Deeply Virtual Compton Scattering and Exclusive Meson Production at HERMES

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(on behalf of HERMES Collaboration)

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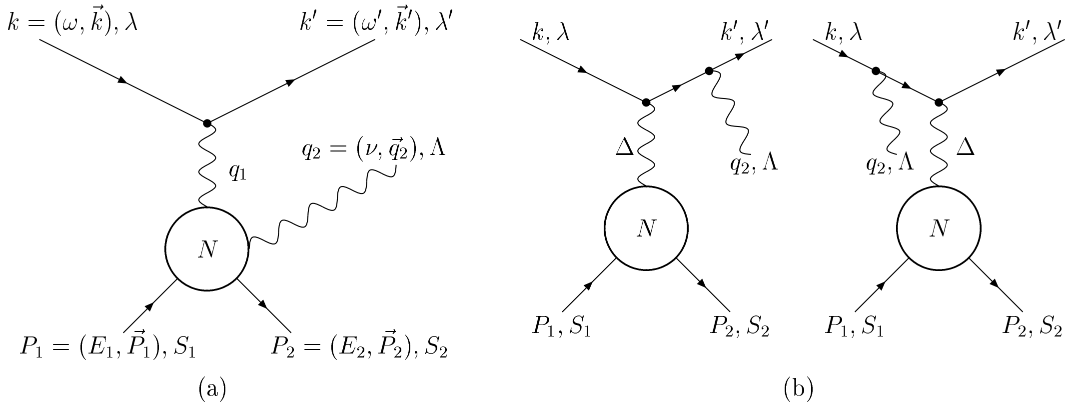
DVCS and Bethe-Heitler



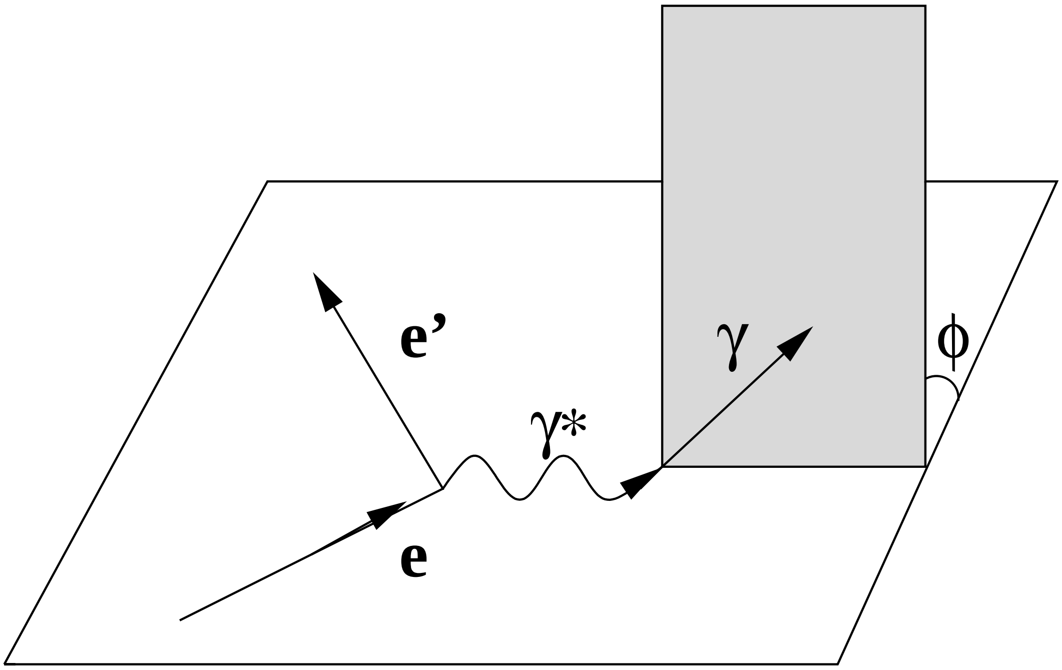
Single Spin Azimuthal Asymmetry

$$A_s = \frac{\int_0^{\pi} d\phi\ (d\sigma^+ - d\sigma^-) - \int_{\pi}^{2\pi} d\phi\ (d\sigma^+ - d\sigma^-)}{< |P_B| > \int_0^{2\pi} d\phi\ (d\sigma^+ + d\sigma^-)}$$

where the $+, -$ superscripts refer to the helicity state

For a sine weighted moment this equation becomes:

$$A_{LU}^{sin\phi} = \frac{2\int_0^{2\pi} d\phi\ (d\sigma^+/d\phi - d\sigma^-/d\phi)\ sin(\phi)}{< |P_b| > \int_0^{2\pi} d\phi\ (d\sigma^+/d\phi + d\sigma^-/d\phi)}$$



Cross Sections and Amplitudes

Below we will present general formulas for unpolarized and polarized cross sections and amplitudes of DVCS, BH and interference DVCS+BH following M.Diehl et al. Phys.Lett. B411:193-202, 1997.

Unpolarized cross section is given by

$$\frac{d\sigma}{d\phi dt dQ^2 dx_{Bj}} = \frac{1}{32\left(2\pi^4\right)} \frac{x_{Bj}y^2}{Q^4} \frac{\left|\tau_{BH} + \tau_{DVCS}\right|^2}{\left(1 + 4x_{Bj}^2 m^2/Q^2\right)^{1/2}}$$

The squared BH contribution formally has the structure

$$\left|\tau_{BH}\right|^2 = f_1\left(\epsilon, x_{Bj}, \Delta_T\right) + \frac{1}{Q} cos\left(\phi\right) f_2\left(\epsilon, x_{Bj}, \Delta_T\right)$$
$$+O\left(1/Q^2\right)$$

Cross Sections and Amplitudes

The squared unpolarized DVCS amplitude reads as follows

$$|\tau_{DVCS}|^2 =$$

$$\frac{e^6}{Q^2}\frac{2}{1-\epsilon}\sum\Big[\frac{1}{2}\Big\{|M^{1,1}_{h,h'}|^2 + |M^{-1,1}_{h,h'}|^2\Big\} + \epsilon|M^{0,1}_{h,h'}|^2$$

$$-cos\,(\phi)\cdot\sqrt{\epsilon\,(1+\epsilon)}Re\{\left(M^{1,1}_{h,h'}\right)^* M^{0,1}_{h,h'} -$$

$$\left(M^{-1,1}_{h,h'}\right)^* M^{0,1}_{h,h'}\}$$

$$-cos\,(2\phi)\cdot\epsilon Re\{\left(M^{1,1}_{h,h'}\right)^* M^{-1,1}_{h,h'}\}\Big]$$

where $M^{\lambda,\lambda'}_{h,h'}$ are helicity amplitudes with λ,λ' being helicity of initial (final) state photon and $h(h')$ that of initial (final) state proton.

