Precision Measurement of the neutron d_2: Towards the Electric χ_E and Magnetic χ_B Color Polarizabilities

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Hall A collaboration proposal

- Goal:
  Determine the neutron d_2^n at $\langle Q^2 \rangle = 3$ GeV^2

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

- An Experiment in Hall A:
  - ➡ A polarized electron beam of 5.7 GeV and polarized ^{3}He target
  - ➡ Measure unpolarized cross section for $^3\vec{\mathrm{He}}(\vec{e},e')$ reaction $\sigma_0^{^3He}$ in conjuction with the parallel asymmetry $A_{\parallel}^{^3He}$ and the transverse asymmetry $A_{\perp}^{^3He}$ for $0.2 < x < 0.65$ with $2 < Q^2 < 5$ GeV^2.

- Beam Request:
  - ➡ 13 days to achieve a statistical uncertainty of $\Delta d_2^n = 5 \times 10^{-4}$

Individual Proposal Report

Proposal: PR-01-111

Title: Measurement of the Neutron d^n_2 Matrix Element: a Linear Combination of the Electric χ_E and Magnetic χ_B Color Polarizabilities.

Spokespersons: X. Jiang and Z.-E. Meziani

Motivation: The motivation is to test model calculations (in particular, lattice models) of the d^n_2 matrix element, which in the framework of the Operator Product Expansion is sensitive to twist-three quark-gluon correlations, and to electric and magnetic color polarizabilities.

Measurement and Feasibility: The measurement uses longitudinally polarized electron scattering from polarized ^{3}He to measure the spin structure functions $g_1(x)$ and $g_2(x)$ at fixed Q^2=2 $(GeV/c)^2$. The spin asymmetry for inclusive electron scattering is measured in the standard Hall A spectrometers. The d^n_2 matrix element is evaluated by integrating $x^2(2g_1+3g_2)$ over the measured region, with extrapolations to x=0 and x=1 to cover the unmeasured regions. Models are used to correct for the difference between a polarized ^{3}He nucleus and a free polarized neutron. The experiment appears to be feasible, building on a foundation of several similar experiments in Hall A. The experiment could provide a factor-of-four smaller error than existing data for the neutron d^n_2 matrix element.

Issues: The principal issue is that the integral will be strongly affected by contributions in the resonance region, which may introduce significant higher-twist contributions, clouding the interpretation in terms of quark-gluon correlations. A secondary concern is the reliability of the extraction of the value of d^n_2 of the neutron from the data on ^{3}He. Since the nuclear effects are largest at high x, it is not obvious that these are negligible in an integral that is weighted by x^2.

Recommendation: Defer

Scientific Rating: N/A

Individual Proposal Report

Proposal: PR 03-107

Scientific Rating: N/A

Title: Measurement of the Neutron d_2:Towards the Electric χ_E and Magnetic χ_B Color Polarizabilities

Spokespersons: Z.-E. Meziani, S. Choi, and X. Jiang

Motivation: The aim of the experiment is a precise determination of moments of the neutron spin structure functions, namely the integral of g_2^n and the x^2-moment of a particular combination of g_1 and g_2, called d_2. In the framework of the Operator Product Expansion, the latter is sensitive to twist-3 quark-gluon correlations, and to electric and magnetic color polarizabilities. This quantity would be compared to lattice QCD predictions and to other model calculations.

Measurement and Feasibility: The measurement uses scattering of longitudinally polarized electrons from a polarized ^3He target, to measure longitudinal and transverse asymmetries, together with the unpolarized cross section, from which the spin structure functions $g_1(x)$ and $g_2(x)$ are extracted at fixed $Q^2 = 2$ $(GeV/c)^2$. The experiment is optimized to minimize the uncertainty on d_2, obtained by integrating $x^2(2g_1 + 3g_2)$ over the measured region (x from 0.24 to 0.8). Extrapolations to x=0 and x=1 are applied to cover the unmeasured regions. A correction to account for the difference between a polarized ^3He and a free polarized neutron is applied. The experiment uses existing equipment and proven techniques. It is judged feasible. It would complement the low Q^2 results obtained by E-94-010 and the (significantly less precise) SLAC determination of d_2^n at 5 $(GeV/c)^2$. Lattice QCD calculations performed at $Q^2 = 2$ $(GeV/c)^2$ should be available in the near future, enhancing the interest in the measurement.

Issues: The principal issue is that the measured integral is dominated by contributions in the resonance region, thus making the interpretation in terms of color polarizabilities doubtful. However, investigating whether the twist expansion breaks down in this region is of interest, and connected to the question of quark-hadron duality. Nuclear corrections seem to be under control for the moment being addressed, d_2^n.

The PAC would have liked to see this experiment performed, but due to limitations in the available beam time, the proposal cannot be accepted at this time.

Recommendation: Defer with Regret.

Polarized deep inelastic cross sections

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

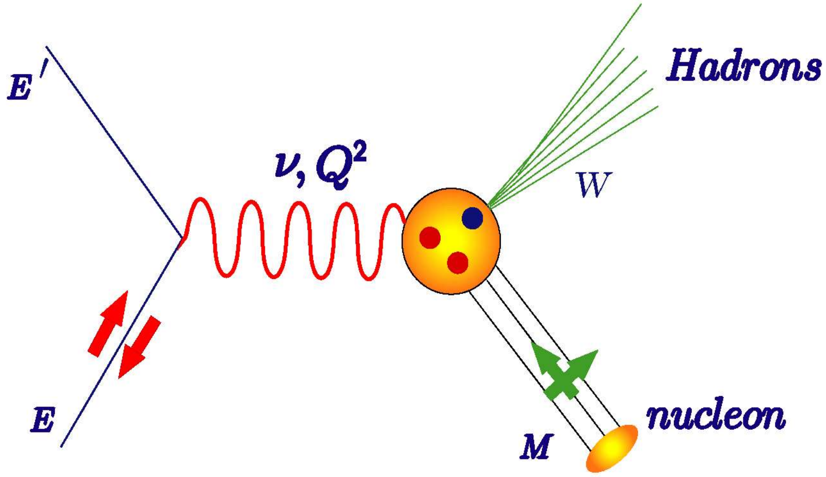
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu \boldsymbol{g_1(x,Q^2)} + 2E\boldsymbol{g_2(x,Q^2)}\right] = \Delta\sigma_{\perp}$$

Q^2 = 4-momentum transfer squared of the virtual photon.

ν = energy transfer.

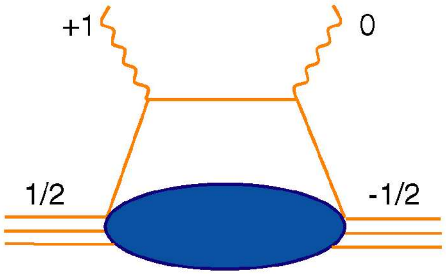
θ = scattering angle.

$x = \frac{Q^2}{2M\nu}$ fraction of nucleon momentum carried by the struck quark.



g_2 and Quark-Gluon Correlations

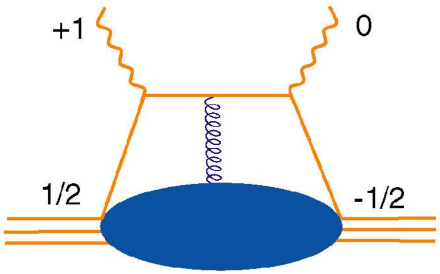
twist-2



Carry one unit of orbital angular momentum

QCD allows the helicity exchange to occur in two ways

twist-3



Couple to a gluon

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$$

- a twist-2 term (Wandzura & Wilczek, 1977):

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}$$

- a twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston, 92):

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$

transversity

quark-gluon correlation

Moments of Structure Functions

$$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2)\, dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + \cdots$$

leading twist

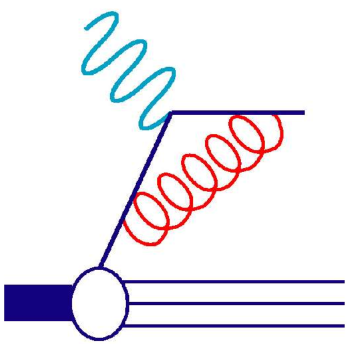
higher twist

$$\mu_2^{p,n}(Q^2) = \left(\pm \frac{1}{12} g_A + \frac{1}{36} a_8\right) + \frac{1}{9}\Delta\Sigma$$ + pQCD corrections

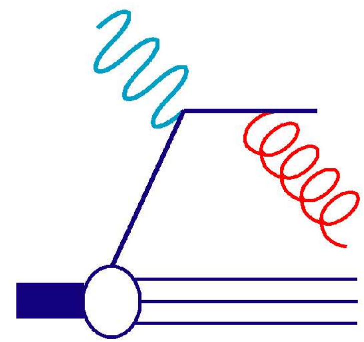
$g_A = 1.257$ and $a_8 = 0.579$ are the triplet and octet axial charge, respectively

