New Horizons in DIS Spin Physics

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DESY-ZEUTHEN

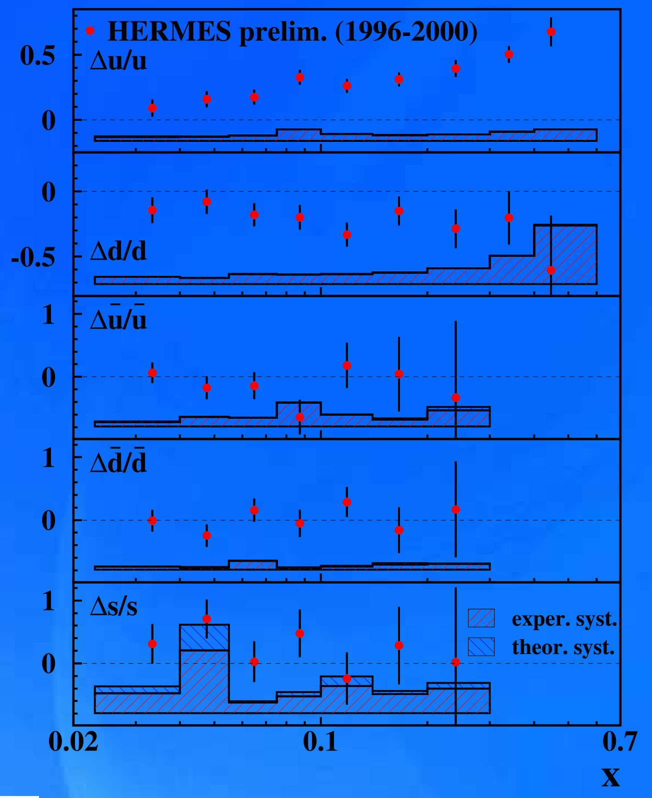
The Spin Structure of the Nucleon

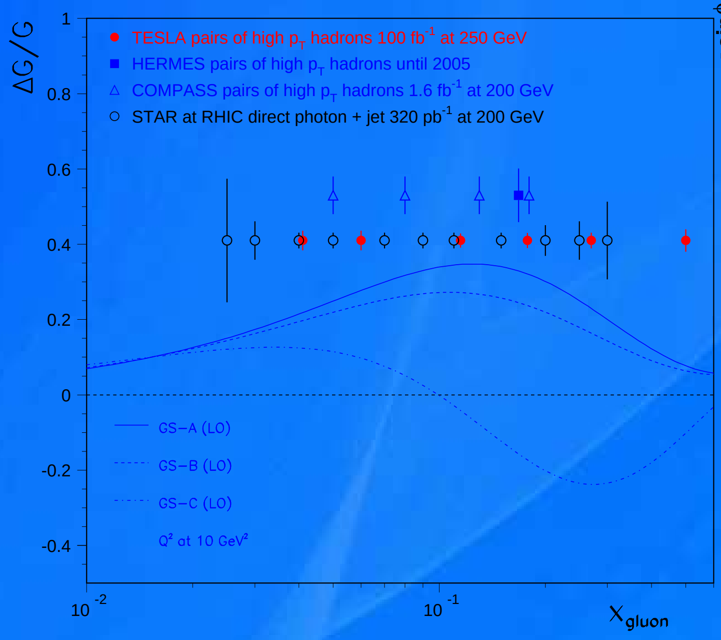
$$\frac{1}{2} = \underbrace{\frac{1}{2}(\Delta u + \Delta d + \Delta s)} + \Delta G + \underbrace{L_q + L_g}$$

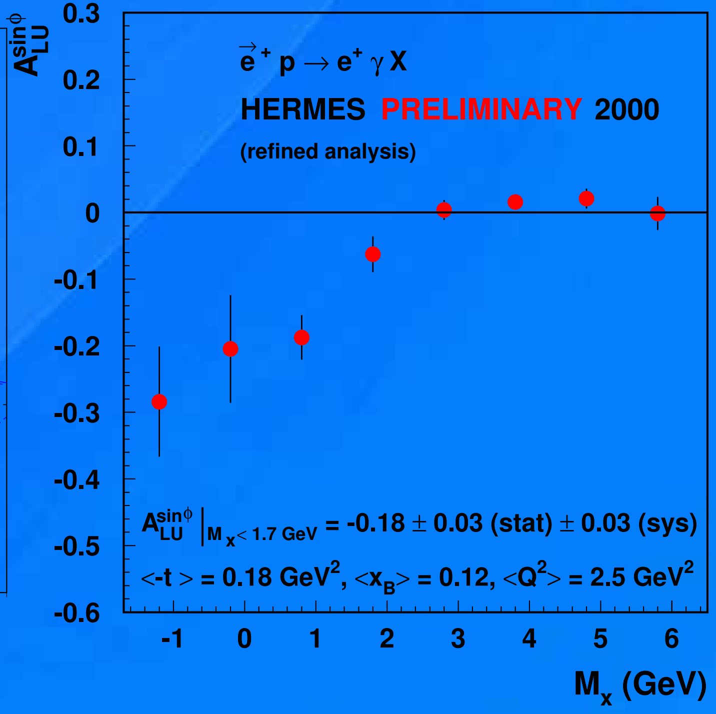
inclusive: g_p^1, $g_n^1 \rightarrow \Delta\Sigma$
semi-incl.: flavor separation

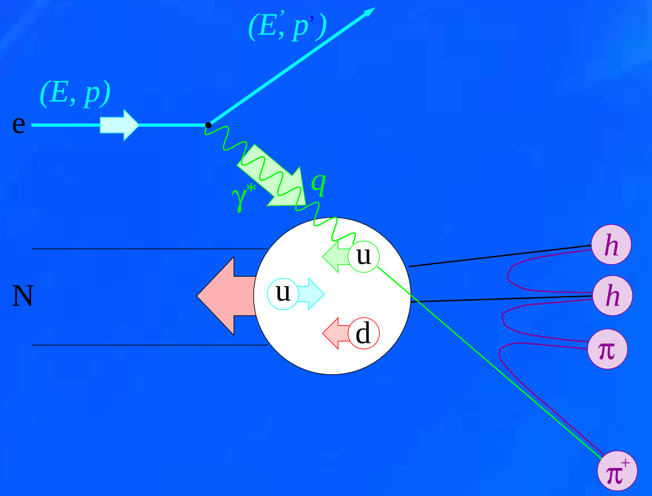
isolate PGF
high-p_t hadrons

exclusive: π, γ
Production









Polarized Deep Inelastic Scattering

Important Variables:

$$Q^2 \stackrel{lab}{=} 4EE'\sin^2(\tfrac{\theta}{2}) \qquad \nu \stackrel{lab}{=} E - E'$$

$$x \stackrel{lab}{=} \frac{Q^2}{2m\nu} \qquad y \stackrel{lab}{=} \frac{\nu}{E} = \frac{p\cdot q}{p\cdot k}$$

$$z \stackrel{lab}{=} \frac{E_h}{\nu}$$

Cross Section: $$\frac{d^2\sigma}{d\Omega dE^2} = \frac{\alpha^2 E'}{Q^2 E} L_{\mu\nu} W^{\mu\nu}$$

$$L_{\mu\nu} = 2[k_\mu k'_\nu + k_\nu k'_\mu - \left(k \cdot k' - m_e^2\right) g_{\mu\nu} + i m_e \epsilon_{\mu\nu\alpha\beta} S^\alpha \left(k - k'\right)^\beta]$$

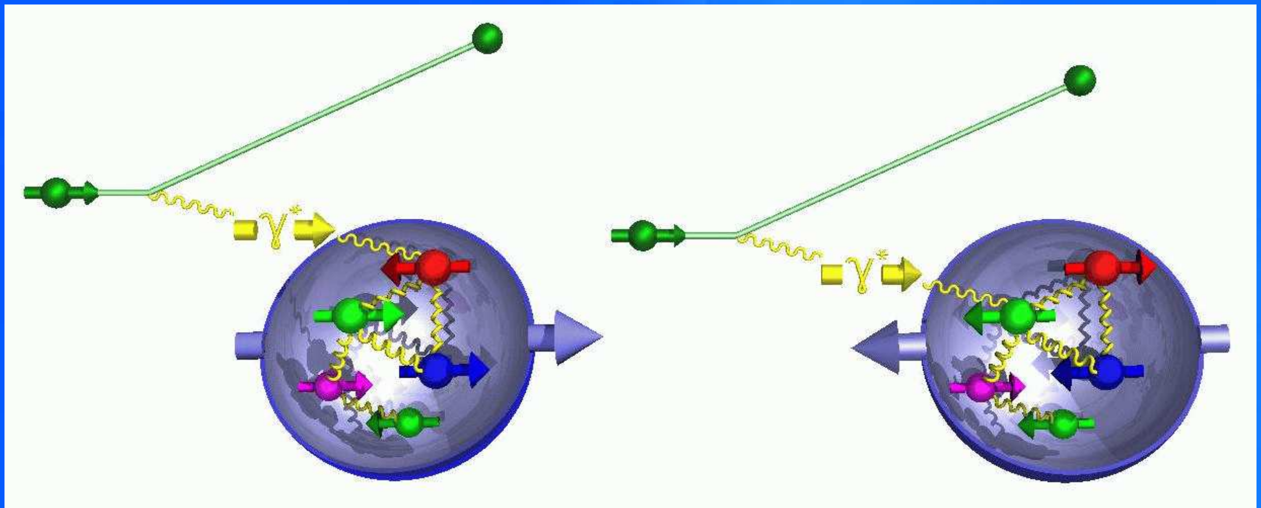
Where: $S^\alpha = \frac{1}{2}\overline{u}\left(k,s\right)\gamma^\alpha\gamma_5 u\left(k,s\right)$

$$W^{\mu\nu} = -g^{\mu\nu} F_1\left(x,Q^2\right) + \frac{p^\mu p^\nu}{\nu} F_2\left(x,Q^2\right) + \frac{i}{\nu}\epsilon^{\mu\nu\lambda\sigma} q_\lambda S_\sigma g_1\left(x,Q^2\right)$$
$$+ \frac{i}{\nu^2}\epsilon^{\mu\nu\lambda\sigma} q_\lambda\left(p\cdot q S_\sigma - S\cdot q p_\sigma\right) g_2\left(x,Q^2\right)$$

(for spin 1) **+ quadropole terms** $\left(b_1, b_2, b_3, b_4\right)$

F_1, F_2 / g_1, g_2 $\Longrightarrow$ **Unpolarized / Polarized Structure Functions**

Virtual Photon Asymmetry



polarized Photon can only probe quarks with spin opposite to its own

$\vec{S}_\gamma$ + $\vec{S}_N$ = 3/2

$\sigma_{3/2} \sim q^-(x)$

$\vec{S}_\gamma$ + $\vec{S}_N$ = 1/2

$\sigma_{1/2} \sim q^+(x)$

unpolarized target + beam

polarized target + beam

flipping target spin

Quark Distributions:

$$\boxed{q_f(x) := q_f^+(x) + q_f^-(x)}$$

Quark Spin Distributions:

$$\boxed{\Delta q_f(x) := q_f^+(x) - q_f^-(x)}$$

($f = u, d, s, \overline{u}, \overline{d}, \overline{s}$)

Virtual Photon Asymmetries:

$$A_1 = \frac{\sigma_{\frac{1}{2}} - \sigma_{\frac{3}{2}}}{\sigma_{\frac{1}{2}} + \sigma_{\frac{3}{2}}} = \frac{g_1 - \gamma^2 g_2}{F_1} \qquad A_2 = \frac{\sigma_{TL}}{\sigma_T} = \frac{\gamma(g_1+g_2)}{F_1}$$

Measurable Asymmetries:

$$A_\parallel = \frac{\sigma^{\overset{\rightarrow}{\Leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}}}{\sigma^{\overset{\rightarrow}{\Leftarrow}} + \sigma^{\overset{\rightarrow}{\Rightarrow}}} \qquad A_\perp = \frac{\sigma^{\uparrow\rightarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\uparrow\rightarrow} + \sigma^{\uparrow\leftarrow}}$$

$$A_\parallel = D(A_1 + \eta A_2) \qquad A_\perp = d(A_2 + \xi A_1)$$

$F_1(x)$ **=** $\frac{1}{2}\sum_i e_i^2(q_i^+(x) + q_i^-(x))$ **=** $\frac{1}{2}\sum_i e^2 q_i(x)$

