Beam-spin induced polarization of Λ and anti-Λ hyperons in semi-inclusive deep-inelastic scattering

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On behalf of the HERMES collaboration

hermes

Polarized Λ production

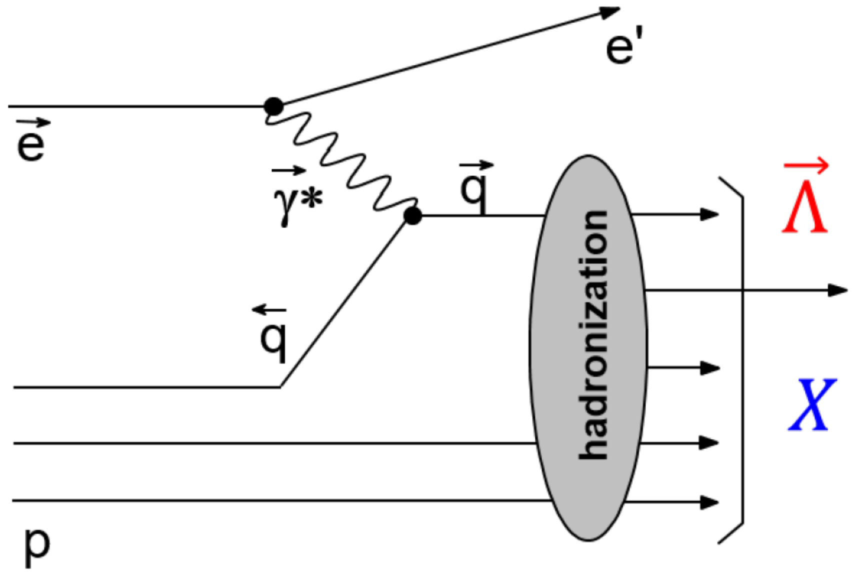
$$\vec{\gamma}^* + p \rightarrow \vec{\Lambda} + X$$
$$\hookrightarrow p\pi^-$$

Angular distribution of protons
(in Λ rest frame)

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}\left(1 + \alpha\, P_{L'}^{\Lambda} \cos\theta_{pL'}\right)$$

Unpolarized distribution

Angle between proton momentum and Λ spin in Λ rest frame



Λ is "self-analyzing" particle due to its parity violation $\Lambda \rightarrow p\pi^-$ decay

Polarization can be extracted just by measuring angular distribution of decay protons, without any additional scattering

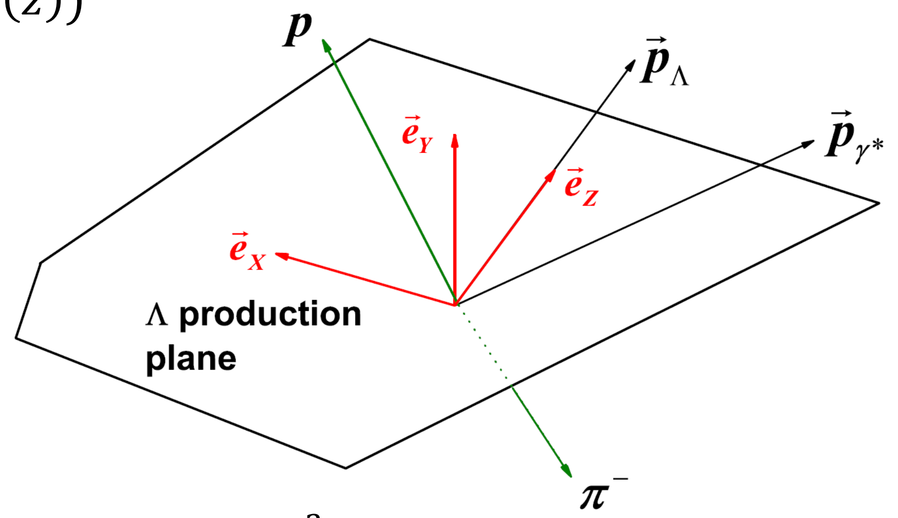
Λ polarization

P.J. Mulders, R.D. Tangerman
Published in: Nucl.Phys.B 461 (1996), 197-237

$$P_X^\Lambda = -P_B D_X(y)\left\{\frac{M}{Q}\frac{\sum_q e_q^2 x_B f_1^q(x_B) H_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)} + \frac{M^\Lambda}{Q}\frac{\sum_q e_q^2 x_B f_1^q(x_B) \tilde{G}_T^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}\right\}$$

$$P_Y^\Lambda = D_Y(y)\frac{M}{Q}\frac{\sum_q e_q^2 x_B f_1^q(x_B) D_{1T}^{\perp(1)q}(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}$$

$$P_Z^\Lambda = P_B D_Z(y)\frac{\sum_q e_q^2 x_B f_1^q(x_B) G_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}$$

