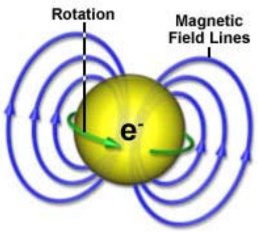

Transverse Lambda Polarization at HERMES

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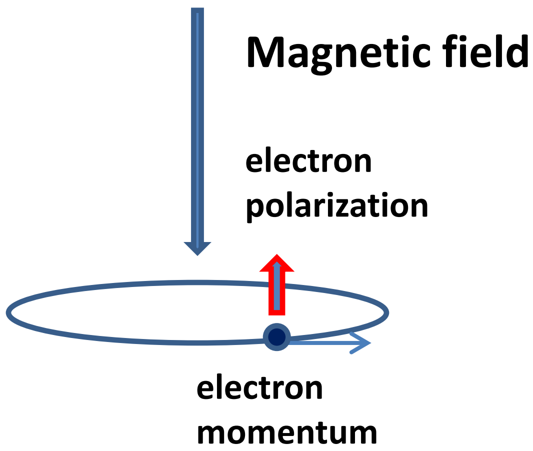
Spontaneous Transverse Polarization

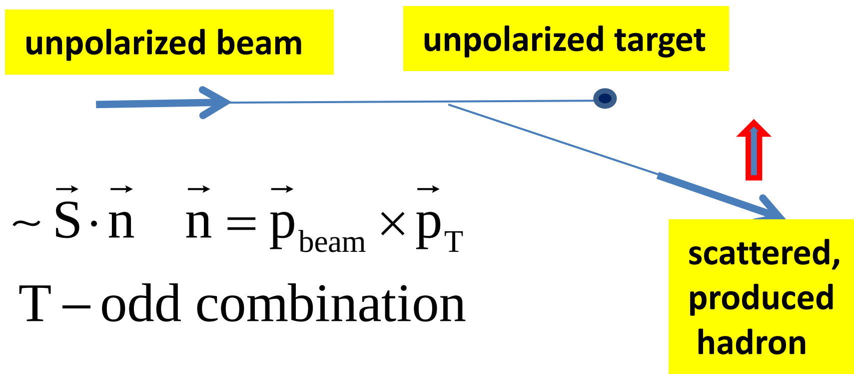
Sokolov-Ternov effect



Directed along magnetic field

Mechanism understood in the frame of QED

Transverse polarization in hadron scattering



$$\vec{P} \sim \vec{S} \cdot \vec{n} \quad \vec{n} = \vec{p}_{beam} \times \vec{p}_T$$

$$T - \text{odd combination}$$

Polarization along normal **n** to scattering (production) plane

Well known phenomenon in pp, πp, pA scattering in GeV energy domain.

In general Single Spin Asymmetry SSA

SSA at High Energies

Perturbative QCD in collinear factorization approach, e.g. contribution subprocess qg → qg : quark of p_{beam} interacts with gluon of p_{target}

$$\sigma \sim q(x_b) \otimes g(x_t) \otimes \hat{\sigma}_{qg\to qg} \otimes D_{q\to\Lambda}(z) \quad (D_{q\to\Lambda}(z) \text{ in collinear approach})$$

$$P_{qg\to qg} \sim \alpha_S \frac{m_q}{\sqrt{S}} \ \textbf{small} \Rightarrow \mathbf{0} \text{ at } m_q \to 0$$

G.L.Kane, et al PRL 1978

At high energy substantial spin effects phenomena of produced hyperons are observed in disagreement with naïve perturbative QCD expectation

In order to see transverse spin transverse momentum to take into account:

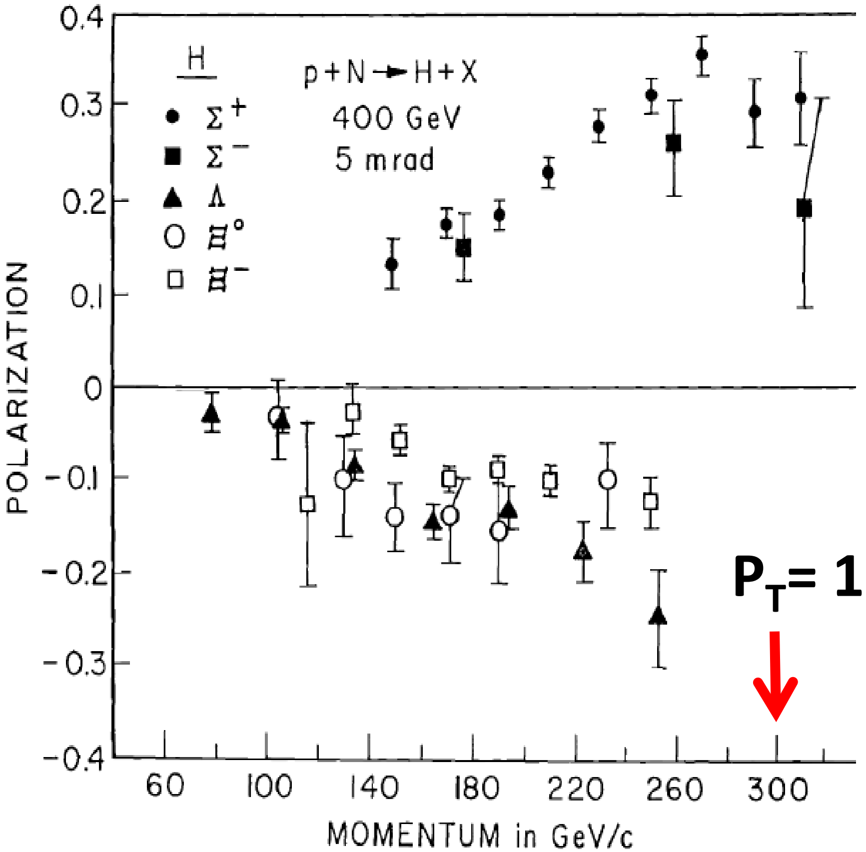
$$D_{q\to\Lambda}(z) \Rightarrow D_{q\to\Lambda}(k_\perp, z) = D^{\uparrow}_{q\to\Lambda}(k_\perp, z) + D^{\downarrow}_{q\to\Lambda}(k_\perp, z)$$

$$P_\Lambda = \frac{\sigma^{\uparrow}_\Lambda - \sigma^{\downarrow}_\Lambda}{\sigma^{\uparrow}_\Lambda + \sigma^{\downarrow}_\Lambda} \sim \frac{D^{\uparrow}_{q\to\Lambda}(k_\perp, z) - D^{\downarrow}_{q\to\Lambda}(k_\perp, z)}{D^{\uparrow}_{q\to\Lambda}(k_\perp, z) + D^{\downarrow}_{q\to\Lambda}(k_\perp, z)}$$

Collins Fragmentation Function, P.J.Mulders and R.D.Tangerman, Nucl.Phys 1996

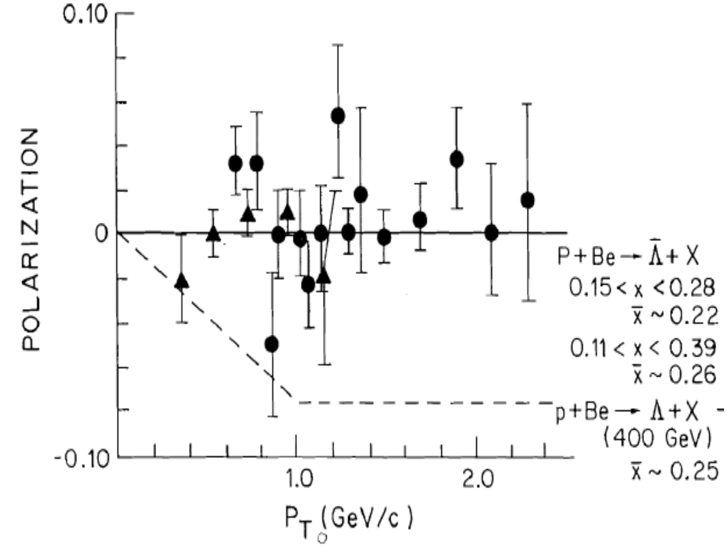
Transverse polarization is nonperturbative effect.
Unpolarized quark becomes polarized in hadronization process.
Recently: twist-3 FF (qark-gluon correlations) → SSA
K.Kanazawa and Y.Koike 2013-2015 based on idea of Efremov and Teryaev

Hyperon Polarization . Famous Fermilab Data.



