Lambda and Hyperon Physics

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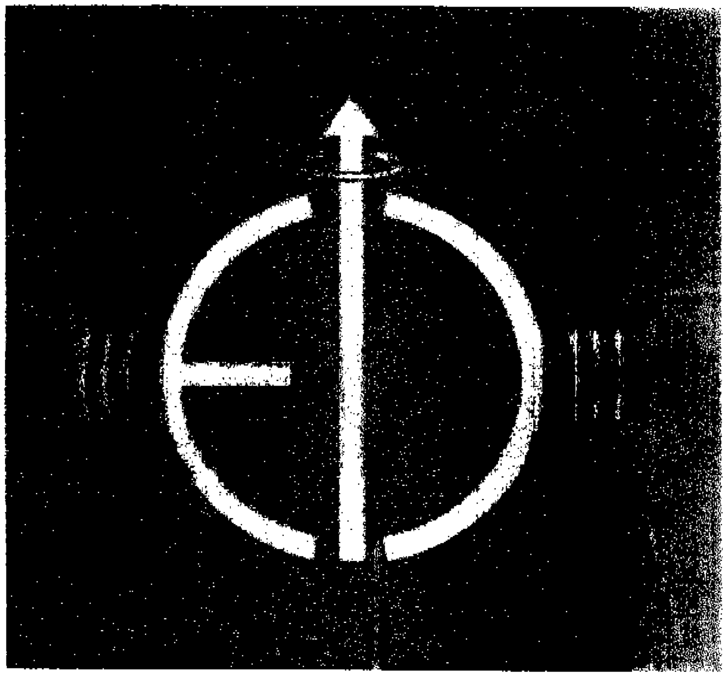
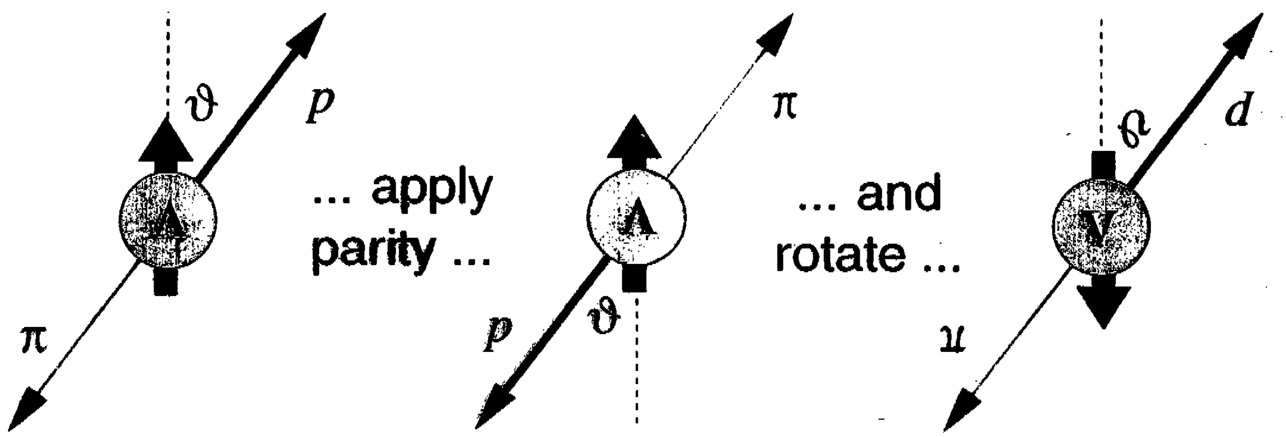


- The Λ ***Hyperon*** : a unique particle in spin physics
- Example: the ***spin-transfer coefficient*** $D_{LL'}$
- ***Monte Carlo model*** of $D_{LL'}$
- ***Outlook*** for EIC

This talk was requested at the last minute ...
my apologies to NOMAD, COMPASS, and E665 for any under-representation of their fine results!

Λ: The Final State Polarimeter

In Λ rest frame, **proton** prefers to be emitted along
Λ spin direction ➡ **parity-violating** weak decay



$$\frac{dN}{d\Omega_p} \sim (1 + \alpha \vec{P}^\Lambda \cdot \hat{k}_p) = (1 + \alpha P^\Lambda \cos\theta_p)$$

$\alpha = 0.642$ ... θ_p is relative to ***true*** Λ polarization direction

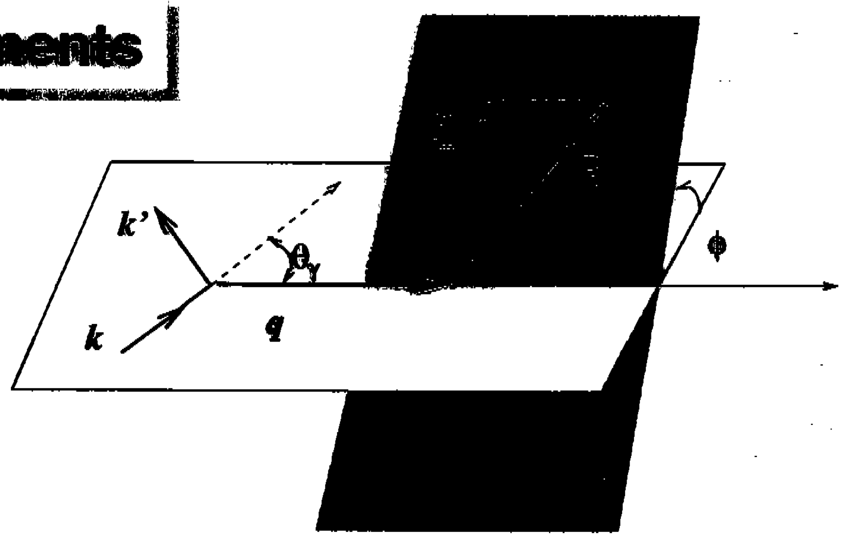
Λ spin structure

	Constituent q Model			SU(3) from nucleon*		
	Δu	Δd	Δs	Δu	Δd	Δs
p	+4/3	-1/3	0	+0.83	-0.43	-0.10
n	-1/3	+4/3	0	-0.43	+0.83	-0.10

* ***Burkardt & Jaffe*** : use measured p, n values + SU(3)-symmetric flavour rotation to obtain hyperon values

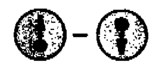
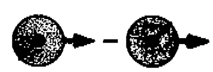
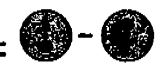
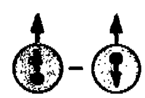
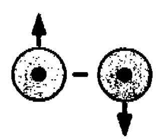
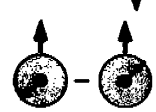
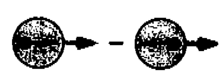
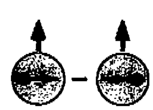
Λ	**0**	**0**	**1**	**-0.17**	**-0.17**	**+0.63**
Σ^0	+2/3	+2/3	-1/3	+0.37	+0.37	-0.43
Ξ^0	-1/3	0	+4/3	-0.43	-0.10	0.83

Azimuthal Moments



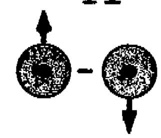
"The Bible":
Mulders & Tangerman,
PLB 461 (1996) 197

Polarized SIDIS xsec at leading order in $1/Q$:

UU	1	$\otimes f_1 =$ 	$\otimes D_1 =$ 
	$\cos(2\phi_h^l)$	$\otimes h_1^\perp =$ 	$\otimes H_1^\perp =$ 
UL	$\sin(2\phi_h^l)$	$\otimes h_{1L}^\perp =$ 	$\otimes H_1^\perp =$ 
UT	$\sin(\phi_h^l + \phi_S^l)$	$\otimes h_1 =$ 	$\otimes H_1^\perp =$ 
	$\sin(\phi_h^l - \phi_S^l)$	$\otimes f_{1T}^\perp =$ 	$\otimes D_1 =$ 
	$\sin(3\phi_h^l - \phi_S^l)$	$\otimes h_{1T}^\perp =$ 	$\otimes H_1^\perp =$ 
LL	1	$\otimes g_1 =$ 	$\otimes D_1 =$ 
LT	$\cos(\phi_h^l - \phi_S^l)$	$\otimes g_{1T} =$ 	$\otimes D_1 =$ 

