Spin structure functions at low Q^2 from JLab data

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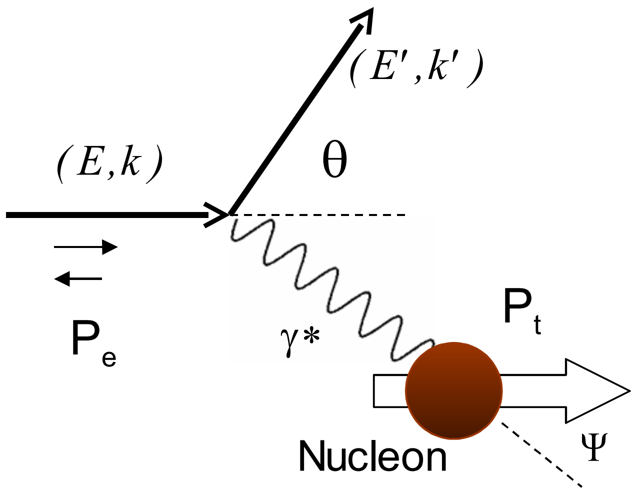
for the CLAS collaboraton

OUTLINE

- Formalism and physics overview
- Overview of the experiment
- Results
- Summary

Double polarized inclusive electron scattering



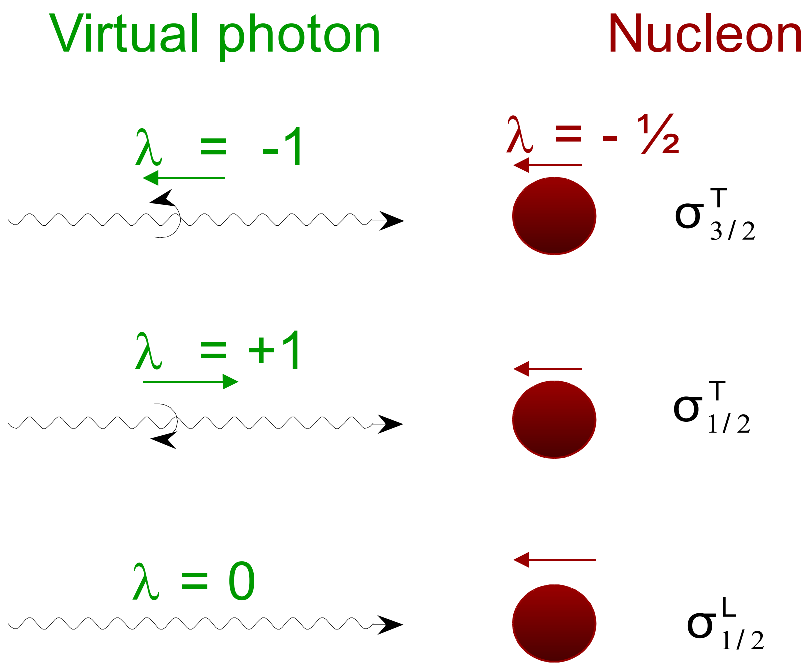
- Longitudinally polarized beam and target
- Inclusive electron scattering

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

Electron asymmetry

$$A_{\parallel}(\nu,Q^2) = \frac{\frac{d\sigma}{dE'd\Omega}(\uparrow\downarrow) - \frac{d\sigma}{dE'd\Omega}(\uparrow\uparrow)}{\frac{d\sigma}{dE'd\Omega}(\uparrow\downarrow) + \frac{d\sigma}{dE'd\Omega}(\uparrow\uparrow)}$$

Virtual photon asymmetries



$$A_1 = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}}$$

$$A_2 = \frac{2\sigma^{TL}_{1/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}}$$

$$A_{\parallel} = D(A_1 + \eta A_2)$$

Spin structure function

$$g_1(x,Q^2) = \frac{\nu^2}{Q^2}\left(A_1 + \sqrt{\frac{Q^2}{\nu^2}}A_2\right)F_1$$

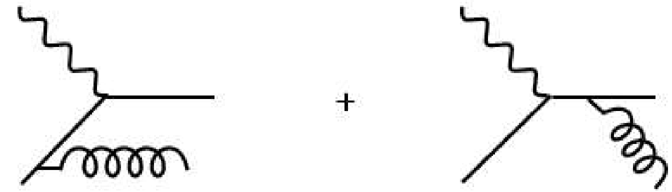
$$D = \frac{1-\varepsilon E'/E}{1+\varepsilon R}, \quad \eta = \frac{\varepsilon\sqrt{Q^2}/E}{1-\varepsilon E'/E}$$

Q^2 evolution of the spin structure function g_1

- $Q^2 \rightarrow \infty$ quarks behave as free particles

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i(x)$$

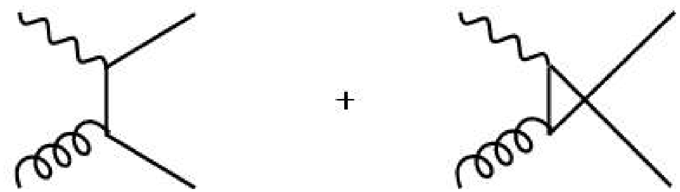
Gluon radiation



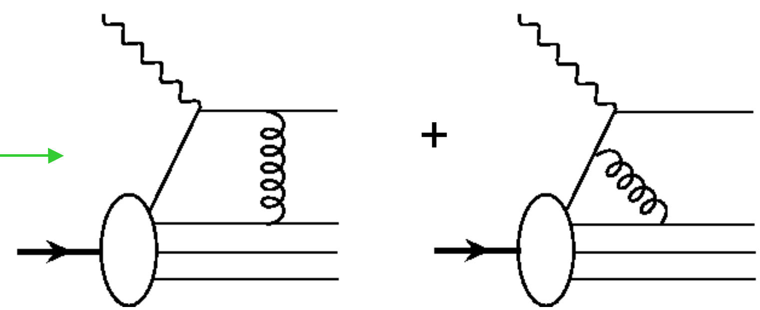
- At finite but large Q^2 additional corrections
- •Describable in pQCD
- •Distribution functions in DGLAP equations
- •Slow logarithmic Q^2 dependence

NLO

$g \rightarrow q + \bar{q}$

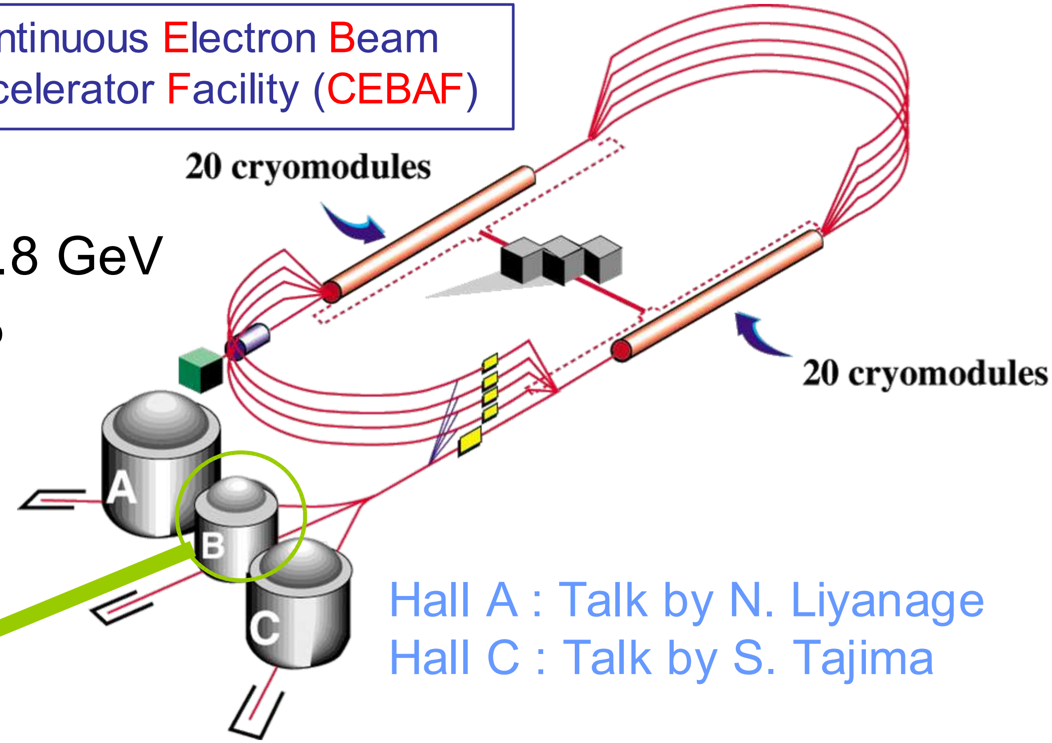


- At moderate Q^2 higher twist effects
- •Interactions between the struck quark and the other quarks in the nucleon
- •Inversely proportional to Q^2 $\rightarrow$ large at small Q^2



Jefferson Lab

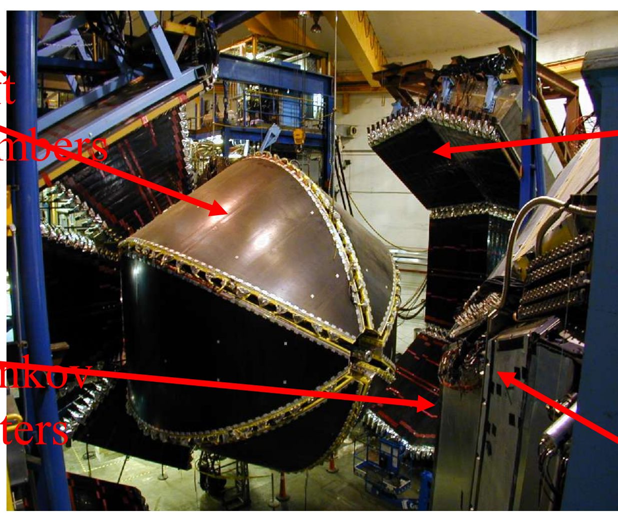
Continuous Electron Beam Accelerator Facility (CEBAF)



Energies between 800 MeV to 5.8 GeV
Typical beam polarization ~ 75%

CEBAF Large Acceptance Spectrometer (CLAS)

