# Measurement of the Proton Form Factor Ratio, $G^P_E/G^P_M$ from Double Spin Asymmetries

**S**pin **A**symmetries of the **N**ucleon **E**xperiment

( E07-003)

## Outline

- Introduction
- Physics Motivation
- Detector Setup & Polarized Target
- Data Analysis
- Future Work/Conclusion

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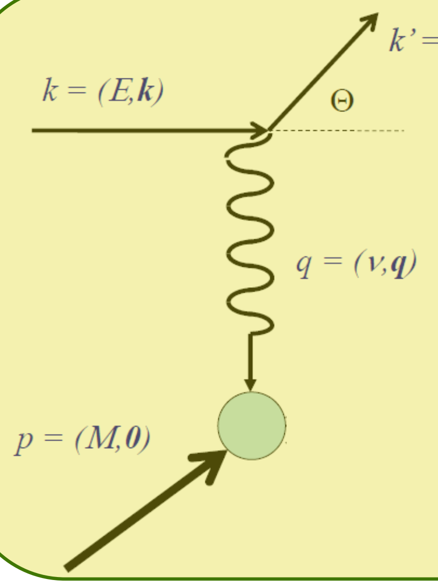
# Introduction

From 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, $q^2$

The four-momentum transfer squared,

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

$$E - E' = Q^2/2M$$

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**

