# **BETA**:
# **B**ig **E**lectron **T**elescope **A**rray

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Jefferson Lab

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# Outline

- BETA
- Proton Spin Structure
- SANE
- Other Physics
- Summary

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# Outline

- BETA
  - Overview
  - Details of Components
  - Calibrations
  - Simulations
- Proton Spin Structure
- SANE
- Other Physics
- Summary

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# In the beginning .... Lunch

If we can do neutron spin structure at JLab, why not the proton?

- Neutron Target has higher luminosity and better dilution factor
- SLAC has copious proton data
  - same target, which limits luminosity
  - kinematics of JLab and SLAC experiments with the same acceptance have equivalent similar FOM.
- Only knob we have to tweak is acceptance

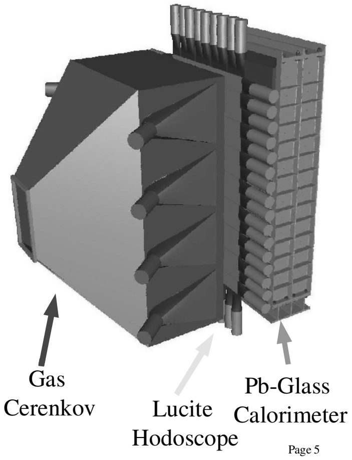
... and BETA was born.

# BETA Overview

Gas Cerenkov
- Particle Identification
- Minimal knock-on

Lucite Cerenkov
- Redundant PID
- Tracking

Pb-Glass Calorimeter
- Calorimetry
- Hadron reduction


Gas Cerenkov
Lucite Hodoscope
Pb-Glass Calorimeter

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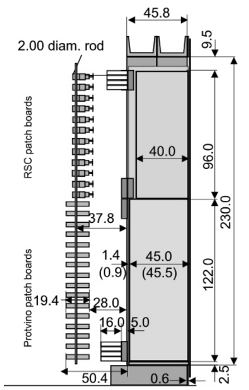
# Big Electron Telescope Array

- Use $G_{Ep}$-III BigCal Calorimeter:
  - ~1700 Pb-Glass blocks that are 4 x 4 x 40 cm
  - good angular resolution, adequate energy resolution,
  - 218 cm x 128 cm ( vert x horz),
- d$\Omega$ ~ 200 mSr at 3.5 m drift:
  - compared to ~6 mSr for HMS.
- Large energy acceptance:
  - lower limit is experiment dependent (~0.5 GeV),
  - no practical upper limit.
- d$\Omega\Delta$E of BETA > 100 times HMS for high $x$ measurements


45.8
9.5
2.00 diam. rod
RSC patch boards
40.0
96.0
230.0
37.8
1.4
(0.9)
45.0
(45.5)
122.0
Protvino patch boards
19.4
28.0
16.0
5.0
50.4
0.6
2.5

Side View of BigCal

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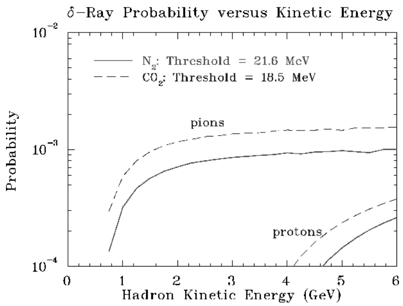
# Big Electron Telescope Array

Require Impeccable Electron Identification:

- Gas Cerenkov designed to give 1000:1 pion rejection,
- Redundant particle ID via Lucite hodoscope.



Gas Cerenkov

- $N_2$ gas for fewer delta rays.
- Point-to-point focusing.
- Baffled PMTs.
- Same approach to describing HMS pion rejection.

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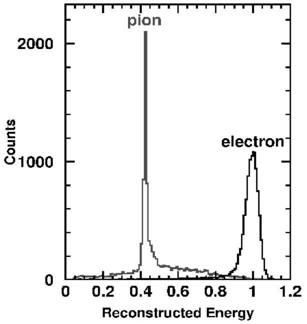
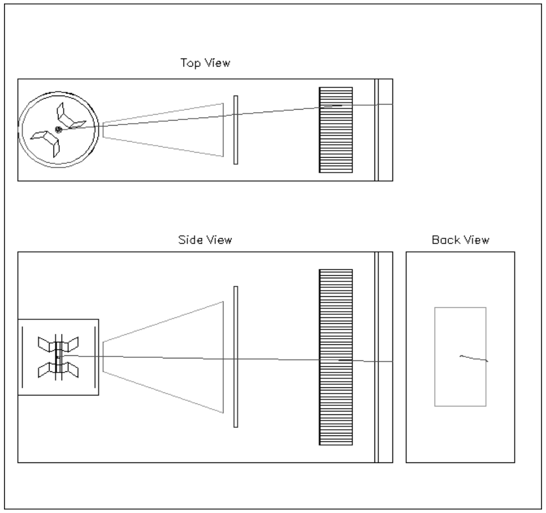
# Hadron Rejection

- Electromagnetic Calorimeter offers some inherent hadron rejection.
- Run in GEANT simulation:
  - throw 1 GeV pions and electrons at calorimeter,
  - look at visible energy in calorimeter,
  - Most of pions are minimum ionizing,
  - Pion wall after calorimeter will reduce pion contributions by two-thirds.



