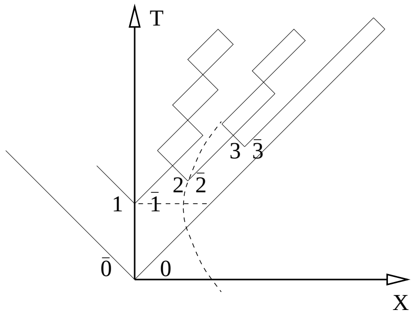
Hadronization: The Long-Range Dynamics of Confinement

What do we know?

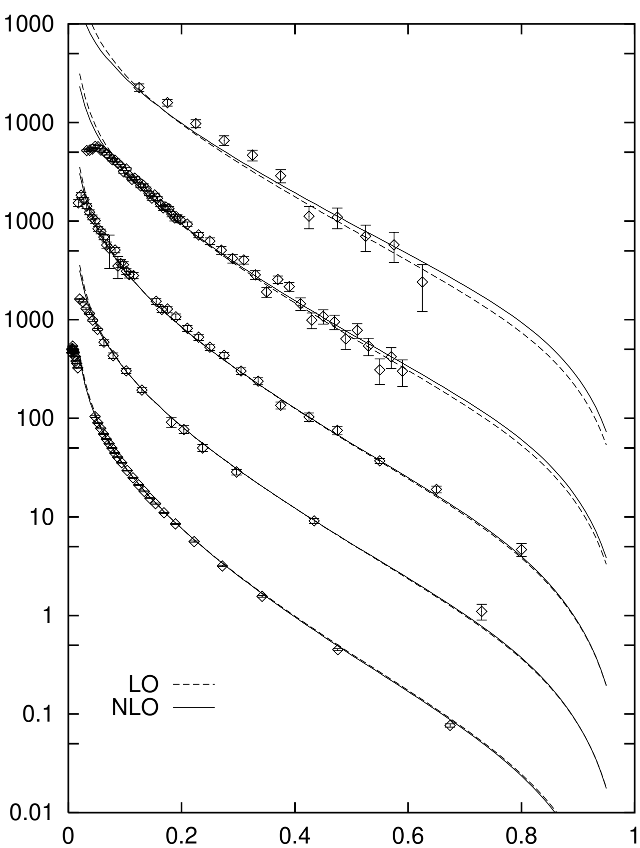


The Lund Model

Phenomenlogical description of the fragmentation process in terms of colour-string breaking and parton clustering.

Evolution of the fragmentation functions

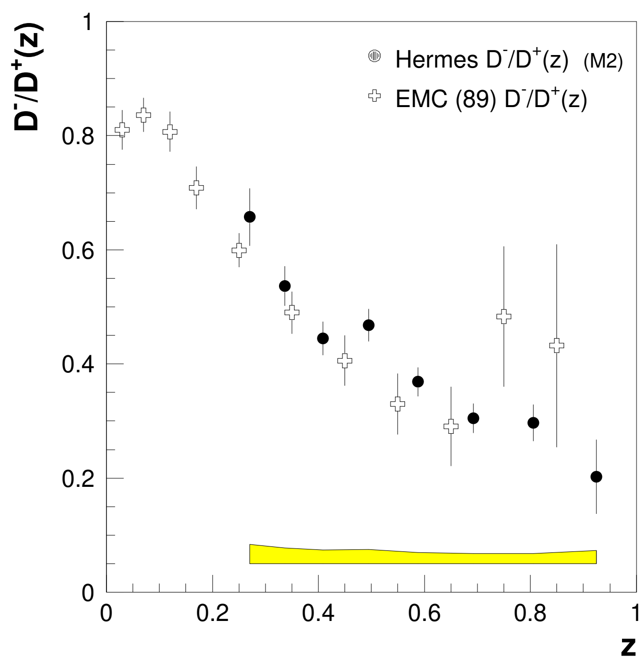
$$\sigma \sim \sum_q e_q^2 q(x) D_q^h(z, Q^2)$$