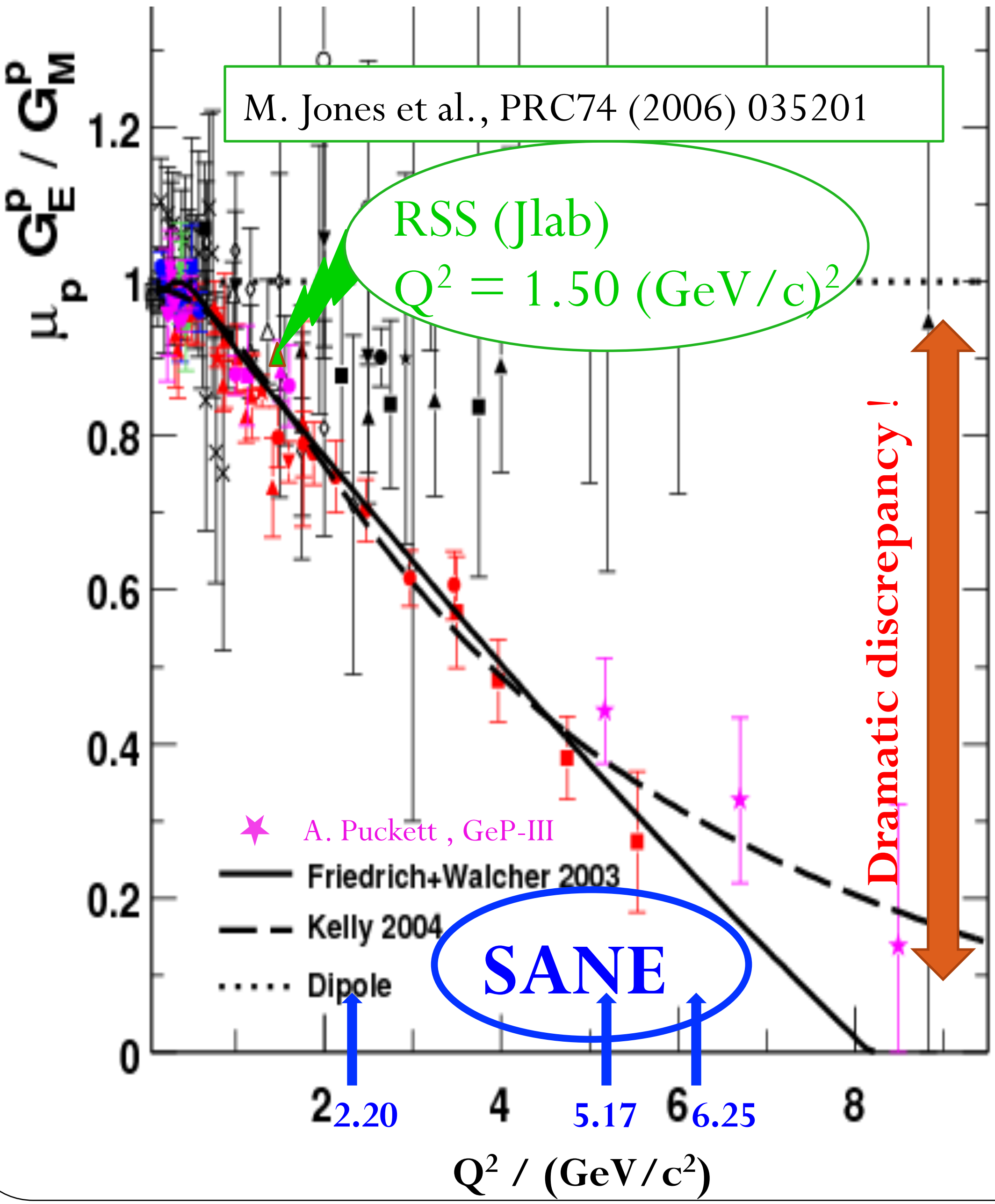
At $q^2 = 0$

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

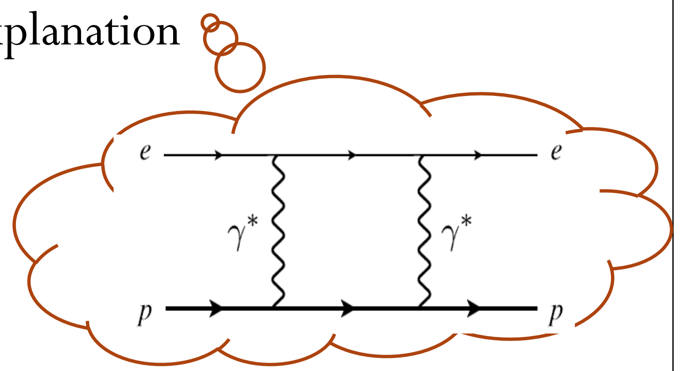
$$G_M(0) = \int \mu(\bar{r}) d^3\bar{r} = \mu_P = +2.79$$

$$\mu \, G_E^p / G_M^p = 1$$

# Physics Motivation



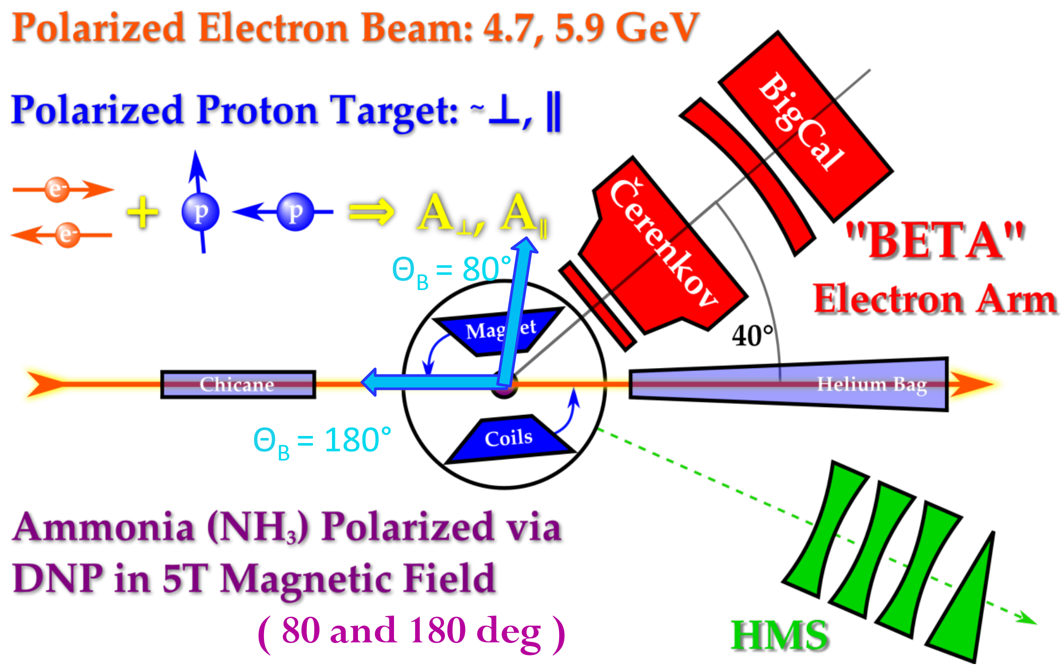

- Dramatic discrepancy between Rosenbluth and recoil polarization technique.
- Multi-photon exchange considered the best candidate for the explanation

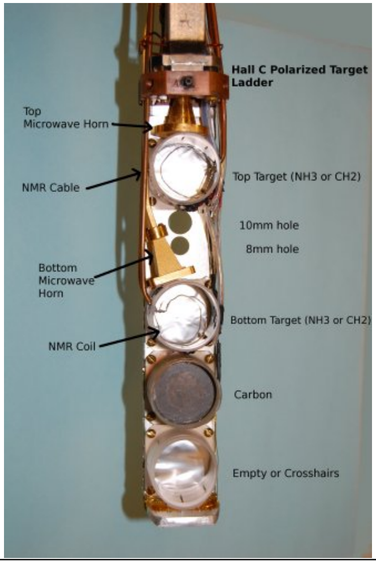



- **Double-Spin Asymmetry is an Independent Technique to verify the discrepancy**

