

Future Spin Observables Measurements with the PANDA Detector at FAIR

Walter Ikegami Andersson
on behalf of the PANDA collaboration

FAIRness 2019

Arenzano, Genova, Italy
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2019-05-23

Walter Ikegami Andersson

Outline

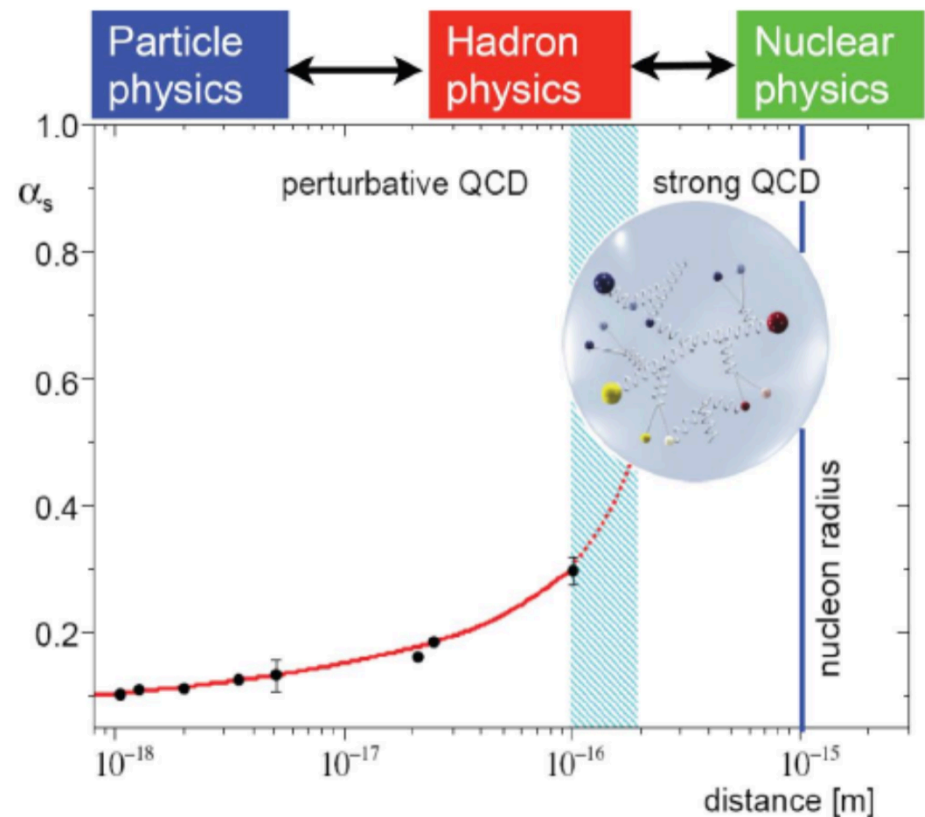
- QCD and the Strong Interaction
- The PANDA experiment at FAIR
- Spin observables in $\bar{p}p \rightarrow \bar{Y}Y$
- Results
- Summary



QCD and the Strong Interaction

Open questions in QCD:

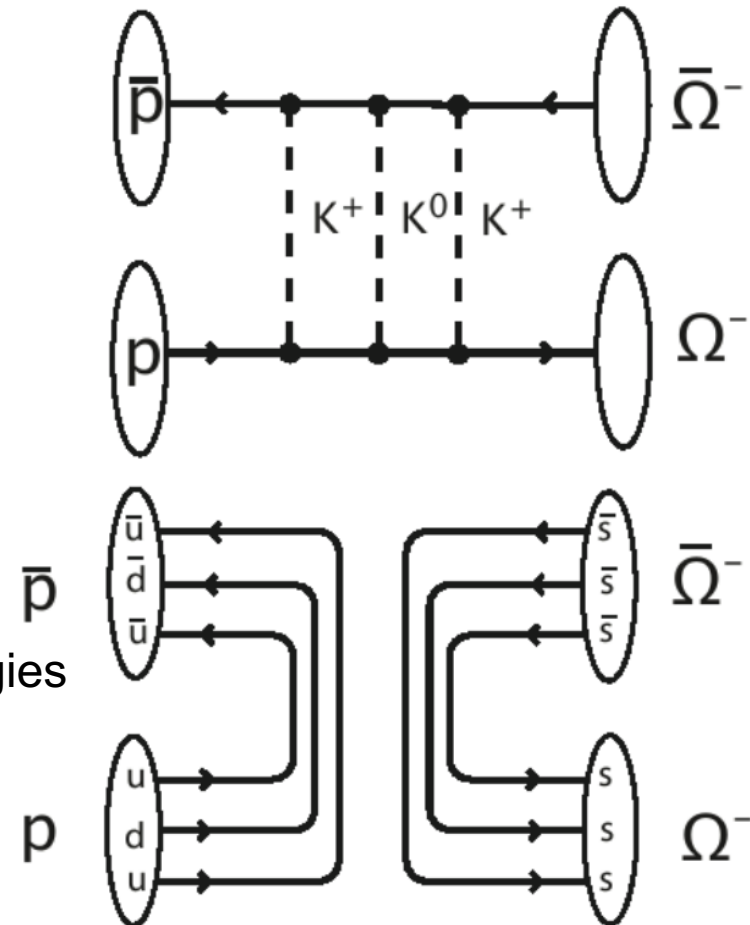
- **Confined quark states:**
 - Only $q\bar{q}$ and qqq quark systems?
 - Exotic states/excitations?
- **The Quark Model:**
 - Comparison of prediction and experiment?
- **QCD in the intermediate domain:**
 - Relevant degrees of freedom?



Hyperons in $\bar{p}p \rightarrow \bar{Y}Y$

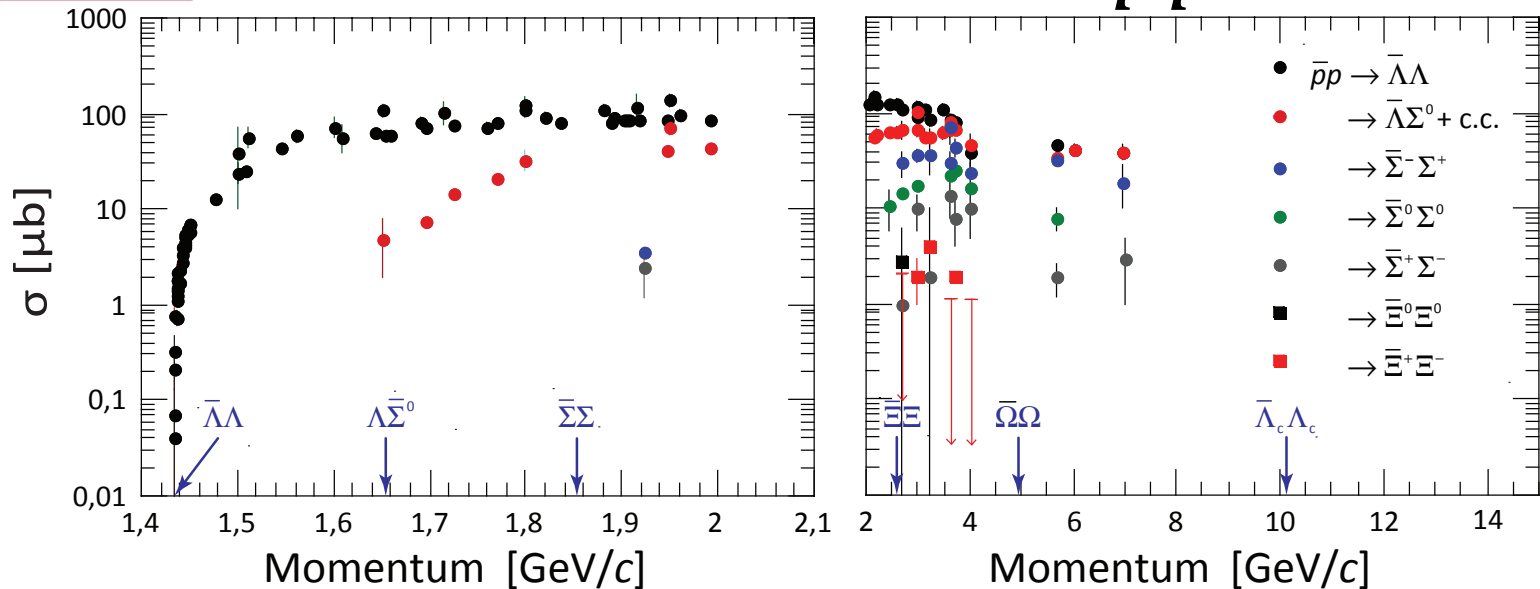
- **Light quark (u, d) production**
 - Non-perturbative
 - Hadrons as relevant d.o.f
- **Strangeness production**
 - Relevant d.o.f?
 - **Probe QCD in intermediate domain**
- **Heavier quark (c, b) production**
 - Quarks and gluons more relevant d.o.f
 - Perturbative QCD applicable at high energies

Kohno M and Weise W 1986 Phys. Lett. B 179 15
Ortega P G et al. 2011 Phys. Lett. B 696 352





Measured $\bar{p}p \rightarrow \bar{Y}Y$ data



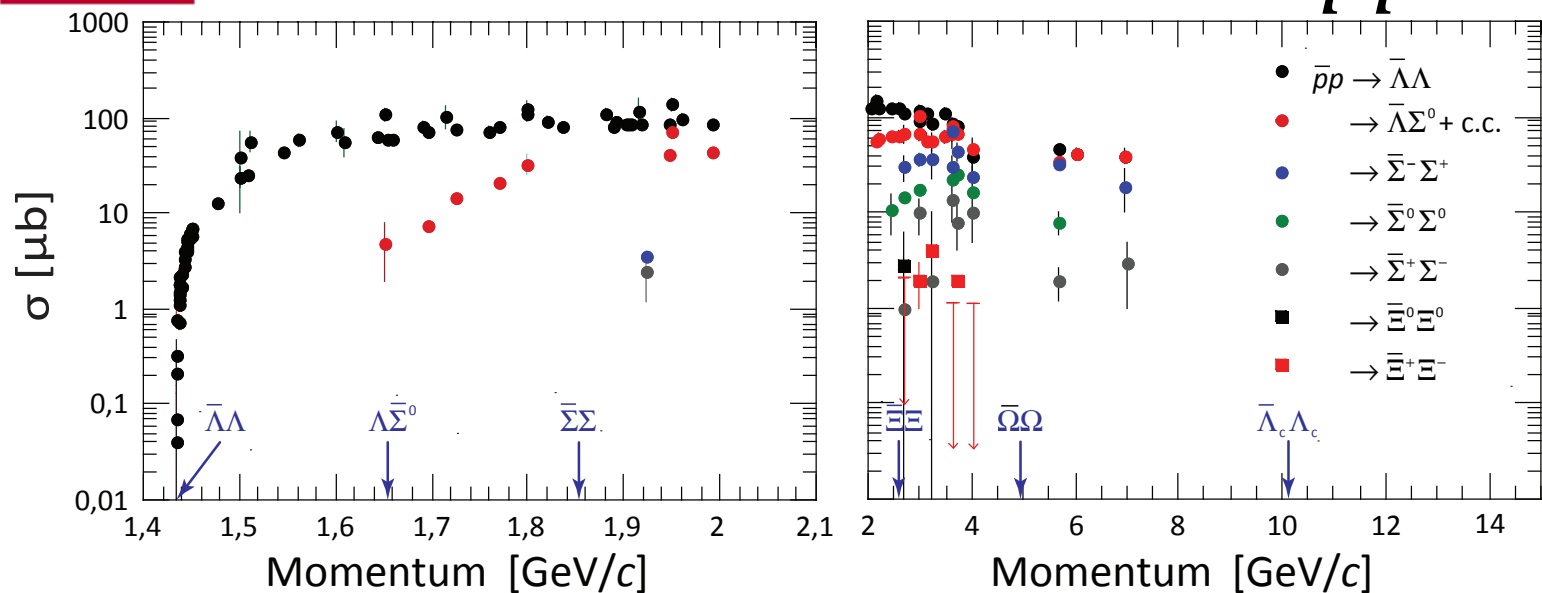
Johansson T 2003 Proceedings of 8th Int. Conf. on Low Energy Antiproton Physics 95

- Previous measurements of $\bar{p}p \rightarrow \bar{Y}Y$ exist, mainly from PS185 experiment at LEAR.
- Above 4 GeV/c beam momentum, available data becomes scarce
- No data on $\bar{p}p \rightarrow \bar{\Omega}\Omega$ or $\bar{p}p \rightarrow \bar{\Lambda}_c\Lambda_c$



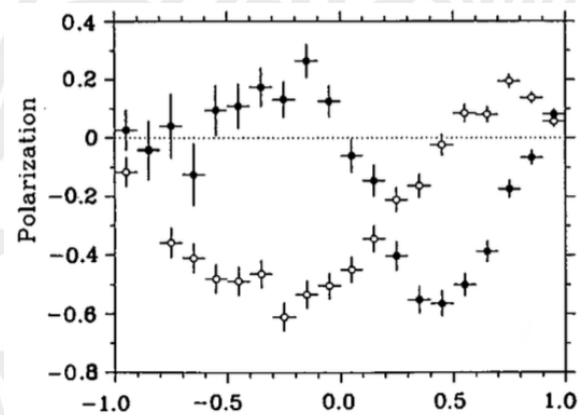
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$$\bar{p}p \rightarrow \bar{\Lambda}\Lambda$$