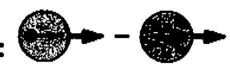
Moments with Final State Polarization

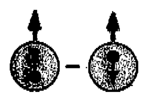
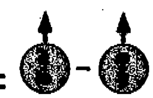
Main topic of this talk – polarizing frag func $\mathbf{D}_{1T}^{\perp}$:

UUT $\sin(\phi_h^l - \phi_{S_h}^l)$ $\otimes f_1 =$  $\otimes \mathbf{D}_{1T}^{\perp} =$ 

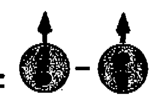
Spin Transfer in Fragmentation:

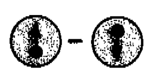
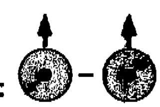
LUL 1 $\otimes f_1 =$  $\otimes G_1 =$ 

ULL 1 $\otimes g_1 =$  $\otimes G_1 =$ 

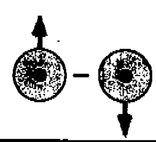
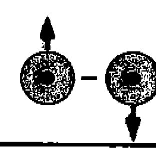
UTT $\cos(\phi_S^l + \phi_{S_h}^l)$ $\otimes h_1 =$  $\otimes H_1 =$ 

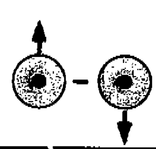
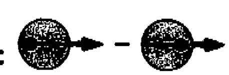
The rest involve T-odd distribution functions:

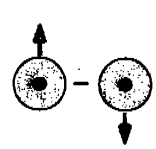
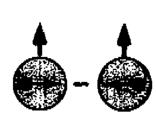
UUT $\sin(\phi_h^l + \phi_{S_h}^l)$ $\otimes \mathrm{h}_1^{\perp} =$  $\otimes H_1 =$ 

$\sin(3\phi_h^l - \phi_{S_h}^l)$ $\otimes \mathrm{h}_1^{\perp} =$  $\otimes H_{1T}^{\perp} =$ 

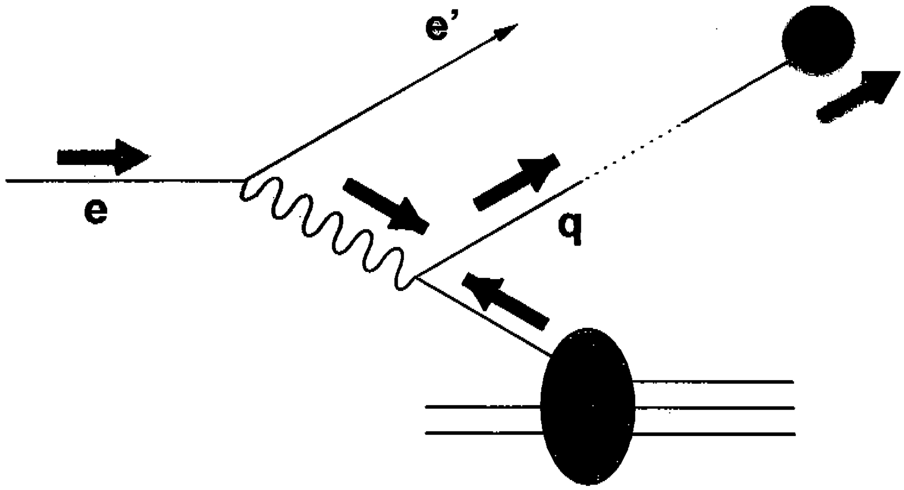
UUL $\sin(2\phi_h^l)$ $\otimes \mathrm{h}_1^{\perp} =$  $\otimes H_{1L}^{\perp} =$ 

UTT $\cos(\phi_S^l - \phi_{S_h}^l)$ $\otimes \mathbf{f}_{1T}^{\perp} =$  $\otimes \mathbf{D}_{1T}^{\perp} =$ 

LTL $\sin(\phi_h^l + \phi_S^l)$ $\otimes \mathbf{f}_{1T}^{\perp} =$  $\otimes G_1 =$ 

LTT $\sin(\phi_S^l - \phi_{S_h}^l)$ $\otimes \mathbf{f}_{1T}^{\perp} =$  $\otimes G_{1T} =$ 

Longitudinal Λ Polarization



$$z \equiv \frac{E_\Lambda}{\nu}$$

Using **polarized beam** and unpolarized target, measure ***longitudinal spin transfer*** in fragment$^{\underline{n}}$ **from struck** $q \rightarrow \mathbf{\Lambda}$

$$P_\Lambda = P_{\rm beam} \cdot D(y) \;\; \mathbf{D_{LL'}}$$

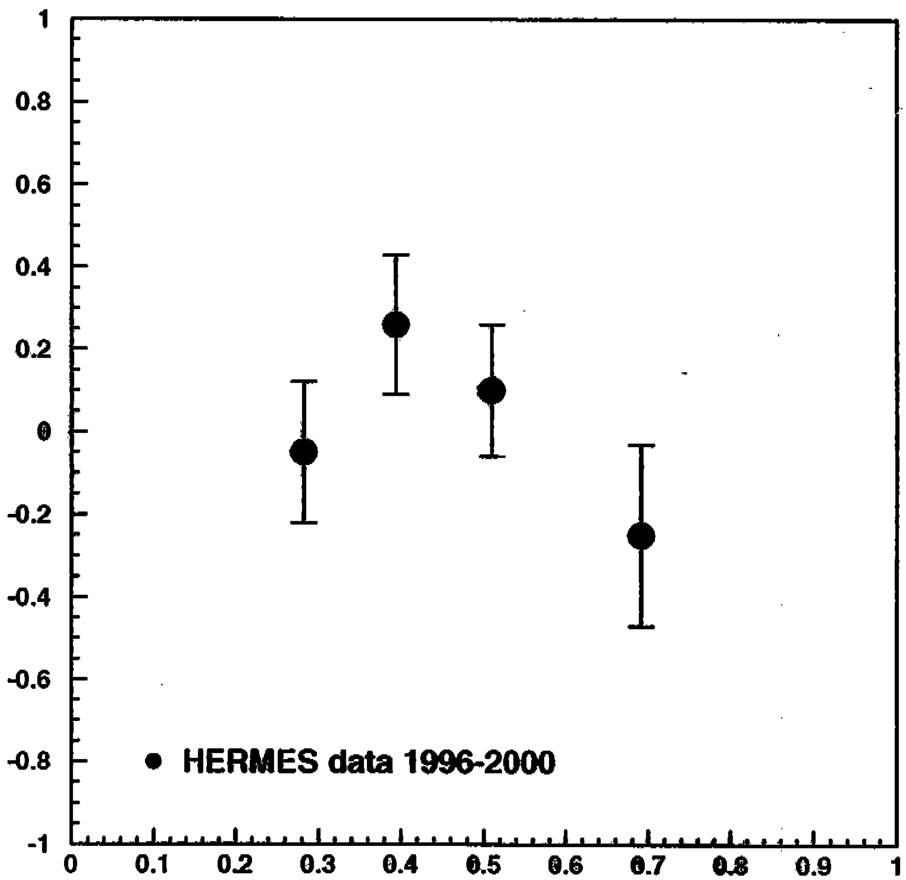
final state Λ polarization — struck quark polarization — spin transfer

$$\mathbf{D_{LL'}} = \frac{\sum e_q^2 q(x) \Delta D_q^\Lambda(z)}{\sum e_q^2 q(x) D_q^\Lambda(z)} = \sum \frac{\Delta D_q^\Lambda(z)}{D_q^\Lambda(z)} \cdot \omega_q^\Lambda(x)$$

"purity"

Spin transfer $\mathbf{D_{LL'}}$ **sensitive** to

- ***helicity conservation*** of quarks in fragmentation
- ***spin structure*** Δq^Λ of Λ itself

