Spin Physics at HERMES

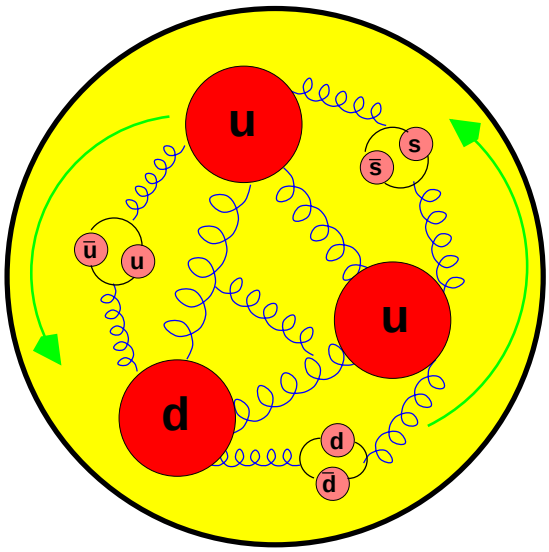
Alessandra Fantoni (LNF - INFN)
on behalf of the HERMES Collaboration

2nd International Symposium on
the Gerasimov-Drell-Hearn Sum Rule and
the Spin Structure of the Nucleon

Genova, July 3-6, 2002

- Introduction to polarised DIS
- The HERMES experiment
- Double-Spin Asymmetries
  - ▷ inclusive ⇒ Polarized SF g_1
  - ▷ semi-incl $h^{\pm}$ ⇒ Polarized PDF Δq
  - ▷ High p_t $h^{\pm}$ ⇒ Gluon polarization $\Delta G/G$
- Single-Spin Asymmetries
  - ▷ semi-incl $\pi^{\pm}$ & transversity ⇒ Talk V. M.
  - ▷ exclusive processes: DVCS
- Other Physics Results
- Summary

The Nucleon Spin



proton (neutron) = complex object with moving and interacting quarks (valence and sea) and gluons that contribute to the total spin

$$1/2 = 1/2\Sigma + \Delta G + \Delta L_{\mathrm{q/g}}$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

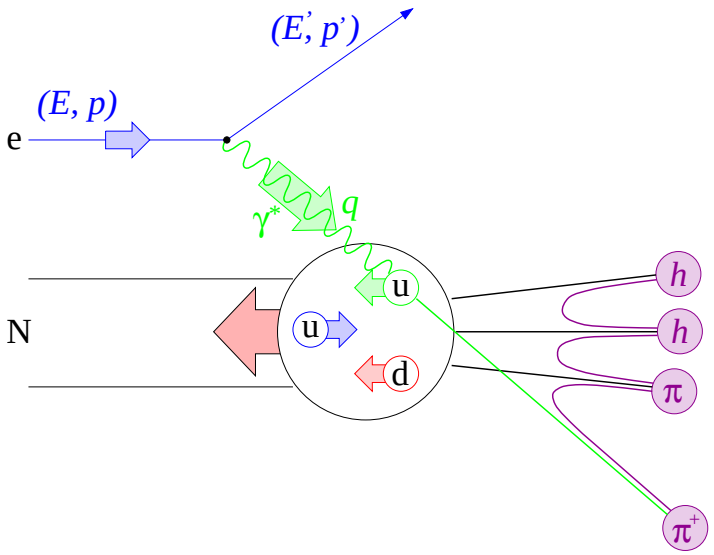
$$\Delta u + \Delta d = \Delta V \longrightarrow \text{inclusive}$$

$$\Delta s \longrightarrow \text{semi} - \text{inclusive}$$

$$\Delta G \longrightarrow \text{PGF}$$

$$\Delta L_{\mathrm{q/g}} = L_{\mathrm{q}} + L_{\mathrm{g}} \longrightarrow \text{GPD} \quad \text{(DVCS)?}$$

Polarised DIS and SIDIS



DIS Variables:

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

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

$$W^2 \overset{lab}{=} -Q^2 + M^2 + 2M\nu \qquad z \overset{lab}{=} \frac{E_h}{\nu}$$

- Inclusive: detect E'

  ▷ DIS limit : Q^2 (> 1 GeV^2) and ν ($\gg 1$ GeV) $\rightarrow$ elastic scattering on the parton

  ▷ x = DIS scaling variable = fraction of the proton momentum carried by the struck quark

- Semi-inclusive: detect E' and h

  ▷ z = SIDIS scaling variable = fraction of the energy of the quark carried by the hadron

How to measure g_1

Measurable Asymmetries:

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

$A_{\parallel} = D(A_1 + \eta A_2)$ where ηA_2 is small
$A_{\perp} = d(A_2 + \xi A_1)$
D, η, d, ξ are kinematic variables

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1}$$

$$A_2 = \frac{\sigma_{TL}}{\sigma_T} = \frac{\gamma(g_1 + g_2)}{F_1} \qquad \gamma = \frac{2Mx}{\sqrt{Q^2}}$$

Neglecting $g_2 \Longrightarrow g_1(x) \approx \frac{F_1(x)}{D} A_{\parallel}$

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

D,d: virtual photon depolarization factor

R: ratio of long. to trans. photo-absorption

ϵ: transverse pol. of the virtual photon

Sum Rules

No prediction for $g_1(x)$ (Q^2-evolution from QCD)
Fundamental prediction for the first moments:

$$\begin{aligned}\Gamma_1^p = \int g_1^p(x) &= \tfrac{1}{2}(\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s)\\ \Gamma_1^n = \int g_1^n(x) &= \tfrac{1}{2}(\tfrac{1}{9}\Delta u + \tfrac{4}{9}\Delta d + \tfrac{1}{9}\Delta s)\end{aligned}$$

Δu, Δd and Δs polarized quark distribution functions

- Bjorken Sum Rule

$$\int (g_1^p(x) - g_1^n(x))dx = \frac{1}{6}\frac{g_A}{g_V} \cdot \left[1 - \frac{\alpha_s(Q^2)}{\pi} - ...\right]$$

- Ellis-Jaffe Sum Rule

$$\Gamma_1^p = \frac{1}{18}(9F - D) = 0.185 + QCD \;\; corr.$$

$$\Gamma_1^n = \frac{1}{18}(6F - 4D) = -0.024 + QCD \;\; corr.$$

- Gerasimov-Drell-Hearn Sum Rule

$$\int_0^\infty \frac{d\nu}{\nu}\Big[\sigma_{1/2}(\nu, Q^2 = 0) - \sigma_{3/2}(\nu, Q^2 = 0)\Big] = -\frac{2\pi^2\alpha}{m_p^2}\kappa^2$$

- Generalised Gerasimov-Drell-Hearn Sum Rule

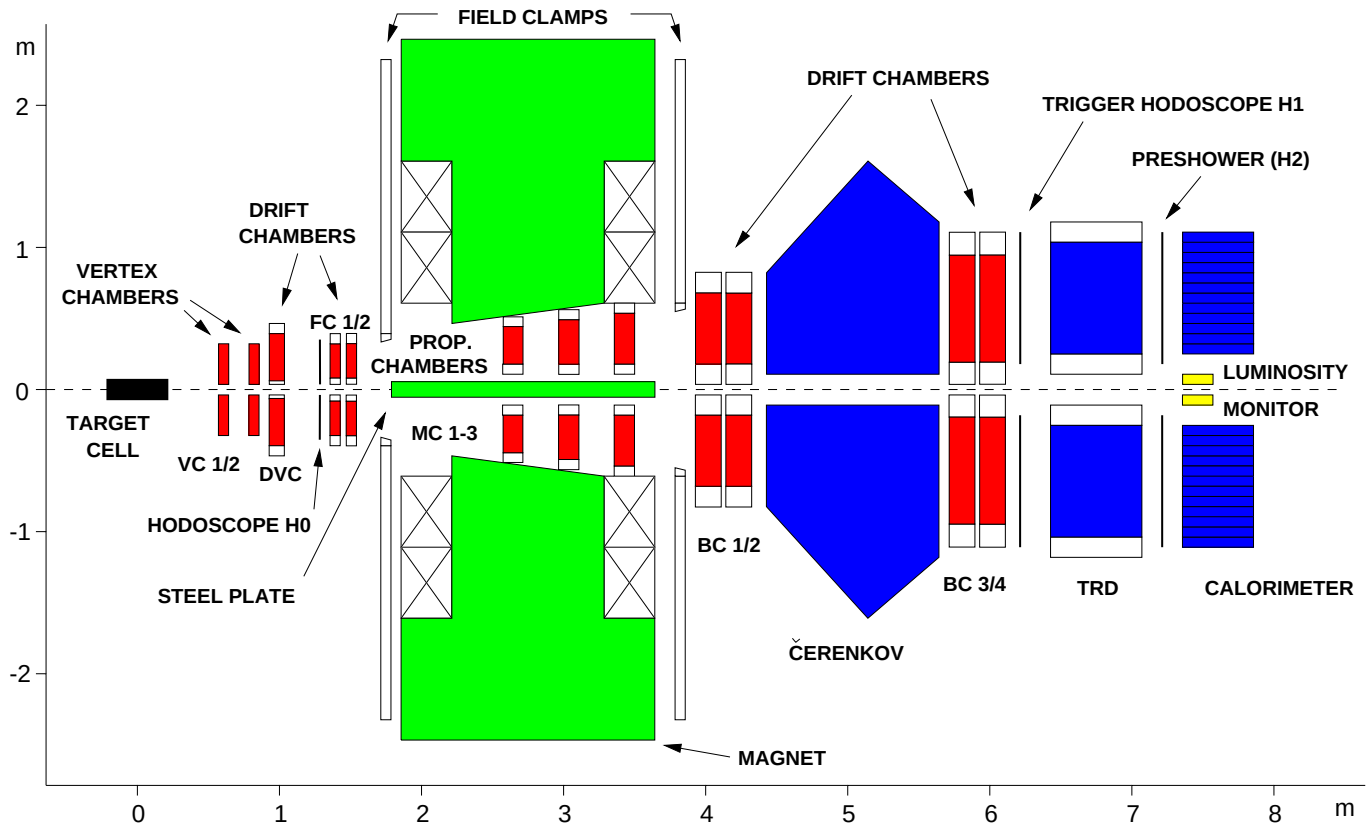
$$\int_0^\infty \frac{d\nu}{\nu}\Big[\sigma_{1/2}(\nu, Q^2 \gg 1) - \sigma_{3/2}(\nu, Q^2 \gg 1)\Big] \to \frac{16\pi^2\alpha}{Q^2}\Gamma_1$$

- Gottfried Sum Rule

$$\int_0^1 \frac{F_2^p(x) - F_2^n(x)}{x}dx = 0.235 \pm 0.026 \neq 1/3$$

Light quark sea not flavor symmetric ($\bar{u}(x) \neq \bar{d}(x)$)

