# STRUCTURE of the NUCLEON and NUCLEI STUDIED by HERMES

The expanding horizons of spin physics at HERMES

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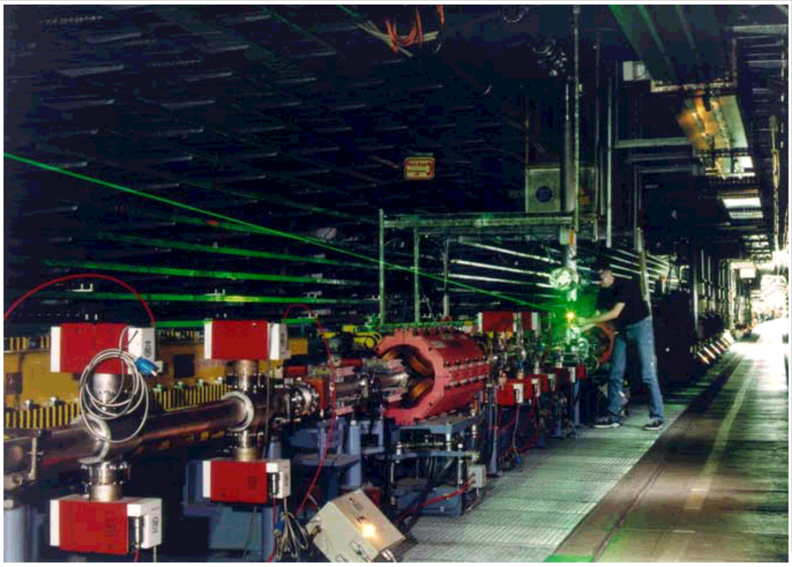
On behalf of the HERMES Collaboration

Outline:

1. Introductory remarks on the HERMES experiment.
2. Recent results from inclusive measurements.
3. Flavor tagging and a new flavor decomposition of polarized quark distributions.
4. Transverse spin physics and Deep Virtual Compton scattering.
5. Studies of quark propagation and hadronization.
6. Concluding remarks.

# HERMES(HERA Measurement of Spin)

**Laser polarimeter in the HERA tunnel**
HERMES uses the polarized electrons from HERA to find out how the different quarks and gluons account for the "spin" (the intrinsic angular momentum) of the protons. During HERA operation, the green laser beam is directed inside the beam pipe against the electron beam, to observe to what extent the electrons are polarized, i.e. how their spins are aligned preferring a forward or backward direction. In this picture, the laser beam is outside the beam pipe for adjustment.
This image is copyright protected. DESY

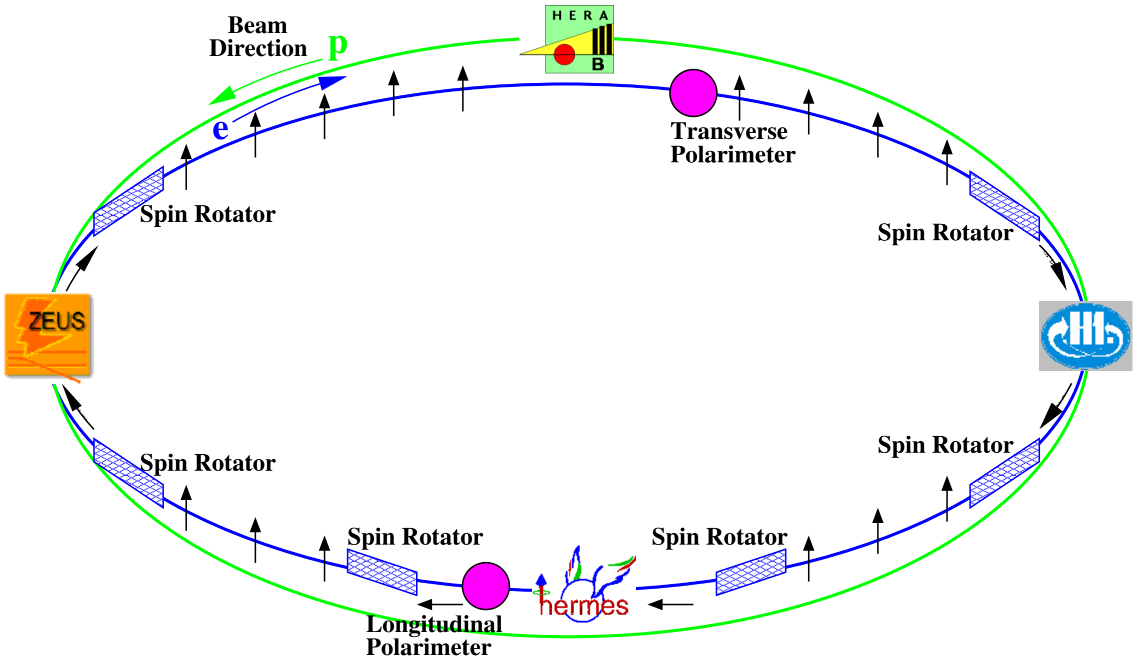


hermes

**A second generation experiment designed to study the spin structure of the nucleon at HERA**

Alberta
Argonne
Bari
Beijing
Colorado
DESY-Hamburg
DESY-Zuethen
Erlangen
Ferrara
Freiburg
Gent
Glasgow
Geissen
Illinois
INFN-Frascati
INFN-Rome
JINR-Dubna
Liverpool
Marburg
MIT
Moscow
MPI-Heidelberg
Munich
NIKHEF
Protvino
Regensburg
St. Petersburg
Tokyo
TRIUMF
Warsaw
Yerevan

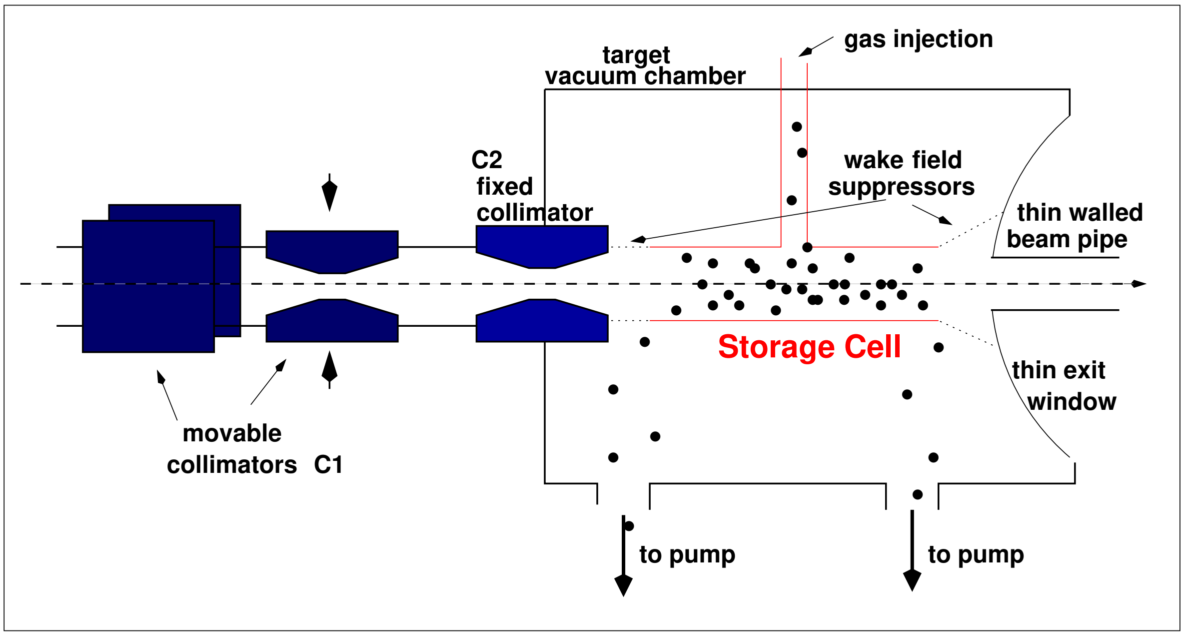
# POLARIZED ELECTRONS in HERA




Polarization measured by two Compton Polarimeters.

