Quark-Hadron Duality and Q^2 evolution of the GDH integral in the HERMES experiment

Electron-Nucleus Scattering VII

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on behalf of the HERMES Collaboration

- Concept of Duality
- Duality in unpol. & pol. structure functions
- HERMES analysis and results
- The GDH sr and its extension for virtual photons
- Results for the measurement of the resonance contribution to the GDH sum rule for p, n and d
- Results of first determination of the DIS contribution to the GDH sum rule for p, n and d
- Conclusions

Concept of Duality (1)

DUALITY = RELATION BETWEEN DIS AND RESONANCE REGIONS

Bloom & Gilman, PRL 25 (1970) 1140; PR D4 (1971) 290

The curve measured in DIS processes at high Q^2 is in average equal to the curve measured in the nucleon resonance region at lower Q^2 for a fixed range of the Bjorken variable scaling x.

Originally formulated for hadron-hadron scattering $\longrightarrow$ relationship between s and t channel behaviors of scattering amplitude

low energy: $A(s,t) = \Sigma_{\rm res} A_{\rm res}(s,t)$

high energy: $A_{|\rm R}(s,t) \sim s^{\alpha(t)}$ $\qquad \alpha(t) = \alpha(0) + \alpha' t$

$$\Sigma_{\rm res} A_{\rm res}(s,t) \approx \Sigma_{|\rm R} A_{|\rm R}(s,t)$$

Dolen, Horn & Schmid, PRL 19 (1967) 402; PR 166 (1968) 1768

Veneziano, Nuovo Cimento 57A (1968) 190

Later $\longrightarrow$ generalisation of s and t channel duality, including both resonant and non resonant contributions to cross section Harari, PRL 20 (1968) 1395

In inclusive electron scattering $\longrightarrow$ duality between resonances and valence quarks, with the background dual to the sea quarks

Concept of Duality (2)

pQCD:
BG duality reformulated in OPE $\longrightarrow$ weak dependence of F_2 low momenta indicates that non-leading terms do not play a major role even at low Q^2 (~ 1 GeV^2)

De Rujula, Georgi & Politzer, PL B64 (1976) 428

Duality is used to describe the rare cases where the average of hadronic observables is described by a pQCD calculation (i.e. DIS)
pQCD picture in inelastic electron scattering must fail for $Q^2 \to 0$

- breakdown of duality at sufficiently low Q^2
- details of duality expected to be process dependent

Close & Isgur, PL B509 (2001) 81; Isgur *et al.*, PRD 64 (2001) 054005

Check of Duality

Comparison between integrals of the structure function in DIS and resonance regions, in the same x interval

$$I(Q^2) = \int_{x_m}^{x_M} F_2^{\mathrm{Res}}(x)\, dx$$

$$S(Q^2) = \int_{x_m}^{x_M} F_2^{\mathrm{Scaling}}(x)\, dx$$

$(x_M - x_m)$ delimited by $\Delta \mathrm{W}^2$ region

$R = I/S$ independent of $Q^2 \Longrightarrow$ first test of duality

- Resonances oscillate around an average scaling curve
- The resonance strengths average to a global scaling curve if averaged over large kinematic region
- Resonance region can be described in terms of quark degrees of freedom

Distinction between resonance & DIS region is artificial

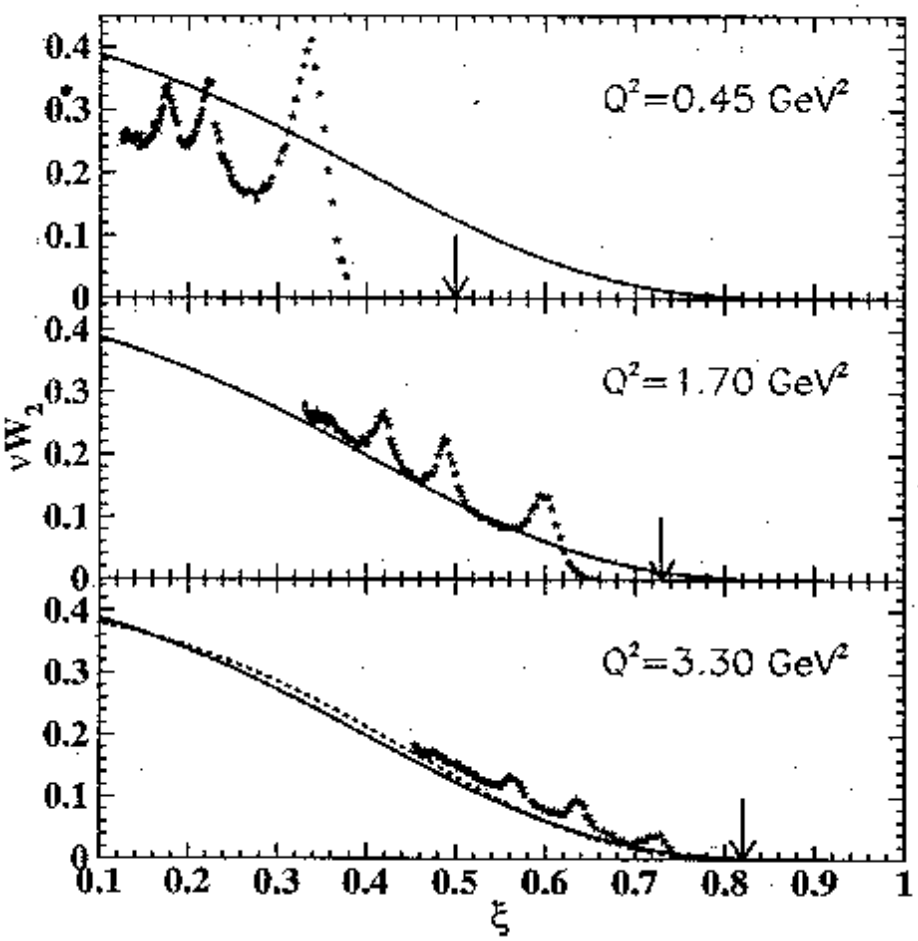
Duality in unpolarised structure function (1)

