# *Proton Form Factor Ratio*, $G^P_E/G^P_M$ *From* *Double Spin Asymmetries*

## Spin Asymmetries of the Nucleon Experiment (E07-003)

### Outline

- Introduction
- Physics Motivation
- Detector Setup
- Elastic Kinematic
- Data Analysis
- Results & Conclusion

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# Form Factor Ratio Measurements

## 1. Rosenbluth separation method.

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

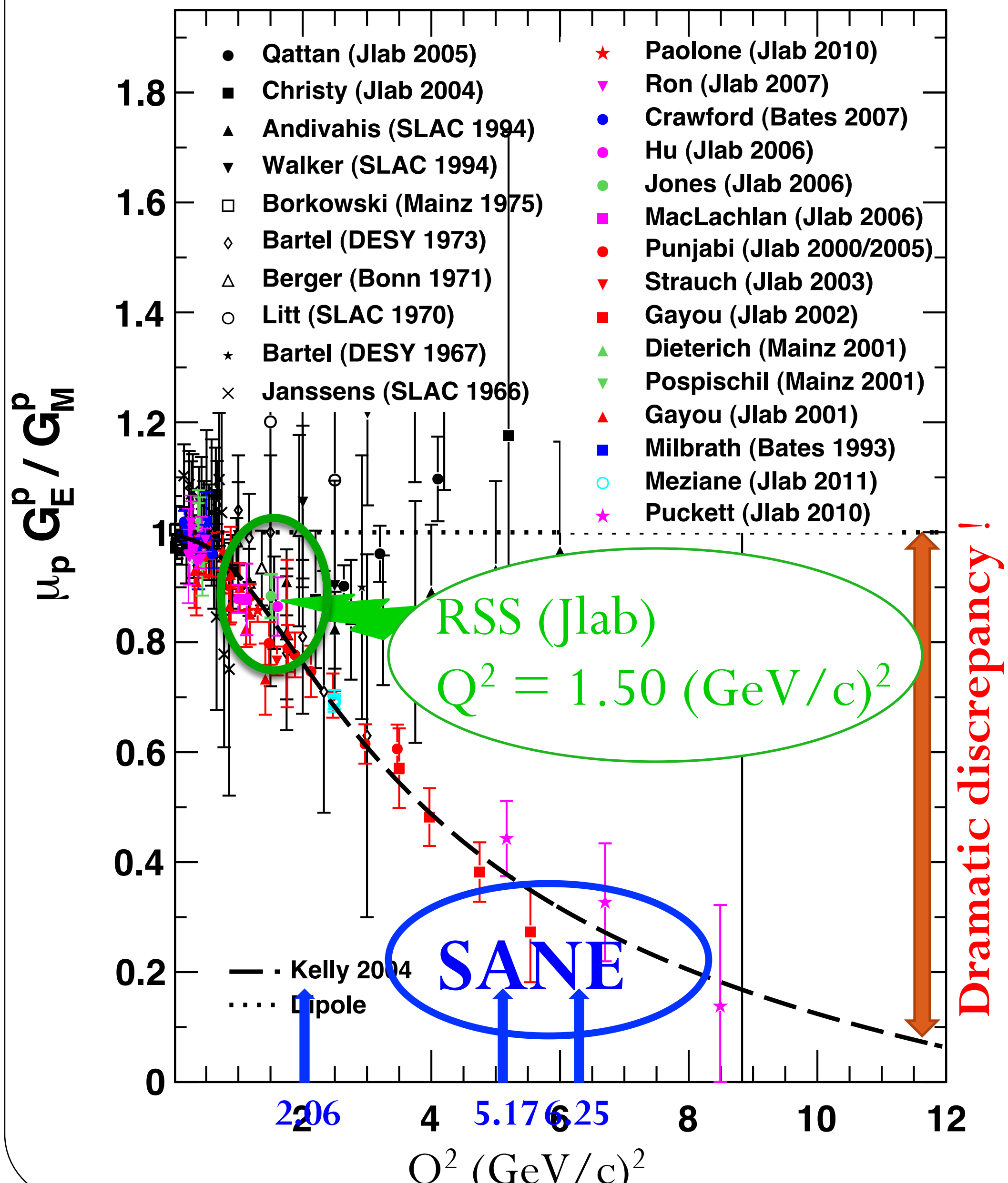
## 2. Polarization Transfer Technique.

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

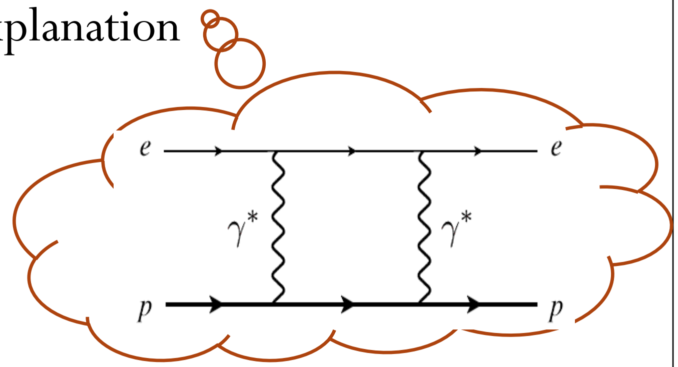
## 3. Double-Spin Asymmetry.

- Measure the double asymmetry between even (++, --) and odd (+-, -+) combinations of electron and proton polarization.
- Different systematic errors than Rosenbluth or proton recoil polarization methods.
- The sensitivity to the form factor ratio is similar to that of the Polarization Transfer Technique.

# Physics Motivation




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

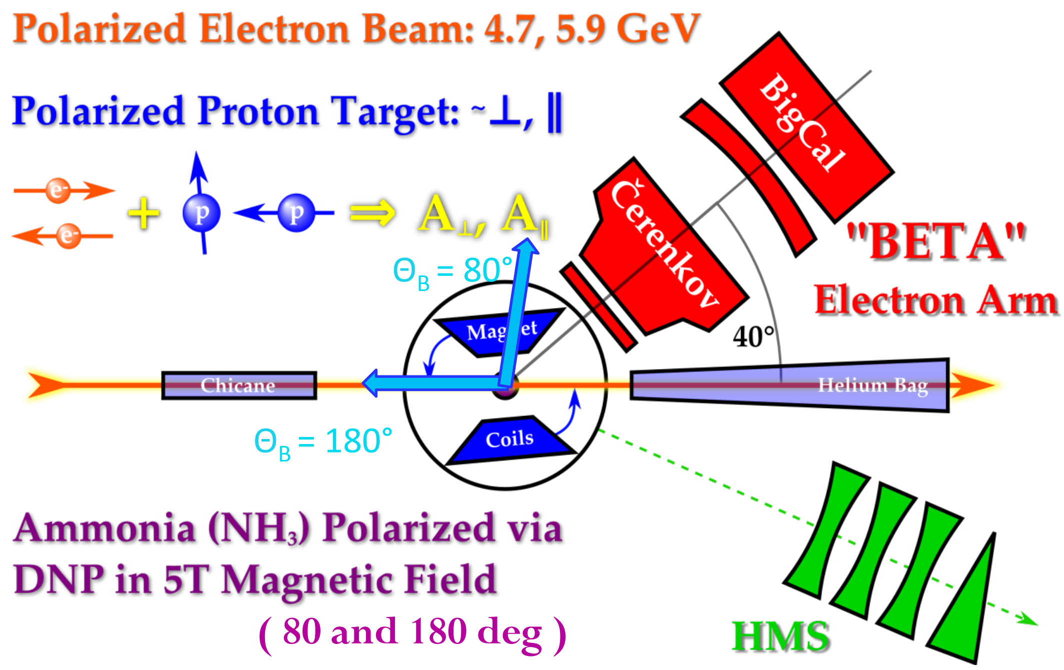



- **Double-Spin Asymmetry is an independent technique to verify the discrepancy**

# Detector Setup

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

- Used only perpendicular magnetic field configuration for the elastic data



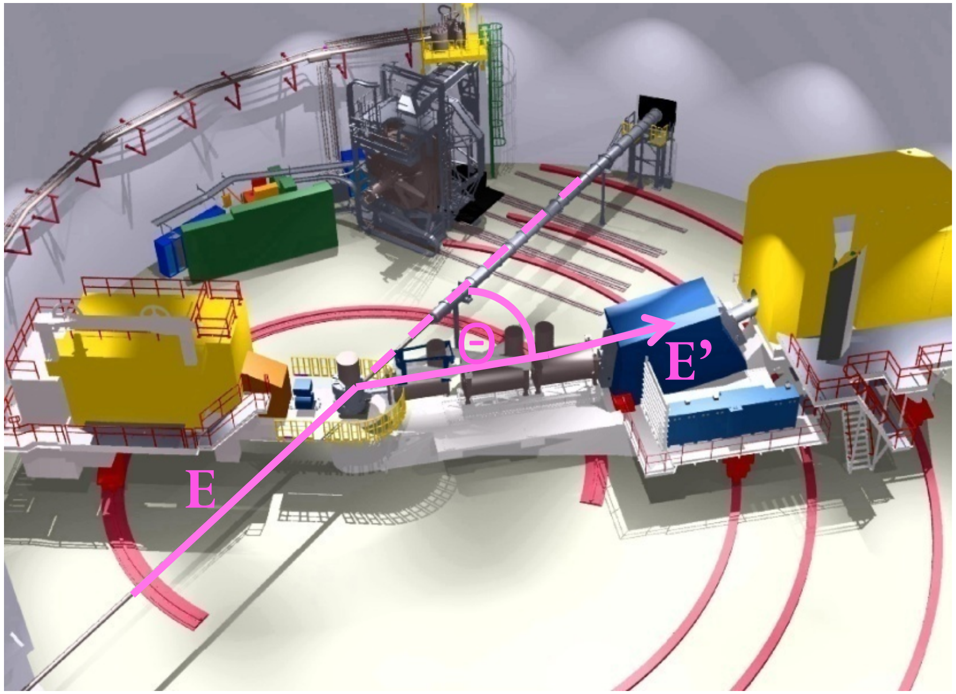

- Average target polarization is ~ 70 %
- Average beam polarization is ~ 73 %

# 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 |
| $\Theta_{HMS}$ (Deg) | 22.30 | 22.00 | 15.40 |
| $Q^2$ $(GeV/c)^2$ | 5.17 | 6.26 | 2.06 |
| Total Hours (h) | ~40 (~44 runs) | ~155 (~135 runs) | ~12 (~15 runs) |
| Elastic Events | ~113 | ~1200 | ~5x10$^4$ |

# Single-arm Data
# (Electrons in HMS)




By knowing,

the incoming beam energy, $E$,

scattered electron energy, $E'$

and

the scattered electron angle, $\theta$

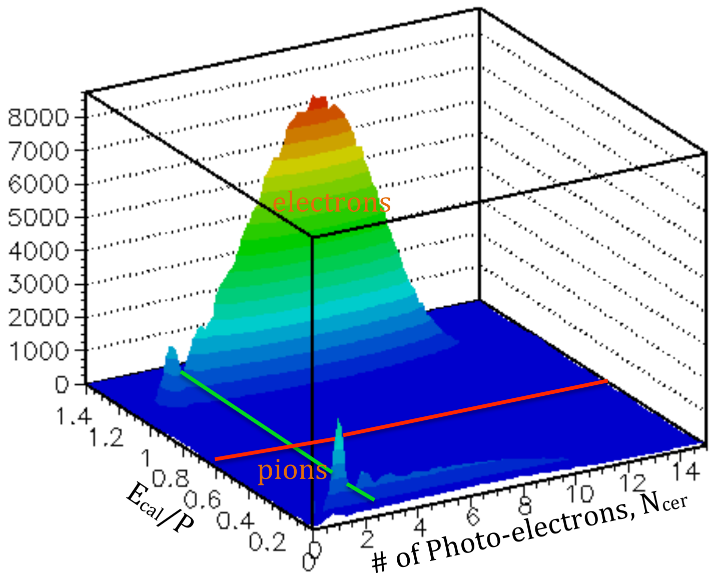
$$\vec{e}^- \vec{p} \longrightarrow e^- p$$

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

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

# Elastic Event Selection

- Particle Identification (PID)




Used the Cherenkov and calorimeter cuts,

# of Cerenkov photoelectrons > 2

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

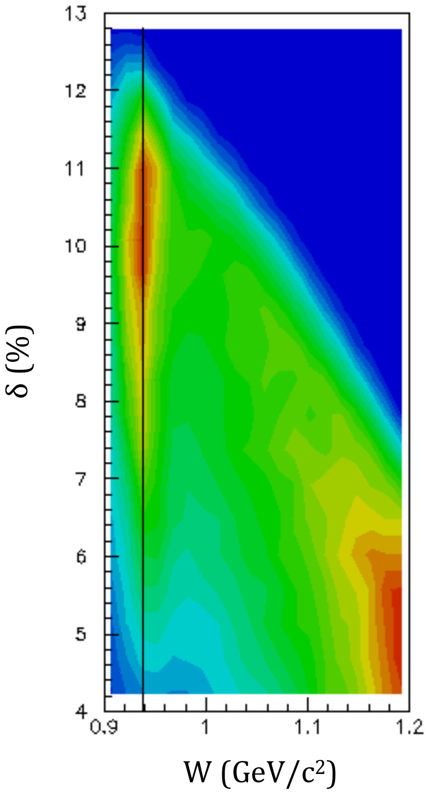
$E_{Cal}$ - Total measured shower energy of a chosen electron track by HMS Calorimeter

- The Relative Momentum ( $\delta$ )

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

$P$ - 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*

$\Delta A_r$ = *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 $(GeV/c)^2$ )

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

$P_BP_T$ = *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…..

