HERMES Measurements of the Generalized GDH-Integral and of Quark-Hadron Duality

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(1) Generalized Gerasimov-Drell-Hearn Integral

* Motivation
* Analysis of HERMES data
* Q^2-Dependence for deuteron, proton and neutron
  - Nucleon resonance region
  - Deep Inelastic Scattering (DIS) region
* Proton-Neutron difference

(2) Quark-Hadron Duality

GDH: Motivation I

• Real-photon absorption by a nucleus:

[S.B. Gerasimov, Sov. J. Nucl. Phys. 2 (1966) 430]
[S.D. Drell, A.C. Hearn, Phys. Rev. Lett. 16 (1966) 908]
[H. Ahrenhoevel, nucl-th/0006083]

$$I_{GDH} = \int_{\nu_0}^{\infty} [\sigma^{\overset{\rightarrow}{\Leftarrow}}(\nu) - \sigma^{\overset{\rightarrow}{\Rightarrow}}(\nu)] \frac{d\nu}{\nu} = -\frac{4\pi^2 I\alpha}{M_t^2}\kappa^2$$

Connects helicity-dependent dynamics and static ground-state property of nucleus(on)

$\sigma^{\overset{\rightarrow}{\Leftarrow}}$, $\sigma^{\overset{\rightarrow}{\Rightarrow}}$: photoabsorption cross sections for anti–parallel, parallel spin orientation

I,M_t,α: nucleus spin, mass, electromagnetic fine-structure constant
κ: anomalous contribution to magnetic moment of nucleus(on)
ν: photon energy in the target rest frame, ν_0: photoabsorption threshold

target	κ	$I_{GDH}^{\gamma p}$ in μb
proton	1.79	-204
neutron	-1.91	-233
deuteron	-0.143	-0.65

• Polarized DIS on nucleus(on)

⇒ Generalized Gerasimov-Drell-Hearn Integral:

[R. Pantförder, hep-ph/9805434, and references therein]

$$I_{GDH}(Q^2) = \int_{\nu_0}^{\infty} [\sigma^{\overset{\rightarrow}{\Leftarrow}}(\nu, Q^2) - \sigma^{\overset{\rightarrow}{\Rightarrow}}(\nu, Q^2)] \frac{d\nu}{\nu}$$

Nice tool to study transition of helicity-dependent dynamics from (perturbative) DIS region to (non-perturb.) photoabsorption

$\sigma^{\overset{\rightarrow}{\Leftarrow}}$, $\sigma^{\overset{\rightarrow}{\Rightarrow}}$: virtual-photon absorption cross sections for anti–parallel, parallel spin orientation

Q^2: photon virtuality

GDH: Motivation II

- Spin $\frac{1}{2}$ target:

$$I_{GDH}(Q^2) = \frac{8\pi^2\alpha}{M}\int_0^{x_0} \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{K}\frac{dx}{x}$$

g_1, g_2: polarised structure functions of the nucleon

$\gamma^2 = Q^2/\nu^2$, $x = Q^2/2M\nu$, $x_0 = Q^2/2M\nu_0$

K: virtual–photon flux factor

ν: photon energy in the target rest frame, ν_0: photoabsorption threshold

For larger virtuality ($Q^2 \geq 1$ GeV^2):

$\int_0^1 g_2(x,Q^2)dx = 0$ (Burkhardt-Cottingham sum rule)

$$I_{GDH}(Q^2) = \frac{16\pi^2\alpha}{Q^2}\Gamma_1(Q^2) \;\; \text{with} \;\; \Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)dx$$

Generalized GDH Integral given by first moment of spin structure function $g_1(x,Q^2)$

$\Longrightarrow$ does the 'hard $1/Q^2$-regime' stay intact down to lowest measured Q^2 ?