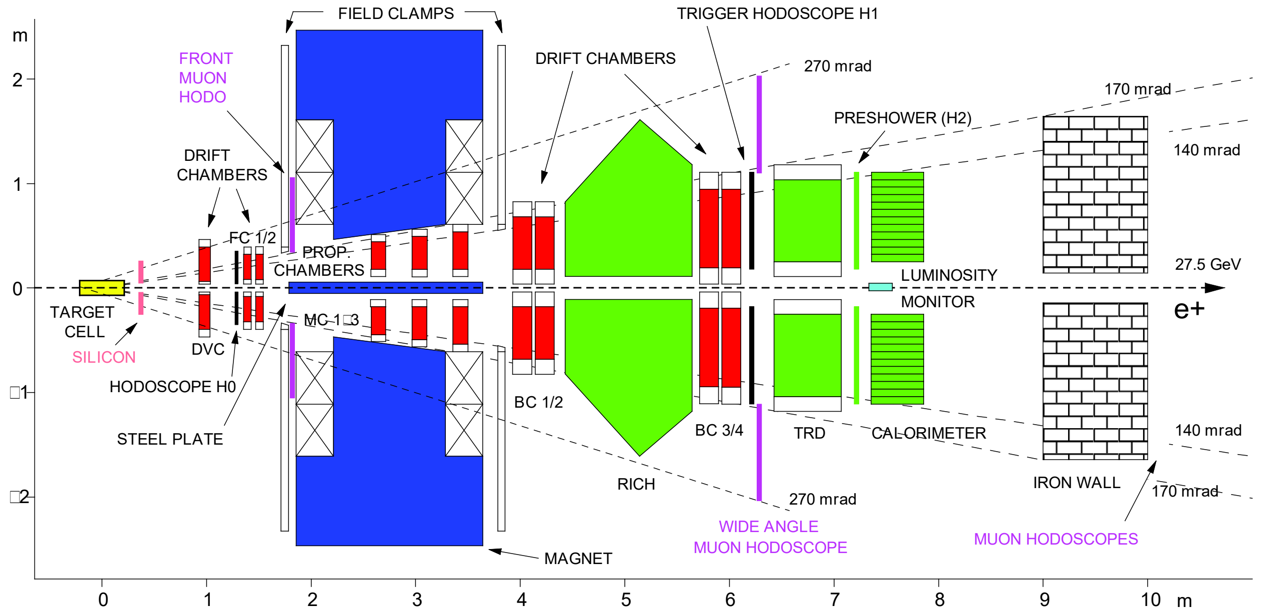


Virtual photon depolarization factor $D(y)$ is different for X and Z axis

$$D_X(y) = \frac{2y\sqrt{1-y-\frac{\gamma^2 y^2}{4}}}{1-y+\frac{y^2}{2}+\frac{\gamma^2 y^2}{4}} \qquad D_Z(y) = \frac{y\left(1-\frac{y^2}{2}\right)}{1-y+\frac{y^2}{2}+\frac{\gamma^2 y^2}{4}}$$

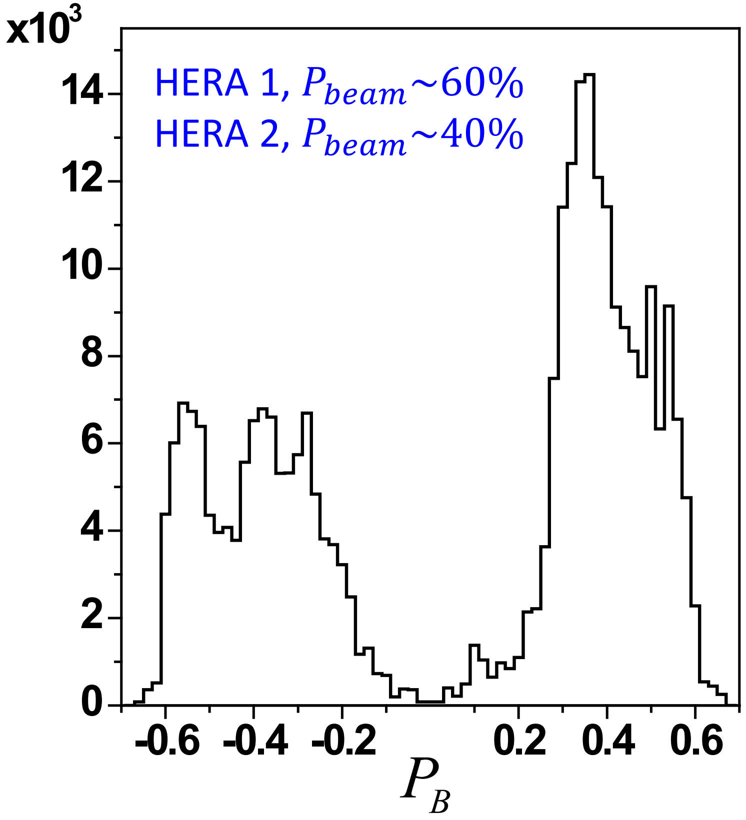
Give us access to twist-2 (H_1^q) and twist-3 ($\tilde{G}_1^q$, $D_{1T}^{\perp(1)q}$) fragmentation functions as well as for polarized FF (G_1^q) and unpolarized FF (D_1^q)