R = const. (inside of errors) for $Q^2 > 4$ GeV^2

Carlson & Mukhopadhyay, PR D47 (1993) 1737

New data from JLAB in 2000

Niculescu *et al.*, PRL 85 (2000) 1182; PRL 85 (2000) 1186

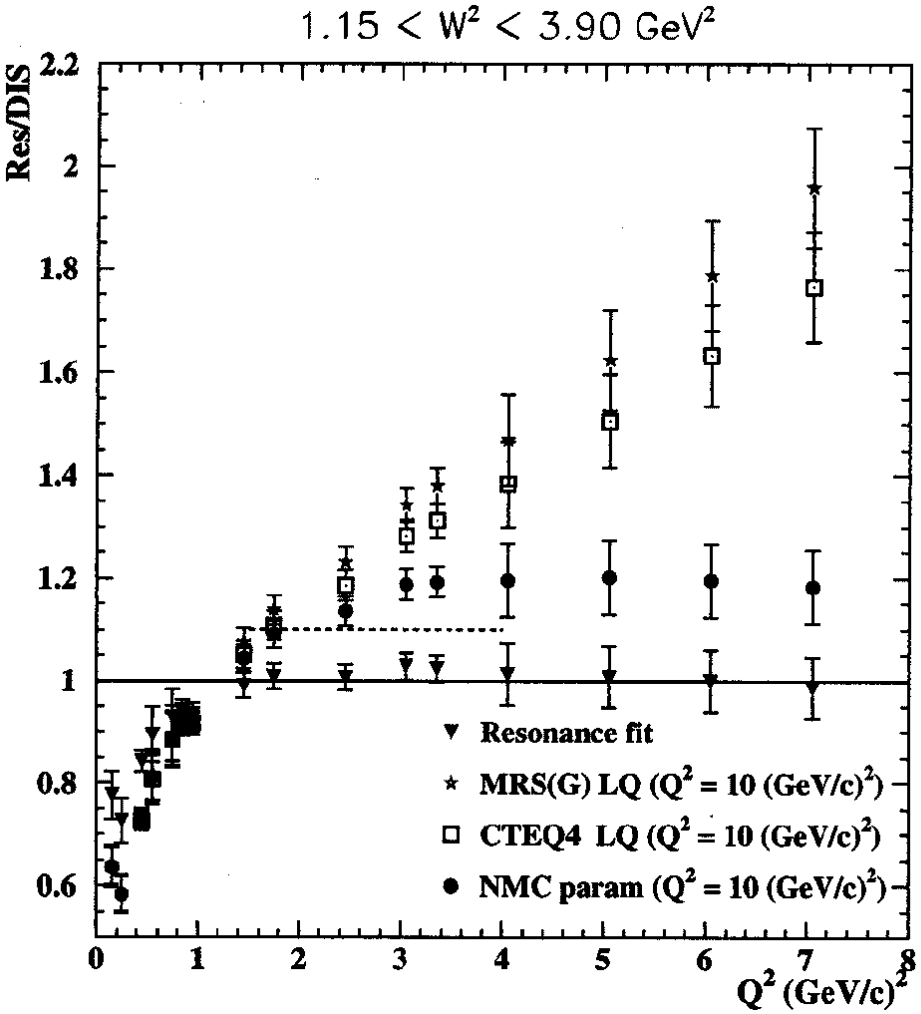


Resonance spectra at different Q^2 appear at different x (or ξ) on DIS curve; DIS curve represents average of data (manifestation of Bloom and Gilman observation)

Duality in unpolarised structure function (2)

Quantification of observed duality →

Q^2 dependence of the ratio of the $F_2^{\mathrm{Res}}/F_2^{\mathrm{DIS}}$ integrated from pion threshold to DIS onset in the same region of the Bjorken variable x:



In all cases the ratio R drops for $Q^2 < 1.5$ GeV^2

Duality in polarised structure function (1)

Interest for Duality in the polarised case started in 1998

Carlson & Mukhopadhyay, PR D58 (1998) 94029

"Data with polarised structure functions in the resonance region at higher Q^2 can throw significant new light on the issue of duality.
Facilities such as TJNAF, SLAC and HERMES can all contribute over a significant range in Q^2 and W^2."

Experimental situation $\longrightarrow$ only 2 points from SLAC:

$$Q^2 = 0.5 \text{ GeV}^2 \longrightarrow \Gamma_1^p = 0.022 \text{ GeV}^{-2}$$
$$Q^2 = 1.2 \text{ GeV}^2 \longrightarrow \Gamma_1^p = 0.039 \text{ GeV}^{-2}$$

E143 Collaboration, PR D58 (1998) 112003

Quark-hadron duality in spin structure function non trivial for the different helicities amplitude of the nucleon resonance

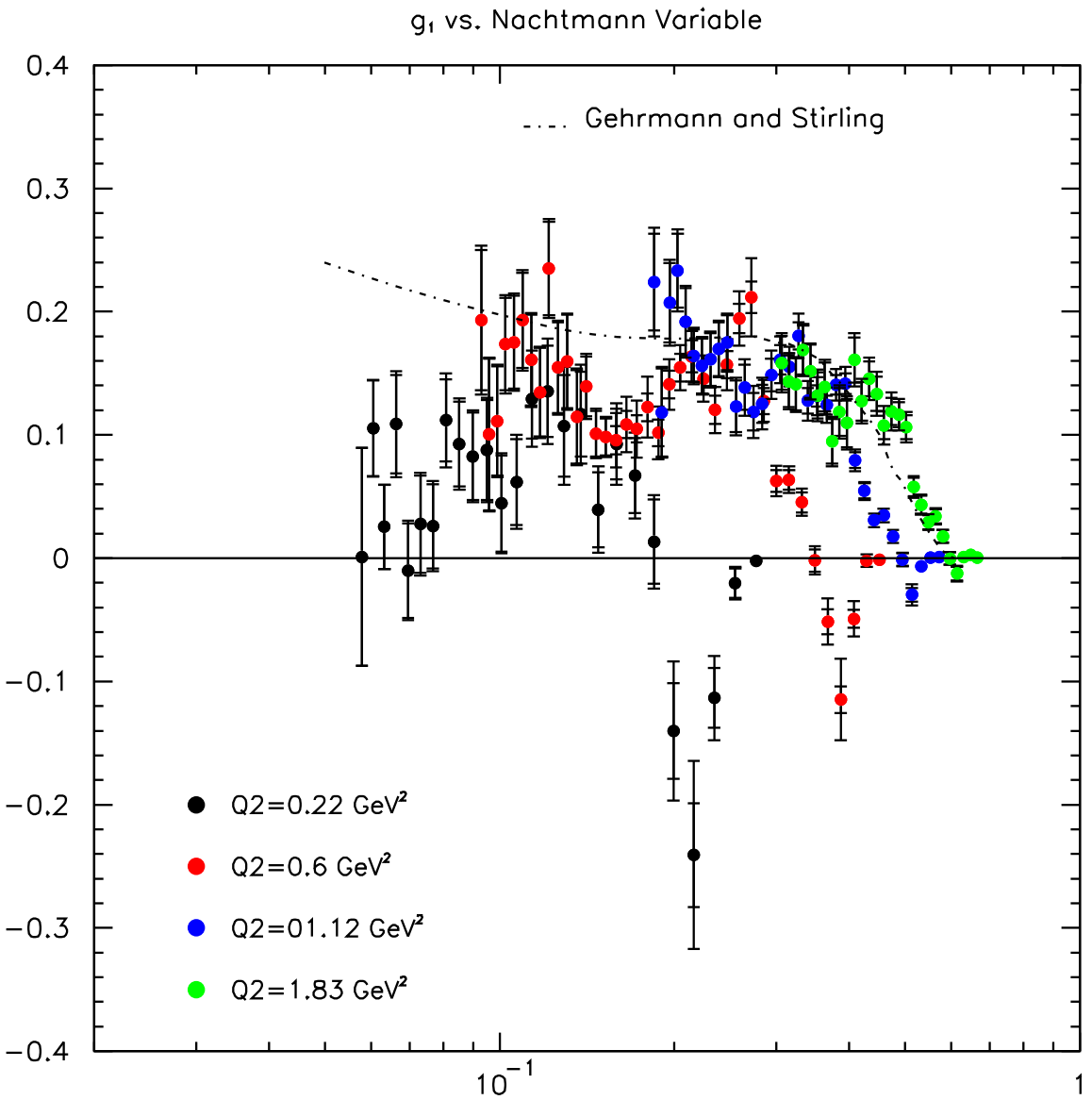
The Δ resonance is the dominant nucleon resonance in the photon case (Q^2=0) and has opposite helicity of the polarised DIS processes

Duality in polarised structure function (2)

Jlab/CLAS E=2.4/4.3 GeV

V. Burkert, Santorini, October 2-7, 2001

$g_1(\xi, Q^2)$



Approach to duality in highest Q^2 bin only
($Q^2 = 1.8$ GeV^2)