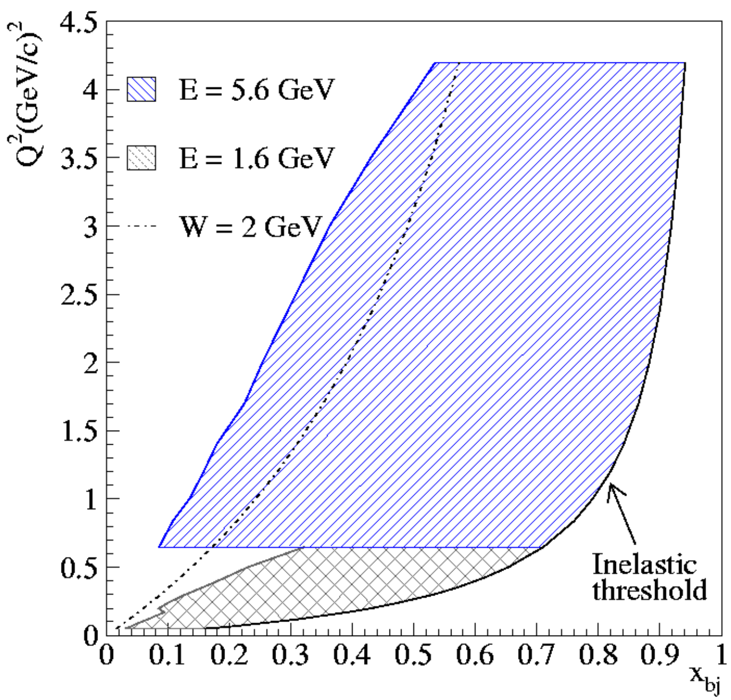
Hall A : Talk by N. Liyanage
Hall C : Talk by S. Tajima

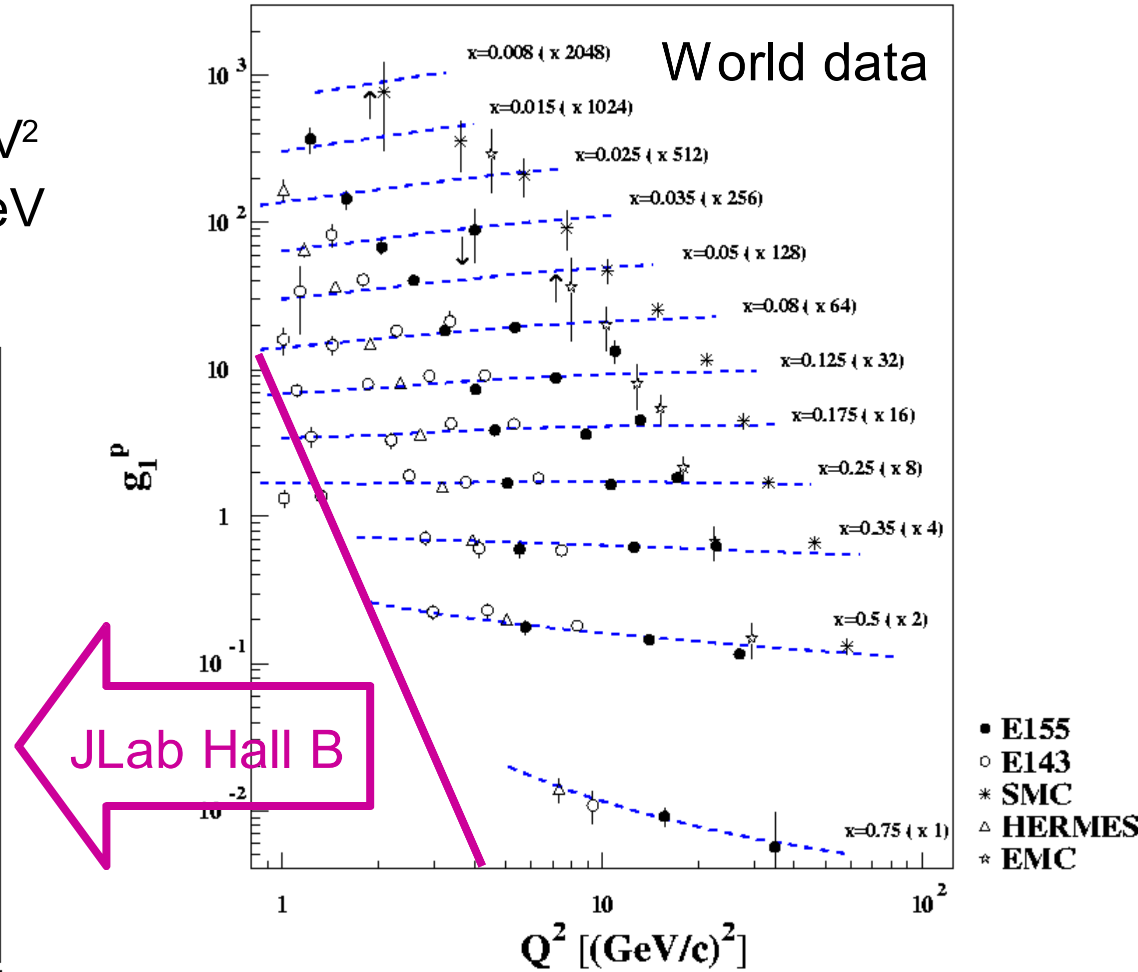


- Dynamically polarized NH_3 and ND_3 targets
- ^{12}C, ^{15} N and ^{4}He targets to measure the dilution factor

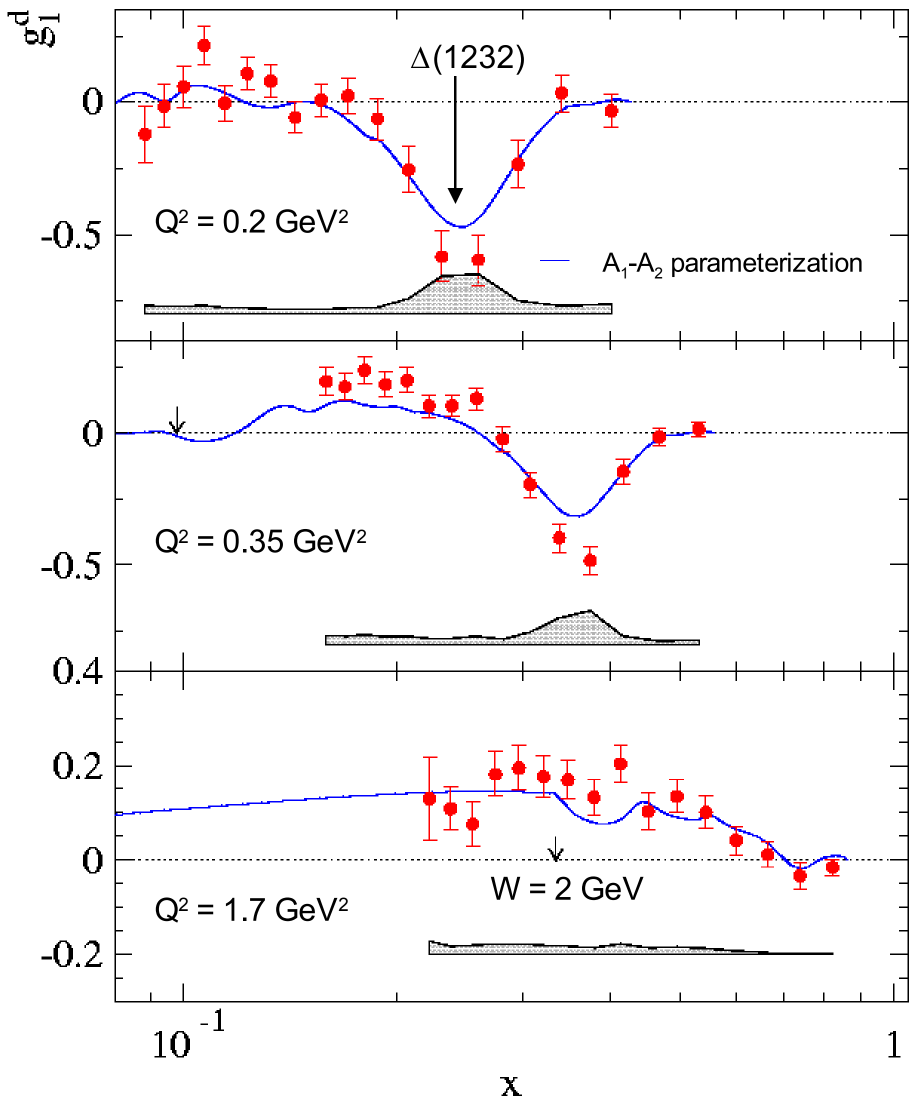
Experimental Status of Spin SF g_1

- Large x, moderate to low Q^2
- 4 different beam energies 1.6, 2.5, 4.2 and 5.6 GeV
- Q^2 coverage 0.05-4.2 GeV^2
- Results of 1.6 and 5.7 GeV data





