# Nucleon Spin Structure with CLAS at Jlab

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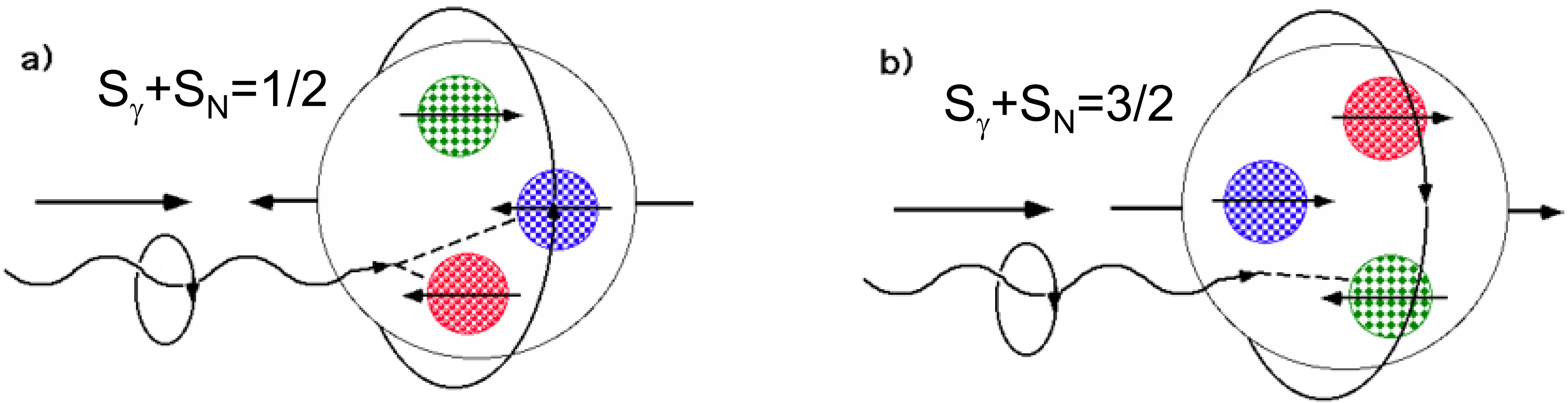
# Outline

- Spin physics in the transition region
- Asymmetry Analysis
- Nucleon Structure Functions:
  - Measurements in the resonance region
  - Large x behavior
  - Sum rules and moments
  - Quark-Hadron Duality
- Summary

# Spin Structure Function $g_1$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \, \Delta q + \Delta\bar{q} = \frac{1}{2}\sum_q e_q^2 \left(q^+(x) - q^-(x) \; + \bar{q}^+(x) - \bar{q}^-(x)\right)$$




$\sigma_{1/2} \approx q^+(x)$ $\sigma_{3/2} \approx q^-(x)$

- **Virtual photon couples to quarks of opposite helicity**
- **$q^+(x)$ or $q^-(x)$ are chosen by changing the configuration of the incident lepton and target nucleon spin**
- **$g_1(x) \sim \sigma_{1/2} - \sigma_{3/2}$**

# Spin structure vs distance scale

photon interacts with

$Q^2 \rightarrow \infty$

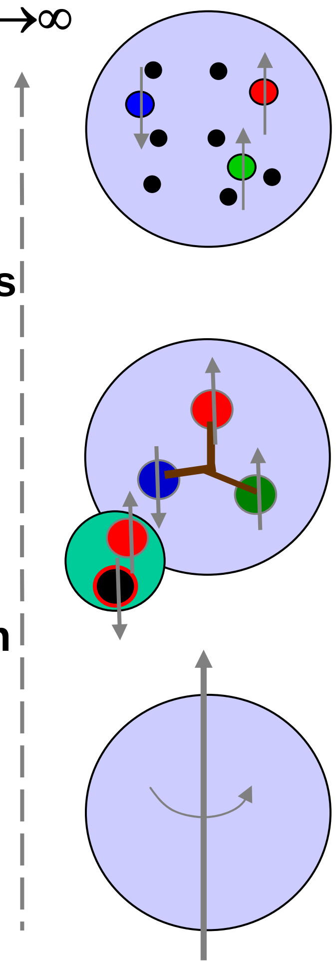
**single partons**

**multiple partons**

**constituent quarks, N***

**pions, nucleon**

**magnetic moment (GDH SR)**



$Q^2 = 0$

**Bjorken Sum Rule**
**Asymptotic freedom**

**Perturbative QCD**

**Lattice QCD (?)**

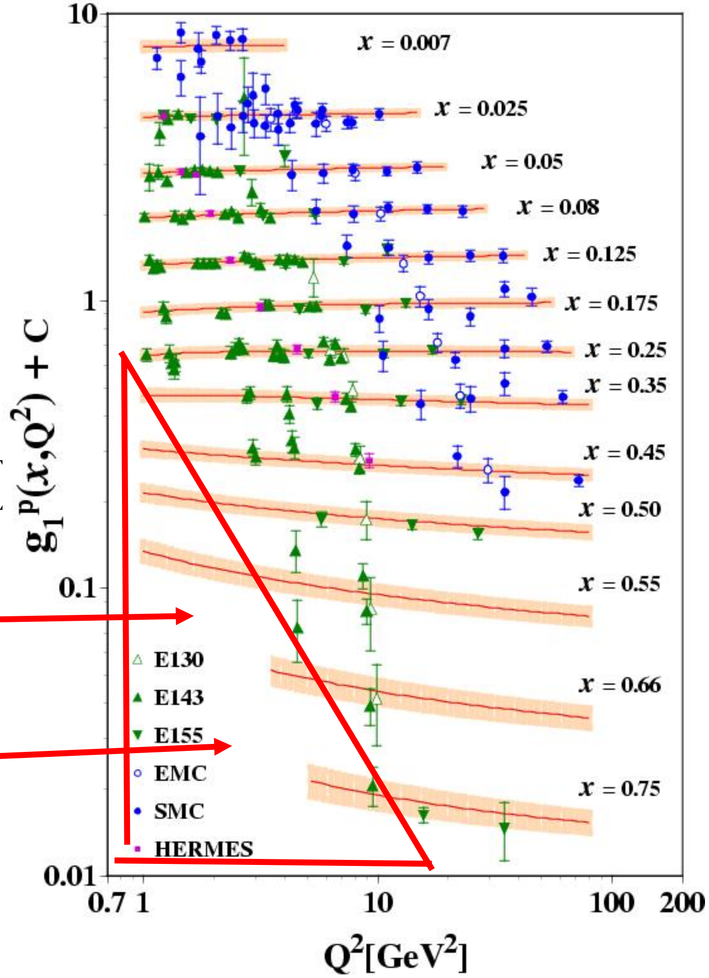
**Chiral Perturbation Theory**

**GDH Sum Rule**

# Status of $g_1(x,Q^2)$

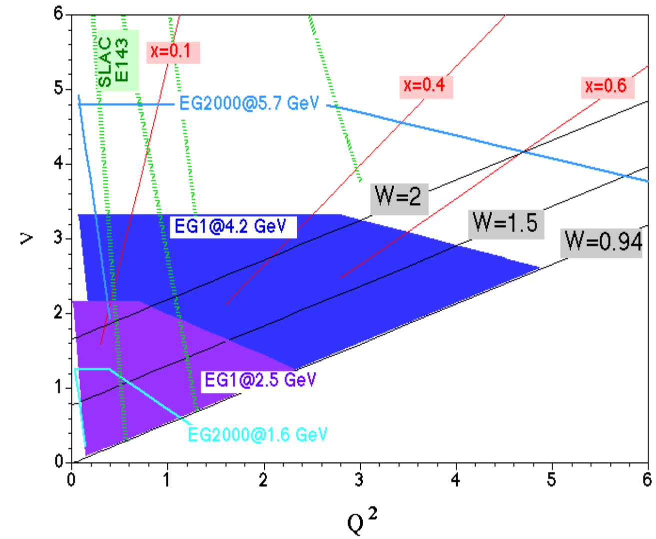
$$g_1^{NLO}(x,Q^2) = g_1^{LO} + \frac{1}{2}\langle e^2\rangle \sum_q e_q^2 [\Delta q(x,Q^2)\otimes C_q + \Delta g(x,Q^2)\otimes C_g]$$

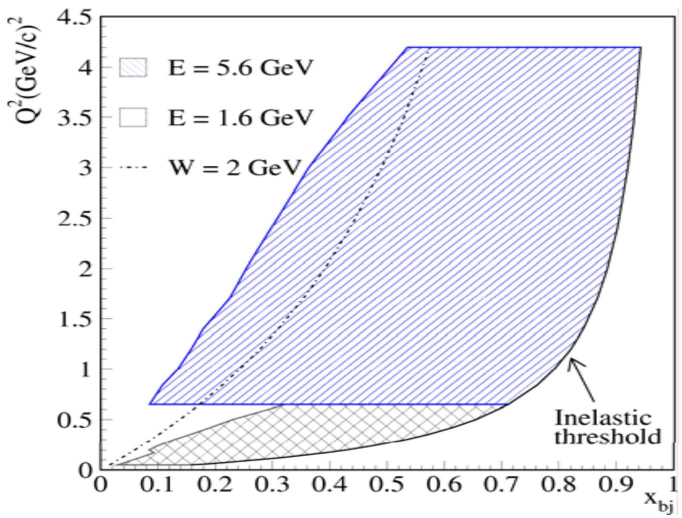
- **Data mostly for DIS and low x**
- **Remains to be done:**
  - **ΔG (RHIC,COMPASS)**
  - **ΔL (DVCS: COMPASS, HERMES,Jlab)**
  - **Transversity(HERMES, Jlab, RHIC)**
  - **Large x precision measurements (Jlab)**
  - **Measurement in non-perturbative region (Jlab)**



# Experimental Program

- ◆ **measurement of the nucleon spin structure functions in the resonance region**
- ◆ **test of the generalized Gerasimov-Drell-Hearn Sum Rule on the proton and deuteron**
- ◆ **test of duality of spin structure function**
- ◆ **extraction of the moments of the proton and neutron structure functions**
- ◆ **study of the nucleon resonance structure from polarization observables in exclusive meson production**
- ◆ **measurement of spin asymmetries in semiinclusive processes**
- ◆ **deeply virtual compton scattering on polarized target**

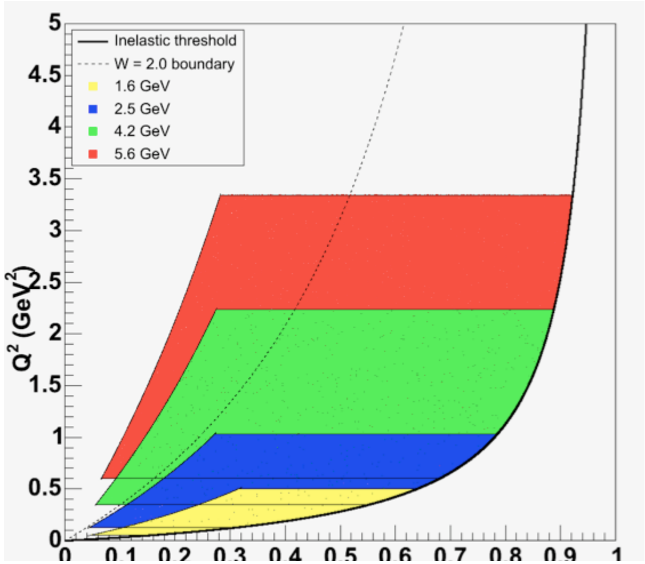


# Recent Experiments

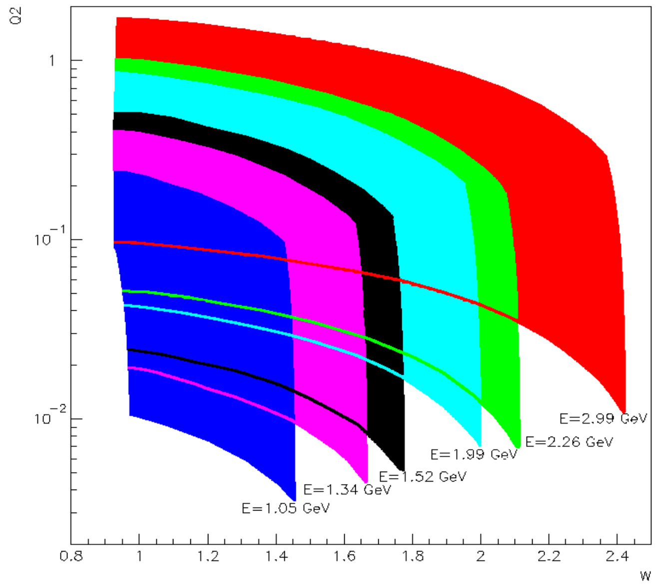
## "EG1":

- Longitudinally polarized electrons, Jefferson Lab
  - Polarization was ~ 70% (measured by Moller Polarimeter)
  - Beam energies: 1.6, 2.5, 4.2, 5.7 GeV
- CEBAF Large Acceptance Spectrometer (CLAS) in Hall B
  - Multi-particle final states
  - Measure large range in $Q^2$ and W
- Polarized solid ammonia targets
  - $NH_3$ polarization: 70-90%
  - $ND_3$ polarization: 10-35%
  - $^{12}C$, $^{15}N$, $^{4}He$ targets for background subtraction
- Two running periods:
  - 1998: 3 billion triggers. (EG1a)
  - 2000-2001: 23 billion triggers (EG1b)



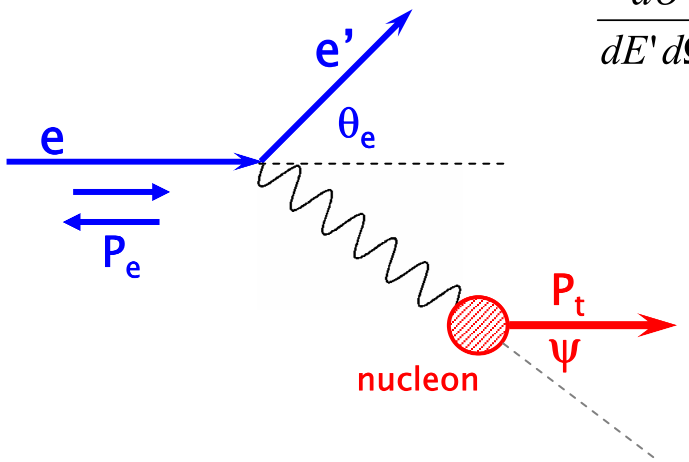

## "EG4":

- Similar conditions to EG1
- Kinematical coverage extended down to $Q^2 = 0.015$ GeV$^2$
- Beam energies: 1.3, 1.5, 2.2, 3.0 GeV
- New Cerenkov Counter to detect scattered elecrons down to ~ 6 deg. (INFN-Genova)



