Polarized Parton Distributions

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$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

- Some Phenomenological Models
- Quark and Gluon Polarization
- Studies with Polarized Λ Production
- New Structures: Transversity and Friends

Some Phenomenological Models

Non-relativistic Quark Model

Pure valence description of consituent quarks:

$$\Delta u = +4/3, \qquad \Delta d = -1/3 \qquad \rightarrow \qquad \Delta\Sigma = 1$$

Relativistic Quark Model

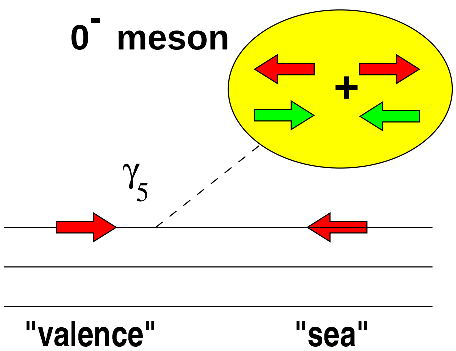
Jaffe, Manohar, NP B337 (1990) 509

Relativistic current quarks with light masses: orbital angular momentum is important, and accounts for the deficit of $\Delta\Sigma$.

$$\Delta\Sigma \simeq 0.60 - 0.75, \qquad L_q = \frac{1}{2}(1 - \Delta\Sigma)$$

Meson Cloud Models

Li, Cheng, hep-ph/9709293



Quark sea generated by cloud of pseudoscalar mesons.

$\rightarrow \Delta q_{valence} > 0$

$\rightarrow \Delta q_{sea} < 0$, but ...

$\rightarrow \Delta\overline{q} = 0$

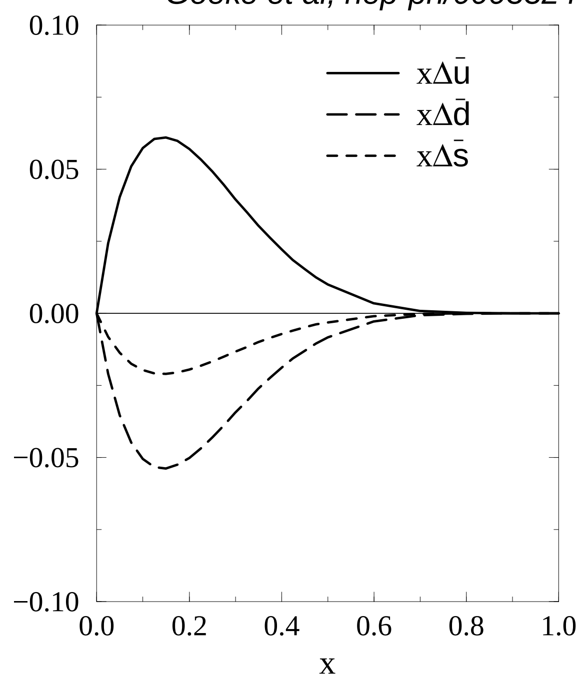
Large N_c Limit and the Chiral-Quark Soliton Model

Nucleon = chiral soliton in pion field.

$$\Delta\overline{u} - \Delta\overline{d} \sim N_c^2$$
$$\Delta\overline{u} + \Delta\overline{d} \sim N_c$$

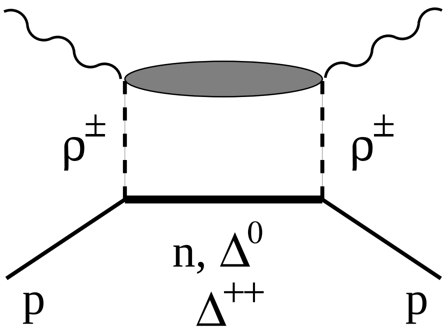
$\Rightarrow$ Light sea quarks have significant polarization, but with $\Delta\overline{u} \simeq -\Delta\overline{d}$.

Goeke et al, hep-ph/0003324



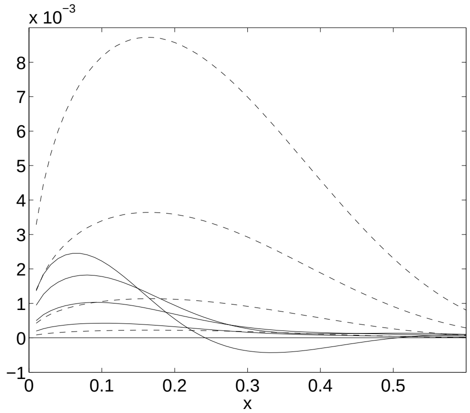
Rho Meson Cloud

Rho: lightest polarizable meson



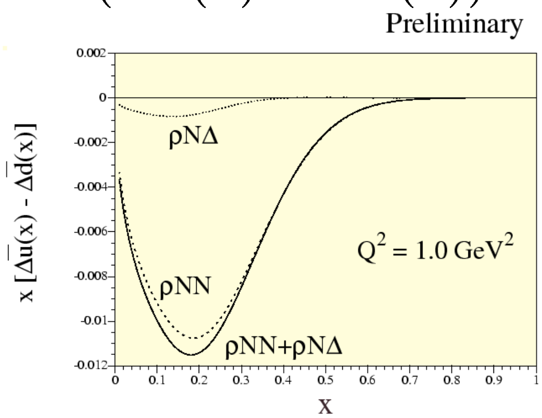
Fries, Scäfer, PLB 443 (1998) 40

$x\,(\Delta\overline{d}(x) - \Delta\overline{u}(x))$



Miyama, DIS 2001

$x\,(\Delta\overline{u}(x) - \Delta\overline{d}(x))$

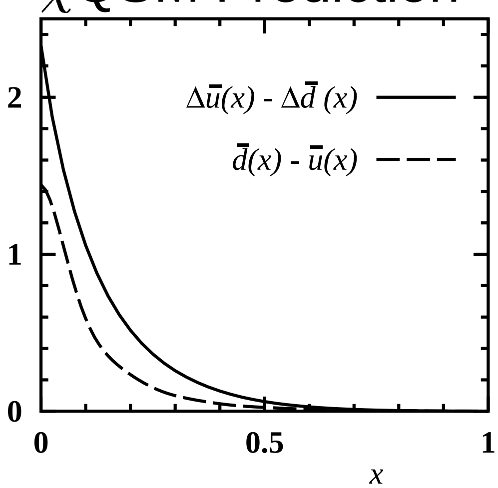


$\rightarrow \Delta\overline{u} - \Delta\overline{d} < 0$ **!**

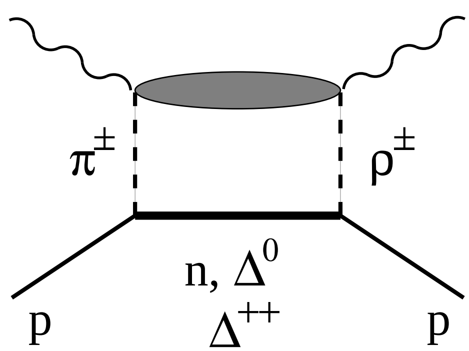
Interference Terms

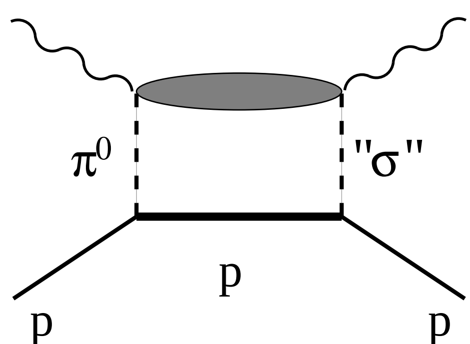
Apparent discrepancy with χQSM might be resolved by interference terms ...

χQSM Prediction



Boreskov, Kaidalov EPJC 10 (1999) 143



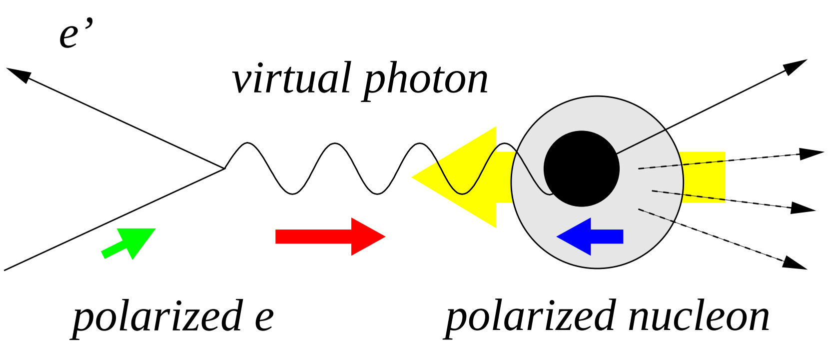


Calculation in progress: R. Fries, Ch. Weiss

Large contributions indicated ...

Spin-dependent Deep Inelastic Scattering

In polarized DIS, using polarized lepton beams and polarized nuclear targets, one probes the polarization of the partons in the nucleon.



$$F_1 = \frac{1}{2}\sum_i e_i^2 q_i$$

$$g_1 = \frac{1}{2}\sum_i e_i^2 \Delta q_i$$

$$\Delta q_i = q_i^{\uparrow} - q_i^{\downarrow}$$

QCD Fits to $g_1(x, Q^2)$ at NLO

$$g_1^{p(n)} = \frac{1}{9}\left(C_{NS} \otimes \left[\pm\frac{3}{4}\Delta q_3 + \frac{1}{4}\Delta q_8\right] + C_S \otimes \Delta\Sigma + 2N_f C_g \otimes \Delta g\right)$$

Using g_1 measurements on both proton and neutron (deuterium) targets, one can *in principle* separate these polarized PDF's:

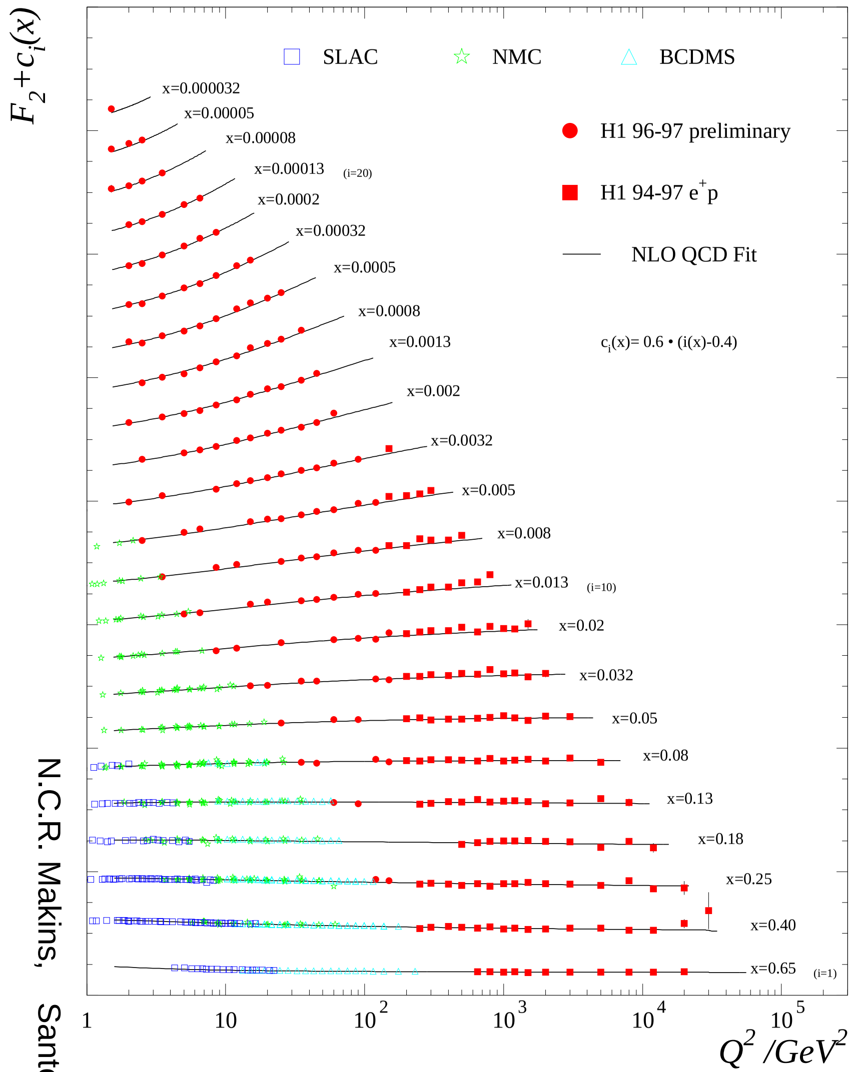
$$\begin{aligned}
\Delta q_3(x, Q^2) &= \Delta u - \Delta d, \\
\Delta q_8(x, Q^2) &= \Delta u + \Delta d - 2\Delta s, \\
\Delta\Sigma(x, Q^2) &= \Delta u + \Delta d + \Delta s, \\
\Delta g(x, Q^2) &
\end{aligned}$$

