Probing the Nucleon with Spin

Overview of the talk

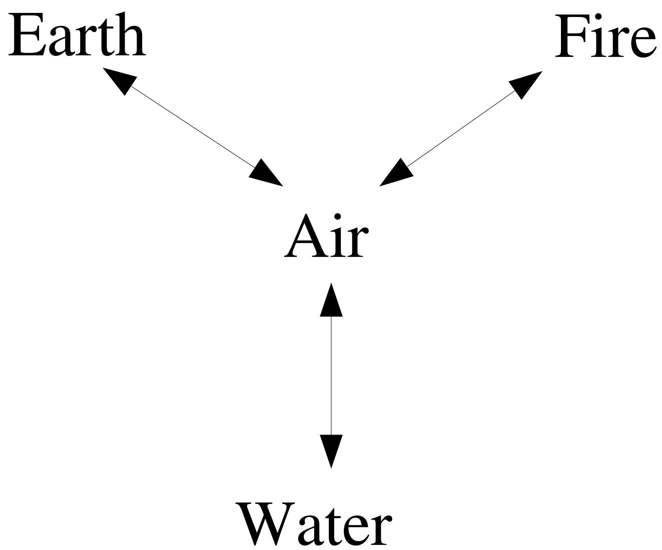
- This talk will be less focused on detailed nuclear physics, and more of a general overview.
  - ➡ Where did our field come from, and where are we now?
- Start at the beginning (several thousand years ago) and end with an upcoming spin-physics measurement at JLab.
  - ➡ all in 55 minutes or less,
  - ➡ I'm going to gloss over a few details...

. . . Overview

- What is the point of our effort?
  - ➡ We're trying to understand what the world is made of.
    - The world is beautiful, there is pleasure in the study.
    - Knowledge = control (more "practical" reason).
  - ➡ What do we know so far?
- Overview of Particle scattering Formalism and Jargon
  - ➡ *x, ν, Q^2, W, F_1, g_2, Θ, ... huh?*
  - ➡ Polarized and unpolarized structure functions
    - (experimental meat and potatoes)
- d_2^n : Measuring quark/gluon correlations in the nucleon
  - ➡ *An upcoming experiment at JLab*

What is that stuff made of?

- Anaximenes
  (Greek philosopher: 6^{th} century BC)
  - ➡ Air was universal, everything is air at different densities.
  - ➡ Theory later expanded to include 4 elements



Alchemy

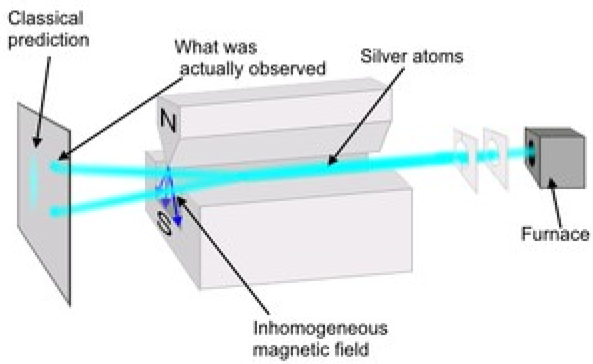
- Alchemy (practiced in one form or another for 2000 years):
  - Latin dictum:
    - SOLVE ET COAGULA (Separate and Join together)
  - Precursor to:
    - Chemistry, metallurgy, physics
  - Reagents:
    - Water, Metal (and oxides), Salts, Acids, ...
    - Refinement and reduction was an important goal, but few true elemental chemicals.

Chemistry

- Chemistry
  - ➡ 1809: 47 true elements identified, patterns in chemical combination being recognized.
  - ➡ Mendeleev's Periodic Table (1869)
    - arranged elements by atomic mass
    - columns (periods) have similar chemical properties (ie. valence electron structure)
    - predicted other elements and left spaces in the table for them
  - ➡ Getting pretty complicated – hints that this is a manifestation of some simpler underlying structure.
    - ie. quantization of the atomic masses

Atomic Physics

- 1886: Radioactivity discovered (Bequerel, Curies)
- 1897: Thompson discovers atomic electrons
- 1914: Rutherford identifies discrete protons exist within nucleus
- 1922: Stern-Gerlach experiment proves angular momentum is quantized
  - ➡ but "intrinsic" spin not on the table yet...



Atomic Physics

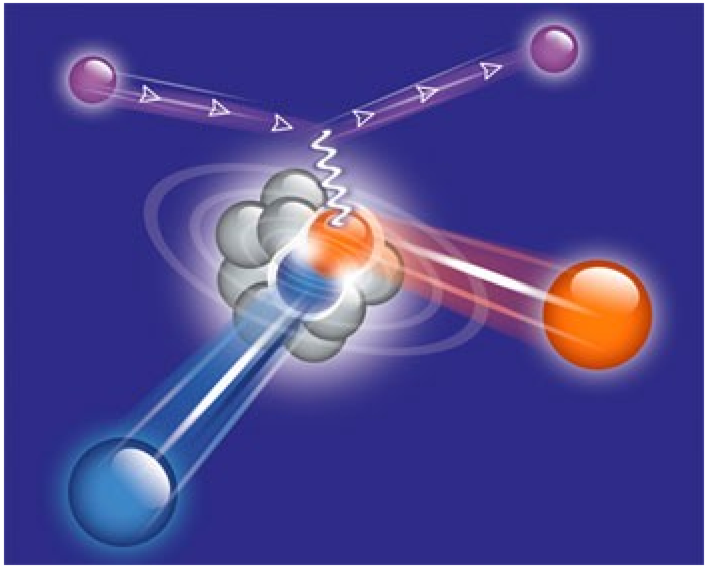
- 1925: Spin invoked to explain Zeeman splitting of atomic spectra in external magnetic field (later incorporated into Pauli's exclusion principle and the spin quantum number)
- 1925: Heisenberg wave mechanics, Schrodinger eqn
- 1928: Dirac equation
  - ➡ Relativistic QM description of a spin-1/2 particle
- 1932: Chadwick discovers the neutron
  - ➡ Final key to explaining the Periodic Table

Nuclear Physics

- 1930s on:
  - ➡ dozens and dozens of strongly interacting fermion states (spin 1/2, 3/2, 5/2...) have been identified
    - Δ, Θ, Λ, Σ... (Baryons)
  - ➡ dozens and dozens of strongly interacting bosons (spin 0, 1, ...) have been identified
    - σ, ρ, ω, η, ... (Mesons)
- That's a *lot* of "elementary" particles...
  - ➡ Remind you of the Periodic Table?
  - ➡ Something more is going on here

Scattering Experiments

- Most of these particles discovered by smashing sub-atomic particles into a target and measuring what comes out.