$E_{beam} = 27.5 GeV \quad \langle P \rangle = (55 \pm 2_{sys})\%$

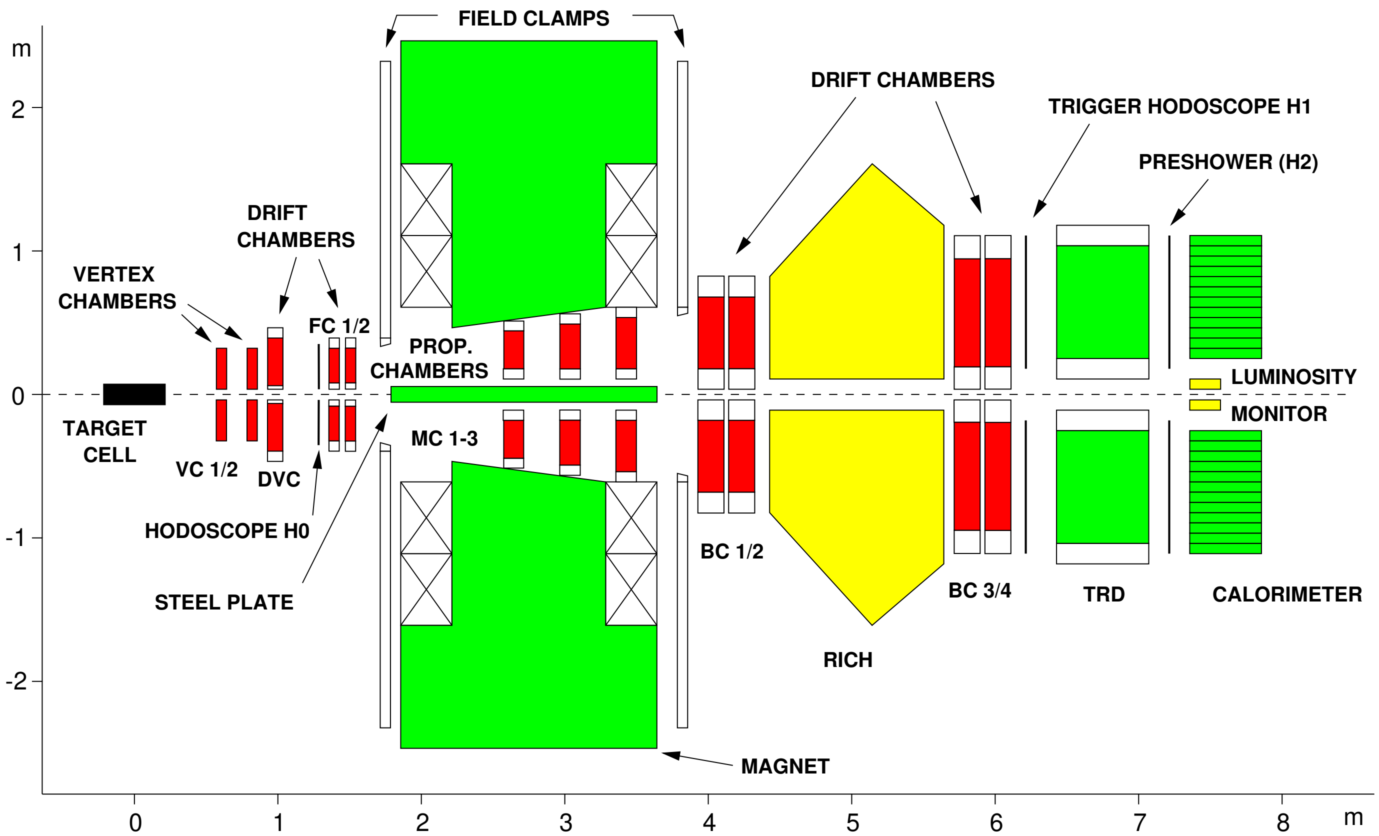
# INTERNAL POLARIZED GAS TARGET



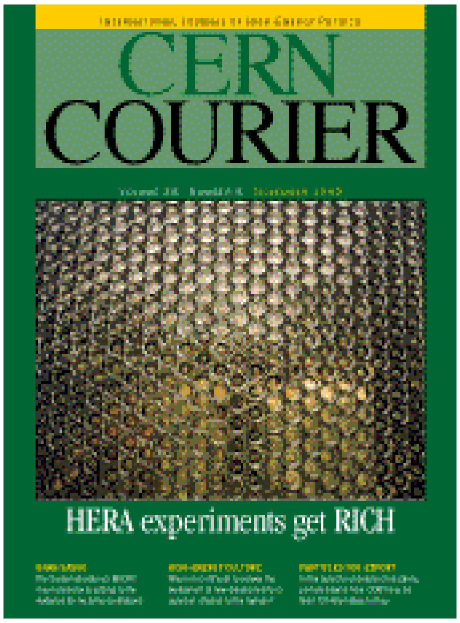

H,D target - Cell filled by Atomic beam source.

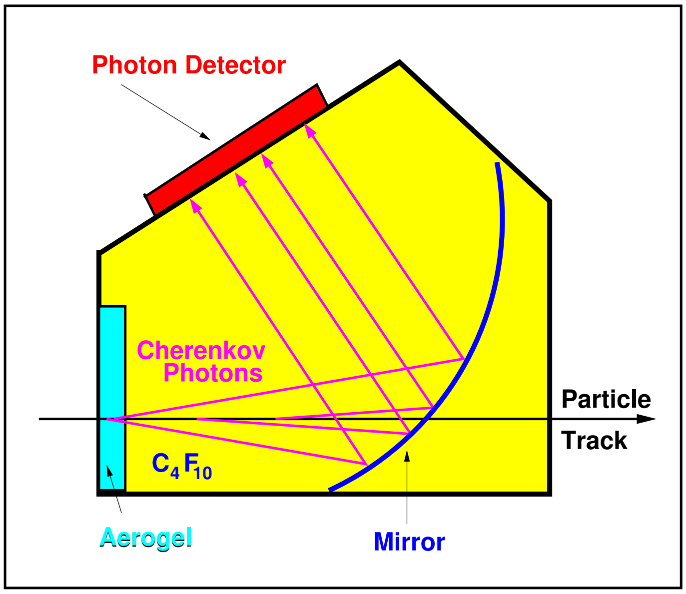
$\rho = 7.6 \cdot 10^{13}$ atoms/cm$^2$ $\quad \langle P \rangle = (82 \pm 4_{sys})\%$

# SPECTROMETER




# The RICH Detector

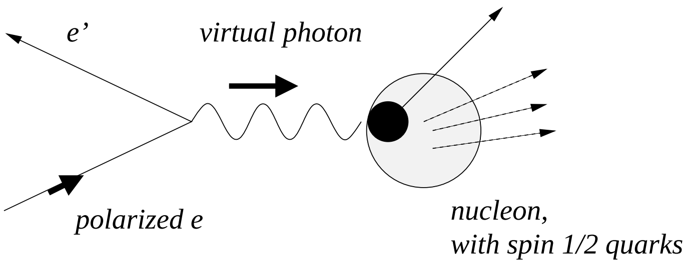



Installed in 1998, - $\pi$, K, p separation for $1 < p < 15$ GeV.

# Spin-Dependent Deep Inelastic Scattering

In polarized DIS using polarized lepton beams and polarized nuclear targets, one probes the polarization of the partonic constituents of the nucleon. For Inclusive (e,e') scattering:




One measures double spin asymmetries:

$$A_{\parallel}(e,e') = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

which are interpreted in terms of spin-dependent structure functions:

$$A_1 = \frac{A_{\parallel}}{D(1+\gamma\eta)} \simeq \frac{g_1}{F_1} = \frac{\Sigma_q e_q^2 \Delta q(x,Q^2)}{\Sigma_q e_q^2 q(x,Q^2)} \qquad \begin{array}{c} x = Q^2/2m\nu \\ Q^2 = 4EE' sin^2(\Theta/2) \end{array}$$

$\Delta q(q)$:polarized(unpolarized) quark distribution functions

QPM: $F_1 = \frac{1}{2}\Sigma_i e_i^2 q_i, \quad g_1 = \frac{1}{2}\Sigma_i e_i^2 \Delta q_i, \quad \Delta q_i = q_i^{\uparrow} - q_i^{\downarrow}.$

Early History of $\Delta\Sigma = \Delta u + \Delta d + \Delta s$

Non-relativistic Quark Model (constituent quarks):

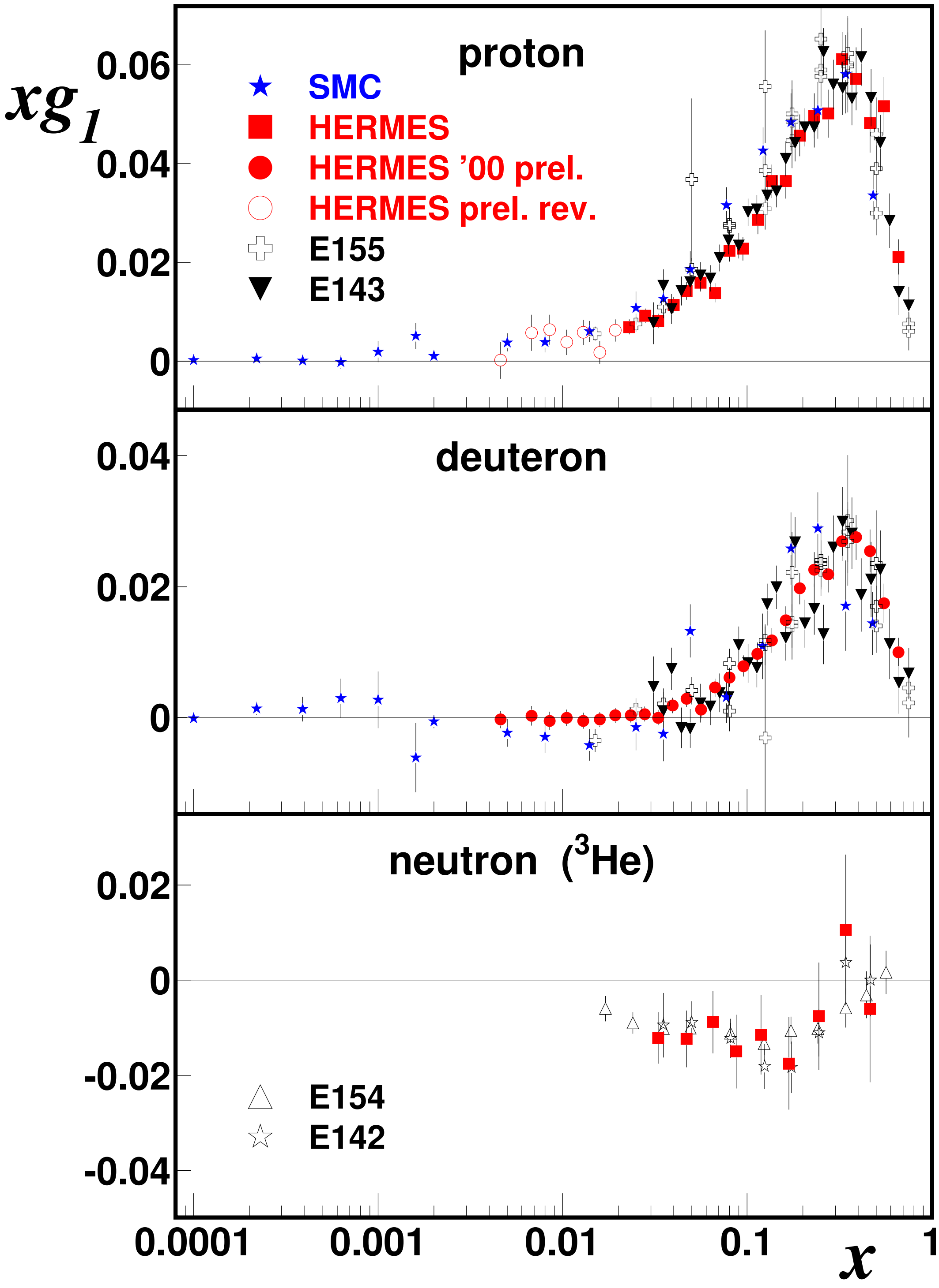
$$\Delta u = +4/3, \qquad \Delta d = -1/3 \quad \rightarrow \quad \Delta\Sigma = 1$$

SPIN CRISIS-DIS at SLAC/CERN('90's)-

$$\Delta\Sigma \approx 0$$

# Comparison of Data for $g_1(x)$

Inclusive data have become a benchmark:




But, new physics continues to emerge:

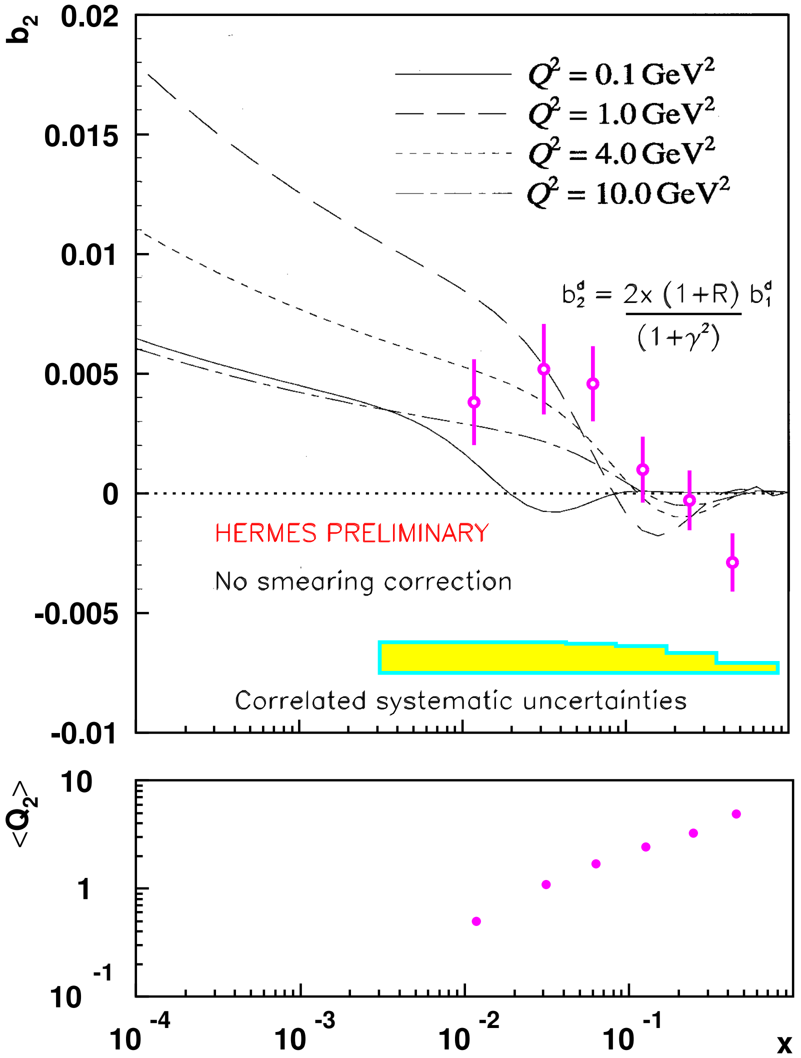
# $b_1(x, Q^2)$ in the deuteron

For a spin 1 target, a new leading twist tensor polarized structure function given by:

$$b_1(x, Q^2) = \frac{1}{2}\sum_i e_i^2[2q_i^0(x, Q^2) - q_i^+(x, Q^2) - q_i^-(x, Q^2)]$$

can be measured. For partons at rest or in an s-wave state $b_1 = 0$. HERMES has measured $b_1$ by varying the vector(V) and tensor(T) polarizations of the deuteron target:

$$\sigma = \sigma_0[1 + P_b V A_{\|} + \frac{1}{2} T A_T] \quad A_T \sim \frac{2}{3}\frac{b_1(x, Q^2)}{F_1(x, Q^2)}$$




Calculation confirms that

$$b_1 > 0$$

at small x due to quadrupole deformation of the deuteron.

Bora and Jaffe, PRD 57, 6909

$b_1(x, Q^2)$ provides a new window on nuclear binding effects at the partonic level.

# POLARIZATION OF THE QUARK SEA

The flavor decomposition of the polarized quark distributions, $\Delta q_f$, is one of the major missions of HERMES.

From early analysis of $\int g_1(x, Q^2)dx$ by SMC,SLAC:

$$\Delta u = +0.78 \pm 0.06$$

$$\Delta d = -0.47 \pm 0.06$$

$$\Delta s = -0.19 \pm 0.06$$

A NLO analysis of all inclusive proton data gives:

$$a_0^s = -0.07 \pm 0.04$$

D. Adams et al., Phys. Rev **D56**, 5330

Inclusive DIS is sensitive only to $e_i^2$.

$\Rightarrow$ Inclusive DIS can't distinguish quark from anti-quark.

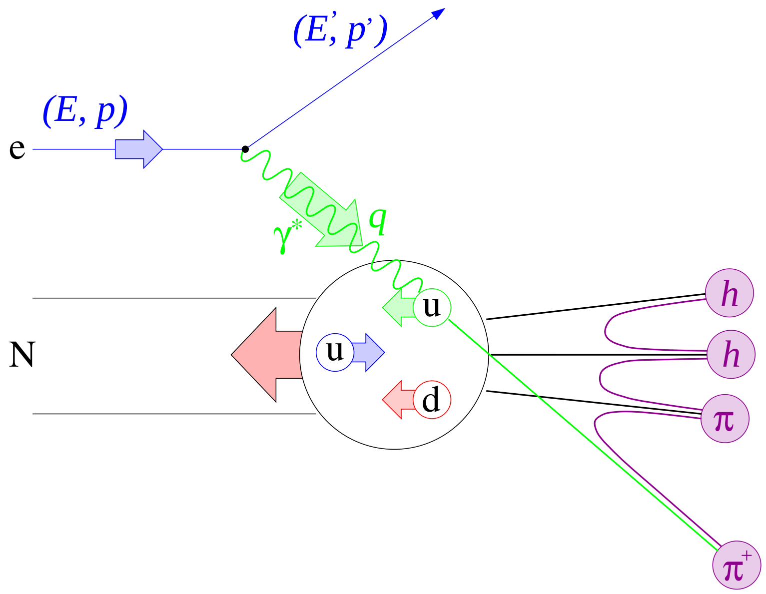
Use hyperon $\beta$-decay + SU(3)-symmetry to extract flavor distributions.

With flavor tagging in DIS, individual spin contributions, $\Delta q_f(x)$ can be determined directly from hadron spin asymmetries

$$A_{\parallel}^{(h)} = \frac{N_{(h)}^{\uparrow\downarrow} - N_{(h)}^{\uparrow\uparrow}}{N_{(h)}^{\uparrow\downarrow} + N_{(h)}^{\uparrow\uparrow}}, \quad A_1^h = \frac{A_{\parallel}^h}{D(1+\eta\gamma)}$$

# Polarized Semi-Inclusive DIS

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




$$Q^2 = 4EE' sin^2(\Theta/2)$$
$$\nu = E - E'$$
$$x = Q^2/2M\nu$$

Typical Kinematics:
$E_{e^+} = 27.5 GeV$
$x > 0.02,\ W^2 > 10 GeV^2$
$1.0 GeV^2 < Q^2 < 15 GeV^2$
$\nu < 24 GeV$

Cuts for Current fragmentation:
$z = E_h/\nu > 0.2$
$x_F \approx 2p_{\|}/W > 0.1$

## Flavor Tagging

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

$$A_1^h(x, Q^2) = \frac{\int_{z_{min}}^{0.8} dz \sum_q e_q^2 \Delta q(x, Q^2) \cdot D_q^h(z, Q^2)}{\int_{z_{min}}^{0.8} dz \sum_{q'} e_{q'}^2 q'(x, Q^2) \cdot D_{q'}^h(z, Q^2)}$$

# Purity Analysis of Asymmetries

- Perform a simultaneous global analysis of all $A_1^h(x,z)'s$

- The photon-nucleon Asymmetry is

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

- The hadron quark-purity $P_q^h(x,z)$ is the probability that a quark q was struck in an event $l + N \longrightarrow l' + h + X$

