Probing transversity by measuring Λ polarization in SIDIS

Andrea Moretti

on behalf of the COMPASS Collaboration

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- Introduction
- Experimental access to transversity

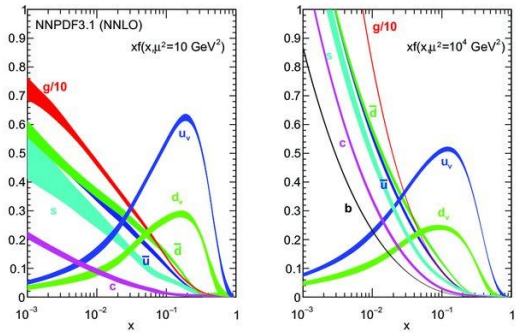
  Spin transfer to final-state baryon
- COMPASS measurement of $\Lambda(\overline{\Lambda})$ polarization
- Results and Interpretation
- Outlook

Introduction

The collinear structure of the nucleon is described by three Parton Distribution Functions (PDFs):

unpolarized PDF $f_1^q(x, Q^2)$

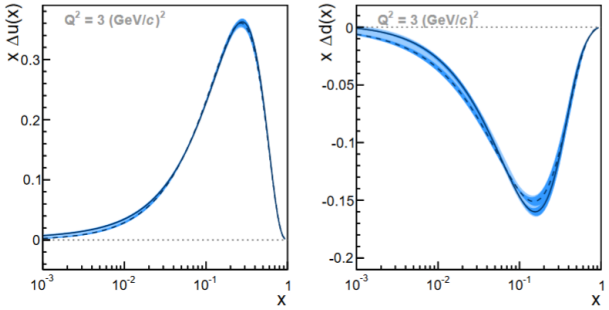
probabilistic interpretation
number density of
unpolarized parton in unpolarized nucleon



NNPDF Collaboration, *Eur.Phys.J. C 77 663 (2017)*

helicity $g_1^q(x, Q^2)$

probabilistic interpretation
difference of probability that the quark is
polarized parallel and anti-parallel to the
longitudinally polarized nucleon

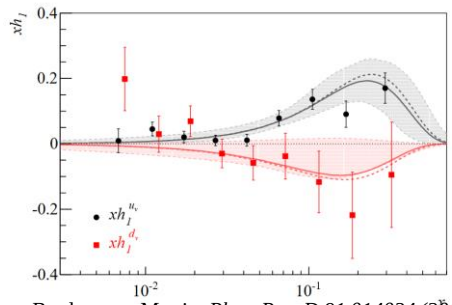


COMPASS Collaboration, *Phys.Lett. B769 (2017) 34-41*

transversity $h_1^q(x, Q^2)$

probabilistic interpretation
difference of probability that the quark is
polarized parallel and anti-parallel to the
transversely polarized nucleon

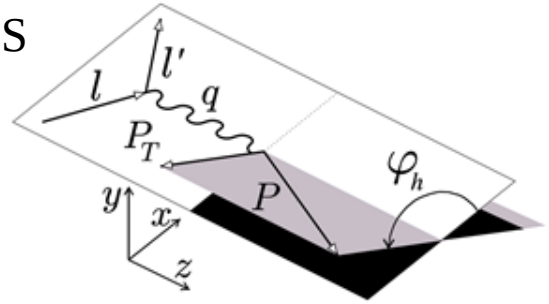
Large uncertainties: will be reduced thanks to
COMPASS 2021/2022, JLAB12, EIC (future)



