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
  - Polarized Target
- Elastic Kinematic
- Data Analysis
- Conclusion

Hampton University 1868

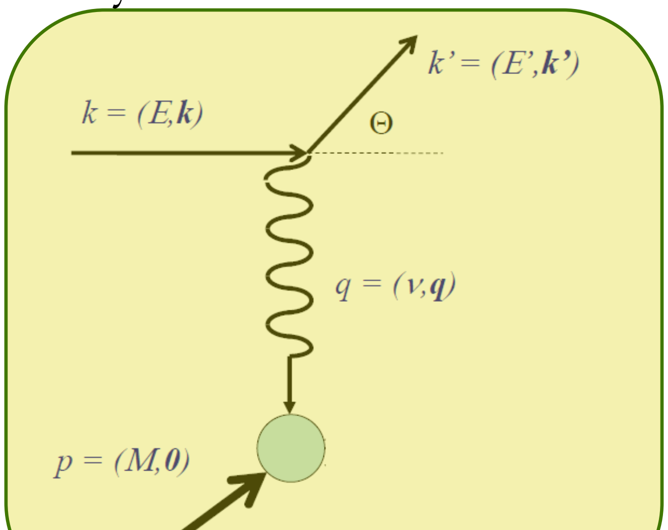
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Anusha Liyanage

12th Annual Graduate Research Symposium
The College of William and Mary
(March 22, 2013)

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



The four-momentum transfer squared,

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

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 $q^2 = 0$

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

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

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

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, θ_e.
- Strongly sensitive to the radiative corrections.

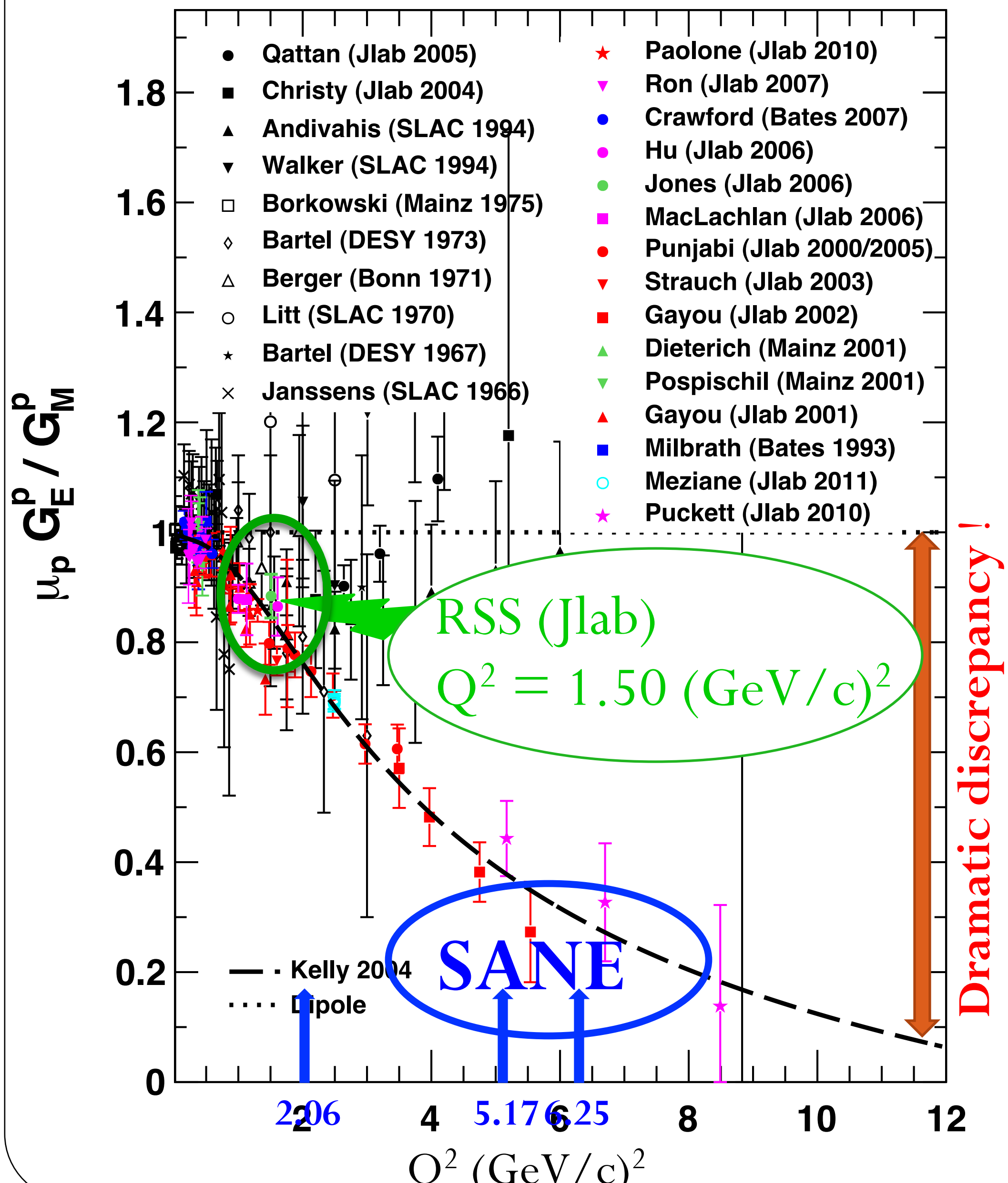
2. Polarization Transfer Technique.

- 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.

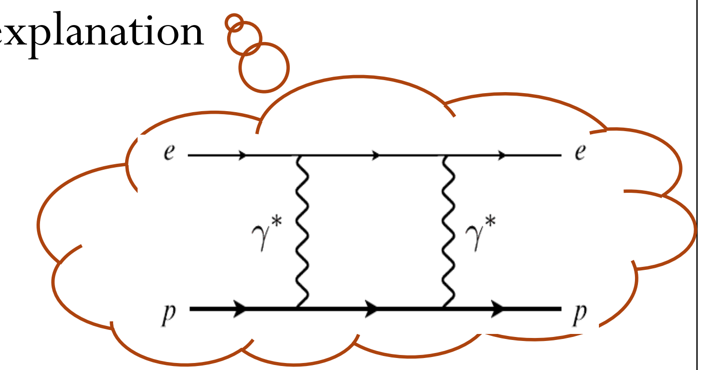
3. Double-Spin Asymmetry.

- 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



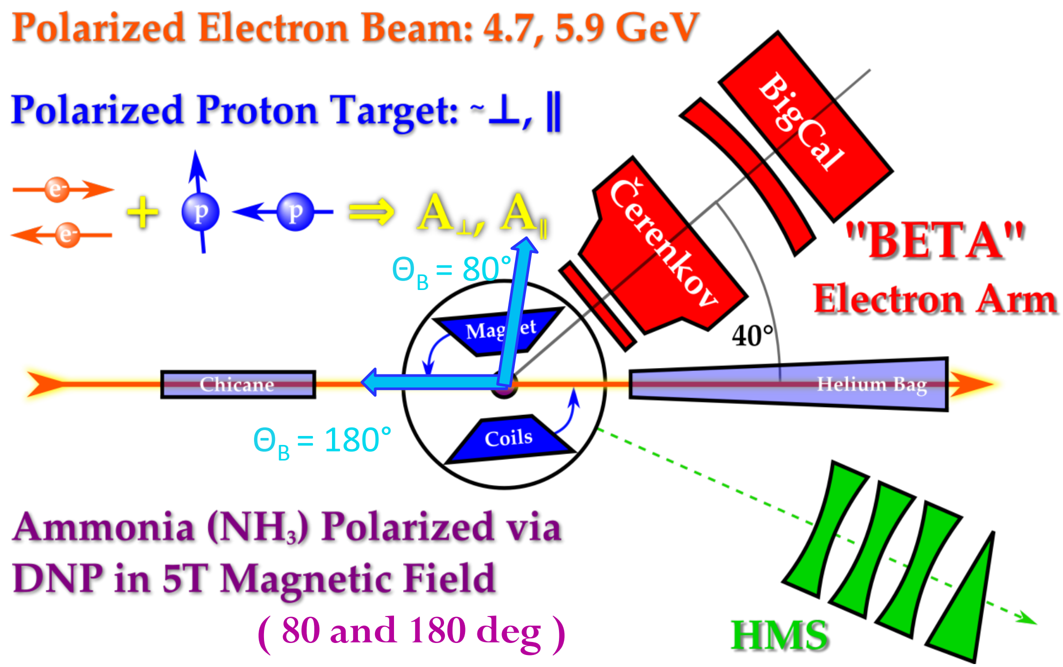
- Dramatic discrepancy between Rosenbluth and recoil polarization technique.
- Multi-photon exchange considered the best candidate for the explanation

