The Recoil Polarization Experiments at Jefferson Lab

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Introduction

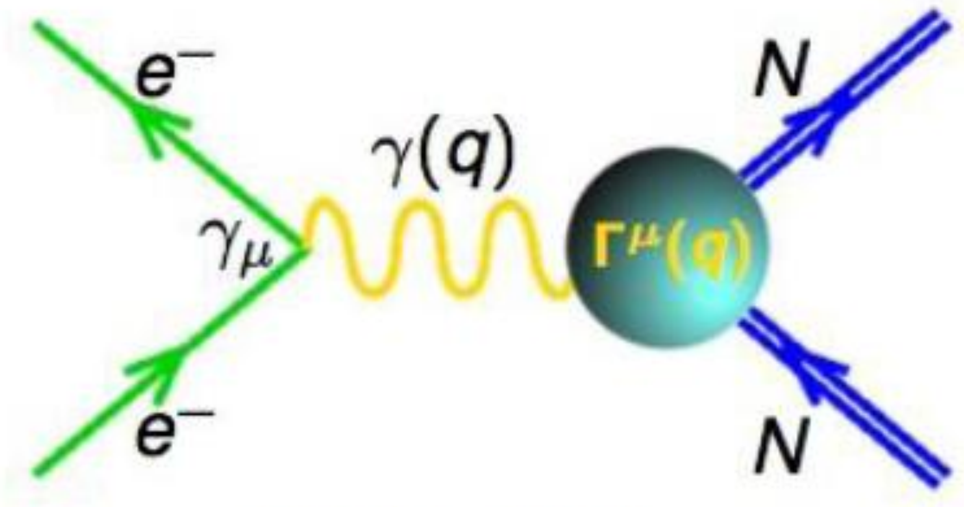
This talk limited to the use of the recoil polarization technique
to obtain the **ratio** of the Electric and Magnetic form factors, G_{Ep}/G_{Mp}.

The first suggestion that double polarization would be a better way
to obtain nucleon form factors in elastic **ep** goes back to a paper by Akhiezer
and Rekalo (1968). Several possible double-polarization experiments:

Pol. electron on unpol. p(n), measure p(n) polarization
Pol. electron on pol. p(n) measure angular asymmetry of p(n)
unpol. electron on pol. p, measure p polarization (never done, see Kuraev).

This talk limited to proton and large Q^2 range, 0.5 to 8.5 GeV^2, and
future beyond.

Elastic Electron-Nucleon Scattering



(Born Term)

$$\Gamma^\mu = F_1(q^2)\gamma^\mu + F_2(q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}$$

$$Q^2 = -q^2 > 0$$

$$\tau \equiv \frac{Q^2}{4M^2}$$

One-photon exchange (OPEX) for elastic *eN* scattering in QED.

- Form factors:
- F_1 (Dirac): electric charge and Dirac magnetic moment
- F_2 (Pauli): anomalous magnetic moment

Sachs versus Dirac and Pauli form factors

The Sachs form factors G_E (electric) and G_M (magnetic) are more convenient experimentally. The two sets of form factors are connected by linear relations:

$$G_E = F_1 - \tau F_2, \qquad G_M = F_1 + F_2$$

or in the opposite direction, as we actually measure G_E and G_M:

$$F_1 = (G_E + \tau G_M)/(1 + \tau), \qquad F_2 = (G_M - G_E)/(1 + \tau)$$

Hence, F_2/F_1 can be obtained directly from measured G_E/G_M ratio:

$$\frac{F_2}{F_1} = \frac{1 - G_E/G_M}{\tau + G_E/G_M}$$

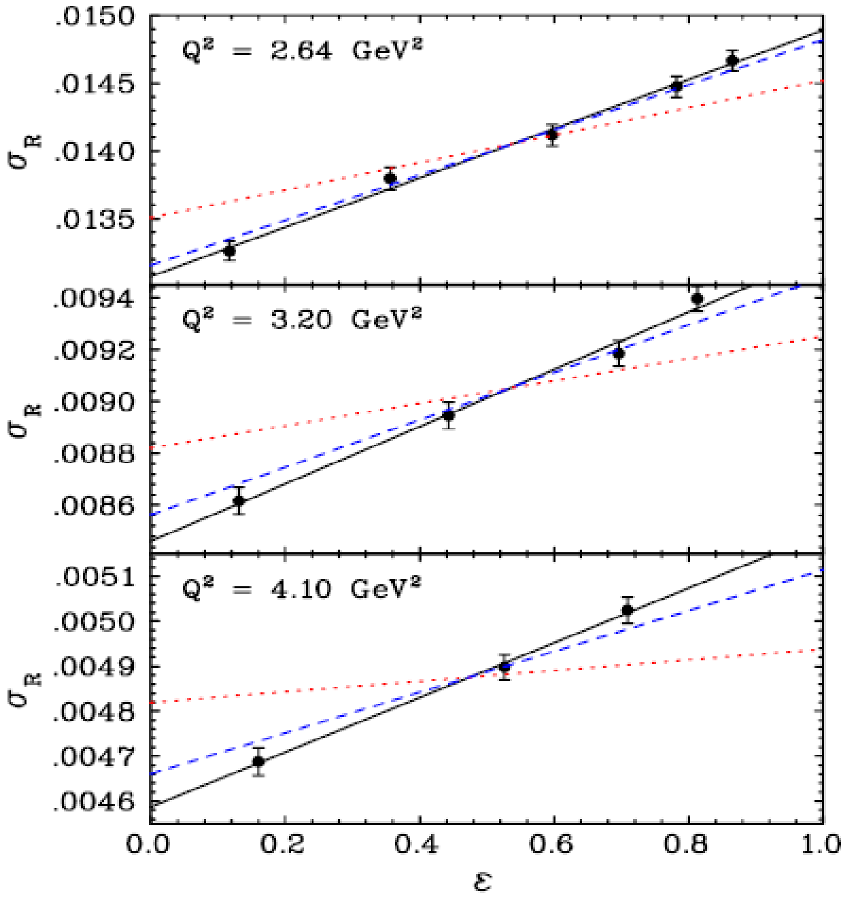
Rosenbluth Separation Method

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}$$

Qattan et al.,PRL 94, 142301 (2005)

$$\epsilon \equiv \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

$$\sigma_R \equiv \epsilon(1+\tau)\frac{\sigma}{\sigma_{Mott}} = \epsilon G_E^2 + \tau G_M^2$$

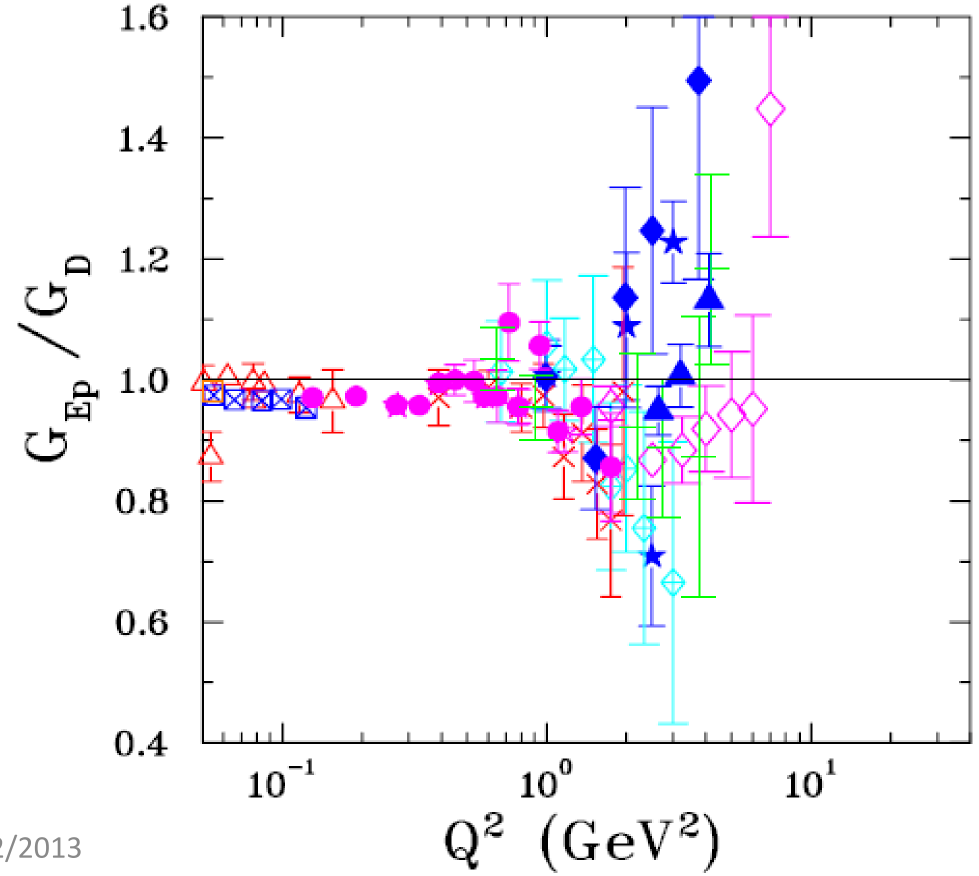


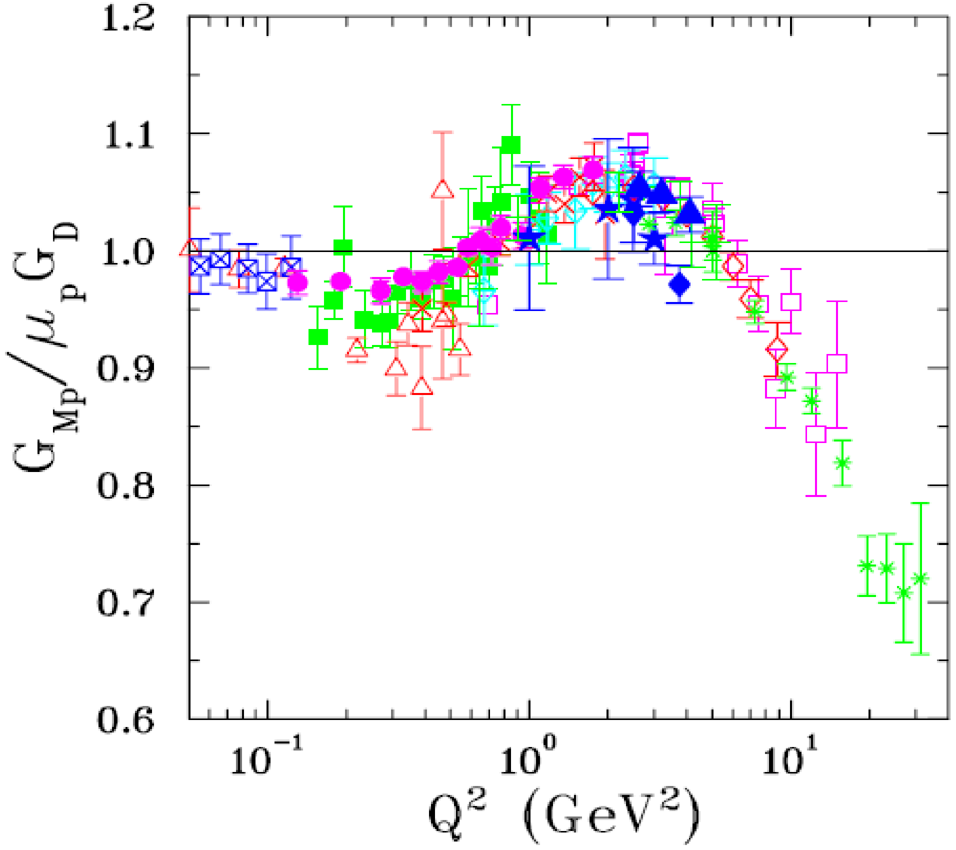
- Measure angular dependence of cross section at fixed Q^2

- In OPEX ε-dependence of "reduced" cross section σ_R is linear, with slope G_E^2 and intercept τG_M^2.

