# Verification of quark-hadron duality in spin structure function

Electromagnetic Interactions with Nucleons and Nuclei

Santorini - October 2-7, 2001

A. Fantoni (LNF - INFN)

on behalf of the HERMES Collaboration

- Concept of Duality
- Duality in unpolarised structure function
- Duality in polarised structure function
- HERMES experiment
- HERMES analysis:
  cuts and kinematical plane,
  $g_1^{Res}$ and $g_1^{Scaling}$,
  preliminary results
- Conclusions

# Concept of Duality (1)

DUALITY = RELATION BETWEEN THE DIS REGION AND THE RESONANCE REGION

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

The smooth scaling 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 $x$.

Before QCD:
B.G. duality interpreted in the context of finite-energy sum rules $\longrightarrow$ relationship between $s$ and $t$ channel behaviors of scattering amplitude

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

Veneziano, Nuovo Cimento 57A (1968) 190

Later:
generalisation of $s$ and $t$ channel duality, including both resonant and non resonant background contributions to cross section $\longrightarrow$ duality between resonances and valence quarks, with the background dual to the sea quarks

Harari, PRL 20 (1968) 1395

# Concept of Duality (2)

QCD:

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 $Q^2$ ($\sim 1$ GeV$^2$)

Distinction between resonance & DIS region is artificial

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

Clarification:

Duality is used to describe the rare cases where the average of hadronic observables is described by a pQCD calculation. DIS as example

pQCD picture in inelastic electron scattering must fail for $Q^2 \to 0$

For duality to hold for the nucleon structure functions in this case, the elastic proton and neutron form factors, which take the value of the nucleon charge for $Q^2 \to 0$, would have to be reproduced by electron scattering off corresponding $u$ and $d$ quarks

For the neutron, local duality must fail for $Q^2 \to 0$

Close & Isgur, hep-ph/0102067; Isgur *et al.*, hep-ph/0104022

# Check of Duality

Quark-hadron duality is an expression of the relationship between confinement and asymptotic freedom and it is intimately related to the nature of the transition from no-perturbative to perturbative QCD

This can be checked comparing the integrals of the structure function in the DIS and resonance region, in the same $x$ interval

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

$(x_M - x_m)$ delimited by $\Delta W^2$ 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

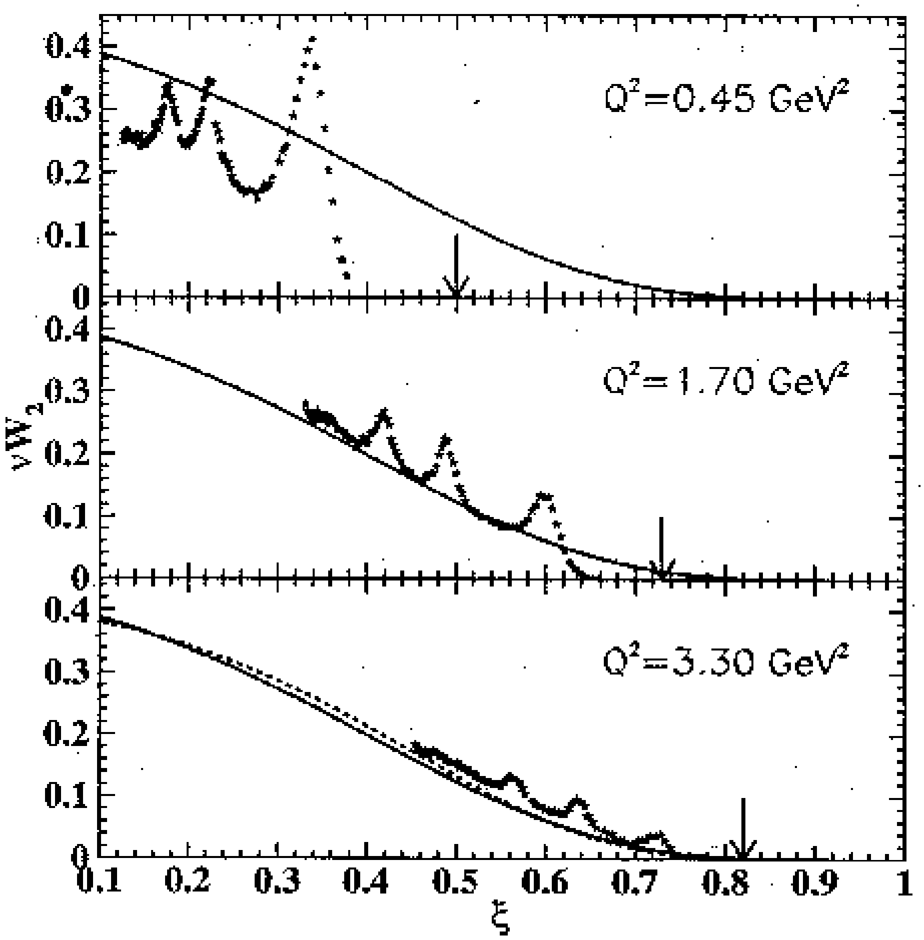
# Duality in unpolarised structure function (1)