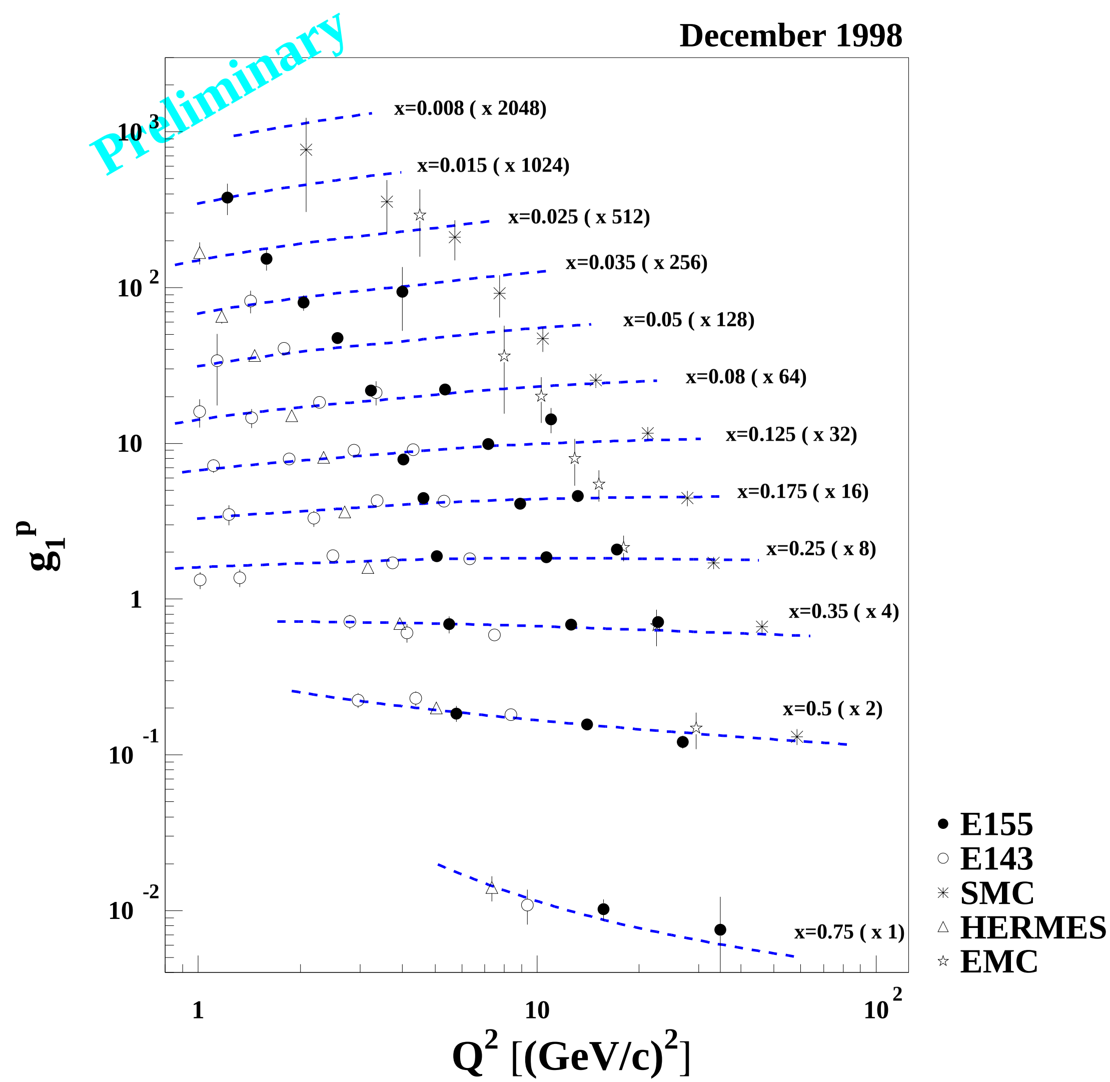
by exploiting the different Q^2-dependent behaviour of each term.

However ...

World data on F_1^p

World data on g_1^p





QCD Fits to $g_1(x, Q^2)$: Challenges

- Precision and range of present polarized data is insufficient to perform a complete separation. Present analyses also use information from **hyperon β-decay** to constrain non-singlet matrix elements:

$$a_3 = \Delta q_3 = F + D = 1.2601 \pm 0.0025 \text{ (Bj. sum rule)}$$
$$a_8 = \Delta q_8 = 3F - D = 0.579 \pm 0.032$$

However, expression for a_8 depends on assumption of **SU(3)-symmetry** among hyperons, which is known to be inexact ...

- **Momentum sum rule** not available. In unpolarized case:

$$\int dx\, x\, [u(x) + d(x) + s(x) + g(x)] = 1$$

In polarized case, the unknown angular momentum appears:

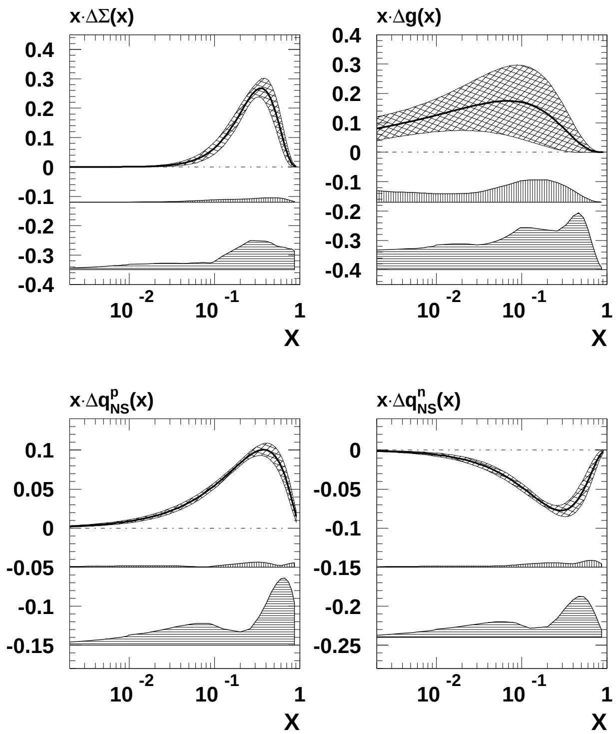
$$\int dx\, [\frac{1}{2}\Delta\Sigma(x) + \Delta g(x)] = \frac{1}{2} - L$$

- The net quark polarization $\Delta\Sigma(Q^2)$ is maximally **scheme dependent** ... connection between measured $\Gamma_1^p = \int dx\, g_1$ and $\Delta\Sigma$ may involve the gluon polarization.

$\Rightarrow$ In the $\overline{\text{MS}}$ scheme, $\Delta\Sigma$ is not conserved.
$\Rightarrow$ In the AB or JET schemes, $\Delta\Sigma$ is conserved:

$$\Delta\Sigma(Q^2)_{\overline{\text{MS}}} = \Delta\Sigma_{\text{AB(JET)}} - 3\frac{\alpha_s(Q^2)}{2\pi}\Delta g(Q^2)_{\text{AB(JET)}}$$

SMC: NLO QCD Fit



First moments at Q_0^2 = 1 GeV^2:

SMC, PRD 58 (1998) 112002

$$\Delta\Sigma_{(\overline{\rm MS})} = 0.19 \pm 0.05 \pm 0.04$$

$$\Delta\Sigma_{(\rm AB)} = 0.38 \,^{+0.03}_{-0.03} \,^{+0.03}_{-0.02} \,^{+0.03}_{-0.05}$$

$$\Delta g_{(\rm AB)} = 0.99 \,^{+1.17}_{-0.31} \,^{+0.42}_{-0.22} \,^{+1.43}_{-0.45}$$

Sensitivity to SU(3) symmetry breaking

Consider variation of a_8 matrix element from hyperon β-decay, around SU(3)-symmetric value of $3F - D = 0.58$. In JET scheme:

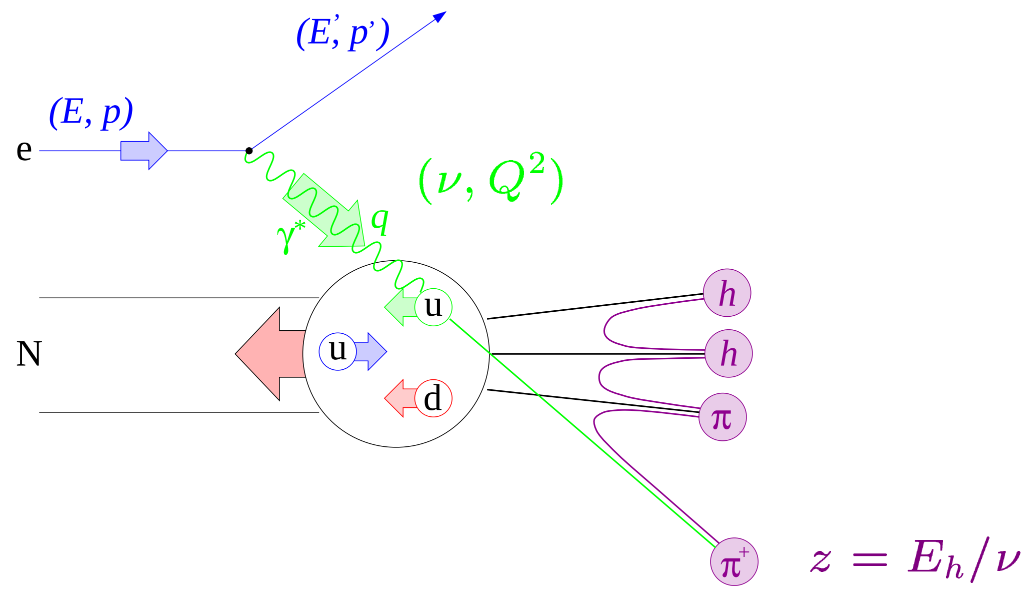
E.Leader, A.Sidorov, D.Stamenov, hep-ph/0004106

a_8	χ^2/DOF	$\Delta\Sigma$	Δg	Δs
0.40	0.82	0.34 $\pm$ 0.05	0.13 $\pm$ 0.14	-0.02 $\pm$ 0.01
0.58	0.83	0.40 $\pm$ 0.04	0.57 $\pm$ 0.14	-0.06 $\pm$ 0.01
0.86	0.82	0.40 $\pm$ 0.06	0.84 $\pm$ 0.30	-0.15 $\pm$ 0.02

$\Rightarrow$ Gluon and strange quark polarizations are strongly dependent on the SU(3)-symmetry assumption.

Quark Polarization from Semi-Inclusive DIS

In semi-inclusive DIS a hadron h is detected in coincidence with the scattered lepton



Flavour Tagging

The flavour content of the final state hadrons is related to the flavour of the struck quark through the agency of the **fragmentation functions** $D_q^h(z, Q^2)$. In LO QCD:

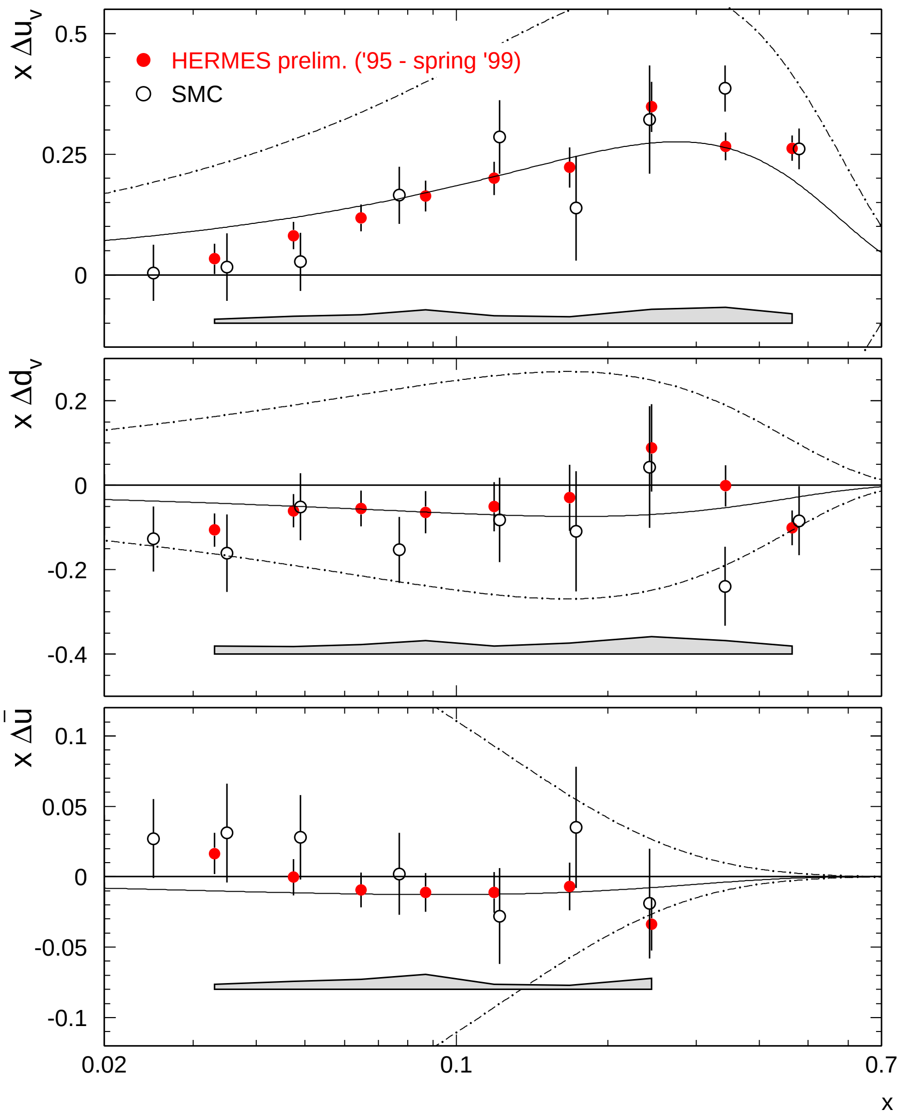
$$A_1^h(x, Q^2) = \frac{\int_{z_{\min}}^1 dz \sum_q e_q^2 \, \Delta q(x, Q^2) \cdot D_q^h(z, Q^2)}{\int_{z_{\min}}^1 dz \sum_q e_q^2 \, q(x, Q^2) \cdot D_q^h(z, Q^2)}$$