A Tool for hadron structure studies (e.g. flavour-tagging)

$$D_1 = D_u^{\pi+} = D_d^{\pi-} = \ldots$$

$$D_2 = D_d^{\pi+} = D_u^{\pi-} = \ldots$$



Hadronization: The Long-Range Dynamics of Confinement

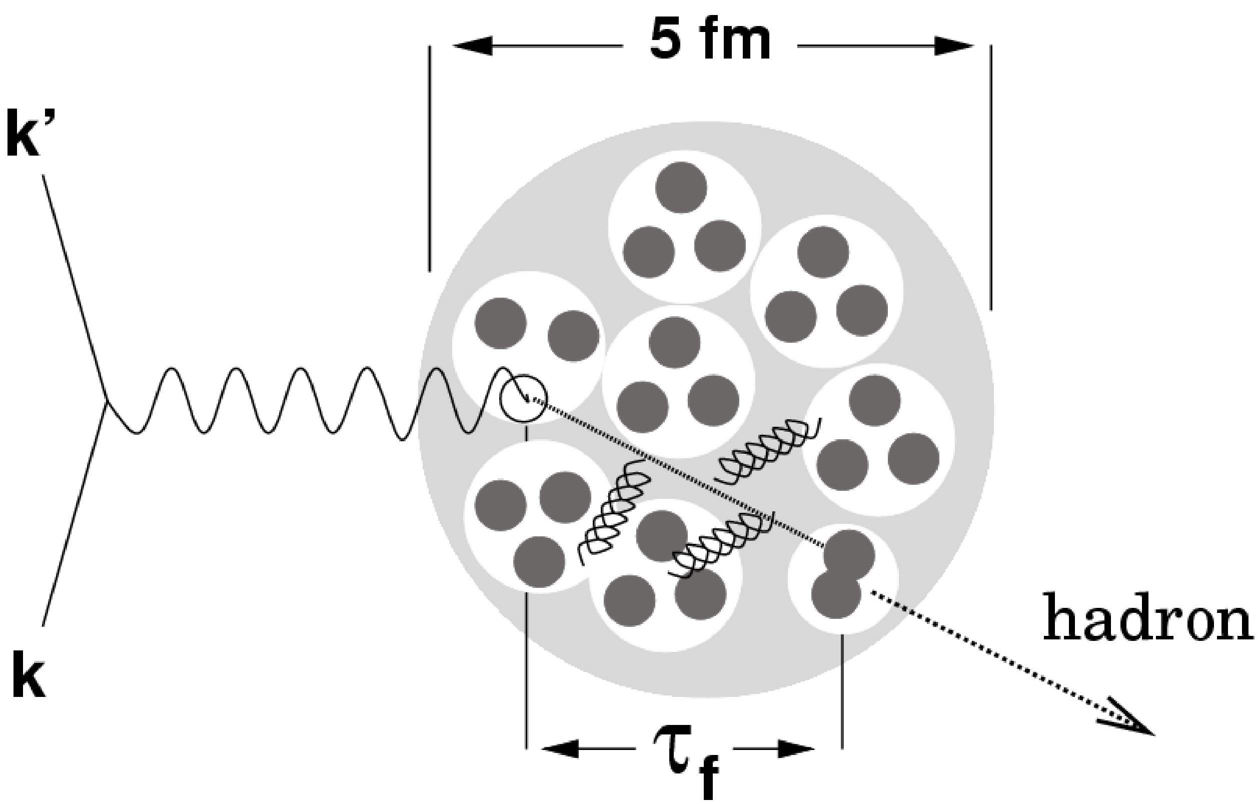
What are we not so sure about?

- **Space-time structure**: How long does it take to form a hadron?
- **Spin transfer**: Is the spin of the struck quark communicated to the hadronic final state?
- **Single-spin asymmetries**: How important is intrinsic transverse momentum? phase coherence?
  $\Rightarrow$ access to new structure functions
- **Hyperon polarization**: How are spin and angular momentum correlated in the fragmentation process?

A-Dependence of Fragmentation

The Space-Time Structure of Fragmentation

By embedding the fragmentation process within a nucleus, one can use the nuclear radius as a yardstick against which to measure the **time scale of hadron formation** .



