A Measurement of g_2^p at Low Q^2

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On Behalf of the E08-027 Collaboration
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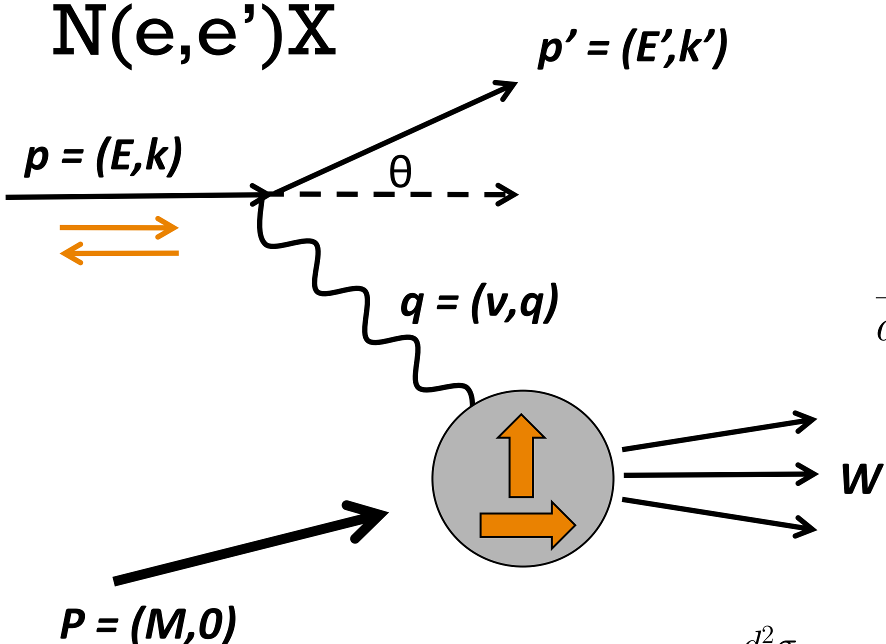
Jefferson Lab

Inclusive Electron Scattering

N(e,e')X



$$\vec{q} = \vec{k} - \vec{k}'$$

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

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

Inclusive inelastic
unpolarized *cross section:*

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

Inclusive ***polarized*** *cross sections:*

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

$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Rightarrow - \uparrow\Rightarrow) = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1(x,Q^2) + 2Eg_2(x,Q^2)\right]$$

g_1,g_2 are related to the spin distribution

Quark-Parton Model

- Bjorken Scaling Limit:

$$Q^2 \to \infty \quad \nu \to \infty$$

such that: $x = \frac{Q^2}{2M\nu}$ is finite

- Structure functions can be written in terms of quark distribution functions:

$$F_1(x) = \frac{1}{2}\sum_f z_f^2[q_f(x) + \bar{q}_f(x)]$$

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

$$g_1(x) = \frac{1}{2}\sum_f z_f^2[q_f(x) - \bar{q}_f(x)]$$

No simple interpretation for g_2

g_2 includes contributions from quark gluon interactions

What is g_2?

(Parton Model Description)

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

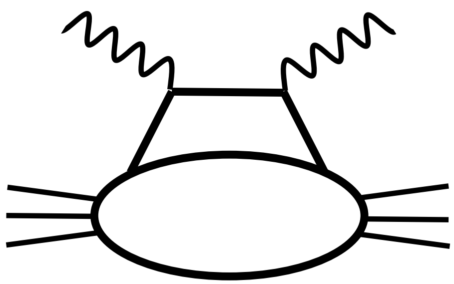
What is g_2?

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

Wandzura–Wilczek Relation:

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

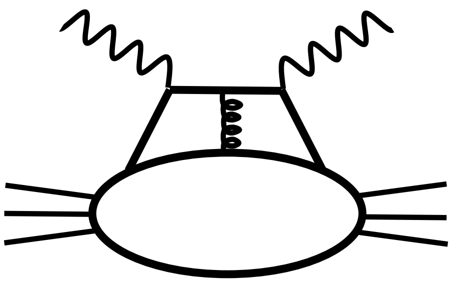
Leading twist-2 term



What is g_2?

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

$$\int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M} h_T(y,Q^2) + \zeta(y,Q^2)\right]\frac{dy}{y}$$



h_T: Arises from quark transverse polarization distribution

ζ: Arises from quark-gluon interactions (twist-3)

Measurements of g_2 and its Moments

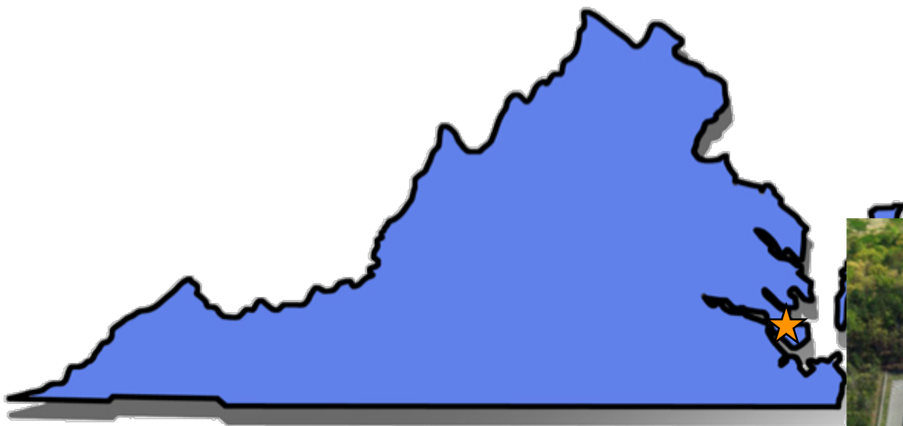
Measurements of g_2 require a transversely polarized target – more difficult experimentally

- 0^{th} moment (no x-weighting): Burkhardt-Cottingham Sum Rule
  - Valid at all Q^2

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

- 2^{nd} moment (x^2 weighting):
  - High Q^2 – d_2, twist-3 color polarizability, test of lattice QCD
  - Low Q^2 – spin polarizabilities, test of χPT