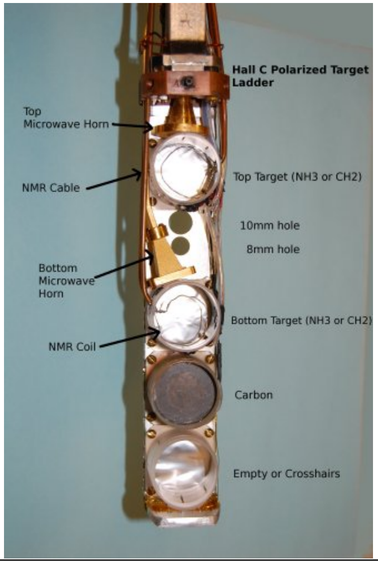


- **Double-Spin Asymmetry is an independent technique to verify the discrepancy**

Detector Setup/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





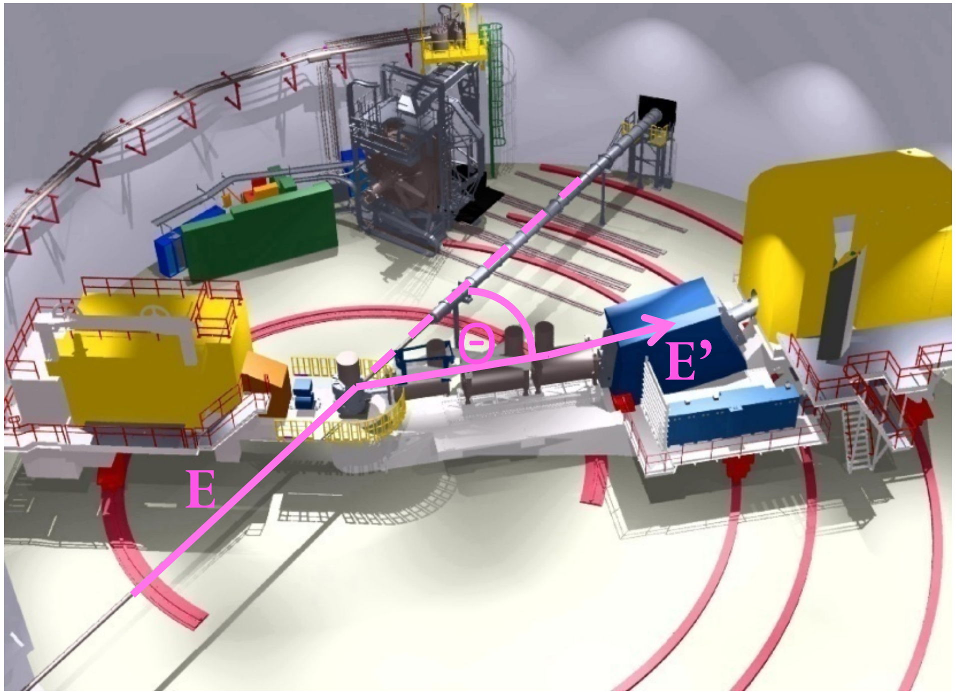
- Used only perpendicular magnetic field configuration for the elastic data
- Average target polarization is ~ 70 %
- Average beam polarization is ~ 73 %

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
Θ_{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

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

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

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

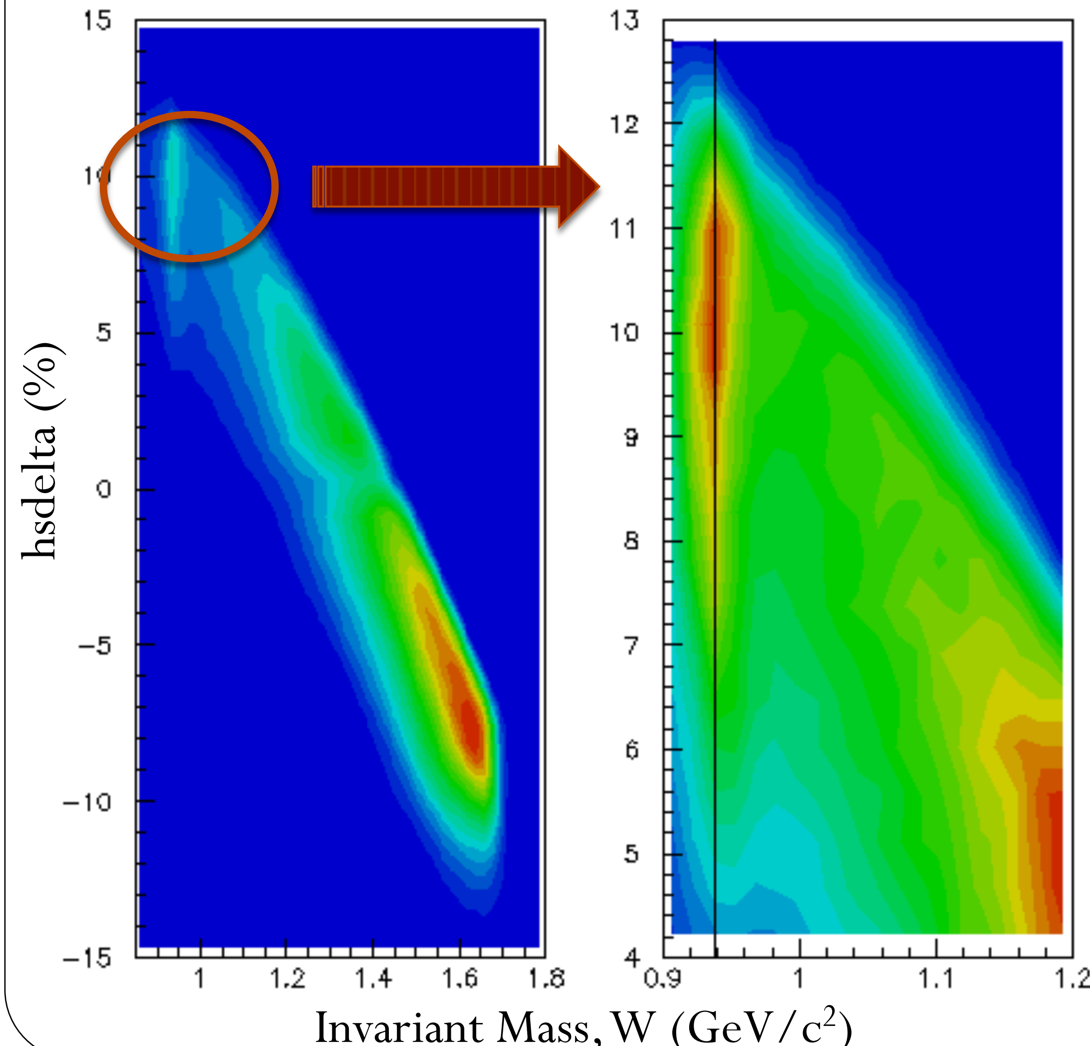
Extract the electrons

The relative momentum deviation from the HMS central momentum,

$$hsdelta = \left(P - P_c \middle/ P_c \right) = \frac{\delta p}{p}$$

P - Measured momentum in HMS

P_c - HMS central momentum



Used momentum acceptance cuts

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

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

Together with,

Cherenkov and Calorimeter cuts,

\# of Cerenkov photoelectrons > 2

$$E_{sh} \big/ p > 0.7$$

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

Extracted the Asymmetries .....