Can rewrite in terms of a **purity matrix** :

$$A_1^h(x, z) = \sum_q P_q^h(x, z) \frac{\Delta q(x)}{q(x)}$$

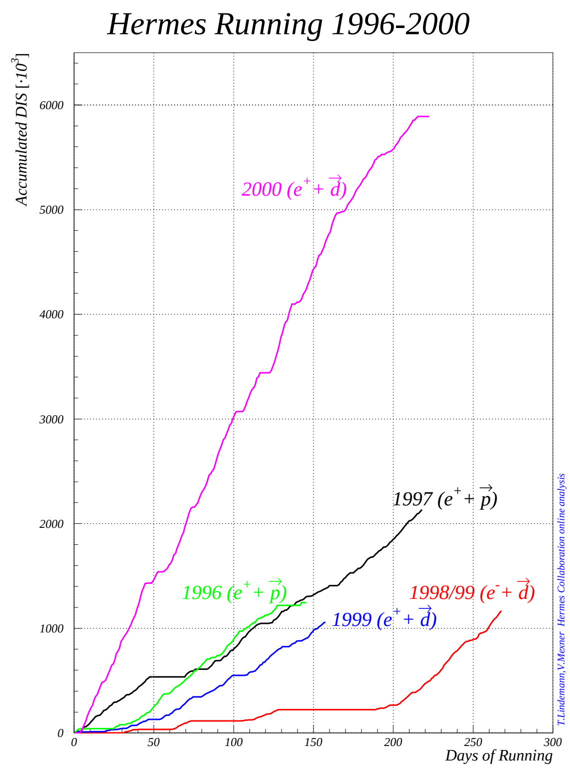
Purities are *spin-independent*, and may be computed via Monte Carlo.

Quark Polarizations at LO



Not yet included ...

- **large 2000 data set** on Deuterium
- **Kaon asymmetries** from RICH detector → access to Δs



- So far: agreement with Gehrmann, Stirling fit to **inclusive data** (Gluon A, LO)
- Result insensitive to choice of SU(3)-symmetric **sea assumption** :

$$\frac{\Delta q_s}{q_s} \equiv \frac{\Delta u_s}{u_s} = \frac{\Delta d_s}{d_s} = \frac{\Delta s}{s} = \frac{\Delta \overline{u}}{\overline{u}} = \frac{\Delta \overline{d}}{\overline{d}} = \frac{\Delta \overline{s}}{\overline{s}}$$

$$\Delta q_s \equiv \Delta u_s = \Delta d_s = \Delta s = \Delta \overline{u} = \Delta \overline{d} = \Delta \overline{s}$$

There are other possibilities ... 2000 data will permit 4- and 5-parameter fits

Global Fit with Semi-Inclusive Data

deFlorian & Sassot 2000

de Florian, Sassot, PRD 62 (2000) 094025

- Assume isospin / charge conjug$^{\underline{n}}$ sym betw fragmentation functions:

FAVOURED	$D_1^\pi \equiv D_u^{\pi+} = D_{\bar{u}}^{\pi-} = D_d^{\pi-} = D_{\bar{d}}^{\pi+}$
DISFAVOURED	$D_2^\pi \equiv D_u^{\pi-} = D_{\bar{u}}^{\pi+} = D_d^{\pi+} = D_{\bar{d}}^{\pi-}$
STRANGE	$D_s^\pi \equiv D_s^{\pi+} = D_{\bar{s}}^{\pi+} = D_s^{\pi-} = D_{\bar{s}}^{\pi-}$

- Relax F, D constraints:

$$\Delta q_3 = (F + D)(1 + \epsilon_{\mathrm{Bj}}) \qquad \Delta q_8 = (3F - D)(1 + \epsilon_{\mathrm{SU(3)}})$$

- Try 3 choices for $\int \Delta g$ @ μ_0: ① $\Delta G|_{\mu_0} < 0.4$ ② $0.4 < \Delta G|_{\mu_0} < 0.7$ ③ $\Delta G|_{\mu_0} > 0.7$ ... χ^2 same for all 3

- 2 scenarios for light quark sea:
  "+" scenario: $\delta\bar{u} = \delta\bar{d}$
  "-" scenario: $\delta\bar{u} = -\delta\bar{d}$
  @ μ_0

MOMENTS:	$\Delta\Sigma$	ΔG	Δq_{sea}
@ $Q^2 = 10$	0.15 – 0.19	0.8 – 1.8	Δs = -0.06 – -0.07 $+$ scen: $\Delta\bar{u}$ = 0.06 $\Delta\bar{d}$ = 0.06 $-$ scen: $\Delta\bar{u}$ = 0.04 $\Delta\bar{d}$ = -0.05

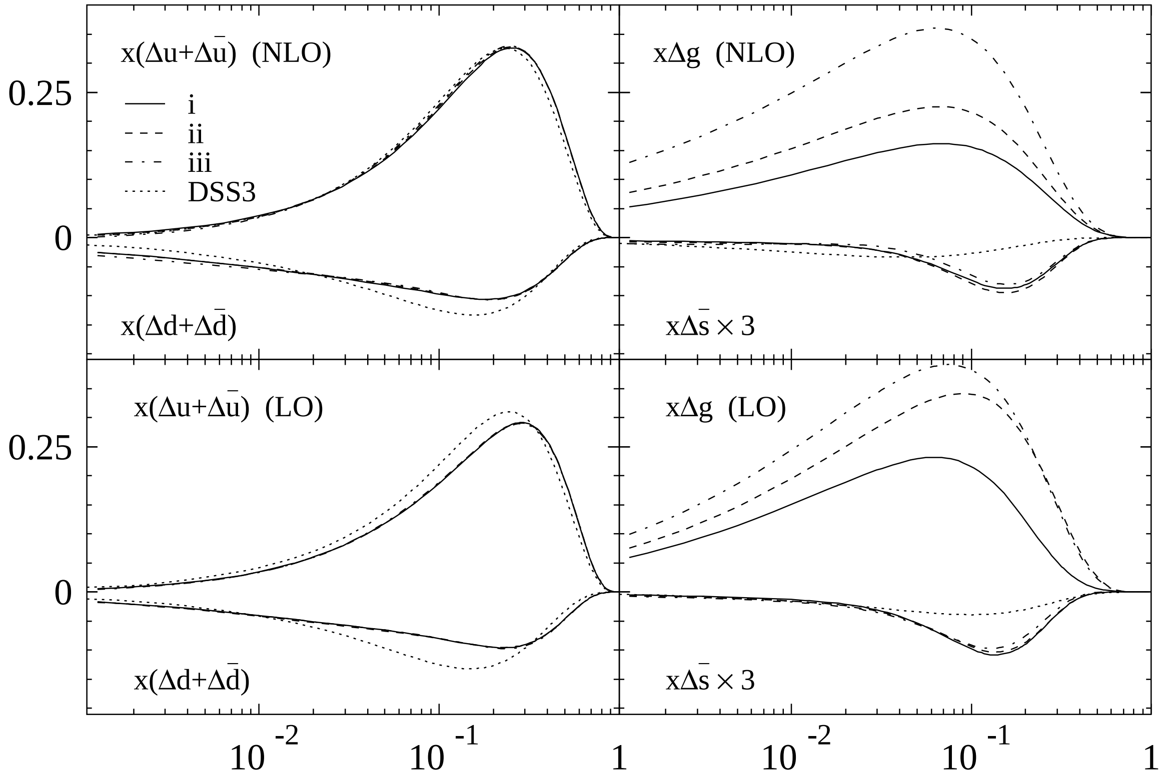
Conclusions:

- SIDIS data $\Rightarrow$ $\delta\bar{u} > 0$ but $\delta\bar{d}$ unconstrained
  $\rightarrow$no χ^2 change between $+$ and $-$ scenarios
- $\Delta s < 0$ indicated, with $\epsilon_{\mathrm{Bj}} \approx$ -2% and $\epsilon_{\mathrm{SU(3)}} \approx$ -6% – 7%

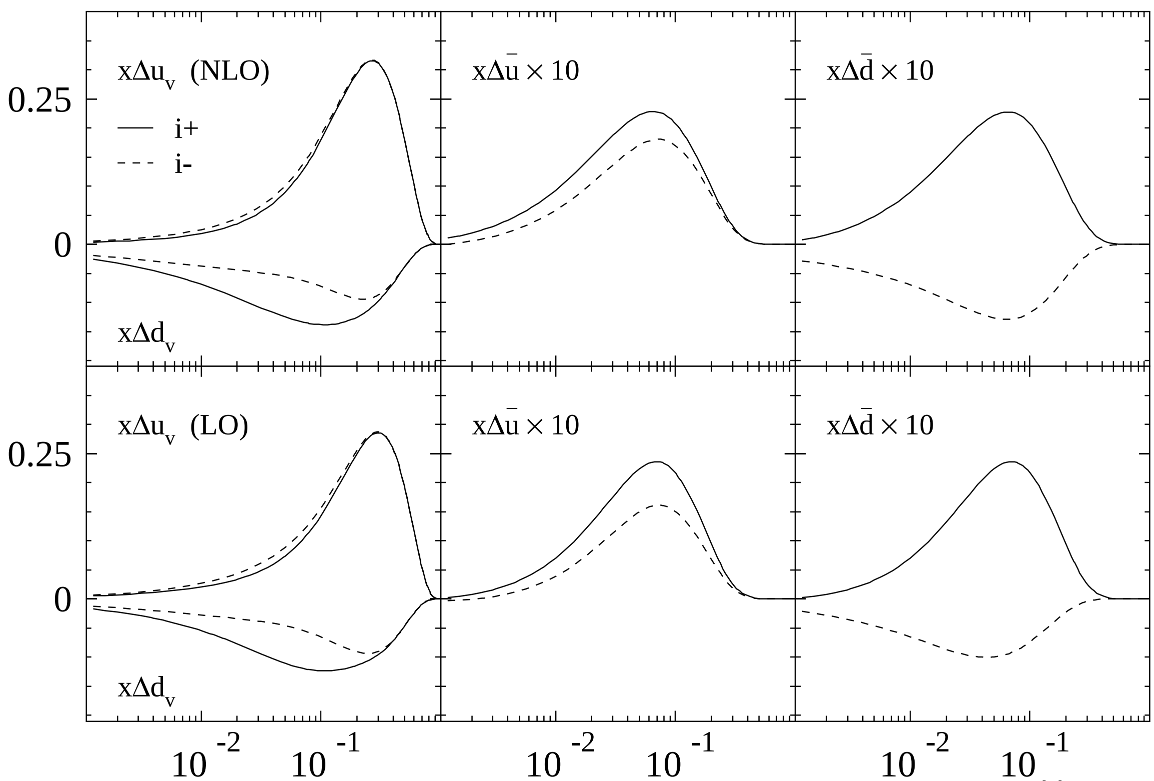
Global Fit with Semi-Inclusive Data

Using inclusive data only ...

de Florian, Sassot, PRD 62 (2000) 094025

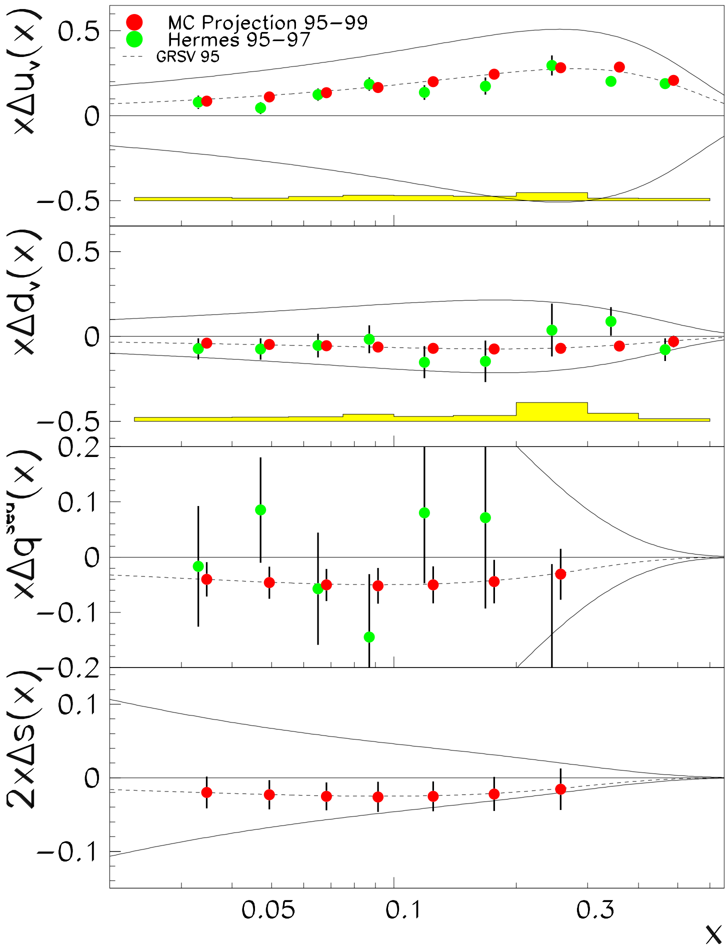


Adding semi-inclusive data ...