HERMES experiment



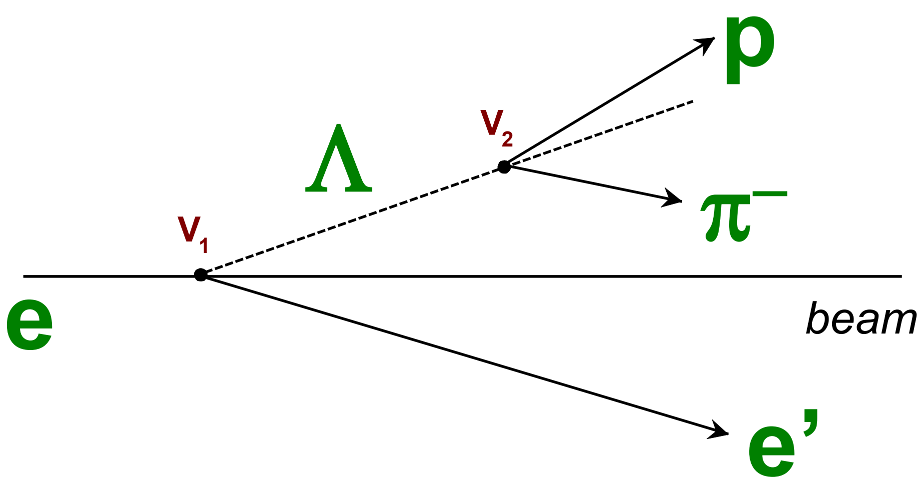
HERMES was forward spectrometer

$1\ \text{GeV} \leq p_\Lambda \leq 16\ \text{GeV}$



- *Long. polarized lepton (e^-/e^+) beam $E_e = 27.5$ GeV*
- *Beam spin flipped every few month*
- *Long. / trans. polarized gas targets H, D, flipped every 60-180 sec, $[\![P_{targ}]\!] \approx 0$*
- *Unpolarized targets H, D, He, N, Ne, Kr, Xe*

Λ event selection



SIDIS Λ selection

- Event with scattered lepton same charge as beam and at least two oppositely charged hadrons

$$x = \frac{Q^2}{2M\nu},\ y = \frac{\nu}{E_e} = \frac{E_e - E_e'}{E_e},\ z = \frac{E^\Lambda}{\nu},\ x_F = \frac{p_\parallel^\Lambda}{p_{max}^\Lambda}$$

SIDIS variables

Background suppression

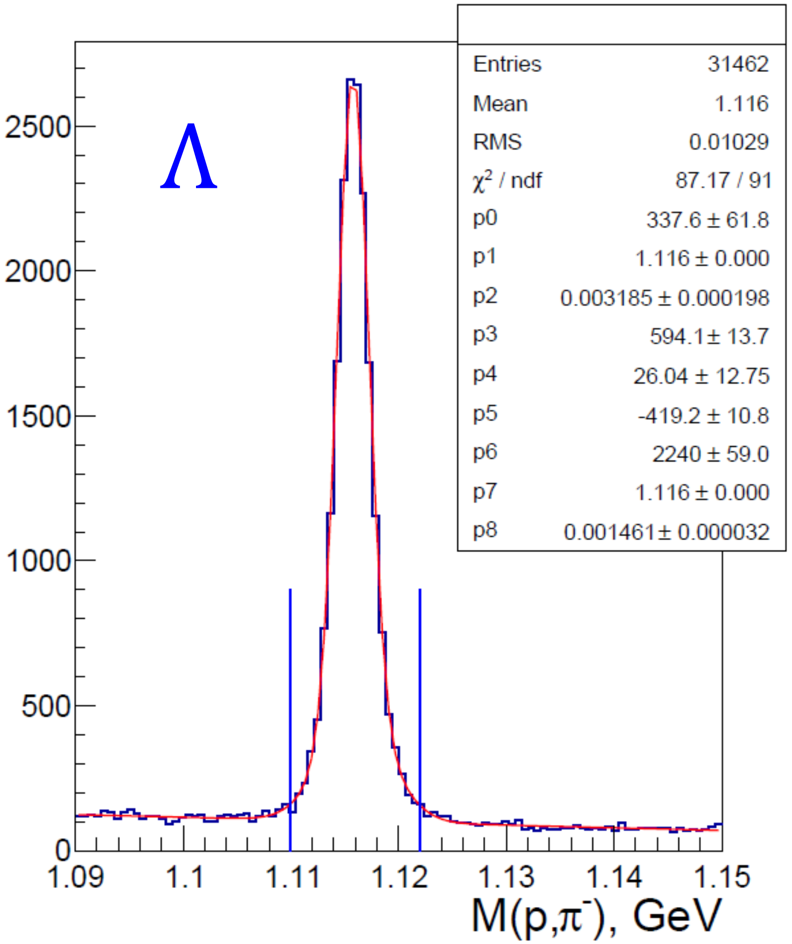
- leading π rejection (in HERMES kinematics proton is always leading) :
  - *Threshold Cherenkov det. 1996-1997*
  - *Ring imaging Cherenkov 1998-2007*
- h^+h^- pair background (coming from V_1) rejection :
  - *Vertex separation $d(V_1,V_2) > 11$ cm*

