The Structure of the Nucleon

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APS Spring Meeting
Washington D.C., USA
Apr 28 - May 1, 2001

Flavour and Spin

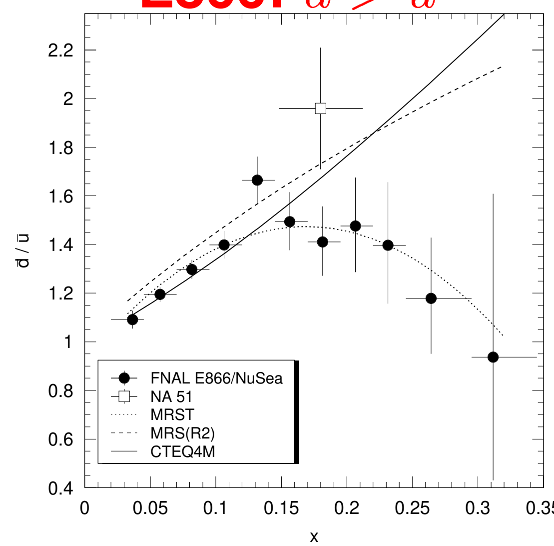
- Some Phenomenological Models
- Quark Polarization
- Gluon Polarization

New Directions

- Off-Forward Parton Distributions:
  Correlations and Angular Momentum
- Transverse Spin: Transversity and the Collins Effect

Phenomenological Models: Flavour

E866: $\overline{d} > \overline{u}$



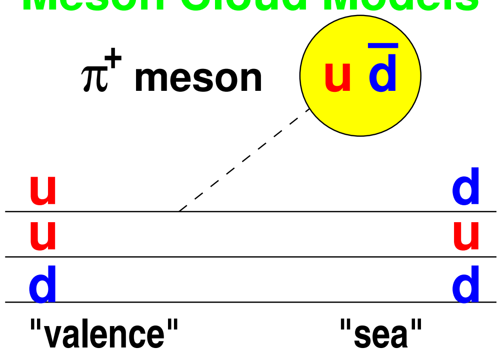
Constituent Quark Model

Pure valence description: proton = 2 u + d
$\rightarrow$ only degrees of freedom necessary to describe hadronic spectrum

Perturbative Sea Sea quark pairs from $g \rightarrow q\overline{q}$ should be flavour symmetric: $\overline{u} = \overline{d}$

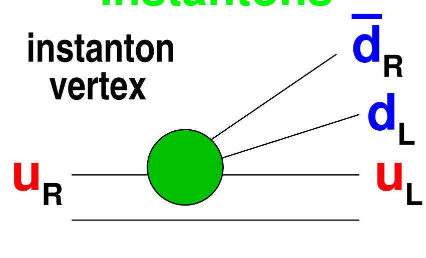
Non-perturbative models : alternate degrees of freedom

Meson Cloud Models



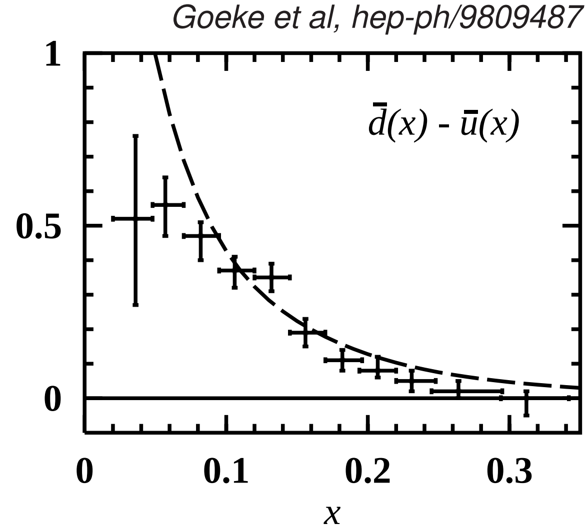
Quark sea generated by cloud of pseudoscalar mesons. $\Rightarrow \overline{d} > \overline{u}$

Instantons



Vertex $\sim \overline{u}_R u_L \overline{d}_R d_L \Rightarrow \overline{d} > \overline{u}$

Goeke et al, hep-ph/9809487



Large N_c Limit and the Chiral-Quark Soliton Model

Nucleon = chiral soliton in pion field.

$$\overline{d} + \overline{u} \sim N_c^2$$
$$\overline{d} - \overline{u} \sim N_c \qquad \Rightarrow \text{predict } \overline{d} > \overline{u}$$

Spin Structure of the Proton

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

"You think you understand something? Now add spin ..." – *R. Jaffe*

Non-relativistic Quark Model

Pure valence description of consituent quarks:

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

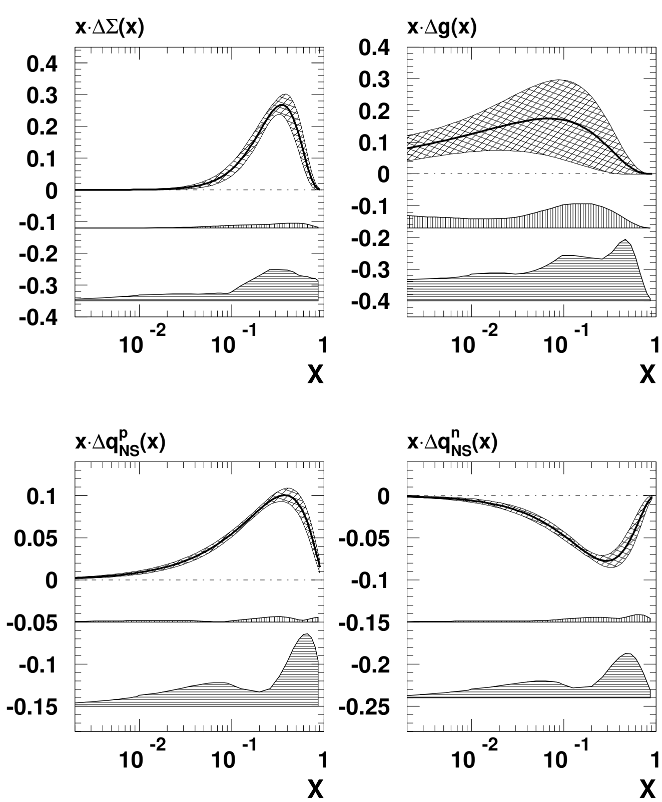
Relativistic Quark Model

Jaffe, Manohar, NP B337 (1990) 509

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

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

From inclusive experiments ...



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

SMC, PRD 58 (1998) 112002

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

$$\Delta\Sigma_{(\mathrm{AB})} = 0.38 \begin{smallmatrix} +0.03 \\ -0.03 \end{smallmatrix} \begin{smallmatrix} +0.03 \\ -0.02 \end{smallmatrix} \begin{smallmatrix} +0.03 \\ -0.05 \end{smallmatrix}$$

$$\Delta g_{(\mathrm{AB})} = 0.99 \begin{smallmatrix} +1.17 \\ -0.31 \end{smallmatrix} \begin{smallmatrix} +0.42 \\ -0.22 \end{smallmatrix} \begin{smallmatrix} +1.43 \\ -0.45 \end{smallmatrix}$$

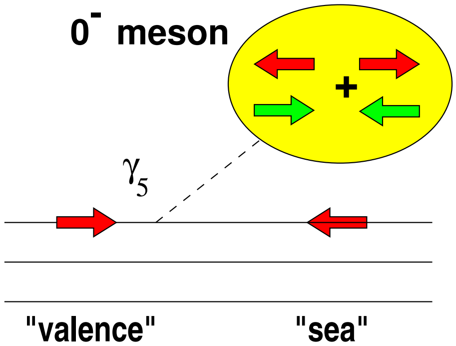
$$\Delta s = -0.02 \rightarrow -0.15 \pm 0.02$$

depending on SU(3) symmetry assumptions

Phenomenological Models: Anti-quark Spin

Meson Cloud Models

Li, Cheng, hep-ph/9709293



Quark sea generated by cloud of *pseudoscalar* mesons.

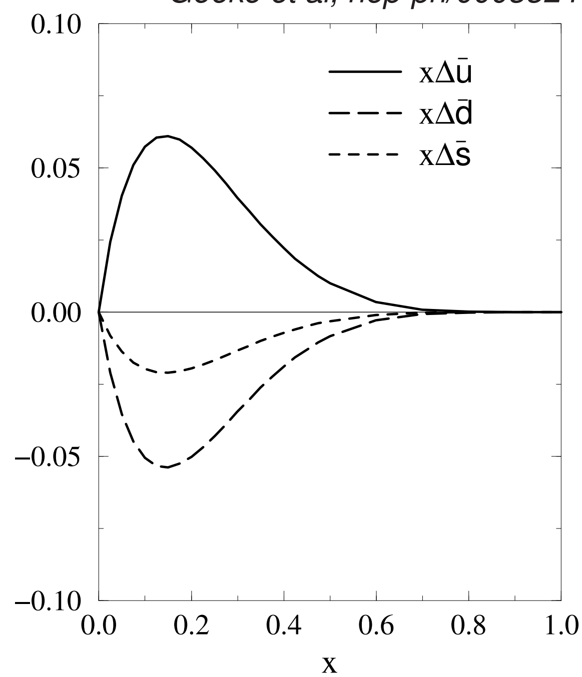
$\rightarrow \Delta q_{valence} > 0$

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

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

Large N_c Limit and the Chiral-Quark Soliton Model

Goeke et al, hep-ph/0003324

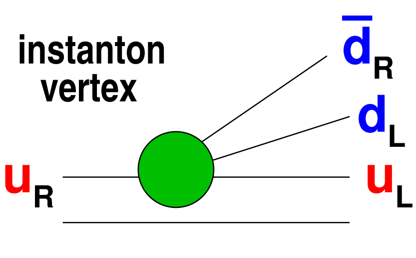


Nucleon = chiral soliton in pion field.