# Minimum Ionizing $\pi^-$ Track



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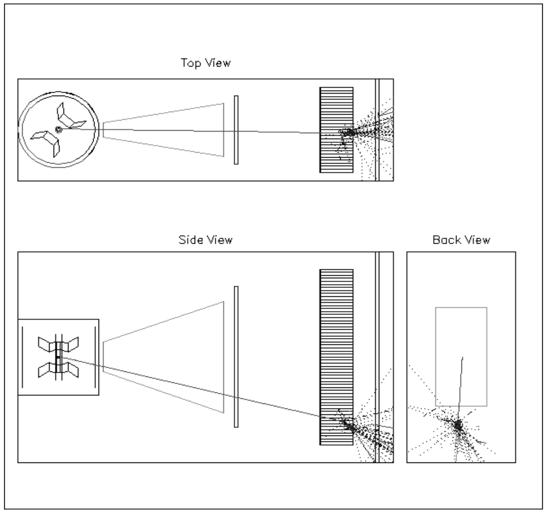
# Converting $\pi^-$ Track



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# Big Electron Telescope Array

Need to know that particle is coming from target.

- BETA swims in a deep sea of background:
  - target related (PID),
  - beam line related (tracking).
- BETA designed to be used as a single arm device:
  - Cannot rely on another arm or timing cut to reduce background.

How Is BETA a Telescope?

- Design of Gas Cerenkov:
  - With point-to-point focusing only sensitive to electrons coming from target.
- Lucite Hodoscope:
  - very rate hard,
  - segmented: position info.
- Drift between Lucite and Calorimeter:
  - gives adequate tracking.

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# Big Electron Telescope Array

.... gives us the cool acronym
for an electron detector

B: Big
E: Electron
T: Telescope
A: Array

$\beta$

# Gain Calibration and Monitoring

Two possibilities for absolute calibration:

- Elastic H(e,e'p):
  - run at higher luminosities without target polarization.
- Reconstruct $\pi^0$ mass from two photon events:
  - done by RADPHI and E582 (10 MeV resolution for E582 with similar setup),
  - do short elastics run as check,
  - measure simultaneously with production data.

Gain Monitoring

- Lucite system:
  - layer of Lucite in front of calorimeter through which pulse light into Pb-Glass blocks,
  - Used at E582 at Brookhaven.
- Punch-through pions:
  - most pions deposit about 450 MeV in calorimeter,
  - pion wall after calorimeter to identify pions.
- Cosmics:
  - come for free.

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# Simulations

Simulations of BETA are absolutely critical. Fold in:

- generation of background,
- detector acceptance,
- detector response to $e^{\pm}$, $\gamma$, $\pi^{\pm}$, p and n,
- passage of particles through various materials,
- decays of various particles,
- effect of target magnet and field.

Invaluable for studying:

- background reduction,
- detector optimization,
- event reconstruction,
- resolution,
- impact of background on reconstruction.

Approach:

- GEANT simulation of BETA,
- incorporate target field,
- weight events by cross section models.

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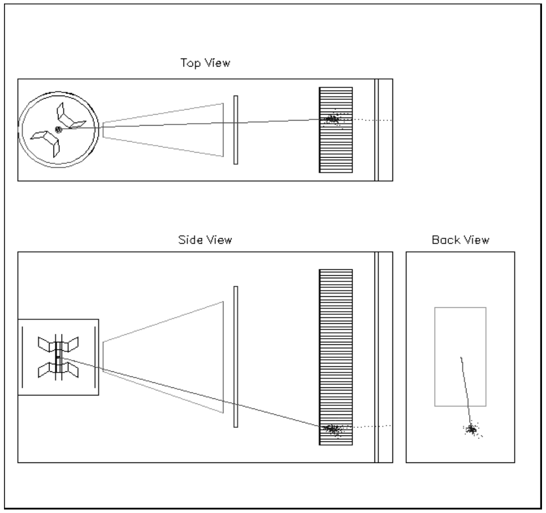
# Clean e$^-$ Track in BETA



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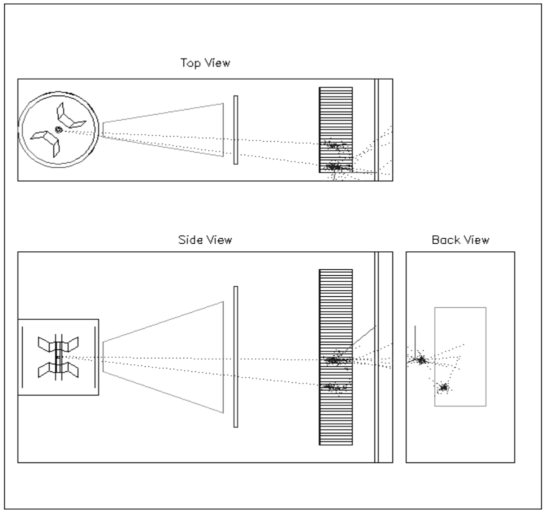
# Clean $\pi^0$ Track in BETA



# Cone of Death

Couple BETA with UVa $NH_3$ target:

- Target has 5 T field.
- Field sweeps low energy charged particles in direction of field creating the *Cone of Death!*
- Need minimum momentum to escape field:
  - minimum depends on setup.
- Significantly reduces background in BETA.

