The Super Rosenbluth Experiment
(The E01-001 collaboration)

Jefferson Lab
April 16, 2004

Magnetic moments

Dirac

point particle: $\mu_B = q\hbar/(2mc)$

electron: $\mu_e = gs\mu_B = g(1/2)\mu_B$; $g = 2$

Experiment

electron: $\mu = q\hbar/(2mc) \times 1.002$; $(g = 2.004)$

proton $\mu = 2.793\ \mu_N = q\hbar/(2m_p c) \times 2.793$

neutron $\mu = -1.913\ \mu_N = q\hbar/(2m_n c) \times \infty$

Scattering from point (heavy) nucleus (Rutherford):

$$\frac{d\sigma}{d\omega} = \frac{(Z_1 Z_2 e^2)^2}{16E^2 \sin^4 \frac{\theta}{2}} = \frac{4m^2 (Z_1 Z_2 e^2)^2}{q^4}$$

where $\mathbf{q} = \mathbf{p}_i - \mathbf{p}_f = 2p\sin\theta/2$ (elastic scattering)

extended nucleus:

$$\frac{d\sigma}{d\omega} = \left(\frac{d\sigma}{d\omega}\right)_{point} |F(q^2)|^2$$

F = form factor

$= 1 - (1/6)q^2 \langle r^2 \rangle + \ldots$

Electron (s = ½) scattering from point nucleus:

$$\left(\frac{d\sigma}{d\varpi}\right)_{Mott} = \frac{4(Ze^2)^2 E^2}{q^4}\left(1 - \beta^2 \sin^2 \frac{\theta}{2}\right)$$

$$\approx \frac{4Z^2 e^4 E^2}{q^4} \cos^2 \frac{\theta}{2}$$

Rosenbluth separation

$$\frac{d\sigma}{d\omega}(E,\theta) = (\frac{d\sigma}{d\omega})_{Mott}(G_E^2 + \varepsilon^{-1}(\frac{1}{2m_p})^2 Q^2 G_M^2)$$

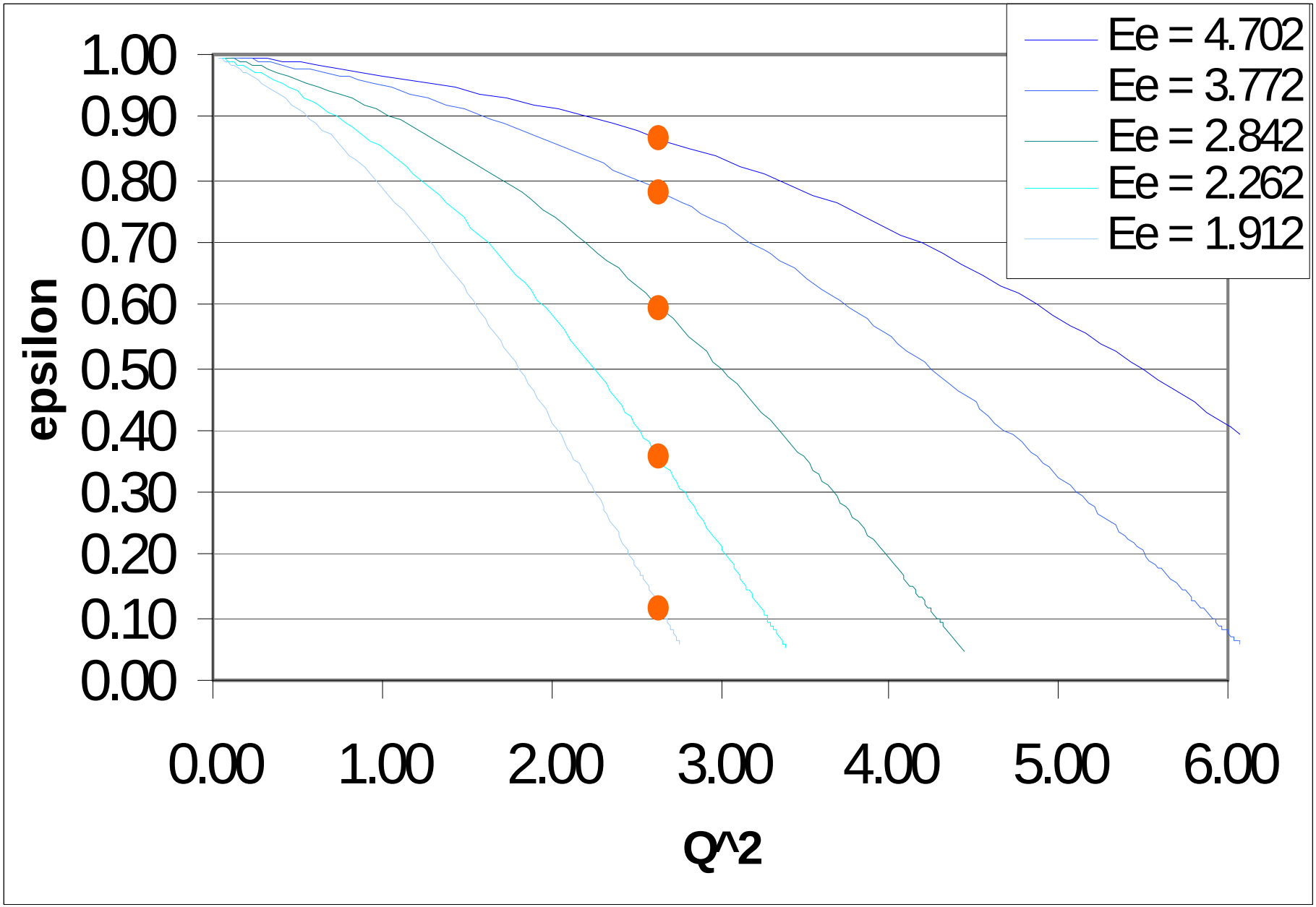
$$= (\frac{d\sigma}{d\omega})_{Mott}\frac{1}{\varepsilon}(\varepsilon G_E^2 + (\frac{1}{2m_p})^2 Q^2 G_M^2)$$

$$\varepsilon = (1 + 2(1+\tau)\tan^2\frac{\theta}{2})^{-1};\ \tau = \frac{|q|^2}{Q^2} - 1$$

ε = virtual polarization parameter

$$G_E \equiv G_E(Q^2) \to 1 \quad as \quad Q^2 \to 0$$

$$G_M \equiv G_m(Q^2) \to \mu_p \quad as \quad Q^2 \to 0$$


Ee = 4.702
Ee = 3.772
Ee = 2.842
Ee = 2.262
Ee = 1.912
epsilon
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Q^2

Rosenbluth extractions of G_E and G_M

$$\sigma_R = \frac{d\sigma}{d\Omega}\frac{\varepsilon(1+\tau)}{\sigma_{Mott}} = \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2)$$

First Rosenbluth separations-1961

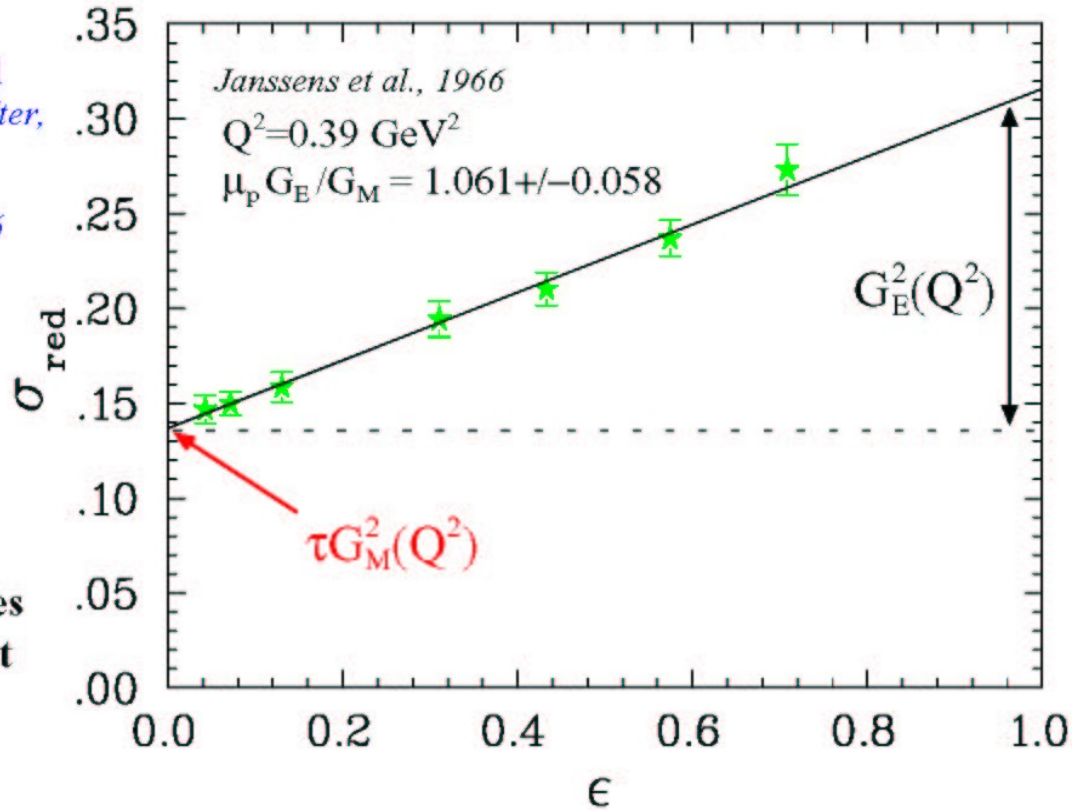
Bumiller, Croissiaux, Dally, and Hofstadter, Phys. Rev. ***124****, 144*

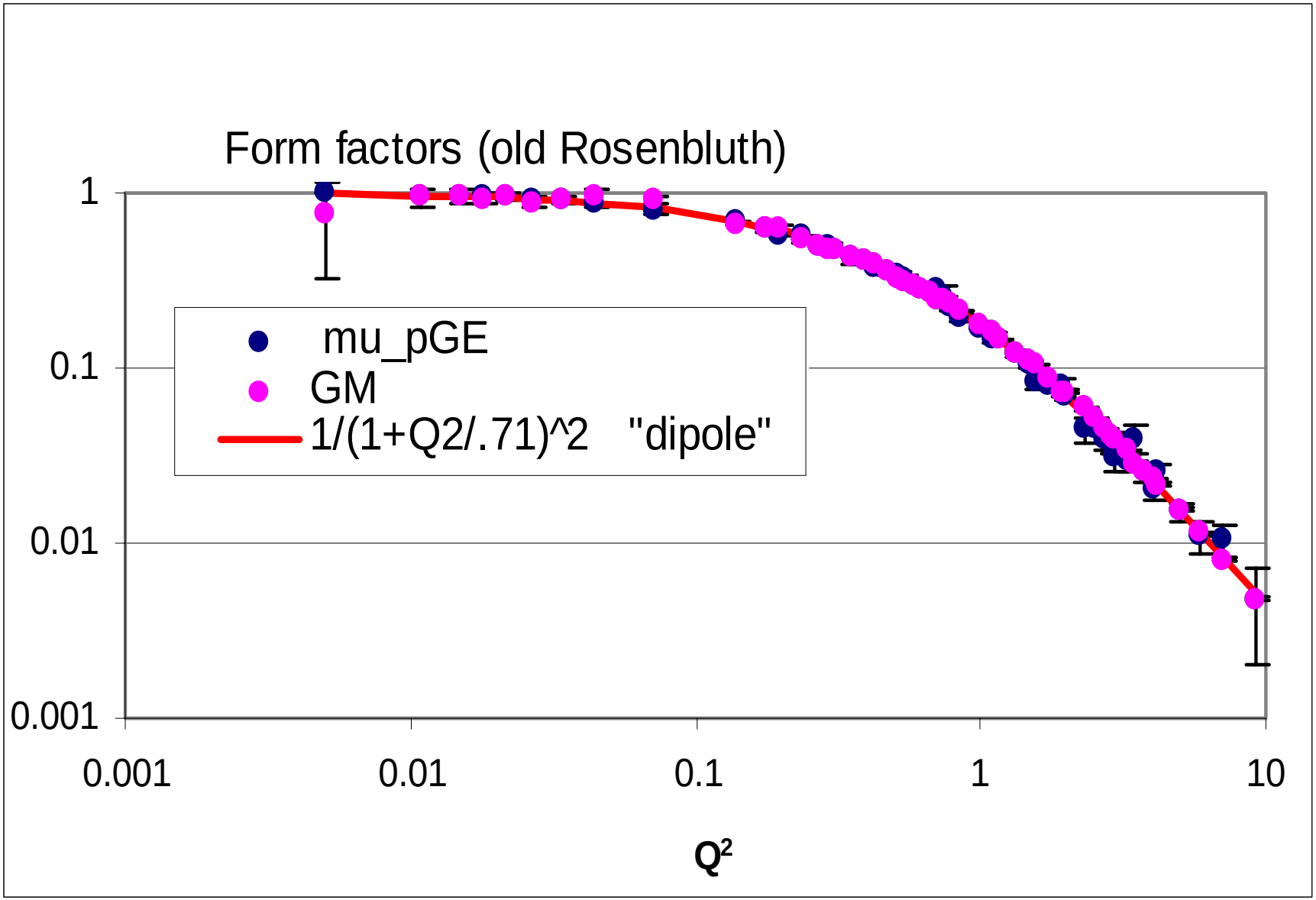
Olson, Schopper, and Wilson, PRL ***6****, 286*

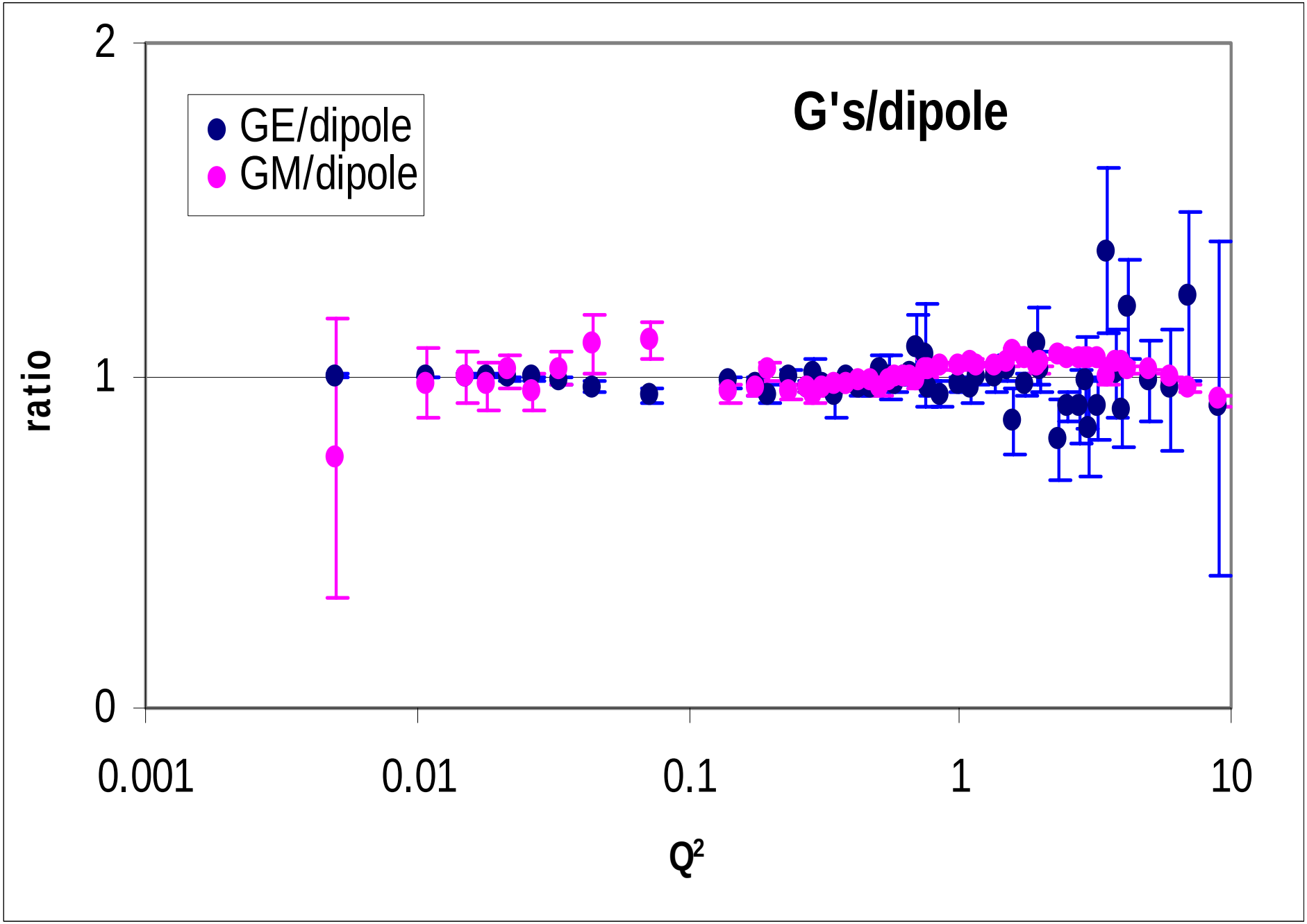
Initial Rosenbluth measurement (up to Q^2=1 GeV^2) consistent with form factor scaling

$$G_M(Q^2) \cong \mu_p G_E(Q^2)$$

For large Q^2 values, τG_M^2 dominates and G_E^2 becomes difficult to extract




Form factors (old Rosenbluth)
1
0.1
0.01
0.001
0.001
0.01
0.1
1
10
Q2
mu_pGE
GM
1/(1+Q2/.71)^2 "dipole"


G's/dipole
GE/dipole
GM/dipole
ratio
2
1
0
0.001
0.01
0.1
1
10
Q2

Rosenbluth separation

$$\frac{d\sigma}{d\omega}(E,\theta) = (\frac{d\sigma}{d\omega})_{Mott}(G_E^2 + \varepsilon^{-1}(\frac{1}{2m_p})^2 Q^2 G_M^2)$$

$$= (\frac{d\sigma}{d\omega})_{Mott}\frac{1}{\varepsilon}(\varepsilon G_E^2 + (\frac{1}{2m_p})^2 Q^2 G_M^2)$$

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$$G_M \equiv G_m(Q^2) \to \mu_p \quad as \quad Q^2 \to 0$$

When longitudinally polarized electrons scatter from unpolarized protons polarization is transferred to the recoil proton with:

$$P_t = \frac{2\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta}{2}}{G_E^2 + \frac{\tau}{\varepsilon}G_M^2}$$

and

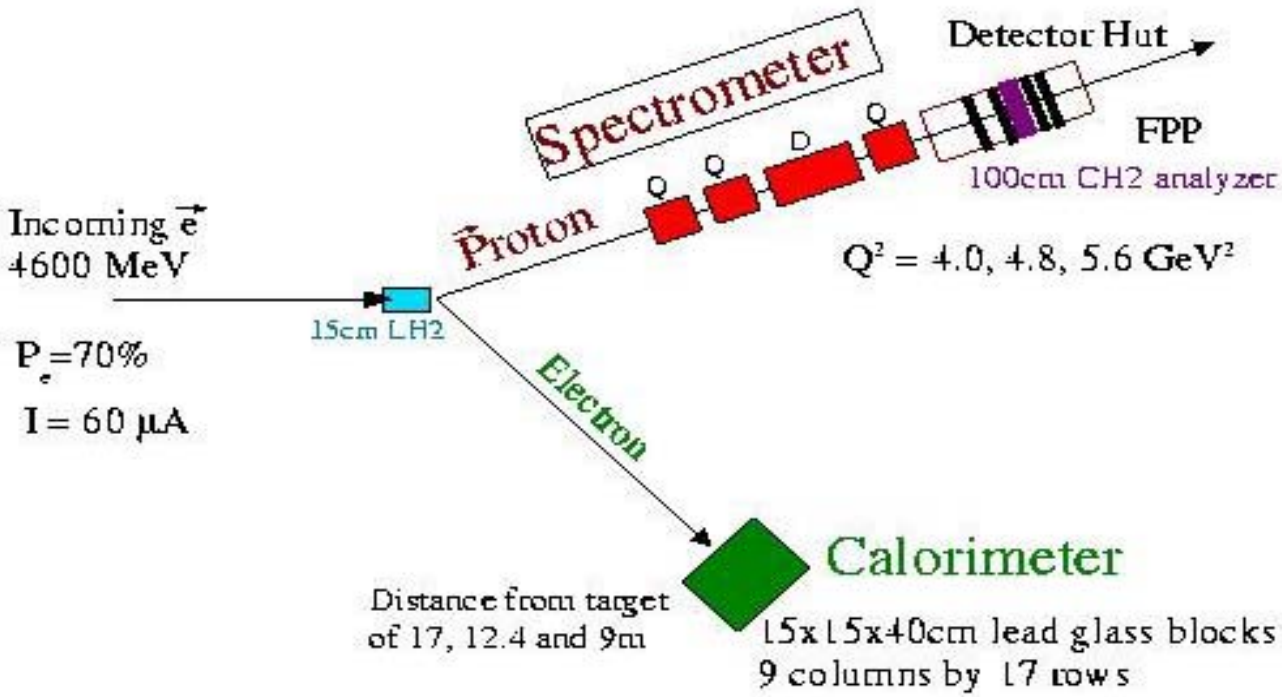
$$P_l = \frac{(E_e + E_{e'})\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta}{2}}{m_p(G_E^2 + \frac{\tau}{\varepsilon}G_M^2)}$$

