Measurement of the Two-Photon Exchange Contribution in ep Elastic Scattering Using Recoil Polarization

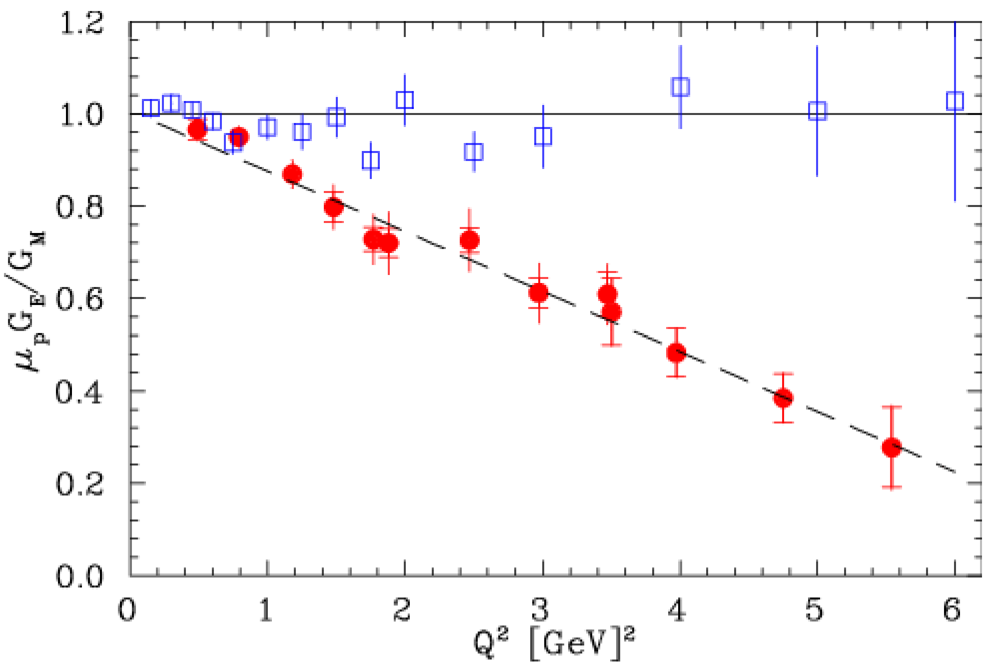
PR04-019

Merger of two experiments, p_y from Riad Suleiman (LOI03-101), and P_l, P_t from Lubomir Pentchev

Gilman, Pentchev, Perdrisat, Suleiman with 41 coauthors from 20 institutions especially: large overlap with G_E^p-III

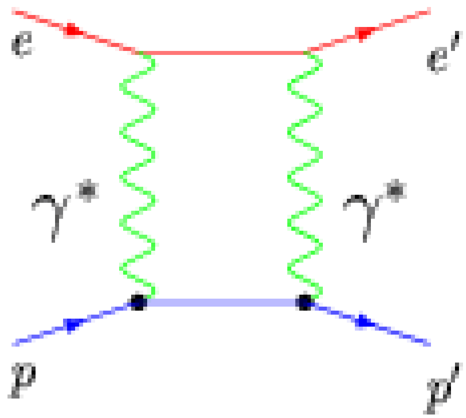
Measure all 3 recoil polarizations, p_y, P_l, P_t at 4 ϵ points for constant Q^2, not just P_t/P_l at one ϵ

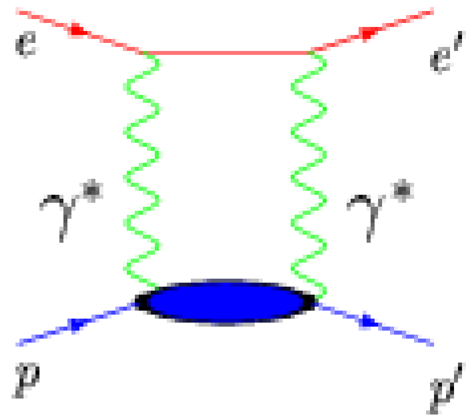
Motivation – The Problem



- Two Jlab and SLAC (Andivahis et al, PRD 50, 5491, 1994) Rosenbluths agree well
- Four Jlab polarization transfer experiments with FPP in Hall A HRS-R and HRS-L agree well (Jones et al., PRL 84, 1398, 2000; Gayou et al., PRC 56, 038202, 2001, Gayou et al, PRL 88, 092301, 2002; Strauch et al, PRL 91, 052301, 2003)

The Likely Solution –
Two-Photon Exchange (TPEX)

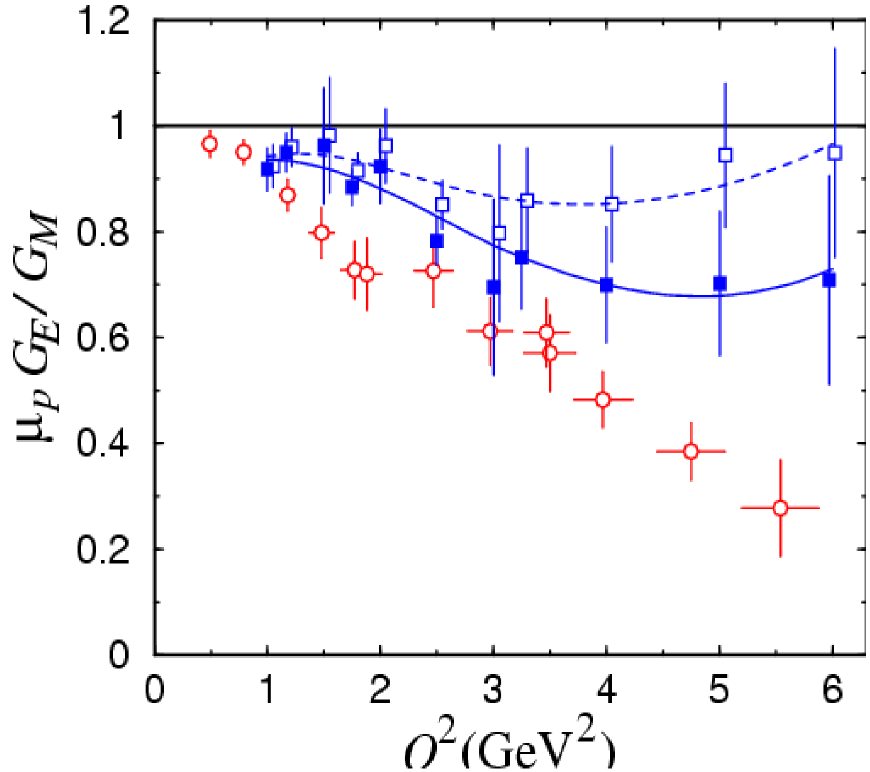




- Intermediate-elastic-state contribution is theoretically certain for imaginary part of amplitude
- Model-dependent intermediate-inelastic-state contribution is theoretically uncertain: data are necessary constraints

TPEX Modifications

- Studies indicate few % TPEX leads to few % correction in polarization transfer, but large correction to Rosenbluth slope, since G_E^p contributes a few % to σ at high Q^2



- Differences in details, but similar overall conclusions from Guichon and Vanderhaeghen, PRL 91, 142303 (2003), Blunden, Melnitchouk, and Tjon, PRL 91, 142304 (2003), Afanasev axial-exchange model (unpublished), and unpublished GPD models by Afanasev, Brodsky, Carlson, Vanderhaeghen

Importance of TPEX

- Demonstrations that TPEX might explain the G_E^p discrepancy are not proofs it does explain the G_E^p discrepancy
- ⇨ we need data that both (1) indicate which models of TPEX are viable, and (2) more cleanly indicate TPEX resolves problem
- Implications beyond the discrepancy include:
  - New combinations of / constraints on GPDs
  - Extractions of strange form factors
  - Similar radiative corrections dominate theoretical uncertainty for understanding meson decays
  - Nucleon (nuclear) radii
  - Nuclear form factors – low-lying inelastic states and softer form factors lead to larger TPEX?