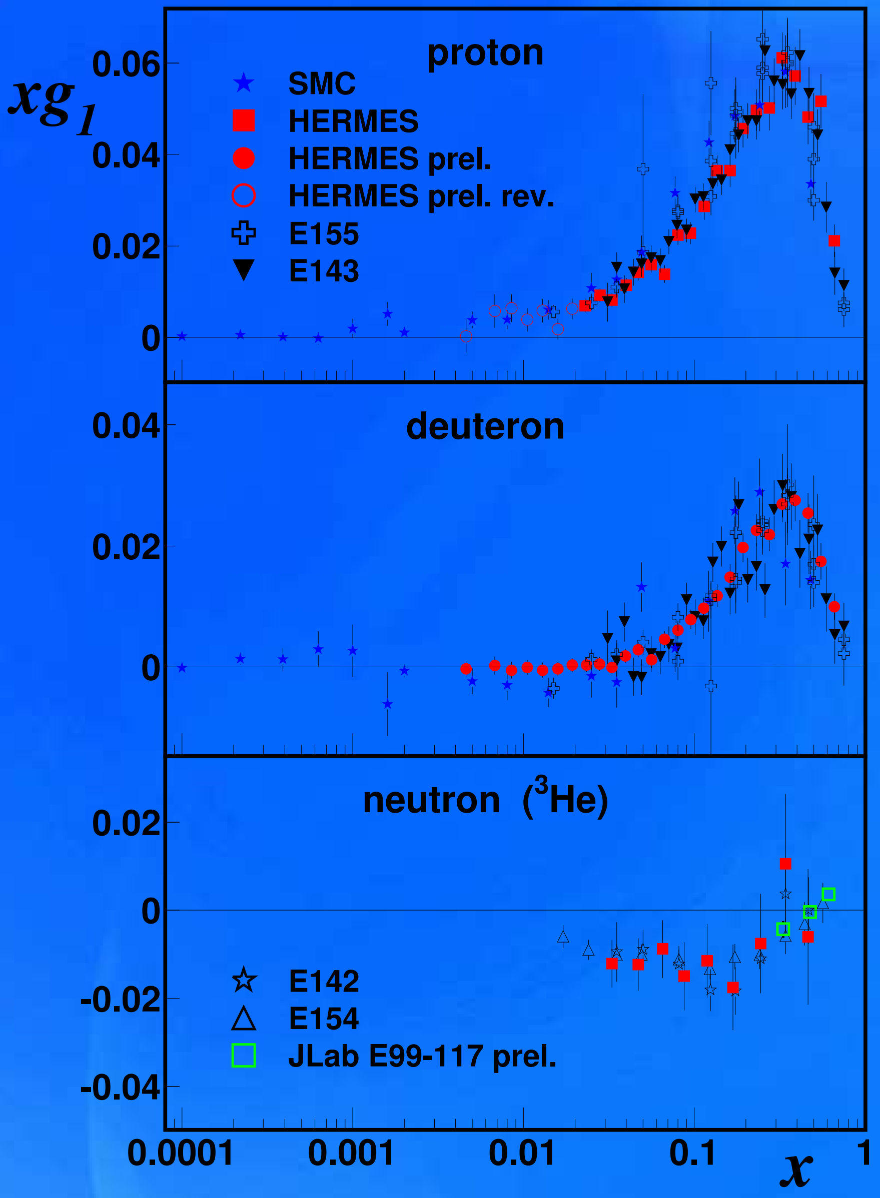
2xF$_1$ measures the momentum distribution of quarks

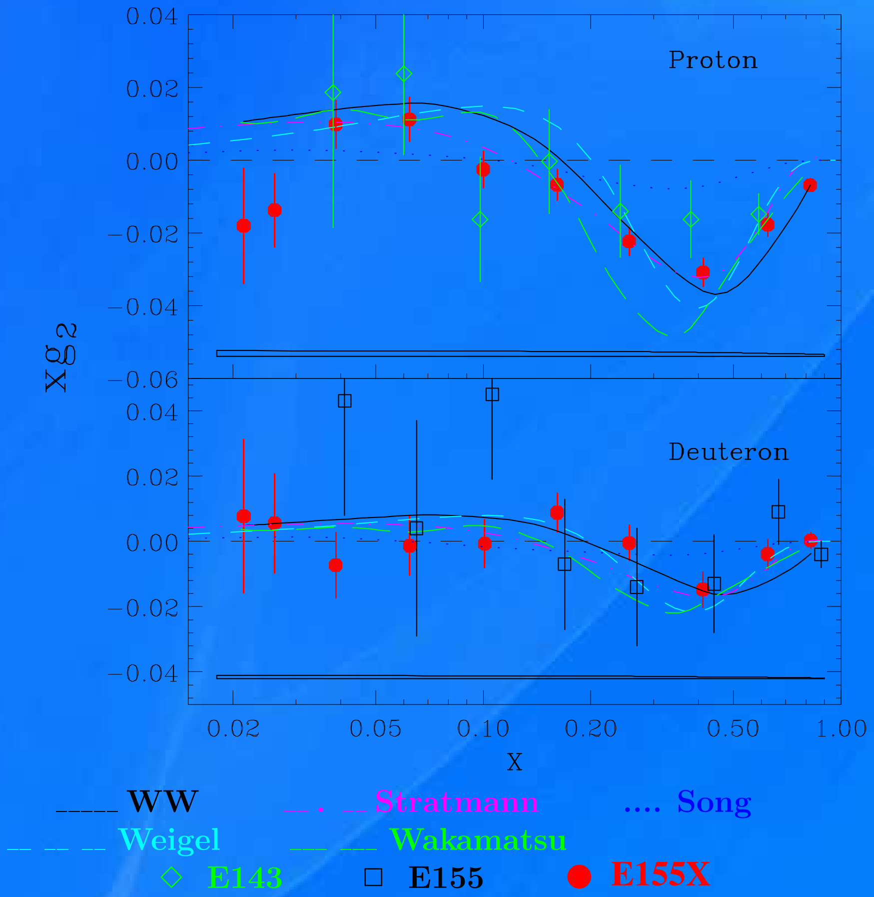
$g_1(x)$ **=** $\frac{1}{2}\sum_i e_i^2(q_i^+(x) - q_i^-(x))$ **=** $\frac{1}{2}\sum_i e^2 \Delta q_i(x)$

g$_1$ measures the spin distribution of quarks

With: $D, d, R, \epsilon, \gamma$ **being kinematic factors**

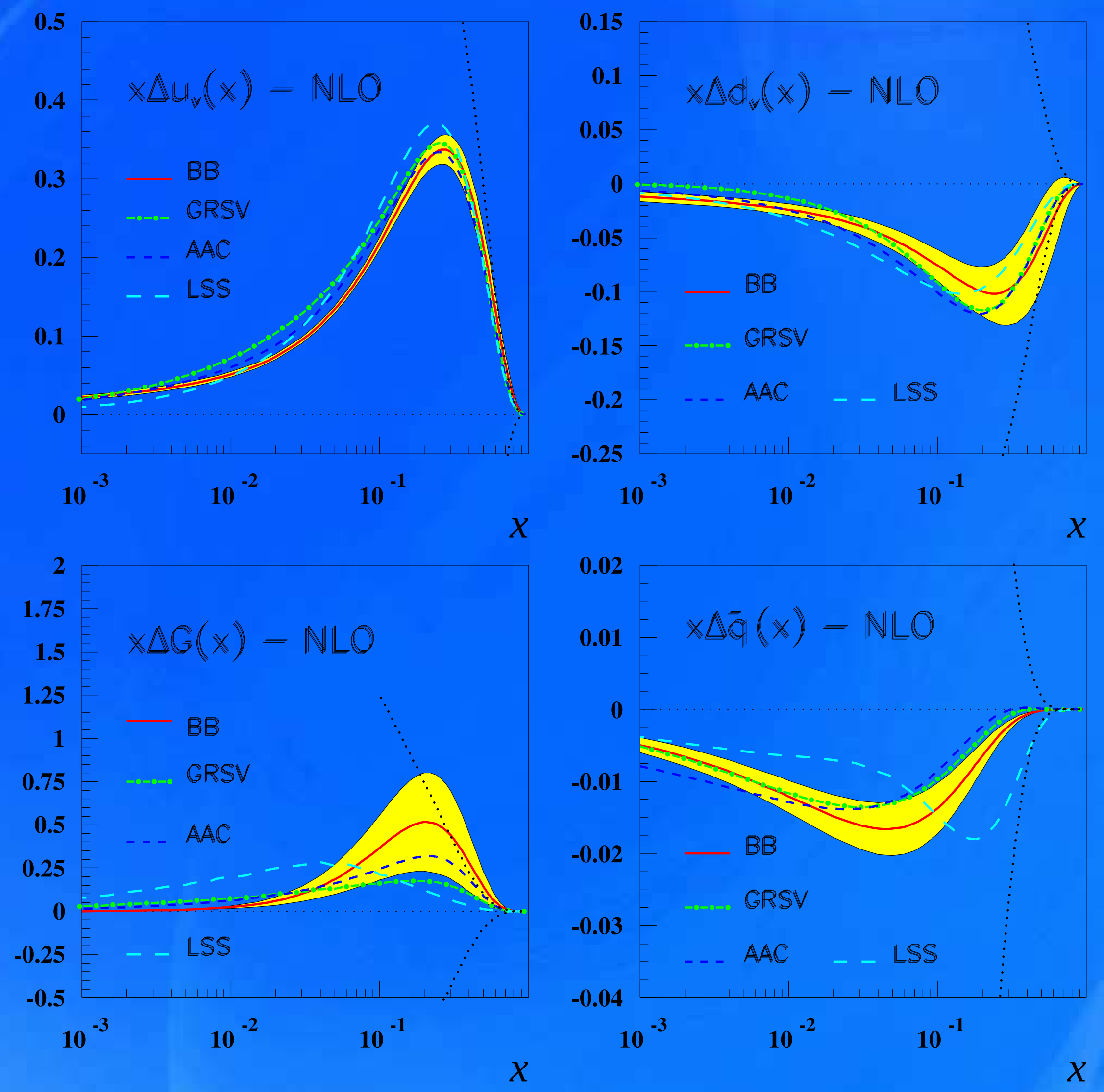
World data on g1(x) and g2(x)





Data given at measured $< Q^2 >$: 0.02 - 58 GeV^2

NLO pQCD Fits to g1(x,Q)^2



NLO QCD ($\bar{M}\bar{S}$) fit at Q^2 = 4 GeV^2 fully propagated stat. uncertainties (yellow bands BB 2002)

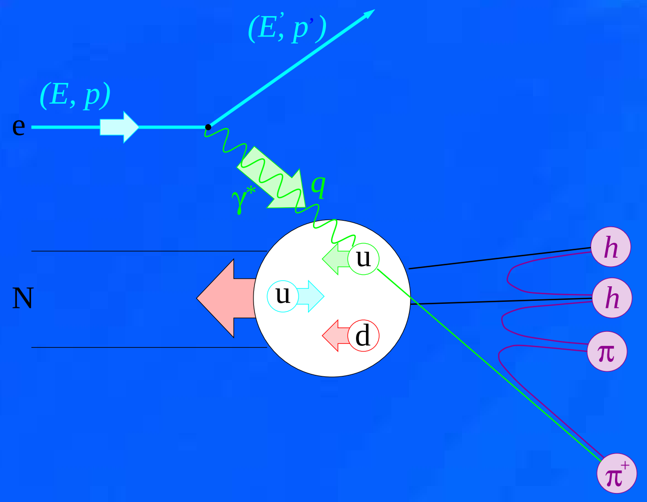
$$\Delta s(\bar{q}) \quad = \quad \textbf{-0.07} \pm \textbf{0.02 (stat.)} \quad < 0$$
$$\Delta G \quad = \quad \textbf{1.03} \pm \textbf{0.55 (stat.)} \quad > 0$$

BUT SU(3)$_f$ symmetry breaking?

