Status of GEp-III high Q^2 form factor ratio analysis

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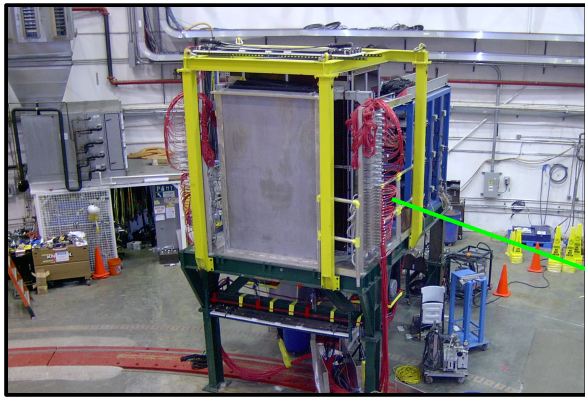
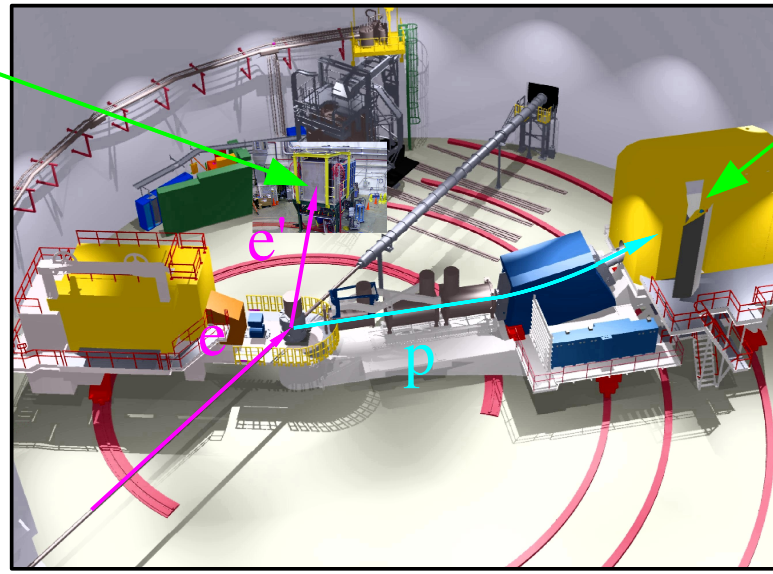
on behalf of the

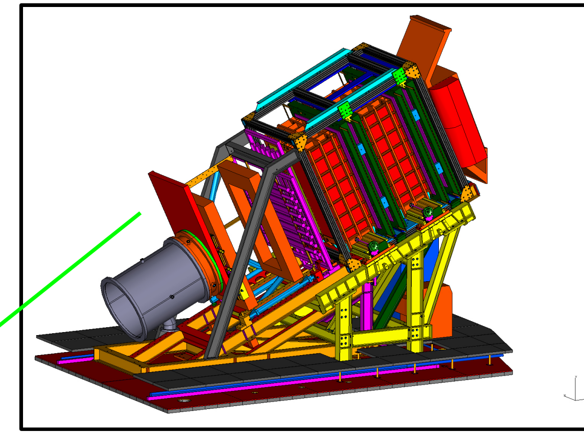
GEp-III Collaboration

Experiments E04-108 and E04-019



$$^1H(\vec{e}, e'\vec{p})$$





$$
\begin{aligned}
I_0 P_l &= (\hat{k}\cdot\mathbf{h}_e)\sqrt{\tau(1+\tau)}\tan^2\frac{\theta_e}{2}\frac{E_e+E'_e}{M}G_M^2 \\
I_0 P_t &= -2(\hat{k}\cdot\mathbf{h}_e)\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}G_E G_M \\
I_0 P_n &= 0 \\
I_0 &\equiv G_E^2 + \frac{\tau}{\epsilon}G_M^2
\end{aligned}
$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e+E'_e}{2M}\tan\frac{\theta_e}{2}$$

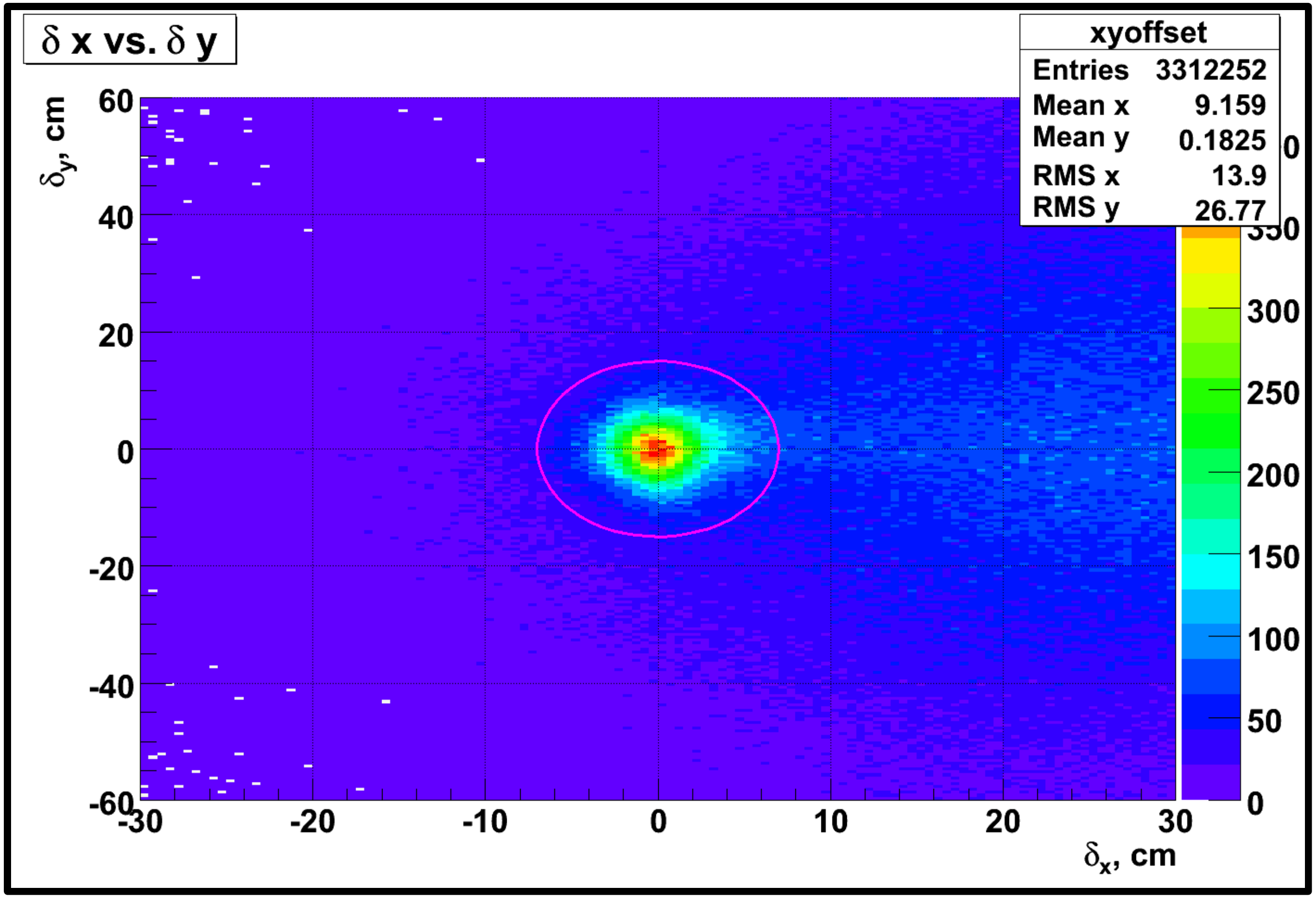
Q^2, GeV^2	ϵ	E_{beam}, GeV	θ_p, °	p_p, GeV	χ, °	θ_e,°	R_{cal}, m	Ω_e, msr
2.5	0.154	1.873	14.495	2.0676	108.5	105.2	4.93	111.2
2.5	0.633	2.847	30.985	2.0676	108.5	44.9	12.00	18.8
2.5	0.789	3.680	36.10	2.0676	108.5	30.8	11.03	22.2
5.2	0.377	4.053	17.94	3.5887	177.2	60.3	6.05	73.9
6.8	0.507	5.714	19.10	4.4644	217.9	44.4	6.00	75.1
8.5	0.236	5.714	11.6	5.407	262.2	69.0	4.30	146.2