- Purities are spin-independent quantities

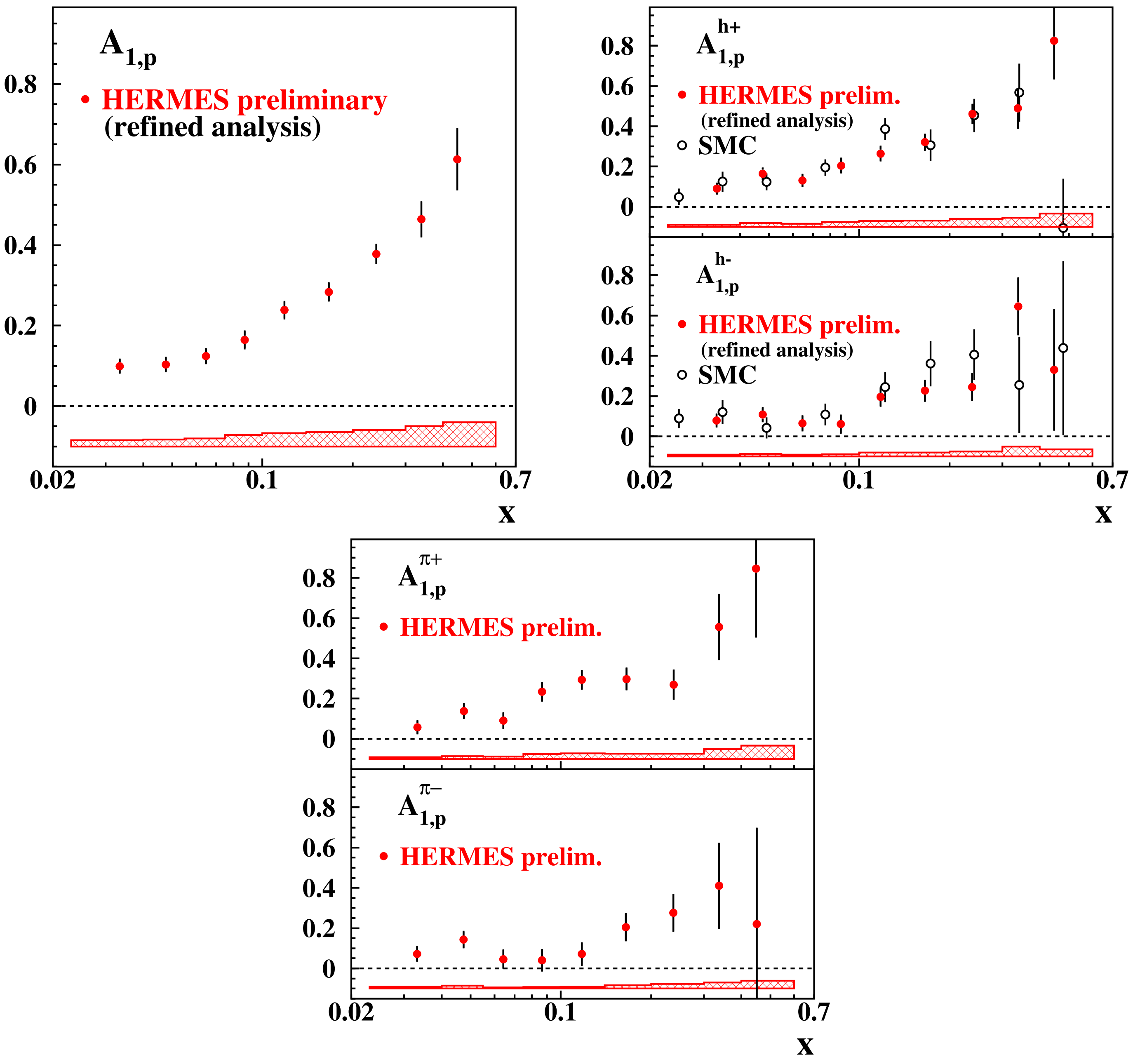
- Define

$$\vec{A} = \begin{pmatrix} A^{h_1}(x) \\ \ldots \\ A^{h_n}(x) \end{pmatrix}, \vec{Q} = \begin{pmatrix} \Delta q_1(x)/q_1(x) \\ \ldots \\ \Delta q_n(x)/q_n(x) \end{pmatrix}, P = [P_q^h(x)]$$

**Determine quark polarizations by inverting**

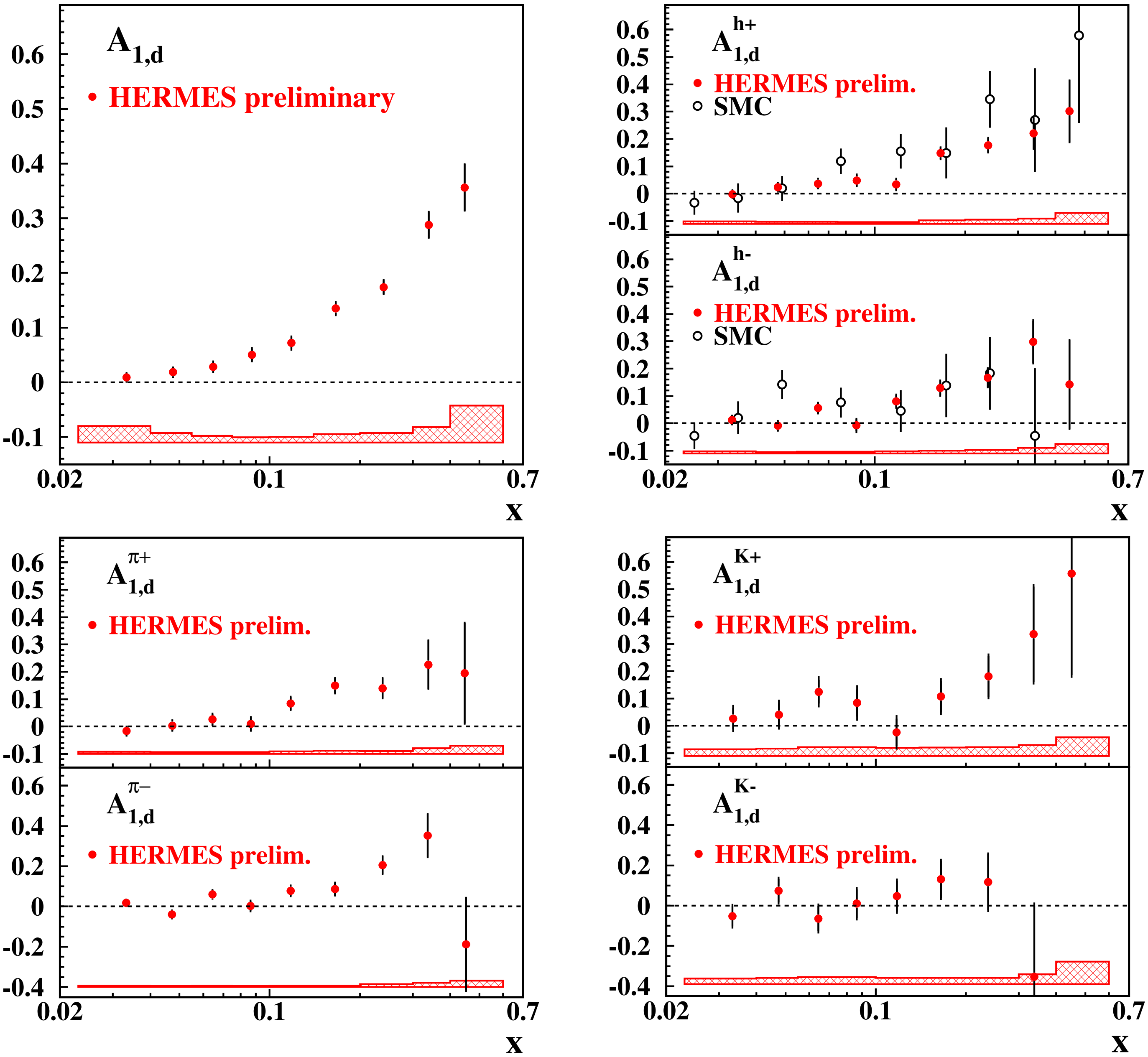
$$\vec{A} = P\vec{Q}$$

# Asymmetries On The Proton




- 1996–97 data: threshold Čerenkov counter identifies $\pi^{\pm}$
- $0.2 < z < 0.7$
- Asymmetries are independent of $z$ in this range
  $\Rightarrow$ No evidence of target fragmentation

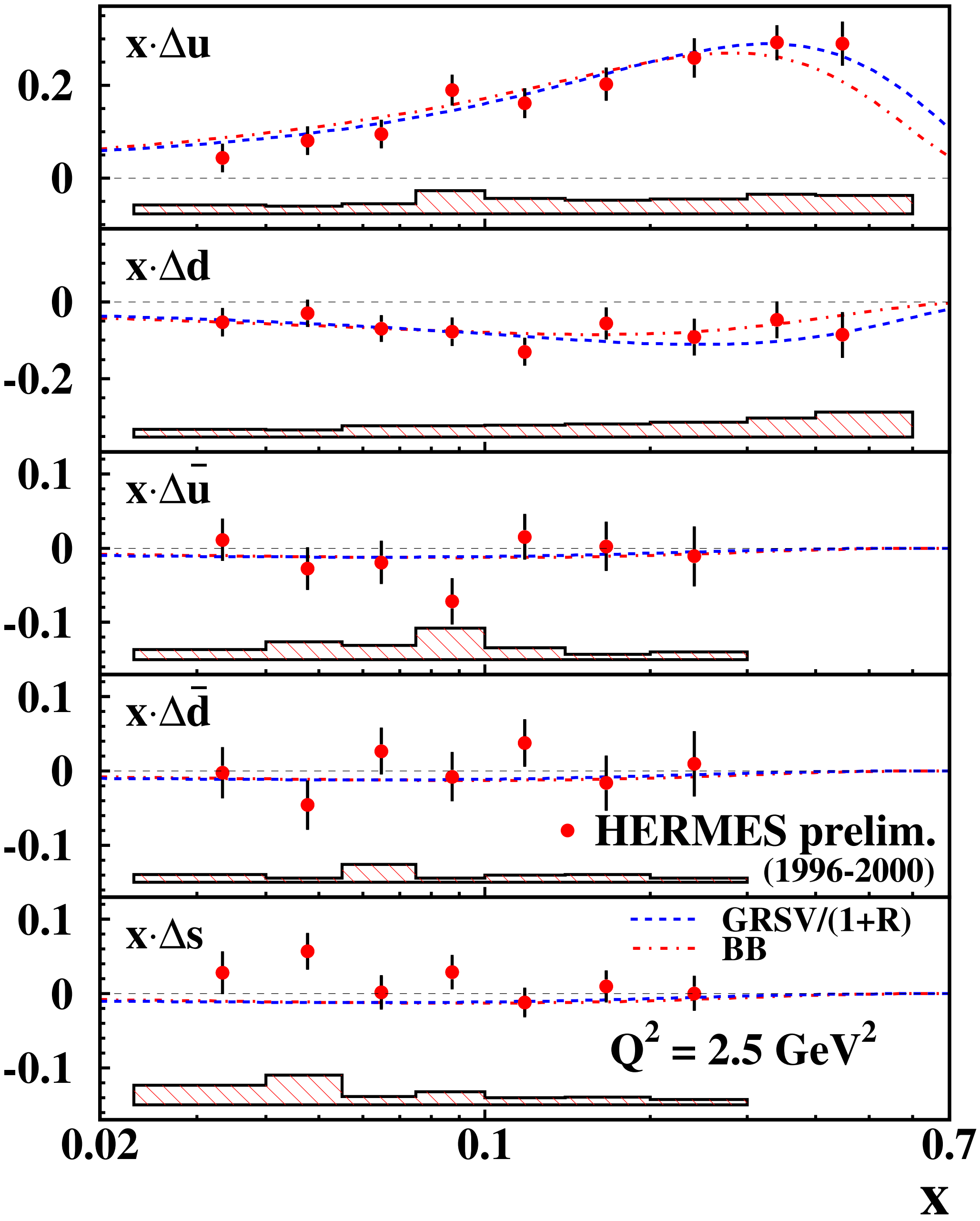
# Asymmetries On The Deuteron




- 1998–2000 data: RICH detector identifies $\pi^{\pm}$ and $K^{\pm}$
- $0.2 < z < 0.7$
- Asymmetries are independent of $z$ in this range

# HERMES Flavor Decomposition

For the first time, a five component, $\Delta u, \Delta\overline{u}, \Delta d, \Delta\overline{d}, \Delta s = \Delta\overline{s}$, decomposition using $\pi's, K's, p's$:

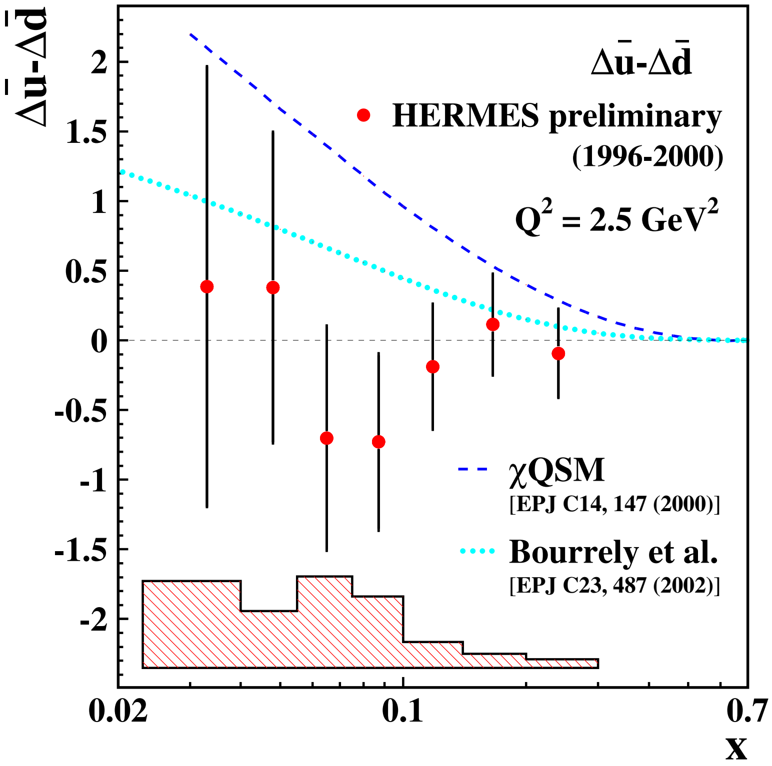



- No evidence for significant polarization of nonstrange sea.

- The strange sea appears to be positively polarized

# Remarks and Conclusions

- Helicity dist's confirm inclusive DIS results, i.e. $\Delta u >> 0$, $\Delta d < 0$; light sea is unpolarized, i. e. $\Delta \overline{u} = \Delta \overline{d} \approx 0$.
- No strong breaking of the flavor symmetry of the light sea.




- Result $\Delta(s + \overline{s}) > 0$ is unexpected. Can make a measurement of $\Delta s$ using $A_1^D(x)$ and $A_{1,D}^{K^+ + K^-}$:
  - Use fragmentation functions from $e^+e^-$ collider exp's.
  - Provides an independent check on strange polarization result.
  - Two component analysis also shows $\Delta(s + \overline{s}) > 0$.
- Analysis will continue with a comparison of $\Delta q_8 = \Delta u + \Delta d - 2\Delta s$ with predictions of SU(3) symmetry, i.e.

$$\Delta q_8 = (3F - D) \times C_{QCD} = 0.46 \pm 0.03$$

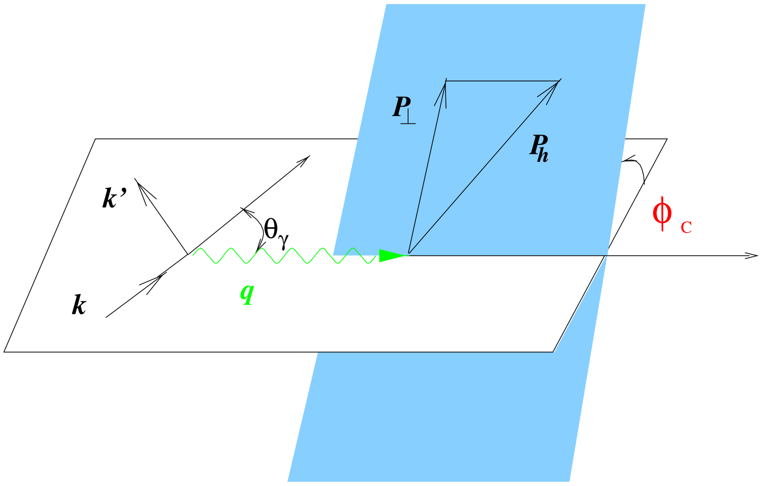
- The hypothesis of a large negative strange sea polarization as an explanation for the violation of the Ellis- Jaffe sum rule in inclusive scattering is ruled out.

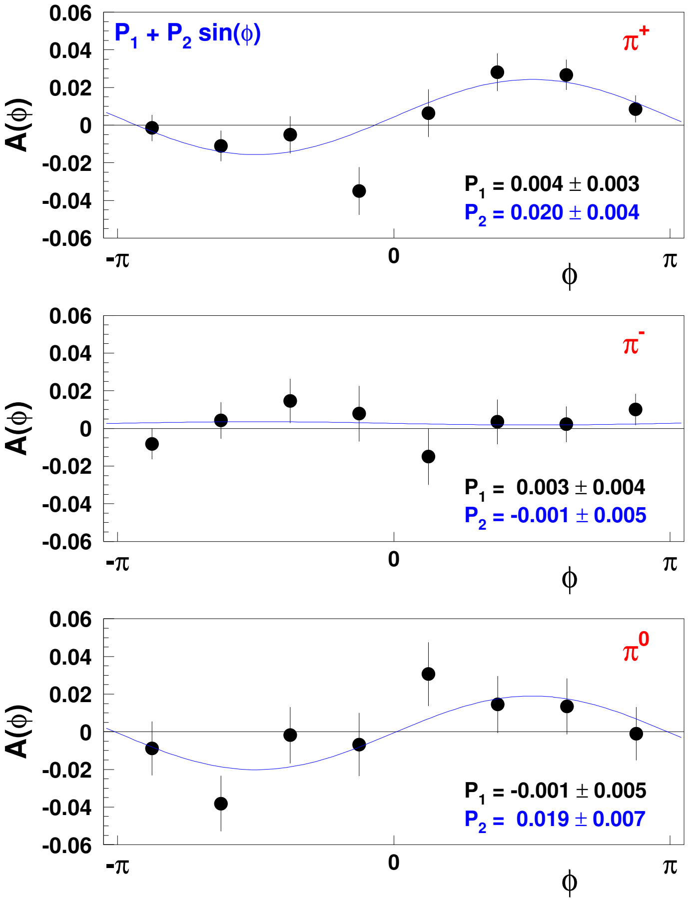
# Transverse Spin Physics -A Surprise

At leading order because of conservation of helicity, etc single-spin azimuthal asymmetries, $SSA's \approx 0$ - but -

Longitudinal target spin asymmetry:

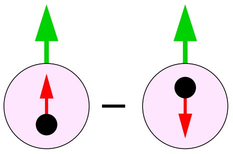
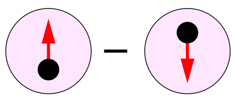
$$A_{UL}(\phi) = \frac{1}{P}\frac{N^-(\phi) - N^+(\phi)}{N^-(\phi) + N^+(\phi)}$$




- significant $sin(\phi)$ dependence for $\pi^+$ and $\pi^0$

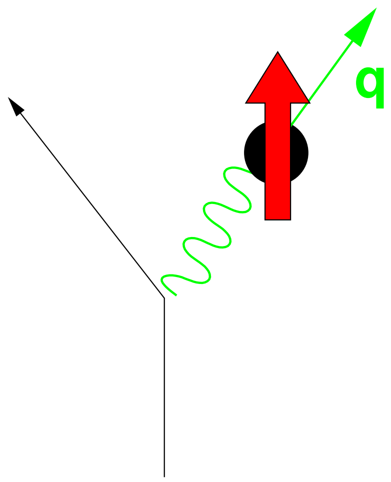
*$sin(\phi)$ moment $A_{UL}^{sin\ \phi}$ related to product of transversity $h_1(x)$ and Collins fragmentation function $H_1^\perp(z)$*

$$A_{UL}^{sin\ \phi} \sim h_1 =$$  $$\cdot\ H_1^\perp =$$ 

*$h_1(x, Q^2)$ with $f_1(x, Q^2)$ and $g_1(x, Q^2)$ provide complete description of nucleon quark structure at leading order.*

# Interpretation of $A_{UL}(\phi)$

"Longitudinally polarized" target has 2 spin components relative to virtual photon direction:




$$A(\phi) = \frac{1}{P_{target}} \frac{N^-(\phi) - N^+(\phi)}{N^-(\phi) + N^+(\phi)}$$
$$= \frac{S_L d\sigma_{UL}(\phi) + S_T d\sigma_{UT}(\phi)}{S d\sigma_{UU}(\phi)}$$

with $S_L/S \approx 1$ and $S_T/S \approx 1/Q$

Extract $sin\ \phi$ and $sin\ 2\phi$ moments:

$$A_{UL}^{sin\ \phi} = \frac{S_L \langle sin\ \phi\rangle_{UL} + S_T \langle sin\ \phi\rangle_{UT}}{S\langle 1\rangle_{UU}}$$

