Quark – Gluon correlations and Color Polarizabilities in the Nucleon

A precision measurement of the neutron d_2

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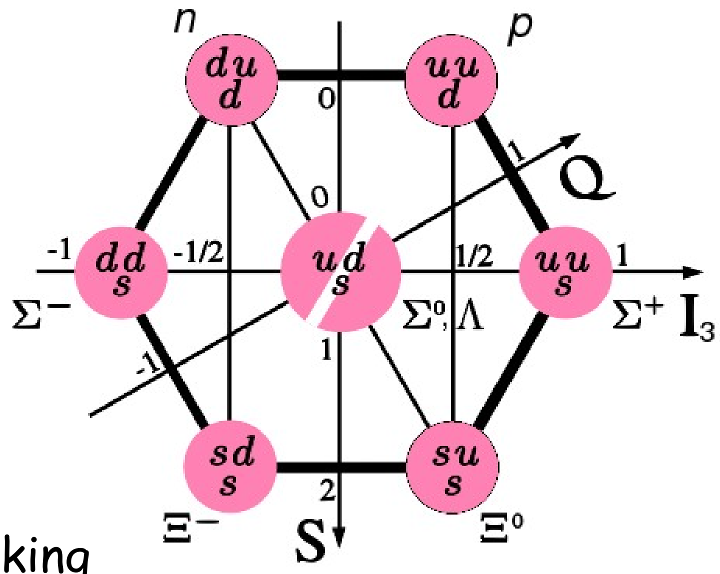
Motivation in 60s or less…



- 1960s: Parton/Quark model proposed
  - ➡ "8-fold way" (Gell-Mann)
  - ➡ Quarks confirmed (SLAC)
- 1970s: QCD refined/developed
  - ➡ quarks, gluons, color fields
  - ➡ valence-quark dominated models/thinking
- 1987: CERN measures the quark contribution to the proton spin
  - ➡ naïve expectation: 100%
  - ➡ after relativistic corrections: 75%
  - ➡ measured: 12 ± 16%

Spin structure in the nucleon

- Total nucleon spin $\frac{1}{2} = (\frac{1}{2})\ \Delta q + \Delta G + L_q + L_G$
  - ➡ Δq = quark spin (valence + sea quarks)
  - ➡ ΔG = gluon spin
  - ➡ $L_G + L_q$ = orbital angular momenta of gluons and quarks
    - Valence quark contribution: ~20%
    - Sea quark contribution: <5%
    - RHIC/COMPASS/HERMES: ΔG

- Understanding the gluon contribution is still underway
  - ➡ But how do we explore the gluon field?
    - direct hadronic probe (ie. RHIC)
    - exploit the spin interaction!

Polarized deep inelastic cross sections

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

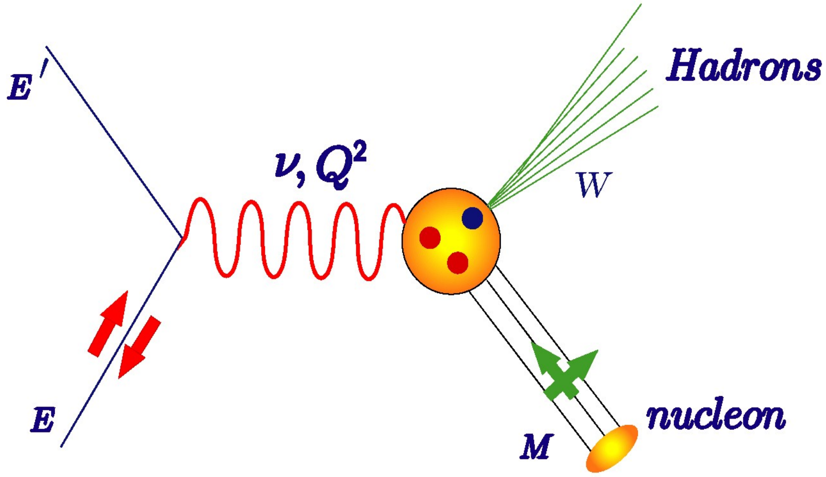
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2E g_2(x,Q^2)\right] = \Delta\sigma_{\perp}$$

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

ν = energy transfer.

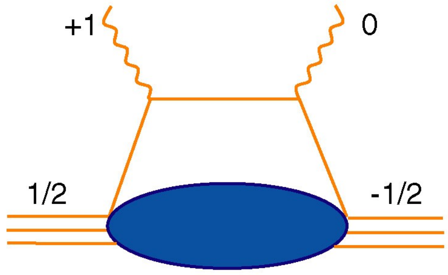
θ = scattering angle.

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



g_2 and Quark-Gluon Correlations

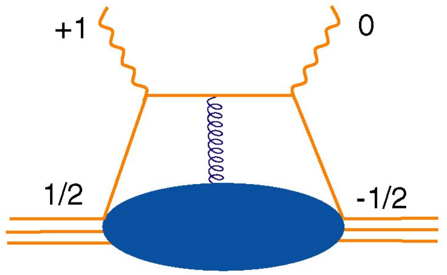
twist-2



Carry one unit of orbital angular momentum

QCD allows the helicity exchange to occur in two principle 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

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

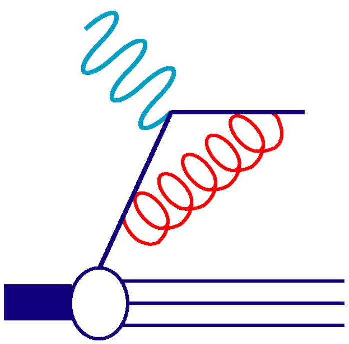
leading twist — higher twist

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

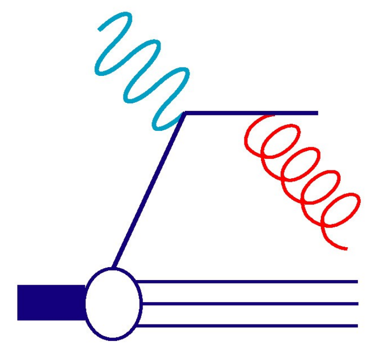
$g_A = 1.257$ and $a_8 = 0.579$ are the triplet and octet axial charge, respectively

$\Delta\Sigma$ = singlet axial charge

(Extracted from neutron and hyperon weak decay measurements)



$$g_A = \Delta u - \Delta d$$
$$a_8 = \Delta u + \Delta d - 2\Delta s$$
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$



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

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

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

Color "polarizabilities"

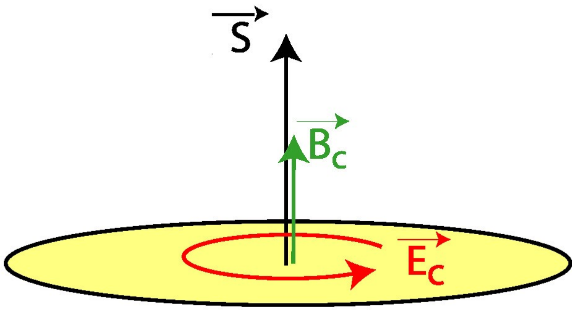
How does the gluon field respond when a nucleon is polarized ?