Measurements of g_2 and its Moments



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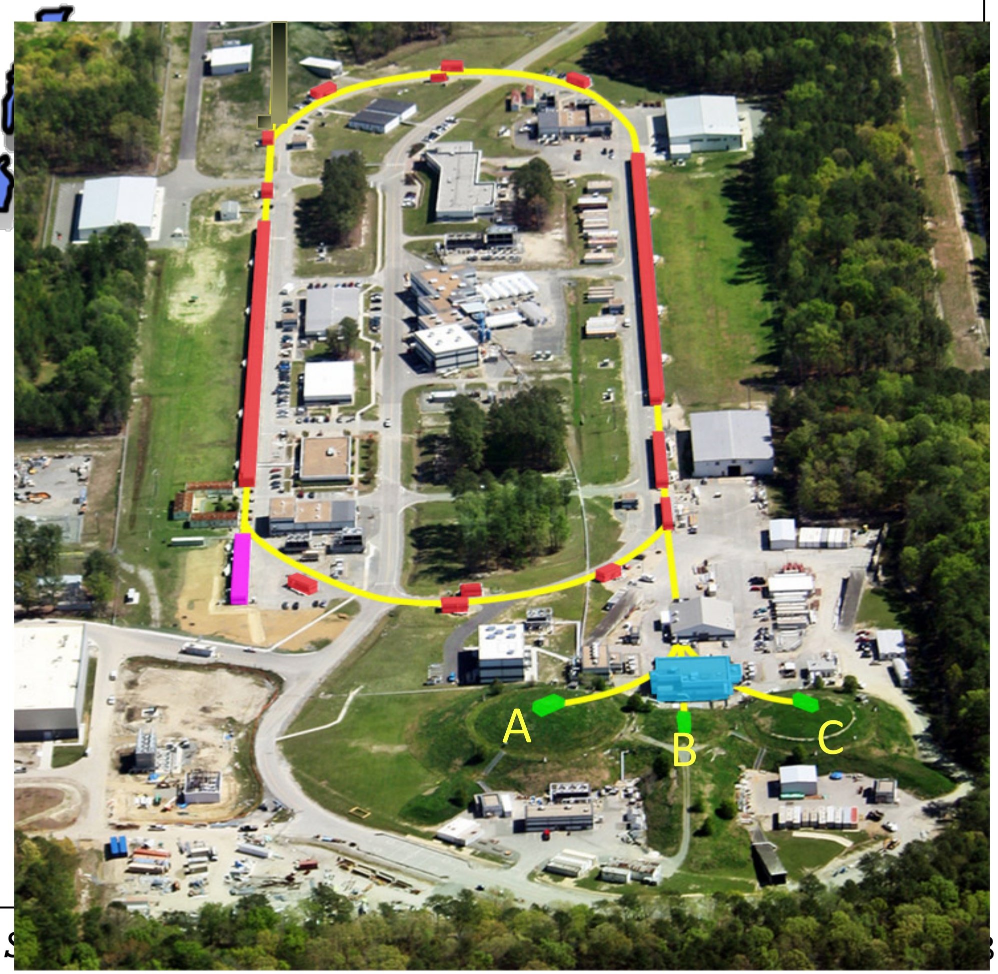


CEBAF

- High intensity electron accelerator based on CW SRF technology
- E_{max} = 6 GeV
- I_{max} = 200 μA
- Pol_{max} = 85%

Recently upgraded to 12 GeV

Measurements of g_2 and its Moments

- Prior to measurements at JLab, first dedicated experiment was SLAC E155x

- g_2 Measurements on the **neutron** at JLab:
  - E97-103: W>2 GeV, $Q^2 \approx 1$ GeV^2, $x \approx 0.2$, study higher twist (published)
  - E99-117: W>2 GeV, high Q^2 (3-5 GeV^2) (published)
  - E94-010: moments at low Q^2 (0.1-1 GeV^2) (published)
  - E97-110: moments at very low Q^2 (0.02-0.3 GeV^2) (analysis)
  - E01-012: moments at intermediate Q^2 (1-4 GeV^2) (submitted)
  - E06-014: moments at high Q^2 (2-6 GeV^2) (analysis)

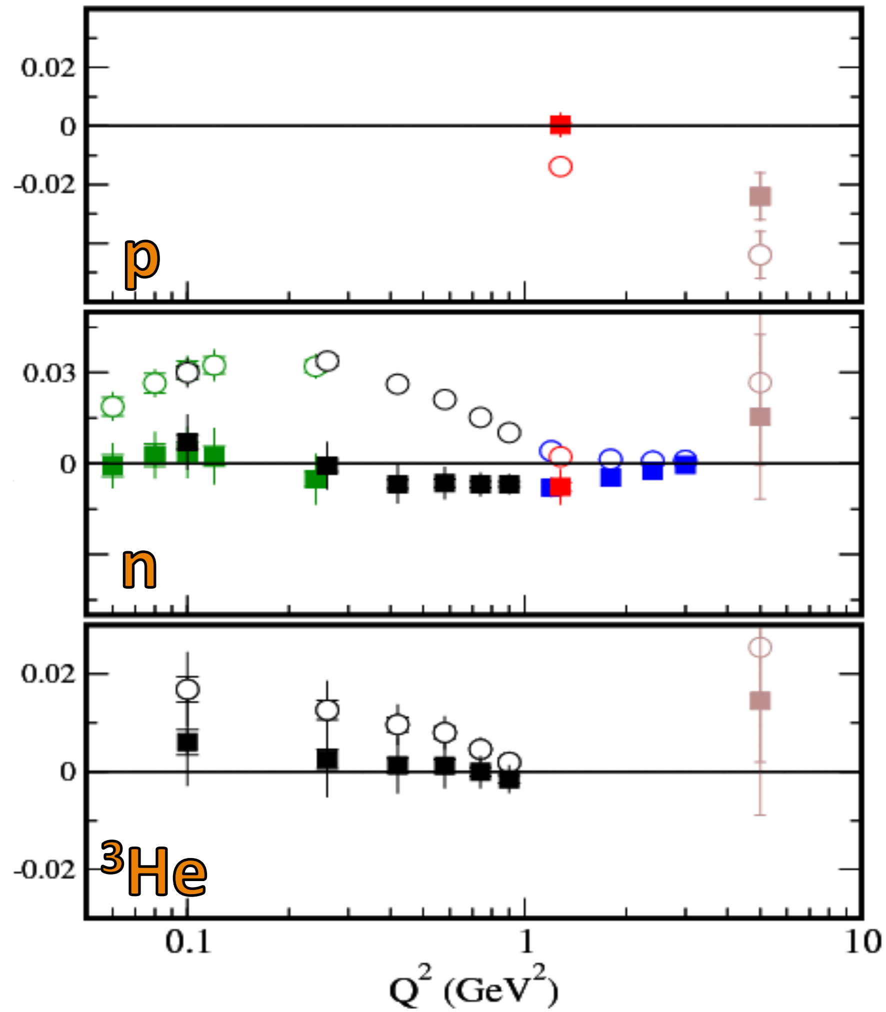
  Measurements on the **proton** at JLab:
  - RSS: moments at intermediate Q^2 (1-2 Gev^2) (published)
  - SANE: moments at high Q^2 (2-6 GeV^2) (analysis)
  - → E08-027 (g_2^p): moments at very low Q^2 (0.02-0.2 GeV^2) (analysis)

0^{th} Moment of g_2

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

Brown: SLAC E155x
Red: Hall C RSS
Black: Hall A E94-010
Green: Hall A E97-110 (preliminary)
Blue: Hall A E01-012 (submitted)