The raw asymmetry, A_r

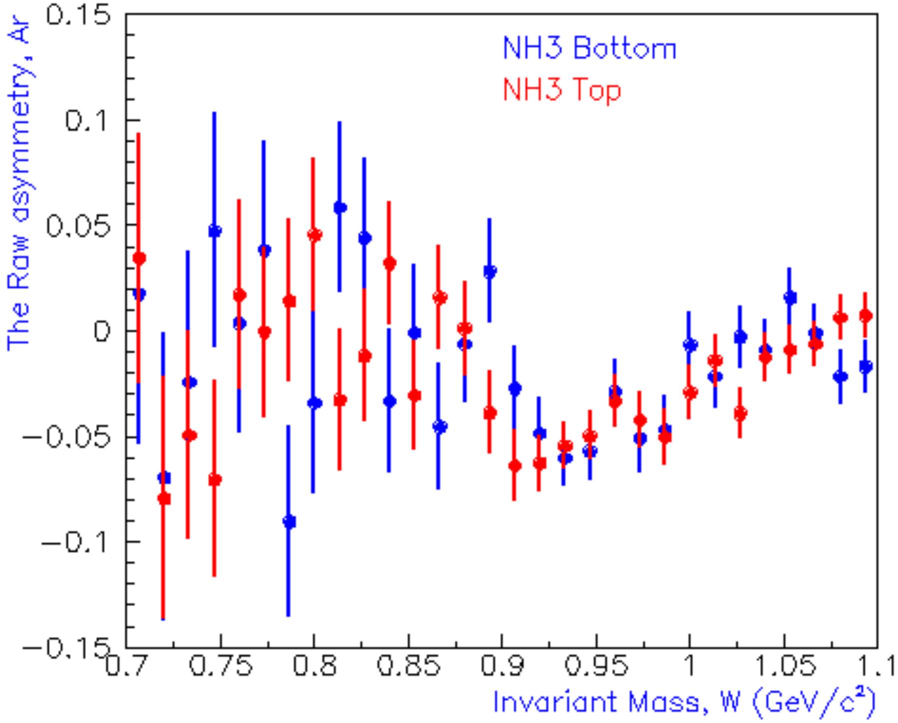
$$A_r = \frac{N^+ - N^-}{N^+ + N^-}$$

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

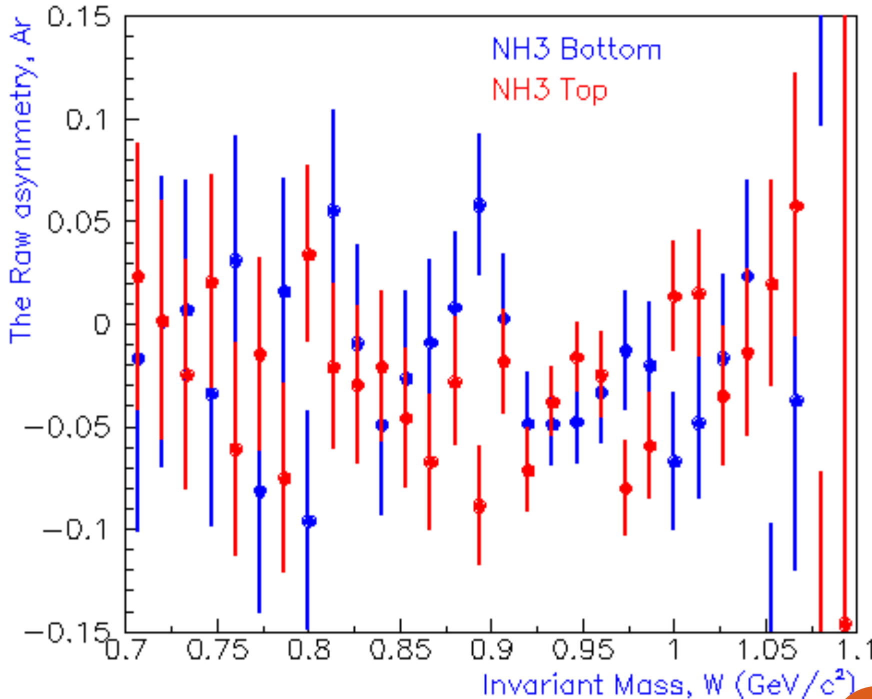
N^+ / N^- = *Charge and live time normalized counts for the +/- helicities*

ΔA_r = *Error on the raw asymmetry*

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



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



Extracted the Asymmetries …..

Need

dilution factor, f

in order to determine the

physics asymmetry,

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

and $G^p{}_E / G^p{}_M$

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

$P_B P_T$ = *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…..

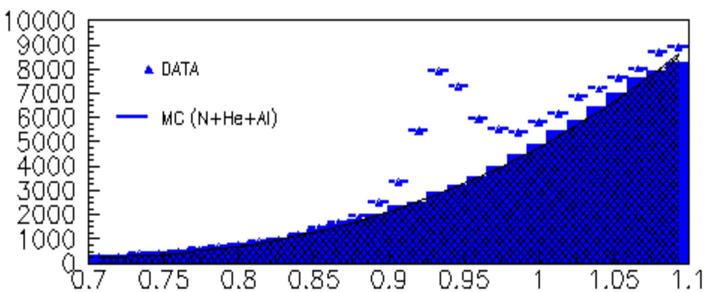
Determination of the Dilution Factor

What is the Dilution Factor ?

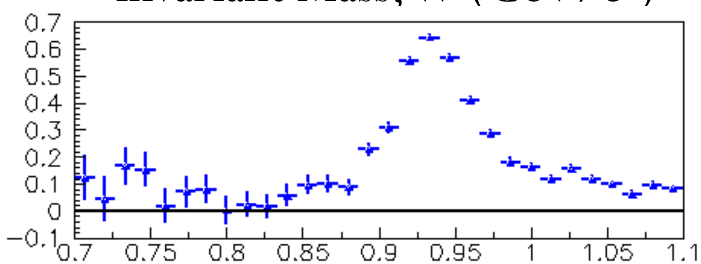
The dilution factor is the ratio of the yield from scattering off free protons(protons from H in NH_3) to that from the entire target (protons from N, H, He and Al)

Dilution Factor,

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

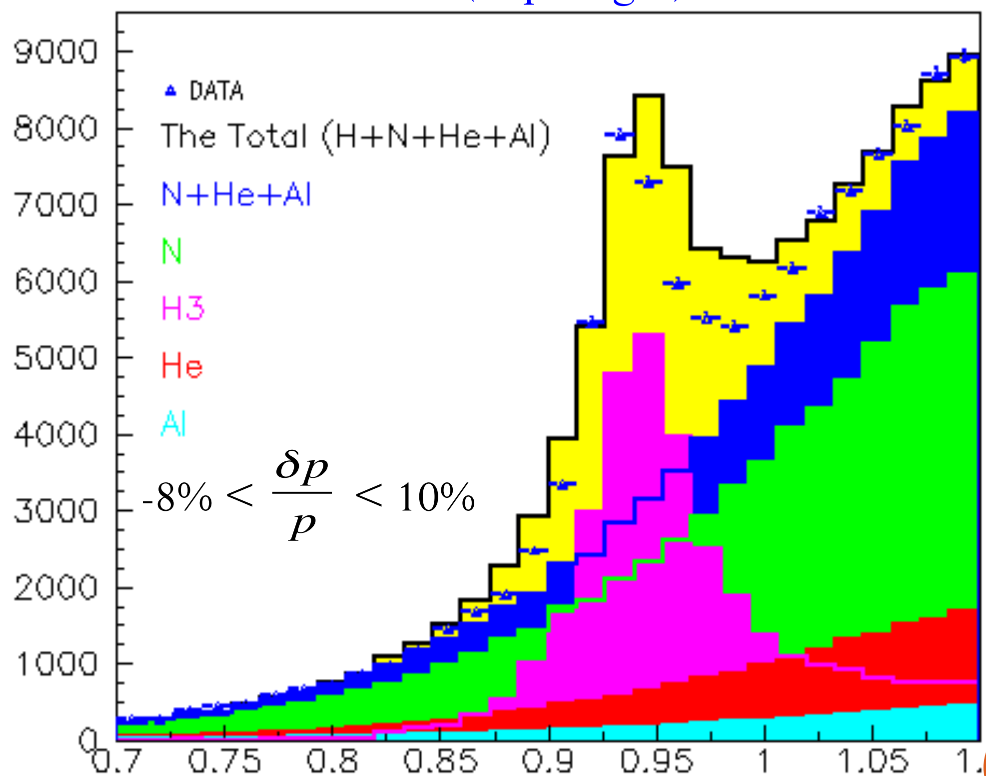


Invariant Mass, W (GeV/c^2)



The Relative Dilution Factor

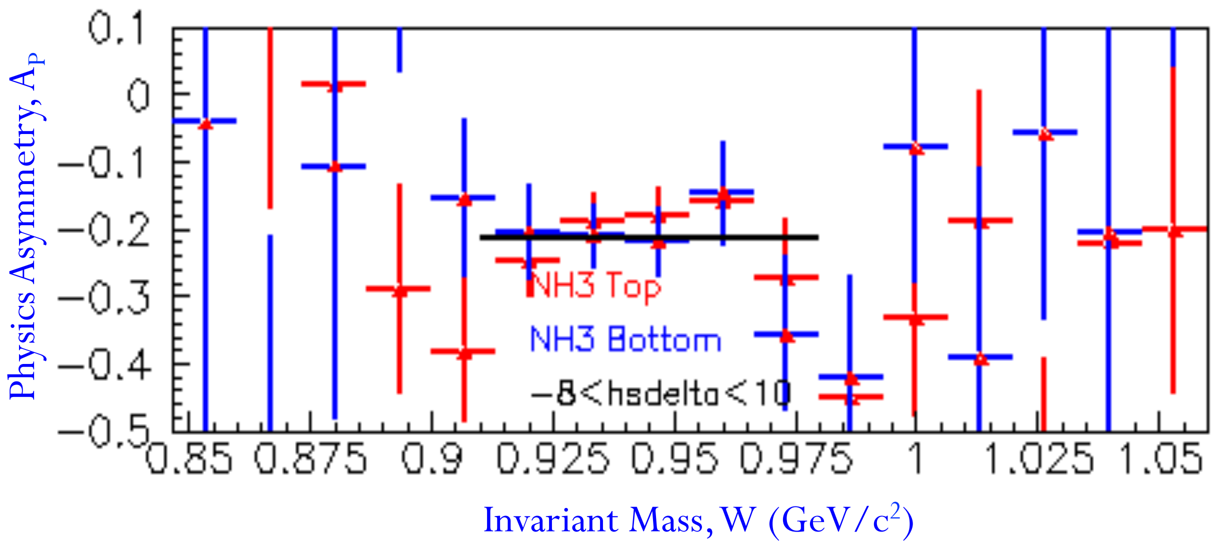
Each target type contributions
(Top target)



