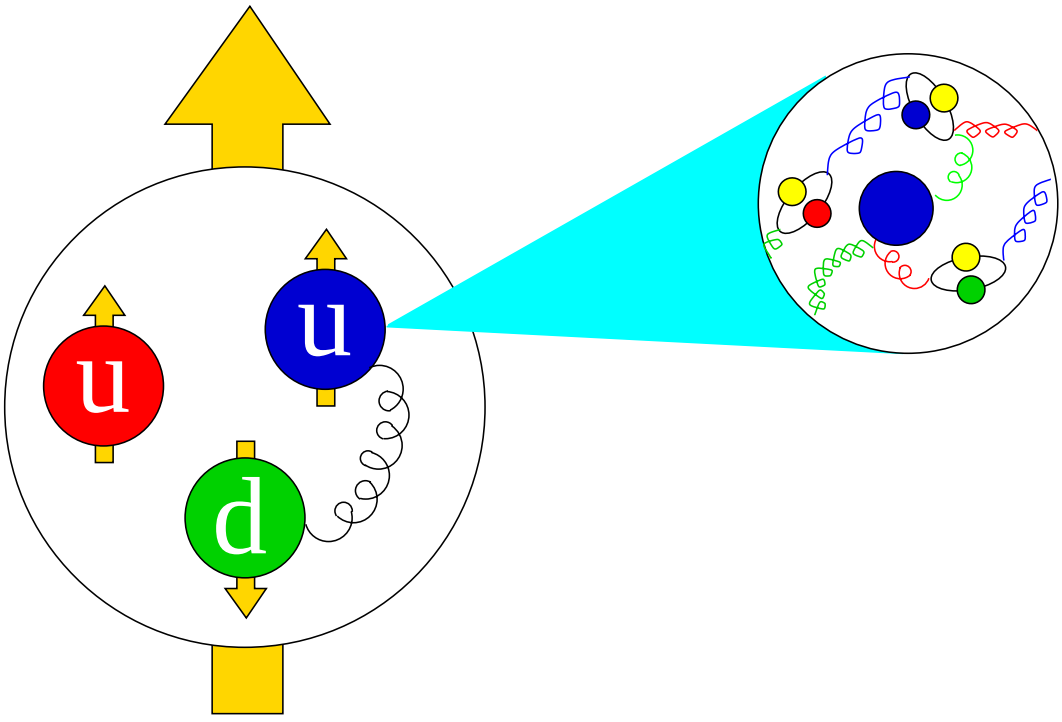
Polarized Structure Functions

Gerard van der Steenhoven (NIKHEF)

JLab, Newport News, 4 March 2002



9^{th} Int. Conference on the Structure of Baryons

Introduction

- The origin of spin in the baryon octet:

$$\tfrac{1}{2} = \tfrac{1}{2}\Delta\Sigma_q + \Delta G + L_z$$

- Developing insight:
  - EMC (SLAC, SMC and HERMES): $\Delta\Sigma_q \approx 0.3 \pm 0.1$
  - The quark model: $\Delta\Sigma_q = (\uparrow\downarrow\uparrow) = 1.0$
  - Relativistic MIT bag model: $\Delta\Sigma_q \simeq 0.60 - 0.75$

- Experimental questions:
  - What about flavour dependence?

    $\Delta u(x)$, $\Delta d(x)$, $\Delta s(x)$
  - What about gluons?

    $\Delta G(x)$
  - What about orbital angular momentum?

    Deeply Virtual Compton Scattering: L_z?
  - What about other baryons?

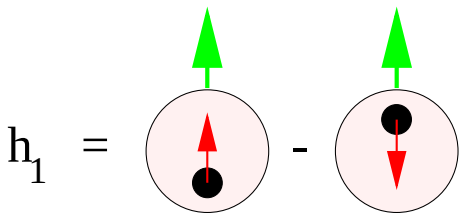
    n,Λ^0,...
  - What about lattice QCD?

    longitudinal spin: $\Delta\Sigma_q \simeq 0.18 \pm 0.10$

    transverse spin: $\delta\Sigma_q \simeq 0.56 \pm 0.09$

Outline

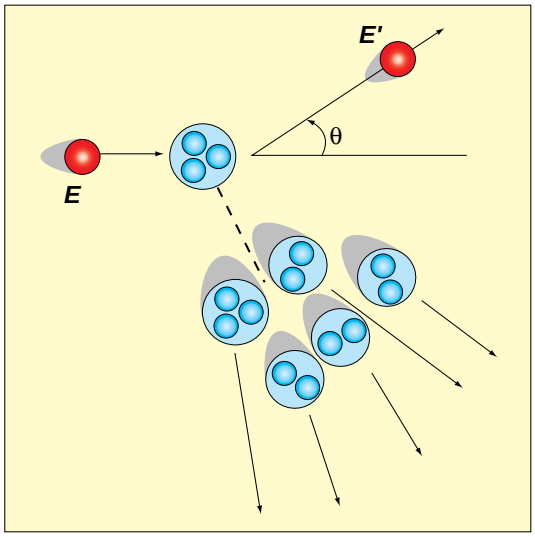
- Introduction
- Longitudinal spin:
  - Inclusive experiments: $g_1^{n,p}(x), g_2^{n,p}(x)$
  - Semi-inclusive experiments: $\Delta q_f(x)$
  - Photo-production of high p_T-pairs: $\Delta G(x)$
  - Deeply-virtual Compton scattering: $L_z(x)$
  - Hyperon production: Λ-spin
- Transverse spin:
  - Single-spin asymmetries in π-production: $h_1(x)$

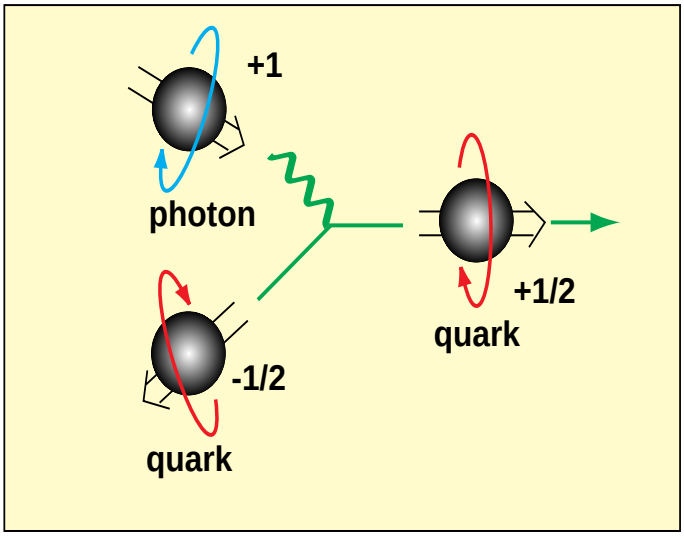


- Future perspectives:
  - HERMES Run-II
  - COMPASS
  - RHIC-spin
  - SLAC
  - TESLA-N, EIC,...

Introduction

- Polarized Deep Inelastic Lepton Scattering:





- Asymmetry w.r.t. to target spin orientation:

$$A_1 = \frac{1}{D P_T P_B} \frac{N_{\uparrow\downarrow} - N_{\uparrow\uparrow}}{N_{\uparrow\downarrow} + N_{\uparrow\uparrow}}$$

- The spin-dependent structure function $g_1(x)$:

$$A_1 \simeq \frac{g_1(x)}{F_1(x)} \simeq \frac{1}{F_1(x)} \sum_f e_f^2 \Delta q_f(x)$$

with the quark polarization:

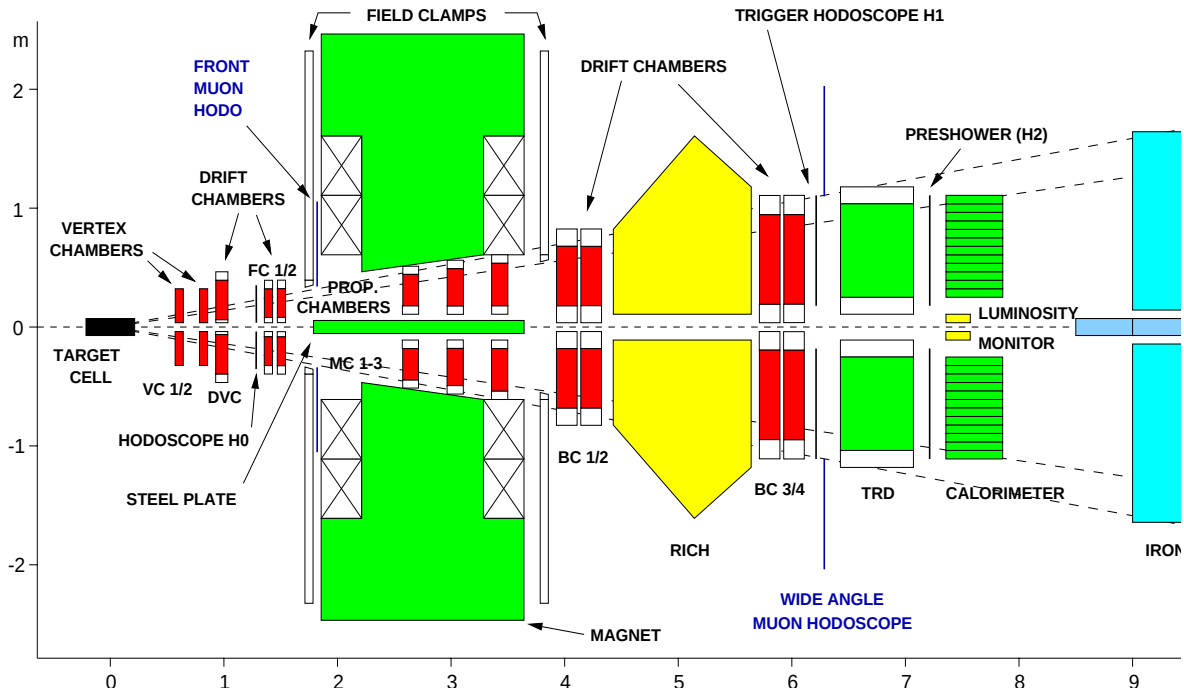
$$\Delta q_f(x) = q_f^+(x) - q_f^-(x)$$

- General objective:

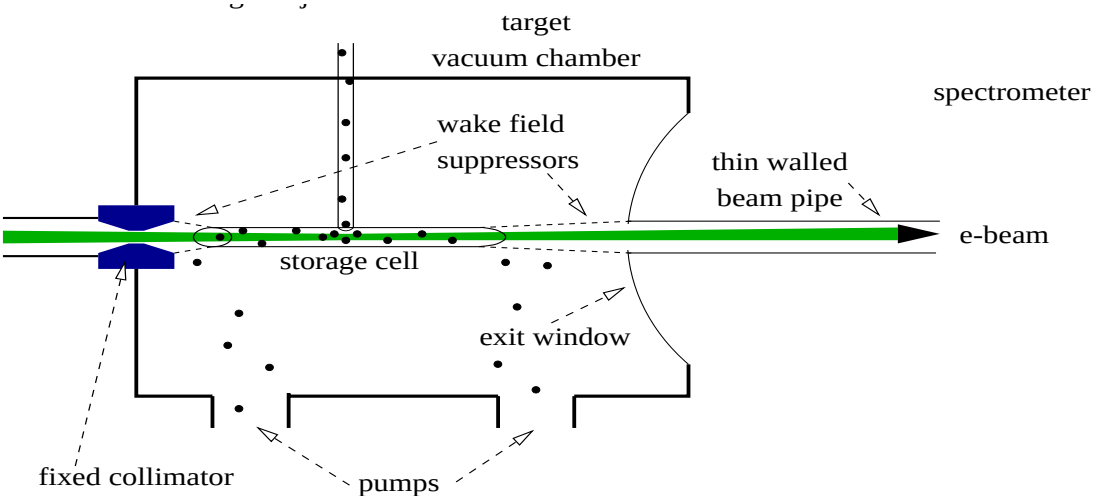
Spin structure of the nucleon

The HERMES experiment

- The HERMES spectrometer at DESY:

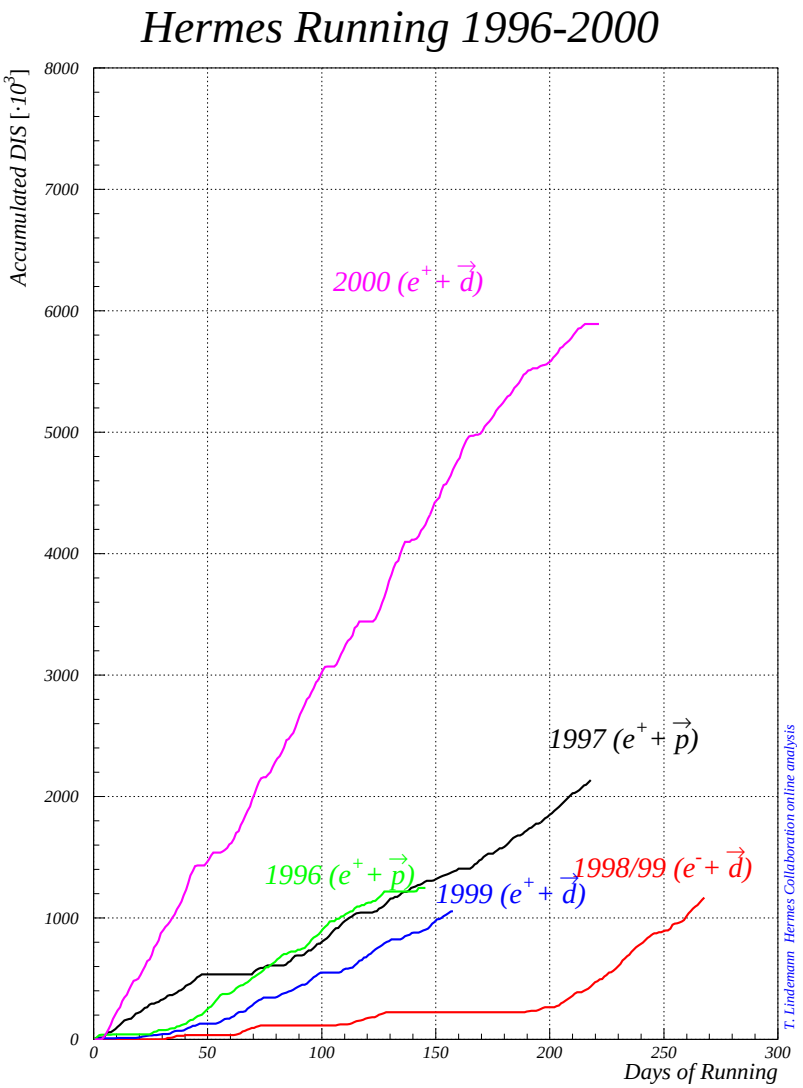


- Internal Target ($^1\overrightarrow{H}$, $^2\overrightarrow{H}$, $^3\overrightarrow{He}$, ^4He, ^{14}N, ^{20}Ne, ^{84}Kr) :



Data collected in Run I

- Accumulated polarized DIS events per year:

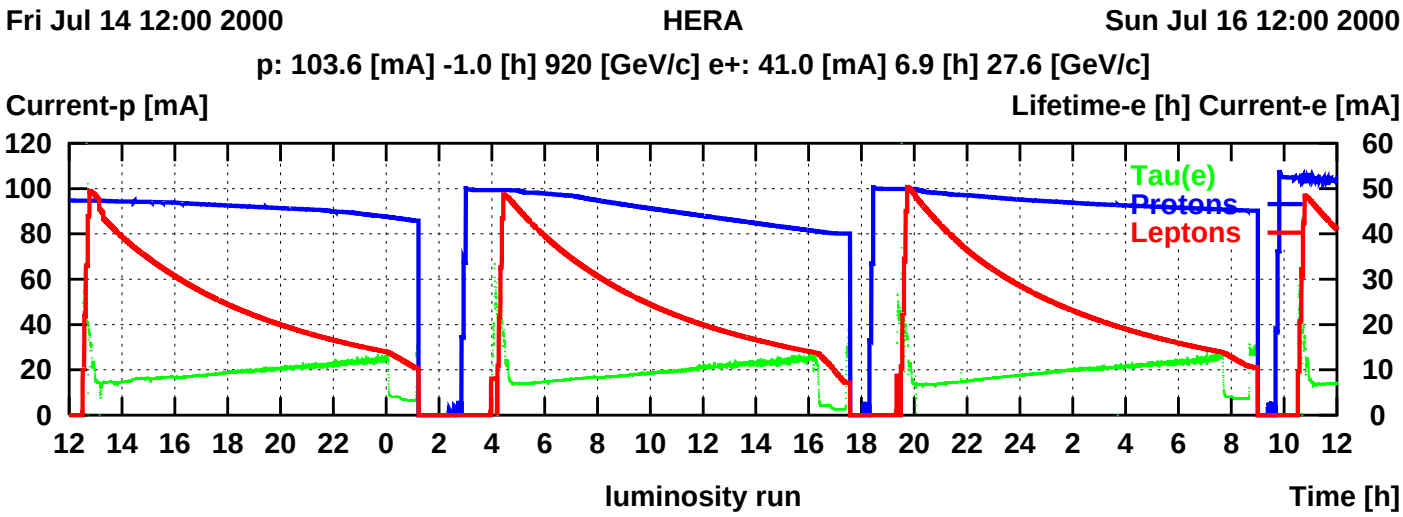


- Data taking in 2000:
  - cell size reduced to 21 X 8.9 mm^2
  - lower cell temperature: 96 $\rightarrow$ 62 K

Luminosity increased by factor 2.5 !!

Unpolarized data taking

- End-of-Fill running:
  - Last hour of every fill: high-density targets
  - Loss of normal data taking: few %
  - Targets used: ^{1}H, ^{2}H, ^{4}He, ^{20}Ne
  - Positron beam life time: 0.5 – 2 hours
  - Data collected: 13.6 Million DIS events



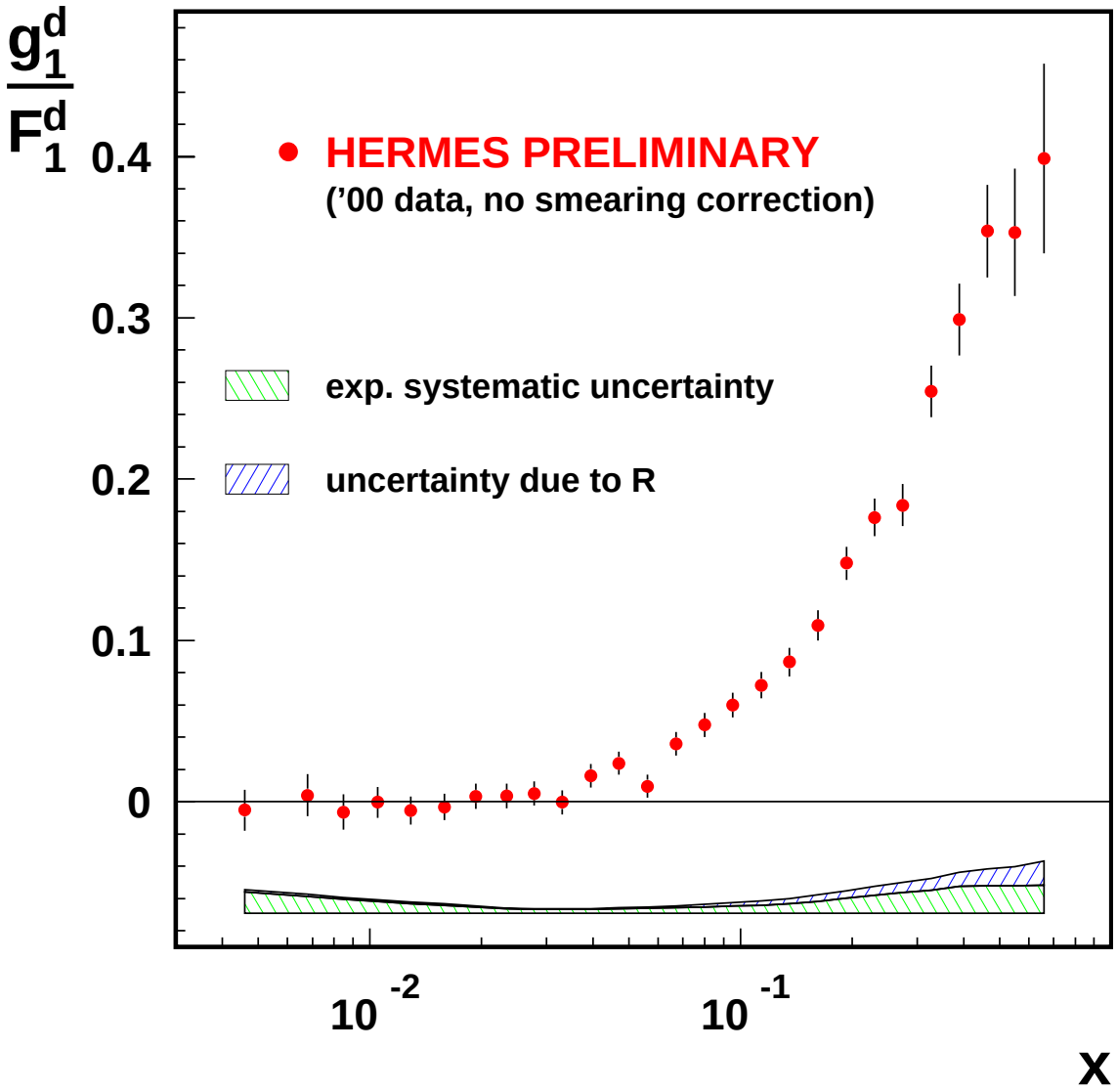
Maximum luminosity: 4×10^{33} N/cm^2/s

- Dedicated HERA run at E = 12 GeV:
  - HERMES spectrometer operated well
  - Collected: 1 Million DIS ev. on ^{1}H, ^{2}H, ^{14}N, ^{84}Kr.

Inclusive measurements - 1

- New deuterium data on $g_1^d(x)/F_1^d(x)$:

$$\frac{g_1^d}{F_1^d} = \frac{1}{1+\gamma}\left(\frac{A_{//}^d}{D} - (\eta-\gamma)A_2^d\right)$$

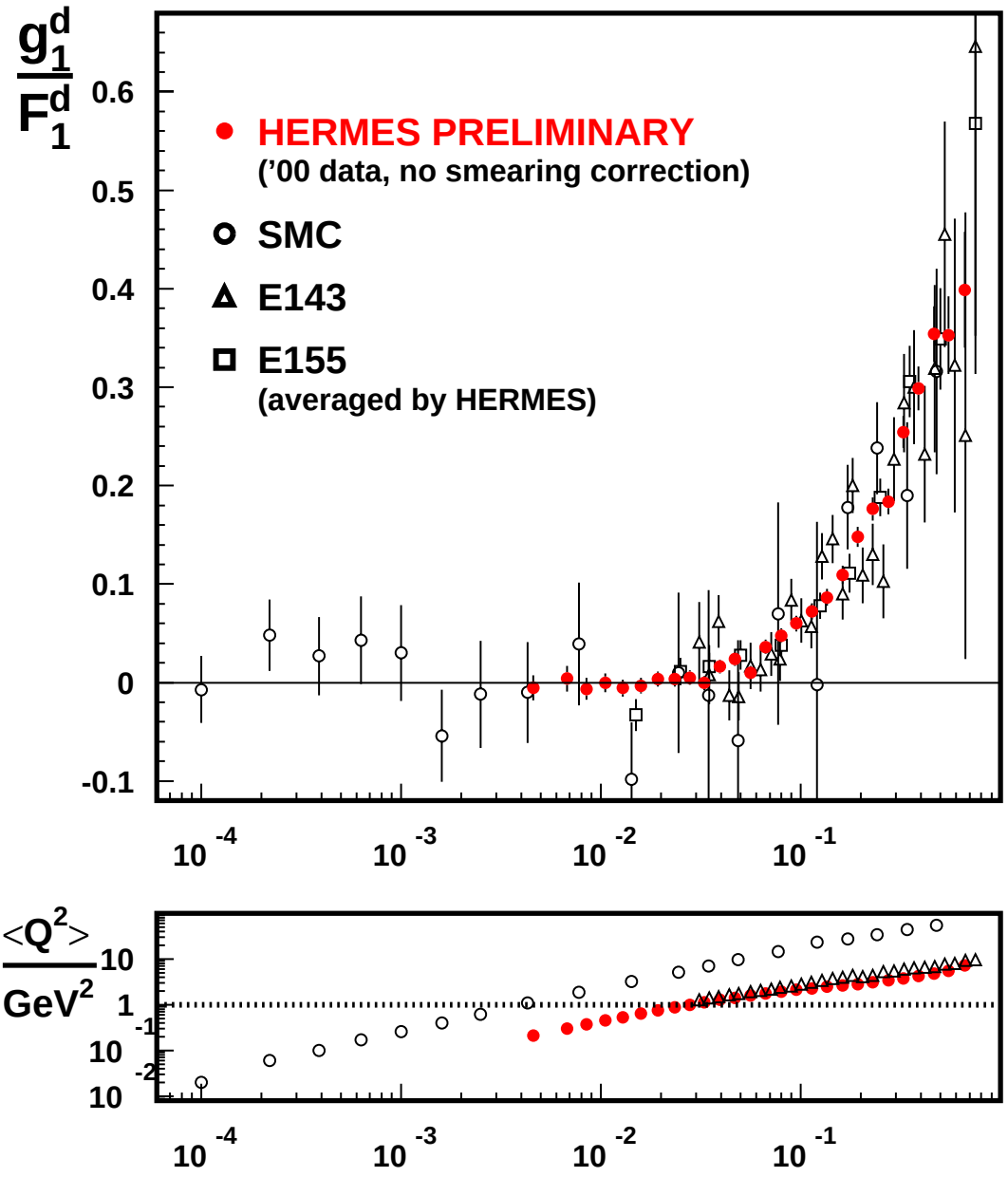


- Observation:

HERMES probes down to $x \approx 4 \times 10^{-3}$

Inclusive measurements - 2

- Compare to existing data:

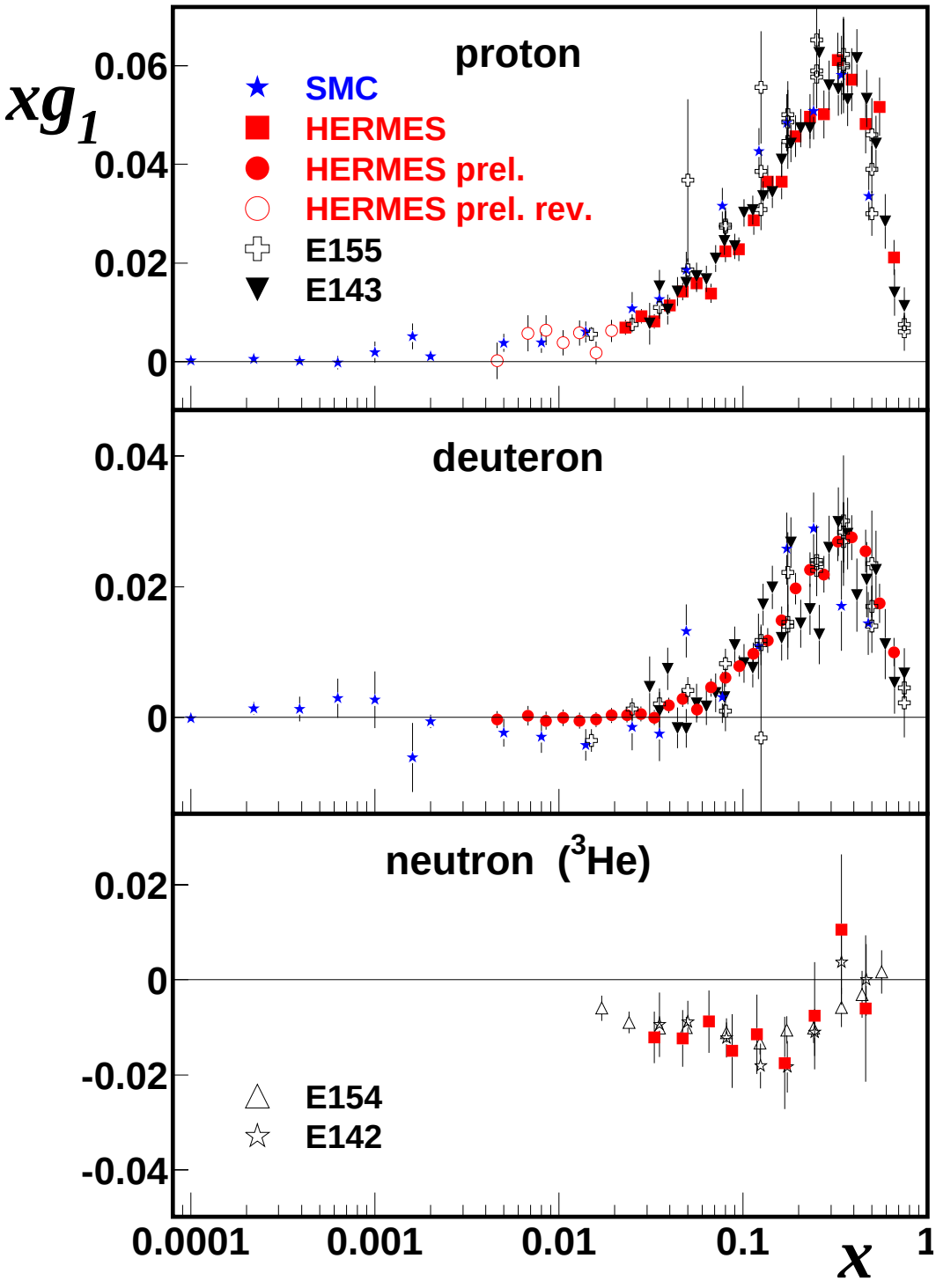


- Conclusion:

$g_1^d(x)$: no strong Q^2 dependence

Polarized Structure Functions

- Overview of existing $xg_1(x)$ data:

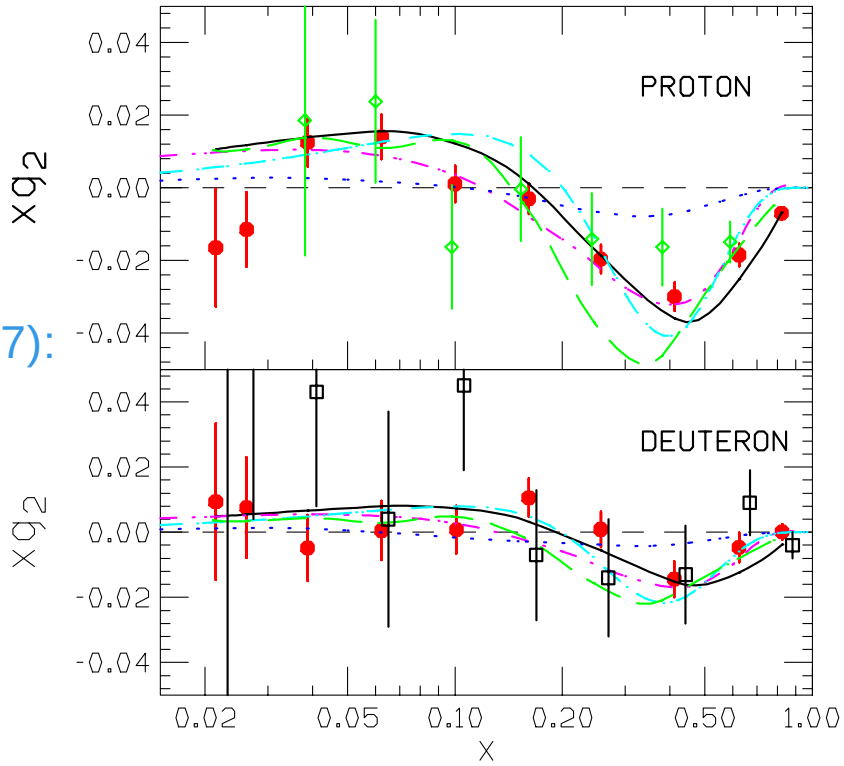


The structure function $g_2(x)$

- Preliminary data from SLAC E143 and E155x:

[$g_2(x)$ is sensitive to qg-correlations and higher twist]

$g_2^{WW}(x)$ exp.:
→ solid;
M. Stratmann (93):
→ dot-dash;
Gamberg-Weigel (97):
→ short-dash;
Song (96):
→ dotted;
Wakamatsu (96):
→ long-dash;



- Wandzura - Wilczek interpretation:

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{g_1(y,Q^2)}{y} dy$$

$g_2(x,Q^2)$ dominated by twist-2 part

Semi-Inclusive Asymmetries

- Asymmetry for semi-inclusive hadron (h) production:

$$A_1^h(x) = \frac{\int dz \sum_f e_f^2 \, \Delta q_f(x) \, D_f^h(z)}{\int dz \sum_f e_f^2 \, q_f(x) \, D_f^h(z)} \propto \frac{N_{\uparrow\downarrow}^h - N_{\uparrow\uparrow}^h}{N_{\uparrow\downarrow}^h + N_{\uparrow\uparrow}^h}$$

- Define purity $P_f^h(x)$:

$$P_f^h(x) = \frac{e_f^2 q_f(x) \int D_f^h(z) dz}{\sum_f e_f^2 q_f(x) \int D_f^h(z) dz}$$

[probability that hadron h is produced when quark f is hit]

- Measure asymmetries on various targets:

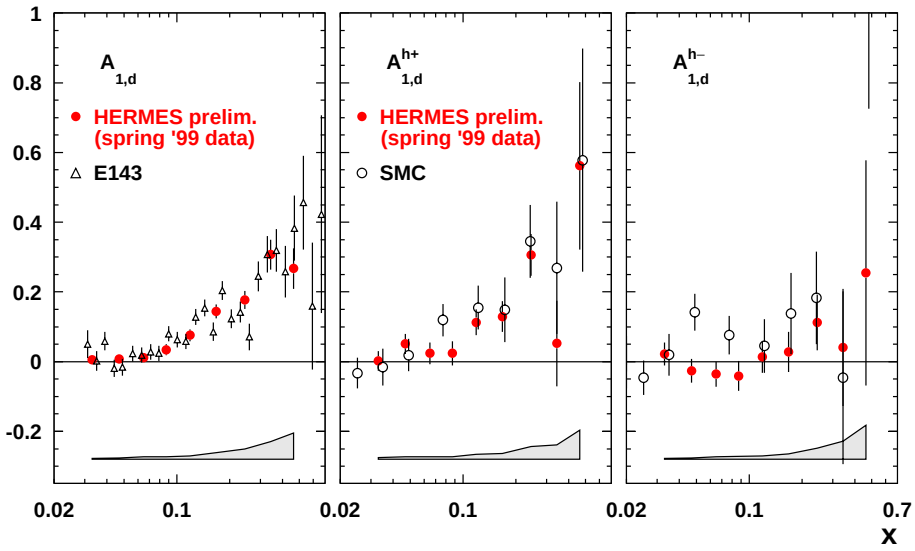
$$\boxed{\vec{A}(x) = \mathbf{P}(x) \, \vec{Q}(x)}$$

with $\vec{A}(x)$ = (A_{1p},$A_{1p}^{h^+}$, $A_{1p}^{h^-}$, A_{1d}, ...)
and $\vec{Q}(x)$ = ($\Delta u(x)$, $\Delta d(x)$, $\Delta \bar{u}(x)$, ...)

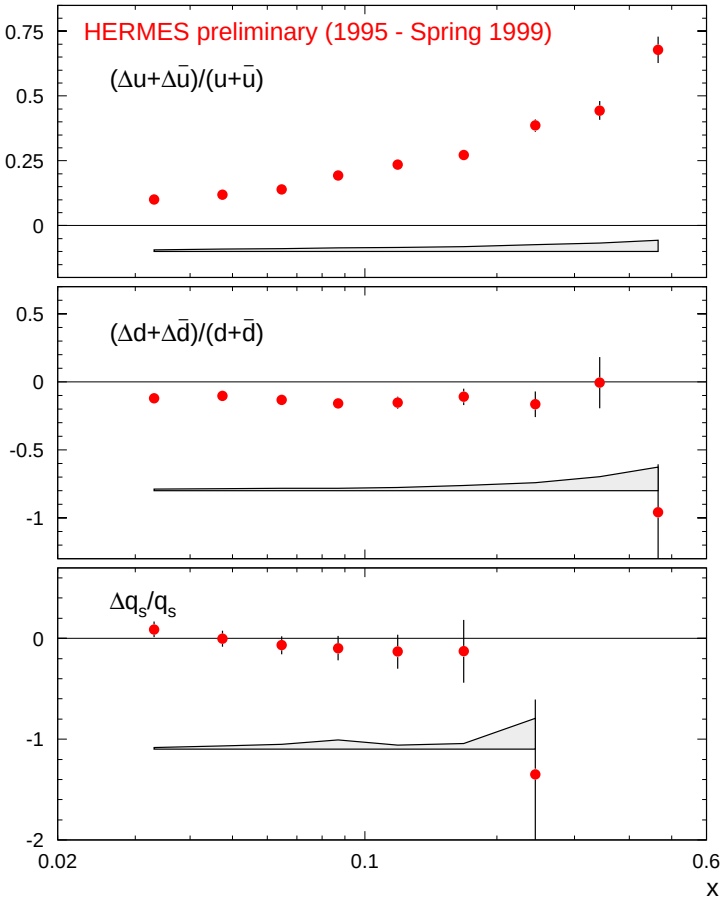
$\Rightarrow$ Polarized quark distributions: $\Delta u(x)$, $\Delta d(x)$, ...

Polarized quark distributions - 1

- Measured semi-inclusive asymmetries $A_1^h(x)$:



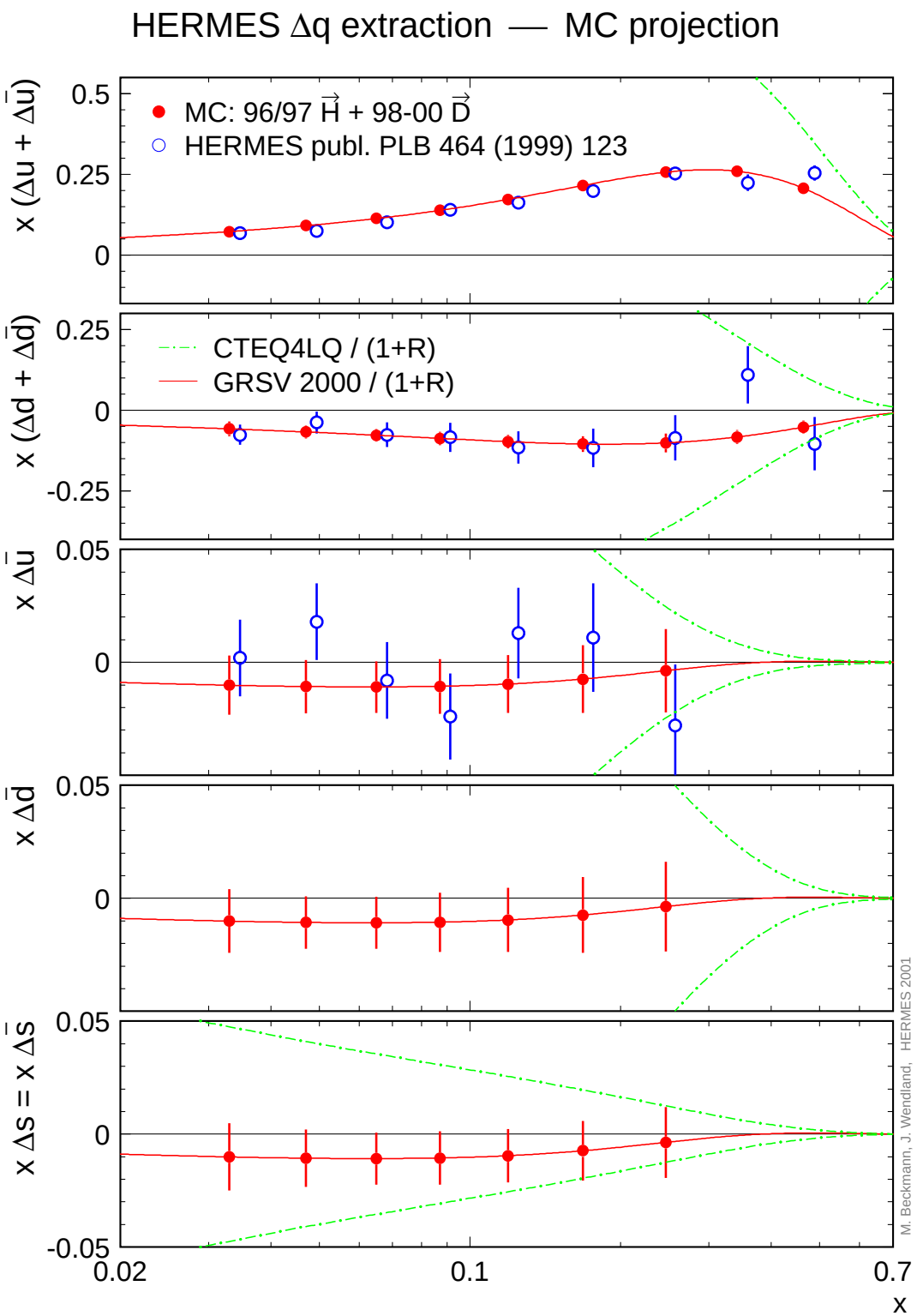
- Extracted quark spin distributions:



Spin - flavour separation.