# Asymmetry Analysis

# Measuring Asymmetries




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

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

**the asymmetries $A_1$ and $A_2$ can be extracted by varying the direction of the nucleon polarization**

$$A^{\parallel} = D\left(A_1 + \eta A_2\right)$$
$$A^{\perp} = d\left(A_1 + \zeta A_2\right)$$

**where D, η, d, ξ are function of $Q^2$, W, $E_0$, R**

**the structure functions $g_1$ and $g_2$ are linear combination of $A_1$ and $A_2$**

$$g_1(x,Q^2) = \frac{Q^2}{Q^2+4M^2x^2}\left(A_1 + \frac{2Mx}{\sqrt{Q^2}}A_2\right)F_1(x,Q^2)$$

$$g_2(x,Q^2) = \frac{Q^2}{Q^2+4M^2x^2}\left(\frac{\sqrt{Q^2}}{2Mx}A_2 - A_1\right)F_1(x,Q^2)$$

# Asymmetry analysis

$$A_{raw} = \frac{N^- / Q^- - N^+ / Q^+}{N^- / Q^- + N^+ / Q^+}$$

- **$N^{+/-}$ Yield for electron/target spins**
- **antiparallel (-) or parallel (+)**
- **$Q^{+/-}$ gated FC**

Physics asymmetry $A_{||}$

$$A_{||} = \frac{C_{back} A_{raw}}{P_e P_t \times DF}$$

- **$P_e$ Beam polarization**
- **$P_t$ Target polarization**
- **DF Dilution factor**
- **$C_{back}$ Background processes**

**(pion contamination & pair symmetric)**

$$A_1 + \eta A_2 = \frac{A_{//}}{D}$$

**$A_1$ , $g_1$ can be extracted**

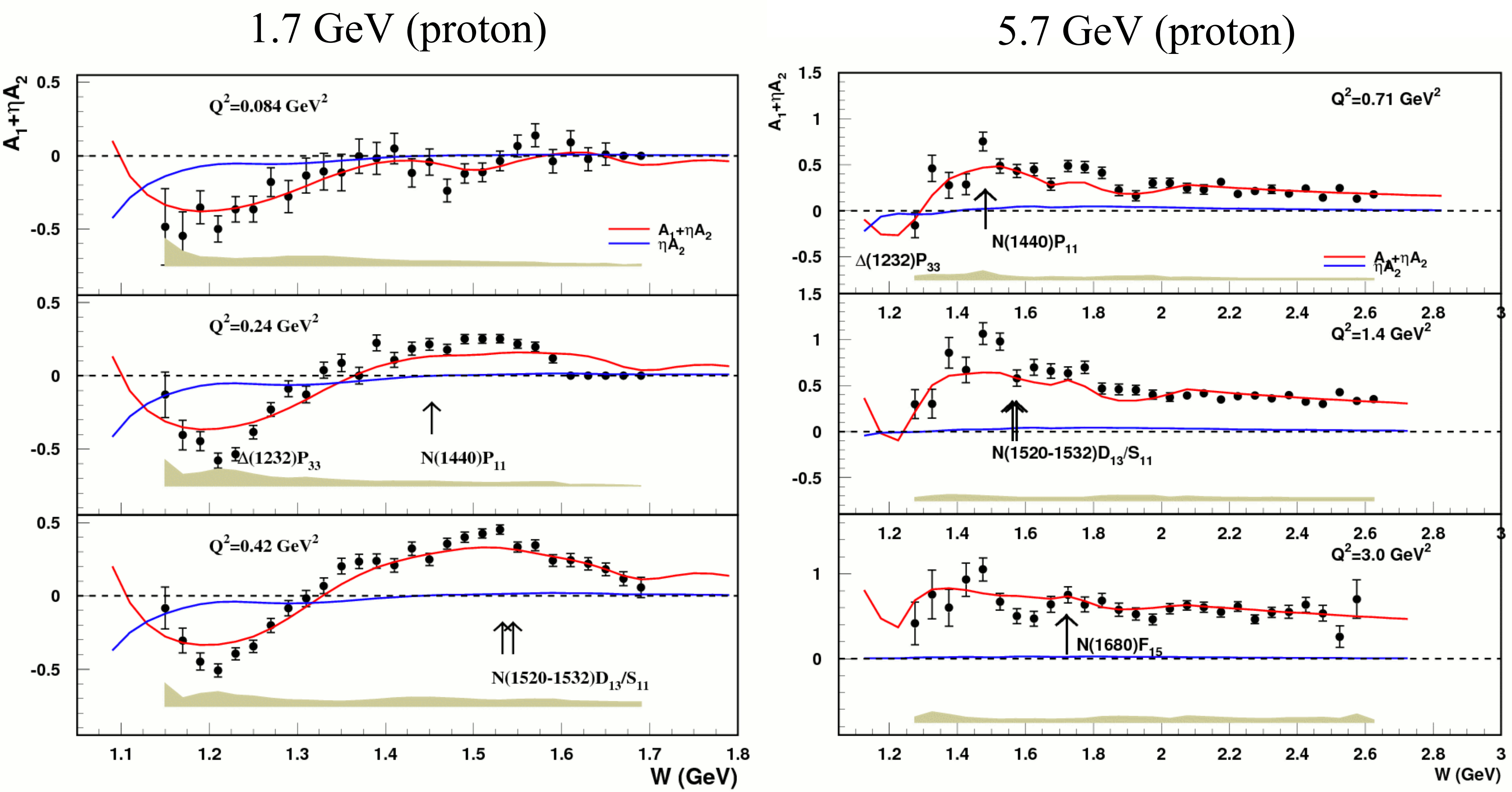
$$D = \frac{1 - E'\varepsilon / E}{1 + \varepsilon R}; \quad \eta = \frac{\varepsilon \sqrt{Q^2}}{E - E'\varepsilon} \quad R = \frac{\sigma_L}{\sigma_T}$$

Parameterization of the world data is used for R and $A_2$

# Nucleon Structure Functions

## 1. Measurements in the resonance region

# $A_1+\eta A_2$ for proton



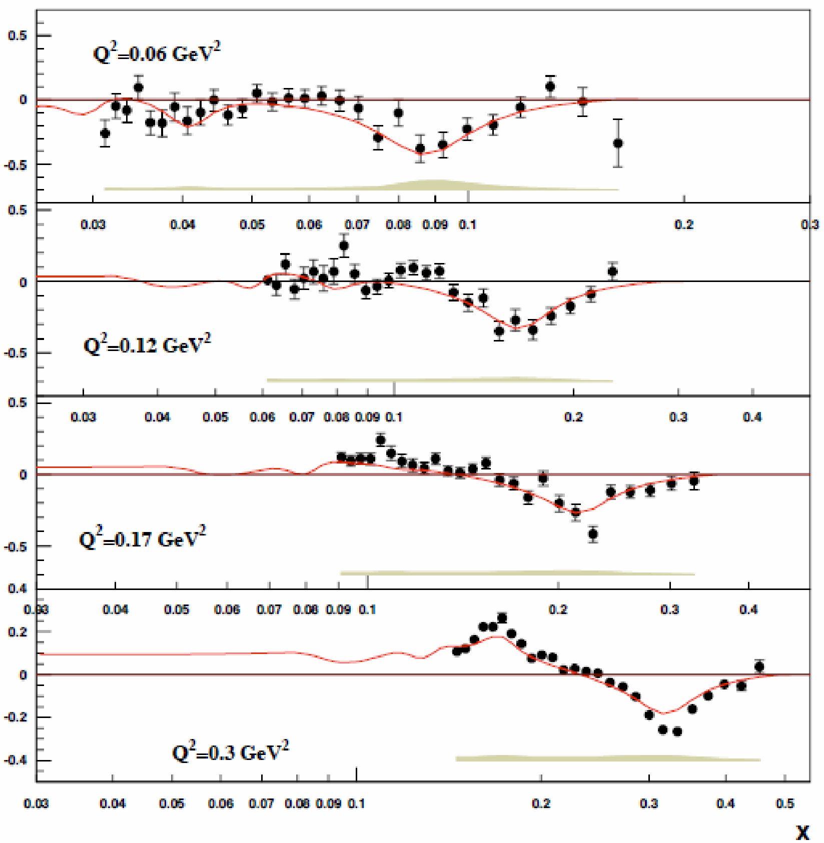

Red solid line = Parametrization of previous world data, including CLAS data (S. Kuhn et al. following original work from L. Stuart at SLAC, further updated to include "AO" and "MAID2000" codes for resonance region)

Blue solid line = Estimated contribution from the unmeasured asymmetry $A_2$ to the asymmetry $A_1+\eta A_2$

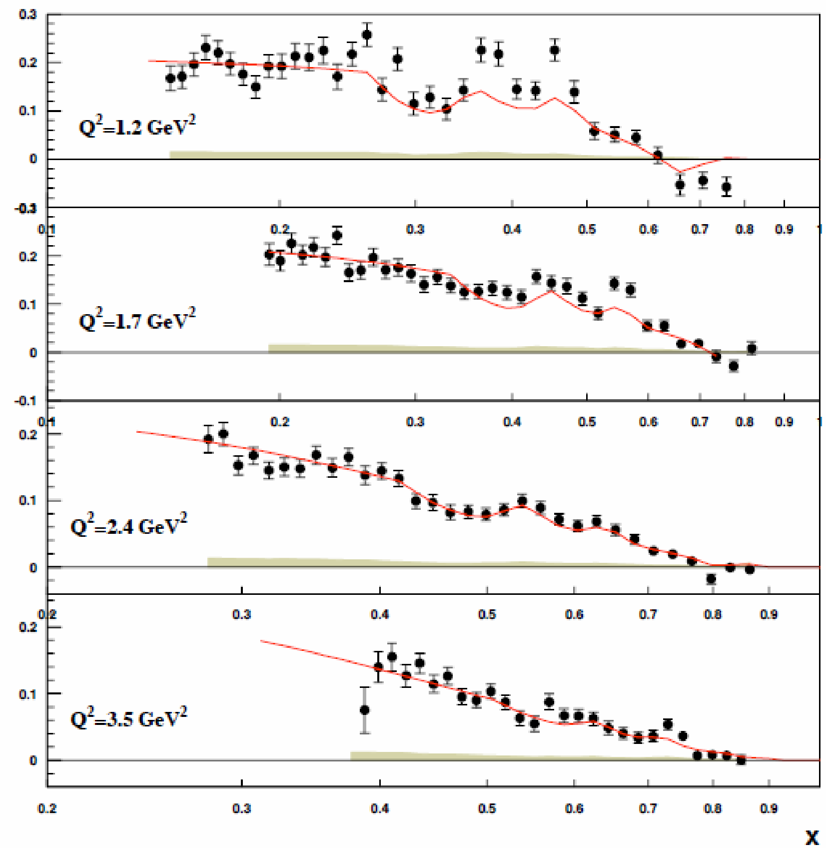
# $g_1(x,Q^2)$ for the proton

$$g_1(x,Q^2) = \frac{F_1}{1+°^2}\,[(A_1+´\,A_2)+(°-´)A_2]$$

1.7 GeV (proton)




5.7 GeV (proton)



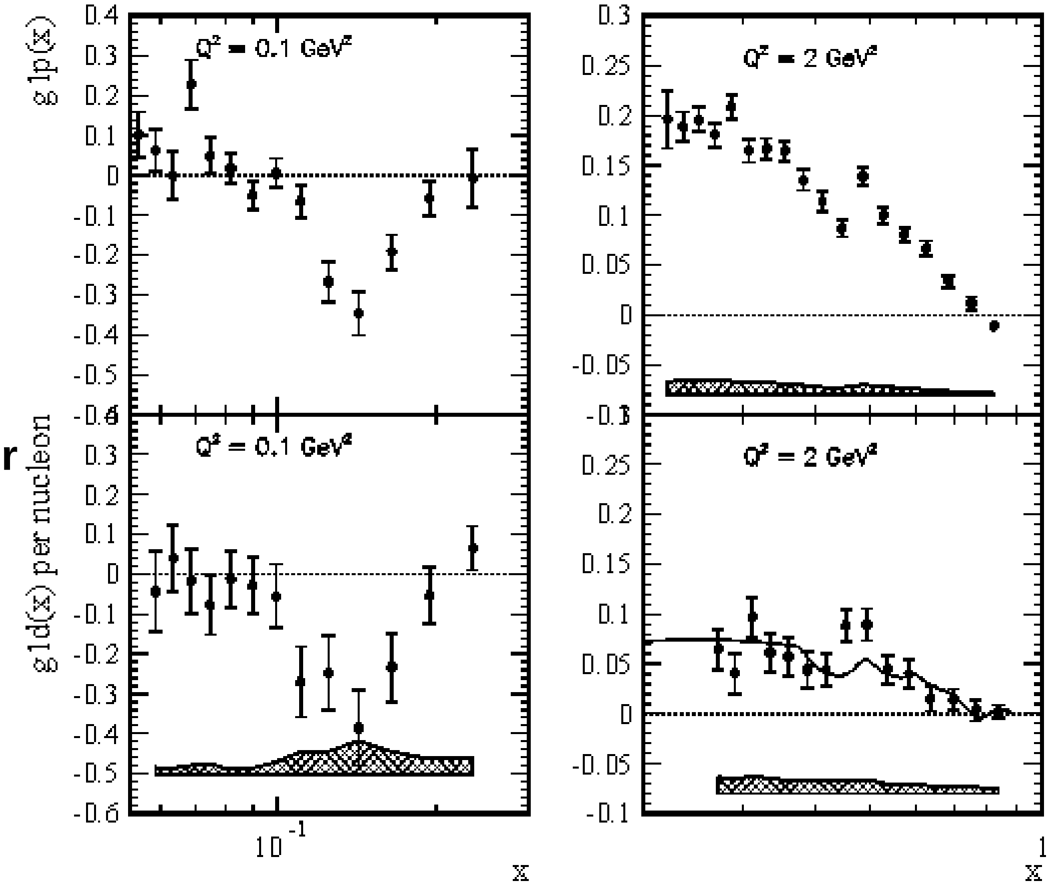

Red solid line =

Parameterization of previous world data, including CLAS data

# Proton/deuteron comparison

- In the ¢(1232) region and at low $Q^2$, $g_1^d/2$ is consistent with $g_1^p$ as expected for a transition to an isospin 3/2 state

- At high $Q^2$, $g_1^p$ is significantly larger than $g_1^d/2$ , indicating a negative contribution from the neutron