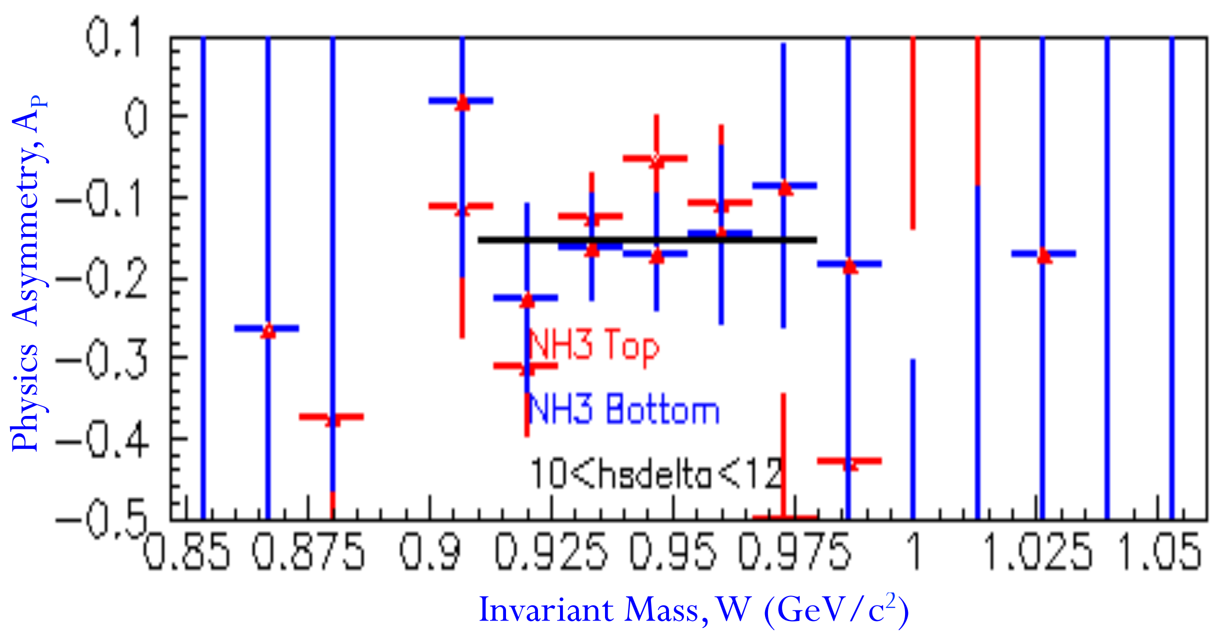
Invariant Mass, W (GeV/c^2)

The Physics Asymmetry

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



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



- ## 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*

θ^*, ϕ^* = *pol. and azi. Angles between* $\vec{q}$ *and* $\vec{S}$

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

- ## Error propagation from the experiment

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

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

$$\Delta r = \Delta\left(\frac{G_E}{G_M}\right) = \left|\frac{c}{b\sin\theta^* \cos\varphi^*}\right| \Delta A_p$$

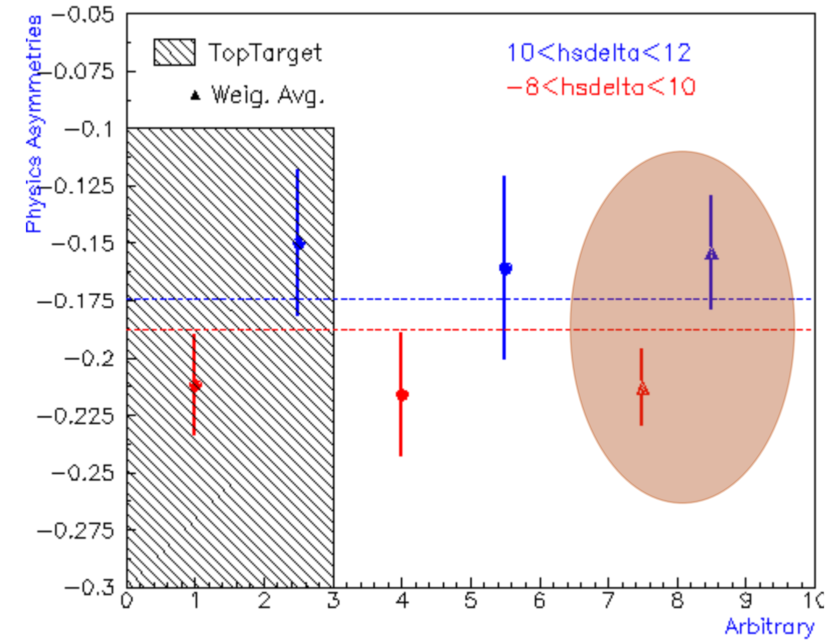
$$\Delta(\mu r) = \Delta\left(\mu \frac{G_E}{G_M}\right)$$

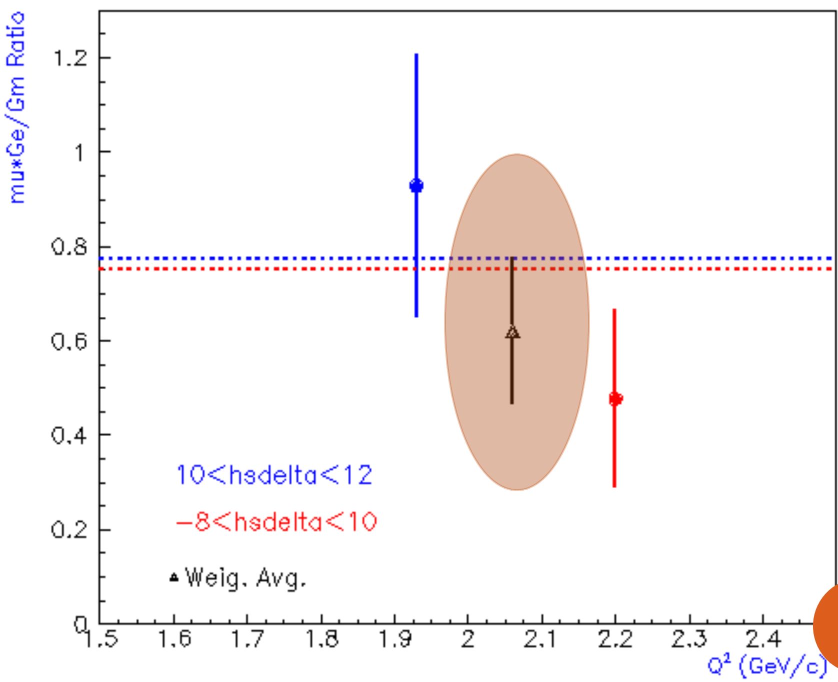
Where , μ – Magnetic Moment of the Proton=2.79

Preliminary .....

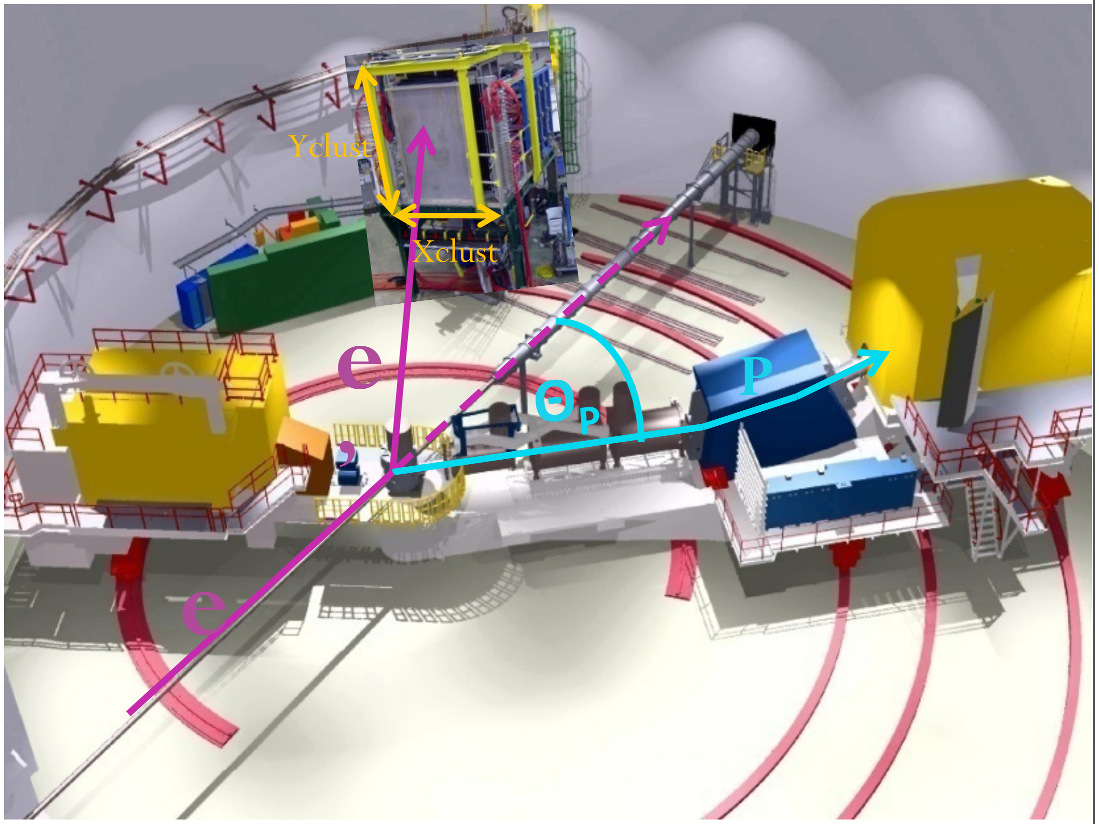
	$-8 < \frac{\delta p}{p} < 10$	$10 < \frac{\delta p}{p} < 12$
Top Ap±eAp	-0.212±0.022	-0.150±0.032
Bot Ap±eAp	-0.216±0.027	-0.161±0.040
Avg. Ap±eAp	-0.213±0.017	-0.154±0.025
θ^* (Deg)	45.68	
ϕ^* (Deg)	190.49	
Q^2 $(GeV/c)^2$	2.2	1.927
$\mu\, G_E/G_M$	0.477±0.190	0.928±0.279
Pred. $\mu\, G_E/G_M$	0.75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