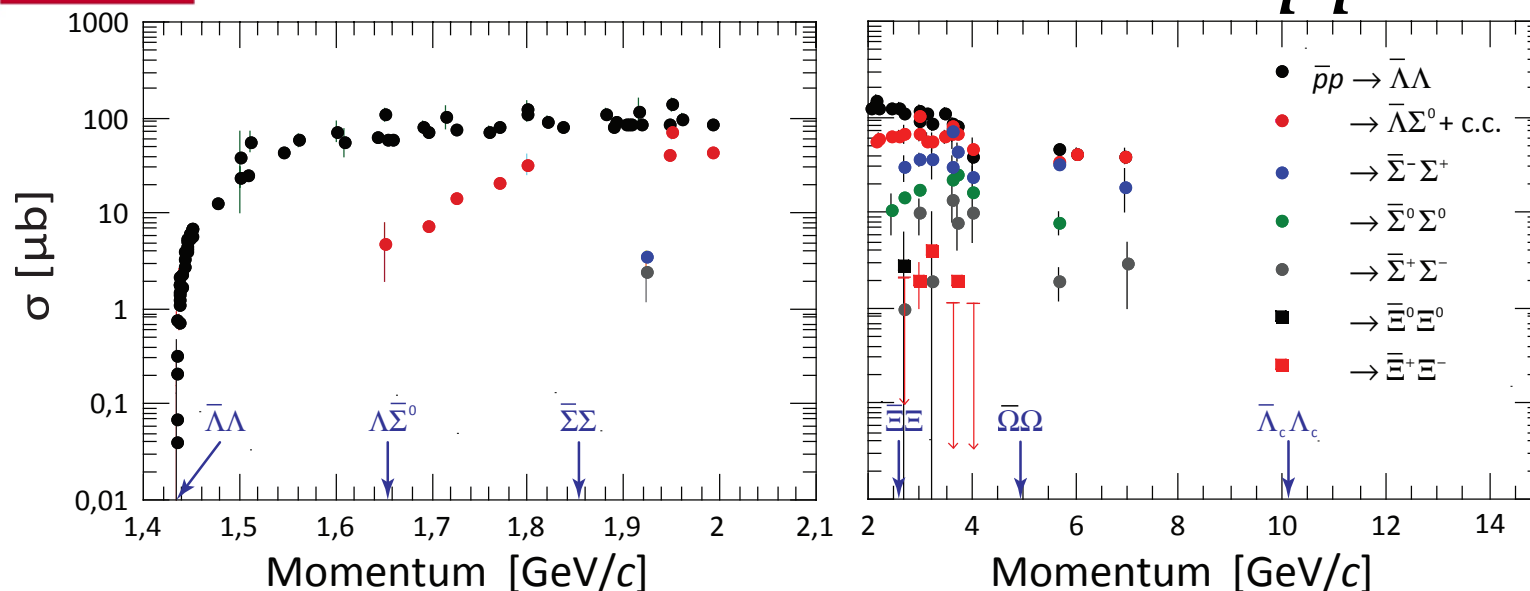
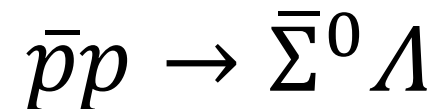
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- A lot of data on $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ mainly from PS185 at LEAR.
- Largest data sample at $p_{beam} = 1.642$ GeV/c
- Spin Observables measured
- Primary benchmark channel for PANDA
- Verify or reject LEAR measurements



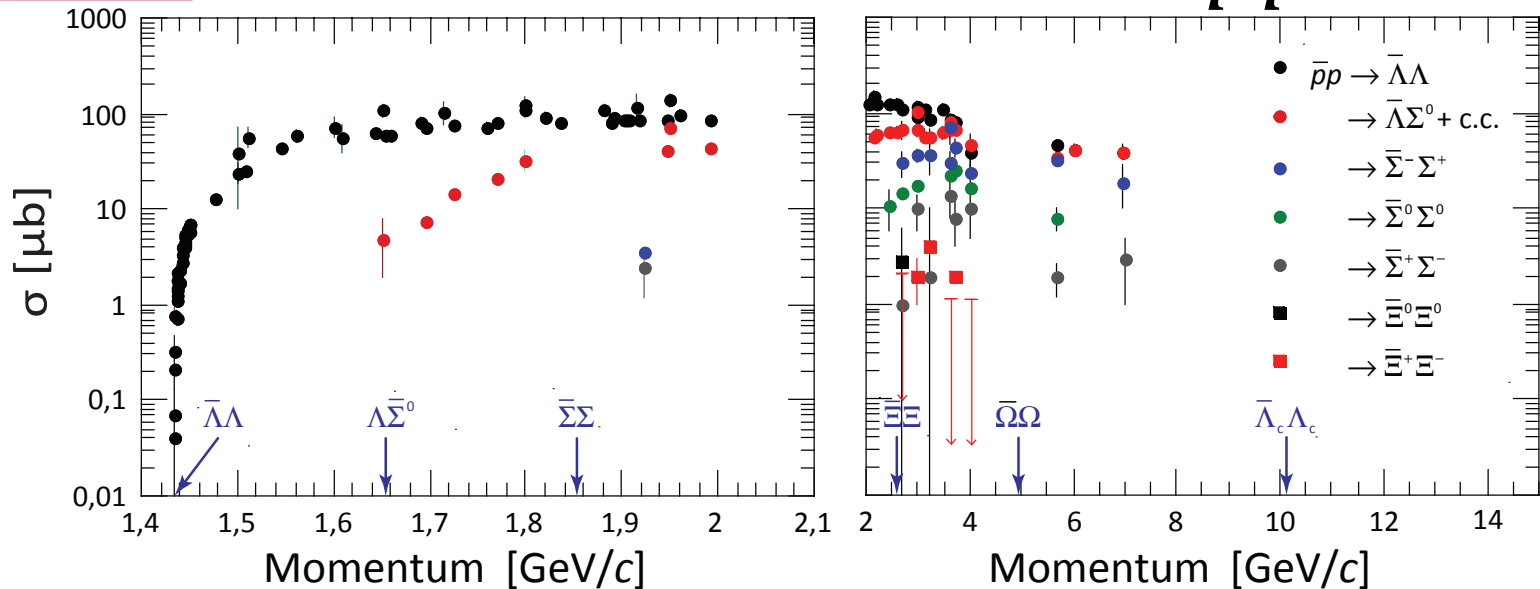
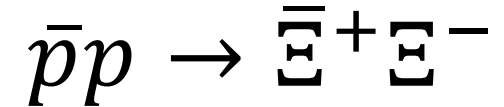
2019-05-23

Walter Ikegami Andersson P.D. Barnes et al. Phys. Rev. C54, 1996. $\cos(\theta_K^+)$



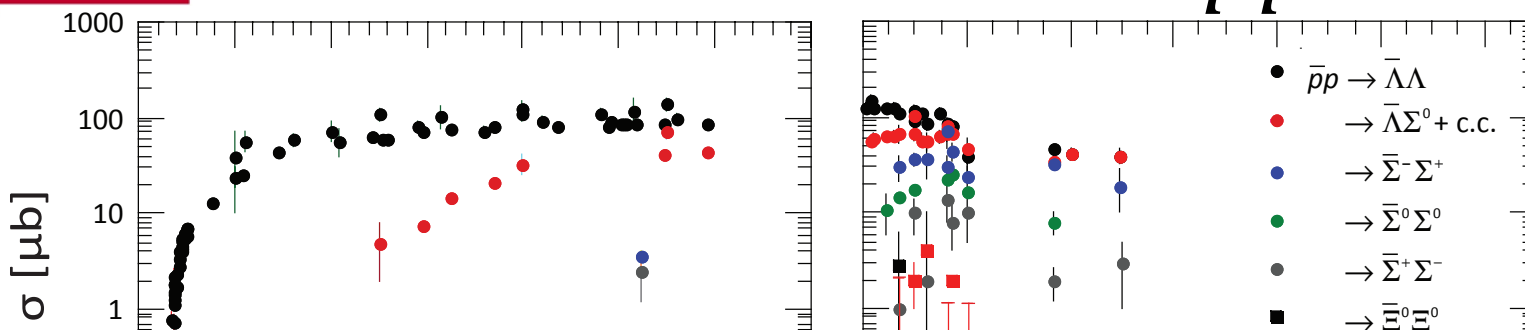
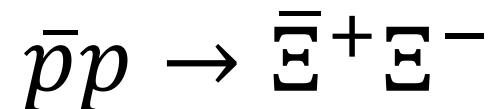
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- Data on $\bar{p}p \rightarrow \bar{\Sigma}^0 \Lambda$ exists, mainly from PS185 at LEAR.
- Verify or reject LEAR measurements
- $\bar{\Sigma}^0$ and Λ have same quark content but different isospin
Learn how isospin plays a role in the reaction dynamics



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- Only a handful of reconstructed $\bar{p}p \rightarrow \Xi^- \Xi^+$ events exists
- Measurements were performed with bubble chambers
- Only total cross section measured, no differential distributions or spin observables



Measure Spin Observables at multiple energies!

For now, test feasibility of measurement!

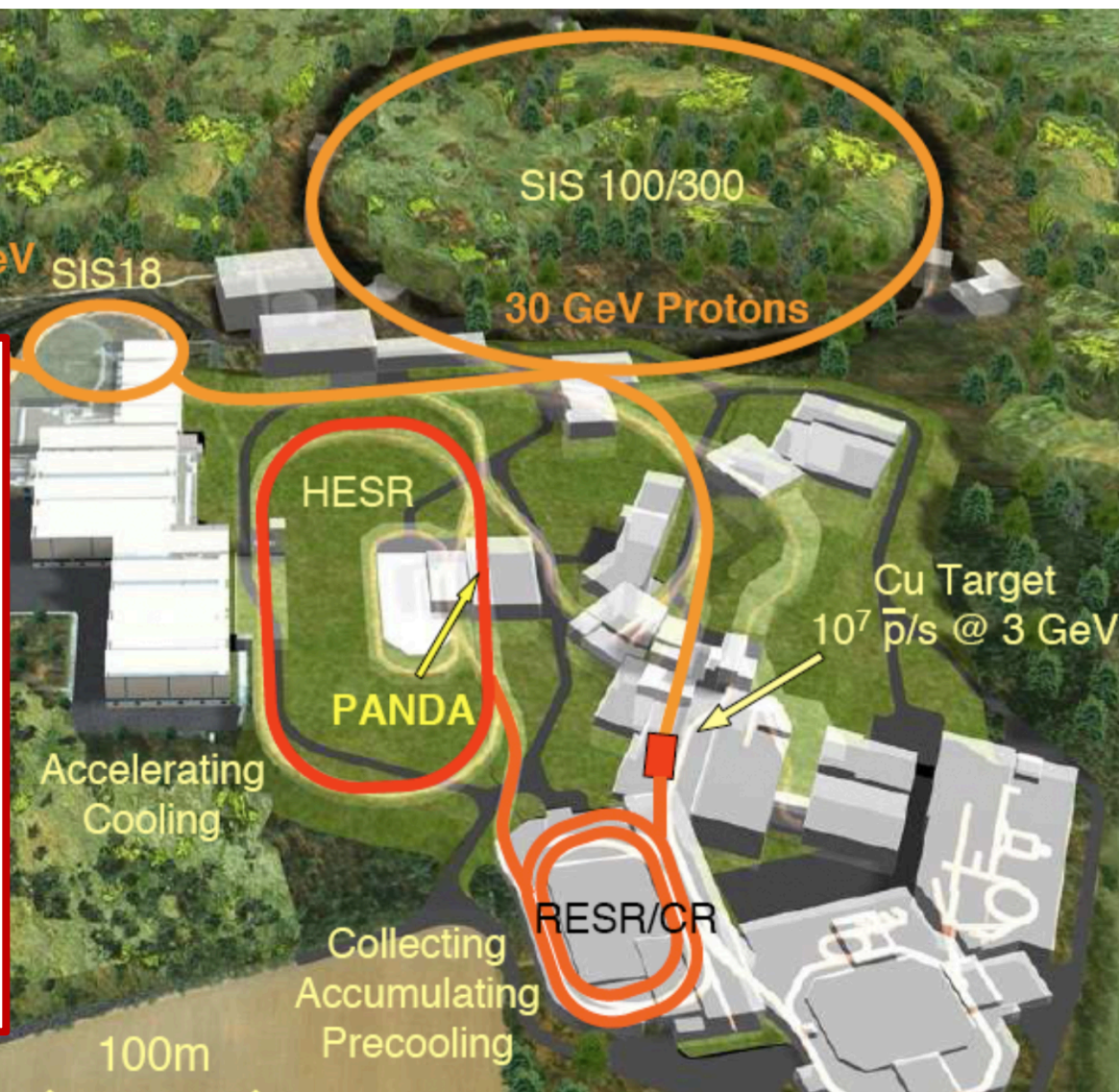
Johansson T 2003 Proceedings of 8th Int. Conf. on Low Energy Antiproton Physics 95

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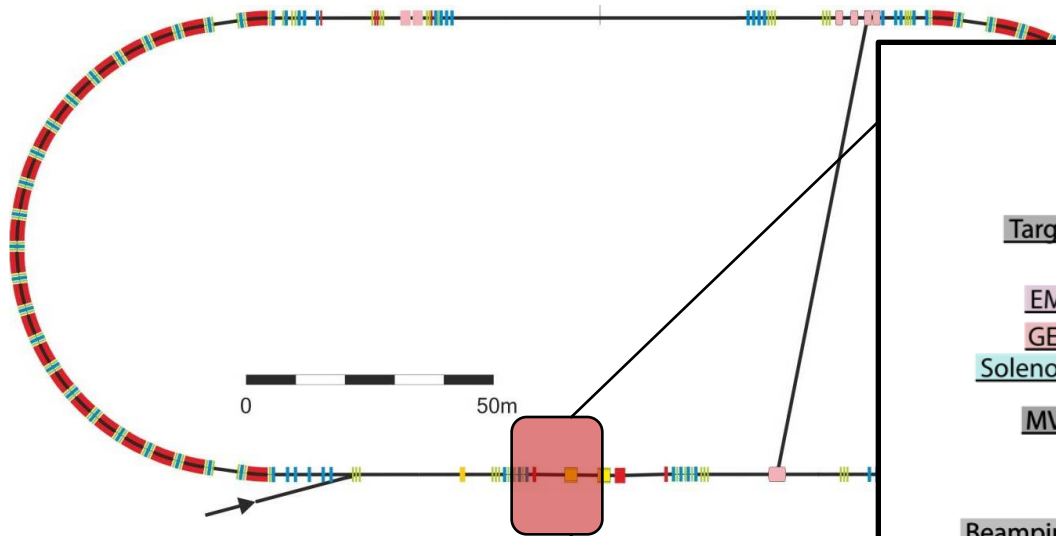
Facility for Antiproton and Ion Research (under construction)

HESR

- Antiproton beam
 - $1.5 < p_{\bar{p}} < 15 \text{ GeV}/c$
- **High Resolution Mode**
 - $L = 2 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
 - Stochastic cooling
 - $\Delta p/p \leq 5 \times 10^{-5}$
 - (Electron cooling)
- **High Luminosity Mode**
 - $L = 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
 - Stochastic cooling
 - $\Delta p/p \leq 1 \times 10^{-4}$

