Nucleon Structure Studies with Polarized Photons and Polarized Nucleons

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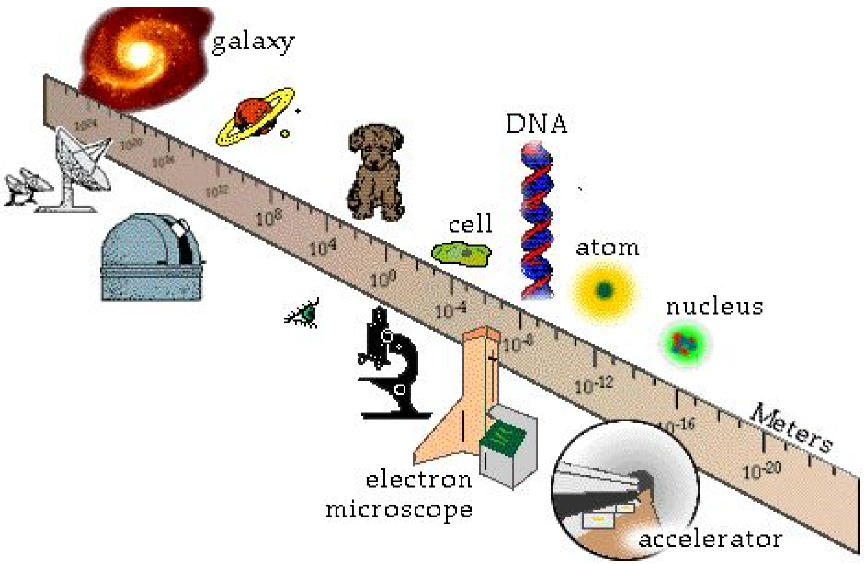
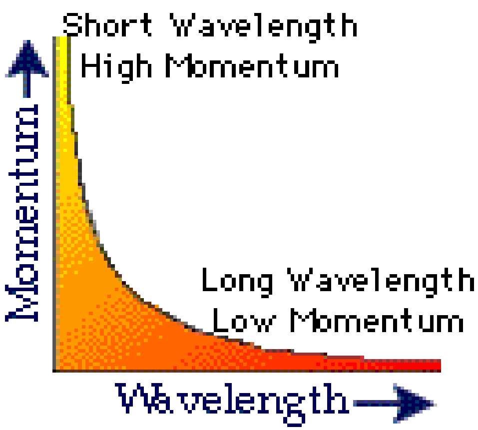
Colloquium
U. of Virginia
April 7, 2006

Probing the Structure of Matter

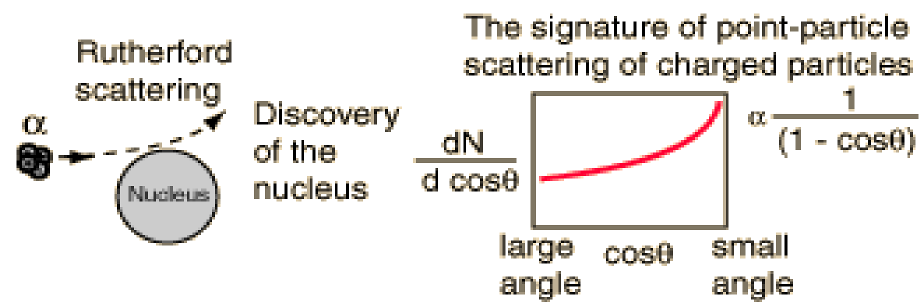
- To study the structure of matter in small detail we need to use small wavelength probes:
  - radar $\lambda \sim$ 1-10 cm
  - γ rays $\lambda \sim 10^{-18}$ m
- Light's wavelength, energy E and momentum p are related by $\lambda = hc/E = h/p$
- Short wavelength (=*high E*) light acts like a particle
- Particles also obey $\lambda = h/p$

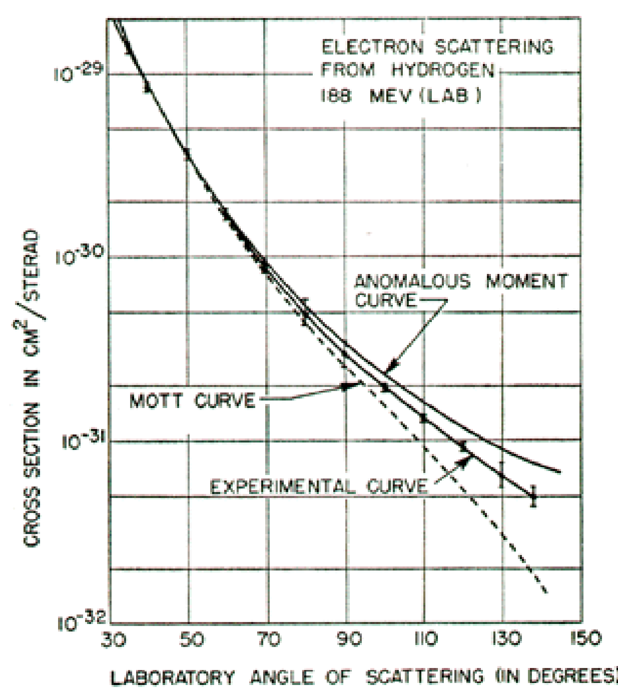




Scattering and Proton Structure

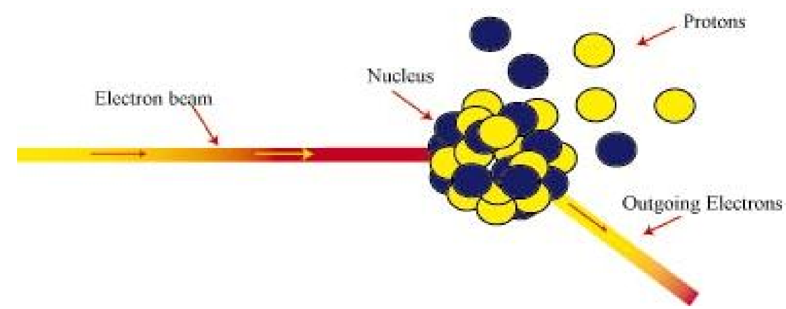
- Rutherford discovered nuclei scattering α particles on gold: low particle energy (= long wavelength) could not resolve nuclear structure
  - probability of scattering at a given angle (= cross section) follows point-particle rules
- R. Hofstaedter found proton was not a point particle using electron scattering at SLAC

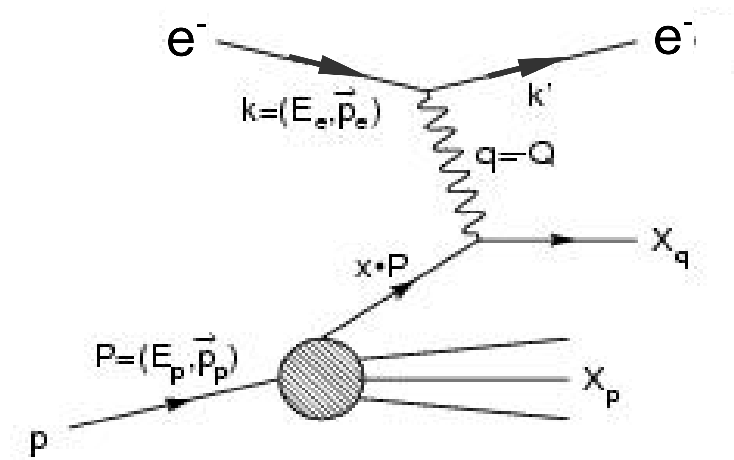




Electron (lepton) scattering

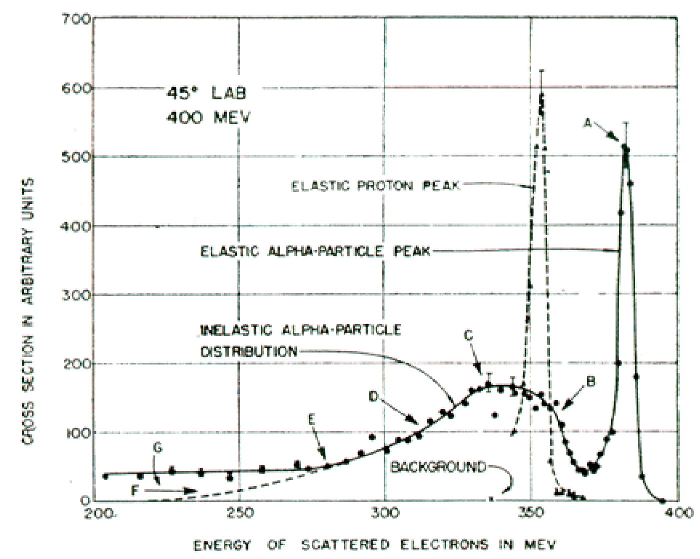
- Scattering high energy electrons makes short wavelength light
  - Coulomb scattering produces virtual photons ($2\pi dt < h/dE$)
  - *Bremsstrahlung* ("braking radiation") produces real photons
- Other "electron-like" particles (leptons) can also be used
  - charged (muons)
  - neutral (neutrinos)

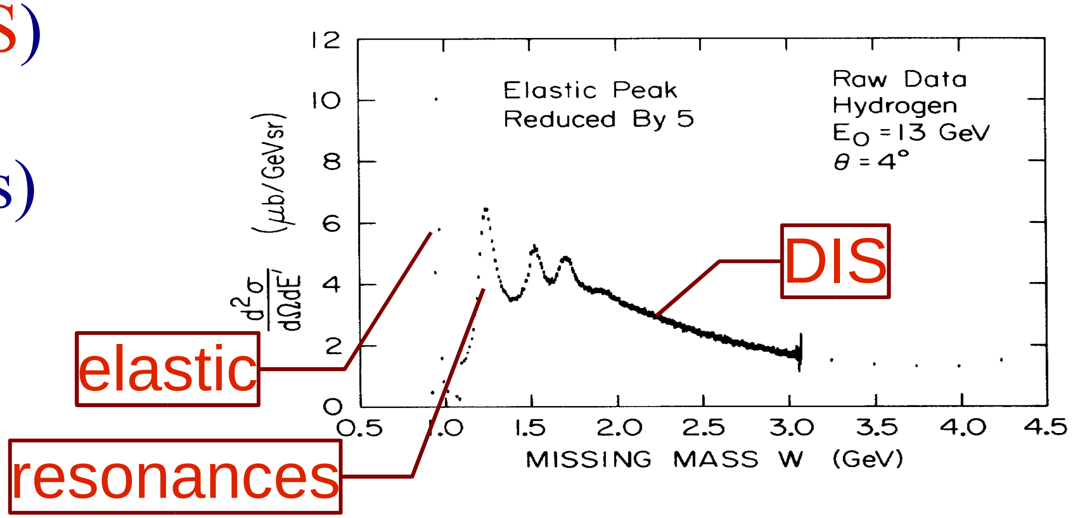




Examples of electron scattering

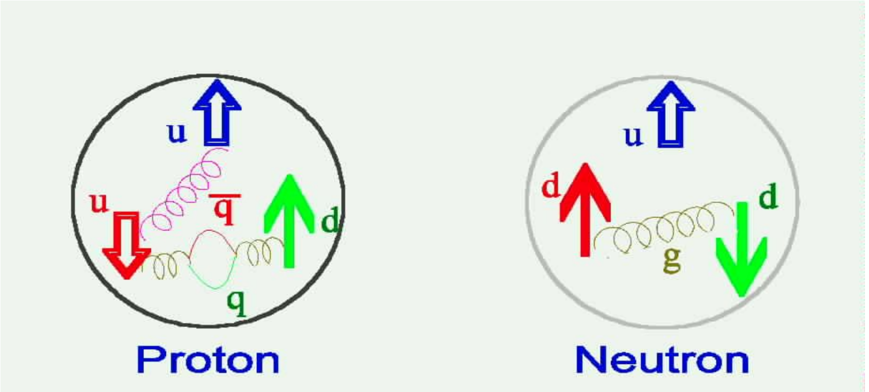
- Elastic, quasi-elastic scattering:
  - $e + A \rightarrow e' + A'$
  - $e + N \rightarrow e' + N'$
- Inclusive inelastic scattering
  - $e + A \rightarrow e' + X$ or $A(e,e')X$
- Deep Inelastic Scattering (DIS) of leptons probes inside the nucleon (protons and neutrons)

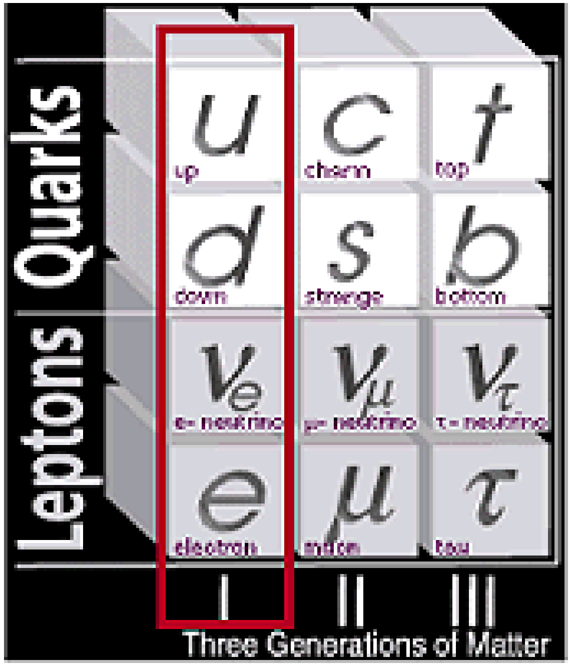




Partons inside the nucleon

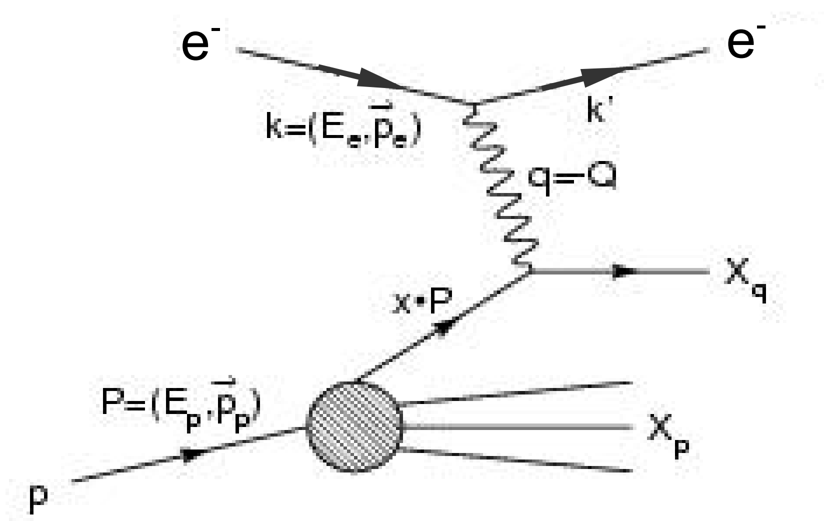
- Partonic structure of the nucleon established from DIS
- Partons:
  - colored quarks, anti-q, gluons form colorless hadrons
  - six quark flavors
- Quantum ChromoDynamics QCD:
  - Strong interactions between partons





Scaling and DIS

- Parton, QCD predictions:
  - DIS scattering same at all energy scales
    - Scattering depends on one dimensionless parameter
      $x = Q^2/(2M\upsilon)$
    - Q^2 = four-momentum squared of virtual photon
    - υ = energy of virtual photon
  - Deviations of $\boldsymbol{F}_2\,(\boldsymbol{x})$ from scaling: gluon radiation



$$\frac{d^2\sigma}{d\Omega\, dE'} \approx \left(\frac{d^2\sigma}{d\Omega\, dE'}\right)_{point} f(E, E', \theta)\, \boldsymbol{F}_2(\boldsymbol{x})$$

$\boldsymbol{F}_2(\boldsymbol{x})$ = nucleon structure function

$\boldsymbol{x}$ = fraction of proton's $|\vec{p}|$ carried by parton

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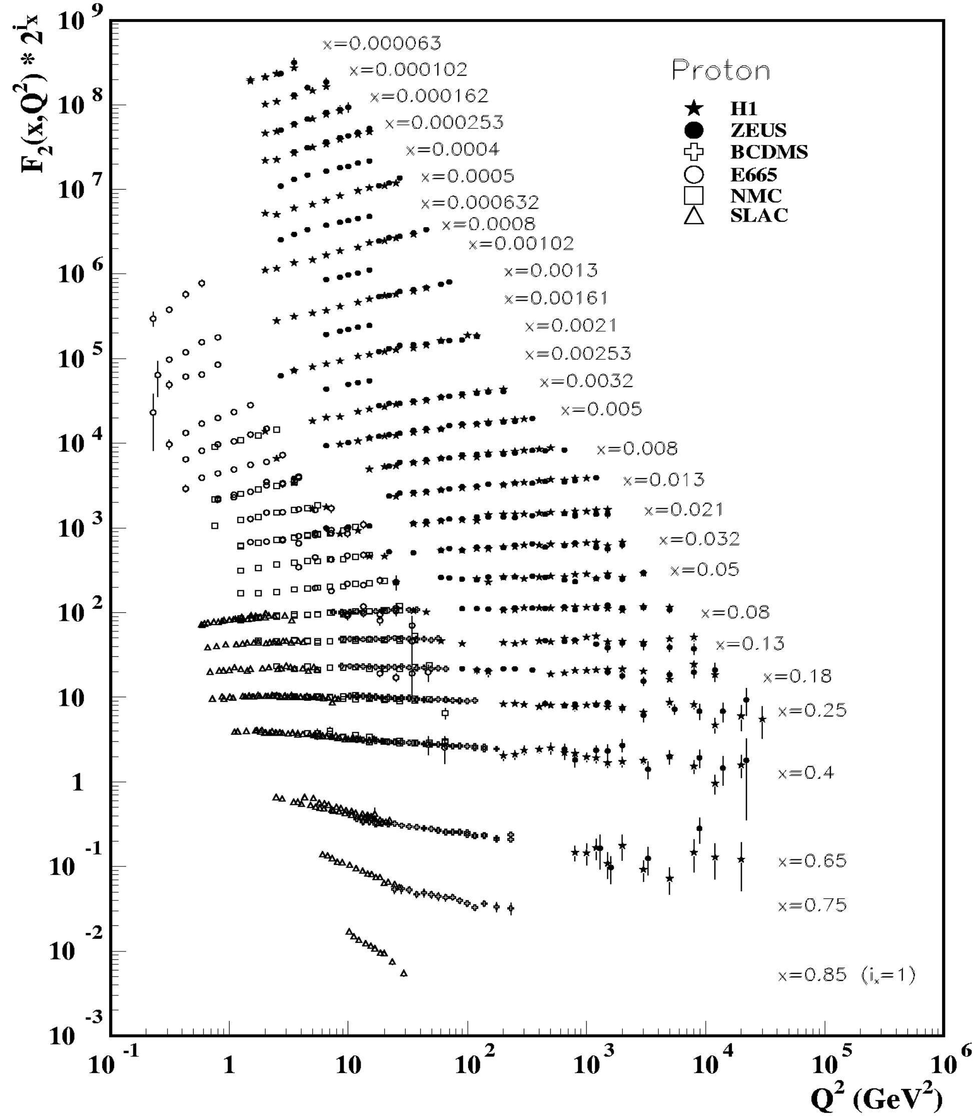
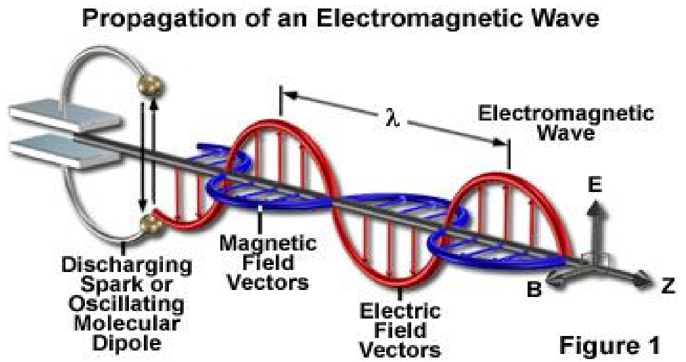
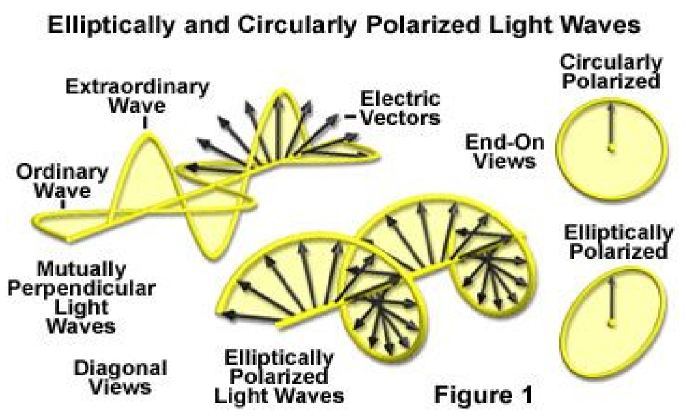


Polarized photons

- Real and virtual photons can be polarized
  - real photons are transverse waves only; **E** and **B** fields perpendicular to motion
    - linear and circular polarization
  - virtual photons can have longitudinal polarization: photon spin $\boldsymbol{J} = 1\hbar$, $J_z = \pm 1, 0$
  - virtual photon mass squared $-Q^2 \neq 0$ allows $J_z = 0$





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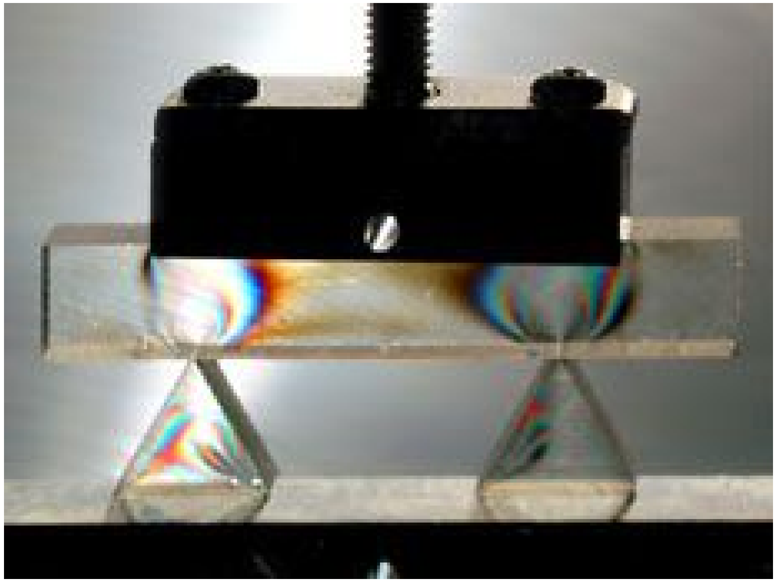

Polarized light reveals features (stress patterns) not seen otherwise

Polarized photons

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polarized photons   Search   Advanced Search   Preferences

Web

Results **1** - **10** of about **157,000** for **polarized photons**. (**0.33** seconds)

Tip: Looking for pictures? Try Google Images

Polarization of the **Photon**
... **Polarization** of the **Photon**. And what about the **photon**? ... We can use symbols and to describe linearly **polarized photons** in the x or y directions. ...
beige.ovpit.indiana.edu/B679/node52.html - 19k - Cached - Similar pages

The **polarization** of **photons**
... A beam of light which is plane **polarized** in a certain direction is made up of a stream of **photons** each plane **polarized** in that direction. ...
farside.ph.utexas.edu/ teaching/qm/fundamental/node6.html - 10k - Cached - Similar pages

PHSC 1121 - Lab 6
... second, with each **photon polarized** in a different plane. This combination of randomly **polarized photons** is called unpolarized light. ...
hp73.pvamu.edu/phsc/lab6.html - 8k - Cached - Similar pages

Re: Linearly **polarized photons**
... Re: Linearly **polarized photons**. Subject: Re: Linearly **polarized photons**; From: n__bates@my-deja.com; Date: Tue, 05 Dec 2000 01:50:04 GMT; ...
www.lns.cornell.edu/spr/2000-12/msg0030008.html - 5k - Cached - Similar pages

