Second International Conference
on Perspectives in Hadronic Physics

Measurements of the Proton Form Factor at Large Timelike Momentum Transfers from E-835 at Fermilab

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Physical Motivation

In general, form factors *parameterize* the structure of composite objects in terms of the behavior of point-like objects, for interpreting experimental data. A theory that explains the composite structure, predicts the form factors.

The electromagnetic form factors give information on the *structure* of the proton.

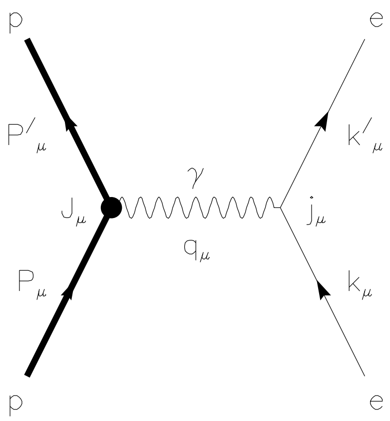
Experiments are not feasible where theoretical predictions are more easily calculable, whereas data exist where theory faces difficulties which have shown to be insormountable so far.

Data presented here is at the limit of today's experimental possibilities; theoretical semplifications might be applicable.

E-835 apparatus, designed for charmonium physics, particularly suitable for form factor physics.

The Physics of Electromagnetic Form Factors

In QED, they can parameterize the electromagnetic structure of the proton:



$$e^- p \to e^- p$$

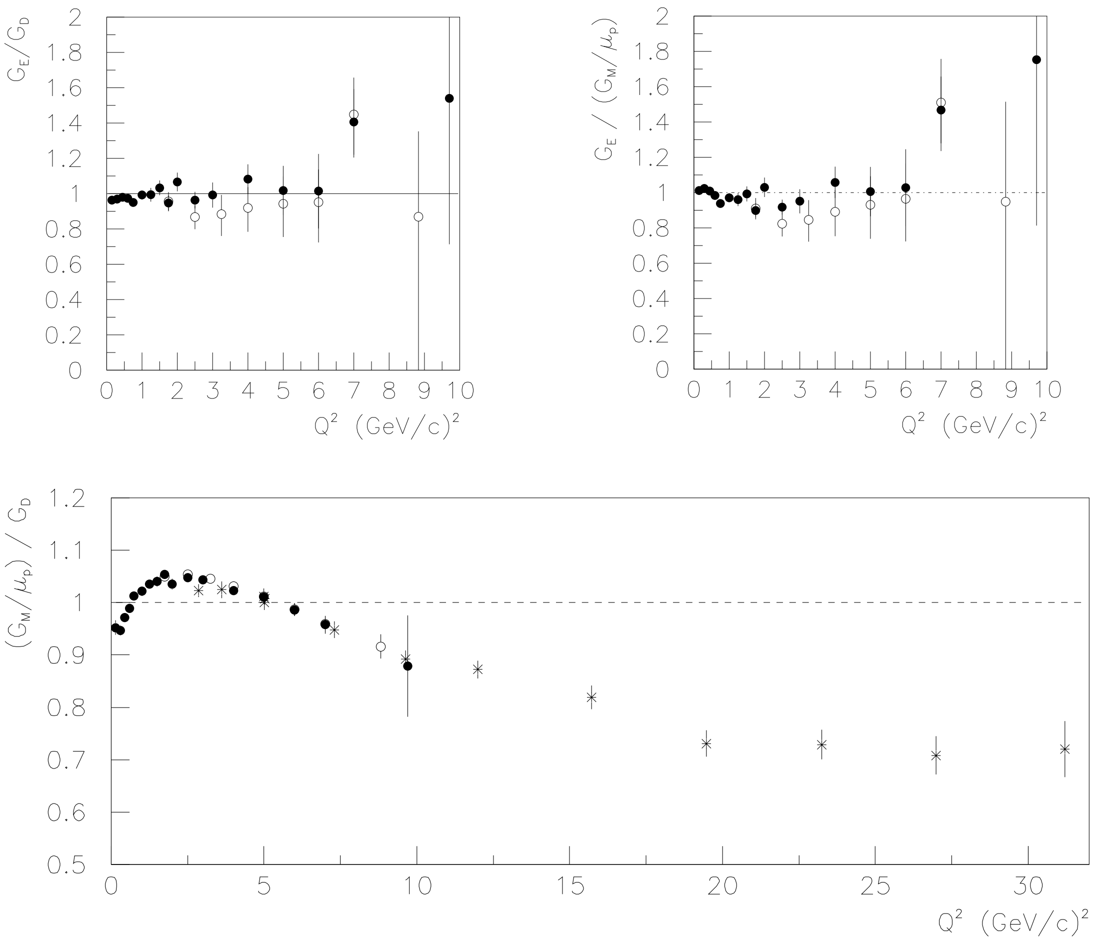
$$(q^2 = -4EE'\sin^2(\theta/2) < 0 \Rightarrow \textit{spacelike})$$

Reduced Rosenbluth cross section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{rid} = \frac{\epsilon(q^2,\theta)}{\tau(q^2)} G_E^2 + G_M^2 \quad 0 \leq \epsilon \leq 1$$

G_E and G_M are used because they are strictly related to the charge and magnetic moment of the proton.

Measurements in the Spacelike Region



Dipolar behavior and scaling for $Q^2 < 10$ (GeV/c)^2:

$$G_E = G_M/\mu_p = \left(1 + \frac{Q^2}{\Lambda}\right)^{-2} \equiv G_D$$

The Timelike Region

Starting from the 1960s, e^+e^- colliders and antiproton beams have made it possible to study the reactions