P_T= 1.5 GeV

$P_{\bar{\Lambda}} \approx 0$



Interpretation: DeGrand and Mettinen PRD 1981,1985

Hyperon Octet Spin Structure $SU(3)_f$

	$\Delta(u+\bar{u})$	$\Delta(d+\bar{d})$	$\Delta(s+\bar{s})$
p(uud)	0.84	-0.43	-0.09
n(udd)	-0.43	0.84	-0.09
Λ^0(uds)	-0.16	-0.16	0.64
Σ^+ (uus)	0.84	-0.09	-0.43
Σ^0 (uds)	0.375	0.375	-0.43
Σ^-(dds)	-0.09	0.84	-0.43
Ξ^0 (uss)	-0.43	-0.09	0.84
Ξ^-(dss)	-0.09	-0.43	0.84

$\Delta\Sigma$=0.32 HERMES/COMPASS

$$\Delta\Sigma = \Delta(u+\bar{u}) + \Delta(d+\bar{d}) + \Delta(s+\bar{s})$$

Assuming that

u(d) quark positively polarized

Λ^0 Ξ^0 Ξ^- polarization negative

$\Sigma^+\Sigma^-$ polarization positive

Lattice-QCD

$\Delta u=\Delta d=$ **-0.02** $\Delta s=$ **0.68 (±0.04)**

More about Λ polarization. LHC/ATLAS Results.

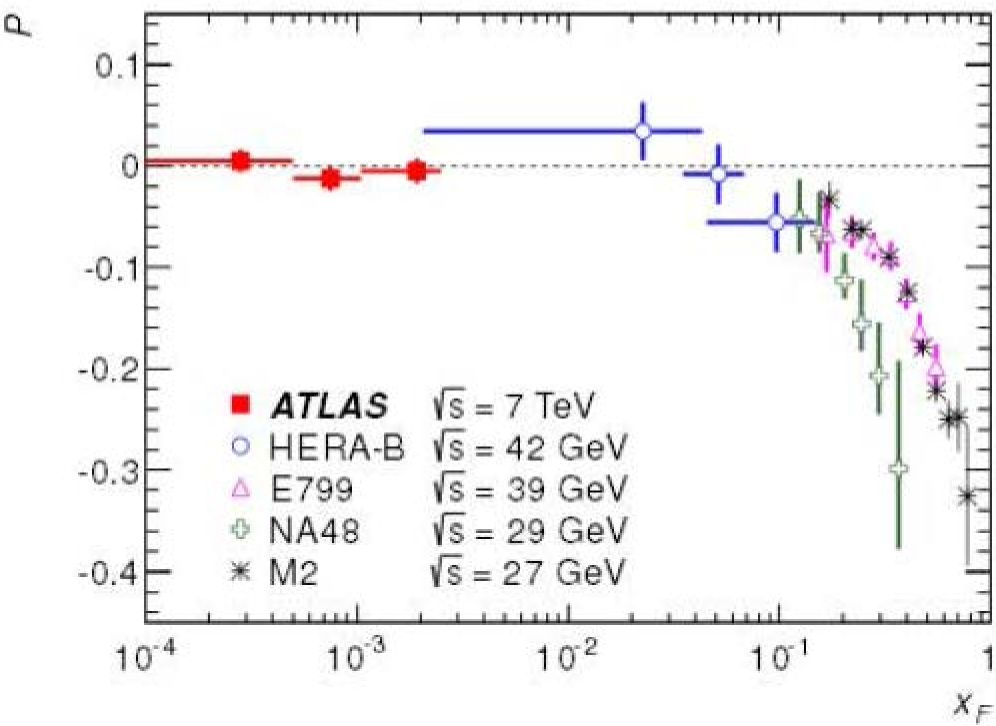
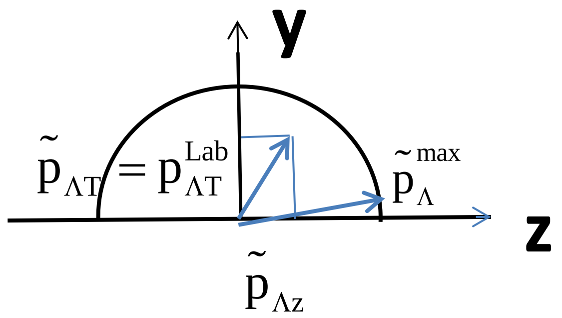


FIG. 8. The Λ transverse polarization measured by ATLAS compared to measurements from lower center-of-mass energy experiments. HERA-B data are taken from Ref. [5], NA48 from Ref. [4], E799 data from Ref. [3], and M2 from Ref. [2]. The HERA-B results are transformed to positive values of x_F using Eq. (1).

X_F variable



$$x_F = \frac{\tilde{p}_{\Lambda z}}{\tilde{p}_{\Lambda}^{max}} \qquad -1 < x_F < +1$$

$\tilde{p}_{\Lambda z}, \tilde{p}_{\Lambda}^{max}$ in beam-target c.m. frame ,

z along beam particle momentum

Transverse Λ polarization summary

- *P_Λ weakly depending of the beam momentum*
- *Its magnitude rises with p_T and x_F up to $P_\Lambda \approx 0{,}3 \div 0.4$ at $p_T = 1$ GeV*
- *At $1 < p_T < 3$ GeV P_Λ stays constant (at larger p_T no data available)*
- *In pp, pA inclusive production P_Λ negative*
- *Polarization of antiΛ compatible with zero*
- *For K^-, Σ^- beams P_Λ positive (valence s-quark)*
- *P_Λ shows a tendency to decrease with A (by 20% for Cu vs Be)*
- *At heavy ion collisions P_Λ similar to pp at $p_T > 2$ GeV*
- *P_Λ in electro/photo production practically unknown*
  (2 tagged experiments CERN ,SLAC very poor statistics)

Transverse Λ polarization in photoproduction at HERMES

Deep Inelastic Scattering regime $\vec{e} + p, A \rightarrow e' + \vec{\Lambda} + X \quad Q^2 > 1\,\mathrm{GeV}^2 \quad \mathrm{DLL}$

both detected, Q^2 defined

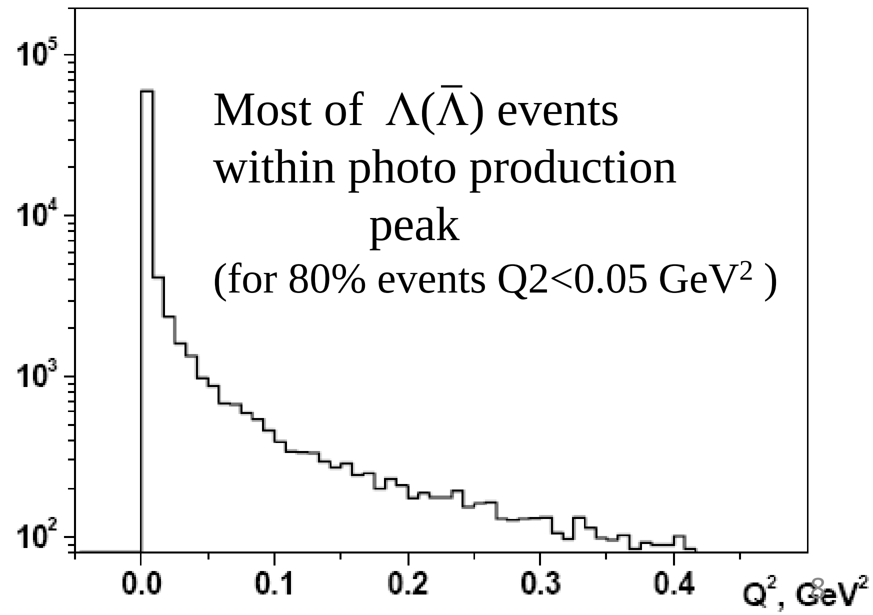
$$Q^2 = -4E_e E_{e'} \sin^2 \frac{\theta_{Lab}}{2} \quad Q^2 \rightarrow 0 \ \text{ at } \theta_{Lab} \rightarrow 0$$

Quasi-real photoproduction regime

$$e + p, A \rightarrow \vec{\Lambda} + X \quad Q^2 \approx 0$$

only detected (inclusively)

Λ yield



Kinematics of Quasi-Real Photoproduction

$$\gamma^* + p, A \rightarrow \Lambda + X \qquad \Lambda \Rightarrow p\pi^- \qquad \langle E_{\gamma^*} \rangle \approx 15\,\mathrm{GeV} \ \text{ at HERMES}$$

$$\gamma^* + p, A \rightarrow \overline{\Lambda} + X \qquad \overline{\Lambda} \Rightarrow \overline{p}\pi^+$$

As photons not tagged and only measured are Λ (antiΛ) momentum components $p_{\Lambda T}$ and $p_{\Lambda z}$, x_F cannot be built (!)