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

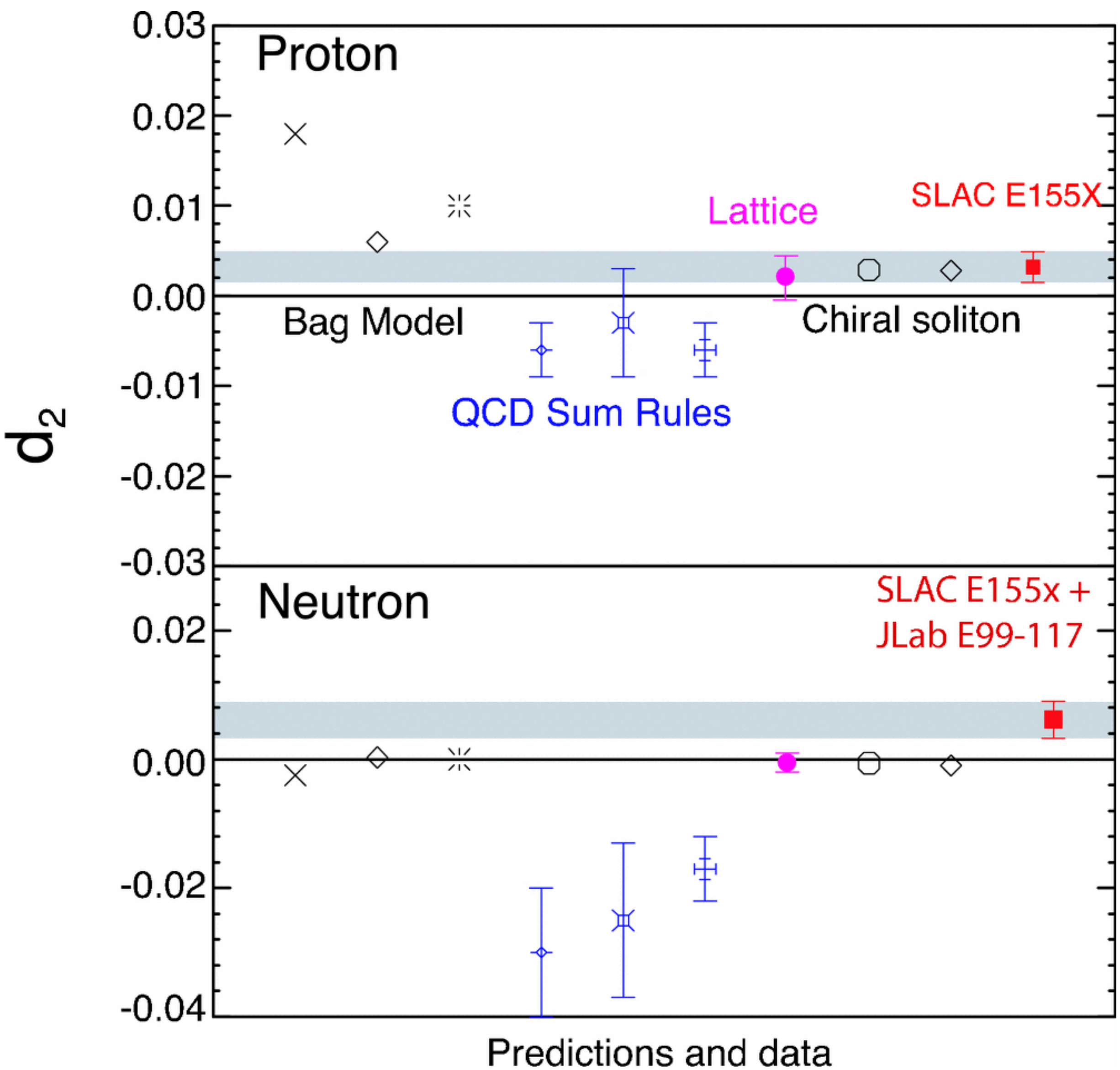
$$\vec{O}_E = \psi^\dagger \vec{\alpha} \times g \vec{\boldsymbol{E}} \psi$$



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

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

Model evaluations of d_2



The Experiment

- A 4.6 and 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 $\sigma_0^{^3\mathrm{He}}$ in conjunction with the parallel asymmetry $A_\parallel^{^3\mathrm{He}}$ and the transverse asymmetry $A_\perp^{^3\mathrm{He}}$ 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

$$\tilde{d}_2(x,Q^2) = x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]$$

$$= \frac{MQ^2}{4\alpha^2}\frac{x^2y^2}{(1-y)(2-y)}\sigma_0\left[\left(3\frac{1+(1-y)\cos\theta}{(1-y)\sin\theta} + \frac{4}{y}\tan\frac{\theta}{2}\right)A_\perp + \left(\frac{4}{y}-3\right)A_\parallel\right]$$

where,

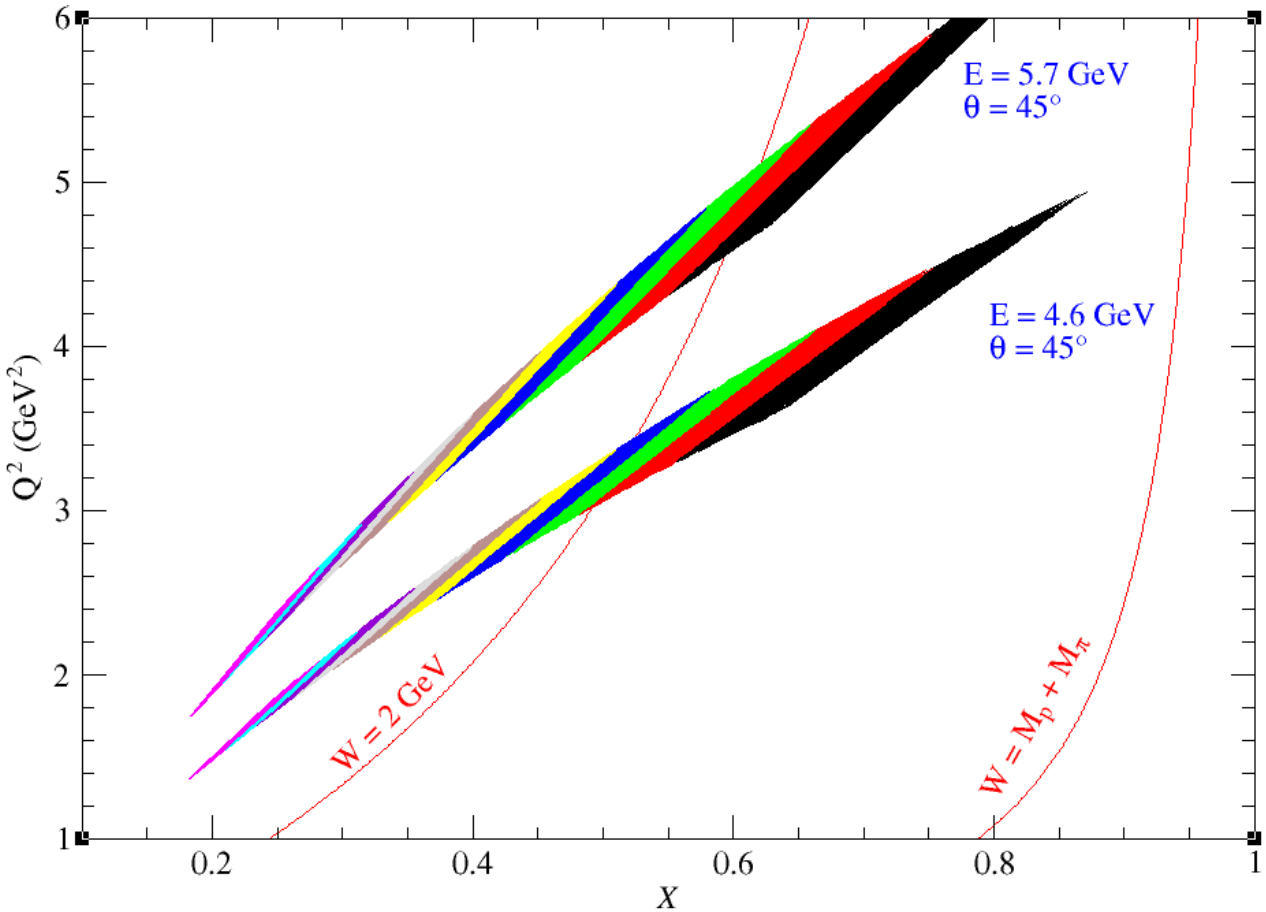
$$A_\perp = \frac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{2\sigma_0} \qquad A_\parallel = \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{2\sigma_0}$$

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

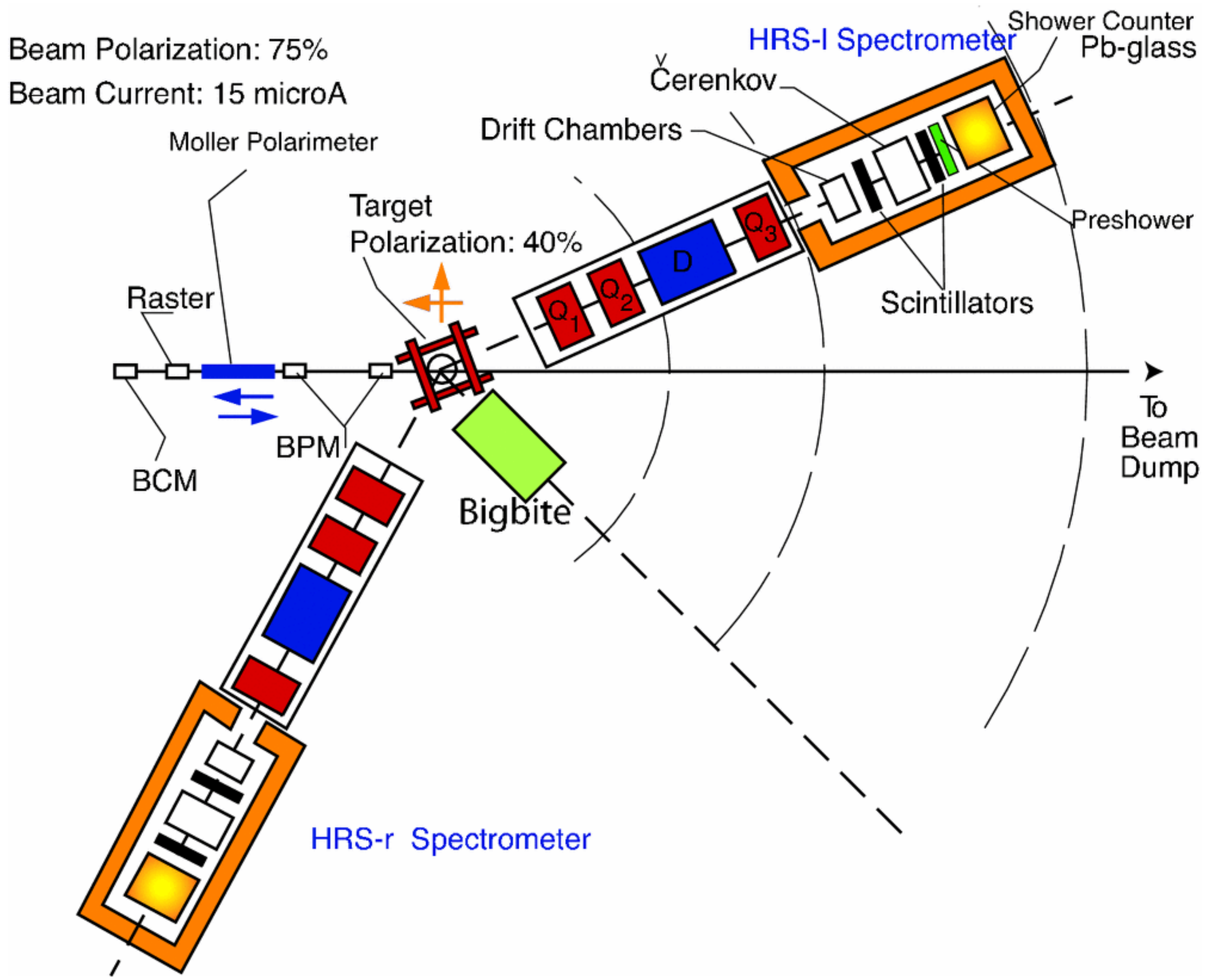
$$\Delta_\perp = \frac{(N^{\uparrow\Rightarrow} - N^{\uparrow\Rightarrow})}{(N^{\uparrow\Rightarrow} + N^{\uparrow\Rightarrow})} \qquad \Delta_\parallel = \frac{(N^{\downarrow\Uparrow} - N^{\uparrow\Uparrow})}{(N^{\downarrow\Uparrow} + N^{\uparrow\Uparrow})}$$