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

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

Instanton Mechanism



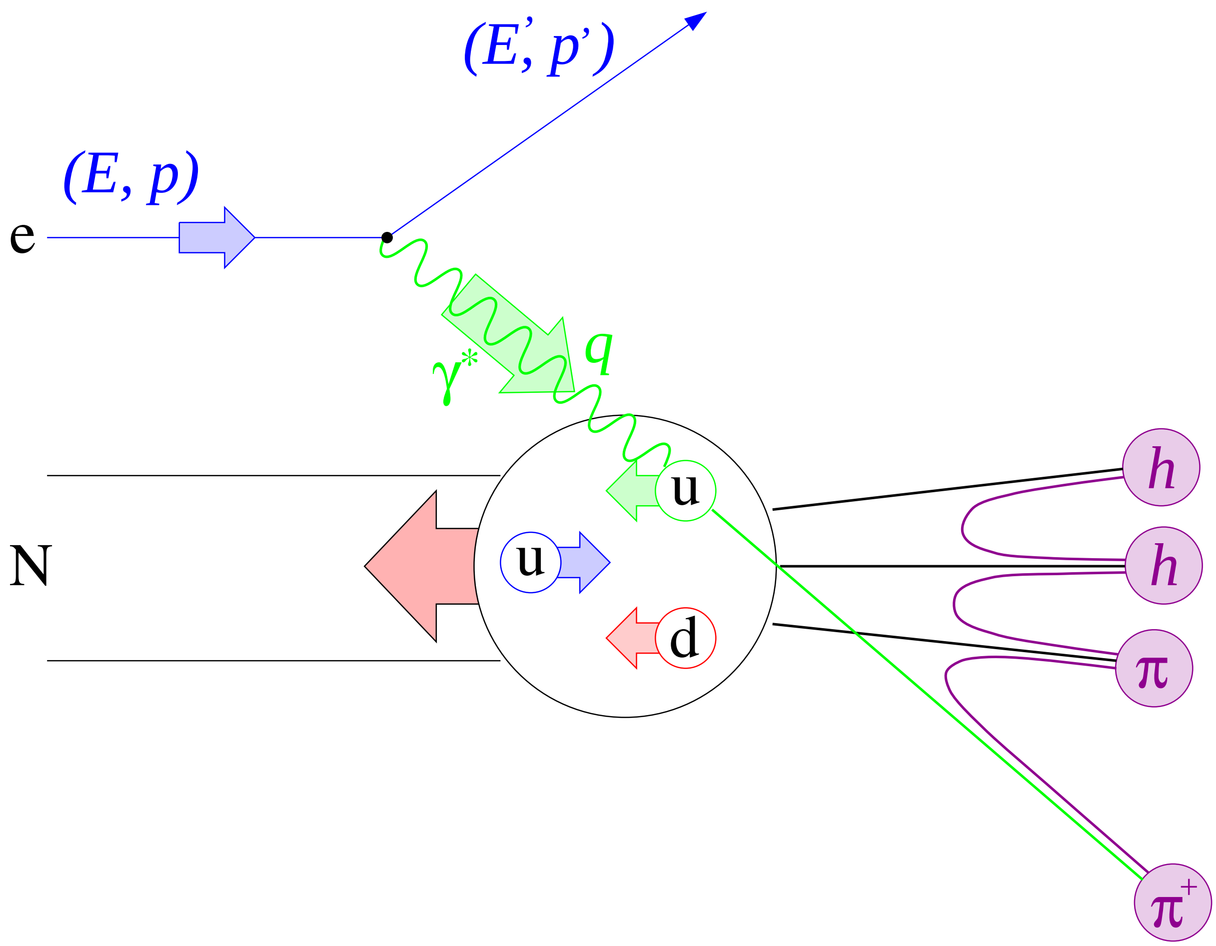
t'Hooft instanton vertex $\sim \overline{u}_R u_L \overline{d}_R d_L$ transfers helicity from valence u quarks to $d\overline{d}$ pairs of sea quarks.

$\Rightarrow \Delta\overline{d} > 0, \quad \Delta\overline{u} < 0$?

No such calculation performed yet ...

Semi-Inclusive DIS

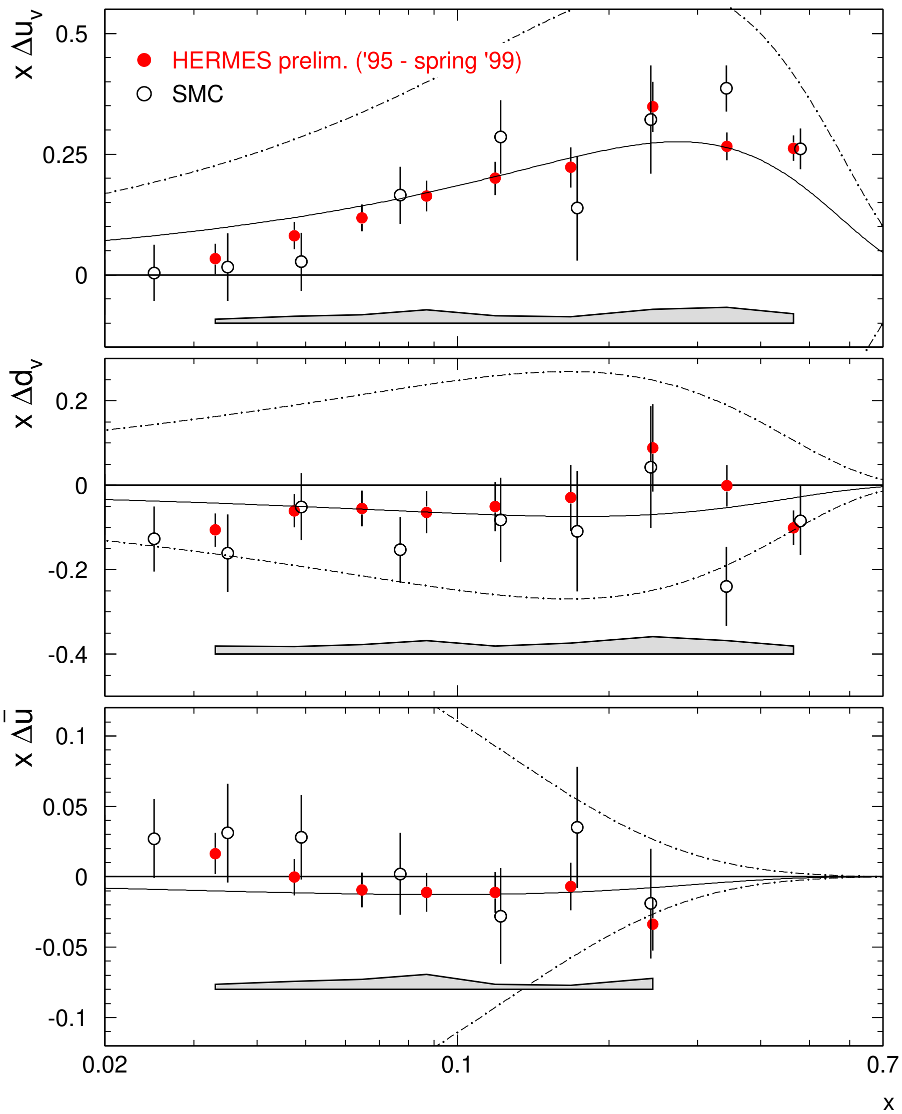
In semi-inclusive DIS a hadron h is detected in coincidence with the scattered lepton



Flavour Tagging:

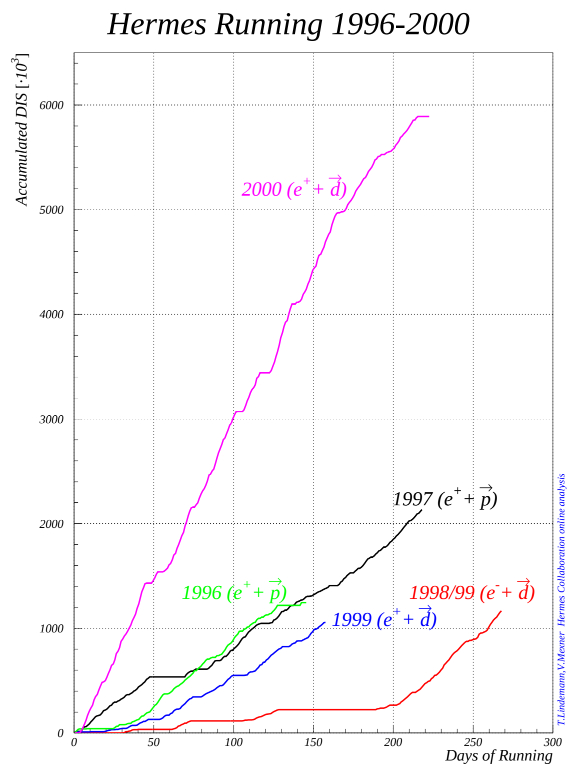
$\Rightarrow$ Determine polarizations of individual quark flavours

Quark Polarizations at LO



Not yet included ...

- **large 2000 data set** on Deuterium
- **Kaon asymmetries** from RICH detector $\rightarrow$ 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** :

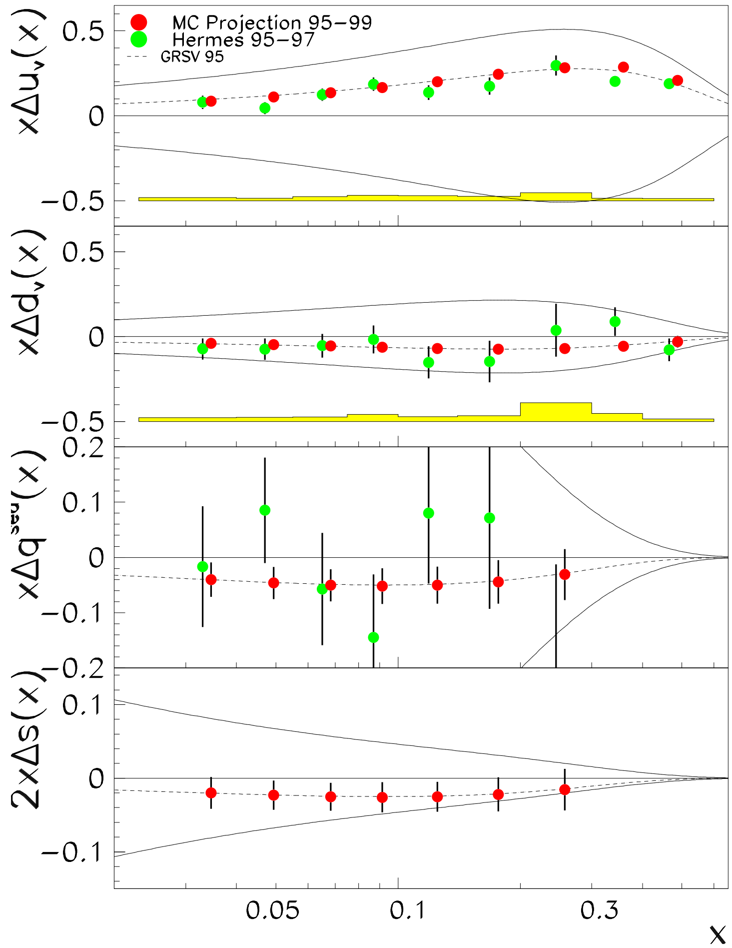
$$\frac{\Delta q_s}{q_s} \equiv \frac{\Delta u_s}{u_s} = \frac{\Delta d_s}{d_s} = \frac{\Delta s}{s} = \frac{\Delta \overline{u}}{\overline{u}} = \frac{\Delta \overline{d}}{\overline{d}} = \frac{\Delta \overline{s}}{\overline{s}}$$

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

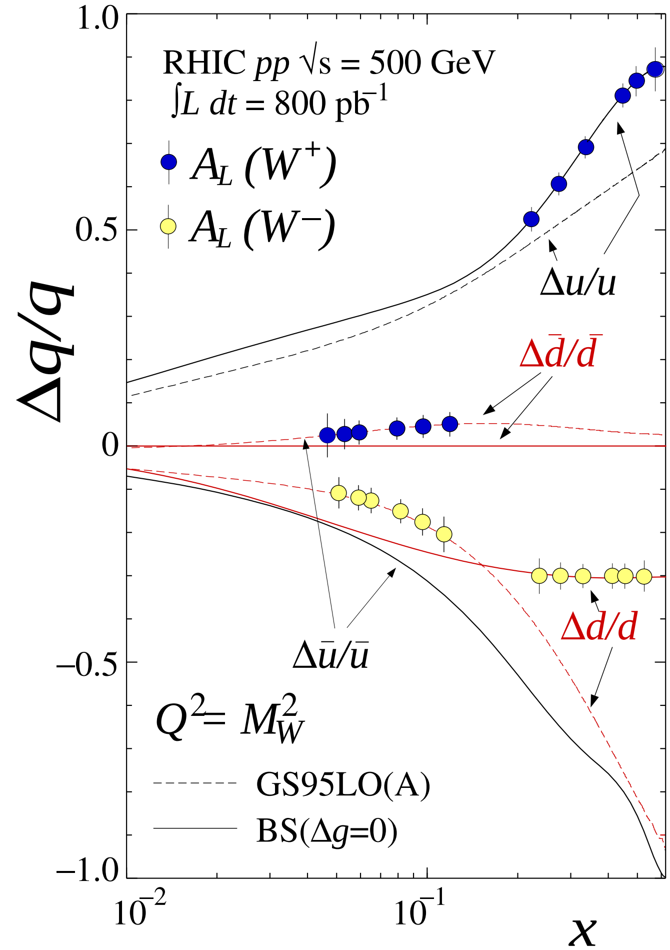
There are other possibilities ... 2000 data will permit 4- and 5-parameter fits

