



# Fermi National Accelerator Laboratory

FERMILAB-Pub-77/86-EXP  
7100.288

(Submitted to Phys. Rev. Lett.)

## OBSERVATION OF STRUCTURE IN THE $\Upsilon$ REGION

W. R. Innes, J. A. Appel, B. C. Brown,  
C. N. Brown, K. Ueno, and T. Yamanouchi  
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

S. W. Herb, D. C. Hom, L. M. Lederman,  
J. C. Sens, H. D. Snyder, and J. K. Yoh  
Columbia University, New York, New York 10027

and

R. J. Fisk, A. S. Ito, H. Jöstlein,  
D. M. Kaplan, and R. D. Kephart  
State University of New York at Stony Brook  
Stony Brook, Long Island, New York 11794

September 1977



## OBSERVATION OF STRUCTURE IN THE $\Upsilon$ REGION

W. R. Innes, J. A. Appel, B. C. Brown,  
C. N. Brown, K. Ueno, and T. Yamanouchi  
Fermi National Accelerator Laboratory  
Batavia, Illinois 60510

S. W. Herb, D. C. Hom, L. M. Lederman,  
J. C. Sens,<sup>(a)</sup> H. D. Snyder, and J. K. Yoh  
Columbia University, New York, New York 10027

R. J. Fisk, A. S. Ito, H. Jöstlein,  
D. M. Kaplan, and R. D. Kephart  
State University of New York at Stony Brook  
Stony Brook, Long Island, New York 11794

The properties of the dimuon enhancement seen in 400 GeV proton-nucleus collisions have been clarified by a three-fold increase in data. We find two peaks whose widths are consistent with our resolution:  $M_1 = 9.4$  GeV with  $B d\sigma/dy|_{y=0} = 1.8 \times 10^{-37}$  cm<sup>2</sup>/nucleon and  $M_2 = 10.0$  GeV with  $B d\sigma/dy|_{y=0} = 0.7 \times 10^{-37}$  cm<sup>2</sup>/nucleon. Evidence for the possible existence of a third peak near 10.4 GeV is discussed as are the comparisons with the properties of a  $q\bar{q}$  system, where  $q$  is a new heavy quark.

---

(a) Permanent address: Foundation for Fundamental Research on Matter, The Netherlands.

In a previous publication<sup>1</sup> we presented evidence for a broad enhancement near 9.5 GeV in dimuon production in 400 GeV proton-nucleus collisions based upon a study of 9000 muon pairs with invariant mass greater than 5 GeV. We present here conclusions based on 26,000 events above 5 GeV. The data were obtained with a fixed spectrometer setting (1500 A) and represent  $2 \times 10^{16}$  proton interactions in Pt and Cu targets. The mass spectrum is given in Fig. 1. The acceptance calculation has been improved by better knowledge of the  $p_T$  distribution of dileptons. Excluding the mass interval 8.8 to 11.0 GeV we find a fit to the continuum of the form<sup>2</sup>

$$\left. \frac{d^2\sigma}{dm dy} \right|_{y=0} = A e^{-bm} \quad \text{with} \tag{1}$$
$$A = 1.26 \pm 0.02 \times 10^{-33} \text{ cm}^2/\text{GeV/nucleon}$$
$$b = 0.953 \pm 0.01 \text{ GeV}^{-1}.$$

We stress that the errors are statistical only. We have, to date, studied the systematic errors only in so far as they affect the continuum subtraction process. An analysis of the continuum data will be published separately.

Figure 2 shows the excess of the data over the fit of Eq. (1). The enhancement represents  $\sim 1200$  events, i. e. the continuum fit predicts  $1300 \pm 36$  events and 2500 are observed. We note that the new picture which emerges from the improved statistics is in agreement with the earlier results but now clearly establishes the two (or more) narrow peak interpretation.

Table I presents the results of a fitting program under the hypotheses of 2 and 3 narrow peaks. "Narrow" here means a natural width less than one-half the resolution. These fits use the calculated resolution of 2.1% (r. m. s). If the resolution is varied, the best fit width is  $2.1 \pm 0.14\%$ .

It remains to discuss the systematic uncertainties. Clearly the relative intensities (although not the spacing of  $M_1$  and  $M_2$ ) depend on the precise form of the continuum. The first test is to vary the slope parameter,  $b$ , in Eq. (1). Variation each way by  $2\sigma$  yields the results given in Table II. A detailed study has been made of the error matrix representing correlated uncertainties in the multi-parameter fit. The correlations increase the uncertainties of Tables I and II by  $\leq 15\%$ .

