Proton Form Factor Ratio, $\mu_p G^P_E / G^P_M$
From
Double Spin Asymmetry

Spin
Asymmetries of the
Nucleon
Experiment
(E07-003)

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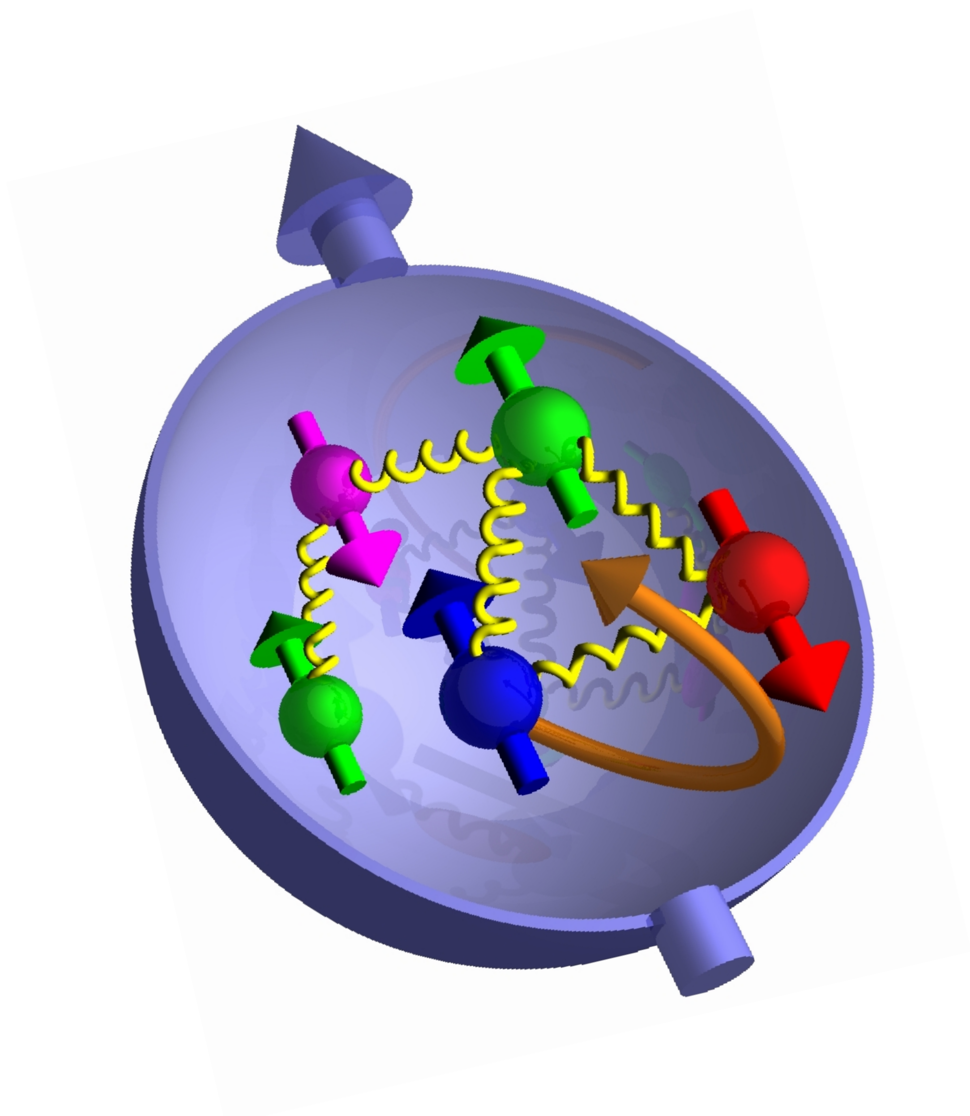
May 16th, 2016

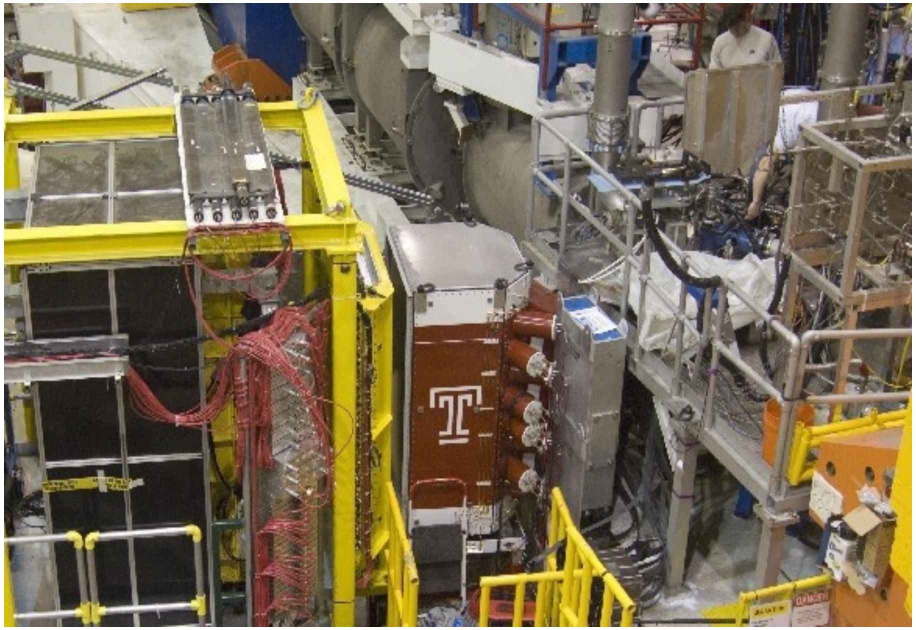
Outline

- Goal of the Experiment
- Physics Motivation
- Experiment Setup
  - BETA Detector
  - HMS Detector
  - Polarized Target
- Data Analysis
  - Elastic Kinematics
  - Elastic Event Selection
  - Physics asymmetries
  - Results
- Conclusion



Goal of the SANE

- SANE is a single arm inclusive scattering experiment. Used
  - **Big Electron Telescope Array** – **BETA** In single arm mode
  - **High Momentum Spectrometer** – **HMS** in both single arm and coincidence mode

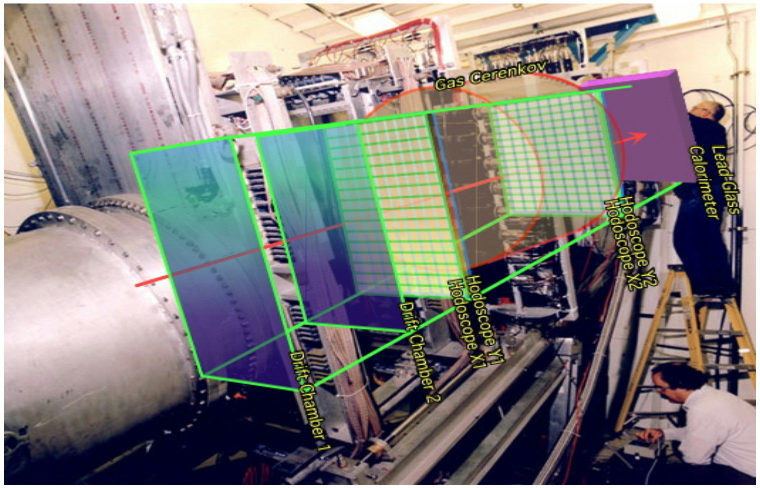


Physics from BETA:

- Measure proton spin structure function $g_2(X,Q^2)$ and spin asymmetry $A_1(X,Q^2)$ at four-momentum transfer $2.5 < Q^2 < 6.5$ GeV^2 and $0.3 < X < 0.8$ by measuring anti-parallel and near-perpendicular spin asymmetries.
- Study twist -3 effects (d2 matrix element) and moments of g_2 and g_1
- Comparison with Latice QCD, QCD sum rule
- Explore "High" X_B region: A_1 at $X_B \sim 1$

Physics from HMS :

HMS detected electrons with momenta from 1 to around 5 GeV/c



1. Packing fraction determination.
   - Used the ratio of data/MC yields for C target to determine the packing fraction.

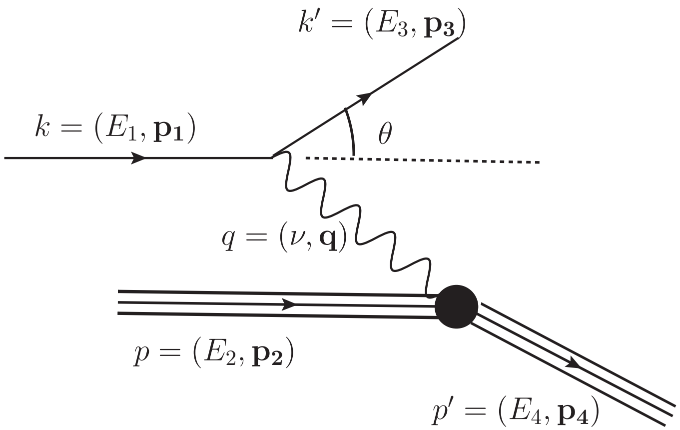
2. Asymmetry measurements.
   - Inclusive Asymmetries: Q^2 of 0.8, 1.3 and 1.8 $(GeV/c)^2$
   - Elastic Asymmetries:

     Measured the elastic asymmetries at magnetic field of 80^0 and hence the ratio of form factors, $\mu_p G_E^p / G_M^p$

     - From single arm data at $Q^2 = 2.06\ (GeV/c)^2$
     - From coincidence data at $Q^2 = 5.66\ (GeV/c)^2$

Physics Motivation

Elastic scattering in one-photon exchange (BORN) approximation



The differential cross section describing the scattering of a particle into an element of solid angle, dΩ in the lab frame,

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2}\left(\frac{E_3}{ME_1}\right)^2 \mid M_{fi} \mid^2$$

The invariant amplitude of the e$^-$N reaction is,

$$-iM = \bar{u}(k')(ig_e\gamma^\mu)u(k)\left(-i\frac{g_{\mu\nu}}{q^2}\right)\bar{u}(p')(-ig_e\Gamma^\nu)u(p)$$

For pure QED interactions,

$$\Gamma^\nu = \gamma^\nu F_1(q^2) + i\sigma^{\nu\alpha}\frac{q_\alpha}{2M}F_2(q^2)$$

The four-momentum transfer squared,

$$Q^2 = -q^2 = 4E_1E_3\sin^2\left(\frac{\theta}{2}\right)$$

$$E_1 - E_3 = Q^2/2M$$

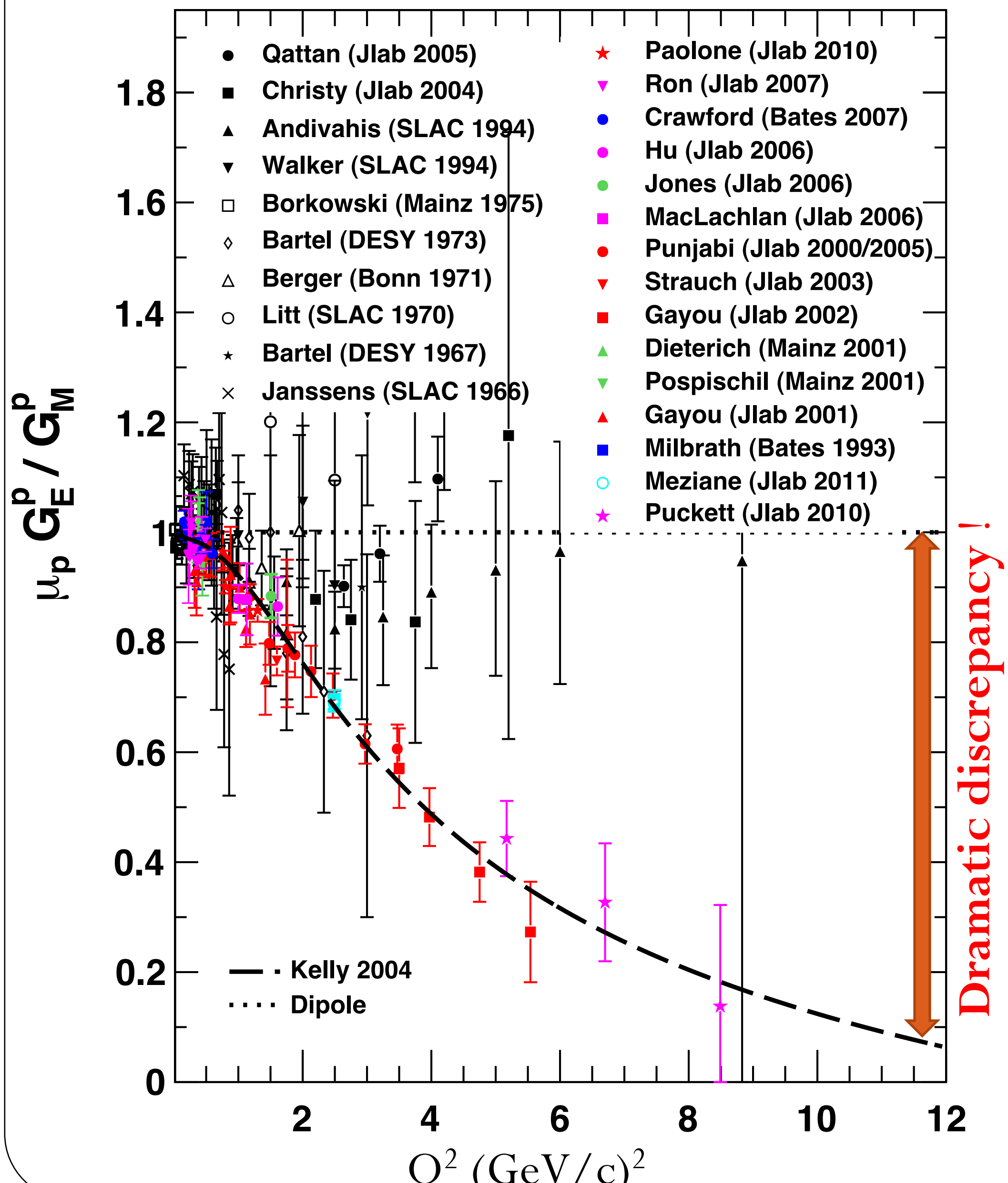
F_1 – non-spin flip (Dirac Form Factor) describe the charge distribution

F_2 – spin flip (Pauli form factor) describe the magnetic moment distribution

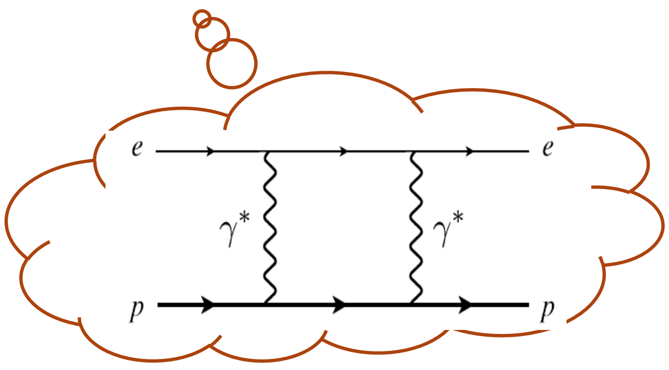
Sachs Form Factors $G_E(q^2) = F_1(q^2) - \tau F_2(q^2)$; $G_M(q^2) = F_1(q^2) + F_2(q^2)$

$$\tau = \frac{Q^2}{4M^2} = \frac{-q^2}{4M^2}$$

Form Factor Ratio at High Q^2



- Dramatic discrepancy between Rosenbluth and recoil polarization technique.
- Not only the slope of G^p_E at low Q^2 and hence the charge radius still uncertain, but also G^p_E/G^p_M is uncertain at high Q^2.
- Multi-photon exchange considered the best candidate for the dramatic discrepancy between Rosenbluth and recoil polarization technique.

