Spin Asymmetries of the Nucleon Experiment
An Update

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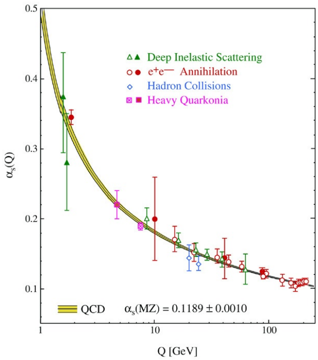
Outline

Outline

The Strong Force

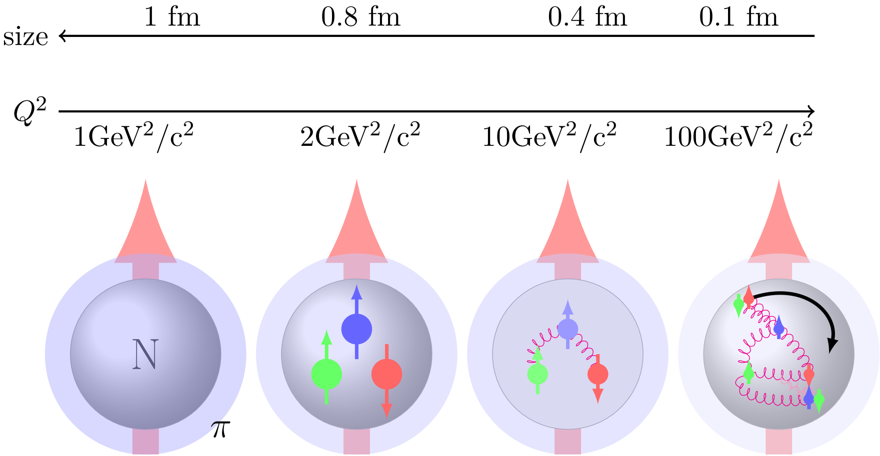
Quantum Chromodynamics

- $L_{QCD} = \bar{\psi}(i\not{D} - m)\psi - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$
- The degrees of freedom are the QCD quark and gluon fields, **not the constituent quarks!**
- The QCD coupling constant α_s is a function of Q^2.
- Asymptotic freedom → 2004 Nobel prize (Gross,Wilczek,Politzer)
- Many successful predictions from pQCD at high energies.



QCD is believed to be the correct theory of the strong force.
QCD should be able to describe the structure of the proton and neutron.
However, perturbative techniques cannot describe the complex bound state of quark and gluon fields composing the proton.

What does the nucleon look like?



Use our understanding of pQCD at high Q^2 to begin to test our understanding at lower $Q^2 \rightarrow$ Operator Product Expansion

Deep Inelastic Scattering

$$\sigma_0 = \frac{4\alpha^2 E'^2}{q^4}\left[\frac{2}{M}F_1 \sin^2(\theta/2) + \frac{1}{\nu}F_2 \cos^2(\theta/2)\right]$$

$$2\sigma_0 A_{\parallel} = -\frac{4\alpha^2}{Q^2}\frac{E'}{E}\left[\frac{E + E'\cos\theta}{M\nu}g_1 - \frac{Q^2}{M\nu^2}g_2\right]$$

$$2\sigma_0 A_{\perp} = -\frac{4\alpha^2}{MQ^2}\frac{E'^2}{E}\sin\theta\cos\phi\left[\frac{1}{M\nu}g_1 + \frac{2E}{M\nu^2}g_2\right]$$

Structure Functions

$$F_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2\ q_i(x,Q^2)$$

$$F_2(x,Q^2) = 2xF_1(x,Q^2)$$

$$g_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2\ \Delta q_i(x,Q^2)$$

$$g_2(x,Q^2) = ?$$

Asymmetries

$$A_{\parallel} = \frac{\sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}}{\sigma^{\Uparrow\downarrow} + \sigma^{\Uparrow\uparrow}}$$

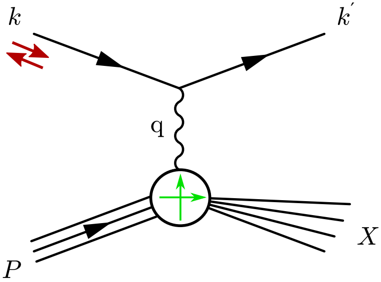
$$A_{\perp} = \frac{\sigma^{\Leftarrow\downarrow} - \sigma^{\Leftarrow\uparrow}}{\sigma^{\Leftarrow\downarrow} + \sigma^{\Leftarrow\uparrow}}$$

$$x = Q^2/(2M\nu)$$

$$\nu = E - E'$$

$$W_X^2 = M^2 + 2M\nu - Q^2$$

$$Q^2 = -q^2 = 4EE'\sin^2(\theta/2)$$



Why is a transversely polarized target needed?

$$A_{\parallel} \propto g_1 - \frac{2Mx}{\nu}g_2$$

$\rightarrow$ g_2 suppressed by $1/\nu$

$$A_{\perp} \propto g_1 + g_2$$

$\rightarrow$ In DIS region both contribute.

