# Forward and Off-Forward Nucleon Structure Measurements at HERMES

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  - → $A_1$, $g_1$ from hydrogen and deuterium
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- Semi-Inclusive Results
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  - → Deeply Virtual Compton Scattering
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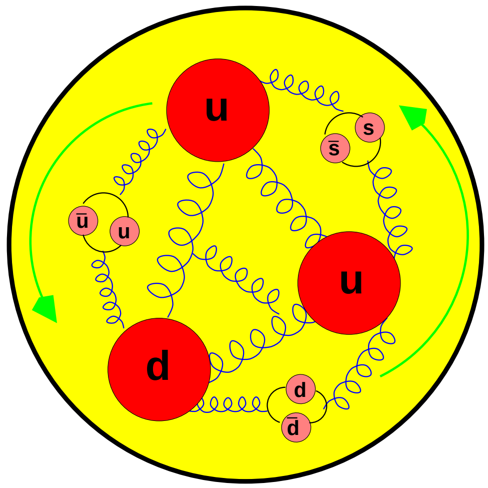
# Partonic Structure

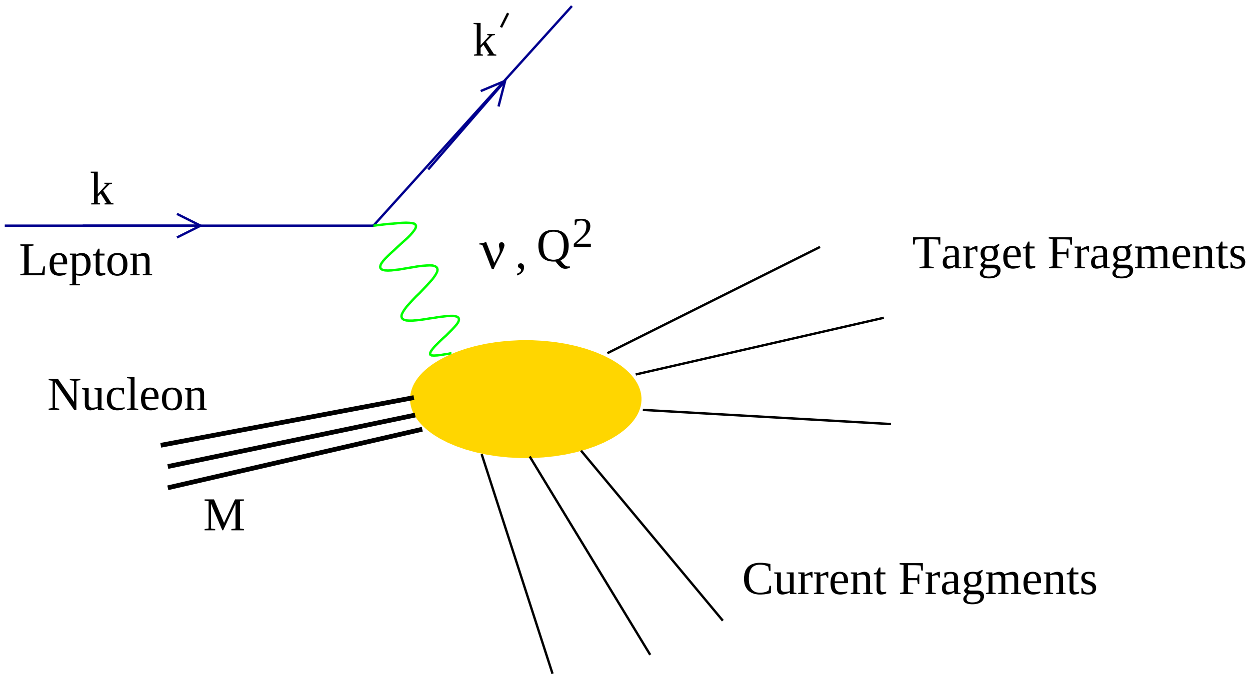
- Goal: Quantitative Understanding of Nucleon Structure




- Basic Questions:
  - → How does the nucleon mass arise from quarks and gluons?
  - → How is the spin formed from quarks and gluons?

- Technical Questions:
  - → What are the structure functions $F_i(x, Q^2)$ of the nucleon?
  - → What are the spin structure functions $g_i(x, Q^2)$ of the nucleon?
  - → How can these functions be understood in terms of polarized, flavored quark and gluon constituent structure functions, e.g., $u(x, Q^2)$?

# Deep Inelastic Scattering




- Virtual photon of energy $\nu$ and rest mass $Q^2$ is absorbed by nucleon
- "Quark Momentum" $\approx$ Bjorken $x = Q^2/2M\nu$
- "Resolution of Probe" $\approx Q^2 = -(k - k')^2$
- Hadrons (jet) carrying photon momentum are Current Fragments
- Hadrons from "spectator" remnants of nucleon are Target Fragments

# Nucleon Spin Structure

Whence spin?

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

$\Delta\Sigma$ is small!

- 1980: First measurements at SLAC (E80,E130)
- 1988: $\Delta\Sigma = 0.012 \pm 0.17$ at EMC $<<$ Ellis-Jaffe Sum
- 2000: SLAC,CERN, DESY give $\Delta\Sigma \approx 0.2 \leftrightarrow 0.4$

Explanations?

- Strange sea polarization $\Delta s$ large and negative?
- Larger than expected gluon polarization $\Delta G$?
- Large orbital angular momentum contributions $L_q$, $L_g$?

# DIS Measurements

- Inclusive - Only the scattered lepton is detected
  - → Cross Section is product of hard QED interaction and initial hadronic structure functions
  - → Independent of final hadronic state
- Semi-Inclusive - Hadrons coincident with lepton are detected
  - → Cross Section is product of hard QED interaction, initial hadronic structure functions, final hadronic fragmentation functions
  - → Kinematic correlation with virtual photon allows flavor separation
  - → Typically 1 or 2 hadrons detected out of many in final state
- Exclusive - Final state = lepton + nucleon + only one additional particle
  - → Cross Section is product of hard QED interaction, generalized structure function of nucleon and asymptotic particle distribution
  - → New kinematic dependence: momentum transfer to nucleon

# The HERMES Experiment

- Deep inelastic scattering of polarized electrons from polarized nucleon (fixed) gas targets

- Forward open geometry spectrometer capable of detecting and identifying electrons, hadrons, and photons

- Primary Research Goal: Study of Nucleon Spin Structure

  $\rightarrow$ Inclusive Structure Functions $g_1, g_2, h_1, b_1$
  $\rightarrow$ Flavor dependence of $g_1$ from semi-inclusive DIS
  $\rightarrow$ Gluon polarization using photon-gluon fusion process
  $\rightarrow$ Total quark angular momentum from Exclusive Reactions

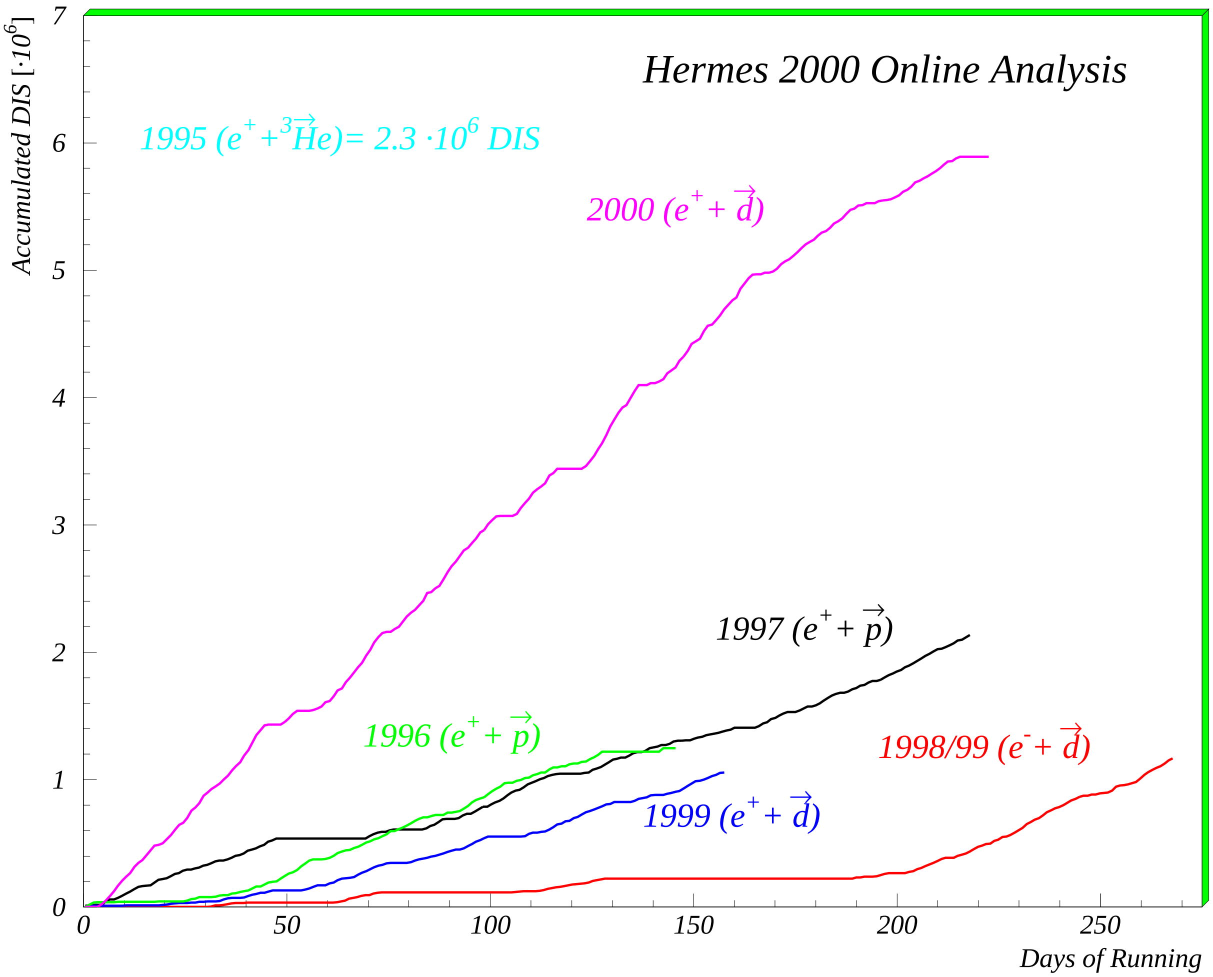
- Bonus Research Goals:

  $\rightarrow$ Diffraction Physics
  $\rightarrow$ Polarized Fragmentation
  $\rightarrow$ Hadronization in Nuclei
  $\rightarrow$ Light-sea flavor structure
  $\rightarrow$ Generalized Parton Distributions
  $\rightarrow$ ...

# The HERMES Collaboration

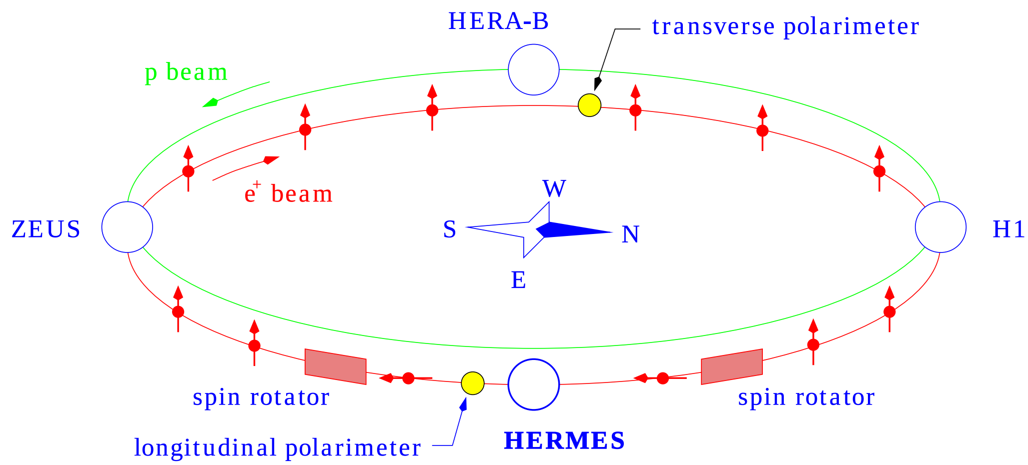
- Experiment located at DESY in Hamburg, Germany
- Members Insitutions from: Armenia, Belgium, Canada, China, Germany, Italy, Japan, Netherlands, Poland, Russia, UK, and USA
- Homepage: http://www-hermes.desy.de
- Run/target History:

$\rightarrow$ 1995: Commissioning/ Polarized $^{3}$He
$\rightarrow$ 1996/97: Polarized $^{1}$H, Unpolarized $^{1}$H, $^{2}$H, $^{3}$He, $^{14}$N
$\rightarrow$ 1998/99: Electrons, Polarized $^{2}$H, +RICH and Charm Upgrades
$\rightarrow$ 2000: Polarized $^{2}$H, Unpolarized $^{1}$H, $^{2}$H, $^{84}$Kr

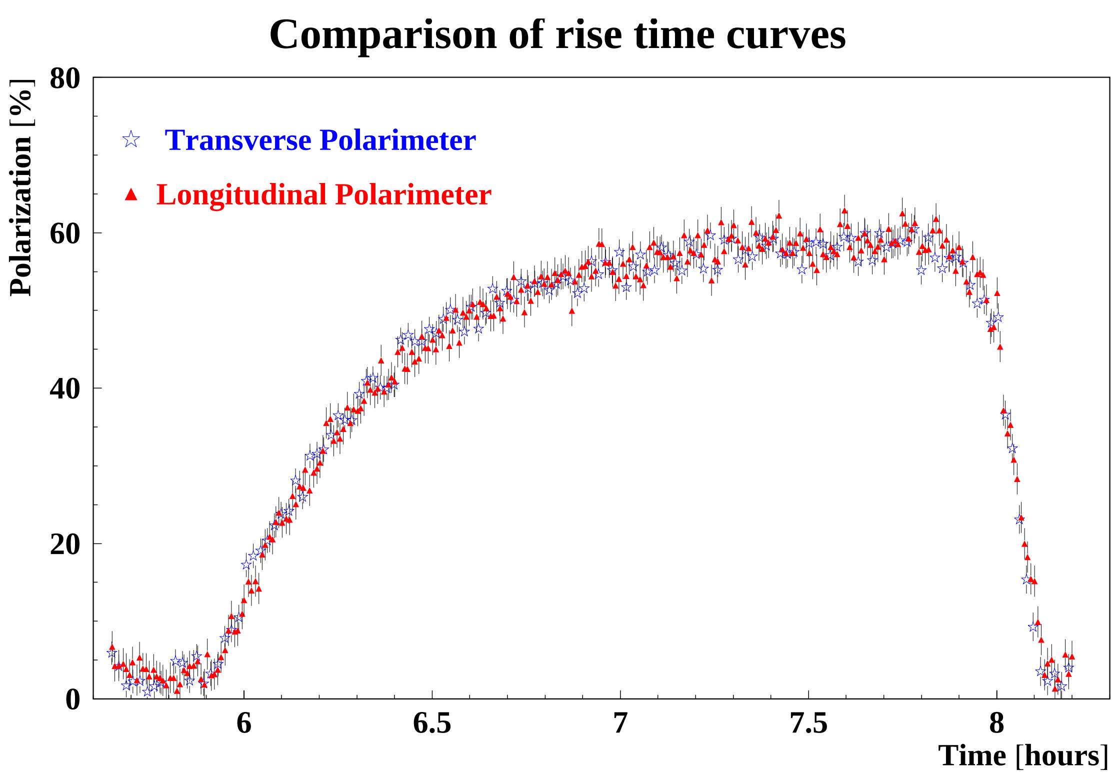


Hermes 2000 Online Analysis
1995 ($e^+ + {}^3\vec{He}$)= 2.3 $\cdot 10^6$ DIS
2000 ($e^+ + \vec{d}$)
1997 ($e^+ + \vec{p}$)
1996 ($e^+ + \vec{p}$)
1998/99 ($e^- + \vec{d}$)
1999 ($e^+ + \vec{d}$)
Accumulated DIS [$\cdot 10^6$]
Days of Running
0
1
2
3
4
5
6
7
0
50
100
150
200
250

