# The GEp-2γ Experiment at Jefferson Lab Hall-C

12th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon
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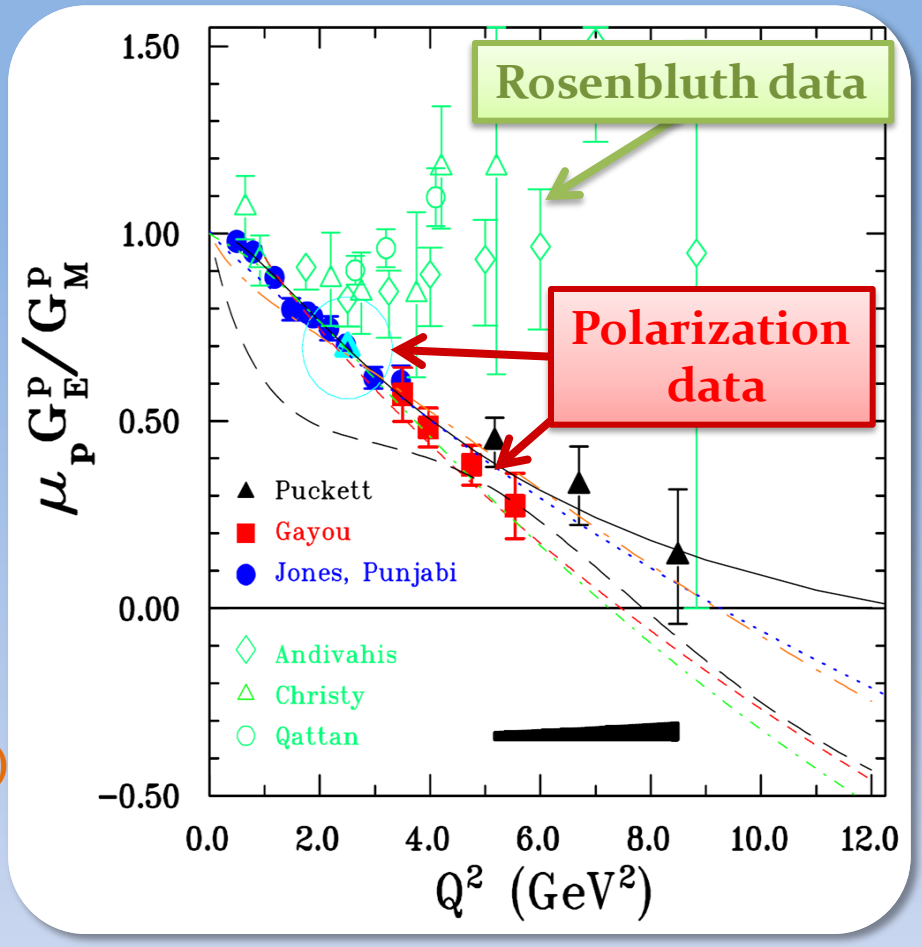
The College of William and Mary
On behalf of the Jlab GEp-2γ Collaboration

# OUTLINE

- Introduction
- Beyond the Born Approximation
- The GEp-2γ Experiment at Jlab:
  - Goal
  - Analysis
  - Form Factor Ratio, $P_l$ preliminary results
- Conclusion

# Polarization/Rosenbltuth data crisis

- Over the past decade both intensive theoretical and experimental effort have been done aiming at explaining the Rosenbluth/Polarization discrepancy.
- The difference between the two experimental ratios increases systematically with $Q^2$ for $Q^2 > 2\ GeV^2$
- Two methods, two different results
  - Incomplete radiative corrections?
  - Something beyond the Born Approximation? (one photon exchange)
  - Possible Two-photon exchange effect? (TPEX)
- This experiment is a search for a kinematical dependence in $G_{Ep}/G_{Mp}$ vs $\varepsilon$




Jones *et al.*, Phys. Rev. Lett. 84, 1398 (2000);
Gayou *et al.*, Phys. Rev. Lett. 88, 092301 (2002);
Punjabi *et al.*, Phys. Rev. C 71, 055202 (2005);
Puckett *et al.*, arXiv:1005.3419 (2010);

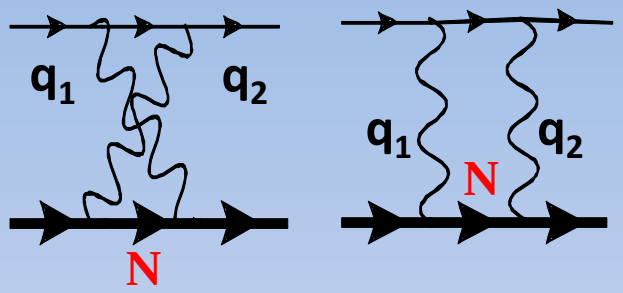
# Beyond the Born-Approximation

Parity, Wigner time reversal invariance and lepton helicity conservation give the following expansion of the hadronic vertex function (not unique):

(P.A.M Guichon, M. Vanderhaeghen, Phys. Rev. Lett. 91, 142303 (2003))

$$\Gamma^{\mu}(p,p') = \tilde{G}_M \gamma^{\mu} - \tilde{F}_2 \frac{P^{\mu}}{M} + \tilde{F}_3 \frac{\gamma . K P^{\mu}}{M^2}$$

Beyond the Born Approximation a third complex amplitude arises.



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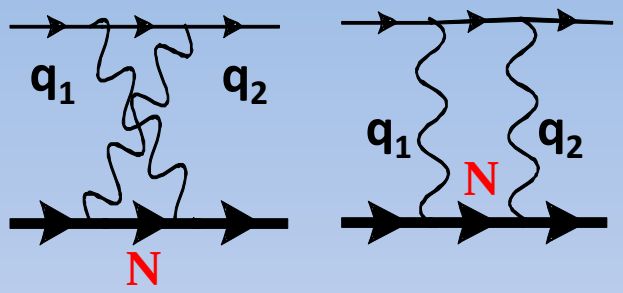

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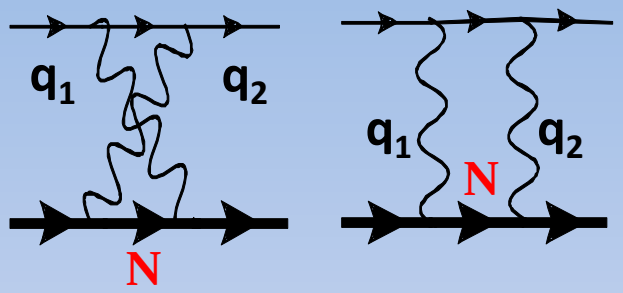
| Born Approx. | Beyond Born Approx. |
|---|---|
| $G_M(Q^2), F_2(Q^2)$ | $\tilde{G}_M(Q^2,\varepsilon), \tilde{F}_2(Q^2,\varepsilon)$ |
| $\tilde{F}_3(Q^2,\varepsilon) = 0$ | $\tilde{F}_3(Q^2,\varepsilon)$ |
| real | complex |




The kinematical parameter $\varepsilon$ is: $\varepsilon = \dfrac{(s-u)^2 + t(4M^2 - t)}{(s-u)^2 - t(4M^2 - t)}$

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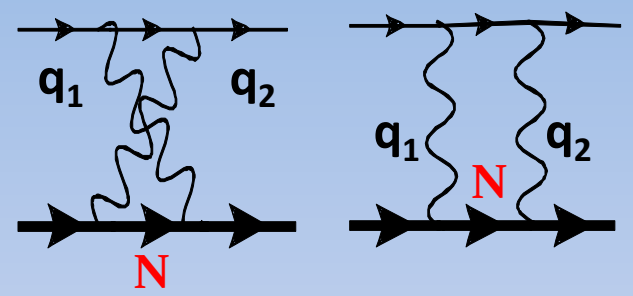


$$\tilde{G}_M(Q^2,\varepsilon) = G_M(Q^2) + \delta\tilde{G}_M(Q^2,\varepsilon)$$
$$\tilde{G}_E(Q^2,\varepsilon) = G_E(Q^2) + \delta\tilde{G}_E(Q^2,\varepsilon)$$

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# Beyond the Born-Approximation formalism

$$P_t = -\sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_r}\{G_E G_M\}$$

Transverse polarization.

$$P_l = \sqrt{1-\varepsilon^2}\,\frac{1}{\sigma_r}\{G_M^2\}$$

Longitudinal polarization.

$$\sigma_r = G_M^2 + \frac{\varepsilon}{\tau}G_E^2$$

Reduced cross section.

Born Approx.

# Beyond the Born-Approximation formalism

$$P_t = -\sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_r}\{G_E G_M + G_E \mathrm{Re}(\delta\tilde{G}_M) + G_M \mathrm{Re}(\delta\tilde{G}_E + \frac{\upsilon}{M^2}\tilde{F}_3)\} + O(e^4)$$

$$P_l = \sqrt{1-\varepsilon^2}\,\frac{1}{\sigma_r}\{G_M^2 + 2G_M \mathrm{Re}(\delta\tilde{G}_M + \frac{\varepsilon}{1+\varepsilon}\frac{\upsilon}{M^2}\tilde{F}_3)\} + O(e^4)$$

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Born Approx.

Beyond Born Approx.