Spin structure function g_1 for the deuteron



A_1-A_2 parameterization from the code "AO" & "MAID2000" together with a fit of the world DIS data and old JLab data

$$g_1(x,Q^2) = \frac{v^2}{Q^2}\left(A_1 + \sqrt{\frac{Q^2}{v^2}}A_2\right)F_1$$

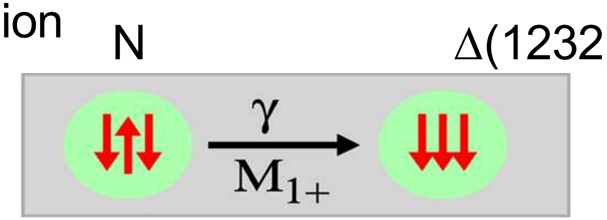
- For a resonance A_1 (and g_1) can be written in terms of helicity amplitudes

$$\sigma^T_{1/2} \rightarrow |A_{1/2}|^2$$

$$\sigma^T_{3/2} \rightarrow |A_{3/2}|^2$$

$$A_1 = \frac{|A_{1/2}|^2 - |A_{3/2}|^2}{|A_{1/2}|^2 + |A_{3/2}|^2}$$

- For a pure magnetic dipole transition

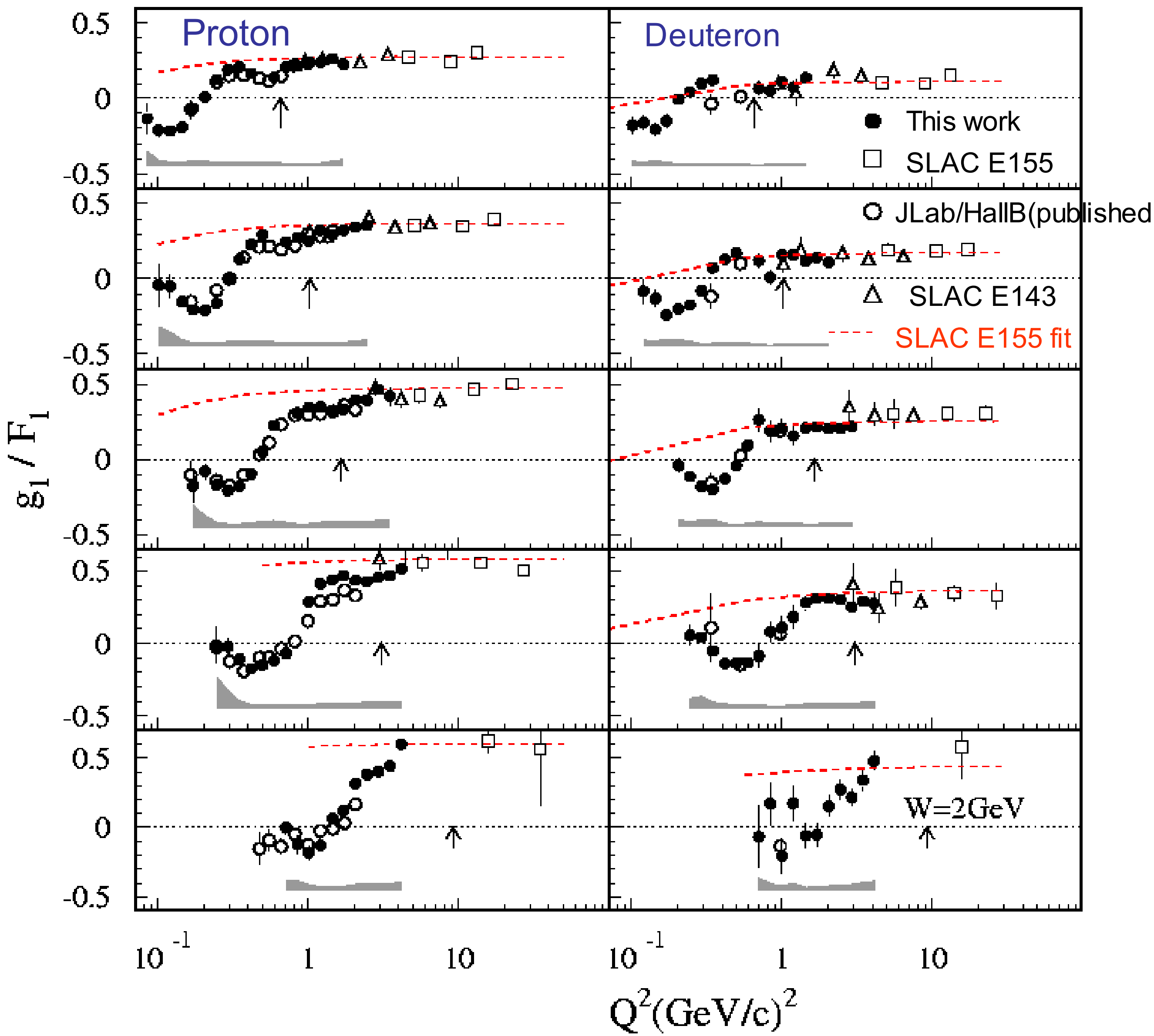


SU(6) → Pure spin flip

$A_1 \rightarrow -0.5$

Q^2 dependence of g_1/F_1

- Q^2 dependence of g_1 at fixed x is very similar to F_1 in the DIS region
- Our data show a decrease in g_1/F_1 even in the DIS region
- Resonance region
  - different Q^2 dependence
  - goes negative at Δ



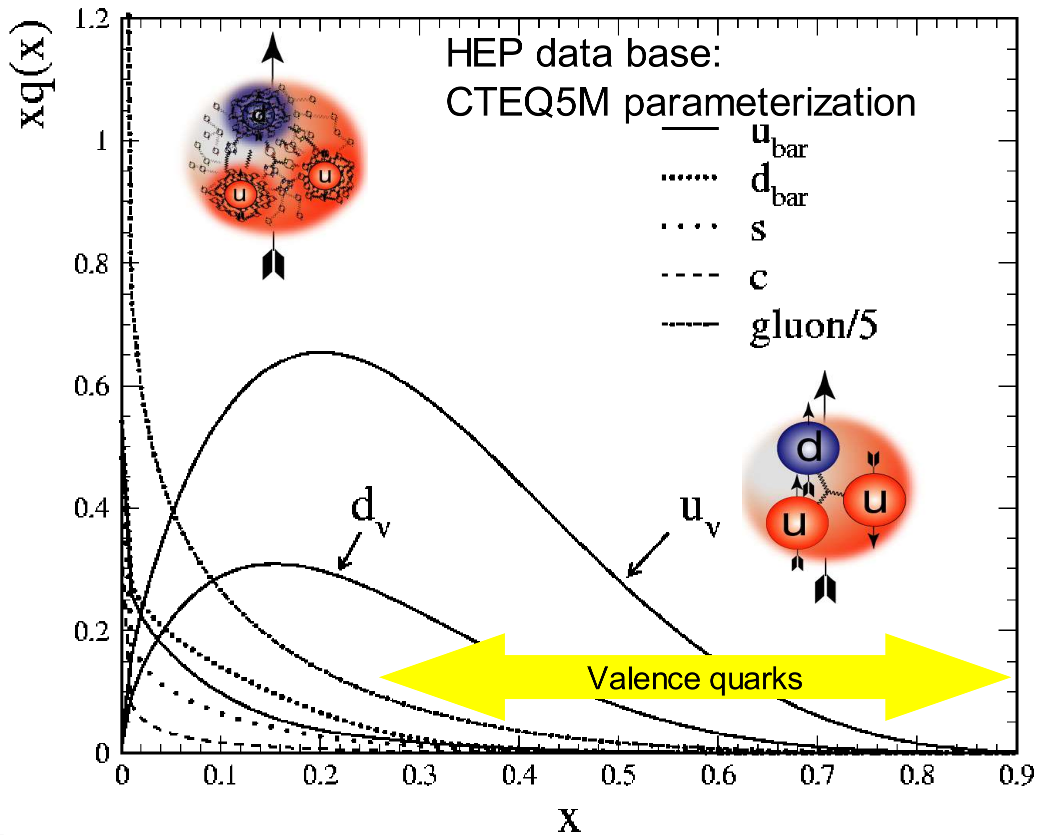
Virtual photon asymmetry A_1 at large x

DIS region

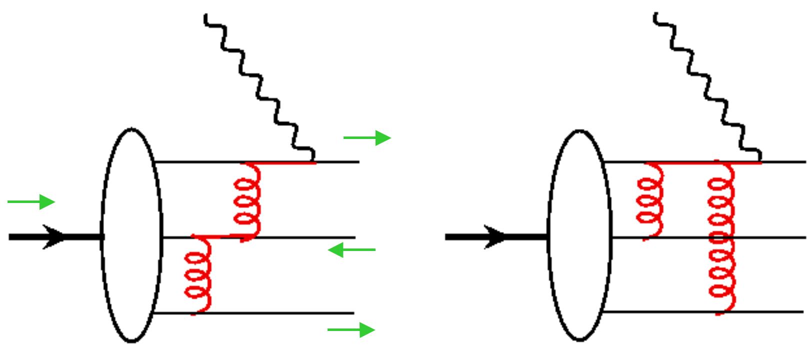
minimal Q^2 dependence

$$A_1(x,Q^2) \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)} \xrightarrow{LO} \frac{\sum e_i^2 \Delta q_i(x)}{\sum e_i^2 q_i(x)}$$

- Valence quarks dominate at large x



- x → 1 in pQCD



- Minimal gluon exchanges
- Spectator pair have opposite helicities
- $A_1 \rightarrow 1$

Farrar and Jackson
PRL 35, 1416 (1975)

Virtual photon asymmetry A_1 for the proton

- **SU(6)**

$$A_1^p = \frac{5}{9}, \quad A_1^n = 0$$

- **Hyperfine perturbed QM**
  - makes S=1 pairs more energetic than S=0 pairs
  - At large x struck quark carry the spin of the nucleon