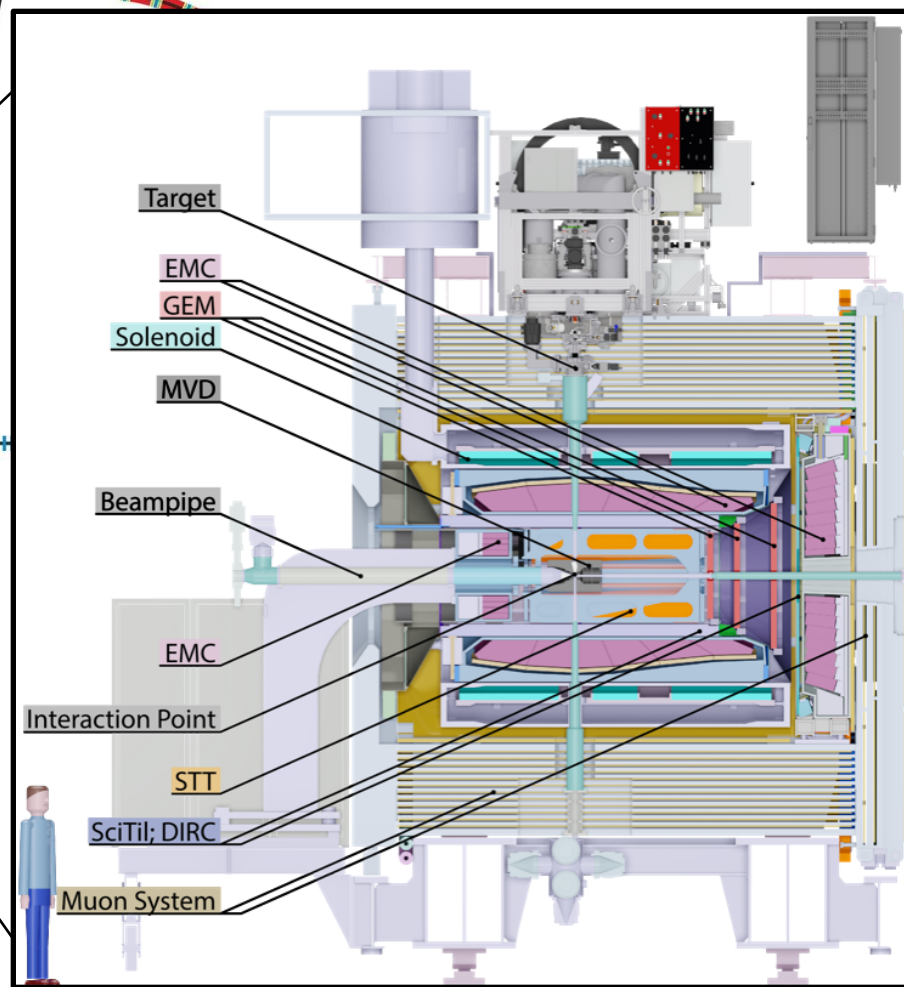


antiProton ANnihilation at DArmstadt

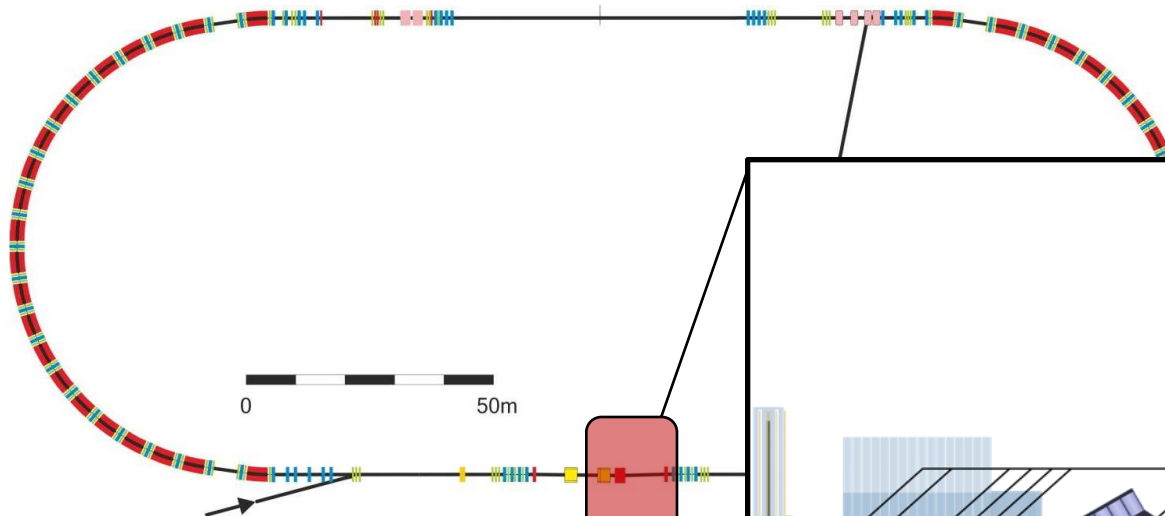


Target and forward spectrometer:

- 4π coverage
- Vertexing
- Tracking
- Calorimetry
- PID

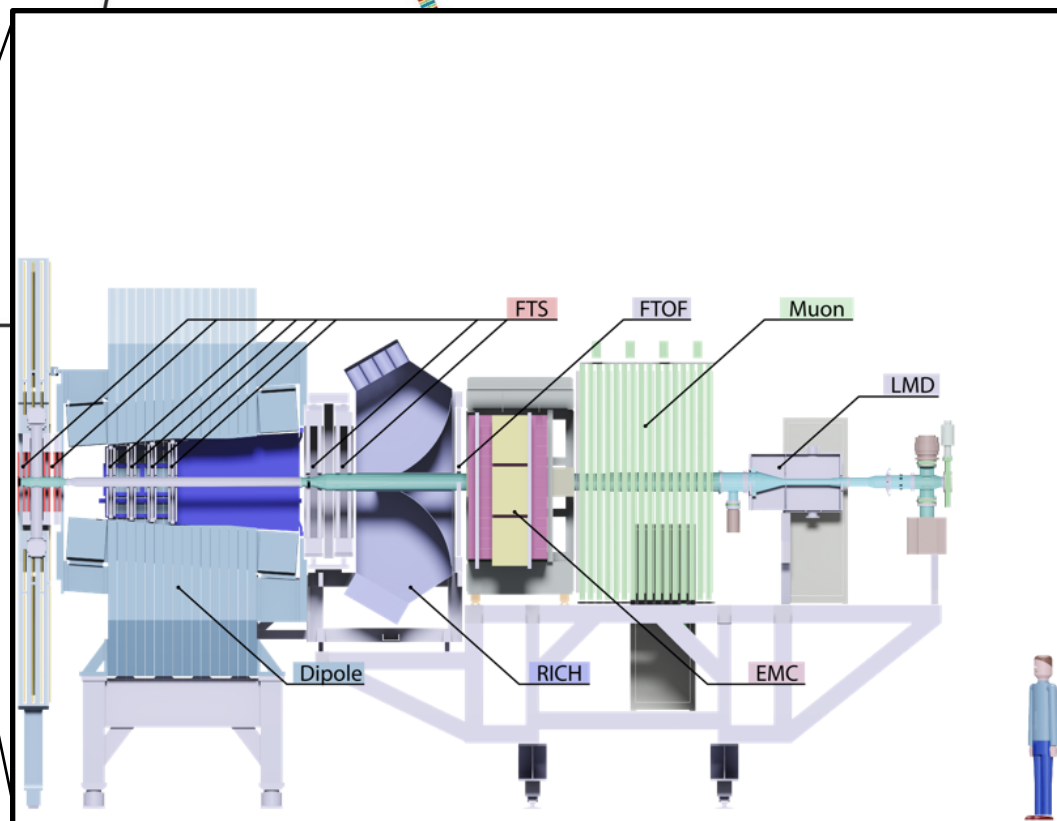


anti**P**roton **A**Nnihilation at **D**Armstadt



Target and **forward** spectrometer:

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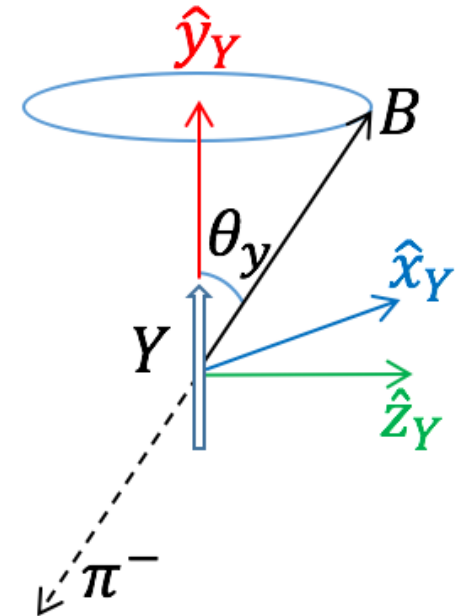
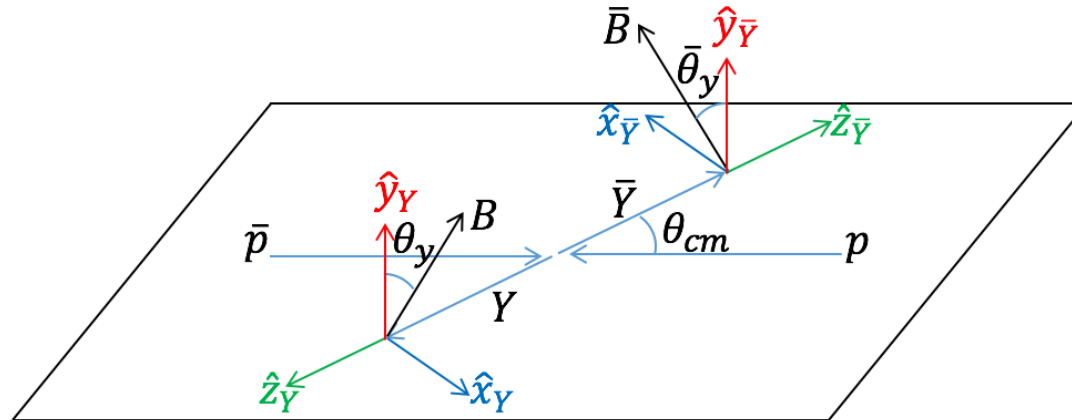




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Formalism

Spin observables



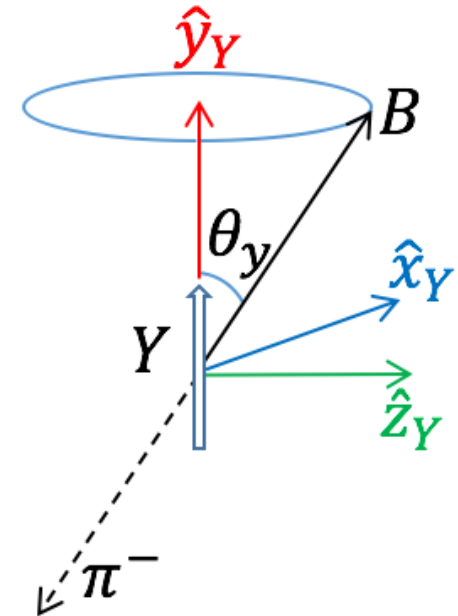
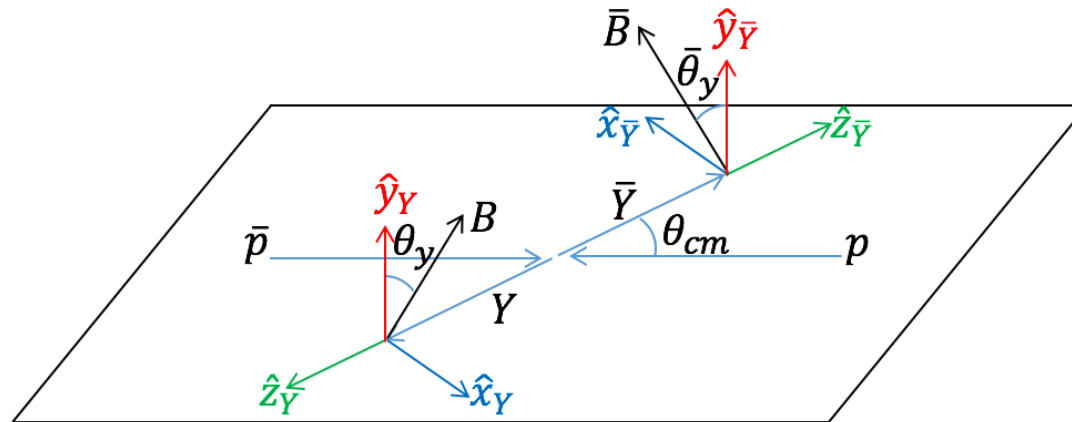
With unpolarised beam and target:

- **Differential cross section**
- Polarisation
- Spin correlation

For $\bar{p}p \rightarrow \bar{Y}Y \rightarrow \bar{B}\pi^+ B\pi^-$ reaction at scattering angle θ_{cm} :

$$I(\theta_i, \theta_j) = N(\mathbf{1} + \bar{\alpha} \sum_i P_i^{\bar{Y}} \cos \theta_i + \alpha \sum_j P_j^Y \cos \theta_j + \alpha \bar{\alpha} \sum_{i,j} C_{ij} \cos \theta_i \cos \theta_j)$$