Possible Experiments

- Six independent complex helicity amplitudes in ep → ep
- Neglect 3 amplitudes, which are proportional to m_e and flip electron spin
- Imaginary[OPEX ◆ TPEX] leads to single-spin observables being nonzero: transverse polarized beam asymmetry, or polarized target asymmetry A_y = induced polarization p_y, from time-reversal invariance
- Real[OPEX ◆ TPEX] leads to:
  - Differences between e^+p and e^-p observables
  - P_l, P_t, and σ do not follow OPEX formulas

$$d\sigma_{reduced}(\varepsilon) \propto I_0 \equiv \tau G_M^2 + \varepsilon G_E^2 \qquad \frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{\tau(1+\varepsilon)}}\,\frac{G_E}{G_M}$$

$$I_0 P_l = \tau\sqrt{1-\varepsilon^2}\,G_M^2 \qquad I_0 P_t = -\sqrt{\tau}\sqrt{2\varepsilon(1-\varepsilon)}\,G_E G_M$$

Our Approach

- High Q^2 ⇨ in region of G_E^p discrepancy
- 3 observables at constant Q^2: OPEX constant
- Constrain imaginary part of amplitude with p_y:
  - Compare to 0 / elastic-only calculation and models
  - $Re[F(Q^2, s)] = (1/\pi) \int^{\infty}_{\pi \text{ threshold}} ds' \, Im[F(Q^2, s')]/(s'-s)$ relates $P_t(Q^2, s)$ and $p_y(Q^2, s')$
- Constrain real part of amplitude with P_l, P_t, and with σ:
  - Compare to model calculations
  - Comparison with OPEX / ϵ independence of G_E^p/G_M^p - deviations indicate TPEX but not how much
  - Additional analysis techniques, discussed later - 3 observables determine 3 amplitudes: generalized form factors $G_{E2\gamma}^p$, $G_{M2\gamma}^p$ and pure TPEX piece $Y_{2\gamma}$

The Experiment

- Hall C, 75 μA 80 % polarized beam, polarization determined to ~ 1 % (point-to-point) with Møller
- 15 cm cryogenic LH_2 target
- ep → ep elastic
  - Protons into HMS with FPP, being built for G_E^p-III
  - Electrons into BIGCAL, to reduce background
- Technique proved by Hall A G_E^p-II, approved for Hall C G_E^p-III, E01-109
- Same equipment needs as G_E^p-III, and can save several weeks of installation time by running together ⇨ we request PAC recommendation that these two experiments run together

Kinematics: $Q^2 = 3.2\ GeV^2$

E (GeV)	ε	θ_e (deg)	p_e (GeV/c)	θ_e (deg, cm)	θ_p (deg)	p_p (GeV/c)
2.2624	0.131	105.632	0.5571	145.095	12.538	2.4714
2.8416	0.443	59.704	1.1363	113.477	23.390	2.4714
3.7713	0.696	37.377	2.0661	90.963	30.497	2.4714
4.7003	0.813	27.583	2.9950	78.347	34.134	2.4714

- Q^2 and ϵ matches Hall A E01-001, ``super-Rosenbluth'', which expects ~0.7-0.8 % point-to-point uncertainties for σ (~5 % absolute cross sections)
- Q^2 nearly matches SLAC Andivahis et al. (3.25 GeV^2)

Kinematic Flexibility

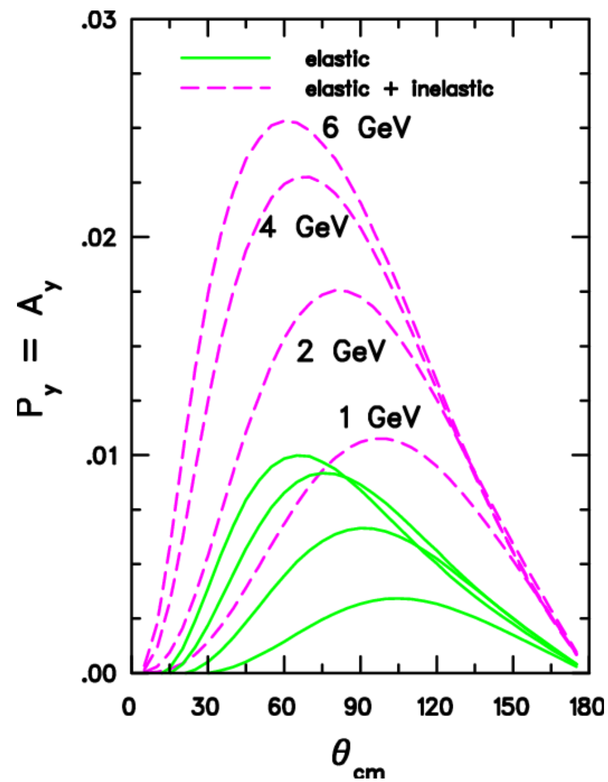
- As long as the ϵ points are close to those of E01-001, we can interpolate between different ϵ, since reduced cross section, P_l, and P_t are all smooth functions of ϵ - $\Delta\epsilon$ of 0.01 ⇨ ~0.1 % change in σ ⇨ want lowest beam energy reproduced to ~ 10 MeV, highest beam energy reproduced to ~ 100 MeV
- If ϵ points are far from those of E01-001, it might be necessary to perform a reduced analysis, using only P_l and P_t
- Measuring good cross sections requires little beam time, but much systematic care – we do not believe we can be competitive with E01-001