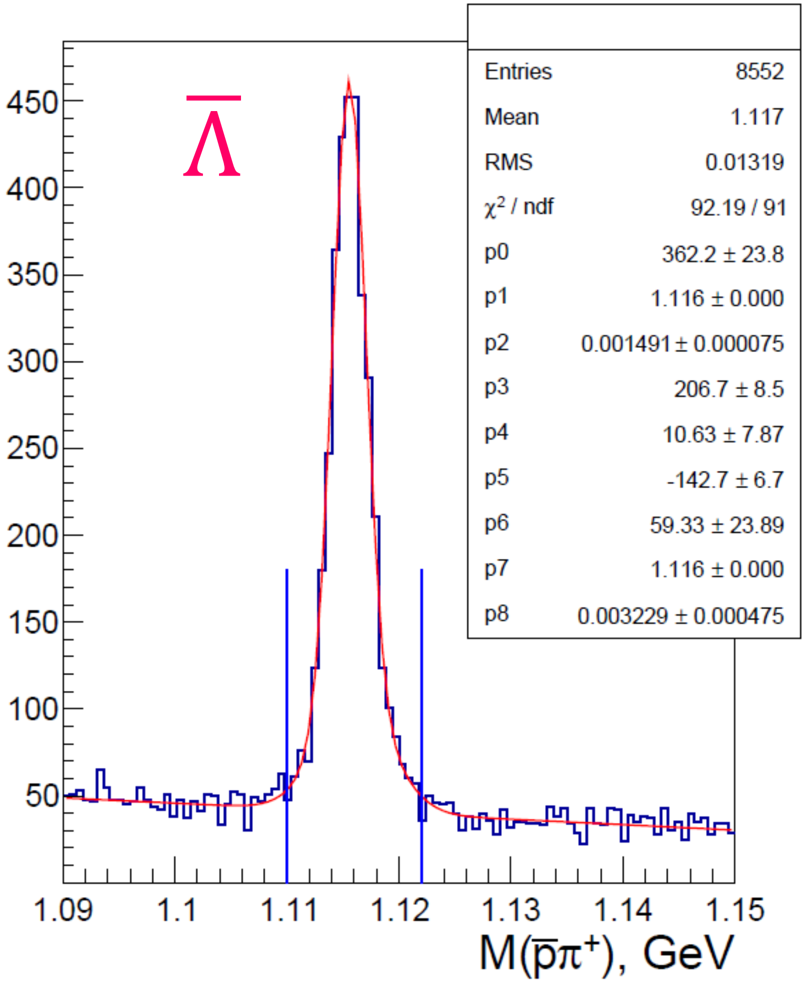
DIS cuts

- $0.8 < Q^2 < 24\ GeV^2$
- $W^2 > 10\ GeV^2$
- $0.2 < y < 0.85$

Example of invariant mass spectra for 2006-2007 data

Total numbers:
$N_{\Lambda} = 36996$
$N_{\bar{\Lambda}} = 6075$



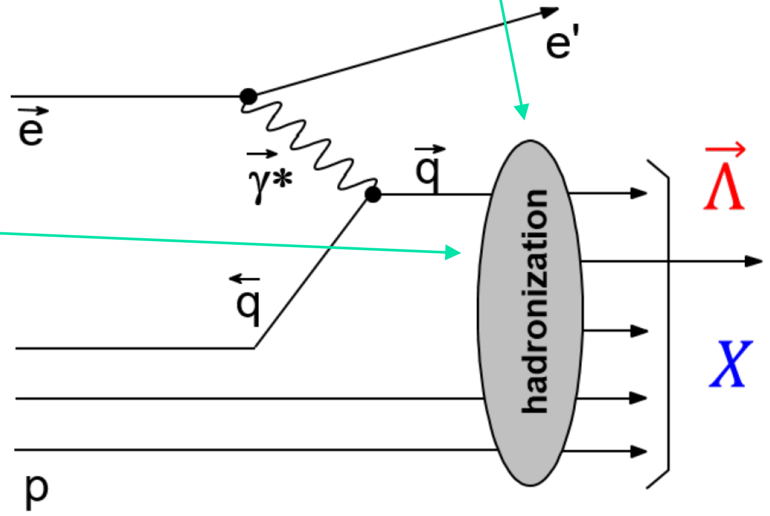


Spin transfer $D_{LL'}^{\Lambda}$

$$P_X^\Lambda = -P_B D_X(y)\left\{\frac{M}{Q}\frac{\sum_q e_q^2 x_B f_1^q(x_B) H_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)} + \frac{M^\Lambda}{Q}\frac{\sum_q e_q^2 x_B f_1^q(x_B)\tilde{G}_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}\right\} = -P_B D_X(y) D_{LX}(x_B, z)$$

$$P_Y^\Lambda = D_Y(y)\frac{M}{Q}\frac{\sum_q e_q^2 x_B f_1^q(x_B) D_{1T}^{\perp(1)q}(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)}$$

$$P_Z^\Lambda = P_B D_Z(y)\frac{\sum_q e_q^2 x_B f_1^q(x_B) G_1^q(z)}{\sum_q e_q^2 x_B f_1^q(x_B) D_1^q(z)} = P_B D_Z(y) D_{LZ}(x_B, z)$$



- P_Y^Λ is independent of beam polarization P_B → only 2 components $D_{LX}(x_B, z)$ and $D_{LZ}(x_B, z)$
- Virtual photon depolarization factor $D(y)$ is different for X and Z axis

