What Can We Learn From Λ Polarization ?

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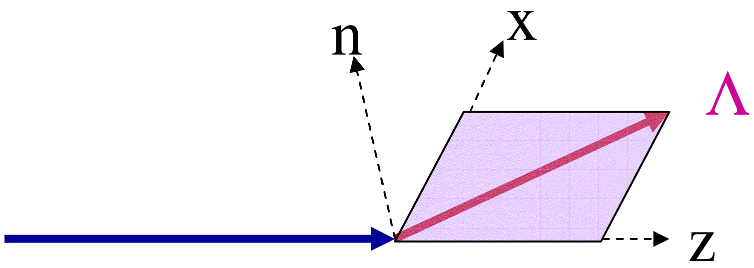
Outline

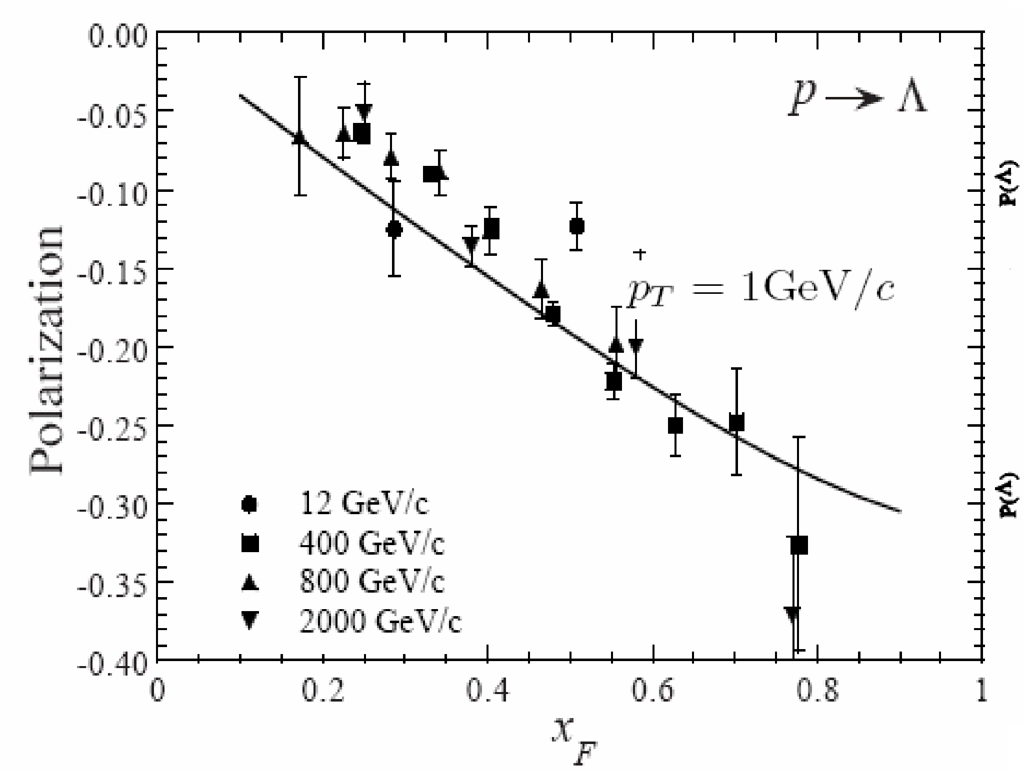
- Transverse polarization of Λ
  - Data
    - Models
  - Transversity
- Longitudinal polarization of Λ
  - LEP data
    - Models
  - Semi-Inclusive DIS (SIDIS)
    - Target and Current Fragmentation
      - Production mechanism and models
- Some conclusions

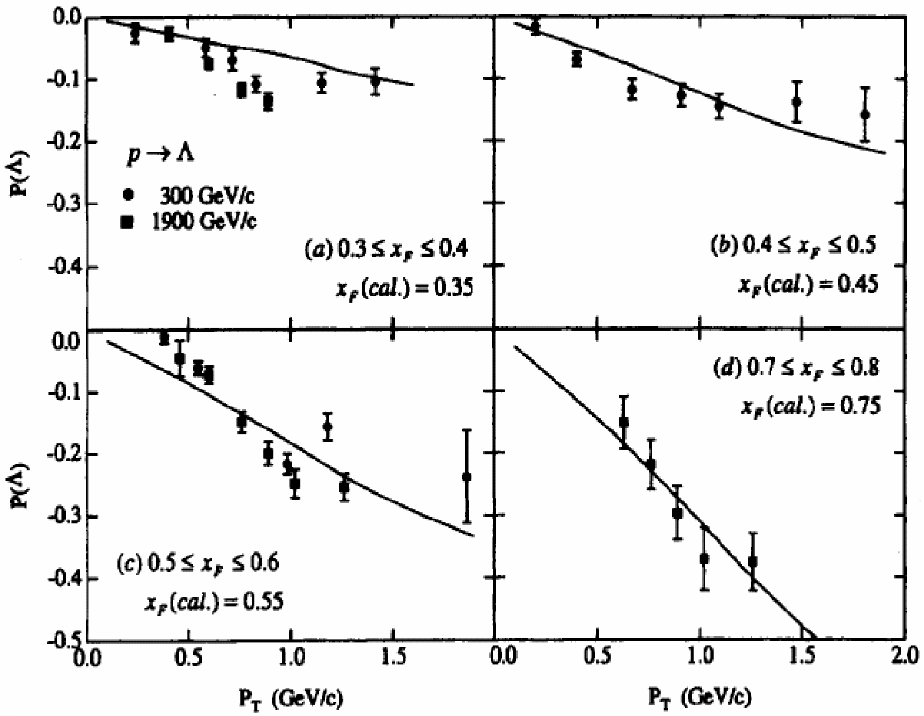
Transverse Polarization of Λ



Normal to production plane

$$\mathbf{n} = \frac{\mathbf{P}_{\text{Beam}} \times \mathbf{P}_{\Lambda}}{\left|\mathbf{P}_{\text{Beam}} \times \mathbf{P}_{\Lambda}\right|}$$





Empiric relation: $S_T^{\Lambda} \propto x_F P_T^{\Lambda}$

Models for Transverse Polarization

- DeGrand & Miettinen model (1981)
  - Quark recombination
- Anderson, Gustafson & Ingelman (1979)
  - String fragmentation
- Anselmino, Boer, D'Alesio & Murgia (2001)
  - New polarizing Fragmentation Functions
- Szwed (1981)
  - Multiple scattering of s-quark on quark-gluon matter
- Barni , Preparata & Ratcliffe (1992)
  - Diffractive triple-Regge model

