Spin Physics Program
in Jefferson Lab Hall C

Oscar A. Rondón
University of Virginia

Users Group Meeting
Jefferson Lab
June 20, 2007
Hall C Spin Structure Program

- Spin Structure Functions at 6 GeV:
  - Inclusive measurements
    - SSF's in the Nucleon Resonances Region - RSS
    - Proton SSF at high Bjorken $x$ - SANE
    - Precision Deuteranion spin structure - $g_1^d/F_1^d$
  - Semi-inclusive measurements
    - Flavor Decomposition of Nucleon Spin - SemiSANE
- Real Polarized Photons:
  - Polarized Compton Scattering
- Current four experiments rated A or A-
- Future: Spin Structure Functions with 12 GeV upgrade
**RSS - Resonances Spin Structure**

Precision Measurement of the Nucleon Spin Structure Functions in the Region of the Nucleon Resonances

**TJNAF E01-006**


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 $Q^2 \approx 1.3 \text{ GeV}^2$ and $0.8 \leq W \leq 1.91 \text{ GeV}$
- Study $W$ dependence, onset of polarized local duality, twist-3 effects, using inclusive polarized scattering
## Resonances SSF Experiments

<table>
<thead>
<tr>
<th>Lab</th>
<th>Experiment</th>
<th>Target</th>
<th>(Q^2) [GeV/c]^2</th>
<th>Measured quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC</td>
<td>E143 (E80)</td>
<td>(\text{NH}_3) p(rotons) &amp; d(eutrons)</td>
<td>0.5 1.3</td>
<td>(A\parallel)</td>
</tr>
<tr>
<td>JLab</td>
<td>Hall A 94-010</td>
<td>(\text{He}^3)</td>
<td>0.1 to 0.9 (6 values)</td>
<td>(A\parallel, A\perp)</td>
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<tr>
<td>CLAS</td>
<td>eg1a-b</td>
<td>(\text{NH}_3) p &amp; d</td>
<td>0.2 to 5 (over 12 values)</td>
<td>(A\parallel)</td>
</tr>
<tr>
<td>Hall C</td>
<td>RSS</td>
<td>(\text{NH}_3) p &amp; d</td>
<td>1.3</td>
<td>(A\parallel, A\perp)</td>
</tr>
<tr>
<td>Hall A</td>
<td>01-012</td>
<td>(\text{He}^3)</td>
<td>~1. to ~4.</td>
<td>(A\parallel, A\perp)</td>
</tr>
</tbody>
</table>

- **RSS** is only complete spin structure experiment in the resonances:
  - proton and neutron (from deuteron)
  - parallel and perpendicular asymmetries
RSS Technique

- **Equipment: TJNAF Hall C**
  - CEBAF polarized electron beam
    - 2 cm diameter raster at target
    - $I = 85$-150 nA
  - Target: polarized ammonia $\text{NH}_3$, $\text{ND}_3$.
    - Luminosity $\sim 10^{35} \text{ s}^{-1} \text{cm}^{-2}$
  - HMS electron detector
- **Data run: Jan.-Feb. 2002**
  - 160 M proton triggers
  - 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
- $\langle Q^2 \rangle = 1.28 \text{ [GeV/c]}^2$
Measured asymmetries $A_{\parallel}$, $A_{\perp}$

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

$$\epsilon = \frac{N^- - N^+}{N^- + N^+}$$

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

<table>
<thead>
<tr>
<th>Polarization [%]</th>
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</thead>
<tbody>
<tr>
<td>$A_{\parallel}$</td>
</tr>
<tr>
<td>Moller - Beam</td>
</tr>
<tr>
<td>NMR - NH$_3$</td>
</tr>
<tr>
<td>NMR - ND$_3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proton Elastic</th>
<th>$G_E/G_M$ Sensitivity</th>
<th>Use</th>
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<tbody>
<tr>
<td>$A_{\parallel}$</td>
<td>Low</td>
<td>$P_b P_t$</td>
</tr>
<tr>
<td>$A_{\perp}$</td>
<td>High</td>
<td>$G_E/G_M$</td>
</tr>
</tbody>
</table>

