BETA:
Big Electron Telescope Array

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Jefferson Lab

Outline

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

Outline

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

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

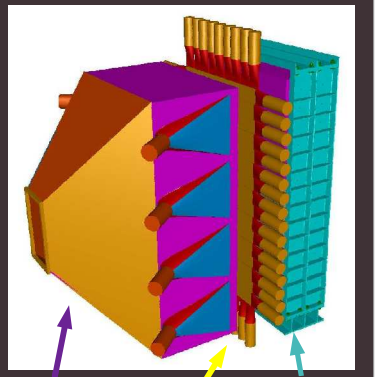
... and BETA was born.

BETA Overview

Gas Cerenkov
- Particle Identification
- Minimal knock-on

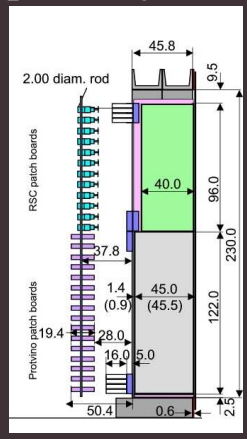
Lucite Cerenkov
- Redundant PID
- Tracking

Pb-Glass Calorimeter
- Calorimetry
- Hadron reduction



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),
- dΩ ~ 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.
- dΩΔE of BETA > 100 times HMS for high *x* measurements

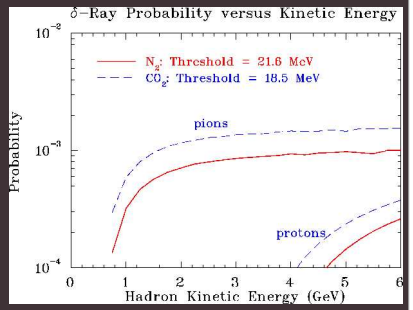


Side View of BigCal

Big Electron Telescope Array

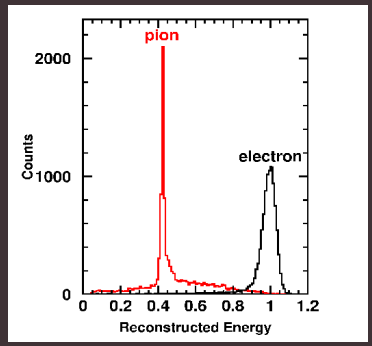
Require Impeccable Electron Identification:
- Gas Cerenkov designed to give 1000:1 pion rejection,
- Redundant particle ID via Lucite hodoscope.

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

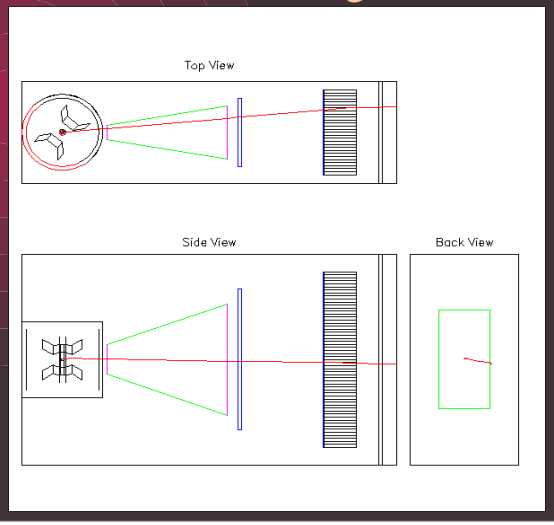


Hadron Rejection

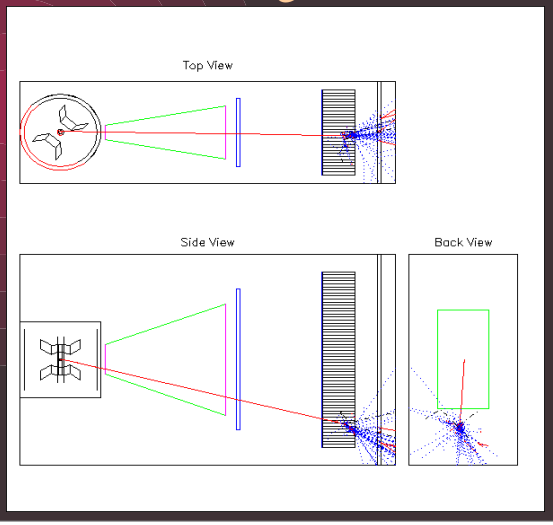
- Electromagnetic Calorimeter offers some inherent hadron rejection.
- Run in GEANT simulation:
  - throw 1 GeV pions and electrons at calorimeter,
  - look at visible energy in calorimeter,
  - Most of pions are minimum ionizing,
  - Pion wall after calorimeter will reduce pion contributions by two-thirds.