Analysis Method

- Two primary tasks for form factor ratio analysis
  - Elastic event selection
  - Extraction of polarization observables
- Identification of elastic events requires kinematic correlation of detected electron and proton—reconstruction of angles, momentum, and vertex position for the proton arm, angles + energy for the electron arm. No particle identification used.
- Extraction of polarization observables requires
  - Track reconstruction in FPP for protons scattered in CH_2
  - Calculate spin precession in HMS magnets for each event—requires spectrometer model
  - Maximum likelihood analysis to extract physics observables.

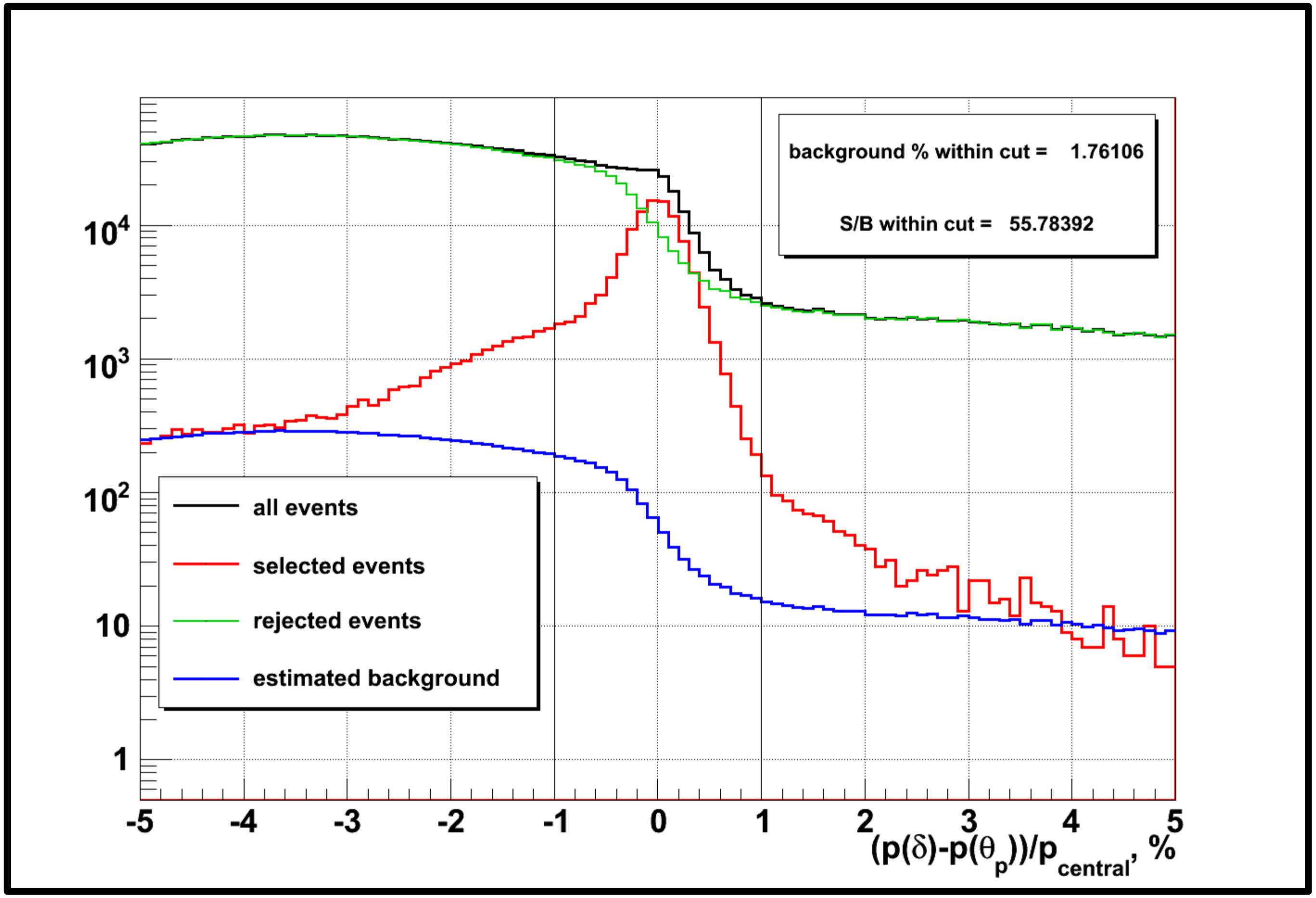
Elastic Event Selection I

- BigCal shower coordinate reconstruction—shower has transverse size of ~3x3 cells—sufficient granularity to achieve ~5 mm position resolution
- Combined with 1-2 mm y vertex resolution of HMS at 11.6 degrees, angular resolution of BigCal is ~2 mrad
- At 8.5 GeV^2 kinematics, this angular resolution corresponds to ~5x10^{-4} determination of expected proton momentum
- Compare to ~1.4x10^{-3} momentum resolution for HMS with S0 detector
- HMS resolution is dominant
- Analysis at different kinematics suggests actual position resolution is no worse than 8 mm, and Monte Carlo/SIMC studies suggest that the advertised 5 mm is in fact achieved.