BB: Blümlein Böttcher hep/ph 0203155
LSS: Leader et al. hep/ph 0111267
GRSV: Glück et al. hep/ph 0011215
AAC: Goto et al. hep/ph 0001046

more direct probes for Δ G and Δ s needed

Semi-inclusive DIS



Correlation between detected hadron and struck q_f

$\longrightarrow$ 'Flavor - Separation'

Target fragments

Current fragments

Inclusive DIS: $\Delta\Sigma = (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})$

Semi-inclusive DIS: Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$, Δs, $\Delta\bar{s}$

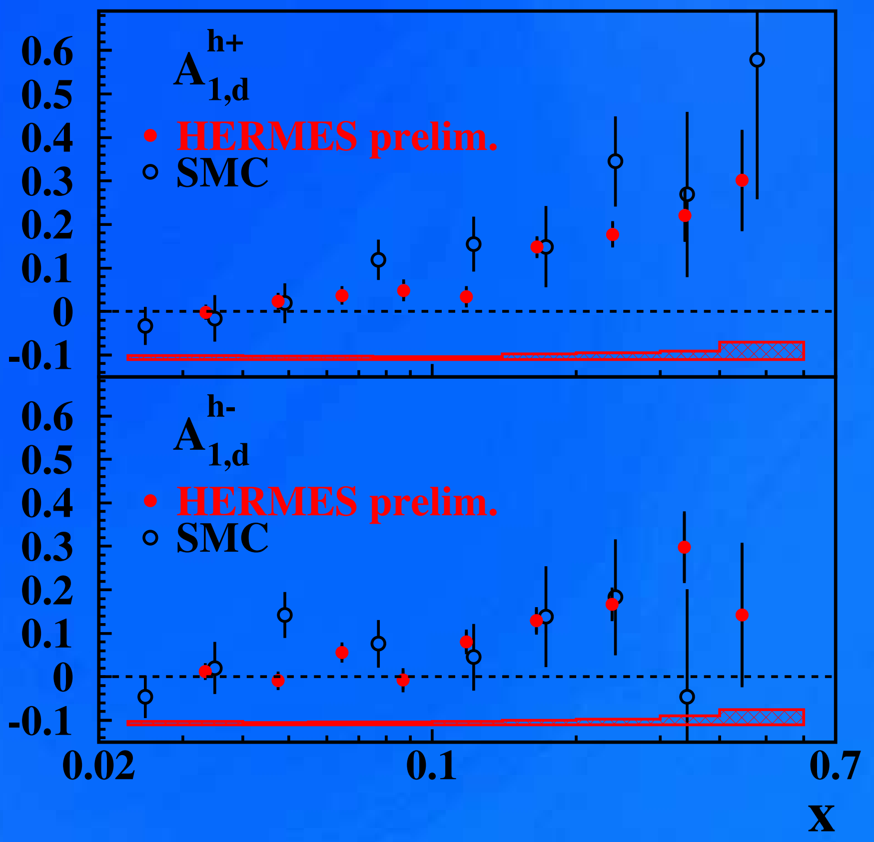
In LO-QCD:

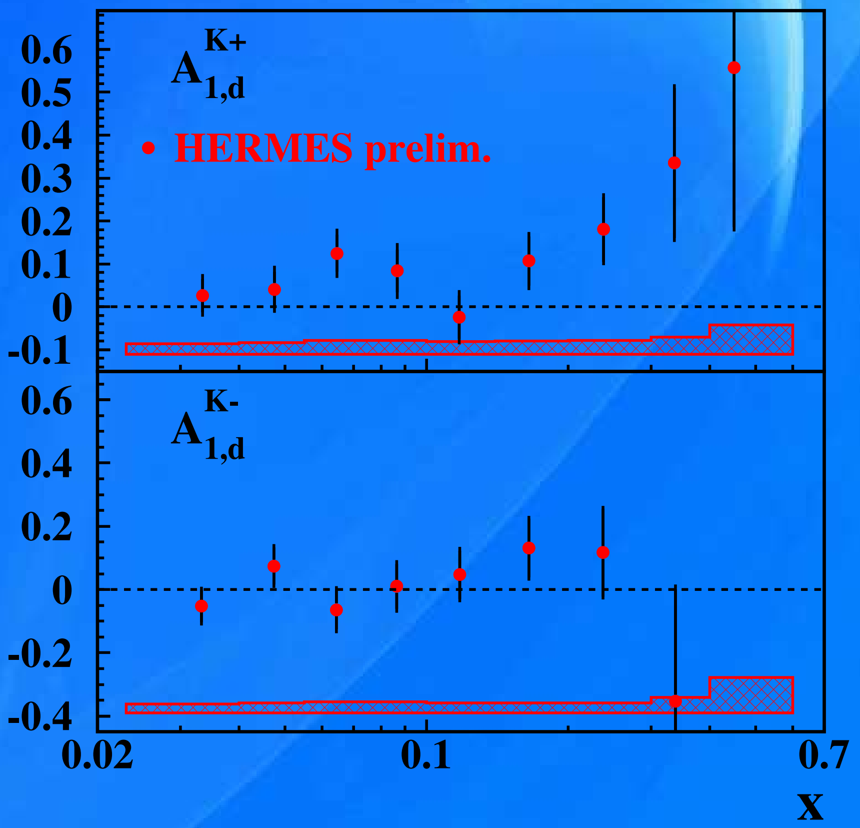
$$A_1^{\mathrm{h}}(x,Q^2) = \frac{\sigma^h_{1/2} - \sigma^h_{3/2}}{\sigma^h_{1/2} + \sigma^h_{3/2}} = \frac{1+R(x,Q^2)}{1+\gamma^2} \cdot \frac{\sum_f e_f^2 \Delta q_f(x,Q^2) \int dz D_f^{\mathrm{h}}(z,Q^2)}{\sum_f e_f^2 q_f(x,Q^2) \int dz D_f^{\mathrm{h}}(z,Q^2)}$$

$(\Delta q_f), q_f$ (Polarized) quark distributions

$D_f^{\mathrm{h}}(z)$ fragmentation functions giving the probability that a (struck) quark of flavor f fragments into a hadron of type h.

Hadron Asymmetries on the Deuteron





- **HERMES selects hadrons with the following cuts:**
  - $0.2 \leq z = E_h/\nu \leq 0.8$ **and** $x_F \geq 0.1$ **and** $W^2 \geq 10GeV^2$
  - **HERMES-Deuterium** $\pi^{\pm}$ **and** $\mathrm{K}^{\pm}$ **data identified by RICH**

- **Rewrite Photon-Nucleon Asymmetry**

$$\mathbf{A_1^h(x)} \overset{\mathbf{g_2=0}}{\simeq} \mathbf{C} \cdot \sum_{\mathbf{q}} \underbrace{\frac{e_q^2 q(x) \int dz D_q^{\mathrm{h}}(z)}{\sum_{q'} e_{q'}^2 q\prime(x) \int dz D_{q'}^{\mathrm{h}}(z)}}_{P_q^h(x,z)} \frac{\mathbf{\Delta q(x)}}{\mathbf{q(x)}}$$

- $P_q^h(x,z)$ **Purity, the prob. a hadron h originates from an event with struck quark f**
  Effective Purities accounting for detector effect may be computed via Monte Carlo based on the JetSet model for fragmentation

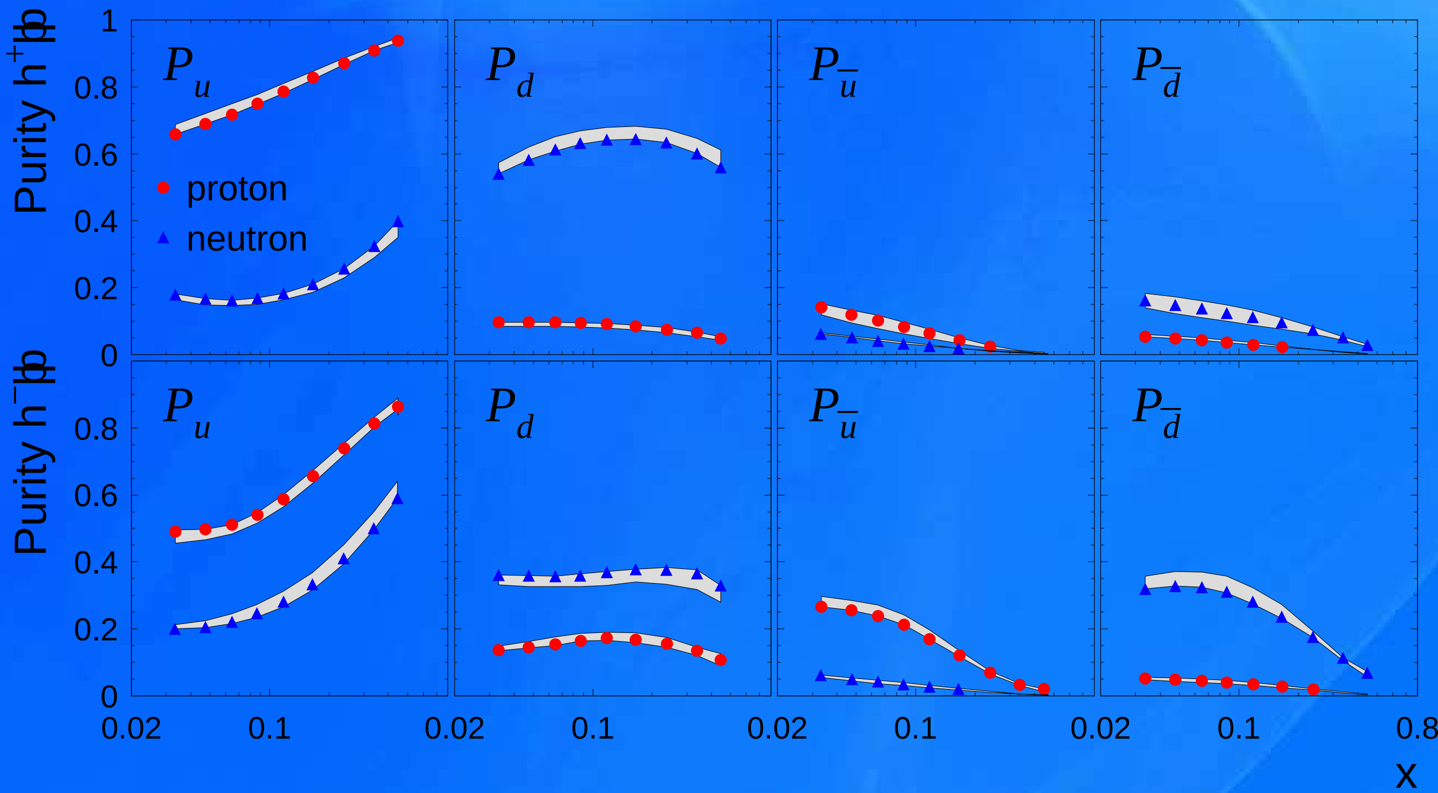
- **Solve linear system for $\vec{Q}$ with**

$$\vec{\mathbf{A}} = (\mathbf{A_{1,p}(x)}, \mathbf{A_{1,d}(x)}, \mathbf{A_{1,p}^{\pi^\pm}(x)}, \mathbf{A_{1,d}^{\pi^\pm}(x)}, \mathbf{A_{1,d}^{K^\pm}(x)})$$

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

$$\vec{\mathbf{Q}} = \left(\frac{\mathbf{\Delta u}}{\mathbf{u}}, \frac{\mathbf{\Delta d}}{\mathbf{d}}, \frac{\mathbf{\Delta \bar{u}}}{\mathbf{\bar{u}}}, \frac{\mathbf{\Delta \bar{d}}}{\mathbf{\bar{d}}}, \frac{\mathbf{\Delta s + \Delta \bar{s}}}{\mathbf{s + \bar{s}}}\right)$$

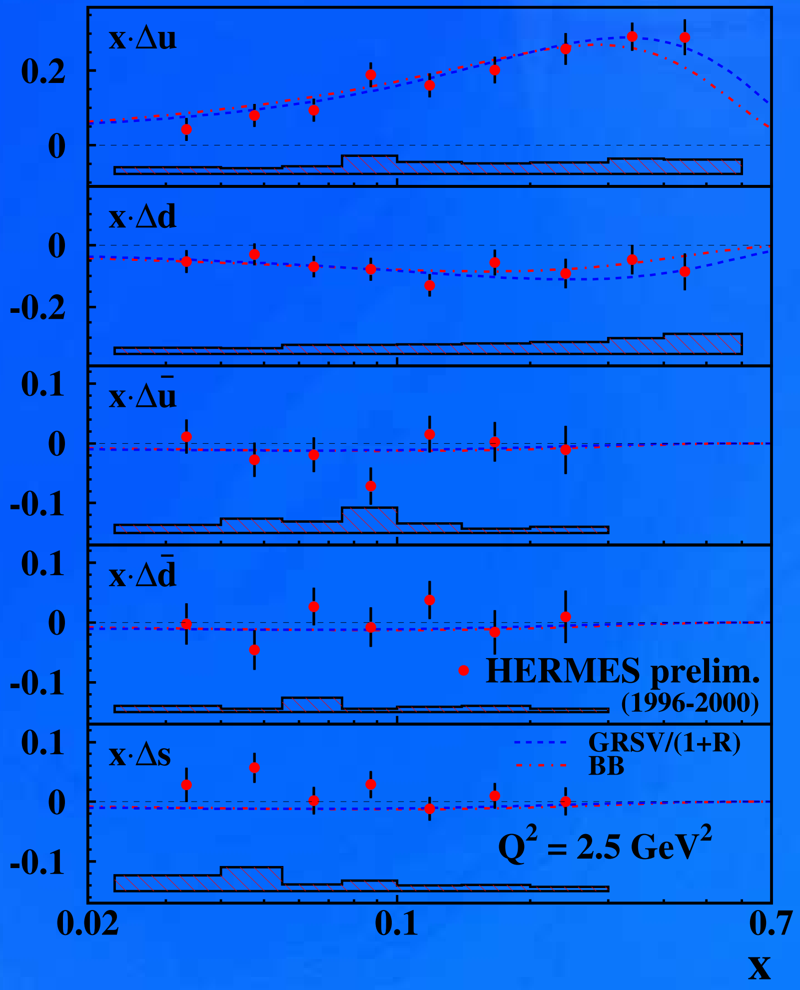
Purities for charged Hadrons

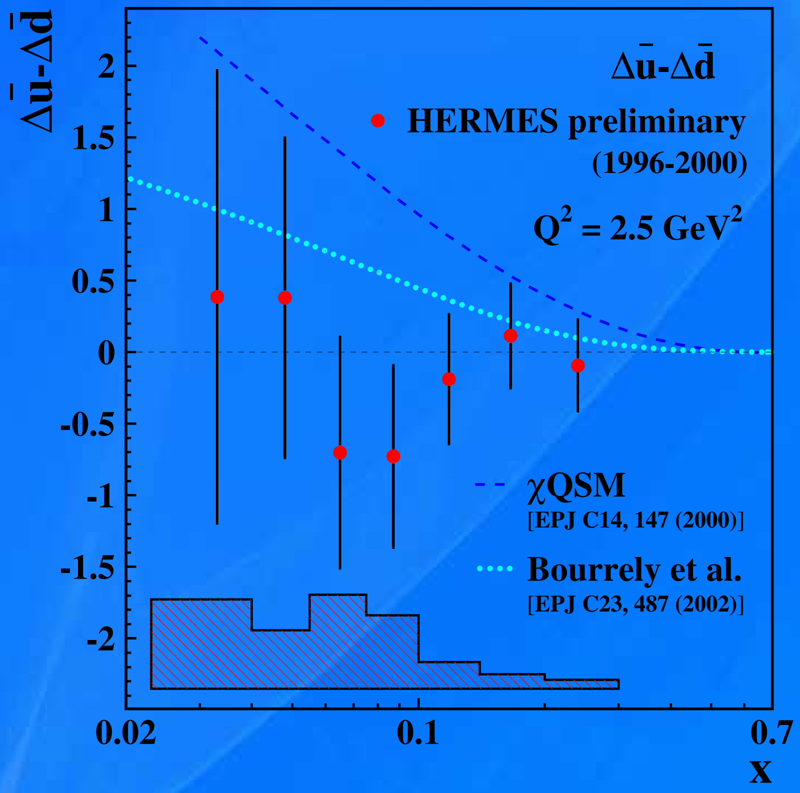


shaded bands indicate the systematic uncertainties

- **An adequate degree of orthogonality is provided**
  - u **versus** d **from h**$+$
  - **valence versus sea from hadron charged**
  - $\bar{u}$ **versus** $\bar{d}$ **from h**$-$
- **Kaons have about 10% sensitivity of the strange sea (not shown)**

