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Threshold Behavior of Electron Pair Production in p-Be Collisions

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We report on the measurements of electron pair production in p-Be collisions at 1.0, 2.1 and 4.9 GeV beam kinetic energies. The invariant mass and transverse-momentum spectra along with the total cross sections are presented. A rapid decrease in the integrated cross section is observed as the beam energy is reduced. A structure in the mass spectra at twice the pion mass and the energy dependence of the total cross sections are consistent with the interpretation that the dominant production mechanism at beam kinetic energies 2.1 and 4.9 GeV is $\pi^+\pi^-$ annihilation.

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The study of low-mass electron-positron pairs (0.2 GeV/c^2 < M < 1.0 GeV/c^2) in proton-nucleus collisions has been a subject of considerable theoretical and experimental interest. Measurements in the early seventies at Fermilab[1] showed that the low-mass di-lepton and low transverse-momentum (p_t) single-lepton yields were not fully understood. To address these questions, a series of additional experiments over a large range of center of mass energies, were conducted[2–7]. These experiments demonstrated that di-lepton production was observable down to a beam kinetic energy of 12 GeV and that the low-mass continuum could neither be explained by meson decays nor by Drell-Yan processes. A simple extrapolation of the Drell-Yan model to low masses yielded an underestimate of the cross section by an order of magnitude.

Many mechanisms, such as hadronic annihilations[8], hadronic bremsstrahlung[9] and soft-parton annihilations[10], have been suggested to explain the low-mass continuum. However, experiments have not yet been able to distinguish between these mechanisms. Within existing experimental uncertainties, the low-p_t single-lepton yield has been found to be consistent with the hypothesis that it originates predominantly from low-mass lepton pairs[5]. The null results of a direct single-electron experiment[11] in proton-proton collisions at a beam kinetic energy of 0.8 GeV suggested a production *threshold* between 0.8 and 12 GeV. We present here the study of e^+e^- production in p-Be interactions at 1.0, 2.1, and 4.9 GeV beam kinetic energies.

The present data were obtained with the Dilepton Spectrometer (DLS) at the Bevalac. The experimental apparatus employed a large acceptance spectrometer to measure the expected small di-lepton cross section. Detector segmentation was adequate to discriminate between hadrons and electrons (e^+ or e^-) for the heavier systems (i.e. Ca+Ca at 2.1 GeV) that we planned to investigate. A segmented Be target was used at the vertex of two symmetrical detector arms. Each arm covered a laboratory angular range of $17^0 < \Theta < 63^0$ with respect to the beam axis. This translates to an electron pair kinematic range of approximately 0.05 to 1.25 GeV/c^2 in mass, 0.0 to 0.8 GeV/c in p_t and 0.5 to 1.9 in units of laboratory rapidity (y).

In each arm, electrons were identified by using two large segmented gas Čerenkov counters which have an electron detection efficiency better than 97.5% and a hadron misidentification probability of approximately 10^{-5}. Momentum reconstruction in each arm was obtained by the use of one drift chamber before and two drift chambers behind a large dipole magnet. A compromise between good momentum resolution and large acceptance for low-mass pairs was reached by setting the magnetic field at 0.15 T. This setting yielded a momentum resolution of 15%. Sixteen element scintillator hodoscopes at the front and back of each arm were used in combination with the Čerenkov counters to trigger the apparatus, as well as to provide first order tracking.

The di-electron signal (true pairs) is found by subtracting the like-sign pairs (false pairs) from opposite-sign pairs. This procedure is justified because the electrons in the false pairs are independently produced through the combinatorics of π^0 Dalitz decay or γ conversions or both. Thus, the production of false pairs is charge symmetric. However, the like-sign subtraction does not remove events in which the e^+e^- pairs with a large opening-angle from a single Dalitz decay are detected, one in each arm of the spectrometer. This contribution to the di-electron cross section is estimated by Monte Carlo methods. Distributions of e^+e^- pairs arising from the Dalitz decay of π^0, η, ω, K^0 and $\Delta(1232)$ were generated using the known production cross sections[12] from pp interactions, Dalitz decay kinematic dependences[13], and branching ratios. The pairs were then propagated through the apparatus, and analyzed in a way similar to that of the actual data. These results and comparisons with our measurements are discussed later.