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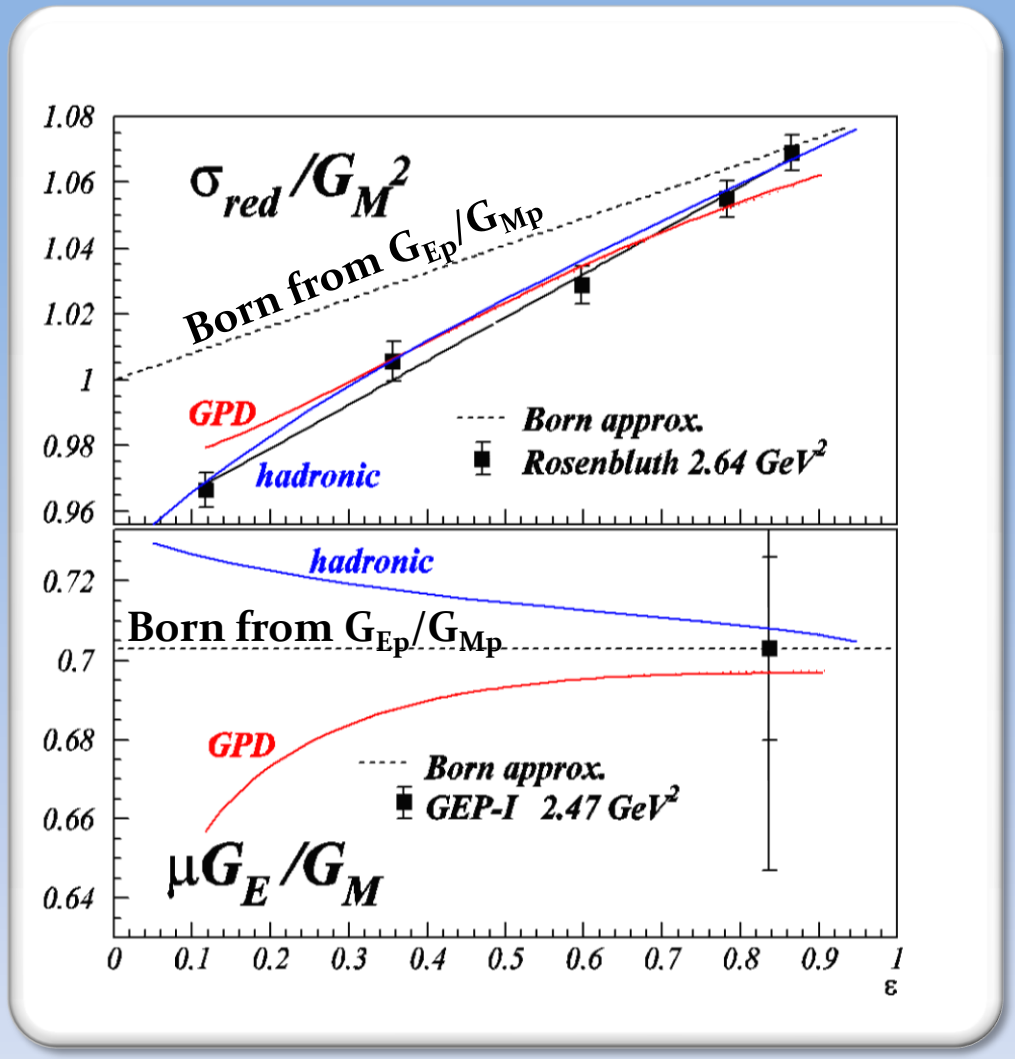
$$P_n = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_r}\{-G_M \mathrm{Im}(\delta\tilde{G}_E + \frac{\upsilon}{M^2}\tilde{F}_3) + G_E \mathrm{Im}(\,\delta\tilde{G}_M + \frac{2\varepsilon}{1+\varepsilon}\frac{\upsilon}{M^2}\tilde{F}_3)\,\} + O(e^4)$$

Normal polarization: directly proportional to 2 (or multi-) photon exchange

Born Approx.

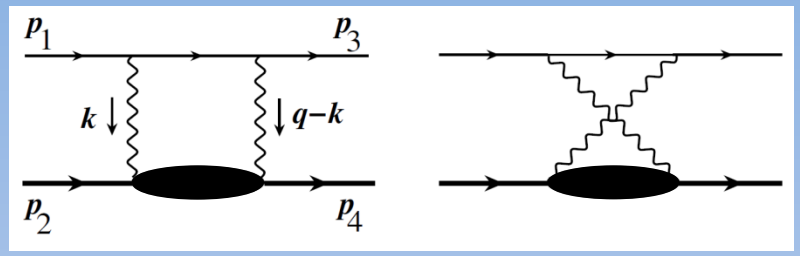
Beyond Born Approx.

# Theoretical Estimates



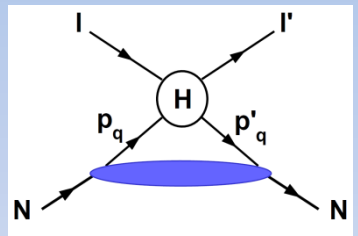

**Hadronic (elastic) :** keep the nucleon intermediate state + higher resonances, dominated by correction to $G_M$.

*P.Blunden et al., Phys.Rev.C72: 034612 (2005)*




**GPD:** hard lepton-quark scattering, quarks are embedded in the nucleon through the GPDs. Dominated by $F_3$ correction and correction to $G_E$.

*A.Afanasev et al., Phys. Rev.D72:013008 (2005)*




**Both theories describe Rosenbluth data but have opposite prediction for $G_{Ep}/G_{Mp}$.**

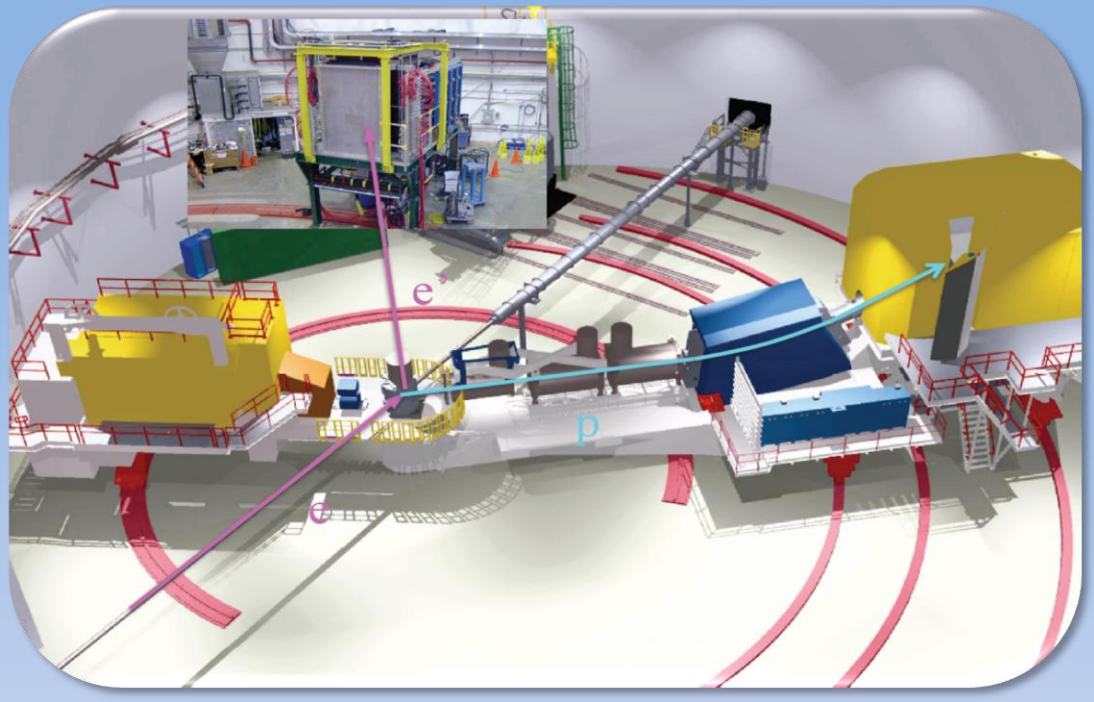
# The GEp-2γ Experiment

- We look for a kinematical dependence of $G_{Ep}/G_{Mp}$ to detect a possible two-photon exchange effect in the ep-scattering.

**Key idea:**

- fixed $Q^2$.
- same spin transport. (spin precession fixed)
- same analyzing power. ($P_p$ fixed)

↳ precision limited only by statistics (~ 0.01 for a ratio value of 0.7)




unlike Rosenbluth, very small p.t.p systematics: Ay , h cancel out in the $P_t/P_l$ ratio.

80μA beam current.
85% pol.
20cm LH target.

| $E_e$, GeV | $p_p$ | $E_e'$ | $\theta_p$, deg | $\theta_e$ | ε range | $\langle Q^2 \rangle$ |
|---|---|---|---|---|---|---|
| 1.867 | 2.068 | 0.527 | 14.13 | 106 | .130-.160 | 2.49 |
| 2.839 | 2.068 | 1.507 | 30.76 | 45.3 | .611-.647 | 2.49 |
| 3.549 | 2.068 | 2.207 | 35.39 | 32.9 | .765-.786 | 2.49 |

