Measurement of
Spin Structure Functions in

Mark Jones

Jefferson Lab

GDH2004 at ODU

June 2004

Hall C Program

- Spin Structure Functions (SSF)
  - Inclusive measurements
    - SSF in the Nucleon Resonance Region
      E01-006 prelimary data
    - SSF at high Bjorken x
      E03-109 Cond. approved
  - Semi-Inclusive in DIS measurements
    - Spin asymmetries in $(e, e'h)$ $\quad h = \pi^{\pm}, K^{\pm}$
      PAC26 proposal
- Tools
  - CEBAF Polarized beam
  - Solid Polarized NH_3 and ND_3 targets
    Target field direction parallel and perpendicular to beam direction
  - Hall C High Momentum Spectrometer (HMS) for E01-006
  - Non-magnetic detector, BETA (Big Electron Telescope Array) for E03-109 and PAC26 proposal

Resonances Spin Structure (RSS)

Precision Measurement of the Nucleon Spin Structure Functions

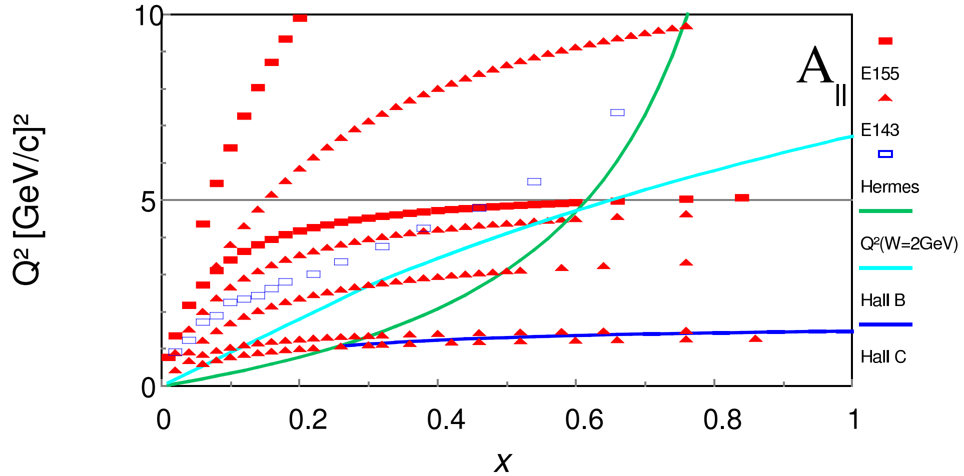
in the Region of the Nucleon Resonances

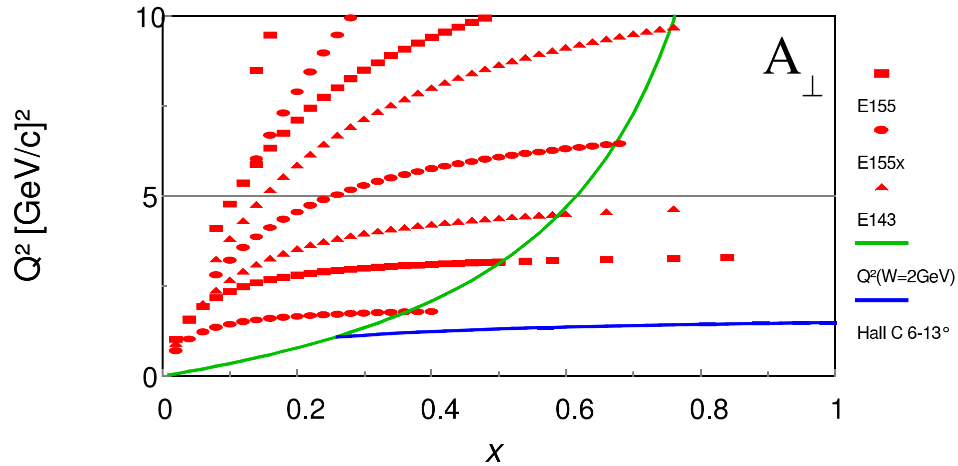
U. Basel, Florida International U., Hampton U., U. Massachusetts, U. Maryland, Mississippi S. U., North Carolina A&T U., U. of N. C. at Wilmington
Norfolk S. U., Old Dominion U.,S.U. New Orleans, U. of Tel-Aviv, TJNAF, U. of Virginia, Virginia P. I. & S.U., Yerevan Physics I.

Spokesmen: Oscar A. Rondon (U. of Virginia) and Mark K. Jones (Jefferson Lab)

- Measure proton and deuteron spin asymmetries $A_1(W, Q^2)$ and $A_2(W, Q^2)$ at momentum transfer $Q^2 \approx$ 1.3 GeV^2 and invariant mass 0.8$< W <$ 2 GeV.
- Extract g_1 and g_2 structure functions and study:
  - W dependence
  - Onset of polarized local duality
  - twist-3 effects in d_2 matrix element

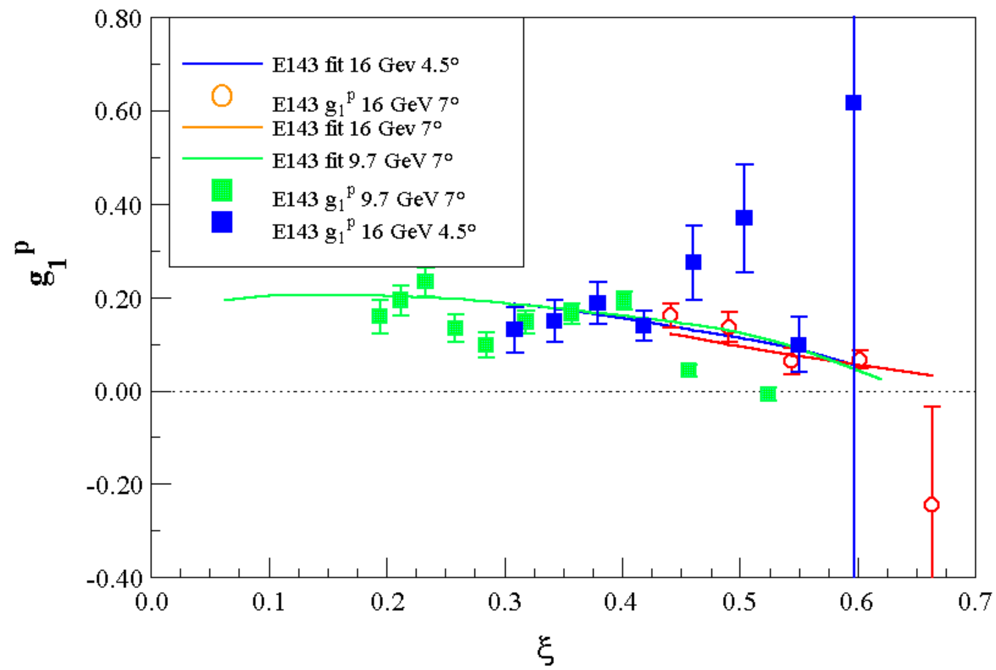
RSS Motivation: SSF in Resonance region





- Final state mass region W $<$ 2 GeV (resonances) dominates kinematic plane for four-momentum transfer Q^2 $<$ 5 GeV^2
  - few data in high Bjorken x region
  - DIS-resonances connection (duality)
- Good W resolution required for resonances (Not available at HEP labs - SLAC, HERMES, SMC)
  - JLab Hall C High Momentum Spectrometer (HMS) has ΔW $<$ 30 MeV

Polarized Duality



- Quantative tests of duality of unpolarized SF (SLAC, JLab) and to a lesser degree polarized SF (SLAC, Hermes, JLAB). (Talk by S. Liuti)
- SLAC 143: g_1 from $A_{||}$ assuming $A_2 = 0$
- Resolution in W too wide for local duality test
- Global duality ratio of integrals has large error bars.

Structure functions in DIS and in resonances

- Polarized and unpolarized structure functions share common interpretation:
  - DIS: Parton model and Operator Product Expansion (OPE)

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

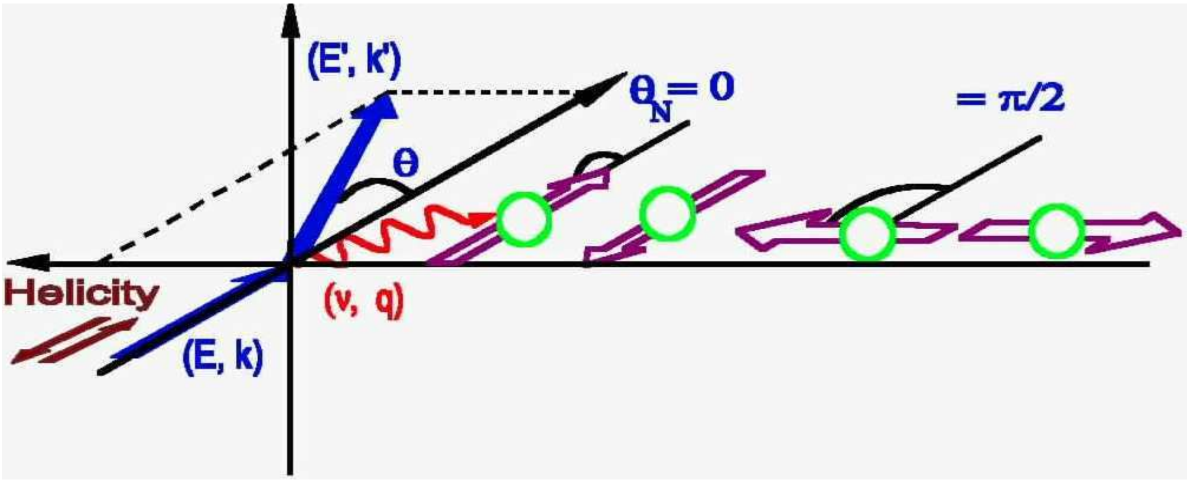
  - Resonances: forward virtual Compton scattering

$$A_1(Q^2,\nu) = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{M\nu G_1(Q^2,\nu) - Q^2 G_2(Q^2,\nu)}{W_1(Q^2,\nu)}$$

  - Connection: scaling limit

$$\lim_{Q^2,\nu\to\infty} M\nu G_1(Q^2,\nu) = g_1(x) \qquad \lim_{Q^2,\nu\to\infty} M W_1(Q^2,\nu) = F_1(x)$$

Electron-Nucleon Polarized Scattering



$$\Delta\sigma(\theta, \theta_N, \phi) = \frac{d^2\sigma^{\uparrow\uparrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\downarrow}}{d\Omega dE'}$$

$$\begin{aligned}
\Delta\sigma(\theta_N = 0) &= \frac{4\alpha^2 E'}{Q^2 E}\left\{(E + E'\cos\theta)MG_1 - Q^2 G_2\right\} = 2\sigma_u A_{\parallel} \\
\Delta\sigma(\theta_N = \frac{\pi}{2}) &= \frac{4\alpha^2 E'}{Q^2 E} E' \sin\theta\cos\phi(MG_1 + 2EG_2) = 2\sigma_u A_{\perp}
\end{aligned}$$

Relation between A_1, A_2 and $A_\|, A_\perp$

- Clean extraction of A_1, A_2 for protons and deuterons is crucial.
- Solution: measure $A_\|, A_\perp$ on polarized ammonia

$$
\begin{aligned}
A_1 &= \frac{C}{D}(A_\| - dA_\perp) \\
A_2 &= \frac{C}{D}(c' A_\| - d' A_\perp)
\end{aligned}
$$

- Kinematic variables $C, c', d, d'(E, E', \theta), D(E, E', \theta, R)(R = \sigma_L/\sigma_T)$
- $d' \approx 1, c' \approx d \leq 1$ (at RSS kinematics)
- Comparable systematic errors for both $A_\|, A_\perp$ is important.

