# Measurement Of the Proton Electric to Magnetic Form Factor Ratio, $G^{P}_{E}/G^{P}_{M}$ with Polarized Beam and Target

**S**pin
**A**symmetries of the
**N**ucleon
**E**xperiment
( E07-003)

Jefferson Lab
Thomas Jefferson National Accelerator Facility

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W&M
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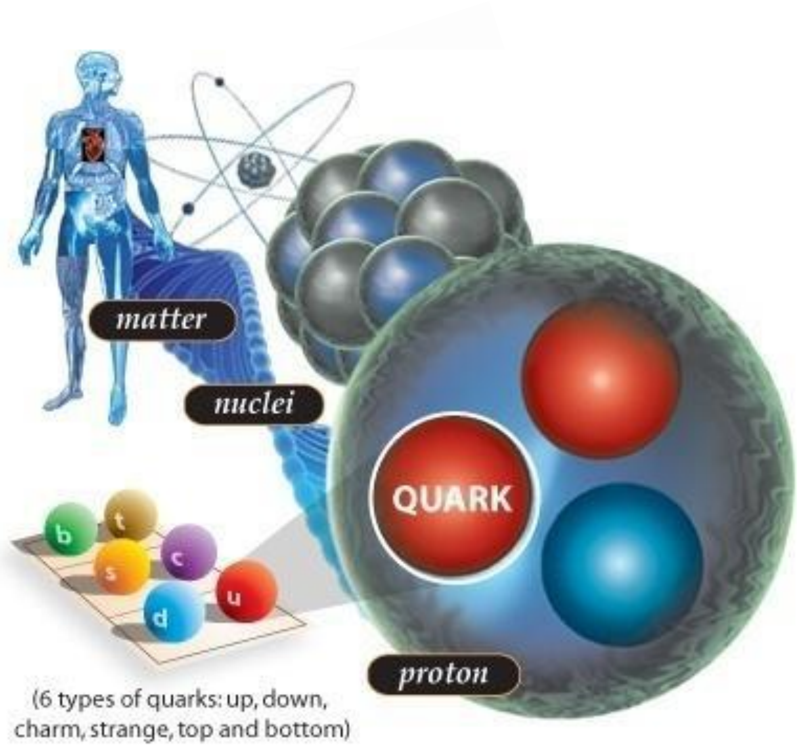
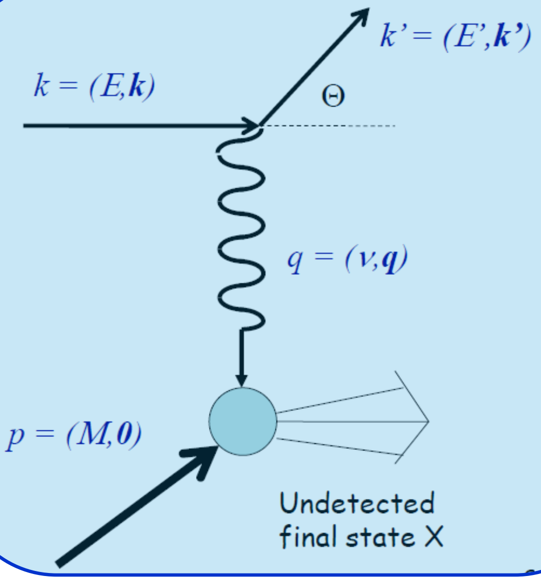


# Introduction




The four-momentum transfer squared,

$$q^2 = (k-k')^2 = k^2 + k'^2 - 2kk'$$

For electron, $k^2 = E^2 - k^2 = m_e{}^2 = 0$

$$q^2 = -2kk' = -2(E,k)(E',k')$$

$$q^2 = -2(EE' - k\cdot k')$$

$$q^2 = -2EE'(1-\cos\Theta)$$

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

Considering the elastic scattering of electron from the proton target,

$G_E^P(q^2)$ and $G_M^P(q^2)$ →

- Elastic,
- Electric and Magnetic Form Factors (Sachs form factors)
- Provide the information on the spatial distribution of electric charge and magnetic moment within the proton
- Are functions of the four-momentum transfer squared, $q^2$