Minimum Ionizing π^- Track



Converting π^- Track



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.

Big Electron Telescope Array

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

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

β

Gain Calibration and Monitoring

Two possibilities for absolute calibration:

- Elastic H(e,e'p):
  - run at higher luminosities without target polarization.
- Reconstruct π^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.

Simulations

Simulations of BETA are absolutely critical. Fold in:

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

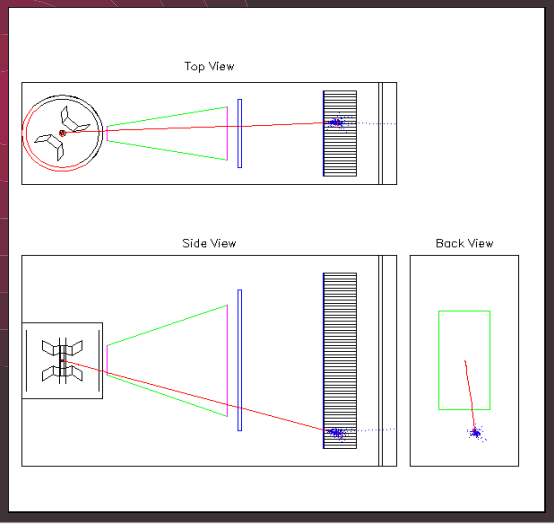
Invaluable for studying:

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

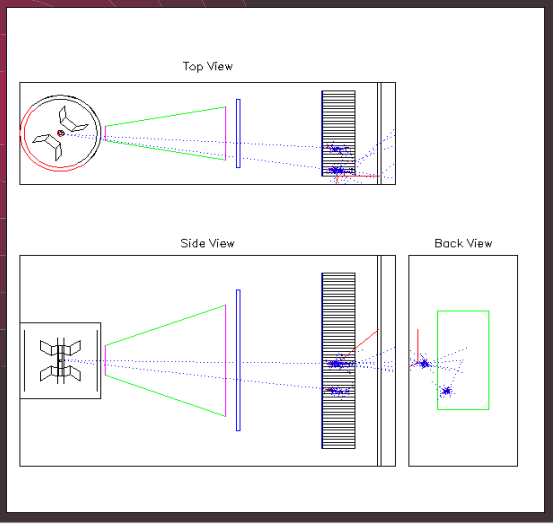
Approach:

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

Clean e^- Track in BETA



Clean π^0 Track in BETA

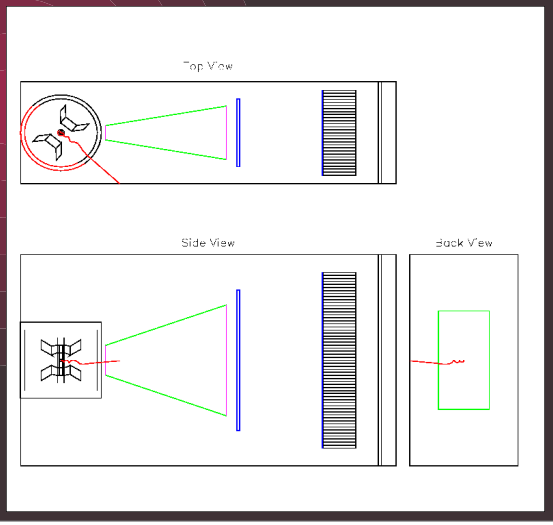


Cone of Death

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.