# Nucleon Structure Functions

## 2. Large x behavior

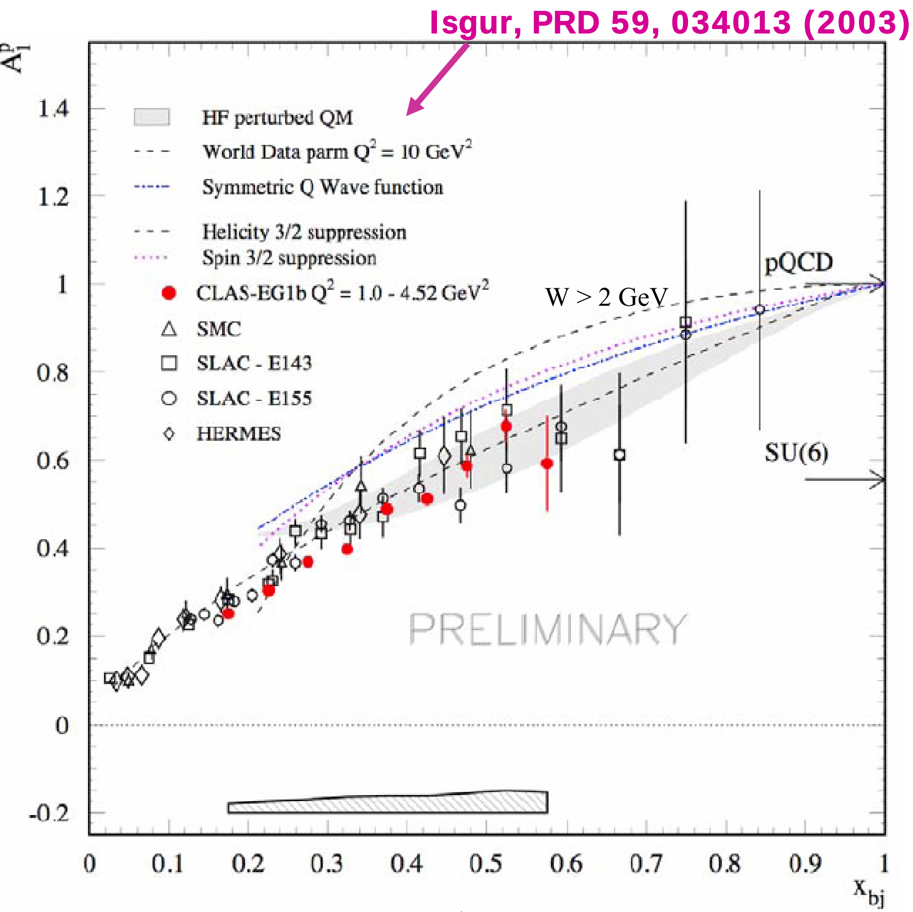
# Large-x behavior of the $A_1$ asymmetry

**Large x region dominated by valence quarks → can test quark models**

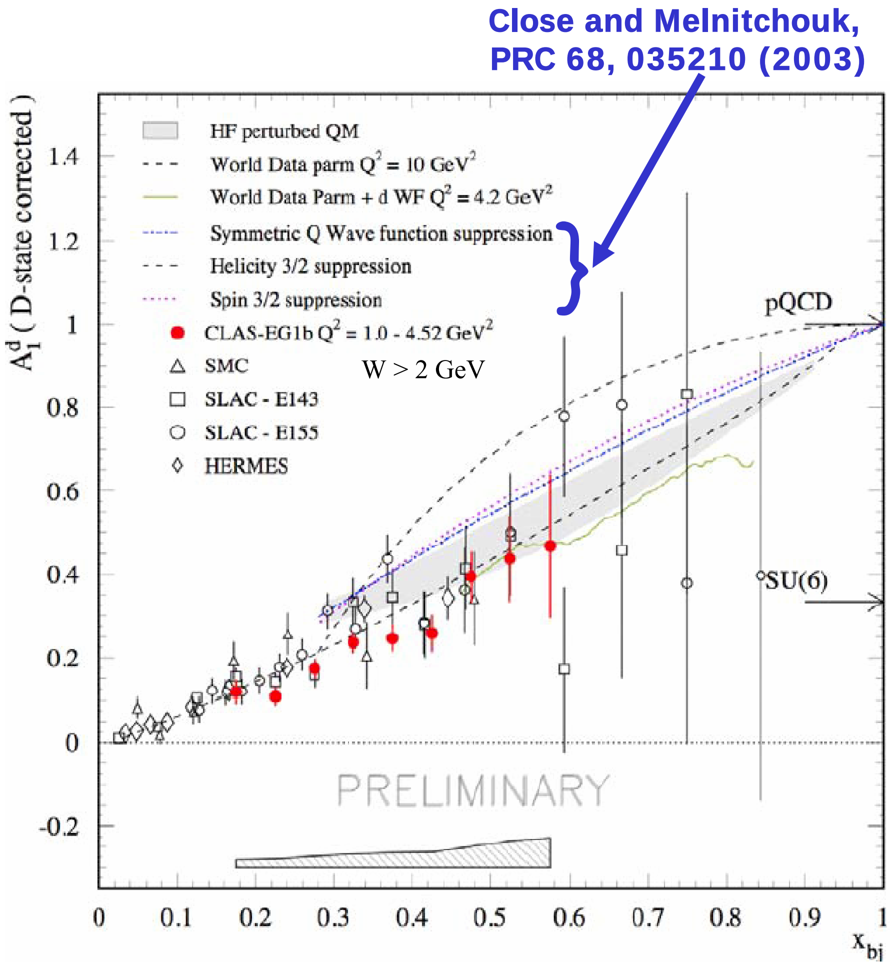
- SU(6) QM: Exact SU(6) symmetry
  Equal probability for S=0 and S=1 di-quark configuration
- Hyperfine perturbed QM **Isgur, PRD 59, 034013 (2003)**
  makes S=1 pairs more energetic than S=0 pairs
- Duality **Close and Melnitchouk, PRC 68, 035210 (2003)**
  Suppress transitions to specific resonances ($56^+$ and $70^-$)
- In DIS, pQCD: Minimal gluon exchanges
  Spectator pair: quarks have opposite helicities **Farrar and Jackson, PRL 35, 1416 (1975)**

| Model for x --> 1 | $A_1^p$ | $A_1^n$ | d/u | $\Delta u/u$ | $\Delta d/d$ |
|---|---|---|---|---|---|
| SU(6) | 5/9 | 0 | 1/2 | 2/3 | -1/3 |
| w/ hyperfine ($E_{S=0} < E_{S=1}$) | 1 | 1 | 0 | 1 | -1/3 |
| One gluon exchange | 1 | 1 | 0 | 1 | -1/3 |
| Suppressed symmetric WF | 1 | 1 | 0 | 1 | -1/3 |
| S=1/2 dominance | 1 | 1 | 1/14 | 1 | 1 |
| $\sigma_{1/2}$ dominance | 1 | 1 | 1/5 | 1 | 1 |
| pQCD (conserved helicity) | 1 | 1 | 1/5 | 1 | 1 |

# Large-x behavior of $A_1$




proton




deuteron

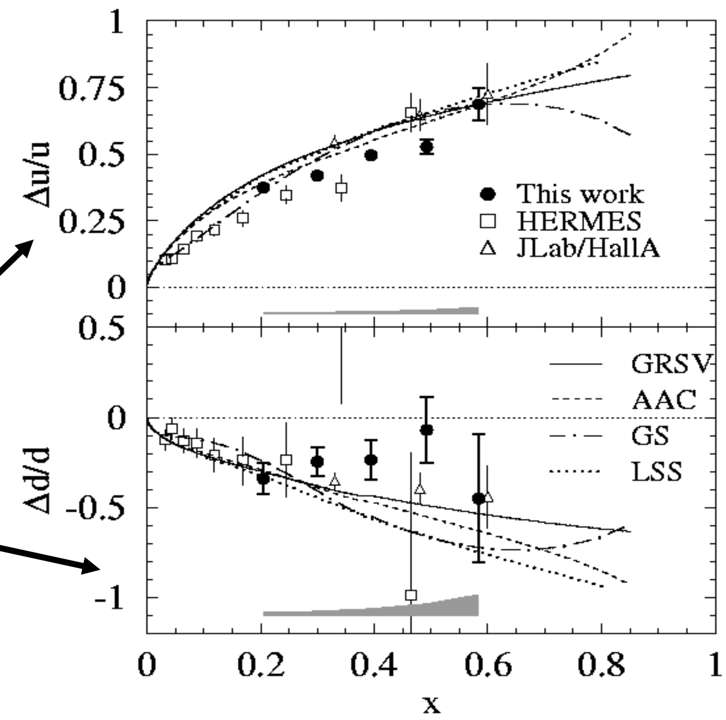
- P and d results fall below parameterization of world data at 10 GeV$^2$ → include in DGLAP fits
- To be used to extract $\Delta q/q$ in this momentum transfer region
- P and d results are in better agreement with the HFP quark model

# Quark polarization in the valence region

**Assuming the naïve parton model with no sea contribution, quark polarizations in the valence region can be estimated directly from the data:**

**¢u/u = $[5g_1^p - 2g_1^d/(1-1.5w_D)]/[5F_1^p - 2F_1^d]$**

**¢d/d = $[8g_1^d/(1-1.5w_D) - 5g_1^p]/[8F_1^d - 5F_1^p]$**




**¢u /u $\rightarrow$ 1 as x $\rightarrow$ 1**
**(consistent with pQCD and QM, with exception of SU(6) )**

**¢d /d < 0 up to the highest x (~0.6)**
**(consistent with Hyperfine Perturbed QM**
**Disagrees with pQCD w/o orbital angular momentum )**

# Nucleon Structure Functions

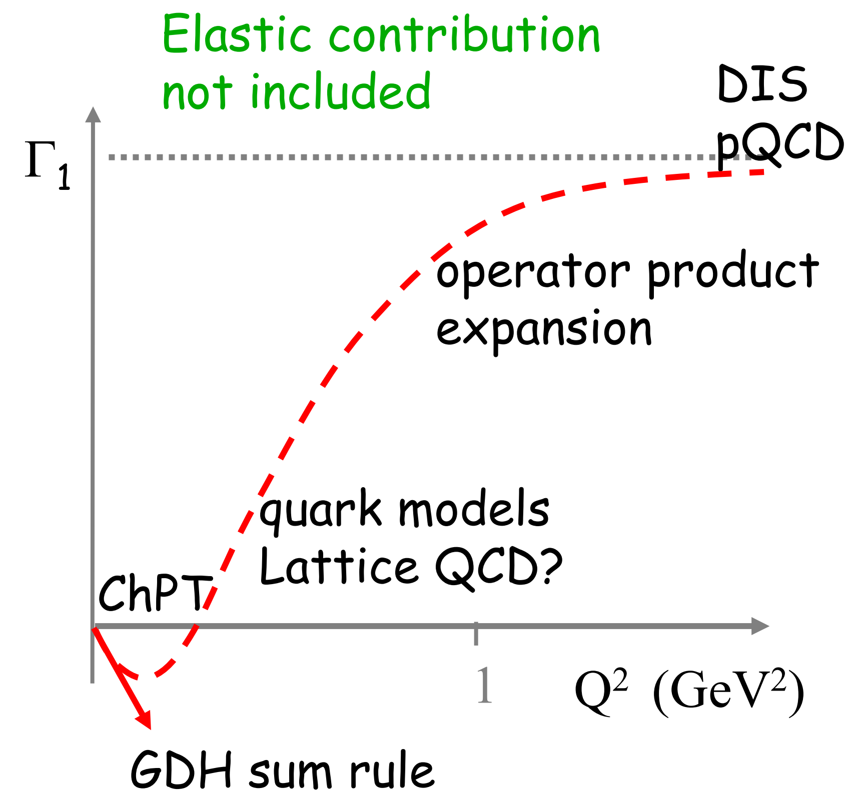
## 3. Moments and Sum Rules

# First moment $\Gamma_1$

How to go from $g_1(x,Q^2)$ to ¢§ ?

$\rightarrow$ integrate over x(0,1):

$$\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)dx$$




Ellis-Jaffe, pQCD ($Q^2 \rightarrow \infty$)

$$\Gamma_1^p = \frac{3}{36}a_3 + \frac{1}{36}a_8 + \frac{4}{36}a_0 \quad \text{+QCD corr}$$

$$\Gamma_1^n = -\frac{3}{36}a_3 + \frac{1}{36}a_8 + \frac{4}{36}a_0 \quad \text{+QCD corr}$$

Gerasimov-Drell-Hearn Sum Rule ($Q^2 = 0$)

$$\frac{M^2}{8\pi^2\alpha}\int_{thr}^{\infty}(\sigma^{\frac{1}{2}} - \sigma^{\frac{3}{2}})\frac{d\nu}{\nu} = M^2\int_{thr}^{\infty}G_1(\nu,0)\frac{d\nu}{\nu} = -\frac{1}{4}\kappa^2$$

$$M\nu G_1(\nu,Q^2) = g_1(\nu,Q^2)$$

# Generalized GDH Integral

**A generalization of the GDH sum rule has been suggested by Ji and Osborne by relating the virtual-photon forward Compton amplitude $S_1$ to the nucleon structure function $g_1$ using dispersion relations**

X.Ji et al., Phys.Lett.B472 (2000) 1

$S_1(0,Q^2)$

$$I_{GDH}(Q^2) = \frac{16\pi\alpha}{Q^2}\int_{x_0}^{\infty} dx\, g_1(x,Q^2)$$

**calculable** ($I_{GDH}$) **measurable** ($g_1$)

$Q^2 < 0.1$ GeV$^2$ → GDH sum rule and Chiral Perturbation Theory

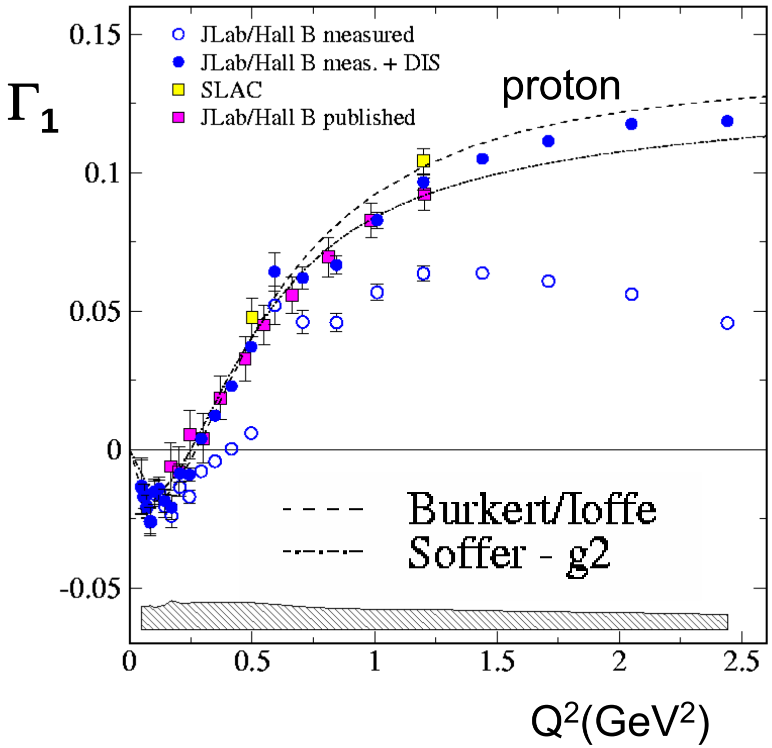
$$-\frac{\kappa^2}{M^2} + cQ^2 + O(Q^4)$$