Coincidence Data
(Electrons in BETA and Protons in HMS)



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, 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 Kinematics

(From HMS Spectrometer)

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Total Hours (h)	~40 (~44 runs)	~155 (~135 runs)	~12 (~15 runs)
e-p Events	~113	~1200	~5 x 10^4

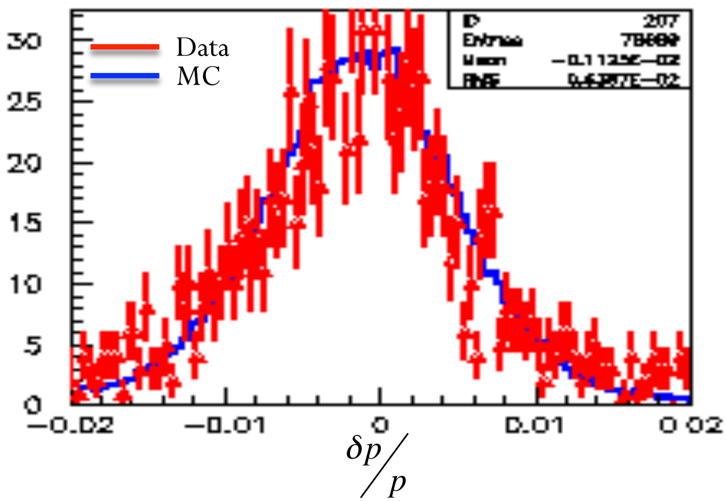
Extract the electrons

Fractional momentum difference,

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

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

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

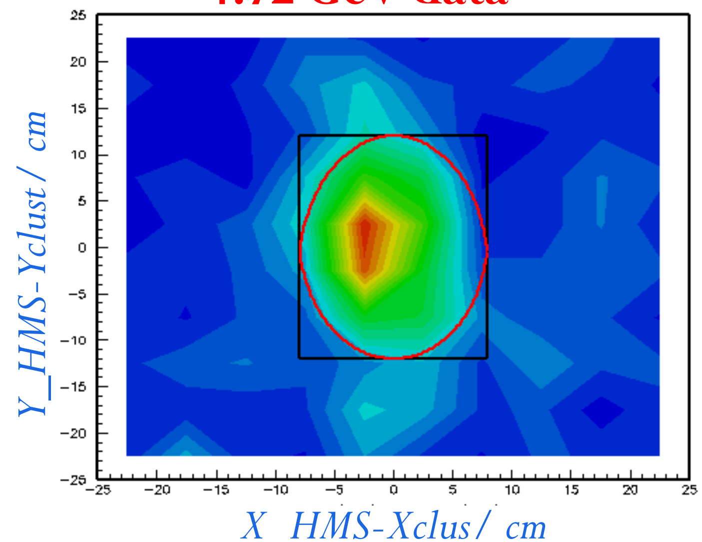


P_{HMS} – *Measured proton momentum by HMS*

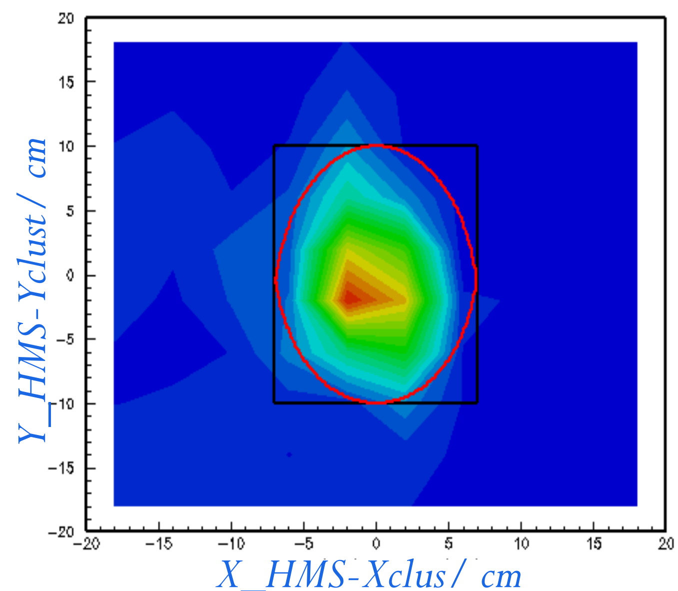
P_{cal} - *Calculated proton momentum.*

P_{cent} – *HMS central momentum*

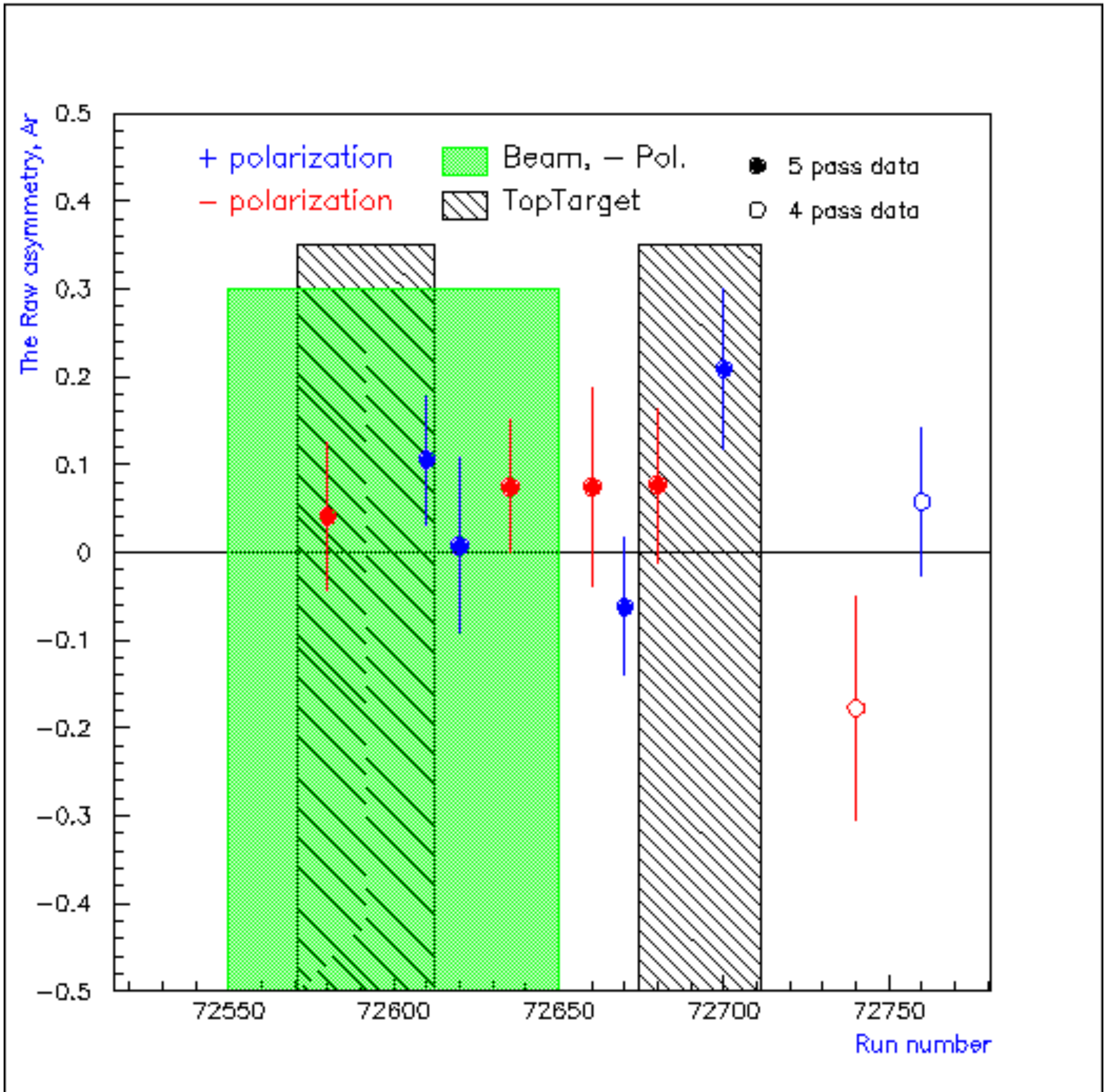
4.72 GeV data