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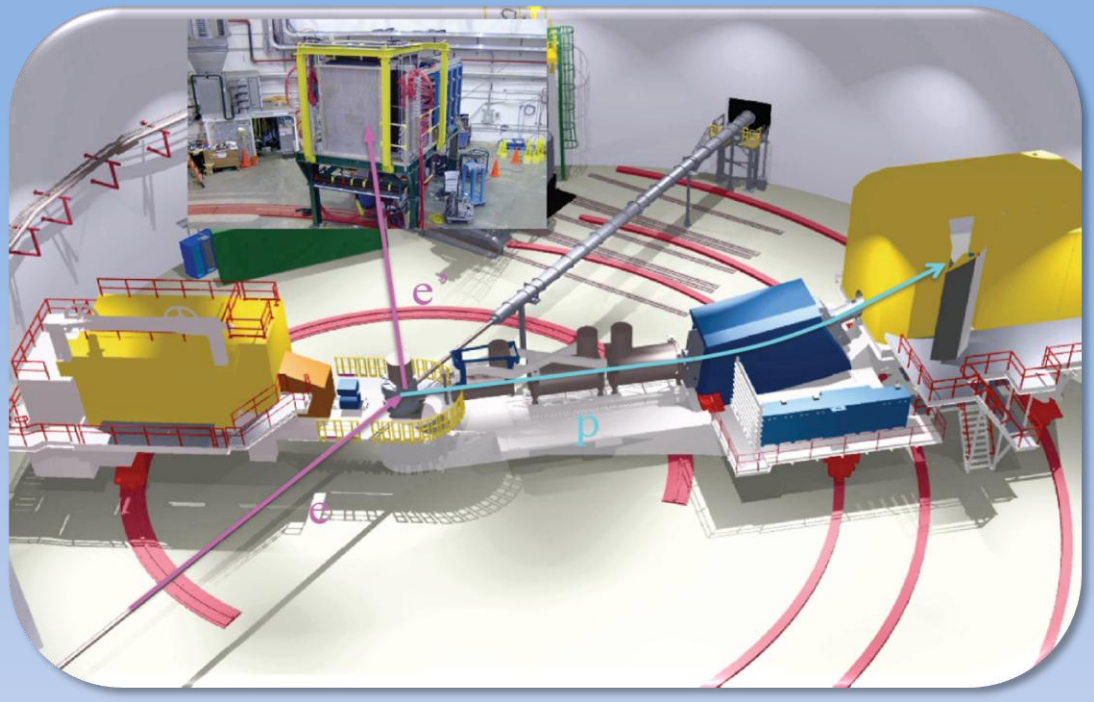


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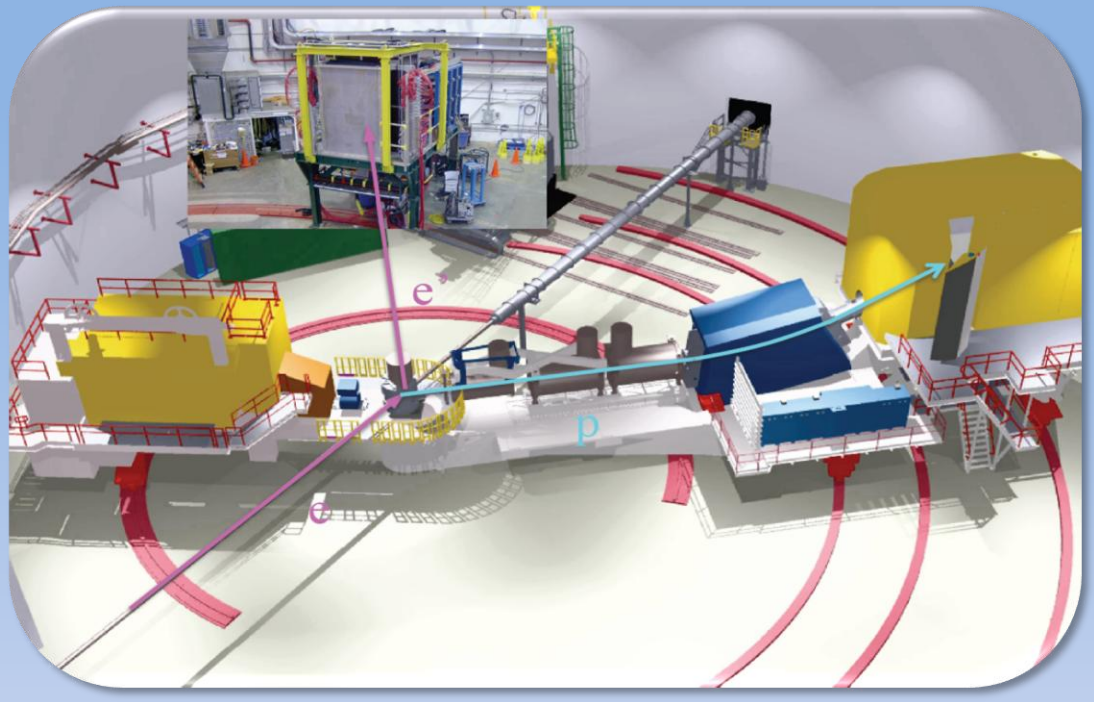


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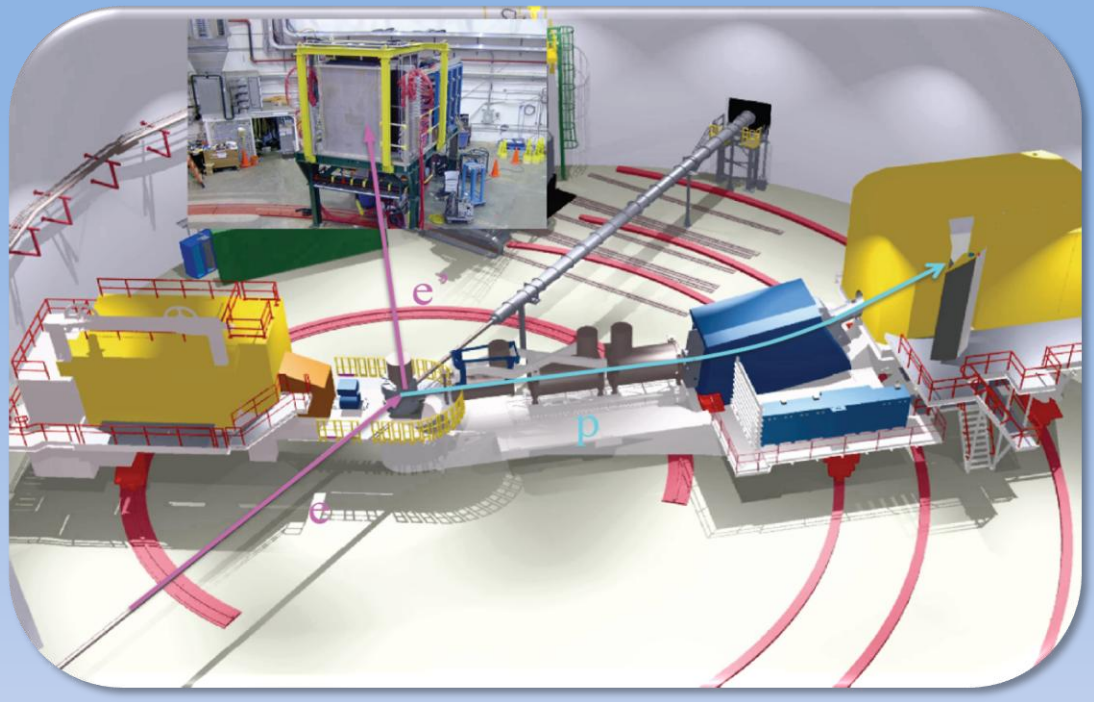


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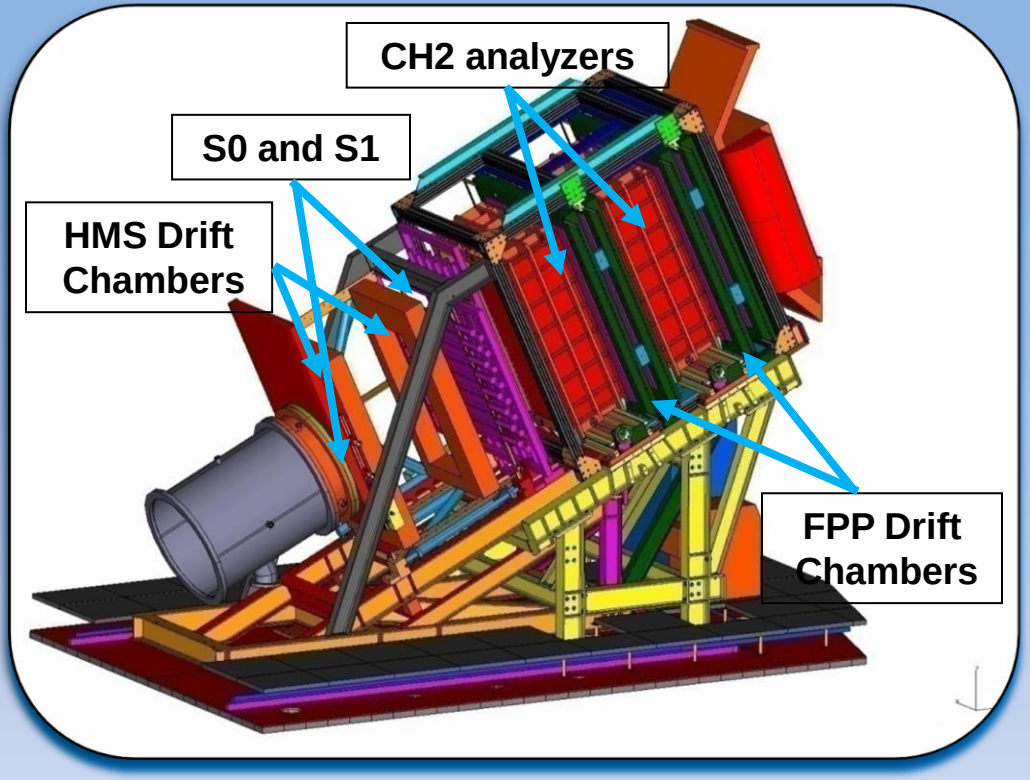
# HMS with Focal Plane Polarimeter

- Two HMS drift chambers for tracking--measure proton momentum and define incident trajectory for FPP.

- Scintillator hodoscopes So and S1 for trigger and timing.

- Focal Plane Polarimeter
  - Two $CH_2$ analyzers, 55 cm thick
  - Two sets of drift chambers track protons scattered in analyzer.