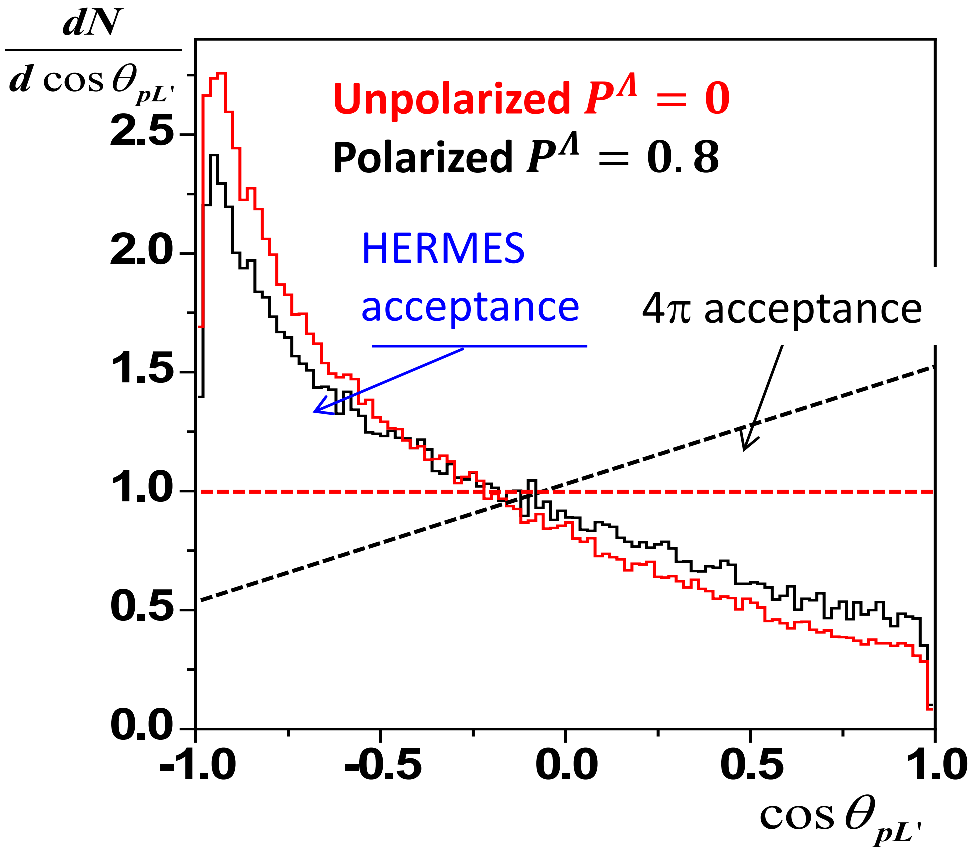
Formalism extraction of $D_{LL'}^{\Lambda}$

- Angular distribution of decay protons

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}\left(1 + \alpha\, P_{L'}^{\Lambda} \cos\theta_{pL'}\right)$$

Unknown, need MC simulation of acceptance

Major source of systematic uncertainty !

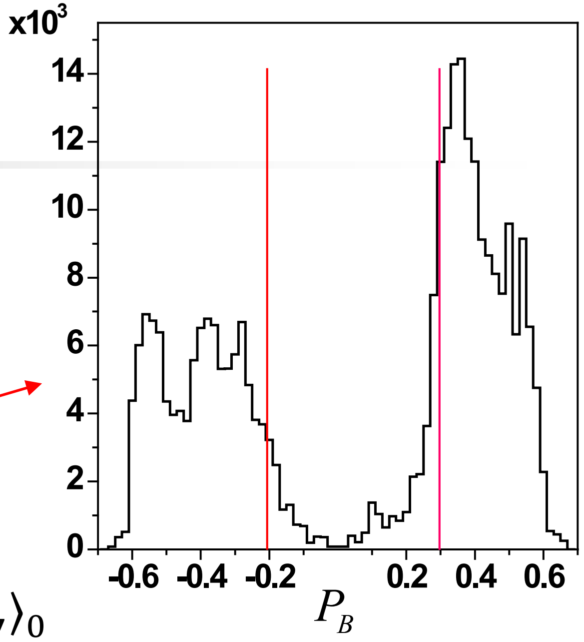


- **NOMAD, 4π acceptance**
- **COMPASS, simulate acceptance**
- **HERMES, cancel acceptance effect by using two beam polarization**

Extraction formalism of $D^{\Lambda}_{LL'}$

Moment method

- calculate $\langle P_B cos\theta_{pL'}\rangle$ and $\langle cos^2\theta_{pL'}\rangle$ with $\frac{d\omega}{d\Omega_p} = \frac{d\omega_0}{d\Omega_p}(1 + \alpha \vec{P}^{\Lambda}\vec{k}_p)$
- In simple 1D case and helicity balanced data sample $[\![P_B]\!] = \frac{1}{L}\int P_B\, dL = 0$



$$\langle P_B \cos\theta_{pL'}\rangle = \frac{[\![P_B]\!]\langle\cos\theta_{pL'}\rangle_0 + \alpha D_{LL'}[\![P_B^2]\!]\langle\cos^2\theta_{pL'}\rangle_0}{1 + \alpha D_{LL'}[\![P_B]\!]\langle\cos\theta_{pL'}\rangle_0} \overset{[\![P_B]\!]=0}{=} \alpha D_{LL'}[\![P_B^2]\!]\langle\cos^2\theta_{pL'}\rangle_0$$

$$\langle \cos^2\theta_{pL'}\rangle = \frac{\langle\cos^2\theta_{pL'}\rangle_0 + \alpha D_{LL'}[\![P_B]\!]\langle\cos^3\theta_{pL'}\rangle_0}{1 + \alpha D_{LL'}[\![P_B]\!]\langle\cos\theta_{pL'}\rangle_0} \overset{[\![P_B]\!]=0}{=} \langle\cos^2\theta_{pL'}\rangle_0$$

Unpolarized moment (unknown)

$$D^{\Lambda}_{LL'} = \frac{1}{\alpha\,[\![P_B^2]\!]} \cdot \frac{\langle P_B \cos\theta_{pL'}\rangle}{\langle cos^2\theta_{pL'}\rangle}$$

No MC simulation of acceptance needed

- *Slightly more complicated iteration procedure used in case of unbalanced P_B*
- *Extended for 3D case*