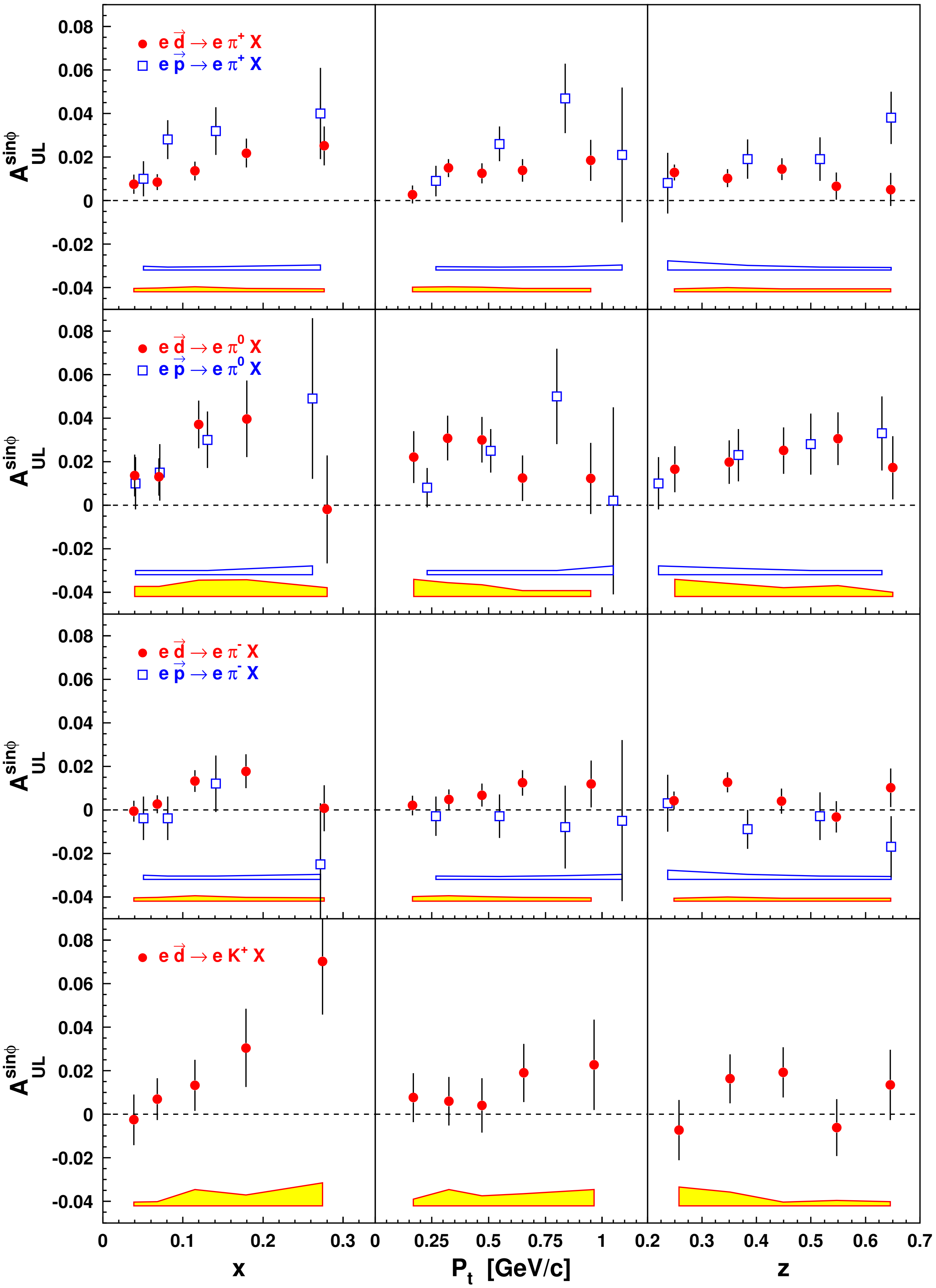
Complete treatment follows formalism of Mulders and coworkers

Mulders & Tangerman, NPB 461, 197 (1996)

$\langle sin\ \phi\rangle_{UL}$ involves interaction-dependent twist-3 functions $\tilde{h}_L$ and $\tilde{H}$ , but vanishing $\langle sin\ 2\phi\rangle$ suggests $\tilde{h}_L = h_1(x)$ and $\langle sin\ \phi\rangle \sim \frac{1}{Q} h_1 \cdot H_1^{\perp}$

- A single-spin asymmetry is time-odd and $h_1(x, Q^2)$ is chiral-odd.
- The Collins effect, descibed by t-odd chiral-odd fragmentation function, preserves the symmetries required by QCD.
- $A_{UL}^{sin\ \phi} > 0$ provides a "quark polarimeter" for measurement of $h_1(x, Q^2)$ in the nucleon.

# SSA's on Proton and Deuteron



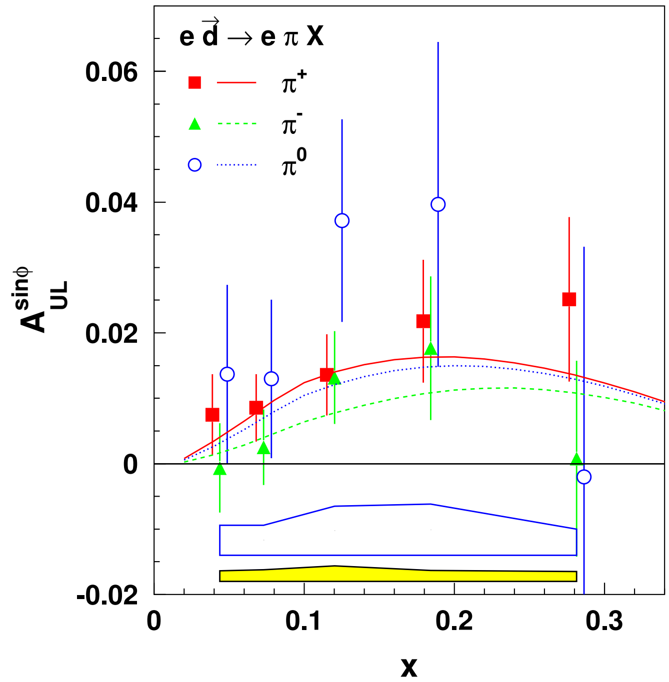

Deuteron data are preliminary

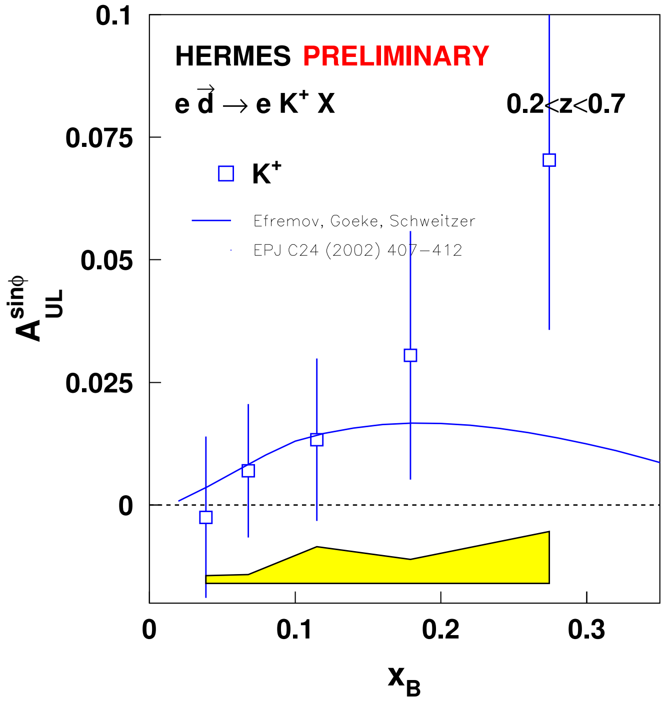
H. E. Jackson, PANIC02 Osaka

# Model Calculations

## $\chi$ Quark Soliton Model:

Efremov, Goeke & Schweitzer (Eur. Phys. J. C 24 (2002) 407)




Assumptions for the calculations:

- $h_1$ from the $\chi$ Quark Soliton Model
- $h_1^s = h_1^{\bar{s}} = 0$
- $\tilde{h}_L = 0$ (neglect interaction-dependent part of $h_L$)
- Collins function parameterised to fit HERMES proton data (and "optimistic" result from DELPHI $e^+e^- \longrightarrow 2$ jets):

$$\frac{\langle H_1^{\perp(1)} \rangle}{\langle D_1 \rangle} = (12.5 \pm 1.4)\%$$

- N.B. There was previously a sign error, resulting in a Collins function only half this size

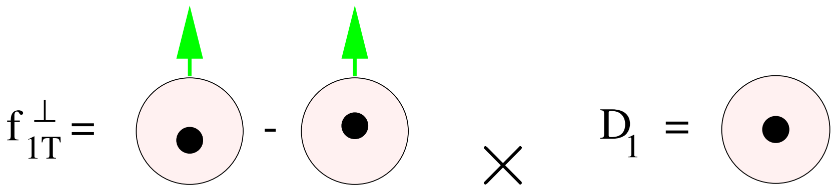
# SSA's - status and plans

## Original Predictions of Collins

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

But there are other possible mechanisms:

- "Sivers effect": Finding in a transverse-polarised target nucleon a quark with correlated primordial transverse momentum

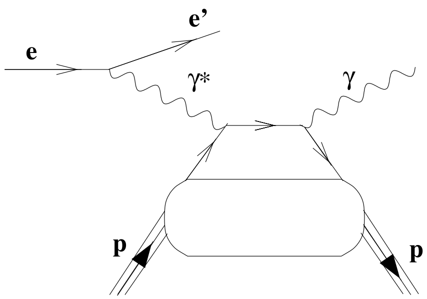


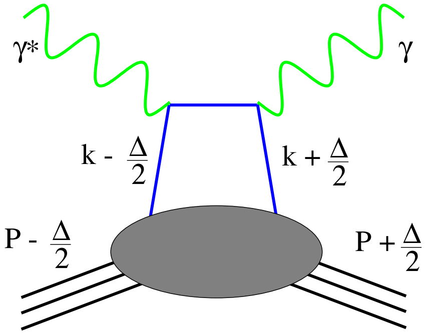

chiral-even, T-odd chiral-even, T-even

## Status of Measurements of Transversity

- Data being recorded now by HERMES and COMPASS with transverse target polarisation can distinguish leading-twist mechanisms through azimuthal dependence of the asymmetry:
  - Sivers effect depends on the azimuthal angle difference between the target spin axis and hadron plane $\propto \sin(\theta_h^l - \theta_S^l)$
  - Collins effect depends on the sum of these angles relative to the lepton scattering plane: $\propto \sin(\theta_h^l + \theta_S^l)$
- If the Collins effect is confirmed to be dominant, the first measurements of transversity can be extracted

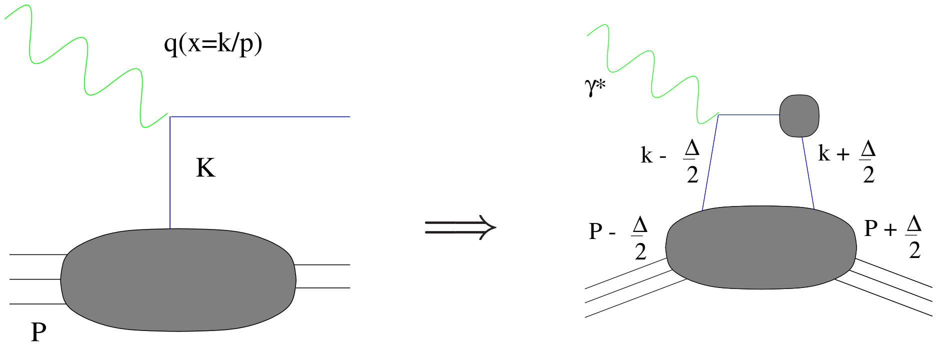
# Deep Virtual Compton Scattering and GPD's




On the lightcone:
$x \equiv k^+/P^+$
$\xi \equiv -\Delta^+/2P^+$
$t \equiv \Delta^2$

1.Simplest example of a new class of parton distributions - generalization of $q(x)$.