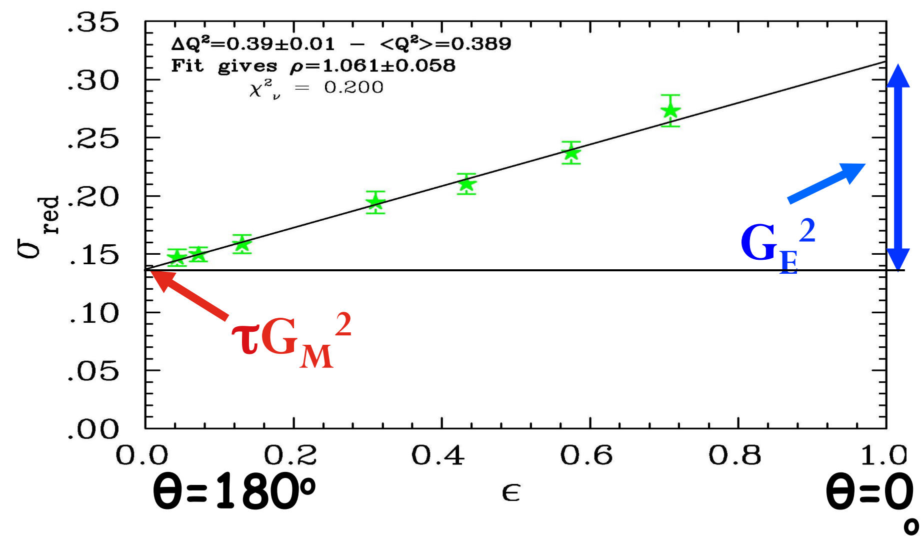


Form Factor Ratio Measurements

1. Rosenbluth Seperation Method.

- Measure the electron - unpolarized proton elastic scattering cross section at fixed Q^2 by varying the scattering angle, θ_e.
- Strongly sensitive to the radiative corrections.

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 E' \cos^2\frac{\theta_e}{2}}{\underbrace{4(1+\tau)E^3\sin^4\frac{\theta_e}{2}}_{\sigma_{Mott}/(1+\tau)}}\left[G_E^2 + \frac{\tau}{\varepsilon}G_M^2\right]$$



$$\frac{d\sigma}{d\Omega}\cdot\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = G_E^2\varepsilon + \tau G_M^2$$

$$Q^2 = 2EE'(1-\cos\theta_e) \qquad \tau = \frac{Q^2}{4M^2}$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

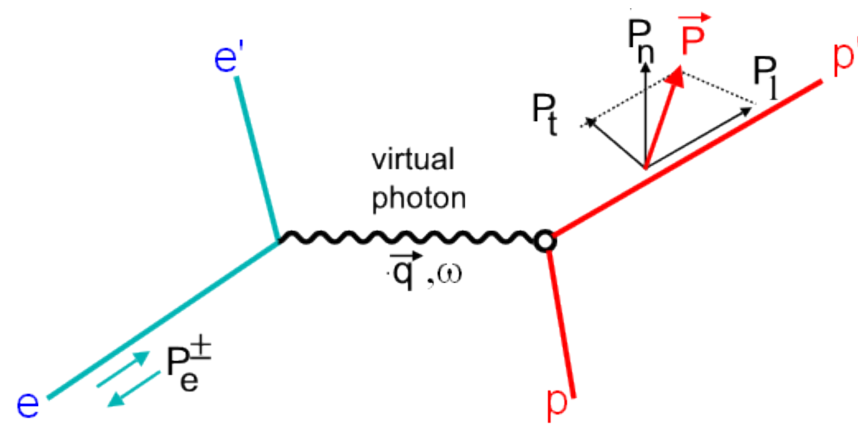
→ **Determine** $|G_E|$, $|G_M|$, $|G_E/G_M|$

E - Incoming electron energy
E′ - Outgoing electron energy
θ_e - Outgoing electron scattering angle
M - Proton mass

2. Polarization Transfer Technique.

- Measure the recoil proton polarization from the elastic scattering of polarized electron-unpolarized proton.
- Insensitive to absolute polarization, analyzing power.
- Less sensitive to radiative correction.

$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{(E+E')\tan\left(\theta_e/2\right)}{2M_p}$$



E - Incoming electron energy
E' - Outgoing electron energy
θ_e - Outgoing electron scattering angle
M_p - Proton mass

$$P_L = M_P^{-1}(E+E')\sqrt{\tau(1+\tau)}G_M^2\tan^2(\theta_e/2)$$ → Polarization along q

$$P_T = 2\sqrt{\tau(1+\tau)}G_E G_M\tan(\theta_e/2)$$ → Polarization perpendicular to q (in the scattering plane)

$$P_N = 0$$ → Polarization normal to scattering plane.

3. Double-Spin Asymmetry.

- Measure the cross section asymmetry between + and – electron helicity states in elastic scattering of a polarized electron on a polarized proton.
- The systematic errors are different when compared to either the Rosenbluth technique or the polarization transfer technique.
- The sensitivity to the form factor ratio is the same as the Polarization Transfer Technique.

$$A_P = \frac{-br\sin\theta^*\cos\phi^* - a\cos\theta^*}{r^2 + c}$$

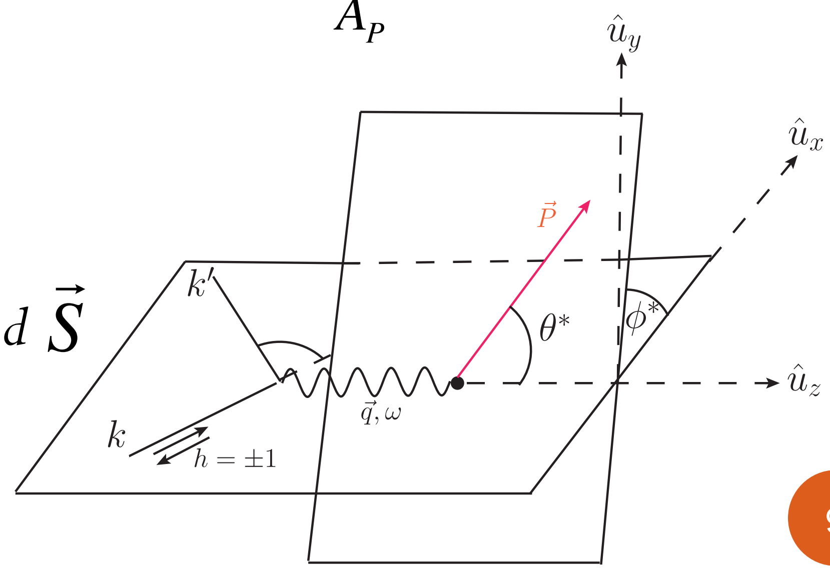
$$\frac{G_E}{G_M} = -\frac{b}{2A_p}\sin\theta^*\cos\phi^* + \sqrt{\frac{b^2}{4A_p^2}\sin^2\theta^*\cos^2\phi^* - \frac{a}{A_P}\cos\theta^* - c}$$

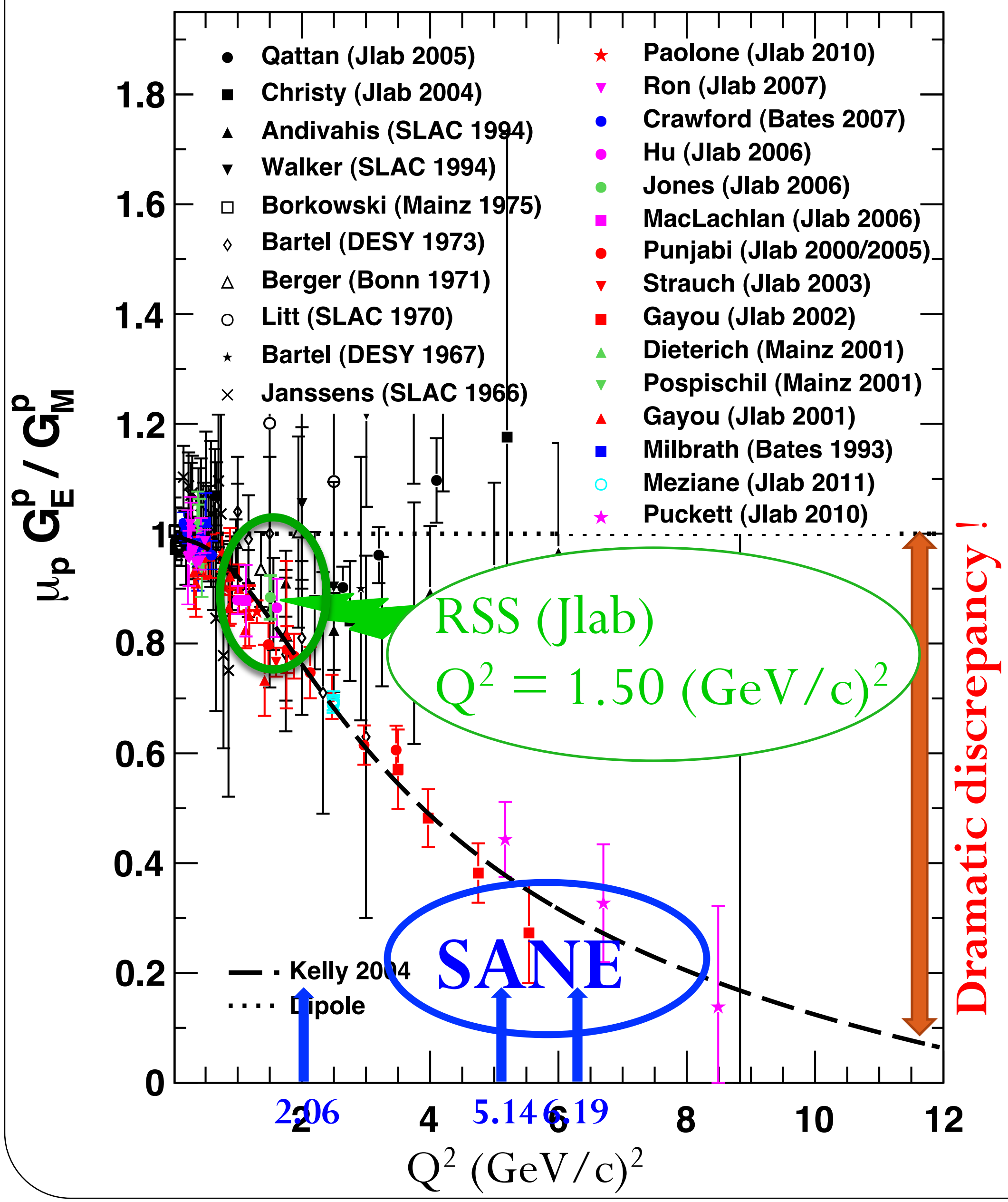
Here, $r = G_E / G_M$

$a, b, c = \textit{kinematic factors}$

$\theta^*, \phi^* = \textit{pol. and azi. Angles between } \vec{q} \textit{ and } \vec{S}$

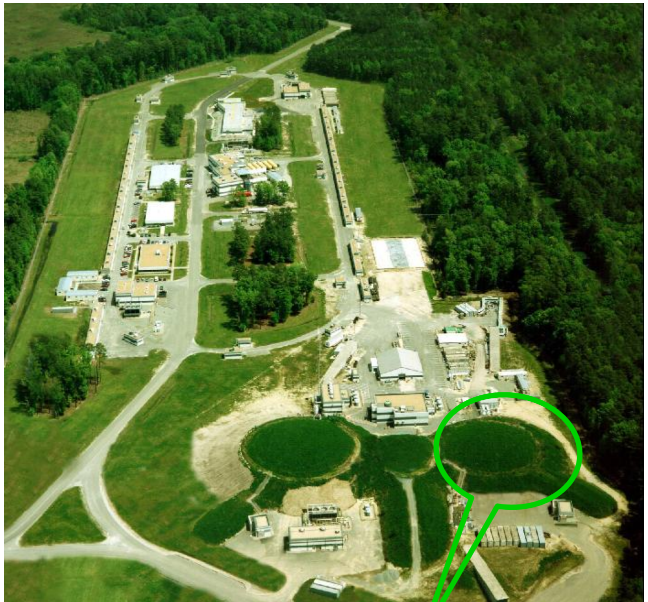
$A_p = \textit{The beam - target asymmetry}$

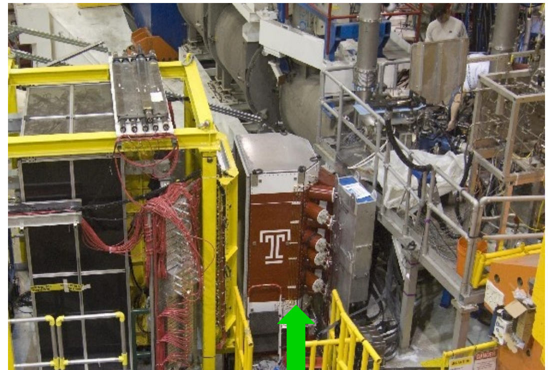




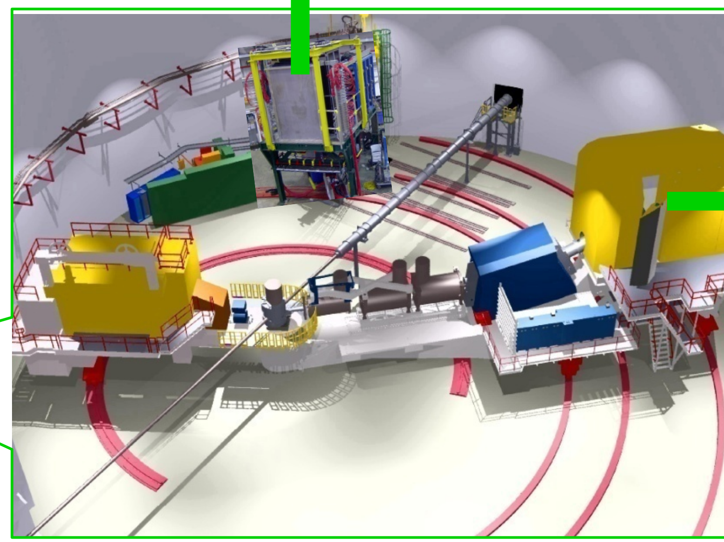
- Double-Spin Asymmetry is an independent technique to verify the discrepancy.