# The HERMES experiment

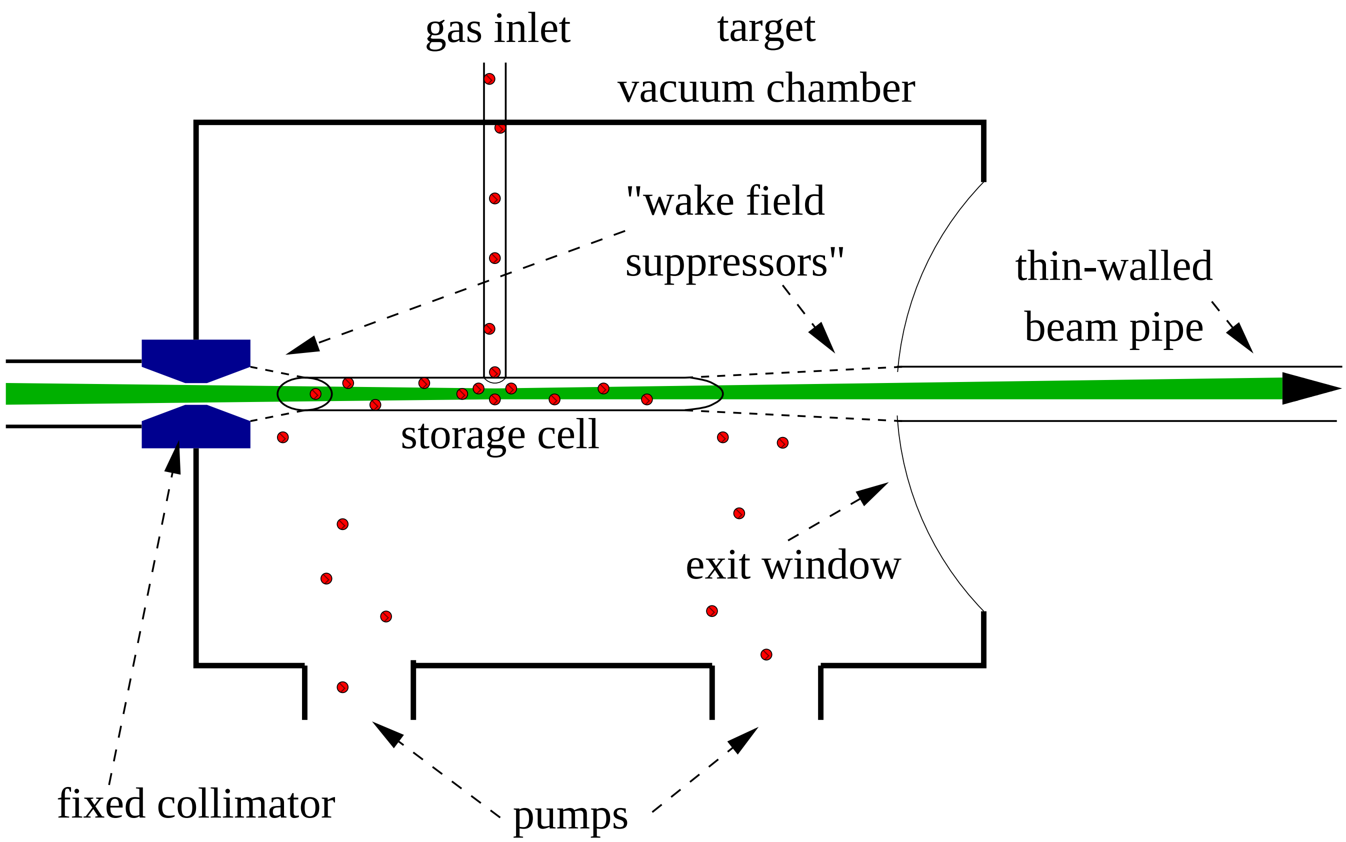



The HERMES experiment at HERA/DESY
Current ≈ 30 mA
⟨Beam Polarization⟩ ≈ 50%




HERA Electron Polarization during a single Fill

# The HERMES Gas Target

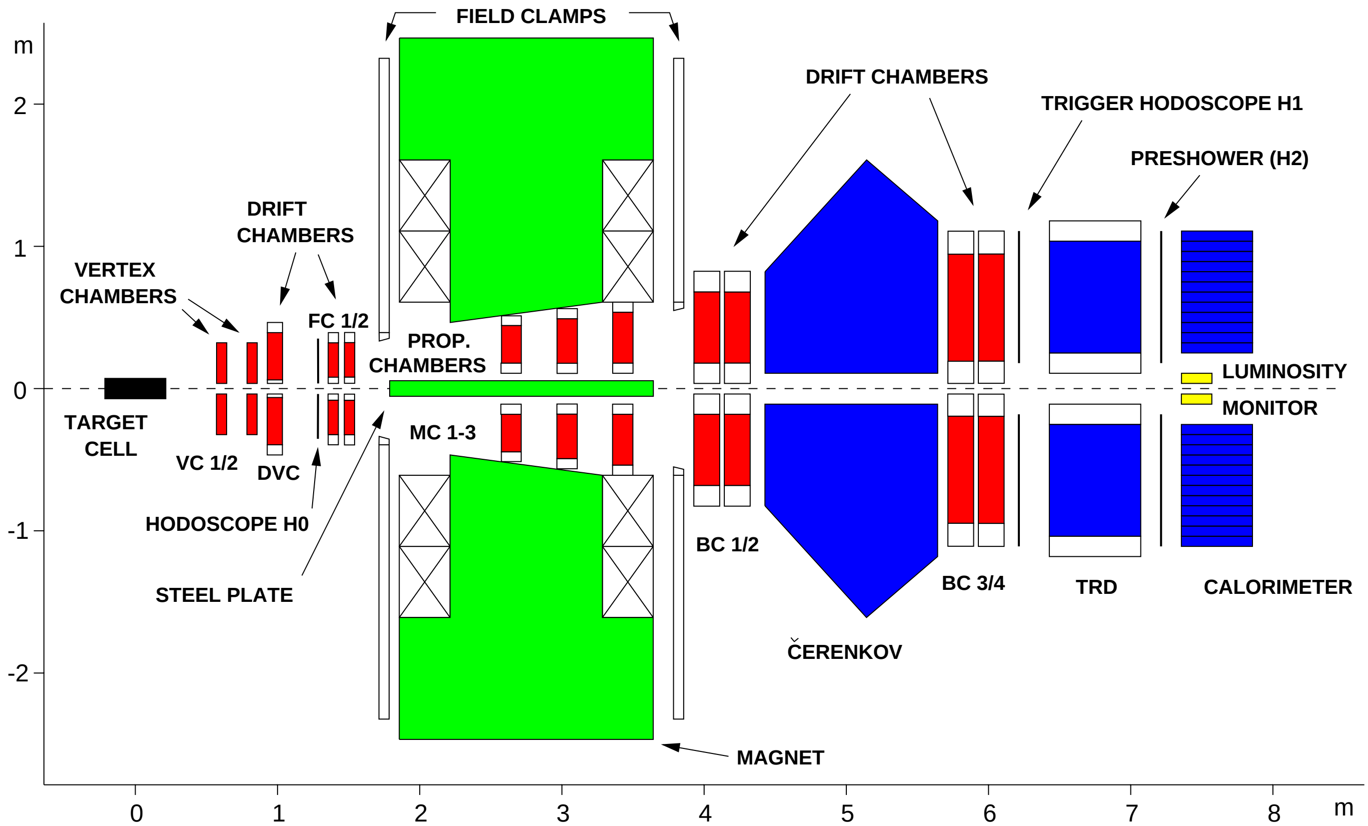



Polarized: H, D, $^3$He

Unpolarized: $H_2$, $D_2$, $^{3,4}$He, Ne, $N_2$, Kr

$\langle$Target Thickness $\rangle \approx 10^{13} - 10^{15} \mathrm{atoms/cm^2}$

# The HERMES spectrometer




- large solid angle: $|\theta_x| < 170$ mrad
  $40 < \theta_y < 140$ mrad
- momentum resolution $\sim$ 1% from 1 to 27 GeV
- hadron/lepton contamination $<$ 1% (with high efficiency)
- calo energy resolution $\sim 2\% + 5.1\%/\sqrt{E} + 10\%/E$

# Polarized DIS

- Inclusive cross section for polarized nucleon and longitudinally polarized beam depends on $F_1$, $F_2$, $g_1$, $g_2$, where in the quark parton model

$$F_1(x) = \frac{1}{2} \sum_f e_f^2 q_f(x)$$

$$F_2(x) = 2xF_1(x)$$

$$g_1(x) = \frac{1}{2} \sum_f e_f^2 \Delta q_f(x)$$

$$g_2(x) = 0$$

- $q_f$ and $\Delta q_f$ are helicity sum and difference parton distributions for quark flavor $f$

- Both longitudinal and transverse nucleon polarizations necessary for independent extraction of the four inclusive structure functions

# Asymmetry Measurements

Polarized DIS experiments typically measure asymmetries $A_{\parallel}$ and $A_{\perp}$ to determine physics asymmetries $A_1$ and $A_2$:

$$A_{\parallel} = \frac{\sigma^{\overset{\rightarrow}{\Leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}}}{\sigma^{\overset{\rightarrow}{\Leftarrow}} + \sigma^{\overset{\rightarrow}{\Rightarrow}}} = D(A_1 + \eta A_2)$$

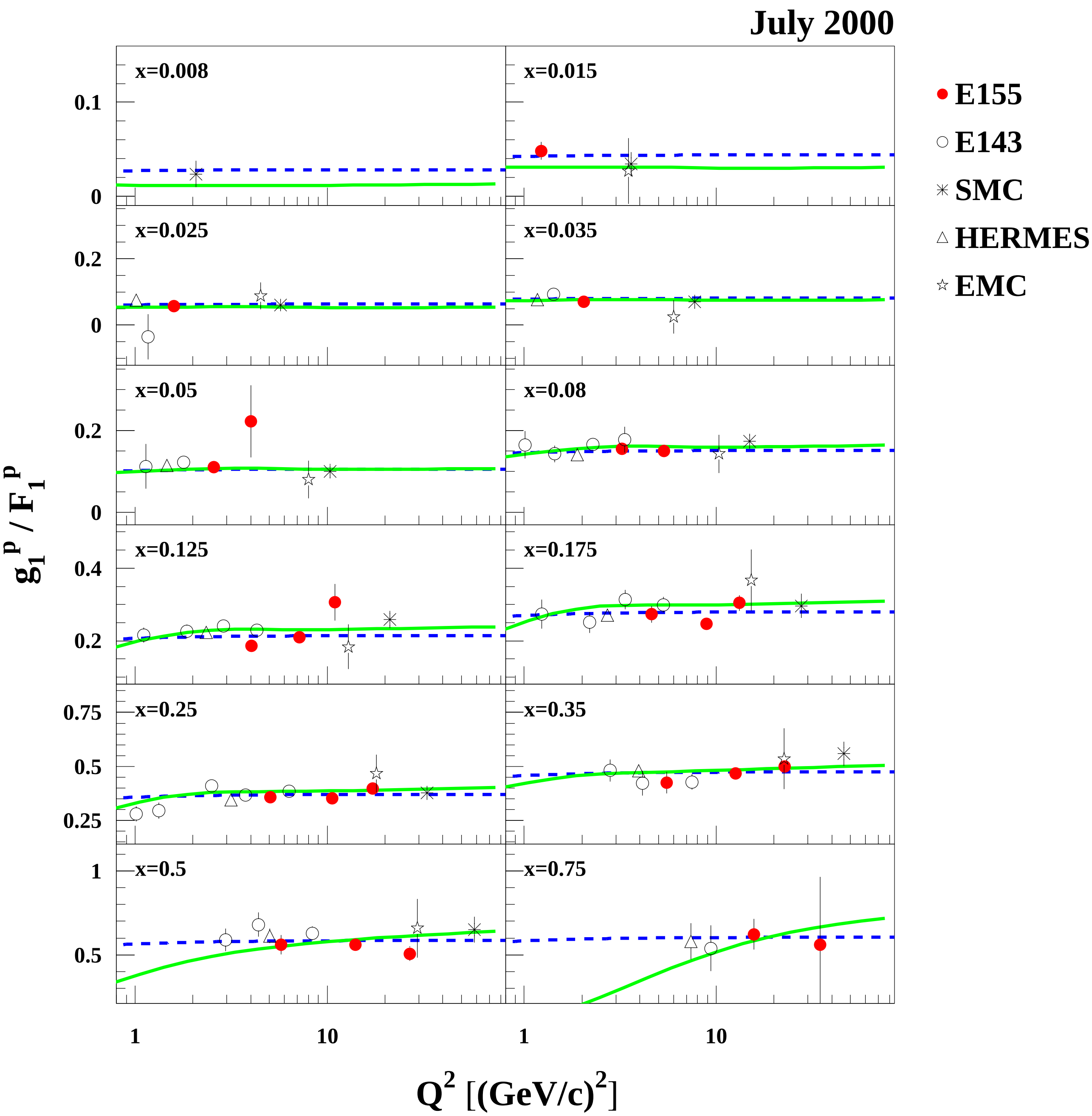
$$A_{\perp} = \frac{\sigma^{\overset{\rightarrow}{\Downarrow}} - \sigma^{\overset{\rightarrow}{\Uparrow}}}{\sigma^{\overset{\rightarrow}{\Downarrow}} + \sigma^{\overset{\rightarrow}{\Uparrow}}} = d(\zeta A_1 + A_2)$$