SSF g_1, g_2 and Spin Asymmetries A_1, A_2

- g_1, g_2 can be extracted directly from $A_{||}, A_{\perp}$ or A_1, A_2

$$g_1 = \frac{F_1}{1+\gamma^2}(A_1 + \gamma A_2)$$

$$g_2 = \frac{F_1}{1+\gamma^2}(\frac{A_2}{\gamma} - A_1)\ ;\ \gamma^2 = \frac{Q^2}{\nu^2}$$

  - Need $F_1 = F_2(1+\gamma^2)/2x/(1+R)$ in the resonance region.
    Measurement of F2 and R in resonance region (see E. Christy's talk)

- Also can get g_1, g_2 directly from cross section differences:
  F_2 and R not needed

- g_1 can be extracted from $A_{||}$ and SSF model for g_2

Determining the Asymmetry

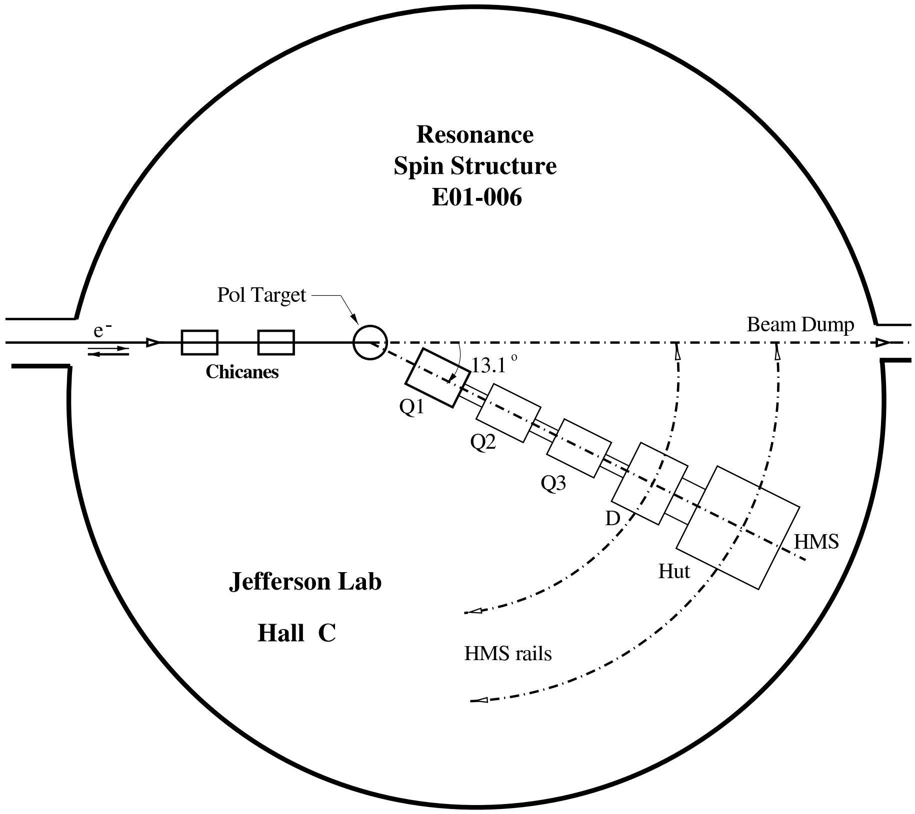
- Raw Asymmetry , $\epsilon = \frac{N^+ - N^-}{N^+ + N^-}$
  in which N^+, N^- are the number of counts normalized by the charge and deadtime for opposite beam helicities.

- Parallel and perpendicular asymmetries

$$A_{\parallel,\perp} = \frac{1}{C_N f_{rc}}\left(\frac{\epsilon}{f P_b P_t} - C_D\right) + A_{rc}$$

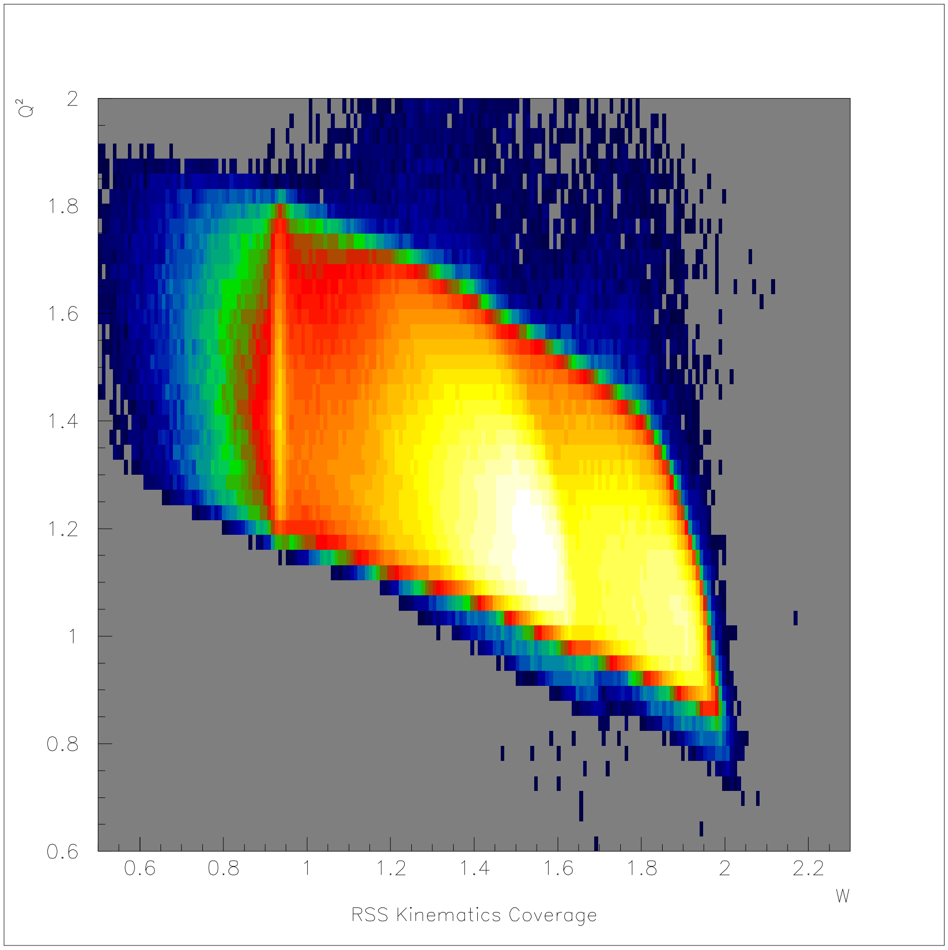
  – f = dilution factor ; ratio of rates from polarized nucleons to all nucleons
  – P_b, P_t = beam and target polarizations
  – C_N, C_D = corrections of N in ammonia
  – f_{rc}, A_{rc} = radiative corrections
    Use code for polarized scattering in resonances
    (I. Akusevich)

Experimental Setup



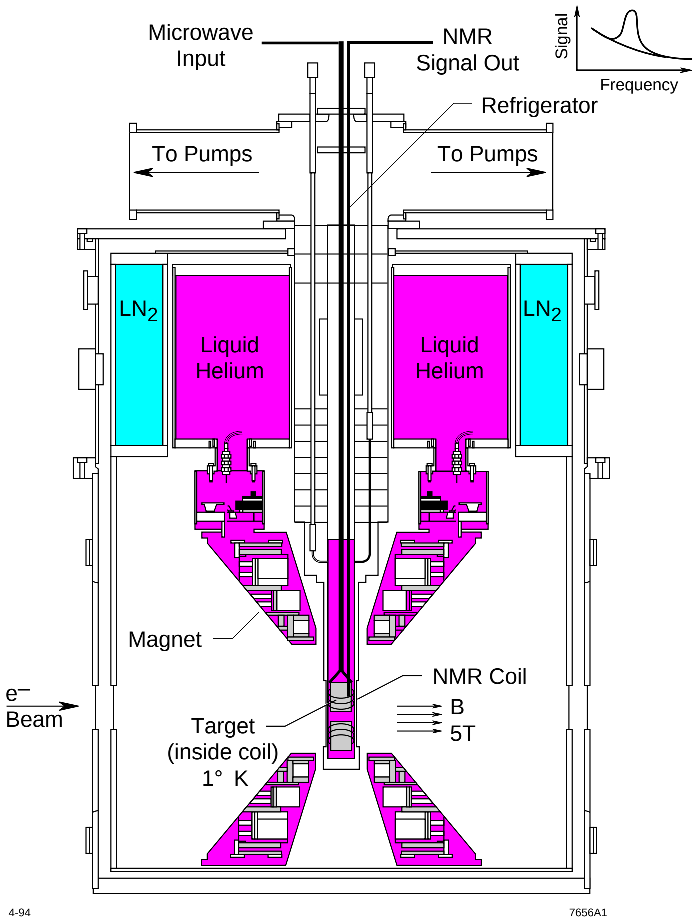
- Incident beam rastered in circular pattern with 2cm diameter.
- Before target, chicane magnets bend the beam to compensate for target field to make beam horizontal at target..
- Polarized target rotated so target field direction either parallel or perpendicular to beam direction.