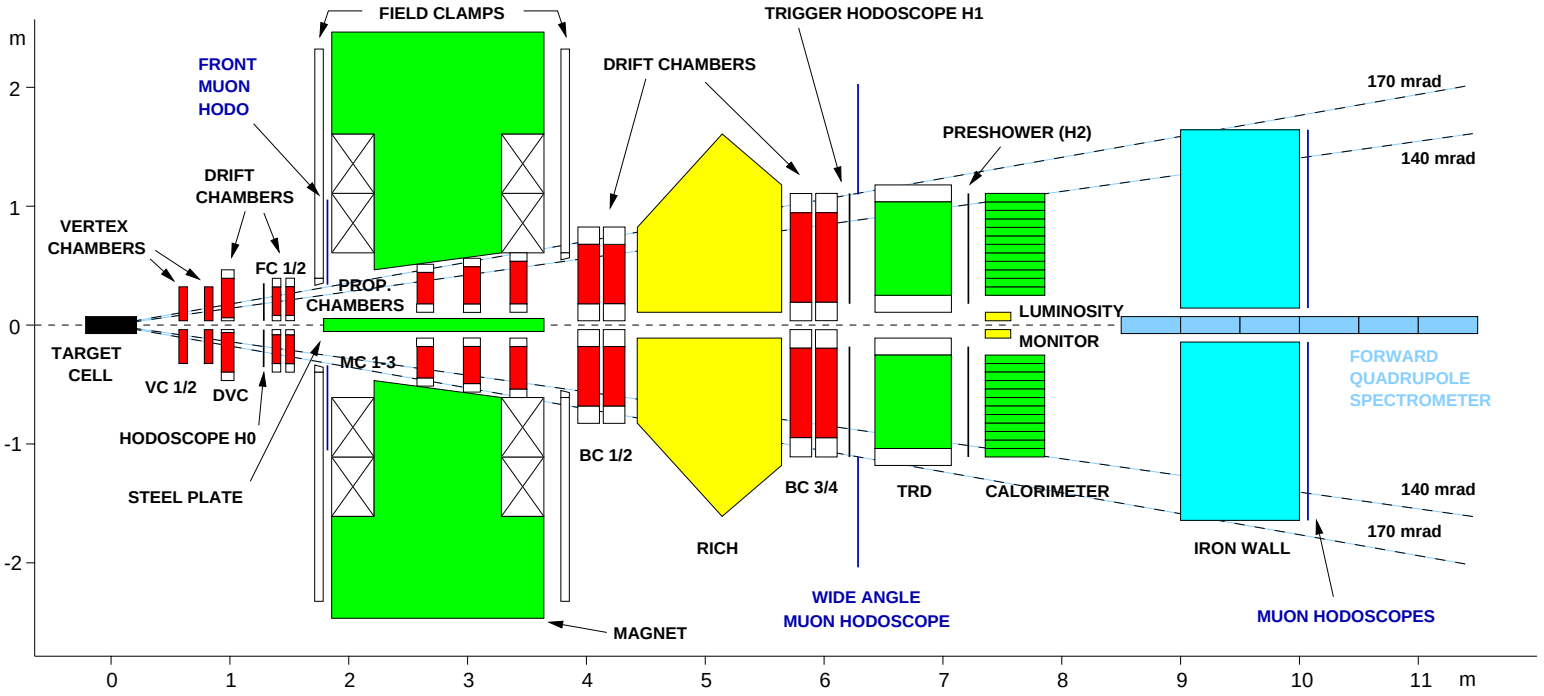
HERMES Spectrometer



- Forward dipole spectrometer:
  1.5 Tesla·m , 40< θ <220 mrad
- Charge particle tracking: 57 tracking planes,
  $\delta P/P = (0.7 - 1.3)\%$, $\delta\theta < 0.6$ mrad
- Calorimeter: 840 lead-glass blocks,
  $\delta E/E \sim 5\%/\sqrt{E}$, $\delta\theta \sim 1$ mrad
- Particle identification:
  Threshold Čerenkov, TRD, Preshower, Calorimeter

NIM A417 (1998) 230

HERMES Upgrade



- Double radiator [Aerogel (n=1.03) + C_4F_{10} gas (n=1.0014)] RICH detector for complete PID in 98
- Muon hodoscope for charm physics in 98
- Forward quadrupole spectrometer for low Q^2 physics in 99
- Large acceptance silicon detector Λ physics in 00
- Silicon recoil detector for exclusive physics in 01

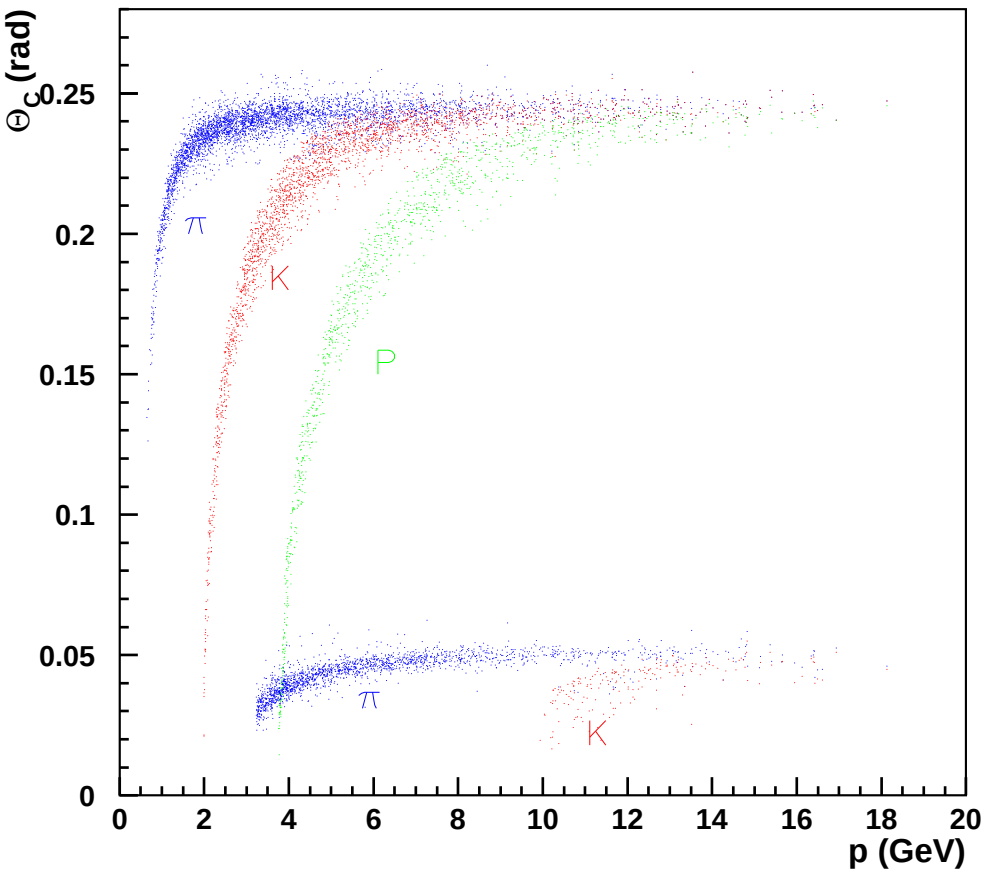
Particle Identification

- ('95-'97) Lepton-hadron separation → Čerenkov + TRD + Preshower + Calo:
  - ▷ e^+ contamination $< 1\%$
  - ▷ $\pi^\pm$ identification → Čerenkov threshold:

$$4.5\ GeV < P_{\pi^\pm} < 13.5\ GeV$$

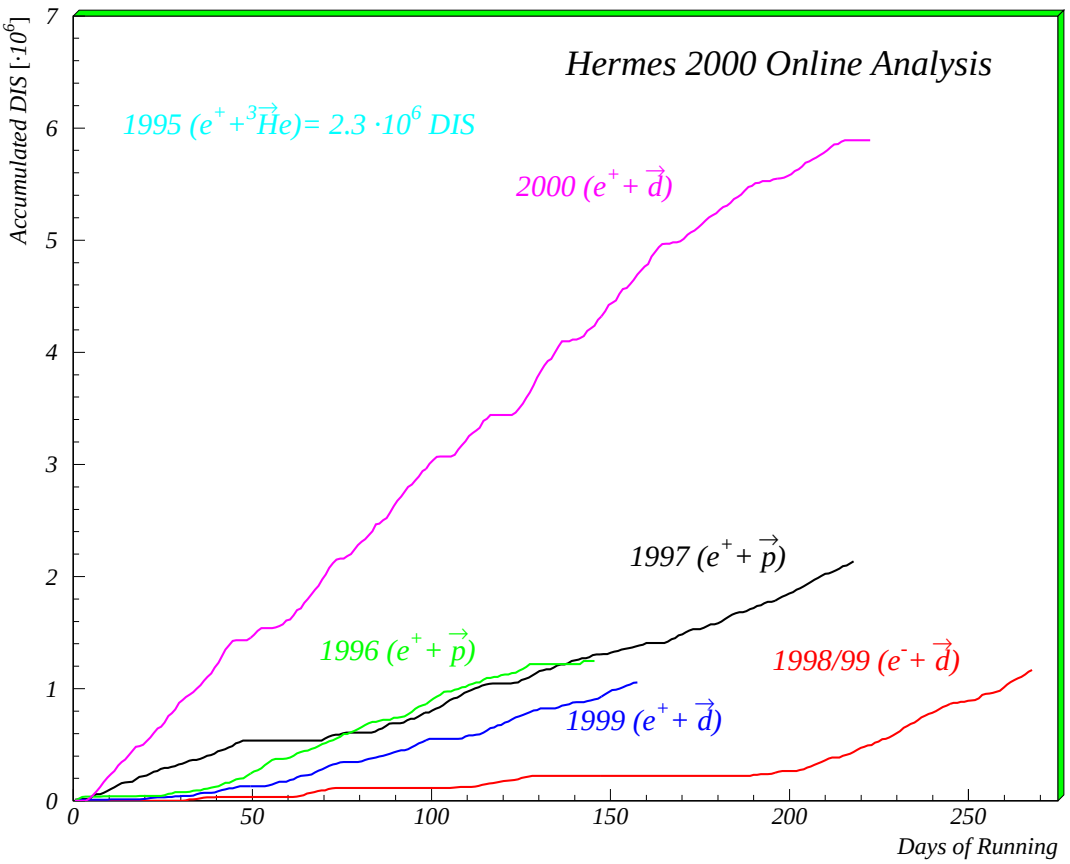
- (>'98) Hadron Identification → 2 RICH detectors:
  - ▷ Detection efficiencies:

93% (π), 85% (K), 85% (p)



NIM A440 (2000) 338; NIM A479 (2002) 2-3, 511

HERMES data



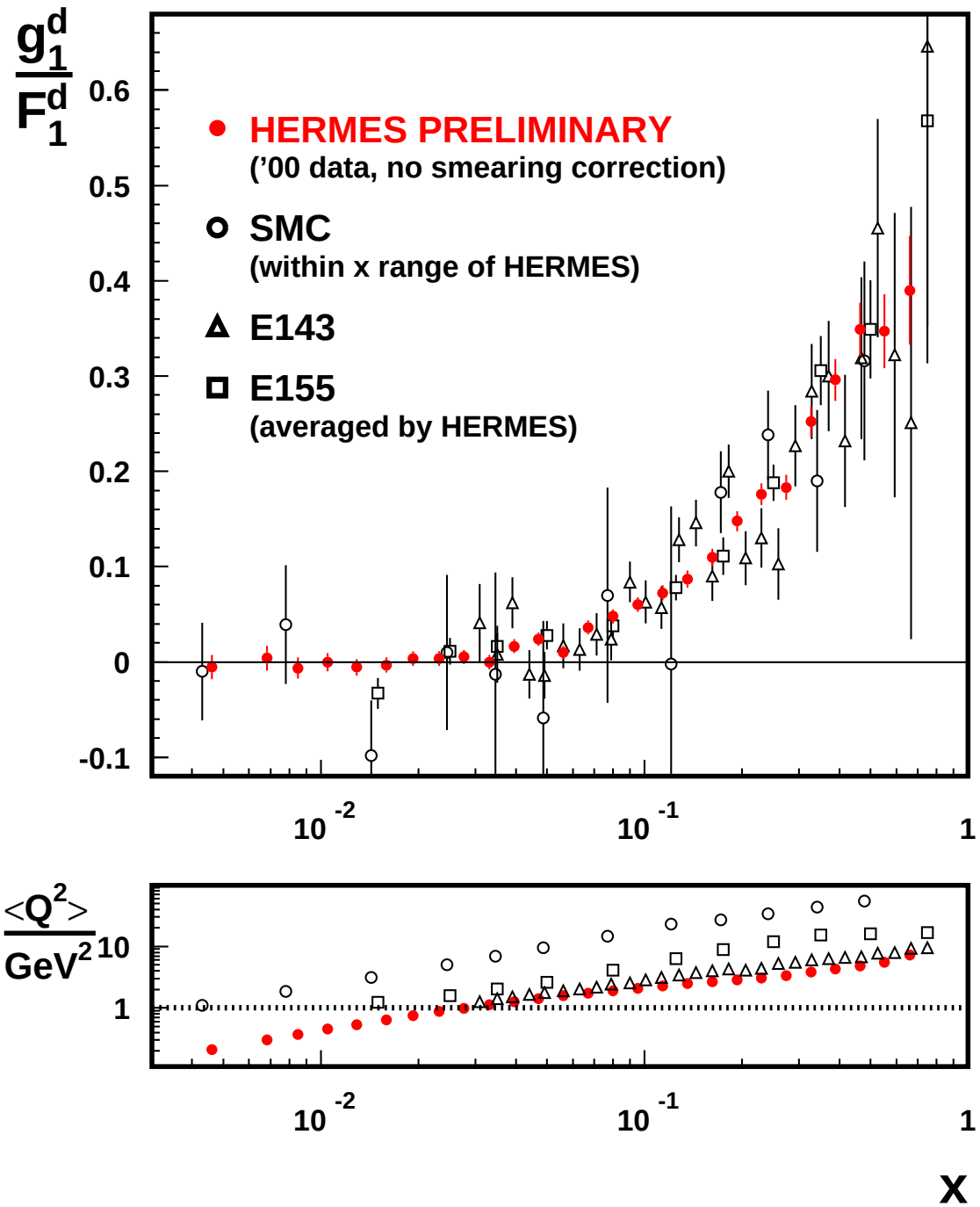
Year	1995	1996	1997	1998	1999	2000
Target	$^3\vec{He}$	$\vec{H}$	$\vec{H}$	$\vec{D}$	$\vec{D}$	$\vec{D}$
DIS (x10^6)	2.2	0.7	1.5	1.0	1.1	6.8