- Time to define some technical terms so we can talk about how scattering experiments are done…

"Unpolarized deep inelastic cross sections"

- Cross section measures the probability you'll find an electron of energy E' scattered into a solid angle $d\Omega$:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left(\frac{2}{M} F_1(x, Q^2) \sin^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \cos^2 \frac{\theta}{2} \right)$$

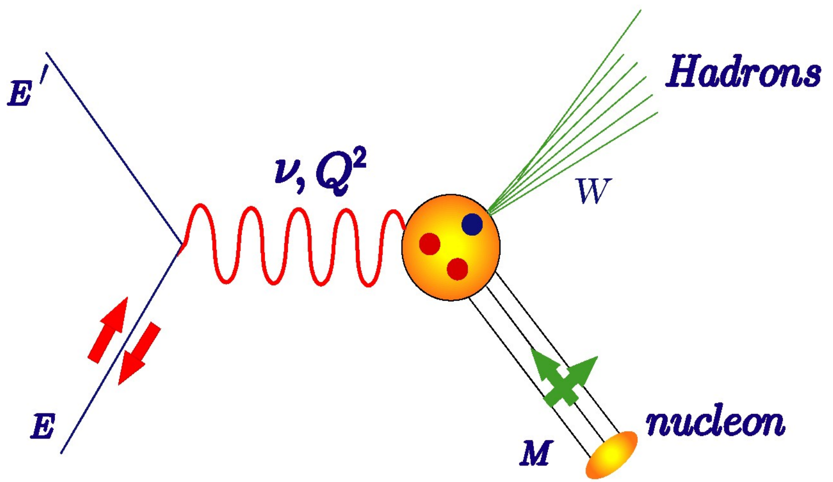
- F's are Structure Functions. They encode our (lack of) knowledge about the target nucleon.

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

ν = energy transfer.

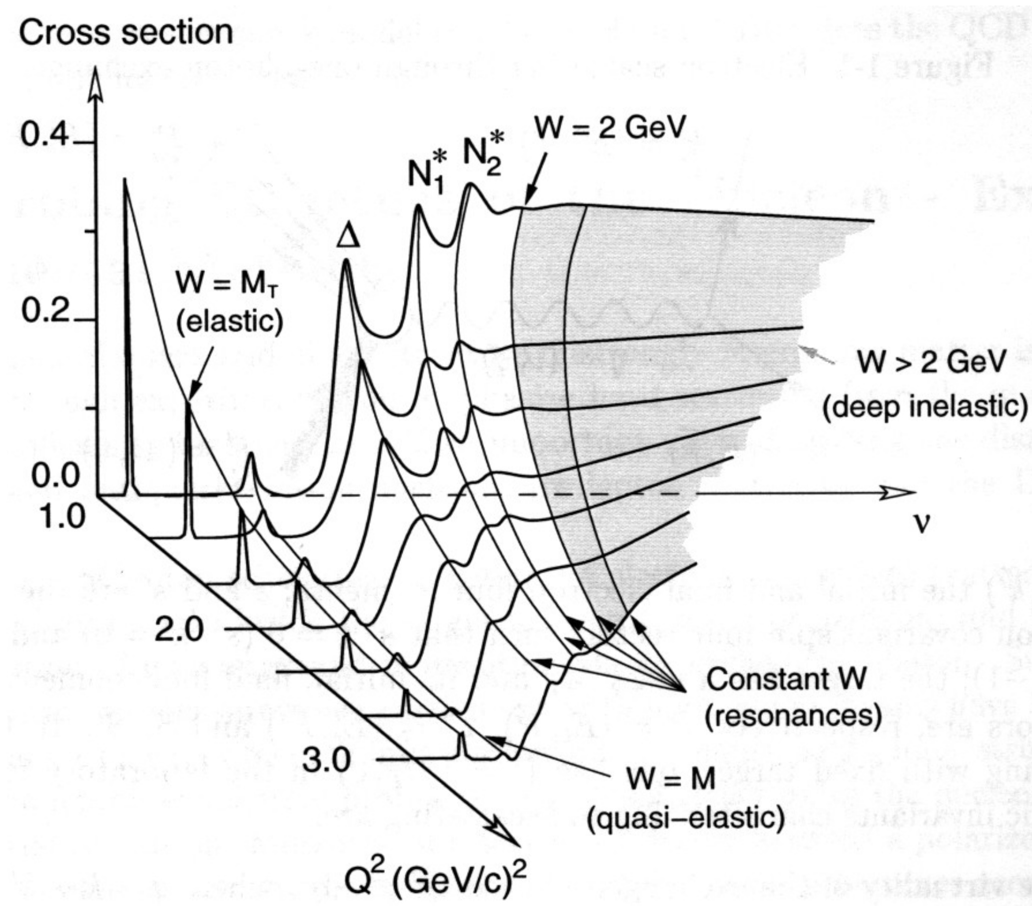
θ = scattering angle.

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



Interpreting the Cross Section

- *$W^2 = M^2 + 2M\nu + Q^2$*
  - ➡ M = nucleus (or nucleon) mass
  - ➡ W = "invariant mass" after collision
- Four regions
  - ➡ Elastic scattering
    - nucleus intact
  - ➡ Quasi-elastic scattering
    - photon interacts with a single nucleon
    - nucleus breaks up
  - ➡ Resonances
    - excited nucleon states
    - nucleon substructure starting to be probed
  - ➡ Deep inelastic scattering
    - internal structure (partons) resolved

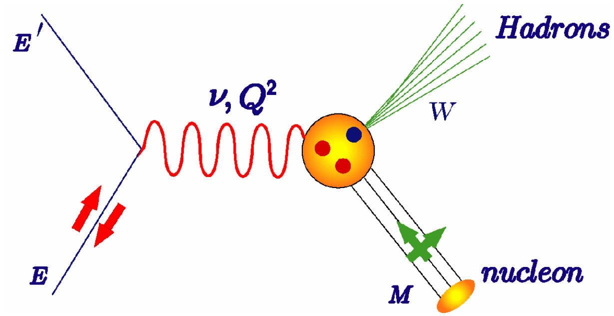


What the Structure Functions?

- The "F's" in the unpolarized cross section are Structure Functions:

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left(\frac{2}{M} F_1(x,Q^2) \sin^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x,Q^2) \cos^2 \frac{\theta}{2} \right)$$

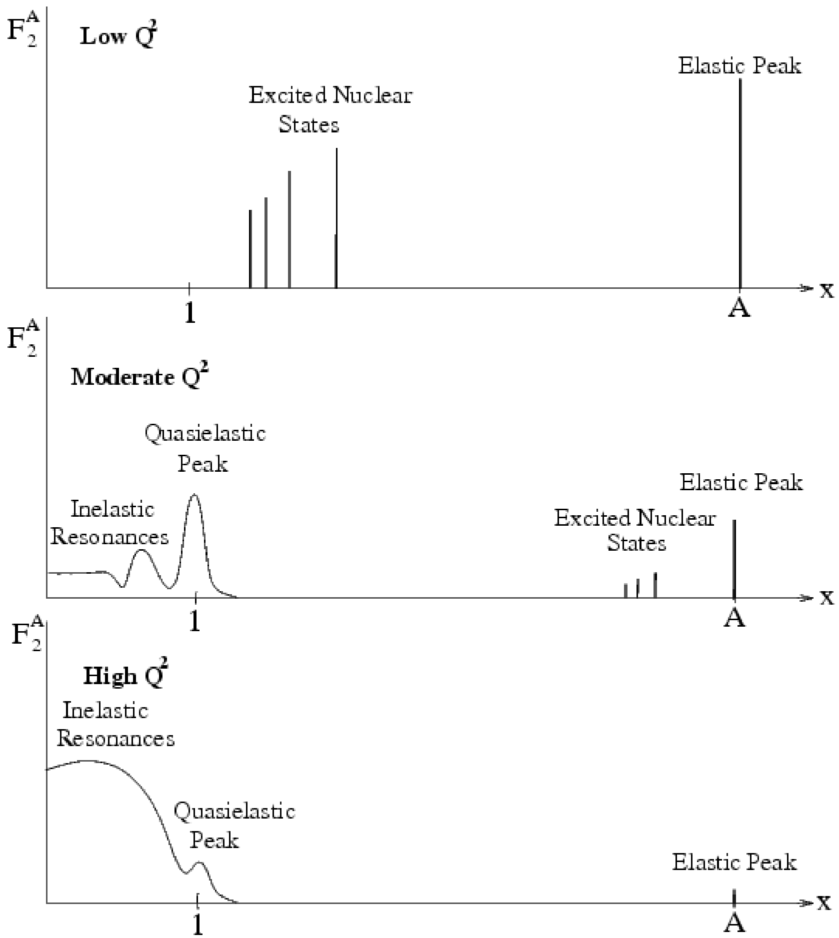
- They encode information about the internal structure of the target nucleon
  - ➡ You can measure them,
  - ➡ You can compute them,
  - ➡ But what do they mean?