PRC 74, 035201 (2006)
Measured asymmetries $A_\parallel$, $A_\perp$

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

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

- $N^-, N^+ = \text{charge normalized, dead time and pion corrected yields for +/- beam helicities}$
- $P_b, P_t = \text{beam, target polarizations}$
- $f = \text{dilution from N, He and others}$
- $C_N, C_D = \text{polarized nucleons in } ^{15,14}\text{N}$
  - proton $C_D = 0$, deuteron $C_N \approx 1$
- $A_{rc} = \text{radiative correction}$
Measured asymmetries $A_{\parallel}$, $A_{\perp}$

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$$\epsilon = \frac{N^- - N^+}{N^- + N^+}$$

- $N^-, N^+ = \text{charge normalized, dead time and pion corrected yields for +/- beam helicities}$

- $P_b, P_t = \text{beam, target polarizations}$

- $f = \text{dilution factor}$

- $C_N, C_D = \text{polarized nucleons in } ^{15,14}\text{N}$
  - proton $C_D = 0$, deuteron $C_N \approx 1$

- $A_{rc} = \text{radiative correction}$
Spin Asymmetries $A_1, A_2$

- Combine $A_{||}, A_{\perp}$ to get virtual Compton absorption asymmetries:

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

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

- $A_1, A_2$ have minimal model dependence
  - $D'(E,E',\theta,R)$ is function only of kinematics and $R = \sigma_L / \sigma_T$
    - Proton $R, F_1$ from E. Christy's fit to Hall C $e-p$ data
    - Deuteron $R, F_1$ from P. Bosted's fit to world 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 final results
  - PRL 98, 132003 (2007)

- Deuteron, neutron
  - in preparation
Proton 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 $g_2^p$

$$\bar{g}_2(x, Q^2) = g_2(x, Q^2) - g_2^{WW}(g_1(x, Q^2))$$
Bloom-Gilman Local Duality for $g_1^p$

- Integrate (at $\langle Q^2 \rangle = 1.28 \text{ GeV}^2$)
  - $g_1$ fit over $A_1$ fit resonances
  - $g_1$ from PDF's evolved to same $Q^2$ with target mass corrections
- Polarized (B-G) Local Duality:
  - ratio of integrals = 1

<table>
<thead>
<tr>
<th>RESONANCES</th>
<th>W LOW</th>
<th>W HIGH</th>
<th>AVERAGE</th>
<th>ERROR DATA</th>
<th>ERROR PDFS</th>
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<tbody>
<tr>
<td>DELTA</td>
<td>1.11</td>
<td>1.30</td>
<td>3.93</td>
<td>0.58</td>
<td>0.37</td>
</tr>
<tr>
<td>R1350</td>
<td>1.30</td>
<td>1.39</td>
<td>1.36</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>R2</td>
<td>1.39</td>
<td>1.68</td>
<td>0.78</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>R3</td>
<td>1.68</td>
<td>1.81</td>
<td>0.79</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>GLOBAL</td>
<td>1.08</td>
<td>1.91</td>
<td>1.17</td>
<td>0.08</td>
<td>0.06</td>
</tr>
</tbody>
</table>

- Only *approximate* Global Duality in RSS
  - Large $x$ resummations increase discrepancy by 1.3 (S. Liuti *et al.*)
Bloom-Gilman Local Duality for $g_1^p$

- Integrate (at $\langle Q^2 \rangle = 1.28$ 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 (B-G) Local Duality:
  - ratio of integrals = 1

![Graph showing integral ratios of polarized PDFs across different regions and $Q^2$ values.](image)

- Polarized global duality seems to work above $Q^2 \approx 1.8$ GeV$^2$

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<tr>
<th>Resonances</th>
<th>$W_{\text{LOW}}$</th>
<th>$W_{\text{HIGH}}$</th>
<th>Average</th>
<th>Error</th>
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<td>1.91</td>
<td>1.17</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Sum Rules (Proton)

- First moment of $g_1$ (extended GDH or Ellis-Jaffe sum rule)

$$\overline{F}_1(Q^2) = \int_0^{1-e\ell} g_1(x, Q^2) \, dx$$

$$= \frac{1}{36} \left( (a_8 + 3a_3) C_{NS} + 4a_0 C_S \right)$$

- First moment of $g_2$
  (Burkhardt-Cottingham)

$$\overline{\Gamma}_2(Q^2) = \int_0^1 g_2(x, Q^2) \, dx = 0$$
Twist-3 in $g_2^p$

- Third moment of $g_2$ is related by the OPE to twist-3 matrix element $d_2^c$ representing $q$-$g$ correlations

$$d_2^{\text{Cornwall-Norton}}(Q^2) = 3 \int_0^1 x^2 \overline{g}_2(x, Q^2) \, dx$$

$$= \int_0^1 x^2 (2 g_1(x, Q^2) + 3 g_2(x, Q^2)) \, dx$$

- At low $Q^2$ Nachtmann moments probe clean dynamic higher twists

$$d_2^{\text{Nachtmann}}(Q^2) = \int_0^1 \xi^2 \left( 2 \frac{\xi}{x} g_1(\xi, M^2) + 3 \left( 1 - \frac{\xi^2 M^2}{2 Q^2} \right) g_2(\xi, Q^2) \right) \, dx$$

