Measurements of the Magnetic Form Factor of the Proton for Large Timelike Momentum Transfers

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E835 Meeting
Fermilab, March 02 2002

- Selection of form factor events
- Samples of real data and comparison with Monte Carlo simulation
- Efficiency of the analysis
- Energy ranges used
- Evaluation of background contamination
- Results of the analysis
- Attempt to measure of the angular distribution

Looking for $\bar{p}p \to e^+e^-$ events

$$\left(\frac{d\sigma}{d\Omega}\right)_{\overline{p}p\to e^+e^-} = \frac{\alpha^2}{4\beta_p s}\cdot\left[|G_M|^2\,(1+\cos^2\theta^*) + \frac{4m_p^2}{s}\,|G_E|^2\sin^2\theta^*\right]$$

Trigger and preselection

- Charged trigger for e^+e^- final state
- Off-line Preselection:

$$M_{ee} > 2.0\ \mathrm{GeV/c^2}$$

$$\log_{10}(ew1 * ew2) > -1$$

Selection of the e^+e^- final state

- Fiducial volume $[15^o < \theta < 60^o]$

- e^+e^- on-time

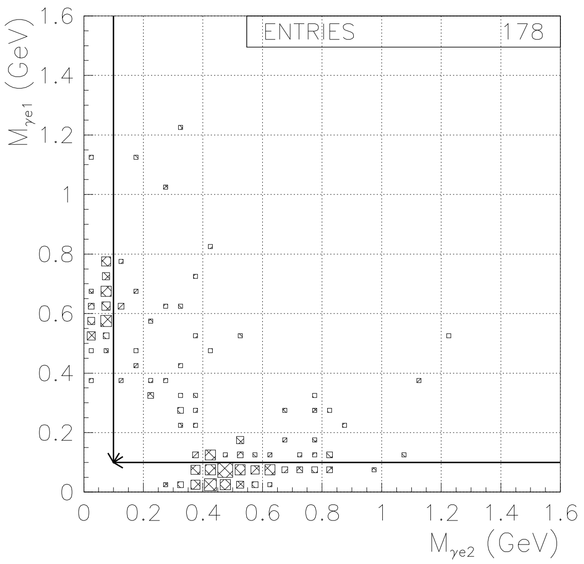
- $\log_{10}(ew1 * ew2) > 0$

- $Prb(e^+e^-) > Prb(J/\psi X)$ AND $Prb(e^+e^-) > 1\%$

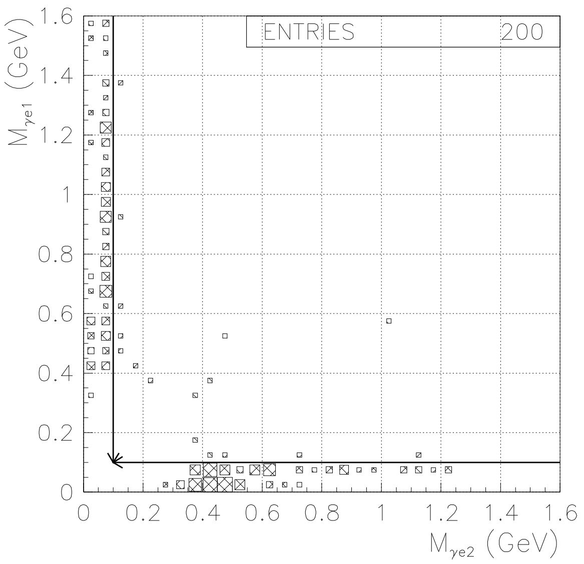
- For each extra cluster on-time

$$M_{\gamma e^1} \leqslant 100 \text{ MeV} \texttt{ OR } M_{\gamma e^2} \leqslant 100 \text{ MeV}$$

Bremsstrahlung photons



Data sample



MC simulation

The sample of $\psi' \to e^+e^-$ has been selected with tight cuts:

- $M_{ee} > 3.4$ GeV/c^2
- $\log_{10}(ew1 * ew2) > 0$
- $Prb(e^+e^-) > Prb(J/\psi X)$ AND $Prb(e^+e^-) > 1\%$
- Only 1 extra cluster on-time

The same reaction has been simulated with MC.