Quark Polarization: Future

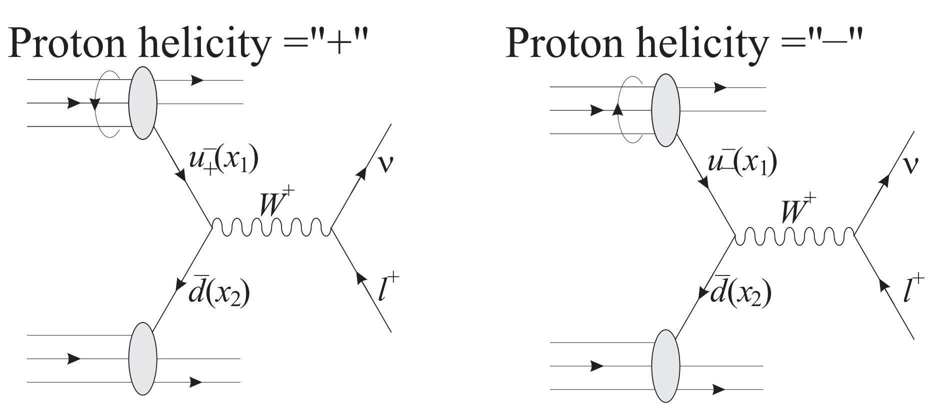
HERMES : data up to 2000



RHIC-spin : 2002 - ...



- Pion & Kaon asymmetries
  $\rightarrow$ Δs, $\Delta\bar{s}$ sensitivity
- Polarized W production
  $\rightarrow$ $\Delta\bar{u}$ vs $\Delta\bar{d}$, $\Delta\bar{s}$ sensitivity



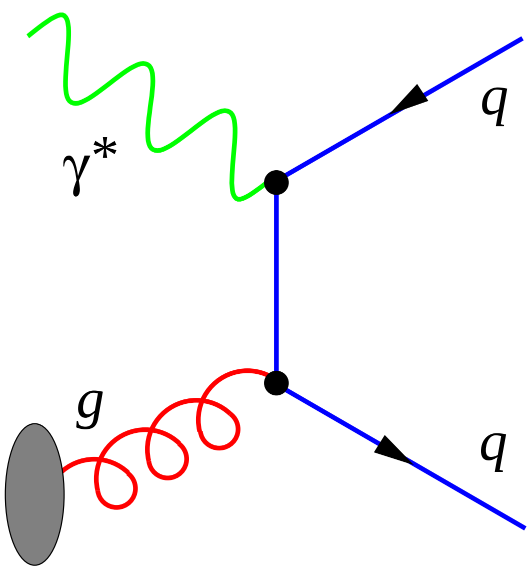
And further DIS data expected from COMPASS and HERMES Run II

Gluon Polarization

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

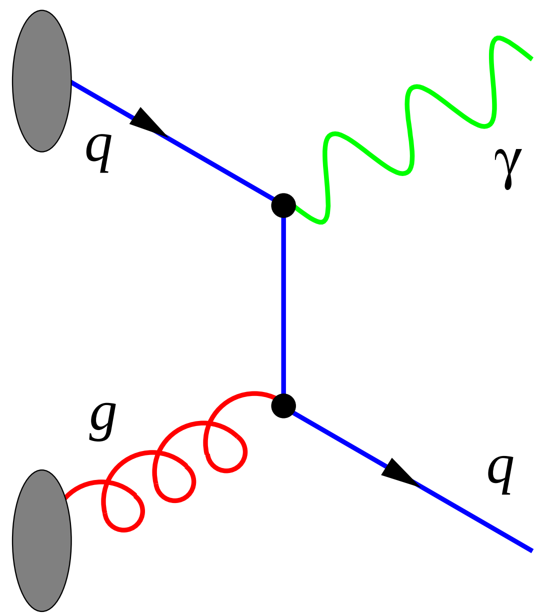
For direct measurement of ΔG, must measure some process dominated by scattering from gluons ...

In ep experiments ...
Photon-gluon fusion



- charm production
- high-p_T hadron pairs

In pp experiments ...
Direct γ production



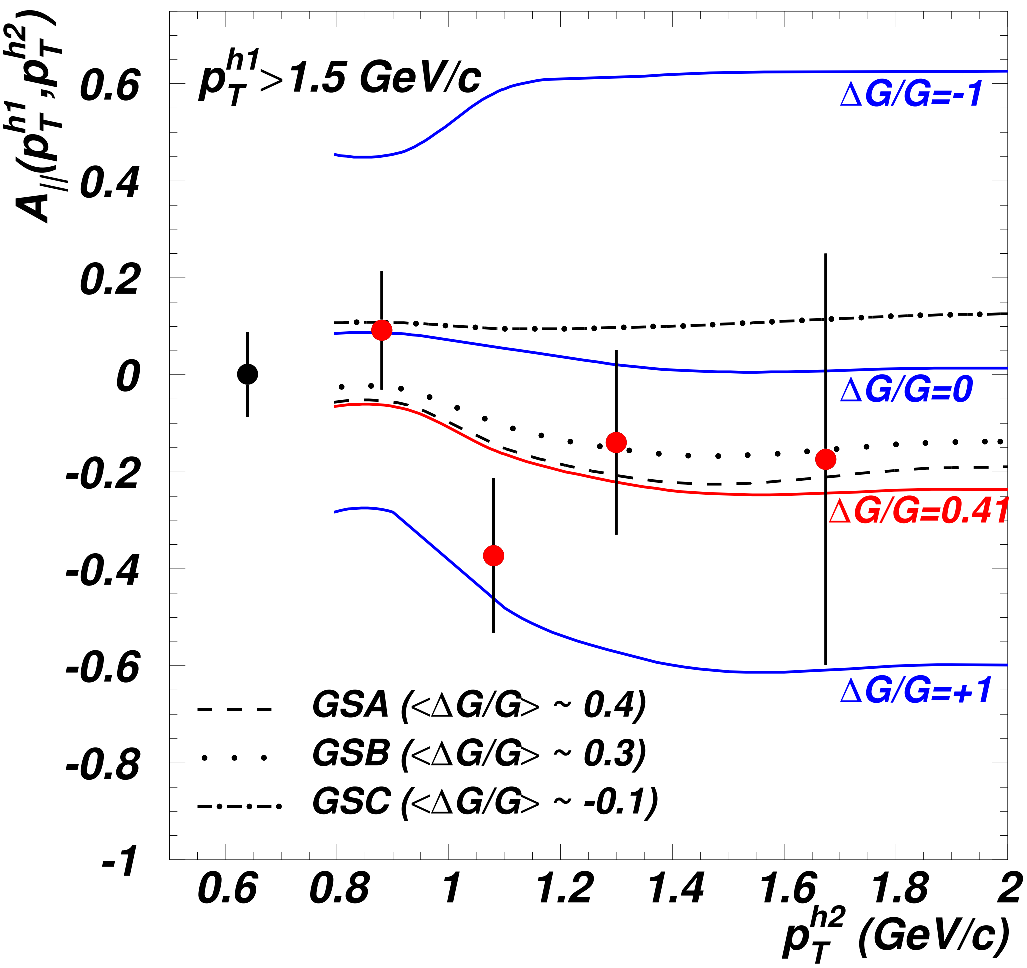
- $\vec{p} + \vec{p} \to \gamma + jet + X$

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

Result Using PYTHIA Model

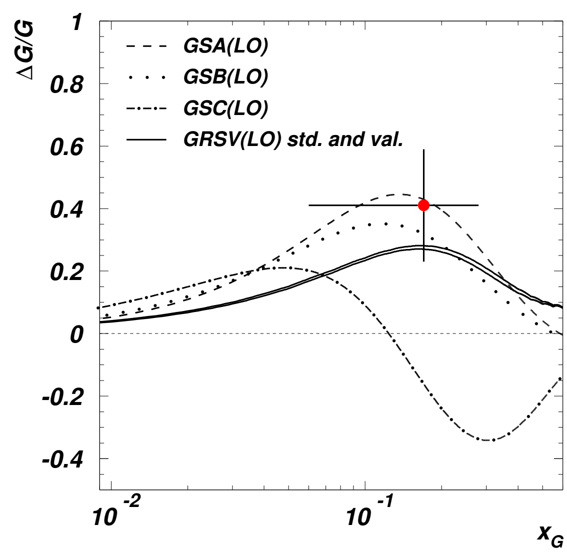
HERMES, PRL 84 (2000) 2584



In LO Pythia model ...

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

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

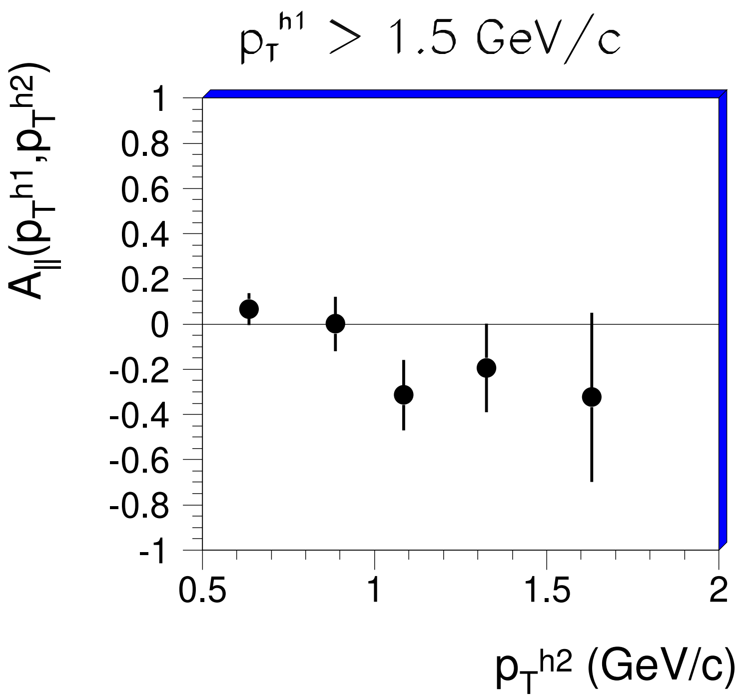


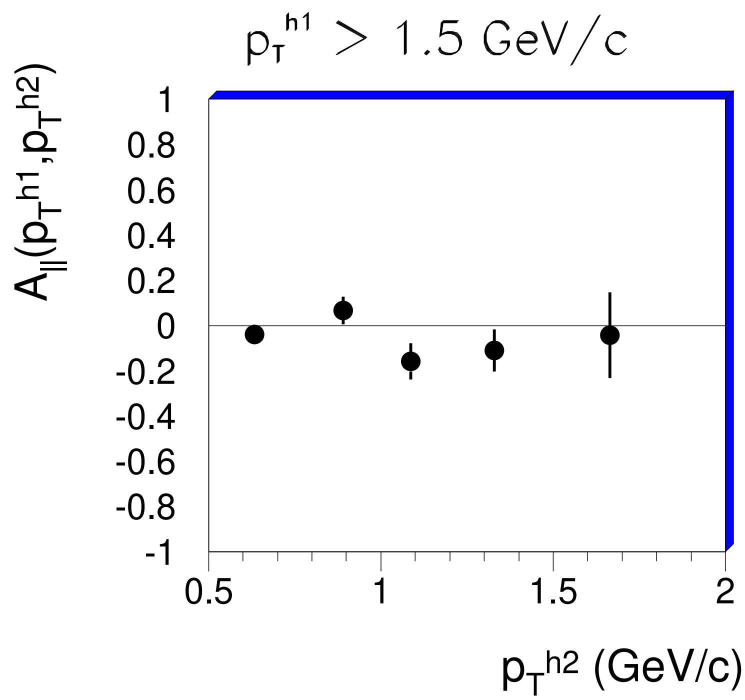
Unknown theoretical uncertainty from contribution and spin asymmetry of NLO QCD corrections and anomalous photon ...

