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PEP-4 TPC Collaboration

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ϕ Meson Production in e^+e^- Annihilations at 29 GeV

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Abstract

Production of ϕ mesons in e^+e^- annihilation at a center of mass energy of $29\,GeV$ has been observed using the Time Projection Chamber detector in the PEP-4 experiment. The ϕ production rate has been measured in the energy range $0.075 < x < 0.55$ ($x = E_\phi/\sqrt{s}$), giving 0.077 ± 0.012(stat)± 0.016(syst) ϕ's per event. The average value of p_t^2 relative to the thrust axis is $1.0 \pm 0.4\,(GeV/c)^2$.

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The investigation of resonance production in electron-positron (e^+e^-) annihilation at high energies provides important information on the mechanism of parton fragmentation. While high statistics inclusive data on final state stable hadrons have been reported[1-3], their interpretation in terms of parton fragmentation is hindered by the fact that the shapes of the spectra may be dominated by decay products of heavier particles. The behaviors of vector mesons and other resonances are, on the other hand, more directly related to the quantum number and energy flow of the original partons and their hadronization.

We have measured the inclusive ϕ production in e^+e^- annihilation at a center of mass energy of $29\,GeV$. The data were collected with the PEP-4 Time Projection Chamber (TPC) detector at the Stanford Linear Accelerator Center PEP storage ring. The TPC was used to identify kaons by dE/dx and to reconstruct the decay $\phi \rightarrow K^+K^-$. The apparatus, monitoring, calibration and event selection have been described elsewhere[3-4]. The results presented here are based on a sample of 25900 hadronic events, corresponding to an integrated luminosity of $69\,pb^{-1}$.

In this analysis all reconstructed tracks in the TPC are required to meet the following conditions: 1) the distance of closest approach to the average incident beam-beam interaction point is smaller than $3\,cm$ in the plane transverse to the beam and smaller than $5\,cm$ along the beam, 2) $|\cos\theta| < 0.84$, where θ is the polar angle of the track relative to the beam, 3) the momentum p is larger than $0.15\,GeV/c$, 4) the estimated error in the momentum measurement satisfies either $dp_{xy}/p_{xy} < 0.3$ or $dp_{xy}/p_{xy}^2 < 0.3(GeV/c)^{-1}$, where p_{xy} is the momentum component transverse to the beam. These cuts reduce contributions from nuclear interactions and electron-positron pairs from photon conversions in the material in front of the TPC.

The charged particle species were identified by a simultaneous measurement of

the momentum and of up to 183 samples of dE/dx ionization energy loss. We define dE/dx for each track to be the mean of the smallest 65% of the individual samples. On the average 110 dE/dx samples are used per track in multi-hadronic events, giving a typical dE/dx resolution of 3.7%. The momentum resolution was $(dp/p)^2 \simeq (0.06)^2 + (0.035p)^2$.

From the measured dE/dx and momentum for each particle, χ^2 values for $e/\pi/K/p$ hypotheses are calculated using an empirically determined formula to relate dE/dx to particle momentum. The parameters in this formula have been established by measuring minimum ionizing particles, cosmic ray muons and Bhabha electrons. Then weights are defined for the $e/\pi/K/p$ hypotheses as

$$W(i) = f(i,p)\exp(-\chi(i)^2/2)/N$$

where $i = e, \pi, K, p$, $f(i,p)$ is the particle fraction of particle type i measured at momentum p in the hadronic event sample[3], and N is a normalization factor to ensure that $W(e) + W(\pi) + W(K) + W(p) = 1$. A track is counted as one kaon if it satisfies $W(K) > 0.7$. The purity of the kaon sample selected in this way is about 70% and nearly constant over the entire momentum range. The momentum-dependent acceptance for kaons is typically 50%. It is particularly small (10-15%) in the range $0.6 < p < 1.5 GeV/c$, where π and K bands overlap in the dE/dx vs. momentum plane. This is because $W(K)$ is reduced by the large value of $f(\pi)$ relative to $f(K)$.