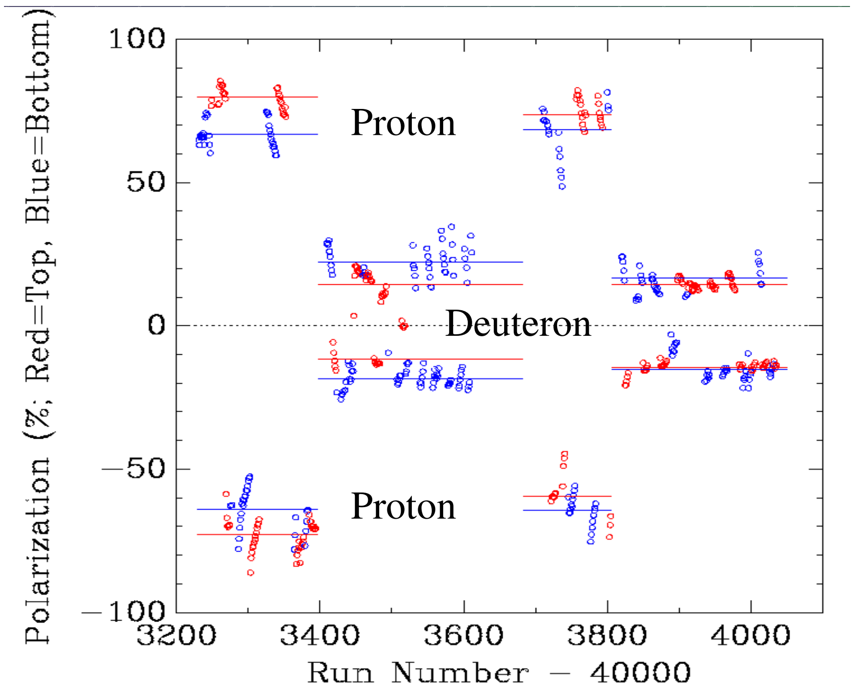
Kinematic coverage



- Beam Energy = 5.755 GeV
- Electron scattering angle 13.15°
- HMS central momentum settings of 4.7 and 4.1 GeV/c
- $< Q^2 >$ = 1.3 GeV^2 over W range of 0.8 to 2.0 GeV.

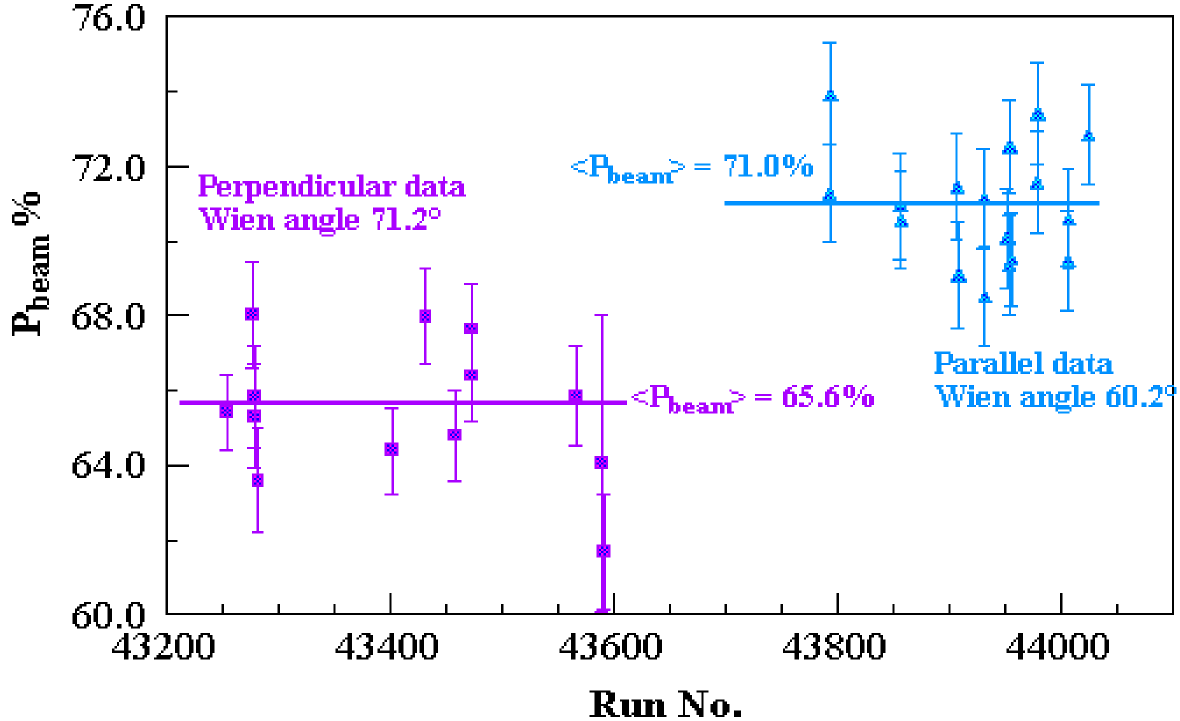
Polarized Target



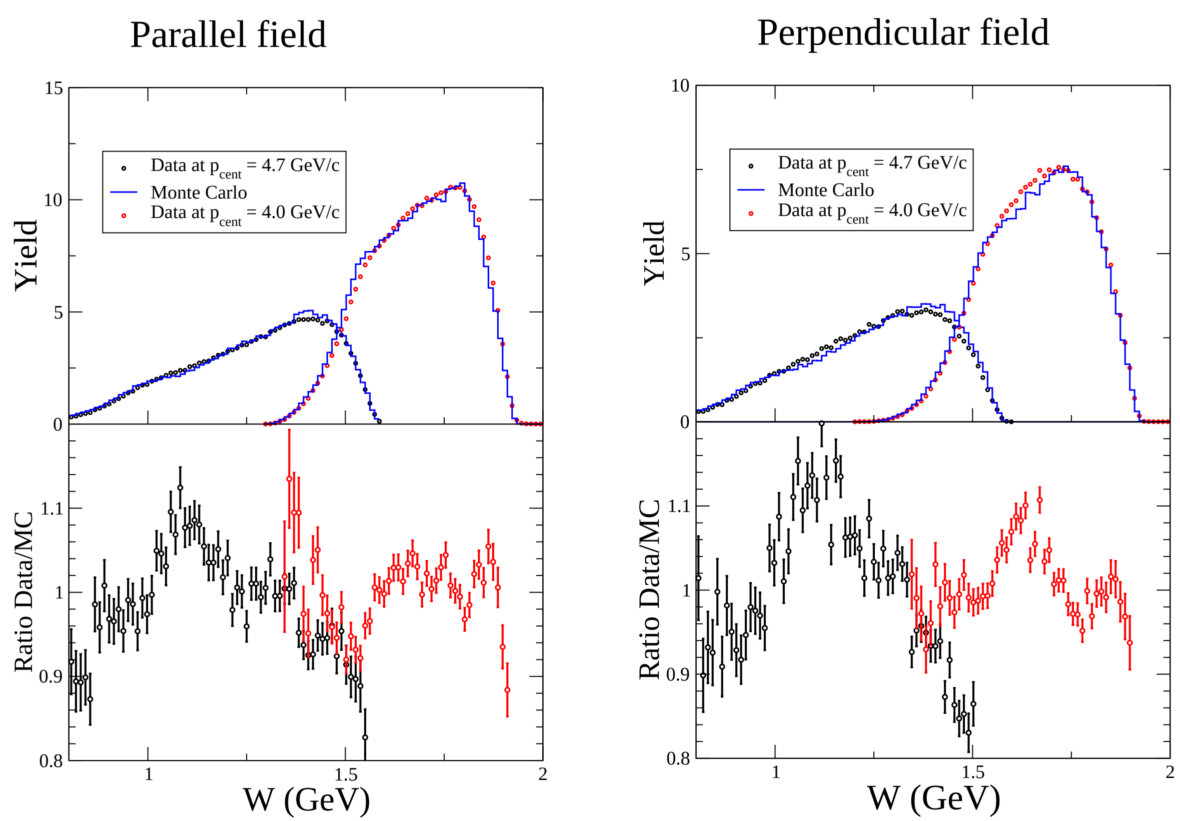


Beam Characteristics

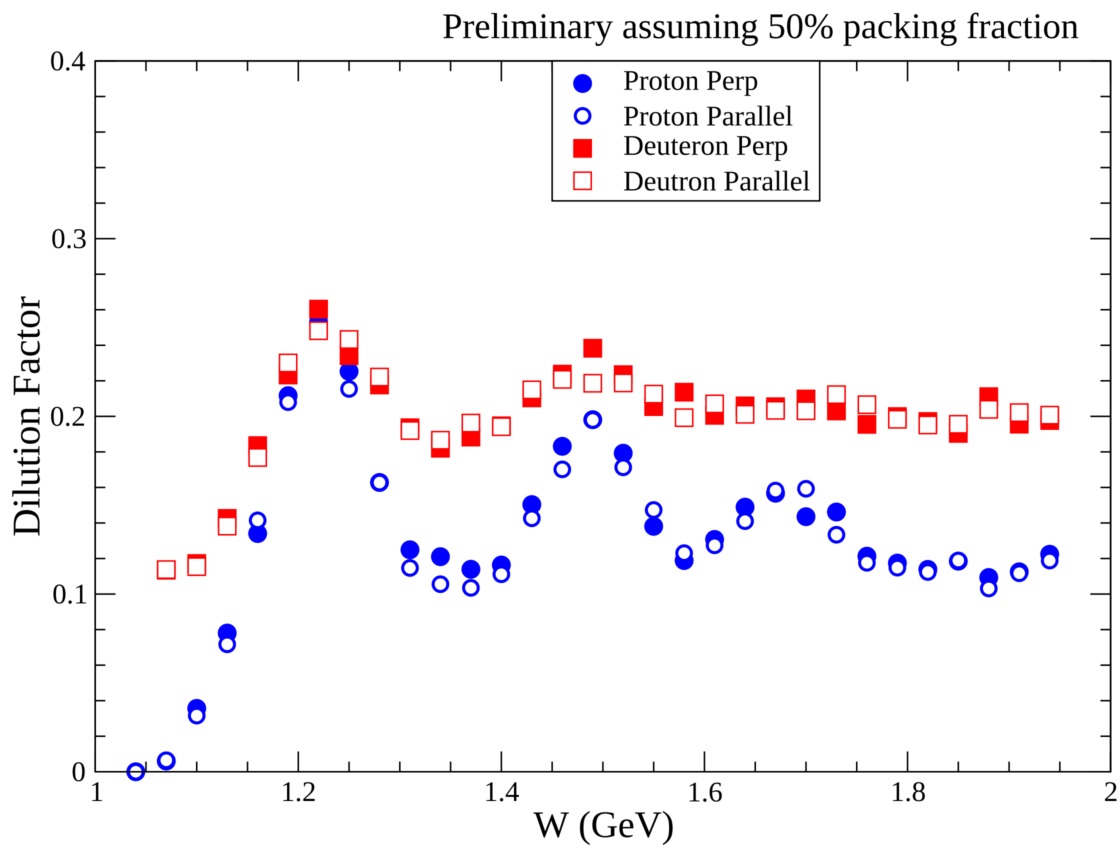
- Beam current
  - 150 - 200 nA for ND_3, C, He
  - 85 - 100 nA for NH_3
- Beam polarization measured in the Hall with Moller