From above distribution we define two zones:

- Allowed zone:
  $M_{\gamma e^1} \leqslant 100$ MeV OR $M_{\gamma e^2} \leqslant 100$ MeV
- Forbidden zone:
  $M_{\gamma e^1} > 100$ MeV AND $M_{\gamma e^2} > 100$ MeV

Trigger efficiency

The efficiency of the charged trigger calculated with:

- special runs results:

$$\epsilon_{trig}^{data} = 0.90 \pm 0.02$$

- simulation of e^+e^- final state (e^+e^- and e^+e^-X) and results:

$$\epsilon_{trig}^{mc} = 0.897 \pm 0.014$$

Preselection efficiency with data at ψ'

The efficiency of preselection has been calculated with 4 samples of mdst data:

sample	run	E_{cm}	$\int L dt$ (pb^{-1})
1	5006-5038 5076-5084 5076-5084 5076-5084	ψ' peak	2.40
2	5571-5574 5818-5837 5840-5842 7143-7148	ψ' peak	4.95
3	7248-7252 7254-7259 7269-7271	ψ' peak + bckg	4.52
4	7273-7278	ψ' peak	1.94

selected requiring:

- only 2 on-time clusters
- tight topological cuts relative to two body hypothesis

results:

sample	ϵ_{pres}
1	0.969 ± 0.021
2	0.960 ± 0.030
3	0.966 ± 0.024
4	0.967 ± 0.026

averaging:

$$\epsilon_{pres}^{data} = 0.966 \pm 0.013(stat)^{+0.027}_{-0.036}(syst)$$

Preselection efficiency with MC

The efficiency of the preselection has been calculated with MC simulating the reaction $\psi^{'} \to e^+e^-$ at 4 different run conditions:

	run	ϵ_{pres}
1	7277	0.927 ± 0.007
2	7144	0.919 ± 0.007
3	5078	0.921 ± 0.007
4	5572	0.919 ± 0.007

averaging:

$$\epsilon_{pres}^{mc} = 0.921 \pm 0.004(stat)^{+0.013}_{-0.010}(syst)$$

Selection efficiency with data at ψ'

Sample	run	E_{CM} (MeV)	$\int Ldt$ (pb^{-1})
1	$5006 \div 5084$ $5235 \div 5432$	3686	2.399
2	$5571 \div 5574$ $5818 \div 5842$	3686	2.380
3	$7144 \div 7259$	3686	5.944
4	$7273 \div 7278$	3686	2.401
bkg	$7280 \div 7283$	3666	0.779
bkg	$7269 \div 7271$	3704	1.153

Efficiency of selection:

Sample	ϵ_{sel}
1	$0.603^{+0.050}_{-0.049}$
2	$0.657^{+0.055}_{-0.053}$
3	$0.662^{+0.030}_{-0.029}$
4	$0.680^{+0.046}_{-0.044}$

bkg at 3666 MeV

Sample	ϵ^{I}_{sel}
1	$0.603^{+0.052}_{-0.049}$
2	$0.656^{+0.057}_{-0.054}$
3	$0.662^{+0.039}_{-0.038}$
4	$0.679^{+0.047}_{-0.045}$

bkg at 3704 MeV

Average efficiency of the selection results:

$$\epsilon^{data}_{sel} = 0.650^{+0.017}_{-0.016}(stat)^{+0.030}_{-0.048}(syst)$$

Selection efficiency with MC

Using same rection used to evaluate preselection efficiency we find:

Sample	ϵ_{sel}
1	0.642 ± 0.010
2	0.653 ± 0.010
3	0.645 ± 0.010
4	0.641 ± 0.010

Average efficiency of the selection results:

$$\epsilon_{sel}^{mc} = 0.645 \pm 0.005(stat)^{+0.018}_{-0.014}(syst)$$

Form factor analysis efficiency

Using $\epsilon_{ana} = \epsilon_{trig} \cdot \epsilon_{pres} \cdot \epsilon_{sel}$ we find:

- $\epsilon_{ana}^{data} = 0.565^{+0.021}_{-0.020}(stat)^{+0.030}_{-0.047}(syst)$

- $\epsilon_{ana}^{mc} = 0.533 \pm 0.010(stat)^{+0.017}_{-0.013}(syst)$

Energy ranges for the form factor analysis

We find the form factor events at the following energy:

- Data at background above and below energy peak of χ_0 (out of about $1.5 - 2\Gamma_{\chi_0}$)
- All data at h_c energy
- Data at two high energies ($\sim$ 3.8 GeV and $\sim$ 4.2 GeV)

summarized in the following table:

Sample	$\sqrt{s}$ Interval (GeV)	Mean±Rms (GeV)	$\int Ldt$ (pb^{-1})	N
1	3.340-3.392	3.379±0.014	8.52	8
2	3.430-3.470	3.455±0.019	3.95	3
3	3.523-3.529	3.526±0.006	50.50	31
4	3.770-3.836	3.795±0.050	5.17	0
5	4.267-4.270	4.268±0.002	2.10	0

Measurements of the $\bar{p}p \rightarrow e^+e^-$ cross section

From N, L and ϵ we measure: $\sigma_{acc} = \frac{N}{\epsilon L}$

s (GeV^2)	L (pb^{-1})	N	σ_{acc} (pb)	$\lvert\cos\theta^*\rvert_{max}$
11.42±0.09	8.52	8	$1.66^{+0.82+0.08}_{-0.58-0.12}$ $(1.76^{+0.87+0.06}_{-0.61-0.04})$	0.568
11.93±0.13	3.95	3	$1.34^{+1.31+0.06}_{-0.73-0.10}$ $(1.42^{+1.39+0.05}_{-0.78-0.03})$	0.585
12.43±0.01	50.50	31	$1.09^{+0.23+0.05}_{-0.20-0.08}$ $(1.15^{+0.25+0.04}_{-0.21-0.03})$	0.601
14.40±0.19	5.17	0	< 0.87 (< 0.90)	0.603
18.22±0.01	2.10	0	< 2.13 (< 2.22)	0.512

Between parenthesis the results calculated with MC efficiency.

Evaluation of background contamination

The reaction which could simulate the same signal of e^+e^- final state are:

- $J/\psi X$ events, mainly in the energy range of χ_0 :

$$\chi_0 \rightarrow J/\psi\gamma \rightarrow e^+e^-\gamma$$

- Photon conversion and π^0 Dalitz decays:

$$\overline{p}p \rightarrow \pi^0\pi^0$$
$$\overline{p}p \rightarrow \pi^0\gamma$$
$$\overline{p}p \rightarrow \gamma\gamma$$

- Hadronic two body final state, mainly:

$$\overline{p}p \rightarrow \pi^+\pi^-$$

Evaluation of $\chi_0 \to J/\psi\gamma$ contamination

- At χ_0 peak $(M_{\chi_0} - \frac{\Gamma_{\chi_0}}{2} \leqslant E_{cm} \leqslant M_{\chi_0} - \frac{\Gamma_{\chi_0}}{2})$ form factor analysis selects 10 events, with $L = 11.07\ \mathrm{pb}^{-1}$.

- Considering all these events as due to $J/\psi\gamma$ background

  and

  rescaling with Breit-Wigner formula we calculate the background contribution to cross section at different energy.

- The background contribution to the cross section at the two energy out of the χ_0 peak results:

s (GeV^2)	σ_{ff} (pb)	$\sigma_{J/\psi\gamma}$ (pb)
11.42 ± 0.09	$1.66^{+0.82+0.08}_{-0.58-0.12}$	$< 3.1 \cdot 10^{-2}$
11.93 ± 0.13	$1.34^{+1.31+0.06}_{-0.73-0.10}$	$< 2.4 \cdot 10^{-2}$

Evaluation of photon convertion, π^0 Dalitz decays and $\pi^+\pi^-$ background contamination

In runI of E835 these backgrounds have been studied very well and the results are:

$$\sigma_{\pi^0,\gamma}(s = 12.25\ \mathrm{GeV}^2) < 3 \cdot 10^{-3}\ \mathrm{pb}$$

$$\sigma_{\pi^+\pi^-}(s = 12.96\ \mathrm{GeV}^2) < 1.3 \cdot 10^{-3}\ \mathrm{pb}$$

From data of runII these backgrounds have not yet been evaluated. These are the last checks which be done.