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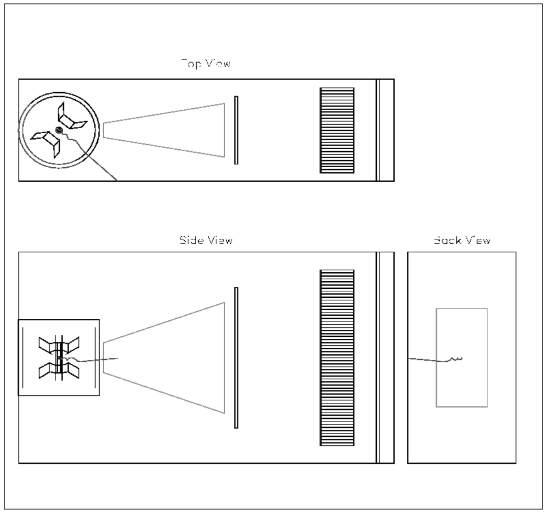
# 30 MeV/c Electron Thrown at BETA



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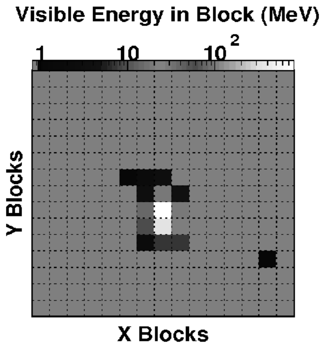
# Cluster Reconstruction

Cluster reconstruction impacted by low energy noise in calorimeter :

- Particles will deposit energy over a group of calorimeter blocks.
- Block included in cluster if energy exceeds threshold.
- As raise threshold, reduce sensitivity to background but worsen energy resolution.

  Need simulation to optimize.

Example of Visible Energy Distribution for Hit in Calorimeter



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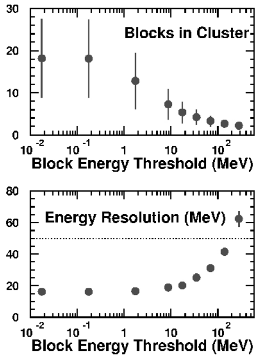
# Cluster Reconstruction

Study cluster reconstruction as vary block energy threshold:

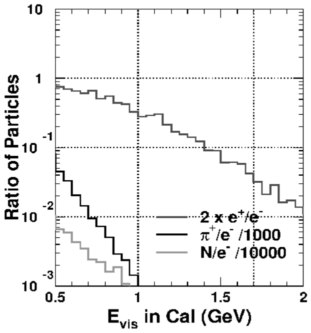
- Cluster size decreases as increase threshold.
  - cluster size important for pileup.
- Energy resolution worsens as increase threshold:
  - probably position resolution as well.
- 50 MeV block threshold gives small cluster size and does not impact resolution.



# Background Studies

- For single-arm experiments, understanding the background processes is critical.
- Backgroud will vary with setup. For example, look at SANE:
  - UVa $NH_3$ target; 5 T field,
  - 6 GeV beam,
  - BETA at 40°,
  - Electron energies > 1 GeV.
- Plot ratio of background particles to electrons, include Cerenkov reduction:
  - Hadron contamination is insignificant.
  - Charge symmetric processes are leading background. This estimate is conservative.

Ratio of Background Particles to Electrons as seen by BETA



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# Outline

- BETA
- Proton Spin Structure
  - introduction
  - extraction from observables
  - why high x?
- SANE
- Other Physics
- Summary

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# Spin Structure

Deep inelastic lepton scattering data has yielded wealth of knowledge of nucleon structure. Quark distributions inside nucleon are described by four structure functions:

- Structure functions: $F_1$, $F_2$ - cross section,
- Spin Structure Functions: $g_1$, $g_2$ - polarization observables.

In Quark-Parton Model, we can write $F_1$ and $g_1$ in terms of helicity dependent quark distribution functions, $q_i^{\pm}(x)$:

$$F_1(x)=\frac{1}{2}\sum_i e_i^2[q_i^+ + q_i^-]$$

$$g_1(x)=\frac{1}{2}\sum_i e_i^2[q_i^+ - q_i^-]$$

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# $g_2$

$g_2(x,Q^2)$ does not have as simple an interpretation as $g_1$. It can be divided into a twist 2 and a mixed twist term:

$$g_2 = g_2^{WW} + \overline{g_2}$$

where $g_2^{WW}$ depends only on $g_1$ (twist 2):

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

$\overline{g_2}$ vanishes when all twist-3 ($d_n$) matrix elements vanish in **O**perator **P**roduct **E**xpansion (OPE), e.g.