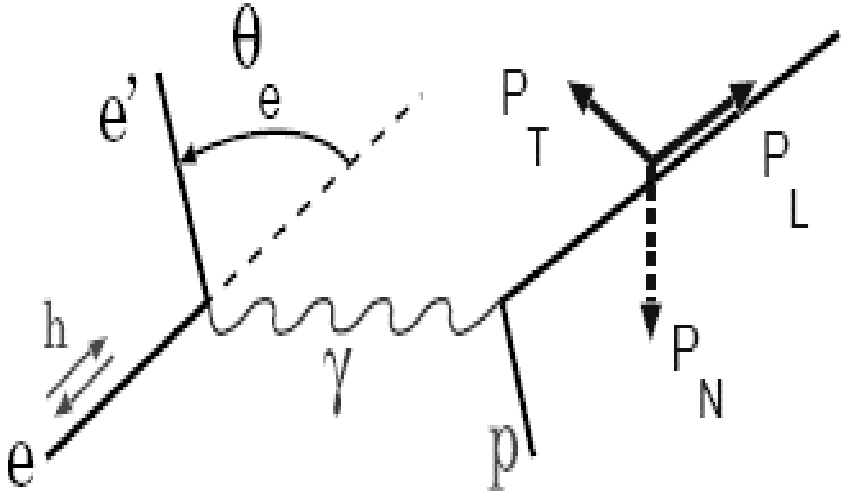
all Rosenbluth separation data for the proton Form Factors

The results from all published Rosenbluth separation data for G_{Ep} and G_{Mp}.
The “scaling” apparent after dividing by the dipole FF, $G_D=(1+Q^2/0.71)^{-2}$.





Polarization Transfer Method



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

$$P_t = -hP_e\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{r}{1+\frac{\epsilon}{\tau}r^2}$$

$$P_\ell = hP_e\frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau}r^2}$$

$$\boxed{r = \frac{G_E}{G_M}}$$

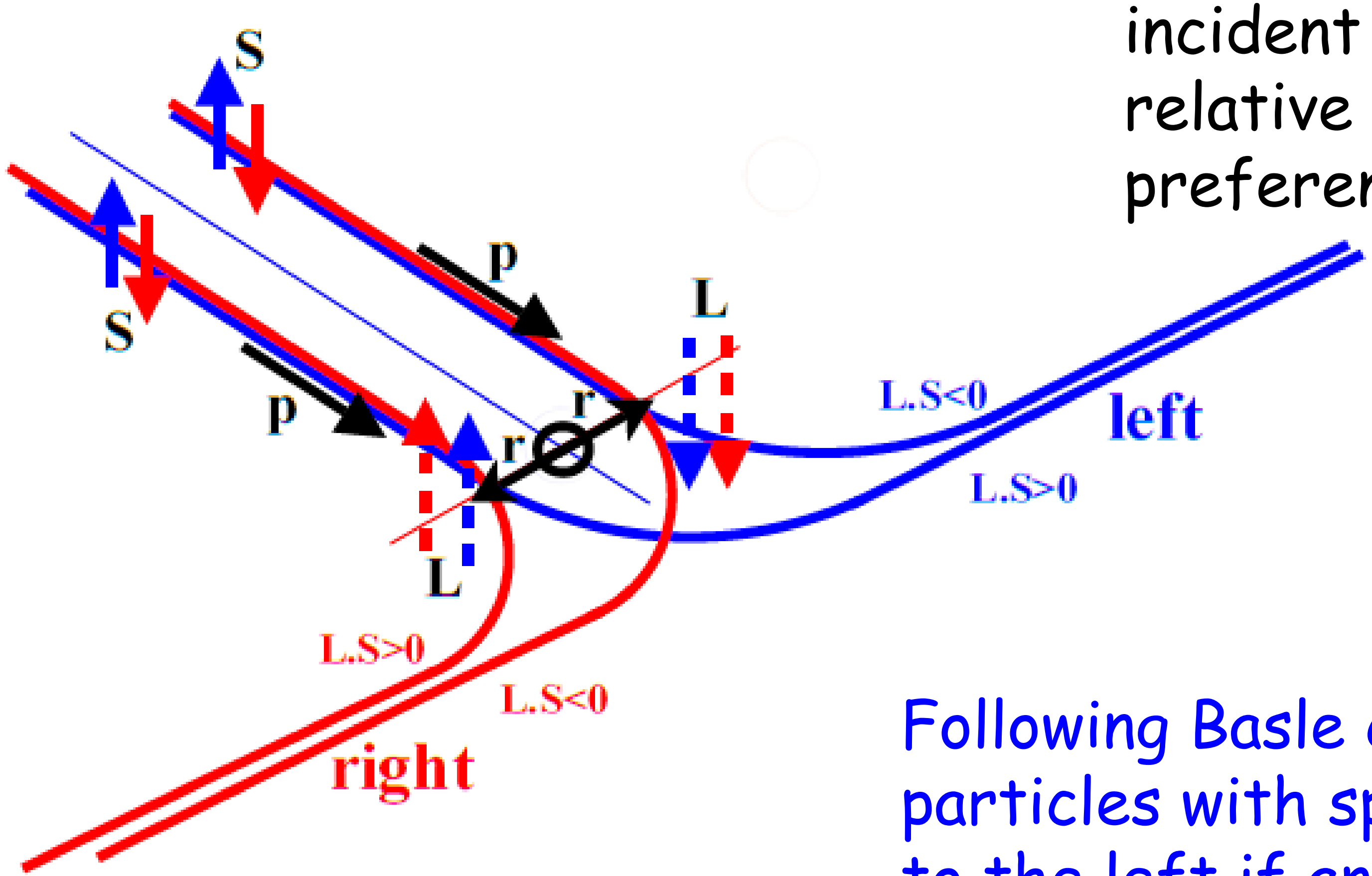
$$P_n = 0$$

$$R = \mu\frac{G_E}{G_M} = -\mu\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}$$

***h* beam helicity, P_e beam polarization**

Pioneering theoretical work by: Akhiezer, Rosentweig, Shmushkevich (1958), Akhiezer, Rekalo (1968, 1974), Dombey (1969), Arnold, Carlson, Gross (1981).