Correlation between position of detected electron in BigCal and predicted position using elastic kinematics of the detected proton, and illustration of cut used to select elastic events

Elastic Event Selection II

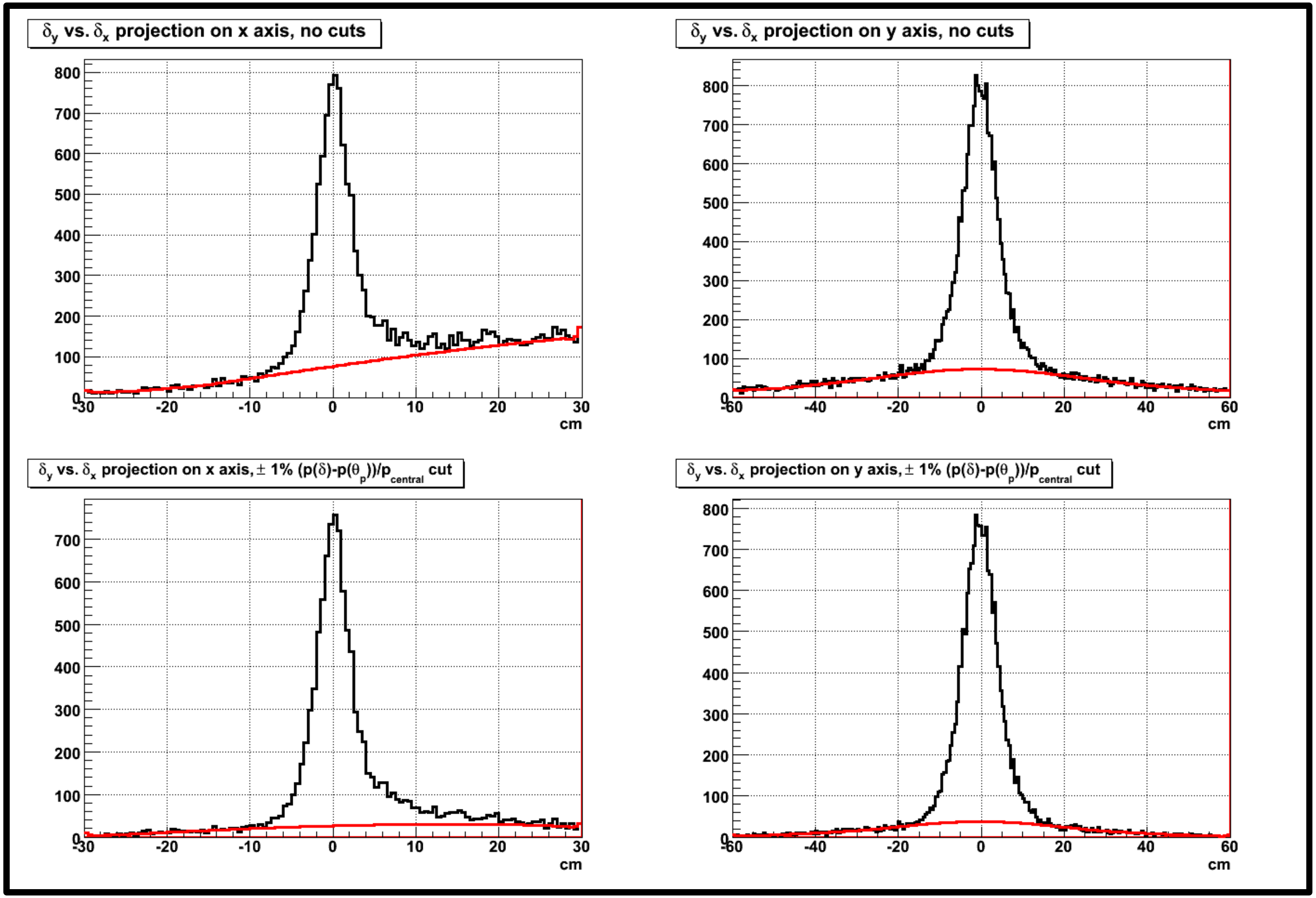


Even in the narrow region around the elastic peak (±1% on this plot), only ~24% of all events are elastic (as defined by the BigCal cut on the previous slide)

- HMS measures proton momentum and scattering angle precisely
- For elastically scattered protons, these two quantities are correlated
- At very forward angles, large inelastic backgrounds are present
- With BigCal, clean separation of the elastic peak is demonstrated

Elastic Event Selection III

- Going the other way, we can estimate the background under the elastic peak from the position correlation spectrum in BigCal—much cleaner than proton δ-θ spectrum.
- After applying final cut on proton δ-θ, a similar estimate of 1-2% remaining inelastic background is obtained.

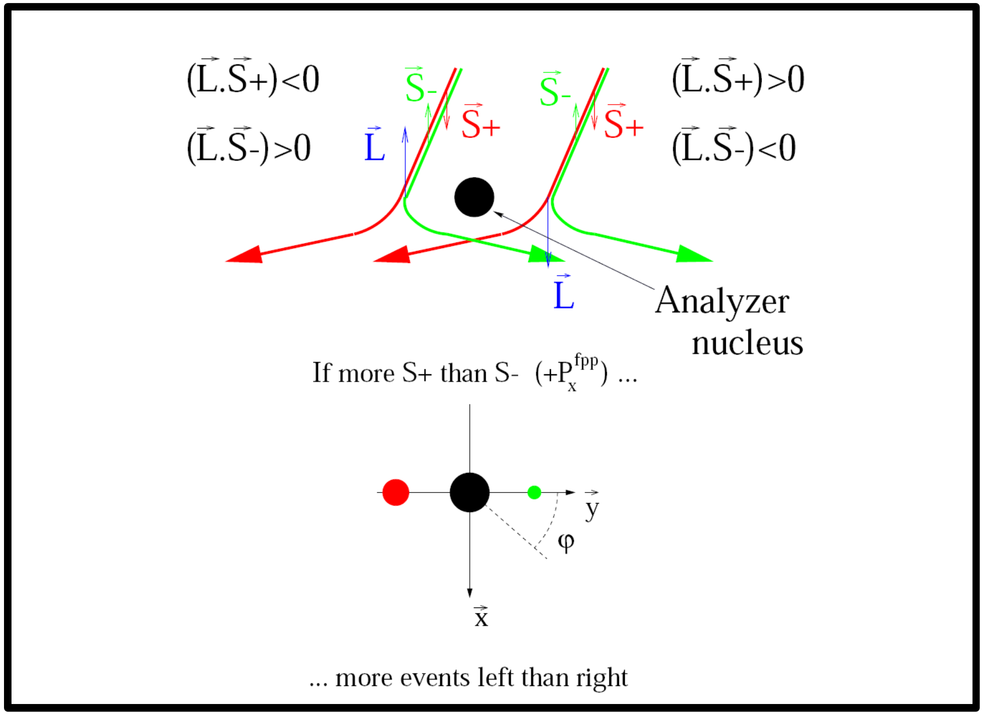


Projections of dx—dy spectra, before and after ± 1% cut on proton delta-theta correlation