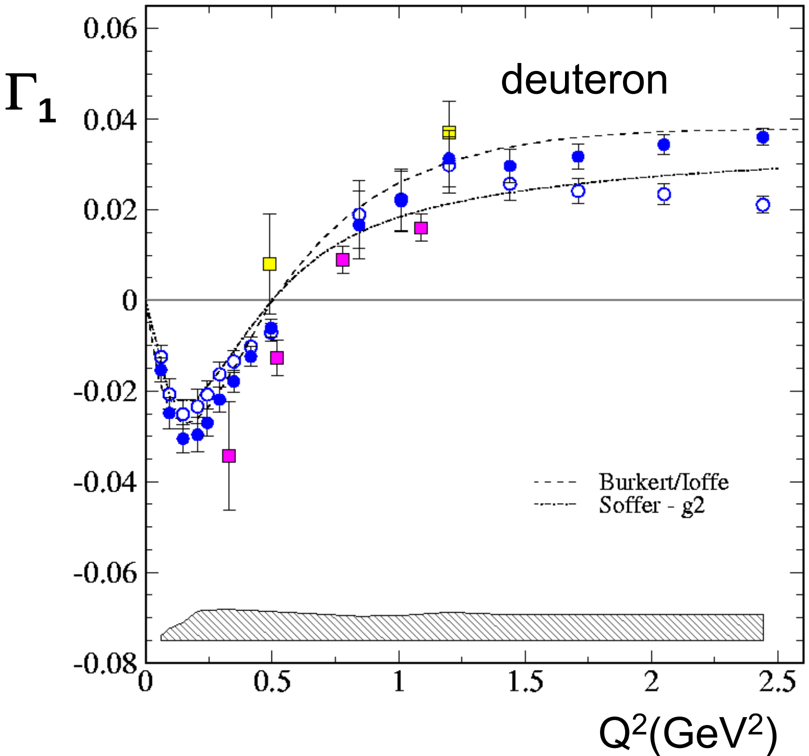
$0.1 < Q^2 < 0.5$ GeV$^2$ → Lattice?

$Q^2 > 0.5$ GeV$^2$ → Ellis-Jaffe Sum rule and Operator Product Expansion

$$\sim \sum_{\tau=2,4,\ldots} \frac{\mu_\tau(Q^2)}{Q^{\tau-2}}$$

# $\Gamma_1$ for the proton and deuteron




- $X_{min}$=0.001, $x_{max}$= pion production threshold
- shows strong $Q^2$ dependence varying from negative to positive values as $Q^2$ increases

Phenomenology:

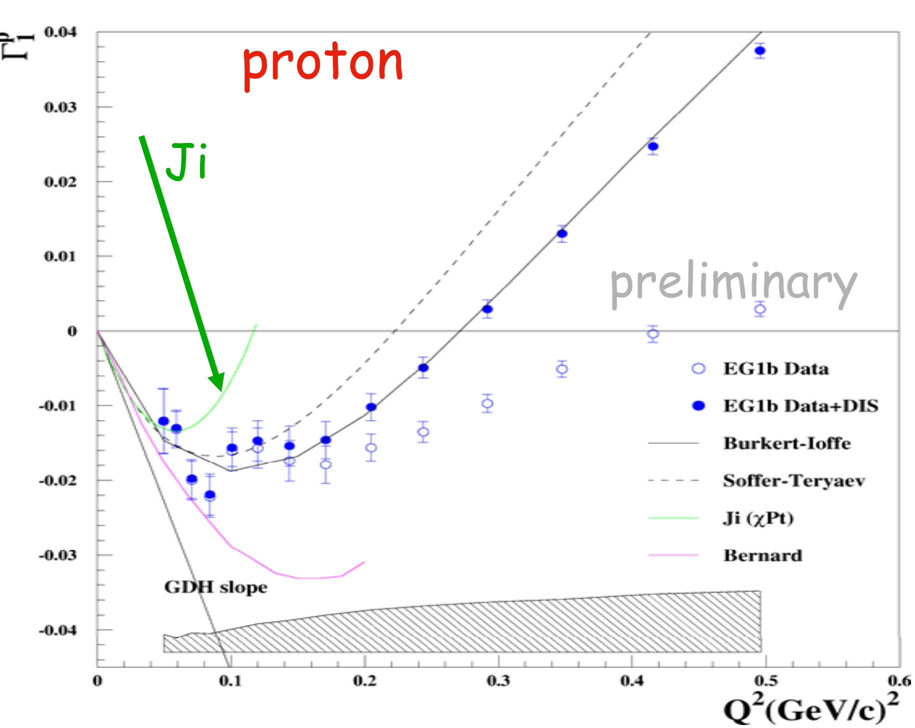
Burkert/Ioffe

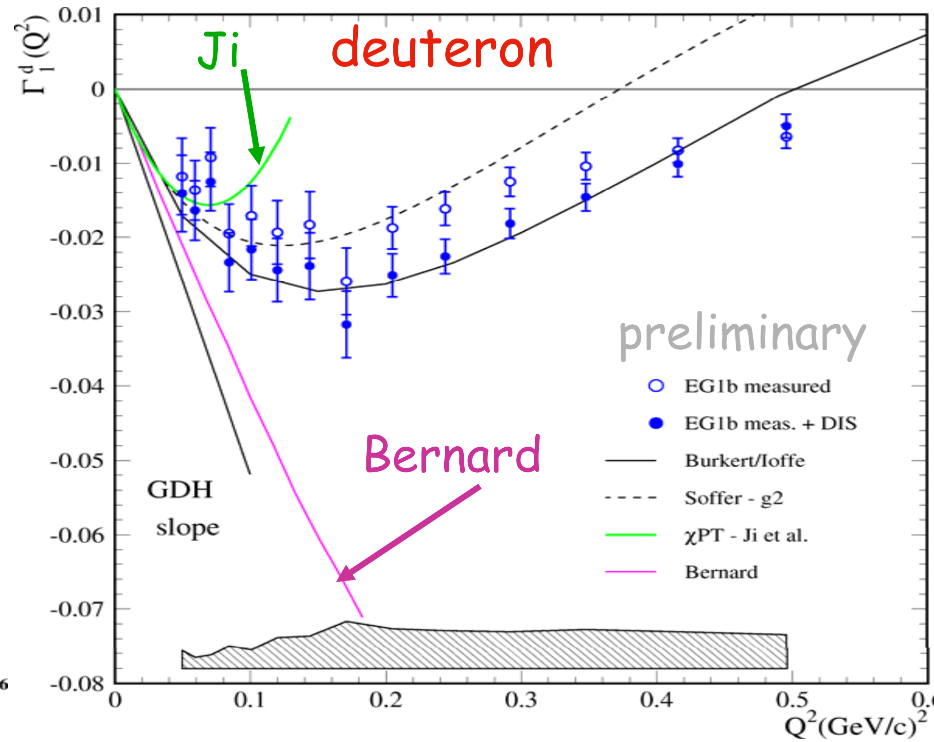
- Resonance contribution based on pion electroproduction analysis
- Vector meson dominance model

Soffer/Teryaev

- Interpolation of the integral over $(g_1+g_2)dx$

# Low $Q^2$ behavior of $\Gamma_1$ - $\chi$PT




$$\Gamma_1^p(Q^2) = -\frac{\kappa_p^2}{8M^2}Q^2 + 3.89Q^4 + \ldots$$

$$\Gamma_1^n(Q^2) = -\frac{\kappa_n^2}{8M^2}Q^2 + 3.15Q^4 + \ldots.$$

GDH + $\chi$pT

Ji, Kao and Osborne, Phys. Lett. B 472 (2000) 1

**Heavy Baryon approach (HB$\chi$PT) M $\rightarrow \infty$**

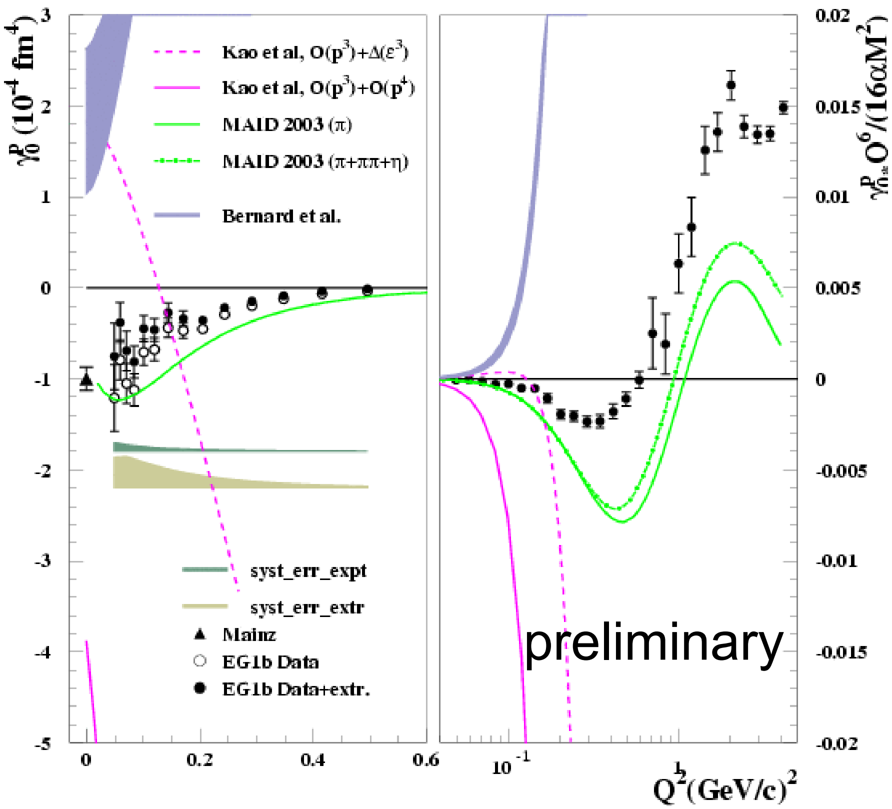
Bernard, Hemmert and Meissner, Phys. Rev. D 67 (2003) 076008

**4th order (one loop) in the chiral expansion**

**$\Delta$ and vector meson contributions can be included, with large uncertainty**

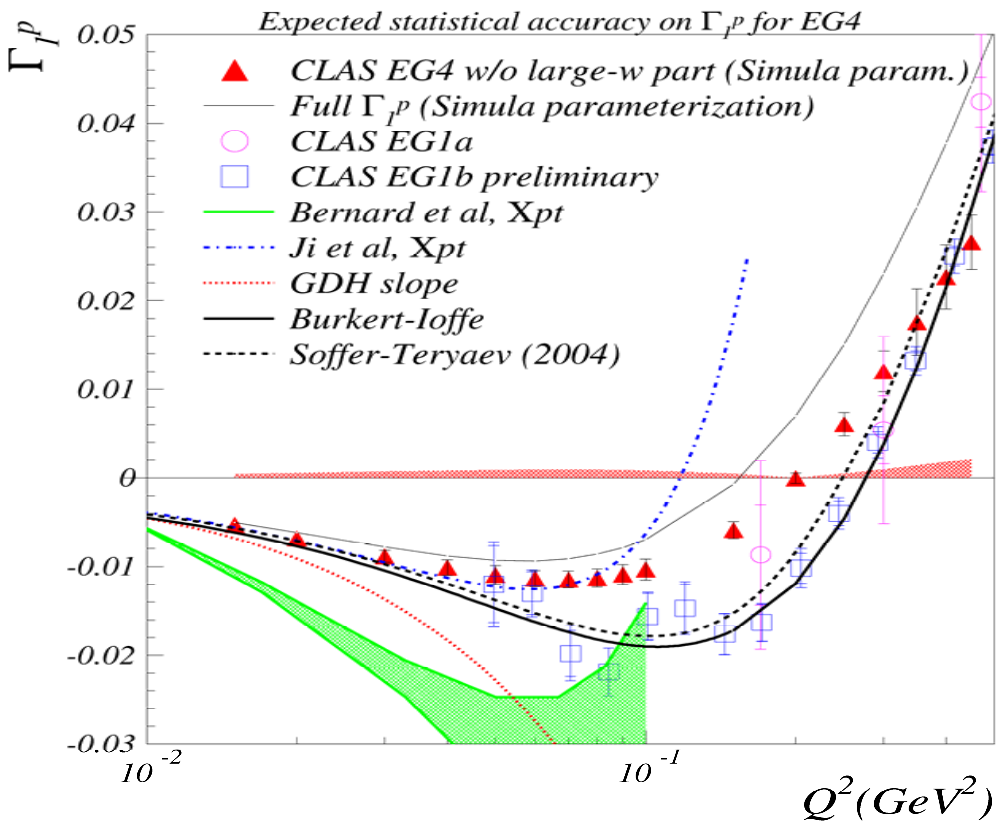
# Forward Spin Polarizability

$$\gamma_0(Q^2) = \frac{4e^2M^2}{\pi Q^6}\int_0^{x_0} dx\, x^2 \left\{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)\right\}$$




- $\chi$PT expected to work at low $Q^2$ (up to ~ 0.1 GeV$^2$?)
- **Significant disagreement between data and both $\chi$PT calculations**
- Qualitative agreement with MAID model predictions

# EG4 projection




- Extends to very low $Q^2$ of 0.015 $GeV^2$ both proton and deuteron
- Data taken earlier this year.