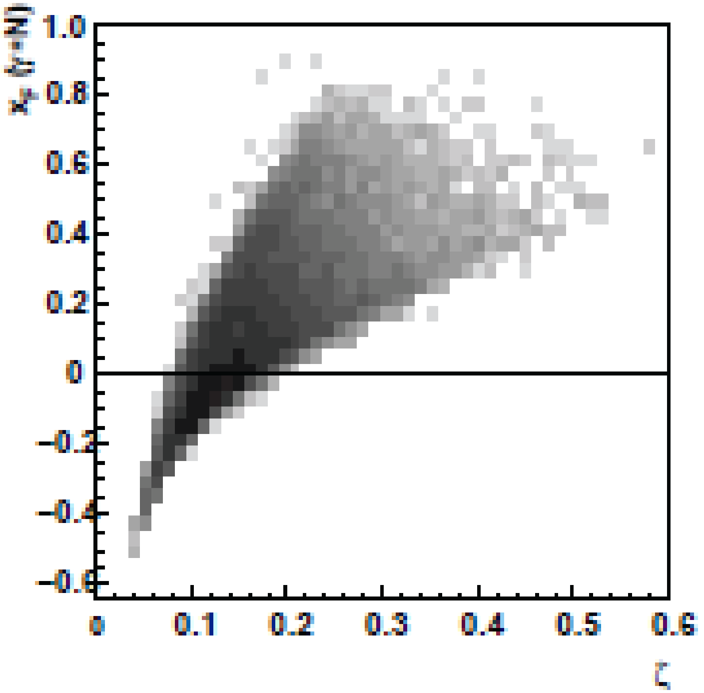
$$x_F \rightarrow \varsigma = \frac{E_\Lambda + p_{z\Lambda}}{E_e + p_{z\Lambda}} \quad \text{light cone variable}$$

two variables define reaction kinematics

transverse momentum $p_{\Lambda T}$

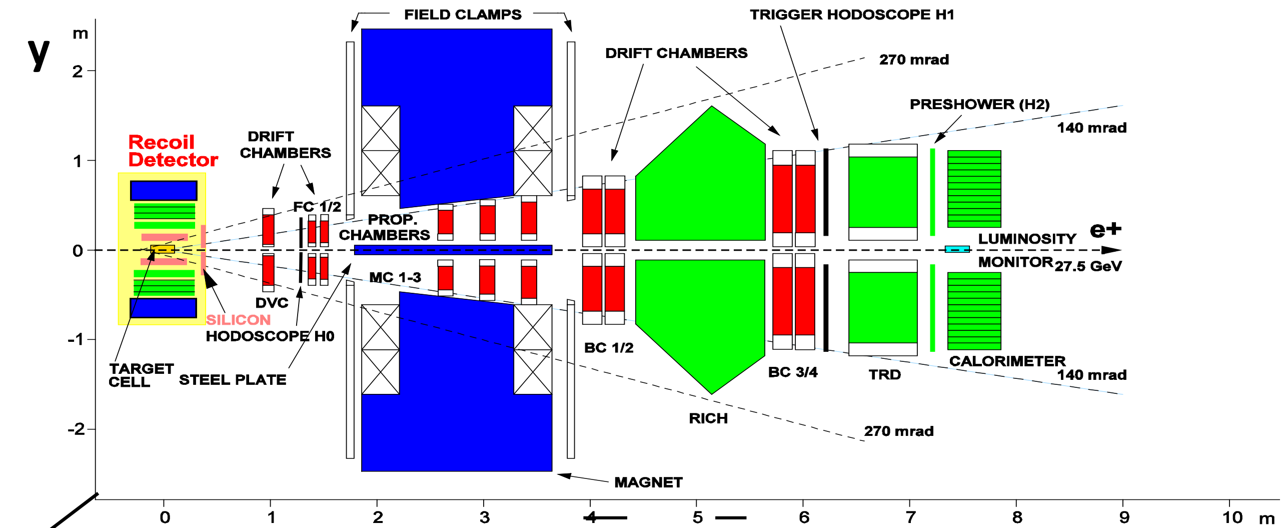
and

light - cone variable ζ

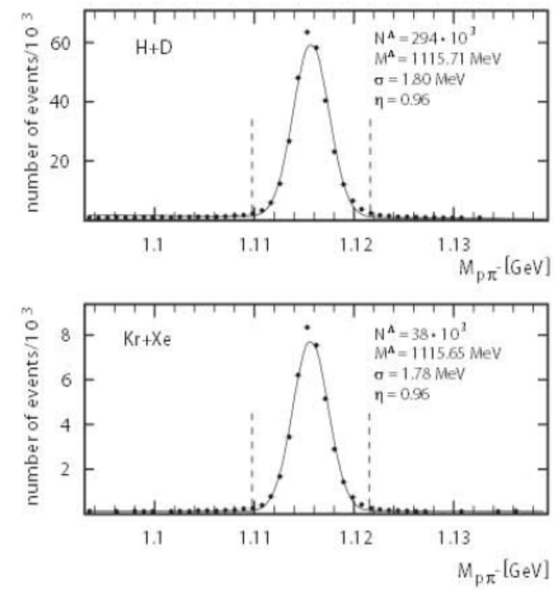


x_F vs light –cone variable for HERMES from PYTHIA MC

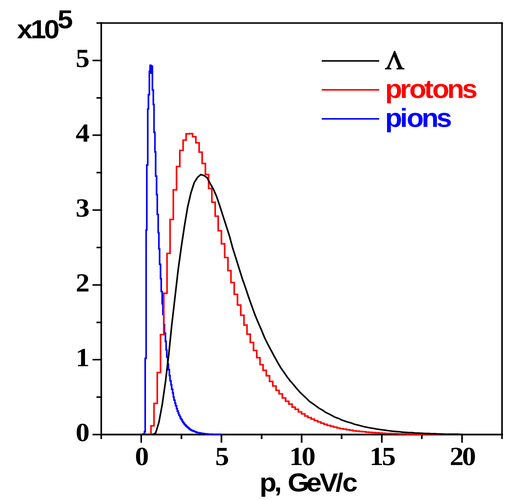
Λ detection with HERMES spectrometer



$\Lambda \Rightarrow p\pi^-$ $\Lambda \Rightarrow p\pi^+$



- Forward spectrometer with Δp/p=0.01 and Δθ=0.001
- Polarized beam and H,D targets
- Gas targets H, D, He, Ne, Kr, Xe
- Up/down mirror symmetry (except solenoid fields)
- 0.6 <p_π<2.5 GeV cutoff low momentum pions
- Well-operational RICH, effective bgr suppression



Λ polarization measurement

Standard way to measure particle polarization is scattering off analyzing target:

$$\frac{d\sigma}{d\Omega_{anal}} = \frac{d\sigma}{d\Omega_0}(1 + PA\cos\phi)$$

P from azimuthal (left-right) asymmetry measurements.

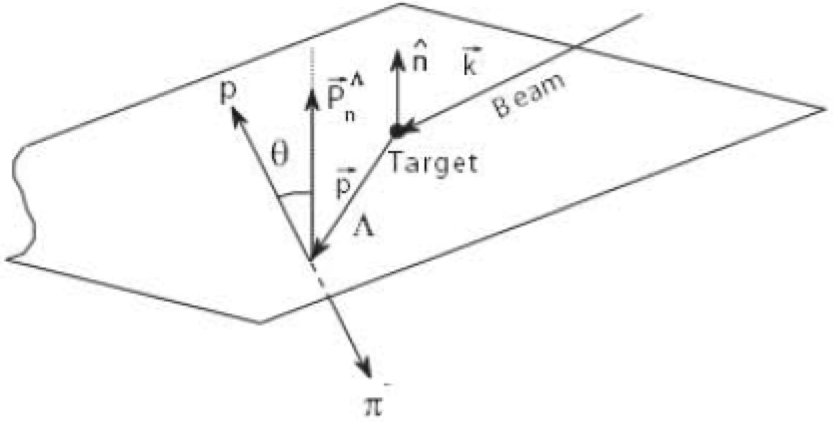
Difficulty: at high energy A small

$\Lambda \to p\pi$ weak decay is self –analyzing:

$$\frac{d\sigma}{d\Omega_p}(\Lambda \to p\pi) = \frac{d\sigma}{d\Omega_{p0}}(1 + P_\Lambda \alpha \cos\theta_p) \quad \text{in } \Lambda \text{ rest frame}$$

