HERMES
Present Status and Outlook

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Trieste
18.02.02

- The **HERMES** experiment

- Spin-structure of the Nucleon

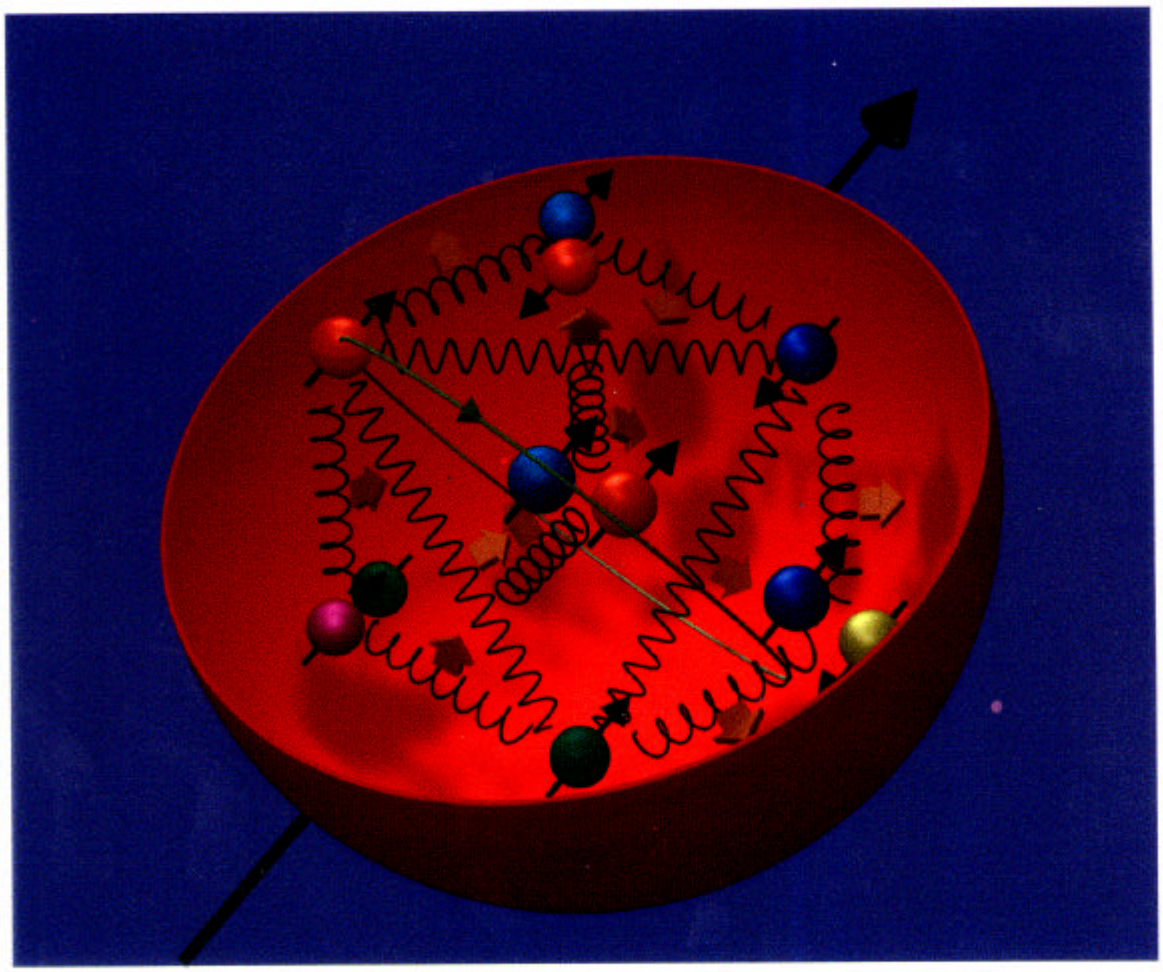
  * Polarised structurefunctions $g_1^{p,d}(x,Q^2)$, $\Delta\Sigma$
  * Hadron asymmetries, $\Delta q_f(x)$
  * Pairs of high-p_t hadrons, ΔG
  * Orbital angular momentum contributions of quarks L_z^q $\Leftrightarrow$ GPDs
    Deeply Virtual Compton-Scatt. DVCS
    Exclusive meson production,
    Single-Spin-Asymmetries SSA
  * The Structurefunction h_1 – ‚*Transversity*‘
    Semi-inclusive SSA

- Spin-structure of the Λ-hyperon

- Further **HERMES** results (esp. nuclear targets)

- Programme until 2006

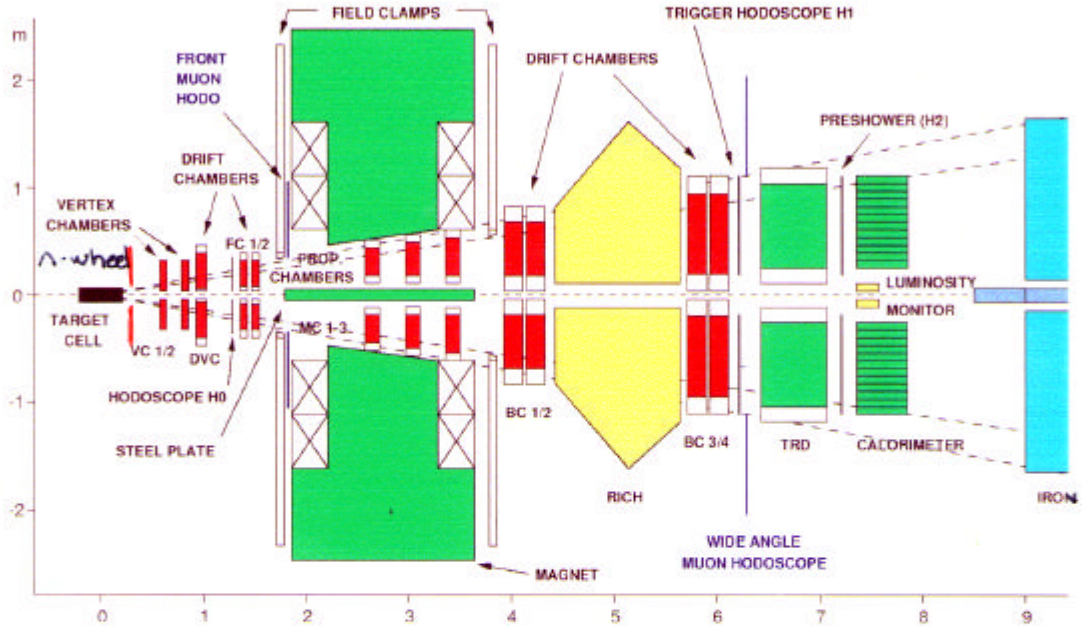
Nucleon Spin Structure



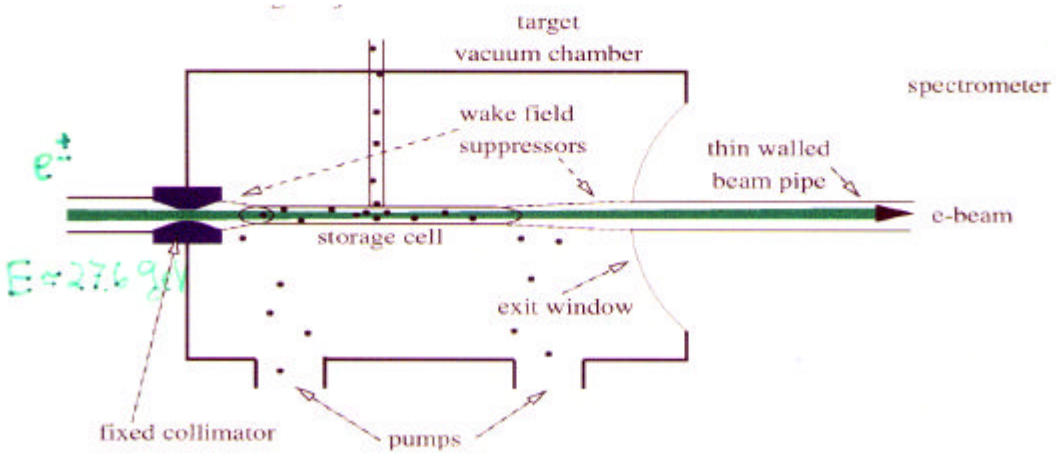
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_z^q + \Delta G + L_z^g$$

The HERMES experiment

- The HERMES spectrometer at DESY:



- Internal Target:



- Targets used: $^{1}\overrightarrow{\mathrm{H}}$, $^{2}\overrightarrow{\mathrm{H}}$, $^{3}\overrightarrow{\mathrm{He}}$, $^{4}\mathrm{He}$, $^{14}\mathrm{N}$, $^{20}\mathrm{Ne}$, $^{84}\mathrm{Kr}$

Detector

- Several upgrades since 1995
  (RICH, muon hodoscopes, Forward Quadrupole Spectrometer, Λ-wheels, DAQ)

- Extended target (40 cm) ⇒ require detectors in front region

- High target polarisation (~88%), no dilution

- RICH: π, K, p separation in full acceptance

- Tracking
  - * 57 tracking planes
  - * $\delta p/p = (0.7 - 1.3)\%$, $\delta\theta < 0.6$ mrad

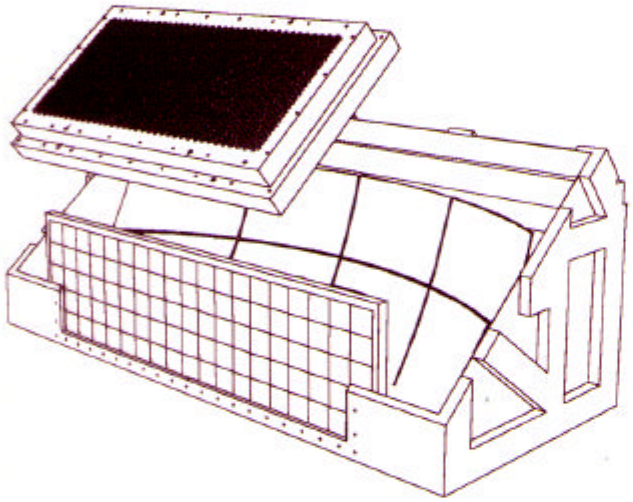
- Calorimeter
  - * $\sigma(E)/E \cong (5.1 \pm 1.1)/\mathrm{sqrt}(E)$ %

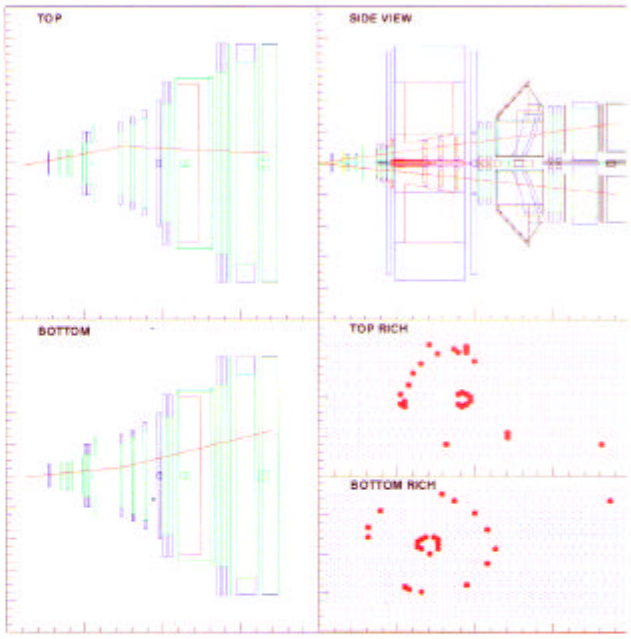
- Luminosity
  - * $L \cong 4*10^{31}$ N/(cm^{2}s) (polarised)
    But no dilution!!!
  - * $L \cong 4*10^{33}$ N/(cm^{2}s) (unpolarised D_2)

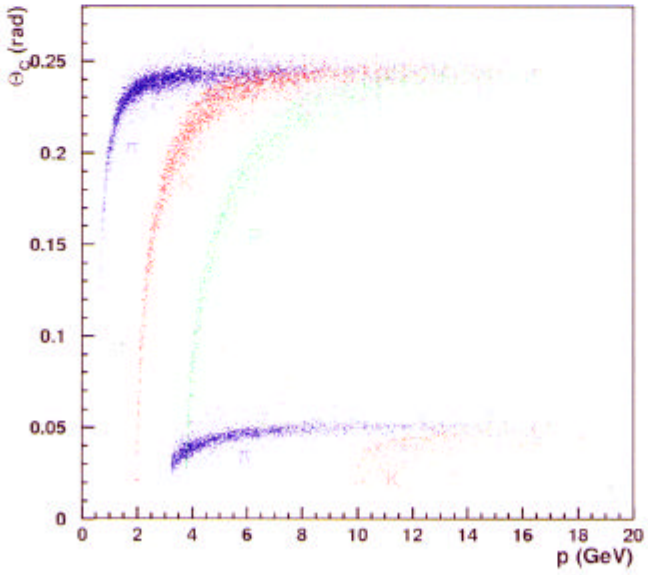
RICH

The RICH, at HERMES, has a double radiator : Aereogel (n=1.03) and C_4F_{10} gas (n=1.0014). Čerenkov photons are detected by two matrix of $\sim$ 4000 PMTs.

Detection efficiencies : 85% (π), 93%(K), 73%(p)