# BigCal Calorimeter

(close-up of the front of BigCal)

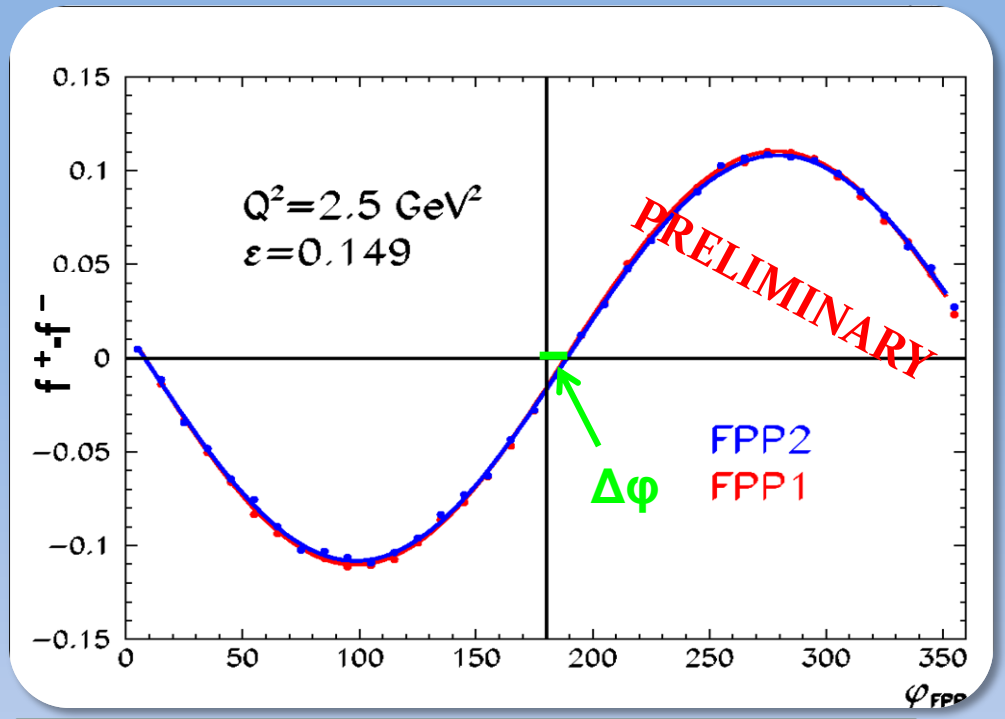
- 1744 channels electromagnetic calorimeter
- Measure electron angles and energy
- Separate elastic from inelastic using angular correlation
- From $\frac{6.8\%}{\sqrt{E}}$ to $\frac{23\%}{\sqrt{E}}$ energy resolution (E in GeV) due to radiation damage
- Position resolution not very sensitive to radiation damage ~5 mm

# PHYSICAL ASYMMETRIES

Physical asymmetries (helicity dependent) are obtained by taking the difference between the angular distributions of events of the two helicity states: $f^{+}(\theta, \phi)-f^{-}(\theta,\phi)$

Focal plane asymmetry can be written as a sine function with a phase shift which is related to the ratio of the polarization components at the focal plane.

With the FPP, we measure the proton polarization after undergoing precession through the HMS magnets.




$$f^{+}(\theta - \varphi) - f\ (\theta - \varphi) = B\sin(\varphi + \Delta\varphi)$$

$$B = hA_y\sqrt{(P_t^{FPP})^2 + (P_n^{FPP})^2}$$

$$\tan\Delta\varphi = -\frac{P_t^{FPP}}{P_n^{FPP}}\ ,\ P_n^{FPP} \approx P_l^{Tgt}\sin\chi_\theta$$

# Spin Precession Check

The F.F. ratio is independent of the reconstructed target variables and δ for both FPPs.

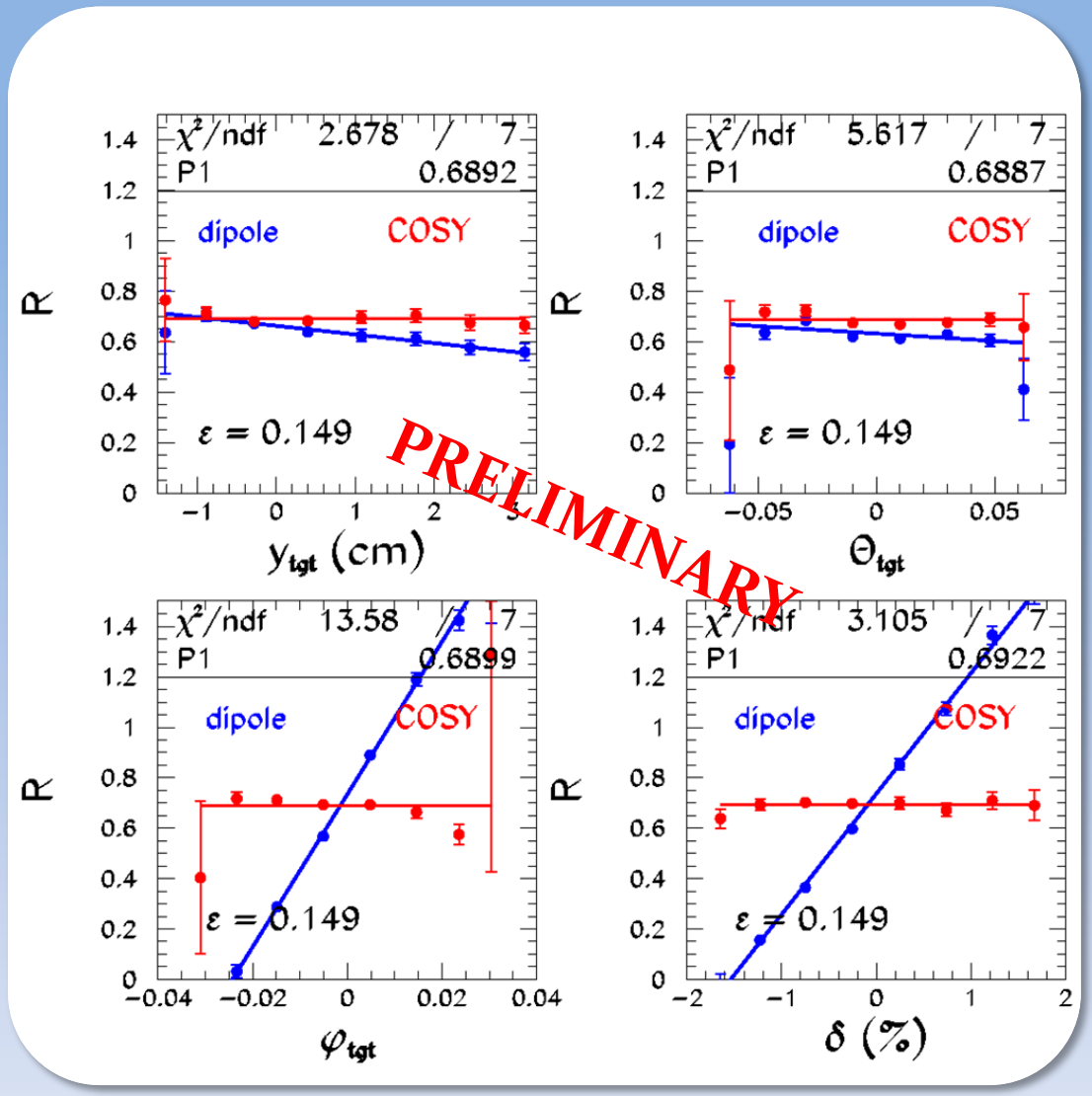
δ: relative momentum of the spectrometer with respect to the central momentum $p_o$=2.0676 GeV/c

$$R = \mu \frac{G_{Ep}}{G_{Mp}} = -\mu \frac{P_t}{P_l} \frac{(E_e + E_{e'})}{2M} \tan\frac{\theta_e}{2}$$

$\theta_{tgt}$ (dispersive) and $\phi_{tgt}$ (non-dispersive) are the angles at the target.

Good understanding of the spin precession calculation through the spectrometer magnets.

Good quality of the COSY Spin transport matrix.



# FALSE ASYMMETRIES

- The angular distribution is given by:

$$N^{\pm}(p,\theta,\varphi) = N_0^{\pm}\frac{\varepsilon(p,\theta)}{2\pi}[1 + (c_1 \pm A_y P_y^{fpp})\cos\varphi + (s_1 \mp A_y P_x^{fpp})\sin\varphi + c_2\cos(2\varphi) + s_2\sin(2\varphi) + \ldots]$$

| | |
|---|---|
| $N_0^{\pm}$ | Number of incident proton with ± helicity state. |
| $\varepsilon(p,\theta)$ | Fraction of proton with momentum p scattered with an angle θ. |
| $A_y(p,\theta)$ | Analyzing power of the $\vec{p} + CH_2$ reaction. |
| $P_x^{fpp}, P_y^{fpp}$ | Polarization components at the focal plane. |
| $c_1, s_1, \ldots$ | Fourier coefficients of helicity independent instrumental asymmetries. (sum of $N^+$ and $N^-$, *cancelled in first order)* |

- Maximizing the Likelihood function: ($S_{ij}$ COSY spin transport matrix elements)

$$L(P_t,P_l) = \prod_{i=1}^{N_{event}}[1 + h\varepsilon_i A_y^{(i)}(S_{yt}^{(i)}P_t + S_{yl}^{(i)}P_l)\cos\varphi_i - h\varepsilon_i A_y^{(i)}(S_{xt}^{(i)}P_t + S_{xl}^{(i)}P_l)\sin\varphi_i + \Lambda_0^{(i)}]$$

Small negative correction at the 2nd order in the F.F. ratio for the 3 kin. : $|\Delta R| \approx 0.01$

