Local Duality
in spin structure functions g_1^p and g_1^d

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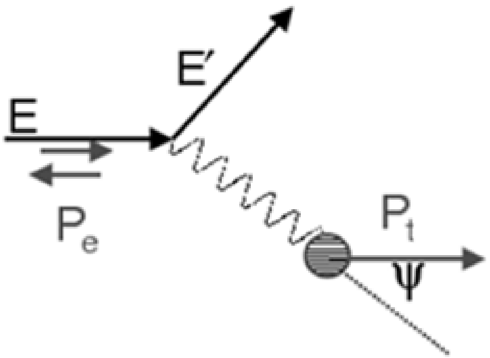
Outline

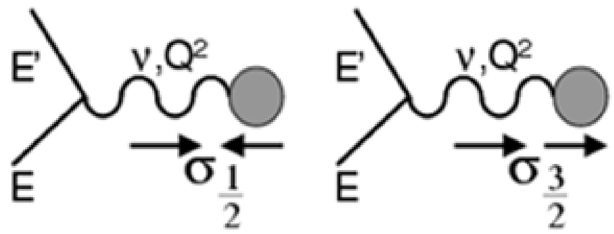
1. Measurement of spin structure functions
2. Duality in spin structure functions ?
3. Jefferson Lab Hall B Experiment ‘EG2000’
4. Data Analysis
5. Testing for global and local duality
6. Conclusions

Asymmetry Measurements

$$\frac{d\sigma}{dE'd\Omega} = \Gamma_\nu \left[\sigma_T + \varepsilon\sigma_L + P_e P_t \left(\sqrt{1-\varepsilon^2}\, A_1 \sigma_T \cos\psi + \sqrt{2\varepsilon(1-\varepsilon)}\, A_2 \sigma_T \sin\psi\right)\right]$$

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{2\sigma_T} \qquad A_2 = \frac{\sigma_{LT}}{\sigma_T}$$



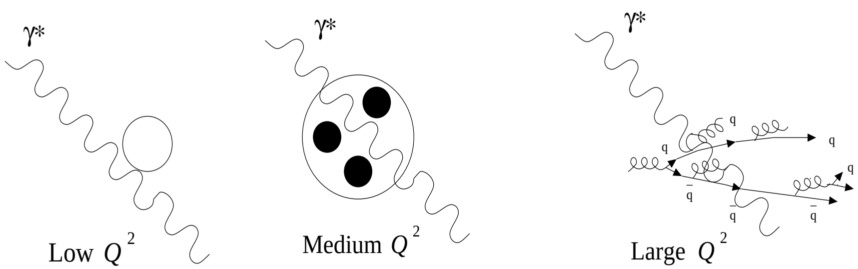


The structure functions can be extracted from the measured asymmetries

$$g_1(x,Q^2)=F_1\ [A_1+\gamma\ A_2]\ /\ [1+\gamma^2],\ \gamma=Q^2/\nu^2$$

Why is g_1 interesting

- Describes the spin structure of a nucleon, which depends on the Q^2 of the process
- Low Q^2 (< 0.2 GeV^2) $\rightarrow$ Nucleon-Meson degrees of freedom
- Medium Q^2 (<1 GeV^2) $\rightarrow$ Nucleon Resonances, Constituent Quarks
- Large Q^2 (>2 GeV^2) $\rightarrow$ pQCD, gluon radiation
- Very high Q^2 ($\rightarrow \infty$) $\rightarrow$ Parton Model, free quarks



Quark-Hadron duality

- An observation that the hadronic and partonic degrees of freedom can sometimes both be successfully used to describe the structure of hadrons is called quark-hadron duality.

- It was discovered experimentally by Bloom and Gilman (Phys.Rev.Lett. 25 (1970) 1140) who observed that the spin averaged structure function $F_2(\nu,Q^2)$ measured in the resonance region was on average equivalent to the deep inelastic one, if averaged over the variable $w'=(2M\nu+M^2)/Q^2$

- In the QCD-based approach, the moments of structure functions in the low and high Q^2 regions are related to each other. The Q^2 dependence of the moments reflects the perturbative evolution of the single quark scattering, and the interaction between the struck quark and the remainder of the target.

- The moments of F_2 taken in the low Q^2 and the DIS region were shown to be equivalent within a given range and precision of the data (Phys.Lett.B 64 (1976) 428)), leading to the conclusion that the multiparton interactions terms were small or canceling in the calculation.

Quantifying the quark-hadron duality

- Quark-hadron duality can be quantified by considering partial moments of the resonance structure functions at fixed Q^2:

$$\int_\xi F_2^p(\xi,Q^2)\, d\xi, \quad \xi=2x/(1+(1+4m^2x^2/Q^2)^{-0.5})$$

- Such moments can be compared to the integrals of the 'scaling' structure functions in the same range of ξ and at the same Q^2

- The resonance data can be compared with the PDF based fits at the same values of (ξ,Q^2), and with the phenomenological fits to DIS scattering at high Q^2, with the ξ values corresponding to those of the resonance data.

- The equivalence of the moments of structure functions at high and low Q^2 is referred to as 'global' duality, if the integration is taken over the whole resonance region. If the averaging is taken over the restricted resonance regions, the 'local' duality is tested.

Duality for g_1?

- A recent study of the quark-hadron duality was reported by Niculescu et. al (Phys.Rev.Lett 85, 1186 (2000)), who used the high statistical precision data from Jefferson Lab to perform the global and local duality studies. The global and local duality, centered on three resonance regions (ΔP_{33}(1232), S_{11}(1535), F_{15}(1680)) were verified at 10 % level for $Q^2 > 1$ GeV^2

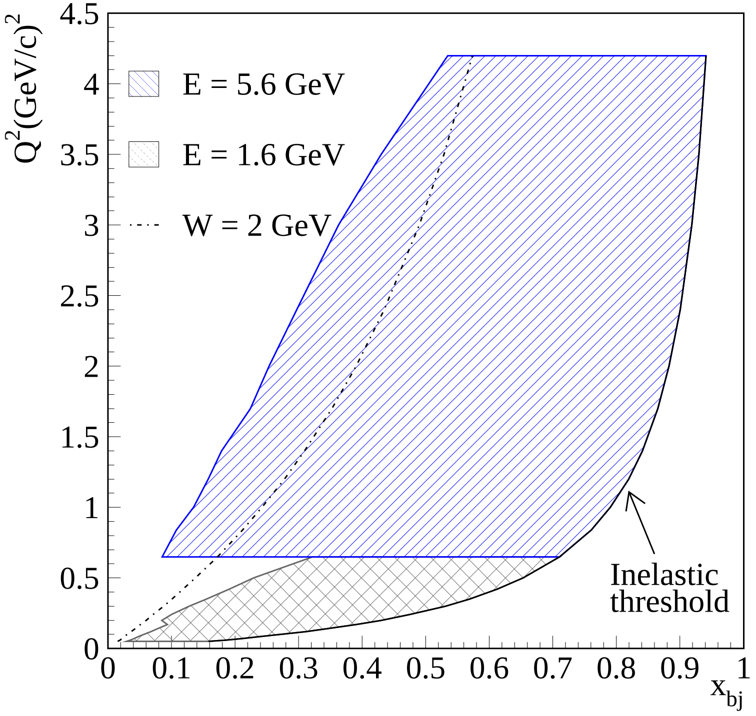
- Duality for the spin structure function $g_1(x,Q^2)$ has not been as well investigated, and can help to understand the transition region from the large Q^2 region to the $Q^2 \rightarrow 0$ region, where the Gerasimov-Drell-Hearn sum rule applies.