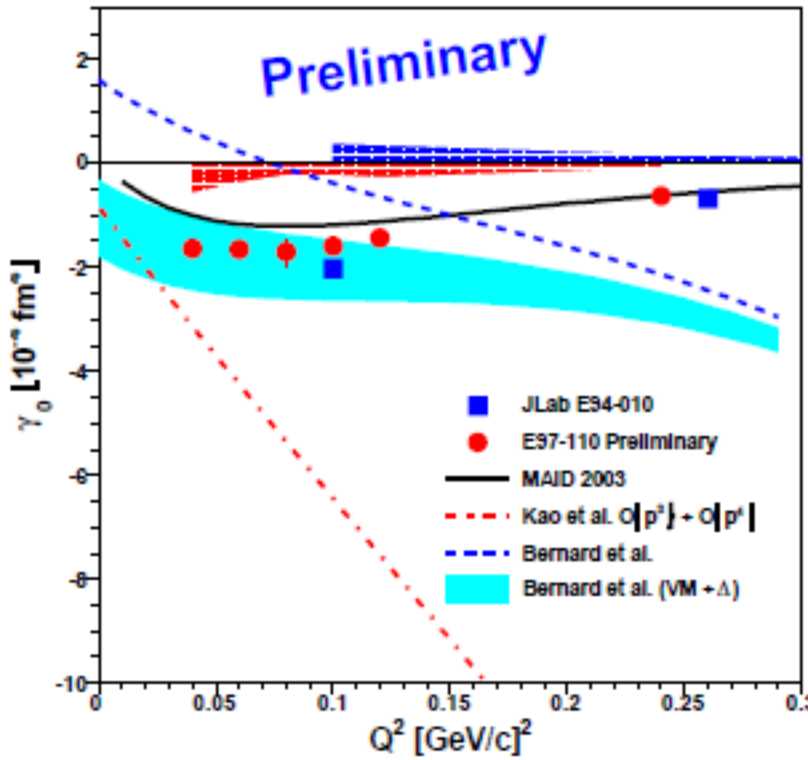
BC Sum = Measured + Low x + Elastic
Measured: open circles
Low x: unmeasured low-*x* part of the integral – assume leading twist behavior
Elastic: obtained from well known Form Factors



2^{nd} Moment: Spin Polarizabilities

(V. Sulkosky)

- Generalized spin polarizabilities γ_0 and δ_{LT} are a benchmark test of χPT
    - Difficulty is how to include the nucleon resonance contributions
    - γ_0 is sensitive to resonances, δ_{LT} is not
- Neutron results for γ_0

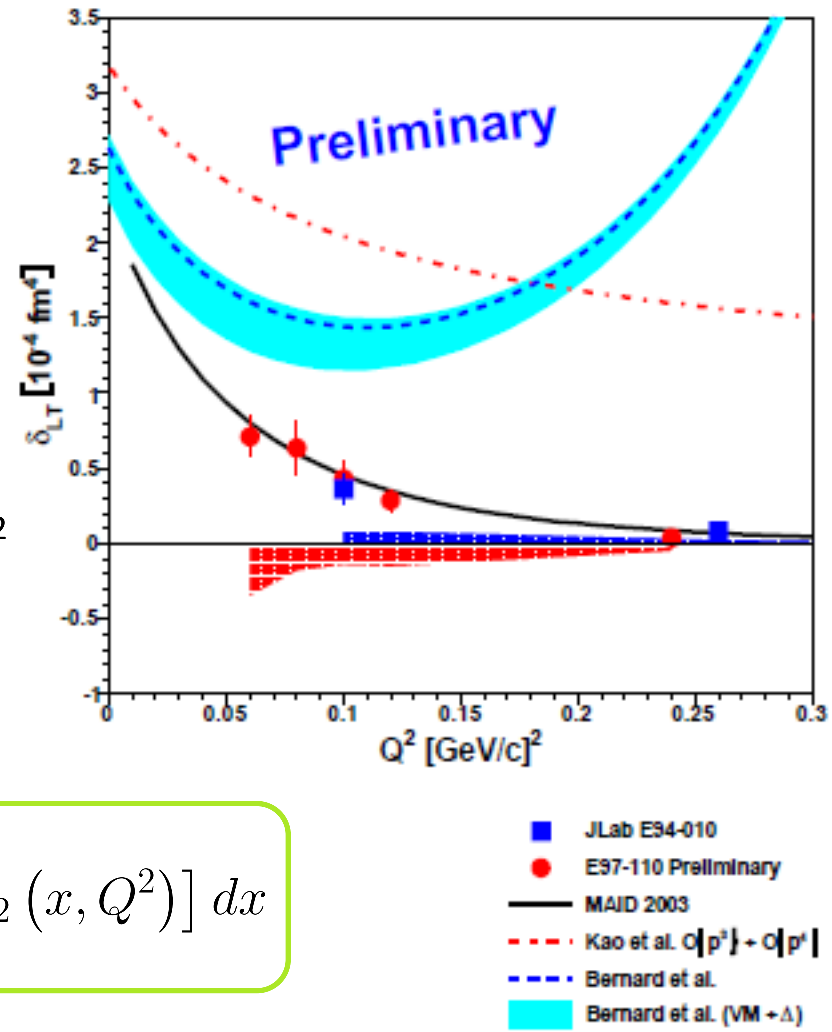


$$\gamma_0\left(Q^2\right) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1\left(x,Q^2\right) - \frac{4M^2}{Q^2}x^2 g_2\left(x,Q^2\right)\right]dx$$

2^{nd} Moment: Spin Polarizabilities

(V. Sulkosky)

- Neutron results for δ_{LT}
- δ_{LT} is seen as a more suitable testing ground – insensitive to Δ-resonance
- Data is in significant disagreement with χPT calculations
- g_2^p experiment will provide test at low Q^2



$$\delta_{LT}\left(Q^2\right) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} x^2\left[g_1\left(x,Q^2\right)+g_2\left(x,Q^2\right)\right]dx$$

Finite Size Effects

Hyperfine Splitting of Hydrogen

- Splitting is defined in terms of Fermi Energy E_f

$$\Delta_E = (1 + \delta)\, E_F$$

Where:

$$\delta = 1 + (\delta_{QED} + \delta_R + \delta_{small}) + \Delta_S$$

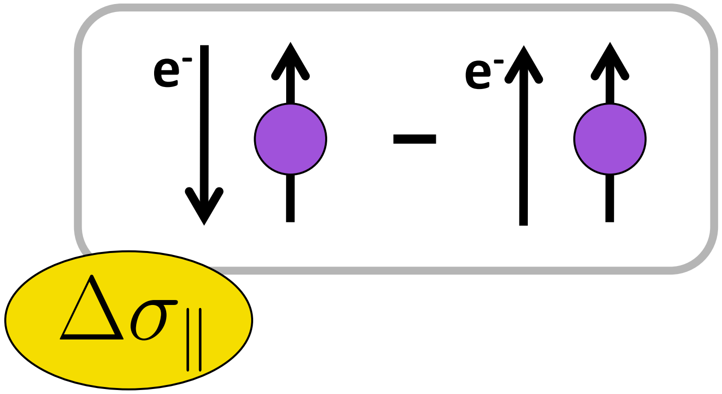
Correction for proton structure – contains contribution from g_2 (dominated by g_2 at low Q^2)