S. Matsuda and T. Uematsu, NP B168 (1980) 181

**RSS measured** ($0.29 < x < 0.84$)

$$d_2^{\text{C-N}}(1.3 \text{ GeV}^2) = 0.0057 \pm 0.0011$$

(published)

$$d_2^{\text{Nachtmann}} = 0.0036 \pm 0.0006$$

(preliminary)
Neutron Spin Structure

- Extract neutron quantities from \( p \) and \( d \)
- Bodek-Ritchie version of Atwood-West smearing
  - generate smeared proton \( \Delta \sigma^s_\parallel, \Delta \sigma^s_\perp \) by convolution of \( G_1, G_2 \) with nucleon momentum distribution to get \( g^s_1, g^s_2 \)
  - subtract smeared proton from deuteron to get smeared neutron quantities
  - \( x \)-dependent D-state correction \( w_d(x) \)


\[
g^{n(s)}_{1,2}(x, Q^2) = \frac{g^d_{1,2}(x, Q^2)}{w_d(x)} - g^{p(s)}_{1,2}(x, Q^2)
\]
Neutron Spin Structure

- Extract neutron quantities from $p$ and $d$
- Bodek-Ritchie version of Atwood-West smearing
  - generate smeared proton $\Delta \sigma_s^\parallel, \Delta \sigma_s^\perp$ by convolution of $G_1, G_2$ with nucleon momentum distribution to get $g_1^s, g_2^s$
  - subtract smeared proton from deuteron to get smeared neutron quantities
  - $x$-dependent D-state correction $w_d(x)$


$$g_n^{n(s)}(x, Q^2) = \frac{g_1^d(x, Q^2)}{w_d(x)} - g_1^{p(s)}(x, Q^2)$$
Outlook

- Two publications, two more in preparation:
  - Deuteron and neutron spin structure
  - Complete set of sum rules for both nucleons:
    - first moment of $g_1$: extended GDH and Ellis-Jaffe
    - first moment of $g_2$: Burkhardt-Cottingham
    - third moments of $g_2$: twist-3
    - combined $p$ and $n$ first moments
      - non-singlet: Bjorken
      - singlet: deuteron
    - combined $p$ and $n$ $g_{1,2}$ second moment:
      - Efremov-Leader-Teryaev (valence quarks)
Credits

Analysis Team
- Karl Slifer
- Shigeyuki Tajima
- Frank Wesselmann
- Peter Bosted
- Eric Christy
- Paul McKee
- Hongguo Zhu
- Mark Jones
- Oscar Rondon

Special Thanks
- Don Crabb
- Donal Day
- Mahbub Khandaker
- Hamlet Mkrtchyan
- JLab Hall C
- JLab Target group
SANE
Spin Asymmetries on the Nucleon Experiment
(TJNAF E07-003)

SANE Collaboration
U. Basel, C. Newport U., Florida International U., Hampton U.,
Norfolk S. U., North Carolina A&T S. U., IHEP-Protvino, U. of Regina,
Rensselaer Polytechnic I., Rutgers U., Seoul National U., 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)

- Measure proton spin structure function \( g_2(x, Q^2) \) and spin asymmetry \( A_1(x, Q^2) \) for \( 2.5 \leq Q^2 \leq 6.5 \text{ GeV}^2 \) and \( 0.3 \leq x \leq 0.8 \)

- **SANE meets DOE 2011 Milestone for Proton Spin Structure**
SANE Physics

- Goal is to learn all we can about proton SSF's from an inclusive double polarization measurement:
  - twist-3 effects from moments of $g_2$ and $g_1$
  - comparisons with Lattice QCD, QCD sum rules, bag models, chiral quarks
  - Study $x$ dependence (test nucleon models) and $Q^2$ dependence (evolution)
  - Exploration of "high" $x$ region: $A_1$'s approach to $x = 1$
  - Test polarized local duality for final state mass $W > 1.4$ GeV