DeGrand & Miettinen model

- An empirical rule for spin direction of recombining quark:
  - Slow partons – Down, fast partons – Up
  - SU(6) wave functions for baryons
- Semiclassical dynamic is based on Thomas precession

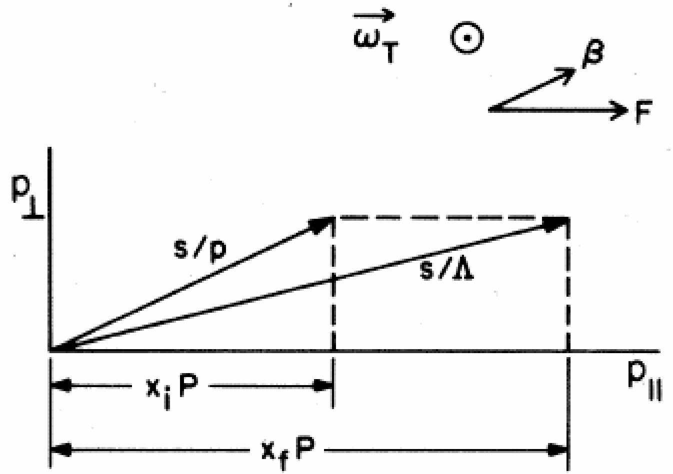


FIG. 2. Momentum vectors for the s quark in the scattering plane in the sea of the proton (labeled by subscripts s/p) and in the Λ (labeled by subscript s/Λ). The recombination force is along the beam direction and the Thomas frequency $\vec{\omega}_T$ is out of the scattering plane.

New term in effective interaction Hamiltonian:

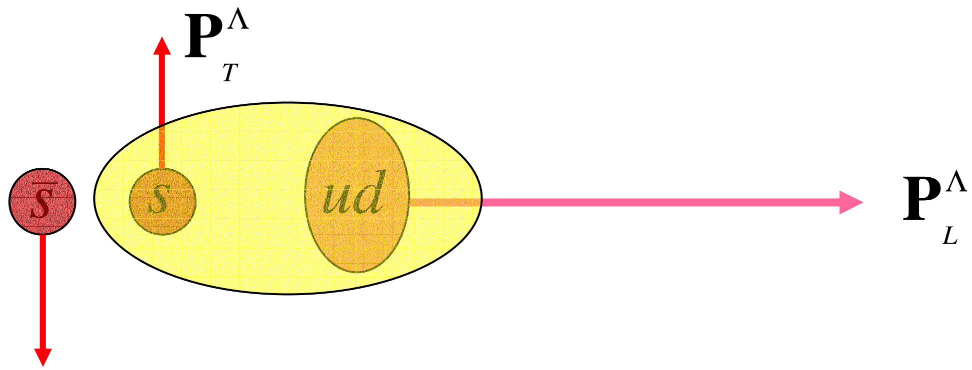
$$U = \vec{S} \cdot \vec{\omega}_T$$

where Thomas frequency is

$$\vec{\omega}_T = \frac{\gamma}{\gamma+1} \frac{\vec{F}}{m_s} \times \vec{V}$$

Anderson, Gustafson & Ingelman model

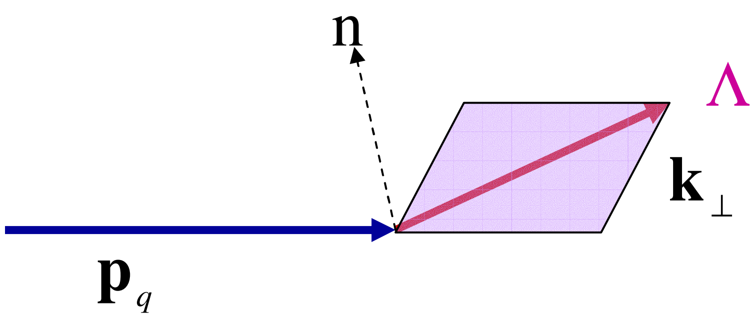
- Semiclassical string fragmentation model
  - Vacuum quantum numbers of quark-antiquark pair: ${}^{3}P_{0}$-state



- Normal to production plane – out of picture
- $s\bar{s}$-pair orbital moment is compensated by spin
  - Negative transverse polarization of Λ

Polarizing Fragmentation Functions

- In unpolarized quark fragmentation with nonzero transverse momentum, $\mathbf{k}_\perp$, Λ can be polarized



$$\hat{D}_{h\uparrow/q}(z,\boldsymbol{k}_\perp) = \frac{1}{2}\hat{D}_{h/q}(z,k_\perp) + \frac{1}{2}\Delta^N D_{h\uparrow/q}(z,k_\perp)\frac{\hat{\boldsymbol{P}}_h\cdot(\boldsymbol{p}_q\times\boldsymbol{k}_\perp)}{|\boldsymbol{p}_q\times\boldsymbol{k}_\perp|}$$

$$\Delta^N D_{h\uparrow/a}(z,\boldsymbol{k}_\perp) \equiv \hat{D}_{h\uparrow/a}(z,\boldsymbol{k}_\perp) - \hat{D}_{h\downarrow/a}(z,\boldsymbol{k}_\perp) = \hat{D}_{h\uparrow/a}(z,\boldsymbol{k}_\perp) - \hat{D}_{h\uparrow/a}(z,-\boldsymbol{k}_\perp),$$

- Probabilistic interpretation – no interference effects

Szwed model

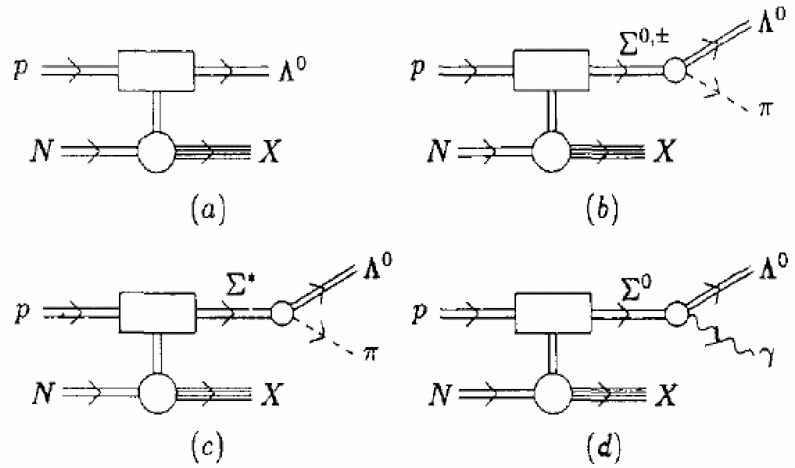
- main assumption is that the s-quark obtains the required transverse momentum by multiple scattering on quark-gluon matter (approximate by external gluonic field $\Phi^a(q) = 4\pi g I^a / q^2$
- Polarization appears already in the second order of the perturbation calculation and reads then

$$\mathbf{S}_{\mathrm{T}}^{\mathrm{q}} = \frac{2C\alpha_s m|k|}{E^2} \frac{\sin^3\theta/2 \ln \sin\theta/2}{[1-(k^2/E^2)\sin^2\theta/2]\cos\theta/2} \mathbf{n}$$