$\Delta\Sigma$ = singlet axial charge

(Extracted from neutron and hyperon weak decay measurements)



$$\begin{aligned} g_A &= \Delta u - \Delta d \\ a_8 &= \Delta u + \Delta d - 2\Delta s \\ \Delta\Sigma &= \Delta u + \Delta d + \Delta s \end{aligned}$$



pQCD radiative corrections

Moments of Structure Functions (continued)

$$\mu_4(Q^2) = \frac{M^2}{9}\left[a_2(Q^2) + 4d_2(Q^2) + 4f_2(Q^2)\right]$$

Twist - 2 (TMC) Twist - 3 Twist -4

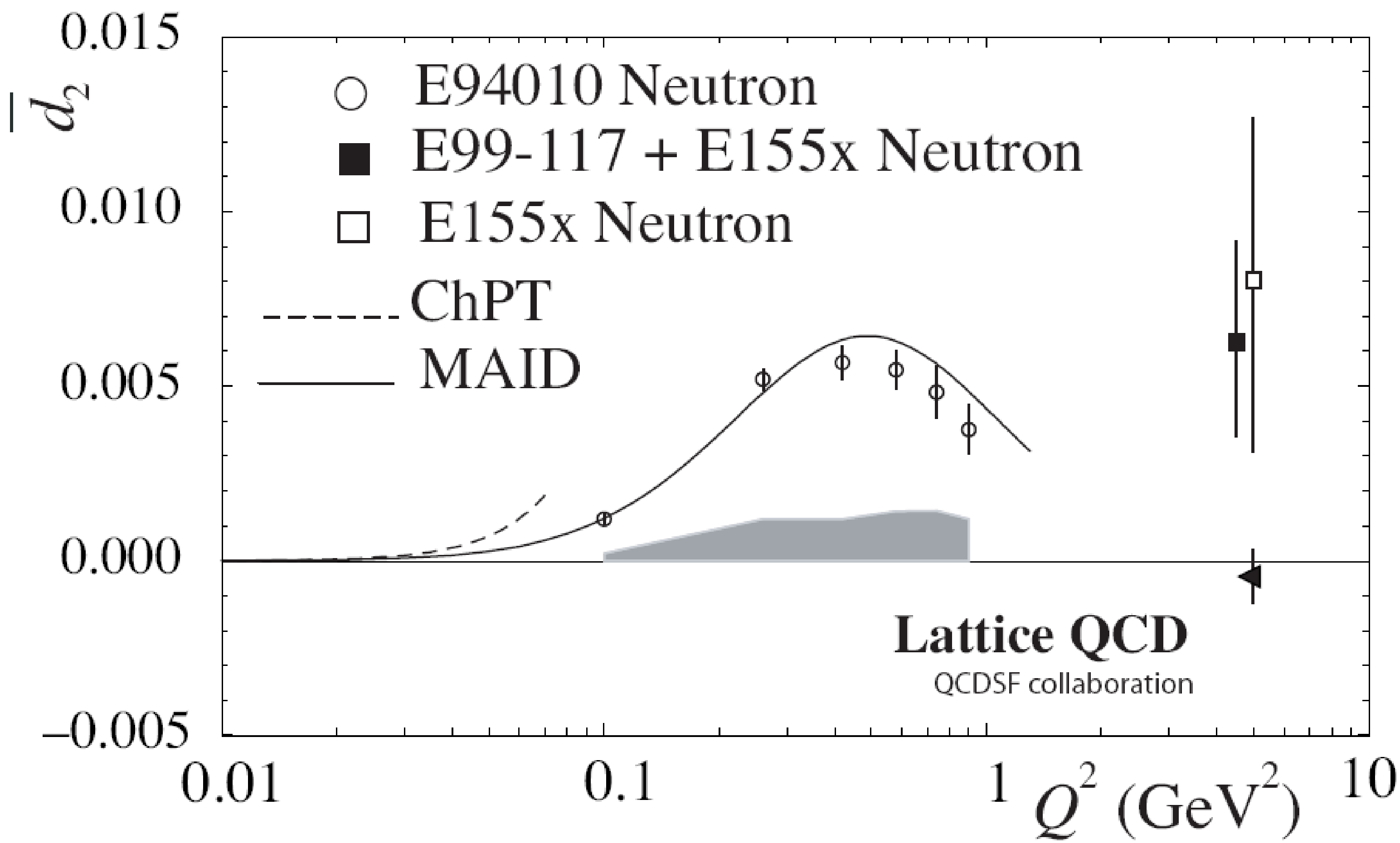
where a_2, d_2 and f_2 are higher moments of g_1 and g_2

e.g. $$d_2(Q^2) = \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx = \int_0^1 x^2\,\overline{g_2}(x,Q^2)dx$$

$$a_2(Q^2) = \int_0^1 x^2 g_1(x,Q^2)\,dx$$

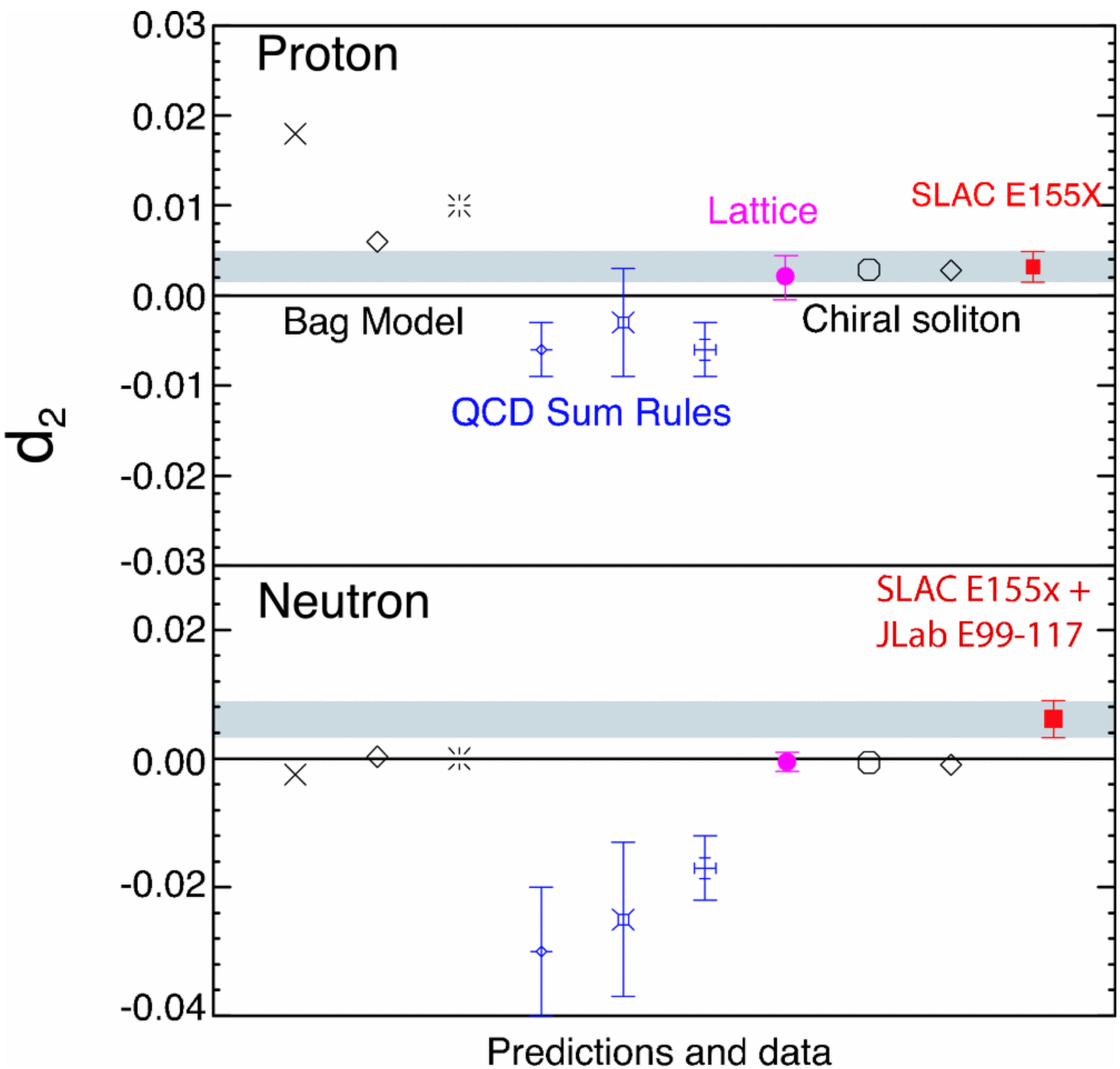
- To extract f_2, d_2 needs to be determined first.
- Both d_2 and f_2 are required to determine the color polarizabilities

World Data on $\bar{d}_2$



(nucleon elastic contribution suppressed)

Model evaluations of d_2



Color "polarizabilities"

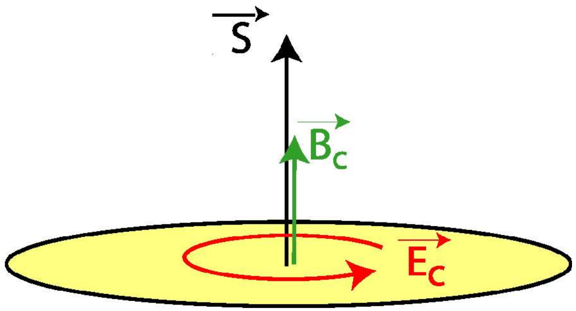
How does the gluon field respond when a nucleon is polarized ?