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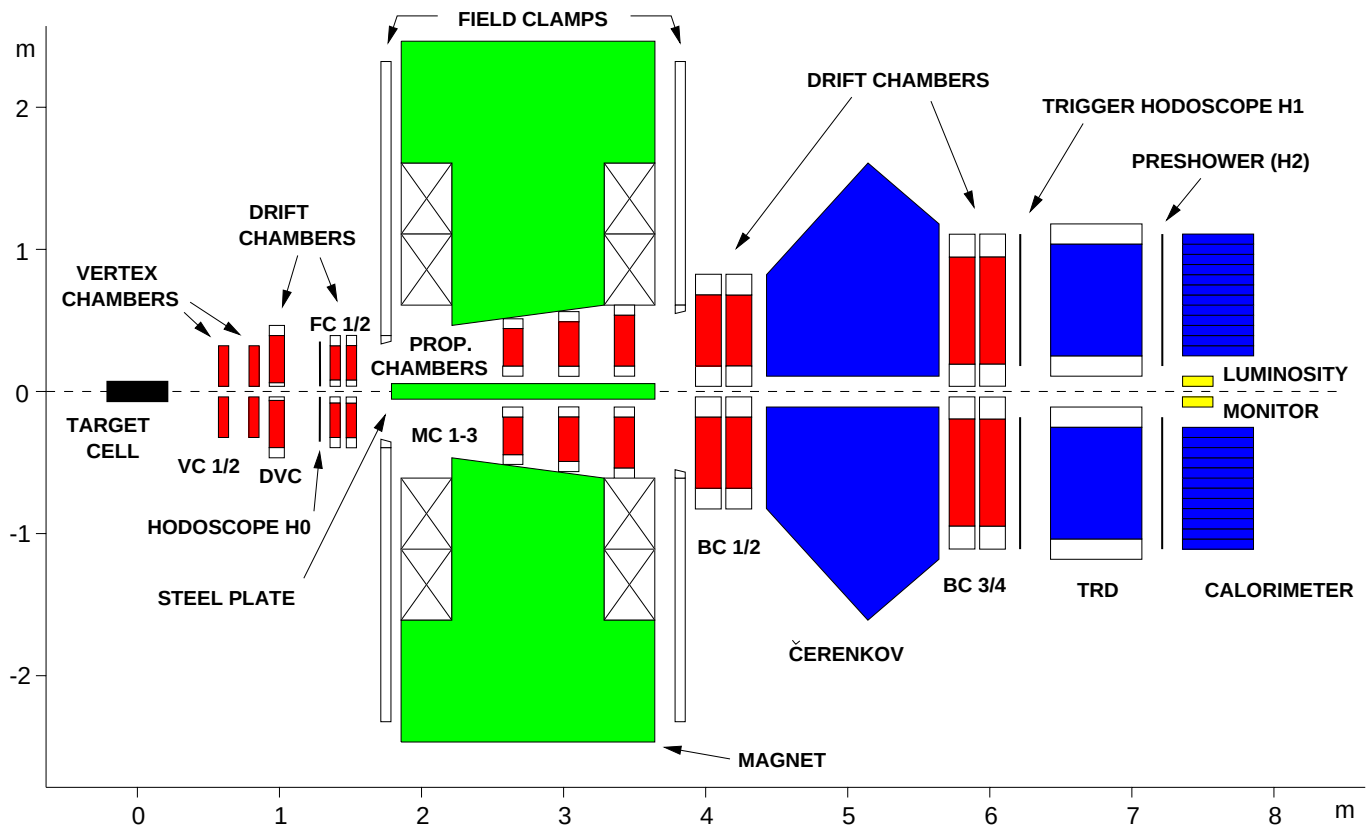
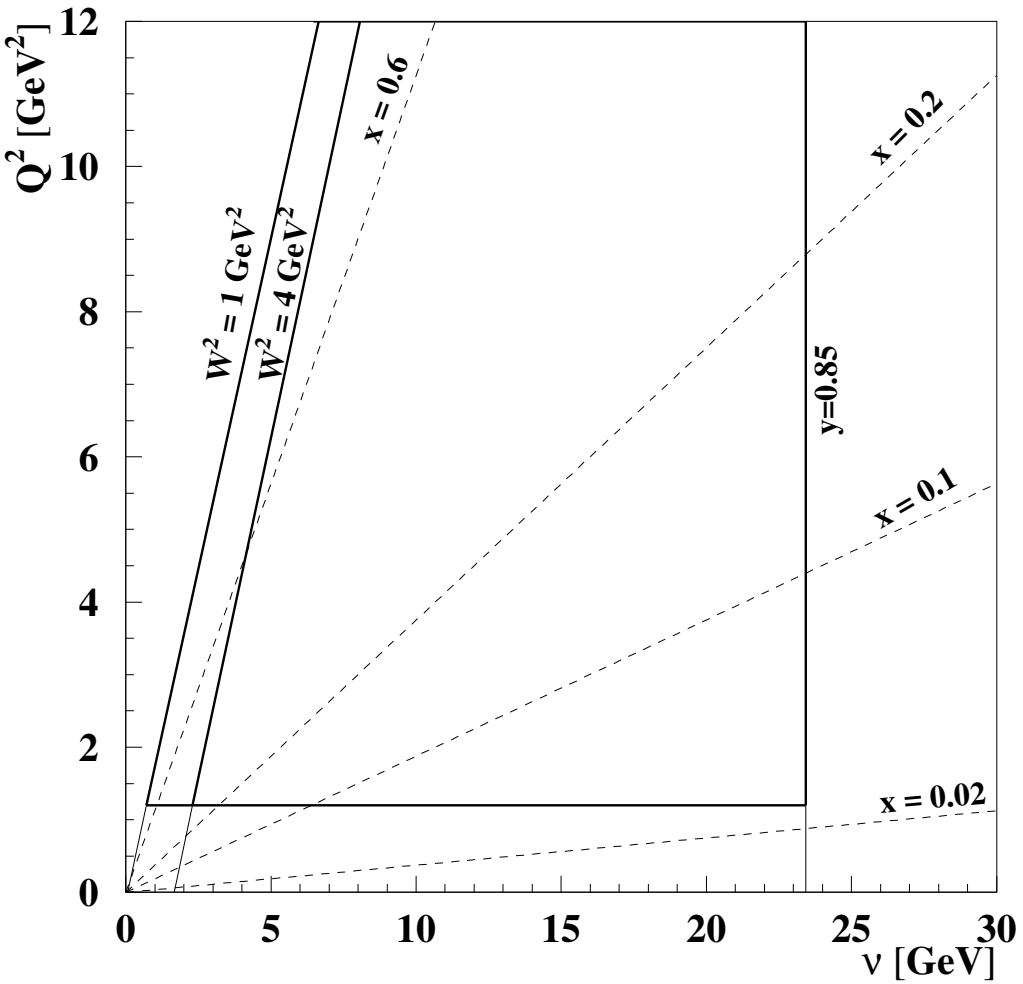
HERMES experiment



- Forward dipole spectrometer:
  1.5 Tesla·m , $40 < \theta < 220$ 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 kinematic



Kinematic region:

$$1.2 \leq Q^2 \leq 12 \text{ GeV}^2$$

$$1 \leq W^2 \leq 4 \text{ GeV}^2$$

HERMES Analysis: g_1^{Res} and g_1^{Scaling}

$$g_1^{\mathrm{Res}}(x,Q^2) = \mathrm{A_1(x)} \cdot \mathrm{F_1(x,Q^2)}$$

- $\mathrm{A_1} = \mathrm{A_{\parallel}} \;/\; \mathrm{D} - \eta \cdot A_2$
- $\mathrm{F_1} = \mathrm{F_2} \;/\; [2\mathrm{x}(1+\mathrm{R})]$