$$\bar{p}p \rightleftharpoons e^+e^-$$

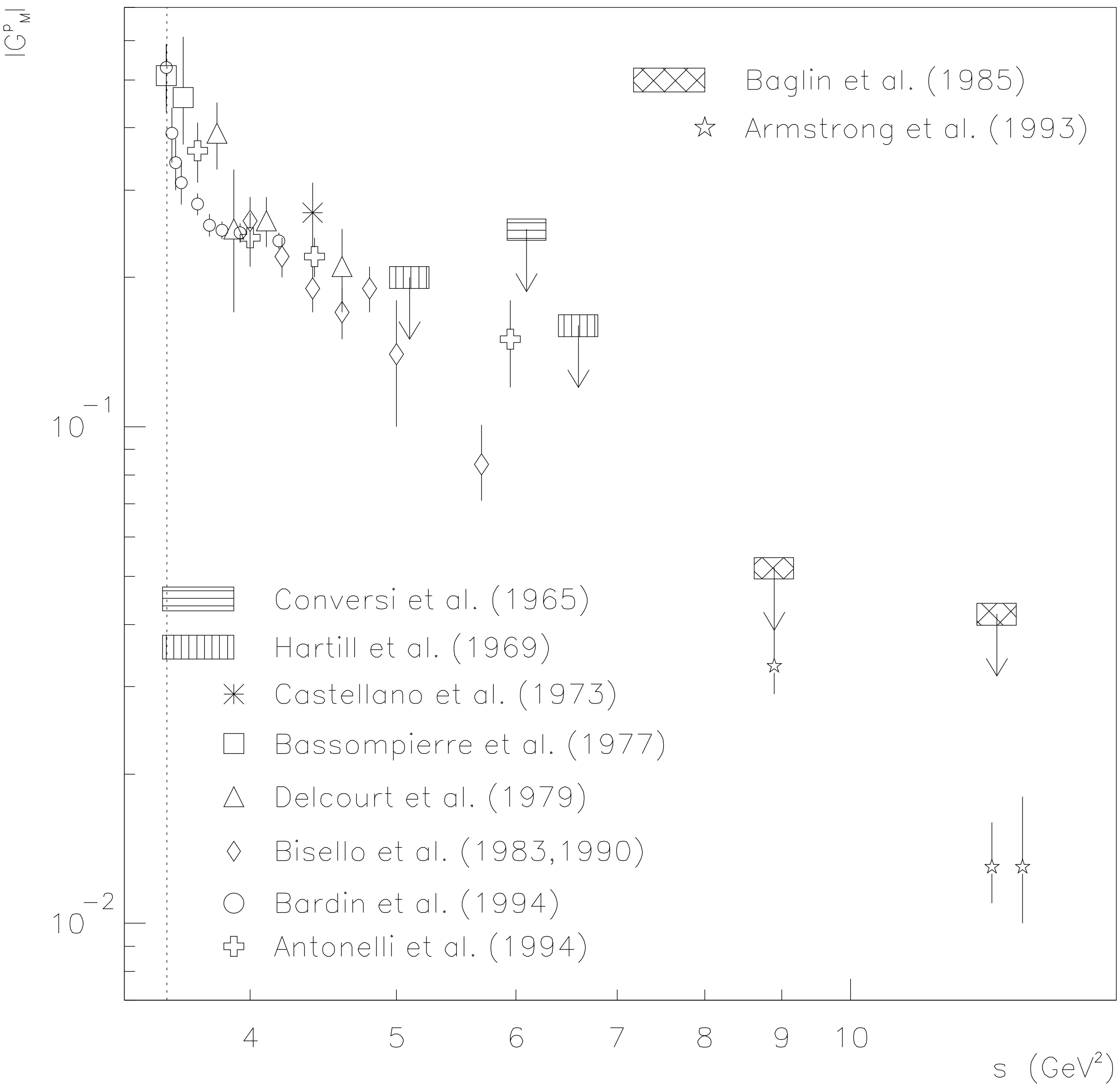
$$(q^2 = s > 0 \Rightarrow \textit{timelike}).$$

The $\bar{p}p \to e^+e^-$ cross section is

$$\frac{\pi\alpha^2}{8EP} \cdot \left\{ |G_M|^2 \cdot \left[1 + \cos^2(\theta^*)\right] + \frac{4m_p^2}{s} \cdot |G_E|^2 \cdot \sin^2(\theta^*) \right\}$$

At threshold ($s = 4m_p^2$) G_E and G_M are equal. At high energy, only $|G_M|$ is relevant and, therefore, measurable.

Timelike Measurements



The total cross section varies between *nb* and *pb*.

Experiment 835 at Fermilab

Study of *charmonium spectroscopy* ($c\bar{c}$) in $\bar{p}p$ annihilations into electromagnetic final states:

$$\bar{p}p \to J/\psi(\to e^+e^-) + X, \gamma\gamma, \ldots$$

Resonances are scanned by decelerating the antiproton beam. Detector as event counter.

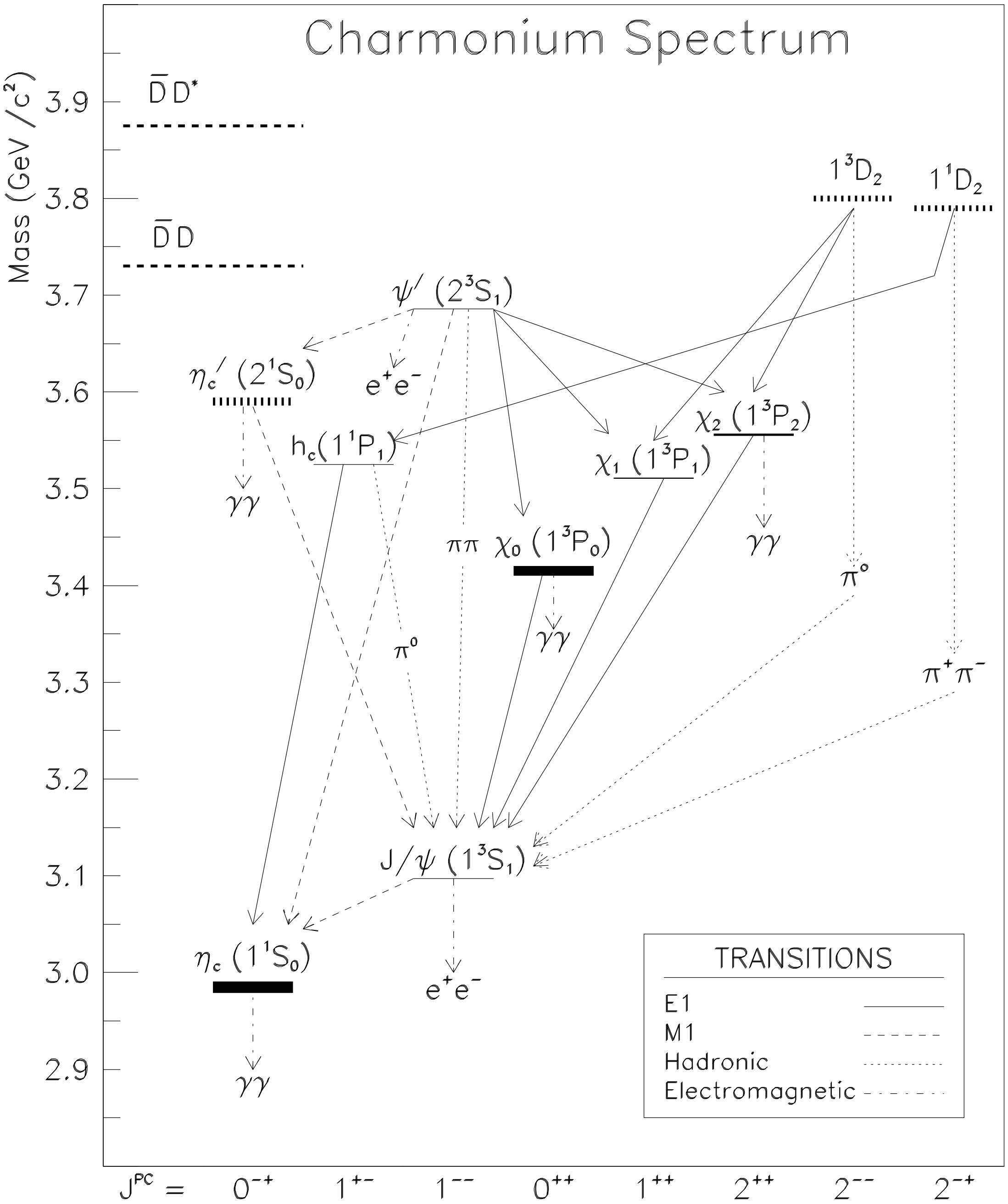
Data ($143\ \mathrm{pb}^{-1}$) collected between Oct 1996 and Sep 1997 at Fermilab Antiproton Accumulator in energy range $2.9 < \sqrt{s} < 4.4$ GeV .