Kinematics of the measurement

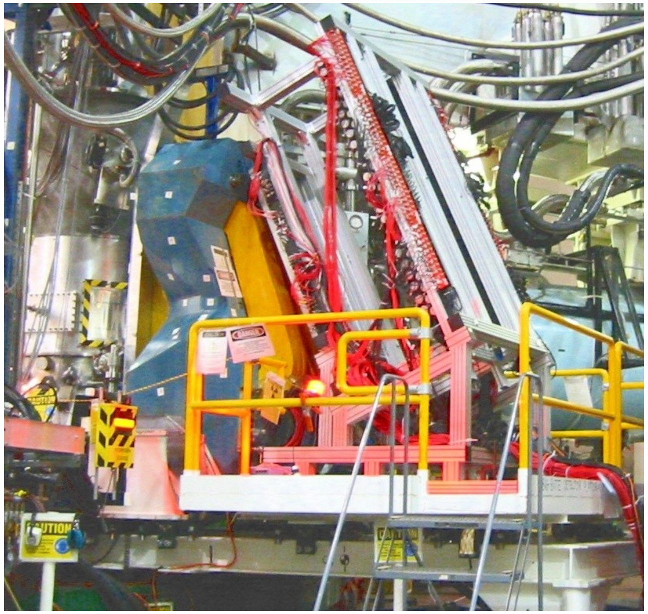
- Two beam energies
  4.6 and 5.7 GeV
  (4 pass, 5 pass)
- BigBite fixed at single scattering angle (q =45°)
  (data divided into 10 bins during analysis)
- Avoid resonance region as much as possible.

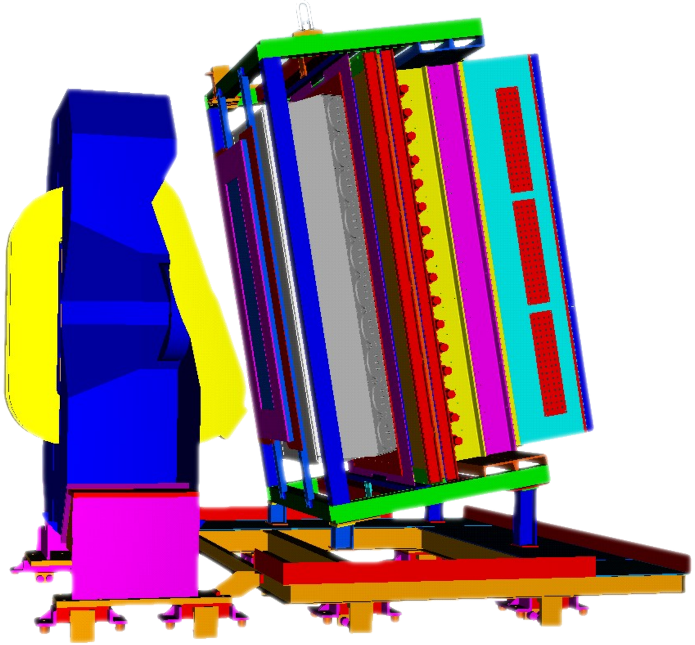


Floor configuration for this experiment



BigBite Configuration

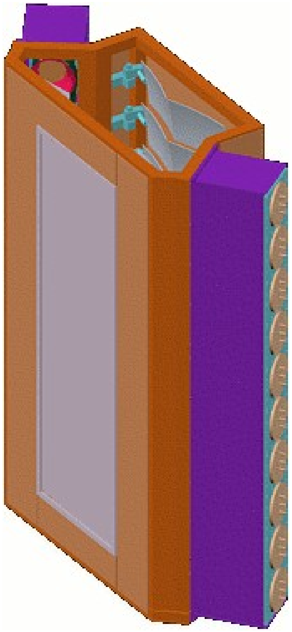


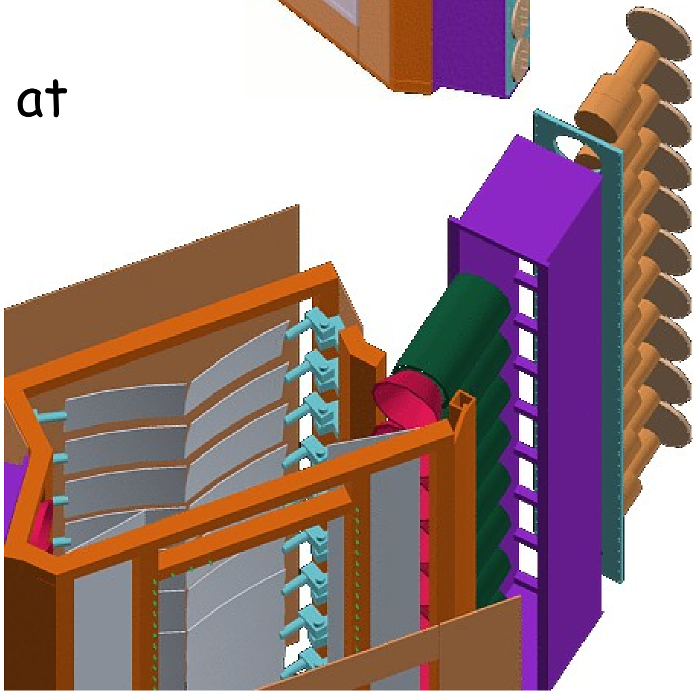


- Non-focusing, Large acceptance, Open geometry
- $\Delta p/p$ = 1 – 1.5% (@ 1.2 T) $\sigma(W)$ = 50 MeV
- Angular resolution 1.5 mr, extended target resolution 6 mm
- Large solid angle: ~64 msr
- Detector package:
  - ➡ 3 MWDCs, scintillator plane,
    Pb-glass pre-shower + shower
  - ➡ Gas Cherenkov (new)

