Spin Physics

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

Progress in Spin Physics

- Quark and Gluon Polarizations
- Spin-Azimuthal Asymmetries
  $\Rightarrow$ Transversity
- Higher Twist Effects
- Hard Exclusive Processes
  $\Rightarrow$ Skewed Parton Distributions

1999

2000

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

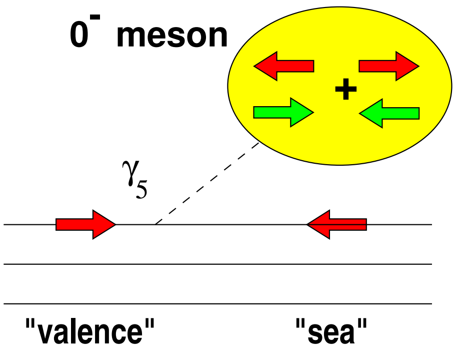
Jaffe, Manohar, NP B337 (1990) 509

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 ...

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

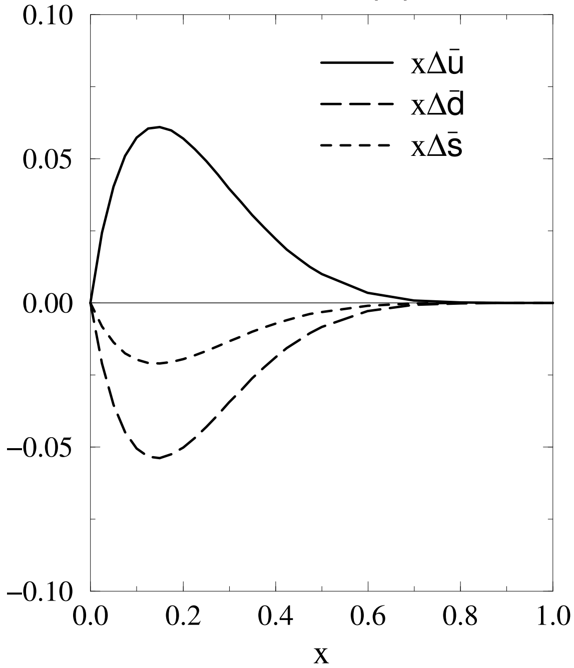
Large N_c Limit and the Chiral-Quark Soliton Model

Nucleon = chiral soliton in pion field.

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

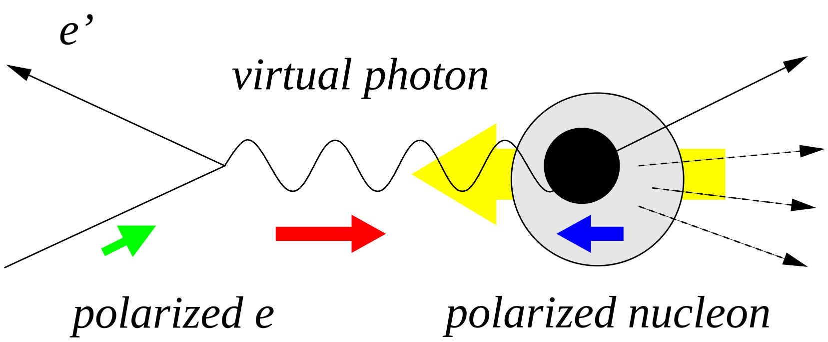
$\Rightarrow$ Light sea quarks have significant polarization, but with $\Delta\overline{u} \simeq -\Delta\overline{d}$.

Goeke et al, hep-ph/0003324



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

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

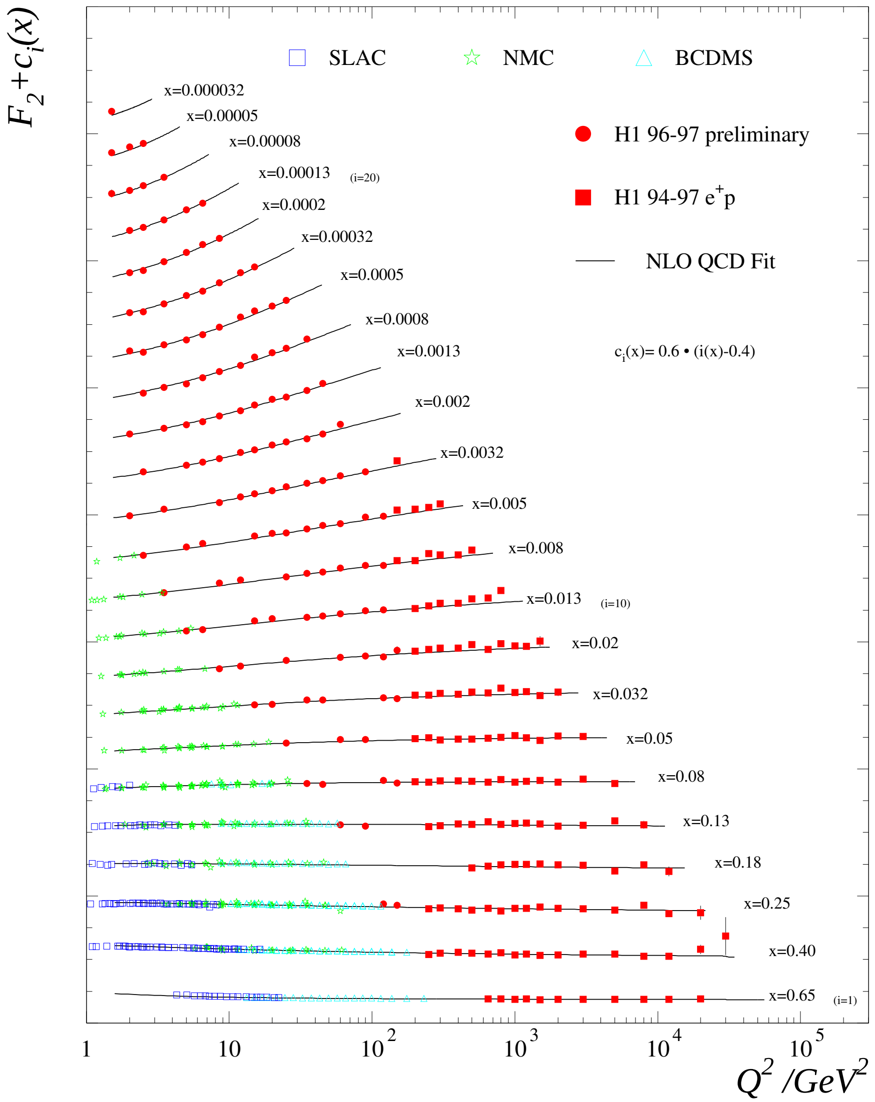
Using g_1 measurements on both proton and neutron (deuterium) targets, one can *in principle* separate these polarized PDF's:

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

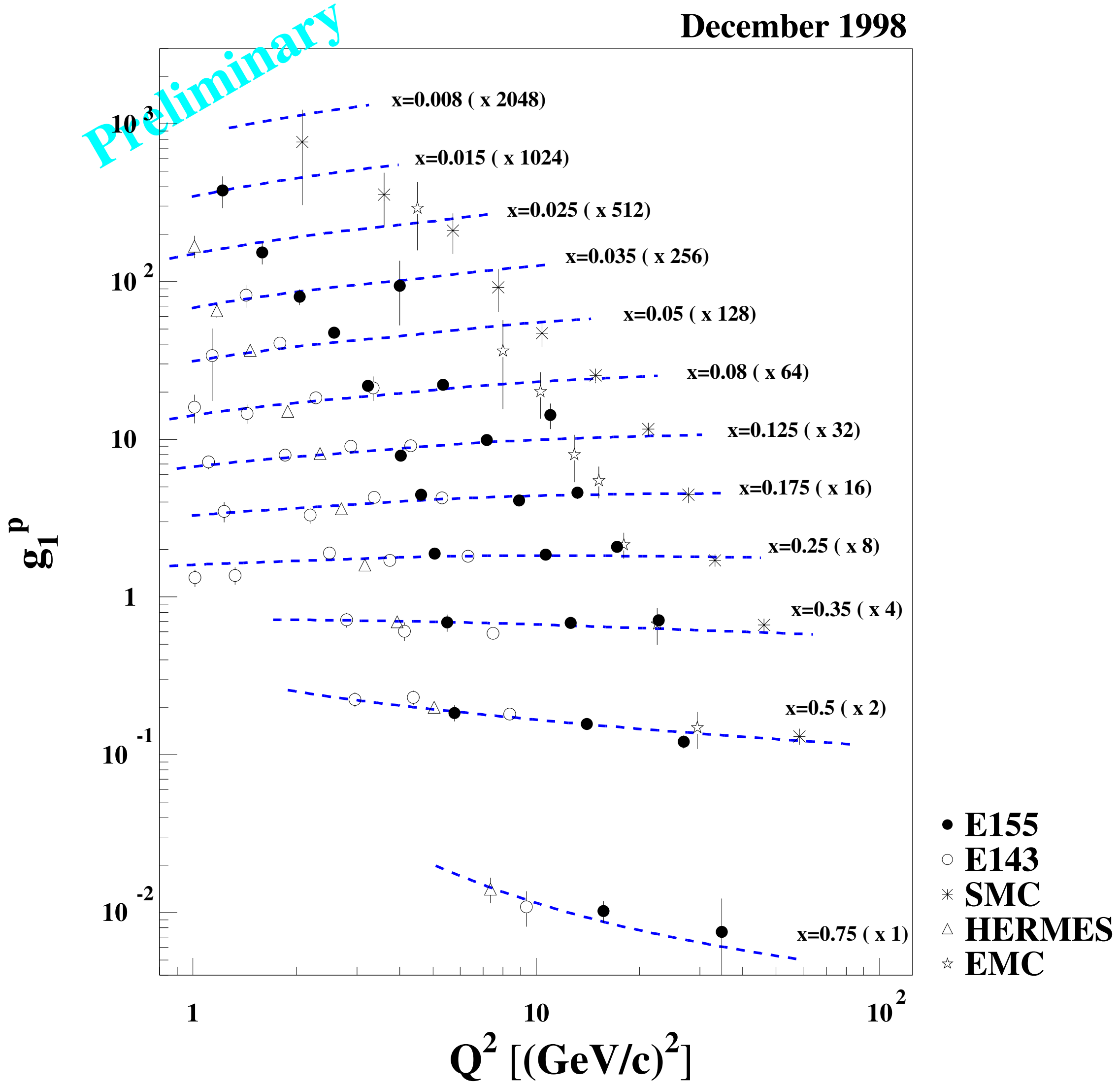
by exploiting the different Q^2-dependent behaviour of each term.

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:

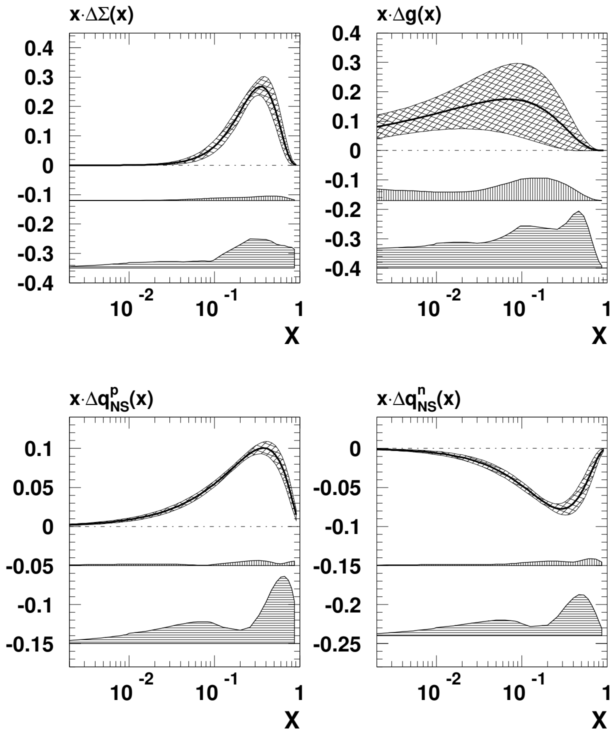
$$\int dx\, [\frac{1}{2}\Delta\Sigma(x) + \Delta g(x)] = \frac{1}{2} - L$$

- 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

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

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

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

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.

A New Probe is needed ...

• Given the limited range and precision of present $g_1(x, Q^2)$ measurements, one would like

a direct measurement of $\Delta g(x, Q^2)$

• To avoid dependence on F, D values, and associated assumption of SU(3) symmetry, one would like

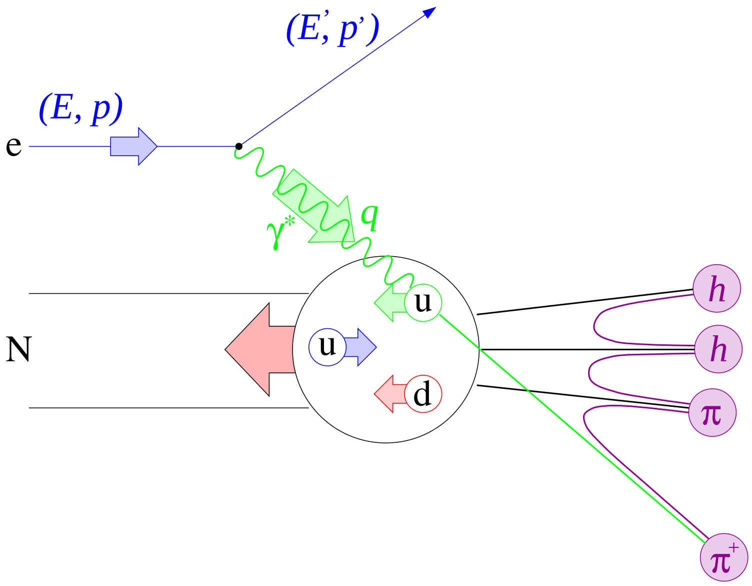
a direct measurement of $\Delta s(x, Q^2)$

• Inclusive measurements are sensitive only to e_i^2, not to e_i, and thus a new probe is needed to

separate quark and anti-quark polarizations

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:

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

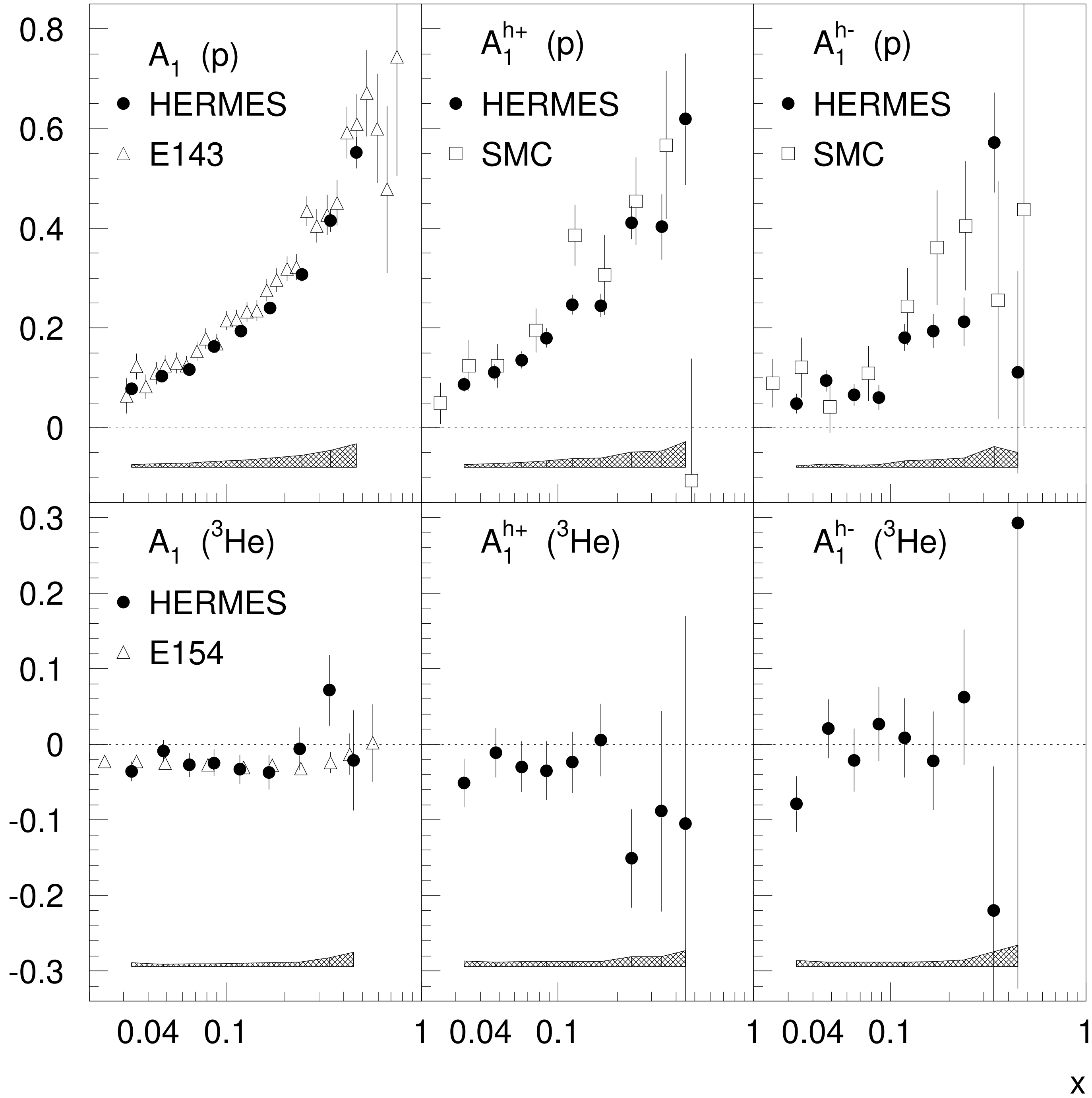
Can rewrite in terms of a **purity matrix** :

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

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

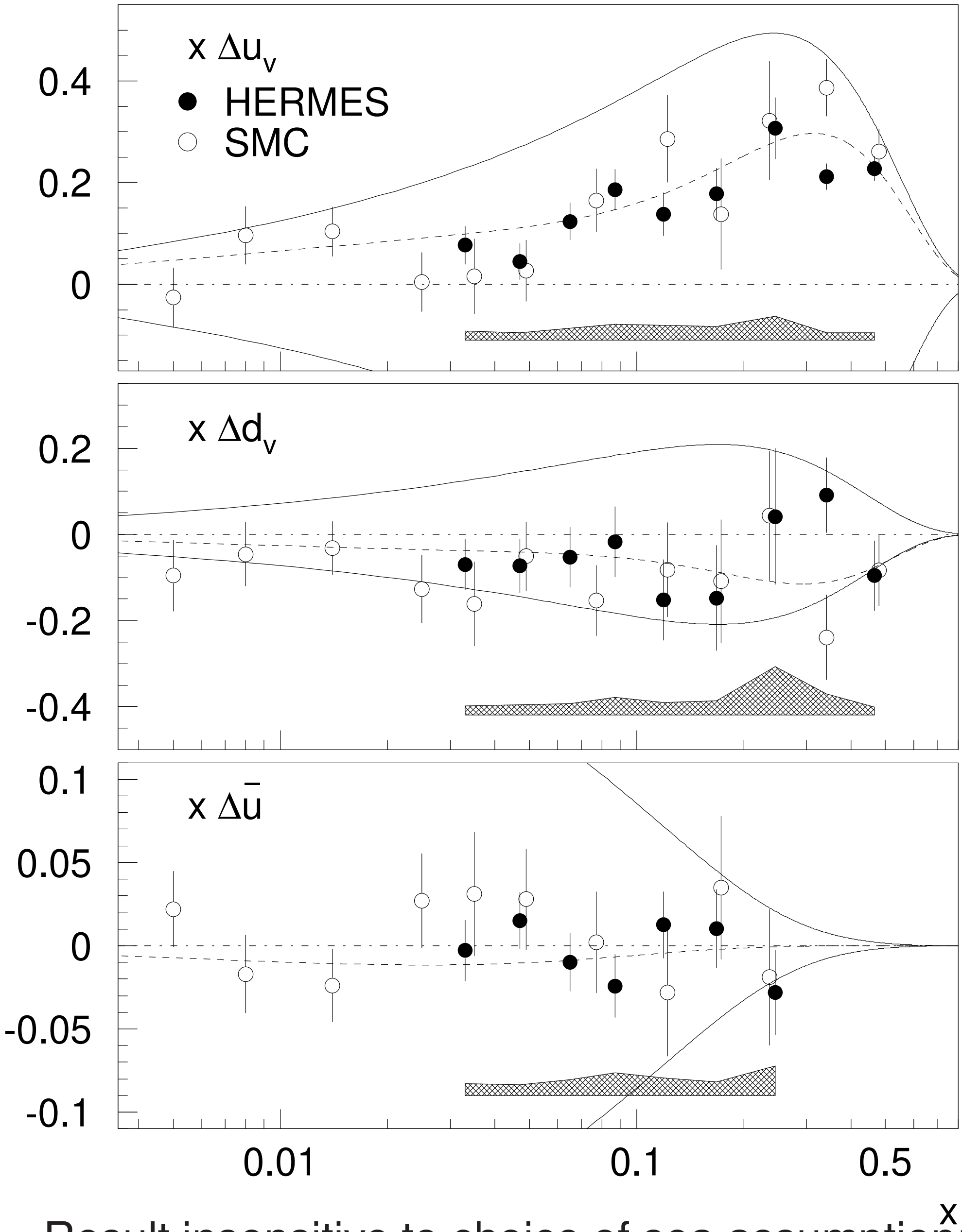
Semi-Inclusive Asymmetries

Asymmetries collected so far ...



Data given at mean Q^2 of each x. Error bars of HERMES (SLAC and SMC) are statistical (total) uncertainties. Bands are HERMES systematic error. Inclusive results compared to SLAC g_1/F_1.

