Quark-hadron duality in neutron spin structure

Patricia Solvignon

Argonne National Laboratory

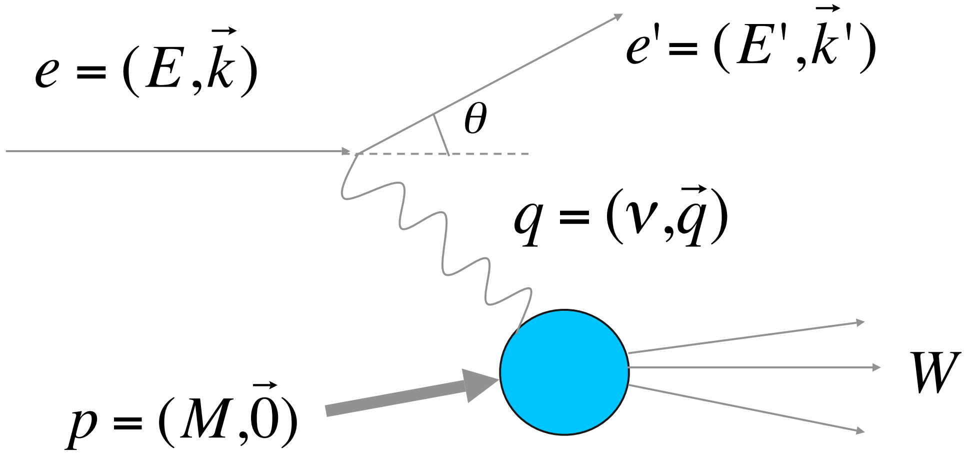
Jefferson Lab Seminar

November 14, 2008

Outline

- Brief introduction to inclusive scattering
- Review of Quark-Hadron duality:
    - Theoretical interpretations
    - Sample of related world data
- Hall A experiment E01-012
    - Experimental setup
    - Neutron (^{3}He) "Spin duality" results
- More results from E01-012
- Summary

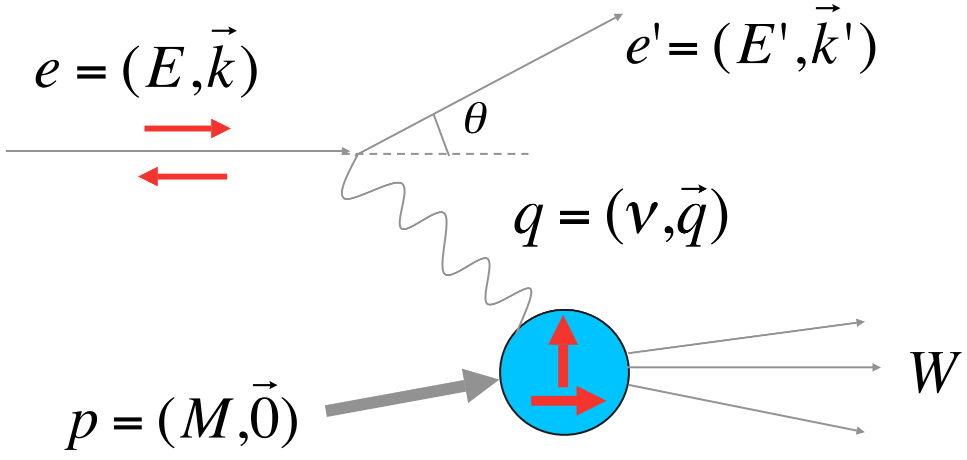
Inclusive electron scattering



Unpolarized case $\Big\{$

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}\boxed{F_2(x,Q^2)} + \frac{2}{M}\boxed{F_1(x,Q^2)}\tan^2\tfrac{\theta}{2}\right]$$

Inclusive electron scattering



Unpolarized case

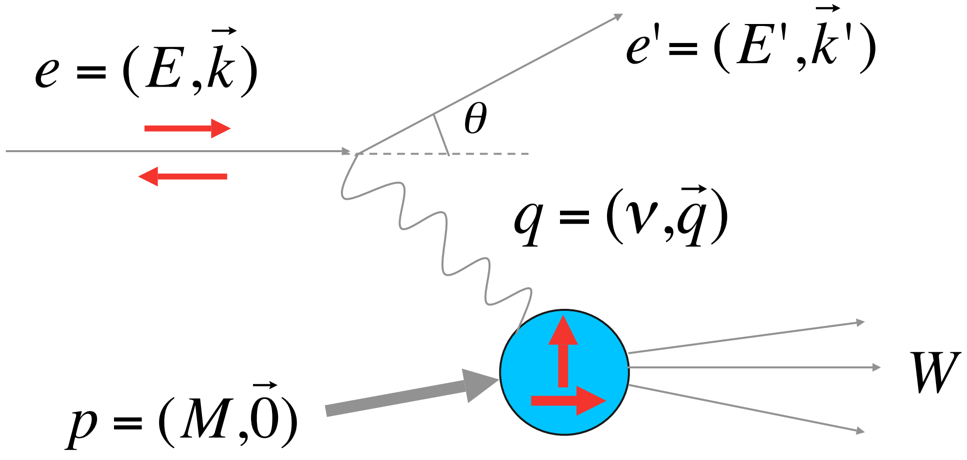
$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\tfrac{\theta}{2}\right]$$

Polarized case

$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{\nu E Q^2}\left[(E + E'\cos\theta)g_1(x,Q^2) - 2Mx g_2(x,Q^2)\right]$$

$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2 E'}{\nu E Q^2}\sin\theta\left[g_1(x,Q^2) + \frac{2ME}{\nu}g_2(x,Q^2)\right]$$

Inclusive electron scattering



4-momentum transfer squared

$$Q^2 = -q^2 = 4EE'\sin^2\tfrac{\theta}{2}$$

Invariant mass squared

$$W^2 = M^2 + 2M\nu - Q^2$$

Bjorken variable

$$x = \frac{Q^2}{2M\nu}$$

Unpolarized case

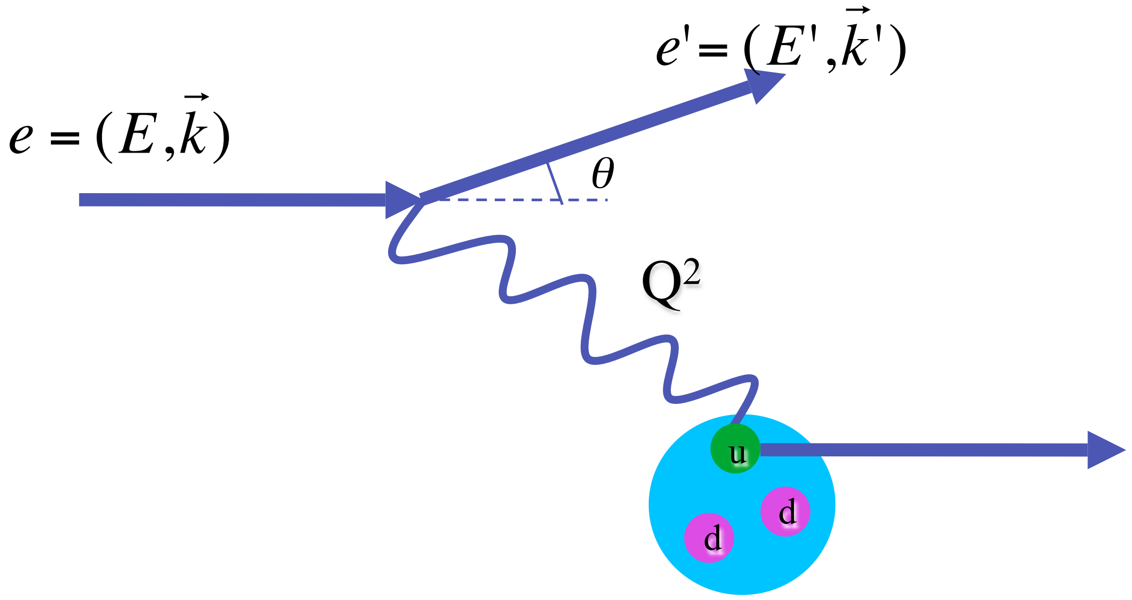
$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{Mott}\left[\frac{1}{\nu}\boxed{F_2(x,Q^2)} + \frac{2}{M}\boxed{F_1(x,Q^2)}\tan^2\tfrac{\theta}{2}\right]$$

Polarized case

$$\frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Uparrow}}{d\Omega dE'} = \frac{4\alpha^2E'}{\nu EQ^2}\left[(E+E'\cos\theta)\boxed{g_1(x,Q^2)} - 2Mx\boxed{g_2(x,Q^2)}\right]$$

$$\frac{d^2\sigma^{\uparrow\Rightarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\downarrow\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2E'}{\nu EQ^2}\sin\theta\left[\boxed{g_1(x,Q^2)} + \frac{2ME}{\nu}\boxed{g_2(x,Q^2)}\right]$$

Deep inelastic scattering



High Q^2 and W>2GeV: fine resolution → we see partons

→ scaling → asymptotic freedom of the strong interaction

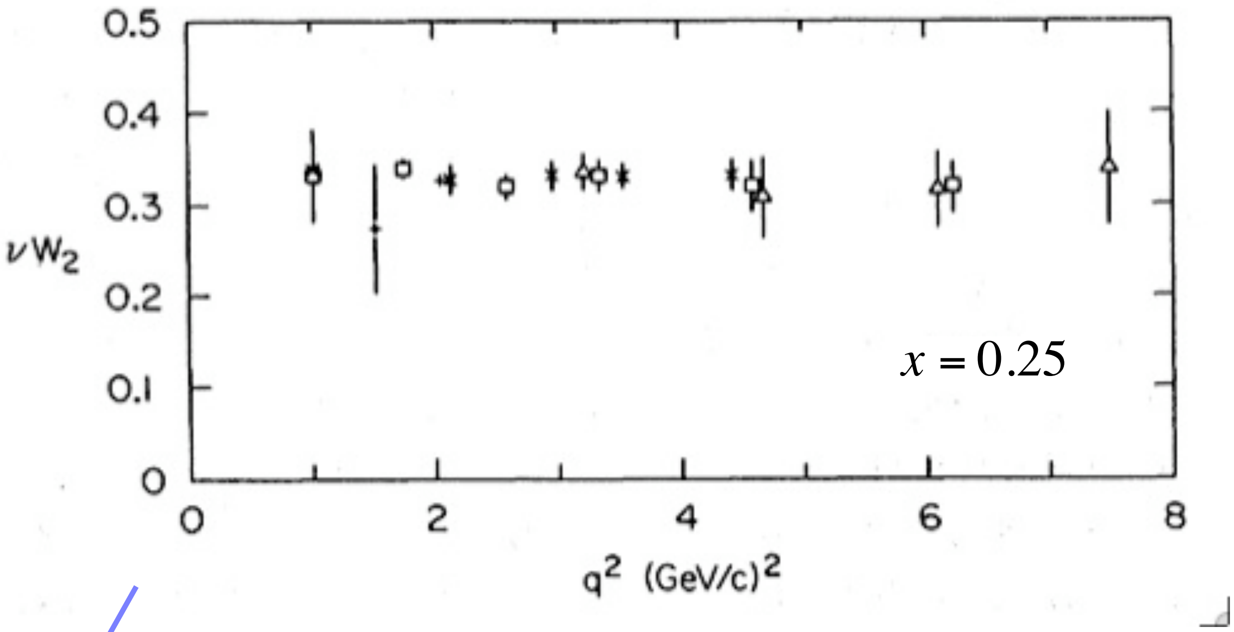
→ 2004 Nobel Prize

D. J. Gross, H. D. Politzer and F. Wilczek

Scaling of F_2

H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597

$F_2 =$



1990 Nobel Prize

J. I. Friedman, H. W. Kendall and R. E. Taylor

Structure functions in the parton model

In the infinite-momentum frame, partons are point-like non-interacting particles:

$$\sigma_{\text{Nucleon}} \approx \Sigma_i \, \sigma_i$$

$$F_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i^{\uparrow}(x) + q_i^{\downarrow}(x)]$$

$$g_1(x) = \frac{1}{2} \sum_i e_i^2 [q_i^{\uparrow}(x) - q_i^{\downarrow}(x)]$$

Structure functions in the parton model

In the infinite-momentum frame, partons are point-like non-interacting particles:

$\sigma_{\text{Nucleon}} \approx \Sigma_i \sigma_i$

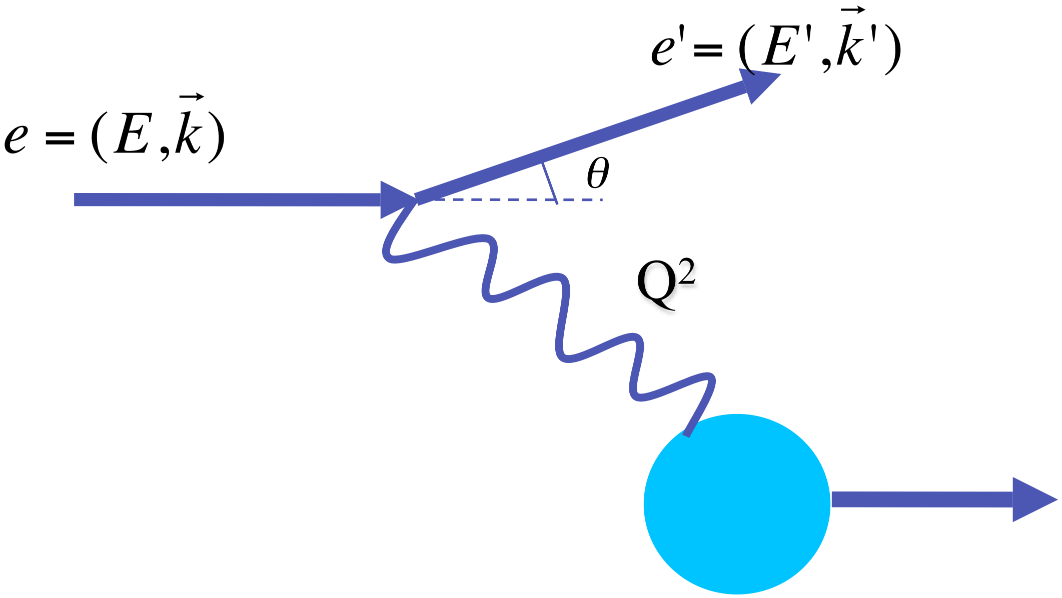
$$F_1(x) = \frac{1}{2}\sum_i e_i^2[q_i^{\uparrow}(x) + q_i^{\downarrow}(x)] = \frac{1}{2x}F_2(x)$$

Callan-Gross relation

$$g_1(x) = \frac{1}{2}\sum_i e_i^2[q_i^{\uparrow}(x) - q_i^{\downarrow}(x)]$$

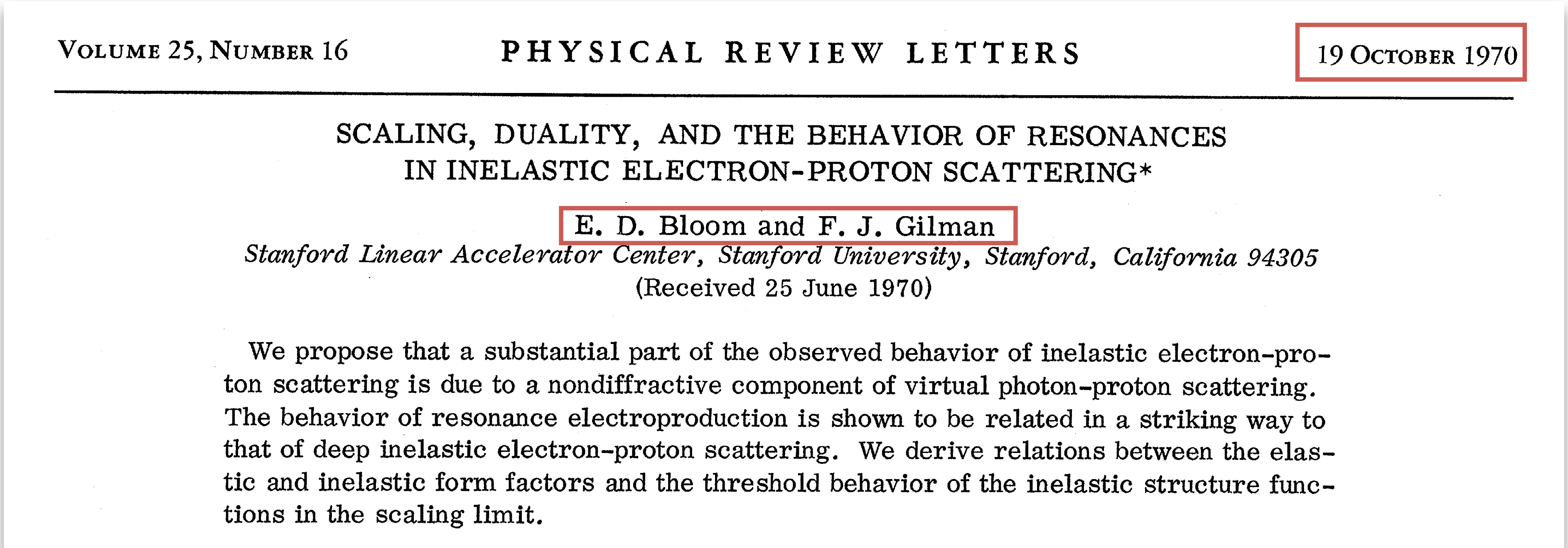
No simple partonic description for g_2

The resonance region



Low Q^2 and $W<2$ GeV : coarse resolution → we don't see individual partons.

The nucleon goes through different excited states: the resonances



VOLUME 25, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1970

SCALING, DUALITY, AND THE BEHAVIOR OF RESONANCES IN INELASTIC ELECTRON-PROTON SCATTERING*

E. D. Bloom and F. J. Gilman
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 25 June 1970)

We propose that a substantial part of the observed behavior of inelastic electron-proton scattering is due to a nondiffractive component of virtual photon-proton scattering. The behavior of resonance electroproduction is shown to be related in a striking way to that of deep inelastic electron-proton scattering. We derive relations between the elastic and inelastic form factors and the threshold behavior of the inelastic structure functions in the scaling limit.