Barone Bradamante Martin, *Phys. Rev. D 91 014034 (2015)*

Experimental channels to access h_1^q in SIDIS

Several experimental channels exist to access transversity in SIDIS

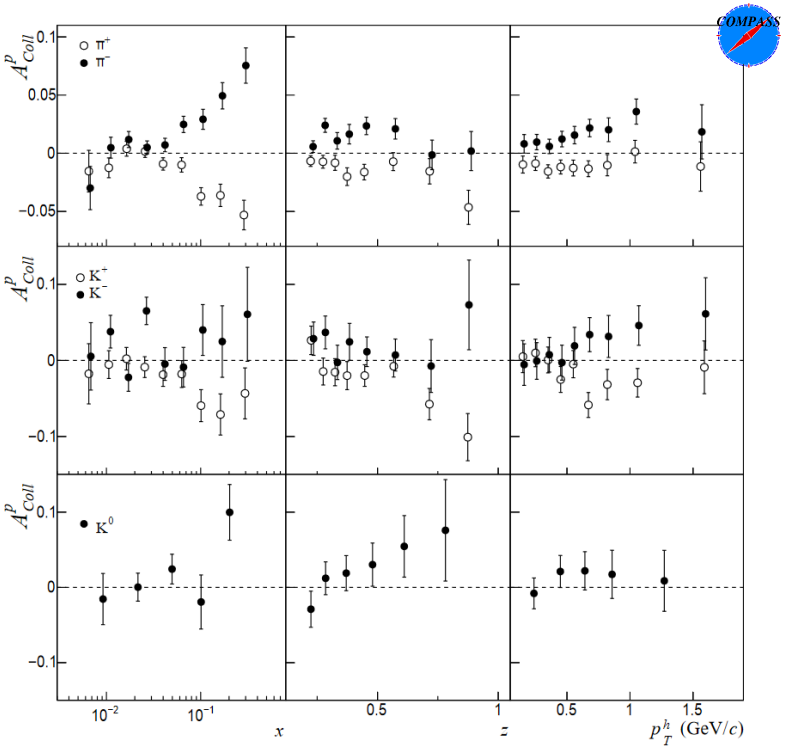


- **Collins asymmetries**

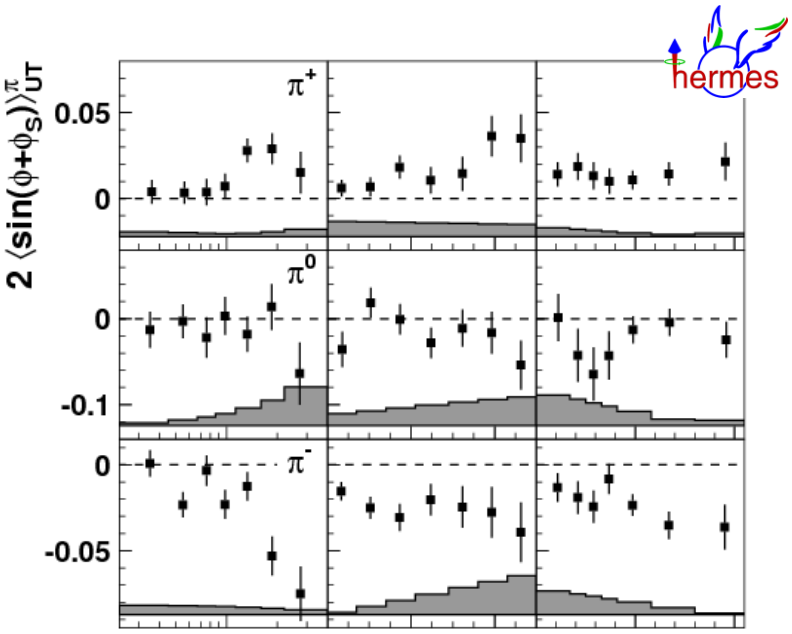
  hadrons produced in SIDIS off transversely polarized nucleons

  $\sim h_1^q(x,Q^2)H_1^\perp(z,Q^2)$: transversity coupled to Collins FF.

  first measured in 2005



COMPASS Collaboration, *Phys.Lett.B 744 (2015) 250-259*



HERMES Collaboration, *Phys.Lett.B 693 (2010) 11-16*

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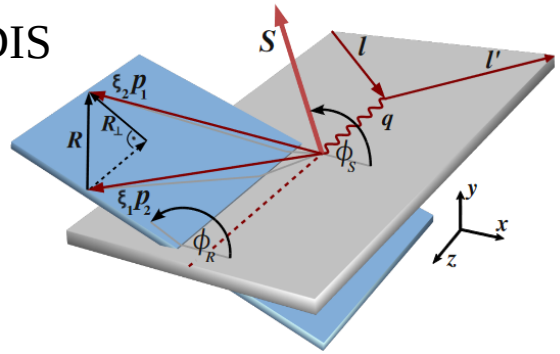
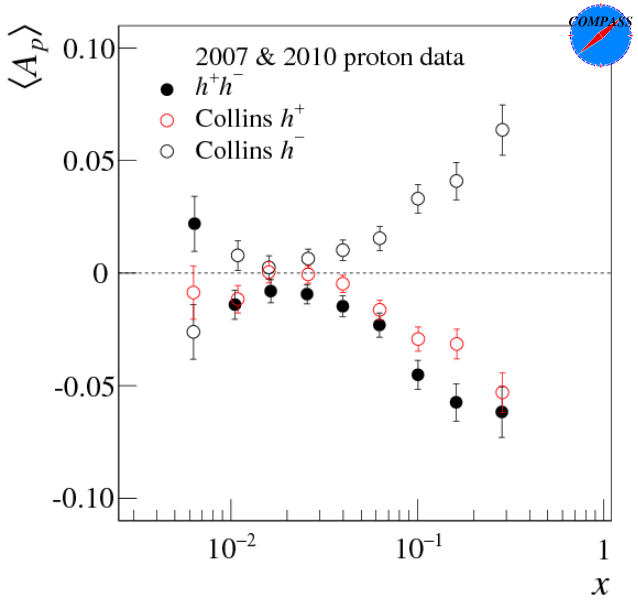


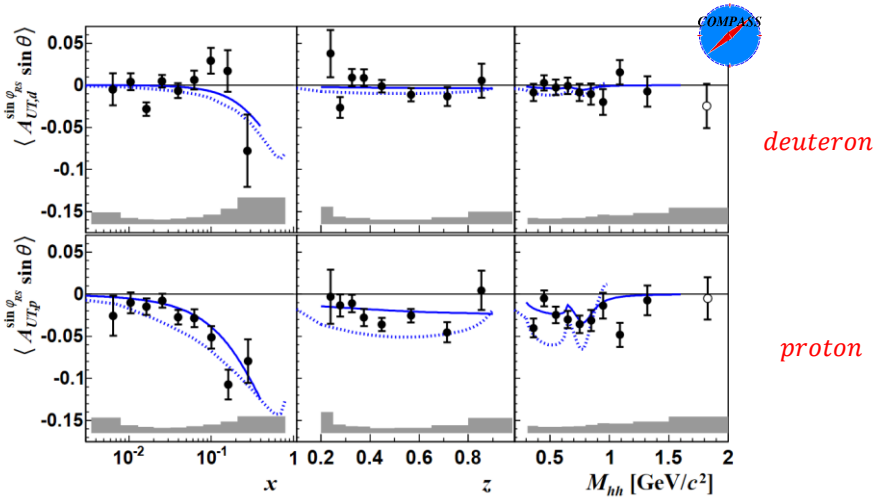
- **Azimuthal asymmetries of hadron pairs**