Gluon Polarization

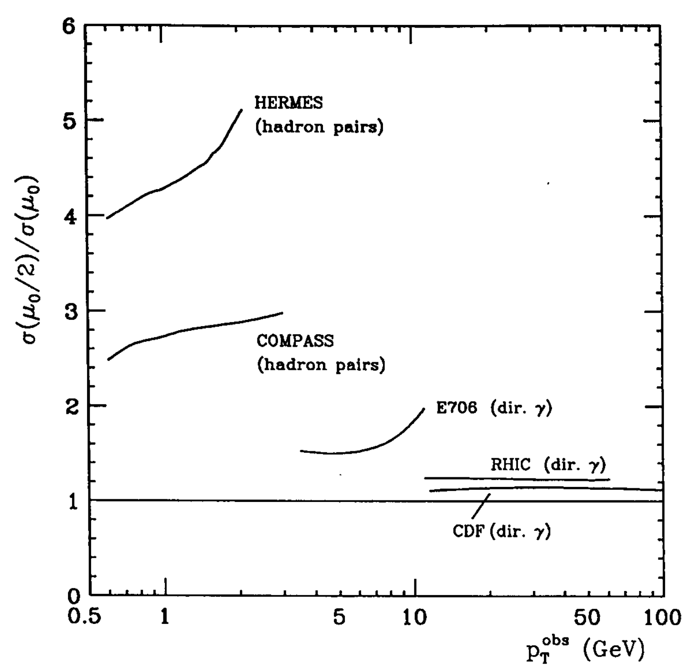
NEW! **Asymmetry including 1998-2000 Deuterium data**

H data: 1996-1997 **... plus D data: 1996-2000**

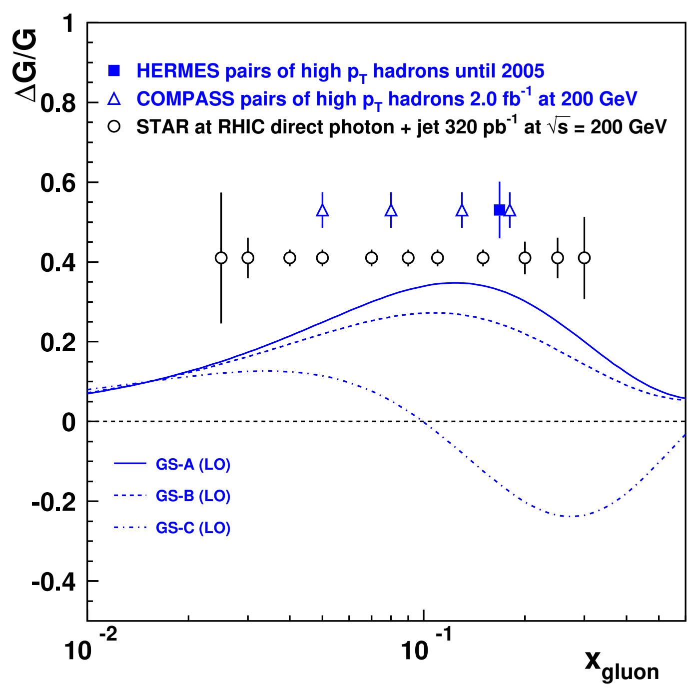




Scale dependence
of *unpolarized* xsec at NLO ...

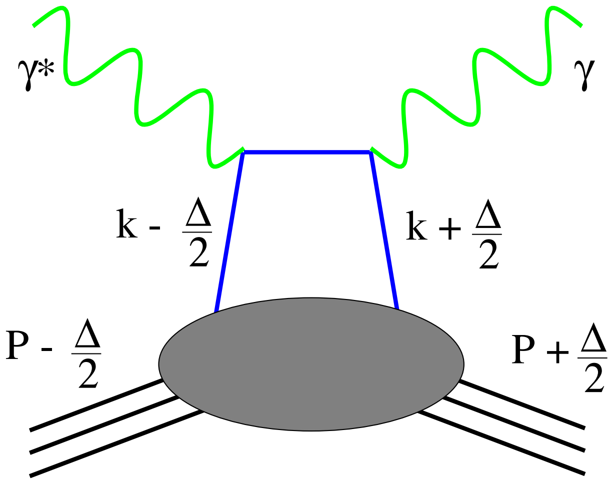


Projected measurements from
RHIC-spin, HERMES, COMPASS



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

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

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

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

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

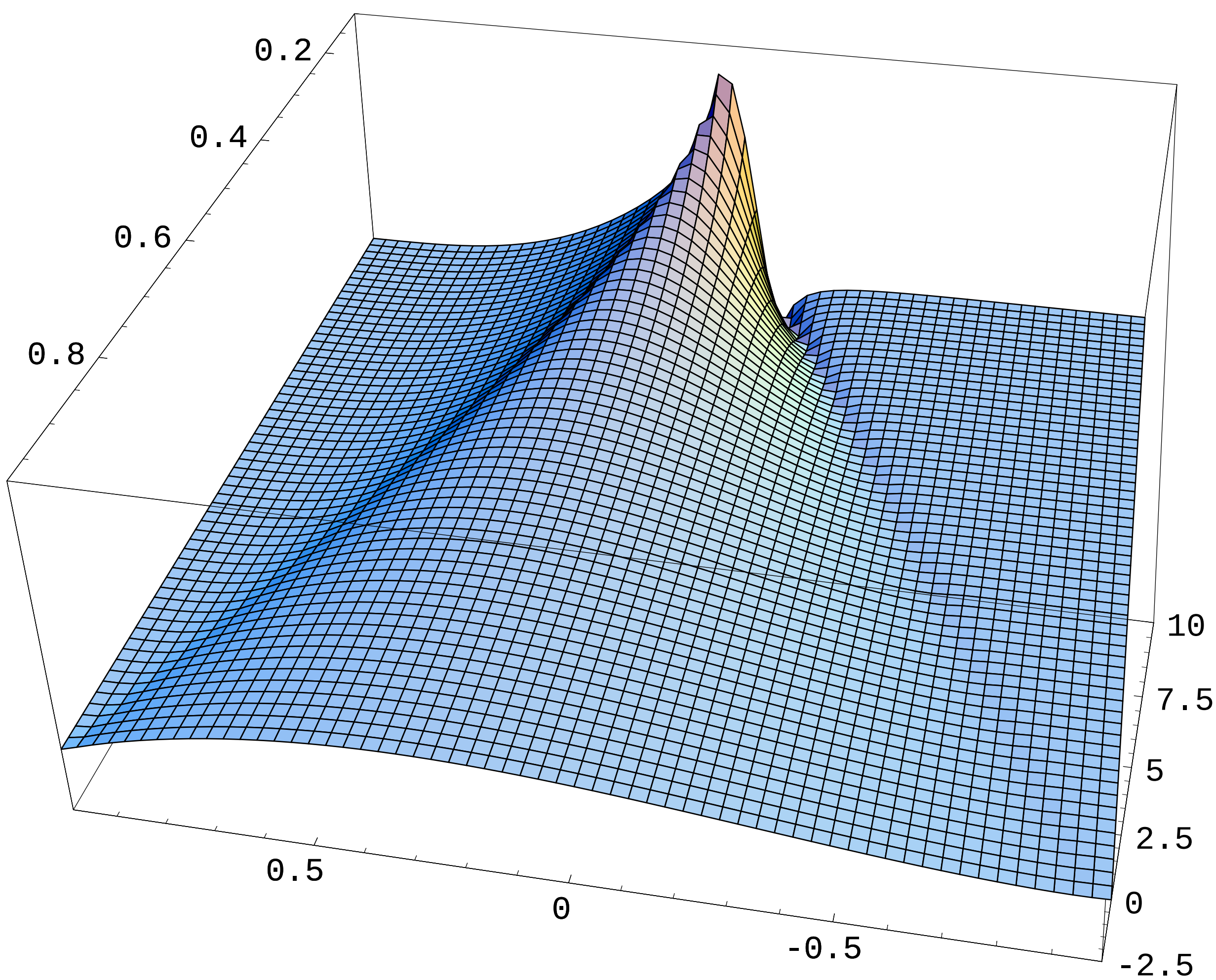
Connection with **quark angular momentum** : second moments

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

Modelling the OFPD's

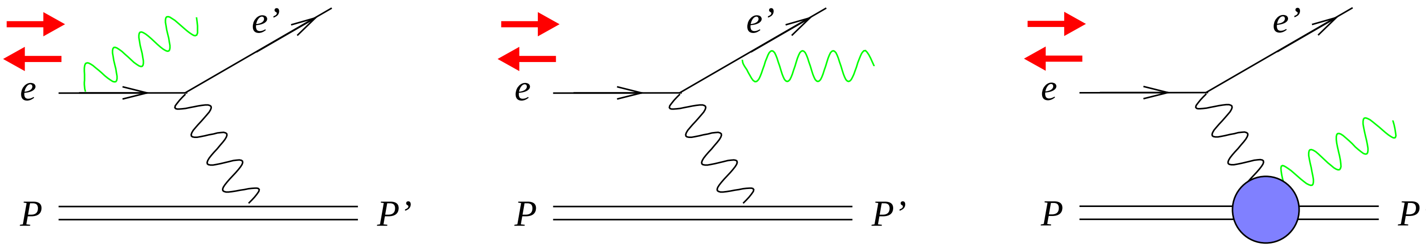
Vanderhaeghen, Guichon, Guidal, PRD 60 (99) 094017

- **t–dependence** from elastic form factors
- **ξ–** (skewedness) and **x– dependence** — interpolate betw 2 regions:
  $|x| > \xi \;\rightarrow\; x_1, x_2$ both > 0 (quarks), or both < 0 (anti-quarks)
  $\Rightarrow$ PDF's recovered in limit $\xi \rightarrow 1$
  $|x| < \xi \rightarrow$ probe correlation between q and $\overline{q}$
  $\Rightarrow$ "meson-like" distributions as $\xi \rightarrow 0$



Plot shows $H^d(x, \xi, t = 0)$ (forward limit)

DVCS: Azimuthal Asymmetries



Bethe-Heitler **DVCS**

- **Beam Spin Asymmetry**

$$\sigma_{\rightarrow} - \sigma_{\leftarrow} \sim \mathrm{Im}(L \cdot T^{*})\ \sin\phi \sim \mathrm{Im}\,(\mathrm{BH} \cdot \mathrm{DVCS}^{*})$$