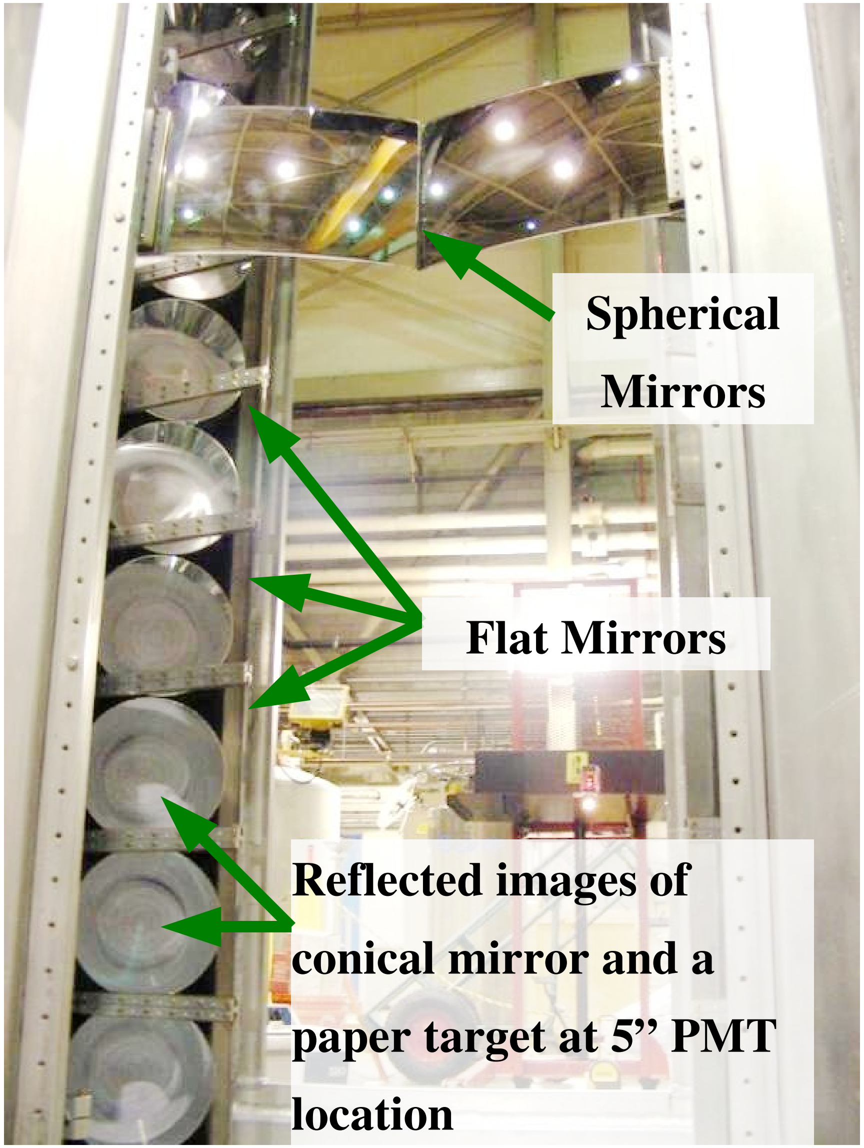
Cherenkov Design Parameters

- Dimensions: 200cm x 60cm x 60cm
  - ➡ sandwiched between wire chambers
- Radiator gas: C_4F_8O
  - ➡ π threshold: 2.51 GeV/c
  - ➡ ~20 photo-electrons / 40 cm electron track
    - Quartz PMT (Photonis XP4518)
    - mirror reflectivity: ~90%, 10% loss at PMT-gas interface
- >99% efficient with 3-4 p.e. threshold
  - negl. pion contamination
    minimum π/e rejection ratio
    1000:1 online





BB Cerenkov During Assembly (viewed from rear)



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

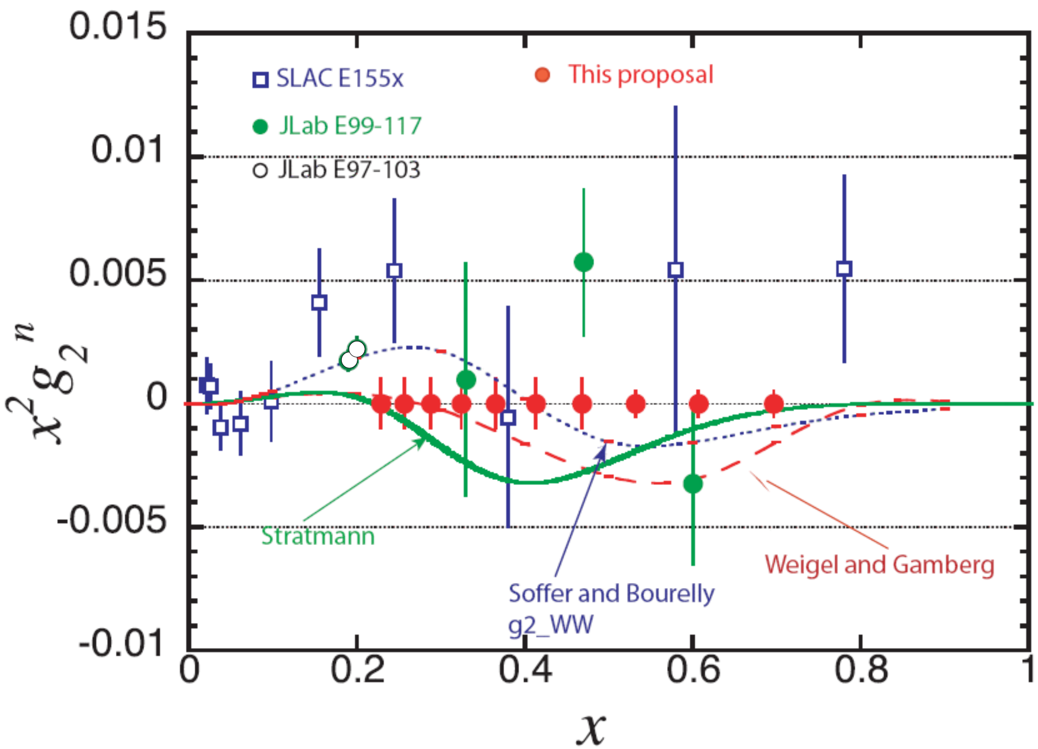
Online triggers

e-	2-5 kHz
e+	<1 kHz

π-	90 kHz
π+	90 kHz
p	50 kHz
n	50 kHz

Removed via online cuts

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

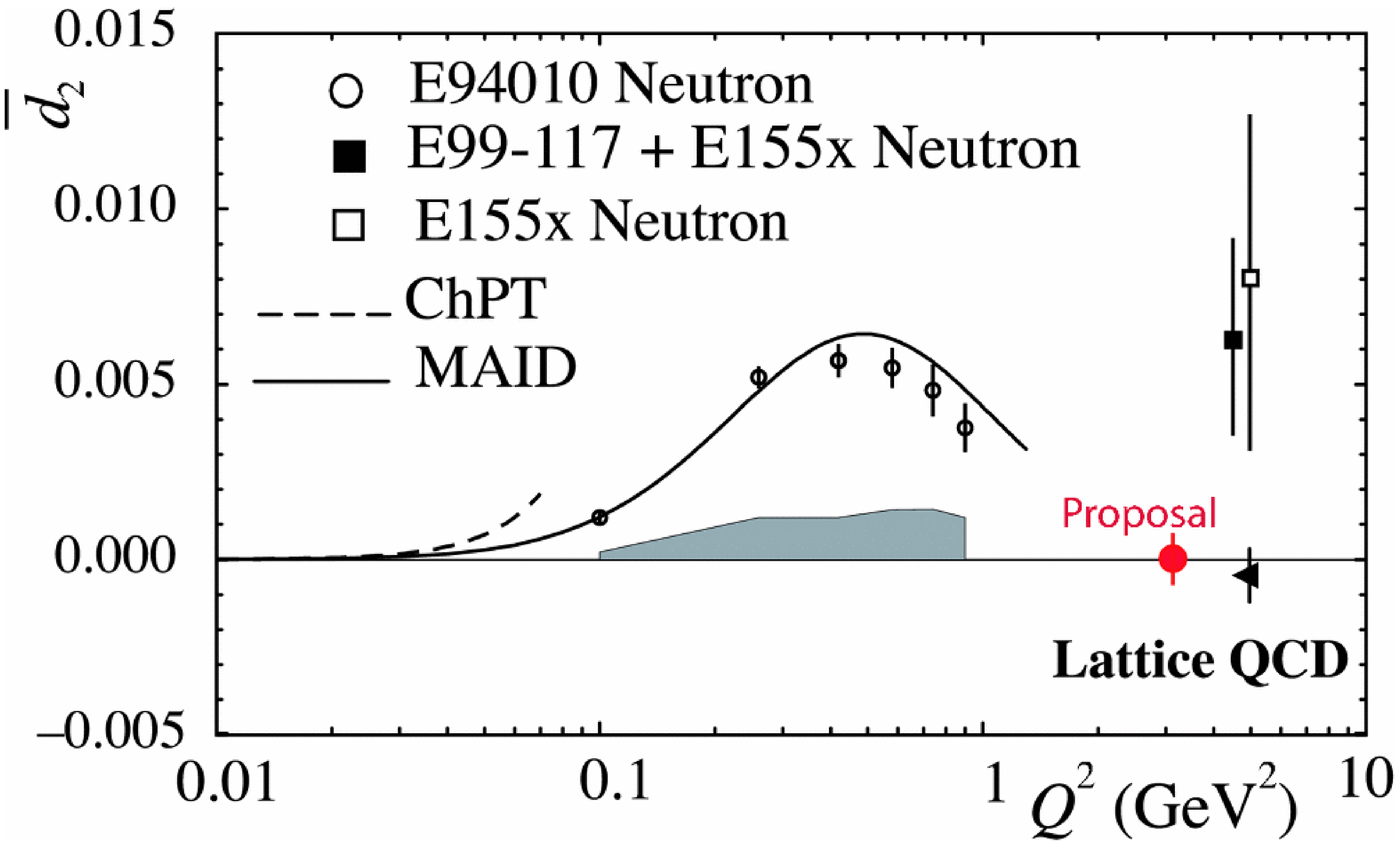


- g_2 for ^{3}He is extracted directly from L and T spin-dependent cross section measurements within the same experiment.
- The nuclear corrections will be applied to the moments not to the structure functions.
- SLAC E155x g_2 data points at high x are evolved from Q^2 as large as 16 GeV^2 to 5 GeV^2