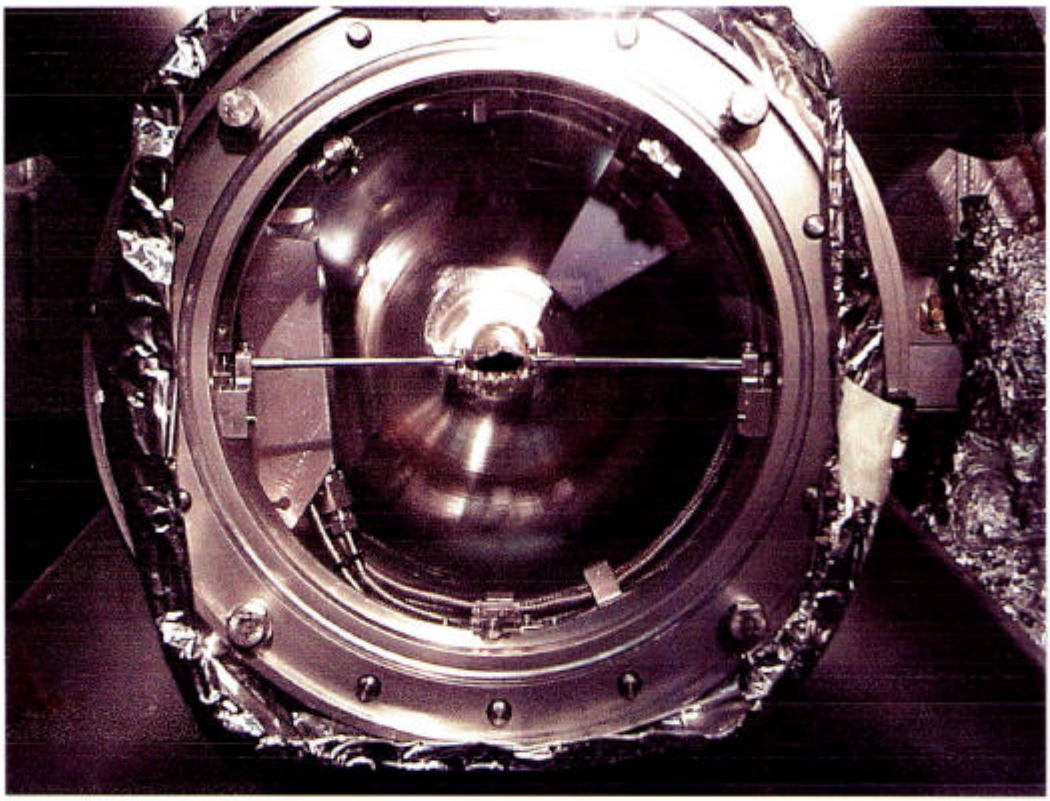




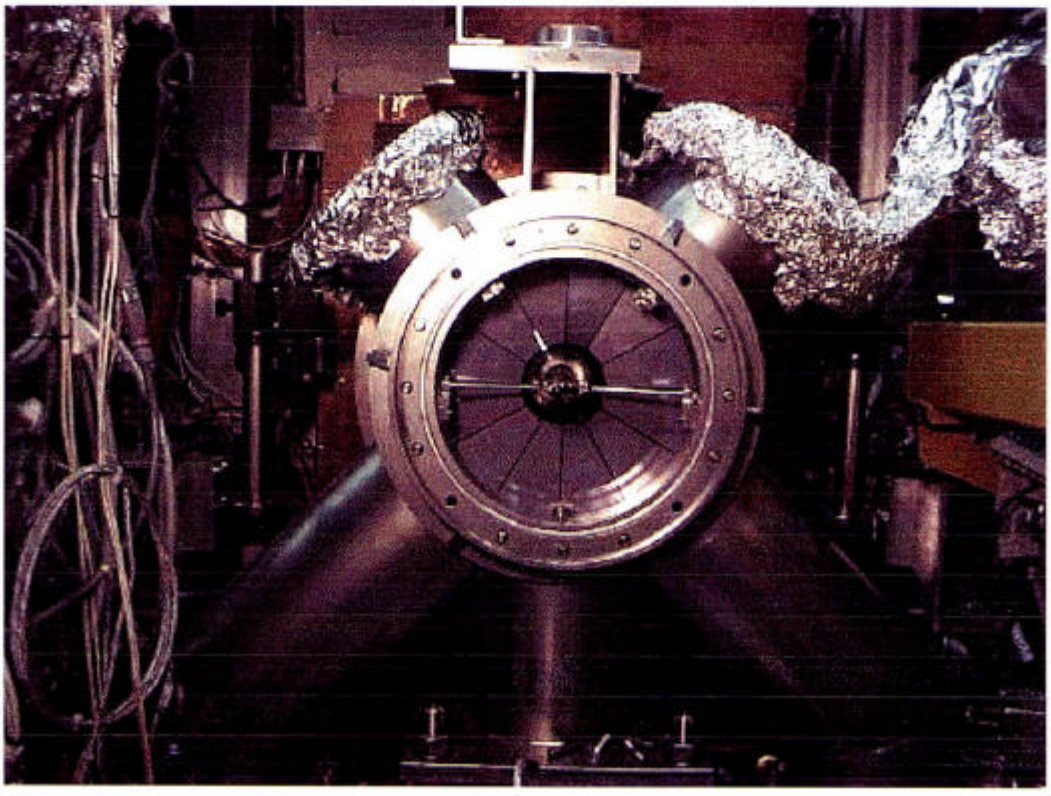


physics/0104033

Lambda Pie in 2000

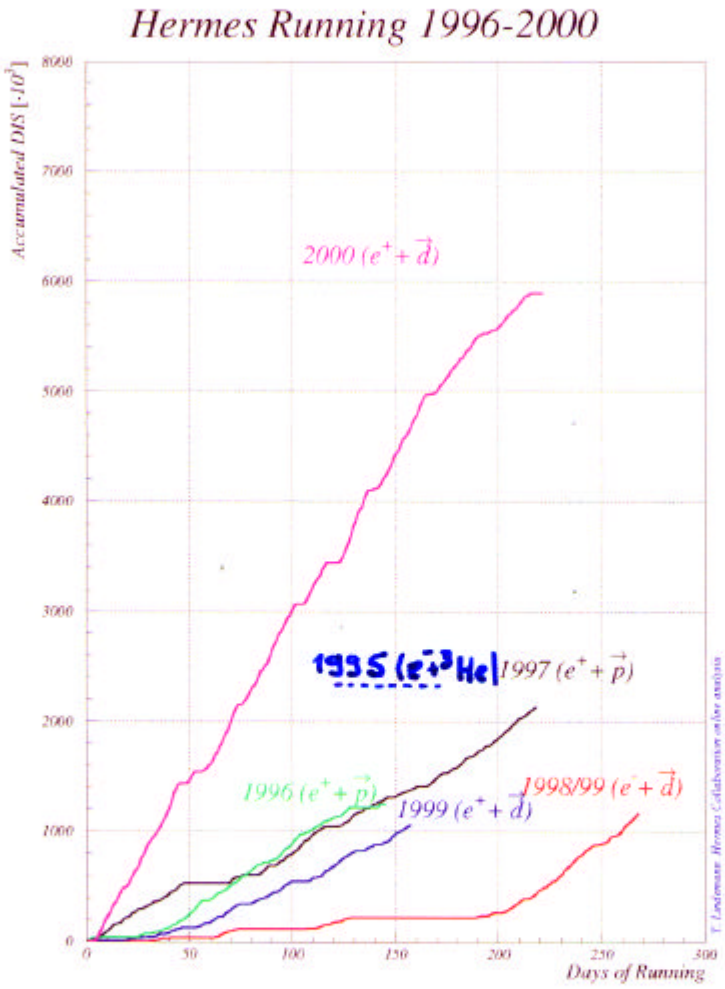


Lambda Wheel in 2002



Data collected in Run I

- Accumulated polarized DIS events per year:



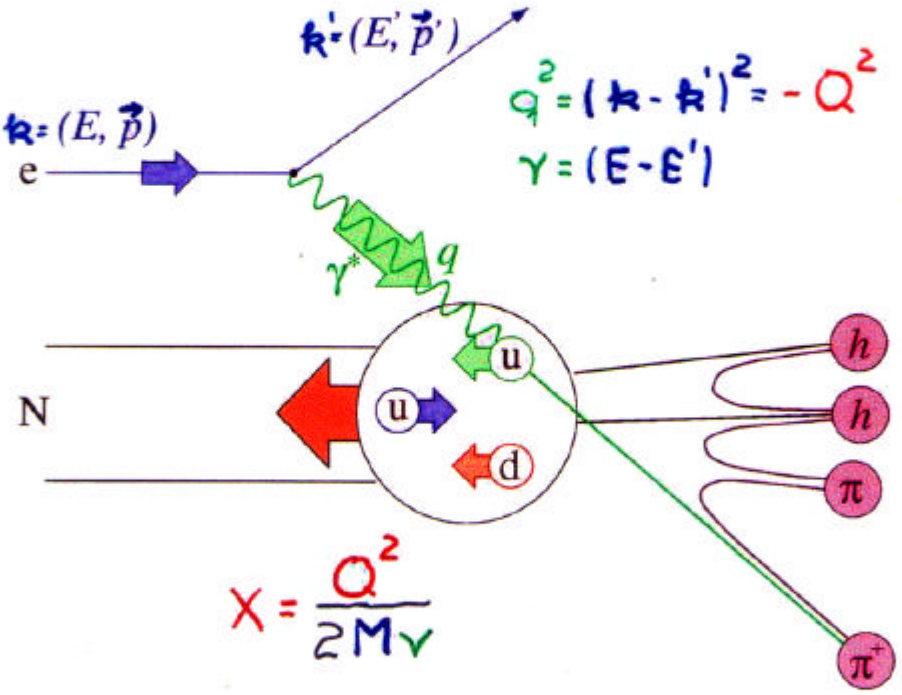
- Data taking in 2000:
  - cell size reduced to 21 X 8.9 mm^2
  - lower cell temperature: 96 → 62 K

Luminosity increased by factor 2.5 !!

Polarised Semi-Inclusive DIS

In semi-inclusive DIS a hadron h is detected in coincidence with the scattered lepton

- Inclusive: $e + N \rightarrow e' \qquad + X$
- Semi-inclusive: $e + N \rightarrow e' + h + X$

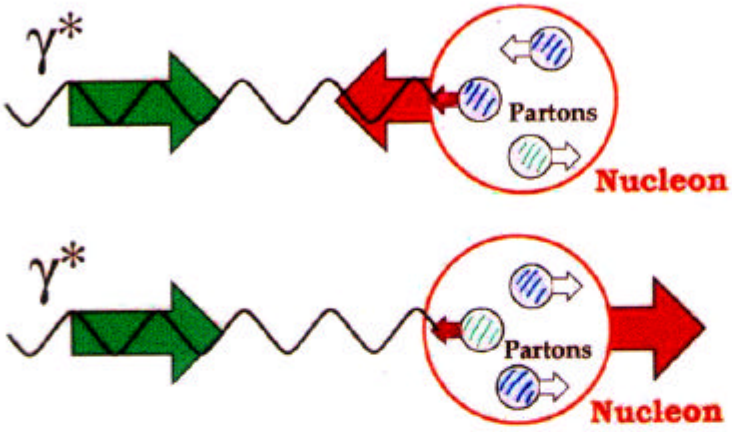


- Select hadrons from the current fragmentation region by cuts on

$$z = E_h/\nu \geq 0.2$$
$$X_F = 2p_{||}/W \geq 0.1$$

Virtual Photon Asymmetry

QPM: Polarised Photon (Spin 1) can only probe quarks with spin opposite to its own:



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

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

Flipping of target or beam polarisation
$\Rightarrow$ Quark Spin Distributions $\Delta q_f(x)$:

$$\Delta q_f(x) \equiv q^+_f(x) - q^-_f(x)$$
$$q_f(x) \equiv q^+_f(x) + q^-_f(x)$$

$$\Delta q_f = \int_0^1 dx\, \Delta q_f(x)$$

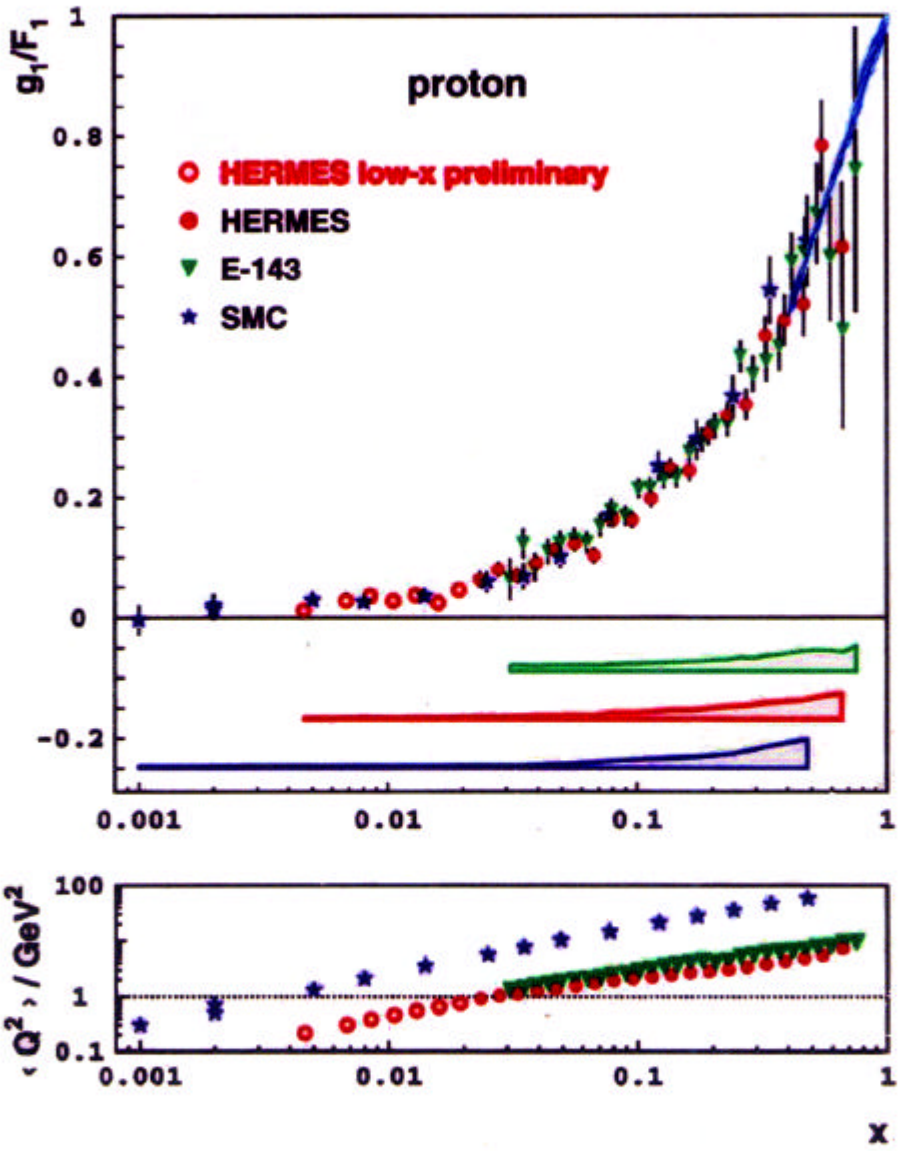
with $f = u, d, s, \bar{u}, \bar{d}, s$

A_1 relates to the nucleon structure functions:

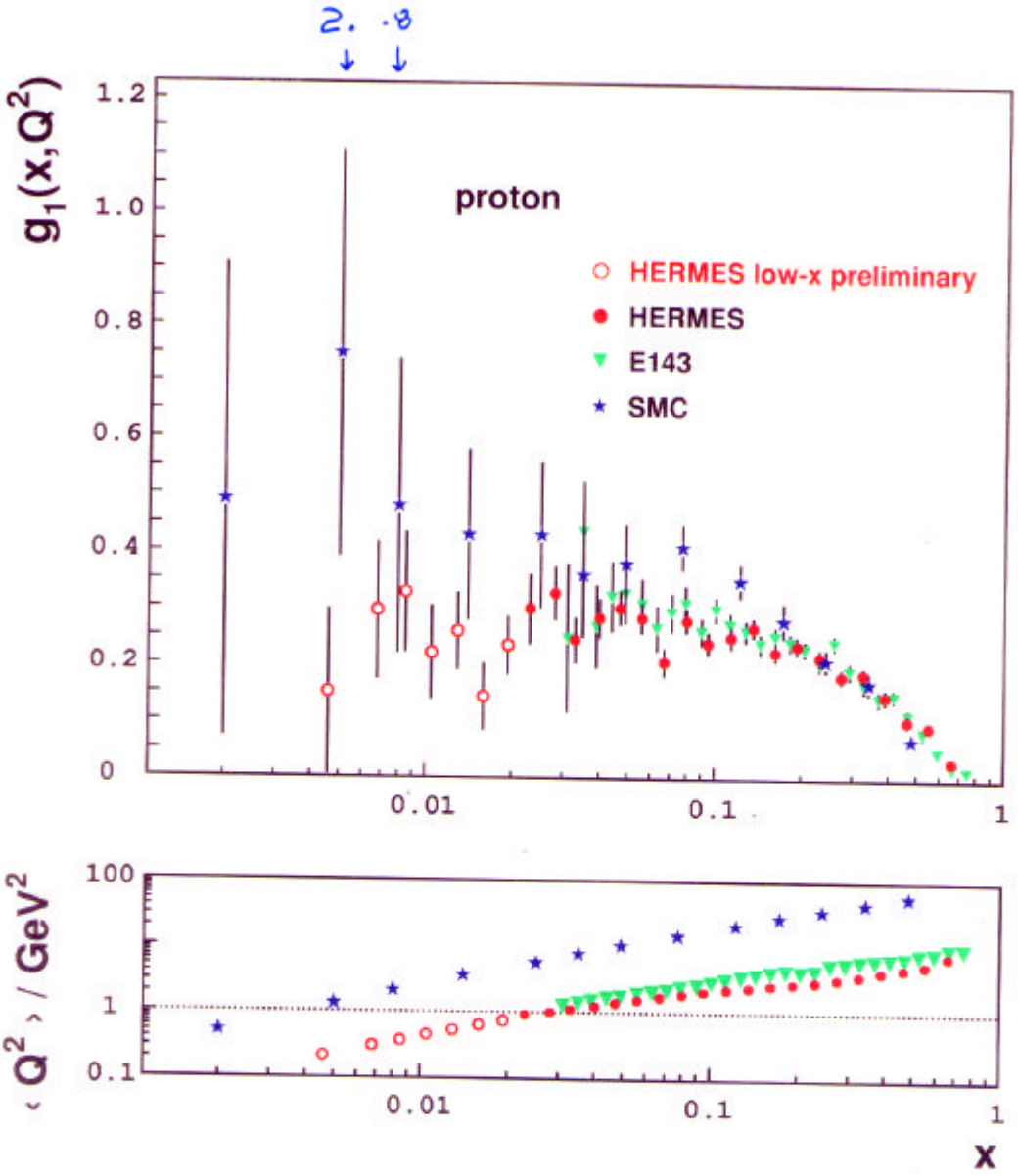
$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1} = \frac{\sum_f e_f^2\, \Delta q_f(x)}{\sum_f e_f^2\, q_f(x)}$$

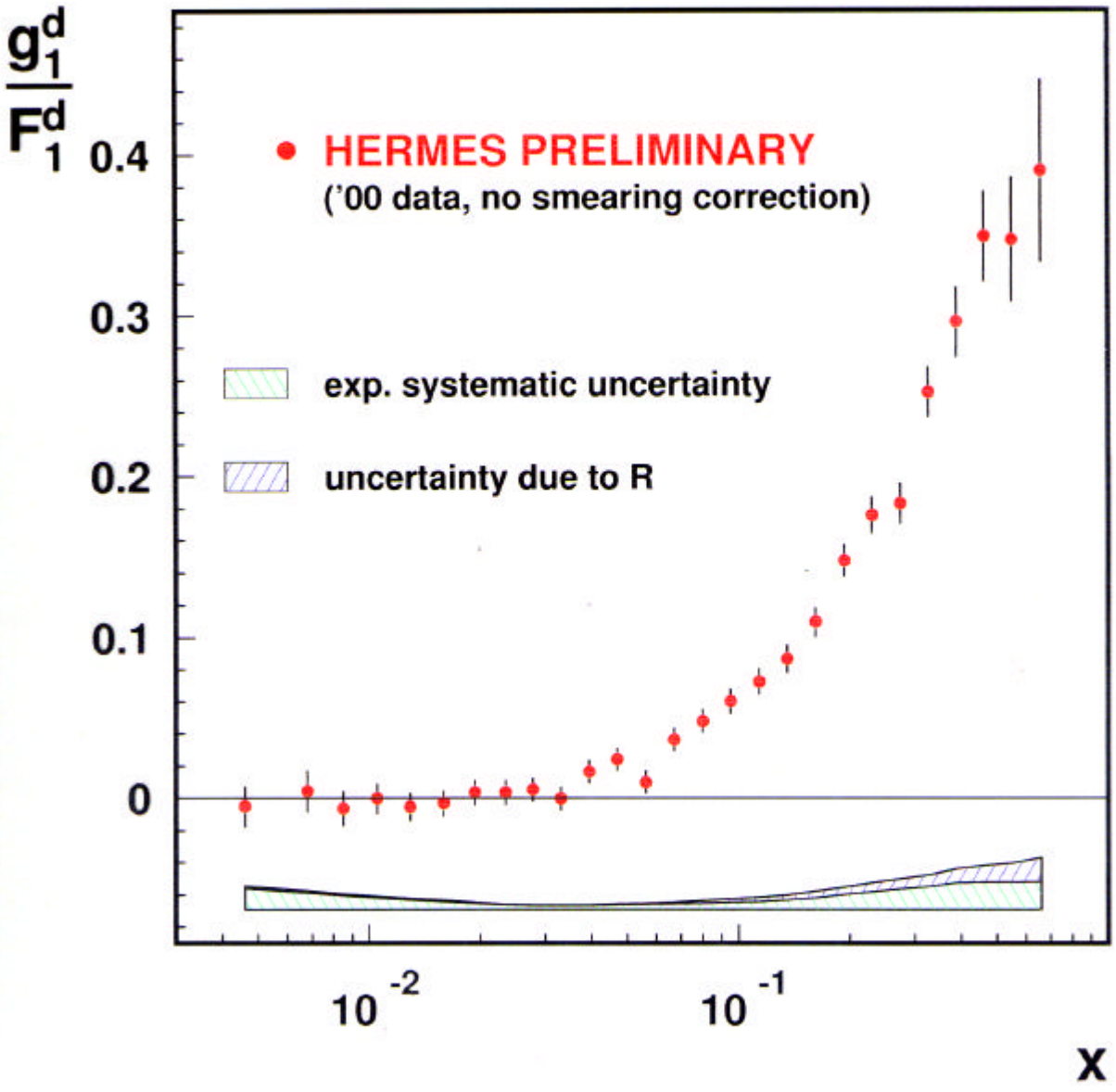
$$g_1(x) = \frac{1}{2} \sum_f e_f^2 \Delta q_f(x)$$