Define color magnetic and electric polarizabilities (in nucleon rest frame):

$$\chi_{B,E}\, 2M^2\vec{S} = \langle PS|\vec{O}_{B,E}|PS\rangle$$

where $\vec{O}_B = \psi^\dagger g\vec{\boldsymbol{B}}\psi$

$$\vec{O}_E = \psi^\dagger\vec{\alpha}\times g\vec{\boldsymbol{E}}\psi$$



$$\chi_E^n = (4d_2^n + 2f_2^n)/3$$
$$\chi_B^n = (4d_2^n - f_2^n)/3$$

χ_E and χ_B represent the response of the color $\vec{B}$ & $\vec{E}$ fields to the nucleon polarization

The proposal

- A 5.7 GeV polarized electron beam scattering off a polarized ^{3}He target
- Measure unpolarized cross section for $^3\vec{\mathrm{He}}(\vec{e}, e')$ reaction $\sigma_0^{^3He}$ in conjuction with the parallel asymmetry $A_{\parallel}^{^3He}$ and the transverse asymmetry $A_{\perp}^{^3He}$ for $0.23 < x < 0.65$ with $2 < Q^2 < 5$ GeV^2.
  - ➡ Asymmetries measured by BigBite at a single angle: $\theta = 45°$
  - ➡ Absolute cross sections measured by L-HRS
- Determine d_2^n using the relation

$$
\begin{aligned}
\tilde{d}_2(x, Q^2) &= x^2[2g_1(x, Q^2) + 3g_2(x, Q^2)] \\
&= \frac{MQ^2}{4\alpha^2}\frac{x^2y^2}{(1-y)(2-y)}\sigma_0\left[\left(3\frac{1+(1-y)\cos\theta}{(1-y)\sin\theta} + \frac{4}{y}\tan\frac{\theta}{2}\right)A_\perp + \left(\frac{4}{y} - 3\right)A_\parallel\right]
\end{aligned}
$$

where,

$$
A_\parallel = \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{2\sigma_0}, \qquad A_\perp = \frac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{2\sigma_0}
$$

$$
A_\perp^{^3He} = \frac{\Delta_\perp}{P_b P_t \cos\phi} \qquad A_\parallel^{^3He} = \frac{\Delta_\parallel}{P_b P_t}
$$

$$
\Delta_\perp = \frac{(N^{\uparrow\Rightarrow} - N^{\uparrow\Rightarrow})}{(N^{\uparrow\Rightarrow} + N^{\uparrow\Rightarrow})} \qquad \Delta_\parallel = \frac{(N^{\downarrow\Uparrow} - N^{\uparrow\Uparrow})}{(N^{\downarrow\Uparrow} + N^{\uparrow\Uparrow})}
$$

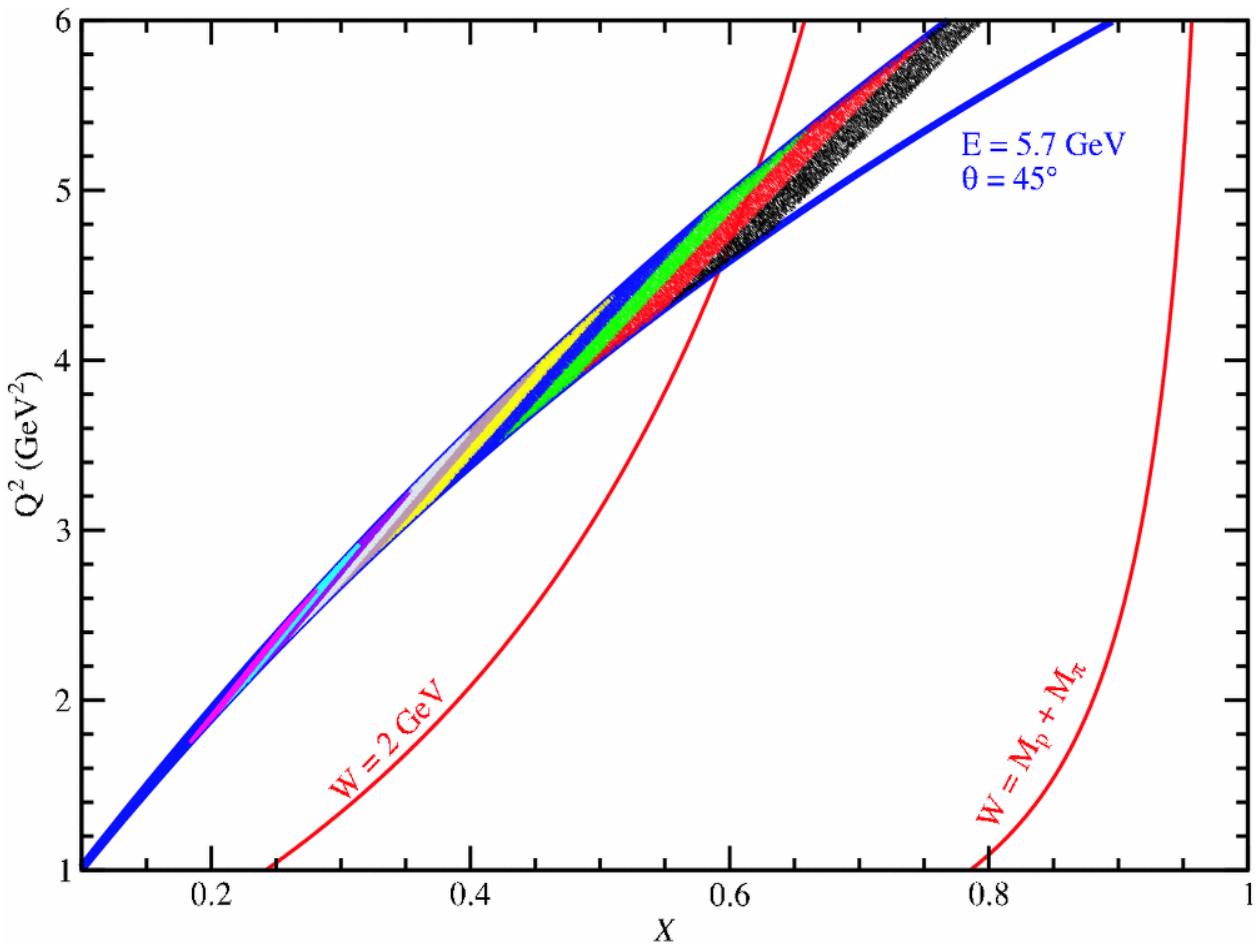
Kinematics of the proposed measurement

E_i (GeV)	bin central p (GeV)	x	Δx	Q^2 (GeV^2)	W (GeV)	Rate (Hz)		
5.700	1.603	.696	.969E-01	5.35	1.79	0.90		
5.700	1.450	.607	.814E-01	4.84	2.00	1.5		
5.700	1.312	.532	.691E-01	4.38	2.18	2.1		
5.700	1.187	.468	.591E-01	3.96	2.32	2.7		
5.700	1.074	.413	.509E-01	3.59	2.44	3.1	Single Spectrometer Setting	
5.700	0.971	.324	.440E-01	3.24	2.55	3.5		
5.700	0.878	.365	.383E-01	2.93	2.65	3.8		
5.700	0.794	.288	.335E-01	2.65	2.73	3.9		
5.700	0.718	.256	.293E-01	2.40	2.80	4.1		
5.700	0.650	.229	.259E-01	2.17	2.86	4.1		
							$\text{Time}_\perp$ hours	$\text{Time}_\parallel$ hours
Total							257	10