2000

- 10x10^6 $\vec{D}$ DIS events including low-x region
- 1x10^6 tensor-polarised D $\Longrightarrow$ first meas. of b_1^d
- 30x10^6 unpolar. gas (^{1}H, ^{2}D, ^{3}He, ^{14}N, ^{20}Ne, ^{84}Kr)

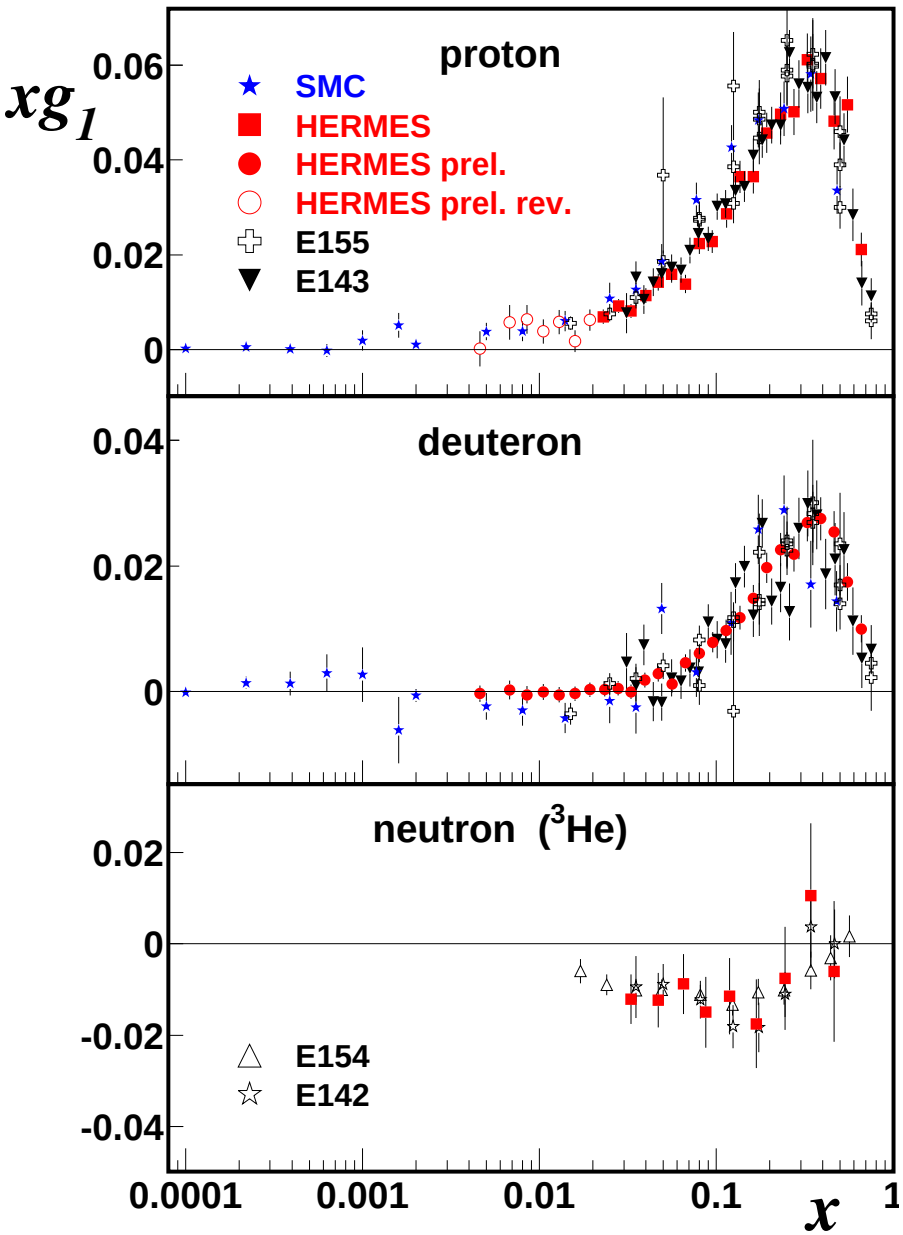
High quality data sample of polarised data plus a lot of data on heavy nuclei

Recent Results on $A_1^d(x)$



- High statistical precision
- no significant Q^2-dependence
- Different Q^2 from SMC
- Tensor polarised d data $\rightarrow$ analyse b_1

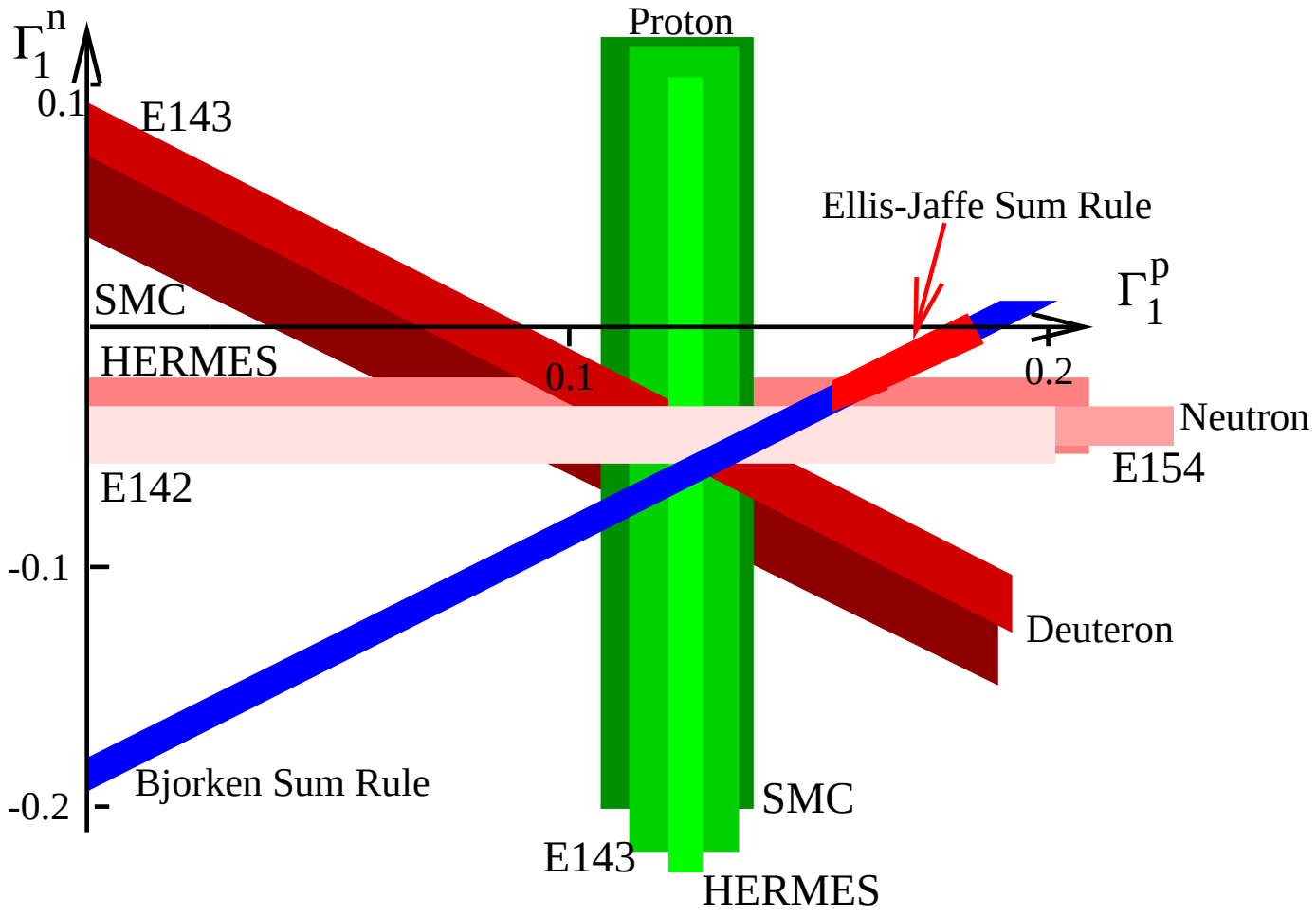
Nucleon Spin SF $g_1(x)$



- Most complete and precise data set for HERMES
- Almost final upshot of 10 year of world studies
- No big improvement is foreseen in the near future

→ Precise Determination of the Bjorken, Ellis-Jaffe, Generalized GDH sum rules

Bjorken sum rule



$$\Gamma_1^p = \int_{x=0}^{x=1} g_1^p(x)dx \quad \Gamma_1^n = \int_{x=0}^{x=1} g_1^n(x)dx$$

$$\int (g_1^p(x) - g_1^n(x))dx = \frac{1}{6}\frac{g_A}{g_V} \cdot \left[1 - \frac{\alpha_s(Q^2)}{\pi} - ...\right]$$

- Bjorken Sum Rule OK @ 10% level
- $\Delta\Sigma \approx 0.3$ small fraction of the nucleon spin is carried by quarks

GDH Sum Rule

The GDH sum rule relates the anomalous contribution κ to the magnetic moment of the nucleon (κ_{p}=1.79, κ_{n}=$-$1.91, κ_{d}=-0.143) with the total absorption cross sections for circularly polarised real photons on polarised nucleons:

$$\int_0^\infty \left[\sigma_{\uparrow\downarrow}(\nu) - \sigma_{\uparrow\uparrow}(\nu)\right]\frac{d\nu}{\nu} = -\frac{2\pi^2\alpha}{M^2}\kappa^2$$

Never been tested directly

The integral can be generalised to the absorption of virtual photons with energy ν and squared four-momentum $-Q^2$:

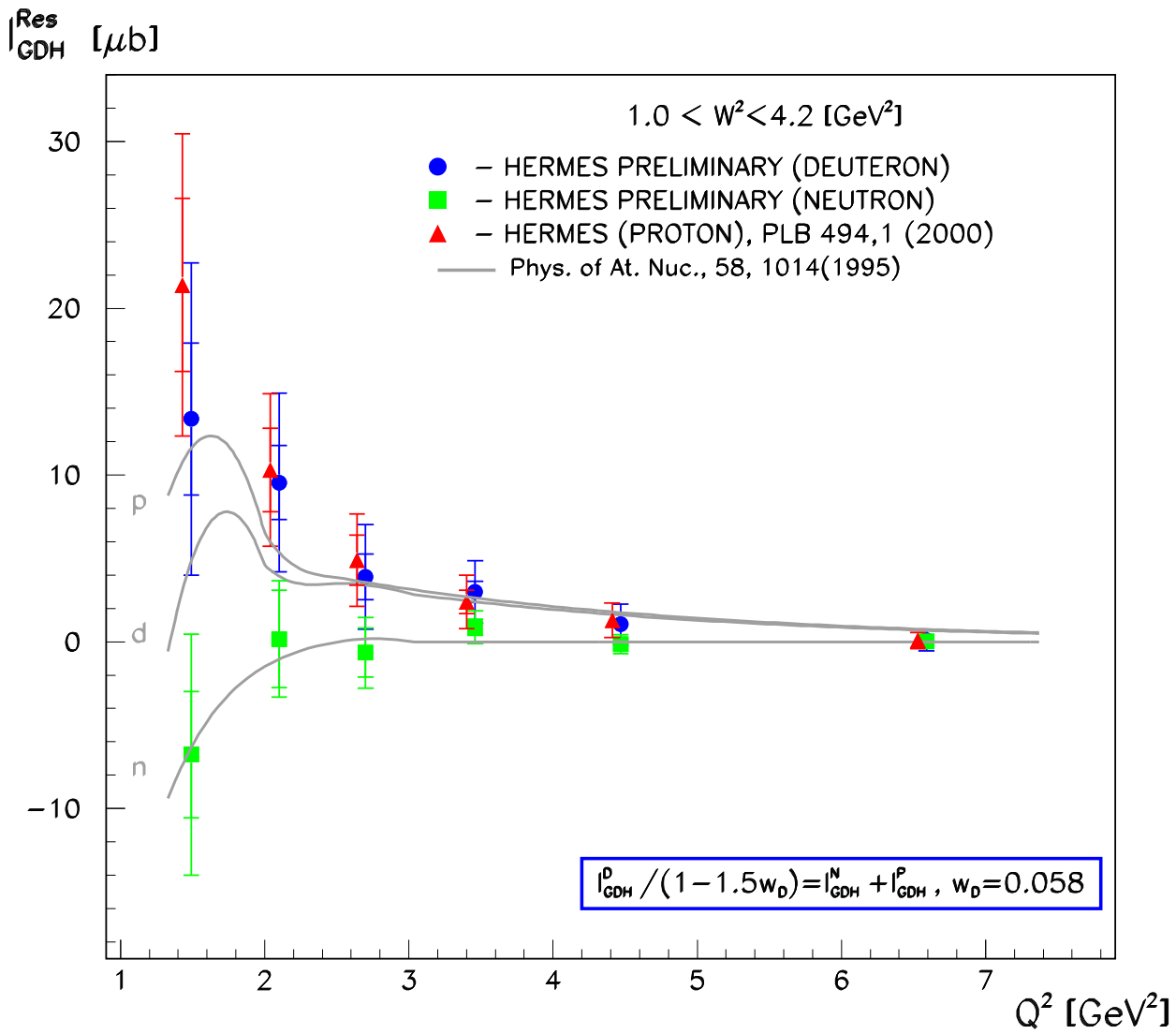
$$I(Q^2) \equiv \int_{Q^2/2M}^\infty \left[\sigma_{\uparrow\downarrow}(\nu,Q^2) - \sigma_{\uparrow\uparrow}(\nu,Q^2)\right]\frac{d\nu}{\nu}$$

$$= \frac{8\pi^2\alpha}{M}\int_0^1 \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{K}\frac{dx}{x}$$

$I(Q^2)$ connects the GDH expectation for real photon with the Ellis-Jaffe (or Bjorken in the case of p-n) in the asymptotic region

The Q^2 dependence of $I(Q^2)$ connects the static ground state properties of the nucleon with its helicity structure as measured in inelastic scattering in the resonance and deep inelastic regions

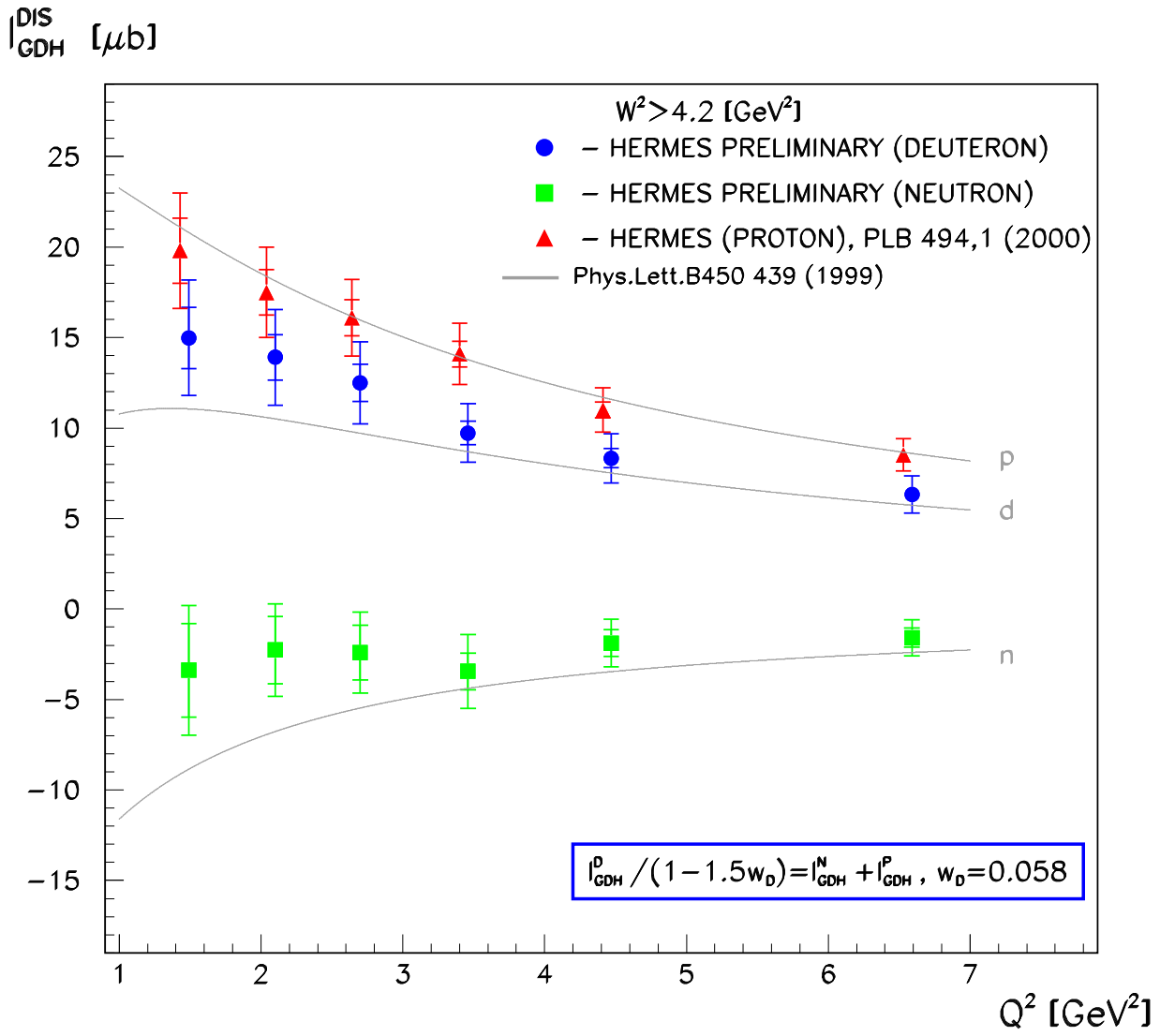
RES contribution to I_{GDH}



- I^{res}_{GDH} strongly decrease with Q^2 (strong reduction of the available x range for W^2 <4.2 GeV^2 as Q^2 increase)
- Comparison between models and data suggests that the resonance excitation models are not sufficient to well reproduce the experimental I^{res}_{GDH} for Q^2 <2.5 GeV^2

p: HERMES Collaboration, Phys. Lett. **B 494 (2000) 1**

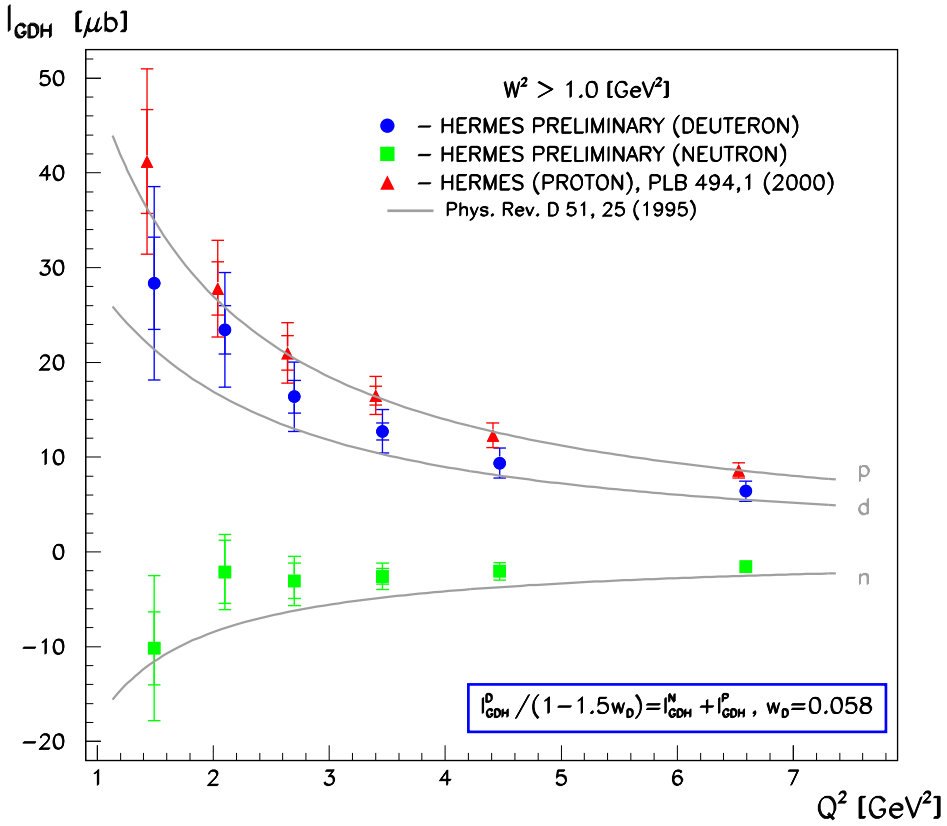
DIS contribution to I_{GDH}



- I^{DIS}_{GDH} sizeable down to the lowest measured Q^2
- Agreement with parameterisation for Q^2 >3 GeV^2

p: HERMES Collaboration, Phys. Lett. **B 444 (1998) 531**

Combined results from RES and DIS to I_{GDH}

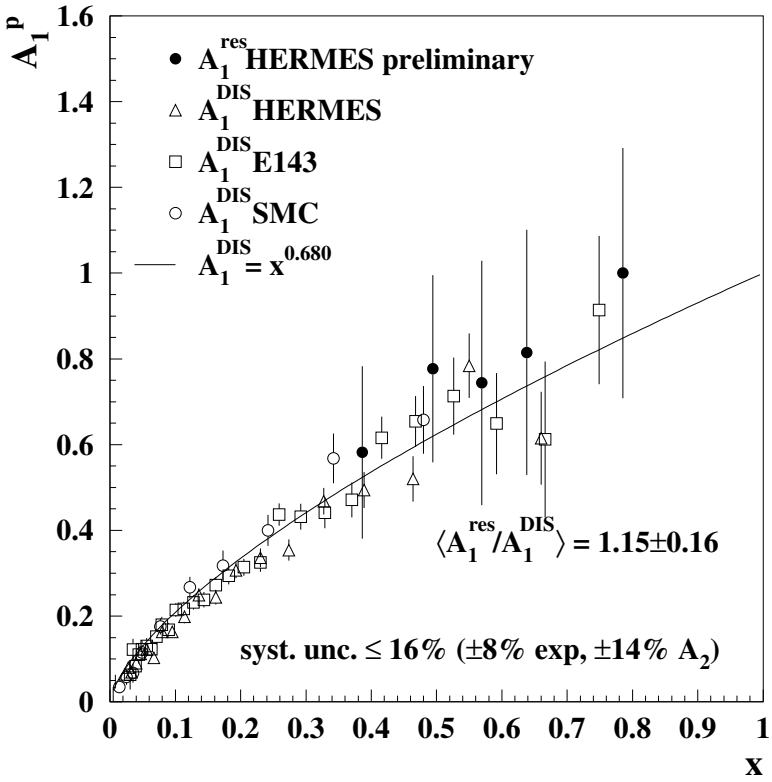


- Q^2-dependence of the generalised GDH integral for p, n and d determined for the first time in $1.2 < Q^2 < 12$ GeV^2
- Total I_{GDH} shows a $1/Q^2$ behavior $\longrightarrow$ no large effects from either resonances or non-leading-twist
- DIS contribution dominant for Q^2>3 GeV^2
- For Q^2 <2.5 GeV^2, existing resonance-excitation models are not sufficient to fully explain the experimental results for I^{res}_{GDH}
- The strong turn down of $I^{p,d}_{GDH}(Q^2)$ toward the real photon prediction of -204 μb and -0.65 μb should occur at Q^2 lower than 1.5 GeV^2

Quark-hadron duality (1)