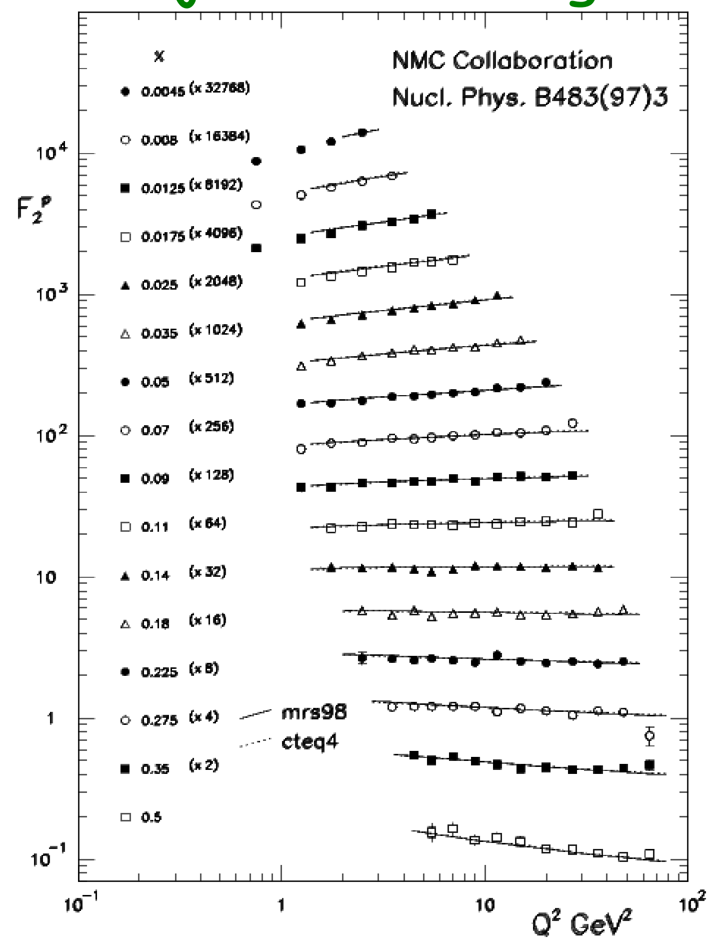
- The Parton Model
  - ➡ Assume hadrons composed of free particles called 'partons'
  - ➡ F_1 (and F_2) reflect the probability of finding a parton (ie. quark) with momentum fraction 'x'

Interpreting the Structure Functions

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\left(\frac{2}{M}F_1(x,Q^2)\sin^2\frac{\theta}{2} + \frac{1}{\nu}F_2(x,Q^2)\cos^2\frac{\theta}{2}\right)$$



Bjorken Scaling

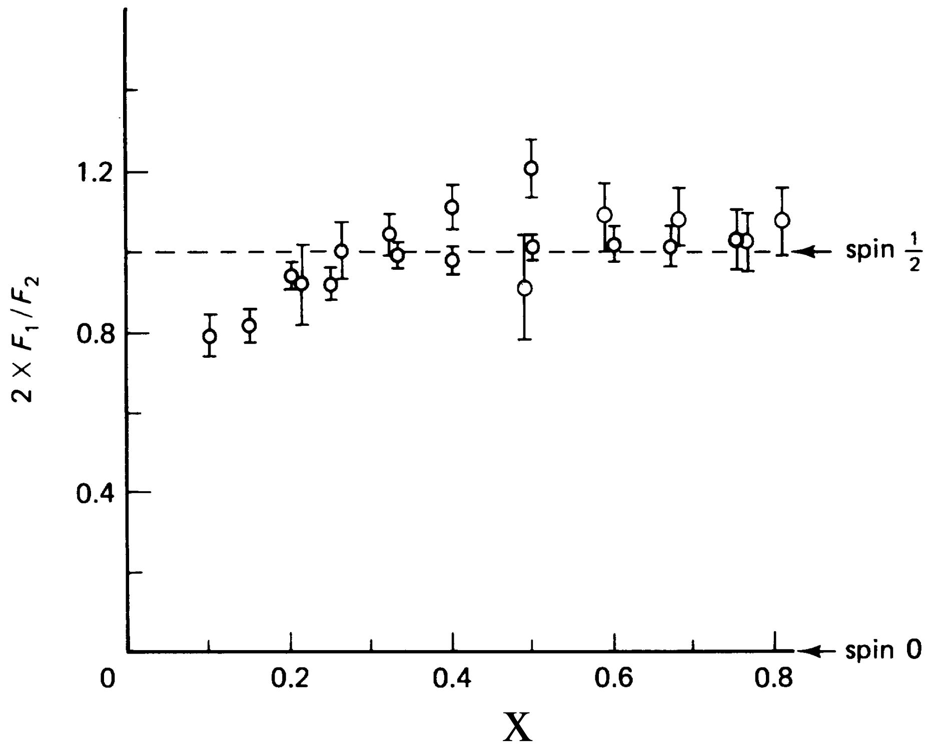


What happened to F_1?

- Callan-Gross Relation
  - ➡ If the point-like partons are spin 0, then
    - $2xF_1(x)/F_2(x) = 0$
  - ➡ If they are spin $\frac{1}{2}$, then
    - $2xF_1(x)/F_2(x) = 1$
- So,

  $2xF_1(x) = F_2(x)$

  ➡ *the partons are spin $\frac{1}{2}$*



So, we've got it cased now?

- The partons in the nucleon look like quarks
  - ➡ quarks are point-like, spin $\frac{1}{2}$ particles
  - ➡ a proton is a spin $\frac{1}{2}$ particle
    - therefore you expect to have two quarks with spin $+\frac{1}{2}$ and one with spin $-\frac{1}{2}$
    - (quark spin sum) $\frac{1}{2} + \frac{1}{2} - \frac{1}{2} = +\frac{1}{2}$ (proton spin)

- CERN designed an experiment to explicitly measure the quark contribution to the proton spin (1987)
  - ➡ naïve expectation: 100%
  - ➡ after relativistic corrections: 75%
  - ➡ measured: $12 \pm 16\%$

!?!