$\alpha = 0.642 \pm 0{,}13$ for $\Lambda \to p\pi^-$

and $\alpha = -0.642$ for $\overline{\Lambda} \to \overline{p}\pi^+$

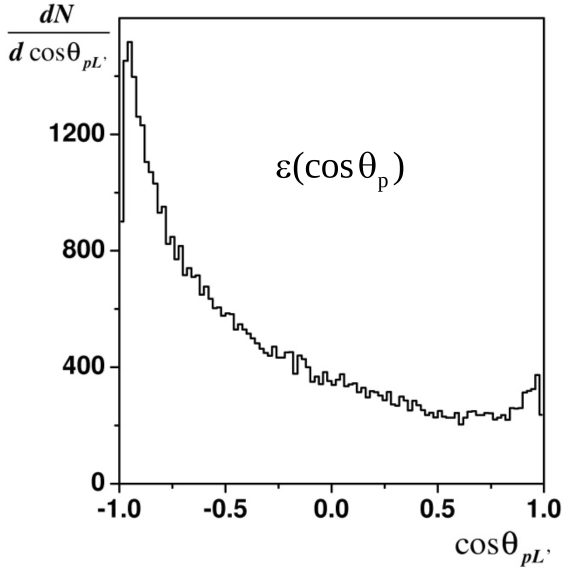


p_Λ from forward – backward decay asymmetry in Λ rest fame

Extraction of Λ polarization

$$\frac{dN}{d\Omega_p} = \frac{dN_0(\cos\theta_p)}{d\Omega_p}(1+\alpha P_\Lambda \cos\theta_p)$$

$$\frac{dN_0(\cos\theta_p)}{d\Omega_p} \sim \varepsilon(\cos\theta_p)$$



__Maximum likelihood (Moment method)__

Normalized probability to detect Λ event

$$\omega_i = \frac{1+\alpha P_\Lambda \cos\theta_{pi}}{1+\alpha P_\Lambda < \cos\theta_p >_0}$$

$$<\cos\theta_p>_0 = \frac{\int \varepsilon(\cos\theta_p)\cos\theta_p d\Omega}{\int \varepsilon(\cos\theta_p) d\Omega = 1} = \int \varepsilon(\cos\theta_p)\cos\theta_p d\Omega$$

$$\cos\theta_p = \frac{p_{\pi x}p_{py} - p_{\pi y}p_{px}}{q \cdot p_{\Lambda T}}$$

$\cos\theta_p \to -\cos\theta_p$ at $y \to -y$

Up/Down mirror symmetry $\Rightarrow$ $\varepsilon(-p_{\pi y}, -p_{py}) = \varepsilon(p_{\pi y}, p_{py})$ $\quad <\cos\theta_p>_0 = 0$

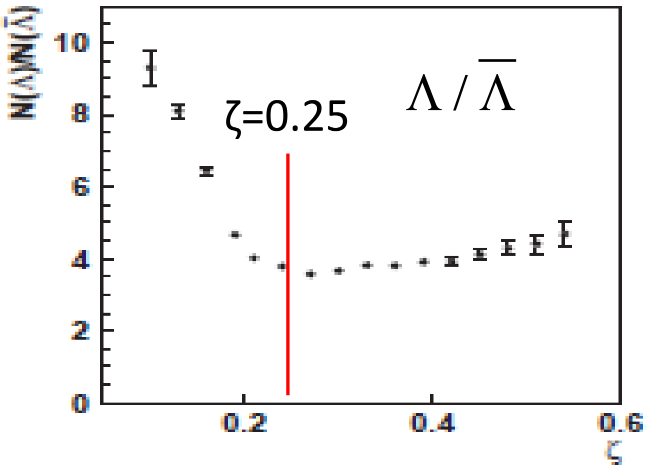
$$\omega_i = 1+\alpha P_\Lambda \cos\theta_{pi} \qquad L = \prod_{i=1}^{N_\Lambda}(1+\alpha P_\Lambda \cos\theta_{pi}), \quad \frac{\partial \ln L}{\partial P_\Lambda} = \sum_{i=i}^{N_\Lambda}\frac{\alpha\cos\theta_{pi}}{1+\alpha P_\Lambda \cos\theta_{pi}} = 0$$

$$\sum_{i=i}^{N_\Lambda}\frac{\alpha\cos\theta_{pi}}{1+\alpha P_\Lambda \cos\theta_{pi}} \simeq \sum_{i=i}^{N_\Lambda}\alpha\cos\theta_{pi}(1-\alpha P_\Lambda \cos\theta_{pi}) = 0$$

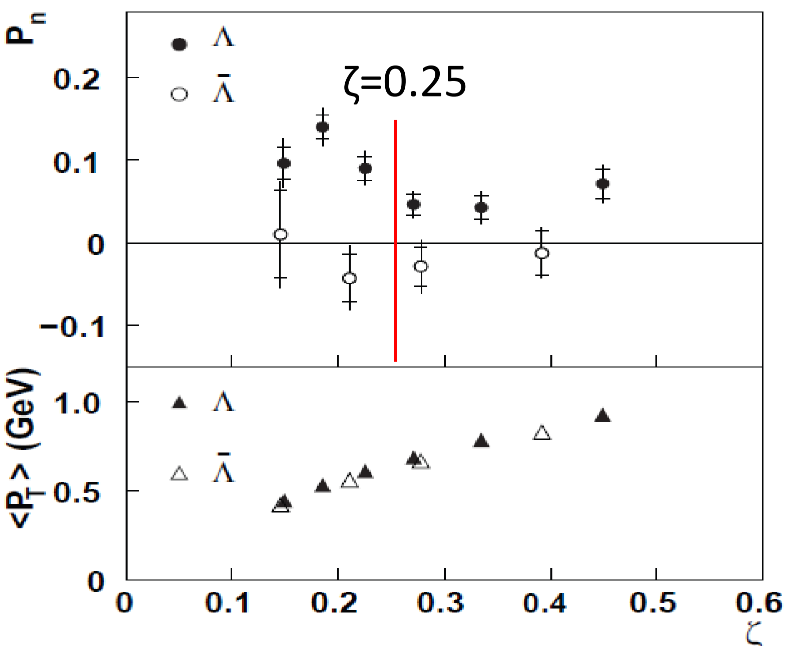
neglecting $(\alpha P_\Lambda \cos\theta_{pi})^n$ $n \geq 2$

$$P_\Lambda = \frac{\sum_i^{N_\Lambda}\cos\theta_{pi}}{\alpha\sum_i^{N_\Lambda}\cos^2\theta_{pi}}$$

