Future Transversity Measurements with HERMES

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Transversity Distribution

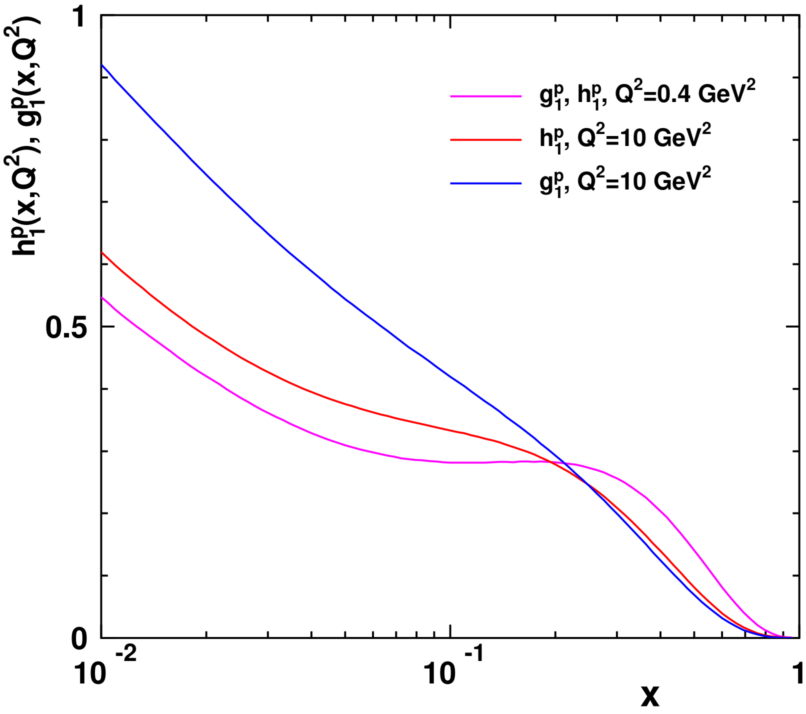
Three twist-2 quark distributions:

- quark number density distribution $q(x, Q^2)$
- quark helicity distribution $\Delta q(x, Q^2)$
- quark transversity distribution $\delta q(x, Q^2)$

For non-relativistic quarks: $\delta q(x) = \Delta q(x)$.

No transversity distribution for gluons. $\Longrightarrow$ $\delta q(x, Q^2)$ does not mix with gluons under QCD evolution.

QCD-evolution of $\delta q(x, Q^2)$ is well established theoretically.
Example for LO evolution of proton structure functions
$g_1(x, Q^2) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x, Q^2)$ and $h_1(x, Q^2) = \frac{1}{2}\sum_i e_i^2 \delta q_i(x, Q^2)$



Possible methods to measure $\delta q(x)$ in SIDIS

The $\delta q(x, Q^2)$ is a chiral-odd distribution and as such it decouples from all hard processes that involve only one quark distribution (or fragmentation) function.

$$A \sim \sum_i e_i^2 \delta q_i(x) H_i(z)$$

i) Twist-3 pion production in SIDIS (Jaffe, Ji, 93)

ii) Measurement of the transverse polarization of Λ's in the current fragmentation region (Baldracchini,82 Jaffe,96)

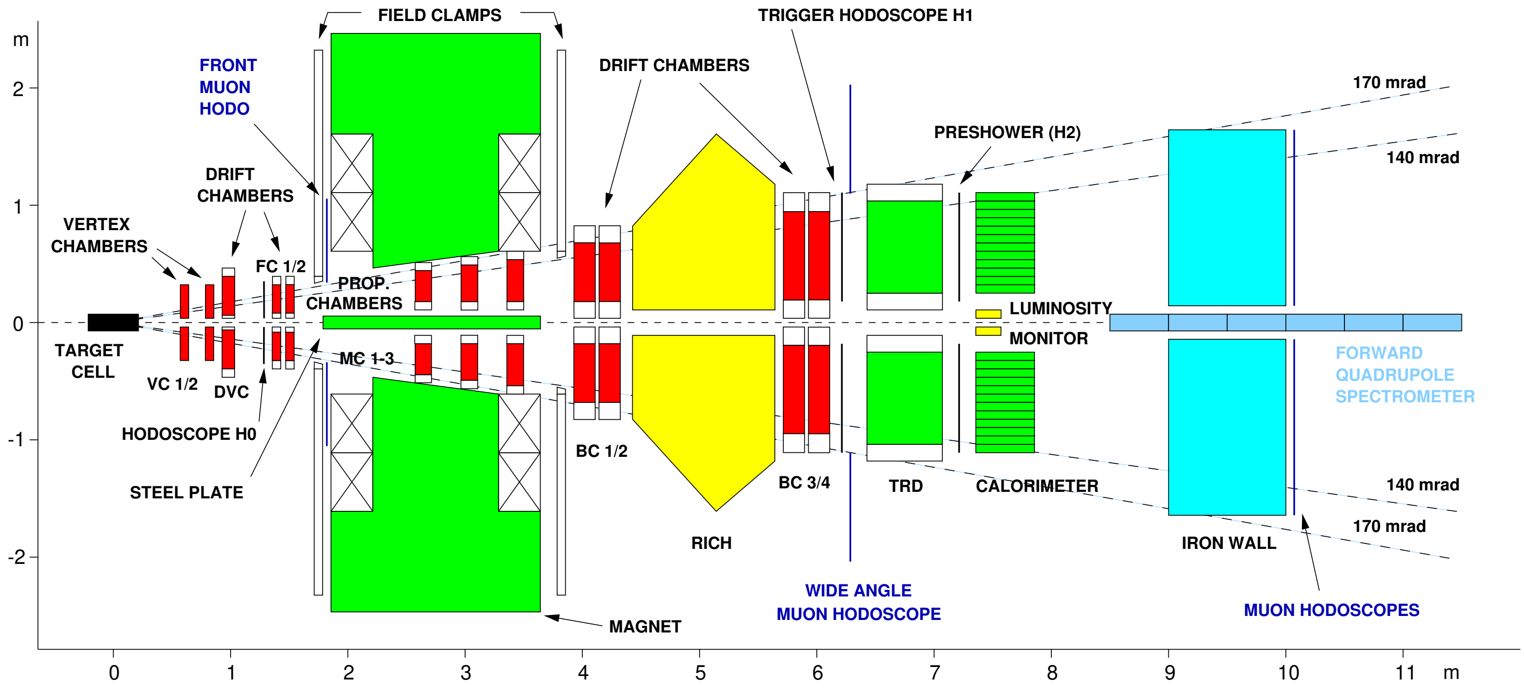
iii) Observation of the Collins effect in quark fragmentation through the measurement of pion single target-spin asymmetries (Collins,93, Kotzinian, 95, Mulders et al,96).