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| $P_x^{fpp}, P_y^{fpp}$ | Polarization components at the focal plane. |
| $c_1, s_1, \ldots$ | Fourier coefficients of helicity independent instrumental asymmetries. (sum of $N^+$ and $N^-$, *cancelled in first order)* |

- Maximizing the Likelihood function: ($S_{ij}$ COSY spin transport matrix elements)

$$L(P_t, P_l) = \prod_{i=1}^{N_{event}}[1 + h\varepsilon_i A_y^{(i)}(S_{yt}^{(i)}P_t + S_{yl}^{(i)}P_l)\cos\varphi_i - h\varepsilon_i A_y^{(i)}(S_{xt}^{(i)}P_t + S_{xl}^{(i)}P_l)\sin\varphi_i + \Lambda_0^{(i)}]$$

Small negative correction at the 2nd order in the F.F. ratio for the 3 kin. : $|\Delta R| \approx 0.01$

# FALSE ASYMMETRIES

- The angular distribution is given by:

$$N^{\pm}(p,\theta,\varphi) = N_0^{\pm}\frac{\varepsilon(p,\theta)}{2\pi}[1 + (c_1 \pm A_y P_y^{fpp})\cos\varphi + (s_1 \mp A_y P_x^{fpp})\sin\varphi + c_2\cos(2\varphi) + s_2\sin(2\varphi) + \ldots]$$

| | |
|---|---|
| $N_0^{\pm}$ | Number of incident proton with ± helicity state. |
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$$\lambda_0 = \sum_i c_i\cos\varphi + s_i\sin\varphi$$

- Maximizing the Likelihood function: ($S_{ij}$ COSY spin transport matrix elements)

$$L(P_t, P_l) = \prod_{i=1}^{N_{event}}[1 + h\varepsilon_i A_y^{(i)}(S_{yt}^{(i)}P_t + S_{yl}^{(i)}P_l)\cos\varphi_i - h\varepsilon_i A_y^{(i)}(S_{xt}^{(i)}P_t + S_{xl}^{(i)}P_l)\sin\varphi_i + \lambda_0^{(i)}]$$

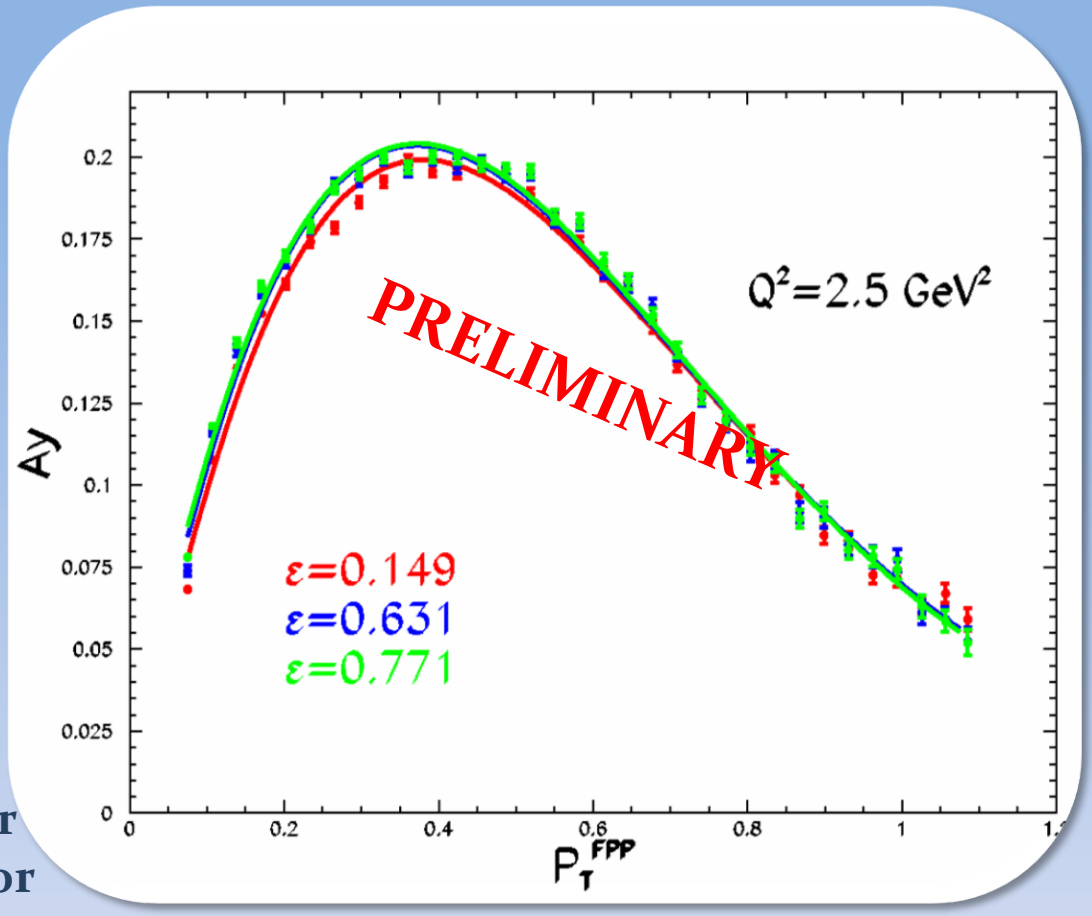
Small negative correction at the 2nd order in the F.F. ratio for the 3 kin. : $|\Delta R| \approx 0.01$

# Analyzing Power

- Tight analyzer cuts
- Single track events selection.
- Correction for the energy loss in $CH_2$ applied.
- Transverse momentum:

$$P_T^{FPP} = P_{HMS}^{loss} \sin\theta_{FPP}$$

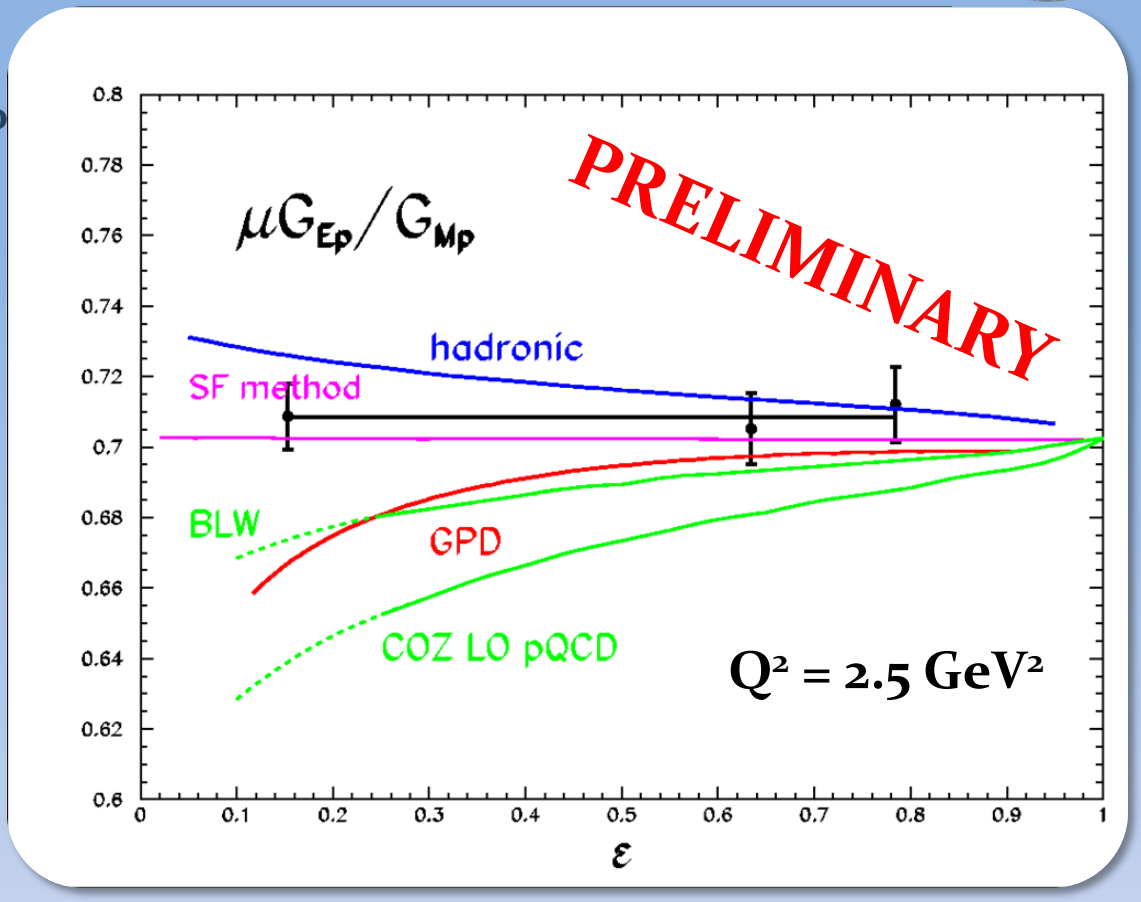
Good stability of the analyzing power over the 3 kinematics.




- Even if $A_y$ cancels in the form factor ratio, it is an important quantity for the extraction of $P_\ell$ since we measure $hA_yP_\ell$.