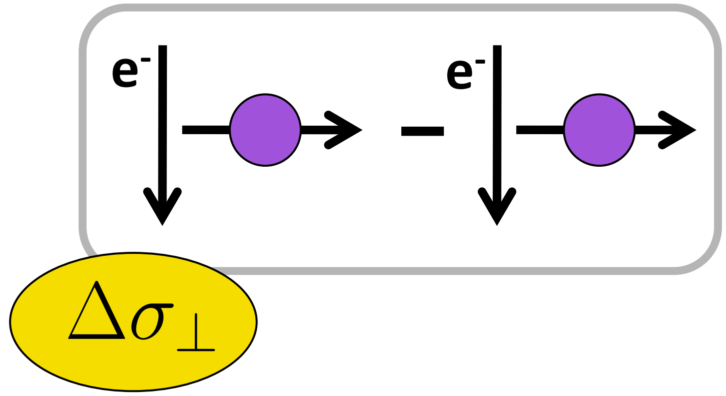
- Proton Charge Radius
  - Results from μP disagrees with eP scattering result by ~7σ
  - Main uncertainties arise from proton polarizability and differing values of the Zemach radius

g_2^p Experiment at JLab (E08-027)

- Will provide the first measurement of g_2 for the proton at low to moderate Q^2
- Will provide insight on several outstanding physics puzzles:
  - BC sum rule
    - Discrepancy suggested for high-Q^2 data
  - δ_{LT} polarizability
    - χPT calculations do not match data
  - Finite size effects:
    - Hydrogen hyperfine splitting: proton structure contributes to uncertainty
    - Proton charge radius: proton polarizability contributes to uncertainty
- Data was taken in Hall A in 2012 – analysis is currently underway

Experimental Technique





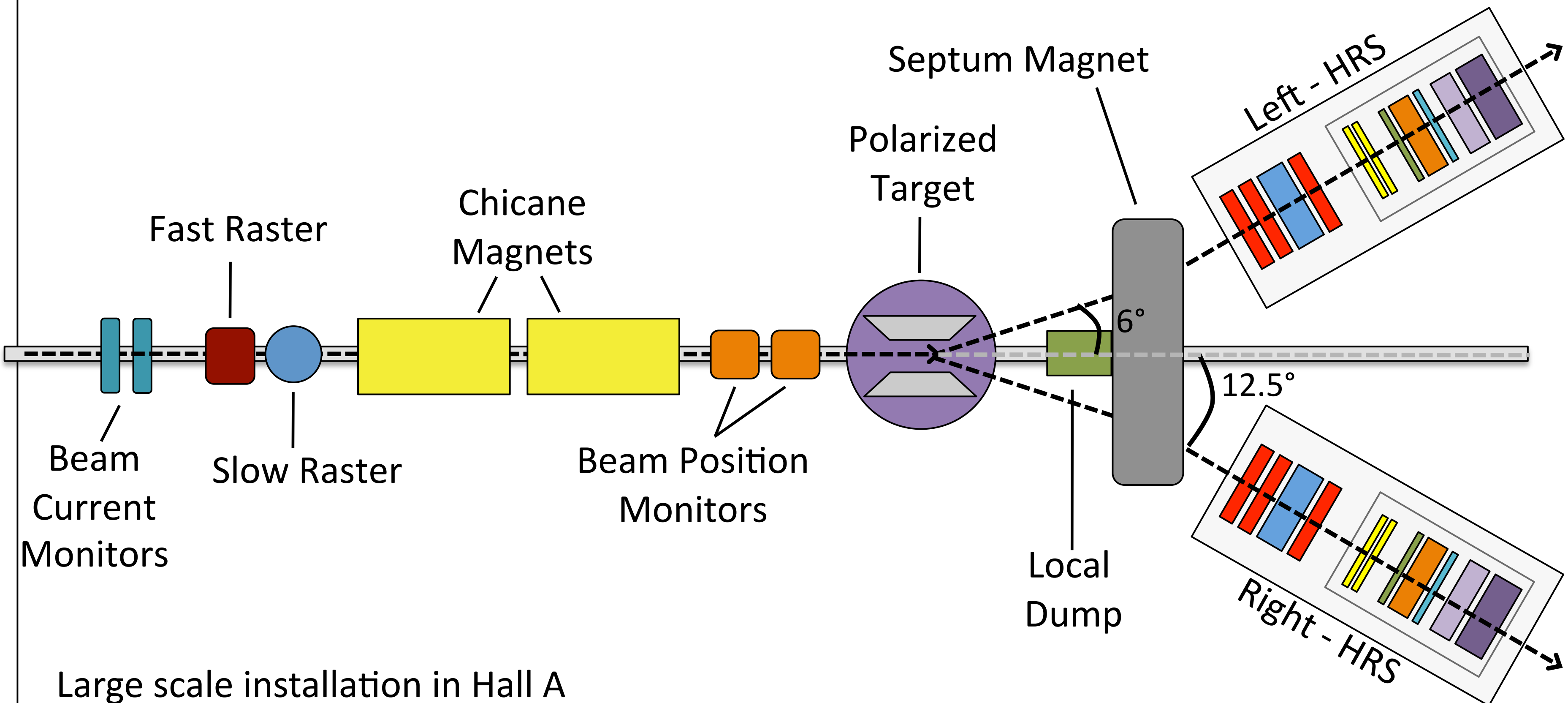
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow - \uparrow\Uparrow) = \frac{4\alpha^2 sin\theta}{MQ^2}\frac{E'}{\nu E}\left[(E + E'cos\theta)\, g_1\left(x, Q^2\right) - \frac{Q^2}{\nu} g_2\left(x, Q^2\right)\right]$$

$\Delta\sigma_{||}$ measured during EG4 experiment in Hall B: will extract g_1^p at low Q^2