Polarization Observables I

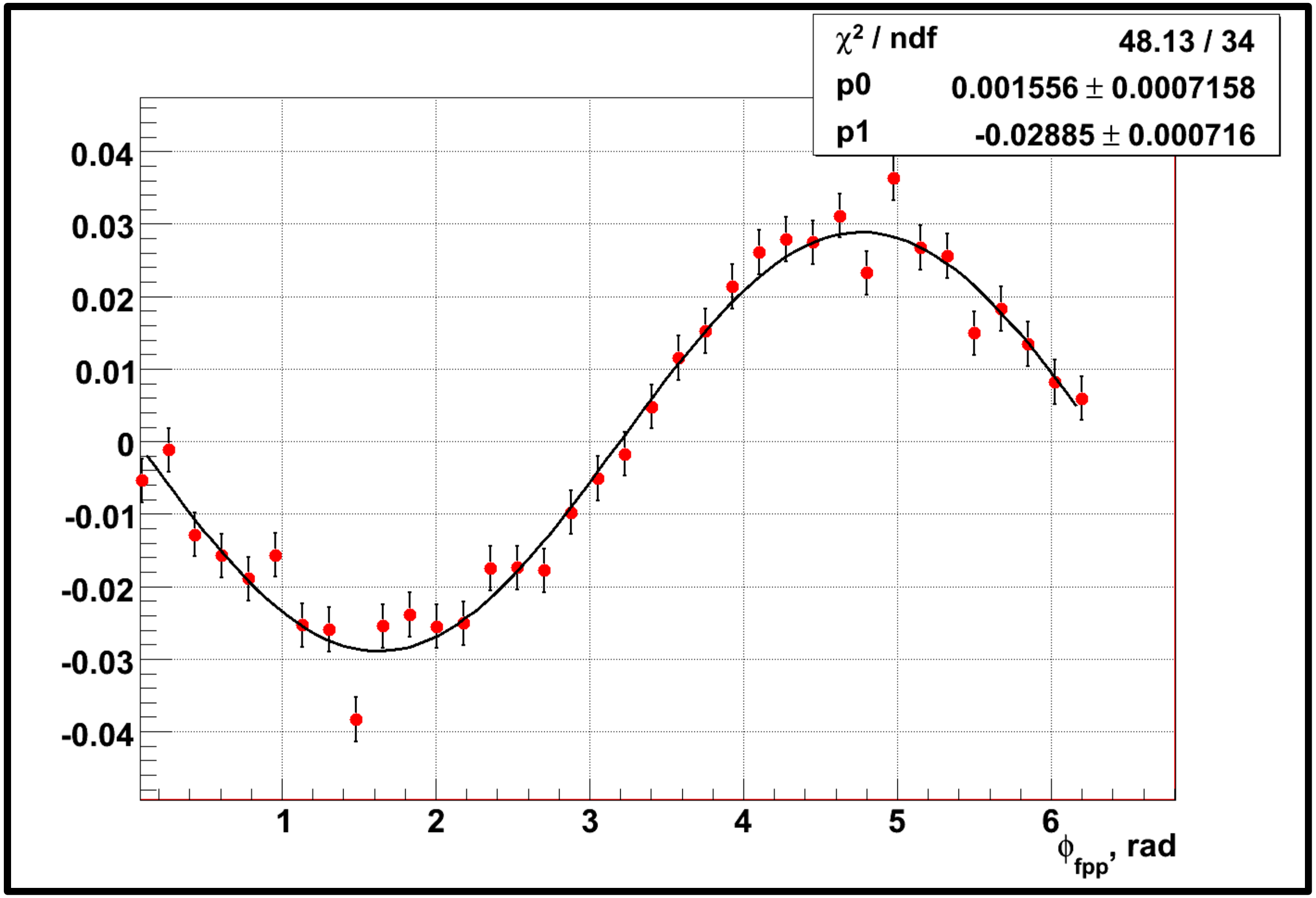
$$
\begin{aligned}
f^{\pm}(\vartheta,\varphi) &= \frac{1}{2\pi}\left[1+\left(\pm hA_y(\vartheta)P_t^{fpp}+a_{inst.}\right)\cos\varphi+\left(\mp hA_y(\vartheta)P_n^{fpp}+b_{inst.}\right)\sin\varphi\right]\\
N^{\pm}(\vartheta,\varphi) &= N^{\pm}_{incident}\,\varepsilon(\theta)f^{\pm}(\vartheta,\varphi)\\
(N^{+}\pm N^{-})(\vartheta,\varphi) &= \frac{\varepsilon(\theta)}{2\pi}\left[\left(N^{+}_{incident}\pm N^{-}_{incident}\right)\left(1+a_{inst.}\cos\varphi+b_{inst.}\sin\varphi\right)+\right.\\
&\left. A_y(\vartheta)\left(h^{+}N^{+}_{incident}\mp h^{-}N^{-}_{incident}\right)\left(P_t^{fpp}\cos\varphi-P_n^{fpp}\sin\varphi\right)\right]
\end{aligned}
$$

- Polarization of the recoil proton gives rise to an azimuthal asymmetry in the angular distribution of scattered protons in CH_2. In addition, there are false/instrumental asymmetry terms arising from chamber misalignments/wire efficiency variations, etc.
- To the extent that there are equal numbers of incident protons for both beam helicity states and the beam polarization is the same in both helicity states, the physical polarizations cancel exactly in the sum distribution, and the false asymmetries cancel exactly in the difference distribution, allowing perfect separation of the two effects.



Polarization Observables II

- Azimuthal asymmetry measures the two components of the proton polarization which are perpendicular to the proton momentum at the focal plane
- Spin-orbit coupling is insensitive to longitudinal polarization
- What is measured is proton polarization after precession in the HMS magnets



Focal plane asymmetry @ Q^2=8.5 GeV^2

Spin Precession

• Relativistic equation of motion for spin precession for a charged particle in a magnetic field

• Compare to equation of motion for the velocity—precession relative to velocity is proportional to $\gamma\kappa_p$

• For each event, the proton spin undergoes a slightly different rotation which depends on the magnetic field it sees as it traverses the HMS magnets.