GDH: Motivation III

- GDH p–n difference $\longrightarrow$ Bjorken sum rule:

$$I^p_{GDH}(Q^2) - I^n_{GDH}(Q^2) \xrightarrow{Q^2 large} \frac{16\pi^2\alpha}{Q^2}[\Gamma^p_1(Q^2) - \Gamma^n_1(Q^2)]$$

Fundamental Bjorken SR derived from current algebra and isospin symmetry:

$$\Gamma^p_1(Q^2) - \Gamma^n_1(Q^2) = \tfrac{1}{6} \cdot g_a \cdot C_{ns}(\alpha_s(Q^2))$$

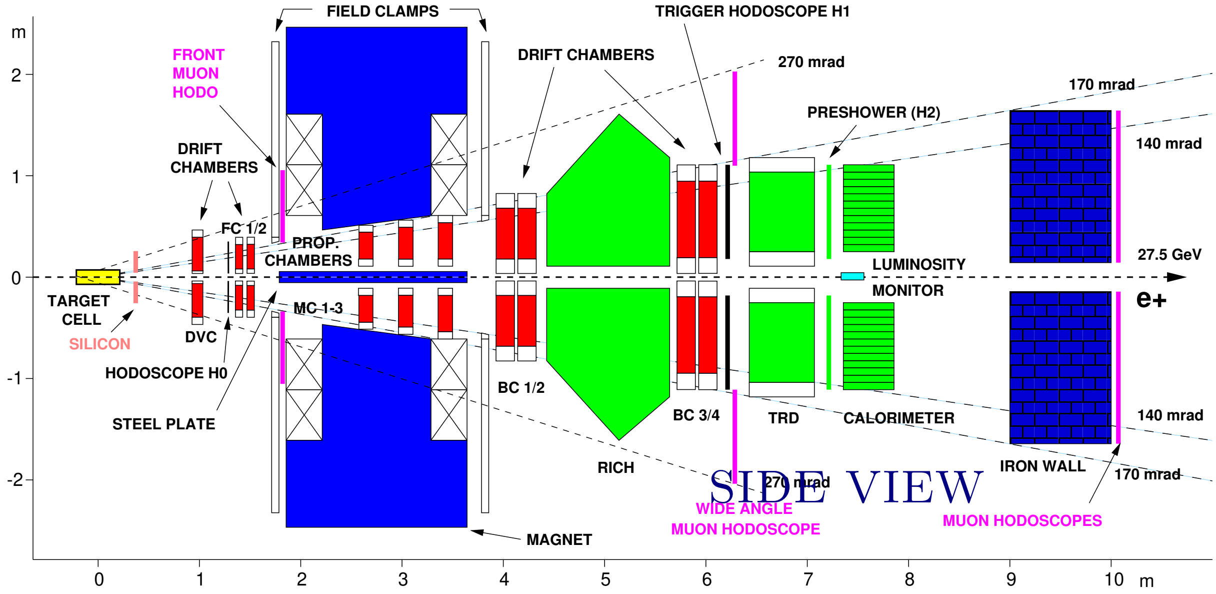
$g_a = |g_A/g_V| = 1.2670 \pm 0.0035$: neutron beta–decay coupling constant

Q^2-dependence: given by DGLAP-evolution

$\Rightarrow$ GDH data from HERMES kinematics
essential to connect
two important properties of the nucleon:
κ and g_A

The HERMES Experiment at DESY

$\rightarrow e^{\pm}$



- Tracking: forward dipole magnet spectrometer with 57 chamber planes ($40\,\mathrm{mrad} < \theta < 220\,\mathrm{mrad}$); resolution: $\delta\theta < 0.6$ mrad, $\delta p/p < 1.5\%$

- Particle ID: threshold/Ring-imaging(>1998) Cerenkov, TRD, preshower (H2), lead-glass calorimeter: e/h misidentification $< 0.4\%$

- Fast Trigger: scintillator hodoscopes H0, H1, H2; calorimeter: energy threshold 1.4 GeV

GDH Measurements at HERMES

- **Reaction:**

Doubly polarized inclusive e^+ or e^- scatt. on ^{2}H (^{1}H)

- **Longitudinally polarized beam:**

E_0=27.6 GeV, $<P_B>$=$0.55 \pm 0.01_{syst.}$ ($0.55 \pm 0.02_{syst.}$)

- **Longitudinally polarized internal gas target:**

$<P_T>$=$0.85 \pm 0.03_{syst.}$ ($0.86 \pm 0.04_{syst.}$)