At low $|q^2|$

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

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

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

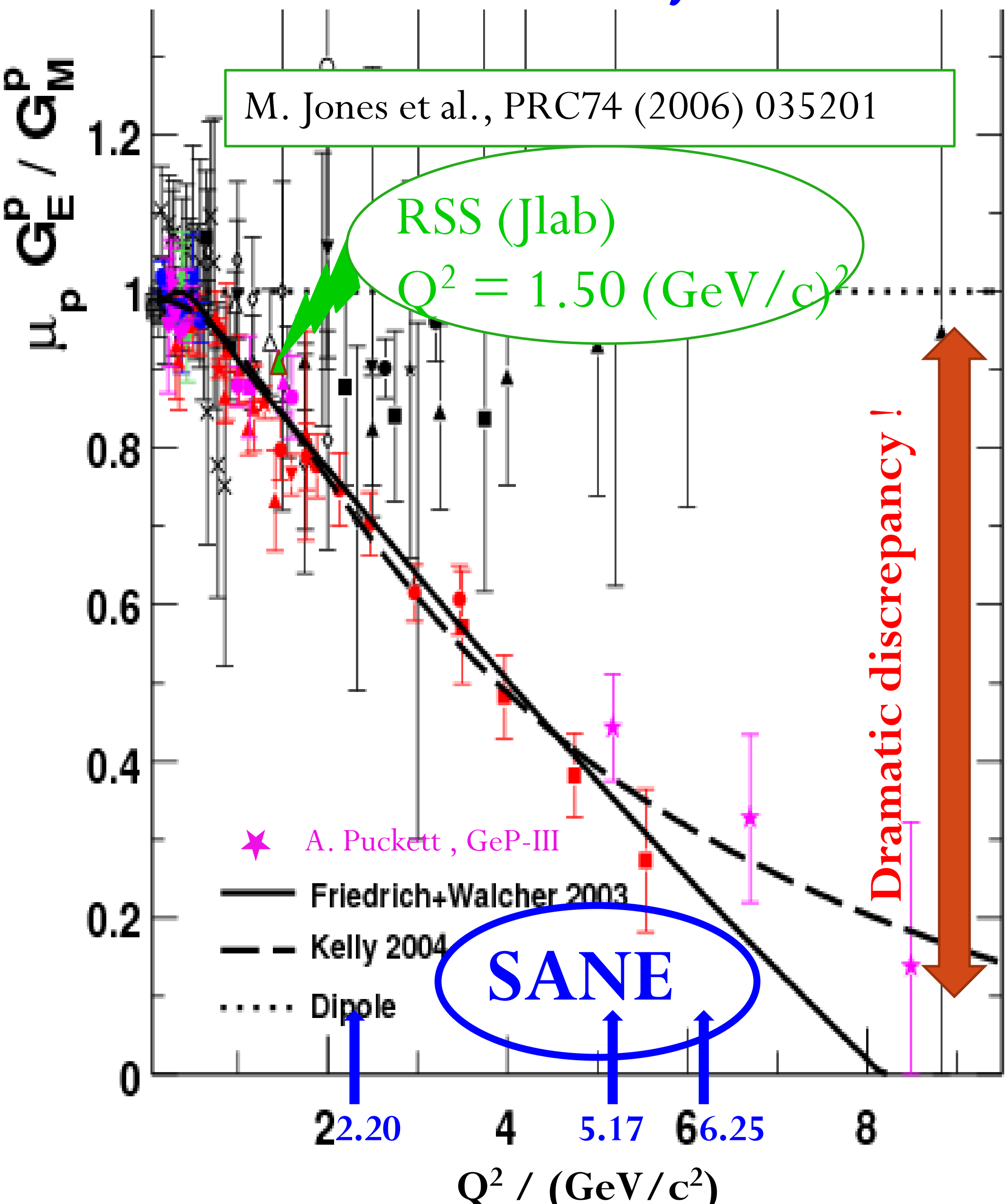
At $q^2 = 0$

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

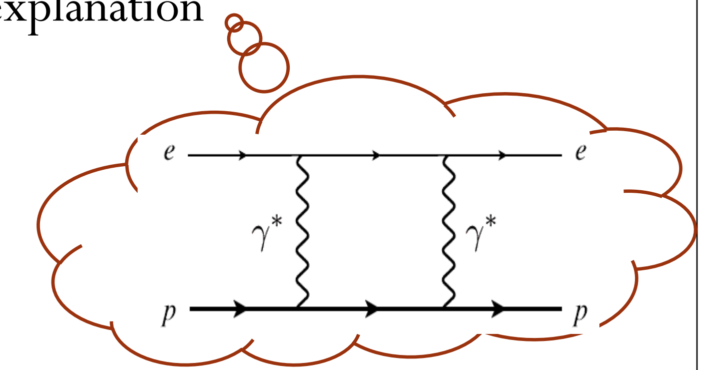
$$G_M(0) = \int \mu(\bar{r})d^3\bar{r} = \mu_P = +2.79$$

$$\mu \frac{G_E^p}{G_M^p} = 1$$

# Physics Motivation

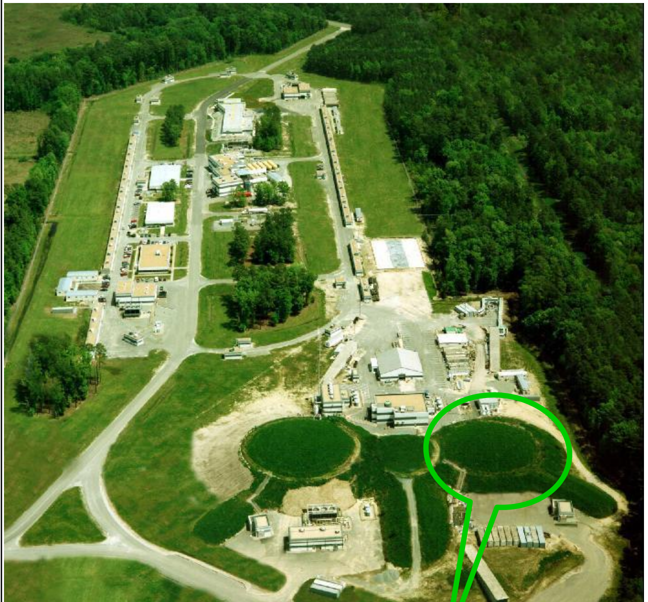



- Dramatic discrepancy between Rosenbluth and recoil polarization technique.
- Multi-photon exchange considered the best candidate for the explanation

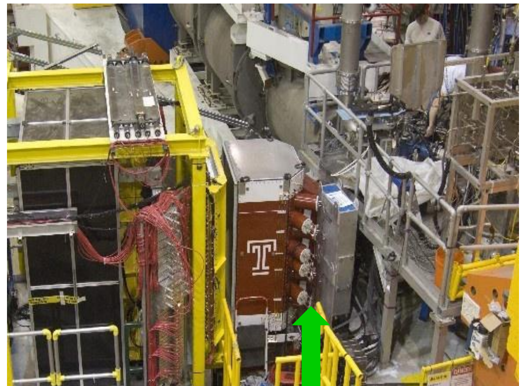



- **Double-Spin Asymmetry is an Independent Technique to verify the discrepancy**

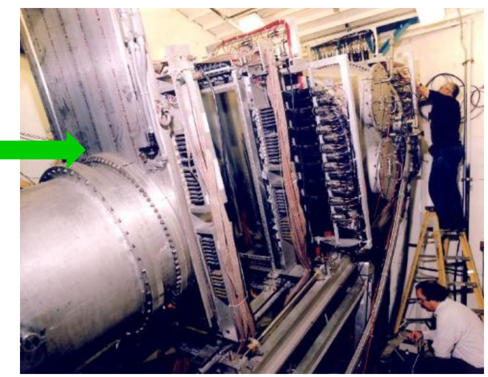
# Experiment Setup/ Detectors



Hall C at Jefferson Lab



- BETA detector package
  - Forward Tracker - tracking
  - Gas Cerenkov – ID
  - Lucite Hodescope – tracking
  - Lead Glass Calorimeter - ID