$\Rightarrow$ $A_{\perp}$ **directly sensitive to non-perturbative effects!**

The dynamical twist-3 matrix element: d_2

$$\int_0^1 dx x^{n-1}\{g_1 + \frac{n}{n-1} g_2\} = \frac{1}{2} d_{n-1} E_2^n(Q^2, g)$$

For $n = 3$ $$\int_0^1 x^2\{2g_1 + 3g_2\}dx = d_2$$

Interpretations of d_2

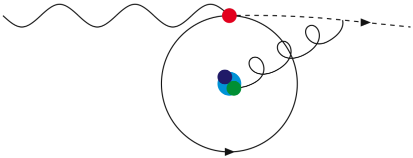
- Color Polarizabilities (X.Ji 95, E. Stein et al. 95)
- **Average Color Lorentz force** (M.Burkardt)

M. Burkardt Phys.Rev.D 88,114502 (2013)Âăand Nucl.Phys.AÂă735,185Âă(2004).

$$d_2 = \frac{1}{2MP^{+2}S^x}\langle P, S \mid \bar{q}(0) g G^{+y}(0)\gamma^+ q(0) \mid P, S\rangle$$

but with $\vec{v} = -c\hat{z}$

$$\sqrt{2}G^{+y} = -E^y + B^x = -(\vec{E} + \vec{v}\times\vec{B})^y$$

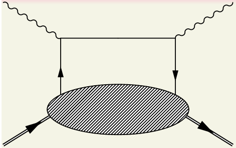


$d_2 \Rightarrow$ average color Lorentz force acting on quark moving backwards (since we are in inf. mom. frame) the instant after being struck by the virtual photon.

$\langle F^y\rangle = -2M^2 d_2$

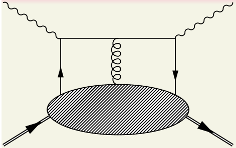
Quark-gluon Correlations : $g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$

Twist-2 (Wandzura, Wilczek, 1977)



$$g_2^{WW}(x,Q^2) = -g_1^{LT}(x,Q^2) + \int_x^1 g_1^{LT}(y,Q^2)\mathrm{d}y/y$$
$$\equiv g_2^{tw2}(x,Q^2)$$

Twist-3 (Cortes, Pire, Ralston, 1992)



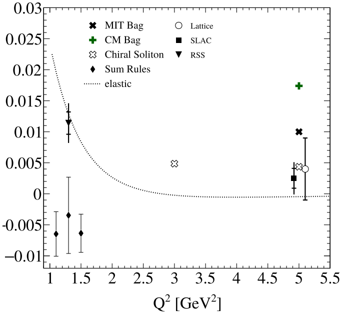
$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left(\frac{m_q}{M}h_T(y,Q^2) + \xi(y,Q^2)\right)\frac{dy}{y}$$
$$\equiv g_2^{tw3}(x,Q^2)$$

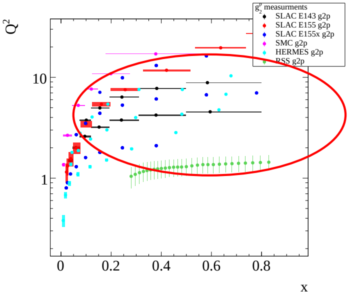
$$d_2(Q^2) = 3\int_0^1 x^2 \bar{g}_2(x,Q^2)dx$$
$$= \int_0^1 x^2(2g_1(x,Q^2) + 3g_2(x,Q^2))dx$$

As Q^2 decreases,
when do higher twists begin to matter?
When is the color force non-zero?

$d_2(Q^2) = 3\int^1 x^2 \bar{g}_2(x,Q^2)dx$

Predictions and previous measurements of d_2





Lattice QCD

- Ab initio calculations can be done on the lattice
- Existing d_2 lattice results in the quenched approximation (PRD.63.074506)
- Proton results agree with SLAC but neutron results do not.
- Updated and improved lattice results long overdue

Physics with g_2

- Polarized DIS is uniquely poised to provide insight into quark-gluon correlations.
- Direct access to higher twist using transversely polarized target.
- Twist-3 matrix element d_2^p proprotional to an average Lorentz color force.
- Ab initio QCD calculations from the lattice are tested
- $\bar{g}_2$ and d_2 connected to quark OAM
- JLab provides best opportunity to explore valence region

Precision measurments of g_1 and g_2 at JLab provide great insight into the non-perturbative structure of the nucleon and test our understanding of QCD

Important starting point for Nucleon Tomography

- Extraction of $\bar{g}_2$ is clean (free of non-local effects, fragmentation functions).
- Higher twist distribution $\bar{g}_2$ provides important boundary condition for HT GPDs
- Quark OAM calculated from Higher twist GPDs
- First point in Qui-Sterman M.E. found in SIDIS

Outline

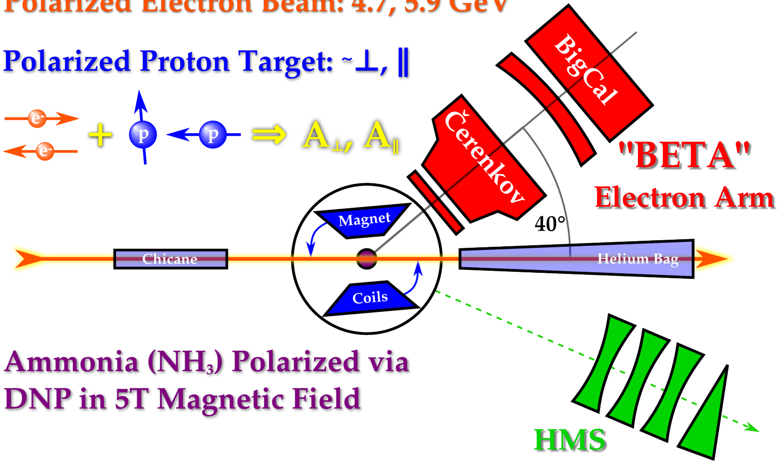
E07-003 : Spin Asymmetries of the Nucleon Experiment