All backgrounds together

Summing all backgrounds at similar energy we obtain the total contribution:

s (GeV^2)	σ_{ff} (pb)	σ_B (pb)
11.42 ± 0.09	$1.66^{+0.82+0.08}_{-0.58-0.12}$	$< 3.5 \cdot 10^{-2}$
11.93 ± 0.13	$1.34^{+1.31+0.06}_{-0.73-0.10}$	$< 2.8 \cdot 10^{-2}$
12.43 ± 0.01	$1.09^{+0.23+0.05}_{-0.20-0.08}$	$< 4.3 \cdot 10^{-3}$

$\Longrightarrow$ no subtraction from number of candidate events is performed.

Measurements of the form factor

Integrated cross section in acceptance region (σ_{acc}) previosly calculated is a function of $|G_E|$ and $|G_M|$:

$$\sigma_{acc} = \int_0^{2\pi} d\phi \int_{-|\cos\theta^*|_{max}}^{+|\cos\theta^*|_{max}} \frac{d\sigma}{d\Omega} d(\cos\theta^*)$$
$$= \frac{\pi\alpha^2}{2\beta_p s} \cdot \left[A \cdot |G_M|^2 + \frac{4m_p^2}{s} \cdot B \cdot |G_E|^2 \right]$$

where A and B are:

$$A = 2 \cdot \int_0^{+|\cos\theta^*|_{max}} (1 + \cos^2\theta^*) d(\cos\theta^*)$$
$$B = 2 \cdot \int_0^{+|\cos\theta^*|_{max}} (1 - \cos^2\theta^*) d(\cos\theta^*)$$

... Measurements of the form factor

Our statistic is low $\Rightarrow$ we can not measure angular distribution

$\Rightarrow$ we can calculate $|G_M|$ with 2 different hypothesis

(a) $|G_E| = |G_M|$:

$$|G_M| = \left[\frac{2\ \beta_p\ s\ N}{\pi\ \alpha^2\ \left[A + \frac{4m_p^2}{s} B\right]\ L\ \epsilon} \right]^{\frac{1}{2}}$$

(b) electric contribution negligible:

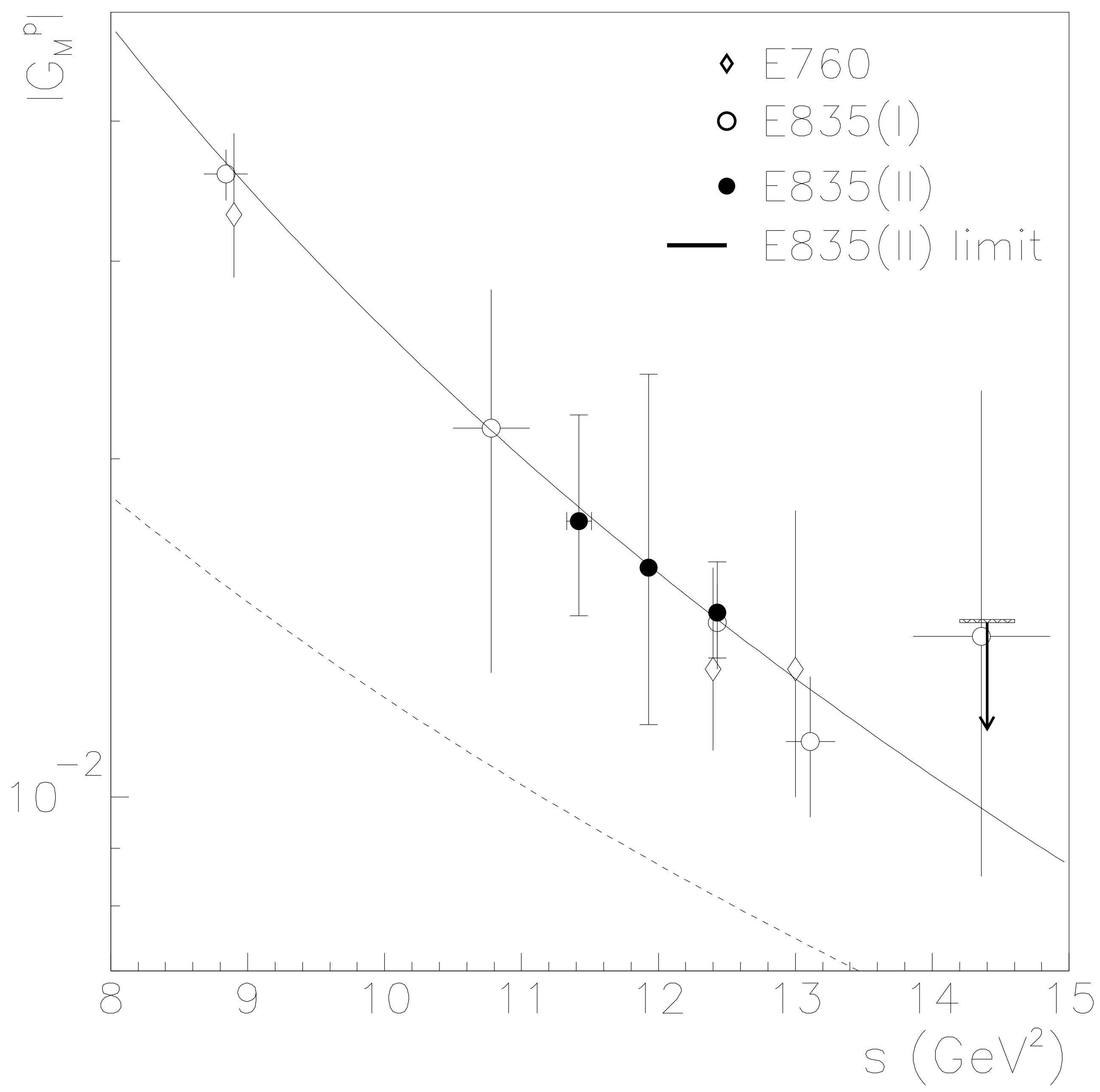
$$|G_M| = \left[\frac{2\ \beta_p\ s\ N}{\pi\ \alpha^2\ A\ L\ \epsilon} \right]^{\frac{1}{2}}$$