VOLUME 25, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1970

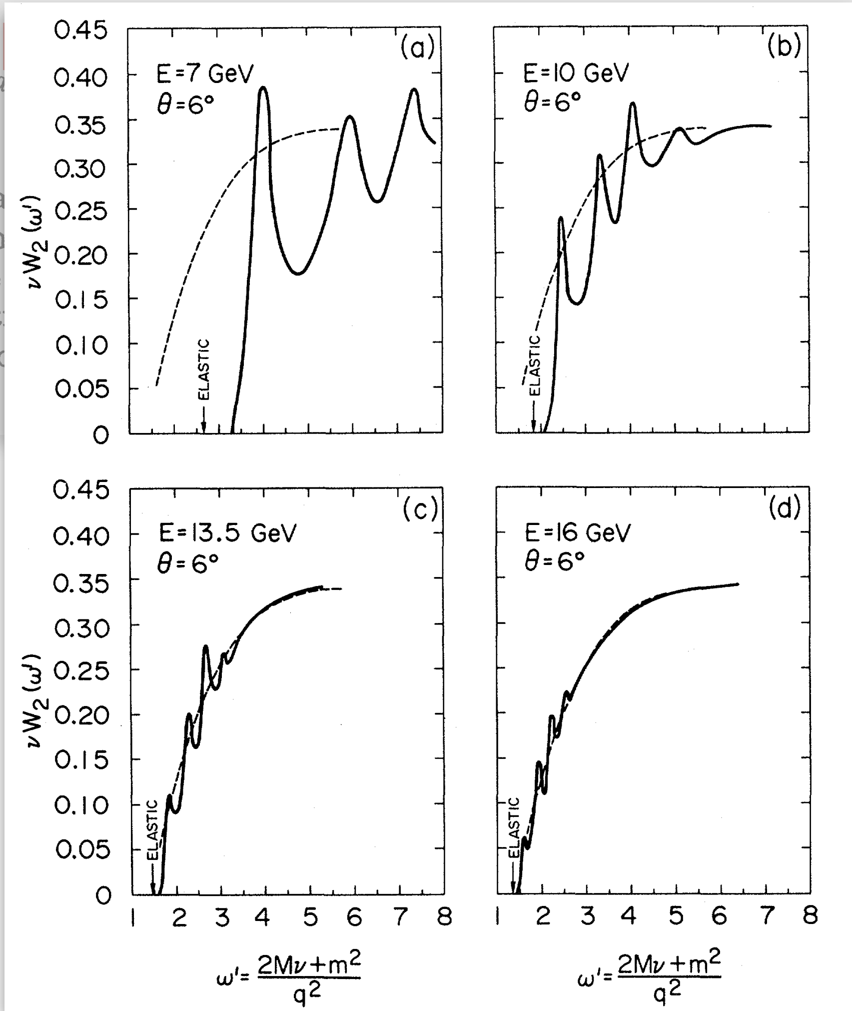
SCALING, DUALITY, AND THE BEHAVIOR OF RESONANCES
IN INELASTIC ELECTRON-PROTON SCATTERING*

Stanford Linear Accelera

4305

We propose that a substa
ton scattering is due to a n
The behavior of resonance
that of deep inelastic elect
tic and inelastic form facto
tions in the scaling limit.

-pro-
ing.
ay to
elas-
func-

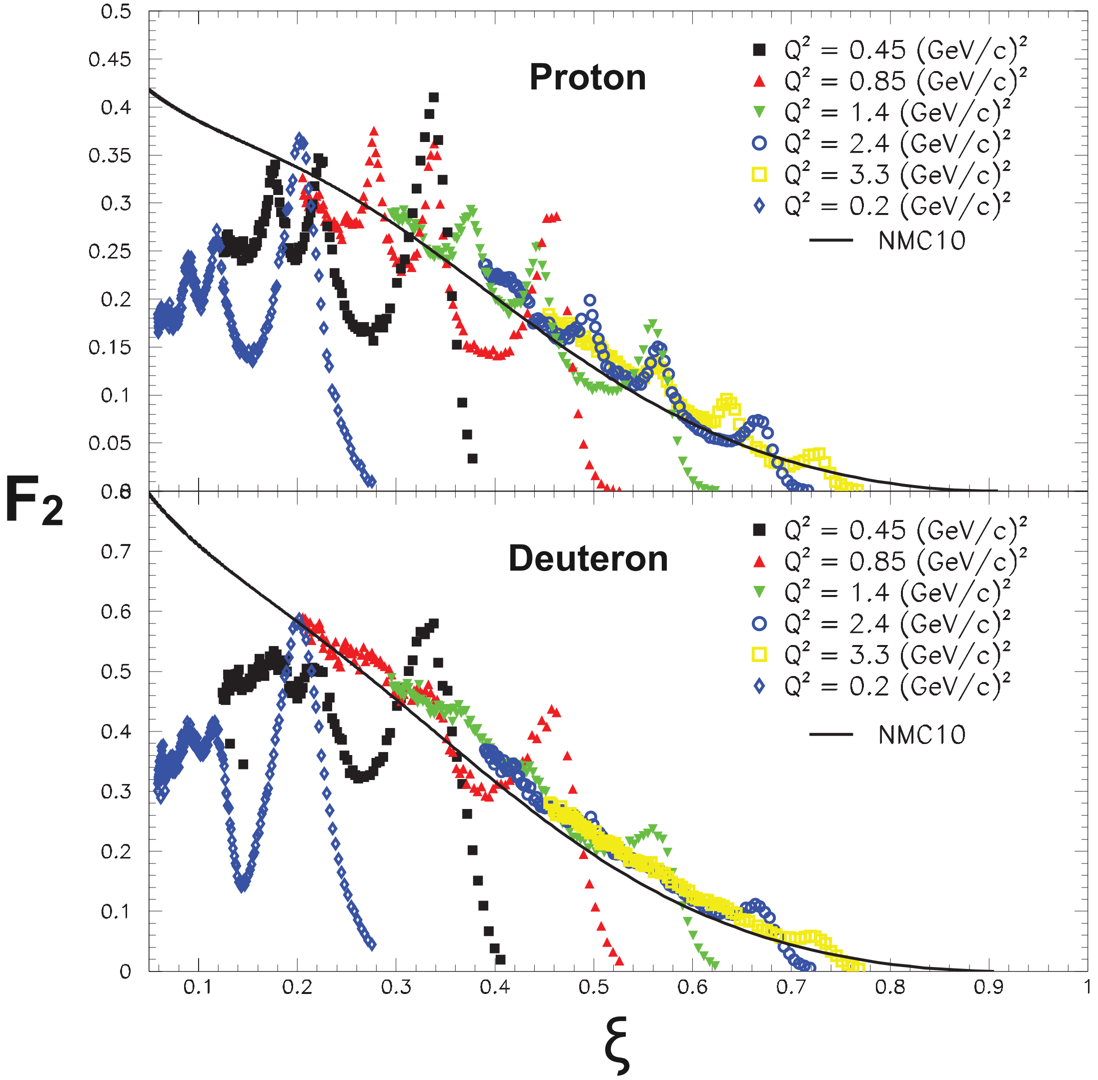


Scaling curve seen at high Q^2 is an accurate average over the resonance region at lower Q^2

Quark-hadron duality

I. Niculescu et al., PRL 85 (2000) 1182

High precision Hall C data allowed the confirmation global duality and the observation of local duality for F_2



What about spin-dependent structure functions ?

Theoretical interpretations

Lattice QCD

χPT Quark models OPE pQCD

$Q^2 = 0$ $Q^2 = \infty$

pQCD (Carlson, Mukhopadhyay):

➡ Q^2 dependence of transition form factors vs. x dependence of parton distribution functions

In resonance

$$g_1 = \frac{M_N^2}{\pi M_R \Gamma_R}\frac{g_+^2}{Q^6} \approx \frac{M_N^2}{\pi M_R \Gamma_R}\frac{g_+^2}{\left(M_R^2 - M_N^2\right)^3}\left(1-x\right)^3$$

In DIS

$$\lim_{x\to 1} g_1(x) \propto \left(1-x\right)^3$$

Theoretical interpretations

Operator Product Expansion (Rujula, Georgi, Politzer):

➥ Higher twist corrections are small or cancel.

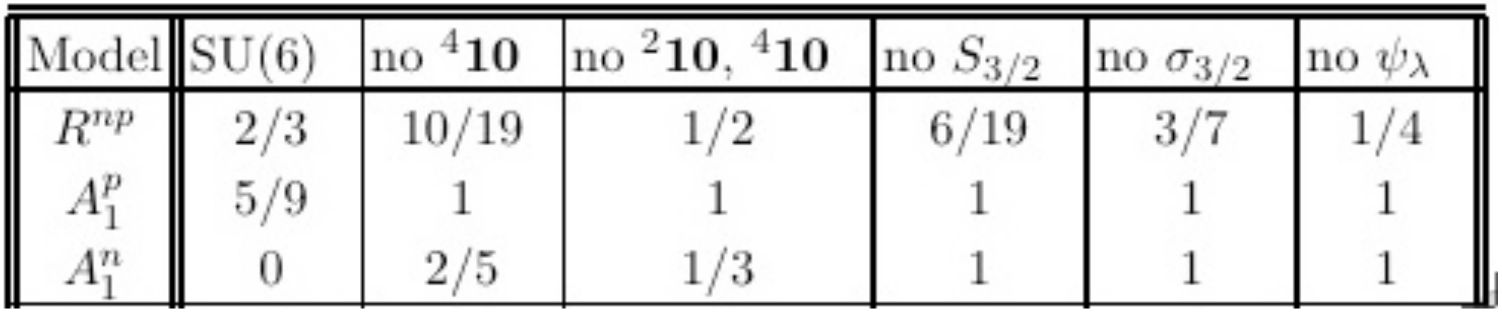
$$\Gamma_1(Q^2) = \underbrace{\mu_2(Q^2)}_{\text{Leading twist}} + \underbrace{\frac{\mu_4(Q^2)}{Q^2} + \frac{\mu_6(Q^2)}{Q^4} + O\left(\frac{1}{Q^6}\right)}_{\text{Higher twists}}$$

Theoretical interpretations

SU(6) symmetry breaking in the quark model (Close, Isgur and Melnitchouk):

➥ investigate several scenarios with suppression of spin-3/2, helicity-3/2 or symmetric wave function

$$|N\rangle = \cos\theta_w |\psi_\rho\rangle + \sin\theta_w |\psi_\lambda\rangle$$



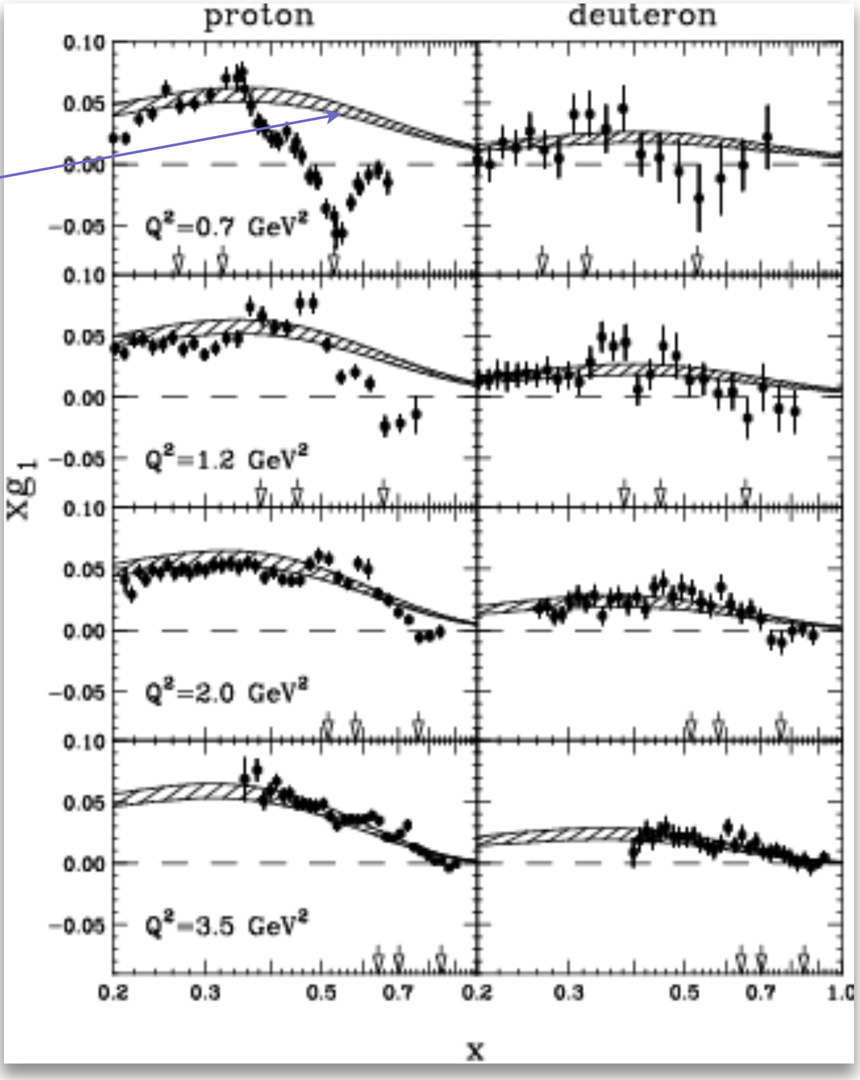
Model	SU(6)	no $^4\mathbf{10}$	no $^2\mathbf{10}$, $^4\mathbf{10}$	no $S_{3/2}$	no $\sigma_{3/2}$	no ψ_λ
R^{np}	2/3	10/19	1/2	6/19	3/7	1/4
A_1^p	5/9	1	1	1	1	1
A_1^n	0	2/5	1/3	1	1	1

Existing data on "spin duality"

P. Bosted et al, Phys. Rev. C 75 (2007) 035203

Hall B

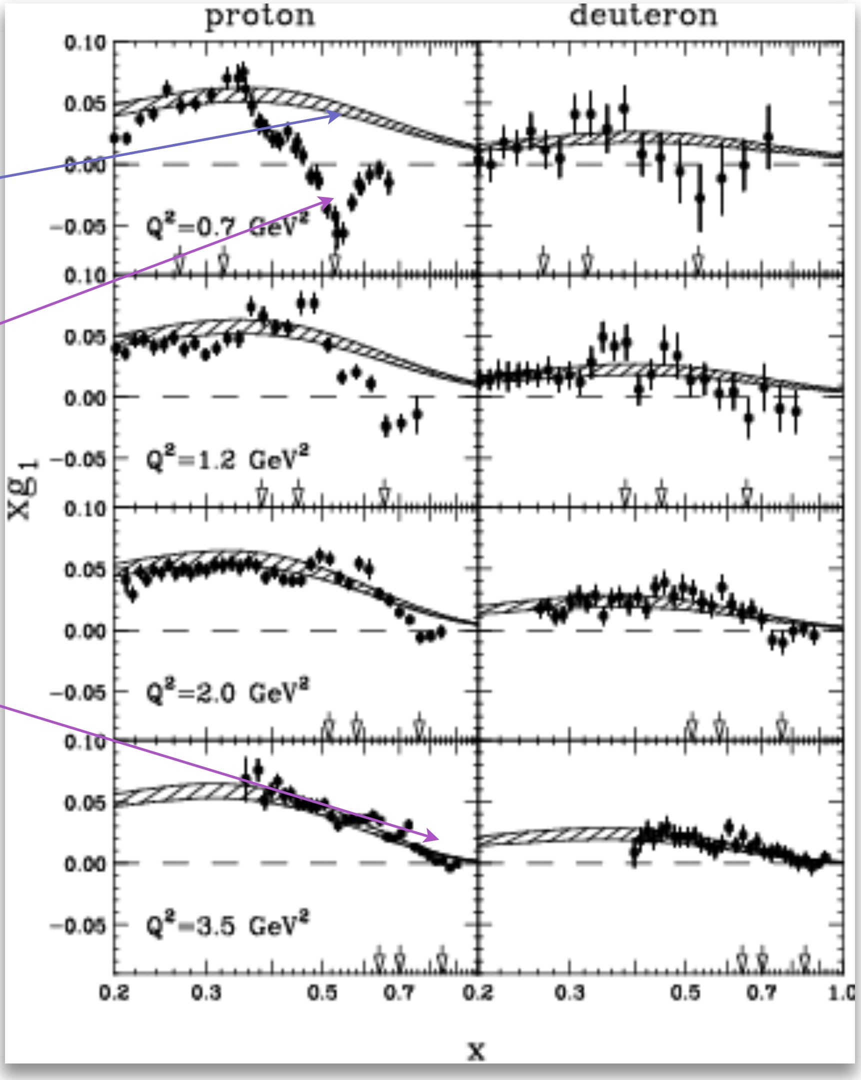
$g_1^p(DIS) > 0$



Existing data on "spin duality"

P. Bosted et al, Phys. Rev. C 75 (2007) 035203

Hall B



g_1^p(DIS) > 0

but $g_1^p(\Delta) < 0$ even

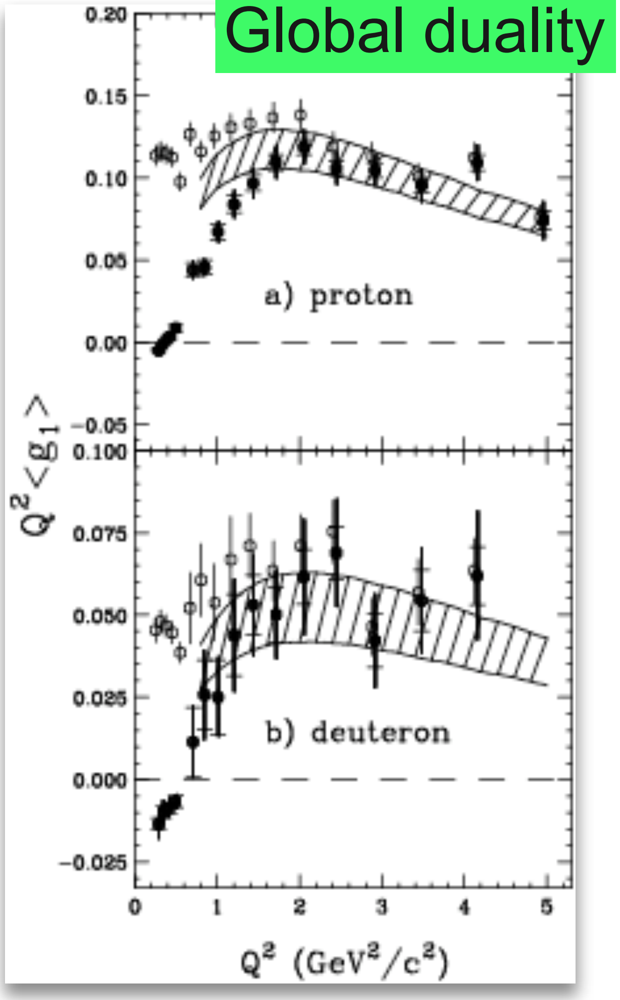
at Q^2 as high as 3.5 GeV^2

Duality for g_1^p ?