  $\mathrm{R} = 0.18 \;;\; \mathrm{F_2} = \mathrm{F_2^{Res}}$

  Bodek *et al.*, PR D20 (1979) 1471

$$g_1^{\mathrm{Scaling}}(x,Q^2) = \mathrm{A_1^{DIS}(x)} \cdot \mathrm{F_1(x,Q^2)}$$

- $\mathrm{A_1^{DIS}} = \mathrm{x}^{\alpha} \longrightarrow A_1^{\mathrm{DIS}} \neq f(Q^2)$
- $\mathrm{F_1} = \mathrm{F_2} \;/\; [2\mathrm{x}(1+\mathrm{R})]$

  $\mathrm{R} = \mathrm{R(x,Q^2)} \;;\; \mathrm{F_2} = \mathrm{F_2^{DIS}}$

  L.W. Whitlow *et al.*, PL B250 (1990) 193;

  NMC, PL B364 (1995) 107

HERMES Analysis: g_1^{Res} and g_1^{Scaling}

$$R_i = I_i / S_i$$

$$I_i(Q^2) = \int_{x_{\mathrm{min_i}}}^{x_{\mathrm{max_i}}} g_1^{\mathrm{Res}}(x)\, dx$$

$$S_i(Q^2) = \int_{x_{\mathrm{min_i}}}^{x_{\mathrm{max_i}}} g_1^{\mathrm{Scaling}}(x)\, dx$$

Δx_i delimited by $\Delta \mathrm{W}^2$ region
$\Delta \mathrm{W}^2 = 1.0$ - 4.0 GeV^2

Q_i^2 (GeV^2)	Δx_i
1.2 - 2.4	0.35 - 0.93
2.4 - 4.0	0.49 - 0.96
4.0 - 12.0	0.63 - 0.98

HERMES Analysis: Resonance region (1)

Contamination from Elastic and DIS

Calculation done using Monte Carlo with parameterization for elastic cross section and DIS cross section and F_2^{Res}

$$A_{meas} = f_{el} A_{El} + f_{Res} A_{Res} + f_{dis} A_{DIS}$$

$$A_{\parallel}^{Res} = (A_{meas} - f_{el} A_{El} - f_{dis} A_{DIS})/f_{el}$$

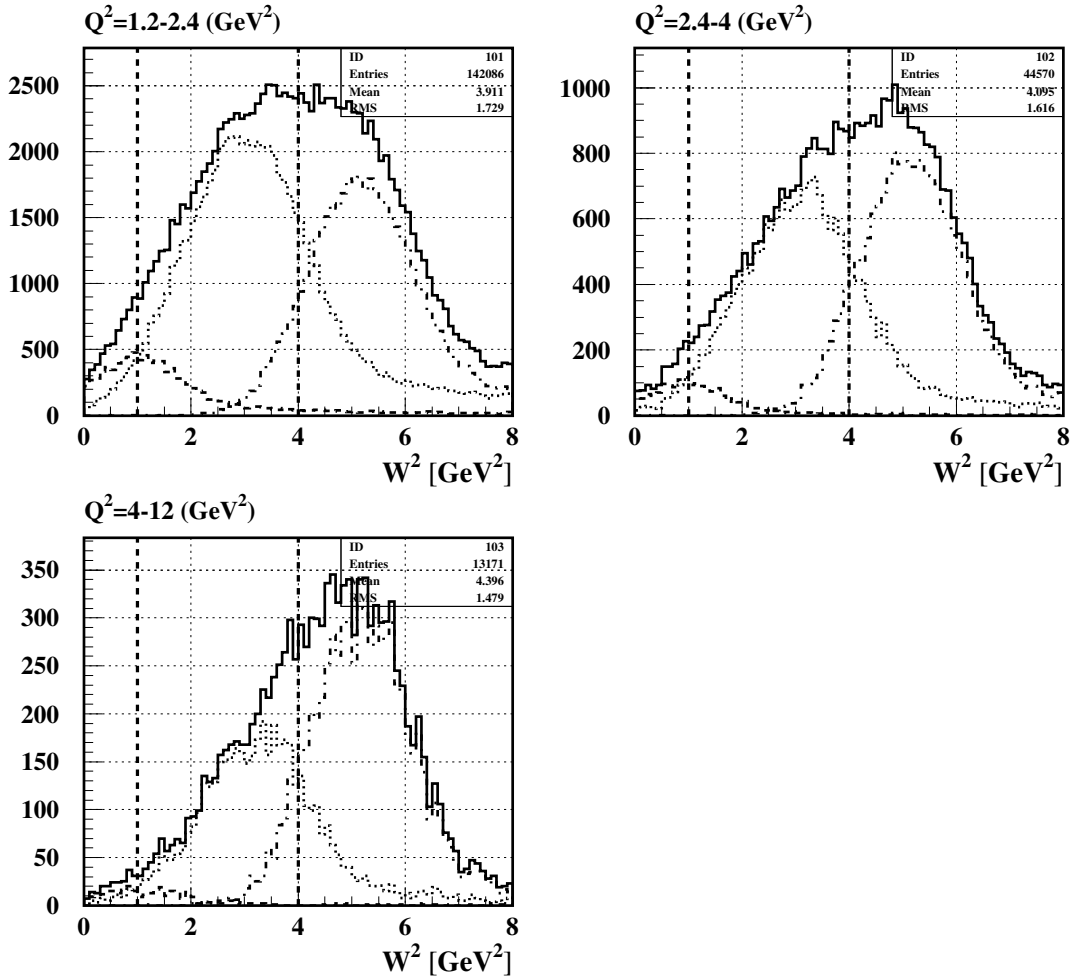
$$f_{el} = \frac{\#\text{ Elastic events } (W^2 < 1.0) \text{ in RES region}}{\#\text{ total events in } W^2}$$

$$f_{res} = \frac{\#\text{ Resonance events } (1.0 < W^2 < 4.0) \text{ in RES region}}{\#\text{ total events in } W^2}$$

$$f_{dis} = \frac{\#\text{ DIS events } (W^2 > 4.0) \text{ in RES region}}{\#\text{ total events in } W^2}$$

HERMES Analysis: Resonance region (2)

Contamination from Elastic and DIS



Q^2 bin	elastic peak	resonance region	DIS region
1	0.0906	0.8105	0.0990
2	0.0538	0.8110	0.1352
3	0.0376	0.7784	0.1840

600 kevents reconstructed

A. Fantoni, Elba 2002

HERMES Analysis: Resonance region (3)