- Method:
  - Measure inclusive spin asymmetries for two orientations of target spin relative to beam helicity (anti-parallel and near-perpendicular)
  - Detect electrons with novel large solid angle electron telescope BETA
SANE Expected Results

\[
\int_{x_{\text{min}}}^{x_{\text{max}}} x^2 (2g_1 + 3g_2) \, dx
\]

- SANE expected errors for \( \bar{d}_2 = \int_{x_{\text{min}}}^{x_{\text{max}}} x^2 (2g_1 + 3g_2) \, dx \)
  
  - \( \delta \bar{d}_2 (Q^2 = 3 \text{ GeV}^2) = 7 \times 10^{-4}, \quad 0.29 < x < 0.85 \)
  
  - \( \delta \bar{d}_2 (3.5 \text{ to } 6.5 \text{ GeV}^2) = 2 \times 10^{-4}, \quad 0.41 < x < 0.96 \)
SANE Expected Results

- SANE expected errors for $\overline{d}_2 = \int_{x_{\text{min}}}^{x_{\text{max}}} x^2 (2g_1 + 3g_2) dx$
  
  - $\delta d_2 (Q^2 = 3 \text{ GeV}^2) = 7\times10^{-4}, \quad 0.29 < x < 0.85$
  
  - $\delta d_2 (3.5 \text{ to } 6.5 \text{ GeV}^2) = 2\times10^{-4}, \quad 0.41 < x < 0.96$
SANE Expected Results (Ia)
SANE Expected Results (II)

- $x$ dependence at constant $Q^2$ and $Q^2$ dependence at fixed $x$ (illustrative binning)
- data are concentrated in the region most sensitive to $x^2g_{2,1}$
  - (estimates based on 75% beam and target polarization and 85 nA beam current)
Constrain extrapolations of $A_1^p$ to $x = 1$ within +/- 0.1 (using duality)

Both $A_\parallel$ and $A_\perp$ are required to get accurate, model-free $A_1$: $A_2 > 0$

SANE's measured $A_2$ will contribute to improve world's $A_1$ data set
World data on $A_{\parallel}$, $A_{\perp}$ and SANE kinematics

- Two beam energies: 6 GeV, 4.8 GeV
- Very good high $x$ coverage with detector at 40°
Big Electron Telescope Array - BETA

- **BigCal** lead glass calorimeter: main detector, being built for *GEp-III*.
- **Gas Cherenkov**: additional pion rejection
- Tracking **Lucite hodoscope**
- Tracking fiber-on-scintillator **forward hodoscope**
- BETA's characteristics
  - Effective solid angle = 0.194 sr
  - Energy resolution 5%/√*E*(GeV)
  - 1000:1 pion rejection
  - vertex resolution ~ 5 mm
  - angular resolution ~ 1 mr
- Target field sweeps low $E'$ background

(Artist view of Reference design)
# Beam Time

## PAC31 "A" rating

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<thead>
<tr>
<th>Energy</th>
<th>$\theta_N$</th>
<th>Time (h)</th>
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<tbody>
<tr>
<td>Calibration</td>
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<td>off, 0, 180</td>
</tr>
<tr>
<td>Production</td>
<td>4.8</td>
<td>180</td>
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<tr>
<td></td>
<td>4.8</td>
<td>80</td>
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<td></td>
<td>6.0</td>
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<td></td>
<td>6.0</td>
<td>180</td>
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<td>Systematics</td>
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<td>Mollers</td>
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<td></td>
<td>Total beam time</td>
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## Overhead

<table>
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<th>Time (h)</th>
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<td>Anneals</td>
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</tr>
<tr>
<td>Energy Change</td>
<td>48</td>
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<tr>
<td>Target Rotation</td>
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<tr>
<td>Stick Changes</td>
<td>48</td>
</tr>
<tr>
<td>Total Overhead</td>
<td>206</td>
</tr>
</tbody>
</table>

## Commissioning

14 calendar days

## Total

70 calendar days
SANE Membership

J. Jourdan, M. Kotulla
University of Basel, Basel, Switzerland

E. Brash, E. Jensen, A. Marsh
Christopher Newport University, Newport News, VA

W. Boeglin, S. Dhamija, P. Markowitz, J. Reinhold
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Byungwuk Lee, Yoomin Oh, Jeongseog Song
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Yerevan Physics Institute, Yerevan, Armenia
SANE Status