- **Integrated luminosity / nucleon:** 111 (70) pb^{-1}

- **Kinematics:** $1.2 < Q^2 < 12$ GeV^2 in 6 bins

$$1.0 < W^2 < 45 \text{ GeV}^2$$

W: γ^*-nucleon invariant mass

$\Longrightarrow$ Sufficient kinematic coverage and statistics to study for the 1st time the Generalized GDH Integral on deuteron, proton and neutron separately in DIS region and nucleon-resonance region:

Region	W^2-range	Statistics ^{2}H (^{1}H)
nucleon-resonance	$1.0 < W^2 < 4.2$ GeV^2	0.13 M (0.55 M)
DIS	$4.2 < W^2 < 45$ GeV^2	1.4 M (7.7 M)
unmeasured	$W^2 > 45$ GeV^2	extrapolation [*]

* N. Bianchi, E. Thomas, Phys. Lett. B450 (1999), 439

Gen. GDH Integral: Data Analysis

Photon flux factor: $K = \nu\sqrt{1+\gamma^2}$ (Gilman notation):

$$I_{GDH}(Q^2) = \frac{8\pi^2\alpha}{Q^2}\int_0^{x_0} \frac{1}{\sqrt{1+\gamma^2}}\tilde{A}_1 F_1 dx$$

$F_1 = F_2(1+\gamma^2)/(2x(1+R))$ and F_2: unpolarized structure functions

F_2 by fit of A. Bodek, Phys. Rev. D8 (1973) 2331

$R = \sigma_L/\sigma_T$: ratio of absorption cross sections for long. and transverse virtual photons

(Resonance region: $R = 0.18$, DIS region: fit L. W. Whitlow et al., Phys. Lett. B 250 (1990) 193)

Measured longitudinal cross-section asymmetry

$$A_{\parallel} = \frac{1}{P_B P_T}\frac{N^{\overrightarrow{\Leftarrow}}L^{\overrightarrow{\Rightarrow}} - N^{\overrightarrow{\Rightarrow}}L^{\overrightarrow{\Leftarrow}}}{N^{\overrightarrow{\Leftarrow}}L^{\overrightarrow{\Rightarrow}} + N^{\overrightarrow{\Rightarrow}}L^{\overrightarrow{\Leftarrow}}}$$

Photon-helicity asymmetry

$$\tilde{A}_1 = \frac{A_{\parallel}}{D} - \eta\tilde{A}_2$$

$N^{\overrightarrow{\Leftarrow}}$, $N^{\overrightarrow{\Rightarrow}}$: no. of scattered e^+ (e^-) for anti–parallel, parallel spin orientation

$L^{\overrightarrow{\Leftarrow}}$, $L^{\overrightarrow{\Rightarrow}}$: deadtime-corrected luminosity for anti–parallel, parallel spin orientation

$y = \nu/E_0$: inelasticity of the reaction; $\eta(y,\gamma^2)$: kinematic factor

$D(y, Q^2, \gamma^2, R)$: virtual-photon (de)polarization factor

$\tilde{A}_2^d$, A_2^p : Resonance region: 0.06 (0.); DIS region: $c\ M\ x/\sqrt{Q^2}$ with c=0.5 (0.05)

For spin $\frac{1}{2}$ target: $\tilde{A}_1 \equiv A_1$: virtual-photon asymmetry

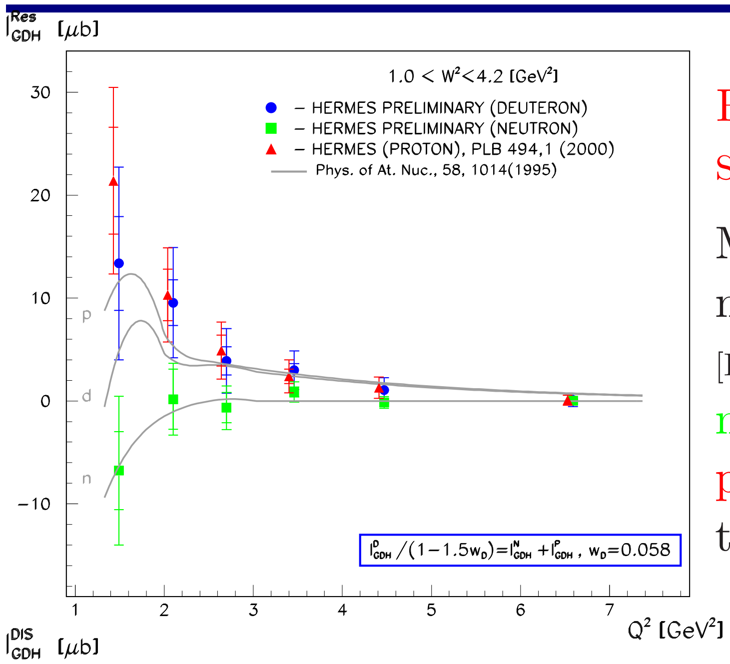
- Generalized GDH Integral for the neutron:

$$I^n_{GDH} = \frac{I^d_{GDH}}{1-1.5\omega_d} - I^p_{GDH}$$

I^n_{GDH}: C. Ciofi degli Atti et al., Phys. Lett. B 376 (1996) 309

$\omega_d = 0.058 \pm 0.010$: probability of the deuteron to be in a D-state
(M. Lacombe et al., Phys. Lett. B 101 (1981) 139)

Gen. GDH Integral: Results I



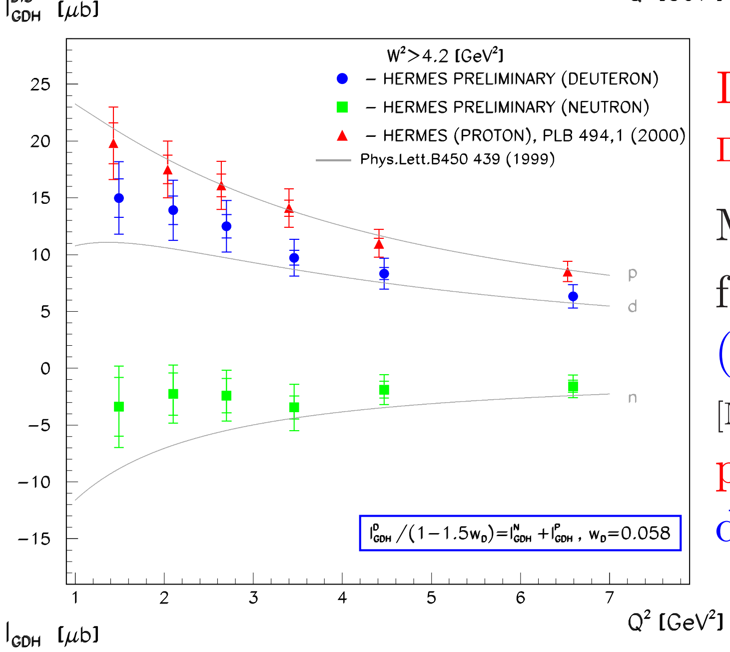
Resonance contribution: small for $Q^2 > 3$ GeV^2

Model using Q^2-evolution of nucleon resonance amplitudes:

[I.G.Aznauryan,Phys.of At.Nuc.,58(1995)1014]

n-data: well described

p- and d-data: described within total exp. errors



DIS contribution: sizeable down to lowest measured Q^2.

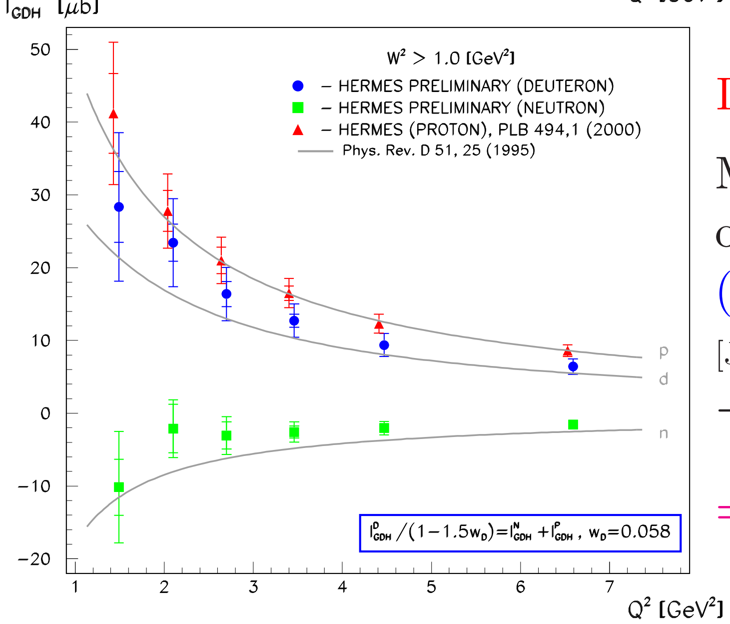
Mult.–Reggeon-exchange param. for $\sigma^{\leftleftarrows} - \sigma^{\rightrightarrows}$ at high energy