^{12}C yield compared to Monte Carlo

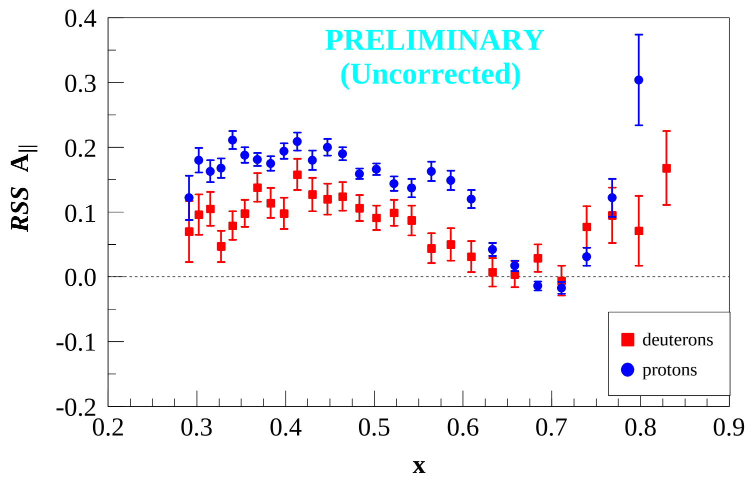


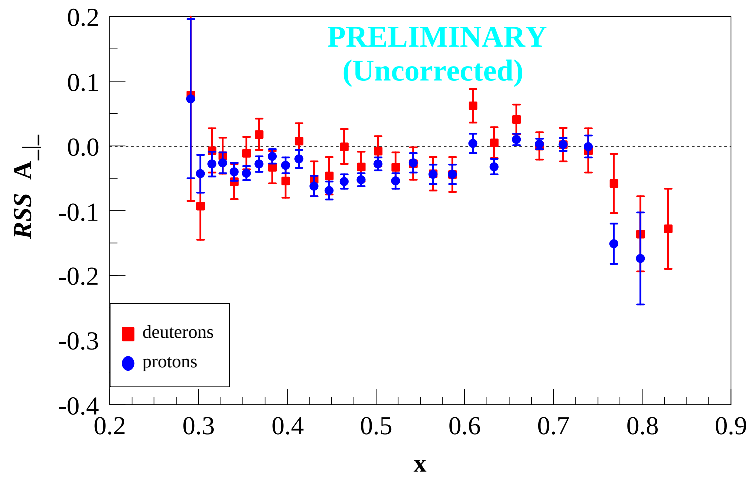
Dilution factors



- need to determine packing fraction for target cell (8 in total)
- Packing fraction between 0.5 to 0.6 determined by ratio on ammonia to carbon rates.

Extracted $A_{\|}$ and $A_{\perp}$



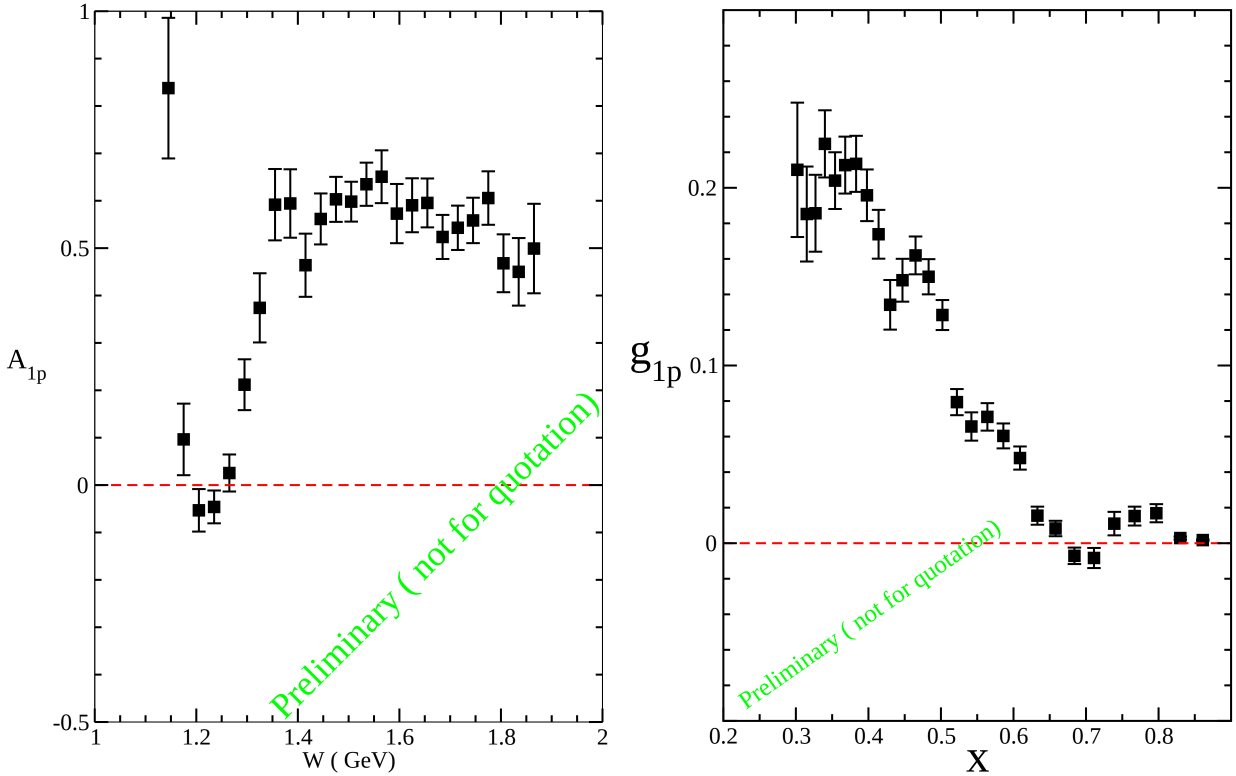


- Preliminary dilution factor (same packing fraction for all targets).
- **Not applied:** Radiative corrections, individual packing fractions, N asymmetry.

Sources of Systematic Error

	$^{15}NH_3$	$^{15}ND_3$
Nitrogen polarization	$<$1%	1%
Radiative corrections	2%	3%
Beam Polarization	1.5%	1.5%
Target polarization	2.5%	4%
Dilution factor	3%	3%
Pions, deadtime	1%	1%
Errors from R and F2	3%	3%
Total error	5.5%	6.8%

Extracted A_{1p} and g_{1p}



Use hall C fit to F_{2p} and R

Spin Asymmetries on the Nucleon Experiment

U. Basel, Florida International U. , Hampton U., IHEP Protvino, Norfolk State U. ,Rensselaer Polytechnic I.,
Temple U., TJNAF, U. of Virginia, College of William & Mary, Yerevan Physics I.

Spokesmen: Oscar A. Rondon (U. of Virginia), Zein-Eddine Meziani (Temple U.) and Seonho Choi (Temple U.)

- Measure inclusive electron scattering spin asymmetries, $A_{||}$ and $A_{\perp}$, on NH_3 target. Two beam energies: 4.8 and 6 GeV so large kinematic range
  - 2.5 $< Q^2 <$ 6.5 GeV^2
  - 0.3 $< x <$ 0.8
- Extract proton $g_2(x, Q^2)$ and $A_1(x, Q^2)$
- Study x and Q^2 dependence, twist-3 effects, moments of g_2 and g_1, comparison with Lattice QCD predictions, test polarized local duality for W$>$ 1.4 GeV.