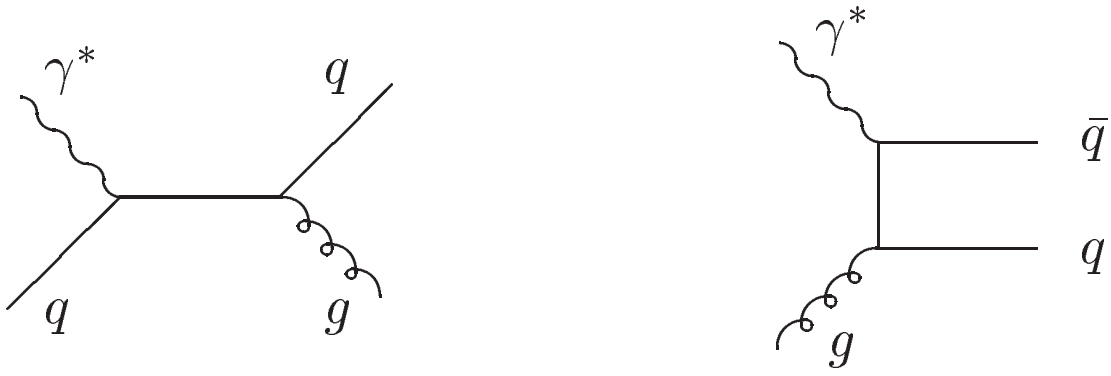
Polarized quark distributions - 2

- Expected data quality with '00 data included:



High-p_T hadron pairs from ^{1}H

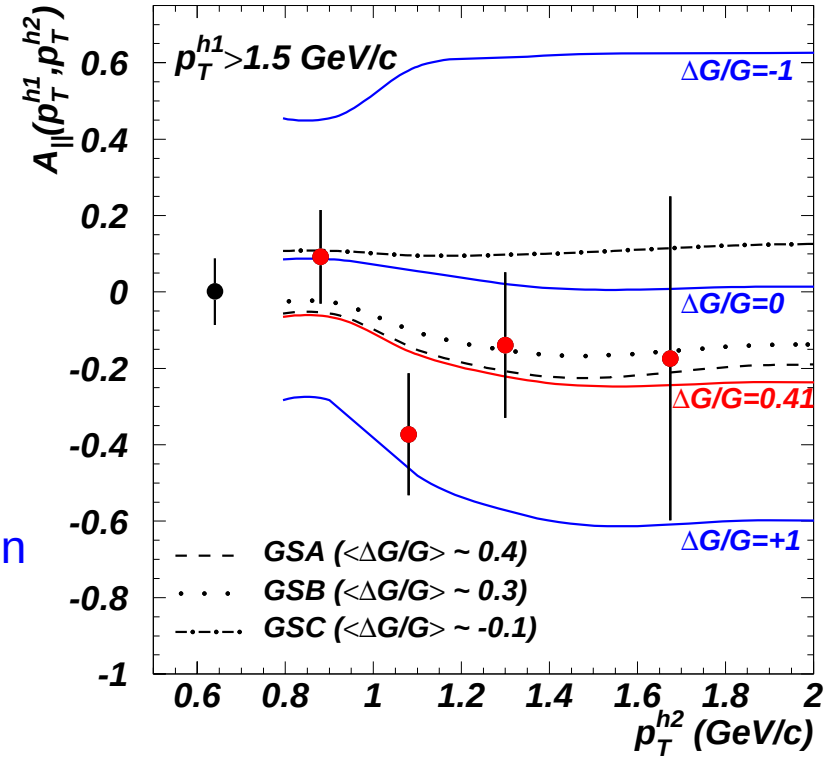
- pQCD Compton graph and Photon-Gluon Fusion:



- Asymmetry for high-p_T pions ($R = \sigma_{PGF}/\sigma_{Com}$) :

$$A_{LL}^{eN\to h_1 h_2} = \hat{a}_{QCDC}\frac{\Delta q}{q}\frac{1}{1+R} + \hat{a}_{PGF}\frac{\Delta G}{G}\frac{R}{1+R}$$

- Target spin-asymmetry on long. polarized ^{1}H:

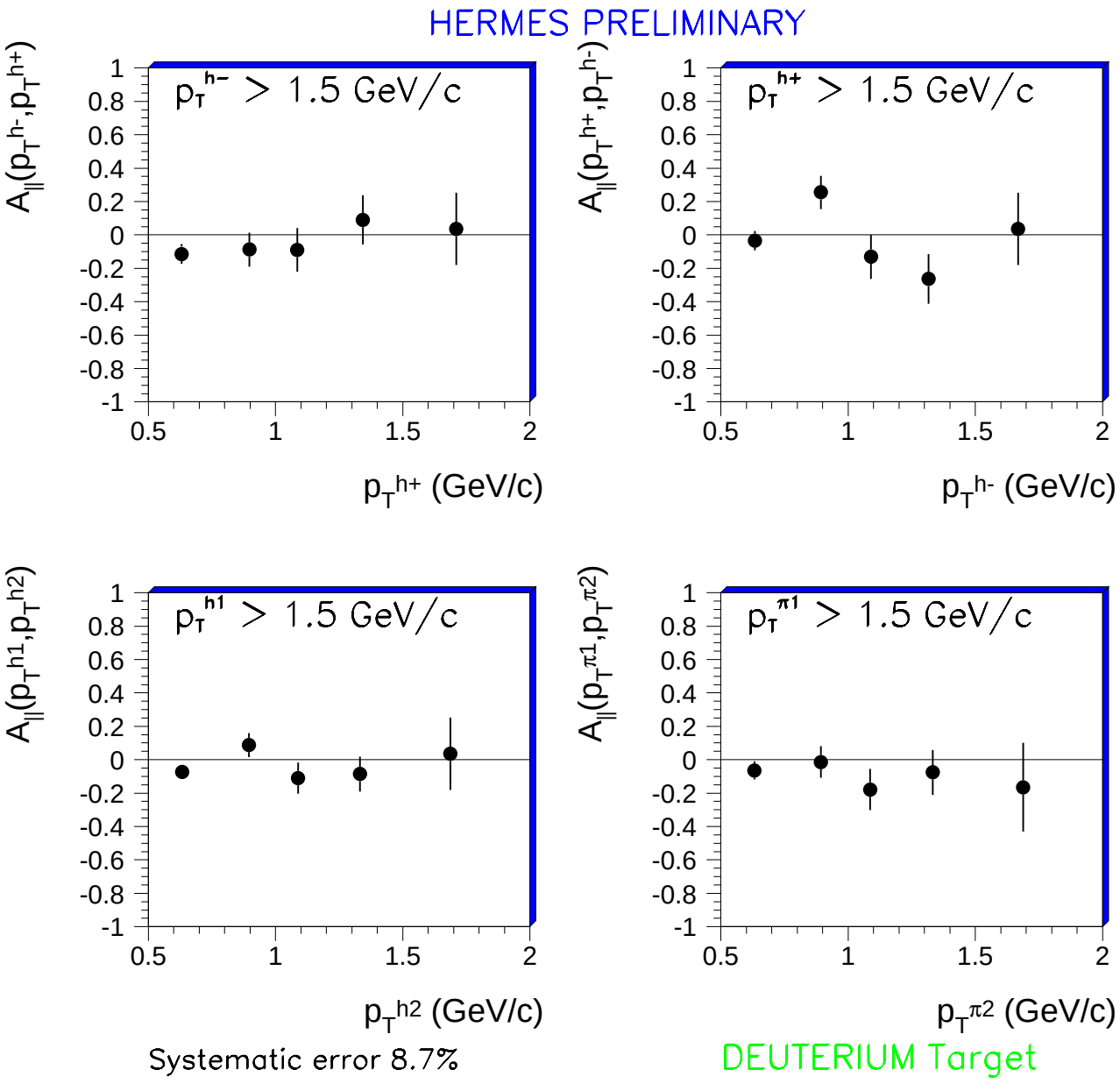


HERMES Collaboration
PRL 84 (2000) 2584

High-p_T hadron pairs on ^{2}H

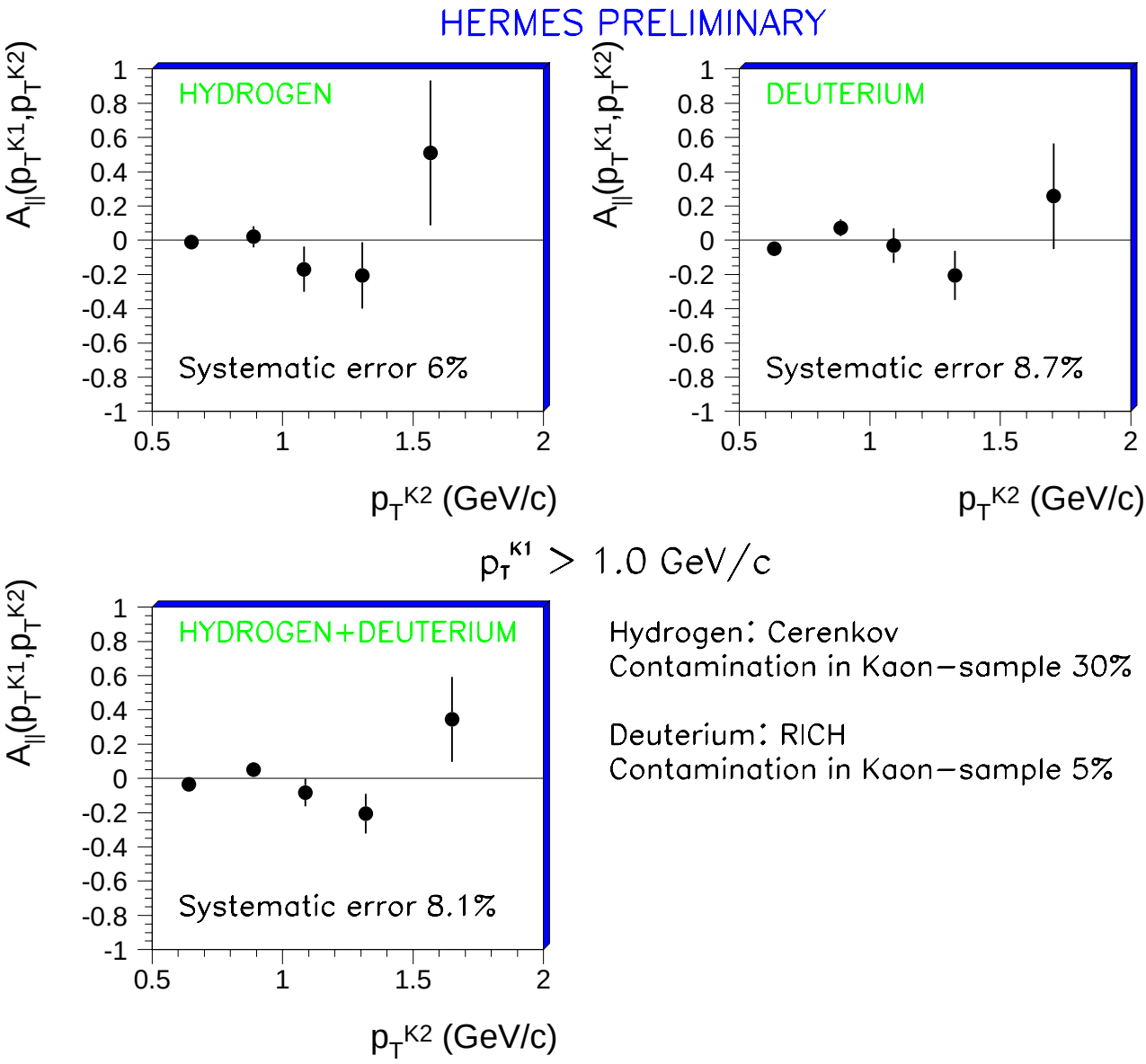
- Require oppositely charged hadron pairs:
  - PGF produces only (+ –) pairs: favored
  - pQCD on ^{1}H $\rightarrow$ more + hadrons: disfavored