N. Isgur, Phys. Rev. D 59, 34013

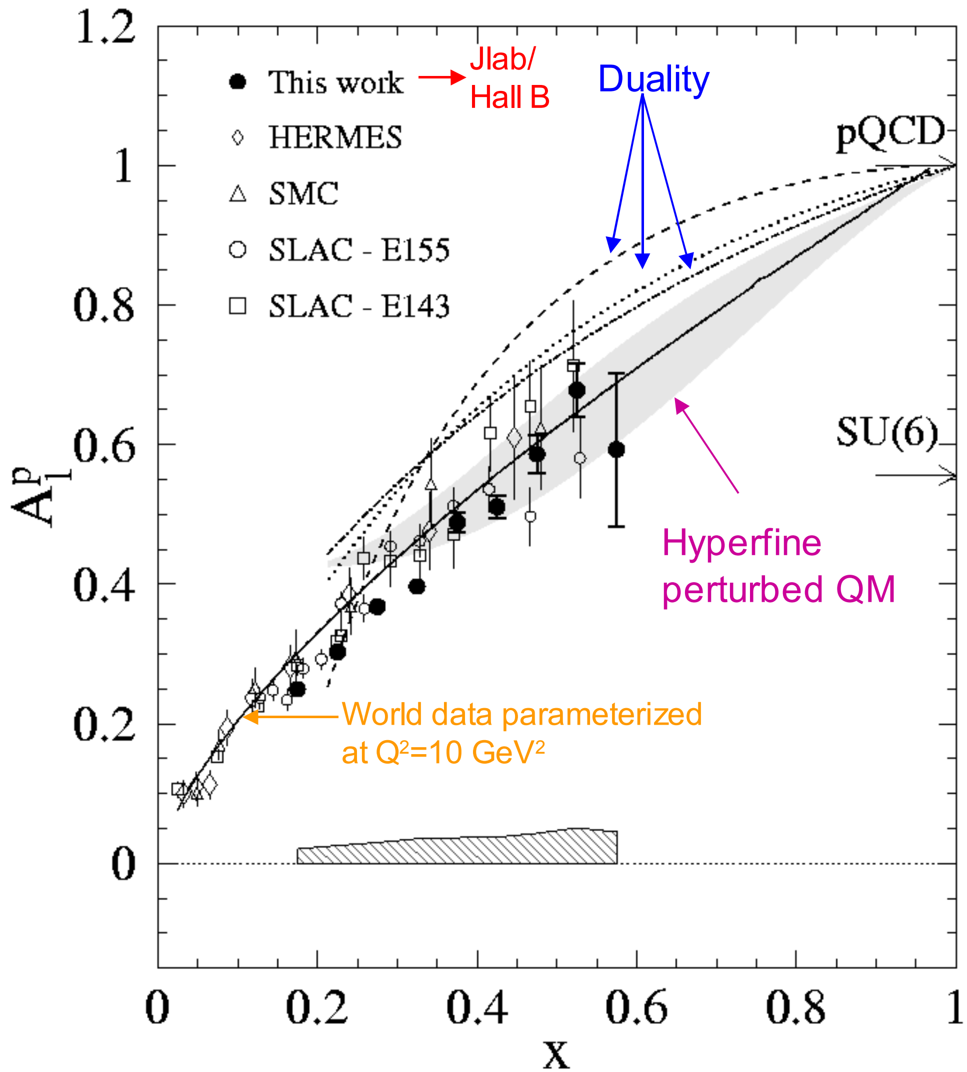
- **Duality**

suppress transitions to specific resonances in the final state

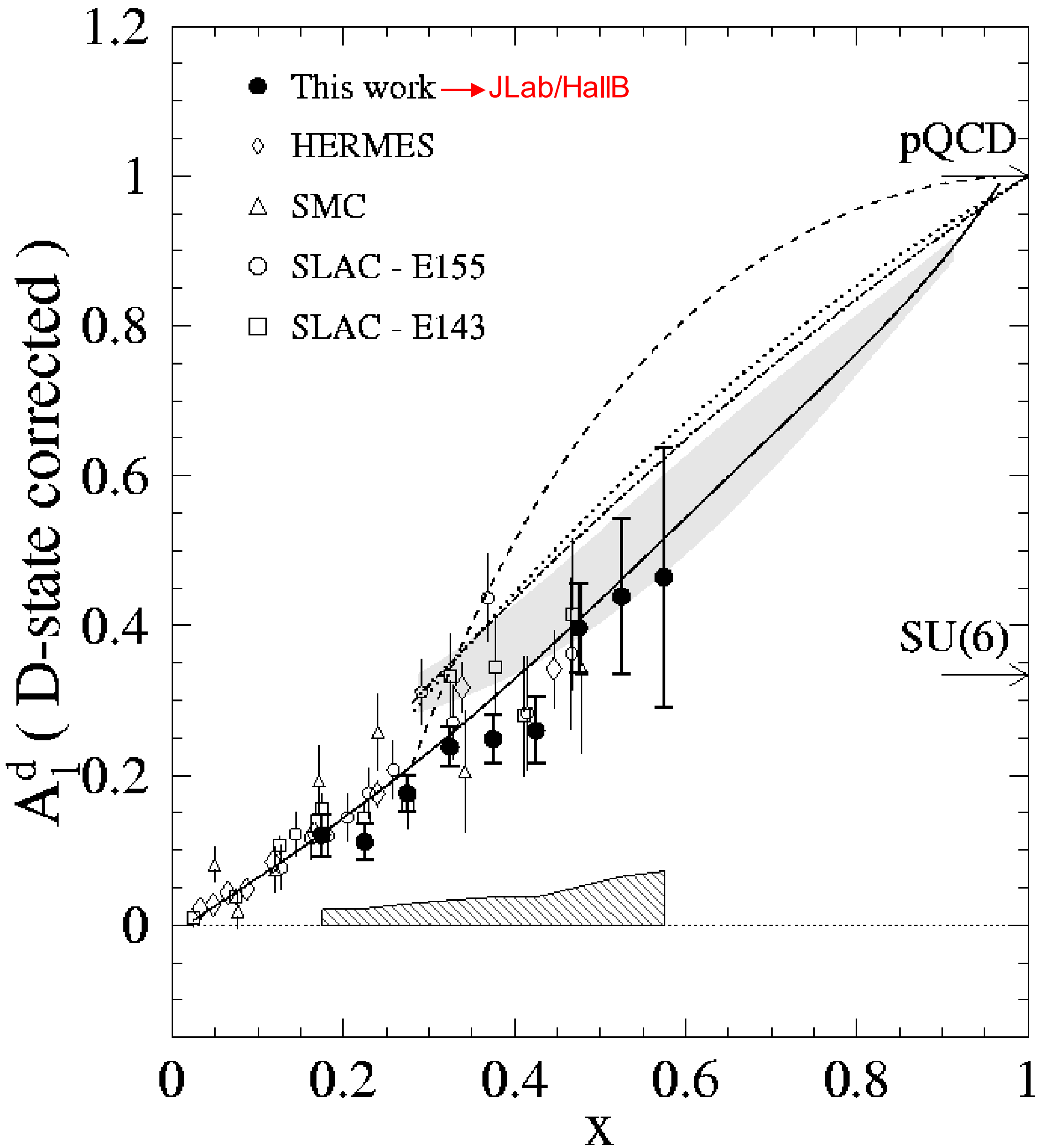
$\gamma + N \rightarrow N^*$

states in 56^+ and 70^-

F. Close and W. Melnitchouk
Phys. Rev. C 68, 035210

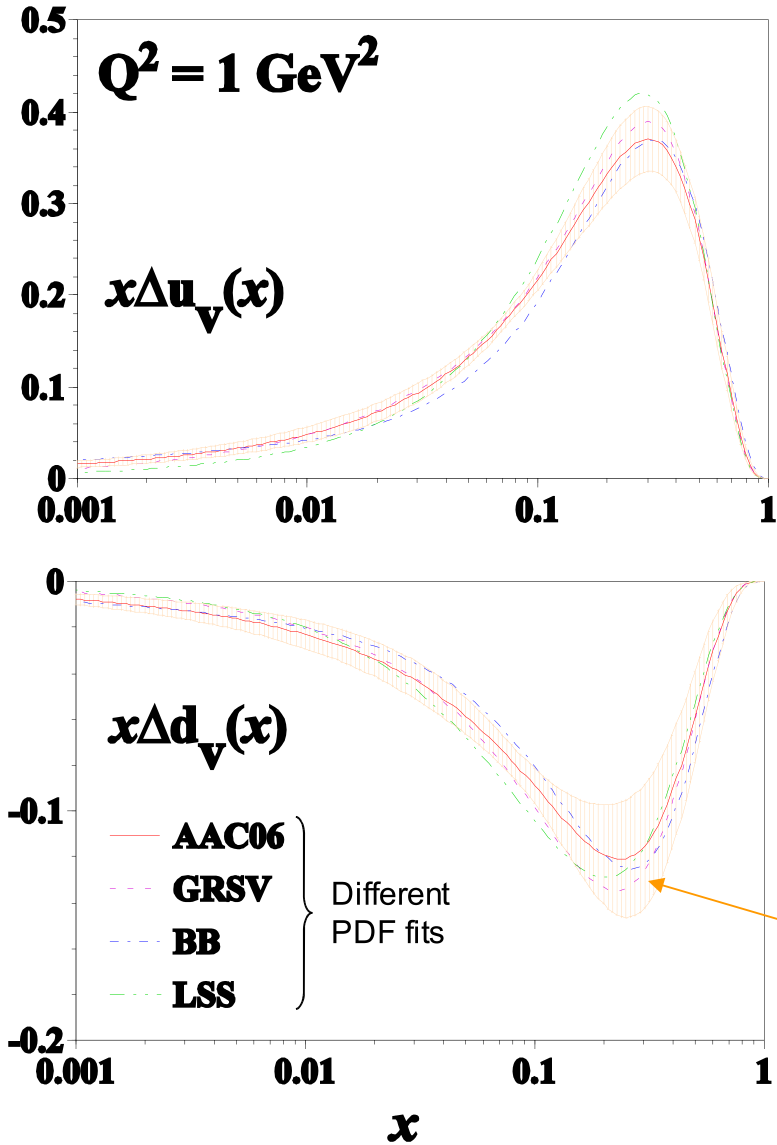


Virtual photon asymmetry A_1 for the deuteron



- Proton and deuteron results fall below the parameterization of the world data at $Q^2 = 10$ GeV^2
  - A_1 is Q^2 dependent
  - Data need to be included in pQCD DGLAP analyses
- Proton and deuteron results are in better agreement with the HFP quark model