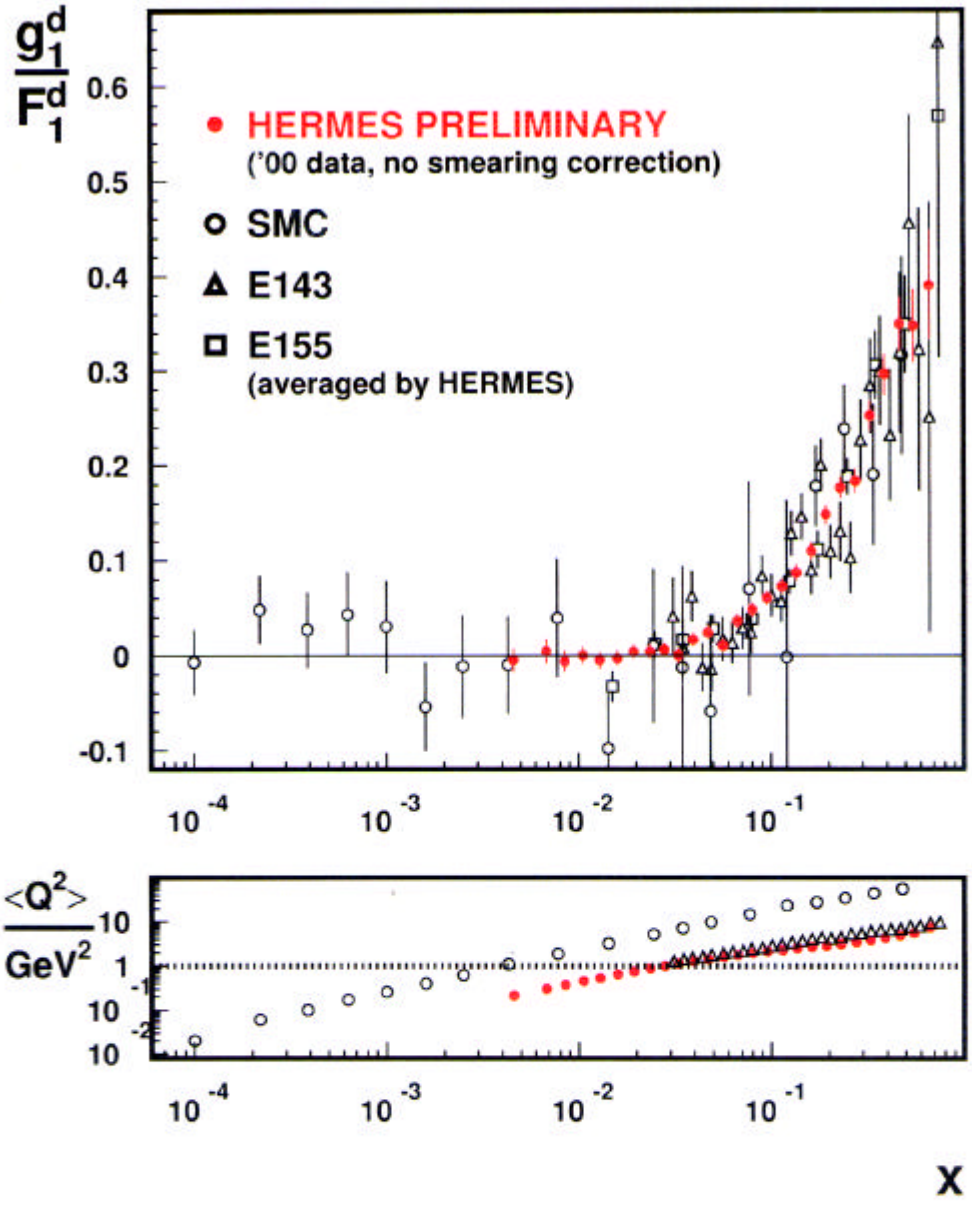
Proton Asymmetry g_1^p/F_1^p

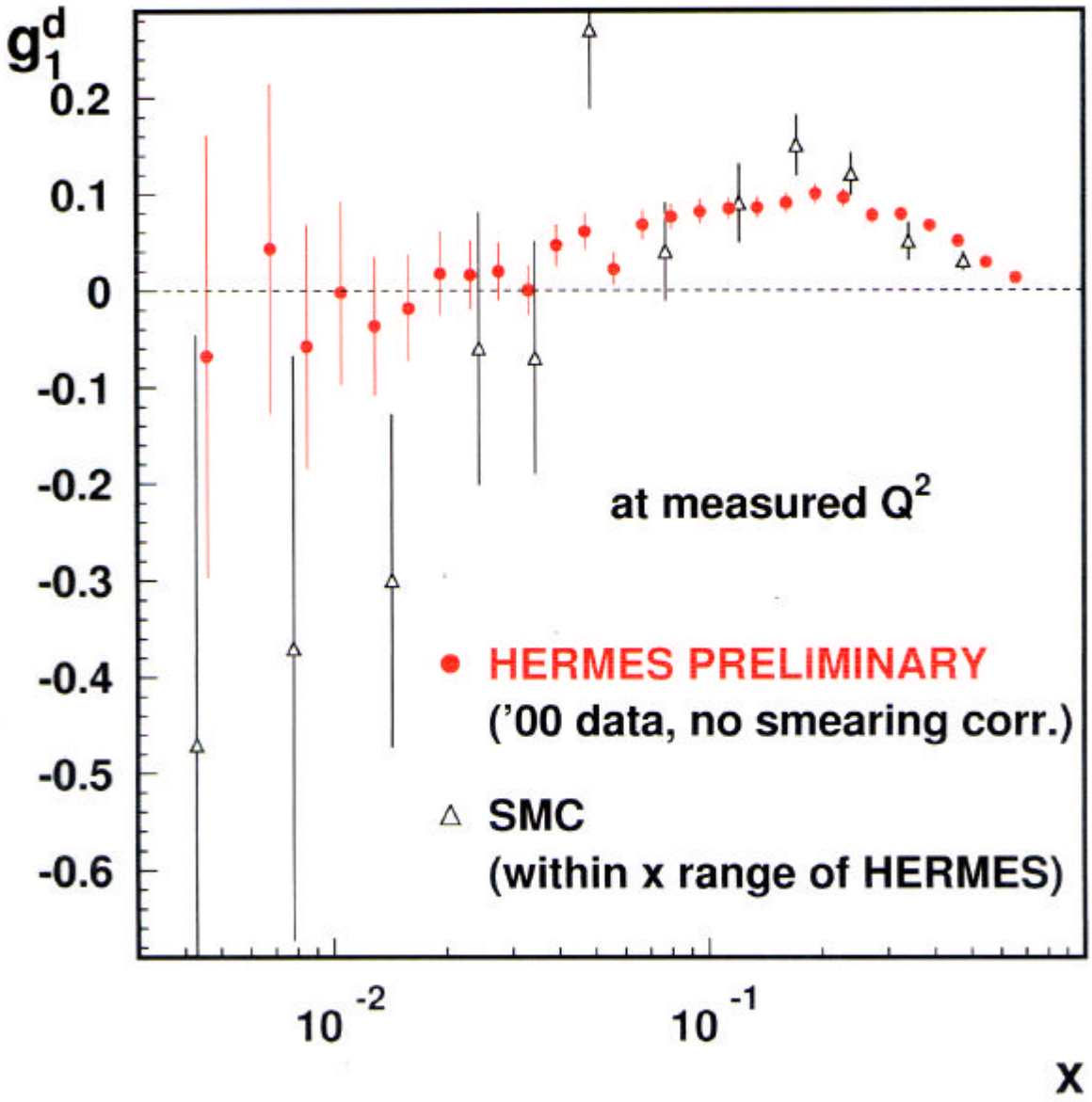


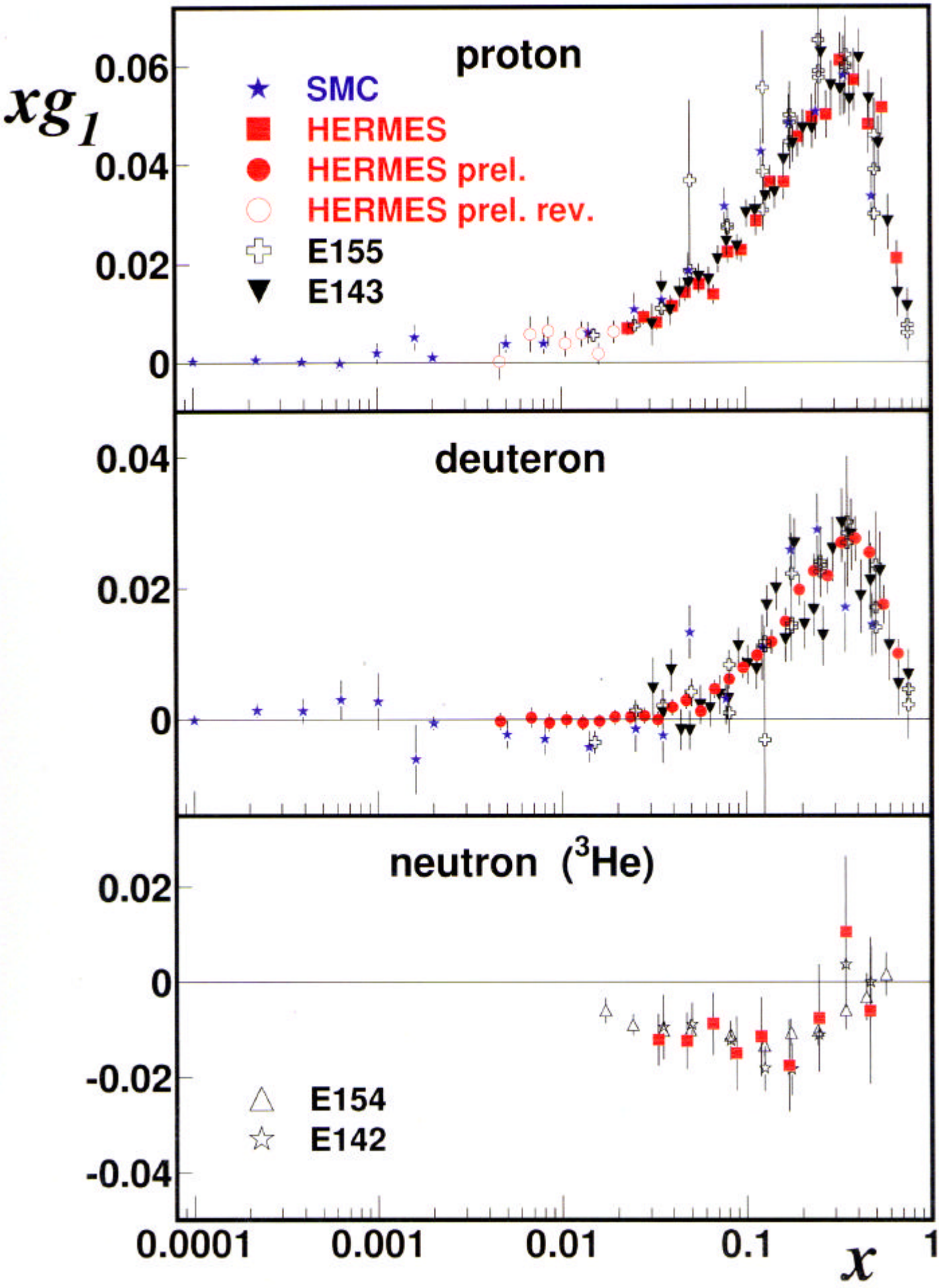
- g_1^p/F_1^p very well known down to $x \approx 10^{-3}$
- Perfect agreement between all experiments
- g_1^p/F_1^p independent of Q^2 within errors


2. ·8
$g_1(x,Q^2)$
1.2
1.0
0.8
0.6
0.4
0.2
0
proton
HERMES low-x preliminary
HERMES
E143
SMC
0.01
0.1
1
$\langle Q^2 \rangle$ / GeV^2
100
1
0.1
0.01
0.1
1
X

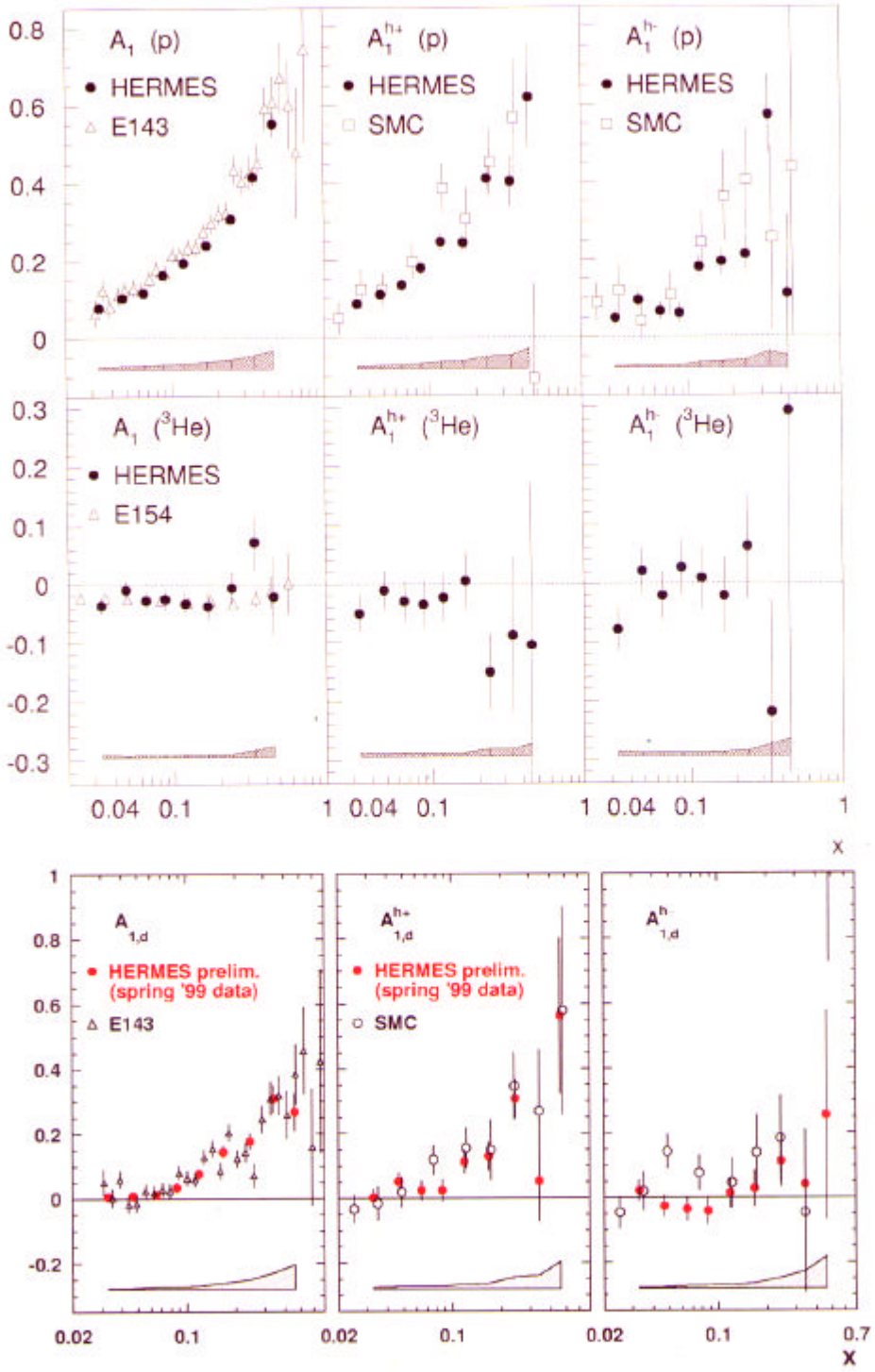

g_1^d / F_1^d
0.4
0.3
0.2
0.1
0
HERMES PRELIMINARY
('00 data, no smearing correction)
exp. systematic uncertainty
uncertainty due to R
10^{-2}
10^{-1}
x


g_1^d / F_1^d
HERMES PRELIMINARY
('00 data, no smearing correction)
SMC
E143
E155
(averaged by HERMES)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\langle Q^2 \rangle$ / GeV^2
10
1
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x


g_1^d
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
at measured Q^2
HERMES PRELIMINARY
('00 data, no smearing corr.)
SMC
(within x range of HERMES)
10^{-2}
10^{-1}
x