Barni , Preparata & Ratcliffe

$$S_T^{\Lambda} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{\Delta\sigma}{\sigma}, \qquad \sigma = 2F^{B}_{++}, \quad \Delta\sigma = 2\,\mathrm{Im}\,F^{B}_{-+}$$

Interference between diagrams with different intermediate baryons give rise to polarization



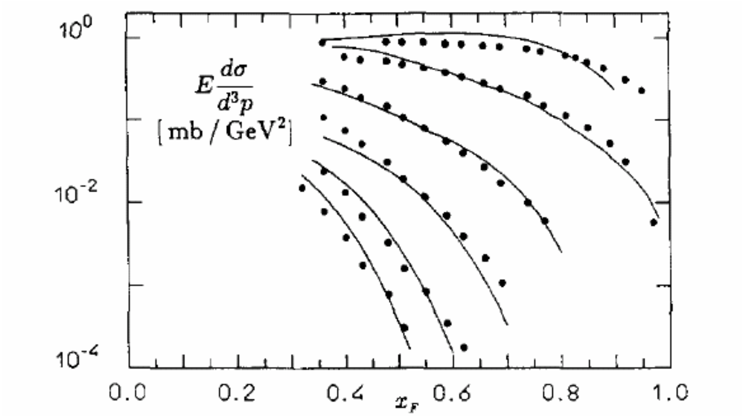


Fig. 2. The triple-Regge prediction of the Λ^0 cross section compared to the data of ref. [11], the curves from top to bottom refer to $\theta_{\mathrm{lab}} = 0.5, 2, 4, 6, 8.1, 10$ mrad.

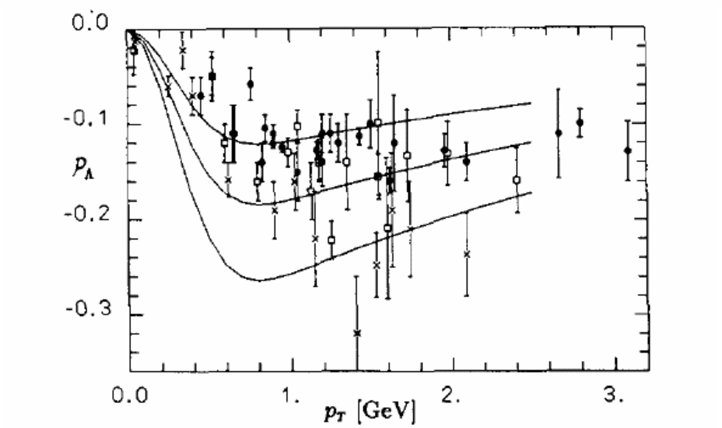
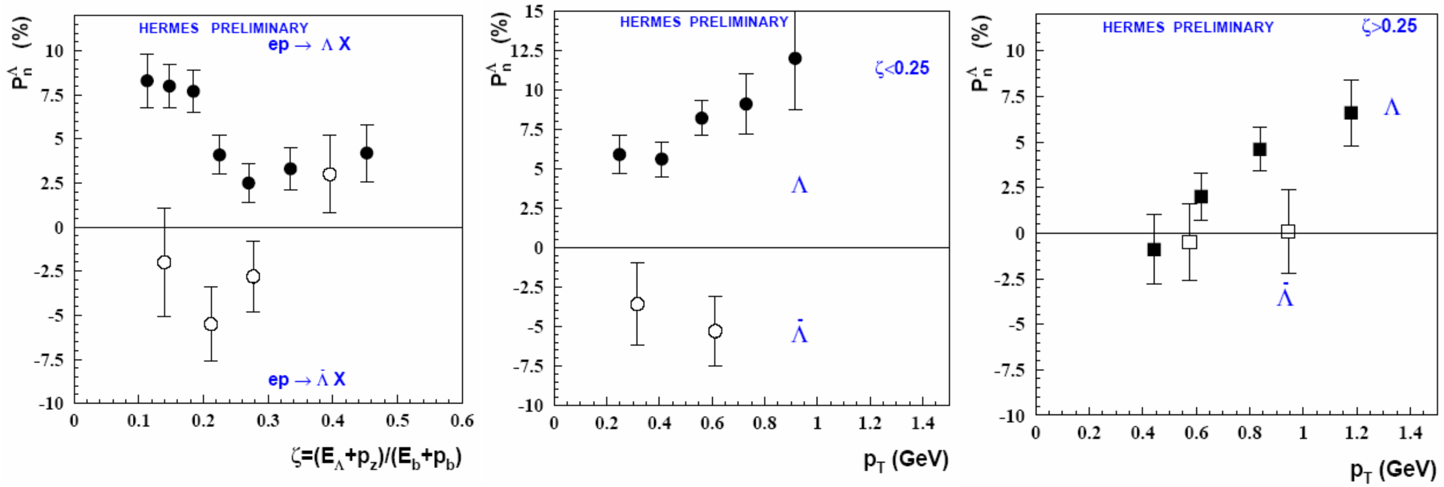
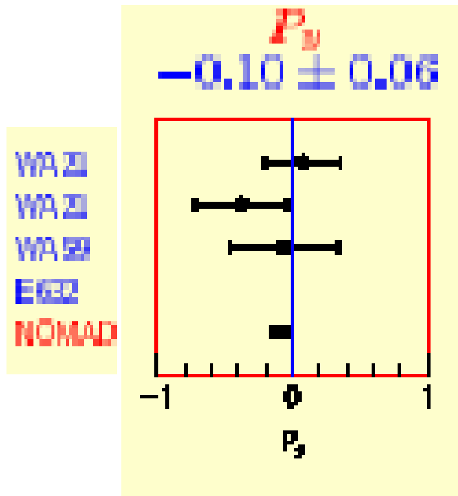


Fig. 5. Our results for the Λ^0 polarization as a function of p_T for $x_F = 0.40,\ 0.55,\ 0.70$ (upper, middle and lower curves respectively) compared with the data (●, □, ×) of refs. [11,18].