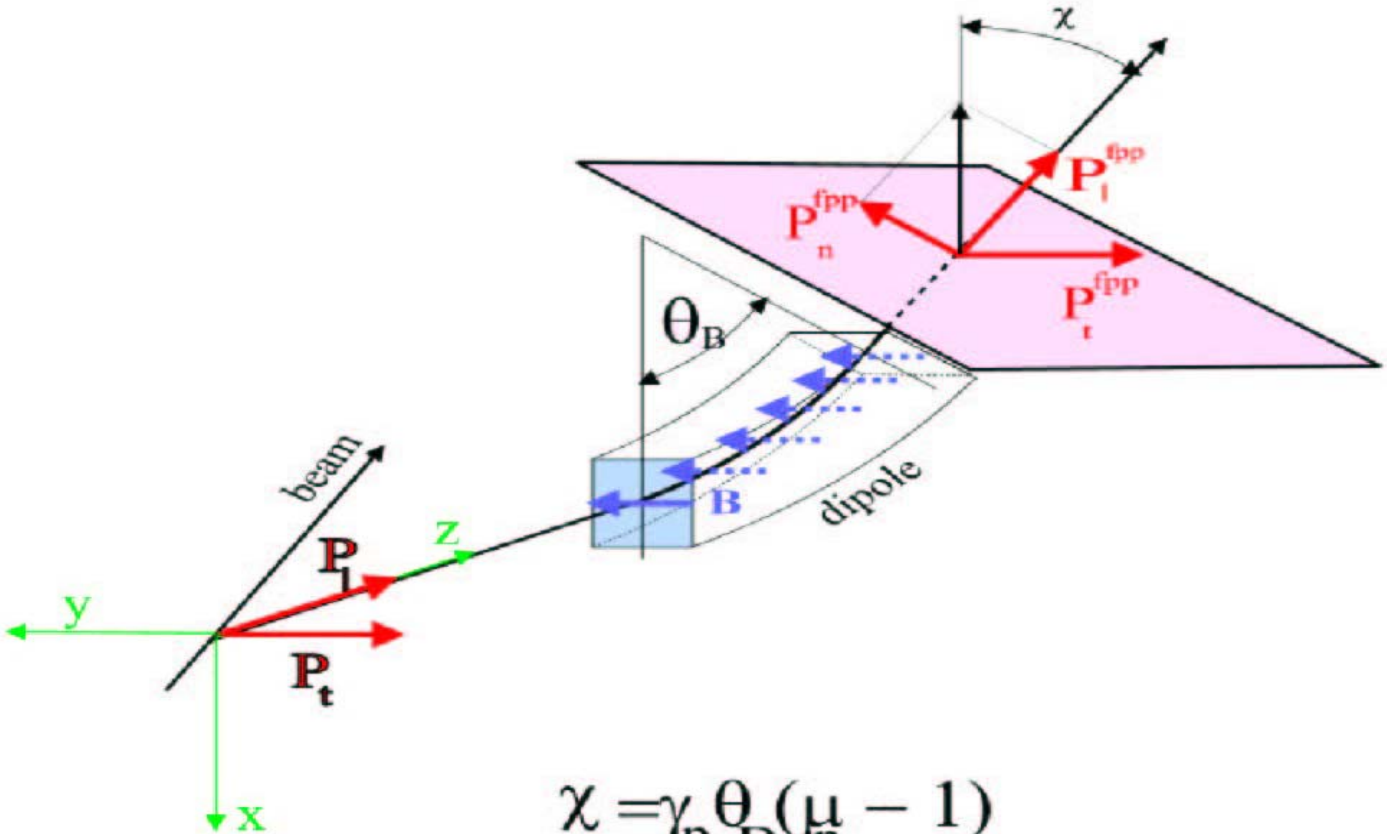
where P_t = proton polarization in the plane of the reaction perpendicular to the proton momentum

P_l = proton polarization parallel to the proton momentum

Jefferson Lab experiments E93-027 and E99-007 measured P_t/P_l to determine :

$$\frac{G_E}{G_M} = \frac{P_t}{P_l}\frac{(E_e + E_{e'})\tan(\frac{\theta}{2})}{2m_p}$$

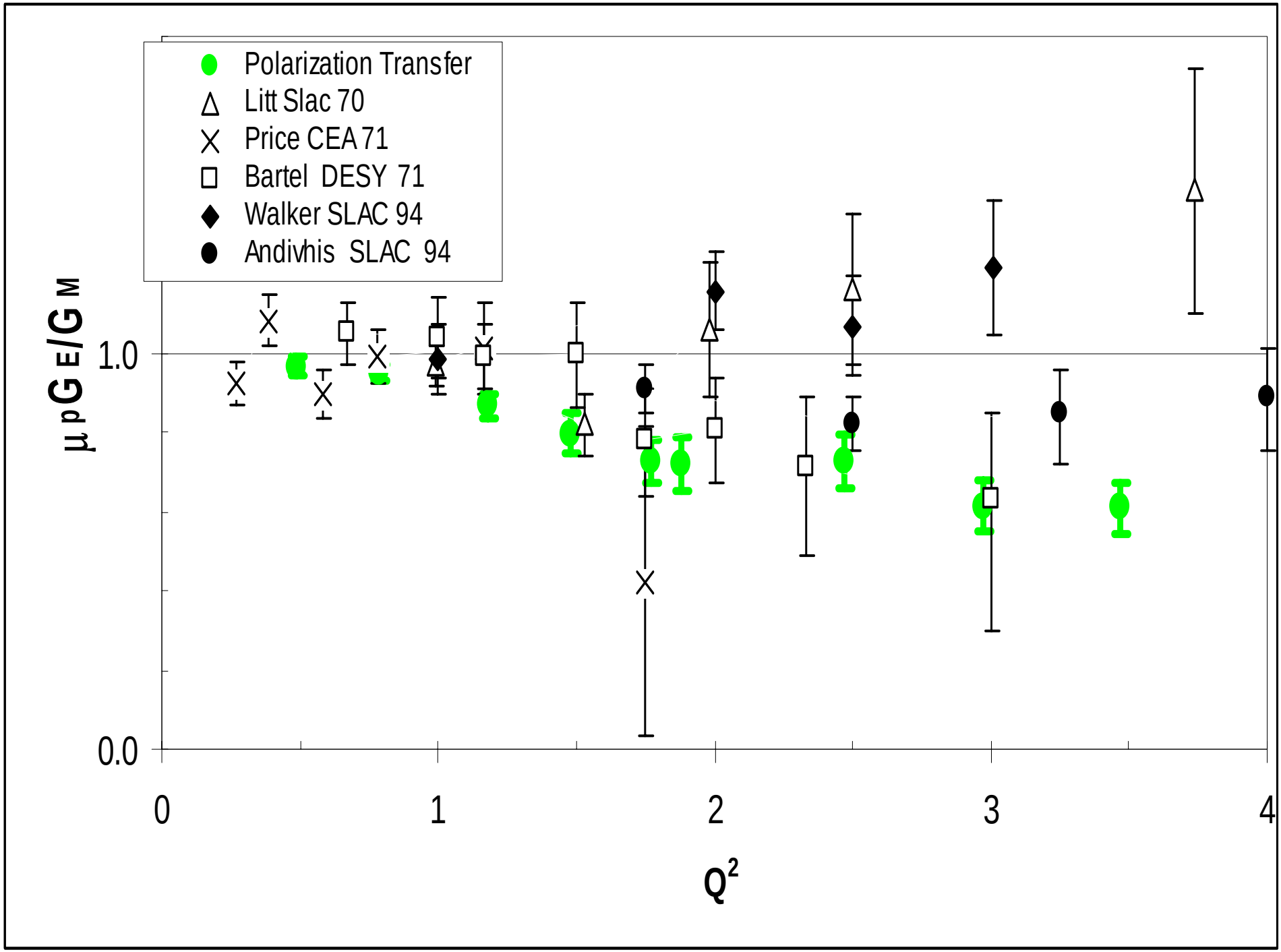

Spectrometer
Detector Hut
FPP
100cm CH2 analyzer
Q
Q
D
Q
Proton
Incoming e
4600 MeV
15cm LH2
Q^2 = 4.0, 4.8, 5.6 GeV^2
P_e=70%
I = 60 μA
Electron
Calorimeter
Distance from target
of 17, 12.4 and 9m
15x15x40cm lead glass blocks
9 columns by 17 rows

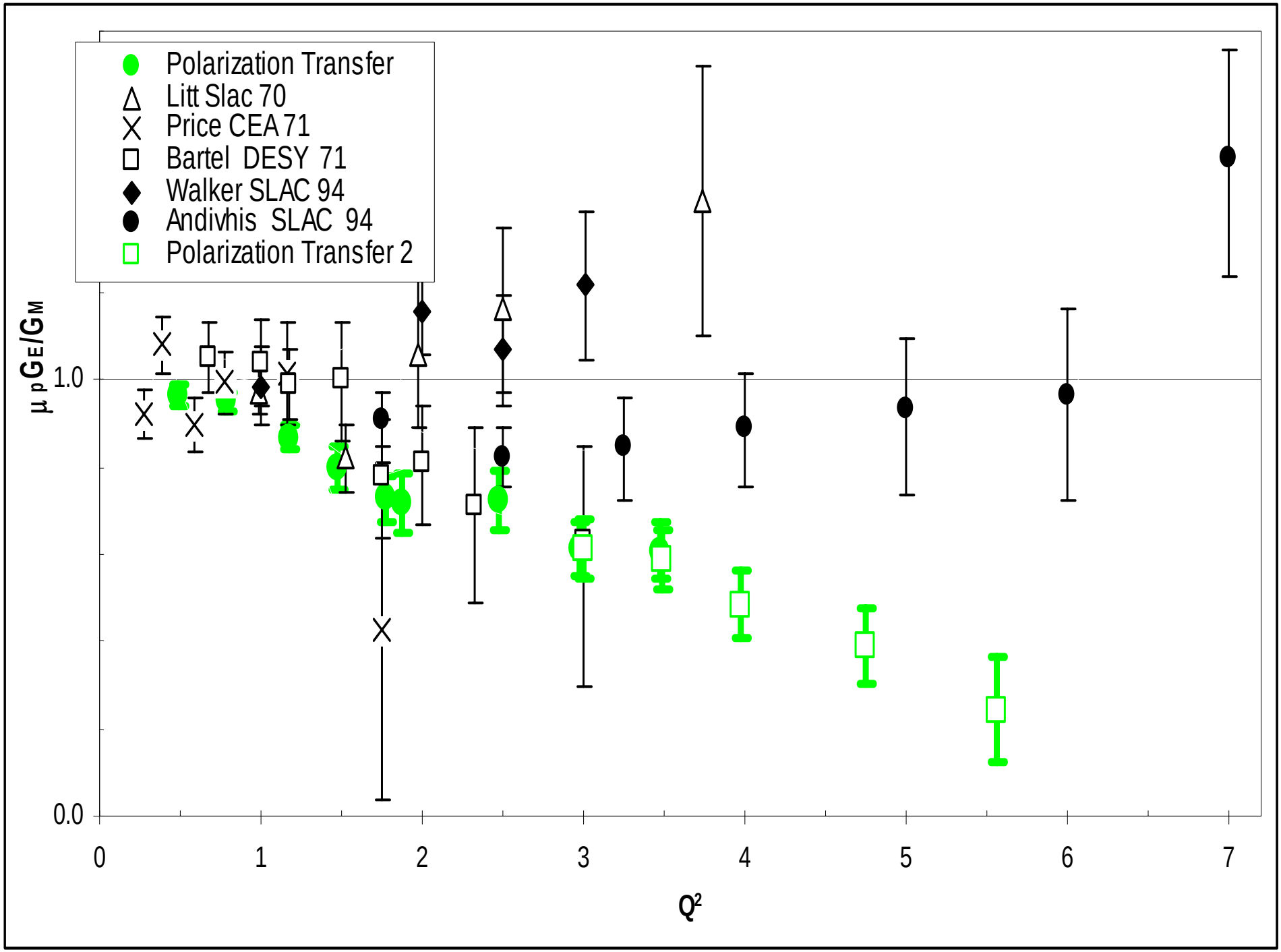


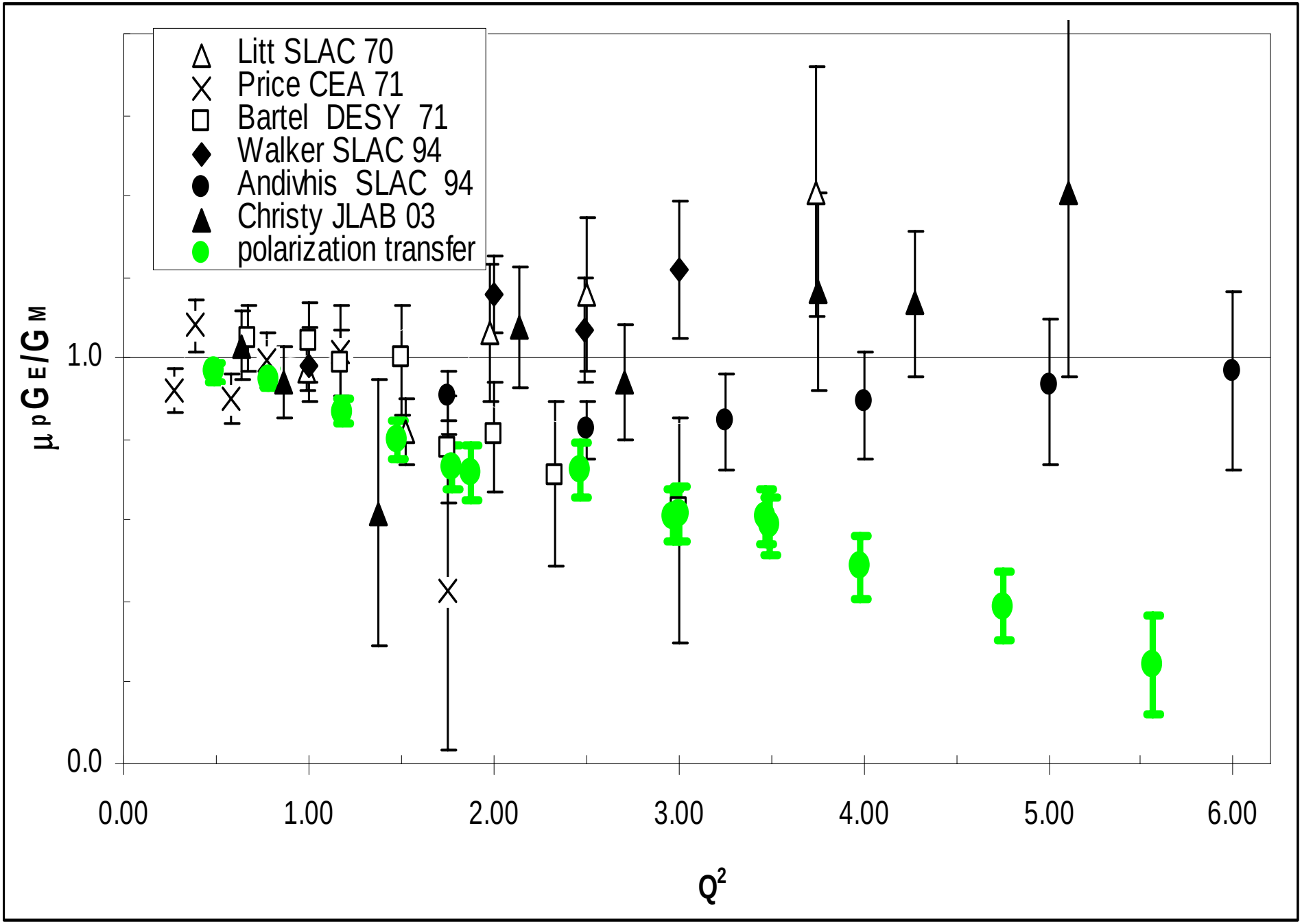
$$\chi = \gamma_p \theta_B (\mu_p - 1)$$

$$P_t^{fpp} = P_t$$

$$P_n^{fpp} = P_l \sin\chi$$


Polarization Transfer
Litt Slac 70
Price CEA 71
Bartel DESY 71
Walker SLAC 94
Andivhis SLAC 94
μpGE/GM
1.0
0.0
0
1
2
3
4
Q2


Polarization Transfer
Litt Slac 70
Price CEA 71
Bartel DESY 71
Walker SLAC 94
Andivhis SLAC 94
Polarization Transfer 2
μ pGE/GM
1.0
0.0
0
1
2
3
4
5
6
7
Q2


Litt SLAC 70
Price CEA 71
Bartel DESY 71
Walker SLAC 94
Andivhis SLAC 94
Christy JLAB 03
polarization transfer
$\mu_p G_E/G_M$
1.0
0.0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Q^2

E01-001: New Measurement of (G_E/G_M) for the Proton

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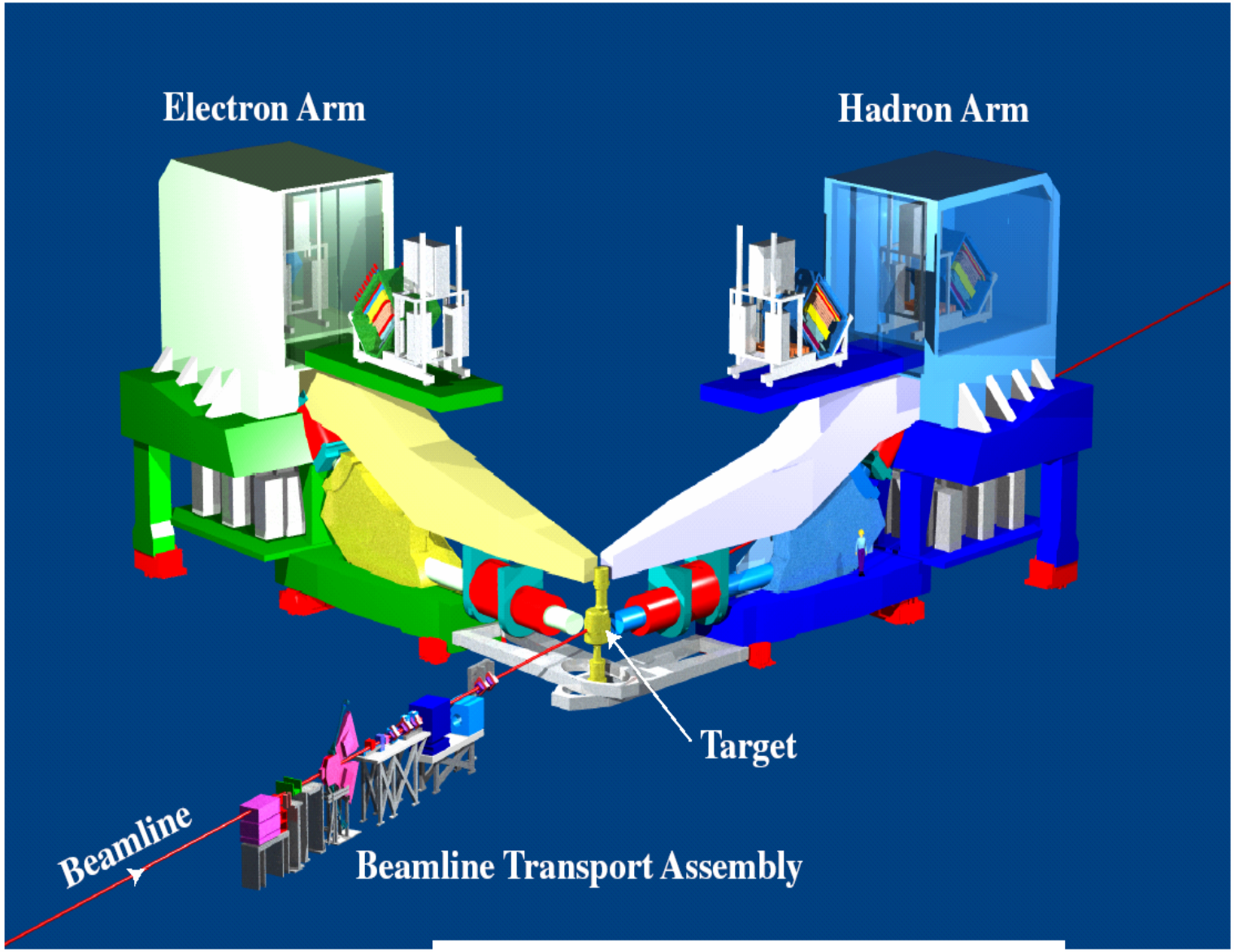
John Arrington	Argonne	spokesperson
Issam Qattan	Northwestern	PhD student
Dave Gaskell	Jefferson Lab	period coordinator
Dave Meekins	Jefferson Lab	period coordinator
Xiaochao Zheng	Argonne	simulations