• COSY model is used to calculate the spin matrix elements as polynomials up to 5th order in the target quantities x, y, θ, ϕ and δ. Since reconstructed target variables are input to COSY STM calculation, knowledge of HMS optics is important!

• This is the dominant source of systematic uncertainty for the recoil polarization technique.

$$\frac{d\mathbf{S}}{dt} = \frac{e}{m\gamma}\mathbf{S} \times \left[\frac{g}{2}\mathbf{B}_{\parallel} + \left(1 + \gamma\left(\frac{g}{2} - 1\right)\right)\mathbf{B}_{\perp}\right]$$

$$\frac{d\hat{v}}{dt} = \frac{e}{m\gamma}\hat{v} \times \mathbf{B}$$

$$\begin{pmatrix} P_t^{fpp} \\ P_n^{fpp} \\ P_l^{fpp} \end{pmatrix} = \begin{pmatrix} S_{tt} & S_{tn} & S_{tl} \\ S_{nt} & S_{nn} & S_{nl} \\ S_{lt} & S_{ln} & S_{ll} \end{pmatrix} \begin{pmatrix} P_t^{tgt.} \\ P_n^{tgt.} \\ P_l^{tgt.} \end{pmatrix}$$

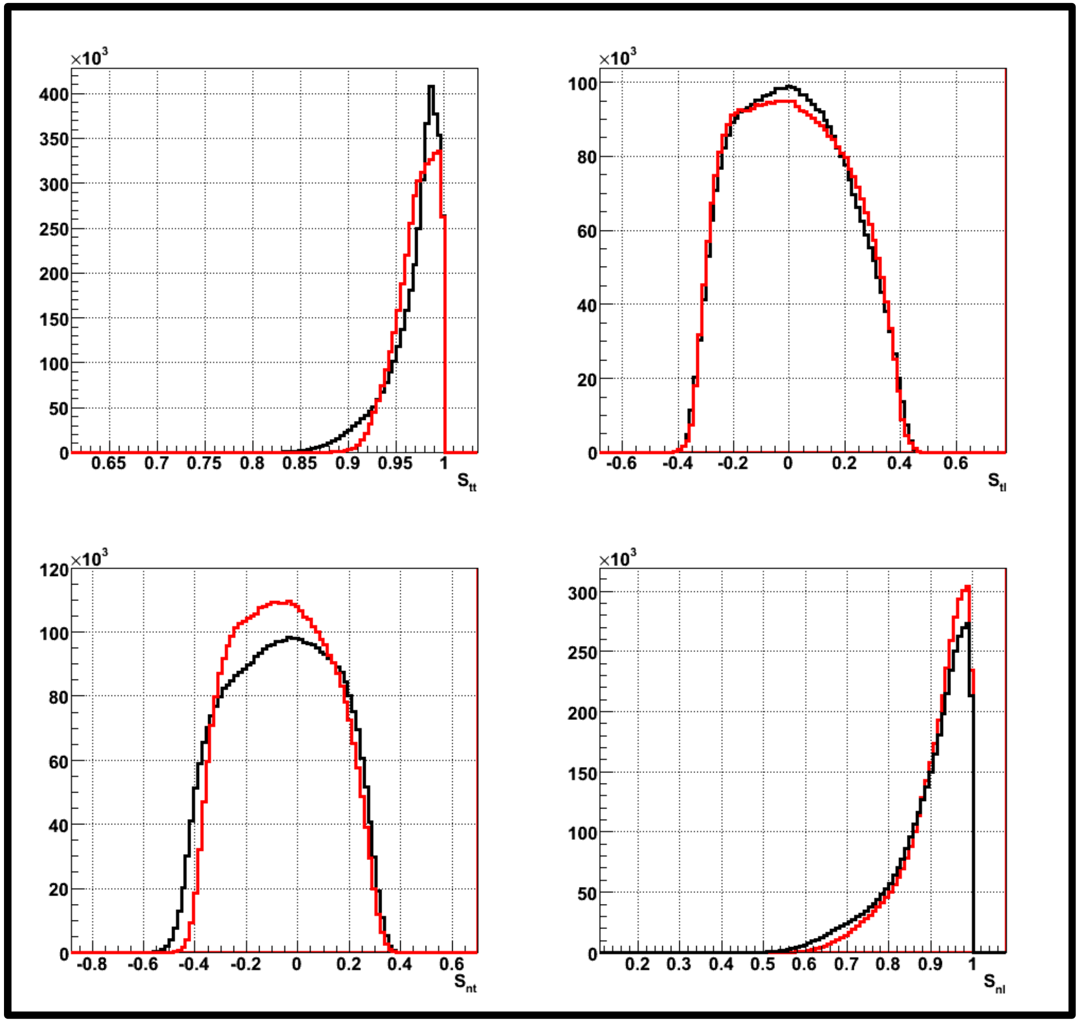
$$S_{ij} = \sum_{\lambda,\mu,\nu,\alpha,\beta=0,n} C_{ij}^{\lambda\mu\nu\alpha\beta}(\theta_{tgt})^{\lambda}(\phi_{tgt})^{\mu}(\delta)^{\nu}(y_{tgt})^{\alpha}(x_{tgt})^{\beta}$$

Spin Precession II

- Spin precession is related to the total trajectory bend angles in the HMS.
- Model-independent "geometric" approximation—precession consists of additive, independent rotations in dispersive and non-dispersive planes, proportional to the respective trajectory bend angles