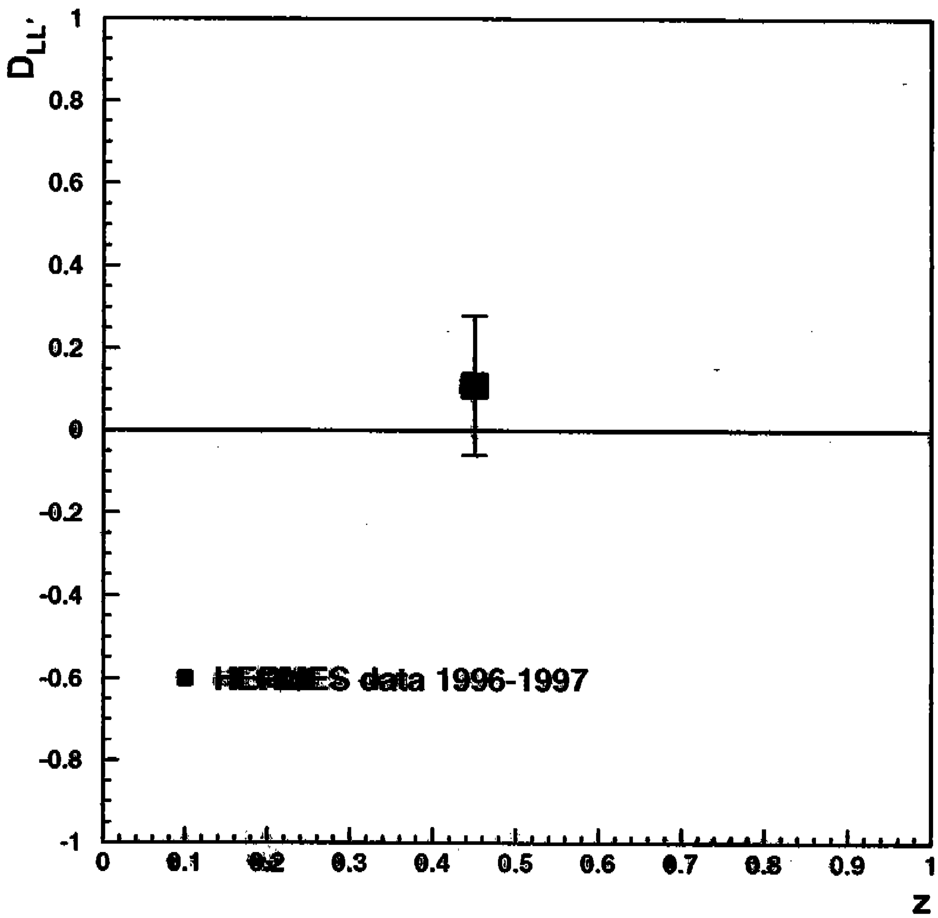


$$D_{LL'}^{\Lambda} = 0.04 \pm 0.09$$

- Spin transfer is small and appears to decrease at high z

Experimental results

Spin–transfer data

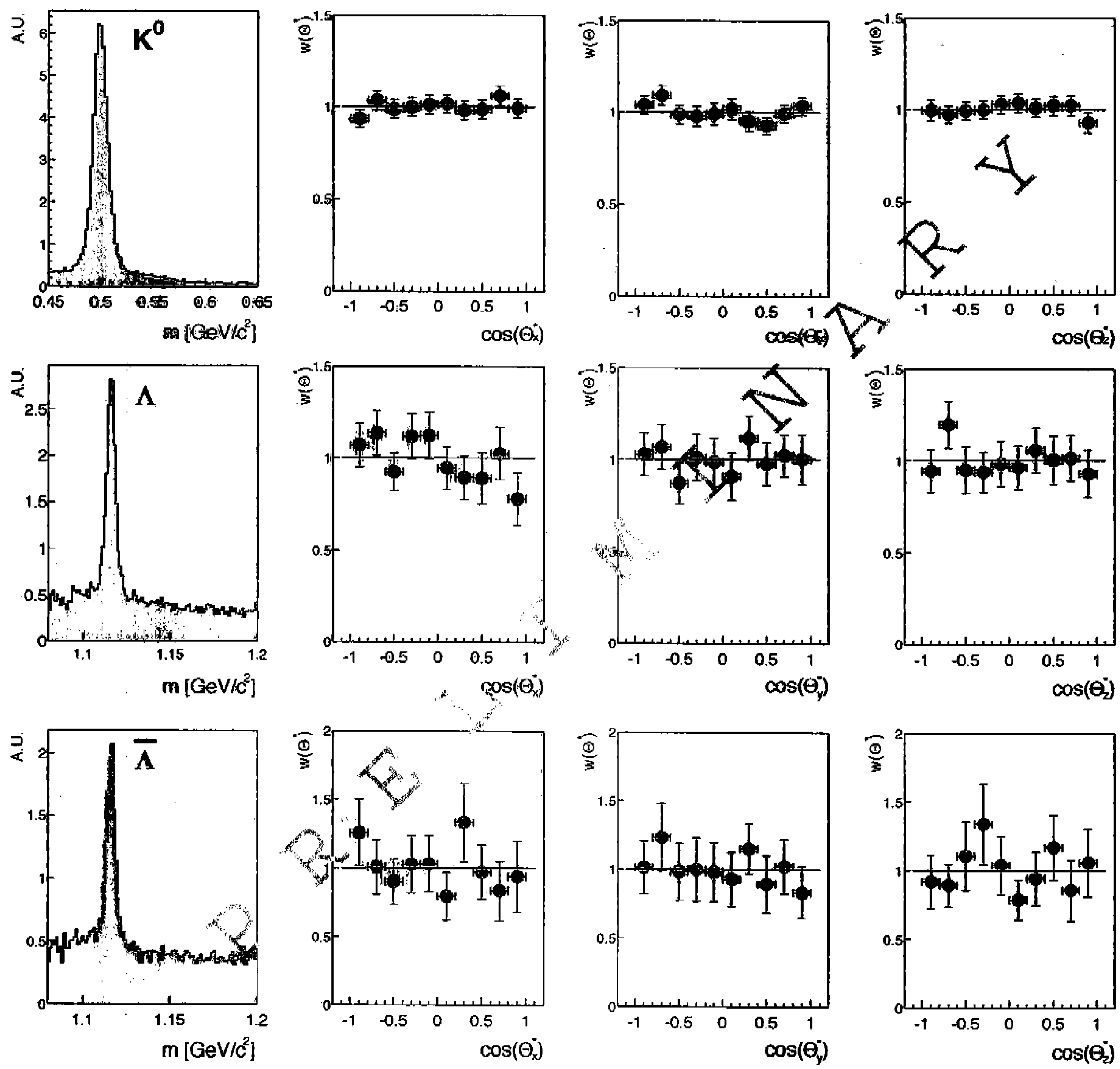


$\cos(\theta_p^\Lambda)$ Moments from COMPASS

COMPASS: polarized 160 GeV μ^+ beam on ^6LiD target

$$D_{LL'} \sim P_L^\Lambda \sim \langle \cos \theta_p \rangle$$

M.G. Sapozhnikov, SPIN 2003



COMPASS also sees a longitudinal Λ polarization consistent with zero

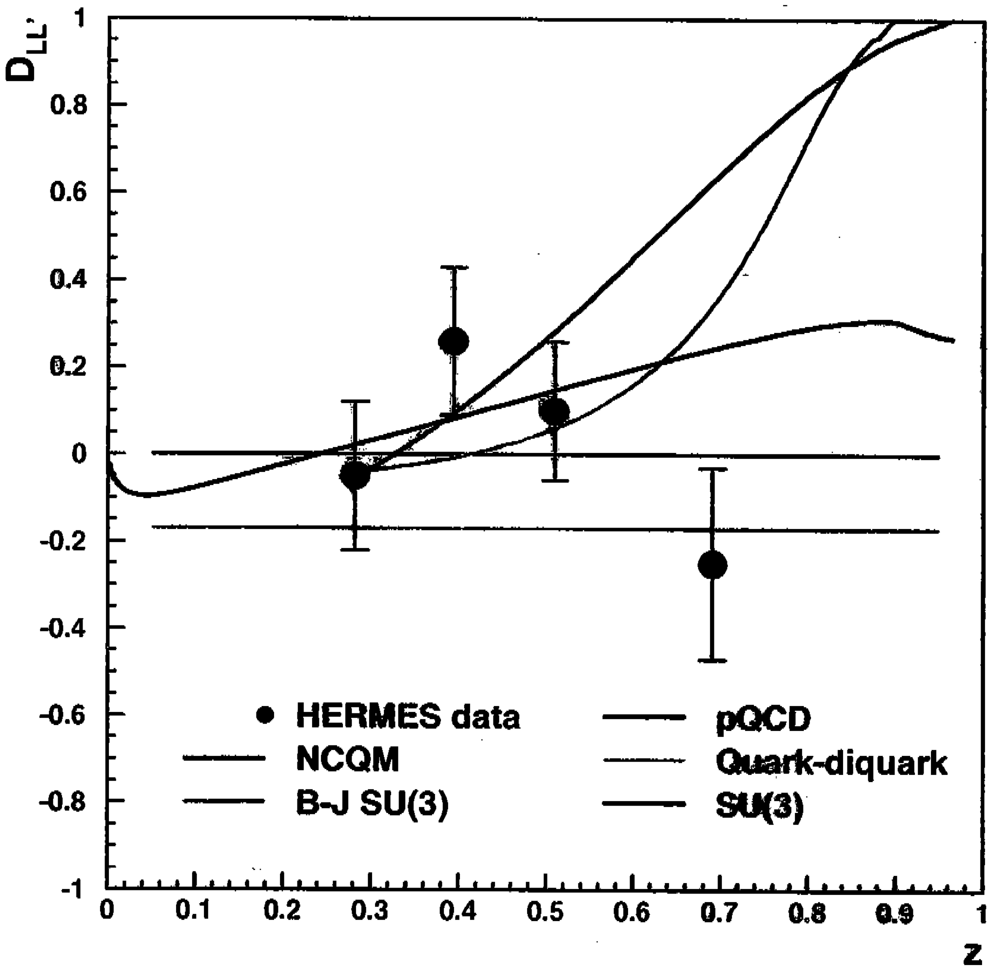
Model Predictions for $D_{LL'}$

Λ produc$^{\underline{n}}$ in DIS dominated by scattering from ***u* quarks**

z-independent estimates

$D_{LL'} \approx \Delta u^{\Lambda}/u^{\Lambda}$

- **CQM** : $D_{LL'} \approx 0$
- **B-J SU(3)** : $D_{LL'} \approx -0.17$



z-dependent estimates

Ma et al, EPJC 16 (2000) 657

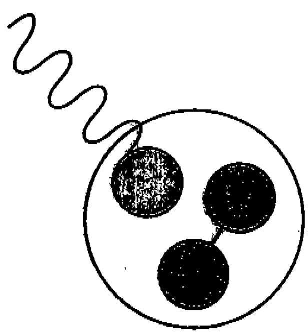
- **pQCD-based** and • **quark-diquark** models predict $\frac{\Delta q^{\Lambda}}{q^{\Lambda}} \rightarrow 1$ for all flavours $\Rightarrow$ spin transfer should ***rise with*** z

Λ Spin Structure as $x \to 1$