Further uncertainties in the results presented above arise from the fact that the continuum fit is dominated by the data below 9 GeV. Nature could provide reasonable departures from Eq. (1) above this mass. These issues must wait for a large increase in the number of events, especially above  $\sim 11$  GeV. However, the primary conclusions are independent of these uncertainties and may be summarized as follows:

i) The structure contains at least two narrow peaks:  $\Upsilon(9.4)$  and  $\Upsilon'(10.0)$ .

ii) The cross section for  $\Upsilon(9.4)$ ,  $(B d\sigma/dy)|_{y=0}$  is  $0.18 \pm 0.07$  pb/nucleon. (The error includes our  $\pm 25\%$  absolute normalization uncertainty and also the estimated uncertainty due to model dependence of the acceptance calculation.)

iii) There is evidence for a third peak  $\Upsilon''$  (10.4) although this is by no means established.

Examination of the  $p_T$  and decay angle distributions of these peaks fails to show any gross difference from adjoining continuum mass bins.

An interesting quantity is the ratio of  $(B d\sigma/dy)|_{y=0}$  for  $\Upsilon$  (9.4) to the continuum cross section  $(d^2\sigma/dm dy)|_{y=0}$  at  $M = 9.40$  GeV: this is  $1.11 \pm 0.06$  GeV.

Table III presents mass splittings and cross sections (including systematic errors) under the 2- and 3-peak hypotheses and compares them with theoretical predictions to be discussed below.

There is a growing literature which relates the  $\Upsilon$  to the bound state of a new quark ( $q$ ) and its antiquark ( $\bar{q}$ ).<sup>3-11</sup> Eichten and Gottfried<sup>3</sup> have calculated the energy spacing to be expected from the potential model used in their accounting for the energy levels in charmonium. Their potential

$$V(r) = -\frac{4}{3} \alpha_s (m_q) \frac{1}{r} + \frac{r}{a^2} \quad (2)$$

predicts line spacings and leptonic widths. The level spacings (Table IIIa) suggest that the shape of the potential may be oversimplified; we note that  $M(\Upsilon') - M(\Upsilon)$  is remarkably close to  $M(\psi') - M(\psi)$ .<sup>12</sup>

Table IIIb summarizes estimates of  $B d\sigma/dy|_{y=0}$  for  $q\bar{q}$  states and ratios of the  $n = 2, 3$  states to the ground state. Cascade models ( $\Upsilon$  produced as the radiative decay of a heavier P-state formed by gluon

amalgamation) and direct production processes seem to prefer  $Q = -1/3$  to  $Q = 2/3$ . We note finally that the ratios in Table III may require modification due to the discrepancy between the observed spacing and the universally used Eichten and Gottfried results.<sup>3</sup>

We appreciate the continuing support of the staffs of our respective institutions. This work was supported in part by the U. S. Energy Research and Development Administration and the National Science Foundation.

REFERENCES

- <sup>1</sup>S. Herb et al., Phys. Rev. Lett. 39, 212 (1977).
- <sup>2</sup>Linear atomic number dependence is assumed in converting to cross section per nucleon.
- <sup>3</sup>E. Eichten and K. Gottfried, Phys. Lett. 66B, 286 (1977).
- <sup>4</sup>R. Cahn and S. D. Ellis, UM HE 76-45.
- <sup>5</sup>J. Ellis, M. K. Gaillard, D. V. Nanopoulos and S. Rudaz, CERN TH-2346 (1977).
- <sup>6</sup>C. E. Carlson, R. Suaya et al., SLAC-PUB-1986 (1977).
- <sup>7</sup>T. Hagiwara, Y. Kazama and E. Takasugi, Fermilab-Pub-77/72-THY (1977).
- <sup>8</sup>F. Halzen and S. Matsuda, CERN TH-2354 (1977).
- <sup>9</sup>D. B. Lichtenberg, J. G. Wills and J. T. Kiehl, Indiana IUHET-23 (1977).
- <sup>10</sup>M. Barnett, European Conference on Particle Physics, Budapest, July 1977.
- <sup>11</sup>T. Gaisser, F. Halzen and E. Paschos, Phys. Rev. 15D, 2572 (1977).
- <sup>12</sup>In particular, if a logarithmic potential is used, the splitting is independent of the assumed quark mass (C. Quigg and J. L. Rosner, Fermilab-Pub-77/82-THY).