30 MeV/c Electron Thrown at BETA



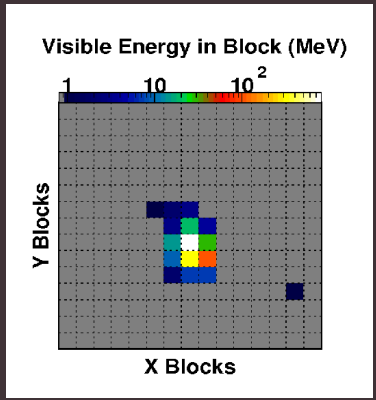
Cluster Reconstruction

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.

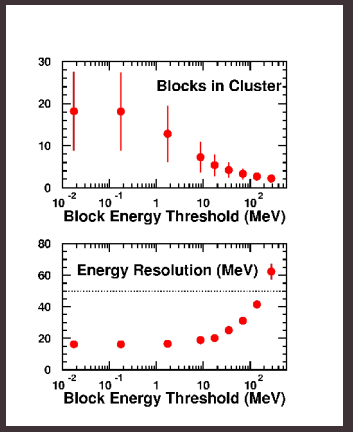
Example of Visible Energy Distribution for Hit in Calorimeter



Cluster Reconstruction

Study cluster reconstruction as vary block energy threshold:

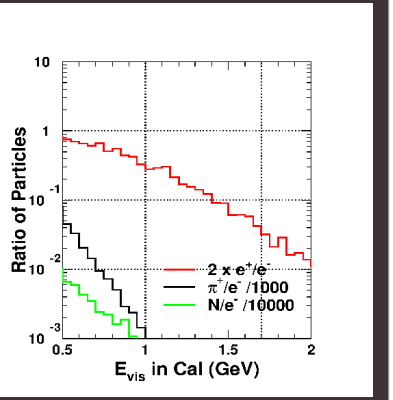
- Cluster size decreases as increase threshold.
  - cluster size important for pileup.
- Energy resolution worsens as increase threshold:
  - probably position resolution as well.
- 50 MeV block threshold gives small cluster size and does not impact resolution.



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



Outline

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

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, $q_i^{\pm}(x)$:

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

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

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.

Extraction

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

For a target field orientation w.r.t. the beam θ_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 θ_N, we can extract A_1 and A_2.

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

Why High x?

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

- Examine predictions of $x \to 1$ of A_{1p} of pQCD and SU(6) models:
  - SU(6) symmetric $A_{1p} \to 5/9$,
  - SU(6) broken and pQCD predicts $A_{1p} \to 1$, 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".