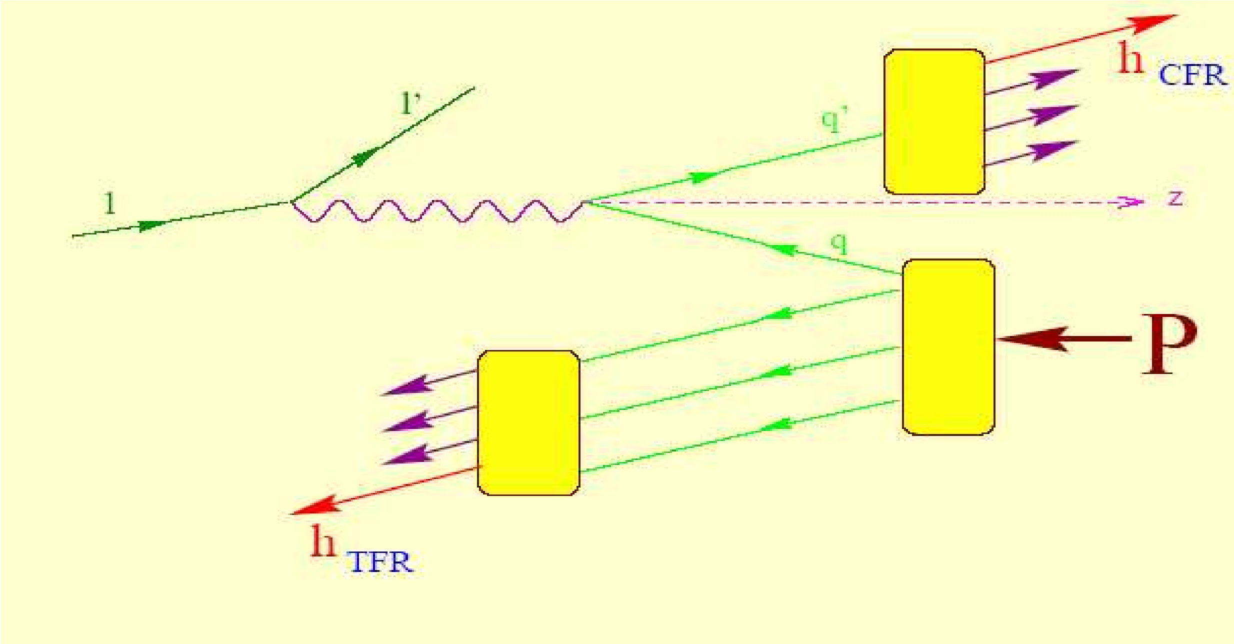
Some Open Questions

- No transverse polarization observed at LEP
- Positive transverse polarization at HERMES
  - Qualitatively can be explained in DM model with VMD approach
  - Parton model: u-quark dominance? Compare with neutrino data.





SIDIS



Virtual boson – nucleon CMS:

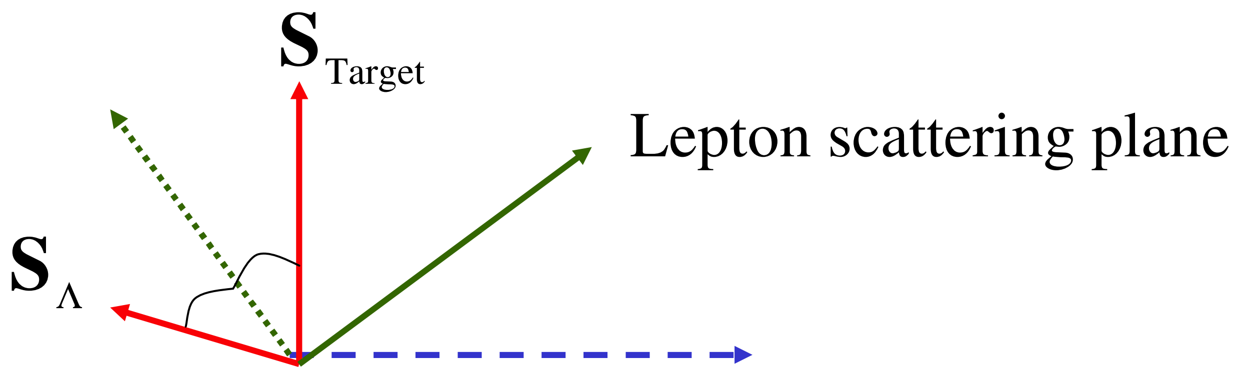
$x_F > 0$ – current fragmentation (CFR)

$x_F < 0$ – target fragmentation (TFR)

Transversity

- Transverse polarization of quarks in the transversely polarized nucleon: $h_{1_q}(x)$ measurement
  - Transverse polarization transfer from quark to Λ

$$S_\Lambda = S_{\text{Target}} \cdot \frac{2(1-y)}{1+(1-y)^2} \frac{\sum_q e_q^2 \, h_{1q}(x) \, \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 \, q(x) \, D_{\Lambda/q}(z)}$$



- s-quark dominance in polarization transfer as in SU(6)?

Longitudinal Polarization of Λ: CFR

- Spin transfer from lepton to produced Λ (unpolarized target)
- Spin transfer in the longitudinally polarized quark fragmentation
  - Spin transfer coefficient: $C_q(z) \equiv \Delta D_q^\Lambda(z)/D_q^\Lambda(z)$
  - NQM: $C_s(z) = 1;\ C_u(z) = C_d(z) = 0$
  - Burkardt & Jaffe: SU(3)&polarized DIS data

$$C_s(z) = 0.6;\ C_u(z) = C_d(z) = -0.2$$

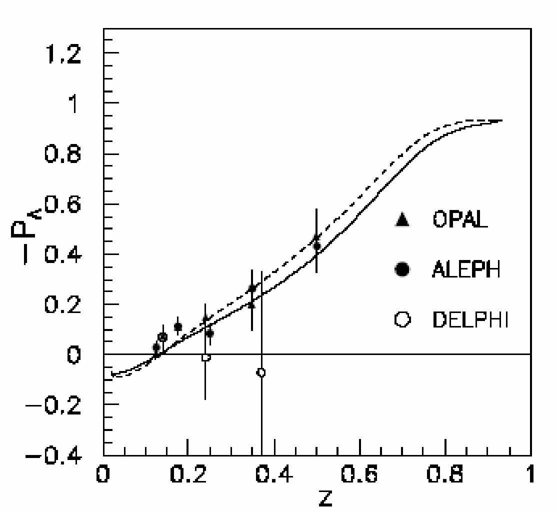
  - Ma, Schmidt, Soffer & Yang: quark-diquark model with SU(6) breaking & pQCD; Boros, Londergan & Thomas: MIT bag model