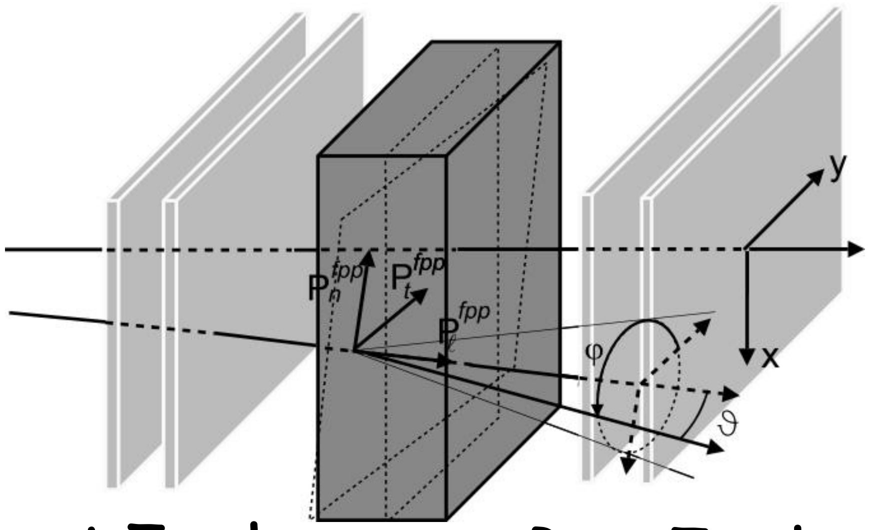
Principle of Polarimetry

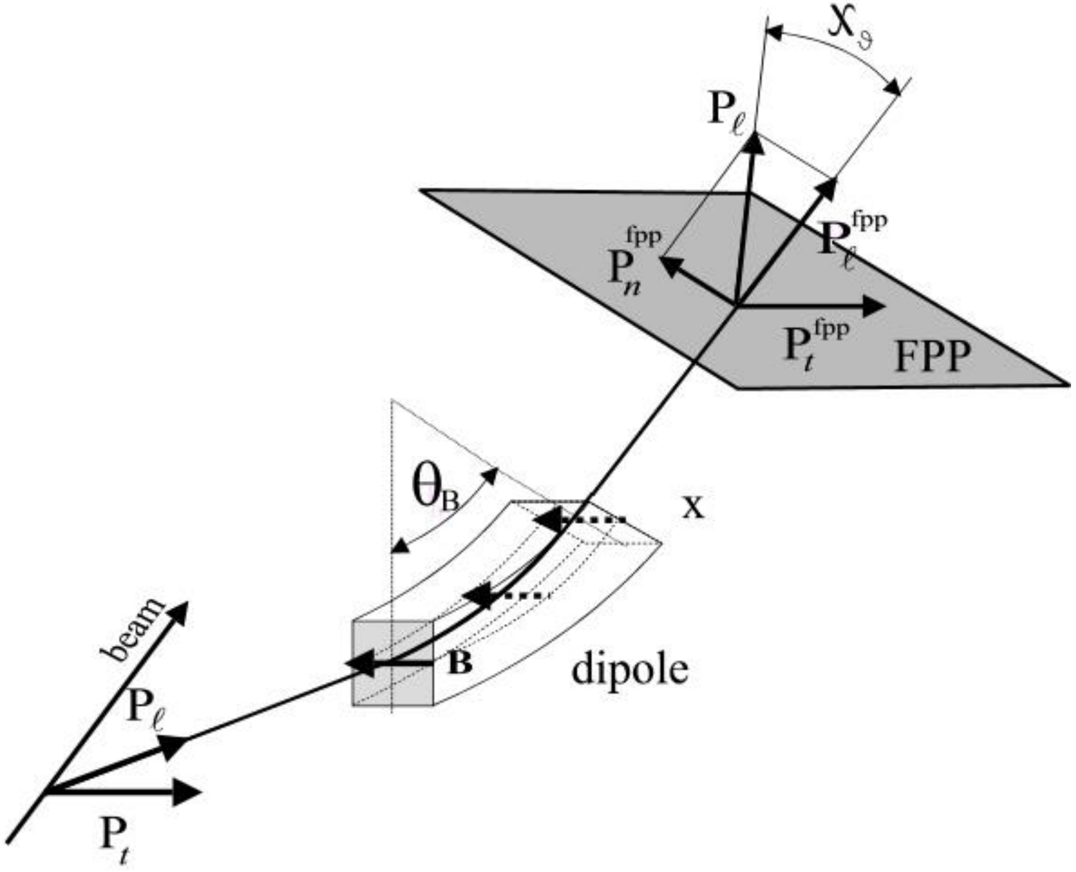


Due to **L.S** coupling in NN interaction, incident particle with spin up or spin down relative to scattering plane scatters preferentially left, respectively right

Following Basle convention (1960), spin-$\frac{1}{2}$ particles with spin up scatters preferentially to the left if analyzing power, Ay, is positive.

Focal Plane Polarimeter, Spin Precession





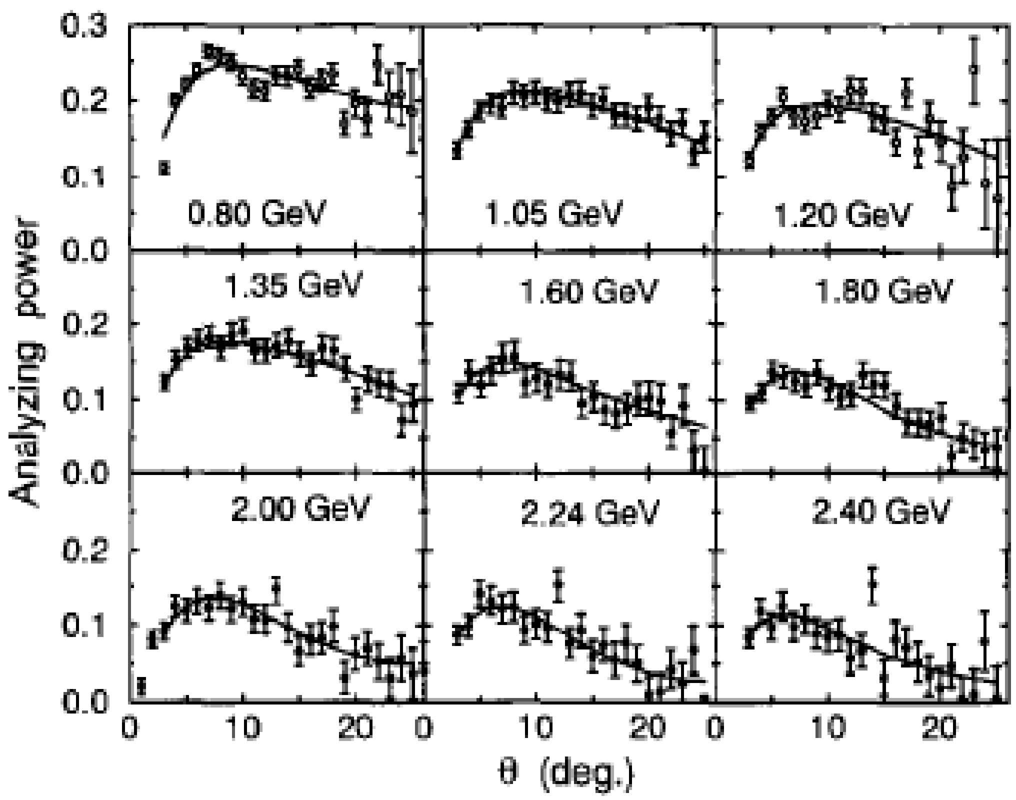
$$f^{\pm}(\vartheta,\varphi)=\frac{\varepsilon(\vartheta,\varphi)}{2\pi}\left[1\pm A_y(P_t^{fpp}\sin\varphi - A_y P_n^{fpp}\cos\varphi)\right]$$

Precession angle, $\chi_\theta = \gamma\,(\mu_p-1)\,\theta_B$

$$P_n^{fpp}=P_\ell^{tgt}\sin\chi_\theta$$

Calibrations at SATURNE, Saclay

The polarimeter POMME (Polarimeter Mobile a Moyenne Energy) was calibrated with polarized protons up to 2.4 GeV (3.2 GeV/c) prior to the Gep(1) experiment at Jlab.

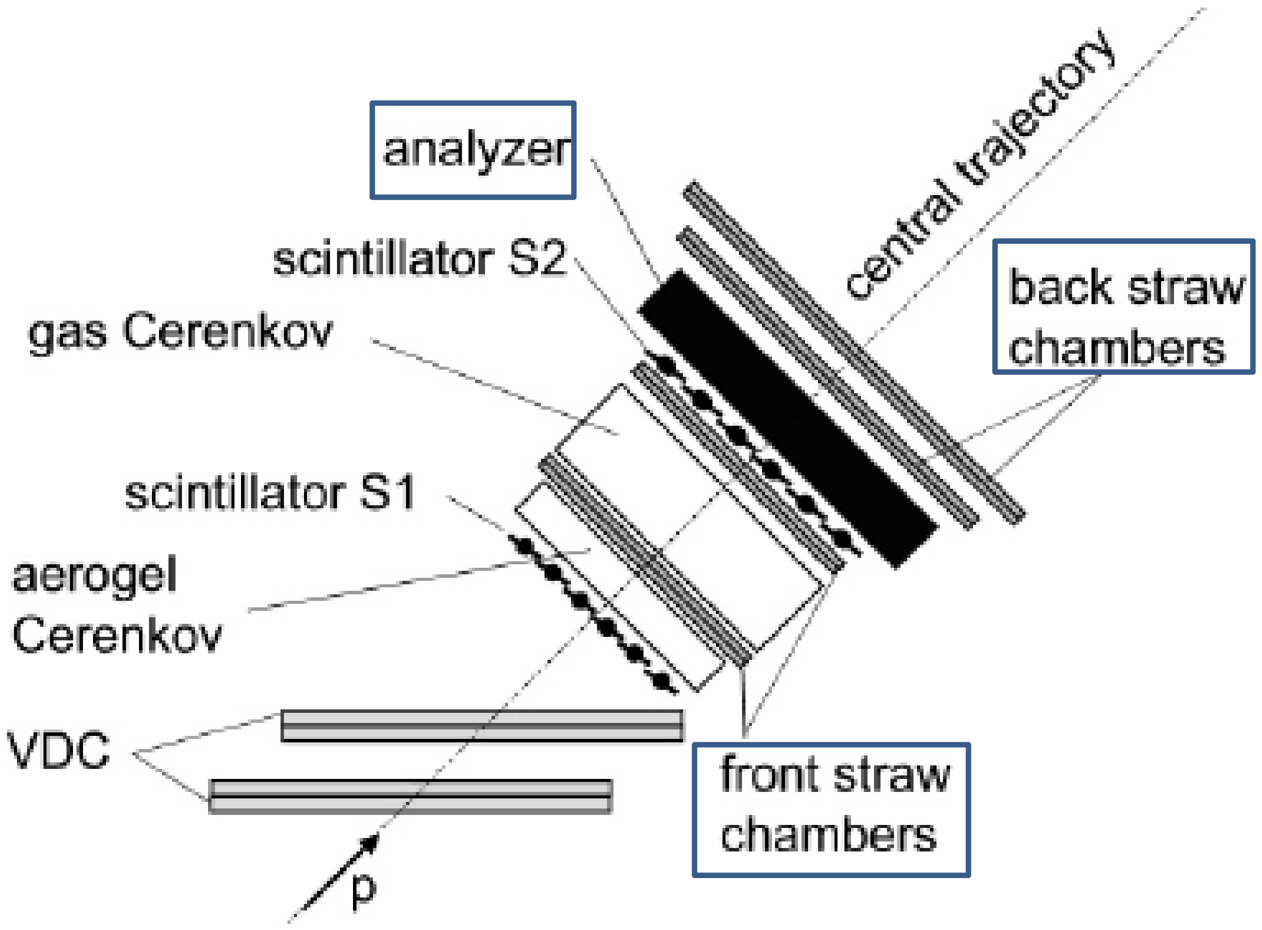


E. Chung et al. NIM in PR A363 (1995) 561.

16-parameter fit as in previous LAMPF calibration (which was limited to 800 MeV).

Note that 2.4 GeV proton kinetic energy corresponds to a Q^2 or 4.5 GeV^2, which was proposal value for GEp(1); PAC6 approved 3.5 GeV^2.

