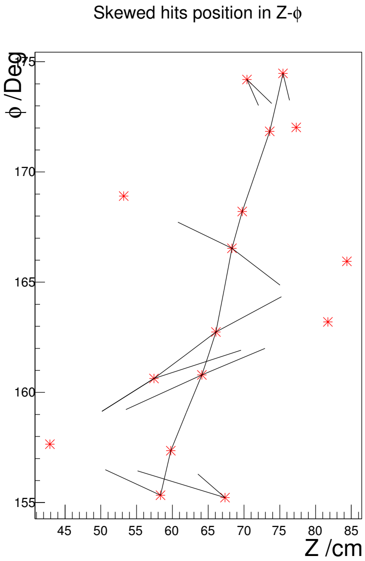

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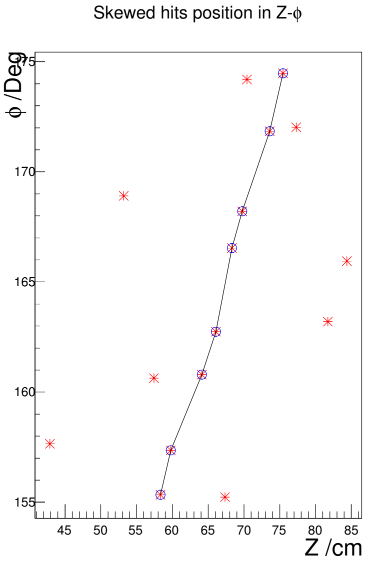
The method:

1. Calculate all lines between (z, ϕ) points in neighboring skewed straws
2. Calculate angle between all possible neighboring lines
3. Ignore paths where $\theta < 160^\circ$ $\rightarrow$ reduces number of combinations
4. Choose path with $\min(\sum \theta_i - 180^\circ)$

Hits in final path chosen as true hits



Summary and outlook

- $\overline{p}p \to \overline{Y}Y$ production probes QCD in the intermediate domain
- $\overline{\text{P}}$ANDA is the ideal experiment for measurement of antihyperon-hyperon channels
- Hyperons pose a challenge due to displaced vertices
- Tracking algorithms dedicated to STT will be extended to reconstruct p_z with skewed straws

Thank you for your attention!

Backup

Code structure

Algorithm implemented in a PndTask.
Input branches:

- PndTrack - Standard $\overline{\text{P}}$ANDA track object
- PndTrackCand - PndSttHits belonging to track
- PndRiemannTrack - Riemann circle parameters to track

Functions:

- MoveSkewedHitstoCircle
  - Calculates all possible (z, ϕ) in skewed straw
- HoughTrueIsoFinder
  - Fills accumulator space, find maximum, rejects fake hits with POCA
- LineCombiIsoFinder
  - Generates lines, calculates angles, find best path
- PzLineFitExtract
  - Simple line fit to true (z, ϕ) hits and extracts helix angle

Hyperon channels in $\overline{\text{P}}$ANDA

Why antihyperon-hyperon production?

- Hyperons produced at scales where QCD is poorly understood
- $\mathcal{CP}$ violation - needed to describe matter in the universe
- Never-before measured hyperon states
- Measure properties *e.g.* spin of hyperons

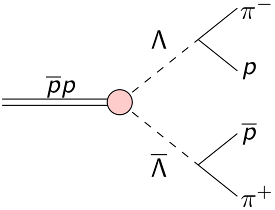


Figure: $\Lambda\bar{\Lambda}$ production channel, scarce data above $\sqrt{s} = 4$ GeV

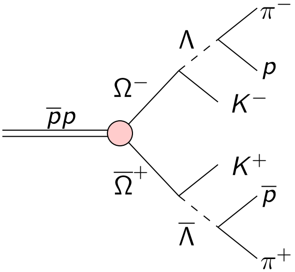


Figure: $\bar{\Omega}^+\Omega^-$ production channel, never measured

Hyperon production $\overline{p}p \to \overline{Y}Y$

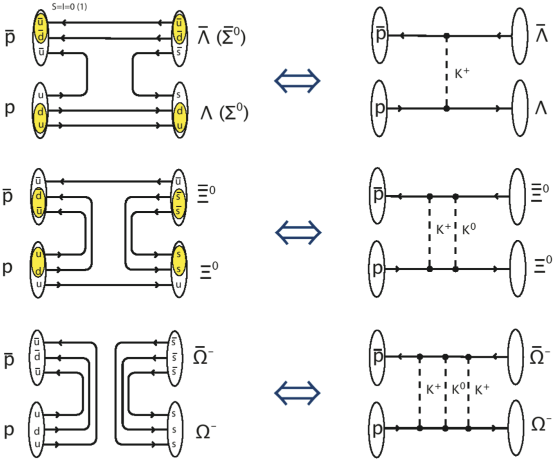


Figure: $\overline{p}p \to \overline{Y}Y$ in quark-gluon picture (left) and in Hadron picture (right).