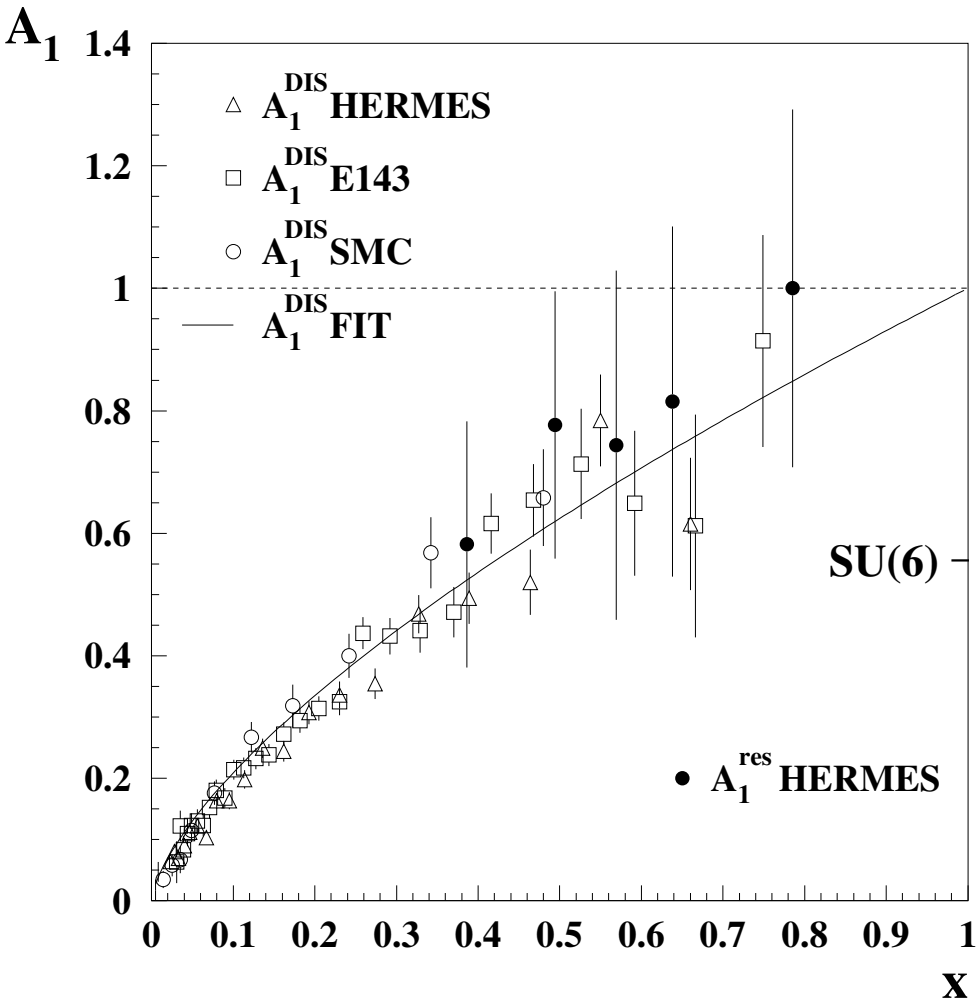
Evaluation of A_1

$$A_1 = \frac{A_\parallel}{D} - \eta A_2,$$

D and η factors that depend on kinematic variables

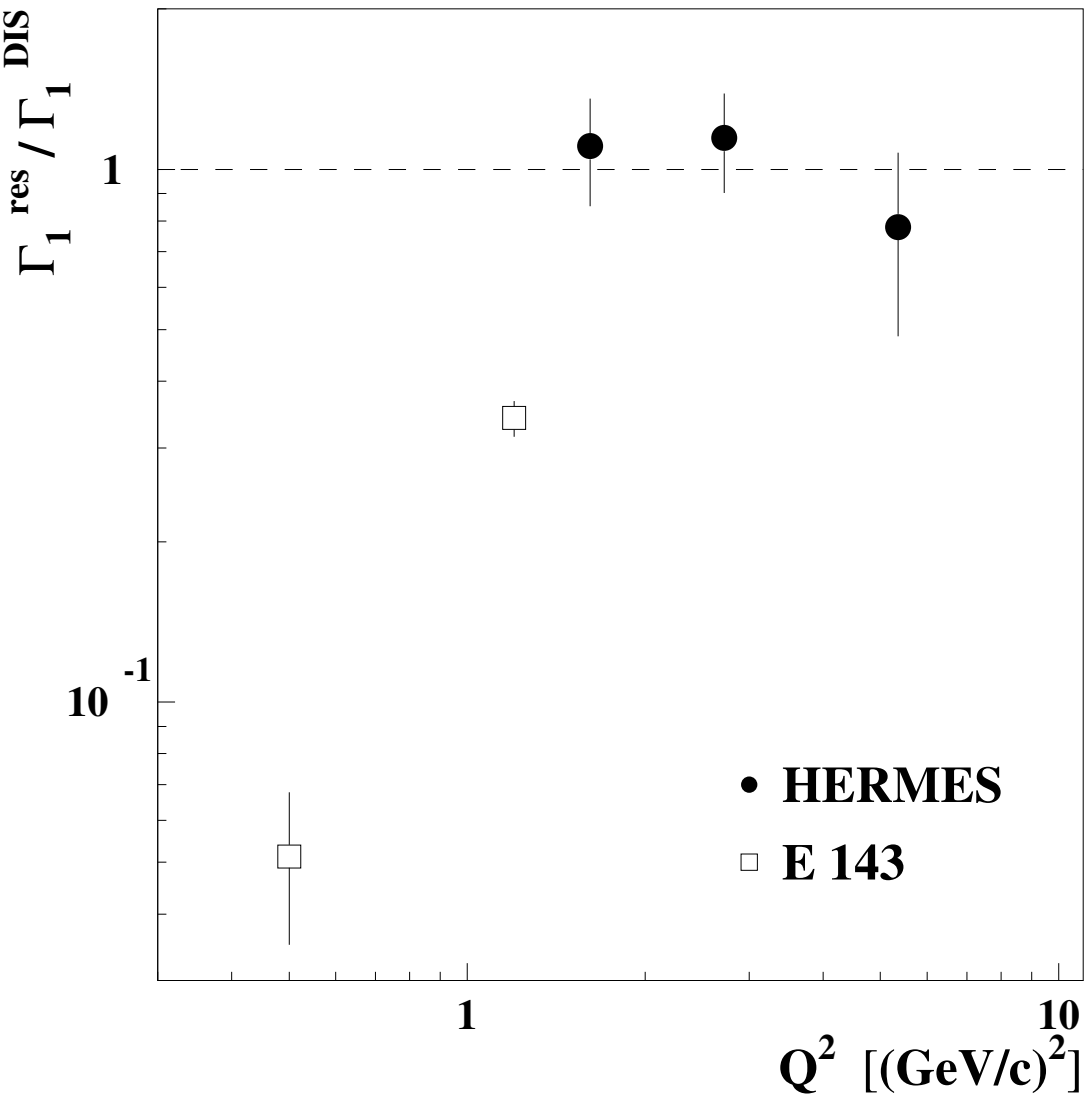
- $A_\parallel^{\mathrm{Res}} = (A_{\mathrm{meas}} - f_{\mathrm{el}} A_{\mathrm{El}} - f_{\mathrm{dis}} A_{\mathrm{DIS}})/f_{\mathrm{el}}$
- $A_2 = 0.06 \pm 0.16$ (SLAC at Q^2=3 GeV^2)
  E143 Collaboration, PR D58 (1998) 112003
- For all the kinematic values it was taken the average over all selected track in given kinematic bin

Preliminary results (1)