Systematic Error Contributions to d_2^n

Item description	Subitem description	Relative uncertainty
Target polarization		3 %
Beam polarization		3 %
Asymmetry (raw)		
	• Target spin direction (0.1°)	$< 5 \times 10^{-4}$
	• Beam charge asymmetry	$<$ 50 ppm
Cross section (raw)		
	• PID efficiency	≈ 1 %
	• Background Rejection efficiency	≈ 1 %
	• Beam charge	$<$ 1 %
	• Beam position	$<$ 1 %
	• Acceptance cut	2-3 %
	• Target density	$<$ 2%
	• Nitrogen dilution	$<$ 2%
	• Dead time	$<$1%
	• Finite Acceptance cut	$<$1%
Radiative corrections		≤ 5 %
From ^{3}He to Neutron correction		5 %
Total systematic uncertainty		≤ 10 %
Estimate of contributions to d_2 from unmeasured regions	$\int_{0.003}^{0.23} \tilde{d}_2^n \, dx$	4.8×10^{-4}
	$\int_{0.70}^{0.999} \tilde{d}_2^n \, dx$	5.0×10^{-5}
Projected absolute statistical uncertainty on d_2		$\Delta d_2 \approx 5 \times 10^{-4}$
Projected absolute systematic uncertainty on d_2 (*assuming* $d_2 = 5 \times 10^{-3}$)		$\Delta d_2 \approx 5 \times 10^{-4}$

Expected Error on d_2



Summary (part 1)

- We will 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 ($0.23 < x < 0.65$)
  - ➡ Also, measure Q^2 evolution of $x^2\bar{g}_2$ over the same x region
- 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!
- Dramatically improve our knowledge of $g_2^n(x)$
  - ➡ double the data points for $x > 0.2$, all with better precision
- **Scheduled for Jan 20 – Feb 22, 2009.**

12 GeV Measurement

The proposal for Hall C and SHMS/HMS

- An Experiment in Hall C: (approved! Pac30, 2007)
  - A polarized electron beam of 11.0 GeV and polarized ^{3}He target
  - Measure $\Delta\sigma_\perp = \sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}$, $\Delta\sigma_{||} = \sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}$ for $^3\vec{\mathrm{He}}(\vec{e}, e')$ reaction using both the SHMS and HMS running in parallel for 3 kinematic settings each
    - SHMS: (p_0= 8.0 GeV/c, θ = 11.0°), (p_0= 7.0 GeV/c, θ = 13.3°), (p_0= 6.3 GeV/c, θ = 15.5°)
    - HMS: (p_0= 4.2 GeV/c, θ = 13.5°), (p_0= 5.0 GeV/c, θ = 16.4°), (p_0= 3.4 GeV/c, θ = 20.0°)
- Determine d_2^n and g_2^n using the relations:

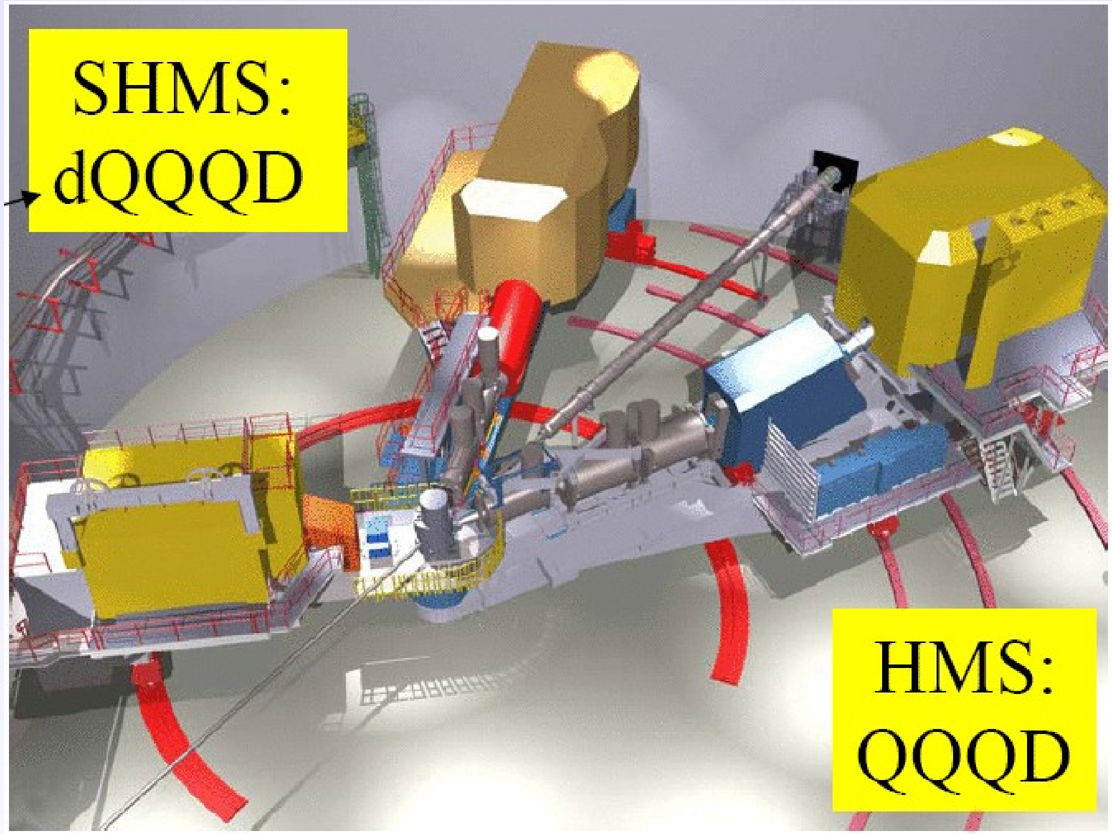
$$\tilde{d}_2 = x^2(2g_1+3g_2) = \frac{MQ^2\nu}{8\alpha_e^2}\frac{E}{E'}\frac{x^2(4-3y)}{(E+E')}\left[\Delta\sigma_{||} + \left(\frac{4-y}{(1-y)(4-3y)\sin\theta_e} - \cot\theta_e\right)\Delta\sigma_\perp\right]$$

$$g_2 = \frac{MQ^2\nu^2}{4\alpha_e^2}\frac{1}{2E'(E+E')}\left[-\Delta\sigma_{||} + \frac{E+E'\cos\theta_e}{E'\sin\theta_e}\Delta\sigma_\perp\right]$$

where $\Delta\sigma_{||} = \sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}$, $\Delta\sigma_\perp = \sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}$ and $y = \nu/E$.