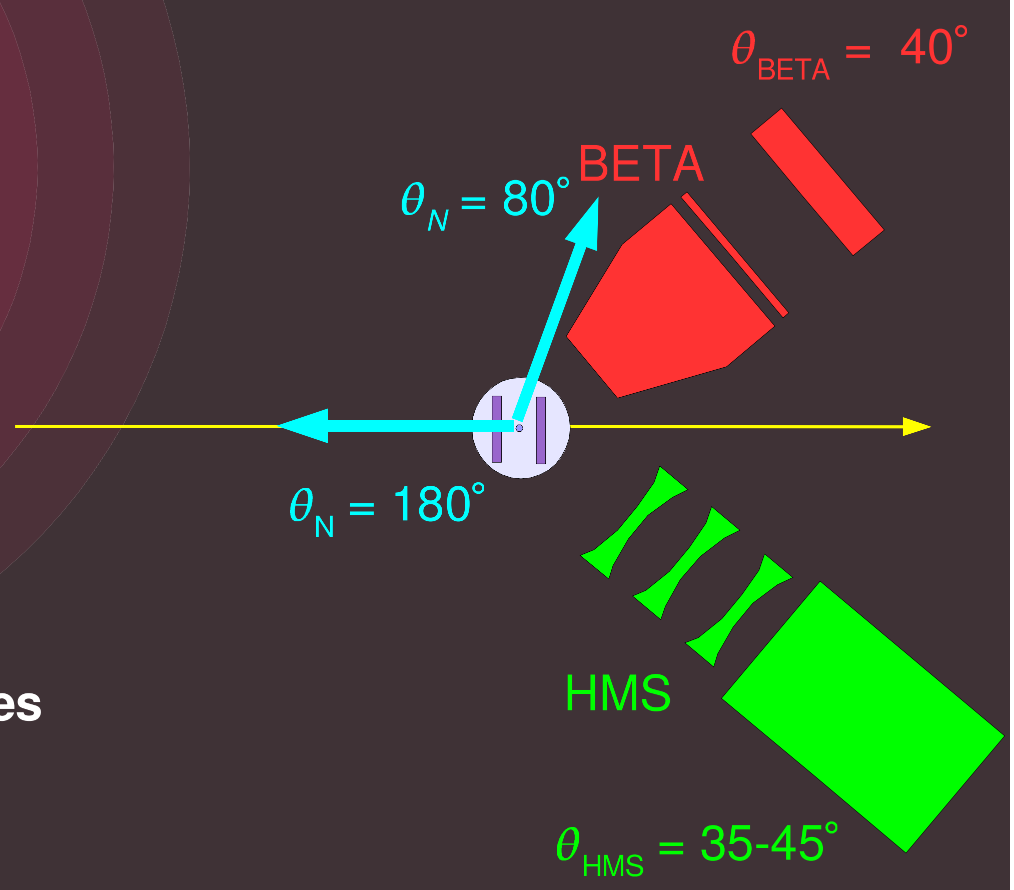
Experimental Setup

Target
- UVa NH3 target
- 5 T field

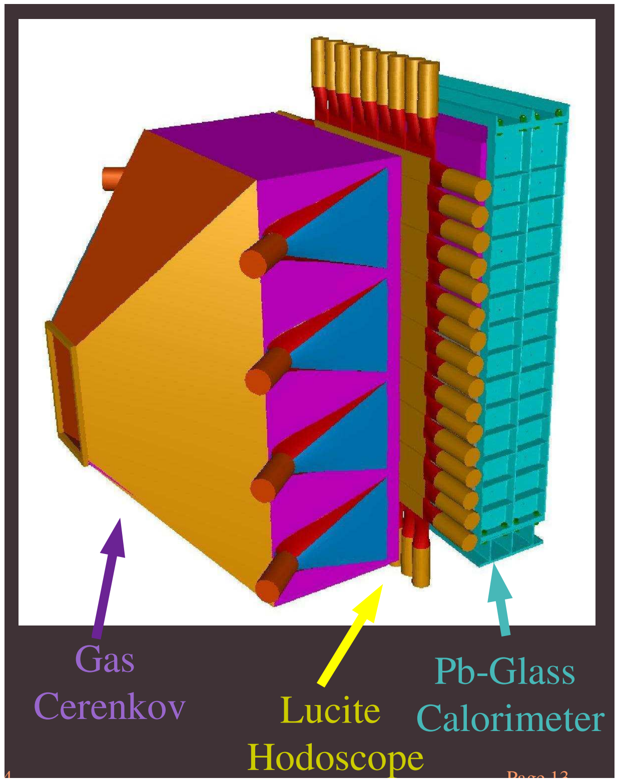
Beamline
- Chicanes
- SEM
- He Bag

Electron Arm
- BETA

Background Studies
- HMS

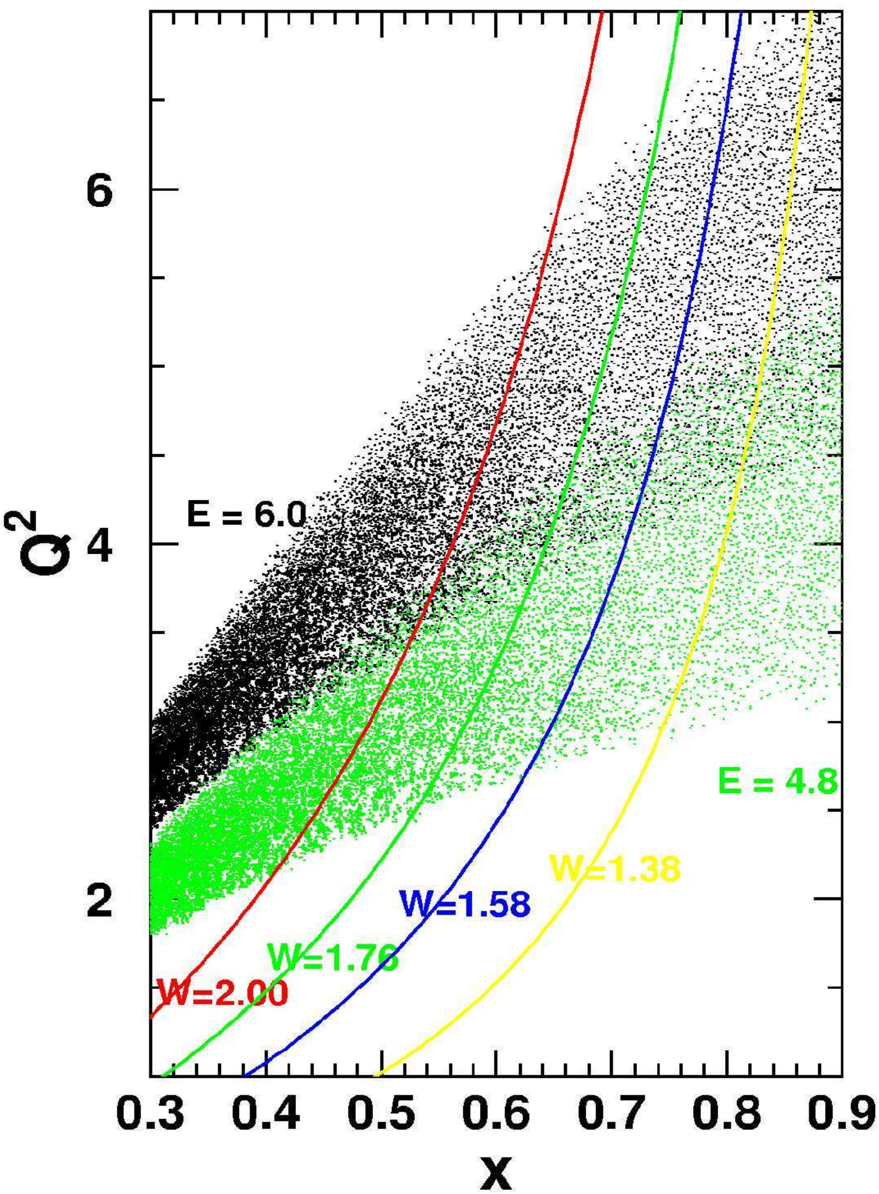


Big Electron Telescope Array (BETA)

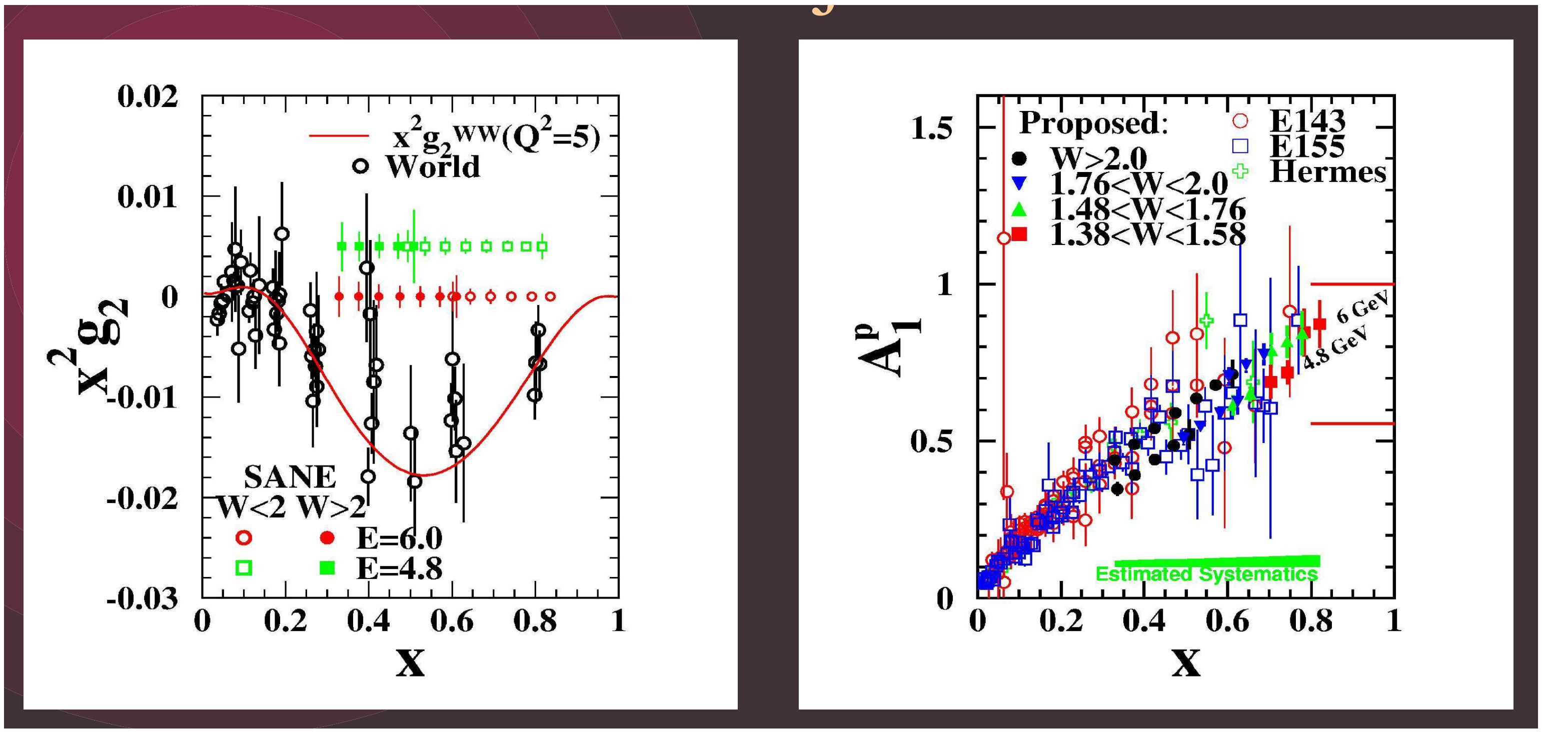


- Lead Glass Calorimeter
  - ΔE/E = 5%/$\sqrt{\text{E}}$
  - Large solid angle (194msr)
  - Highly segmented , 1744 blocks (4 x 4 x 40cm)
- Gas Cerenkov
  - π/e separation, 1000:1 rejection factor
- Lucite hodoscope array
  - Redundant PID , Tracking info when combined with Calo.