Spokespeople

S. Choi, M. Jones, Z.-E. Meziani, O.A. Rondon

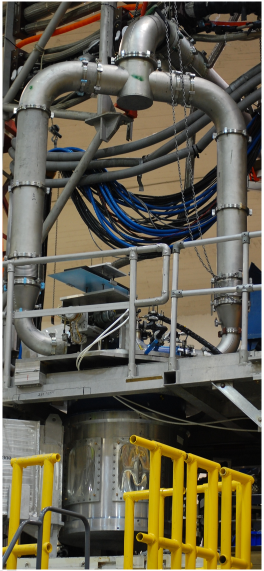
Polarized Electron Beam: 4.7, 5.9 GeV

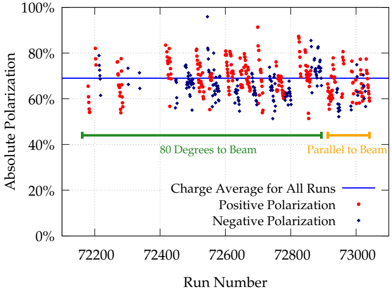
Polarized Proton Target: ~⊥, ∥

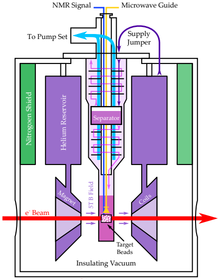


Ammonia (NH_3) Polarized via DNP in 5T Magnetic Field

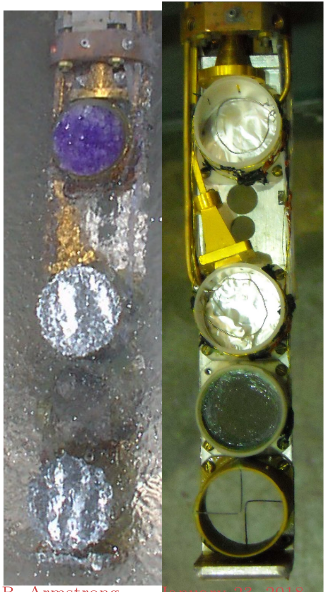
E07-003 : Polarized Ammonia Target



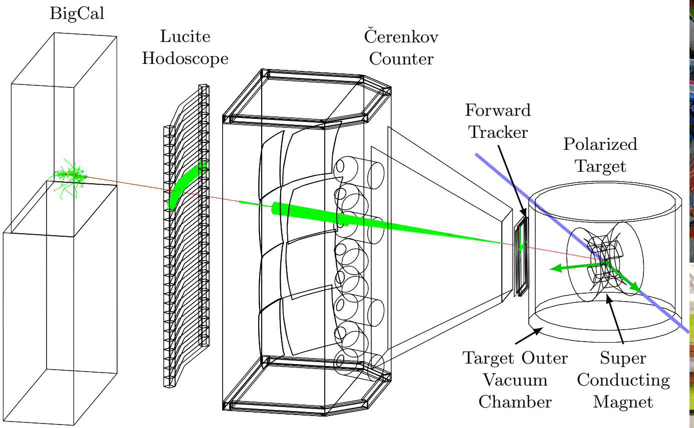


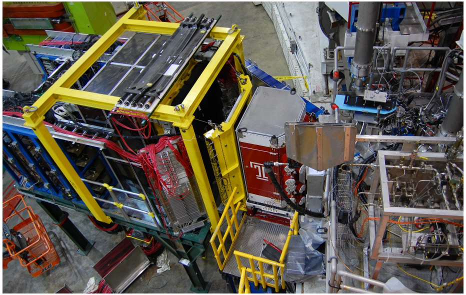


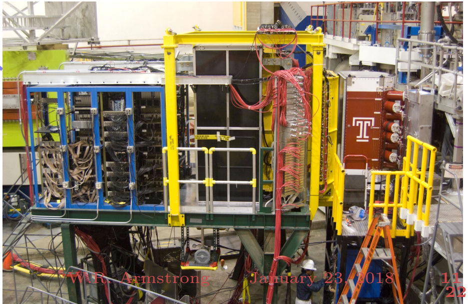
- 5.1 T magnetic field
- Ammonia beads held by a cup, placed in LHe
- Average polarization was about 69%



E07-003 : Big Electron Telescope Array

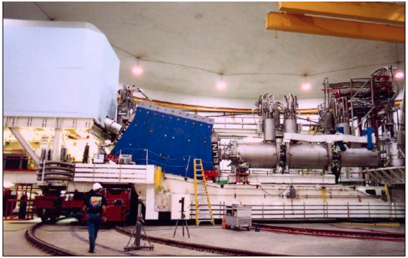


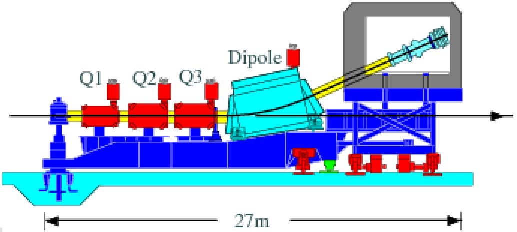


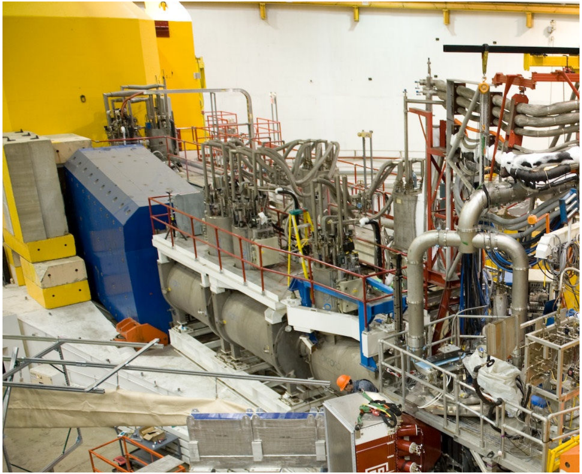


E07-003 : Spin Asymmetries of the Nucleon Experiment

HMS data taken as well for resonance spin structure (Hoyoung Kang) and G_E/G_M (Anusha Liyanage)