iv) Measurement of correlation between the transverse spin vector of the target nucleon and the normal to the two-meson plane (Jaffe et al.,97)

v) Measurement of spin-1 hadron production in SIDIS (Bacchetta, Mulders)

Methods ii) - v) rely on POLARIMETRY of the scattered transversely polarized quark and require a transversely polarized target only.

The HERMES Spectrometer



- Polarized positrons of energy 27.5 GeV in the HERA storage ring, $P_B = 0.55 \pm 0.02$
- Polarized internal hydrogen gas target, $P_T = 0.86 \pm 0.04$
- Forward spectrometer, $0.04 < \theta <$ 0.22 rad.
- Particle ID: RICH (Threshold Čerenkov), TRD, Preshower, Lead Glass Calorimeter.
- Track reconstruction: $\delta P/P = 0.7 \div 1.3\%$, $\delta\theta \leq$ 0.6 mrad.

Transversity Analysis at HERMES

$$ep^{\uparrow}(d^{\uparrow}) \to e'\pi X, \;\; E = 27.5 \text{ GeV}, \;\; P_T = 0.75, \;\; P_B = 0.5$$

Statistics expected for 2002+: $7 \cdot 10^6$ reconstructed DIS events

$$Q^2 > 1 \text{ GeV}^2, \quad W > 2 \text{ GeV}, \quad 0.02 < x < 0.7, \quad y < 0.85.$$

From HERMES Monte-Carlo program: pion distributions, acceptance.

Cuts for the kinematic variables of the pion:

$$x_F > 0., \quad z > 0.1, \quad P_{h\perp} > 0.05 \text{ GeV} .$$

To simulate A_T, the approximation $\delta q(x) = \Delta q(x)$ was used (relatively low Q^2-values at HERMES)

$Q^2 = 2.5$ GeV^2 (average value for the HERMES)

GS LO parameterization for $\Delta q(x)$
GRV94LO parameterization for $q(x)$

Twist-3 Pion Production is SIDIS

$\vec{e}p^{\uparrow} \to e'\pi X$ (Jaffe, Ji 1993)

$$\frac{d^4\Delta\sigma^h}{dxdydzd\phi} = \frac{e^4}{4\pi^2 Q^2}\cos\phi\,\gamma\sqrt{1-y}\Big[G_T^h(x,z) - G_1^h(x,z)(1-\frac{y}{2})\Big]$$

$$G_1^h(x,z) = \frac{1}{2}\sum_q e_q^2 \Delta q(x)\hat{q}^h(z),$$

$$G_T^h(x,z) = \frac{1}{2}\sum_q e_q^2 [\Delta_T q(x)\hat{q}^h(z) + \frac{\delta q(x)}{x}\frac{\hat{e}_q^h(z)}{z}]$$

$\hat{q}^h(z)$ — the usual twist-2 FF

$\hat{e}_q^h(z)$ — unknown chiral-odd twist-3 FF

$\Delta_T q(x)$ — contribution of quark q into $g_T(x) = g_1(x) + g_2(x)$.

A simple relation between $\hat{e}(z)$ and $\hat{q}(z)$ has been obtained in the chiral quark model (Ji, Zhu 1993)

$$\hat{e}(z) = z\hat{q}(z)\frac{m_q}{M} \approx \frac{1}{3}z\hat{q}(z)$$

where $m_q \approx \frac{1}{3}M$ is the constituent quark mass.