I_{beam} = 10 μA
P_{beam} = 0.8
P_{targ} = 0.5

Floor layout for Hall C

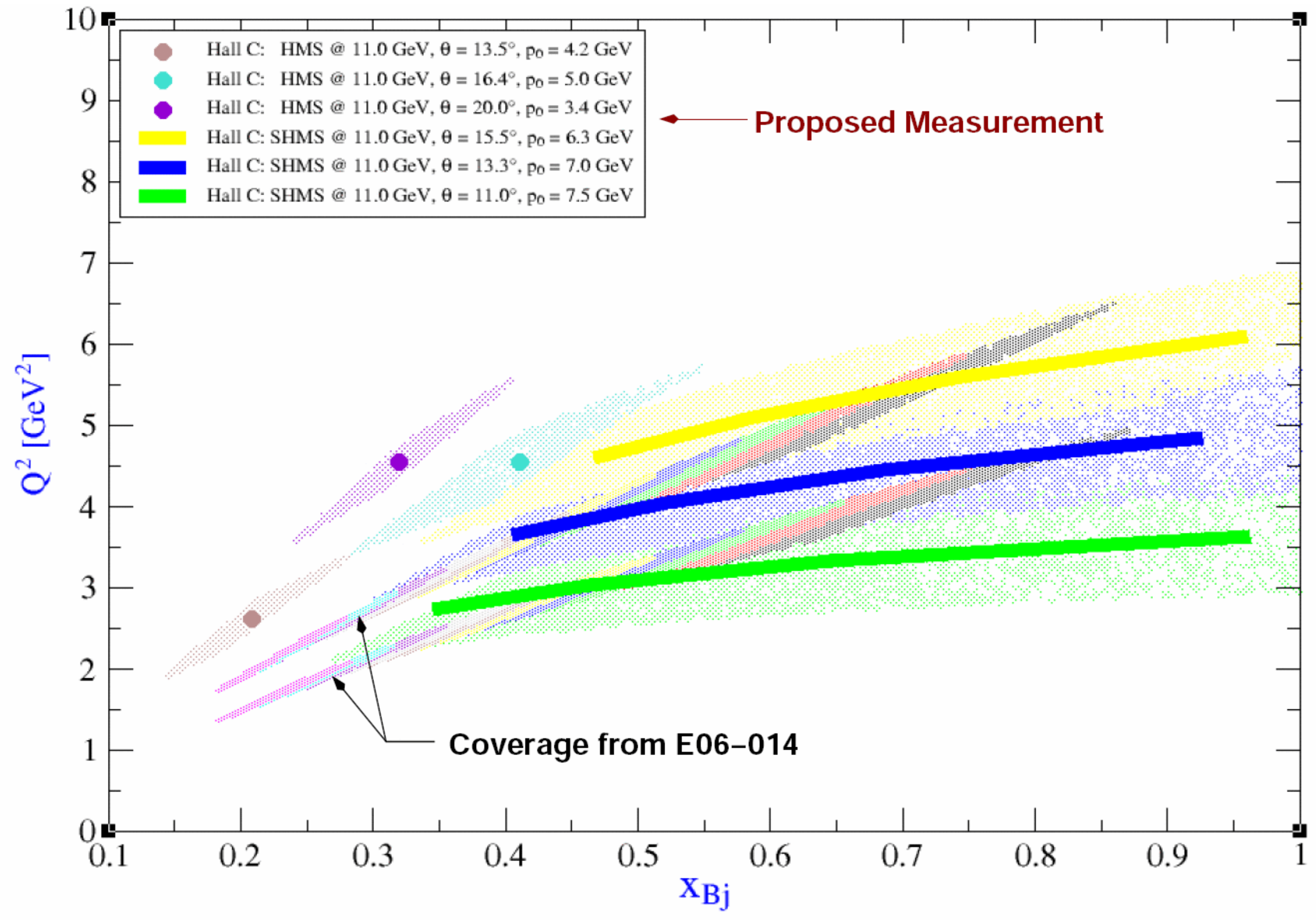


Hall C

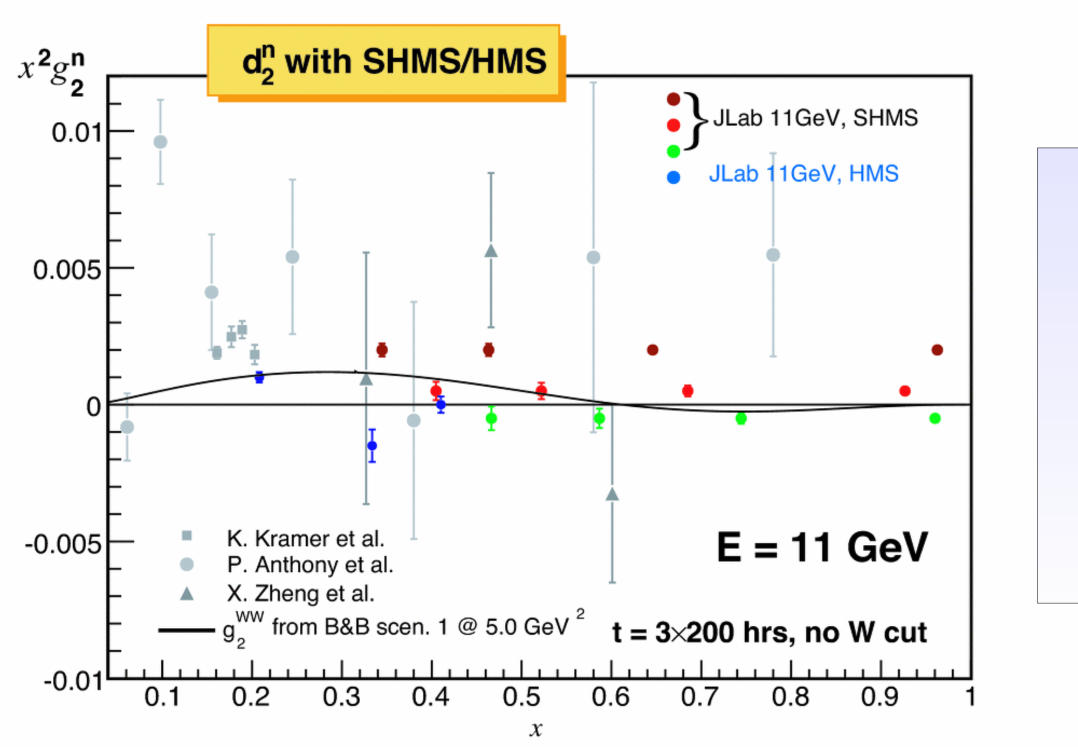
- One beam energy
  - ➡ 11 GeV
- Each arm measures a total cross section independent of the other arm.
- Experiment split into three pairs of 200 hour runs with spectrometer motion in between.

- SHMS collects data at Θ = 11°, 13.3° and 15.5° for 200 hrs each
  - ➡ data from each setting divided into 4 bins
- HMS collects data at Θ = 13.5°, 16.4° and 20.0° for 200 hrs each

Kinematics for Hall C (cont...)



Projected $x^2 g_2(x,Q^2)$ results from Hall C



Projected points are vertically offset from zero along lines that reflect different (roughly) constant Q^2 values from 2.5—6 GeV^2.

- g_2 for ^3He is extracted directly from L and T spin-dependent cross sections measured within the same experiment.
- Strength of SHMS/HMS:
  nearly constant Q^2 (but less coverage for $x < 0.3$)

The End

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

Nuclear corrections (continued)

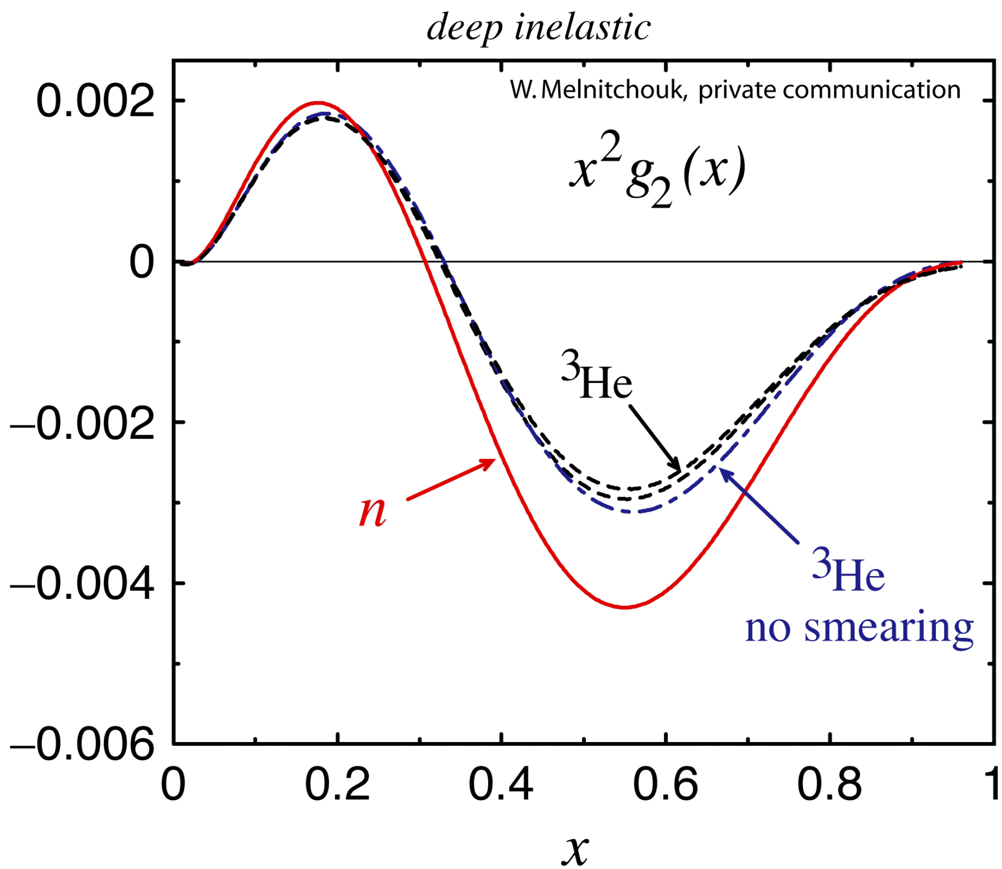
$$S(\vec{p}, E) = \frac{1}{2}\left(f_0 + f_1 \vec{\sigma}_N \cdot \vec{\sigma}_A + f_2 \left[\vec{\sigma}_N \cdot \hat{p}\ \vec{\sigma}_A \cdot \hat{p}\ - \frac{1}{3}\vec{\sigma}_N \cdot \vec{\sigma}_A\right]\right)$$