($\longrightarrow$ extrap. into unmeas. region)

[N. Bianchi,E.Thomas,Phys.Lett.B450(1999),439]

p-data: well described

d- and n-data: $Q^2 > 3$ GeV^2: ok



DIS & Resonance region:

Model: leading-twist Q^2-evol. of 1st moments of g_1, g_2

(w/o any resonance contribution)

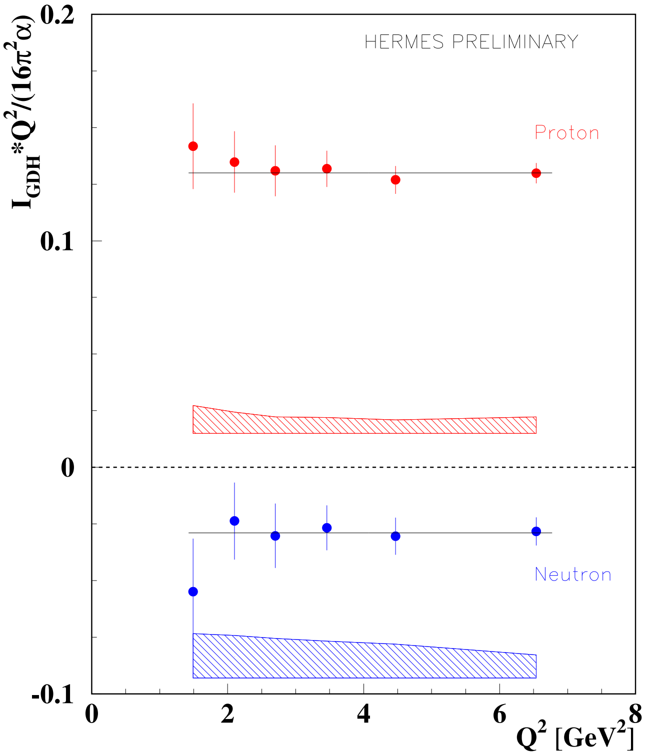
[J.Soffer,O.V.Teryaev,Phys.Rev.**D56**(1997)7458]

$\longrightarrow$ all data well described

$\Longrightarrow$ hint on quark-hadron duality

Gen. GDH Integral: Results II

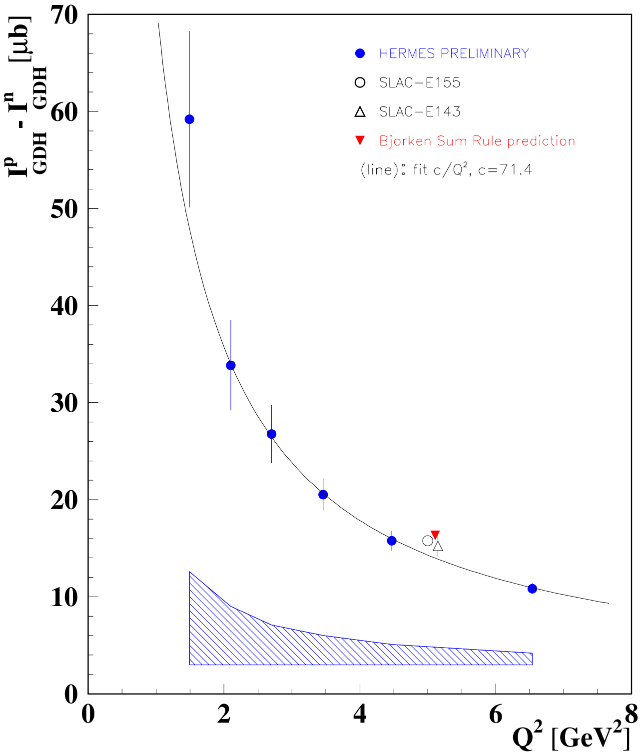
- Q^2-dependence $\sim 1/Q^2$?