- Submitted Beam Request on 9/14/06
- Hall C schedule: SANE tentatively to start in 7/2008
- Readiness review in July 2007

SUMMARY
Steady progress over 3+ years
SANE is pioneering spin physics with large non-magnetic detectors
A High Precision Measurement of the Deuteron Spin Structure Function $g_1^d/F_1^d$

TJNAF E07-011

Spokespersons: P. Bosted (JLab), F. Wesselmann (Norfolk), X. Jiang (Rutgers)

• Make definitive measurement of deuteron spin structure function $g_1^d/F_1^d(x,Q^2)$ in DIS kinematics with a 6 GeV beam
• Goal is to provide anchor points to NLO pQCD with higher twist corrections fit to extract the gluon polarization $\Delta g(x)$
• Also, test nuclear effects on spin structure with ND$_3$ and $^6$LiD targets
Method and Sample of Expected Results

- Fit pQCD evolution in $Q^2$ of $g_1^d(x, Q^2)$ data to extract polarized quark and gluon distributions
  - $1 < Q^2 < 5$ GeV$^2$ and $0.15 < x < 0.6$ with BETA at 30° and 6 GeV beam
  - low $Q^2$ medium $x$ data with HMS, 4.8 GeV
  - $A_{||}$ data taken in part during SemiSANE
- Test nuclear effects on deuteron spin structure comparing $^3$ND vs $^6$LiD data (spin "EMC" effect)
- Approved for 8 days plus SemiSANE time on deuterium, with A rating
Method and Sample of Expected Results

- Fit pQCD evolution in $Q^2$ of $g_1^d(x, Q^2)$ data to extract polarized quark and gluon distributions
  - $1 < Q^2 < 5$ GeV$^2$ and $0.15 < x < 0.6$ with BETA at $30^\circ$ and 6 GeV beam
  - low $Q^2$ medium $x$ data with HMS, 4.8 GeV
  - A$_||$ data taken in part during SemiSANE
- Test nuclear effects on deuteron spin structure comparing ND$_3$ vs $^6$LiD data (spin "EMC" effect)
- Approved for 8 days plus SemiSANE time on deuterium, with A rating
SemiSANE
Flavor Decomposition of Nucleon Spin

TJNAF E04-113

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

• Measure **proton** and **deuteron** semi-inclusive spin asymmetries in polarized DIS reactions $p(e,e'h)$ and $d(e,e'h)$: **Semi-SANE**
  
  - $h = \pi^+\cdot\cdot, K^+\cdot\cdot, 1.2 \leq Q^2 \leq 3.2 \text{ GeV}^2, 0.12 \leq x \leq 0.43,$ for hadrons with $0.5 \leq z \leq 0.7$
  
  - Extract the $\Delta u, \Delta d, \Delta s$, and anti-quark spin components

• Detect electrons with BigCal at 30° and hadrons with HMS
Method and Sample of Expected Results

- Form $A_{1N}^{\pi^+ - \pi^-}$ to get valence quark helicities (Leader-Christova LO and NLO methods)
  - combine with inclusive data to probe polarized light sea flavor asymmetry
  - three other LO and one NLO methods
- Compare $A_{1N}^{\pi^+ + \pi^-}$ with inclusive result to test factorization
- Expected results for the $u$ and $d$ flavor asymmetries several times more precise than current world data
- Approved for 25 days with A- rating
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**RSS Fit to the SA's**

- Four Breit-Wigner resonance shapes plus DIS background
- Fit $A_1$ and $A_2$ independently
- Reduced $\chi^2 = 1.2 - 1.4$ for 12 d.o.f.
Beyond Inclusive Scattering

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

- Spin Dependent Fragmentation: Semi-Inclusive Leptoproduction
  - Detect hadron ($\pi, \mathrm{K},..$)-lepton in coincidence
  - Semi-inclusive Asymmetry

\[ A_h^h(x, z, Q^2) = \frac{\sum e_f^2 \Delta q_f(x, Q^2) D_f^h(z, Q^2)}{\sum e_f^2 q_f(x, Q^2) D_f^h(z, Q^2)} \bigg|_{z=E_h/\nu} \]

- Spin Dependent Exclusive Scattering: Generalized Parton Distributions