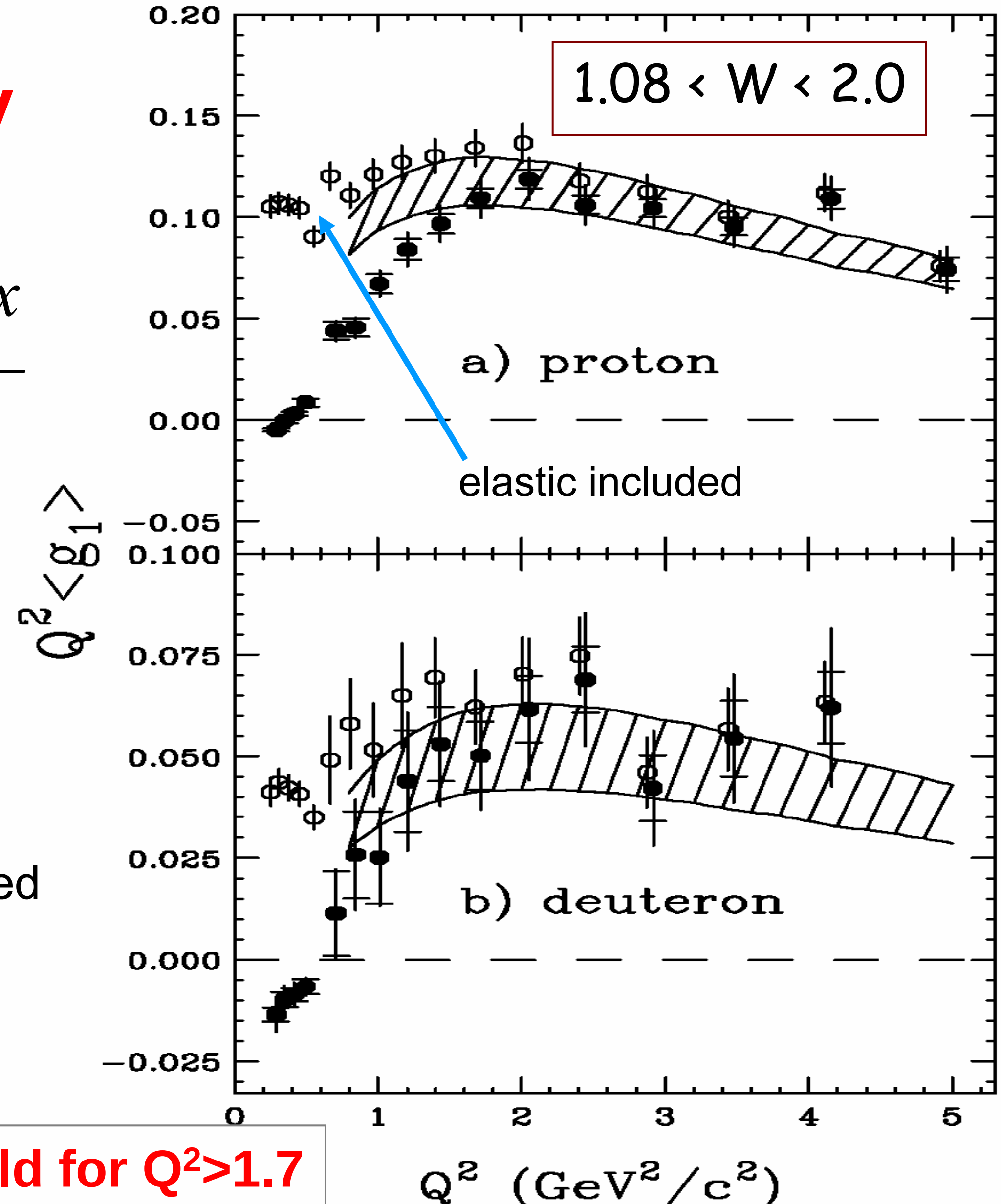
# Quark-Hadron Duality

# Bloom Gilman Duality

- The observation that nucleon resonances at low $Q^2$ average to the scaling curve measured in DIS
  - Bloom and Gilman, PRL 25, 1140 (1970); PRD 4, 2901 (1971)
- Observed with high precision in the unpolarized $F_2^p$ structure function in Hall C, Jlab
  - I. Niculescu *et al.*, PRL 85, 1182, 1186 (2000)
- pQCD: higher twists are small or cancel each other
- QPM: Resonant contribution cancels out when averaging over even and odd parity resonances
- Can we see these effects in spin structure functions?
- Useful tool to define kinematic region in which parton distribution functions can be reliably extracted

# Test of global duality

$$< g_1(Q^2) >= \frac{\int_{x_h}^{x_l} g_1(x,Q^2)dx}{(x_h - x_l)}$$




Hatched bands represent the range of the averages calculated from NLO PDFs (GRSV, AAC) evolved to each $Q^2$, TMC is included

**Global duality appears to hold for $Q^2$>1.7 $GeV^2$ for both $g_1^p$ and $g_1^D$**

# Summary

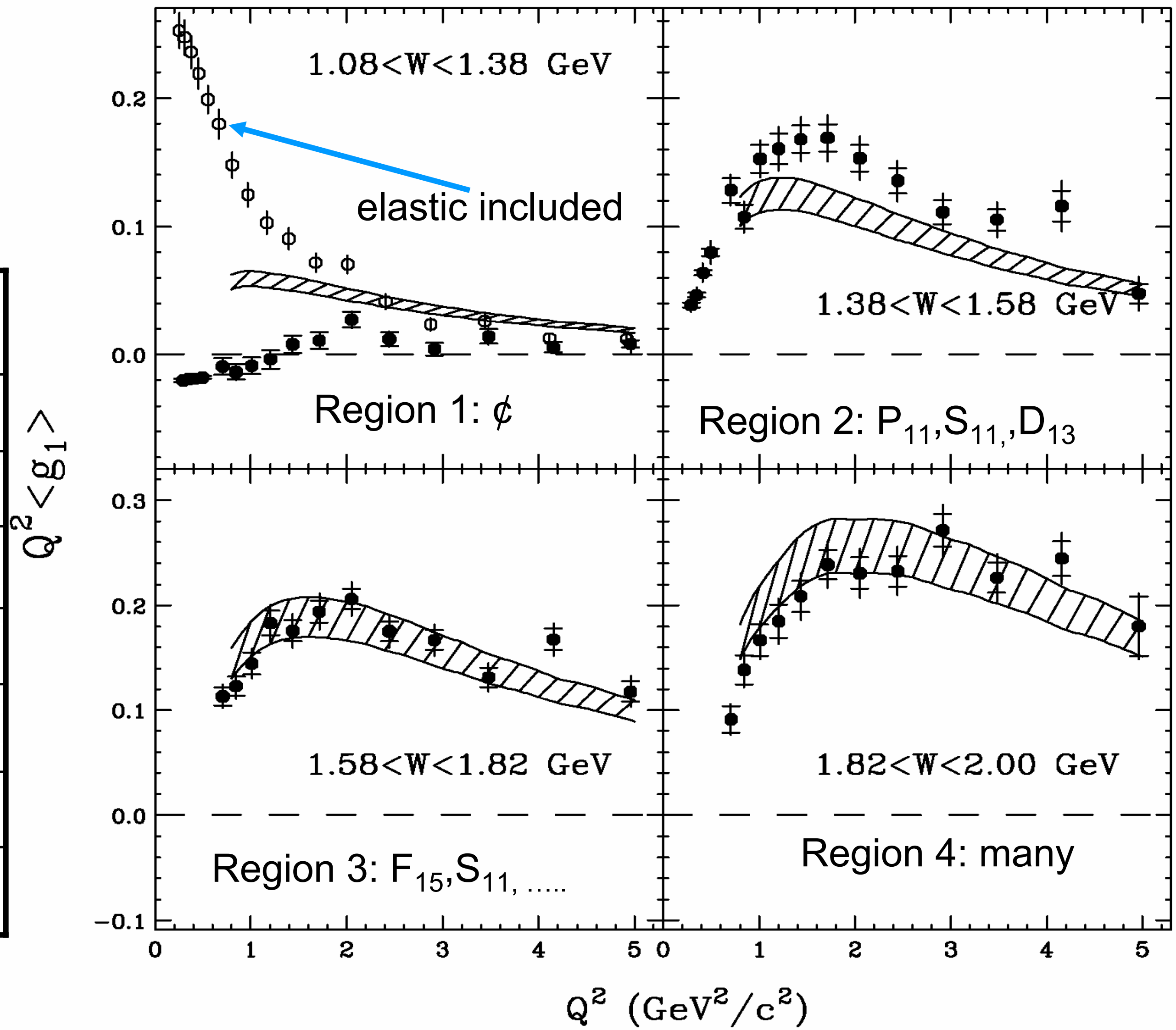
- **A wealth of new data on the nucleon spin structure in the non-perturbative regime has been produced in Hall B at Jefferson Lab as part of a broad spin physics program, still in progress**
- **These measurements provide new information for understanding the transition between hadronic and partonic degrees of freedom by investigating spin structure functions, related sum rules and moments, asymmetries, …**
- **A new measurement to cover the very low momentum transfer region and provide a bridge to the GDH sum rule at the photon point has just been completed recently**
- **12 GeV program at Jlab will offer the opportunity to extend these measurements into new kinematic regions**

# Extra slides

# Test of local duality

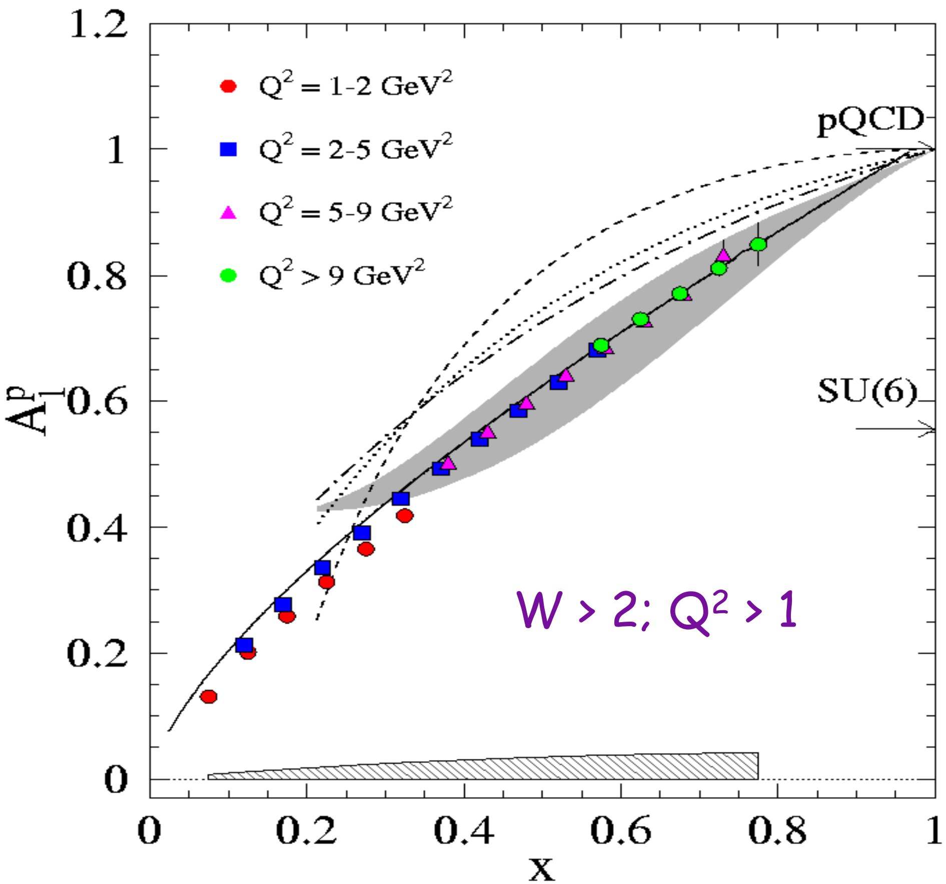
Integration limits correspond to the W limits at a given $Q^2$

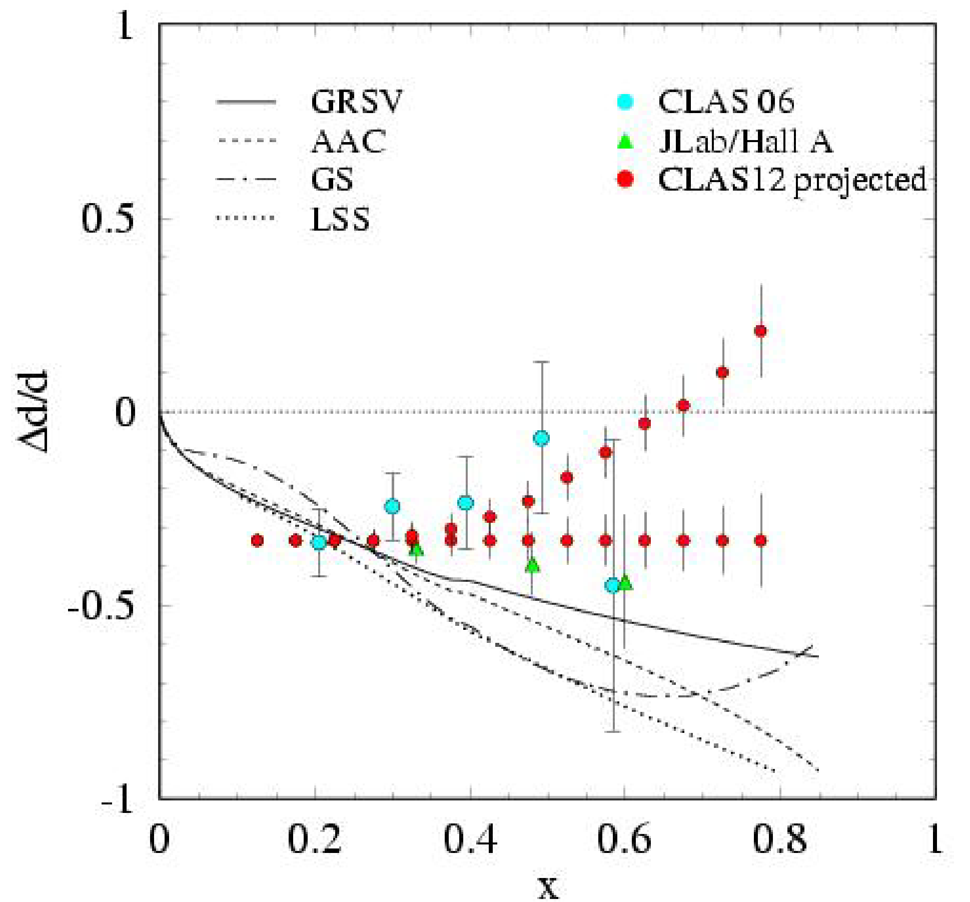
| | |
|---|---|
| Δ(1232) | $\sigma_{3/2}$ |
| $P_{11}$(1440) | $\sigma_{1/2}$ |
| $S_{11}$(1535) | $\sigma_{1/2}$ |
| $D_{13}$(1520) | $\sigma_{1/2}(\sigma_{3/2})$ |
| $F_{15}$(1680) | $\sigma_{1/2}(\sigma_{3/2})$ |
| $S_{11}$(1650) | $\sigma_{1/2}$ |
| $S_{31}$(1620) | $\sigma_{1/2}$ |
| $D_{33}$(1700) | $\sigma_{1/2}$ |