The "Proton Spin Crisis"

Spin Crisis (Puzzle) still not fully understood

- Total spin = $\frac{1}{2}$ $\Delta\Sigma + \Delta G + L_z$
  - ➡ $\Delta\Sigma$ = quark spin (including sea quarks now)
  - ➡ ΔG = gluon spin
  - ➡ L_z = orbital angular momentum of gluons and quarks
- Sea quarks were supposed to solve the puzzle but measurements indicate a very small contribution < 5%
- (L_z is extremely hard to measure)
- Understanding the gluon contribution is now underway
  - ➡ But how do we probe the gluon field?
    - they don't respond to an electromagnetic probe
    - we can't manipulate gluons directly, but we *can* manipulate the nucleon spin

Spin Crisis (Puzzle) still not fully understood

- There's more going on inside the nucleon than we thought
  - ➡ gluons are a big part of it
- How can we get a handle on the quark/gluon interactions?
  - ➡ by manipulating the nucleon spin

Polarized deep inelastic cross sections

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

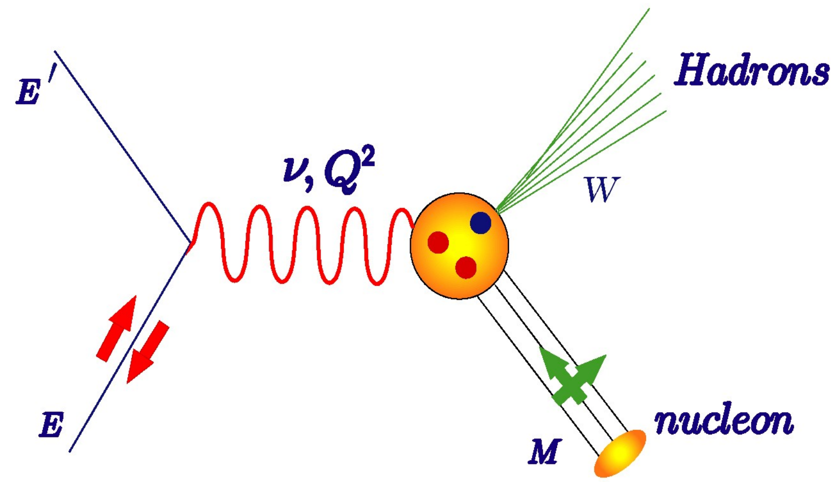
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu\mathbf{g_1}(\boldsymbol{x},\boldsymbol{Q^2}) + 2E\mathbf{g_2}(\boldsymbol{x},\boldsymbol{Q^2})\right] = \Delta\sigma_{\perp}$$

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

ν = energy transfer.

θ = scattering angle.

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



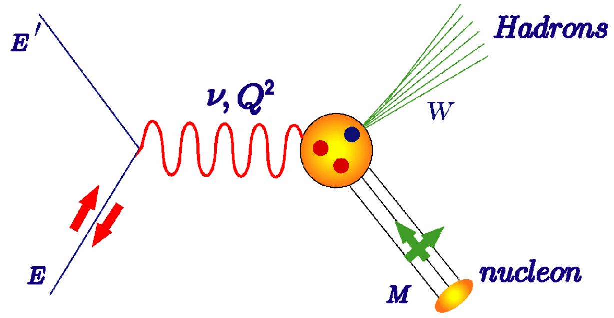
What are g_1 and g_2?

- The "g's" play a role analogous to the "F's" in the unpolarized cross section

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left(\frac{2}{M} F_1(x, Q^2) \sin^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \cos^2 \frac{\theta}{2} \right)$$

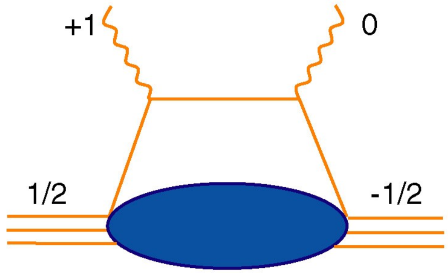
- F encodes information about the momentum structure of the nucleon

- g_1 and g_2 encode information about the spin structure of the target nucleon



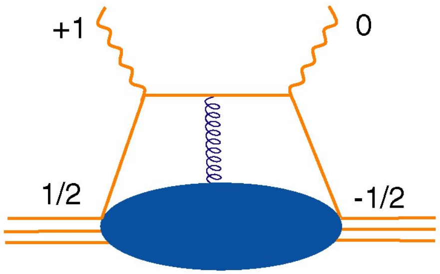
- The Parton Model
  - ➡ g_1 reflects the difference in probabilities between quarks with spin aligned parallel and anti-parallel to the nucleon spin
  - ➡ g_2 ???

g_2 and Quark-Gluon Correlations



Carry one unit of orbital angular momentum

QCD allows the helicity exchange to occur in two principle ways



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

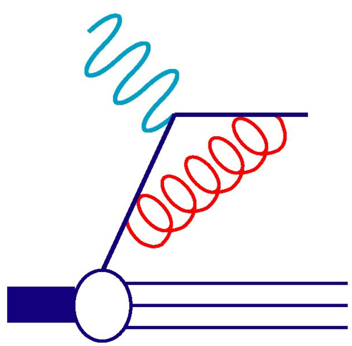
higher twist

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

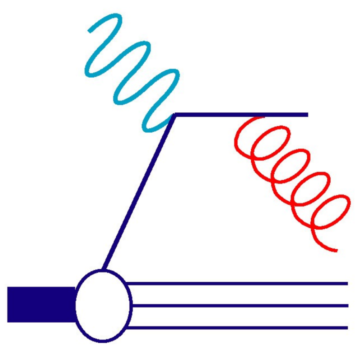
$g_A = 1.257$ and $a_8 = 0.579$ are the triplet and octet axial charge, respectively

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

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

- 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"

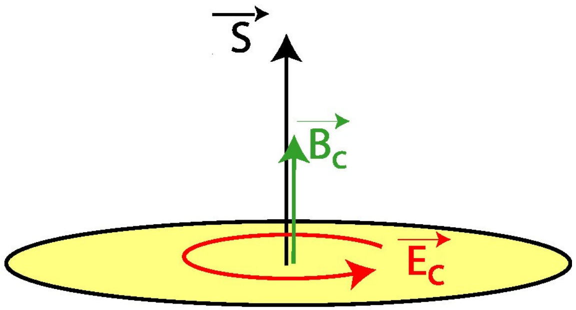
How does the gluon field respond when a nucleon is polarized ?