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

Carlson & Mukhopadhyay, PR D47 (1993) 1737

New data from TJNAF in 2000

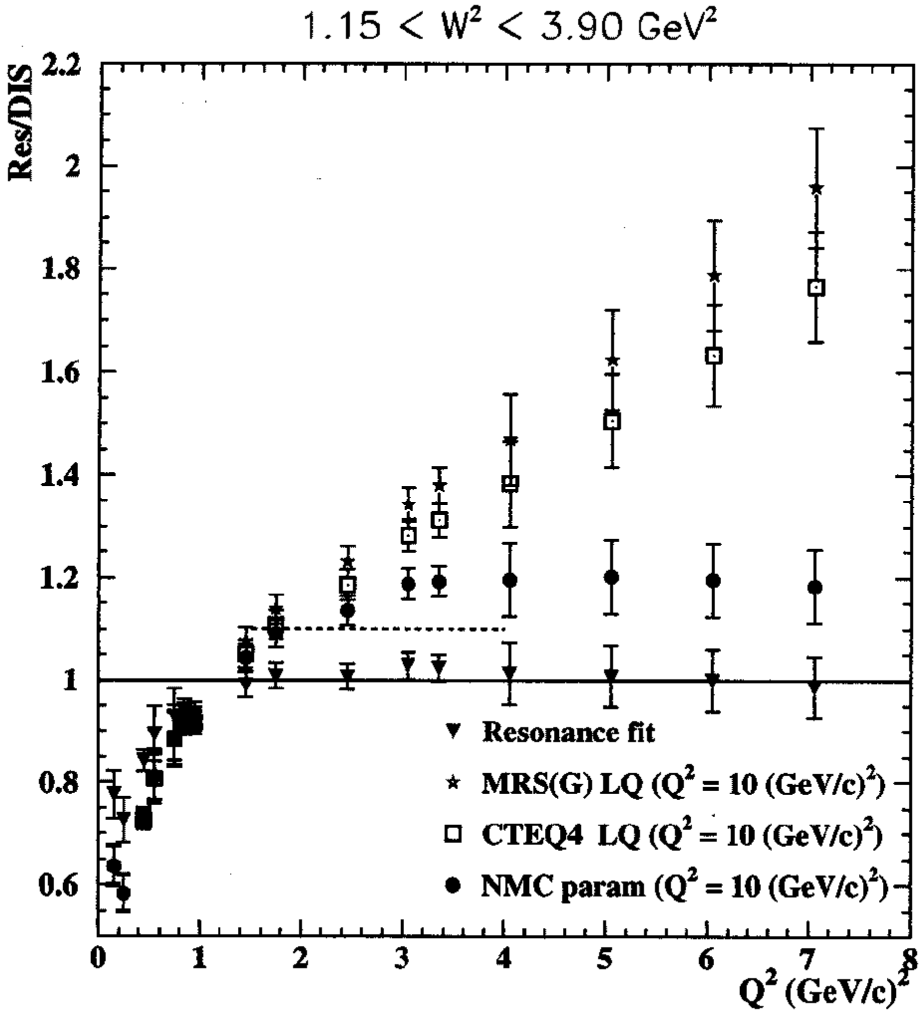
Niculescu *et al.*, PRL 85 (2000) 1182; PRL 85 (2000) 1186