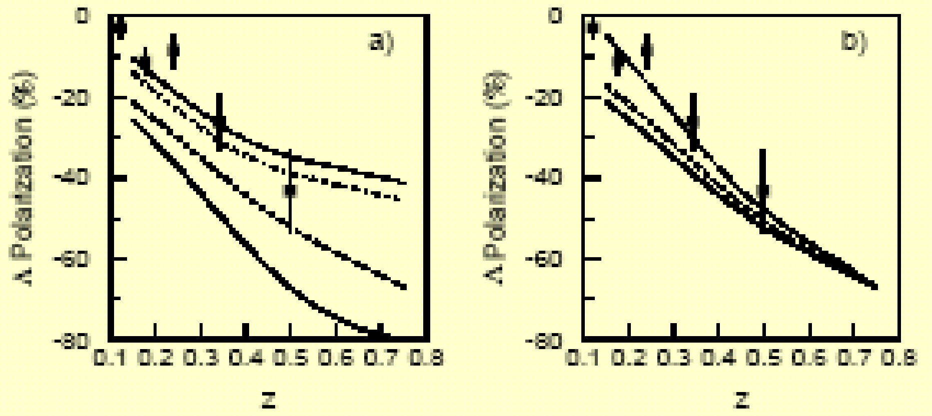
$$C_s(z) \leq 1$$
$$C_u(z) = C_d(z) < 0 \text{ at small } z$$
$$C_u(z) = C_d(z) > 0 \text{ at high } z$$

  - Bigi; Gustafson & Hakkinen: SU(6)+LUND fragmentation $q \to B \to \Lambda$

$$C_s(z) \leq 1$$
$$C_u(z) = C_d(z) > 0 \text{ at small } z$$
$$C_u(z) = C_d(z) < 0 \text{ at high } z$$

LEP data

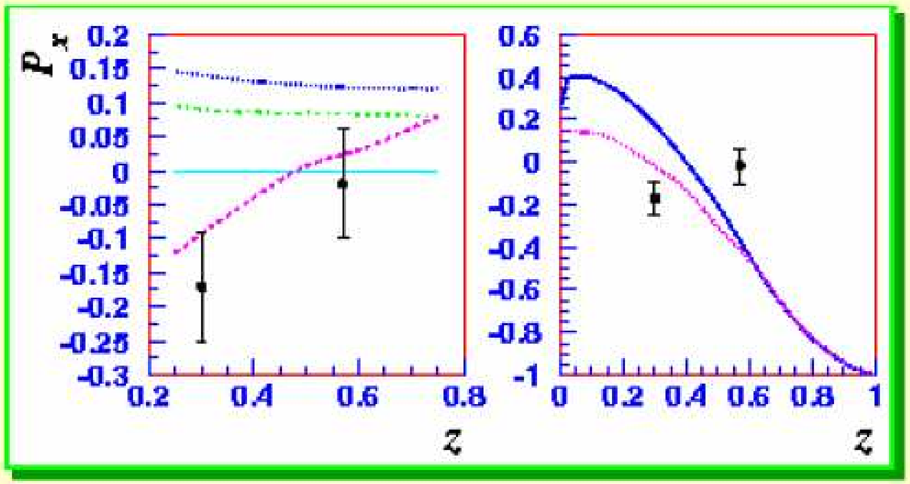




Longitudinal polarization of $\Lambda/\bar{\Lambda}$ in e^+e^- annihilation at Z^0 pole (data from DELPHI (1995), curves: A. K., A. Bravar & D. von Harrach(1998))

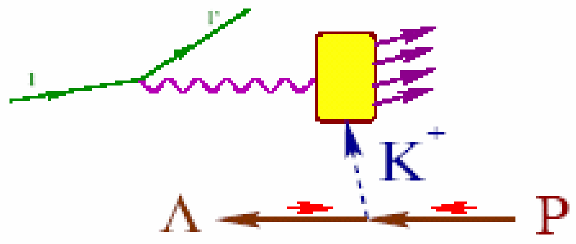
HERMES data

- A.Kotzinian, A.Bravar, D.von Harrach, Eur. Phys. J. C2 (1998) 329 (left)
- B.Ma, I.Schmidt, J.Soffer and J.Yang, hep-ph/0001259 (right)

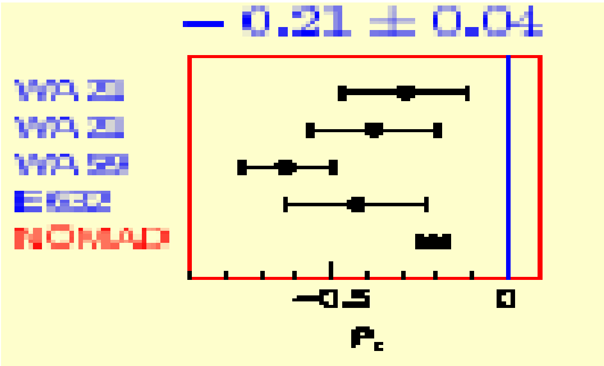


TFR: Meson Cloud Model

- Melnitchouk & Thomas:



  - 100 % anticorrelated with target polarization
    - contradiction with neutrino data for unpolarized target
      - Longitudinal polarization of Λ in the TFR



Intrinsic Strangeness Model

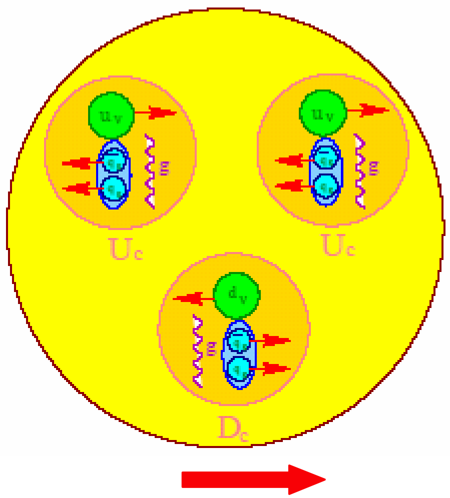
- Karliner, Kharzeev , Sapozhnikov, Alberg,Ellis & A.K.
  - nucleon wave function contains an admixture with $s\bar{s}$ −component:

$$|p\rangle = a\sum_{X=0}^{\infty}|uudX\rangle + b\sum_{X=0}^{\infty}|uud\bar{s}sX\rangle + \ldots$$

  - π, K masses are small at the typical hadronic mass scale $\Rightarrow$ a strong attraction in the $J^P = 0^-$ − channel.
  - $q\bar{q}$ −pairs from vacuum in $^3P_0$ − state

Spin crisis: $\Delta s \approx -0.1$

Polarized proton:

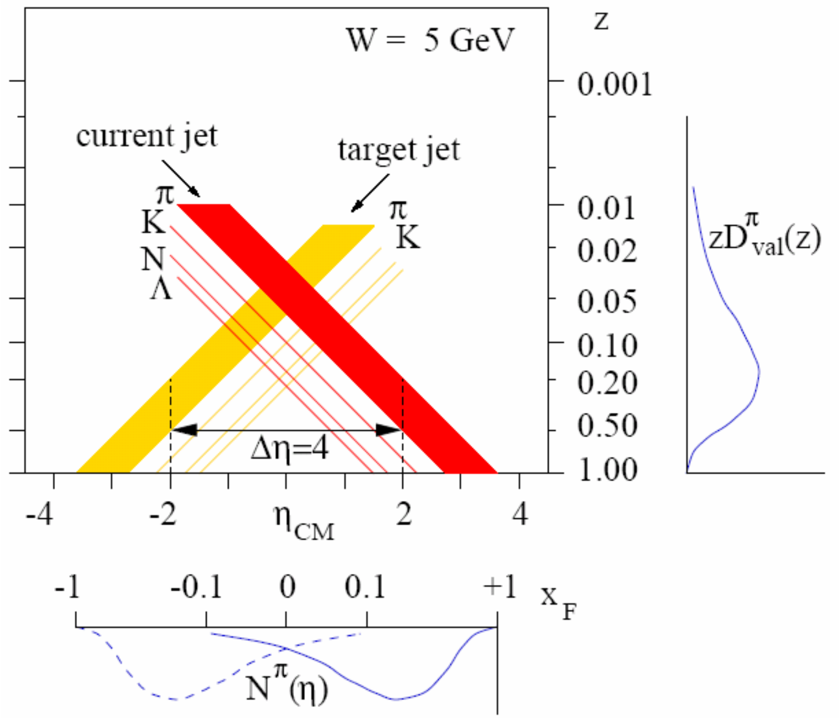


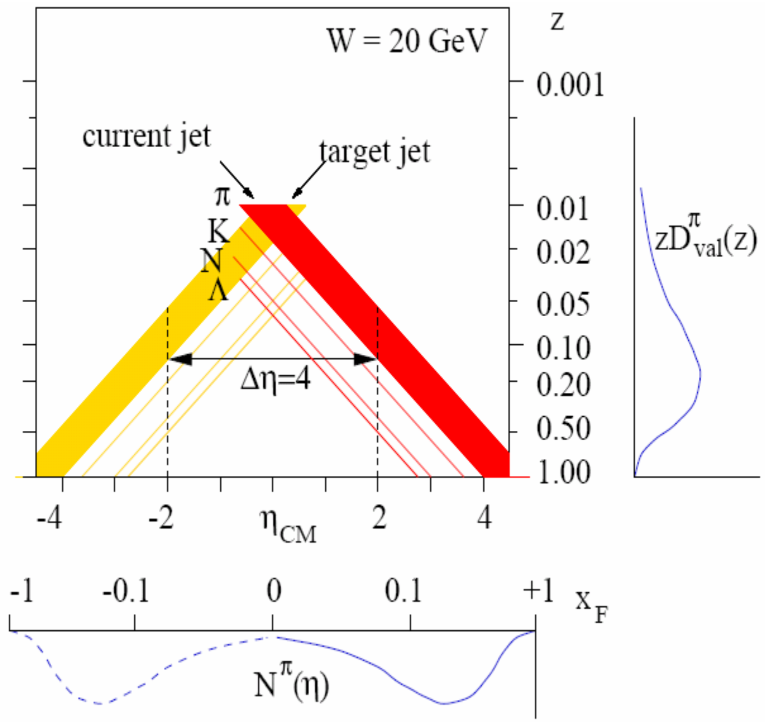
Ed. Berger criterion (separation of CFR &TFR)

The typical hadronic correlation length in rapidity is

$$\Delta y_h \simeq 2$$

Illustrations from P. Mulders:



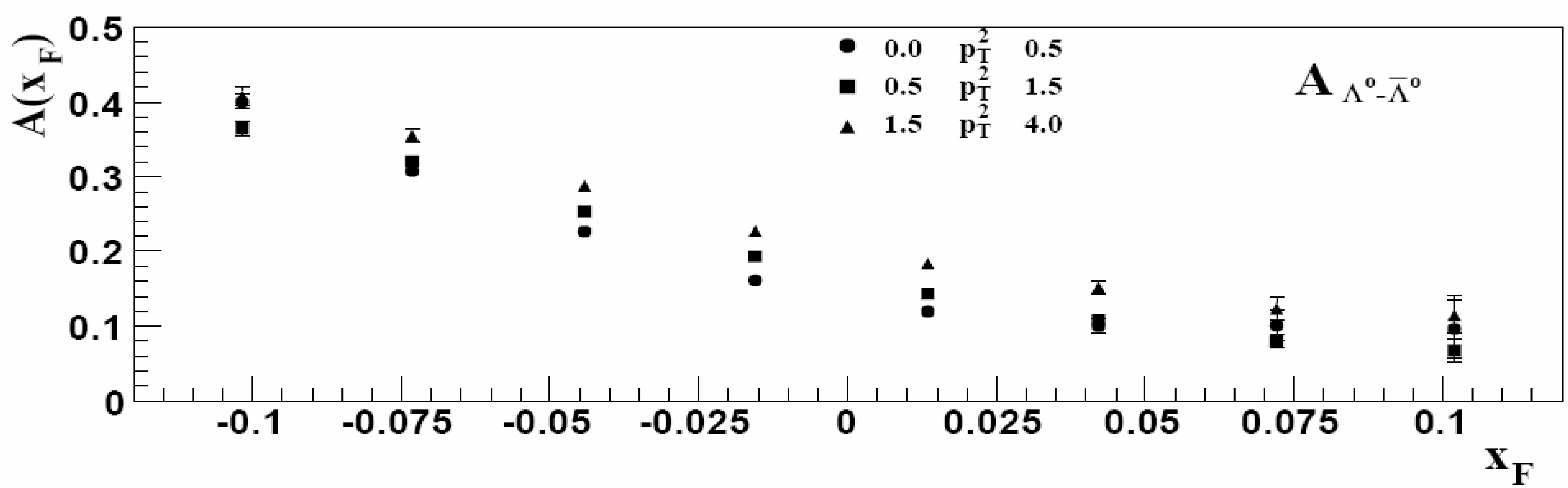


Λ production in 500 GeV/c π^--Nucleon Production

- Fermilab E791 Collaboration, hep-ph/0009016

$$\pi^- = u\bar{d} \quad \Lambda^0 = uds \quad \text{common u}$$
$$\pi^- = u\bar{d} \quad \bar{\Lambda}^0 = \bar{u}\bar{d}\bar{s} \quad \text{common } \bar{d}$$

$$A = \frac{N_{\Lambda^0} - N_{\bar{\Lambda}^0}}{N_{\Lambda^0} + N_{\bar{\Lambda}^0}}$$