Quark Polarizations at LO



HERMES, PL B464 ('99) 123

First moments at
$Q^2 = 2.5$

$\Delta\Sigma =$
$0.30 \pm 0.04 \pm 0.09$

$\Delta q_s =$
$-0.01 \pm 0.03 \pm 0.03$

- Result insensitive to choice of sea assumption:

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

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

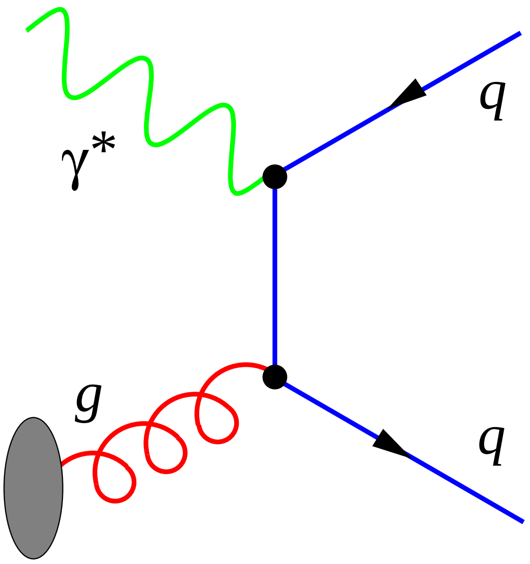
- Agreement with Gehrmann, Stirling fit to inclusive data (Gluon A, LO)
- Conclusion must await HERMES ^{2}D data set $\rightarrow$ DIS 2001

Gluon Polarization

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

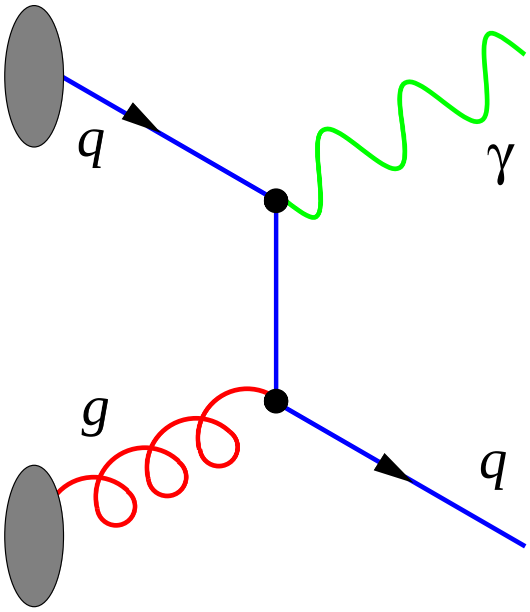
For direct measurement of ΔG, must measure some process dominated by scattering from gluons ...

In ep experiments ...
Photon-gluon fusion



- charm production
- high-p_T hadron pairs

In pp experiments ...
Direct γ production



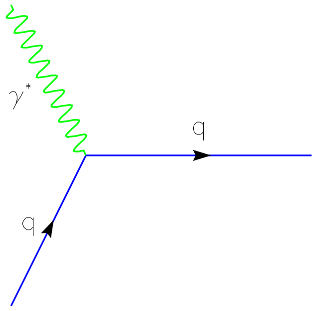
- $\vec{p} + \vec{p} \to \gamma + jet + X$

HERMES: measure asym of pairs of hadrons at high p_T

- require at least **two hadrons of opposite charge**
- do not require scattered e^+ in spectrometer
  $\Rightarrow$ **photoproduction** ($Q^2 \simeq 0$)
- require $M(2\pi) > 1.0$ GeV/c^2 to remove ρ and ϕ resonances

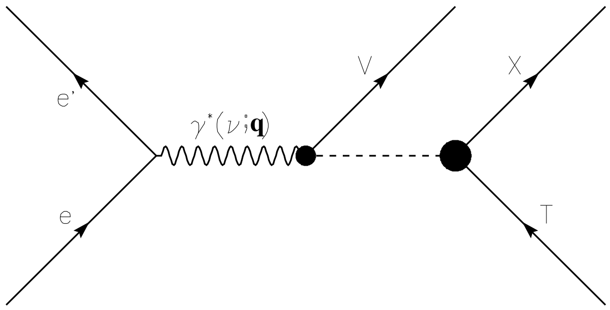
Contributions to $\vec{\gamma}\vec{p} \rightarrow h^+h^-X$

Assume four different processes may contribute:



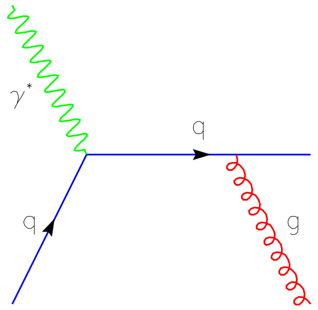
DIS

negligible contribution



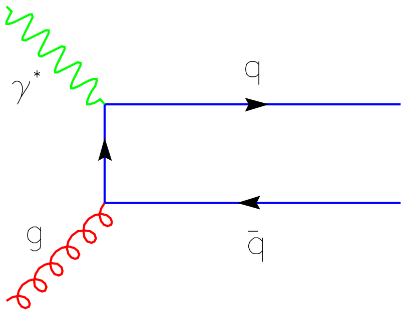
VMD

assume $A_{\mathrm{VMD}} = 0$



QCDC

$A_{\mathrm{QCDC}} \sim 0.5\,\frac{\Delta q}{q}$

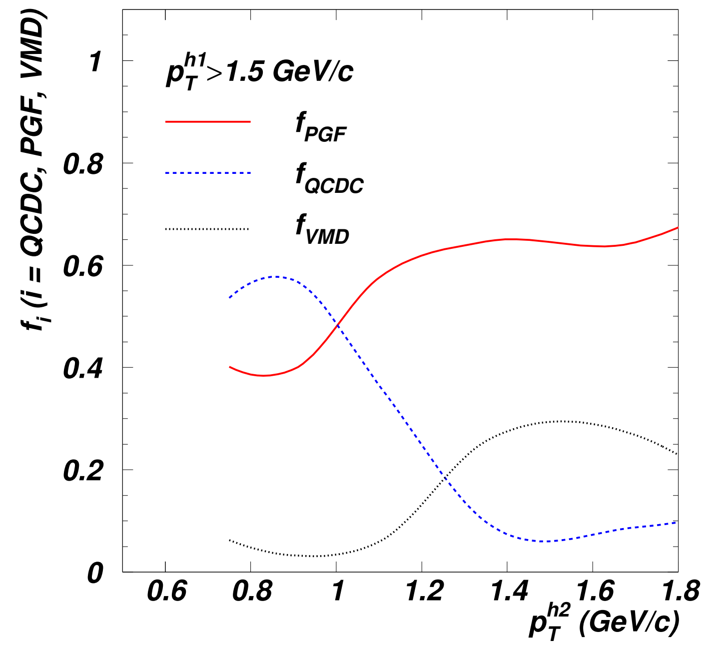


PGF

$A_{\mathrm{PGF}} \sim -\frac{\Delta G}{G}$

... estimate their relative contributions using PYTHIA

$\rightarrow$ extract $\Delta G/G$



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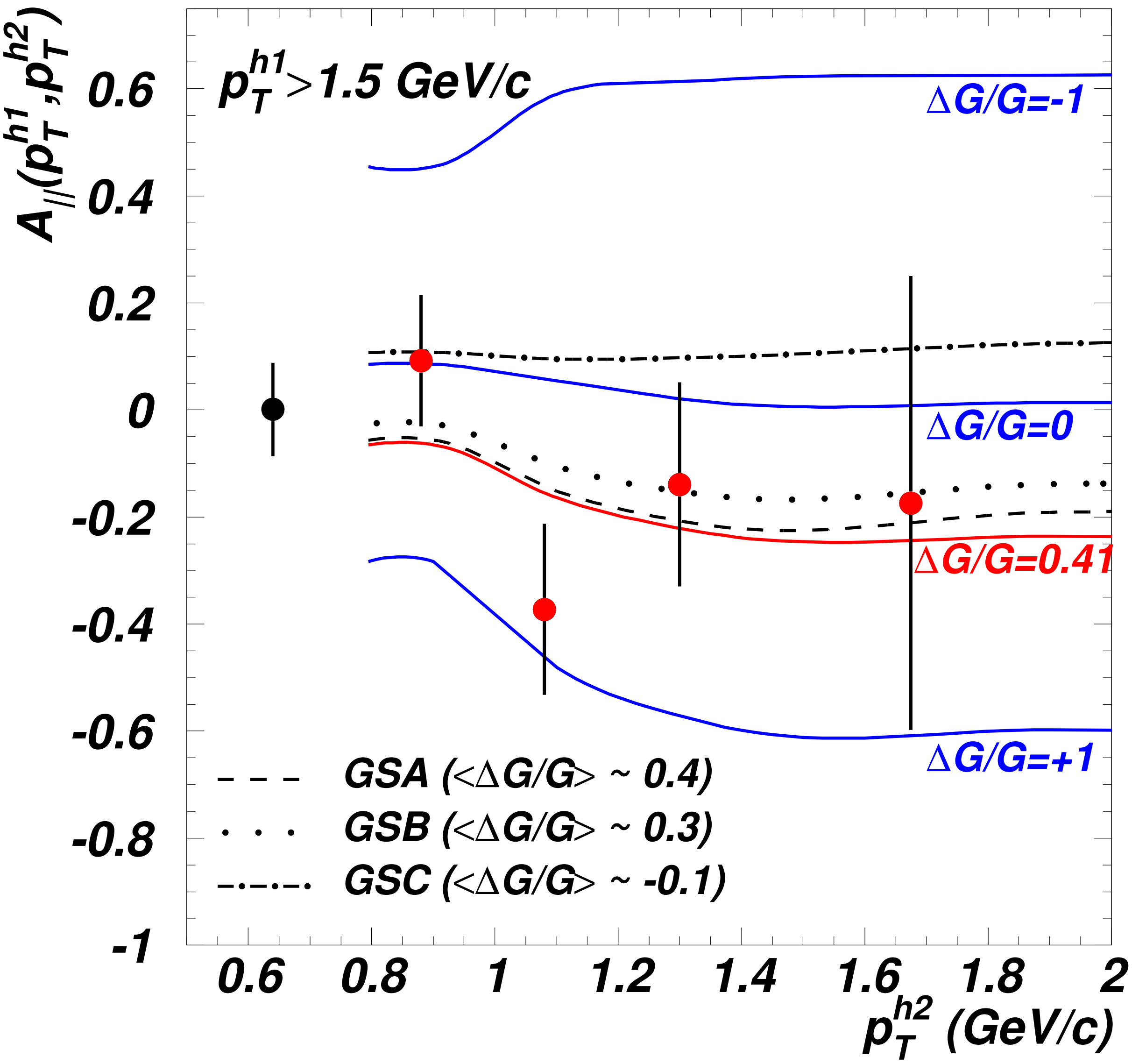
Result Using PYTHIA Model

$$\Delta G/G = 0.41 \pm 0.18\text{(stat)} \pm 0.03\text{ (exp. syst)}$$

at $\langle x_G \rangle = 0.17$ and $\langle \hat{p}_T^2 \rangle = 2.1$ GeV/c^2

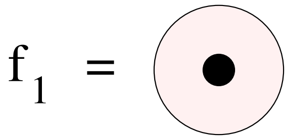
HERMES, PRL 84 (2000) 2584

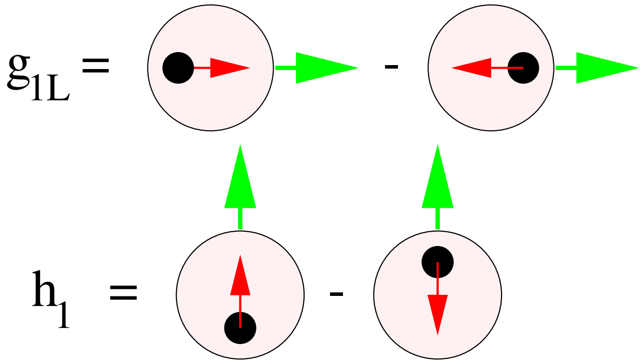


Unknown theoretical uncertainty from contribution and spin asymmetry of anomalous photon and NLO QCD corrections. If only a dilution, value of $\Delta G/G$ will increase but significance of deviation from zero will not change.

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

Features of $h_1(x)$:

- in the absence of relativistic and spin-orbit effects,
$$\delta q(x) = \Delta q(x)$$
- unlike for g_1, the gluon polarization does not mix with quark polarization in h_1 $\rightarrow$ different Q^2 evolution
- h_1 predominantly sensitive to valence quark polarization
- first moment of h_1 = tensor charge of the nucleon $\rightarrow$ possible comparison with lattice QCD
- $h_1(x)$ is a chiral-odd distribution function, related to spin flip of transversely polarized quark

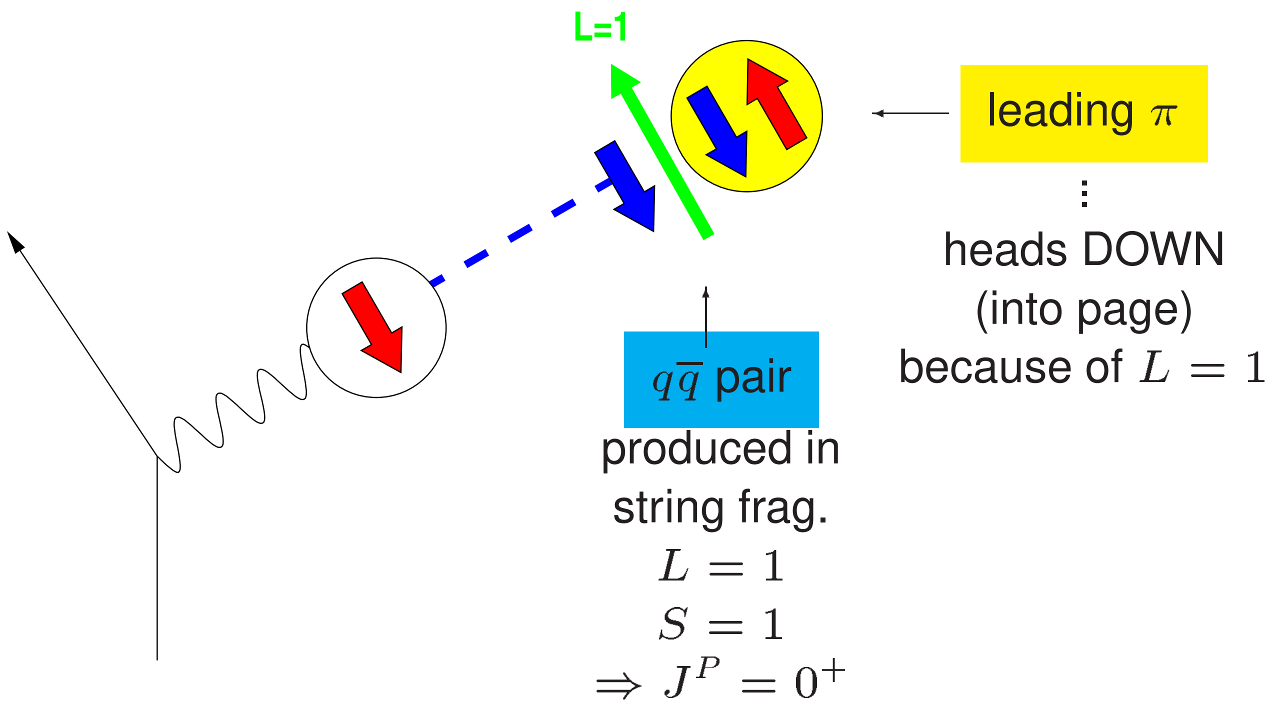
Measurement approach:

Transversity is inaccessible in inclusive DIS, but can be probed via azimuthal distributions in polarized semi-inclusive DIS, especially from a transversely polarized target.