$$e^{-}p \rightarrow e^{-}p$$

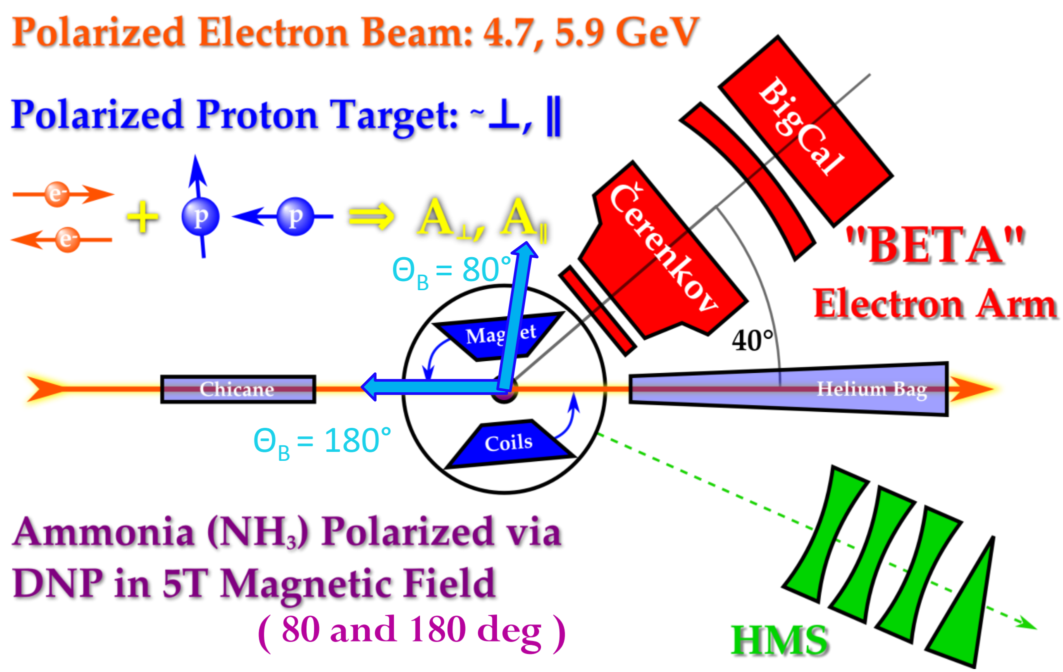
- HMS detector
  - Drift Chambers
  - Hodescope
  - Gas Cerenkov
  - Lead Glass Calorimeter

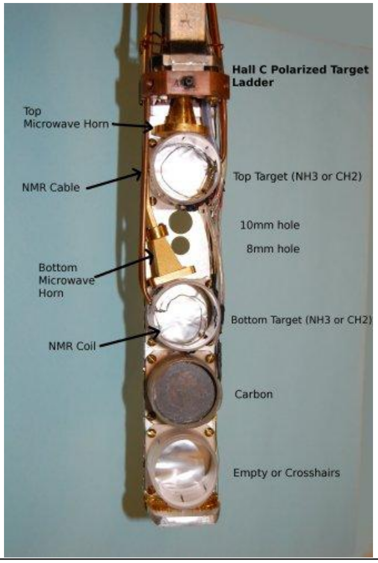
Elastic (e , e'p) scattering from the polarized $NH_3$ target using a longitudinally polarized electron beam

(Data collected from Jan – March ,2009)

# Experiment Setup/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




- Used only perpendicular Magnetic field configuration for the elastic data
- Average target polarization is ~ 70 %
- Average beam polarization is ~ 73 %

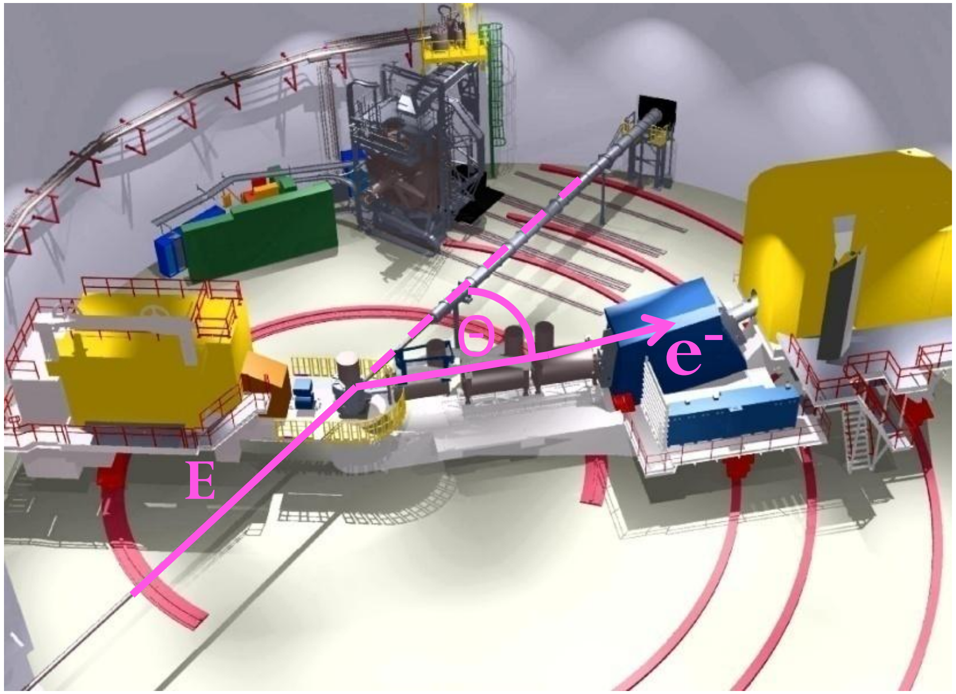
# Elastic Kinematics

( From HMS Spectrometer )

| Spectrometer mode | Coincidence | Coincidence | Single Arm |
|---|---|---|---|
| HMS Detects | Proton | Proton | Electron |
| E Beam GeV | 4.72 | 5.89 | 5.89 |
| P GeV/C | 3.58 | 4.17 | 4.40 |
| $\Theta_{HMS}$ (Deg) | 22.30 | 22.00 | 15.40 |
| $Q^2$ $(GeV/C)^2$ | 5.17 | 6.26 | 2.20 |
| Total Hours (h) | ~40 (~44 runs) | ~155 (~135 runs) | ~12 (~15 runs) |
| e-p Events | ~113 | ~824 | - |

# Data Analysis

# PART I : Electrons in HMS




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

By knowing the incoming beam energy, E and the scattered electron angle, $\theta$

$$E' = E \Big/ \left(1 + \frac{2E\sin^2\left(\theta/2\right)}{M}\right)$$

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

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

# Extract the electrons

- Used only the Electron selection cuts.