In a recent publication[14] we reported that the existence of a di-electron signal has been established in p-Be interactions at 4.9 GeV beam energy. The pair statistics of this result along with 1.0 and 2.1 GeV p-Be data are shown in Table 1. The existence of the di-electron signal is also statistically significant at the two lower energies as well. Pairs were collected by using a loose triggering condition: an eight fold coincidence of the hodoscopes and Čerenkov counters on both arms. No significant dead time was observed during data acquisition. Spills had on the average 2-5 x 10^8 beam particles yielding 2-5 triggers. Off-line analysis used ADC, TDC and time of flight cuts to select good pairs.

Absolute cross sections were obtained by applying the acceptance, the efficiency and the beam normalization factors to the raw data. An acceptance array was generated using Monte Carlo techniques spanning all the accessible phase-space volume in increments of Δp_t, Δy and ΔM. The efficiencies (e.g. from tracking and vertex cuts) were established from examination of both the raw data and the Monte Carlo generated events. Two sets of beam hodoscope counters and a calibrated ion chamber monitored the beam flux. The errors in Table 1 and in Figs. 1-3 reflect only the statistical uncertainty; for each incident energy there is an additional systematic normalization error of approximately +70/-20%, including in particular, a rate dependent trigger efficiency.

The cross section per nucleon (assuming an $A_t^{2/3}$ dependence, where A_t is the target mass) for p-Be as a function of the invariant mass is shown for all three beam energies in Figure 1. The general shape of the 4.9 and 2.1 GeV distributions (Figs. 1(a) and 1(b) respectively) above 0.3 GeV/c^2 are similar to that seen at higher energies. This is shown by the comparison to a parameterization of the KEK 12 GeV p-Be data[5] which is indicated by the solid curve in Fig. 1(b). A recent calculation at 4.9 GeV performed by P. Lichard[15] in the framework of the soft parton model[10,16] is shown as the solid curve in Fig. 1(a). This calculation was filtered with the DLS acceptance and the results of the calculation have been reduced by a factor of two for the sake of presentation. Reasonable agreement with the shape of the data is found above 0.3 GeV/c^2 and below the $\rho - \omega$ region. The contribution from $\rho - \omega$ mesons is seen clearly in the 4.9 GeV data around a mass of 0.77 GeV/c^2. However, no significant enhancement in this mass region is observed in either the 2.1 or 1.0 GeV data. At 2.1 GeV the maximum energy available in the center of mass of the nucleon-nucleon system is 0.854 GeV, just barely above the $\rho - \omega$ threshold.

Our results show in detail the mass spectrum below 0.3 GeV/c^2. A structure is observed in both the 2.1 and 4.9 GeV invariant mass distribution near twice the pion mass. In the 1.0 GeV data, only a steeply falling, structureless behavior is observed. This suggests that $\pi^+\pi^-$ annihilation mechanisms dominate the production above 2 GeV beam energy. Theoretical studies[17] indicate that a thorough understanding of this annihilation structure in heavy systems (e.g. Ca+Ca) could yield information about the pion dispersion relation and thus new information about the density of hot hadronic matter.

At each beam energy a sharp increase in the cross section is observed for masses less than 0.1 GeV/c^2. This is consistent with what is expected due to contribution of the π^0 Dalitz decay. However, due to the limited p_t acceptance in the lowest mass bin (0.05-0.1 GeV/c^2) the corresponding data point is given only for a qualitative understanding of the lowest part of the spectrum. The total Dalitz decay contribution to the di-lepton cross section is shown as dashed curves in Fig. 1. The significant contributions are from π^0 and Δ (1232) at 1.0 GeV, while π^0 and η contribute at 2.1-4.9 GeV beam energies. We find, in agreement with higher energy results, that for beam energies of 2 GeV and above, the Dalitz decay background is approximately an order of magnitude smaller than the observed data and cannot account for electron pair production above 0.2 GeV/c^2. For the 1.0 GeV data, the Dalitz decay of the Δ(1232) is estimated to be approximately 3 times less than the measured data above 0.2 GeV/c^2. However, in particular due to the uncertainties in the Δ(1232) production cross sections and our systematic errors, it is possible that the Δ(1232) Dalitz decay contributes significantly to the di-electron production above 0.2 GeV/c^2. This indicates that this mass spectrum is perhaps a combination of π^0 and Δ(1232) Dalitz decays with some admixture of hadronic Bremsstrahlung and pion annihilation.