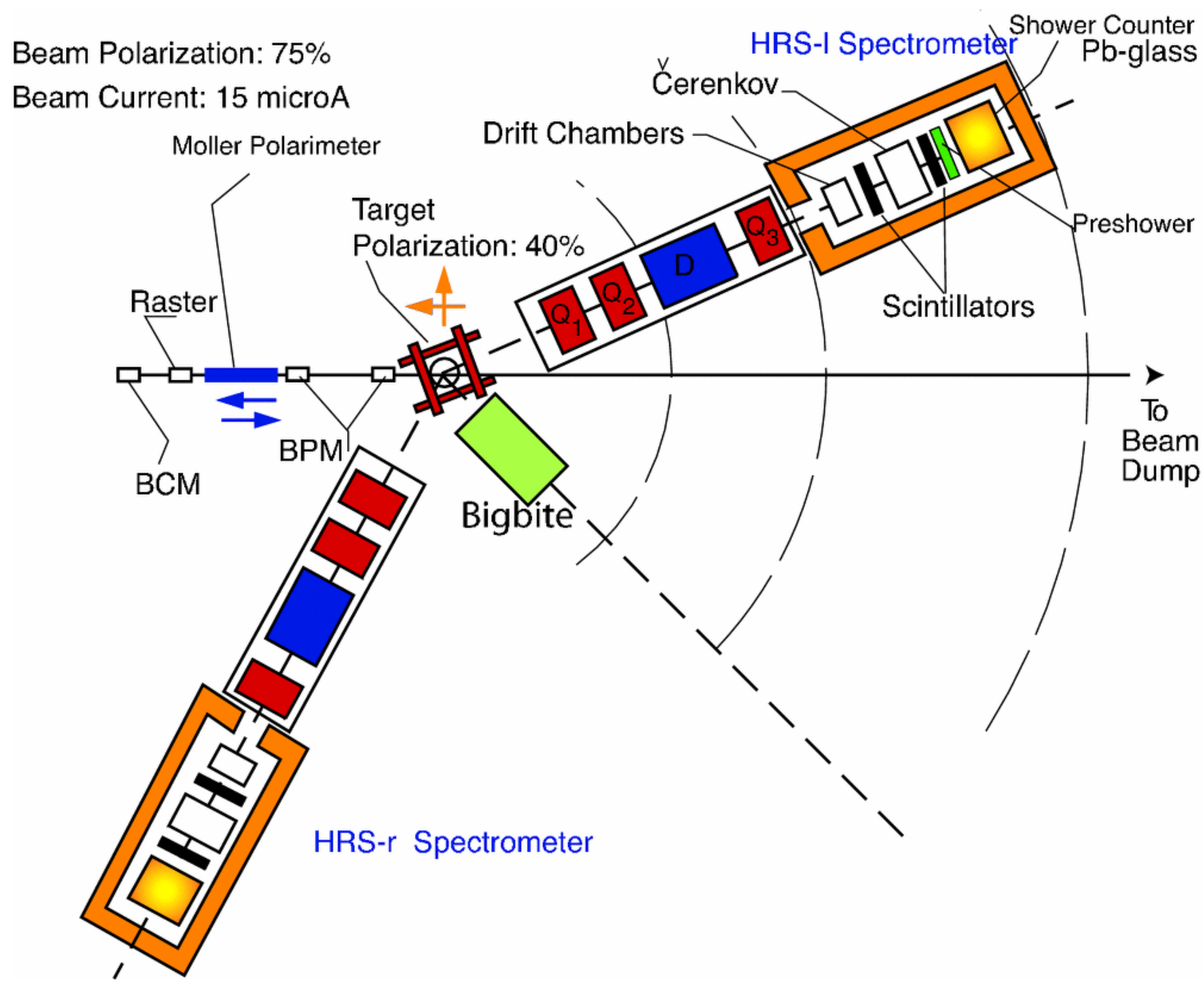
- L-HRS used to measure total cross section at 10 momentum settings.
  - ➡ will also reverse the field to monitor π^-/π^+ and e^-/e^+ asymmetries
- BigBite takes all asymmetry data with single setting.
  - ➡ Data divided into 10 bins during offline analysis.
- 267 + 48 hours for calibration and configuration changes: 13 days

Kinematics of the proposed measurement

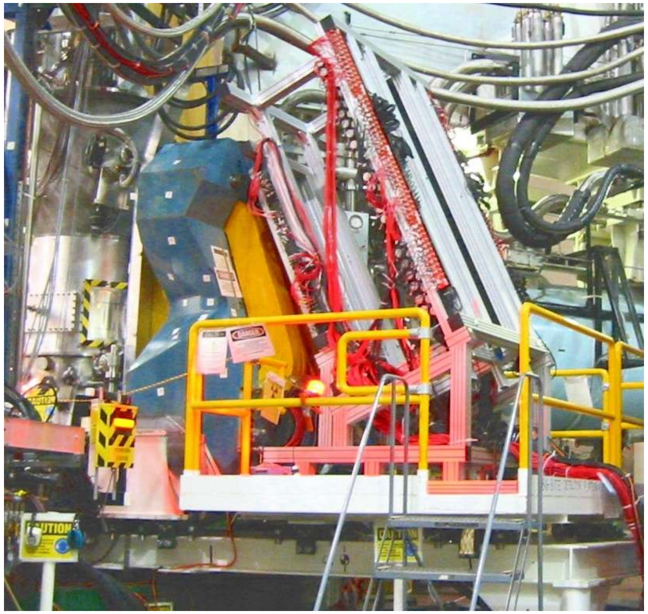
- Single beam energy 5.7 GeV
- BigBite fixed at single scattering angle (data divided into 10 bins during analysis)
- Avoid resonance region as much as possible.

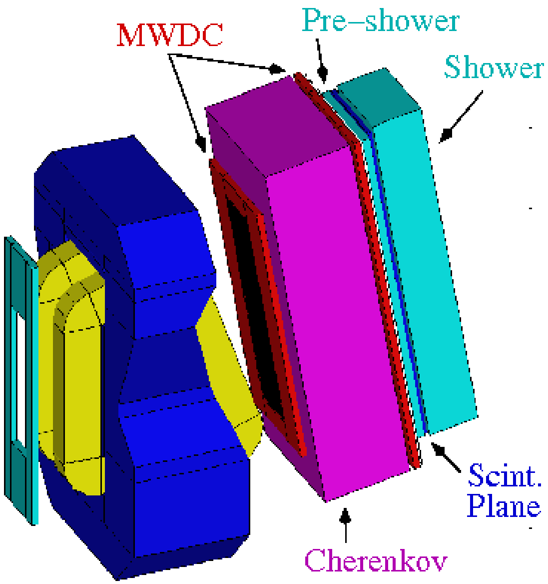


Floor configuration for this proposal



BigBite Configuration





- non-focusing, large acceptance, open geometry
- $\Delta p/p$ = 1 – 1.5% (@ 1.2 T) $\sigma(W)$ = 50 MeV
- angular resolution 1.5 mr, extended target resolution 6 mm
- large solid angle: 64 msr
- detector package
  - 2 MWDCs, segmented trigger, Pb-glass shower
  - Gas Cherenkov (new)

Cherenkov Design Parameters

- Dimensions: 200cm x 60cm x 60cm
  - located in gap between first and second wire chamber with minimal modifications to BigBite frame
- Radiator gas: C_4F_{10} (or Freon12)
  - n = 1.0015 (1.0011)
  - π threshold: 2.51 GeV/c (2.98 GeV/c)
  - ~28 (18) photo-electrons / 40 cm electron track
    - Quartz PMT (Photonis XP4318 or equiv.)
    - mirror reflectivity: ~90%, 10% loss at PMT-gas interface
  - >99% efficient with 4-5 p.e. threshold
    - negl. pion contamination

      minimum π/e rejection ratio 1000:1 online

Background Rates

- MC simulation by Degtyarenko et al. (tested in Halls A and C)
- Online cuts include:
  - BB magnet sweeps particles with p < 200 MeV/c
  - GEN BB trigger: shower+pre-shower+scint
    - provide ~10:1 online hadron rejection (or better)
  - ~550—600 MeV threshold on shower
  - 4—5 p.e. threshold on Cherenkov
    - heavily suppress random background
    - negl. pion contamination (~100 Hz knock-ons)
- Total estimated trigger rate (GEN trig + Cherenkov): 2—5 kHz