> Re: Linearly **polarized photons**
> ... Re: Linearly **polarized photons**. Subject: Re: Linearly **polarized photons**; From: baez@galaxy.ucr.edu (John Baez); Date: 7 Dec 2000 10:43:41 GMT; ...
> www.lns.cornell.edu/spr/2000-12/msg0030038.html - 5k - Cached - Similar pages
> [More results from www.lns.cornell.edu]

Polarized Photon Beams
... **Polarized Photon** Beams. ... With such a cavity operating in the visible (515 nm), scattering against 4 GeV electrons would produce 0.5 GeV **polarized photons**. ...
www.jlab.org/media_relations/ nsac/paragraph3_6_2_9_2.html - 5k - Cached - Similar pages

The Physics with Linearly-**Polarized Photons** in Hall B of JLab
The Physics with Linearly-**Polarized Photons** in Hall B of JLab Dr. Philip Cole Idaho State University Department of Physics Constituent quark models, such as ...
www.physics.isu.edu/colloquium/cole05.html - 3k - Cached - Similar pages

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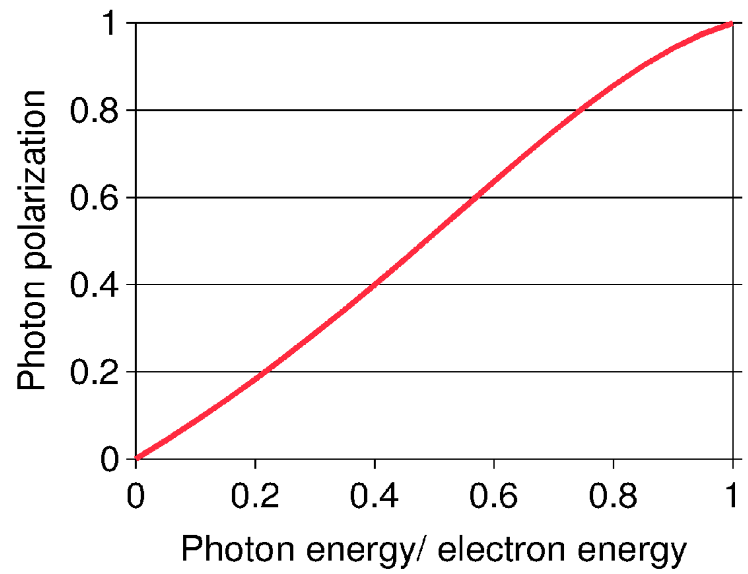
Making Polarized High Energy Photons

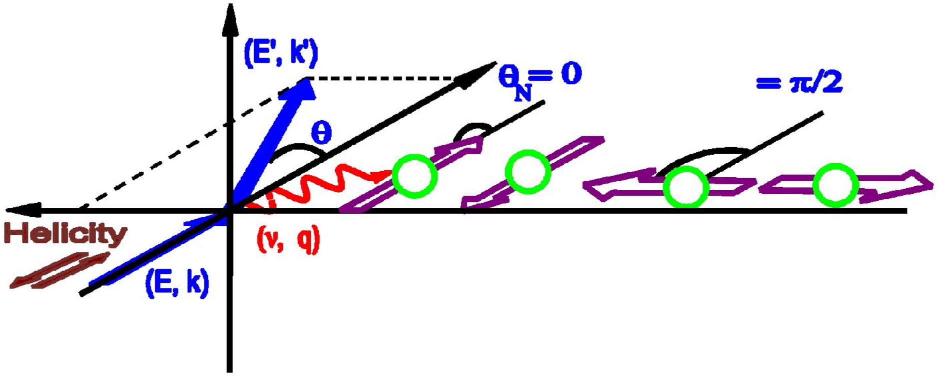
- Polarized leptons radiate polarized photons:
  - Helicity conservation requires transfer of the alignment of electron spin to the photon
  - transfer not 100%, depends on electron, photon energies
  - good for both real and virtual photons

Helicity: average probablity of electrons' spin being parallel to their momenta

$$h = \overline{\langle \sigma \cdot \hat{\boldsymbol{p}} \rangle}$$



Polarized lepton-nucleon scattering



- Polarized lepton beam (e or μ)
  - Leptons polarized along their momentum: helicity ± ½
- Polarized target (analyzer):
  - Nuclei polarized parallel or perpendicular to beam

Nucleon spins **parallel** to beam

$$\frac{d^2\sigma^{(\uparrow\downarrow)}}{d\,\Omega\, dE'} - \frac{d^2\sigma^{(\downarrow\downarrow)}}{d\,\Omega\, dE'} = \frac{4\alpha^2 E'}{Q^2 E}\left[(E+E'\cos\theta)\, M\, \boldsymbol{G_1}(\nu, \boldsymbol{Q^2}) - Q^2\, \boldsymbol{G_2}(\nu, \boldsymbol{Q^2})\right]$$

Nucleon spins **perpendicular** to beam

$$\frac{d^2\sigma^{(\uparrow\rightarrow)}}{d\,\Omega\, dE'} - \frac{d^2\sigma^{(\downarrow\leftarrow)}}{d\,\Omega\, dE'} = \frac{4\alpha^2 E'}{Q^2 E} E'\sin\theta\left[M\, \boldsymbol{G_1}(\nu, \boldsymbol{Q^2}) + 2E\, \boldsymbol{G_2}(\nu, \boldsymbol{Q^2})\right]$$

Spin Structure Functions (SSF)

- Two structure functions that depend on the nucleon's polarization: G_1 and G_2
  - G_1 dominates parallel scattering, G_2 is mainly perpendicular
  - At very high energy they are expected to scale (like F_2):

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

  - $g_1(x)$ can be interpreted in the parton model as the helicity (=spin) distribution of the quarks in the nucleon:

$$g_1(x)=\frac{1}{2}\sum e_i^2(q_i^{\uparrow}(x)-q_i^{\downarrow}(x)),\quad i = \text{index of quark flavor: } u,\bar{u},d,\bar{d},\text{...etc.}$$

SSF' and Spin Asymmetries (SA's)

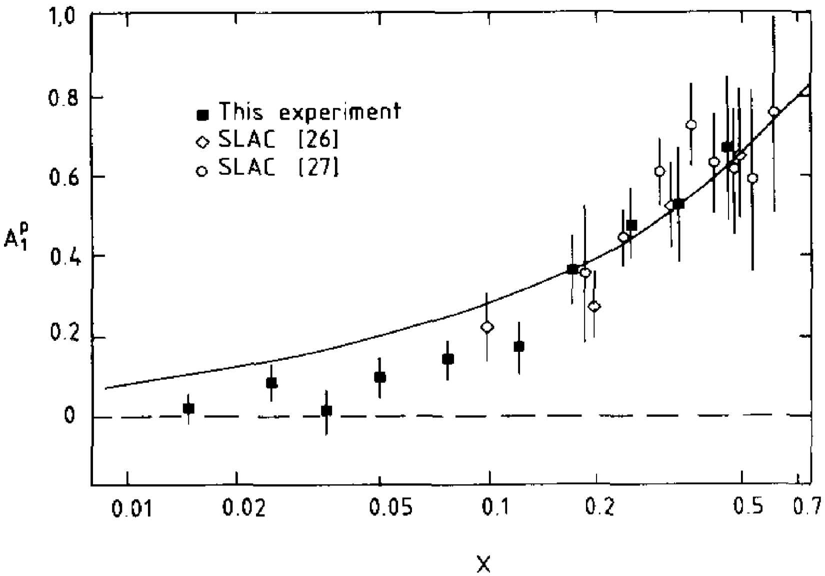
- Asymmetries are ratios of differences over sums of cross sections

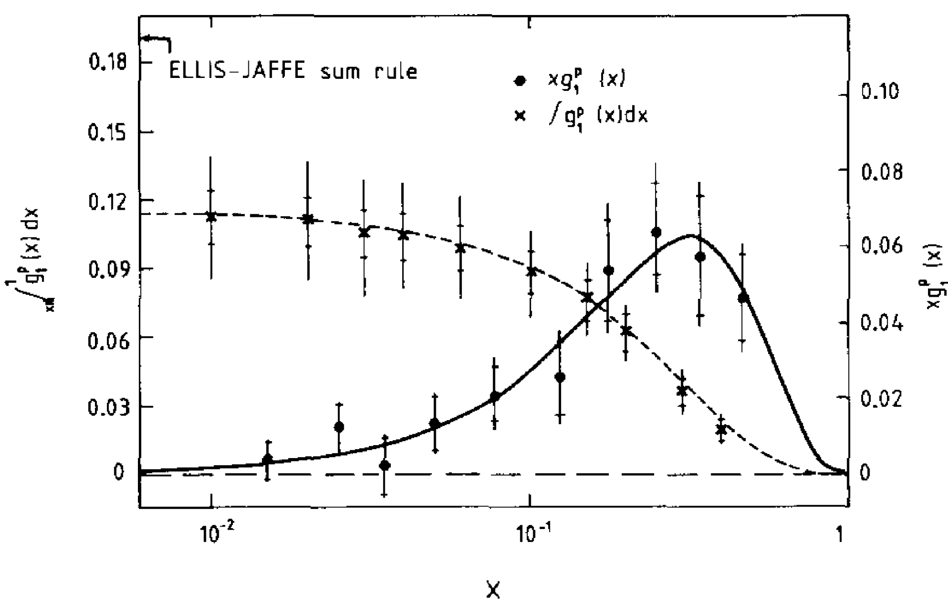
$$A_1(Q^2,\nu)=\frac{\sigma^T_{1/2}-\sigma^T_{3/2}}{\sigma^T_{1/2}+\sigma^T_{3/2}}=\frac{M\nu G_1(Q^2,\nu)-Q^2 G_2(Q^2,\nu)}{W_1(Q^2,\nu)}$$

- SF's in DIS: Related to scaling functions and parton distributions

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

Early Spin Structure Results



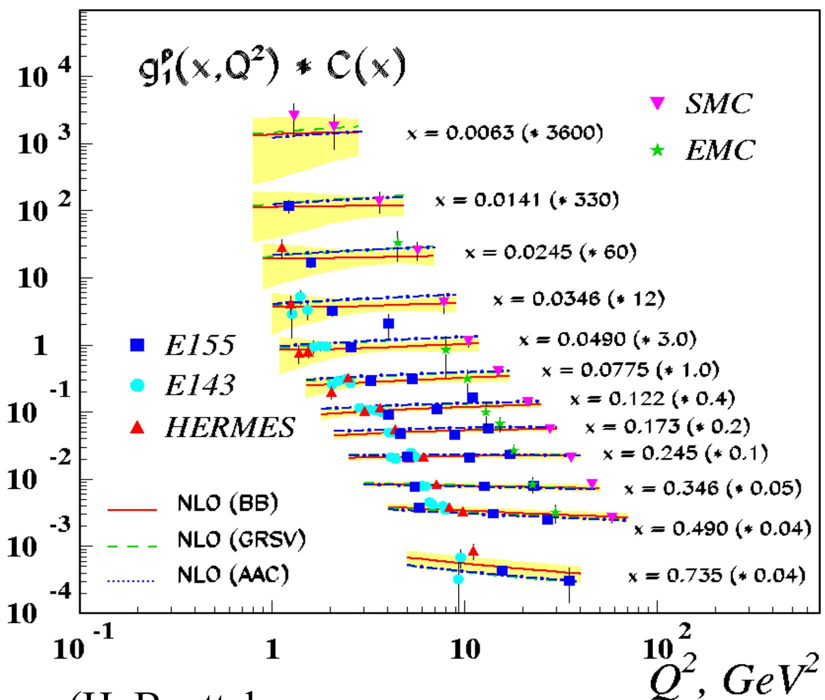


- First measurements of SSF's at SLAC E80 (1978)
  - Measured $A_1^{\text{proton}} \simeq g_1/F_1$
- Improved measurement at CERN EMC experiment:
  - Quarks not carrying all of the proton's spin

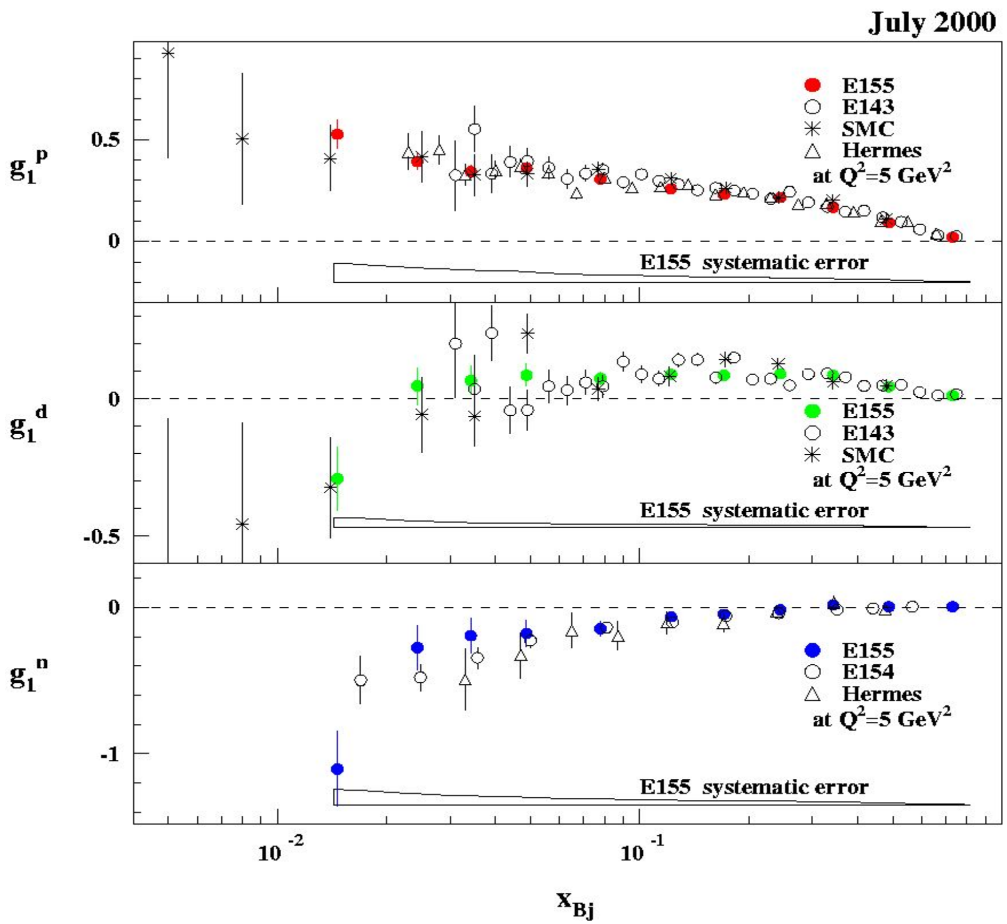
$$\int_0^1 dx\, g_1(x) = \frac{1}{2}\sum e_i^2 \Delta q_i = \frac{1}{18}(4\Delta u + \Delta d + \Delta s)$$

Quark component of spin $\frac{1}{2}\Sigma q = \Delta u + \Delta d + \Delta s \neq \frac{1}{2}$

Final Results from SLAC, CERN, DESY



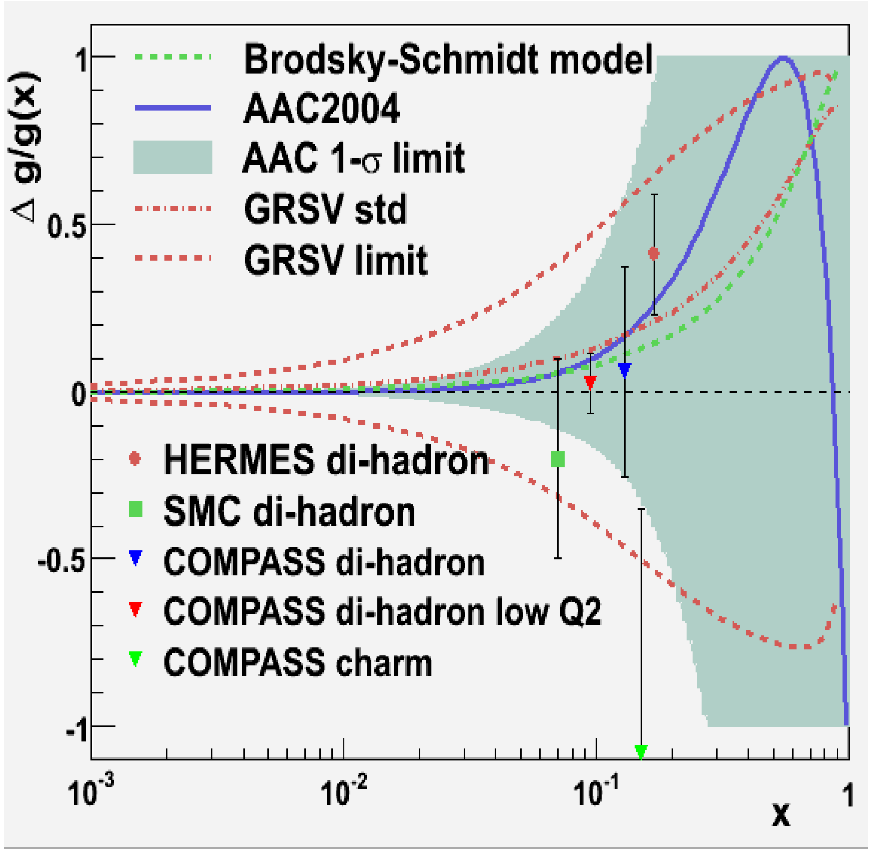
(H. Boettcher, HERMES)



- Quark spin (SLAC E155 global fit): $\sum q$ =0.229±0.041±0.057
- Quarks: only 23% of spin! What carries the remainder? ***gluons***? ***L***?

Gluon Spin

- Gluon contribution not yet established by experiment
- Few data. Seem to favor 0 gluon spin
  - (N. Saito plenary talk, PANIC 2005)



Transverse Spin Structure Functions

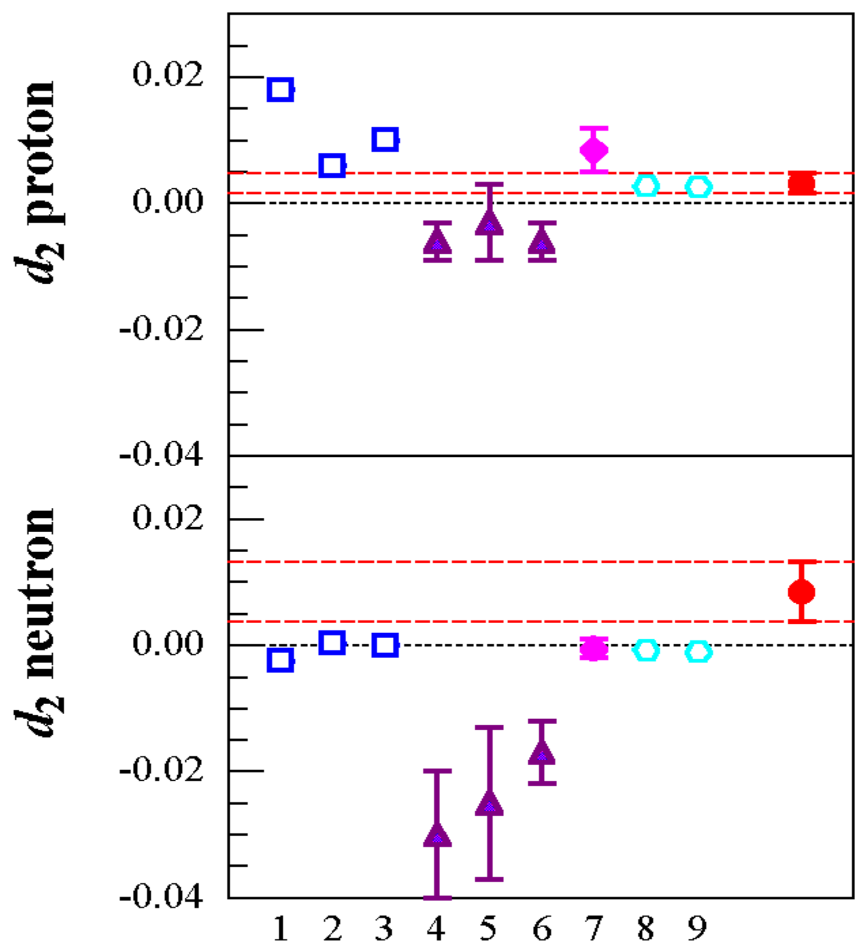
- Unlike g_1, there is no simple parton interpretation for transverse SSF
- g_2 is combination of contributions from *quark-quark* interactions (twist-2, like g_1) and *quark-gluon* correlations (twist-3):

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \overline{g_2}(x,Q^2)$$

$$= -g_1(x,Q^2) + \int_x^1 g_1(x',Q^2)\frac{dx'}{x'} - \int_x^1 \frac{\partial}{\partial x'}\left[\frac{m}{M}h_T(x',Q^2) + \xi(x',Q^2)\right]\frac{dx'}{x'}$$

  - g_2^{WW} (*W*andzura-*W*ilczek) part depends on g_1
  - h_T is leading twist-2 (*q*-*q*) transversity SSF
  - ξ represents the twist-3 *quark-gluon* correlations

Twist-3 d_2: Theory and Experiment



- QCD's Operator-Product Expansion (OPE) relates g_1, g_2 integrals to calculable quantities called matrix elements

$$3\int_0^1 x^2 \overline{g_2}(x, Q^2)\, dx = d_2(Q^2)$$

Models and Data

Bag: 1-Song
2-Stratmann
3-Ji & Unrau

QCD Sum Rules: 4-Stein *et al.*
5-Balitsky *et al.*
6-Ehrnsperger & Schaefer

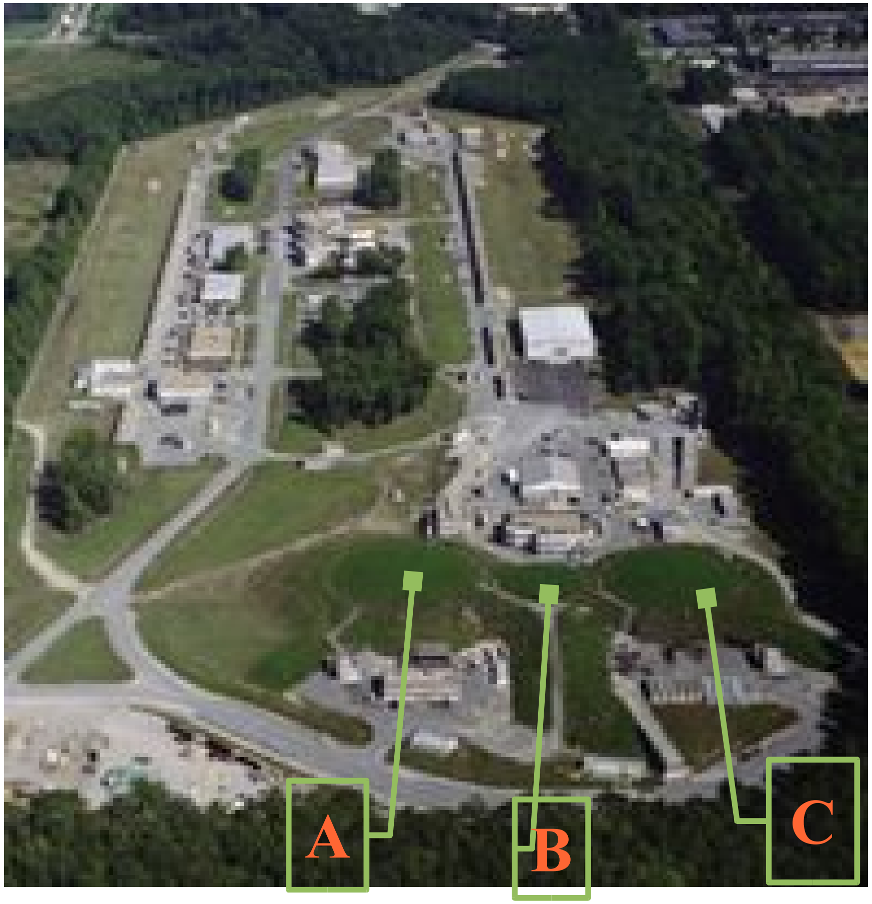
Lattice QCD: 7-Goeckeler et al.