# of Cerenkov photoelectrons > 2 - Cerenkov cut

shtrk/hse > 0.7 - Calorimeter cut

$Abs\left(\frac{P-P_c}{P_c}\right) < 8$ - HMS Momentum acceptance cut

Here,

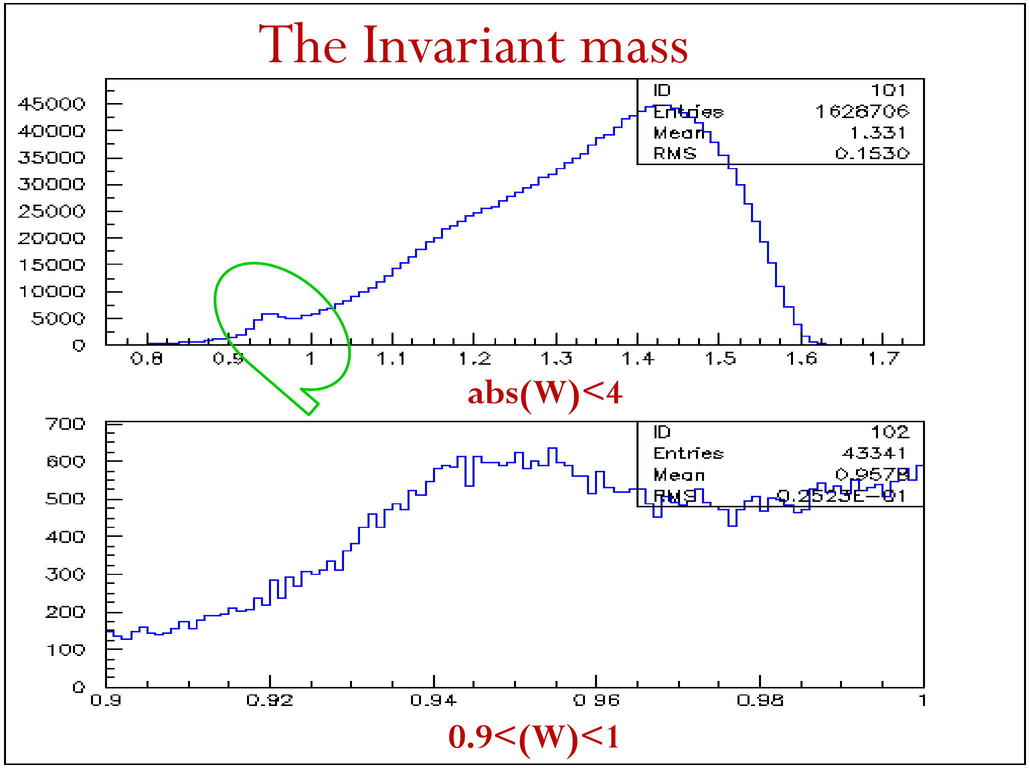
P – Measured electron momentum at HMS

Pc – Central momentum of HMS

shtrk - Total measured shower energy of a chosen electron track

hse - Calculated electron energy by knowing the electron momentum ,

$$hse = \sqrt{P^2 + M^2}$$



# PART I : Continued…..

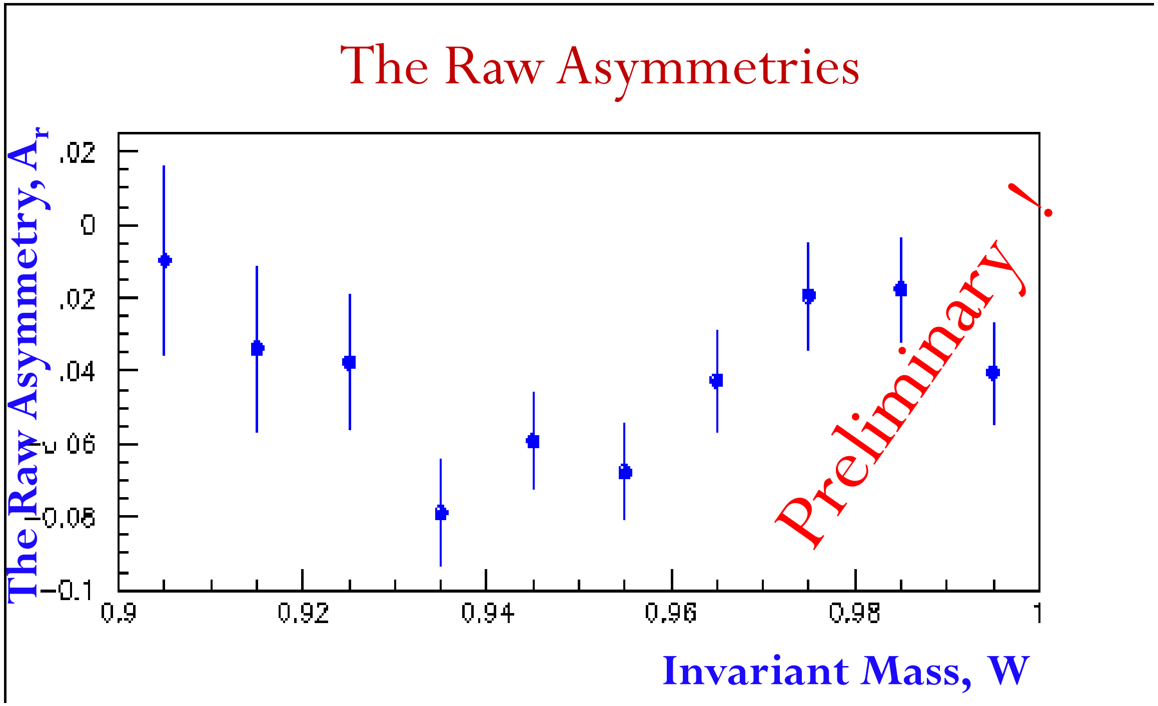
## The raw asymmetry, $A_r$

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

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

*$N^+$ / $N^-$ = Charge normalized Counts for the +/- helicity*

*$\Delta A_r$ = Error on the raw asymmetry*




*Further analysis requires a* ***study of the dilution factor and backgrounds*** *in order to determine the* ***physics asymmetry and $G^p_E/G^p_M$.***