Cross Sections and Amplitudes

unpolarized DVCS+BH interference term can be written as

$$\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH} =$$

$$e_l \cdot \frac{e^6}{t}\frac{m}{Q} \cdot \frac{4\sqrt{2}}{x_{Bj}} \cdot \frac{1}{\sqrt{1-x_{Bj}}} \Bigg[cos\,(\phi) \cdot \frac{1}{\sqrt{\epsilon}\,(1-\epsilon)} Re\tilde{M}^{1,1}$$

$$- cos\,(2\phi) \cdot \sqrt{\frac{1+\epsilon}{1-\epsilon}} Re\tilde{M}^{0,1}$$

$$- cos\,(3\phi) \cdot \sqrt{\frac{\epsilon}{1-\epsilon}} Re\tilde{M}^{-1,1} \Bigg] + O\left(1/Q^2\right)$$

Here the $\gamma^* p \to \gamma p$ amplitudes enter in linear combinations

$$\tilde{M}^{\lambda,\lambda'} =$$

$$\Delta_T \cdot \Big[(1-x_{Bj})\, G_M - (1-x_b/2)\, F_2 \Big] \cdot M^{\lambda,\lambda'}_{-1/2,-1/2}$$

$$+ \frac{\Delta_T}{m} \cdot \Big[G_M - (1-x_b/2)\, F_2 \Big] \cdot M^{\lambda,\lambda'}_{1/2,1/2}$$

$$+ \Big[x^2_{Bj} G_M + \frac{\Delta^2_T}{2m^2} F_2 \Big] \cdot M^{\lambda,\lambda'}_{1/2,-1/2} - \frac{\Delta^2_T}{2m^2} F_2 \cdot M^{\lambda,\lambda'}_{-1/2,1/2}$$

Cross Sections and Amplitudes

Lepton spin dependent part of DVCS amplitude is

$$|\tau_{DVCS}|^2 = \frac{e^6}{Q^2}\frac{2}{1-\epsilon}\cdot 2h_l \sum sin\left(\phi\right)\cdot\sqrt{\epsilon\left(1-\epsilon\right)}\, Im\{\left(M^{1,1}_{h,h'}\right)^* M^{0,1}_{h,h'} - \left(M^{-1,1}_{h,h'}\right)^* M^{0,1}_{h,h'}\}$$

Lepton spin dependent part of DVCS+BH interference amplitude now looks as follows

$$\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH} = \frac{e^6}{t}\frac{m}{Q}\cdot\frac{4\sqrt{2}}{x_{Bj}}\cdot\frac{1}{\sqrt{1-x_{Bj}}}\cdot 2e_l h_l\left[-\,sin\left(\phi\right)\cdot\sqrt{\frac{1+\epsilon}{\epsilon}}Im\tilde{M}^{1,1} + sin\left(2\phi\right)\cdot Im\tilde{M}^{0,1}\right] + O\left(1/Q^2\right)$$

where e_l,h_l are lepton charge and helicity

Data extraction, quality and cuts

1. Event selection from 96+97 data
   - H2 target, polarized and unpolarized
   - Only one e^+, one untracked cluster in calo
   - Main Trigger with E_{calo}>3.5 GeV
2. Data quality
   - Logbook okay, detector okay (no HV trips, etc.)
   - $P_B > 0.4$
3. Event selection cuts
   - standard e^+ PID cut
   - HERMES box acceptance for e^+ and cluster
     - with: $|$ cluster y hit $| > 33$ cm
   - e^+ vtx: $-18cm < z_{vtx} < 18cm$ and $0 < t_{vtx} < 0.75$cm
   - $W^2 > 4$ GeV^2
   - $Q^2 > 1$ GeV^2
   - $\nu < 24$ GeV

Sin Moments

The $\sin(\phi)$ moment is defined as:

$$\frac{2 < sin\phi >_{LU}}{< |P_B| >} = \frac{2 \int_0^{2\pi} d\phi \; (d\sigma/d\phi) \; sin(\phi)}{< |P_b| > \int_0^{2\pi} d\phi \; (d\sigma/d\phi)}$$

which, for the single spin azimuthal asymmetry, is:

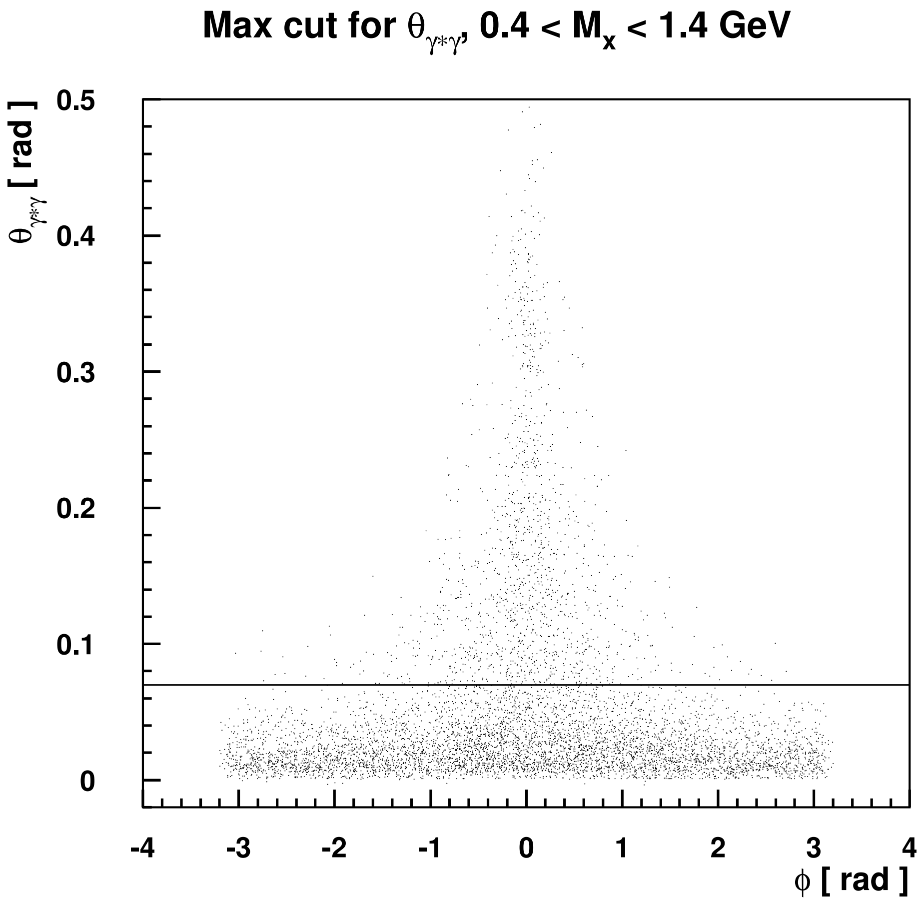
$$A_{LU}^{sin\phi} = \frac{2 \int_0^{2\pi} d\phi \; (d\sigma^+/d\phi - d\sigma^-/d\phi) \; sin(\phi)}{< |P_b| > \int_0^{2\pi} d\phi \; (d\sigma^+/d\phi + d\sigma^-/d\phi)}$$