- The onset of duality for g_1 is expected to be at a larger Q^2 than for F_2 because of the strong Q^2 dependence of g_1 at low Q^2, needed by the GDH sum rule.

Experiment ('EG2000')

- Measured double spin asymmetry $A_{\parallel}$
- Longitudinally polarized electrons
  Polarization $\sim$ 70 %
  Beam energies: 1.6, 2.5, 4.2, 5.7 GeV
- Polarized solid ammonia targets
  $^{15}NH_3$ (polarization $\sim$ 70-90 %)
  $^{15}ND_3$ (polarization $\sim$ 10-30 %)
- Unpolarized targets
  ^{12}C, ^{15}N, ^{4}He
- CLAS in Hall B
  Multi-particle final states
- Wide coverage in Q^2 and W
  $0.05 < Q^2 < 4.5\ \mathrm{GeV}^2$
  $0.8 < W < 3.0$ GeV
- 2000/2001 run: 23 billion triggers

Kinematical Coverage



Good coverage of the resonance region, some coverage of the DIS region

Asymmetry Analysis

- Raw inclusive double spin asymmetry is measured

  $A_{raw} = [N^+/Q^+ - N^-/Q^-] / [N^+/Q^+ + N^-/Q^-]$

  $N^{+/-}$ Counts with beam/target spins anti-aligned(-) or aligned(+)

  $Q^{+/-}$ Integrated beam charge
- Physics asymmetry $A_{\|}$ is obtained

  $A_{\|} = C_{back} A_{raw} / P_b P_t / DF$

  C_{back} correction for the pion and e^+/e^- contamination

  $P_b P_t$ product of beam and target polarization

  DF Dilution factor (to correct for the unpolarized materials in the target)
- Radiative corrections are applied

  Internal RC: Kuchto and Shumeiko

  External RC: Tsai

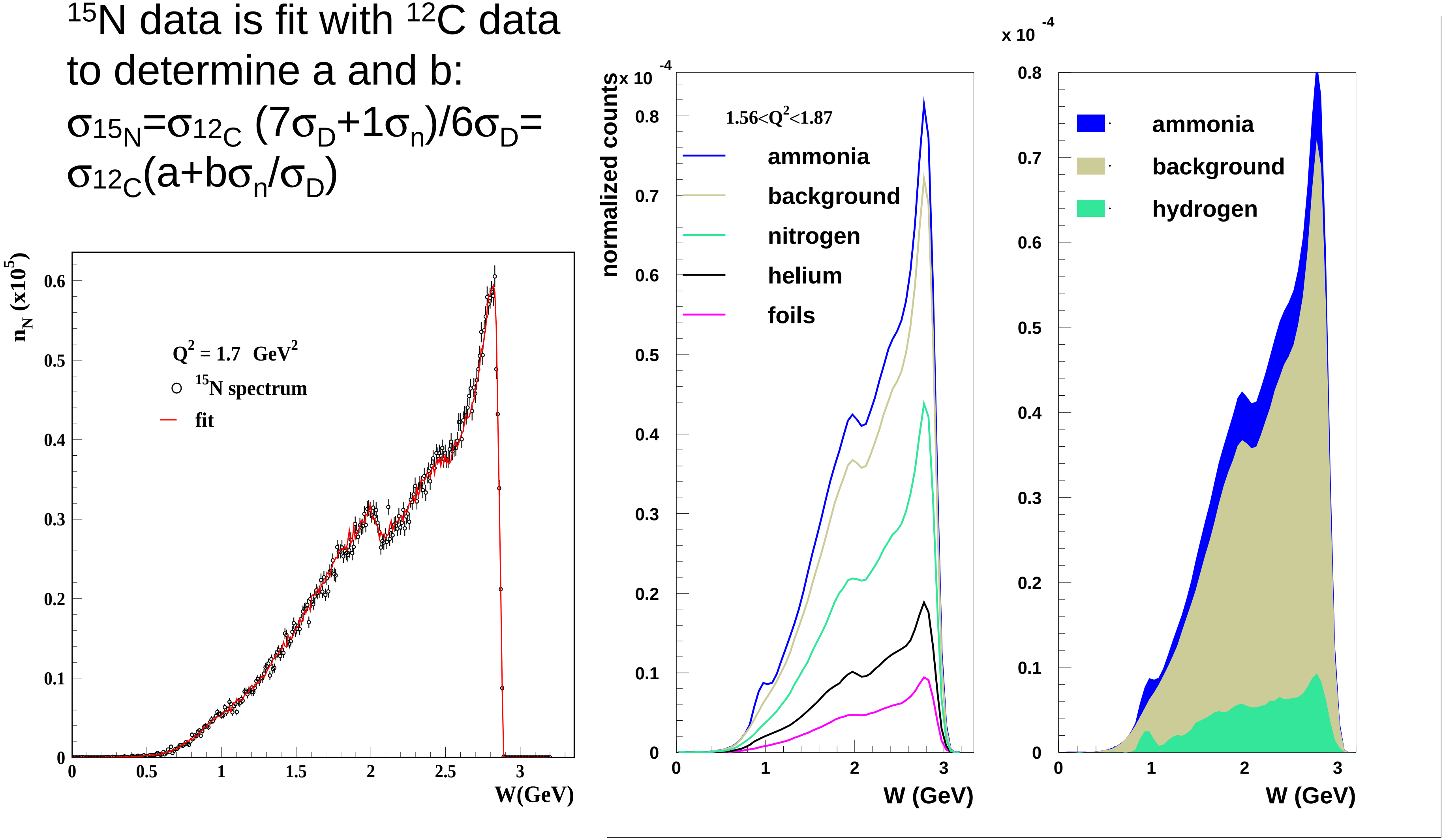
  $A_{\|}^{Born} = A_{\|}^{meas} / F_{RC} + A_{RC}$
- Desired photon-nucleon asymmetries

  $A_1 + \eta\ A_2 = A_{\|}^{Born}/D$, $D(R = \sigma_L/\sigma_T,$ kinematic factors)

Background Subtraction

^{15}N data is fit with ^{12}C data to determine a and b:

$\sigma_{15_N} = \sigma_{12_C}\,(7\sigma_D + 1\sigma_n)/6\sigma_D = \sigma_{12_C}(a + b\sigma_n/\sigma_D)$



Beam and Target Polarization

The product of beam and target polarization is determined by measuring the known elastic peak asymmetry:

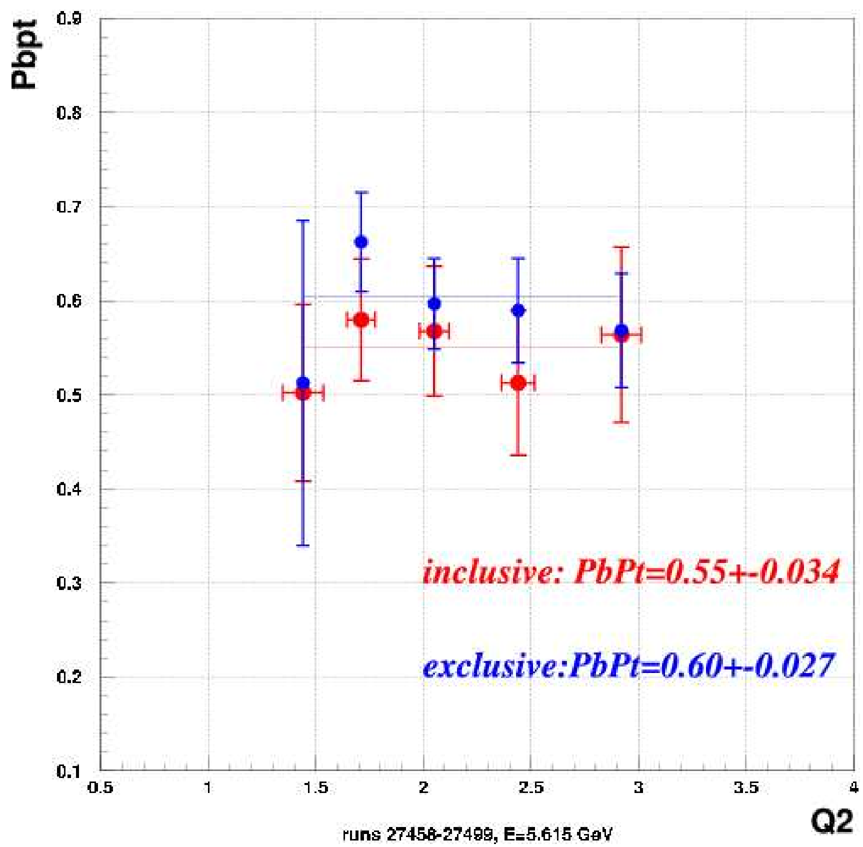
$PbPt=A_{el}^{meas}/A_{el}^{known}$

For the deuteron, the quasielastic asymmetry is calculated:

$[\sigma_n^{el}A_n^{el}+\sigma_p^{el}A_p^{el}] / [\sigma_n^{el} +\sigma_p^{el}]$

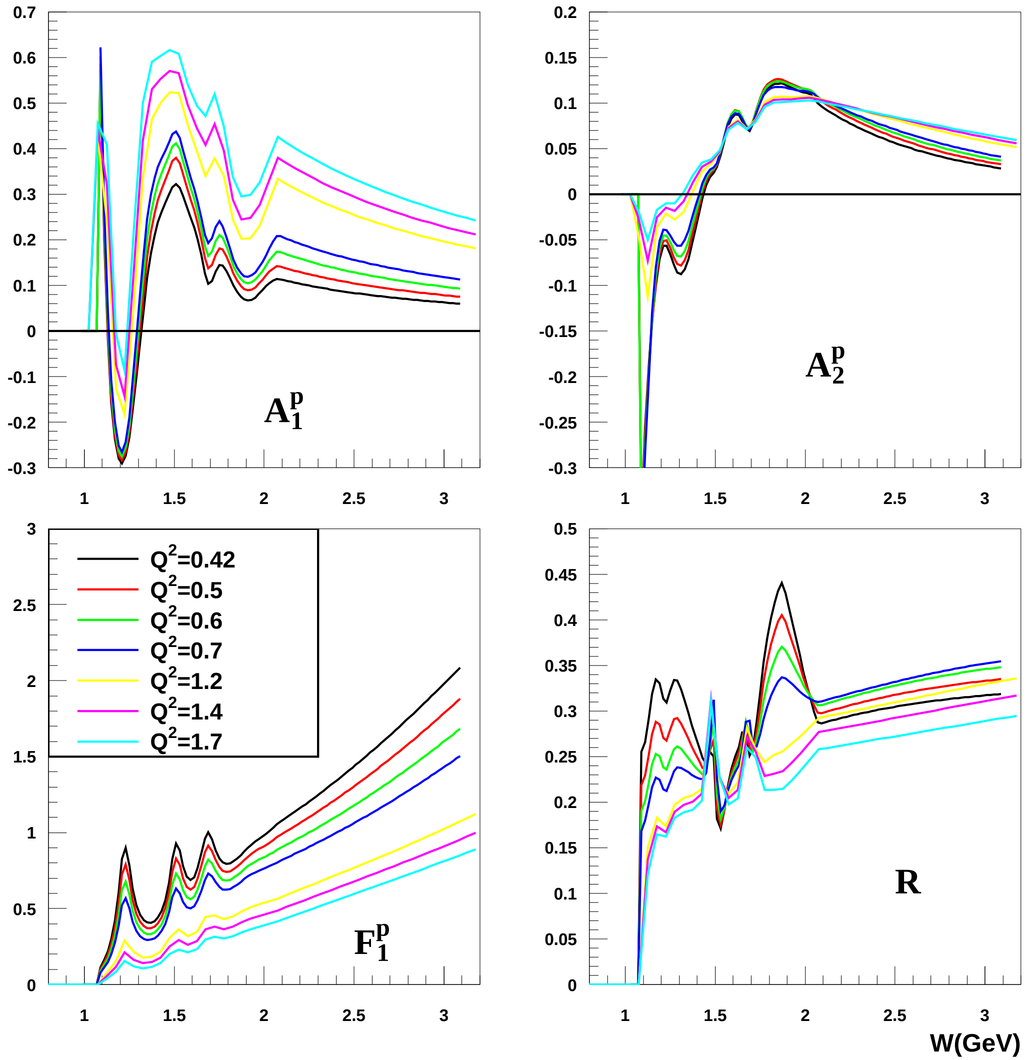
Inclusive or (e,e′p) events are used

5.7 GeV data with the proton target



Model Input

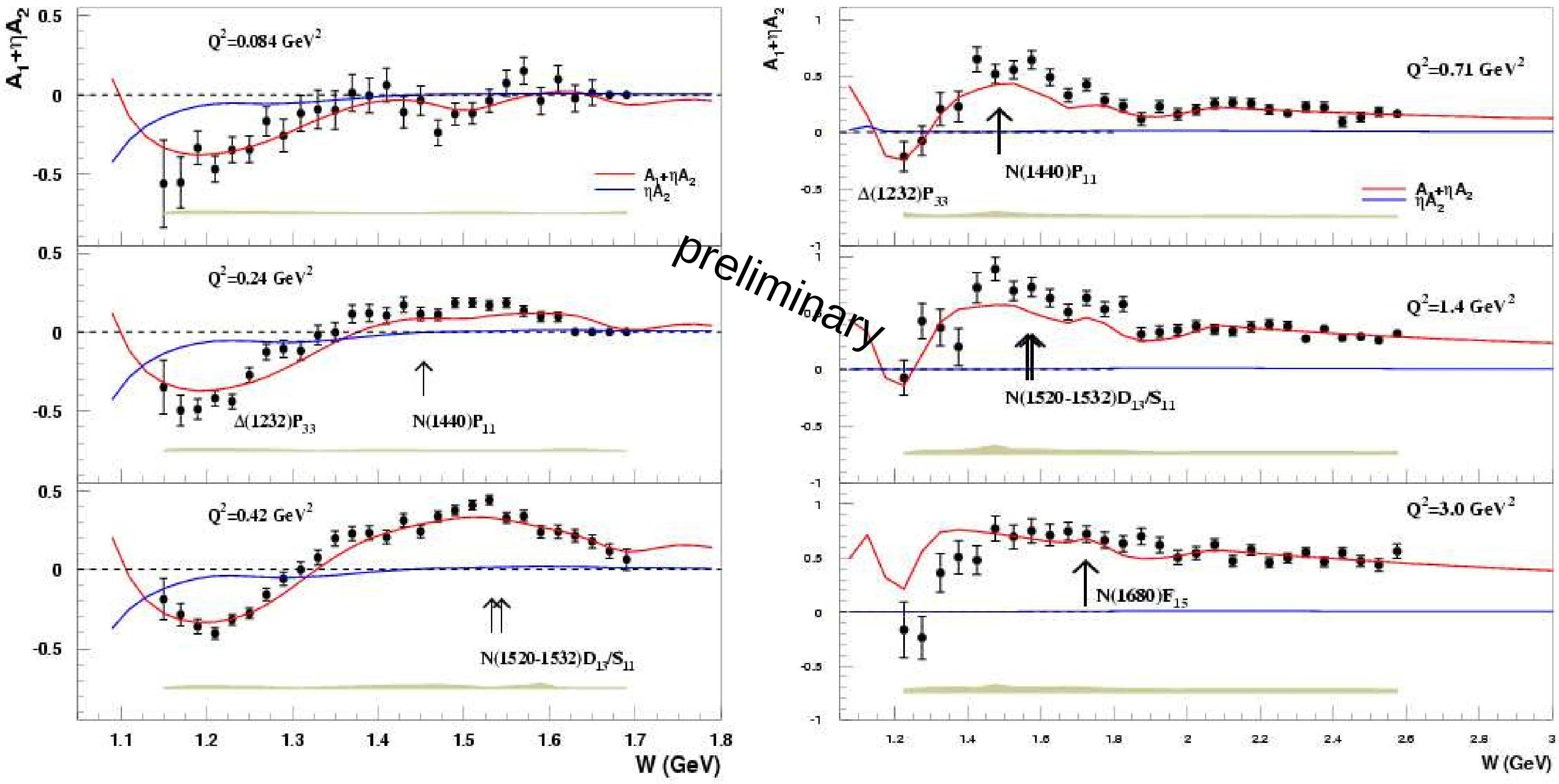
- A_1: fit to the world data in DIS region, AO model in the resonance region
- A_2: g_2^{WW} in the DIS region, MAID in the resonance region
- F_1: fit to the world data
- R: Recent fit from Hall C (nucl-ex/0410027)