The asymmetries $A_1$ and $A_2$ can then be related to the structure functions:

$$A_1 = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1} \qquad A_2 = \gamma \frac{(g_1 + g_2)}{F_1}$$

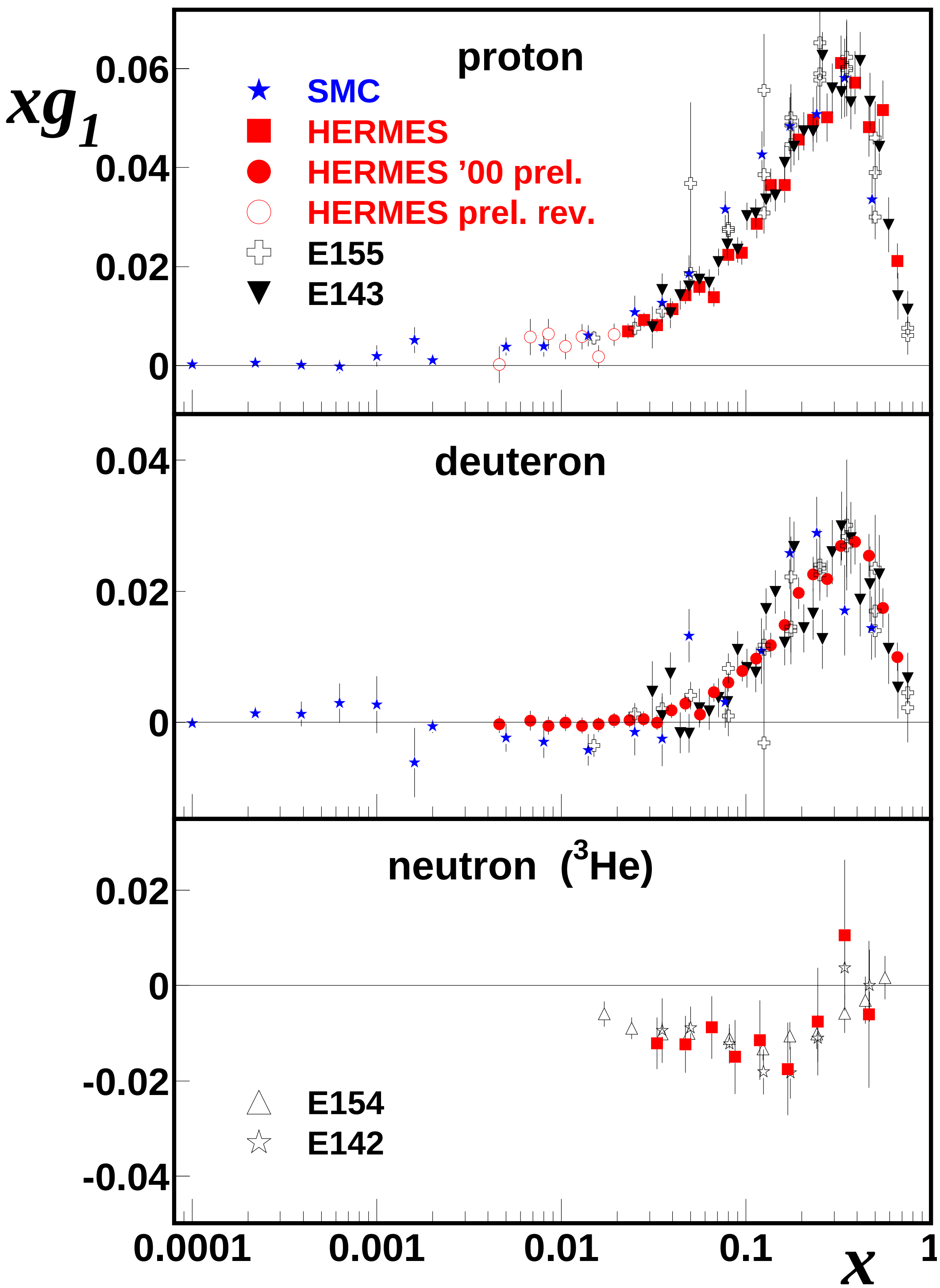
(the undefined variables are all kinematical factors)

# $Q^2$ Dependence of $A_1$




Green = NLO pQCD based fit; Blue = Phenomenological fit
(from SLAC E155 page www.slac.stanford.edu/exp/e155/ )

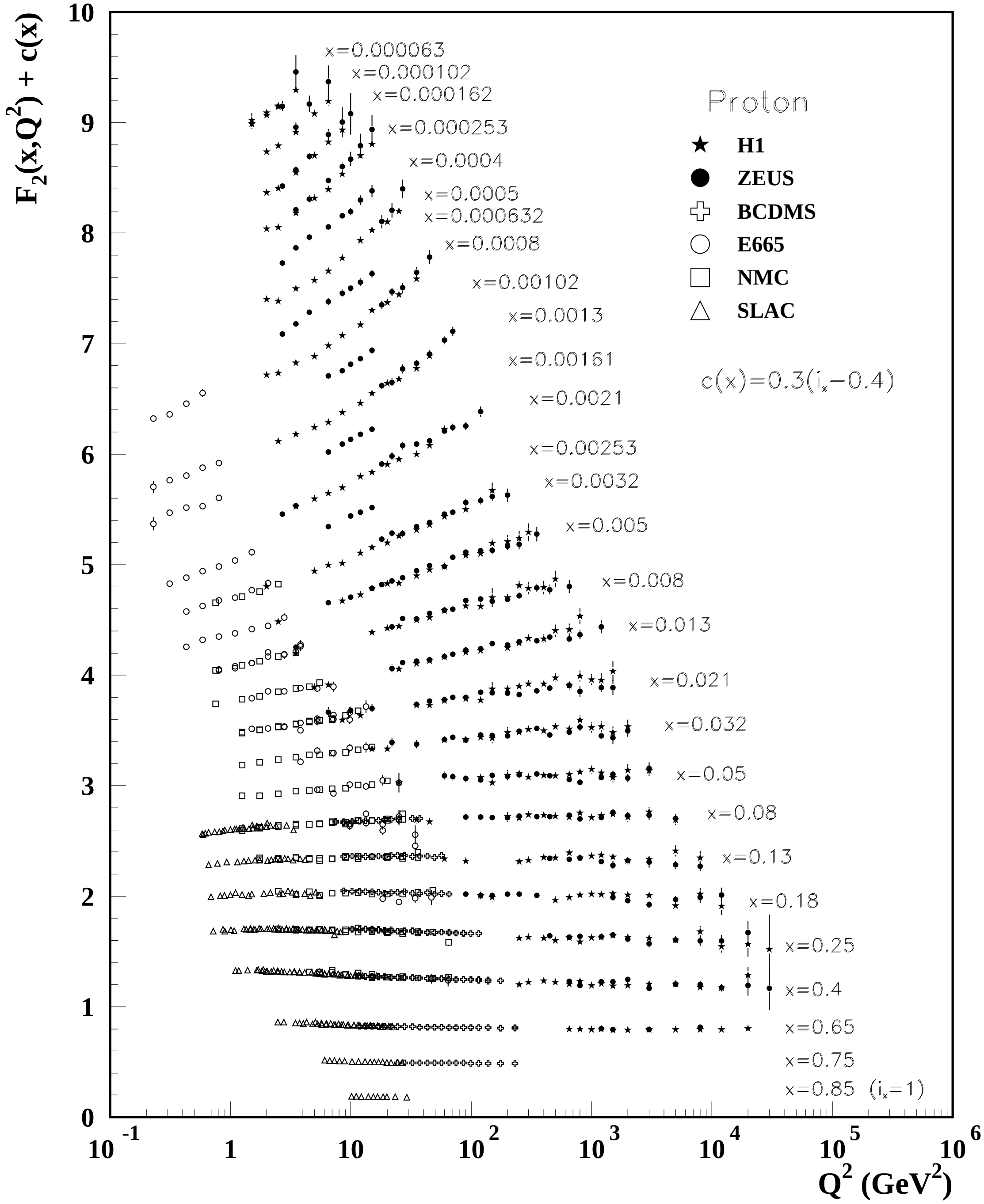
# Latest Measurements of $g_1$




Plots are at measured $Q^2$

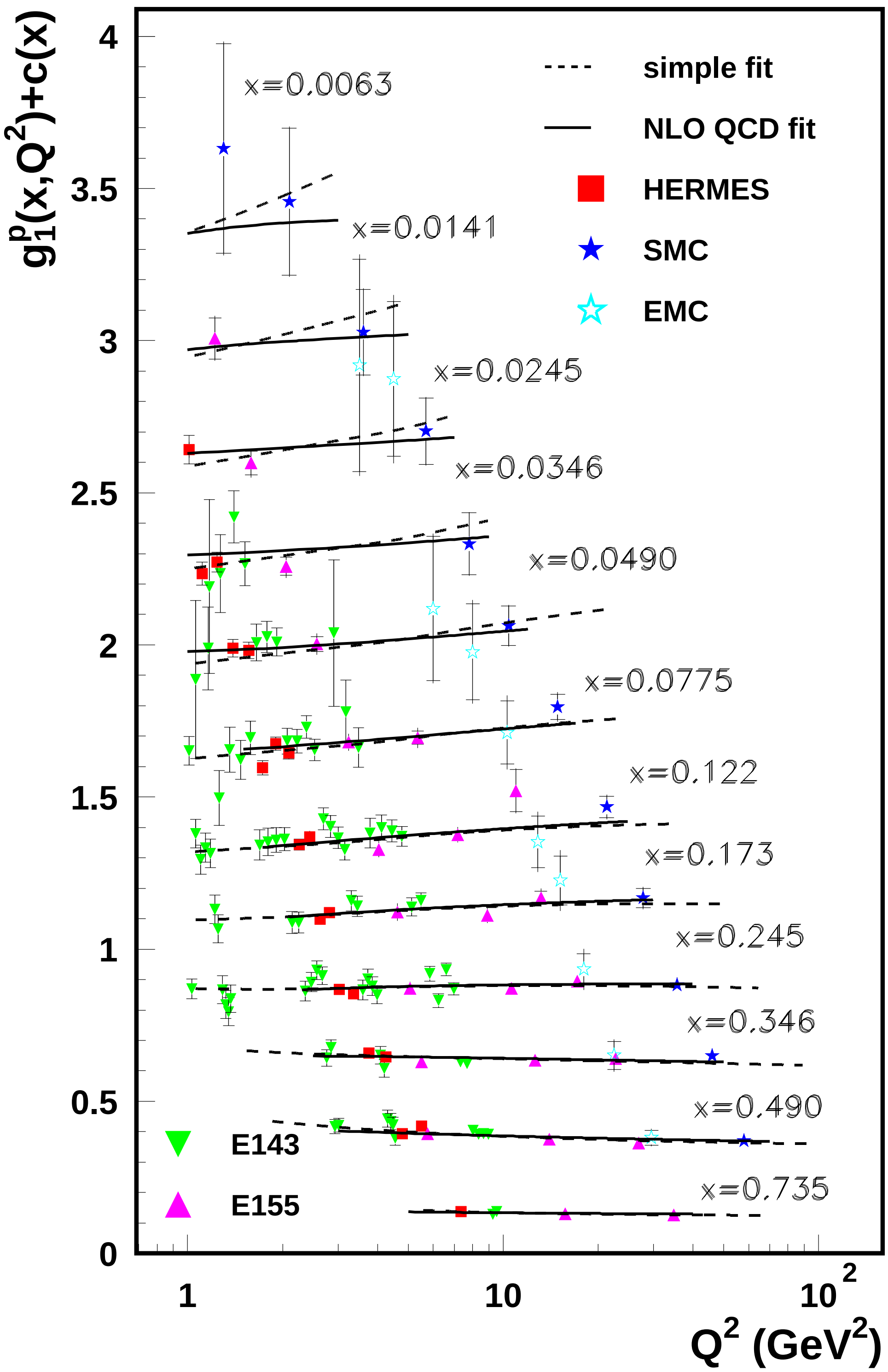
# World Measurements of $F_2$

Unpolarized Structure Functions are measured over broad range of $x$ and $Q^2$



# World Measurements of $g_1$

Polarized Structure Functions from SLAC, CERN and DESY



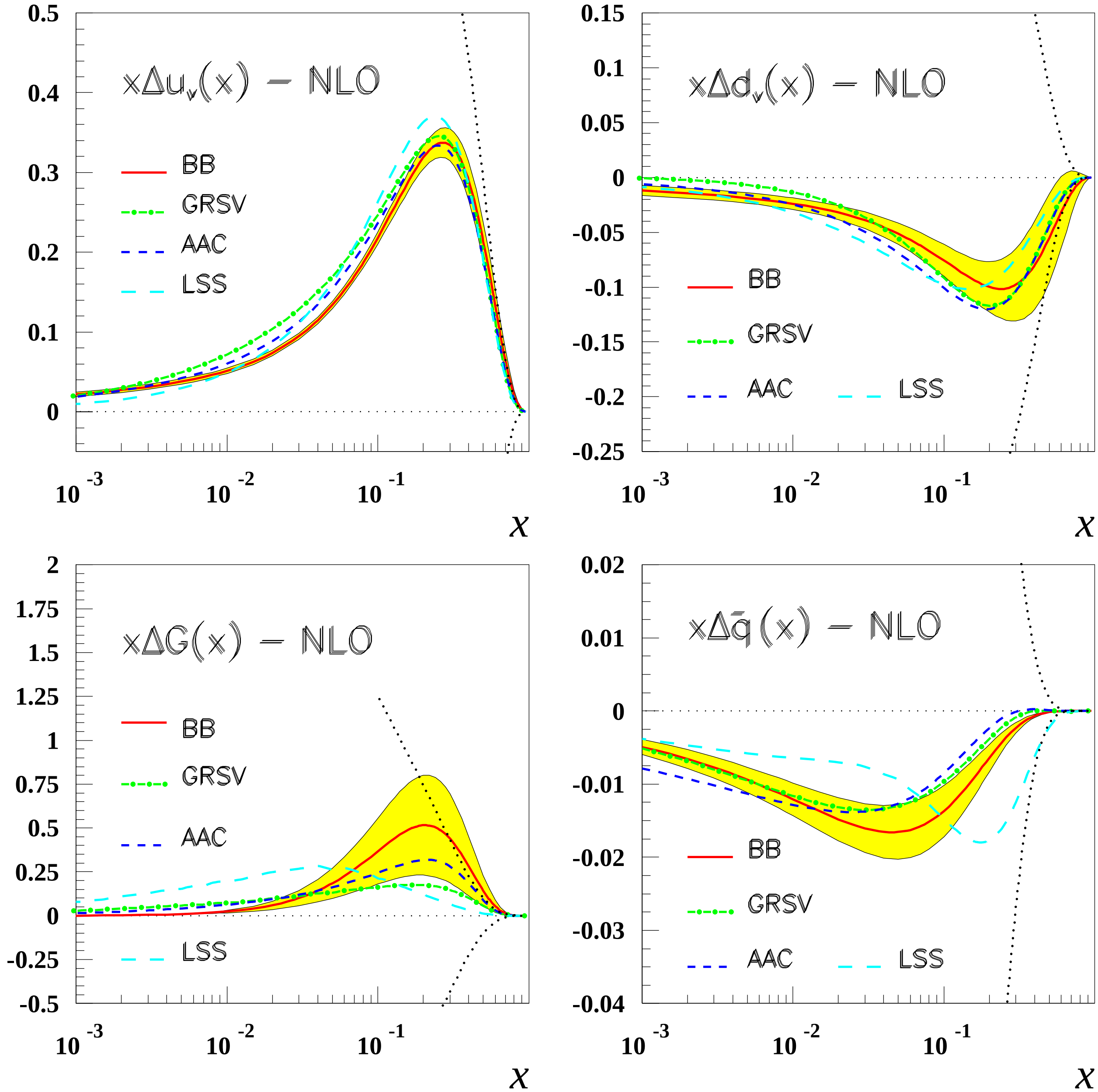
# NLO pQCD Fits to $g_1$

NLO pQCD Fits to $g_1$ at $Q^2 = 4$ GeV$^2$ of Blümlein and Böttcher (hep-ph/0203155) find

$$\Delta\bar{q} = -0.07 \pm 0.02(stat)$$

$$\Delta G = 1.03 \pm 0.55(stat)$$

where SU(3) flavor symmetry has been assumed.