# Form Factor Ratio

- No evidence of an epsilon dependence at a 0.01 level for a ratio of 0.7 in the polarization data at $Q^2 = 2.5\ GeV^2$.
- Models predict a bigger correction (opposite sign) at small ε, not seen in the data.
- Theoretical predictions are with respect to the Born approximation. (calculated from the fit to the polarization data)
- Validate the recoil polarization transfer technique to extract the proton form factor ratio
- Radiative corrections calculated with MASCARAD ~0.01-0.02% (*Afanasev et.al, Phys. Rev. D 64, 113009 (2001)*)





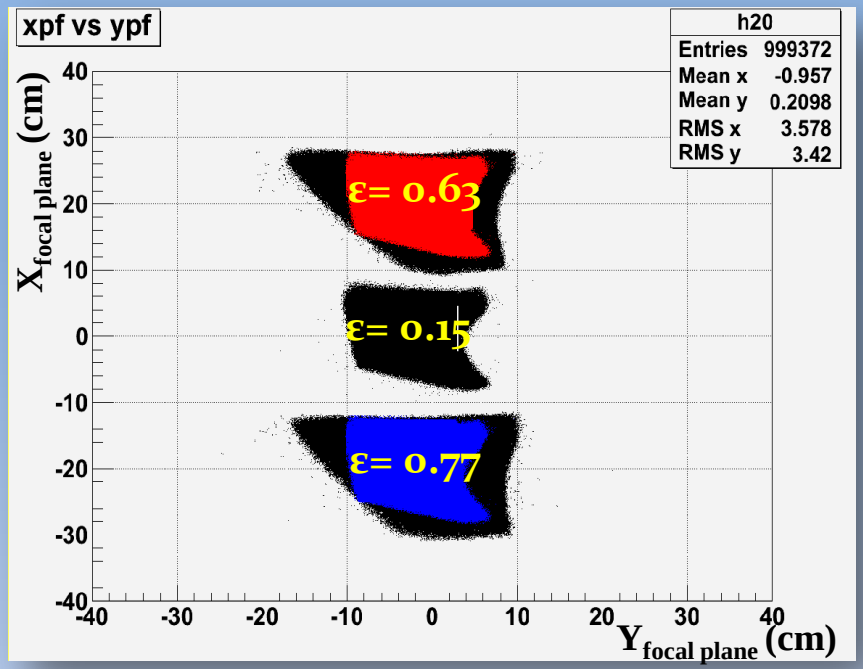
P.Blunden et al., Phys.Rev.C**72**: 034612 (2005)

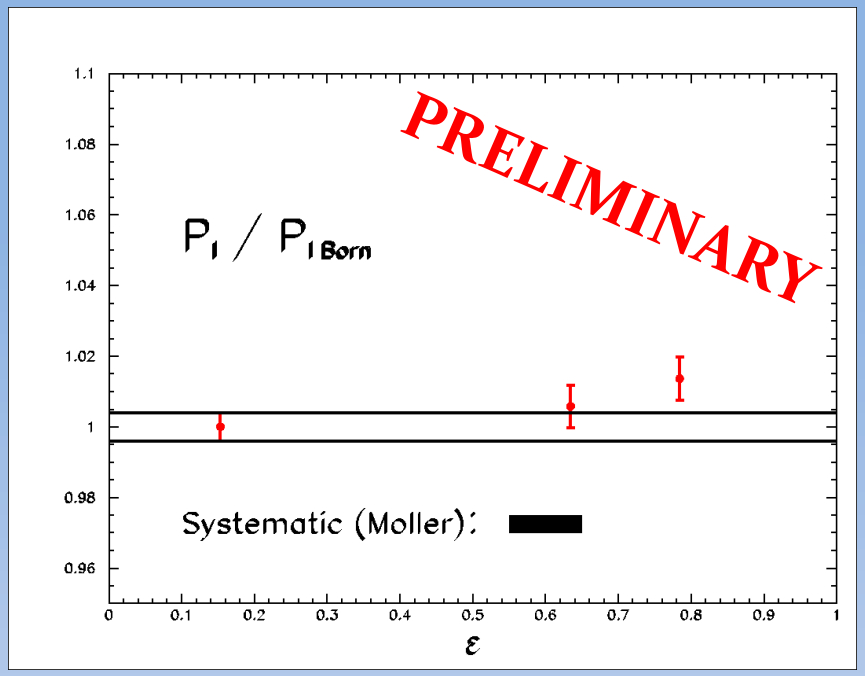
A.Afanasev et al., Phys.Rev.D**72**:013008 (2005)

N. Kivel and M. Vanderhaeghen Phys.Rev.Lett.**103**:092004 (2009)

Bystritskiy, Kuraev and Tomasi-Gustafsson, Phys.Rev.C**75**: 015207 (2007)

# Longitudinal Polarization




- Matching acceptance cut : cut to match the original acceptance of the smallest ε point to cover the same spot for the 3 kinematics at the focal plane.

  ➡ Same spin transport

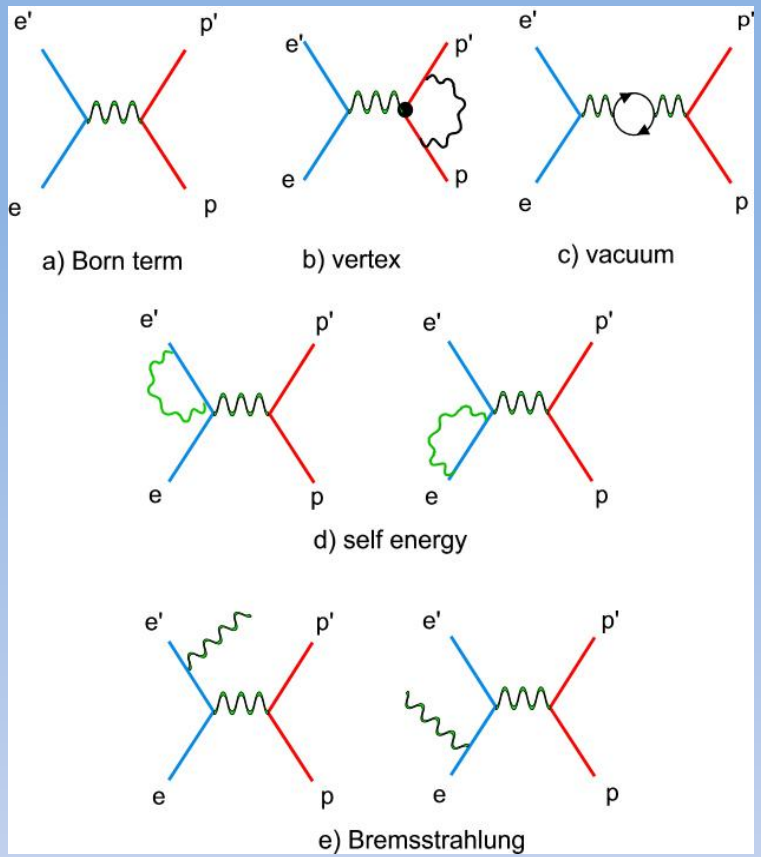
- Normalized $P_\ell/P_{\ell\_Born}$ ratio to the smallest ε kinematic.
- Based on the assumption that $A_y$ is kinematic independent.
- 0.05% systematic errors (Moller measurements)

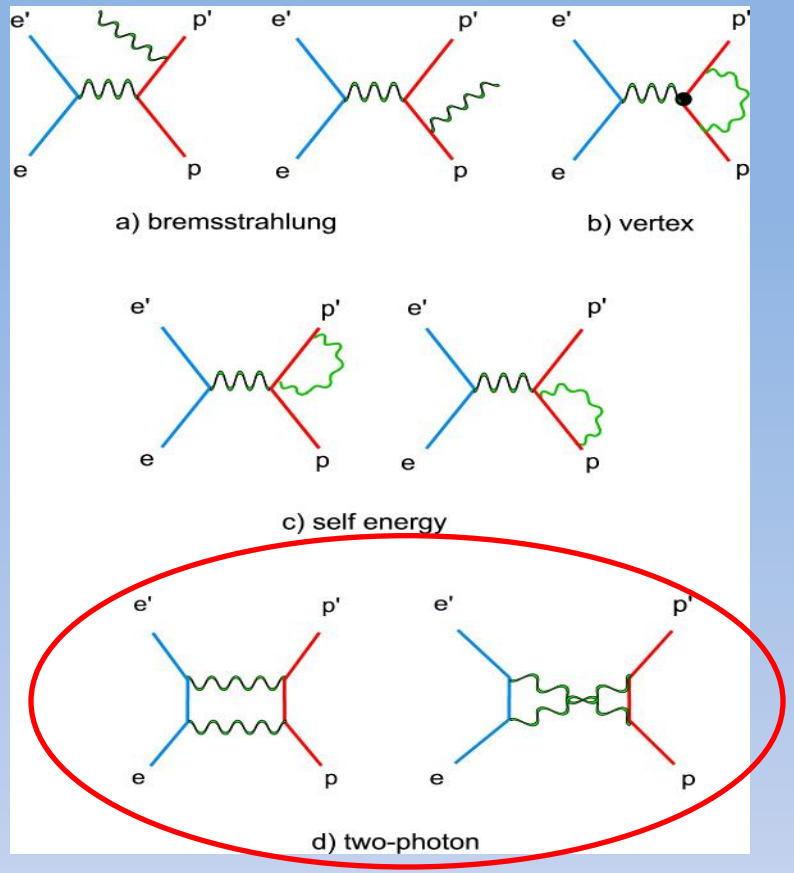
# CONCLUSION

- The form factor ratio is independent of the target variables.
- Good stability of the analyzing power over the 3 kinematics.
- Results statistically consistent with a constant for the longitudinal polarization observable.
- No evidence of an epsilon dependence at a 0.01 level for a form factor ratio of 0.7 at $Q^2$ of 2.5 $GeV^2$.

