Single-spin azimuthal asymmetries in exclusive electroproduction of π^+ mesons

The goal of the measurement presented here is a first exploration a new and powerful description of the structure of the proton: **Generalized Parton Distributions** (GPD's). These new functions provide a much richer description of the proton than anything that has been measured to date ... in fact, they offer the tantalizing possibility to construct a *complete* map of the proton's wavefunction.

We know that the familiar proton is actually an enigmatic composite object made out of pointlike partons: quarks, anti-quarks, and gluons. Presently our description of its structure comes in two different forms: form factors and parton distribution functions (PDF's). These functions are commonly measured by scattering electron beams from proton targets. Quantum mechanically, we describe this scattering by the exchange of a short-lived virtual photon γ^* between the beam and the target (as shown in the top left corner of Fig.1a) ... it is this photon which really 'sees' the target. Form factors describe the overall shape of the target proton: how big is it? is its surface sharply defined or does the charge density fall off gradually? These functions are measured in *elastic* scattering experiments, where the electron essentially bounces off the proton without altering its nature. Classically, you might think of the virtual photon in this situation as having a very long wavelength ... it sees the shape of the proton but not what's inside it. On the other hand, experimenters also perform *deep-inelastic* scattering (DIS) experiments, using very high energy beams. Here, the virtual photon might be thought of classically as having a very short wavelength: it scatters from a single pointlike, electrically charged quark inside the proton and kicks it out, thereby destroying the proton and producing many hadronic particles from the debris. DIS experiments yield *parton-distribution functions*, which are probabilistic descriptions of how much momentum an individual quark carries.

Form factors describe the proton's overall shape, while PDF's describe the distribution of the quarks inside it. What's missing? Let's think about a more familiar system: an atom, and the electrons orbiting around it in shells. A form factor type of description would tell us the average radius of the orbits ... a PDF-type of description would tell us the average speed of an electron and how much it can vary. But neither of these descriptions will reveal the *twisting* motion of the electrons about a particular axis! Another thing we're missing is information about *correlations*: do the electrons like to 'clump together', or do they distribute themselves evenly (like people in an elevator)?[1] GPD's offer us a rich formalism that *does* incorporate this information. They are functions of three variables. If you take certain limits and integrals of the GPD's, you recover both the form factors (which are functions of only one variable) and the PDF's (which are functions of two). The GPD's thus provide a very *general* formalism that incorporates our present descriptions of the proton, and allows us to proceed further. One of the most exciting propects of a full GPD-description of the proton was alluded to above: the possibility of finally measuring the *orbital angular momentum* of the quarks in the proton. To date we know nothing about this!

The GPD formalism, developed recently by theorists, is ready and waiting ... now all we need is some data. How do we measure GPD's? A new type of experiment is required: *hard exclusive scattering.* In the simplest example, we scatter an electron beam from a proton target as before, but now we select a process where there are exactly three particles in the final state: the scattered electron, a proton or neutron, and only one other particle. In the work presented here, the extra particle is a positive charged pion, and the reaction we have studied is $e\,p \to e'\,n\,\pi^+$. The term 'exclusive' refers to the type of measurement involved: when you measure *all* particles in the final state, you know precisely what happened and thus have excluded all other processes from contributing. The term 'hard' refers to the kinematic restrictions placed on the virtual photon: in the classical analogy presented above, it must be of sufficiently small wavelength that we are sure to have scattered from individual quarks. (In technical terms, the usual DIS cuts $Q^2 > 1$ GeV^2 and $W^2 > 4$ GeV^2 are

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[1] In fact, atomic electrons *are* pretty anti-social — electron-electron correlations are very small in atomic physics.

applied.) A schematic view of how our exclusive reaction proceeds is given in Fig. 1a. In words: we are scattering from a quark k in the proton, and then we *put back* a quark k' to make a neutron. Since the wavefunctions of the proton and neutron are very closely related to each other (by isospin symmetry), you can just think of the grey blob at the bottom of the picture as the wavefunction of a nucleon. The figure illustrates how this processes is sensitive to correlations within the blob: we have 'struck' two different quarks in the same event, and so we can see how they are distributed relative to each other.