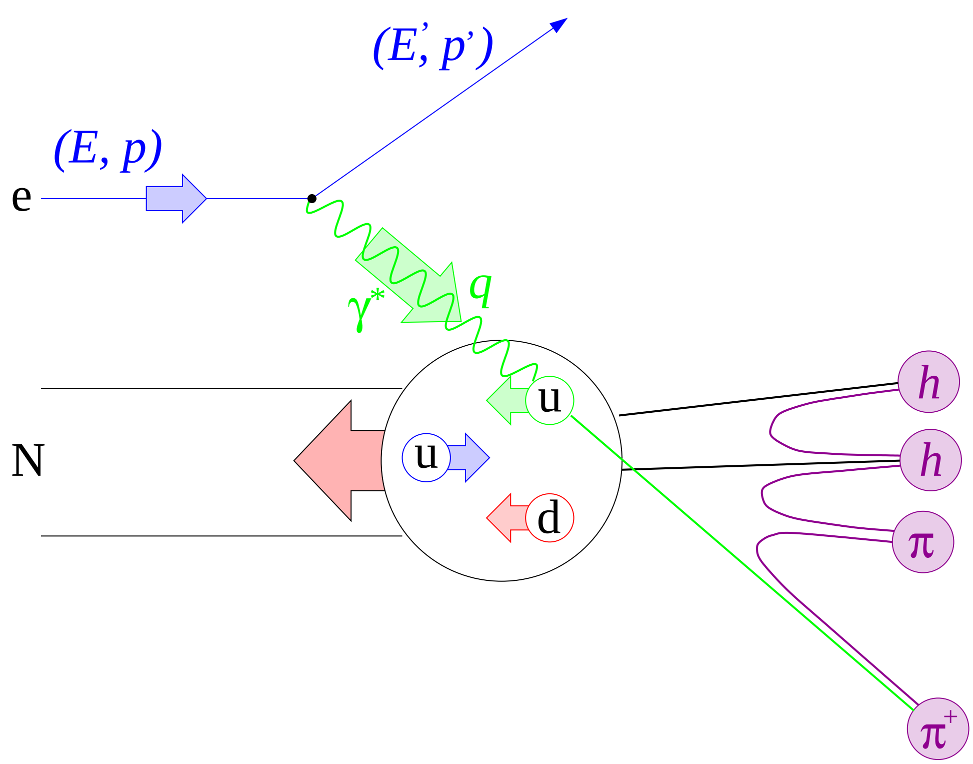

- Yellow band represents propagated 1 $\sigma$ error
- LSS: Leader et al., hep-ph/0111267
- GRSV: Glück et al., hep-ph/0011215
- AAC: Goto et al., hep-ph/0001046

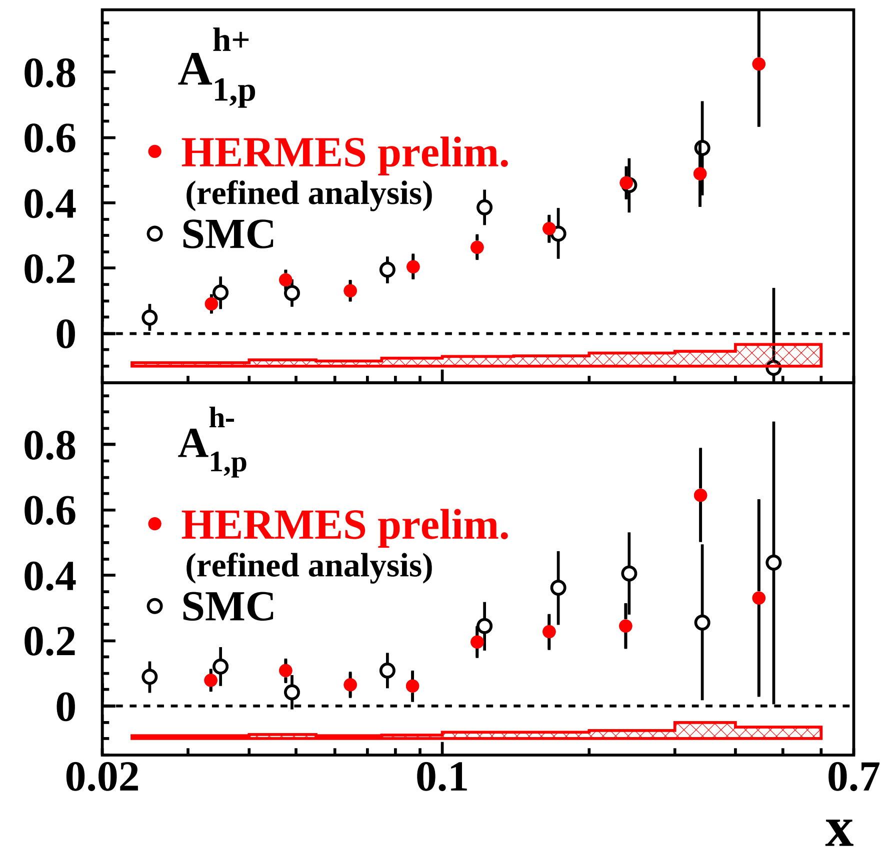
# Semi-Inclusive Asymmetries

Leading hadron detected in coincidence with scattered electron has statistical kinematic correlation with quark which absorbed the virtual photon; hadron identity correlated with quark flavor. In leading order

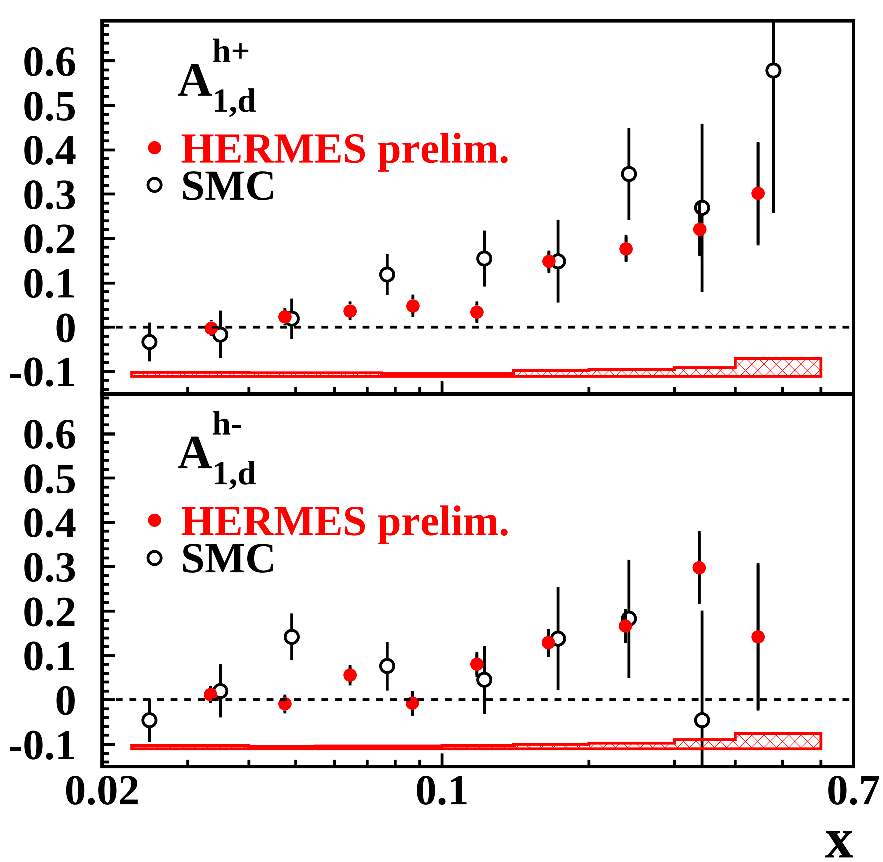
$$A_1^h \approx \frac{g_1^h}{F_1^h}(x,Q^2) = \frac{\int_{z_{min}}^{z_{max}} dz \sum_f e_f^2 \Delta q_f(x,Q^2) \cdot D_f^h(z,Q^2)}{\int_{z_{min}}^{z_{max}} dz \sum_f e_f^2 q_f(x,Q^2) \cdot D_f^h(z,Q^2)}$$

$D_f^h(z,Q^2)$ is the fragmentation function giving the probability that a struck quark of flavor $f$ yields a hadron of fractional energy $z = E_h/\nu$ at a given $Q^2$.

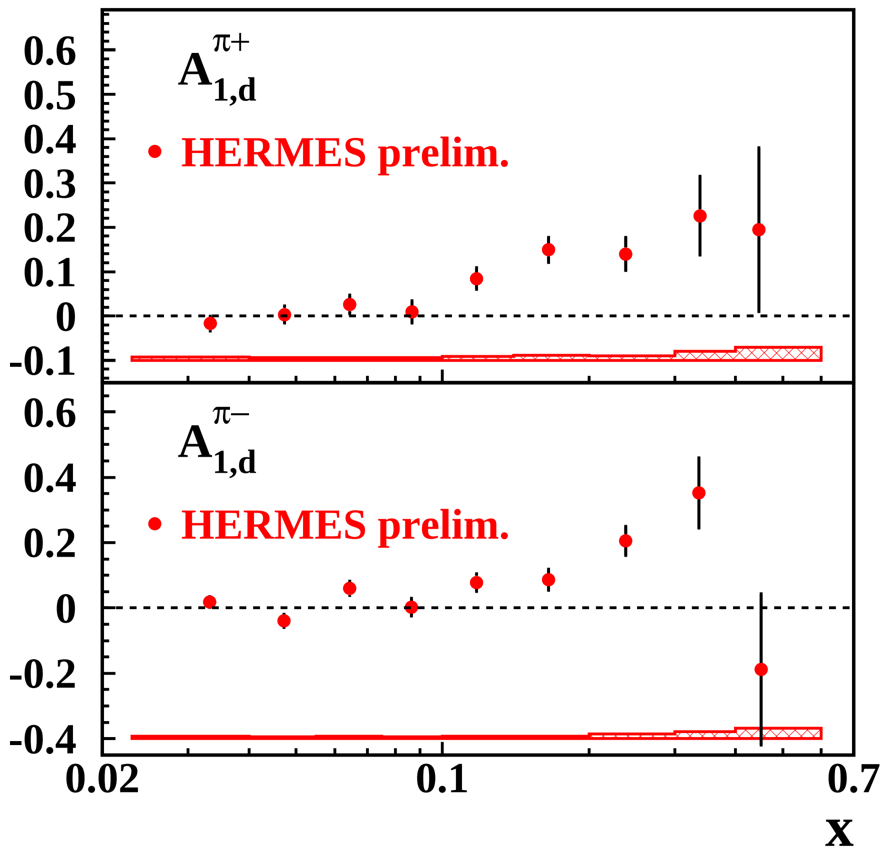




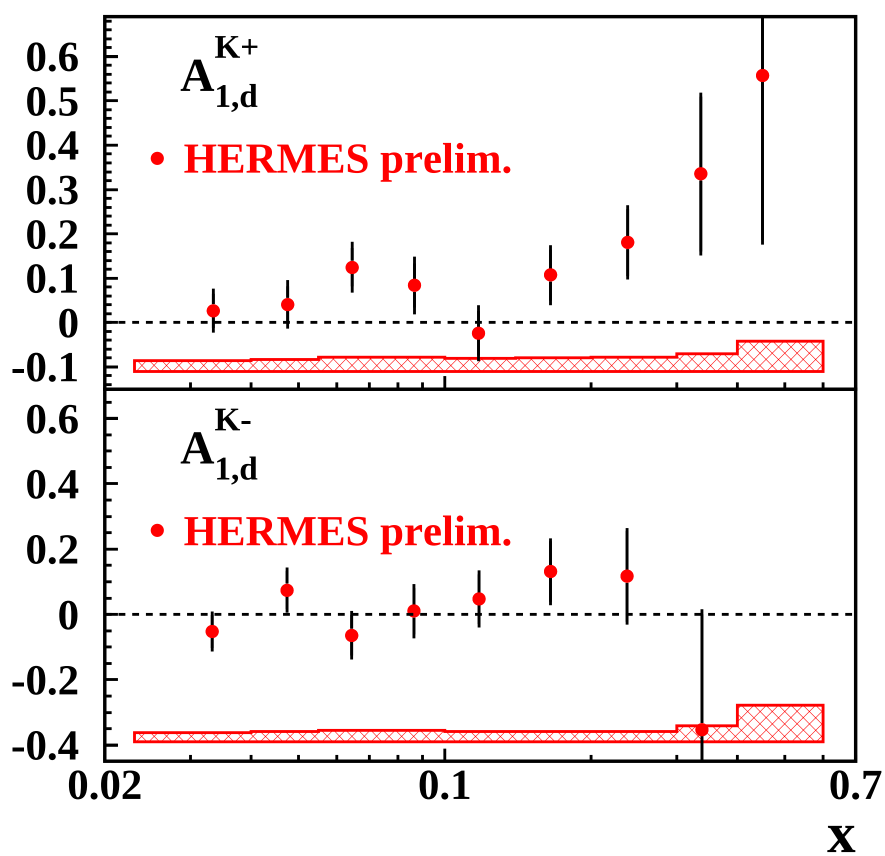
0.8
0.6
0.4
0.2
0
$A^{h+}_{1,p}$
HERMES prelim.
(refined analysis)
SMC
0.8
0.6
0.4
0.2
0
$A^{h-}_{1,p}$
HERMES prelim.
(refined analysis)
SMC
0.02
0.1
0.7
x