Quark Polarization: Future

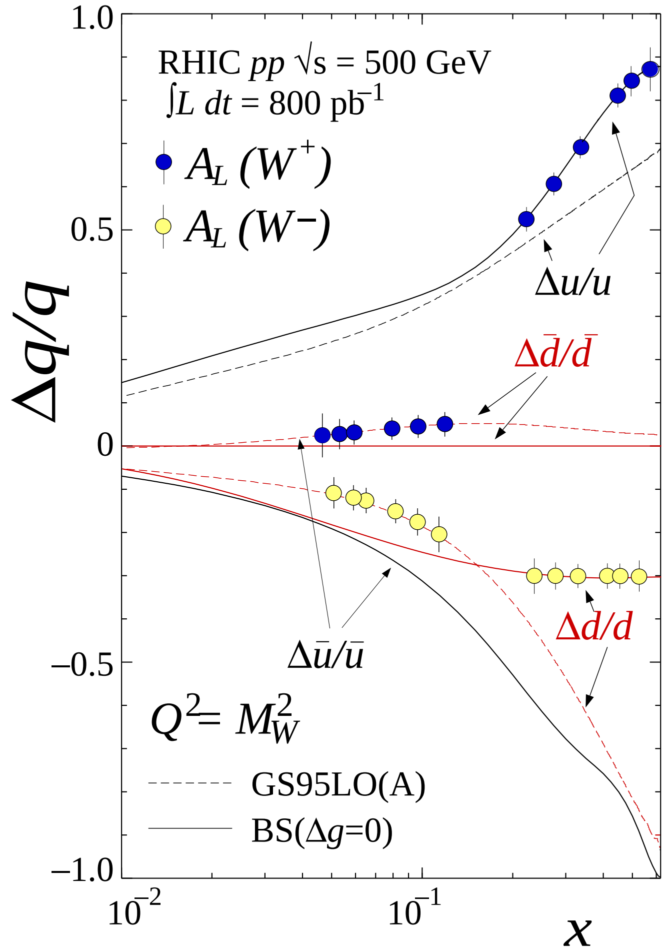
HERMES : data up to 2000



• Pion & Kaon asymmetries

$\rightarrow$ Δs, $\Delta\bar{s}$ sensitivity

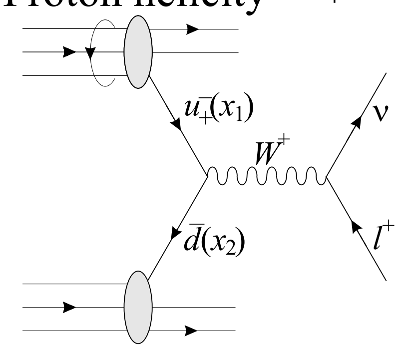
RHIC-spin : 2002 - ...



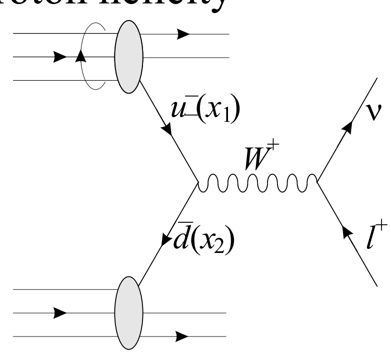
• Polarized W production

$\rightarrow$ $\Delta\bar{u}$ vs $\Delta\bar{d}$ sensitivity

Proton helicity ="+"



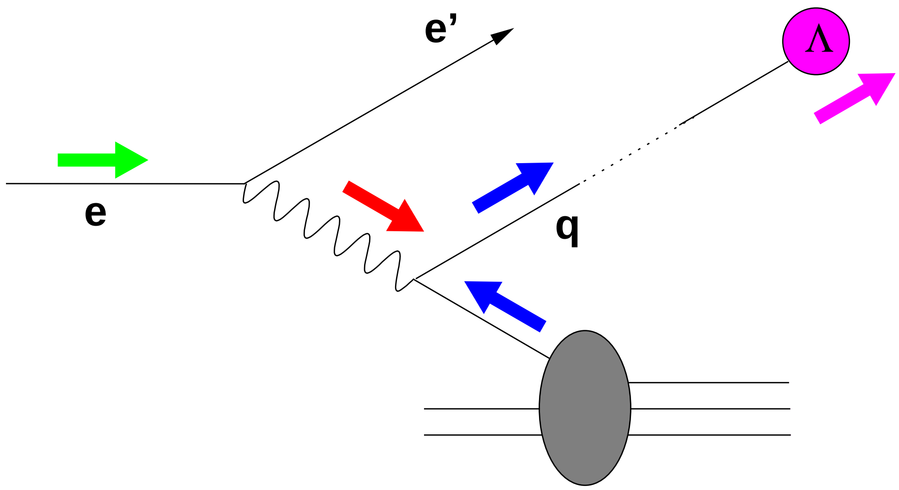
Proton helicity ="–"



And further DIS data expected from COMPASS and HERMES Run II

Longitudinal Λ Polarization

Λ polarization accessible via angular distribution of decay p, π



Using polarized beam and unpolarized target, measure **longitudinal spin transfer** in fragment$^{\underline{n}}$ (from struck q to Λ)

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

final state Λ polarization — struck quark polarization — spin transfer

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

"purity"

Note: In Mulders notation, $\Delta D(z) = G_1(z)$

$\rightarrow$ fragmentation analogue of $g_1(x)$

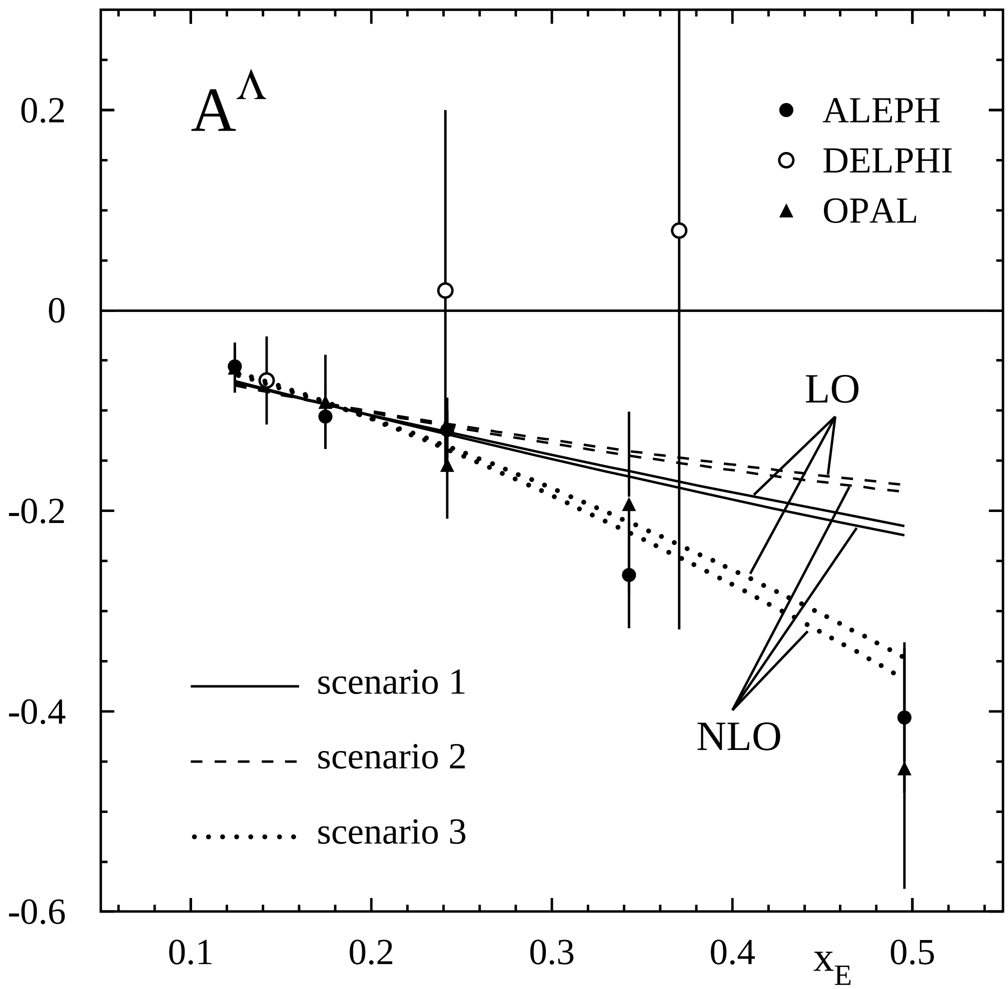
SPIN TRANSFER $\vec{q} \to \vec{\Lambda}$

$$D_{LL'} = \sum \omega_q^\Lambda(x) \frac{G_{1,q}^\Lambda(z)}{D_{1,q}^\Lambda(z)}$$

... IF q helicity conserved in fragmentation ...

$$\Rightarrow \frac{G_{1,q}^\Lambda}{D_{1,q}^\Lambda} \sim \frac{\Delta q^\Lambda}{q^\Lambda}$$

i.e. directly related to quark polarization in Λ



deFlorian, Stratmann, Vogelsang, PRD 57 (1988) 5811

SCENARIO ① **NRQM** : $\Delta u^\Lambda = \Delta d^\Lambda = 0, \quad \Delta s^\Lambda = 1$

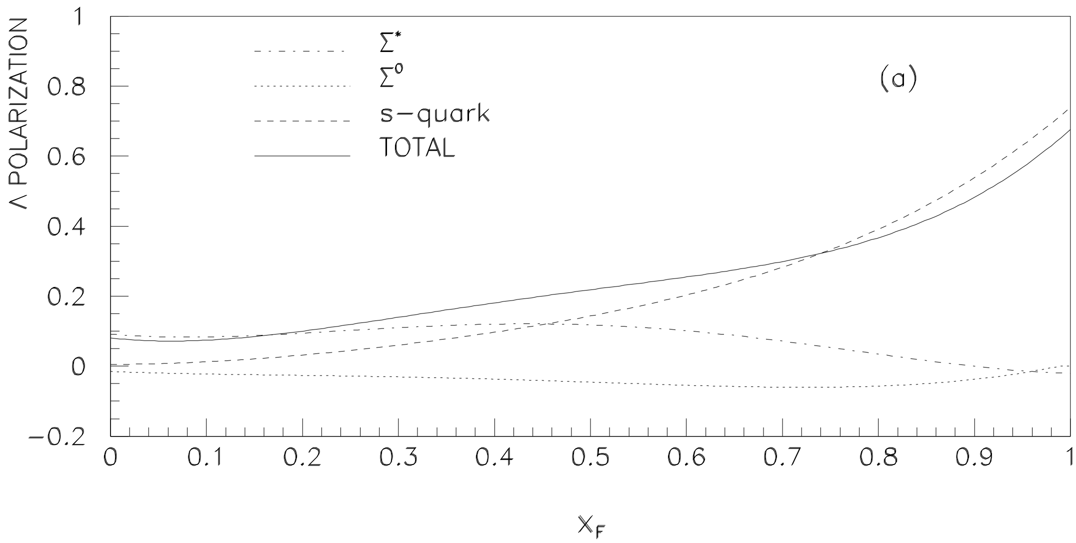
SCENARIO ② **Burkardt & Jaffe** : $\Delta u^\Lambda = \Delta d^\Lambda \approx -0.2$

SCENARIO ③ **"extreme"** : equal polariz^n of flavours $\Delta u^\Lambda \approx \Delta d^\Lambda \approx \Delta s^\Lambda$
(e.g. if ∃ sizable contrib$^{\underline{s}}$ from decays of heavier hyperons)