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

Thus, $g_2$ is interesting for understanding higher twists.

$d_2$ is one of the cleaner quantities that are sensitive to higher twists.

# $g_1, g_2 \leftrightarrow A_1, A_2$

The spin structure functions $g_1$ and $g_2$ are related to the asymmetries $A_1$ and $A_2$ by:

$$A_1 = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{1}{F_1}(g_1 - \gamma^2 g_2) \qquad \gamma = 2Mx/Q$$

$$A_2 = \frac{2\sigma_{LT}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{\gamma}{F_1}(g_1 + g_2)$$

Total photon nucleon helicity

Thus $A_1$ and $A_2$ depend on $F_1$, which helps to reduce the $Q^2$ dependence of these asymmetries.

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# Extraction

Measure inclusive beam-target asymmetries with polarized electron beam and polarized proton target.

For a target field orientation w.r.t. the beam $\theta_N$ the measured asymmetry is related to $A_1$ and $A_2$ by:

$$A_{meas}(\theta_N) = \alpha A_1[\cos(\theta_N) - \rho\sin(\theta_N)] + \beta A_2[\rho\cos(\theta_N) + \sin(\theta_N)]$$

$$\alpha = \alpha(E, E', \theta, R)$$
$$\beta = \beta(E, E', \theta, R)$$
$$\rho = \rho(E, E', \theta)$$

By measuring the beam-target asymmetry for two values of $\theta_N$, we can extract $A_1$ and $A_2$.

- Most sensitive to $A_1$ for $\theta_N = \theta_q$ $A_{meas} \sim A_{\|}$ - field $\|$ beam
- Most sensitive to $A_2$ for $\theta_N \approx 90^\circ$ $A_{meas} \sim A_{\perp}$ - field $\perp$ beam

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# Why High *x*?

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

- Examine predictions of $x \rightarrow 1$ of $A_{1p}$ of pQCD and SU(6) models:
  - SU(6) symmetric $A_{1p} \rightarrow 5/9$,
  - SU(6) broken and pQCD predicts $A_{1p} \rightarrow 1$, but different reasons.
- Study *x* dependence of $A_{1p}$.
- Higher twist effects become more significant at higher *x*.
- Region in which sea quarks play only minor role.
- Understanding higher order moments to compare to Lattice QCD and QCD predictions.
- Existing data at large *x* is limited compared to lower *x* region. Region is“ statistically challenged”.

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# Outline

- BETA
- Proton Spin Structure
- SANE
  - setup
  - $A_{1p}$ as $x \rightarrow 1$
  - *x* dependence
  - $g_2$ and $d_2$
- Other Physics
- Summary

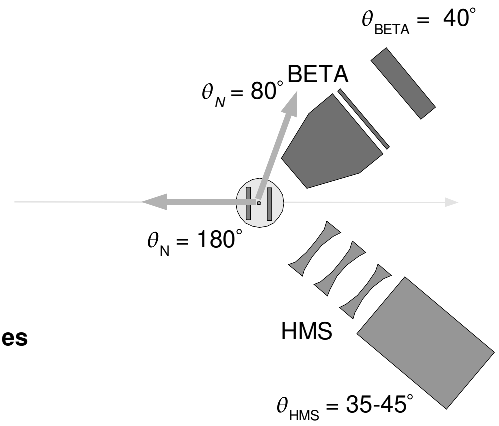
# Experimental Setup

**Target**
- UVa NH3 target
- 5 T field

**Beamline**
- Chicanes
- SEM
- He Bag

**Electron Arm**
- BETA

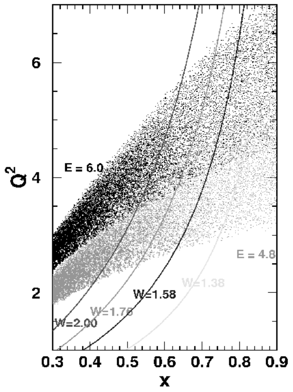
**Background Studies**
- HMS



# Two Beam Energies

We propose to take measurements at 4.8 and 6.0 GeV beam energies because:

- Provides limited test of local duality for spin observables. If demonstrated, then can significantly extend maximum *x* for $A_{1p}$.
- Study $Q^2$ dependence for constant *x*.
- Study *x* dependence for constant $Q^2$.