$\Uparrow$

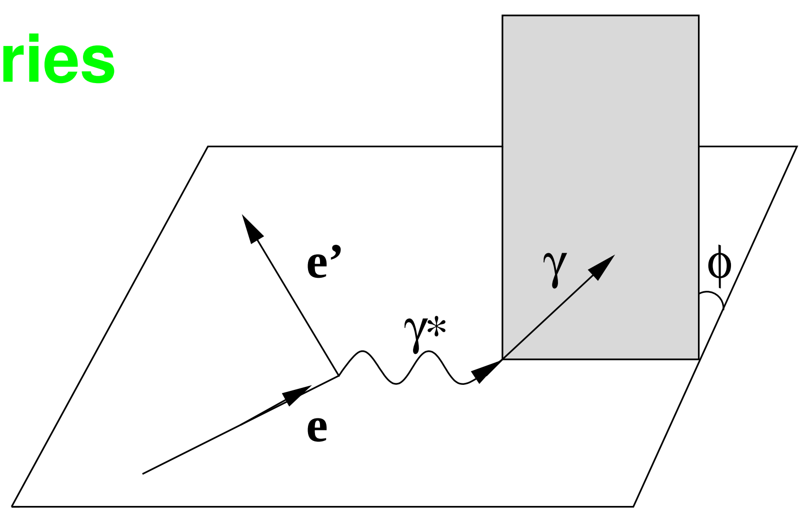
BH purely **real** ... **DVCS** **Interference**: BH should not be too small

- **Beam Charge Asymmetry**

$$\sigma_{e^{+}} - \sigma_{e^{-}} \sim \mathrm{Re}\,(\mathrm{BH} \cdot \mathrm{DVCS}^{*})$$

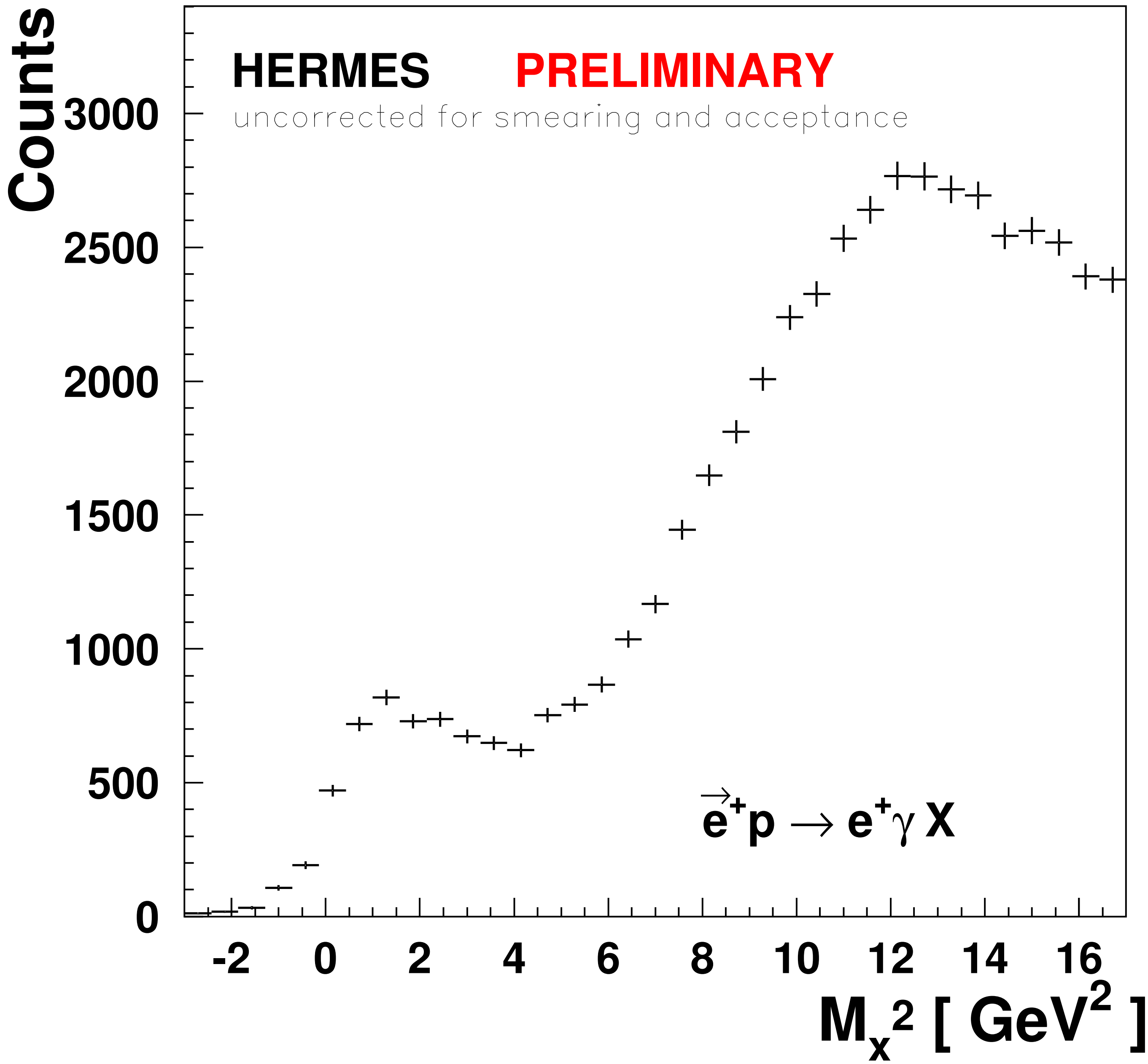
$\Rightarrow$ Azimuthal Asymmetries

Single spin/charge asym's expected to show $\boxed{\sin\phi}$ behaviour ...