Experiment 835 at Fermilab (cont'd)

Ideal for study of form factors as well:

- *high energy*, but cross section still detectable,
- *high luminosity*,
- *efficient reconstruction of e^+e^- pairs* with high invariant mass,
- *low background level*.

A new six-month run is being prepared and will start next fall.


Charmonium Spectrum
Mass (GeV/c^2)
3.9
3.8
3.7
3.6
3.5
3.4
3.3
3.2
3.1
3.0
2.9
$\bar{D}D^*$
$\bar{D}D$
ψ' (2^3S_1)
η_c' (2^1S_0)
e^+e^-
$h_c(1^1P_1)$
$\gamma\gamma$
$\pi\pi$
χ_0 (1^3P_0)
χ_1 (1^3P_1)
χ_2 (1^3P_2)
1^3D_2
1^1D_2
π^0
$\gamma\gamma$
$\pi^+\pi^-$
π^0
$\gamma\gamma$
J/ψ (1^3S_1)
η_c (1^1S_0)
e^+e^-
$\gamma\gamma$
TRANSITIONS
E1
M1
Hadronic
Electromagnetic
J^{PC} = 0^{-+} 1^{+-} 1^{--} 0^{++} 1^{++} 2^{++} 2^{--} 2^{-+}

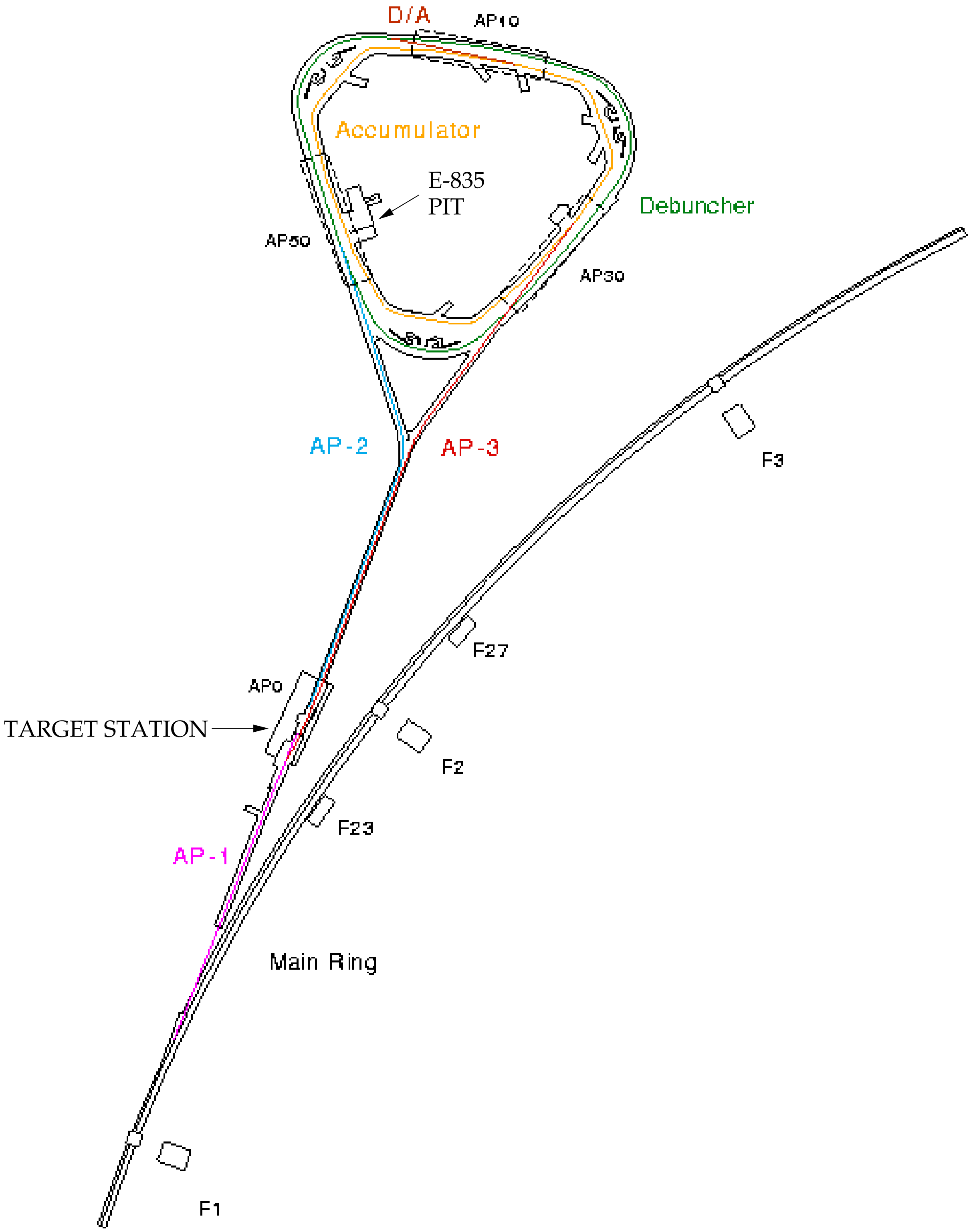
Beam, Target, Luminosity

The antiproton *beam* (8×10^{11} particles) is stacked in about 24 h. Stochastic cooling makes $\Delta p/p = 2 \times 10^{-4}$.