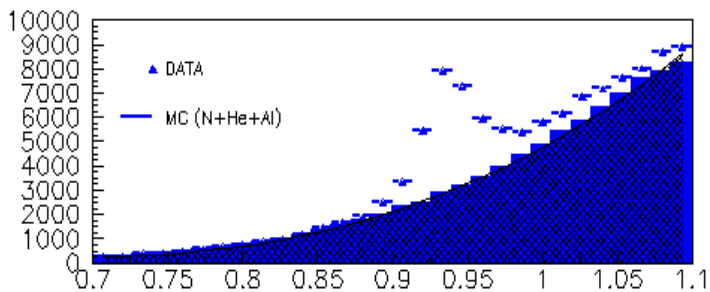
# Determination of the Dilution Factor

## What is the Dilution Factor ?

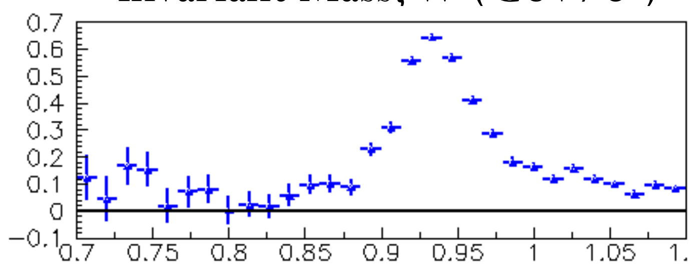
**The dilution factor is the ratio of the yield from scattering off free protons(protons from H in $NH_3$) to that from the entire target (protons from N, H, He and Al)**

*Dilution Factor,*

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



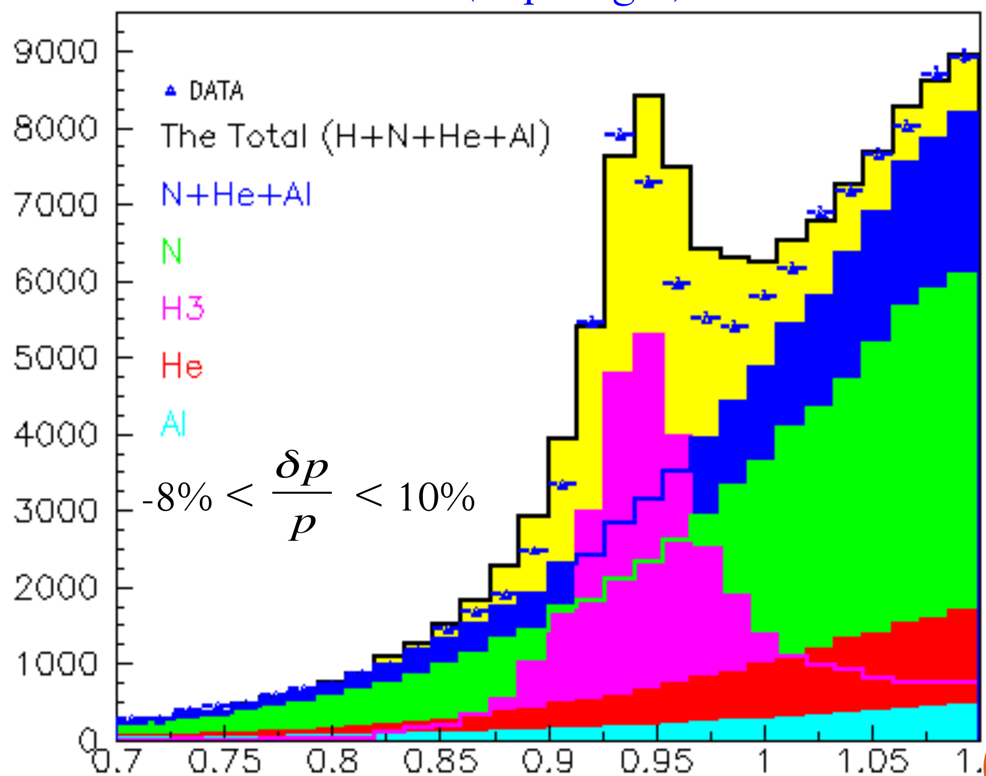

Invariant Mass, W (GeV/c$^2$)



The Relative Dilution Factor

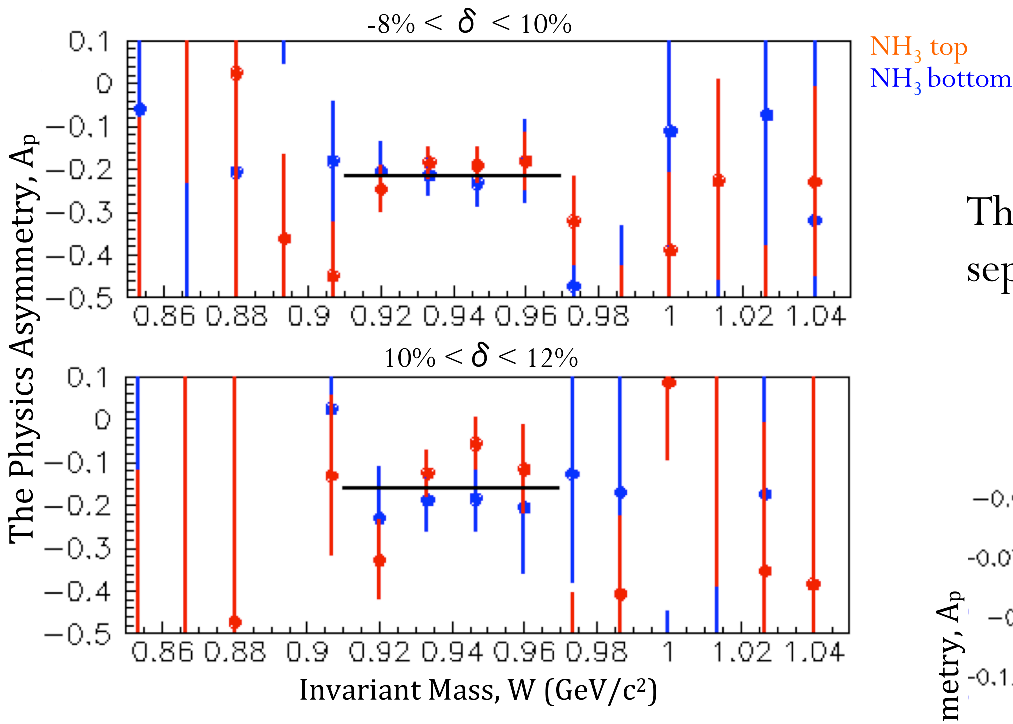
Each target type contributions

(Top target)




Invariant Mass, W (GeV/c$^2$)

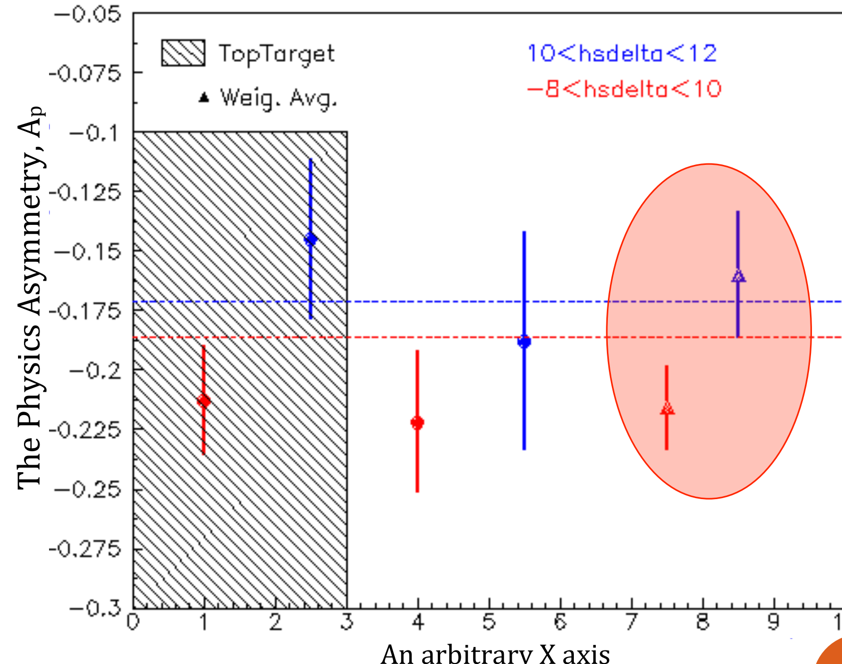
# The Physics Asymmetry




The constant physics asymmetry, Ap were read separately,

For each target type and

For two different $\delta$ 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 $\delta$ regions.

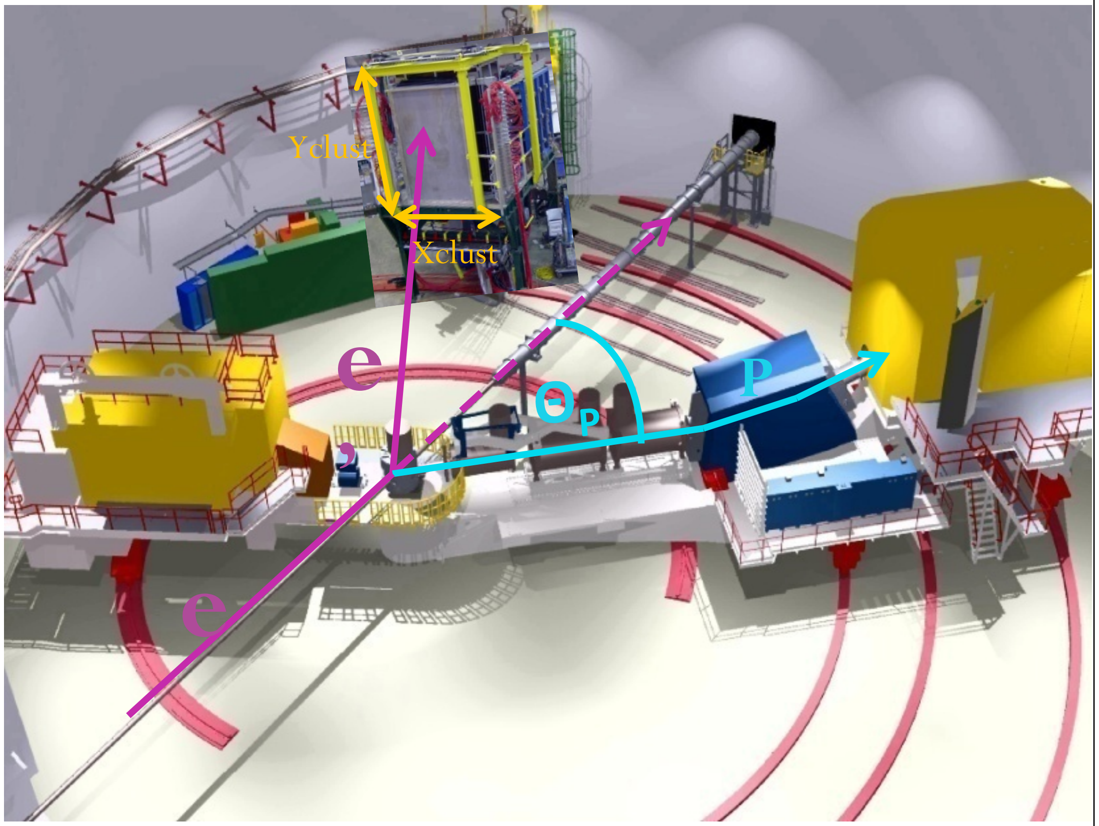
# Coincidence Data
# (Electrons in BETA and Protons in HMS)

<u>Definitions :</u>

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

  *X = horizontal / in-plane coordinate*

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



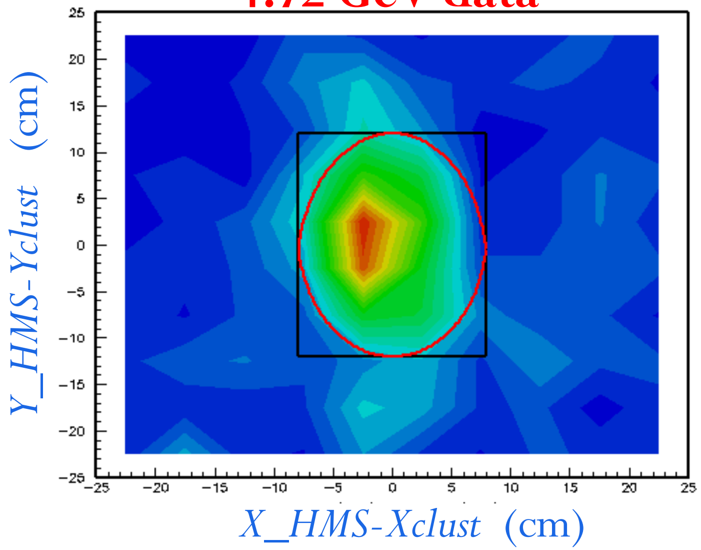

By knowing
the energy of the polarized electron beam, $E_B$
and
the scattered proton angle, $\Theta_P$

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

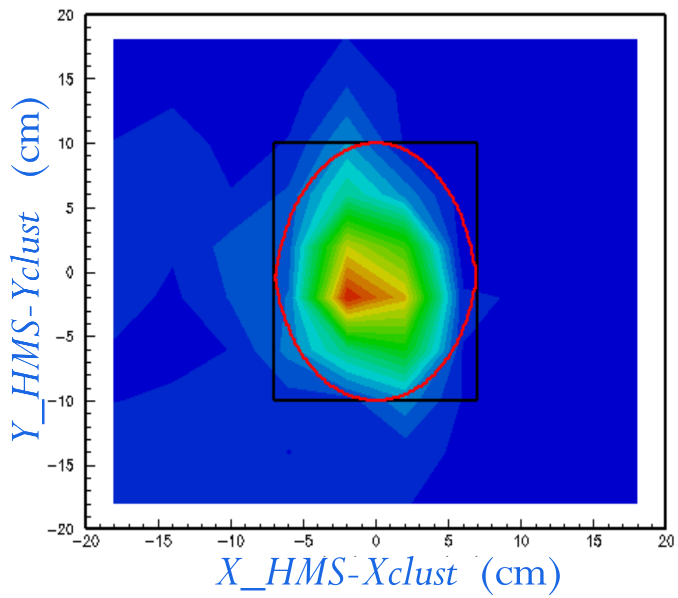
$$\Delta X = X\_HMS - Xclust$$
$$\Delta Y = Y\_HMS - Yclust$$

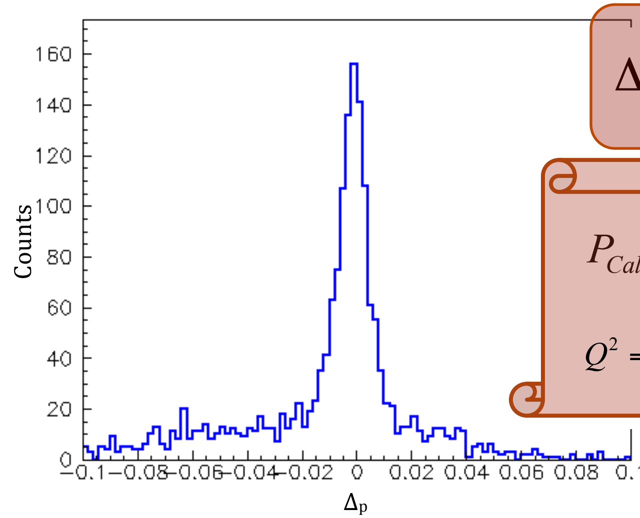
# Elastic Event Selection

**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,

$$-0.02 \leq \Delta_P \leq +0.02$$

- 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

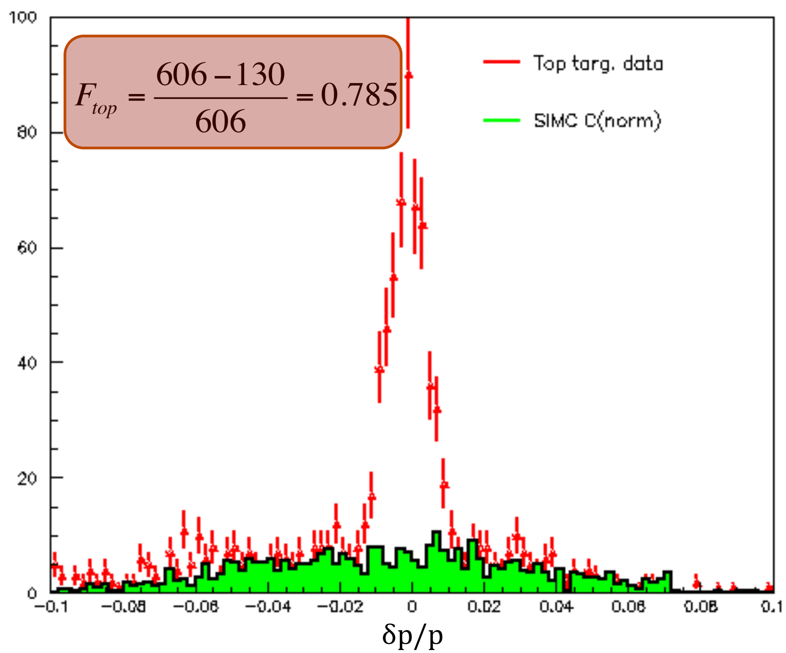
*Here,* $X(Y)_{max}$ *= The effective area cut, 10 (7) cm*