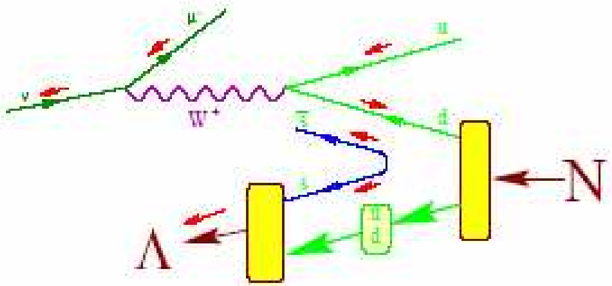


J.Ellis, A.K. & D.Naumov (2002)

$$P_\Lambda^{lN}(B) = \frac{\sum_M P_s(B(J,M)) \mid \langle B(J,M) \mid \text{diquark-quark remnant + s quark} \rangle \mid^2}{\sum_M \mid \langle B(J,M) \mid \text{diquark-quark remnant + s quark} \rangle \mid^2}$$

— $P_s(B(J,M))$ is the polarization of the strange quark in the baryon B with the spin state $\mid B(J,M)\rangle$,

— $\mid$ diquark-quark remnant + s quark $\rangle$ is the product of the wave function of the remnant diquark and the wave function of polarized s quark.



The remnant diquark-quark wave functions are:

$$|p \ominus d^\uparrow\rangle = \frac{1}{\sqrt{36}}[-\sqrt{2}(uu)_{1,0} + 2(uu)_{1,-1}]$$

$$|n \ominus d^\uparrow\rangle = \frac{1}{\sqrt{36}}[3(ud)_{0,0} + (ud)_{1,0} - \sqrt{2}(ud)_{1,-1}]$$

The wave function of polarized s quark is:

$$|s\rangle_{pol} = \frac{1}{\sqrt{2}} \mid \sqrt{(1+C_{sq})}s^\uparrow + \sqrt{(1-C_{sq})}s^\downarrow \rangle$$

Finally, the Λ^0 polarization in lN DIS is:

$$P_\Lambda^{lN} = \sum_B \xi_B P_\Lambda^{lN}(B), \text{ where } \xi_B \text{ is the fraction of } \Lambda^0 \text{ produced via B}$$

Λ polarization in quark & diquark fragmentation

Λ polarization from the quark fragmentation

$$P_\Lambda^q(B) = -C_q^\Lambda(B) P_q,$$

Table 1: Spin correlation coefficients in SU(6) and BJ models

Λ's parent	C_u^Λ		C_d^Λ		C_s^Λ	
	SU(6)	BJ	SU(6)	BJ	SU(6)	BJ
quark	0	-0.18	0	-0.18	1	0.63
Σ^0	-2/9	-0.12	-2/9	-0.12	1/9	0.15
Ξ^0	-0.15	0.07	0	0.05	0.6	-0.37
Ξ^-	0	0.05	-0.15	0.07	0.6	-0.37
Σ^*	5/9	5/9	5/9	5/9	5/9	5/9

Λ polarization from the diquark fragmentation

$$P_\Lambda^{\nu\, d}(prompt; N) = P_\Lambda^{e\, u}(prompt; N) =$$
$$P_\Lambda^{l\, u}(prompt; N) = C_{sq} \cdot P_q,$$

$$P_\Lambda^{\nu\, d}(\Sigma^0; n) = P_\Lambda^{e\, u}(\Sigma^0; p) =$$
$$P_\Lambda^{l\, u}(\Sigma^0; p) = P_\Lambda^{l\, d}(\Sigma^0; n) = \frac{1}{3} \cdot \frac{2 + C_{sq}}{3 + 2C_{sq}} \cdot P_q,$$

$$P_\Lambda^{\nu\, d}(\Sigma^{*0}; n) = P_\Lambda^{\nu\, d}(\Sigma^{*+}; p) =$$
$$P_\Lambda^{e\, u}(\Sigma^{*0}; p) = P_\Lambda^{e\, u}(\Sigma^{*+}; n) =$$
$$P_\Lambda^{l\, u}(\Sigma^{*0}; p) = P_\Lambda^{l\, d}(\Sigma^{*0}; n) =$$
$$P_\Lambda^{l\, d}(\Sigma^{*+}; p) = P_\Lambda^{l\, u}(\Sigma^{*-}; n) = -\frac{5}{3} \cdot \frac{1 - C_{sq}}{3 - C_{sq}} \cdot P_q.$$

Spin Transfer

- We use Lund string fragmentation model incorporated in LEPTO6.5.1 and JETSET7.4.
- We consider two extreme cases when polarization transfer is nonzero:
  - **model A:**
    - the hyperon contains the stuck quark: $Rq = 1$
    - the hyperon contains the remnant diquark: $Rqq = 1$
  - **model B:**
    - the hyperon originates from the stuck quark: $Rq \geq 1$
    - the hyperon originates from the remnant diquark: $Rqq \geq 1$

Fixing free parameters

- We vary two correlation coefficients ($C_{sq_{val}}$ and $C_{sq_{sea}}$) in order to fit our models A and B to the NOMAD Λ polarization data.
- We fit to the following 4 NOMAD points to find our free parameters:

  - νp: $P_x^\Lambda = -0.26 \pm 0.05(stat)$,
  - νn: $P_x^\Lambda = -0.09 \pm 0.04(stat)$,
  - $W^2 < 15$ GeV^2: $P_x^\Lambda = -0.34 \pm 0.06(stat)$,
  - $W^2 > 15$ GeV^2: $P_x^\Lambda = -0.06 \pm 0.04(stat)$.