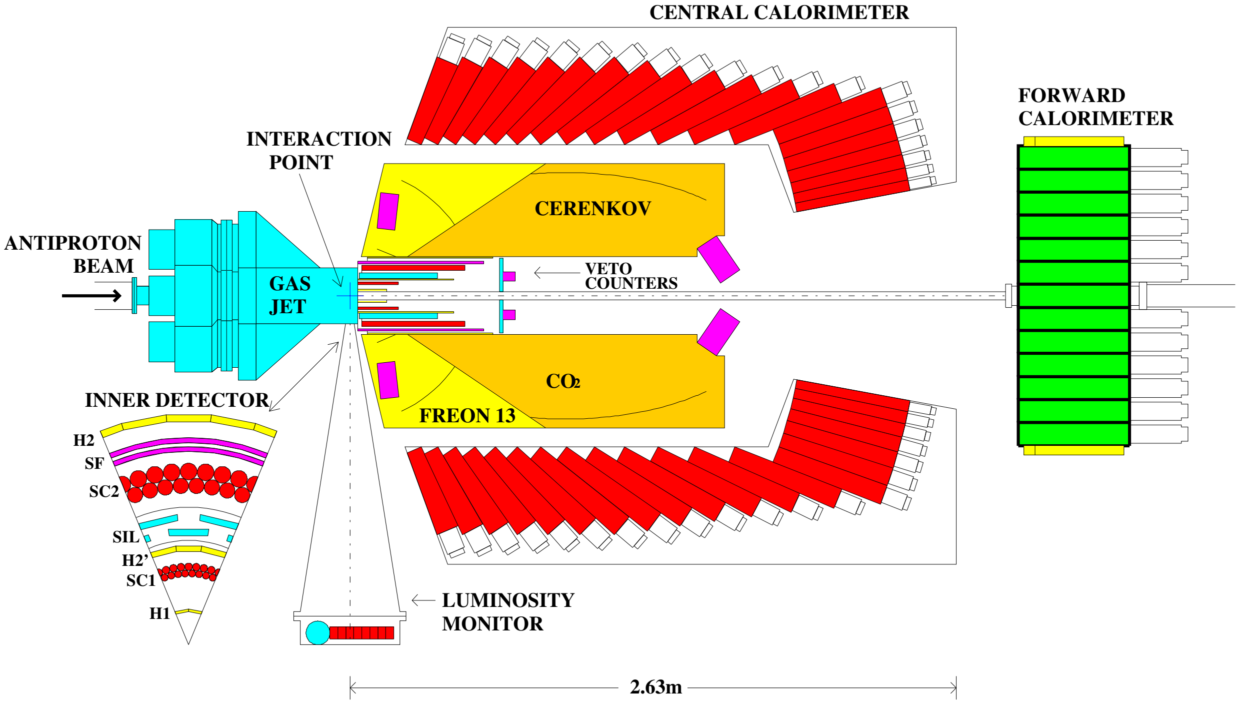
The hydrogen gas jet *target* intersects the beam. Density is varied during data taking to maximize instantaneous luminosity (typically, 2×10^{31} cm^{-2} s^{-1}).

Luminosity measured recording elastic recoil protons with silicon detectors; 3% precision.

Interaction *vertex*, as determined by intersection of beam and jet target, is $5 \times 5 \times 7$ mm^3.

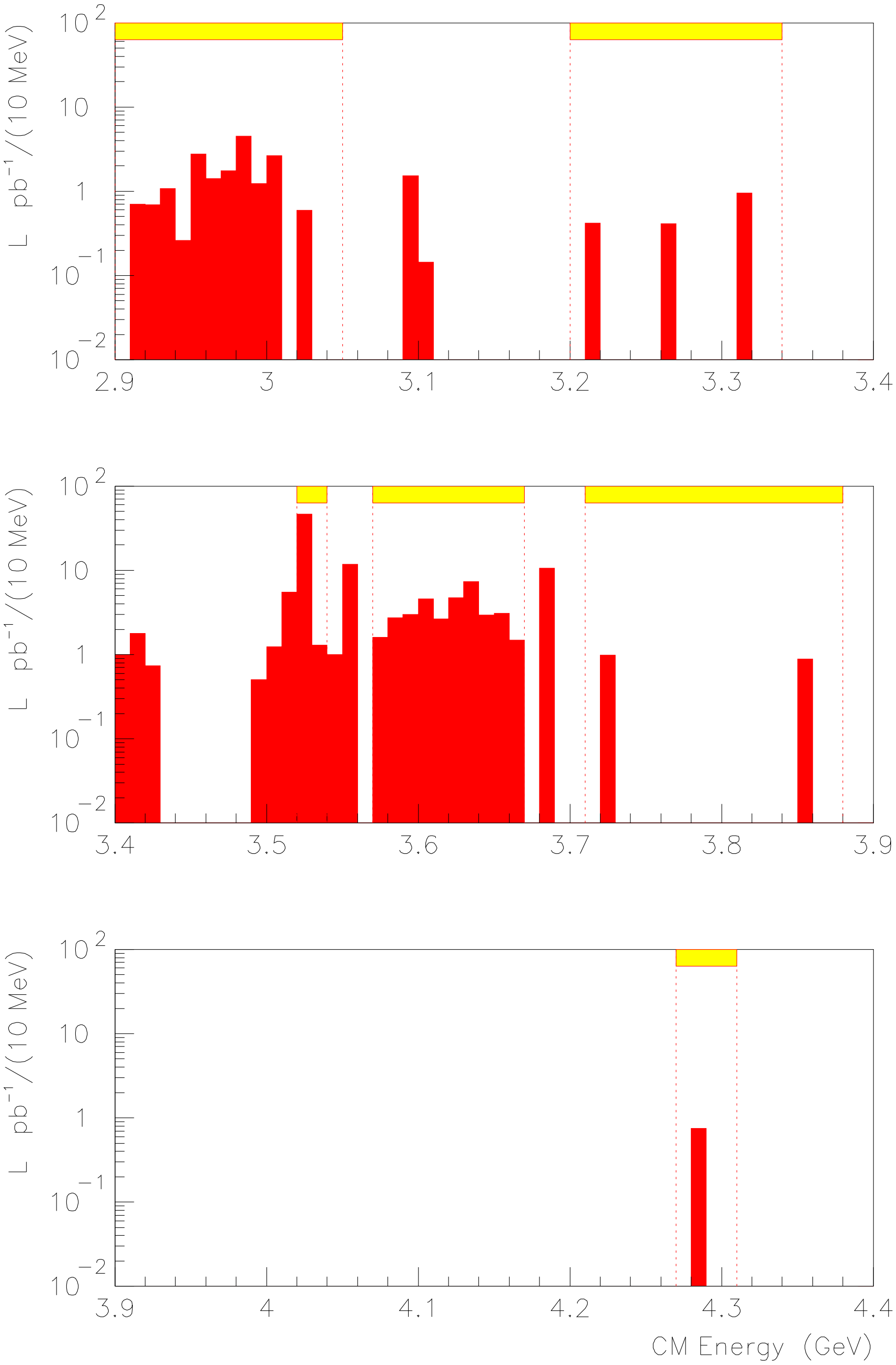

D/A
AP10
Accumulator
E-835
PIT
Debuncher
AP50
AP30
AP-2
AP-3
F3
F27
AP0
TARGET STATION
F2
F23
AP-1
Main Ring
F1

The Detector



Three *hodoscopes* for charged trigger and pulse height. Electromagnetic *calorimeter* for measuring energy and momentum of electrons, positrons and photons. Threshold *Čerenkov* counter for hadron rejection at trigger level. *Tracking* system includes straw chambers and scintillating fibers.