# Detector 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



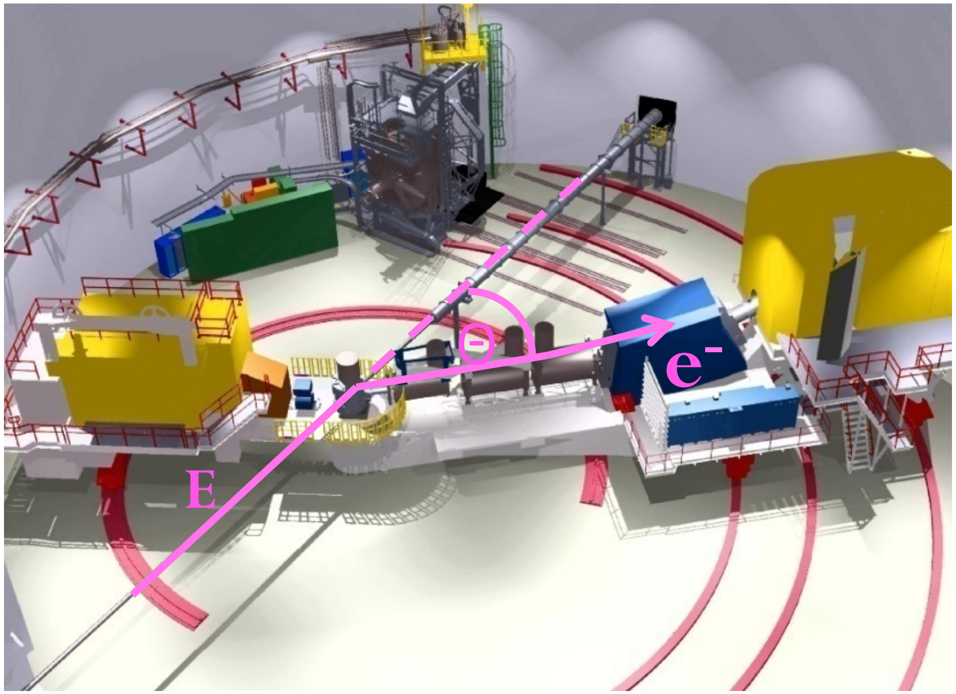

- Used only perpendicular magnetic field configuration for the elastic data
- Average target polarization is ~ 70 %
- Average beam polarization is ~ 73 %

# 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 |
| $P_{HMS}$ 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 | - |

# 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, $\theta$

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

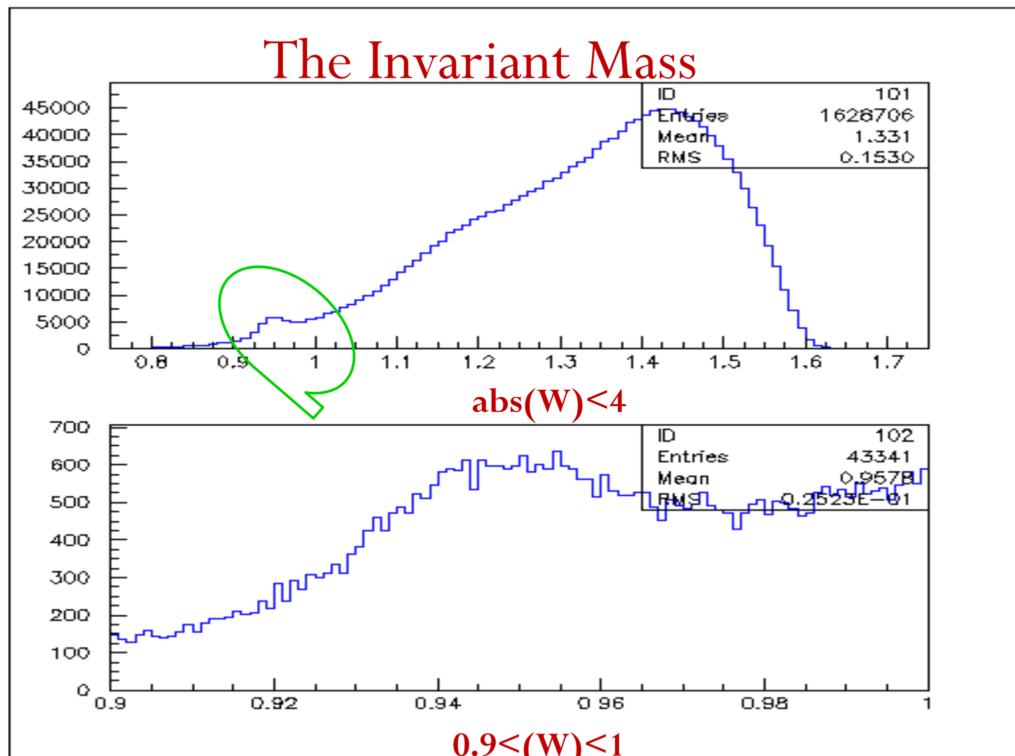
$$Q^2 = 4EE'\sin^2\left(\frac{\theta}{2}\right)$$

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

# Extract the electrons

- Used only Electron selection cuts.

| Cut | |
|---|---|
| # of Cerenkov photoelectrons > 2 | - Cerenkov cut |
| $E_{sh}/E' > 0.7$ | - Calorimeter cut |
| $Abs\left(\frac{P - P_c}{P_c}\right) < 8$ | - HMS Momentum Acceptance cut |