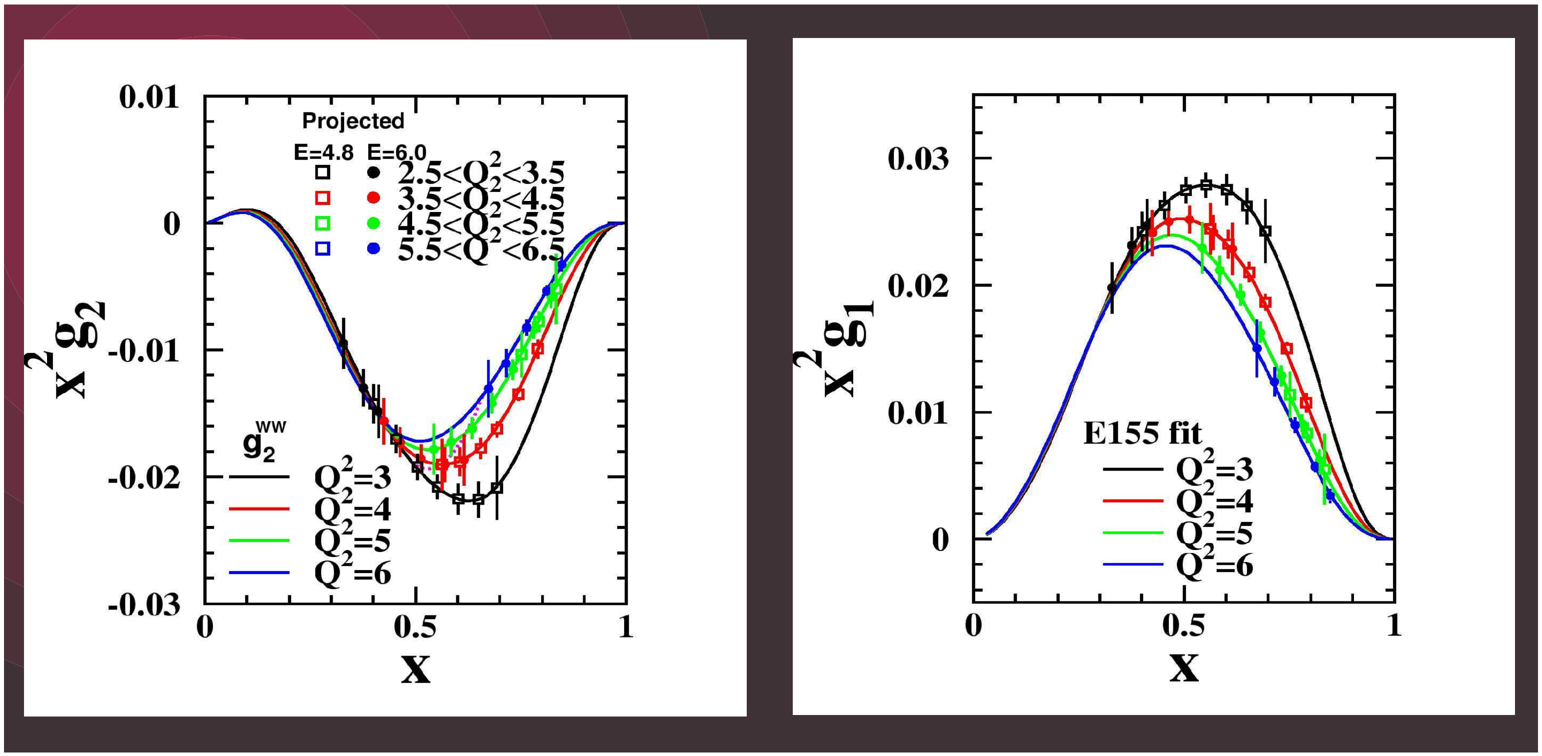
Kinematic coverage with two beam energies



Expected Results for proton g_2 and A_1



Expected Results x and Q^2 dependence



Semi-Inclusive Spin Asymmetries on the Nucleon Experiment

Argonne National Lab, Duke U., Florida International U., Hampton U.,
U. Kentucky, U. Maryland, U. Massachusetts, Rensselaer Polytechnic I., Norfolk S. U.,
Old Dominion U., U. Regina, Rutgers U., Temple U., TJNAF, U. of Virginia, C. of William & Mary, Yerevan Physics I.

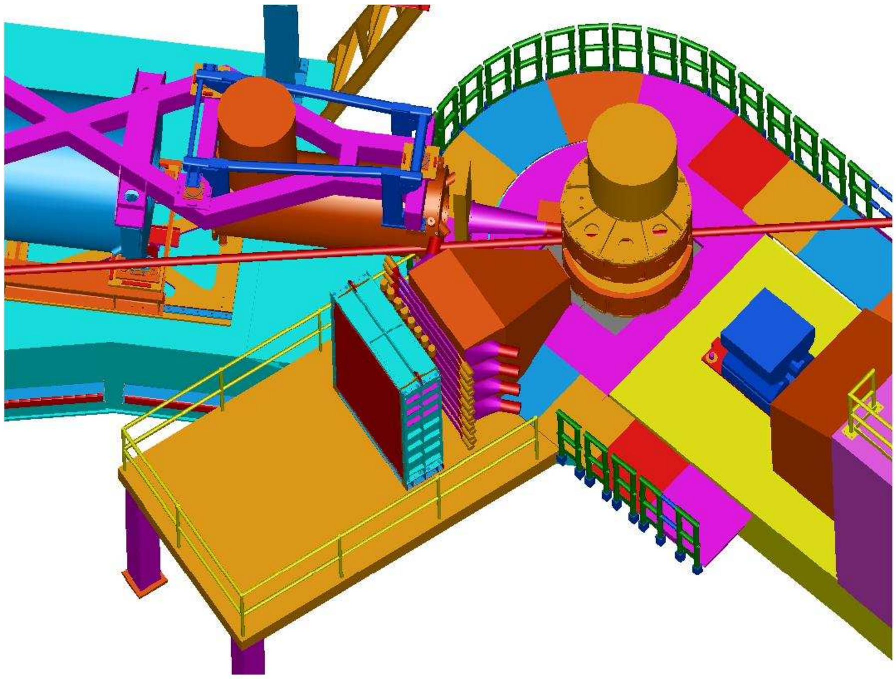
Spokesmen: P. Bosted (Jlab) , D. Day (U. of Virginia), X. Jiang (Rutgers); M. Jones (JLab)

- Measure proton and deuteron semi-inclusive longitudinal spin asymmetries in polarized DIS reactions $p(e, e'h)$ and $d(e, e'h)$ for h = $\pi^{\pm}$,$K^{\pm}$
at 1.2 $< Q^2 <$3.1 GeV^2, 0.12 $< x <$ 0.43,
with hadrons carrying 0.5 $< z(= E_h/\nu) <$ 0.7 of the energy transfer ν

- Spin flavor decomposition with special emphasis on NLO spin flavor decomposition to extract Δu_v, Δd_v and $\Delta\overline{u} - \Delta\overline{d}$ based on measurement of combined asymmetry, $A_{1N}^{\pi^+ - \pi^-}$. Christova and Leader PLB 468 (1999), NPB 607 (2001)

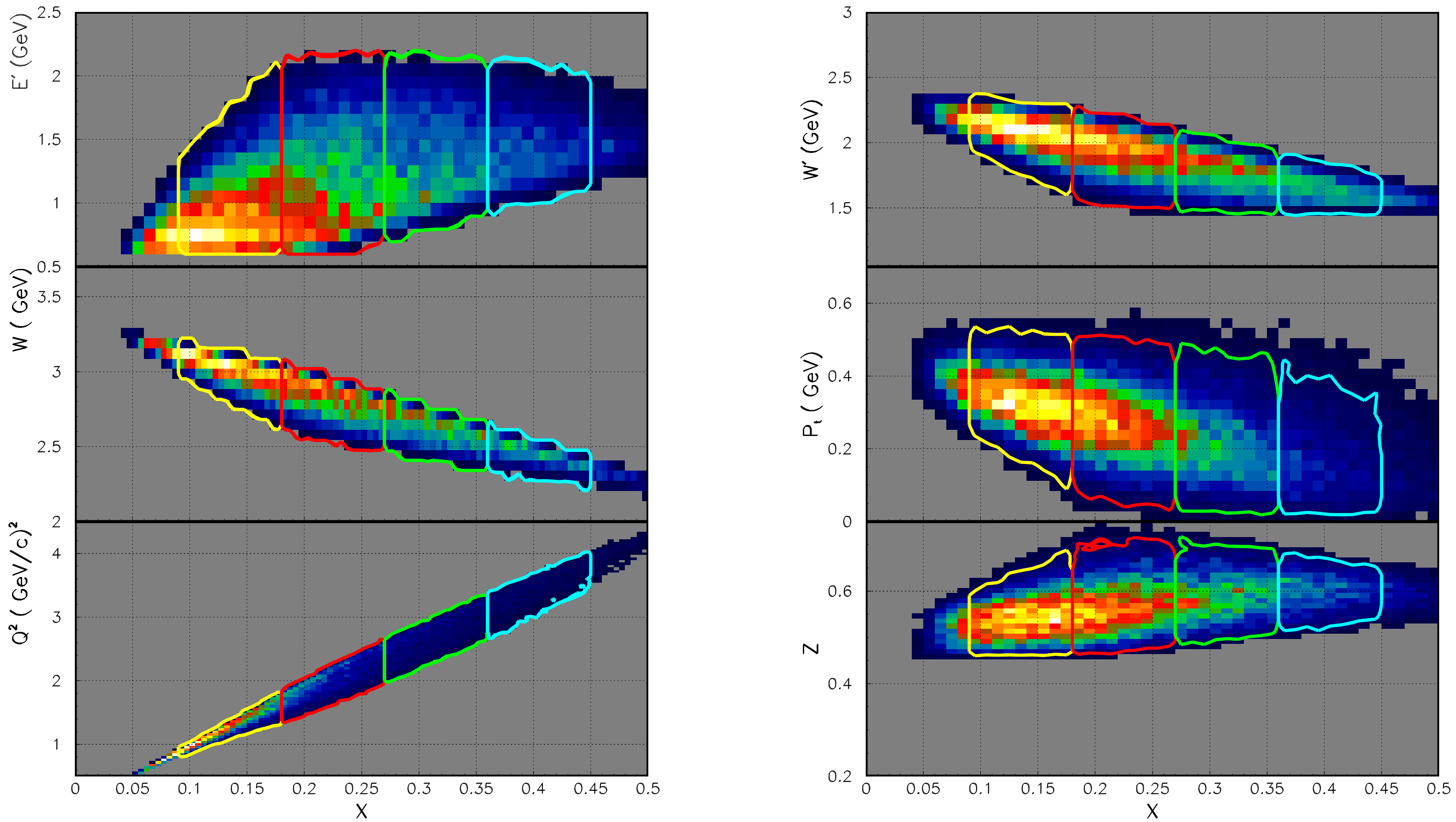
- Examine deviation from factorization by comparing combined asymmetry, $A_{1N}^{\pi^+ + \pi^-}$ with the inclusive asymmetry, A_{1N}.