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



Azimuthal angles with respect to lepton scattering plane

hadron (e.g. π)	$\phi_h^l = -\pi/2$
final q spin S'	$\phi_{S'}^l = 0$
initial q spin S	$\phi_S^l = \pi$

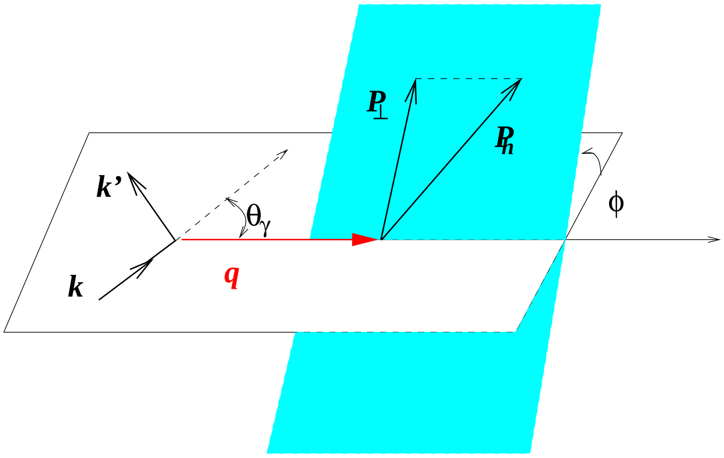
Collins Angle

$$\phi_c = \phi_h - \phi_{S'} = \phi_h + \phi_s - \pi = -\pi/2 \text{ here}$$

$$\langle \frac{Q_T}{M_h} \sin\phi_c \rangle \sim -h_1(x) \cdot H_1^{\perp}(z)$$

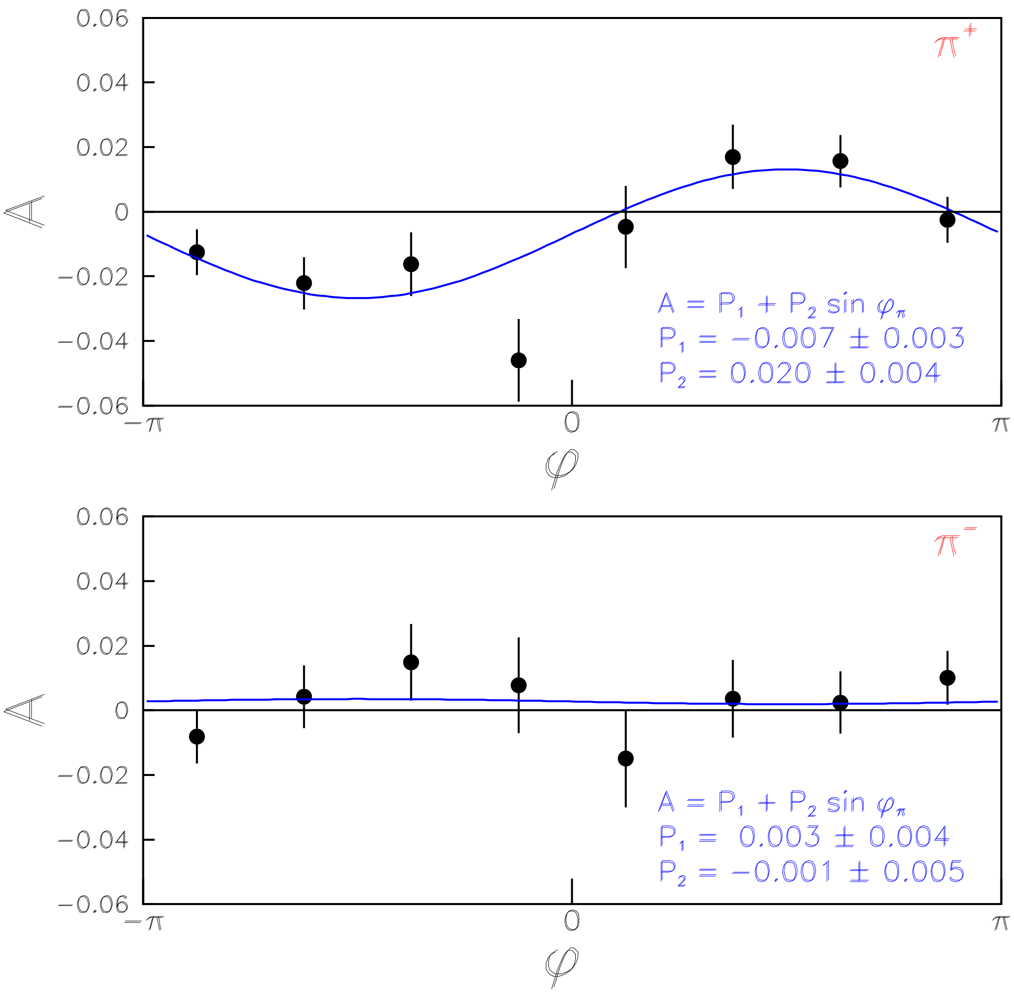
Spin-Azimuthal Asymmetry

Consider distribution of pions in angle ϕ = azimuthal angle of pion relative to lepton scattering plane, around the q vector.



Longitudinal target single-spin asymmetry:

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

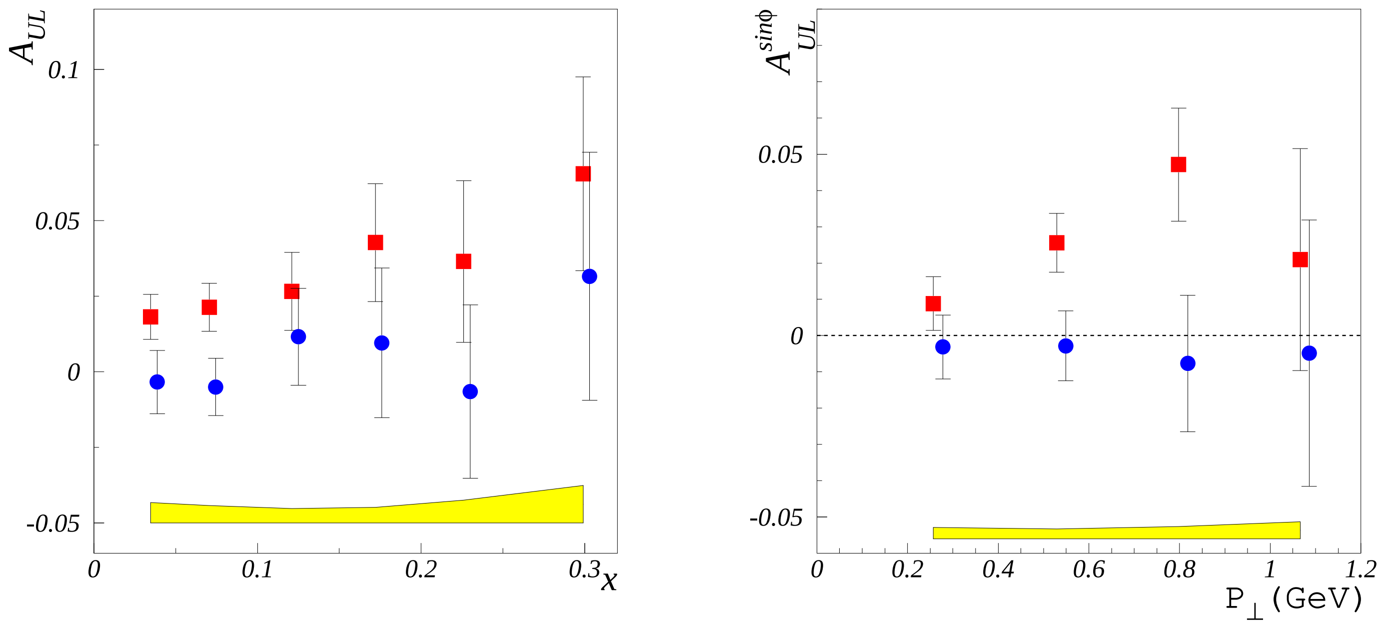


$A_{UL}^{\sin\phi}$ Behaviour

$A_{UL}^{\sin\phi} = \langle \sin\phi \rangle$ 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