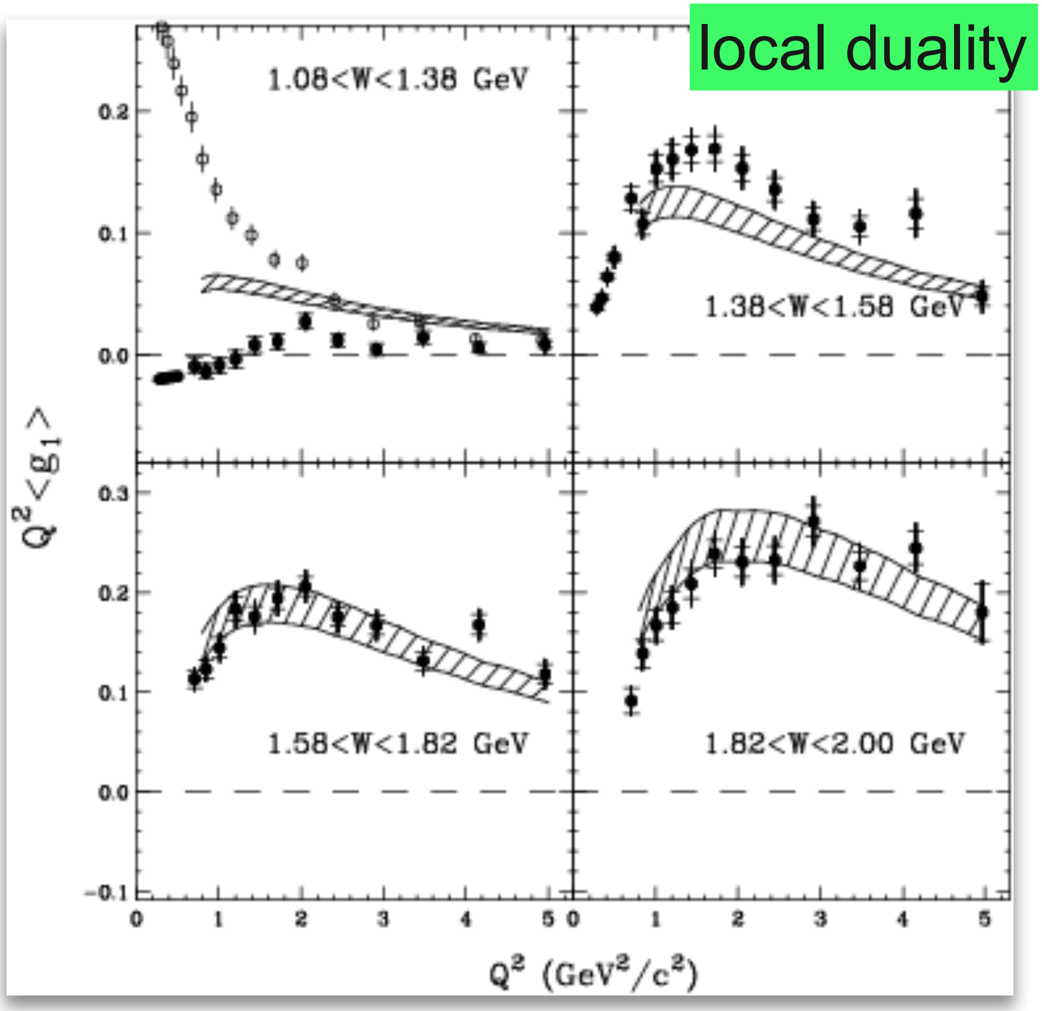
Existing data on “spin duality”

P. Bosted et al, Phys. Rev. C 75 (2007) 035203

Hall B



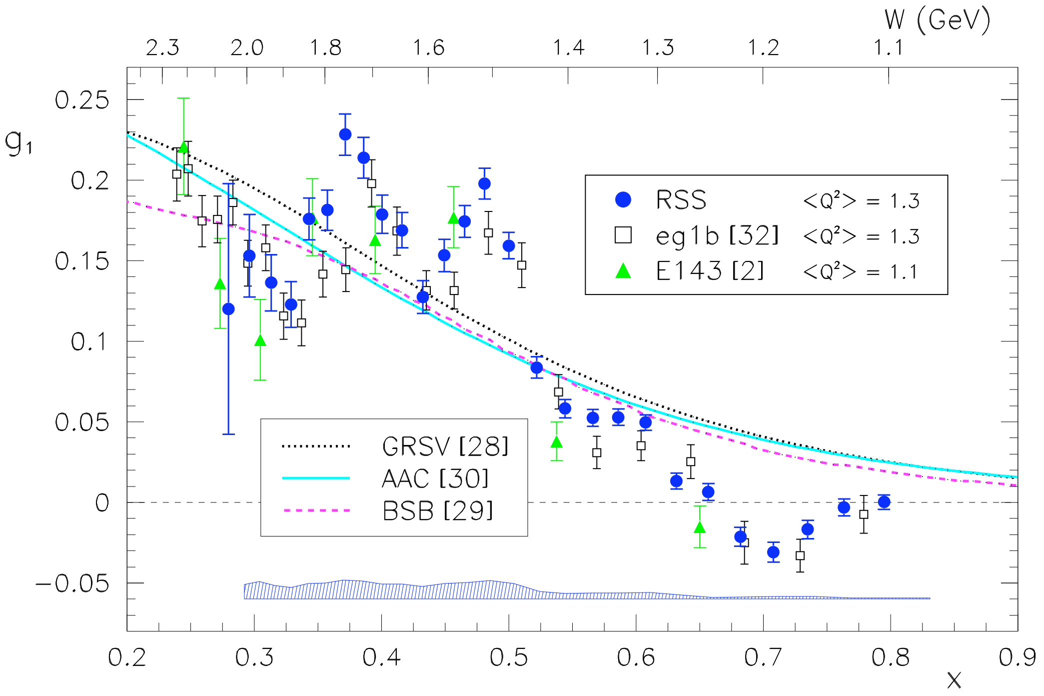
Global duality



local duality

Existing data on “spin duality”

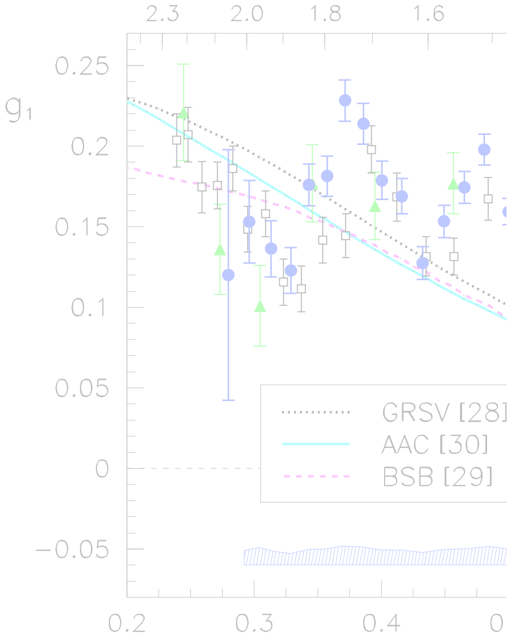
Hall C



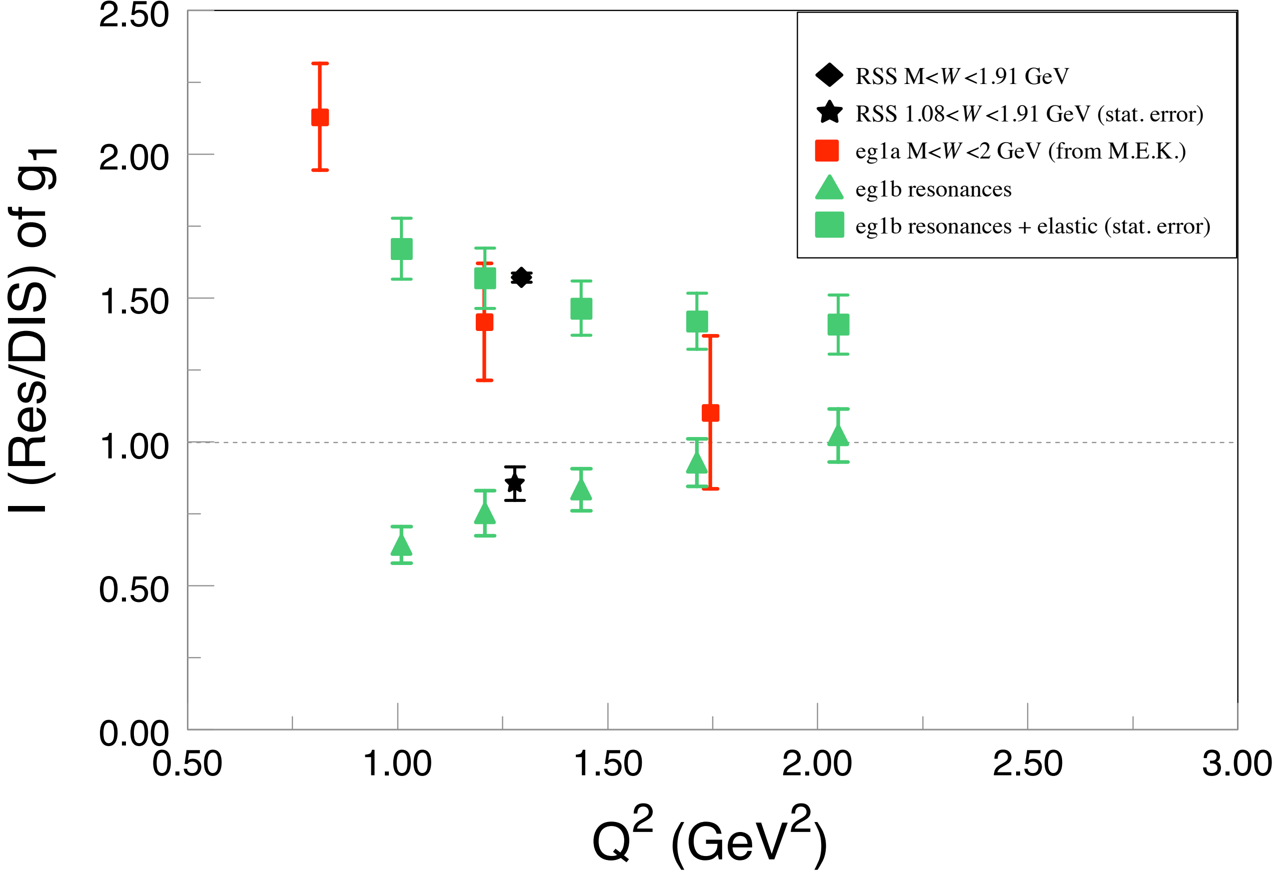
F. Wesselmann et al, Phys. Rev. Lett. 98 (2007) 132003

Existing data on "spin duality"

Hall C



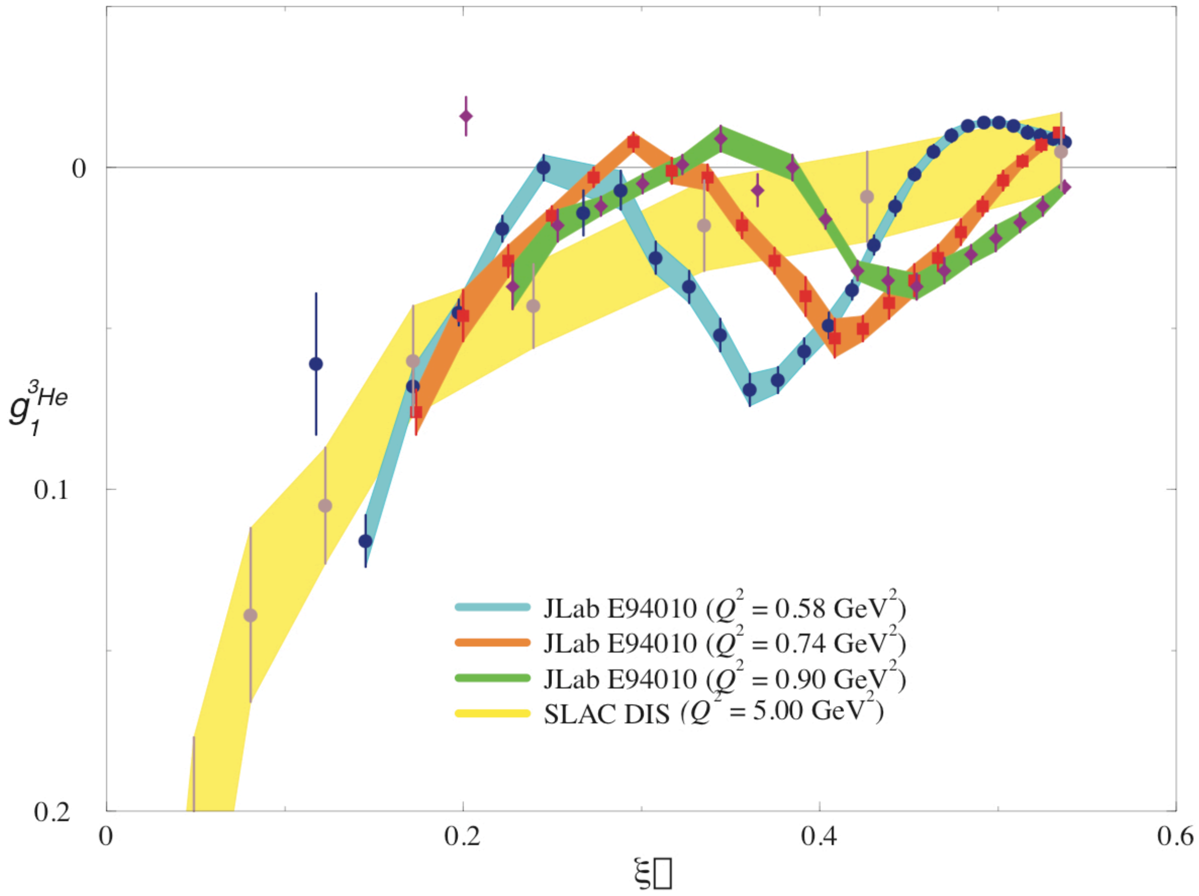
Global duality



F. Wesselmann et al, Phys. Rev. Lett. 98 (2007) 132003

Existing data on "spin duality"

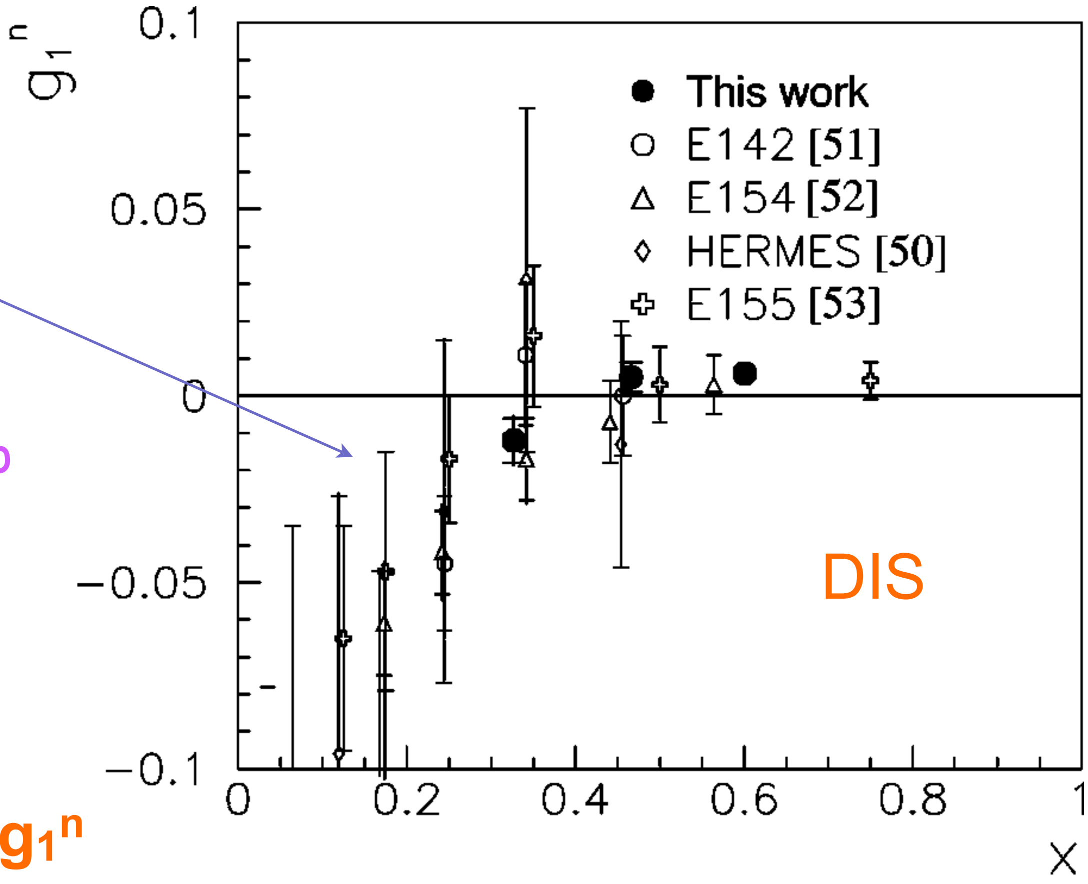
Indication of duality for g_1^{3He} from **Hall A** (E94-010)



Neutron spin duality ?