Polarized Quark Densities at LO

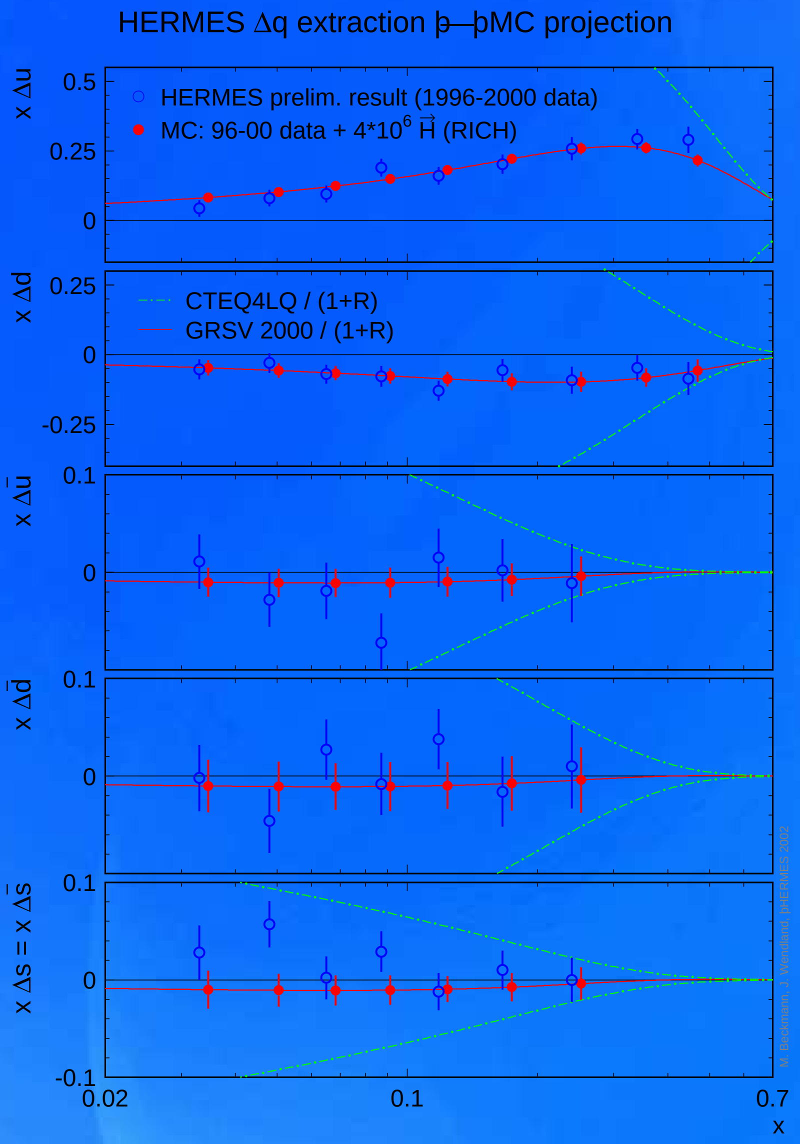


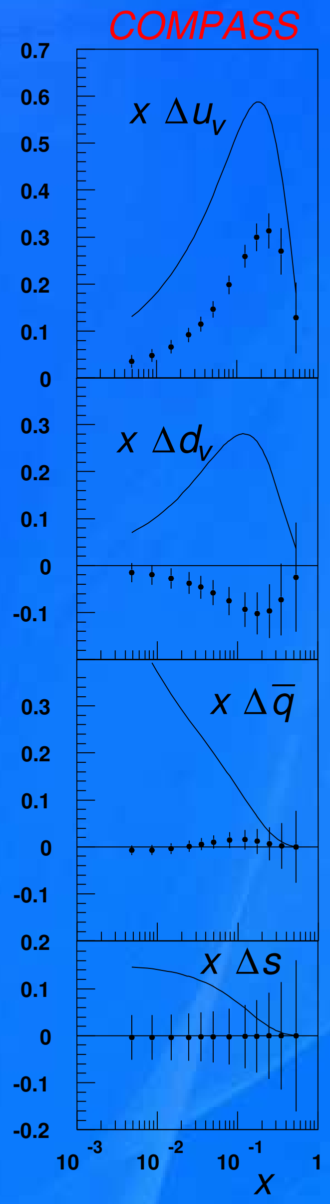


strange sea polarization $\Delta s \geq 0$

The Hermes data are consistent with $SU(3)_f$ symmetry
Data disfavor χQSM of Dressler et al.

Future of Polarized Quark Densities



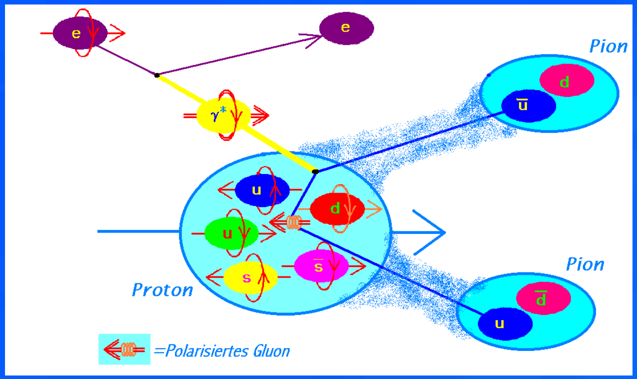


HERMES
additional 4 Million DIS
with polarized $\bar{\mathrm{H}}$ and the RICH

COMPASS
will extend to lower x
expected luminosity: 2 fb^{-1} / year

Direct Measurements of ΔG

Isolate the photon-gluon fusion process (PGF)

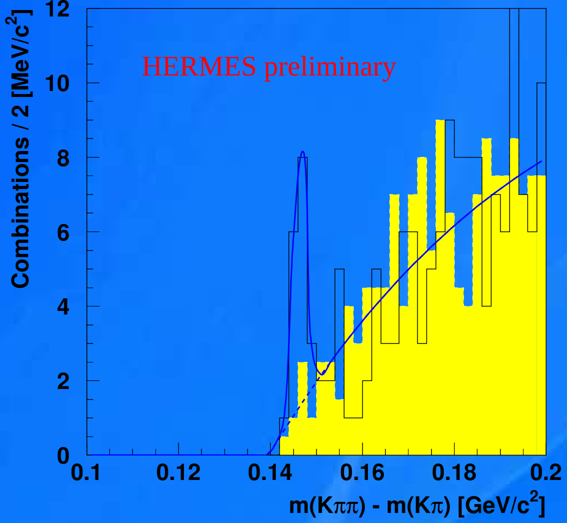


OPEN CHARM

reconstruct D^*, D^0

$$A_{||} = \frac{N_{c\bar{c}}^{\leftrightarrows} - N_{c\bar{c}}^{\rightrightarrows}}{N_{c\bar{c}}^{\leftrightarrows} + N_{c\bar{c}}^{\rightrightarrows}}$$

$$A^{\gamma p \to c\bar{c}} \sim \Delta G/G$$



$$D^* \to K + \pi + \pi_{slow}$$

HIGH-P_T

pairs of high-P_T hadrons

$$A_{||} = \frac{N_{h\pm}^{\leftrightarrows} - N_{h\pm}^{\rightrightarrows}}{N_{h\pm}^{\leftrightarrows} + N_{h\pm}^{\rightrightarrows}}$$

$$A^{\gamma p \to h^+ h^-} \sim \Delta G/G$$

additionally:

use identified hadrons

pairs of high-P_T Pions

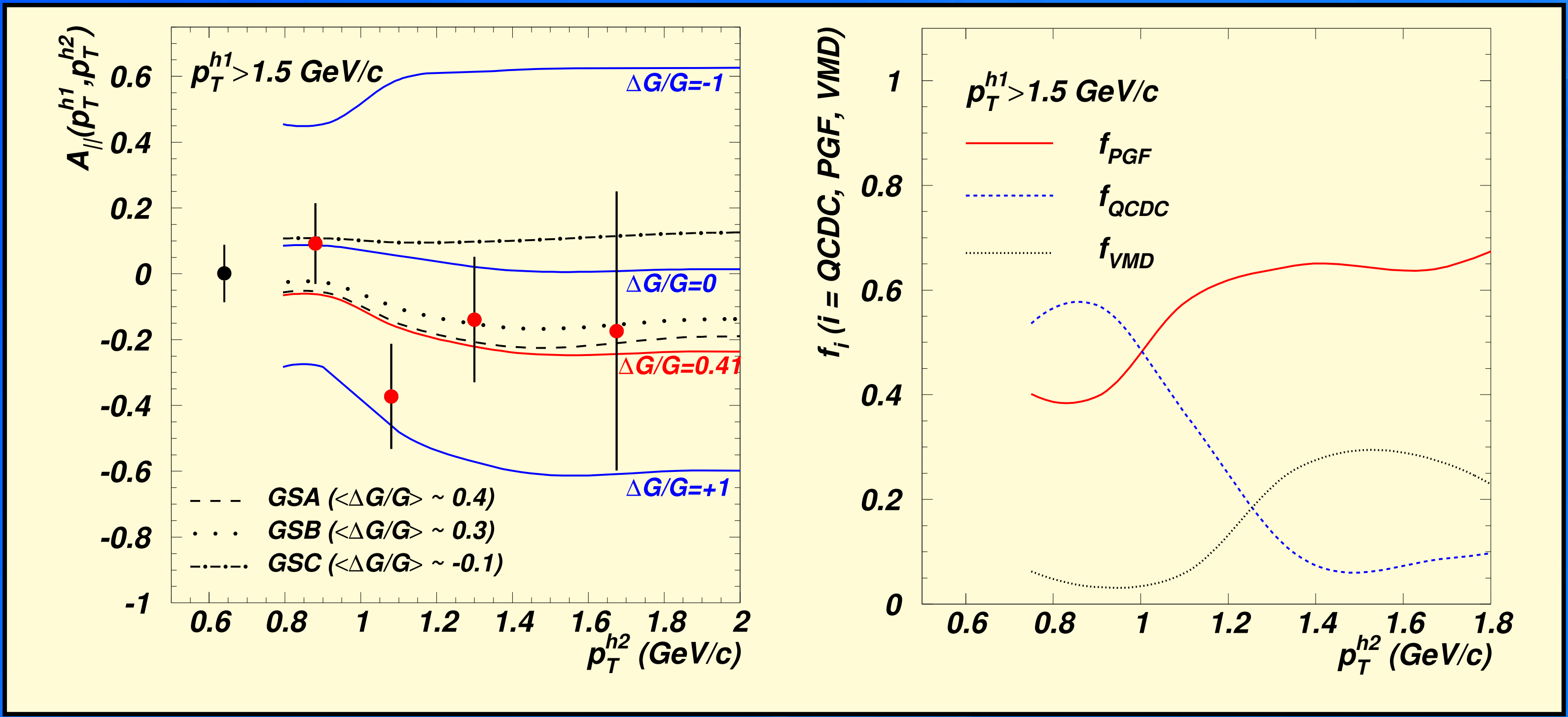
pairs of high-P_T Kaons

Can be measured by HERMES and COMPASS

Pairs of high-P_T Hadrons
within LO pQCD and PYTHIA5 MC model

$\Delta G/G$ = $0.41 \pm 0.18\ (\text{stat.}) \pm 0.03\ (\text{exp.syst.})$

at $\langle x_G \rangle = 0.17$ **and** $\langle \hat{p}_T^2 \rangle = 2.1$ **GeV**^{2}