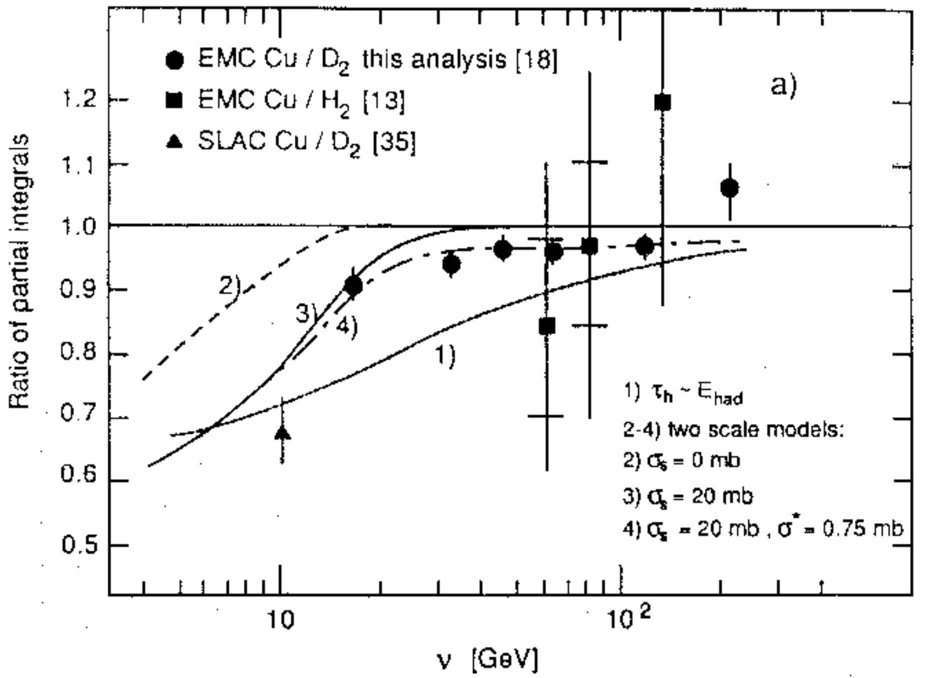
Single Time Scale Model

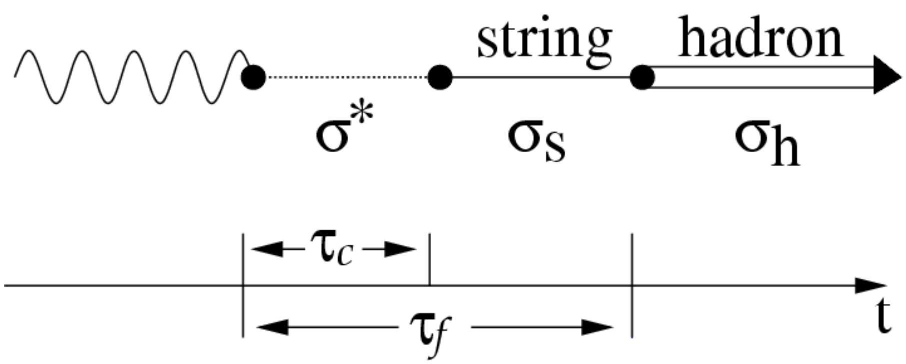
Postulate: hadron formation time is a constant (τ_h), apply Lorentz boost

$$\tau_f = \tau_h \frac{E_h}{m_h} = \tau_h \frac{z\nu}{m_h}$$

$\rightarrow$ τ_f depends on ν, and z, m_h

Measure hadron attenuation $\frac{N^h/N^{\rm DIS}(A)}{N^h/N^{\rm DIS}(D)}$





2 scale model seems necessary:

τ_c = time for string formation
τ_f = total time for hadron formation
$\tau_f - \tau_c = z_h\nu/\kappa$ ... κ = string tension $\simeq$ 1 GeV/fm

3 cross-sections:

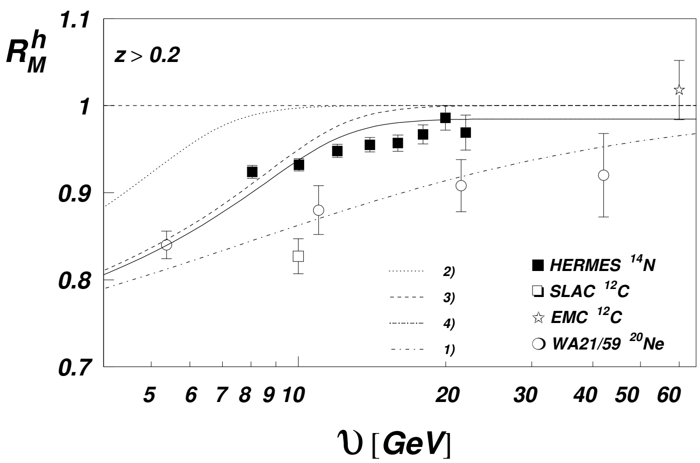
σ_h = known hadron - nucleon xsec
σ_s = string - nucleon xsec
σ^* = color field - nucleon xsec (before string formation)

Best fit to EMC Cu data: σ_s = 20 mb, σ^* = 0.75 mb

z-Dependence

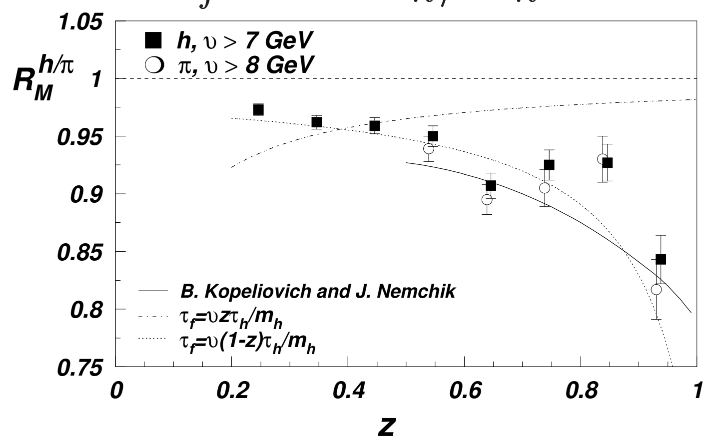
New data from HERMES ...

ν **dependence** seems to favour 2-time-scale models ...