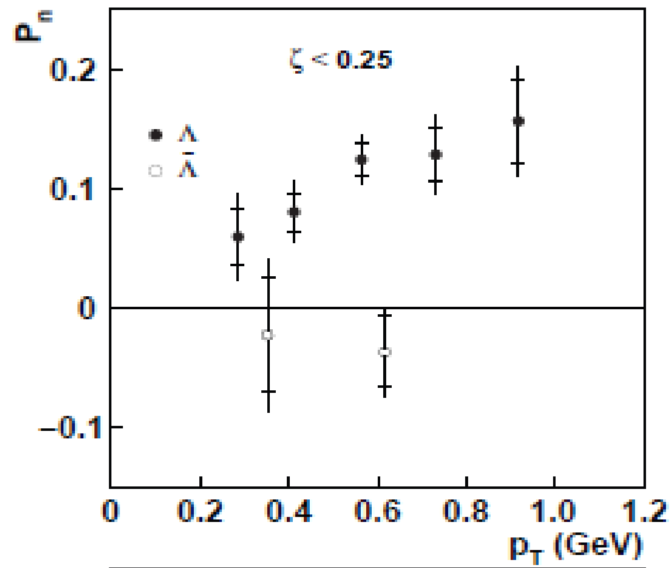
Results



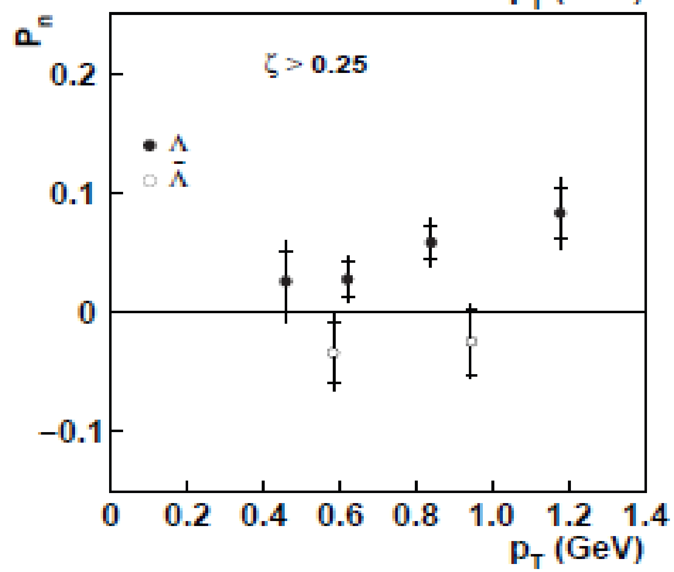
N(Λ)/N(Λ̄)
ζ=0.25
Λ / Λ̄
ζ



P_n
Λ
Λ̄
ζ=0.25
$<P_T>$ (GeV)
ζ

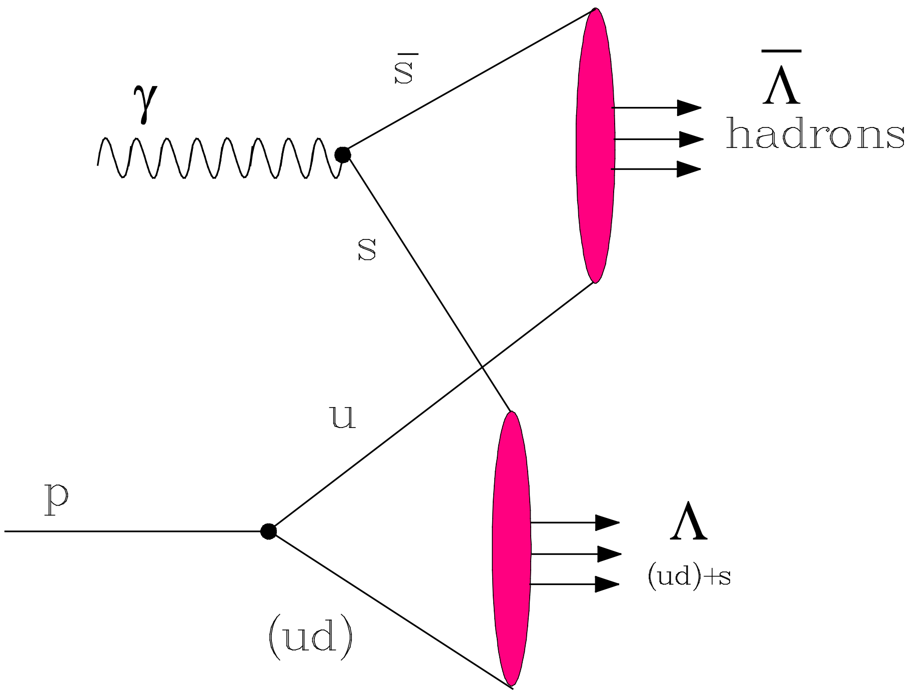


P_n
ζ < 0.25
Λ
Λ̄
p_T (GeV)



P_n
ζ > 0.25
Λ
Λ̄
p_T (GeV)

Possible Interpretation



Current fragmentation

Λ production $s\,(\text{beam}) + (ud)_{0,1}(\text{string})$

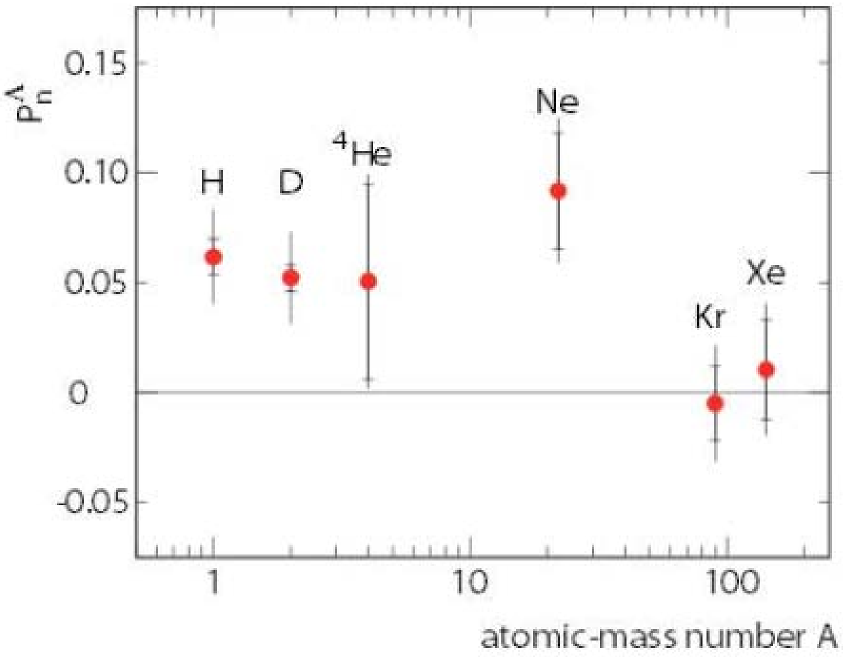
$\bar{\Lambda}$ production $\bar{s}(\text{beam}) + \overline{(ud)}_{0,1}(\text{string})$

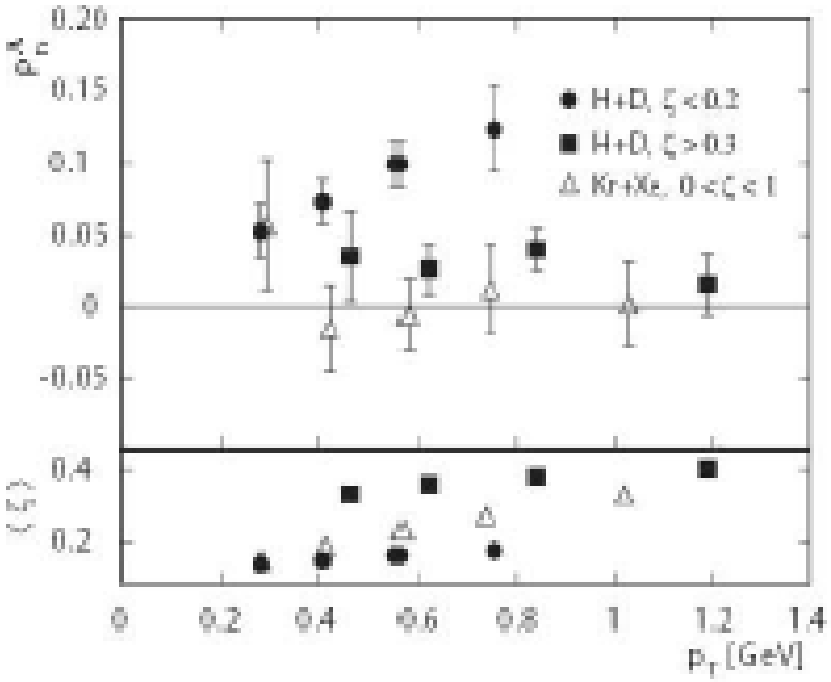
Target fragmentation

Λ production $s\,(\text{beam}) + (ud)_{0,1}(\text{target})$

$\bar{\Lambda}$ production $\bar{s}(\text{beam}) + \overline{(ud)}_{0,1}(\text{target sea})$

A-dependence





Conclusion

- Polarization of Λ in inclusive photoproduction at p_T<1GeV

  $P_\Lambda = 0.078 \pm 0.006_{stat} \pm 0.012_{stat}$

positive as in the case of K^- or Σ^- beam

- Λbar polarization compatible with zero:

  $P_{\Lambda bar} = -0.025 \pm 0.015_{stat} \pm 0.018_{stat}$

- Λ polarization in target fragmentation (ζ<0.25) essentially larger than that in current fragment (ζ>0.25)

- Yield of Λ in target fragmentation surpasses substantially Λbar

- A possible interpretation of production mechanism and (partly) observed polarizations relates photon dissociation to quark-antiquark pair

- A-dependence: polarization vanishes for A≈100

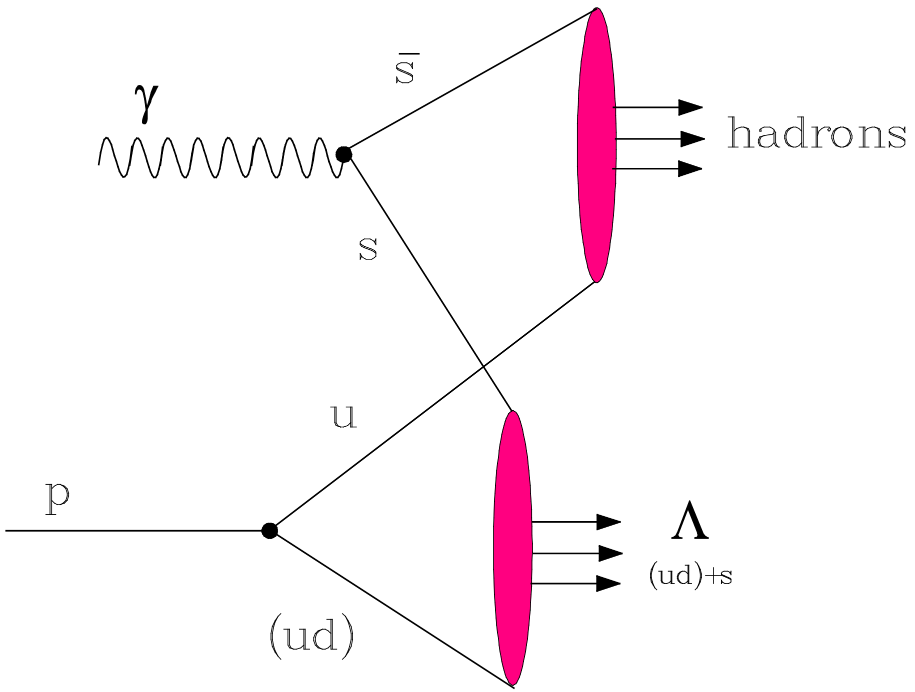
- Polarizations for H and D targets coincides within error bars