X. Zheng et al, Phys. Rev. C 70 (2004) 065207

g_1^n(DIS) < 0



and g_1^n(Δ) is negative up to the its FF fall off

Onset of duality for g_1^n is expected "sooner"

Quark-hadron duality: accidental or universal phenomenom ?

In order to improve our understanding of duality, we need to explore duality in:

polarized SF vs. unpolarized SF

and

proton vs. neutron

a dedicated experiment to study spin duality on the neutron was necessary

The experiment 01-012

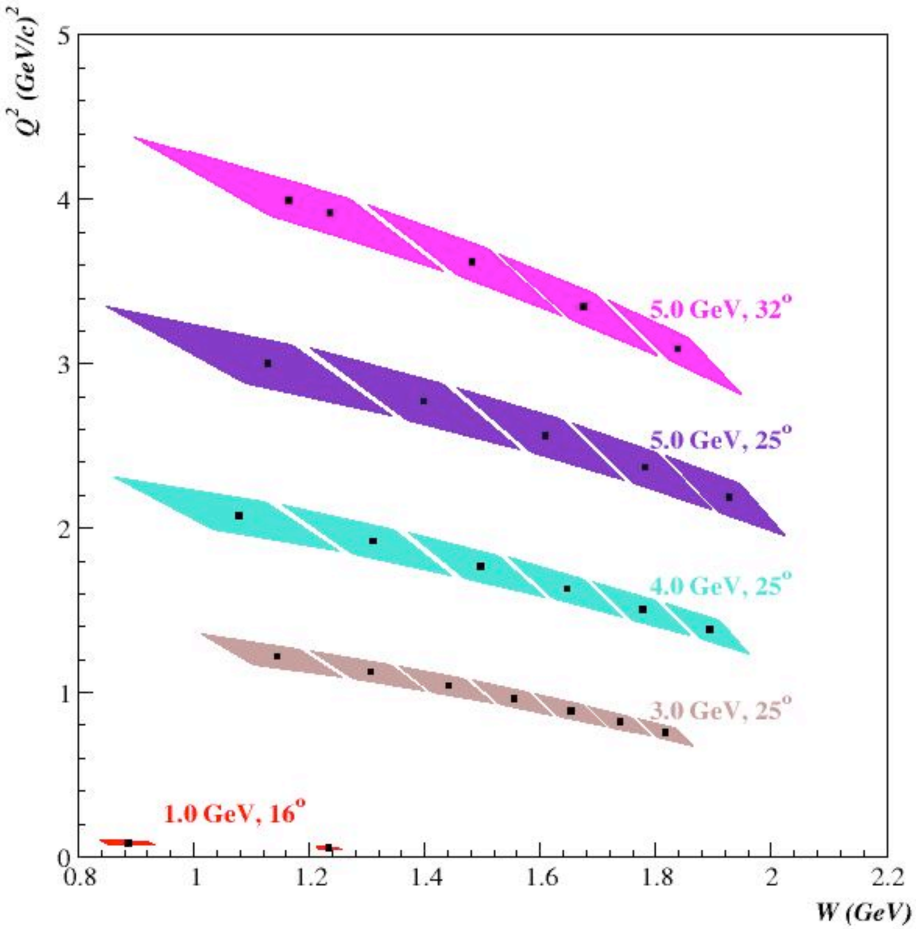
- Ran in Jan.-Feb. 2003

- Inclusive experiment: $^3\vec{He}(\vec{e},e')X$
    - Polarized electron beam:

      70 < P_{beam} < 85%
    - Hall A in standard equipment
    - Pol. ^{3}He target (para and perp):

      $\langle P_{targ} \rangle = 37\%$

- Measured polarized cross section differences and form g_1 and g_2 for ^{3}He

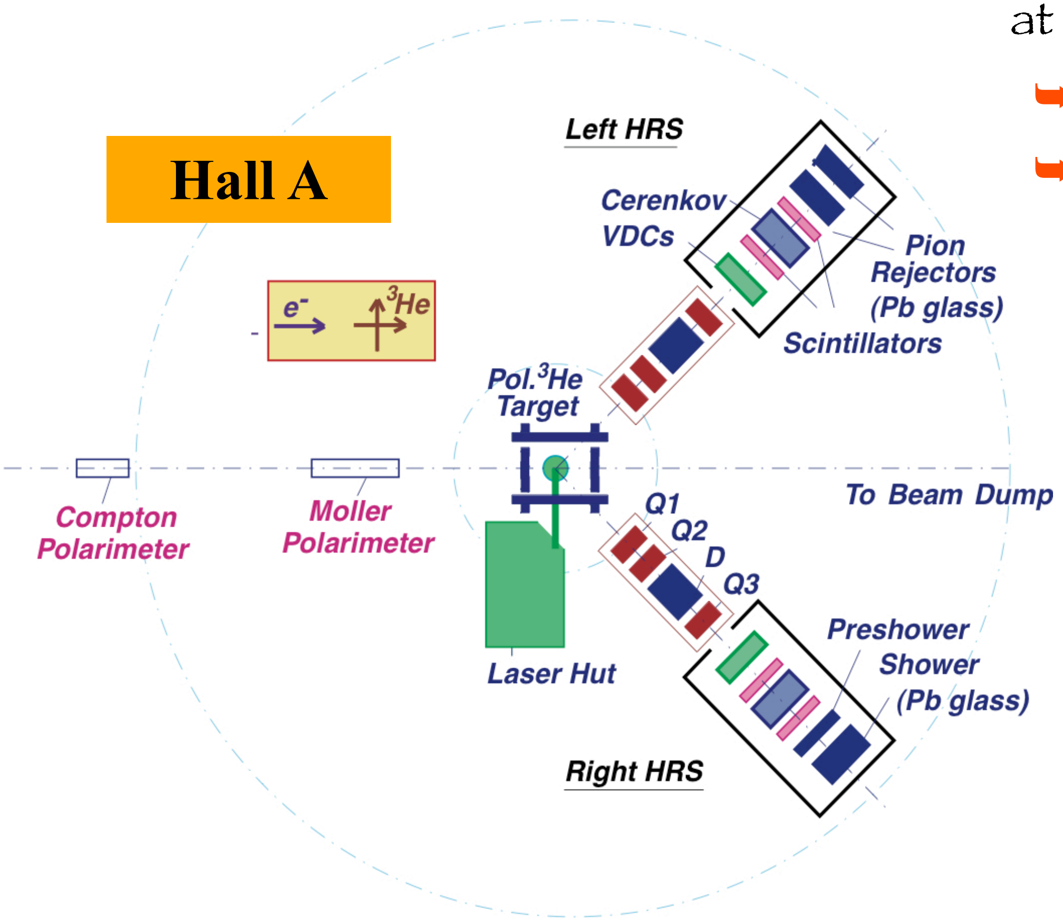


➥ Test of spin duality on the neutron (^{3}He)

The E01-012 Collaboration

K. Aniol, T. Averett, W. Boeglin, A. Camsonne, G.D. Cates,
G. Chang, J.-P. Chen, Seonho Choi, E. Chudakov, B. Craver,
F. Cusanno, A. Deur, D. Dutta, R. Ent, R. Feuerbach,
S. Frullani, H. Gao, F. Garibaldi, R. Gilman, C. Glashausser,
O. Hansen, D. Higinbotham, H. Ibrahim, X. Jiang, M. Jones,
A. Kelleher, J. Kelly, C. Keppel, W. Kim, W. Korsch,K. Kramer,
G. Kumbartzki, J. LeRose, R. Lindgren, N. Liyanage, B. Ma,
D. Margaziotis, P. Markowitz, K. McCormick, Z.-E. Meziani,
R. Michaels, B. Moffit, P. Monaghan, C. Munoz Camacho,
K. Paschke, B. Reitz, A. Saha, R. Sheyor, J. Singh, K. Slifer,
P. Solvignon, V. Sulkosky, A. Tobias, G. Urciuoli, K. Wang,
K. Wijesooriya, B. Wojtsekhowski, S. Woo, J.-C. Yang,
X. Zheng, L. Zhu

Experimental setup

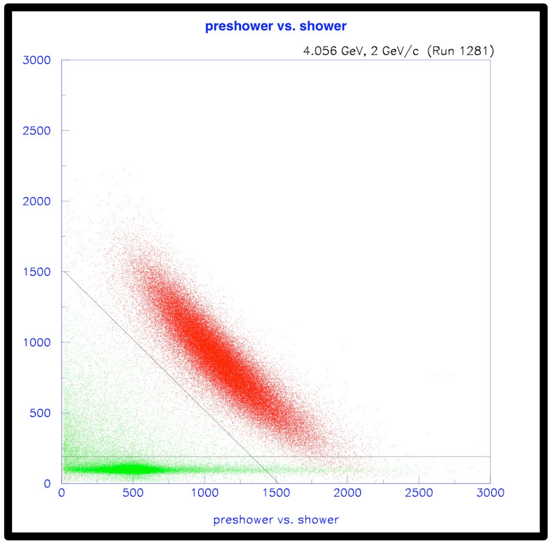


Both HRS in symmetric configuration at 25° and 32°

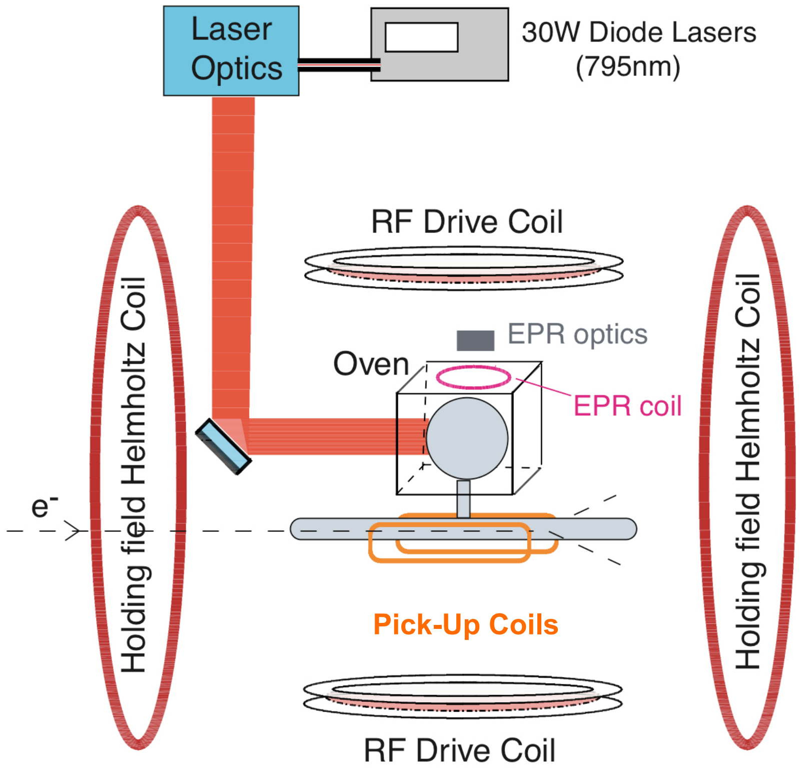
- ➡ Double the statistics
- ➡ Control the systematics