The first polarimeter in the HRS, Hall A, for GEp(1)



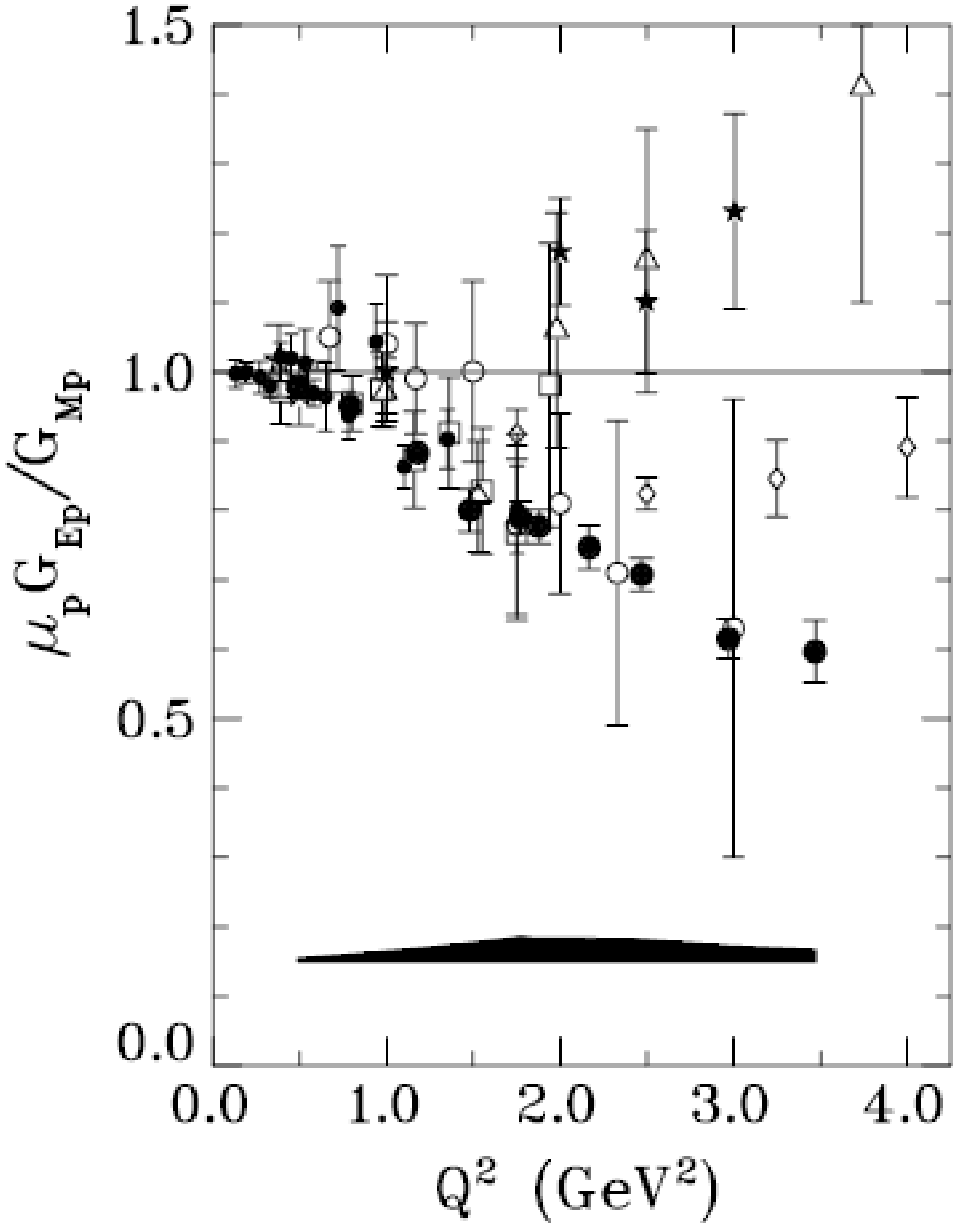
RESULTS OF GEp(1)

Exp. 93-027, PAC6, 1997

The first JLab recoil polarization results are the filled black circles.

Note the small error bars, almost entirely statistical.

V. Punjabi et al, PR C 71, 055202



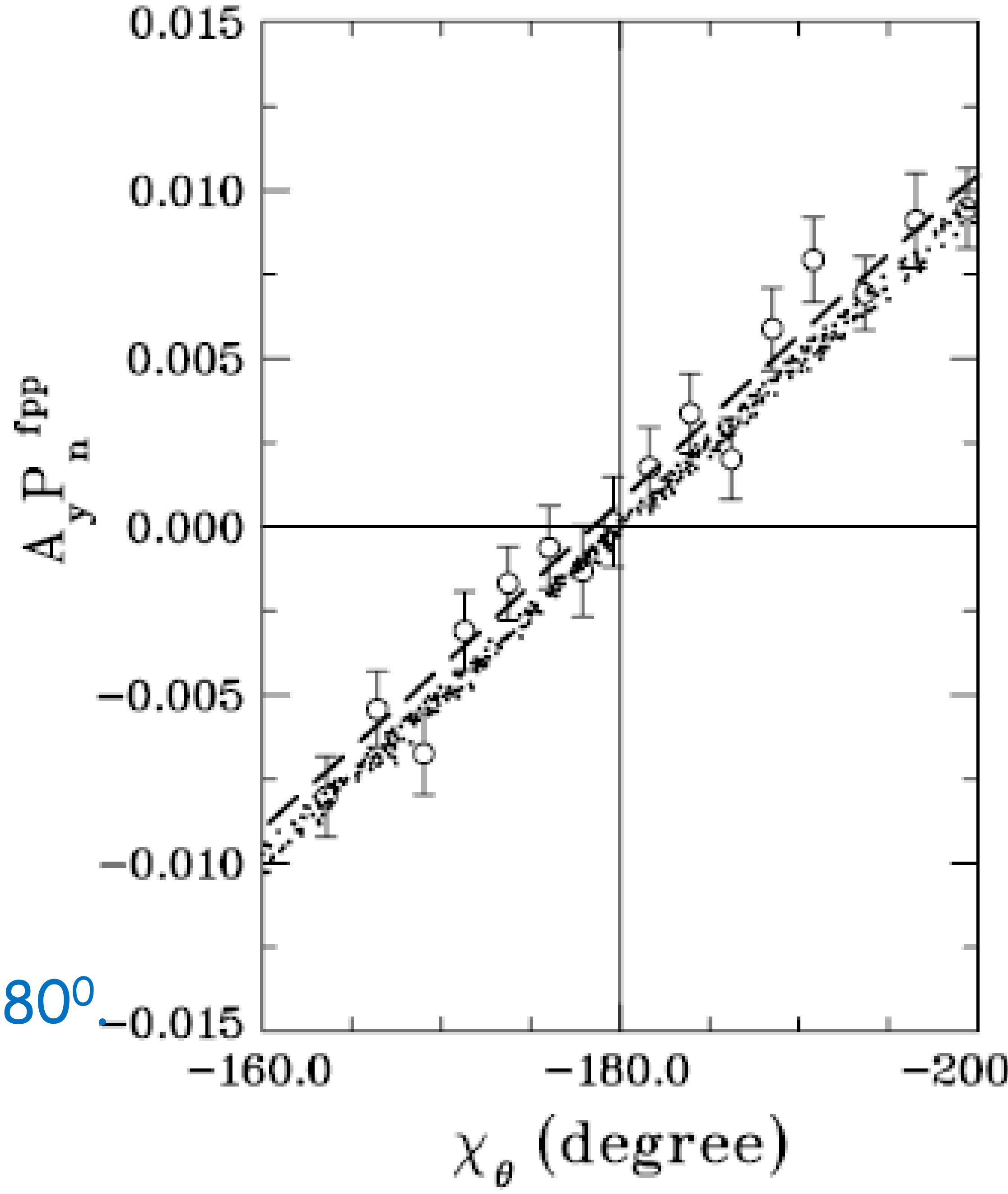
How do we know that we understand the precession?

Zero crossing of $P_n^{f\,pp}$:

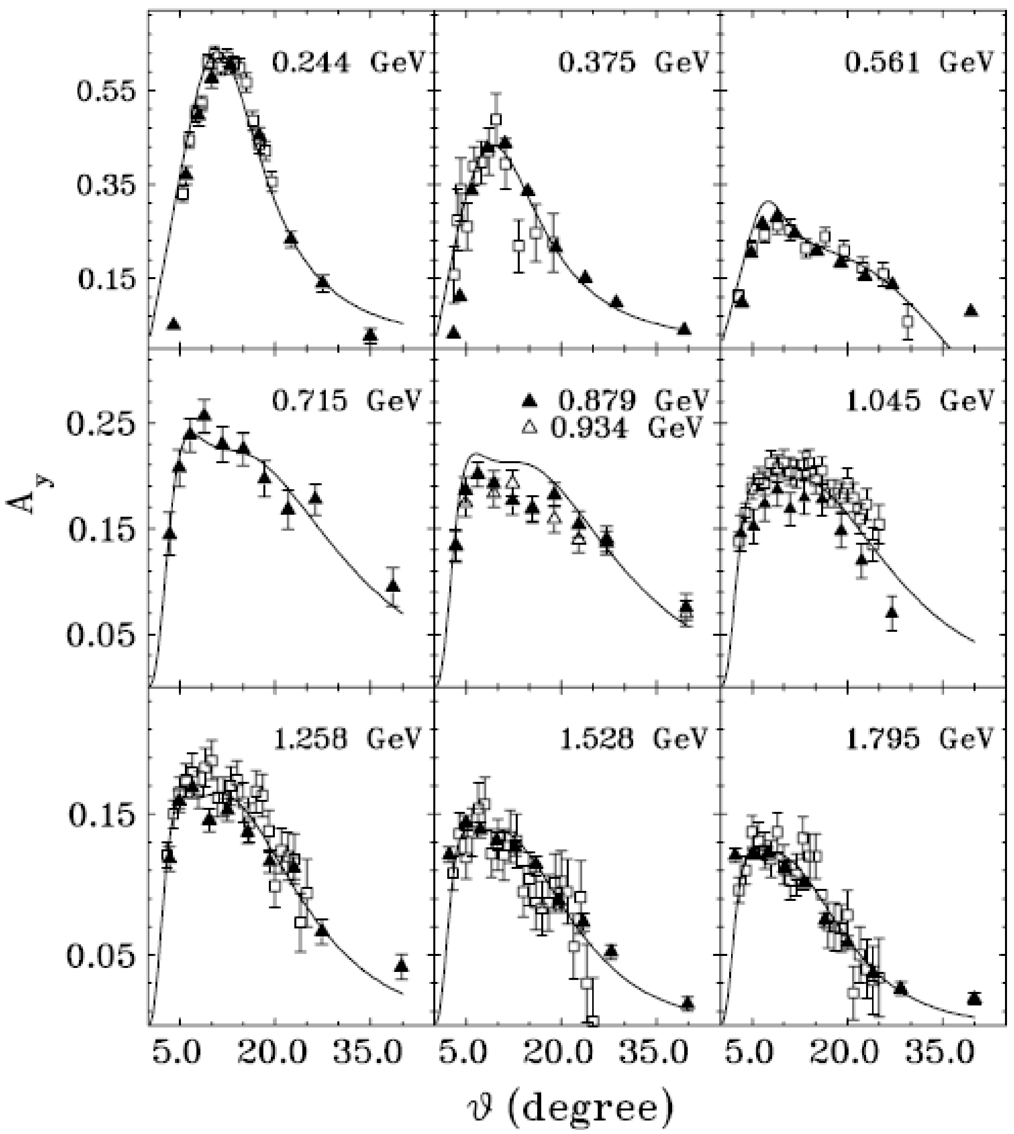
$$P_n^{fpp} = P_\ell^{tgt} \sin \chi_\theta$$

Showing the normal component at the FPP as a function of precession angle χ_θ.
Open circle: data from GEp(1).
Dashed line: fit to data.
Dots: calculated from COSY.