- No virtual photon depolarization factor used
- Sine moment $\sim$ interference term in cross section

Investigation of cuts on event sample

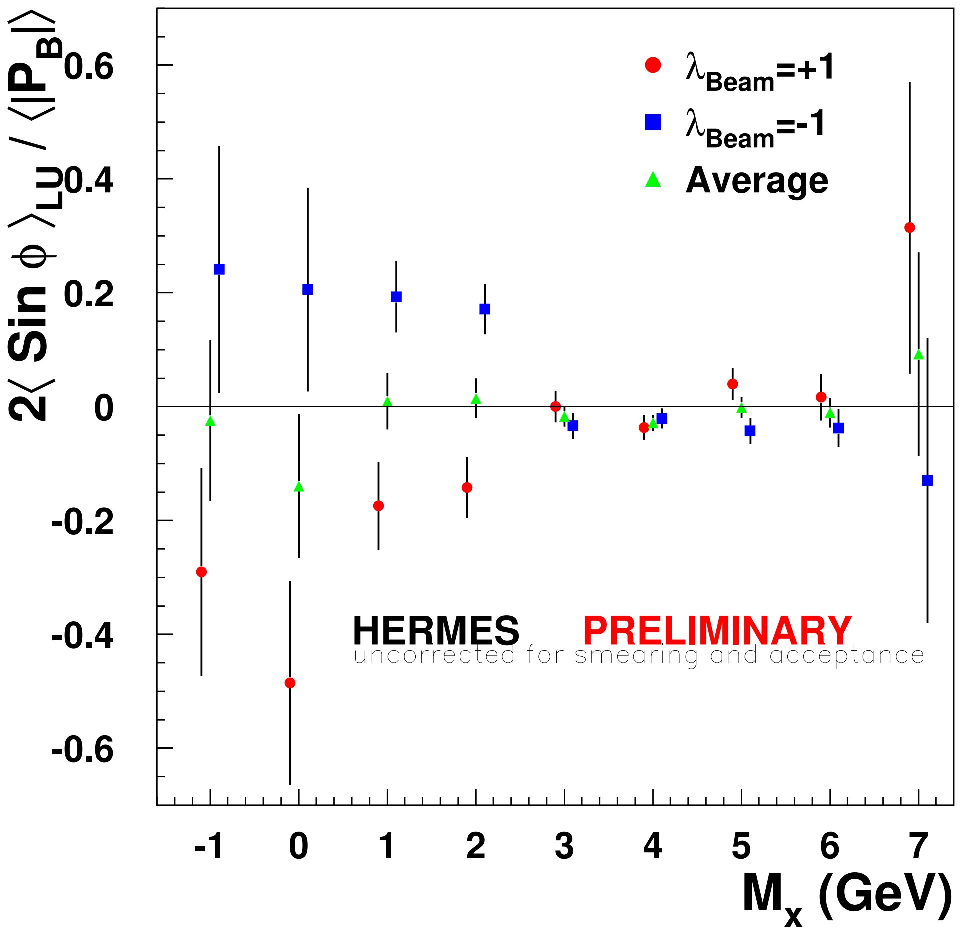
- Preshower cut:
  - photon must convert in preshower; removes events with incorrectly reconstructed energy
- H1 cut:
  - photon must have NO response in H1; eliminates possible charged background
- Opening angle ($\theta_{\gamma^*\gamma}$) cut:
  - Minimum cut to reduce position reconstruction dependence
  - Maximum cut to assure full ϕ acceptance
- Maximum t cut:
  - needed to insure events in theoretical DVCS regime

Maximum opening angle cut



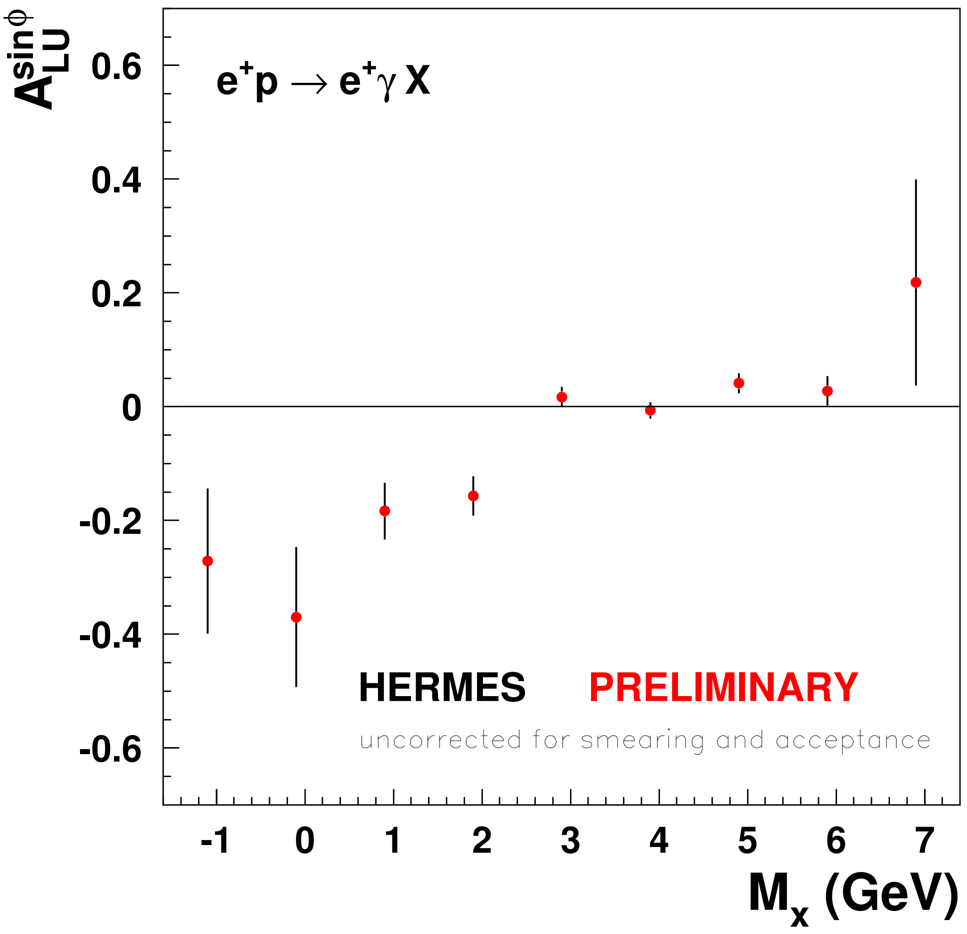
- Cut at 70 millirad to obtain full ϕ coverage
- Proposed cut at 15 millirad from MC studies and calo block size