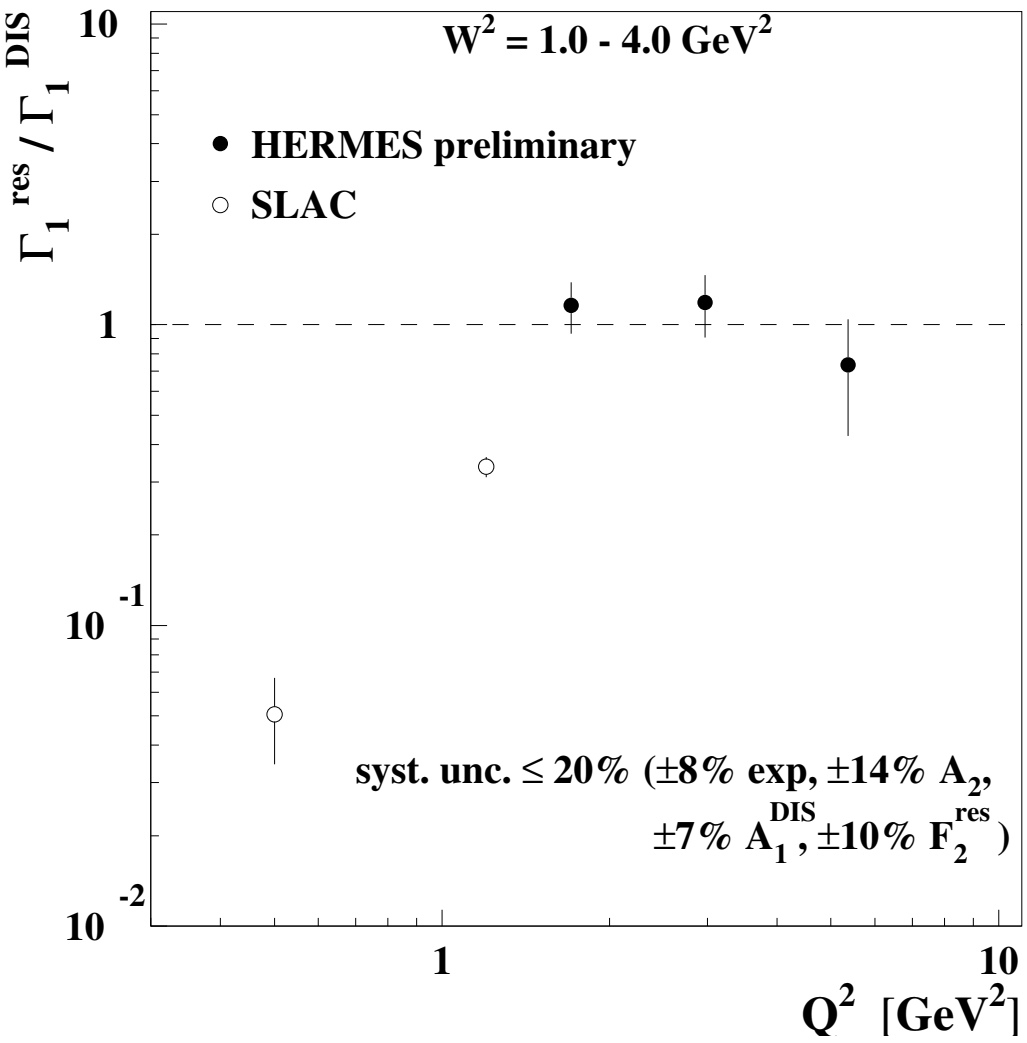
Asymmetry in Δ and N^* excitation should be driven by the resonance helicity structure (P_{33}, D_{13}, F_{15}, ..)

For $Q^2 > 1.5$ GeV, the resonance excitation strength averages to the global DIS scaling curve $\rightarrow$ Quark (x, Q^2) - Hadron (W, Q^2) duality for unpolarised SF



- $A_1^{DIS}(x,Q^2) \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)} \approx A_1^{DIS}(x)$ is increasing at large values of x and seems to exceed the SU(6) prediction of 5/9
- A_1^{res} in agreement within experimental errors with previous DIS data at higher Q^2 and W^2 (same x)
- The description of the spin asymmetry in terms of quark degrees of freedom is valid also in the resonance region for $Q^2 > 1.7$ GeV^2

Quark-hadron duality (2)



- Ratio $\Gamma_1^{\mathrm{Res}}/\Gamma_1^{\mathrm{DIS}}$ independent of Q^2 in HERMES region
- Duality holds for $Q^2 \approx 1.7$ GeV^2, as for the unpolarised case
- Results are not changing (inside errors) using the Nachtmann variable
- First study of Duality for polarised case g_1^{p}

SIDIS asymmetries (1)

Correlation between struck q_f and detected h

$$A_1^{\rm h}(x,Q^2) \simeq \frac{g_1^{\rm h}(x,Q^2)}{F_1^{\rm h}(x,Q^2)} = \frac{\int dz \sum_f e_f^2 \Delta q_f(x,Q^2) D_f^{\rm h}(z,Q^2)}{\int dz \sum_f e_f^2 q_f(x,Q^2) D_f^{\rm h}(z,Q^2)}$$

- $A_1^{\rm h}$ = Measured semi-inclusive asymmetry
- Δq_f (q_f) = Polarized (unpolarized) quark distributions
- $D_f^{\rm h}(z)$ = Fragmentation Functions (FF)
  $\Longrightarrow$ probability of a given flavor f to produce a given type of leading hadron

Unpolarized inputs:

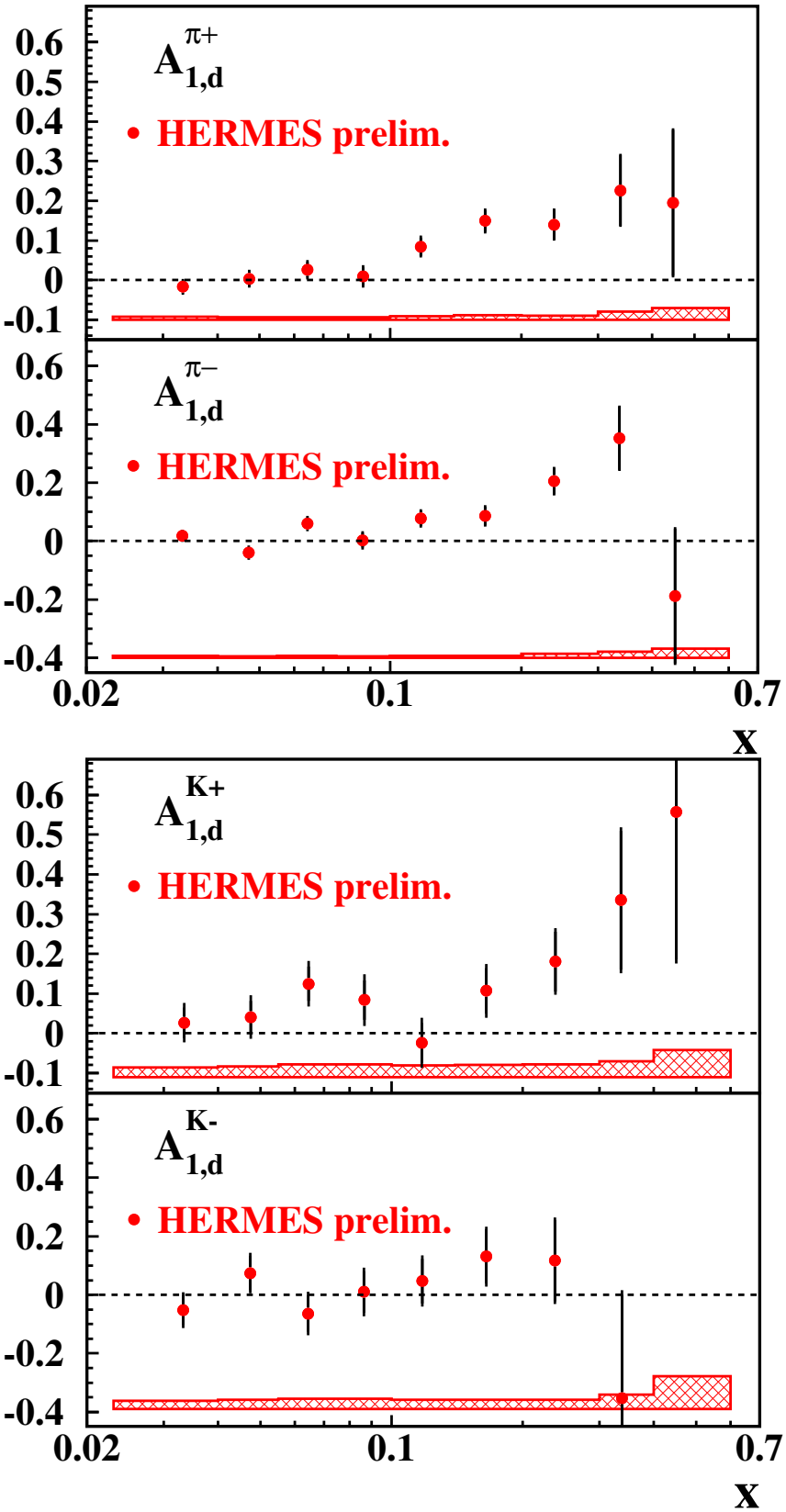
- $q_f(x,Q^2)$ parameterization (CTEQ5 LO)
- $D_f^{\rm h}(z,Q^2)$ from LUND MC

Can be rewritten in terms of a Purity matrix:

$$A_1^{\rm h}(x,z) = \sum_q P_q^{\rm h}(x,z) \frac{\Delta q(x)}{q(x)}$$

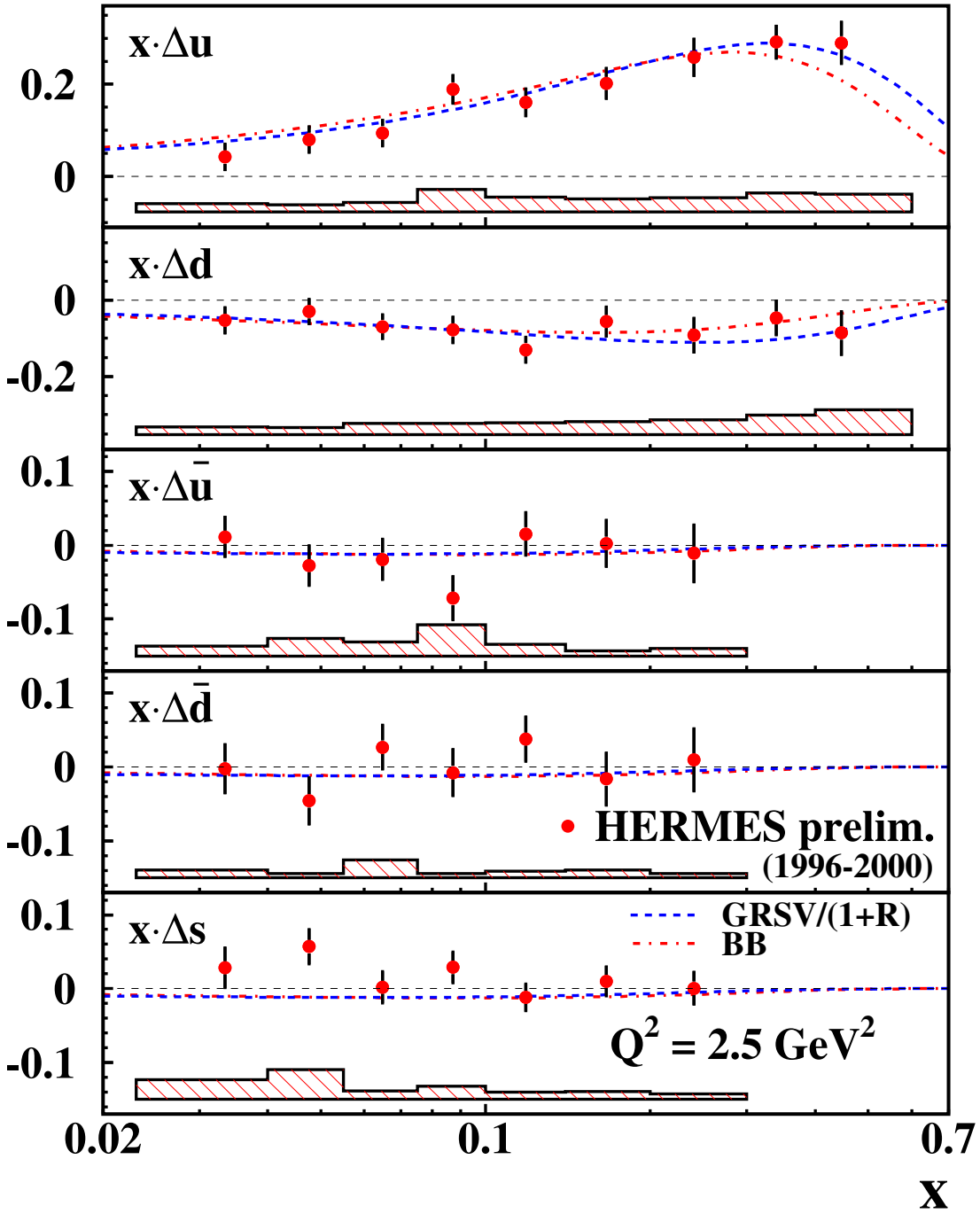
Purities $P_q^{\rm h}$ are spin-independent quantities and can be calculated in Monte Carlo

SIDIS asymmetries (2)



First measurement of π and K asymmetries

Polarised Quark Distr.