The resonance spectra at different $Q^2$ appear at different $x$ (or $\xi$) on the DIS curve; the DIS curve generally represents an average of the data (manifestation of Bloom and Gilman observation)

# Duality in unpolarised structure function (2)

To quantify the observed duality → $Q^2$ dependence of the ratio of the $F_2$ structure function obtained from the resonance data, integrated from pion threshold to the onset of DIS ($W^2 = 4$ GeV$^2$), compared to the $F_2$ DIS structure function integrated in the same region of the Bjorken variable $x$:




In all cases the ratio $R$ drops for $Q^2 < 1.5$ GeV$^2$. This effect is largely negated if the elastic cross section is also included in the integral.

# Duality in polarised structure function

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:

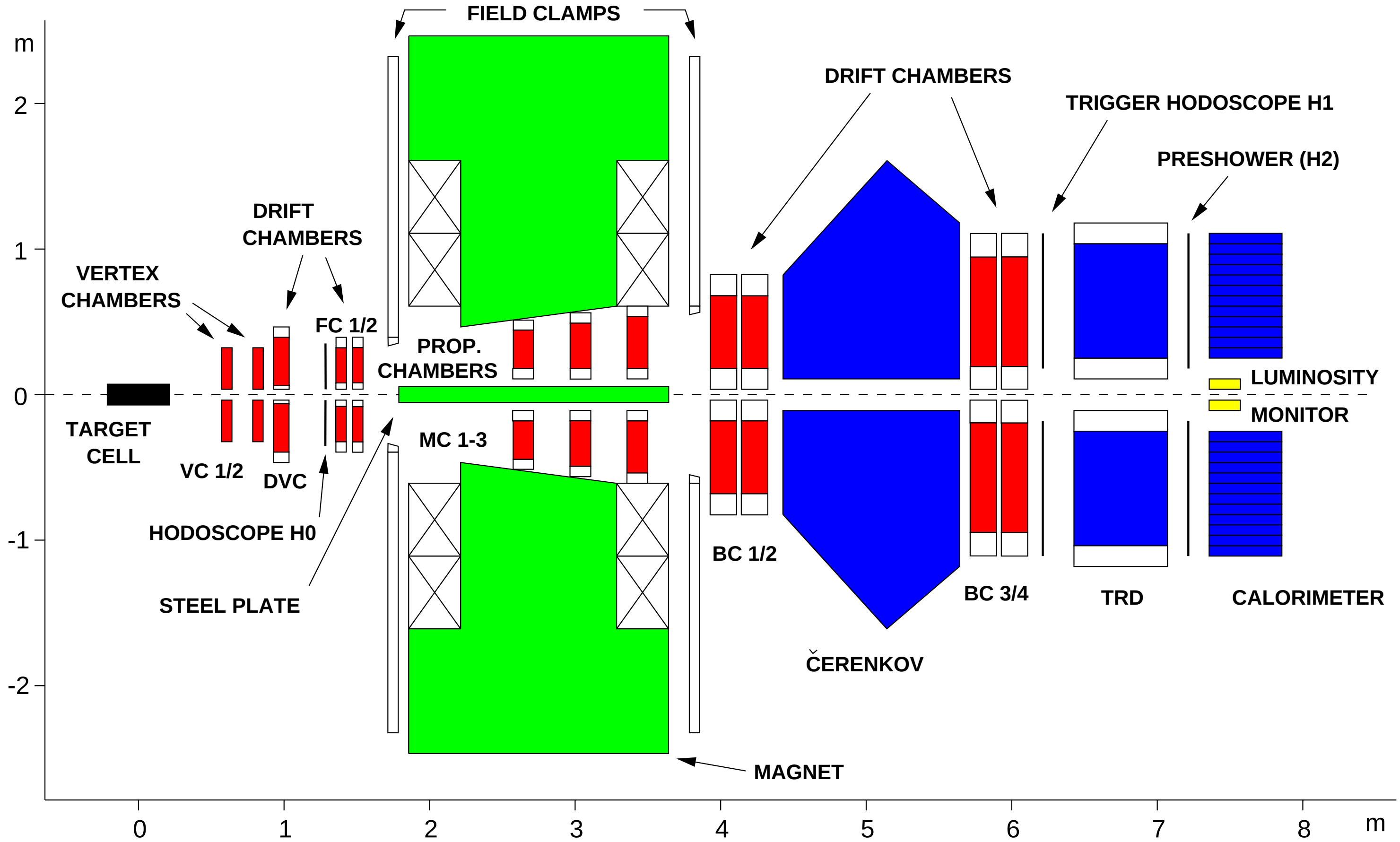
$$Q^2 = 0.5 \text{ GeV}^2 \longrightarrow \Gamma_1^p = 0.022 \text{ GeV}^{-2}$$
$$Q^2 = 1.2 \text{ GeV}^2 \longrightarrow \Gamma_1^p = 0.039 \text{ GeV}^{-2}$$