Chiral Quark Soliton: 8-Weigel *et al.*
9- Wakamatsu

E155, E155x, E142, E143, E154

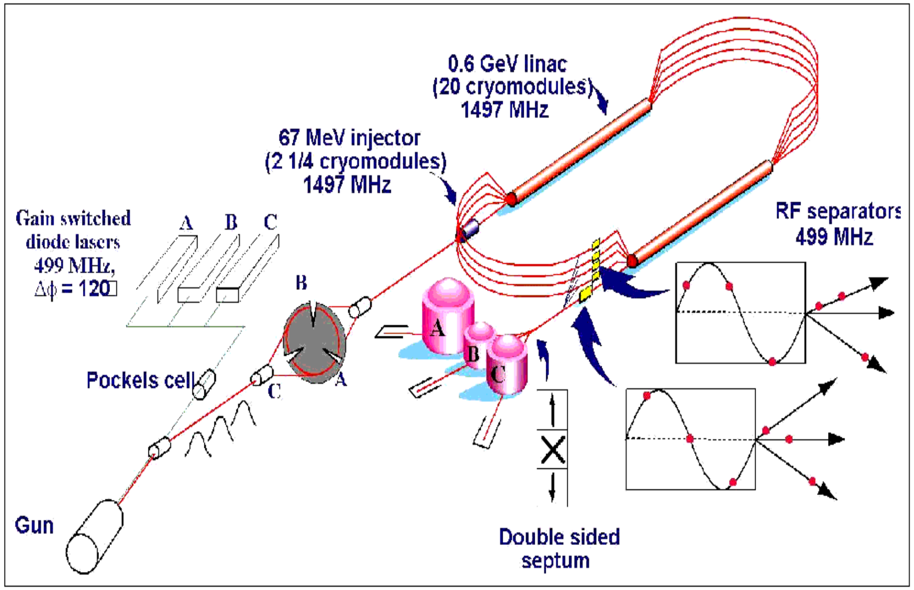
DIS and Beyond - JLab Spin Physics

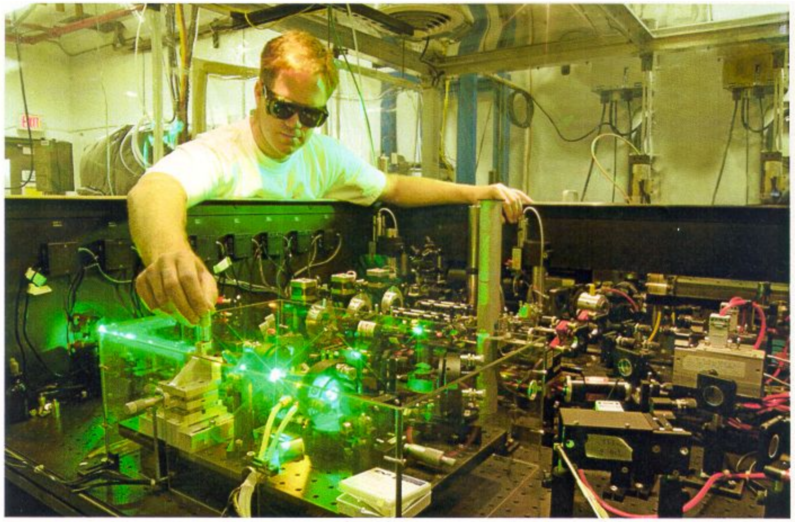
- DIS does not exhaust possibilities of spin structure physics
- New player in spin physics: TJNAF or JLab
- Lower energy than SLAC but very high intensity
- Three experimental halls:
  - A, B and C (!)



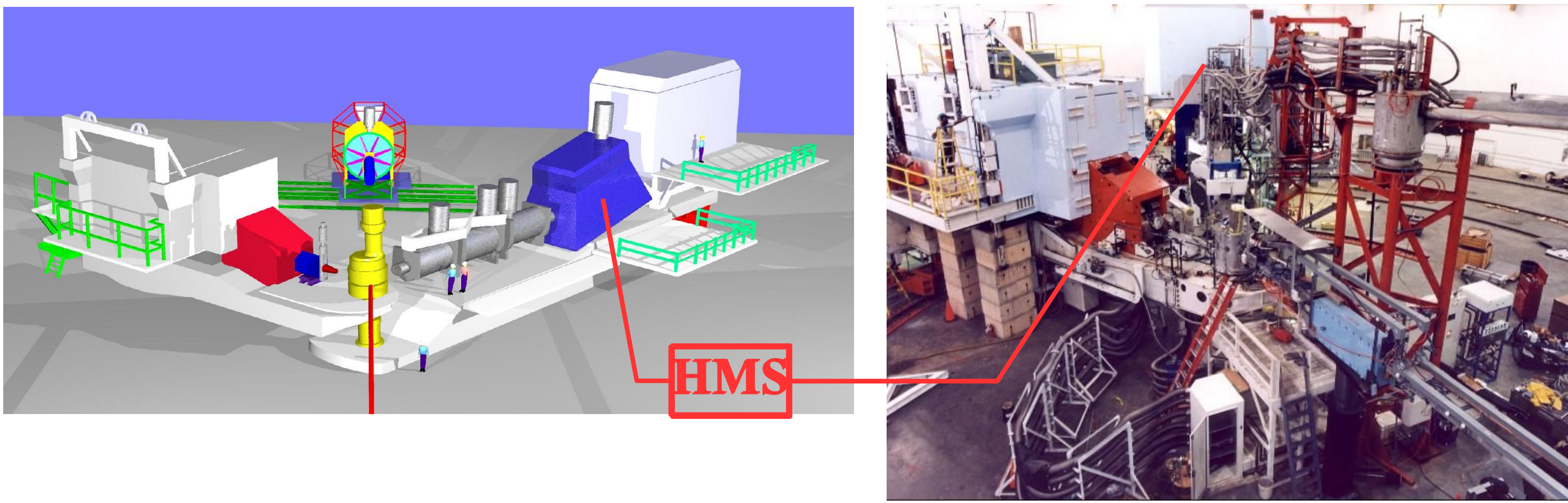
JLab Polarized Electron Beam

- CEBAF recirculating linear accelerators: final energy $\propto$ number of passes
  - $E_{\text{maximum}} = 5.78$ GeV
  - $I_{\text{maximum}} = 140\ \mu$A
- Electrons emitted by photoelectric effect with polarized laser light
  - Maximum source polarization ~ 75-85%





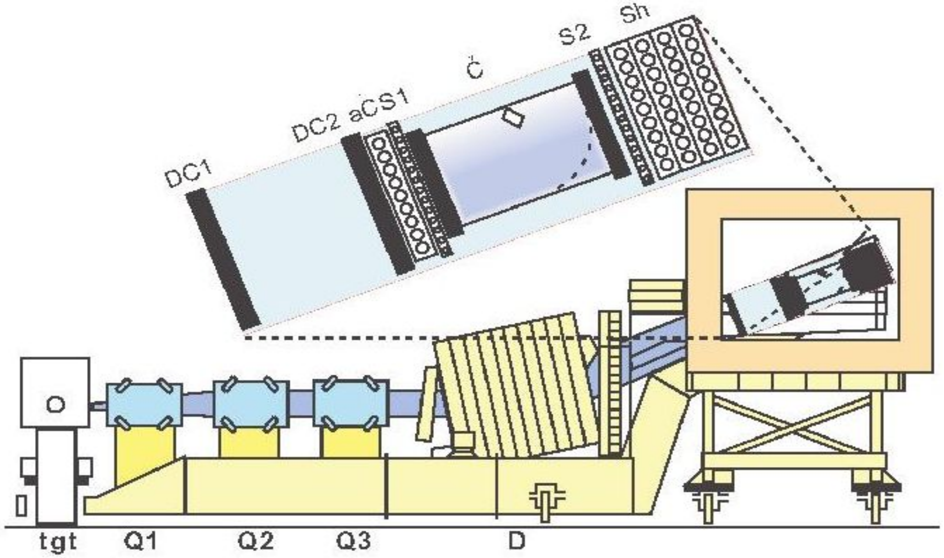
Hall C Facility

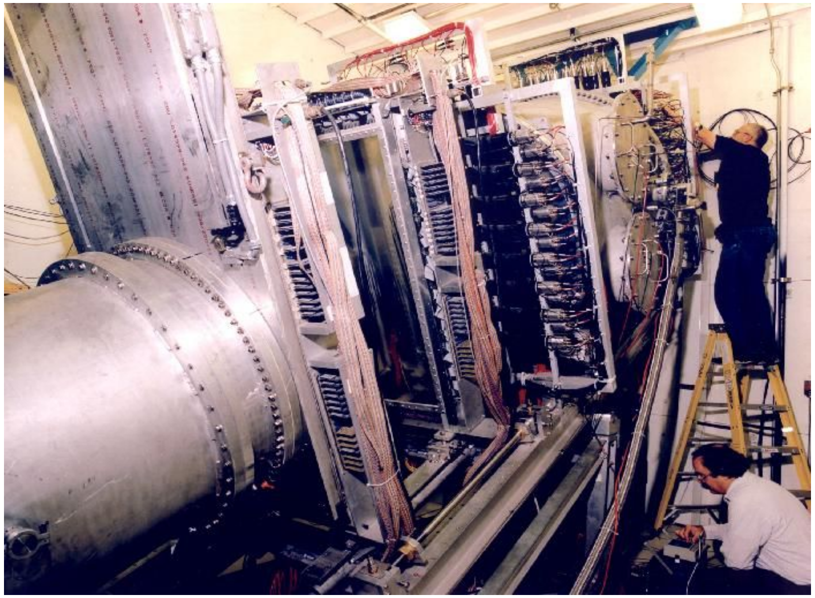


- Three spectrometers
  - All purpose High Momentum Spectrometer (HMS) is used for Spin Physics
  - Short Orbit Spectrometer (SOS) and experiment G0

HMS

- Quadrupole magnets focus particles
- Dipole disperses particles by momentum
  - $r = p/(qB)$
- Detectors
  - Drift chambers track particles
  - Cherenkov and shower calorimeter identify particles
  - Scintillators give time of flight





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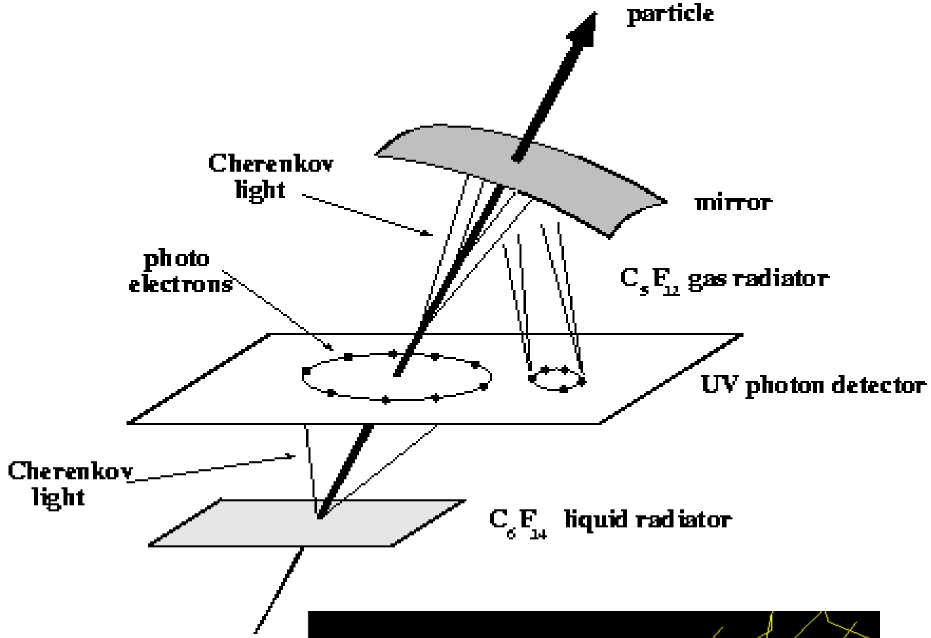
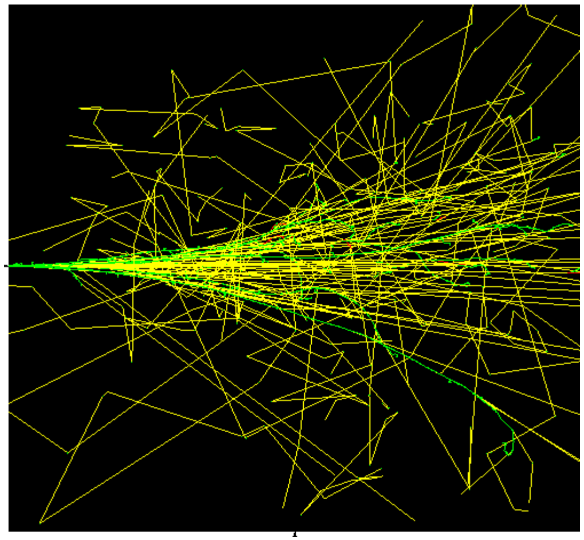
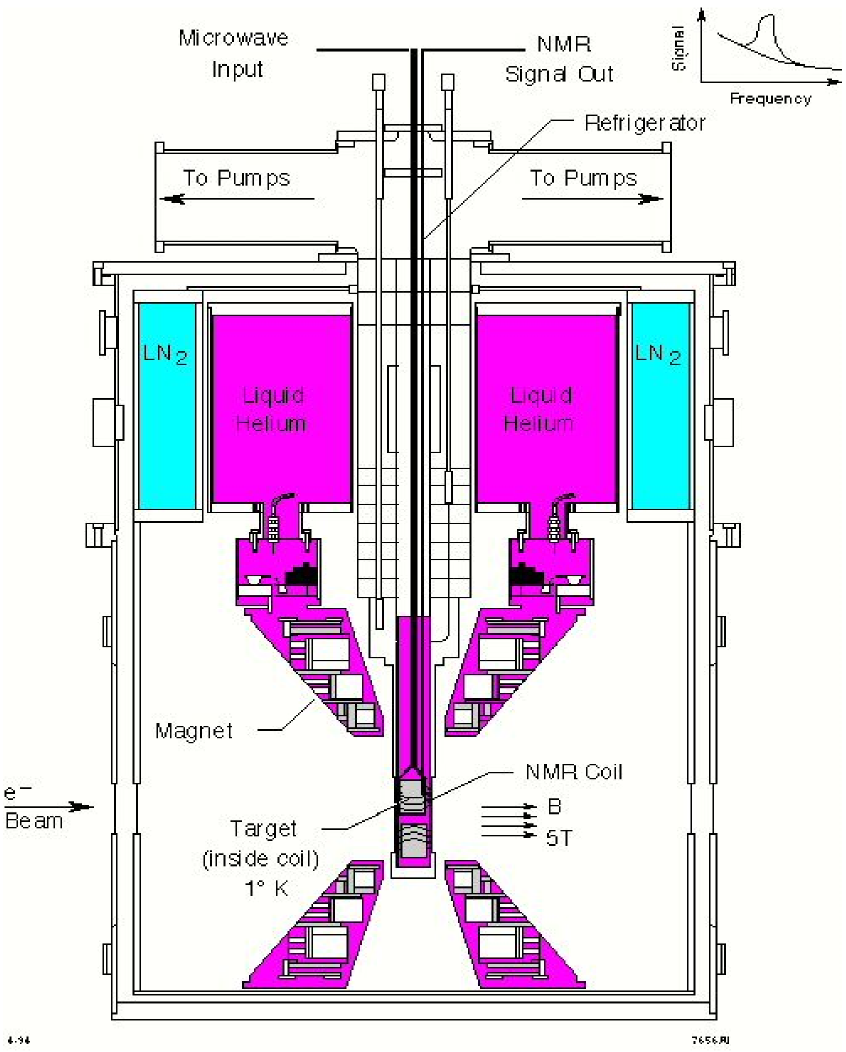




Polarized Target

- Dynamic Nuclear Polarization
  - hyperfine transitions induced by microwave pumping
- Typical characteristics:
  - very high magnetic field
    - B > 2.5 Tesla (5 T common)
  - low temperature ≤ 1K
  - frozen solids: NH_3, LiD
  - NMR to measure polarization
  - maximum $I_{beam} \approx 200$ nA



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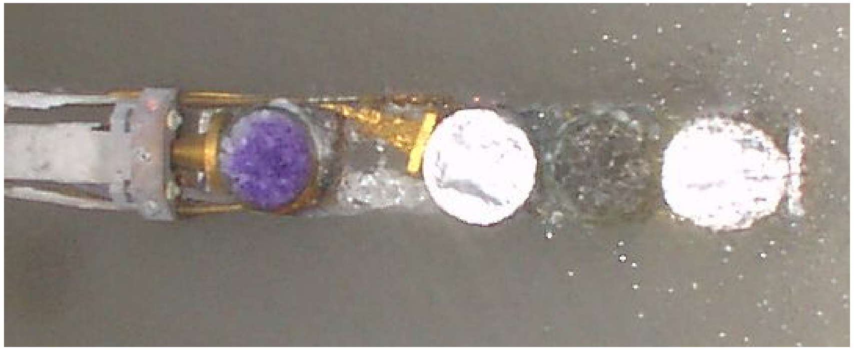

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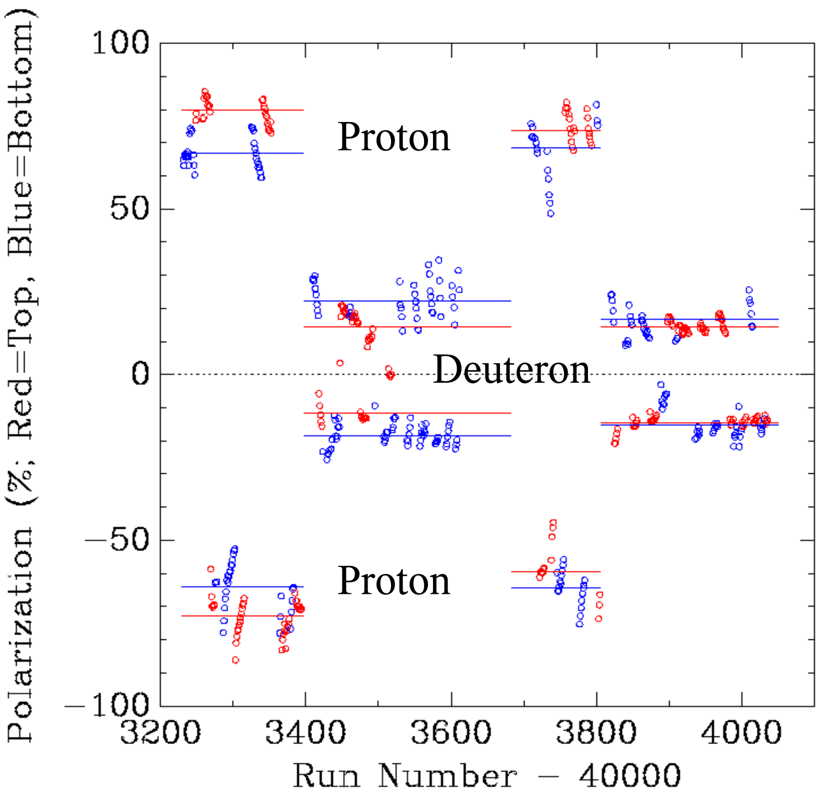


Hall C Spin Structure Program

- Spin Structure Functions at 6 GeV:
  - Inclusive measurements
    - SSF's in the Nucleon Resonances Region - *RSS*
    - SSF's at high Bjorken x (proton) - SANE
  - Semi-inclusive measurements
    - Flavor Decomposition of Nucleon Spin - SemiSANE
- Real Polarized Photons:
    - Polarized Compton Scattering
- Spin Structure Functions at 11 GeV: Inclusive, semi-inclusive and exclusive up to $Q^2 \sim 10$ GeV^2

JLab E01-006: *R*esonances *S*pin *S*tructure

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)

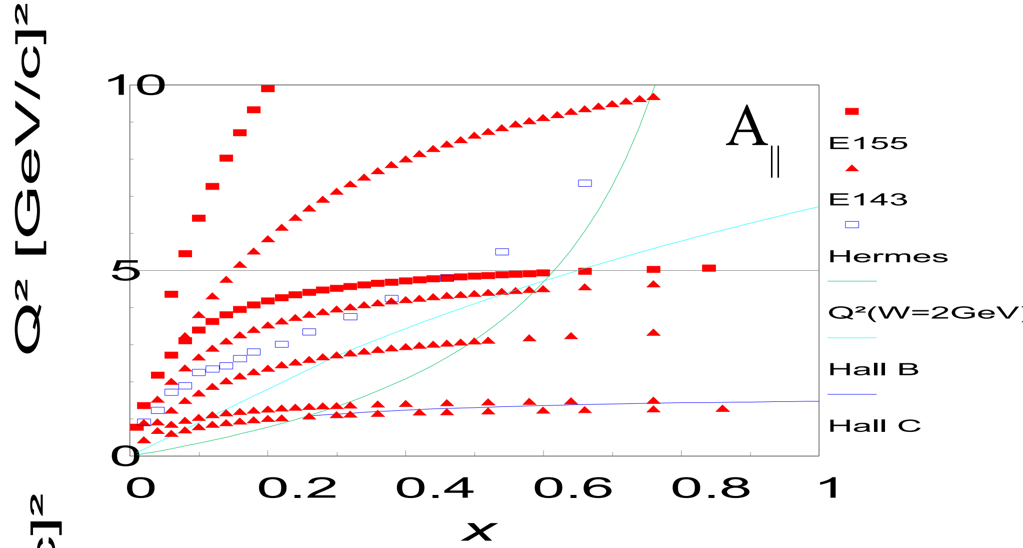
- Measure *proton* and *deuteron* spin asymmetries $\mathbf{A_1}(W, Q^2)$ and $\mathbf{A_2}(W, Q^2)$ at four-momentum transfer $Q^2 \approx 1.3$ GeV² and invariant mass $0.8 \leq W \leq 2$ GeV
- Study W dependence, onset of polarized local duality, twist-3 effects, using inclusive polarized scattering

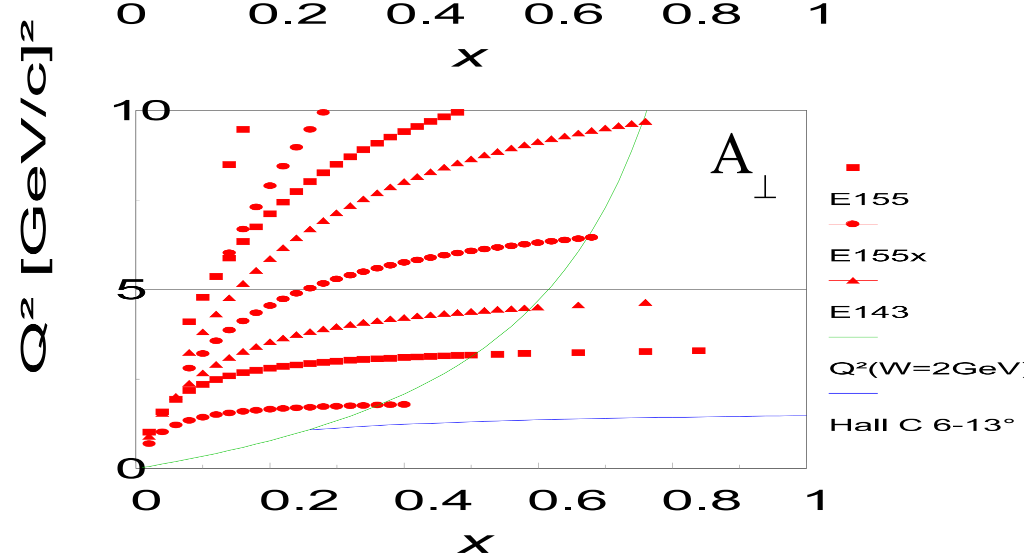
$A_\parallel$ and $A_\perp$ data on protons and deuterons