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

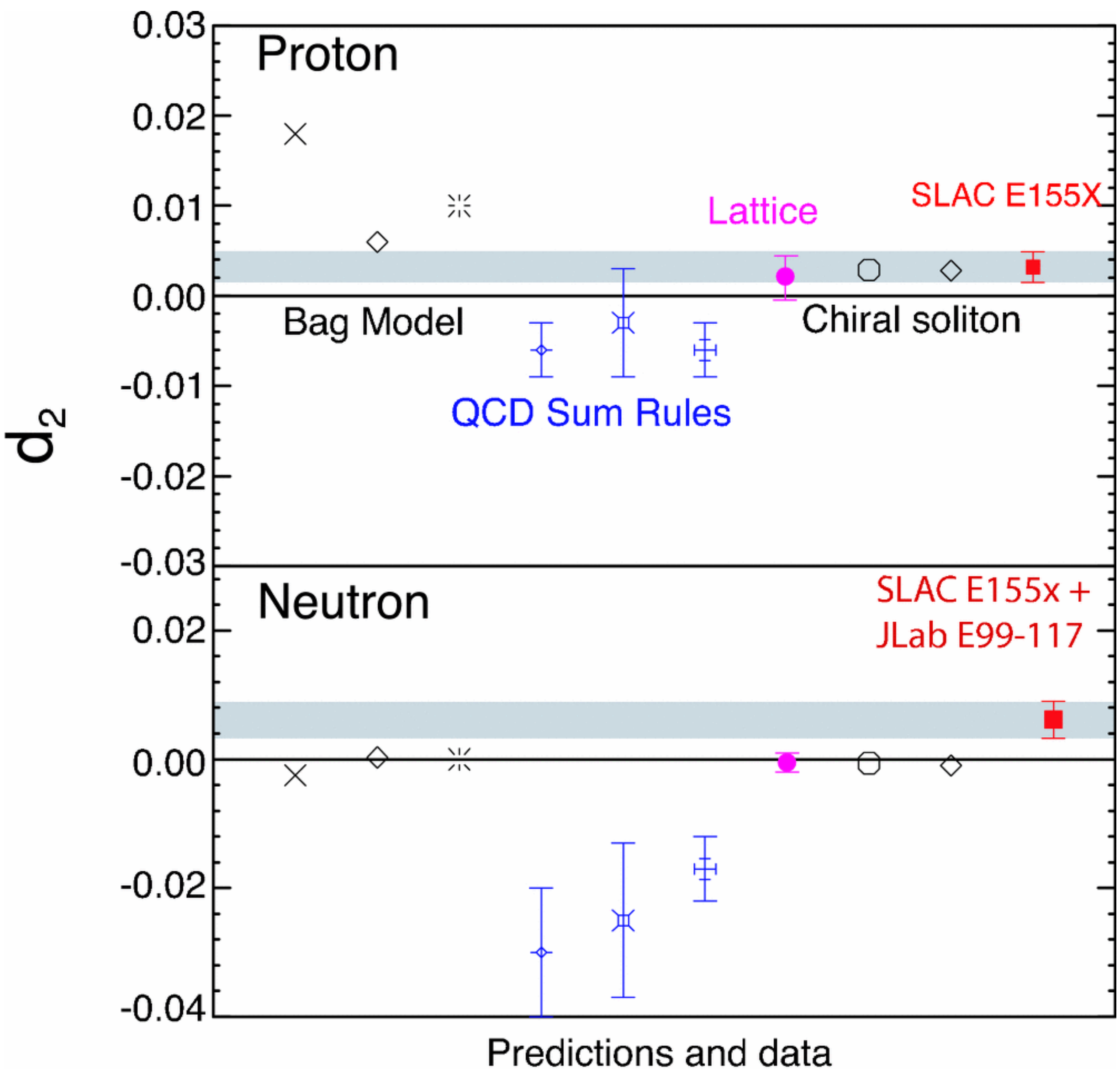
$$\vec{O}_E = \psi^\dagger\vec{\alpha} \times g\vec{\boldsymbol{E}}\psi$$



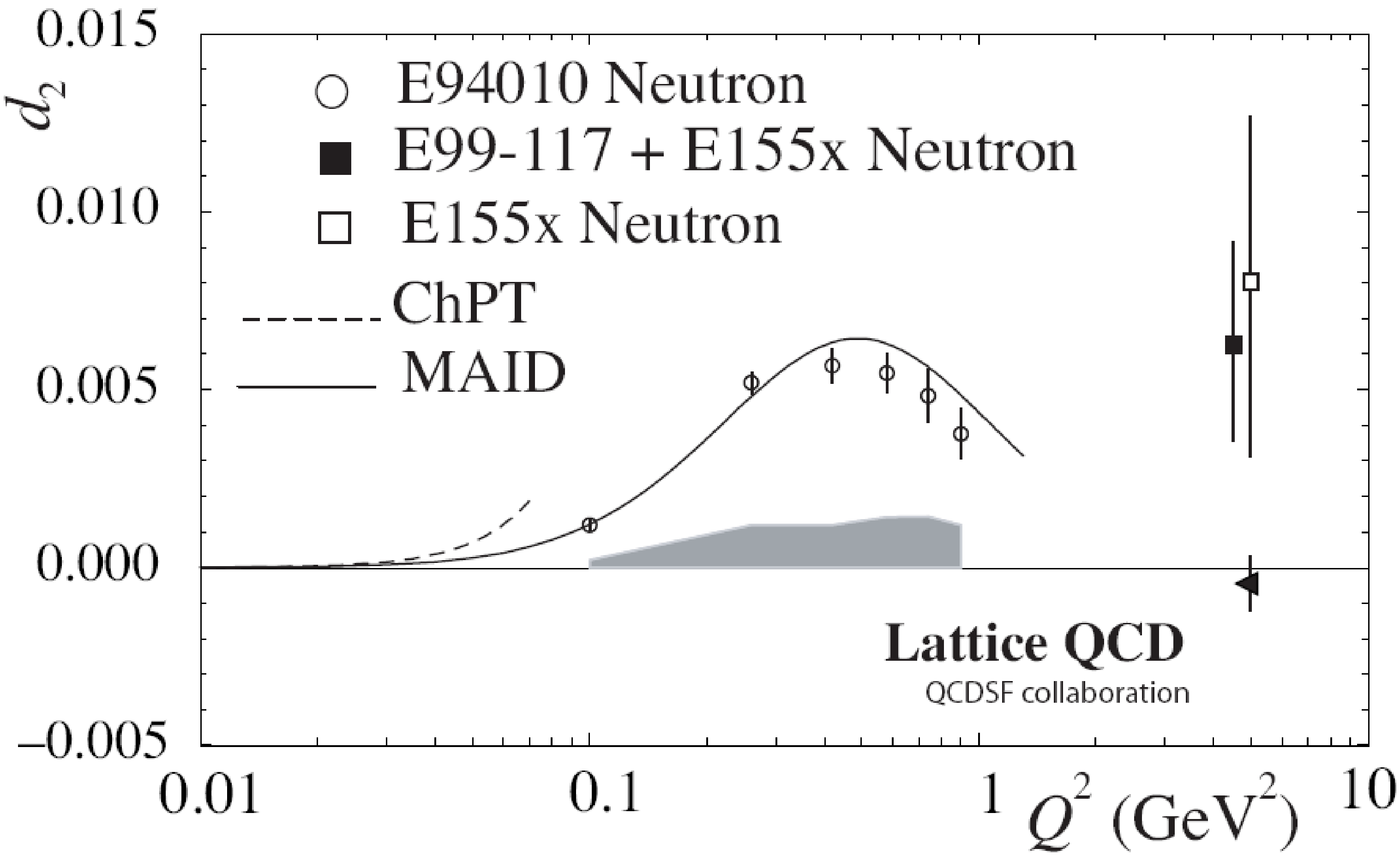
$$\chi_E^n = (4d_2^n + 2f_2^n)/3$$
$$\chi_B^n = (4d_2^n - f_2^n)/3$$

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



World Data on $\bar{d}_2$



(nucleon elastic contribution suppressed)