Figure 1(a) shows the K^+K^- invariant mass distribution in the range $0.075 < x < 0.55$, where $x = 2E(K^+K^-)/\sqrt{s}$, and $E(K^+K^-)$ is the sum of two kaon energies. A clear peak is observed in the ϕ mass region just above the K^+K^- threshold. No such structure is seen in the like-sign combinations of kaons, as shown in Figure 1(b). Contributions from photon conversion pairs, K^0_S decays and other resonances, whose products are taken to be kaons, are estimated to be small (less than 2 entries in $1.00 <$

$M(K^+K^-) < 1.05 GeV$) and flat, so that they cannot contribute to the sharp peak in the ϕ region. Fitting the distribution in Figure 1(a) with a Gaussian line shape plus a smooth background gives 62.2 ± 10.5 entries in the peak, $M(K^+K^-) = 1.019 \pm 0.002 GeV$, and RMS width $= 6.2 \pm 0.4\ MeV$ which is consistent with the estimated detector resolution for $\phi \to K^+K^-$. Thus, we attribute the peak in Figure 1(a) to ϕ production.

The detection efficiencies are evaluated with a Monte-Carlo calculation which generates multi-hadron events with initial state radiative corrections[5], and an analysis procedure identical to that used for the data. The simulation of the detector includes geometrical acceptance, track pattern recognition, decay-loss of pions and kaons, particle energy loss in the material, multiple scattering, nuclear interactions, loss of dE/dx wire samples due to overlapping tracks and its effect on the dE/dx resolution. The estimates of the particle identification efficiencies and purities were checked in two ways for consistency. First, using particle identities determined by imposing various cuts on $W(\pi)$, $W(K)$ and $W(p)$ for tracks in multihadron events, we observed that the numbers of $\pi/K/p$'s, corrected for purities and efficiencies, lead to results consistent with those reported in Ref.3. Second, using low energy electrons and positrons from conversion pairs in Bhabha events, we found that the numbers of electrons and positrons misidentified as π, K or p agree with predictions from the Monte-Carlo.

We searched for signatures of spin alignment of the observed ϕ's by looking at decay angular distributions in the ϕ rest frame. We tried two helicity axes: A) the flight direction of ϕ's, and B) the line perpendicular to the plane determined by the event thrust axis and the ϕ flight direction. For various angle and energy intervals, K^+K^- invariant mass spectra were fitted with combinations of a Gaussian peak and a background term. Then the number of entries in each peak, corrected for the ϕ detection efficiency, was fitted with a curve $(1 + \alpha \cos^2 \theta_{KK})$, where θ_{KK} is the ϕ decay

angle with respect to one of the reference axes defined above. In the region integrated over $0.075 < x < 0.55$, we obtained $\alpha = -0.01 \pm 0.60$ for the axis A and -0.02 ± 0.60 for the axis B, without significant dependence on the ϕ energy. They are statistically consistent with no spin alignment. For evaluation of the inclusive ϕ rate, therefore, it was assumed that the ϕ's are unaligned.

For each of three energy bins, $0.075 < x < 0.15$, $0.25 < x < 0.40$ and $0.40 < x < 0.55$, the K^+K^- invariant mass spectrum was fitted with a Gaussian peak at $M(K^+K^-) = 1.02 GeV$ plus a background whose shape was obtained by Monte-Carlo and parameterized with a smooth function. Figure 2(a) and Table 1 show the corresponding scaled cross sections $(1/\sigma_h\beta)d\sigma_\phi/dx$, where σ_h is the total annihilation cross section into hadrons. The errors include both statistical and systematic contributions from ambiguities in particle identification, estimates of backgrounds, track acceptance, and dependence on the Monte-Carlo event generator used in the efficiency calculation. Figure 2(b) shows the efficiency for ϕ detection, including the known branching ratio for $\phi \rightarrow K^+K^-$ (49.1%). The loss of efficiency in the vicinity of $x = 0.2$ results from the reduced kaon acceptance due to π-K overlap in dE/dx.