Polarized parton distributions

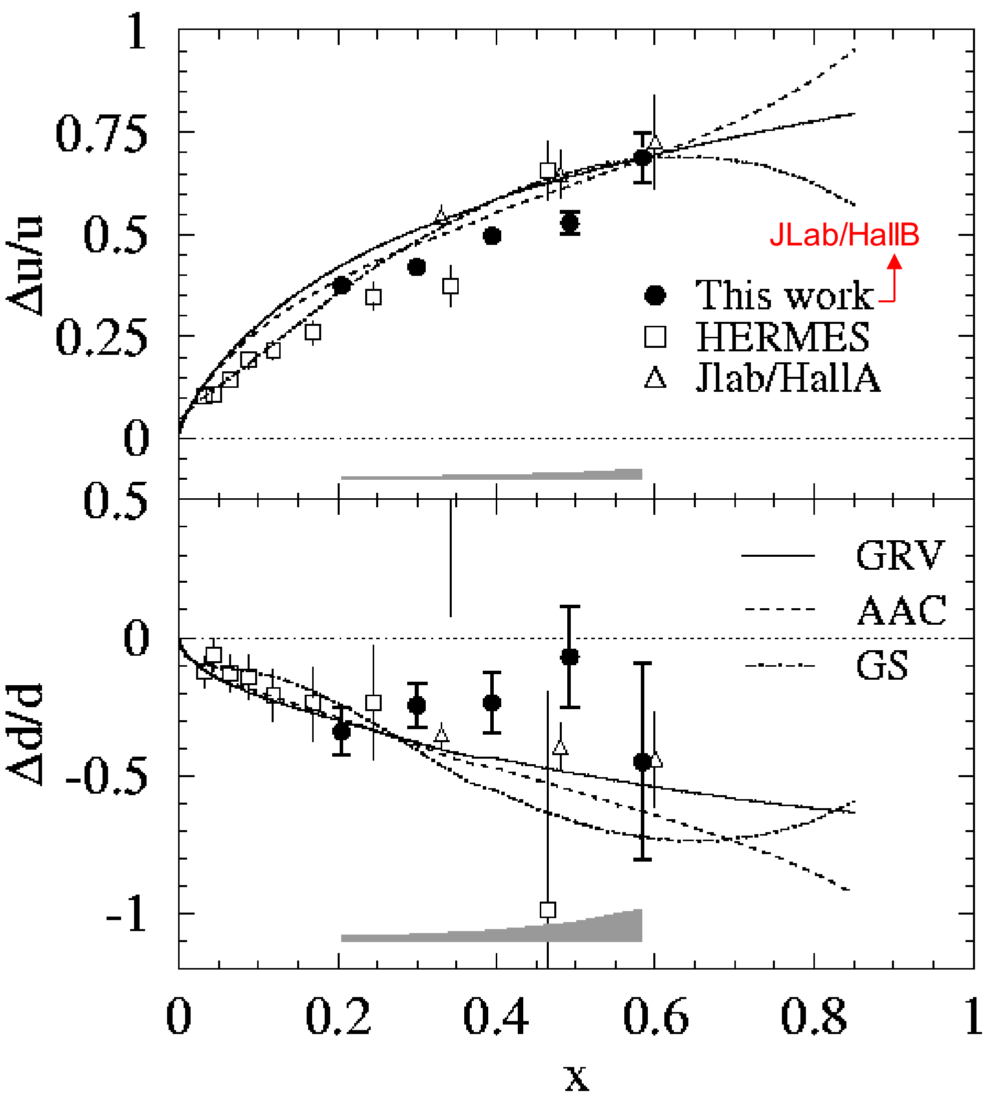


- Not well known at large x
- Predictions for x ⟶ 1

	d/u	Δu/u	Δd/d
SU(6)	½	2/3	-1/3
HFP quark model	0	1	-1/3
pQCD	1/5	1	1

Recent analysis by
M. Harai, S. Kumano and N. Saito

Polarized parton distributions



- Contribution from the s quark is ignored

LO →

$$\frac{\Delta u}{u} \approx \frac{5g_1^p - 2g_1^d/(1-1.5\omega_D)}{5F_1^p - 2F_1^d}$$

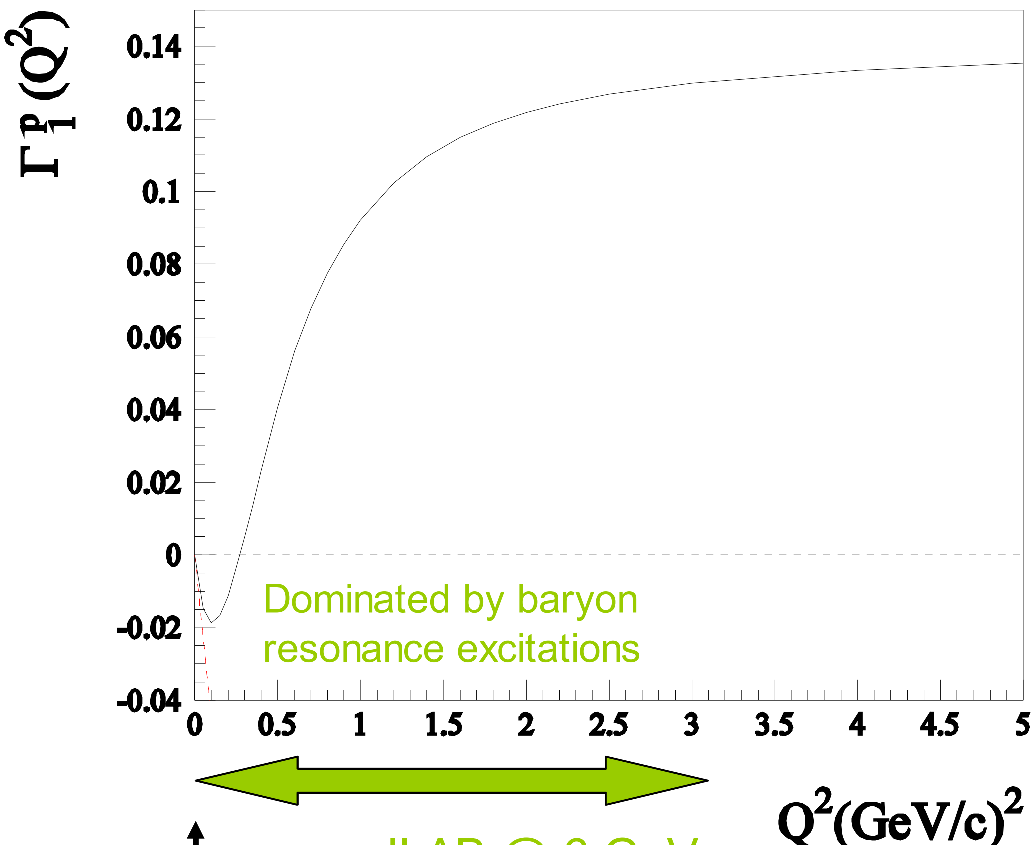
$$\frac{\Delta d}{d} \approx \frac{8g_1^d/(1-1.5\omega_D) - 5g_1^p}{8F_1^d - 5F_1^p}$$

- Our data for the Δu/u are the statistically most precise available
- A_1^p or A_1^d not very sensitive to Δd/d
- JLab Hall A and Hall B results for Δd/d show no indication of a sign change
  - Disagree with pQCD predictions (assume hadron helicity conservation)

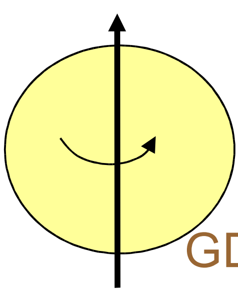
First moment of $g_1(x,Q^2)$

$$\Gamma_1(Q^2) = \int_0^{x(W=1.07)} g_1(x,Q^2)\,dx$$

Elastic contribution excluded



JLAB @ 6 GeV



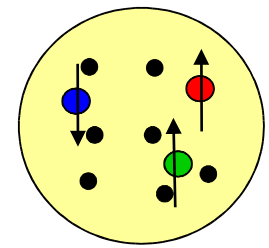
$Q^2 = 0$ $\frac{M^2}{8\alpha\pi^2}\int_{\nu_{th}}^{\infty}(\sigma_{1/2}(\nu)-\sigma_{3/2}(\nu))\frac{d\nu}{\nu} = -\frac{1}{4}\kappa^2$

GDH Sum rule

Single partons Bjorken Sum Rule

$$\Gamma_1^p - \Gamma_1^n = \frac{g_A}{6}$$

$Q^2 \rightarrow \infty$



- Closely related to the spin carried by quarks

At large Q^2

- Along with the other known quantities the fraction of the nucleon spin carried by quarks can be extracted

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

30±10% SLAC data Evaluated at $Q^2 = 5$ GeV^2

Generalized sum rules for Γ_1

Ji & Osborne

Spin structure function $g_1(x,Q^2)$ is related to the forward virtual compton scattering amplitude S_1

(X. Ji *et al*., J. Phys. G **27**, 127)

$$S_1(0,Q^2) = \frac{8}{Q^2}\int_0^1 g_1(x,Q^2)\,dx$$

Calculable ↑ Measurable ↑

Includes the elastic contribution

Parton description

Operator Product Expansion

$$\Gamma(Q^2) = \frac{1}{8}Q^2 S_1(0,Q^2) = \sum_{\tau=2,4,\ldots} \frac{\mu_\tau(Q^2)}{(Q^2)^{(\tau-2)/2}}$$

$$\Gamma_1(Q^2) = \Gamma(Q^2) - \Gamma(el)$$

- Twist-2 part is known
- Higher twist terms yet to be evaluated

- Transition between parton and hadron degrees of freedom
- calculable in Lattice QCD