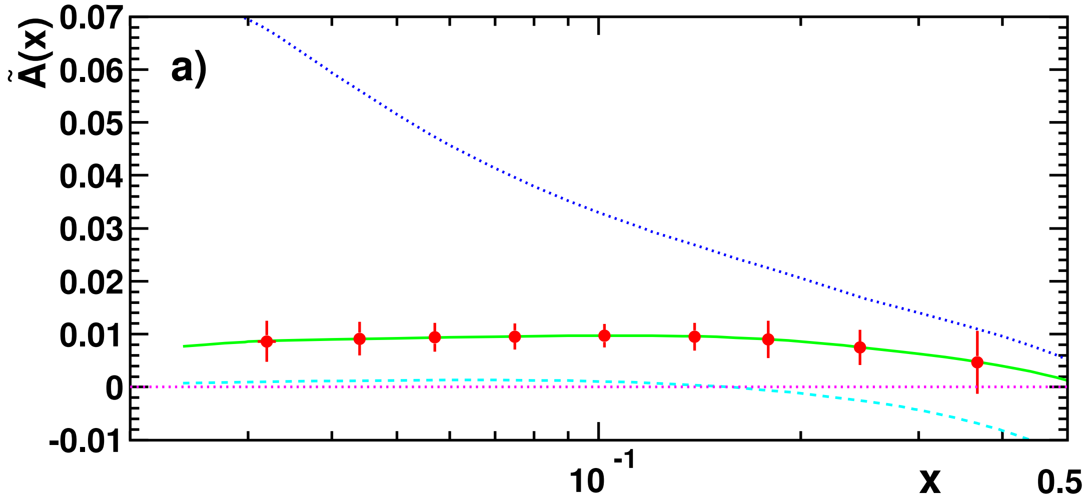
Twist-3 Pion Production at HERMES

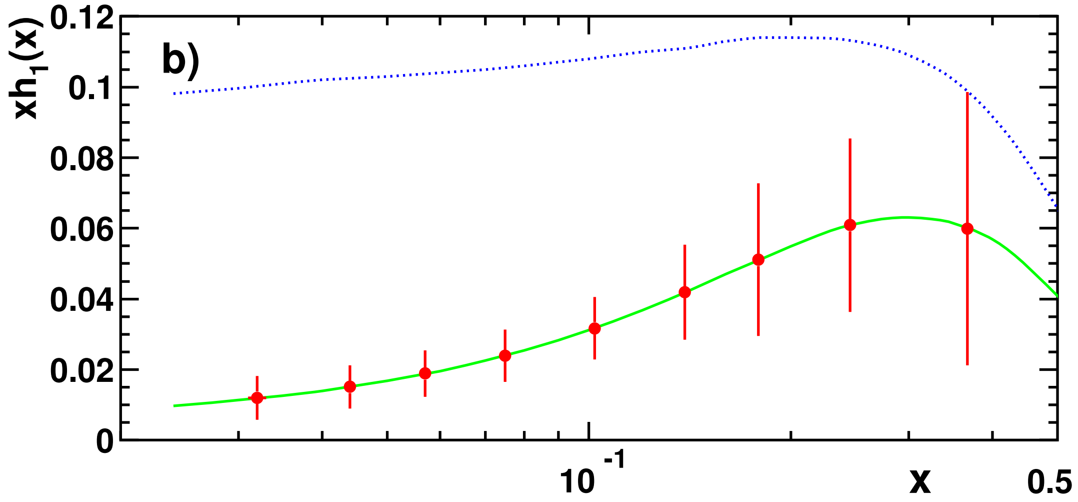
We use the asymmetry $\tilde{A}^h(x,y,z) = \frac{1}{\cos\phi} A^h(x,y,z,\phi)$.

A particular simple case is for $\pi^+ + \pi^-$ asymmetry:

$$\tilde{A}^{\pi^+ + \pi^-} = \frac{g_T(x) + \frac{1}{x} h_1(x) r(z) - (1 - y/2) g_1(x)}{F_1(x)}$$

where $r(z) = \frac{1}{z}\frac{\hat{e}(z)}{\hat{q}(z)}$ was taken to be $1/3$ (Ji, Zhu 1993).





Dashed curves — $\delta q(x) = 0$, dotted curves — saturation of the Soffer's inequality.

Two-Meson Correlation with Transverse Spin

The interference effect between the s- and p-waves of the two-meson system allows the quark's polarization information to be carried through $\vec{k}_+ \times \vec{k}_- \cdot \vec{S}_\perp$. (Jaffe et al., 1998)

For $eN^\uparrow \to e'\pi^+\pi^- X$

$$\mathcal{A}_{\perp T} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2}\cos\phi \;\; \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1) \times \frac{\sum_a e_a^2 \delta q_a(x)\, \delta\hat{q}_I^a(z)}{\sum_a e_a^2 q_a(x)\left[\sin^2\delta_0 \hat{q}_0^a(z) + \sin^2\delta_1 \hat{q}_1^a(z)\right]}$$

$\delta\hat{q}_I^a(z)$ — unknown chiral-odd interference quark FF

$\delta_{0,1} = \delta_{0,1}(m^2)$ — strong interaction $\pi\pi$ phase shifts

$\cos\phi = \vec{k}_+ \times \vec{k}_- \cdot \vec{S}_\perp / |\vec{k}_+ \times \vec{k}_-||\vec{S}_\perp|$ — analog of the Collins angle defined by the $\pi^+\pi^-$ system

$\hat{q}_0$ and $\hat{q}_1$ — spin-average FF for the σ and ρ resonances.