Here,

$P/E'$ - Detected electron momentum/energy at HMS

$P_c$ - Central momentum of HMS

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

# PART I : Continued…..

## The raw asymmetry, $A_r$

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

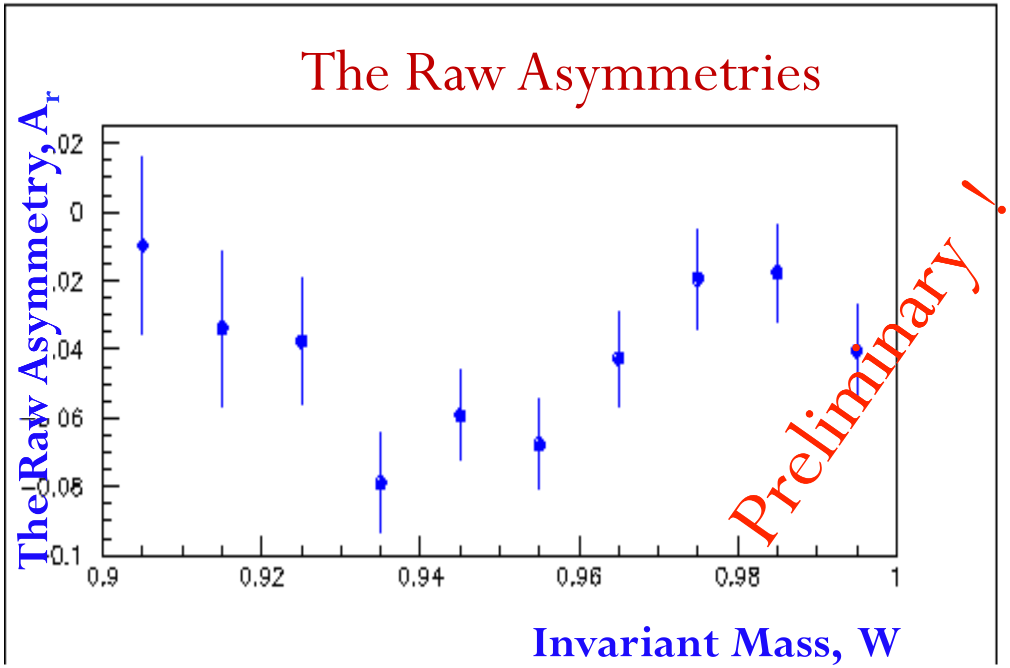
$$\Delta A_r = \frac{2\sqrt{N^+}\sqrt{N^-}}{(N^+ + N^-)\sqrt{(N^+ + N^-)}}$$

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

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

*$P_B P_T$ = Beam and Target polarization*

*$N_c$ = A correction term*




***Need dilution factor, f and backgrounds***

*in order to determine the*

***physics asymmetry,***

$$A_p = \frac{A_r}{f P_B P_T} + N_C$$

***and $G^p_E / G^p_M$***

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

# Determination of the Dilution Factor

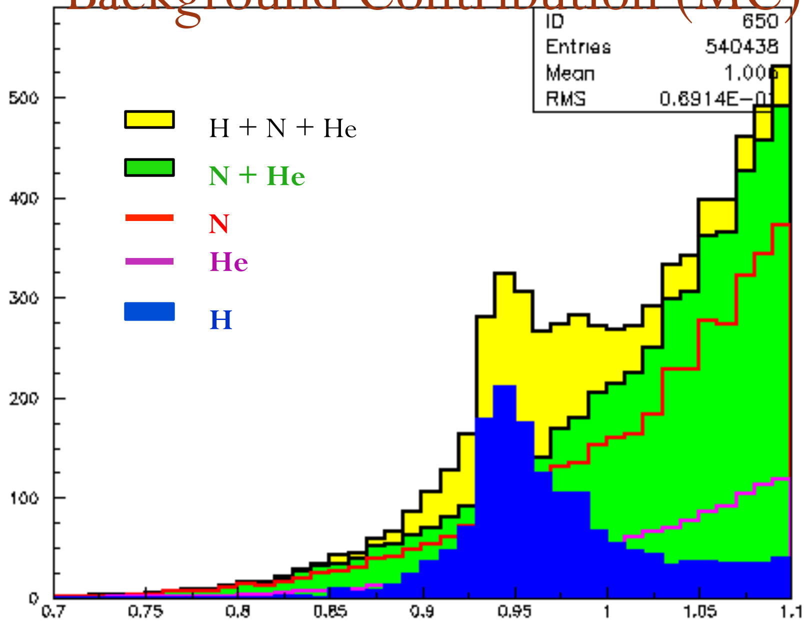
## What is the Dilution Factor ?

**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 and He)**

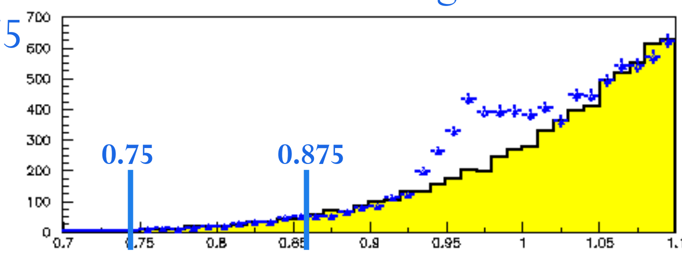
*Dilution Factor,*

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

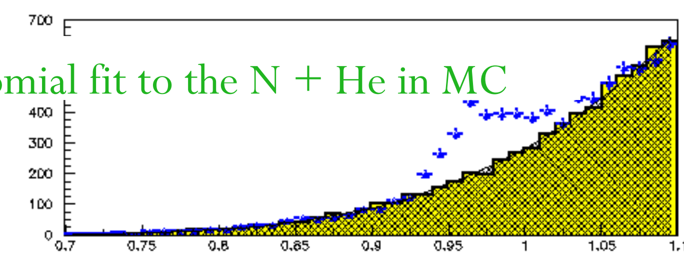
## Background Contribution (MC)