# Coming Attractions

# EG12 projections

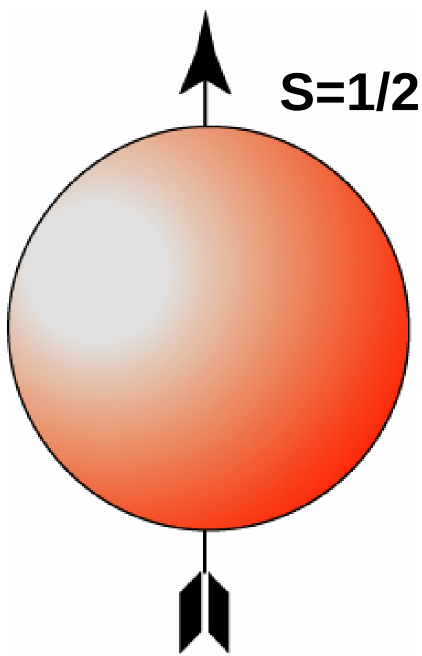


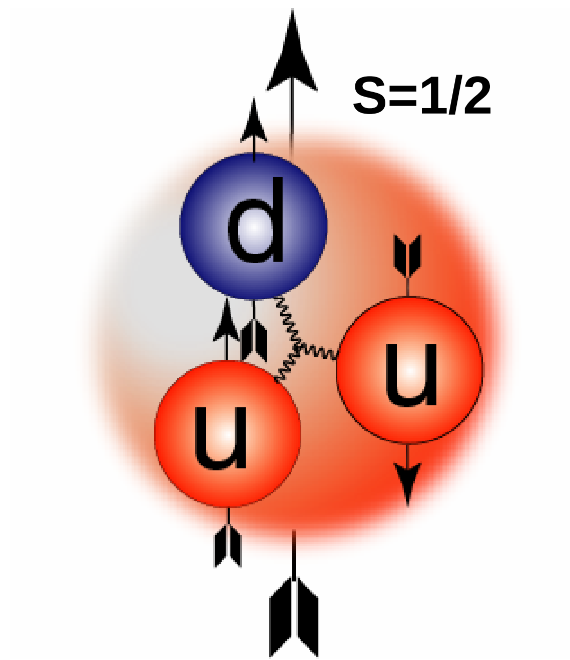

**11 GeV beam at Jefferson Lab will allow to determine whether the x → 1 behavior Of spin structure functions follows any of the models described earlier**

# What we see changes with spatial resolution

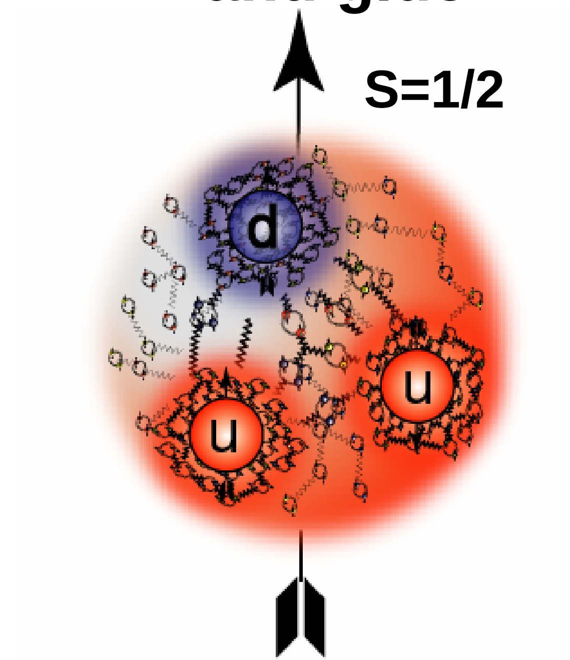
**>1 fm**
**Nucleons**




**0.1 — 1 fm**
**Constituent quarks and glue**



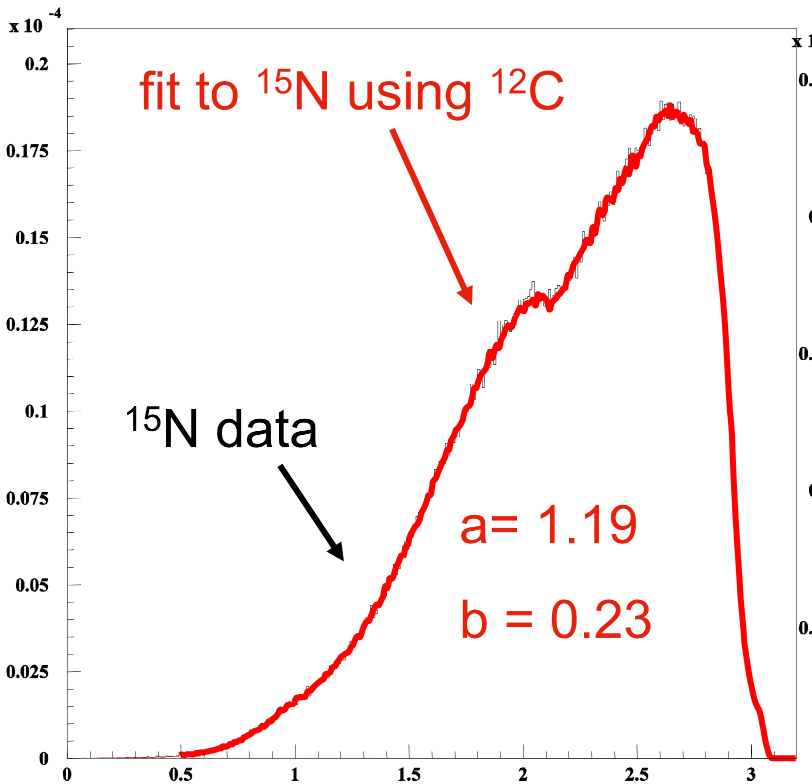

**< 0.1 fm**
**“bare” quarks and glue**

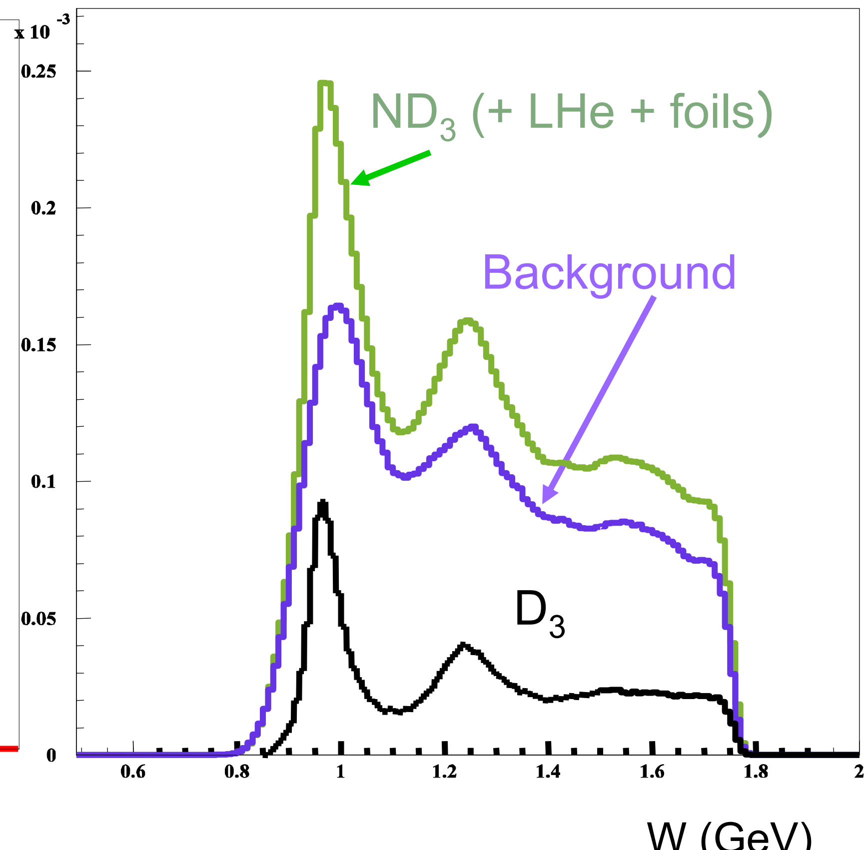


# Modeling the Background

$$\sigma(^{15}\mathrm{N}) = \left( a + b\frac{\sigma_{\mathrm{n}}}{\sigma_{\mathrm{D}}} \right) \sigma(^{12}\mathrm{C})$$

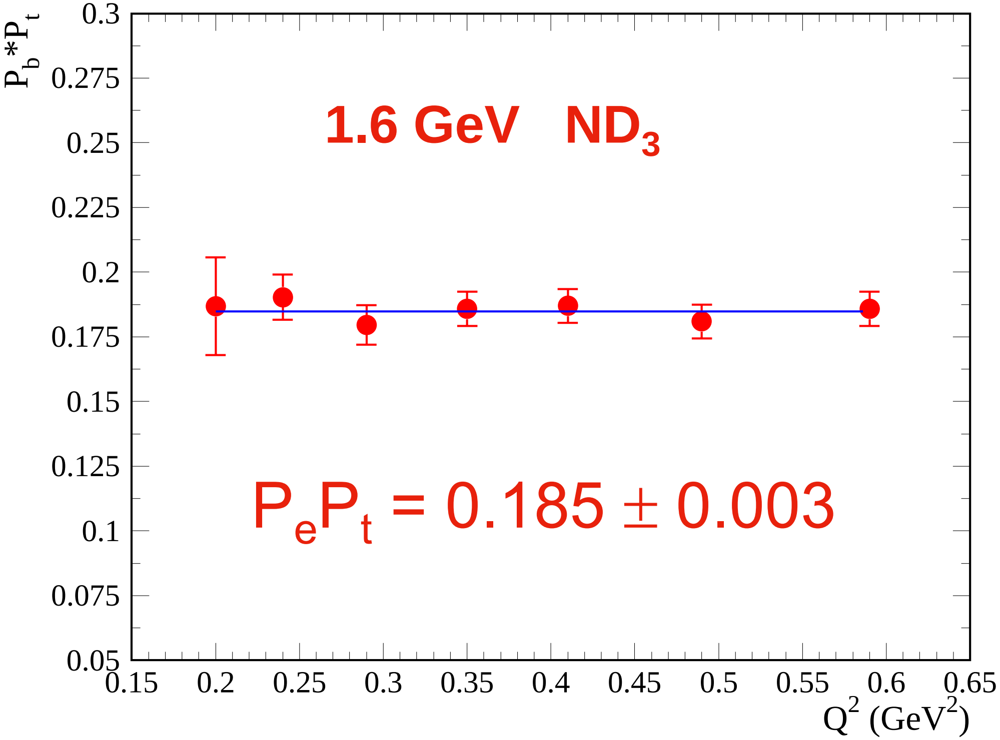
**We construct a background spectrum that includes $^{15}$N, LHe and foils.**



# Target and Beam Polarization

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

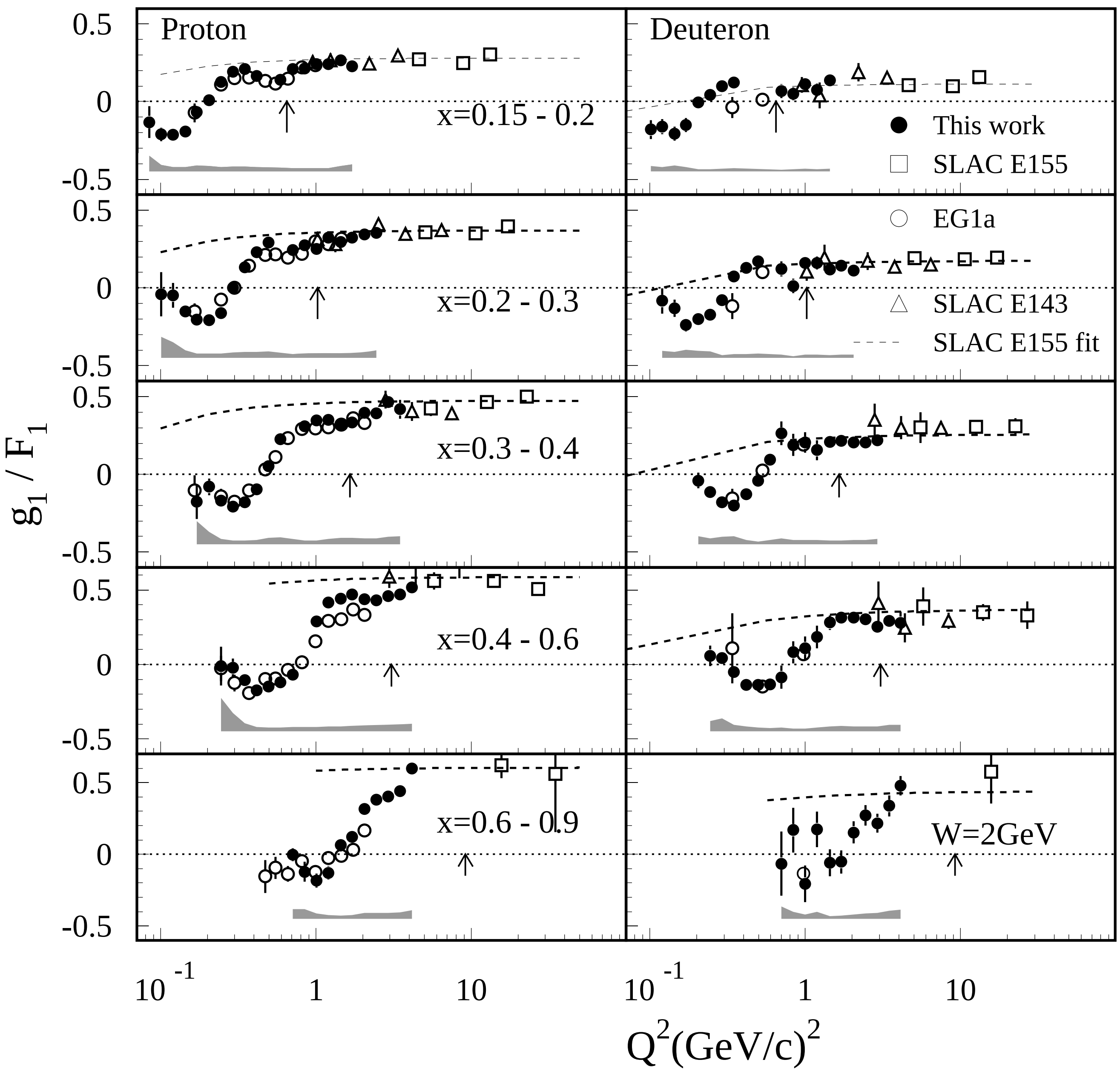



$$\frac{\sigma_n^{el} A_n^{el} + \sigma_p^{el} A_p^{el}}{\sigma_n^{el} + \sigma_p^{el}}$$