The interference FF $\delta\hat{q}_I$ has an upper bound

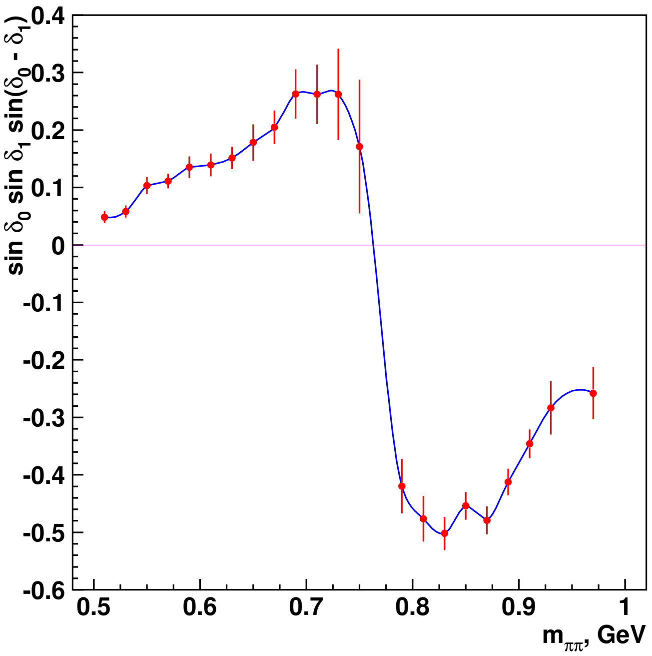
$$\delta\hat{q}_I^2 \leq 4\hat{q}_0\hat{q}_1/3$$

for each flavor.

It could be measured in $e^+e^- \rightarrow (\pi^+\pi^- X)(\pi^+\pi^- X)$.
Nothing has been published yet.

The final state phase generated by the s-p interference is crucial to the method. If the data are not kept differential in enough kinematic variables, the effect will almost certainly average to zero.

In particular the two-meson invariant mass, m, must be kept differential. The interference averages to about zero when integrating over the mass of the two-pion system due to a factor $\sin(\delta_0 - \delta_1)$.



Two-Meson Correlations at HERMES

For the proton target the asymmetry takes the form:

$$\mathcal{A}_{\perp\top} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2}\cos\phi\ \sin\delta_0\sin\delta_1\sin(\delta_0-\delta_1)\ \times$$

$$\frac{\delta u_v(x) - \frac{1}{4}\delta d_v(x)}{(u(x)+\bar{u}(x)) + \frac{1}{4}(d(x)+\bar{d}(x))}\cdot\frac{\delta\widehat{u}_I(z)}{\sin^2\delta_0\widehat{u}_0(z) + \sin^2\delta_1\widehat{u}_1(z)}\,.$$

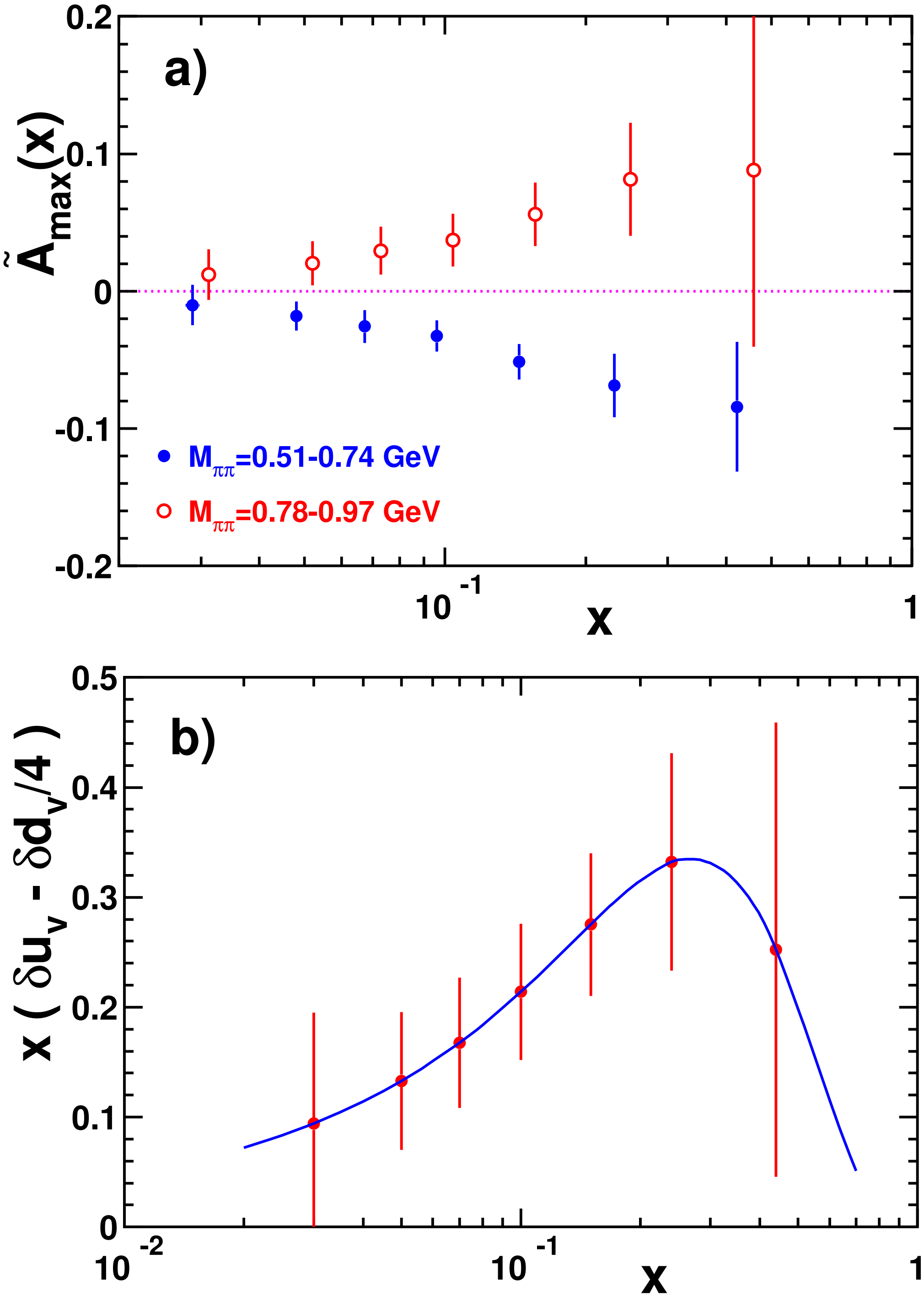
A *maximally* possible asymmetry with $\delta\widehat{u}_{I}{}^2 = 4\widehat{u}_0\widehat{u}_1/3$.