- Preliminary results on ^{2}H:



High-p_T kaon pairs

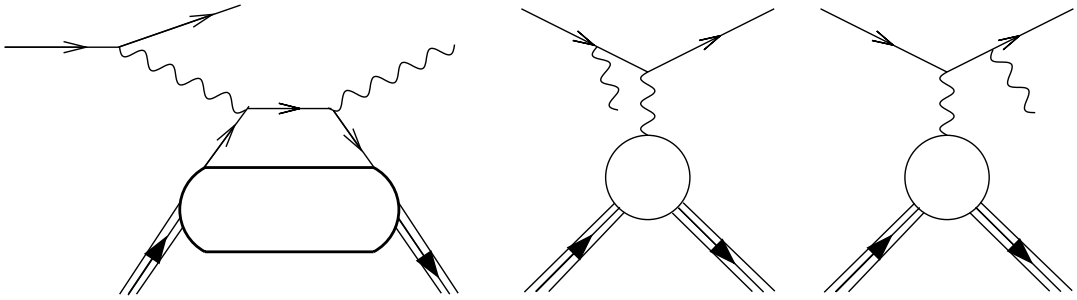
- Strangeness production suppressed in pQCD....
- High-p_T kaon pairs on ^{1}H and ^{2}H:



- More statistics needed (+ MC studies)

Deep Virtual Compton Scattering

- Off-shell photon*-quark scattering:
  - Detect e' and γ, and require: $E_{miss} = 0$



- Ji's sumrule [Phys. Rev. Lett. 78 (1997) 610]:

$$\int x dx [H(x, \Delta^2, \xi) + E(x, \Delta^2, \xi)] = A_q(\Delta^2) + B_q(\Delta^2)$$

with $\Delta^2 = -t$ and

$$\lim_{\Delta^2 \to 0} [A_q(\Delta^2) + B_q(\Delta^2)] = 2J_{quark} = \Sigma_q + 2L_q$$

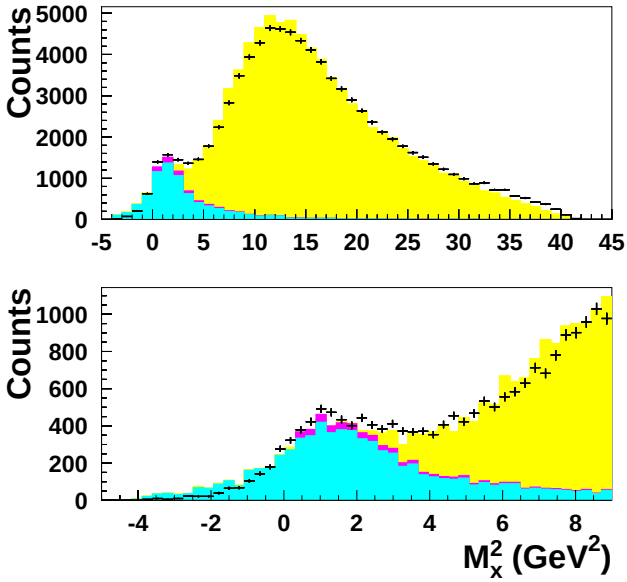
$\Rightarrow$ DVCS: total quark angular momentum

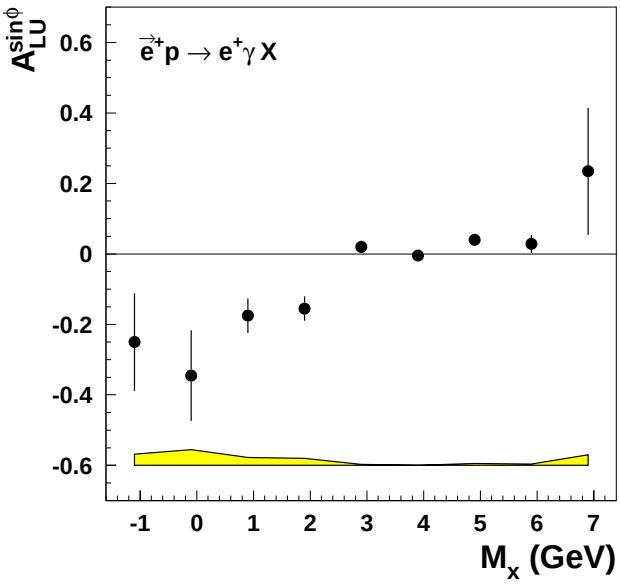
- Experimental considerations:
  - Interference with Bethe-Heitler process:

    DVCS $\otimes$ BH makes DVCS measurable
  - Detect scattered photon, but suppress π^0's
  - Observe azim. asymmetry: $A_{LU}^{BetheHeitler} = 0$

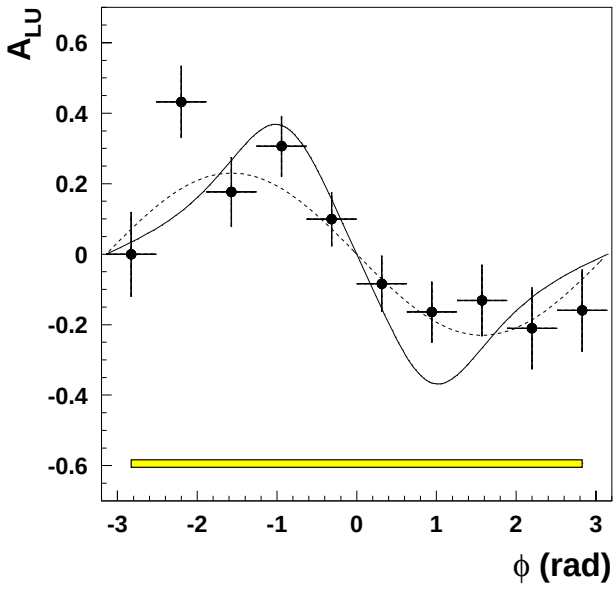
First observations of DVCS

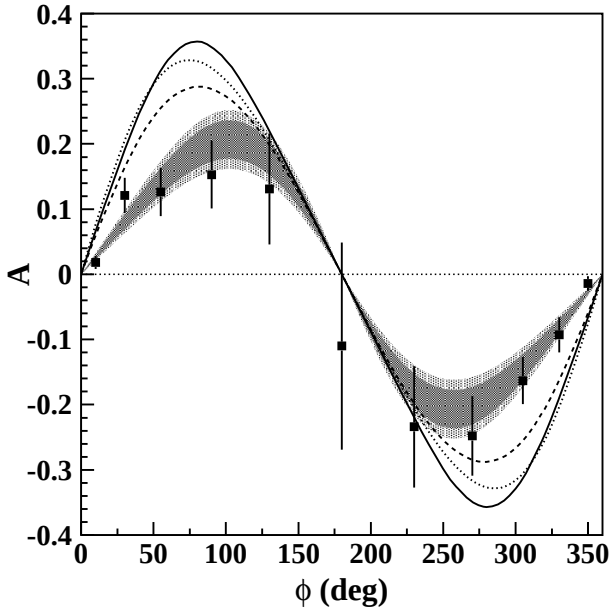
- Missing mass spectrum and $A_{LU}^{\sin\phi} = \frac{2}{N}\sum_{i=1}^{N}\frac{\sin\phi_i}{(P_l)_i}$:





- Azimuthal (ϕ) distributions from HERMES & JLab:





HERMES, PRL 87('01)182001 CLAS Collab., PRL 87('01)182002

DVCS: helicity dependence

- Exclusive leptoproduction of photon:

$$\frac{d^4\sigma}{d\phi dt dQ^2 dx} = \frac{xy^2}{32\,(2\pi)^4\,Q^4\,(1+4x^2m^2/Q^2)^{1/2}} \frac{|\tau_{\rm BH}+\tau_{\rm DVCS}|^2}{}$$

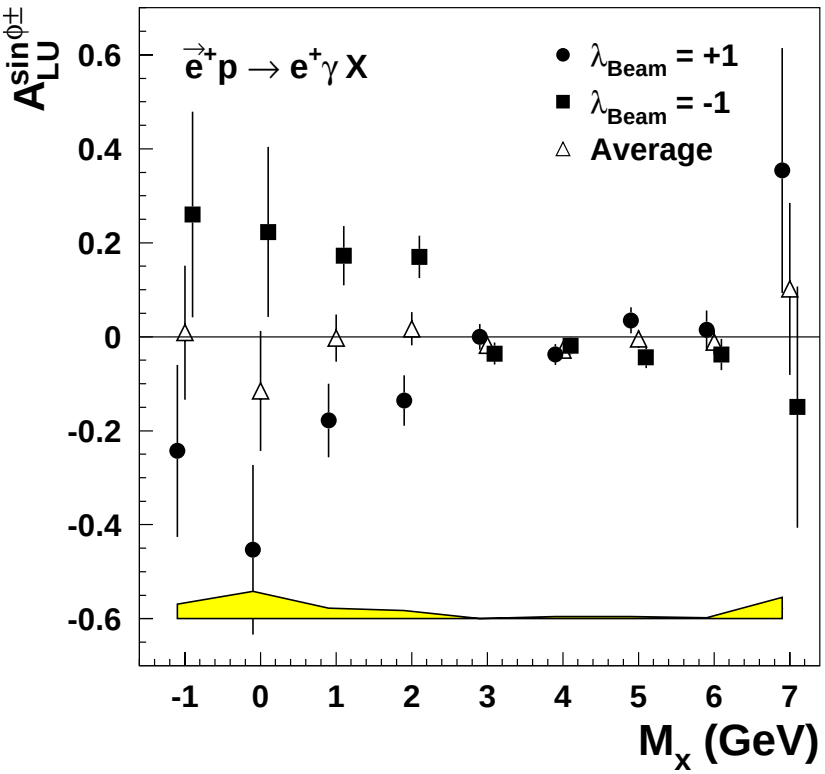
- Leading order interference term:

$$(\tau^*_{\rm BH}\tau_{\rm DVCS} + \tau^*_{\rm DVCS}\tau_{\rm BH})_{pol} = \frac{4\sqrt{2}\,me^6}{tQx}\cdot\frac{1}{\sqrt{1-x}}$$

$$\times e_l \times P_l\left[-\sin\phi\cdot\sqrt{\frac{1+\epsilon}{\epsilon}}\mathrm{Im}\tilde{M}^{1,1}\right]$$

- Extract $\sin(\phi)$-moment, $A_{LU}^{\sin\phi^\pm} = \frac{2}{N^\pm}\sum_{i=1}^{N^\pm}\frac{\sin\phi_i}{|P_l|_i}$:

Data show expected helicity dependence!



DVCS: formalism

- Beam-charge asymmetry with unpolarised leptons:

$$d\sigma(e^+p) \quad - \quad d\sigma(e^-p) \sim \cos\phi_\gamma \times$$
$$\mathrm{Re}\left\{ F_1\mathcal{H}_1 + \frac{x_B}{2-x_B}(F_1+F_2)\widetilde{\mathcal{H}}_1 - \frac{\Delta^2}{4M^2}F_2\mathcal{E}_1 \right\}$$

- Beam-spin asymmetry with polarised positrons:

$$d\sigma(\overrightarrow{e^+}p) \quad - \quad d\sigma(\overleftarrow{e^+}p) \sim \sin\phi_\gamma \times$$
$$\mathrm{Im}\left\{ F_1\mathcal{H}_1 + \frac{x_B}{2-x_B}(F_1+F_2)\widetilde{\mathcal{H}}_1 - \frac{\Delta^2}{4M^2}F_2\mathcal{E}_1 \right\}$$

- Relate DVCS amplitudes $\mathcal{H}_1, \widetilde{\mathcal{H}}_1$,.. to GPDs:

$$\mathrm{Im}\,\mathcal{H}_1 = -\pi\sum_q e_q^2(H(\xi,\xi,\Delta^2) - H(-\xi,\xi,\Delta^2))$$

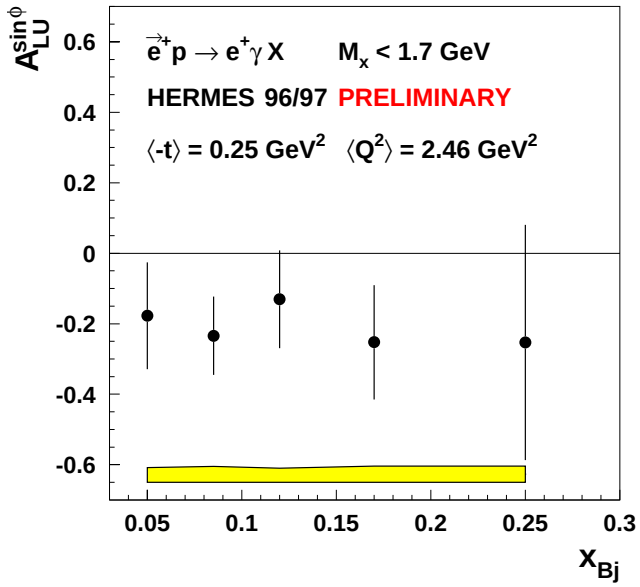
$$\mathrm{Im}\,\widetilde{\mathcal{H}}_1 = -\pi\sum_q e_q^2(\widetilde{H}(\xi,\xi,\Delta^2) + \widetilde{H}(-\xi,\xi,\Delta^2))$$