Hadron description

Inelastic part of S_1

$$\bar{S}_1(0,Q^2) = -\frac{\kappa^2}{M^2} + cQ^2 + \ldots\ldots\ldots\ldots$$

c calculable in χPT

$$\Gamma_1(Q^2) = \frac{Q^2}{8}\bar{S}_1(0,Q^2)$$

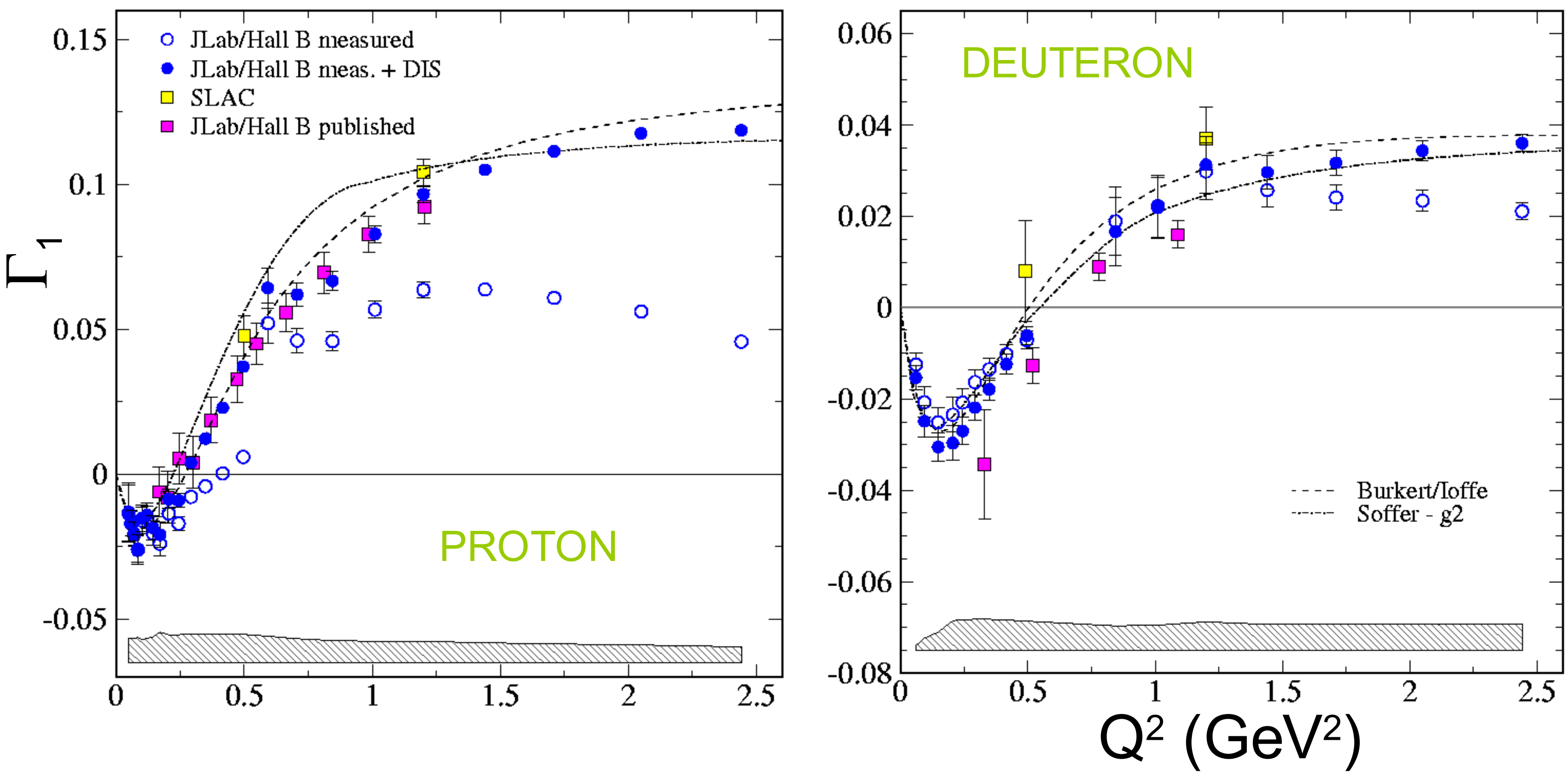
First moment Γ_1 for the proton and deuteron

$$\Gamma_1 = \underbrace{\int_{x=0.001}^{x_{min}} g_1 dx}_{\text{DIS (unmeasured) Parameterization of world data}} + \underbrace{\int_{x_{min}}^{x(W=1.07)} g_1 dx}_{\text{without elastic contribution}}$$

DIS (unmeasured) Parameterization of world data

without elastic contribution

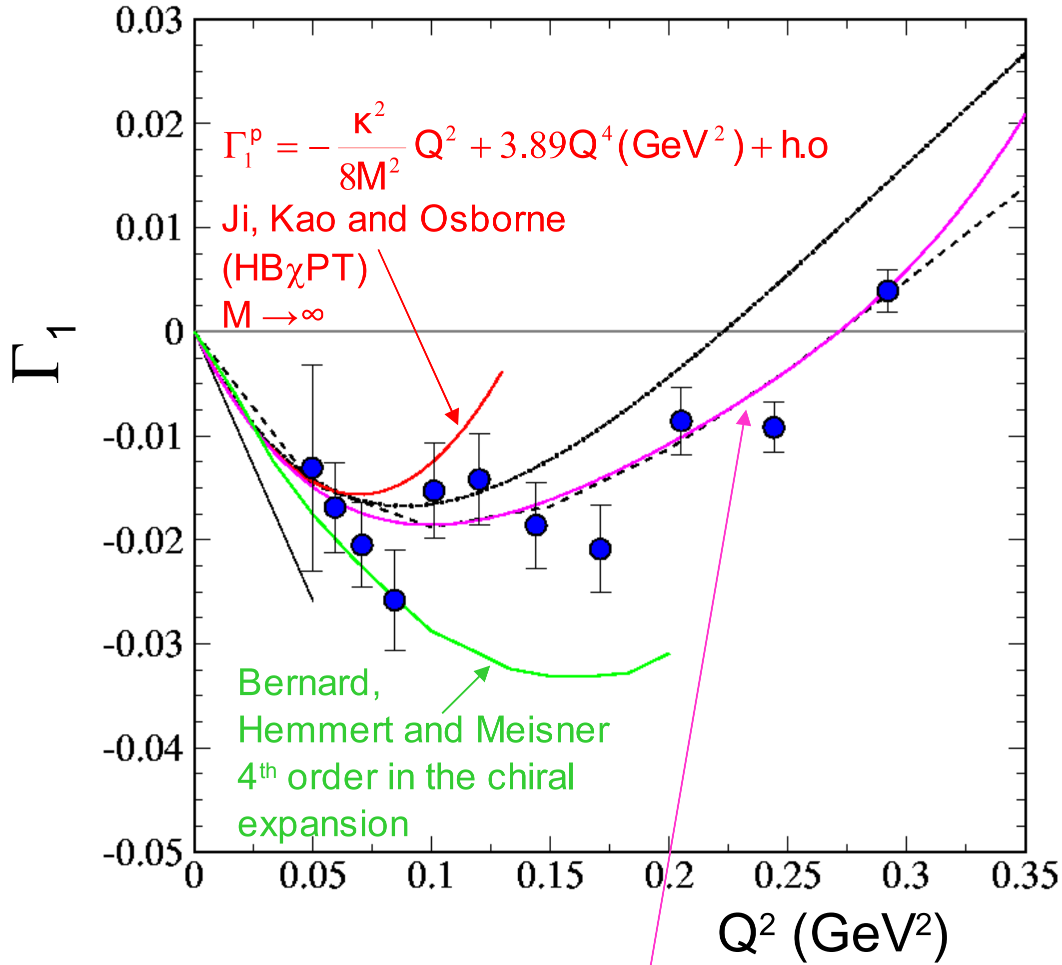
- Phenomenological Models
  - Burkert/Ioffe
    Resonance contribution pion electroproduction analysis
  - Soffer/Teryaev
    Interpolation of the integral $\int (g_1+g_2)dx$



Γ_1 for the proton : low Q^2

$$\Gamma_1 = \frac{Q^2}{8}\left[-\frac{\kappa^2}{M^2} + \overline{S}_1'(0,0)Q^2 + ...\right]$$

- Expand in chiral perturbation theory in a power series of pion mass
  - Calculations at next-to-leading order in momenta
- For the proton-neutron difference the ChPT expansion should hold for higher Q^2
  - In the proton-neutron difference $\Delta(1232)$ contribution drops out. Other resonances are reduced as well



A fit to data

$$\Gamma_1 = -\frac{\kappa^2}{8M^2}Q^2 + bQ^4 + cQ^6 + dQ^8$$

χ-sq = 1.158

$$b = 3.66 \pm 0.33(\text{stat}) \pm 0.18(\text{syst})$$

SUMMARY

- A broad physics program to study the spin structure of the proton, neutron and their excited states in progress at Jefferson Lab Hall B.

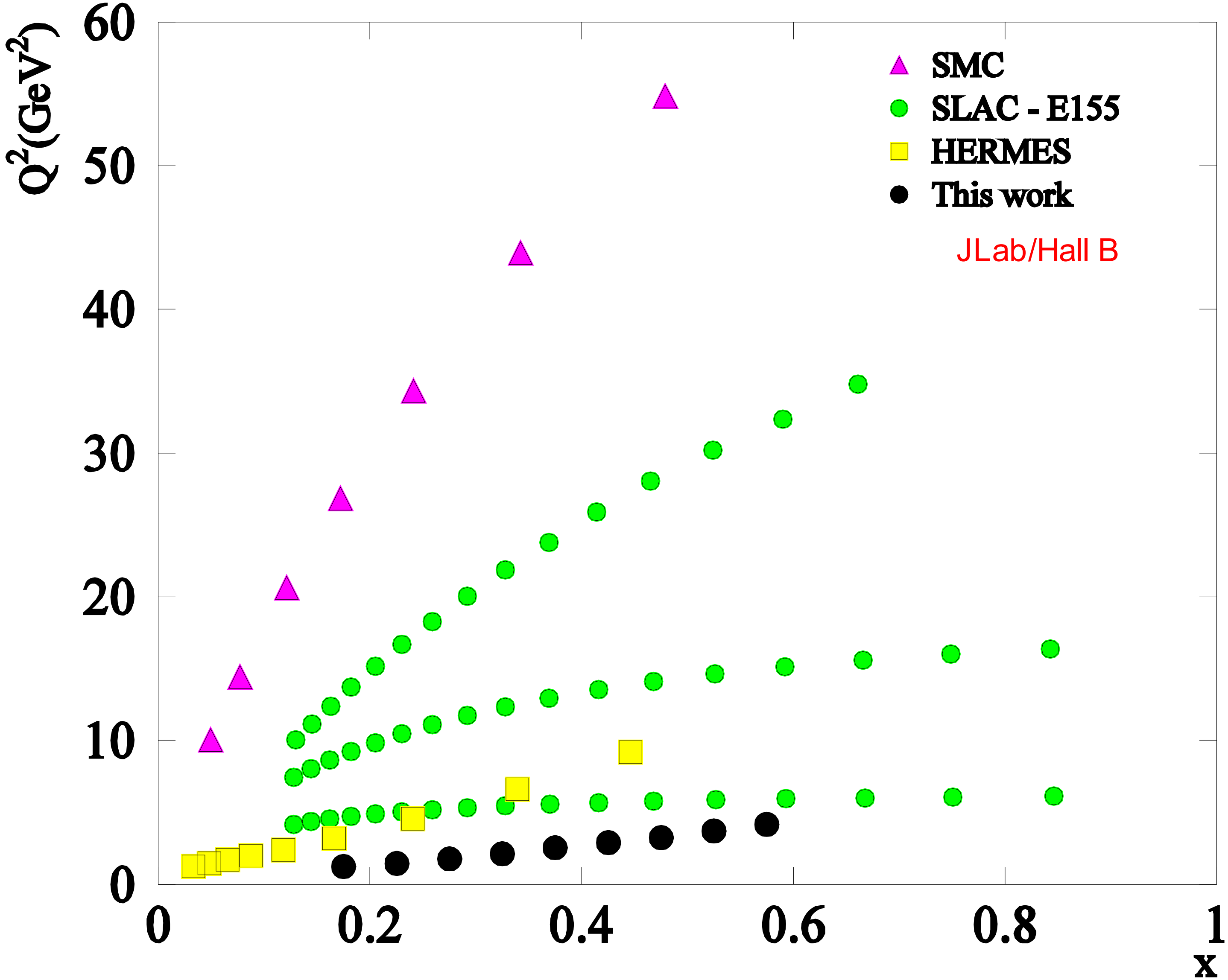
- g_1 and Γ_1 cover a wide kinematic range