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

$\Delta\sigma_{\perp}$ obtained from g_2^p experiment

Experimental Setup

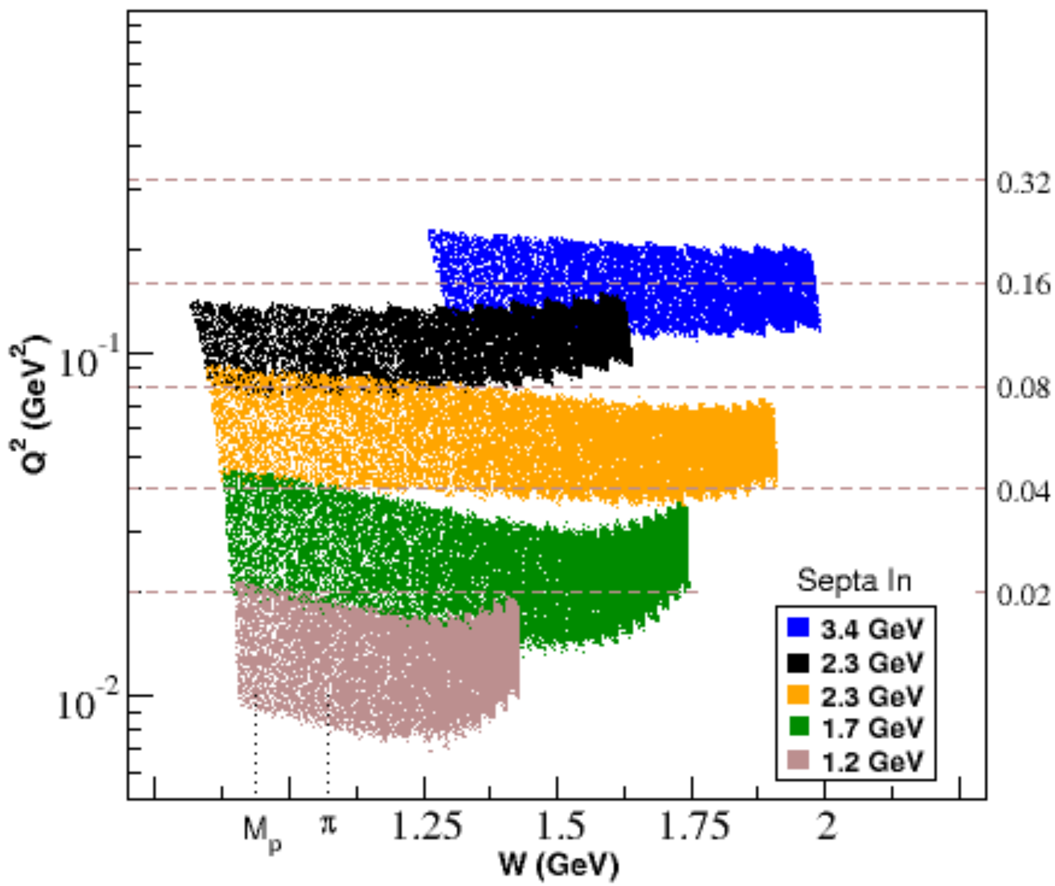


Large scale installation in Hall A

- DNP NH_3 target with 2.5/5 T magnetic field (longitudinal and transverse configurations)
- New beamline diagnostics for low current (<100 nA) running
- Chicane and septum magnets
- Local dump

Kinematic Coverage

First data on g_2 for proton at low Q^2



$W < 2$ GeV

$0.02 < Q^2 < 0.2$ GeV^2

Beam Energy (GeV)	Target Field (T)
2.2	2.5
1.7	2.5
1.1	2.5
2.2	5.0
3.3	5.0

Status of Analysis

Completed

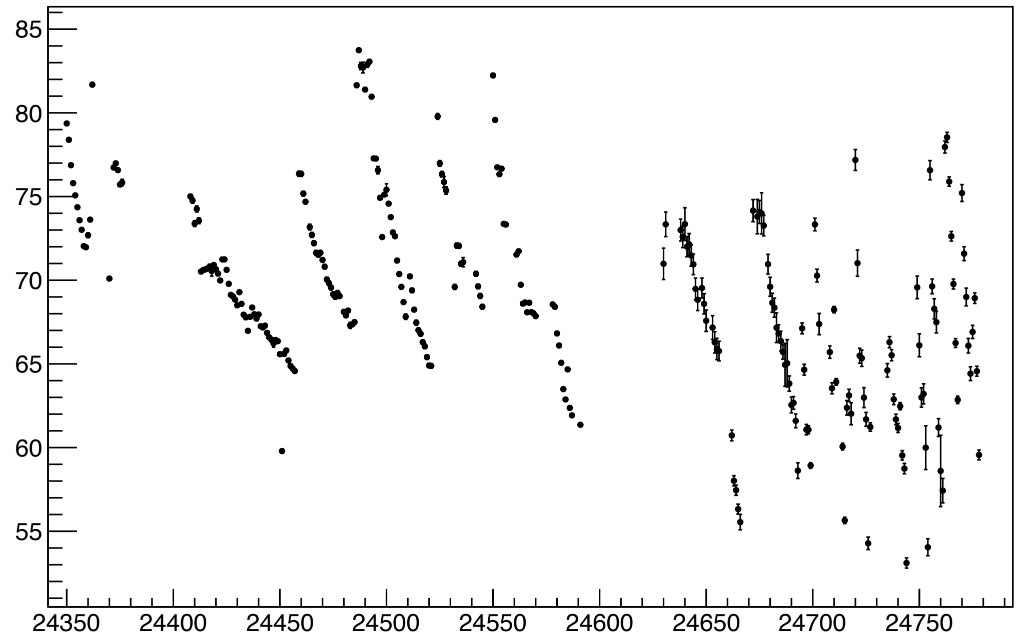
- Run Database
- HRS Optics
    - Field measurement analysis
    - VDC t_0 calibration
    - Simulation Package
    - Optics with target field (LHRS)
- Detector Calibrations/Efficiency Studies
    - Gas Cherenkov
    - Lead Glass Calorimeters
    - Scintillator trigger efficiencies
    - Multi-track analysis
- Scalers
    - BCM calibration
    - Helicity decoding
    - Dead time calculations
- Target Polarization Analysis
- BPM Calibrations

In Progress

- Raster Size Calibrations
- Packing Fraction/Dilution Analysis
- Elastic Analysis
- Yields/Radiative Corrections