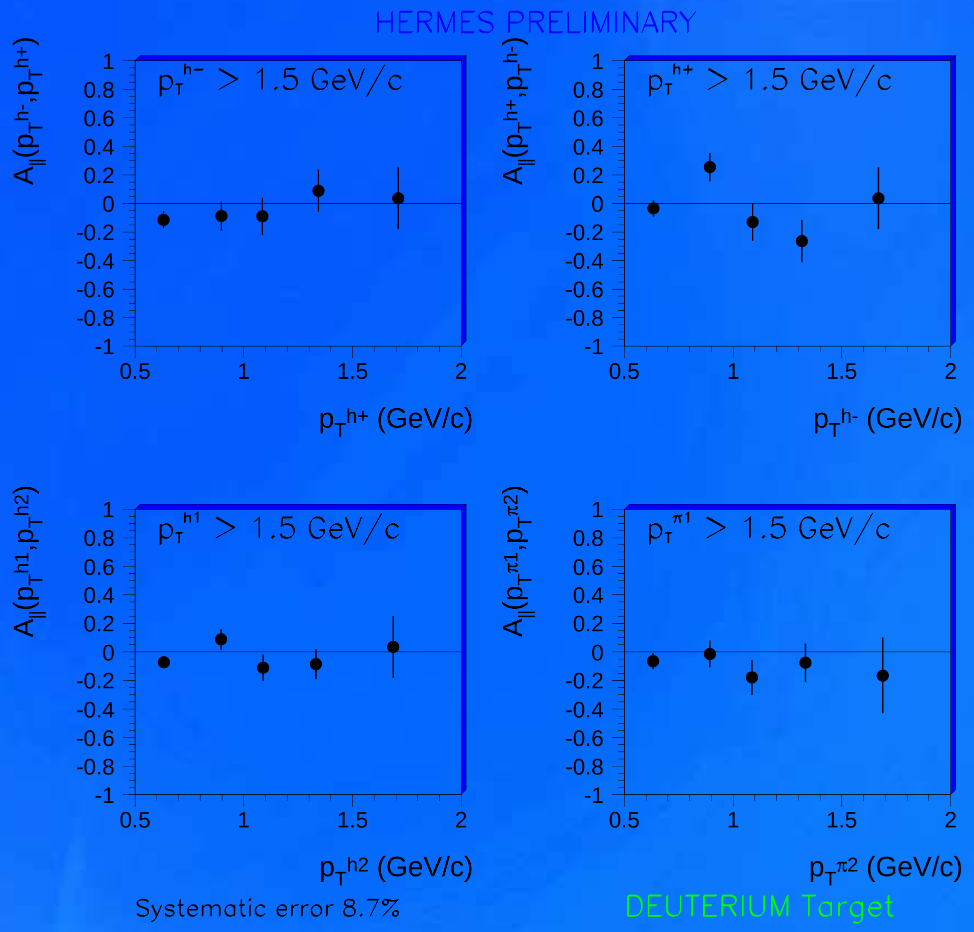
A. Airapetian et al, Phys. Rev. Lett. 84 (2000) 2584

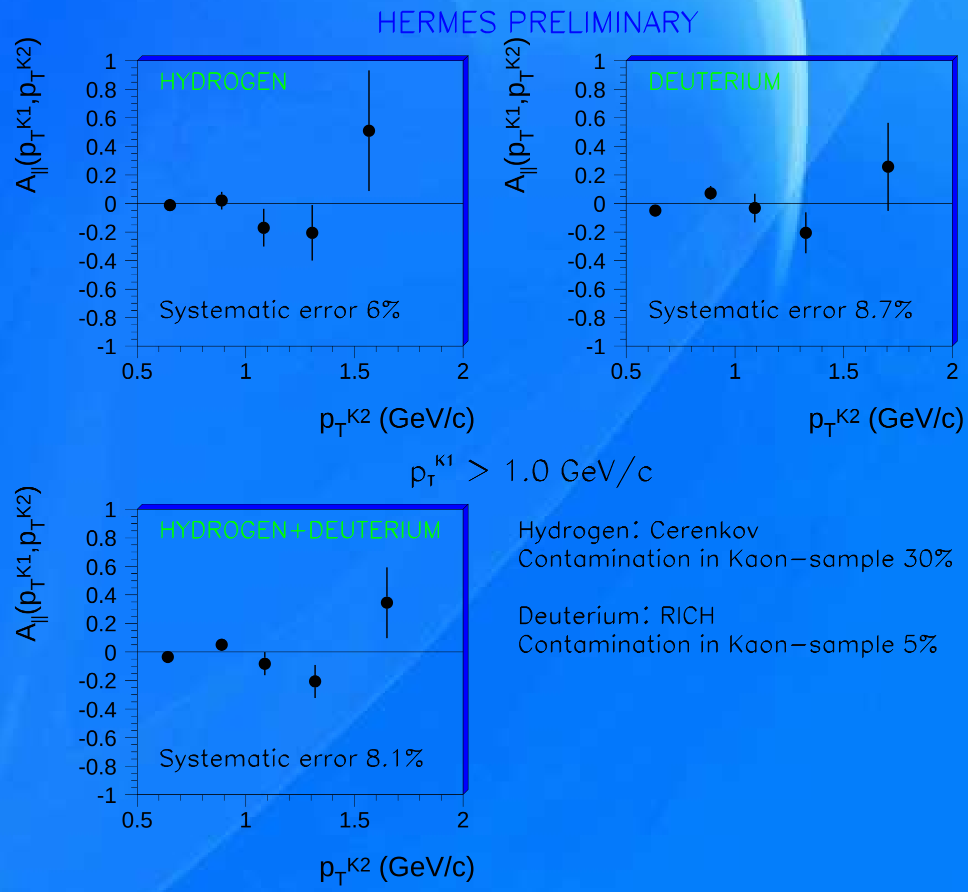
Target: Hydrogen

Extraction strongly Model dependent

Deuterium Results

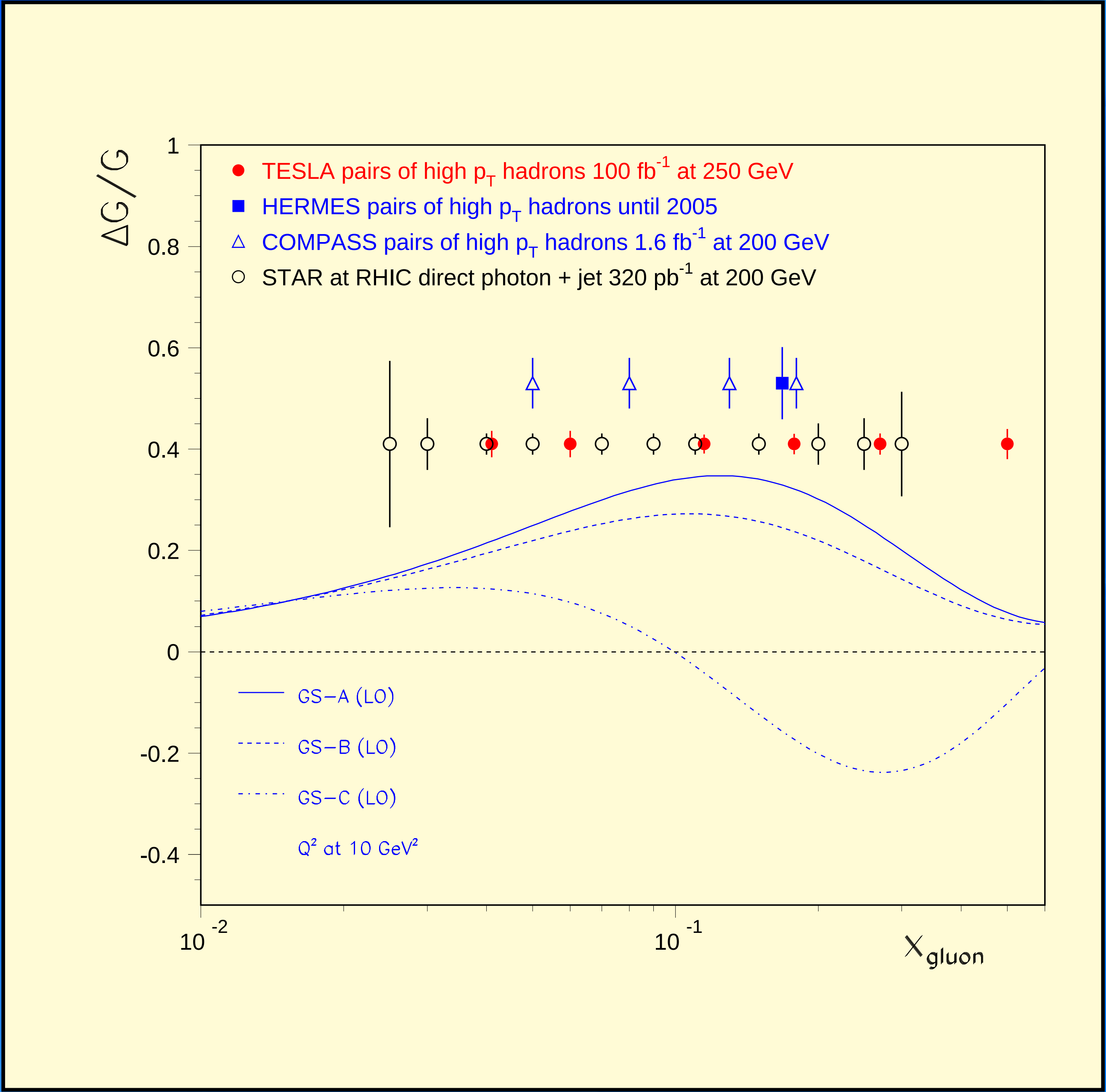
Statistics: $\sim$ 3 x hydrogen statistics