- **Gribov-Lipatov relation** $\boxed{q_h(x) \propto D_q^h(z)}$

endpoint easy to see: $z_\Lambda \to 1$ *Λ carries all energy ν of struck quark* ➡ $x_\Lambda \to 1$ *struck q carries all energy of Λ*

① Quark-Diquark Model



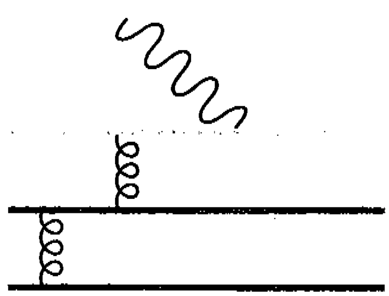
spectator diquark D in scalar or vector state

$$\psi_D(x, k_\perp) \sim \exp -\left[\frac{1}{8\beta_D^2}\left(\frac{m_q^2 + k_\perp^2}{x} + \frac{m_D^2 + k_\perp^2}{1-x}\right)\right]$$

... as $x \to 1$, VECTOR diq config$^{\underline{n}}$ suppressed

➡ $$\frac{d}{u} \to 0 \quad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$$
$$\frac{\Delta u}{u} \to 1 \quad \frac{\Delta d}{d} \to -\frac{1}{3}$$

② pQCD Model



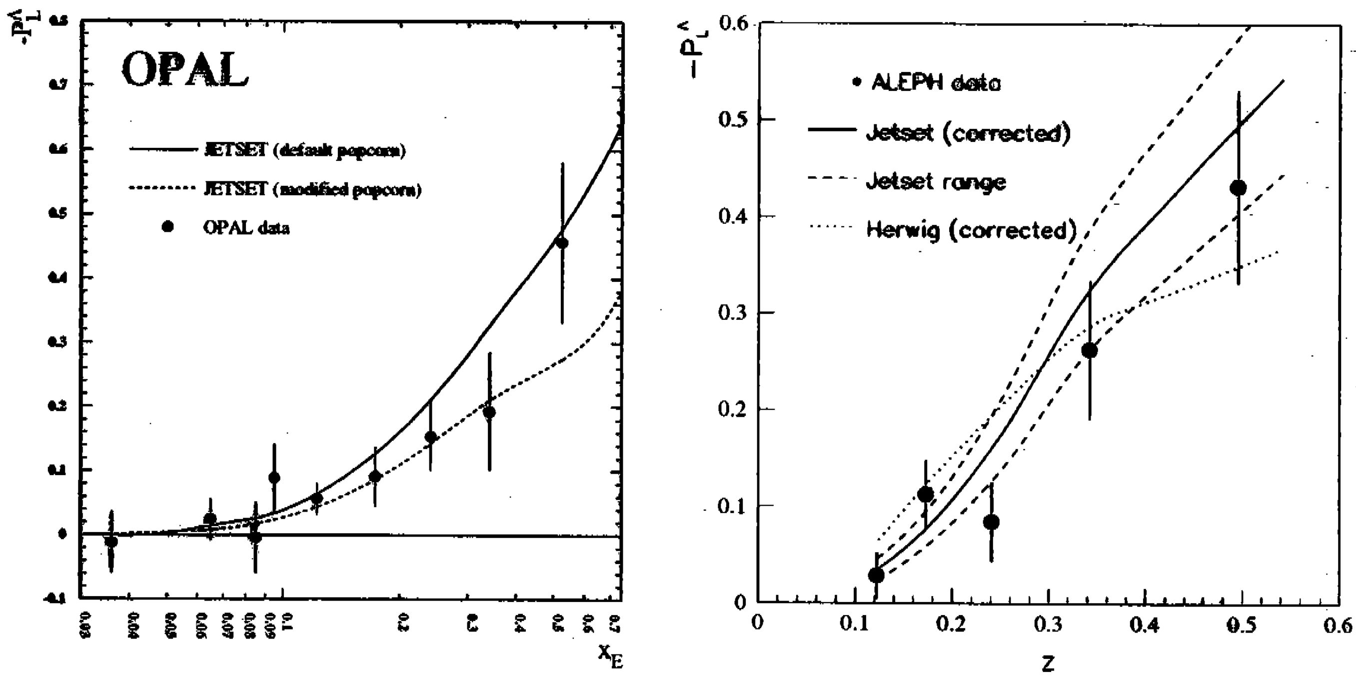
$x \to 1$ wavefn obtained from "normal" wavefn by exchange of large invariant mass gluons from spectator q's ... propagators $\sim \frac{1}{p^2}$ small
$\to$ small couplings, perturbative methods possible

➡ $\frac{d}{u} \to \frac{1}{5}$ thus $\frac{F_2^n}{F_2^p} \to \frac{3}{7}$, $\frac{\Delta q}{q} \to 1$ for u and

For Λ: Both models predict $\frac{\Delta q^\Lambda}{q^\Lambda} \to 1$ for all flavours!