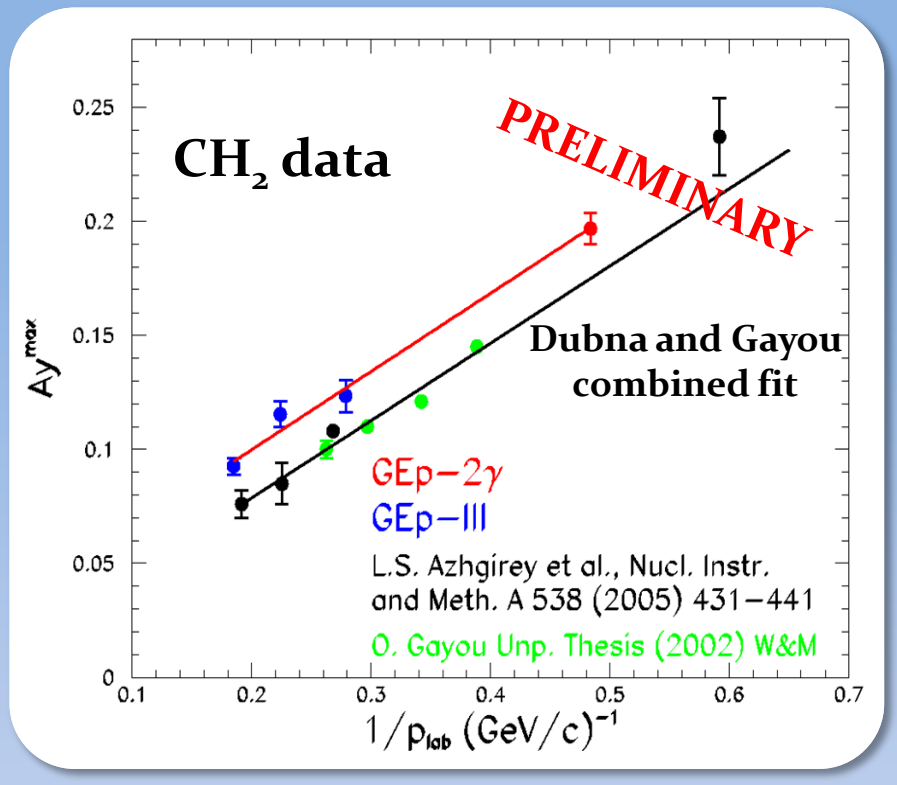
# BACK-UP SLIDES

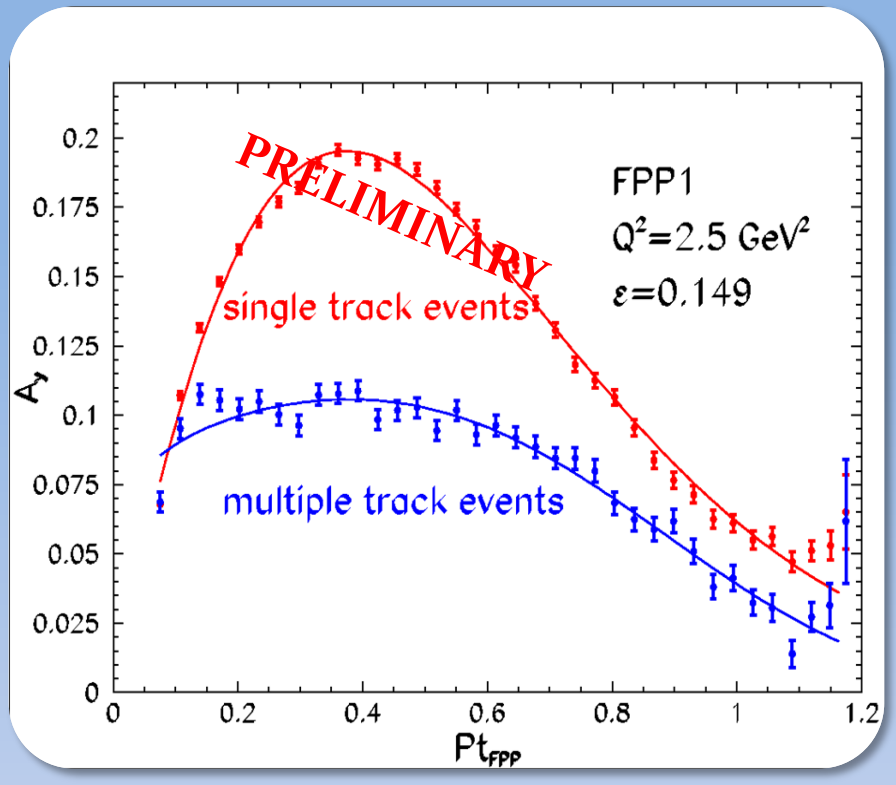
# “Standard” Radiative Corrections



# Analyzing Power

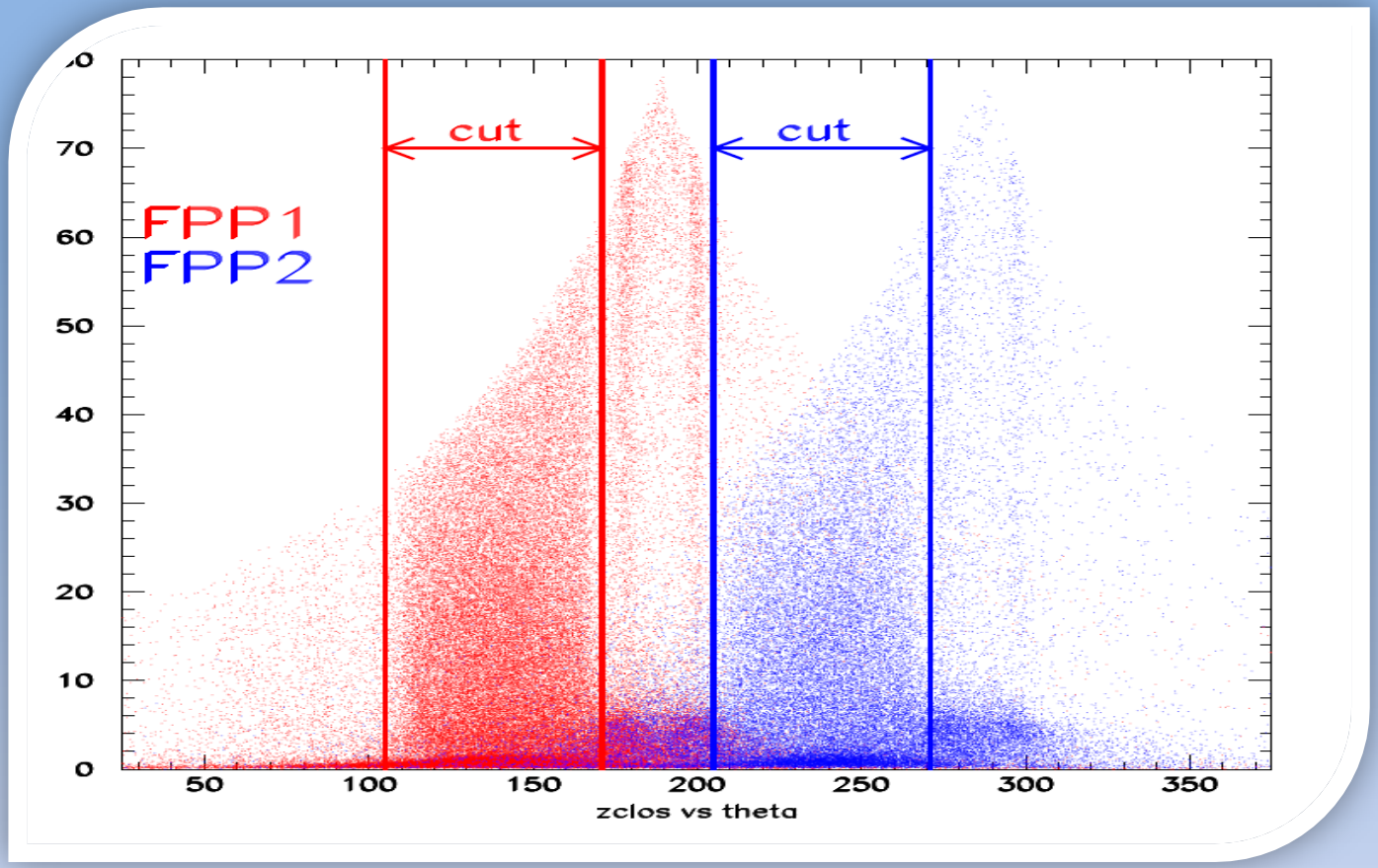



- Experimental result from the Dubna (Azhgirey et al.) data.
- Single track events and FPP1 only.
- Maximum of analyzing power follows the $1/p_{lab}$ trend of the Dubna and Gayou results but with a systematic shift.

→ Track multiplicity???