Azimuthal Asymmetry



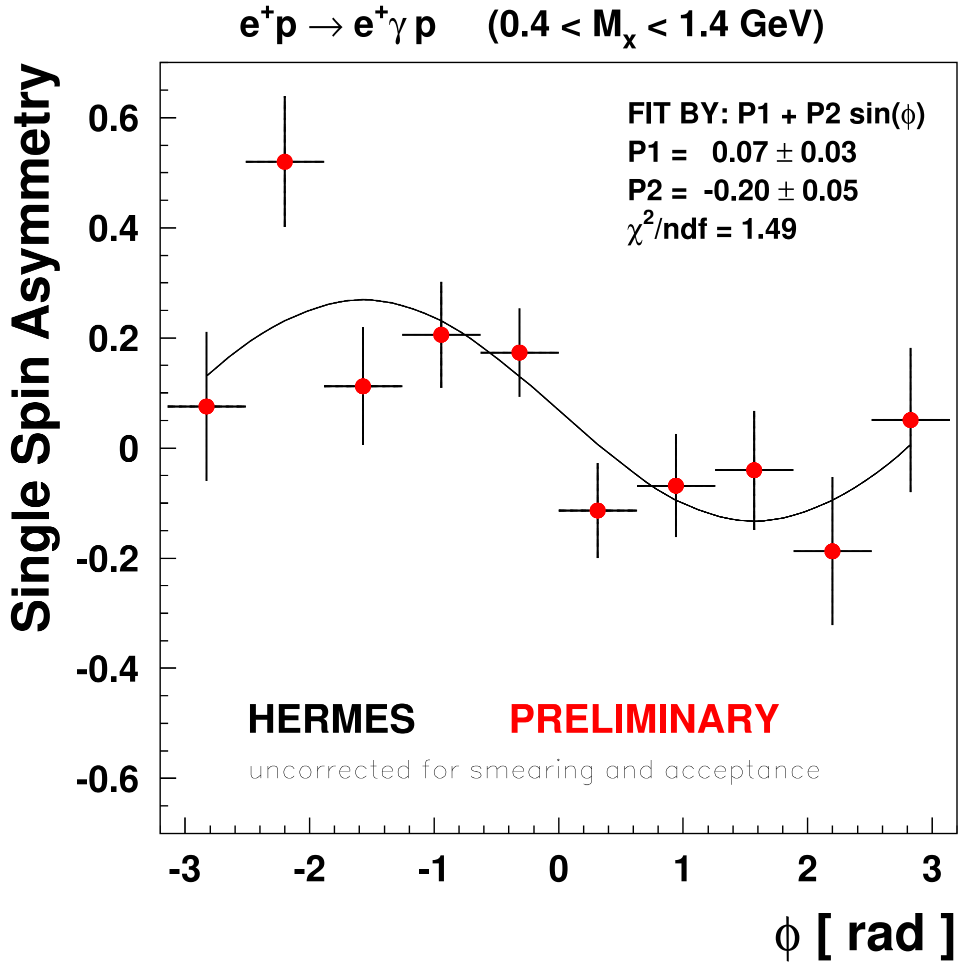
$$\frac{2 < sin\phi >_{LU}}{< |P_B| >} = \frac{2 \int_0^{2\pi} d\phi\ (d\sigma/d\phi)\ sin(\phi)}{< |P_b| > \int_0^{2\pi} d\phi\ (d\sigma/d\phi)}$$