Dividing out $\sim 1/Q^2$ dependence (leading-twist) leads to flat Q^2-behaviour for both p and n

$\Longrightarrow$ down to $Q^2 \simeq 1.5$ GeV^2
no indications for sizeable contributions from higher-twists or nucleon-resonance form factors

- Proton-Neutron difference



- At $Q^2 = 5$ GeV^2: Agreement with Bjorken sum rule prediction (16.33 ± 0.45 μb) and SLAC E-143/155 data)

- NOTE: Real-photon point $I^p_{GDH}|_{Q^2=0} - I^n_{GDH}|_{Q^2=0} = 29\mu b$
$\Longrightarrow$ turn-over point not seen in HERMES kinematics

- Q^2-dependence of p-n difference also follows $1/Q^2$ behaviour down to lowest measured values

Quark-Hadron duality I

• Development of Duality concept over history

* Origin from hadron-hadron scattering:

relationship between $s-$ and $t-$ channel behaviours of scatt. ampl.

[R. Dolen, D. Horn, C. Schmid, Phys. Rev. Lett. 19 (1967) 402; Phys. Rev. 166 (1968) 1768]
[G. Veneziano, Nuovo Cimento 57A (1968) 1395]

* Generalization of $s-$ and $t-$ channel duality:

including both resonant and non-resonant contrib.'s to cross section

[H. Harari, Phys. Rev. Lett. 20 (1968) 1395]

* In Inclusive electron scattering:

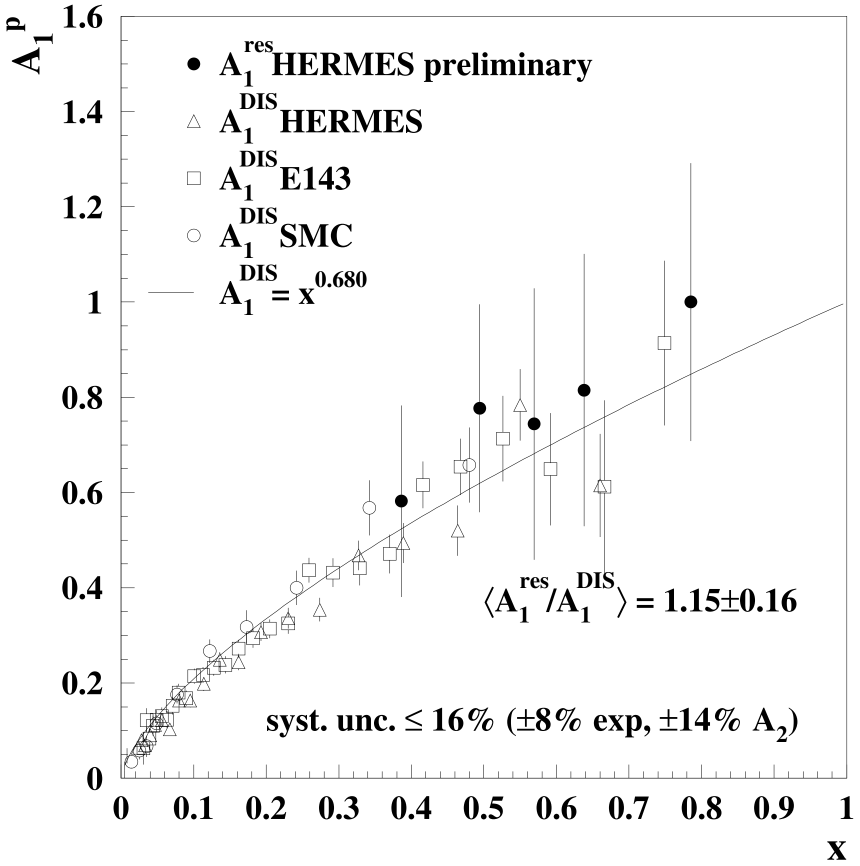
duality between resonances and valence quarks
(resp. background dual to sea quarks)