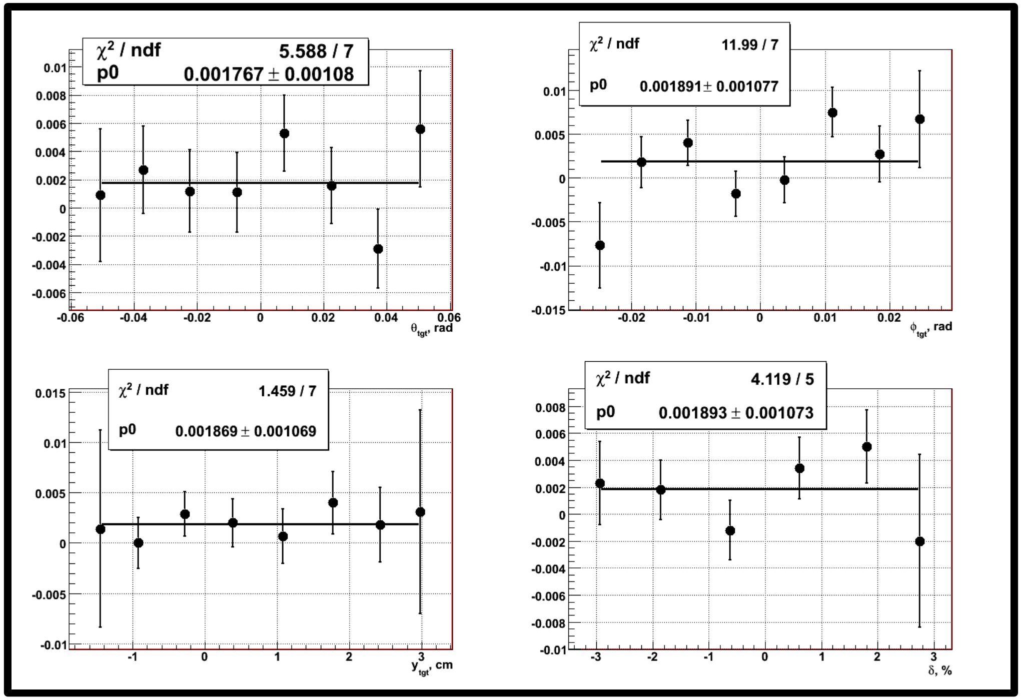
$$\chi_\theta \equiv \gamma\kappa_p(\Theta_{bend} + \theta_{tgt} - \theta_{fp})$$
$$\chi_\phi \equiv \gamma\kappa_p(\phi_{tgt} - \phi_{fp})$$

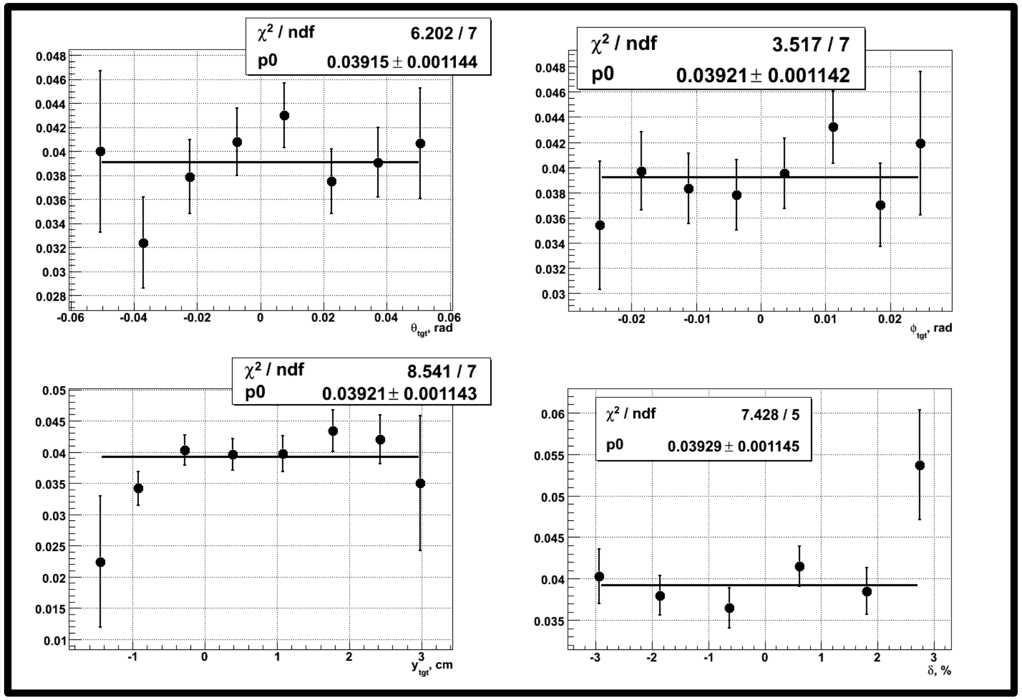
- Same technique as L. Pentchev TN-03-024, but HMS case (QQQD) is even simpler than HRS (QQDQ)--making this an even better approximation for the HMS
- Mainly useful for studying systematics—estimate the uncertainties in physics observables in terms of the uncertainties on reconstructed trajectory bend angles