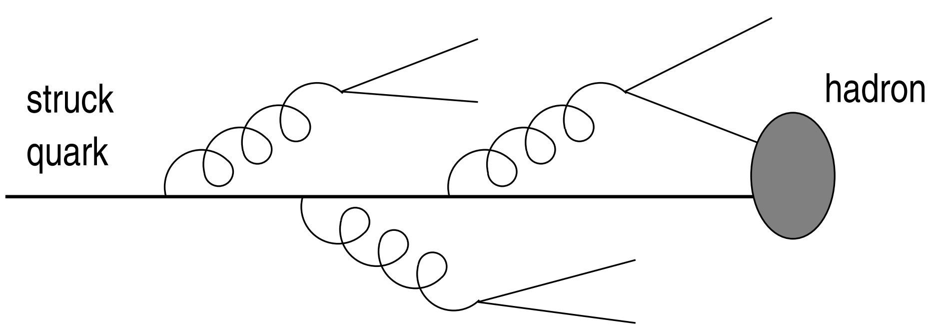


However z **dependence** does not show the expected Lorentz behaviour

$$\tau_f = \nu\ z\ \tau_h / m_h$$



Gluon Bremsstrahlung Model



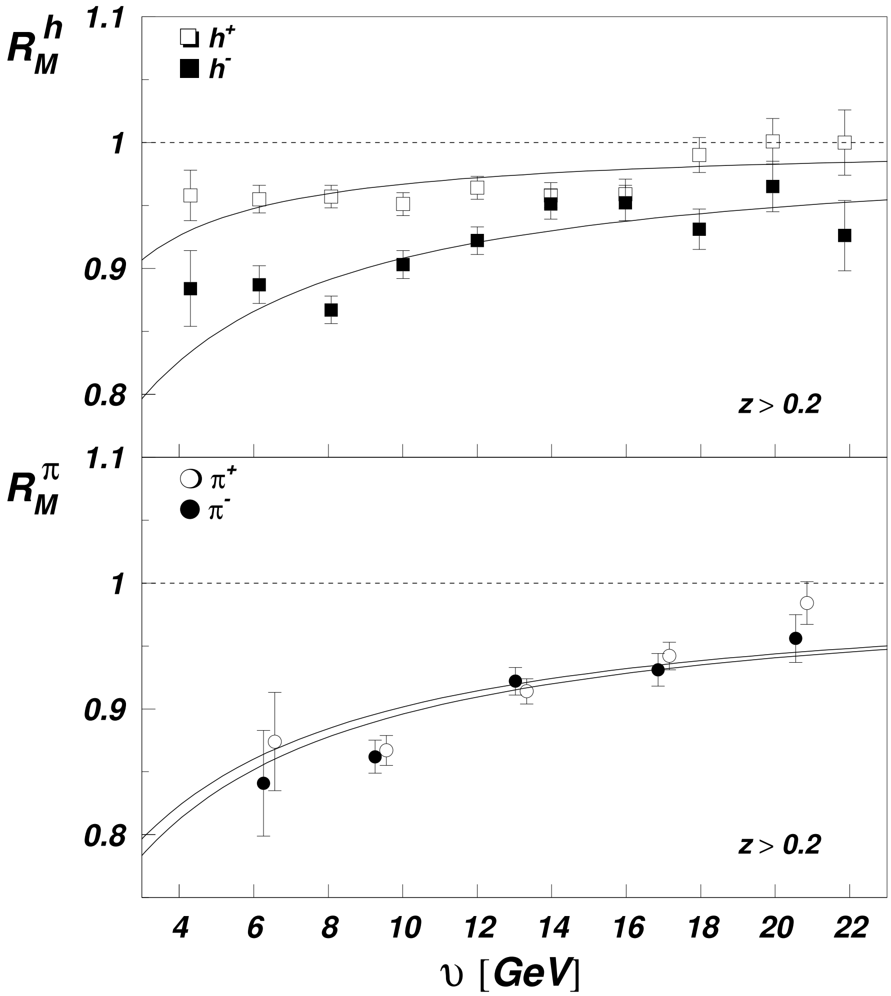
At high z: $\rightarrow$ few gluons radiated

$\rightarrow$ short formation time $\tau_f = \nu(1-z)\tau_h/m_h$

$\rightarrow$ larger attenuation by nuclear rescattering

Mass Dependence

Using the modified z-dependence, $\tau_f = \nu(1-z)\tau_h/m_h$, good fits to the ν-dependence are now obtained with **one time scale** :



For **pions** : $\tau_{\pi+}/m_\pi = \tau_{\pi-}/m_\pi \simeq$ 1 fm/GeV

For **all charged hadrons** :

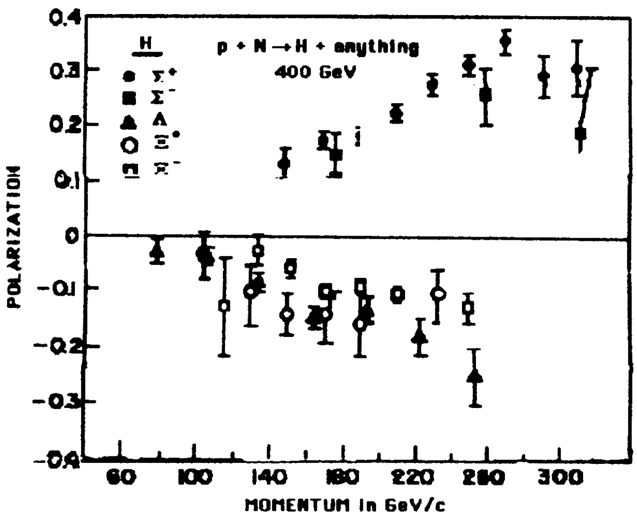
$\tau_{h-}/m_{h-} \simeq$ 1.5 fm/GeV $\rightarrow$ 84% π^-, 10% K^-, **6%** $\overline{p}$
$\tau_{h+}/m_{h+} \simeq$ 5 fm/GeV $\rightarrow$ 63% π^+, 13% K^+, **24%** p

First direct indication that formation time for baryons is significantly larger than that for mesons.