Experiment Set-up



- Electrons detected in BETA at 30°
- Hadrons detected in HMS at 10.8° and p_{cent} = 2.7 GeV/c
  - HMS had $\pm$ 10% momentum bite
  - Kaon PID by hit in aerogel but not gas cerenkov
  - Pion PID by hit in aerogel and gas Cerenkov
  - Positrons elminated by energy in HMS calorimeter.
- Longitudinally polarized target of NH_3 and LiD.

Kinematic coverage



SIDIS Spin Asymmetries

- In leading order , the hadron production cross sections factorize

$$A_{1N}^{h}(x,Q^2,z) = \frac{\sum_f e_f^2 \Delta q_f(x,Q^2)\cdot D_f^h(z,Q^2)}{\sum_f e_f^2 q_f(x,Q^2)\cdot D_f^h(z,Q^2)}.$$

- In well defined z-bin, then each asymmetry can be related to quark polarization, e.g. :

$$A_{1p}^{\pi^+}(x,z) \quad = \quad \frac{4\Delta u + \Delta\bar{d} + (4\Delta\bar{u} + \Delta d)\,\lambda_\pi + 2\Delta s\xi_\pi}{4u + \bar{d} + (4\bar{u} + d)\,\lambda_\pi + 2s\,\xi_\pi}$$

$$\lambda_\pi(z) = D_\pi^-(z)/D_\pi^+(z) \qquad \xi_\pi(z) = D_s^\pi(z)/D_\pi^+(z)$$

are ratios of fragmentation functions (FF).

- Ratios of FF better known than FF themselves.

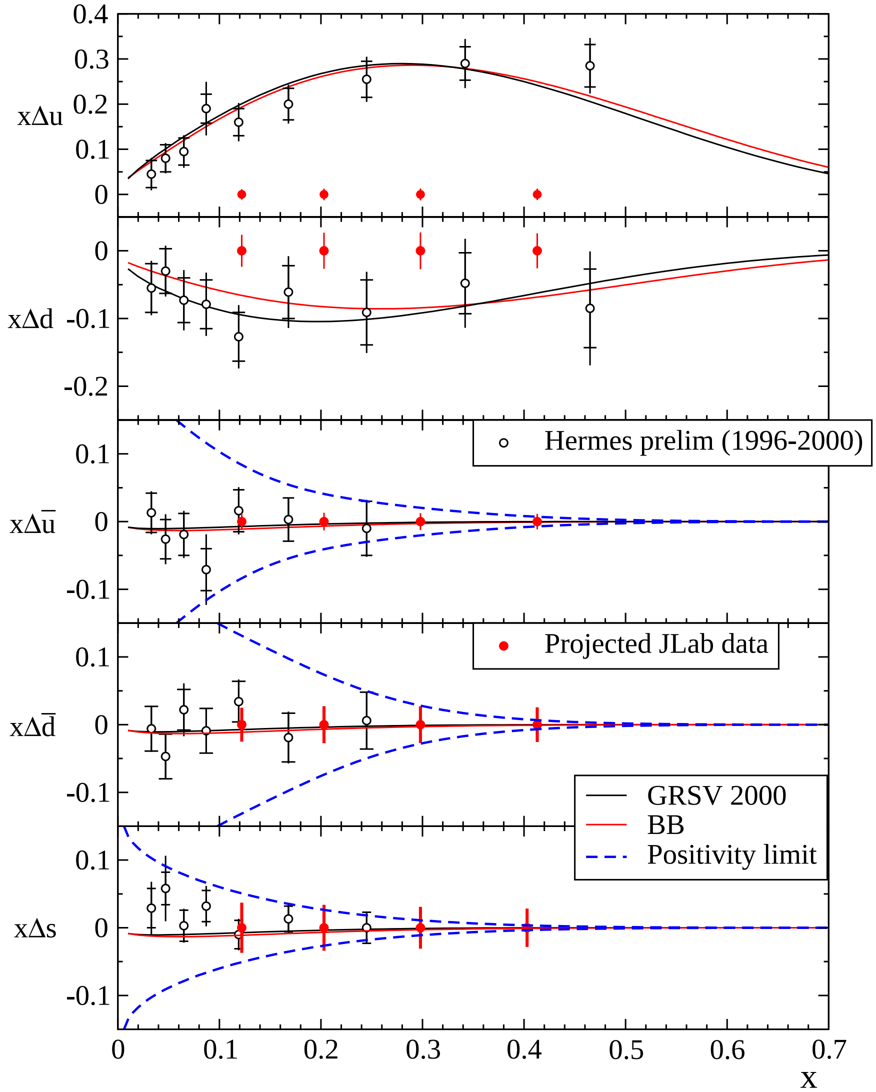
- Measure 10 double-spin asymmetries

$$\vec{A} = \left(A_{1p}^{\pi^\pm}, A_{1d}^{\pi^\pm}, A_{1p}^{K^\pm}, A_{1d}^{K^\pm}, A_{1p}, A_{1d}\right)$$

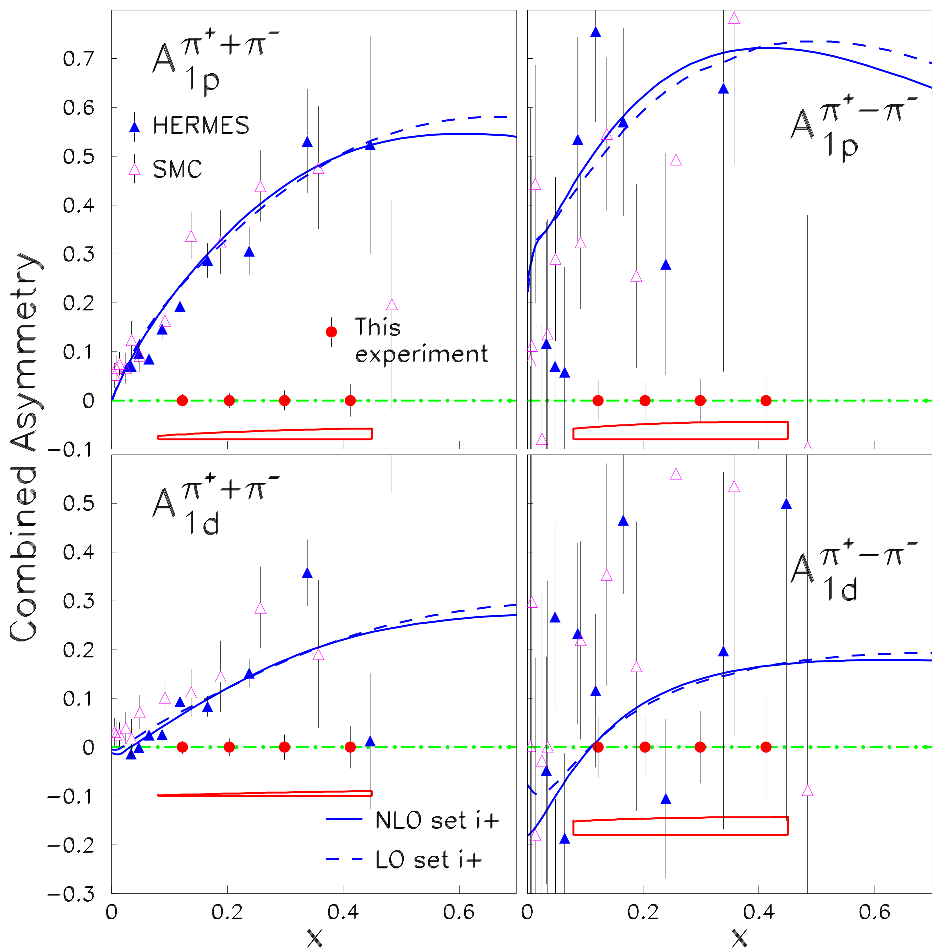
and the extract 5 quark polarization

$$\vec{Q} = \left(x\Delta u, x\Delta d, x\Delta\bar{u}, x\Delta\bar{d}, x\Delta s\right)$$

Flavor Decomposition



Combined Asymmetries



$$A_{1p}^{\pi^+ \pm \pi^-}(x, Q^2, z) = \frac{\Delta\sigma_p^{\pi^+} \pm \Delta\sigma_p^{\pi^-}}{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}}$$

$$A_{1d}^{\pi^+ \pm \pi^-}(x, Q^2, z) = \frac{\Delta\sigma_d^{\pi^+} \pm \Delta\sigma_d^{\pi^-}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}}$$

Calculations from D. de Florian and R.Sassot PRD 62, (2000),D. de Florian, O. A. Sampayo and R.Sassot PRD 58, (1998).