0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
$A^{h+}_{1,d}$
HERMES prelim.
SMC
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
$A^{h-}_{1,d}$
HERMES prelim.
SMC
0.02
0.1
0.7
x



$A_{1,d}^{\pi+}$
HERMES prelim.
$A_{1,d}^{\pi-}$
HERMES prelim.
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.4
0.02
0.1
0.7
x

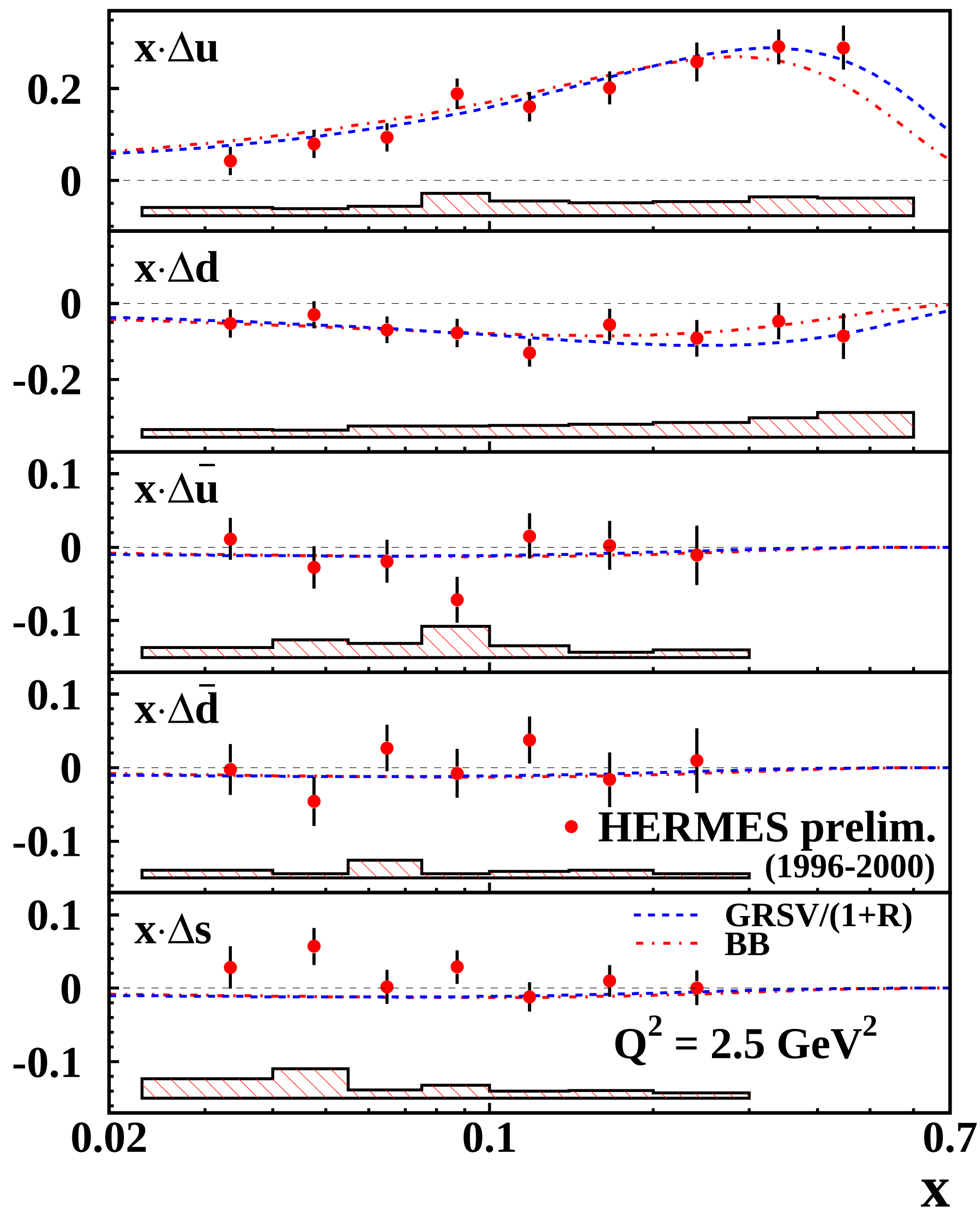
$A_{1,d}^{K+}$
HERMES prelim.
$A_{1,d}^{K-}$
HERMES prelim.
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.4
0.02
0.1
0.7
x

# Flavor Separated Polarized Quark Distributions

New Extraction using deuterium data and RICH hadron id

$$\frac{\Delta u}{u}, \quad \frac{\Delta d}{d}, \quad \frac{\Delta \bar{u}}{\bar{u}}, \quad \frac{\Delta \bar{d}}{\bar{d}}, \quad \frac{\Delta s + \Delta \bar{s}}{s + \bar{s}}$$

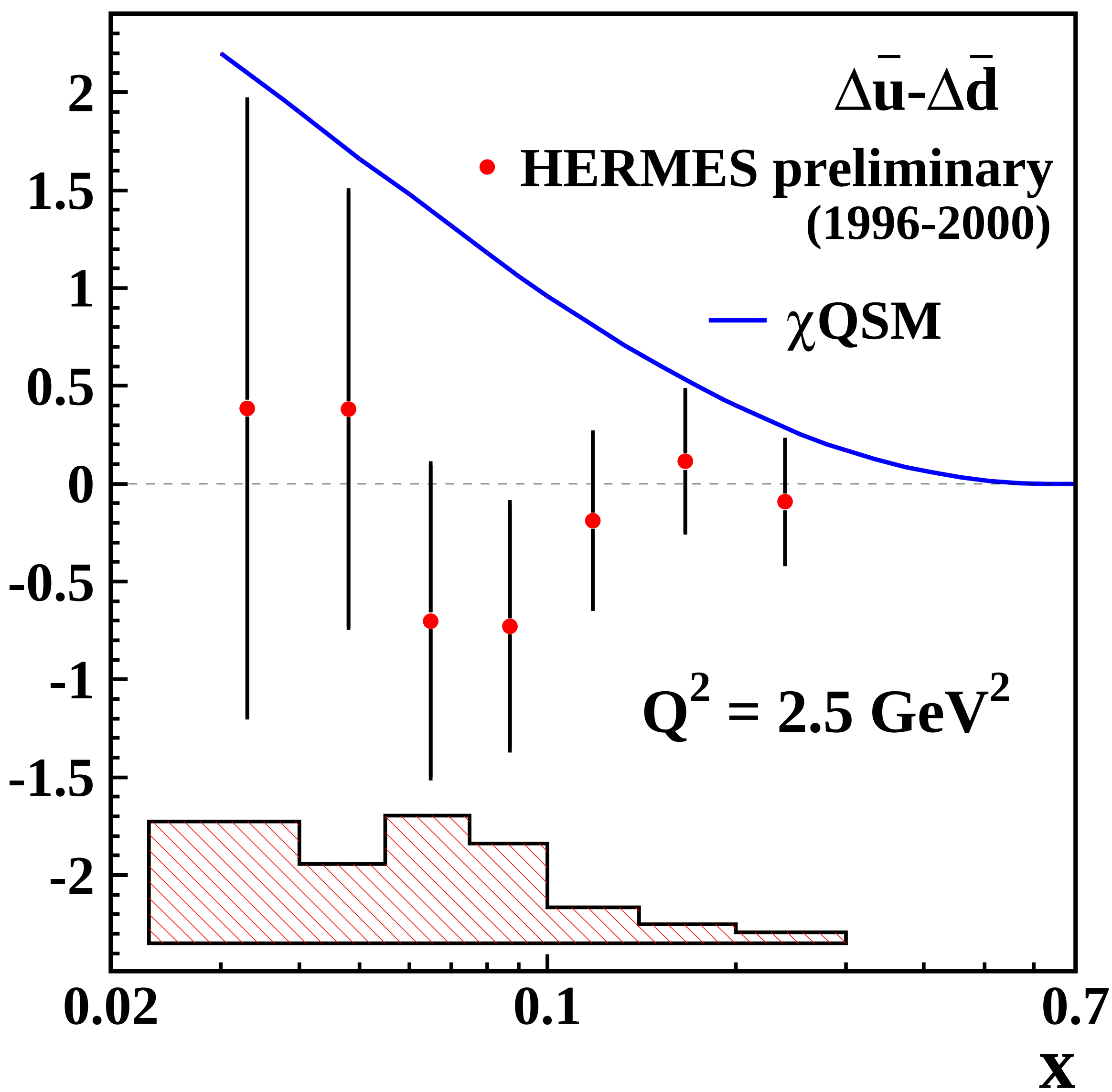
- Five independent polarizations fit to each $x$ bin:
- In measured $x$ range, $A_1$'s $\approx$ 10% sensitive
- Systematic Uncertainty dominated by limited knowledge of fragmentation functions and unpolarized $q_f$'s.



x·Δu
0.2
0
x·Δd
0
-0.2
x·Δū
0.1
0
-0.1
x·Δd̄
0.1
0
-0.1
HERMES prelim.
(1996-2000)
x·Δs
0.1
0
-0.1
GRSV/(1+R)
BB
Q^2 = 2.5 GeV^2
0.02
0.1
0.7
x

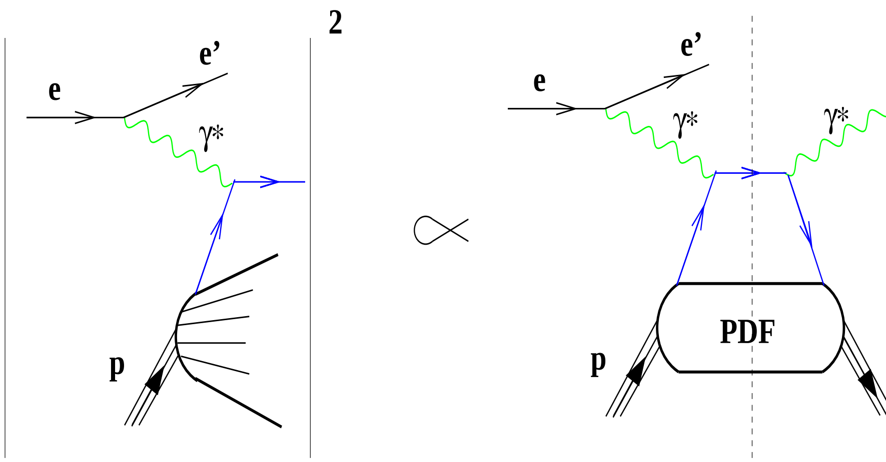
# Polarized Light Sea Asymmetry

- No strong breaking of the flavor symmetry in the light sea is observed within the limits of the data.
- Predictions from e.g., the chiral quark soliton model are not favored by this data (Dressler et al., EPJC 14 (2000) 147.)

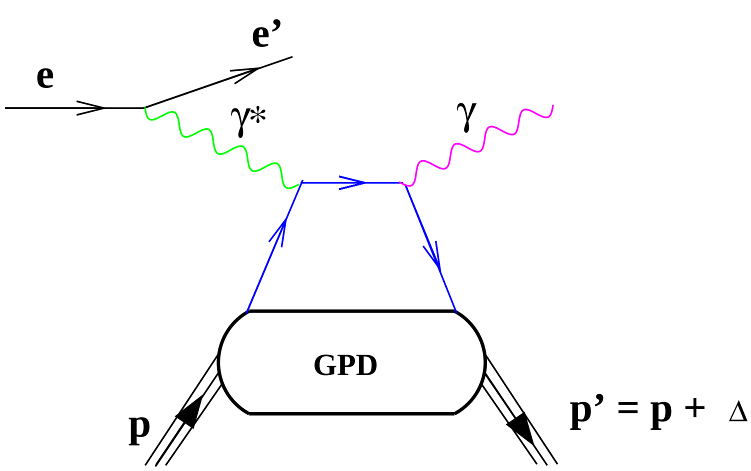


# Forward vs Off-Forward Distributions

DIS is typically understood in terms of Forward amplitudes using the optical theorem




Using an Exclusive reaction, such as Deeply Virtual Compton Scattering (DVCS) one explores the Off-Forward amplitude:



# GPDs

At leading twist (twist 2), there are 4 independent GPDs for each quark and gluon type

| | |
|---|---|
| $\mathrm{H}^{\mathrm{q,g}}(x,\xi,t)$ spin avg no hel. flip | $\mathrm{E}^{\mathrm{q,g}}(x,\xi,t)$ spin avg helicity flip |
| $\tilde{\mathrm{H}}^{\mathrm{q,g}}(x,\xi,t)$ spin diff no hel. flip | $\tilde{\mathrm{E}}^{\mathrm{q,g}}(x,\xi,t)$ spin diff helicity flip |

Where:

- $x$ defined by: $k^+ = x(p+\Delta/2)^+$

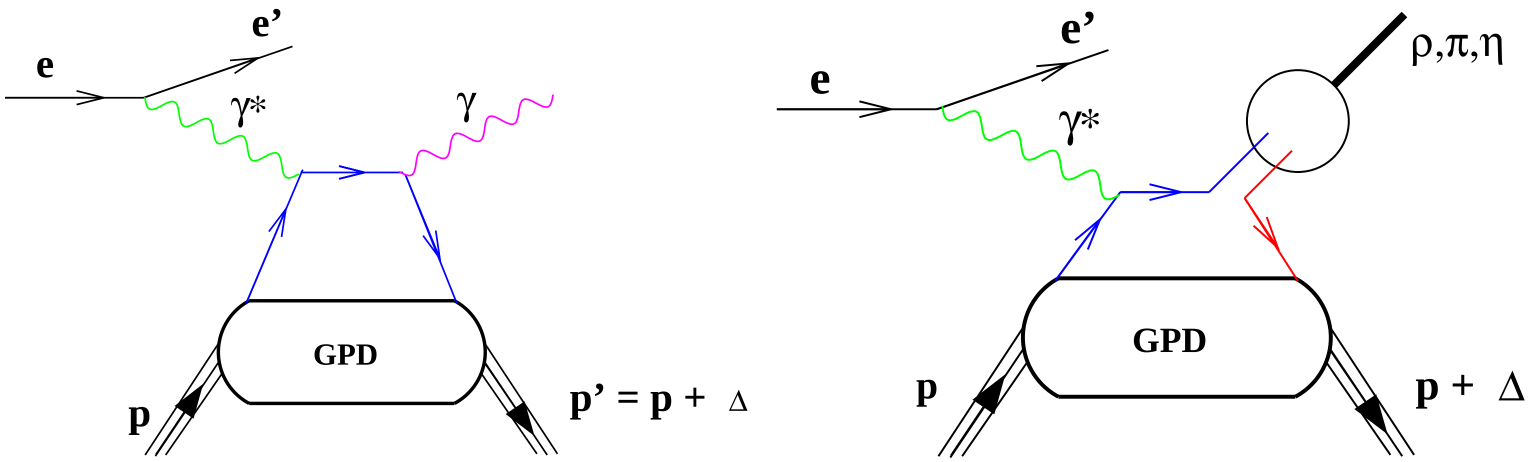
  the light cone momentum fraction of the struck parton