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

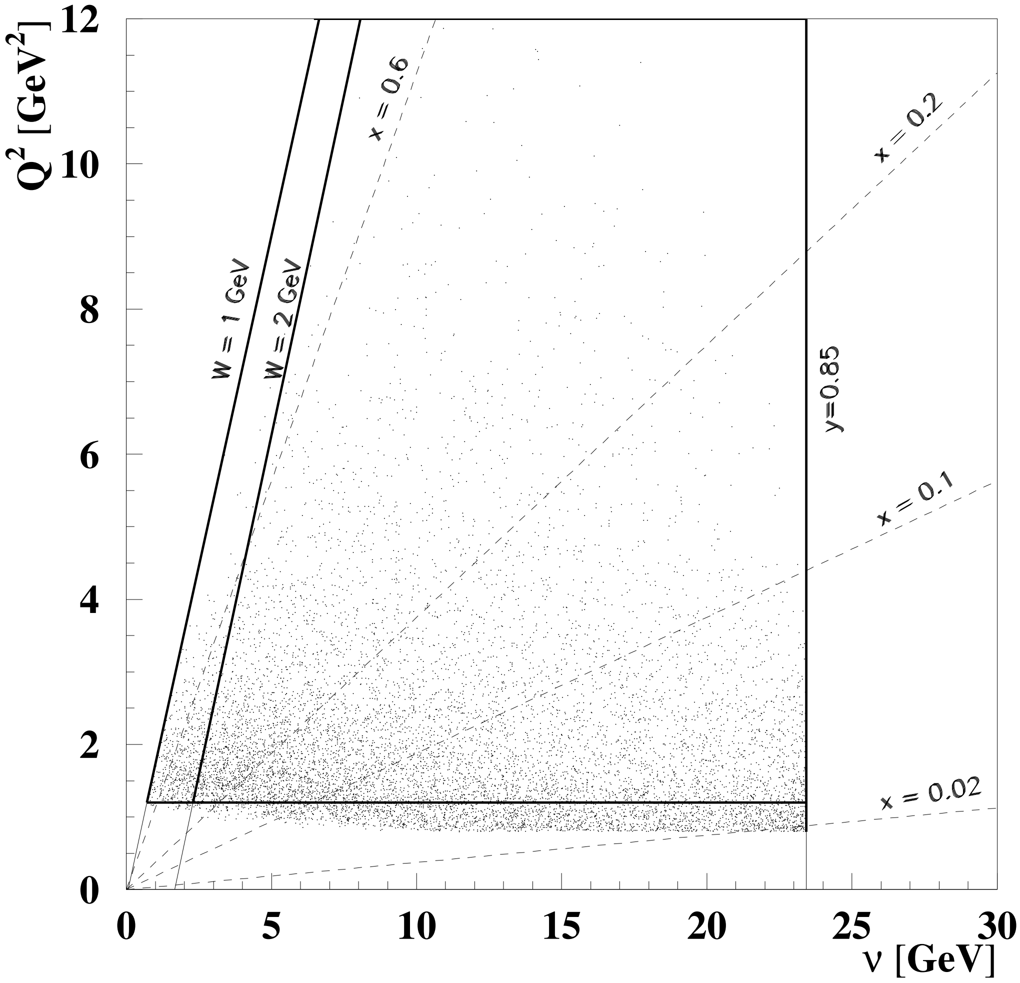
# HERMES experiment




- 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: $g_1^{\mathrm{Res}}$ and $g_1^{\mathrm{Scaling}}$

$$g_1^{\mathrm{Res}}(x,Q^2) = \mathrm{A}_1(\mathrm{x}) \cdot \mathrm{F}_1(\mathrm{x},\mathrm{Q}^2)$$