Extraction of $A_1+\eta A_2$

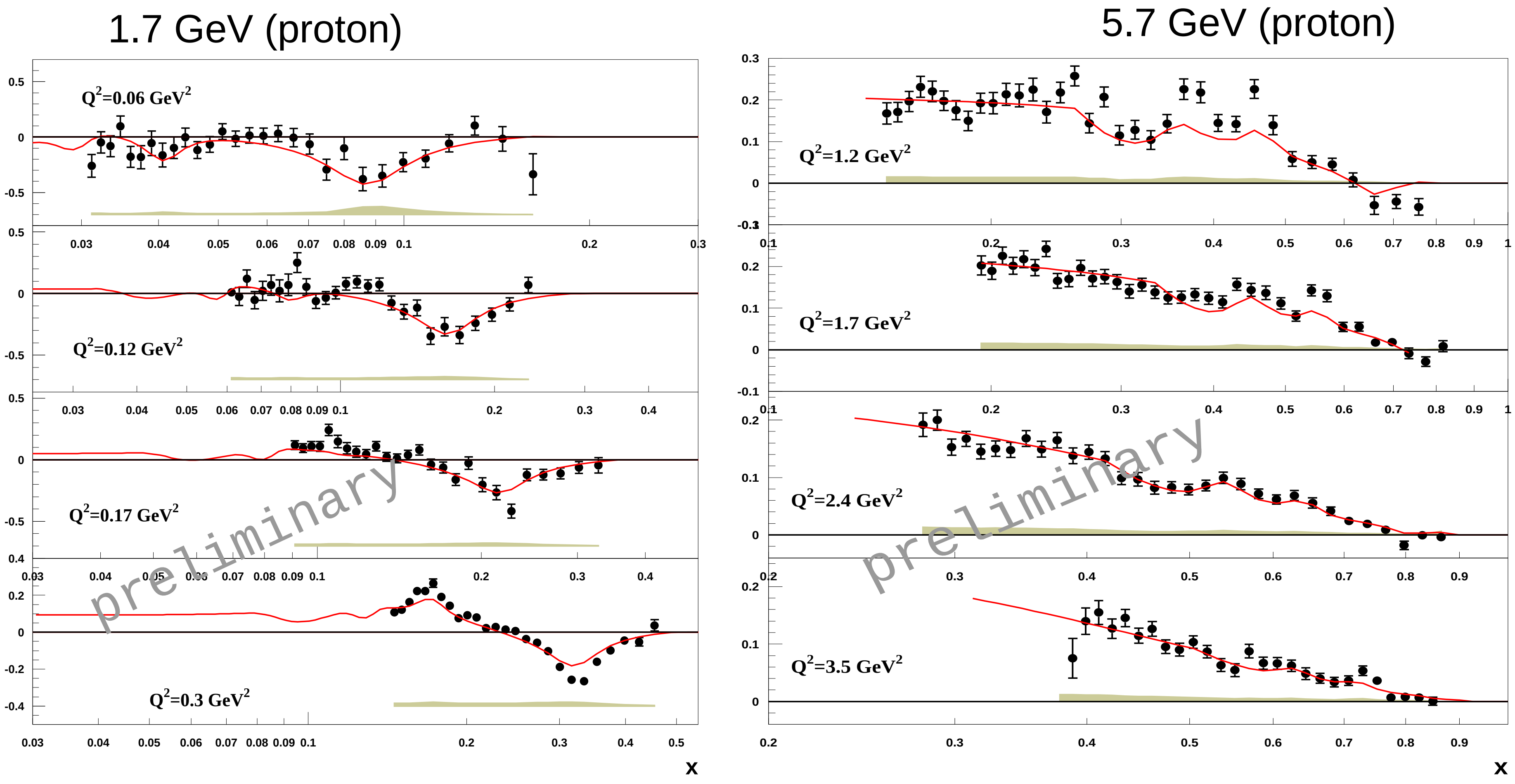
$$A_1+\eta A_2=A_{\|}/D(R)$$

1.7 GeV (proton) 5.7 GeV (proton)



Extraction of $g_1(x,Q^2)$

$$g_1 = F_1\,[A_{\|}/D + (\gamma-\eta)A_2]\,/[1+\gamma^2]$$

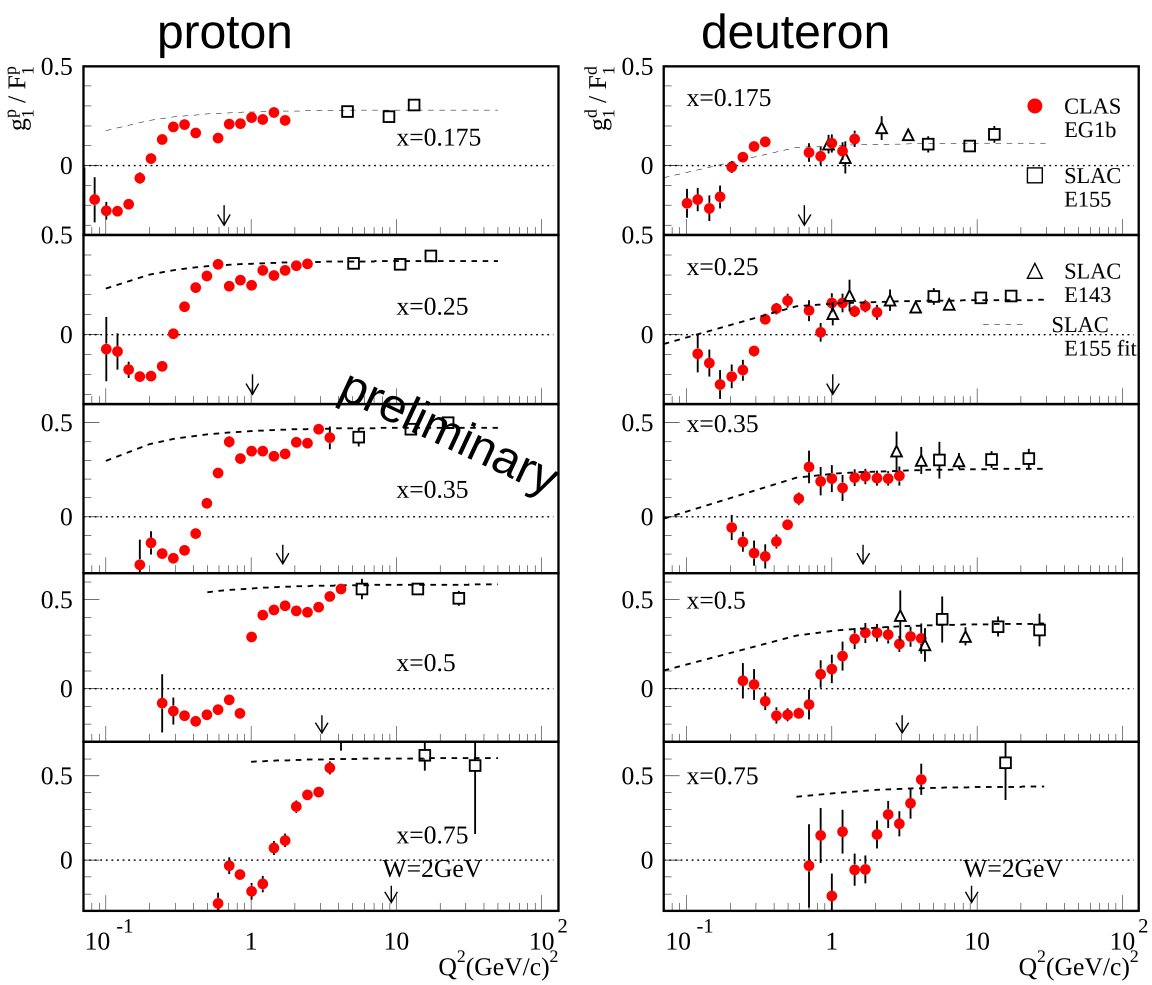


Ratio $g_1^{p,d}/F_1^{p,d}$ (x,Q^2)

No clear Q^2 dependence above W=2 GeV

Below W=2 GeV, the ratio decreases with the decreasing Q^2

Above W=2 GeV, the ratio rises with $x \rightarrow 1$



Testing the onset of quark-hadron duality

- Compare the resonance region g_1 with the scaling g_1 in the DIS region, and the PDF-based pQCD global fits:

1. World data fit at Q^2=10 GeV^2 (Phys.Lett. B493 (2000),19)
2. pQCD NLO std. calculation (GRSV) (Phys.Rev.D 63 (2001), 094005)