Reducing uncertainties

1. Better facility.
2. Concentrated on (G_E/G_M)
3. Detected protons (not electrons).
4. Luminosity monitor.

Hall A



older/acombo.ai jm 7/26/00

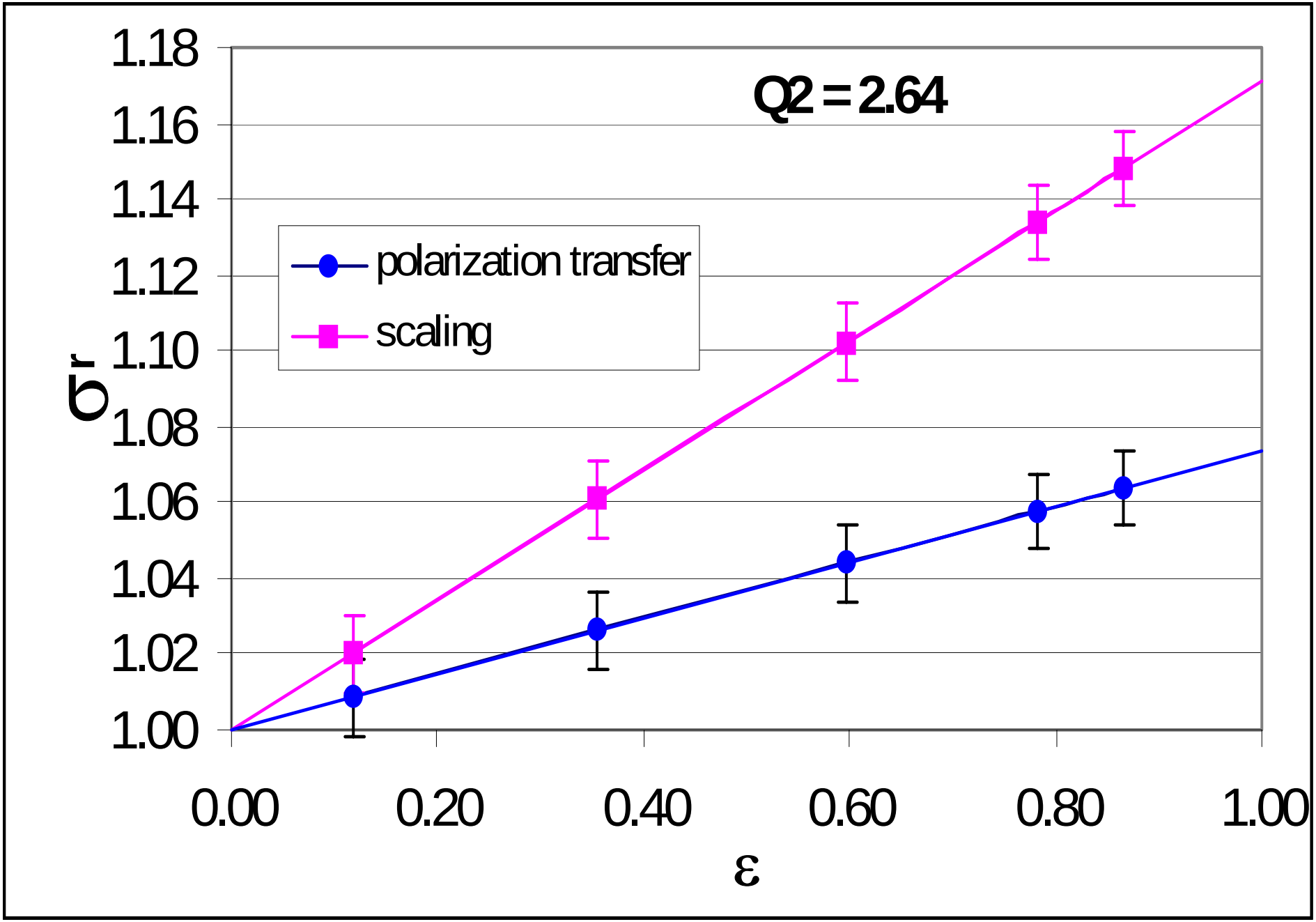
Jefferson Lab

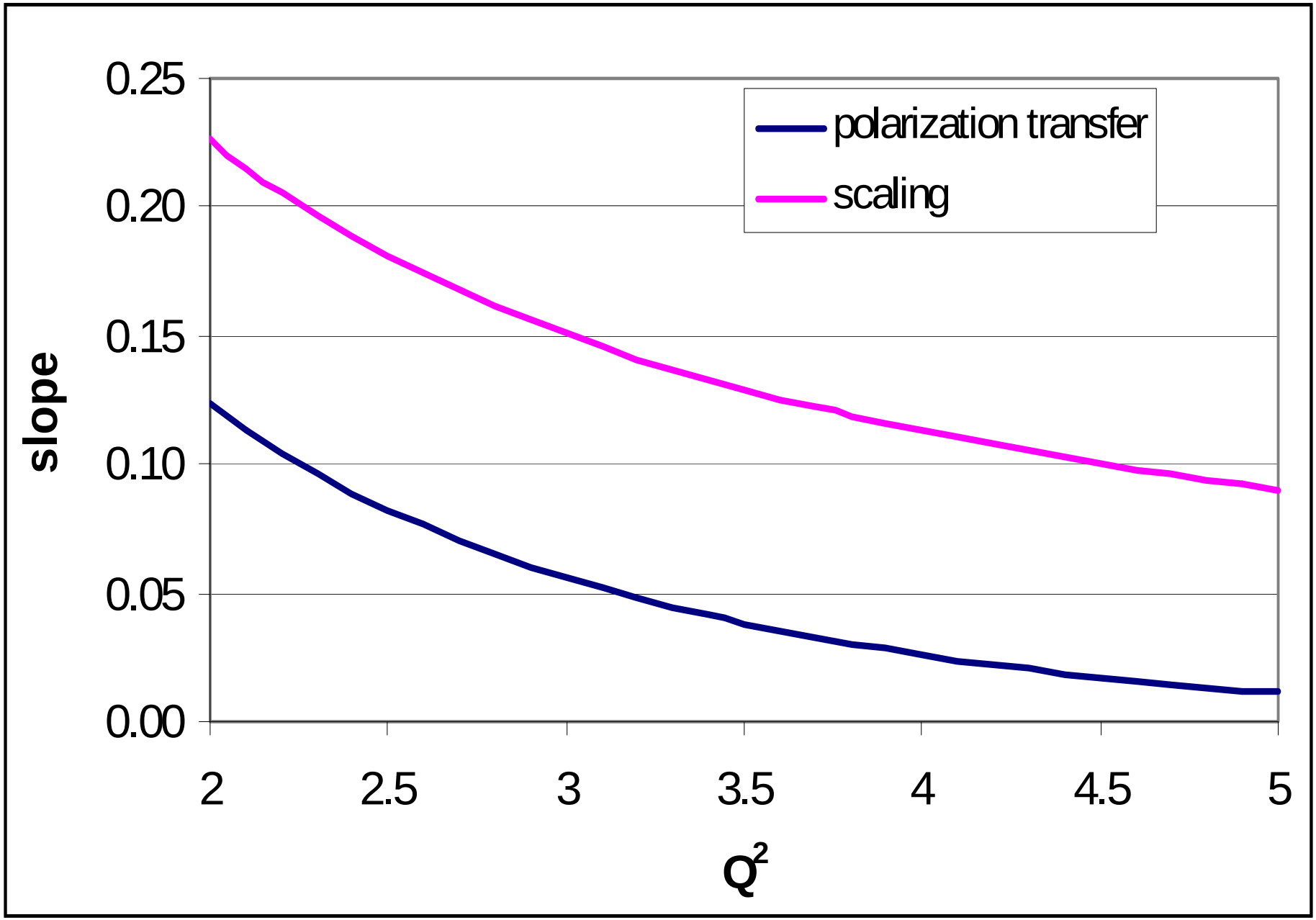
$$\frac{d\sigma}{d\omega}(E,\theta) = (\frac{d\sigma}{d\omega})_{Mott} \frac{1}{\varepsilon}\left(\varepsilon G_E^2 + (\frac{1}{2m_p})^2 Q^2 G_M^2 \right)$$

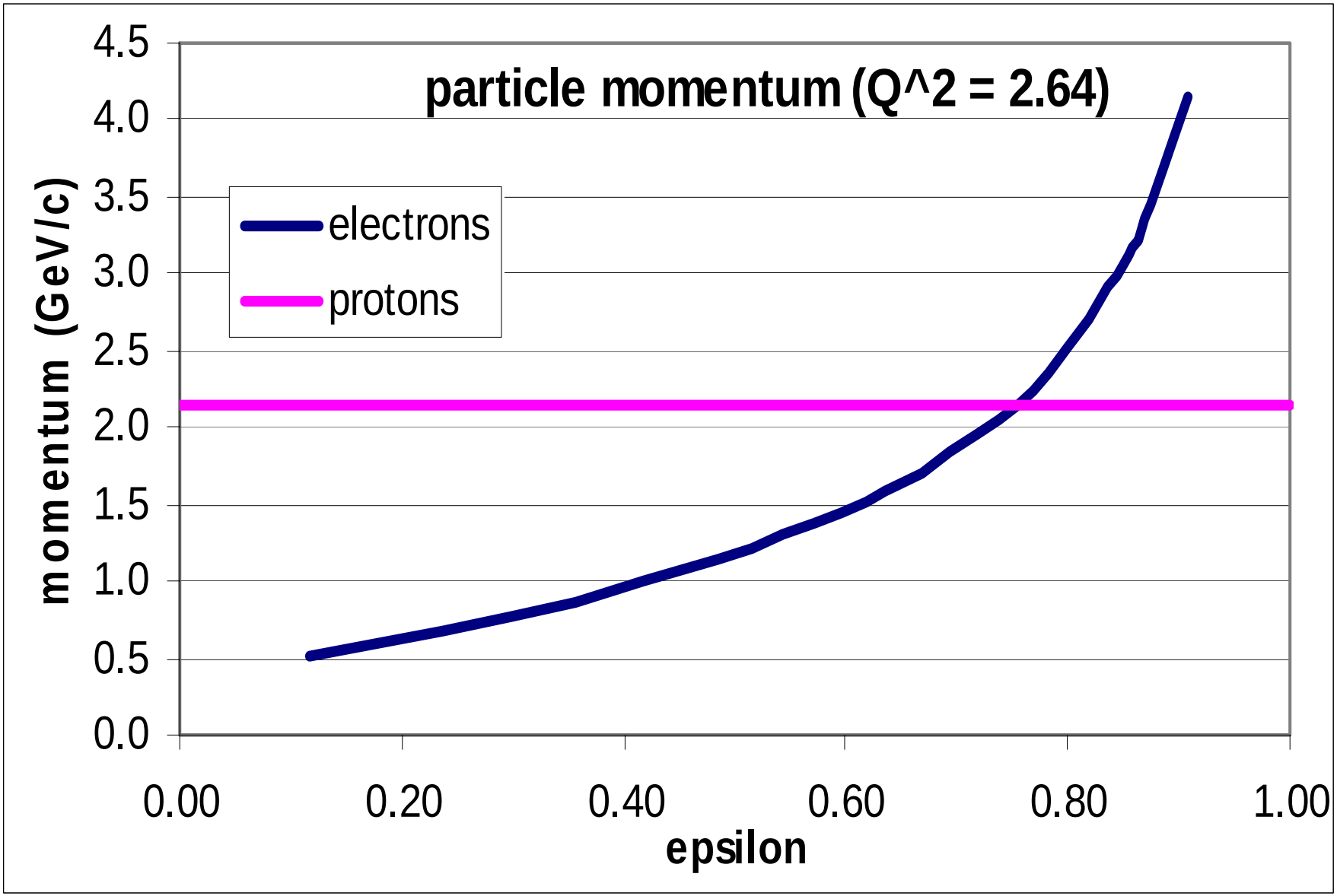
$$= (\frac{d\sigma}{d\omega})_{Mott} \frac{G_M^2}{\mu_p^2 \varepsilon}\left(\varepsilon (\frac{\mu_p G_E}{G_M})^2 + (\frac{\mu_p}{2m_p})^2 Q^2 \right)$$

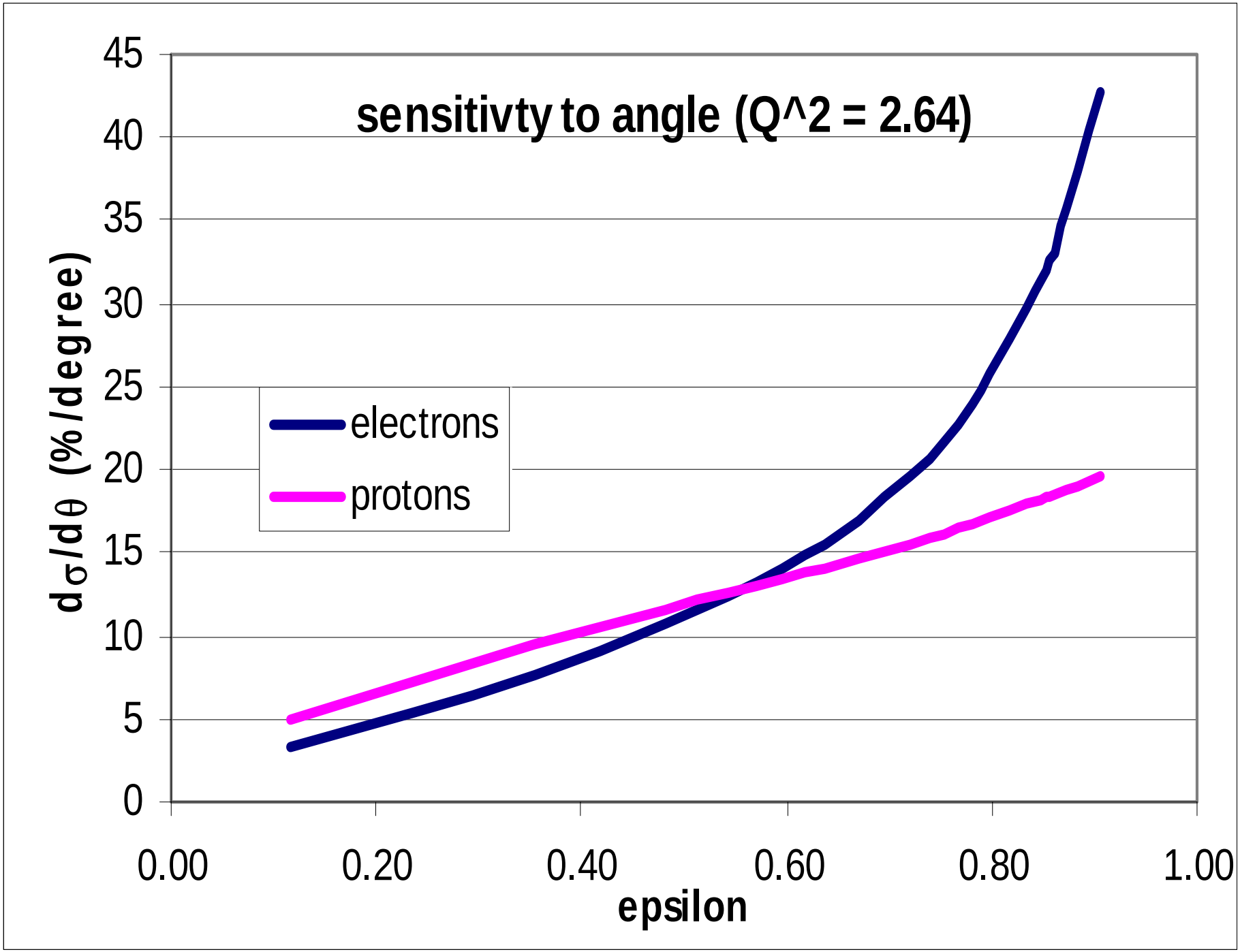
$$= (\frac{d\sigma}{d\omega})_{Mott} \frac{G_M^2}{4m_p^2 \varepsilon} Q^2 \left(1 + (\frac{2m_p}{\mu_p})^2 (\frac{\mu_p G_E}{G_M})^2 \frac{\varepsilon}{Q^2}) \right)$$

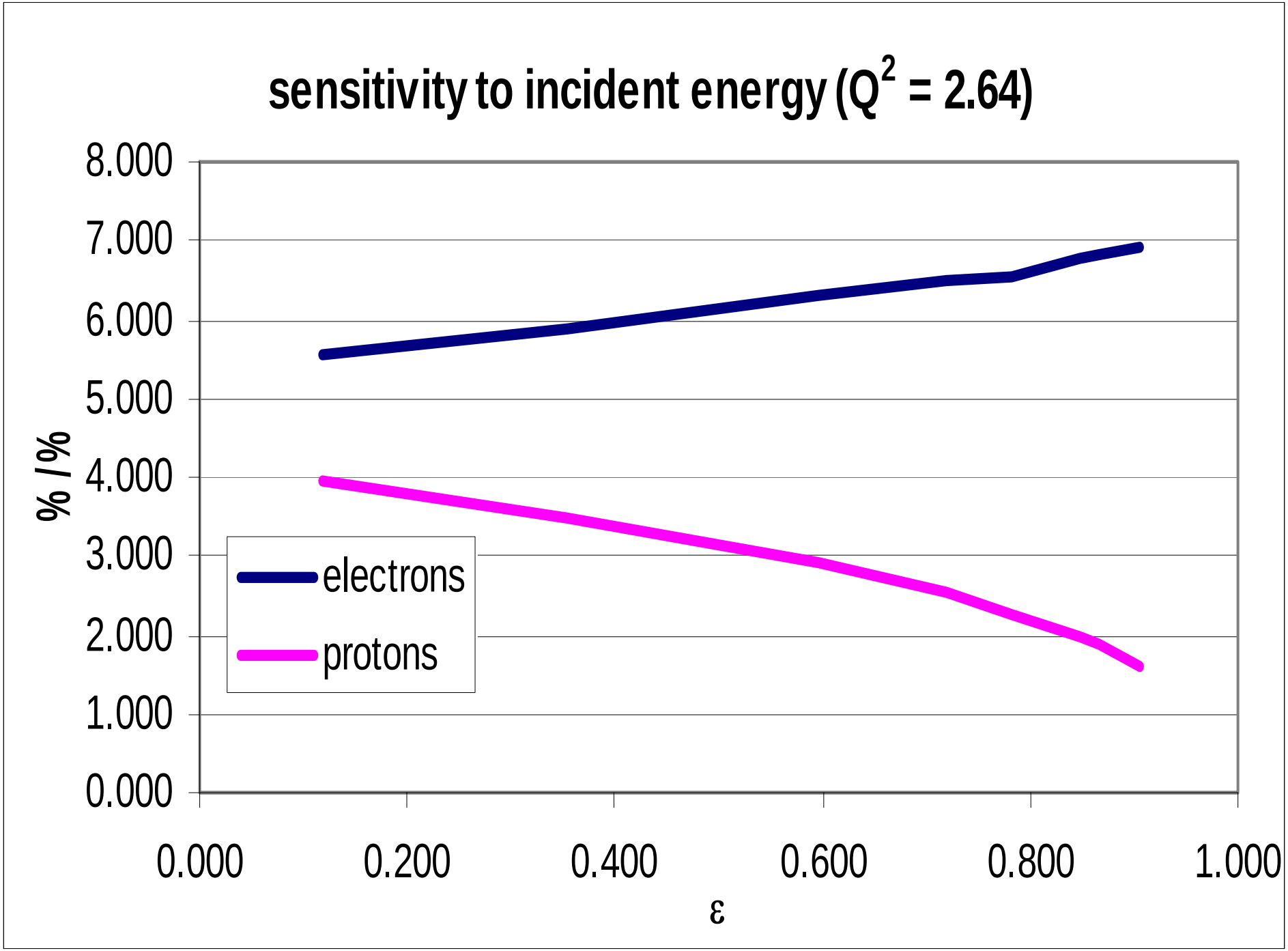
$$= K(E,\theta)\left(1 + \frac{0.452}{Q^2} (\frac{\mu_p G_E}{G_M})^2 \varepsilon) \right)$$

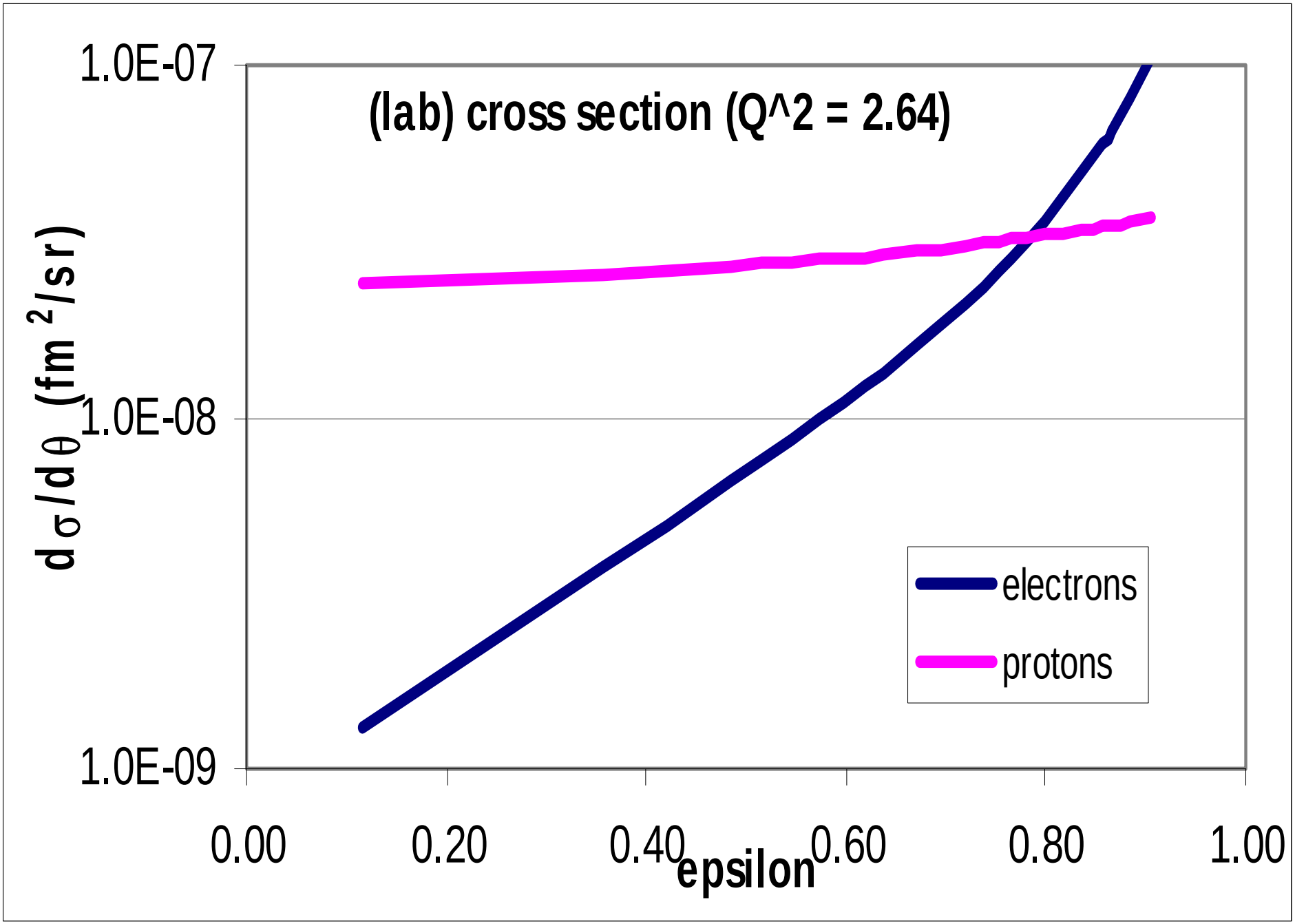

Q2 = 2.64
polarization transfer
scaling
1.18
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.00
0.20
0.40
0.60
0.80
1.00
ε

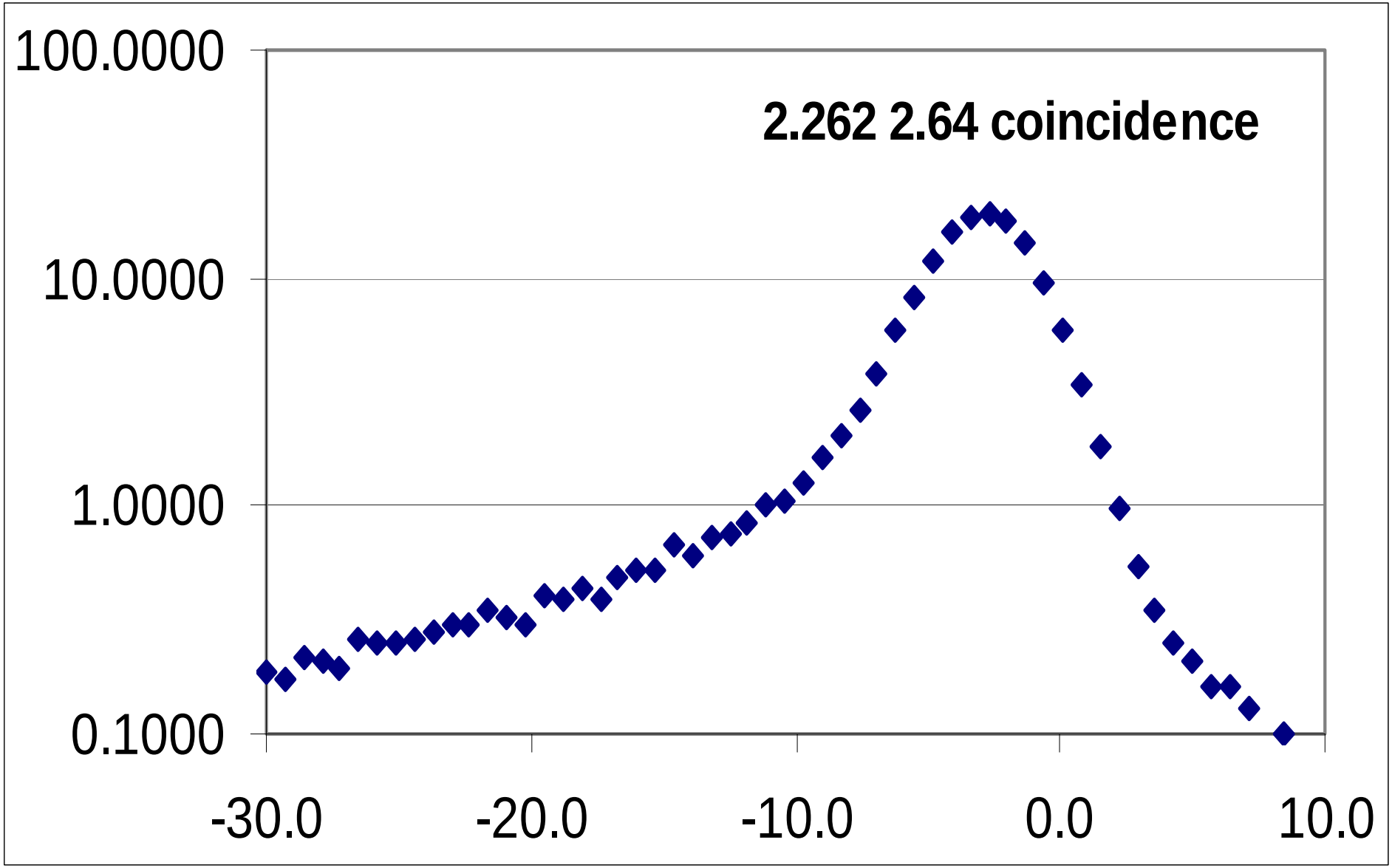

0.25
0.20
0.15
0.10
0.05
0.00
slope
2
2.5
3
3.5
4
4.5
5
Q2
polarization transfer
scaling