  hadron pairs produced in SIDIS off transversely polarized nucleons

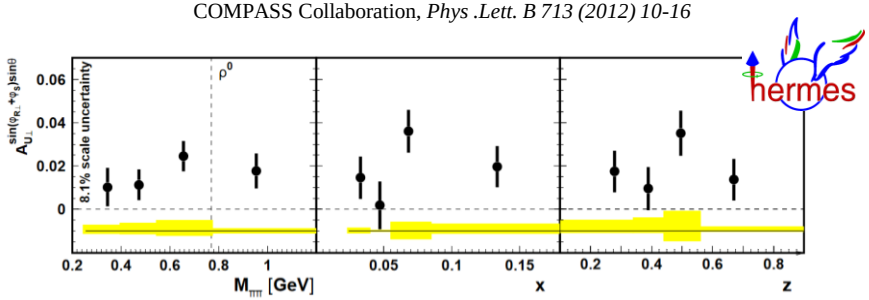
  $\sim h_1^q(x,Q^2)H_1^{\sphericalangle}\left(z_{h_1}+z_{h_2}, M_{h_1h_2}, Q^2\right)$: transversity coupled to interference FF.



COMPASS Collaboration, *Phys. Lett. B 713 (2012) 10-16*



COMPASS Collaboration, *Phys .Lett. B 713 (2012) 10-16*



HERMES Collaboration, *JHEP 06 (2008) 017*

Spin transfer to a final-state baryon

A third, independent channels to access transversity in SIDIS

- **Spin transfer to final-state baryon**

  - polarization transfer from the struck quark to the final state baryon proportional to transversity
  - the most suitable baryon type: Λ, due to its self-analyzing decay
  - the decay proton angular asymmetry reveals the parent polarization

.

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In the collinear approximation and in the current fragmentation region:

$$P_{\Lambda(\bar{\Lambda})}(x,z,Q^2) = \frac{\mathrm{d}\sigma^{\ell p^{\uparrow}\to \ell' \Lambda(\bar{\Lambda})^{\uparrow} X} - \mathrm{d}\sigma^{\ell p^{\uparrow}\to \ell' \Lambda(\bar{\Lambda})^{\downarrow} X}}{\mathrm{d}\sigma^{\ell p^{\uparrow}\to \ell' \Lambda(\bar{\Lambda})^{\uparrow} X} + \mathrm{d}\sigma^{\ell p^{\uparrow}\to \ell' \Lambda(\bar{\Lambda})^{\downarrow} X}}$$

$$= f P_T D_{NN} \frac{\sum_q e_q^2 h_1^q(x,Q^2) H_{1,q}^{\Lambda(\bar{\Lambda})}(z,Q^2)}{\sum_q e_q^2 f_1^q(x,Q^2) D_{1,q}^{\Lambda(\bar{\Lambda})}(z,Q^2)}$$

f: dilution factor

P_T: target polarization

D_{NN}: depolarization factor

Measured in COMPASS for the first time

Topic of this talk

CERN-EP-2021-072

STAR@RHIC: transverse spin transfer in pp *collision found compatible with zero*
Phys. Rev. D 98, 091103 (2018)

The COMPASS experiment at CERN

COMPASS contribution to the understanding of the nucleon structure (also beyond collinear)

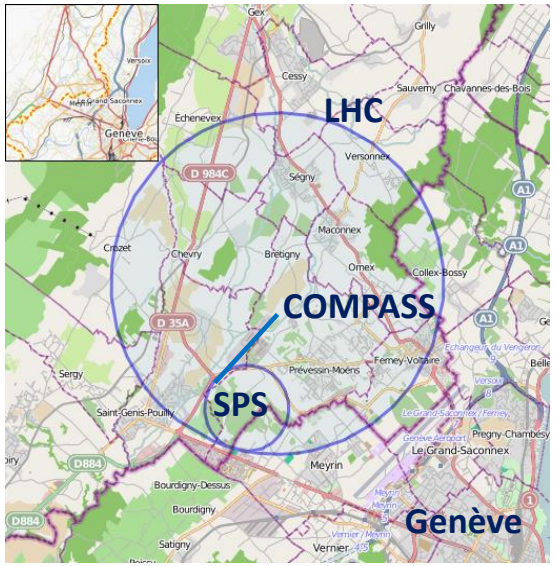
- spin asymmetries with transverse and longitudinal spin polarization (nuclear and/or lepton beam)
  - g_1, quark helicity, gluon polarization
  - transversity and Sivers functions
  - …
- SIDIS with unpolarized target
  - azimuthal asymmetries and P_T^2-distributions on deuteron, collinear multiplicities
  - …

COMPASS (COmmon Muon Proton Apparatus for Structure and Spectroscopy):

- 24 institutions from 13 countries (about 220 physicists)
- a fixed target experiment
- located in the CERN North Area, along the SPS M2 beamline

Broad research program:

- SIDIS with μ beam, with (un)polarized deuteron or proton target.
- Drell-Yan measurement with π^- beam with polarized target
- Deeply Virtual Compton Scattering (DVCS)
- Hadron spectroscopy with hadron beams and nuclear targets
- …



The COMPASS location at CERN

The COMPASS experiment at CERN

Data used in this analysis: collected in 2007 and 2010 with a transversely polarized NH_3 (proton) target