Spin observables



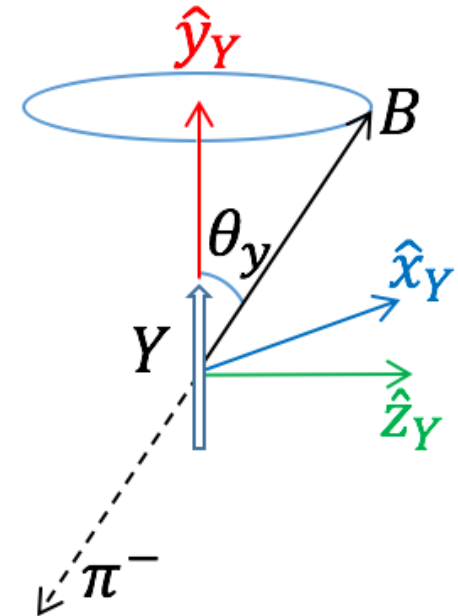
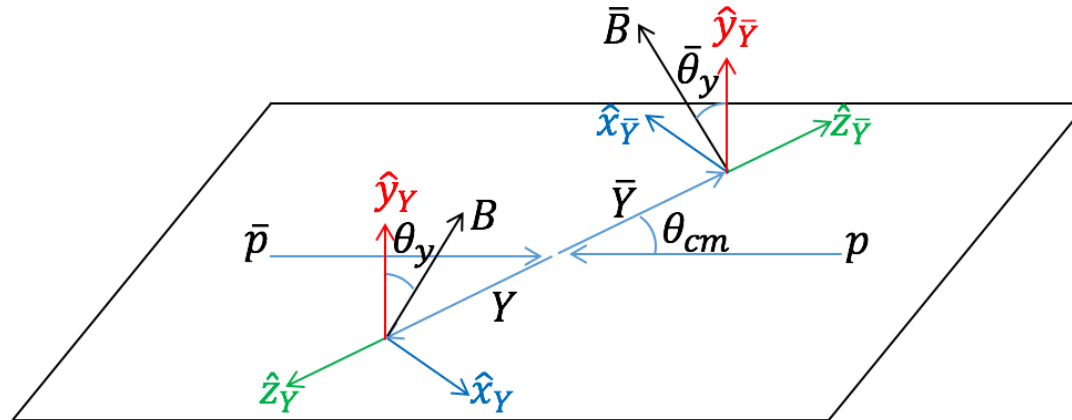
With unpolarised beam and target:

- Differential cross section
- **Polarisation**
- Spin correlation

For $\bar{p}p \rightarrow \bar{Y}Y \rightarrow \bar{B}\pi^+ B\pi^-$ reaction at scattering angle θ_{cm} :

$$I(\theta_i, \theta_j) = N(1 + \bar{\alpha} \sum_i P_i^{\bar{Y}} \cos \theta_i + \alpha \sum_j P_j^Y \cos \theta_j + \alpha \bar{\alpha} \sum_{i,j} C_{ij} \cos \theta_i \cos \theta_j)$$

Spin observables



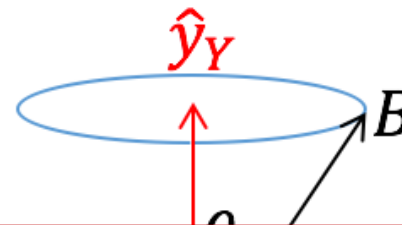
With unpolarised beam and target:

- Differential cross section
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Spin observables



Considered decays in this presentation:

$$\Lambda \rightarrow p\pi^- \quad \text{BR: 63.9 \%}$$

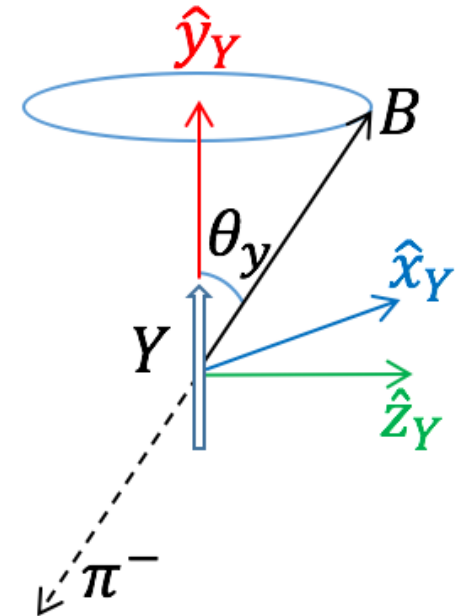
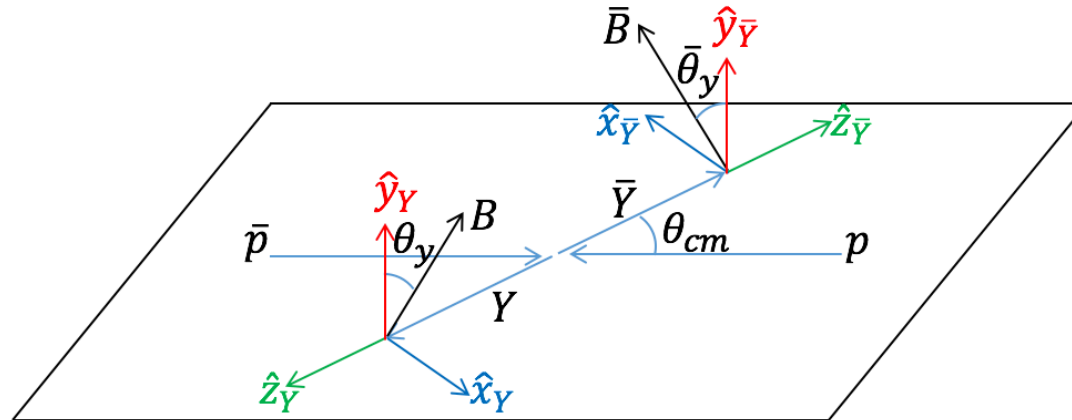
$$\Sigma^0 \rightarrow \Lambda\gamma \quad \text{BR: } \sim 100 \%$$

$$\Xi^- \rightarrow \Lambda\pi^- \quad \text{BR: 99.9 \%}$$

For $\bar{p}p \rightarrow \bar{Y}Y \rightarrow \bar{B}\pi^+ B\pi^-$ reaction at scattering angle θ_{cm} :

$$I(\theta_i, \theta_j) = N(1 + \bar{\alpha} \sum_i P_i^{\bar{Y}} \cos \theta_i + \alpha \sum_j P_j^Y \cos \theta_j + \alpha \bar{\alpha} \sum_{i,j} C_{ij} \cos \theta_i \cos \theta_j)$$

Spin observables



- Symmetry conservation requires**

➤ $P_x = P_z = 0, \quad P_y(\theta_{cm} = 0) = P_y(\theta_{cm} = \pi) = 0, \quad P_y^{\bar{Y}} = P_y^Y$

➤ $C_{xy} = C_{yx} = C_{yz} = C_{zy} = 0, \quad C_{xz} = C_{zx}$

- Spin Observables can be estimated using Method of Moments**

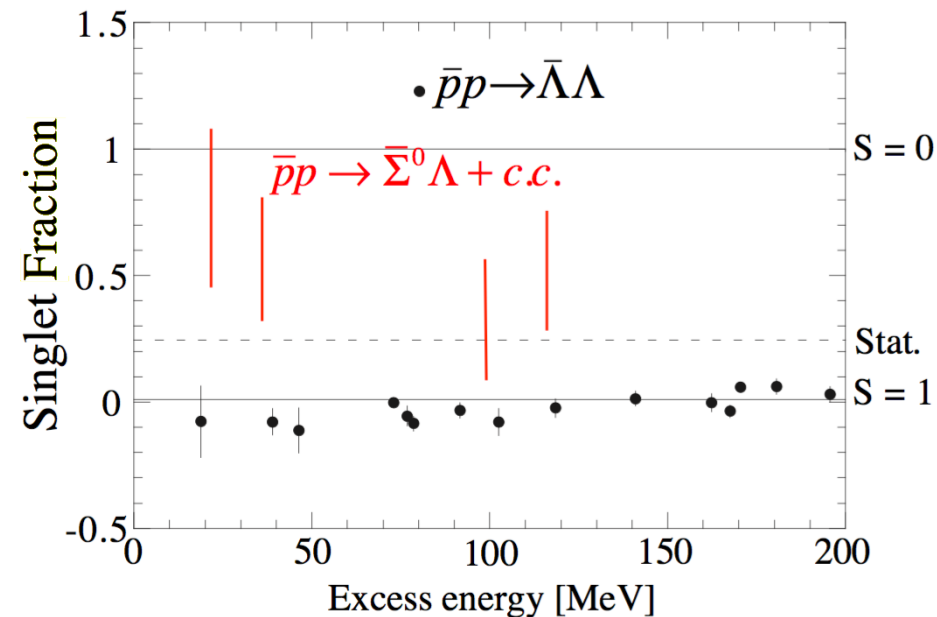
$$\langle \cos \theta_y \rangle = \langle k_y \rangle = \int_{-1}^1 \int_{-1}^1 I(\bar{k}_y, k_y) \times k_y d\bar{k}_y dk_y \quad P_y = \frac{3}{\alpha} \langle k_y \rangle$$

Singlet Fraction

The Singlet Fraction is given by

$$F_S = \frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz})$$

- Singlet Fraction tells whether the $\bar{Y}Y$ pair was produced with parallel or antiparallel spin
- It takes the following values:
 - 0 parallel
 - 1 antiparallel
 - $\frac{1}{4}$ uncorrelated
- Previous measurements shows $\bar{\Lambda}\Lambda$ pair produced with parallel spin



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Results

Reconstruction rates at PANDA

First, the reconstruction feasibility of the reactions must be assessed:

- For polarisation measurements, inclusive event reconstruction would suffice...
- However, for spin correlation measurements, full event reconstruction necessary
- Pure sample with background contamination of $S/B > 100$ is desired for the parameter extraction procedure

Reconstruction rates at PANDA

Given:

- Lowest estimate of *Day One* luminosity
- Model prediction of $\bar{p}p \rightarrow \bar{\Xi}^+ \Xi^-$ cross section at 7.0 GeV/c
- **In High Luminosity mode, reconstruction rates increase by factor of 30 - 50**

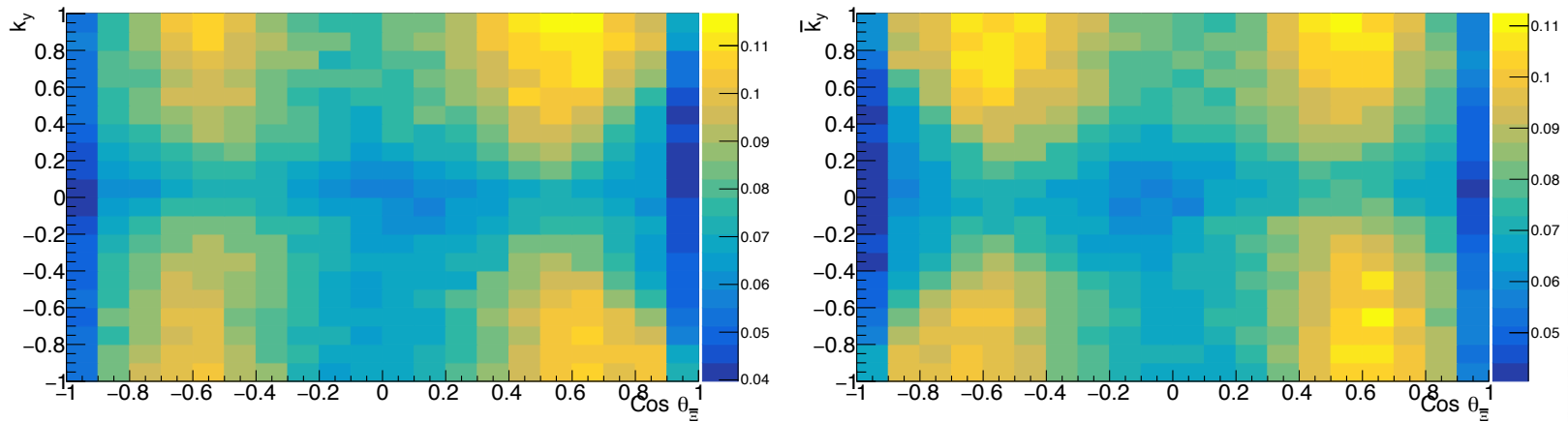
Momentum (GeV/c)	Reaction	σ (μb)	Efficiency (%)	Rate (s^{-1})
1.64	$\bar{p}p \rightarrow \bar{\Lambda} \Lambda$	64	16	10
1.771	$\bar{p}p \rightarrow \bar{\Sigma}^0 \Lambda^*$	11	5.3	0.6
6.0	$\bar{p}p \rightarrow \bar{\Sigma}^0 \Lambda^*$	20	6.1	1.6
4.6	$\bar{p}p \rightarrow \bar{\Xi}^+ \Xi^-$	~ 1	8.2	0.1
7.0	$\bar{p}p \rightarrow \bar{\Xi}^+ \Xi^-$	~ 0.3	7.9	0.03

*G. Pérez Andrade, Master Thesis,
<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-375552>
 Walter Ikegami Andersson



Spin Observables in $\bar{p}p \rightarrow \bar{\Xi}^+ \Xi^-$ at 7 GeV/c

Acceptance Correction



When using Method of Moments, an acceptance correction is needed

For Polarisation:

- Scattering angle of Ξ^+
- Outgoing $\bar{\Lambda}$ angle w.r.t y-axis

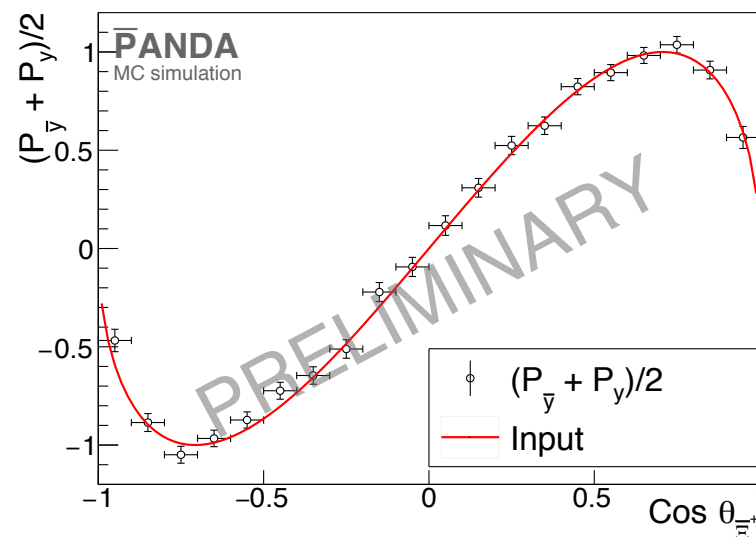
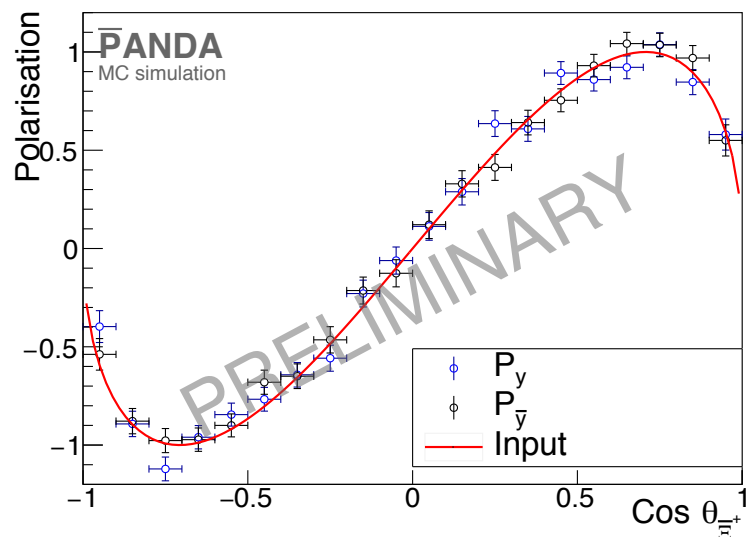
For Spin Correlation: (not shown)