$$x g_1^{^3\mathrm{He}}(x, Q^2) + (1-\gamma^2) x g_2^{^3\mathrm{He}}(x, Q^2)$$
$$= \sum_{N=p,n} \int d^3p\ dE\ (1 - \frac{\epsilon}{M})\left\{\left[\left(1 + \frac{\gamma p_z}{M} + \frac{p_z^2}{M^2}\right) f_1 + \left(-\frac{1}{3} + \hat{p}_z^2 + \frac{2\gamma p_z}{3M} + \frac{2p_z^2}{3M^2}\right) f_2\right]\ z g_1^N(z, Q^2)\right.$$
$$\left. + (1-\gamma^2)(1 + \frac{\epsilon}{M}\left[f_1 + \left(\frac{p_z^2}{\vec{p}^2} - \frac{1}{3}\right) f_2\right] \frac{z^2}{x} g_2^N(z, Q^2)\right\}$$

$$x g_1^{^3\mathrm{He}}(x, Q^2) + x g_2^{^3\mathrm{He}}(x, Q^2)$$
$$= \sum_{N=p,n} \int d^3p\ dE\ (1 - \frac{\epsilon}{M})\left\{\left[\left(1 + \frac{p_x^2}{M^2}\right) f_1 + \left(\vec{p}_x^2 - \frac{1}{3} + \frac{2p_x^2}{3M^2}\right) f_2\right] z g_1^N(z, Q^2)\right.$$
$$\left. + \left[\left(1 + \frac{p_x^2}{M^2}(1 - z/x)\right) f_1 + \left(\vec{p}_x^{\ 2} - \frac{1}{3} + \frac{2p_x^2}{3M^2}(1 - z/x) - \frac{\gamma p_z \hat{p}_x^2}{M}\frac{z}{x}\right) f_2\right] z g_2^N(z, Q^2)\right\}$$

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 $z = x/(1 + (\epsilon + \gamma p_z)/M)$.

From ³He to Neutron

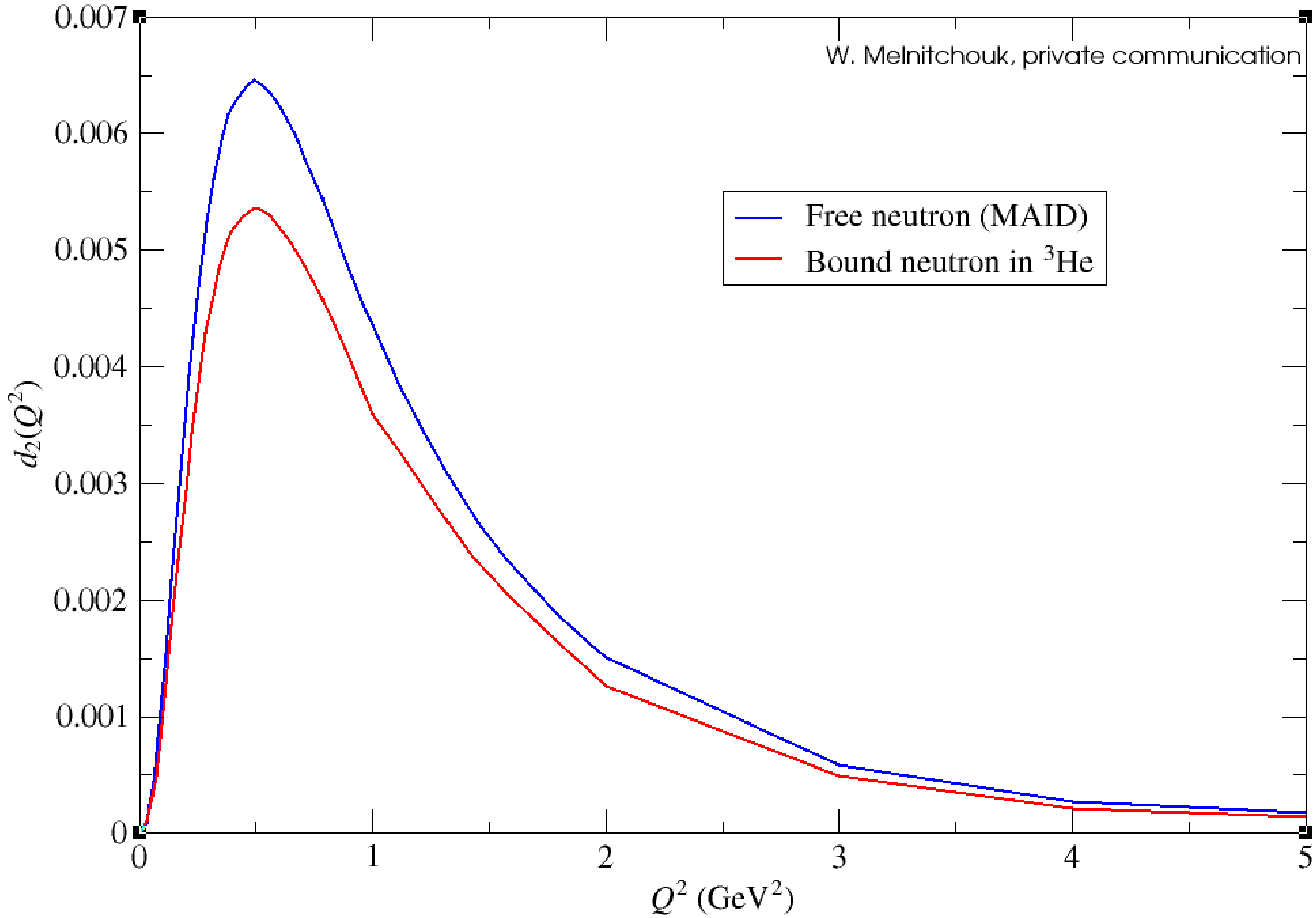


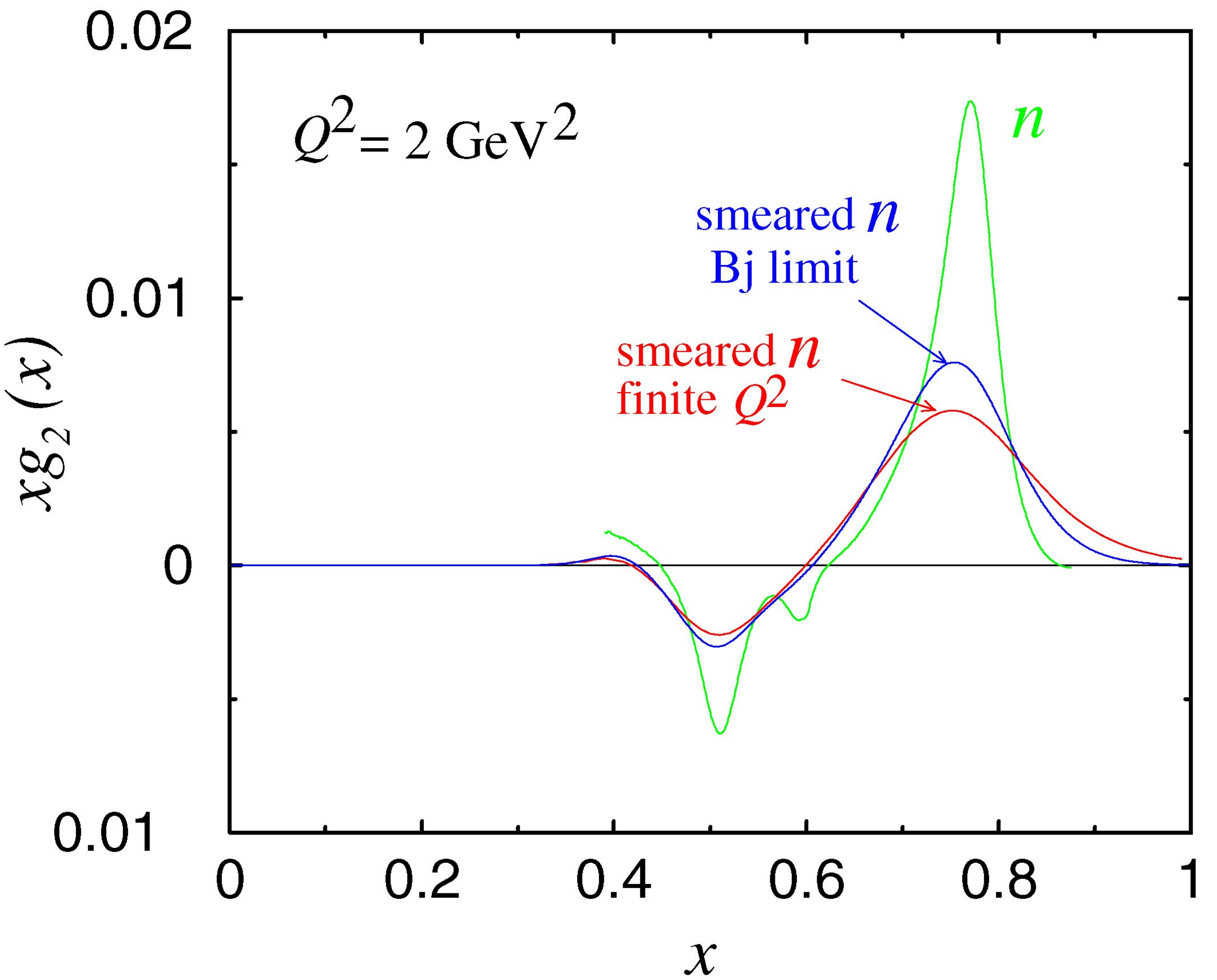
- ✓Correction large for g_2 but much smaller for d_2
- ✓About 5% difference between additive or convolution methods or between potential models