- Results for 1.6 GeV and 5.6 GeV data show strong Q^2 dependence and have better precision than existing data
  - Low Q^2 Γ_1 results agree with HBχPT calculations
  - Improvements in the precision of the polarized parton distributions at large x

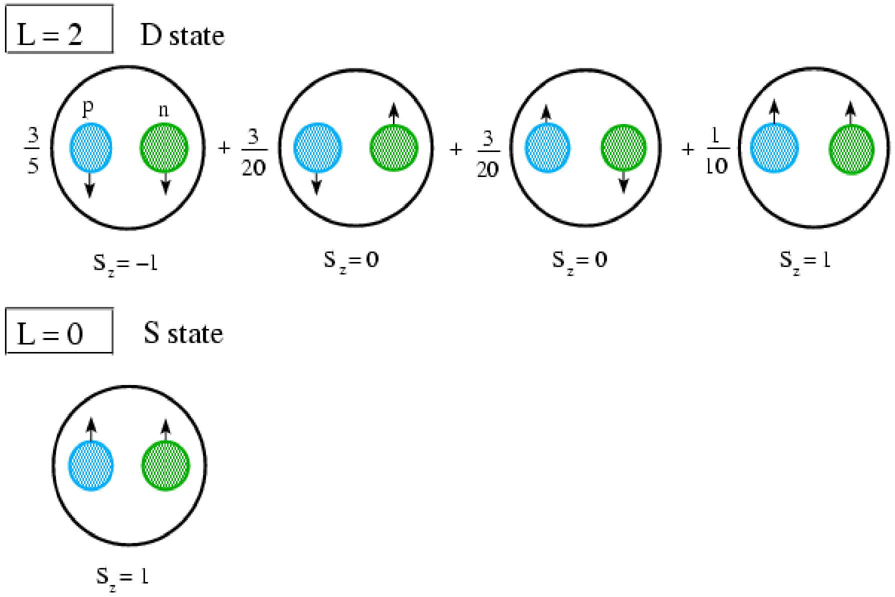
- 2.5 and 4.2 GeV data will fill in the intermediate Q^2 region with more precision

ADDITIONAL SLIDES

Comparison of kinematics for A_1



Deuteron as a proton+neutron target



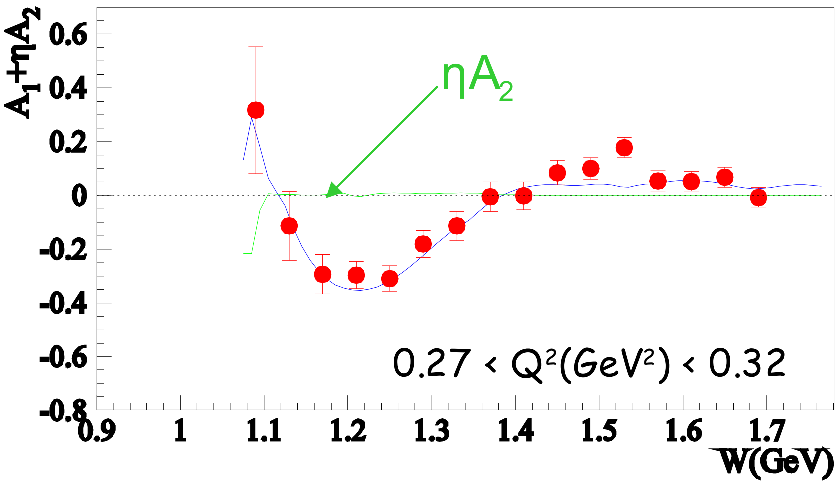
$\omega_d \approx 0.056$

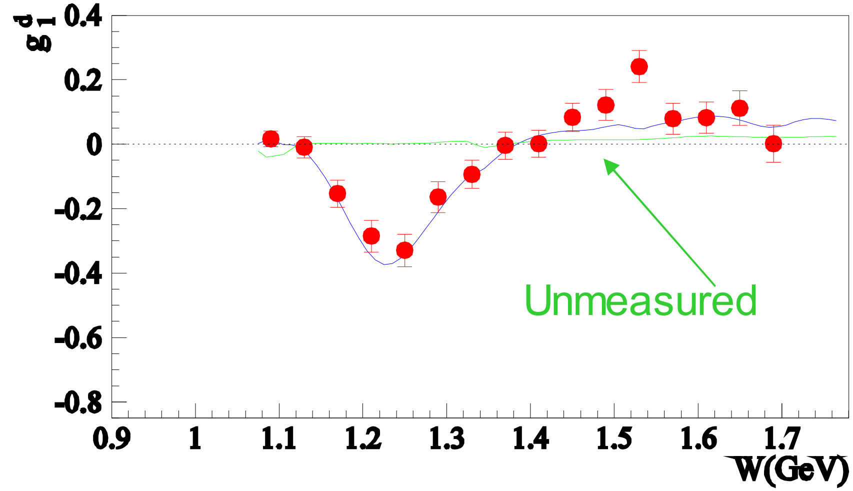
- Deuteron can be in a S state or a D state
- In the S state the spin of the proton and the neutron are aligned with the deuteron spin
- The probability of being in the D state ≈ 0.056

$$2\Gamma_1^d = \left(1 - \frac{3}{2}\omega_d\right)\left(\Gamma_1^p + \Gamma_1^n\right)$$

From asymmetries to spin structure function g_1

$$A_1 + \eta A_2 = \frac{A_{\parallel}}{D} \quad \Longrightarrow \quad g_1^d(W,Q^2) = \frac{\tau}{1+\tau}\left(\frac{A_{\parallel}}{D} + \left(\frac{1}{\sqrt{\tau}} - \eta\right) A_2\right) F_1$$

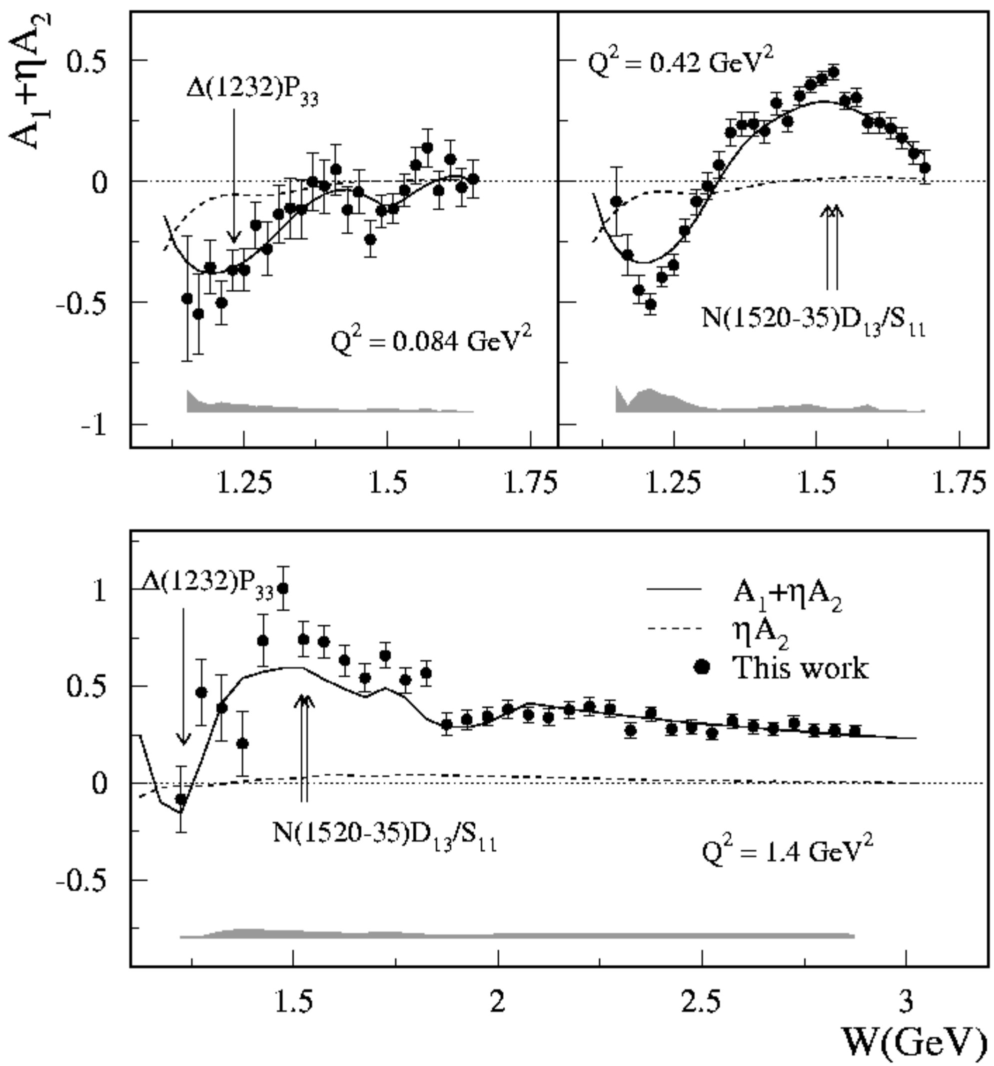




Models

- A_2 → Wandzura-Wilczek relation in the DIS region and the code MAID 2000 in the resonance region
- F_1 → Fit to world data
- A_1 → Fit to DIS data and AO in the resonance region
  EG1a data to optimize the parameters