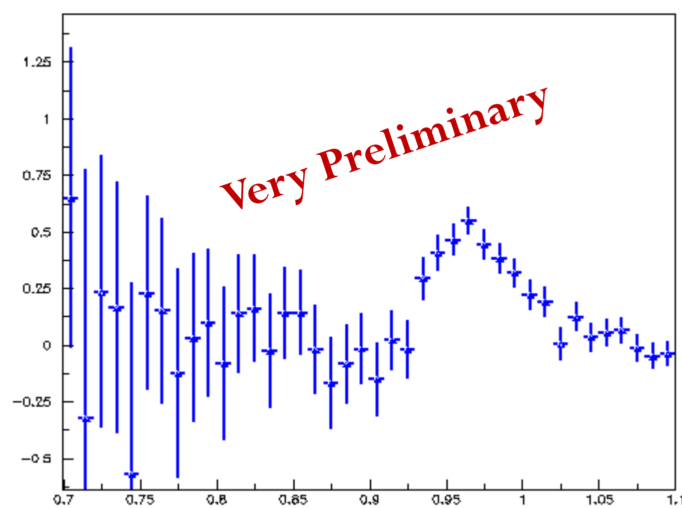

- MC is normalized with the data for the region 0.75 < W<0.875




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



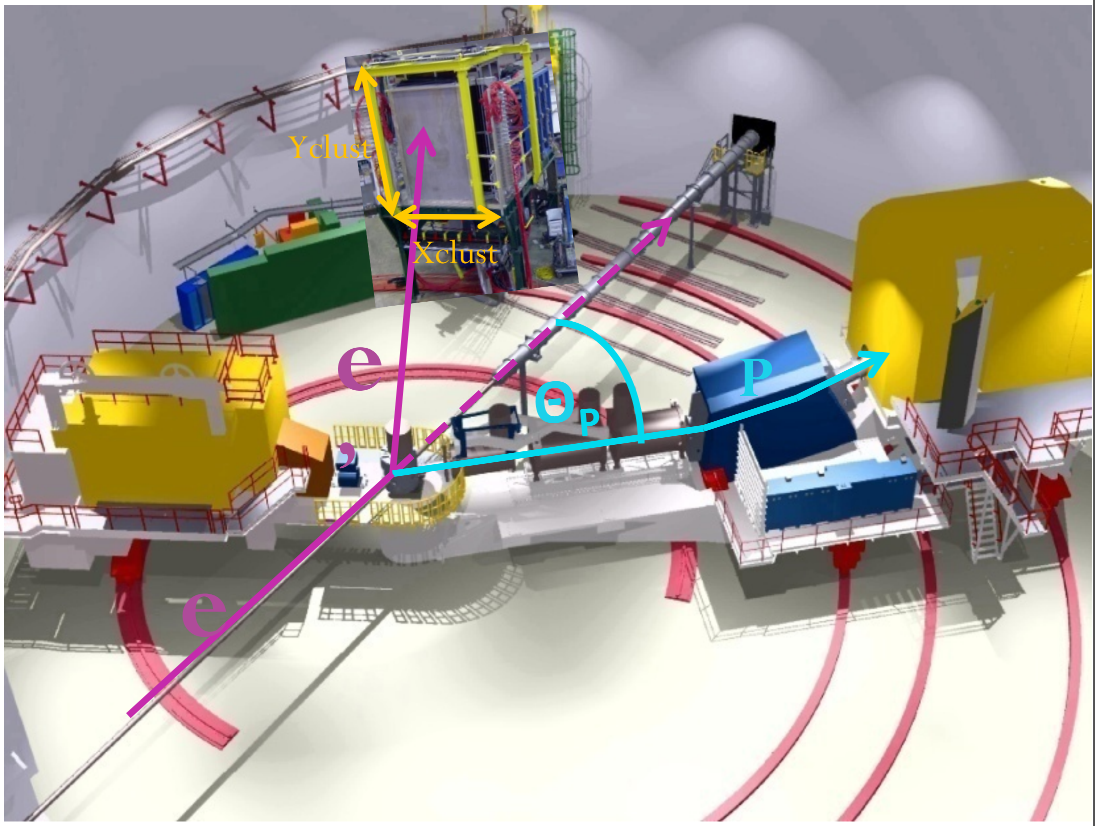
Invariant Mass, W (GeV)




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*

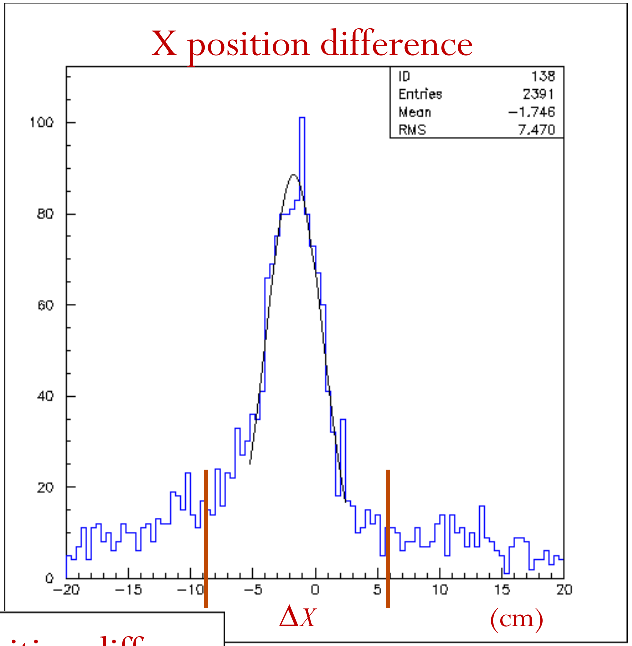
By knowing
the energy of the polarized electron beam, $E_B$
and
the scattered proton angle, $\Theta_P$