2.Generalized parton dist's(GPD's) describe removal of $q(k-\frac{\Delta}{2})$ and implantation of $q'(k+\frac{\Delta}{2})$.

For $\Delta = 0$ the GPD gives a simultaneous measurement of x and $p_T$. Its Fourier transform wrt $t$ gives parton impact parameter distribution.

Parton spatial distribution

Four new distributions:

| | |
|---|---|
| helicity conserving: | $H(x,\xi,t)$, $E(x,\xi,t)$ |
| helicity-flip: | $\tilde{H}(x,\xi,t)$, $\tilde{E}(x,\xi,t)$ |

Forward limit:

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

First moments: nucleon form factors

$$\int_{-1}^{1} dx H^q(x, \xi, \Delta^2) = F_1^q(\Delta^2)$$

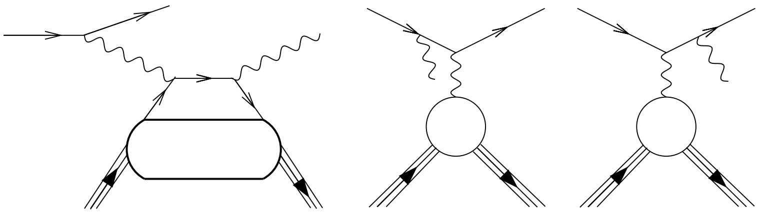
Second moment: $J^q = \frac{1}{2}\Delta\Sigma + L^q$

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

*Ji, PRL78(1997),610*

Complete description of $\psi_{proton}$!

# Single Spin and Charge Azmuthial Asymmetries

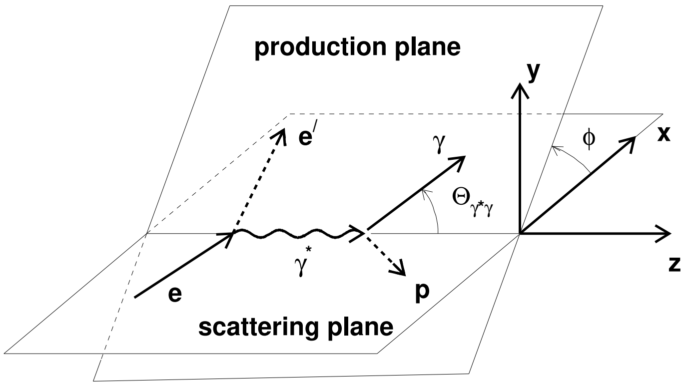


(a) (b)

DVCS is coherent with Bethe-Heitler bremsstrahlung

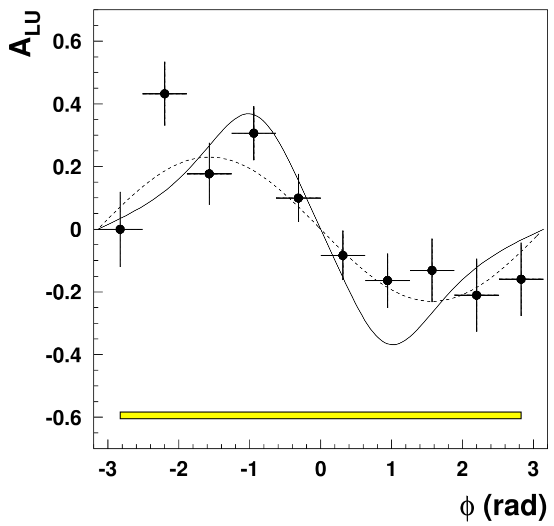
- Interference gives opportunity to isolate DVCS amplitudes:
$$d\sigma \propto |\tau_{DVCS} + \tau_{BH}|^2 =$$
$$|\tau_{DVCS}|^2 + |\tau_{BH}|^2 + (\tau^*_{DVCS}\tau_{BH} + \tau^*_{BH}\tau_{DVCS})$$
- Reverse charge of incident lepton(unpolarized beam)
$$d\Delta\sigma_{ch} \equiv d\sigma_{e^+} - d\sigma_{e^-} \sim cos(\phi) \times Re(\tau_{DVCS}\tau_{BH})$$
- Spin asymmetry w.r.t. beam helicity
$$d\Delta\sigma_{LU} \equiv d\sigma_{\leftarrow} - d\sigma_{\rightarrow} \sim sin(\phi) \times Im(\tau_{DVCS}\tau_{BH})$$
- Can measure absolute value and phase
- $(\tau_{DVCS}\tau_{BH})$ are functions of GPD's for DVCS

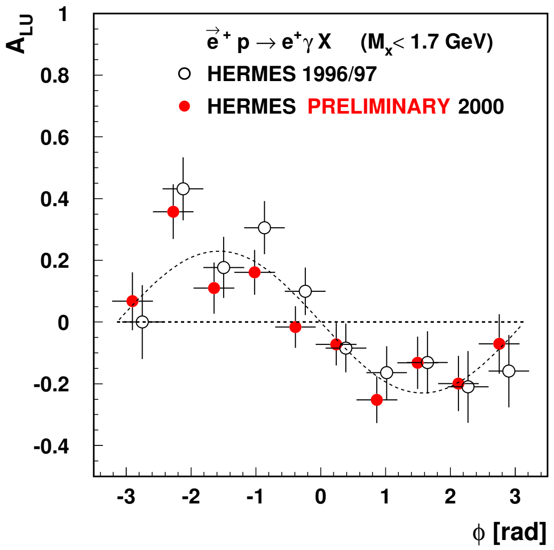
# HERMES DVCS Data



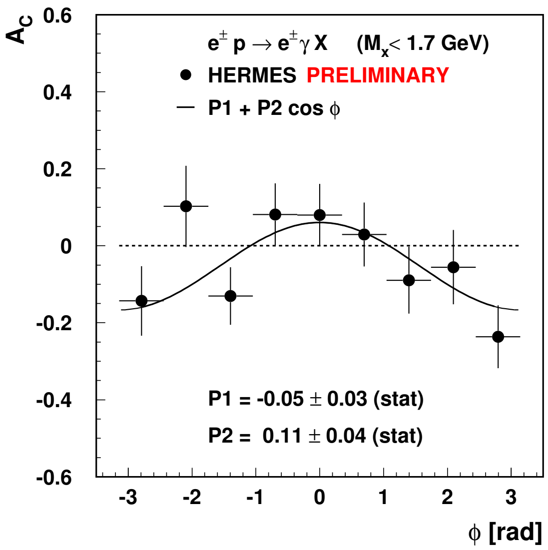

- 27.5 GeV $e^+$, both helicities
- beam polarization $\approx 50 - 60\%$
- polarized & unpolarized targets
- $Q^2 > 1GeV^2$, $W^2 > 4GeV^2$, $15 < \Theta_{\gamma^*\gamma} < 70mrad$

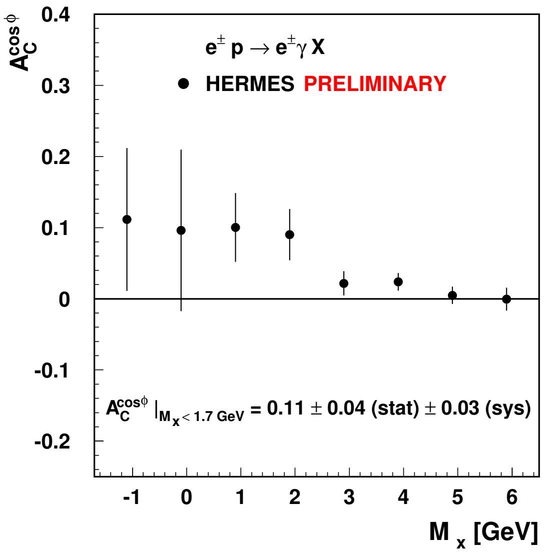
## Beam-spin asymmetry



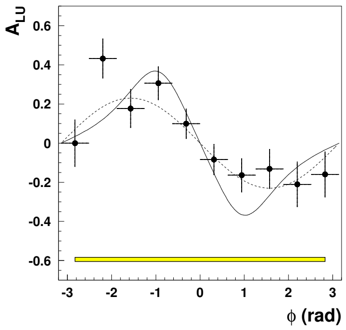




## Beam-charge asymmetry



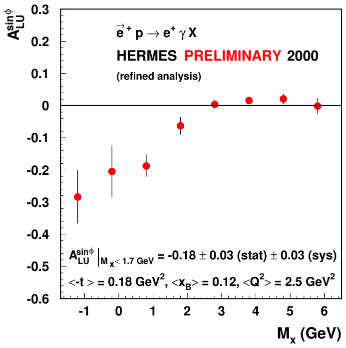



# DVCS - Outlook




Solid curve: GPD calulation for $t \approx 0$ assuming factorization into form factor and parton distributions

Kivel, Polyakov, and Vanderhaegen, Phy. Rev D63(2001),114014




Extracted sin($\phi$) moment:

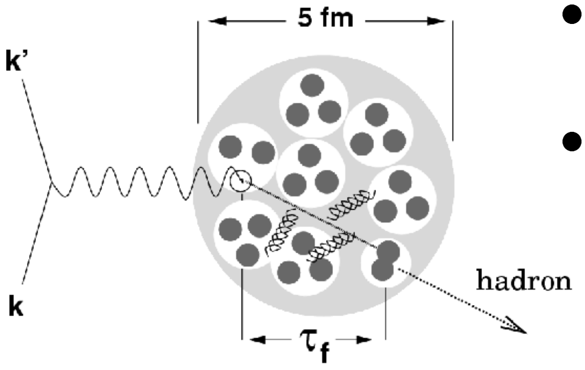
$$A_{LU}^{sin\phi} = -0.23 \pm 0.04(stat.) \pm 0.03(system)$$

$$theory = -0.37$$

ibid., Kivel, Polyakov, and Vanderhaegen

- Both real and imaginary parts of DVCS are being measured.
- Data at HERMES, CLAS(JLAB), and ZEUS are described by GPD calculations.
- Important issue - Is it feasible in future experiments to map out GPD's as a function of (x,$\xi$,t)?
- HERMES will measure DVCS in 2004-2005 with new Recoil Detector to improve exclusivity of data