P_n^{fpp} fit crosses 0 at χ_θ=178.4^0, instead of 180^0.
Ideal χ_θ for experiment is of course 90^0.



Analyzing power from GEp(1)



P_t and P_l are measured: we can either obtain G_E and G_M separately

But requires knowing absolute analyzing power and beam polarization,

or

obtain ratio G_E/G_M AND absolute analyzing power Ay

(must know beam polarization for A_y).

Second solution was first proposed by V. Punjabi and CFP in 1997 (PAC6).

A_y determines the error bars as

$\Delta P_t^{fpp} = \Delta P_l^{fpp} = \mathrm{sqrt}(2/\varepsilon A_y^2 N)$

N: #events, A_y analyzing power,

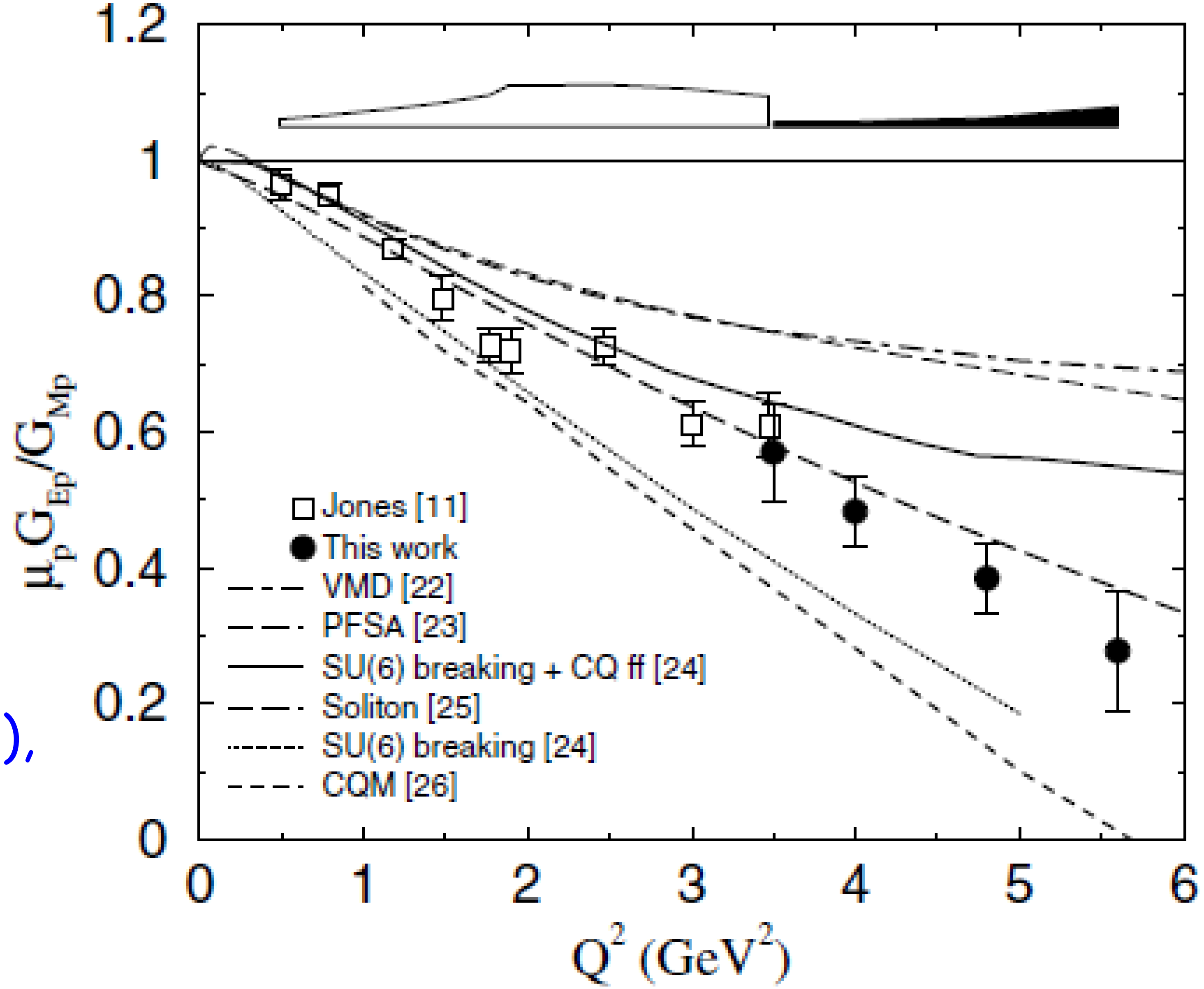
ε efficiency.

Results of GEp(2)

Exp.99-007, PAC15, 1999

As published, Gayou et al., in PRL 88, 092301 (2002).

Has been reanalyzed since and published, Puckett et al., P.R. C 85 (2012), 045203.

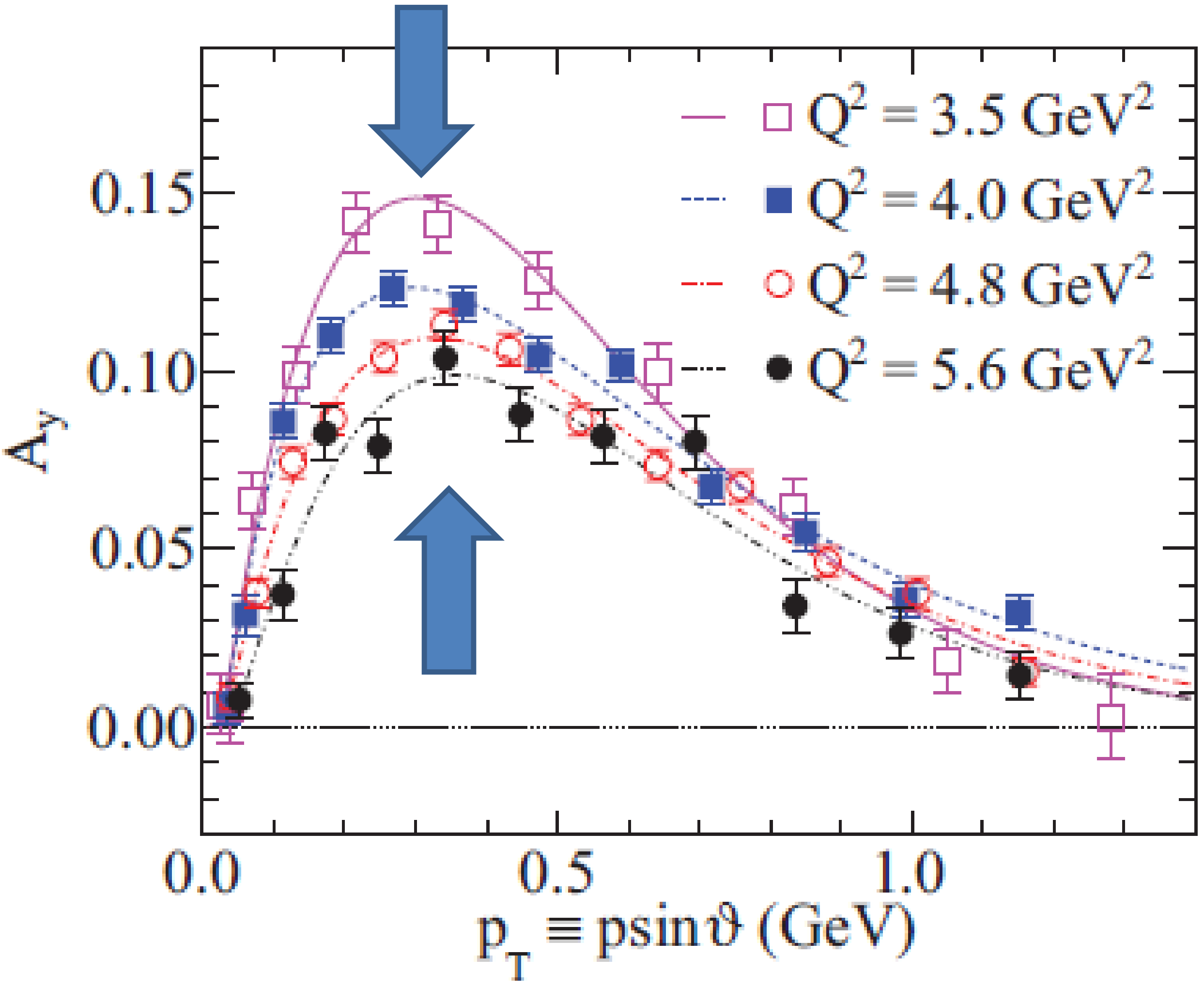


Analyzing powers from GEp(2)

Note apparent "scaling":

Maximum of Ay appears at a nearly constant transverse momentum p_T.

Confirms scaling observed in Dubna calibration.