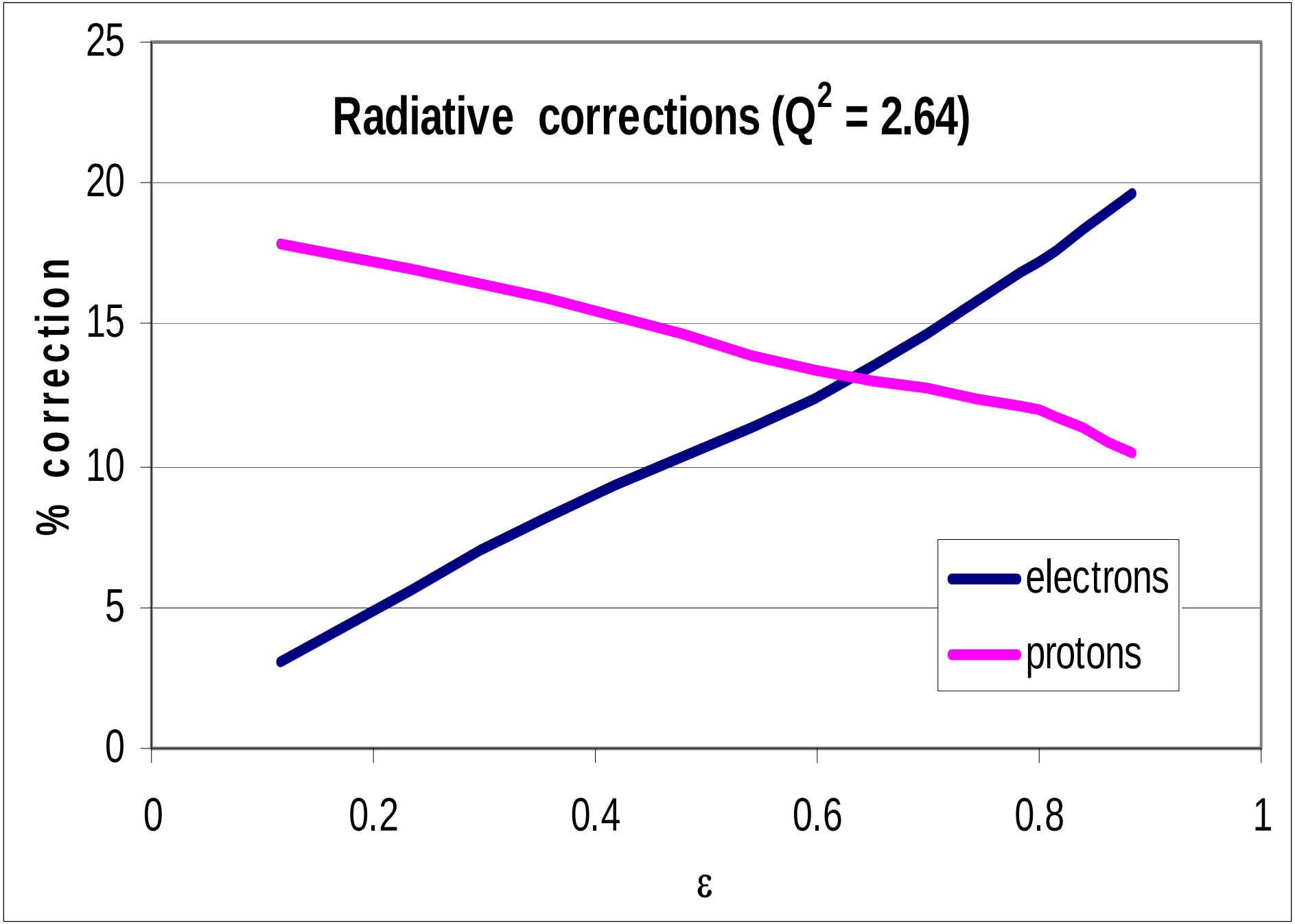

particle momentum (Q^2 = 2.64)
electrons
protons
momentum (GeV/c)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.00
0.20
0.40
0.60
0.80
1.00
epsilon


sensitivty to angle (Q^2 = 2.64)
dσ/dθ (%/degree)
45
40
35
30
25
20
15
10
5
0
0.00
0.20
0.40
0.60
0.80
1.00
epsilon
electrons
protons

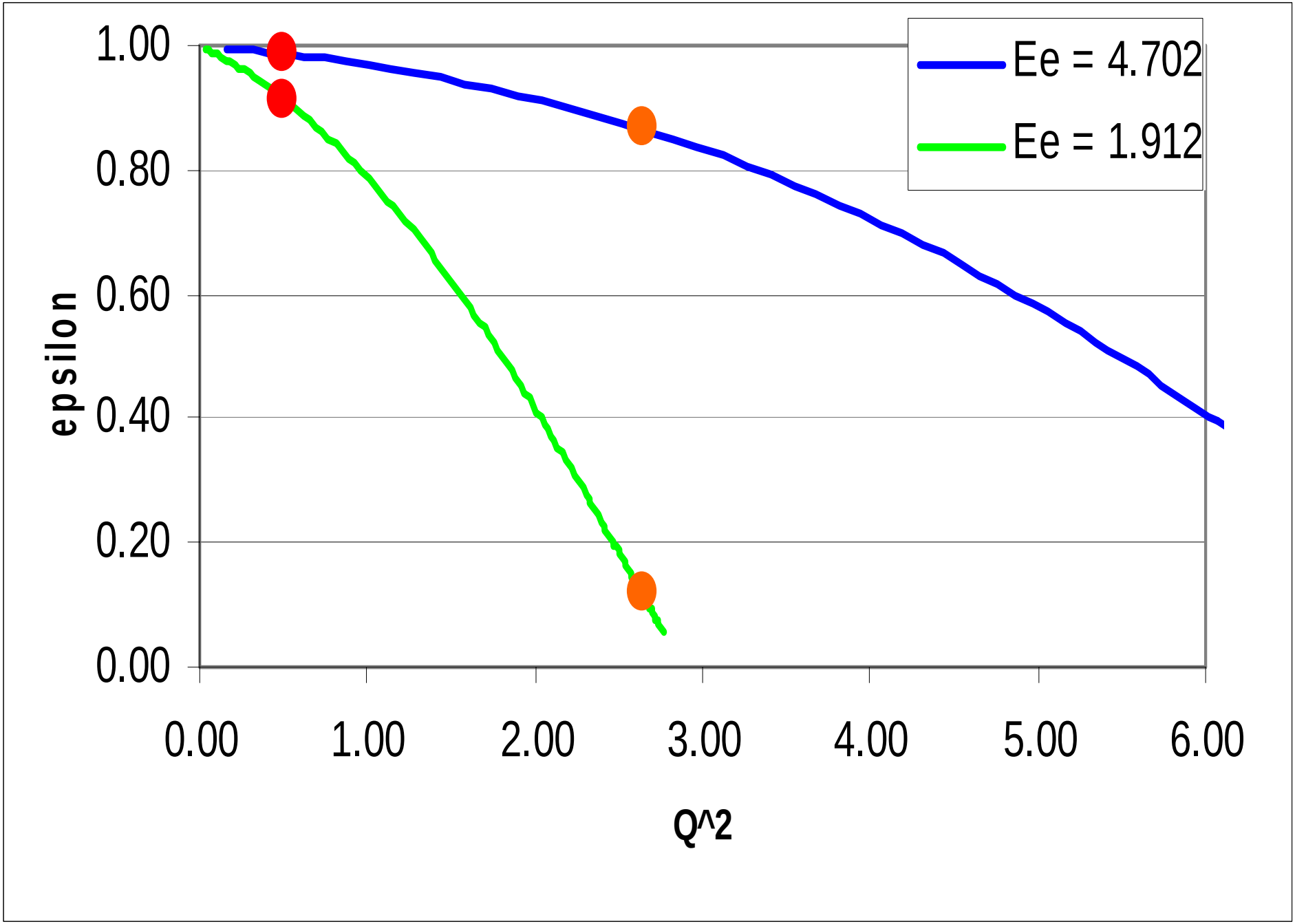

sensitivity to incident energy (Q^2 = 2.64)
8.000
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
% /%
electrons
protons
0.000
0.200
0.400
0.600
0.800
1.000
ε

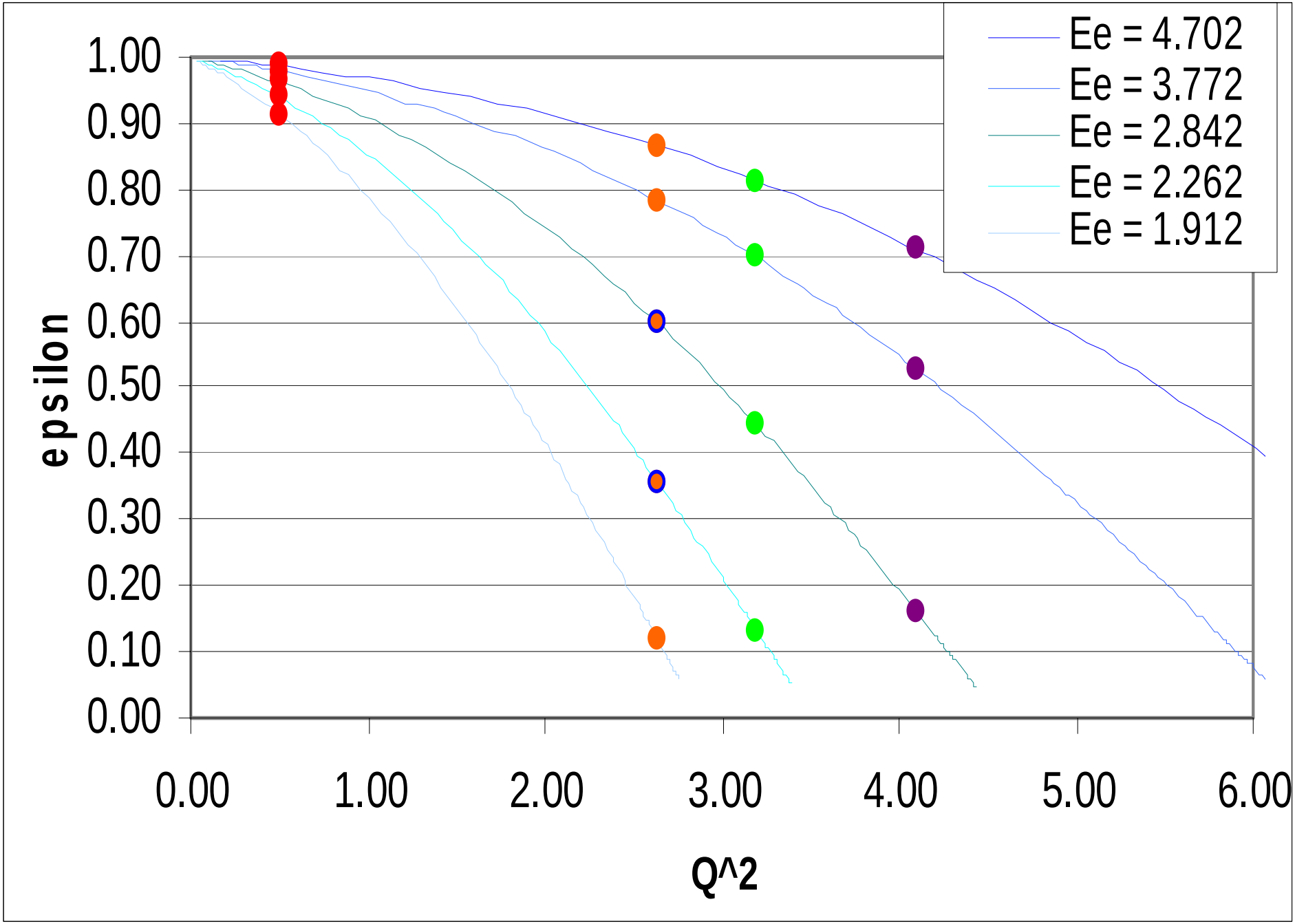

(lab) cross section (Q^2 = 2.64)
1.0E-07
1.0E-08
1.0E-09
dσ/dθ (fm 2/sr)
0.00
0.20
0.40
0.60
0.80
1.00
epsilon
electrons
protons


2.262 2.64 coincidence
100.0000
10.0000
1.0000
0.1000
-30.0
-20.0
-10.0
0.0
10.0


Radiative corrections (Q^2 = 2.64)
% correction
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
ε
electrons
protons

		Radiative Corrections $Q^2 = 2.64$				
	protons			electrons (to π threshold)		
ε		Monte Carlo	Andrei A		Monte Carlo	Andrei A
0.117		**1.178**	**1.113**		**1.030**	**1.075**
0.356		**1.160**	**1.107**		**1.081**	**1.099**
0.597		**1.134**	**1.098**		**1.124**	**1.135**
0.782		**1.121**	**1.087**		**1.168**	**1.163**
0.865		**1.105**	**1.078**		**1.197**	**1.190**
$\Delta\ \varepsilon=1/\varepsilon=0$		**-0.080**	**-0.040**		**0.215**	**0.142**

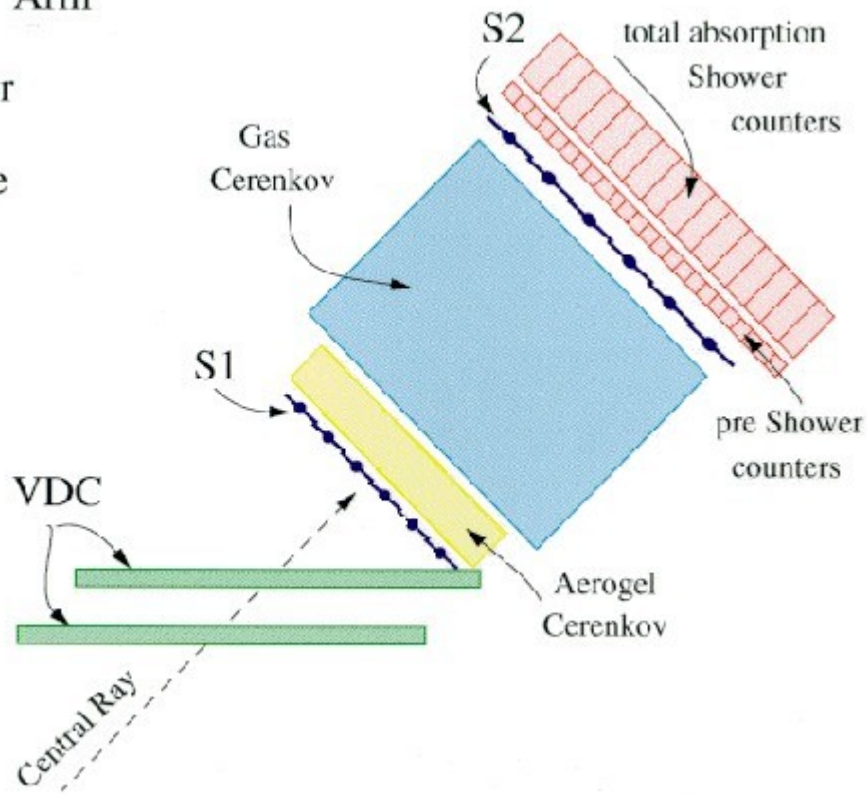

1.00
0.80
0.60
0.40
0.20
0.00
epsilon
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Q^2
Ee = 4.702
Ee = 1.912

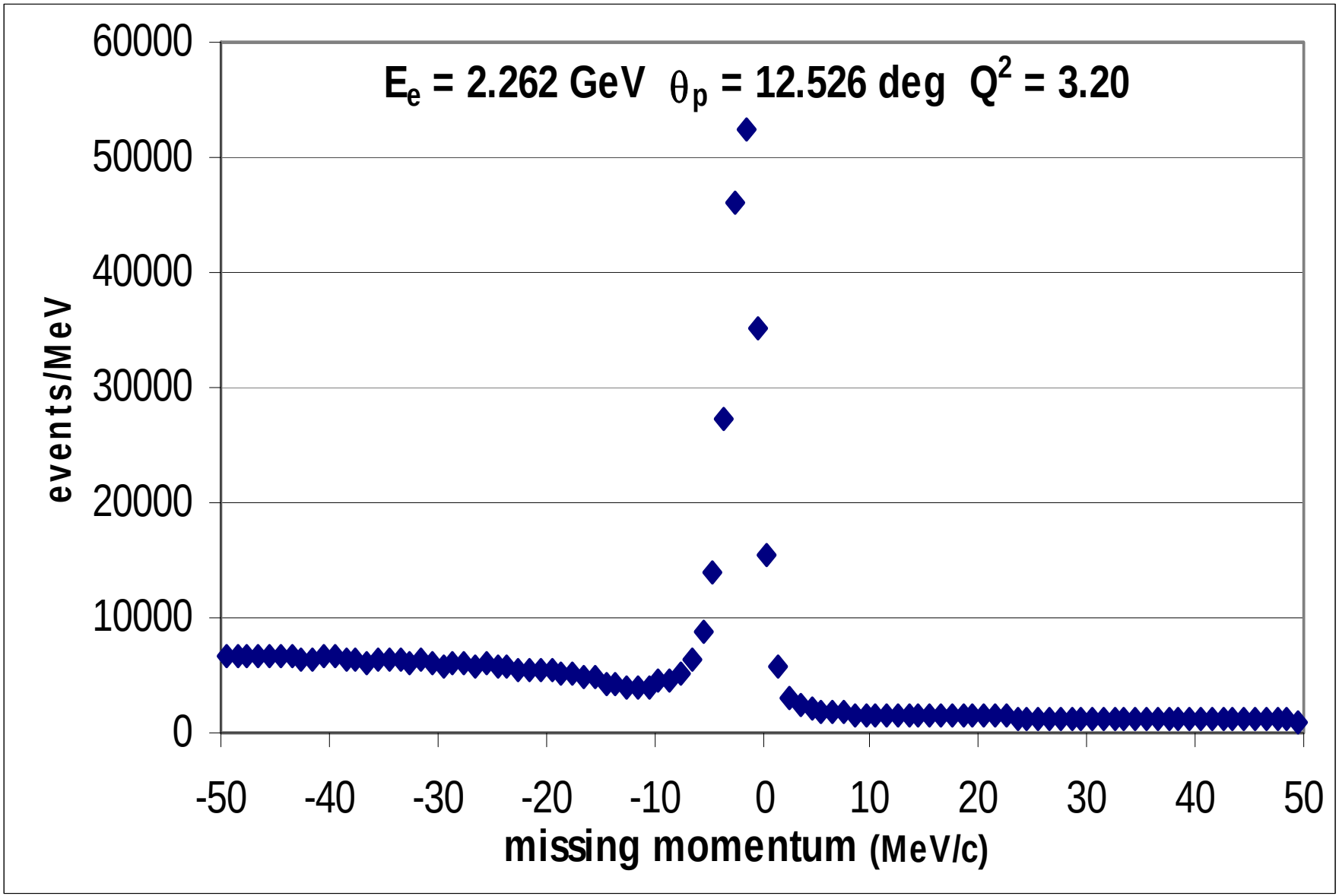

Ee = 4.702
Ee = 3.772
Ee = 2.842
Ee = 2.262
Ee = 1.912
epsilon
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Q^2