# Potential Physics from SANE

$A_{1p}$ as $x \rightarrow 1$

$g_2$ and $d_2$
higher twists

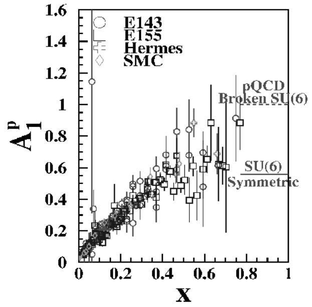
SANE

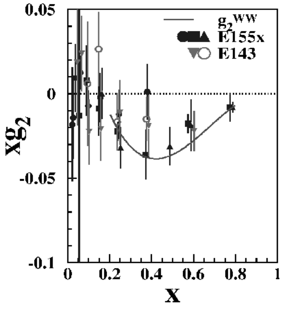
$\Delta u$, $\Delta d$

*x* dependence
Moments

$Q^2$ dependence
Glue

# World's Data at High *x*

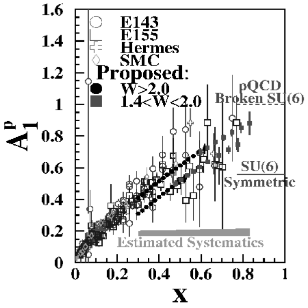


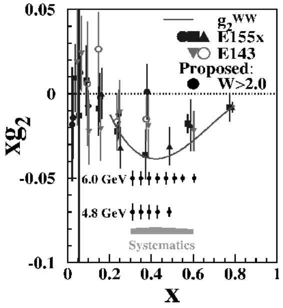


- Dominated by $NH_3$ experiments.
- CLAS data under analysis.

- $g_2^{WW}$ is twist 2 - from $g_1$.
- Significant spread at x~0.4.

# World and Projected Data





For JLab Energies, it is necessary to do two asymmetry measurements to extract $A_{1p}$ and $g_2$ in a model independent way.

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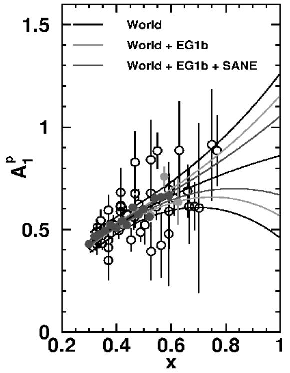
# $A_{1p}$ as $x \rightarrow 1$

- Plot of world's data for $A_{1p}$.
- Fit to $x^{\alpha}(b+cx^2)$ for x>0.3:
  - allows for pathologies at high *x*,
  - too simple to constrain all of *x*.
- World data alone cannot distinguish 1 and 5/9.
- Add estimated EG1b uncertainties.
- Add projected SANE uncertainties.
- In 140 h, SANE will have the same impact on $A_{1p}$ as $x \rightarrow 1$ as the rest of the World+EG1b data.



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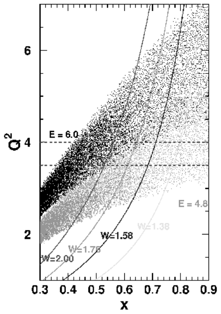
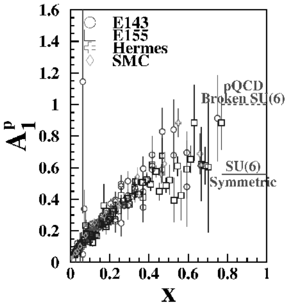
# Example of *x* Dependence Study

3.5<$Q^2$<4.0 and *W*>1.4:





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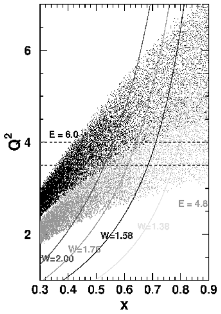
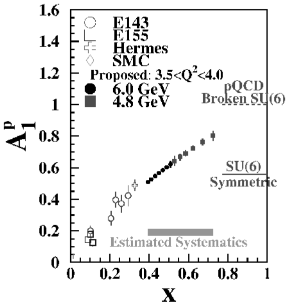
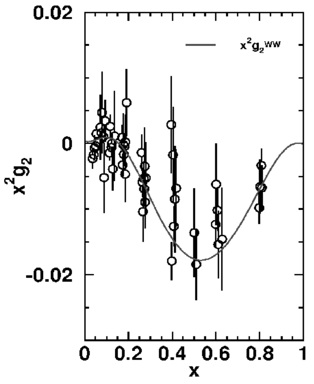




# World's data for $x^2 g_2$

- World's data on $g_2$ plotted as $x^2 g_2$.
  - plot $x^2$ dependence to reflect $x$ weighting for $d_2$ integral.
- There is a lot of scatter in the points: $Q^2$ dependence?
- To get to twist-3: interested in difference between $g_2$ and $g_2^{WW}$.



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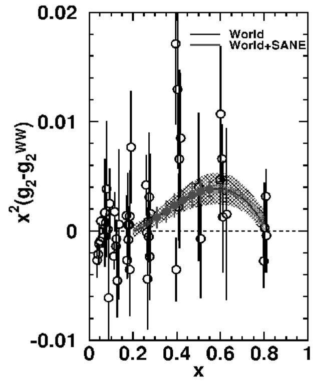
# Toy Fit to $x^2\overline{g_2}$



- Plot integrand of $d_2$:

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

- Fit from $x$ = 0.2 to 0.8 only:
  - for x>0.8 negligible,
  - for x<0.2 small and measured at SLAC.
- $\chi^2$/DOF ~ 2:
  - either bad function,
  - or bad data.
- Error of world data fit in black.
- Error band including projected SANE data in red.
- Significant improvement.