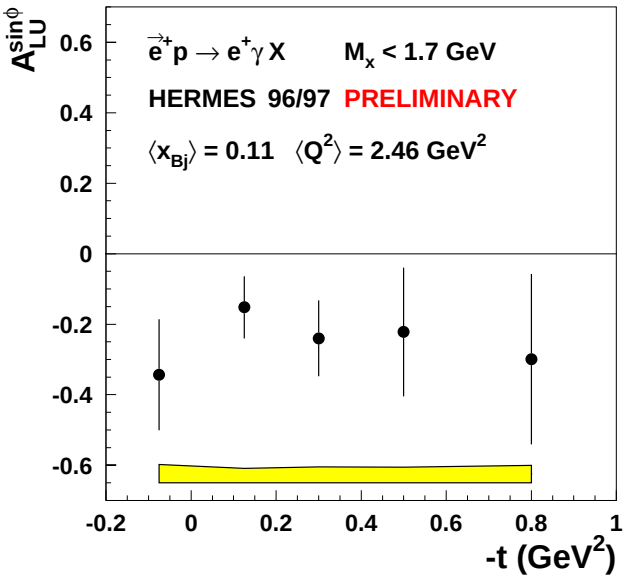
$$\mathrm{Re}\,\mathcal{H}_1 = \sum_q e_q^2[P\int_{-1}^{+1} H(x,\xi,\Delta^2)\,(\frac{1}{x-\xi}+\frac{1}{x+\xi})dx\,]$$

$$\mathrm{Re}\,\widetilde{\mathcal{H}}_1 = \sum_q e_q^2[P\int_{-1}^{+1} \widetilde{H}(x,\xi,\Delta^2)\,(\frac{1}{x-\xi}-\frac{1}{x+\xi})dx\,]$$

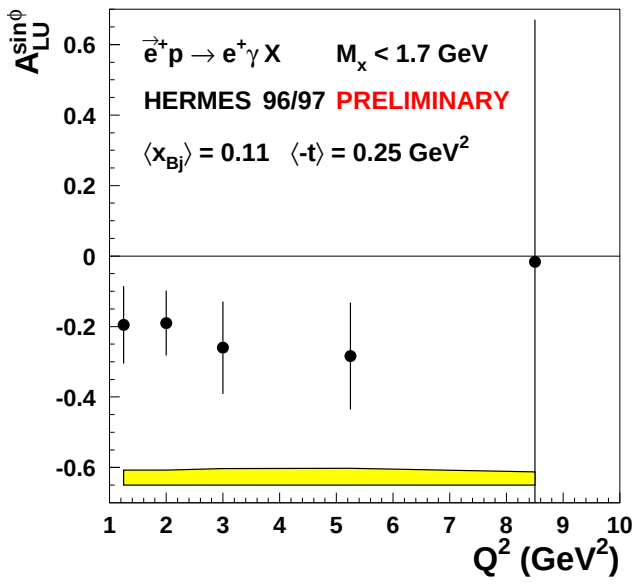
New DVCS results

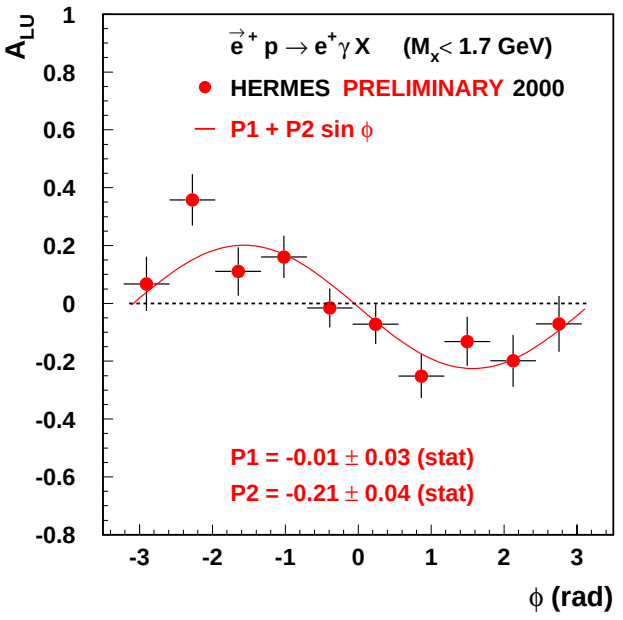
- Dependence of $A_{LU}^{\sin\phi}$ on x and $-t$:





- Q^2-dependence and new 2000 data for $A_{LU}^{\sin\phi}$:

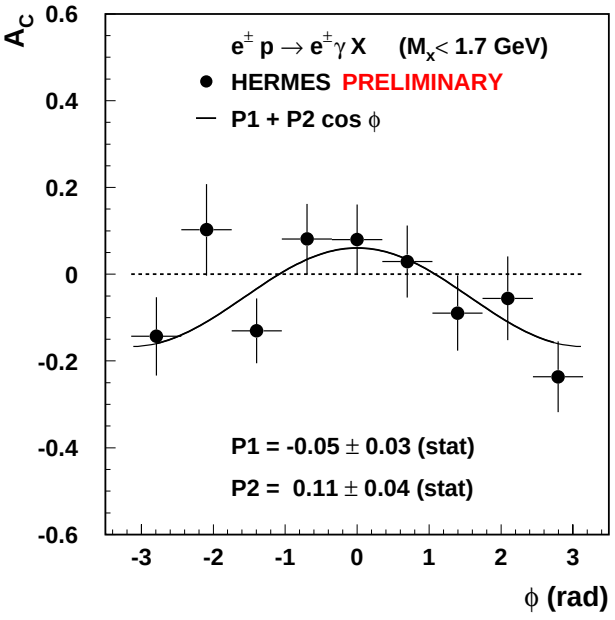


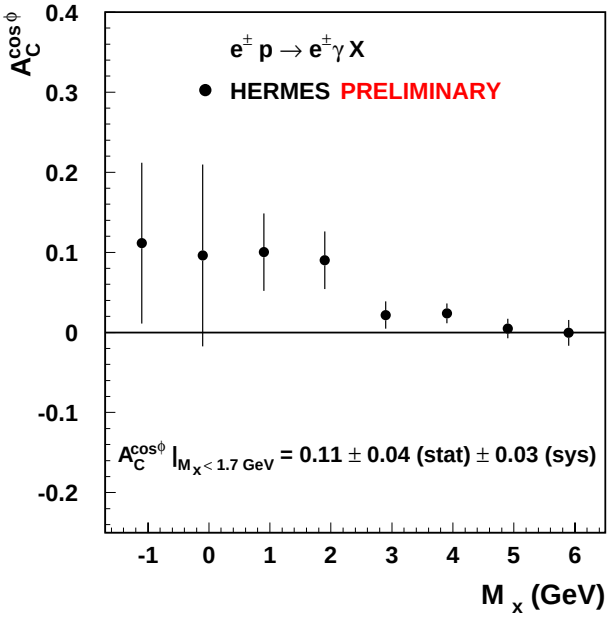


No Q^2-dependence: hard scattering regime!

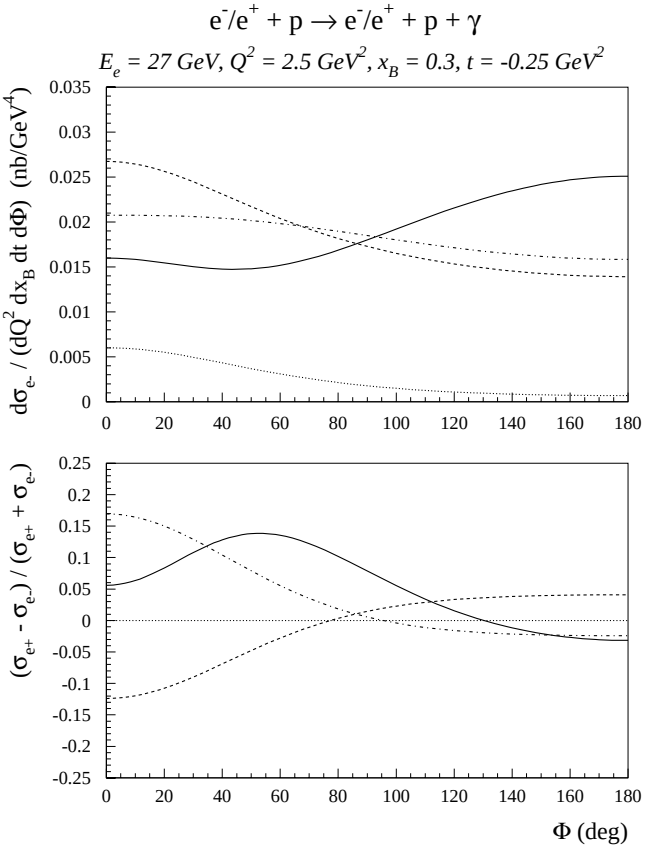
DVCS: beam-charge asymmetry

- First data for $A_C = \frac{N^{e^+} - N^{e^-}}{N^{e^+} + N^{e^-}}$ on ^{1}H:





- Calculation by Kivel et al. [hep-ph/0012136]:



BH + twist 2 + D-term

BH + tw 2 + tw 3 + D-term

BH only

BH + twist 2 - D-term

The Λ spin structure - 1

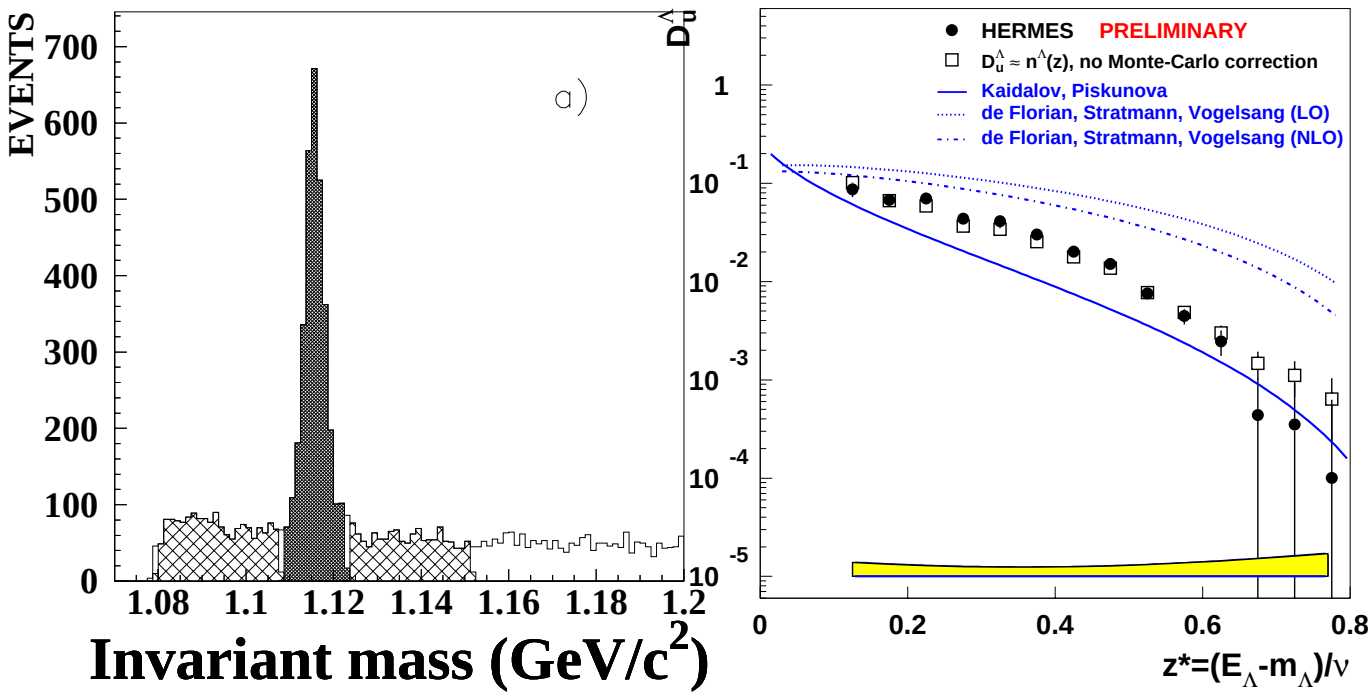
- Two schemes for the Λ spin content:
  - Quark parton model: Δs = 1.00
  - SU(3) flavour symm.: Δs = 0.6, $\Delta u = \Delta d$ = -0.2
- Measure the Λ polarization from $\Lambda \to p\pi^-$:

$$\frac{1}{N}\frac{dN}{d\Omega} = \frac{1}{4\pi}\left(1 + 0.64\,\vec{P}_\Lambda \cdot \hat{p}\right)$$

- Determine $u \to \Lambda$ spin transfer $D^\Lambda_{LL'}$:

$$D^\Lambda_{LL'} = \frac{\vec{P}_\Lambda \cdot \hat{L}'}{P_B D(y)} = \frac{\sum_f e_f^2\, q_f^N(x)\, \Delta D_f^\Lambda(z)}{\sum_f e_f^2\, q_f^N(x)\, D_f^\Lambda(z)} \approx \frac{\Delta D_u^\Lambda(z)}{D_u^\Lambda(z)}$$