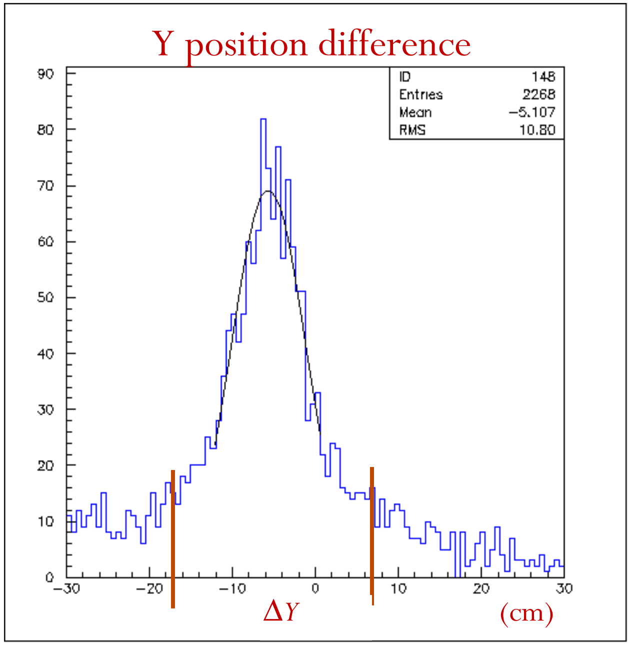
We can predict the
- X/Y coordinates , X_HMS, Y_HMS on the BigCal
  (Target Magnetic Field Corrected)