Asymmetry $A_1+\eta A_2$ for the proton



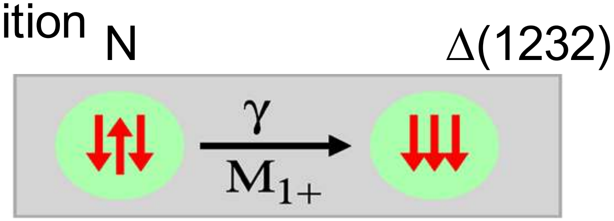
- For a resonance A_1 can be written in terms of helicity amplitudes

$$A_1 = \frac{|A_{1/2}|^2 - |A_{3/2}|^2}{|A_{1/2}|^2 + |A_{3/2}|^2}$$

$$A_{1/2} = -\frac{1}{2}\left(M_{1+}^{(3/2)} + 3E_{1+}^{(3/2)}\right)$$

$$A_{3/2} = -\frac{\sqrt{3}}{2}\left(M_{1+}^{(3/2)} - E_{1+}^{(3/2)}\right)$$

- For a pure magnetic dipole transition



SU(6) → Pure spin flip

$$A_1 = \frac{\left(-\frac{1}{2}\right)^2 - \left(-\frac{\sqrt{3}}{2}\right)^2}{\left(-\frac{1}{2}\right)^2 + \left(-\frac{\sqrt{3}}{2}\right)^2} = -0.5$$

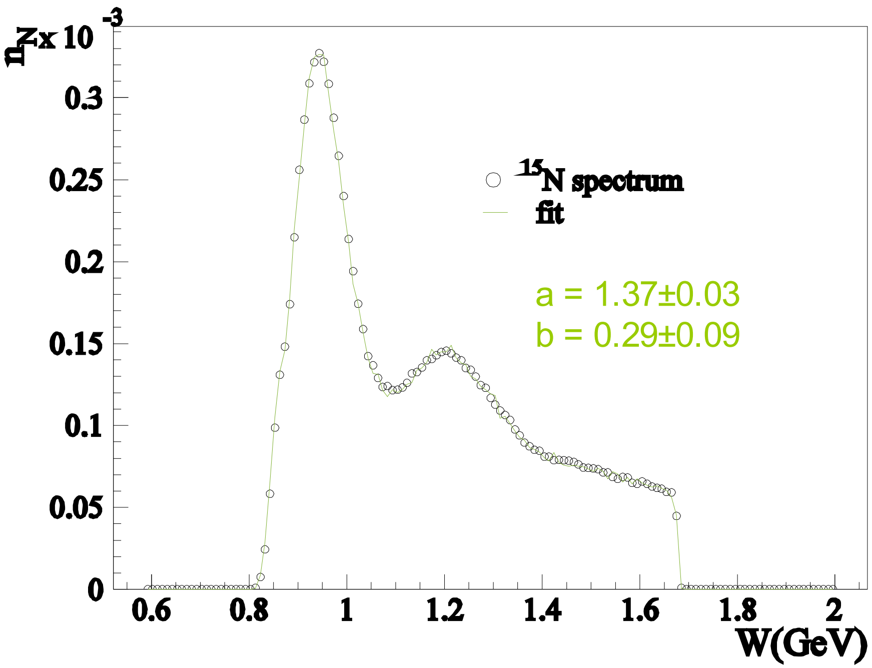
Background subtraction

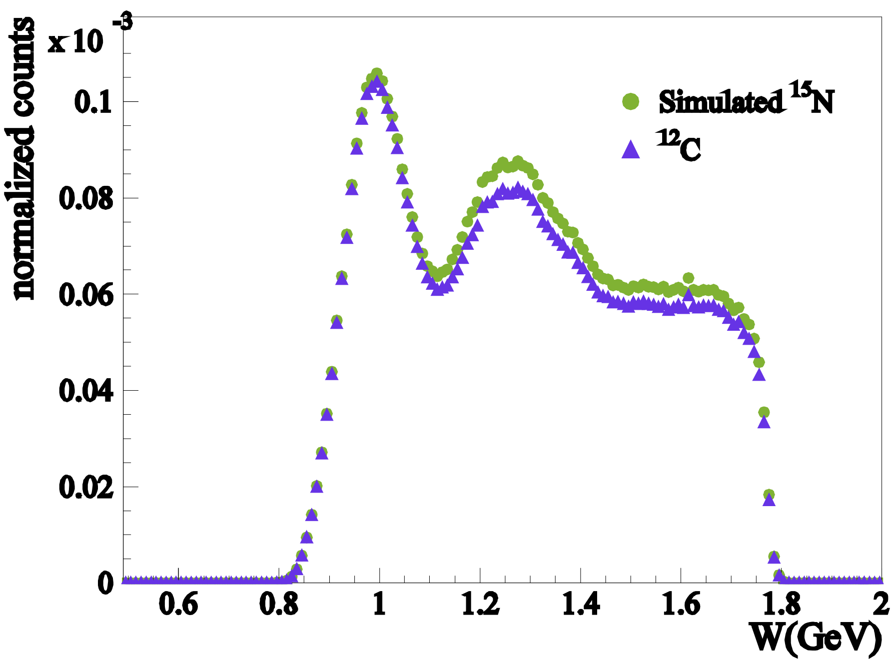
- ^{12}C data were used to simulate ^{15}N background

$$\sigma_{^{15}N} = \left(a + b\frac{\sigma_n}{\sigma_D}\right)\sigma_{^{12}C}$$

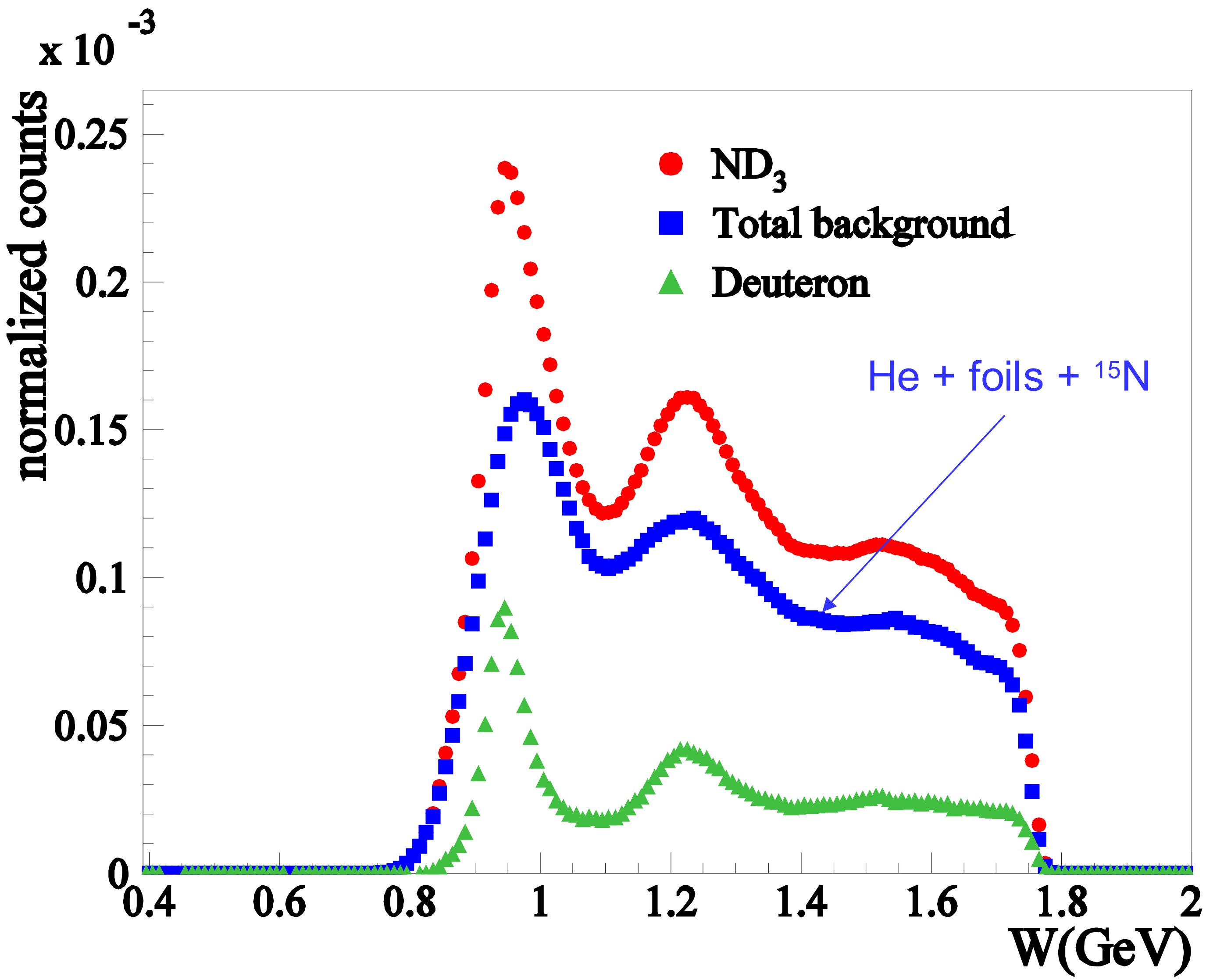
- Limited statistics ^{15}N data were fitted with high statistics ^{12}C data.

- *a* and *b* are in good agreement with the expected numbers; a=7/6, b=1/6





Background subtraction



Dilution Factor

- Gives the contribution to the count rates from unpolarized target constituents

$$DF = \frac{^{15}ND_3 - \text{Background}}{^{15}ND_3}$$

- No Q^2 dependence