Results of the form factor analysis

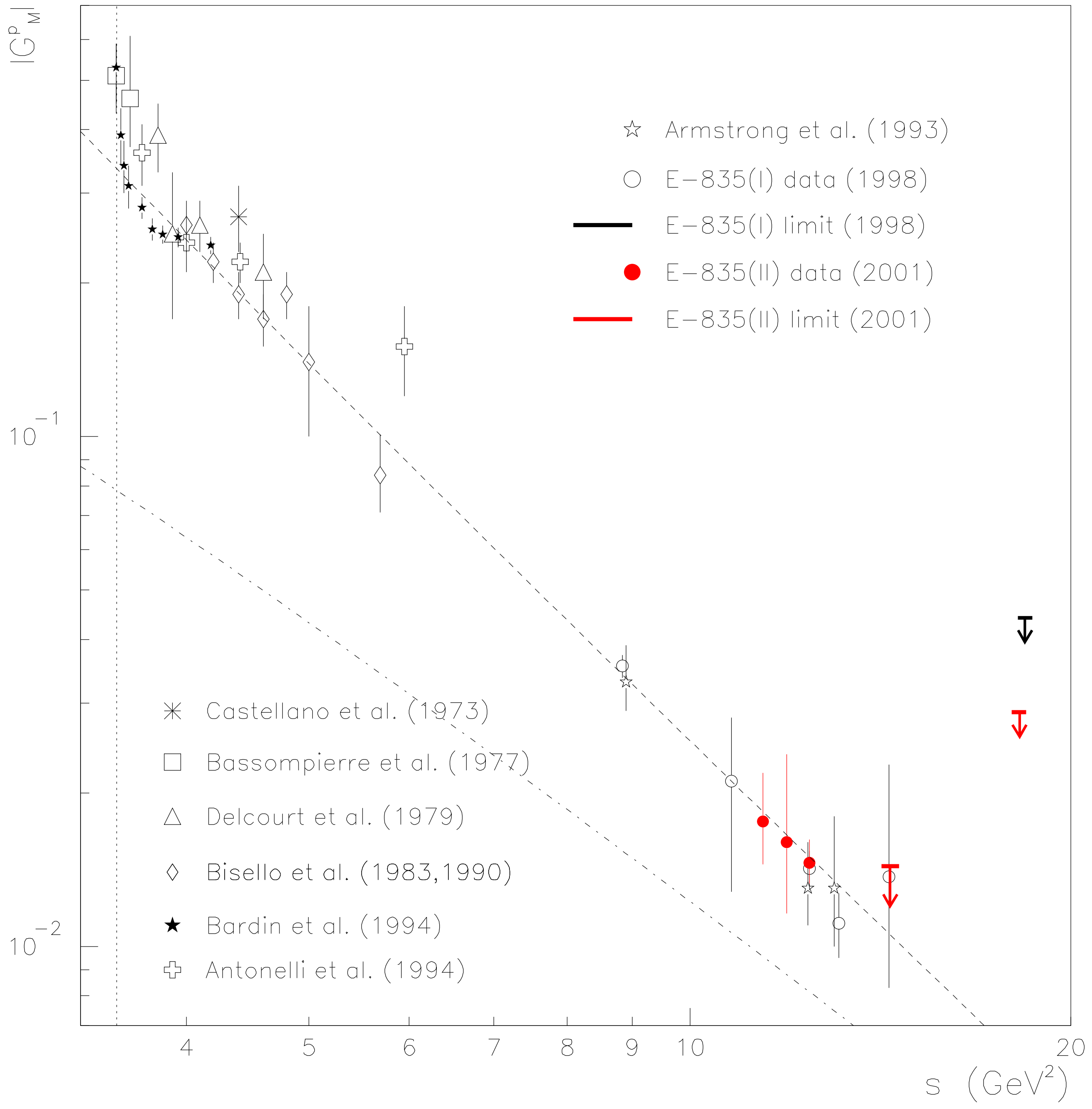
s (GeV^2)	$10^2 \times \lvert G_M \rvert$ (a)	(b)
11.42±0.09	$1.76^{+0.43+0.04}_{-0.31-0.06}$ ($1.81^{+0.45+0.03}_{-0.31-0.02}$)	$1.96^{+0.49+0.05}_{-0.34-0.07}$ ($2.02^{+0.50+0.03}_{-0.35-0.03}$)
11.93±0.13	$1.60^{+0.78+0.04}_{-0.44-0.06}$ ($1.65^{+0.80+0.03}_{-0.45-0.02}$)	$1.78^{+0.87+0.04}_{-0.49-0.07}$ ($1.83^{+0.89+0.03}_{-0.50-0.03}$)
12.43±0.01	$1.46^{+0.16+0.03}_{-0.13-0.05}$ ($1.50^{+0.16+0.02}_{-0.14-0.02}$)	$1.61^{+0.17+0.04}_{-0.15-0.06}$ ($1.66^{+0.18+0.03}_{-0.15-0.02}$)
14.40±0.19	< 1.43 (< 1.47)	< 1.57 (< 1.60)
18.22±0.01	< 2.88 (< 2.94)	< 3.10 (< 3.17)

Between parenthesis the results calculated with MC efficiency.