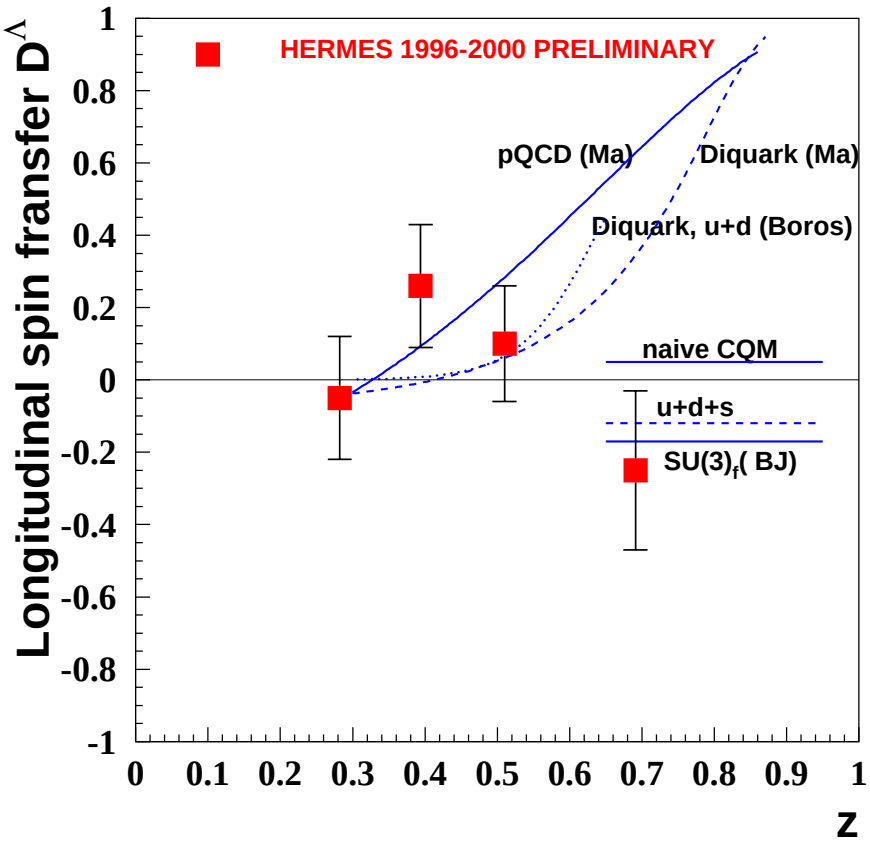
- Electroproduction of Λ hyperons at HERMES:



The Λ spin structure - 2

- Data for $u \to \Lambda$ spin transfer:

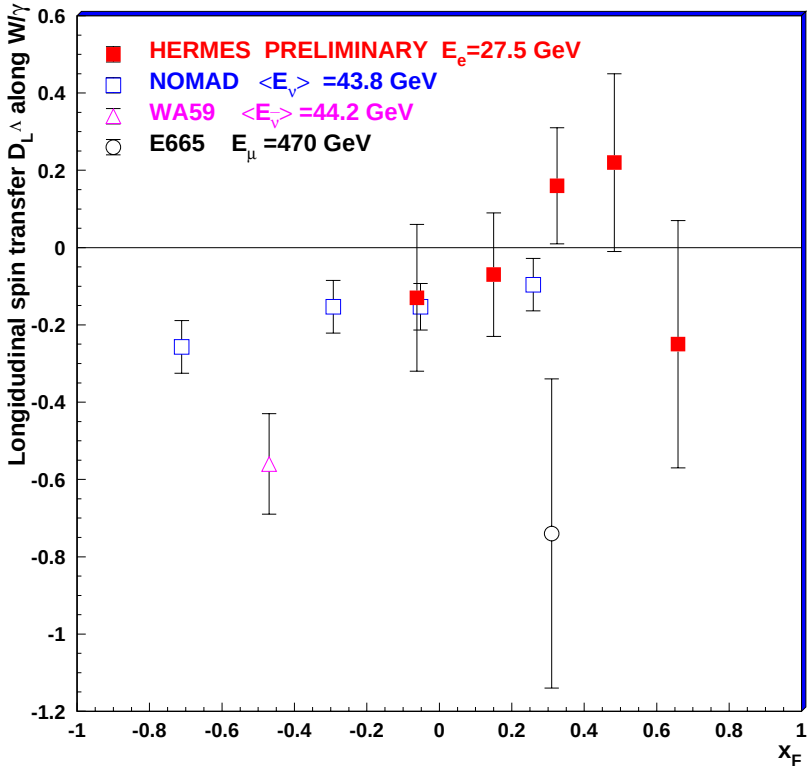
$< D^{\Lambda}_{LL'} >$ = 0.04(9) consistent with $\Delta u^{\Lambda} \approx 0$ (CQM prediction).



- Negative polarisation for x_F $(= \frac{2p_L}{W})$ < 0:

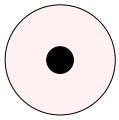
NOMAD Collab.
NPB 588 (2000) 3

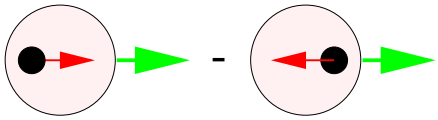
Contributions from:
$\Sigma^* \to \Lambda\pi$
$\Sigma^0 \to \Lambda\gamma$
$\Xi^0 \to \Lambda\pi^0$

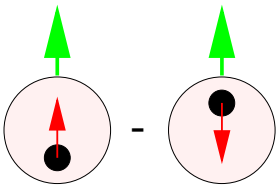


Transverse polarization

- Three leading order distribution functions:

f_1 =  momentum carried by quarks

g_1 =  longitudinal quark spin, $\Delta\Sigma$

h_1 =  transverse quark spin, $\delta\Sigma$

- Importance of $h_1(x)$ measurements:
  - HERMES data: $\Delta\Sigma = 0.30 \pm 0.04 \pm 0.09$
  - $\Delta\Sigma$ is so small because of axial anomaly:
    - Redistribution of angular momentum in nucleon:

$$\tfrac{1}{2}\Delta\Sigma \approx +0.15, \quad \Delta G \approx +1.0, \quad L_z \approx -0.65$$

    - Redistribution is less in transverse case:

$$\Delta\Sigma \; < \; \delta\Sigma \; < \; 1 \quad \text{(Quark Parton Model)}$$

    - Lattice QCD calculation (Phys. Rev. D 56 (1997) 433):

$$\Delta\Sigma = 0.18(10) \quad \text{and} \quad \delta\Sigma = 0.56(9)$$

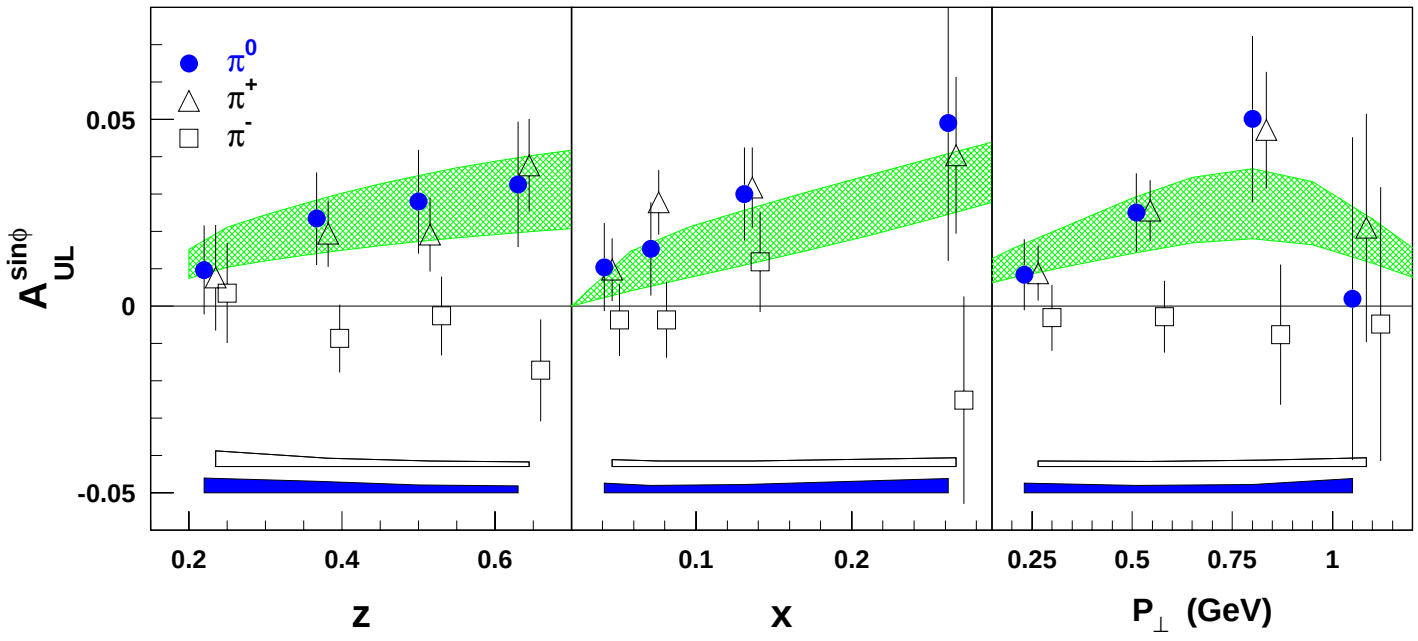
Measurements of $h_1(x)$

- The structure function $h_1(x)$ is chirally odd :
  - Not accessible in inclusive DIS
  - Use semi-inclusive DIS with chirally-odd $H_1^{\perp(1)u}(z)$
  - Assume u-quark dominance
  - Asymmetry for Collins process:

$$A_T^{\pi^+}(x,y,z) = P_T \cdot D_{nn} \cdot \frac{\delta u(x)}{u(x)} \cdot \frac{\mathrm{H}_1^{\perp(1)u}(z)}{\mathrm{D}_1^u(z)},$$

  - $\mathrm{H}_1^{\perp(1)u}$ depends on $\phi_c = \phi_h + \phi_s - \pi$

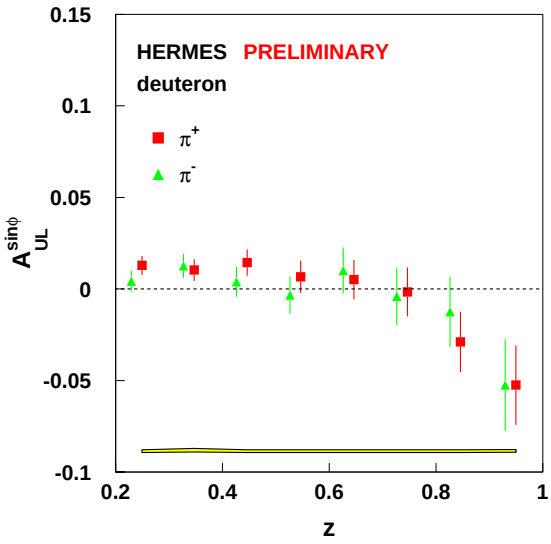
- Evidence for transversity from HERMES ^{1}H data:

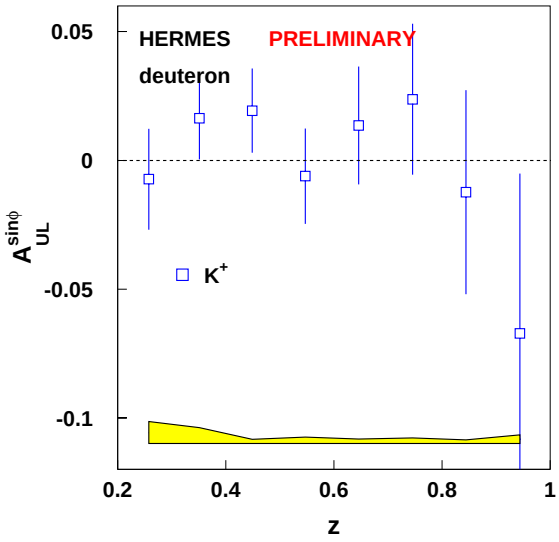


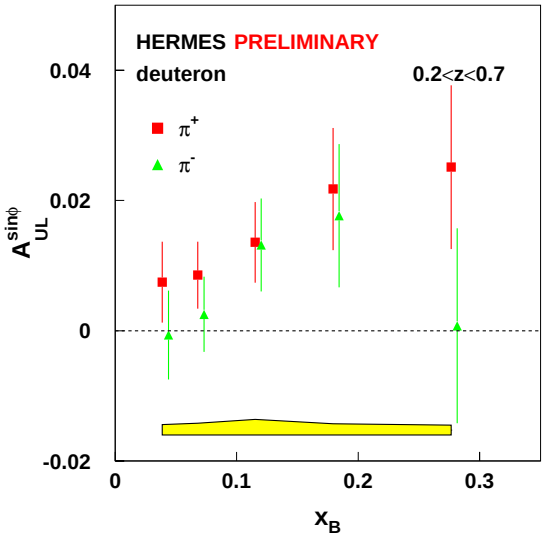
[HERMES, PRL 84 (2000) 4047 and PRD 64 (2001) 097101]