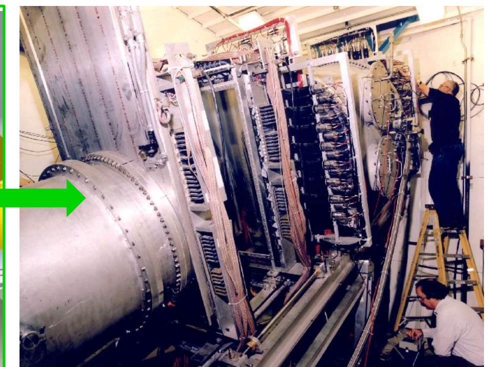
Experiment Setup





- BETA for coincidence electron detection
- Central scattering angle: 40°
- Over 200 msr solid angle coverage





Hall C at Jefferson Lab

- HMS for the scattered proton detection
- Central angles are 22.3° and 22.0°
- Solid angle ~10 msr

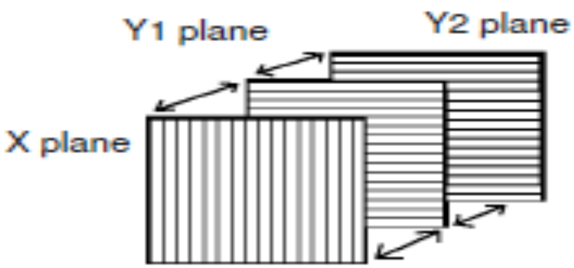
Elastic (e, e'p) scattering from the polarized NH_3 target using a longitudinally polarized electron beam

(Data collected from Jan – March, 2009)

Big Electron Telescope Array – BETA

Forward Tracker

- 3 planes of Bicron Scintillator provide early particle tracking

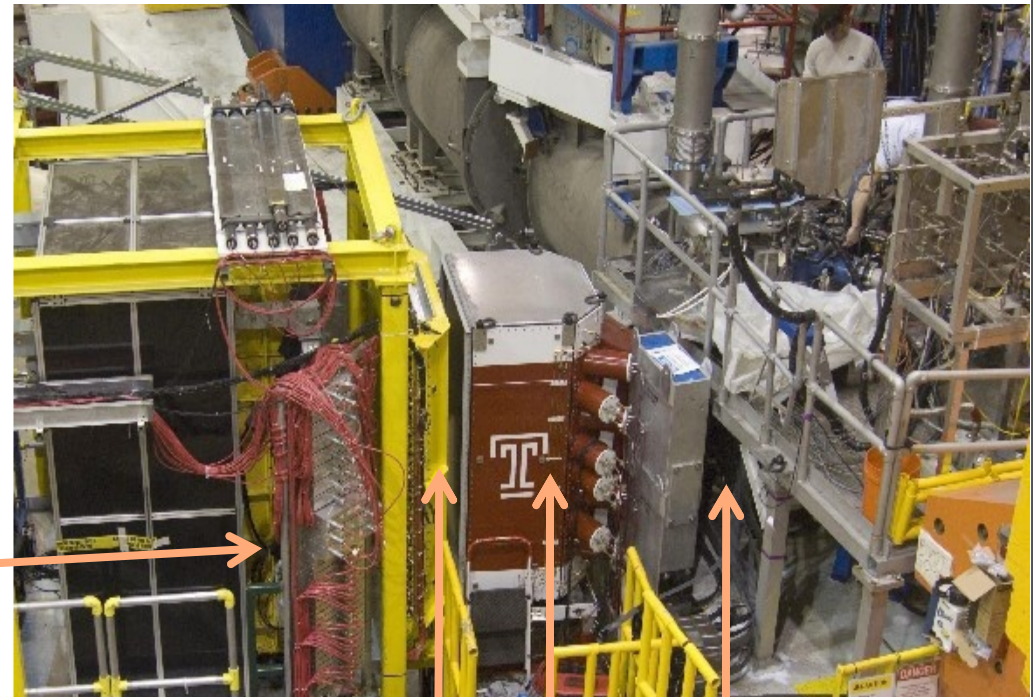


Cerenkov

- N_2 gas cerenkov
- Provides particle ID
- 8 mirrors and 8 PMTs

Lucite Hodescope

- 28 bars of 6cm wide Lucite
- Bars oriented horizontally for Y tracking
- PMTs on either side of bar provides X resolution



Big Cal (GEP III Collaboration)

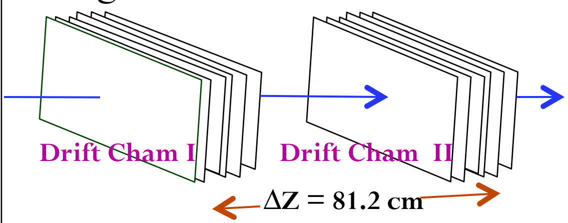
Lead glass calorimeter

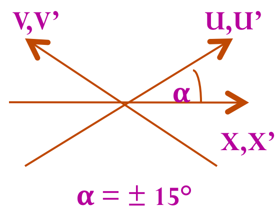
- 1744 blocks aprx. 4cm x 4cm
- energy and position measurement

High Momentum Spectrometer – HMS

Drift Chambers

- Each plane has a set of alternating field and sense wires Filled with an equal parts Argon-Methane mixture

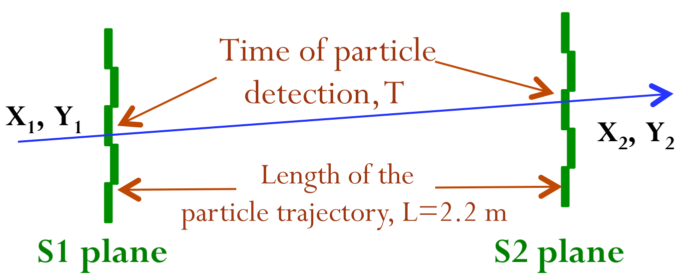




- Track particle trajectory by multiple planes.
- χ^2 fitting to determine a straight trajectory.

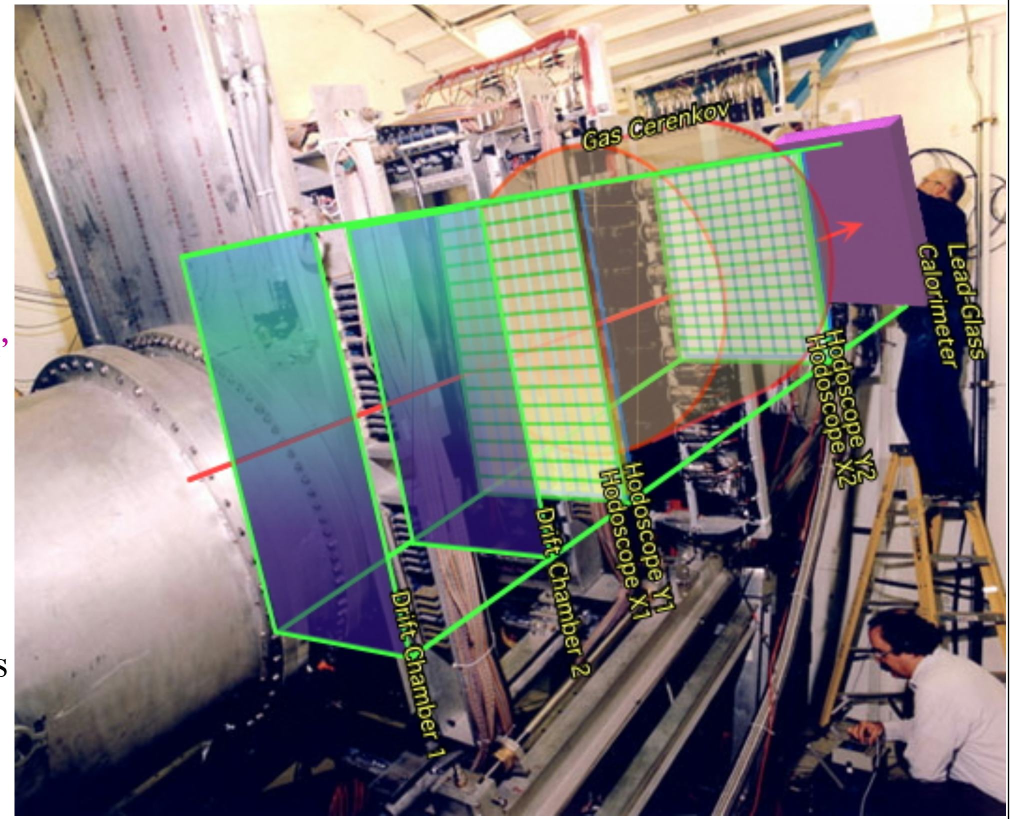
Hodoscopes

- Each plane contains 10 to 16 Scintillator paddles with PMTs on both ends
- Each Paddle is 1.0 cm thick and 8.0 cm wide



- Fast position determination & triggering
- Time of Flight (TOF) = T2-T1 determines β

($\beta = L/c \times TOF$)



Gas Cerenkov

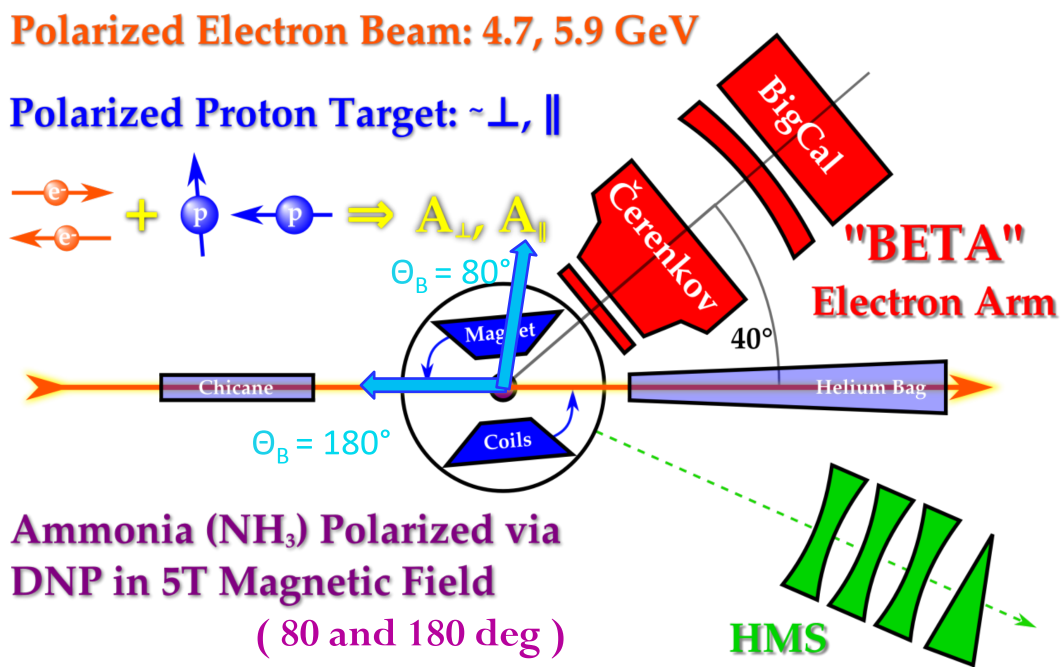
- Two mirrors (top & bottom) connected to two PMTs
- Used as a Particle ID

Lead Glass Calorimeter

- 4 layers of 10 cm x 10cm x70cm blocks stacked 13 high.
- Used as a Particle ID

Polarized Target Magnetic Field

- Used Dynamic Nuclear Polarization (DNP) to polarized NH_3 target.



