PRODUCTION OF MASSIVE MUON PAIRS BY 300 AND 400 GeV PROTONS[*]

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ABSTRACT

We have observed muon pairs with effective masses in the range $7 \leqslant M_{\mu\mu} \leqslant 11$ GeV/c^2 produced by 300 and 400 GeV protons incident on a Cu target at Fermilab. The production cross section per nucleon, $d\sigma/dM_{\mu\mu}$, for 400 GeV incident protons is found to fall from 1×10^{-36} cm^2/GeV/c^2 at $M_{\mu\mu} = 7.7$ GeV/c^2 to 2.7×10^{-38} cm^2/GeV/c^2 at $M_{\mu\mu} = 11.2$ GeV/c^2.

We report here preliminary results of an experiment which bears on two related problems. The first concerns the nature of the source of directly-produced single leptons observed at high transverse momentum ($p_\perp$) at Fermilab[1-3], ISR[4] and Serpukhov[5] ; the second is the magnitude of production of lepton pairs whose mass represents a substantial fraction of the available energy in a hadron-hadron interaction. The observation of a continuum of lepton pairs would not only shed light on the nature and distribution of point-like constituents in the proton[6], but would also be of practical value in the estimation of the production cross section of charged and neutral heavy vector bosons[7].

Experiments on dilepton production in proton-nucleon collisions have been performed at Brookhaven National Laboratory[8,9], and more recently at Fermilab[10-15], ISR[16] and Serpukhov[17]. In the present experiment our original motivation was to investigate further the production, at large $p_\perp$, of direct single muons measured in our previous experiment[1]. We ask the simple question : What fraction of the single muons is accompanied by a high $p_\perp$ muon on the opposite side of the beam ?

Figure 1 shows a schematic view of the apparatus. A magnetic spectrometer[18], which selects particles produced at $\sim 90^{\circ}$ in the proton-nucleon c.m. system, was used to obtain a nearly pure sample of direct muons (~ 70 % pure) in a manner identical to that described in a prior publication[1]. The Fermilab incident proton beam and the magnetic spectrometer are located in tunnels and pits approximatively 3.5 m below the nominal surface of the ground. A second arm, called the Multihole Spectrometer (MHS), consisted of 10 $3.6 \times 1.1 \times 0.1$ m^3 liquid scintillation counters inserted into holes in the ground. The counters, shielded from the target by steel and earth, are placed along a line parallel to the incident proton beam and displaced by ~ 6 m so that only muons with $p_\perp \gtrsim 3.2$ GeV/c are detected[19]. A steel absorber could be inserted close to the target to modulate backgrounds in the MHS from pion and kaon decay. For 400 GeV incident protons the MHS covers in the c.m. system a polar angle of $60^{\circ} < \theta < 126^{\circ}$, and an azimuthal angle of $-8^{\circ} < \phi < 25^{\circ}$.

Runs were taken as a function of $p_\perp^s$, the transverse momentum selected by the magnetic spectrometer. The MHS counters were interrogated each time a particle was detected in the magnetic spectrometer. Pulses were recorded within a time gate extending from −70 nsec to +250 nsec with respect to the trigger particle in the magnetic spectrometer. Both the time with respect to the trigger and the magnitude of each pulse were recorded.

The beam spill had an RF structure which contained bunches ∿ 2 nsec wide, 18.9 nsec apart. The time resolution of a given MHS counter was 5 nsec (FWHM). The time of arrival of a muon at the MHS could be associated unambiguously with a given RF bunch of the incident beam which produced the trigger particle.

Figure 2 shows the result of a run with 400 GeV incident protons with the magnetic spectrometer set at $p_\perp^s$ = 4.5 GeV/c. A time distribution of counts in the MHS is plotted in units of the RF period of the Fermilab accelerator. The RF bin labelled 4 was independently established to be the RF bin coincident with the trigger particle. In Fig. 2 (a) μμ events are plotted. These are events for which a muon is identified in the magnetic spectrometer. A clear coincidence signal is observed in the fourth RF bin. The level of counts in the other bins gives a measure of the accidental background. Figure 2 (b) shows the time distribution of MHS counts associated with a pion trigger in the magnetic spectrometer. Here there is no evidence of an excess in the coincidence bin. These data, taken <u>simultaneously</u> with the data of Fig. 2 (a), demonstrate in a most conclusive manner that the signal of μμ coincidences ·is real.