- u-quark positively polarised
- d-quark negatively polarised
- light sea quark polarisation small
- s-quark polarisation somewhat positive

→ First separation of the quark sea

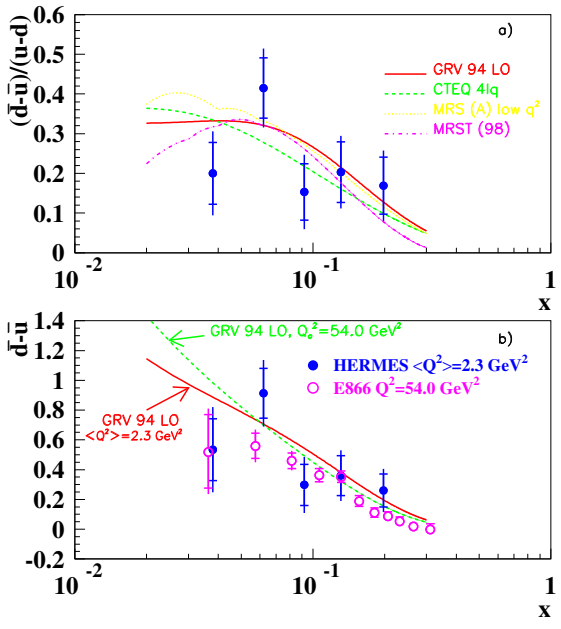
Polarised light sea

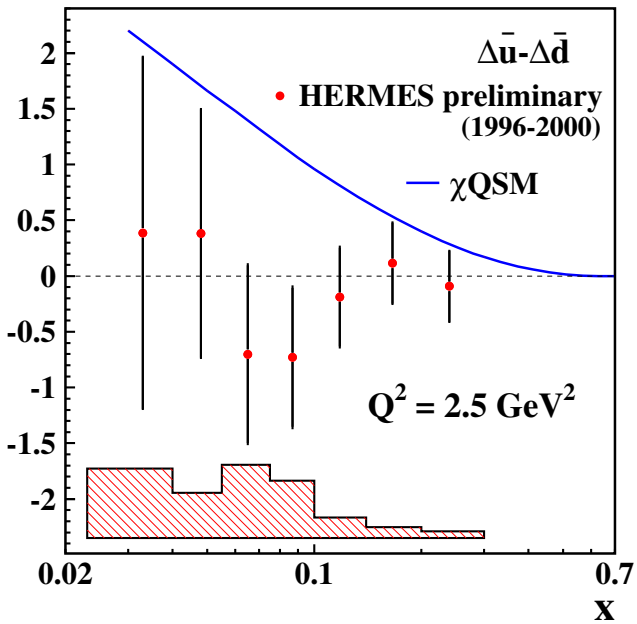
$(\bar{d}-\bar{u})/(u-d)$ found to be non-zero in x range measured $\Longrightarrow$ excess of $\bar{d}$ quarks over $\bar{u}$ quarks in the proton sea

$\int_{0.02}^{0.3}(\bar{d}(x)-\bar{u}(x))/(u-d)$=0.107±0.021±0.017 at Q_0^2=2.3 GeV^2 (accounts 2/3 of the Gottfried SR deficit)

The unpolarised light sea is not flavor symmetric $\overline{d} > \overline{u}$

Phys. Rev. Lett. 81 (1998) 5519

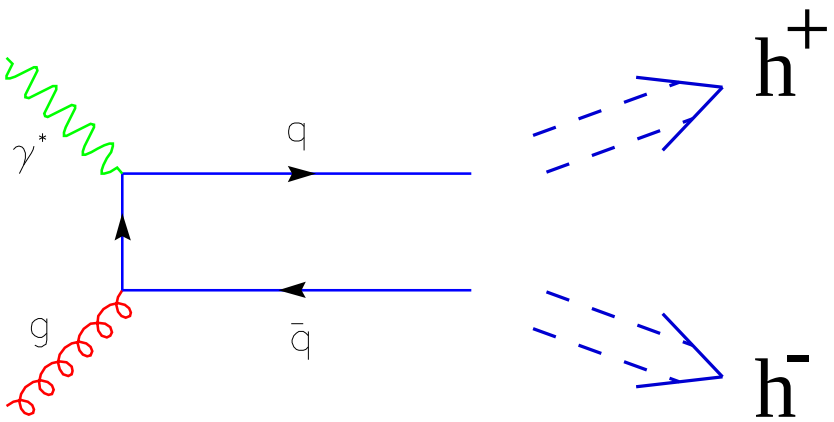




- Prediction for large breaking of $SU(3)_f$ for the polarised light sea (χQSM, statistical models, pQCD DIS analysis) while small breaking from pQCD analysis of DIS+SIDIS data
- Preliminary HERMES data do not favor large flavor symmetry breaking of the polarised light sea
- New data from future data taking

Gluon Contribution

- QCD analysis of inclusive DIS poorly constrains $\Delta G(x_G)$: predictions of different sign
- Photon Gluon Fusion process probes $G(x_G)$
- Spin asymmetry in PGF probes $\Delta G/G$

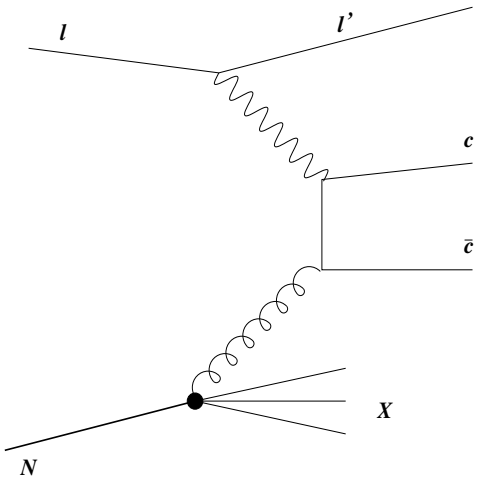


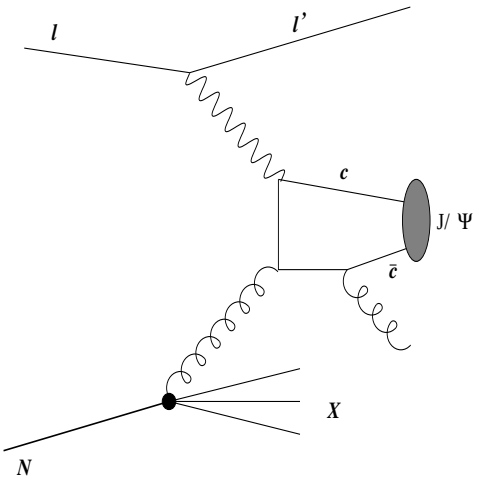
Possible experimental signatures for $G(x)$ or $\Delta G(x)$:

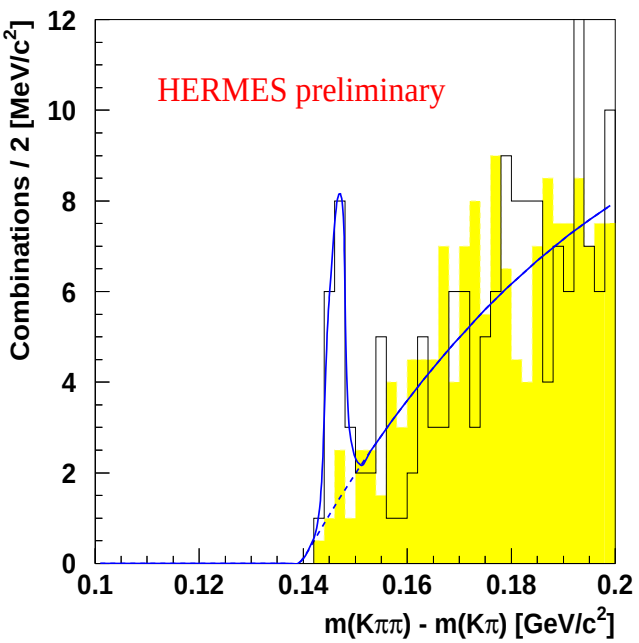
- Open and hidden charm: $\gamma^* G \to c\bar{c} \rightsquigarrow$ D, J/ψ
- Hadron pairs with large transverse momentum p_T

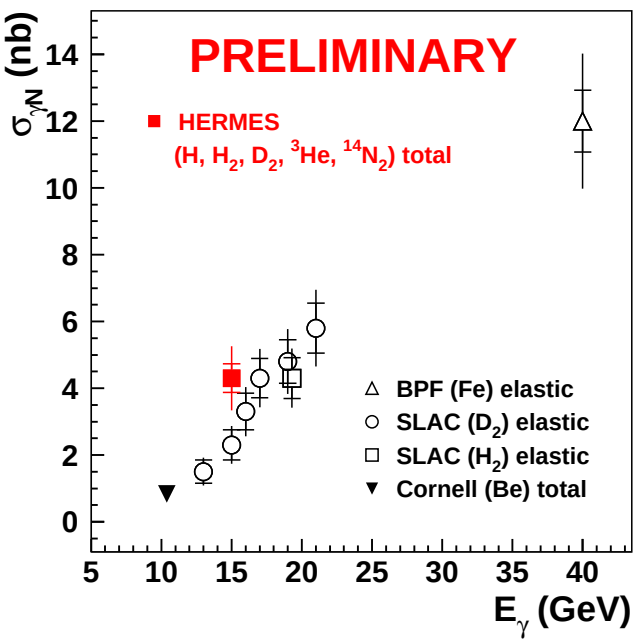
$$A_{||} = \frac{N^{\uparrow\downarrow}_{h^\pm} - N^{\uparrow\uparrow}_{h^\pm}}{N^{\uparrow\downarrow}_{h^\pm} + N^{\uparrow\uparrow}_{h^\pm}} \qquad A^{\gamma^* p \to h^\pm} \sim \Delta G/G$$

Charm Production









- Clear signature of open charm ($D^* \to D^0\pi^0$) and of hidden charm J/Ψ
- Charm production cross section is low in the HERMES energy range

$\Longrightarrow$ HERMES detector upgrade to improve charm detection

High p_T at HERMES

HERMES approach:

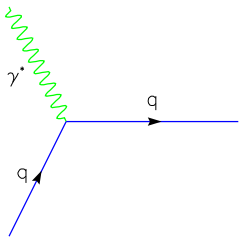
→ Measure asym of high p_T hadron pairs

→ Choose phase space where $(\gamma g \to q\bar{q})$ dominates

Require:

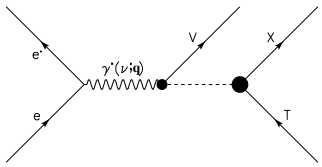
- at least one h^+ and one h^-
- high momentum ($p_{h^\pm}$ >4.5 GeV) and high p_T (p_T >0.5 GeV)
- $M(2h) > 1.0$ GeV, to remove ρ and ϕ resonances
- do not require scattered e^+ in the spectrometer
  ⇒ Photoproduction $Q^2 \approx 0$ (maximize cross sect.)