Hyperons: Spin observables in $\overline{p}p \to \overline{Y}Y$

Spin observables can be used to test theoretical model. Angular distribution related to

$$I \propto \sum_{\mu,\nu=0}^{3} \sum_{k,l=0}^{3} \overline{\alpha}\alpha\chi_{kl\mu\nu} P_k^B P_l^T \overline{k}_\mu k_\nu$$

With unpolarised beam and unpolarised target, differential cross section χ_{0000}, polarisation $\chi_{00\mu0} = P_{\bar{i}}$, $\chi_{000\nu} = P_i$ and the spin correlations $\chi_{00\mu\nu} = C_{ij}$ are accessible.

Polarisation

- 3 polarisation parameters for spin-$\frac{1}{2}$ hyperons: P_x, P_y, P_z
- $P_x = P_z = 0$ due to strong production
- $P_y = P_{\overline{y}}$ due to rotational invariance

Spin correlation

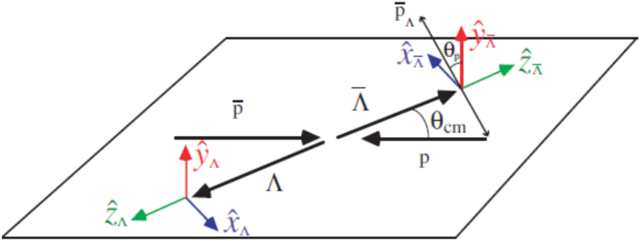
- 9 spin correlation parameters for spin-$\frac{1}{2}$ hyperons: $C_{i,j}$
- $C_{xy} = C_{yx} = C_{yz} = C_{zy} = 0$ due to strong production
- $C_{xz} = C_{zx}$ due to rotational invariance

Hyperons: Spin observables in $\overline{p}p \to \overline{Y}Y$

Polarised Particle	**None**	**Beam**	**Target**	**Both**
None	I_{0000}	A_{i000}	A_{0j00}	A_{ij00}
Scattered	$P_{00\mu0}$	$D_{i0\mu0}$	$K_{0j\mu0}$	$M_{ij\mu0}$
Recoil	$P_{000\nu}$	$K_{i00\nu}$	$D_{0j0\nu}$	$N_{ij0\nu}$
Both	$C_{00\mu\nu}$	$C_{i0\mu\nu}$	$C_{0j\mu\nu}$	$C_{C_{ij\mu\nu}}$

- In $\overline{p}p \to \overline{Y}Y$ there are 256 spin variables in total

Hyperons: Spin observables in $\overline{p}p \to \overline{Y}Y$



Polarisation

Proton angular distribution:

$$I(\theta_p) = \frac{1}{4\pi}(1 + \alpha P_Y \cos\theta_p)$$

$\overline{\alpha}, \alpha$ - decay asymmetry parameter

Spin correlation

Nucleon angular distribution:

$$I(\theta_i, \theta_j) = \frac{1}{16\pi^2}(1+$$

$$\overline{\alpha}\alpha \sum_{i,j} C_{ij} \cos\theta_i \cos\theta_j)$$

Accessible hyperons at $\overline{\text{P}}$ANDA

$$\bar{p}p \rightarrow \bar{\Lambda}\Lambda,\ \bar{\Sigma}^-\Sigma^+,\ \bar{\Sigma}^0\Sigma^0,\ \bar{\Sigma}^-\Sigma^+,\ \bar{\Xi}^0\Xi^0,\ \bar{\Xi}^+\Xi^-,\ \bar{\Omega}^+\Omega^-,\ \bar{\Lambda}_c^-\Lambda_c^+$$

$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$	$\downarrow$
$p\pi^-$	$p\pi^0$	$\Lambda\gamma$	$n\pi$	$\Lambda\pi^0$	$\Lambda\pi$	ΛK	$\Lambda\pi$
64%	52%	$\approx$ 100%	$\approx$ 100%	$\approx$ 100%	$\approx$ 100%	68%	$\approx$ 1%