- $t = \Delta^2$; the squared momentum transfer to the nucleon

- $\xi$ defined by: $\Delta^+ = -2\xi(p+\Delta/2)^+$

  $\rightarrow$ is the longitudinal fraction of the momentum transfer $t$
  
  $\rightarrow$ parameterizes the skewedness (how far off-forward)

# Exclusive Processes




- Deeply Virtual Compton Scattering, vector meson and pseudo-scalar production involve different combinations, flavors of GPDs

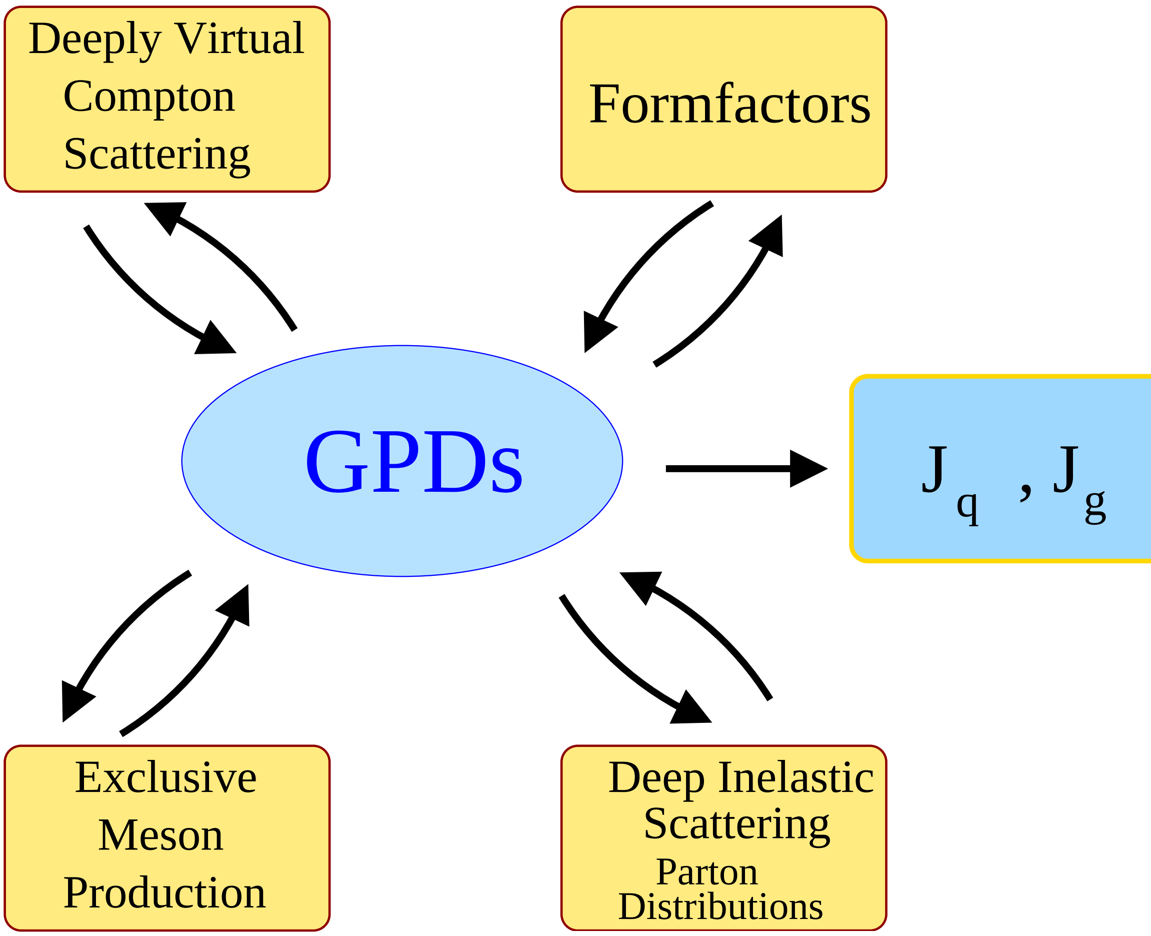
- DVCS $\rightarrow H$, $E$, $\tilde{H}$,$\tilde{E}$

- Vector mesons ($\rho_L, \omega_L, \phi_L$) $\rightarrow H$, $E$

- Pseudo-scalar mesons ($\pi$, $\eta$) $\rightarrow \tilde{H}$, $\tilde{E}$

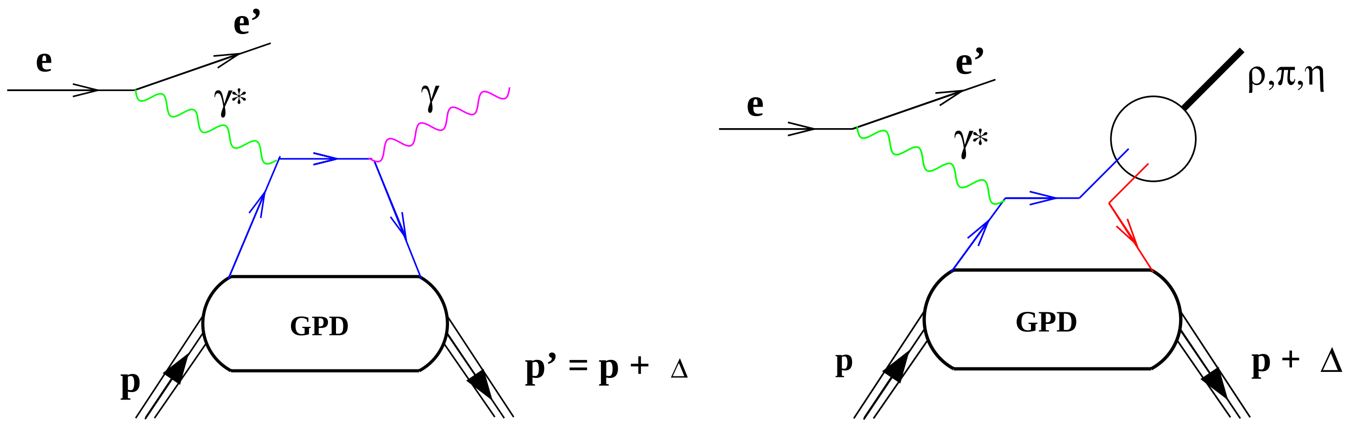
- Meson production also involves the meson distribution function

# GPD Review




GPDs provide a link between the inclusive (parton distributions) and exclusive (form factors) characteristics of the nucleon.

# GPD's - Generalizations of PDF's

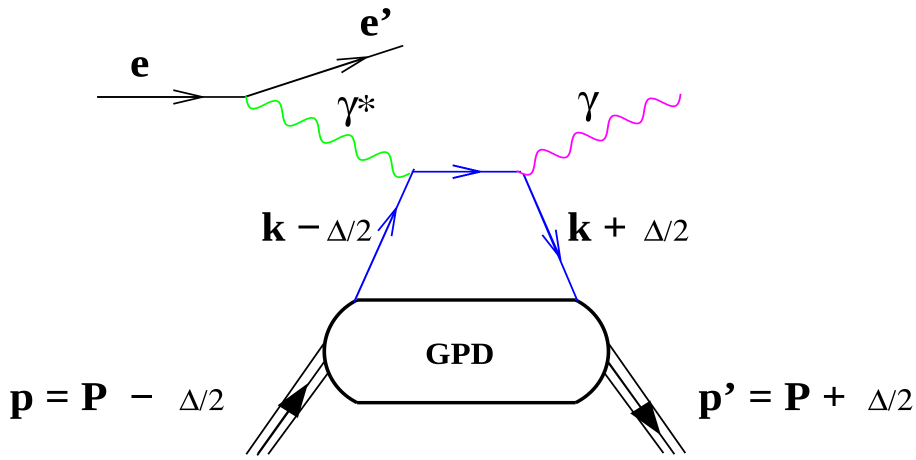



- When the final state momentum differs from the initial $\rightarrow$ off-forward kinematics

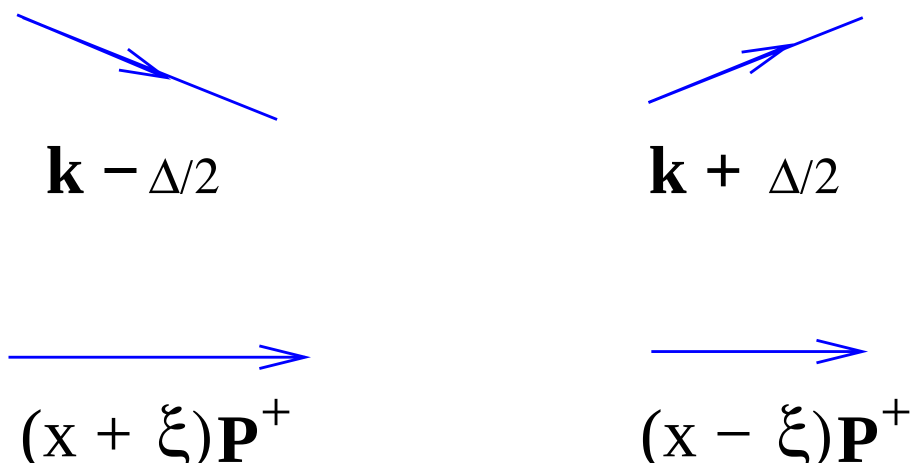
- Factorization for non-forward kinematics has been recently proven

- GPDs give information on the correlations between partons of different momentum

# DVCS – The Parton Momentum




Momenta in symmetric representation $P = p + \Delta/2$




- $\xi$ defines the momentum transfer fraction in the longitudinal (+) direction
- $x \neq x_{Bj}$ in Bjorken limit; no simple probability interpretation possible
- GPDs describe correlations between partons of different momenta

# GPDs and DIS

In the limit of $\xi \to 0$ and $t \to 0$, $H$ and $\widetilde{H}$ reduce to the ordinary parton distributions:

$$H^q(x,0,0) = \begin{cases} q(x), & x > 0\,, \\ -\bar{q}(-x), & x < 0\,. \end{cases}$$

$$\tilde{H}^q(x,0,0) = \begin{cases} \Delta q(x), & x > 0\,, \\ \Delta\bar{q}(-x), & x < 0\,. \end{cases}$$

$E(x,0,0)$ and $\widetilde{E}(x,0,0)$ not accessible in DIS, as nucleon (parton) helicity flip is forbidden (angular momentum conservation)

# GPDs and Elastic Scattering

Integration over $x$ gives the following sum rules:

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

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

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

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

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

$\rightarrow$ Link to elastic scattering

# GPDs and Angular Momentum

Burkardt has shown an intuitive link to total angular momentum when:

$$\xi = 0, \quad \Delta = \Delta_\perp$$


- At $\xi = 0$, $x = x_{Bj}$ and the probability interpretation is again valid
- $\Delta_\perp$ is viewed as the Fourier transform of an impact parameter $b_\perp$
- GPDs describe the probability to probe a parton of (longitudinal) momentum fraction $x$ at a perpendicular distance $b_\perp$

$\rightarrow$ Similar to simple angular momentum $\vec{L} = \vec{r} \times \vec{p}$

# GPDs and Angular Momentum

The expectation values of the nucleon spin carried by quarks and gluons have been shown by Ji to be related to the second moments of the GPDs at
$t = 0$ (Ji ,Phys. Rev. Lett. **78**):

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

The nucleon spin can be written as:

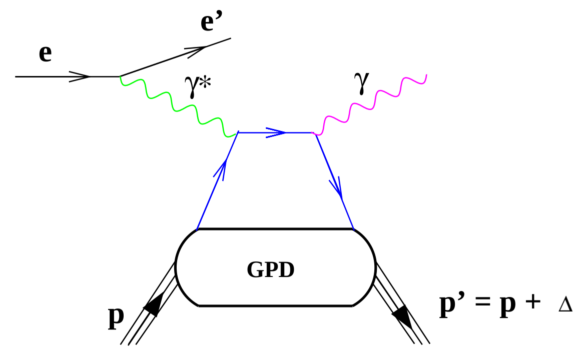
$$\begin{aligned} \frac{1}{2} &= \hat{J}_q + \hat{J}_g \\ \frac{1}{2} &= \hat{L}_q + \frac{1}{2}\Sigma + \hat{J}_g \end{aligned}$$

$\hat{L}_q$ can be obtained by
measuring $\hat{J}_q$(from GPDs) and $\frac{1}{2}\Sigma$ (from DIS)

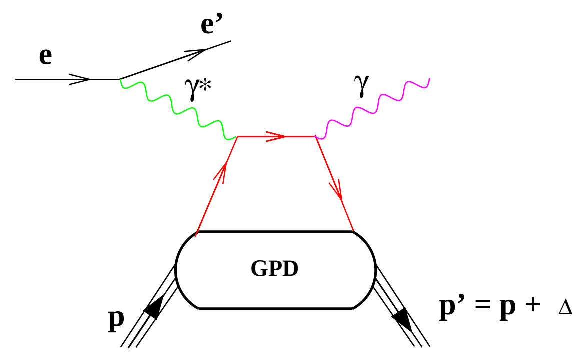
$\rightarrow$ appears to be analysis scheme dependent
(Jaffe hep-ph/0102281)