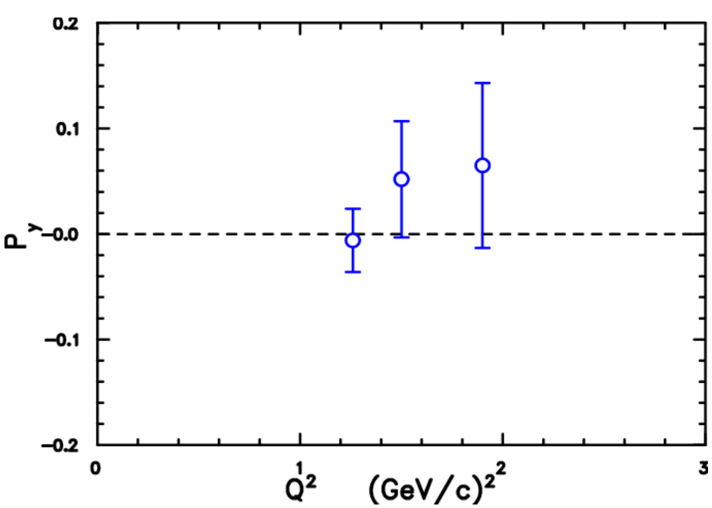
Constant Q^2 and Systematics

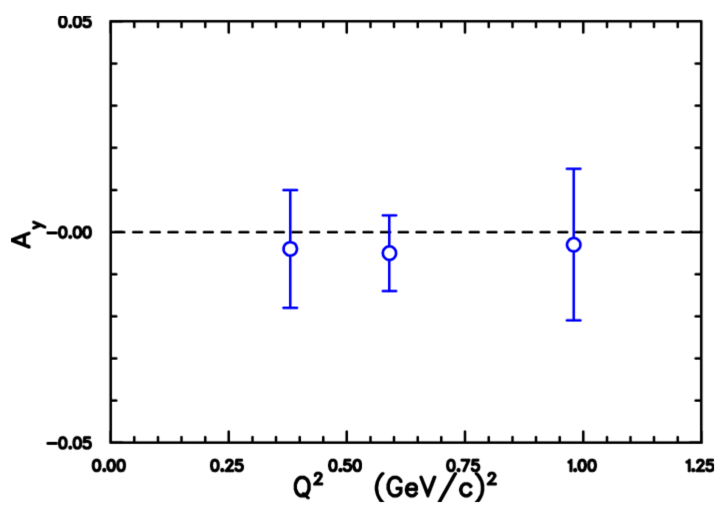
- Point-to-point (p-t-p) systematics are reduced by taking all data at the same proton energy ⇨ constant Q^2
- Insensitive to cross section systematics: Q, $\Delta\Omega$, $x\rho_{target}$, ...
- While absolute polarizations depend on spin transport, polarimeter analyzing power, and false asymmetries (only for p_y), relative (p-t-p) polarizations are insensitive to these systematics, as they are the same for all data points
- Dominant p-t-p uncertainties are statistics, for p_y (~0.004) and P_t (3 %), and beam polarization, for P_l (1 %)
- For the ratio P_t/P_l, beam polarization and analyzing power systematics cancel, statistical uncertainty dominates
- Induced polarization p_y is totally decoupled from transferred polarizations P_t and P_l

Predicted p_y

- Figures: Afanasev, Akusevich, Merenkov, hep-ph/0208260: inelastic ~ elastic contribution; $p_{y\,exp}$ ~ 0.02, $A_{y\,exp}$ ~ -0.01
- Preliminary GPD predictions of p_y from Vanderhaeghen (not shown): inelastic ~ half elastic
- Reminder (e.g. beam asymmetries): in-elastic theoretically uncertain

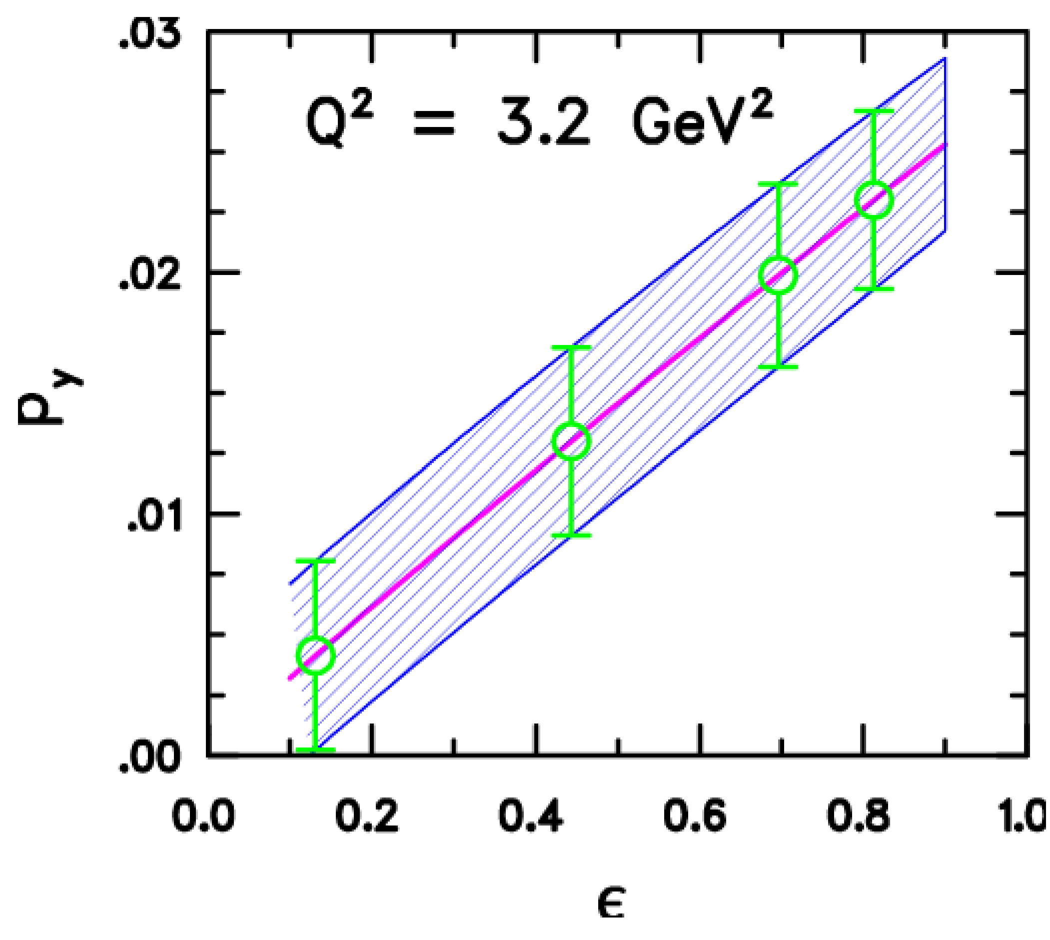






Expected Results for p_y

- Central values based on Afanasev, Akusevich, Merenkov, hep-ph/0208260
- Statistical uncertainties assume 4 days of data for each point, 75 μA, εA^2 from G_E^p-I
- Highest ϵ point 6σ (statistical) from 0
- Dominant systematic uncertainty: false asymmetry, measured with same size as statistical uncertainty, several times



Four False Asymmetry Tests

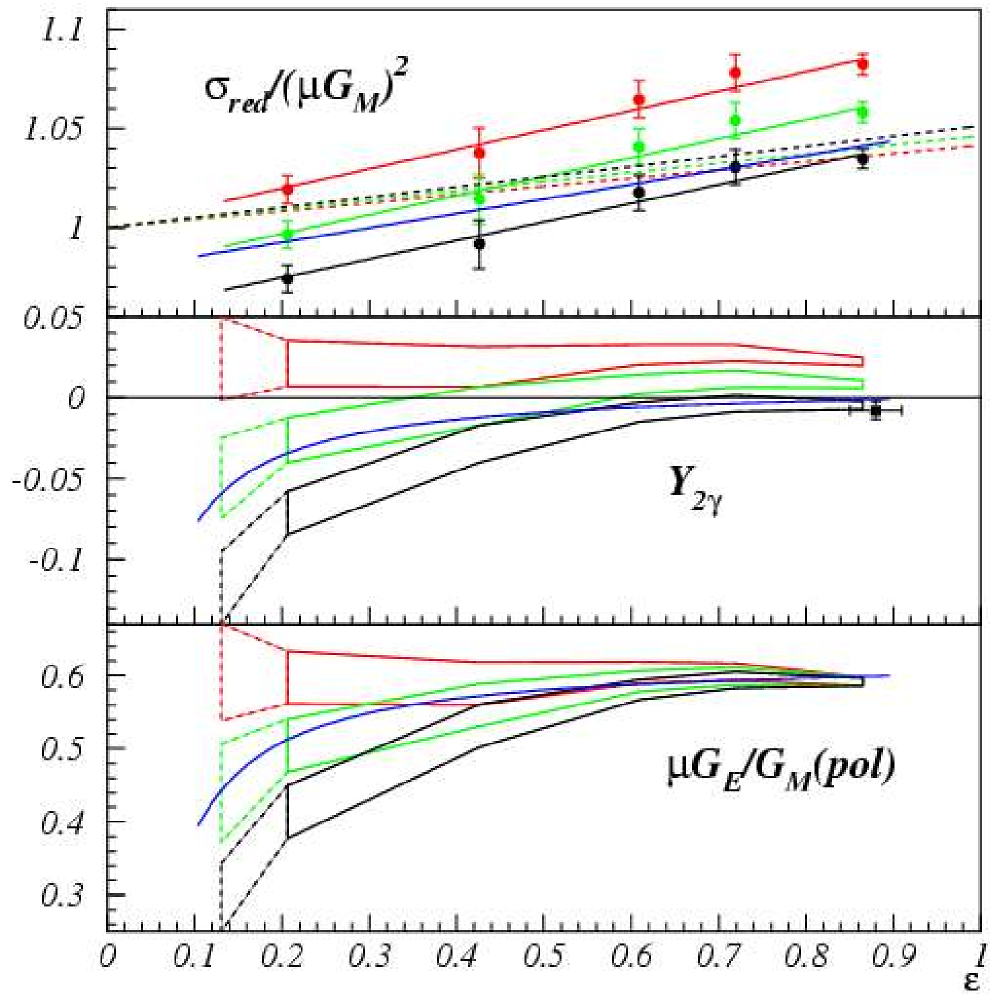
- All measurements are at the same Q^2 / proton energy, so false asymmetries (A_F) are identical in leading order
- (1) For lowest ϵ point, $p_y \sim 0$, ``measure'' A_F
- (2) Request 4 days at $Q^2 = 1.775$ GeV^2, $\chi_{central} = 90°$, and induced polarization rotates away
- (3) Request 3 days for 3 tests with p(e,e'π)X: spin-0 pions, check A_F(time)
- (4) Dual FPP system ⇨ we measure the same p_y in two systems with different A_F ⇨ consistency check
- (5) PAC suggested beam left vs. beam right test, but it is not feasible – needs a Hall A vs. Hall C comparison
- Several reasons to be optimistic about small false asymmetries in new Hall C FPP, but it is not built yet