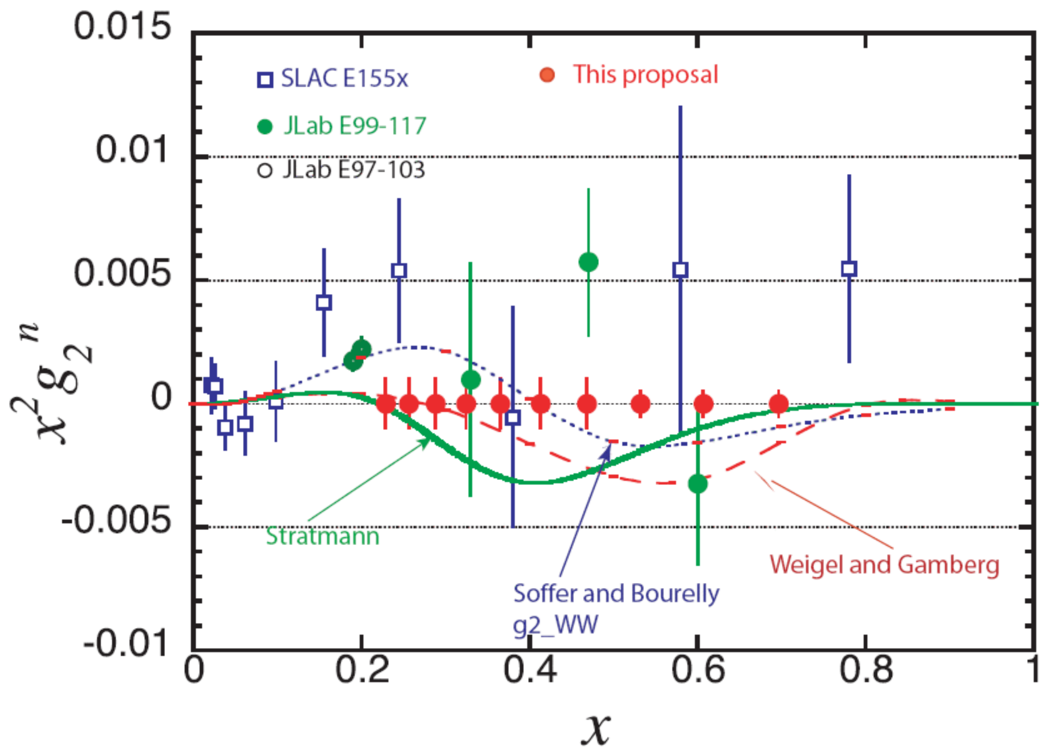
Online triggers

e-	2-5 kHz
e+	<1 kHz

π-	90 kHz
π+	90 kHz
p	50 kHz
n	50 kHz

Removed via online cuts

Projected $x^2 g_2(x,Q^2)$ results



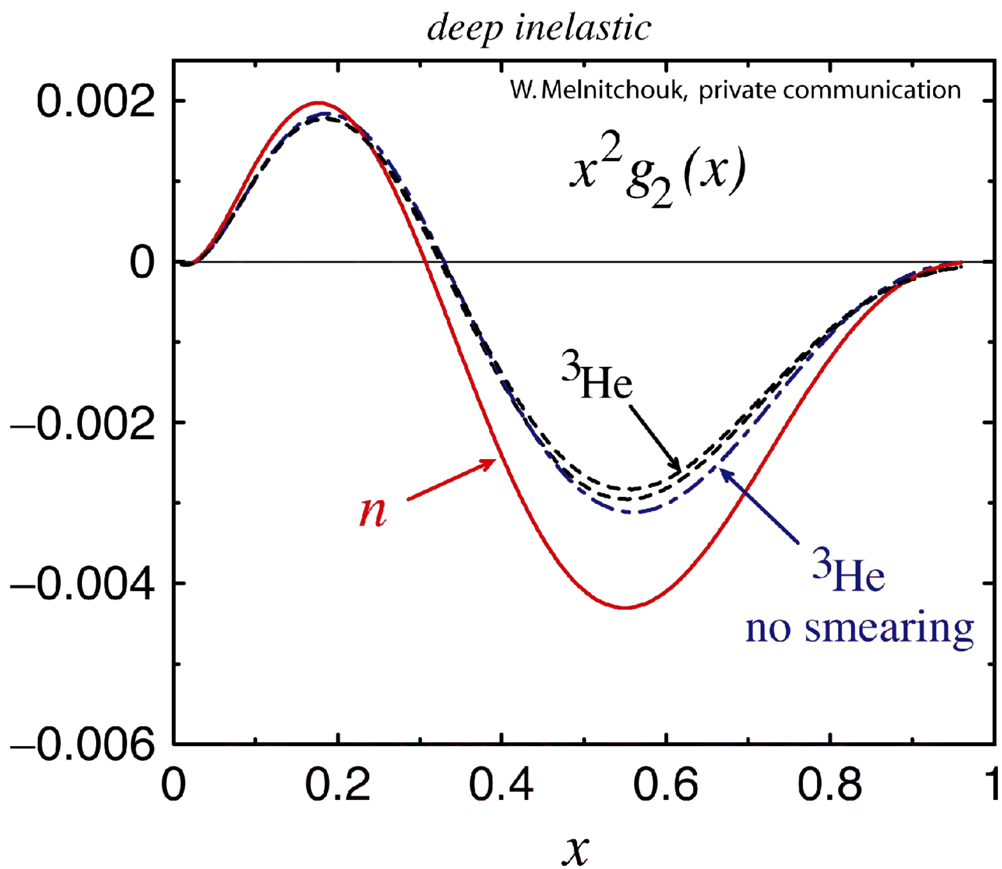
- g_2 for ^3He is extracted directly from L and T spin-dependent cross sections measurements within the same experiment.
- The nuclear corrections will be applied to the moments not to the structure functions.
- SLAC E155x g_2 data points at high x are evolved from Q^2 as large as 16 GeV^2 to 5 GeV^2

Nuclear corrections

- Convolution method using the impulse approximation and realistic ground state wave functions of ^{3}He (in Bjorken limit: $g_1^{^3He}$ related to g_1^N).
  - Variational Method,
    - C. Ciofi degli Atti & S. Scopetta, Phys. Lett. B 404 (1997) 223, for g_1, for g_2 , S. Scopetta. private communication
  - Faddeev
    - F. Bissey et al. Phys. Rev. C 64 (2001) 024004

- Finite Q^2 effects (both g_1^N and g_2^N contribute to $g_1^{^3He}$ and to $g_2^{^3He}$)
  - S.A. Kulagin and W. Melnitchouk

From ^{3}He to Neutron



✓Correction large for g_2 but much smaller for d_2

✓About 5% difference between additive or convolution methods or between potential models

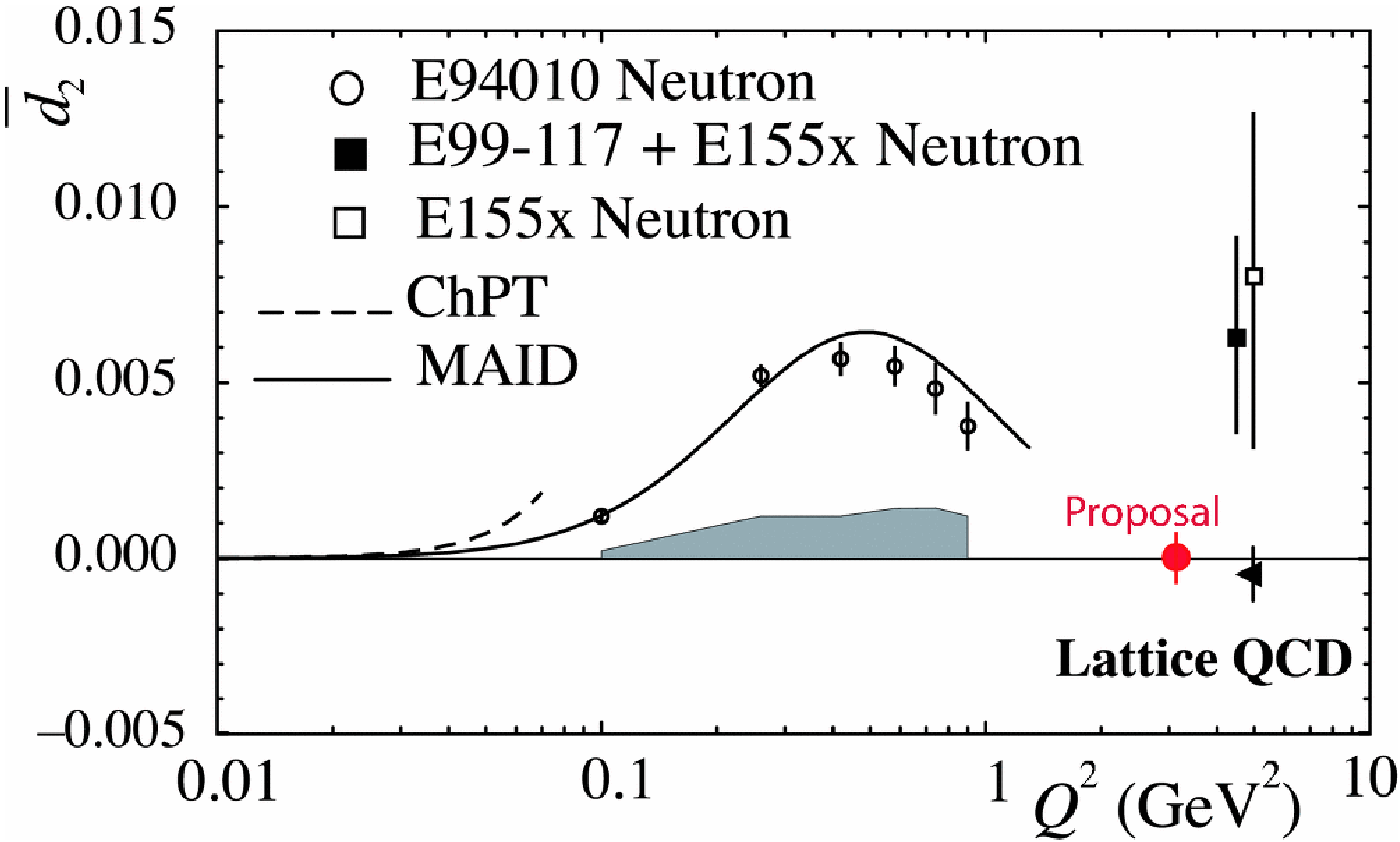
$$d_2^n = d_2^{^3He}/(1-\delta^c) \qquad \text{with} \qquad \delta^c \approx 0.35$$

$$\Delta\delta^c \approx 0.15\delta^c \approx 0.05 \qquad \Rightarrow \qquad \Delta d_2^n/d_2^n \approx 5\%$$

Systematic Error Contributions to d_2^n

Target polarization		4 %
Beam polarization		3 %
Asymmetry (raw)		
	• Target spin direction (0.5°)	$\approx 1.5 \times 10^{-3}$
	• Beam charge asymmetry	200 ppm
Cross section (raw)		
	• PID efficiency	≈ 1 %
	• Background Rejection efficiency	≈ 1 %
	• Beam charge	$<$ 1 %
	• Beam position	$<$ 1 %
	• Acceptance cut	2-3 %
	• Target density	2-3 %
	• Nitrogen dilution	2-3 %
	• Dead time	<1 %
	• Finite Acceptance cut	<1%
Radiative corrections		≤ 10 %
From ^{3}He to Neutron correction		5 %
Total effect		≤ 10 %
Estimate of contributions	$\int_{0.003}^{0.23} \tilde{d}_2^n \, dx$	4.8×10^{-4}
from unmeasured regions	$\int_{0.70}^{0.999} \tilde{d}_2^n \, dx$	5.0×10^{-5}
Projected absolute statistical uncertainty		$\Delta d_2 \approx 5.4 \times 10^{-4}$
Projected absolute systematic uncertainty assuming $d_2 = 5 \times 10^{-3}$		$\Delta d_2 \approx 5 \times 10^{-4}$

Expected Error on d_2



Summary

- We propose to precisely measure the neutron d_2^n at $Q^2 \approx 3.0$ GeV^2.
  - ➡ Determine asymmetries in conjunction with an absolute cross section measurement over the region ($0.23 < x < 0.65$)
- Provide a benchmark test for theory (lattice QCD).
  - ➡ we can achieve a statistical uncertainty of $\Delta d_2^n = 5 \times 10^{-4}$
    - four times better then existing world average!
- Utilize standard Hall A equipment with one addition:
  - ➡ new Gas Cerenkov detector for BigBite

We request

- 13 days of polarized beam at 5.7 GeV.
  - ➡ 257 hours of transverse settings, 10 hours of longitudinal settings, and 48 hours of overhead and calibration.