Outline

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

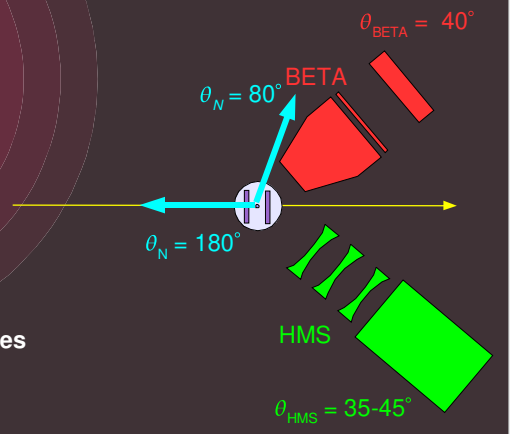
Experimental Setup

Target
- UVa NH3 target
- 5 T field

Beamline
- Chicanes
- SEM
- He Bag

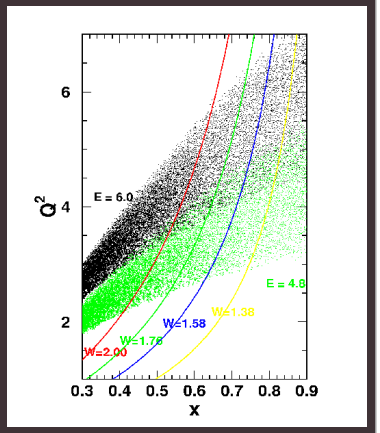
Electron Arm
- BETA

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

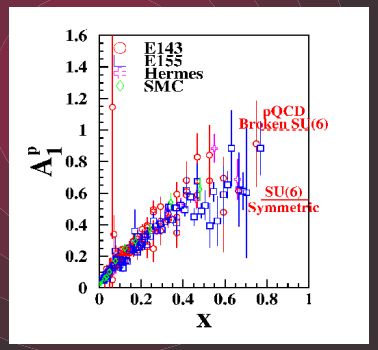
SANE

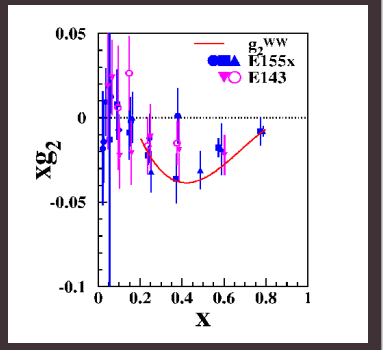
Δu, Δd

x dependence
Moments

Q^2 dependence
Glue

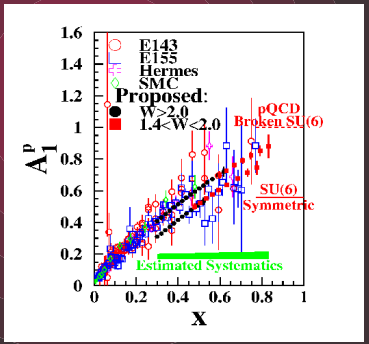
World's Data at High x

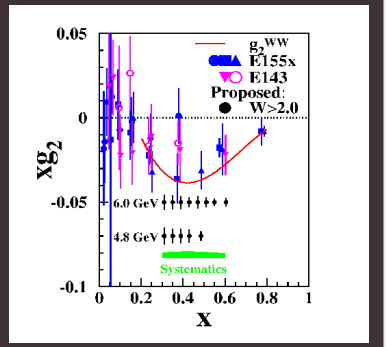




- Dominated by NH_3 experiments.
- CLAS data under analysis.
- g_2^{WW} is twist 2 - from g_1.
- Significant spread at x~0.4.

World and Projected Data

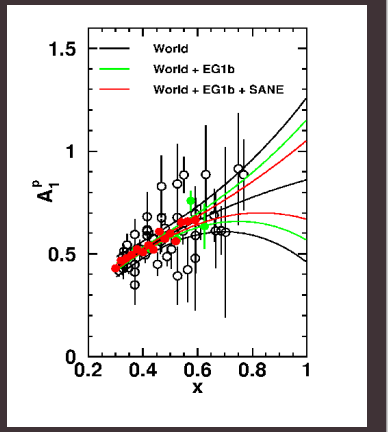




For JLab Energies, it is necessary to do two asymmetry measurements to extract A_{1p} and g_2 in a model independent way.

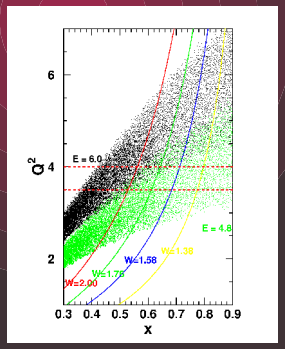
A_{1p} as $x \to 1$

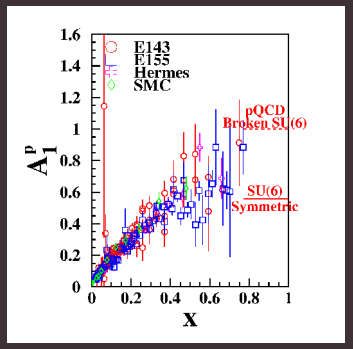
- Plot of world's data for A_{1p}.
- Fit to $x^{\alpha}(b+cx^2)$ for x>0.3:
  - allows for pathologies at high x,
  - too simple to constrain all of x.
- World data alone cannot distinguish 1 and 5/9.
- Add estimated EG1b uncertainties.
- Add projected SANE uncertainties.
- In 140 h, SANE will have the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