Polarization Transfers (and Cross Section)

- The OPEX formulas with two form factor are modified:
  - $G_{M,E2\gamma}(Q^2,\epsilon) = G_{M,E1\gamma}(Q^2) + \Delta G_{M,E2\gamma}(Q^2,\epsilon)$
  - $R_{2\gamma}(Q^2,\epsilon) = R_{1\gamma}(Q^2) + \Delta R_{2\gamma}(Q^2,\epsilon)$
  - $Y_{2\gamma}(Q^2,\epsilon)$ is a new term arising solely from TPEX
- Observables are:
  - $d\sigma_{red}/G_{M2\gamma}{}^2 = 1 + (\epsilon/\tau)R_{2\gamma}{}^2 + 2\epsilon\left(1+R_{2\gamma}/\tau\right)Y_{2\gamma}$
  - $P_t\, d\sigma_{red}/G_{M2\gamma}{}^2 = -[2\epsilon(1-\epsilon)/\tau]^{1/2}\{R_{2\gamma} + Y_{2\gamma}\}$
  - $P_l\, d\sigma_{red}/G_{M2\gamma}{}^2 = [(1+\epsilon)(1-\epsilon)]^{1/2}\{1 + [2\epsilon/(1+\epsilon)]Y_{2\gamma}\}$
  - $P_t/P_l = -[2\epsilon/(1+\epsilon)\tau]^{1/2}\{R_{2\gamma} + Y_{2\gamma}\}/\{1 + [2\epsilon/(1+\epsilon)]Y_{2\gamma}\}$
- Theory poorly constrained by existing data ⇨
  - 1) We make rough estimate using simplifying assumptions
  - 2) Examples of the analyzes that can be done will follow

Simple Analysis of Existing Data

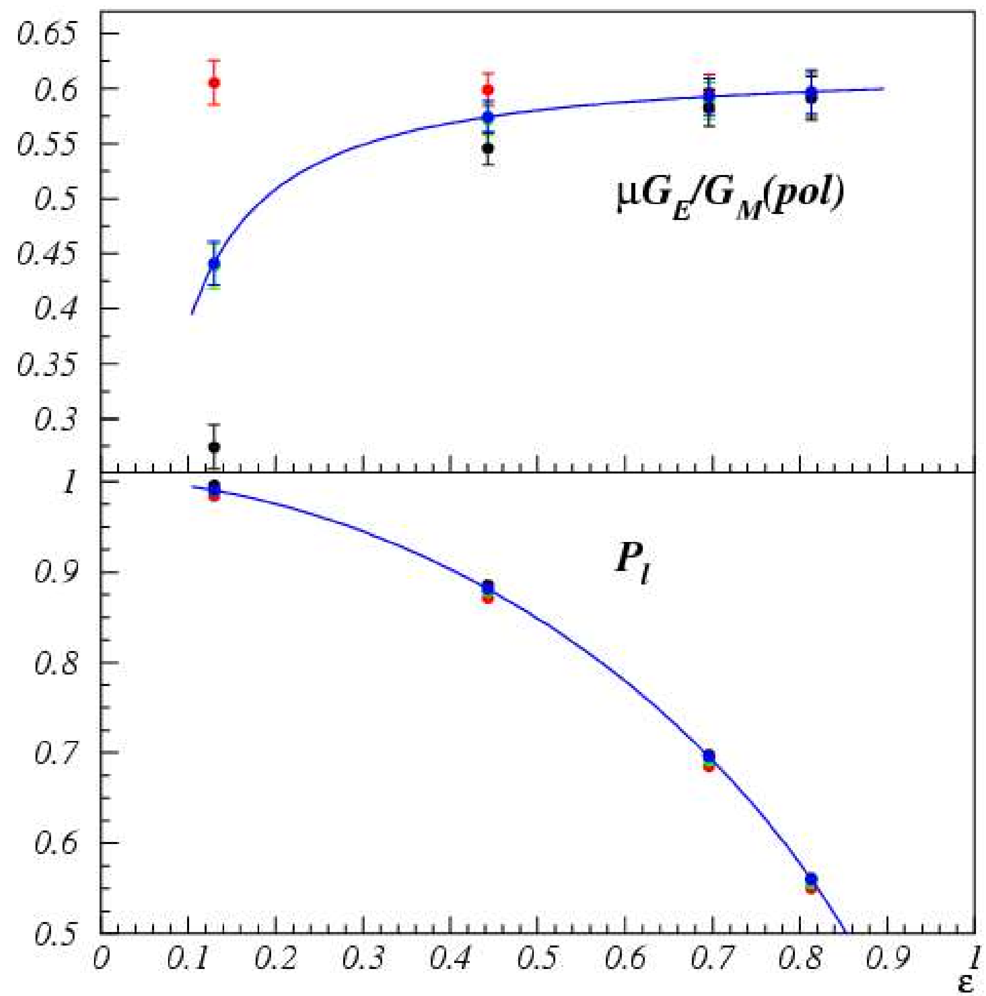
- Use $R_{1\gamma}$, $G_{M1\gamma}$, but $Y_{2\gamma}$
- Analyze SLAC Andivahis data + Hall A polarization transfer ratio for 3 different choices of $G_{M1\gamma}$
- Linearity of Rosenbluth
  ⇨ $\epsilon Y_{2\gamma} \sim a + b\epsilon$ ⇨ $Y_{2\gamma} \sim b + a/\epsilon$
- e^+/e^- ratio at ϵ=0.88 favors $Y_{2\gamma}<0$
- TPEX can be large despite linearity of σ



- Analysis, BMT (blue line) suggest significant sensitivity, TPEX effects (for real part of interference) at low ϵ