# Crossover Behavior

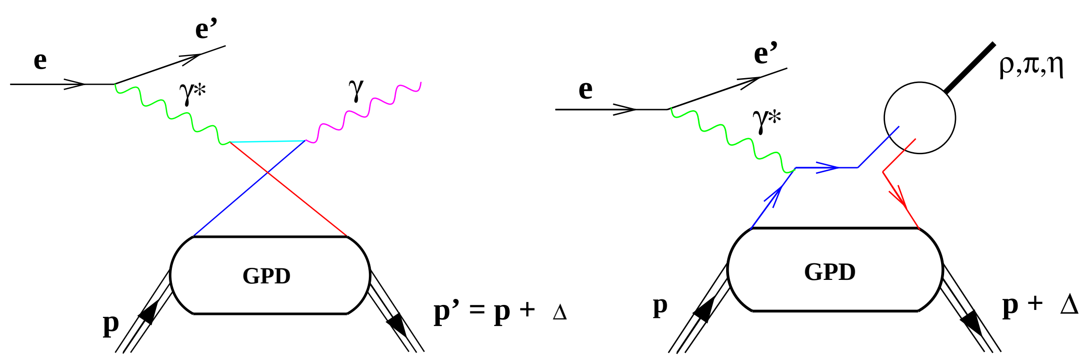
- Regime 1: $x > \xi$



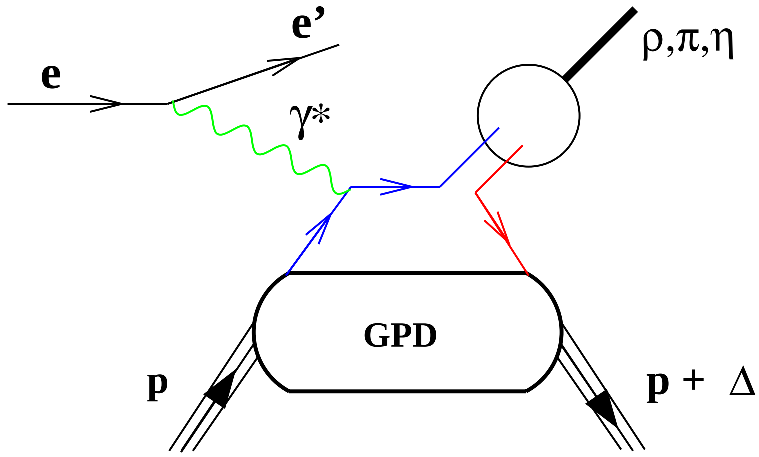

- Regime 2: $x < -\xi$




- Regime 3: $-\xi < |x| < \xi$



# Exclusive Meson Production

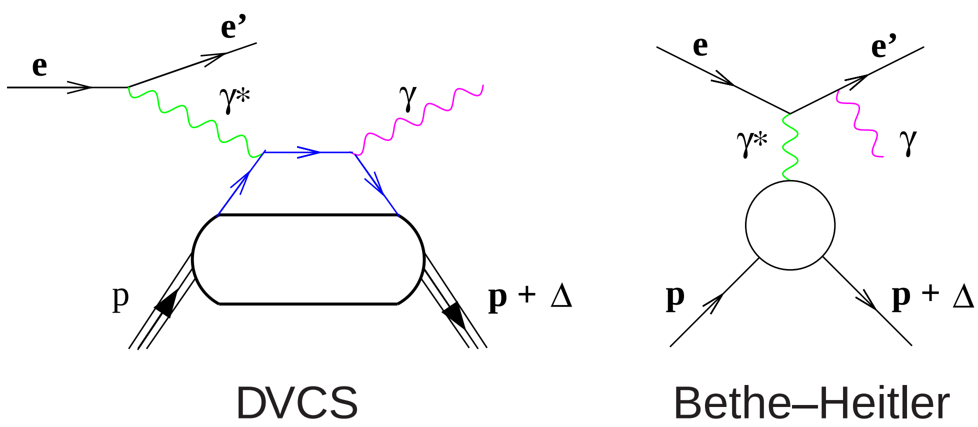



- Easy to detect final state of charged particles
- But convoluted with the meson wave function
- Several different final states: $\pi, \eta, \rho, \omega, \phi$
- Different combinations, flavors of GPDs

$\rightarrow$ longitudinal polarized channels ($\rho_L, \omega_L, \phi_L$) sensitive to H and E

$\rightarrow$ pseudo scalar channels ($\pi, \eta$) sensitive to $\tilde{H}$ and $\tilde{E}$

# Deeply Virtual Compton Scattering (DVCS)

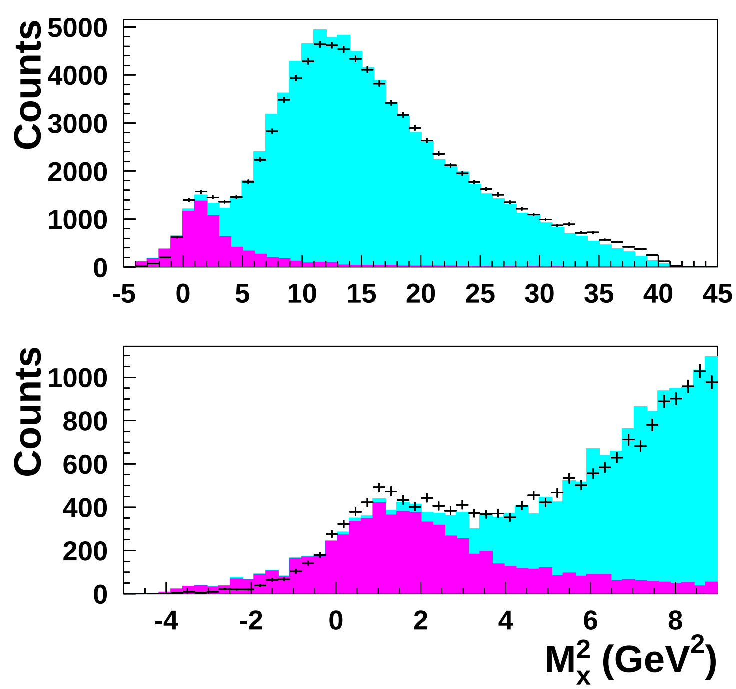



- DVCS - electroproduction of real photon from parton inside the nucleon

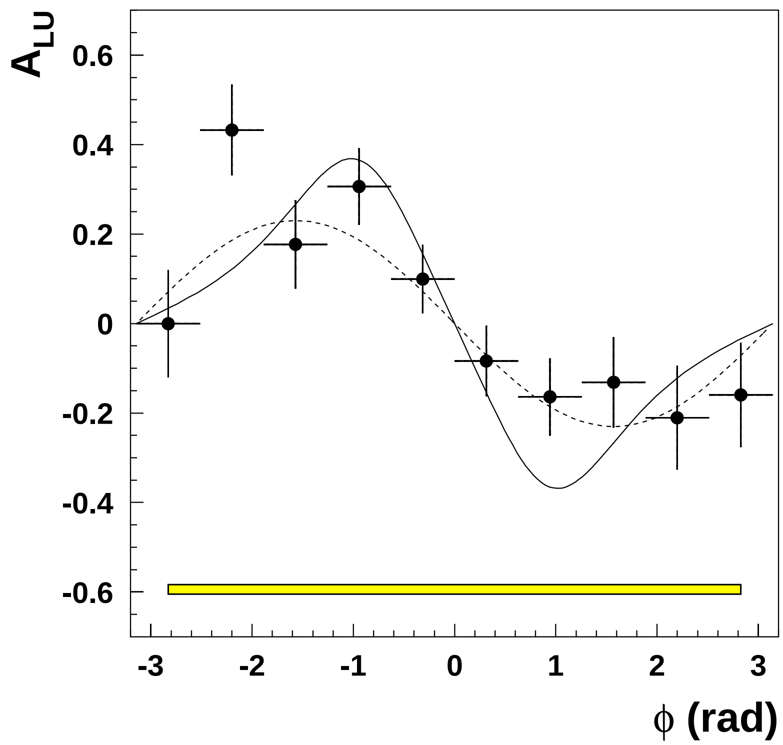
- Interferes with the Bethe-Heitler (radiative) process

$$d\sigma \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + (\mathcal{T}^*_{BH}\mathcal{T}_{DVCS} + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH})$$

- HERMES detects scattered lepton and real photon, reconstructs re–coiling proton



# DVCS: Beam–Spin Asymmetry




$$A_{LU}(\phi) = \frac{[N^+(\phi) - N^-(\phi)]}{<|P_{beam}|> [N^+(\phi) + N^-(\phi)]}$$

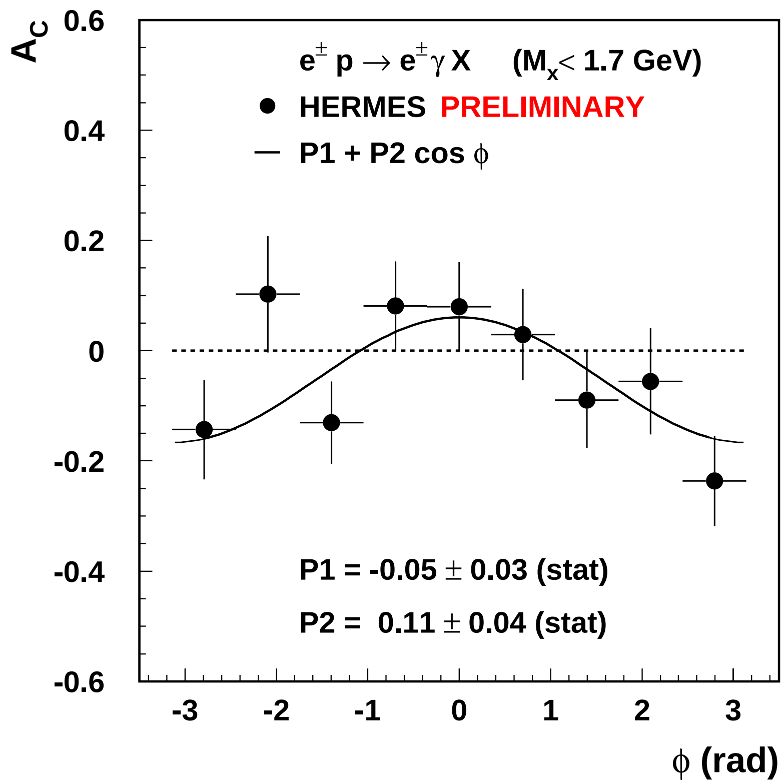
- Using polarized beam, unpolarized target, can measure the beam–spin asymmetry

- Sensitive to the imaginary part of the DVCS+BH interference

- Using method of moments,

$$A_{LU}^{\sin\phi} = 0.23 \pm 0.04(\mathrm{stat}) \pm 0.03(\mathrm{sys})$$

# DVCS: Beam–Charge Asymmetry




$$\mathrm{A_C}(\phi) = \frac{N^{e^+}(\phi) - N^{e^-}(\phi)}{N^{e^+}(\phi) + N^{e^-}(\phi)}$$

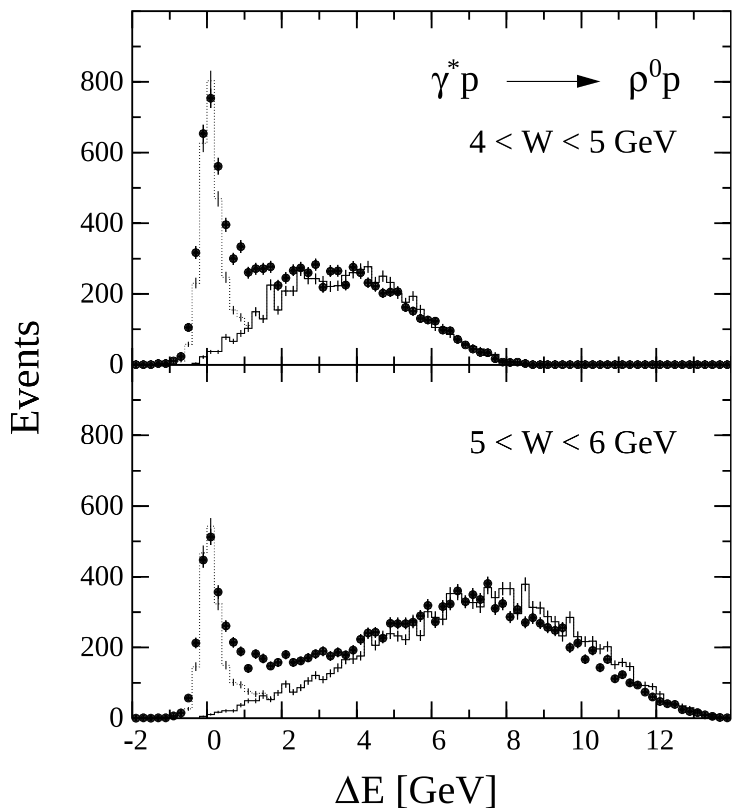
- Using unpolarized positron and electron beams, can measure the beam–charge asymmetry

- Sensitive to the real part of the DVCS+BH interference

- Using method of moments,

$$\mathrm{A}_\mathrm{C}^{\cos\phi} = 0.11 \pm 0.04(\mathrm{stat}) \pm 0.03(\mathrm{sys})$$

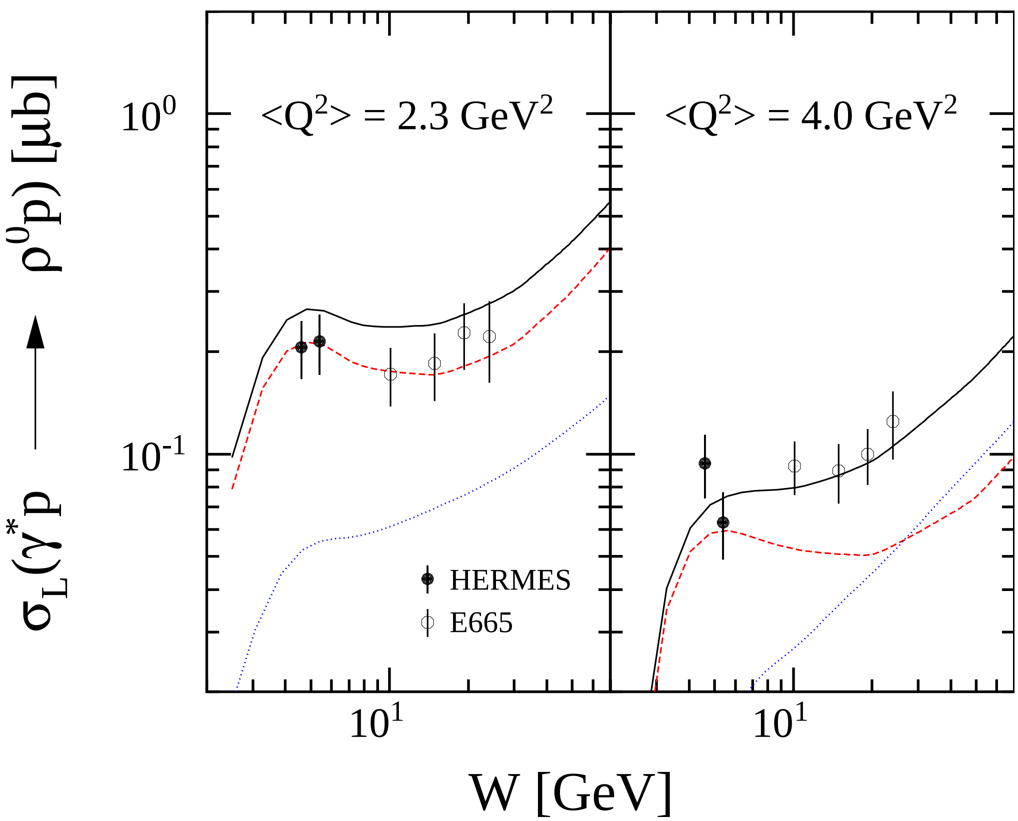
# Diffractive $\rho^0$ Production




- $\rho^0$ selected via reconstruction of $\pi^+\pi^-$ pairs
- Exclusive $\rho^0$ events selected using cut in $\Delta E$ $(= \frac{M_x^2 - m_p^2}{2m_p})$
- $R = \frac{\sigma_L}{\sigma_T}$ extracted by determination of $r_{00}^{04}$ spin density matrix element