In Table I we present a summary of the raw results obtained in each of the seven runs. The steel absorber was periodically inserted and removed during each run. In no case was any effect of the shutter observed within statistics. The sixth column of Table I gives the fraction of single direct muon which are accompanied by a count in the MHS detector. At $p_\perp^s$ = 5.25 GeV/c, ∿ 13 % of the single muons also have a count in the MHS. Using only up-down symmetry with respect to the production plane and a conservative extrapolation of the observed distribution beyond the solid angle subtended, one can estimate

that $\gtrsim$ 30 % of the single μ's have their origin as one member of a high mass muon pair. One should also note that the production of dimuons is the same, within statistics, when either positive or negative muons are selected at $p_\perp^S$ = 4.5 GeV/c in the magnetic spectrometer. This fact strengthens our implicit assumption that the two muons are of opposite sign.

We have evaluated the production cross section for the dimuons as a function of their mass. If the transverse momentum of the dimuon parent is limited ($\lesssim$ 300 MeV/c), its mass would be approximately twice the transverse momentum setting of the magnetic spectrometer $(p_\perp^S)$. If the transverse momentum of the parent is significantly larger, the mass acceptance of the apparatus would be broadened but still centered about 2 $p_\perp^S$. Typically, the mass acceptance (FWHM) is $\sim$ 2 GeV/c^2 at 10 GeV/c^2 for a mean $p_\perp$ of the dimuon of 1.25 GeV/c. Two effects alter this simple conclusion. First, the minimum mass that can be accepted by the system is effectively set by the sum of $p_\perp^S$ and the MHS cut-off of 3.2 GeV/c. Secondly, the sharply falling cross section with increasing mass means that the average mass observed for $p_\perp^S$ > 3.2 GeV/c is lower than the peak of the acceptance curve.

To evaluate the cross section $d\sigma/dM_{\mu\mu}$ we must assume a model for the $p_\perp$ and x dependences of the cross section $(x = p_{//}/p_{//}^{max})$. The efficiency of the detector for various $M_{\mu\mu}$ can then be evaluated. We have used two models of dimuon production. The first model (I), which has x and $p_\perp$ dependences derived from J/ψ production[13], viz.,

$$d\sigma/dM_{\mu\mu} \propto e^{-1.6\, p_\perp}\, (1 - |x|)^{4.3},$$

corresponds to a mean transverse momentum of 1.25 GeV/c. The second model (II),

$$d\sigma/dM_{\mu\mu} \propto e^{-b p_\perp}\, (1 - |x|)^{4.3},$$

where b = 6/$M_{\mu\mu}$ is characterized by $<p_\perp>$ = $M_{\mu\mu}$/3. Table II gives the results of the cross section <u>per Cu nucleus</u> for each model.

Inspection of these results shows that the cross section dependence on mass is the same for the two models, i.e. $d\sigma/M_{\mu\mu} \sim \exp(-1.1\ M_{\mu\mu})$, and that the cross sections differ by a factor ~ 2. We have computed $d\sigma/dM_{\mu\mu}$ for x dependences $(1 - |x|)^1$ and $(1 - |x|)^{10}$ and find changes of less than a factor 2. A variation of $\pm$ 300 MeV/c in the transverse momentum cut-off for the MHS causes changes of less than 20 %.

To make a comparison with the recent work of Hom et al.[13] on dielectron production at Fermilab, we show in Fig. 3 the cross section per nucleon, $(d^2\sigma/dM_{\mu\mu}\,dy)_{y=o}$, evaluated for Model I over the rapidity interval $-0.3<y<0.2$. (An A^1 dependence of the cross section has been assumed.) Model I is identical to the model used by Hom et al.[13] to evaluate their own apparatus efficiency.

Our data at the two energies are statistically consistent with the scaling relation

$$M^3_{\mu\mu}\,d\sigma/dM_{\mu\mu} = f(M^2_{\mu\mu}/s),$$

where $f(M^2_{\mu\mu}/s)$ is a universal function of $M^2_{\mu\mu}/s$, and s is the square of the c.m. energy. We plan to carry out further measurements on the scaling properties of dimuon production.