TABLE I

Resonance Fit Parameters<sup>a</sup>

	2 peak	3 peak	
$\Gamma$	$M_1$	$9.41 \pm 0.013$	$9.40 \pm 0.013$ GeV
	$B \frac{d\sigma}{dy} \Big _{y=0}$	$0.18 \pm 0.01$	$0.18 \pm 0.01$ pb
$\Gamma'$	$M_2$	$10.06 \pm 0.03$	$10.01 \pm 0.04$ GeV
	$B \frac{d\sigma}{dy} \Big _{y=0}$	$0.069 \pm 0.006$	$0.065 \pm 0.007$ pb
$\Gamma''$	$M_3$	---	$10.40 \pm 0.12$ GeV
	$B \frac{d\sigma}{dy} \Big _{y=0}$	---	$0.011 \pm 0.007$ pb
$\chi^2/DF$	$19.3 / 18$	$14.2 / 16$	

<sup>a</sup>Continuum subtraction is given by Eq. (1). Errors are statistical only.



TABLE II

Sensitivity of Resonance Parameters to Continuum Slope<sup>a</sup>

	$b = 0.977 \text{ GeV}^{-1}$	$b = 0.929 \text{ GeV}^{-1}$	
$\Gamma$	$M_1$	$9.40 \pm 0.013$	$9.40 \pm 0.014$ GeV
	$B \frac{d\sigma}{dy} \Big _{y=0}$	$0.18 \pm 0.01$	$0.17 \pm 0.01$ pb
$\Gamma'$	$M_2$	$10.00 \pm 0.04$	$10.01 \pm 0.04$ GeV
	$B \frac{d\sigma}{dy} \Big _{y=0}$	$0.068 \pm 0.007$	$0.061 \pm 0.007$ pb
$\Gamma''$	$M_3$	$10.43 \pm 0.12$	$10.38 \pm 0.16$ GeV
	$B \frac{d\sigma}{dy} \Big _{y=0}$	$0.014 \pm 0.006$	$0.008 \pm 0.007$ pb
	$\chi^2 / \text{DF}$	$14.1 / 16$	$15.4 / 16$

<sup>a</sup>Continuum subtraction of Eq. (1) but with  $b$  varied by  $\pm 2\sigma$ . Errors are statistical only.

TABLE III

Comparison with Predictions of Some  $q\bar{q}$  Models

a) Mass Splittings				
		$\Delta m (\Upsilon' - \Upsilon)$ (MeV)	$\Delta m (\Upsilon'' - \Upsilon)$ (MeV)	
This Experiment	<sup>a</sup> (2 peak fit)	$650 \pm 30$		
	(3 peak fit)	$610 \pm 40$	$1000 \pm 120$	
Eichten and Gottfried (Ref. 3)		420	750	
b) Cross Sections				
	<sup>b</sup> Q	<sup>c</sup> $\sum B \frac{d\sigma}{dy} \Big _{y=0}$ (pb)	<sup>d</sup> $\Upsilon'/\Upsilon$	<sup>d</sup> $\Upsilon''/\Upsilon$
This Experiment	<sup>a</sup> (2 peak fit)	$0.25 \pm 0.07$	$0.38 \pm 0.04$	
	(3 peak fit)	$0.25 \pm 0.07$	$0.37 \pm 0.04$	$0.06 \pm 0.04$
Cahn and Ellis (Ref. 4)	-1/3	$\sim 0.15$		
	2/3	$\sim 2.4$		
Ellis et al. (Ref. 5)	-1/3	$\sim 1$	0.3	0.15
	2/3	$\sim 4$	0.12	0.05
Carlson et al. <sup>e</sup> (Ref. 6)	-1/3	$\sim 0.5$	0.3	0.08
	2/3	$\geq 5$		
Hagiwara et al. (Ref. 7)	-1/3	$\sim 3 / N^{2f}$		
	2/3	$\sim 12 / N^{2f}$		
Barnett (Ref. 10)	-1/3	$\sim 0.4$	$\sim 0.4$	
	2/3	$\sim 1.6$		

<sup>a</sup> Systematic errors have been included (except for the uncertainty of the extrapolation to cross section per nucleon).