Influence of Heavy Hyperon Decays

Heavier Hyperons at E665

Ashery, Lipkin, PLB 469 (1999) 263

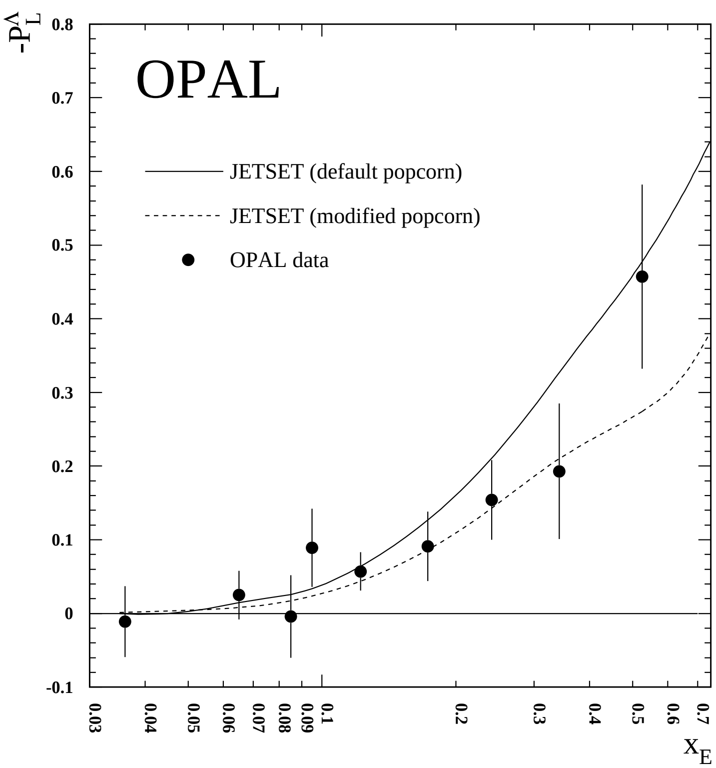


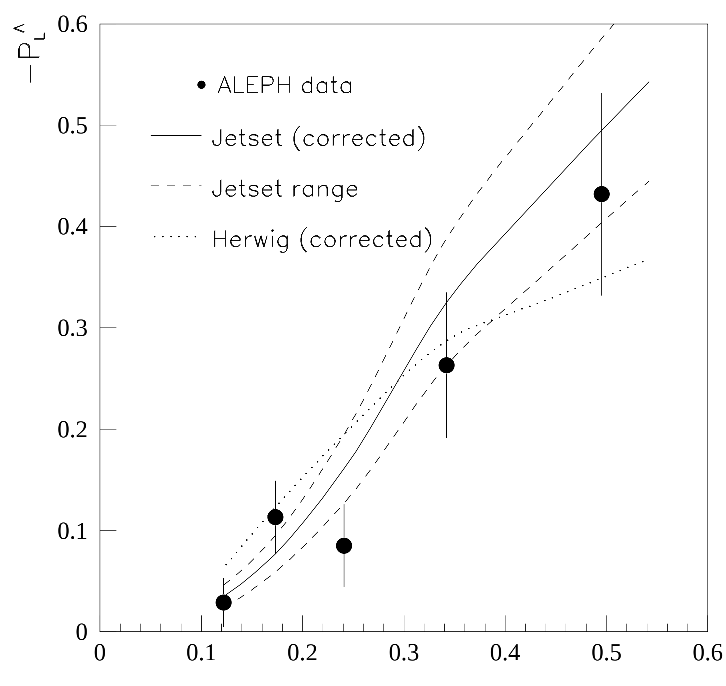
LEP Analyses

OPAL, EPJ C2 (1998) 49; ALEPH, PLB 374 (1996) 319

OPAL and ALEPH data on P_Λ confronted with Monte Carlo models:

- simple SU(3)-symmetric hyperon spin structure
- hyperons **not** containing primary q unpolarized
- perfect helicity conservation of primary q





Λ Spin Structure as $x \to 1$

• Gribov-Lipatov relation

$$q_h(x) \propto D_q^h(z)$$

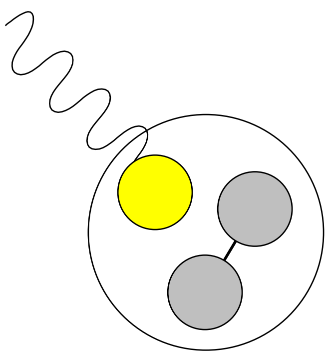
endpoint easy to see:

$z_\Lambda \to 1$
Λ carries all energy ν of struck quark

$\Rightarrow$

$x_\Lambda \to 1$
struck q carries all energy of Λ

① Quark-Diquark Model



spectator diquark D in scalar or vector state

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

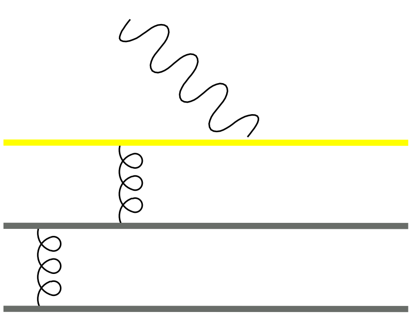
... as $x \to 1$, VECTOR diq config$^{\underline{n}}$ suppressed

$\Rightarrow$

$$\frac{d}{u} \to 0 \qquad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$$

$$\frac{\Delta u}{u} \to 1 \qquad \frac{\Delta d}{d} \to -\frac{1}{3}$$

② pQCD Model

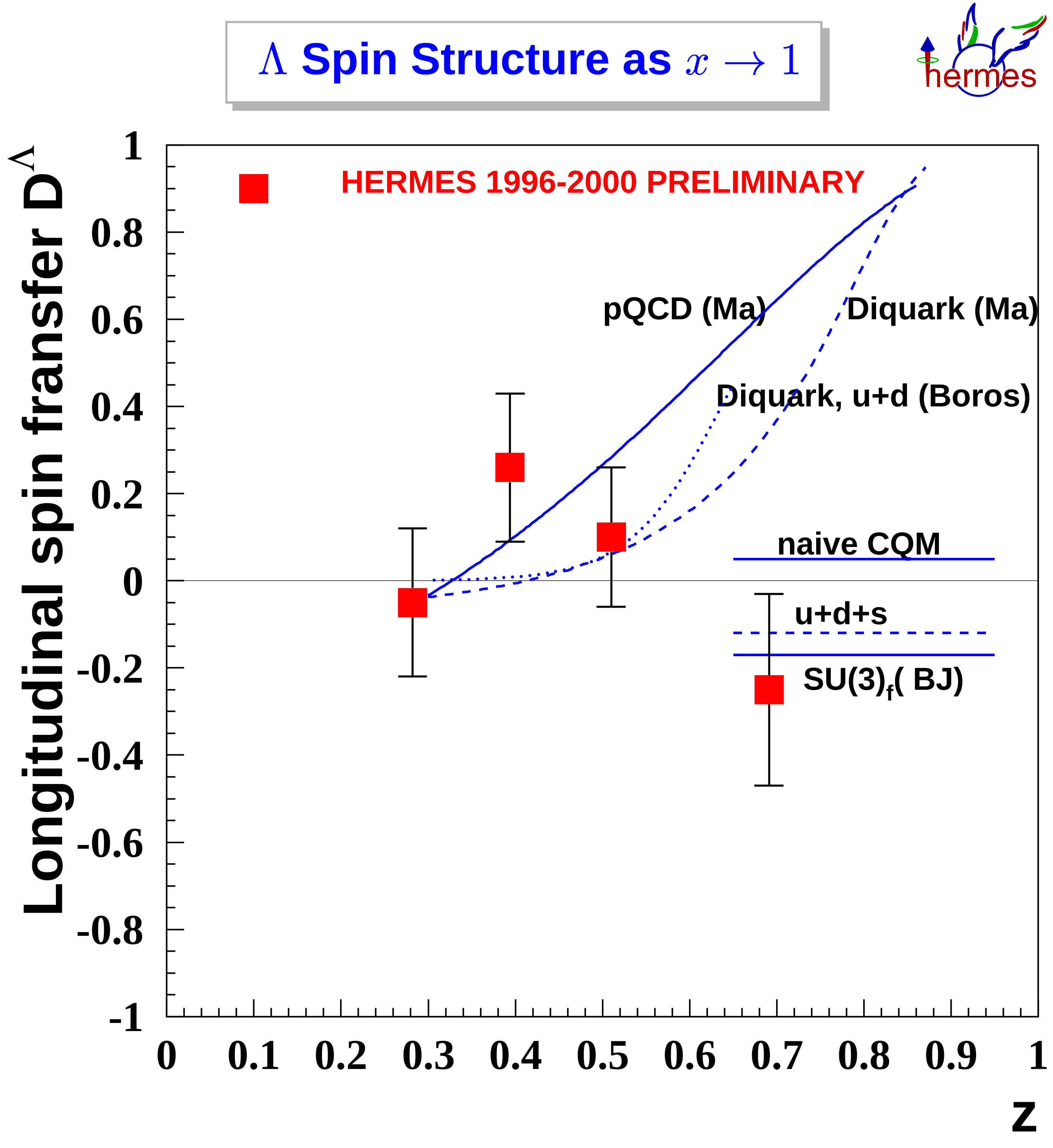


$x \to 1$ wavefn obtained from "normal" wavefn by exchange of large invariant mass gluons from spectator q's ... propagators $\sim \frac{1}{p^2}$ small
$\to$small couplings, perturbative methods possible

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

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

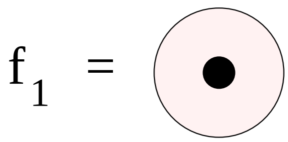
Λ Spin Structure as $x \to 1$



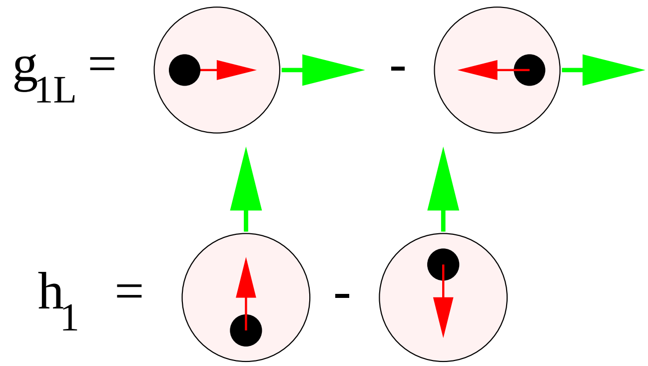
N.C.R. Makins, Santorini 2001

Transversity

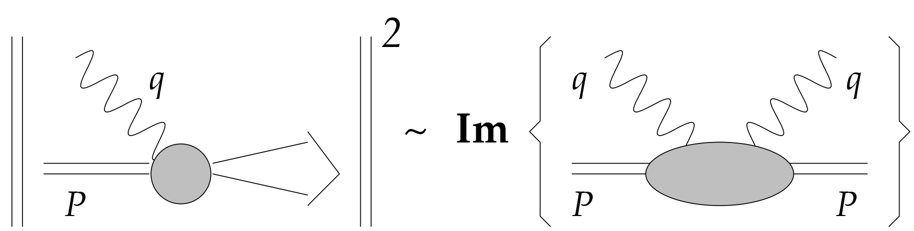
A complete description of the momentum and spin structure of the nucleon at leading twist requires the third parton distribution $\delta q(x)$.

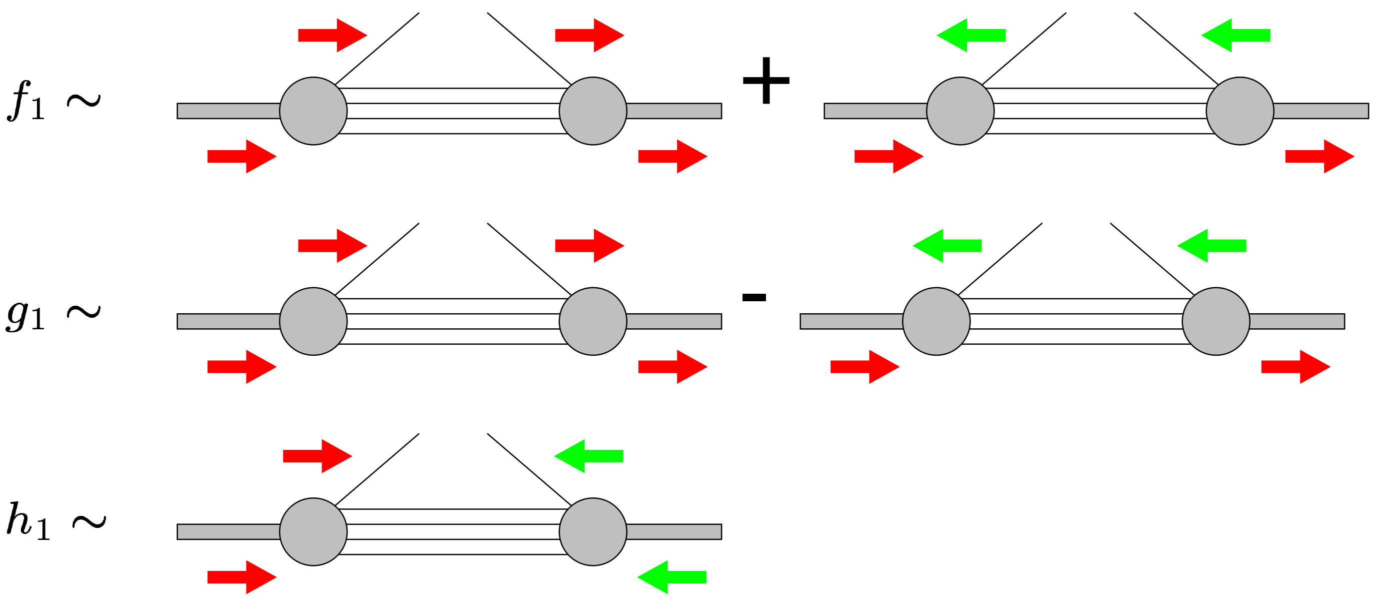


transversity:
$h_1(x) \sim \delta q(x)$

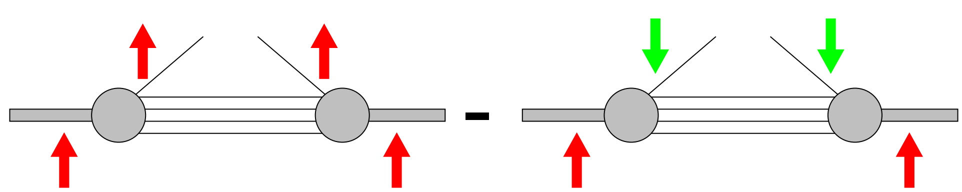


Helicity Flip Amplitudes





Target not in
helicity eigenstate
$\Rightarrow$ **transversity basis**



In Non-Relativistic Case ...