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# Outline

- BETA
- Proton Spin Structure
- SANE
- Other Physics
  - $G_{Ep}/G_{Mp}$
  - Deuteron Spin Structure
  - Transverse target measurements
  - 12 GeV possibilities
- Summary

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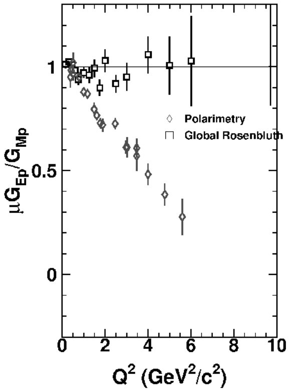
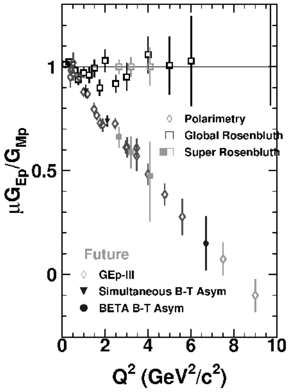
# Why Measure $G_{Ep}/G_{Mp}$?

- SLAC Rosenbluth experiments: $\mu G_{Ep}/G_{Mp}$ ~ 1
- Polarimetry experiments: $\mu G_{Ep}/G_{Mp}$ decreasing.
- Falling ratio caused by orbital angular momentum of quarks.
- Analysis by J. Arrington of SLAC measurements reveals no inconsistencies.
- More cross section and polarimetry experiments coming.



# Future $G_{Ep}/G_{Mp}$ Measurements

- Super Rosenbluth completed in '02:
  - detect protons,
  - ratio of cross sections.
- Polarimetry measurement at high $Q^2$.
- PR01-105: precision simultaneous beam-target asymmetry measurement.
- Possible to use BETA in coincidence with HMS for high $Q^2$ measurement (400 h).



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# Deuteron Spin Structure

- Everything we do with proton we can do with deuteron.
  - use deuteron spin structure to extract neutron spin structure
  - Provide a check on $A_1^n$ results extracted from measurements on $^3$He.
- Deuterium target polarization is lower than both proton target and $^3$He target.
- Higher luminosity and polarization of $^3$He measurement compensated by larger acceptance of BETA.

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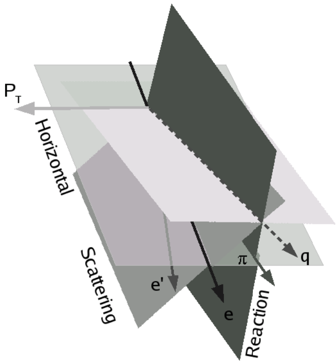
# Transverse Target Measurements

- Use large out of plane acceptance of BETA to push $\vec{q}$ out of plane. For example: $\vec{p}(e,e'\pi)X$ reaction.
- Orient target polarization horizontal and transverse to beam (huge technical effort to orient vertically).
- Picture drawn from physical perspective, not relative to scattering plane!



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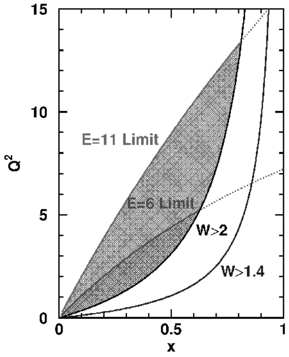
# 12 GeV Upgrade

Proton Spin Structure:

- Able to go to higher *x* for DIS.
- Wider $Q^2$ range for better test of gluons.

BETA provides proof of principle for higher resolution calorimeter, Son Of BETA (SOB).

- Experience with BETA will help improve the second generation of electron calorimeter detectors.



# Summary

BETA

- Excellent particle ID.
- Handle high background rates.
- High angular resolution, low energy resolution.
- Developing sophisticated simulations package.
- Provides proof of principle for 12 GeV.

Possible Physics:

- SANE as inaugural experiment:
  - $A_{1p}$ and $g_2$ in DIS at high $x$.
  - Study of $x$ and $Q^2$ dependence.
  - Limited test of local duality.
  - Simultaneously collect data in resonance region.
- Deuteron Spin Structure.
- $G_{Ep}/G_{Mp}$.
- Transverse target measurements.

BETA allows us to study reactions involving the polarized proton target that were previously limited by statistics.

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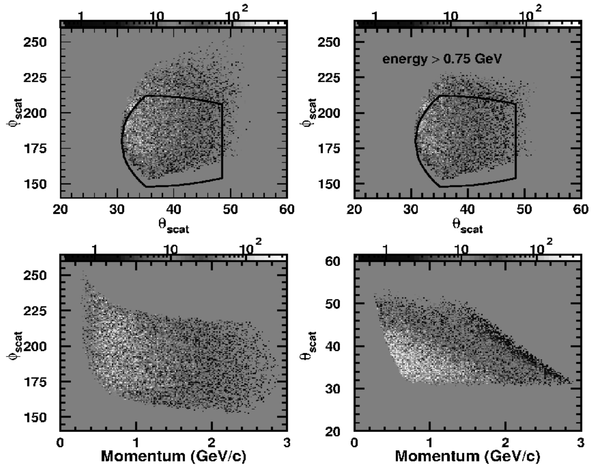
# Example of Acceptance from SANE



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# Systematics

Calorimeter Gains:

- Calibrated with proton elastics (using HMS in coincidence).
- Monitored through Lucite light system, punch-through pions and cosmics.