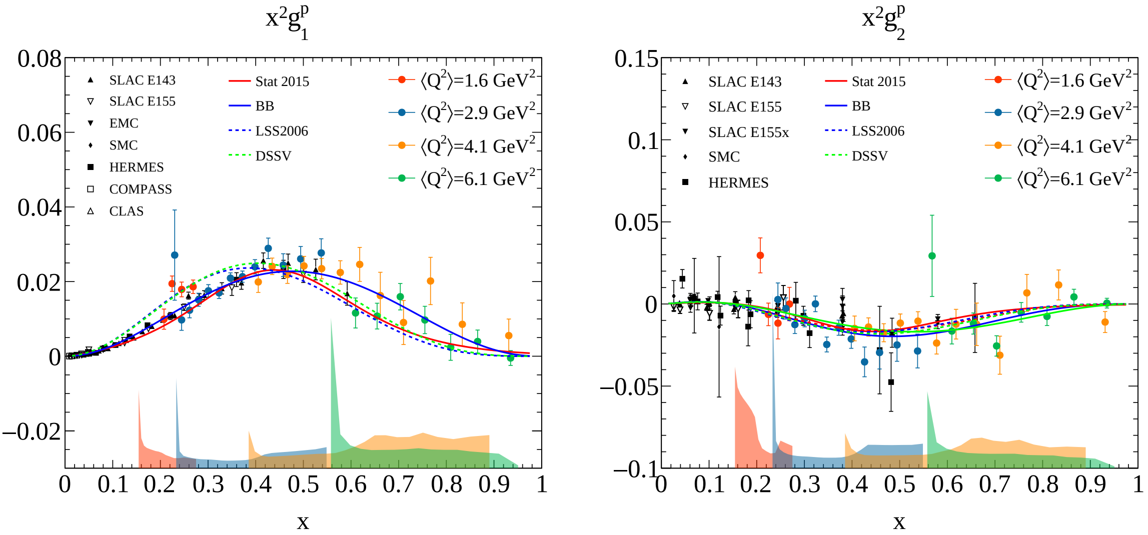


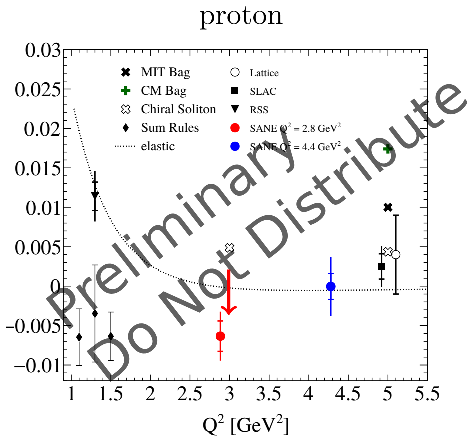


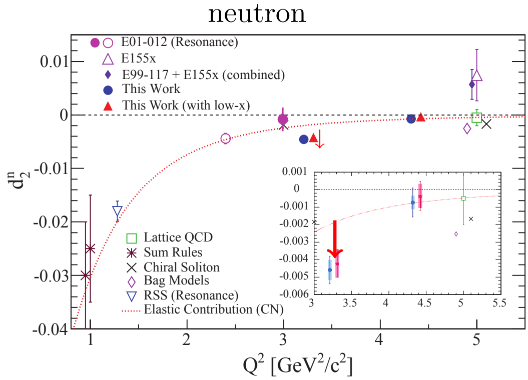


Outline

SANE results for $x^2 g_1^p$ and $x^2 g_2^p$





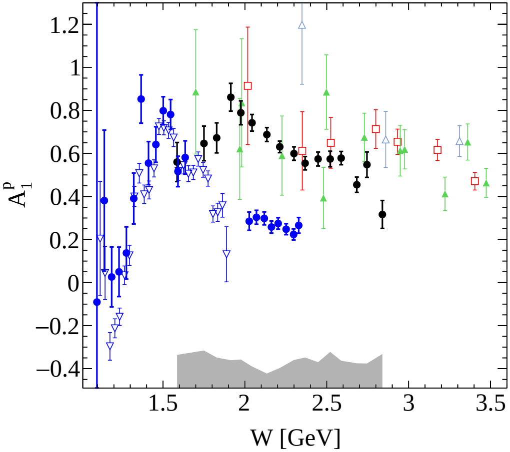


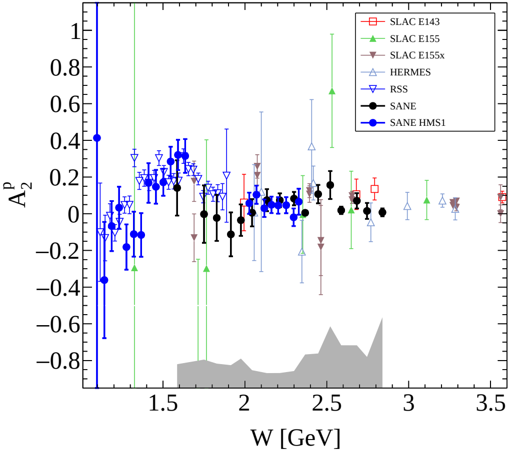
Neutron from d_2^n experiment: M.Posik, et.al. PRL.113(2014) and D.Flay, et.al. PRD.94(2016)no.5,052003