BACKUP

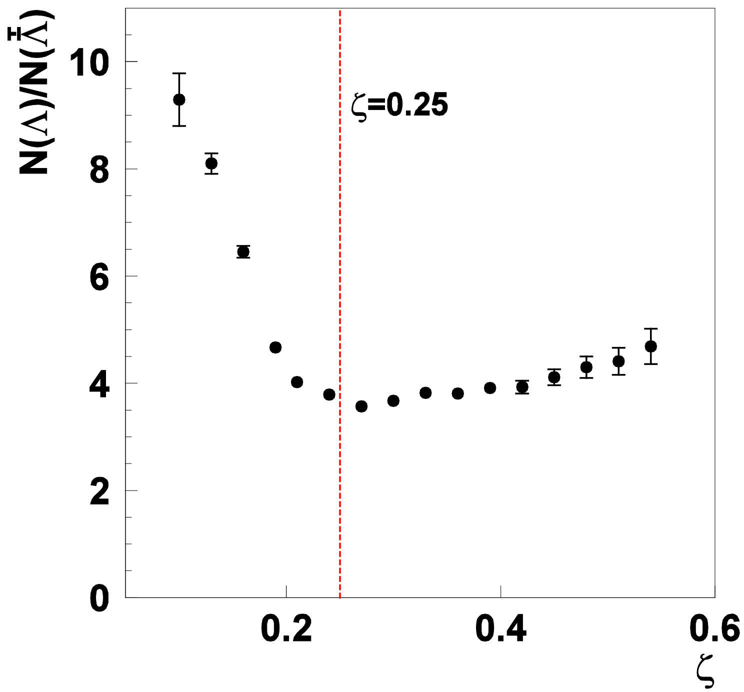
Λ photoproduction mechanism by PYTHIA

$$\langle E_\gamma \rangle = \langle E_e - E_{e'} \rangle \simeq 15.6\ GeV$$

$$\gamma \to q\bar{q} \quad (s\bar{s})$$



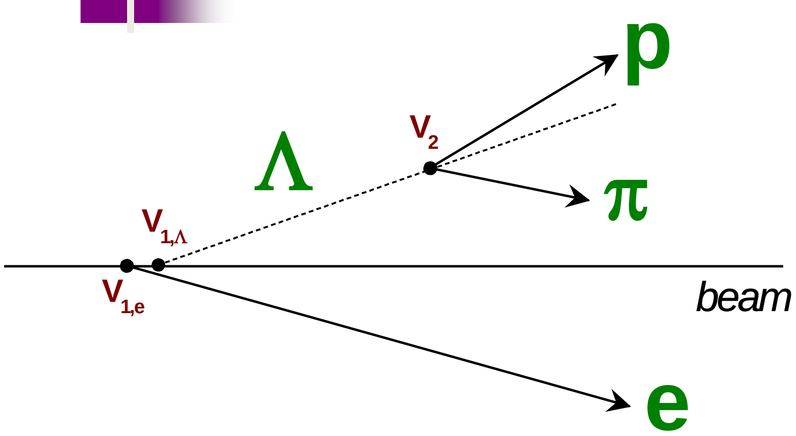
Λ to $\bar{\Lambda}$ yield ratio

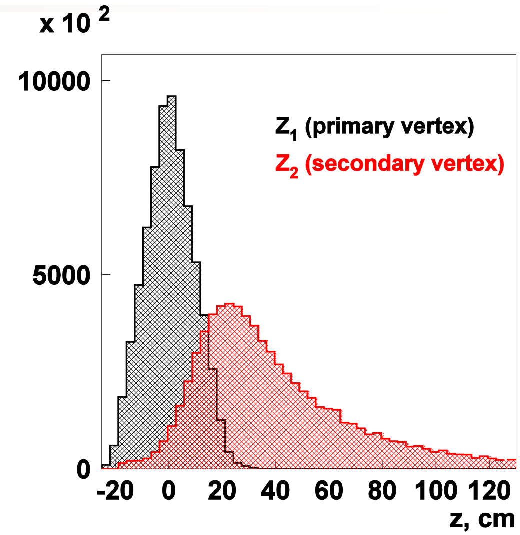


$$\zeta^{\Lambda} \simeq \frac{E^{\Lambda}}{E_e} < 0.25\ or\ \sqrt{t} < 3.31 GeV$$

→ *target (ud) fragmentation mechanism*

Λ and $\bar{\Lambda}$ events selection





main bgr is π+ π- and K π pairs production;

bgr supression cuts:

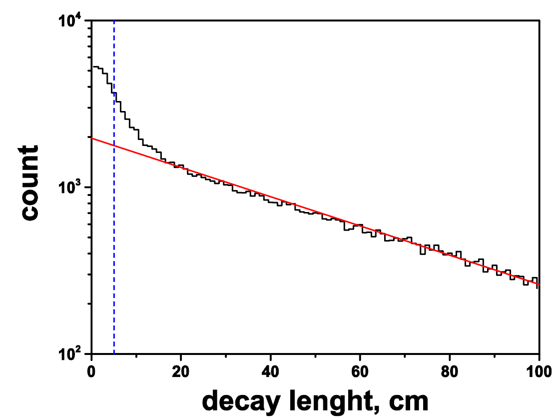
- Leading π rejection

using threshold Cherenkov det. (1996-1997)

or RICH (1998-2007)

- Vertex separation.

Distance between V1 and V2 vertices > 5 cm



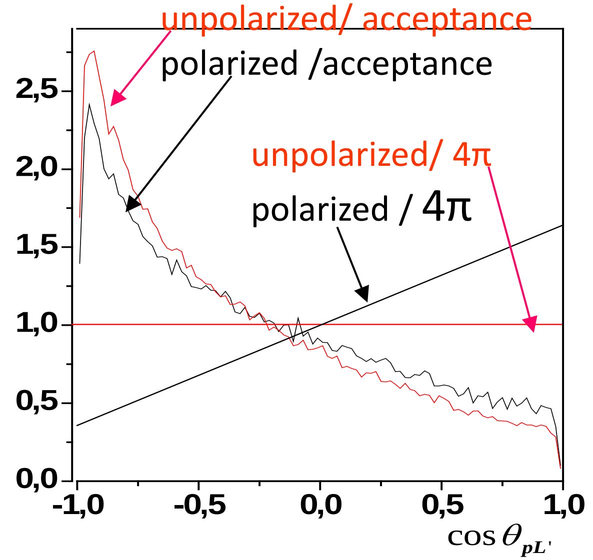
Extraction of D_{Li} components from experimental data sample

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}(1+\alpha \vec{P}^{\Lambda}\cdot \hat{\vec{k}}_p) = \frac{dN_0}{d\Omega_p}(1+\alpha_\Lambda P_B \sum_{i=x,y,z} D^{\Lambda}_{Li}\cos\theta_i) \text{ in } \Lambda \text{ rest frame}$$

$$\alpha_{\Lambda\to p+\pi^-} = 0.642 \pm 0.013 \qquad \alpha_{\bar{\Lambda}\to \bar{p}+\pi^+} = -0.642 \pm 0.013$$

Spectrometer acceptance results in strong distortion of decay angular distribution,

intensive MC acceptance simulation (COMPSS)



For beam helicity balance case $[\![\mathbf{P_B}]\!] = \mathbf{0}$

MC simulation of spectrometer acceptance is not needed, acceptance correction does not affect measured asymmetries. D_{Li} components are extracted using experimental data sample only !!

$$\sum_{k=x,y,z} D_{Lk} A_{ik} = \frac{1}{\alpha}\frac{B_i}{[\![P_B^2]\!]} \quad i = x,y,z$$

$$A_{ik} = \frac{1}{N^\Lambda}\sum_{\nu=1}^{N^\Lambda}\left(D^2(y)\cos\theta_i\cos\theta_k\right)_\nu$$