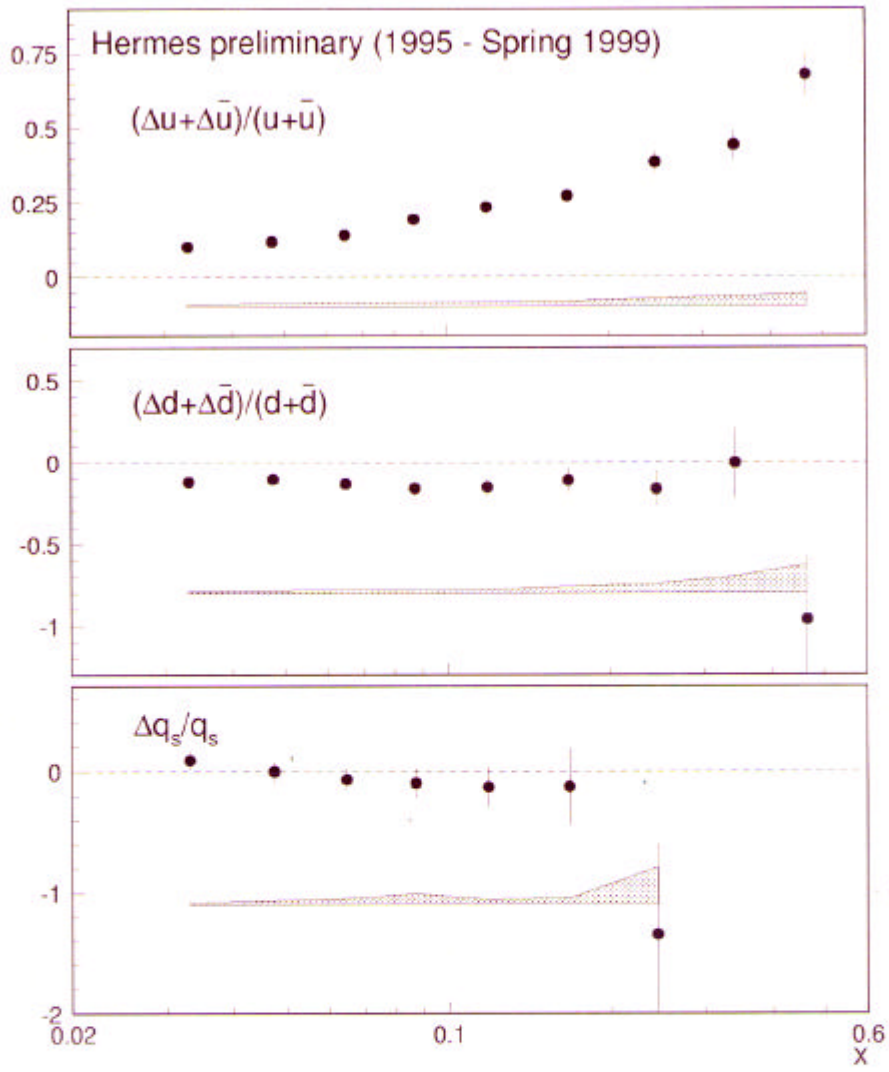

proton
SMC
HERMES
HERMES prel.
HERMES prel. rev.
E155
E143
deuteron
neutron (^{3}He)
E154
E142
xg_1
x
0.06
0.04
0.02
0
-0.02
-0.04
0.0001
0.001
0.01
0.1
1

Semi inclusive Asymmetries



Inclusive and semi inclusive asymmetries on $^3\vec{\mathrm{He}}$, $\vec{\mathrm{H}}$ and $\vec{\mathrm{D}}$ targets. Data shown at mean measured Q^2 in each bin.

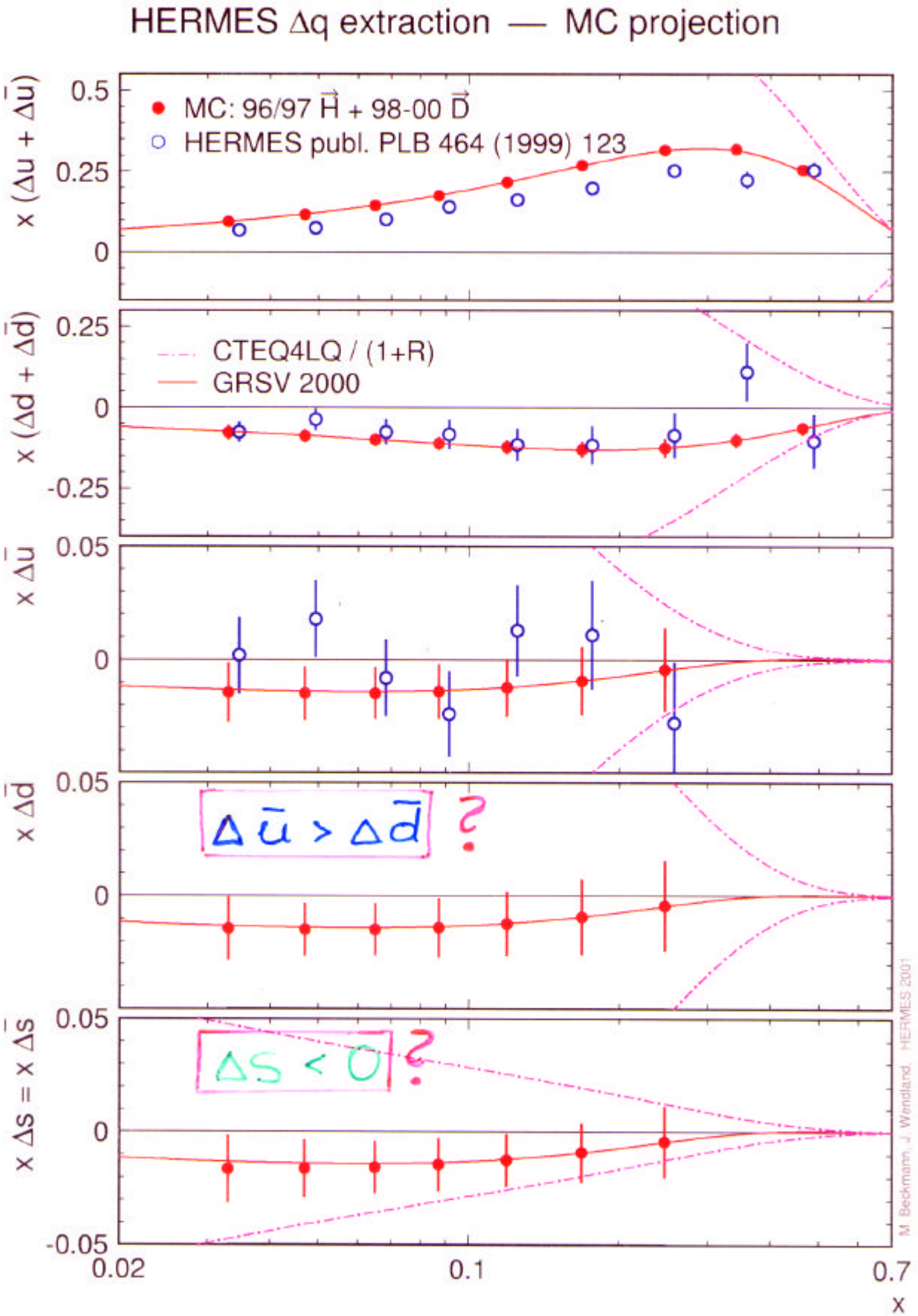
Extracted Quark Polarisations



Flavour decomposition of quark polarisations as a function of x at measured Q^2.
Assume: Symmetric sea polarisation:

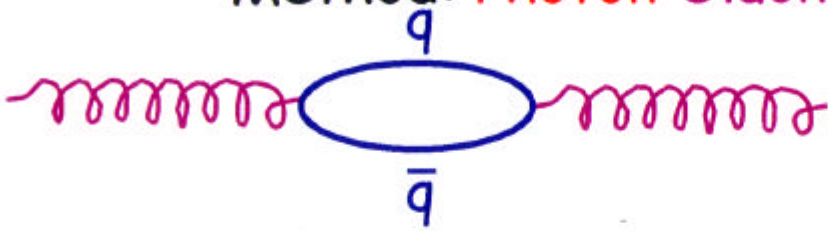
$$\frac{\Delta q_s(x)}{q_s(x)} \equiv \frac{\Delta u_s(x)}{u_s(x)} = \ldots = \frac{\Delta \bar{s}(x)}{\bar{s}(x)}$$

Result: $\Delta\Sigma \approx 0.3$ Rest: ΔG, $q, \bar{q}$, s


HERMES Δq extraction — MC projection
MC: 96/97 H + 98-00 D
HERMES publ. PLB 464 (1999) 123
CTEQ4LQ / (1+R)
GRSV 2000
x (Δu + Δū)
x (Δd + Δd̄)
x Δū
x Δd̄
x Δs = x Δs̄
Δū > Δd̄ ?
Δs < 0 ?
0.5
0.25
0
-0.25
0.05
-0.05
0.02
0.1
0.7
x
M. Beckmann, J. Wendland, HERMES 2001

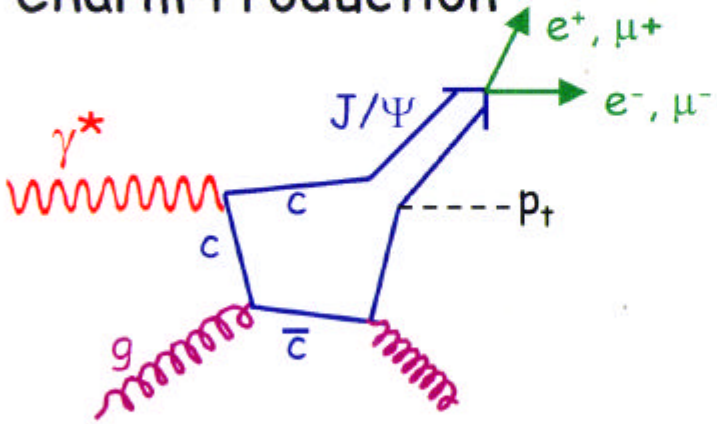
Gluon-Polarisation $\Delta G/G$

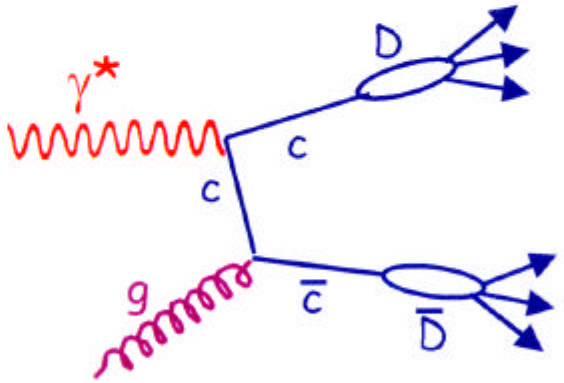
Method: Photon-Gluon-Fusion



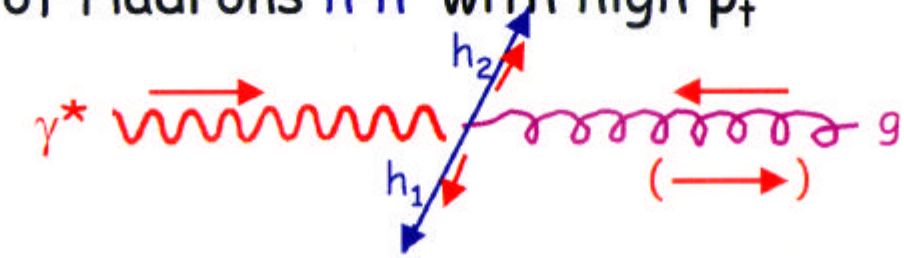
$\Delta t \sim \hbar/2m_q$

- Charm-Production





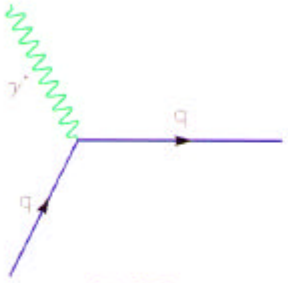
- Pairs of Hadrons h^+h^- with high p_t



$\Delta G/G$

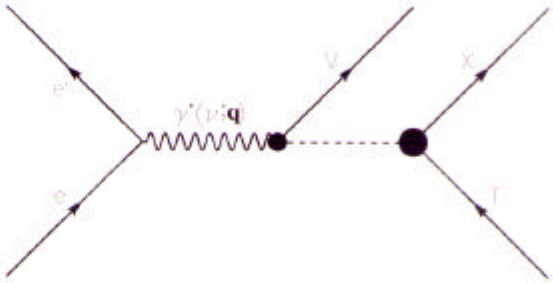
Contributions to $\vec{\gamma}\vec{p} \to h^+h^-X$

Assume four different processes may contribute:



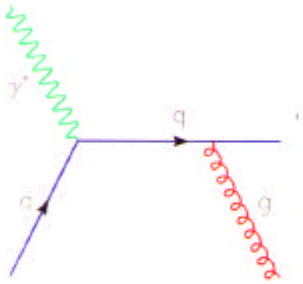
DIS

negligible contribution



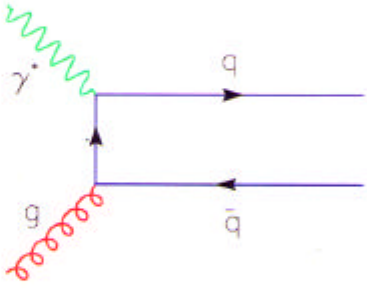
VMD

assume $A_{\mathrm{VMD}} = 0$



QCDC

$A_{\mathrm{QCDC}} \sim 0.5\,\frac{\Delta q}{q}$

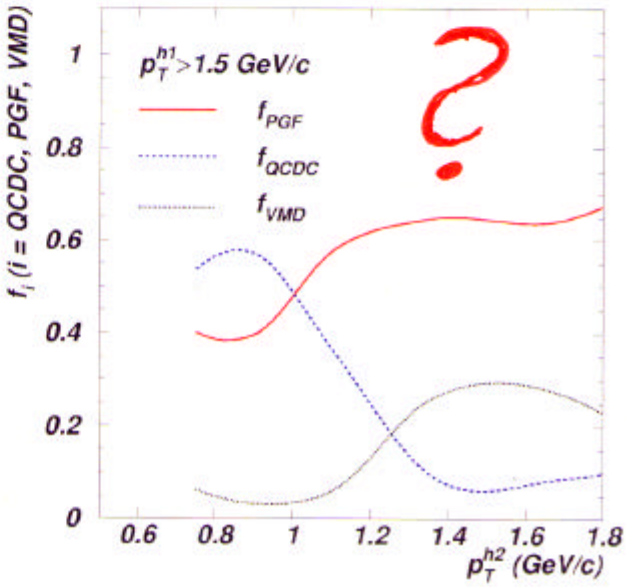


PGF

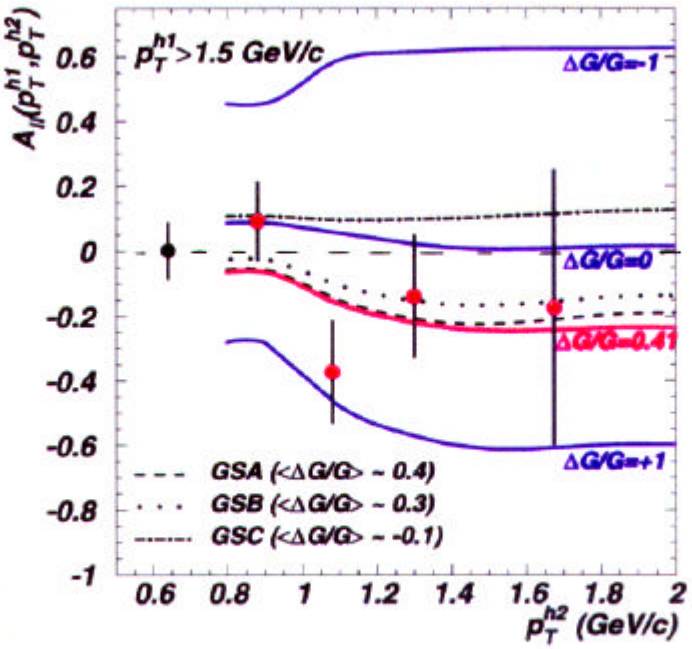
$A_{\mathrm{PGF}} \sim -\frac{\Delta G}{G}$