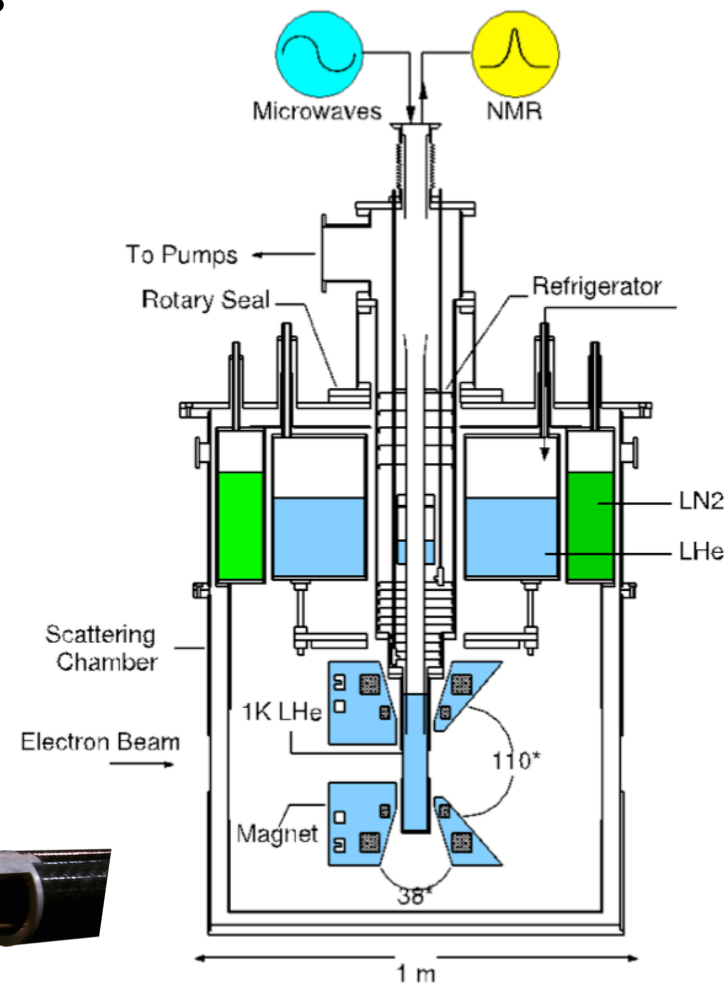
Polarized NH_3 Target

Target Polarization Results for 5T Field Setting



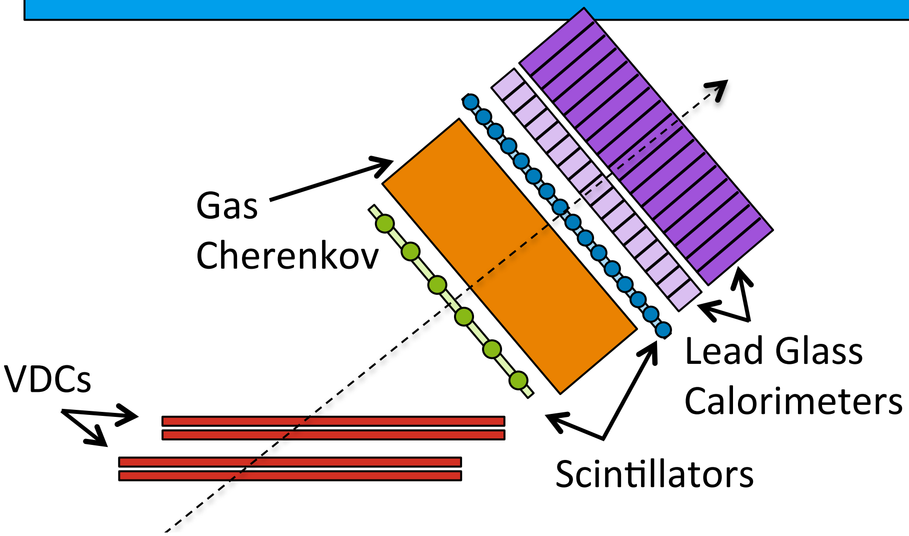
(analysis done by T. Badman)

Run #

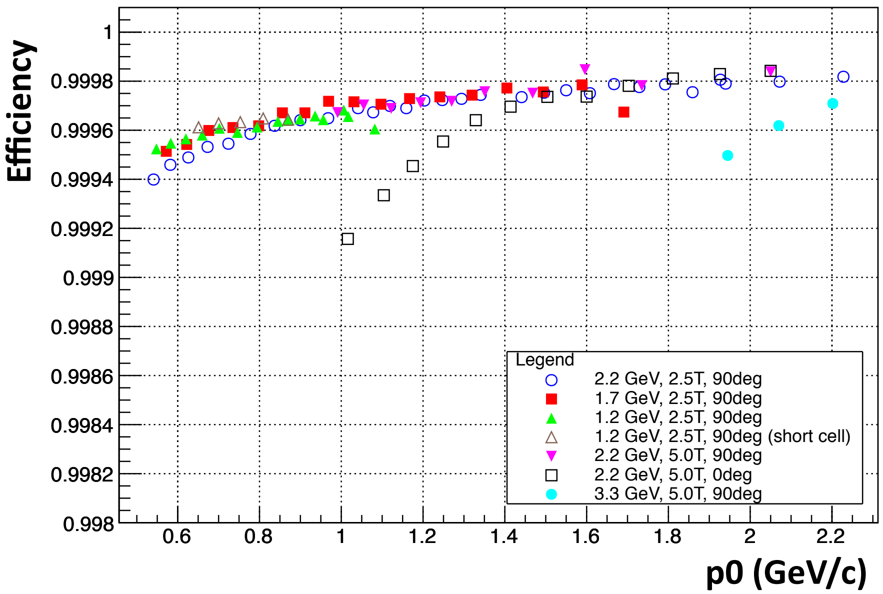


Average Polarization:
5T: ~70%
2.5T: ~15%

Detector Stack



Gas Cherenkov Detector Efficiency

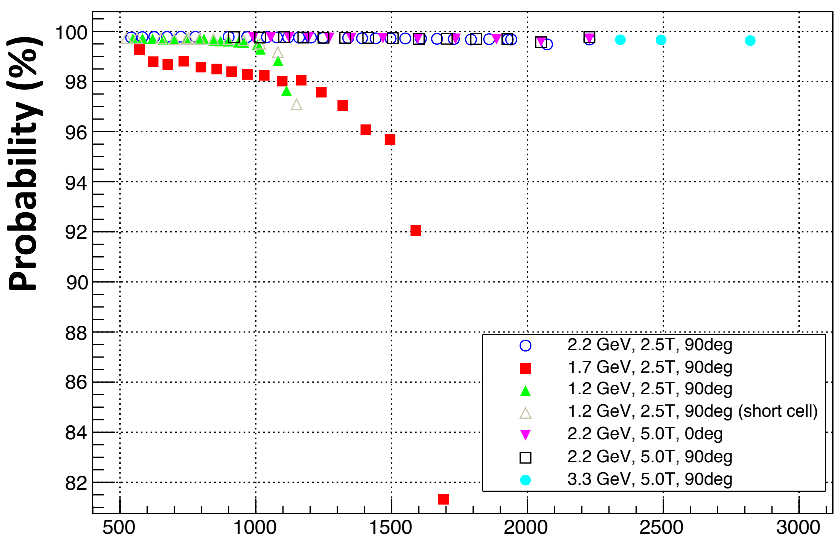


- Gas Cherenkov and lead glass electromagnetic calorimeters used for particle identification
- High Efficiency (>99%) for gas Cherenkov and lead glass calorimeters
- Two planes of scintillators used to create singles trigger
- High Trigger efficiency (>98%) for production runs

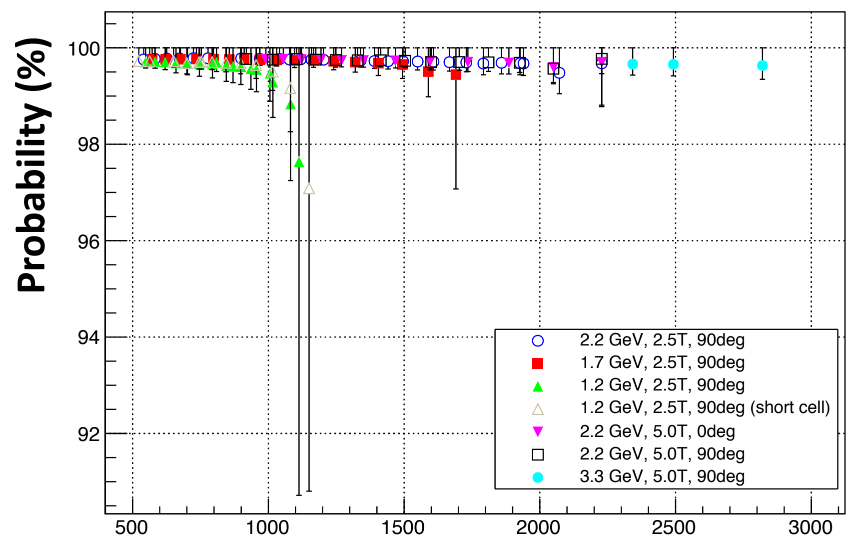
VDC Multi-track Analysis

- VDC efficiency is the fraction of events with a successful track reconstruction
- Number of multi-track events can reach ~20% for some kinematic settings
- Cluster energy of tracks is examined to determine inefficiency