Existing dataSANE and d_2^n Result

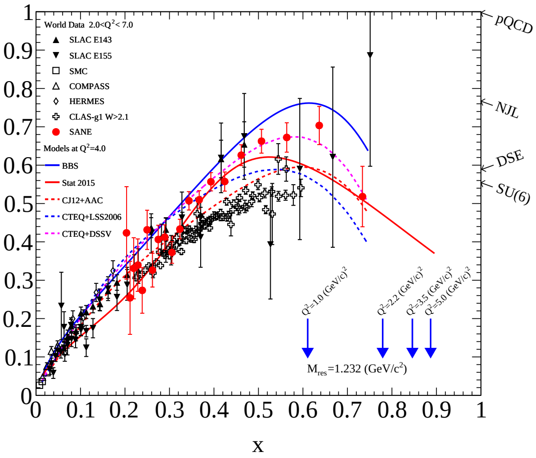
- d_2 dips around $Q^2 \sim 3$ GeV^2 for proton and neutron
- Is this an isospin independent average color force?
- Updated Lattice calculations are long over due!

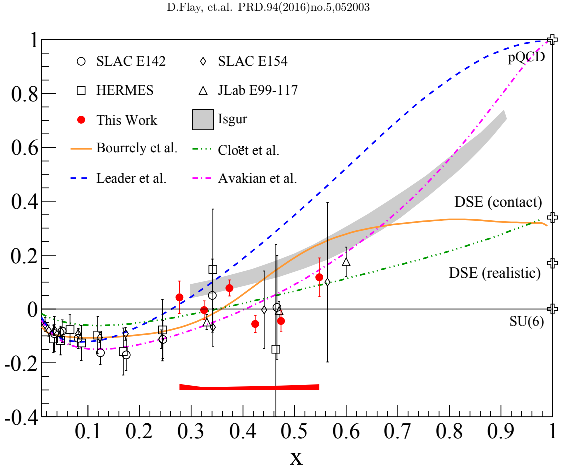
Virtual Compton Scattering Asymmetries





Valence domain: A_1 at high x





- A_1 as x→ 1
- CLAS data. Note: only the combination $A_1 + \eta A_2$ is measured by CLAS.
- Many predictions from models and fits
- Dyson-Schwinger Equations (DSE) $x = 1$ predictions (Roberts, Holt, Schmidt)
- SANE data goes out to x≃0.8 → use duality to check limit

Outline

SANE Publications and Manuscripts

Instrumentation Papers:

- J.D. Maxwell, et.al., *Design and Performance of the Spin Asymmetries of the Nucleon Experiment* Nucl.Instrum.Meth. A885 (2018) 145-159
- W.R. Armstrong, et.al., *A threshold gas Cherenkov detector for the Spin Asymmetries of the Nucleon Experiment* Nucl.Instrum.Meth. A804 (2015) 118-126

Manuscripts in the works

- d_2^p Paper (to be circulated for comments soon)
- Resonance spin structure functions
- A_1 at large x
- Elastic FF Ratio

SANE Analysis Archive and Data Management Plan

A quick look at Data Management Plan for: Hall-C and it is clear the main items are:

1. Raw and Processed Data
2. Run Conditions, databases, Log Books
3. Calibration and Geometry databases
4. Analysis software source code and build systems (started here)
5. Documentation

Use containerization to archive everything possible to easily re-deploy later

A new approach

- (1) is assumed to be responsibility of JLab IT division.
- (2) and (3) can be easily containerized and deployed with any analysis (see example).
- (4) is an image containing the full software stack (done).
- (5) presents SANE a nice possibility to archive the SANE wiki (which stands alone)

`https://hallcweb.jlab.org/experiments/sane/wiki/index.php/Main_Page`

Data and analysis archiving with containers

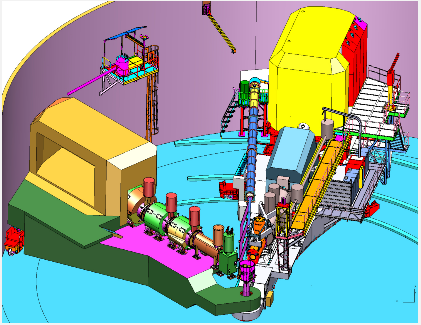
- All reconstruction/analysis software provided by `docker/singularity` images
- All binaries and source codes come with container
- All databases and documentation from service container
- **Maintain only data storage and container registry** (not a big list of stuff)