ALEPH and OPAL: $e^+e^- \to Z \to \vec{q}\vec{\bar{q}} \to \vec{\Lambda}$

Large Λ polarization observed



Monte Carlo Model explains data well:

- **<u>Hyperon Spin Structure:</u>** simple CQM model
- **<u>Fragmentation Process:</u>**

  (1) Perfect ***helicity conservation*** of primary quark

  (2) Quarks from string breaks ***unpolarized***

- Λ's originating from decay of **<u>Heavier Hyperons</u>** taken into account

➡ only hyperons ***containing*** the primary, polarized quark are polarized

Modelling $D_{LL'}$

Calculate spin-xfer from $q^{\uparrow} \to \Lambda^{\uparrow}$, through decay of Σ^*, Σ^0, Ξ

following Ashery, Lipkin, PLB 469 (1999) 263

q $\left|\frac{1}{2},+\frac{1}{2}\right\rangle_{J_q,m_q}$ ...... Σ^*: $\left|\frac{3}{2},+\frac{3}{2}\right\rangle_{J_{\Sigma^*},m_{\Sigma^*}}$, $\left|\frac{3}{2},+\frac{1}{2}\right\rangle_{J_{\Sigma^*},m_{\Sigma^*}}$, $\left|\frac{3}{2},-\frac{1}{2}\right\rangle_{J_{\Sigma^*},m_{\Sigma^*}}$, $\left|\frac{3}{2},-\frac{3}{2}\right\rangle_{J_{\Sigma^*},m_{\Sigma^*}}$ ...... Λ: $\left|\frac{1}{2},+\frac{1}{2}\right\rangle_{j_\Lambda,m_\Lambda}$, $\left|\frac{1}{2},-\frac{1}{2}\right\rangle_{j_\Lambda,m_\Lambda}$

production probability $R^{q\uparrow}_{m_{\Sigma^*}}$ $\otimes$ decay probability $D_{m_{\Sigma^*}\to m_\Lambda(m_x)}$

$$R^{q\uparrow}_{m_{\Sigma^*}} = \frac{\langle \Sigma^*; m_{\Sigma^*}|\hat{n}^{\uparrow}_q|\Sigma^*; m_{\Sigma^*}\rangle}{\sum_{m_{\Sigma^*}}\langle \Sigma^*; m_{\Sigma^*}|\hat{n}^{\uparrow}_q|\Sigma^*; m_{\Sigma^*}\rangle}$$

$$D_{m_{\Sigma^*}\to m_\Lambda(m_x)} = |\langle J_{\Sigma^*}, m_{\Sigma^*}|m_\Lambda m_x\rangle|^2$$

e.g. Polarization of Λ formed from quark $q^{\uparrow}$ via Σ^* decay:

$$P^{\Lambda}_q = \sum_{m_{\Sigma^*}} R^{q\uparrow}_{m_{\Sigma^*}} \sum_{m_\Lambda} D_{m_{\Sigma^*}\to m_\Lambda(m_x)} \cdot \left(\frac{m_\Lambda}{j_\Lambda}\right)$$

① Decay part

C-G coefficients, model-independent

Σ^* (spin-3/2) $\to \Lambda\pi$ (p-wave): $\boxed{P^{\Lambda} = P^{\Sigma^*}}$

$\Sigma^0 \to \Lambda\gamma$: $\boxed{P^{\Lambda} = -\frac{1}{3}P^{\Sigma^0}}$

$\Xi \to \Lambda\pi$: $\boxed{P^{\Lambda} = P^{\Xi}}$

$$\Sigma^*$$

q → ...... → $\left|\frac{3}{2},+\frac{3}{2}\right\rangle_{J_{\Sigma^*},m_{\Sigma^*}}$ ↗ $\left|\frac{3}{2},+\frac{1}{2}\right\rangle_{J_{\Sigma^*},m_{\Sigma^*}}$ ↖ $\left|\frac{3}{2},-\frac{1}{2}\right\rangle_{J_{\Sigma^*},m_{\Sigma^*}}$ ← $\left|\frac{3}{2},-\frac{3}{2}\right\rangle_{J_{\Sigma^*},m_{\Sigma^*}}$ ...... → Λ

$\left|\frac{1}{2},+\frac{1}{2}\right\rangle_{J_q,m_q}$

Λ: $\left|\frac{1}{2},+\frac{1}{2}\right\rangle_{j_\Lambda,m_\Lambda}$ → ; $\left|\frac{1}{2},-\frac{1}{2}\right\rangle_{j_\Lambda,m_\Lambda}$ ←

② Production part

Expectation values of number operator $\hat{n}^{q\uparrow}$ related to first moments of parton distributions. In hyperon Y,

$$\langle \hat{n}_q^\uparrow \rangle_{m_Y=+J_Y} = \frac{q_Y + \Delta q_Y}{2}$$

$$\langle \hat{n}_q^\uparrow \rangle_{m_Y=-J_Y} = \langle \hat{n}_q^\downarrow \rangle_{m_Y=+J_Y} = \frac{q_Y - \Delta q_Y}{2}$$

... for other m_Y states, interpolate betw these limiting values

➡ Polarization of hyperon Y formed from quark $q^\uparrow$:

$$\langle P_q^Y \rangle = \sum_{m_Y} \langle \hat{n}_q^\uparrow \rangle_{m_Y} \cdot \left(\frac{m_Y}{J_Y}\right) = \frac{\Delta q_Y}{q_Y} \cdot \frac{1}{2J_Y+1} \sum_{m_Y} \left(\frac{m_Y}{J_Y}\right)^2$$

<u>for spin-1/2 baryons (Λ,Σ,Ξ)</u>

$$\langle P_q^Y \rangle = \frac{\Delta q^Y}{q^Y}$$

<u>for spin-3/2 baryons (Σ*)</u>

$$\langle P_q^Y \rangle = \frac{5}{9}\frac{\Delta q^Y}{q^Y}$$

⇒ Polarization of a hyperon produced from a polarized quark ~ polarization of the quark in that hyperon

Spin-Transfer Coefficients C_q^Y

Spin transfer $D_{LL'}$ = Λ polarization given 100% polarized struck quarks (i.e. after γ-depolarizaton correction).

[illegible] $= \sum_q \sum_Y$ [illegible]

$\mathbf{f_q^Y}$ = **subprocess fraction** for producing Λ containing struck quark q, through parent hyperon Y

$\mathbf{q} = u, d, s$ (struck quark present in top-level hyperon Y)
$= n$ (struck quark NOT present in Y)

$\mathbf{C_q^Y}$ = **spin-transfer coefficient** for same process:

$C_q^Y = \langle P_q^Y \rangle \cdot$ (decay part for $Y \to \Lambda$)

Δq^Y in Constituent Quark Model

$Y \backslash q$	Δu	Δd	Δs
Λ	0	0	+1
Σ^{*0}	+1	+1	+1
Σ^0	+2/3	+2/3	-1/3
Ξ^0	-1/3	0	+4/3

C_q^Y in Constituent Quark Model

$Y \backslash q$	u	d	s	n
Λ	0	0	+1	0
Σ^{*0}	+5/9	+5/9	+5/9	0
Σ^0	-2/9	-2/9	+1/9	0
Ξ^0	-1/3	0	+2/3	0

C_q^Y in SU(3) Symmetric Model (Burkardt & Jaffe)

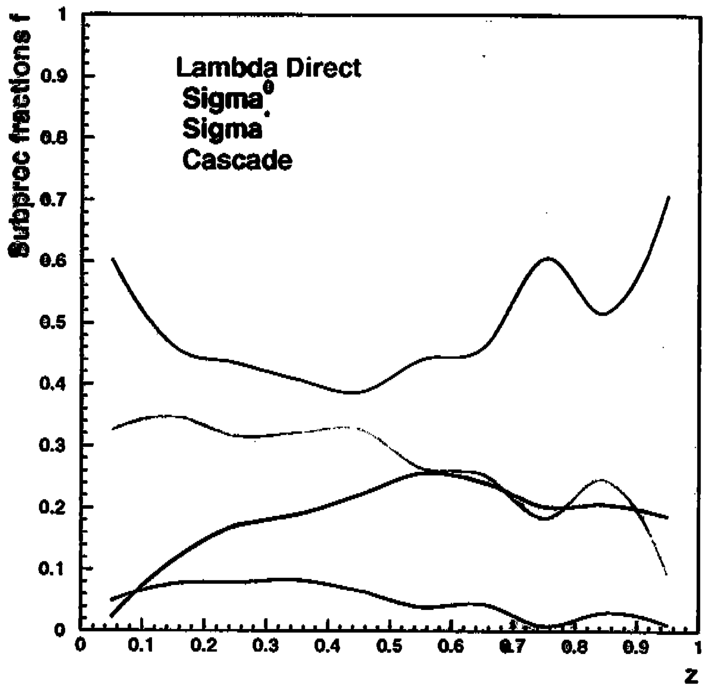
$Y \backslash q$	u	d	s	n
Λ	-0.17	-0.17	+0.63	0
Σ^{*0}	+0.13	+0.13	+0.18	0
Σ^0	-0.12	-0.12	+0.14	0
Ξ^0	-0.43	-0.10	+0.42	0