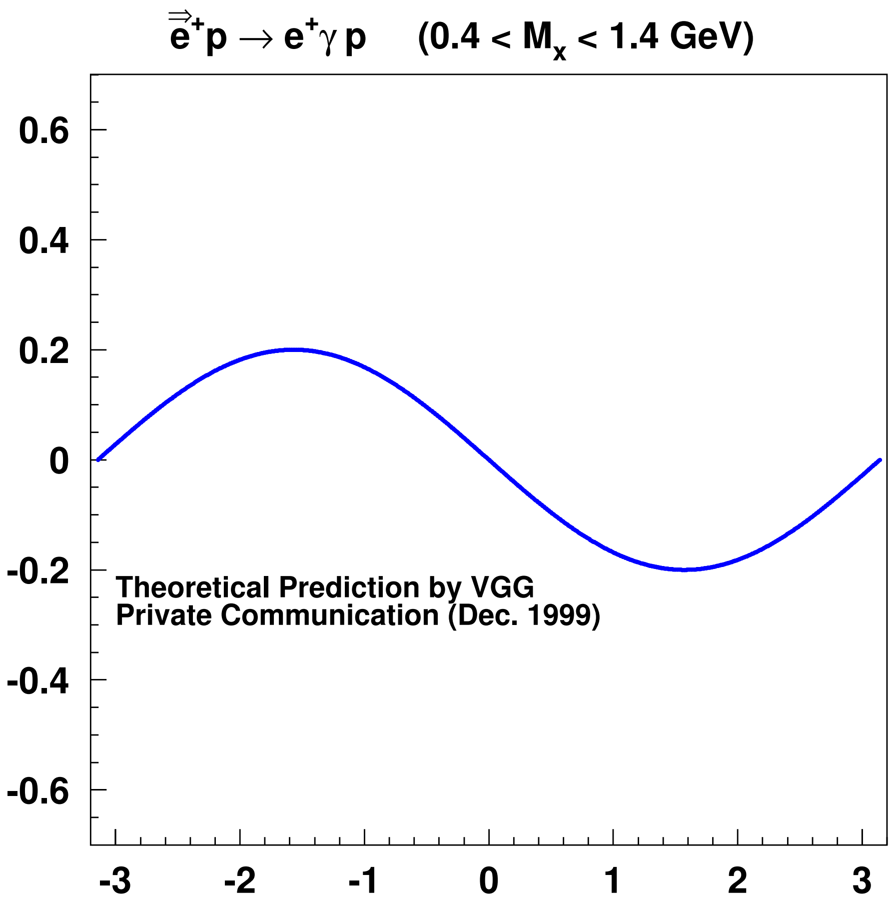
Single Spin Asymmetry



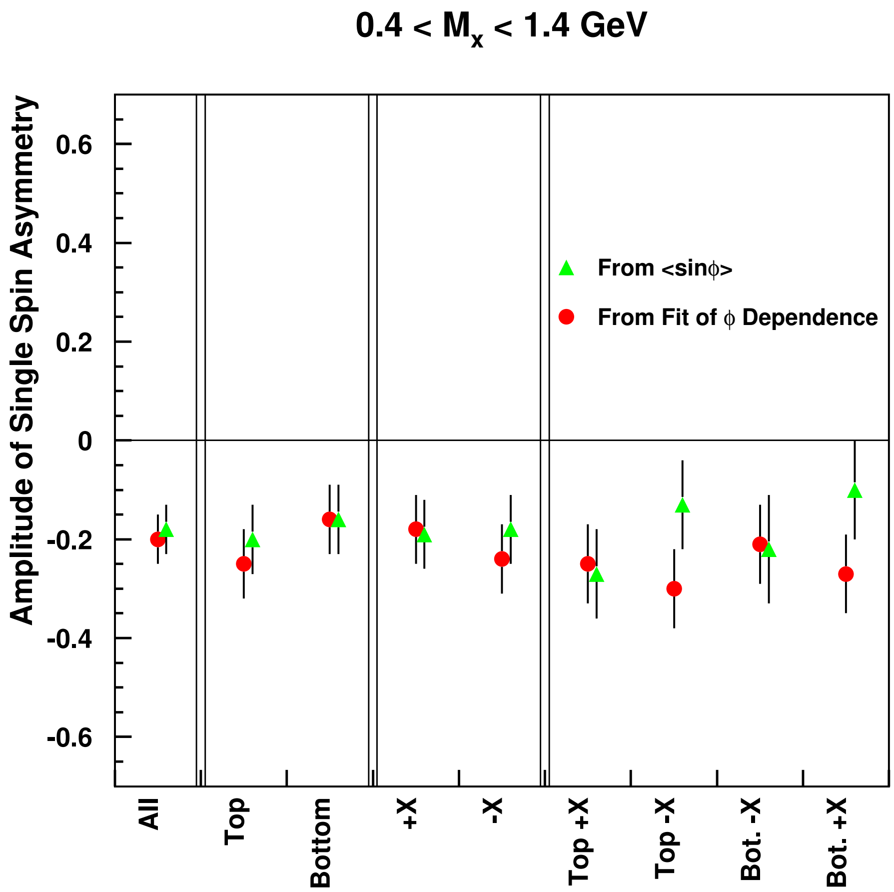
$$A_{LU}^{sin\phi} = \frac{2\int_0^{2\pi} d\phi\ (d\sigma^+/d\phi - d\sigma^-/d\phi)\ sin(\phi)}{<|P_b|> \int_0^{2\pi} d\phi\ (d\sigma^+/d\phi + d\sigma^-/d\phi)}$$

ϕ Dependence of SSA



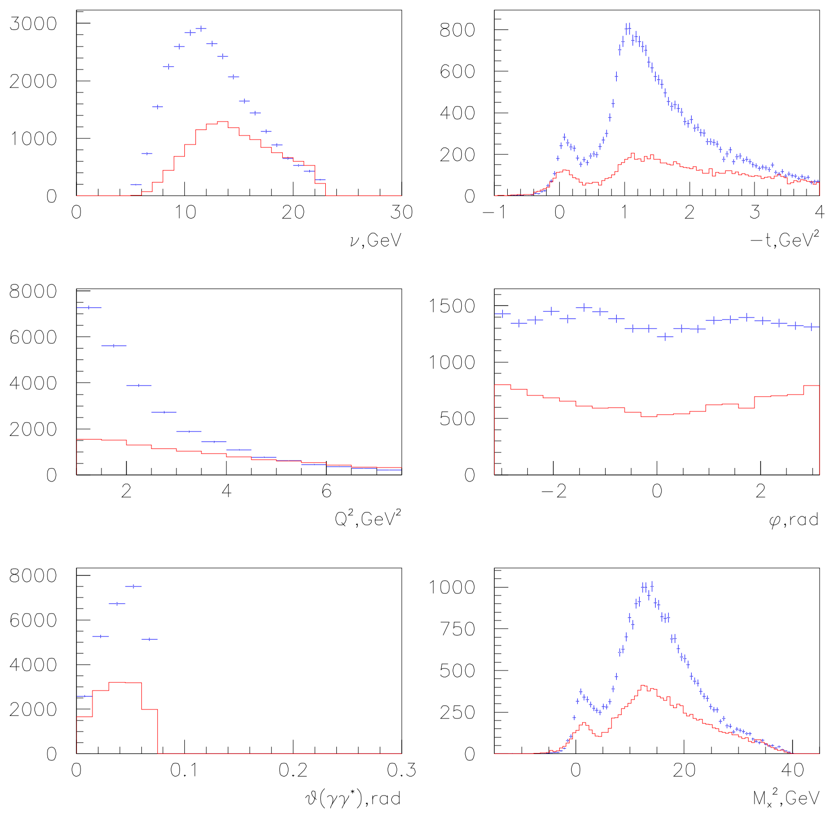

$\vec{\vec{e}}^{+}p \rightarrow e^{+}\gamma\, p$ (0.4 < M_x < 1.4 GeV)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-3
-2
-1
0
1
2
3
Theoretical Prediction by VGG
Private Communication (Dec. 1999)

Detector Geometrical Uniformity



- Fit for $\sin(\phi)$ moment of single spin asymmetry fairly consistent across all divisions of detector
- Asymmetry not a result of asymmetric detector
- $<\sin(\phi)> \sim$ fit result, so acceptance mixing of the $\sin(2\phi)$ moment of the cross section is small

Excess of Experimental Data



- blue points are data, red histograms - MC with BH only – BH alone does not descibe data
- semi-inclusive π^0 and η contribution is estimated to be below 0.01
- rate of exclusive π^0's, i.e. misidentified 2γ was estimated to be below 0.05 using ratios of exclusive π^+/γ and π^0/π^+

Exclusive Meson Production

SPD formalism can be applied also to exclusive meson production, main interest is to the reactions:

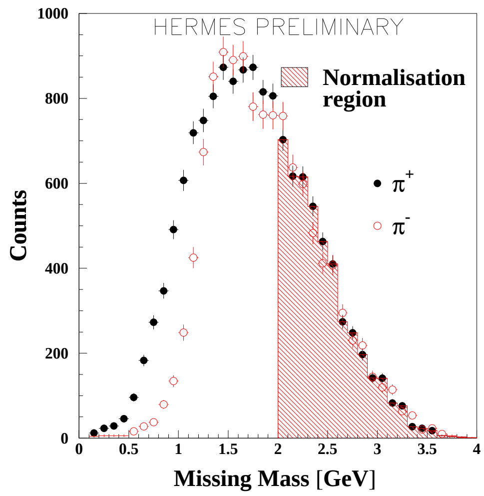
$$\gamma_L^*(q) + B_1(p) \to P(q') + B_2(p')$$