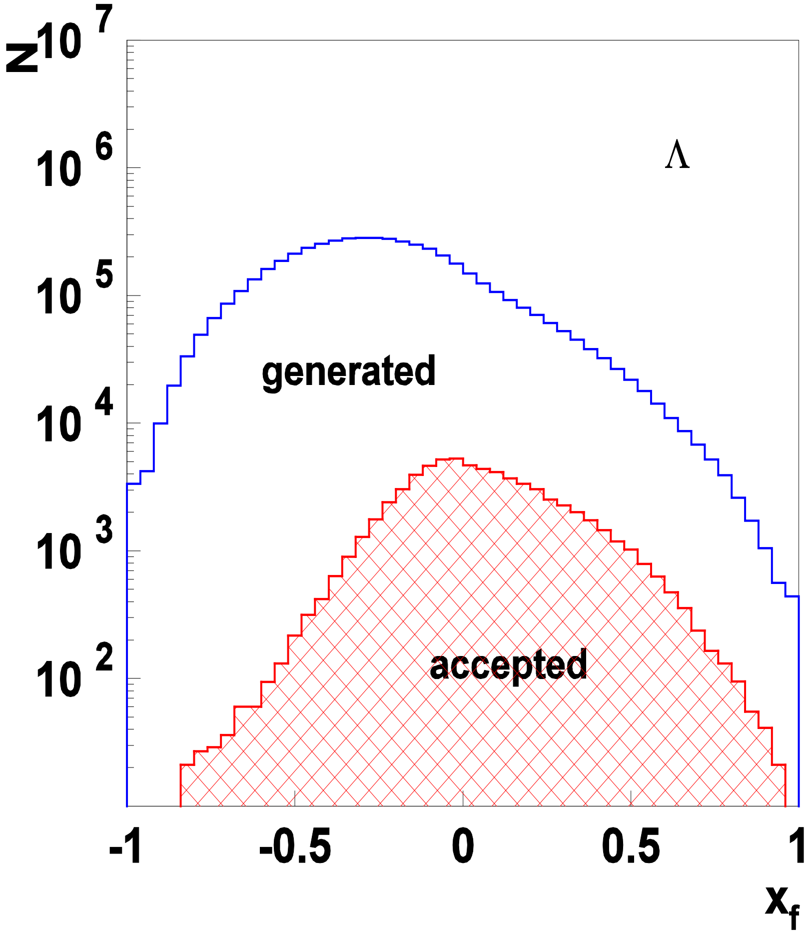
$$B_i = \frac{1}{N^\Lambda}\sum_{\nu=1}^{N^\Lambda}\left(P_B D(y)\cos\theta_i\right)_\nu$$

$$[\![P_B^2]\!] = \frac{\int P^2(t)L(t)dt}{\int L(t)dt}$$

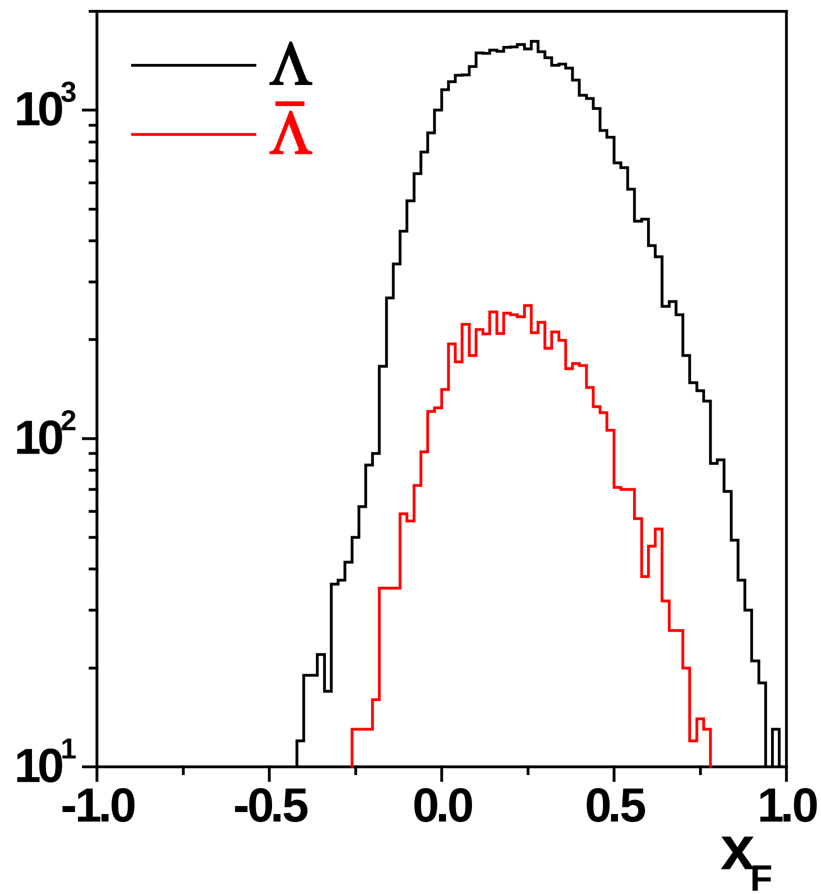
average over experimental data sample

X_F distributions (semi-inclusive DIS)

Pythia MC for Λ



Experiment for Λ and $\bar{\Lambda}$



HERMES is a forward spectrometer → p_Λ(min)~1 GeV

Extraction of $D_{LL'}$

- Angular distribution of decay protons in Λ rest frame

$$\frac{dN}{d\Omega_p} = \frac{dN_0}{d\Omega_p}\left(1 + \alpha P_{Beam} \vec{D}^{\Lambda}_{LL'} \bullet \hat{\vec{k}}_p\right)$$

$$\alpha = 0.642 \pm 0.013$$

$\frac{dN_0}{d\Omega_p} = \text{const}$ for 4π acceptance

for restricted acceptance

$\frac{dN_0}{d\Omega_p}$ depends on $\cos\theta_{pL'}$

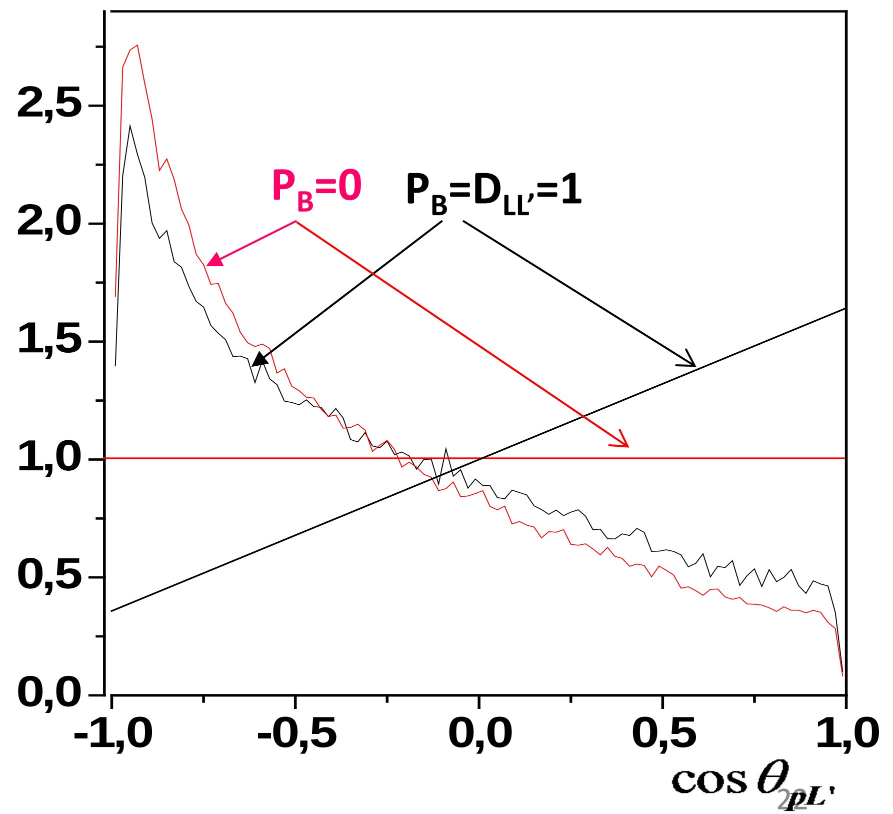
↓

Distorted by spectrometer acceptance

↓

May in principle be calculated using MC

➡ **difficulty to avoid false asymmetry induced by MC acceptance simulation**



Effect of longitudinal magnetic field (solenoid)

$$\cos\theta_p = \frac{p_{\pi x} p_{py} - p_{\pi y} p_{px}}{p_{\Lambda T}\, q}$$

$$\cos\theta_p = \frac{p_{\pi x} p_{py} - p_{\pi y} p_{px}}{q \cdot p_{\Lambda T}} \quad \cos\theta_p \to -\cos\theta_p \ \text{at}\ y \to -y$$

$$\cos\theta_p \to -\cos\theta_p \quad at\ y \to -y$$

$\cos\theta_p$ *in Λ rest frame,*

$q = 101\ Mev$ *decay momentum*

$p_{\pi x,y}$, $p_{px,y}$, $p_{\Lambda T}$ *in Lab frame* (!)