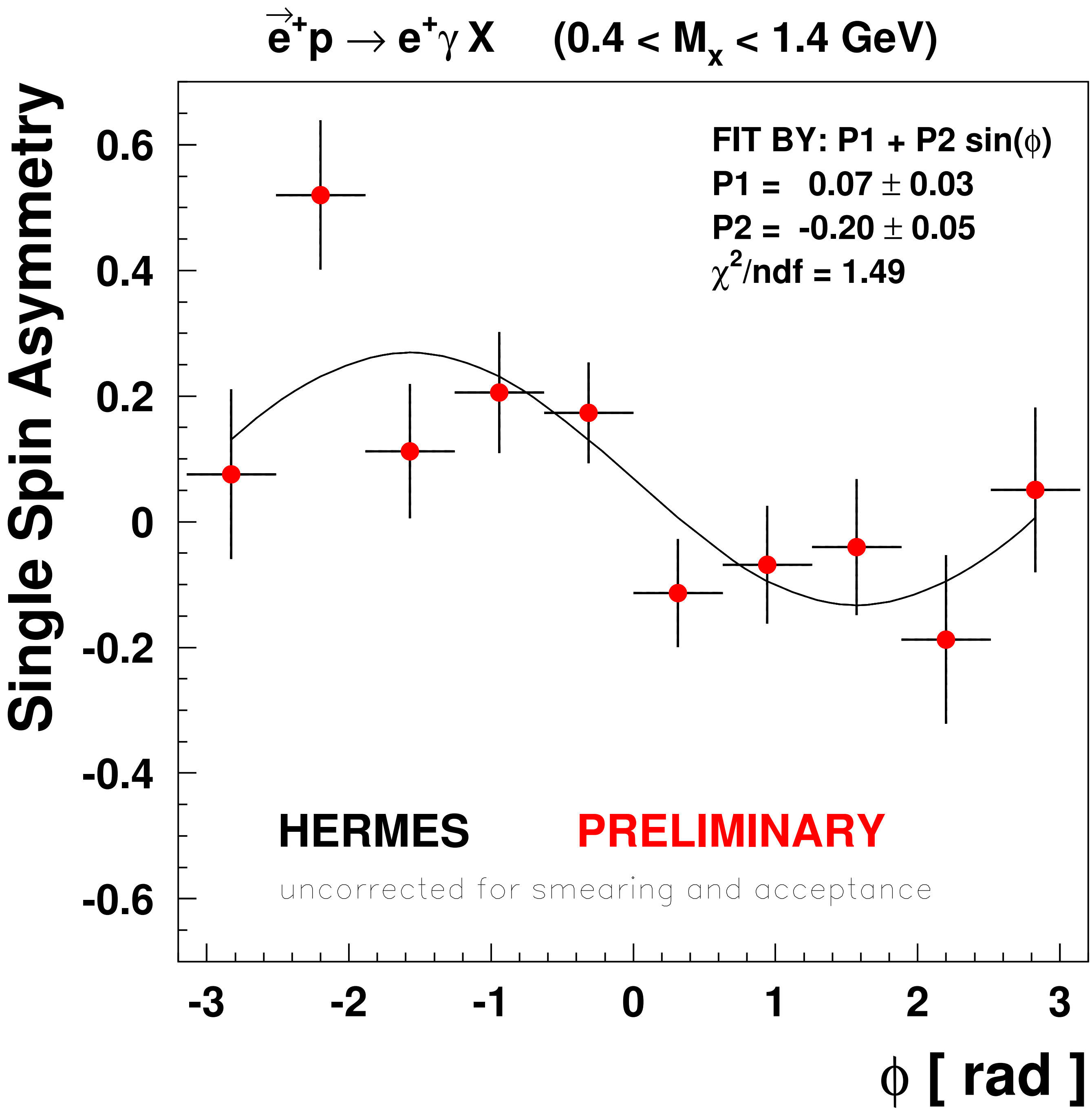
Real Photon Production

Missing Mass Spectrum

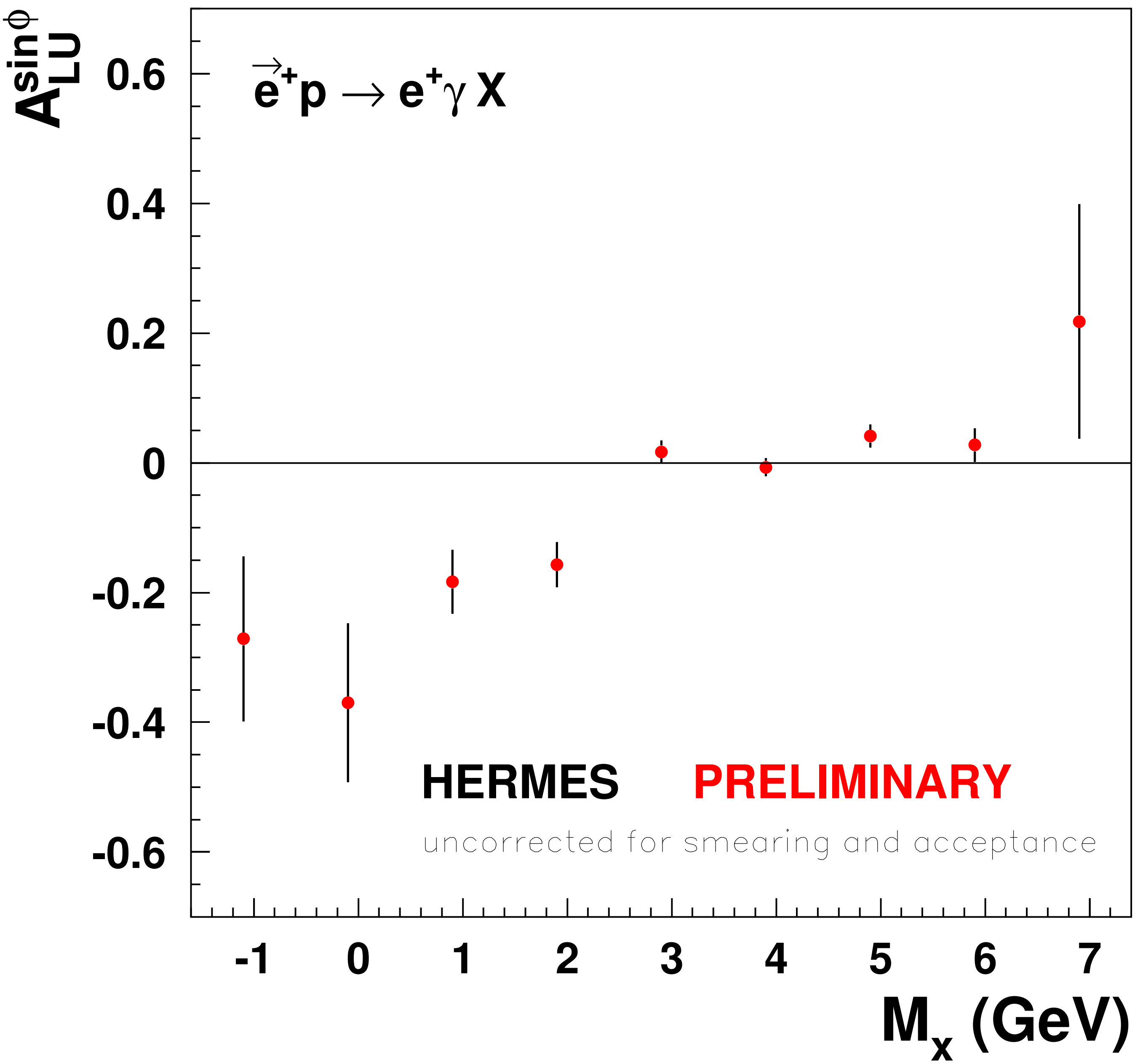


Semi-Exclusive γ Production

Beam Spin Asymmetry $A_{LU}(\phi) = \frac{1}{P_B}\frac{N^+(\phi)-N^-(\phi)}{N^+(\phi)+N^-(\phi)}$



Semi-Exclusive γ Production



Angular Momentum Sum Rule

Much recent theoretical work has surrounded the definition of the components of the spin sum rule ... trouble is: there is **no** local, gauge-invariant operator that can represent the gluon spin Δg .

Version 1: Local Operators

Ji, PRL 78 (1997) 610

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \hat{L}_q + \hat{J}_g$$

- Each term related to **local** , **gauge-invariant** operators.
- $\hat{J}_q = \Delta\Sigma + \hat{L}_q$ **measurable** via DVCS.
- **BUT**: No way to express terms as parton model **x-distributions** .
- **BUT**: $\hat{L}_q$ and $\hat{J}_g$ represent **roughly** the quark orbital and total gluon angular momentum.
- **BUT**: Terms are **not Lorentz-covariant** (i.e. frame independent)
- **BUT**: No way to separate out spin (Δg) part of $\hat{J}_g$, since there is no corresponding local operator ...

Version 2: "Classic" sum rule

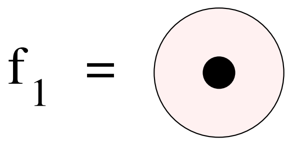
Bashinsky, Jaffe, NPB 536 (1998) 303

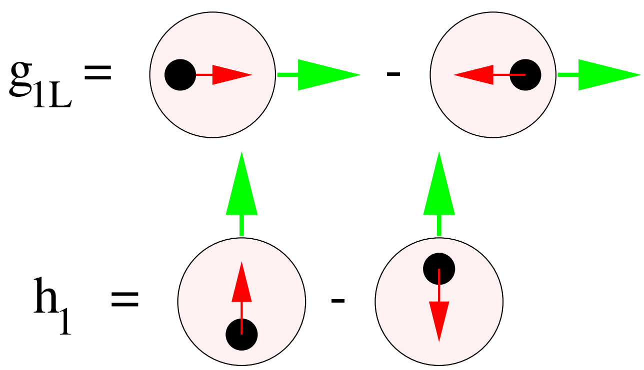
$$\frac{1}{2} = \int_0^1 dx \left\{\frac{1}{2}\Delta\Sigma(x) + \Delta g(x) + L_q(x) + L_g(x)\right\}$$

- Each term = integral over **partonic x-distribution** (PDF).
- All terms are **gauge-** and **boost-invariant** .
- Terms are **precisely** the spin and orbital angular momentum distributions of quarks and gluons.
- **BUT**: Distribution functions defined in terms of **bi-local** operators.
- **BUT**: No idea how to **measure** $L_q(x)$ and $L_g(x)$ ...

Transversity

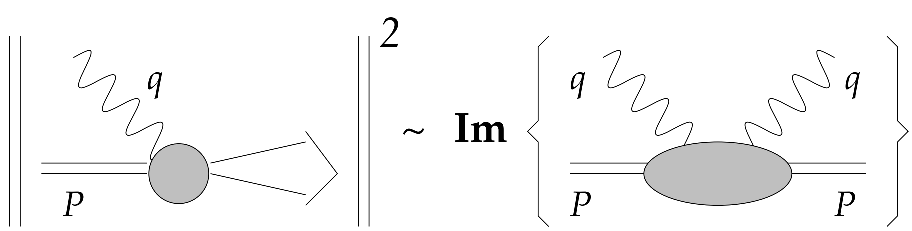
A complete description of the momentum and spin structure of the nucleon at leading twist requires the third parton distribution $\delta q(x)$.

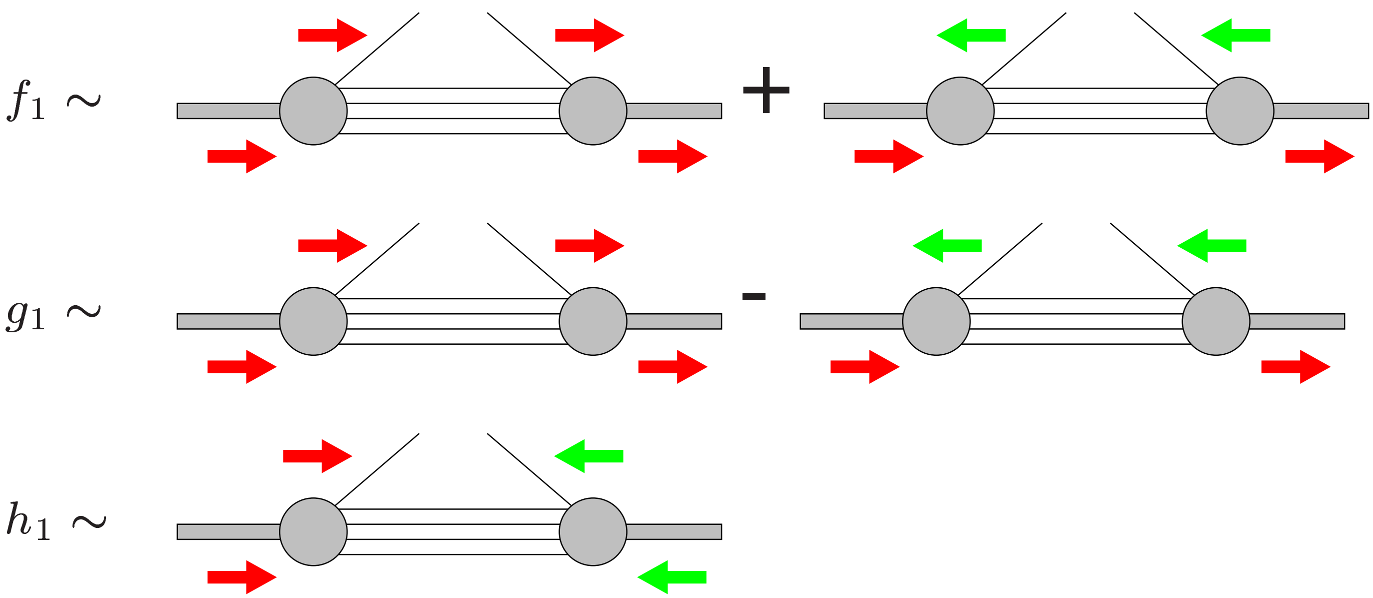




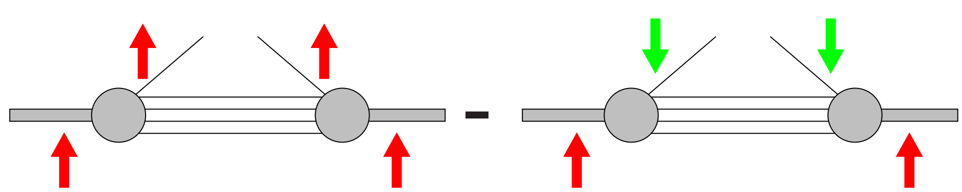
transversity:
$h_1(x) \sim \delta q(x)$

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

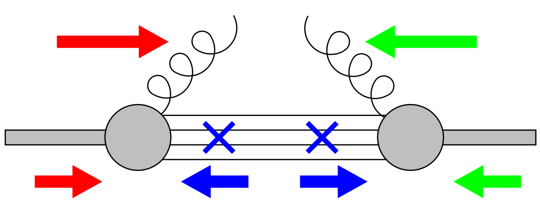
Fundamental matrix elements:

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

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

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

No Gluons

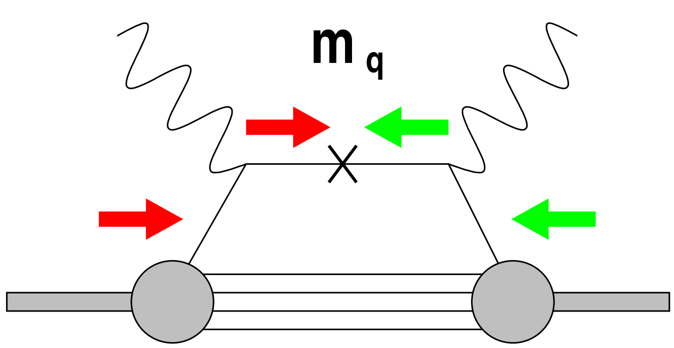


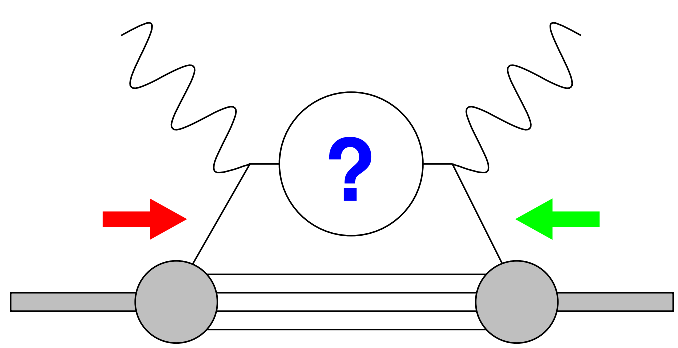
Angular momentum conservation
$\Rightarrow \Lambda - \lambda = \Lambda' - \lambda'$
Different Q^2 **evolution** than g_1.