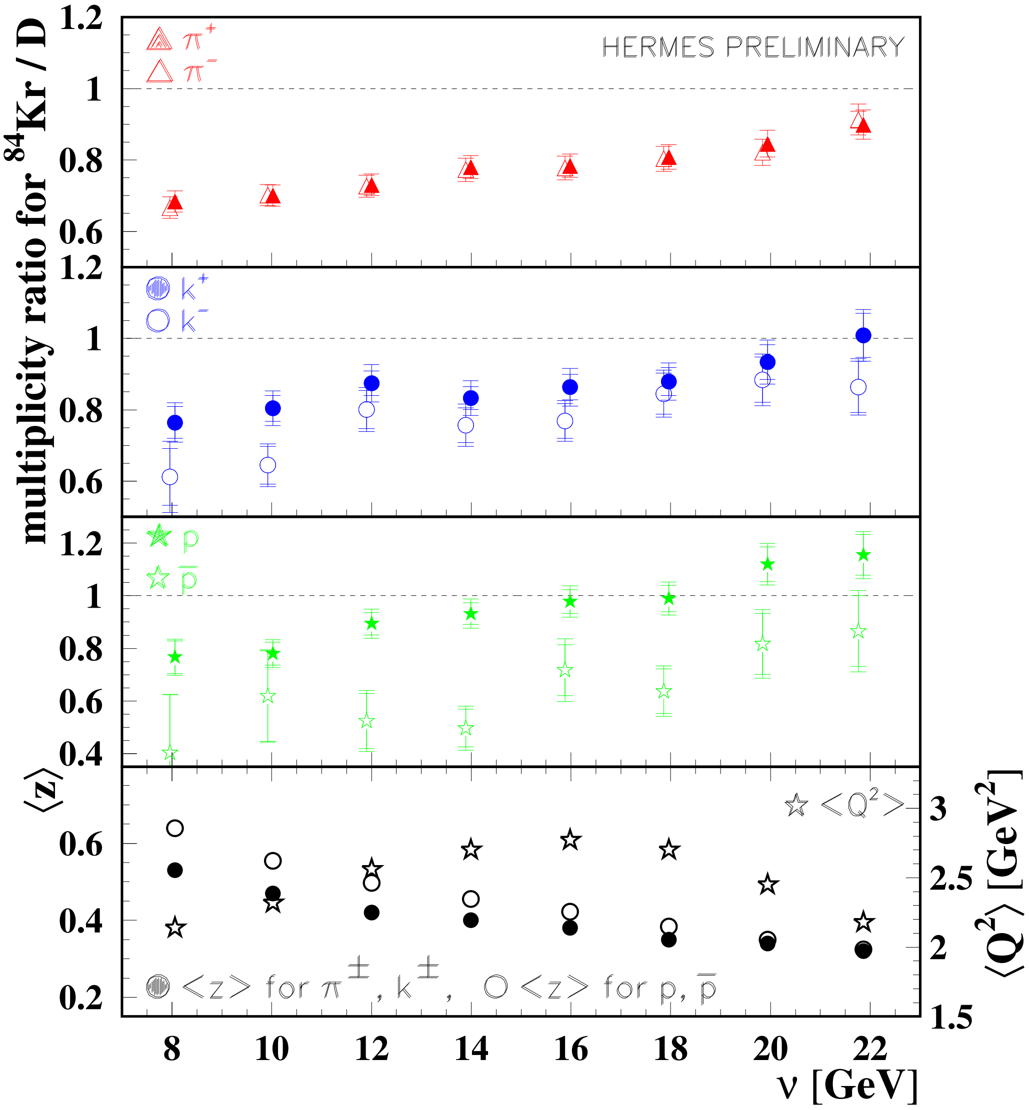
# Hadron formation in Nuclei




- Use nuclear medium(vary nuclear radius) as filter to study hadronization
- Measure the mass dependence of hadron multiplicity:

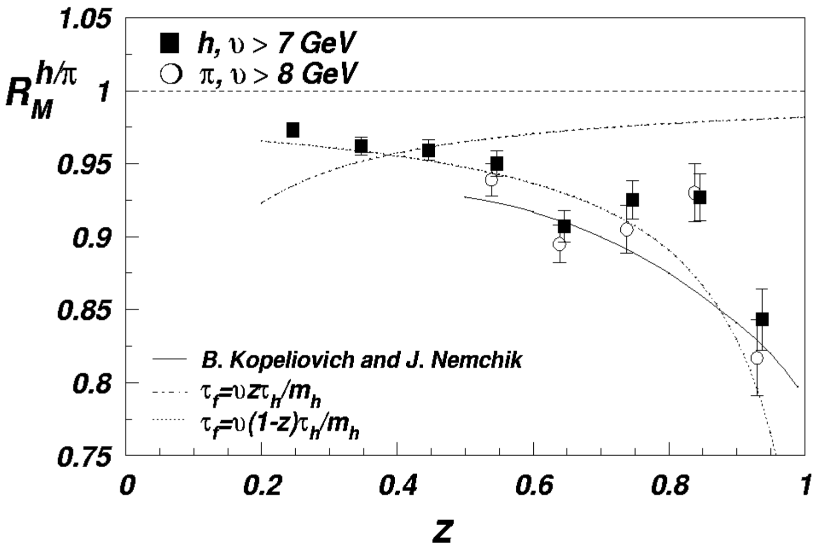
$$R_A^h(z,\nu) = \left(\frac{1}{N_e}\frac{d^2N_h}{dz\,d\nu}\right)_A \Bigg/ \left(\frac{1}{N_e}\frac{d^2N_h}{dz\,d\nu}\right)_D$$

New RICH detector gives clean measurements of $\pi$'s, $K$'s and $p(\overline{p})$'s:

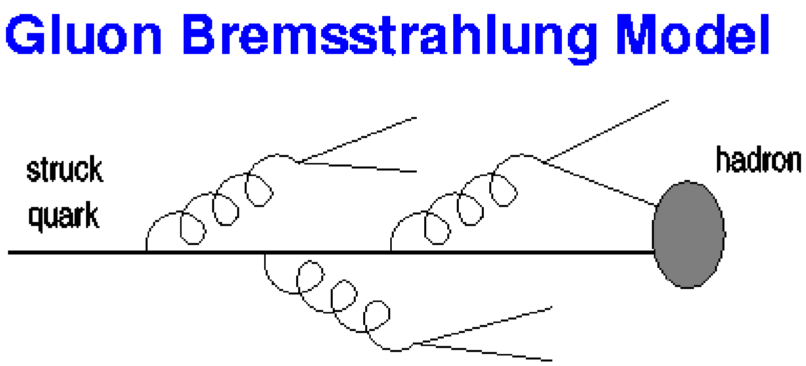


# Quark scattering and energy loss

Simple "time-scale" models do not work - need some kind of quark rescattering/gluon bremsstrahlung.




Data trends reproduced by Gluon- bremsstrahlung model:



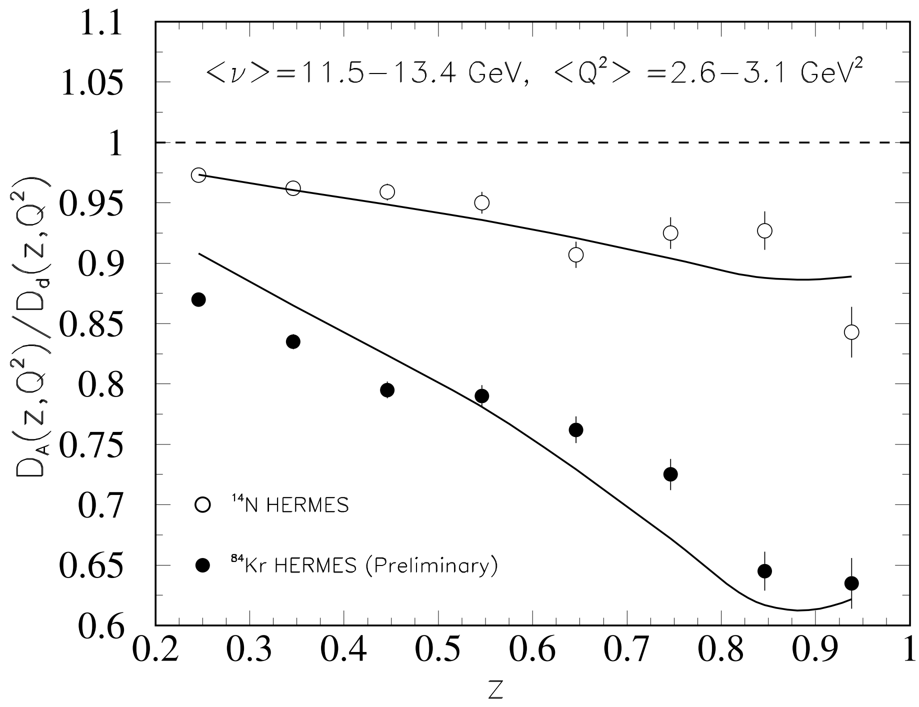

At high $z$:

- quark emits few gluons
- formation time is short $\tau_f = \nu(1-z)c_h$
- large nuclear attenuation of hadron

# Quark scattering and energy loss(cont'd)

Medium modification of parton fragmentation by multiple scattering and gluon bremsstrahlung:

E. Wang and X. N. Wang, *hep-ph/0202105*




Can calculate a parton energy loss from the medium modification:

$$\tilde{D}_{a\to h}(z) \approx \frac{1}{1-\Delta E/E} D_{a\to h}\left(\frac{z}{1-\Delta E/E}\right)$$

$dE/dx \approx 0.5$ GeV/fm

Compared to:

$dE/dx \approx 7$ GeV/fm

For Au + Au collisions($\sqrt{s} = 130$ GeV) at RHIC.

# Final words

- Decomposing the nucleon spin remains a challenge

$$\boxed{< {s^N}_z >= \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L_z}$$

  But we are making progress - a flavor decomposition of $\Delta q$ is emerging - GPD's may provide access to $L_q$.

- Measurements of transversity, $h_1$, will provide a complete description at L.O. of parton distributions.

- With GPD's "at least in principle" we can probe the nucleon wave function at the partonic level.

- A host of other interesting questions such as quark hadronization, parton duality, ... are accessible in DIS, even now with the limited luminosities available.