Up/down mirror symmetry: acceptance function

$$\varepsilon^{up}(\cos\theta_p, \ldots) \to \varepsilon^{down}(-\cos\theta_p, \ldots) \quad \text{at} \quad y \to -y$$

Transverse magnetic field of the dipole magnet (transverse pol target and spectrometer dipole)

$$B_x^{up} = -B_x^{down} \quad B_y^{up} = B_y^{down} \quad B_z^{up} = -B_z^{down}$$

Lorentz force

$$F_x^{up} = F_x^{down} \quad F_y^{up} = -F_y^{down} \quad F_z^{up} = F_z^{down}$$

up / down mirror symmetry

Longitudinal magnetic field of solenoid (longitudinal pol target and RD solenoid)

$$B_x^{up} = B_x^{down} \quad B_y^{up} = -B_y^{down} \quad B_z^{up} = B_z^{down}$$

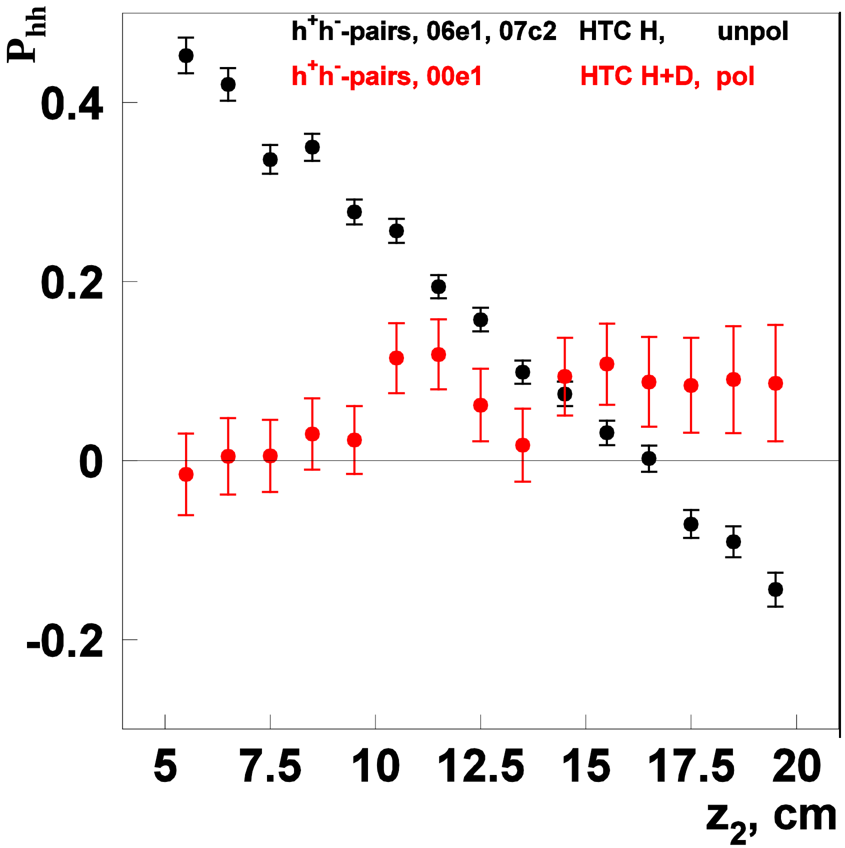
Lorentz force

$$F_x^{up} = -F_x^{down} \quad F_y^{up} = F_y^{down} \quad F_z^{up} = -F_z^{down}$$

no up/down mirror symmetry

EXP

False polarization of hh pairs 00 and 06,07



hh - pairs false polarization
1996-2005

-20 < z1 < 20 cm

pol + unpol 0.0088+- 0.0034
pol 0.0232+- 0.0054
unpol -0.0006+- 0.0044

5 < z1 < 20 cm (recoil target size)

pol + unpol 0.0455+- 0.0059
pol 0.0608+- 0.0093
unpol 0.0355+- 0.0076

Published false polarization of Ks is: $P_{Ks} = 0.012 \pm 0.004$

Published false polarization of hh pairs is: $P_{hh} = 0.012 \pm 0.002$

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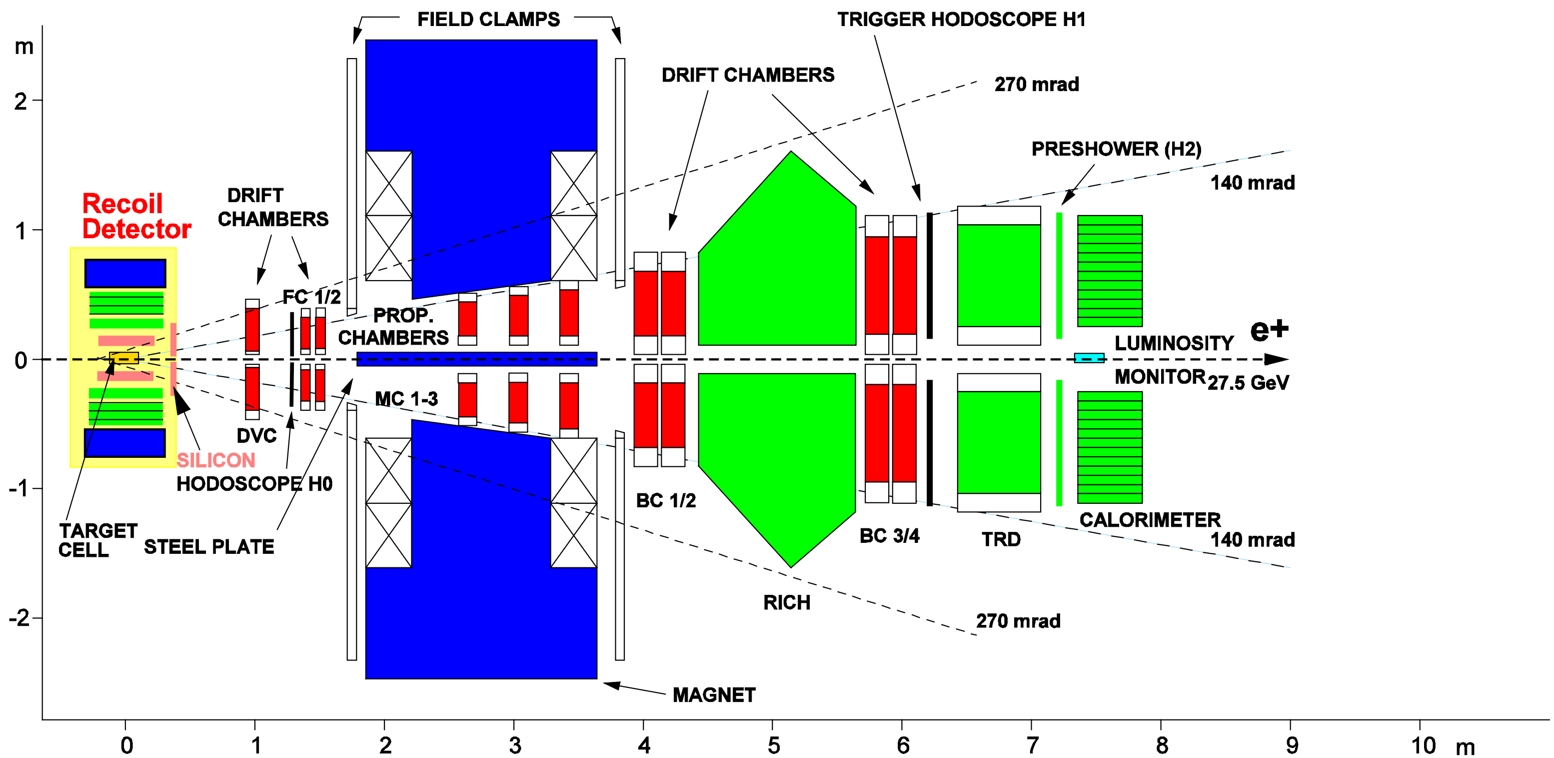
HERMES SPECTROMETER



HERMES dipole BL=1.3 TM

$$\frac{\Delta p}{p} \simeq 1\% \qquad \Delta\theta_x, \Delta\theta_y \simeq 1mrad$$

$$-170 < \theta_x < +170\,mrad \qquad -140 < \theta_y < -40mrad \qquad 140 > \theta_y > 40mrad$$

$$40 < \theta < 220mrad$$

Very good PID !!