... estimate their relative contributions using PYTHIA

$\rightarrow$ extract $\Delta G/G$

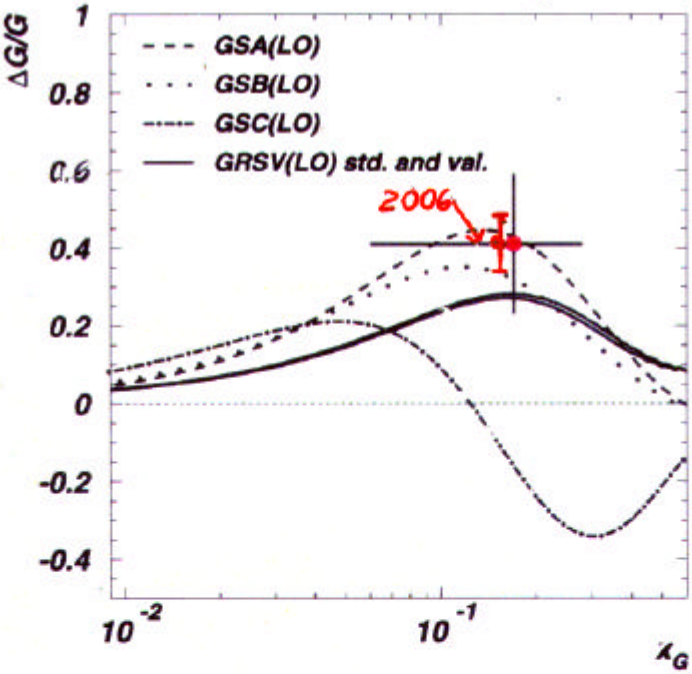


- Asymmetry for hadron pairs:



- Extracted value of $\Delta G/G$: $0.41 \pm 0.18 \pm 0.08$

P.R.L. 84 (2000) 2584

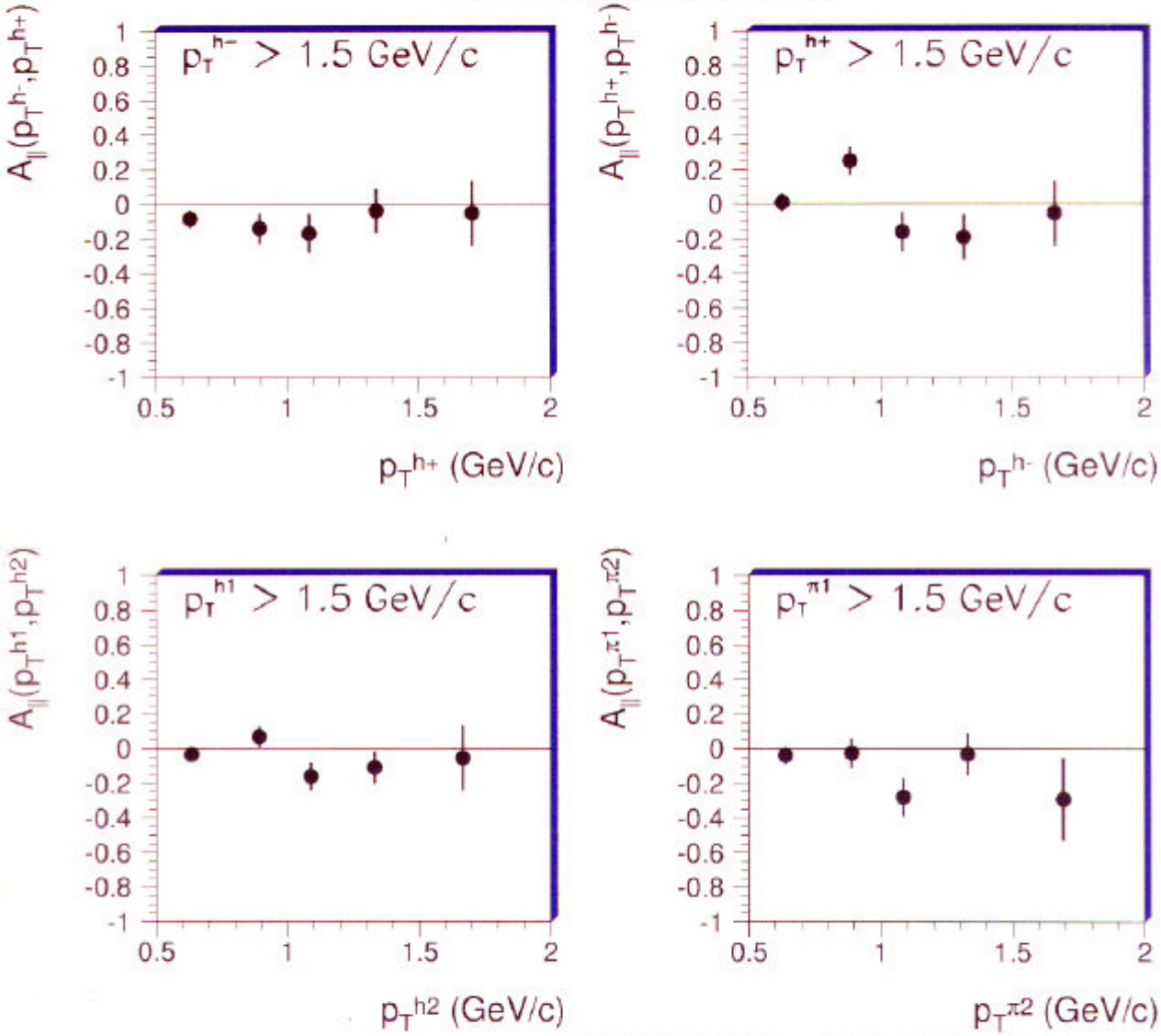


$\langle x \rangle = 0.17$

$$\Rightarrow \int_{0.06}^{0.28} \Delta G/G \cdot G(x)\,dx \approx 0.6 \pm \cdots$$

$\int_{0.28}^{1} \cdots$ small , $\int_{0}^{0.06} \cdots$? $\Rightarrow$ COMPASS, RHIC

HERMES PRELIMINARY



Systematic error 8.1%

HYDROGEN + DEUTERIUM Target

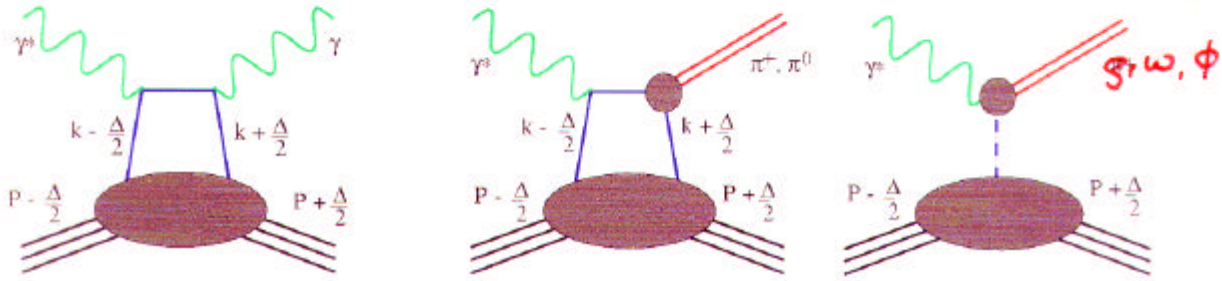
Asymmetry negative ➡ $\Delta G(x) > 0$

precise number ⬌ PYTHIA-MC

L_z^q

GPDs

new observables in hard exclusive processes:
Generalised Parton Distributions ($H, E, \tilde{H}, \tilde{E}$)
related to parton distribution functions and
elastic form factors



$\Rightarrow$ access to orbital angular momentum:

$$\frac{1}{2}\int x\mathrm{d}x(H+E)_{|\Delta=0} = J_q \quad = \frac{1}{2}\Delta\Sigma + L_z^q$$

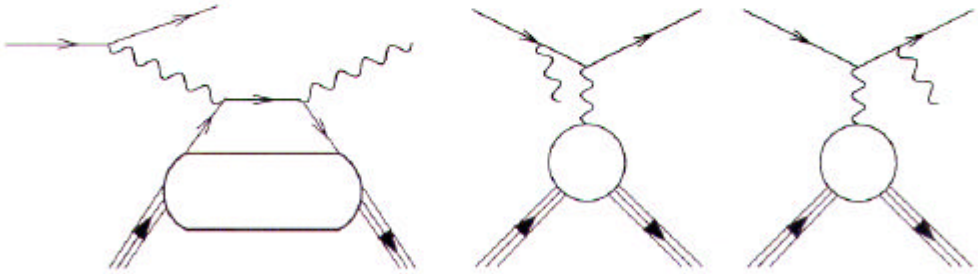
quantum numbers of final state $\rightarrow$ select different GPDs
DVCS: $H, E, \tilde{H}, \tilde{E}$
vector mesons: H, E
pseudoscalar mesons: $\tilde{H}, \tilde{E}$

quadratic combination of GPDs appear in unpolarised xsection
$\rightarrow$ **polarisation** provide **new observable**

hermes

Deep Virtual Compton Scattering

- Off-shell photon*-quark scattering:
  - Detect e' and γ, and require: $E_{miss} = \not{0}\ M_p$



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

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

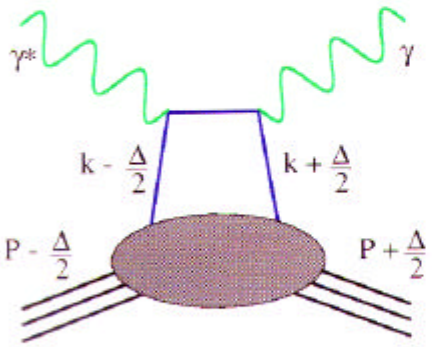
with $\Delta^2 = -t$ and

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

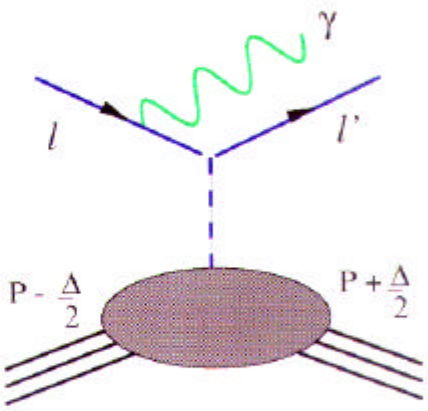
$\Rightarrow$ DVCS: total quark angular momentum

- Experimental considerations:
  - Interference with Bethe-Heitler process:
    DVCS $\otimes$ BH makes DVCS measurable
  - Detect scattered photon; suppress π^0's
  - Observe azim. asymmetry: $A_{LU}^{BetheHeitler} = 0$

DVCS/Bethe-Heitler Interference



DVCS



Bethe-Heitler

$$\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH} = e_l \cdot \frac{e^6}{t}\frac{m}{Q} \cdot \frac{4\sqrt{2}}{x_{Bj}} \cdot \frac{1}{\sqrt{1-x_{Bj}}} \cdot$$

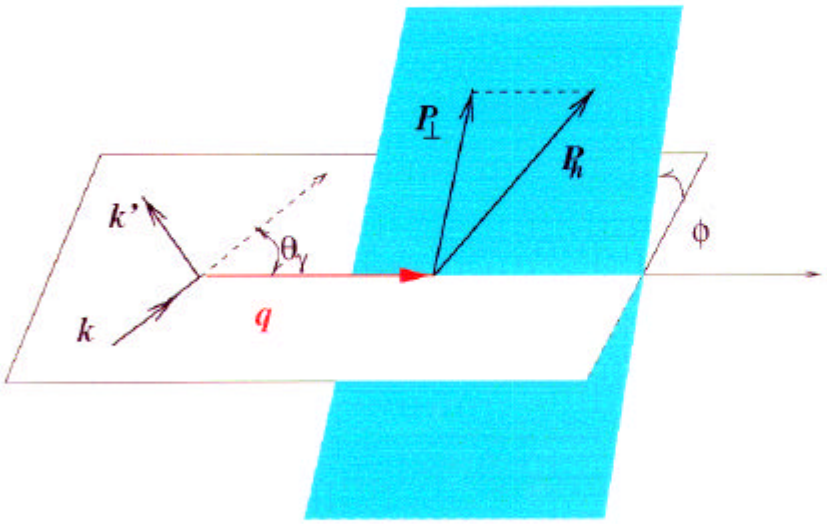
$$e_\ell \frac{\epsilon}{1-\epsilon}\left[\cos\phi \frac{1}{\sqrt{\epsilon(1-\epsilon)}} \mathrm{Re}\,\widetilde{M}_{1,1} - \cos 2\phi \sqrt{\frac{1+\epsilon}{1-\epsilon}} \mathrm{Re}\,\widetilde{M}_{1,0}\right.$$

$$\left. - \cos 3\phi \sqrt{\frac{\epsilon}{1-\epsilon}} \mathrm{Re}\,\widetilde{M}_{1,-1}\right.$$

$$\left. + 2P_\ell \left\{ - \sin\phi \sqrt{\frac{1+\epsilon}{\epsilon}} \mathrm{Im}\,\widetilde{M}_{1,1} + \sin 2\phi\, \mathrm{Im}\,\widetilde{M}_{1,0} \right\} + \mathcal{O}\left(\frac{1}{Q}\right)\right]$$

- $e_\ell = \pm 1$ is the lepton charge
- $P_\ell = \pm 1$ is the lepton beam helicity
- $\widetilde{M}_{j,i}$ are the DVCS amplitudes; i, j are photon helicities

Spin Azimuthal Asymmetries

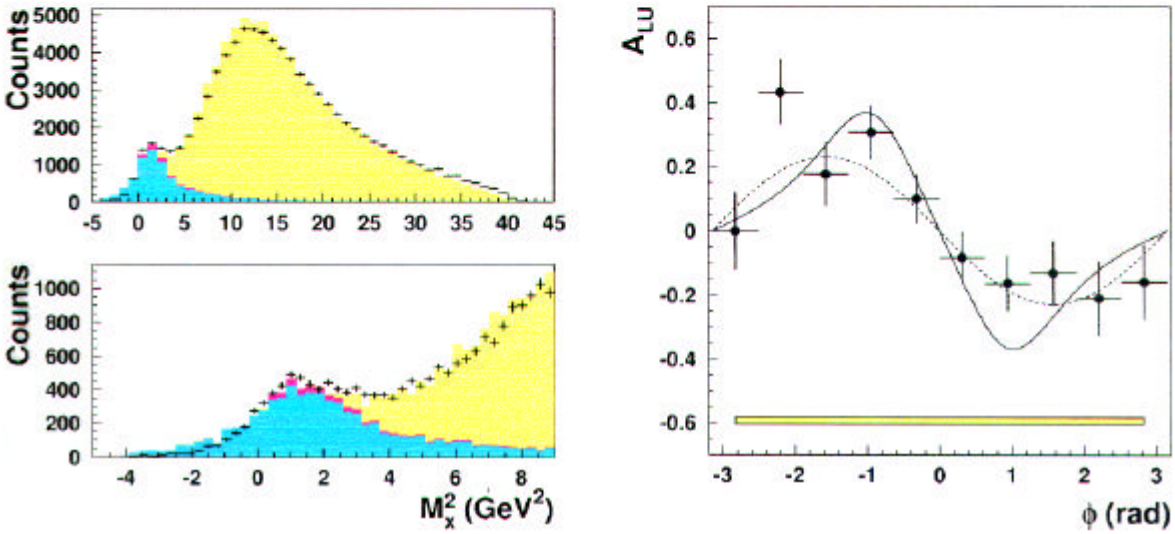


Look for ϕ-dependence of *single-spin* asymmetries.

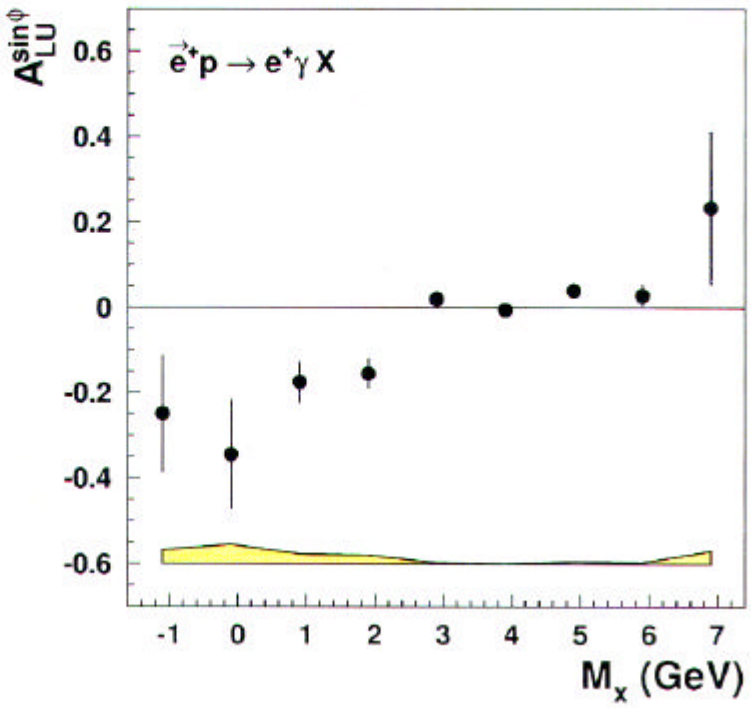
$$A_{UL}(\phi) = \frac{N^\uparrow L^\downarrow - N^\downarrow L^\uparrow}{N^\uparrow L^\downarrow P^\downarrow + N^\downarrow L^\uparrow P^\uparrow}$$

First observations of DVCS

- Missing mass spectrum and azimuthal distribution:



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

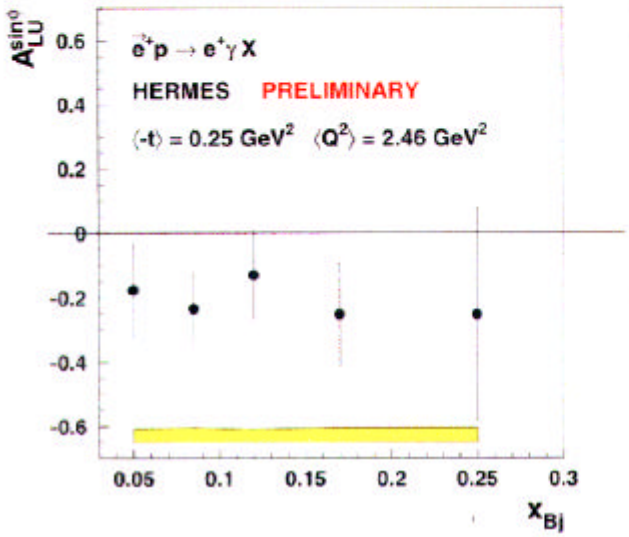


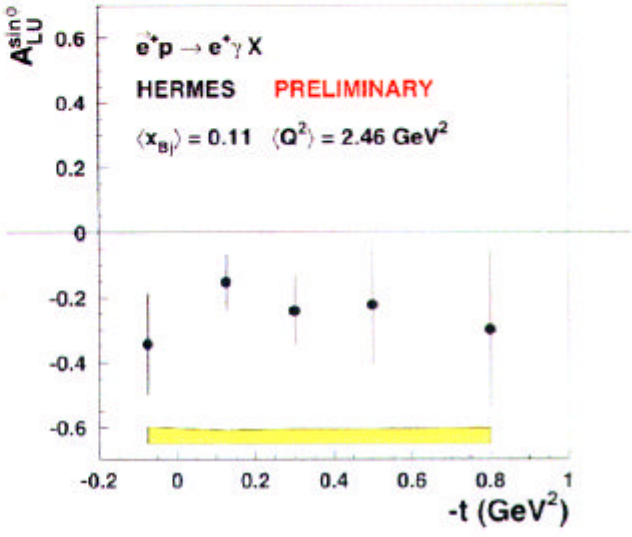
DVCS observed !