Extraction of spin transfer in 3D

$$\sum_{k=x,z} D_{Lk} \left\langle \frac{D_k(y) D_i(y) cos\theta_k cos\theta_i}{1 + \alpha [\![P_b]\!] \sum_{j=x,z} D_j(y) D_{Lj} \; cos\theta_j} \right\rangle = \frac{1}{\alpha} \frac{\langle P_b D_i(y) cos\theta_i \rangle - [\![P_b]\!] \langle D_i(y) cos\theta_i \rangle}{[\![P_b^2]\!] - [\![P_b]\!]^2}$$

Statistical uncertainty

- System of linear equations

$$\sum_k D_{Lk} a_{ik} = c_i$$

$$\begin{bmatrix} a_{xx} & a_{xz} \\ a_{zx} & a_{zz} \end{bmatrix} \begin{bmatrix} D_{Lx} \\ D_{Lz} \end{bmatrix} = \begin{bmatrix} c_x \\ c_z \end{bmatrix}$$

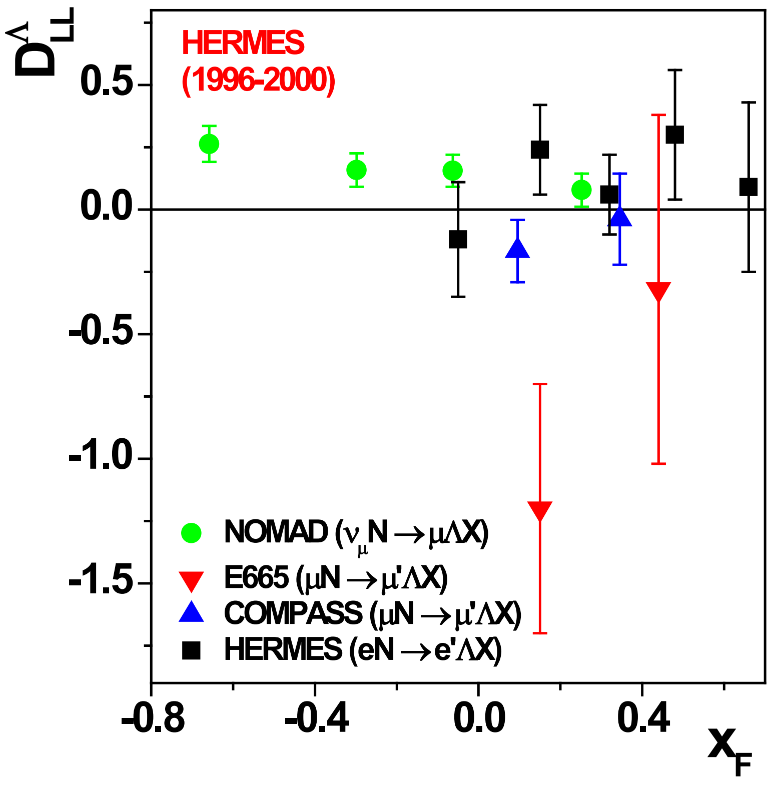
- Coefficients a_{ij} are depend from D_{Li}
- To solve given system, an iteration procedure is used

$${D_{L}}_k^{(0)} \xrightarrow{\text{calculate } a_i^k} a_i^{k\,(0)} \xrightarrow{\text{solve } a_i^k D_{Lk} = c_i} {D_{L}}_k^{(1)} \rightarrow \dots$$

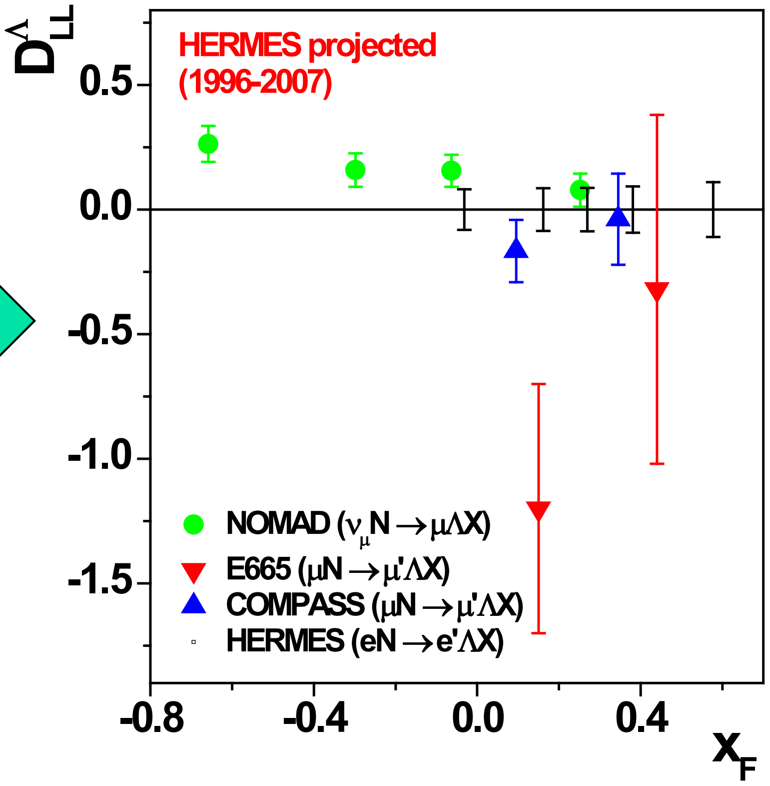
- 3 steps are sufficient to converge $\alpha [\![P_b]\!] \sum_{j=x,z} D_j(y) D_{Lj} \; cos\theta_j \sim 0$