***(at $Q^2$=2.2 $(GeV/C)^2$ )***

# Study of a Dilution Factor

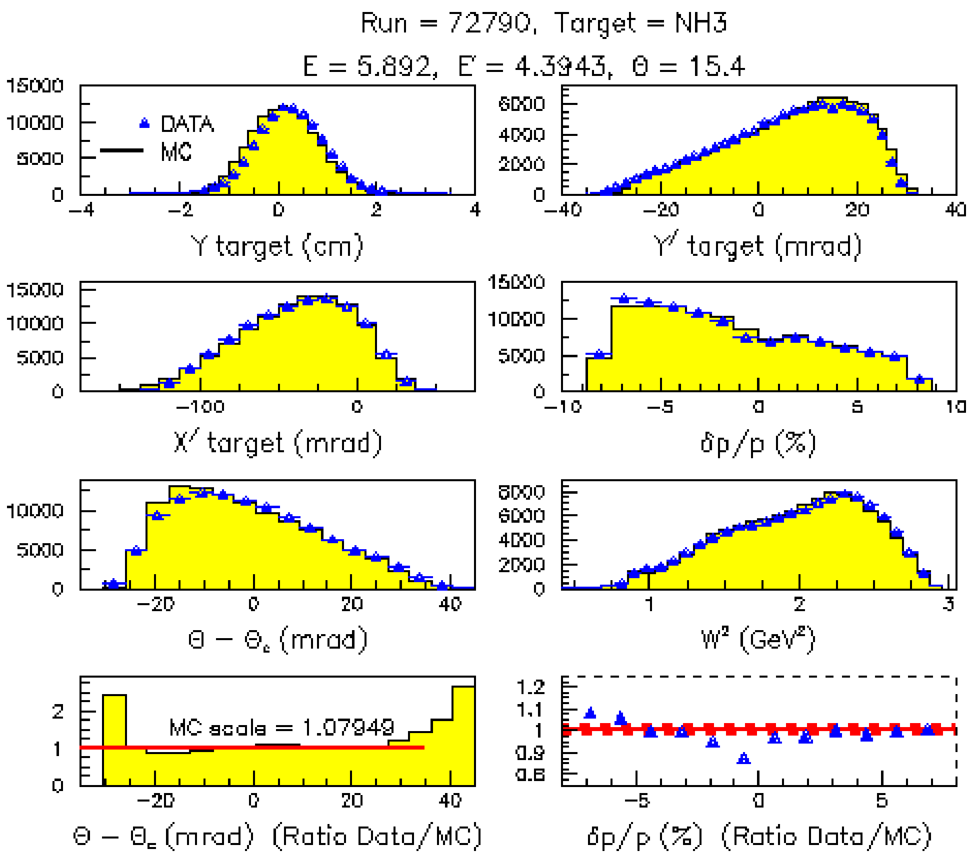
## What is the Dilution Factor ?

**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 and He)**

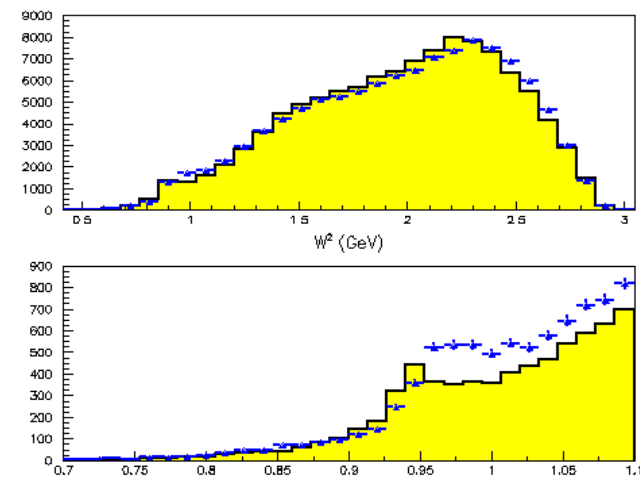
*Dilution Factor,*

$$F = \frac{Yield_{Data} - Yield_{MC}}{Yield_{Data}}$$

## Comparing MC for NH3 target



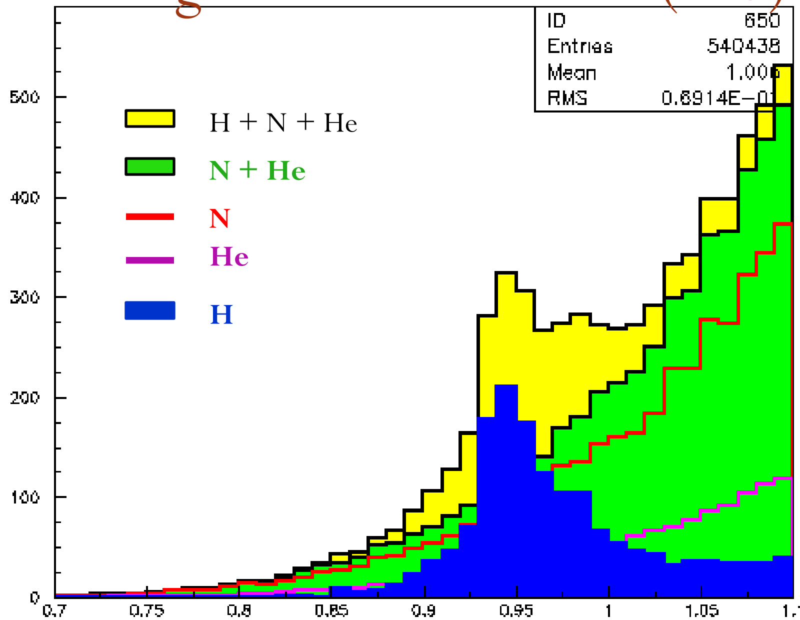

In order to consider $NH_3$ target, Used N, H and He separately




Invariant Mass, W (GeV)