Assume four different processes may contribute (in LO QCD) to the high p_T $h^\pm$ pair production:



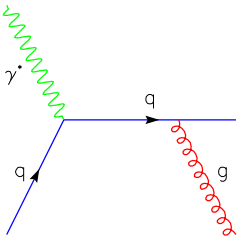
DIS

negligible



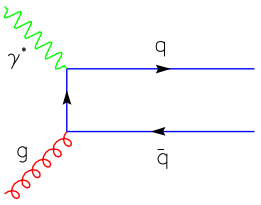
VMD

$A_{VMD} = 0$



QCDC

$A_{QCDC} \sim \frac{\Delta q}{q}$



PGF

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

$$A_{\parallel} = A_{\rm QCDC} f_{\rm QCDC} + A_{\rm PGF} f_{\rm PGF} + A_{\rm DIS} f_{\rm DIS} + A_{\rm VMD} f_{\rm VMD}$$

f_i evaluated by MC → PGF dominates for $p_T > 1$ GeV

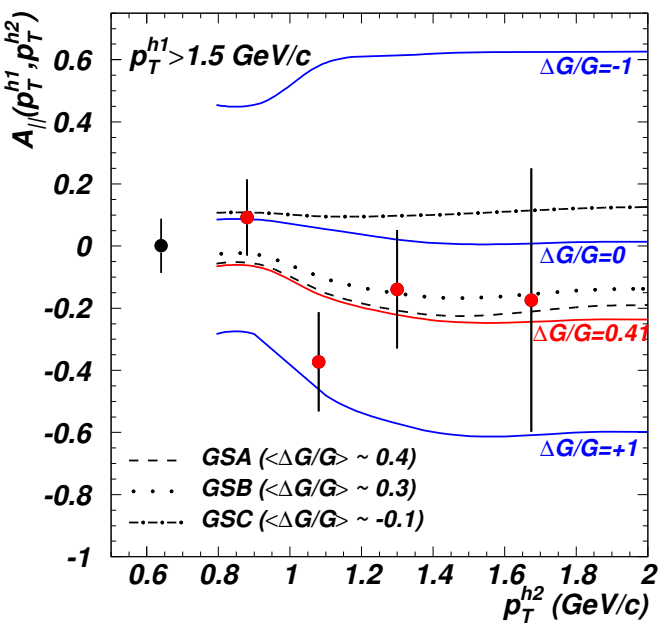
$f_{DIS} \sim 0$, $A_{VMD} \sim 0 \Longrightarrow$

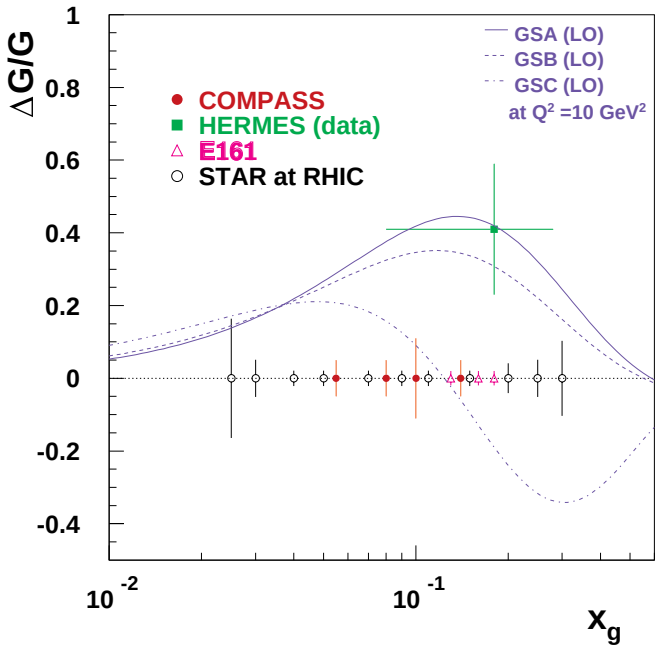
$A_{||} \approx A_{\rm QCDC} f_{\rm QCDC} + A_{\rm PGF} f_{\rm PGF}$

$A_{QCDC} = a(\gamma q \to qg)\Delta q/q \sim +0.5 \Delta q/q$

$A_{PGF} = a(\gamma g \to q\bar{q})\Delta G/G \sim \Delta G/G < 0$

First result for $\Delta G/G$





- Observed negative asymmetries in contrast to the positive DIS asymmetries
- Extraction strongly Model dependent

$\Delta G/G$ is positive

$\Delta G/G = +0.41 \pm 0.18 \pm 0.03$

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

Phys. Rev. Lett. 84 (2000) 2584

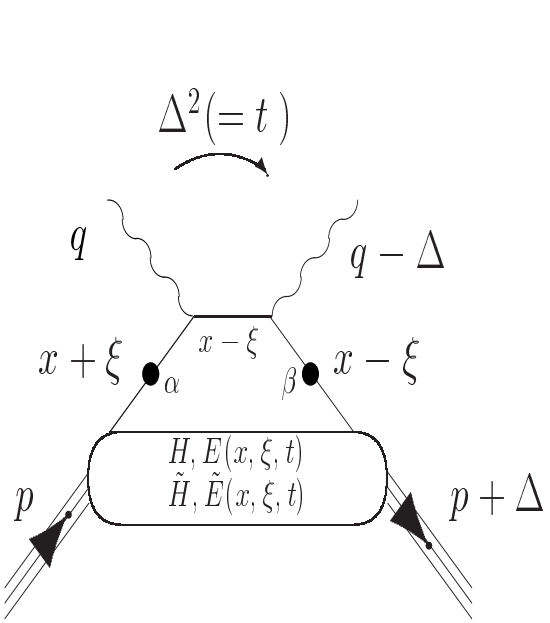
Ongoing analysis on high p_T deuteron data

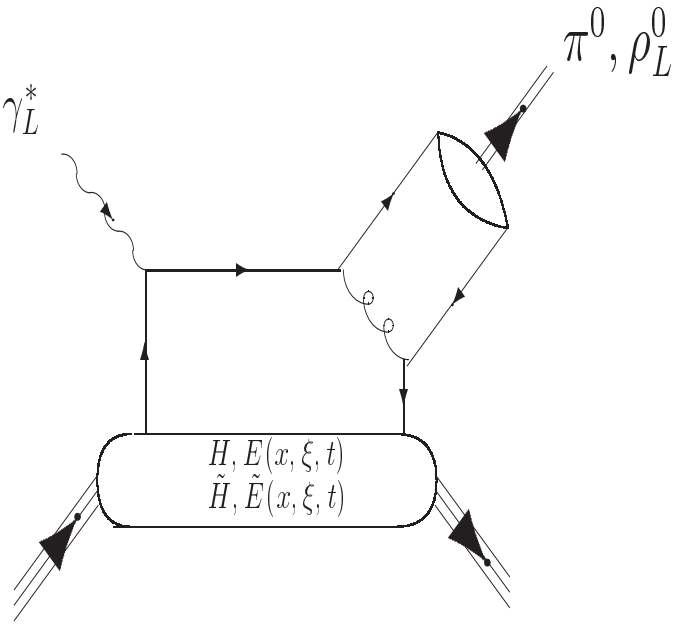
Gluon polarization will be studied at COMPASS, SLAC and RHIC by measuring the open charm production and the high-p_T hadron pairs in the photon-gluon fusion in $\vec{\gamma} + \vec{p}$ experiments and in the direct γ production and two-jet events in $\vec{p} + \vec{p}$ experiments

Exclusive processes

HERMES $\Longrightarrow$ mainly designed for SIDIS to study ordinary polarized parton distributions

Recently $\Longrightarrow$ study Genaralised Parton Distribution GPD via exclusive processes



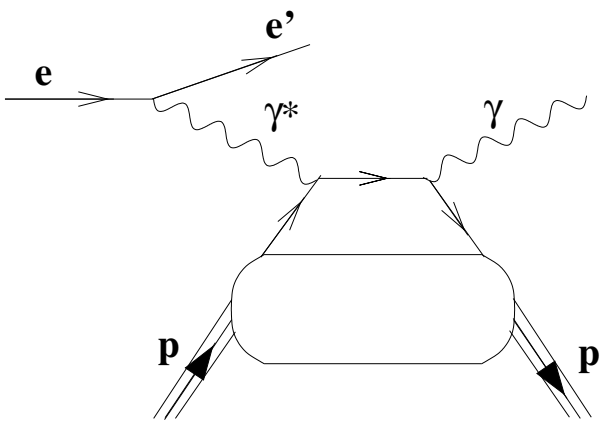


Quantum numbers of final states $\rightarrow$ select different GPD

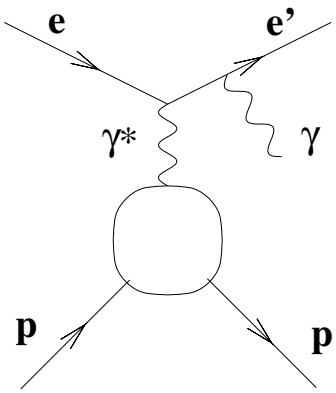
- Vector mesons : $\rho_L^0 \rightarrow$ unpol. GPD E, H
- Pseudoscalar mesons : $\pi^0 \rightarrow$ pol. GPD $\tilde{E}, \tilde{H}$
- Pseudoscalar mesons : $\pi^+ \rightarrow$ pol. GPD + pion pole
- DVCS : $\gamma \rightarrow$ pol. and unpol. GPD $\tilde{E}, \tilde{H}, E, H \rightarrow$ information on the orbital angular momentum contribution to the nucleon spin

$$\frac{1}{2} = \frac{1}{2}\Sigma + \Delta G + Lq/g$$

DVCS



DVCS process



Bethe-Heitler process

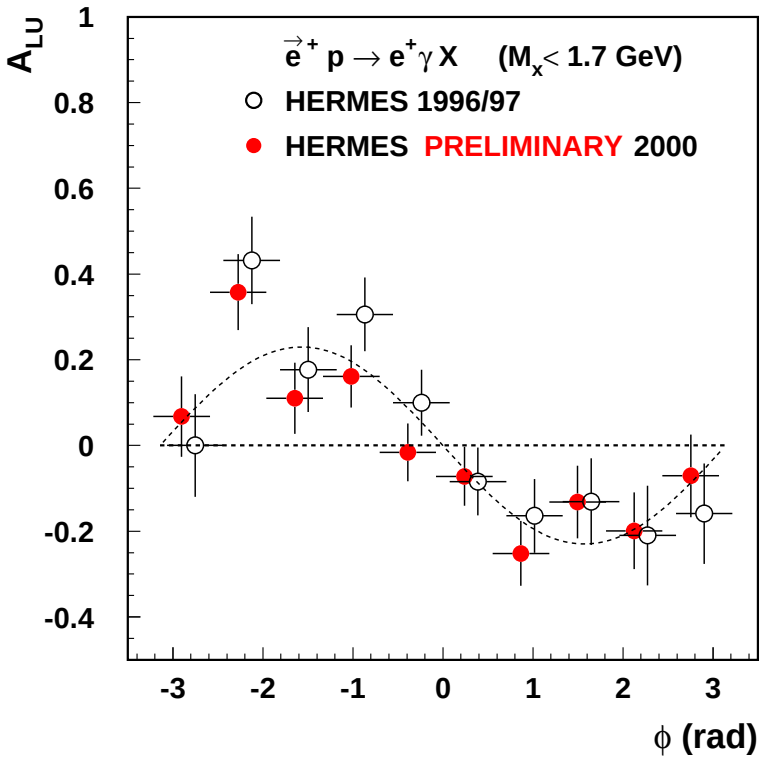
Amplitudes add up coherently, BH dominant
$\rightarrow$ access to real and imaginary parts of amplitudes throught interference by measuring asymmetries in ϕ_γ, the azimuthal angle between scattering plane and reaction plane

Beam spin asymmetry
Imaginary part of interference
Pol. beam, unpol. target
$\propto sin\phi$