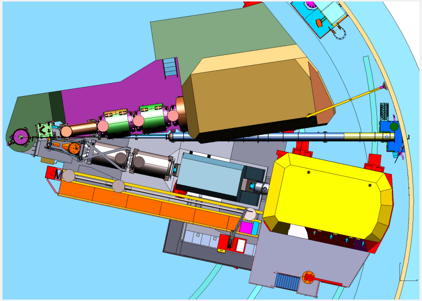
```
$> singularity pull docker://whit2333/insane:latest  #get main image
$> singularity pull docker://whit2333/sane_db:latest #get database
$> singularity instance.start sane_db.simg sane_db #launches MySQL service
$> singularity instance.list
DAEMON NAME      PID      CONTAINER IMAGE
sane_db          11138    /home/user/sane_db.simg
$> ./insane.simg  #run main container
@singularity$> ls /opt  #running img
sane08  saneuser
@singularity$> ls /opt/saneuser/
bin  README.md  sane08  saneuser.bashrc  setup.sh
@singularity$> ls /opt/sane08/
Analyzer_new  BETAG4  insane  InSANE  Linux  sane_replay
@singularity$> cat /etc/issue  #image built on ubuntu
Ubuntu 17.10
```

Jlab at 12 GeV

- JLab 12GeV neutron experiments (Hall C and Hall A) will extend to higher Q^2 with more uniform coverage.
- A dedicated experiment with transversely polarized proton target is worthwhile effort at 12 GeV.
- Proposal to match the expected neutron precision, possible options: Hall C, SOLID, CLAS12
- High x and high Q^2 data on g_1 **and** g_2 is needed to **cleanly** extract the leading twist PDFs $\rightarrow$ At present many fits use data down to $Q^2 = 1\text{GeV}^2$!
- While a future EIC will mainly focus on the **sea** quarks and gluons, JLab will continue to present a unique opportunity for studying QCD and the structure of the nucleon to high precision in the **valence region**.

SHMS in Hall C





Outline

Summary

- SANE results *significantly* improve world data on g_2^p and g_1^p
- d_2^p and d_2^n result seems to indicated a negative or zero value around $Q^2 \sim 3-6$ GeV^2 at the one standard deviation level, consistent with the neutron result.
- *Precision* g_2 measurements are important for future unraveling PDFs, TMDs, and GPDs.
- Working on archiving and preserving data for the future use.

Thank You!

Backup Slides

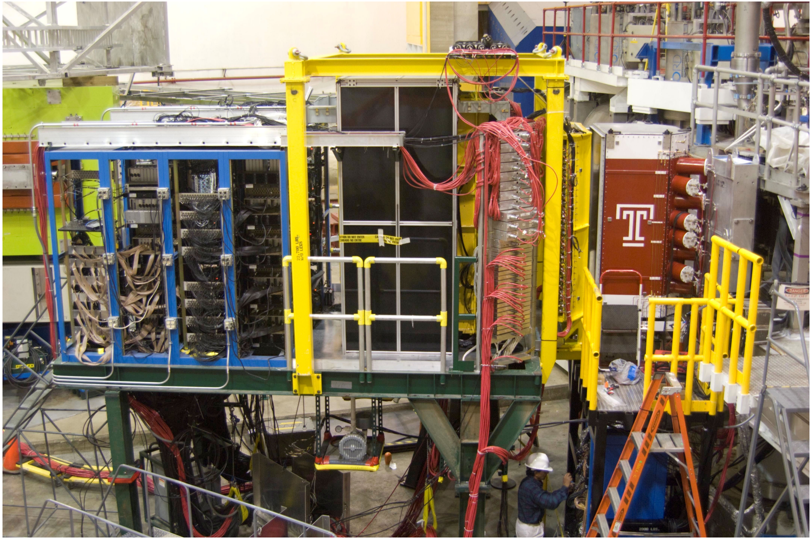
Data and analysis archiving with containers

Using SANE wiki container to browse documentation

```
# an idea for how the wiki can be examined later
$> singularity pull docker://whit2333/sane_wiki:latest #get main image
$> singularity instance.start sane_wiki.simg wiki #launches MySQL service
    and http server
# Open browser to
    https://localhost:8080/experiments/sane/wiki/index.php/Main_Page
```

- All reconstruction/analysis software provided by `docker/singularity` images
- All binaries and source codes come with container
- `MySQL` database runs in service container

Big Electron Telescope Array



SANE used BETA to detect inclusive electrons with a large acceptance at angles around

BigCal

Two Sections

The upper section from Yerevan Physics Institute used during RCS experiment.

- It consists of $4 \times 4 \times 40cm^3$ lead-glass blocks
- They are arranged in a 30×24 array

Lower section from IHEP in Protvino, Russia.

- It consists of $3.8 \times 3.8 \times 45cm^3$ lead-glass blocks
- They are arranged in 32×32 array

1,744 lead glass blocks total.

Figure: Bigcal lead-glass blocks

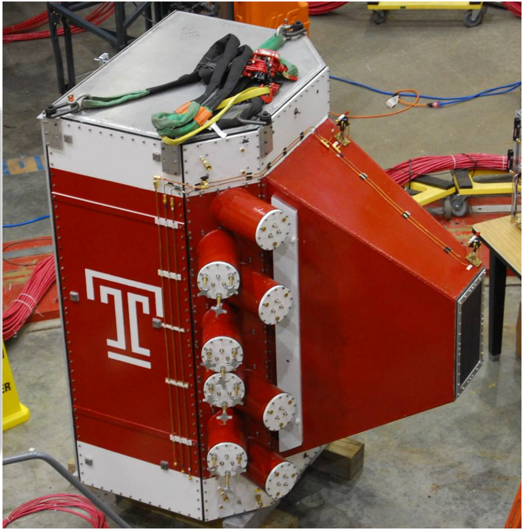
Bigcal was previously used in the GEp series of experiments