Electron Arm

Detector

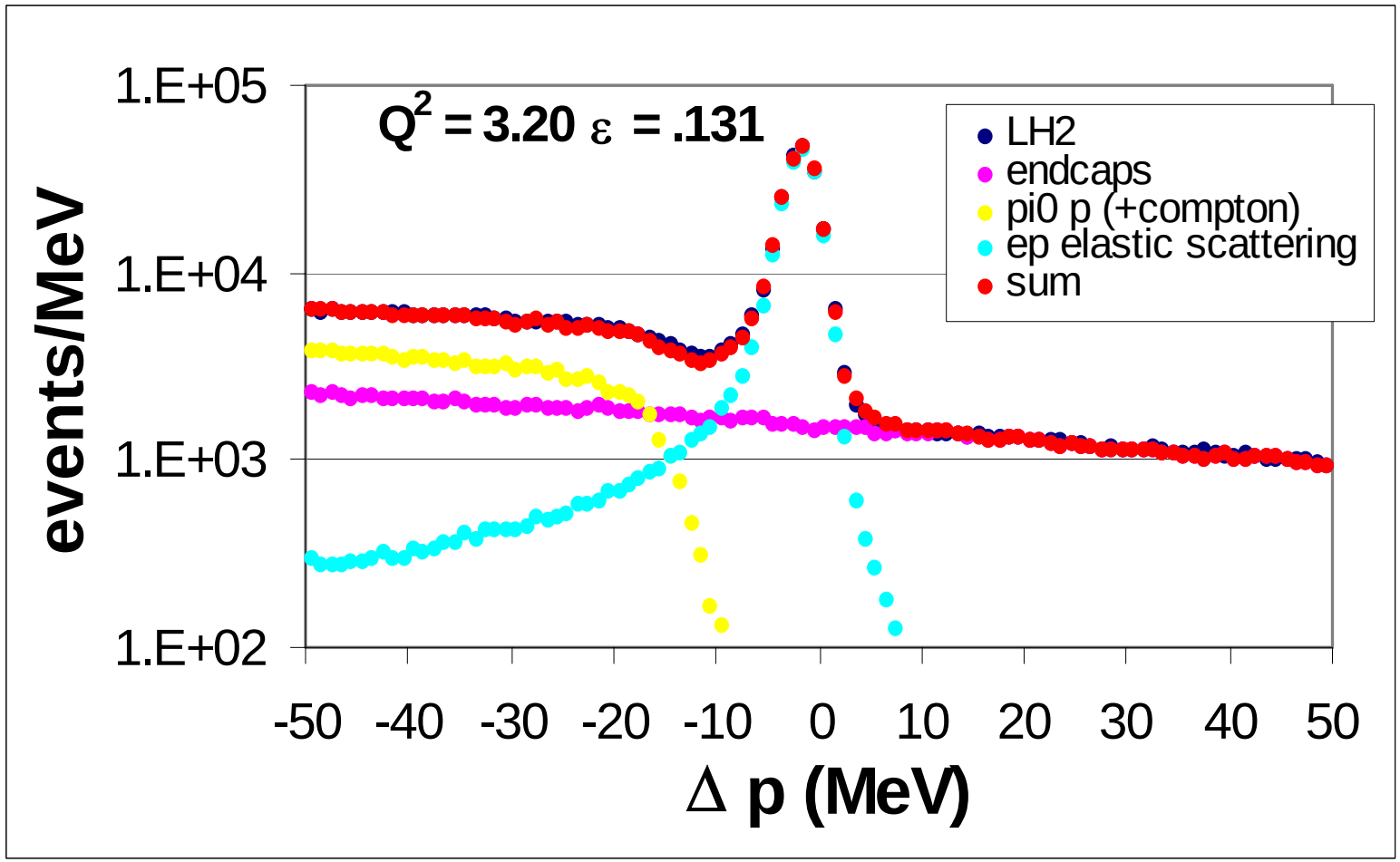
Package

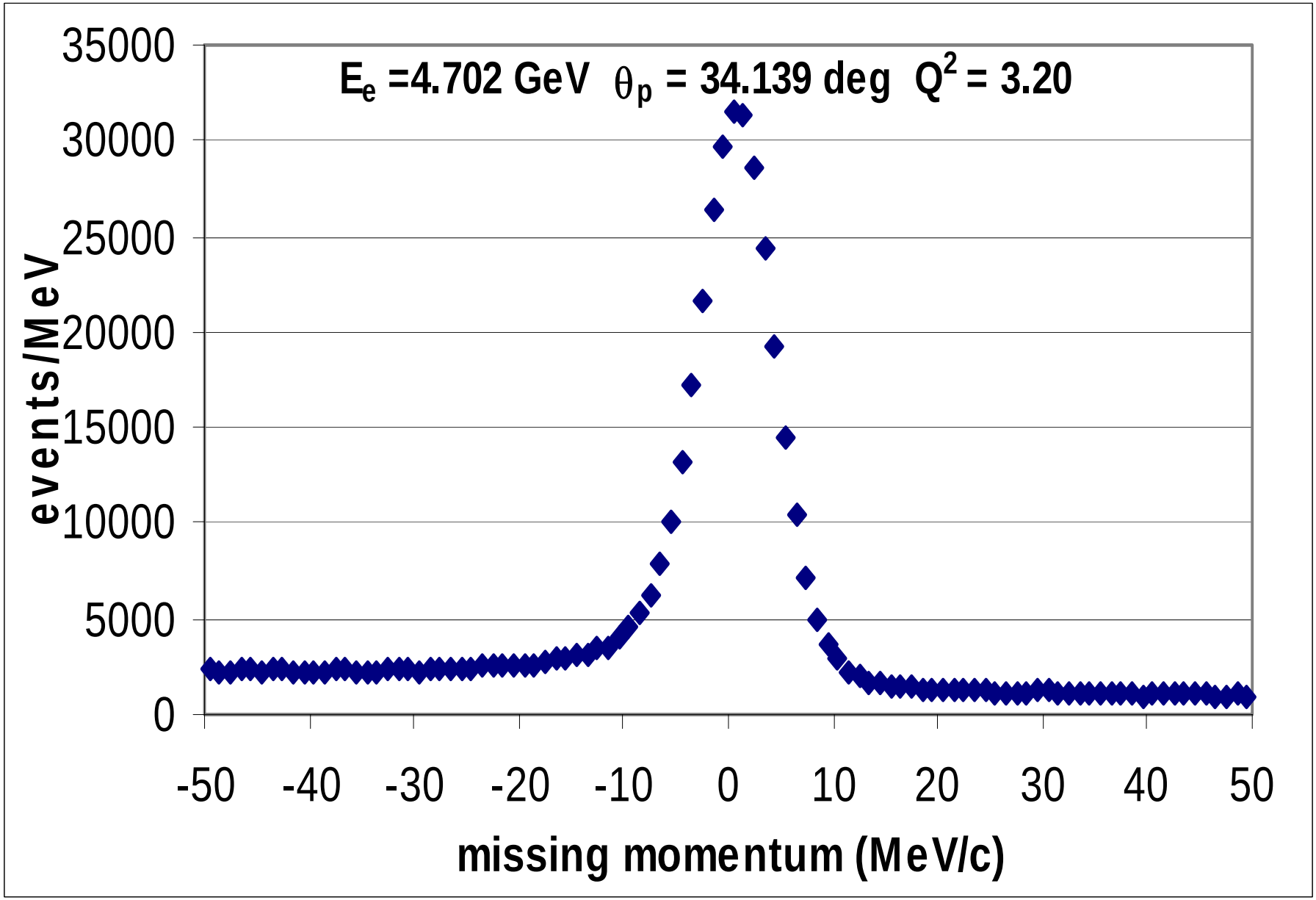


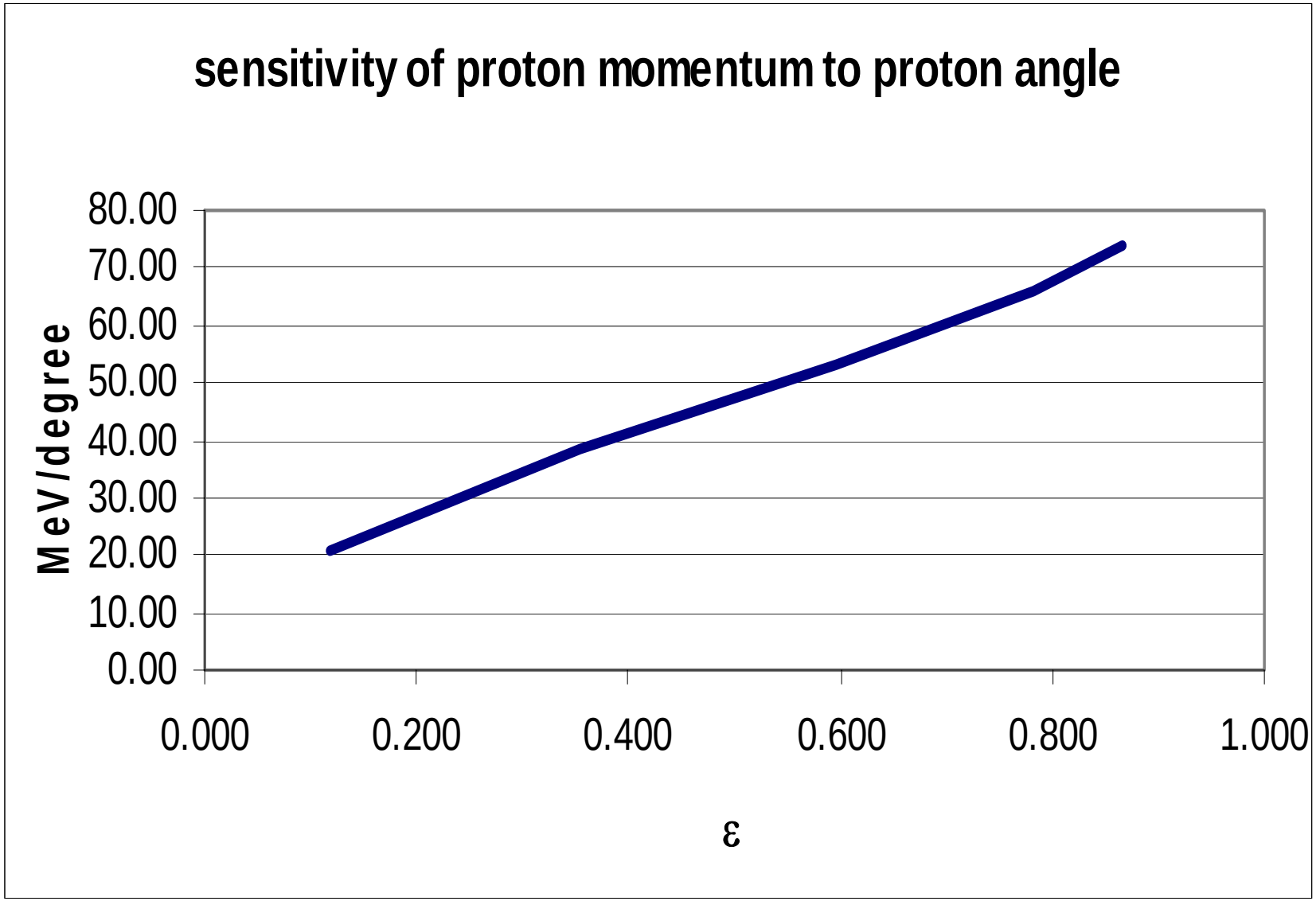

E_e = 2.262 GeV θ_p = 12.526 deg Q^2 = 3.20
60000
50000
40000
30000
20000
10000
0
events/MeV
-50
-40
-30
-20
-10
0
10
20
30
40
50
missing momentum (MeV/c)

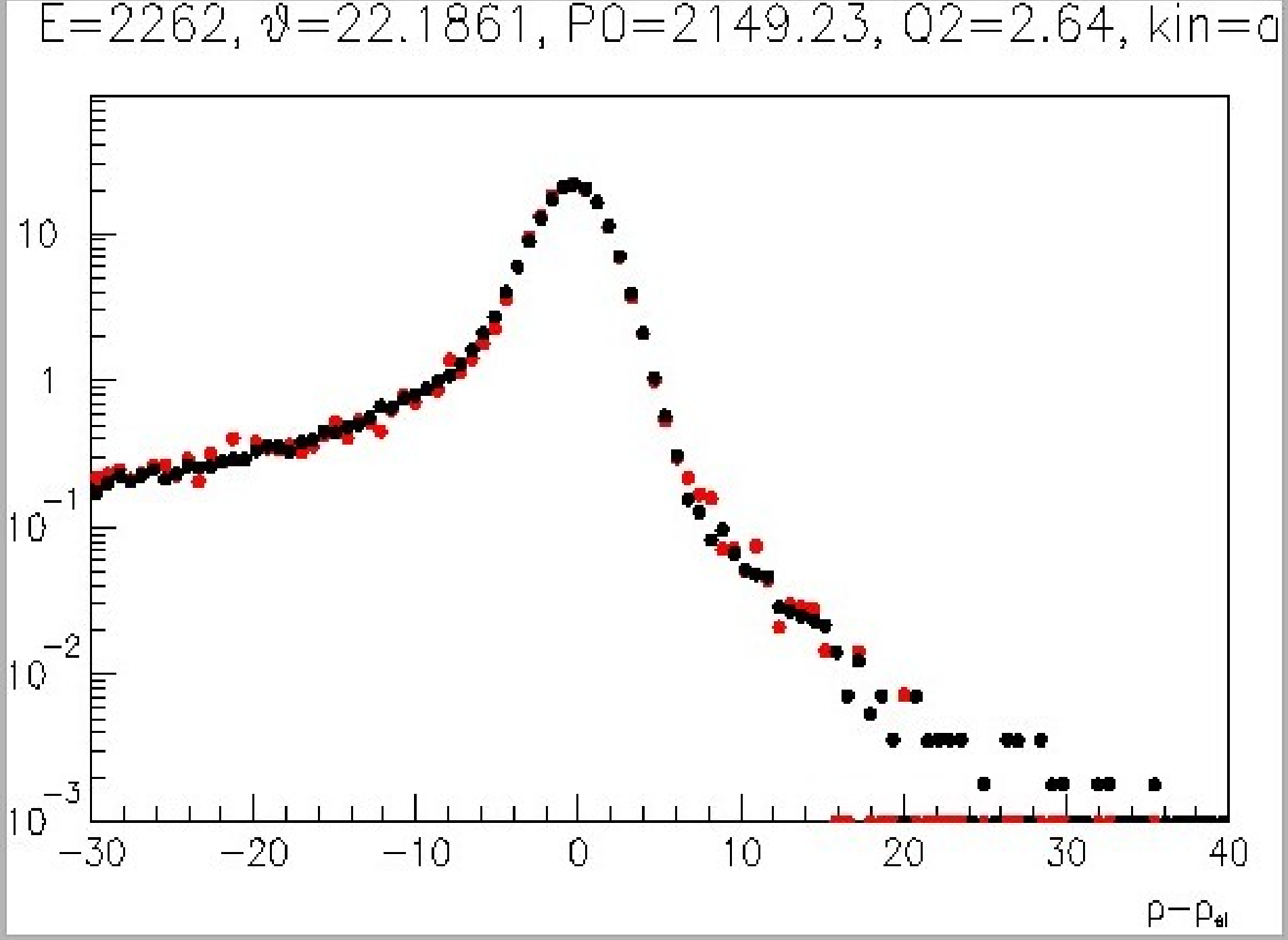
Spectrum Components

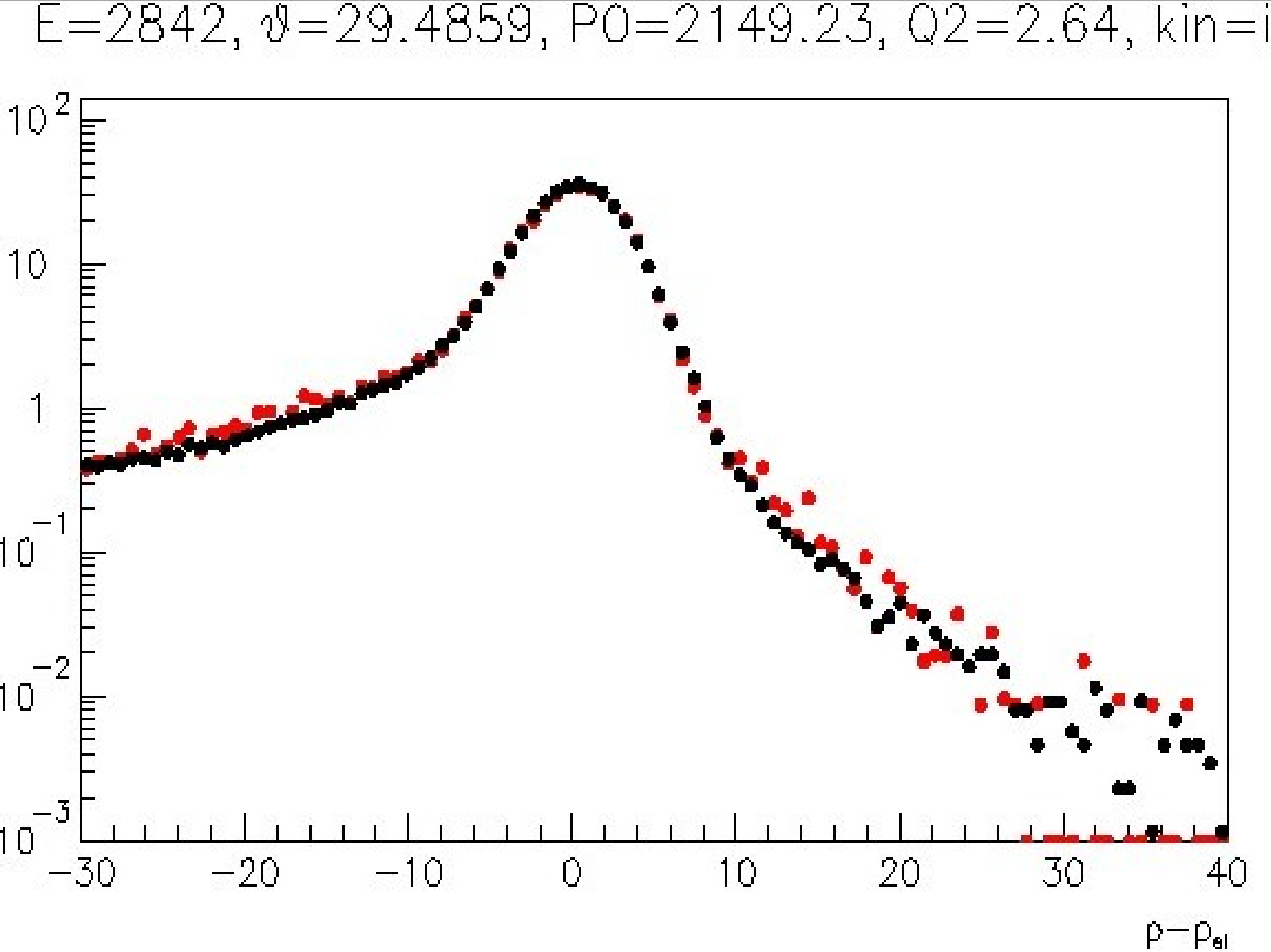
$e^- p \rightarrow e^- p$	physics
reactions in end caps, primarily quasi-elastic scattering	take data with empty (dummy) target
$\gamma p \rightarrow \pi^0 p$	simulate with bremsstrahlung spectrum,
s-7 cross section dependence - some data available	
$\gamma p \rightarrow \gamma p$ ("Compton")	~2% of π^0 production – some data available


Q^2 = 3.20 ε = .131
LH2
endcaps
pi0 p (+compton)
ep elastic scattering
sum
1.E+05
1.E+04
1.E+03
1.E+02
events/MeV
-50
-40
-30
-20
-10
0
10
20
30
40
50
Δ p (MeV)


E_e =4.702 GeV θ_p = 34.139 deg Q^2 = 3.20
35000
30000
25000
20000
15000
10000
5000
0
events/MeV
-50
-40
-30
-20
-10
0
10
20
30
40
50
missing momentum (MeV/c)


sensitivity of proton momentum to proton angle
MeV/degree
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0.000
0.200
0.400
0.600
0.800
1.000
ε

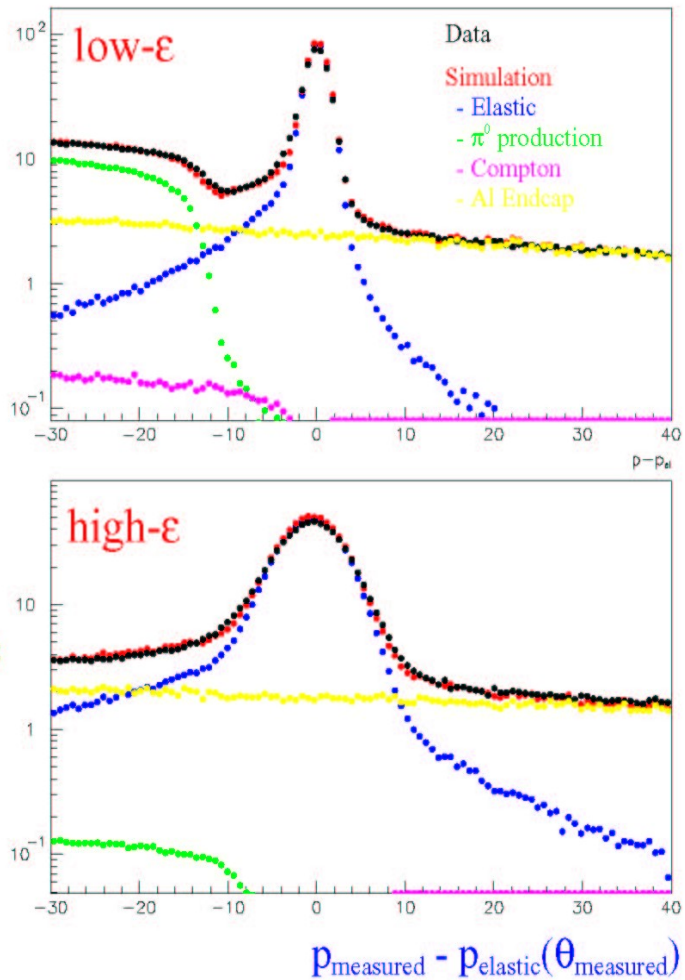

E=2262, ϑ=22.1861, P0=2149.23, Q2=2.64, kin=a
10
1
10^-1
10^-2
10^-3
−30
−20
−10
0
10
20
30
40
P−P_el

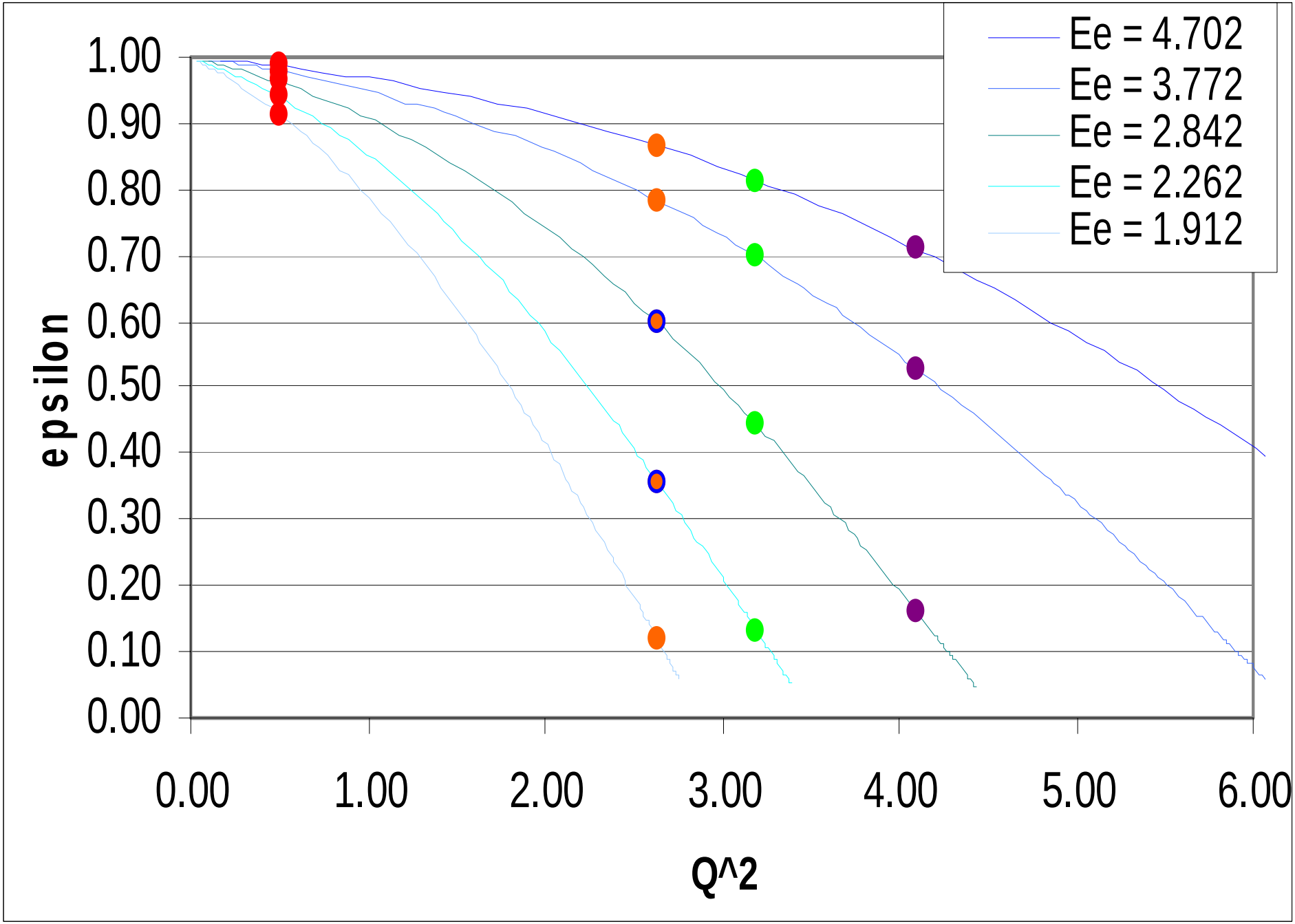

E=2842, ϑ=29.4859, P0=2149.23, Q2=2.64, kin=i
10^2
10
1
10^-1
10^-2
10^-3
−30
−20
−10
0
10
20
30
40
p−p_el