- Spin Structure g_1 and g_2 obtained from $A_\parallel$ and $A_\perp$

$$A_\parallel = \frac{\sigma^{(\uparrow\downarrow)} - \sigma^{(\downarrow\downarrow)}}{\sigma^{(\uparrow\downarrow)} + \sigma^{(\downarrow\downarrow)}}, \quad A_\perp = \frac{\sigma^{(\uparrow\rightarrow)} - \sigma^{(\downarrow\leftarrow)}}{\sigma^{(\uparrow\rightarrow)} + \sigma^{(\downarrow\leftarrow)}}$$

- Few $A_\perp$ data for W<2 GeV
- JLab E01-006 (*RSS*) first complete measurement on *protons* and *deuterons* in the resonances





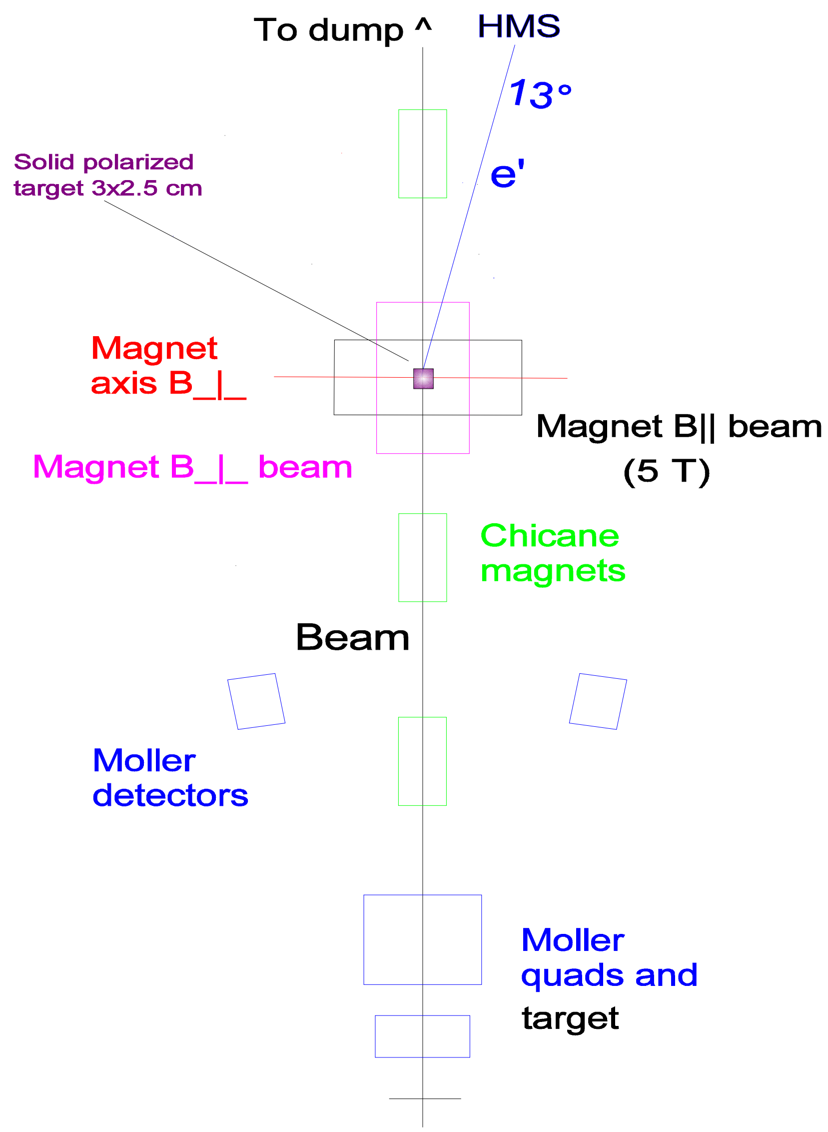
Central kinematics of world's p, d data ($Q^2 < 10$ GeV^2; upper Q^2 limit for Hall B)

Resonances SSF Experiments

Lab	Experiment	Target	Q^2 $[\mathrm{GeV/c}]^2$	Measured quantity
SLAC	E143 (E80)	NH_3 p(rotons) & d (euterons)	0.5 1.3	$A_{\parallel}$
JLab	Hall A 94-010	^3He	0.1 to 0.9 (6 values)	$A_{\parallel}$,$A_{\perp}$
	CLAS eg1a-b	NH_3 p & d	0.2 to 5 (over 12 values)	$A_{\parallel}$
	Hall C RSS	NH_3 p & d	1.3	$A_{\parallel}$,$A_{\perp}$
	Hall A 01-012	^3He	~1. to ~4.	$A_{\parallel}$,$A_{\perp}$

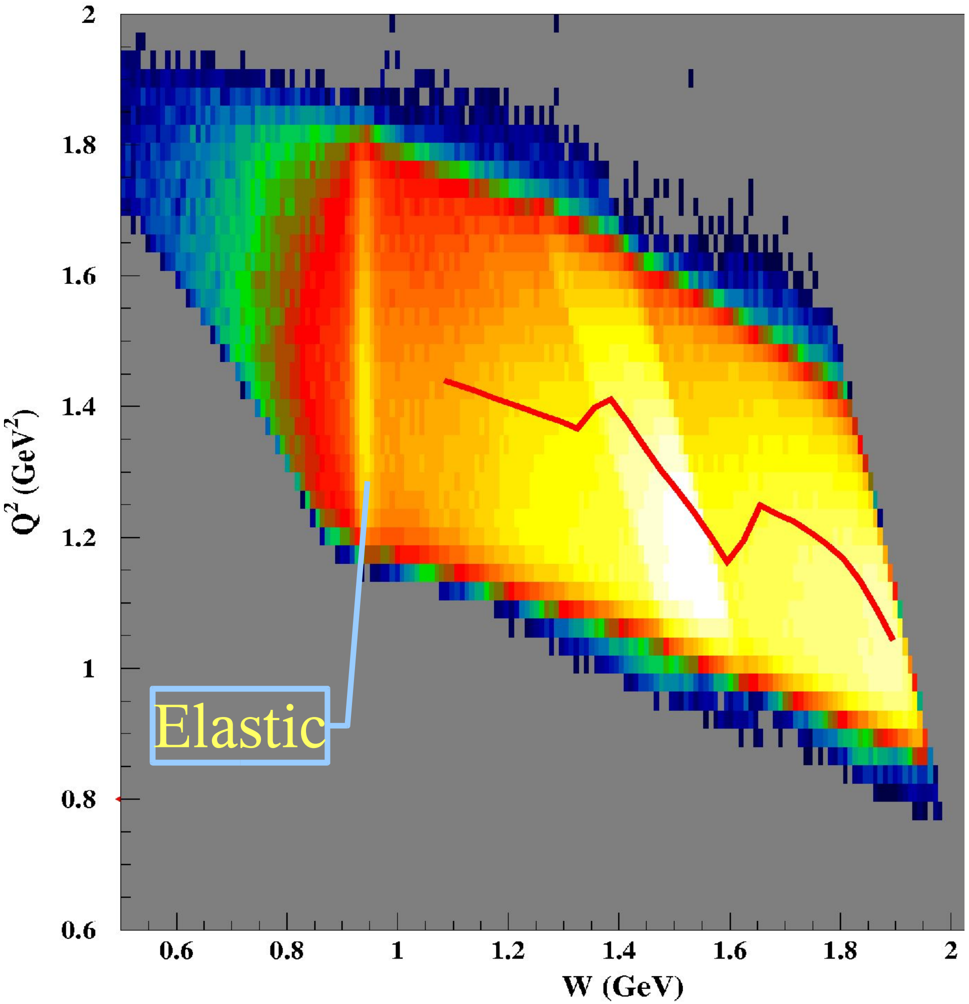
RSS Technique

- Equipment: TJNAF Hall C
  - CEBAF polarized electron beam
    - 2 cm diameter raster at target
    - I = 85-150 nA
  - Target: polarized ammonia NH_3, ND_3.
    - Luminosity ~10^{35} $s^{-1}cm^{-2}$
  - HMS electron detector
- Data run: Jan.-Feb. 2002
    - 160 M proton,
    - 350 M deuteron triggers



RSS Kinematics

- Beam energy 5.755 GeV
- HMS angle 13.15°
- HMS central momenta:
  - 4.71 GeV/c
  - 4.08 GeV/c
- Final state mass range:
  - 0.8 GeV $\leq W \leq$ 2.0 GeV
- $\langle Q^2 \rangle = 1.3\ [\mathrm{GeV/c}]^2$

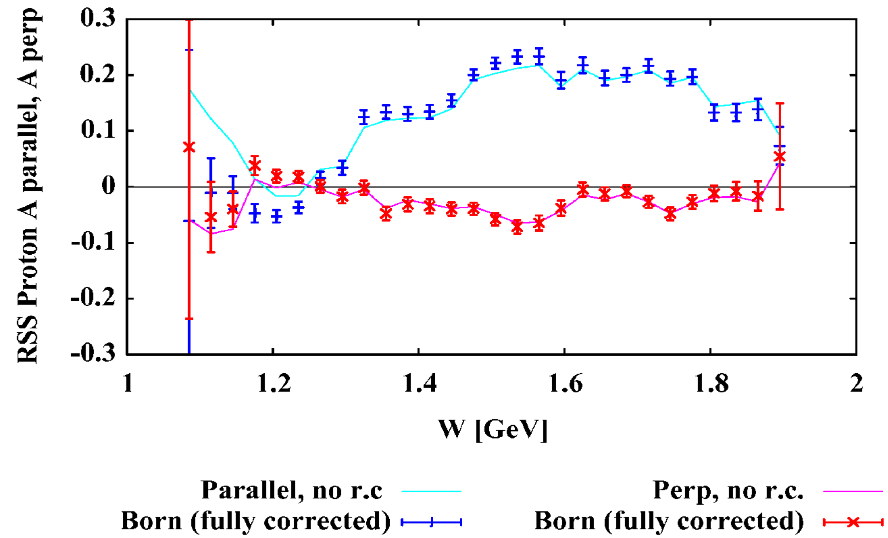


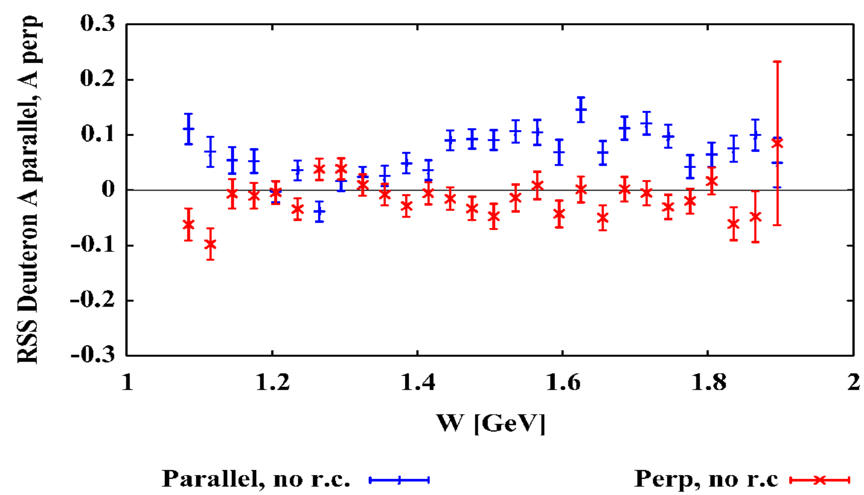
Measured asymmetries $A_{\|}$, $A_{\perp}$

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

$$\epsilon = (N^- - N^+)/(N^- + N^+)$$

- N^-, N^+ = charge normalized, dead time and pion corrected yields for +/- beam helicities
- P_b, P_t = beam, target polarizations
- f = fraction events produced on polarized nucleons (dilution factor)
- C_N, C_D = corrections for ^{15,14}N: proton $C_D = 0$, deuteron $C_N \simeq 1$
- A_{rc} = radiative correction (***p*** only)





Measured asymmetries $A_{\parallel}$, $A_{\perp}$

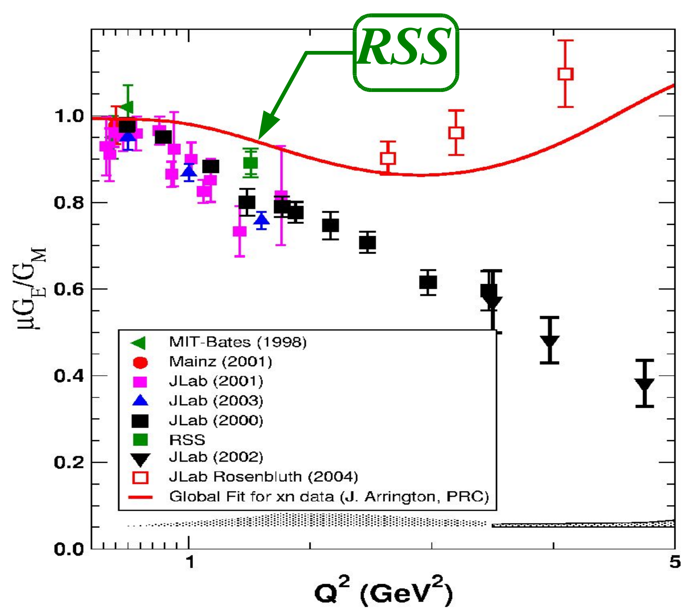
$$A_{\parallel,\perp} = \left(\frac{\epsilon}{f\, \boldsymbol{P_b P_t} C_N} + C_D\right) + A_{rc}$$

$$\epsilon = (N^{-} - N^{+})/(N^{-} + N^{+})$$

- N^{-}, N^{+} = charge normalized, dead time and pion corrected yields for +/- beam helicities
- $\boldsymbol{P_b}$, $\boldsymbol{P_t}$ = beam, target polarizations
- f = fraction events produced on polarized nucleons (dilution factor)
- C_N, C_D = corrections for ^{15,14}N: proton $C_D = 0$, deuteron $C_N \simeq 1$
- A_{rc} = radiative correction

Method - Material	***Polarization* [%]**	
	$\boldsymbol{A_{\parallel}}$	$\boldsymbol{A_{\perp}}$
Moller - Beam	71	66
NMR - NH3	70±1.7	
NMR - ND3	20±2.	

Proton Elastic	***G_E/G_M Sensitivity***	***Use***
$A_{\parallel}$	Low	$P_b\, P_t$
$A_{\perp}$	High	G_E/G_M



How to get A_1, A_2

- Combine $\mathbf{A}_{\|}$, $\mathbf{A}_{\perp}$ to get $\mathbf{A}_1$, $\mathbf{A}_2$:

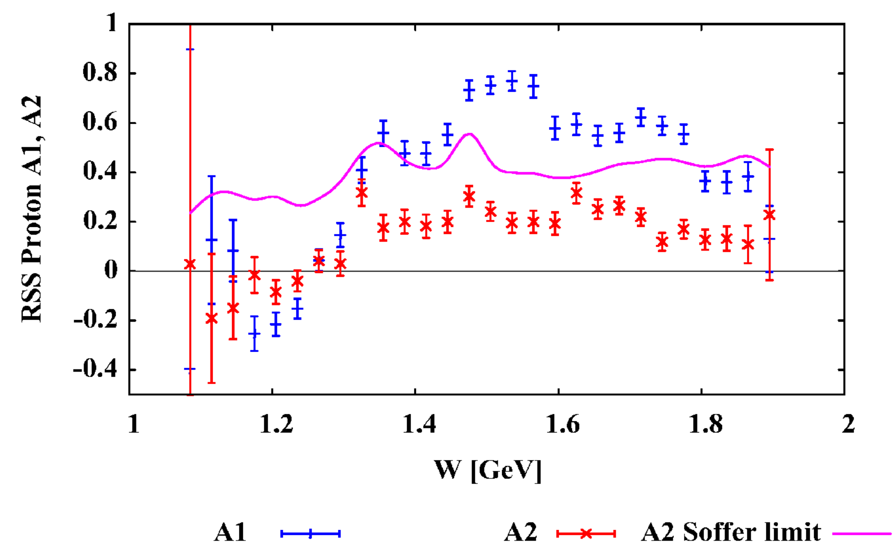
$$A_1 = \frac{1}{(E+E')D'}\left((E-E'\cos\theta)A_{\|} - \frac{E'\sin\theta}{\cos\phi}A_{\perp}\right)$$

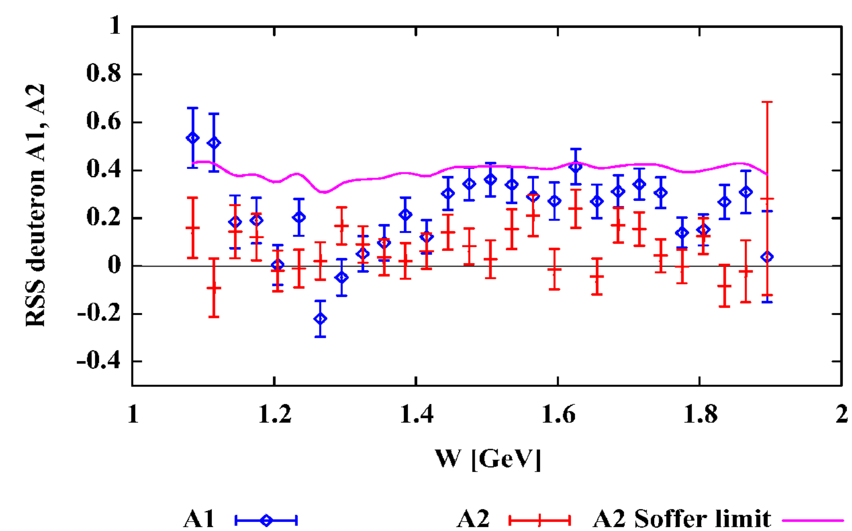
$$A_2 = \frac{\sqrt{Q^2}}{2ED'}\left(A_{\|} + \frac{E-E'\cos\theta}{E'\sin\theta\cos\phi}A_{\perp}\right)$$

- $\boldsymbol{D'}(E,E',\theta,R)$ is function of kinematics and $\boldsymbol{R} = \sigma_L/\sigma_T$
  - (Proton unpolarized SF's from fit to JLab Hall C *e*-*p* data)

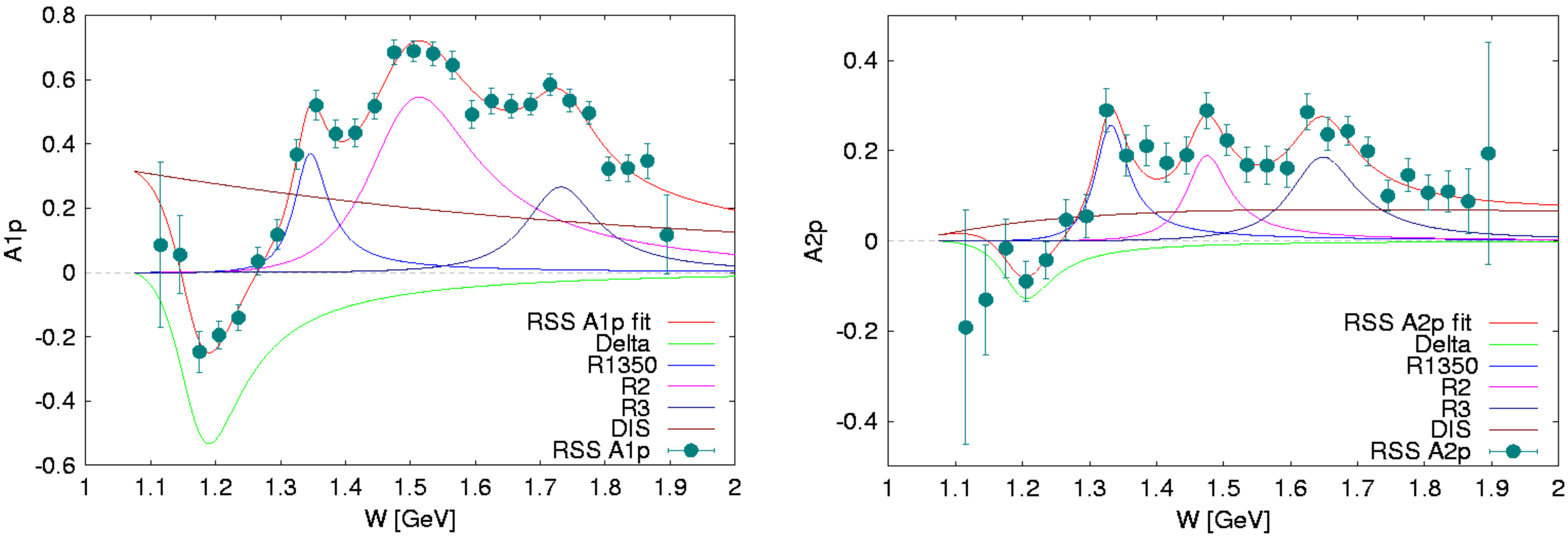
Spin Asymmetry results

- A_1, A_2 for proton, deuteron in resonances are unique:
  - *RSS* is only experiment that can separate A_1, A_2
- Proton (near) final results
- Deuteron radiative corrections not applied yet



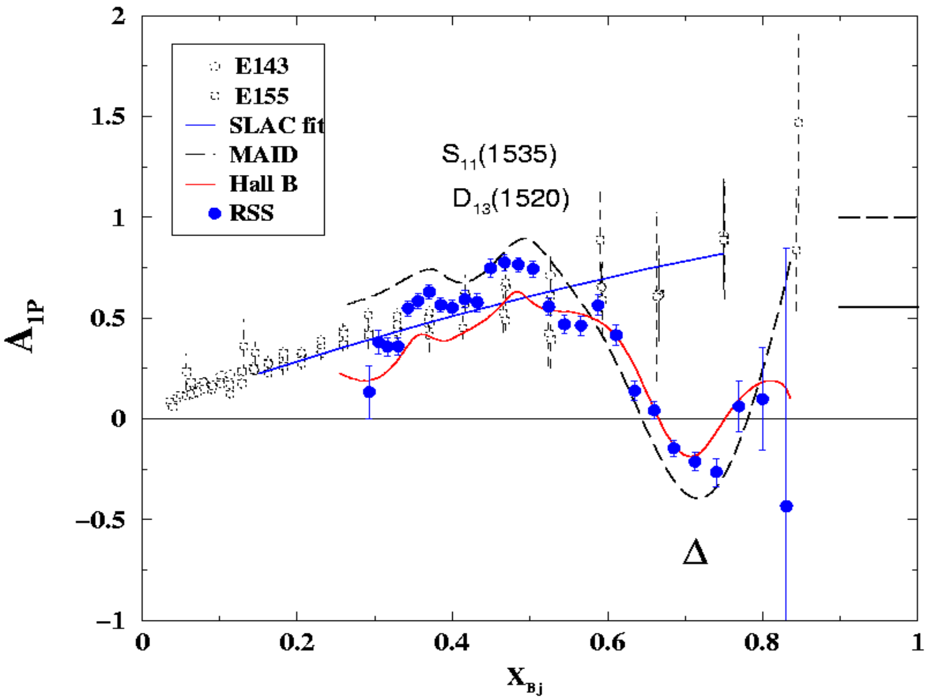


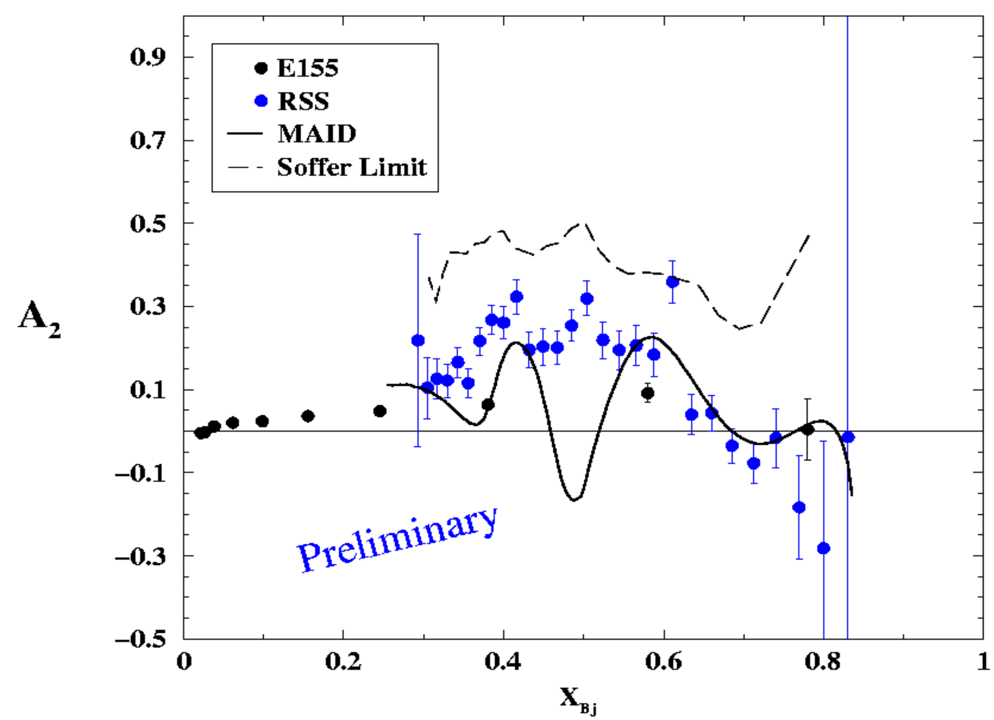
Fit to the Proton SA's



- Four Breit-Wigner resonance shapes plus DIS background
- Fit A_1 and A_2 independently
- Reduced $\chi^2 \sim 1.3 - 1.5$ for 12 d.o.f.