- $\mathrm{A}_1 = \mathrm{A}_\parallel$ / D - $\eta \cdot A_2$
- $\mathrm{F}_1 = \mathrm{F}_2$ / [2x(1+R)]

$\mathrm{R} = 0.18$ ; $\mathrm{F}_2 = \mathrm{F}_2^{\mathrm{Res}}$

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

$$g_1^{\mathrm{Scaling}}(x,Q^2) = \mathrm{A}_1^{\mathrm{DIS}}(\mathrm{x}) \cdot \mathrm{F}_1(\mathrm{x},\mathrm{Q}^2)$$

- $\mathrm{A}_1^{\mathrm{DIS}} = \mathrm{x}^\alpha \longrightarrow A_1^{\mathrm{DIS}} \neq f(Q^2)$
- $\mathrm{F}_1 = \mathrm{F}_2$ / [2x(1+R)]

$\mathrm{R} = \mathrm{R}(\mathrm{x},\mathrm{Q}^2)$ ; $\mathrm{F}_2 = \mathrm{F}_2^{\mathrm{DIS}}$

Withlow thesis; NMC, PL B364 (1995) 107

# HERMES Analysis: $g_1^{\text{Res}}$ and $g_1^{\text{Scaling}}$

$$R_i = I_i / S_i$$

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

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

$\Delta x_i$ delimited by $\Delta \mathrm{W}^2$ region

$\Delta \mathrm{W}^2 = 1.0$ - $4.0$ GeV$^2$

| $\mathrm{Q}_i^2$ (GeV$^2$) | $\Delta x_i$ |
|---|---|
| 1.2 - 2.4 | 0.3537 - 0.9345 |
| 2.4 - 4.0 | 0.4878 - 0.9613 |
| 4.0 - 12.0 | 0.6326 - 0.9782 |