5.89 GeV data



Extract the Raw Asymmetries



Raw yields are normalized with

- Total Charge
- charge average +/- life times

Need

dilution factor, f

in order to determine the

physics asymmetry,

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

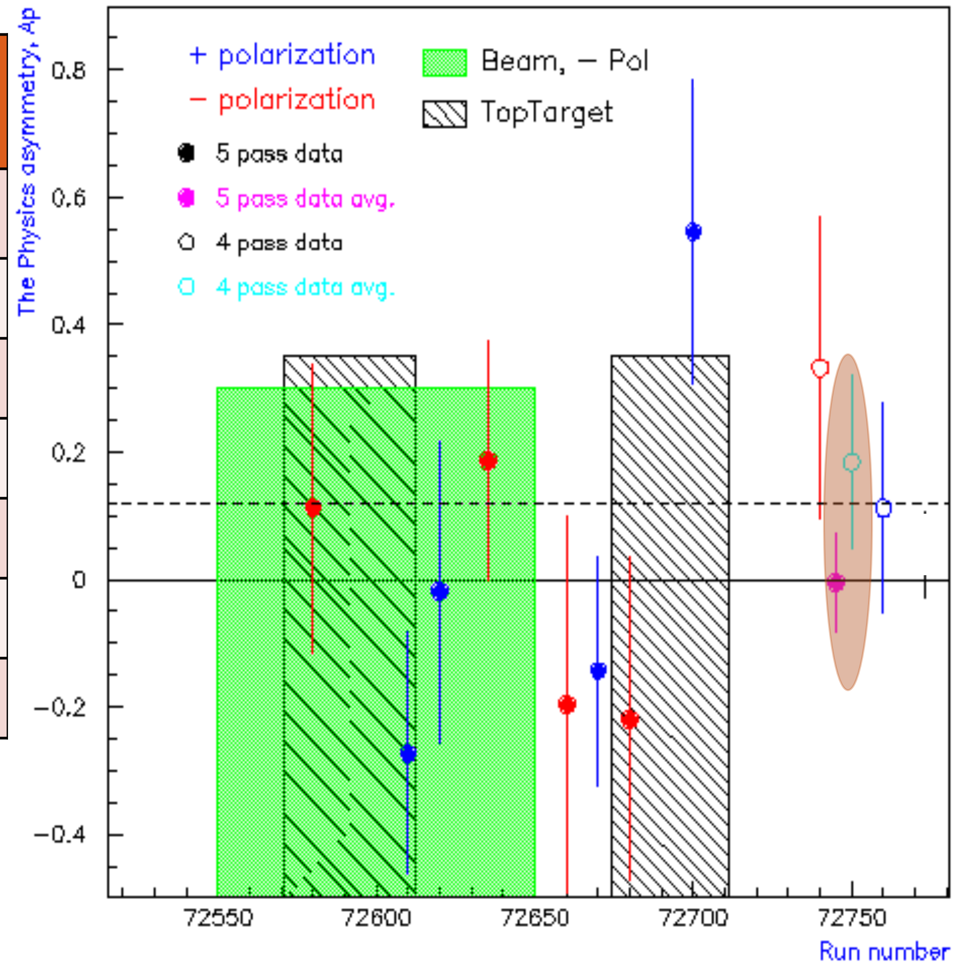
and G^p_E / G^p_M

Extract the Physics Asymmetries

- Used the runs of beam polarization > 60 % and abs(target polarization) > 55 %
- Used the charge average target and beam polarizations.

Beam Energy(GeV)	4.72	5.89
Ap±eAp	0.184±0.136	-0.006±0.077
Dilution Factor, f	0.816	Top (0.785)
		Bot. (0.830)
θ^* (Deg)	102	102
ϕ^* (Deg)	0	0
Q^2 $(GeV/c)^2$	5.17	6.26
$\mu G_E/G_M$	-0.032±0.668	0.875±0.424

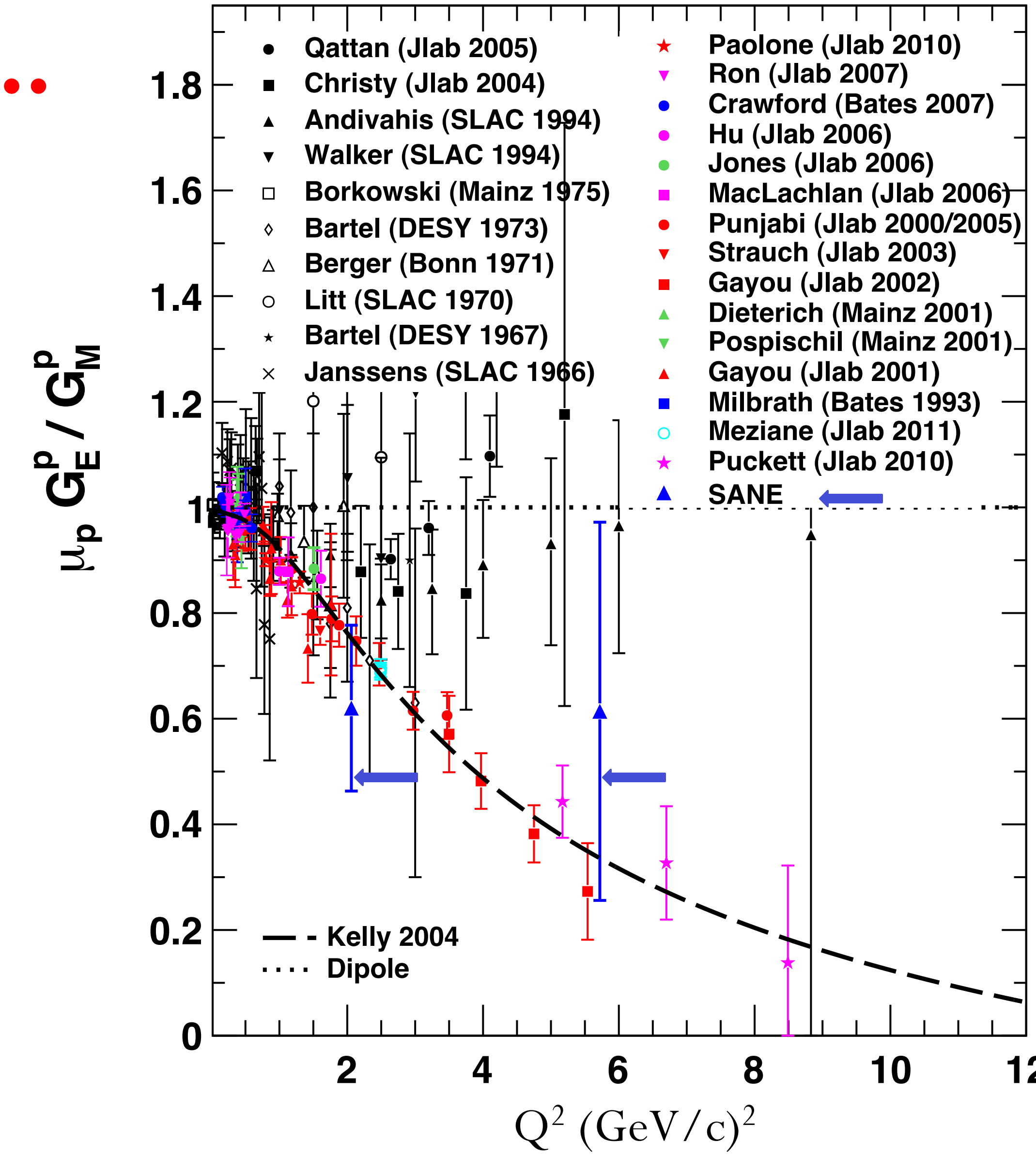
Q^2 $(GeV/c)^2$	5.72
Wei. Avg. $\mu G_E/G_M$	0.614±0.358



Extract the Proton Form Factor Ratio, G^p_E/G^p_M

Preliminary …..