COMPASS apparatus in 2010 (top view)

similar in 2007

Large Angle Spectrometer

+ Small Angle Spectrometer

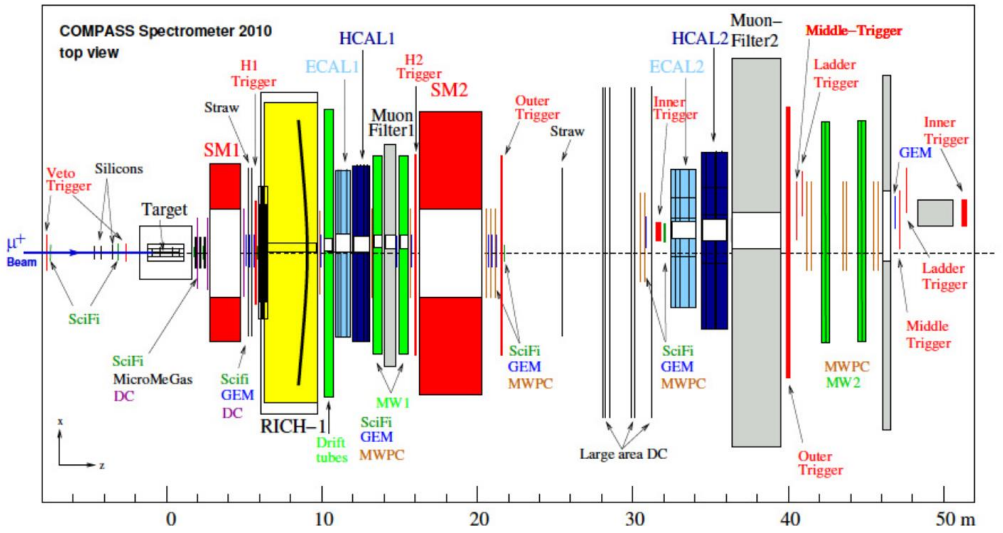
more than 50 m long

built around the magnets (SM1 and SM2)

330 detection plane

RICH for PID

Electromagnetic and hadron calorimeters



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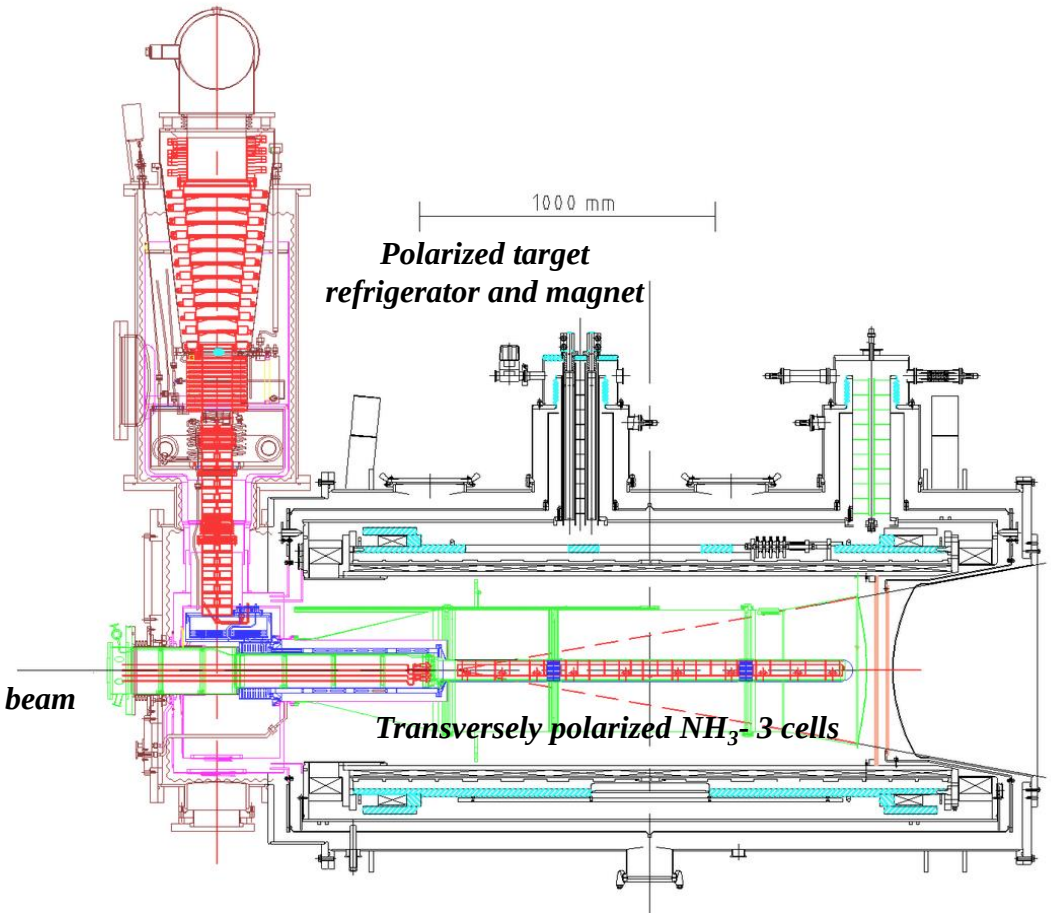


Target

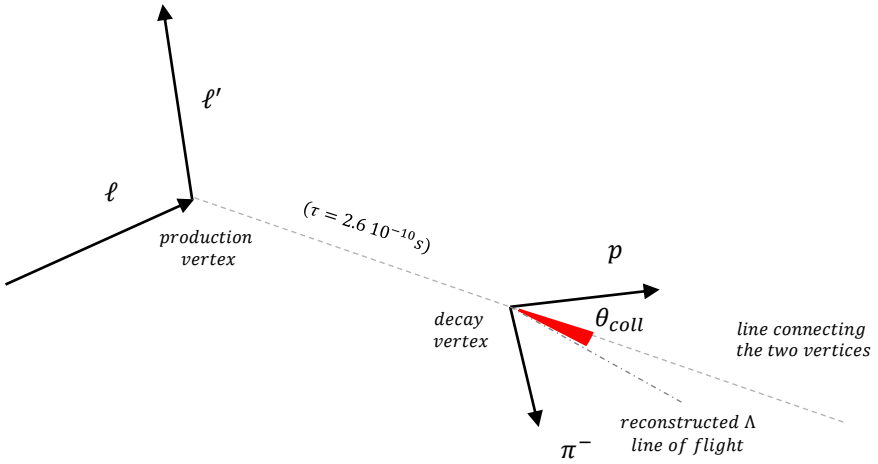
NH_3 (proton) transversely polarized target
dynamic nuclear polarization technique
cryogenic temperature
divided in 3 cells with opposite polarization
polarization reversal every few days
→ *minimization of acceptance effects*