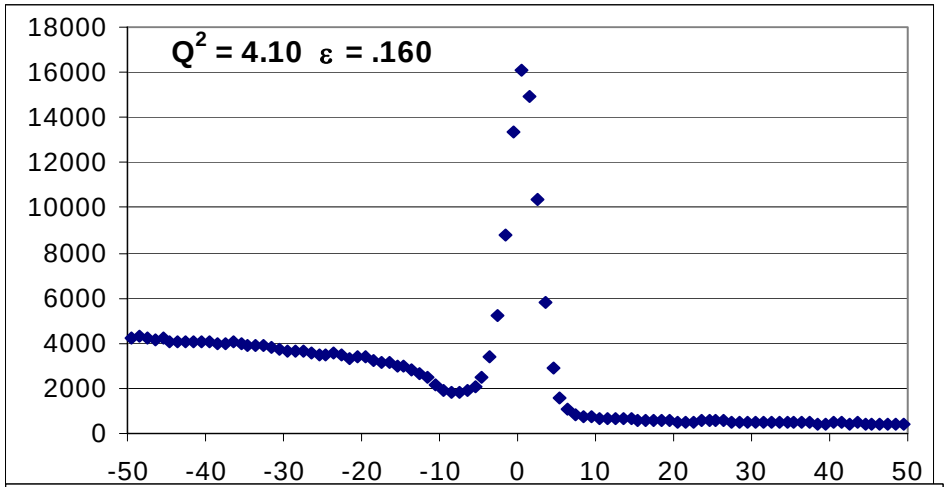
Backgrounds: Q^2=2.64 GeV^2

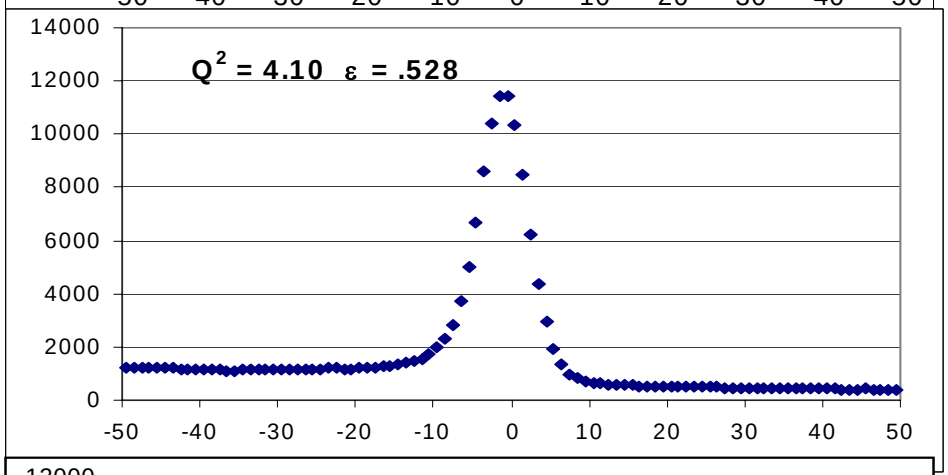
Forward angles:
- -Background large
- -Resolution is good
- –π threshold is low

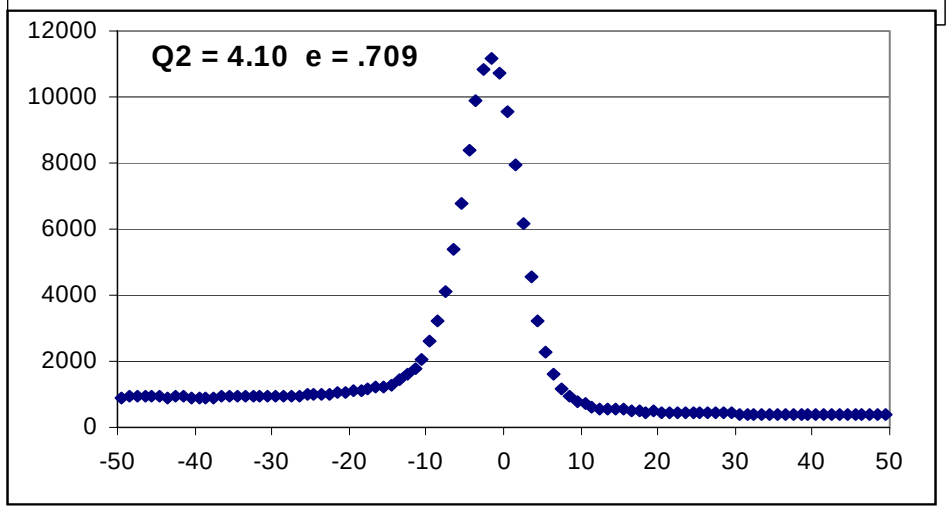
Back angles:
- -Resolution is worse
- -π threshold close to elastic
- -Background small




Ee = 4.702
Ee = 3.772
Ee = 2.842
Ee = 2.262
Ee = 1.912
epsilon
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Q^2


Q^2 = 4.10 ε = .160
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
-50 -40 -30 -20 -10 0 10 20 30 40 50


Q^2 = 4.10 ε = .528
14000
12000
10000
8000
6000
4000
2000
0
-50 -40 -30 -20 -10 0 10 20 30 40 50


Q2 = 4.10 e = .709
12000
10000
8000
6000
4000
2000
0
-50 -40 -30 -20 -10 0 10 20 30 40 50

$$\frac{d\sigma}{d\omega}(E,\theta) = (\frac{d\sigma}{d\omega})_{Mott} \frac{1}{\varepsilon}\left(\varepsilon G_E^2 + (\frac{1}{2m_p})^2 Q^2 G_M^2 \right)$$

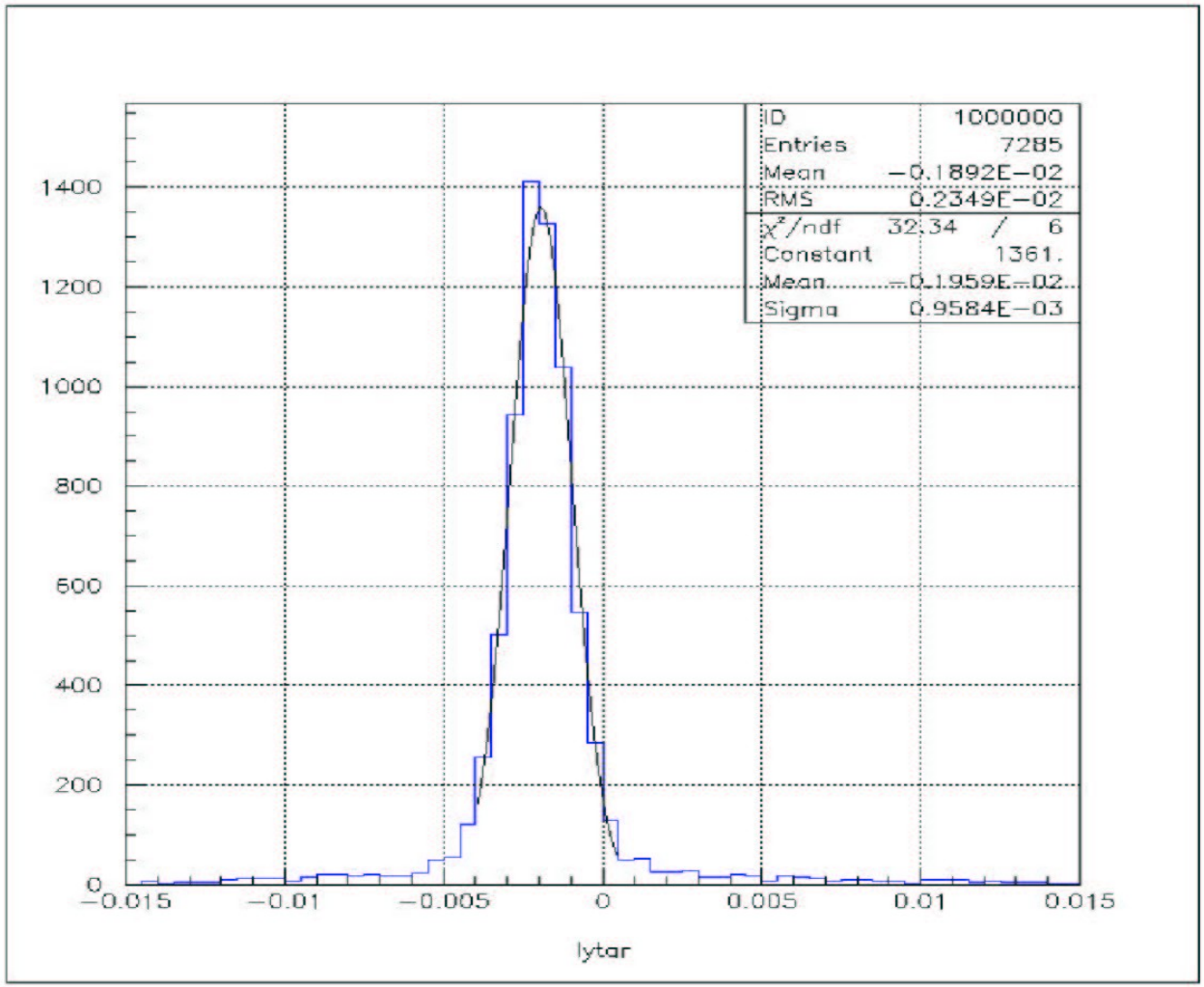
$$= (\frac{d\sigma}{d\omega})_{Mott} \frac{G_M^2}{\mu_p^2 \varepsilon}\left(\varepsilon (\frac{\mu_p G_E}{G_M})^2 + (\frac{\mu_p}{2m_p})^2 Q^2 \right)$$

$$= (\frac{d\sigma}{d\omega})_{Mott} \frac{G_M^2}{4m_p^2 \varepsilon} Q^2 \left(1 + (\frac{2m_p}{\mu_p})^2 (\frac{\mu_p G_E}{G_M})^2 \frac{\varepsilon}{Q^2}) \right)$$

$$= K(E,\theta)\left(1 + \frac{0.452}{Q^2} (\frac{\mu_p G_E}{G_M})^2 \varepsilon) \right)$$

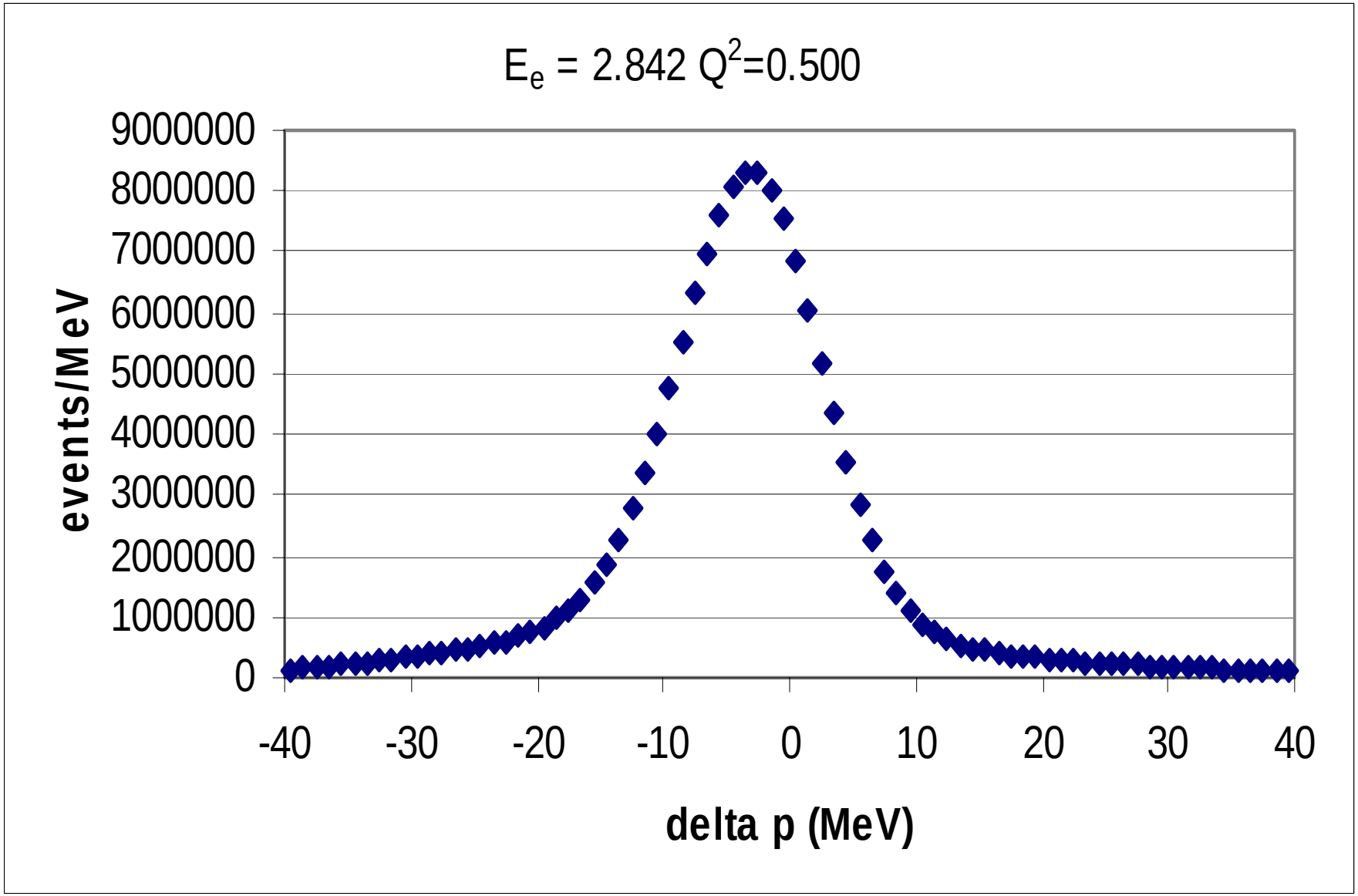
Sensitivity of cross section to proton angle (%/degree)

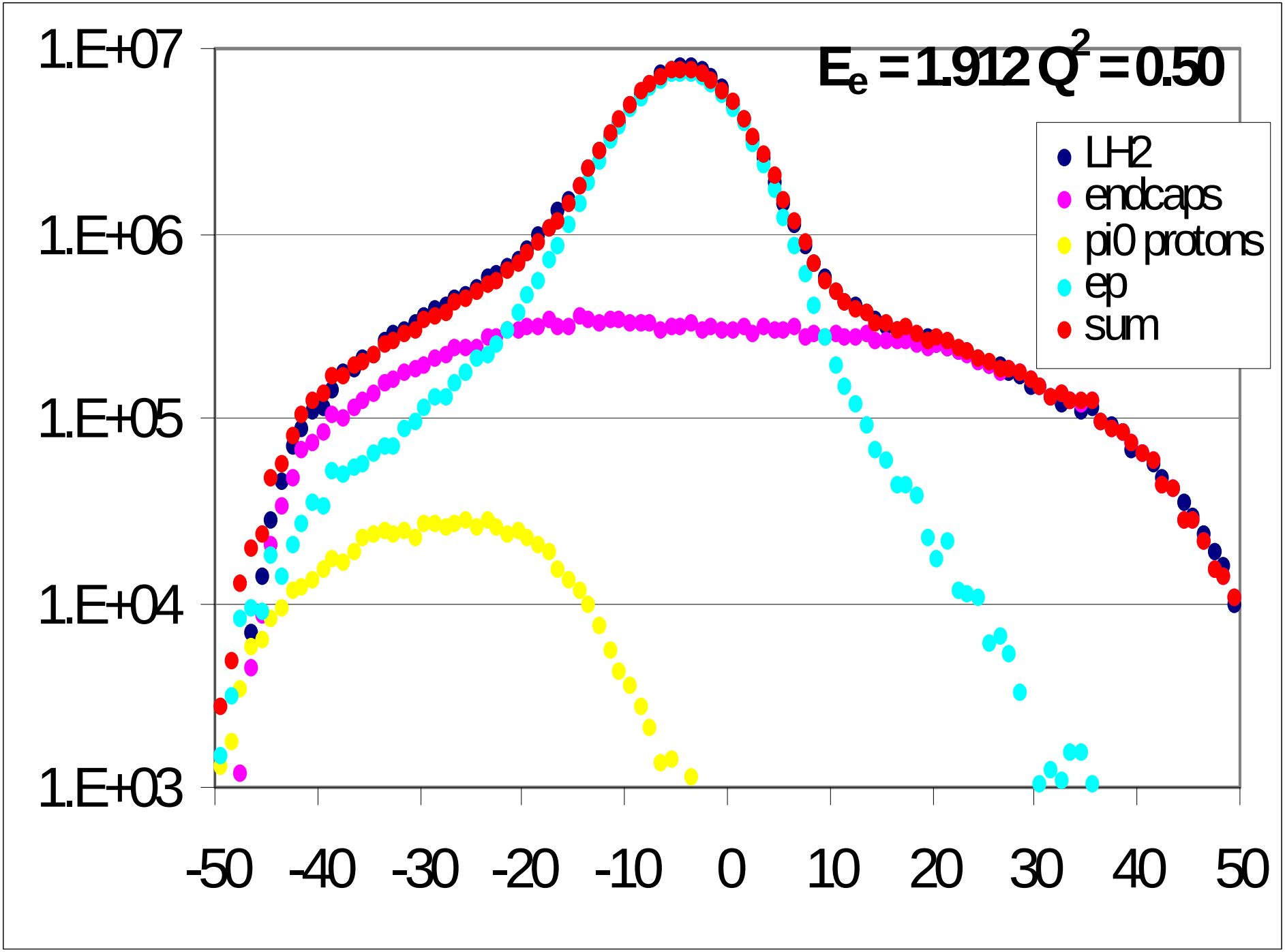
EE\Q^2	0.500	2.640	3.200	4.100
1.912	17.403	5.023		
2.262	18.573	9.449	5.559	
2.842	19.999	13.393	11.302	6.533
3.772	21.504	16.679	15.577	13.409
4.702	22.490	18.492	17.818	16.541

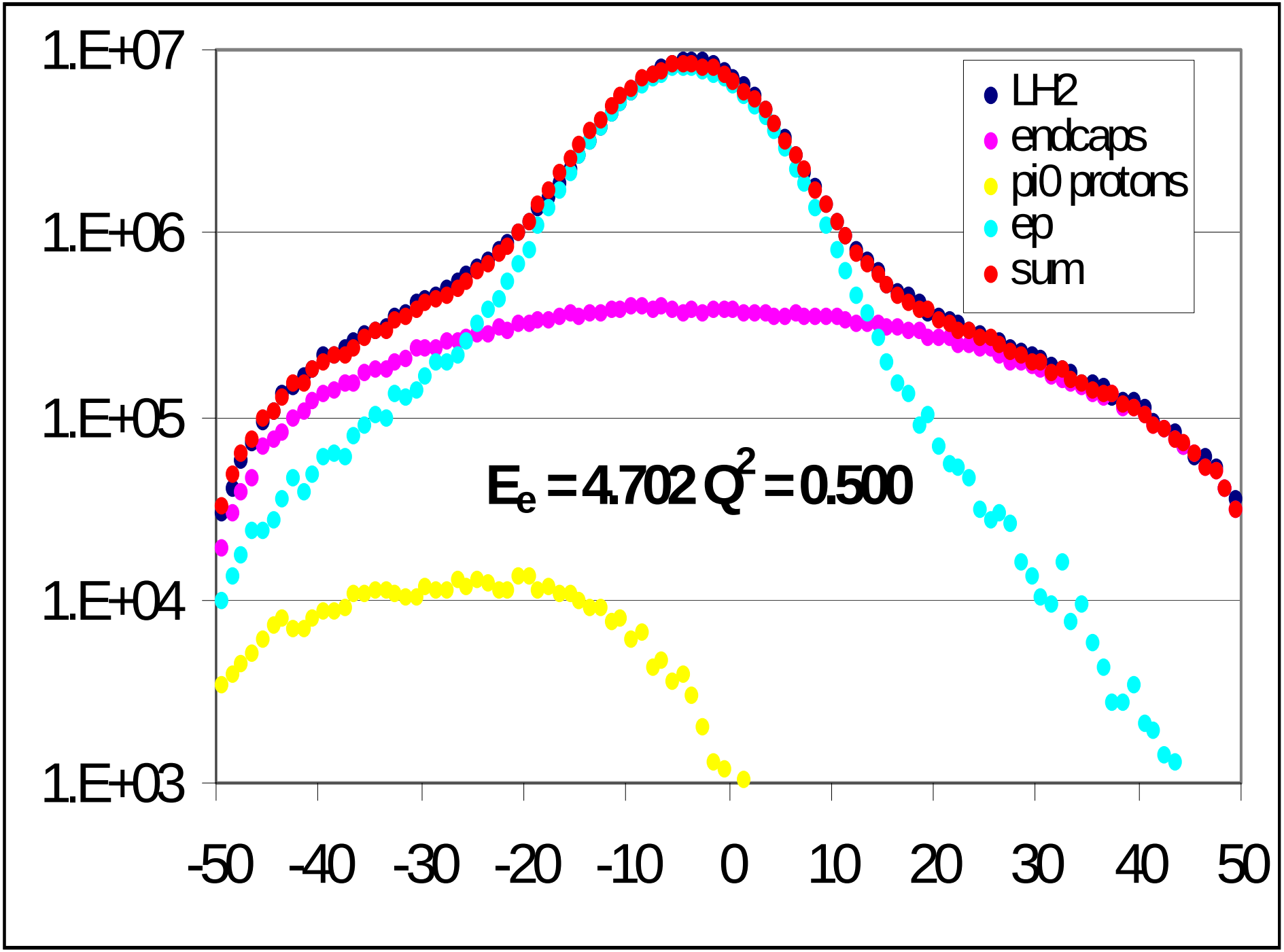

ID 1000000
Entries 7285
Mean −0.1892E−02
RMS 0.2349E−02
χ²/ndf 32.34 / 6
Constant 1361.
Mean −0.1959E−02
Sigma 0.9584E−03
1400
1200
1000
800
600
400
200
0
−0.015
−0.01
−0.005
0
0.005
0.01
0.015
lytar