Background:

- Dominated by charge-symmetric processes, mostly $\pi^0 \rightarrow \gamma e^+ e^-$.
- Measured in HMS.
- Hadron backgrounds measured by ignoring Gas Cerenkov in trigger.

# Estimated Systematics for 6 GeV

| | |
|---|---|
| Radiative Corrections | 1.5% |
| Dilution Factor | 2.0% |
| Target Polarization | 2.5% |
| Beam Polarization | 1.0% |
| Nitrogen Correction | 0.4% |

| | A1p | | g2 | |
|---|---|---|---|---|
| | *x*=0.3 | *x*=0.6 | *x*=0.3 | *x*=0.6 |
| *R* | 2.4% | 1.8% | 4.3% | 2.5% |
| Kinematics | 0.3% | 0.3% | 3.1% | 3.6% |
| Background | 5.7% | 3.0% | 5.7% | 3.0% |
| Local | 4.7% | 3.2% | 5.8% | 4.3% |
| Global | 5.5% | 4.2% | 6.4% | 5.1% |
| Total | 7.2% | 5.1% | 8.6% | 6.5% |

Systematics for 4.8 GeV are very similar

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# Collaboration

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Spin Structure Physics
→ JLab, Temple, UVa,W&M

Detectors
→ Yerevan, LA Tech, JLab

Calorimeter
→ Protvino

Target
→ JLab, UVa

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# Beam Time request

| | Energy | $\theta_N$ | Time (h) | |
|---|---|---|---|---|
| **Production** | 6.0 | 180 | 325 | |
| | 6.0 | 80 | 75 | |
| | 4.8 | 180 | 170 | |
| | 4.8 | 80 | 30 | |
| | 2.4 | - | 50 | |
| **Systematics** | Packing Fraction | | 20 | |
| | Mollers | | 25 | |
| | Total beam time | | 695 | (29 d) |
| **Overhead** | Anneals | | 75 | |
| | Energy Change | | 48 | |
| | Target Rotation | | 48 | |
| | Stick Changes | | 48 | |
| | Total Overhead | | 219 | (9 d) |

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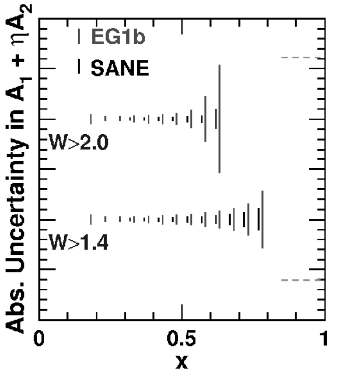
# EG1b and SANE - $A_{||}$

*Projected* statistics for SANE vs *estimated* statistics for EG1b for E = 5.6 – 5.7 GeV runs.

At this time, CLAS cannot be used to measure $A_{\perp}$. EG1b cannot extract $A_1$ without a model.

SANE may also benefit from higher beam energies, possibly up to 6.2 GeV.

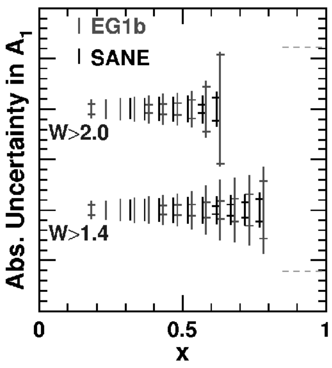


# EG1b vs SANE - $A_1$

Add point-to-point systematic errors to statistics to estimate uncertainties in $A_1$ for local fits to data.

For EG1b:

- Assume same systematics as SANE.
- $A_2$ subtraction:
  - → For DIS: 3% uncertainty.
  - → For Resonance Region: Only quality data is from E01-006 (RSS) at $Q^2$=1.3. Guess 7% uncertainty, based on Soffer limit.



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# Rates and Pileup in BETA

All Rates in kHz

Gas Cerenkov

| E | e± | π± | Trig |
|---|---|---|---|
| 4.8 | 1.7 | 430 | 6.0 |
| 4.8 | 1.1 | 370 | 4.8 |
| 6.0 | 1.3 | 390 | 5.2 |
| 6.0 | 1.2 | 420 | 5.4 |

Calorimeter

| E | e± | π± | π0+N | Trig |
|---|---|---|---|---|
| 4.8 | 0.4 | 3.2 | 69 | 73 |
| 4.8 | 0.3 | 1.6 | 60 | 62 |
| 6.0 | 0.3 | 2.4 | 59 | 62 |
| 6.0 | 0.2 | 1.6 | 62 | 64 |