Chiral Odd

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

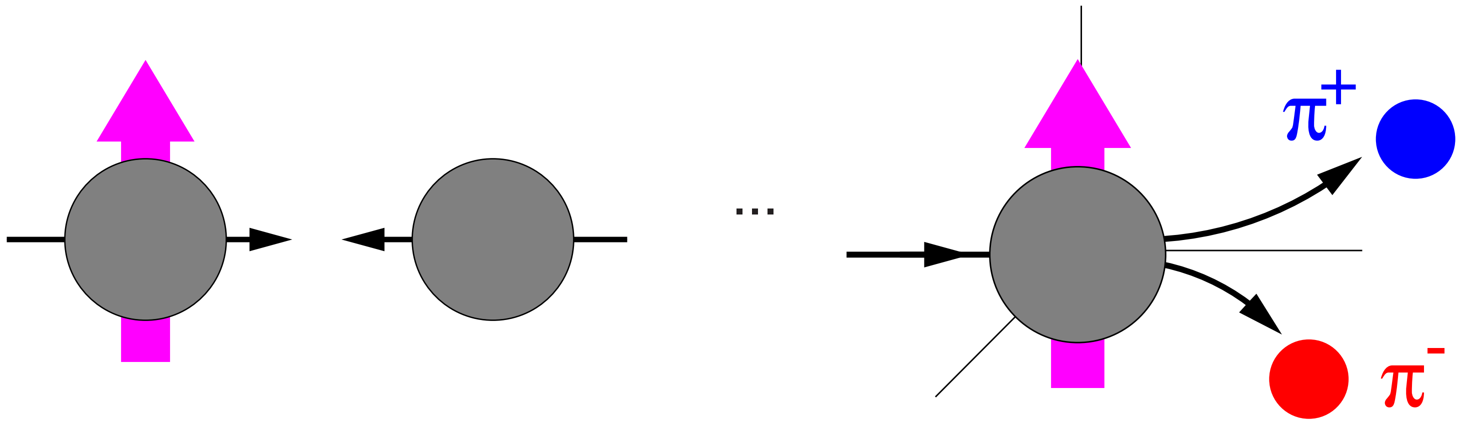
but they are observable in e.g. **semi-inclusive** reactions





Single Spin Asymmetries

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



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

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

with helicity flip in subprocess asymmetry:

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

No large effects possible:

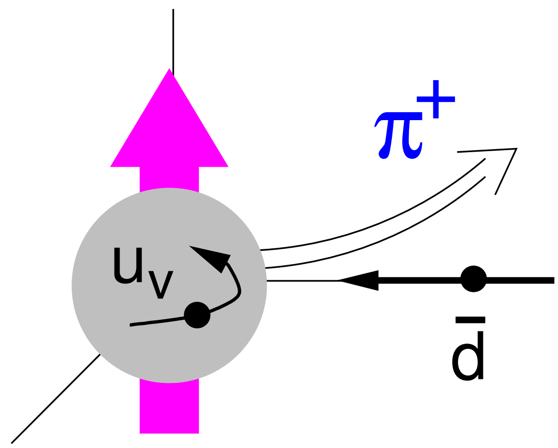
- q helicity flip vanishes in the limit $m_q = 0$
- $\hat{a}_{ab}$ arises from **interference** between a non-flip and a single-flip helicity amplitude ... and no imaginary phases possible at Born level.

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

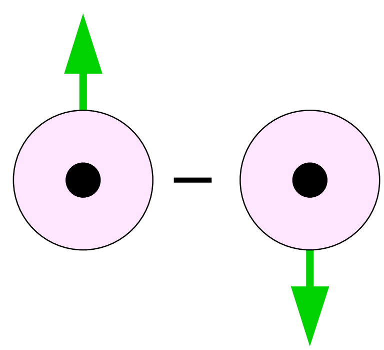
Consider dependence of parton densities on **intrinsic** k_T :

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

- 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

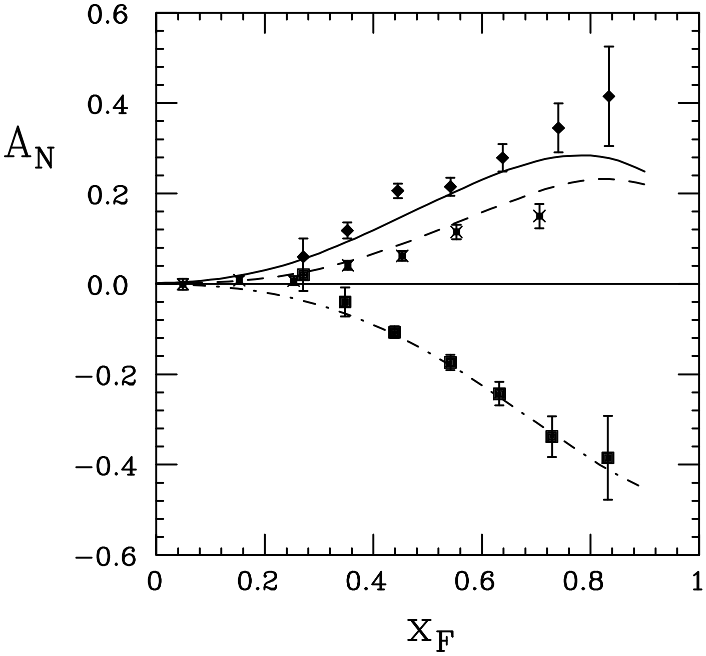


Collins Effect and Transversity

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

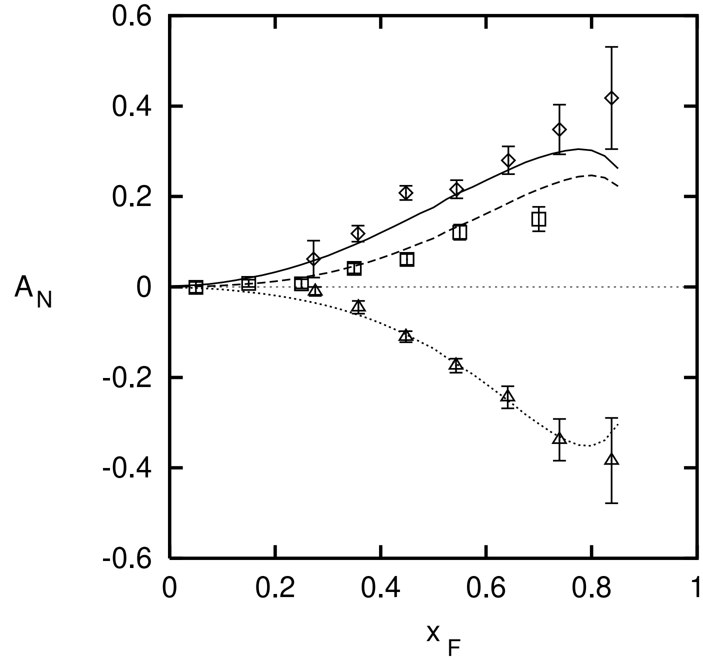
Sivers Effect:

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



Collins Effect:

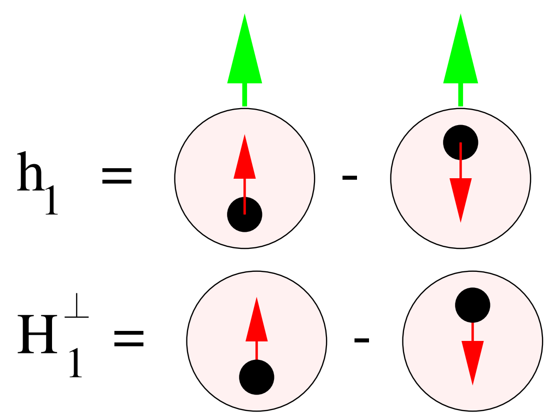
T-odd **fragmentation function** $H_1^{\perp}$



Collins Effect

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

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



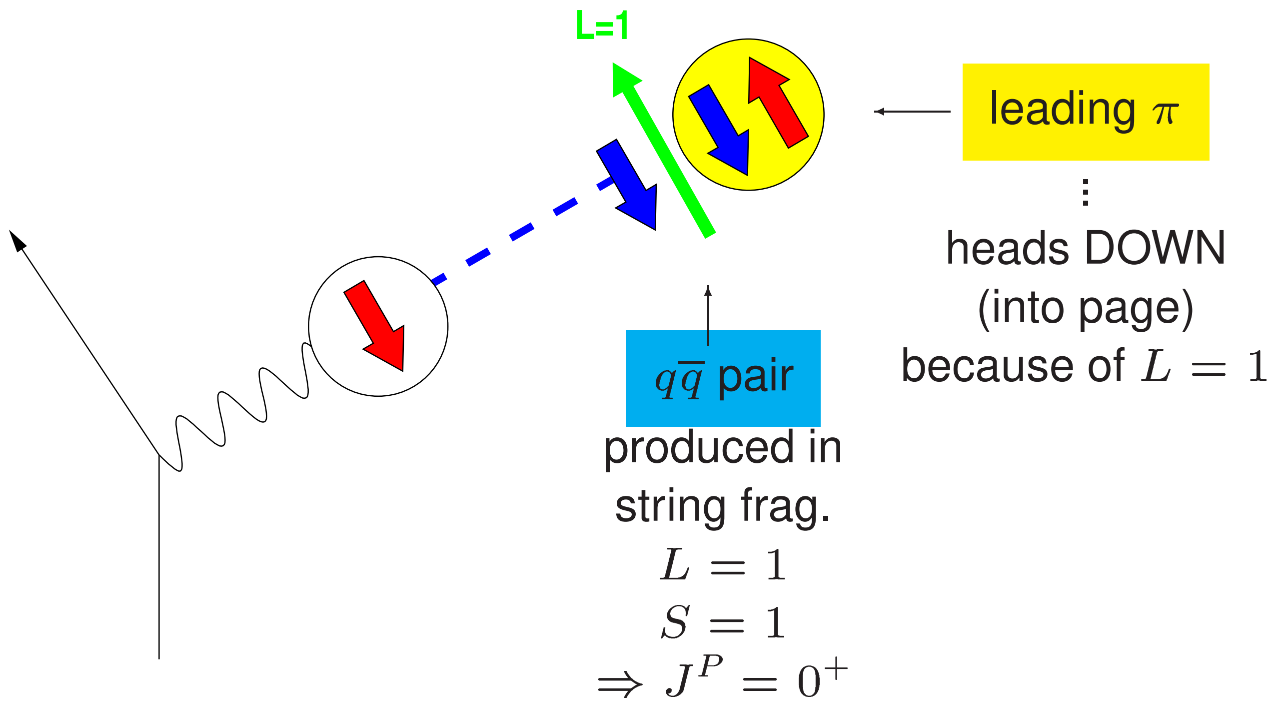
How to separate?