[W. Melnitchouk, hep-ph/0106262]

• BLOOM-GILMAN duality: DIS $\Longleftrightarrow$ resonance region

[E.D. Bloom, F.J. Gilman, Phys. Rev. Lett. 25 (1970) 1140; Phys. Rev. D4 (1971) 2901]

A structure function (or a ratio) measured in the DIS region represents an average of the same function (or ratio) measured in the resonance region



Quark-Hadron duality II

• pQCD re-formulation of Bloom-Gilman Duality:

* Leading terms (non-interacting quarks) $\longrightarrow$ scaling
* Non-leading terms ($q - g$ interactions) $\sim 1/Q^2$

[A. De Rujula, H. Georgi, H.D. Politzer, Phys. Lett. B64 (1976) 428]

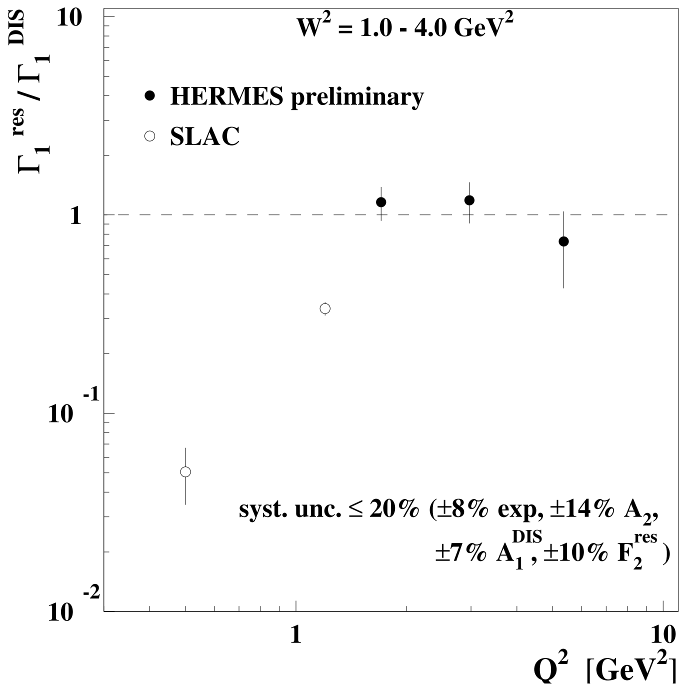
> Duality concept successful in those rare case(s) when a pQCD calculation describes the average of a hadronic observable (like res. region $\leftrightarrow$ DIS)

but: pQCD picture must fail for low virtuality
$\Longrightarrow$ breakdown of Duality unavoidable at low Q^2

• Polarized electron-nucleon scattering:

> Duality in *polarized* structure function (ratio) is *non-trivial* because of different helicity structure of polarized DIS and nucleon resonance(s) [Δ: opposite helicity]

$\Longrightarrow$ Investigate Q^2-dependence of $\Gamma_1^{res}/\Gamma_1^{DIS}$



1^{st} tests in polarized case:

- **SLAC E143:** K. Abe et al., Phys. Rev. D 58, 112001 (1998)

• HERMES kinematics: Duality holds over full measured region

$\longrightarrow$ same behaviour as known from unpolarized case

SUMMARY

- Generalized GDH Integrals for deuteron, proton and neutron measured for the 1st time measured simultaneously in nucleon-resonance and DIS region

  ▷ resonance contribution: small for $Q^2 > 3$ GeV^2
  ▷ DIS contribution: sizeable over full measured Q^2
  ▷ combined data: No effect from higher-twists or resonance form factors down to $Q^2 \simeq 1.5$ GeV^2

- GDH proton-neutron difference:
  ▷ agrees well with Bjorken Sum Rule prediction and SLAC data at $Q^2 = 5$ GeV^2
  ▷ leading-twist $1/Q^2$-behaviour intact down to $Q^2 \simeq 1.5$ GeV^2

- turn-over of proton and deuteron GDH data (towards real-photon point) not observed

- quark-hadron duality in polarized eN scattering:
  $\Longrightarrow$ 'hard regime' (again) intact down to $Q^2 \simeq 1.5$ GeV^2