BETA Trigger Rates

| E | True | Accd |
|---|---|---|
| 4.8 | 0.40 | 0.09 |
| 4.8 | 0.29 | 0.06 |
| 6.0 | 0.33 | 0.06 |
| 6.0 | 0.24 | 0.07 |

⇒ Pileup with reasonable segmentation of calorimeter is low: ~0.2%

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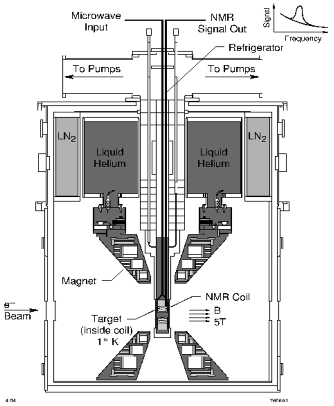
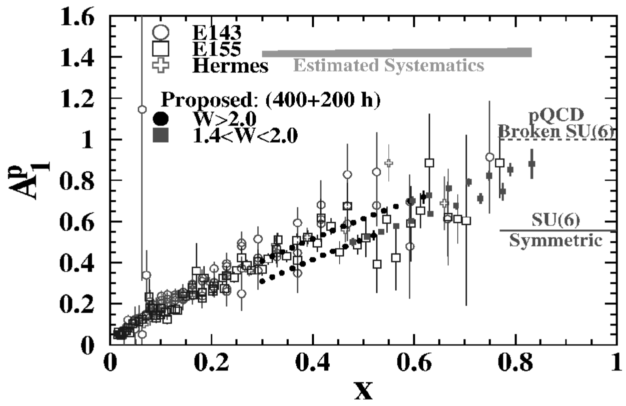
# UVa Polarized Target

- Dynamic Nuclear Polarization
- 5 T Field
  - can steer beam
  - affect optics of scattered electrons
- 1 K evaporative refrigerator
- Composite target: N+H+He
  - asymmetry is diluted by unpolarized materials
- Measure target polarization
  - calibration: thermal equilibrium
  - monitoring: NMR

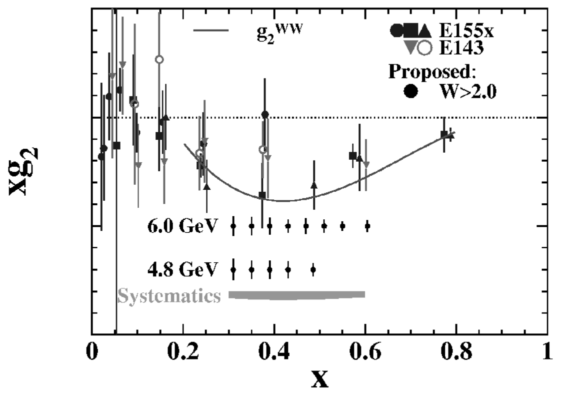

Microwave Input
NMR Signal Out
Signal
Frequency
Refrigerator
To Pumps
To Pumps
LN2
Liquid Helium
Liquid Helium
LN2
Magnet
NMR Coil
e⁻ Beam
Target (inside coil) 1° K
B
5T
4-94
7656A1

---

# $A_1^p$



# $g_2$



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# BETA

| | |
|---|---|
| Tracking Resolutions | |
| Angle | 2° |
| Vertex | 10 cm |
| Reconstruction Resolutions | |
| Angle | 3-17 mrad |
| Momentum | 45-70 MeV |
| Particle Rejection | |
| Pions | >1000 |
| Protons | >10000 |

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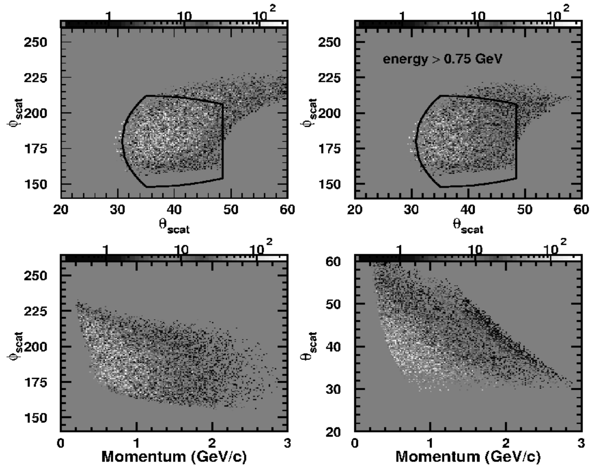
# Acceptance: E = 6.0, $\theta_N$ = 80



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# BigBite and BETA

| | **BigBite** | **BETA** |
|---|---|---|
| **Solid Angle** | ~75 msr | 207 msr |
| **Detector Package** | Calorimeter<br>Gas Cerenkov<br>wire chambers (2) | Calorimeter<br>Gas Cerenkov<br>Lucite Cerenkov |
| **Dispersion** | Open Dipole | None |
| **Advantages** | Better Resolution | Built for high rates |
| **Disadvantages** | Interaction of fringe field with target field | |