C_q^Y in SU(3) Valence Model (Ashery & Lipkin)

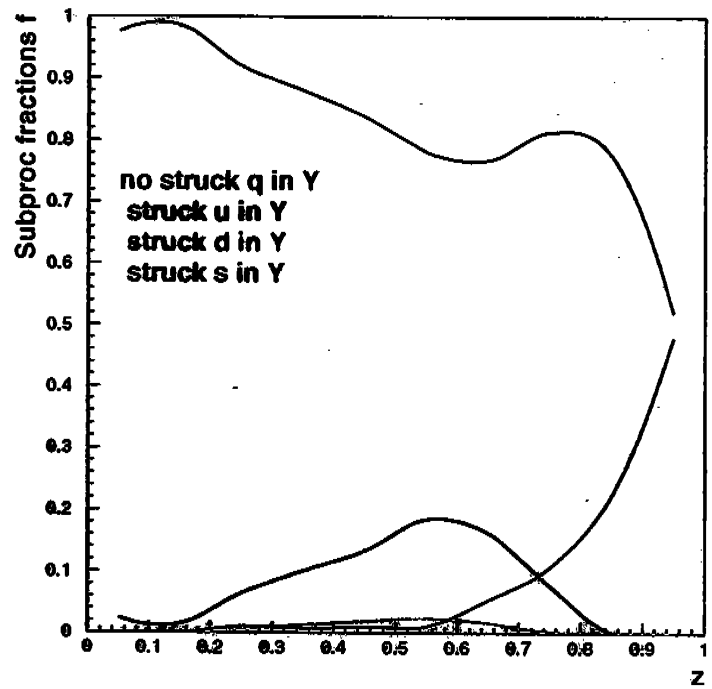
$Y \backslash q$	u	d	s	n
Λ	-0.07	-0.07	+0.73	0
Σ^{*0}	+0.13	+0.13	+0.18	0
Σ^0	-0.16	-0.16	+0.11	0
Ξ^0	-0.33	0.00	+0.47	0

Monte carlo results

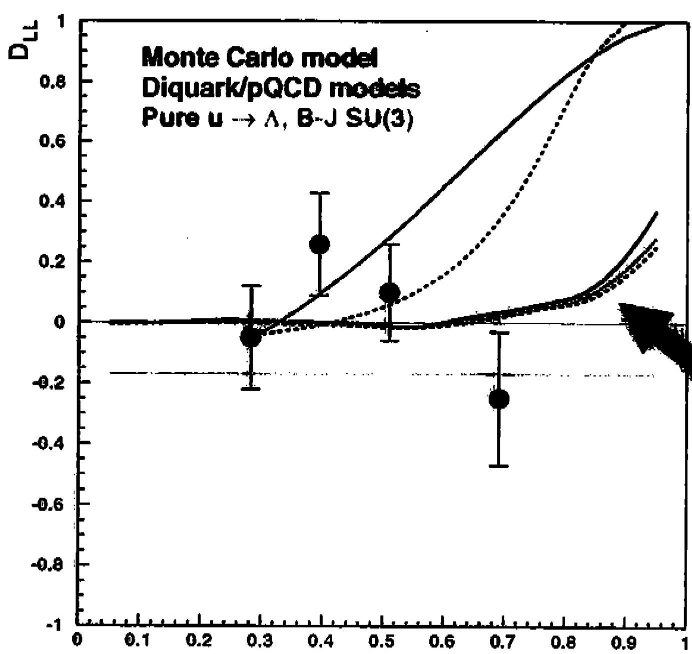
Direct sources of Λ



Quark parents of Λ



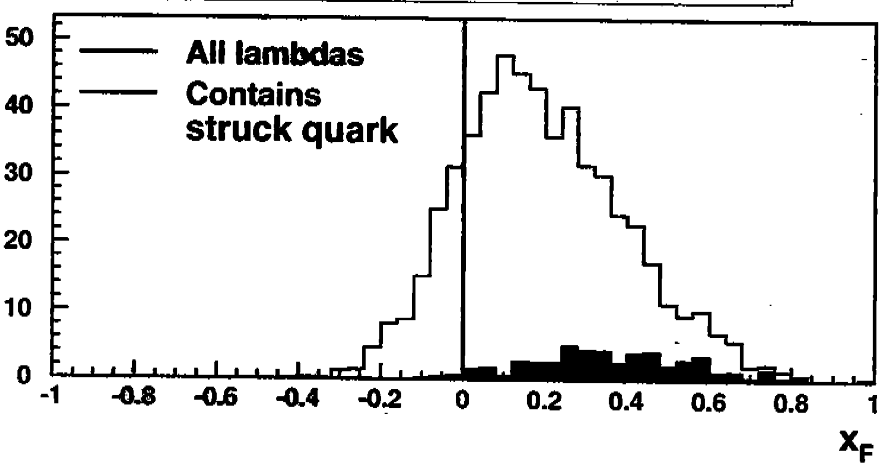
Final spin–transfer models

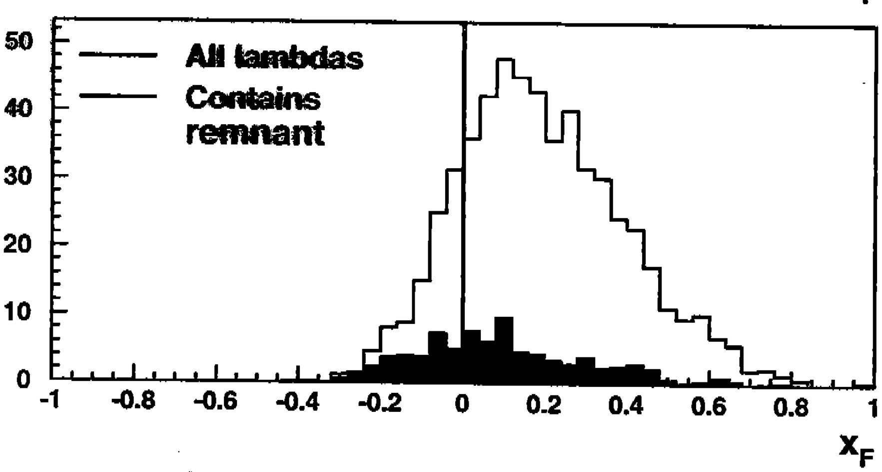


- **Significant contribution from heavy hyperon decays: 40% – 60% of all lambdas**
- **Very few lambdas contain struck quark: about 10% on average!**
- **Spin–structure models are relatively unimportant in comparison with monte carlo subprocess fractions**