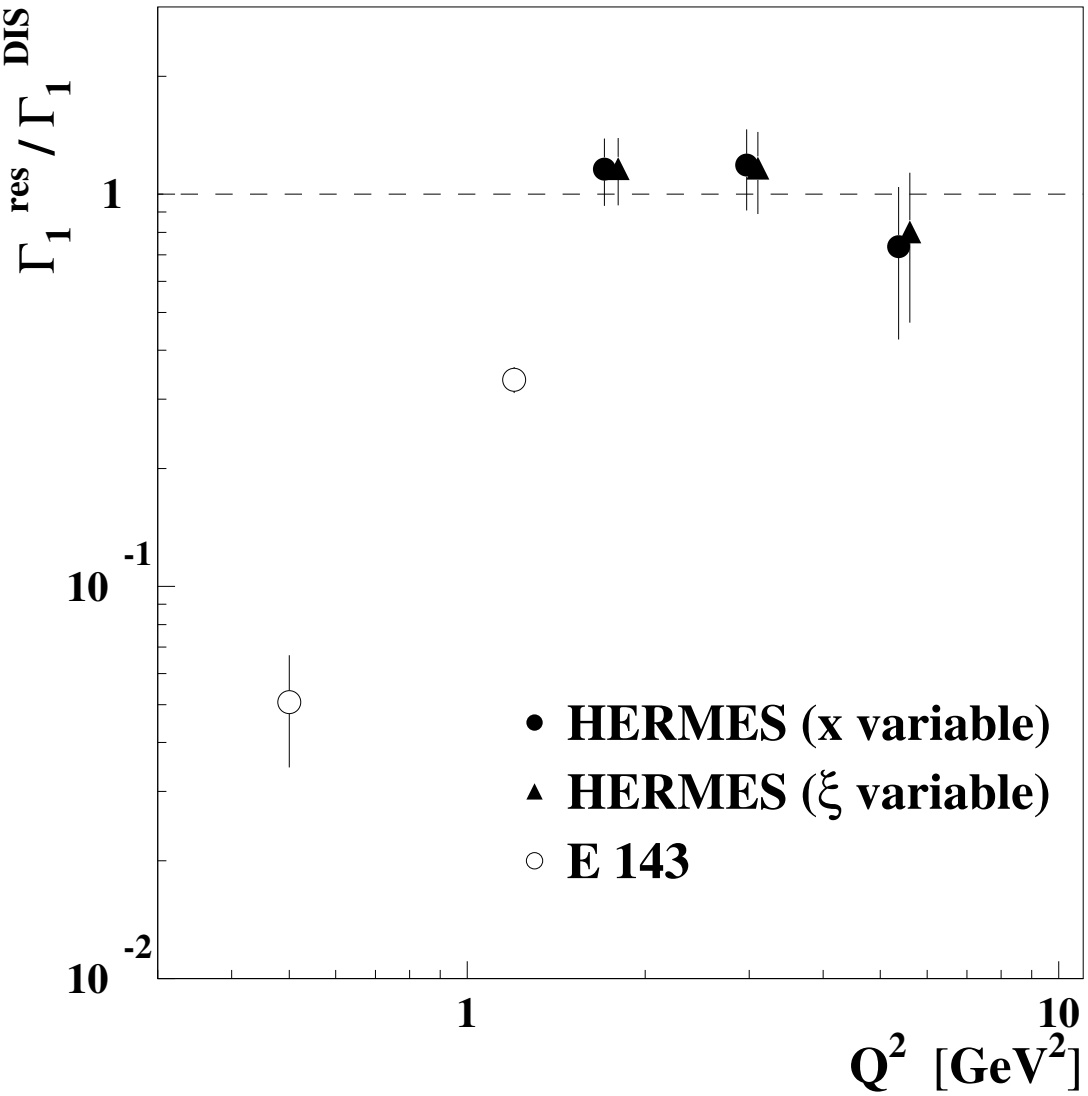
- syst. uncer. 16% (8% exp., 14% A_2)
- $< A_1^{\rm res}/A_1^{\rm DIS} >= 1.15 \pm 0.16 \pm 0.18$
- A_1 measured in the resonance region is in agreement within the experimental errors with previous DIS data at higher Q^2 and W^2 (same x)
- A_1 is increasing at large values of x and seems to exceed the SU(6) prediction of 5/9
- The description of the spin asymmetry in terms of quarks degree of freedom is valid also in the resonance region for Q^2 larger than 1.7 GeV^2

Preliminary results (2)



- syst. uncertainty $\approx 18\%$
  (16% A_1^{res}, 7% A_1^{DIS}, 2% F_2^{DIS}, 2% R)
  E143 Γ_1^{res} syst.: 36% (Q^2=0.5), 8% (Q^2=1.2)
- $\Gamma_1^{res}/\Gamma_1^{DIS}$ independent of Q^2 in HERMES region
- Duality holds for $Q^2 \approx 1.7$ GeV^2, as for the unpolarised case
- First test of duality for polarised structure functions

Preliminary results (3)



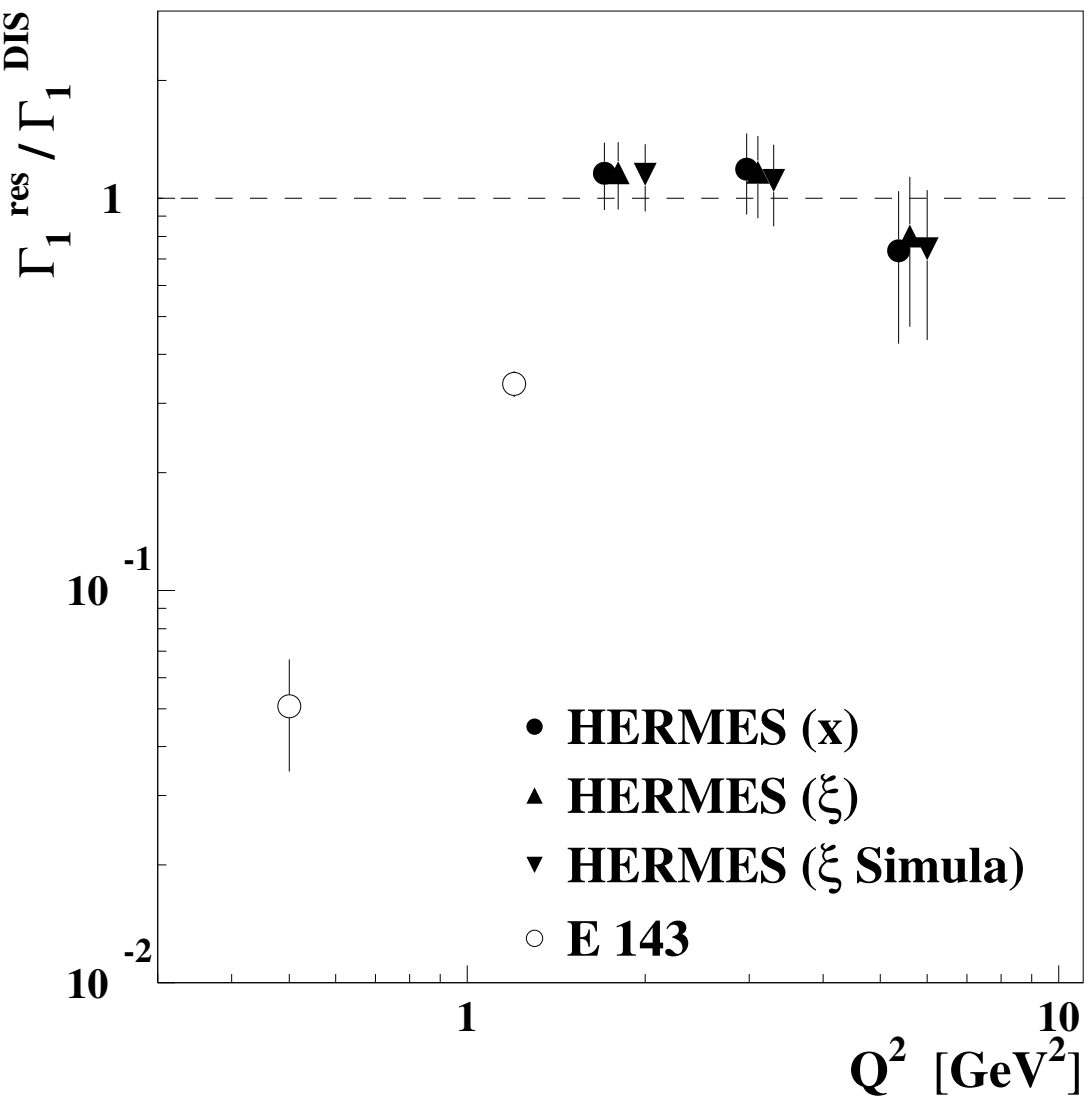
Results are not changing with Nachtmann variable:

$$\xi = \frac{2x}{1 + \sqrt{1 + \frac{4M^2x^2}{Q^2}}}$$

$$F_2^{res} = \xi^{0.870} * (1-\xi)^{0.06} * (0.005 - 0.058 * (1-\xi) - 0.017 * (1-\xi)^2 + 2.469 * (1-\xi)^3 - 0.240 * (1-\xi)^4) \rightarrow \text{JLAB fit}$$