The Data Sample



s (GeV^2)	L (pb^{-1})	N	σ_{acc} (pb)	$\lvert\cos\theta^*\rvert_{max}$	$10^2 \times \lvert G_M \rvert$ (a)	(b)
8.84 ± 0.16	17.69	93	$7.93^{+0.82+1.00}_{-0.82-0.69}$	0.451	$3.59^{+0.18+0.23}_{-0.19-0.17}$	$4.17^{+0.21+0.26}_{-0.22-0.19}$
10.78 ± 0.28	1.78	3	$2.5^{+1.9+0.3}_{-1.6-0.2}$	0.544	$2.13^{+0.70+0.15}_{-0.84-0.11}$	$2.40^{+0.79+0.15}_{-0.95-0.12}$
12.43 ± 0.02	47.84	33	$1.04^{+0.18+0.13}_{-0.18-0.09}$	0.601	$1.43^{+0.12+0.09}_{-0.13-0.07}$	$1.58^{+0.13+0.10}_{-0.14-0.07}$
13.11 ± 0.18	33.99	14	$0.62^{+0.19+0.08}_{-0.16-0.05}$	0.621	$1.12^{+0.16+0.07}_{-0.16-0.06}$	$1.24^{+0.18+0.08}_{-0.18-0.06}$
14.36 ± 0.50	1.86	1	$0.8^{+1.4+0.1}_{-0.5-0.1}$	0.604	$1.39^{+0.91+0.13}_{-0.54-0.11}$	$1.51^{+1.00+0.14}_{-0.59-0.12}$
18.40 ± 0.01	0.76	0	< 4.88	0.508	< 4.40	< 4.74

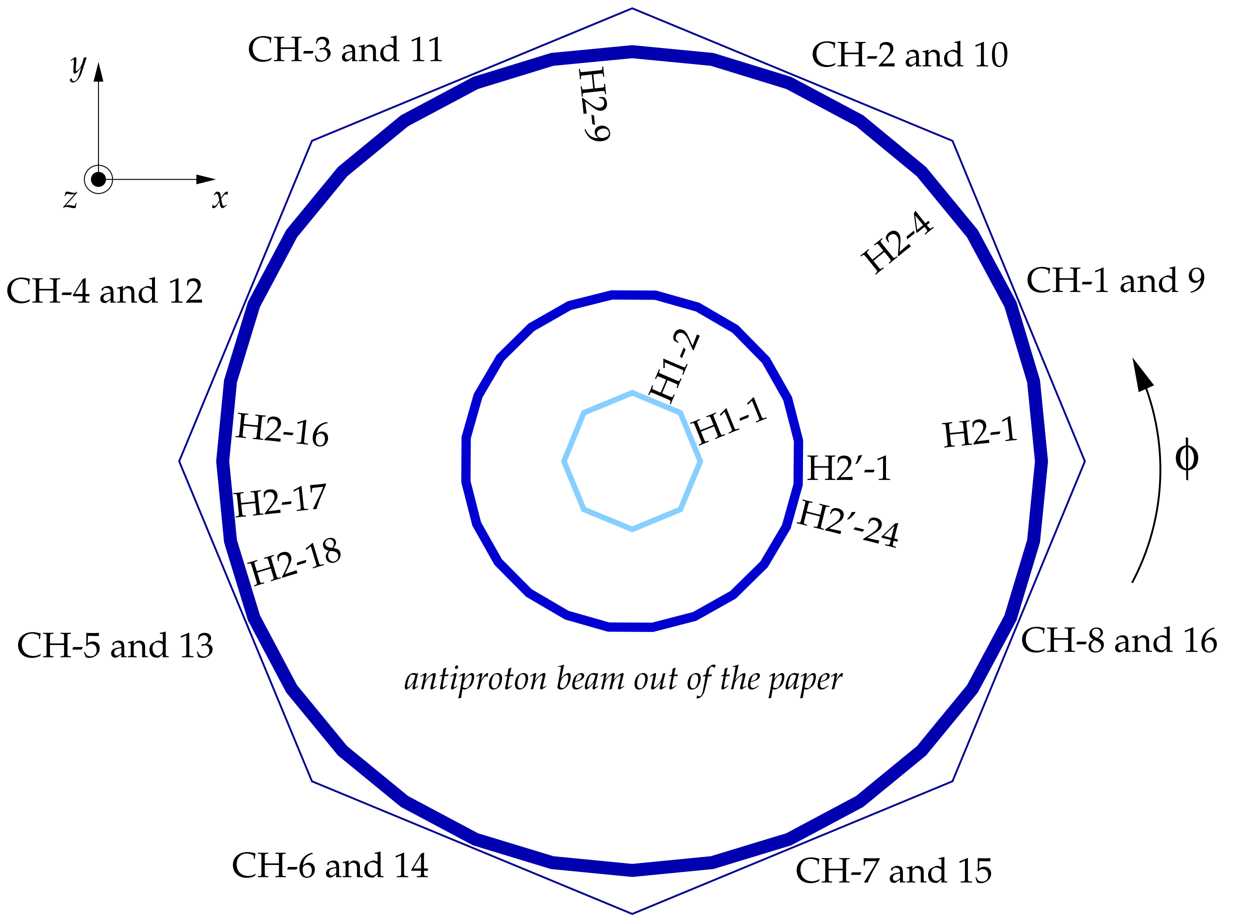
Event Selection Criteria

Goal: identification of e^+e^- final states. Based upon *electron/positron identification* and *two-body kinematics*. Selection process calibrated with samples ($\approx 10^4$ total events) of $J/\psi \rightarrow e^+e^-$ and $\psi' \rightarrow e^+e^-$.

At *trigger* level:

- two coplanar charged tracks (defined by the hodoscopes) associated with Čerenkov counter signal;

- two high invariant mass deposits in the calorimeter.



Cherenkov cells 1 to 8: large angle (Freon)
Cherenkov cells 9 to 16: small angle (CO2)

Event Selection Criteria (cont'd)