Beam charge asymmetry
Real part of interference
e^+ vs e^-
$\propto cos\phi$

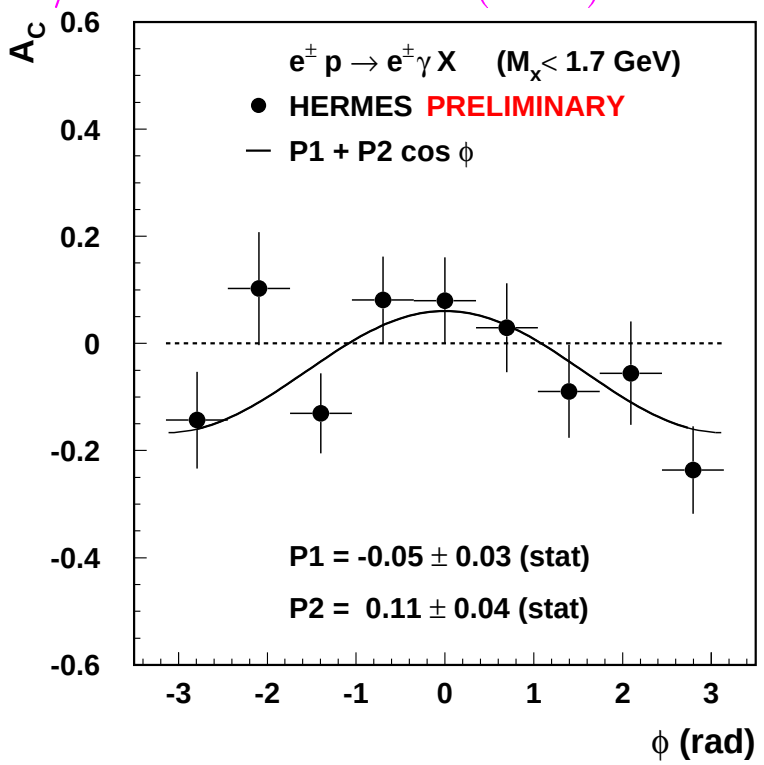
Use of $sin(\phi_\gamma)$ and $cos(\phi_\gamma)$ to moments to extract imaginary and real parts of DVCS amplitude

DVCS: ϕ dependence



Beam spin asymmetry

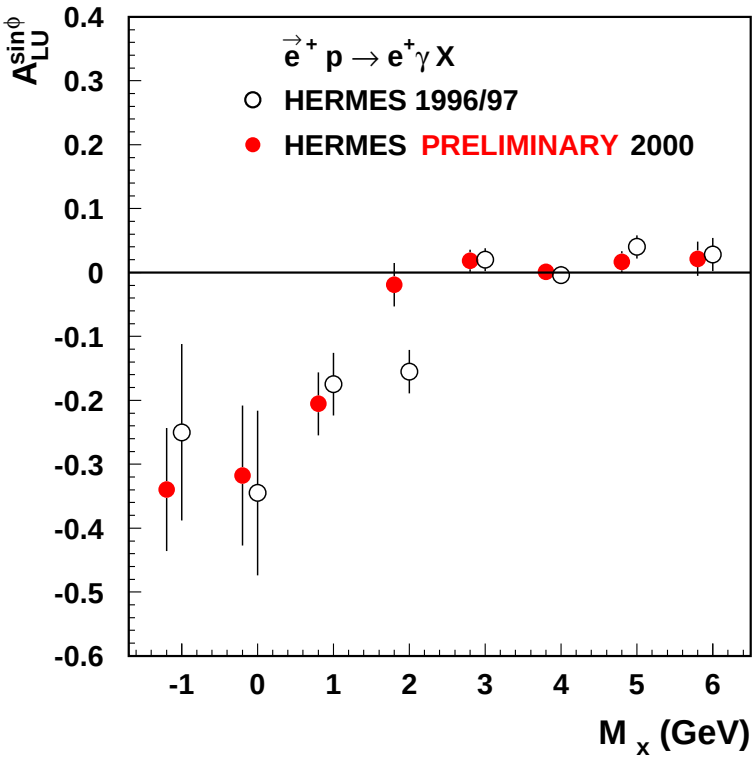
96/97 data in PRL 87 (2001) 182001



Beam charge asymmetry

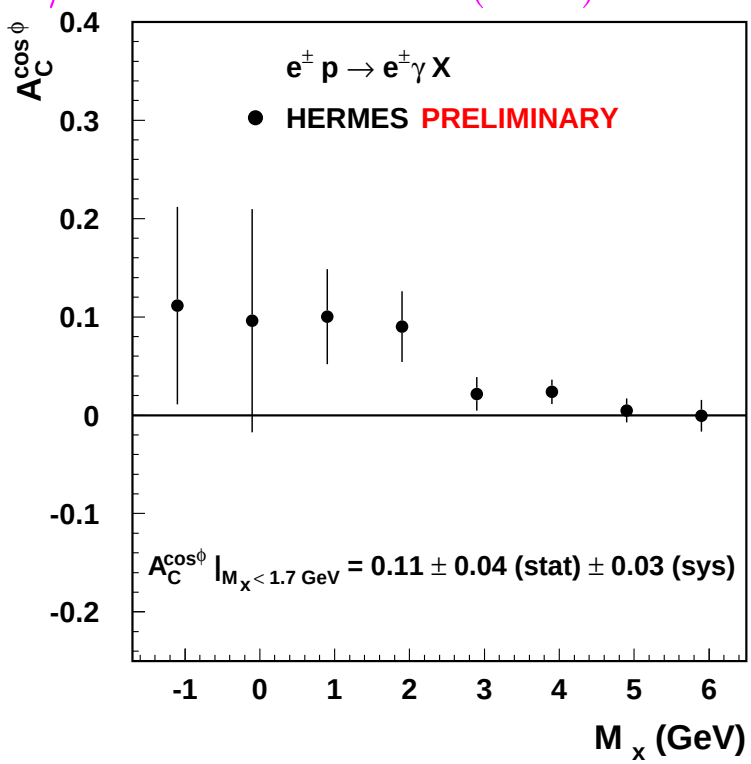
5 millions DIS events, 4000 DVCS-type events

DVCS: MM dependence



Beam spin asymmetry

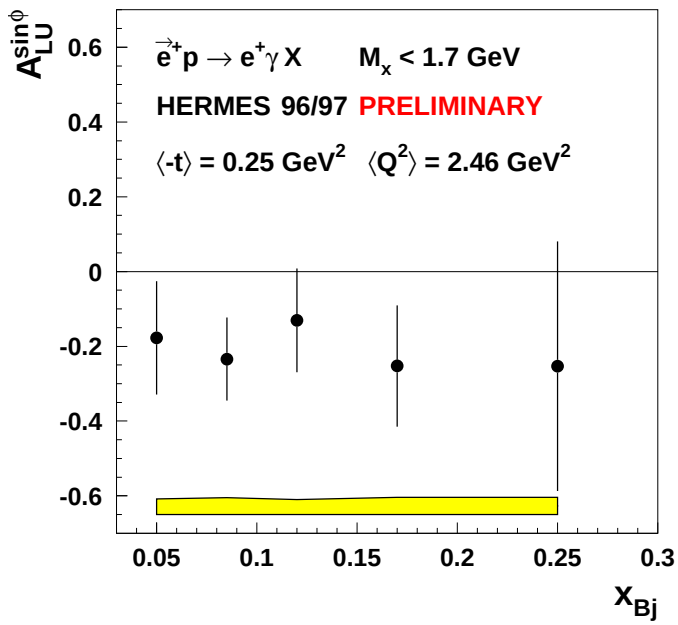
96/97 data in PRL 87 (2001) 182001

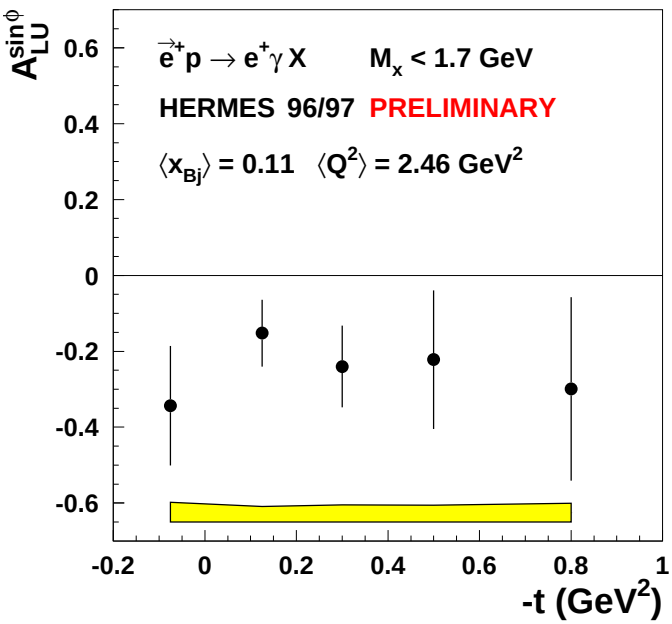


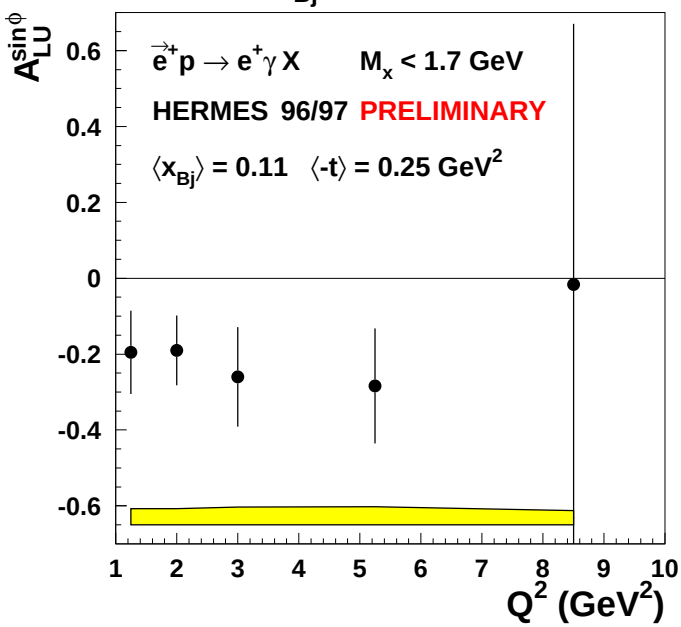
Beam charge asymmetry

Exclusive bin: $-1.5\ \mathrm{GeV} < M_x < 1.7\ \mathrm{GeV}$

DVCS: SSA kinem. dependence







- First kinematic dependences of DVCS Single Spin Asymmetry
- No significant x, t or Q^2 dependence observed
- t dependence limited by resolution
  $\Rightarrow$ Recoil Detector

Other Physics Results

Polarised Physics Program:

- Longitudinal Spin Transfer to Λ
  Phys. Rev. D64 (2001) 112005
- Spin asymmetries in diffractive Vector Meson Production
  Phys. Lett. B513 (2001) 301

Unpolarised Physics Program:

- Multiplicity and Fragmentation Functions EPJ C21 (2001) 599
- Vector Meson Production (VMP)
- Fragmentation Functions for light quarks $\longrightarrow \pi$, K, P, Λ
- Longitudinal and Transverse Polarization of Λ

Nuclear Physics Program:

- Diffractive VMP (coherence length effect)
  Phys. Rev. Lett. 82 (1999) 3025
- $\sigma^{N/He/Kr}/\sigma^{D} \longrightarrow$ HERMES effect on σ_L/σ_T
  Phys. Lett. B475 (2000) 386
- Measurement of the hadron formation times in the fragmentation process
  EPJ C20 (2001) 479

Summary

Inclusive measurements

- Structure Functions $g_1^{p,n,d}$
- Generalised GDH SR in Resonance and DIS regions
- First test of duality for polarised SF

Semi-Inclusive measurements

- Δu positive, Δd negative, Δq_{sea} small
- RICH $\rightarrow$ first separation of the quark sea
- $\Delta\Sigma$=0.30 $\Longrightarrow$ Rest ?
  Gluons (ΔG), orbital angular momentum ($L_z^{q,g}$)

Gluon contribution to the spin

- $\Delta G/G$ positive at $\langle x_G \rangle = 0.17$
- Results from longitudinal $\overrightarrow{\mathrm{D}}$
  $\Longrightarrow$ enhanced stat., diff. signal/background
- RICH + μ wall $\Longrightarrow$ J/Ψ, $\Delta G/G$ at $x_G \sim 0.3$

Exclusive reactions

- Beam Spin Asymmetry in DVCS
- First meas. of Beam Charge Asymmetry in DVCS
- BSA for DVCS on d under investigation
- Study of Target Spin Asymmetry for DVCS on d as well

Future

- 2002-2004: data on transverse target
- $>$ 2004: installation & data taking with Recoil Detector