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TABLE CAPTIONS

Table I   Raw data obtained in the experiment. The event yields
               have been corrected for accidental coincidences.

Table II   Results of cross section evaluation for the two models
               discussed in the text.

Proton Energy (GeV)	$p_\perp^s$ (GeV/c)	Charge of trigger muon	Dimuon Yield (events)	Dimuon Yield per 10^{17} protons	Dimuons per direct single muon (%)
400	3.75	−	51 ± 10	109 ± 18	1.1 ± 0.2
400	4.50	−	64 ± 10	77 ± 10	6.0 ± 1.0
400	4.50	+	45 ± 8	75 ± 12	. . .
400	5.25	−	36 ± 6	37 ± 7	12.7 ± 2.1
400	6.00	−	8 ± 2.8	8.4 ± 3	19 ± 7
300	3.75	−	30 ± 7	35 ± 8	. . .
300	4.50	−	53 ± 8	39 ± 6	. . .

TABLE I

Proton Energy (GeV)	MODEL I		MODEL II	
	$\langle M_{\mu\mu} \rangle$ (GeV/c^2)	$d\sigma/dM_{\mu\mu}$ $(cm^2/GeV/c^2)$	$\langle M_{\mu\mu} \rangle$ (GeV/c^2)	$d\sigma/dM_{\mu\mu}$ $(cm^2/GeV/c^2)$
400	7.7	$(6.4 \pm 1.1)\ 10^{-35}$	7.7	$(1.4 \pm 0.2)\ 10^{-34}$
400	8.8	$(2.7 \pm 0.3)\ 10^{-35}$	8.6	$(7.0 \pm 0.7)\ 10^{-35}$
400	10.0	$(8.9 \pm 1.5)\ 10^{-36}$	9.4	$(2.7 \pm 0.5)\ 10^{-35}$
400	11.2	$(1.7 \pm 0.6)\ 10^{-36}$	10.2	$(5.8 \pm 2.0)\ 10^{-36}$
300	7.6	$(1.8 \pm 0.4)\ 10^{-35}$	7.6	$(3.8 \pm 0.9)\ 10^{-35}$
300	8.6	$(1.2 \pm 0.2)\ 10^{-35}$	8.4	$(3.2 \pm 0.5)\ 10^{-35}$

TABLE II

FIGURE CAPTIONS

Fig. 1   Schematic diagram of the apparatus.

Fig. 2   Time distributions of MHS counts with respect to (a) a muon

                trigger and (b) a pion trigger in the magnetic spectrometer

                (set at $p_{\perp}^{S}$ = 4.5 GeV/c). Time intervals are plotted in units

                of an RF period of the Fermilab accelerator (18.9 nsec).