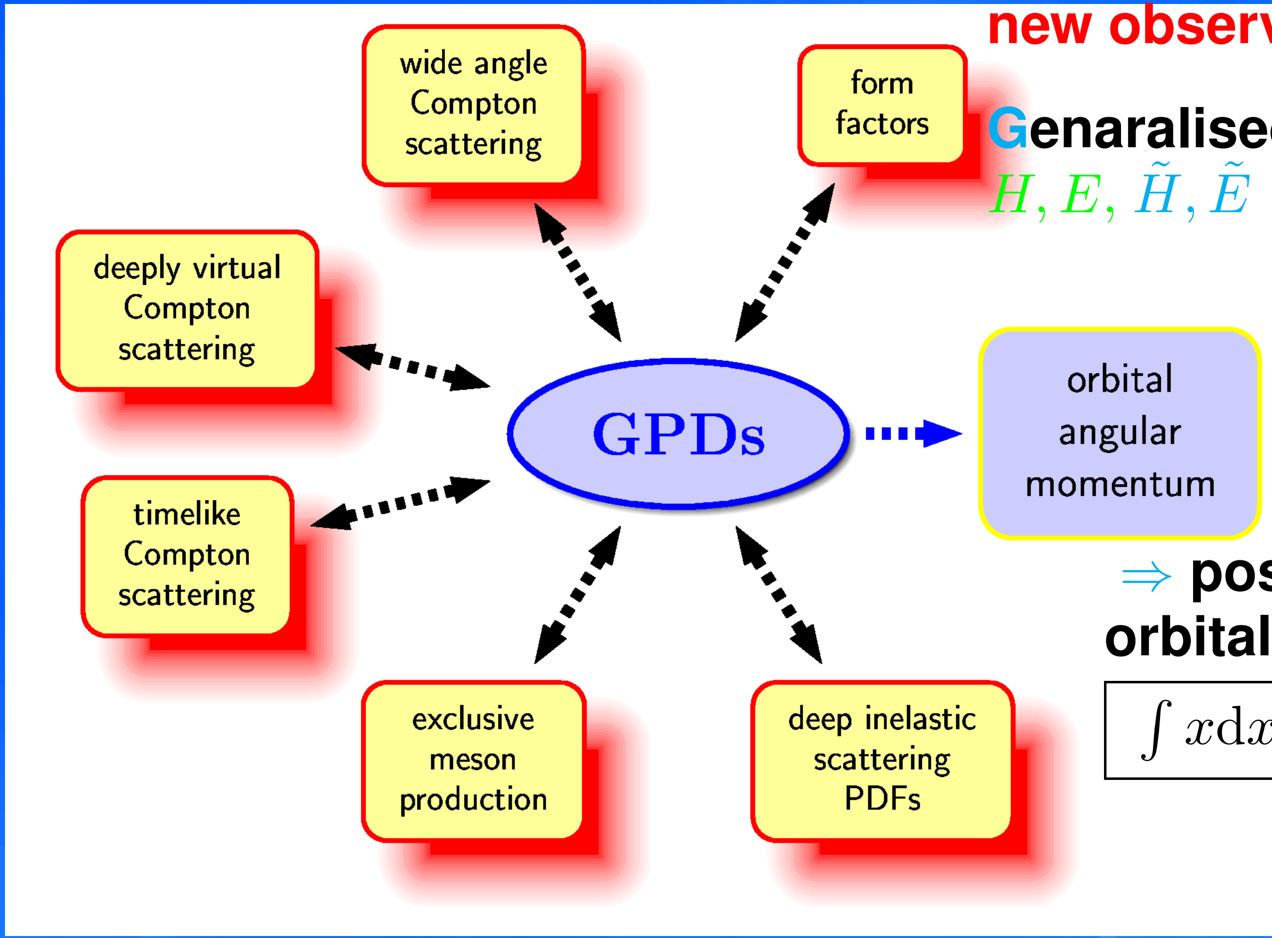




$\Delta G/G$ Extraction still under way

$\Delta G/G$ *in 2010*





new observables in hard exclusive processes

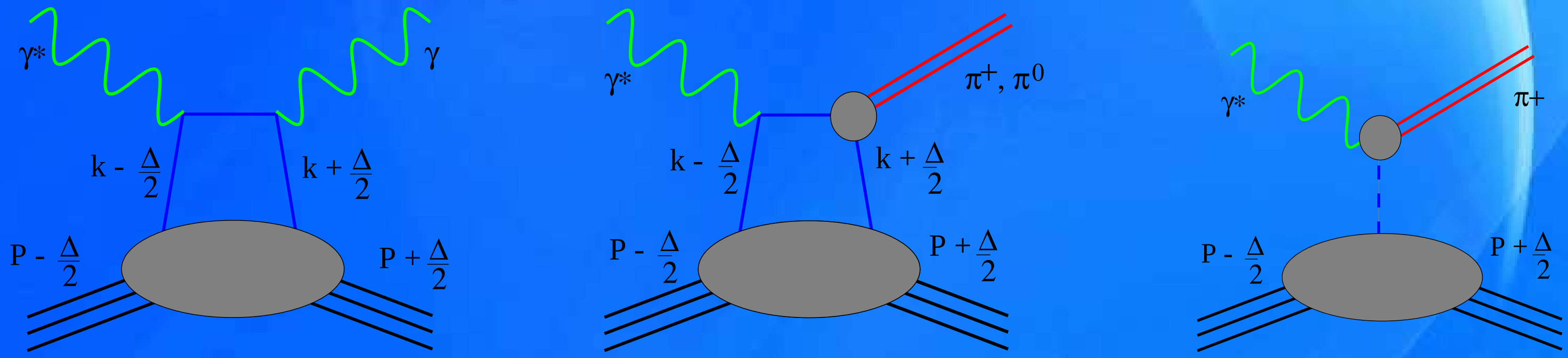
Genaralised Parton Distributions

$H, E, \tilde{H}, \tilde{E}$

$\Rightarrow$ **possible access to orbital angular momentum**

$$\boxed{\int x\mathrm{d}x\,(H + E) = J_q}$$

GPDs introduction II



quantum numbers of final state $\rightarrow$ select different GPDs

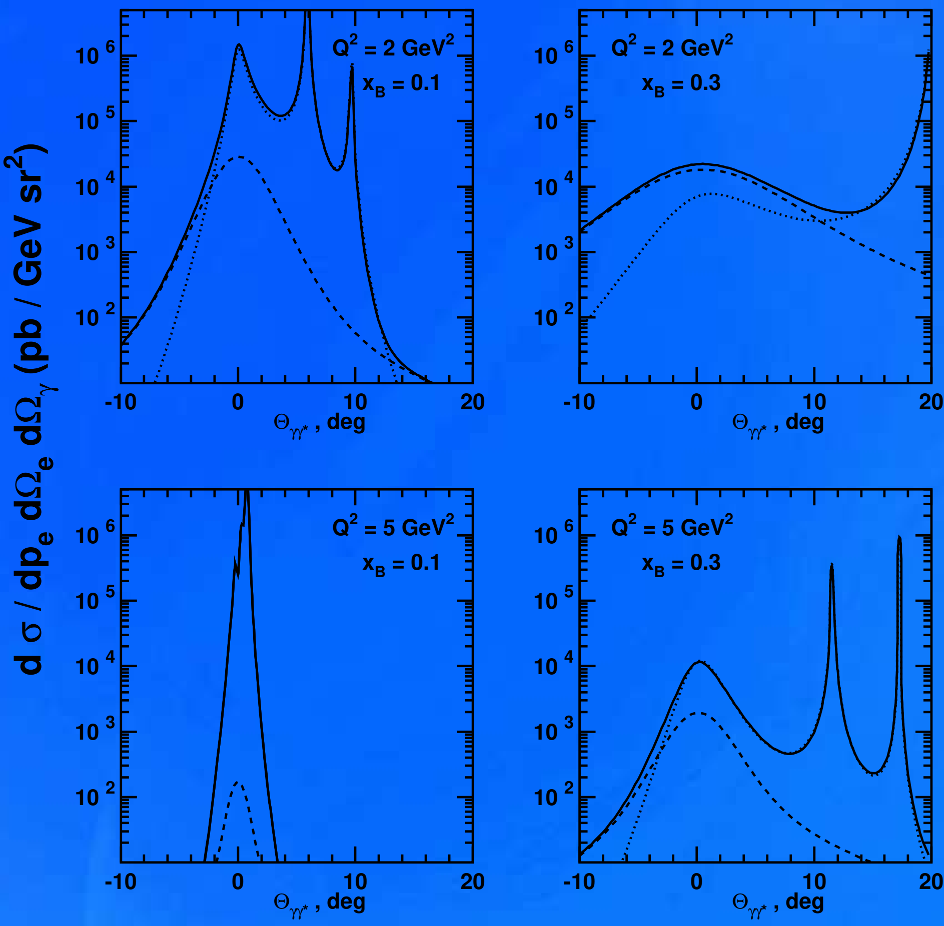
DVCS: $\tilde{H}, \tilde{E}$ $H, E,$
vector mesons: H, E
pseudo-scalar mesons: $\tilde{H}, \tilde{E}$

quadratic combination of GPDs appear in unpolarized cross section

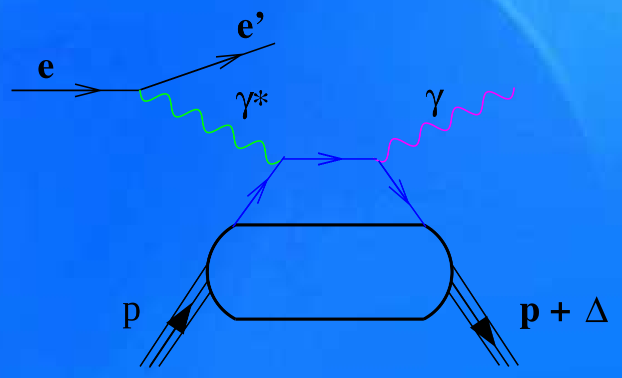
$\rightarrow$ **polarization provides new observables**

DVCS $ep \to e'\gamma p$

HERMES kinematics:
BH process larger than DVCS



[Korotkov, Nowak, hep-ph/0108077]



DVCS **Bethe-Heitler (BH)**

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

HERMES, JLAB:
DVCS-BH interference:

$\longrightarrow$ **use BH as a vehicle to study DVCS**

H1, ZEUS:
measure DVCS cross section directly

DVCS azimuthal asymmetries

isolate BH-DVCS interference term:

- **imaginary part $\propto$ beam helicity asymmetry:**

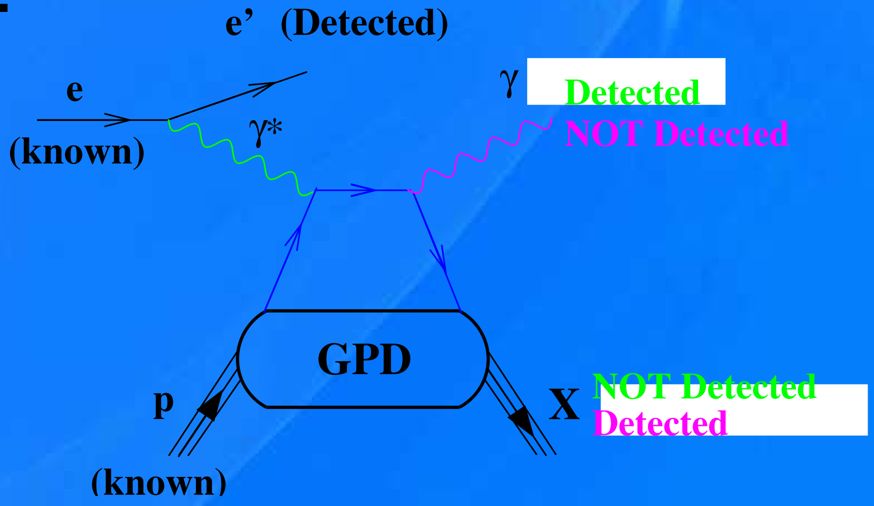
$$d\sigma_{\overset{\leftarrow}{e^+}} - d\sigma_{\overset{\rightarrow}{e^+}} \propto \mathrm{Im}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \propto \sin\phi$$

$\Rightarrow$ asymmetry measured by HERMES and JLAB

- **real part $\propto$ beam charge asymmetry:**

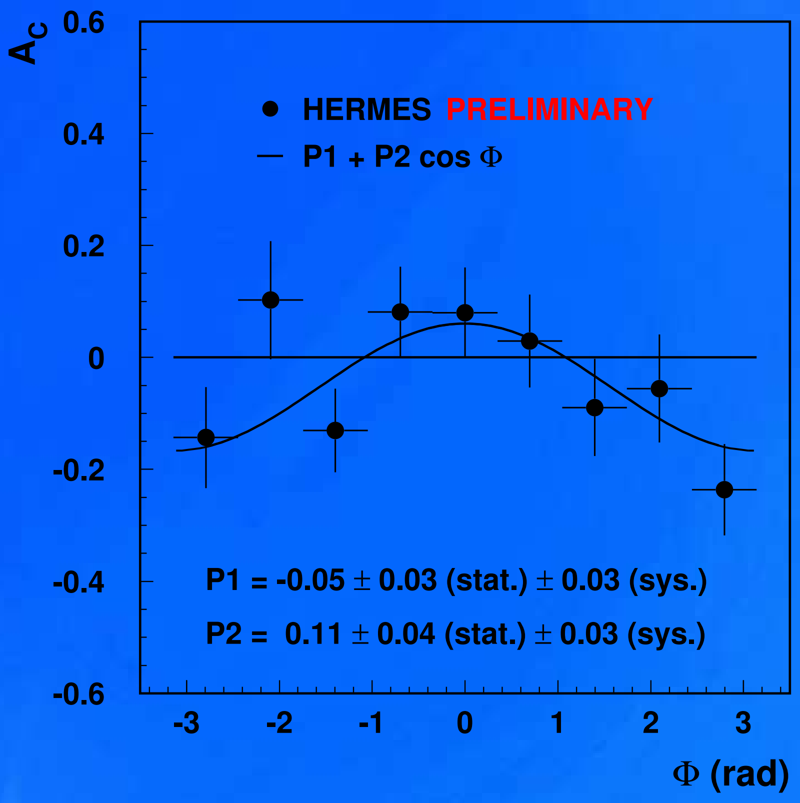
$$d\sigma_{e^+} - d\sigma_{e^-} \propto \mathrm{Re}\,(\mathcal{T}_{BH}\mathcal{T}_{DVCS}) \propto \cos\phi$$

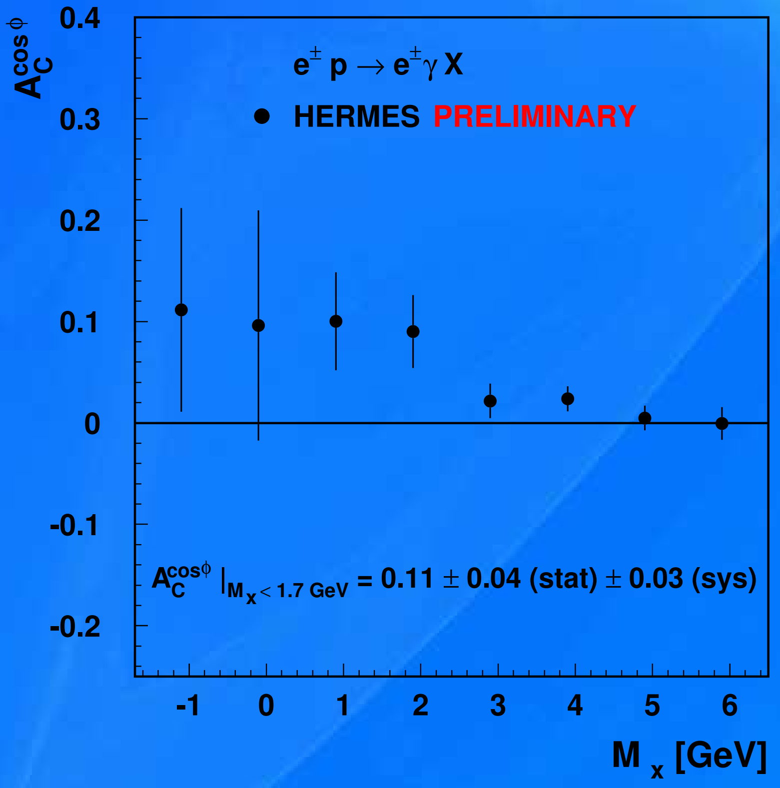
$\Rightarrow$ asymmetry measured by HERMES