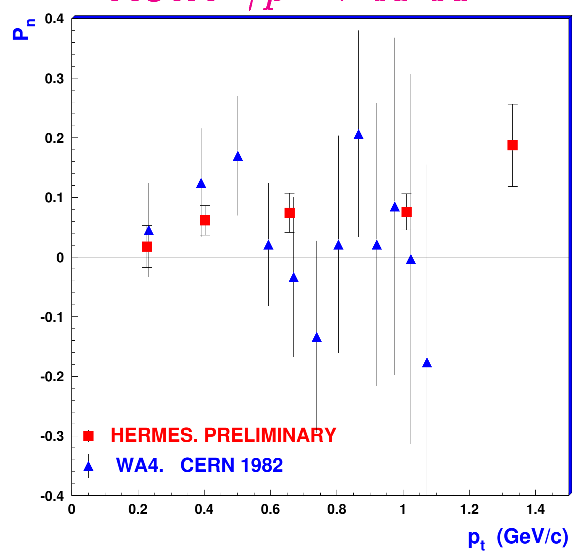
The Wacky World of Hyperon Polarization

Unpolarized beams on unpolarized targets produce hyperons which are strongly polarized! ... direction is $\hat{n} = \mathbf{p}_{\rm beam} \times \mathbf{p}_Y$

$pp \to Y^{\uparrow} X$



New! $\gamma p \to \Lambda^{\uparrow} X$

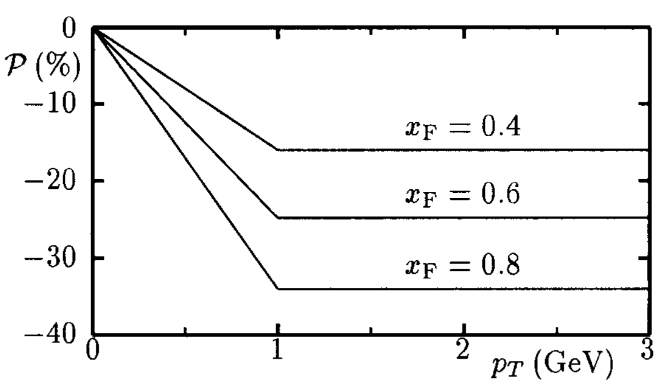


The key seems to be **hyperon spin structure** ... in NRQM:

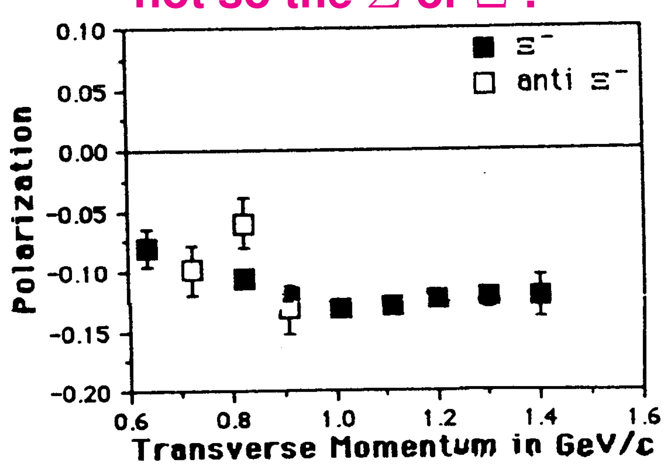
$$
\begin{array}{lll}
\Lambda & \Delta s = +1, & \Delta u = \Delta d = 0 \\
\Sigma^{\pm} & \Delta s = -1/3, & \Delta u, d = +4/3 \\
\Xi^{\pm} & \Delta s = +4/3, & \Delta u, d = -1/3
\end{array}
$$

$\Rightarrow$ sign of polarization is opposite to Δs ...