**inclusive or exclusive (e,e'p) events can be used**

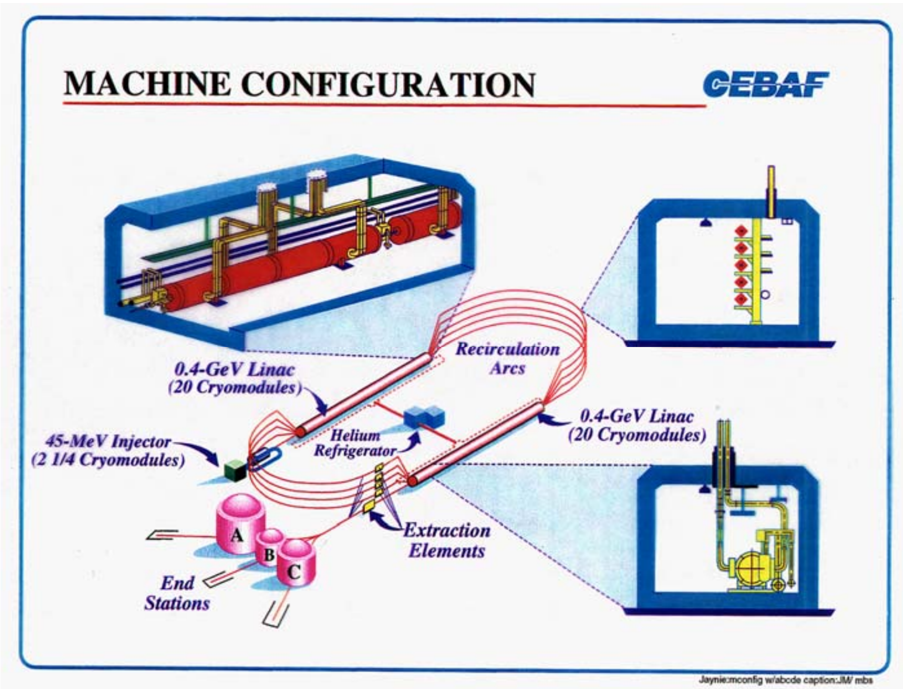
# $Q^2$ dependence of $g_1/F_1$

- ◆ $Q^2$ 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
- ◆ High $Q^2$ results agree with SLAC data



# Experimental Setup

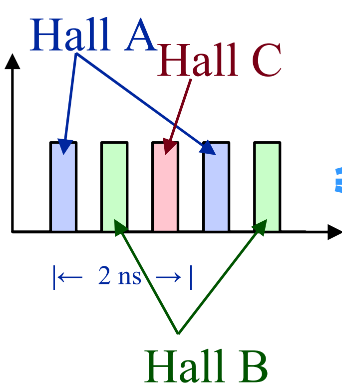
# Jefferson Lab

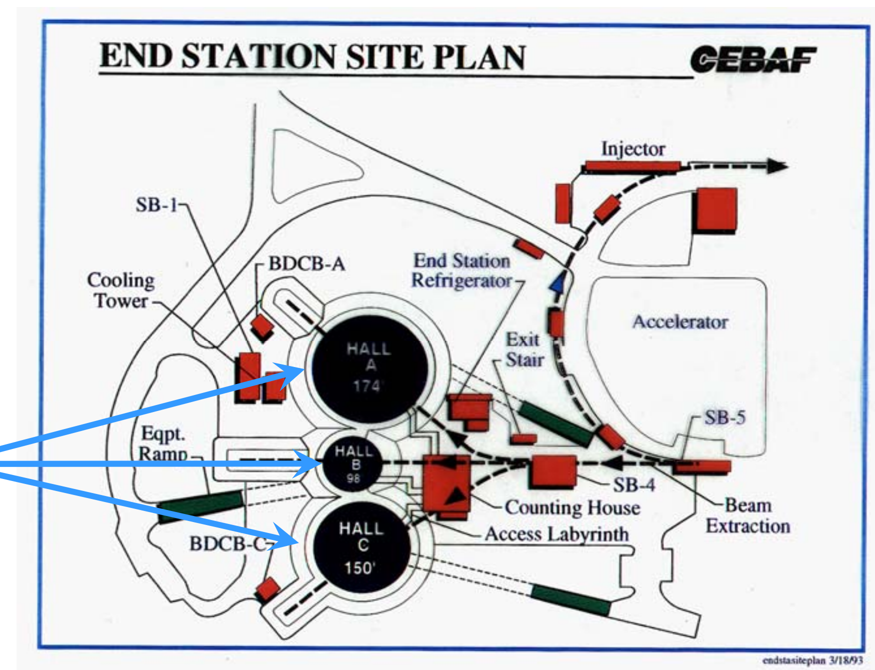



**CEBAF is a superconductive electron accelerator**

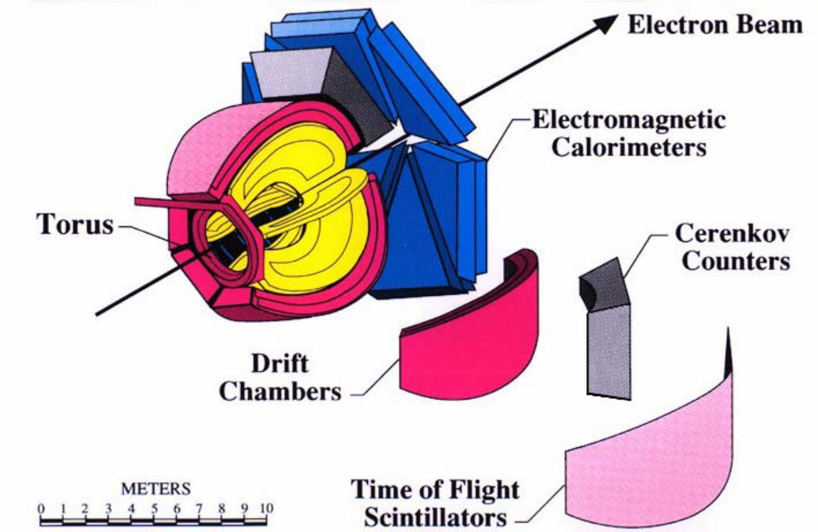
- → **continuous beam**
- → **high longitudinal polarization**
- → **energy range → 0.75 –5.9 GeV**
- → **current range → 0.1 nA –200mA**

**The electron beam can be delivered simultaneously to the three halls with high polarization**

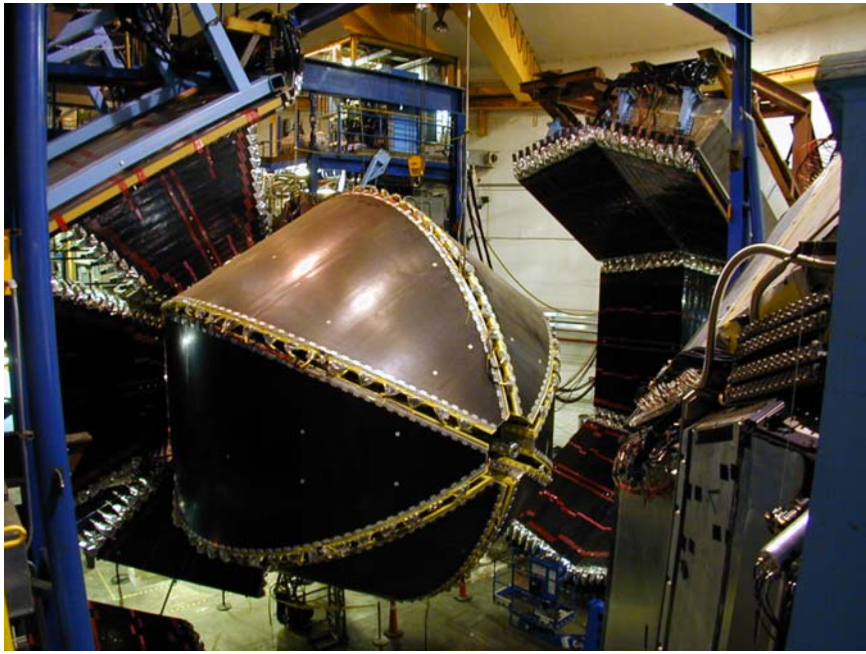


# CLAS in Hall B




**CEBAF**
**Large**
**Acceptance**
**Spectrometer**

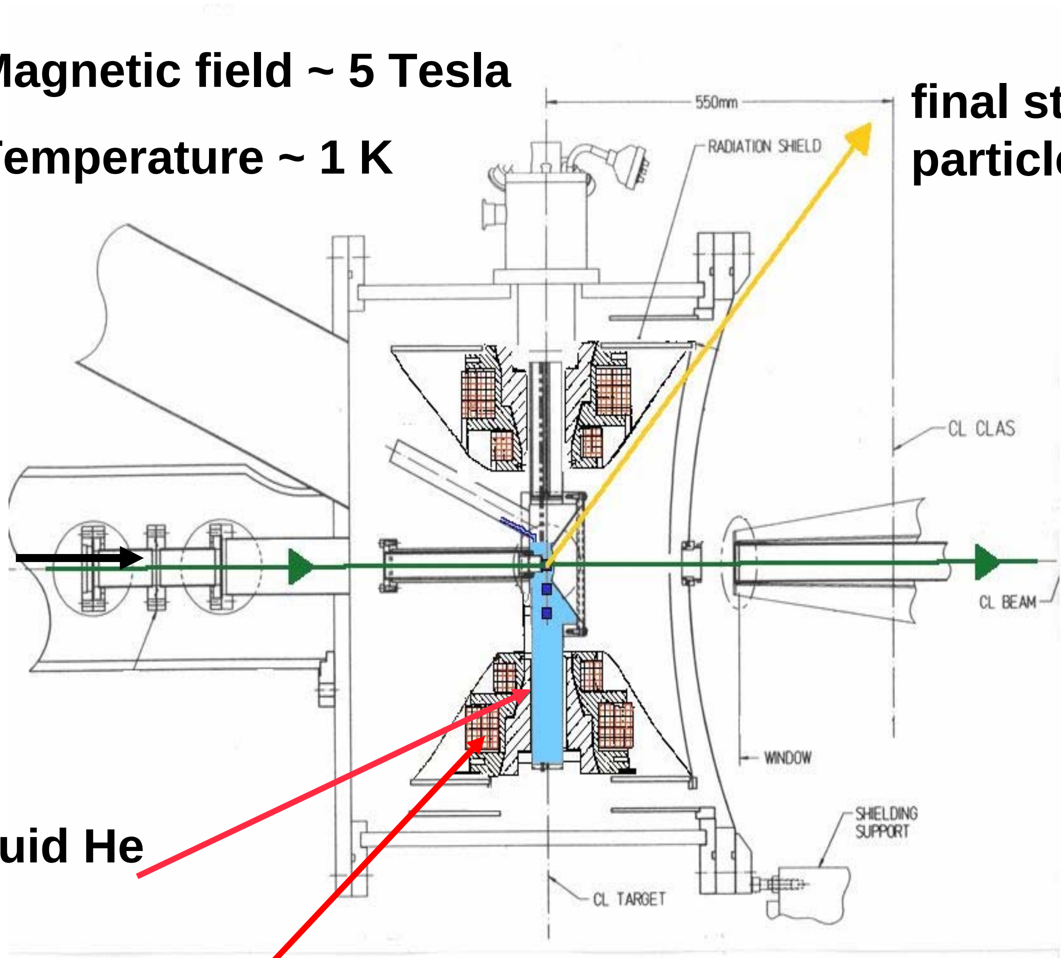


- **large kinematical coverage**
- **simultaneous measurement of exclusive and inclusive reactions**
- **central field-free region well suited for the insertion of the polarized target**