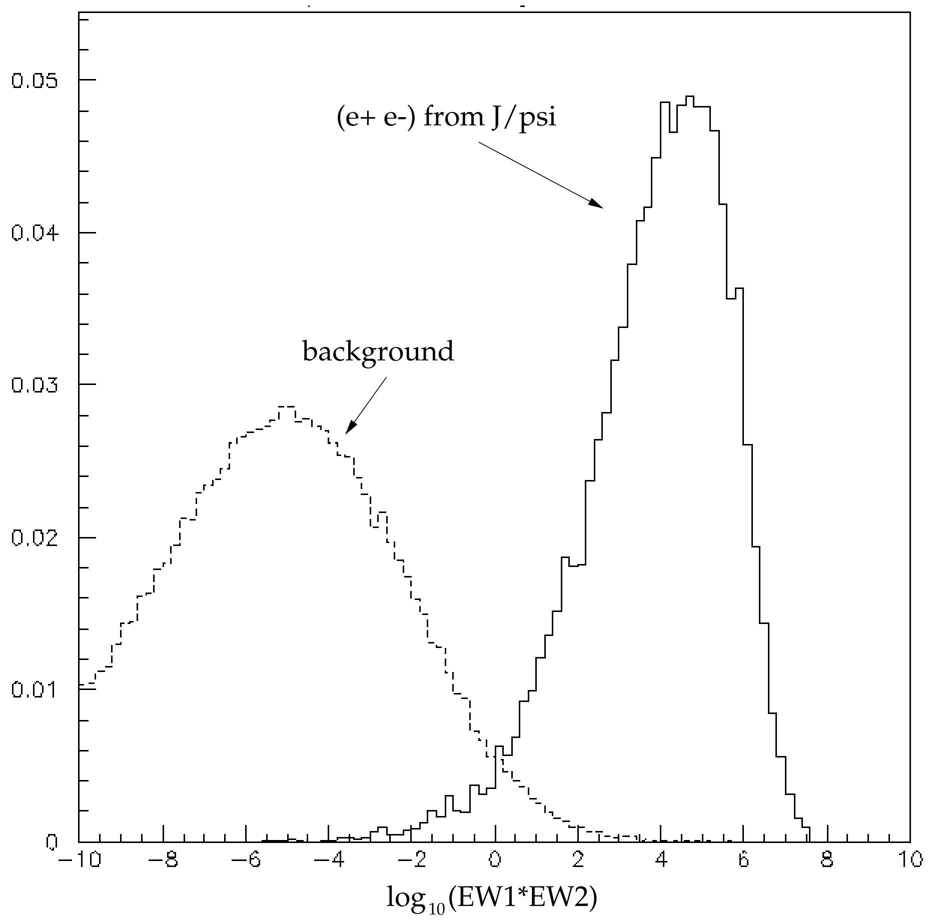
The off-line selection requires:

Fiducial volume. To remove inhomogeneities in the response of the detector at its edges. Both candidate electrons in the region $15^\circ < \theta < 60^\circ$.

Calorimeter multiplicity. Two on-time energy deposits with high invariant mass. Any number of out-of-time or undetermined clusters.

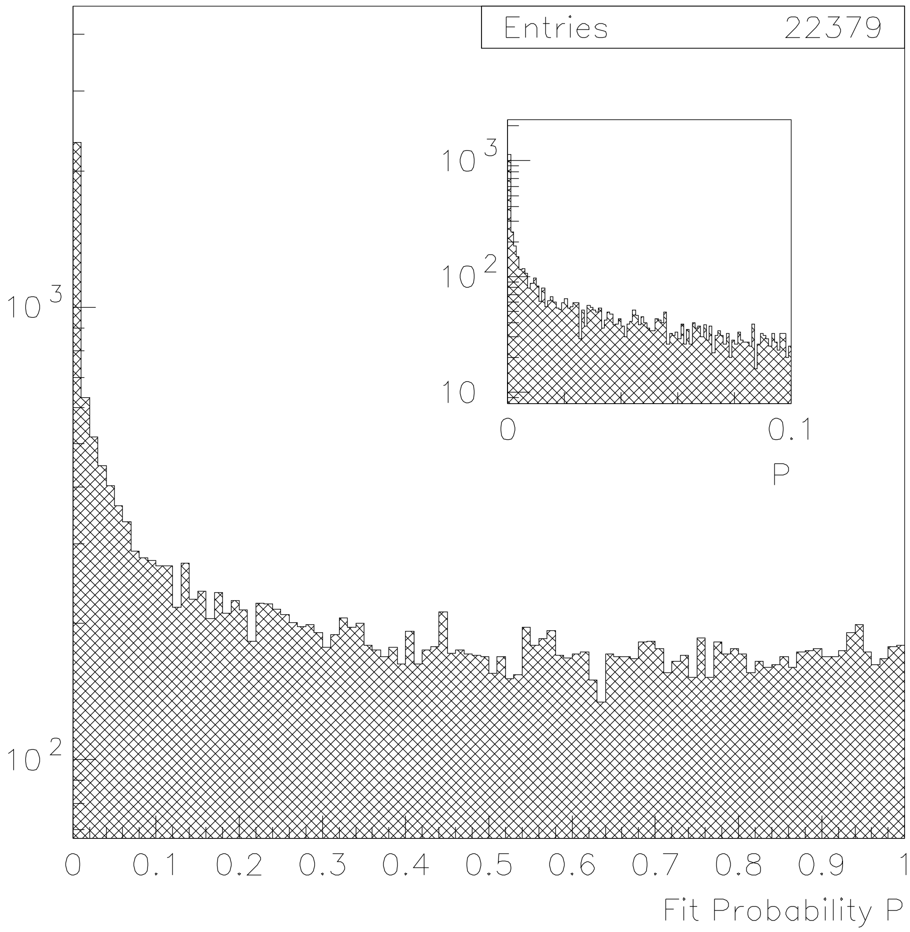
Event Selection Criteria (cont'd)

Electron and positron identification. Based upon hodoscope pulse height, Čerenkov signal and shower shape in the calorimeter ("Electron Weight index").



Event Selection Criteria (cont'd)

Kinematic characteristics of event. Four-momentum conservation imposed with kinematic fit, requiring $P(\chi^2) > 1\%$.



After all cuts, *144* $\bar{p}p \rightarrow e^+e^-$ *events* are selected.