RSS Proton SA's in context





- A_1: highest precision and resolution at $Q^2 \sim 1.3\ \mathrm{GeV}^2$
- A_2: first measurement on proton in the resonances

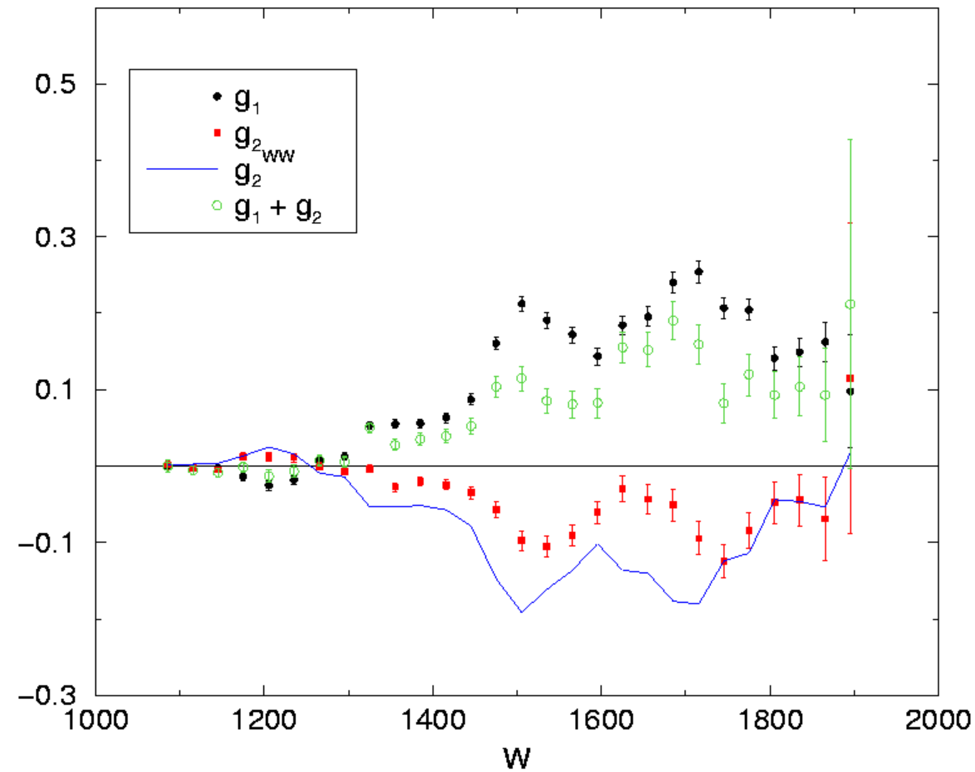
Spin Structure Functions

- Use unpolarized F_1

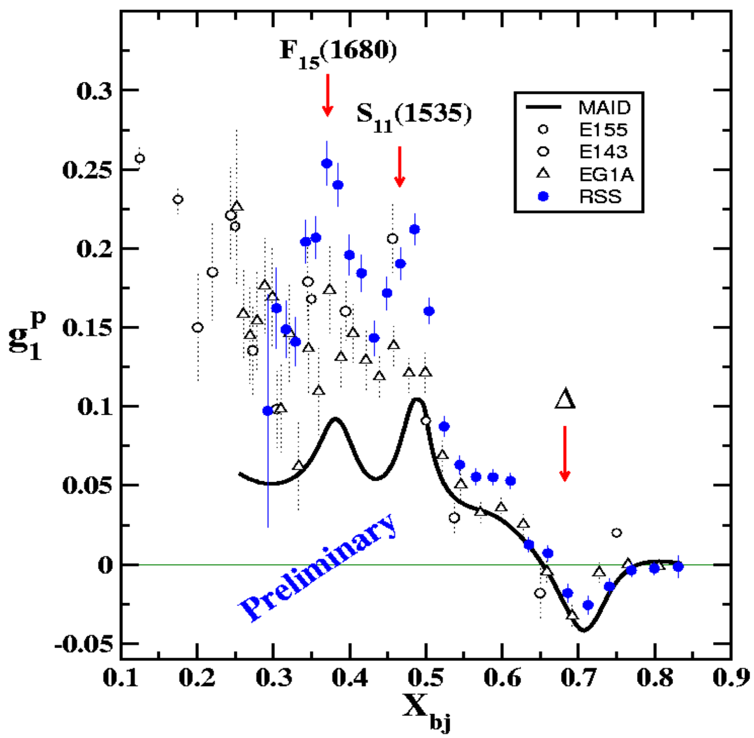
$$g_1 = \frac{F_1}{1+\gamma^2}(A_1 + \gamma A_2)$$

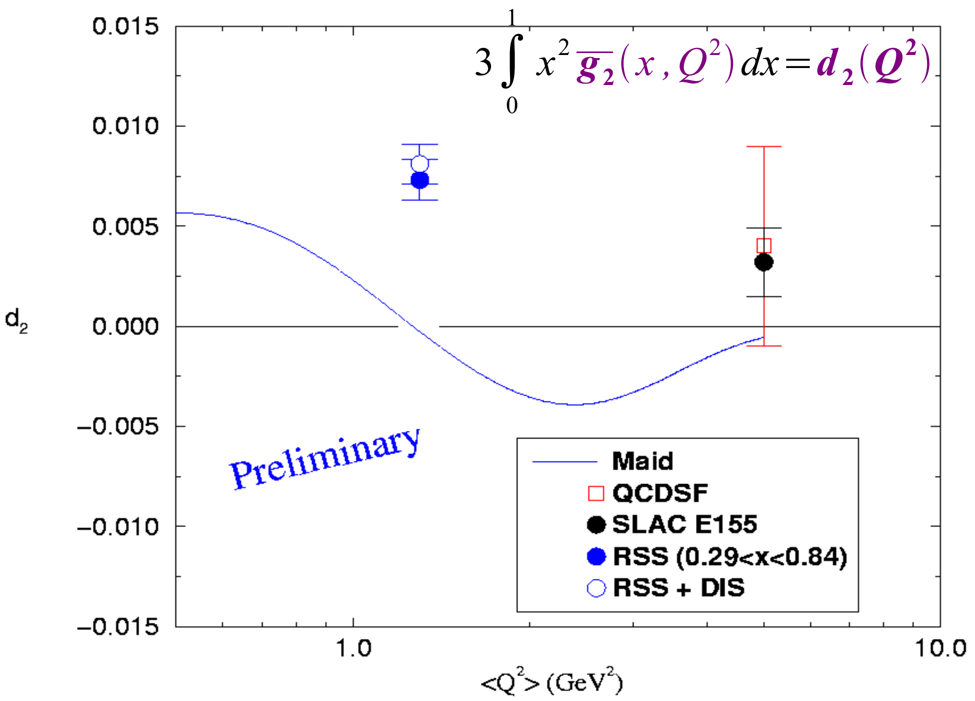
$$g_2 = \frac{F_1}{1+\gamma^2}\left(\frac{A_2}{\gamma} - A_1\right); \quad \gamma = \frac{2xM}{\sqrt{Q^2}}$$

- High precision, high resolution measurement
- First world data for g_2^p in the resonances
- Clear higher-twist in g_2^p



RSS Proton g_1 results in context

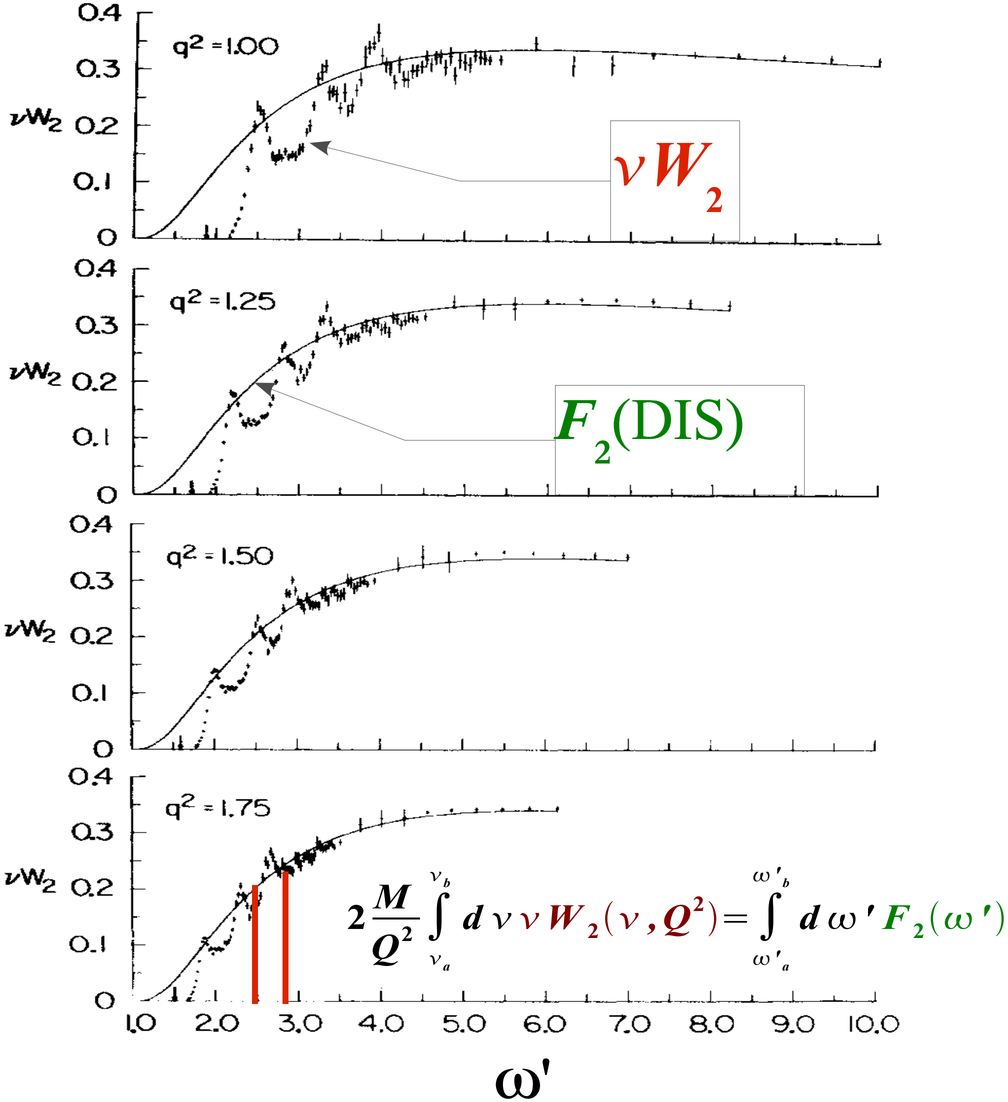




- *RSS* results should help improve SSF models
- Measured $d_2 \neq 0$ is confirms indication of higher twist

Local Duality (Bloom-Gilman 1971)

- Duality: equality of integral of local $W_2(\nu,Q^2)$ to integral of scaling $F_2(\omega')$ ($\equiv \nu W_2$) for proton
- Local duality: equality obtains for each resonance
- Ratio of integrals vs Q^2
  - ~1 for all mass ranges
  - independent of Q^2 above ~ 1GeV^2 ("precocious scaling")
    - Hall C resonances data
    - NMC F_2 and Hall C fit



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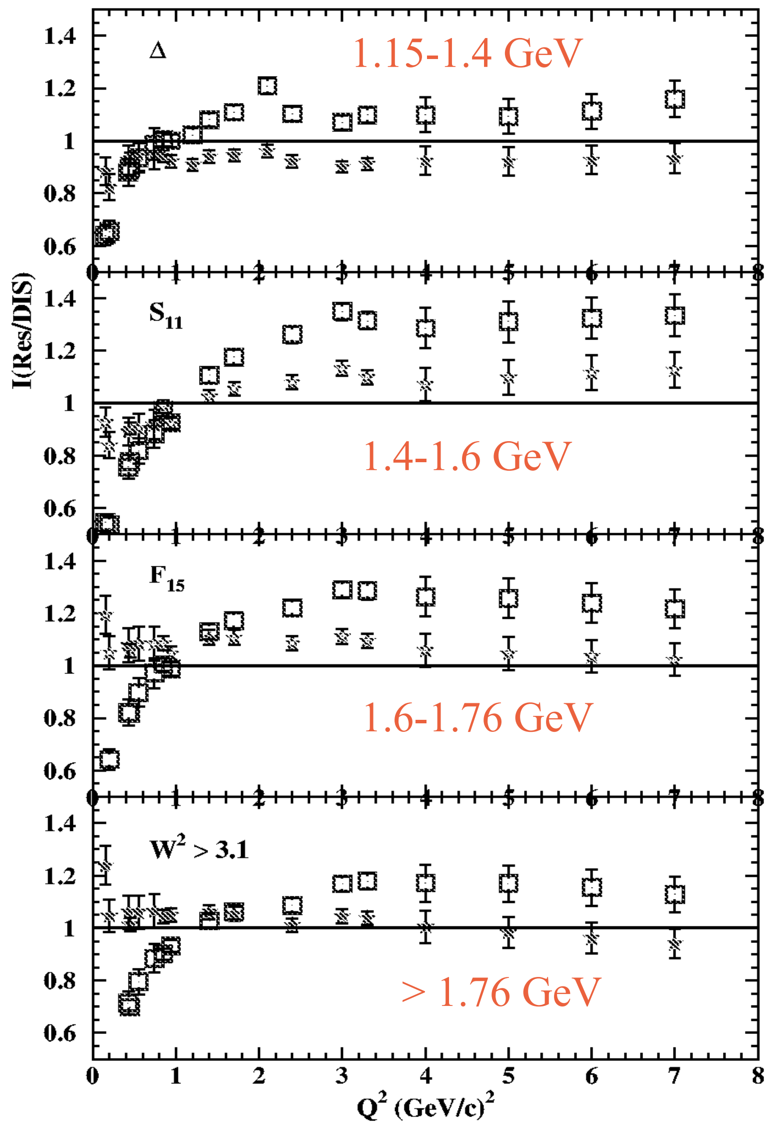
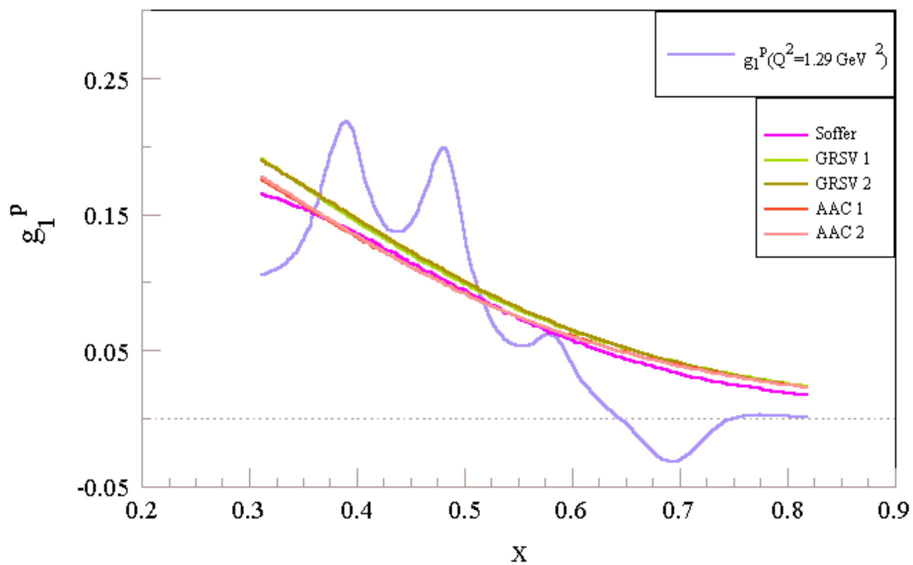


Local Duality for g_1

- Integrate (at mean $Q^2 = 1.28$ GeV^2)
  - g_1 fit over A_1 fit resonances
  - g_1 from PDF's evolved to same Q^2, with target mass corrections
- Polarized Local Duality:
  - ratio of integrals = 1

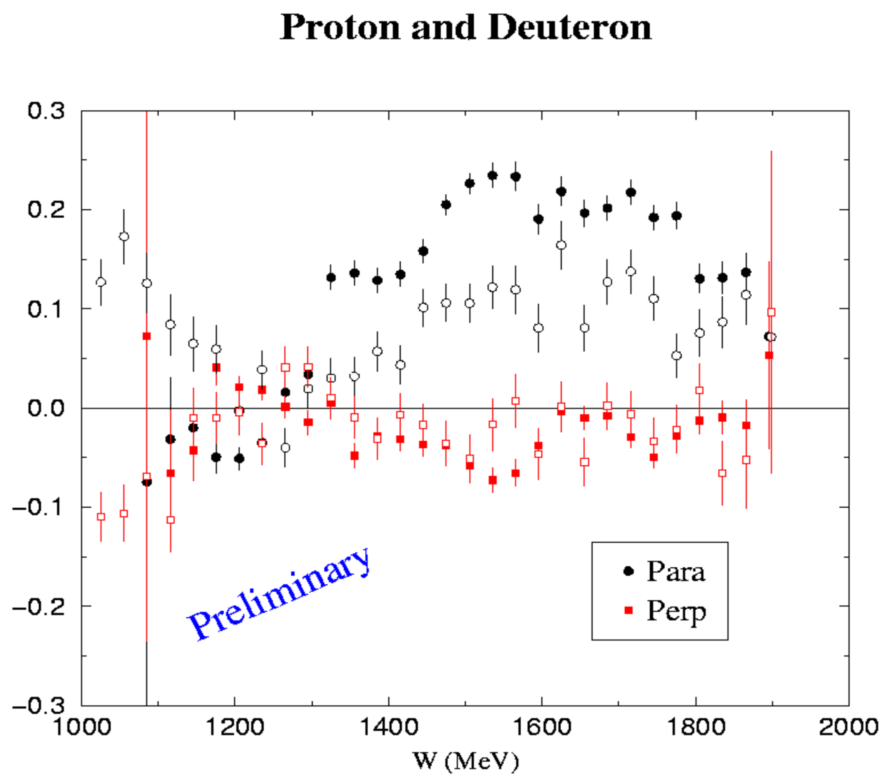


				Integral ratios PDFs/Resonances	Error	
Resonances	Wr GeV	W low	W high	Average	Data	PDFs
Delta	1.209	1.116	1.302	**4.80**	0.71	0.37
R1350	1.348	1.301	1.397	**1.34**	0.07	0.07
R2	1.552	1.396	1.684	**0.78**	0.04	0.04
R3	1.741	1.685	1.805	**0.84**	0.04	0.04
Global		1.080	1.910	**1.17**	0.06	0.06

- Only approximate Global Duality
- Large x resummations increase discrepancy by ~1.3 (S. Liuti)

Next: Neutron Spin Structure

- Extract neutron from *p* and *d*
- Bodek-Ritchie version of Atwood-West smearing
  - generate smeared proton $\mathbf{A}_{\parallel}$, $\mathbf{A}_{\perp}$ from $\boldsymbol{g_1}$, $\boldsymbol{g_2}$
  - subtract from deuteron $\mathbf{A}_{\parallel}$, $\mathbf{A}_{\perp}$ to form smeared neutron quantities
  - unsmear neutron using iterated fit to model



Credits

Analysis Team

- Mark Jones
- Karl Slifer
- Shigeyuki Tajima
- Frank Wesselmann
- Eric Christy
- Paul McKee
- Hamlet Mkrtchyan
- Junho Yun
- Hongguo Zhu
- Oscar Rondon

Special Thanks

- Peter Bosted
- Don Crabb
- Donal Day
- Mahbub Khandaker
- JLab Hall C
- JLab Target group

SANE
Spin Asymmetries on the Nucleon Experiment
(TJNAF E-03-109)

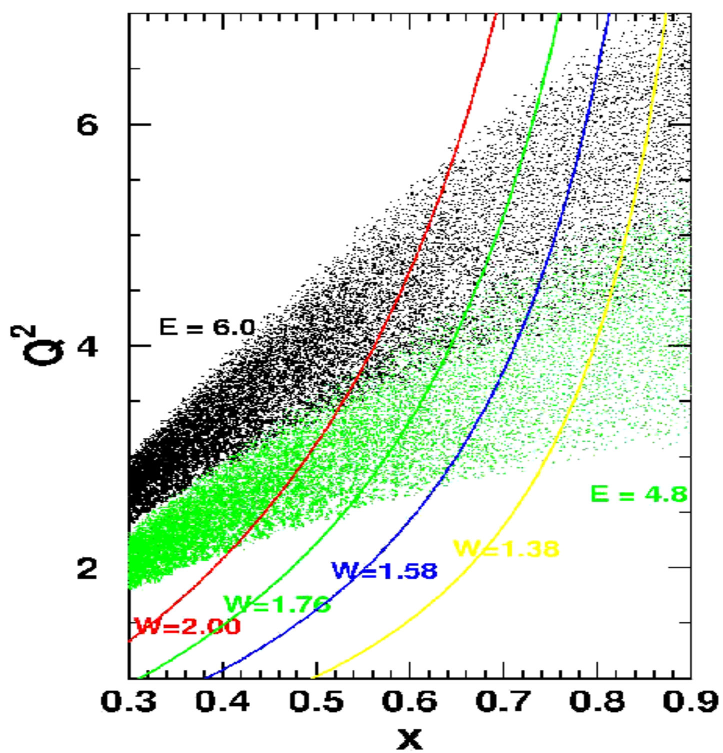
SANE Collaboration
U. Basel, Florida International U., Hampton U., Norfolk S. U., North Carolina A&T S. U., IHEP-Protvino, Kent S. U., U. of Regina, Rensselaer Polytechnic I., St. Norbert College, Temple U., TJNAF, U. of Virginia, College of William & Mary, Yerevan Physics I.