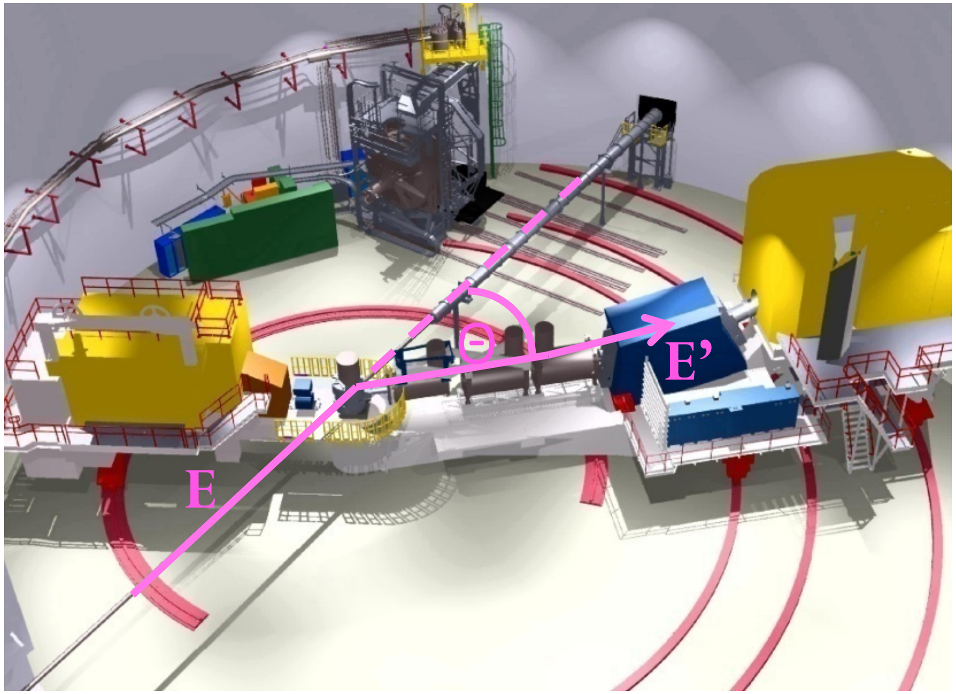
- Used only perpendicular magnetic field configuration for the elastic data

- Average target polarization is ~ 70 %
- Average beam polarization is ~ 73 %

Elastic Kinematics
(From HMS Spectrometer)

Spectrometer mode	Coincidence	Coincidence	Single Arm
HMS Detects	Proton	Proton	Electron
E Beam GeV	4.72	5.89	5.89
P_{HMS} GeV/c	3.58	4.17	4.40
Θ_{HMS} (Deg)	22.30	22.00	15.40
Q^2 $(GeV/c)^2$	5.14	6.19	2.06
Total Hours (h)	~40 (~44 runs)	~155 (~135 runs)	~12 (~15 runs)
Elastic Events	~113	~1200	~2 x 10^4

Single-arm Data
(Electrons in HMS)



$\vec{e}^- \, \vec{p} \longrightarrow e^- \, p$

By knowing,

the incoming beam energy, E,

scattered electron energy, E'

and

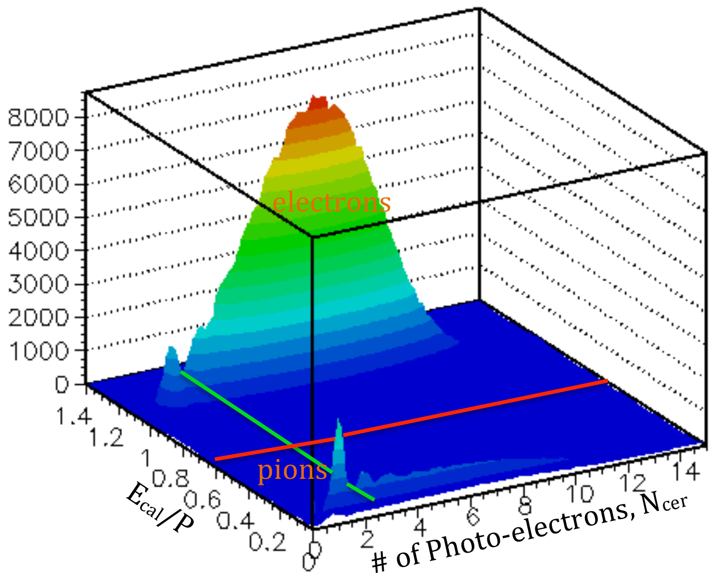
the scattered electron angle, θ

$$Q^2 = 4EE' \sin^2\left(\frac{\theta}{2}\right)$$

$$W^2 = M^2 - Q^2 + 2M(E - E')$$

Elastic Event Selection

- Particle Identification (PID)



Used the Cherenkov and calorimeter cuts,

# of Cerenkov photoelectrons > 2

$$E_{Cal}/P > 0.7$$

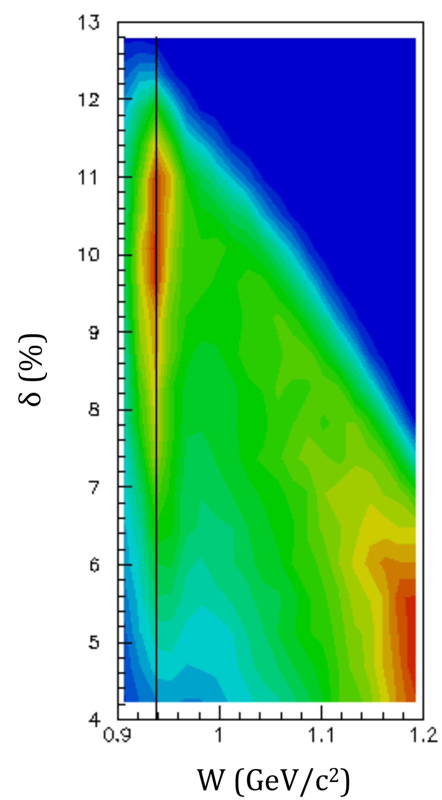
E_{Cal} - Total measured shower energy of a chosen electron track by HMS Calorimeter

- The Relative Momentum (δ)

$$\delta = (P - P_C)/P_C$$

P - Measured momentum in HMS

P_c - HMS central momentum



Used the relative momentum acceptance cuts,

$-8\% < \delta < 10\%$

$10\% < \delta < 12\%$

Extracted the Asymmetries

The raw asymmetry, A_r

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

$$\Delta A_r = \frac{2\sqrt{N^+}\sqrt{N^-}}{(N^+ + N^-)\sqrt{(N^+ + N^-)}}$$

N^+ / N^- = *Charge and live time normalized counts for the +/- helicities*

ΔA_r = *Error on the raw asymmetry*

Need dilution factor, *f* in order to determine the physics asymmetry, and G^p_E/G^p_M(at Q^2=2.2 (GeV/c)^2)

$$A_p = \frac{A_r}{fP_BP_T} + N_C$$

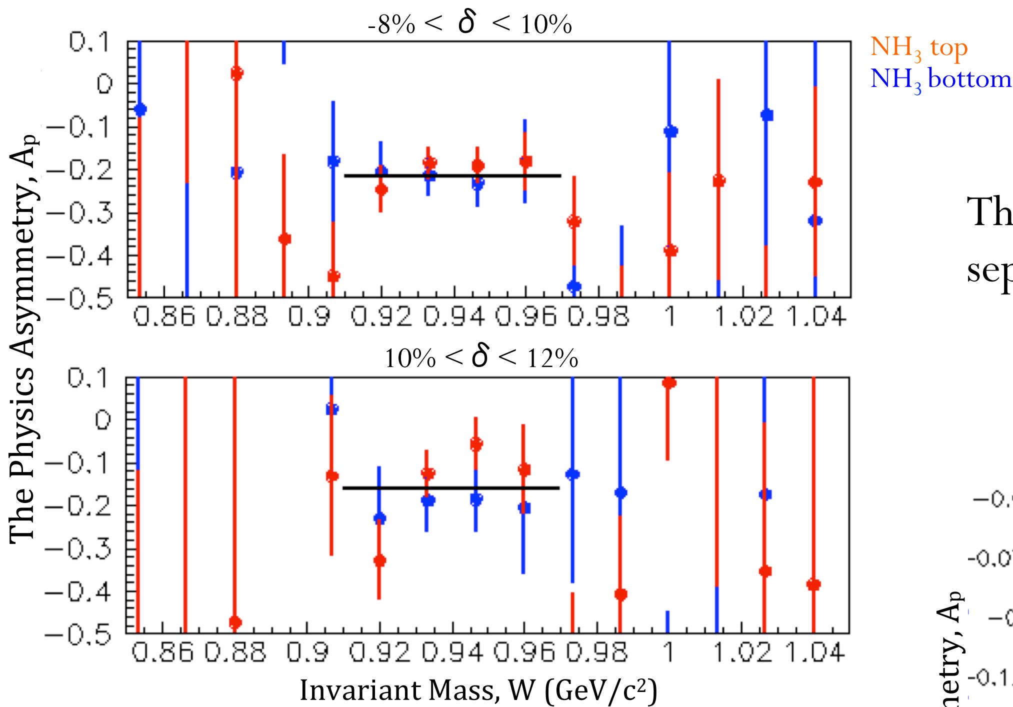
f = *The dilution factor : The ratio of the yield from scattering off free protons (protons from H in NH3) to that from the entire target (protons from N, H, He and Al)*

P_BP_T = *Beam and target polarization*

N_c = *A correction term to eliminate the contribution from quasi-elastic scattering on polarized ^{14}N under the elastic peak (negligible in SANE)*

Use MC/DATA comparison for NH_3 target to extract the dilution factor.....

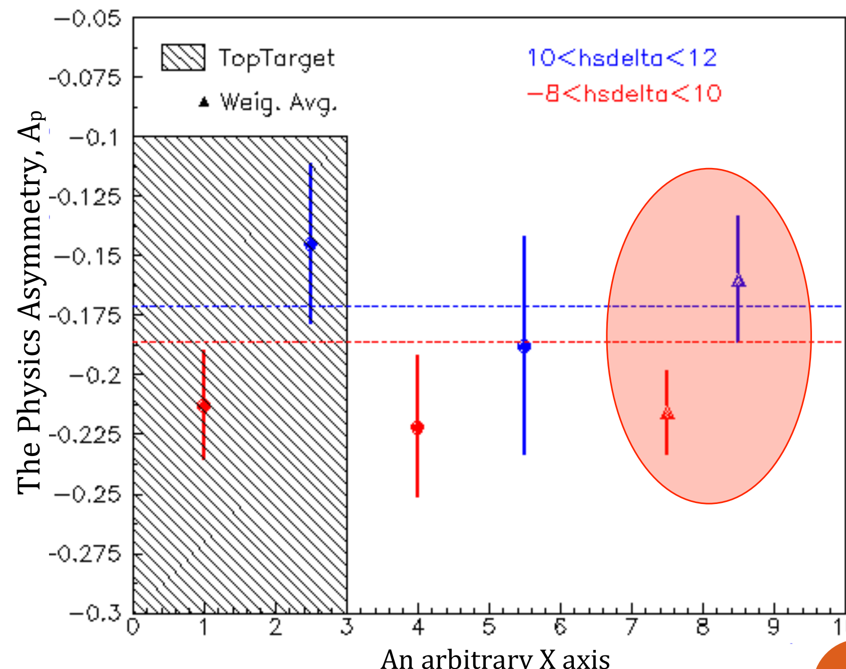
The Physics Asymmetry



The constant physics asymmetry, Ap were read separately,

For each target type and

For two different δ regions.



- The weighted average Ap of top and bottom targets were taken.
- The expected physics asymmetries from the known form factor ratio for each Q^2 by Kellys form factor parameterization (J. J. Kelly, Phys. Rev. C70(6), 2004) are shown by dashed lines separately for the two δ regions.

Elastic Kinematics
(From HMS Spectrometer)

Spectrometer mode	Coincidence	Coincidence	Single Arm
HMS Detects	Proton	Proton	Electron
E Beam GeV	4.72	5.89	5.89
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Total Hours (h)	~40 (~44 runs)	~155 (~135 runs)	~12 (~15 runs)
e-p Events	~113	~1200	~2 x 10^4

Coincidence Data
(Electrons in BETA and Protons in HMS)

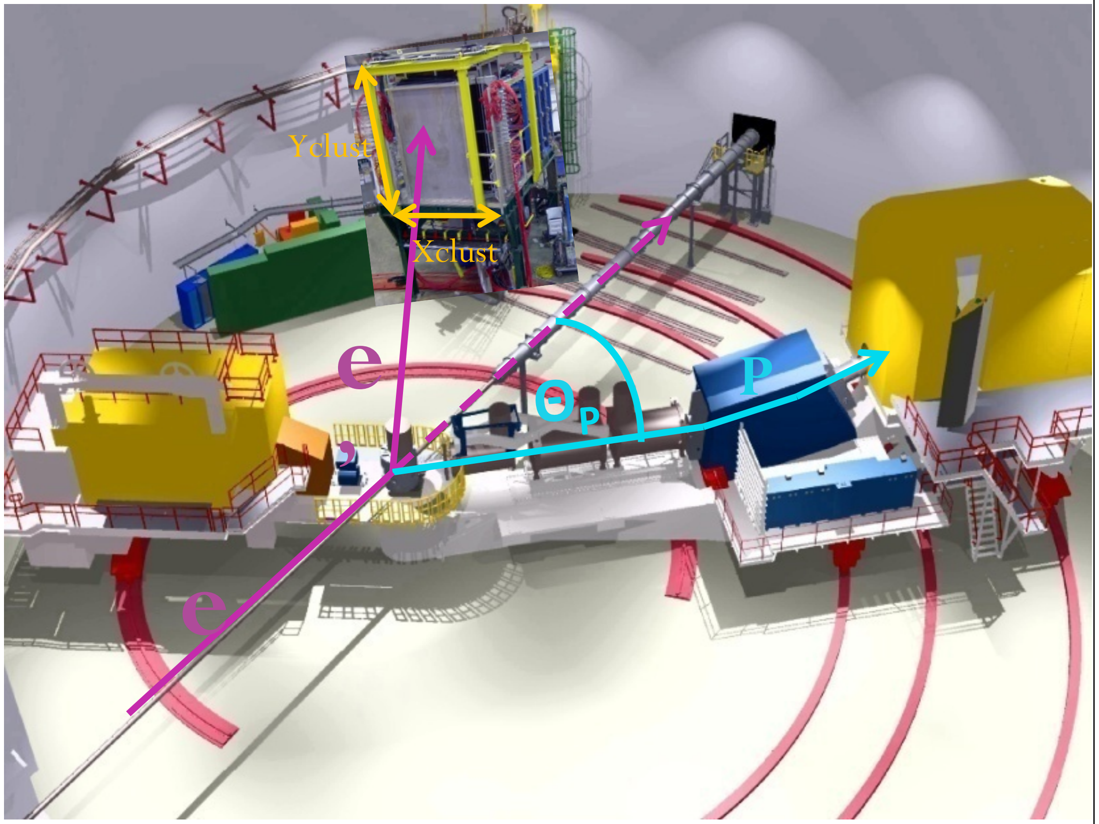
<u>Definitions :</u>

- *X/Yclust - Measured X/Y positions on BigCal*

  X = horizontal /in-plane coordinate

  Y = vertical / out – of – plane coordinate

By knowing
the energy of the polarized electron beam, E_B
and
the scattered proton angle, Θ_P



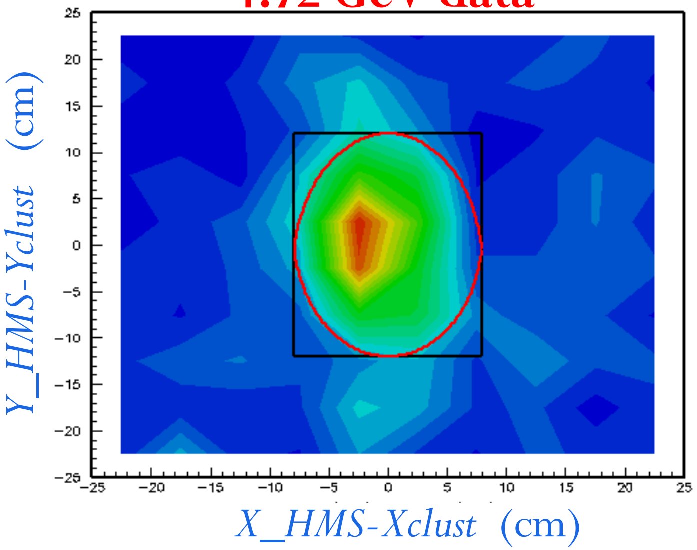
We can predict the
- X/Y coordinates , X_HMS, Y_HMS on the BigCal