3. pQCD NLO calculation (AAC) (Phys.Rev.D 69 (2004) 054021)

- Target mass corrections were applied to the pQCD models according to the formulas of J.Blumlein and A.Tkabladze (Nucl.Phys.B 553, 427 (1999))
- Can quantify duality though the ratio of partial moments

$$R(Q^2) \equiv I^{RES}/I^{DIS} \equiv \int_\xi g_1^{RES}(\xi,Q^2)d\xi \;/\; \int_\xi g_1^{DIS}(\xi,Q^2)d\xi$$

where the integration is performed over the entire resonance region (global duality), and the three lowest lying resonances individually (local duality)

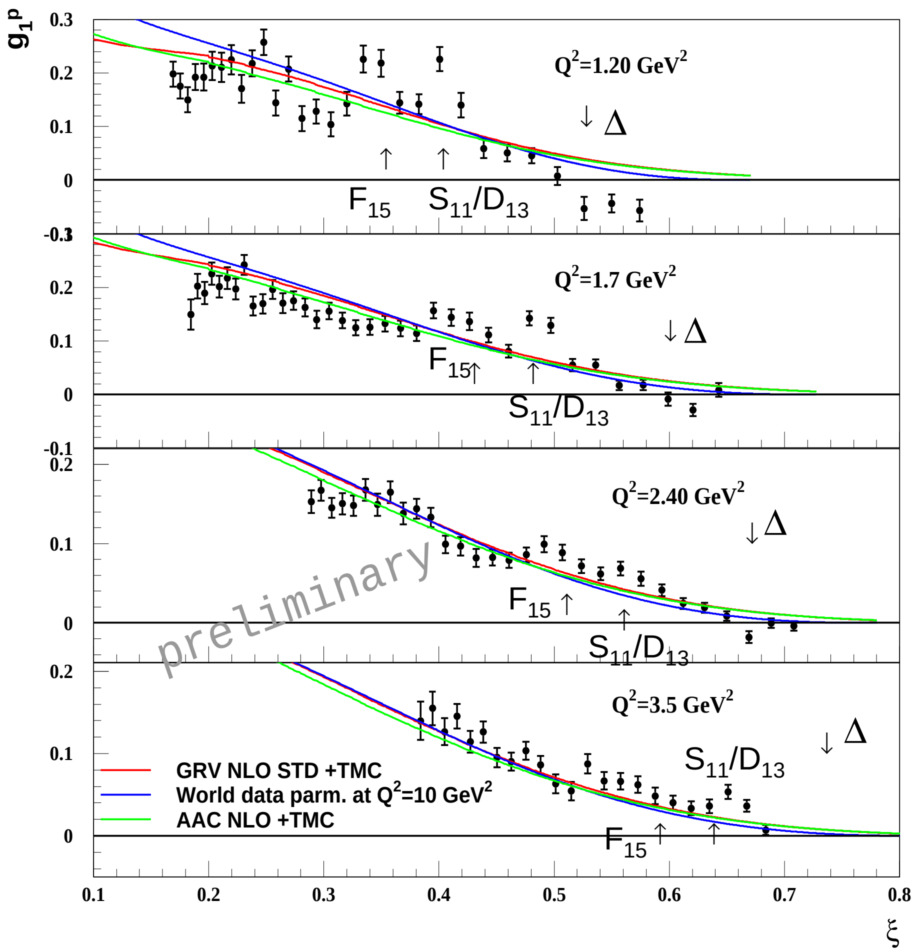
- Can also test the effect of including the elastic contribution, given by

$$I^{el}=G_E(Q^2)\,[G_E(Q^2) + \tau G_M(Q^2)] \,/\, 2(1+\tau), \quad \tau=Q^2/M^2$$