<sup>b</sup> The assumed charge of the quark.

<sup>c</sup> This is the summed cross section for the three states  $\Upsilon$ ,  $\Upsilon'$ , and  $\Upsilon''$ .

<sup>d</sup> These are ratios of  $B d\sigma/dy \Big|_{y=0}$ .

<sup>e</sup> Gluon distribution taken as  $(1 - X)^N$  with  $N = 4$ .

<sup>f</sup> This is the cross section for the  $\Upsilon$  only.  $N$  is the exponent of the gluon distribution as in note e.

FIGURE CAPTIONS

Fig. 1      Dimuon spectrum above 6 GeV.

Fig. 2      Excess of the data over the continuum fit of Eq. (1).  
Errors shown are statistical only. The solid curve is  
the 3-peak fit; the dashed curve is the 2-peak fit.

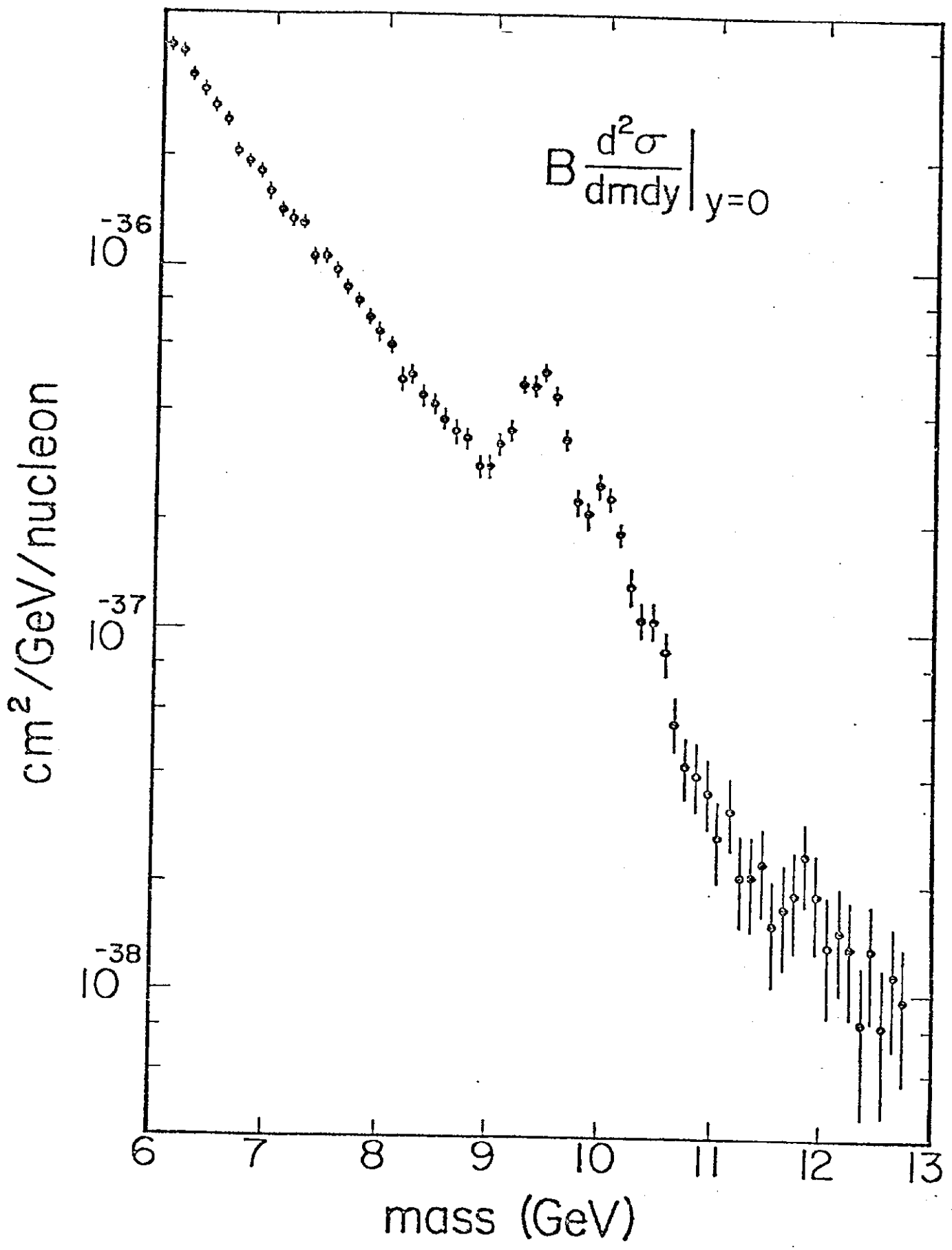


Fig. 1

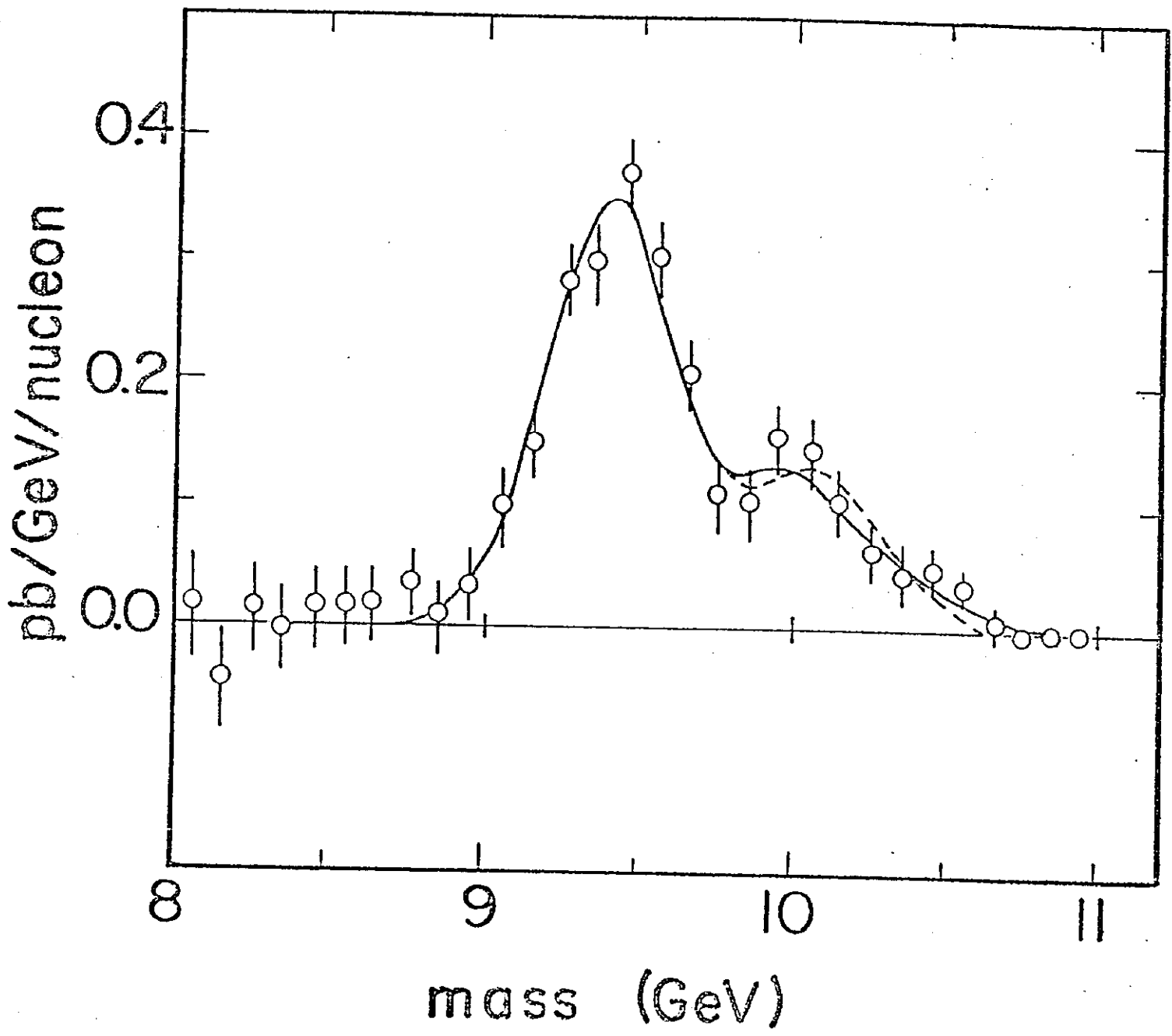


Fig. 2