Projection for full data set

HERMES Collaboration • A. Airapetian et al.
Published in: Phys.Rev.D 74 (2006), 072004



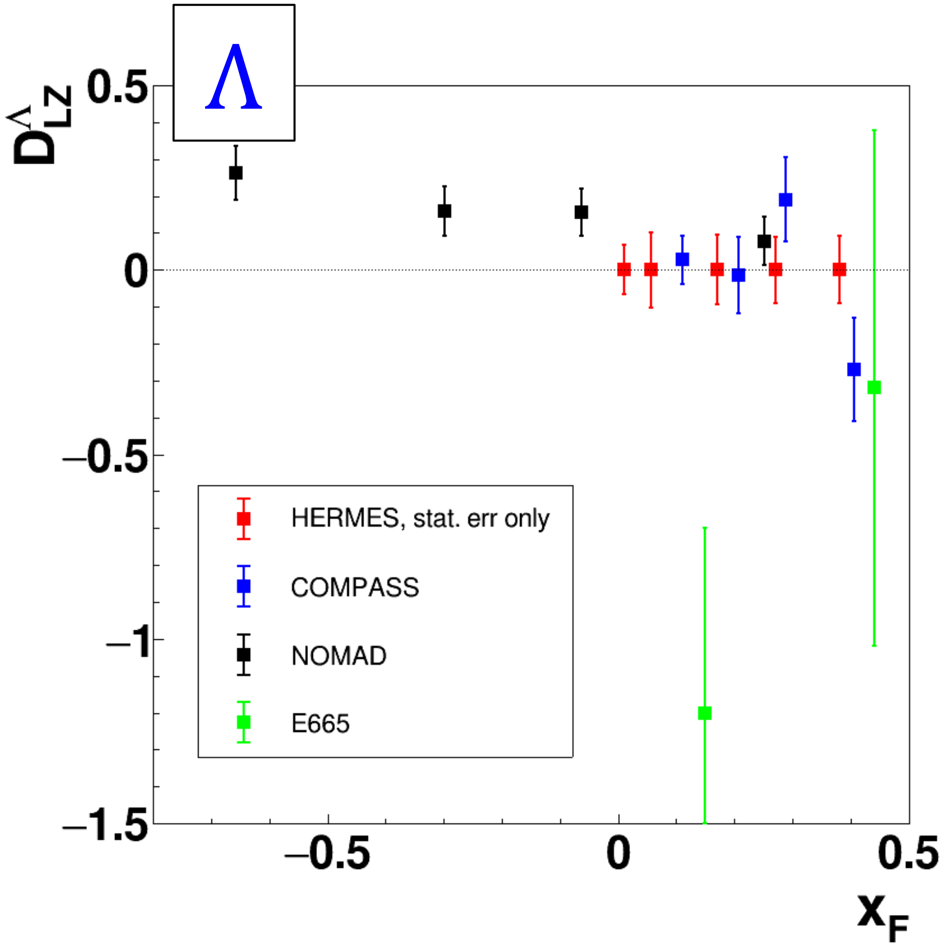
Projection for full data set, stat. uncertainties only