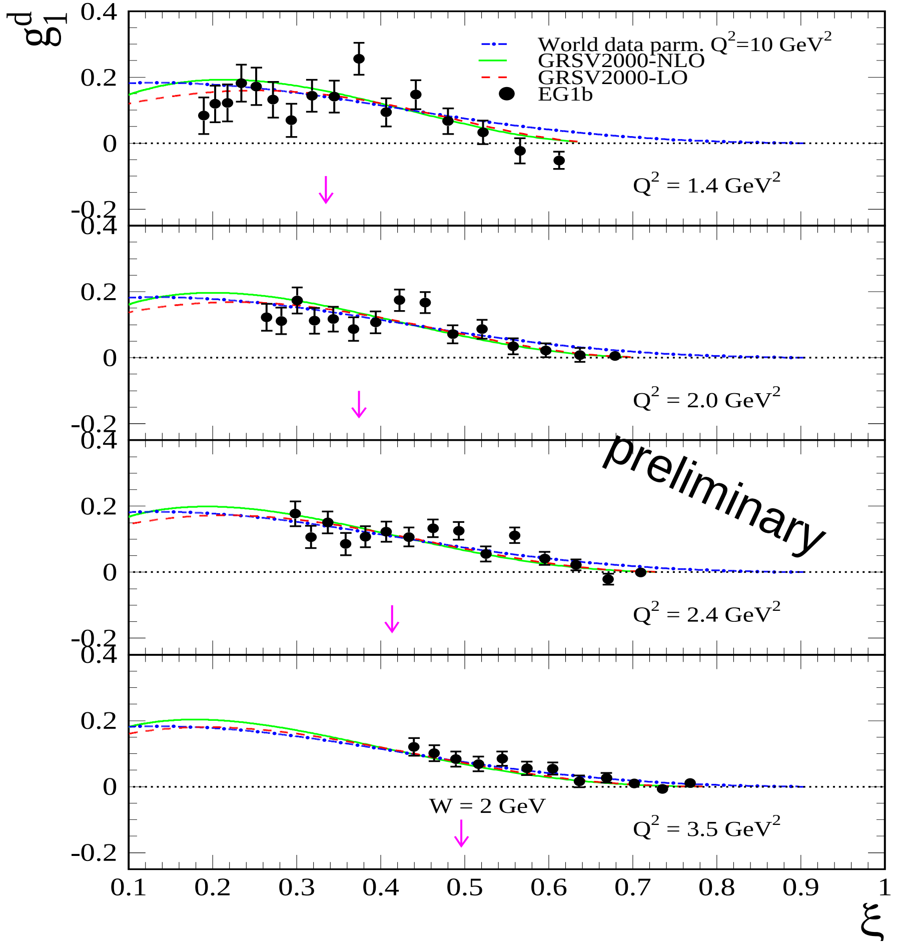
- Deuteron quasi-elastic contribution given by the sum of the proton and neutron elastic contributions

$g_1^{p,d}(\xi,Q^2)$ and pQCD models

$g_1^p(\xi,Q^2)$

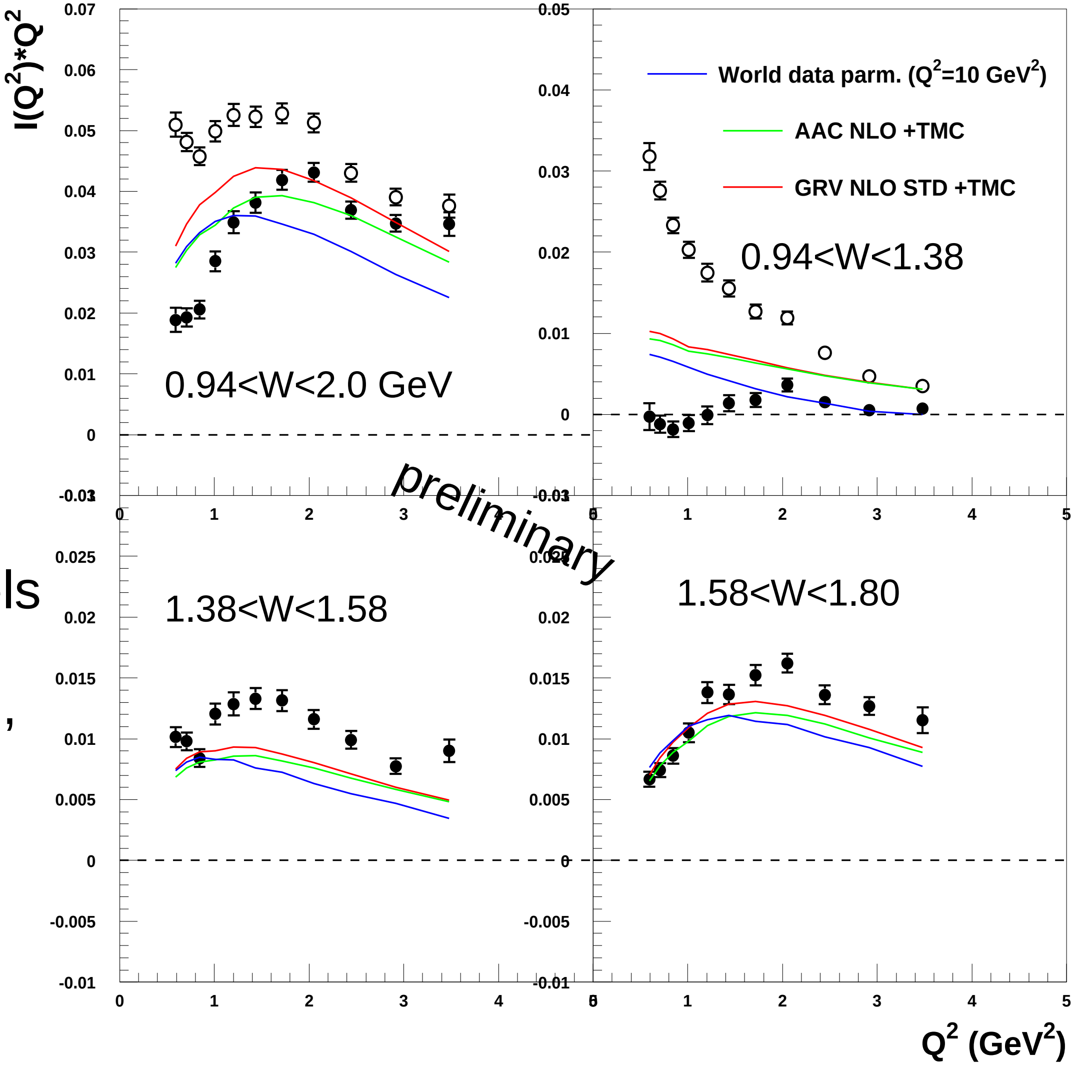


$g_1^d(\xi,Q^2)$



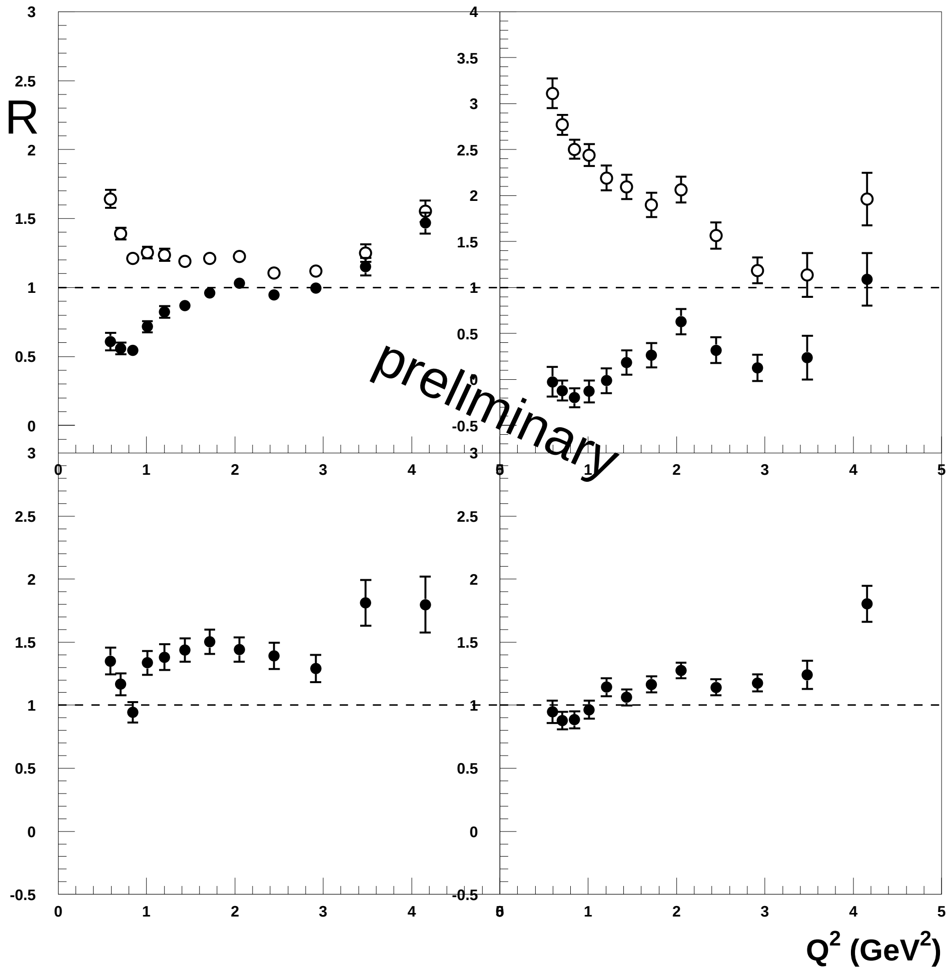
Partial Integrals $I(Q^2)*Q^2$ (proton)