Example of x Dependence Study

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





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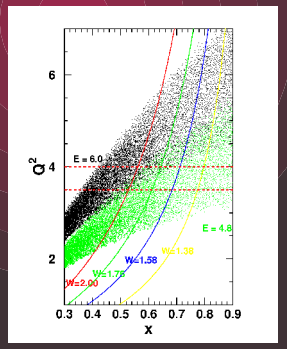
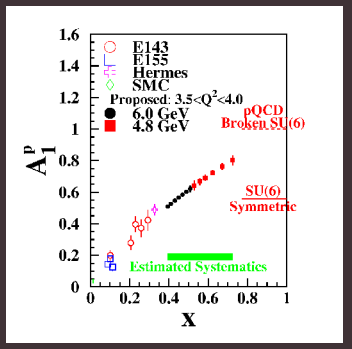
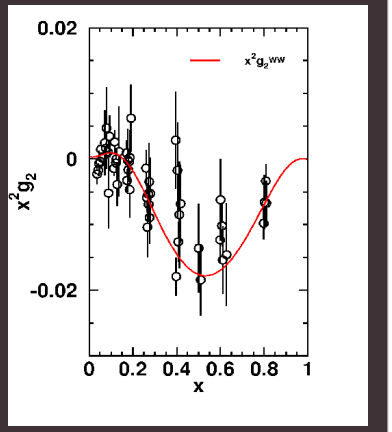


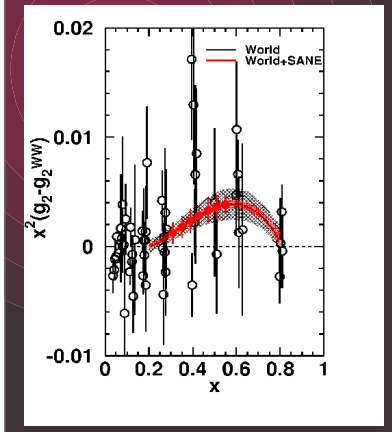


World's data for x^2g_2

- World's data on g_2 plotted as x^2g_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}.



Toy Fit to $x^2\bar{g}_2$



- Plot integrand of d_2:

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

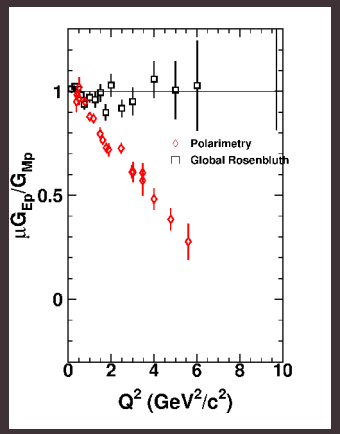
- Fit from x = 0.2 to 0.8 only:
  - for x>0.8 negligible,
  - for x<0.2 small and measured at SLAC.
- χ^2/DOF ~ 2:
  - either bad function,
  - or bad data.
- Error of world data fit in black.
- Error band including projected SANE data in red.
- Significant improvement.

Outline

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

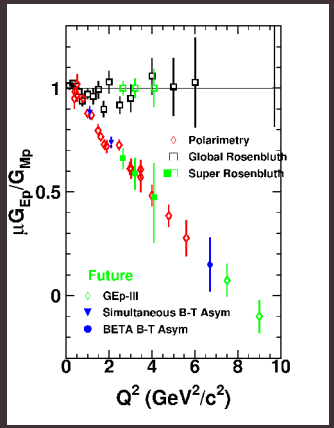
Why Measure G_{Ep}/G_{Mp}?

- 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).

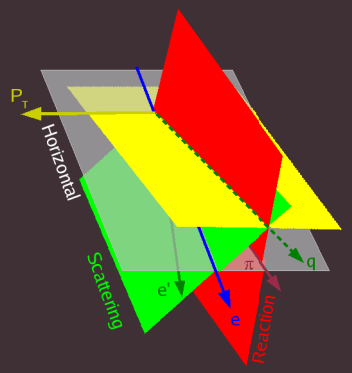


Deuteron Spin Structure

- 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.

Transverse Target Measurements

- Use large out of plane acceptance of BETA to push $\vec{q}$ out of plane. For example: $\vec{p}$(e,e'π)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!