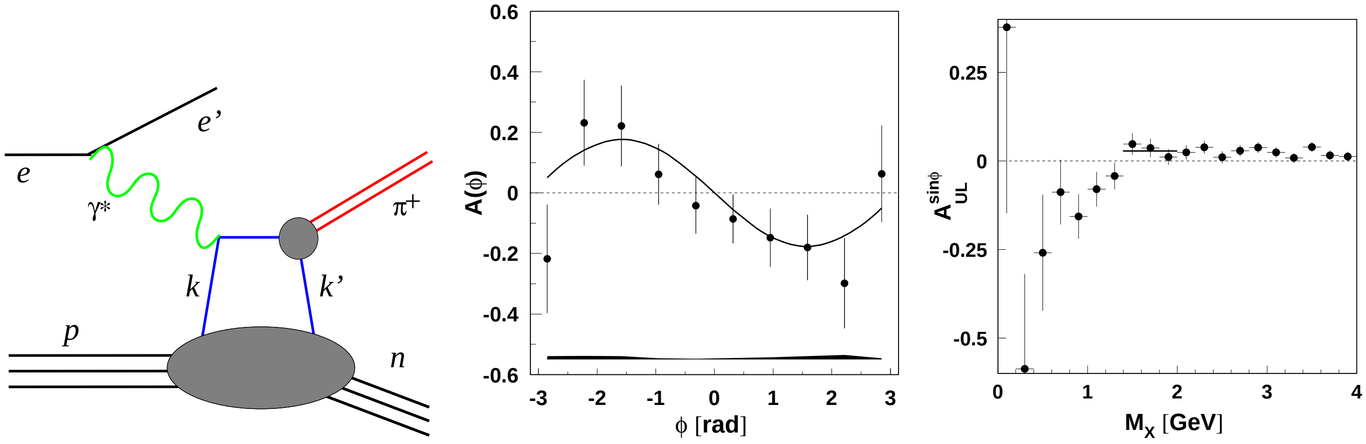

Figure 1: (a) Parton-model diagram of the hard exclusive process $e\,p \to e'\,n\,\pi^+$. (b) Asymmetry $A_{\rm UL}$ versus azimuthal angle ϕ for exclusive π^+ production. (c) $\sin\phi$ moment of $A_{\rm UL}$ versus missing mass M_X. The region $M_X \approx 1$ GeV corresponds to exclusive π^+ production. The vertical bars in panels (b) and (c) indicate the statistical uncertainty of each measured point.

To describe the exact measurement we have made, we need to understand the important azimuthal angle ϕ. The incoming and outgoing electron momenta define a plane — the lepton-scattering plane. Let's imagine that this plane is the surface of your desktop, that beam electron was travelling in the forward direction, and that it scattered slightly to the left. Clearly, the virtual photon also lies in this plane, and went off to the right. We use the vector $\vec{q}$ to describe the photon's 3-momentum. Now consider the single pion that is produced: unless it is produced exactly along the photon direction, its path can be described by an azimuthal angle ϕ, relative to the lepton-scattering plane and around the $\vec{q}$ vector. If the pion went to the left of $\vec{q}$ but stayed in the plane of your desktop, $\phi = 0$. If it went upward, right over the $\vec{q}$ vector, $\phi = 90°$. If it went to the right of $\vec{q}$ in the lepton-scattering plane, $\phi = 180°$, and it it went down, $\phi = -90°$. It is not hard to see how this angular distribution of the pion production plane might be related to orbital angular momentum ...

What we have measured is the following: how the azimuthal distribution of the pion in ϕ *changes* with the *spin of the target proton*. For this measurement we used an unpolarized beam (by averaging over samples with postive and negative polarizations). But our proton target was polarized — longitudinally, which means either along or against the incident beam direction. We formed this *single-spin asymmetry*:

$$A_{\rm UL}(\phi) \equiv \frac{1}{|P|}\frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$$

Here $N^{\uparrow}$ and $N^{\downarrow}$ refer to the (properly normalized) number of exclusive $ep \to e'n\pi^+$ events collected in the two target spin states, each as a function of the pion's azimuthal angle ϕ. $|P|$ is the average magnitude of the target polarization, and the subscript UL makes it clear that we are using an Unpolarized beam and Longitudinally polarized target. If the ϕ distribution of the pions doesn't depend on the target spin, this asymmetry will be flat (will be zero in fact). But what we observe is something quite different: as shown in Fig. 1b, the asymmetry shows a pronounced dependence on ϕ! If we go back to our desktop scattering setup, it seems that if the target spin is pointing forward, the pions like to head for $\phi = -90^\circ$ — *down* into the table ... but if the target spin is pointing backward, the pions prefer to go *upward*. As you can see in the figure, the ϕ-dependence of the asymmetry is rather well described by the simple function $C \sin\phi$, with a negative amplitude C. We call this amplitude $A_{\mathrm{UL}}^{\sin\phi}$ — it is the $\sin\phi$ moment of the asymmetry.

In Fig. 1c, this moment is displayed as a function of *missing mass* M_X. Because of the limitations of our detector, we in fact only measure the e' and π^+ particles in the final state. We then calculate the net invariant mass M_X of whatever other particles there were that we didn't see. If M_X is equal to the nucleon mass (0.94 GeV), it means that the missing particle was a proton or neutron, and that we didn't miss anything else (a single nucleon is the lowest-mass remnant system you can make along with a pion). That's the exclusive reaction we want. However, our resolution in this variable is rather modest: the full-width half-maximum of our exclusive peak in M_X is about 0.4 GeV. (The exclusive data in Fig. 1b correspond to the region $M_X < 1.05$ GeV.) But despite this limited resolution, it is clear from Fig. 1c that something dramatic is happening as one approaches the exclusive region at low M_X. At large M_X, the moment $A_{UL}^{\sin\phi}$ is slightly positive. This result was actually published in an earlier paper, and is sensitive to a new parton-distribution function called transversity. But when we approach the exclusive region where the new information hidden in the GPD's makes its appearance, a strong change in sign is observed.

Unfortunately, we are not yet in a position to interpret our data directly in terms of Generalized Parton Distributions. This area is still very new, these data are exploratory measurements, and theoretical calculations are not yet available for the exact process which we have measured. One reason is the longitudinal polarization of our proton target. Starting in late 2001, HERMES will be taking data with a target oriented *transverse* to the incoming beam, a situation for which calculations are considerably easier.