- Scattering angle of Ξ^+
- Outgoing $\bar{\Lambda}$ angle w.r.t i-axis
- Outgoing Λ angle w.r.t j-axis



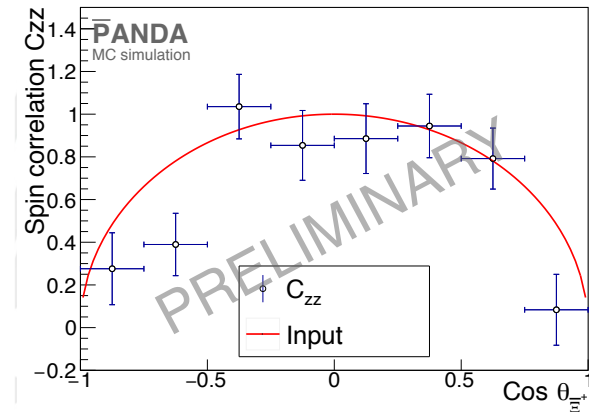
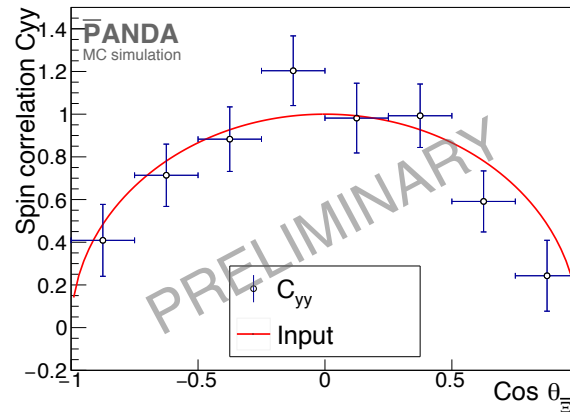
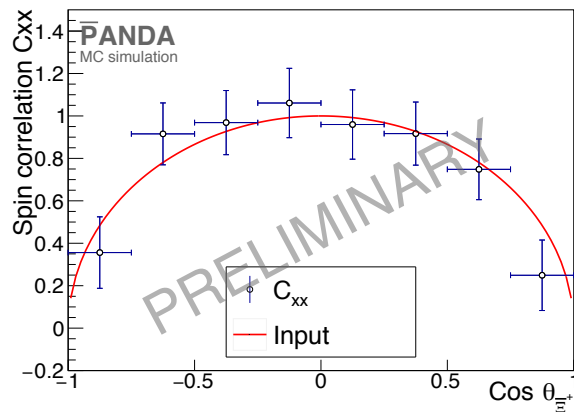
Polarisation

- Polarisation input set to $P_y = \sin 2\theta$
 - Similar to $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ measurements
 - Satisfies symmetry requirements
- **Horizontal bars are bin widths**
Vertical bars are statistical uncertainties



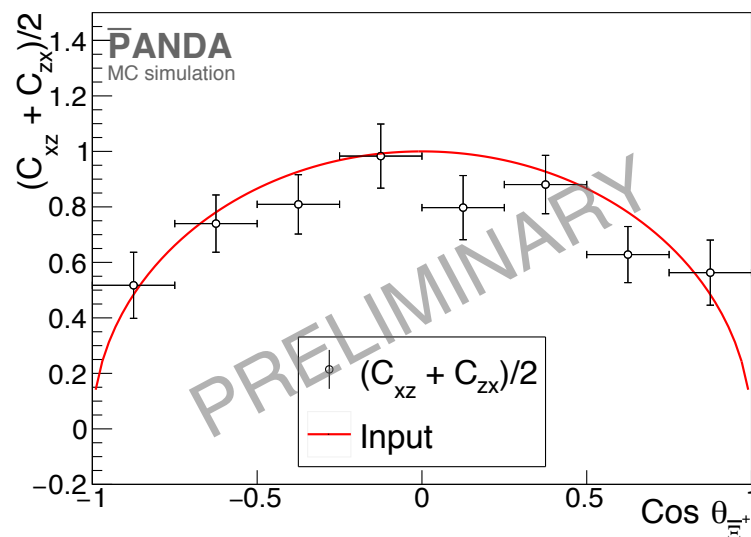
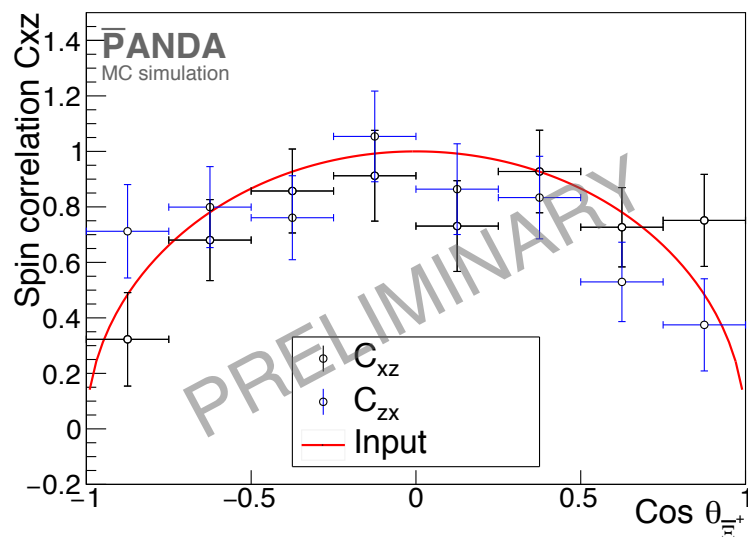
Spin Correlation

- Spin Correlation input set to $C_{ii} = \sin \theta$
 - Satisfies symmetry requirements
- Horizontal bars are bin widths**
Vertical bars are statistical uncertainties



Spin Correlation

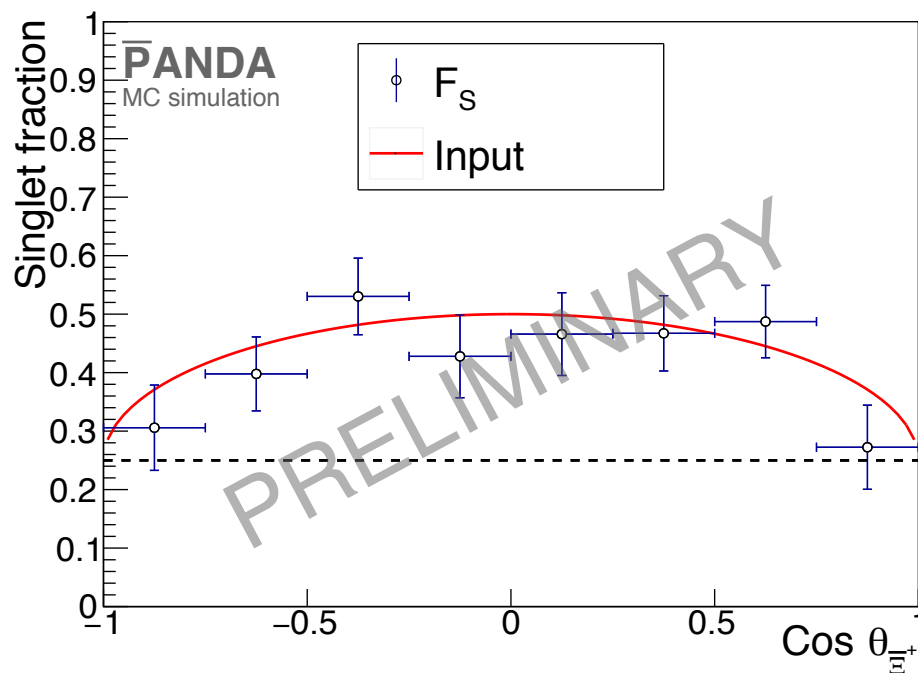
- Spin Correlation input set to $C_{ij} = \sin \theta$
 - Satisfies symmetry requirements
- **Horizontal bars are bin widths**
Vertical bars are statistical uncertainties



Singlet Fraction

- Singlet Fraction input set to

$$\frac{1}{4}(1 + C_{xx} - C_{yy} + C_{zz})$$
- **Horizontal bars are bin widths**
Vertical bars are statistical uncertainties
- With this input model, the $\bar{E}^+ E^-$ pair are produced more frequently with antiparallel spin



Summary

Feasibility studies of event reconstruction and spin observable extraction have been performed

- High exclusive reconstruction efficiencies achievable
 - $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ sample size of LEAR measurement can be collected in a couple of hours
 - First measurement of $\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$ reaction
- Polarisation, Spin Correlations and Singlet Fractions can be extracted

Publication highlighting PANDA physics case coming soon!



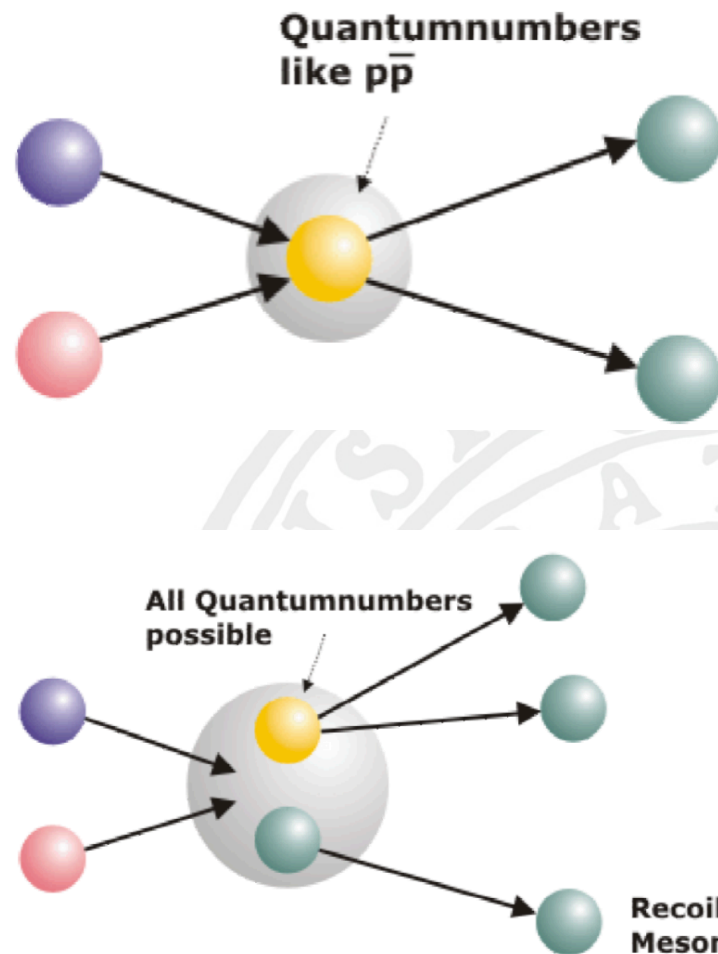
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Backup

Why antiprotons?

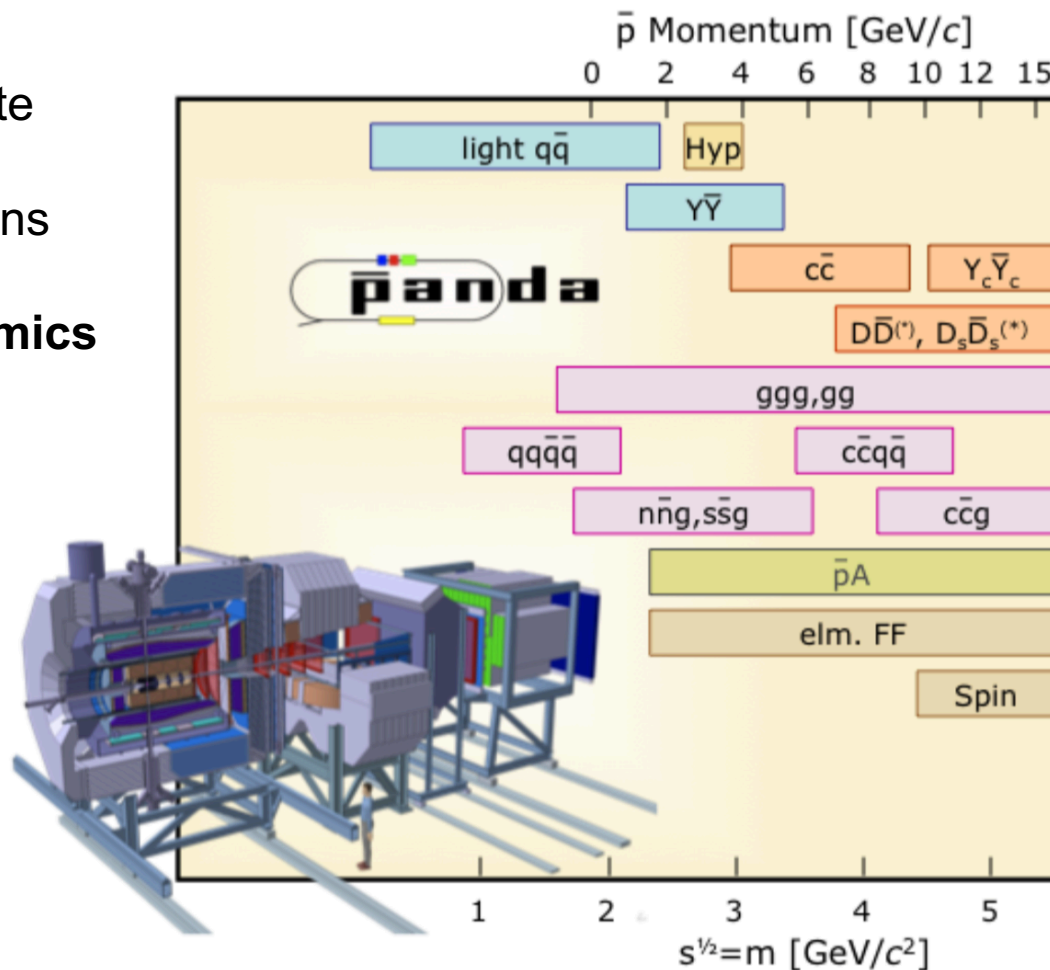
Main features of $\bar{p}p$ collision:

- All non-exotic J^{PC} available through formation (e^+e^- limited to 1^{--})
- Exotic J^{PC} available with recoil meson
- High hadronic cross sections (including background...)