Proposal: <http://www.jlab.org/~brads/PAC29/>

Nuclear corrections (continued)

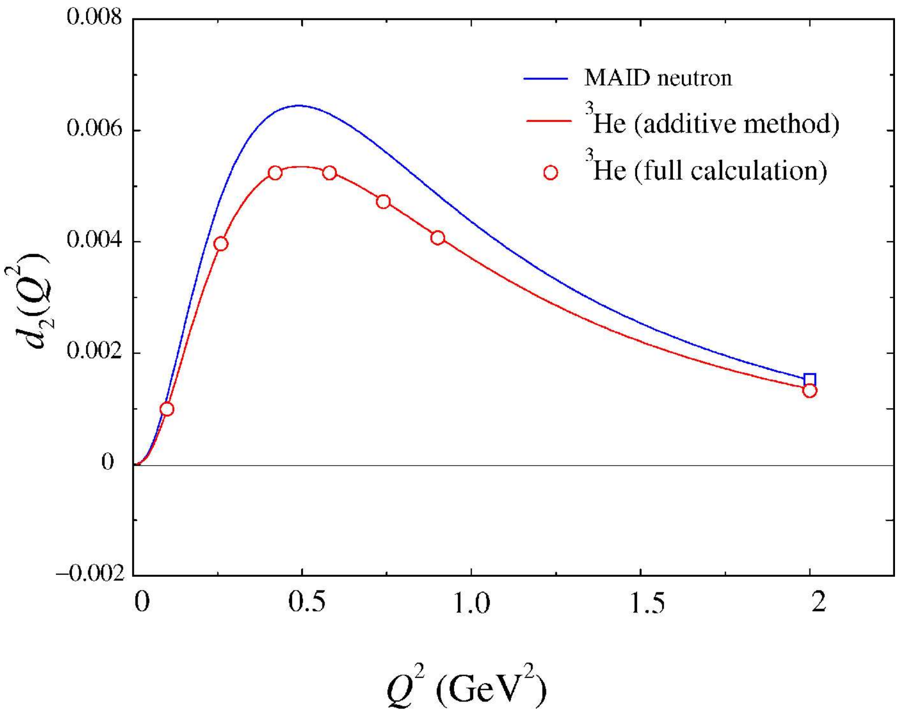
$$S(\vec{p},E) \;=\; \frac{1}{2}\left(f_0 + f_1\vec{\sigma}_N\cdot\vec{\sigma}_A + f_2\left[\vec{\sigma}_N\cdot\hat{p}\;\vec{\sigma}_A\cdot\hat{p}\;-\frac{1}{3}\vec{\sigma}_N\cdot\vec{\sigma}_A\right]\right)$$

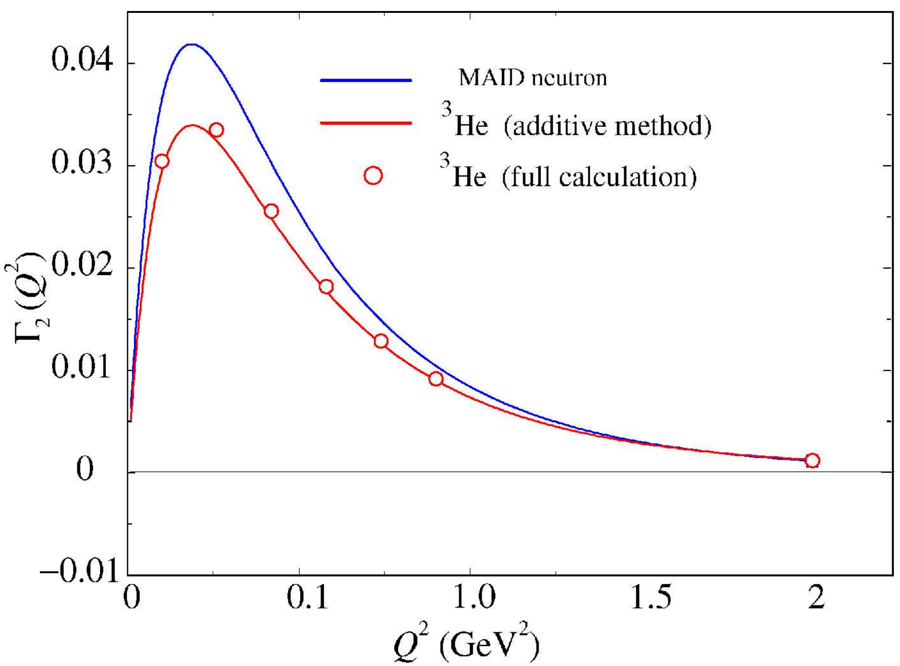
$$\begin{aligned}
&xg_1^{^3\mathrm{He}}(x,Q^2) + (1-\gamma^2)xg_2^{^3\mathrm{He}}(x,Q^2)\\
&= \sum_{N=p,n}\int d^3p\,dE\,(1-\frac{\epsilon}{M})\left\{\left[\left(1+\frac{\gamma p_z}{M}+\frac{p_z^2}{M^2}\right)f_1 + \left(-\frac{1}{3}+\hat{p}_z^2+\frac{2\gamma p_z}{3M}+\frac{2p_z^2}{3M^2}\right)f_2\right]\;zg_1^N(z,Q^2)\right.\\
&\qquad\left. + (1-\gamma^2)(1+\frac{\epsilon}{M}\left[f_1+\left(\frac{p_z^2}{\vec{p}^2}-\frac{1}{3}\right)f_2\right]\frac{z^2}{x}g_2^N(z,Q^2)\right\}
\end{aligned}$$

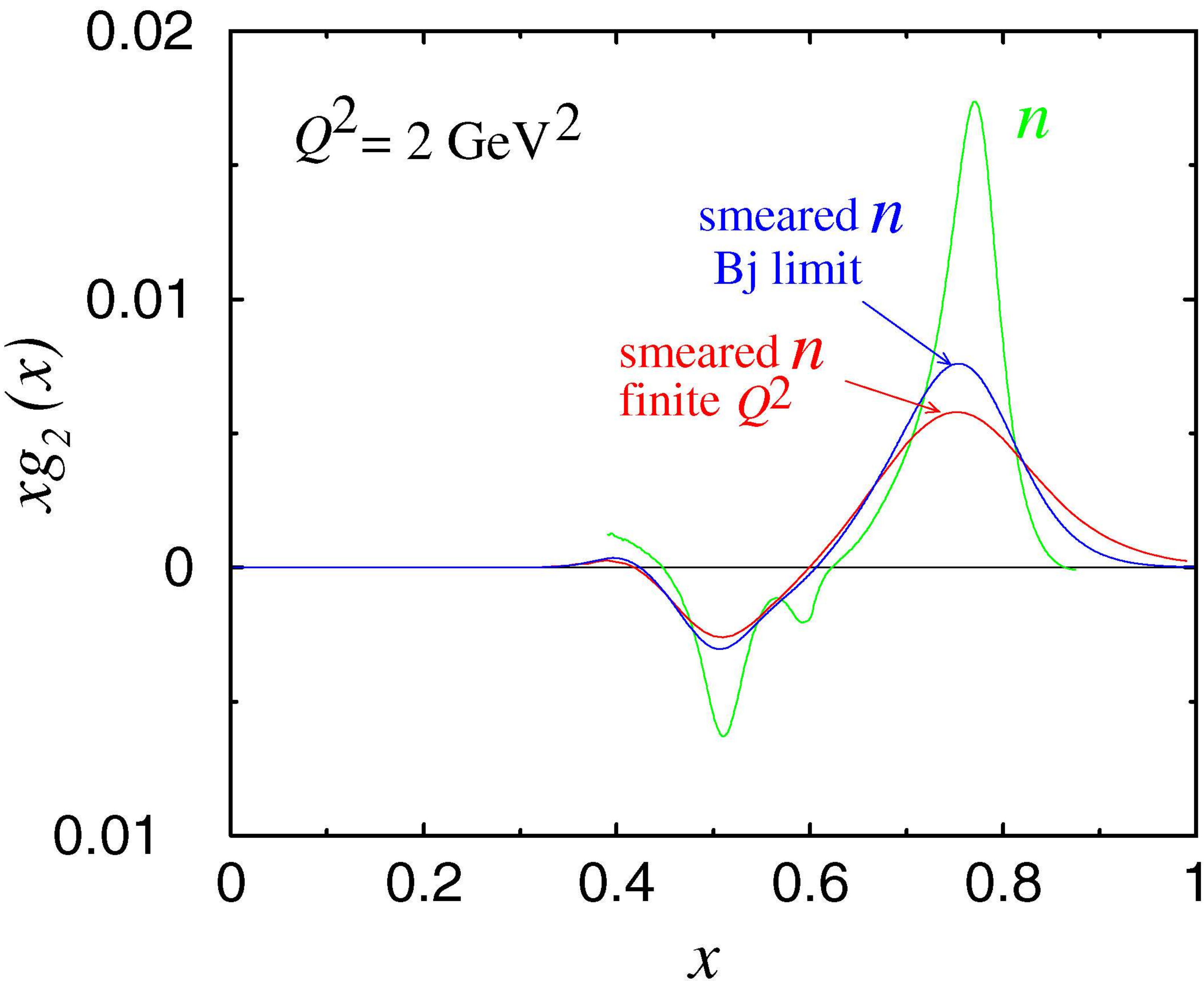
$$\begin{aligned}
&xg_1^{^3\mathrm{He}}(x,Q^2) + xg_2^{^3\mathrm{He}}(x,Q^2)\\
&= \sum_{N=p,n}\int d^3p\,dE\,(1-\frac{\epsilon}{M})\left\{\left[\left(1+\frac{p_x^2}{M^2}\right)f_1+\left(\vec{p}_x^{\,2}-\frac{1}{3}+\frac{2p_x^2}{3M^2}\right)f_2\right]zg_1^N(z,Q^2)\right.\\
&\left. + \left[\left(1+\frac{p_x^2}{M^2}(1-z/x)\right)f_1+\left(\vec{p}_x{}^2-\frac{1}{3}+\frac{2p_x^2}{3M^2}(1-z/x)-\frac{\gamma p_z\hat{p}_x^2}{M}\frac{z}{x}\right)f_2\right]zg_2^N(z,Q^2)\right\}
\end{aligned}$$