(Target Magnetic Field Corrected)

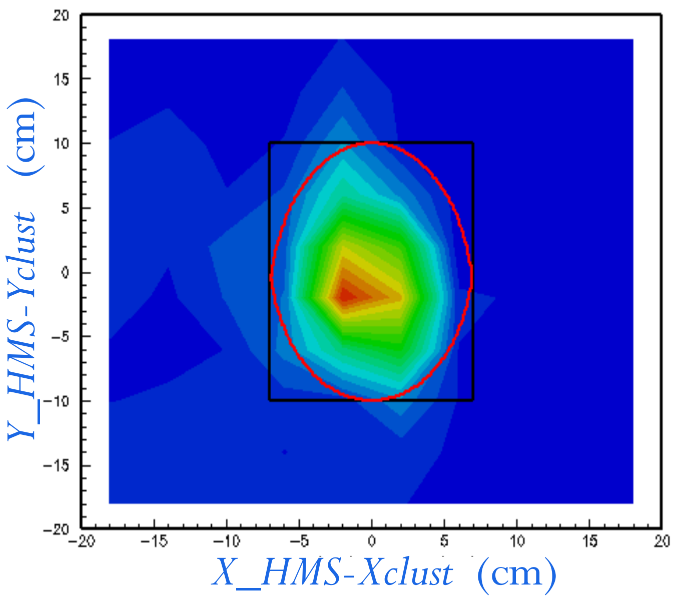
$\Delta X = X\_HMS - Xclust$
$\Delta Y = Y\_HMS - Yclust$

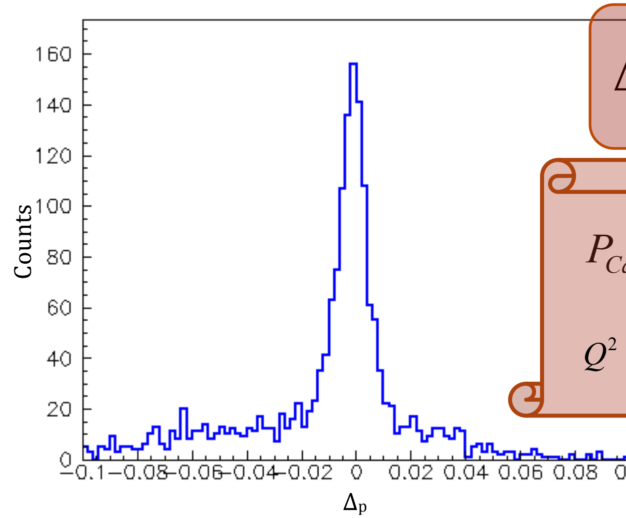
Elastic Event Selection

4.72 GeV data



5.89 GeV data





$$\Delta_P = \frac{\delta p}{p} = \frac{P_{HMS} - P_{Cal}}{P_{cent}}$$

$$P_{Cal} = \sqrt{\left(\nu^2 + 2M\nu\right)} \qquad \nu = \frac{Q^2}{2M}$$

$$Q^2 = \frac{4M^2E^2\cos^2\theta}{M^2 + 2ME + E^2\sin^2\theta}$$

P_{HMS} – Measured proton momentum by HMS

P_{cal} - Calculated proton momentum.

P_{cent} – HMS central momentum

- The relative momentum cut,

$$-0.02 \le \Delta_P \le +0.02$$

- The Elliptic cut,

$$\left(\frac{\Delta X}{X_{\max}}\right)^2 + \left(\frac{\Delta Y}{Y_{\max}}\right)^2 \le 1$$

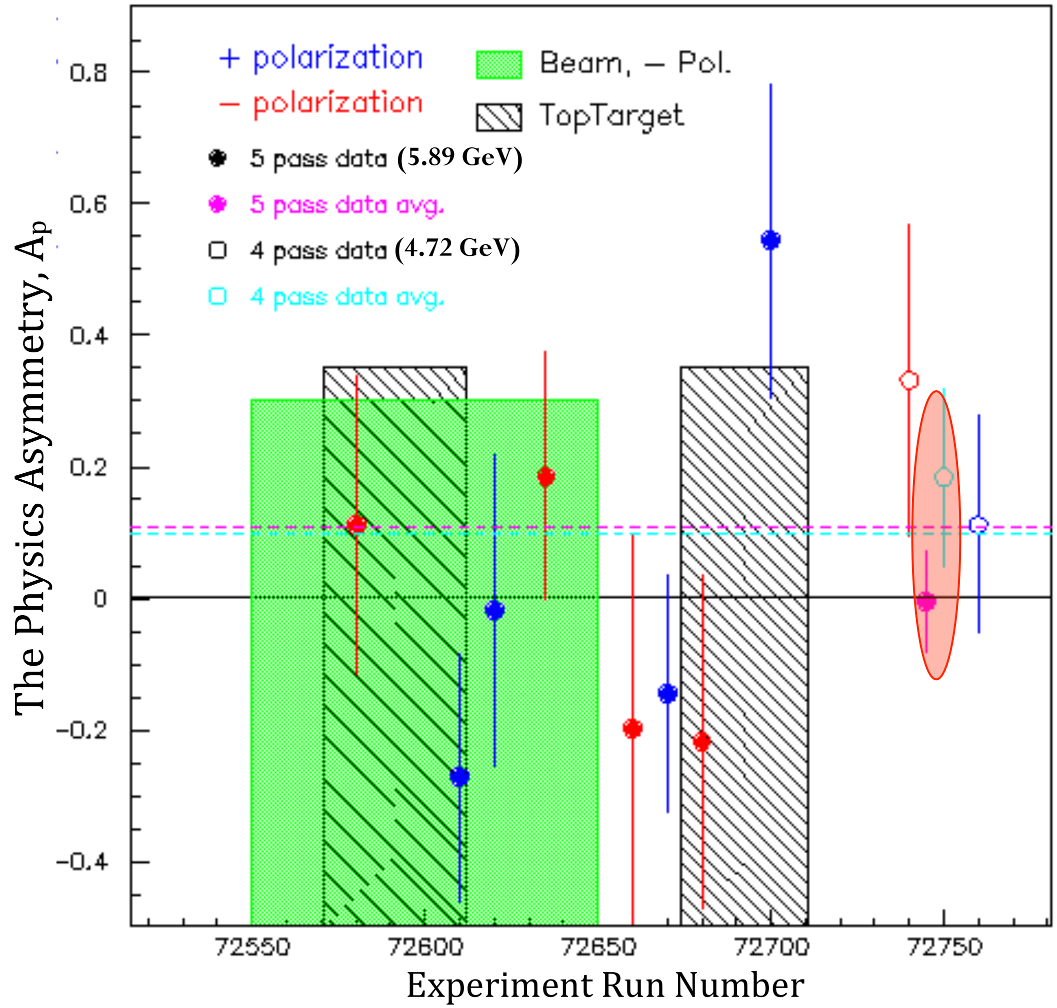
Suppresses background most effectively

Here, $X(Y)_{max}$ = The effective area cut, 10 (7) cm

The Physics Asymmetry

- The weighted average Ap and their errors for the two beam energies, 5.895 GeV and 4.730 GeV are also shown.

- The expected physics asymmetries from the known form factor ratio for each Q^2 by Kelly's form factor parameterization (J. J. Kelly, Phys. Rev. C70(6), 2004) for the two beam energies are shown by dashed lines.



The resulting form factor ratio is obtained by,

Extrapolating both measurements to average Q^2 using Kelly's parameterization and

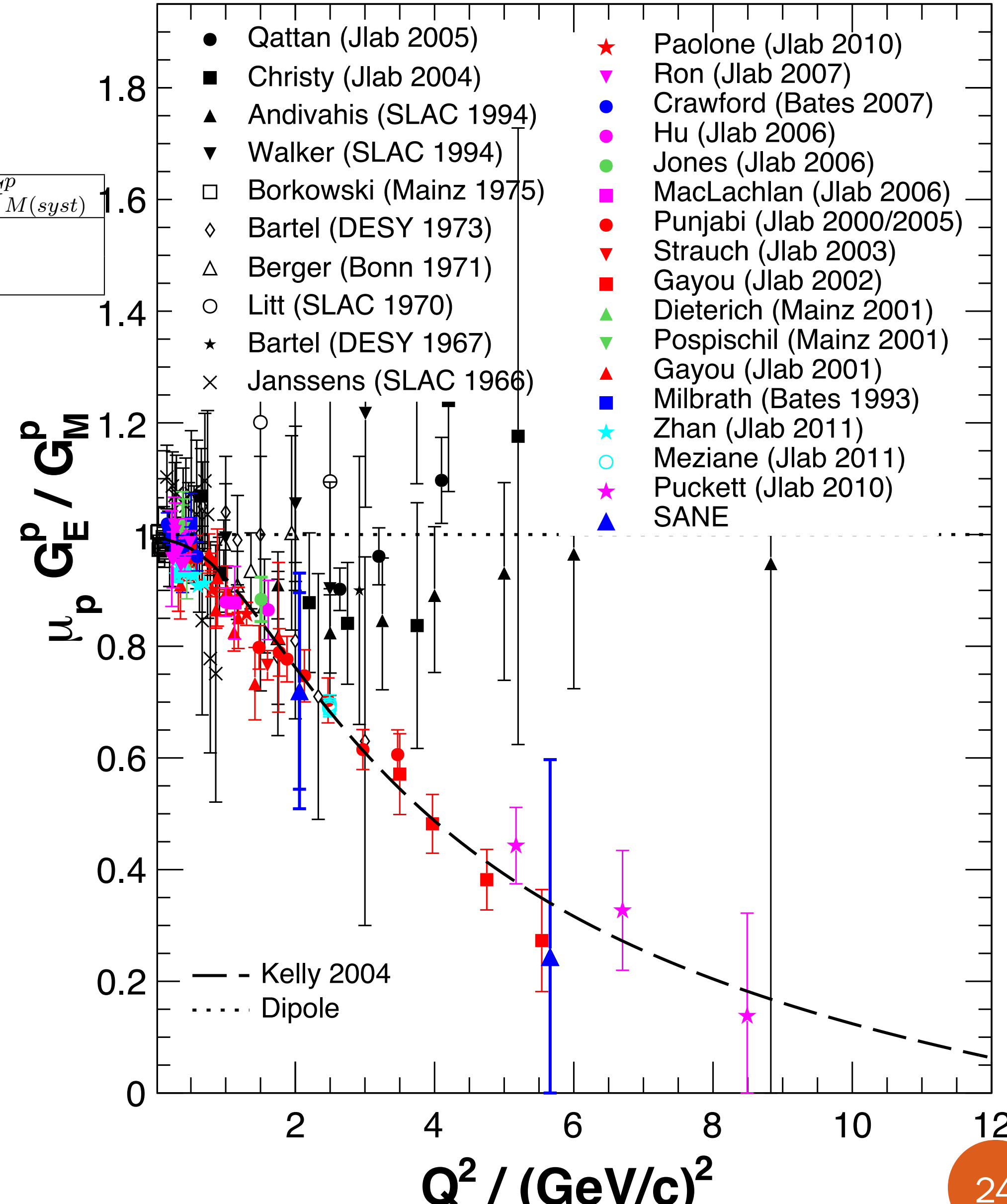
Taking the weighted average.

Q^2_{Avg} (GeV/c)^2	$\mu_p G_E^p/G_M^p \pm \Delta\mu_p G_E^p/G^p_{M(stat)} \pm \Delta\mu_p G_E^p/G^p_{M(syst)}$
2.06	0.720 ± 0.176 ± 0.033
5.66	0.244 ± 0.353

The total relative systematic uncertainty on $\mu_p G^p_E/G^p_M$ has been estimated as 5.44%

- Because of the higher error bar on the coincidence data point at Q^2=5.66 (GeV/c)^2, the systematic uncertainty studies were not done.

For the higher Q^2, Only the statistical error is shown in the plot.



Conclusion

- Extraction of the G^p_E/G^p_M ratio from single-arm electron and coincidence data are shown.
- Measurement of the beam-target asymmetry in elastic electron-proton scattering offers an independent technique of determining the G^p_E/G^p_M ratio.
- **This is an 'exploratory' measurement, as a by-product of the SANE experiment.**
- The data point at $Q^2=2.06$ $(GeV/c)^2$ is very consistent with the recoil polarization data.
- The weighted average data point of the coincidence data at $Q^2=5.66$ $(GeV/c)^2$ has large error due to the lack of elastic events.
- Dedicated precision experiment feasible.
- Publication is underway !

SANE Collaborators:
Argonne National Laboratory, Christopher Newport U., Florida International U., Hampton U., Thomas Jefferson National Accelerator Facility, Mississippi State U., North Carolina A&T State U., Norfolk S. U., Ohio U., Institute for High Energy Physics, U. of Regina, Rensselaer Polytechnic I., Rutgers U., Seoul National U., State University at New Orleans ,Temple U.,Tohoku U., U. of New Hampshire, U. of Virginia, College of William and Mary, Xavier University of Louisiana, Yerevan Physics Inst.

Spokespersons: S. Choi (Seoul), M. Jones (TJNAF), Z-E. Meziani (Temple), O. A. Rondon (UVA)

Thank You

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Backup Slides

Nucleon Elastic Form Factors (G_E, G_M)

- They are functions of the four-momentum transfer squared, Q^2
- Defined in context of single-photon exchange.
- Describe how much the nucleus deviates from a point like particle.
- Describe the internal structure of the nucleons.
- Provide the information on the spatial distribution of electric charge (by electric form factor, G^p_E) and magnetic moment (by magnetic form factor, G^p_M) within the proton.
- Can be determined from elastic electron-proton scattering.