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

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

Nuclear corrections (continued)




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

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

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

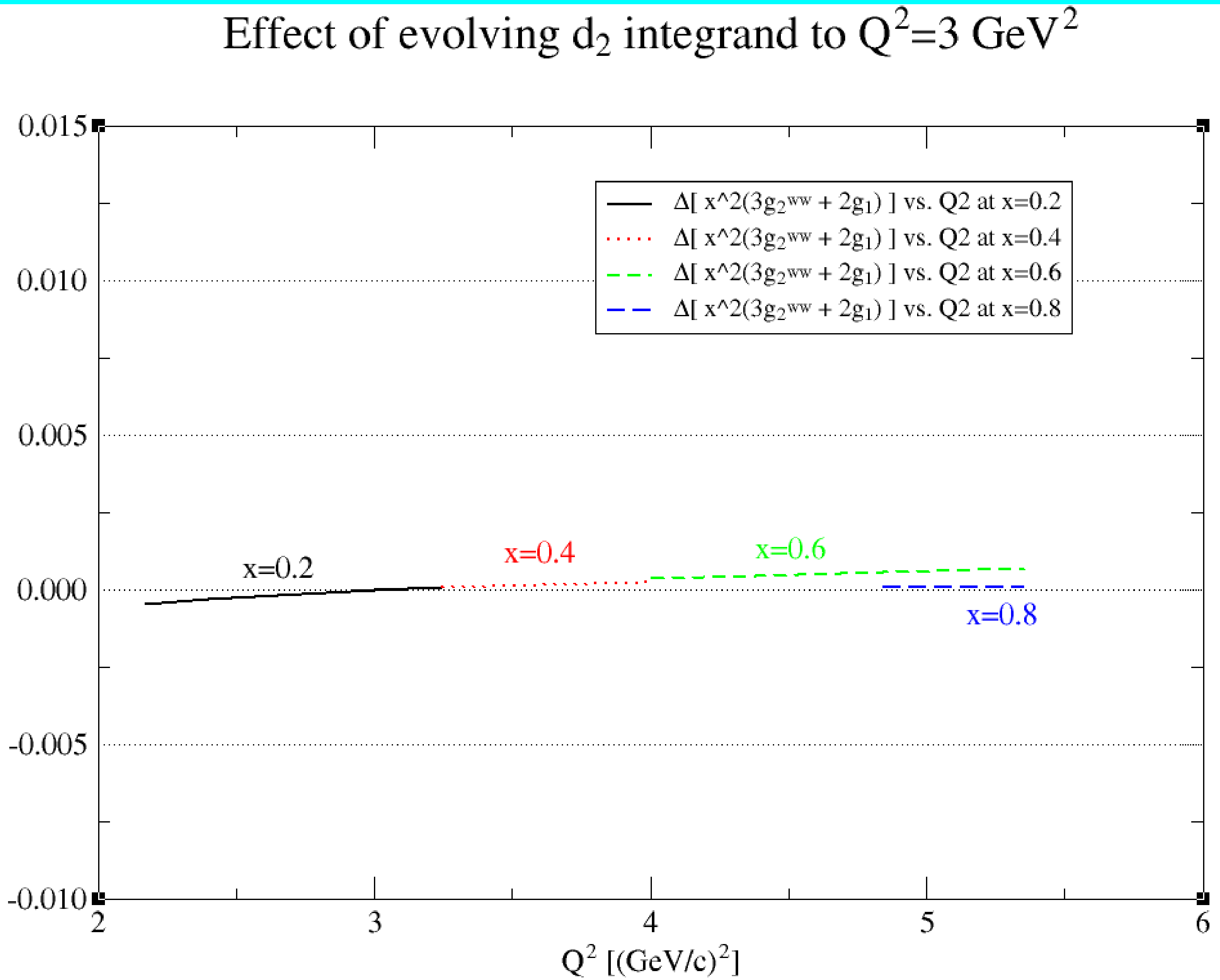
where $\nu = E - E'$, $\gamma^2 = Q^2/\nu^2$ and $\epsilon^{-1} = 1 + 2\left[1+\gamma^{-2}\right]\tan^2\theta/2$

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

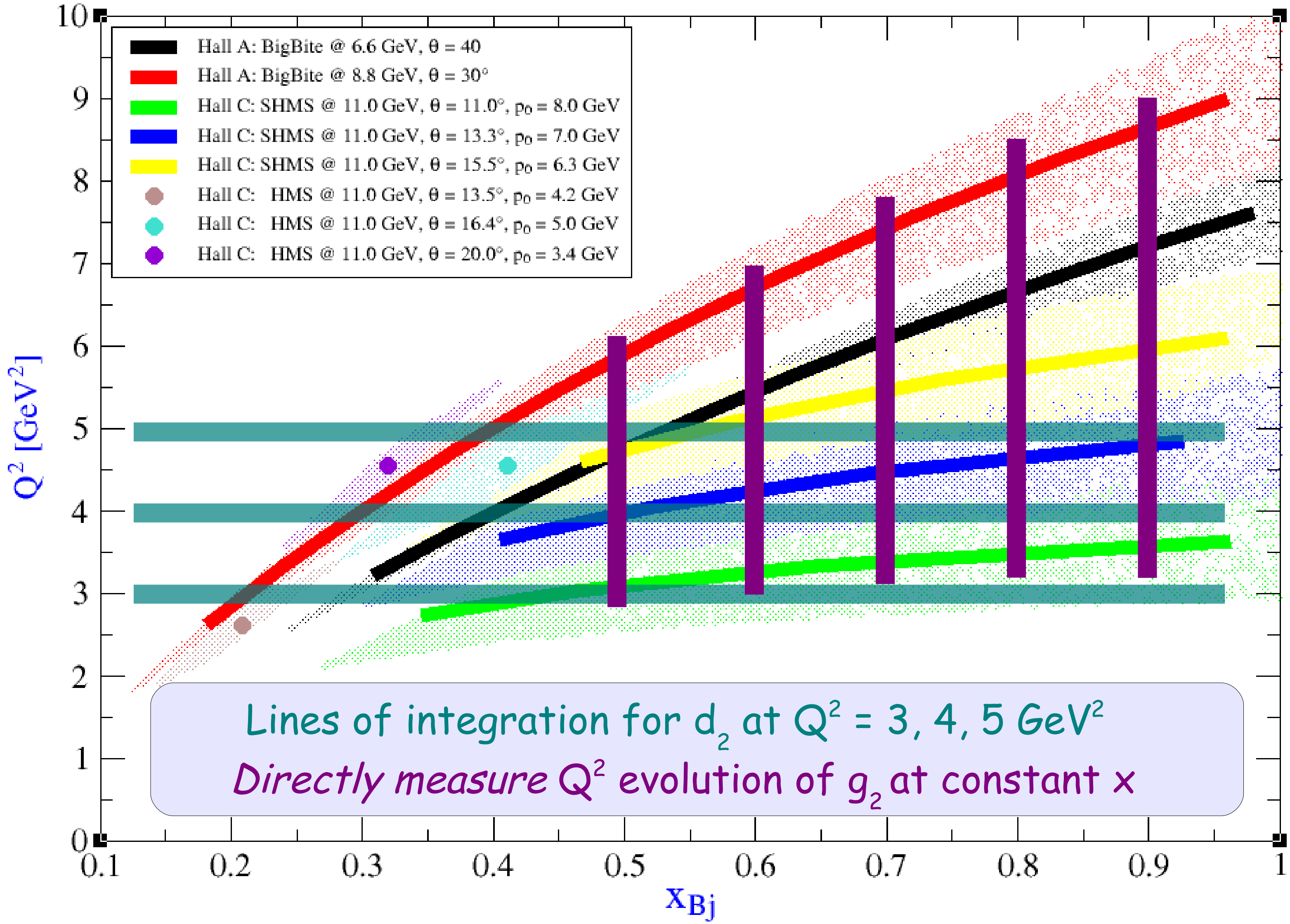
$\boldsymbol{g_1}(x,Q^2)$ Fit to the data and evolution to a constant Q^2

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

d_2 integrand evolution from g_1 and g_2^{ww}



d_2 and g_2 evolution (both Halls)



Lines of integration for d_2 at Q^2 = 3, 4, 5 GeV^2

Directly measure Q^2 evolution of g_2 at constant x

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

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