SANE Gas Cherenkov

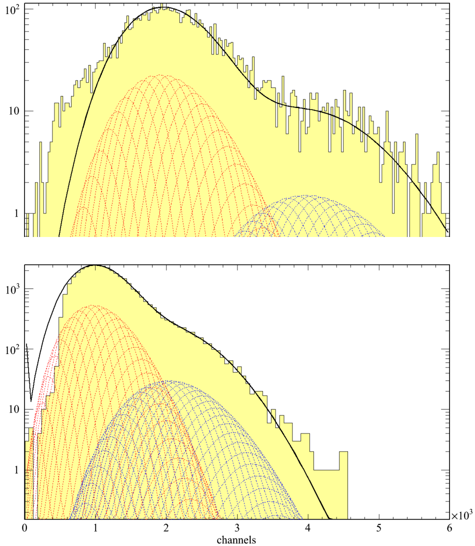
Gas Cherenkov is from Temple University.

Design

- Filled with nitrogen gas at atmosphere.
- Uses 4 spherical and 4 toroidal mirrors to focus light to photomultiplier tubes.
- Used 3 inch quartz window Photonis PMTs for UV transparency
- Mirror blanks were sent to CERN for special coating for high reflectivity far into the UV.



Cherenkov ADCs



- PMT 5
- Spherical mirrors at large scattering angle.

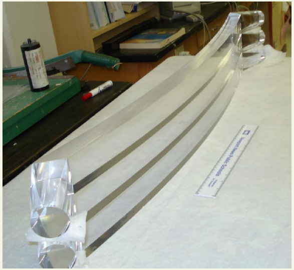
- PMT 4
- Toroidal mirror at small scattering angle.

Lucite Hodoscope

Lucite Hodoscope is from North Carolina A&T State University.

Design

- 28 curved Lucite bars with light guides mounted to edges cut at 45°
- PMT with light guide mounted at both ends of each bar.



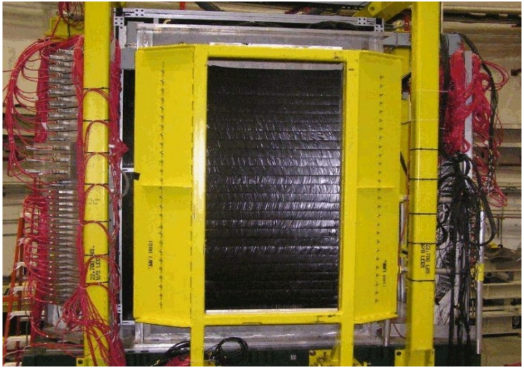


Figure: Lucite Hodoscope in Hall C

Forward Tracker

Forward tracker is from Norfolk State University and University of Regina

Design

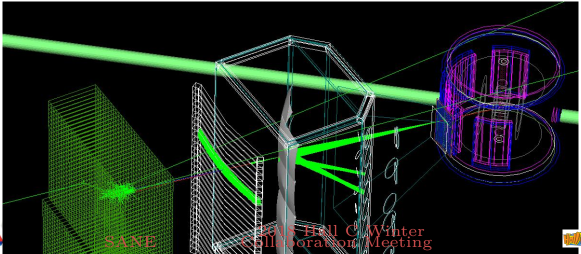
- 3 layers of 3×3 mm^2 scintillators.
- 1 horizontally segmented layer closest to the target consisting of 72 segments
- 2 vertically segmented layers consisting of 128 segments each
- WLS fibers glued to each bar with fibers connected to Hamamatsu 64-Channel PMTs

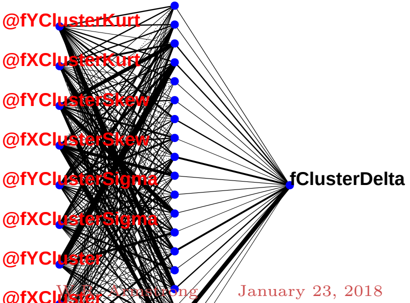
Figure: Forward tracker in position

Neural Network Reconstruction

Three Neural Networks

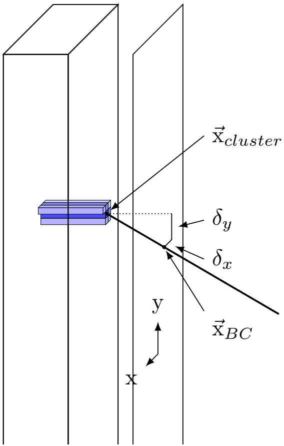
1. Cluster position correction
   - Corrects cluster postion X-Y position
2. Track deflection correction
   - Returns scattering angles at the target
3. Track momentum vector correction
   - Corrections for the momentum vector at the face of BigCal



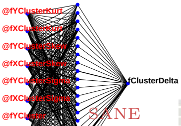


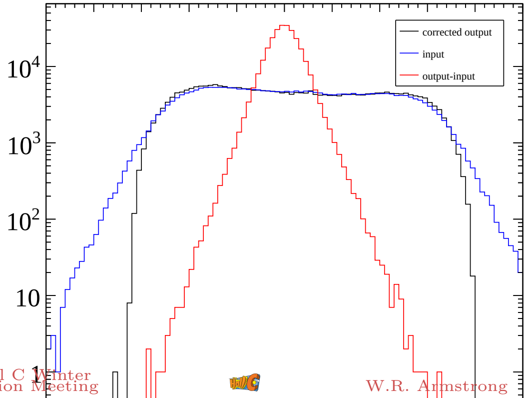
Neural Network Reconstruction

BigCal



First moment → position
Second moment → standard deviation
Third moment → skewness
Fourth moment → peakedness