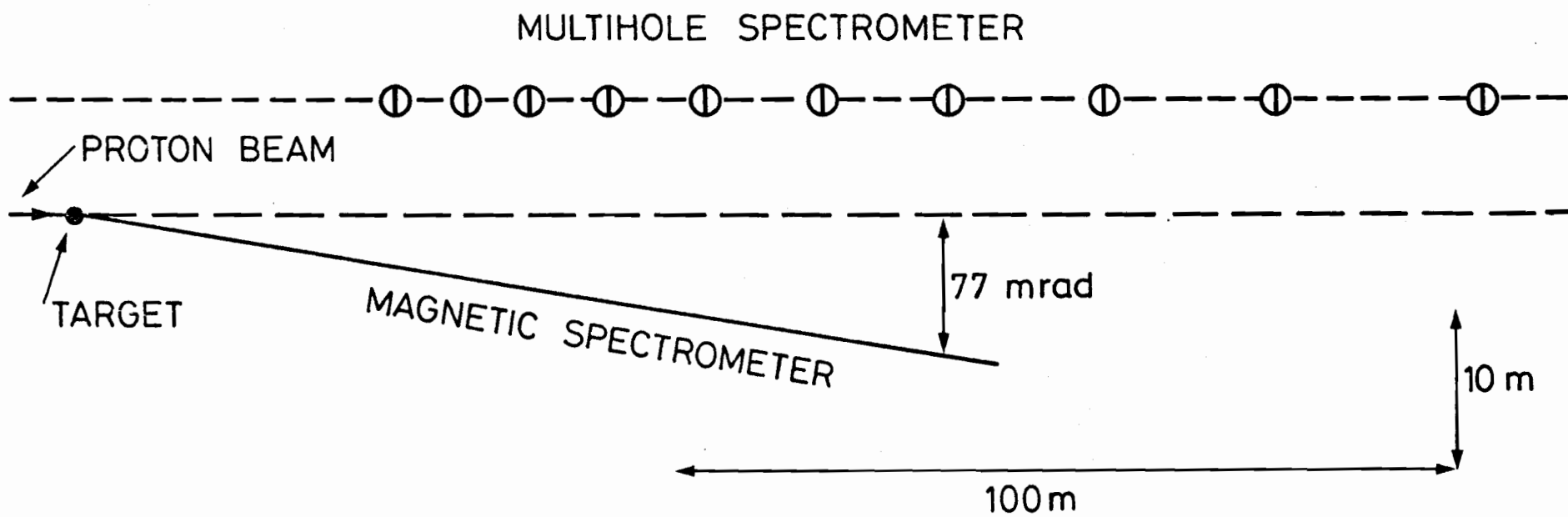Fig. 3   Comparison of this experiment with results