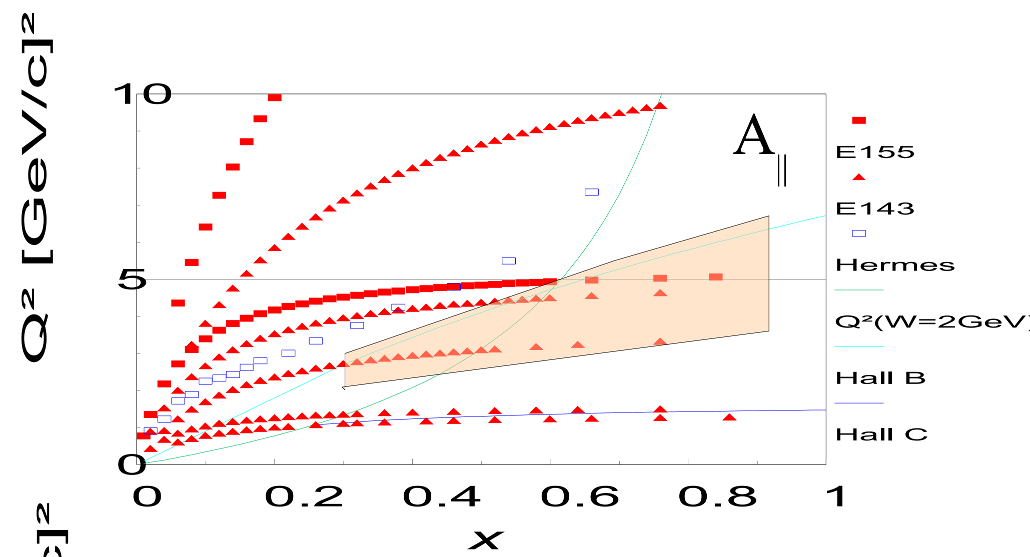
Spokespersons: S. Choi (Seoul), Z-E. Meziani (Temple), O. A. Rondon (U. of Virginia)

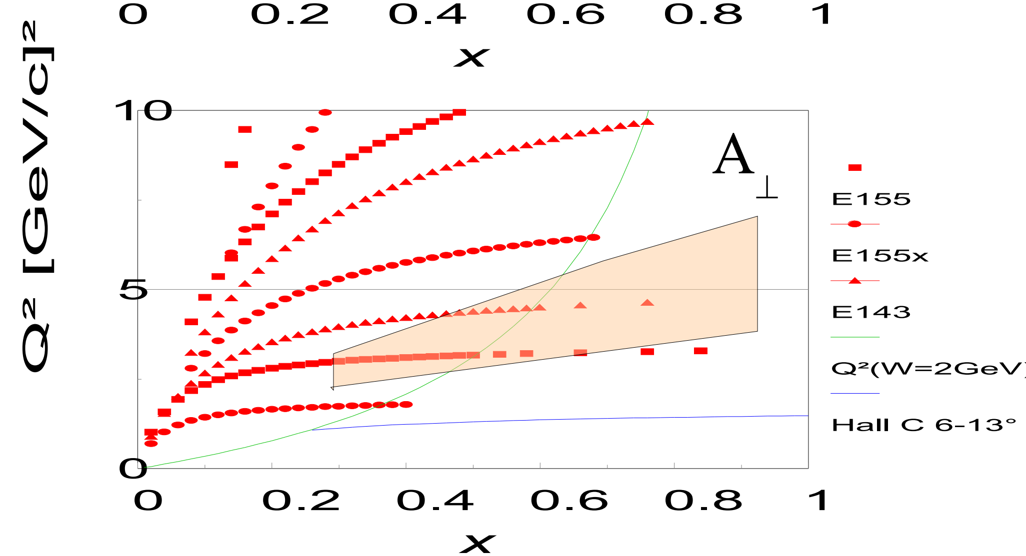
SANE Physics

- Measure proton $\boldsymbol{g_2}(x, Q^2)$ and $\mathbf{A_1}(x, Q^2)$
    - $2.5 \le \boldsymbol{Q^2} \le 6.5$ GeV^2 and $0.3 \le \boldsymbol{x} \le 0.8$
- Goals:
    - x and Q^2 dependence of spin structure functions
    - Twist-3 from moments of $\boldsymbol{g_2}$ and $\boldsymbol{g_1}$, compare with Lattice QCD
    - "High $\boldsymbol{x}$" region: $\mathbf{A_1}$ approach to $\boldsymbol{x} = 1$
    - Test polarized local duality for $W > 1.4$ GeV
- Method:
    - Inclusive parallel and near-perpendicular spin asymmetries
    - Detector: large solid angle electron telescope **BETA**

SANE Kinematics

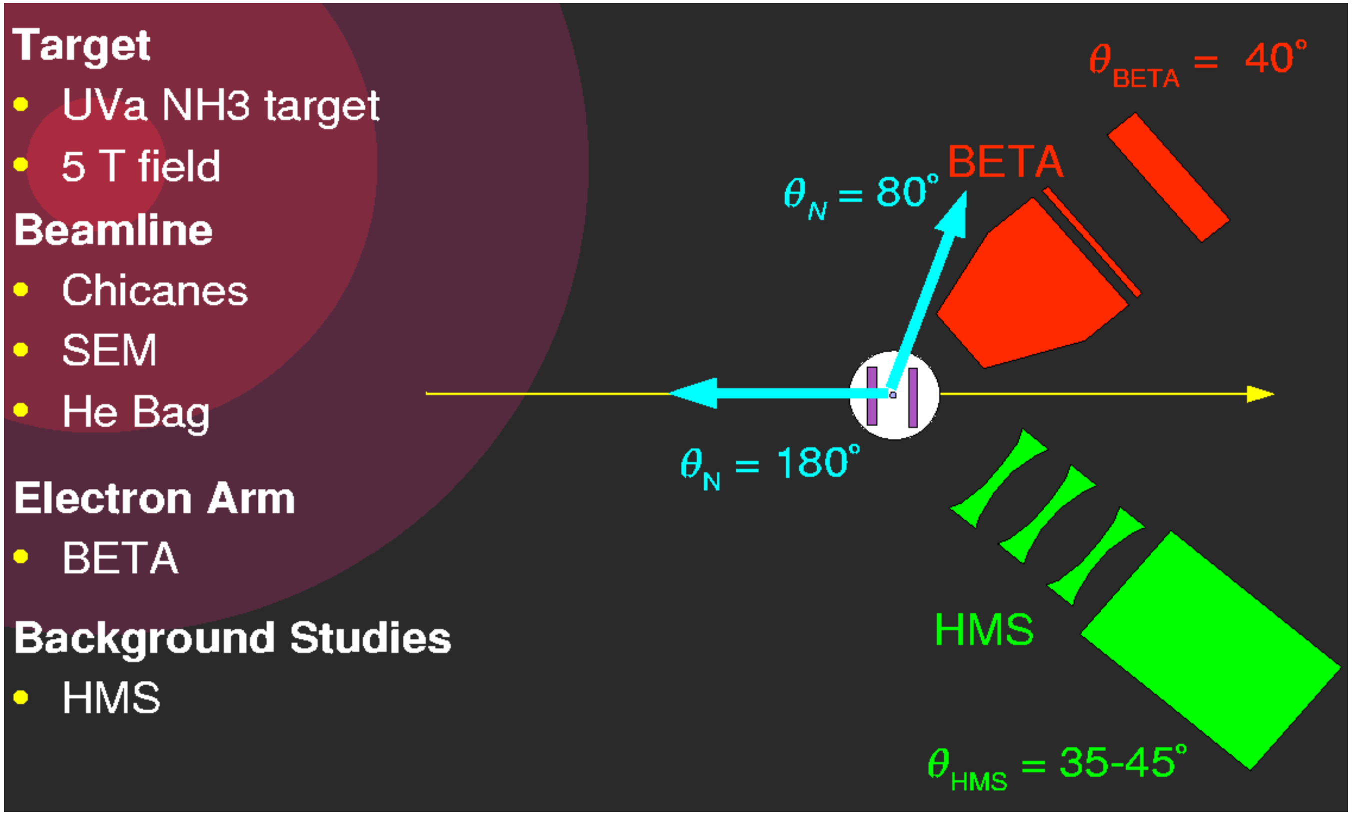






- Two beam energies:
  - **6 GeV**, **4.8 GeV**
- Very good high ***x*** coverage

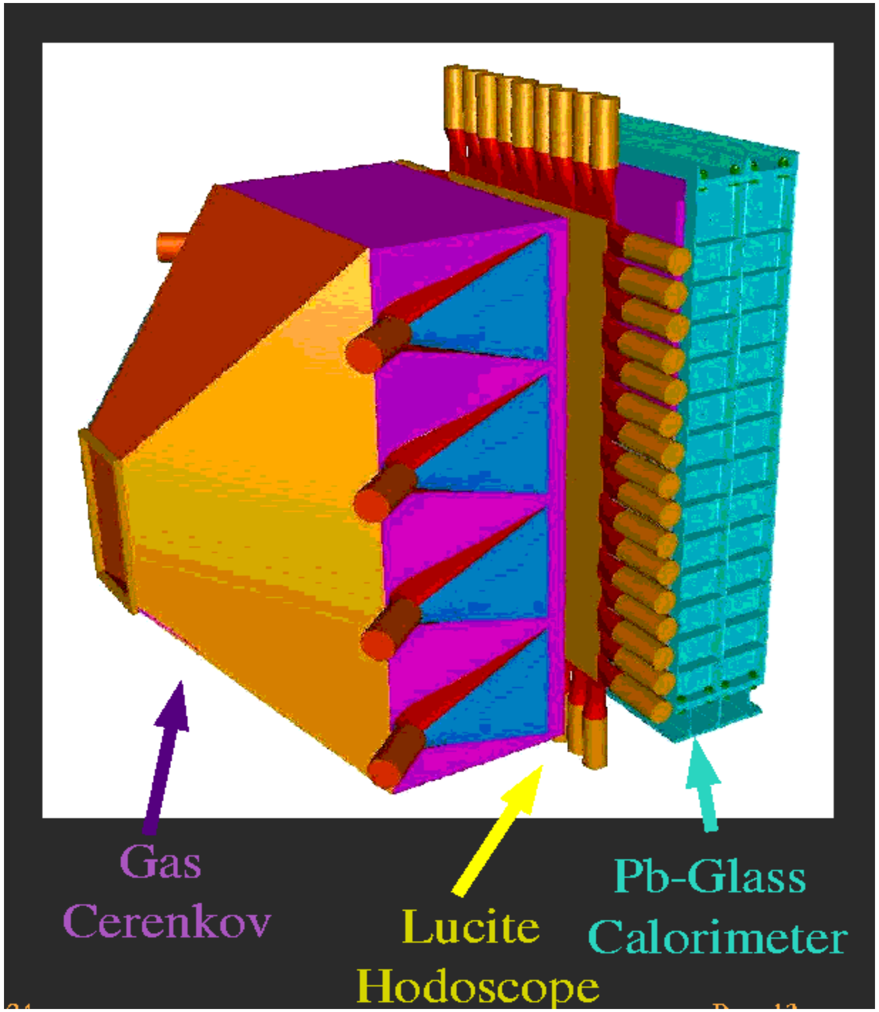
SANE Layout



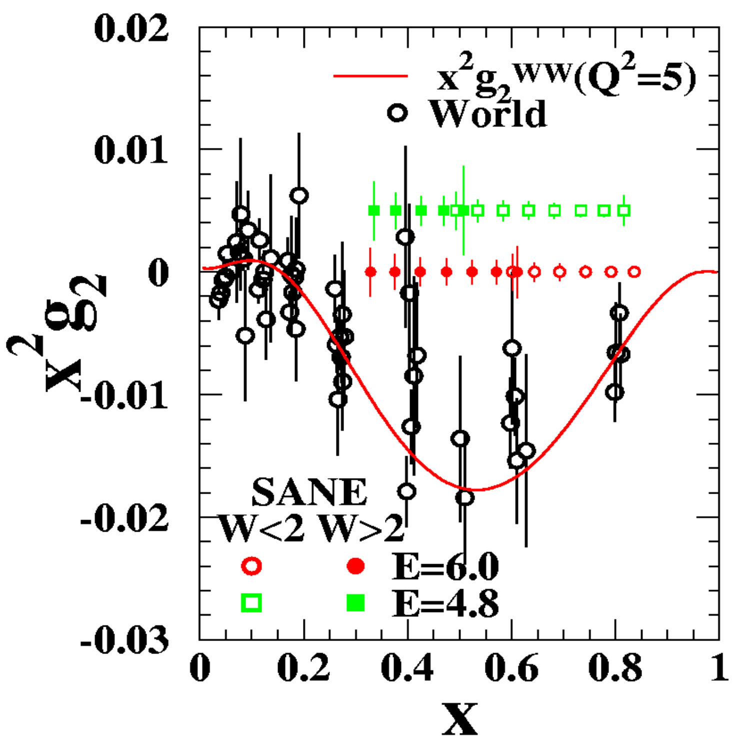
- Target field aligned to measure Parallel and near-Perpendicular asymmetries

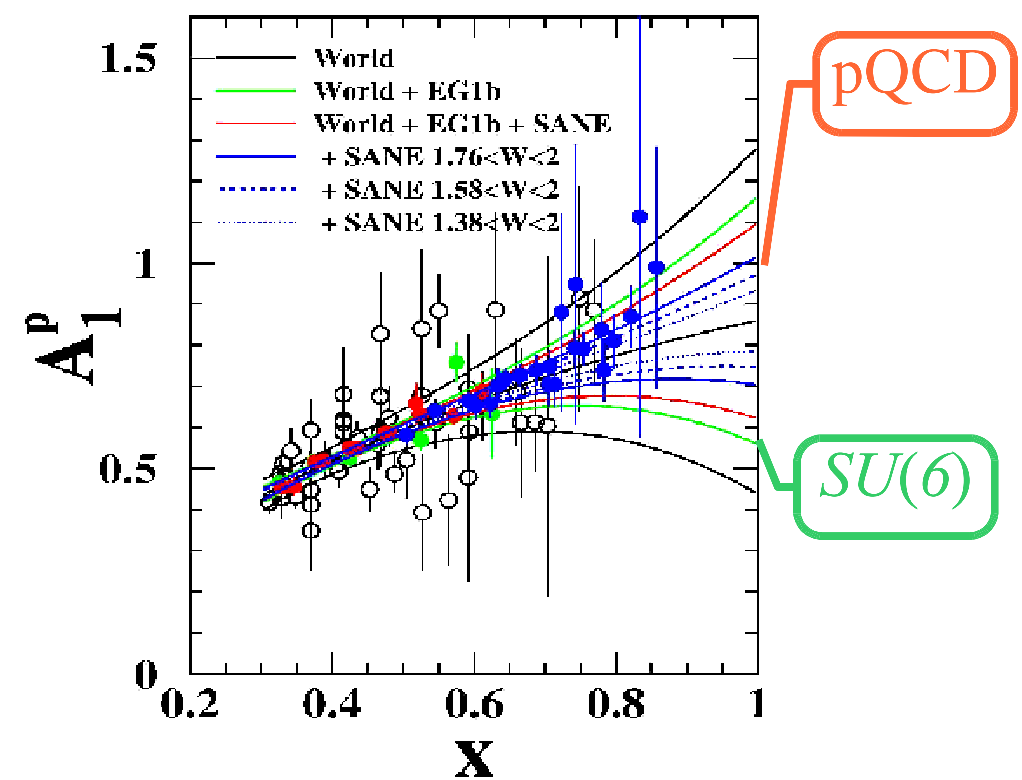
Big Electron Telescope Array - BETA

- BigCal lead glass calorimeter: main detector, being built for *GEp-III*.
- Gas Cherenkov: additional pion rejection
- Tracking Lucite hodoscope (Cherenkov)
- Target field sweeps low *E* background
- BETA's characteristics
  - Effective solid angle = 0.194 sr
  - Energy resolution $5\%/\sqrt{E}$(GeV)
  - angular resolution = 2°
  - 1000:1 pion rejection
- Added: front quartz hodoscope
  - vertex resolution ~ 4 mm (geometric)
  - angular resolution ~ 1 mr



SANE Expected Results

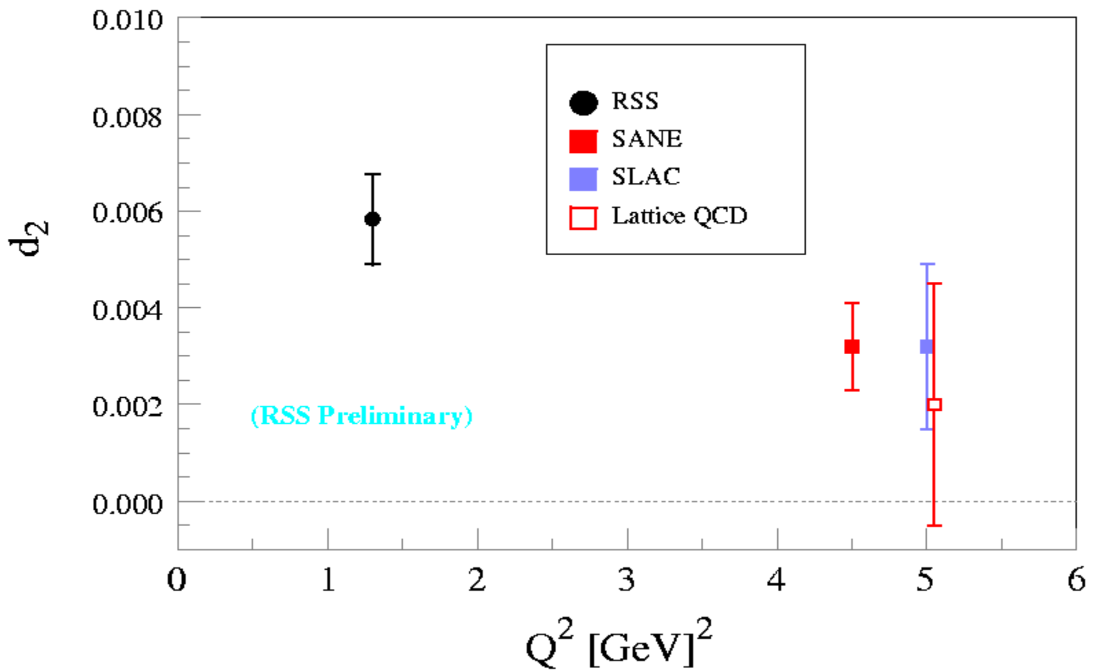




- DIS data for ***x*** up to 0.6 (with 6 GeV)
  - Constrain extrapolations of A1p to x = 1 within +/- 0.1 (using duality)

SANE Expected Results (II)

- Twist-3 matrix element $\boldsymbol{d_2} = \int_0^1 x^2 (2\boldsymbol{g_1} + 3\boldsymbol{g_2})\, dx$ calculable in Lattice QCD
- SANE expected error on $\boldsymbol{d_2}(Q^2 = 2.5 \text{ to } 6.5 \text{ GeV}^2) = 0.0009$ (½ the current world error)



SANE Status

- Conditional approval by PAC24 for 27 days in Hall C with A^- rating
- SANE to run in 2008, followed by Semi-SANE and Polarized Wide Angle Compton Scattering (All three experiments with UVa spokespeople, using UVa polarized target)
- SANE addresses DOE performance milestone for 2011:

2011	Measure the lowest moments of the unpolarized nucleon structure functions (both longitudinal and transverse) to 4 GeV^2 for the proton, and the neutron, and the deep inelastic scattering polarized structure functions $g_1(x, Q^2)$ and $g_2(x,Q^2)$ for $x=0.2$-0.6, and $1 < Q^2 < 5$ GeV^2 for both protons and neutrons.

- SANE Web site: http://www.jlab.org/~rondon/sane/

Beyond Inclusive Scattering

- Eight quark distribution functions:
  - $k_\perp$ independent (leading twist)
    - F_1, g_1: inclusive
    - δ: transversity (h_T)
  - $k_\perp$ dependent
    - $g_T = g_1 + g_2$: inclusive, mixed twist
    - $h_{1L}^{\perp}$, $h_{1T}^{\perp}$: semi-inclusive, T-even
    - $f_{1T}^{\perp}$, $h_1^{\perp}$: semi-inclusive, T-odd

- Spin Dependent Fragmentation: Semi-Inclusive Leptoproduction
  - Detect hadron (π, K,..)-lepton in coincidence
  - Semi-inclusive Asymmetry

$$A_1^h(x,z,Q^2) = \frac{\sum e_f^2 \Delta q_f(x,Q^2) D_f^h(z,Q^2)}{\sum e_f^2 q_f(x,Q^2) D_f^h(z,Q^2)}$$

$$z = E_h/\nu$$

- Spin Dependent Exclusive Scattering: Generalized Parton Distributions

Flavor Decomposition of Nucleon Spin

TJNAF Experiment 04-113

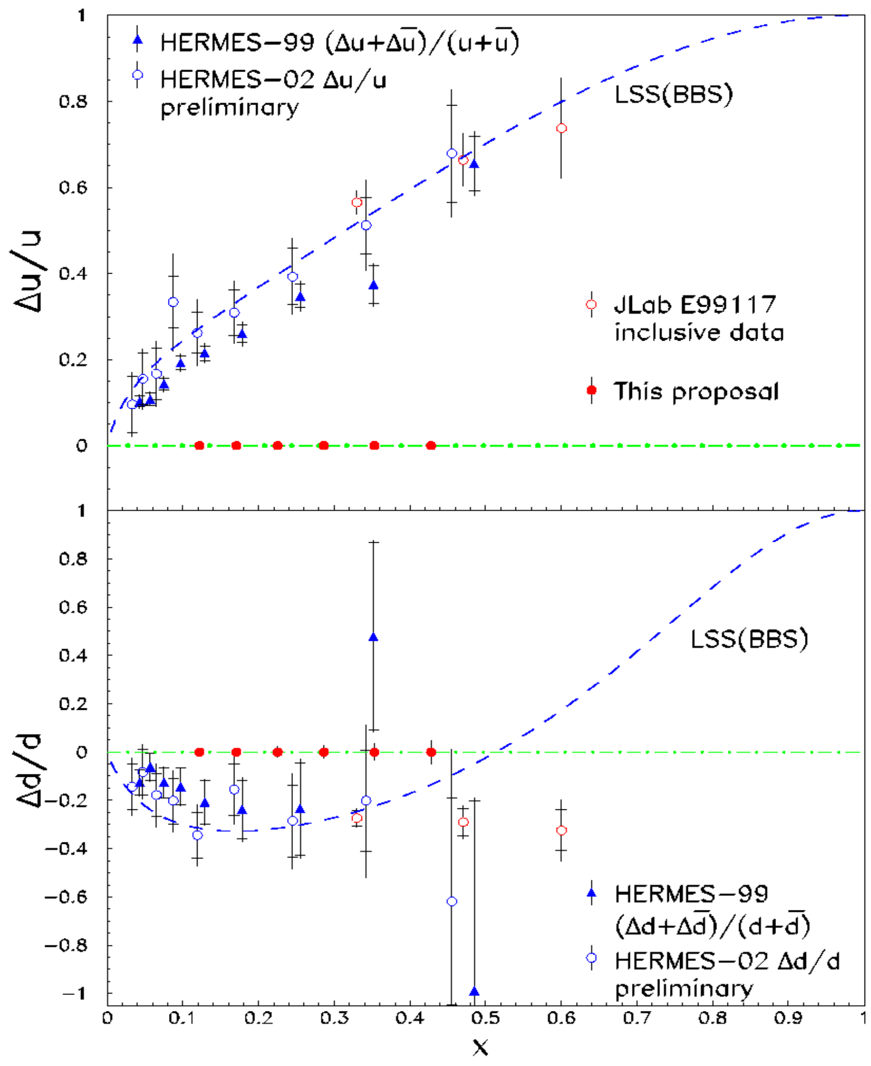
Argonne National Lab, Duke U., Florida International U., Hampton U., U. Kentucky, U. Maryland, U. Massachusetts, Rensselaer Polytechnic I., Norfolk S. U., Old Dominion U., U. Regina, Rutgers U., Temple U., TJNAF, U. of Virginia, C. of William & Mary, Yerevan Physics I.