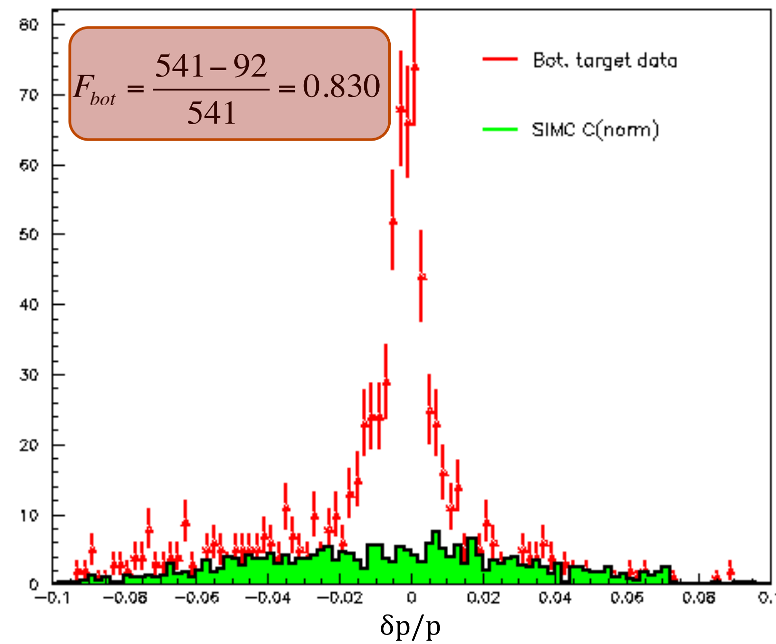
# Determination of the Dilution Factor

- 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< $\delta$ <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< $\delta$ <0.02.

*Dilution Factor,*

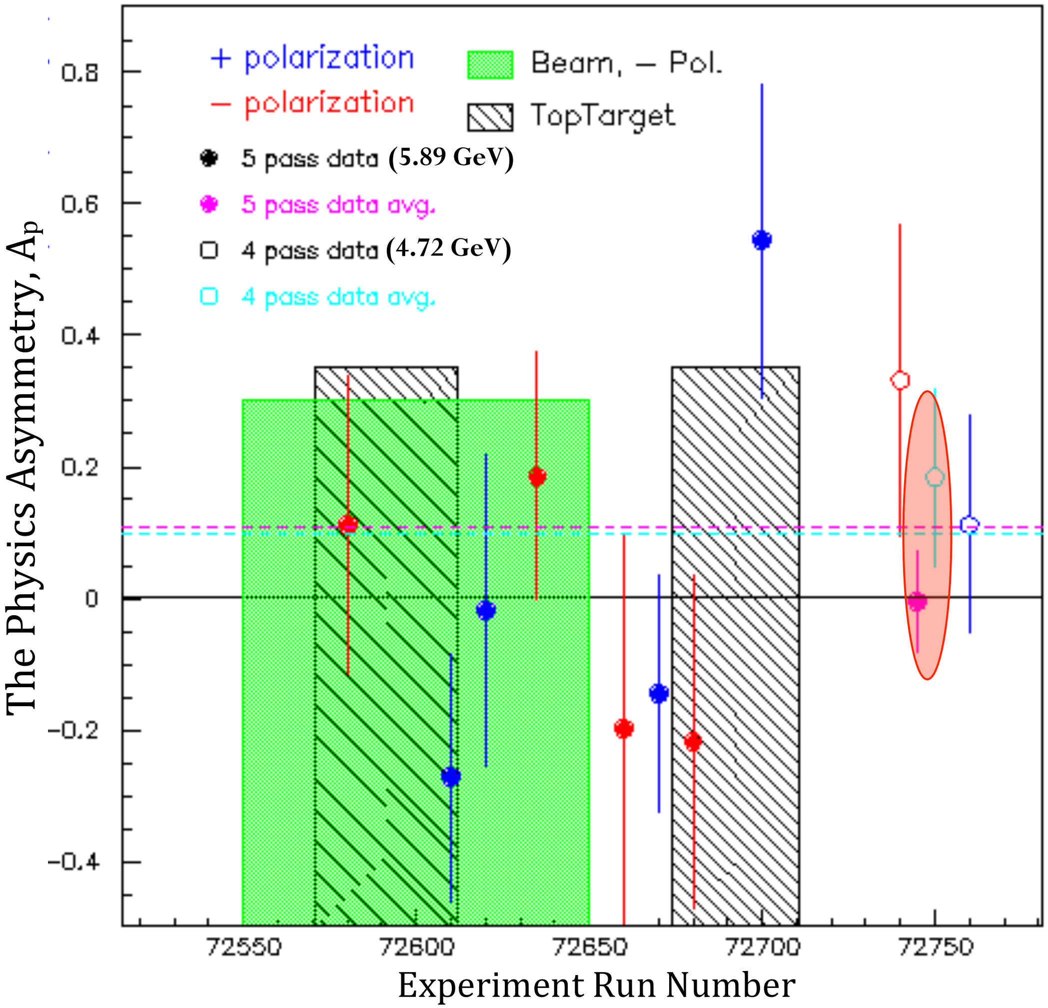
$$F = \frac{Yield_{Data} - Yield_{MC(C)}}{Yield_{Data}}$$



# 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 beam - target asymmetry, $A_p$

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

Here, $r = G_E / G_M$

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

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

$\theta^*$ and $\phi^*$ are calculated from,

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

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

$\theta$ q is the 4-momentum angle determined from data.

$\beta$ 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,

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

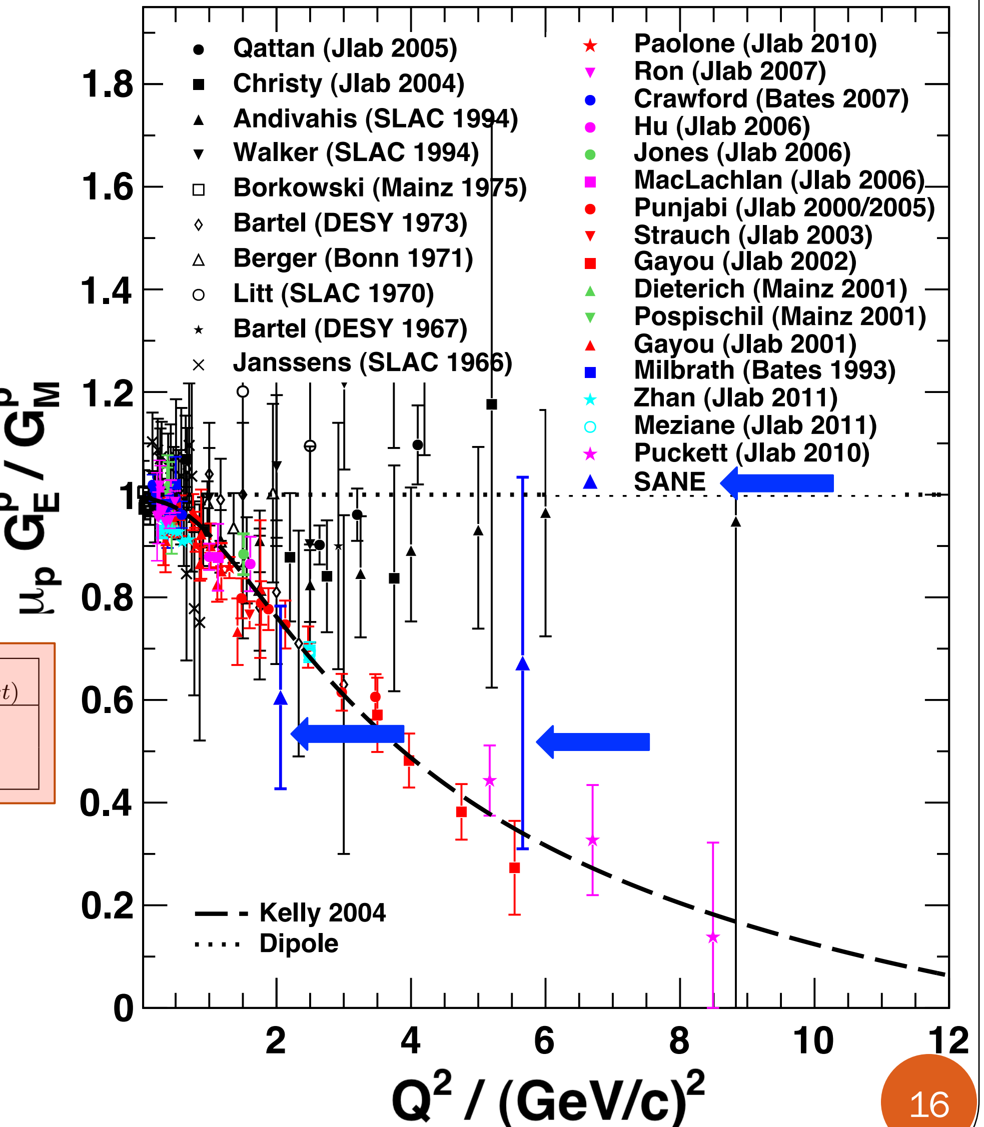
$$\Delta r = \Delta\left(\frac{G_E}{G_M}\right) = \left(\frac{\partial\left(G_E/G_M\right)}{\partial A_p}\right)\cdot \Delta A_p$$

## The systematic Errors

**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.

| $Q^2$ $(GeV/c)^2$ | $\mu G^p_E/G^p_M \pm \Delta\mu G^p_E/G^p_{M(stat)} \pm \Delta\mu G^p_E/G^p_{M(syst)}$ |
|---|---|
| 2.06 | $0.605 \pm 0.178 \pm 0.055$ |
| 5.66 | $0.672 \pm 0.362$ |




Only the statistical errors are shown in the plot.

# Conclusion

- 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

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Thomas Jefferson National Accelerator Facility

# Results

| | Single Arm | | Coincidence | |
|---|---|---|---|---|
| | $-8\%<\delta<10\%$ | $10\%<\delta<12\%$ | | |
| $E$ (GeV) | 5.895 | 5.895 | 5.893 | 4.725 |
| $\theta_q$ (Deg) | 44.38 | 46.50 | 22.23 | 22.60 |
| $\phi_q$ (Deg) | 171.80 | 172.20 | 188.40 | 190.90 |
| $\theta_e$ (Deg) | 15.45 | 14.92 | 37.08 | 43.52 |
| $\phi_e$ (Deg) | 351.80 | 352.10 | 8.40 | 10.95 |
| $Q^2$ (GeV/c)$^2$ | 2.20 | 1.91 | 6.19 | 5.14 |
| $\theta^*$ (Deg) | 36.31 | 34.20 | 101.90 | 102.10 |
| $\phi^*$ (Deg) | 193.72 | 193.94 | 8.40 | 11.01 |
| $A_p \pm \Delta A_p$ | $-0.216 \pm 0.018$ | $-0.160 \pm 0.027$ | $-0.006 \pm 0.077$ | $0.184 \pm 0.136$ |
| $\mu r \pm \Delta(\mu r)$ | $0.483 \pm 0.211$ | $0.872 \pm 0.329$ | $0.937 \pm 0.428$ | $-0.052 \pm 0.678$ |
| predicted $\mu r$ | 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.

| 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 |
| $\theta_e$ (mrad) | 0.5 | 0.54 |
| $\theta^*$ (mrad) | 1.22 | 0.54 |
| $\phi^*$ (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%**

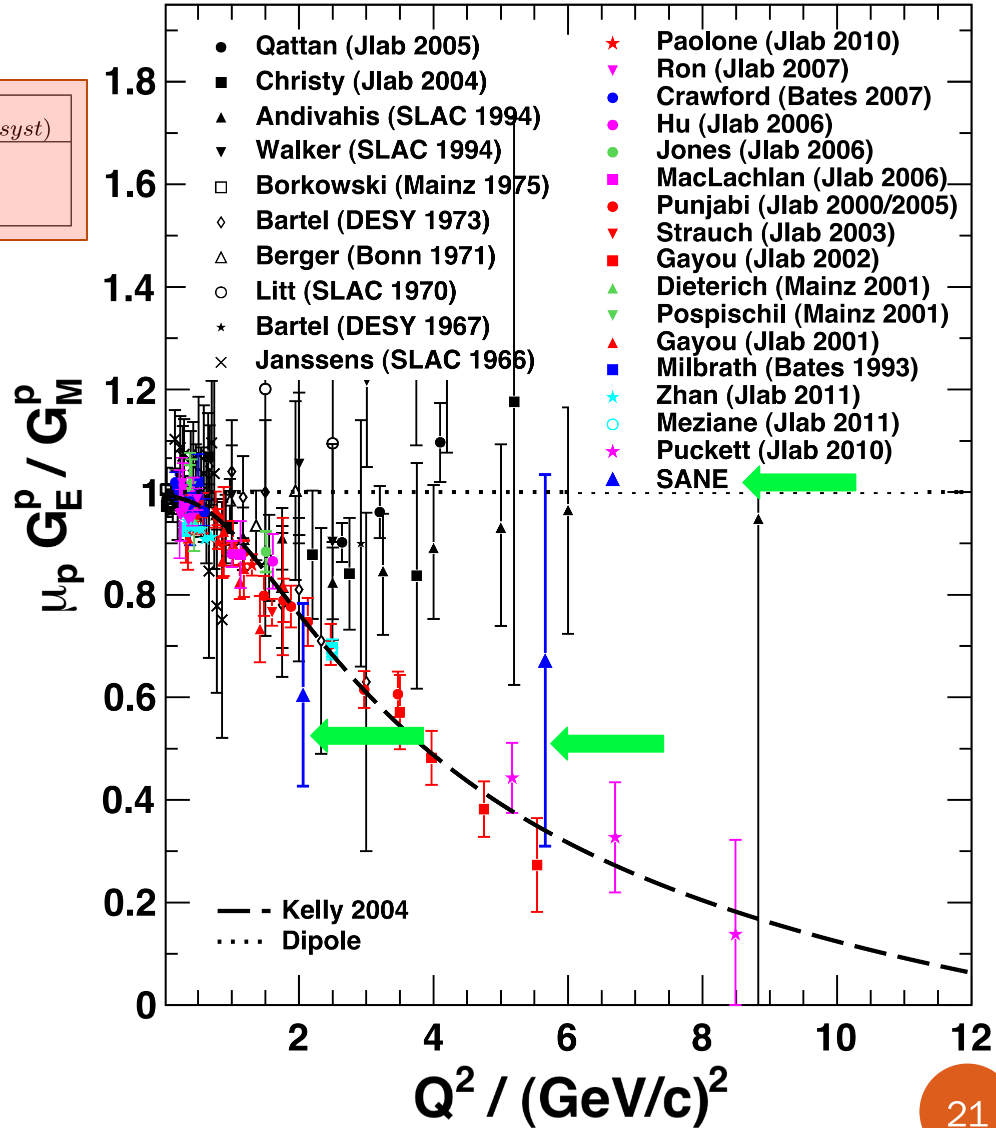
**The resulting form factor ratio is obtained by,**