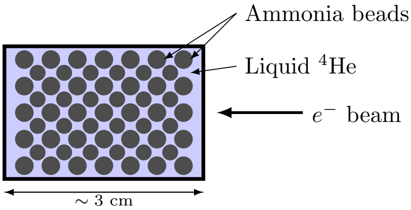


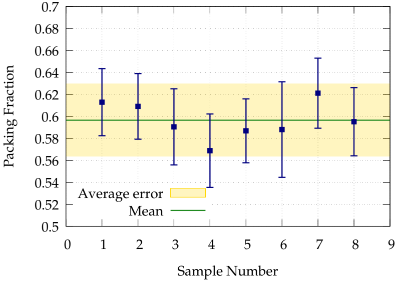


Target Packing Fraction

Packing Fraction

- PF obtained from HMS using F1F209 cross-section model.
- PF determines how much of target-cell volume is ammonia vs He.
- Roughly 60 percent



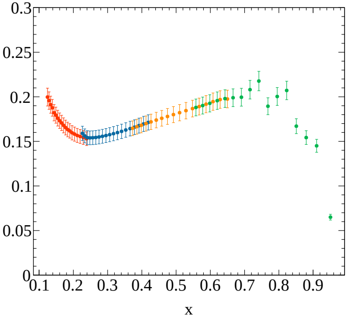


Packing Fraction from HMS. Hoyoung Kang and Narbe Kalantarians

BETA Target Dilution Factor

Dilution

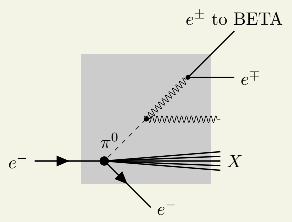
- Takes into account scattering from unpolarized material in target.
- Need to know target geometry and material.
- Function of x and W



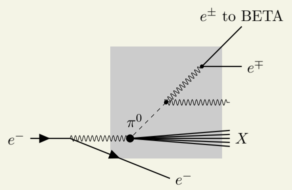
$$f(x,W) = \frac{N_p\sigma_p(x,W)}{N_p\sigma_p + \sum_i N_i\sigma_i(x,W)}$$

Pair Symmetric Background Corrections

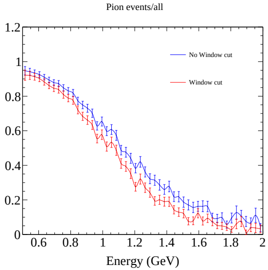
Electroproduction

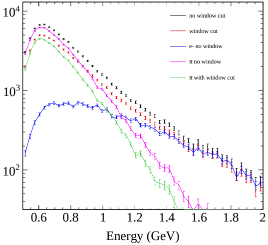


Photoproduction



- Model production cross sections (using Wiser's fits)
- Run monte carlo to get $R = N^{e+}_{pair}/N^{e-}_{total}$
- Pion asymmetry from previous SLAC experiments (analysis by Oscar Rondon)

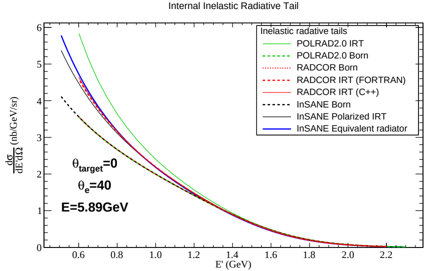




$$A^{bg}_{corr} = \left(\frac{1}{1-2R}\right) A_{raw} - \left(\frac{2RA_{pair}}{1-2R}\right)$$
$$= \frac{1}{f_{bg}} A_{raw} - C_{bg}$$

Currently working on finalizing background corrections.
Fitting inclusive pion electro- and photo- production.
Wiser fit is almost 40 years old → New fit will be very useful for future experiments.

Radiative Corrections



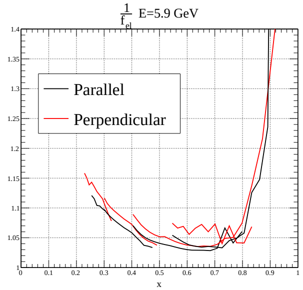
New Radiative Correction Code

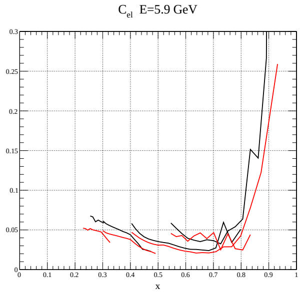
- Unpolarized formalism of Mo and Tsai[?] Includes internal *and* external radiative corrections.
- Polarized formalism of Akushevich, et.al.
- Written in C++ (part of InSANE)
- Check and re-checked against existing codes (RADCOR and POLRAD)

Formalism Differences

- Polarized formalism treats only internal RCs
- External RCs calculated using beam depolarization term
- Unpolarized formalism does internal and external RCs

Elastic Radiative Tail Subtraction





Elastic

- Largest radiative correction
- Treated with polarization following Akushevich, et.al.
- Correction depends on accurate calculation of radiated inelastic cross section

$$A^{el}_{corr} = \frac{A^{bg}_{corr}}{f_{el}} - C_{el}$$

$$\frac{1}{f_{el}} = \frac{\Sigma_T}{\Sigma_{in}}$$

$$C_{el} = \frac{\Delta_{el}}{\Sigma_{in}}$$

$$\Sigma_x = \sigma^+_x + \sigma^-_x$$

$$\Delta_x = \sigma^+_x - \sigma^-_x$$