Selection Efficiency

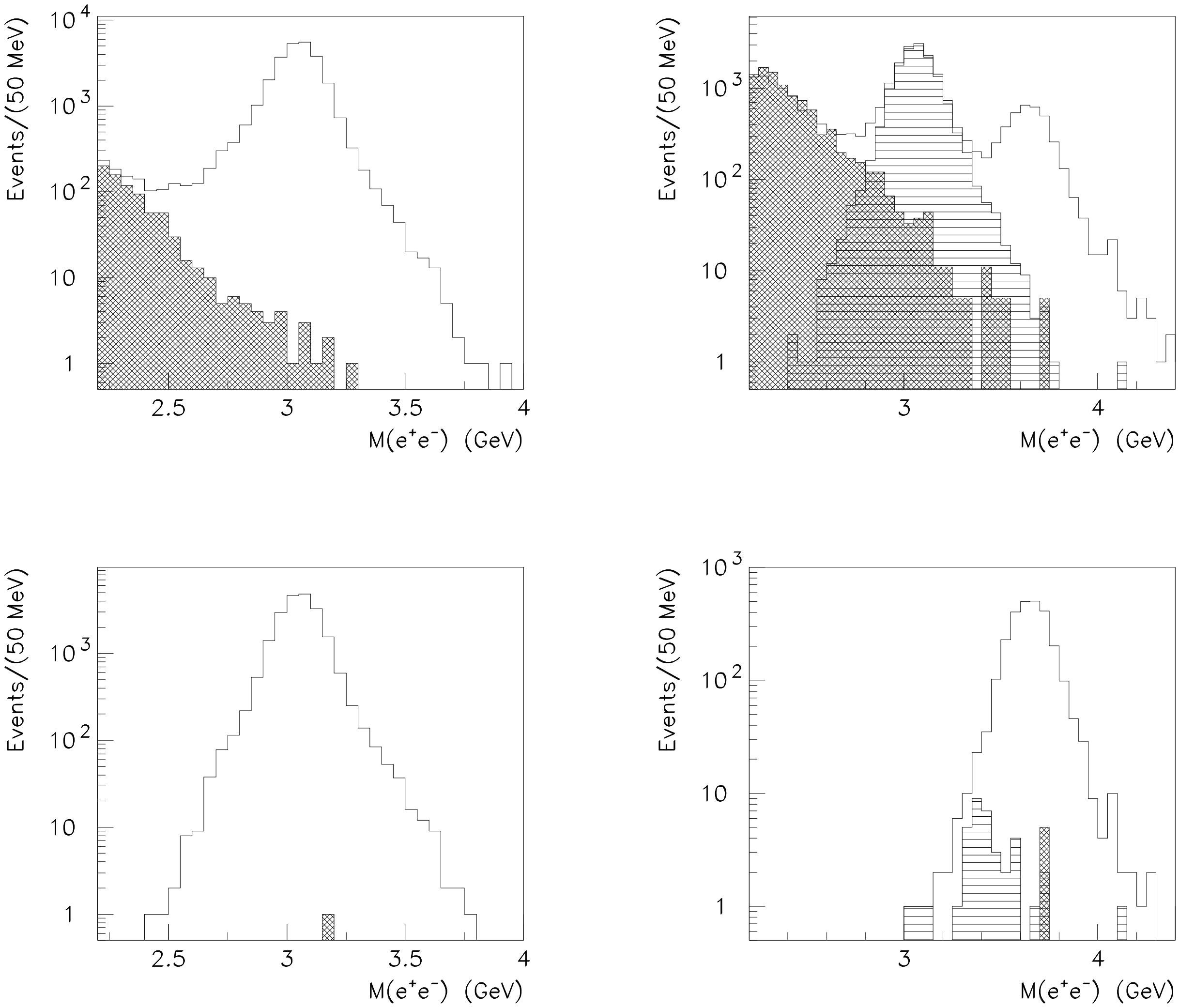
Detection and trigger efficiencies measured on samples collected with looser trigger logic.

$$\epsilon_{\text{tri}} = 0.898 \pm 0.005.$$

Efficiency of off-line selection estimated at J/ψ and ψ', after subtraction of background (evaluated from data taken off-resonance).

$$\epsilon_{\text{ana}} = 0.764 \pm 0.003(\text{stat}) \pm 0.045(\text{sist}).$$

The systematic error includes variations due to $\sqrt{s}$, background subtraction and running conditions.



Events/(50 MeV)
M(e⁺e⁻) (GeV)

Study of Background Contamination

Several reactions can simulate $\bar{p}p \to e^+e^-$ in the E-835 detector.

- *Photon conversions* and *pion Dalitz decays*. The most relevant are $\bar{p}p \to \pi^0\pi^0$ or $\pi^0\gamma$.

- *Two-body hadron final states*, especially $\pi^+\pi^-$, when the Čerenkov detector gives a signal (δ-rays) and there is a calorimeter shower.

- Formation of *inclusive* $J/\psi + X$, if X is not detected and carries little momentum.

The total background is negligible ($\approx 10^{-2}$ pb).

Measurement of the Form Factor

From the formula for the differential cross section:

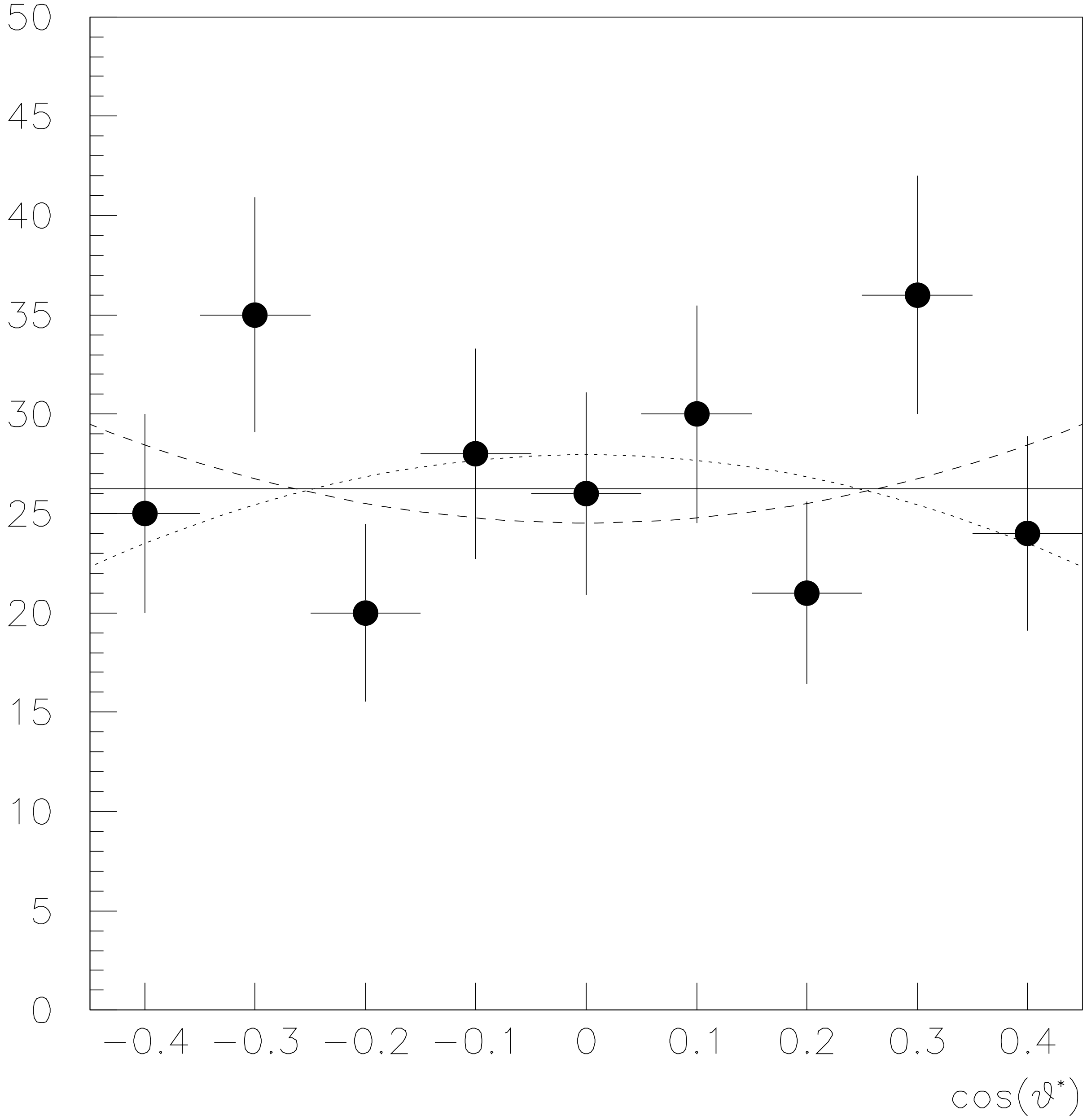
$$|G_M| = \frac{1}{\alpha} \cdot \sqrt{\frac{8}{\pi}} \cdot \left(\frac{EPN}{\epsilon AL}\right)^{1/2}$$

Due to small number of events and limited angular coverage, it is not possible to precisely measure the angular distribution, and, therefore, $|G_E|$ and $|G_M|$ separately.