The p_t^2 dependence of the cross section per nucleon, (integrated over rapidity and for M>0.2 GeV/c^2) is shown in Fig. 2 for all three beam energies. The slopes of the 2.1 and 4.9 GeV data are in reasonable agreement. A least squares fit to the 4.9 GeV data, using the expression $d\sigma/dp_t^2 \propto \exp(-\alpha p_t^2)$, yields $\alpha = 7.8$ (GeV/c)$^{-2}$ and is shown as the solid line in Fig. 2. It is interesting to note that this p_t^2 dependence is similar to the higher energy e^+e^- data and to the well known low-p_t^2 hadronic dependence[18]. At 1.0 GeV beam energy the statistics and the p_t range are too limited for a detailed comparison.

The total integrated e^+e^- cross sections per nucleon (0.2 GeV/c^2 <M< 0.7 GeV/c^2) is shown as a function of the available nucleon-nucleon center of mass energy ($Q = \sqrt{s}$-2m_p) in Fig. 3. At higher energies, the DLS data are consistent with previously published data[5,6] even though the experimental conditions (acceptance range and projectile/target combinations) differ. A rapid decrease in the cross section is seen as one approaches lower energies. One might expect that the Q dependence would be similar to that of the total p-p inelastic cross section or perhaps the π^0 production cross section, as the e/π ratio is constant at higher energies. However, both cross sections are approximately constant in the energy range where our experimental data shows a threshold-like behavior. The dashed line in Fig. 3 shows the π^0 production cross section[19], scaled down by 1.33 x 10^{-5} ($\approx \alpha^2/4$, where α is the fine structure constant). From bubble chamber data[20] we have extracted the inclusive $\pi^+\pi^-$ production cross sections at these low energies. Shown as the solid curve in Figure 3, is the Q dependence of $\pi^+\pi^-$ production, also scaled down by 1.33 x 10^{-5}. The e^+e^- and scaled $\pi^+\pi^-$ production cross sections are observed to have a similar energy dependence. This further supports the interpretation that $\pi^+\pi^-$ annihilation dominates the low-mass di-electron production at 2-5 GeV beam energies.

In summary, di-electron production in p-Be collisions at 1.0, 2.1 and 4.9 GeV has been observed. At the higher energies, the yield of di-electrons with masses above 0.2 GeV cannot be explained by known meson decays. A structure in the invariant mass distribution is observed at about twice the pion mass in both the 2.1 and 4.9 GeV data. The total integrated cross sections are found to decrease rapidly as one goes to lower energies. Both the structure in the mass spectra and the energy dependence of the total cross section are consistent with the interpretation that the dominant production mechanism at 2-5 GeV is due to $\pi^+\pi^-$ annihilation.

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[20] G. Alexander *et al.*, Phys. Rev. **154**, 1284 (1967); note that at the low energies ($Q < 0.5$ GeV) the $\pi^+\pi^-$ cross section is only accurate to within a factor of two.

Figure captions

Figure 1. The invariant mass spectra for p-Be at three beam energies. (a) The 4.9 GeV data. The solid line is a soft parton model calculation (ref. 15,16) and is scaled down by factor of 2. (b) The 2.1 GeV data. The solid line is a fit to the KEK 12 GeV data (ref. 5). (c) The 1.0 GeV data. The dotted line shown in each figure is the estimated contribution due to the wide angle Dalitz decay at each energy.

Figure 2. The cross section per nucleon, $d\sigma/dp_t^2$, as a function of p_t^2 for three beam energies. The solid line is a fit to the 4.9 GeV data [$\exp(-7.8p_t^2)$].