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

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

where,

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

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

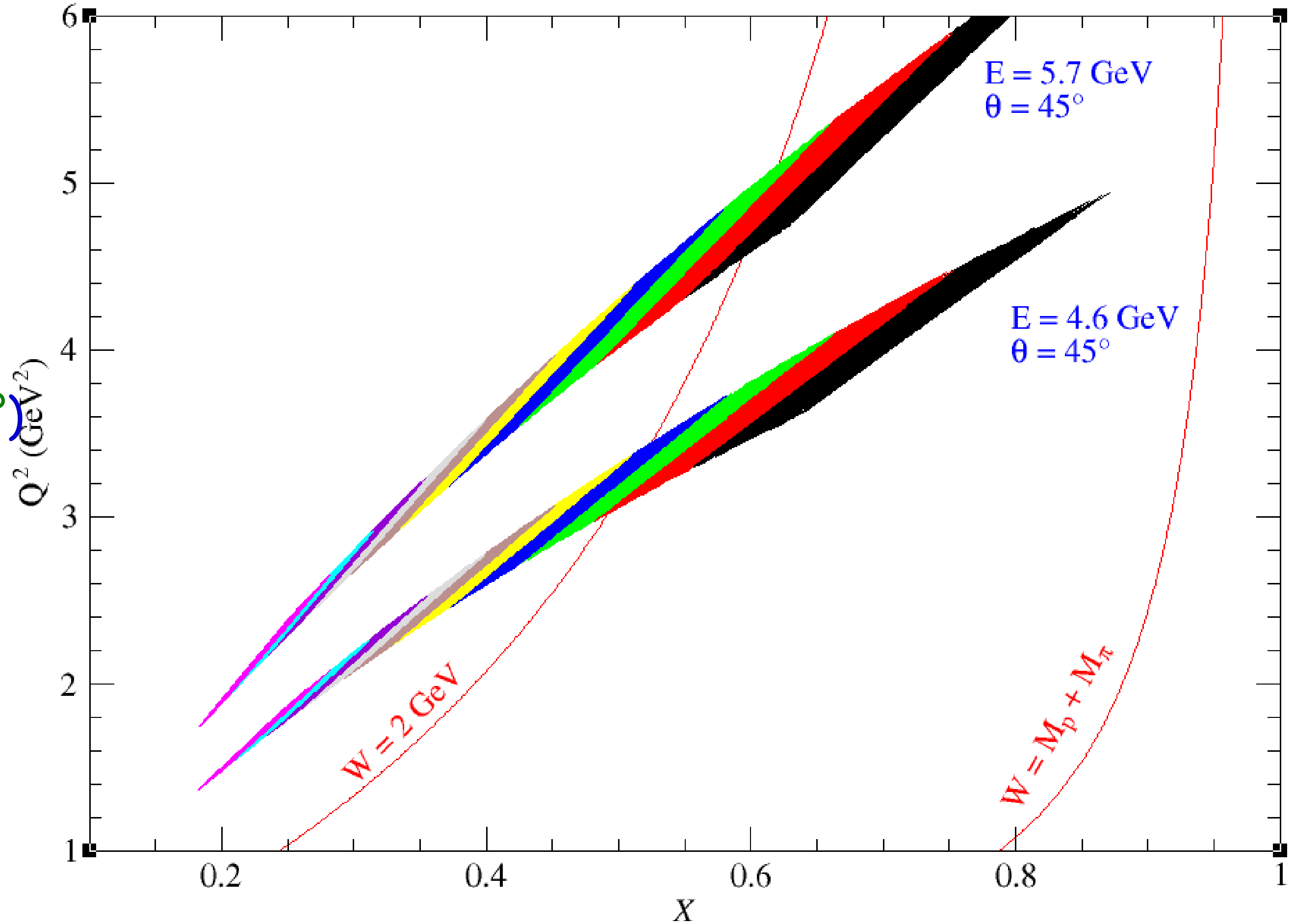
$$\Delta_\perp = \frac{(N^{\uparrow\Rightarrow}-N^{\uparrow\Rightarrow})}{(N^{\uparrow\Rightarrow}+N^{\uparrow\Rightarrow})} \qquad \Delta_\parallel = \frac{(N^{\downarrow\Uparrow}-N^{\uparrow\Uparrow})}{(N^{\downarrow\Uparrow}+N^{\uparrow\Uparrow})}$$

Kinematics of the measurement

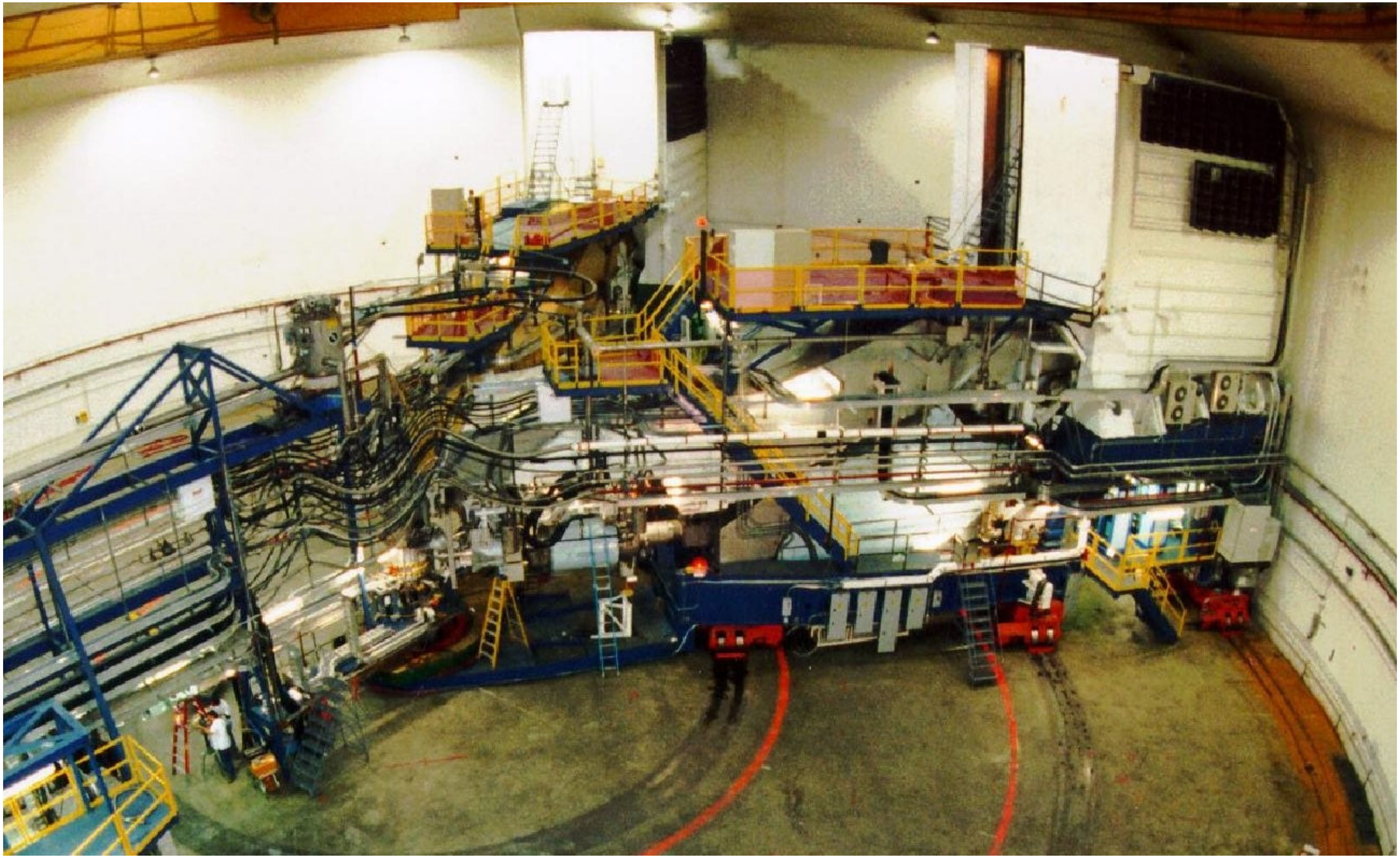
- Two beam energies
  4.6 and 5.7 GeV
  (4 pass, 5 pass)