- $I_{DIS}=\int_\xi g_1^{DIS}(\xi,Q^2)d\xi$
- $I_{RES}=\int_\xi g_1^{RES}(\xi,Q^2)d\xi$
- Integration limits ξ_{min} and ξ_{max} correspond to the W limits at a given Q^2
- Systematic uncertainty in the data is ~ 6 %
- Systematic uncertainty of the DIS fit ~ 10 %
- Uncertainty in the pQCD models ?
- Without the elastic contribution, the data is consistent with the scaling curves above Q^2~ 1.5 GeV^2



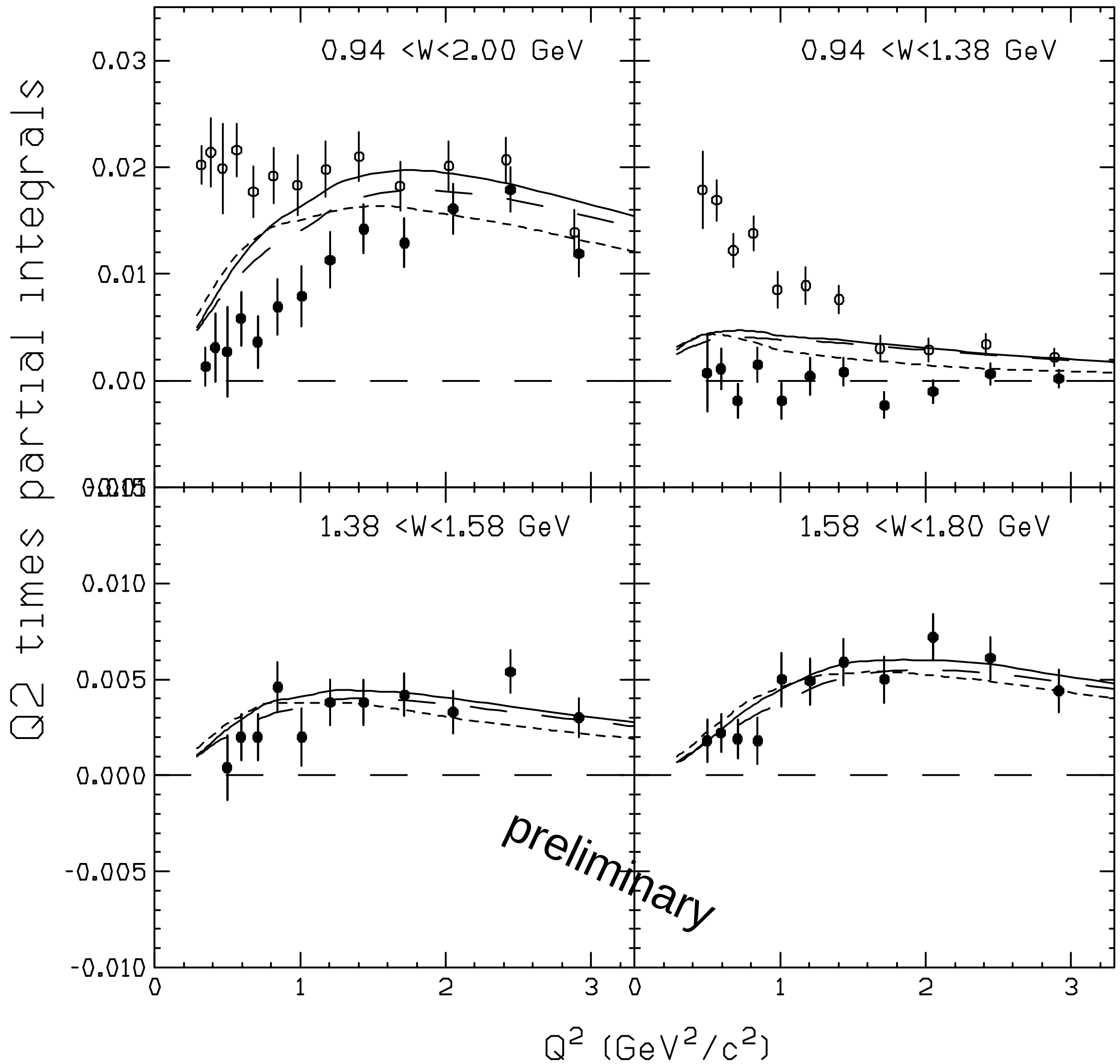
Ratio I_{RES}/I_{DIS} (Q^2) (proton)

- Standard version of the NLO GRSV model is used in the denominator
- At low Q^2 Δ-resonance is dominated by a magnetic dipole transition ($A_{3/2}$ is larger than $A_{1/2}$) leading to a mostly negative contribution to the ratio
- In the second resonance region, a positive asymmetry is due to $A_{1/2}$ of D_{13} and S_{11} increasing with Q^2.



Partial Integral $I(Q^2)*Q^2$ (deuteron)