# 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 $\mathrm{F}_2^{\mathrm{Res}}$

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

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

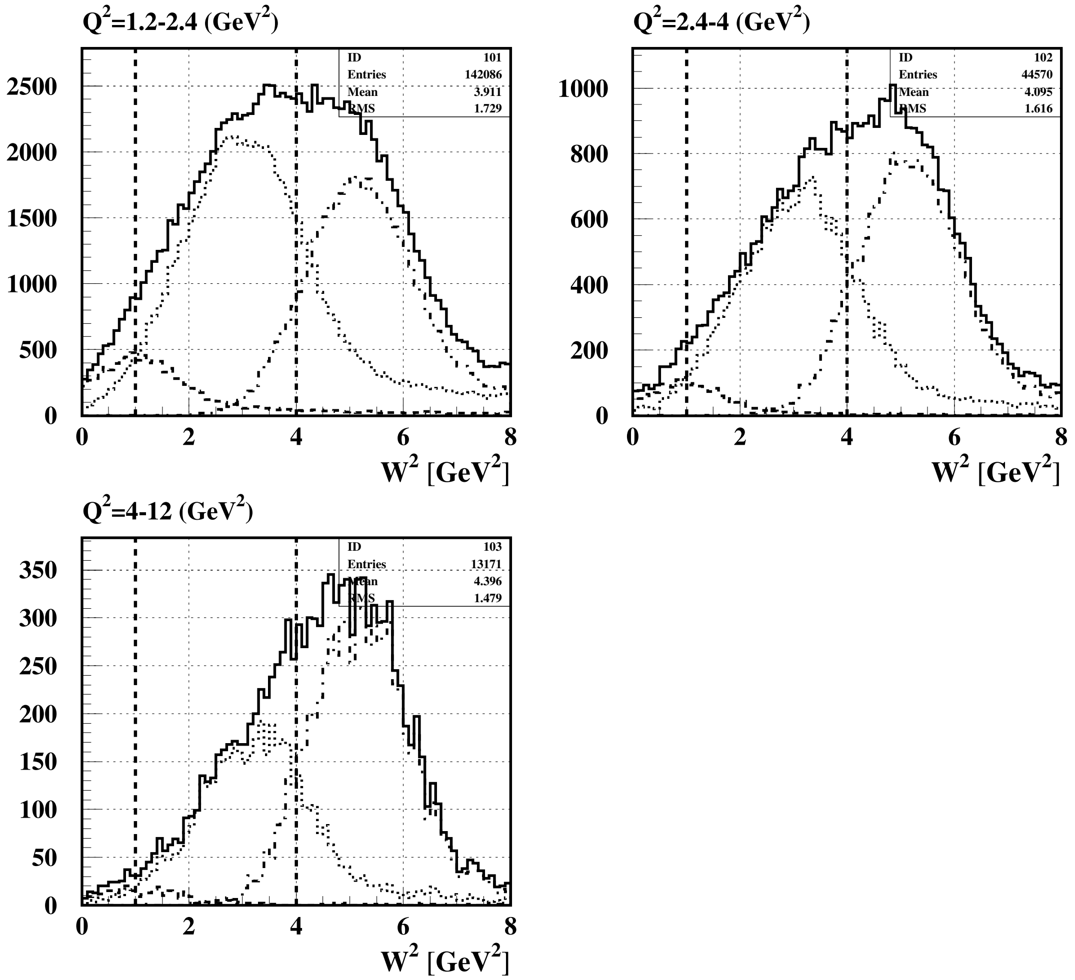
$$f_{\mathrm{el}} = \frac{\#\,\text{Elastic events}\,(W^2 < 1.0)}{\#\,\text{total events in}\,W^2}$$