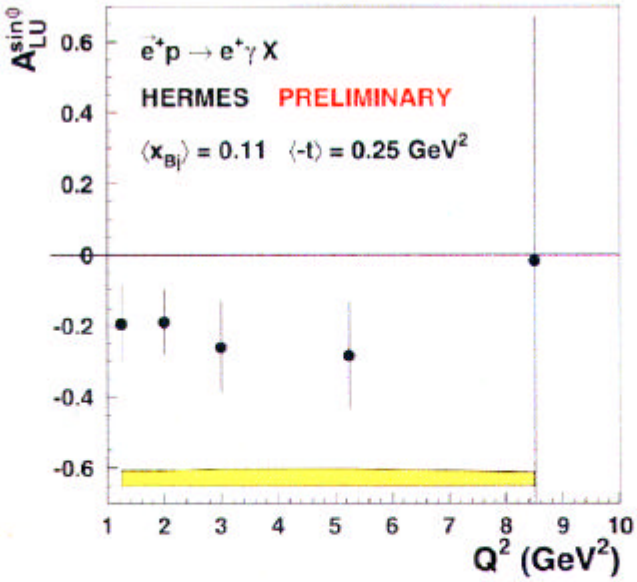
HERMES Collab.,
PRL 87, 182001

CLAS Collab.,
PRL 87, 182002

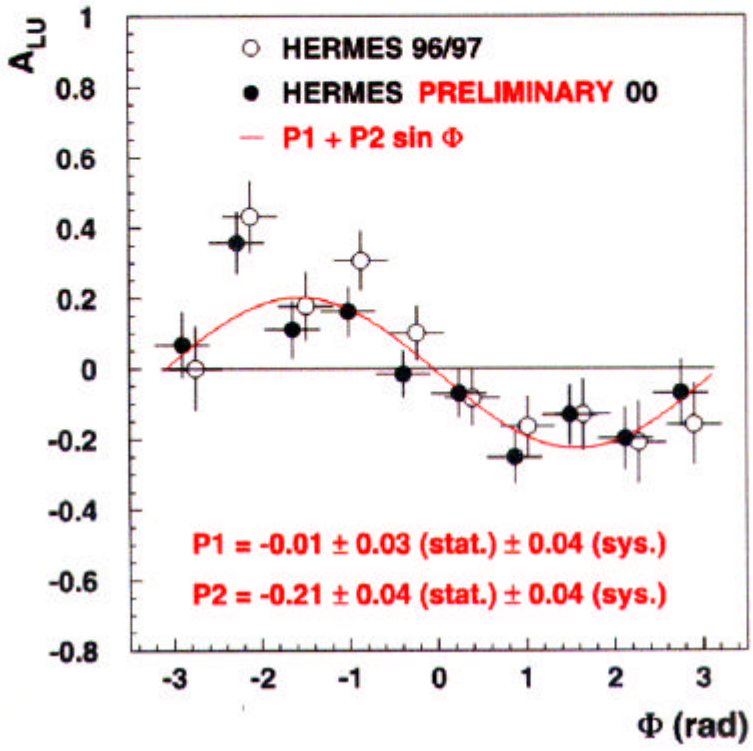
DVCS – kinematical dependencies

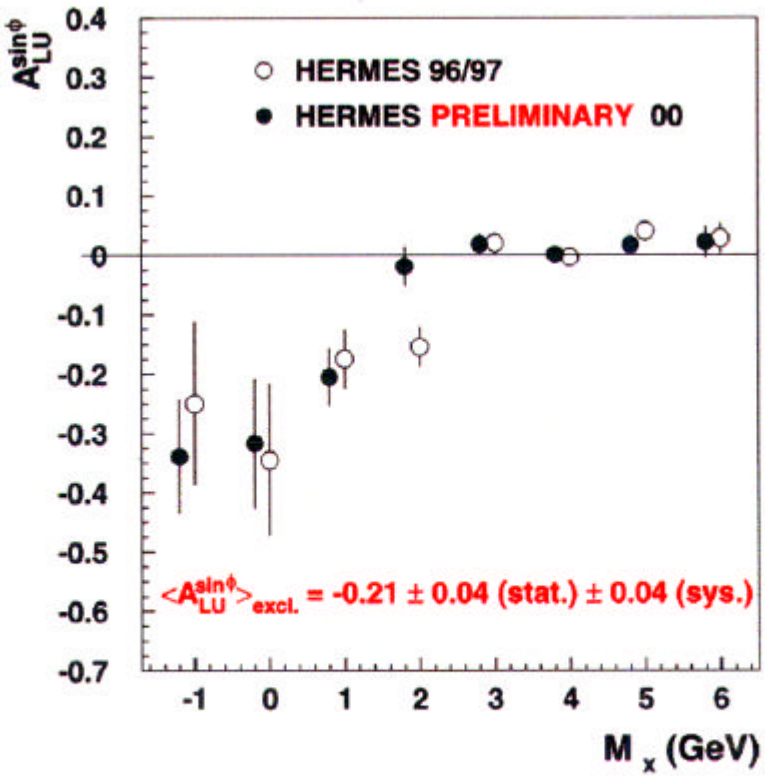




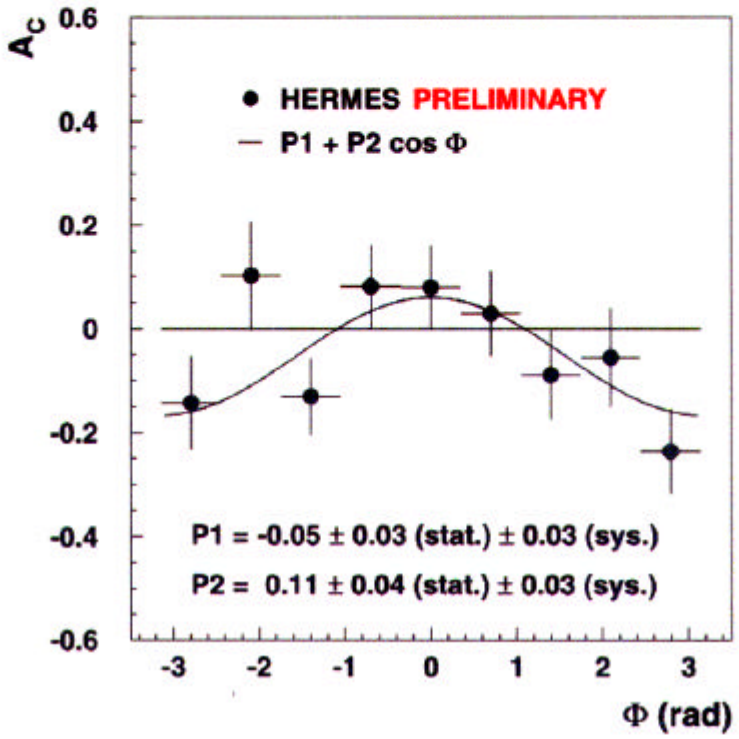


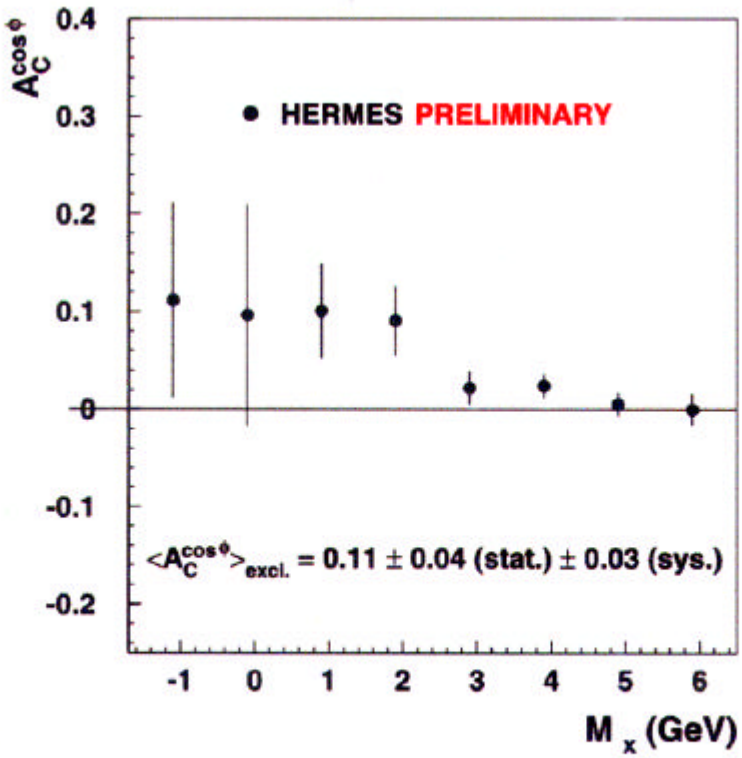
DVCS – 1996/97 and 2000 data



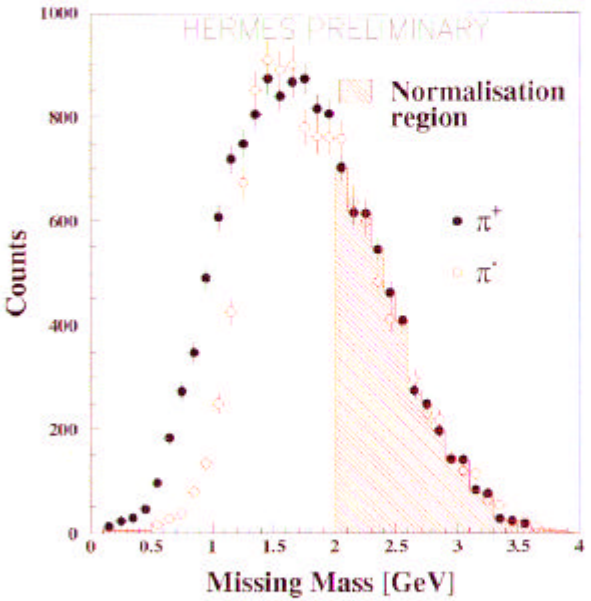


DVCS – charge asymmetry



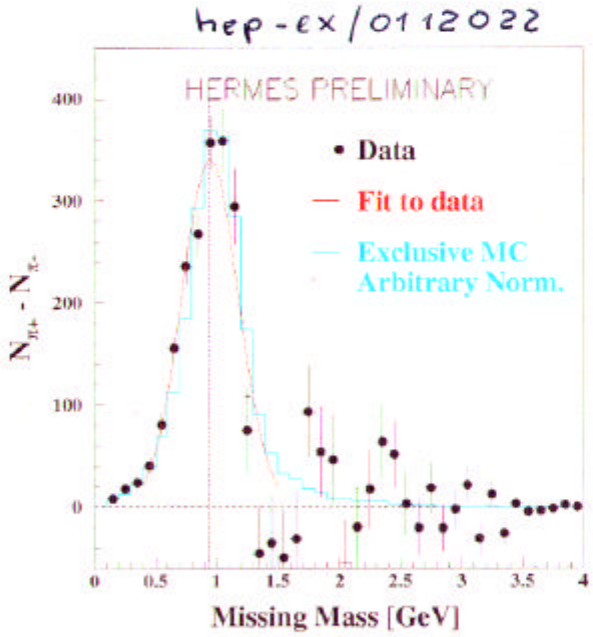


$e\,\vec{p} \to e'\,X\,\pi^+$



$e\,\vec{p} \to e'\,n\,\pi^+$

hep-ex/0112022

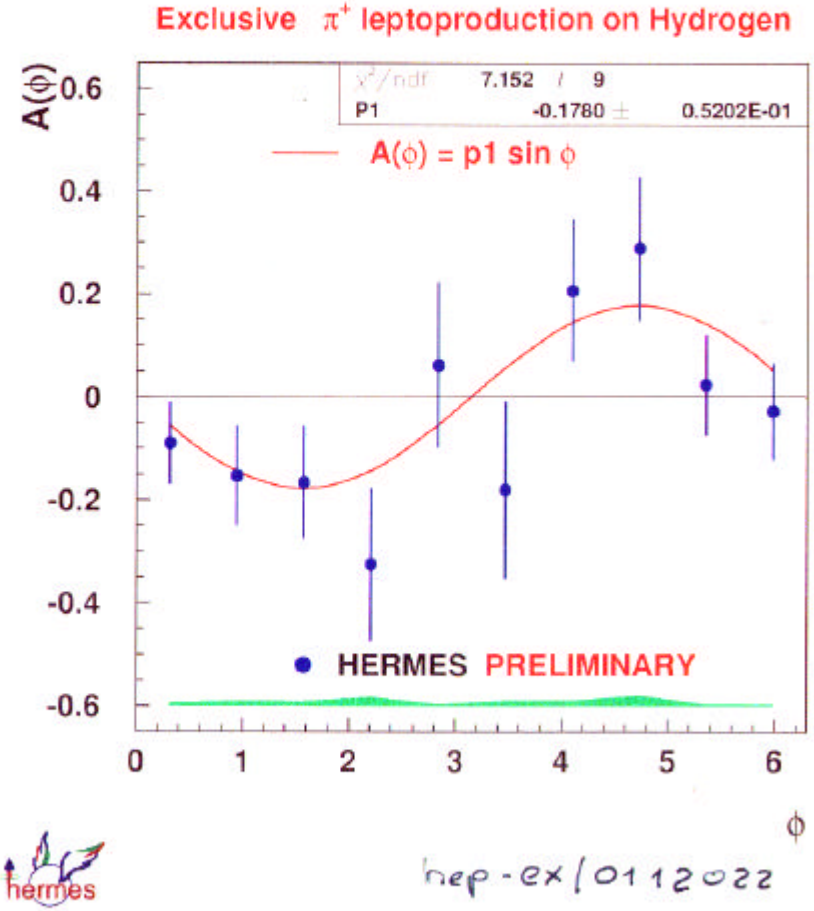


clear peak at missing mass $\approx M_n$
position and width in agreement with GPDs Monte Carlo

possible hints for
$ep \to e'\Delta^{++}\pi^-$ >
$ep \to e'\Delta^0\pi^+$

$\sigma_{M_x} \sim 0.25$ GeV

cross section asymmetry



hep-ex/0112022

$$A(\phi) = A_{\mathrm{UL}}^{\sin\phi} \cdot \sin\phi$$

$\sin 2\phi$, $\cos\phi$, $\cos 2\phi$ moments
compatible with zero

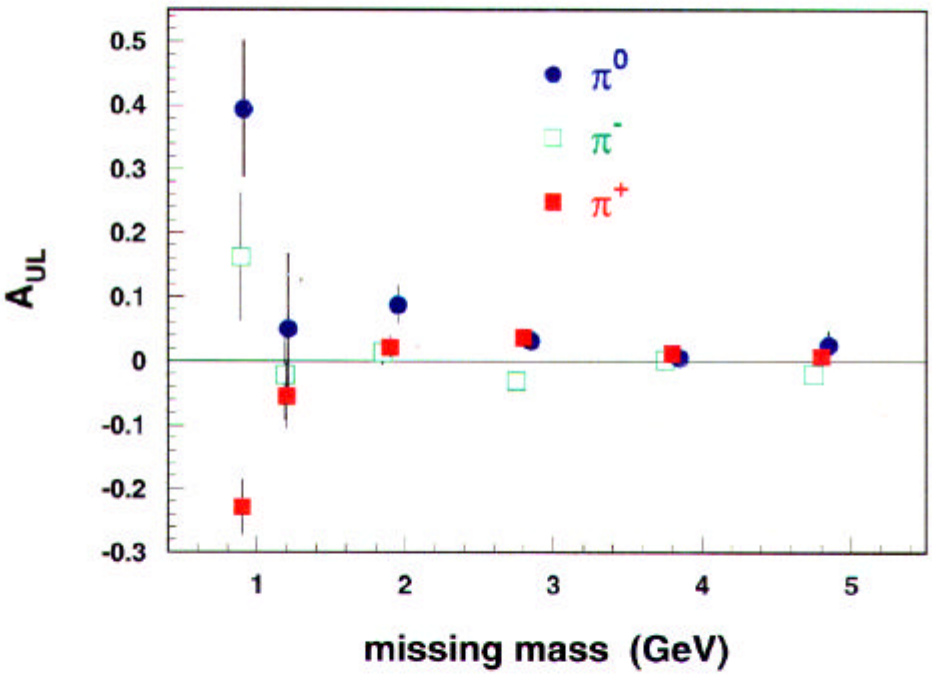
$$A(\phi) = a \sin\phi + b \sin 2\phi + c \cos\phi + d \cos 2\phi$$

systematics:

- 5% on target polarisation
- 2% background correction

Asymmetry vs Missing Mass

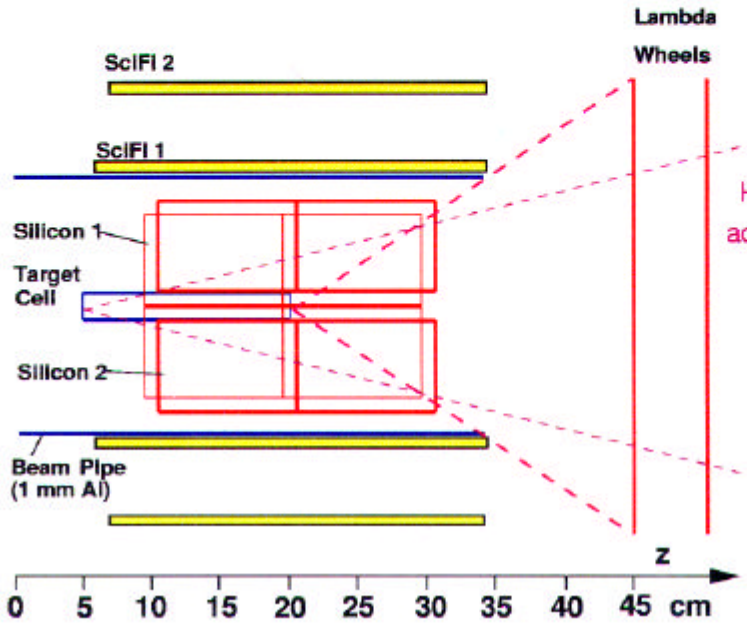
- Unpolarized beam and Longitudinally Polarized Hydrogen Target

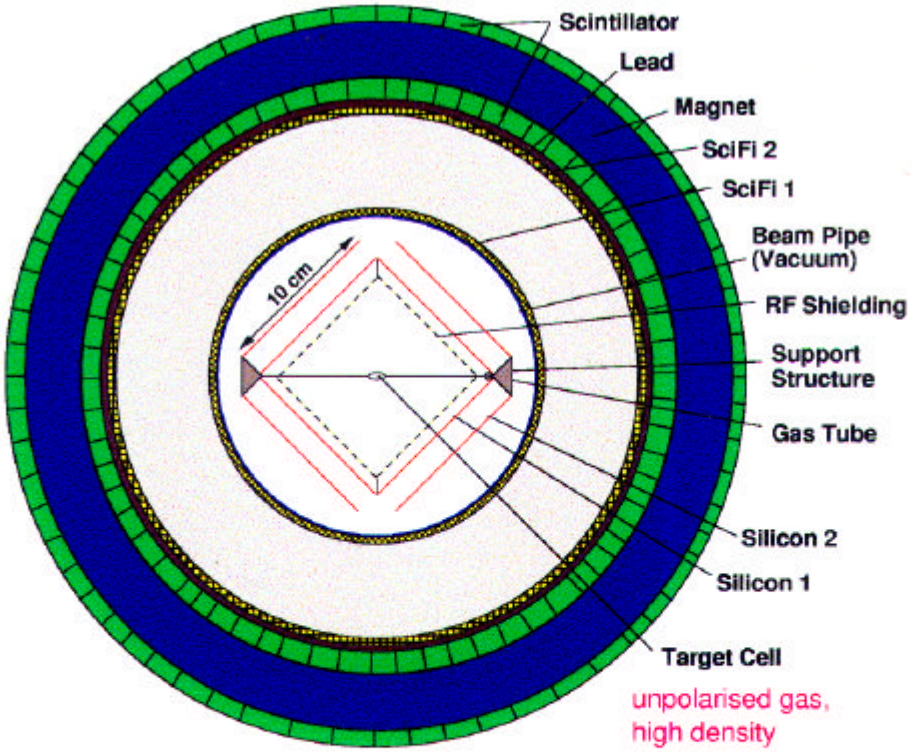


- theoretical prediction is available for transversally polarized target, but opposite sign of asymmetry (Frankfurt et al., Phys.Rev.Lett.84,p2589)
- contradiction with large asymmetry for π^0 in data

HERMES Recoil Detector

Present Design

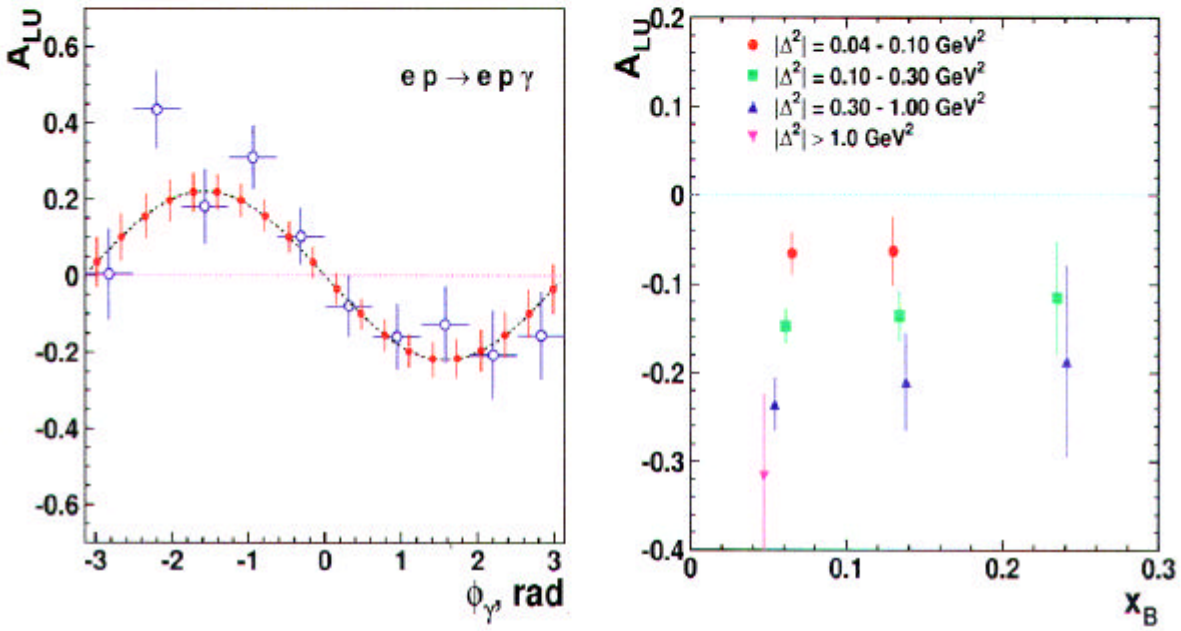




Data taking: ~2004

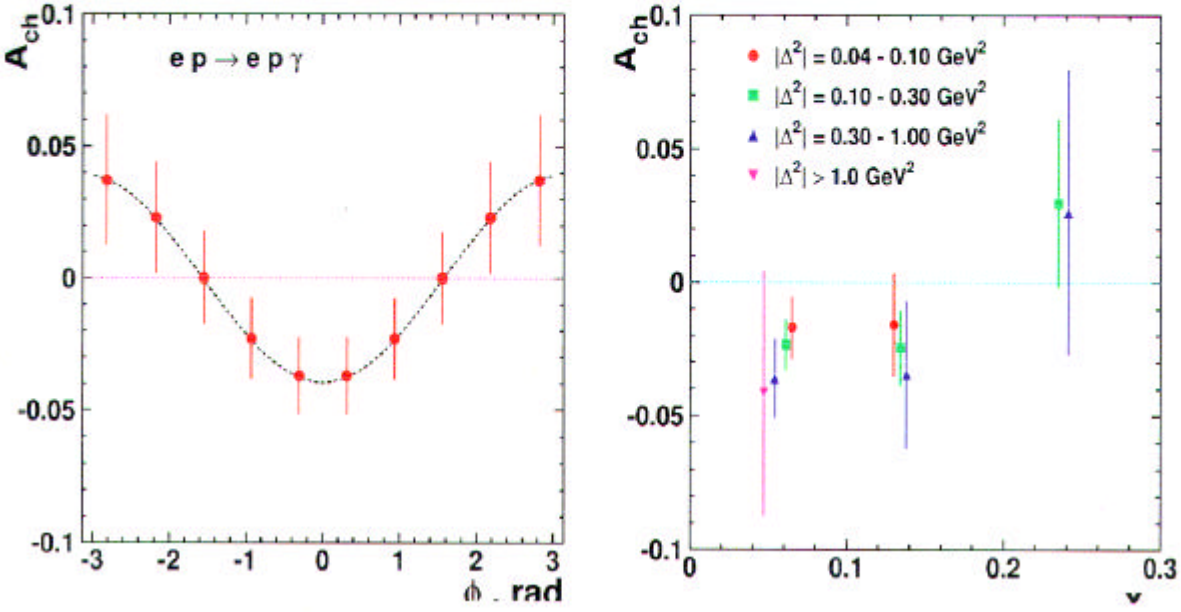
DVCS in 2006

- Beam-spin asymmetry - anticipated data (2 fb^{-1}):



(HERMES Large Acceptance Recoil Detector proposal.)

- Beam-charge asym. - anticipated data (2 fb^{-1}):



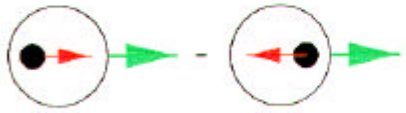
Transverse polarization

- Three leading order distribution functions:

f_1 = 

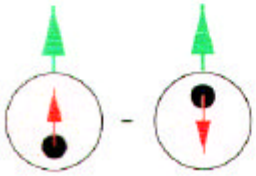
momentum carried by quarks

$\bar{q}\gamma^{\mu}q$

g_1 = 

longitudinal quark spin, $\Delta\Sigma$

$\bar{q}\gamma^{\mu}\gamma^{5}q$

h_1 = 

transverse quark spin, $\delta\Sigma$

$\bar{q}\sigma^{\mu\nu}q$

- 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 $h_1(x)$

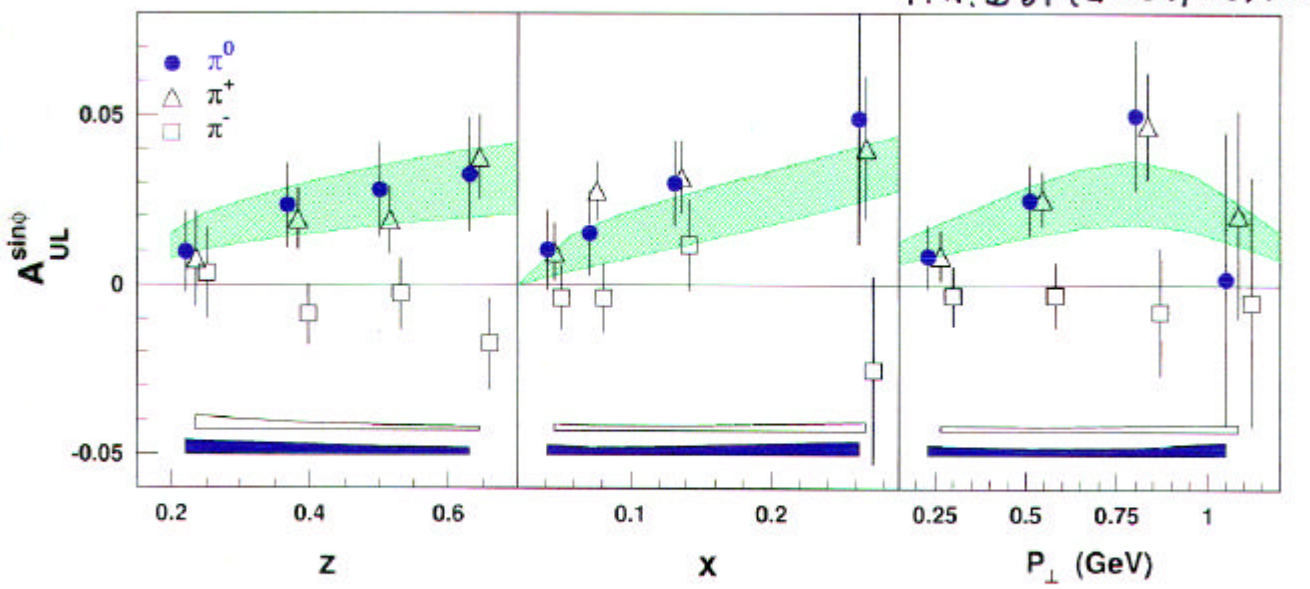
- The structure function $h_1(x)$ is chirally odd :
  - Suppressed in inclusive DIS
  - Use semi-inclusive DIS with chirally-odd $H_1^{\perp(1)u}(z)$
  - Assume u-quark dominance
  - Asymmetry for Collins process:

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

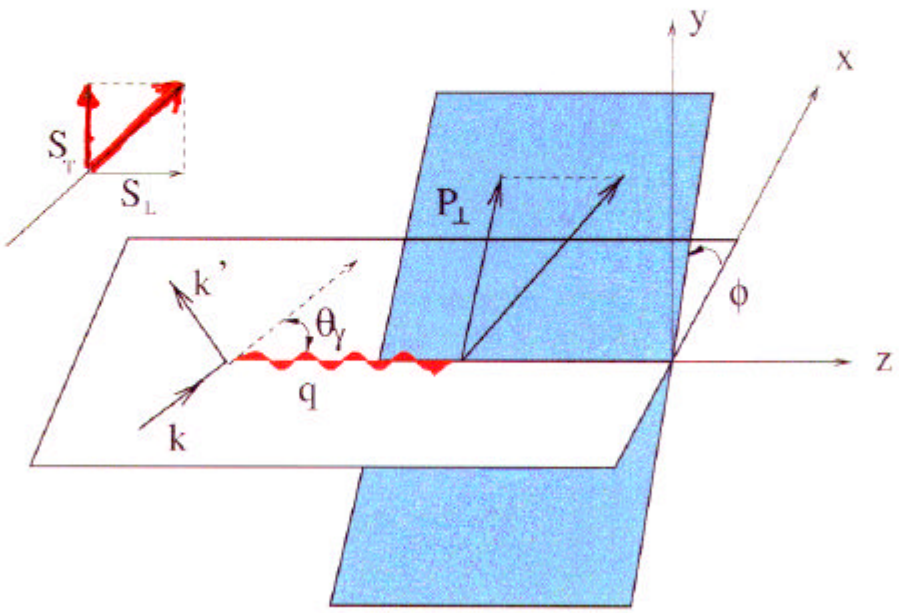
  - $\mathrm{H}_1^{\perp(1)u}$ depends on $\phi_c = \phi_h + \phi_s - \pi$

- Evidence for transversity from HERMES data:

P.R.L. 84 (2000) 4047
P.R.D 64 (2001) 097101



$$\mathbf{e}\ \vec{\mathrm{p}} \rightarrow \mathbf{e'}\ \mathbf{n}\ \pi^+$$



transverse component in γ^* frame: $S_\perp = S_\perp(x, Q^2)$

$$\sigma_{\mathrm{S}} \sim [S_\perp \sigma_{\mathrm{L}} + S_{||} \sigma_{\mathrm{LT}}] \cdot \mathrm{A}_{\mathrm{UL}}^{\sin\phi} \sin\phi$$