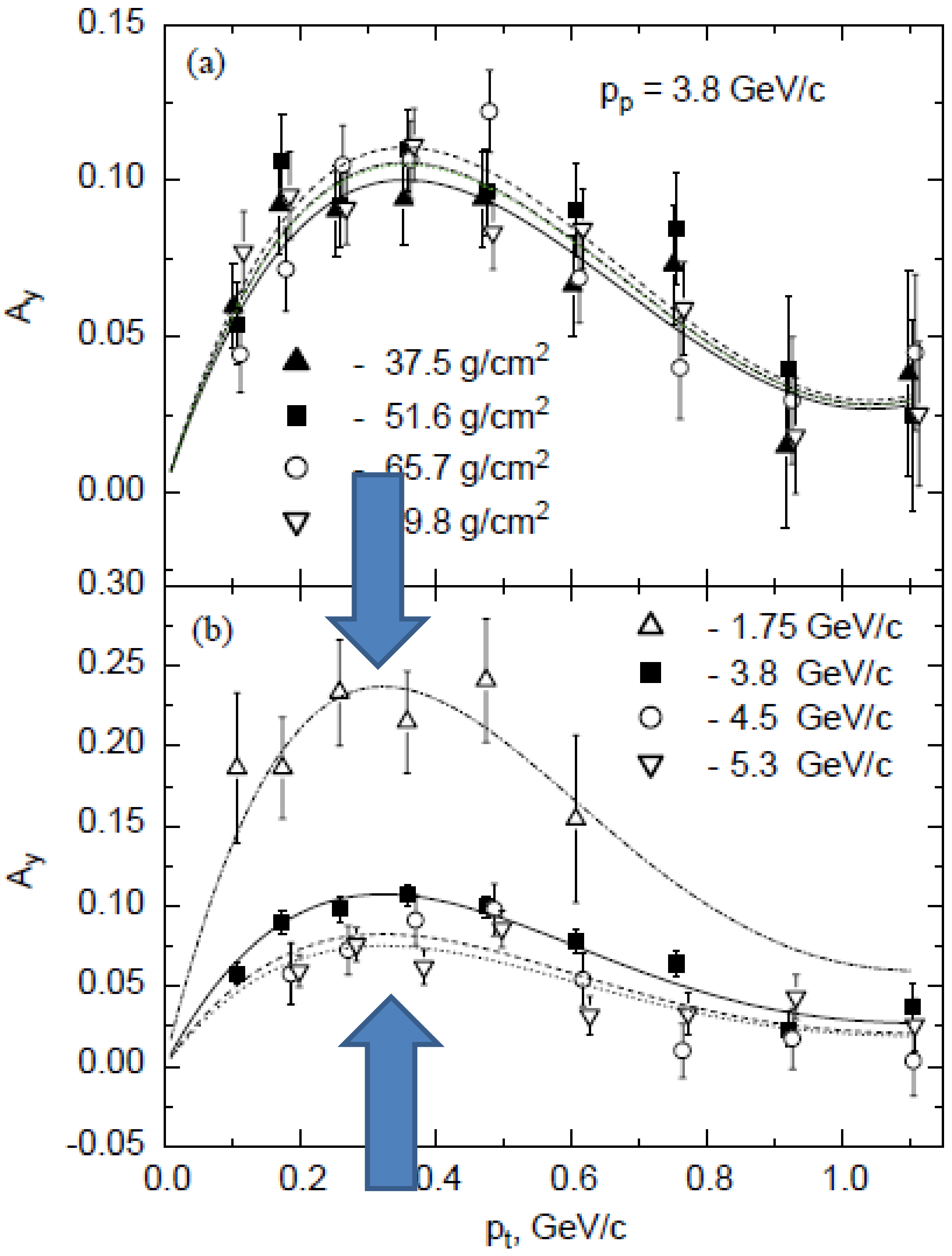
Results of 2001 Dubna calibration

Was necessary to get GEp(3) experiment approved by PAC.

Determine best thickness of CH_2 analyzer.

Observation "scaling" of Ay versus 1/p. And Ay at a nearly constant transverse momentum p_T, a second "scaling".

L.S. Azhgirey et al, NIM in Nuc. Res. A 538 (2005), 431.

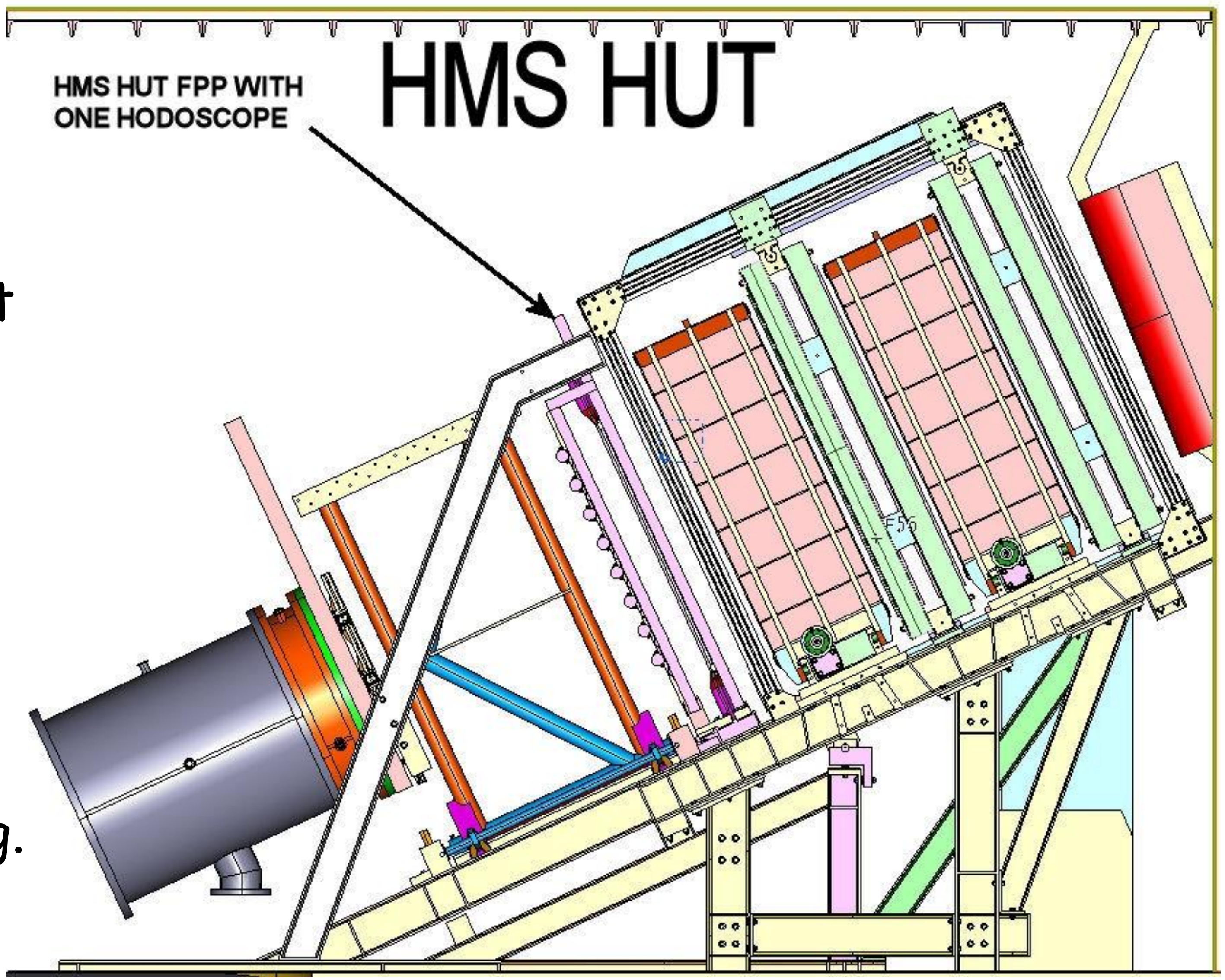


GEp(3) in Hall C
2007-8

The double polarimeter built for GEp(3) in the Hall C HMS spectrometer .

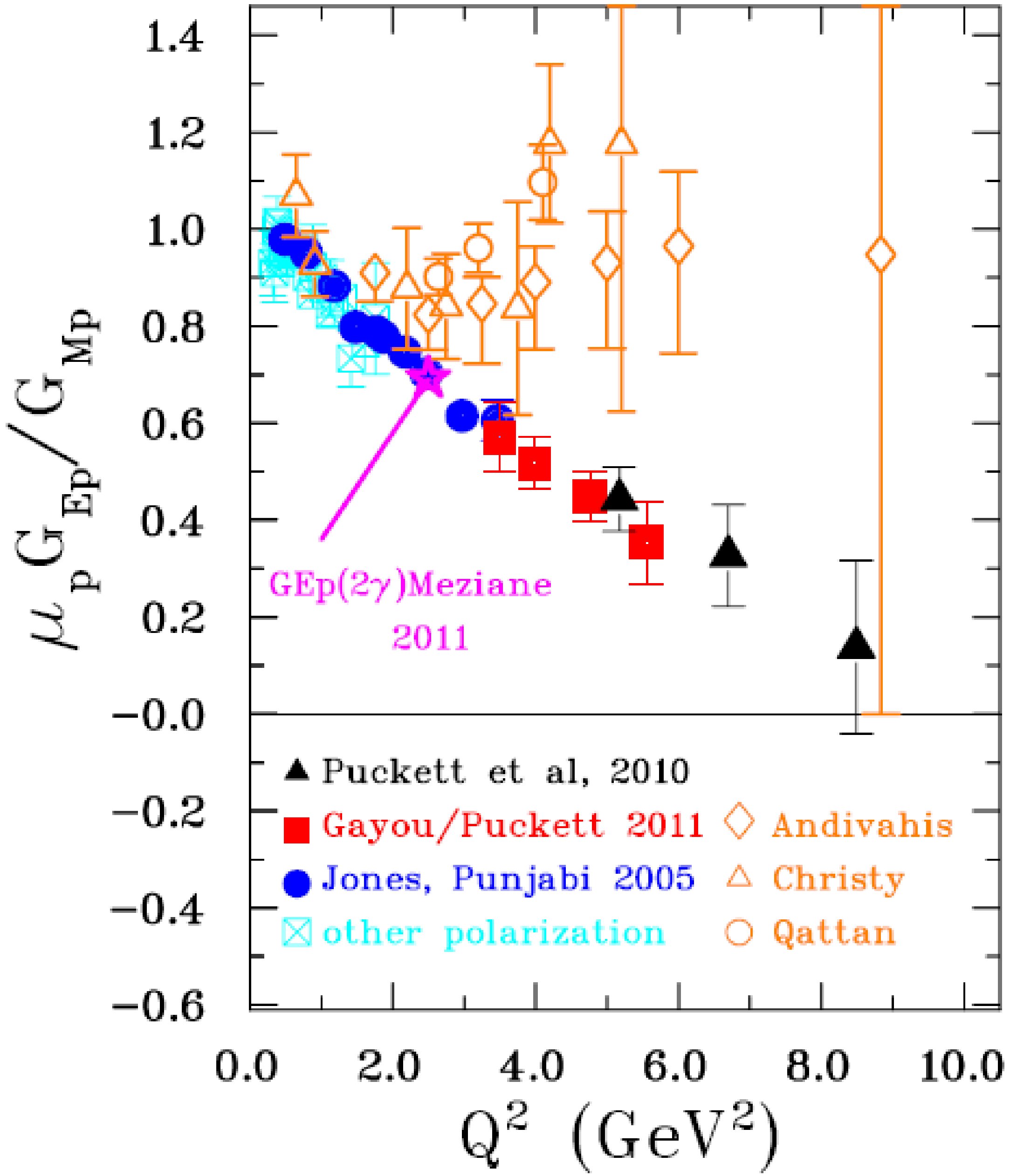
Pink boxes, CH_2 analyzer Blocks (50 gcm^{-2})

Pale blue: 2 drift chambers per polarimeter for tracking.