At low $|q^2|$

$$G_E(q^2) \approx G_E(\vec{q}^{\,2}) = \int e^{i\vec{q}\cdot\vec{r}} \rho(\vec{r}) d^3\vec{r}$$

$$G_M(q^2) \approx G_M(\vec{q}^{\,2}) = \int e^{i\vec{q}\cdot\vec{r}} \mu(\vec{r}) d^3\vec{r}$$

Fourier transforms of the charge, $\rho(r)$ and magnetic moment, $\mu(r)$ distributions in Breit Frame

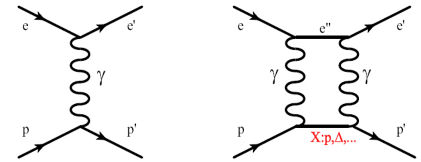
At $q^2 = 0$

$$G_E(0) = \int \rho(\vec{r}) d^3\vec{r} = 1$$

$$G_M(0) = \int \mu(\vec{r}) d^3\vec{r} = \mu_P = +2.79$$

$$\boxed{\mu_P \, G^p_E / G^p_M = 1}$$

Two-Photon Exchange

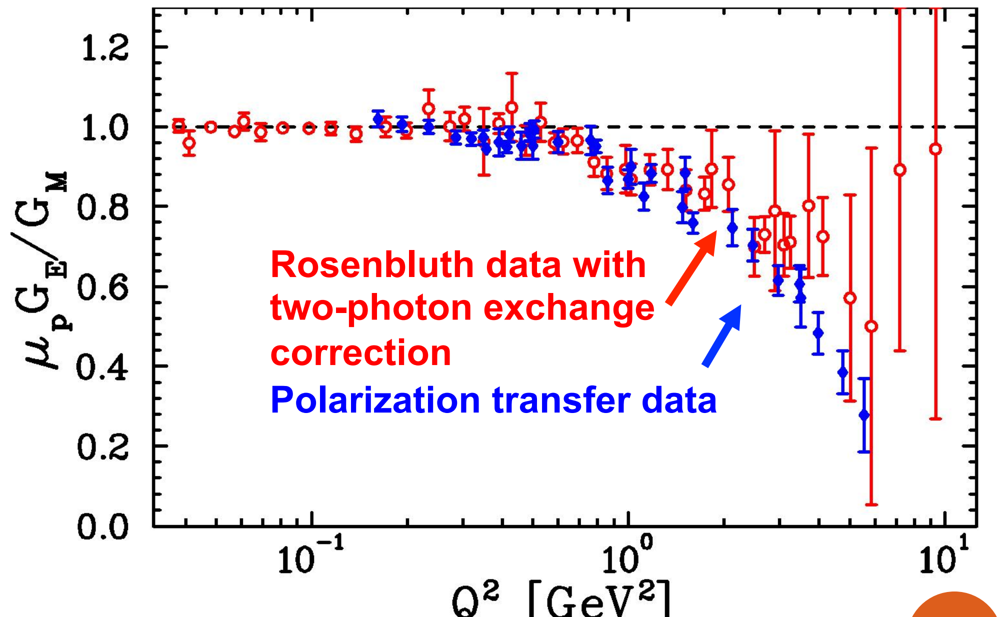


- Theoretically suggested to explain the dramatic discrepancy between Rosenbluth and recoil polarization technique.
- Both Rosenbluth method and the polarization transfer technique account for soft TPE correction, one soft and one hard photon exchange, but neither consider two hard photon exchange.
- TPE amplitude has been calculated theoretically.

$$\frac{\sigma_r}{G_M^2} = \underbrace{1+\frac{\varepsilon}{\tau}\frac{G_E^2}{G_M^2}}_{\text{Born}} + \underbrace{2\varepsilon\frac{G_E}{\tau G_M}\Re\left(\frac{\delta\tilde{G}_E}{G_M}\right)+\ldots..}_{\text{TPE}}$$

σ_r is the reduced cross section

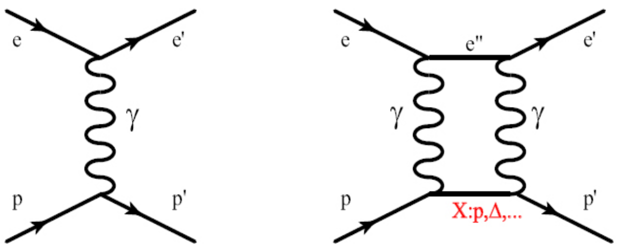
- TPE has an ε dependence that has the same sign as the G_E contribution to the cross section.
- This is large enough to effect the extra- -cted value of G_E
- Therefore, the extracted G_E/G_M for the Rosenbluth technique is reduced.
- TPE can explain form factor discrepancy.
- The effect of TPE amplitude on the polarization components is small, though the size of the contribution change with ε .



J. Arrington, W. Melnitchouk, J.A. Tjon, Phys. Rev. C 76 (2007) 035205

Two-Photon Exchange: Exp. Evidence

Theoretical suggestion is not enough !!!



The size of the TPE can be measured by,

- Taking the ratio of cross sections, R for elastic electron-proton scattering to positron-proton scattering at a fixed Q^2
- Measuring the deviation of R from 1.

$$R = \frac{\sigma_{e+}}{\sigma_{e-}} = \frac{\left(A_{1\gamma} + A_{2\gamma}\right)^2}{\left(A_{1\gamma} - A_{2\gamma}\right)^2} \approx 1 + 4\,\mathrm{Re}\left(A_{2\gamma} / A_{1\gamma} \right)$$

- The dedicated experiments at OLYMPUS, CLAS at Hall B and Novosibirsk/ VEPP-3 test the hypothesis of TPE.

OLYMPUS/DESY: analysis in progress

CLAS/Jlab:
D. Rimal et al., arXiv:1603.00315v1
D. Adikaram et al., PRL 114, 062003 (2015)

Novosibirsk/VEPP-3:
I.A. Rachek et al., PRL 114, 062005 (2015)

Proton Radius Puzzle

Accurate knowledge of G^p_E at low Q^2 is important to determine the proton charge radius.

At low Q^2,

$$G_E(\mathbf{q^2}) = \int_0^\infty \rho(r) r^2\, dr \int_0^\pi \sin\theta\, d\theta \left(1 + i|\mathbf{q}|r\cos\theta - \frac{1}{2}\mathbf{q}^2 r^2 \cos^2\theta + \ldots\right)$$

$$G_E(\mathbf{q^2}) = 1 - \frac{1}{6}\mathbf{q}^2 \int |\mathbf{x}|^2 \rho(|\mathbf{x}|)\, d^3\mathbf{x} + \ldots$$

$$= 1 - \frac{1}{6}\mathbf{q}^2 \left\langle r^2 \right\rangle + \ldots$$

In electron scattering, the root-mean-square radius, r is defined in terms of the slope of the electric form factor at Q^2=0

$$\langle r_E^2 \rangle = -6 \frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

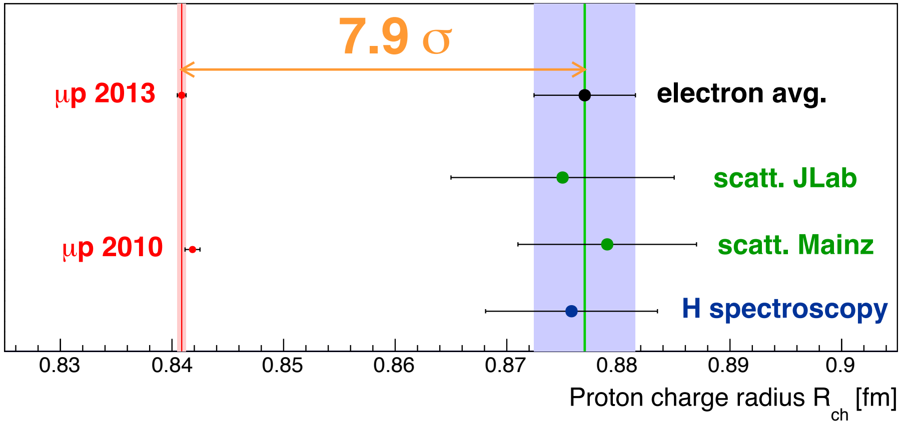
- 7 σ discrepancy between muonic hydrogen Lamb shift and combined electronic Lamb shift and electron scattering

↓

proton radius puzzle

↓

One possible reason is the systematic uncertainty of G^p_E measurement at low Q^2



Plot inherited from J. Bernauer

Test : μ P scattering (MUSE)

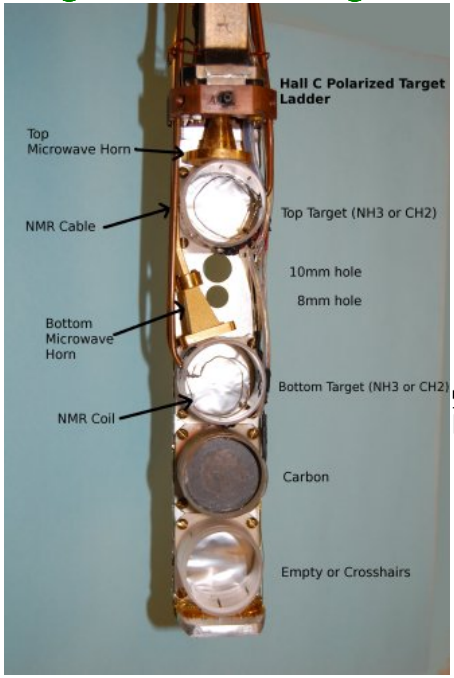
Polarized Target

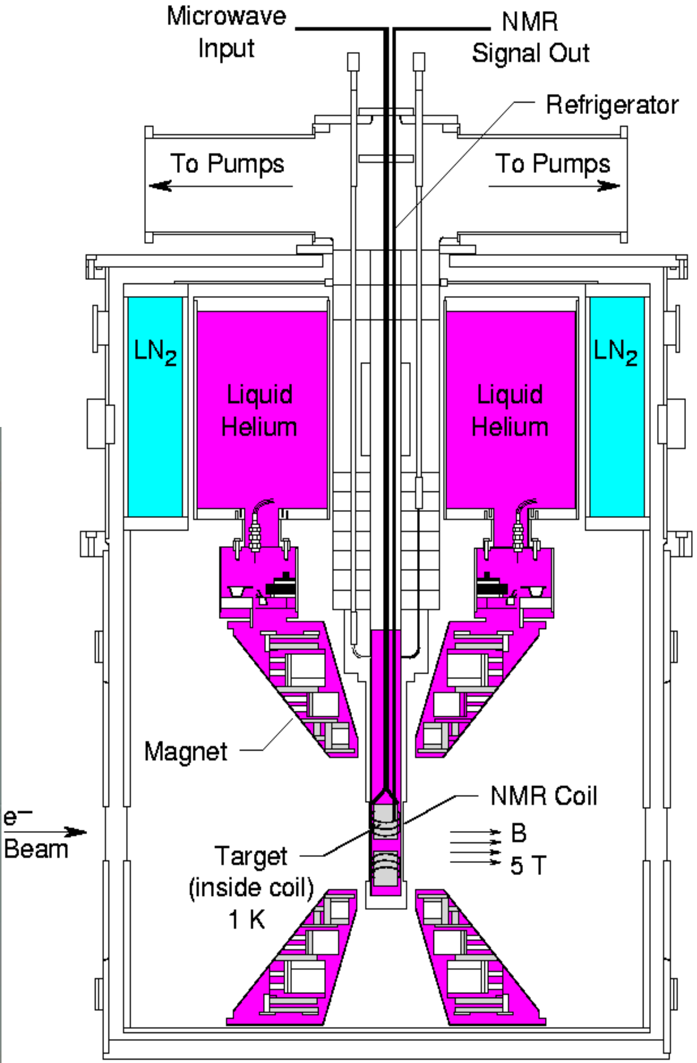
- C, CH_2 and NH_3
- Dynamic Nuclear Polarization (DNP) polarized the protons in the NH_3 target up to 90% at

  1 K Temperature

  5 T Magnetic Field
- Temperature is maintained by immersing the entire target in the liquid He bath
- Used microwaves to excite spin flip transitions

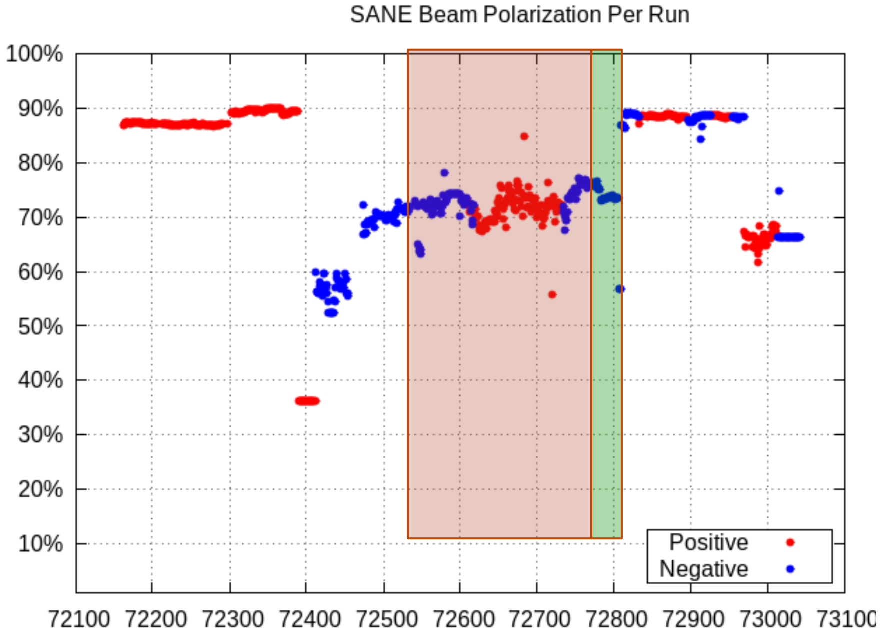
  (55 GHz - 165 GHz)
- Polarization measured using NMR coils
- To maintain reasonable target polarization, the beam current,
  - ➢ limited to 100 nA
  - ➢ was uniformly rastered.