A. Fantoni, Elba 2002

Preliminary results (4)



Jlab fit exhibits anomalous behaviour for $\xi > 0.9$

$F_2^{res} = \xi^{0.94} * (2.65 * (1-\xi)^{3.38} + 0.24 * (1-\xi)^4) \rightarrow$ Simula fit

S. Simula, PR D64 (2001) 038301

$0.33 < \xi < 0.86 \longrightarrow$ no difference with JLAB fit

The GDH sum rule

The GDH sum rule, derived in the sixties by Gerasimov and independently by Drell and Hearn, 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:

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

general dispersion relation for forward Compton scattering
+ low-energy theorem of Low
+ additional assumption that the spin-flip part of the Compton scattering amplitude goes to zero at infinite energy without any poles.

Theoretical predictions:
-204 μb p
-233 μb n
-0.65 μb d

Never been tested directly

The generalised GDH sum rule

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

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

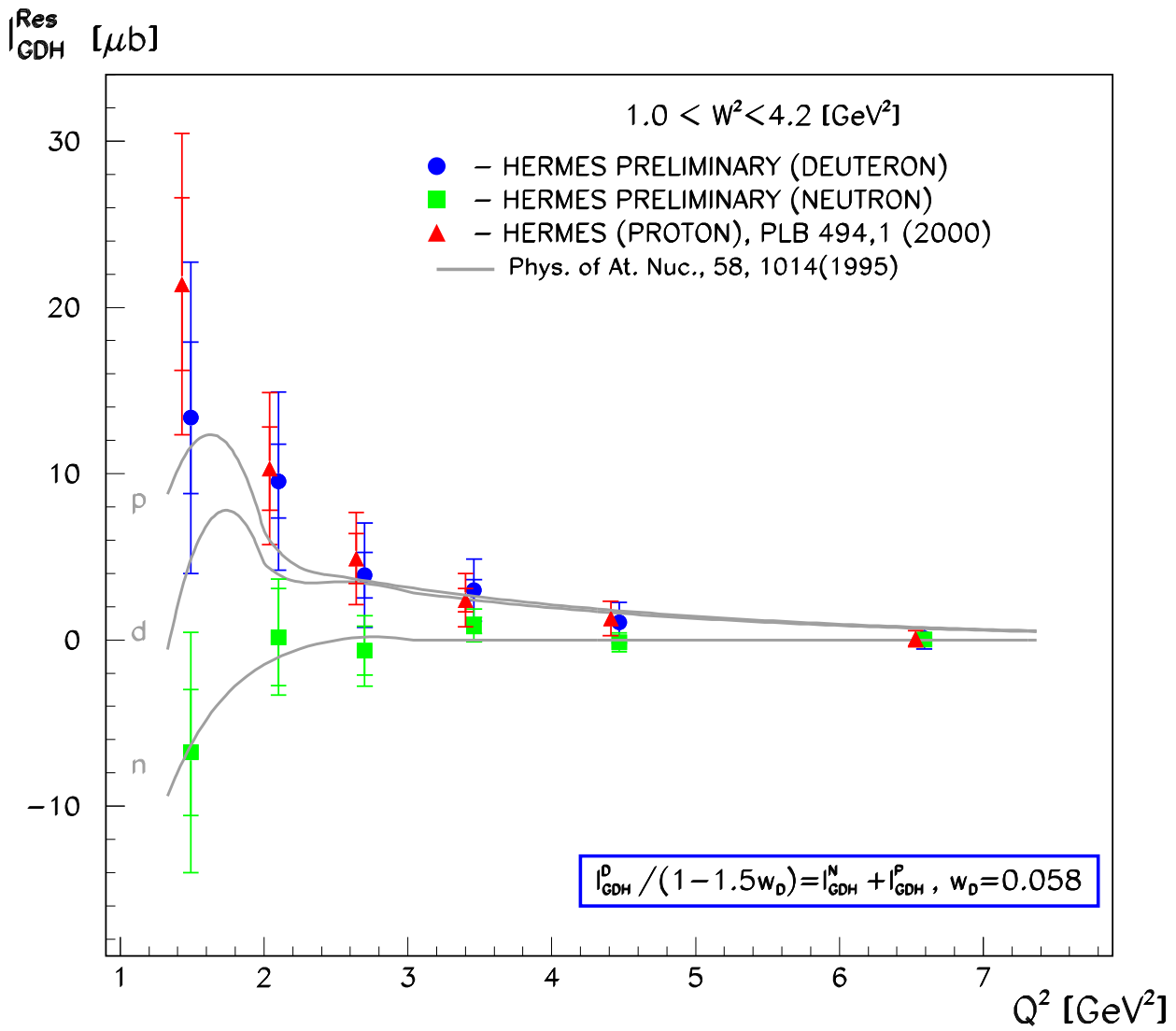
$$= \frac{8\pi^2\alpha}{M} \int_0^1 \frac{g_1(x, Q^2) - \gamma^2 g_2(x, Q^2)}{K} \frac{dx}{x}$$

g_1, g_2 polarised structure functions of the nucleon
x Bjorken variable
$K = \nu\sqrt{1+\gamma^2}$ flux factor of the virtual photons
$\gamma^2 = Q^2/\nu^2$