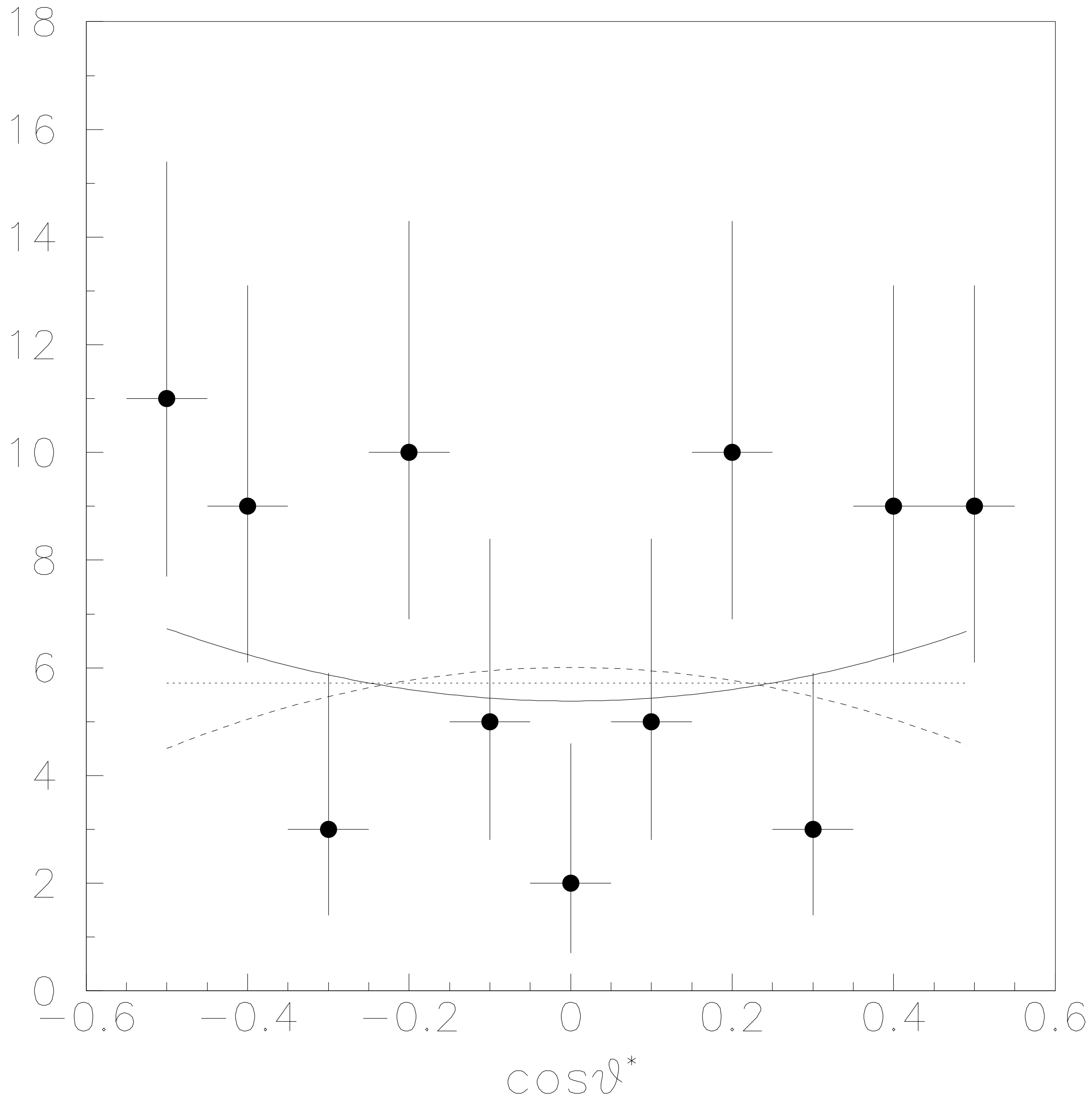
Magnetic form factor from E760, E835(I) and E835(II)



All existing measurements of the magnetic form factor



Angular distribution of all form factor events



- There are 38 events in cm common acceptance
- With the restriction on cm common acceptance we lose 4 form factor events at h_c energy.

Angular distribution of all 31 form factor events at h_c energy