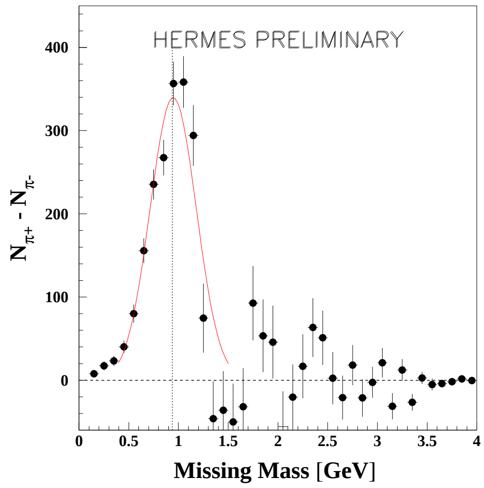
where B_1 is a target baryon, $P = \pi, K, \eta, \eta'$ is a pseudoscalar meson and $B_2 = N, \Lambda, \Sigma, \Delta, \pi N,$ etc. - recoil barion cluster.

Factorization theorem states (Collins, Frankfurt, Strikman - 1997) that the amplitude of this reaction can be expressed as the convolution of:

- skewed parton distributions (SPD's)
- the meson distribution amplitude (DA)
- hard kernel computable in perturbative QCD

Exclusive Pion Production

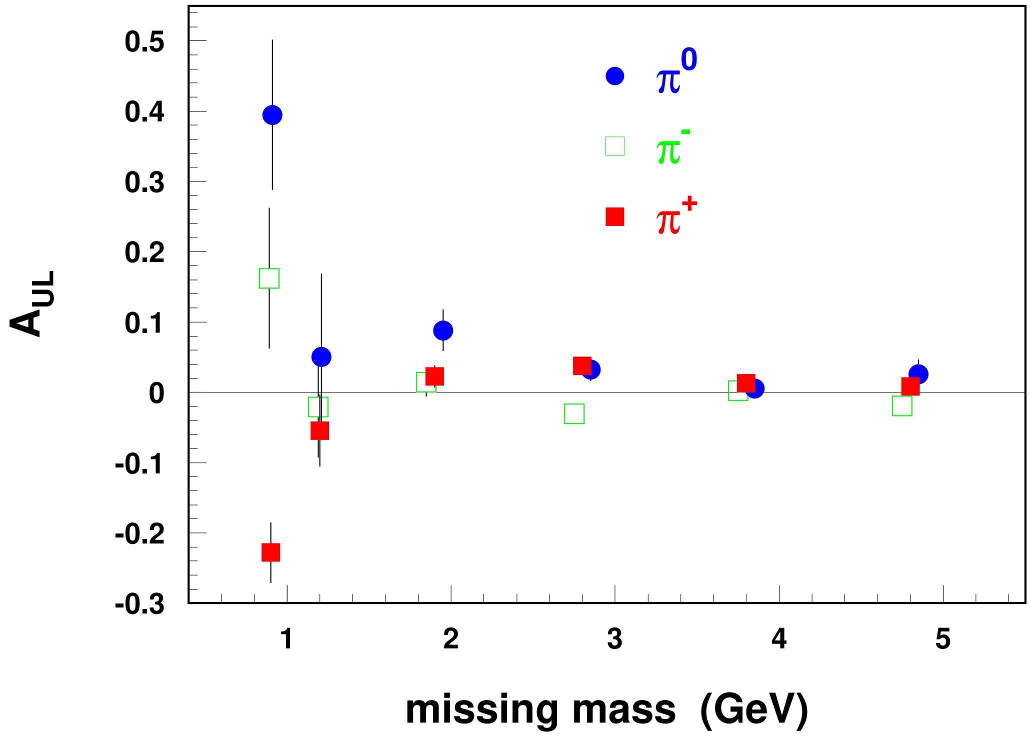




- Exclusive π^+ can be extracted for cross-section studies

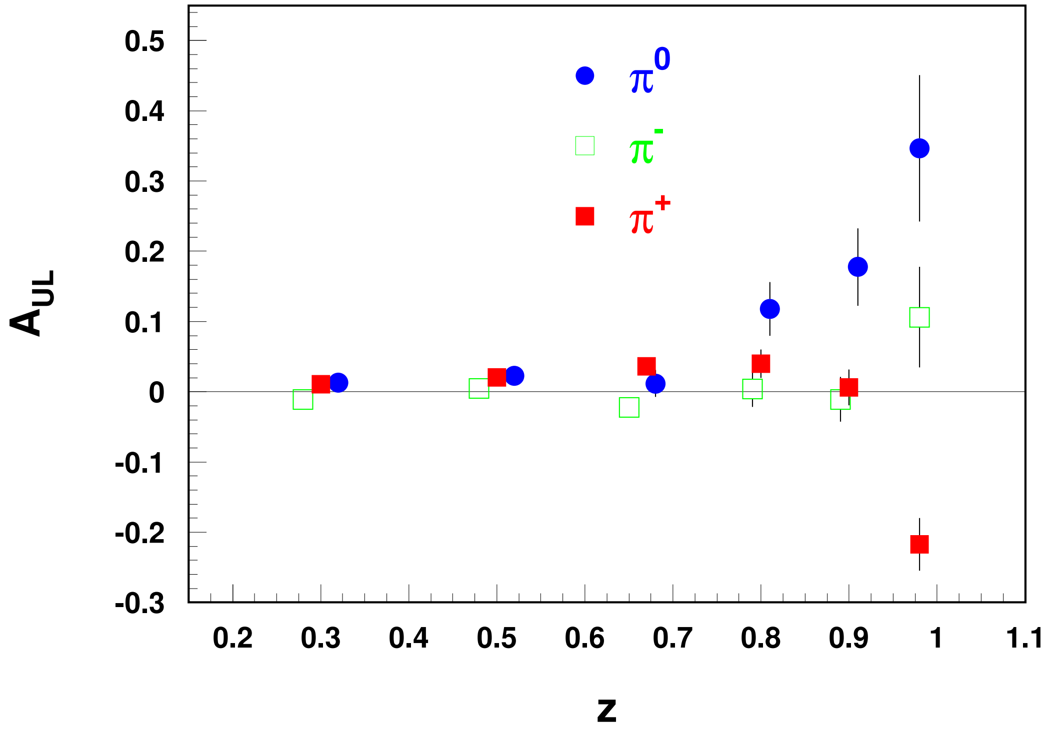
Asymmetry vs Missing Mass

- Unpolarized beam and Longitudinally Polarized Hydrogen Target



- theoretical prediction is available for transversally polarized target, but opposite sign of asymmetry (Frankfurt et al., Phys.Rev.Lett.84,p2589)
- contradiction with large asymmetry for π^0 in data