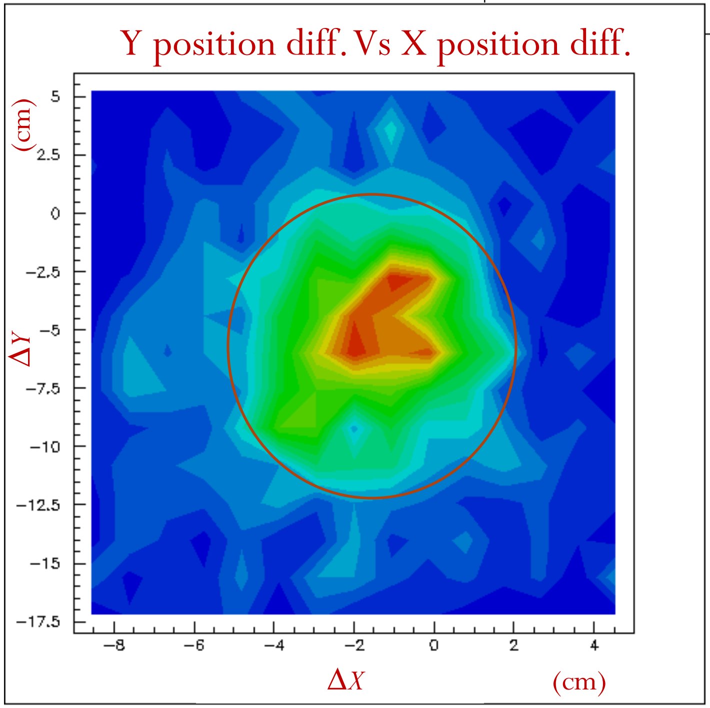
$\Delta X = X\_HMS - Xclust$

$\Delta Y = Y\_HMS - Yclust$

# Extracting the Elastic Events…



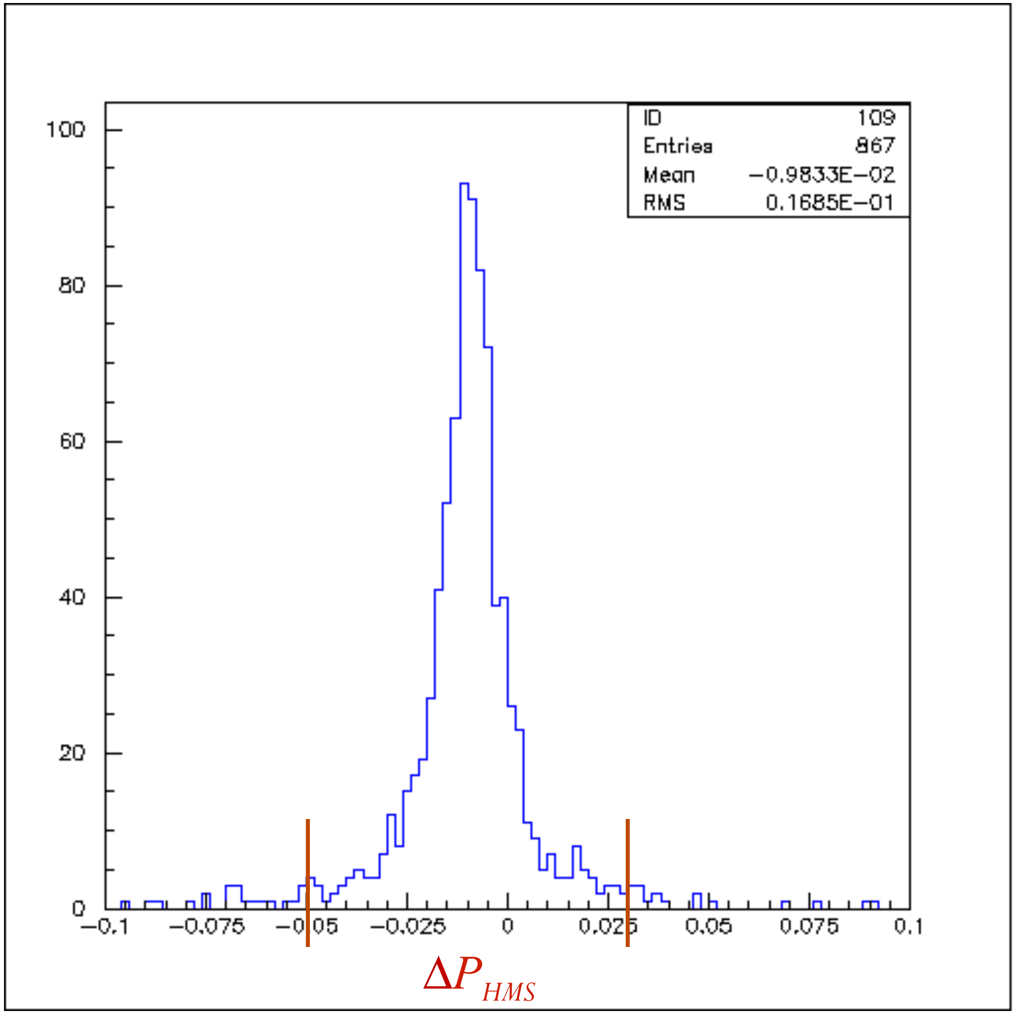

The Elliptic cut,

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

Suppresses background most effectively

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

# The Relative Momentum Difference




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

$P_{Cal}$ – Calculated Proton momentum by knowing the beam energy, $E_B$ and the Proton scattered angle, $\Theta_P$

$P_{Cent}$ – HMS central momentum

$$\Delta P_{HMS} = \frac{P_{HMS} - P_{Cal}}{P_{Cent}}$$

$$Q^2 = \frac{4M_P^{\,2} E_B^{\,2} \cos^2 \Theta_P}{M_P^{\,2} + 2M_P E_B + E_B^{\,2} \sin^2 \Theta_P}$$

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

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

*Here , $M_P$ is the Proton mass.*

The final elastic events are selected by using,

- The Elliptic cut and
- The '$\Delta P_{HMS}$' 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, $A_p$

$$A_p = \frac{A_r}{f P_B P_T} + N_C$$

$$\Delta A_p = \frac{\Delta A_r}{f P_B P_T}$$

The beam - target asymmetry, $A_p$

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

Here, $r = G_E / G_M$

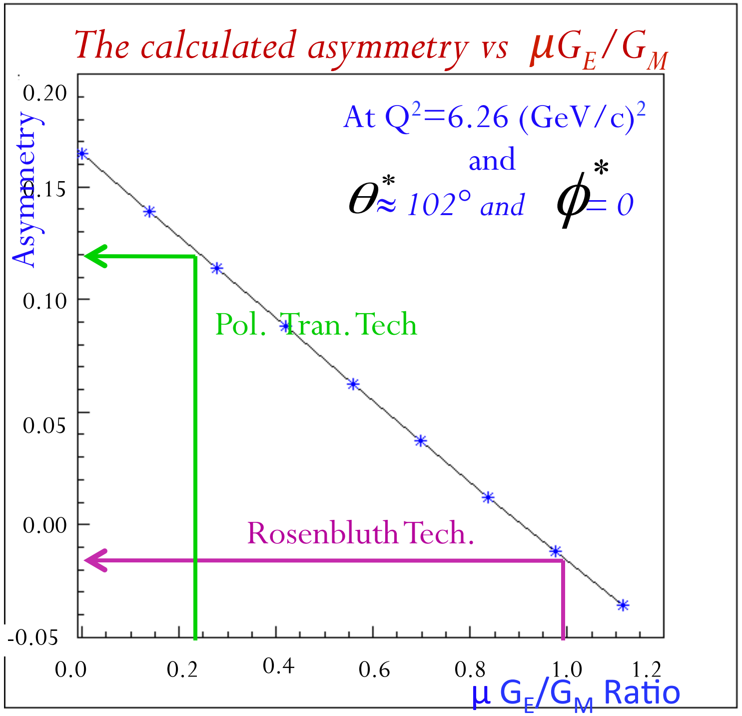
$a, b, c$ = *kinematic factors*

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

$\theta^* \approx 102°$ *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 Average
(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, $\Delta A_p=0.064$***

$\Delta r = 0.127$

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

$\mu\,\Delta r = 0.35$

*Where ,* μ – Magnetic Moment of the Proton

# Need To ..

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

# Conclusion

- Extraction of $G^p_E/G^p_M$ ratio from both 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 $G^p_E/G^p_M$ 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&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