By interpolating the cross section with an exponential curve in the region between the first and second bins in Figure 2(a), we obtain 0.077 ± 0.012(stat)± 0.016(syst) ϕ's per event for $0.075 < x < 0.55$. The smooth line in Figure 2 shows a prediction of the Lund Monte-Carlo program[6], obtained with $s/u = 0.3$ and $V/(V+P) = 0.5$, which is consistent with our measurement. Here s/u is the suppression factor of s quark compared to u or d pair production in the vacuum, and $V/(V+P)$ is the probability for a meson produced in a jet to have spin 1. The Lund model predicts that 93% of produced ϕ's are contained in the region $0.075 < x < 0.55$, as compared to 90 % for a purely exponential distribution. For the total number of ϕ's per event, therefore, we

obtain $0.084 \pm 0.013 \pm 0.018$.

The transverse momentum distribution of ϕ's relative to the event jet axis provides additional information on the parton fragmentation, giving a measure of the transverse energy scale of hadronization. The ϕ production cross sections as a function of p_t^2 relative to the event thrust axis were obtained in the regions $0.075 < x < 0.15$ and $0.25 < x < 0.40$. Then they were extrapolated to represent the range $x < 0.55$, assuming an exponential fall-off with ϕ energy. Figure 3 (filled circles) and Table 2 show the result. Included in Figure 3 for comparison is the measured p_t^2 distribution of $\pi^{\pm}$. The $\pi^{\pm}$ rates are scaled by a factor of 1/140. The solid and dashed curves show predictions of the Lund model for ϕ and $\pi^{\pm}$, respectively. The average value $< p_t^2 >$ of observed ϕ is $1.0 \pm 0.4 (GeV/c)^2$, where the error includes both statistics and systematics. The Lund model predicts $< p_t^2 >= 0.85 (GeV/c)^2$, and gives a reasonable fit to the measured spectra of both ϕ and π. The $< p_t^2 >$ is larger for the ϕ than for the π, suggesting that the ϕ spectrum is, as predicted, less dominated by the decay products of heavier particles.

In summary, for e^+e^- annihilation at $\sqrt{s} = 29\, GeV$ we have measured the inclusive production rate of ϕ mesons in the range $0.075 < x < 0.55$ by reconstructing the decay $\phi \rightarrow K^+K^-$. There are $0.077 \pm 0.012 \pm 0.016$ ϕ's per event in this energy range. The angular distribution of K^+K^- in the ϕ decay rest frame is consistent within statistical errors with no ϕ spin alignment. The p_t^2 distribution for the ϕ is found to be significantly harder than for the π.

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Table 1.

The inclusive ϕ production rate normalized to the total annihilation cross section into hadrons σ_h. Here $x = 2E_\phi/\sqrt{s}$ and β is the ϕ velocity. The first error is statistical, the second is systematic.

x	$(1/\sigma_h\beta)d\sigma_\phi/dx$
$0.075 - 0.150$	$0.38 \pm 0.08 \pm 0.13$
$0.250 - 0.400$	$0.15 \pm 0.04 \pm 0.06$
$0.400 - 0.550$	$0.07 \pm 0.04 \pm 0.04$

Table 2.

The ϕ production rate as a function of p_t^2 measured relative to the event thrust axis. The errors include both statistics and systematics.

$p_t^2\,(GeV/c)^2$	$(1/\sigma_h)d\sigma_\phi/dp_t^2\ (GeV/c)^{-2}$
$0.0 - 0.5$	0.083 ± 0.020
$0.5 - 1.5$	0.021 ± 0.015
$1.5 - 5.0$	0.004 ± 0.004