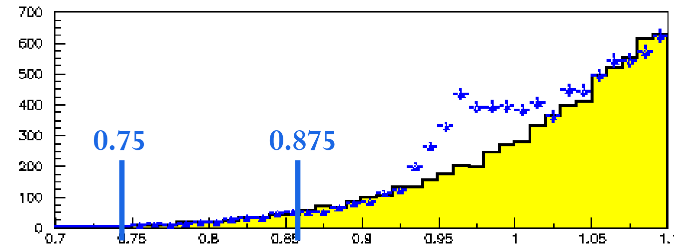
# Determination of the Dilution Factor

## Background contribution (MC)

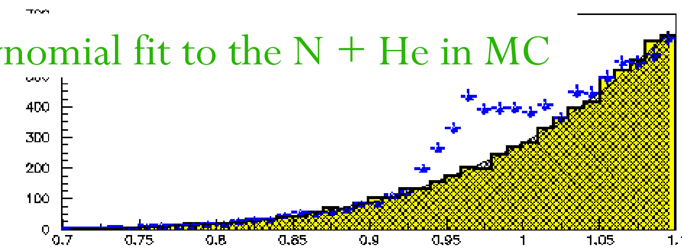



Invariant Mass, W (GeV)

- MC is Normalized with the scale factor 1.30 calculated using the Data/MC ratio for $0.75 < W < 0.875$



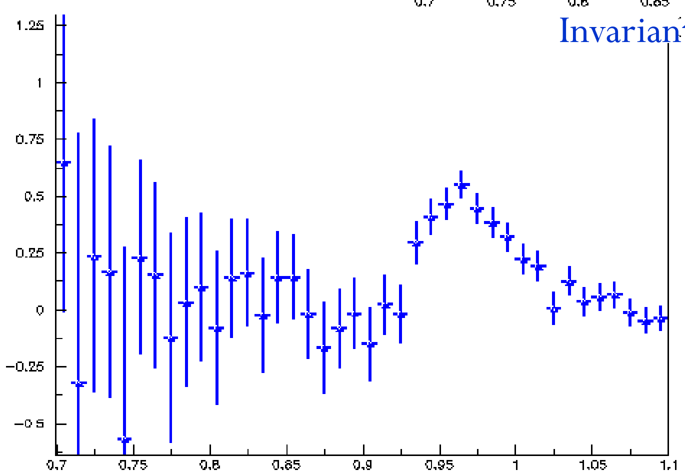

- Used the polynomial fit to the N + He in MC



Invariant Mass, W (GeV)

*Dilution Factor,*

$$F = \frac{Yield_{Data} - Yield_{MC}}{Yield_{Data}}$$



The Relative Dilution Factor, f %

# PART II: Protons in HMS

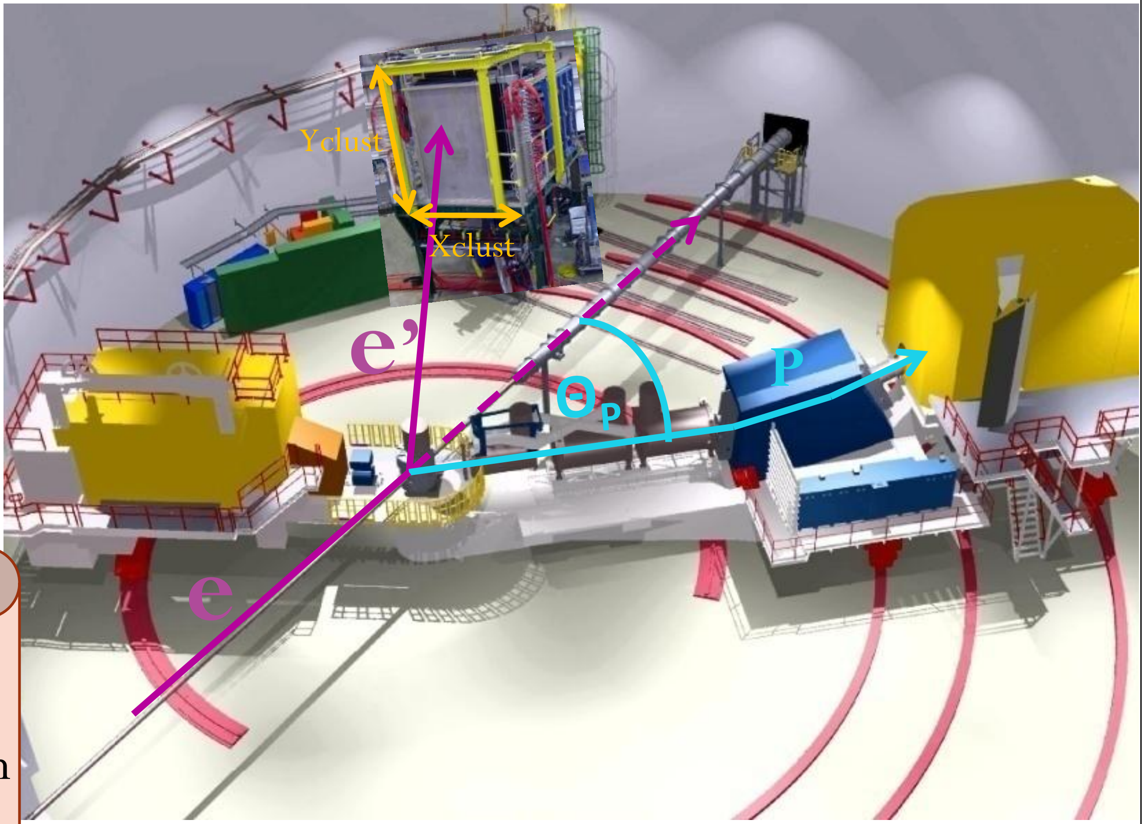
## Extracting the elastic events

Definitions :