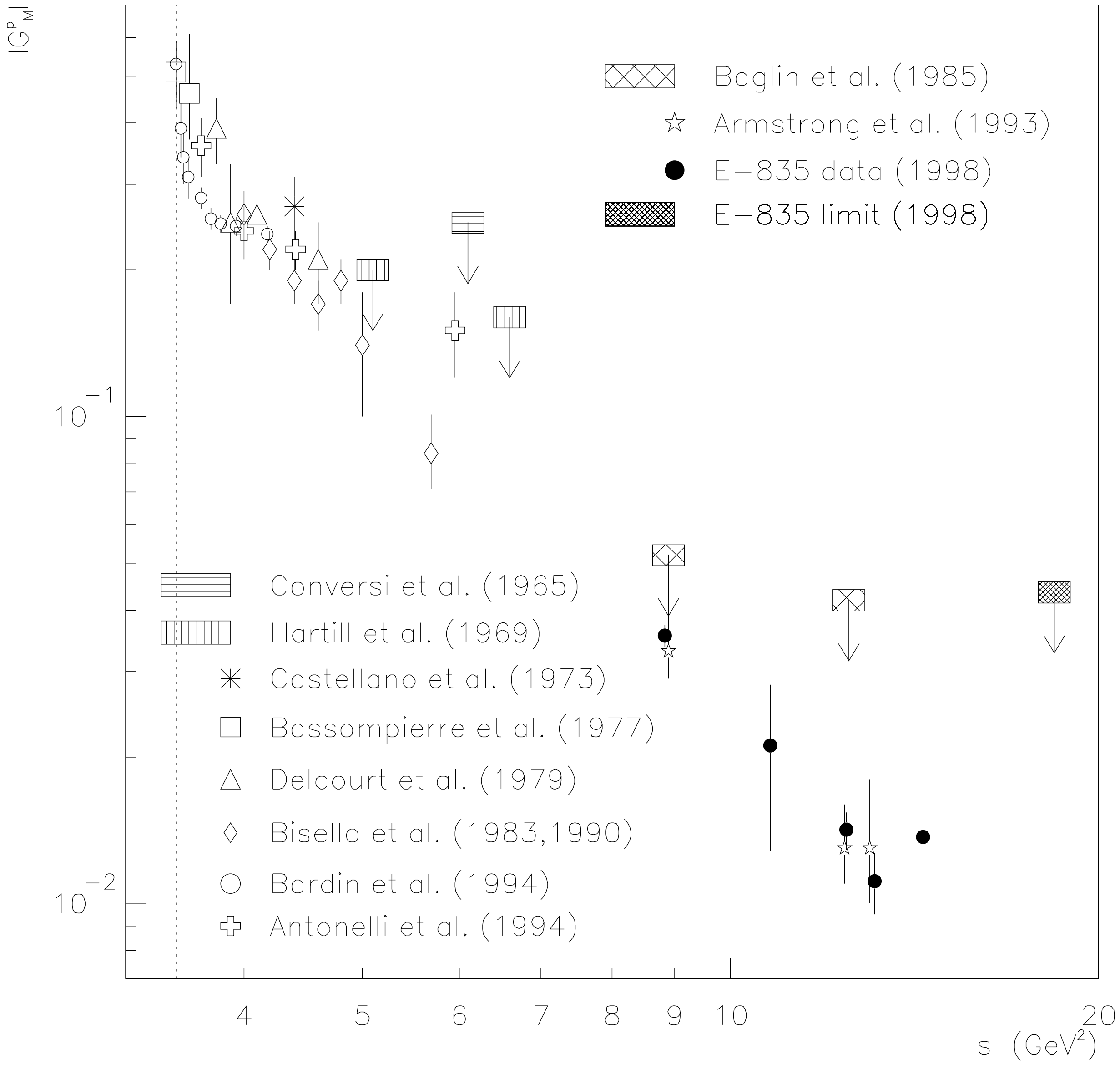
Two alternative hypotheses are made:

- (a) $G_E = G_M$, as it is the case at threshold;
- (b) negligible 'electric' contribution.

Angular Distribution

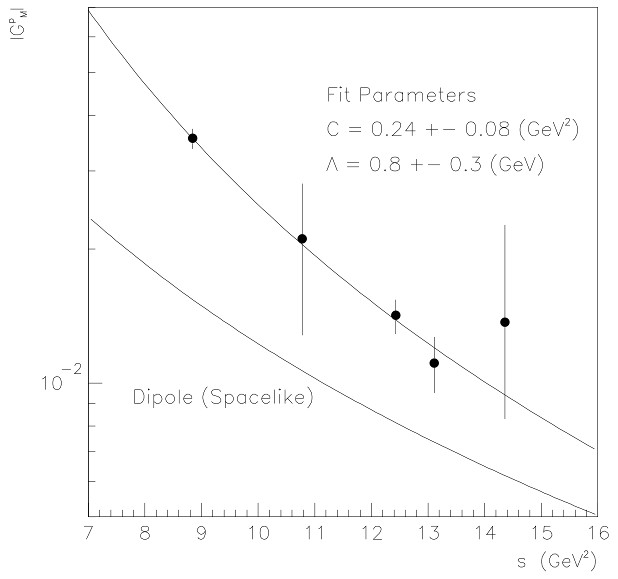


Results



Results are in excellent agreement with those of E-760.

Results (cont'd)



Results follow semi-quantitative QCD predictions:

1. asymptotic pQCD functional form:

$$G_M(q^2) = C^2 \frac{32\pi^2}{9} \frac{\alpha_s^2}{q^4} \left(\ln \frac{q^2}{\Lambda^2} \right)^{-4/27}$$

2. factor of about 2 between spacelike and timelike form factor.

Conclusions

- Form factor physics and charmonium physics share common means and goals.

- This concurrence of goals has yielded the most precise high-energy measurement to date.

- New techniques are needed to investigate the proton structure in the asymptotic timelike regime.