of Hom et al.,
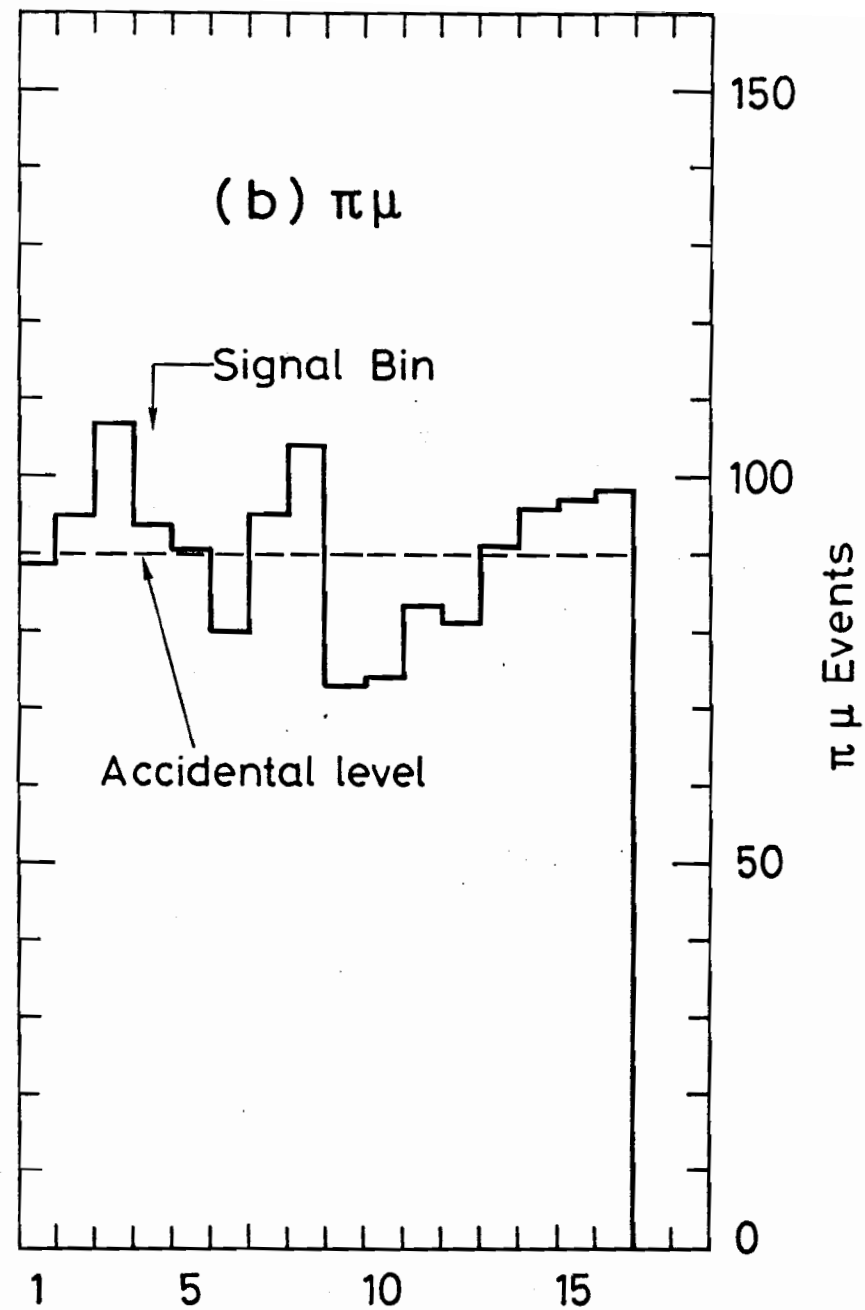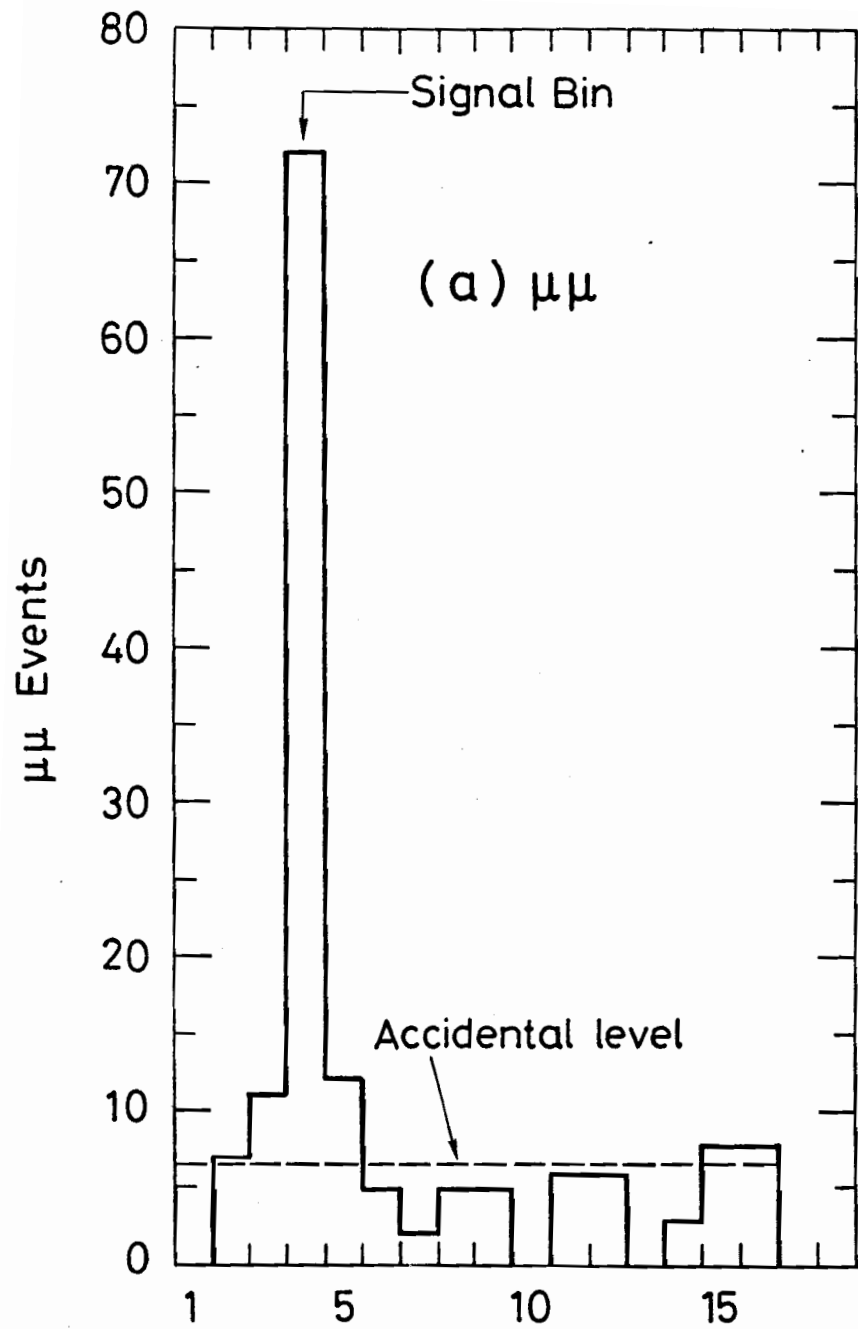