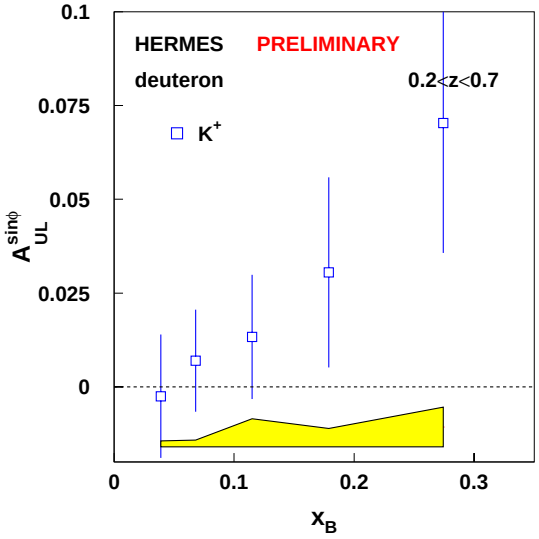
Single-Spin Asymmetries on ^{2}H

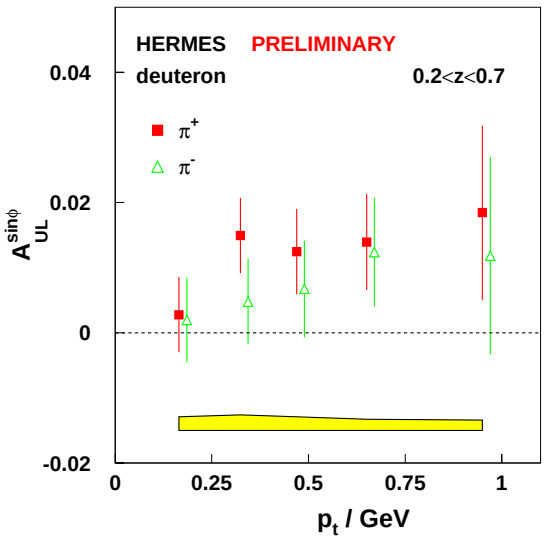
- z, x, $p_\perp$-dependences of $A_{UL}^{\sin\phi}$ for $\pi^{+/-}$ and K^+:

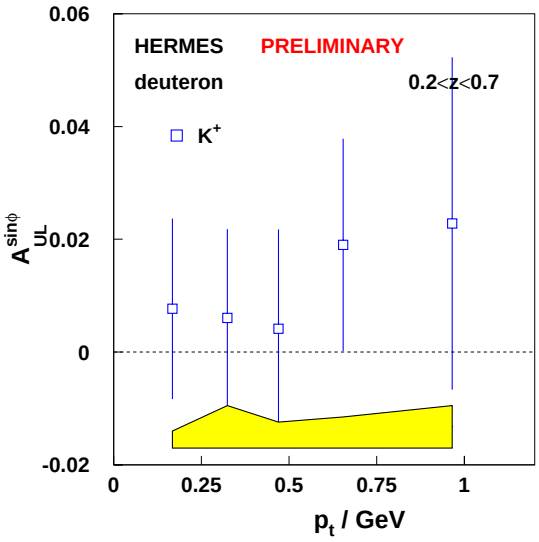








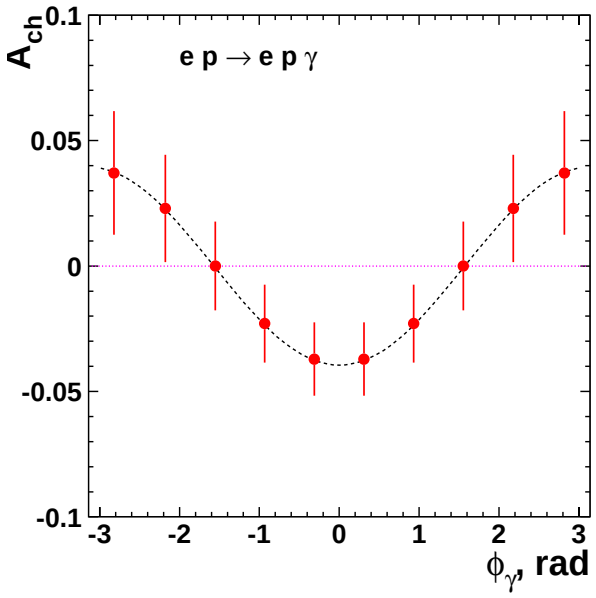


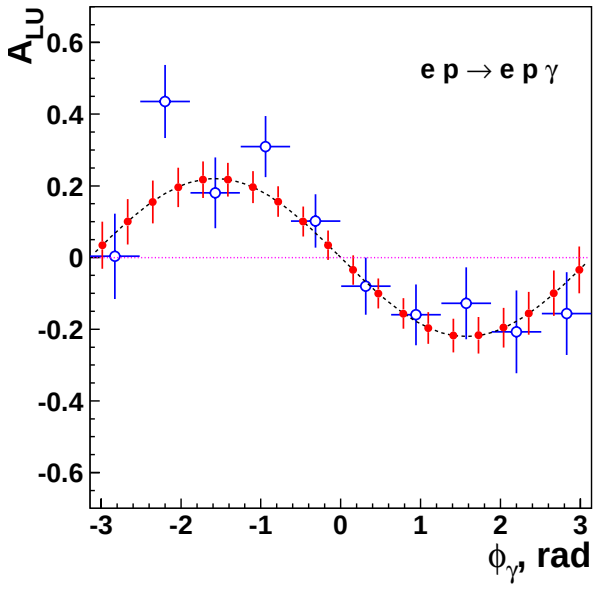


Future: HERMES

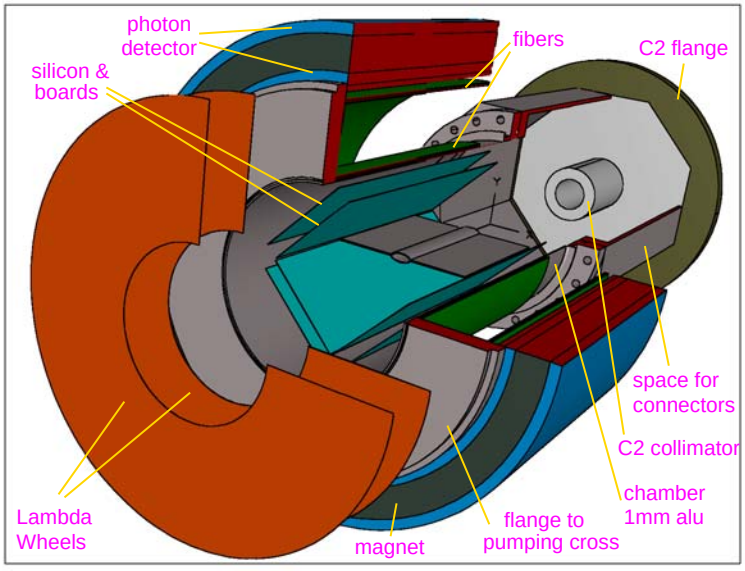
- HERMES - Run II: 2001 – 2006
  - Transverse spin 2001 - 2003
  - Longitudinal spin 2003 - 2004
  - Excl. react. w. Recoil Detector : 2004 - 2006
  - Unpolarized end-of-fill runs 2001 - 2006

Simulated DVCS data with Recoil Detector (1 yr run):



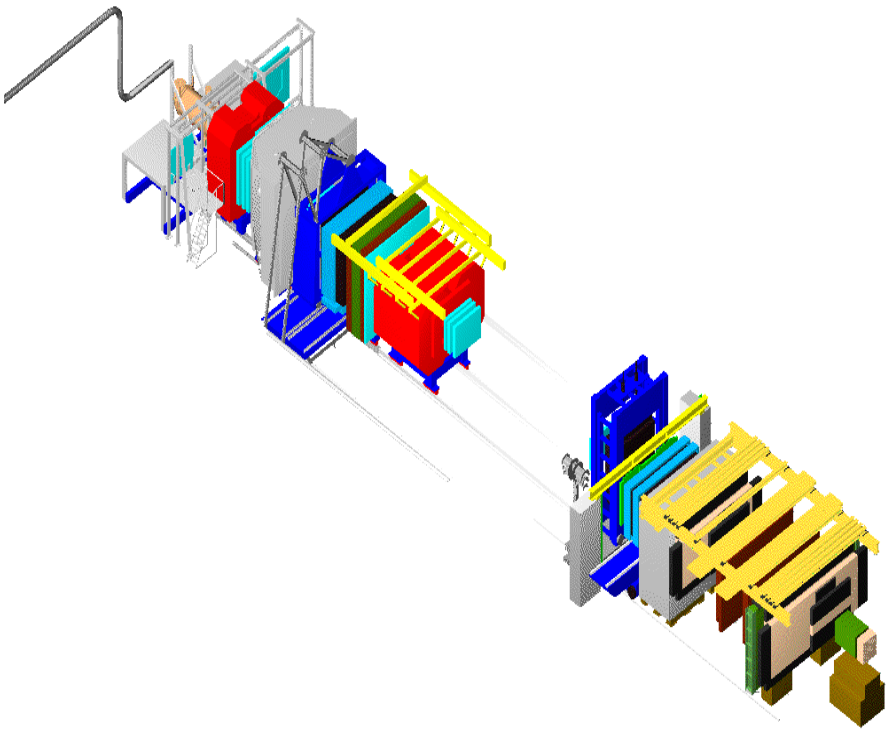


- HERMES - Run III (beyond 2006 ?)



Future: COMPASS

- The Compass experiment at CERN:

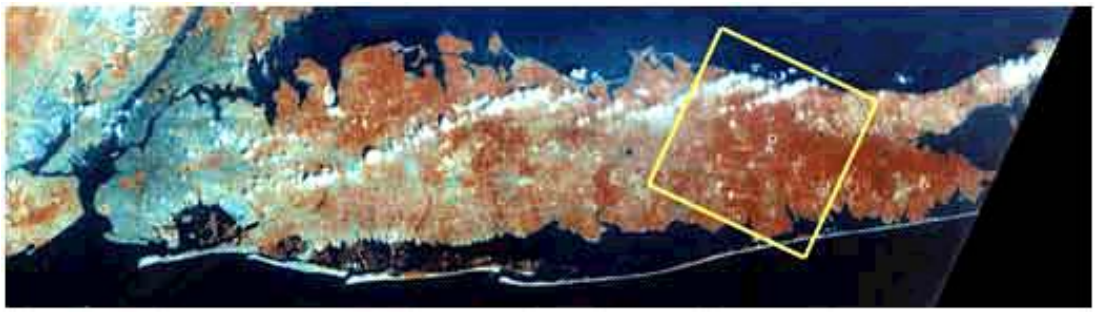


- Successful commissioning in 2001:
  - Most detectors commissioned at 2 10^8 μ/s.
  - Tracking: half of the channels
  - ^{6}LiD target hosted in SMC magnet: $P = \pm 45\%$
  - 2 weeks smooth data taking

- Prospects for 2002:
  - Complete tracking and finish commissioning
  - First measurement of $\Delta G/G$ in 3 month run
  - Other objectives: $\delta q(x)$, $h_1(x)$, ΔD^{Λ}, spectroscopy

Future: RHIC

- RHIC at BNL as seen by LANDSAT:



- Experimental break-through at RHIC:

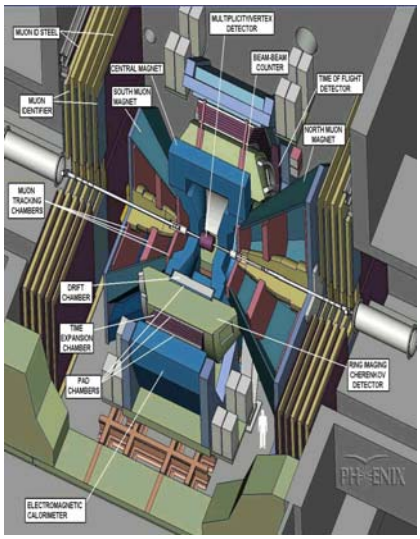
  Colliding polarized protons at $\sqrt{s}$ = 200 GeV

  - P_{proton} = 70% at injection and 25 % at 100 GeV
  - Luminosity: 1.5 10^{30} cm^{-2}s^{-1}
  - Physics: transverse spin asymmetries A_N

- Longitudinal polarization: spin rotators in 2002

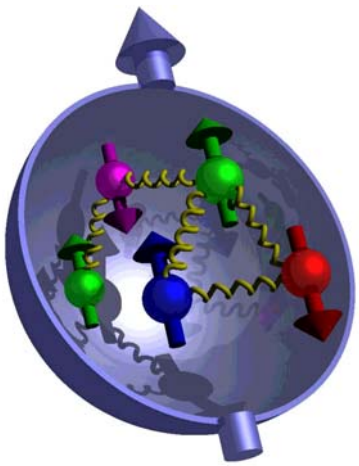
  - Measure $\Delta G/G$ from jets, $c\bar{c}$, ...
  - Measure Δq_f from W^+ production

- The PHENIX experiment:



Outlook

- End-station A at SLAC:
  - E160: single spin-asymm. for inelastic J/Ψ
  - E161: open charm photoproduction $\rightarrow \Delta G/G$
- What to expect in coming years?
  - Polarized quark distributions
  - Polarized gluon distribution



- The big challenges in spin physics:
  - The role of orbital angular momentum:

    Analysis and interpretation of DVCS $\rightarrow J_q$?

  - The role of transverse spin:

    Measure the (x, Q^2)-dependence of $h_1(x)$

- The more distant future ($>$ 2010):
  - Electron-Ion Collider at BNL: 10 $\otimes$ 250 GeV^2
  - TESLA-N at DESY: 250 GeV e^+ on fixed target