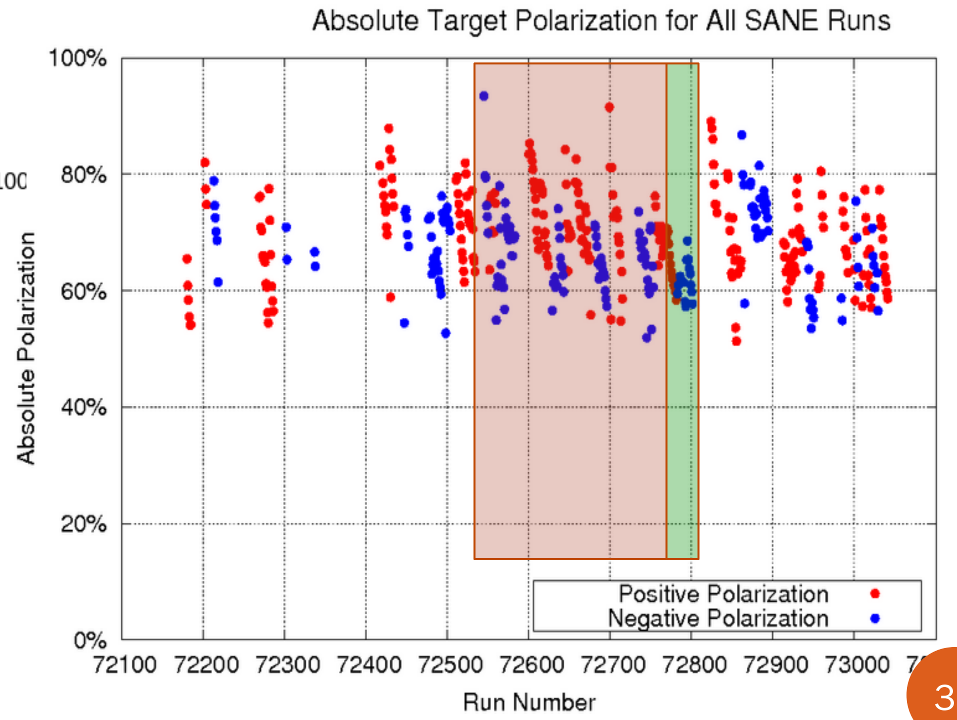
The Polarized Target Assembly

Beam / Target Polarizations



COIN data

Single arm electron data



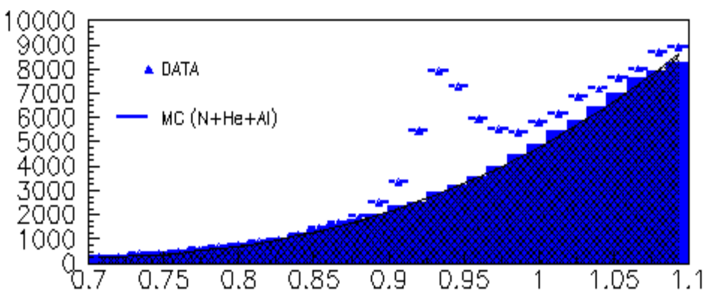
Determination of the Dilution Factor

What is the Dilution Factor ?

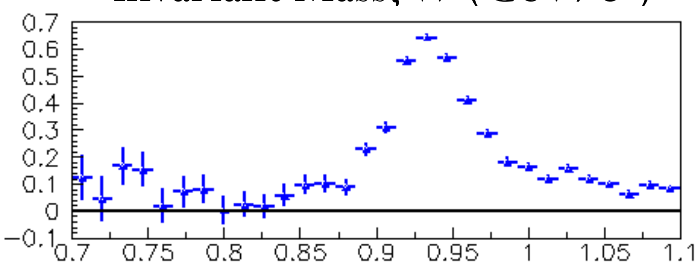
The dilution factor is the ratio of the yield from scattering off free protons(protons from H in NH_3) to that from the entire target (protons from N, H, He and Al)

Dilution Factor,

$$F = \frac{Yield_{Data} - Yield_{MC(N+He+Al)}}{Yield_{Data}}$$



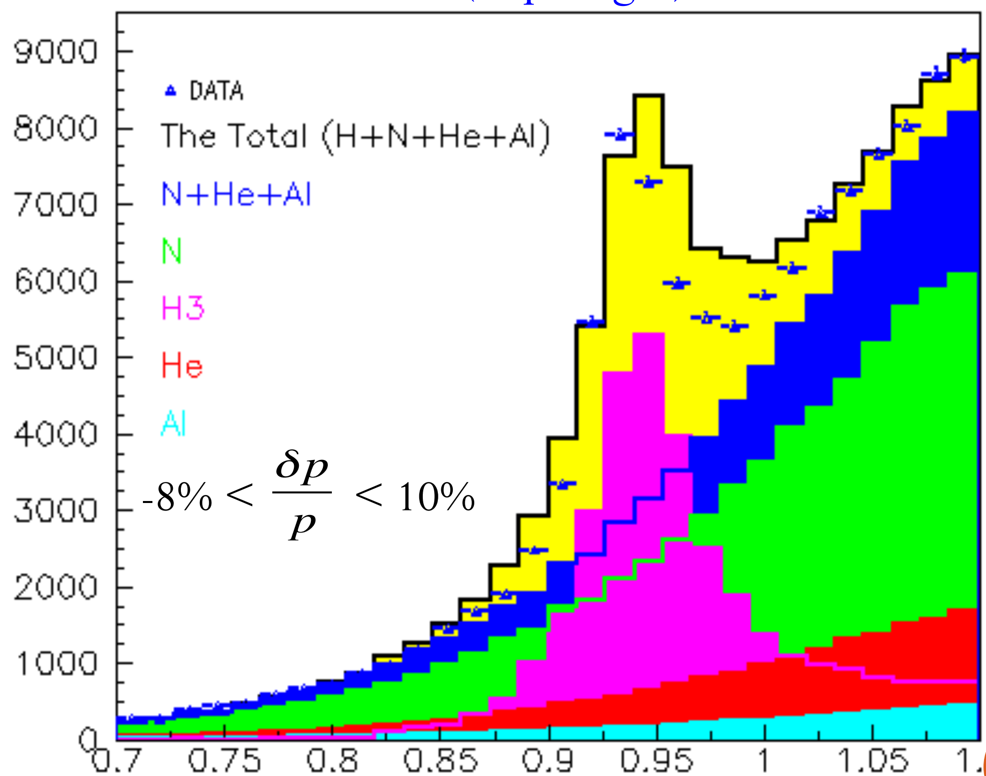
Invariant Mass, W (GeV/c^2)



The Relative Dilution Factor

Each target type contributions

(Top target)



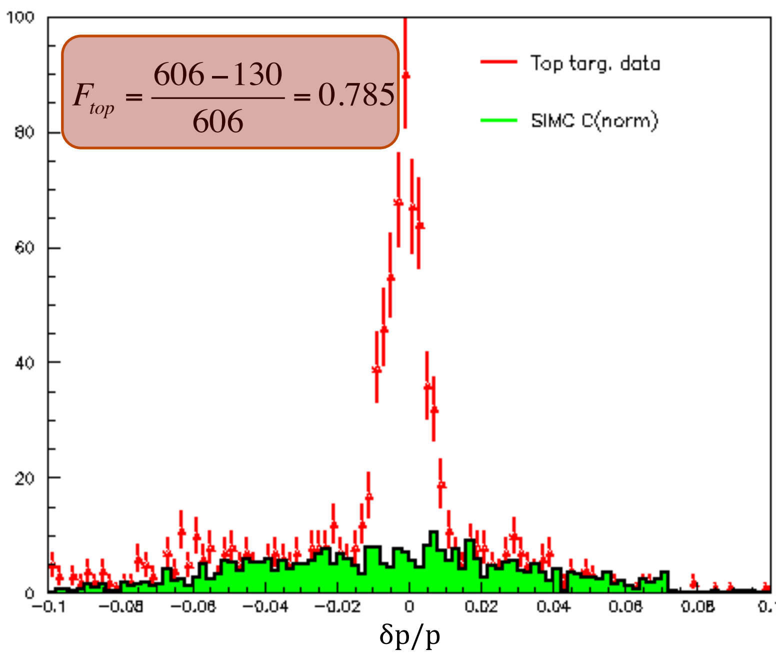
Invariant Mass, W (GeV/c^2)

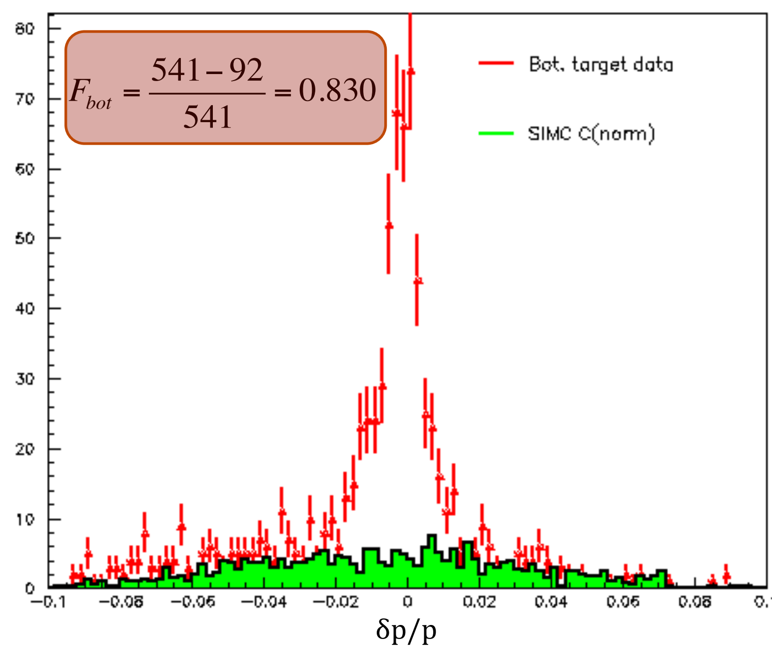
Determination of the Dilution Factor

- The background shape under the elastic peak was generated using carbon target.
- The simulated carbon yields are then normalized by the scaling factor calculated from data/MC yields for the region 0.03< δ <0.08.
- Data were taken using both top and bottom targets.
- Due to low statistics, an average dilution factor has calculated using an integration method.
- Integrals were taken only for the region -0.02< δ <0.02.

Dilution Factor,

$$F = \frac{Yield_{Data} - Yield_{MC(C)}}{Yield_{Data}}$$





Form Factor Ratio Extraction

- The beam - target asymmetry, A_p

$$A_P = \frac{-br\sin\theta^* \cos\phi^* - a\cos\theta^*}{r^2 + c}$$

θ^* and ϕ^* are calculated from,

$$\theta^* = \arccos(-\sin\theta_q \cos\phi_e \sin\beta + \cos\theta_q \cos\beta)$$

$$\phi^* = -\arctan\left(\frac{\sin\phi_e \sin\beta}{\cos\theta_q \cos\phi_e \sin\beta + \sin\theta_q \cos\beta}\right) + 180^\circ$$

θ q is the 4-momentum angle determined from data.
β is the target magnetic field direction, 80° to the beam axis.

a, b, c are the kinematic factors determined from,

$$a = 2\tau \tan\frac{\theta_e}{2}\sqrt{1 + \tau + (1+\tau)^2 \tan^2\frac{\theta_e}{2}}$$

$$b = 2\tan\frac{\theta_e}{2}\sqrt{\tau(1+\tau)}$$

$$c = \tau + 2\tau(1+\tau)\tan^2\frac{\theta_e}{2}$$

with

$$\tau = \frac{Q^2}{4M^2}$$

- The G^p_E/G^p_M is extracted by,

$$\frac{G_E}{G_M} = -\frac{b}{2A_p}\sin\theta^* \cos\phi^* + \sqrt{\frac{b^2}{4A_p^2}\sin^2\theta^* \cos^2\phi^* - \frac{a}{A_P}\cos\theta^* - c}$$

$$\Delta r = \Delta\left(\frac{G_E}{G_M}\right) = \left(\frac{\partial\left(G_E / G_M\right)}{\partial A_p}\right) \cdot \Delta A_p$$

Results

The systematic Errors

- The systematic Error is dominated by the target polarization.
- The final relative systematic uncertainty has been obtained by summing all the individual contributions quadratically.

Measurement	Error	$\Delta\mu G_E/G_M/\mu G_E/G_M$ (%)
E (GeV)	0.003	0.07
E' (GeV)	0.004	0.13
θ_e (mrad)	0.5	0.54
θ^* (mrad)	1.22	0.54
ϕ^* (mrad)	0.3	0.01
P_T %	5.0	5.0
P_B %	1.5	1.5
Packing Fraction, pf %	5	1.34
Total		9.13

The total relative systematic uncertainty on $\mu_p G^p_E/G^p_M$ has been estimated as 5.44%

Asymmetry Measurements

σ - Scattering cross section
σ_0 - Scattering cross section at unpolarized target
σ_B - Scattering cross section from background
$\Delta\sigma$ - σ due to the spin of the target
P_E - Beam polarization
P_T - Target polarization
f - Dilution factor

$$\sigma = \sigma_0 + P_E P_T \Delta\sigma$$

$$\sigma_{++} = \sigma_0 + P_E P_T \Delta\sigma$$

$$\sigma_{+-} = \sigma_0 - P_E P_T \Delta\sigma$$

$$\frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = P_E P_T \cdot \frac{\Delta\sigma}{\sigma_0} = \frac{N_+ - N_-}{N_+ + N_-} = A_r$$

$$\frac{A_r}{P_E P_T} = \frac{\Delta\sigma}{\sigma_0} = A_p$$

With background….

$$\sigma_{++} = \sigma_0 + P_E P_T \Delta\sigma + \sigma_B$$

$$\sigma_{+-} = \sigma_0 - P_E P_T \Delta\sigma + \sigma_B$$

$$A_r = P_E P_T \cdot \frac{\Delta\sigma}{(\sigma_0 + \sigma_B)}$$

$$A_r = P_E P_T \cdot \frac{\Delta\sigma}{\sigma_0} \cdot \frac{\sigma_0}{(\sigma_0 + \sigma_B)} \quad f$$

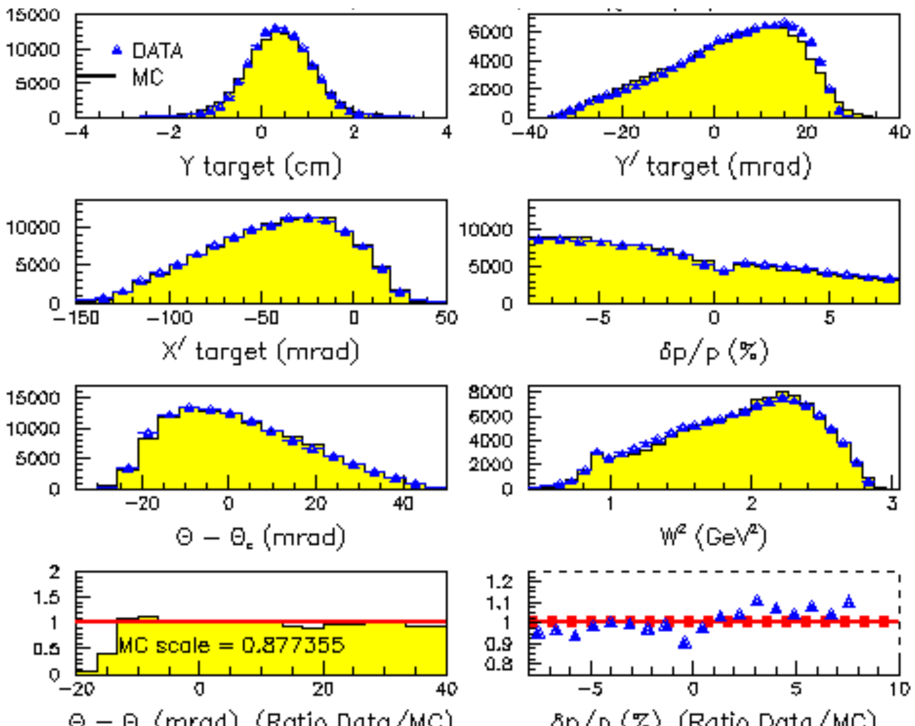
$$A_P = \frac{A_r}{f P_E P_T}$$

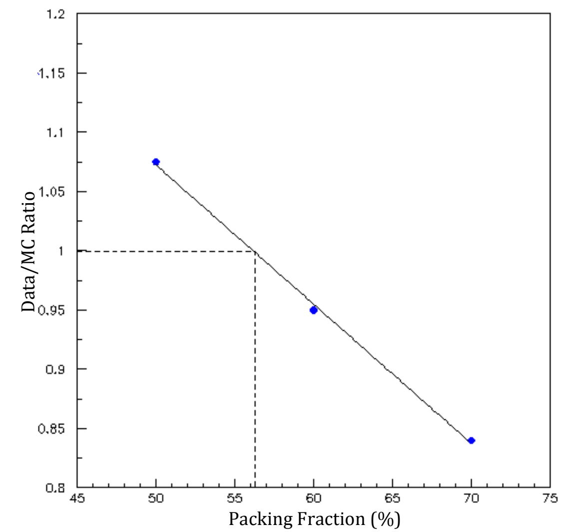
Hence,
the physics asymmetry, A_p is the relative scattering cross section correction due to the spin.
A_r is the raw asymmetry.