Figure 3. The total integrated e^+e^- production cross section as a function of the available nucleon-nucleon center of mass energy Q: squares, this experiment for 0.2 GeV/c^2 $< M <$ 0.7 GeV/c^2; circle, Blockus et al. (ref. 6) π^-p at 16 GeV; star, Mikamo et al. (ref. 5) p-Be at 12 GeV, y=0.0. The solid and dashed curve shows the $\pi^+\pi^-$ and π^0 production cross sections (ref. 19,20) respectively, scaled by 1.33 x 10^{-5}.

TABLE 1

Interaction	**Energy [GeV]**	**# Opposite Sign Pairs**	**# Same Sign Pairs (=F)**	**# Direct Pairs** $D \pm \sigma_D$	**R=D/F**	D/σ_D
p + Be	4.9	732	201	531±31	2.6	17.4
p + Be	2.1	567	148	419±27	2.8	15.7
p + Be	1.0	111	19	92±11	4.8	8.1

Table 1. Pair statistics for each kinetic beam energy.

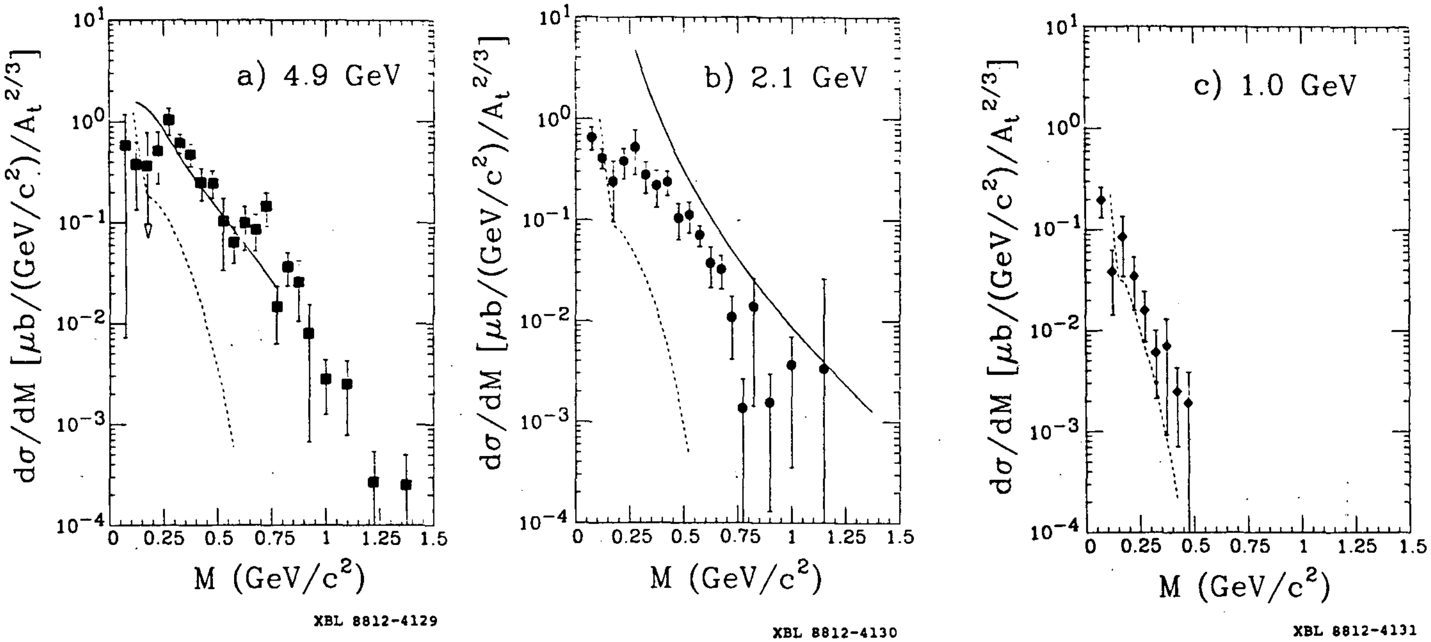
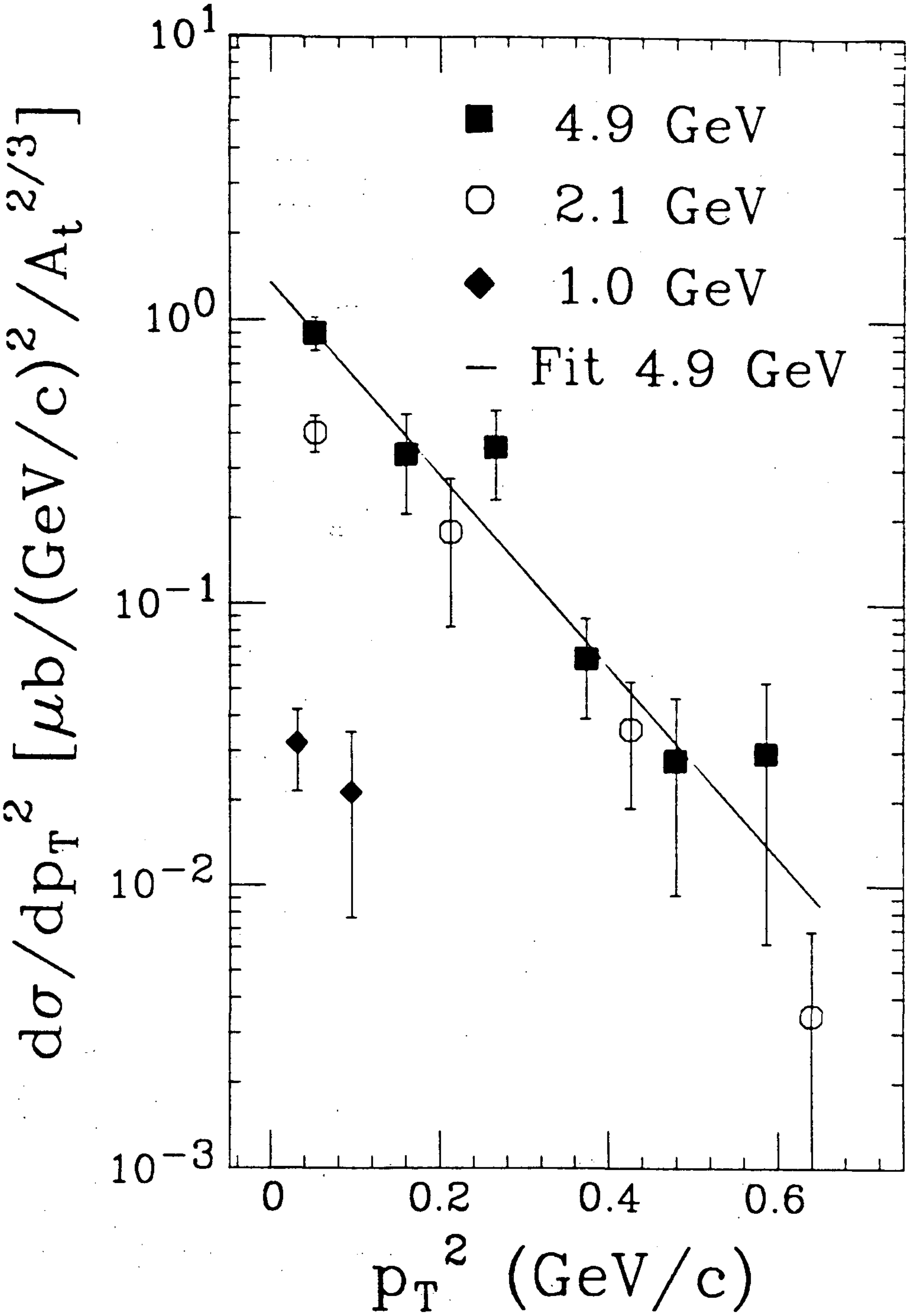

a) 4.9 GeV
b) 2.1 GeV
c) 1.0 GeV
dσ/dM [μb/(GeV/c²)/A_t^{2/3}]
M (GeV/c²)
XBL 8812-4129
XBL 8812-4130
XBL 8812-4131