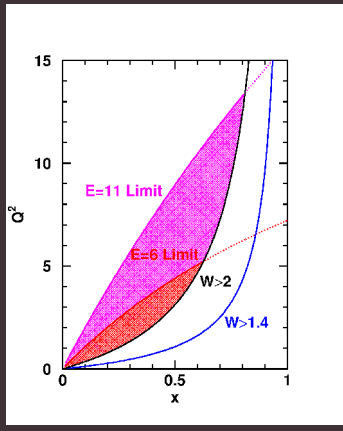
12 GeV Upgrade

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

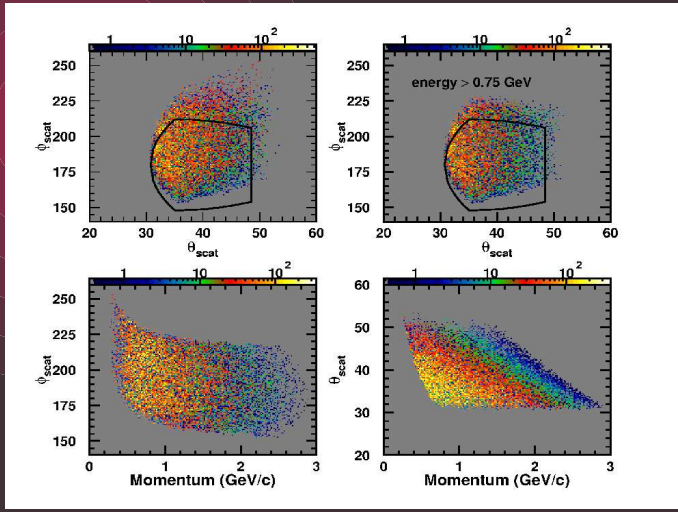
- Excellent particle ID.
- Handle high background rates.
- High angular resolution, low energy resolution.
- Developing sophisticated simulations package.
- Provides proof of principle for 12 GeV.

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.

Example of Acceptance from SANE



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

Collaboration

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

Detectors
→ Yerevan, LA Tech, JLab

Calorimeter
→ Protvino

Target
→ JLab, UVa

Beam Time request

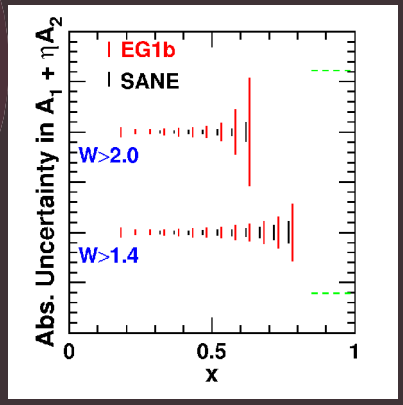
		Energy	θ_N	Time (h)	
Production		6.0	180	325	
		6.0	80	75	
		4.8	180	170	
		4.8	80	30	
		2.4	-	50	
Systematics		Packing Fraction		20	
		Mollers		25	
		Total beam time		695	(29 d)
Overhead		Anneals		75	
		Energy Change		48	
		Target Rotation		48	
		Stick Changes		48	
		Total Overhead		219	(9 d)

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.

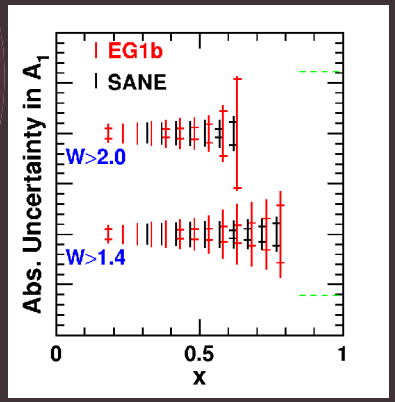


EG1b vs SANE - A_1

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.