- Black = COSY
- Red = Geometric approximation

Extraction of P_t and P_l





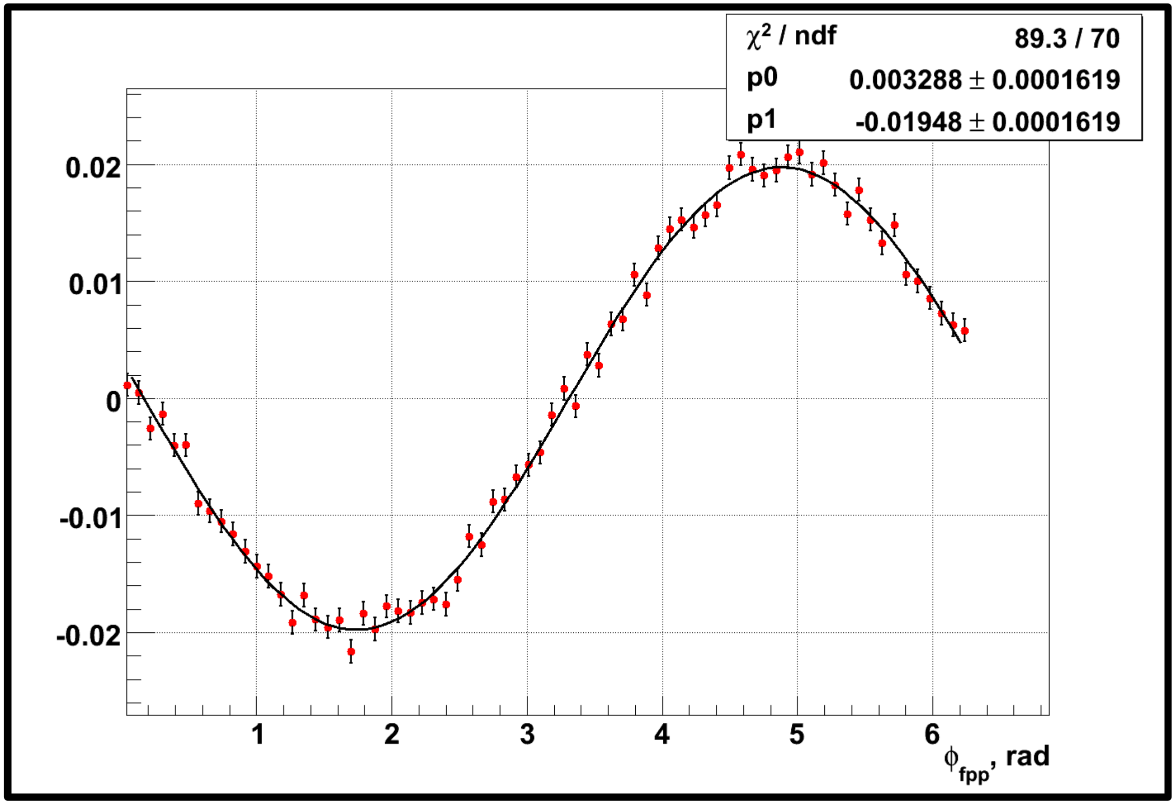
P_t vs. target variables @ 8.5 GeV^2

P_l vs. target variables @ 8.5 GeV^2

$$\mathcal{L}(P_t, P_l) = \prod_{i=1}^{N_p} \frac{1}{2\pi} \left[1 \pm \left(S_{tt(i)} h A_y(\vartheta) P_t + S_{tl(i)} h A_y(\vartheta) P_l\right) \cos\varphi \mp \left(S_{nt(i)} h A_y(\vartheta) P_t + S_{nl(i)} h A_y(\vartheta) P_l\right) \sin\varphi\right]$$

- Physical polarization transfer observables are extracted by maximizing the likelihood function for the parameters P_t, P_l given the observed angular distribution
- If the precession is handled correctly, Pt and Pl should not depend on reconstructed target variables!

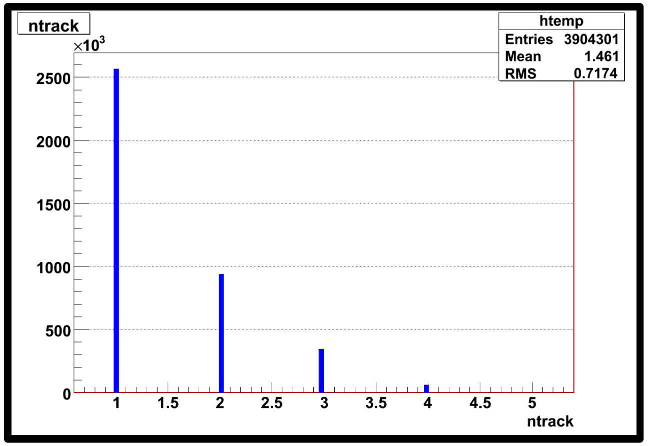
Analysis Issues—Background

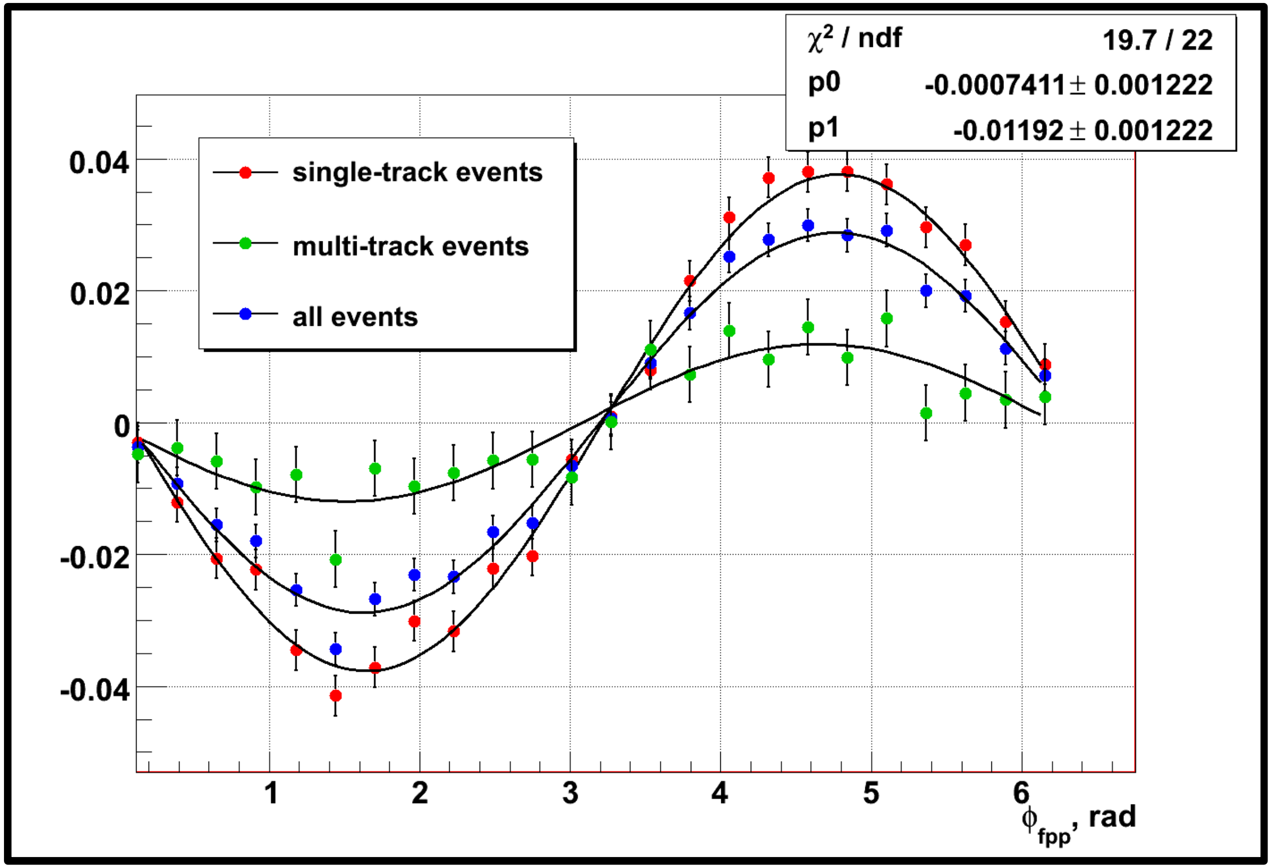


Focal plane asymmetry for rejected events at Q^2=8.5 GeV^2

- With aggressive cuts, we can suppress background to the 1-2% level, and correct the polarization for the background in a single "bin"--approach results in smallest correction, but with lower statistics
- To achieve smallest error bars, would like to open up cuts somewhat and use an unfolding procedure:
    1. accept more elastics+background
    2. bin the data in quantities used to select elastic events
    3. estimate the background fraction in each bin (largest uncertainty)
    4. correct the polarization in each bin for the well-known inelastic polarization (see figure)
- Item 3 requires some knowledge of physics of the background—elastic radiative tail +quasielastic Al(e,e'p)+RCS+π^0

Analysis Issues—FPP multiplicity





- Significant fraction (approaching 40% at 8.5 GeV^2) of events have multiple tracks reconstructed in FPP chambers
- With only six wire planes/chamber there is not much redundancy, unavoidable to mis-identify some tracks
- Size of the asymmetry for multi-track events is <1/3 of the asymmetry for single-track events
- Why such a difference? Reconstruction or physics?