ϕ: azimuthal angle between lepton scattering plane and the $\gamma^*\gamma$ - plane

DVCS beam charge asymmetry (BCA)





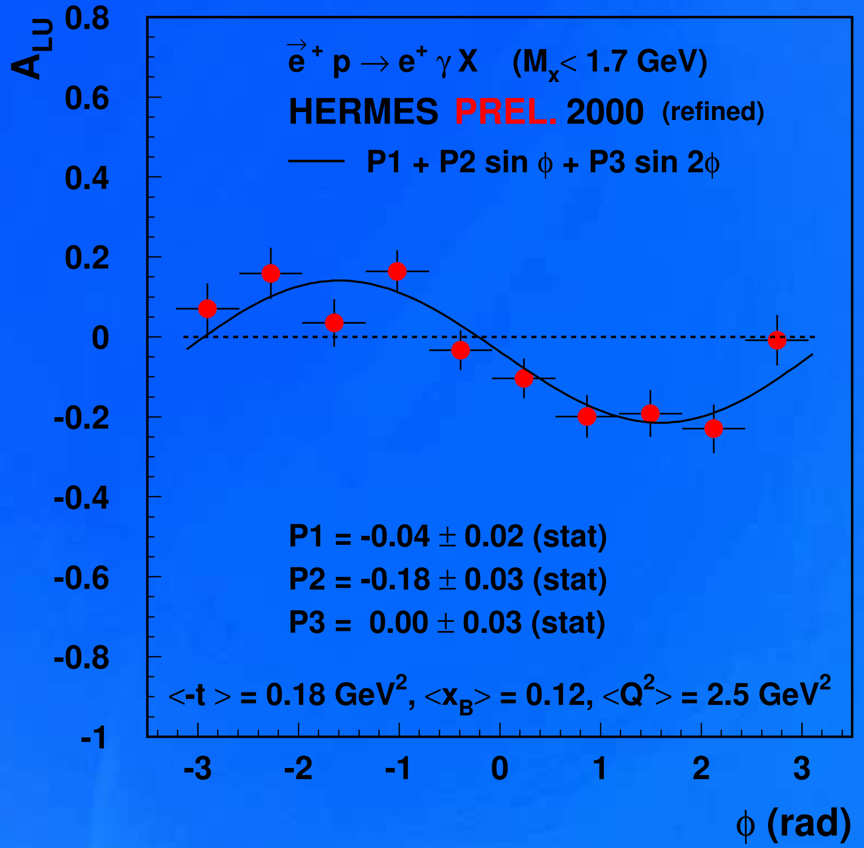
$$A_C(\phi) = \frac{N_{e^+}(\phi) - N_{e^-}(\phi)}{N_{e^+}(\phi) + N_{e^-}(\phi)}$$

$$A_C^{cos\phi} = \frac{1}{N^{e+}} \sum_{i=1}^{N^{e+}} cos(\phi_i) - \frac{1}{N^{e-}} \sum_{i=1}^{N^{e-}} cos(\phi_i)$$

exclusive region: -1.5 $<$ M_x $<$ 1.7 GeV

DVCS single beam-spin asymmetry (SSA)

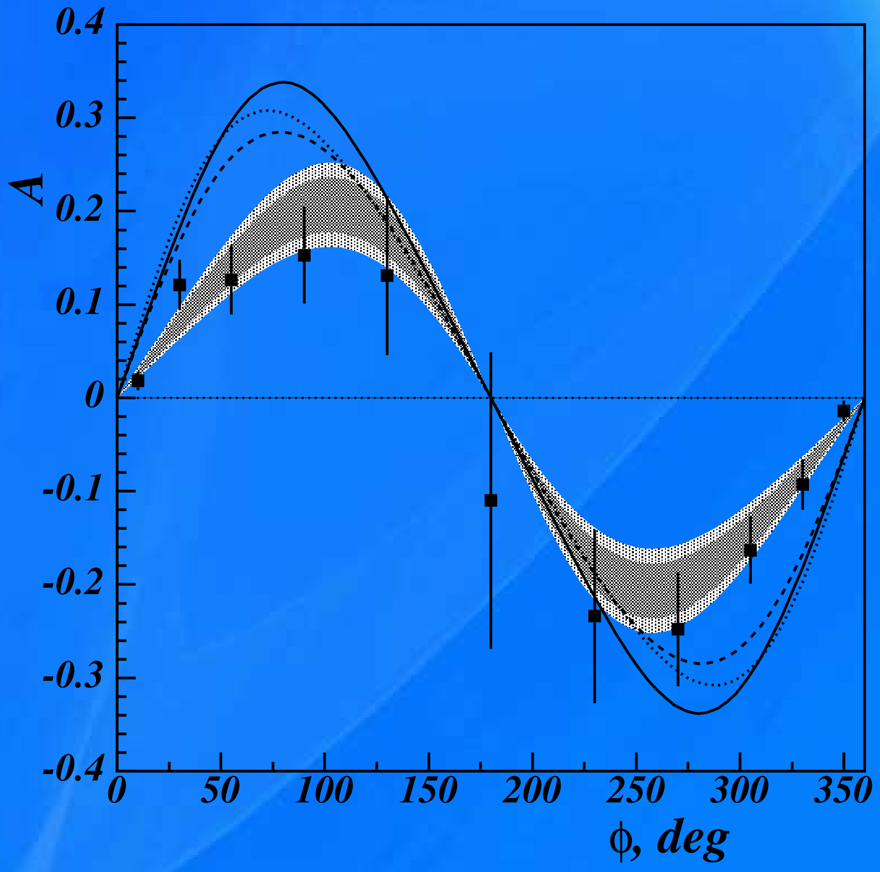
HERMES



96/97: [PRL87 (2001), 182001]

$$A_{LU}^{\sin\phi}(\phi) = -0.18 \pm 0.03 \pm 0.03$$

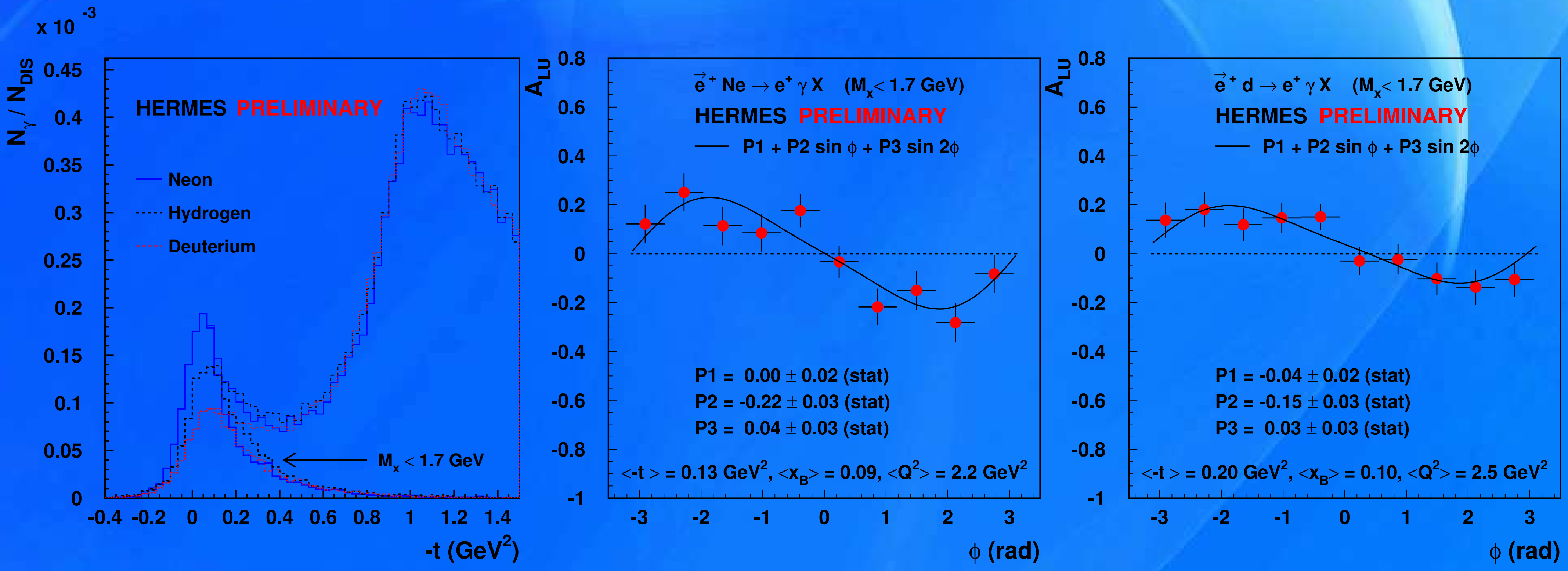
CLAS



[PRL87 (2001), 182002]

$$A_{LU}^{\sin\phi}(\phi) = -0.202 \pm 0.021 \pm 0.009$$

DVCS on Nuclear Targets



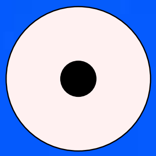
Predictions by A.V. Belitsky et al. (hep-ph/0112108):

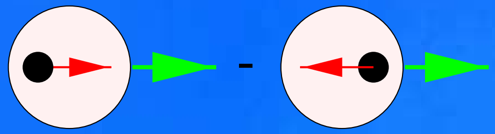
Deuterium: $\mathbf{A_{LU} \sim -0.13 \cdot \sin(\Phi)}$ **at** $\mathbf{Q^2 = 4GeV^2 x = 0.1, t = -0.3GeV^2}$

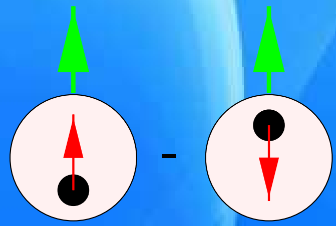
Hydrogen: $\mathbf{A_{LU} \sim -0.16 \cdot \sin(\Phi)}$

Is there an EMC like effect for quarks?

The 3rd Twist-2 Structure function

$f_1^q =$ 

$g_1^q =$ 

$h_1^q =$ 

Unpolarized
quarks and nucleons

vector charge:

$< PS|\bar{\psi}\gamma^{\mu}\psi|PS >=$
$\int_0^1 dx q(x) - \bar{q}(x)$

q(x): spin averaged
well known

Longitudinally polarized
quarks and nucleons

axial charge:

$< PS|\bar{\psi}\gamma^{\mu}\gamma_5\psi|PS >=$
$\int_0^1 dx \Delta q(x) + \Delta\bar{q}(x)$

Δq(x): helicity difference
known

Transversely polarized
quarks and nucleons

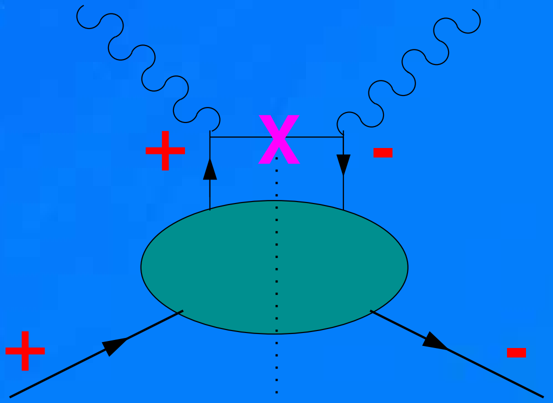
tensor charge :

$< PS|\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS >=$
$\int_0^1 dx \delta q(x) - \delta\bar{q}(x)$

δq(x): helicity flip
unmeasured

Characteristics of Transversity

- **Non-relativistic quarks:** $\Delta q(x) = \delta q(x)$
  $\Rightarrow$ δq **probes relativistic nature of quarks**
- **Angular momentum conservation**
  $\Rightarrow$ **Transversity has no gluon component**
  $\Rightarrow$ **different** Q^2 **evolution than** $\Delta q(x)$
- q **and** $\bar{q}$ **contribute with opposite sign to** $\delta q(x)$
  $\Rightarrow$ **predominantly sensitive to valence quark polarization**
- **Bounds:**
  $\Rightarrow$ $|\delta q(x)| \leq q(x)$
  $\Rightarrow$ **Soffer bound:** $|\delta q(x)| \leq \frac{1}{2}[q(x) + \Delta q(x)]$



- **Transversity distribution CHIRAL ODD**

$\Rightarrow$ **No Access In Inclusive DIS**

How can one measure Transversity?

Need another chiral-odd object!