Polarized light sea asymmetry

$$A_{1p}^{\pi^+-\pi^-} = \frac{\Delta\sigma_p^{\pi^+} - \Delta\sigma_p^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} = \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v},$$

$$A_{1d}^{\pi^+-\pi^-} = \frac{\Delta\sigma_d^{\pi^+} - \Delta\sigma_d^{\pi^-}}{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}.$$

Therefore:

$$(\Delta u_v)_{LO} = \frac{1}{5}\left[\left(4u_v - d_v\right)\cdot A_{1p}^{\pi^+-\pi^-} + (u_v + d_v)\cdot A_{1d}^{\pi^+-\pi^-}\right)\right],$$

$$(\Delta d_v)_{LO} = \frac{1}{5}\left[4\left(u_v + d_v\right)\cdot A_{1d}^{\pi^+-\pi^-} - (4u_v - d_v)\cdot A_{1p}^{\pi^+-\pi^-}\right)\right],$$

$$(\Delta u_v - \Delta d_v)_{LO} = \frac{1}{5}\left[2\left(4u_v - d_v\right)\cdot A_{1p}^{\pi^+-\pi^-} - 3(u_v + d_v)\cdot A_{1d}^{\pi^+-\pi^-}\right)\right].$$

From the inclusive DIS data, we have:

$$g_1^p(x,Q^2) - g_1^n(x,Q^2) = \frac{1}{6}\Delta q_3(x,Q^2)|_{LO},$$

the non-singlet Δq_3 is defi ned as:

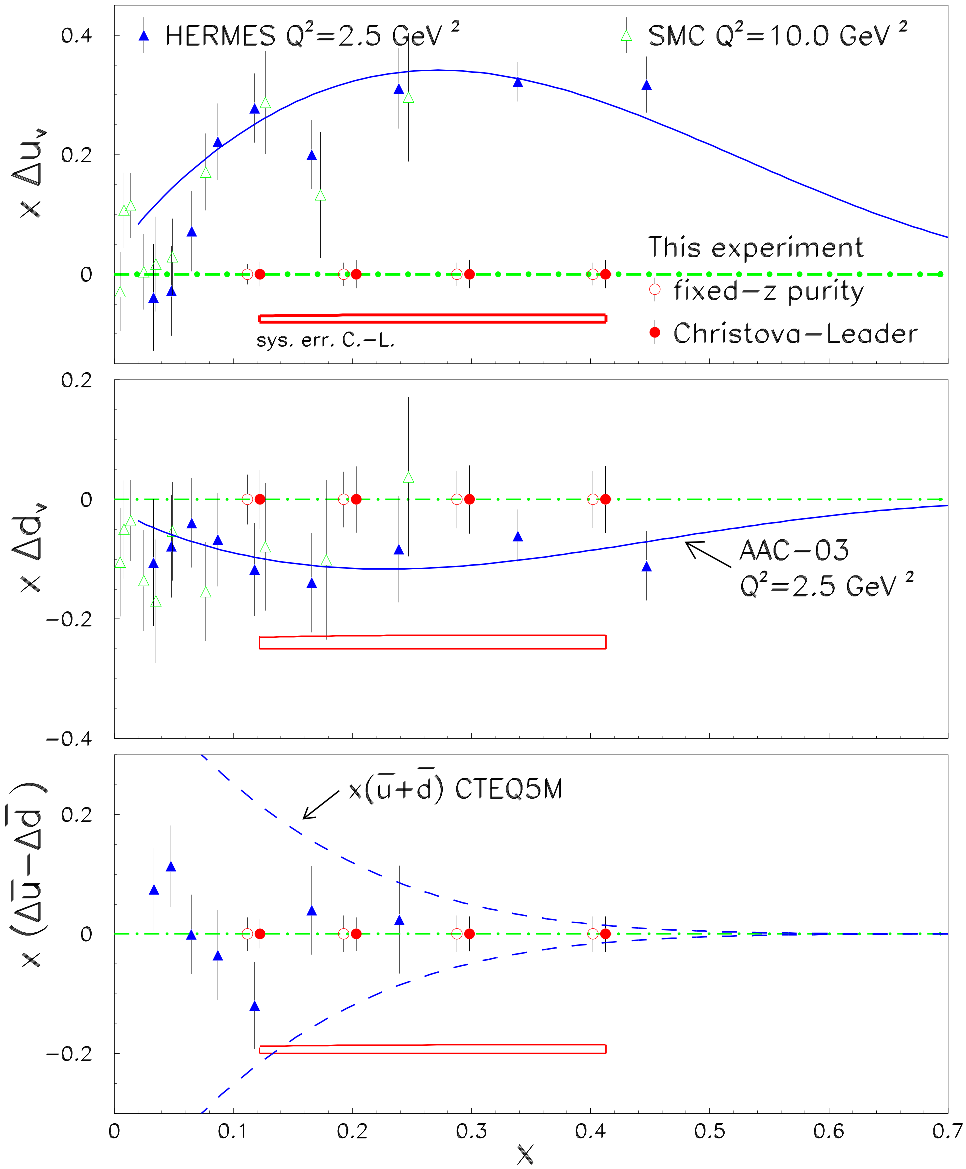
$$\Delta q_3(x,Q^2) \equiv (\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d}).$$

The polarized light sea asymmetry can be extracted through:

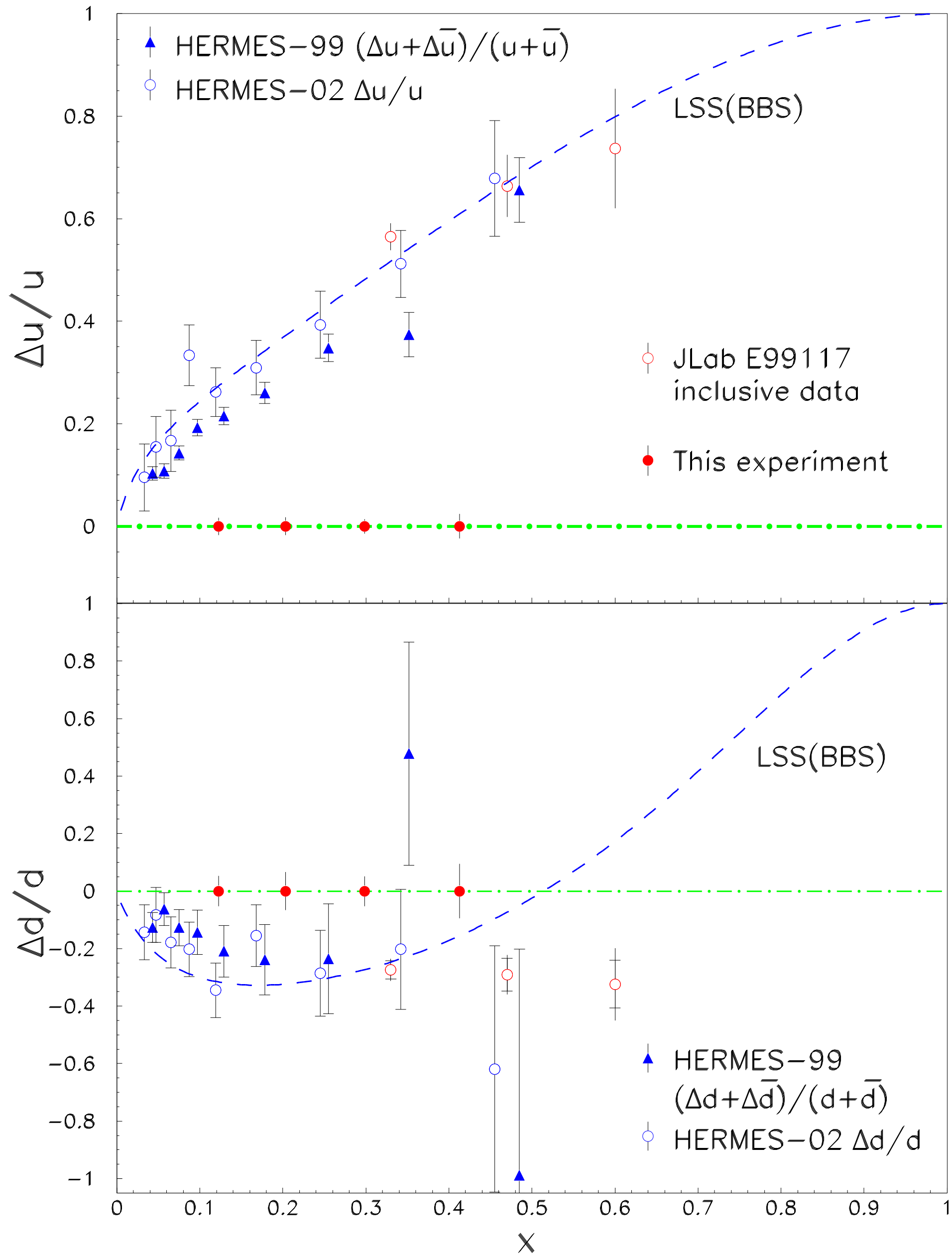
$$(\Delta\bar{u} - \Delta\bar{d})|_{LO} = 3(g_1^p - g_1^n)|_{LO} - \frac{1}{2}(\Delta u_v - \Delta d_v)|_{LO}.$$

A similar relation holds at the NLO.

Polarized light sea asymmetry



Comparison between Inclusive and Semi-Inclusive



Summary of Hall C spin program

- RSS experiment measured $A_{||}$ and $A_{\perp}$ in inclusive electron scattering on protons and deuterons
  - Extract g_1 and g_2 at $Q^2 = 1.3$ GeV^2 and 0.8 $< W <$ 2.0
  - Finished analysis by end of 2004
- Approved experiment to measure $A_{||}$ and $A_{\perp}$ in inclusive electron scattering on proton with large acceptance detector (BETA)
  - Extract g_1 and g_2 in range 2.5 $< Q^2 <$ 6.5 and 0.3 $< x <$ 0.8
  - Tentatively scheduled to run at end of 2006
- Proposed experiment to measure $A_{1N}^{h^{\pm}}$ for SIDIS reactions $p(e, e'h)$ and $d(e, e'h)$ for h = $\pi^{\pm}$,$K^{\pm}$ for protons and deuterons.
  - 1.2 $< Q^2 <$3.1 GeV^2, 0.12 $< x <$ 0.43, 0.5 $< z <$ 0.7
  - Spin flavor decomposition
  - “Test” of validity of factorization by checking if $A_{1N}^{\pi^+ + \pi^-}$ equals the inclusive asymmetry, A_{1N}.