TPEX Analysis - Projected Uncertainty at Q^2=3.2 GeV^2

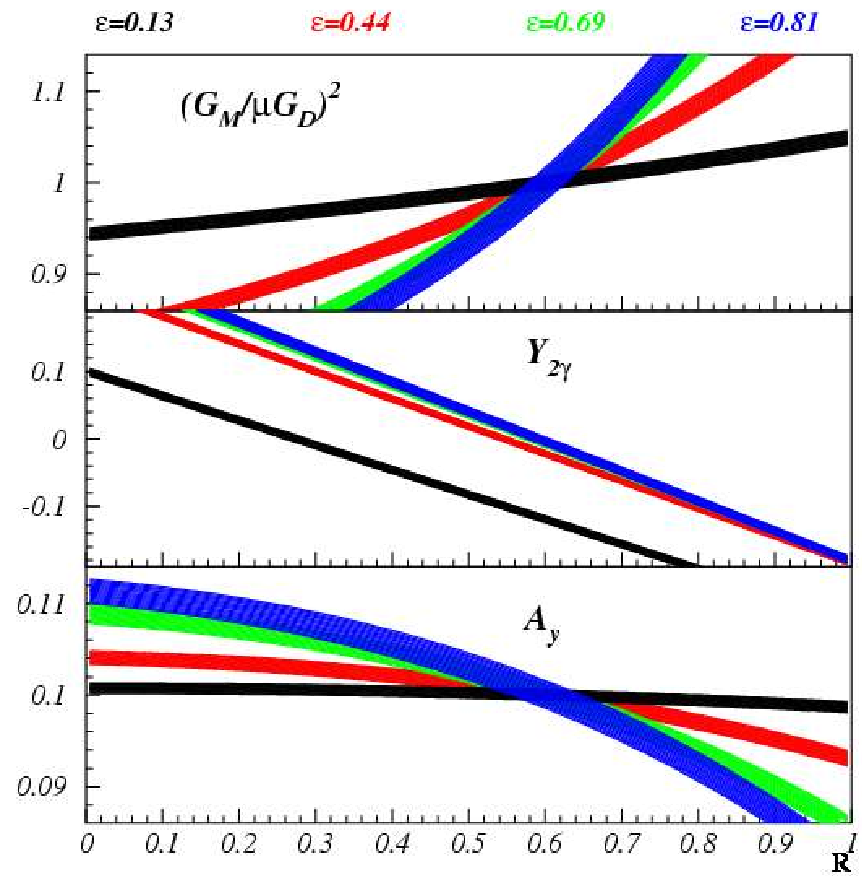
- Analyzes with 3 values of $G_{M1\gamma}$ of existing data used to determine TPEX; OPEX + TPEX formula used to calculate observed P_t/P_l; R_{expt} extracted with OPEX formulas; great sensitivity to TPEX contribution



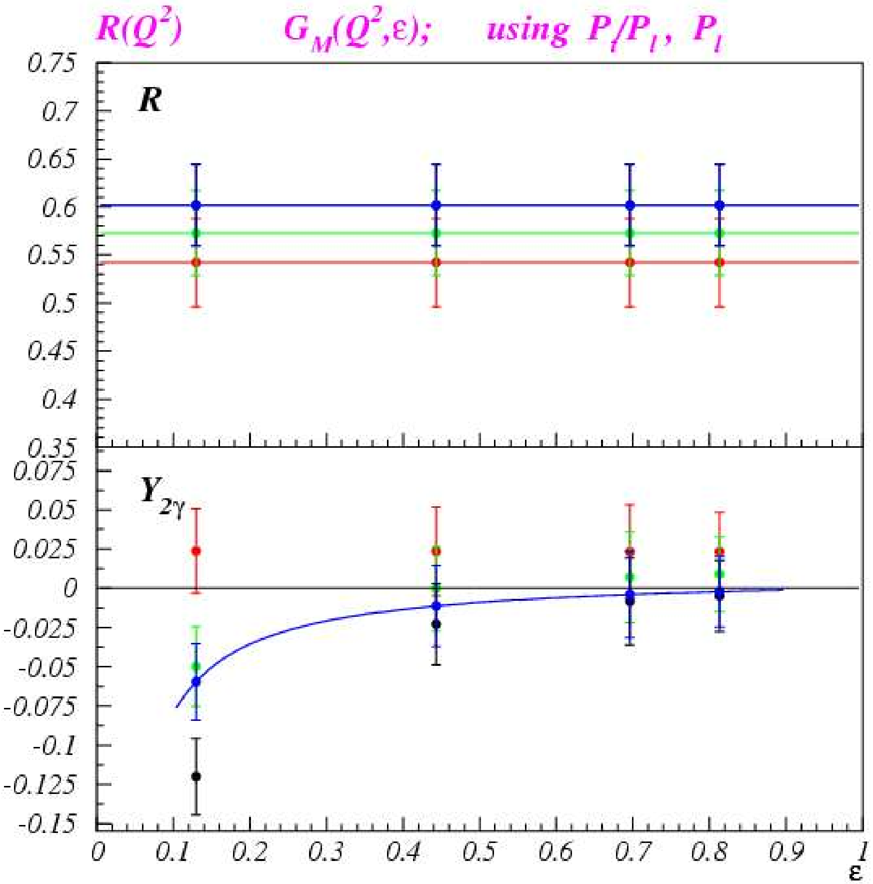
- P_l is insensitive to TPEX ⇨ P_t sensitive to the different choices for $G_{M1\gamma}$
- Uncertainty does not depend on choice of $G_{M1\gamma}$