The maximal asymmetry does not depend on z

$$A_{max}^{ep\to e'\pi^+\pi^-X} = -\frac{\pi}{4}\frac{\sqrt{6}(1-y)}{1+(1-y)^2}\cos\phi\,\frac{1}{\sqrt{3}}\sin(\delta_0-\delta_1)$$

$$\times\frac{\delta u_v(x) - \frac{1}{4}\delta d_v(x)}{(u(x)+\bar{u}(x)) + \frac{1}{4}(d(x)+\bar{d}(x))}\,.$$

$$\tilde{A}_{max} = P_T\cdot A_{max}/\cos\phi$$

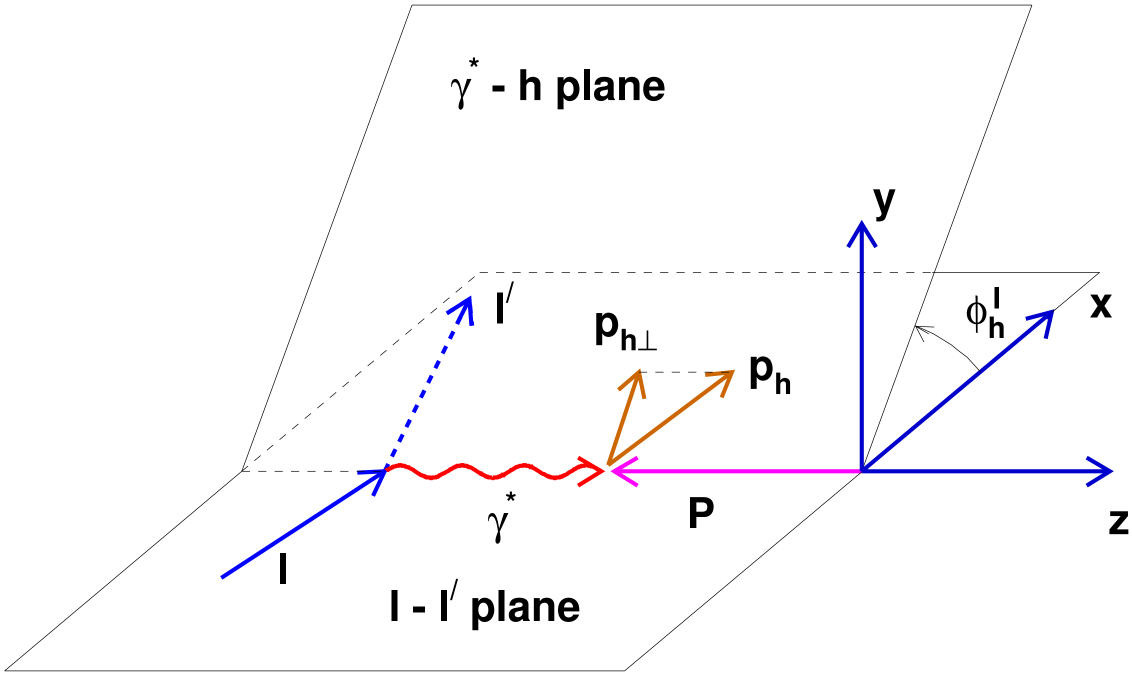


The projected accuracies are the best what could be measured at HERMES. A real level of the accuracy depends on the size of the interference FF $\delta\widehat{u}_I(z)$ and of the two-pion FF's $\widehat{u}_{0,1}(z)$.