Asymmetry vs Z



Conclusions

- Single Spin Asymmetry in the electroproduction of real γ with polarized beam and unpolarized hydrogen target is measured for the first time
- Underlying BH subprocess alone can not explain excess of the data
- Contribution from decaying π^0 and η particles is negligible $\sim 5\%$
- The only known source of observed $sin(\phi)$ asymmetry is the interference of DVCS and BH subprocesses
- The contribution from N-Δ transition is small
- Single Spin Azimuthal Asymmetry in the hard exclusive production of pions with unpolarized beam and polarized hydrogen target is measured for the first time

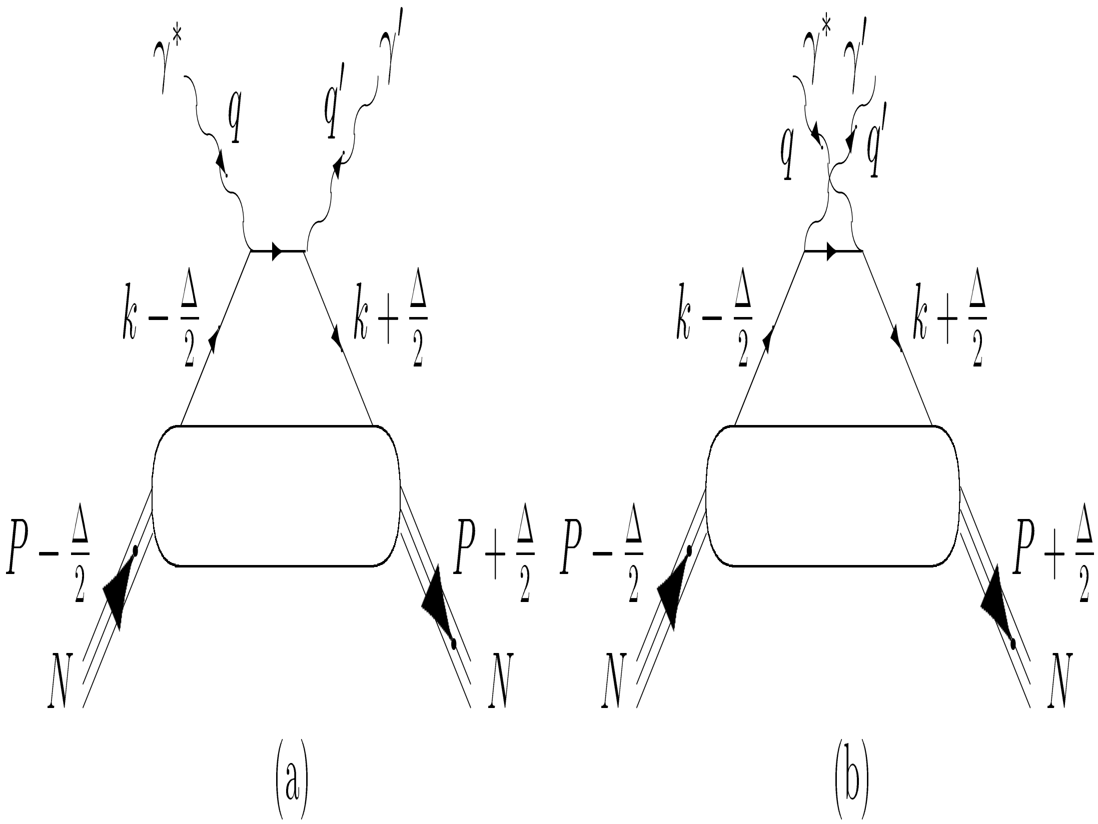
OUTLOOK

- Experimental results on single beam-spin asymmetry have been obtained for the first time for Deeply Virtual Compton Scattering
- Measurement of $sin(n\phi)$ and $cos(n\phi)$ moments in DVCS from collected data at HERMES both on hydrogen and deuteron targets will provide a new information inaccesible in semi-inclusive measurements
- It is believed that experimental data obtained at HERMES will contribute to the future attempts to constrain another unknown part of the spin of nucleon - Orbital Angular Momentum
- Experimental results on single target-spin asymmetry have been obtained for the first time for exclusive pion production
- Very first theoretical predictions for the large single transverse spin asymmetry have been carried out, however clearly more work is needed to bring such courageous attempts under full control

OUTLOOK

- Presented experimental data are based on 96+97 data
- More data have been collected in the last three years. In addition significant change in the running strategy in year 2000, using 1 hr end of fill high-density target, allowed to increase existing unpolarized data sample by factor of 4
- Data have been accumulated with polarized deuteron target including tensor polarized mode
- At the very end data also was taken with 12 GeV positron beam on different targets
- We hope that an opening of a new phase of our understanding of the nucleon structure is a pproaching and obviously there remains much more to be done, both on the theoretical and experimental sides

DVCS Handbag Diagrams



- In hard regime, virtual compton scattering factorizes
- In the off-forward limit described by new functions

Unpolarized Target

Following A.V. Belitsky, D. Müller, L. Niedermeier and A. Schäfer (hep-ph/0004059)

1. Polarized beam :

$$\Delta_{\mathrm{SL}} d\sigma \equiv d\sigma^{\uparrow} - d\sigma^{\downarrow} = -\frac{16(2-y)\sqrt{1-x}}{\sqrt{1-y}\,x\sqrt{-\Delta^2 \mathcal{Q}^2}} \sin(\phi_r)$$

$$\times \mathrm{Im}\left\{ F_1 \mathcal{H}_1 + \frac{x}{2-x}(F_1+F_2)\widetilde{\mathcal{H}}_1 - \frac{\Delta^2}{4M^2} F_2 \mathcal{E}_1 \right\} dM.$$

2. Charge asymmetry in unpolarized experiment:

$$\Delta_{\mathrm{C}}^{\mathrm{unp}} d\sigma \equiv d^{+}\sigma^{\mathrm{unp}} - d^{-}\sigma^{\mathrm{unp}} =$$

$$-\frac{16(2-2y+y^2)\sqrt{1-x}}{\sqrt{1-y}\,yx\sqrt{-\Delta^2 \mathcal{Q}^2}} \cos(\phi_r)$$

$$\times \mathrm{Re}\left\{ F_1 \mathcal{H}_1 + \frac{x}{2-x}(F_1+F_2)\widetilde{\mathcal{H}}_1 - \frac{\Delta^2}{4M^2} F_2 \mathcal{E}_1 \right\} dM.$$