- BigBite fixed at single scattering angle (θ=45°)
  (data divided into 10 bins during analysis)

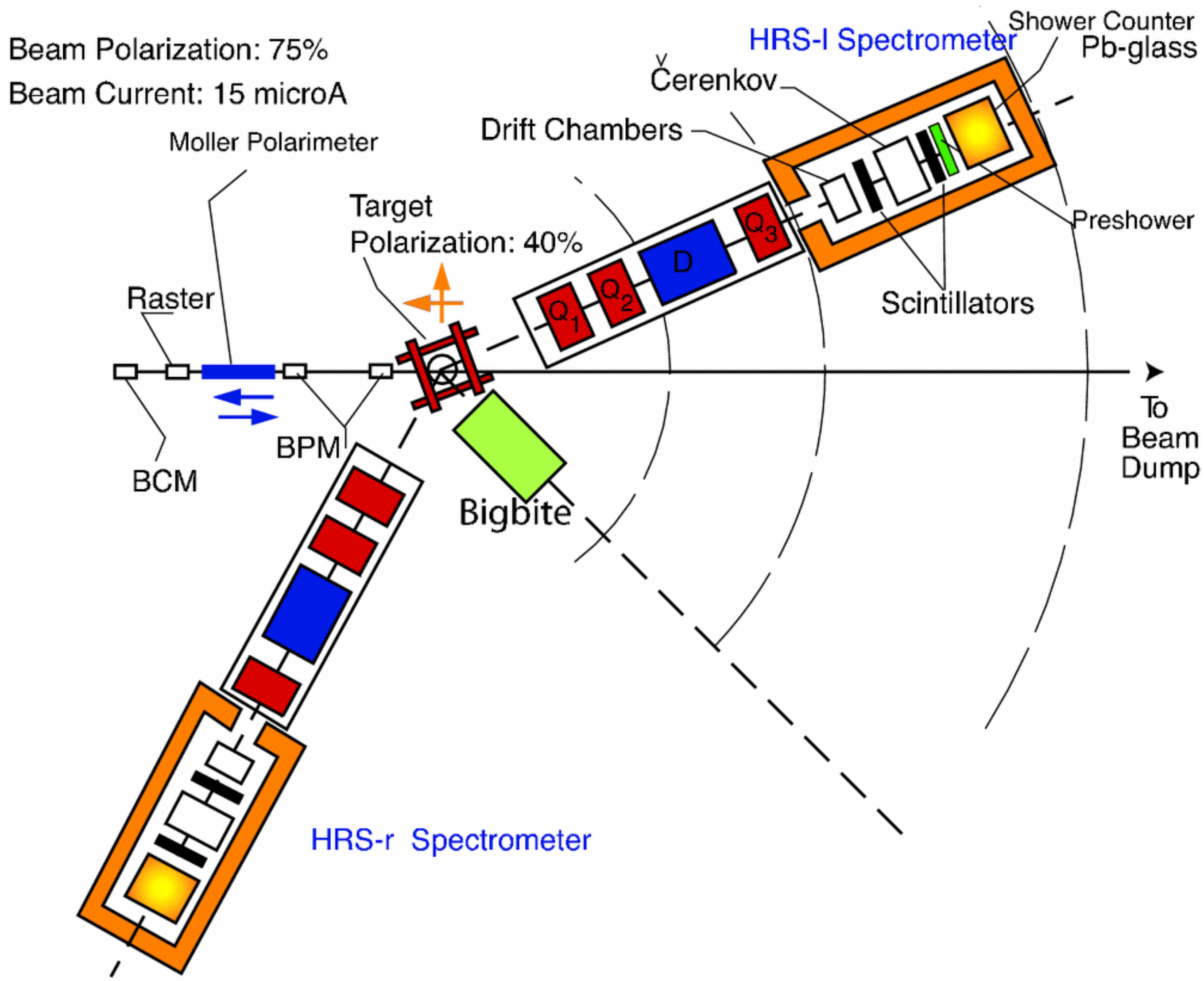
- Avoid resonance region as much as possible.



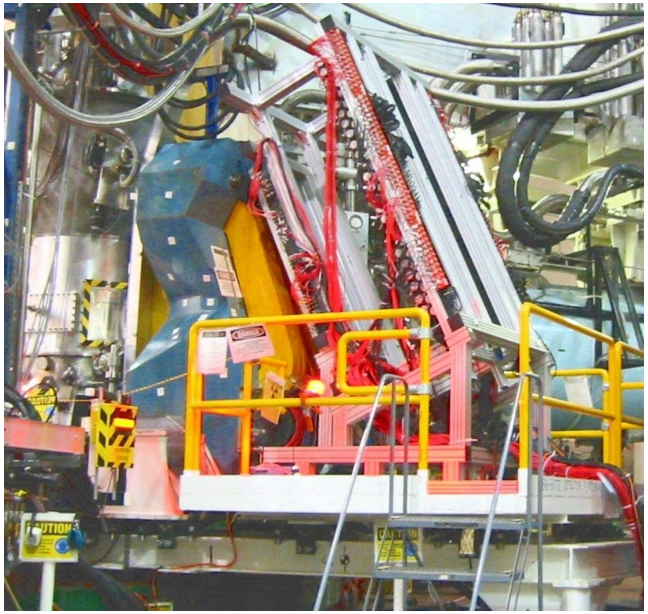
Jefferson Lab – Hall A

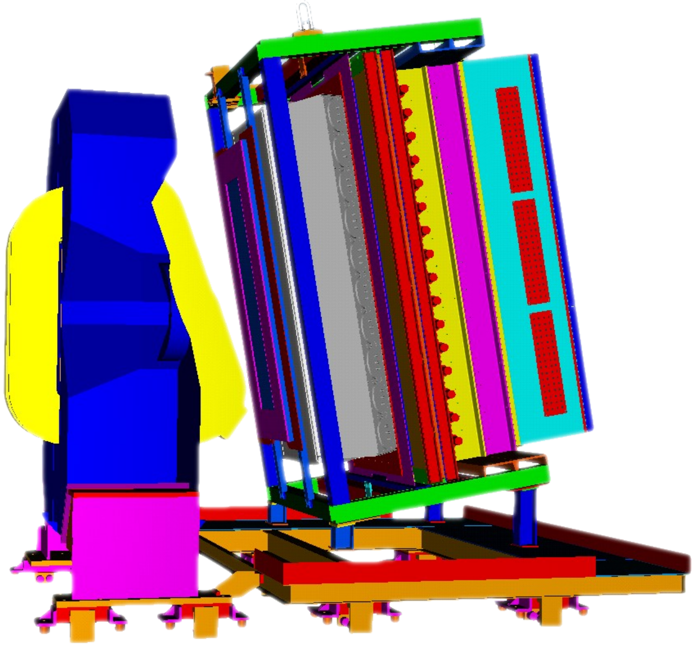


Floor configuration for this experiment



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)