Measurement of $\delta q(x)$ via the Collins effect

Weighted asymmetry [Mulders, Tangermann 96, Kotzinian, Mulders 97]

$$A_T(x,y,z) \equiv \frac{\int d\phi^\ell \int d^2 P_{h\perp} \frac{|P_{h\perp}|}{z M_h} \sin(\phi_s^\ell + \phi_h^\ell)\ \left(d\sigma^\uparrow - d\sigma^\downarrow\right)}{\int d\phi^\ell \int d^2 P_{h\perp} (d\sigma^\uparrow + d\sigma^\downarrow)}$$



Factorization w.r.t. x and z:

$$A_T(x,y,z) = f \cdot P_T \cdot D_{nn} \cdot \frac{\sum_q e_q^2\ \delta q(x)\ H_1^{\perp(1)q}(z)}{\sum_q e_q^2\ q(x)\ D_1^q(z)}$$

$D_{nn} = (1-y)/(1-y+y^2/2)$ - transverse spin transfer coefficient.

u-quark Dominance in π^+ Production

In a first analysis the assumption of u-quark dominance in the π^+ production is quite reasonable:

i) 70÷90% of π^+ originate from the fragmentation of struck u-quark for a proton target (only slightly smaller for a deuteron target);

ii) Sum rule for T-odd fragmentation functions [Schäfer, Teryaev, 99] $\rightarrow$ contributions from non-leading parton fragmention is expected to be severely suppressed:

$$\frac{H_1^{\perp(1)d\rightarrow\pi^+}(z)}{D_1^{d\rightarrow\pi^+}(z)} = \frac{H_1^{\perp(1)\bar{u}\rightarrow\pi^+}(z)}{D_1^{\bar{u}\rightarrow\pi^+}(z)} = 0$$

iii)

$$\frac{\Delta q_{sea}(x)}{q_{sea}(x)} \ll \frac{\Delta q(x)}{q(x)}$$

Assume

$$\frac{\delta q_{sea}(x)}{q_{sea}(x)} \ll \frac{\delta q(x)}{q(x)}$$

Then

$$A_p^{\pi^+}(x,y,z) = P_T \cdot D_{nn} \cdot \frac{\delta u(x)}{u(x)} \cdot \frac{H_1^{\perp(1)}(z)}{D_1(z)}$$

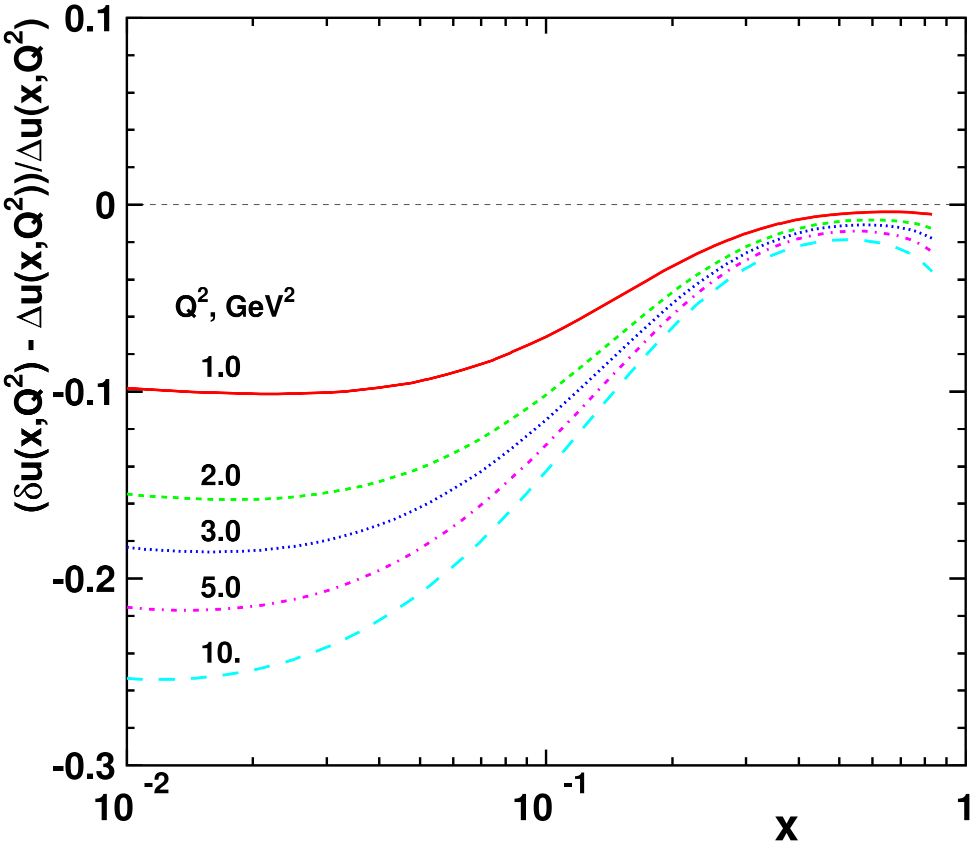
$$A_d^{\pi^+}(x,y,z) = f_D \cdot P_T \cdot D_{nn} \cdot \frac{\delta u(x) + \delta d(x)}{u(x) + d(x)} \cdot \frac{H_1^{\perp(1)}(z)}{D_1(z)}$$

where $f_D = 1 - \frac{3}{2}\omega_D$, $\omega_D = 0.05$

Normalization Ambiguity

The factorized form with respect to x and z allows the simultaneous reconstruction of the SHAPE for both $\delta u(x)$ and $H_1^{\perp(1)}(z)/D_1(z)$, while the relative normalization cannot be fixed without a further assumption.

Use the expectation that $\delta q(x)$ coincides with $\Delta q(x)$ at small Q^2.