Particle ID = Cerenkov + EM calorimeter

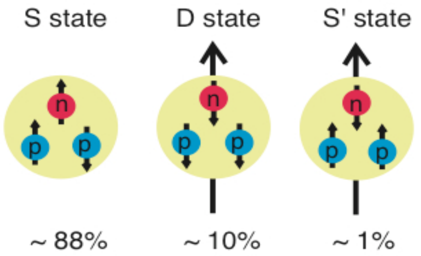
- ➡ π/e reduced by 10^4



The polarized ^{3}He target



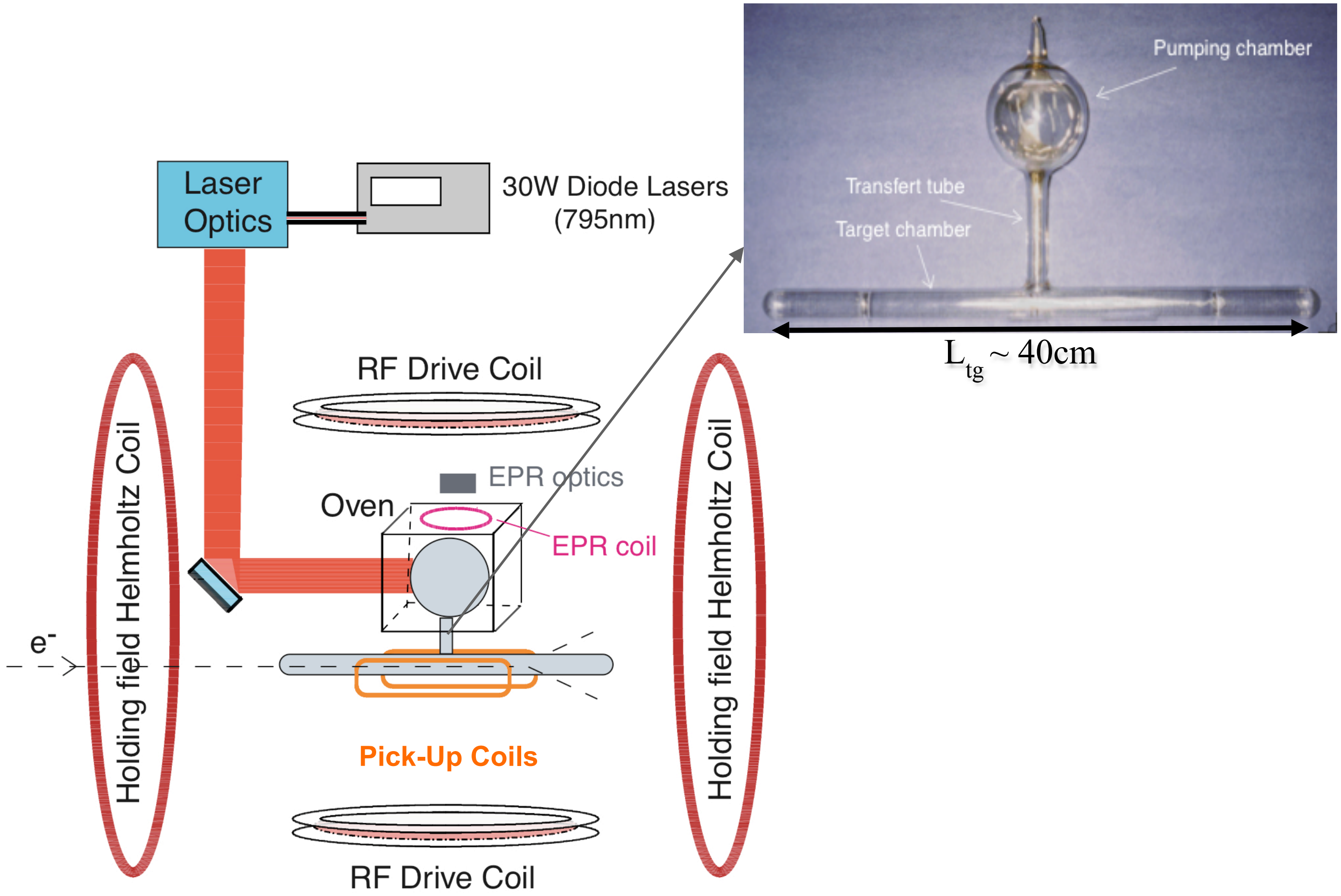
^{3}He as neutron target



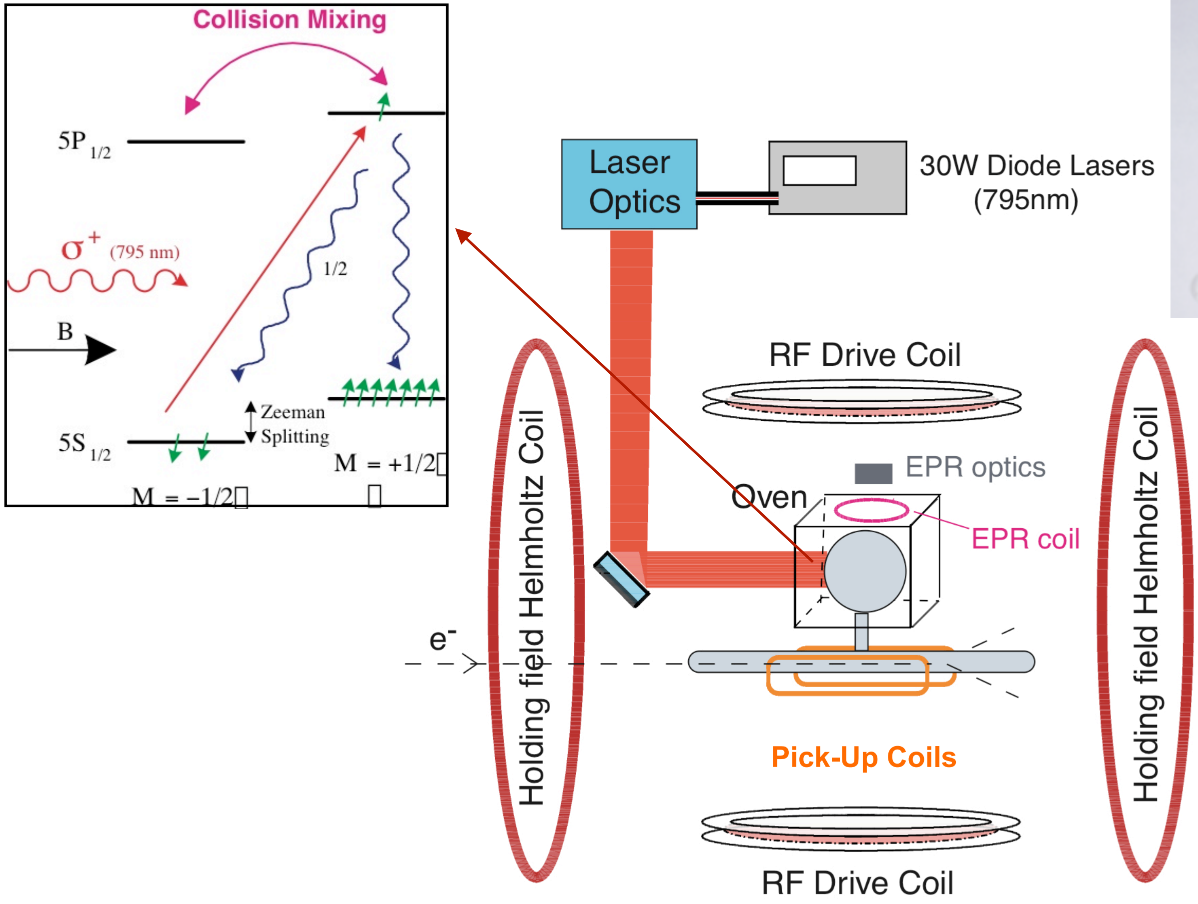
$P_n = 86\%$ and $P_p = -2.8\%$

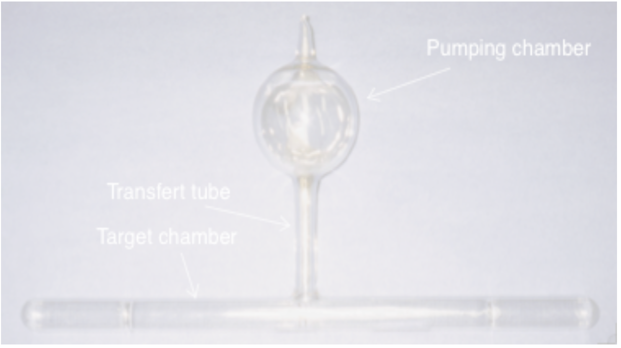
The polarized ^{3}He target

Pressure ~ 14 atm under running conditions
High luminosity: 10^{36} $s^{-1}cm^{-2}$