PANDA Physics Program

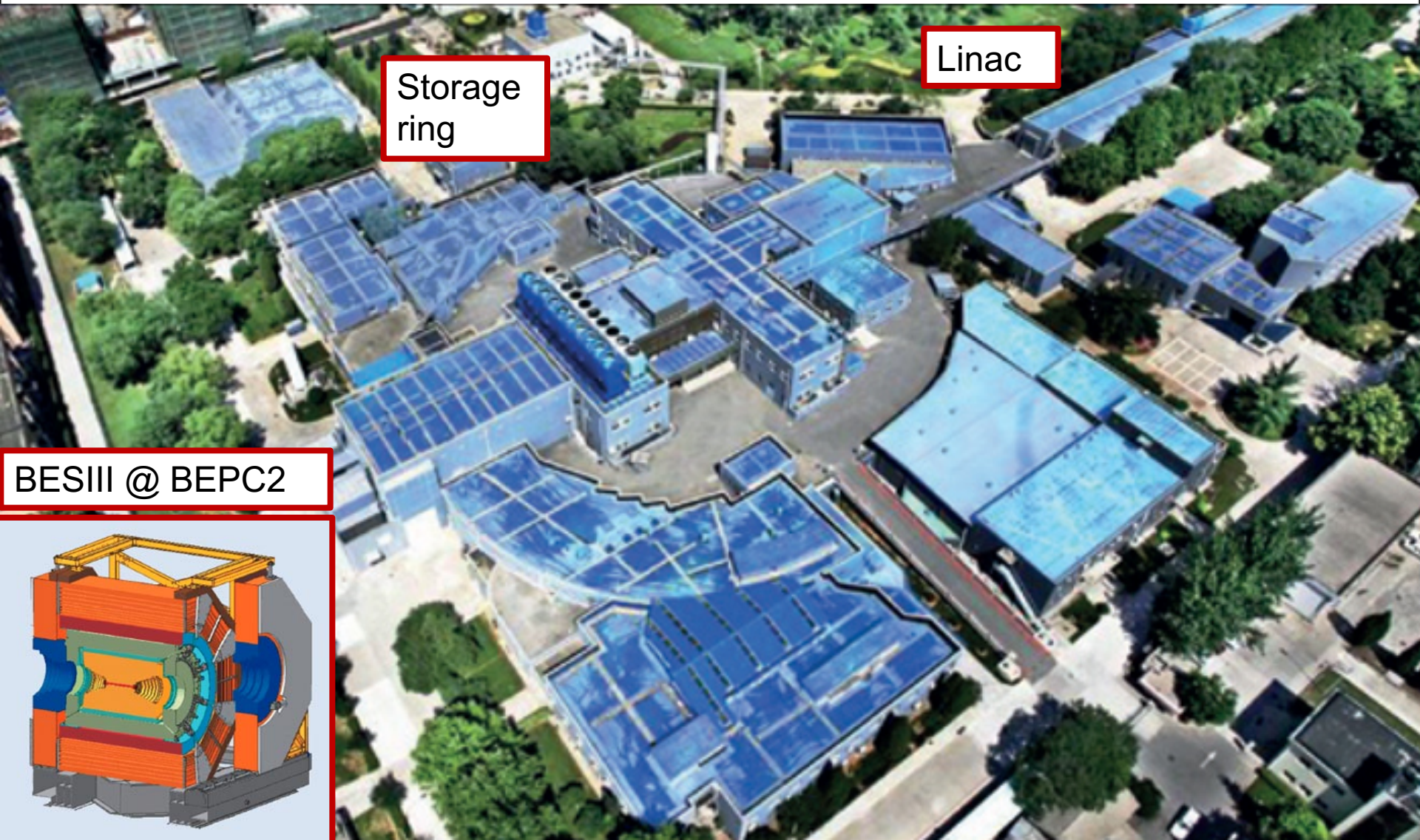
- **QCD bound states**
 - Charmonium
 - Exotic excitations and state
 - Heavy-light systems
 - Strange & charmed baryons
- **Non-perturbative QCD dynamics**
 - $pp \rightarrow YY$
- **Electroweak physics**
 - CP – violation
 - Rare decays
- **Nucleon structure**
 - Form Factor, TDA, ...
- **Hadrons in nuclear medium**
- **Hypernuclear physics**





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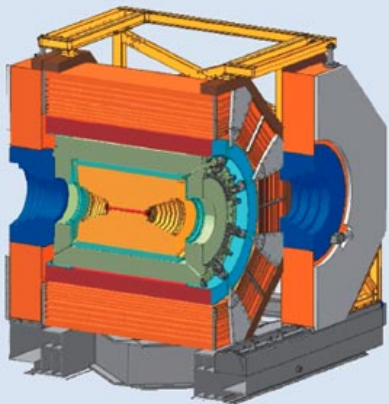
Beijing E₊Positron Collider



Storage
ring

Linac

BESIII @ BEPC2





Measurement of Time Like Form Factors

The cross section is given by:

$$\frac{d\sigma_{Born}(q^2)}{d\Omega} = \frac{\alpha^2\beta}{4q^2} [|G_M(q^2)|^2(1 + \cos^2\theta) + \frac{1}{\tau}|G_E(q^2)|^2(\sin^2\theta)],$$

where G_E and G_M are the Sachs form factors.

Introducing the ratio R

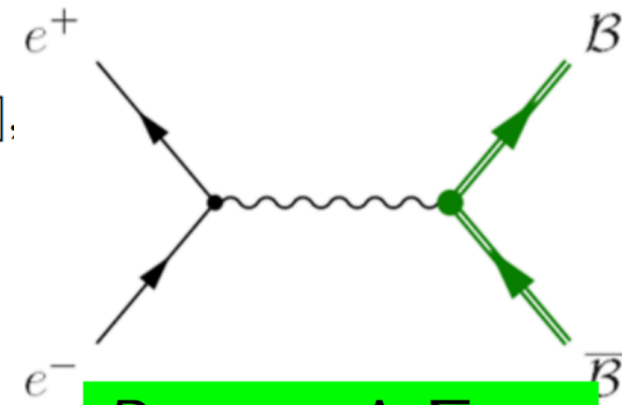
$$R = |G_E(q^2)/G_M(q^2)|$$

The cross section is given by:

$$\frac{d\sigma_{Born}(q^2)}{d\cos\theta} = \frac{2\pi\alpha^2\beta}{4q^2} [(1 + \cos^2\theta) + \frac{1}{\tau}R^2(\sin^2\theta)]$$

In the timelike region, the FFs are complex numbers and related by the phase

$$G_E(q^2) = Re^{i\Delta\Phi}G_M(q^2)$$



$$B = n, p, \Lambda, \Sigma, \dots$$

Measurement of Time Like Form Factors

The polarization is given by:

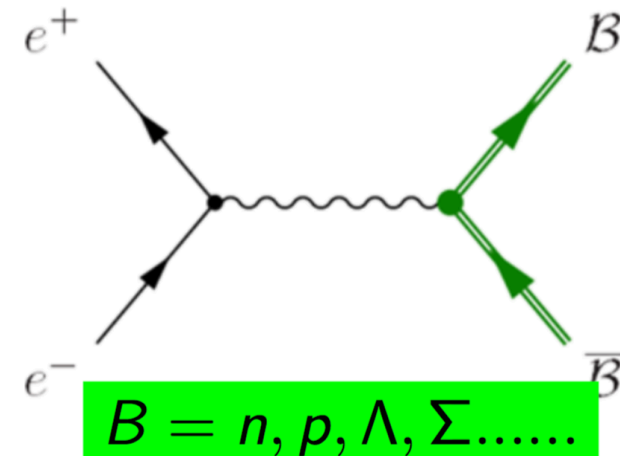
$$P_n = -\frac{\sin 2\theta \operatorname{Im}[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1 + \cos^2 \theta) + \frac{1}{\tau}|G_E(q^2)|^2 \sin^2 \theta}$$

$$= -\frac{\sin 2\theta/\sqrt{\tau}}{(1 + \cos^2 \theta) + \frac{R^2}{\tau}(1 - \cos^2 \theta)} R \sin \Delta\Phi$$

Measuring the polarization gives the modulus of $\Delta\Phi$

$$C_{lm} = \frac{\sin 2\theta \operatorname{Re}[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1 + \cos^2 \theta) + \frac{1}{\tau}|G_E(q^2)|^2 \sin^2 \theta}$$

And measuring the spin correlation gives the sign of $\Delta\Phi$!



Measurement of Time Like Form Factors

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$$P_n = -\frac{\sin 2\theta \operatorname{Im}[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1 + \cos^2 \theta) + \frac{1}{\tau}|G_E(q^2)|^2 \sin^2 \theta}$$

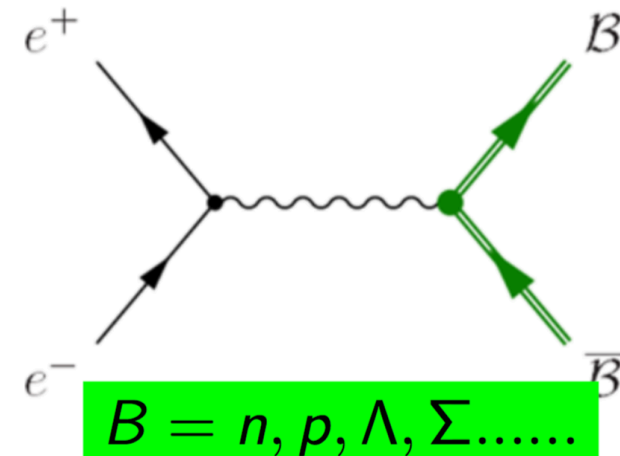
$$= -\frac{\sin 2\theta/\sqrt{\tau}}{(1 + \cos^2 \theta) + \frac{R^2}{\tau}(1 - \cos^2 \theta)} R \sin \Delta\Phi$$

Measuring the polarization gives the modulus of $\Delta\Phi$

$$C_{lm} = \frac{\sin 2\theta \operatorname{Re}[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1 + \cos^2 \theta) + \frac{1}{\tau}|G_E(q^2)|^2 \sin^2 \theta}$$

And measuring the spin correlation gives the sign of $\Delta\Phi$!

By measuring the angles of the $\bar{\Lambda}\Lambda$ decay products, the Λ form factor is completely determined!

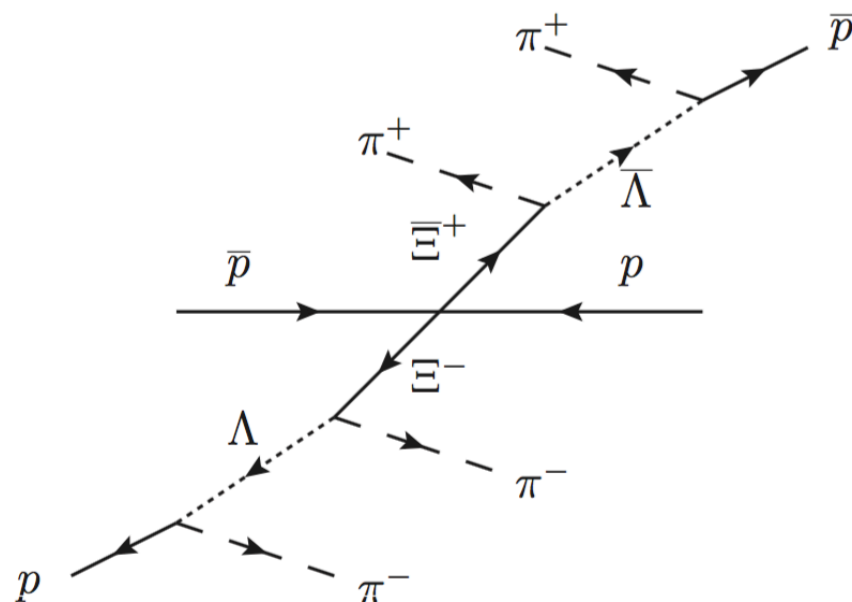




Preselection

Preselection:

- Combinatorics to construct Ξ candidates
- Mass selection $|m_{pdg} - m_{rec}| < 50 \text{ MeV}/c^2$ on Ξ and Λ
- Fit candidates under $\Xi \rightarrow \Lambda\pi \rightarrow p\pi\pi$ hypothesis
- Vertex fit $\bar{\Xi}^+\Xi^-$ to reconstruct I.P.
- Geometric selection criteria
- Kinematic fit of $\bar{\Xi}^+\Xi^-$ with constraints to p_{ini}
- Choose candidate with smallest χ^2