In the absence of **relativistic effects** , boosts and rotations commute:

$$\delta q(x) = \Delta q(x)$$

Tensor Charge of the Nucleon

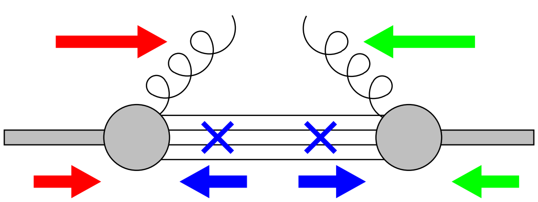
Fundamental matrix elements:

$$\text{axial charge} \quad \Delta q(\mu) = \langle PS|\overline{\psi}\gamma^\mu\gamma_5\psi|PS\rangle = \int_0^1 dx\ g_1(x) + \overline{g}_1(x)$$

$$\text{tensor charge} \quad \delta q(\mu) = \langle PS|\overline{\psi}\sigma^{\mu\nu}\psi|PS\rangle = \int_0^1 dx\ h_1(x) - \overline{h}_1(x)$$

$\Rightarrow$ tensor charge is **pure valence object** ...
promising for comparison with lattice QCD

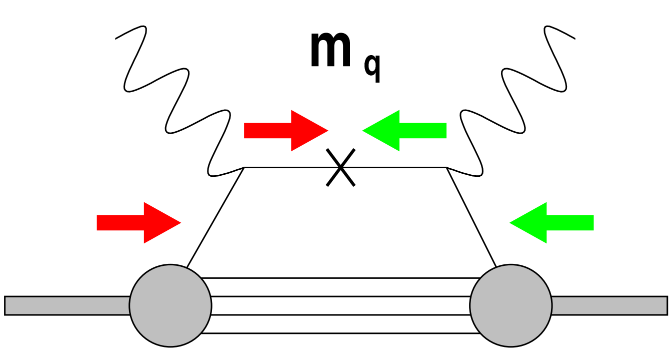
No Gluons



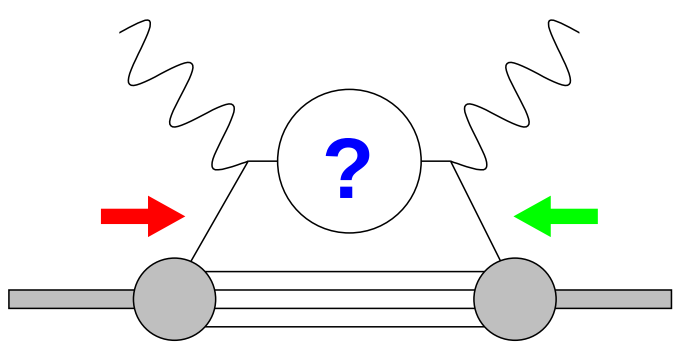
Angular momentum conservation
$\Rightarrow \Lambda - \lambda = \Lambda' - \lambda'$
Different Q^2 **evolution** than g_1.

Chiral Odd

Helicity flip amplitudes occur only at $\mathcal{O}(m_q/Q)$ in inclusive DIS ...



but they are observable in e.g. **semi-inclusive** reactions



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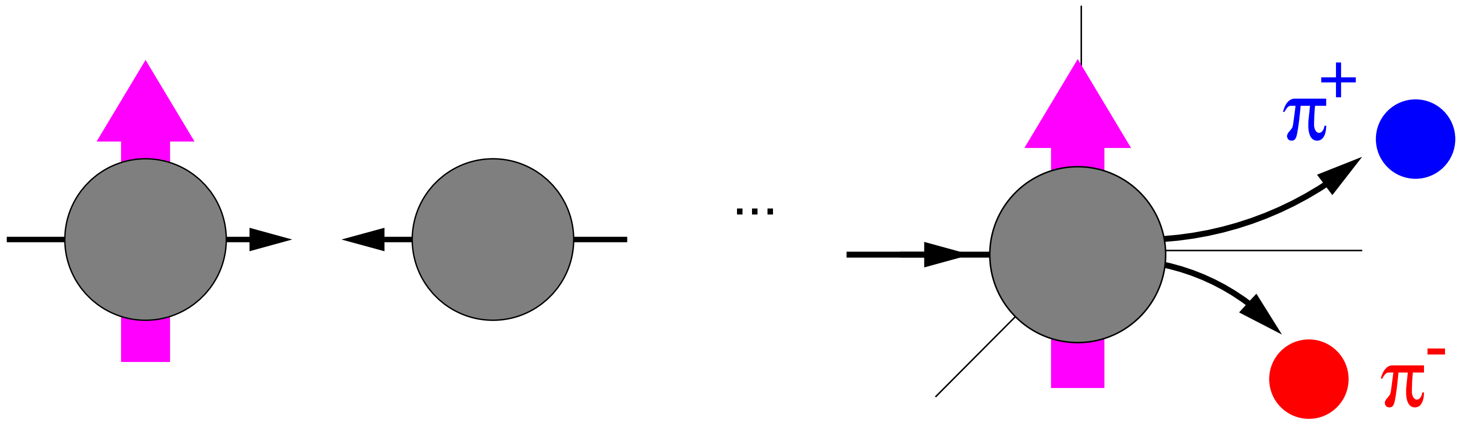
Single Spin Asymmetries

E704: $p^{\uparrow}p \rightarrow \pi X$



From perturbative QCD considerations, it was expected that transverse spin effects would be **small:** $\sim m_q/\sqrt{\hat{s}}$ ...

$$A_N(p^{\uparrow}p \rightarrow \pi X) \sim \int h_1(x_a)f_1(x_b)D_1^{\pi}(x_c)\ \hat{a}_{ab}\frac{d\sigma}{dt}(a^{\uparrow}b \rightarrow cd)$$

with helicity flip in subprocess asymmetry:

$$\hat{a}_ab = \frac{d\sigma(a^{\uparrow}b \rightarrow cd) - d\sigma(a^{\downarrow}b \rightarrow cd)}{d\sigma(a^{\uparrow}b \rightarrow cd) + d\sigma(a^{\downarrow}b \rightarrow cd)}$$

No large effects possible:

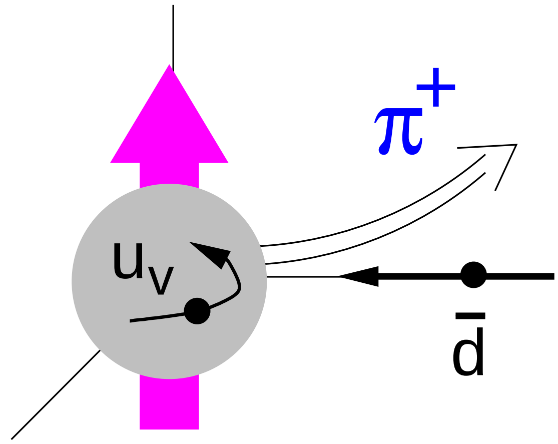
- q helicity flip vanishes in the limit $m_q = 0$
- $\hat{a}_{ab}$ arises from **interference** between a non-flip and a single-flip helicity amplitude ... and no imaginary phases possible at Born level.

Sivers Effect

Chou-Yang Model

Valence quarks = relativistic Dirac particles in central potential

- relativistic quarks in eigenstates of J, which is shared between L and S
- symmetrized wavefunction $\rightarrow \Delta u = +4/3, \Delta d = -1/3$
- forward π^+ produced directly from orbiting u_v quark at front surface of beam proton



Sivers Idea

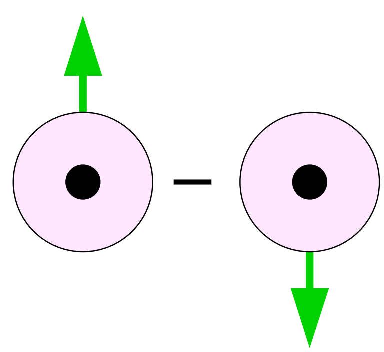
Consider dependence of parton densities on **intrinsic** k_T :

$$A_N \sim \int f_{1T}^{\perp}(x_a, \mathbf{k}_{Ta}) \, f_1(x_b, k_{Tb}) D_1^{\pi}(x_c, k_{Tc}) \, \frac{d\sigma}{dt}(ab \rightarrow cd)$$

- Unknown soft dynamics absorbed into $f_{1T}^{\perp}$ ... hard subprocess merely transmits the asymmetry to large transverse momentum by kinematics.
- Intrinsic k_T introduces hadronic scale M into the problem: transverse effects of order pT/M (not just pT/s)

New structure function: $f_{1T}^{\perp}(x, \mathbf{k}_T)$

- disappears on integration over $\mathbf{k}_T$
- odd under time reversal ... requires initial state interactions between colliding hadrons

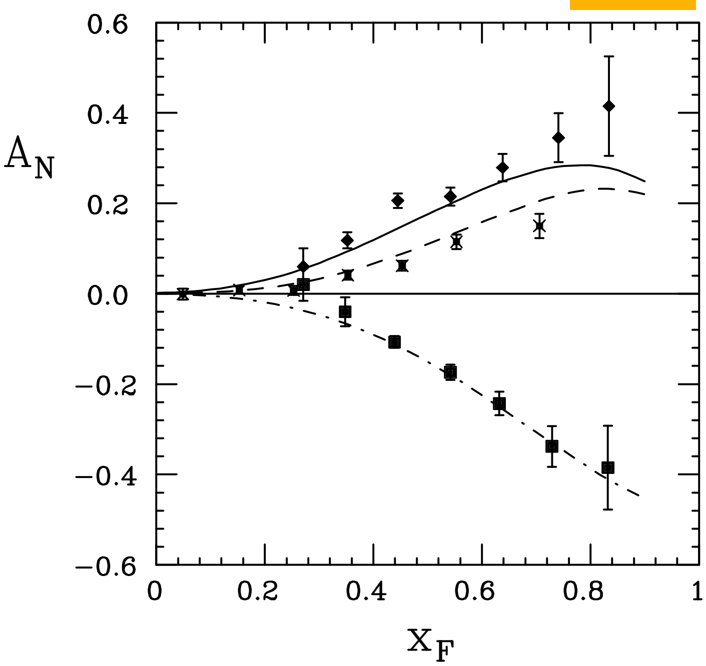


Collins Effect and Transversity

There is another possible explanation ...
the E704 single-spin asymmetry could be due to:

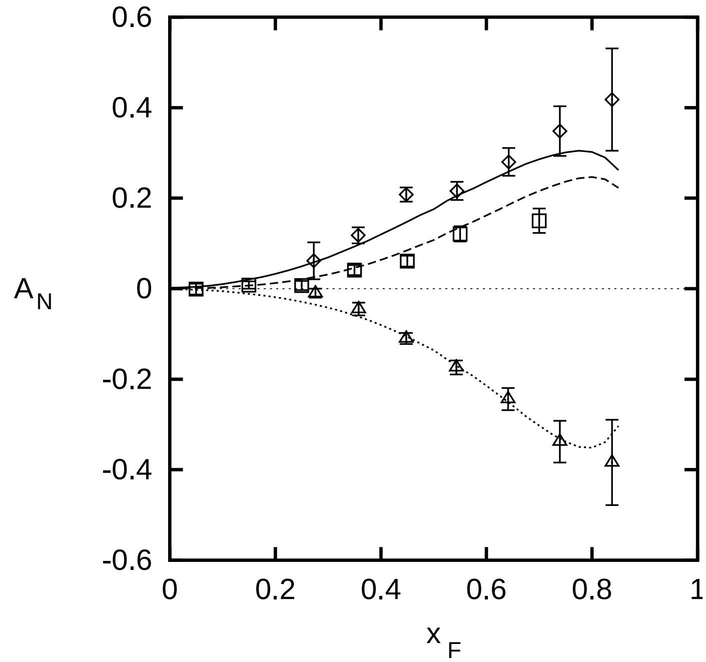
Sivers Effect:

T-odd **distributⁿ function** $f_{1T}^{\perp}$



Collins Effect:

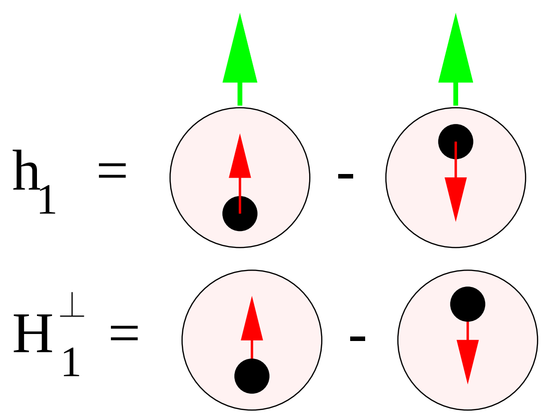
T-odd **fragmentatⁿ function** $H_1^{\perp}$