with $\gamma = \sqrt{1+4M^2x^2/Q^2}$ a kinematical factor parameterizing the finite Q^2 correction, $\epsilon \equiv \vec{p}^2/4M - E$, and $z = x/(1+(\epsilon+\gamma p_z)/M)$.

Nuclear corrections (continued)






0.02
0.01
0
0.01
0
0.2
0.4
0.6
0.8
1
$Q^2 = 2\ \mathrm{GeV}^2$
n
smeared n
Bj limit
smeared n
finite Q^2
$xg_2(x)$
x

How $g_2(x,Q^2)$ is usually obtained

$$g_2(x,Q^2) = \frac{\nu}{2E}\left[\frac{\nu\left[1+\epsilon \boldsymbol{R}(x,Q^2)\right](1+\gamma^2)\boldsymbol{F_2}(x,Q^2)\boldsymbol{A_\perp}(x,Q^2)}{(1-\epsilon)2x\left[1+\boldsymbol{R}(x,Q^2)\right]E'\sin\theta_e} - \boldsymbol{g_1}(x,Q^2)\right]$$

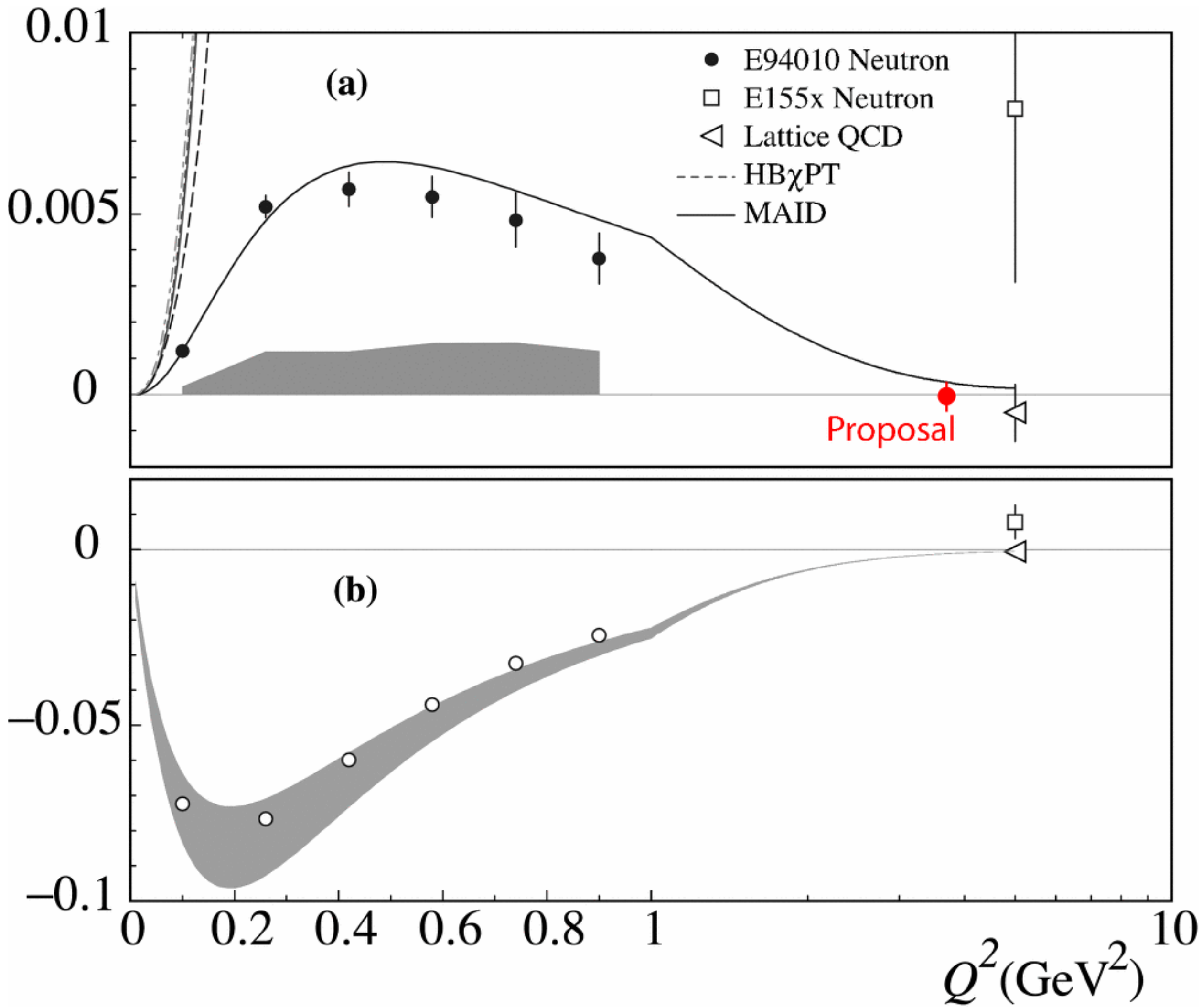
where $\nu = E - E'$, $\gamma^2 = Q^2/\nu^2$ and $\epsilon^{-1} = 1 + 2\left[1+\gamma^{-2}\right]\tan^2\theta/2$