The differences are expected to be smallest for intermediate and large x. Hence the assumption

$$\delta q(x_0) = \Delta q(x_0)$$

at $x_0 = 0.25$ was made to resolve the normalization ambiguity.

Polarized Fragment. Function $H_1^{\perp(1)q}(z)$

Experimental indications that $H_1^{\perp(1)q}(z)$ is non-zero:

i) azimuthal correlations between particles from opposite jets in Z decay at DELPHI [A.Efremov et al., 99]

ii) a single target-spin asymmetry measured at HERMES [PRL **84**, 4047 (2000)]

Analyzing power in transversely polarized quark fragmentation (Collins guess):

$$A_C(z,k_T) \equiv \frac{|k_T| H_1^{\perp q}(z, z^2 k_T^2)}{M_h D_1^q(z, z^2 k_T^2)} = \frac{M_C\,|k_T|}{M_C^2 + |k_T^2|},$$

$M_C \simeq 0.3 \div 1.0$ GeV

Gaussian parameterization for the quark transverse momentum dependence in the unpolarized fragmentation function

$$D_1^q(z, z^2 k_T^2) = D_1^q(z)\,\frac{R^2}{\pi\, z^2}\,\exp(-R^2 k_T^2),$$

leads to

$$H_1^{\perp(1)q}(z) = D_1^q(z)\frac{M_C}{2M_h}\left(1 - M_C^2 R^2 \int_0^\infty dx\,\frac{\exp(-x)}{x + M_C^2 R^2}\right).$$

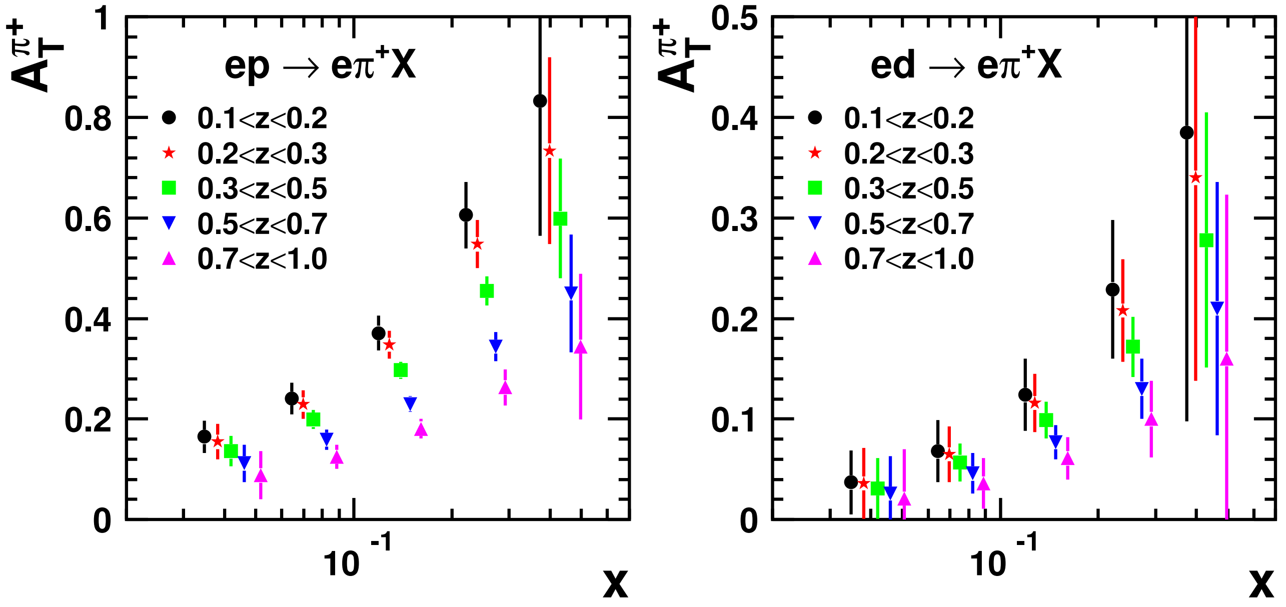
$R^2 = z^2/b^2$

In the following $M_C = 0.7$ GeV and $b^2 = 0.25$ GeV^2
Consistent with the HERMES and DELPHI measurements.

Single Target-Spin Asymmetry

To improve the separation of the struck quark fragm. region, an additional cut $W^2 > 10$ GeV^2 was introduced.

The simulated data were divided into 5x5 bins in (x, z).



The experimental data consist of 25 measured values, as opposed to 9 unknown function values:

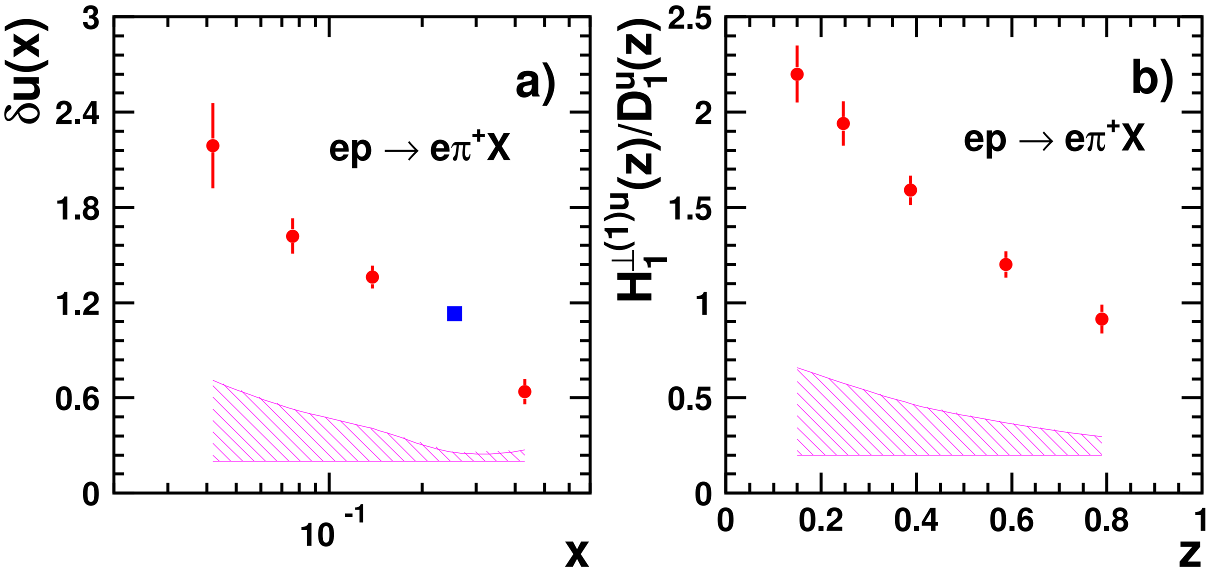
4 values for $\delta u(x_i)$ $[\delta u(x_i) + \delta d(x_i)]$ and

5 values for $H_1^{\perp(1)u}(z_j)/D_1^u(z_j)$

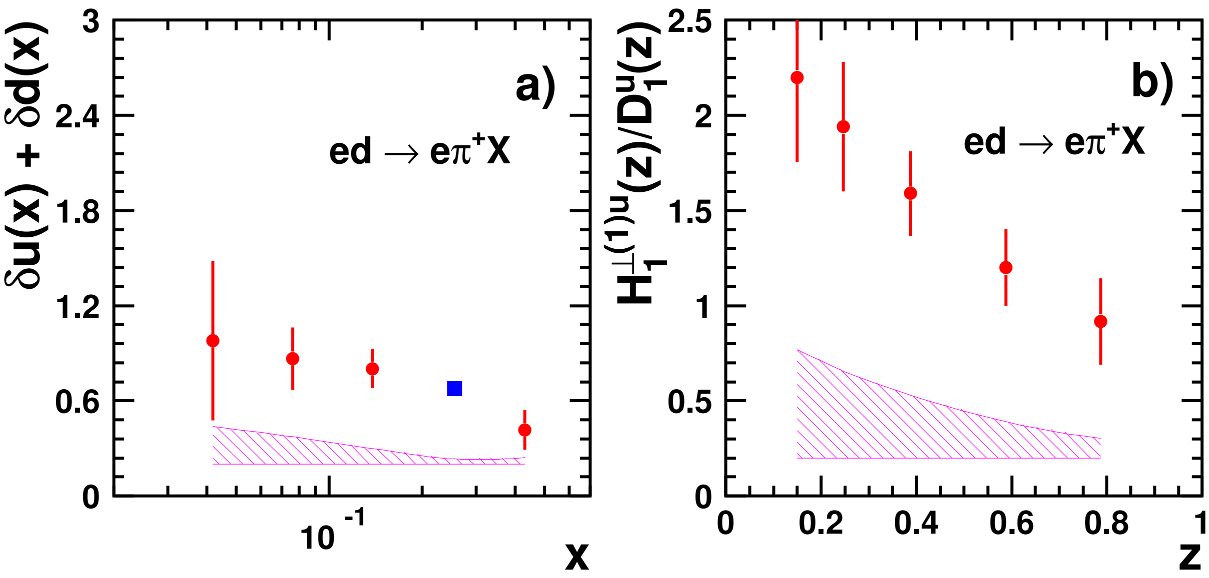
The standard procedure of χ^2 minimization was applied to reconstruct the values for both $\delta u(x)$ $[\delta u(x_i) + \delta d(x_i)]$ and $H_1^{\perp(1)u}(z)/D_1^u(z)$ and to evaluate their projected statistical accuracies.

Projections for Statistical Accuracy

Projections for $\delta u(x)$ and $H_1^{\perp(1)u}(z)/D_1^u(z)$ (PROTON target)



Projections for $\delta u(x) + \delta d(x)$ and $H_1^{\perp(1)u}(z)/D_1^u(z)$
(DEUTERON target)



Summary

- There are many methods proposed to measure the transversity. All of them suffer from a necessity to reconstruct two unknown functions simultaneously.

- HERMES can make a statistically rather precise first measurement of $\delta u(x)$ and of the polarized fragmentation function $H_1^{\perp(1)u}(z)$ with a transversely polarized proton target in 2002+ based on a study of the Collins effect

- A study of the twist-3 pion production may offer another measurement of the $h_1(x)$ if the twist-3 fragmentation function $\widehat{e}(z)$ is quite sizeable

- In addition the HERMES has a capability to access the transversity distribution via measurements of the two-meson correlations and transverse polarization of Λ's

- We need new high luminosity polarized lN experiments to measure the transversity distributions with an accuracy comparable to what we have now for the helicity distributions.