Double FPP in HMS

$\mu_p G_{Ep}/G_{Mp}$ from all double Polarization Experiments



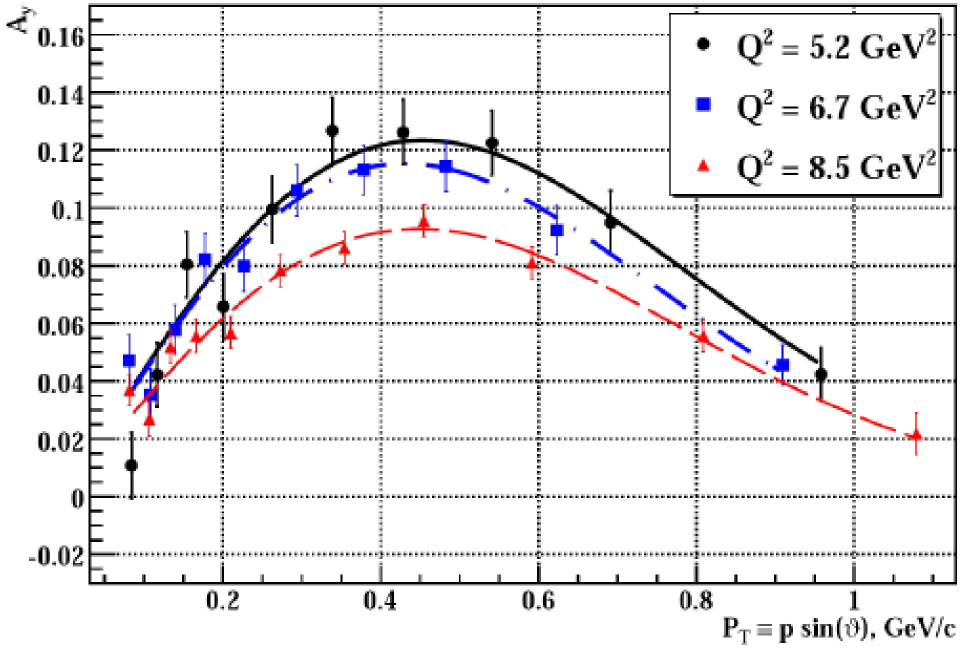
Recent Rosenbluth data including:
L. Andivahis et al., Phys. Rev. D 50, 5491 (1994).
Christy et al., Phys. Rev. C 70, 015206 (2004).
Qattan et al. Qattan I.~A. et al., Phys. Rev. Lett. 94, 142301 (2005).

Other polarization results (cyan, or aqua marine), including recoil polarization and beam-target asymmetry results.

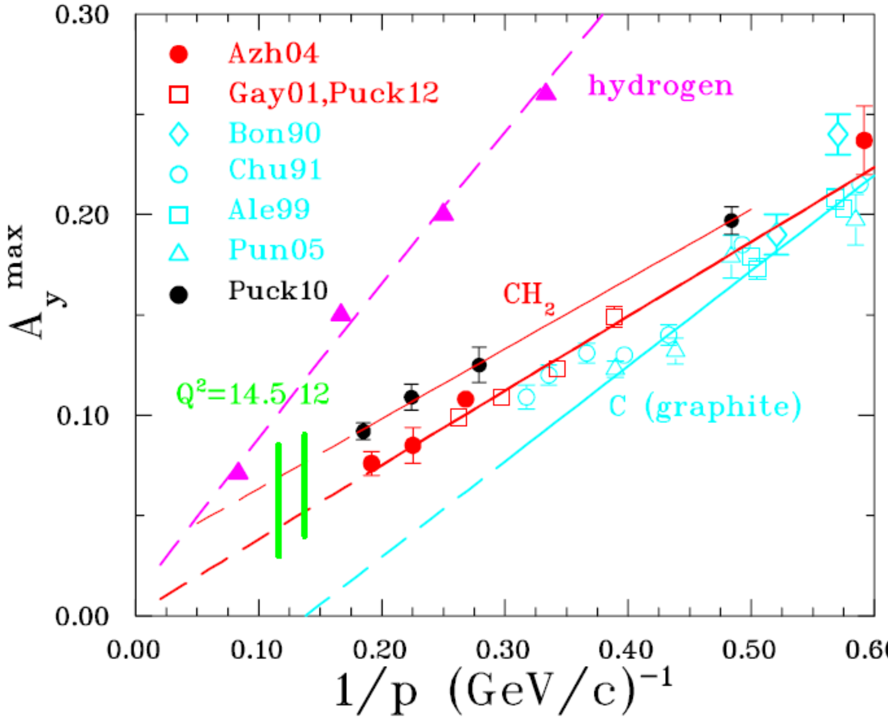
Higher momentum p-CH_2 analyzing power A_y

Ay from GEp(3), to proton momentum of 5.4 GeV/c

The scaling in 1/p. Hydrogen as an analyzer would be twice as good.



A_y vs. p_t=psin(θ) in GEp(3)



All data: A_y^{max} versus 1/p

Will measure A_y to 7.5 GeV/c at JINR (Dubna) in Fall of 2014 (Piskunov et al).

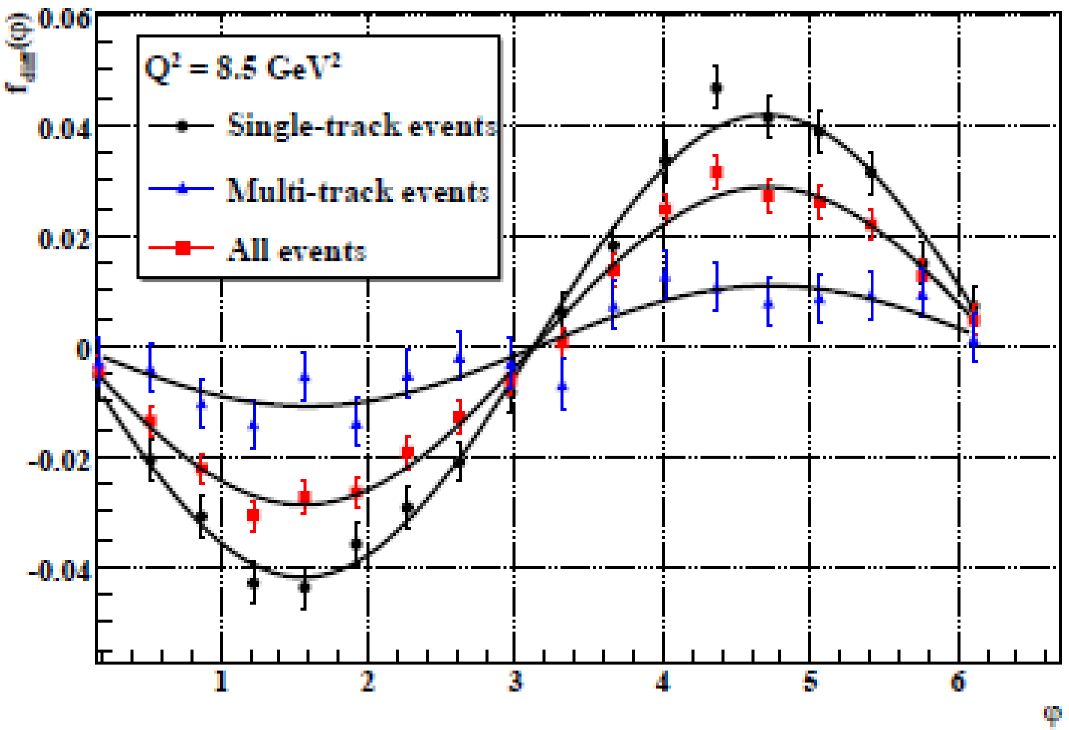
Negative effect of inelastic contribution

Current polarimeters detect charged particles (no identification). Single track events have max Ay; contamination from multi-particle final states degrade Ay.
In future, better tracking resolution and crude measurement of energy behind the polarimeters will increase effective Ay: HCal in SBS for GEp(5).

$$f^{\pm}(\vartheta,\varphi)=\frac{\varepsilon(\vartheta,\varphi)}{2\pi}\left[1\pm A_y\left(P_t^{fpp}\sin\varphi - A_y P_n^{fpp}\cos\varphi\right)\right]$$