VDC Single-Track Probability



VDC Total Good Track Probability



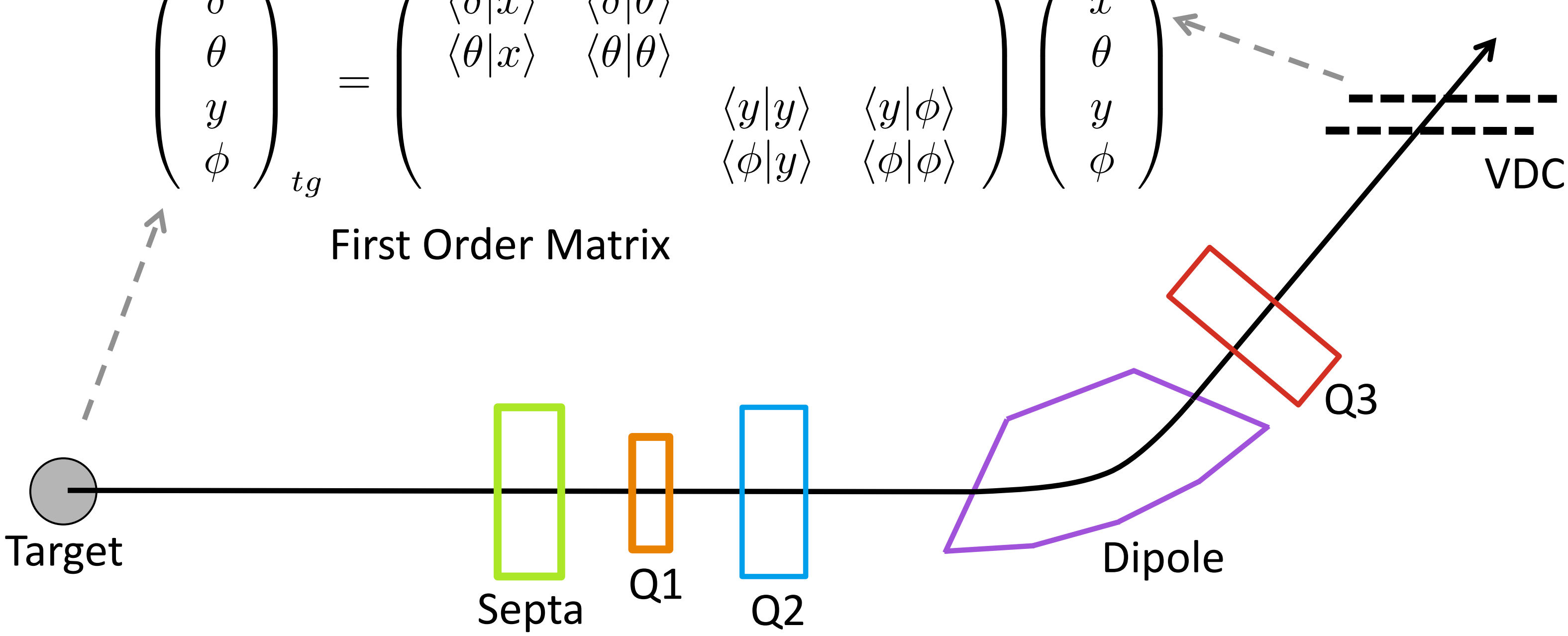
(analysis done by J. Liu) **p0 (MeV/c)** **p0 (MeV/c)**

HRS Optics

- HRS has a series 3 quadrupoles and 1 dipole for focusing and dispersion
- g_2^p experiment also used an additional septum magnet
- Optics study provides a matrix to transform VDC readouts to kinematic variables

$$\begin{pmatrix} \delta \\ \theta \\ y \\ \phi \end{pmatrix}_{tg} = \begin{pmatrix} \langle\delta|x\rangle & \langle\delta|\theta\rangle & & \\ \langle\theta|x\rangle & \langle\theta|\theta\rangle & & \\ & & \langle y|y\rangle & \langle y|\phi\rangle \\ & & \langle\phi|y\rangle & \langle\phi|\phi\rangle \end{pmatrix} \begin{pmatrix} x \\ \theta \\ y \\ \phi \end{pmatrix}$$

First Order Matrix

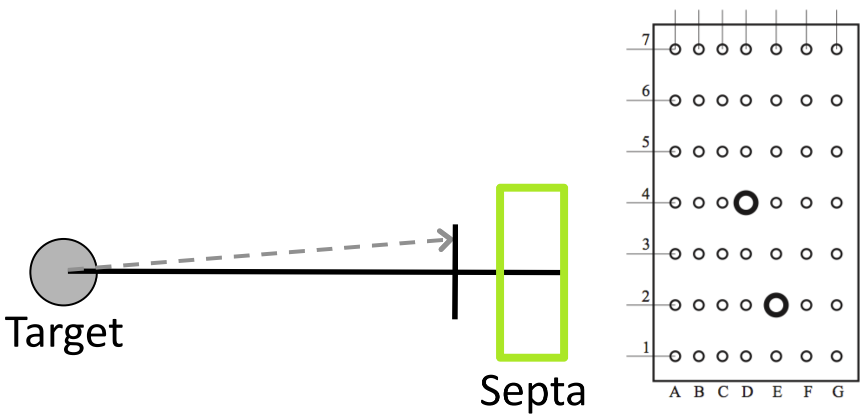


HRS Optics

Without Target Field

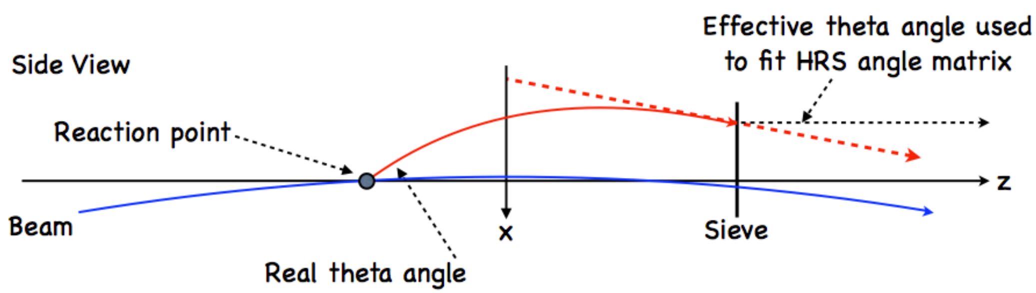
- Calibrations done using a foil target and point beam