Angles in degrees

pointing angle	survey angle	difference
22.170	22.155	0.015
12.692	12.674	0.018
28.384	28.368	0.016
12.642	12.624	0.018
23.670	23.652	0.017

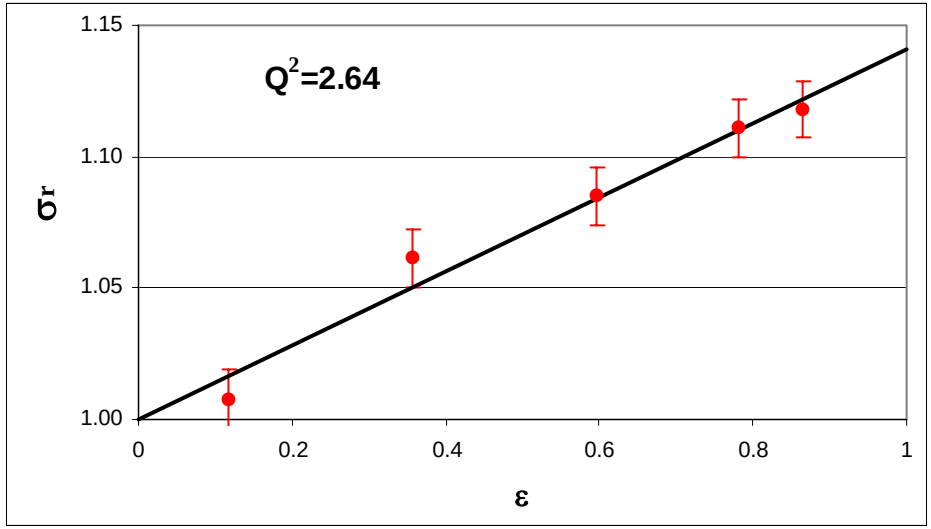

E_e = 2.842 Q^2=0.500
9000000
8000000
7000000
6000000
5000000
4000000
3000000
2000000
1000000
0
events/MeV
-40
-30
-20
-10
0
10
20
30
40
delta p (MeV)

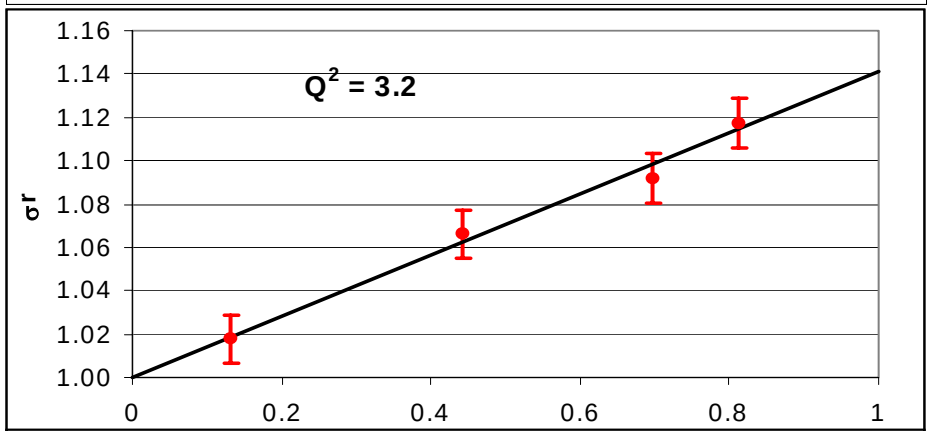

$E_e = 1.912$ $Q^2 = 0.50$
LH2
endcaps
pi0 protons
ep
sum
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
-50
-40
-30
-20
-10
0
10
20
30
40
50

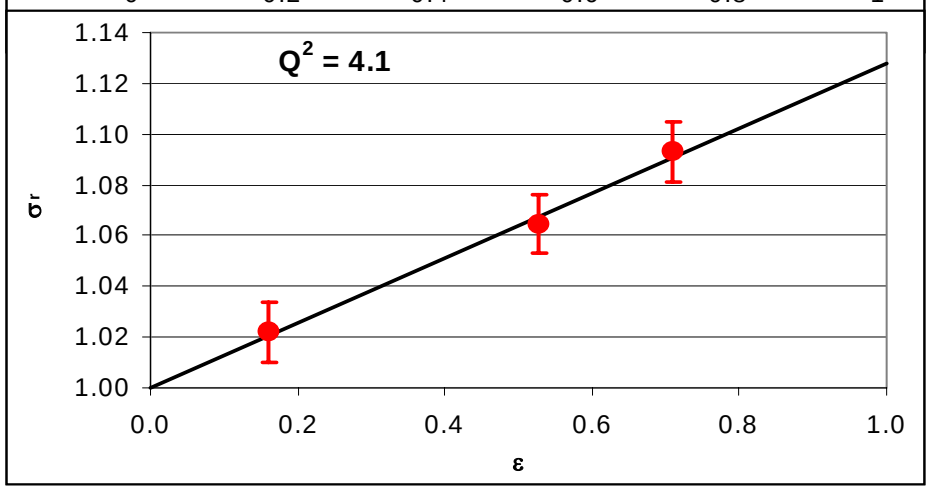

1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
-50
-40
-30
-20
-10
0
10
20
30
40
50
LH2
endcaps
pi0 protons
ep
sum
$E_e = 4.702\ Q^2 = 0.500$

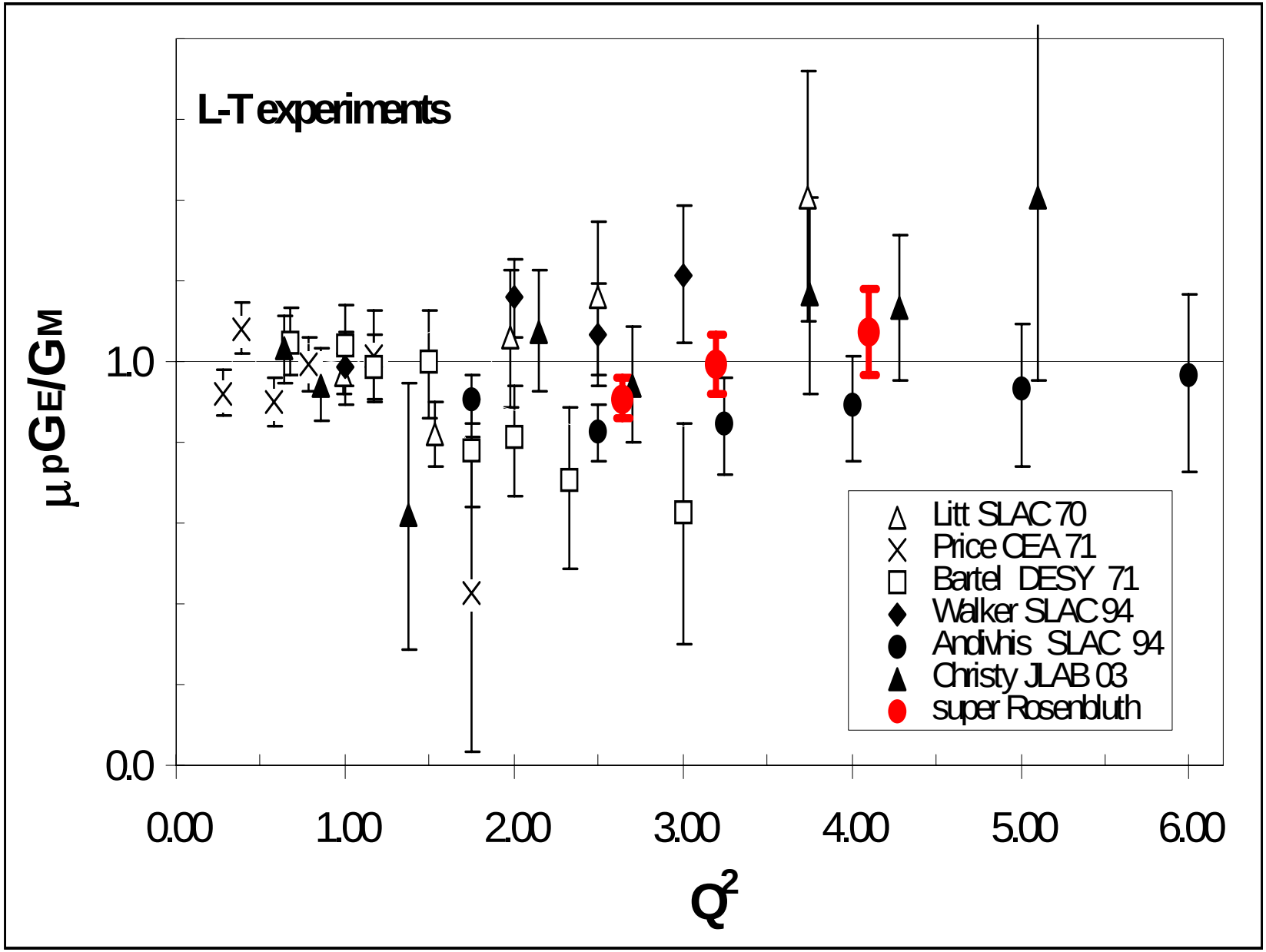
Q^2=0.500 (luminosity monitor)

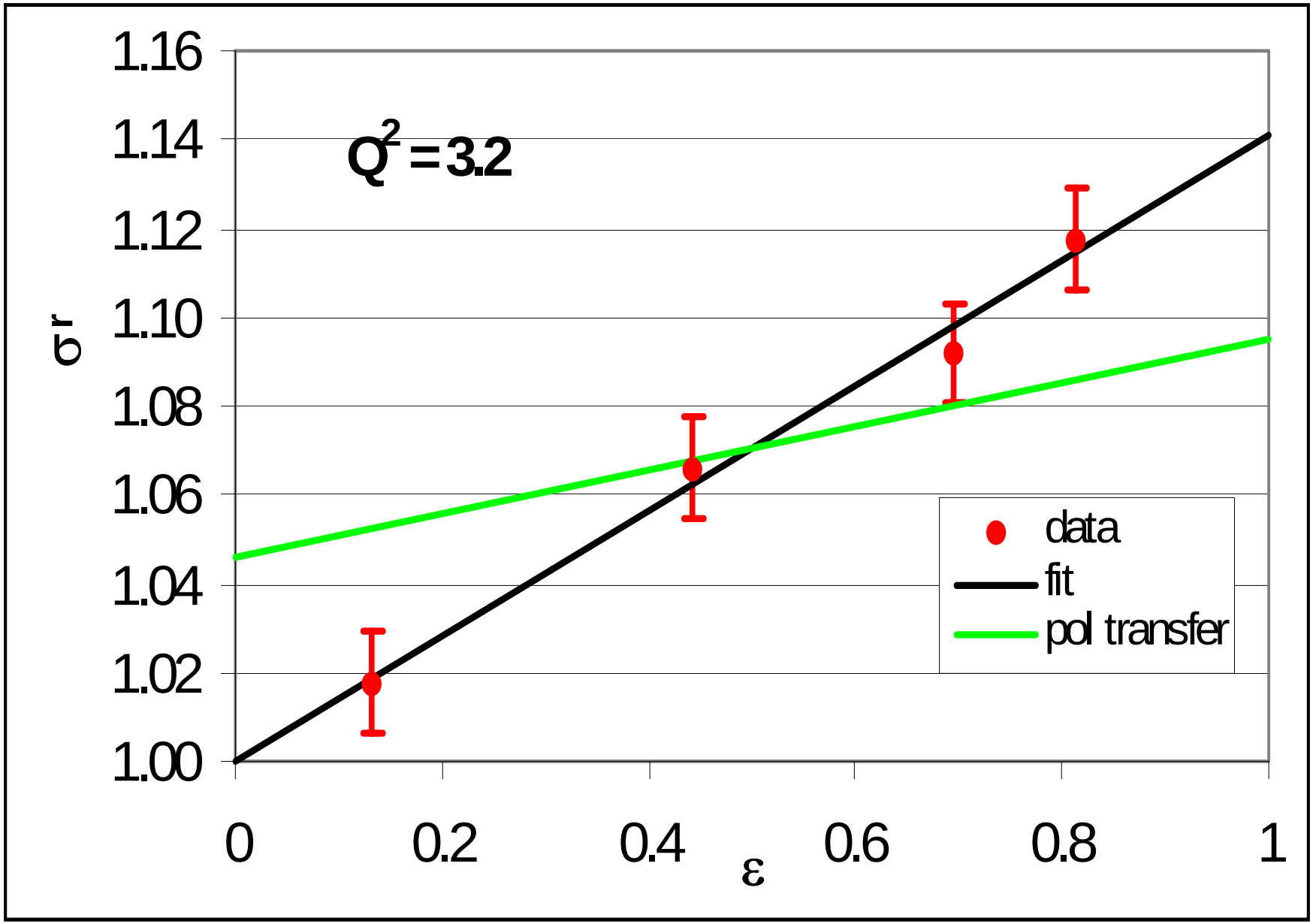
incident electron energy	ratio peak to simulation
1.912	0.962
2.262	0.950
2.262	0.959
2.842	0.956
2.842	0.955
2.842	0.956
3.772	0.957
3.772	0.958
3.772	0.955
4.702	0.963
4.702	0.956
4.702	0.955


Q2=2.64
σr
ε
1.15
1.10
1.05
1.00
0
0.2
0.4
0.6
0.8
1


Q2 = 3.2
σr
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0
0.2
0.4
0.6
0.8
1


Q2 = 4.1
σr
ε
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.0
0.2
0.4
0.6
0.8
1.0


L-T experiments
μpGE/GM
1.0
0.0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Q2
Litt SLAC 70
Price CEA 71
Bartel DESY 71
Walker SLAC 94
Andivhis SLAC 94
Christy JLAB 03
super Rosenbluth


$Q^2 = 3.2$
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
σr
0
0.2
0.4
0.6
0.8
1
ε
data
fit
pol transfer

E01-001 preliminary results: Reduced cross sections

Extraction from single arm *without* luminosity monitor

Not the "SuperRosenbluth" extraction

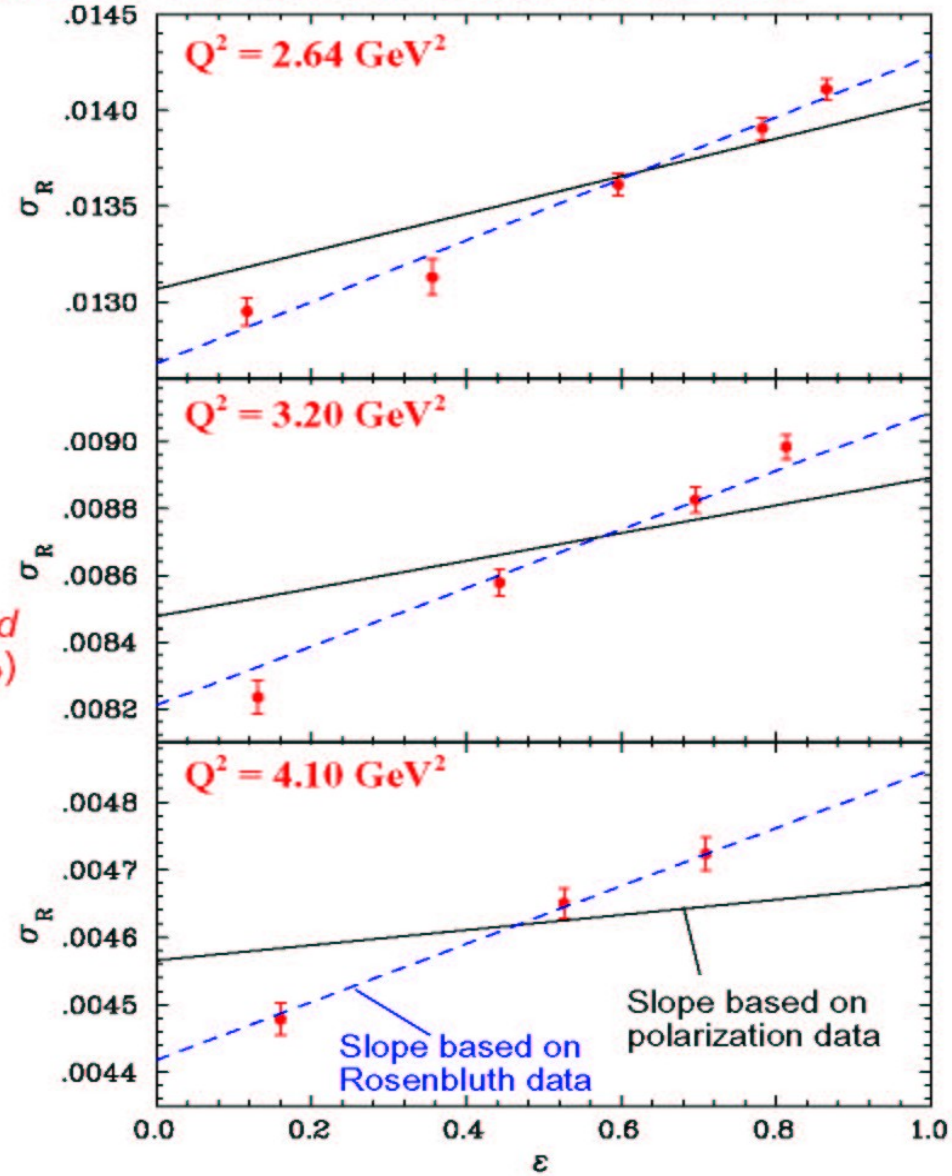
$$\sigma_R = \tau G_M^2 + \varepsilon G_E^{\ 2}$$

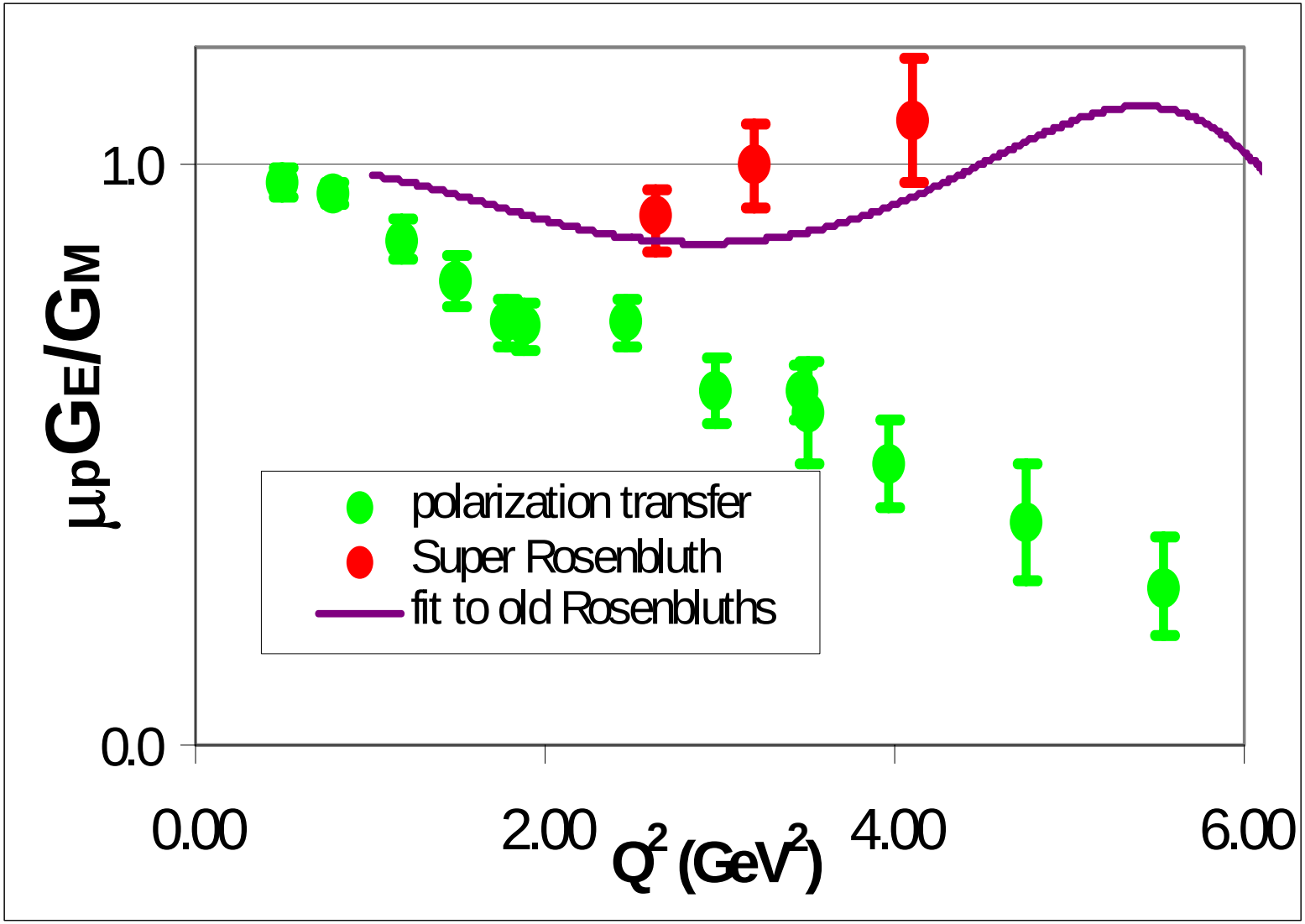
$$= \tau G_M^2 \left[1 + \varepsilon \frac{G_E^2}{\tau G_M^2} \right]$$

Points show statistical plus *uncorrelated* systematic uncertainties (typically 0.5%)

ε-dependent uncertainties applied to extracted ratio (~0.7% ε-dependence)

Large *scale* uncertainty (~5%) applies to G_E and G_M, but not the ratio

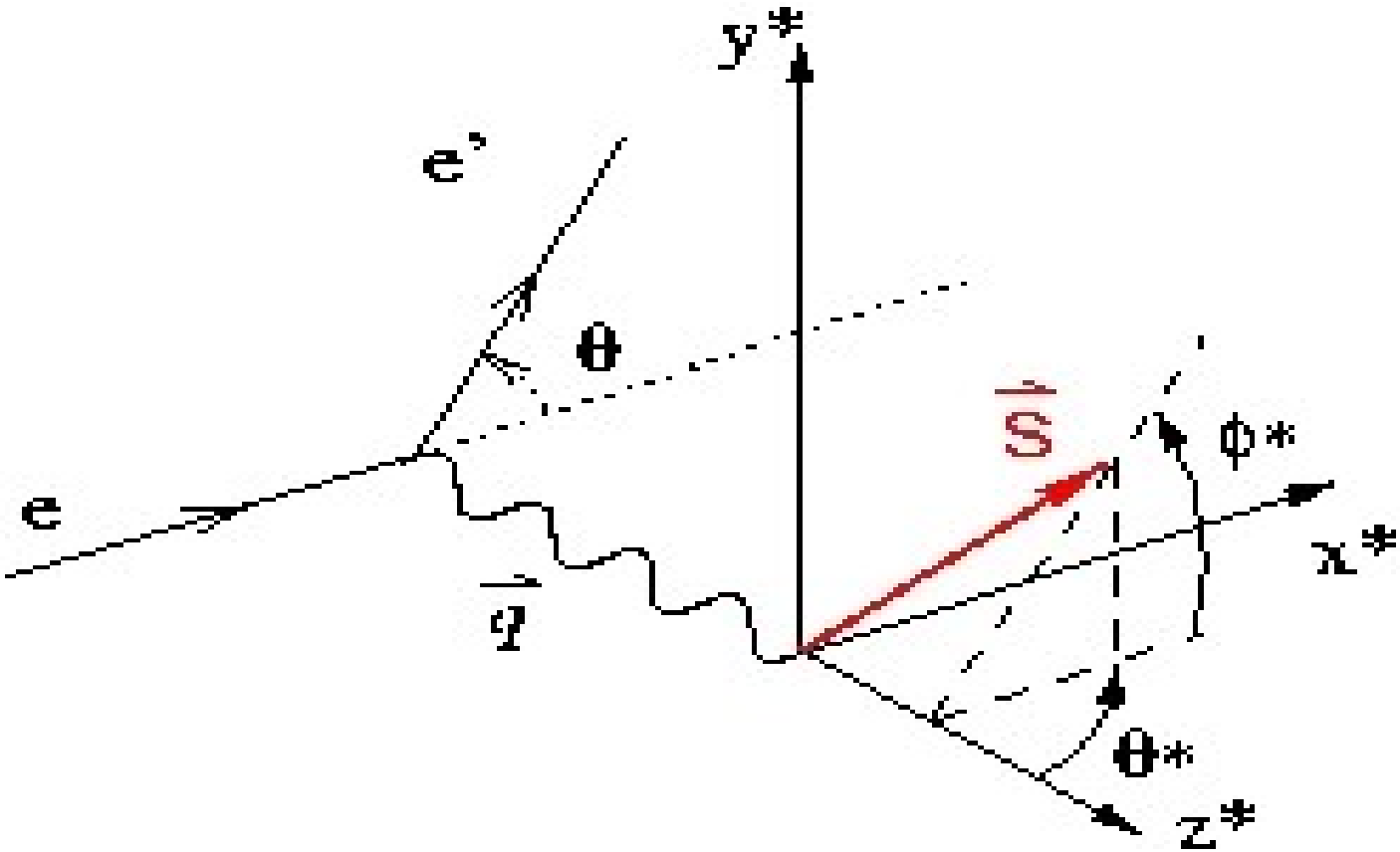



1.0
0.0
μpGE/GM
0.00
2.00
4.00
6.00
Q2 (GeV2)
polarization transfer
Super Rosenbluth
fit to old Rosenbluths

- Rosenbluth experiments are wrong.
- Polarization transfer experiment is wrong.
- Data are being misinterpreted.