$I(Q^2)$ 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

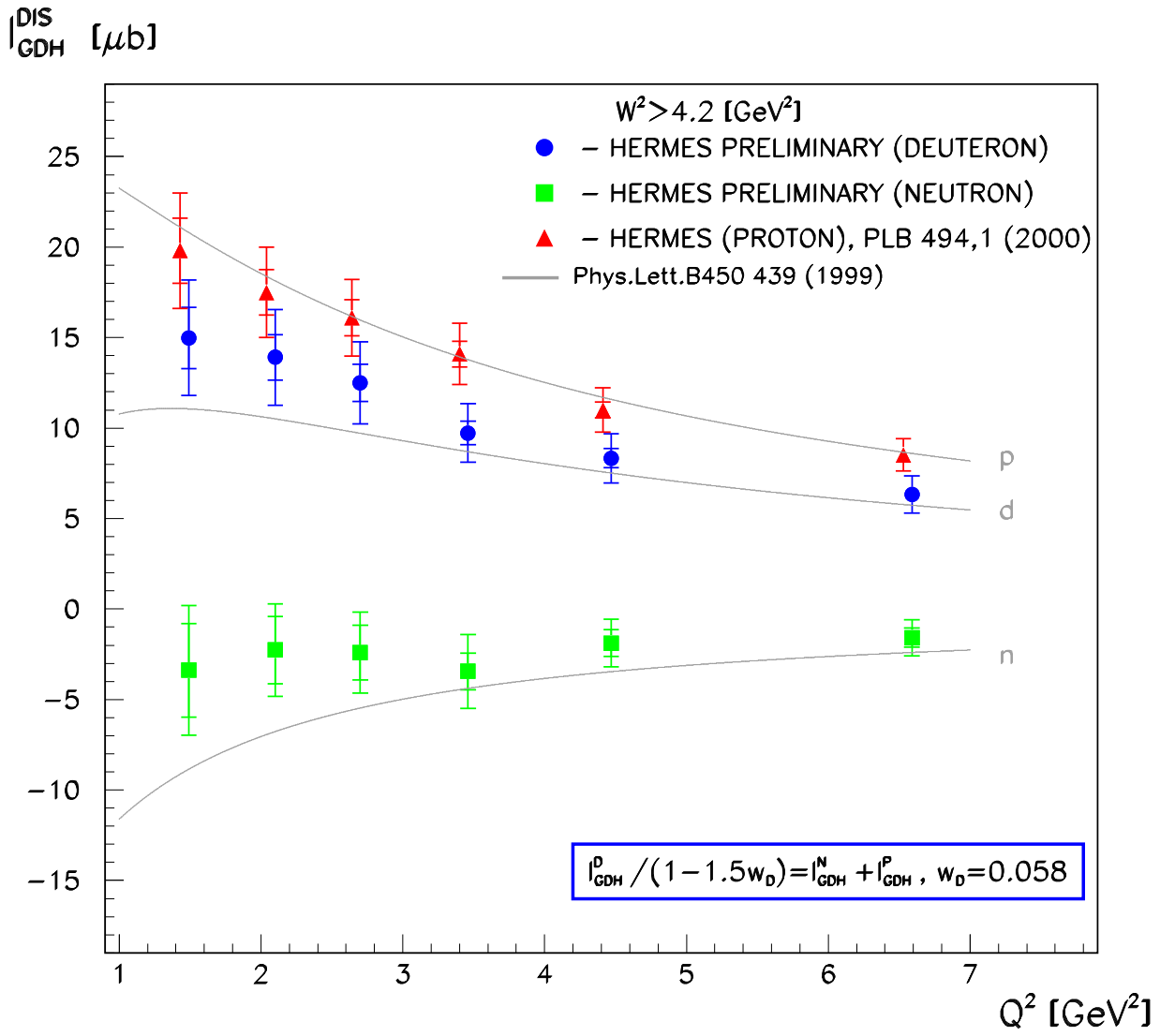
RES contribution to I_{GDH}



- 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**

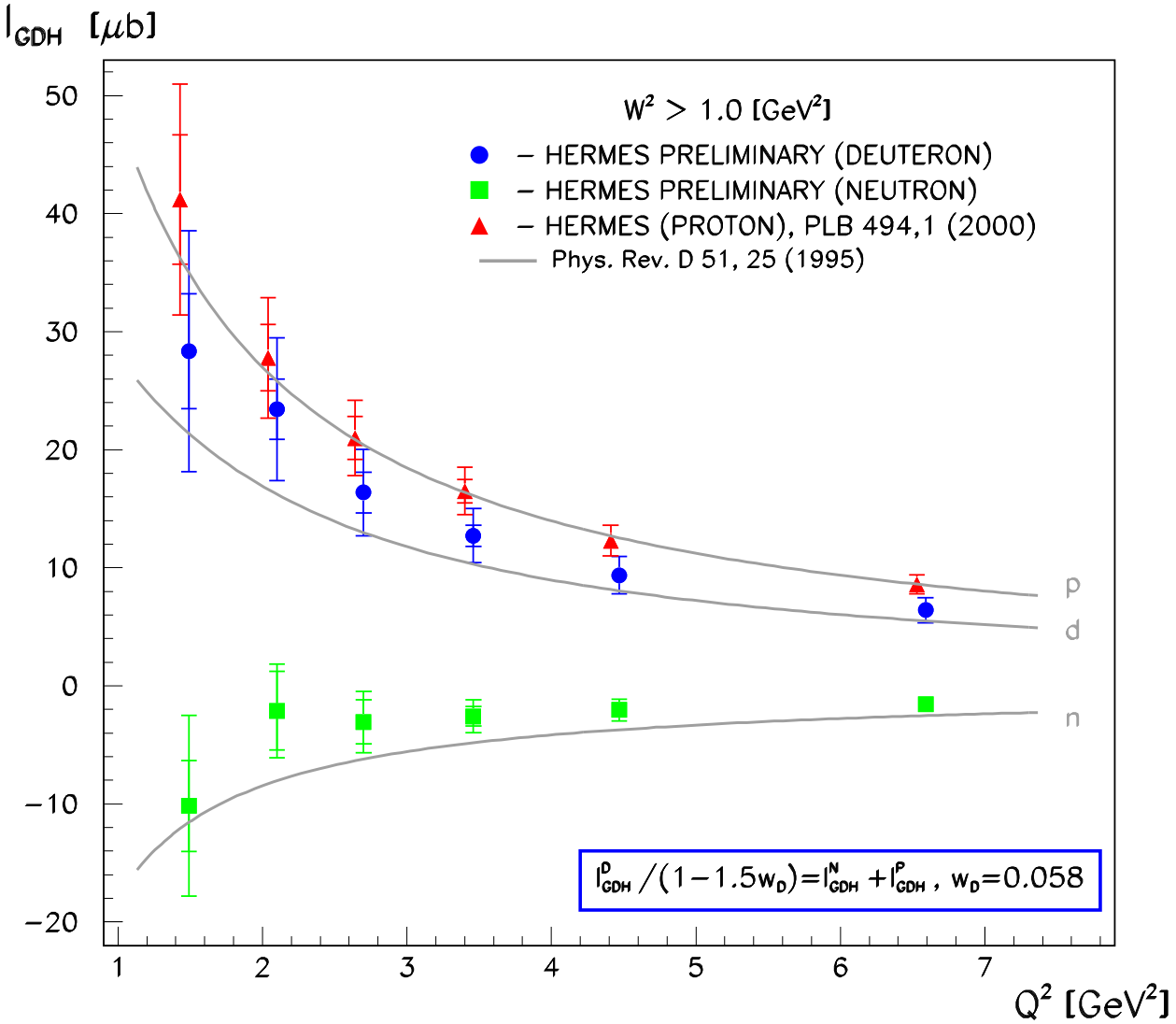
DIS contribution to I_{GDH}



- 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}



- I_{GDH} consistent with $1/Q^2$ law
- Q^2 behavior of I_{GDH} consistent with the pQCD evolution of the integral without considering any additional resonance or higher twist effect
- I^{DIS}_{GDH} dominant for Q^2 above 3 GeV^2 and remains sizeable down to the lowest measured Q^2
- $I^n_{GDH}<0$ and smaller in absolute value than I^p_{GDH}

Conclusions (1)

- A_1 measured in the resonance region is in agreement within the experimental errors with previous DIS data at higher Q^2 and W^2 and same x
- The description of the spin asymmetry in terms of quarks degree of freedom is valid also in the nucleon region for Q^2 larger than 1.7 GeV^2
- A_1 is increasing at large values of x and seems to exceed the SU(6) prediction of 5/9
- First study of Duality for polarised case g_1^p
- Ratio $\Gamma_1^{Res}/\Gamma_1^{DIS}$ 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

$$\xi = \frac{2x}{1+\sqrt{1+\frac{4M^2x^2}{Q^2}}}$$

Outlook:
Study of duality for the neutron g_1^n from deuterium data

Conclusions (2)

- Q^2-dependence of the generalised GDH integral for p, n and d determined for the first time in RES and DIS regions (Q^2 range 1.2-12 GeV^2)

- For Q^2 <2.5 GeV^2, existing resonance-excitation models are not sufficient to fully explain the experimental results for I_{GDH}^{res}

- Above Q^2=3 GeV^2 the DIS contribution is dominant

- Total I_{GDH} shows a $1/Q^2$ behavior $\longrightarrow$ no large effects from either resonances or non-leading-twist

- The strong turn down of $I_{GDH}^{p,d}(Q^2)$ towards the real photon prediction of -204 μb and -0.65 μb should occur at Q^2 lower than 1.2 GeV^2