**Extrapolating both measurements to average $Q^2$ using Kelly's parameterization and Taking the weighted average.**

| $Q^2$ $(\mathrm{GeV/c})^2$ | $\mu G_E^p/G_M^p \pm \Delta\mu G_E^p/G^p_{M(stat)} \pm \Delta\mu G_E^p/G^p_{M(syst)}$ |
|---|---|
| 2.06 | $0.605 \pm 0.178 \pm 0.055$ |
| 5.66 | $0.672 \pm 0.362$ |

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

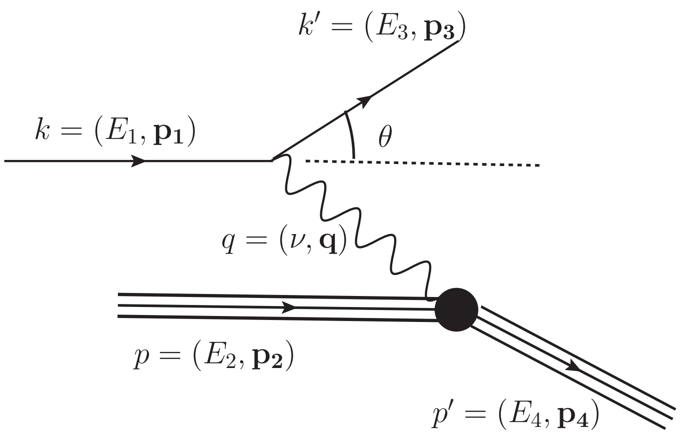
Only the statistical errors are shown in the plot.



# Introduction

## Nucleon Elastic Form Factors

- 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.
- They are functions of the four-momentum transfer squared, $Q^2$




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.**

The four-momentum transfer squared,

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

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

At $q^2 = 0$

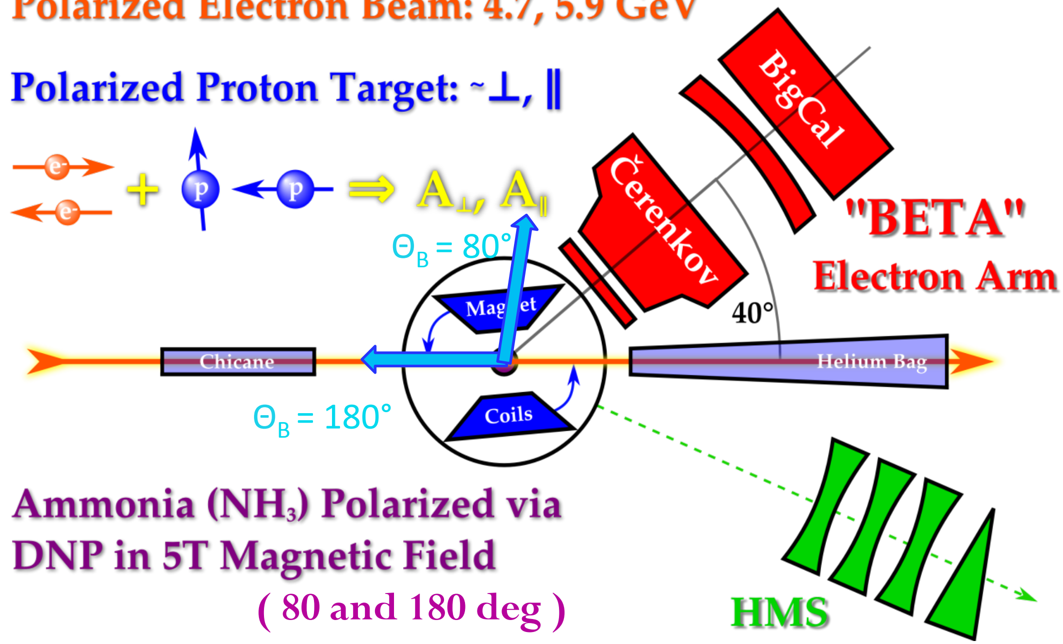
$$G^p_E(0) = \int \rho(\vec{r}) d^3\vec{r} = 1$$

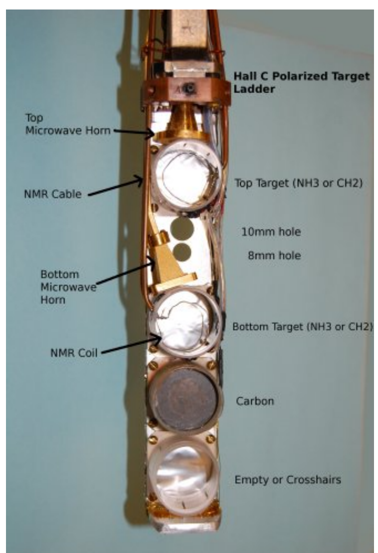
$$G^p_M(0) = \int \mu(\vec{r}) d^3\vec{r} = \mu_P = +2.79$$

$$\mu \, G^p_E / G^p_M = 1$$

# 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 %

# Extracted the Asymmetries …..

The raw asymmetry, $A_r$

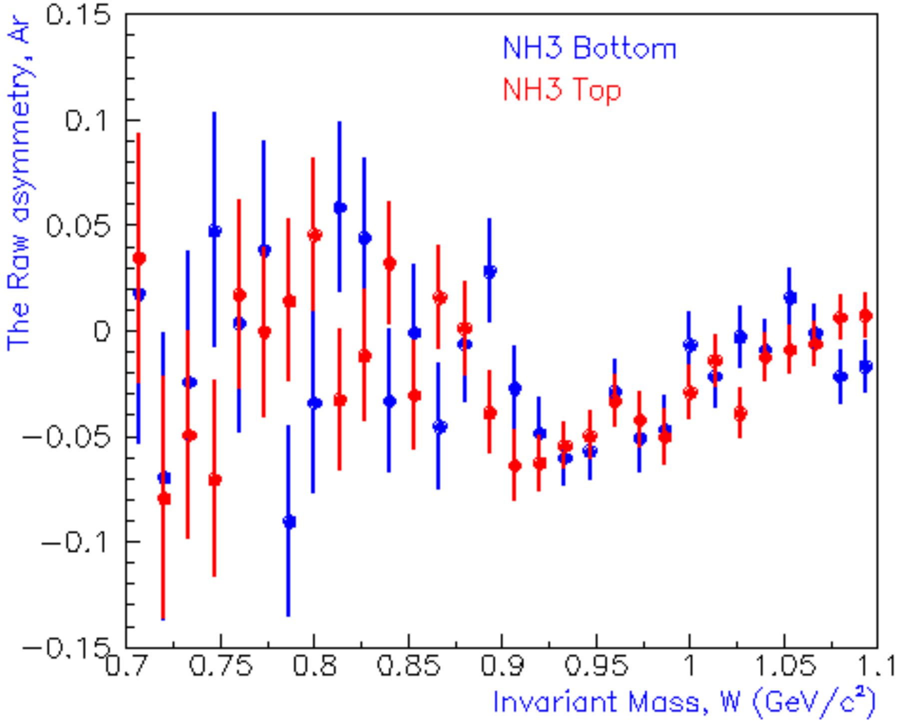
$$A_r = \frac{N^+ - N^-}{N^+ + N^-}$$

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

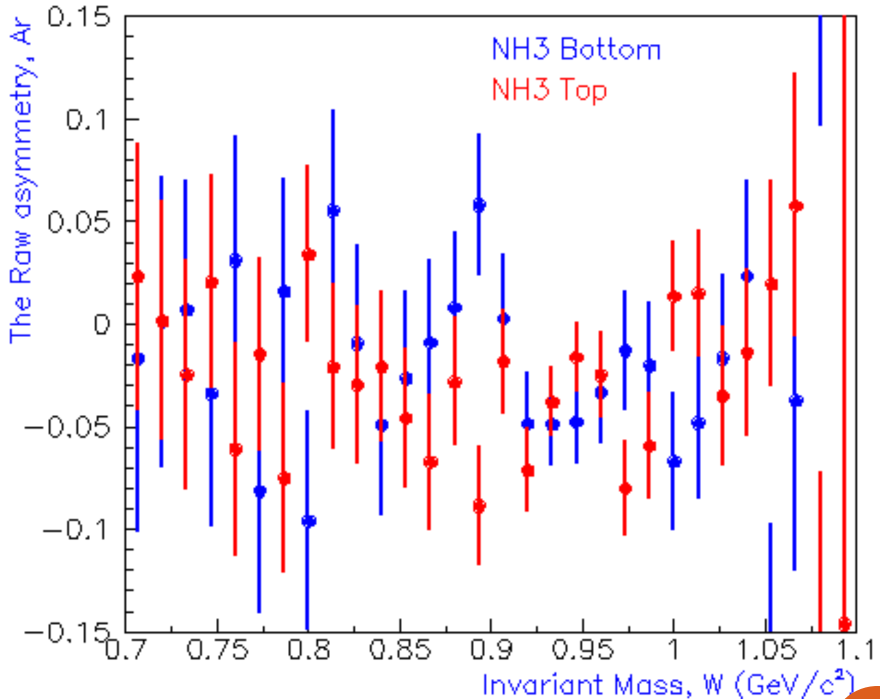
$N^+ / N^-$ = *Charge and live time normalized counts for the +/- helicities*

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

$$-8\% < \frac{\delta p}{p} < 10\%$$




$$10\% < \frac{\delta p}{p} < 12\%$$



# 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 $Q^2=0$

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

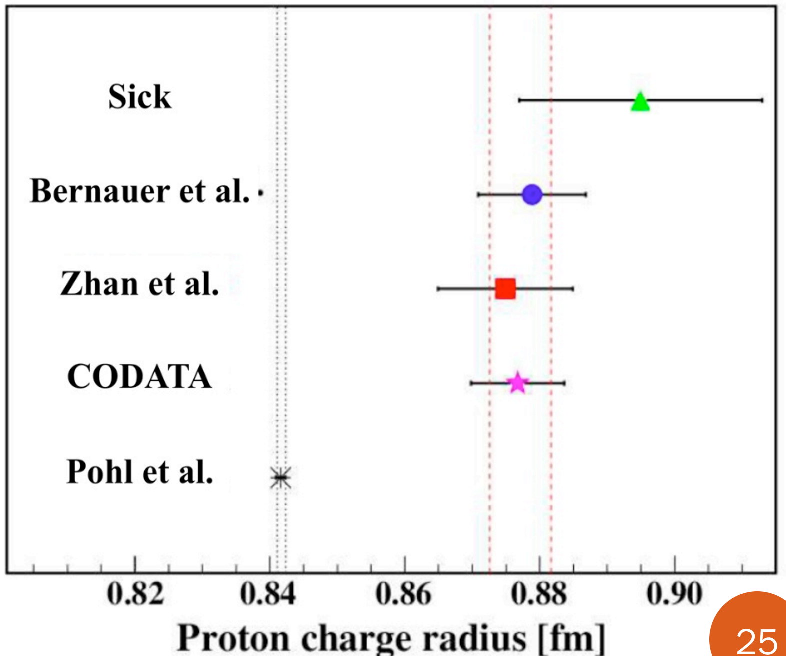
- 7 $\sigma$ discrepancy between muonic hydrogen Lamb shift and combined electronic Lamb shift and electron scattering

↓

proton radius puzzle

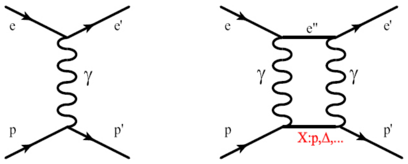
↓

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



# Two-Photon Exchange

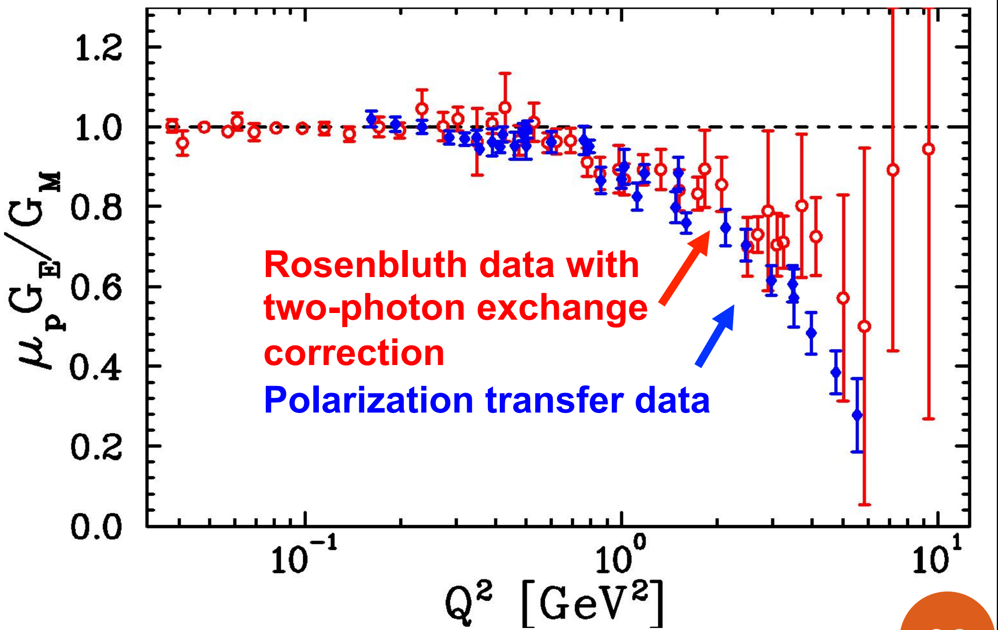
- Theoretically suggested to explain the dramatic discrepancy between Rosenbluth and recoil polarization technique.
- Both Rosenbluth method and the polarization transfer technique account for soft TPE correction, one soft and one hard photon exchange, but neither consider two hard photon exchange.
-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