Kinematic behaviour: linear with p_T and x_F



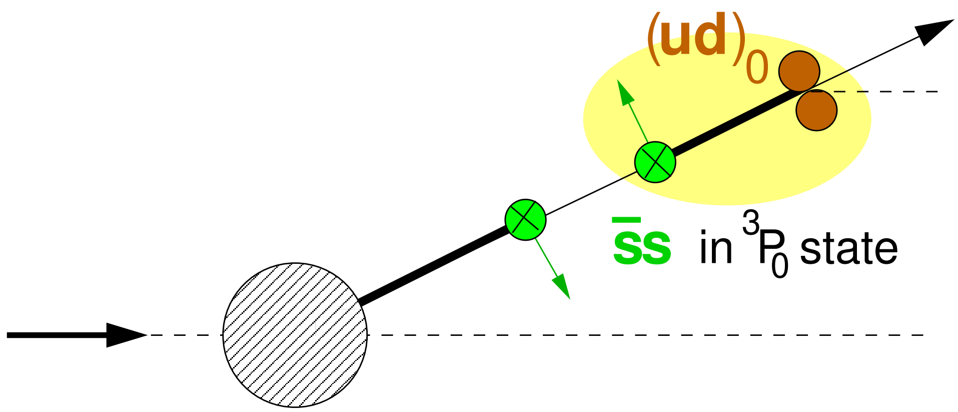
Anti-Λ is unpolarized, but ... not so the $\overline{\Sigma}$ or $\overline{\Xi}$!



The Lund Model

Λ polarization in the Lund string model

- p_T of Λ comes from k_T of s quark
- $s\bar{s}$ pair from string break in $0^{++} \rightarrow ^3 P_0$ state
- spin of s determines spin of Λ



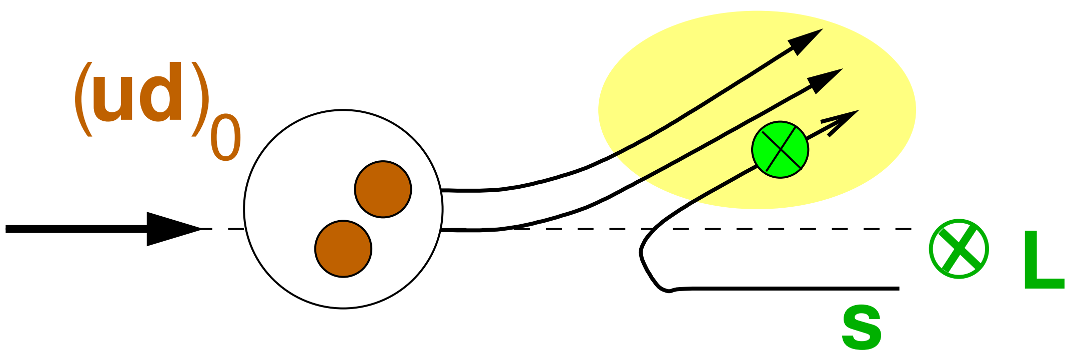
But ...

- Expect $P_\Sigma = -1/3\ P_\Lambda$ ... in fact they are almost equal in magnitude
- How do you get an x_F dependence?
- How does this work for *two* s quarks? ($\Xi^0 = ssu$)
- ***How do you polarize anti-hyperons?***

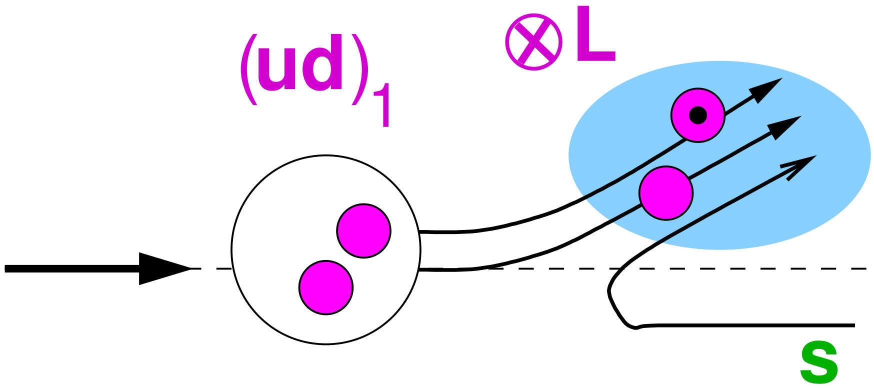
The DGM Model: Parton Recombination

Idea: **Thomas precession** in an attractive potential creates a 'spin-orbit' force that tries to align $\vec{L}$ and $\vec{S}$ of an accelerating quark/diquark.