Packing Fraction

- Packing Fraction, *pf* is the actual amount of target material used.
- Determined by taking the ratio of volume taken by ammonia to the target cup volume.
- Estimated by comparing NH_3 data to MC simulation.
- Need to determine the packing fractions for each of the NH_3 loads used during the data taking.

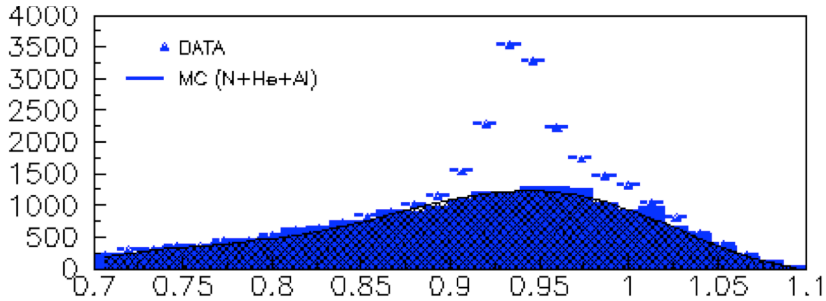
NH_3 data to MC comparison for *pf*=60% (Bottom target)



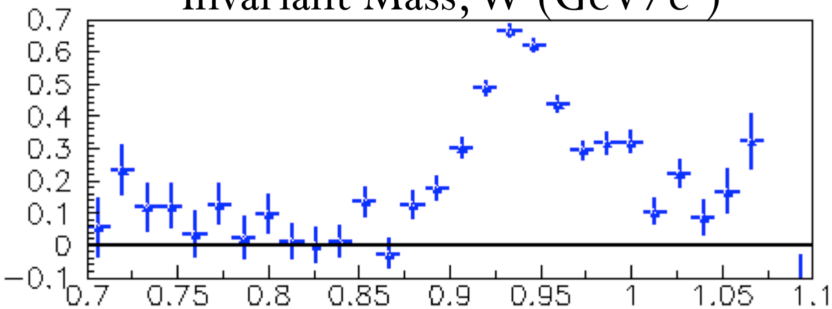


- Take the *pf* which gives a data to MC ratio 1.
- *Pf* for Bottom target is determined as 56%.

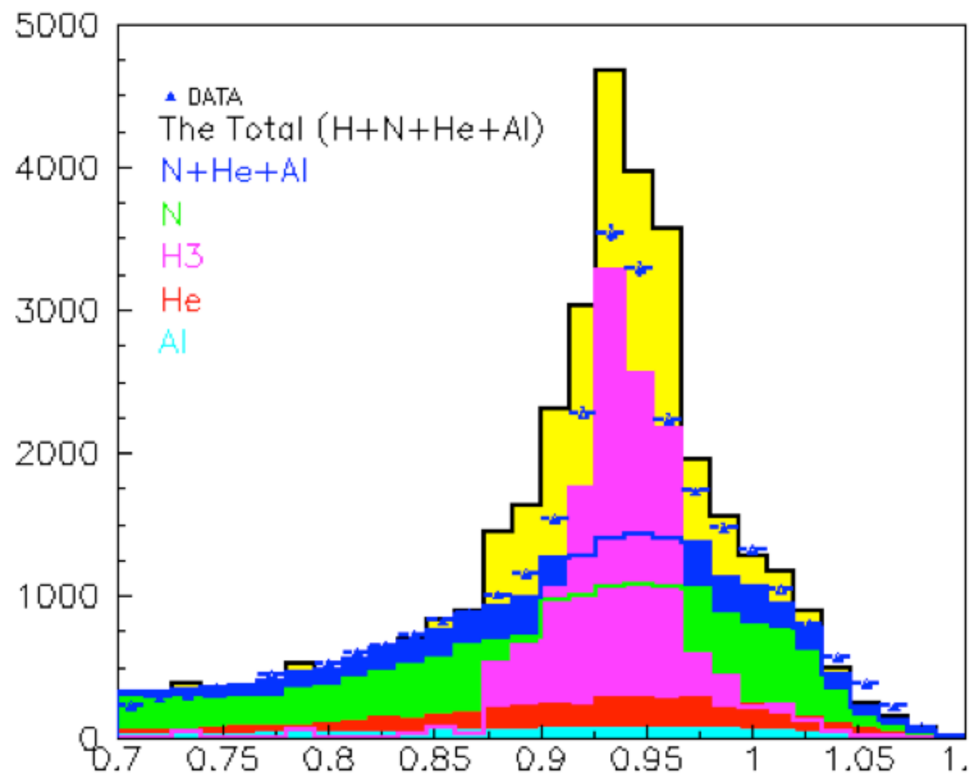
Each target type contributions for the $10\% < \delta < 12\%$
(Top target)



Invariant Mass, W (GeV/c^2)



The Dilution Factor



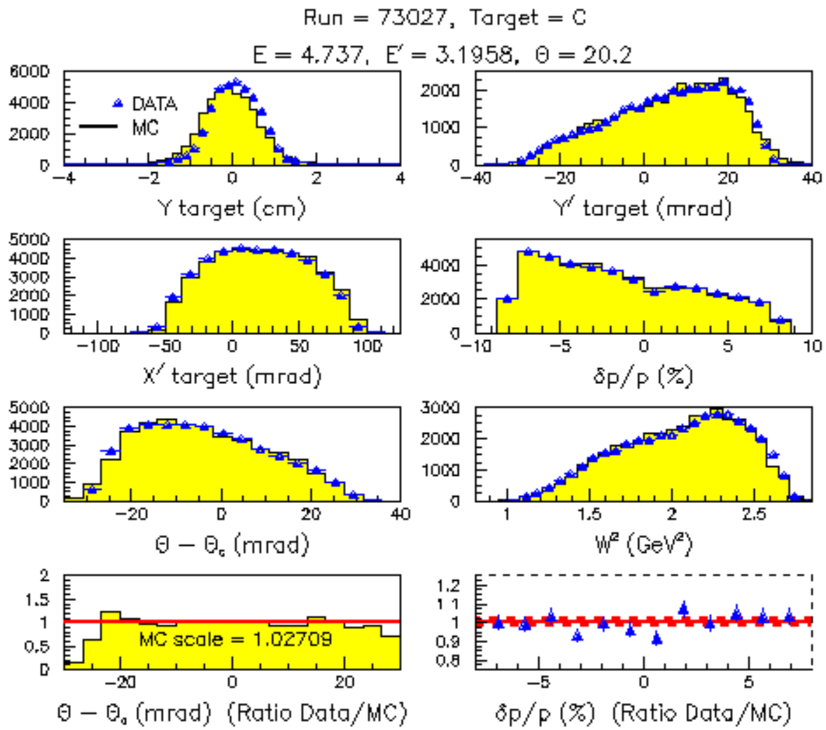
Invariant Mass, W (GeV/c^2)

Parallel field Magnetic Configuration

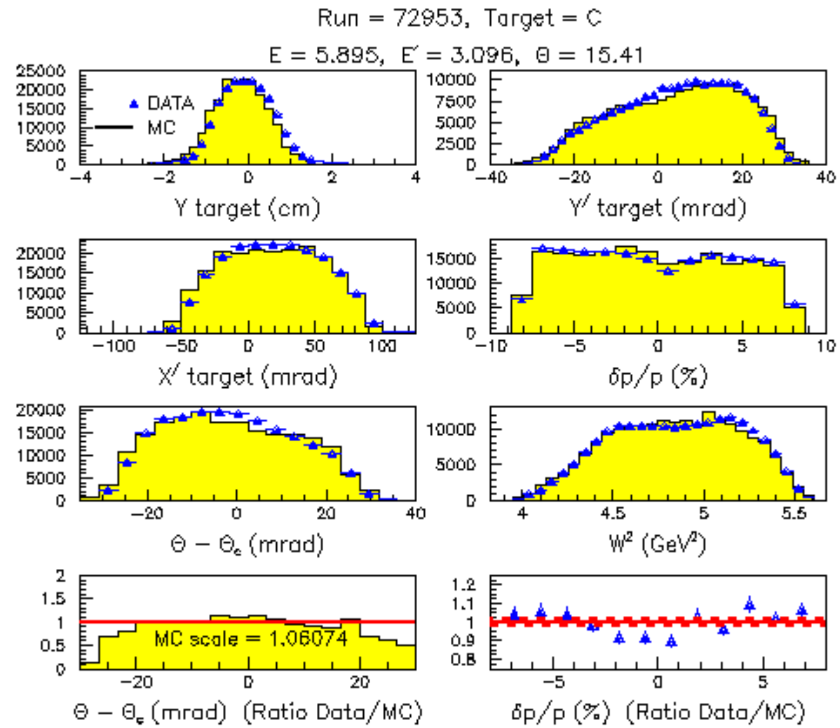
C run 73027 (No He) (ebeam = 4.733 GeV, P=3.2 GeV/C, θ =20.2^0)

C run 72953 (ebeam = 5.895 GeV, P=3.1 GeV/C, θ=15.41^0)

$srast_x$ = 0.10 cm
$srast_y$ = -0.10 cm



$srast_x$ = 0.18 cm
$srast_y$ = -0.02 cm



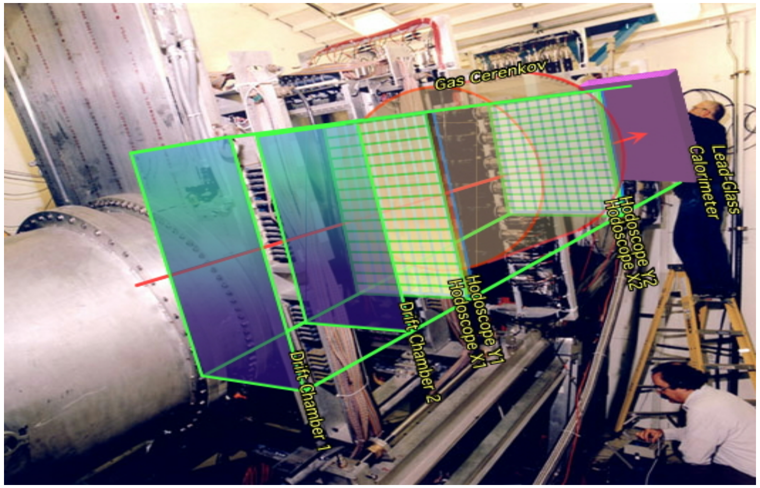
Beam Time

	Energy GeV	Θ_N	Time (Proposal FOM h) Proposal	Actual	Fraction
Calibration	2.4	off, 0 ,180	47	25	53%
Production	4.7	180	70	20	29%
	4.7	80	130	98	75%
	5.9	80	200	143	72%
	5.9	180	100	≥35	≥35%
Commissioning [calendar days]			14.0	99	
Total [calendar days]			70.0	141	

SANE is a single arm inclusive scattering experiment. Measured proton spin structure functions g_1 (X, Q^2) and g_2 (X, Q^2) at four-momentum transfer

$2.5 < Q^2 < 6.5$ $(GeV/c)^2$ and

$0.3 < X < 0.8$



What HMS is used for .....

HMS detected electrons with momenta from 1 to around 5 GeV/c

1. Packing fraction determination.
   - Used the ratio of data/MC yields for C target to determine the packing fraction.

2. Asymmetry measurements.
   - Inclusive Asymmetries: Q^2 of 0.8, 1.3 and 1.8 $(GeV/c)^2$
   - Elastic Asymmetries:

     Measured the elastic asymmetries at magnetic field of 80^0 and hence the ratio of form factors, $\mu_p G_E^p / G_M^p$

     - From single arm data at Q^2 $=2.06$ $(GeV/c)^2$
     - From coincidence data at $Q^2 = 5.66$ $(GeV/c)^2$

Results

	Single Arm		Coincidence	
	$-8\%<\delta<10\%$	$10\%<\delta<12\%$		
E (GeV)	5.895	5.895	5.893	4.725
θ_q (Deg)	44.38	46.50	22.23	22.60
ϕ_q (Deg)	171.80	172.20	188.40	190.90
θ_e (Deg)	15.45	14.92	37.08	43.52
ϕ_e (Deg)	351.80	352.10	8.40	10.95
Q^2 (GeV/c)^2	2.20	1.91	6.19	5.14
θ^* (Deg)	36.31	34.20	101.90	102.10
ϕ^* (Deg)	193.72	193.94	8.40	11.01
$A_p \pm \Delta A_p$	-0.216 ± 0.018	-0.160 ± 0.027	-0.006 ± 0.077	0.184 ± 0.136
$\mu r \pm \Delta(\mu r)$	0.483 ± 0.211	0.872 ± 0.329	0.937 ± 0.428	-0.052 ± 0.678
predicted μr	0.73	0.78	0.305	0.38
predicted A_p	-0.186	-0.171	0.107	0.097

Where, μ – Magnetic Moment of the Proton=2.79

The systematic Errors

- The systematic Error is dominated by the target polarization.
- The final relative systematic uncertainty has been obtained by summing all the individual contributions quadratically.

The total relative systematic uncertainty on $\mu_p G^p_E/G^p_M$ has been estimated as 5.44%

Measurement	Error	$\Delta\mu G_E/G_M/\mu G_E/G_M$ (%)
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