# Polarized Target

Magnetic field ~ 5 Tesla

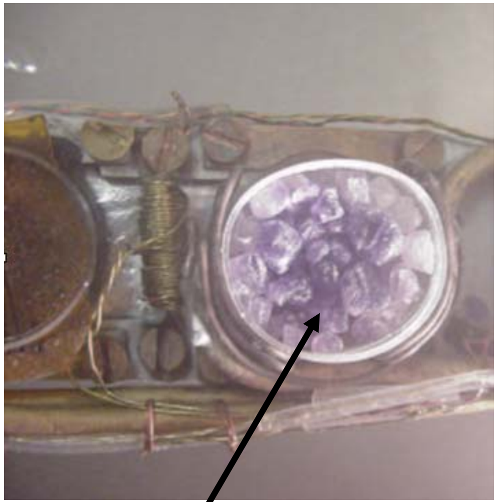
Temperature ~ 1 K




final state particle

Liquid He

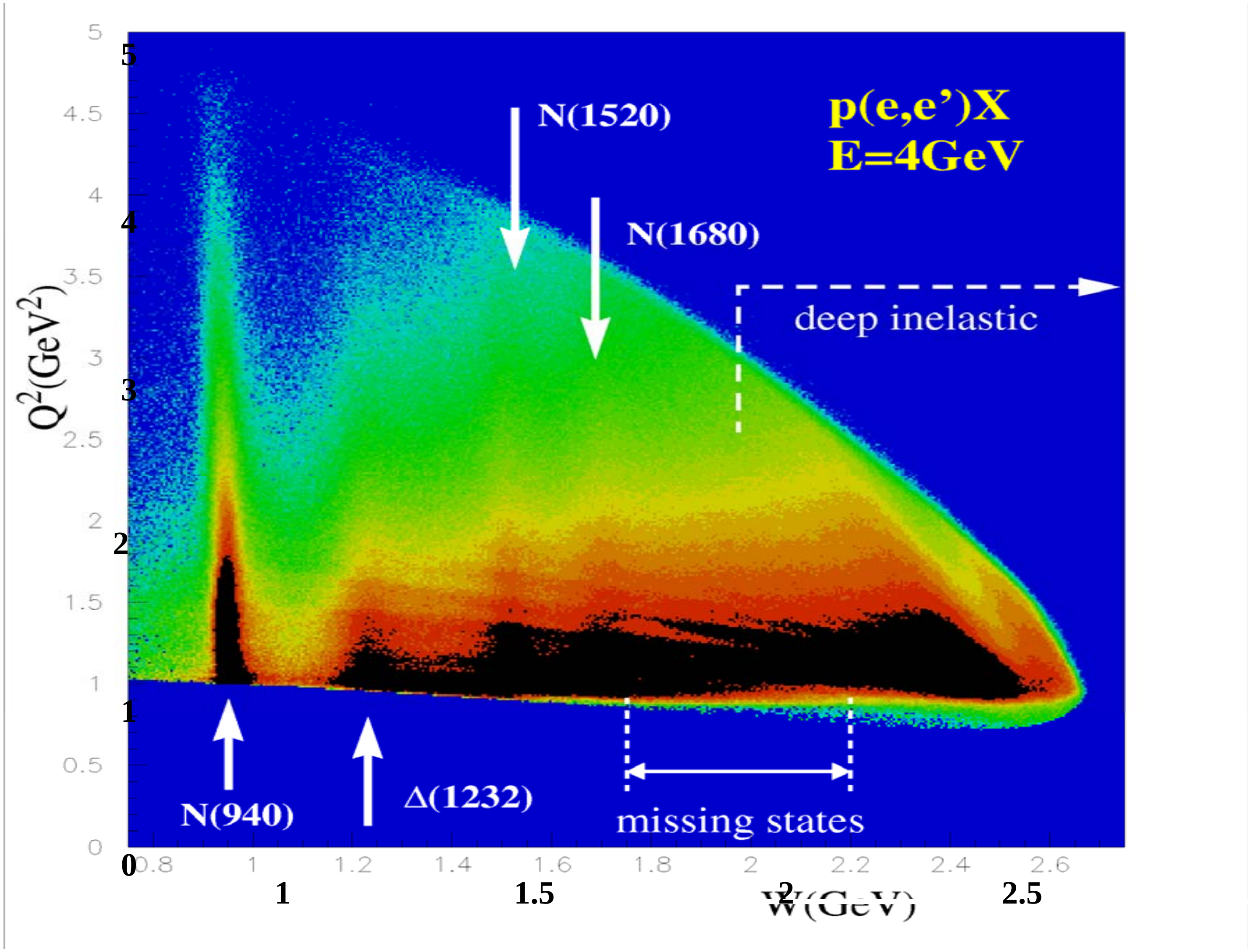
Helmholtz coils



Irradiated ammonia beads

# The Proton Absorption Spectrum

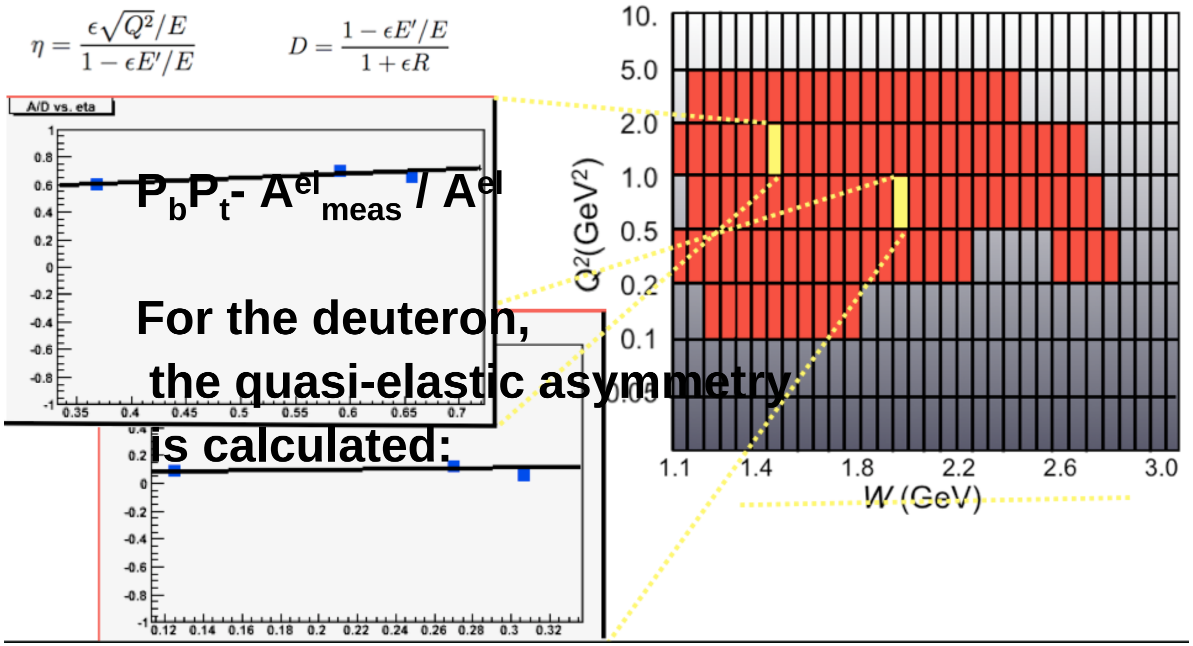
**(CLAS Coverage for e p $\rightarrow$ e' X   E = 4 GeV)**



# EG1 extraction of $A_2$

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

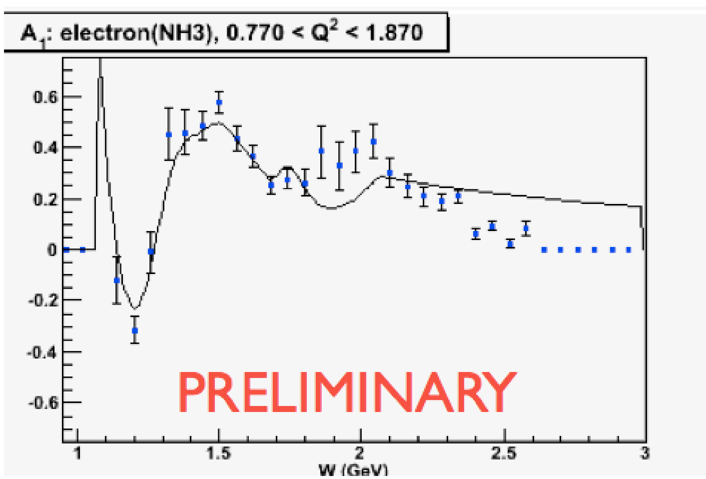
$$\eta = \frac{\epsilon\sqrt{Q^2}/E}{1-\epsilon E'/E} \qquad D = \frac{1-\epsilon E'/E}{1+\epsilon R}$$

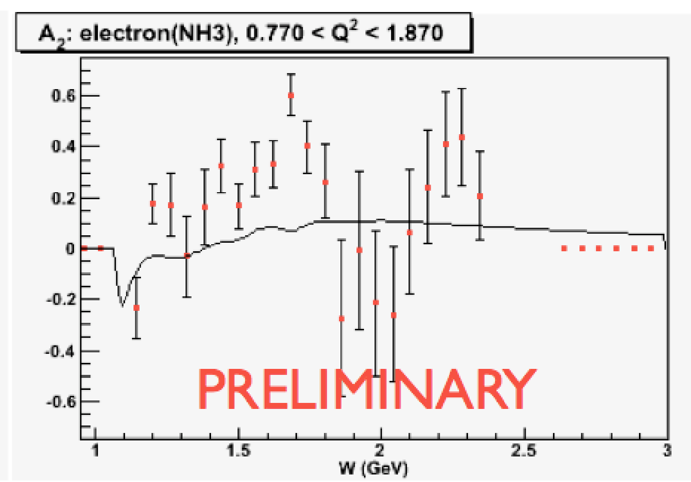



$P_b P_t$ - $A^{el}_{meas}$ / $A^{el}$

For the deuteron, the quasi-elastic asymmetry is calculated:

- Analysis is in progress to obtain both $A_1$ and $A_2$ from the EG1 data
- Intercept gives $A_1$
- Slope gives $A_2$
- $A_2$ is larger than EG1 model (MAID, AO) as is Hall C RSS experiment



# Generalized GDH Integral

**A generalization of the GDH sum rule has been suggested by Ji and Osborne by relating the virtual-photon forward Compton amplitude $S_1$ to the nucleon structure function $G_1$**

X.Ji et al., Phys.Lett.B472 (2000) 1

$S_1(0,Q^2)$

↓

$$I_{GDH}(Q^2) = \frac{16\pi\alpha}{Q^2}\int_{x_0}^{\infty} dx\, g_1(x,Q^2)$$

↑

**the left side is a calculable quantity**

**the right side is a measurable quantity**

$Q^2 < 0.1\ \mathrm{GeV}^2$ → **GDH sum rule and Chiral Perturbation Theory**

$$-\frac{\kappa^2}{M^2} + cQ^2 + O(Q^4)$$

$0.1 < Q^2 < 0.5\ \mathrm{GeV}^2$ → **Lattice?**

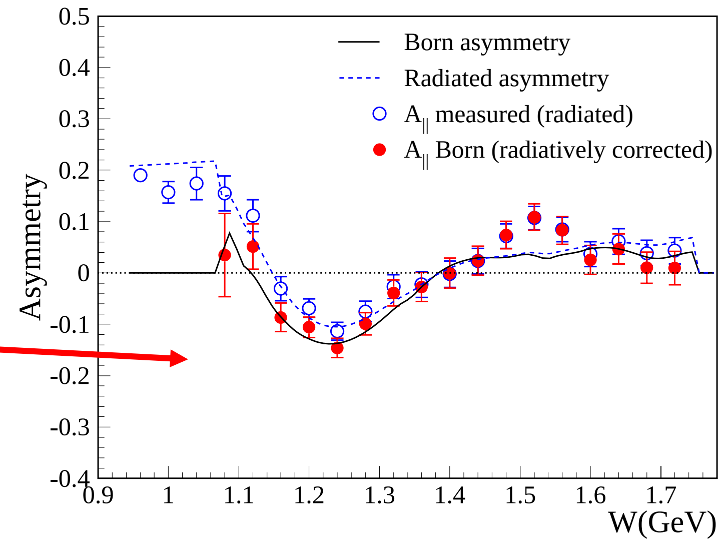
$Q^2 > 0.5\ \mathrm{GeV}^2$ → **Ellis-Jaffe Sum rule and Operator Product Expansion**

$$\sim \sum_{\tau=2,4,\ldots} \frac{\mu_\tau(Q^2)}{Q^{\tau-2}}$$

# Extracting $A_1+\eta A_2$

$$A_1 + \eta A_2 = \frac{A_{//}}{D}$$

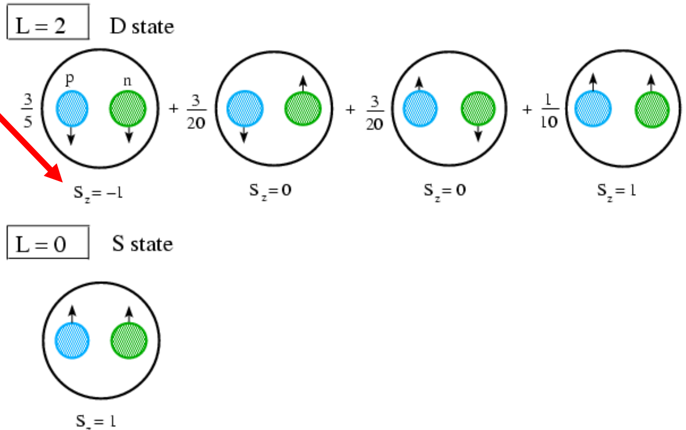
$$A_{\|}^{Born} = \frac{A_{\|}^{Meas}}{F_{RC}} + A_{RC}$$




**For deuteron additional corrections due to D state**

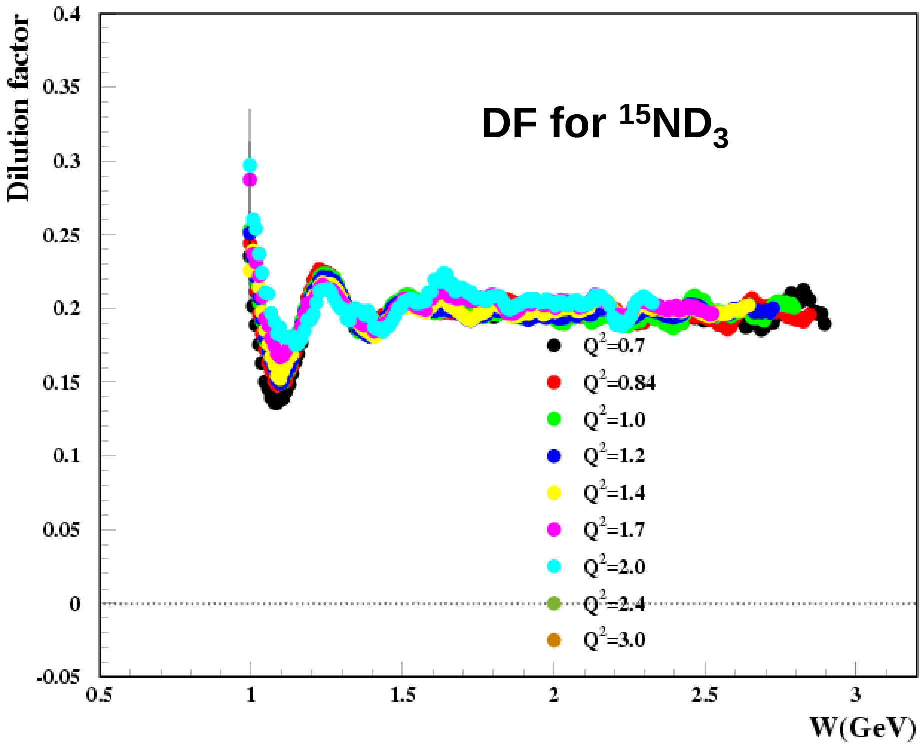
$w_d$ (~0.056) is the probability of finding the deuteron in the D state

The probability of finding a nucleon with spin in the opposite direction as the deuteron is $\frac{3}{4} w_d$.



# Dilution factor

**The dilution factor is the ratio of counts from polarized target nucleons to unpolarized target nucleons.**




**Dilution factor =**

$$\frac{H_3(D_3)}{NH_3(ND_3)} = \frac{NH_3(ND_3) - \text{background}}{NH_3(ND_3)}$$