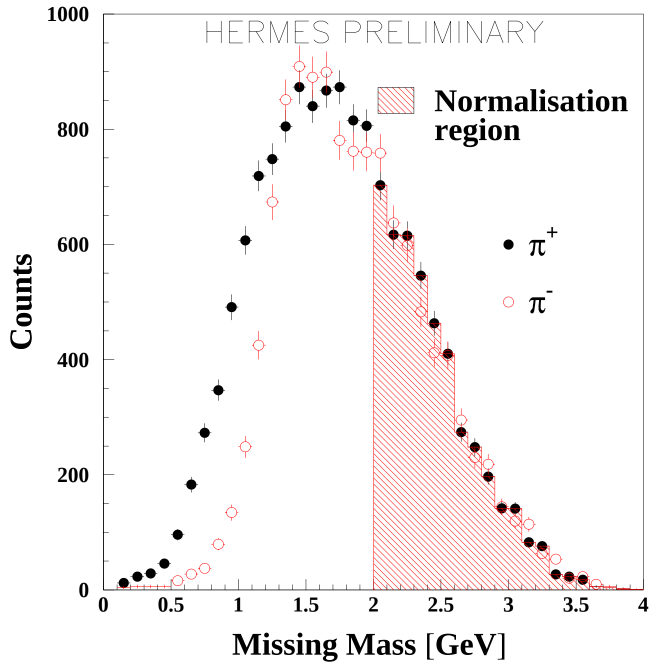
# $\rho^0$ Longitudinal Cross Section

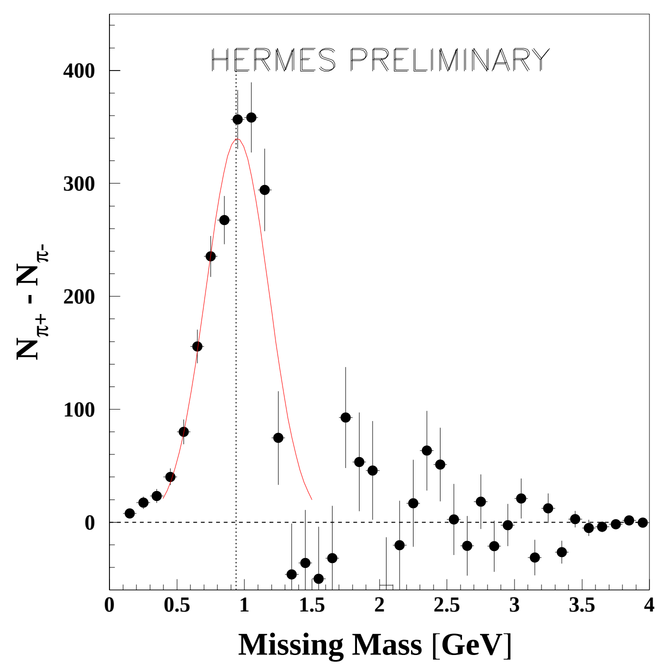
- Factorization proven for longitudinal $\rho^0$ electroproduction
- Use parameterization of $R$ and measurement of $\sigma_{Total}$ to get $\sigma_L$
- HERMES results consistent with GPD-based calculation of Vanderhaeghen *et al* [PRL **80**,5064 (1998)]




gluon–exchange contribution
quark–exchange contribution
quark + gluon

# Exclusive $\pi^+$ Production



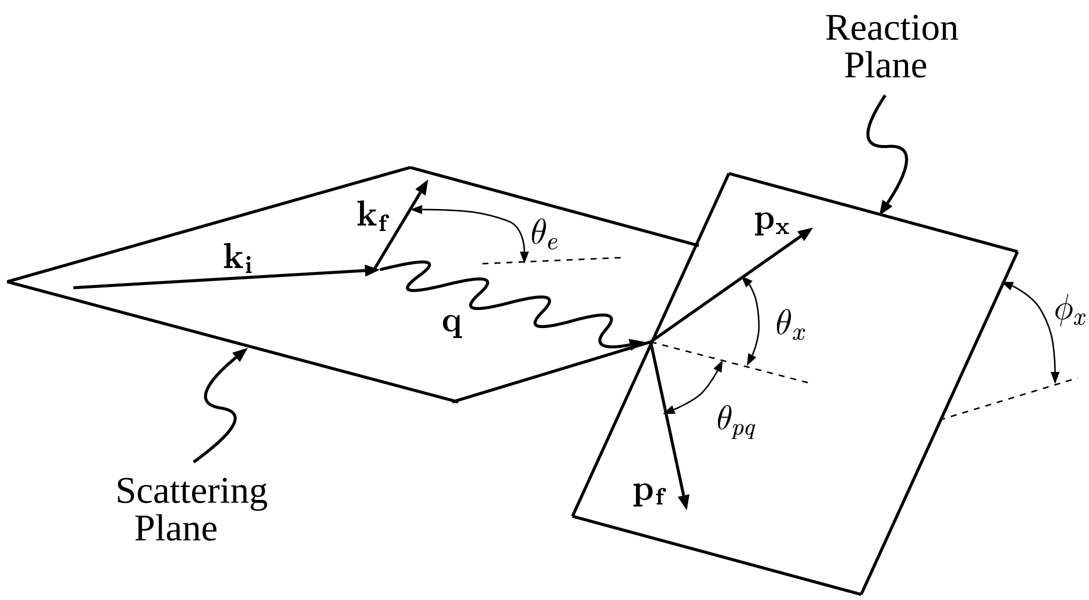




- HERMES missing–mass resolution not sufficient to cleanly identify exclusive $\pi^+$ event–by–event

- Obtain exclusive sample by subtracting semi–inclusive $\pi^-$ spectrum (where exclusive production is impossible) from $\pi^+$ sample

- May be some complication in background subtraction due to differences in $\pi^+$ and $\pi^-$ production with $\Delta$ excitation

# Target–spin Azimuthal Asymmetry from Exclusive $\pi^+$ Production

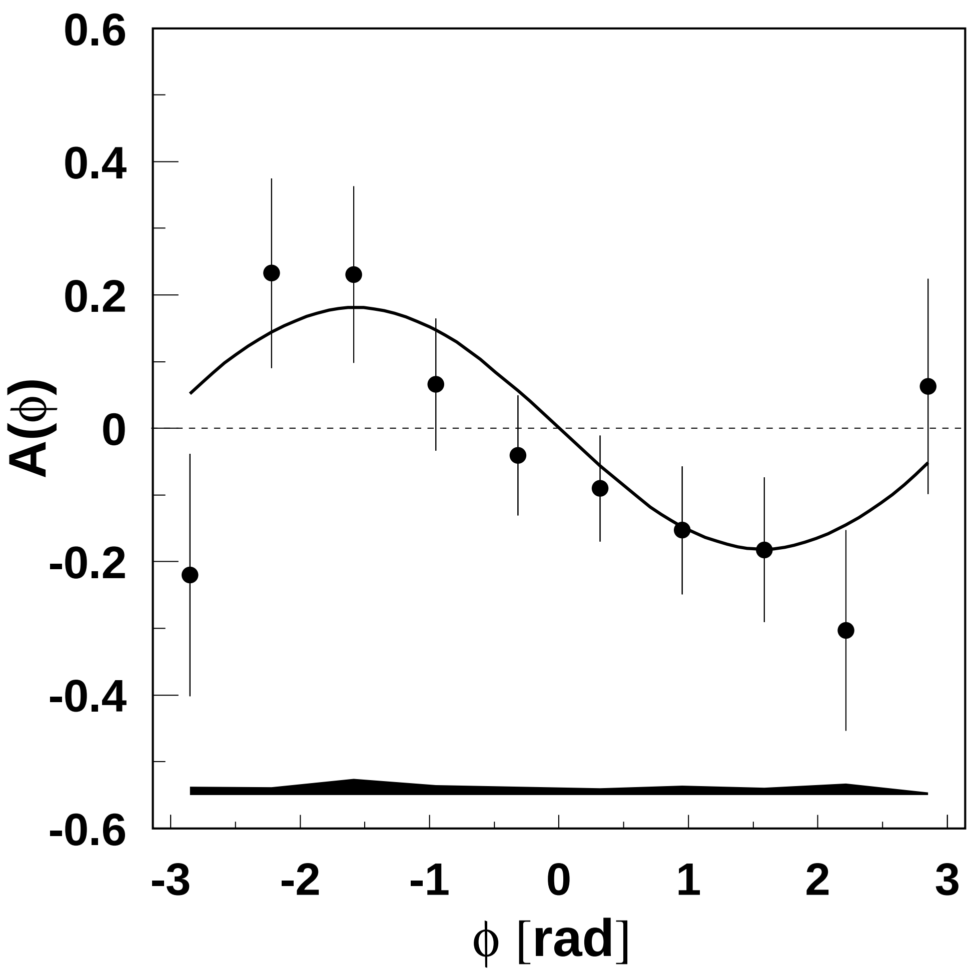



- Frankfurt *et al* [PRL **84** 2589 (2000)]: interference between pseudoscalar $\tilde{E}$ and pseudovector $\tilde{H}$ gives large asymmetry in $\phi$ distribution of target–spin asymmetry (transversely polarized target)

- Target polarized longitudinally with respect to beam direction has a small transverse component, $S_\perp$, with respect to virtual photon direction

- Polarized cross section:
$\sigma_S \sim [S_\perp \sigma_L + S_\| \sigma_{LT}] A_{LU}^{\sin\phi} \sin\phi$

# Results for $\pi^+$ Target–spin Asymmetry




$A_{LU} = \frac{1}{P_{target}} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$ where

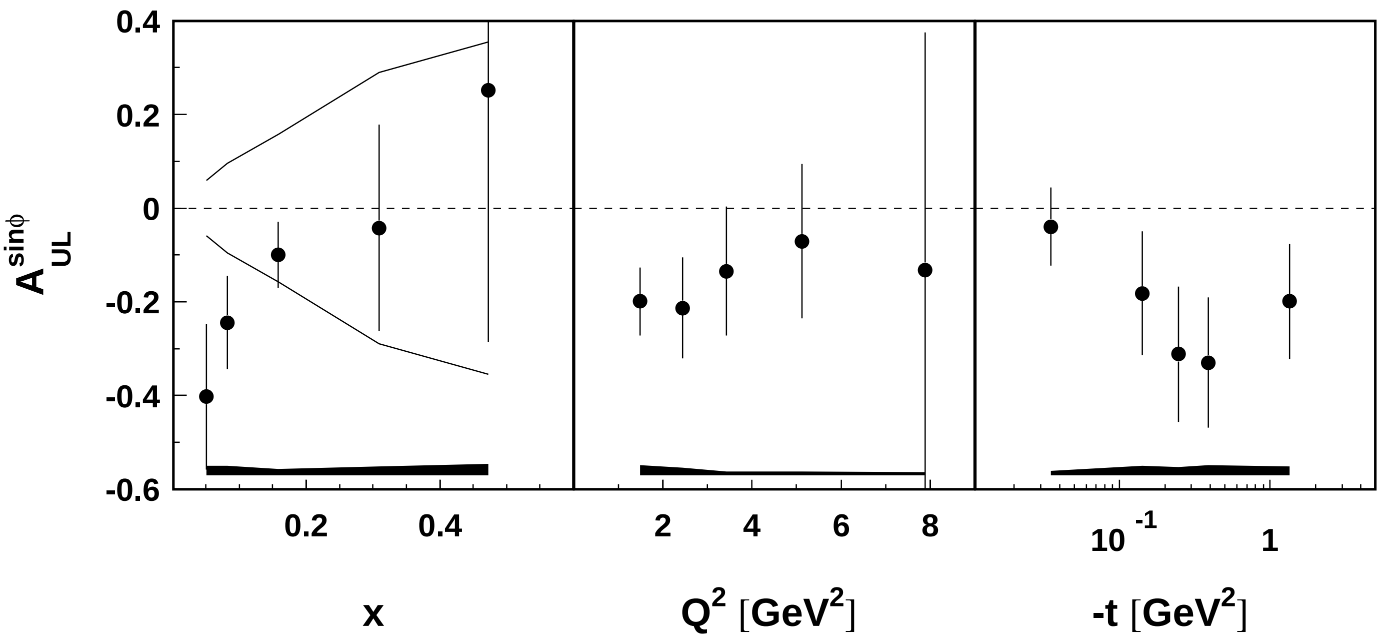
$N^{\uparrow}$($N^{\downarrow}$) = target polarized anti–parallel (parallel) to beam

- Averaged over acceptance:

$$A_{LU}^{\sin\phi} = 0.18 \pm 0.05(\text{stat}) \pm 0.02(\text{sys})$$

- $\langle x \rangle = 0.15$, $\langle Q^2 \rangle = 2.2$ GeV$^2$, $\langle t \rangle = -0.46$ GeV$^2$

# $\pi^+$ TSA – Kinematic Dependence




- Upper lines = maximum contribution from transverse component of target polarization

- No strong $Q^2$ or $x$ dependence

- $\sigma_{LT}$ is suppressed by $1/Q$, but $S_\perp/S \sim 0.16$, so both terms of similar magnitude

# Future Plans of HERMES

- HERA II Run 2002-2006(?)

- Transversely Polarized Hydrogen Target + $\Lambda^0$ Detector

  $\rightarrow$ Transversity Spin Structure Function of the Proton
  $\rightarrow$ Polarized Framentation via Lambda production
  $\rightarrow$ Unpolarized Nuclear Studies

- 2004: Recoil Detector: Focus on Exclusive Reactions

At the same time, new experiments at CERN (COMPASS), BNL (RHIC-Spin), and SLAC (E161) to study gluon polarization. Jefferson Lab and its planned upgrade have a large program of Exclusive Studies.

In long range future, plans for measurements at very low $x$ at a future Electron Ion Collider or Polarized HERA could explore details of sea and gluon polarization. Further plans for facilities at the TESLA version of the NLC are also under study (THERA and TESLA-N).

# Summary

- Inclusive measurements of $g_1$ and $g_2$ (SLAC) cover intermediate kinematic range relatively well. Extremes in $x$ require Jefferson Lab and a new high energy collider.

- Semi-inclusive measurements have yielded new information about details of the sea polarization. Sea polarization effects do not appear to be strong.

- Exclusive reactions are the tool to study the newly developed generalized parton distributions. Mapping out these functions has just begun; potentially provide uniform way to treat both deep inelastic and elastic scattering reactions. Off-forward distributions can be related to the total quark angular momentum.

- The next big news will be the new measurements of gluon polarization!