- F.O.M scales as NA_y^2. With 60% one-track events, FOM actually gets worse if A_y(all tracks) < .77 × A_y(one track)
- Presently, slightly better FOM is achieved using only one-track events.
- If we can improve the asymmetry of multi-track events, we can reduce error bars (by ~25% if Ay(multi-track) = Ay(one-track)). Is this possible?

Analysis Issues—Precession

• Precession effects are proportional to γ. Precision of target variable reconstruction is basically independent of HMS central momentum.

• Uncertainties on the ratio P_t/P_l due to precession are thus magnified at high momentum transfers.

• In first approximation, the target polarizations are related to the focal plane polarizations by a simple formula:

$$\left(\frac{P_t}{P_l}\right)_{tgt} \approx -\sin\chi_\theta \frac{P_t^{fpp}}{P_n^{fpp}} - \chi_\phi$$

• The F. F. ratio is especially sensitive to the non-dispersive bend angle

• Table below shows the approximate absolute shift in R for the three high-Q^2 data points induced by a 1 mrad shift in the non-dispersive bend angle

Q^2, GeV^2	p_p, GeV	$\gamma\kappa_p$	$\mu_p \frac{E_e+E'_e}{2M_p}\tan\frac{\theta_e}{2}$	$\Delta R(1 \text{ mrad } \Delta\phi)$
5.2	3.5887	7.09	4.61	0.0327
6.8	4.4644	8.72	4.72	0.0412
8.5	5.4070	10.48	7.03	0.0737

• With dedicated quadrupole misalignment studies—sieve-slit data with a series of deliberate mis-tunings of the HMS quadrupoles—we expect to set an upper systematic error limit on $\Delta\phi$ well below the 1 mrad level

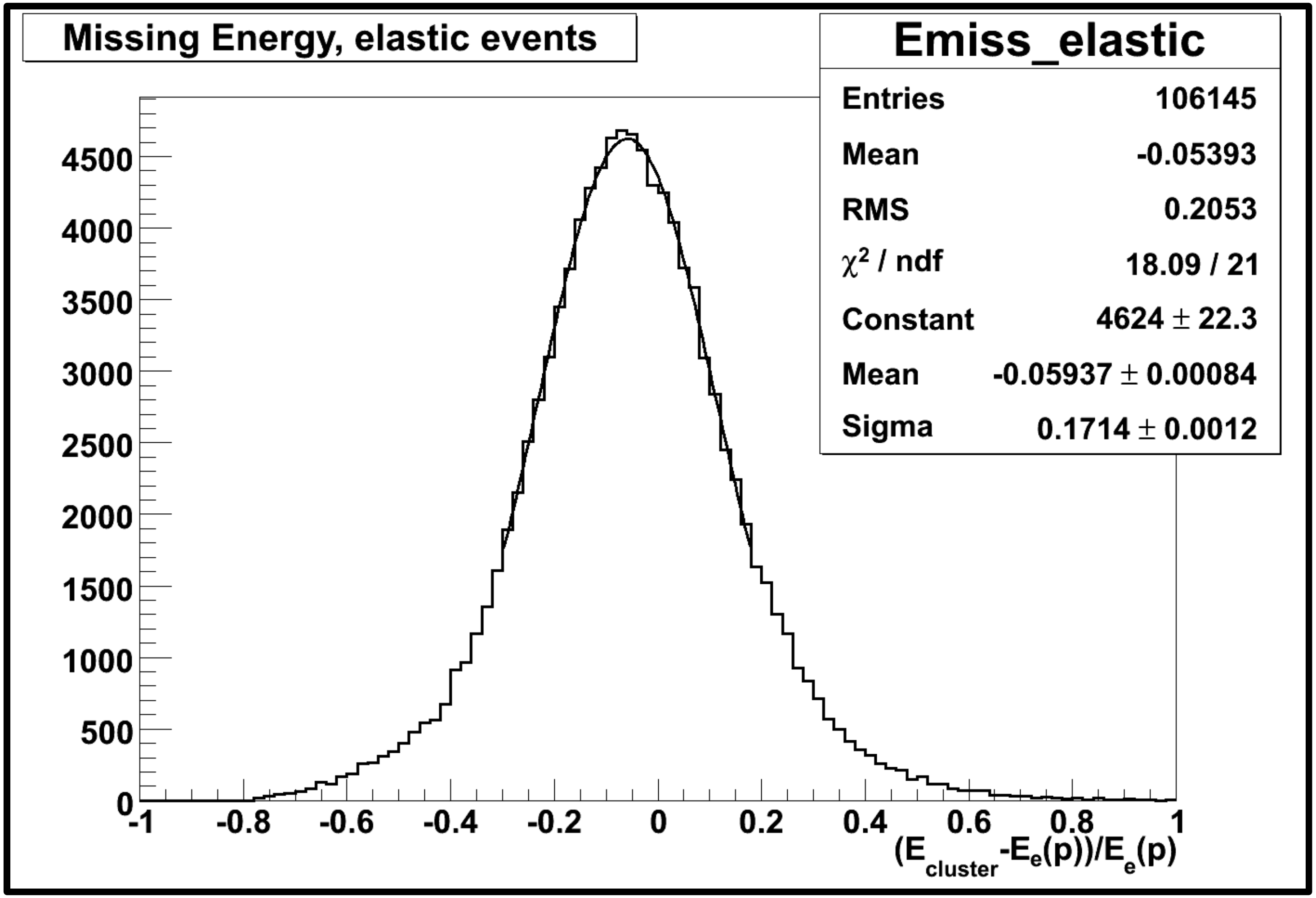
• Note that even the values given in the table are roughly a factor of 2 smaller than anticipated statistical errors.

Conclusion

Q^2, GeV^2	Expected final $\Delta_{stat}\left(\mu_p \frac{G_E^p}{G_M^p}\right)$
5.2	.06
6.8	.11
8.5	.15

- There are no significant obstacles to getting the results out in a timely fashion.
- Major remaining tasks (common to both experiments)
  - Analysis of quadrupole misalignments/precession systematics
  - SIMC study of the inelastic background
  - Further optimize FPP reconstruction+hopefully improve the analyzing power of the multi-track events.
  - Calibrate the analyzing power of the FPP for all kinematics

Backup Slide: BigCal Energy Resolution



BigCal energy resolution is too poor for missing energy to be useful—this is because of rad. damage and 4" Al absorber used to mitigate it. Nonetheless, reaction is still fully determined and coordinate resolution is more than sufficient