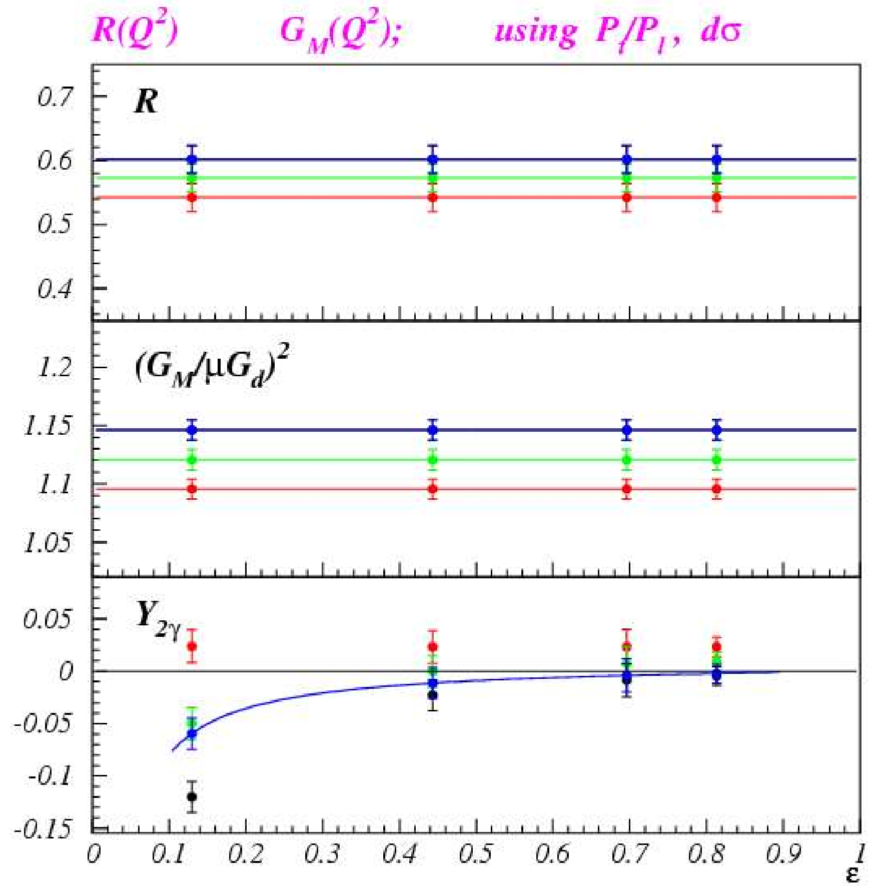
Model-Independent Analysis Example

- Measurements of P_t, P_l, and σ determine curves for $G_M(\epsilon,R)$, $Y_{2\gamma}(\epsilon,R)$, and $A_{FPP}(\epsilon,R)$; width of curves reflects experimental uncertainties
- Assuming R does not depend on ϵ, $Y_{2\gamma}(Q^2, \epsilon)$, $R(Q^2)$, and A_{FPP} are 6 quantities, which can be determined from:
  - our 4 P_t/P_l + 4 P_l data points (no σ's involved!), or
  - our 4 P_t/P_l + the corresponding 4 σ's at the same Q^2, ϵ
  - The two methods provide a consistency check



Projected Analysis Results

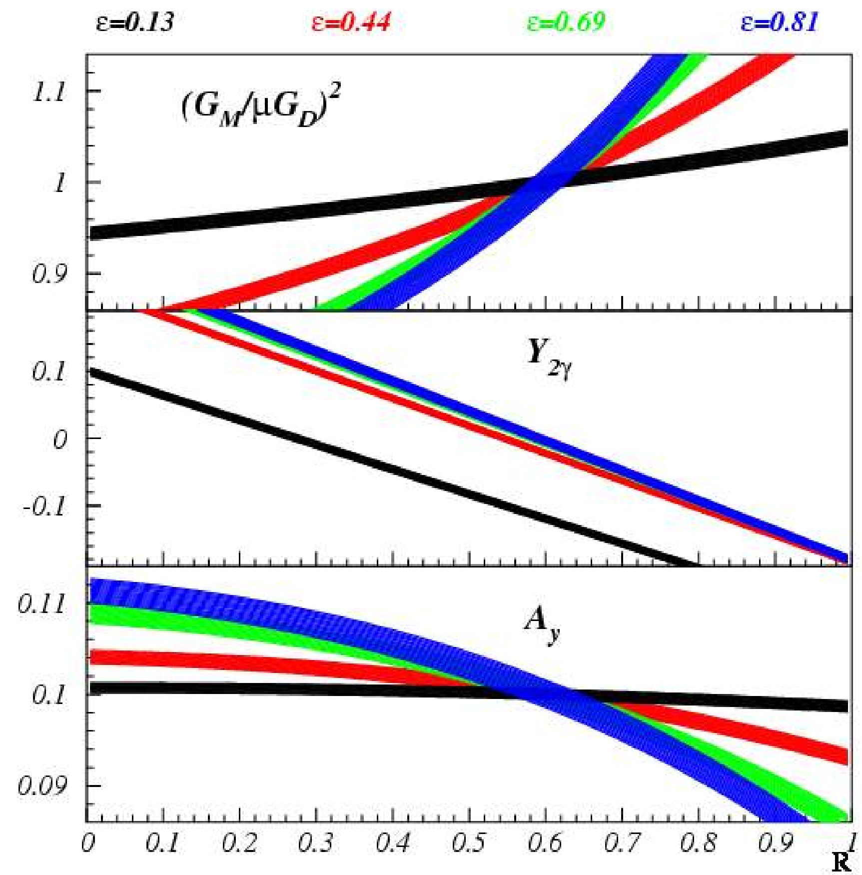




- Left: expected results for analysis using P_t/P_l and P_l has better systematic uncertainty
- Right: expected results for analysis using P_t/P_l and σ has better statistical uncertainty

Testing ϵ Independence of R and G_M

- Constraints on ΔR, ΔG_M
  $R(Q^2,\epsilon) = R(Q^2) + \Delta R(Q^2,\epsilon)$
  $G_M(Q^2,\epsilon) = G_M(Q^2) + \Delta G_M(Q^2,\epsilon)$
- The level at which the $A_y(\epsilon,R)$ curves intersect at a common point sets a limit on the ϵ dependence of $R(\epsilon)$; similarly for the $G_M(\epsilon,R)$ curves



- The consistency of the two intersection points further checks the ϵ dependences
- If both R and G_M depend on ϵ, then at one ϵ point A_{FPP} is determined, and we determine $Y_{2\gamma}$, R, and G_M for the other 3 points – 9 observables determine 9 unknowns

Time Estimate

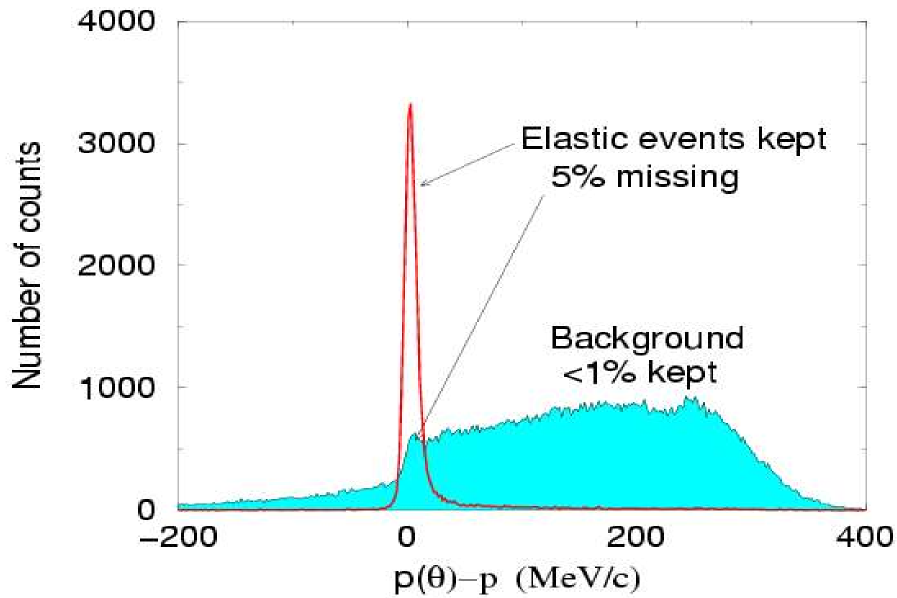
- 18 days for 4 ϵ points, each needs:
  - 4 days beam time
  - $\frac{1}{2}$ day for calorimeter move + Møller measurements
- 4 days for $Q^2 = 1.775$ GeV^2 false asymmetry determination
- 3 days for 3 $(e,e'\pi)$ false asymmetry determinations
- TOTAL TIME: 25 days

Summary / Conclusion

- Like other proposals, we will constrain models of TPEX, but 3 observables constrain real and imaginary parts
- We also go further with model-independent constraints of TPEX – Y, R, and G_M – using existing cross sections
- Estimated effects of TPEX are several times experimental uncertainties, but are highly uncertain
- The ε dependence at constant Q^2, 3.2 GeV^2, is firmly in the region of the G_E^p discrepancy – it is likely we can make a major advance in settling origin of discrepancy
- We request 25 days; we use proved techniques, existing equipment, and minimal overhead (save several weeks of installation, ... time) if run together with G_E^p-III