Possible checks on polarization transfer experiments

- Continuation of Hall A experiments in Hall C with a different magnet and new polarimeter. Approved. Runs in 2006.
- Scatter longitudinally polarized electrons from polarized protons.
- Measure transverse polarization transfer in scattering longitudinally polarized electrons from unpolarized protons.



$$A = \frac{\sqrt{\frac{\tau}{1+\tau}}\tan\frac{\theta}{2}\left(\sqrt{\tau(1+(1+\tau)\tan^2\frac{\theta}{2})}\cos\theta^* + \sin\theta^*\cos\phi^*(G_E/G_M)\right)}{\frac{(G_E/G_M)^2+\tau}{1+\tau} + 2\tau\tan^2\frac{\theta}{2}}$$

When longitudinally polarized electrons scatter from unpolarized protons polarization is transferred to the recoil proton with:

$$P_t = \frac{2\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta}{2}}{G_E^2 + \frac{\tau}{\varepsilon}G_M^2}$$

and

$$P_l = \frac{(E_e + E_{e'})\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta}{2}}{m_p(G_E^2 + \frac{\tau}{\varepsilon}G_M^2)}$$

where P_t = proton polarization in the plane of the reaction perpendicular to the proton momentum

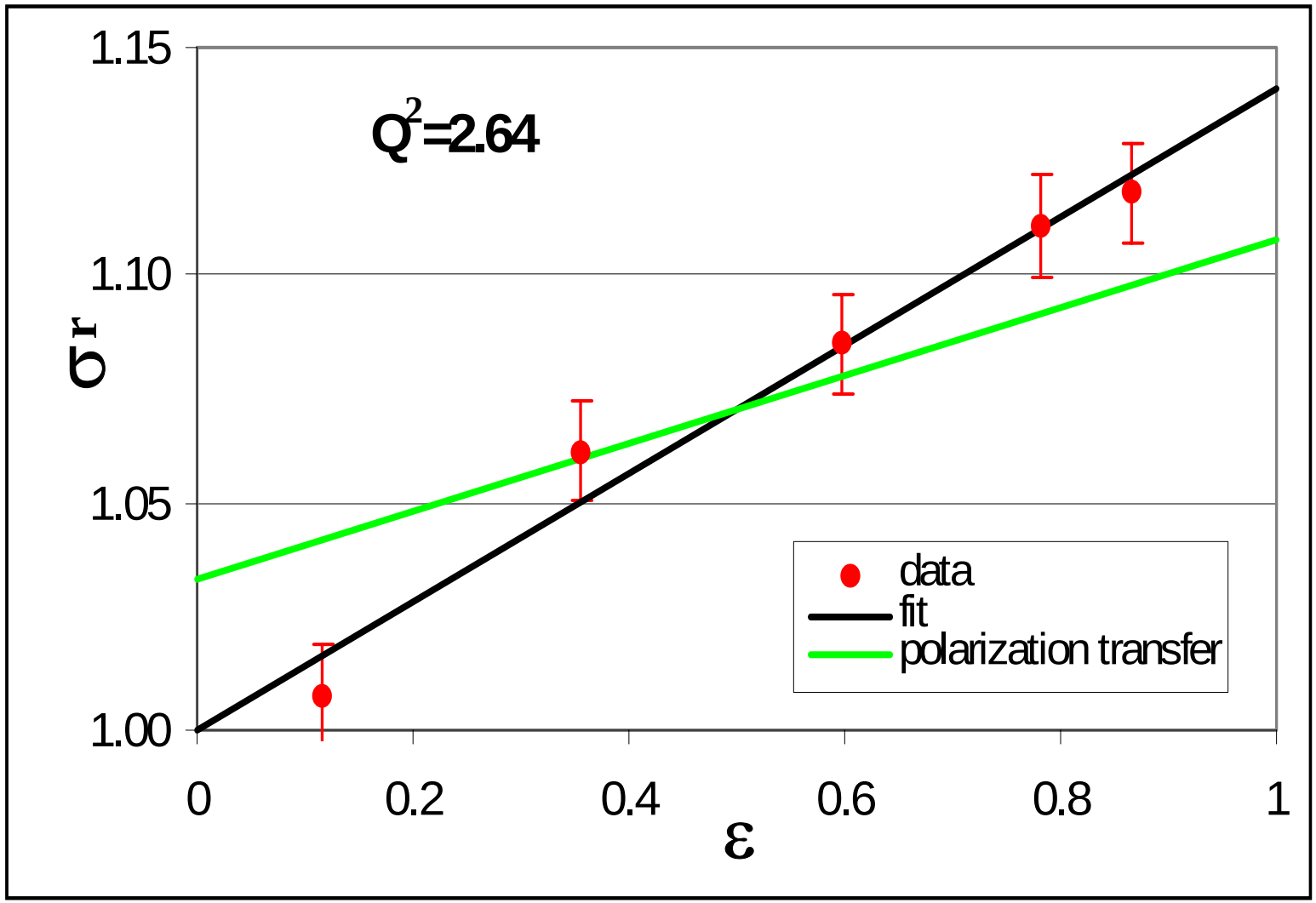
P_l = proton polarization parallel to the proton momentum

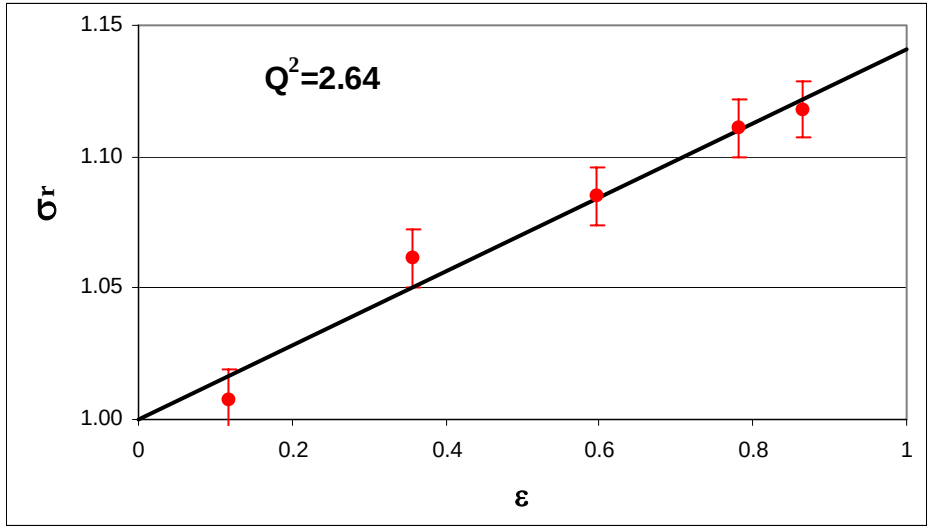
Jefferson Lab experiments E93-027 and E99-007 measured P_t/P_l to determine :

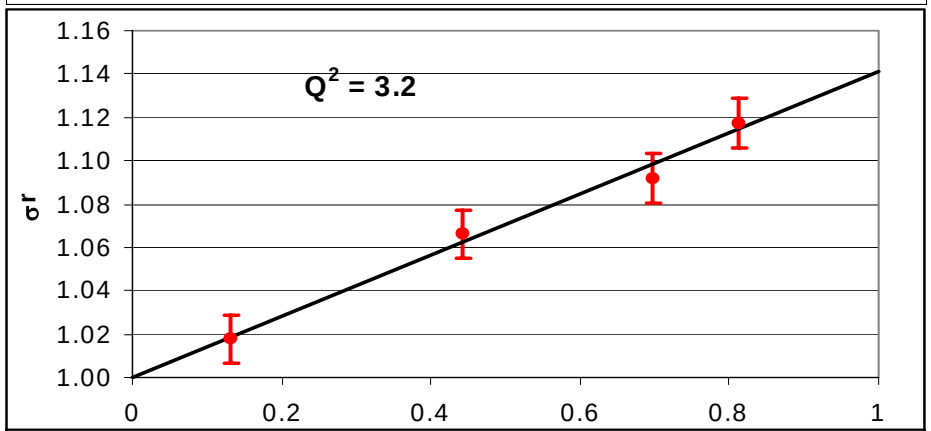
$$\frac{G_E}{G_M} = \frac{P_t}{P_l}\frac{(E_e + E_{e'})\tan(\frac{\theta}{2})}{2m_p}$$

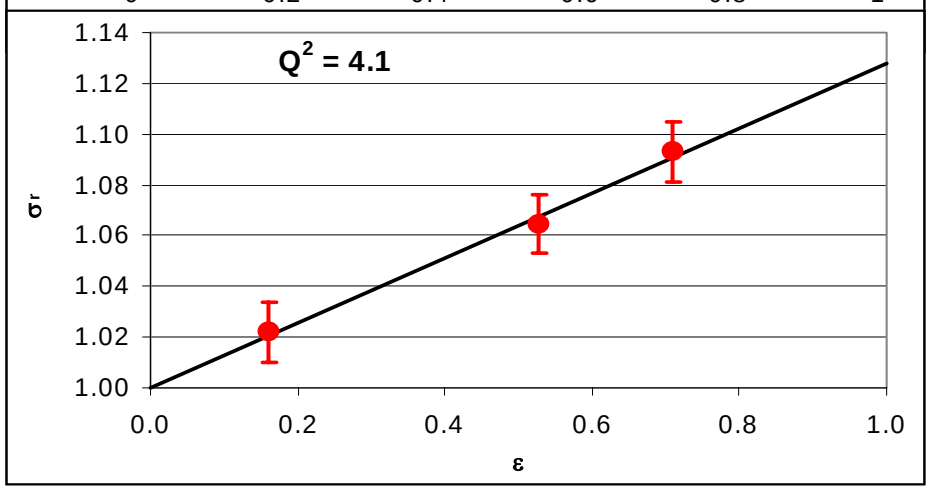
Manifestations of two-photon exchange

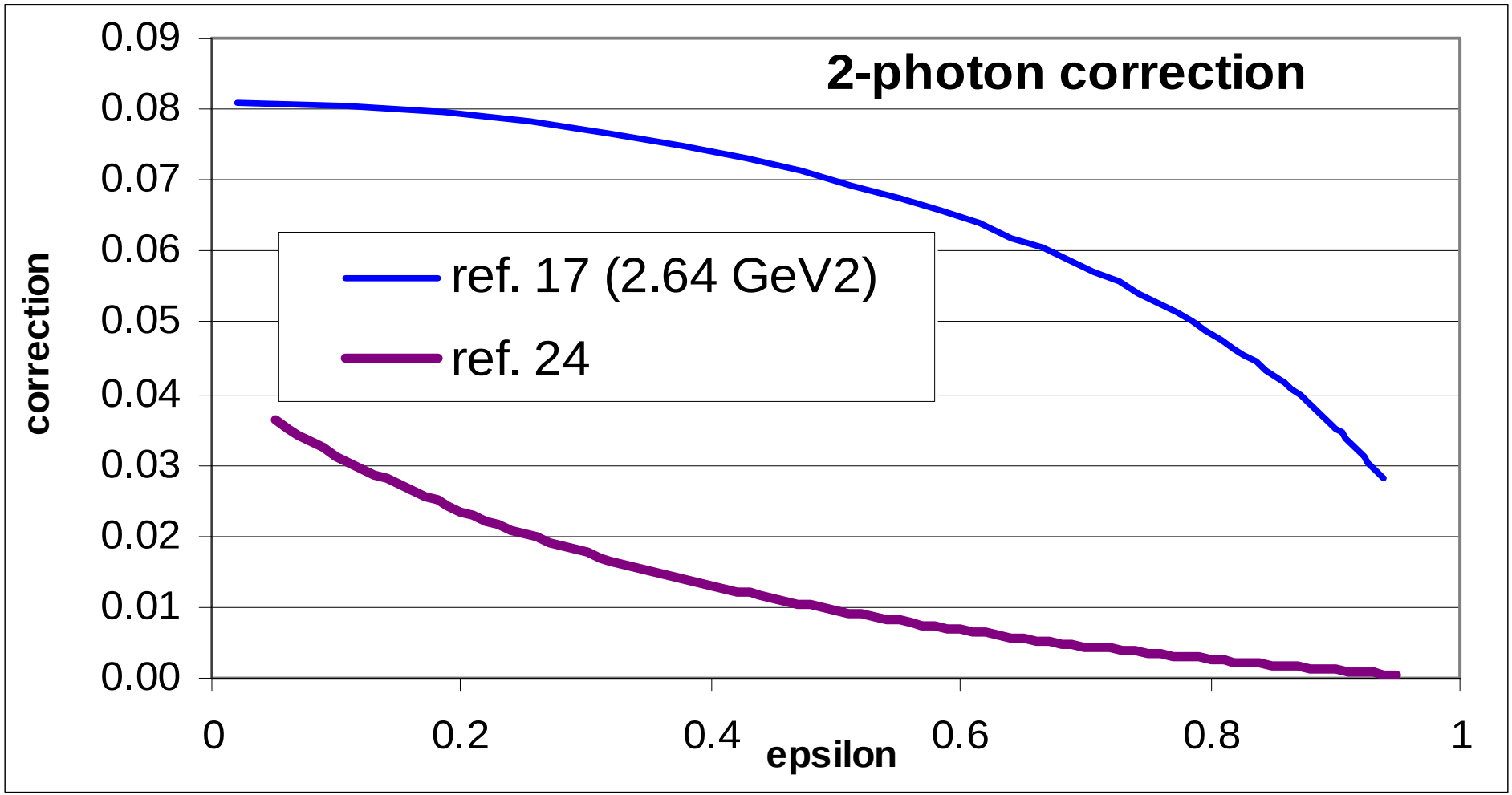
- non-linearity in Rosenbluth plot
- epsilon dependence in polarization transfer
- induced normal polarization in unpolarized e-p scattering
- e^-p and e^+p cross sections unequal


Q^2=2.64
1.15
1.10
1.05
1.00
σr
0
0.2
0.4
0.6
0.8
1
ε
data
fit
polarization transfer


Q2=2.64
σr
ε
1.15
1.10
1.05
1.00
0
0.2
0.4
0.6
0.8
1


Q2 = 3.2
σr
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0
0.2
0.4
0.6
0.8
1


Q2 = 4.1
σr
ε
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.0
0.2
0.4
0.6
0.8
1.0


2-photon correction
ref. 17 (2.64 GeV2)
ref. 24
correction
epsilon
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
0.2
0.4
0.6
0.8
1

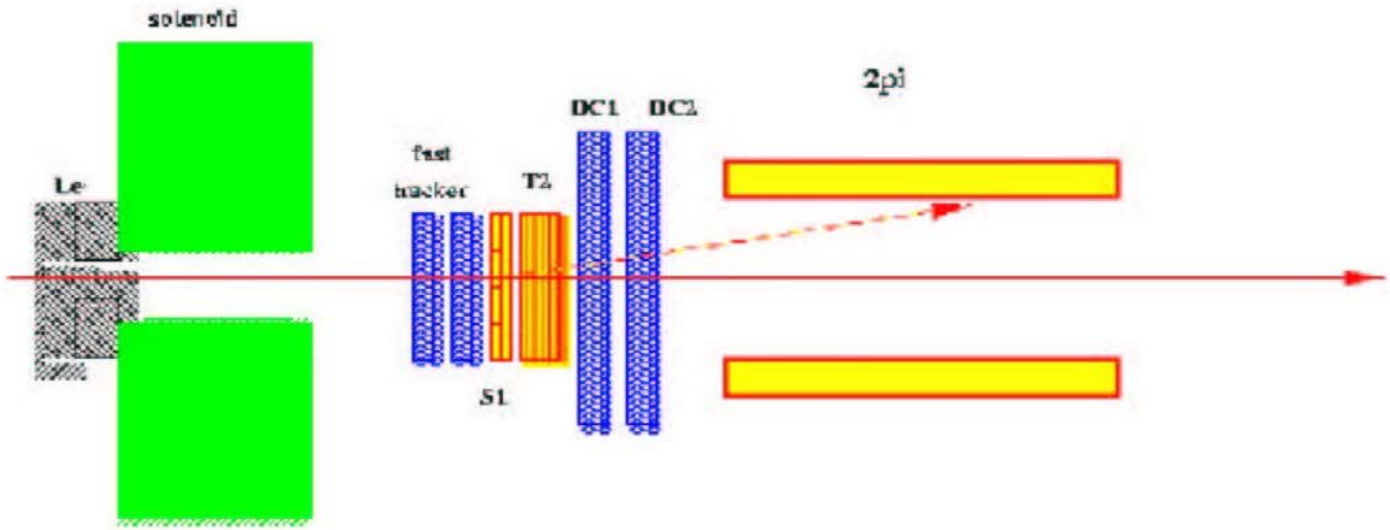
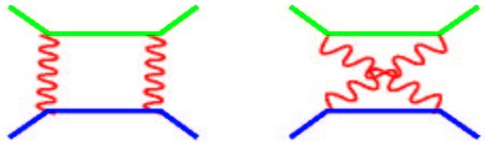


Figure 8: Schematic of the polarimeter. The hatched rectangles represent tracking detectors. S1 is a scintillating trigger hodoscope, T2 is the CH_2 analyzing target (polyethylene), and 2π is a rear cylindrical barrel of scintillator.

Studies of two-photon effects ('50s and '60s)

Definitive test: Positron-proton scattering vs. electron-proton scattering

$$R \equiv \frac{\sigma_{e+}}{\sigma_{e-}} = \frac{(A_{1\gamma}+A_{2\gamma})^2}{(A_{1\gamma}-A_{2\gamma})^2} \approx 1 + 4\,\mathrm{Re}(A_{2\gamma}/A_{1\gamma})$$



e+/e–

<R> = 1.003+/–0.005

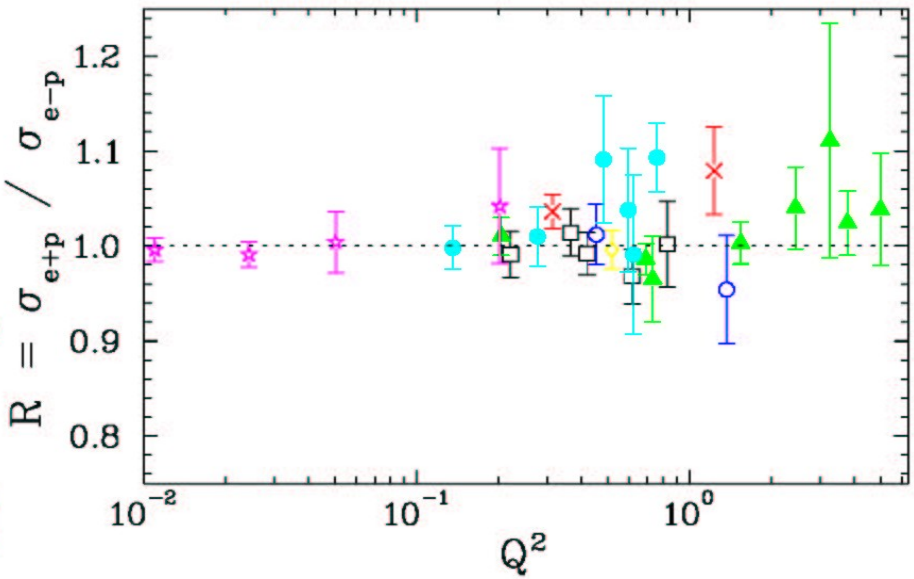
*J. Mar et al., PRL **21**, 482(1968) and refs therein*

μ+/μ–

<R> = 0.993+/–0.006

L. Camilleri et al., PRL 23, 149 (1969)

($Q^2 < 1$ GeV^2)



$\mathrm{Re}\{A_{2\gamma}/A_{1\gamma}\} \approx (0.0+/-0.1)\%$

One-photon approximation assumed to be good to ~1%

Conclusions

- Super-Rosenbluth experiment verifies previous Rosenbluth data on proton form factors
- Polarization transfer and Rosenbluth separation give divergent proton electric form factors for $Q^2 > \sim 1.5\ (\mathrm{GeV})^2$.
- Calculations (very difficult) say two-photon exchange corrections may resolve discrepancy. Experiments in planning stage.