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

  *X = horizontal /in-plane coordinate*

  *Y = vertical / out – of – plane coordinate*

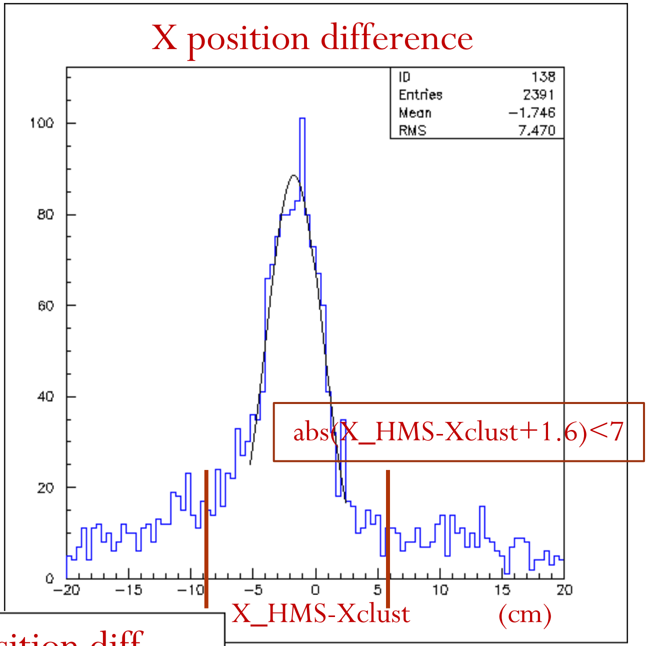


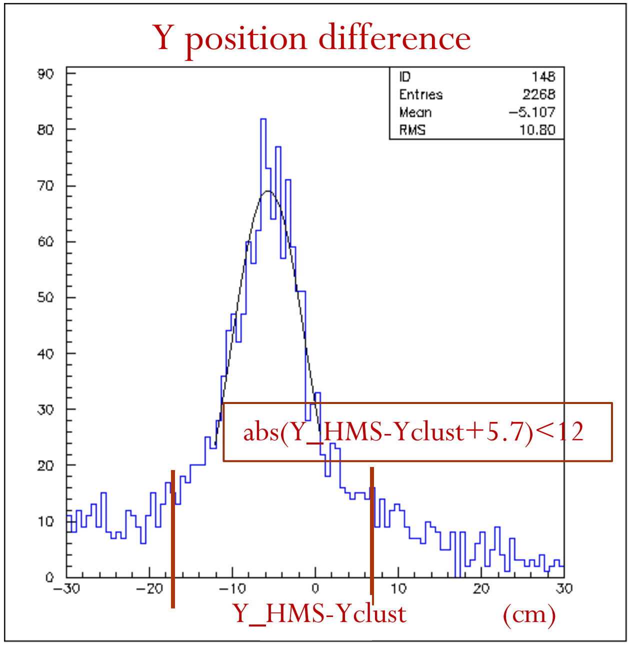

By knowing
the energy of the polarized electron beam, $E_B$
and
the scattered proton angle, $\Theta_P$

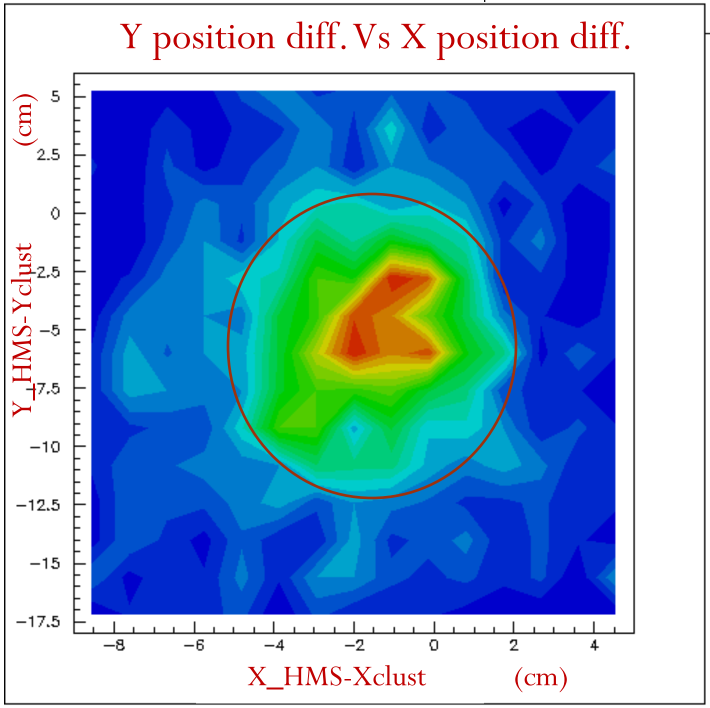
We can predict the
- X/Y coordinates , X_HMS, Y_HMS on the BigCal

(Target Magnetic Field Corrected)