Λ: $\Delta s = +1$ P_Λ from accelerated sea s quark



Σ^+: $\Delta u = +4/3$ P_Σ from accelerated valence $(ud)_1$ diquark



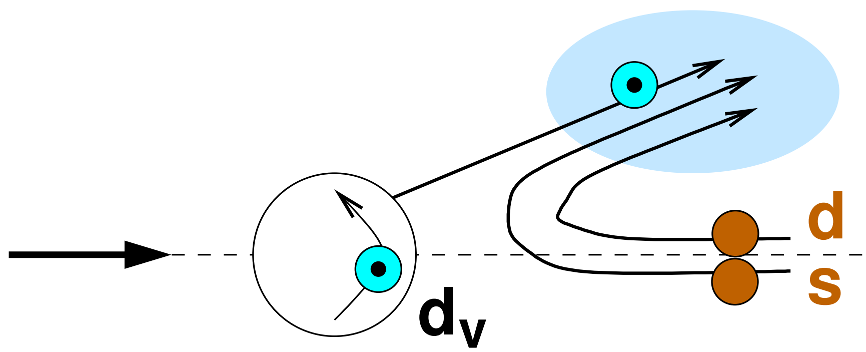
But ...

- Consider **spin transfer** (D_{NN}) from beam to hyperon: $p^\uparrow p \to \Lambda^\uparrow X$
  - $\Rightarrow$ Λ production involves $(ud)_0$ diquarks from beam proton
  - $\Rightarrow$ beam spin is irrelevant, $D_{NN} = 0$
  - $\Rightarrow$ WRONG. E704 again: $|D^\Lambda_{NN}| \simeq |P^\Lambda|$
- ***How do you polarize anti-hyperons?***

The Berlin / Chou-Yang Model

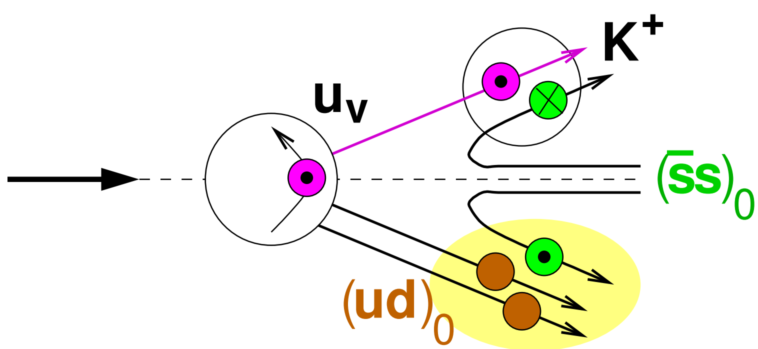
In the beam fragmentation region, orbiting valence quarks from the beam fuse with sea quarks from the target.

Beam and hyperon share one q_v $\rightarrow$ $\boxed{\Sigma^- = dds}$ ... $\Delta d_{\Sigma^-} = +4/3$



Beam and hyperon share TWO q_v $\rightarrow$ $\boxed{\Lambda = uds}$ ... $\Delta s_\Lambda = +1$

Must argue: Λ polarization comes from ***associated production*** of K^+:



But ...

- Associated-production mechanism ...
  $\Rightarrow$ strong **correlation** between Λ spin and relative p_T of Λ, K^+
  $\Rightarrow$ *WRONG*. E766 at BNL: exclusive $pp \rightarrow p\Lambda K^+\pi^+\pi^-$
  ... no such $\Lambda - K$ correlation seen.
- ***How do you polarize anti-hyperons?***