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

$\sigma_r$ is the reduced cross section

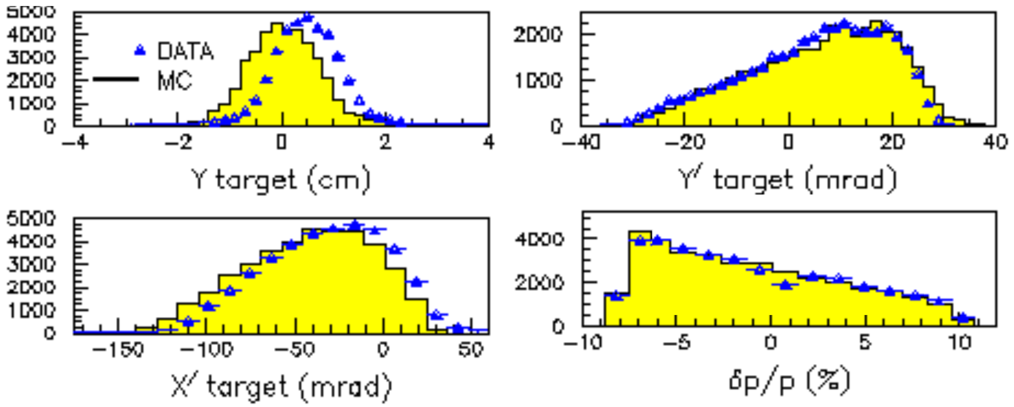
- TPE has an $\varepsilon$ dependence that has the same sign as the $G_E$ contribution to the cross section.
- This is large enough to effect the extra--cted value of $G_E$
- Therefore, the extracted $G_E/G_M$ for the Rosenbluth technique is reduced.
- TPE can explain form factor discrepancy.
- The effect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

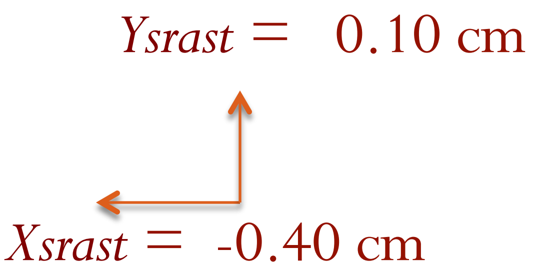



J. Arrington, W. Melnitchouk, J.A. Tjon, Phys. Rev. C 76 (2007) 035205

# Beam Position Offsets

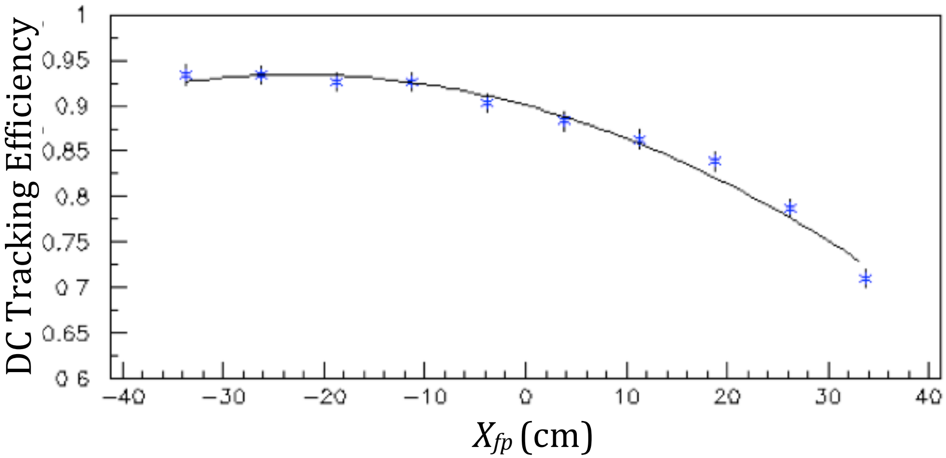
- Generated carbon and added Al come from target end caps and 4K shields.
- Calculated an MC scale factor using the data/MC luminosity ratio for each target type.
- Added all targets together by weighting with the above MC scale factors.




- Adjust acceptance edges in Y target and Y' target from adjusting the horizontal beam position, *Xsrast*.
- Adjust acceptance edge X' target from adjusting the vertical beam position, *Ysrast*.

# Drift Chamber Efficiency




$$DC_{X\_paddle} = \frac{(N_{cer} > 0.5).AND.(0.7 < \beta < 1.3).AND.(dc_{track})}{(N_{cer} > 0.5).AND.(0.7 < \beta < 1.3)}$$

$DC_{x\_paddle}$ - DC tracking efficiency for each scintillator paddle X.

*Ncer* - HMS Cherenkov photo electrons.

$\beta$ - Velocity of the particle calculated from the hodoscope information.

$dc_{track}$ - Good drift chamber track in the focal plane.

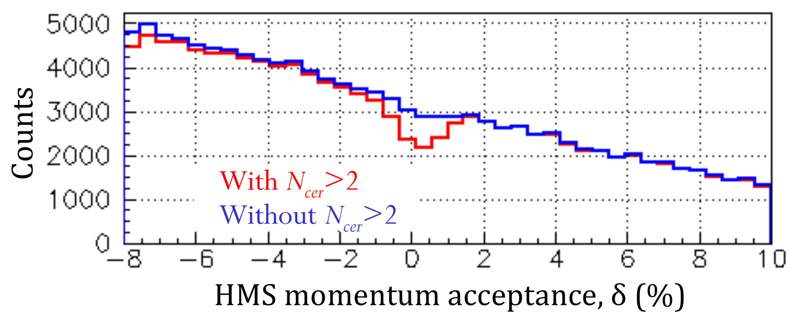
- DC tracking efficiency as a function of the scintillaor paddles was obtained.

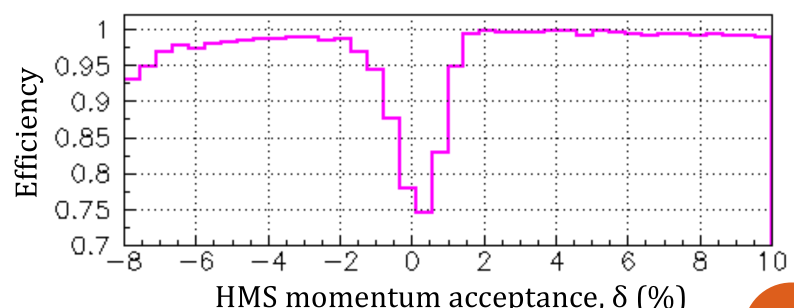
By converting the paddle number to the vertical position

- DC tracking efficiency as a function of the focal plane, $X_{fp}$ was obtained.

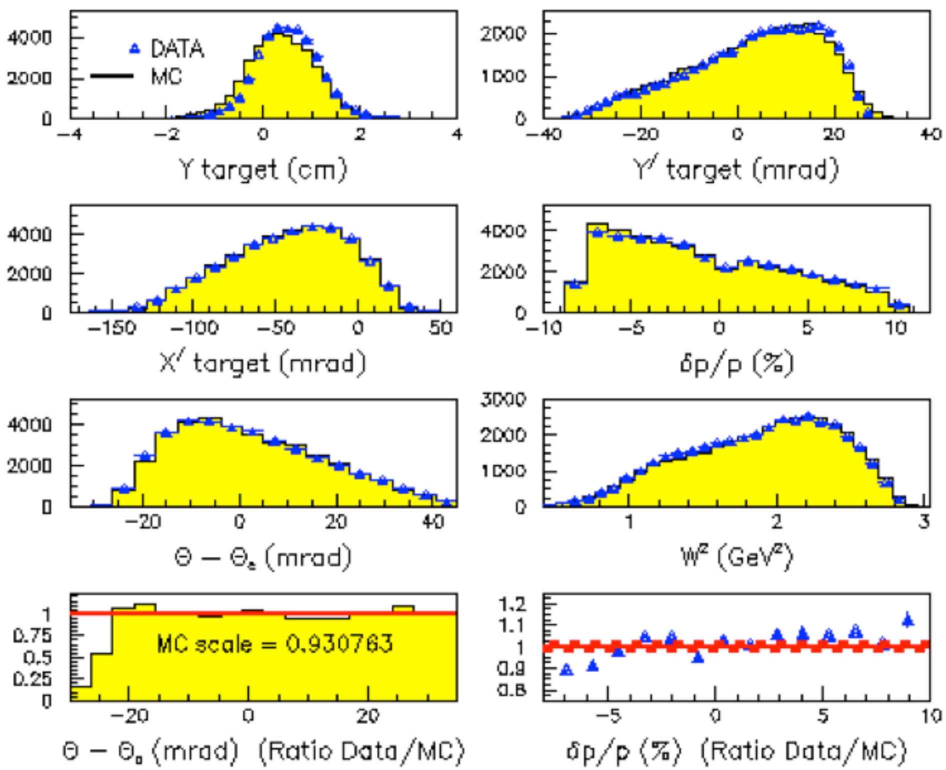
$$Che_{eff} = \frac{(N_{cer} > 2.0)}{(N_{cer} > 0.0)}$$

# Cherenkov Efficiency

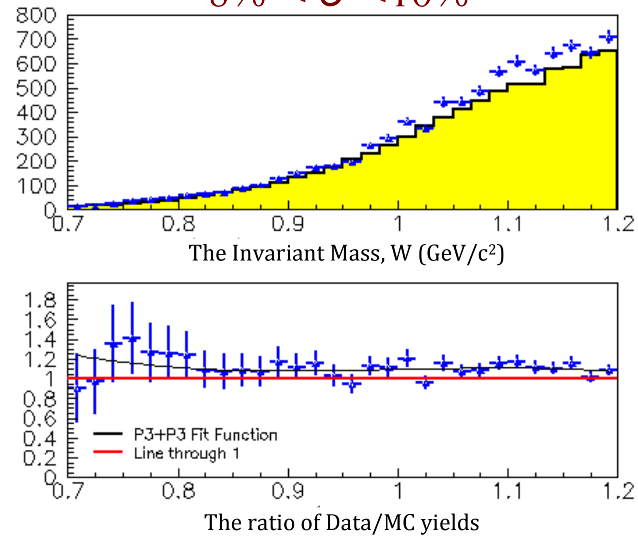


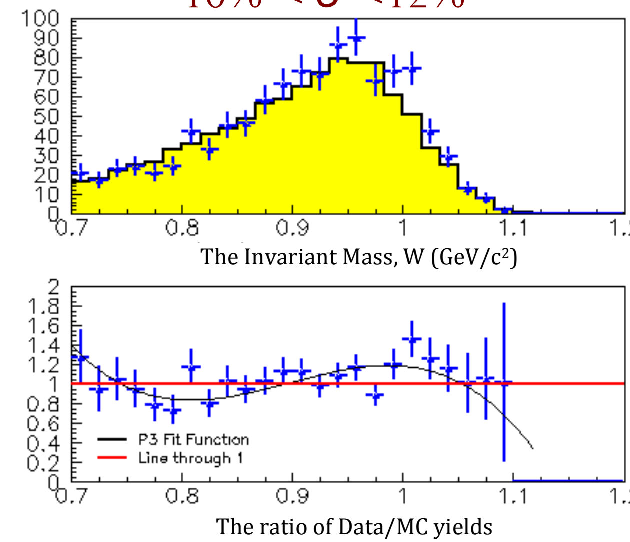
# Detector Efficiency and Beam X and Y offset Corrected C Montecarlo




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



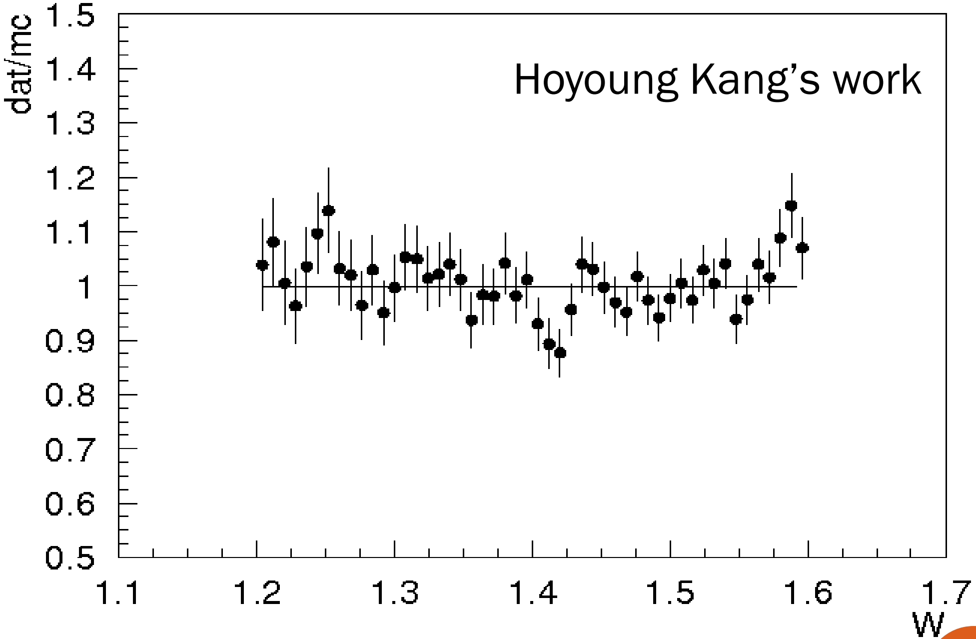

$10\% < \delta < 12\%$




The polynomial fits shown in the ratio of data/MC yields (right plots) were used to correct the MC yields for the carbon target.

# Packing Fraction.

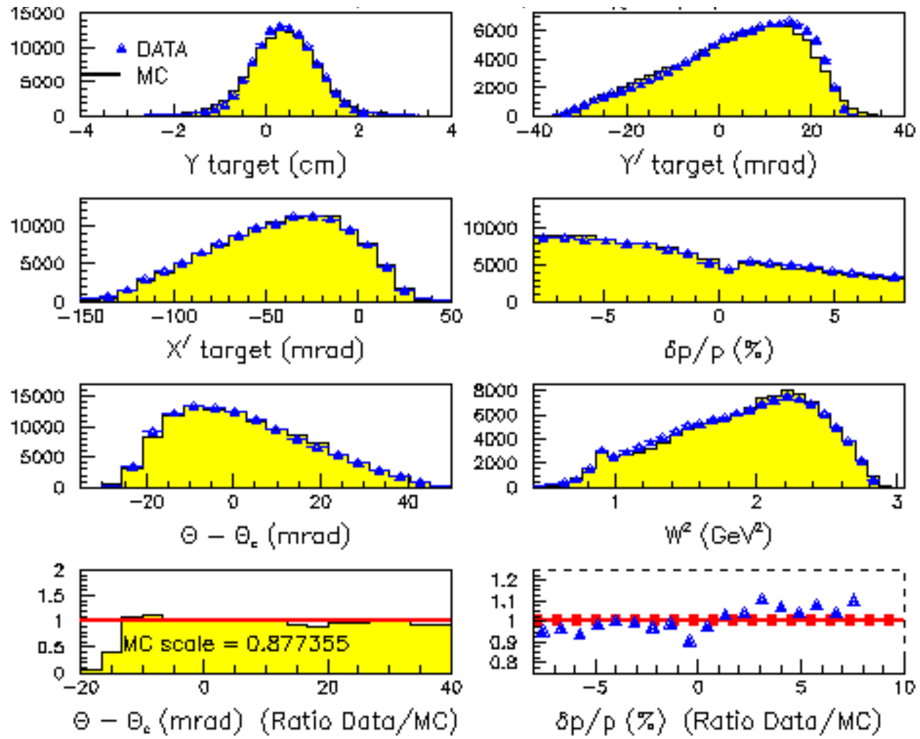
- Packing fraction is the actual amount of target material normalized the nominal amount expected for the target volume.
- Determined by taking the ratio of data to MC as a function of W.
- Need to determine the packing fractions for each of the NH3 loads used during the data taking.