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

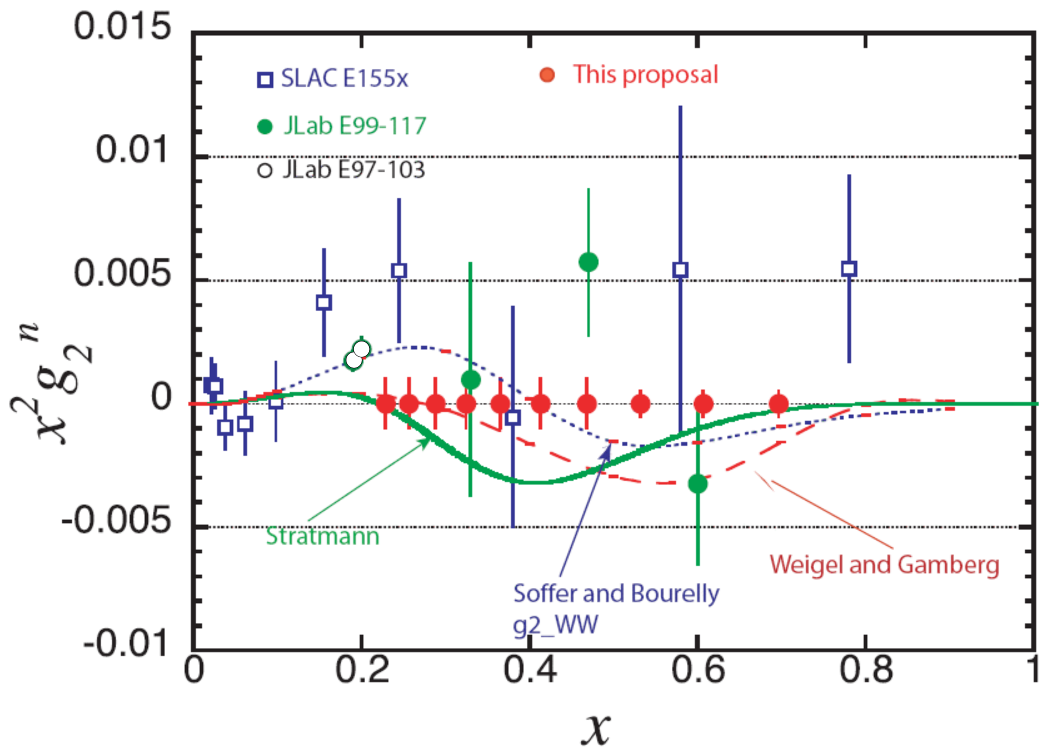
Online triggers

e-	2-5 kHz
e+	<1 kHz

p-	90 kHz
p+	90 kHz
p	50 kHz
n	50 kHz

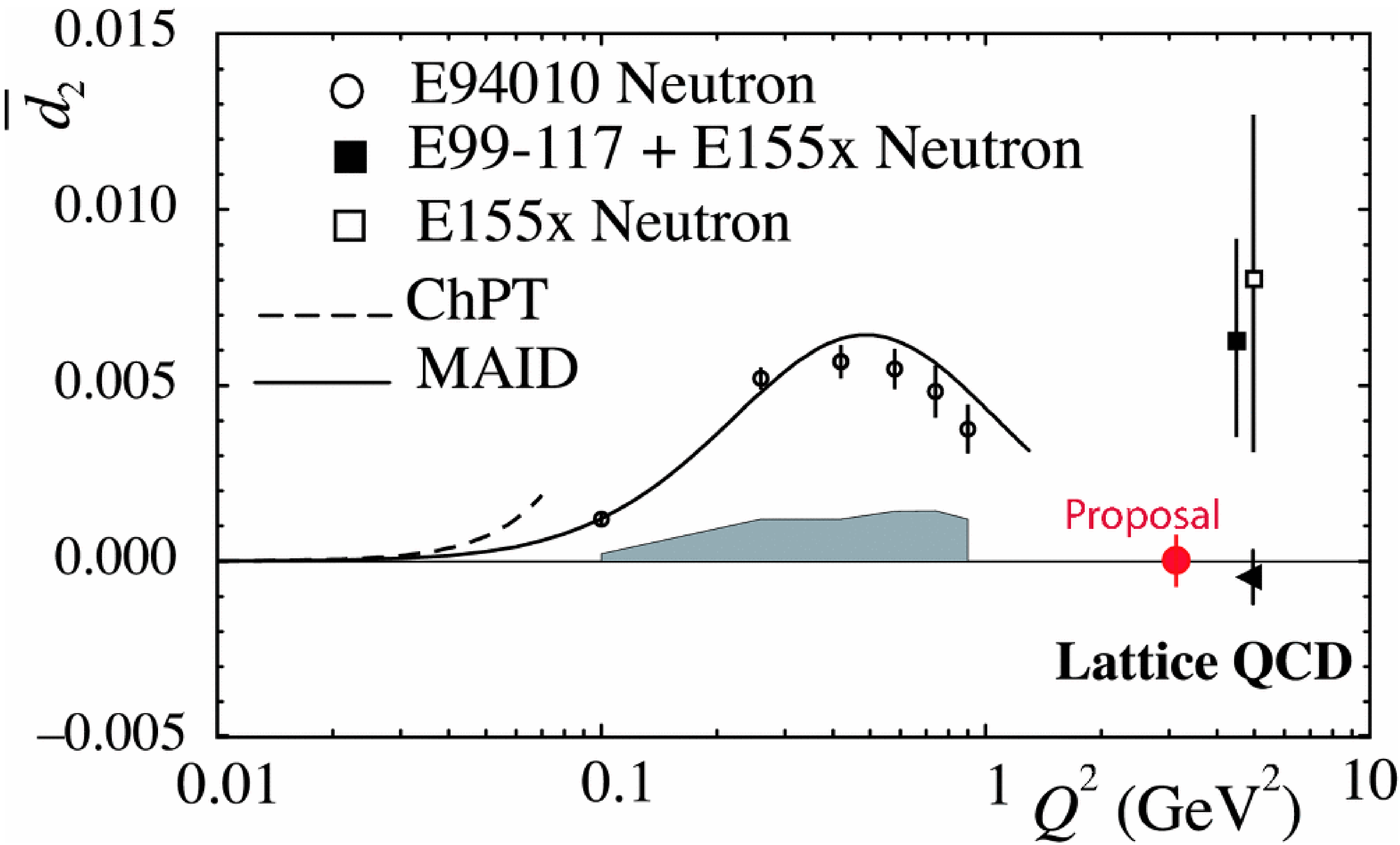
Removed via online cuts

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

Expected Error on d_2



Summary of Experiment

- 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

- The nature of the this quantity (clean measurement, clean calculation) makes the d_2^n an excellent way to precisely probe the strength and character of quark-gluon interactions in the nucleus.