Q^2 $(GeV/c)^2$	2.06	5.72
$\mu\, G_E/G_M$	0.620± 0.157	0.614± 0.358



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.**
- Extraction of the G^p_E/G^p_M ratio from single-arm electron and coincidence data are shown.
- The preliminary data point at Q^2=2.06 (GeV/c)^2 is very consistent with the recoil polarization data.
- The preliminary weighted average data point of the coincidence data at Q^2=5.72 (GeV/c)^2 has large error due to the lack of elastic events.
- Systematic uncertainty estimation 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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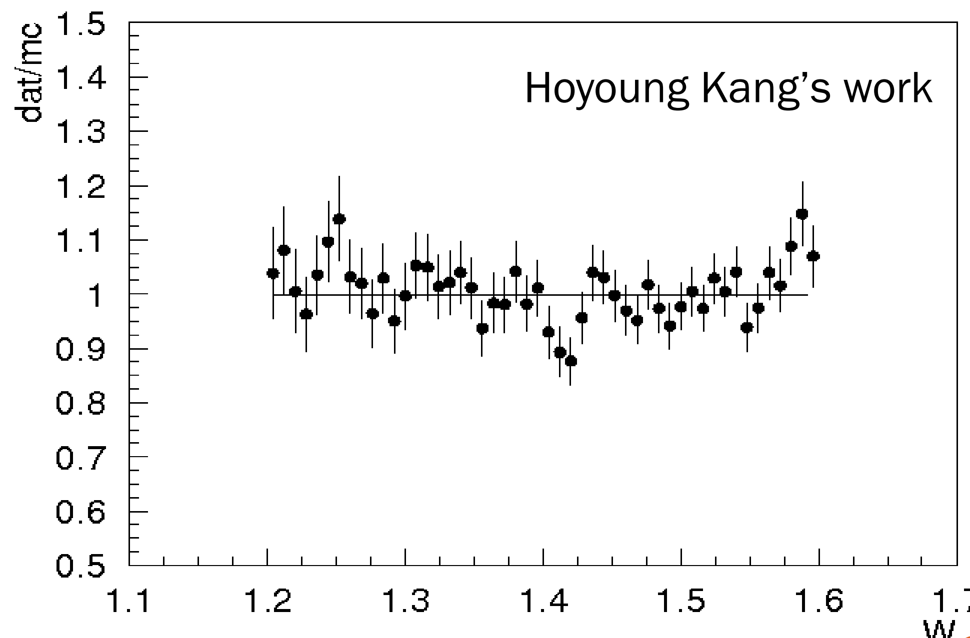
Jefferson Lab
Thomas Jefferson National Accelerator Facility

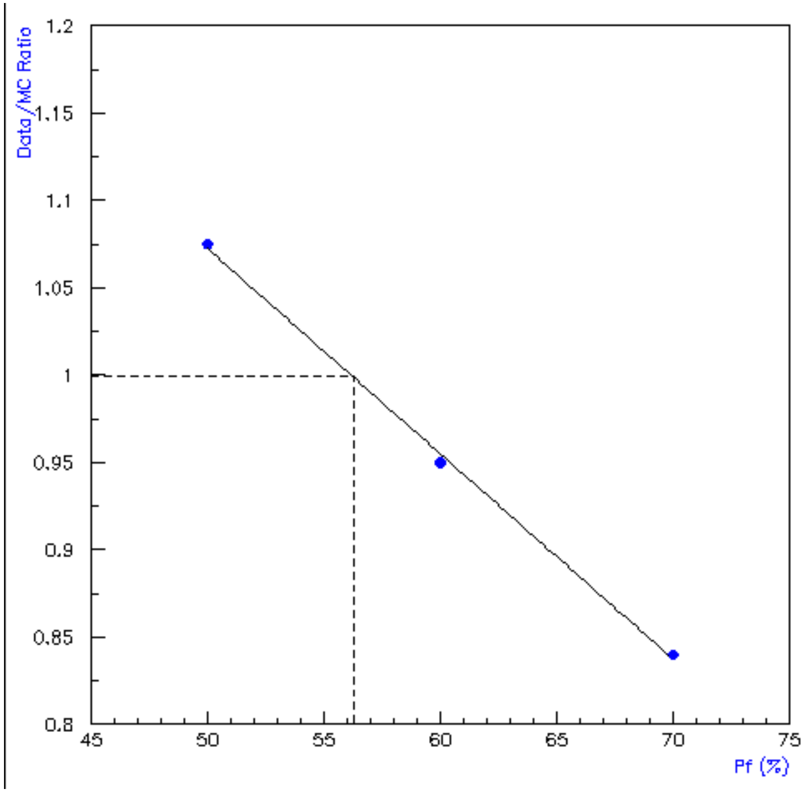
Packing Fraction.

- 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.



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.



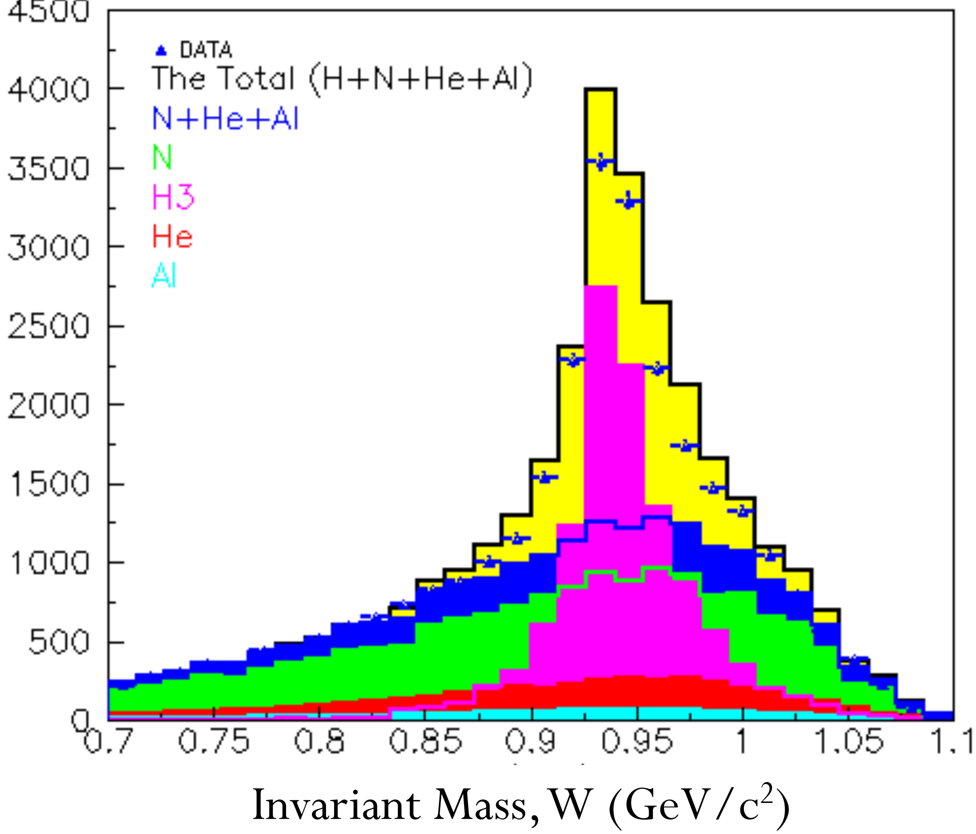
- Determined the packing fraction which brings Data/MC ratio to 1 from the plot.
- Packing Fraction=56.3 %

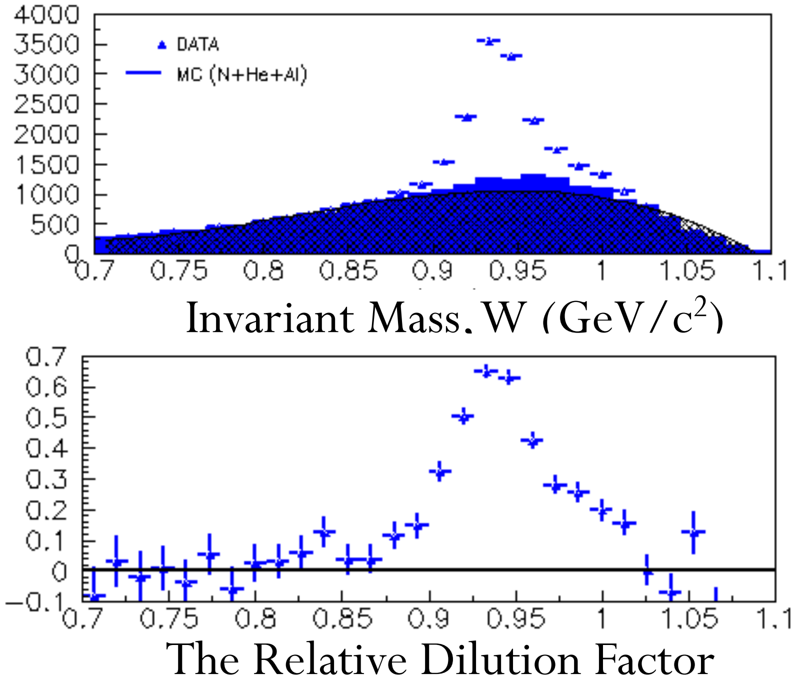
Pf (%)	50	60	70
Data/MC Ratio	1.00	0.88	0.78
Data/MC Ratio/0.93	1.075	0.95	0.84

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

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

Each target type contributions
(Top target)