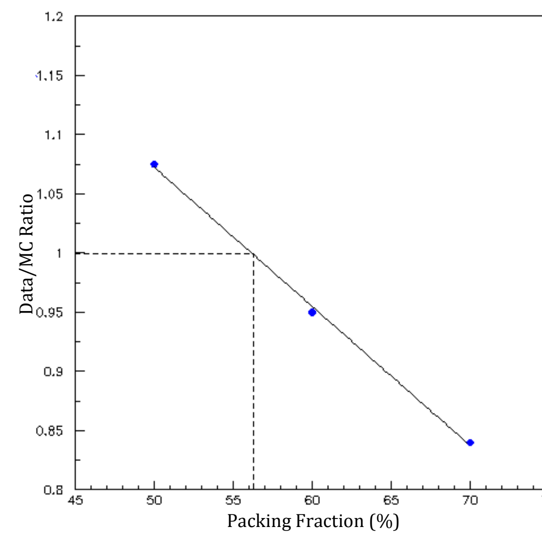


# Packing Fraction

- 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)

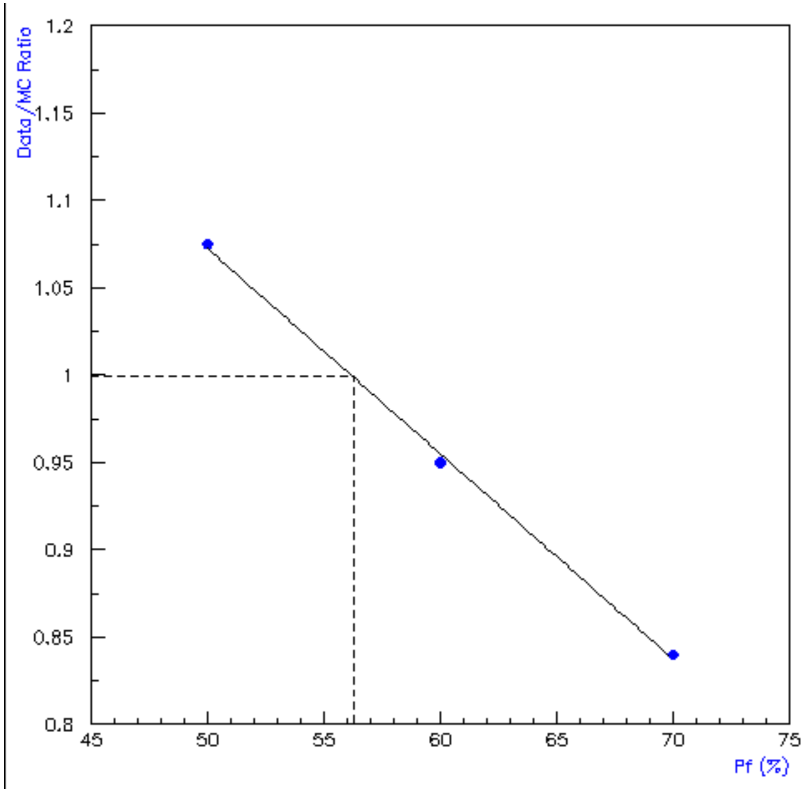



- Take the *pf* which gives a data to MC ratio 1.
- *Pf* for Bottom target is determined as 56%.

# Determine the Packing Fraction

- Compared data to SIMC simulation for the NH3 target for 3 different Packing Fractions.
- Normalized MC_NH3 by 0.93 which is the factor that brings C data/MC ratio to 1.




- Determined the packing fraction which brings Data/MC ratio to 1 from the plot.
- Packing Fraction=56.3 %

| Pf (%) | 50 | 60 | 70 |
|---|---|---|---|
| Data/MC Ratio | 1.00 | 0.88 | 0.78 |
| Data/MC Ratio/0.93 | 1.075 | 0.95 | 0.84 |

Consistent with Hoyoung kang's packing fraction determinations !!!!

# Beam Position Offsets (Using SIMC)

- Used SIMC to generate elastic hydrogen.
- Adjust acceptance edge in "Y target" by changing the horizontal beam position, *Xsrast*.
- Adjust edge in "$\Delta_P$" by changing the vertical beam position, *Ysrast*.

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

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

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

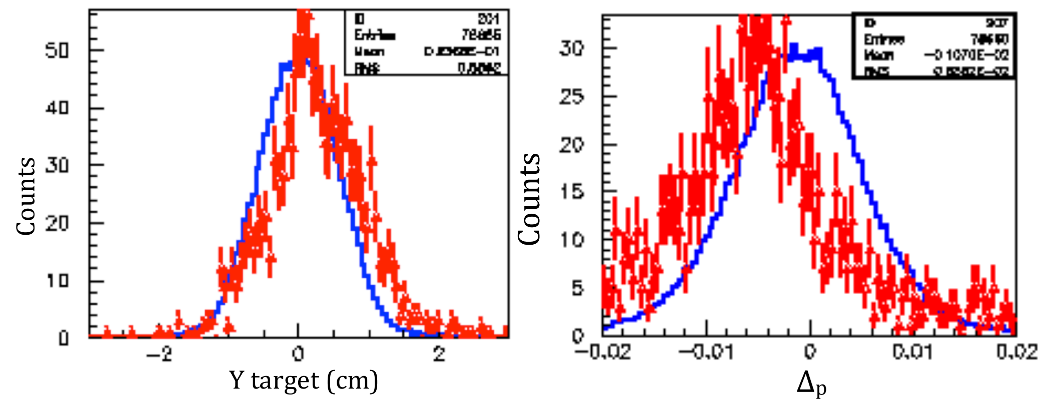
$$Q^2 = \frac{4M^2E^2\cos^2\theta}{M^2 + 2ME + E^2\sin^2\theta}$$

$P_{HMS}$ – *Measured proton momentum by HMS*

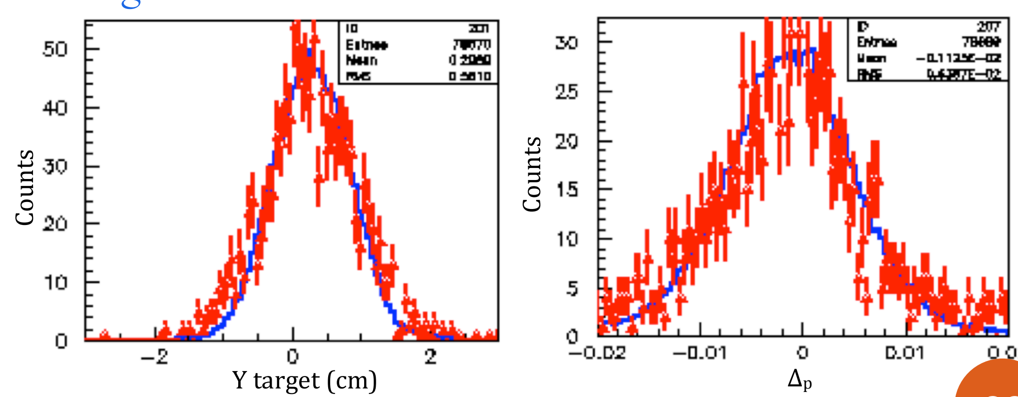
$P_{Cal}$ - *Calculated proton momentum by knowing the beam energy, E and the proton angle,* $\Theta$

$P_{cent}$ – *HMS central momentum*

Before using X and Y offsets



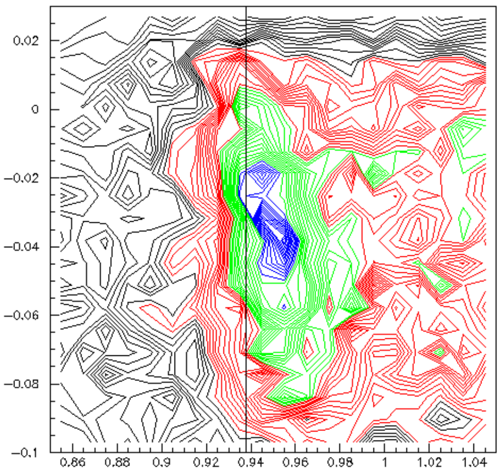

After using X and Y offsets



# Correcting for Correlations

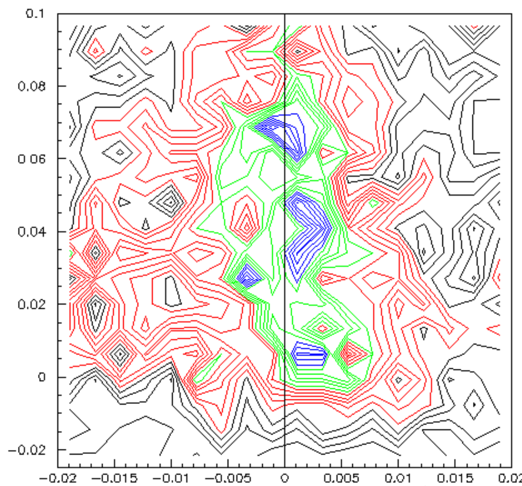
Both single-arm and coincidence data shows some correlations.

**In Single-arm electron data**




X' target (Deg.) vs W $(GeV/c^2)$

**In coincidence HMS data**




X' target (Deg.) vs $\Delta_P$

Reconstructed out-of-plane angle, X' target has a 1st order dependence on the Y position at the target in the reconstruction matrix element

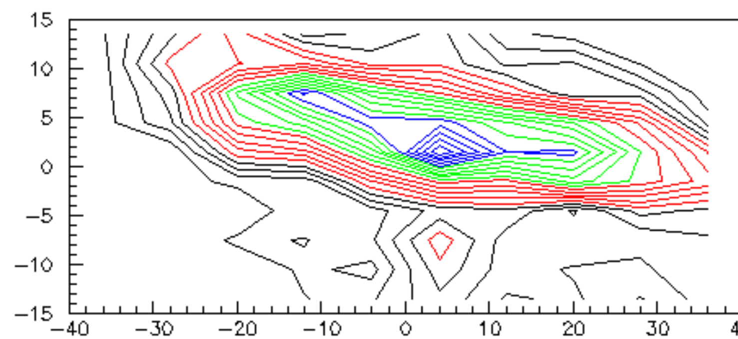
The vertical beam position deviation from the target center can have an effect on the reconstructed X' target

- All correlations are related to the vertical position or angle.

The best explanation

- A correction of azimuthal angle due to the target magnetic field

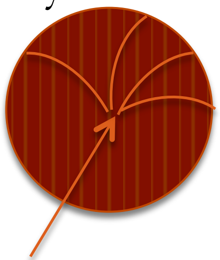
**In coincidence BETA data**




Y_HMS-Yclust (cm) vs Yclust (cm)

# The azimuthal angle correction

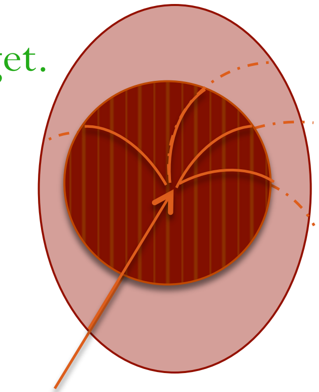
Analysis assumes the target magnetic field is cylindrical around the target which



Undergoes the same field integral, $\int B \cdot dl$

In reality,

- The target magnetic field might not be symmetric around the target.
- It might have some azimuthal (out-of-plane) angle dependence.
- Different $\int B \cdot dl$ with depending on the out-of-plane angle.
- Different deflections.



Solution:

Two new parameters, $\Delta\Phi_0$ and $d\Phi_0$ introduced so that,

$$B_{corr} = (\theta_{azim} - \Delta\phi_0) \times d\phi_0$$

$$B_{scale} = \frac{B_0}{B_0 + abs(B_{corr})}$$

$\Delta\Phi_0$ is the shift to the out-of-plane angle, $\theta_{azim}$

$d\Phi_0$ is the target magnetic field gradient which corrects the magnetic field strength at the new vertical angle, $(\theta_{azim} - \Delta\Phi_0)$

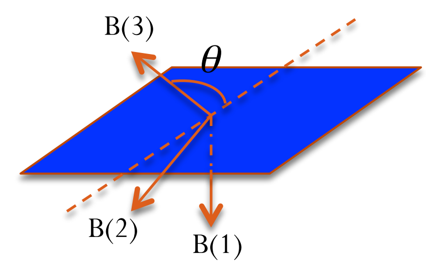
$B_{corr}$ is the magnetic field correction.

$B_{scale}$ is the new re-scaling factor.

The target magnetic field is modified as,

$$B(1) = B(1) - B_{corr}$$
$$B(1) = B(1) \times B_{scale}$$

$$B(3) = B(3) + B_{corr}$$
$$B(3) = B(3) \times B_{scale}$$

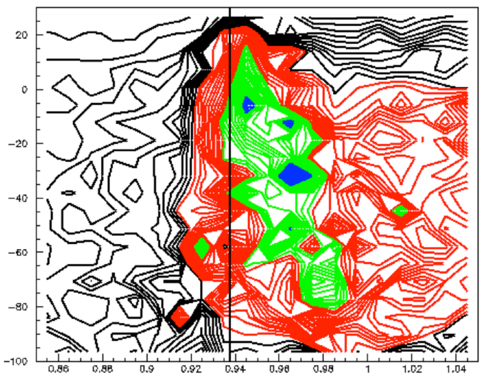


# Correcting for Correlations Cont…

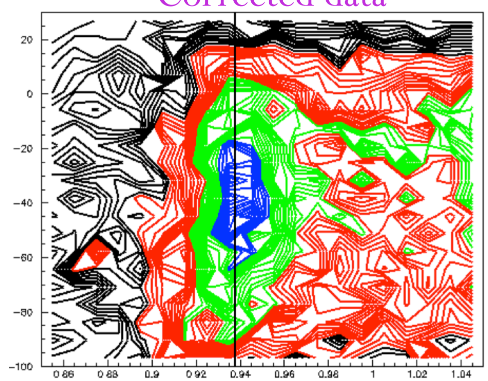
- First make the same correlations on MC/SIMC by applying the correction only for the forward direction and then use the correction on data.
- Different corrections for different detector angles.