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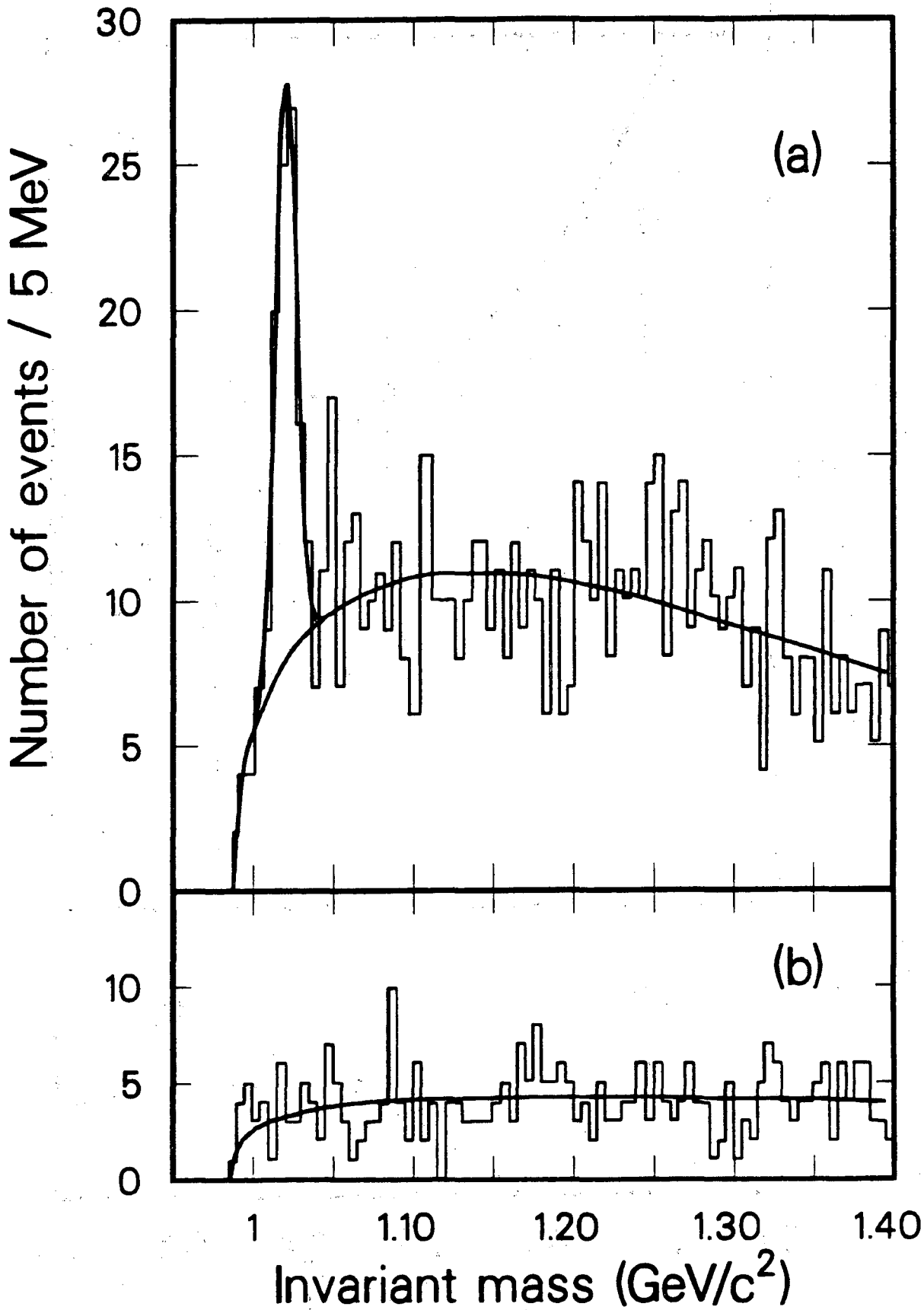
Figure Captions

1. (a) K^+K^- invariant mass spectrum in the energy range $0.075 < x < 0.55$, where $x = 2E/\sqrt{s}$. The fitted curve includes a Gaussian line shape plus a background whose shape has been obtained by Monte-Carlo and parameterized as a smooth function. (b) Sum of K^+K^+ and K^-K^- invariant mass spectra. The smooth curve shows a Monte-Carlo prediction of the spectrum.

2. (a) ϕ inclusive cross section as a function of $x = 2E_\phi/\sqrt{s}$. The solid curve shows a prediction of the Lund model, obtained with parameters $s/u = 0.3$, $V/(V+P) = 0.5$. (b) ϕ detection efficiency as a function of x, including the $\phi \to K^+K^-$ branching fraction and initial state radiative corrections.