Single Spin Asymmetries in DIS

The Collins Effect in the String Fragmentation Model

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

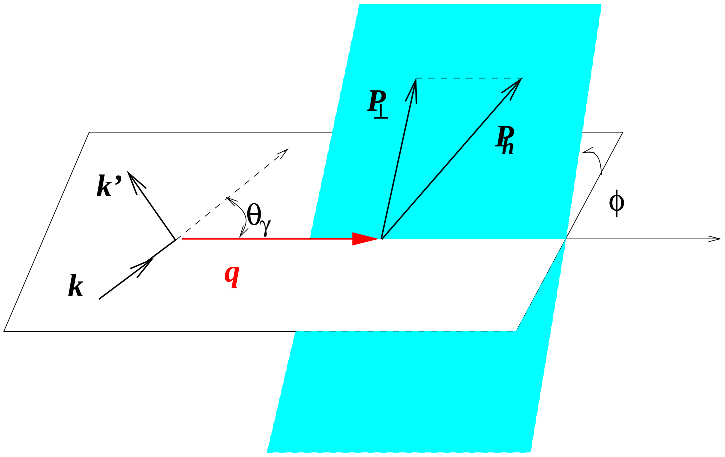
- **chiral-odd** like $h_1(x)$ ... chiral-odd distribution and fragmentation functions appear in pairs in DIS cross-section
- **T-odd** ... one T-odd function required to produce single-spin asymmetry in semi-inclusive DIS



The Collins function is indicative of **phase coherence** in fragmentation

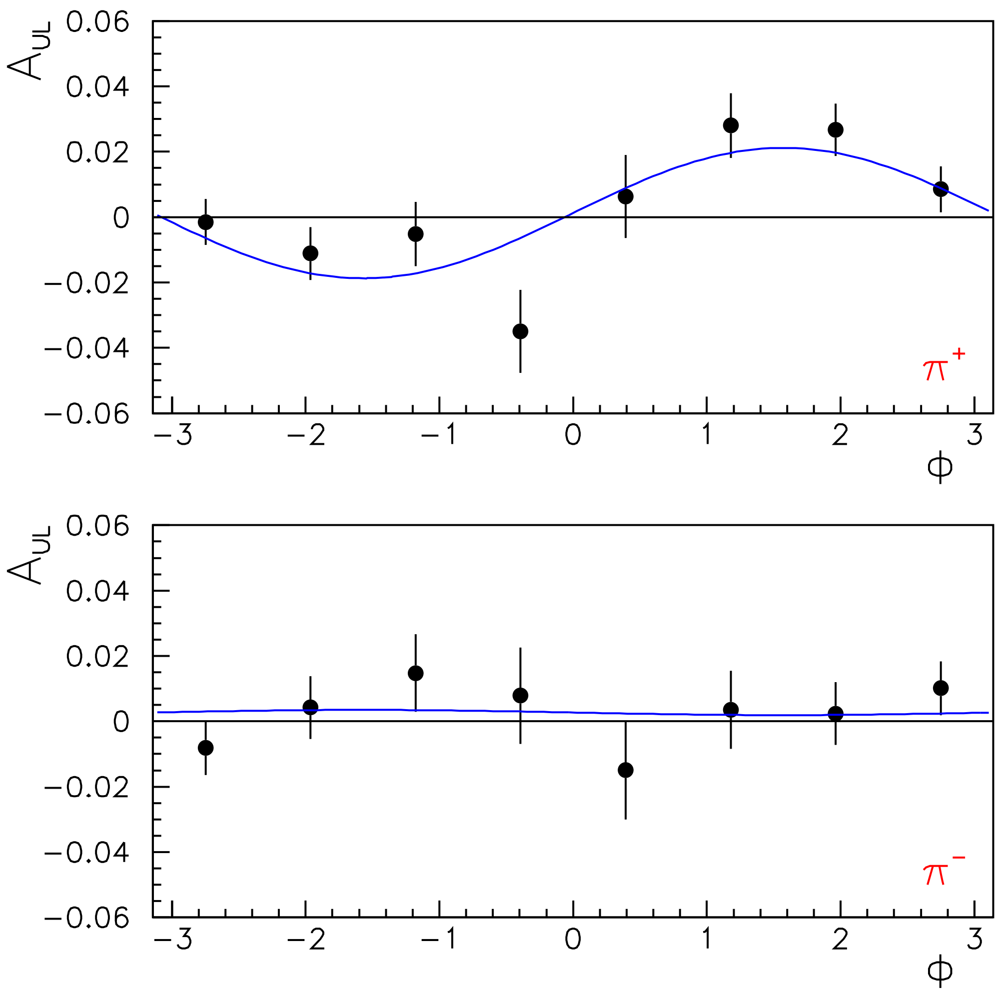
$\Rightarrow$ generate inteference between non-flip and single-flip amplitudes

Spin-Azimuthal Asymmetry



Longitudinal target spin asymmetry:

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



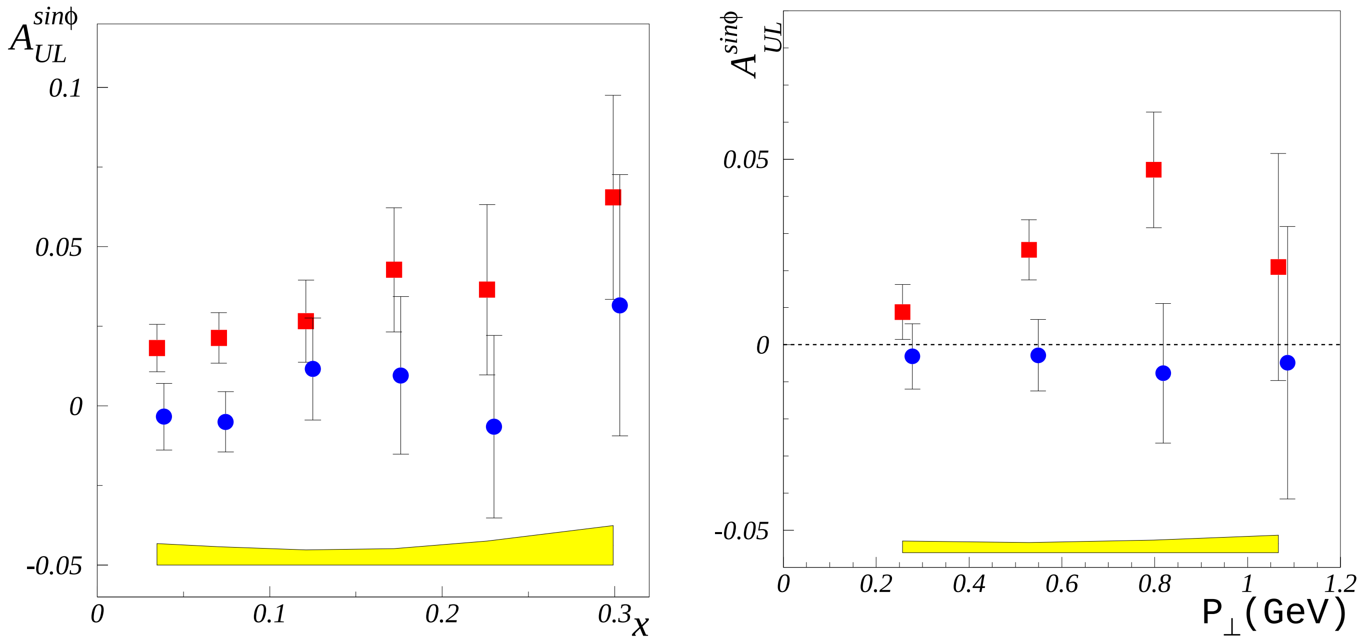
Effect observable even with longitudinally polarized target

⇒ 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

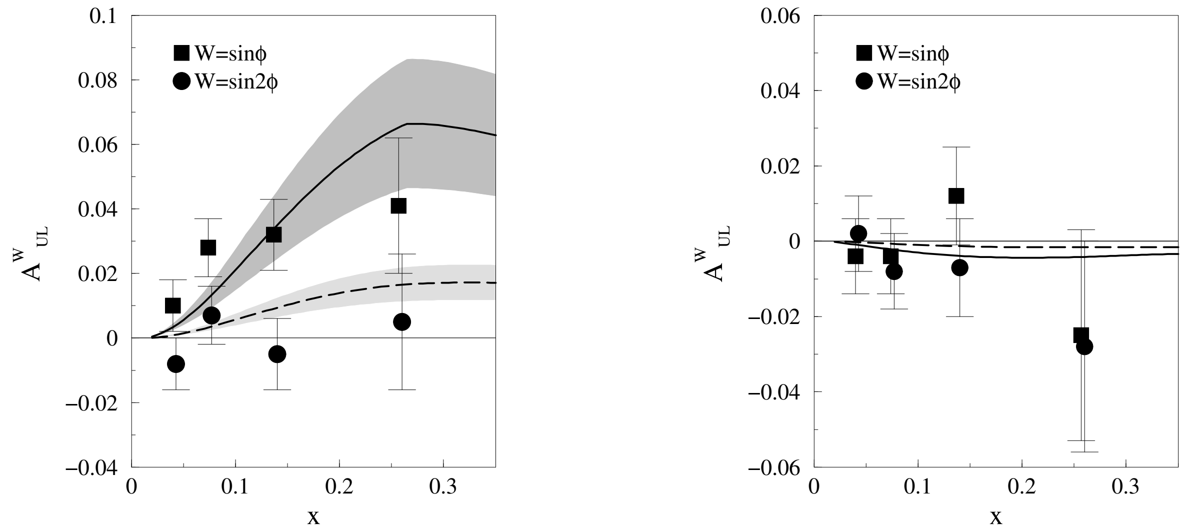
Future Measurements of Transversity

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

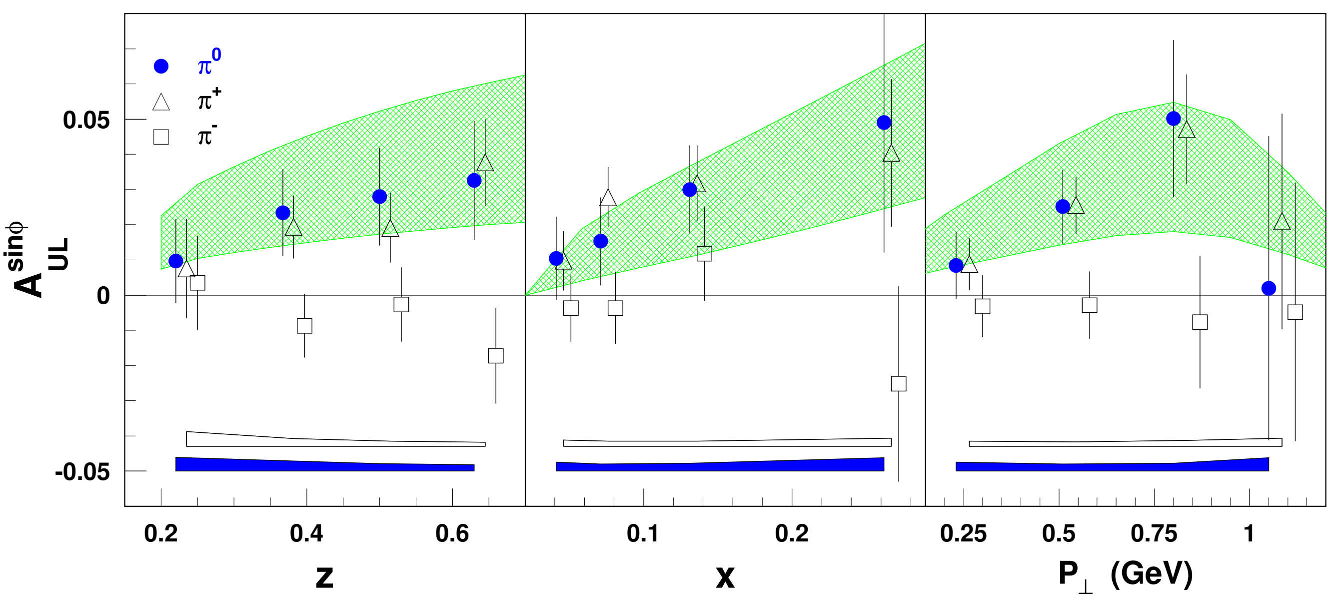
Charged Pion Asymmetry A_{UL}

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

Spin Physics: Prospects

New data being analyzed and collected ...

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

Exciting new results may be expected soon!

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