Λ's from target remnant

Lambda x_F distributions

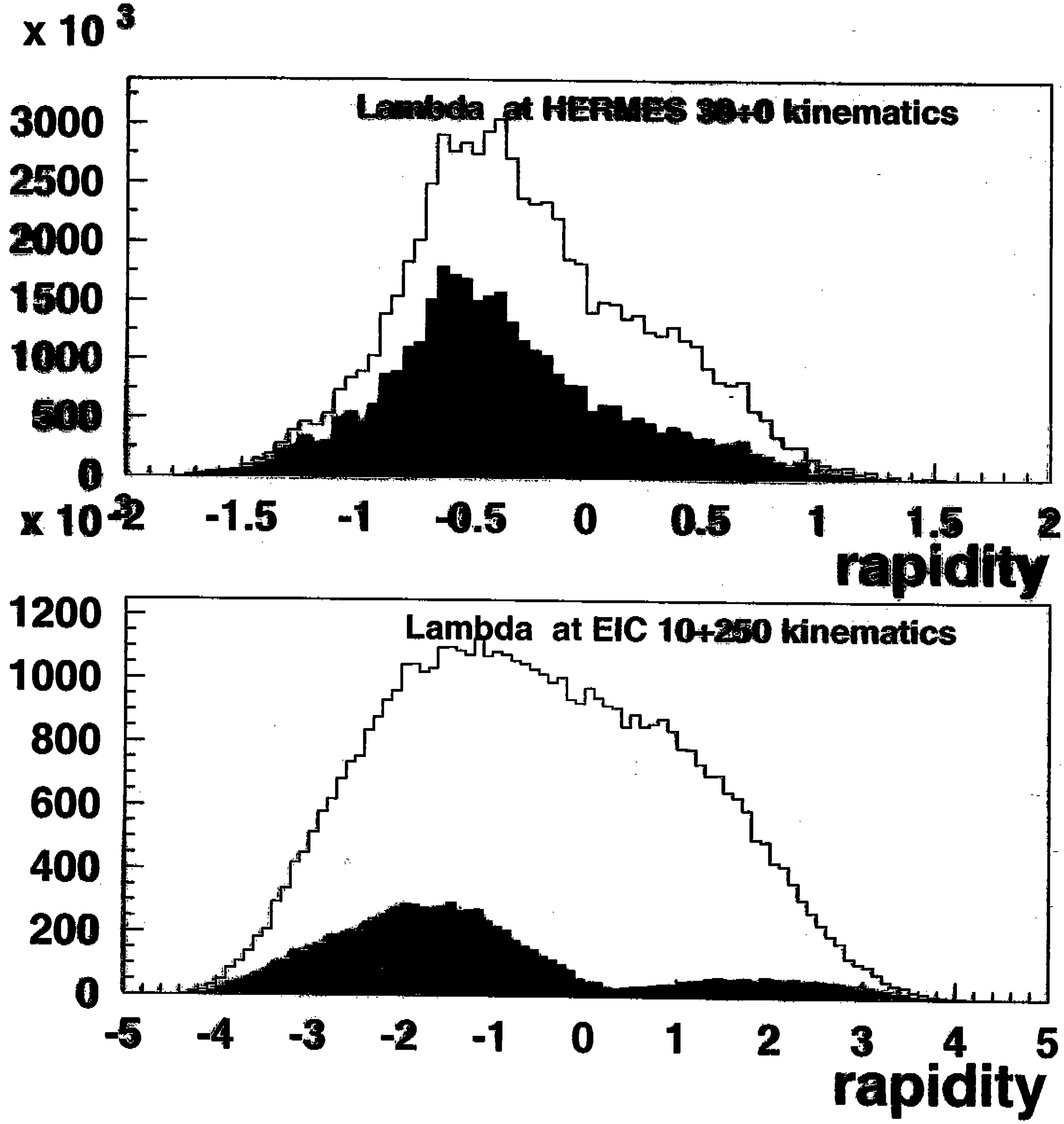




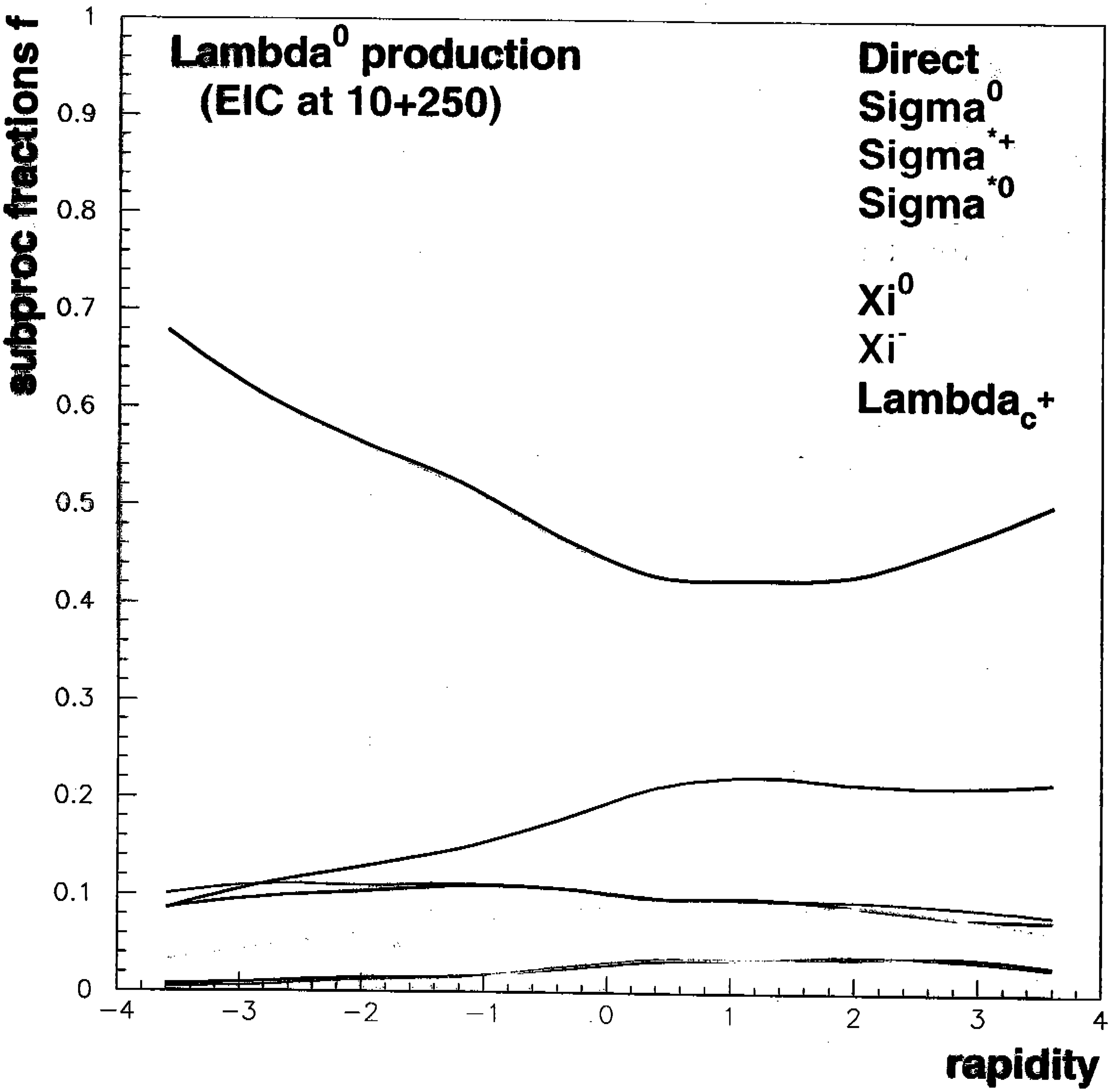
- **Most Λ's from struck quark are produced in forward region ($x_F > 0$)**
- **Significant number of Λ's from target remnant also have $x_F > 0$!!**
- **Lambda production mechanisms are complicated by influence of target remnant**