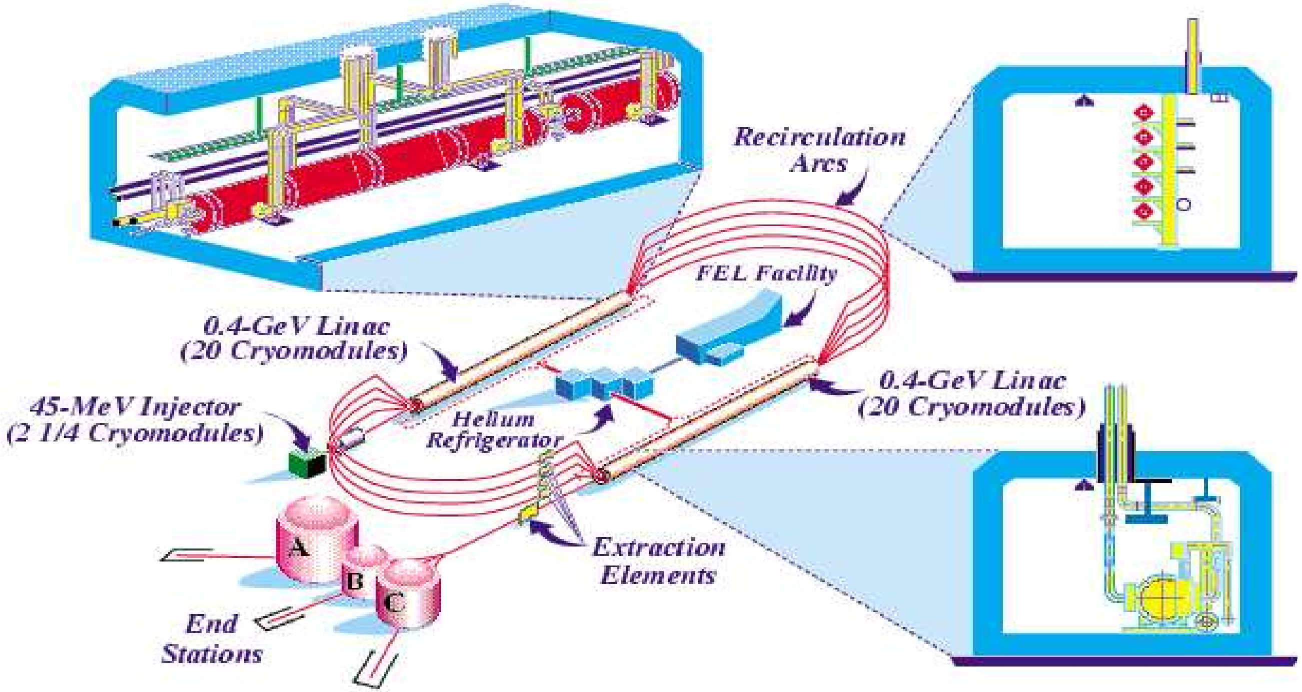
- Suppression of resonant structure
- Fermi momentum contributes to the smearing of the W resolution
- Duality appears to hold in the second and third resonance regions at Q^2>1 GeV^2



Conclusions

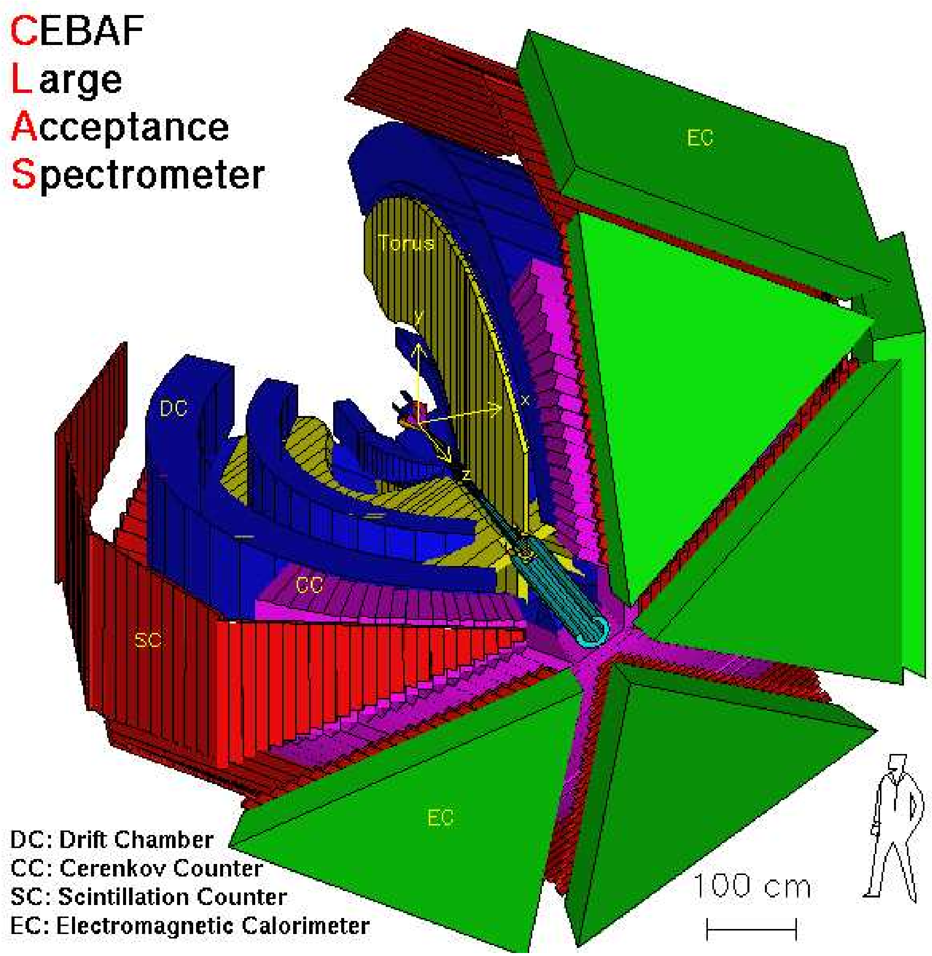
- High statistical precision data on the g_1^p and g_1^d in the resonance region has been analyzed, complementing the existing data and extending it to lower Q^2 region
- The measurements of g_1 support the global quark-hadron duality for $Q^2 > 1.5$ GeV^2 for both the proton and the deuteron
- In the case of a proton, the local duality does not seem to hold in the first and second resonance regions, with the first region showing negative asymmetry due to the Δ contribution, and the second region having a large positive asymmetry due to the negative parity resonances S_{11} and D_{13}. Duality may be present in the third resonance region.
- In the case of a deuteron, the local duality appears to hold in the second and third resonance regions.

Polarized Beam at Jefferson Lab



- Two linac segments
- Nine recirculation arcs
- Polarization $\sim$ 75 %
- Energy up to 5.7 GeV

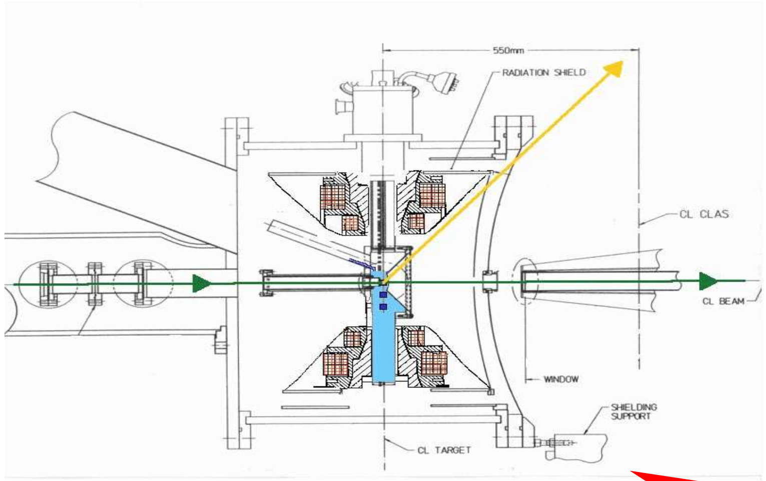
CLAS in Hall B



Polarized Target

Dynamic Nuclear Polarization

(DNP) NH_3 and ND_3 target



B=5 Tesla

$\frac{dB}{B} \approx 10^{-4}$

1^oK ^4He cooling bath

^{12}C and ^{15}N targets

$P_{NH_3} \approx 75 \rightarrow 85\%$

$P_{ND_3} \approx 25 \rightarrow 35\%$

$\frac{\delta(P_b \cdot P_t)}{P_b \cdot P_t} \approx 3\% for NH_3$