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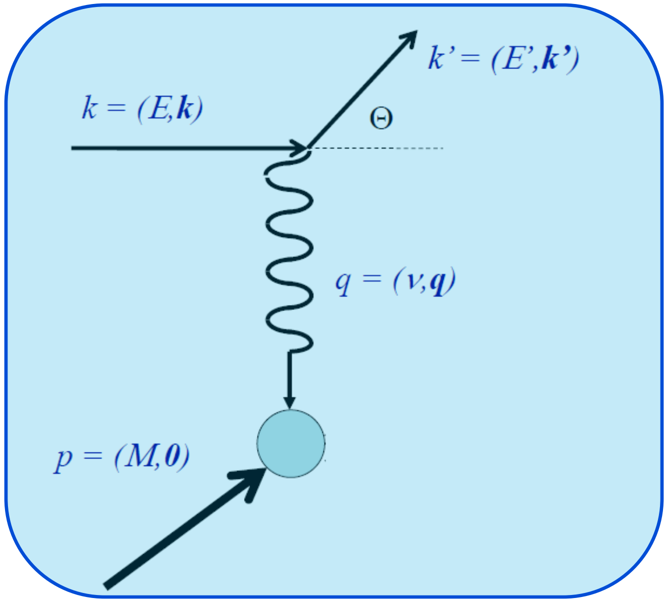
# Backup Slides

# Elastic Scattering




The four-momentum transfer squared,

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

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

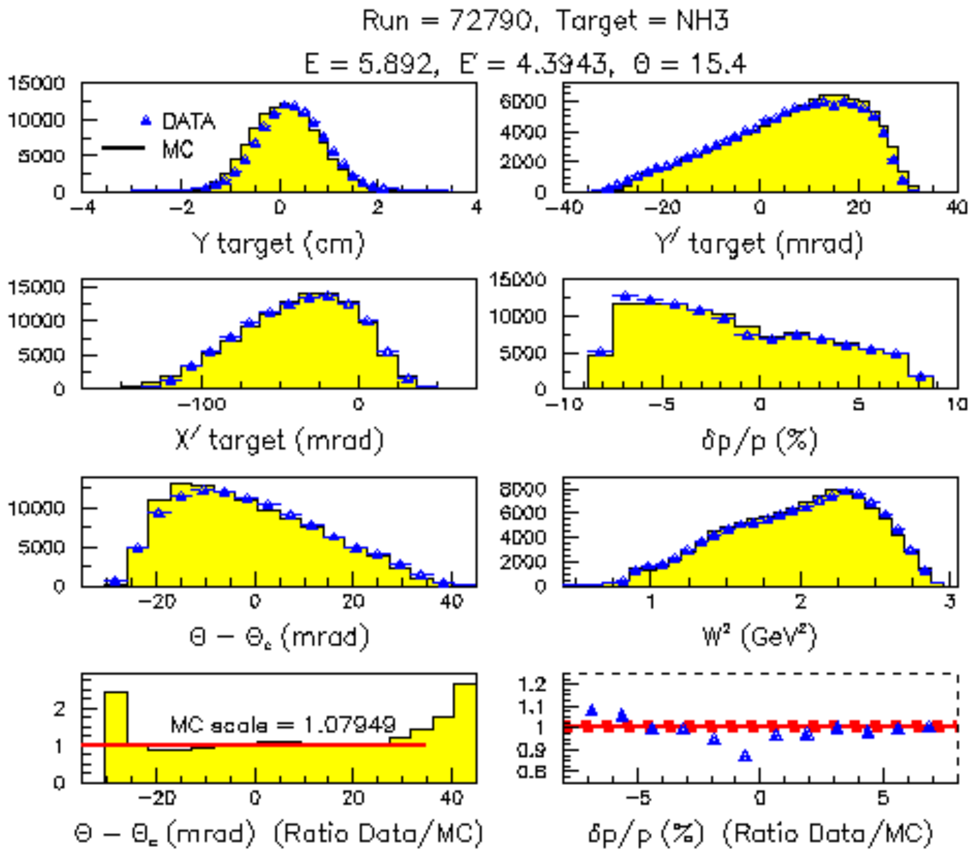
$$q^2 = -2kk' = -2(E,k)(E',k')$$

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

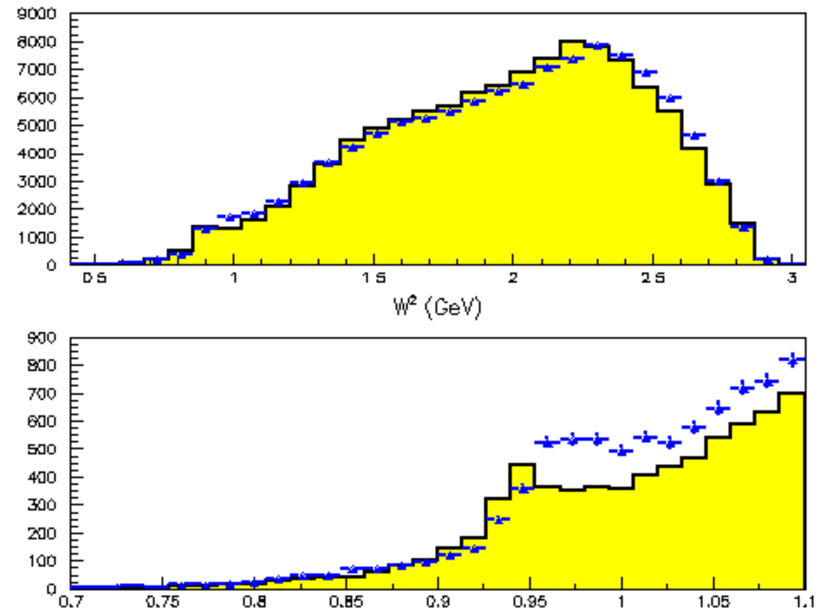
$$q^2 = -2EE'(1 - \cos\Theta)$$

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

# Comparing MC for NH3 target




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




Invariant Mass, W (GeV)