Unpolarized Beam

3. Longitudinally polarized target:

$$d\sigma_{\uparrow} - d\sigma_{\downarrow} = \frac{16(2-2y+y^2)\sqrt{1-x}}{\sqrt{1-y}\,yx\sqrt{-\Delta^2 Q^2}} \sin(\phi_r)$$

$$\times \mathrm{Im}\left\{ \frac{x}{2-x}(F_1+F_2)\mathcal{H}_1 + F_1\widetilde{\mathcal{H}}_1\right.$$

$$\left. + \frac{x}{2-x}\left(\frac{x}{2}F_1 + \frac{\Delta^2}{4M^2}F_2\right)\widetilde{\mathcal{E}}_1 \right\} dM.$$

4. Transversally polarized target:

$$d\sigma_{\rightarrow} - d\sigma_{\leftarrow} = \frac{16(2-2y+y^2)}{\sqrt{1-y}\,yx(2-x)\sqrt{Q^2M^2}}$$

$$\left[\frac{\cos(3\phi_r/2)}{2\pi}(1-x)\mathrm{Im}\left\{2F_2(\mathcal{H}_1+\widetilde{\mathcal{H}}_1)\right.\right.$$

$$\left. -[(2-x)F_1 - xF_2]\mathcal{E}_1 - xF_1\widetilde{\mathcal{E}}_1\right\} + \frac{\cos(\phi_r/2)}{2\pi}$$

$$\times \mathrm{Im}\left\{2(1-x)F_2\left(\mathcal{H}_1 - \widetilde{\mathcal{H}}_1\right) - [(2-x)F_1 + xF_2]\mathcal{E}_1\right.$$

$$\left.\left. + x(F_1 + xF_2)\widetilde{\mathcal{E}}_1\right\}\right] dM.$$

SPD's - General Formalism

- In the notation of Ji there are four OFPD's: H, $\widetilde{H}$, E, $\widetilde{E}$.
- They depend upon three variables: x, ξ, t.
- Where the light-cone momentum fraction is defined by $k^+ = \mathrm{x}P^+$, ξ = -$\Delta^+/2P^+$ ($\Delta = P'$ - P) and t = Δ^2.
- In the Bjorken limit $2\xi \to x_{Bj}/(1\text{-}x_{Bj}/2)$.
- H and $\widetilde{H}$ conserve the nucleon helicity, while E and $\widetilde{E}$ flip the nucleon helicity.
- In the limit of $\xi \to 0$ and t$\to 0$ H and $\widetilde{H}$ reduce to the ordinary parton distributions:

$$H(x,0,0) = q(x)$$
$$\widetilde{H}(x,0,0) = \Delta q(x)$$

SPD's - General Formalism

Integration over x gives the following sum rules:

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

$$\int_{-1}^{1} dx E(x,\xi,t) = F_2(t)$$

$$\int_{-1}^{1} dx \widetilde{H}(x,\xi,t) = G_A(t)$$

$$\int_{-1}^{1} dx \widetilde{E}(x,\xi,t) = G_P(t),$$

where F_1 and F_2 are the Dirac and Pauli form factors and G_A and G_P are the axial-vector and pseudo-scalar form factors.

Angular Momentum

Angular momentum operator in QCD is the sum of quark and gluon contributions

$$\vec{J}_{QCD} = \vec{J}_q + \vec{J}_g$$

where

$$\vec{J}_q = \int d^3x \vec{x} \times \vec{T}_q$$

$$\vec{J}_g = \int d^3x \vec{x} \times (\vec{E} \times \vec{B})$$

Here $\vec{T}_q$ and $\vec{E} \times \vec{B}$ are the quark and gluon momentum densities, respectively. Separate quark and gluon contributions to the nucleon spin can be deduced by an analogy with the magnetic moment, if the form factors of the momentum density are known at zero momentum transfer.

Ji Angular Momentum Sum Rule

Second moments of off-forward parton distributions yield the form factors of the energy-momentum tensor

$$\int_{-1}^{1} dxx[H(x,\xi,t) + E(x,\xi,t)] = A(t) + B(t)$$

where the ξ dependence drops out.

Extrapolating the sum rule to $t \to 0$, one gets fractions of the nucleon spin carried by quarks and gluons:

$$J_{q,g} = \frac{1}{2}[A_{q,g}(0) + B_{q,g}(0)]$$

where

$$J_q + J_g = \frac{1}{2}$$

Spin Structure of the Nucleon

The quark angular momentum decomposes as

$$J_q = \frac{1}{2}\Delta\Sigma + L_q,$$

where $\Delta\Sigma/2$ and L_q are the quark spin and orbital angular momentum, respectively.

Balitsky and Ji (Phys. Rev. Lett.79:1225-1228, 1997) made an estimate using QCD sum rule approach. They found that the spin structure of the nucleon looks like

$$\frac{1}{2} = 0.1(\Delta\Sigma/2) + 0.15(L_q) + 0.25(J_g).$$

Dramatic Predictions

reaction	distributions	pole
$p \to p\pi^0$	$2(\Delta u - \Delta\bar{u}) + (\Delta d - \Delta\bar{d})$	-
$p \to n\pi^+$	$(2\Delta u + \Delta\bar{u}) - (2\Delta d + \Delta\bar{d})$	+
$SU(3)$ relations		
$p \to \Sigma^+ K^0$	$(\Delta d - \Delta\bar{d}) - (\Delta s - \Delta\bar{s})$	+
$p \to \Sigma^0 K^+$	$2(\Delta d - \Delta s) + (\Delta\bar{d} - \Delta\bar{s})$	+
$p \to \Lambda K^+$	$2(\Delta u - \Delta d - \Delta s) + (2\Delta\bar{u} - \Delta\bar{d} - \Delta\bar{s})$	+
Large N_c relations		
$p \to \Delta^{++}\pi^-$	$(\Delta u + 2\Delta\bar{u}) - (\Delta d + 2\Delta\bar{d})$	+
$p \to \Delta^+\pi^0$	$(\Delta u - \Delta\bar{u}) - (\Delta d - \Delta\bar{d})$	-
$p \to \Delta^0\pi^+$	$(2\Delta u + \Delta\bar{u}) - (2\Delta d + \Delta\bar{d})$	+

- Polarization of quarks in the nucleon is accessible in Unpolarized Reactions! (see Polyakov and Vanderhaeghen, DIS2000)
- similar expressions hold for neutron target