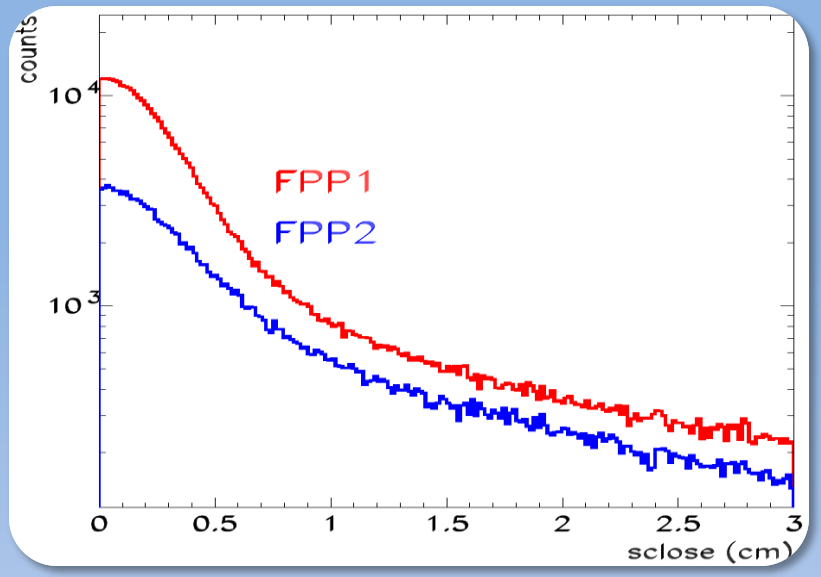
# Reconstructed Scatterings

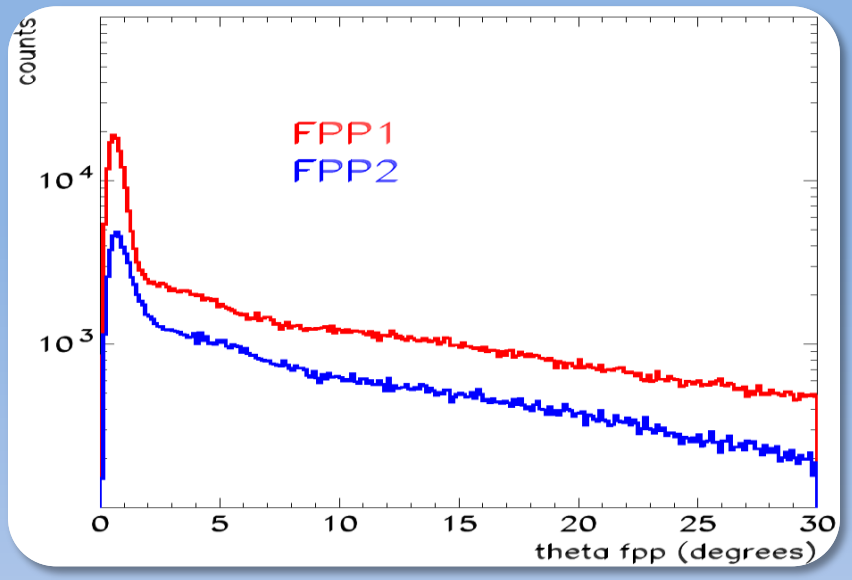



Zclose z-coordinate of the point of closest approach between incident and scattered track

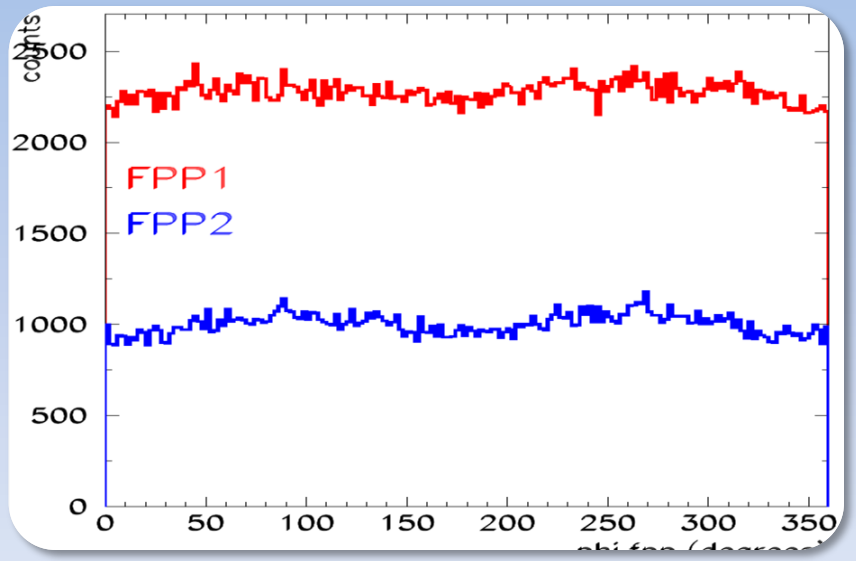
Cone-test exhibits the "razor blade" shape of the events in the z- θ plan

# Reconstructed Scatterings

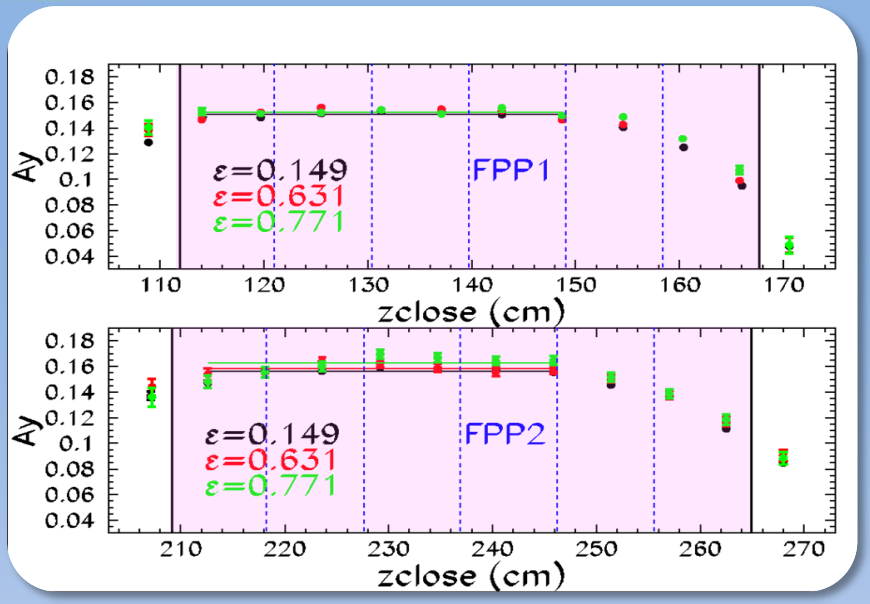


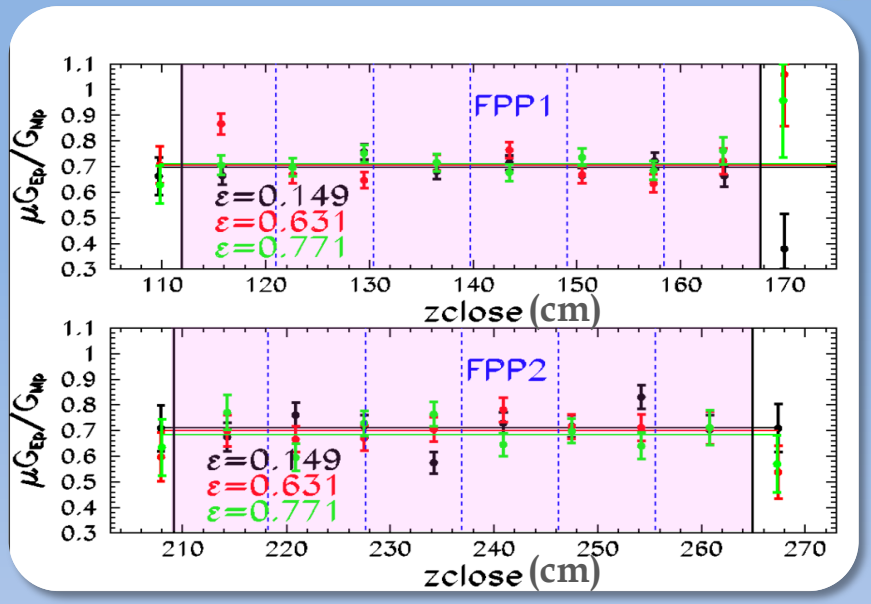



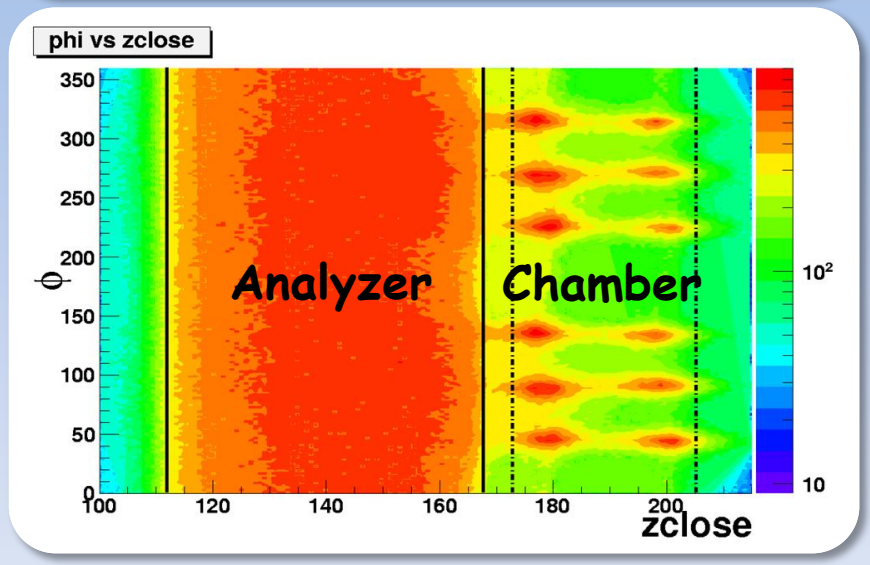

- Distance of closest approach (sclose), θ and ϕ distributions for protons scattered in the $CH_2$ analyzers.
- Peak at small angle due to Coulomb scattering.
- Typically 50% as many events undergo scattering in FPP2 as in FPP1.



# Zclose dependence




- The analyzing power is not constant within the whole width of the analyzer.
- The form factor ratio is constant within the analyzer for the 3 kinematics.
- Dilution of the analyzing power from bad reconstructed events.

# Focal Plane Polarimeter: FPP

- No particle ID capability--importance of coincidence electron detection to eliminate backgrounds.

- Two HMS drift chambers for tracking--measure proton momentum and define incident trajectory for FPP.

- Scintillator hodoscopes So and S1 for trigger and timing.

- Focal Plane Polarimeter
  - Two $CH_2$ analyzers, 55 cm thick
  - Two sets of drift chambers track protons scattered in analyzer.