# Extracting the Elastic Events…




The Elliptic cut,

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

Suppresses background most effectively

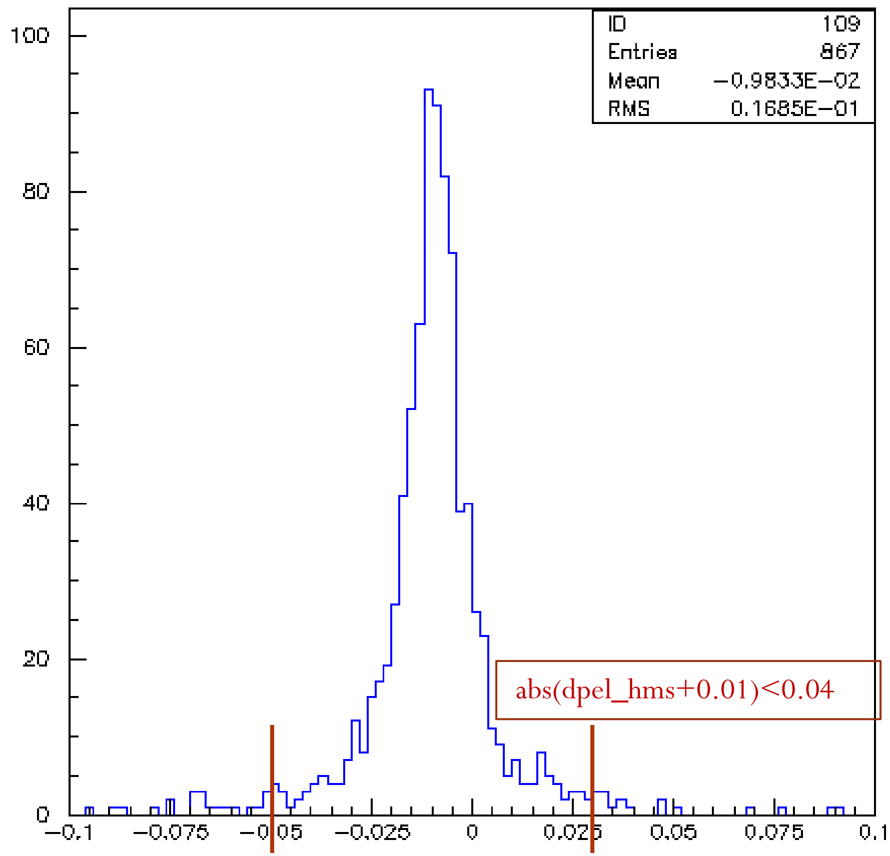
*Here,*

$$\Delta X = X\_HMS - xclust$$

$$\Delta Y = Y\_HMS - yclust$$

$$X(Y)_{max} = \text{The effective area cut}$$

# Momentum difference




$P_{HMS}$ – Measured Proton momentum by HMS

$P_{cal}$ – Calculated Proton momentum by knowing the beam energy, E and the Proton scattered angle, $\theta$

$P_{cent}$ – HMS central momentum

$$dPel\_hms = \frac{P_{HMS} - P_{Cal}}{P_{cent}}$$

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

$$\nu = \frac{Q^2}{2M}$$

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

*Here , M is the Proton mass.*

The final elastic events are selected by using,

- The Elliptic cut and
- The 'dpel_hms' cut

# From The Experiment

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 normalized Counts for the +/- helicity*

$\Delta A_r / \Delta A_p$ = *Error on the raw/physics asymmetry*

$f$ = *Dilution Factor*

$P_B, P_T$ = *Beam and Target polarization*

$N_c$ = *A correction term to eliminates the contribution from quasi-elastic* $^{14}N$ *scattering under the elastic peak*

The elastic asymmetry, $A_p$

$$A_p = \frac{A_r}{fP_B P_T} + N_C$$

$$\Delta A_p = \frac{\Delta A_r}{fP_B P_T}$$

The beam - target asymmetry, $A_p$

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

Here, $r = G_E / G_M$

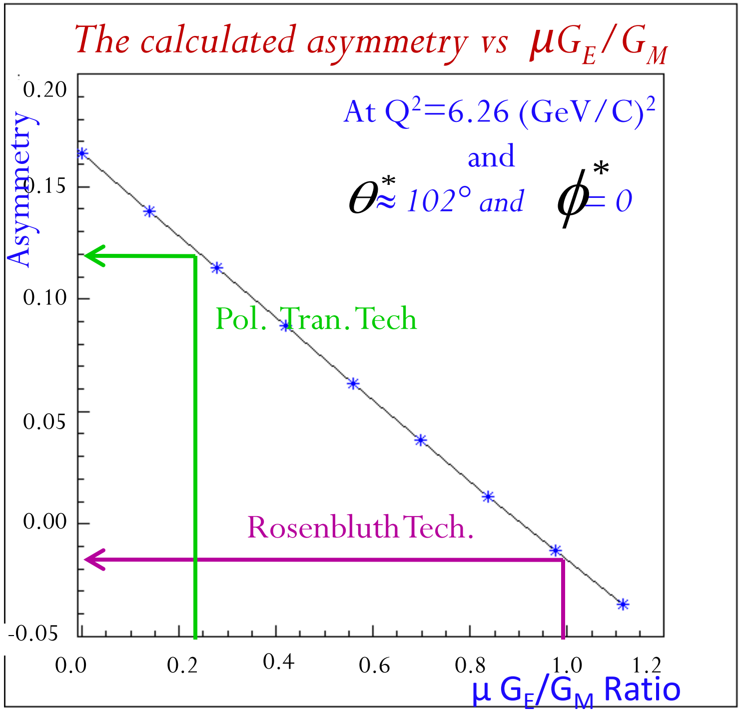
$a, b, c$ = *kinematic factors*

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

$\theta^* \approx 102°$ *and* $\phi^* = 0$

*From the HMS kinematics,* $r^2 << c$

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



# Error Propagation From The Experiment…..

| Positive Polarization | | | | | |
|---|---|---|---|---|---|
| H + Counts | H- Counts | $A_{raw}$ | Error $A_{raw}$ | $A_{phy}$ | Error $A_{phy}$ |
| 259 | 263 | -0.009 | 0.044 | -0.029 | 0.085 |
| **Negative Polarization** | | | | | |
| Tot H + | Tot H - | $A_{raw}$ | Error $A_{raw}$ | $A_{phy}$ | Error $A_{phy}$ |
| 223 | 226 | -0.008 | 0.039 | -0.026 | 0.099 |

Weighted Averaged
(very preliminary )

| $A_{phy}$ | Error $A_{phy}$ |
|---|---|
| -0.028 | 0.064 |

Used the
Average Beam Polarization = 73 %
Average Target Polarization = 70 %

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

$$\Delta A_P = \left| \frac{b\sin\theta^* \cos\phi^*}{c} \right| \Delta r$$

Using the experiment data at
$Q^2$=6.26 $(GeV/C)^2$ ,
***with total ep events ~970, $\Delta A_p$=0.064***

$\Delta r$ = 0.127

$\mu\, \Delta r$ = 2.79 x 0.127

$\mu\, \Delta r$ = 0.35

*Where ,* μ – Magnetic Moment of the Proton

## Future Work ..

- Extract the physics asymmetry and the $G^p_E/G^p_M$ ratio
- Improve the MC/SIMC simulation and estimate the background

## Conclusion ..

- Measurement of the beam-target asymmetry in elastic electron-proton scattering offers an independent technique of determining $G_E/G_M$ ratio.
- This is an 'explorative' measurement, as a by-product of the SANE experiment.

**SANE Collaborators:**

Argonne National Laboratory, Christopher Newport U., Florida International U., Hampton U., Thomas Jefferson National Accelerator Facility, Mississippi State U., North Carolina A&M, 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, Yerevan Physics Inst.

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

# Thank You

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