Background for PAC: Hall C TAC Report Response

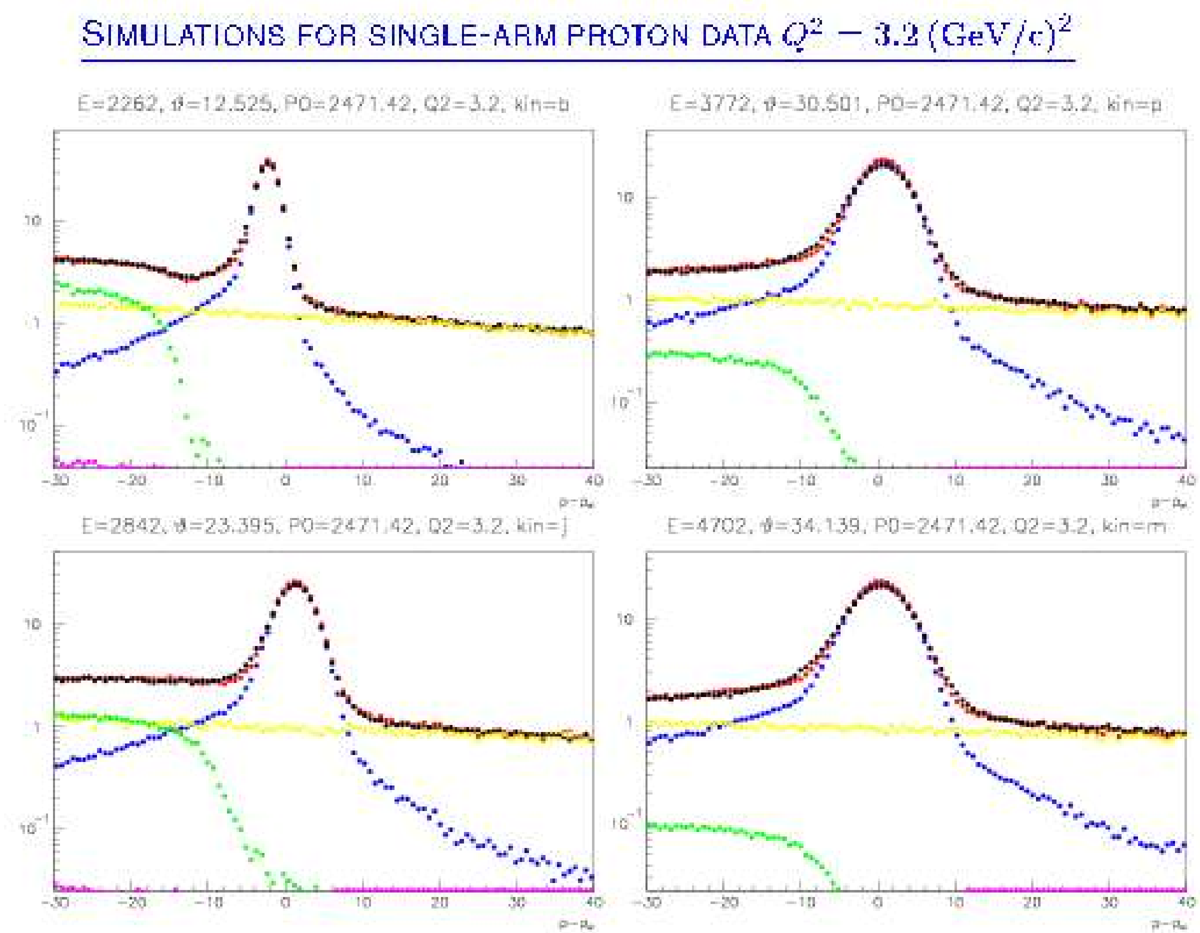
- 1) h=75 % ⇨ +2 days or +10 % uncertainty
- 2) Kinematics are flexible, esp. at high ϵ
- 3) Same as G_E^p-III, 2-3 months installation + removal



- 4) Total calorimeter rates are high, but only tens of kHz once a high energy cut is applied; G_E^p-II operated successfully at Q^2=3.5 GeV^2, E_e=4.6 GeV, θ_e=32°, similar to our most forward point: Q^2=3.2 GeV^2, E_e=4.7 GeV, θ_e=28°
- 5) Backgrounds are at the level of several percent, and will be reduced to negligible - the 5.6 GeV^2 spectrum of G_E^p-II, which had the most background, is shown

Background for PAC: Hall C TAC Report Response

- Spectra from Hall A super-Rosenbluth
- Biggest back-ground: dummy target (target cell walls), at the level of several percent, and nearly ϵ independent
- Role of calorimeter is to remove this background



Hydrogen data (black)

Dummy cell data (yellow)

Sum of all three simulations = Elastic + π^0 production + Compton

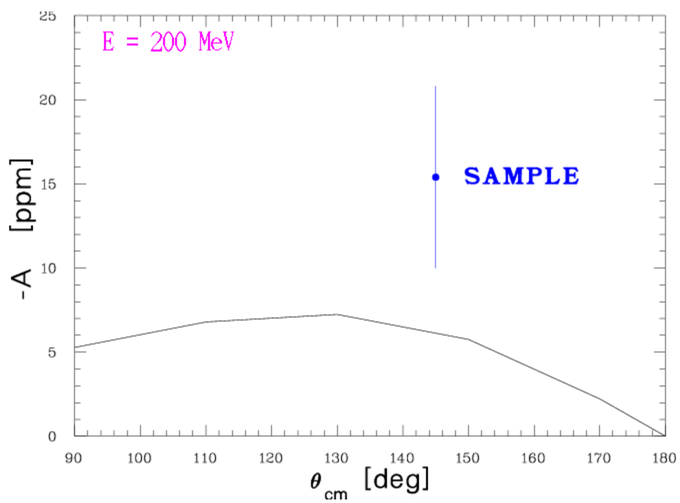
Background for PAC: Hall C TAC Report Response (cont.)

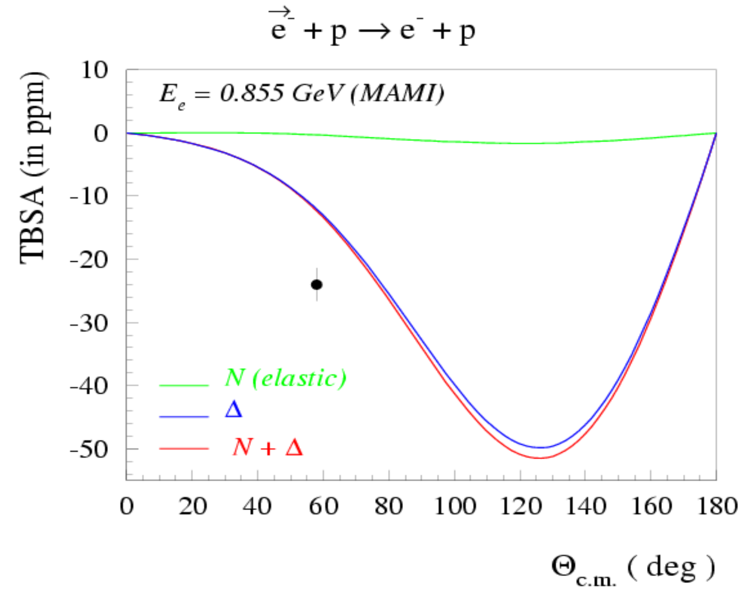
- 6) Cell wall backgrounds are a few percent, partially cut out by y-target cuts, and reduced to negligible by the spread of the QF peak and the conjugate angle-energy requirement in the calorimeter
- 7) We were too restrictive in the proposal - we can use the full X(e,e'π^+)X' reaction – the coincidence is used to help ensure a clean sample of spin-0 pions with coincidence TOF; it makes no difference what reaction produces the π^+

Background for PAC: Theory Review Response

- We agree; we also consider this proposal to be ``a well-thought-out attempt to resolve the E/M form factor puzzle, and to study the physics of two-photon exchange.''