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

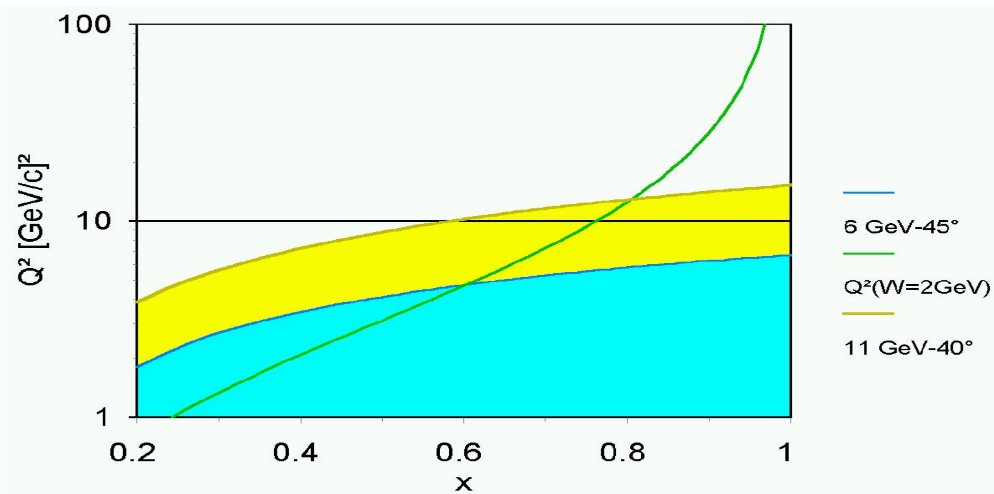
- Measure proton and deuteron semi-inclusive spin asymmetries in polarized DIS reactions $p(e,e'h)$ and $d(e,e'h)$: Semi-SANE
  - $h = \pi^{+,-}$, $K^{+,-}$, $1.2 \leq Q^2 \leq 3.2$ GeV^2, $0.12 \leq \boldsymbol{x} \leq 0.43$, for hadrons with $0.5 \leq z \leq 0.7$
  - Extract the Δu, Δd, Δs, and anti-quark spin components
  - Test factorization comparing $A_{1N}^{\pi+ + \pi-}$ to inclusive A_{1N}
  - Detect electrons with BETA and hadrons with HMS

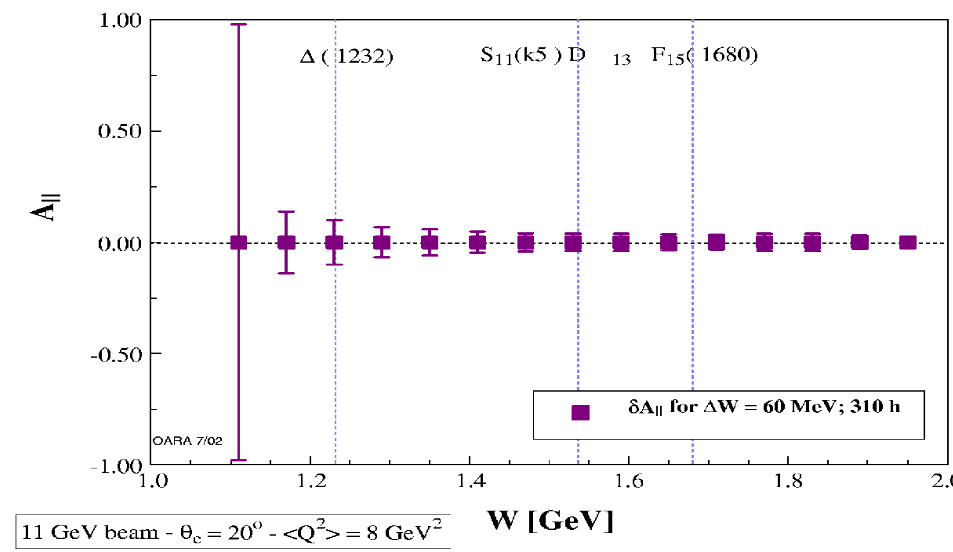
Method and Sample of Expected Results

- Form $A_{1N}^{\pi+ - \pi-}$ to get valence quark helicities
  - combine with inclusive data to probe polarized ligth sea flavor asymmetry
- Compare $A_{1N}^{\pi+ + \pi-}$ with inclusive result to test factorization
- Expected results for the *u* and *d* quark asymmetries and world data
- Approved for 25 days with A- rating



Spin Physics beyond 6 GeV





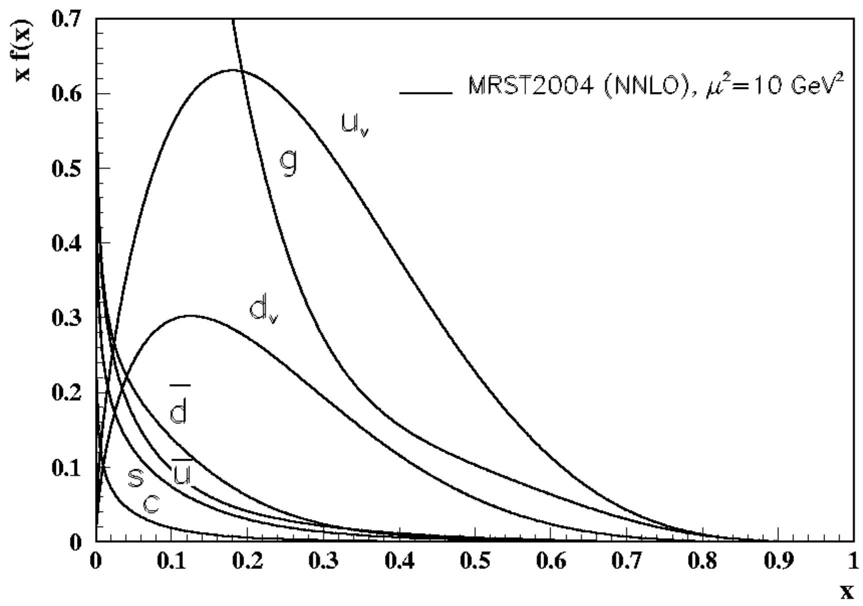
- CEBAF energy upgrade: extended x, Q^2 ranges, better count rates
  - Precision tests of local polarized and unpolarized duality possible
  - Semi-Inclusive spin asymmetries with horizontal and vertical polarized targets (single spin LOI-04-003)
  - Inclusive tests of Collins (time odd) asymmetry= time reversal invariance (LOI-01-002)
  - Effects of nuclear binding on spin structure in ^{6,7}Li and other nuclear targets

CREDITS

- Hypephysics
  - http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html#hph
- Oxford
  - http://www.physics.ox.ac.uk/documents/PUS/dis/index.htm
- DESY (Feynman diag.)
  - http://www.desy.de/~gbrandt/feyn/
- Patterns in Nature
  - http://acept.la.asu.edu/PiN/rdg/polarize/polarize.shtml
- The Physics Classroom
  - http://www.glenbrook.k12.il.us/gbssci/phys/Class/light/u12l1e.html
- Molecular Expressions
  - http://www.microscopy.fsu.edu/primer/index.html

Scaling and DIS

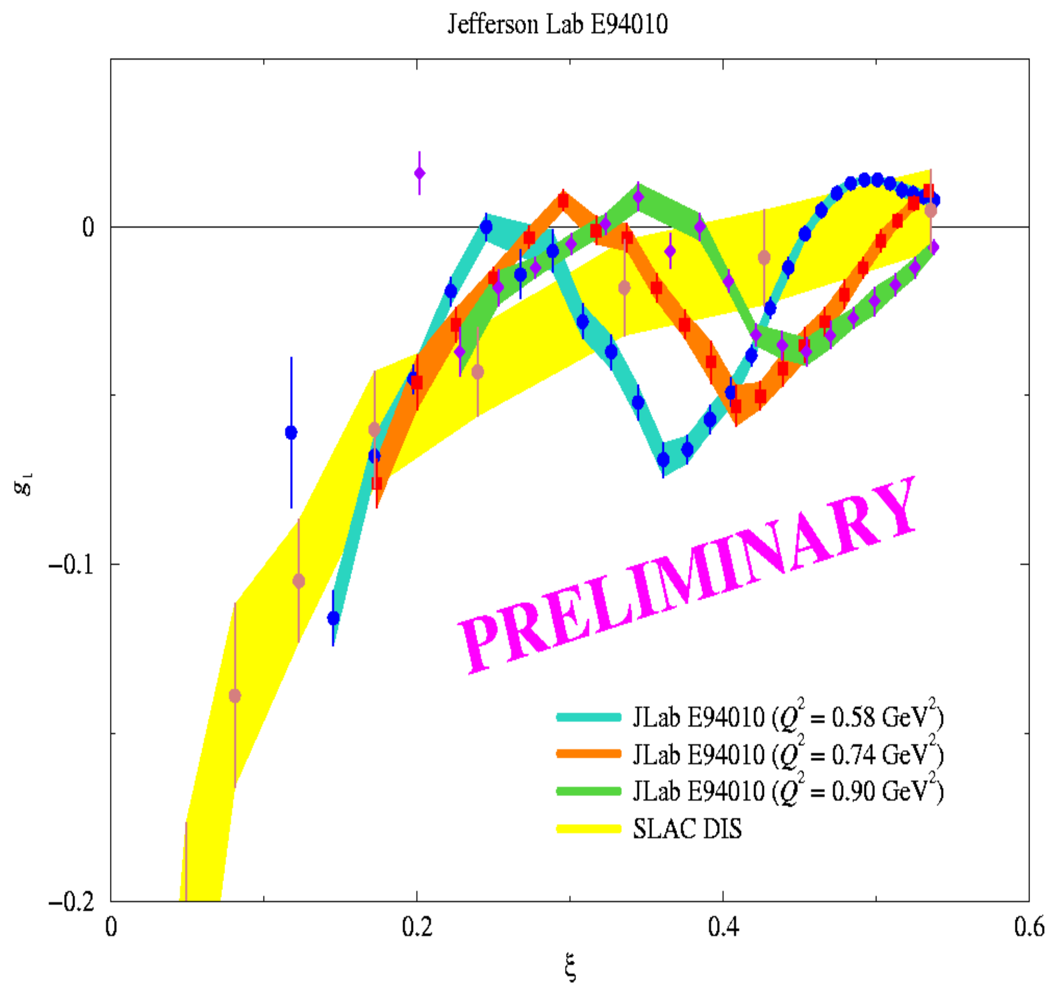
- Parton, QCD predictions:
  - DIS scattering same at all energy scales
    - Scattering depends on one dimensionless parameter
      $x = Q^2/(2M\upsilon)$
    - Q^2 = four-momentum squared of virtual photon
    - υ = energy of virtual photon
  - Deviations of $\boldsymbol{F_2(x)}$ from scaling: gluon radiation



Parton Distribution Functions - PDF's
(Review of Particle Properties 2004)

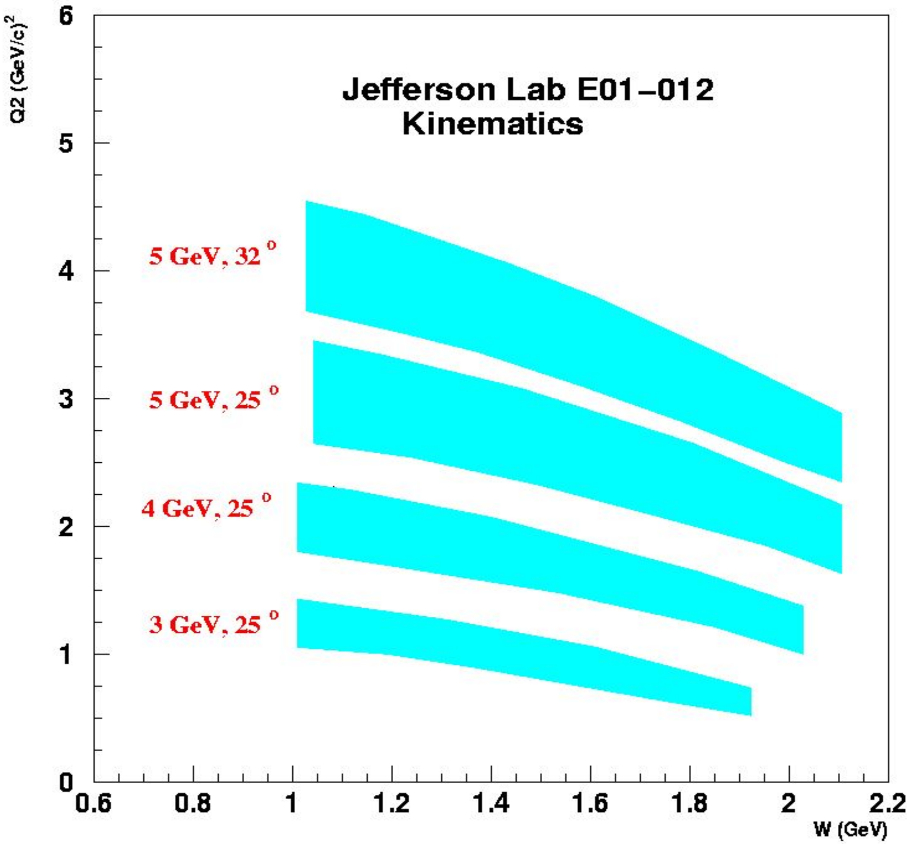
Hall A g_1 duality: low Q^2

- Q^2 low (< 1 GeV^2)
  - Inclusive scattering on ^{3}He
  - Model independent g_1 (measured both $A_{\parallel}$ and $A_{\perp}$)
  - g_1 for neutron vs ^{3}He
- Quantitative test needed
- (Plot from S. Choi, for E94-010)



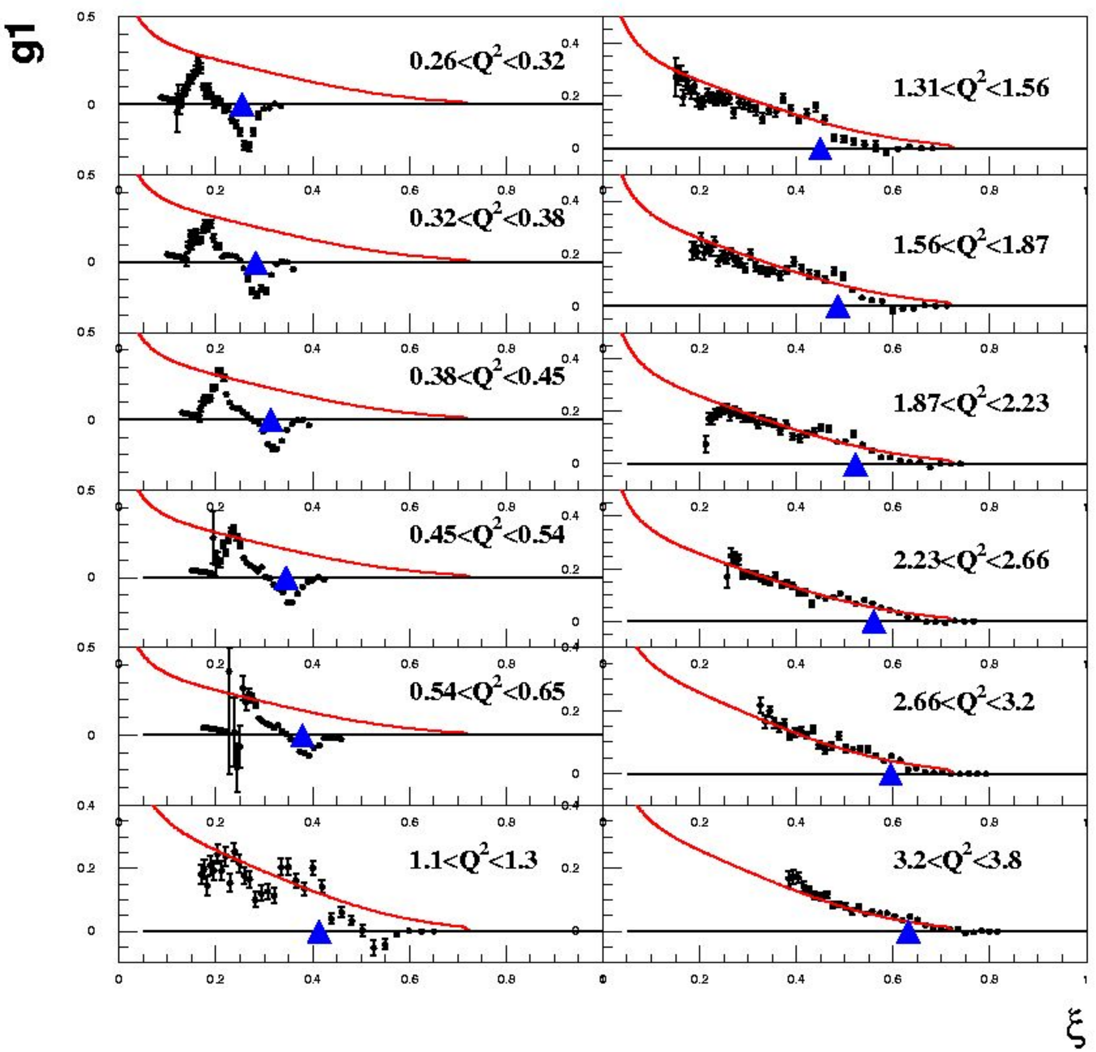
Hall A g_1 duality: intermediate Q^2

- Dedicated experiment on ^{3}He target
- Model independent g_1 (measured both $A_\parallel$ and $A_\perp$)
- g_1 for neutron from ^{3}He
- Took data in early 2003
  - Analysis in progress
- (Plot from P. Solvignon, for E01-012)

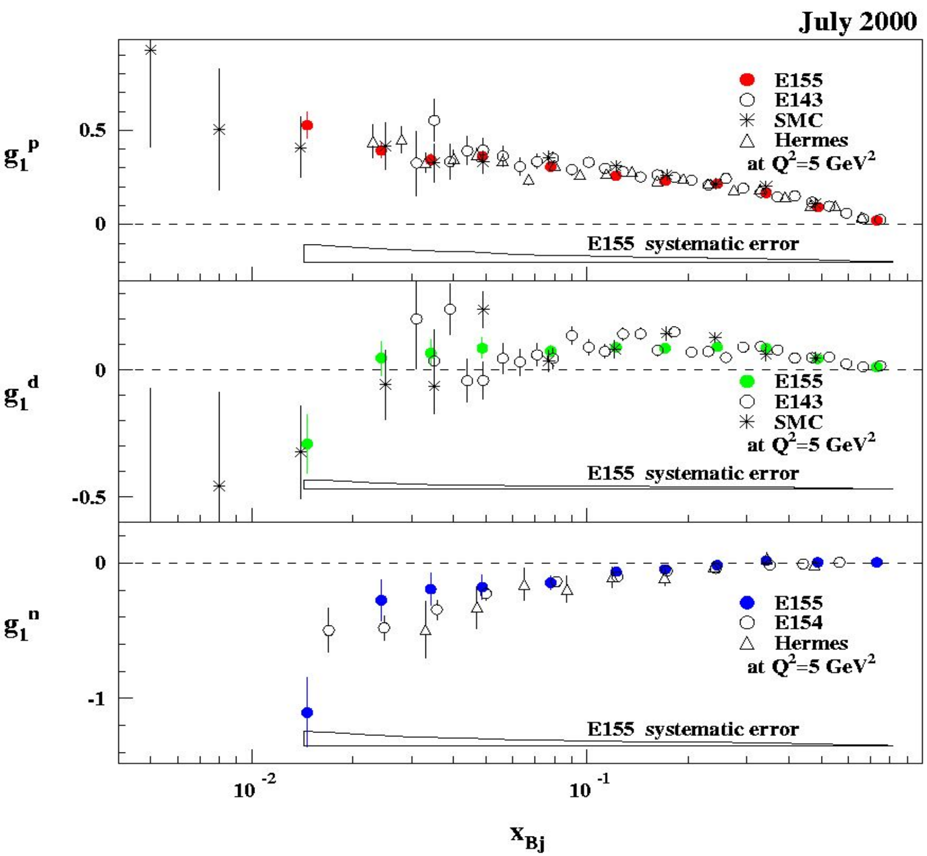


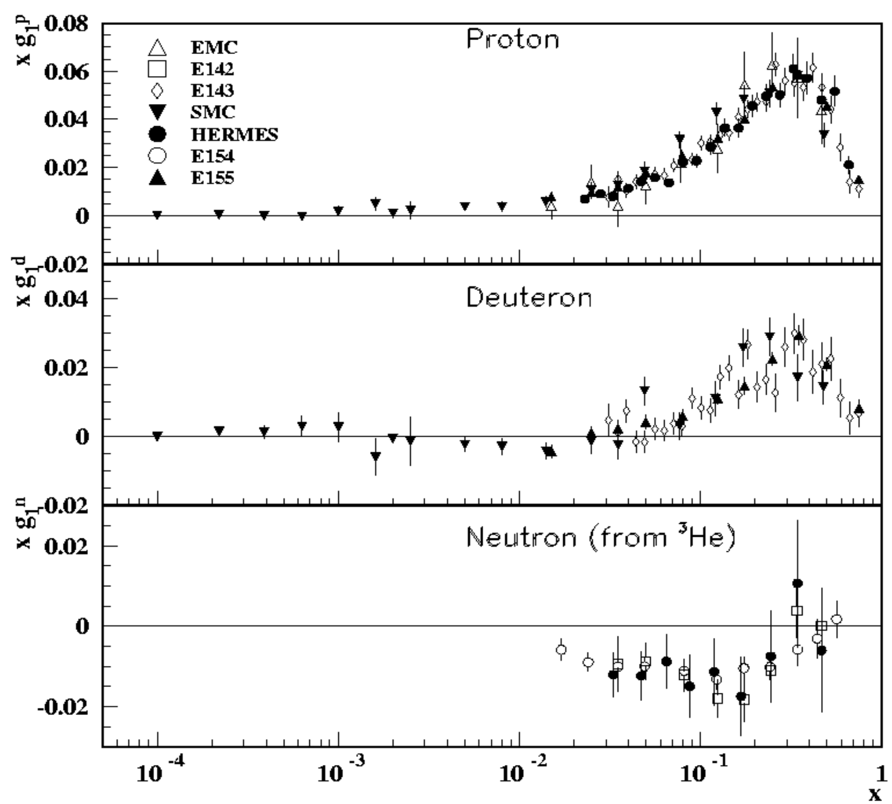
Hall B g_1 duality: proton

- Q^2 low - intermediate
  - g_1 from $A_{\parallel}$ only - A_2 from model (small)
  - E155 DIS global fit at $Q^2 = 10\ \text{GeV}^2$
- Quantitative test pending
- (Preliminary eg1b results)



Final Results from SLAC, CERN, DESY





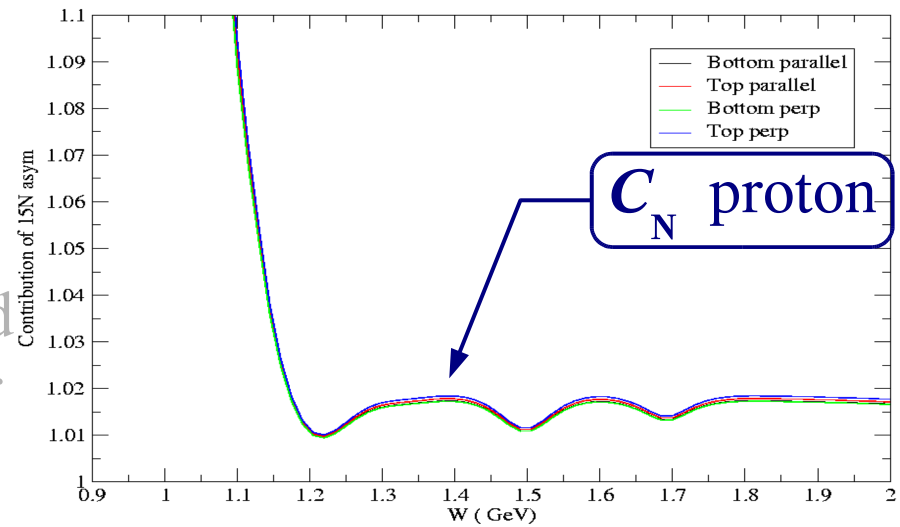
- Quark spin (SLAC E155 global fit): $\sum q$ =0.229±0.041±0.057
- Quarks: only 23% of spin! What carries the remainder? ***gluons***? ***L***?