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

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

# 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

# HERMES Analysis: Resonance region (3)

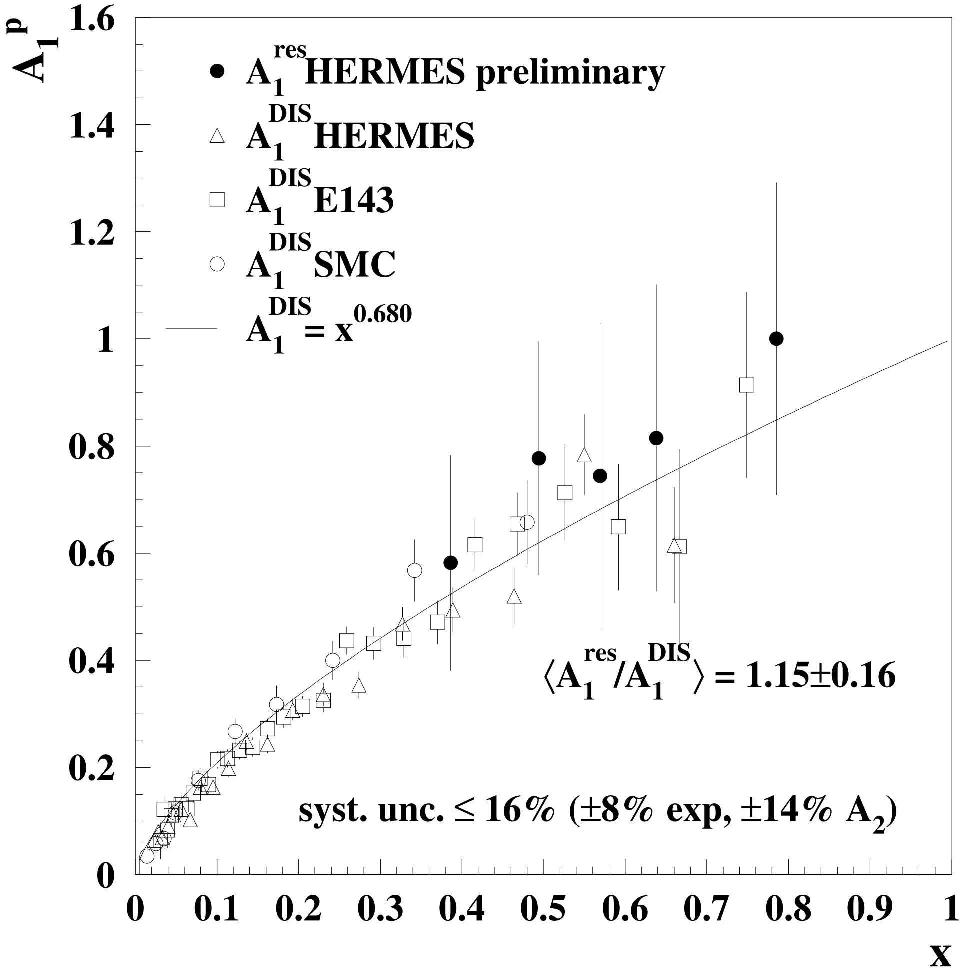
Evaluation of $A_1$

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

$D$ and $\eta$ factors that depend on kinematical variables

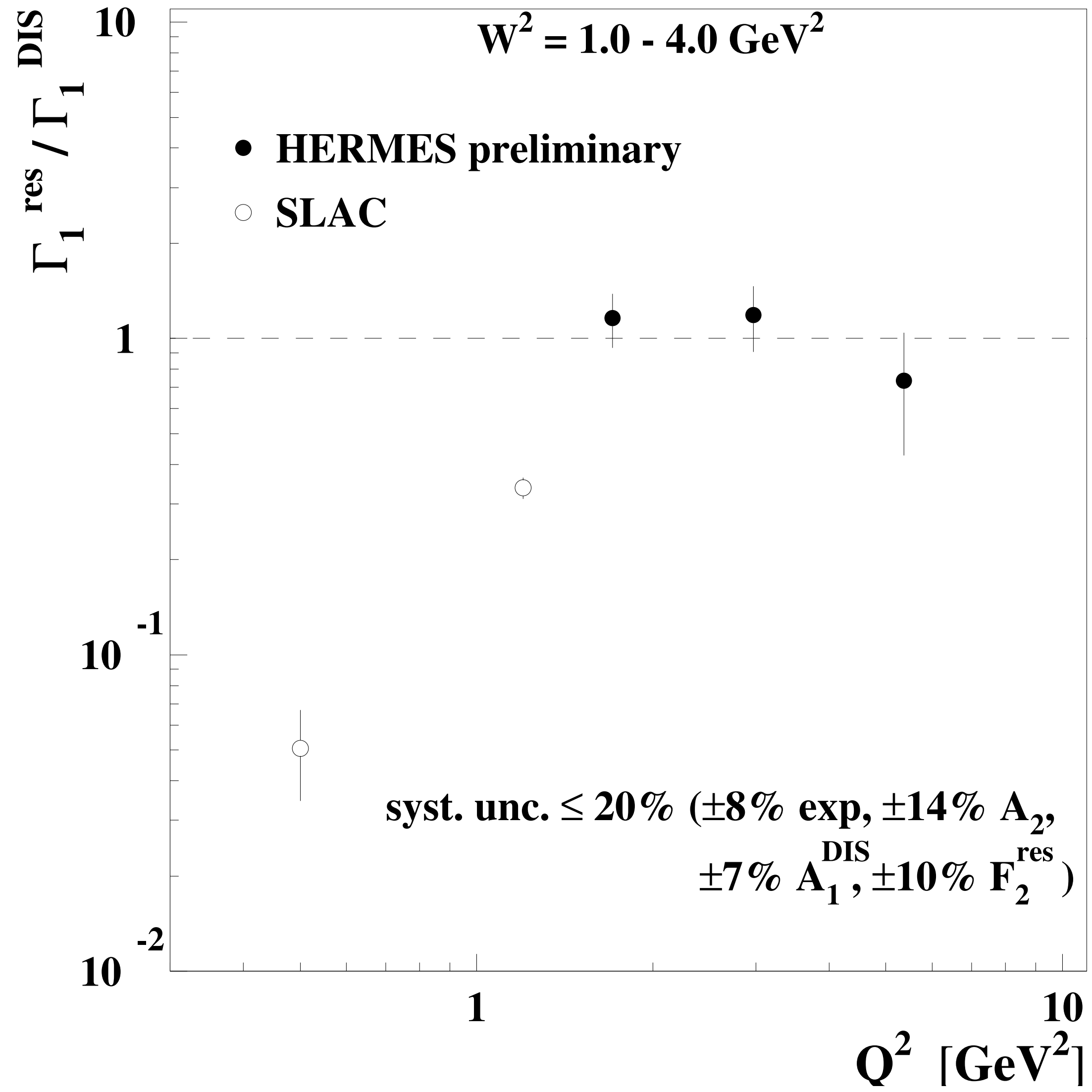
- $A_{\parallel}^{\mathrm{Res}} = (A_{\mathrm{meas}} - f_{\mathrm{el}} A_{\mathrm{El}} - f_{\mathrm{dis}} A_{\mathrm{DIS}})/f_{\mathrm{el}}$
- $A_2 = 0.06 \pm 0.16$ (SLAC at $Q^2$=3 GeV$^2$)
  E143 Collaboration, PR D58 (1998) 112003
- For all the kinematical values it was taken the average over all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