Data selection and statistics

Data used in this analysis: collected in 2007 and 2010 with a transversely polarized NH_3 (proton) target

Selection of Λ ($\bar{\Lambda}$) candidates

- $Q^2 > 1$ (GeV/c) ^{2}
- $0.003 < x < 0.700$
- $W > 5$ GeV/c^2
- $0.1 < y < 0.9$

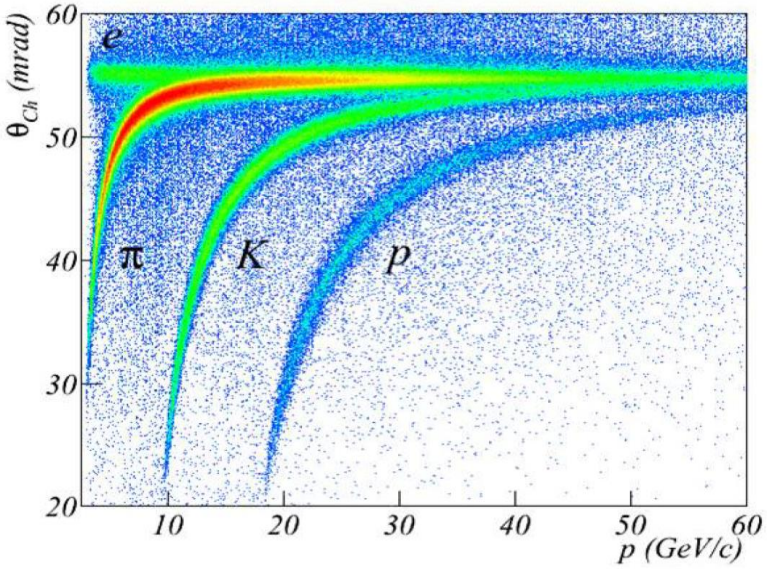


- **Collinearity angle** $\theta_{coll} < 7$ mrad

- **Transverse momentum** of the decay products, in the CMS, $p_\perp > 23$ MeV/c
  to limit the $\gamma \to e^+e^-$ conversion background

- **Particle identification with RICH**
  C_4F_{10} Cherenkov threshold for proton ~ 20 GeV: high

  A veto is preferred to the direct PID:
  In the Λ ($\bar{\Lambda}$) case, the positive (negative) hadron is assumed to be a p ($\bar{p}$) unless identified as $e^+(e^-)$, $K^+(K^-)$ or $\pi^+(\pi^-)$.



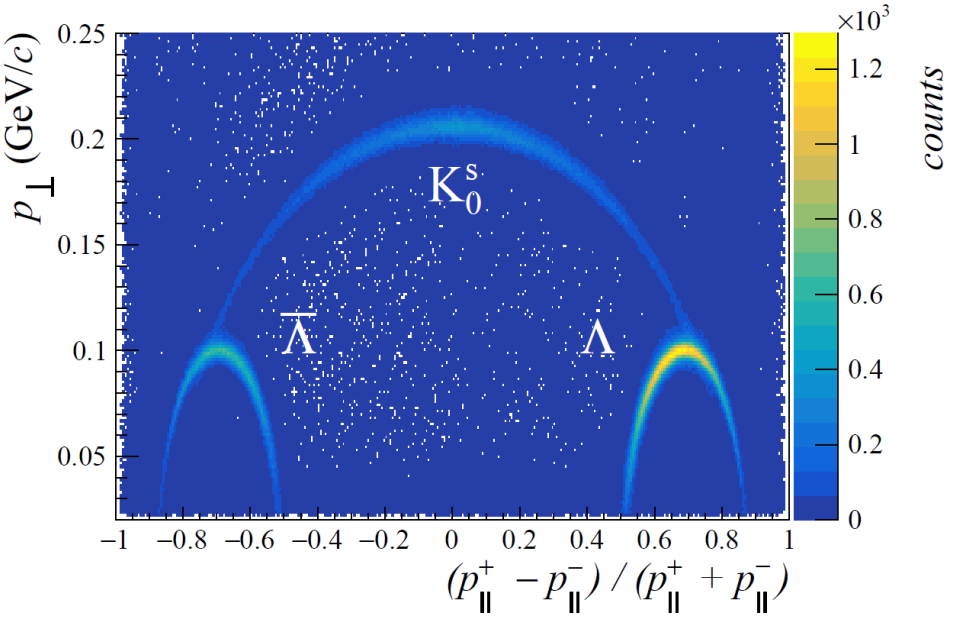
Data selection and statistics

The resulting Armenteros plot:

showing the transverse momentum $p_\perp$ of one of the decay products vs. the $p_\parallel$ asymmetry in the CMS

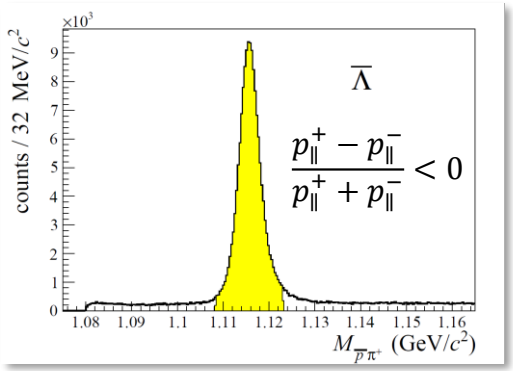
allows identifying the Λ, $\overline{\Lambda}$ and K_0^S contributions