Proof of Two-Photon Exchange

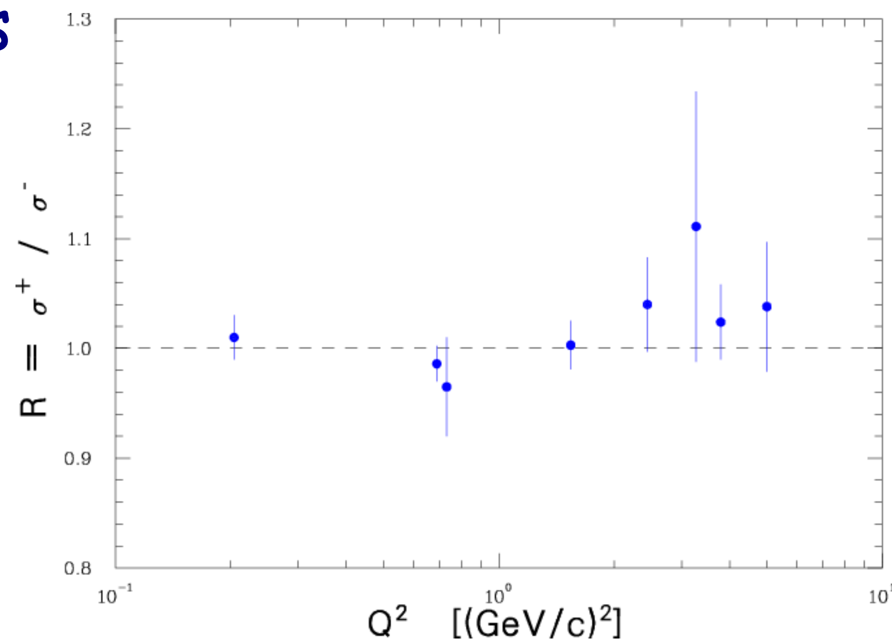




- SAMPLE transverse-polarized beam asymmetry (Wells et al, PRC 63, 064001, 2001) ~ 2.5 x elastic calculation (Afanasev, Akusevich, Merenkov, hep-ph/0208260)
- Preliminary Mainz A4 beam asymmetry ~50 % explained by intermediate Δ state (Vanderhaeghen et al.)
- Inelastic strength uncertain and possibly large

Background for PAC: e+/e- ratio

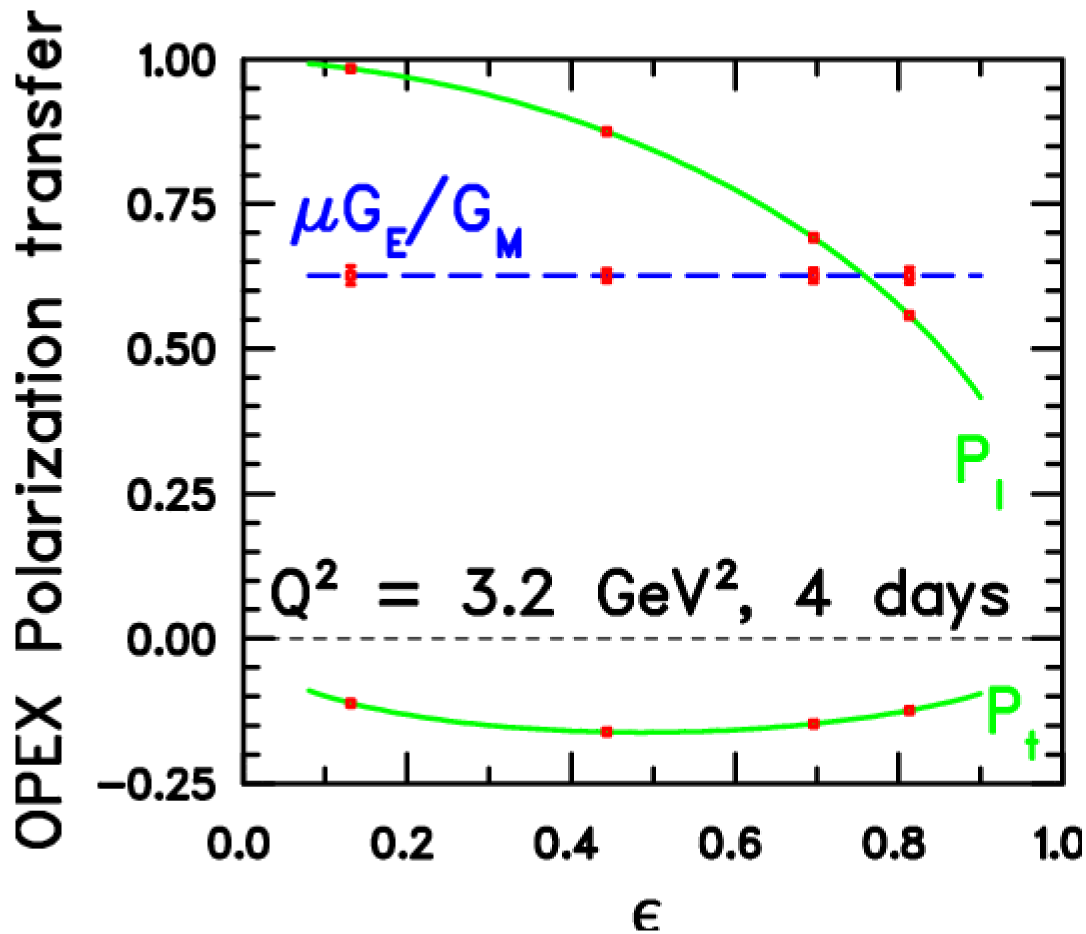
- e^+/e^- cross section ratio $=$ (OPEX+TPEX)/(OPEX-TPEX), the same real part of TPEX as appears in the radiative corrections
- Data shown only from Mar et al., PRL 21, 482 (1968); suggest TPEX increases (decreases) the e^+ (e^-) cross section a few percent, at high ϵ



- Need to measure in Rosenbluth kinematics for model-independent determination of $\delta_{2\gamma}$ - total 2γ effect, including changes from OPEX form factors to generalized form factors - no such proposals at this time, prospects unclear

Background for PAC: Polarization Transfer in OPEX

- Shown: projected data, uncertainties, vs. OPEX
- P_l insensitive to R
- R depends mostly on P_t, which is insensitive to spin-transport
- Polarization transfers are independent of p_y: helicity difference data vs helicity sum data
- Important uncertainties are point-to-point ones:
  - Dominant P_l p-t-p uncertainty: beam polarization, 1 %
  - Dominant P_t and R p-t-p uncertainties: statistics, ~3 %



Background for PAC: ed Elastic Scattering and TPEX

- ed elastic scattering is potentially attractive for studies of TPEX
  - Low inelastic threshold and faster form factor fall off likely make TPEX relatively larger than in ep
  - Sensitive to en + ep TPEX
  - ed much studied, but no real Rosenbluth measure-ments or tests even at moderate Q^2, so TPEX largely unconstrained experimentally
  - But no direct impact on ep issues, so not proposed at this time – plan to return to this topic later
- Similar experimental and theoretical issues for induced and transferred polarizations for ed and ep
- Polarization transfer ratio P_t/P_l measures combination of form factors $(G_C + 1/3\ \eta G_Q)/G_M$