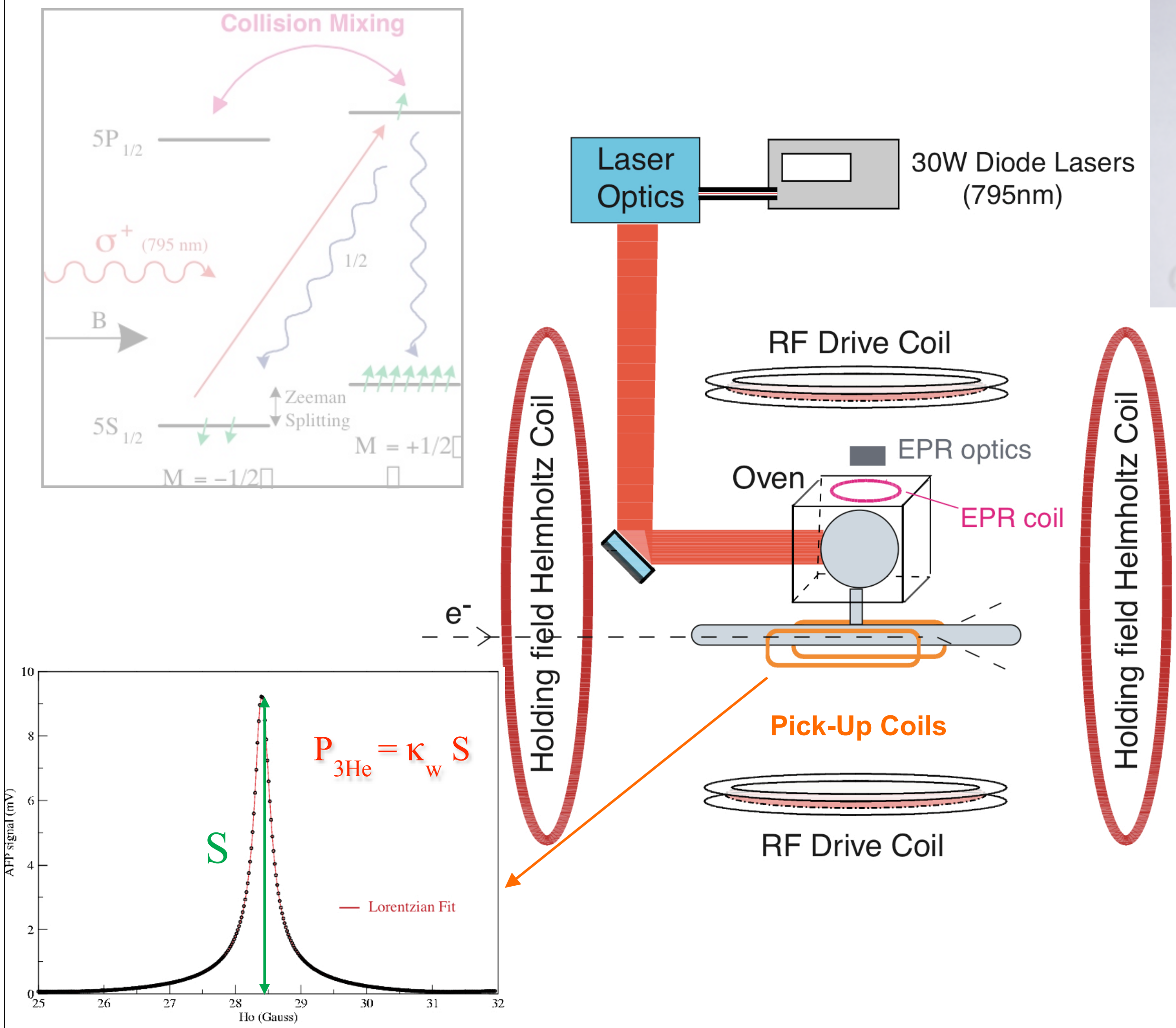


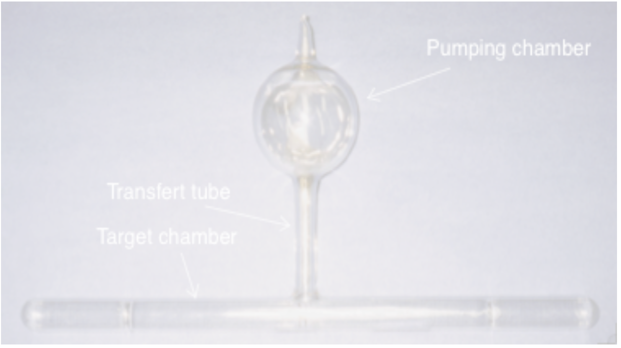
The polarized ^{3}He target



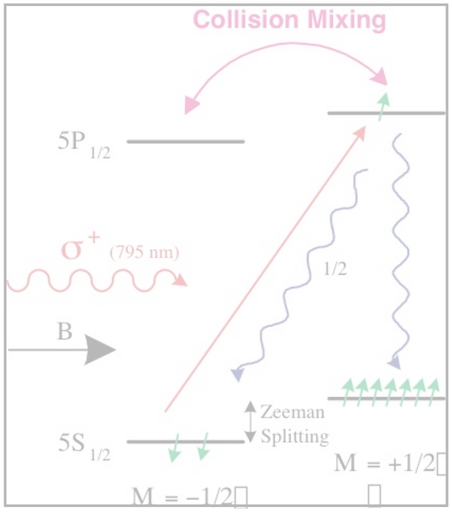


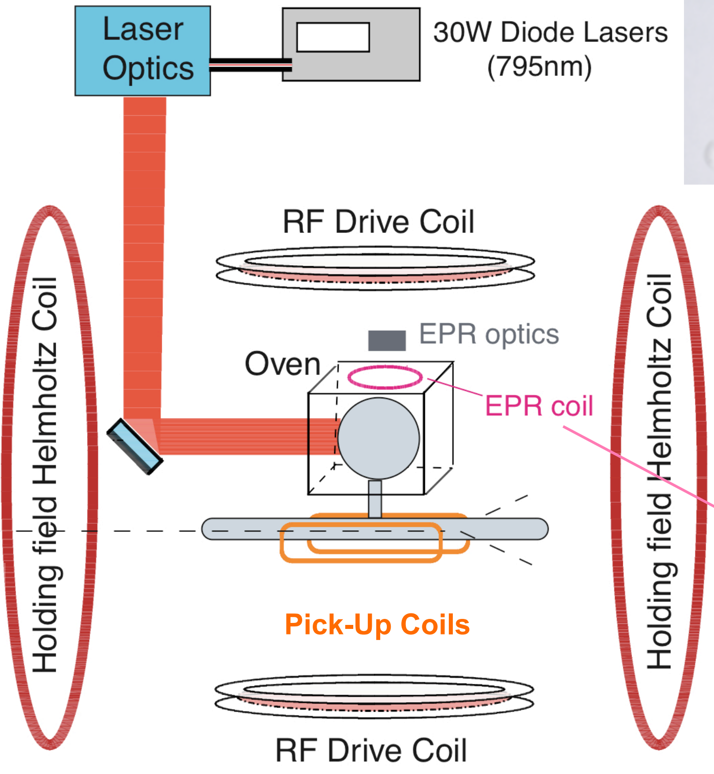
The polarized ^{3}He target

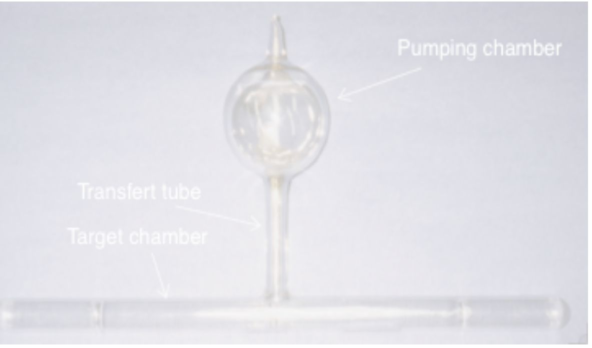


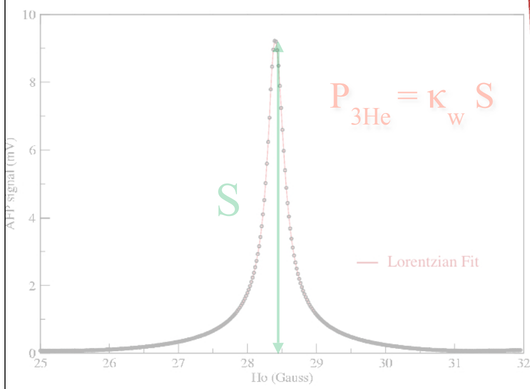


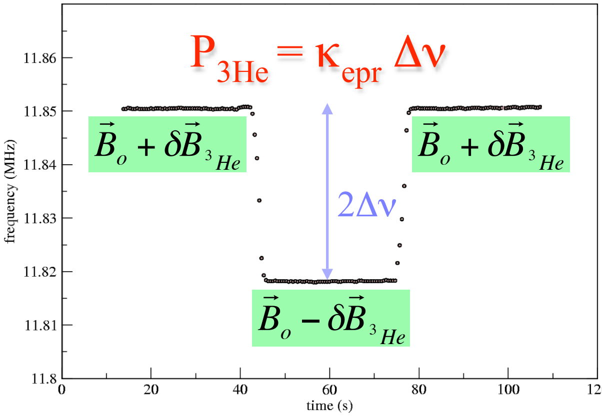
The polarized ³He target





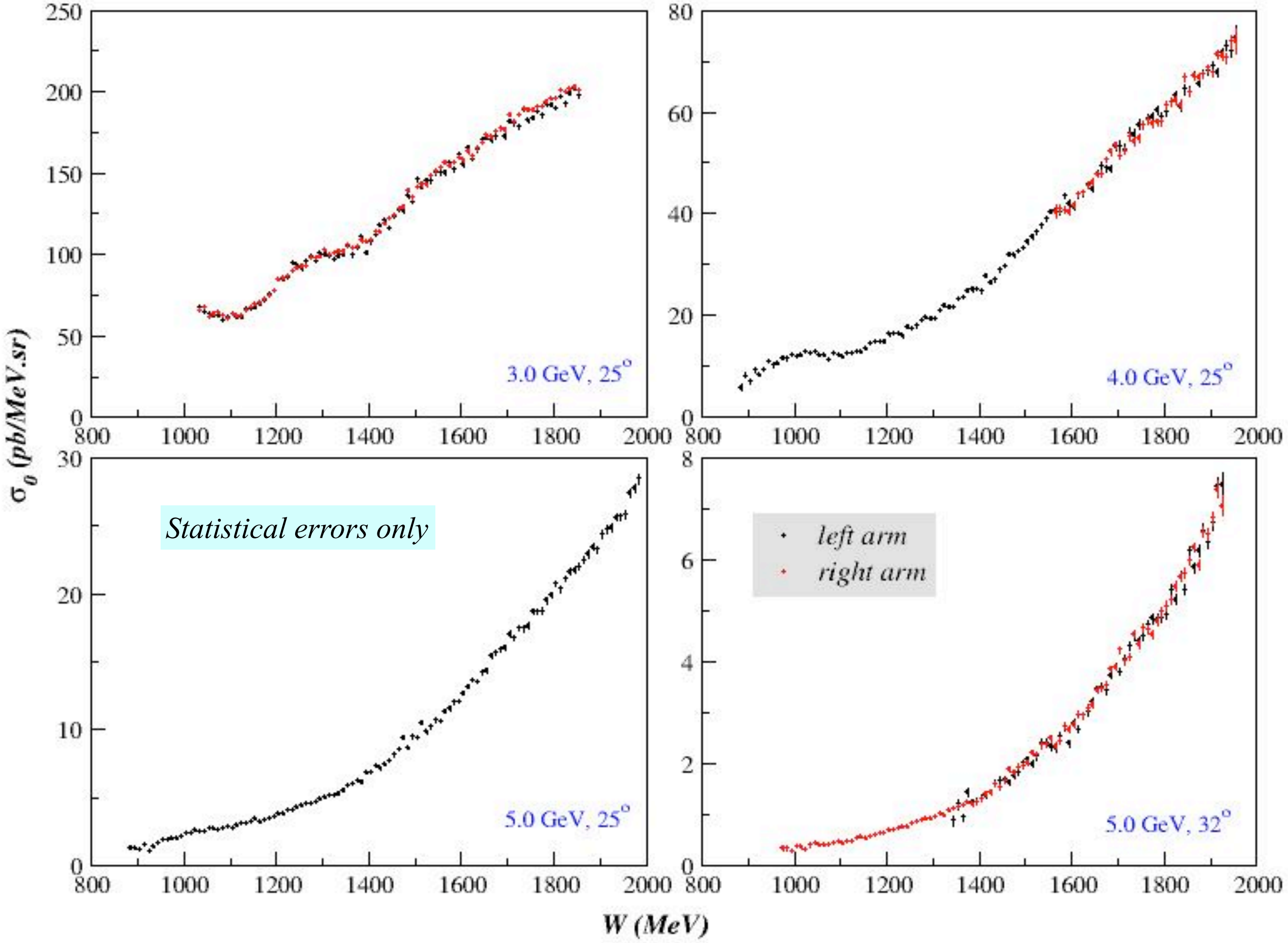




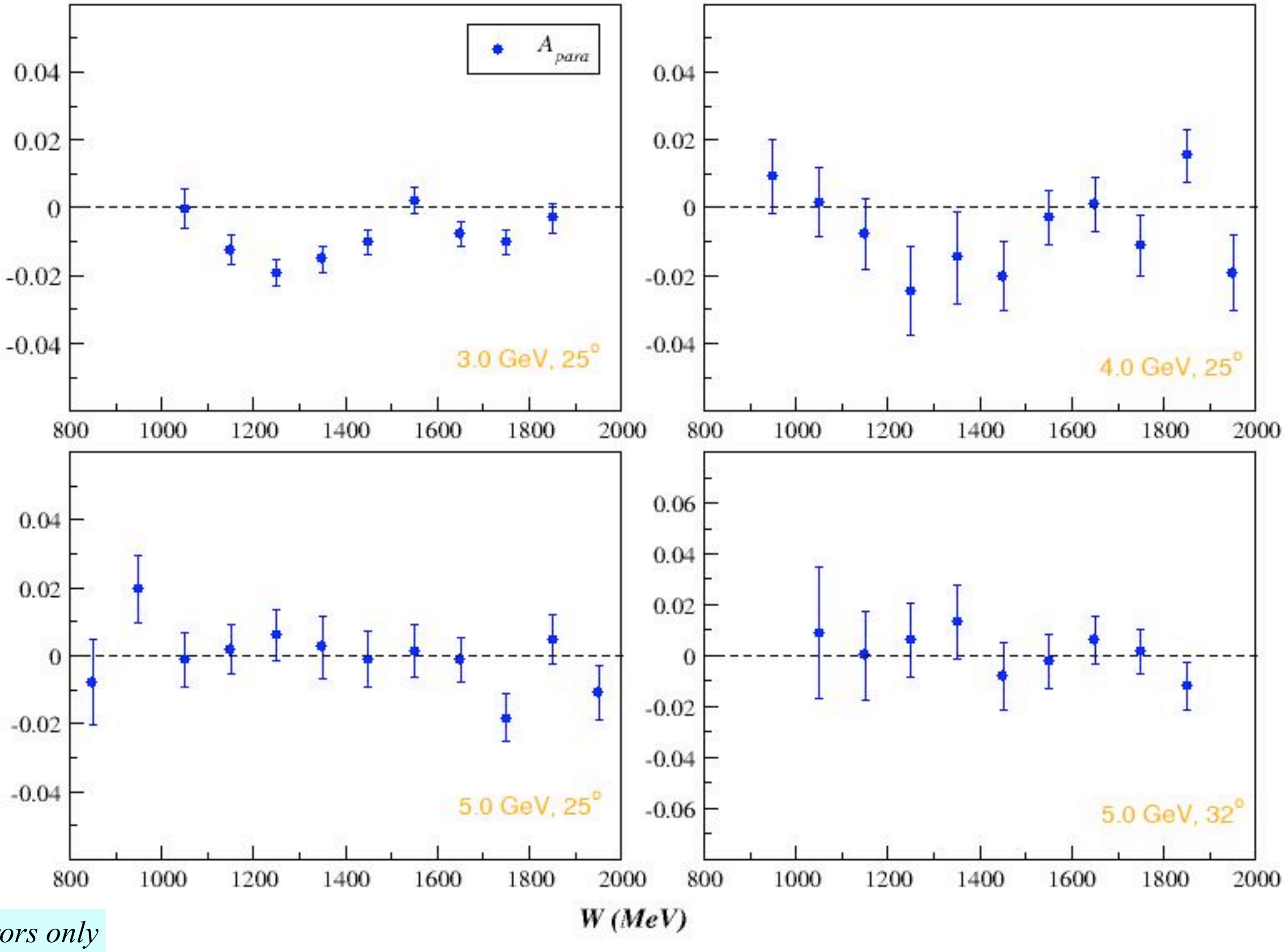


Unpolarized cross sections

Agreement between both HRS better than 2%

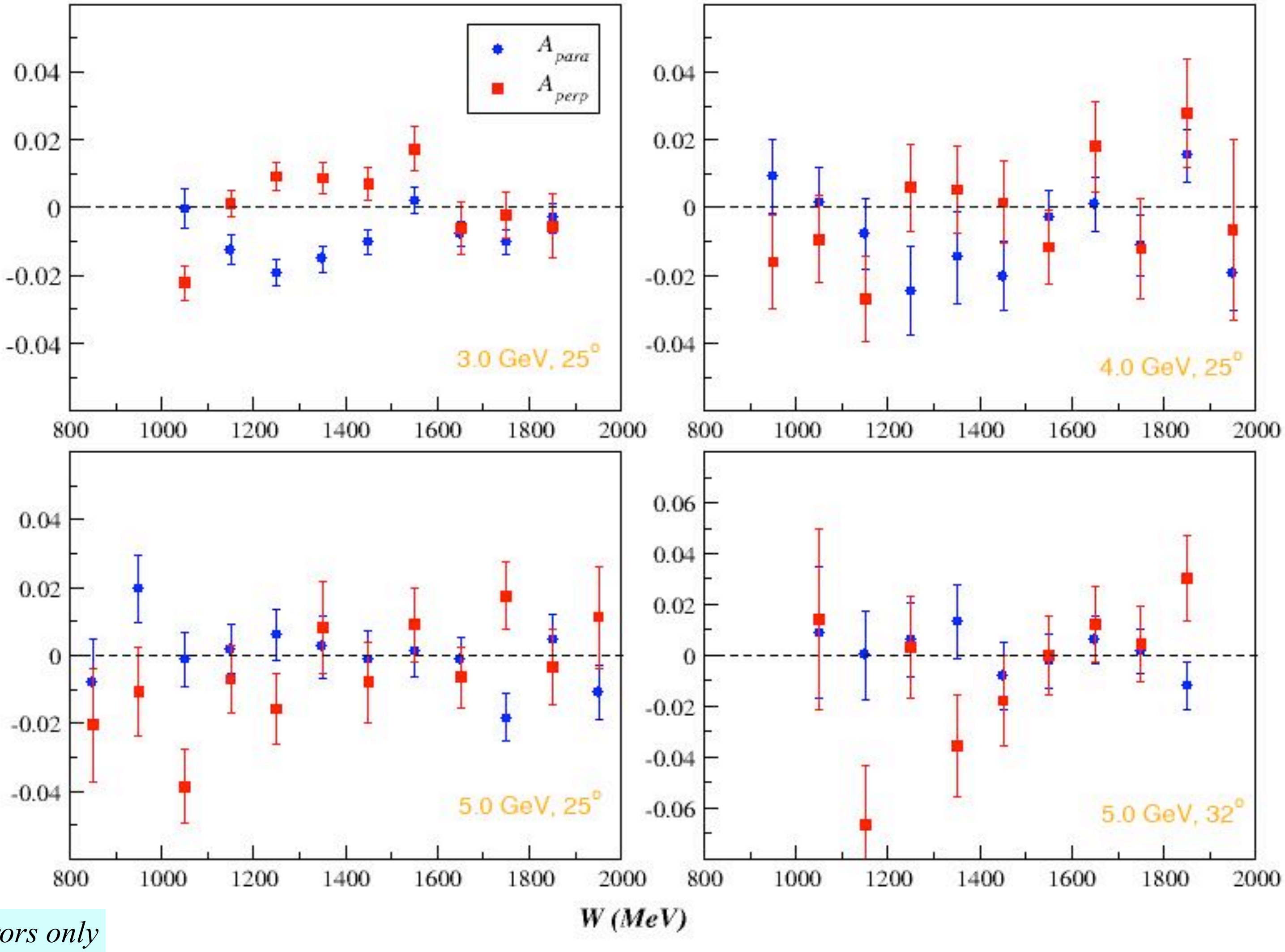


Asymmetries



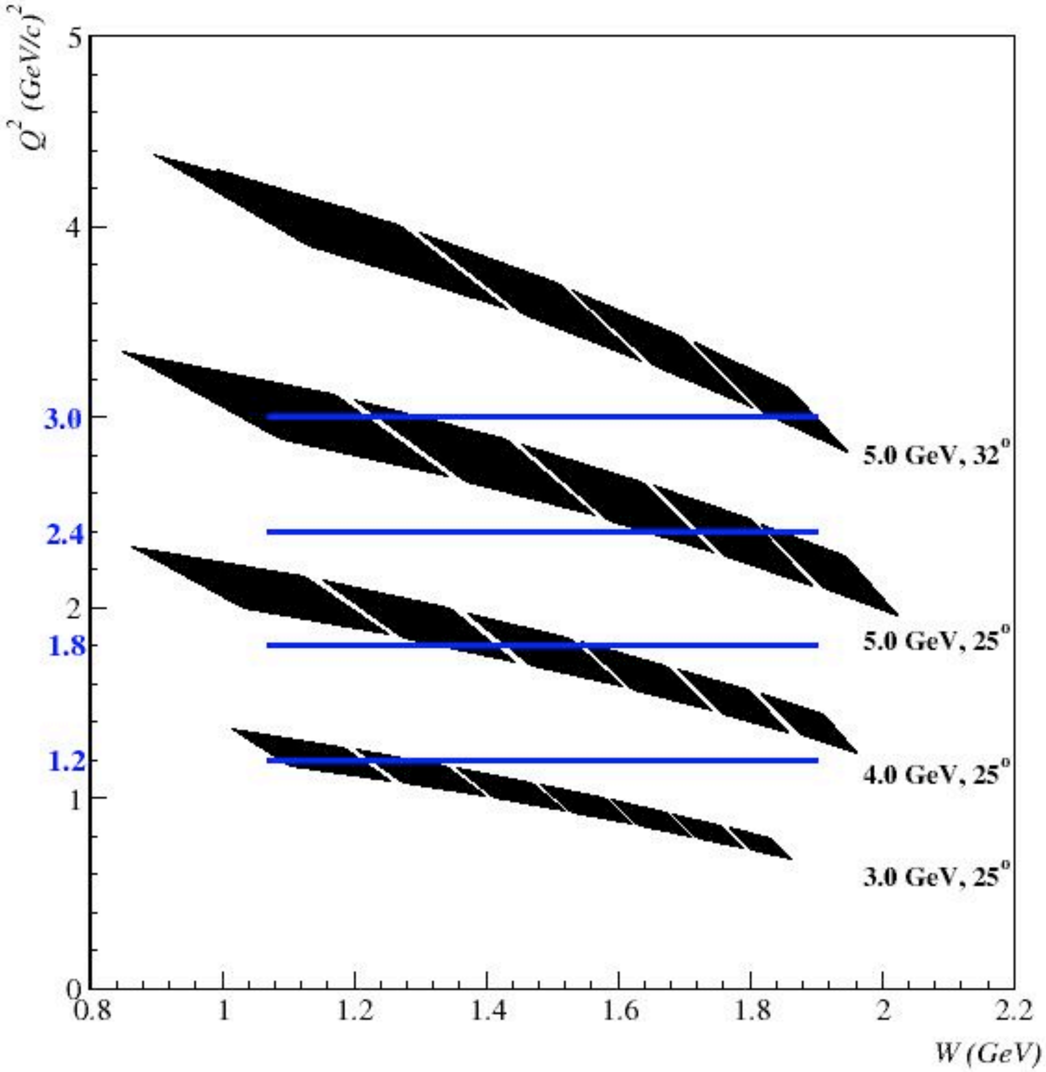
Statistical errors only

Asymmetries



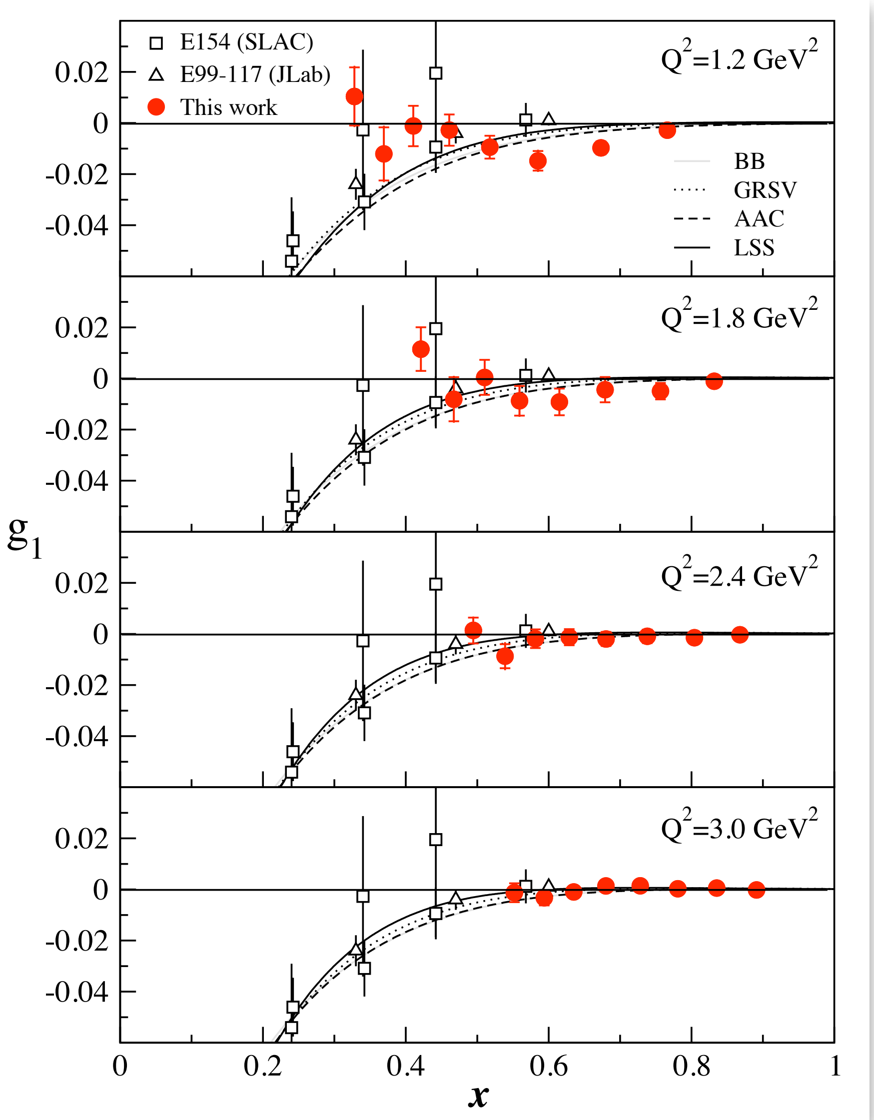
Statistical errors only

From constant (E, θ) to constant Q^2



The structure function g_1 in ^{3}He

P. Solvignon et al., PRL 101, 182502 (2008)



Target mass corrections were applied on PDFs

Spin duality on ³He and neutron

Use partial moments:

Integrate g_1^{res} and g_1^{dis} over the same x-range and at the same Q^2:

$$\tilde{\Gamma}_1^{res} = \int_{x_{\min}}^{x_{\max}} g_1^{res}(x,Q^2)dx$$

$$\tilde{\Gamma}_1^{dis} = \int_{x_{\min}}^{x_{\max}} g_1^{dis}(x,Q^2)dx$$

If $\tilde{\Gamma}_1^{res} = \tilde{\Gamma}_1^{dis}$ duality is verified

Spin duality on ³He and neutron

P. Solvignon et al., PRL 101, 182502 (2008)

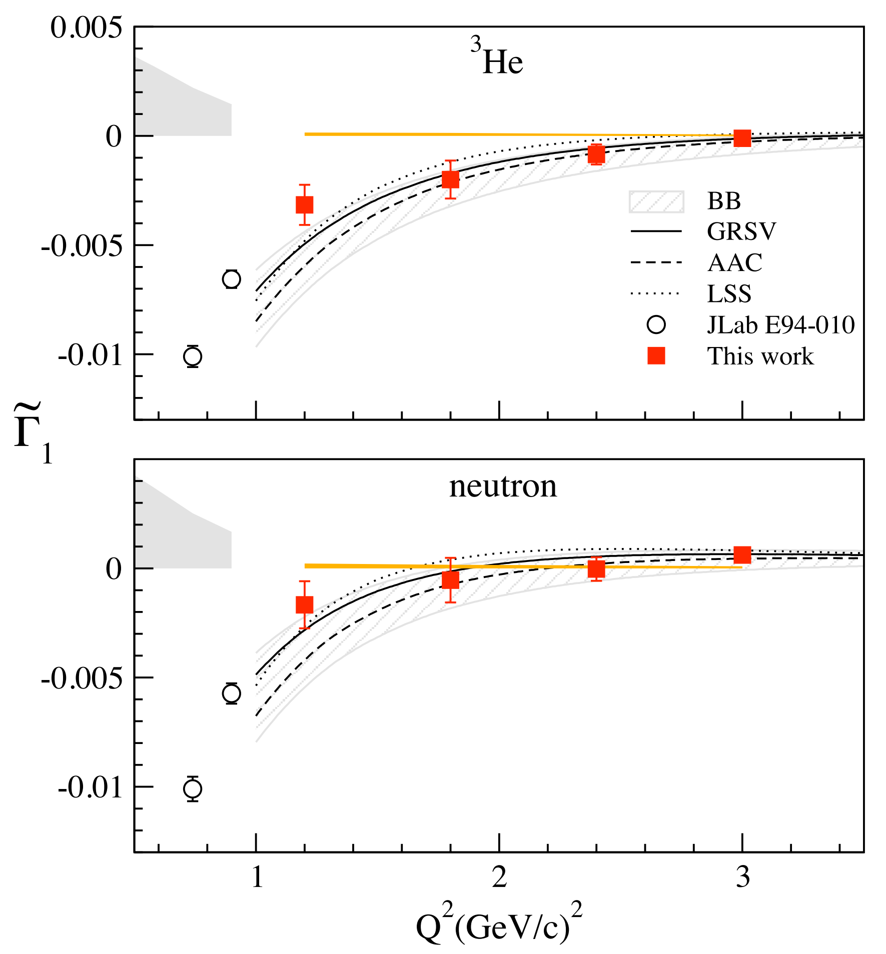
Use partial moments:

Integrate g_1^{res} and g_1^{dis} over the same x-range and at the same Q^2:

$$\tilde{\Gamma}_1^{res} = \int_{x_{\min}}^{x_{\max}} g_1^{res}(x,Q^2)dx$$

$$\tilde{\Gamma}_1^{dis} = \int_{x_{\min}}^{x_{\max}} g_1^{dis}(x,Q^2)dx$$

If $\tilde{\Gamma}_1^{res} = \tilde{\Gamma}_1^{dis}$ duality is verified



Target mass corrections were applied on PDFs

Neutron extraction using the effective polarization equation:

$$\tilde{\Gamma}_1^{^3He} = P_n\tilde{\Gamma}_1^{n} + 2P_p\tilde{\Gamma}_1^{n}$$

P_n=86%

P_p=-2.8%

Virtual photon-nucleon asymmetry

$$A_1(x,Q^2) = \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{F_1(x,Q^2)}$$

with $\gamma^2 = \frac{4M^2x^2}{Q^2}$

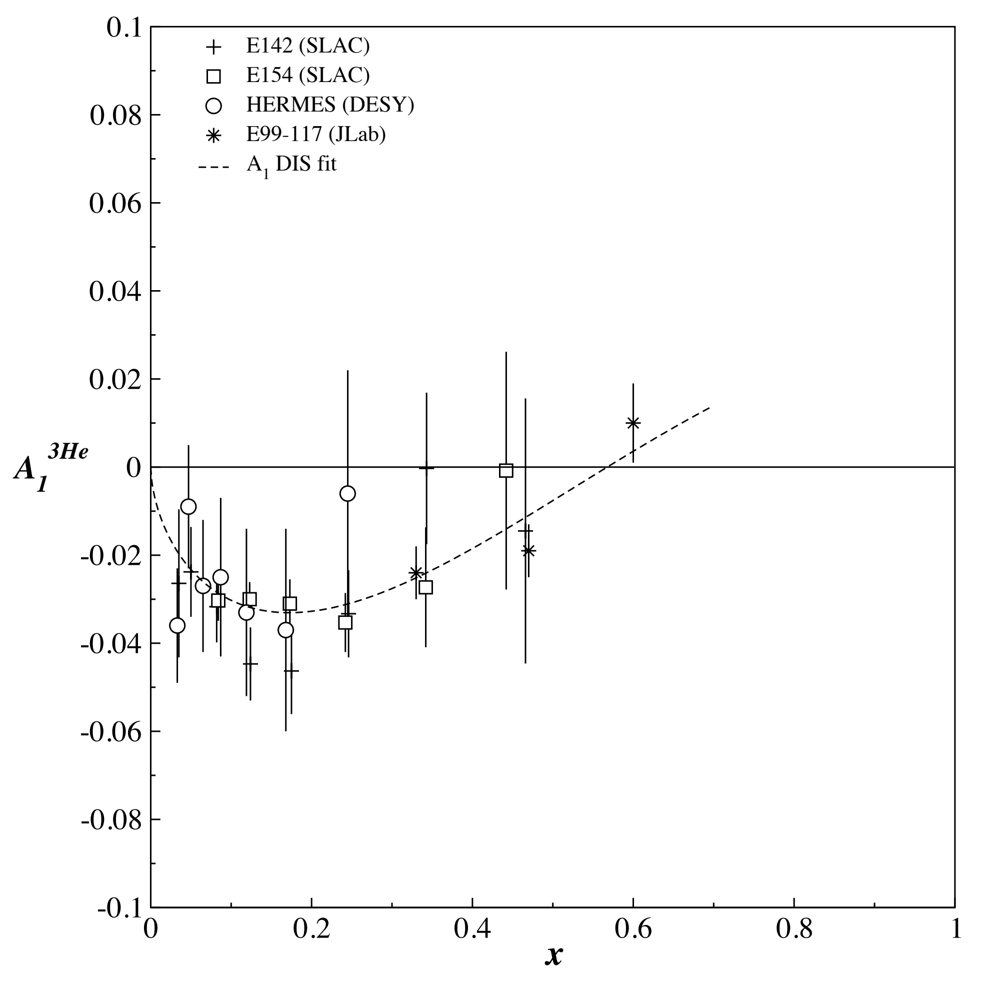
In the parton model:

$$A_1(x,Q^2) \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)} = \frac{\sum_i e_i^2\ \Delta q_i(x,Q^2)}{\sum_i e_i^2\ q_i(x,Q^2)}$$

If Q^2 dependence similar for g_1 and for F_1

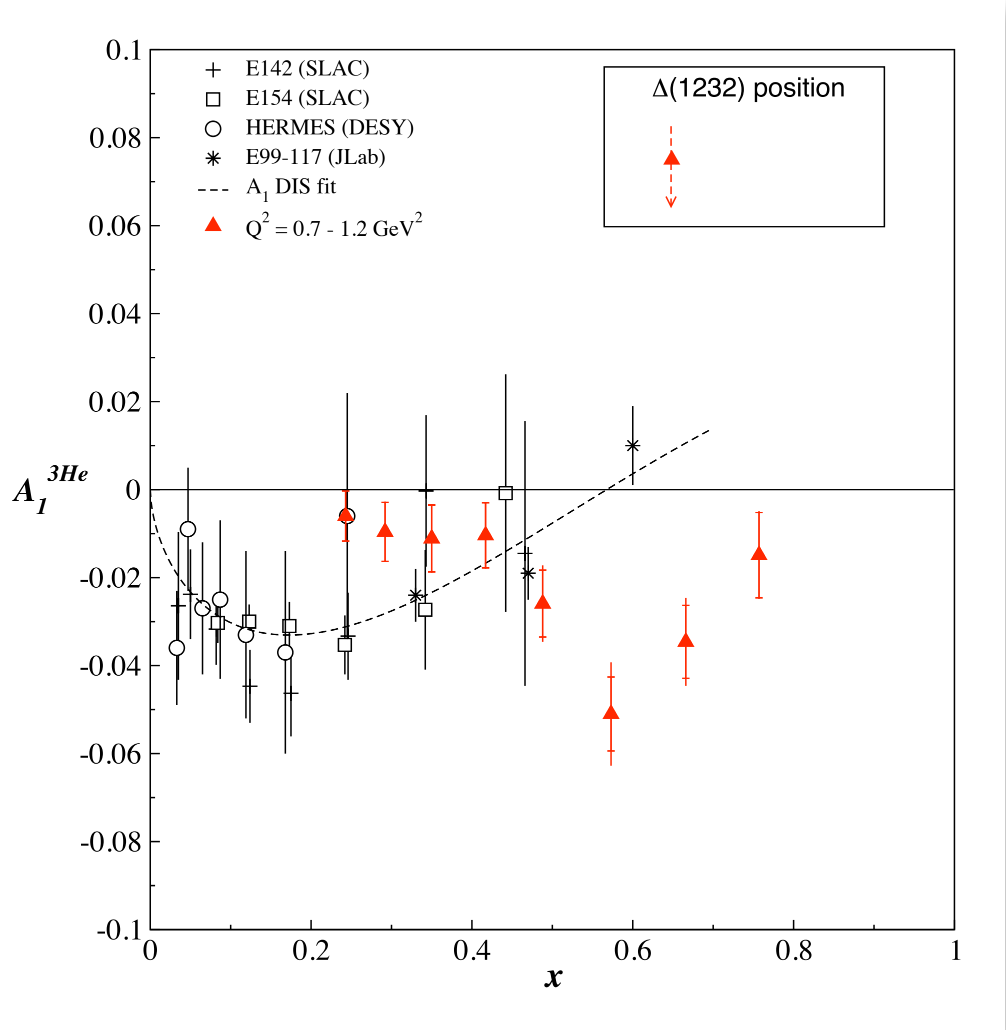
⇒ weak Q^2 dependence of A_1

A_1 for ^{3}He


+ E142 (SLAC)
□ E154 (SLAC)
○ HERMES (DESY)
✳ E99-117 (JLab)
--- A1 DIS fit
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
A1 3He
0
0.2
0.4
0.6
0.8
1
x

A_1 for ^{3}He

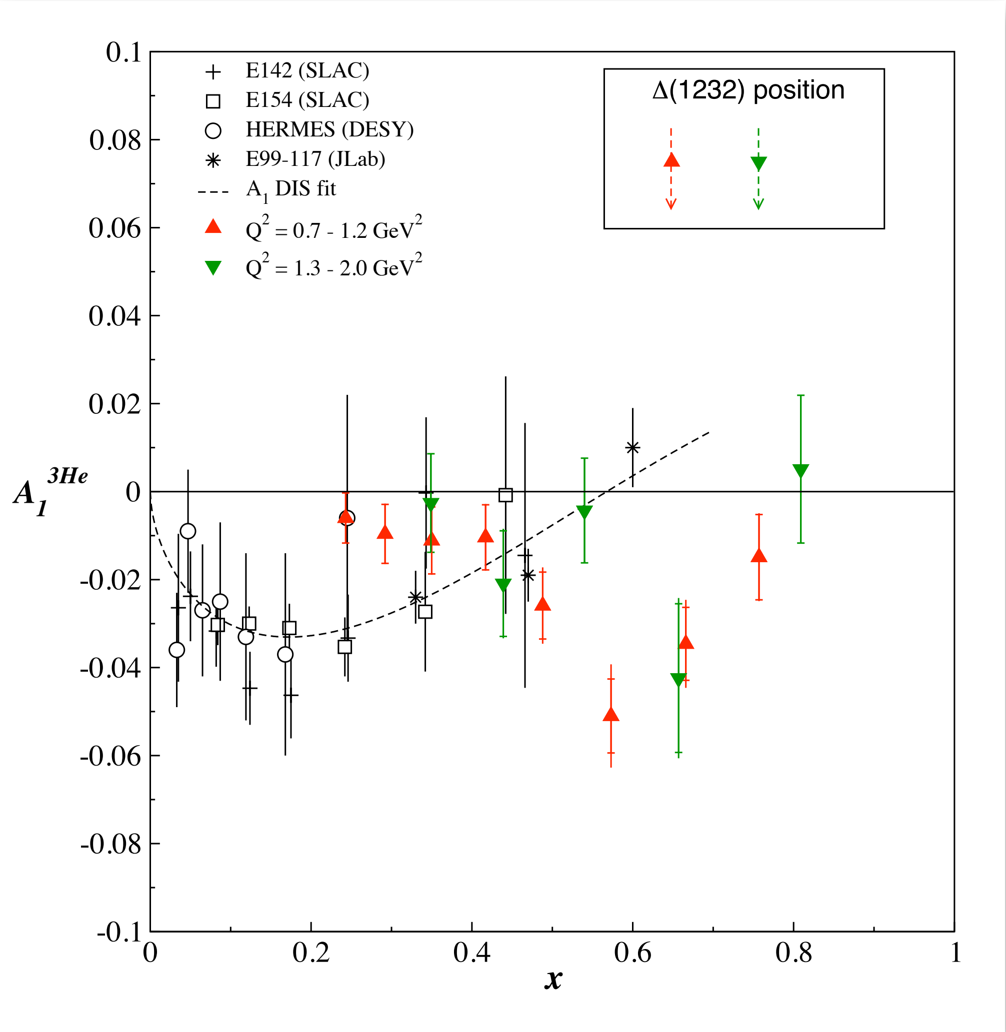
P. Solvignon et al., PRL 101, 182502 (2008)



Large negative value in the Δ(1232) region

A_1 for ^{3}He

P. Solvignon et al., PRL 101, 182502 (2008)

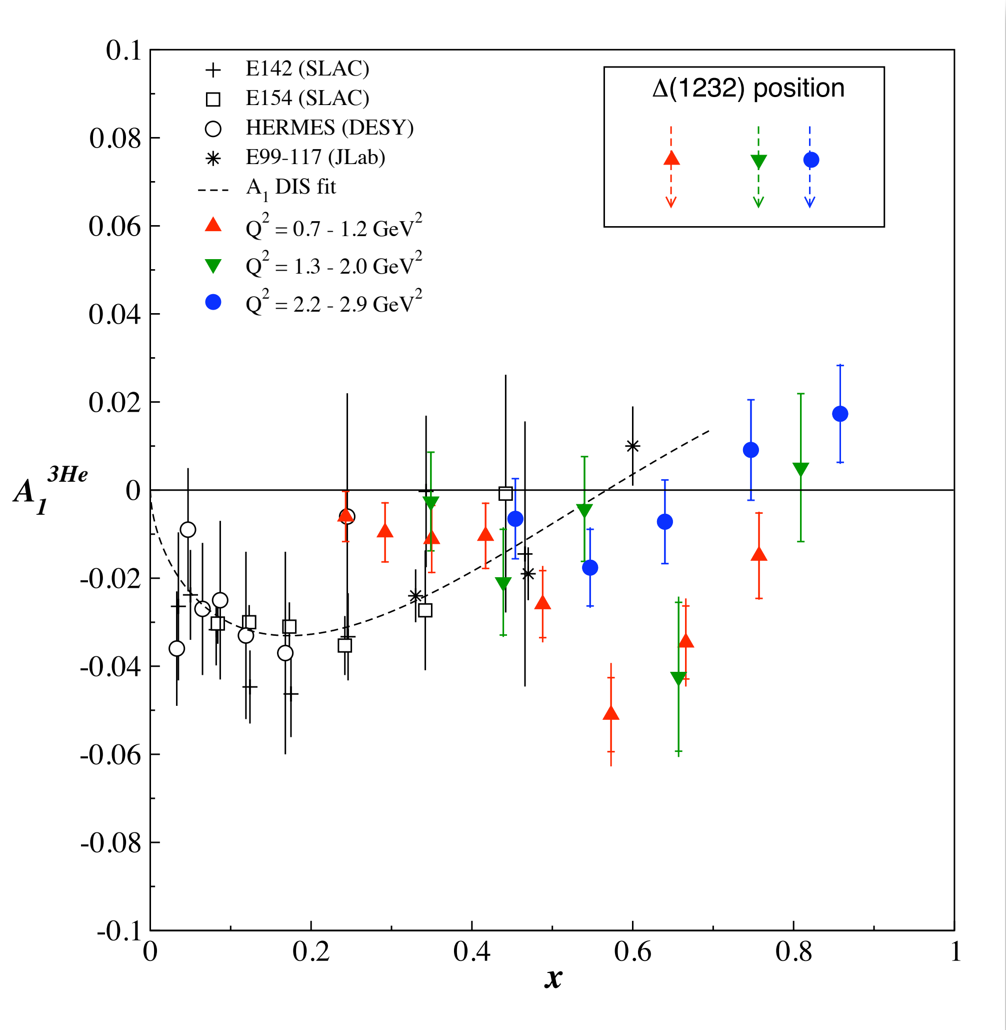


Large negative value in the $\Delta(1232)$ region

Still large negative value in the $\Delta(1232)$ region

A_1 for ^{3}He

P. Solvignon et al., PRL 101, 182502 (2008)



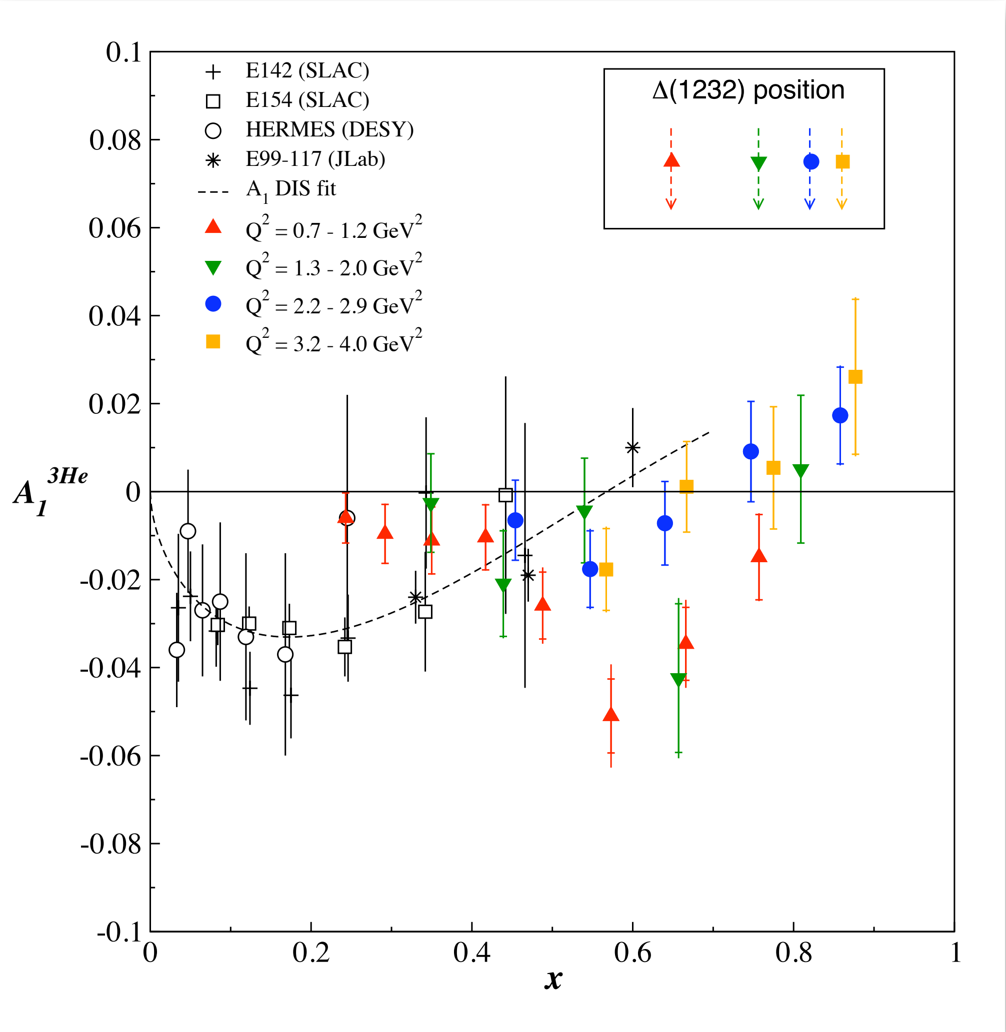
Large negative value in the Δ(1232) region

Still large negative value in the Δ(1232) region

A_1 becomes positive in the Δ(1232) region due to the drop in the Δ FF and the rising of the DIS background

A_1 for ^{3}He

P. Solvignon et al., PRL 101, 182502 (2008)



Large negative value in the Δ(1232) region

Still large negative value in the Δ(1232) region

A_1 becomes positive in the Δ(1232) region due to the drop in the Δ FF and the rising of the DIS background

No strong Q^2-dependence is now observed

A_1^n in the resonance region

$$A_1^n = \frac{g_1^n - \gamma^2 g_2^n}{F_1^n}$$

- Effective equation polarization cannot be used for a pt-to-pt neutron extraction in the resonance region
- Y. Kahn, W. Melnitchouk and S. Kulagin are including a Q^2-dependence in their convolution model (arXiv:0809.4308)
- Goal: test of quark-hadron duality on A_1^n and possible access to high x region