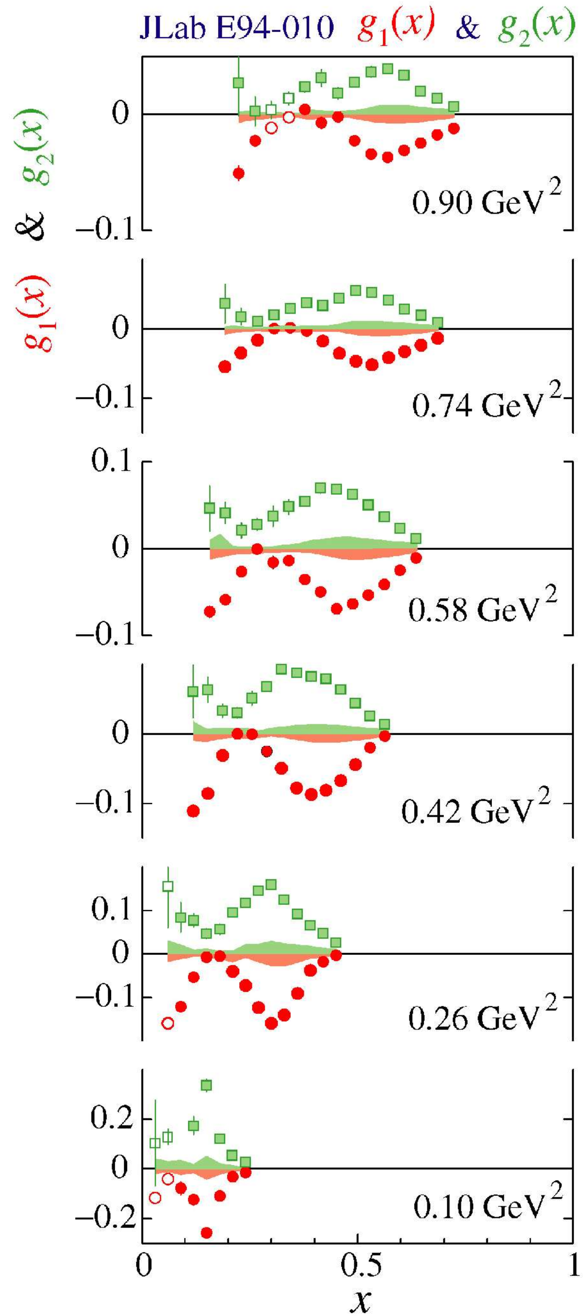
$\boldsymbol{F_2}(x,Q^2)$ NMC fit

$\boldsymbol{g_1}(x,Q^2)$ Fit to the data and evolution to a constant Q^2

$\boldsymbol{R}(x,Q^2)$ SLAC fit

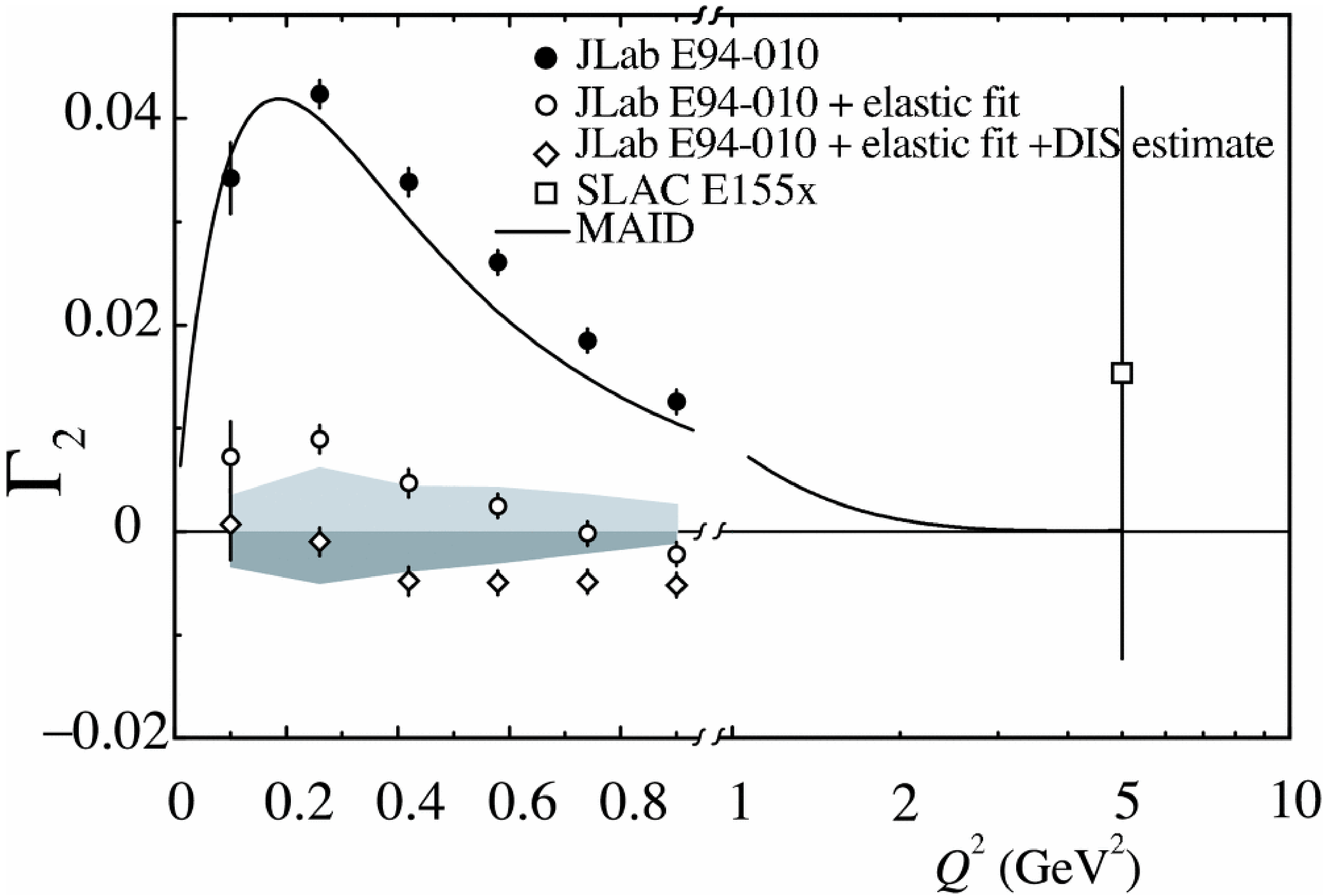
World Data on $\bar{d}_2$





JLab E94-010 $g_1(x)$ & $g_2(x)$
$g_1(x)$ & $g_2(x)$
0
−0.1
0.90 GeV^2
0
−0.1
0.74 GeV^2
0.1
0
−0.1
0.58 GeV^2
0
−0.1
0.42 GeV^2
0.1
0
−0.1
0.26 GeV^2
0.2
0
−0.2
0.10 GeV^2
0
0.5
1
x

JLab and SLAC experimental results on Γ_2



Burkhardt-Cottingham Sum Rule (1965-1966)

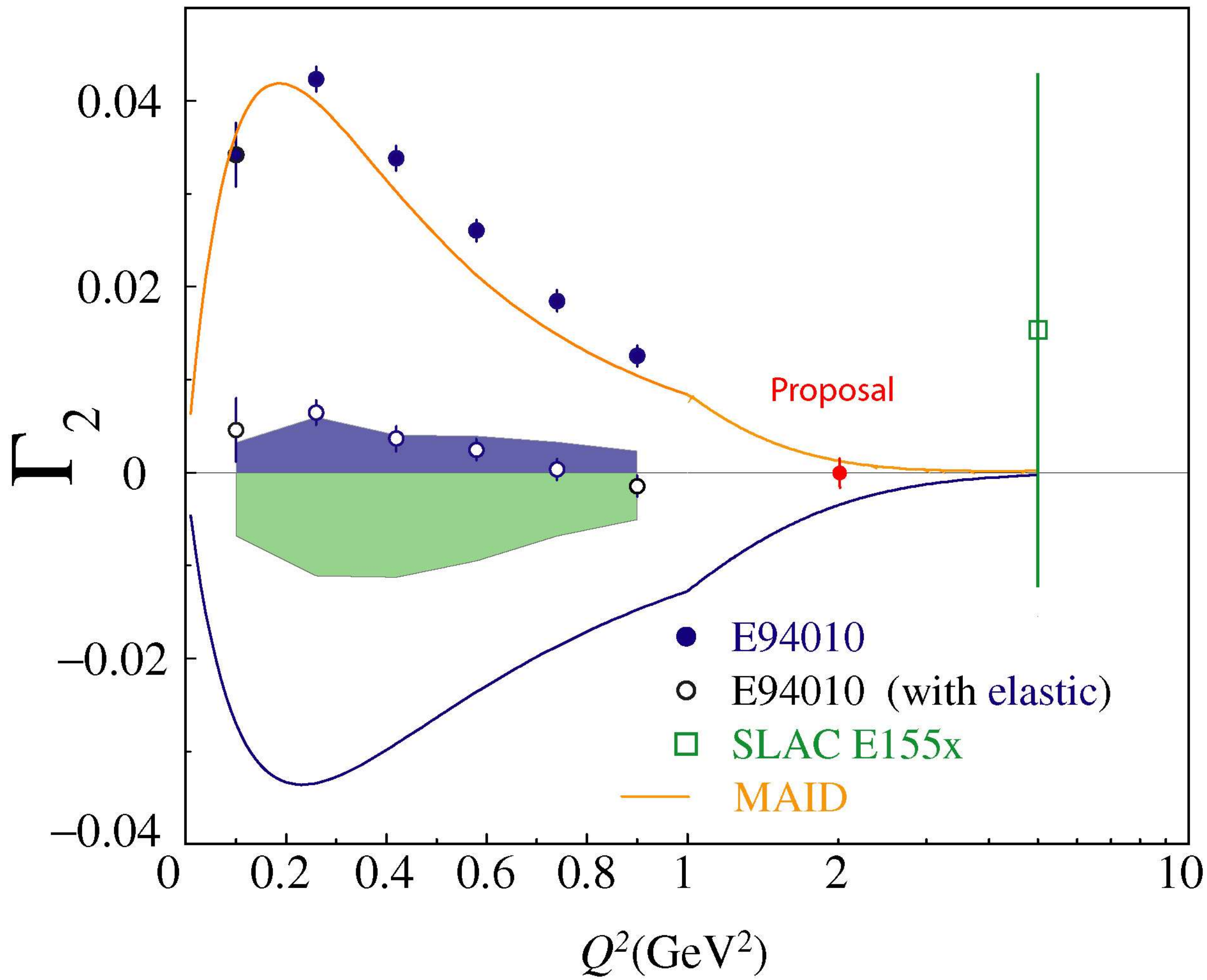
$$\Gamma_2(Q^2) = \int_0^1 g_2(x, Q^2)\; dx = 0$$

- Dispersion relation for a spin-flip Compton amplitude
  - ➡ *Causality*
  - ➡ *Analyticity*
  - ➡ *Absence of a J=0 pole with non polynomial residue*
- Doesn't follow from OPE and is valid at all Q^2

- Many scenarios of g_2's low x behavior which would invalidate the sum rule are discussed in the literature.

Expected Error on Γ_2

UPDATE



Kinematics of the proposed measurement

- Single beam energy 5.7 GeV
- BigBite fixed at single scattering angle (data divided into 10 bins during analysis)
- Avoid resonance region as much as possible.