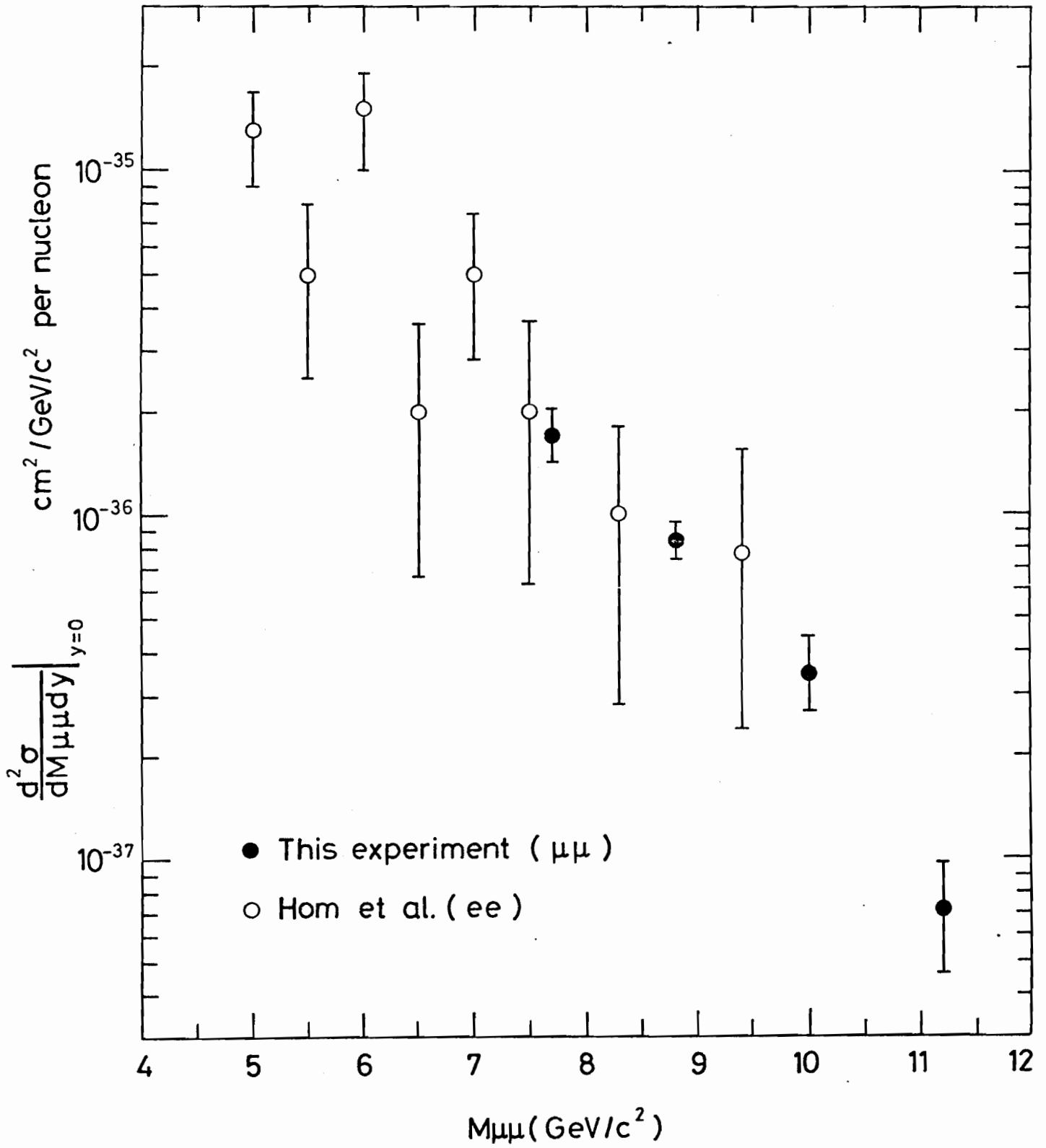
                (Ref. 13).

Fig. 1

Fig. 2

Fig. 3