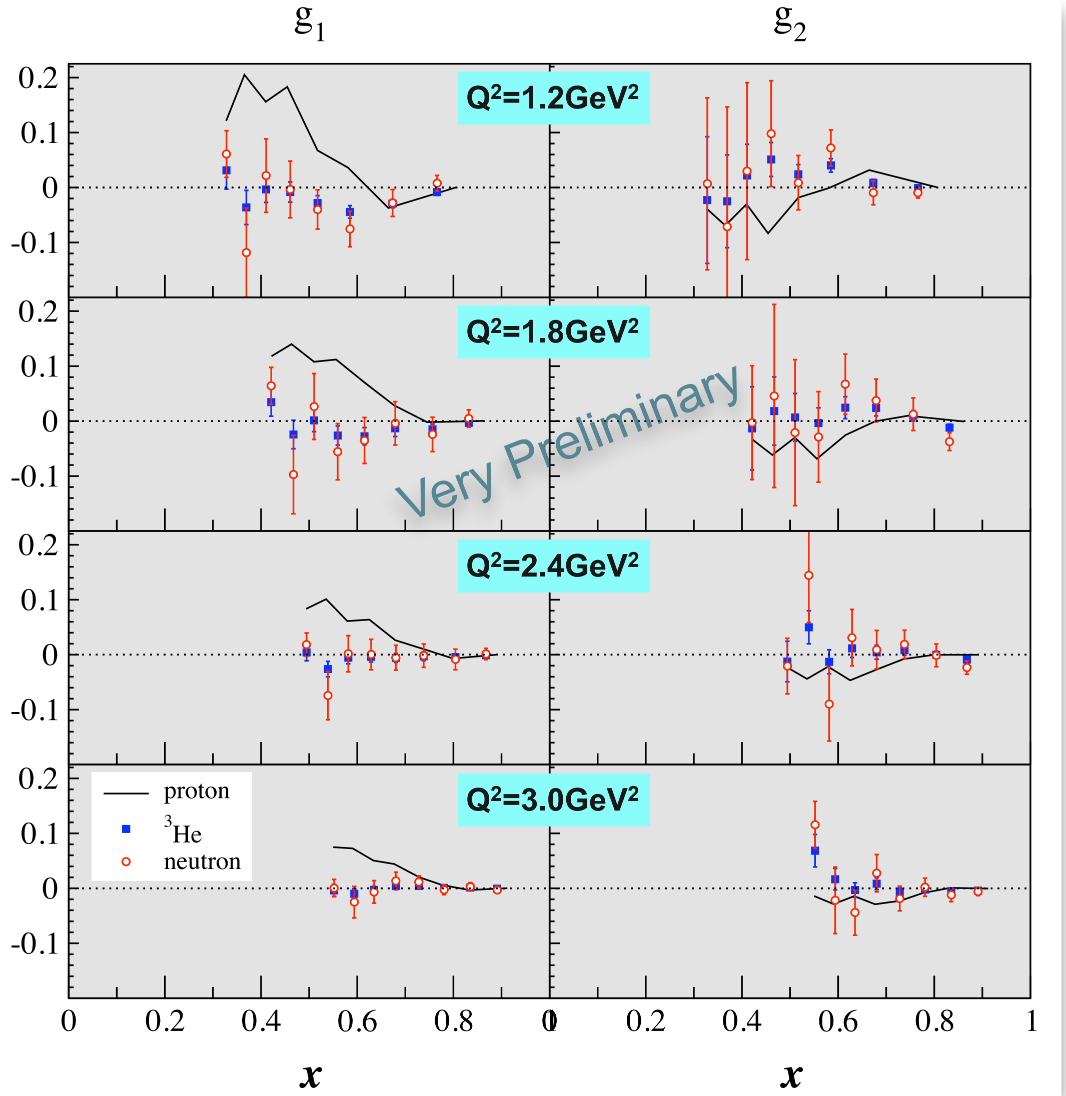
g_1^n and g_2^n in the resonance region

g_1^p from Hall B

g_2^p from MAID: its use is questionable for $Q^2 > 1 GeV^2$

Convolution code: courtesy of Yonatan Kahn

neutron uncertainties will be improved by using fit of our data in the convolution



The g_2 structure function

$$\boxed{g_2 = g_2^{WW} + \bar{g_2}}$$

Leading twist contribution determined entirely from g_1 through the Wandzura-Wilczek relation:

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_0^x dy\, \frac{g_1(y, Q^2)}{y}$$

The g_2 structure function

$$\boxed{g_2 = g_2^{WW} + \bar{g_2}}$$

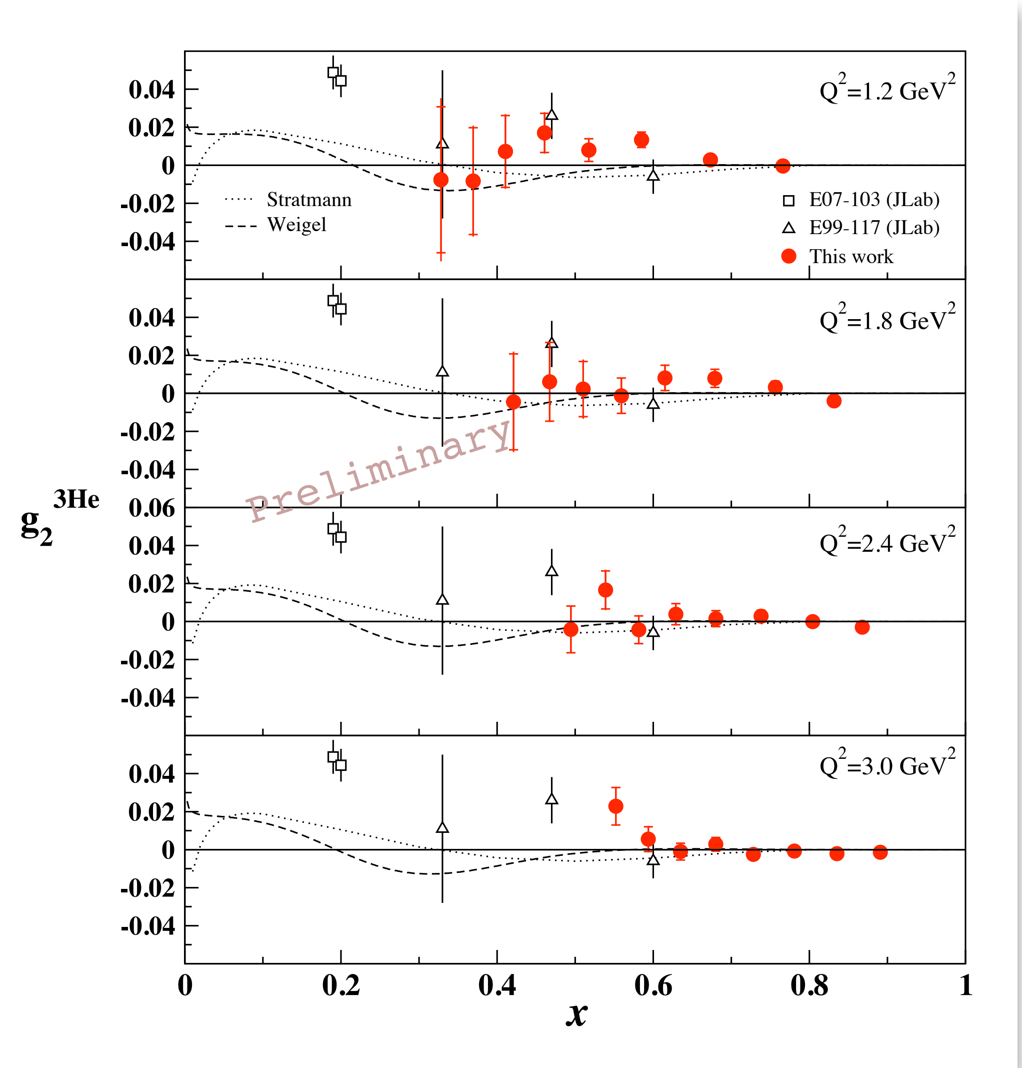
higher twist contribution

Leading twist contribution determined entirely from g_1 through the Wandzura-Wilczek relation:

$$g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_0^x dy \, \frac{g_1(y, Q^2)}{y}$$

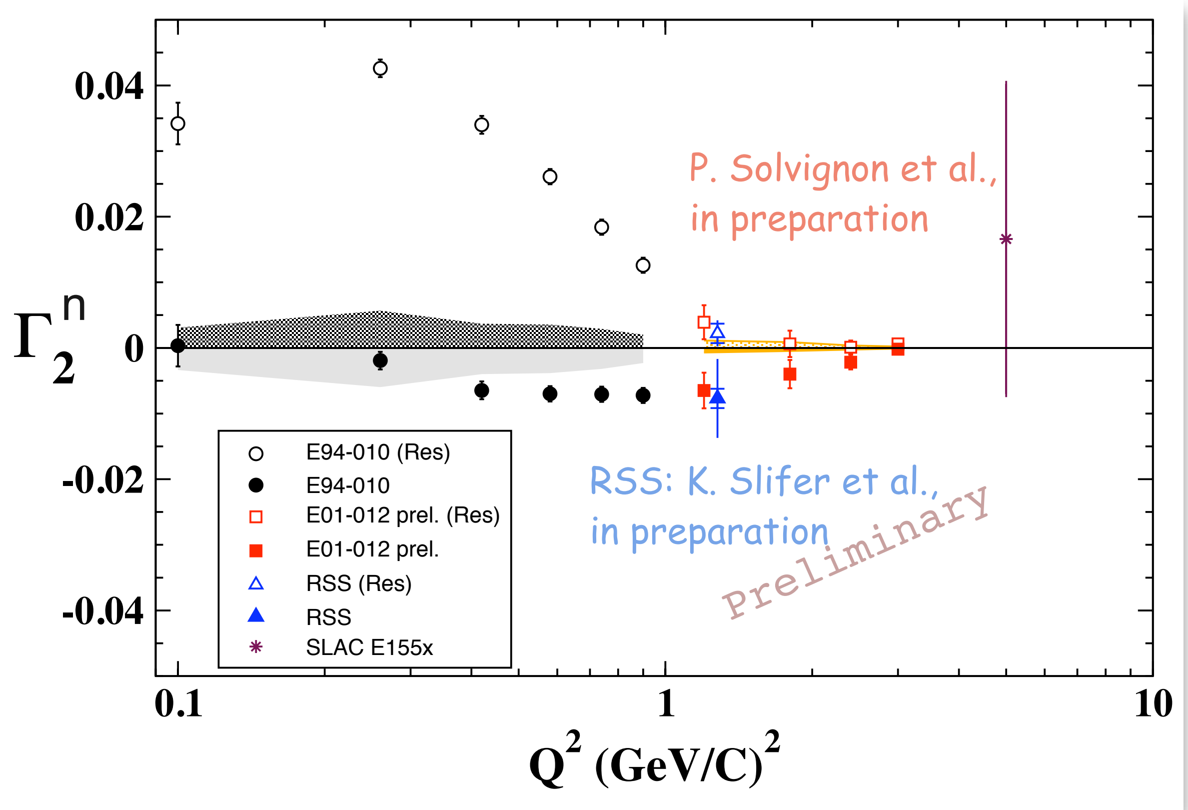
The structure function g_2 in ^{3}He

P. Solvignon et al., in preparation



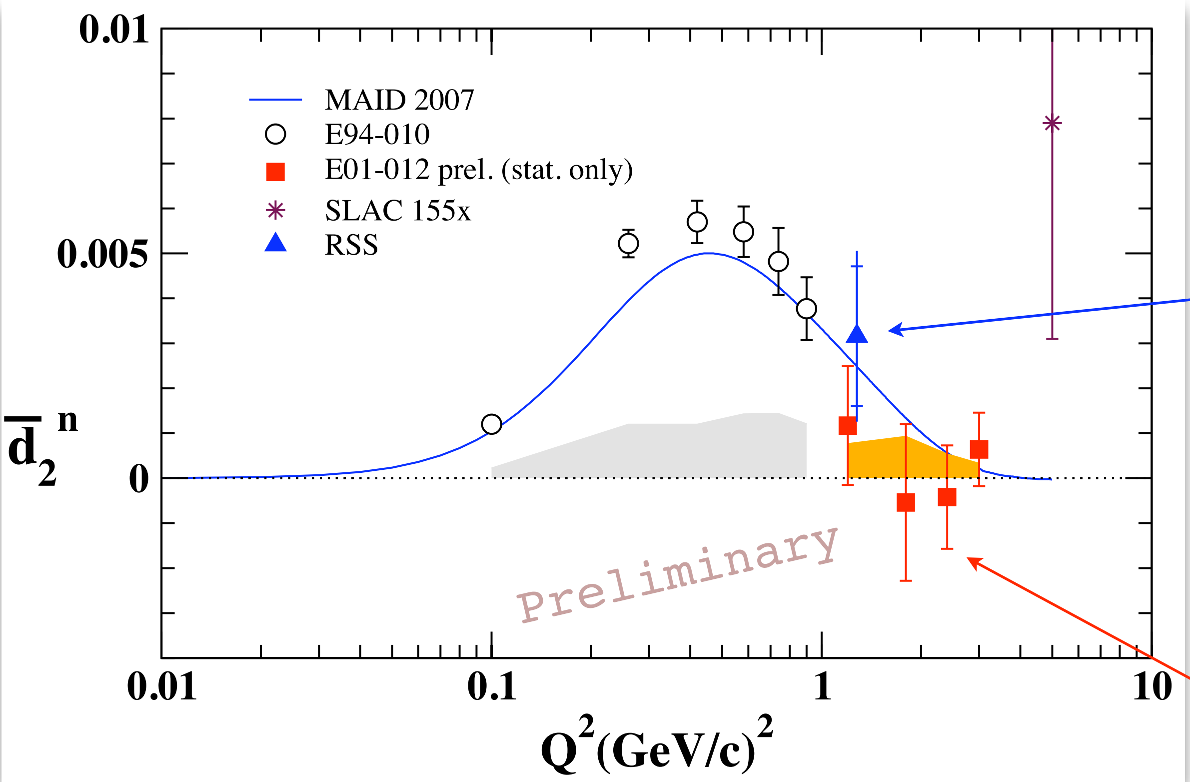
Burkhard-Cottingham sum rule on the neutron

$$\Gamma_2(Q^2) = \int_0^1 dx\ g_2(x, Q^2) = 0$$



Higher moment d_2

$$d_2(Q^2) = \int_0^1 x^2 \left[2\, g_1(x,Q^2) + 3\, g_2(x,Q^2)\right] dx$$

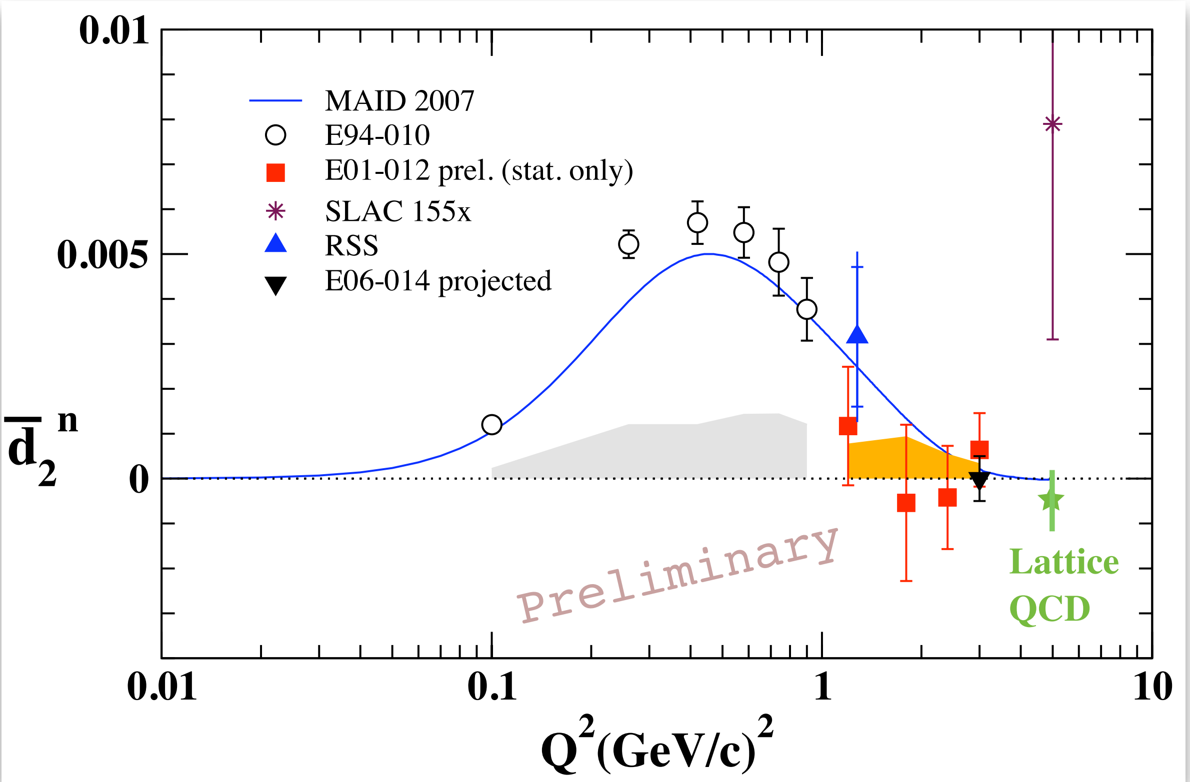


RSS: K. Slifer et al., in preparation

P. Solvignon et al., in preparation

Higher moment d_2

$$d_2(Q^2) = \int_0^1 x^2 \left[2\, g_1(x,Q^2) + 3\, g_2(x,Q^2)\right] dx$$



M. Gockeler et al. PRD 63, 074506(2001). hep-lat/0011091.

Summary

E01-012 provides first precise data of Spin Structure Functions on neutron (^{3}He) in the resonance region for $1.0 < Q^2 < 4.0 GeV^2$

- ✓ Overlap between E01-012 resonance data and DIS data:
  first dedicated test of Quark-Hadron Duality for neutron and ^{3}He SSF
- ✓ No strong Q^2-dependence in resonance A_1^{3He} for $Q^2 > 2.0$ GeV^2
  ➥ DIS-like behavior

Preliminary extraction of g_1^n and g_2^n in the resonance region $\Rightarrow$ A_1^n will come soon

Preliminary results on the Burkhard-Cottingham sum rule and d_2^n at moderate Q^2

and more to come ...

At JLab 12GeV