## In Single-arm electron data

Correction on forward MC



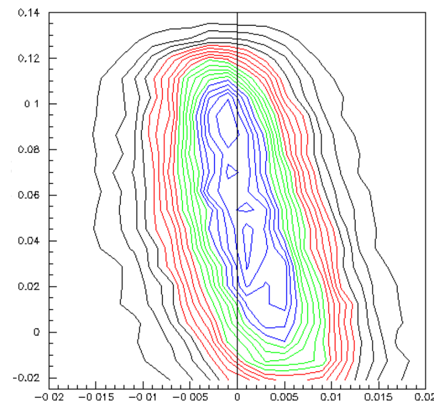
Corrected data



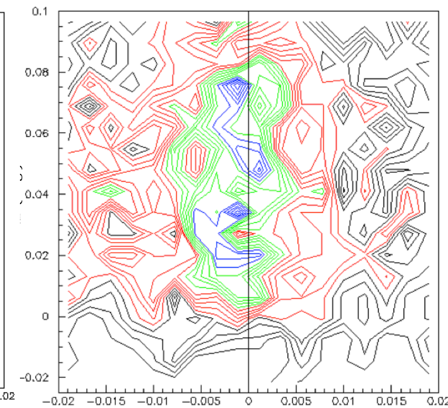
X'target (Deg.) vs W (GeV/$c^2$)

## In coincidence HMS data

Correction on forward MC



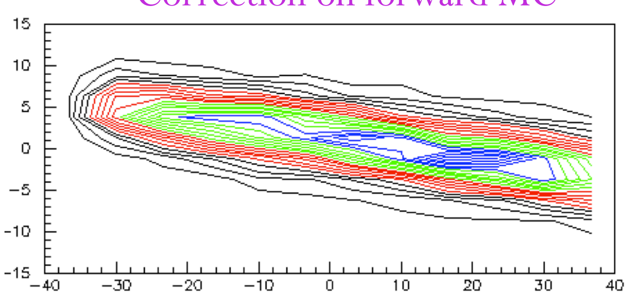
Corrected data



X'target vs $\Delta_P$

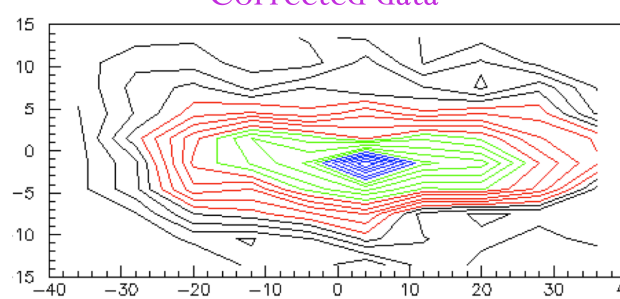
## In coincidence BETA data

Correction on forward MC



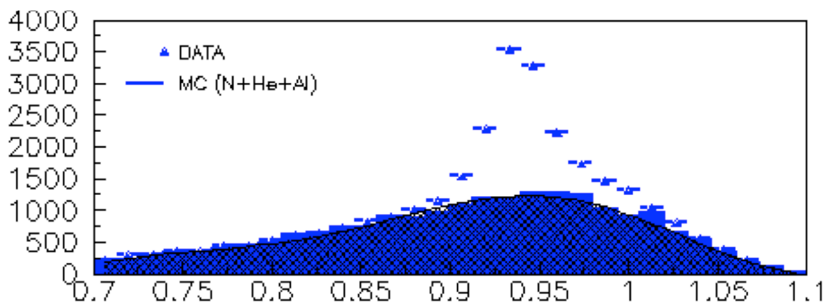

Y_HMS-Yclust (cm) vs Yclust (cm)

Corrected data

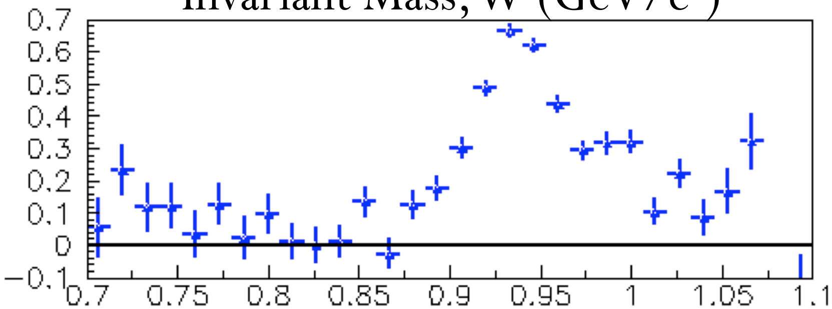



Y_HMS-Yclust (cm) vs Yclust (cm)

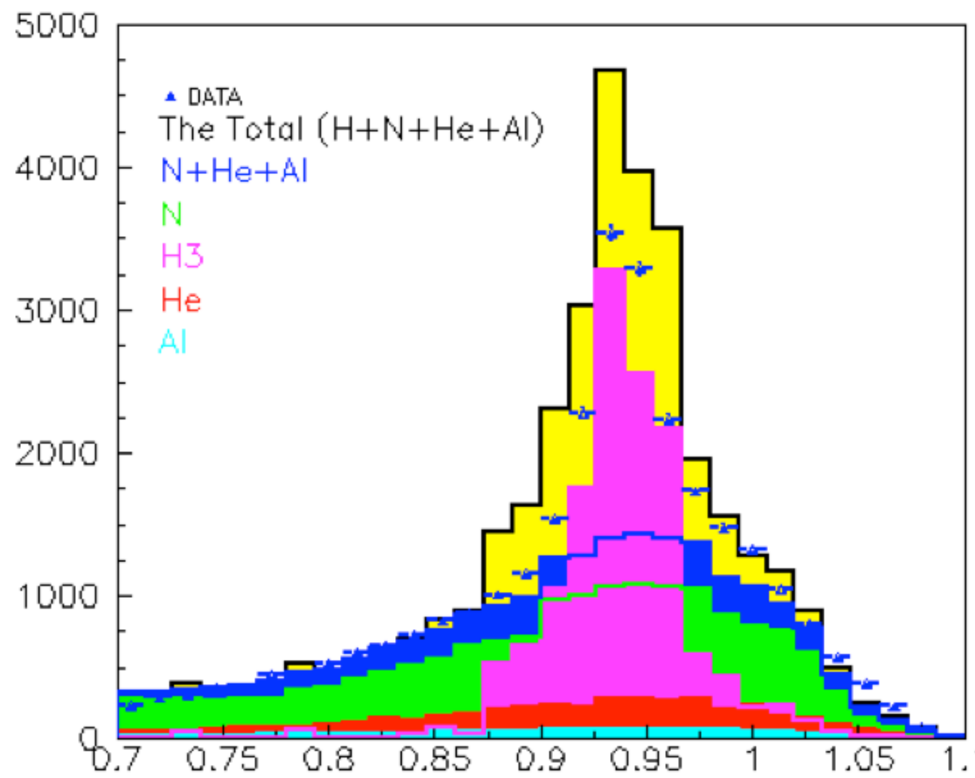
# Each target type contributions for the $10\% < \delta < 12\%$
## (Top target)




Invariant Mass, W (GeV/c$^2$)




The Dilution Factor

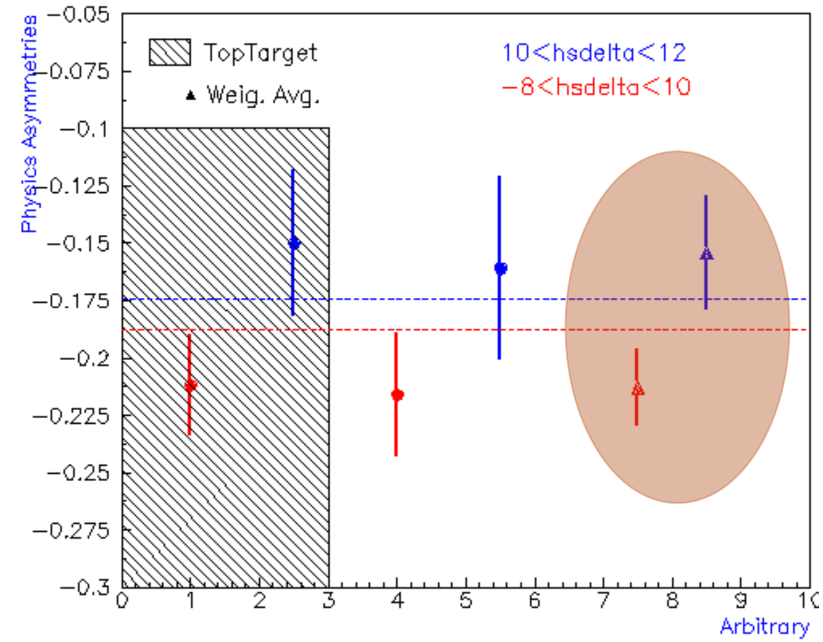


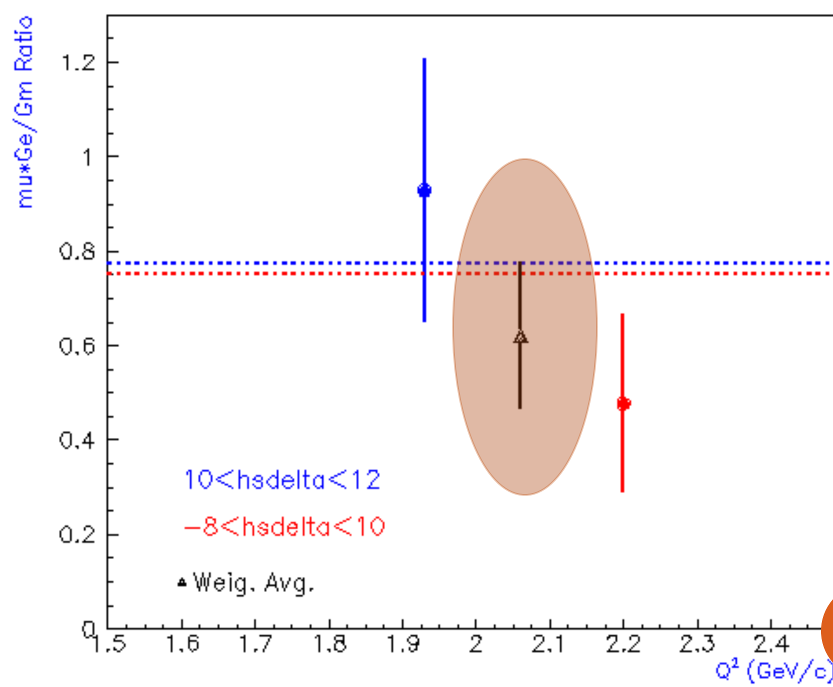

Invariant Mass, W (GeV/c$^2$)

# Preliminary .....

| | $-8 < \frac{\delta p}{p} < 10$ | $10 < \frac{\delta p}{p} < 12$ |
|---|---|---|
| Top Ap±eAp | -0.212±0.022 | -0.150±0.032 |
| Bot Ap±eAp | -0.216±0.027 | -0.161±0.040 |
| Avg. Ap±eAp | -0.213±0.017 | -0.154±0.025 |
| $\theta^*$ (Deg) | 45.68 | |
| $\phi^*$ (Deg) | 190.49 | |
| $Q^2$ $(GeV/c)^2$ | 2.2 | 1.927 |
| $\mu\, G_E/G_M$ | 0.477±0.190 | 0.928±0.279 |
| | | |
| Pred. $\mu\, G_E/G_M$ | 0.75 | 0.775 |
| Pred. Ap | -0.188 | -0.174 |

| | |
|---|---|
| **$Q^2$ $(GeV/c)^2$** | **2.06** |
| Wei. Avg. $\mu\, G_E/G_M$ | 0.62±0.157 |

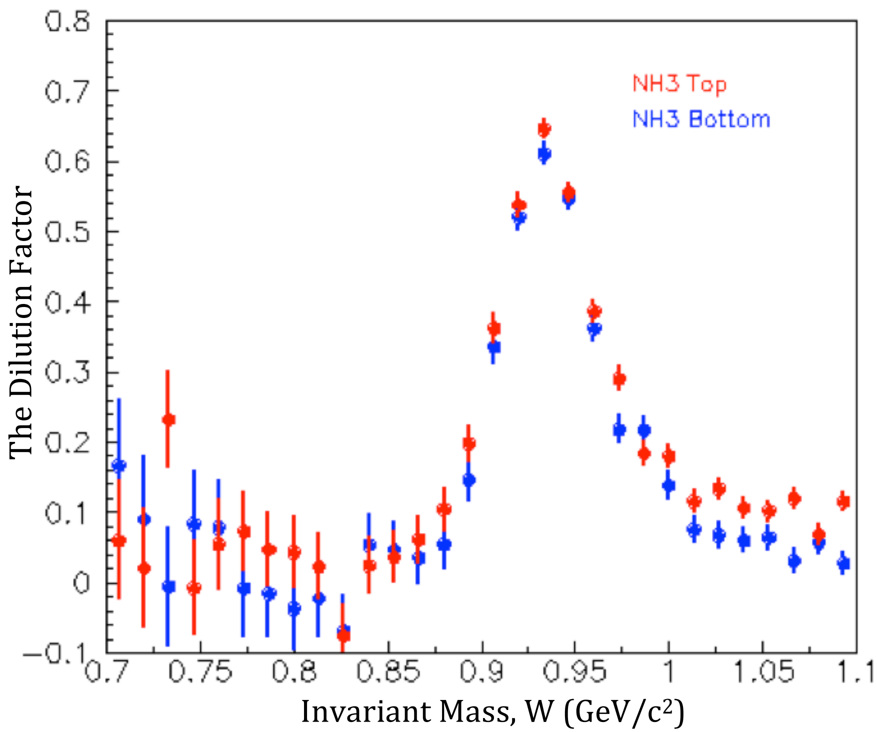


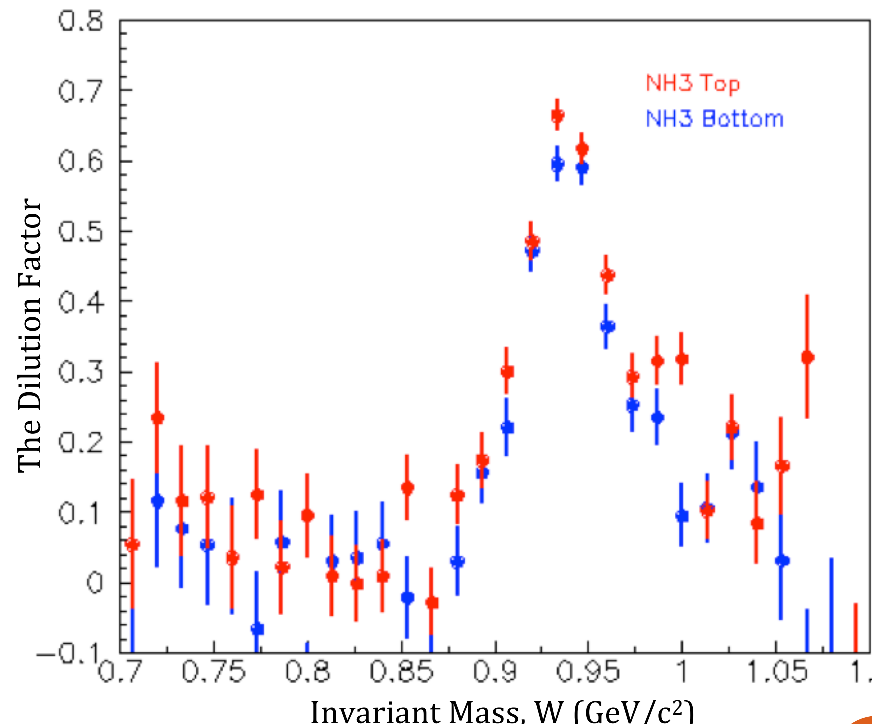
# The Dilution Factor

- We have taken data using both $NH_3$ targets, called $NH_3$ top and $NH_3$ bottom.
- $NH_3$ crystals are not uniformly filled in each targets which arise two different packing fractions and hence two different dilution factors.