Current vs Target Region at EIC

Red = contains struck quark ... Blue = contains remnant

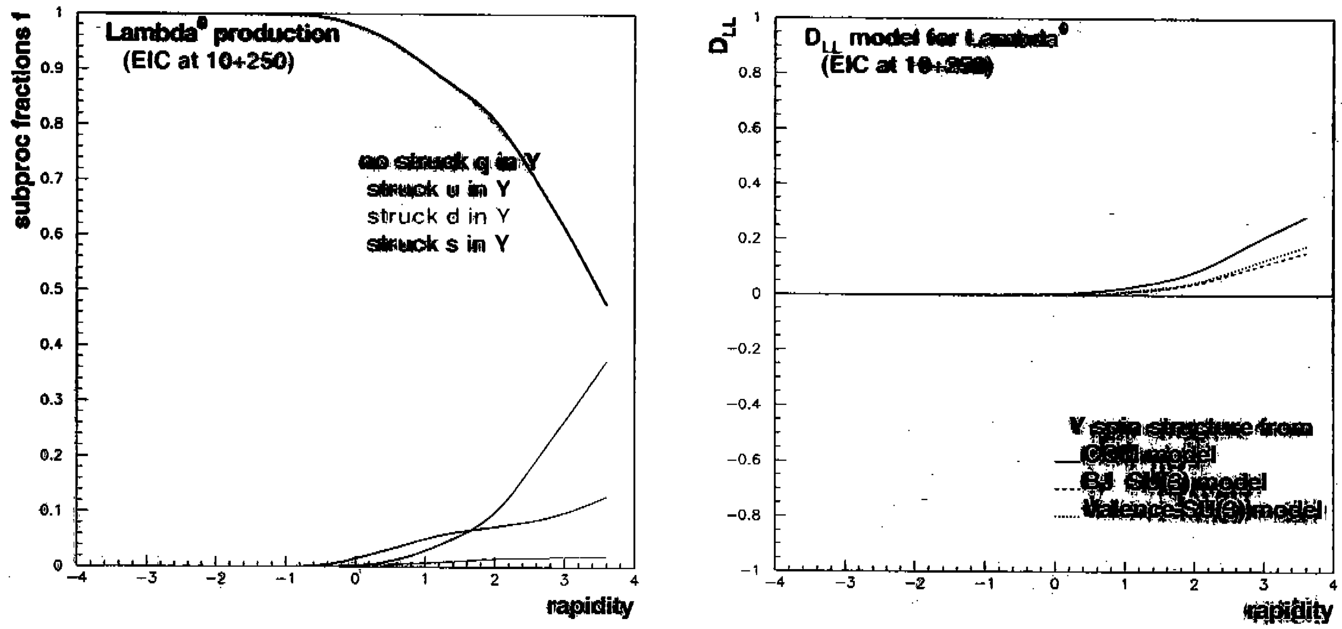


Origin of Λ's at EIC Kinematics

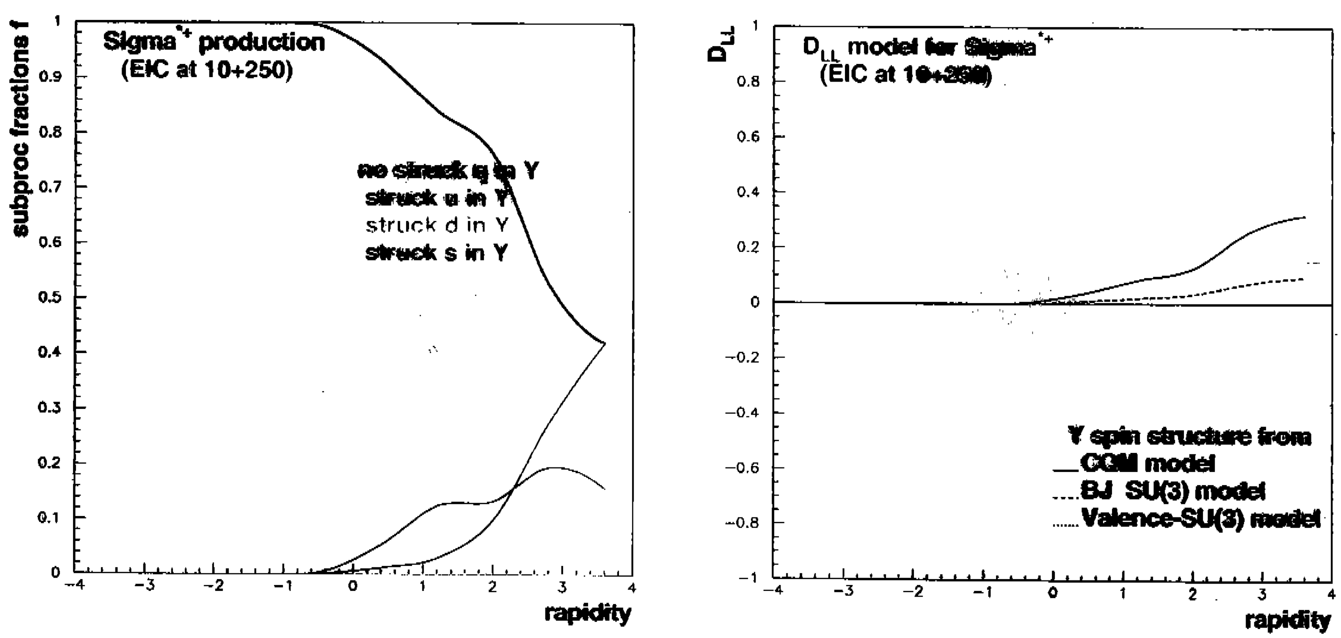


D_{LL} Model at EIC Kinematics

Λ Production

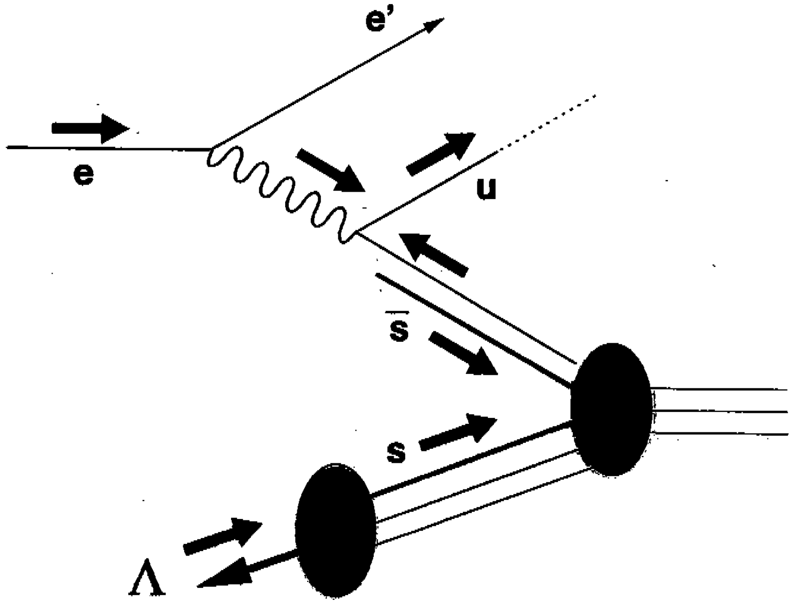


Σ^{*+} Production

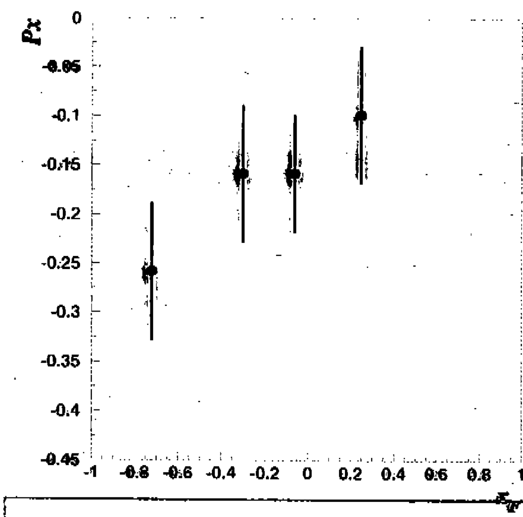


Must see if there's enough /underlinerate at high η

Λ Polarization at $x_F < 0$: Δs in proton



NOMAD, $E_\nu = 43$ GeV



$\Rightarrow$ $D_{LL'} < 0$ at $x_F < 0$

Model of Ellis, Kharzeev, Kotzinian

ZPC 69 (1996) 467

- polarized $\vec{e}$ beam fixes struck u spin
- struck u and remnant $\bar{s}$ are in ***spin-singlet state***
  (attractive channel in QCD)
- $s\bar{s}$ pairs from proton sea are in $^3P_0$ ***state***
  (to get vacuum quantum numbers $J^{PC} = 0^{++}$)
- Λ spin is carried by s quark

... but with polarized beam and target ...

P_Λ directly sensitive to s-quark spin, and $\therefore$ to Δs *in proton*

$$P_\Lambda = \frac{\sum_i e_i^2 \, [\, P_T \Delta \mathrm{q_i(x)} - P_B D(y) q_i(x) \,] c_{sq}}{\sum_i e_i^2 \, [\, q_i(x) - P_B P_T D(y) \Delta \mathrm{q_i(x)} \,]}$$

Conclusions

- **Spin transfer $\approx$ 0** observed at ***fixed-target*** DIS expts:

  $D^{\Lambda}_{LL'} = 0.04 \pm 0.09$ **at $x_F > 0$ from HERMES**

  ➡ Consistent **with no z-dependence from $z = 0.2 \to 0.7$**

  ➡ Similar **results from COMPASS**

- Significant **contribution from heavier hyperon decays** (about **40 - 60%**)

- **Very few Λ's contain struck quark (about 10%)**; explains **small spin** transfer, in one **model**

- Even at $x_F > 0$, **many** Λ's contain **target remnant**

  ➡ can't use Λ **as "polarimeter"** for initial-state quark spin in **intermediate-energy DIS**

  ➡ CAN use Λ **to explore** target fragmentation region ... possible sensitivity to Δs?

- **Very different situation** at EIC : high statistics, energy, and acceptance will make hyperon polarization useful as a final-state polarimeter in DIS!