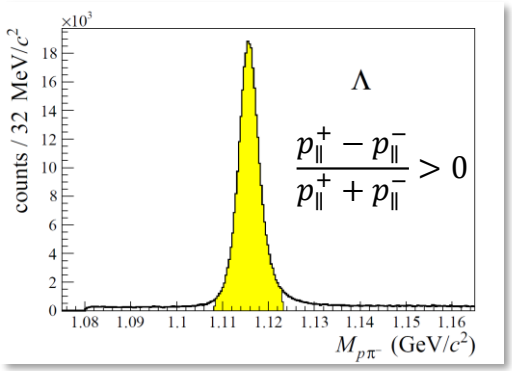
small K_0^S contribution, removed by a cut on the invariant mass of the pair



Invariant mass spectra

fitted with a Gaussian + 3rd order polynomial
selection of events within 3σ (= max FoM)
background under the peak → sideband method





Statistics

Λ: 296 546 $\pm$ 562 events — 63%
$\overline{\Lambda}$: 144 463 $\pm$ 405 events — 68%

directly produced (estimate from LEPTO, COMPASS tuning)

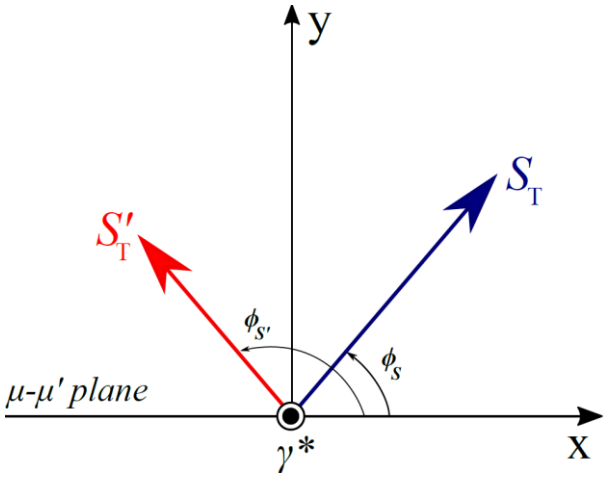
the world's largest sample of Λ ($\overline{\Lambda}$) produced in transversely polarized SIDIS.

Extraction method

$P_{\Lambda(\bar{\Lambda})}$ measured in the hyperon rest frame by looking at the polar angle distribution of the proton

- Taking the outgoing quark spin direction $\boldsymbol{S'_T}$ as the reference axis

- An event-by-event procedure
  1) initial quark spin direction: parallel to the target polarization vector $\boldsymbol{S_T}$
  2) final quark spin direction $\boldsymbol{S'_T}$: reflection of $\boldsymbol{S_T}$ with respect to the normal to the scattering plane



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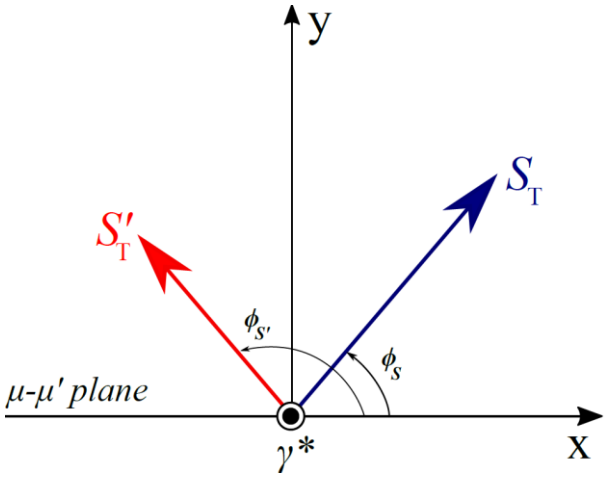
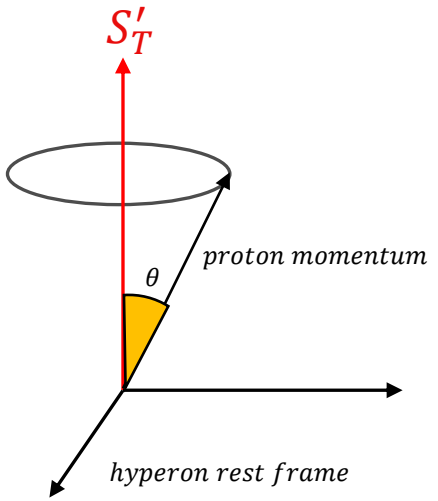


- Number of Λ ($\bar{\Lambda}$) hyperons emitting a p ($\bar{p}$) in each $cos\theta$ bin, from given target cell and cell polarization

$$\mathcal{N}_{\Lambda(\bar{\Lambda})}(cos\theta) = \rho\Phi\bar{\sigma}\left(1 + \alpha_{\Lambda(\bar{\Lambda})}P_{\Lambda(\bar{\Lambda})}cos\theta\right)A(cos\theta)$$

$\bar{\sigma}$: *production cross − section*; ρ: *nucleons per unit area*; Φ: *muon flux*; $\alpha_{\Lambda(\bar{\Lambda})}$: *self − analyzing decay*; $A(cos\theta)$: *acceptance*