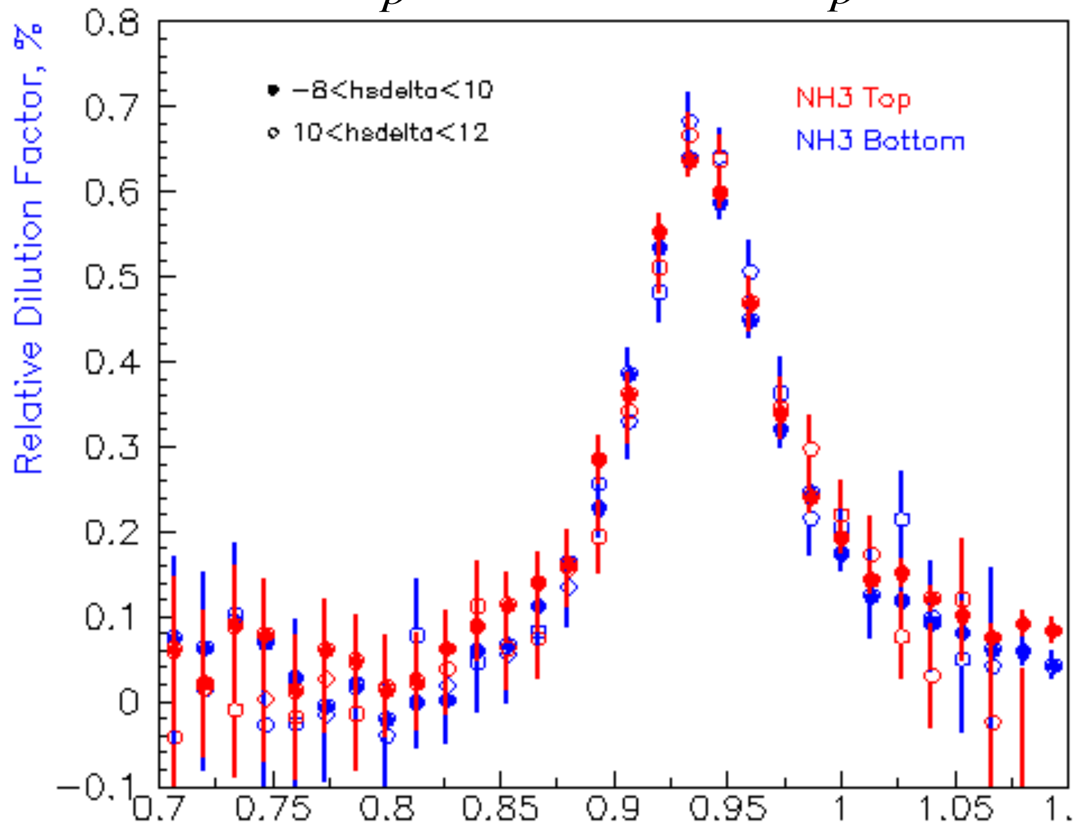


▪ The relative Dilution Factor

- We have taken data using both NH3 targets, called NH3 top and NH3 bottom.
- NH3 crystals are not uniformly filled in each targets which arise two different packing fractions and hence two different dilution factors.

The relative dilution factor for two different targets, top and bottom for two different delta regions,

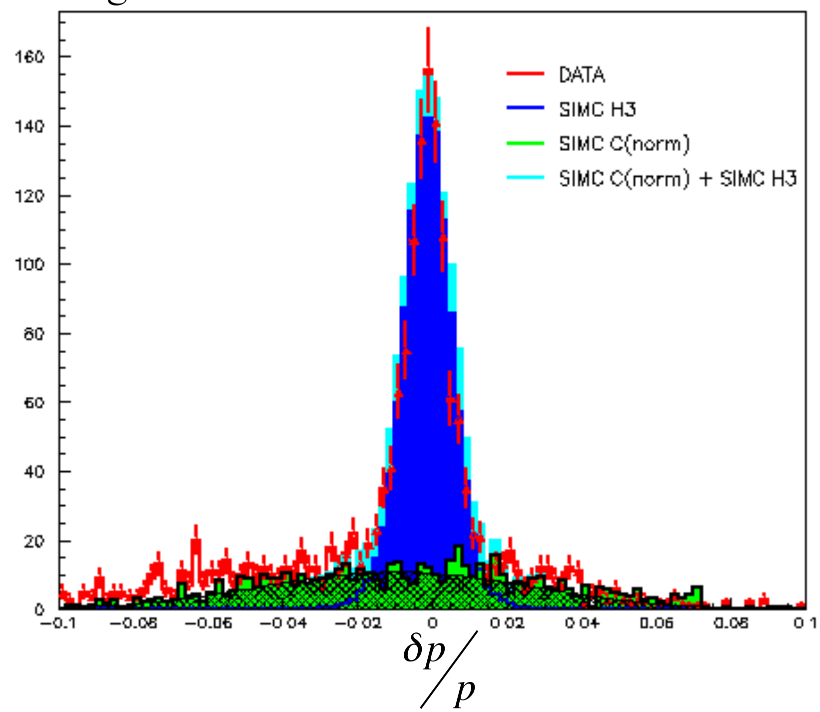
$$-8\% < \frac{\delta p}{p} < 10\% \text{ and } 10\% < \frac{\delta p}{p} < 12\%$$



Invariant Mass, W (GeV/c^2)

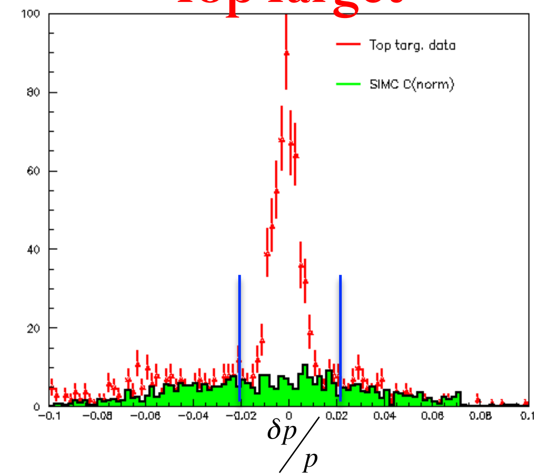
Determine The Dilution Factor

- **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.

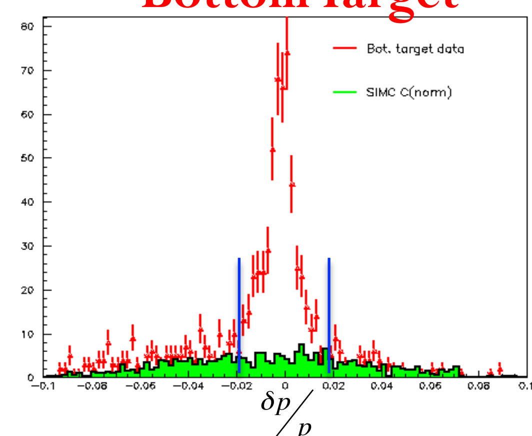
Top Target



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

= 606-130/606 = 0.785

Bottom Target



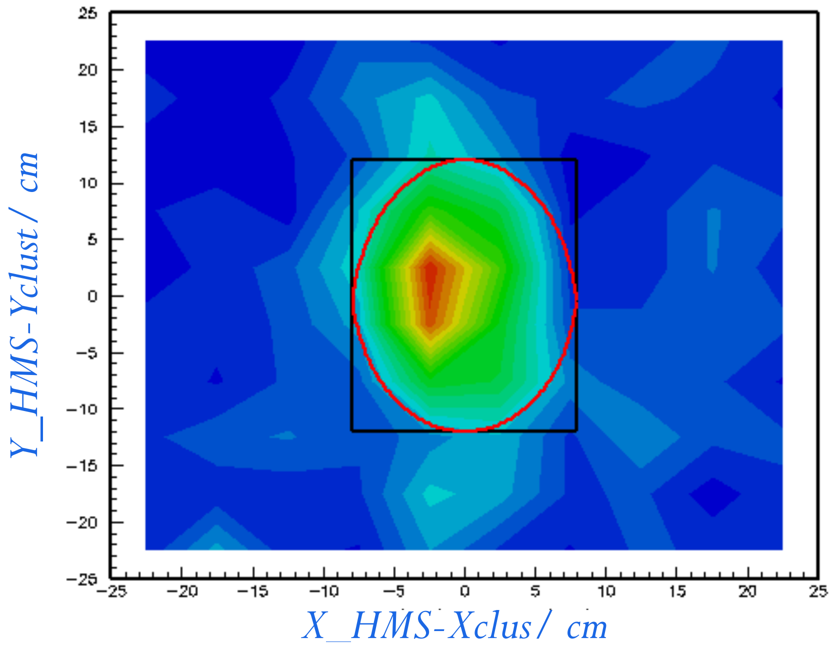
= (data-SIMC_C)_bot/data_bot.

= 541-92/541

= 0.830

Elastic Events

4.72 GeV data



5.89 GeV data