# Preliminary results (1)




- $A_1$ measured in the resonance region is in agreement within the experimental errors with previous DIS data at higher $Q^2$ and $W^2$ (same $x$)
- 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$^2$
- $A_1$ is increasing at large values of $x$ and seems to exceed the SU(6) prediction of 5/9

# Preliminary results (2)




- Ratio $\Gamma_1^{res}/\Gamma_1^{DIS}$ independent of $Q^2$ in HERMES region
- Onset of duality for $Q^2 \approx 1.7$ GeV$^2$, as for the unpolarised case
- First test of duality for polarised structure functions

# Syst. uncertainty (1)

Total systematic uncertainty given by multiple factors:

- Beam and target polarizations: 5.9%
- Knowledge of $A_2^p$: up to 14%
  $A_2^p = 0.06 \pm 0.16 \longrightarrow A_2^{up} = 0.22$, $A_2^{down} = -0.10$
  Range consistent with:
  $A_2^p = 0$
  $A_2^p = 0.53\ Mx\ / \sqrt{Q^2}$, which describes the behavior in deep inelastic region
- Smearing effects: up to 5.2%
  Comparison between:
  generated asymmetry $A^{gen}(kine - gen)$
  reconstructed asymmetry $A^{reco}(kine - reco)$
  assumption $\longrightarrow A_1$ step function:
  $$A_1 = \text{-0.5 for } W^2 < 1.8 \text{ GeV}^2$$
  $$A_1 = 1.0 \text{ for } 1.8 < W^2 < 4.0 \text{ GeV}^2$$
  that is suggested by the hypothesis of the possible dominance of the $P_{33}$ resonance at low $W^2$ and for the $S_{11}$ at higher $W^2$.

# Syst. uncertainty (2)

- Spectrometer geometry: 2.5%
- Knowledge of $F_2^{DIS}$: 2%
- Radiative corrections: up to 1%
  Calculated using the usual POLRAD code
  The effect of radiative corrections have been included in the systematic uncertainty
- Parameterisation of $A_1^{DIS}$: from 4% to 7%
  Calculated using different parameterisation of $A_1^{DIS}$ for the contamination coming from DIS region and for the evaluation of the integral $\Gamma_1^p$
  1. $A_1^{DIS} = 0.03 + 1.55\ x - 0.824\ x^2$ ($g_1^p$ paper)
     with this parametrisation $A(x=1) \neq 1$
  2. $A_1^{DIS} = x^{0.680}$
     fit on world data with $x > 0.3$
- Parameterisation of $F_2^{Res}$: up to 10%
  Calculated using different $F_2^{Res}$ parameterisations:
  1. $F_2^{Res}$ from modified Bodek
  2. $F_2^{Res}$ from Jlab fit

Total uncertainty less than 20%

# Conclusions

- $A_1$ 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 structure functions
- Ratio $\Gamma_1^{res}/\Gamma_1^{DIS}$ independent of $Q^2$ in HERMES region
- Onset of duality 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