- Can use sieve slit to get the real scattering angle from geometry



With Target Field

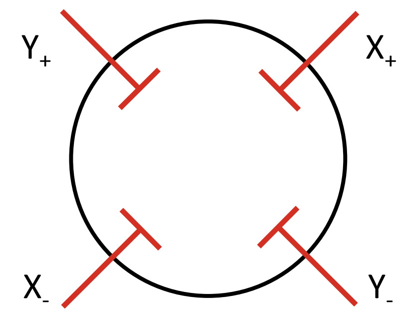
- Must split reconstruction into 2 parts:
  - Can use HRS transform matrix for reconstruction from VDC to sieve slit
  - Then use a target field map to do a ray trace of the scattered particle from the sieve slit to the target

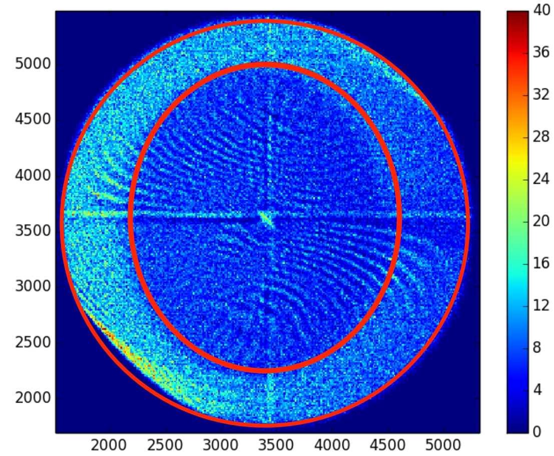


Beam Position Calibrations

- 4 antennas used to determine the beam position
- Fast and Slow raster system used to reduce radiation damage and minimize depolarization of target
- BPMs can only give average beam position, need raster information to get position event-by-event

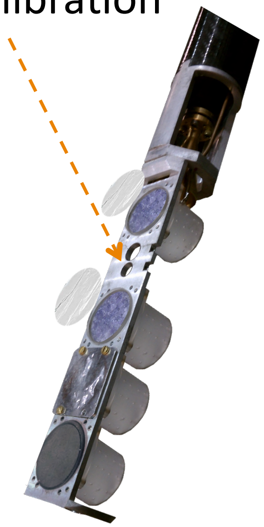
$$X = X_{bpm} + X_{raster_{fast}} + X_{raster_{slow}}$$



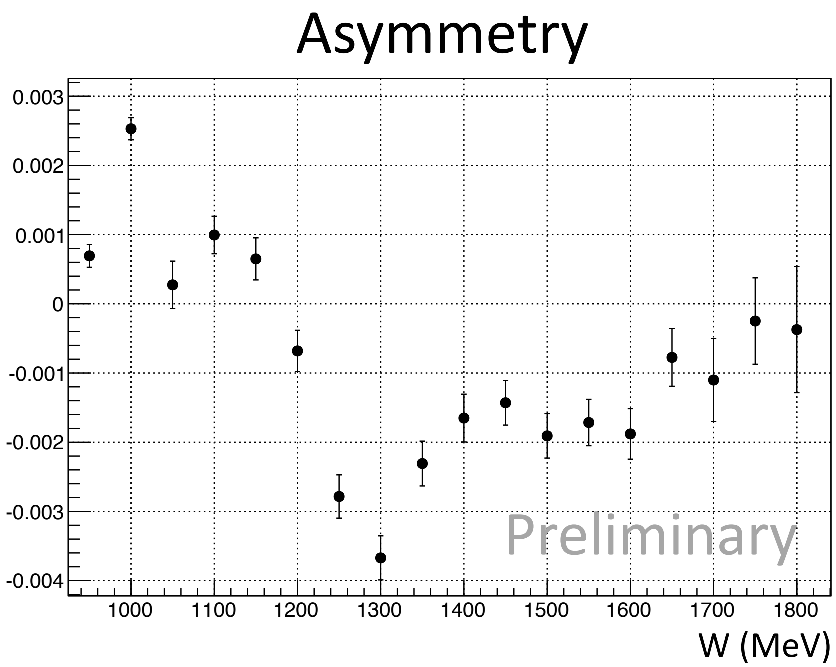


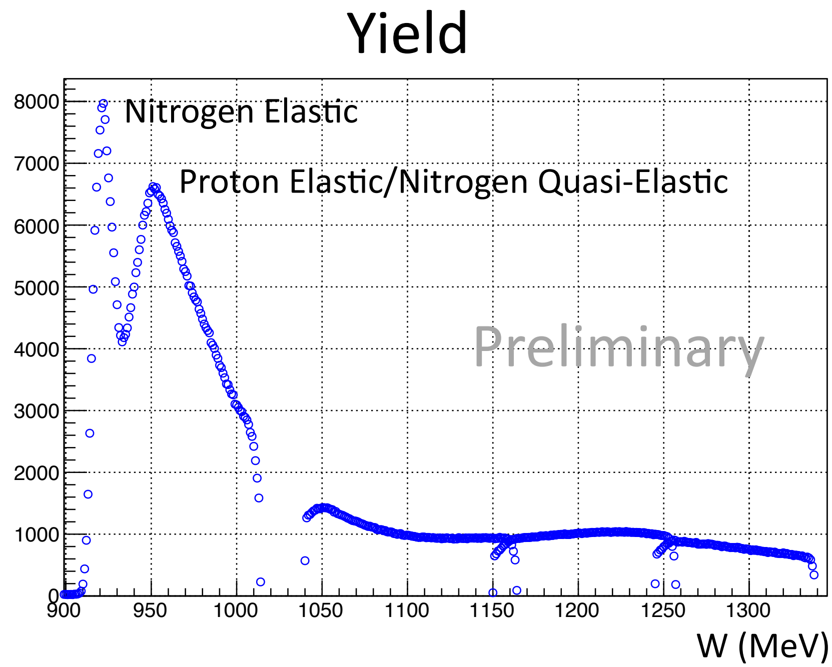
(analysis done by P. Zhu)

hole used for calibration



Preliminary Results





$$A_{\perp} = \left(\frac{1}{P_b P_t}\right)\frac{Y_+ - Y_-}{Y_+ + Y_-}$$

$$\Delta\sigma_{\perp} = \sigma_{total} A_{\perp}$$

$$Y_{\pm} = \frac{N_{\pm}}{Q_{\pm} L T_{\pm}}$$

Summary of g_2^p

g_2^p experiment will provide first precision measurement for proton at low Q^2

$0.02 < Q^2 < 0.2\ \text{GeV}^2$

- Will provide insight on several outstanding physics puzzles
  - BC Sum Rule: Violation suggested for proton at large Q^2 (SLAC E155x)
  - Longitudinal-transverse spin polarizability: benchmark test of χPT, discrepancy seen for neutron data
  - Hydrogen hyperfine splitting: correction for proton structure contributes to uncertainty
  - Proton charge radius: contributions to uncertainty include proton polarizability