Collins Effect

In this case, $A_N \sim h_1(x)\, H_1^{\perp}(z)$

$\Rightarrow$ access to **transversity!**



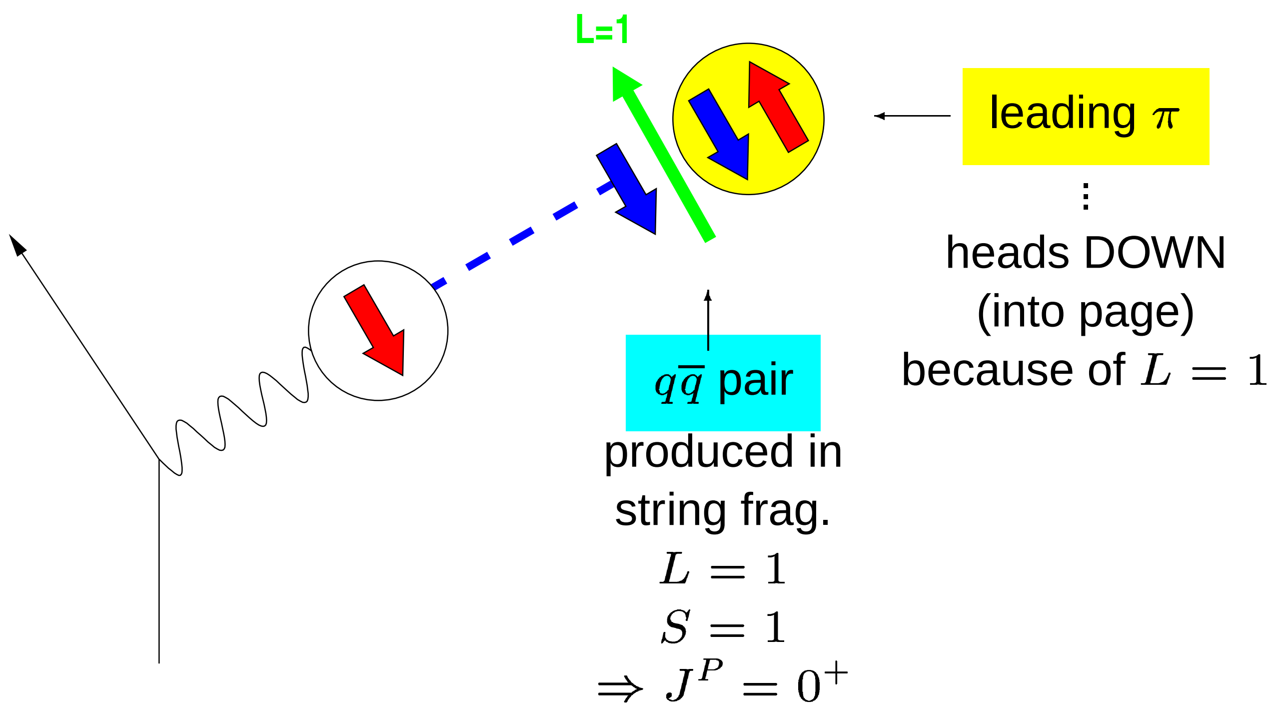
How to separate?

Single Spin Asymmetries in DIS

The Collins Effect in the String Fragmentation Model

Collins Fragmentation Function
$H_1^\perp(z)$

- **chiral-odd** like $h_1(x)$ ... chiral-odd distribution and fragmentation functions appear in pairs in DIS cross-section
- **T-odd** ... one T-odd function required to produce single-spin asymmetry in semi-inclusive DIS

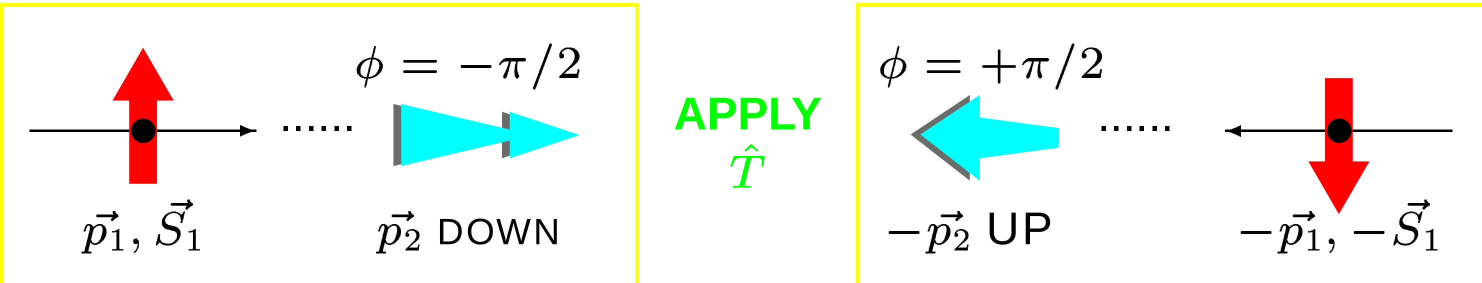


The Collins function is indicative of **phase coherence** in fragmentation
$\Rightarrow$ generate inteference between non-flip and single-flip amplitudes

T-Odd Functions

Spin Spin Azimuthal Asymmetry: $\sigma \sim \vec{S_1} \cdot (\vec{p_1} \times \vec{p_2}) \sim \sin\phi$

ODD under time reversal



$\hat{T}$ transforms ϕ to $-\phi$

But elementary QCD processes are $\hat{T}$-invariant ...
can build $\hat{T}$-odd term in xsec ($\sim \sin\phi$) from **interference**

TOY EXAMPLE

Any amplitude $A = \langle f|\hat{\mathcal{H}}|i\rangle$ for $\hat{T}$-invariant $\hat{\mathcal{H}}$ satisfies

$$A^*(-\phi) = A(\phi)$$

① No spin flip $\quad A_1 = \langle S_1 =\uparrow |\hat{\mathcal{H}}|\phi, S_2 =\uparrow\rangle \sim e^{i\phi}$

② Spin flip $\quad A_2 = \langle S_1 =\uparrow |\hat{\mathcal{H}}|\phi, S_2 =\downarrow\rangle \sim 1$

... suppose $\exists$ **PHASE SHIFT** $e^{i\delta}$ *between amplitudes ...*

$$\sigma \sim |A_1 + e^{i\delta} A_2|^2 = 2 + 2\mathrm{Re}(e^{i\delta} A_1^* A_2) = 2 + \cos\delta \, \cos\phi - \sin\delta \sin\phi$$

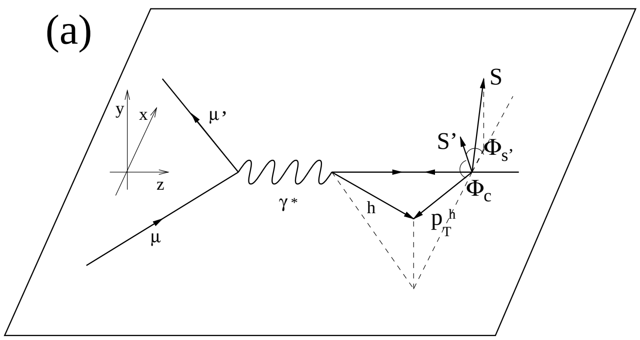
- $e^{i\delta}$ $\Rightarrow$scattering phase shift, from **final / initial state interactions**
- ... but in high energy π production, surely **many** amplitudes contribute

significant $\hat{T}$-odd frag$^{\underline{n}}$ function → **phase coherence** in fragmentation!

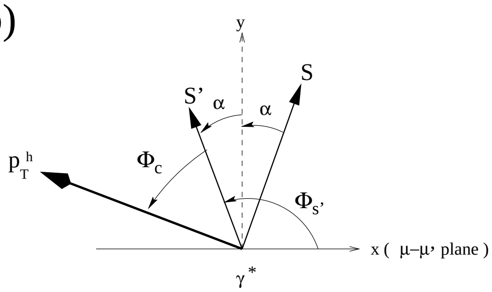
SMC: Azimuthal Asymmetry

$$A_N = \frac{1}{P_T f D_{NN}} \frac{1}{\langle \sin\phi_c \rangle} \frac{N(\phi_c) - N(\phi_c + \pi)}{N(\phi_c) + N(\phi_c + \pi)}$$

(a)

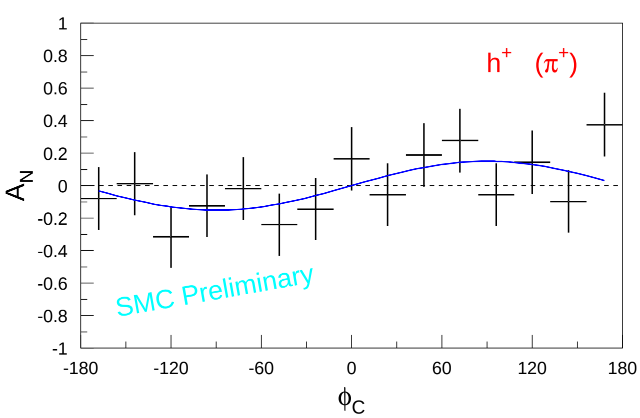


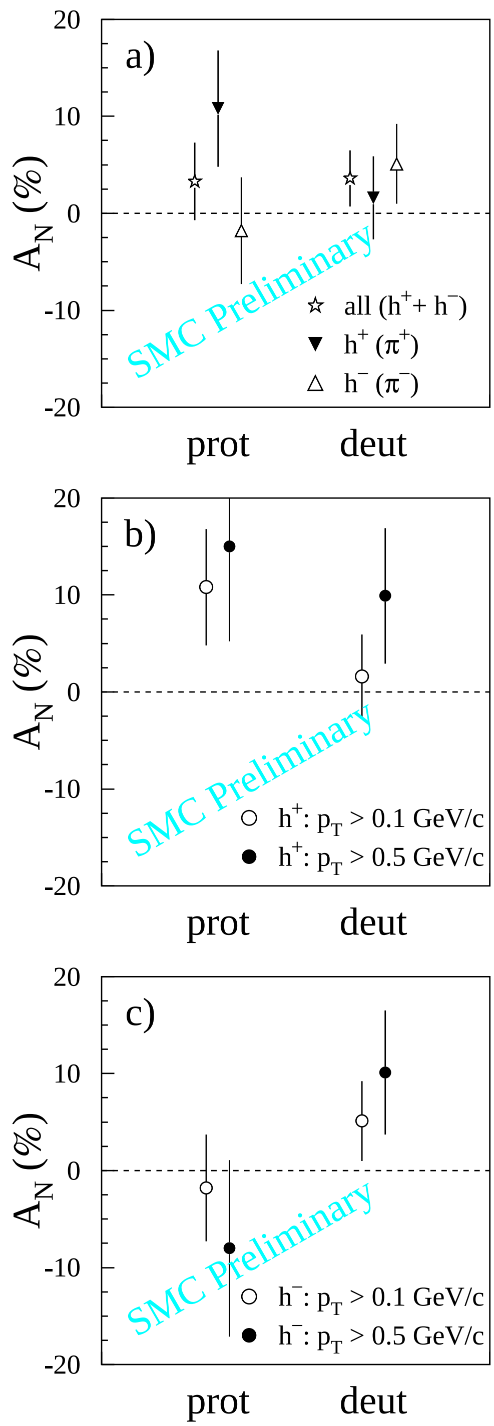
(b)



$$d\sigma \sim (1 + A_N \sin\phi_c) d\phi_c$$

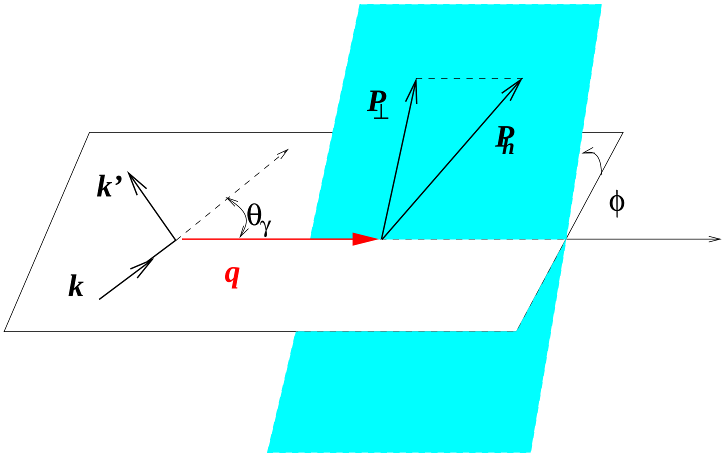
Using transversely polarized target





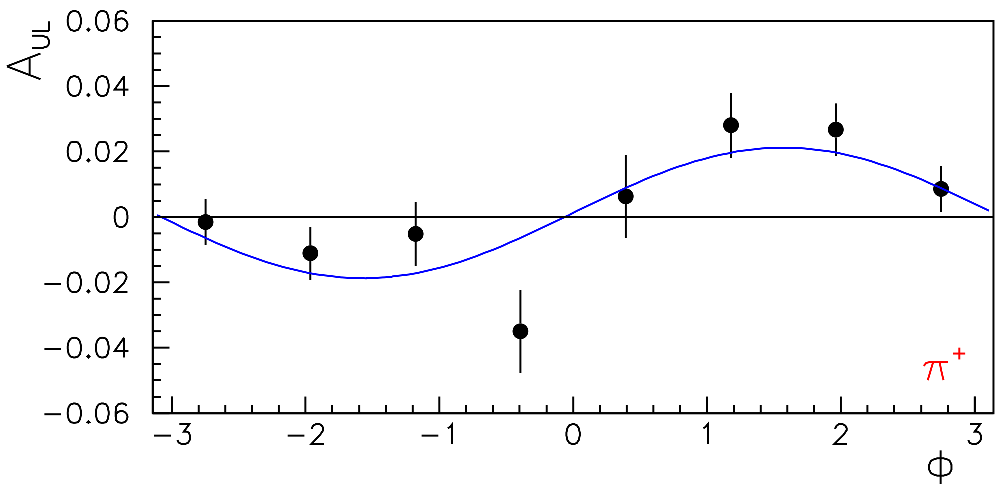
N.C.R. Makins, Santorini 2001

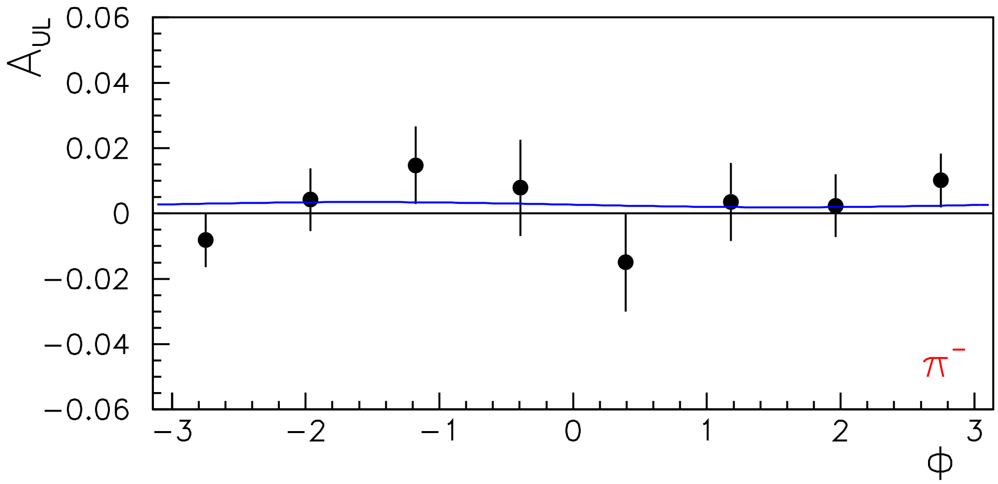
Spin-Azimuthal Asymmetry



Longitudinal target
spin asymmetry:

$$A(\phi) = \frac{1}{P} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$



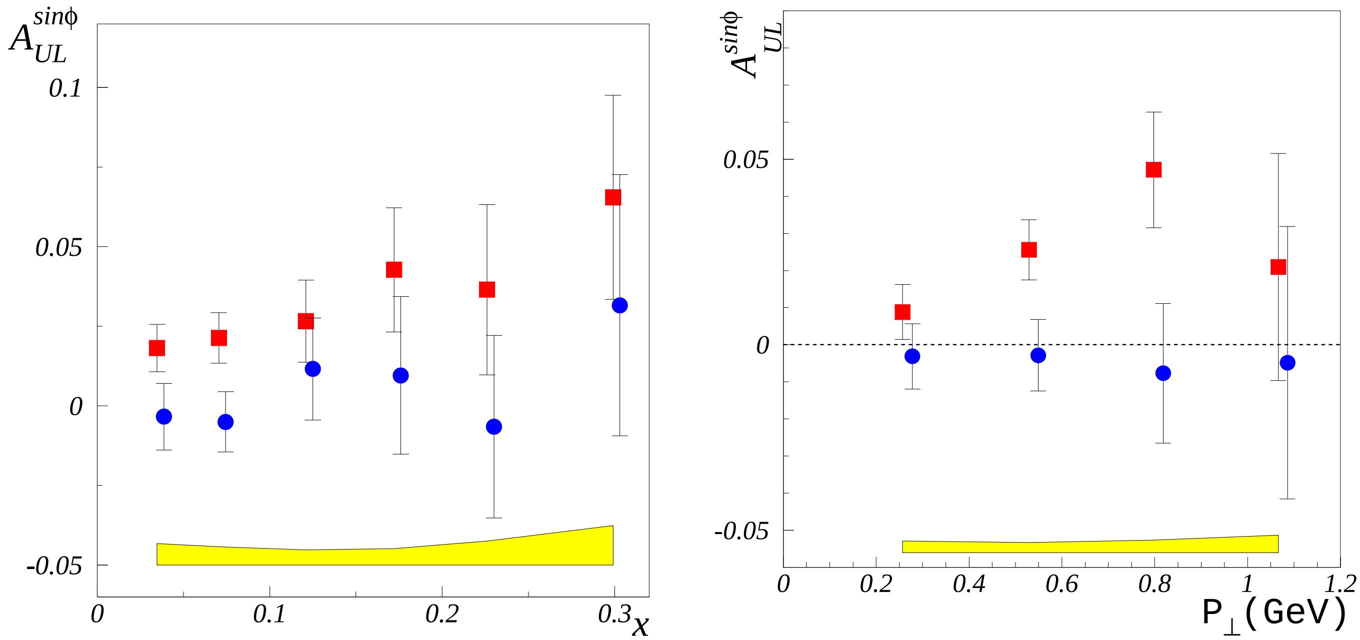


Effect observable even with longitudinally polarized target
$\Rightarrow$ good promise for future **transverse target program**
at HERMES

$A_{UL}^{\sin\phi}$ Behaviour

$A_{UL}^{\sin\phi} = \langle \sin\phi \rangle$ moment of longitudinal target asymmetry
$\rightarrow$ related to product of $h_1(x)$ and $H_1^{\perp}(z)$

Red squares (blue circles) = π^+ *(*π^-*).* *HERMES, hep-ex/9910062*



Original Predictions of Collins

Collins, NP B396 (1993) 161

- Effect should peak at $x \simeq 0.3$ (valence region)
- Effect should be stronger for π^+ than π^- (u-quark dominance)
- Effect should grow with p_T and peak at $p_T \simeq 1$ GeV/c

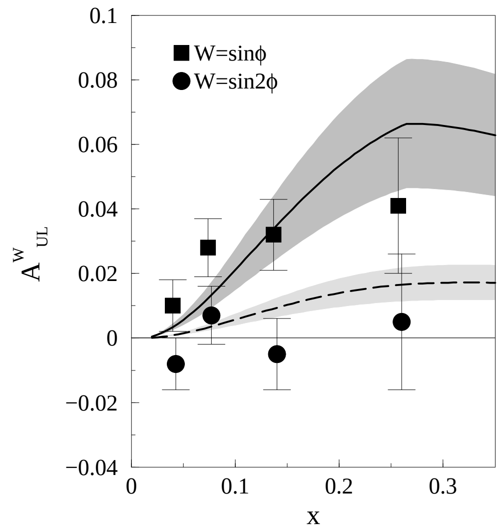
Future Measurements of Transversity

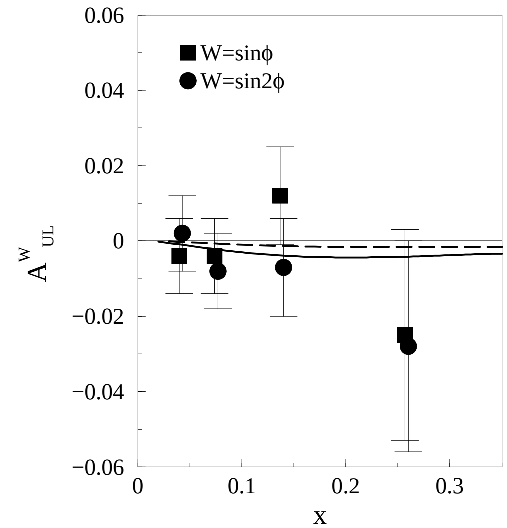
This effect is essentially a **transverse** one ... the fact that it is already visible using a longitudinally polarized target $\Rightarrow$ good promise for future **transverse target programs** , e.g. at HERMES and COMPASS.

Azimuthal Asymmetry in the Chiral Quark Soliton Model

Charged Pion Asymmetry A_{UL}

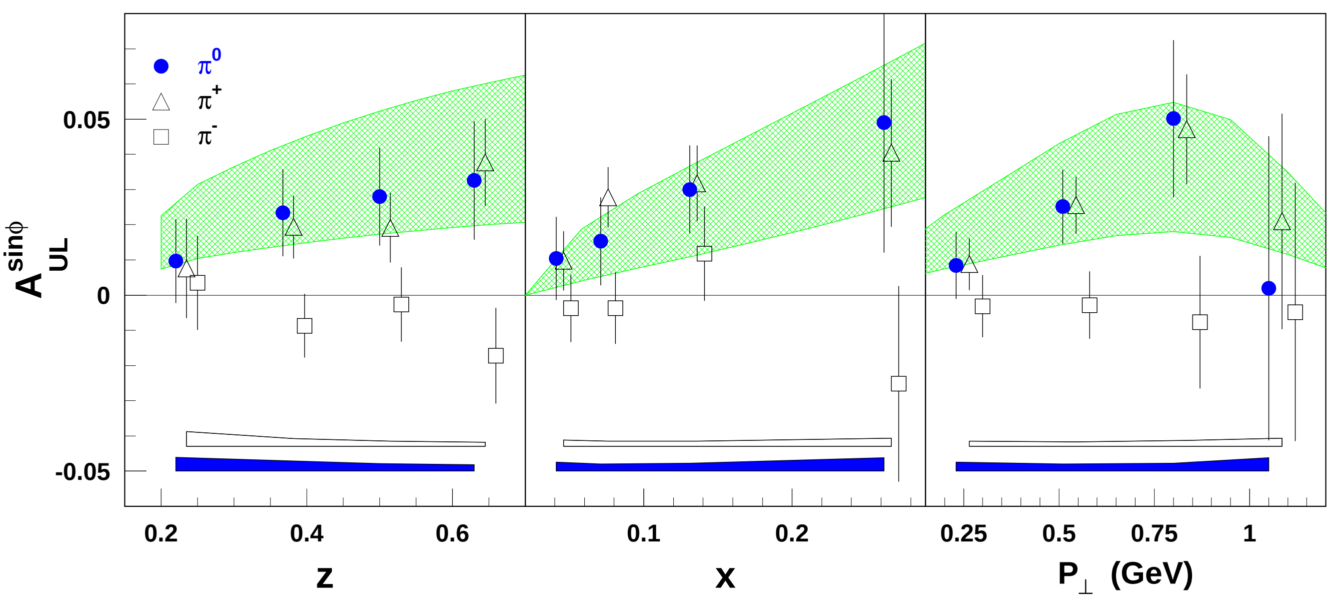
HERMES, PRL 84 (2000) 4047





New: Neutral Pion Asymmetry

HERMES, hep-ph/0104005



Calculation:

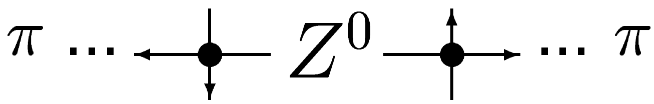
Efremov et al, hep-ph/0001119

- only favoured fragmentation functions $D_1^{a/\pi}$ and $H_1^{\perp a/\pi}$
- $\langle H_1^\perp(z)/z\rangle = \langle H_1^\perp(z)\rangle/\langle z\rangle$ with $\langle z\rangle = 0.41$
- $\langle P_{h\perp}\rangle \approx \langle p_T\rangle \approx 0.4$ GeV
- GRV parametrization for $f_1^a(x)$
- h_1 calculated in chiral soliton model

Size of Collins Function

• DELPHI

Efremov et al., hep-ph/9812522



Transverse q, $\overline{q}$ polarization small but ANTI-CORRELATED (@ $\sim$ 50 % level)

$$\left|\frac{H_1^\perp}{D_1}\right| = 6.3 \pm 1.7\,\%$$

• HERMES / SMC

Efremov et al., hep-ph/0108213

Fit experimental data for $H_1^\perp$, taking $h_1(x)$ from Chiral Quark Soliton Model (χQSM)

$$\left|\frac{H_1^\perp}{D_1}\right| = \begin{cases} 6.1 \pm 0.9 \pm 0.8\% \\ \text{(HERMES)} \\ 10 \pm 5\% \;\; \text{(SMC)} \end{cases}$$

• E704

Boglione & Mulders, PRD 60 (1999) 054007

Fit experimental data, assuming ONLY Collins effect contributes

$$\left|\frac{H_1^\perp}{D_1}\right| = 7.6\%$$

There seems to be general agreement

(although results depend on z-range over which averaging performed)

What about the Sivers Function?

• Note: fit to E704 assuming ONLY Sivers effect contributes:

$$\left|\frac{f_{1T}^\perp}{f_1}\right| = 8.3\% \quad \left(\begin{matrix}\text{“max”} \\ \text{size}\end{matrix}\right)$$

• MORE DATA NEEDED ... e.g. DIS w transverse target

$$A_{UT} \text{ has term } \sim f_{1T}^\perp D_1 \sin(\phi_h^l + \phi_s^l)$$

Summary

Quark & Gluon Polarization

- **Semi-inclusive** data critical to constraining $\Delta\overline{u}$, $\Delta\overline{d}$
  $\rightarrow$ some indication already that $\Delta\overline{u} > 0$
  $\rightarrow$ wait: HERMES analysis of 2000 data ... new data
  upcoming from RHICspin, COMPASS, HERMES Run II

- **Gluon polarization** not constrained by g_1 data
  $\rightarrow$ need direct meas. of photon-gluon-fusion process
  wait: RHICspin, COMPASS, SLAC, HERMES Run II

- Longitudinal spin transfer in Λ **production** high z may provide information on $\Delta q^{\Lambda}/q^{\Lambda}$ as $x \rightarrow 1$

New Structures

- **Transversity**: first data on h_1 in rather good agreement with models

- First clear evidence of T-odd **Collins Fragmentation Func$^{\underline{n}}$** obtained
  $\rightarrow$ strong phase coherence in fragmentation?

- More data required to constrain **Sivers Function** $f_{\mathbf{1T}}^{\perp}$
  $\rightarrow$ sensitive to orbital angular momentum?