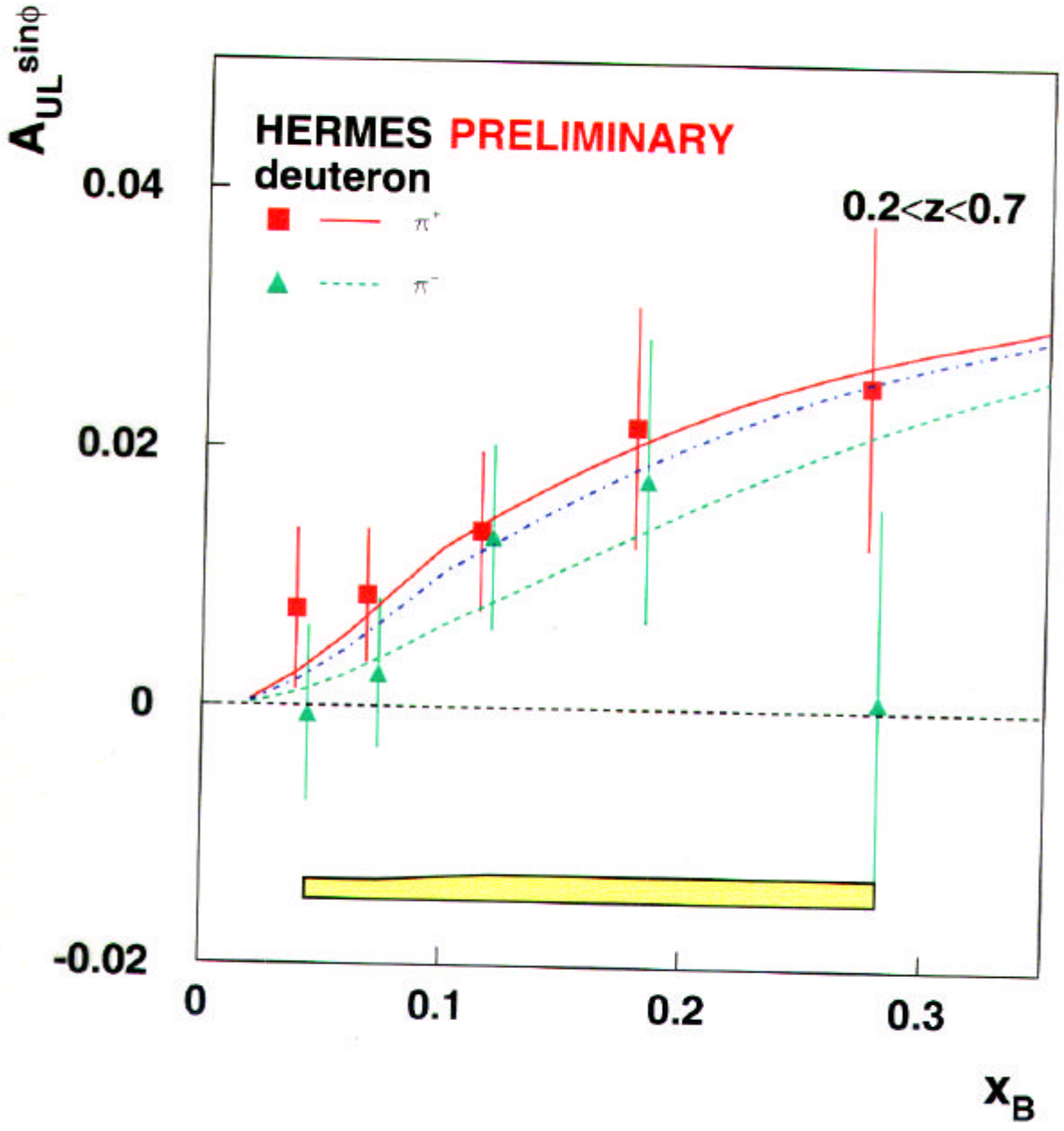
σ_{LT} suppressed by $1/Q \cdots$ but $S_{||} > S_\perp$

HERMES in 1997: $S_\perp / S \sim 0.17$

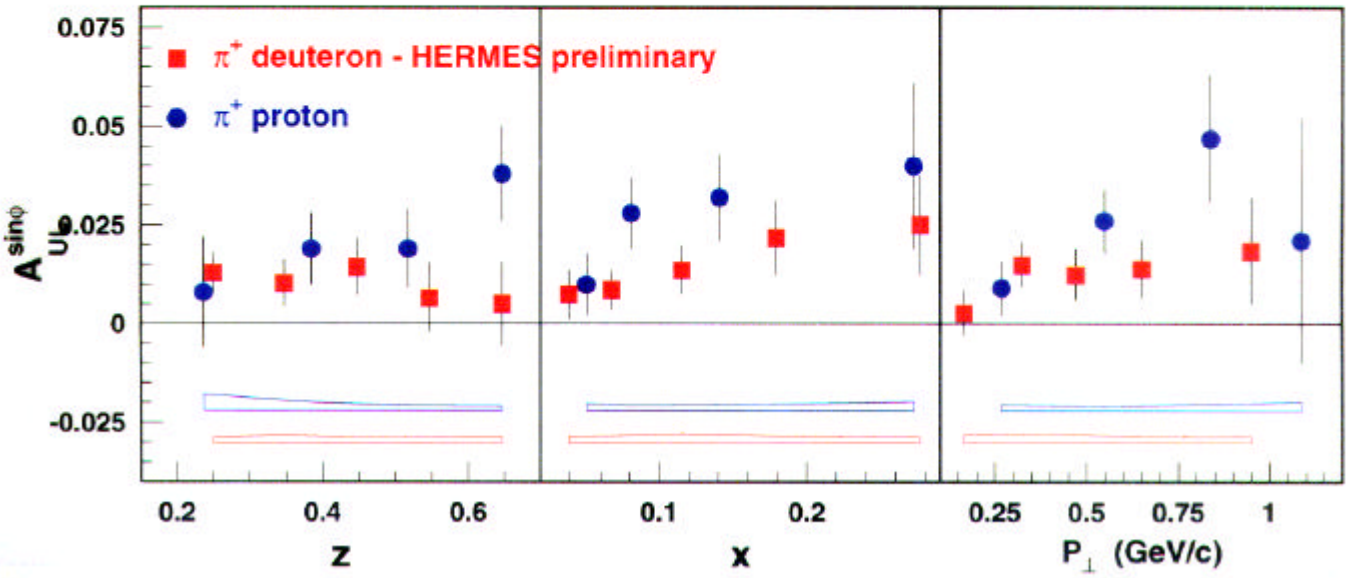
$\Rightarrow$

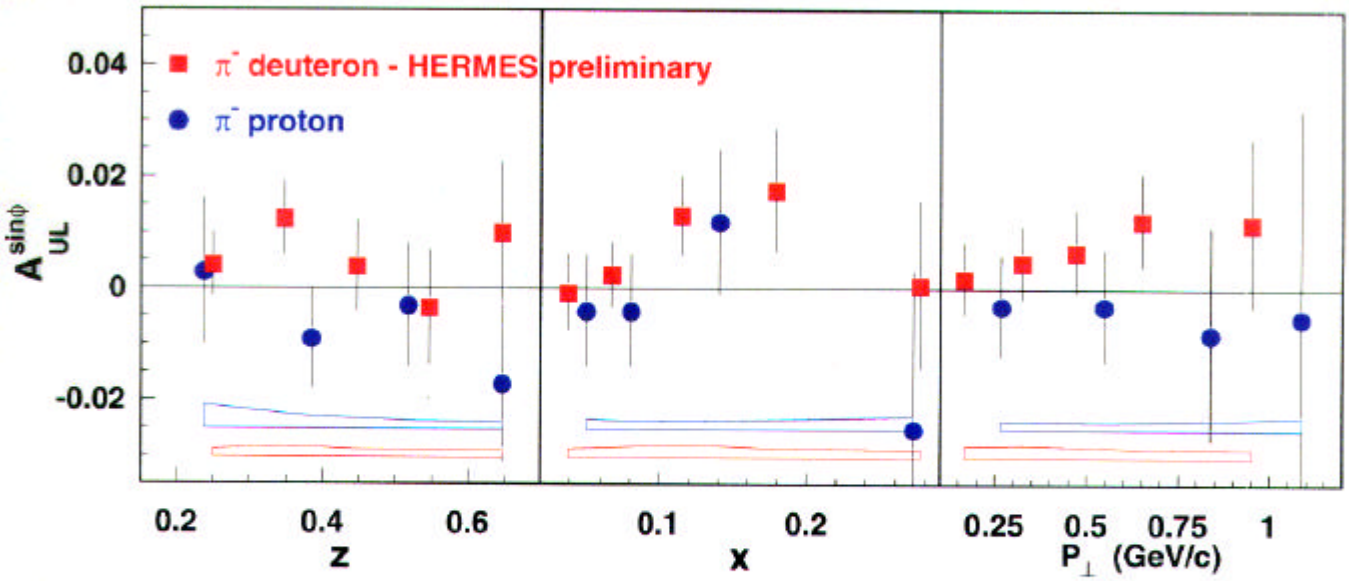
transverse target running in 2001-2!

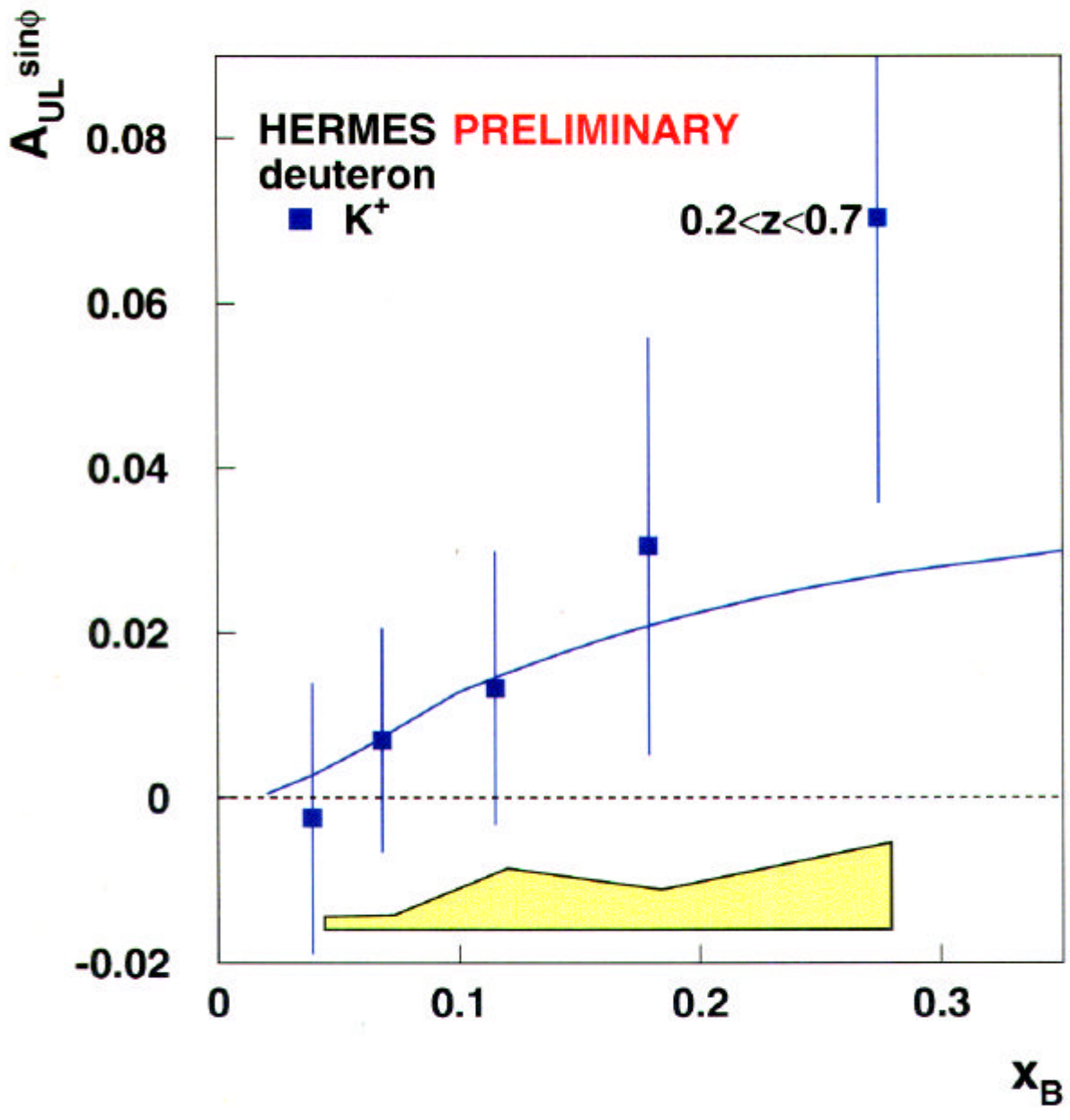
hermes



model predictions: Efremov, Goeke, Schweitzer
hep-ph/0112166


0.075
0.05
0.025
0
-0.025
$A_{UL}^{\sin\phi}$
π^+ deuteron - HERMES preliminary
π^+ proton
0.2
0.4
0.6
z
0.1
0.2
x
0.25
0.5
0.75
1
$P_\perp$ (GeV/c)

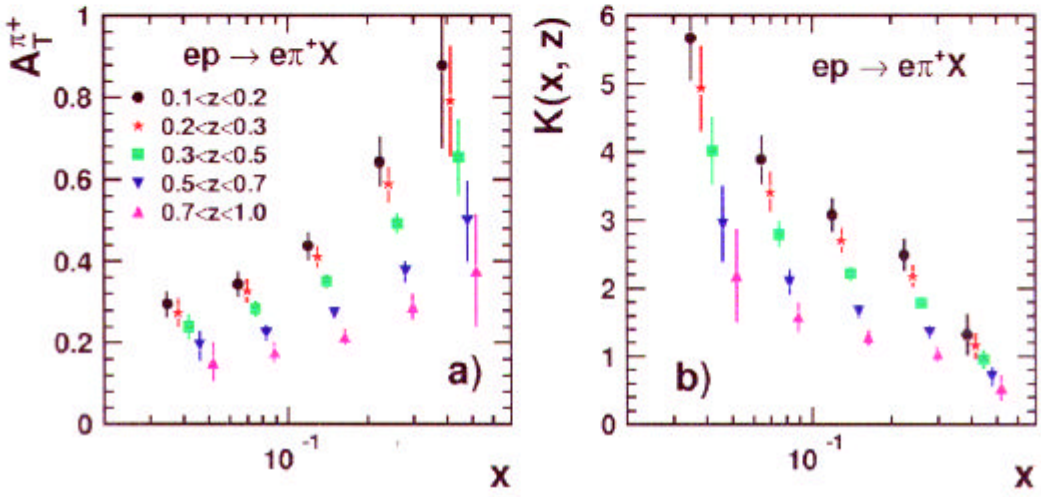

0.04
0.02
0
-0.02
$A_{UL}^{\sin\phi}$
π^- deuteron - HERMES preliminary
π^- proton
0.2
0.4
0.6
z
0.1
0.2
x
0.25
0.5
0.75
1
$P_\perp$ (GeV/c)



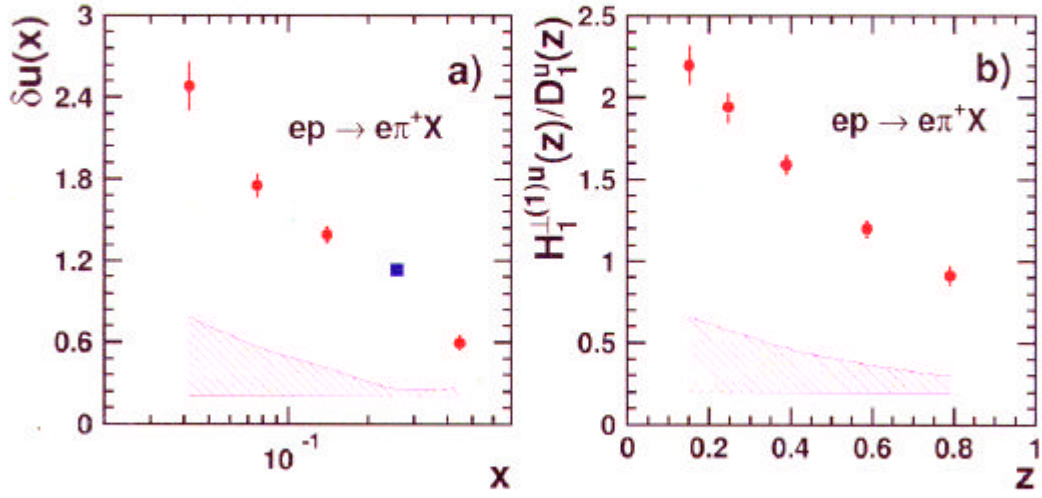
— Efremov et al., hep-ph/0112166

HERMES plans 2001-2006

Projected accuracy for 2 years running on transverse polarized proton target (≈ 200 pb^{-1})



$$K(x,z) = \delta u(x) \cdot \frac{H_1^{\perp(1)u}(z)}{D_1^u(z)}$$



Further results

- Gerasimov-Drell-Hearn Integral
- Flavour asymmetry of light quark sea: $\bar{d}(x) > \bar{u}(x)$
- Vectormesons (ρ, ϕ, ω)
  - Cross section (comparison to GPD)
  - Decay angular distributions (spin density matrix, SCHC)
  - Double-spin-asymmetry
- Hadron production
  - multiplicity distributions
  - fragmentation functions
  - p_t-distributions
- Λ-production
  - longitudinal spin transfer
  - transverse polarisation

Nuclear Targets

- Nuclear attenuation for ρ (and ϕ) mesons
  - * Coherence length for vectormesons
  - * Lifetime of hadronic component of photon

- Nuclear attenuation for other hadrons
  Hadron formation time

- ‚HERMES effect' $\Rightarrow$ gone
  Apparative effect together with radiative corrections
  Now good agreement with world data

Programme until 2006

- 2 years running with transverse target polarisation (H)
  - * First look on transversity distribution: $h_1(x)$
  - * 2^{nd} polarised structure function $g_2(x,Q^2)$

- 1 year of running with longitudinal target polarisation (H) with RICH
  - * $\Delta\tilde{s}$, $\Delta\tilde{u}$

- end of fill runs with high (unpolarised) target density
  - * Λ ($\Rightarrow\Lambda$-wheels)
  - * DVCS (charge asymmetry)
  - * nuclear effects

- 2 years of unpolarised running (H) with Recoil-Detector
  - * Exclusive processes (GPD)