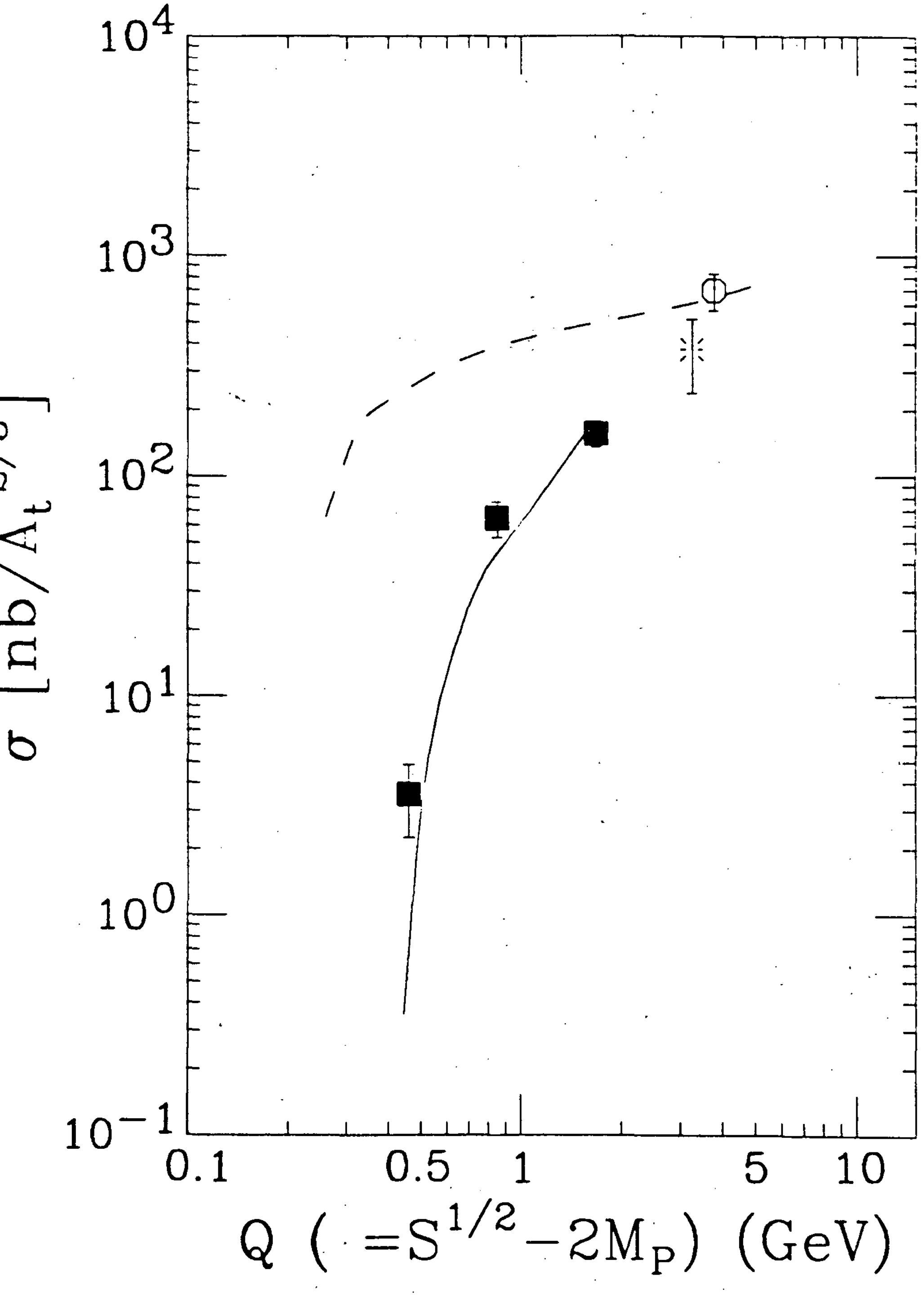
FIGURE 1

FIGURE 2



XBL 8812-4128

FIGURE 3



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