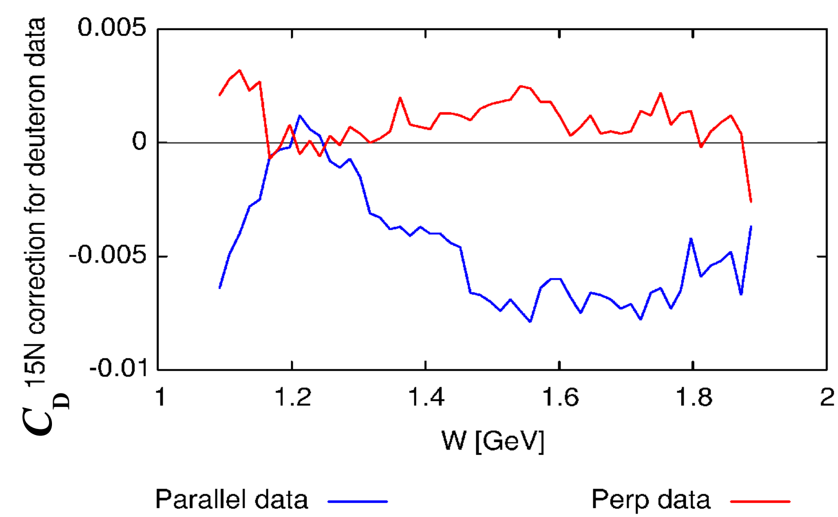
Measured asymmetries $A_{\parallel}$, $A_{\perp}$

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

$$\epsilon = (N^{-} - N^{+})/(N^{-} + N^{+})$$

- N^-, N^+ = charge normalized, dead time and pion corrected yields for +/- beam helicities
- P_b, P_t = beam, target polarizations
- f = dilution factor
- C_N, C_D = corrections for ^{15,14}N: proton C_D= 0, deuteron $C_N \simeq 1$
- A_{rc} = radiative correction



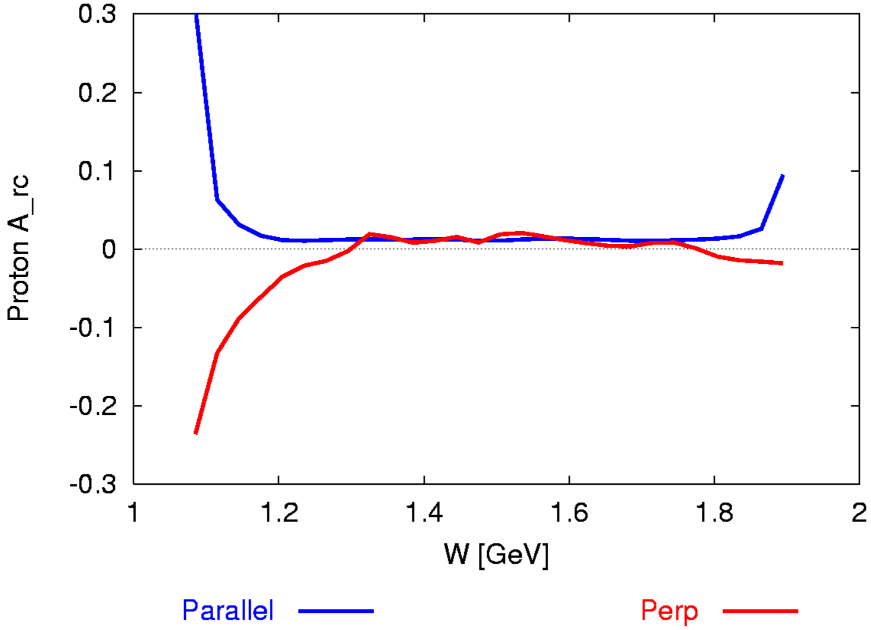


Measured asymmetries $A_{\|}$, $A_{\perp}$

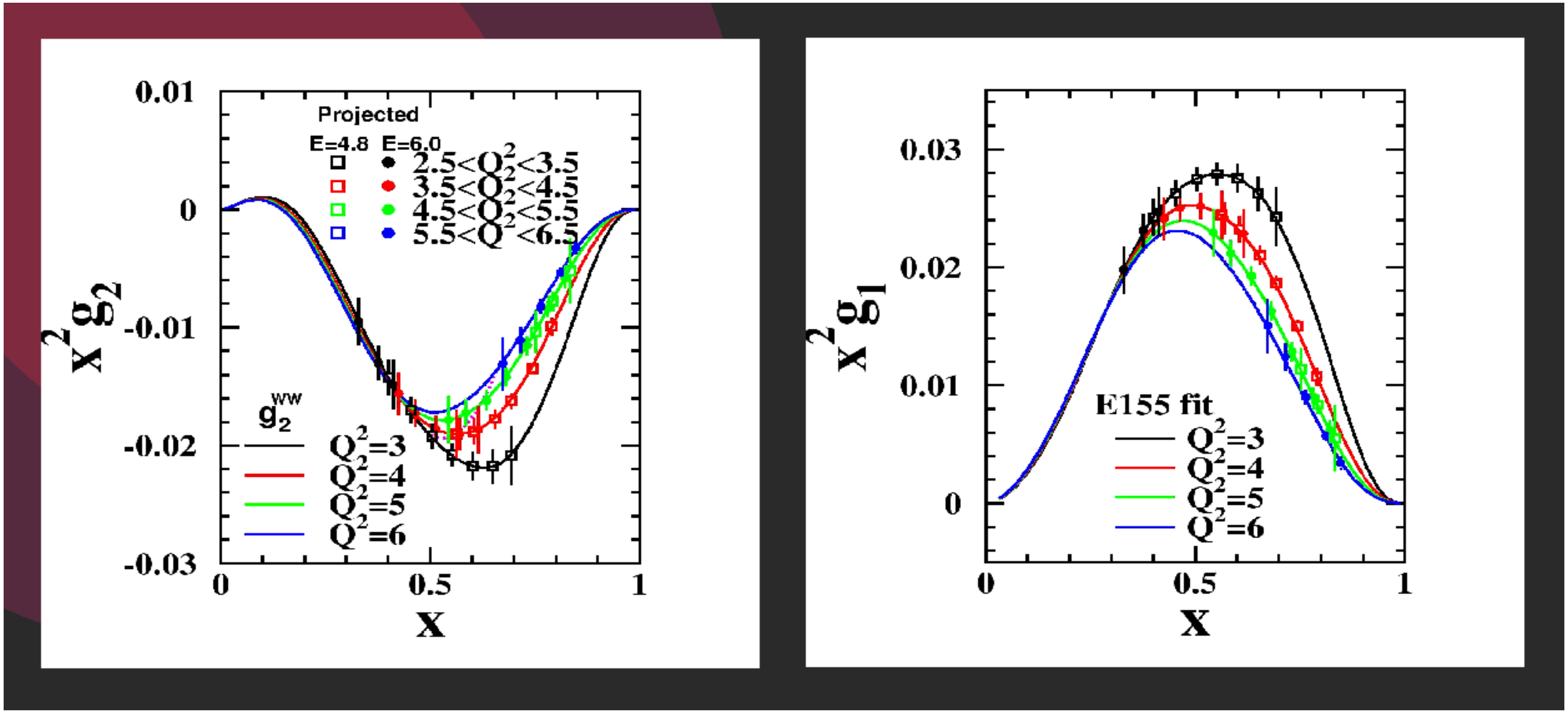
$$A_{\|,\perp} = \left(\frac{\epsilon}{f P_b P_t C_N} + C_D\right) + \boldsymbol{A}_{\mathbf{rc}}$$

$$\epsilon = (N^- - N^+)/(N^- + N^+)$$

- N^-, N^+ = charge normalized, dead time and pion corrected yields for +/- beam helicities
- P_b, P_t = beam, target polarizations
- f = dilution factor
- C_N, C_D = corrections for ^{15,14}N: proton $C_D = 0$, deuteron $C_N \simeq 1$
- A_{rc} = radiative correction

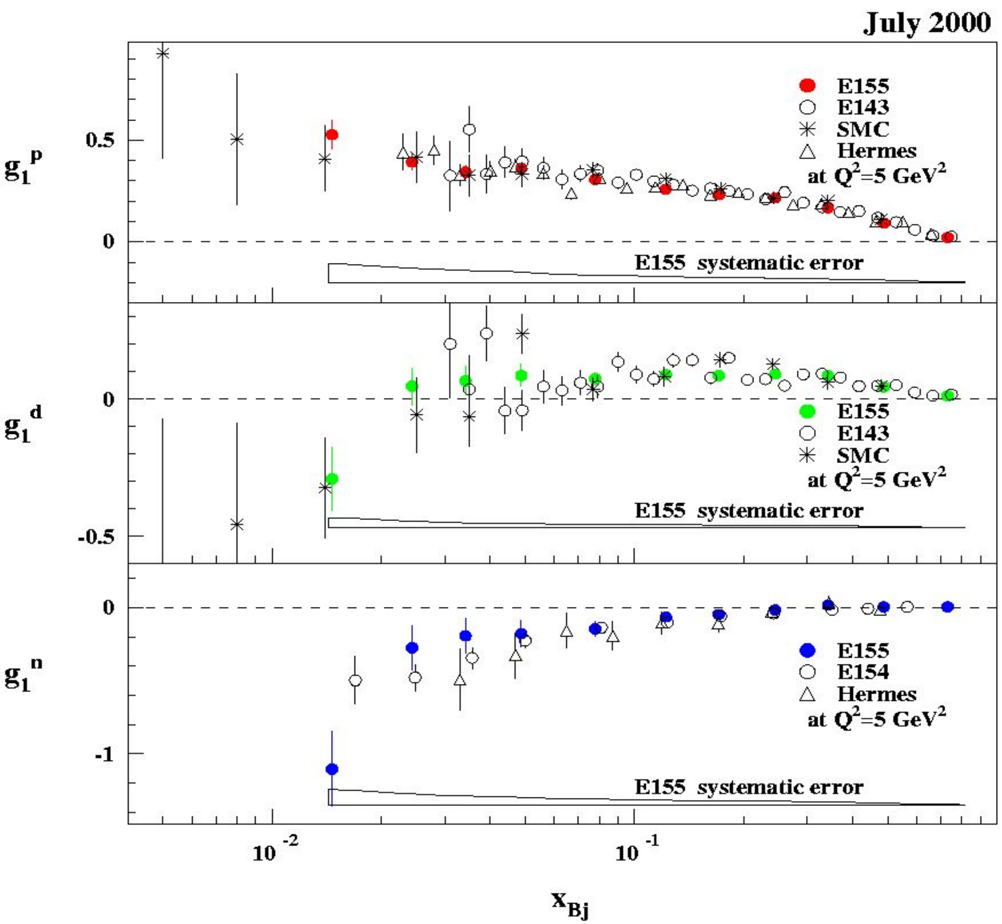


SANE Expected Results (II)

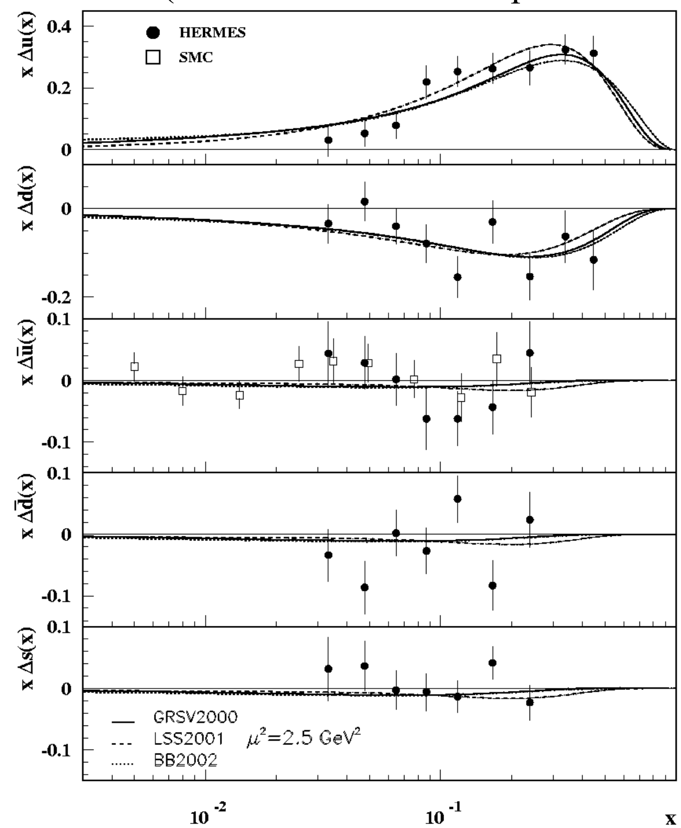


- $\boldsymbol{x}$ dependence at constant $\boldsymbol{Q^2}$ and $\boldsymbol{Q^2}$ dependence at fixed $\boldsymbol{x}$
- data are concentrated in the region most sensitive to $\boldsymbol{x^2g_{2,1}}$

Final Results from SLAC, CERN, DESY

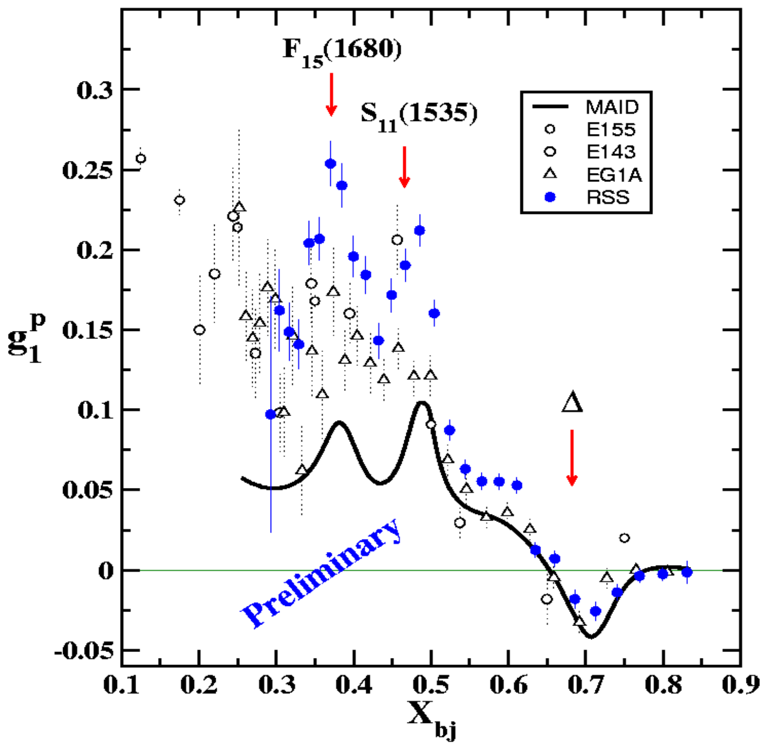


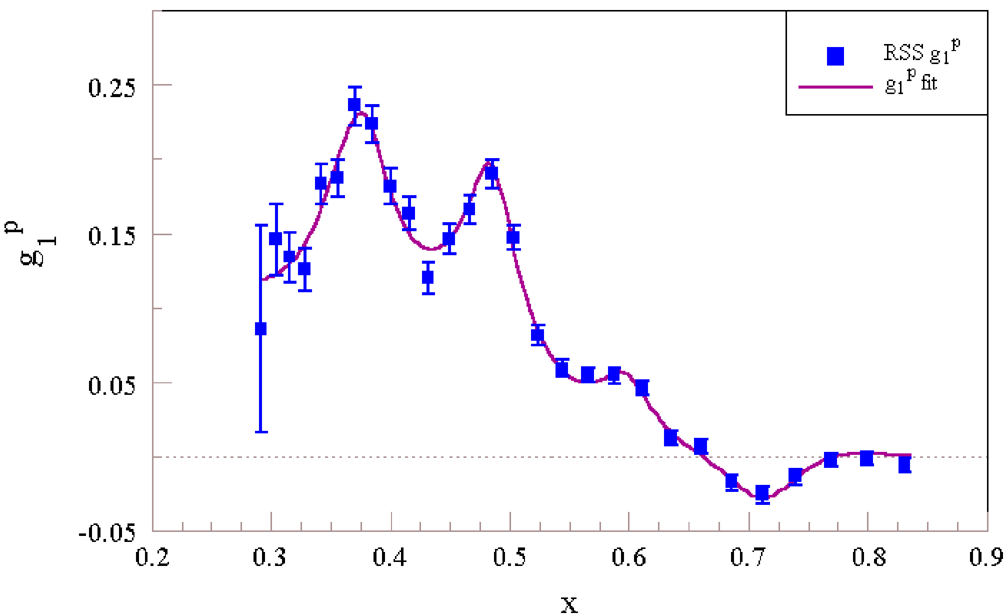
(Review of Particle Properties 2004)



- Quark spin (SLAC E155 global fit): $\sum q$ =0.229±0.041±0.057
- Quarks: only 23% of spin! What carries the remainder? ***gluons***? ***L***?

RSS Proton g_1 results in context

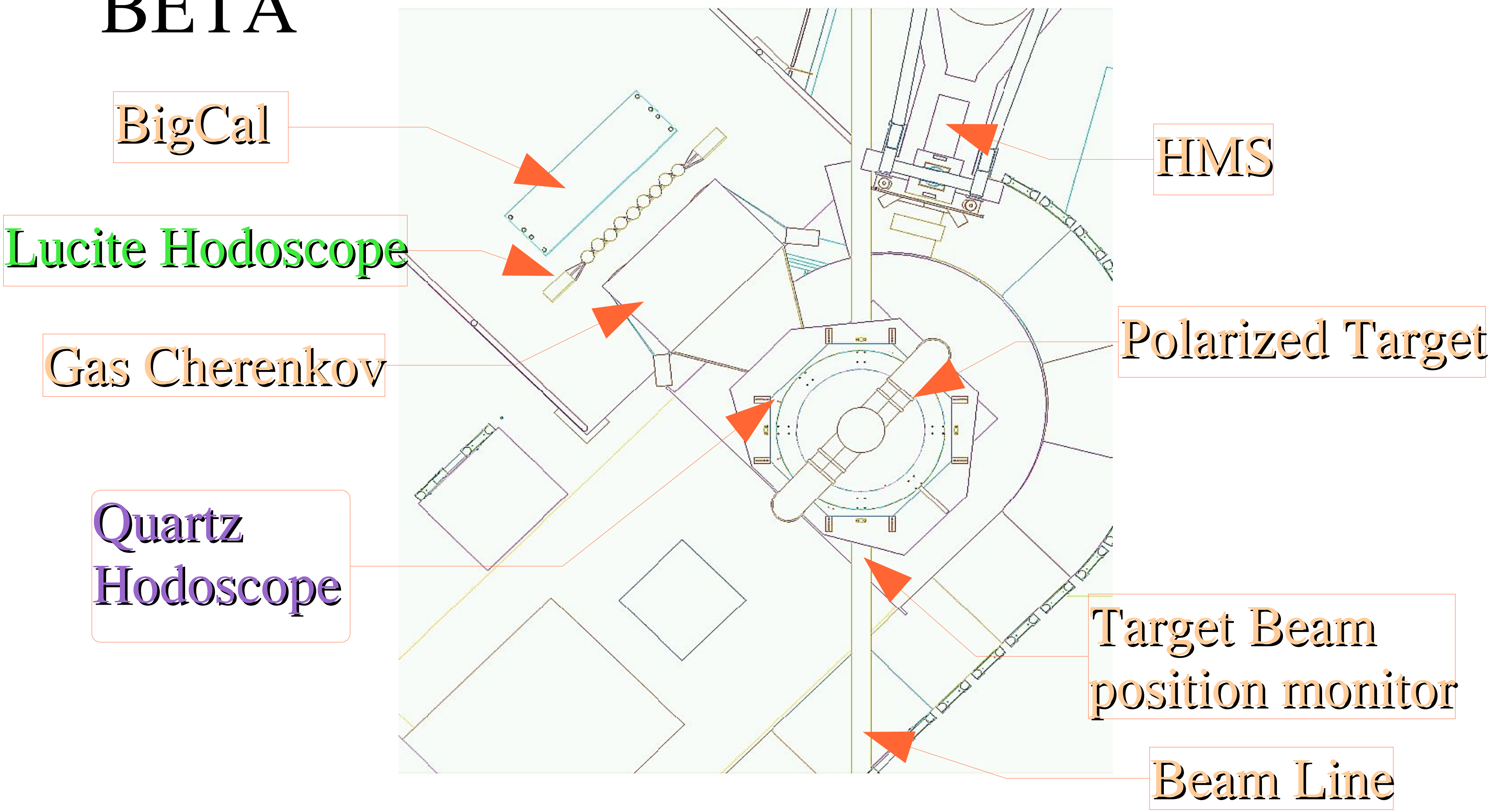




- *RSS* results should help improve SSF models
- Fit to A_1, A_2 gives excellent description of g_1

SANE Current Design (1/06)

BETA



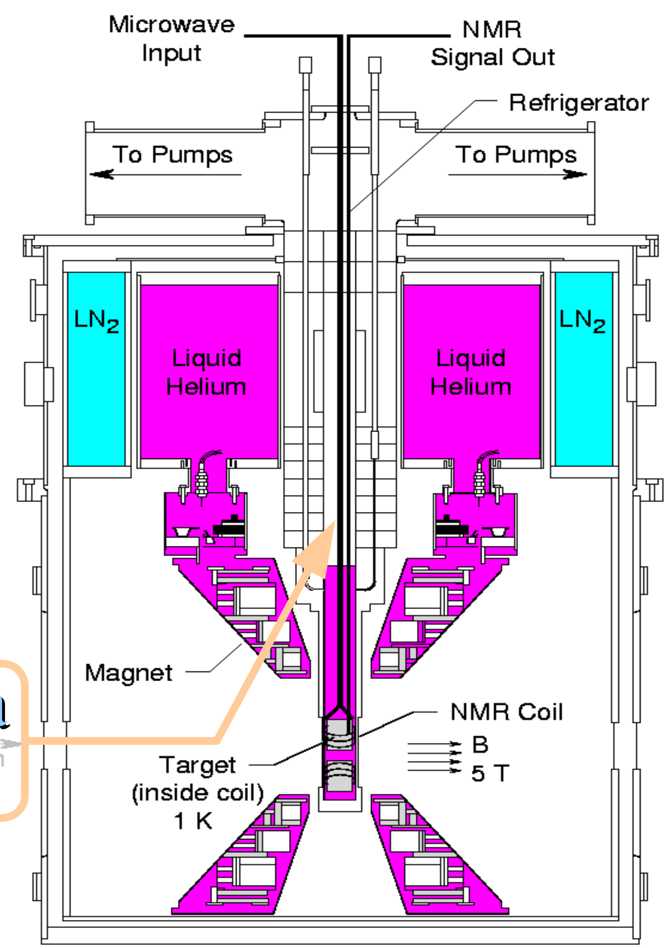
Measured asymmetries $A_\parallel$, $A_\perp$

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

$$\epsilon = (N^- - N^+)/(N^- + N^+)$$

- N^-, N^+ = charge normalized, dead time and pion corrected yields for +/- beam helicities
- P_b, P_t = beam, target polarizations
- $\boldsymbol{f}$ = dilution from N, He and others
- C_N, C_D = corrections for ^{15,14}N: proton $C_D = 0$, deuteron $C_N \simeq 1$
- A_{rc} = radiative correction

Ammonia + LHe



Measured asymmetries $A_{\parallel}$, $A_{\perp}$

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

$$\epsilon = (N^- - N^+)/(N^- + N^+)$$

- N^-, N^+ = charge normalized, dead time and pion corrected yields for +/- beam helicities
- P_b, P_t = beam, target polarizations
- f = dilution factor
- C_N, C_D = corrections for $^{15,14}N$: proton $C_D = 0$, deuteron $C_N \simeq 1$
- A_{rc} = radiative correction

- f = fraction of rate from polarized H, ^2H
  - Monte Carlo radiated rates
- Effective ammonia thickness (packing fraction) is cell specific - 8 cells total
  - obtained from data-MC comparison
  - packing fraction range: 0.52 - 0.61