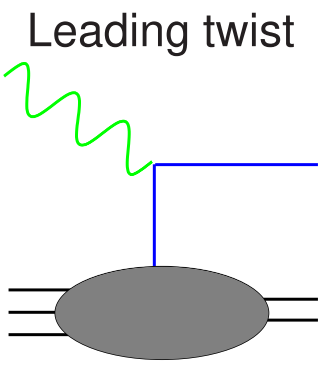
- Effect should peak at $x \simeq 0.3$ (valence region)
- Effect should be stronger for π^+ than π^- (u-quark dominance)
- Effect should grow with p_T and peak at $p_T \simeq 1$ GeV/c

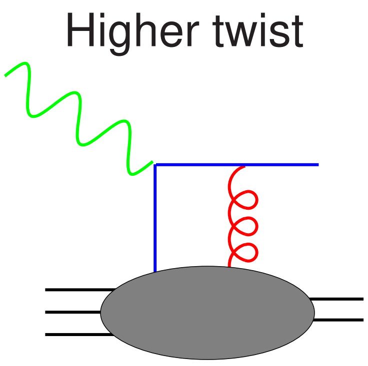
Future Measurements of Transversity

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.

Higher Twist

Origin of higher twist is the Operator Product Expansion ... higher twist effects ('power corrections') become important at low Q^2:





Physics at Low Q^2

- Higher twist not significant? $\Rightarrow$ perturbative analyses remain simple.
- Higher twist significant? $\Rightarrow$ sensitivity to quark-gluon **correlations** in the nucleon wavefunction.

A step in complexity beyond the naive picture of collinear non-interacting quarks

New data concerning higher twist

- The ratio $g_1(x,Q^2)/F_1(x,Q^2)$ seems insensitive to higher twist
  $\rightarrow$ new results from HERMES at low x, low Q^2
- The Gerasimov-Drell-Hearn integral relates spin properties at $Q^2 = 0$ (low-energy theorems) to those at $Q^2 \rightarrow \infty$ (pQCD).
  $\rightarrow$ new results from MAINZ, HERMES, JLAB
- The spin structure function $g_2(x,Q^2)$ is expected to be particularly sensitive to higher twist
  $\rightarrow$ new results from SLAC E155x

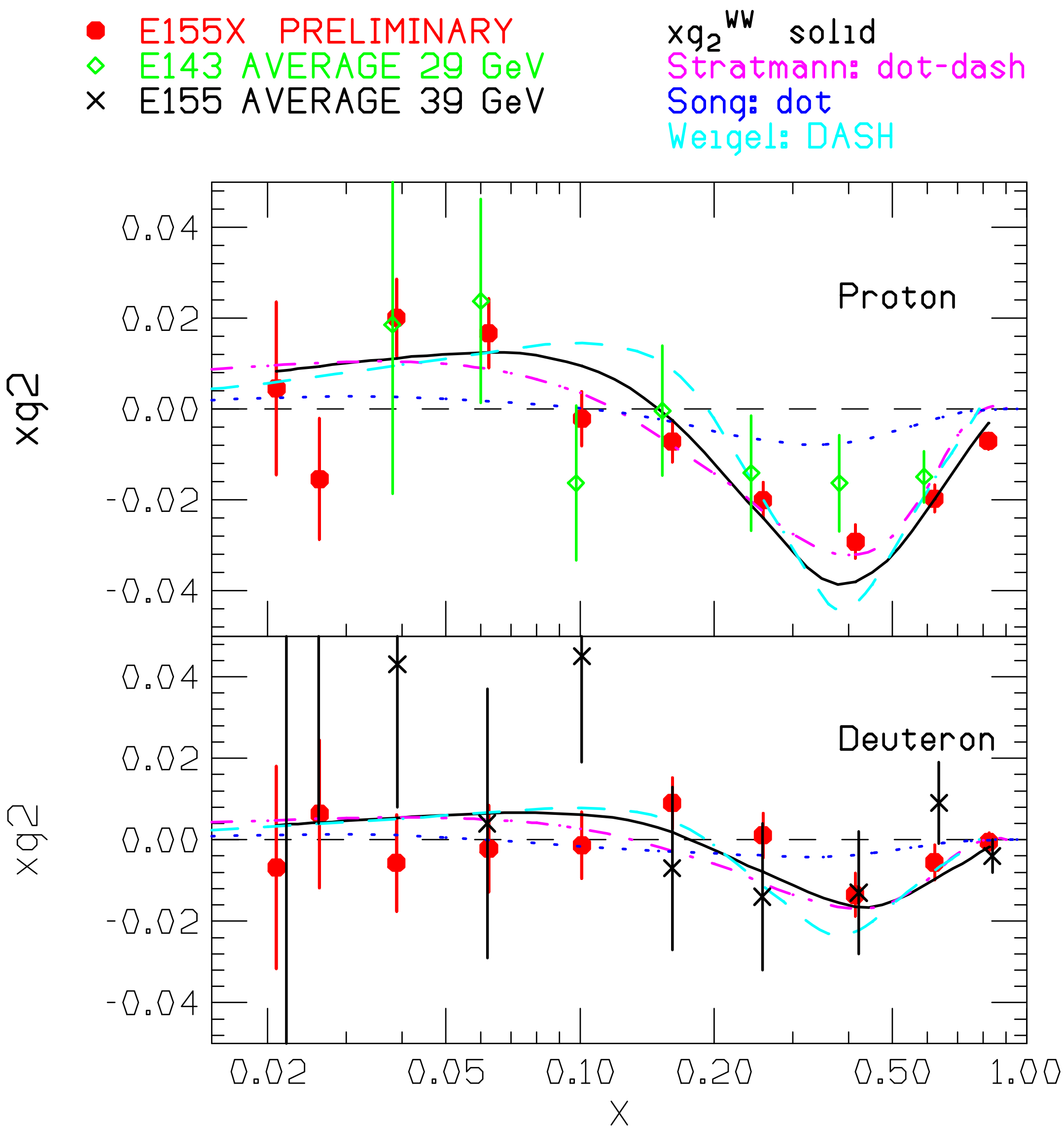
New Results from E155x

Wandzura-Wilczek relation describes **twist-2 part of g_2** :

$$g_2^{\mathrm{WW}}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_1(x,Q^2)$$

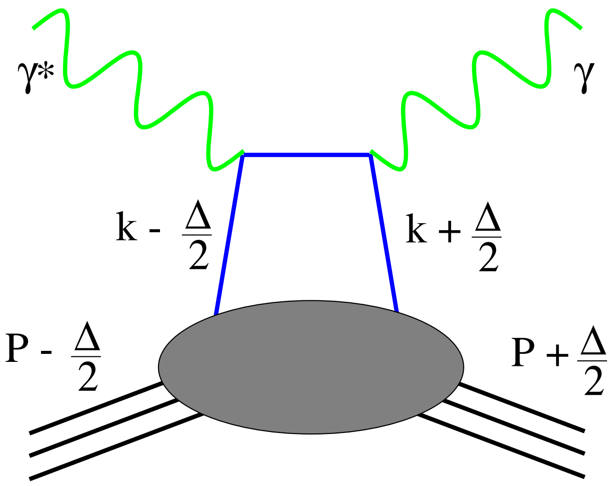
Deviations from this would indicate **higher twist** effects.