- By combining subperiods (') and cells (1,2) with opposite polarizations:

$$\varepsilon_{\boldsymbol{\Lambda(\bar{\Lambda})}} = \frac{\mathcal{N}_{\Lambda(\bar{\Lambda})1}(cos\theta)\mathcal{N}'_{\Lambda(\bar{\Lambda})2}(cos\theta)}{\mathcal{N}'_{\Lambda(\bar{\Lambda})1}(cos\theta)\mathcal{N}_{\Lambda(\bar{\Lambda})2}(cos\theta)} \approx \boldsymbol{1 + 4\alpha_{\Lambda(\bar{\Lambda})}P_{\Lambda(\bar{\Lambda})}cos\theta}$$

fit

Kinematic regions

Transversity-induced polarization measured in the full phase-space and in the following regions:

- $z \geq 0.2$ and $x_F > 0$ (current fragmentation)
- $z < 0.2$ or $x_F < 0$ (target fragmentation)
- $x \geq 0.032$ (valence)
- $x < 0.032$
- $p_T \geq 0.5$ GeV/c
- $p_T < 0.5$ GeV/c

The polarization is found compatible with zero in all regions.

Results

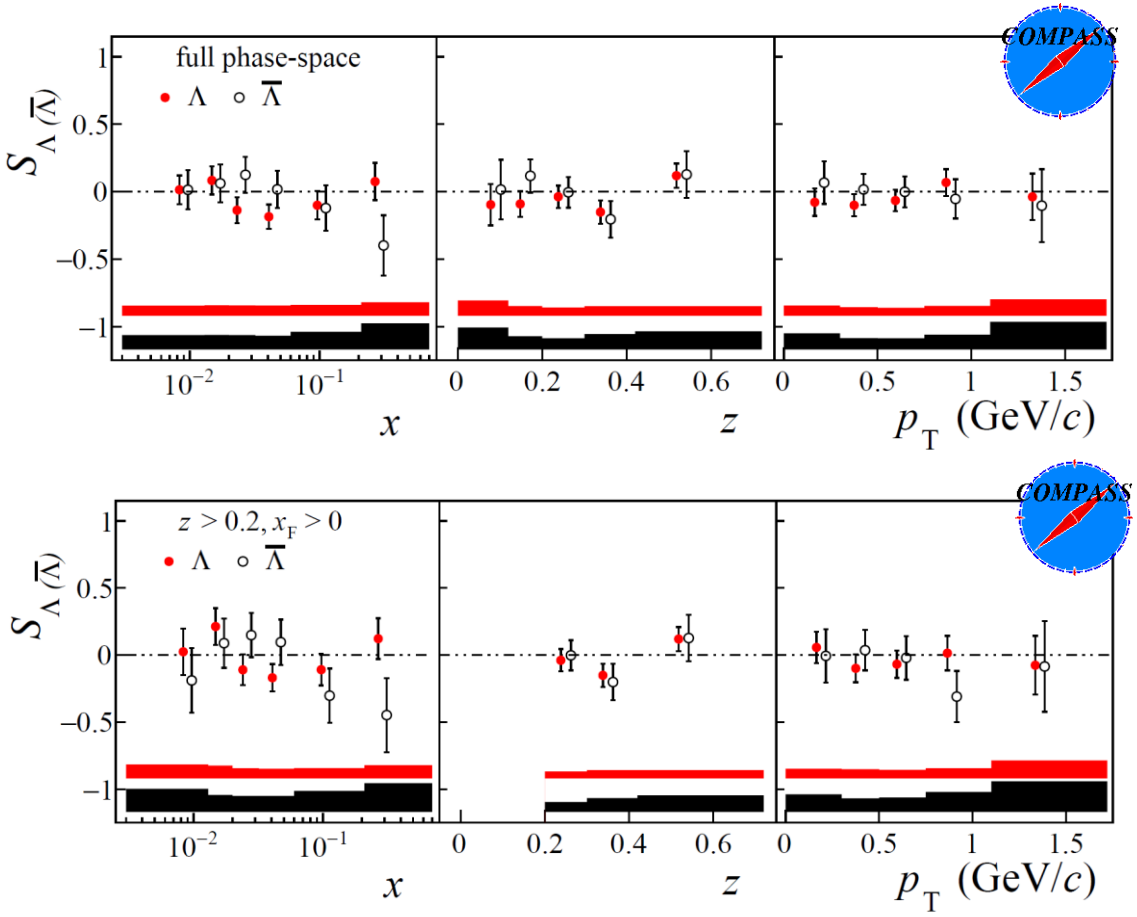
The polarization is found compatible with zero in all regions.

Here shown for the full phase-space and for the current fragmentation

in terms of ***spin transfer***

$$S_{\Lambda(\bar{\Lambda})} = \frac{P_{\Lambda(\bar{\Lambda})}}{f P_T D_{NN}}$$

by definition, $-1 < S_{\Lambda(\bar{\Lambda})} < 1$



$S_{\bar{\Lambda}}$: dominated by unfavored fragmentation functions

Interpretation - I

Assuming all Λ ($\bar{\Lambda}$) to be directly produced and considering only the favored combinations:

$$S_\Lambda = \frac{4h_1^u H_{1,u}^\Lambda + h_1^d H_{1,d}^\Lambda + h_1^s H_{1,s}^\Lambda}{4f_1^u D_{1,u}^\Lambda + f_1^d D_{1,d}^\Lambda + f_1^s D_{1,s}^\Lambda}$$

Introducing $r = \frac{D_{1,s}^\Lambda}{D_{1,u}^\Lambda}$ and using the isospin symmetry,

$$S_\Lambda = \frac{(4h_1^u + h_1^d)H_{1,u}^\Lambda + h_1^s H_{1,s}^\Lambda}{(4f_1^u + f_1^d + r f_1^s)D_{1,u}^\Lambda}$$