-8% < $\delta$ < 10%

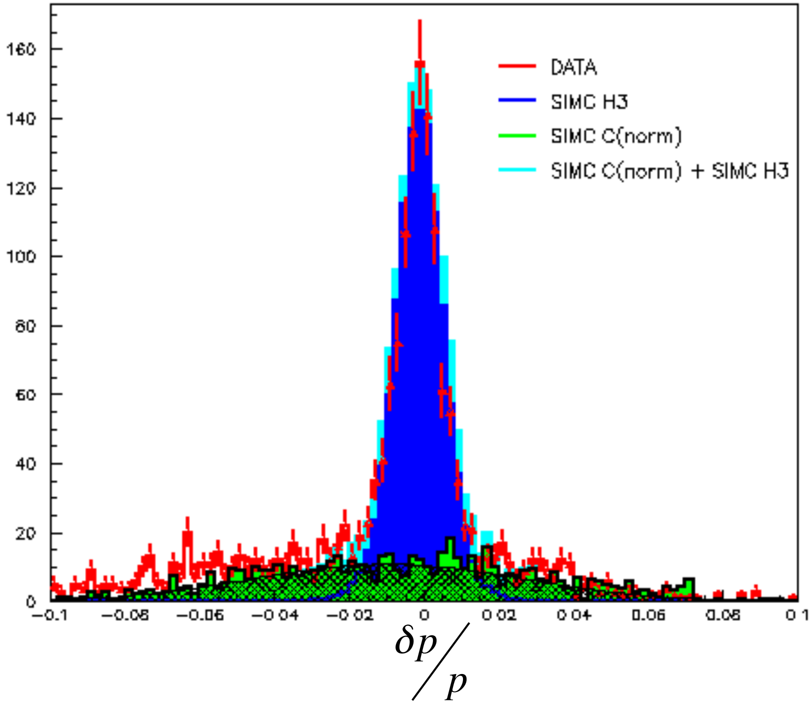



10% < $\delta$ < 12%



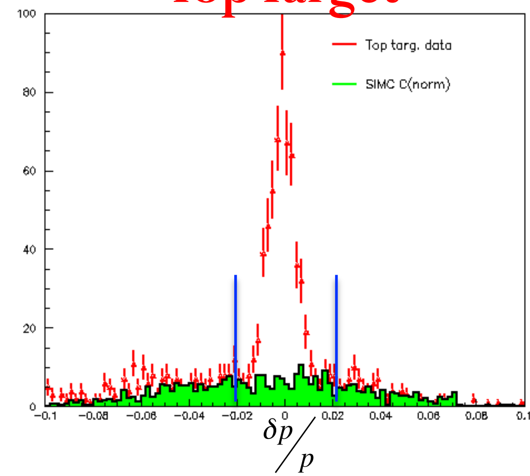
# Determine The Dilution Factor

- Estimate The Background
  - Used the carbon target to estimate the shape of the background.




- Used two different target cups (NH3 top and NH3 bottom) → two different packing fractions → need two different dilution factors.
- Because of the low statistics, It is hard to correct the raw asymmetry for the df as a function of $\delta p / p$
- Just integrate over the $\delta p / p$ region of +/- 0.02 for the top and bottom.

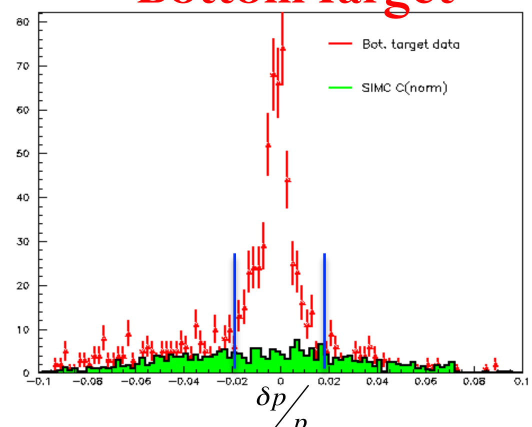
**Top Target**




The relative D.F = (data-SIMC_C)_top/data_top

= 606-130/606 = 0.785

**Bottom Target**



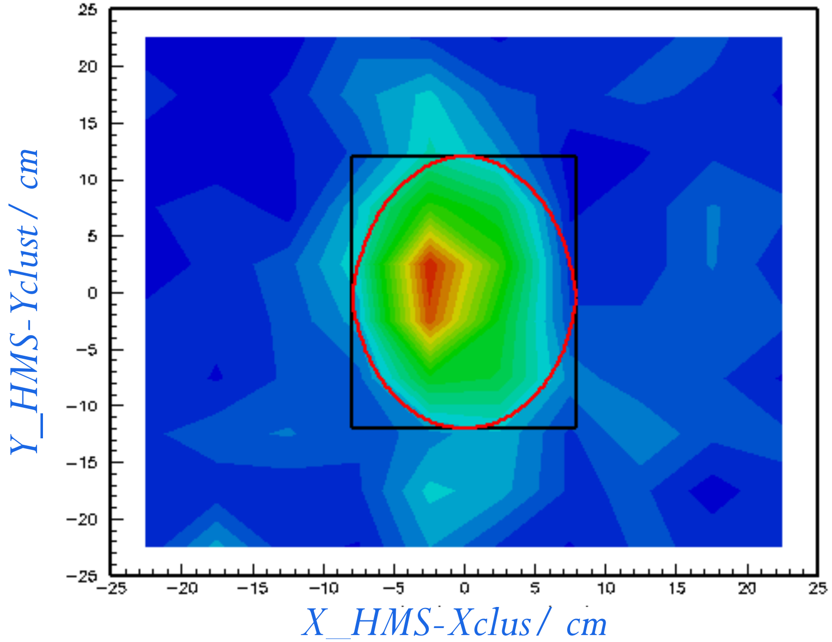

= (data-SIMC_C)_bot/data_bot.

= 541-92/541

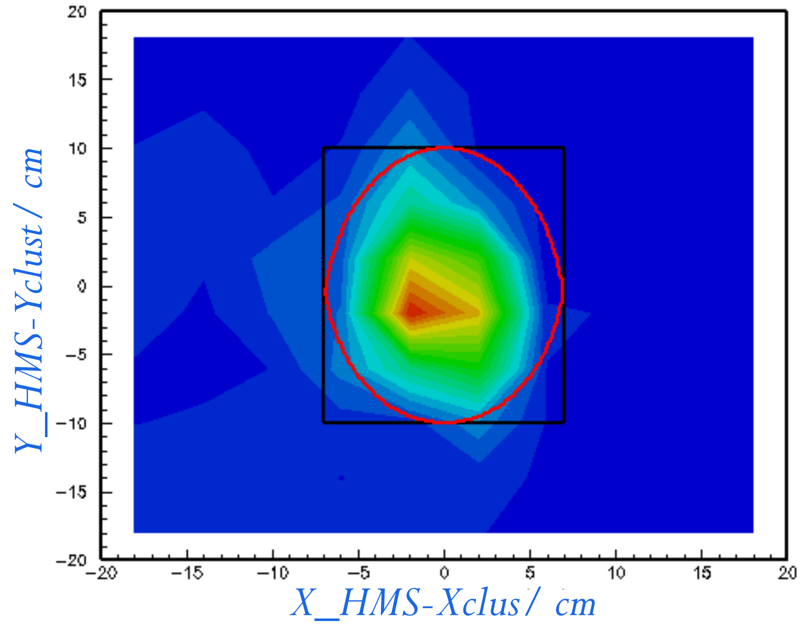
= 0.830

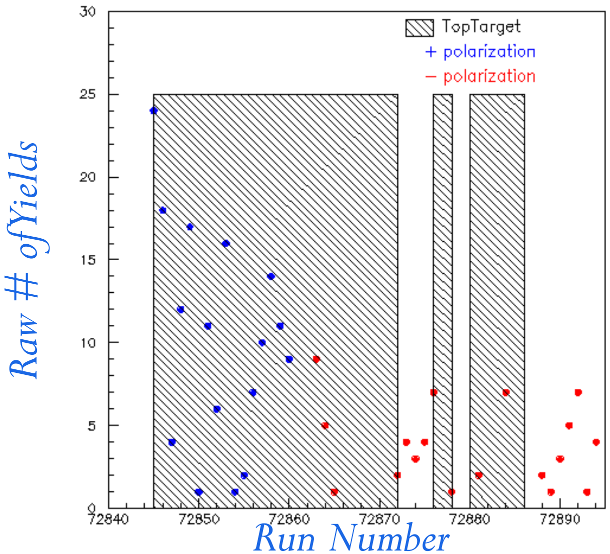
# Elastic Events

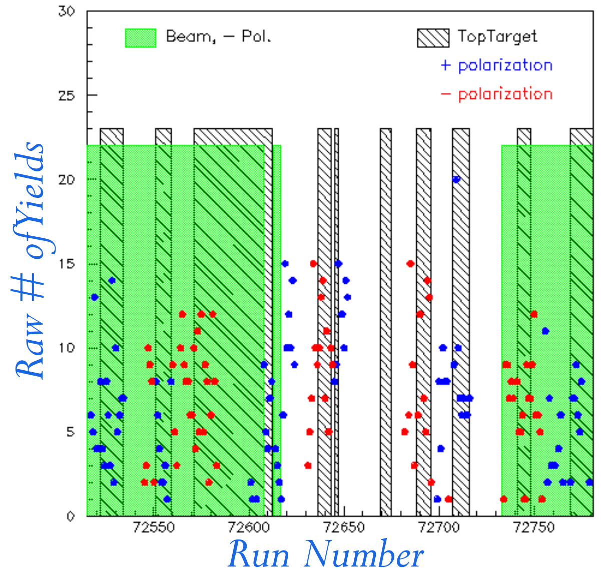
**4.72 GeV data**



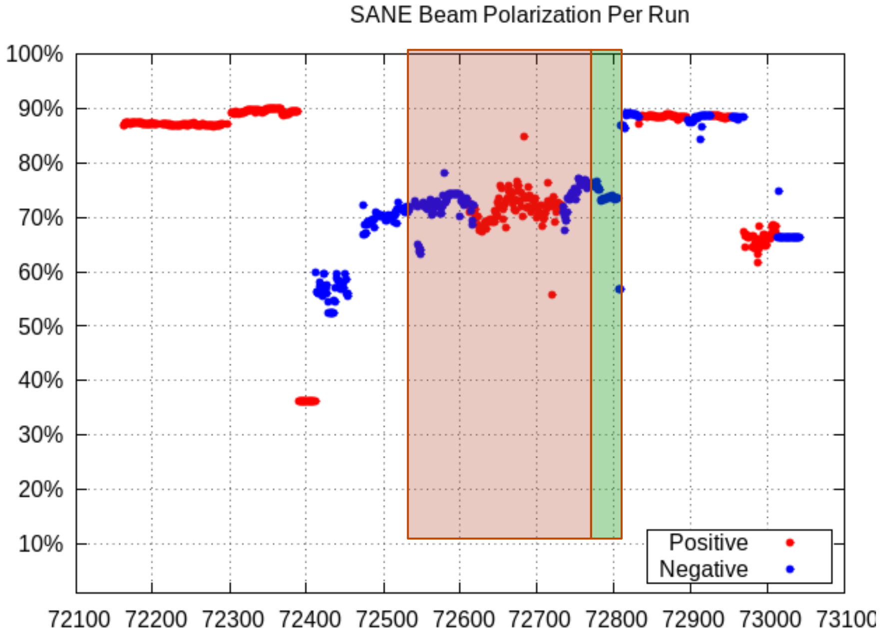

**5.89 GeV data**



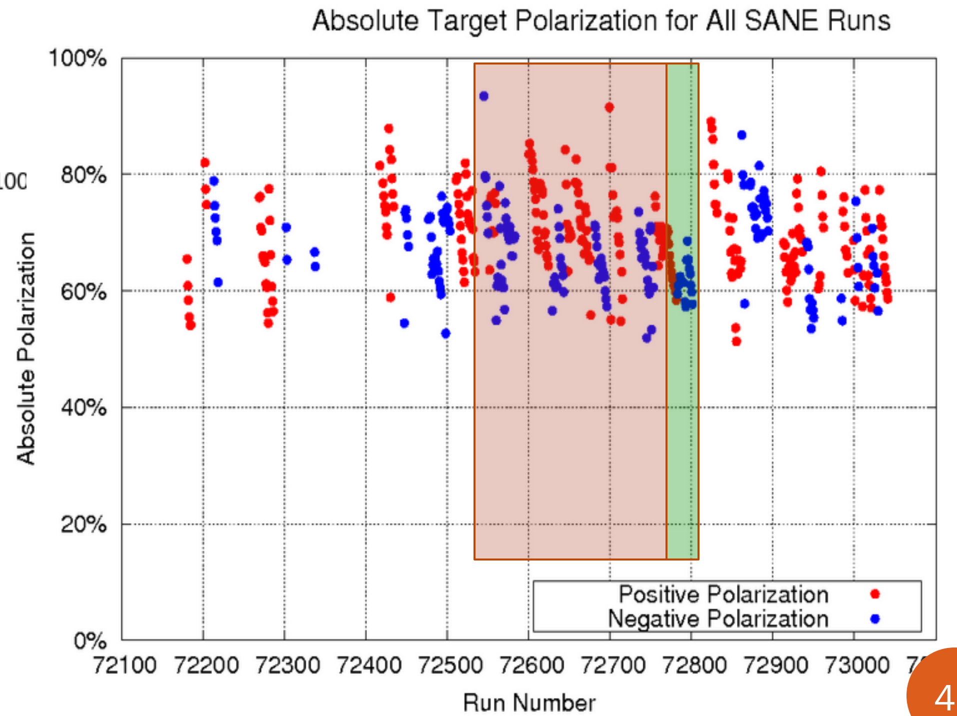



# Beam / Target Polarizations




COIN data

Single arm electron data



# 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.