Results for Q^2-averaged g_2^p, g_2^d



Skewed Parton Distributions

Analysis of **hard exclusive processes** leads to a new class of parton distributions. Simplest example is Deeply Virtual Compton scattering:



On the lightcone:

$$x \equiv k^+/P^+$$
$$\xi \equiv -\Delta^+/2P^+$$
$$t \equiv \Delta^2$$

$\Delta \neq 0 \rightarrow$ **correlations**

$$\langle P'S'|\overline{\psi}(-\frac{y}{2})\gamma^\alpha\psi(\frac{y}{2})|PS\rangle \quad \Rightarrow \quad H(x,\xi,t),\, E(x,\xi,t)$$

$$\langle P'S'|\overline{\psi}(-\frac{y}{2})\gamma^\alpha\gamma_5\psi(\frac{y}{2})|PS\rangle \quad \Rightarrow \quad \tilde{H}(x,\xi,t),\, \tilde{E}(x,\xi,t)$$

Connection with **DIS structure functions** : forward limit

$$q(x) = H^q(x, \xi = 0, t = 0), \qquad \Delta q(x) = \tilde{H}^q(x, \xi = 0, t = 0)$$

Connection with **elastic form factors** : first moments

$$G_M(t) = \int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t) + E^q(x,\xi,t)\right]$$

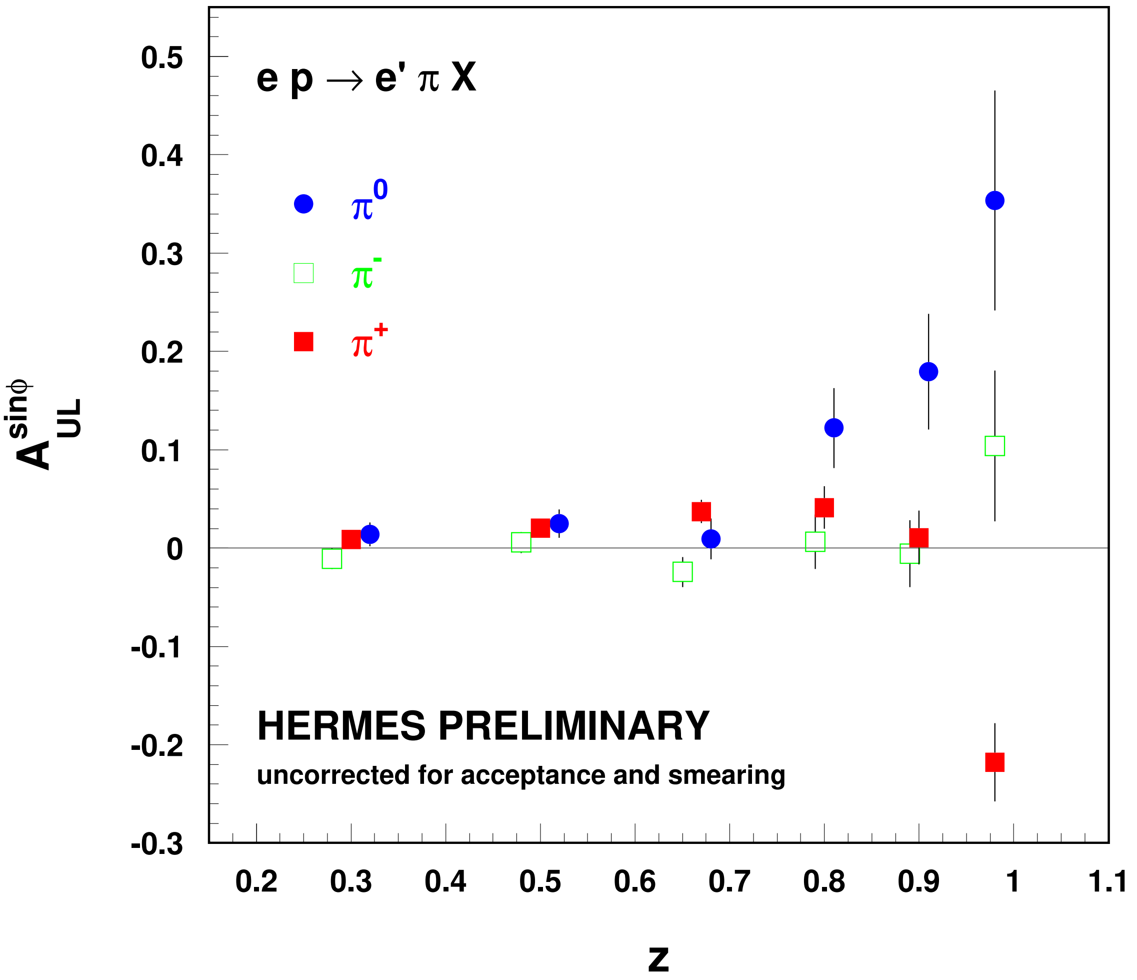
$$G_E(t) = \int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t) + \frac{t}{4M^2}E^q(x,\xi,t)\right]$$

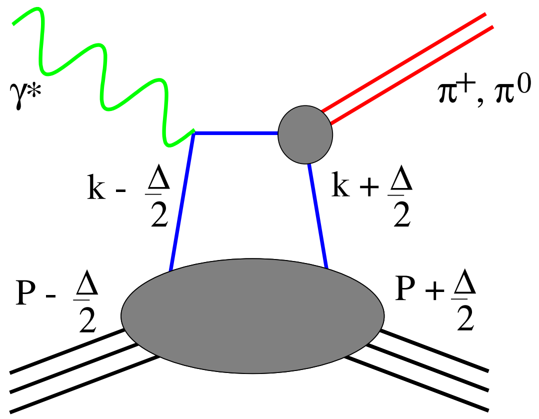
Connection with **quark angular momentum** : second moments

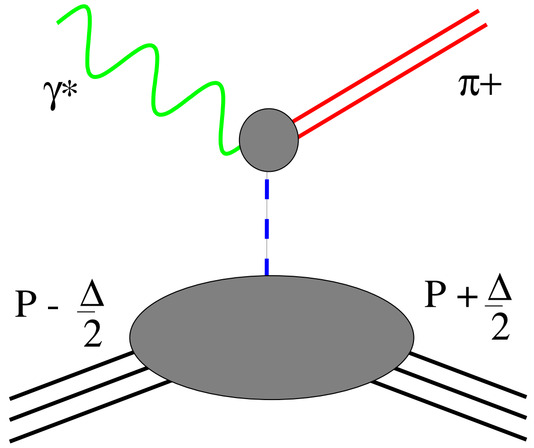
$$J^q = \frac{1}{2}\Delta\Sigma + L^q = \frac{1}{2}\int_{-1}^{1} x\, dx\, \left[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right]$$

Exclusive Pion Production

First look at spin-azimuthal asymmetry $A_{UL}^{\sin\phi}$ for pion production on proton target, in the exclusive limit $z \to 1$:







N.C.R. Makins, DIS 2000

Spin Physics: Prospects

New data being collected ...

- **HERMES** : high-statistics data on ^{2}D, with RICH detector
  $\Rightarrow$ quark and gluon polarization
- **JLAB** : high-statistics spin-structure data at low Q^2 and in the resonance region
- **MAINZ** : higher-energy data on the GDH integral at Q^2 = 0

Exciting results from these experiments may be expected at DIS 2001!

Starting in 2001 ...

Three experiments will begin data taking in 2001. All three will explore quark and gluon polarizations, and transversity, in **complementary** kinematic regions.

- **HERMES Run 2** : Transverse target program
  $\Rightarrow$ focus on transversity
- **COMPASS** : SMC' with higher luminosity and upgraded detector
  $\Rightarrow$ focus on ΔG, via open charm and high-p_T hadron pairs
- **RHIC-SPIN** : high energy $\vec{p}\,\vec{p}$ collisions
  $\Rightarrow$ focus on ΔG, via direct γ production