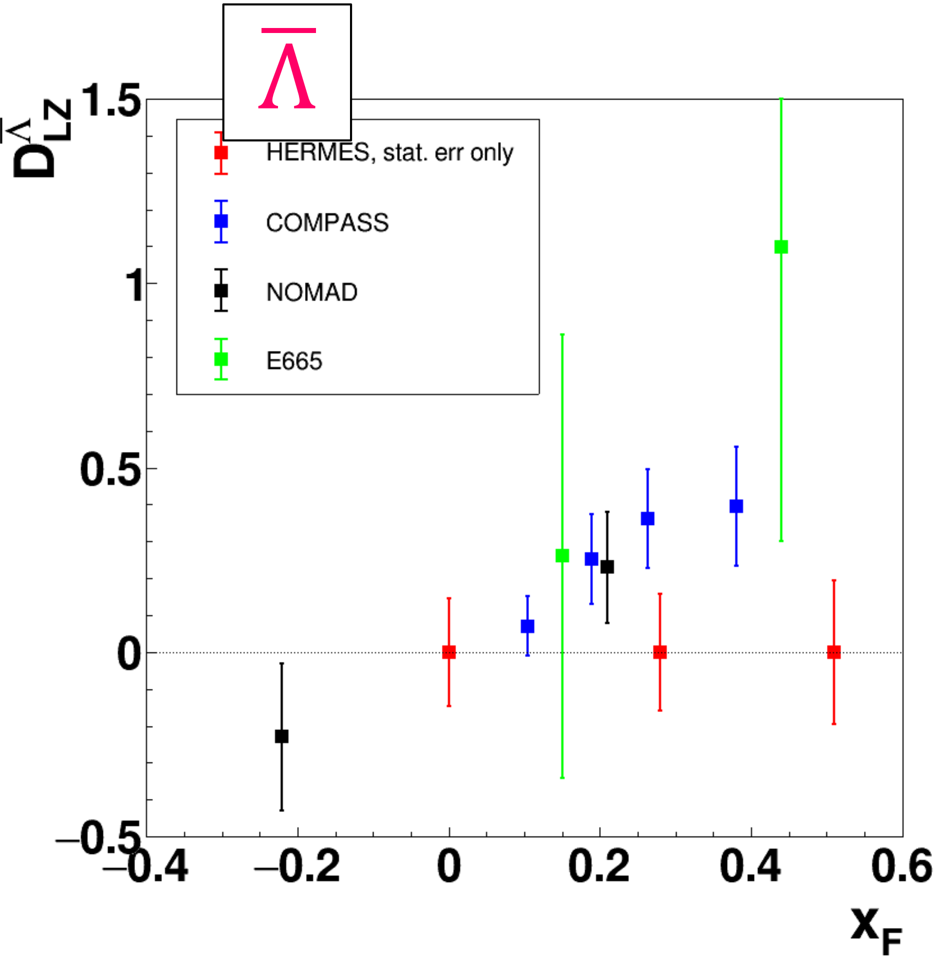


- Statistic increased from 7300 to 37000
- Beam polarization decreased from 60% to 40%, so uncertainties not as small as expected

Spin transfer versus x_F

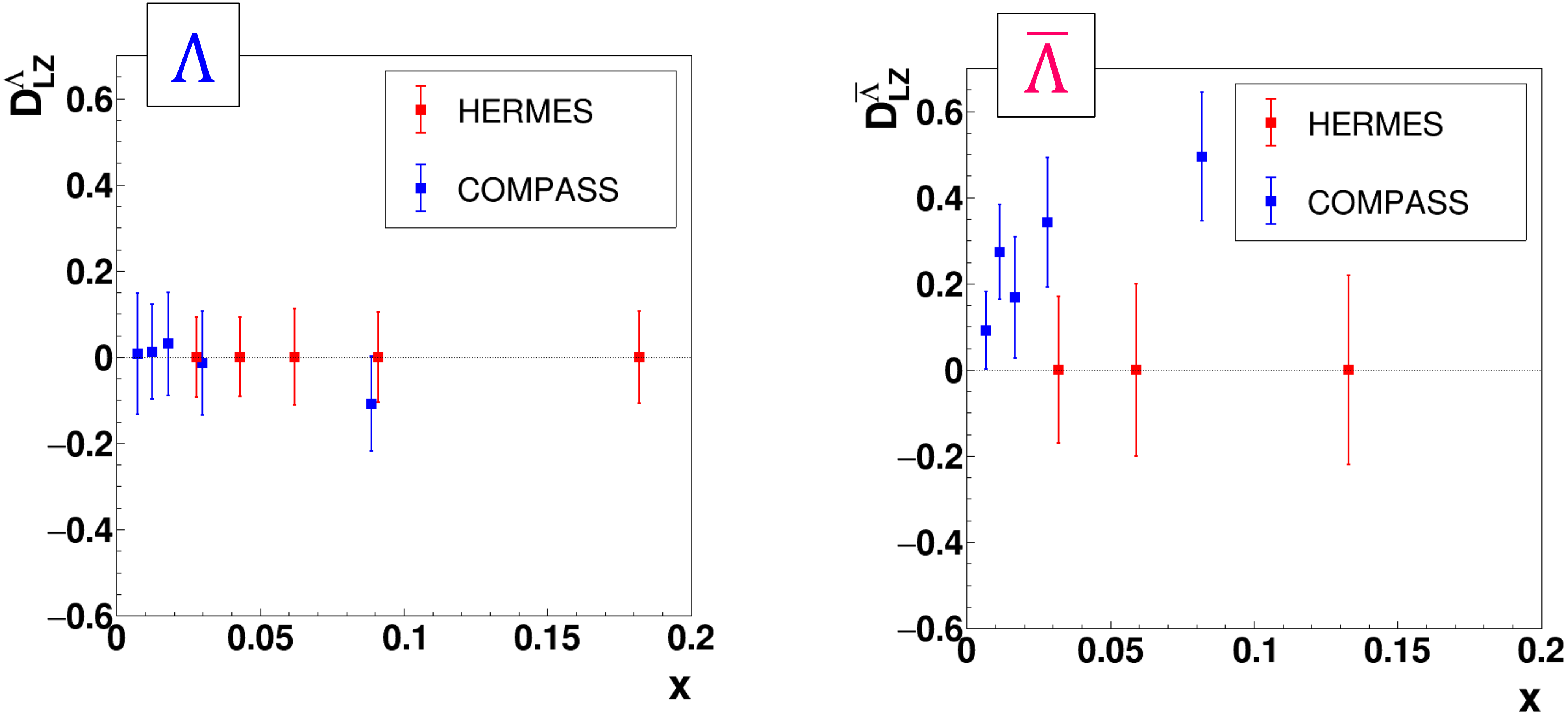
Projected result, only statistical uncertainties shown, all HERMES points are set to 0





Spin transfer versus x

Projected result, only statistical uncertainties shown, all HERMES points are set to 0



Conclusion

- "self-analyzing" decay of Λ hyperon provides unique possibilities to study spin effects
- beam-spin transfer to Λ sensitive to various spin-dependent parton distributions and fragmentation functions (e.g. *e(x)*, $\tilde{G}_1^q$, G_1^q and H_1^q)
- HERMES has a large DIS data set with longitudinal beam polarization
- availability of both beam-helicity states exploited in novel extraction formalism that does not rely on MC simulations
- compared to previous HERMES publications, formalism has been extended to 3D case and to data sets that are not helicity-balanced
- increased data set allows for analysis of also $\overline{\Lambda}$
- analysis in advanced state, final results to come out soon