- h_1^u and h_1^d from a fit of COMPASS data
- f_1^u f_1^d f_1^s → CTEQ5D

Option 1) *If transversity is non-zero only for valence quarks in the nucleon*

the ratio of the integrated fragmentation functions in each x bin reads:

$$\frac{\langle H_{1,u}^\Lambda \rangle}{\langle D_{1,u}^\Lambda \rangle} = \frac{4f_1^u + f_1^d + r f_1^s}{4h_1^u + h_1^d} S_\Lambda$$

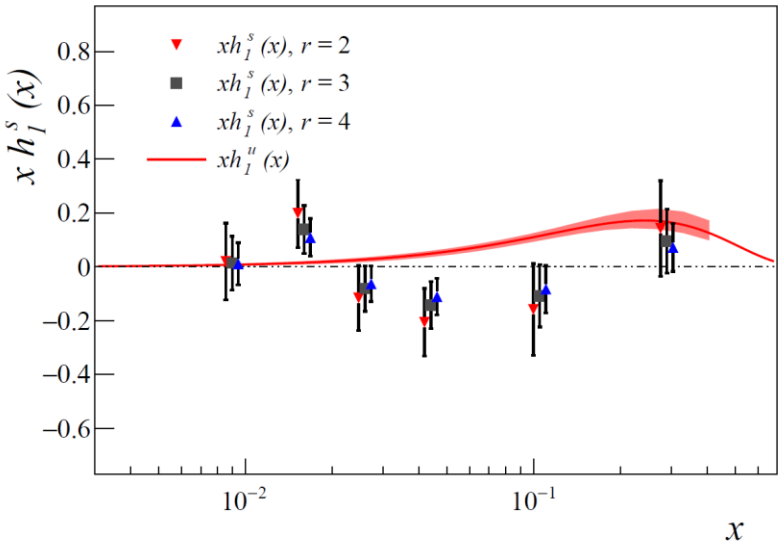
The data suggest $\frac{\langle H_{1,u}^\Lambda \rangle}{\langle D_{1,u}^\Lambda \rangle} < 0$, averaged over x, with large uncertainty and small dependence on r

Interpretation - II

Option 2) *If the Λ polarization is carried by the s-quark only,* assuming $H_{1,s}^{\Lambda} \approx D_{1,s}^{\Lambda}$:

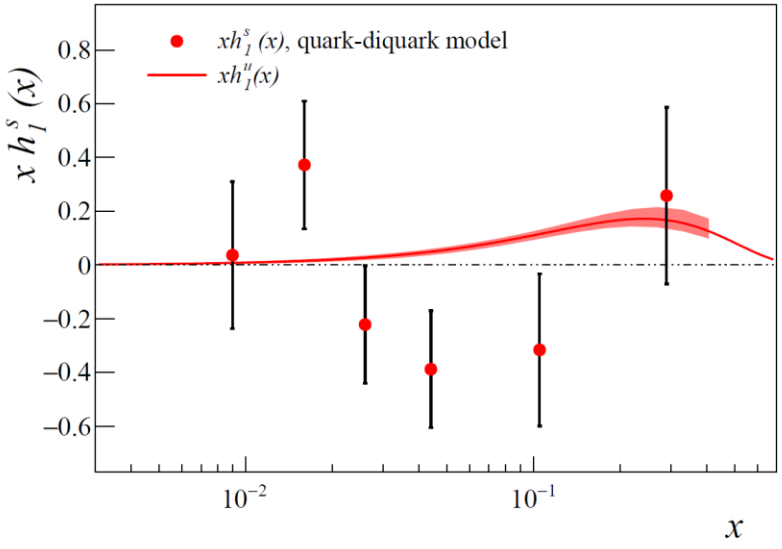
$$S_{\Lambda} = \frac{h_1^s H_{1,s}^{\Lambda}}{\left[4f_1^u + f_1^d + rf_1^s\right] D_{1,s}^{\Lambda}/r} \approx \frac{rh_1^s}{4f_1^u + f_1^d + rf_1^s}$$

→ h_1^s can be extracted, as a function of $r = D_{1,s}^{\Lambda}/D_{1,u}^{\Lambda}$



Red uncertainty band: xh_1^u, for reference

Option 3) *In the context of the quark-diquark model,* the FF are given an explicit expression and can be calculated. This allows extracting h_1^s



Yang, *Nucl. Phys. A 699 (2002) 562-578*
Jacob, Mulders, Rodrigues, *Nucl. Phys. A 626 (1997) 937-965*

Summary and Outlook

Polarization of Λ ($\overline{\Lambda}$) hyperons produced in SIDIS off transversely polarized nucleon:

- an independent channel to access h_1^q.

The COMPASS Collaboration has measured the spin transfer $q^{\uparrow} \rightarrow \Lambda^{\uparrow}(\overline{\Lambda}^{\uparrow})$:

- the world's largest set of Λ ($\overline{\Lambda}$) produced in transversely polarized SIDIS
- within the large uncertainty, the spin transfer is compatible with zero

Under some simplifying assumptions, the results indicate that:

- $\langle H_1^{\Lambda,u} \rangle / \langle D_1^{\Lambda,u} \rangle < 0$ (if h_1^q is non-vanishing only for the valence quarks in the nucleon)
- $h_1^s(x) < 0$ (if the polarization is carried by the s-quark, or in the quark-diquark model)

New SIDIS data to be collected in 2021/2022 at COMPASS on a transversely polarized deuteron target:

possibility to reduce the statistical uncertainties.

Backup

Systematic uncertainties

For each region, evaluation of the systematic uncertainties.

- K_0^S polarization - no contribution
- Period compatibility
- False polarization
- *Weak decay constant*
- *Dilution and polarization factors*

$\sigma_{syst} < 0.85\ \sigma_{stat}$