Topological Selections

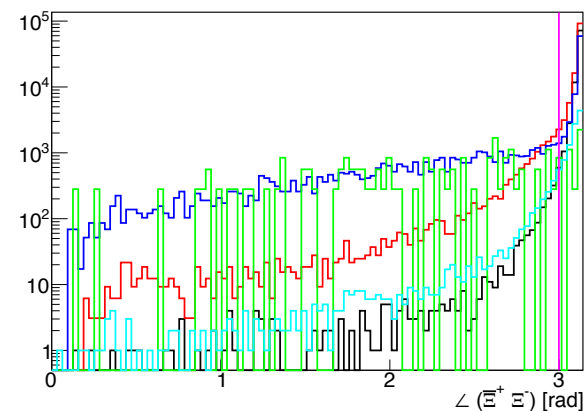
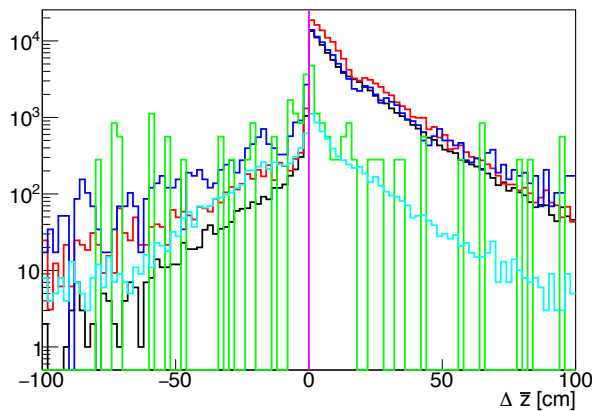
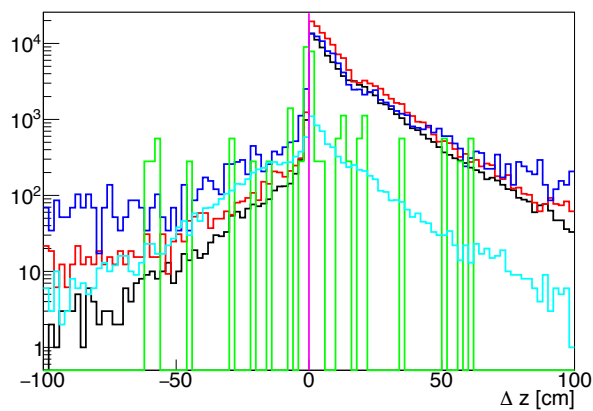
- Black – $\bar{\Xi}^+ \Xi^-$
- Red – $\bar{\Sigma}^+(1385)$
- Blue – $\bar{\Lambda} \Lambda \pi^+ \pi^-$
- Green – $\bar{p} p 2\pi^+ 2\pi^-$
- Cyan – Combinatorics

The Λ decay vertex should be further downstream

- Select $z_{\Lambda} - z_{\Xi} > 0$

$\bar{\Xi}^+ \Xi^-$ should be back-to-back

- Select $\angle(\bar{\Xi}^+ \Xi^-) > 3 \text{ rad}$

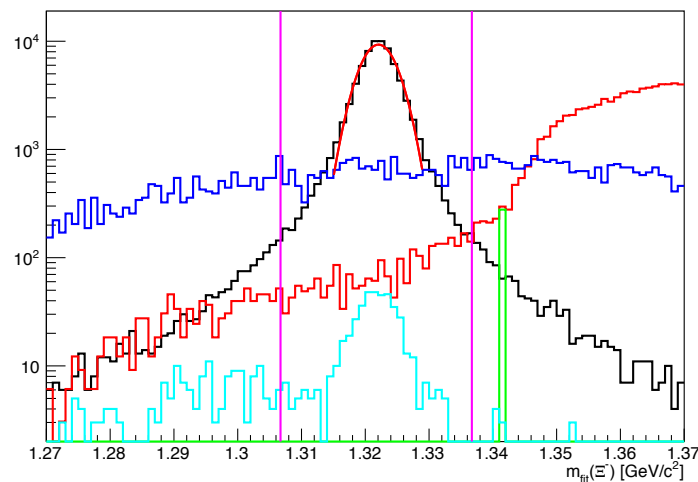
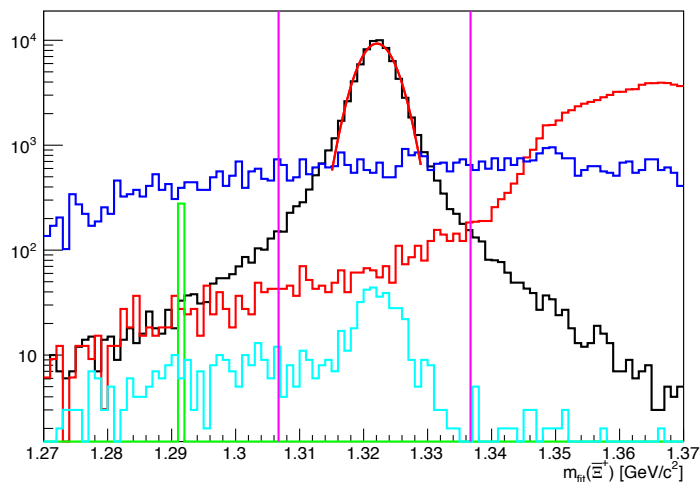


Invariant Mass

- Black – $\bar{\Xi}^+ \Xi^-$
- Red – $\bar{\Sigma}^+(1385)$
- Blue – $\bar{\Lambda} \Lambda \pi^+ \pi^-$
- Green – $\bar{p} p 2\pi^+ 2\pi^-$
- Cyan – Combinatorics

Fit on invariant mass yields:

- $m_{\Xi} = 1322.0 \text{ MeV}/c^2$
- $\sigma_m = 3.0 \text{ MeV}/c^2$
- Select $|m_{\Xi} - m_{fit}(\Lambda\pi)| < 15 \text{ MeV}/c^2$

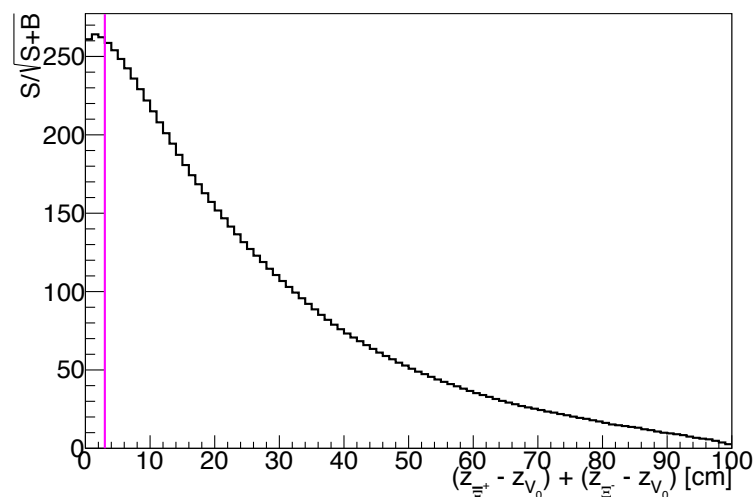
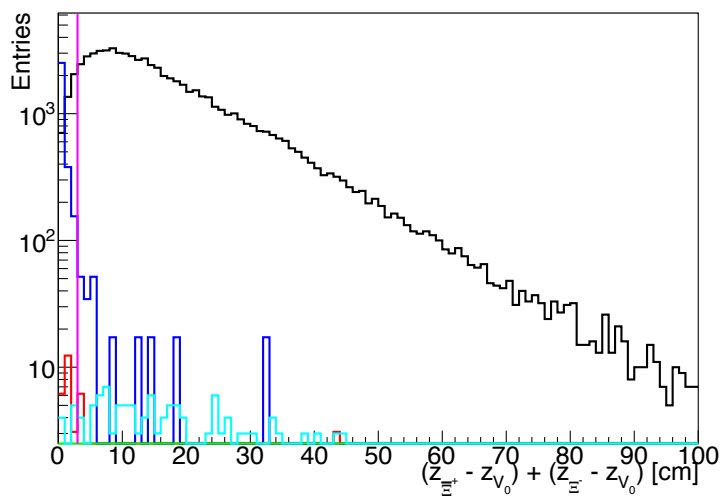


Displaced Vertex

- Black – $\bar{E}^+ E^-$
- Red – $\bar{\Sigma}^+(1385)$
- Blue – $\bar{\Lambda} \Lambda \pi^+ \pi^-$
- Green – $\bar{p} p 2\pi^+ 2\pi^-$
- Cyan – Combinatorics

$\bar{E}^+ E^-$ are displaced from IP

- Select $(z_{\bar{E}^+} - z_{IP}) + (z_{E^-} - z_{IP}) > 3$





Selection Efficiency

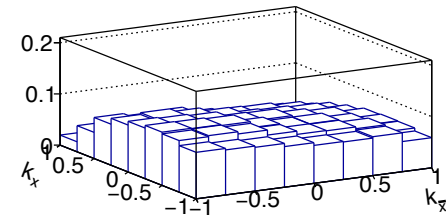
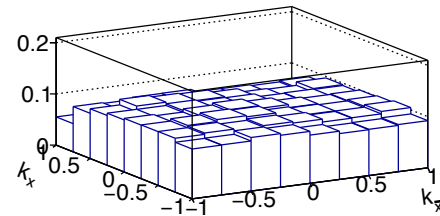
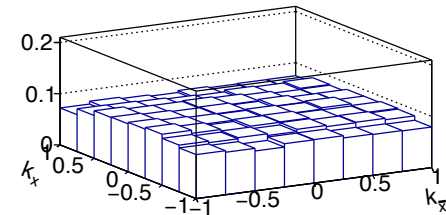
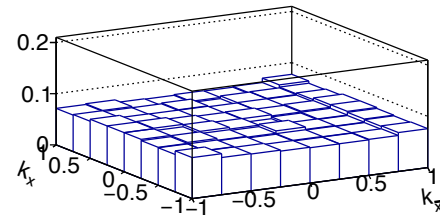
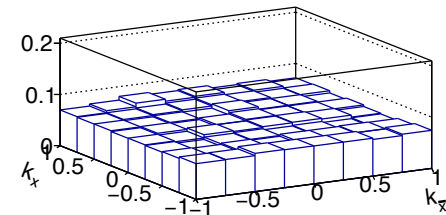
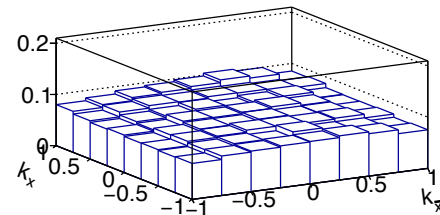
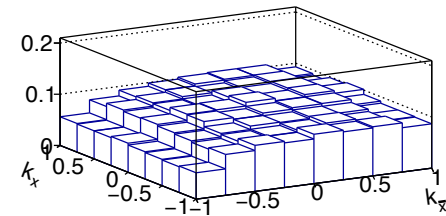
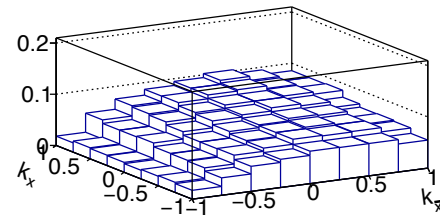
All efficiencies are in %

Channel	$\bar{p}p \rightarrow \bar{E}^+ E^-$	$\bar{\Sigma}^+ (1385)$	$\bar{\Lambda}\Lambda\pi^+\pi^-$	$\bar{p}p2\pi^+2\pi^-$	DPM
Preselection	9.2	0.35	3.5×10^{-2}	1.0×10^{-5}	1.4×10^{-4}
Mass cut	8.5	2.3×10^{-4}	3.9×10^{-3}	0	2.0×10^{-5}
Displaced	7.9	3.0×10^{-5}	1.4×10^{-4}	0	0
N weighted	6.76×10^4	9	239	0	0
S/B	420	7.4×10^3	283	> 106 90% C.L.	> 0.7 90% C.L.

Acceptance Correction Matrices

Acceptance correction used for
 C_{xx}

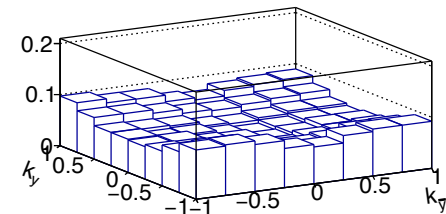
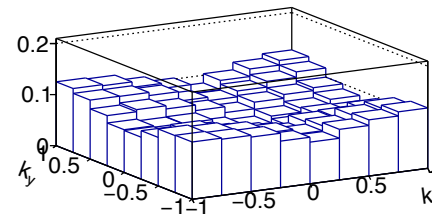
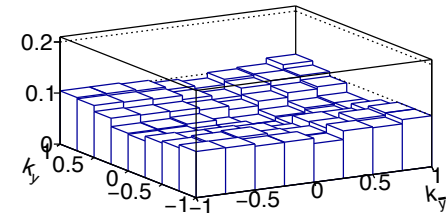
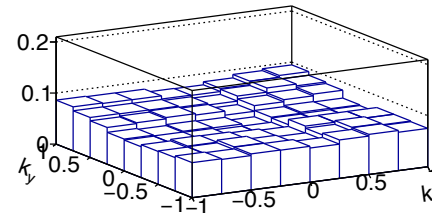
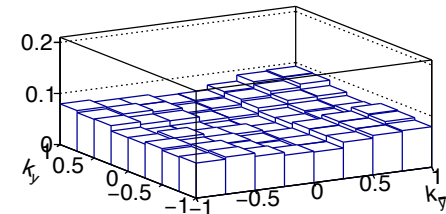
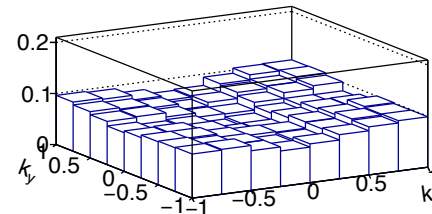
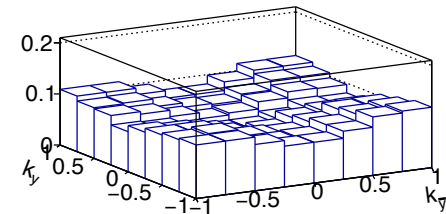
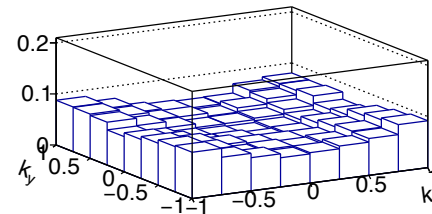
- Top left: $-1 < \cos \theta_{cm} < -0.75$
- Top right: $-0.75 < \cos \theta_{cm} < -0.5$
- And so on...