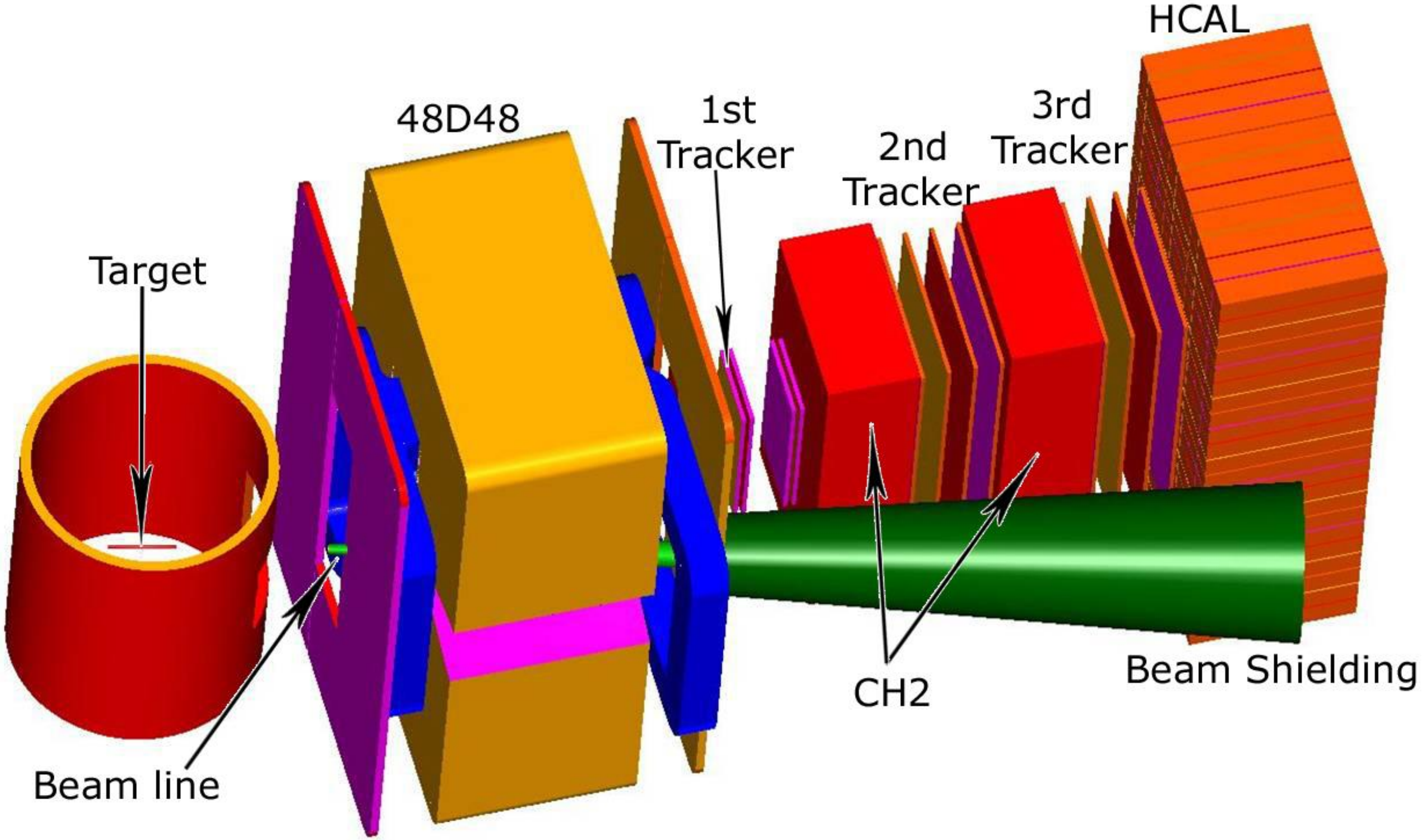
P_t^{fpp} and P_n^{fpp} are the polarization components at the FPP

Physical Asymmetries are obtained from difference distributions

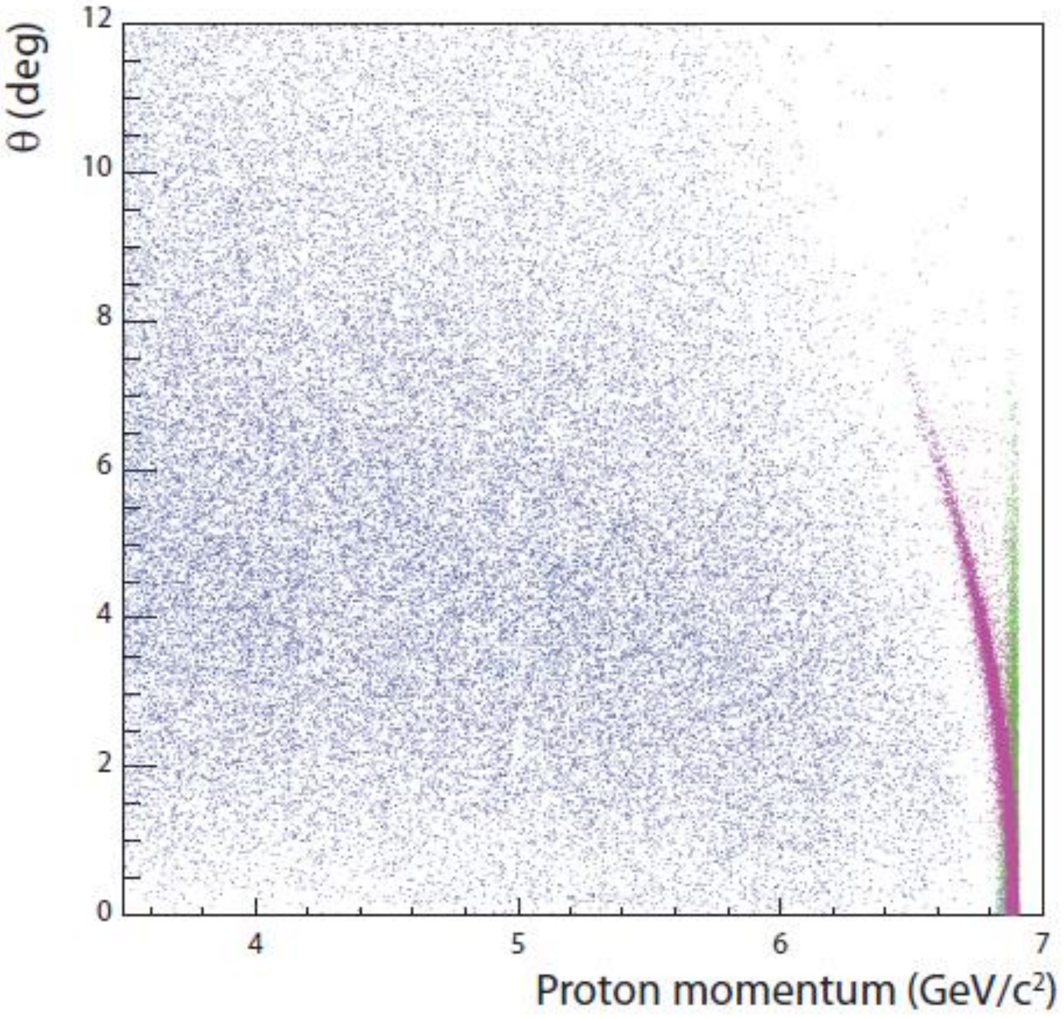


PSTP2013 in Charlottesville

Super Bigbite Spectrometer for GEp(5)

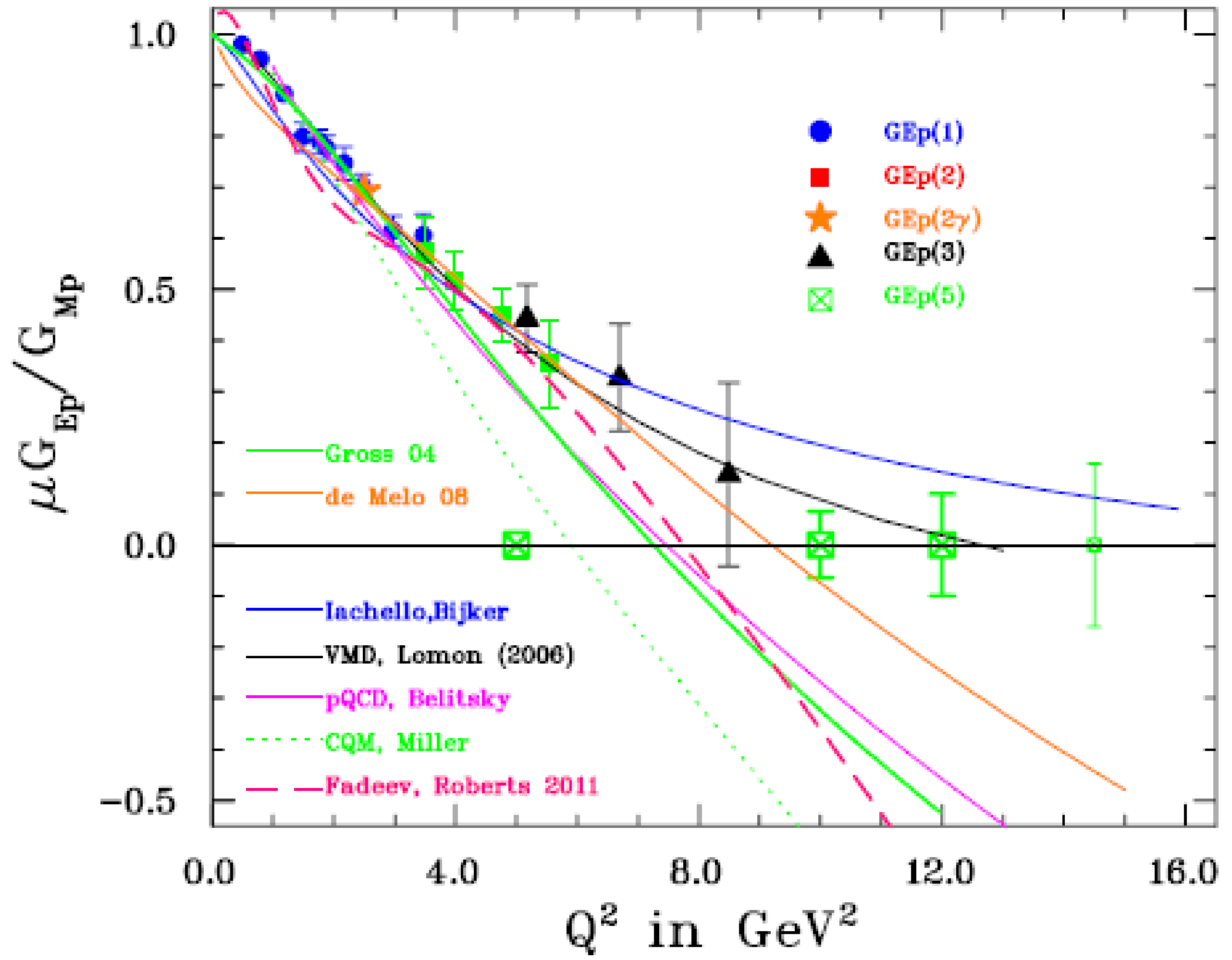


CH_2 analyzer



GEANT3 simulation of the proton momentum vs polar angle from 50 gcm^{-2} block of CH_2, for 7 GeV/c incident momentum (by Yang Wang, WM)
green: elastic pC, single particle.
violet: elastic pp (and pn), single particle
blue, inelastic, all final states.
effective analyzing power can be improved by selecting the energy of the emerging particles.
In GEp(5) with a hadron calorimeter of the COMPASS type.

Expected error bars for GEp(5)



CONCLUSIONS

Recoil polarization experiments became possible with Jlab;
had been tested at Bates at Q^2<0.5 GeV^2 in 1996.

Results of recoil polarization experiments were unexpected, showing an irreducible difference from cross section results with Rosenbluth separation results.

It is now commonly assumed that the difference is due to incomplete radiative corrections to cross section, with double virtual photon exchange the single prime candidate. The size of the two-photon exchange has yet to be determined experimentally; the e^+/e^- cross section ratio should resolve the puzzle (although this ratio is quite sensitive to radiative corrections too).