As a result of these fits we find:

model A: $C_{sq_{val}} = -0.35 \pm 0.03$ and $C_{sq_{sea}} = -0.95 \pm 0.03$

model B: $C_{sq_{val}} = -0.25 \pm 0.03$ and $C_{sq_{sea}} = 0.15 \pm 0.03$

Results

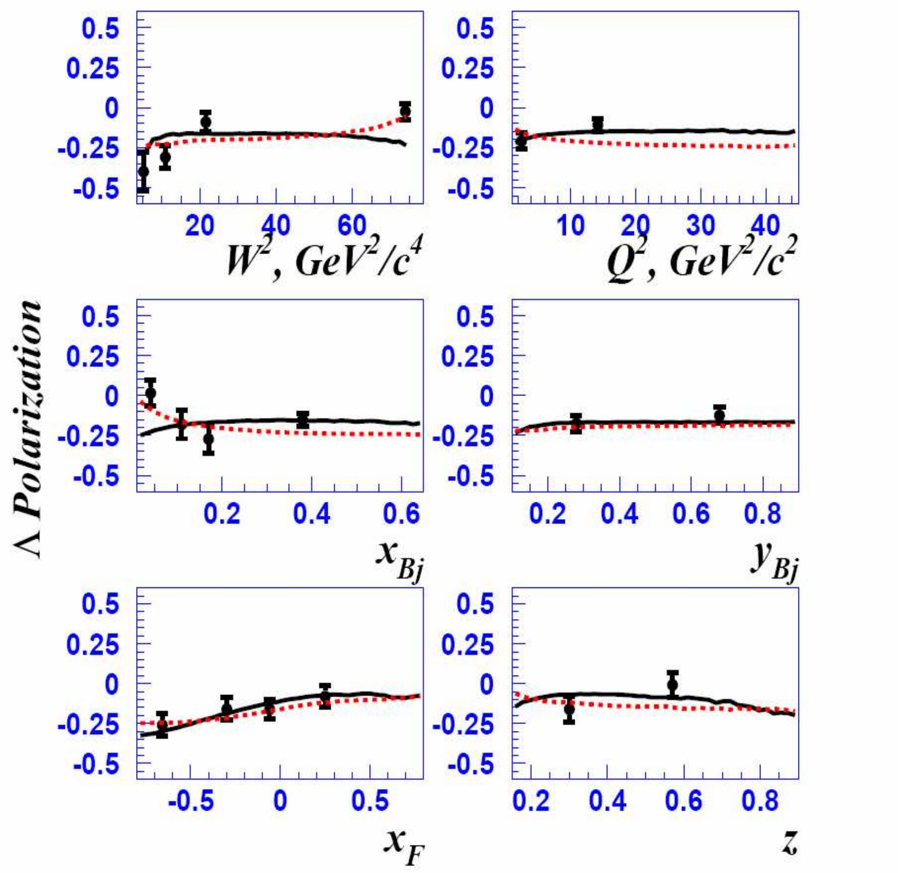


Figure 5: Our model predictions (model A - solid line, model B - dashed line) for polarization of Λ hyperons produced in ν_μ charged current DIS interactions off nuclei as functions of W^2, Q^2, x_{Bj}, y_{Bj}, x_F and z (at $x_F > 0$). The points with error bars are from NOMAD.

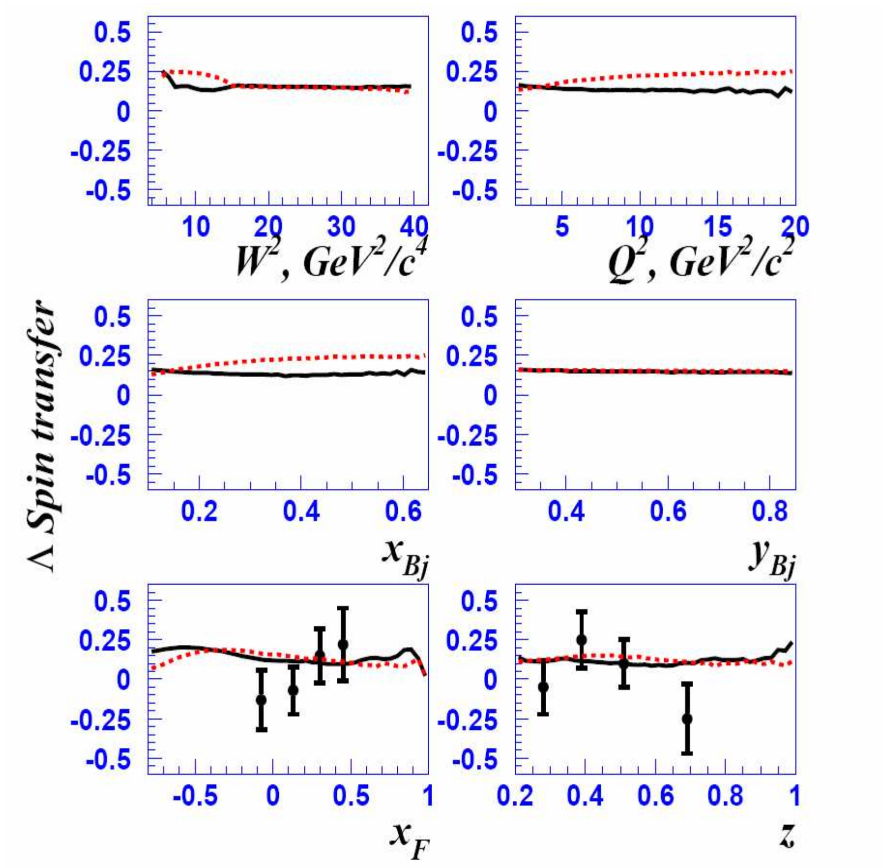


Figure 6: Our model predictions (model A - solid line, model B - dashed line) for the spin transfer of Λ hyperons produced in e^+ DIS interactions off nuclei as functions of W^2, Q^2, x_{Bj}, y_{Bj}, x_F and z (at $x_F > 0$). ($E_e = 27.5$ GeV) The points with error bars are from HERMES

Predictions for COMPASS

The spin-correlation coefficient for the sea quark is different in **model A:** and **model B:**

$x_{min} = 0.003$ in the COMPASS, so we expect different polarizations of Λ^0 in these two cases:

Table 3: Λ *polarization in* μ^+ *DIS predicted for the COMPASS experiment for* $Q^2 > 1.$ *GeV*^{2}, $x_F > -0.2$ *and* $0.5 < y < 0.9$.

P_Λ (%)	Target nucleon		
	isoscalar	proton	neutron
model A	-7.3	-7.3	-7.2
model B	-0.4	-0.4	-0.4

Conclusions

- Λ polarization is a non-perturbative phenomena. We have many models for transverse polarization
  - In spite of almost 30 years of efforts to understand the dynamics of transverse polarization of Λ still lot of questions remain
    - What is real mechanism of spontaneous transverse polarization? Can we understand it starting from first principles of QCD?
    - Why it is small (or zero) at LEP
- Predictions for Λ polarization are very sensitive to production mechanism
- We need models which are able to describe the data both in TFR and CFR simultaneously. For the moment we have Lund model in LEPTO
- A phenomenological polarized intrinsic strangeness + SU(6) model is able to describe all available data on longitudinal polarization of Λ in full kinematic range
- Energies in the running experiments are too low to distinguish between different (SU(6) and BJ) models for spin transfer in quark fragmentation