δq(x) accessible in semi-inclusive DIS

$$\sigma^{ep\to ehX} = \sum_q f^{H\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to h}$$

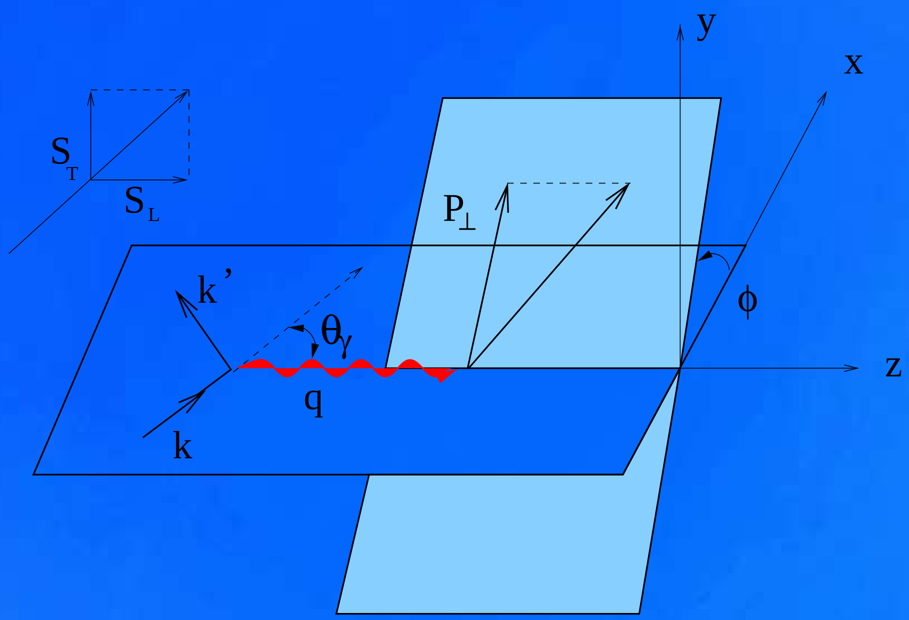
$\Downarrow$ **chiral-odd DF** $\Downarrow$ **chiral-odd FF**

Study SSA with a transversely polarized target at HERMES and COMPASS

1. $ep^{\uparrow} \longrightarrow e'\pi X$ $\Leftarrow$ **Favorite Process**
   Collins,93, Kotzinian,95, Mulders et al,96
2. $ep^{\uparrow} \longrightarrow e'\Lambda^{\uparrow} X$ **Baldracchini,82, Jaffe,96**
3. $ep^{\uparrow} \longrightarrow e'\pi\pi X$ **Jaffe et al,97**

Single Spin Asymmetries

$$ep^{\uparrow} \longrightarrow e'\pi X$$



$\Phi = \phi + \phi_s^l$ **Collins angle**

$\phi_s^l \ldots$ **angle between target spin vector and scattering plane**

study azimuthal distribution of π's:

$$A^{\sin\Phi} \propto \frac{\sum_{i=1}^{N^+} \sin\Phi_i - \sum_{i=1}^{N^-} \sin\Phi_i}{\frac{1}{2}(N^+ + N^-)}$$

Transversely polarized target:

$$A_T^{\sin\Phi} \propto \frac{\sum_q e_q^2 \delta q(x) H_1^{\perp,q}(z)}{\sum_q e_q^2 q(x) D_1^q(z)}$$

$H_1^\perp(z)$ **Collins fragmentation function**

First glimpse on Transversity ?!

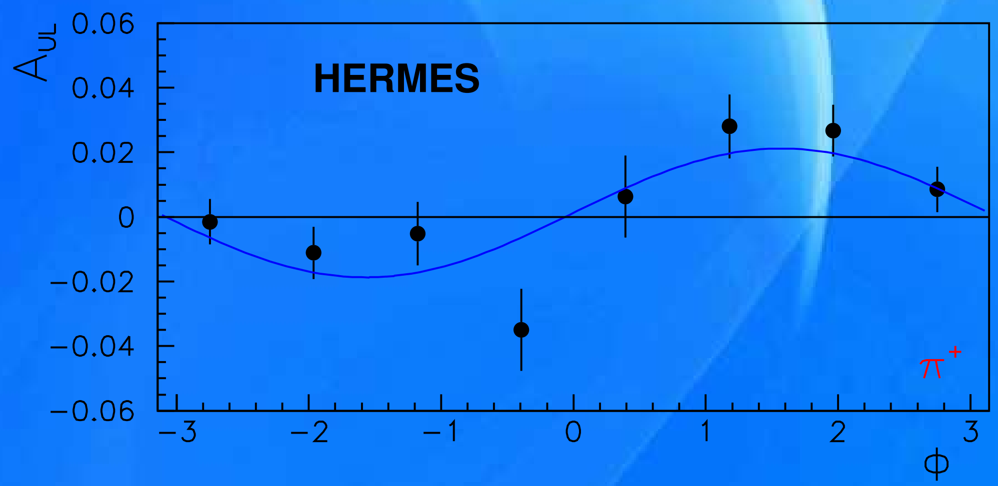
HERMES longitudinal polarized hydrogen target

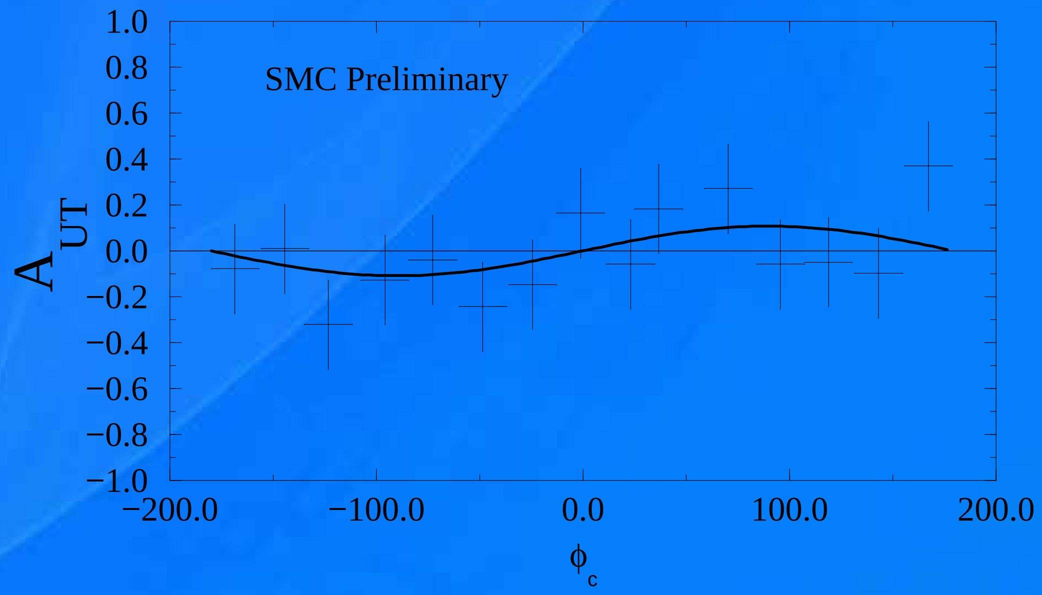
$$A_{UL}(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$

S_T transverse component of target spin w.r.t. virtual photon:

$$S_T \propto \sin\Theta_\gamma \simeq \frac{2Mx}{Q}\sqrt{1-y} \sim \mathbf{0.15}$$

π^0: **hep-ex/0104005,** $\pi^\pm$: **hep-ex/9910062**





SMC transverse polarized hydrogen target

Attempt of Interpretation

- **observe non-vanishing $\langle \sin\phi \rangle$-moments**
- **$\langle \sin 2\phi \rangle$-moment small (consistent with zero)**

Attribute asymmetry to Collins fragmentation and Transversity:

$$A^{\sin\phi}_{UL} \sim S_L \langle \sin\phi \rangle_{UL} - S_T \langle \sin\phi \rangle_{UT}$$

Longitudinally polarized in experiment (along beam direction)

L/T polarized in theory (along virtual gamma direction

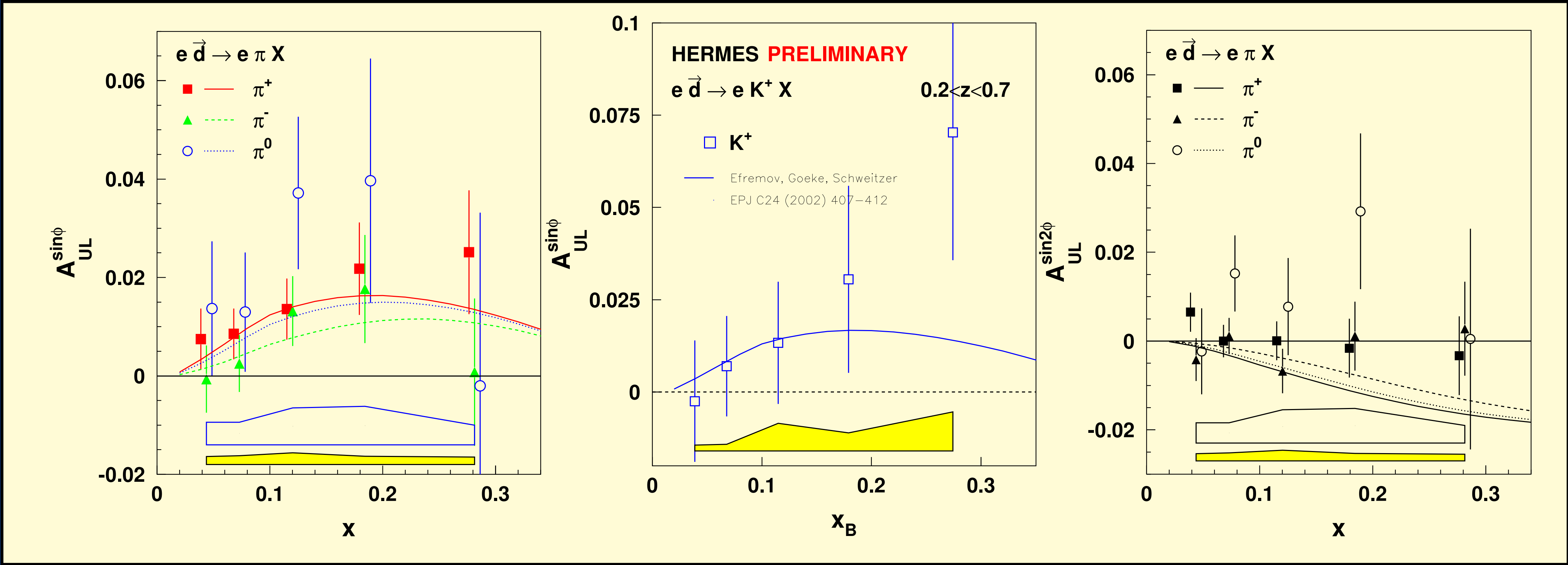
$$\langle \sin\phi \rangle_{UL} \sim \frac{1}{Q} \sum_q e_q^2 \left(h_L^q(x) H_1^{\perp(1),q}(z) - \frac{1}{z} h_{1L}^{\perp(1),q}(x) \tilde{H}(z) \right)$$

$$\langle \sin\phi \rangle_{UT} \sim \sum_q e_q^2 x h_1^q(x) H_1^{\perp(1),q}(z)$$

but $S_T \sim \frac{1}{Q}$ like twist-3

$$\langle \sin 2\phi \rangle_{UL} \sim \sum_q e_q^2 x h_{1L}^{\perp(1),q}(x) H_1^{\perp(1),q}(z)$$

Deuteron Results



- h_1 from χQSM (Efremov et al. Eur.Phys.J. C24 (2002) 407)
- assume reduced twist-3 $\longrightarrow \tilde{h}_L = 0$
- $H_1^{\perp}$: Collins function parametrisation to fit HERMES proton data

optimistic" result from DELPHI $e^+e^- \to 2$jets: $\frac{\langle H_1^{\perp(1)} \rangle}{\langle D_1 \rangle} = (12.5 \pm 1.4)\%$

Challenges in Interpretation

Attribute asymmetry to Sivers effect:

- **Final state interactions (Brodsky et al.)**
- **Sivers function (Sivers, Mulders et al)** $\langle \sin\phi \rangle_{\mathbf{UL}} \sim \mathbf{f}_{\mathbf{1T}}^{\perp(\mathbf{1})} \mathbf{D}_{\mathbf{1}}$

longitudinally polarized target $\Rightarrow$ Sivers and Collins effect indistinguishable

COMPASS and HERMES: Transversely polarized target

- $\langle \sin\phi \rangle_{UT}$ **becomes dominant**
- **Sivers and Collins distinguishable**

$\langle \sin(\phi_{\mathbf{h}}^{\mathbf{l}} - \phi_{\mathbf{s}}^{\mathbf{l}}) \rangle$ **moment** $\langle \sin(\phi_{\mathbf{h}}^{\mathbf{l}} + \phi_{\mathbf{s}}^{\mathbf{l}}) \rangle$ **moment**

Summary

- **Inclusive**
  - **g1(x)/(g2(x)) mature**
- **Semi-Inclusive**
  - **good agreement with NLO-fits to inclusive data**
  - **give more information**

  $\longrightarrow$ $\Delta \mathrm{s}(\bar{\mathrm{s}})$ **and** $\Delta \bar{\mathrm{u}} - \Delta \bar{\mathrm{d}}$
- $\Delta \mathrm{G}$
  - **wait till 2010**
- $\mathbf{L_q + L_g}$
  - **exclusive reactions exclusively established**

  $\longrightarrow$ **need more work**
- **Transversity**
  - **results coming soon**