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

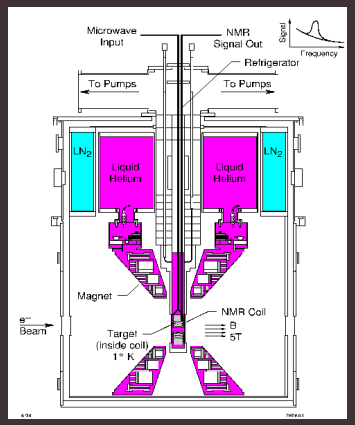
BETA Trigger Rates

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

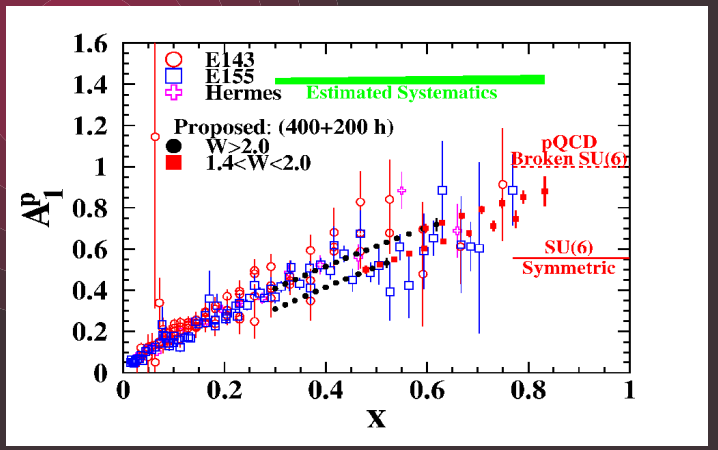
⇒ Pileup with reasonable segmentation of calorimeter is low: ~0.2%

UVa Polarized Target

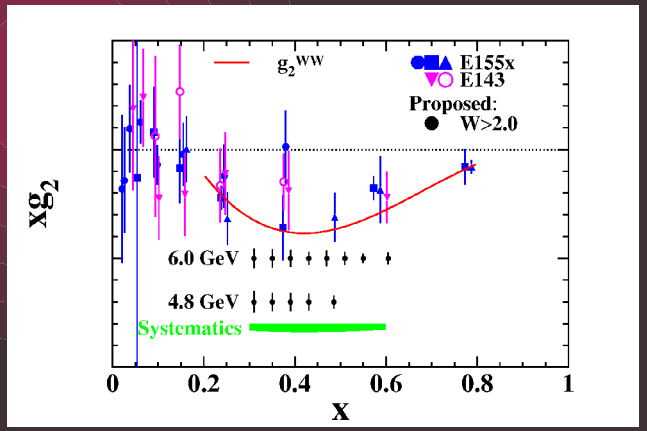
- Dynamic Nuclear Polarization
- 5 T Field
  - can steer beam
  - affect optics of scattered electrons
- 1 K evaporative refrigerator
- Composite target: N+H+He
  - asymmetry is diluted by unpolarized materials
- Measure target polarization
  - calibration: thermal equilibrium
  - monitoring: NMR



A_1^p



g_2



BETA

Tracking Resolutions

Angle	2°
Vertex	10 cm

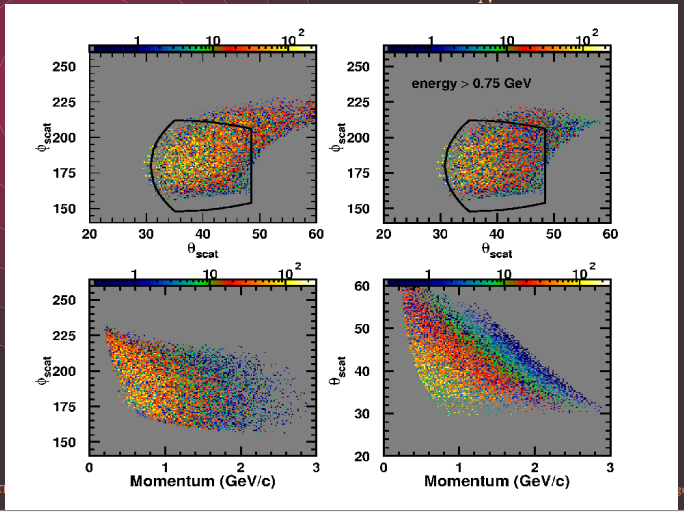
Reconstruction Resolutions

Angle	3-17 mrad
Momentum	45-70 MeV

Particle Rejection

Pions	>1000
Protons	>10000

Acceptance: E = 6.0, θ_N = 80



BigBite and BETA

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