Acceptance Correction Matrices

Acceptance correction used for C_{yy}

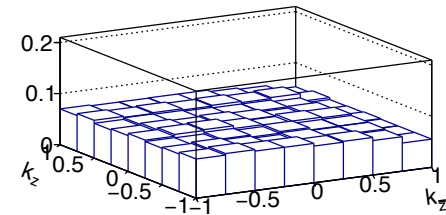
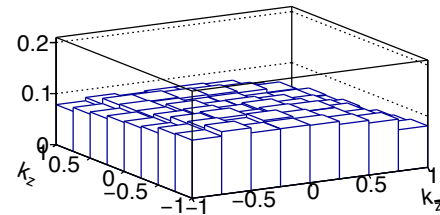
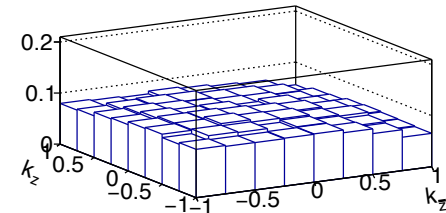
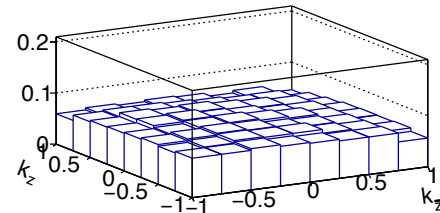
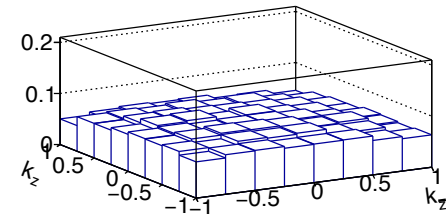
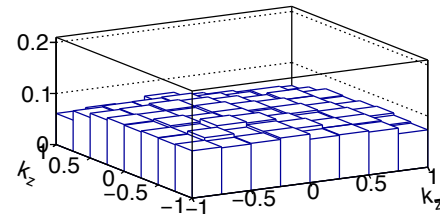
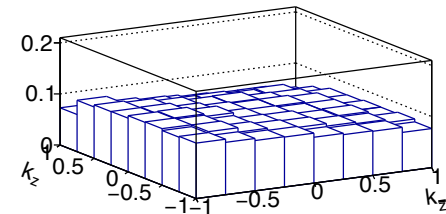
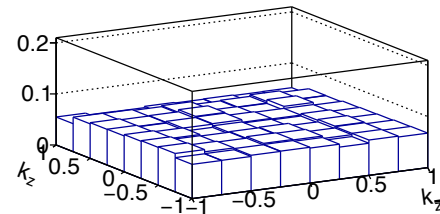
- Top left: $-1 < \cos \theta_{cm} < -0.75$
- Top right: $-0.75 < \cos \theta_{cm} < -0.5$
- And so on...



Acceptance Correction Matrices

Acceptance correction used for C_{zz}

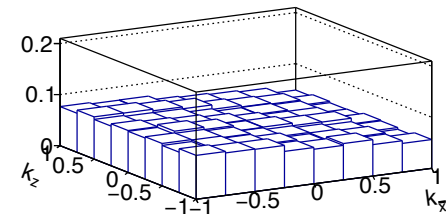
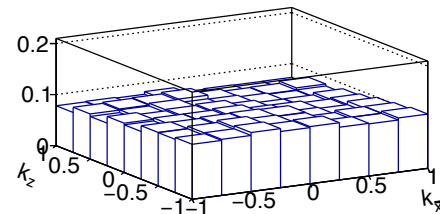
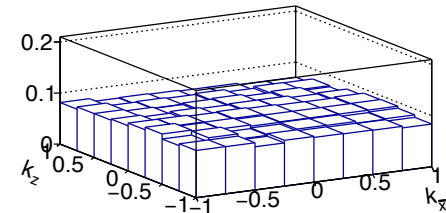
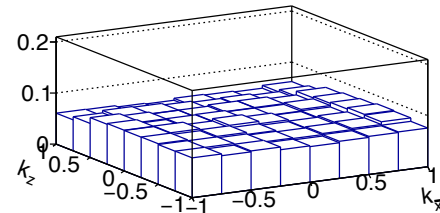
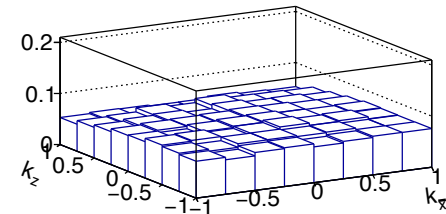
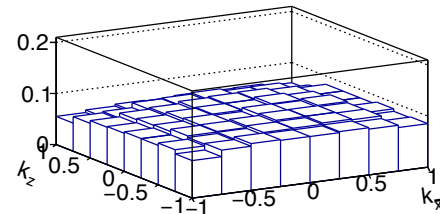
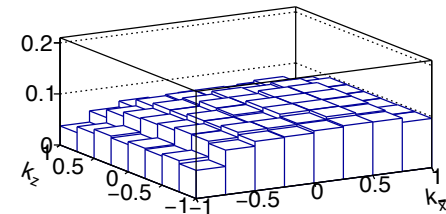
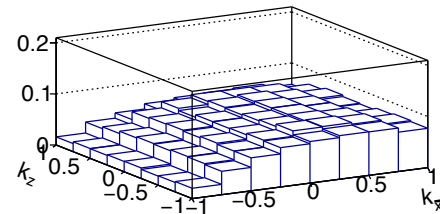
- Top left: $-1 < \cos \theta_{cm} < -0.75$
- Top right: $-0.75 < \cos \theta_{cm} < -0.5$
- And so on...



Acceptance Correction Matrices

Acceptance correction used for
 C_{xz}

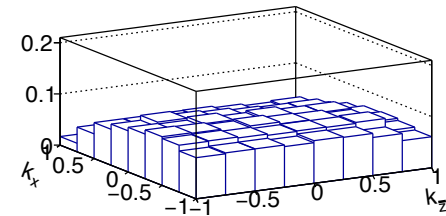
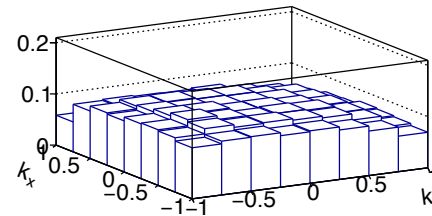
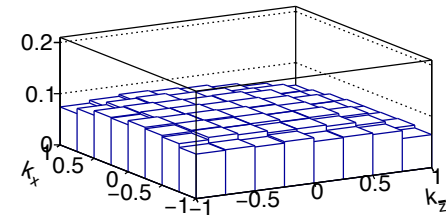
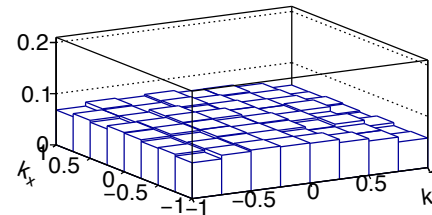
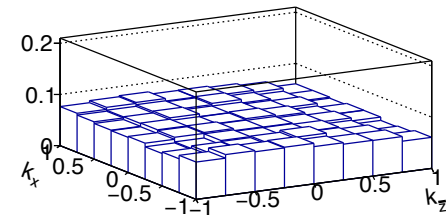
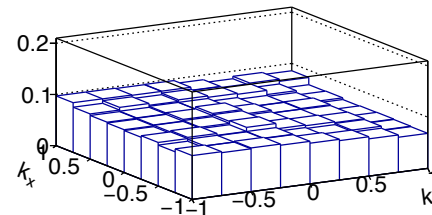
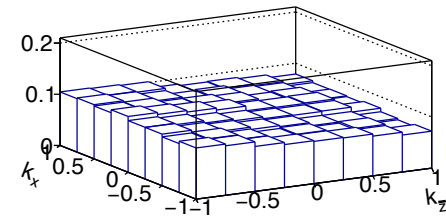
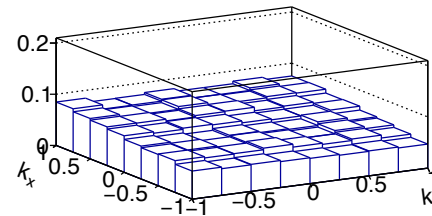
- Top left: $-1 < \cos \theta_{cm} < -0.75$
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- And so on...



Acceptance Correction Matrices

Acceptance correction used for
 C_{zx}

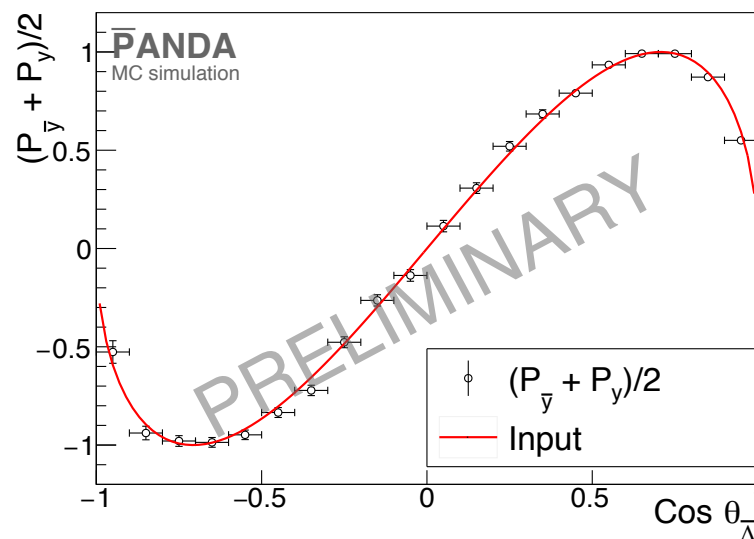
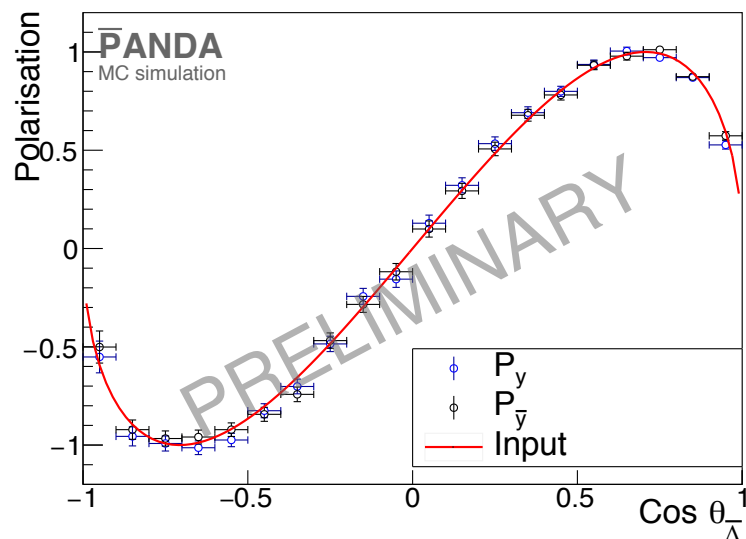
- Top left: $-1 < \cos \theta_{cm} < -0.75$
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- And so on...





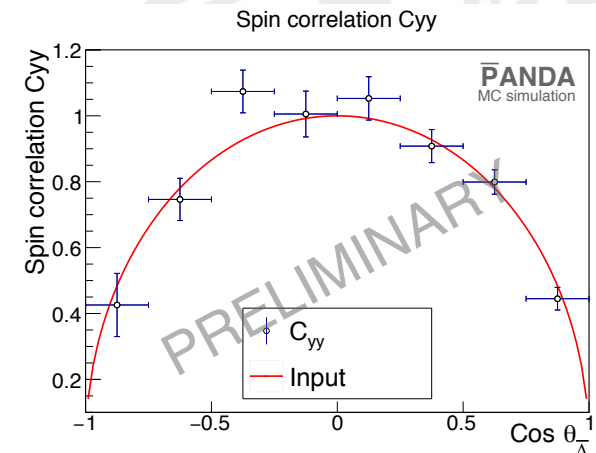
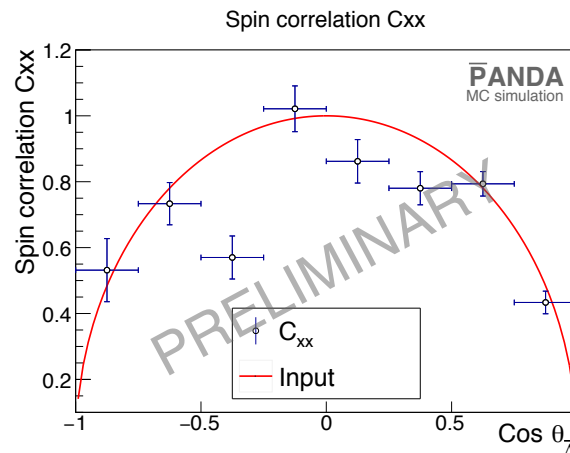
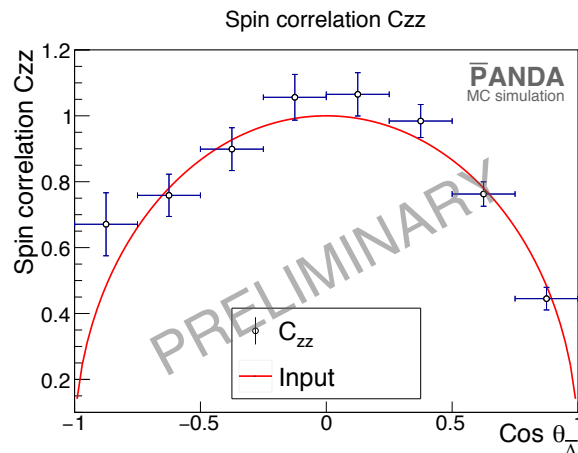
Polarisation

- **Polarisation input set to $P_y = \sin 2\theta$, Studied in $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$**
 - Satisfies symmetry requirements
 - Resembles measurement at LEAR
- **Horizontal bars are bin widths**
Vertical bars are statistical uncertainties



Spin Correlation

- **Spin Correlation input set to $C_{ii} = \sin \theta$**
 - Satisfies symmetry requirements
- **Horizontal bars are bin widths**
Vertical bars are statistical uncertainties



Spin Correlation

- **Spin Correlation input set to $C_{ij} = \sin \theta$**
 - Satisfies symmetry requirements
- **Horizontal bars are bin widths**
Vertical bars are statistical uncertainties