3. Distribution of the square of the ϕ transverse momentum with respect to the thrust axis in the range $x < 0.55$ (indicated by filled circles). The open circles give the distribution observed for $\pi^\pm$ scaled by a factor of 1/140 for comparison. The solid and dashed curves show predictions of the Lund model for ϕ and $\pi^\pm$ (scaled by 1/140), respectively.



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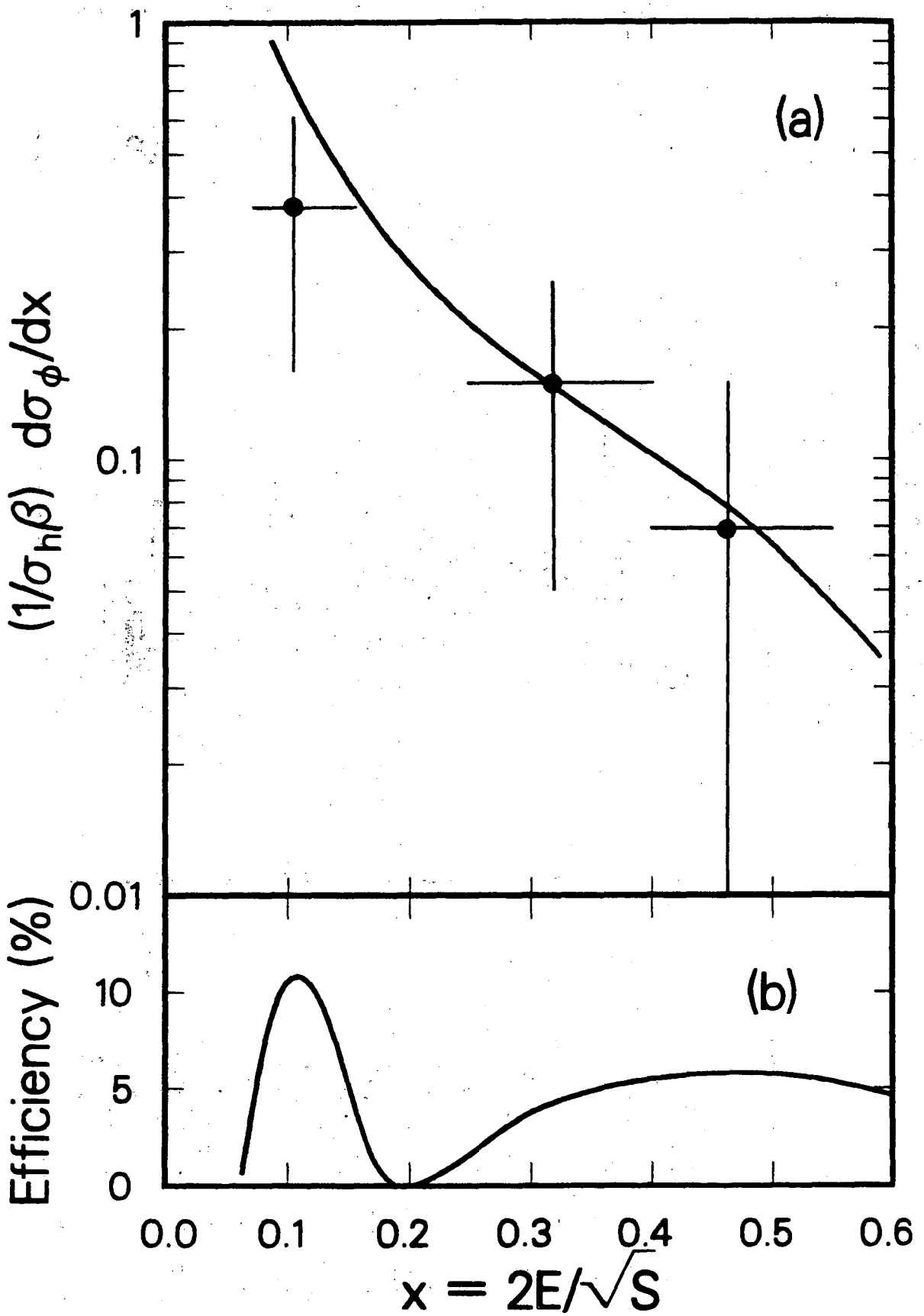

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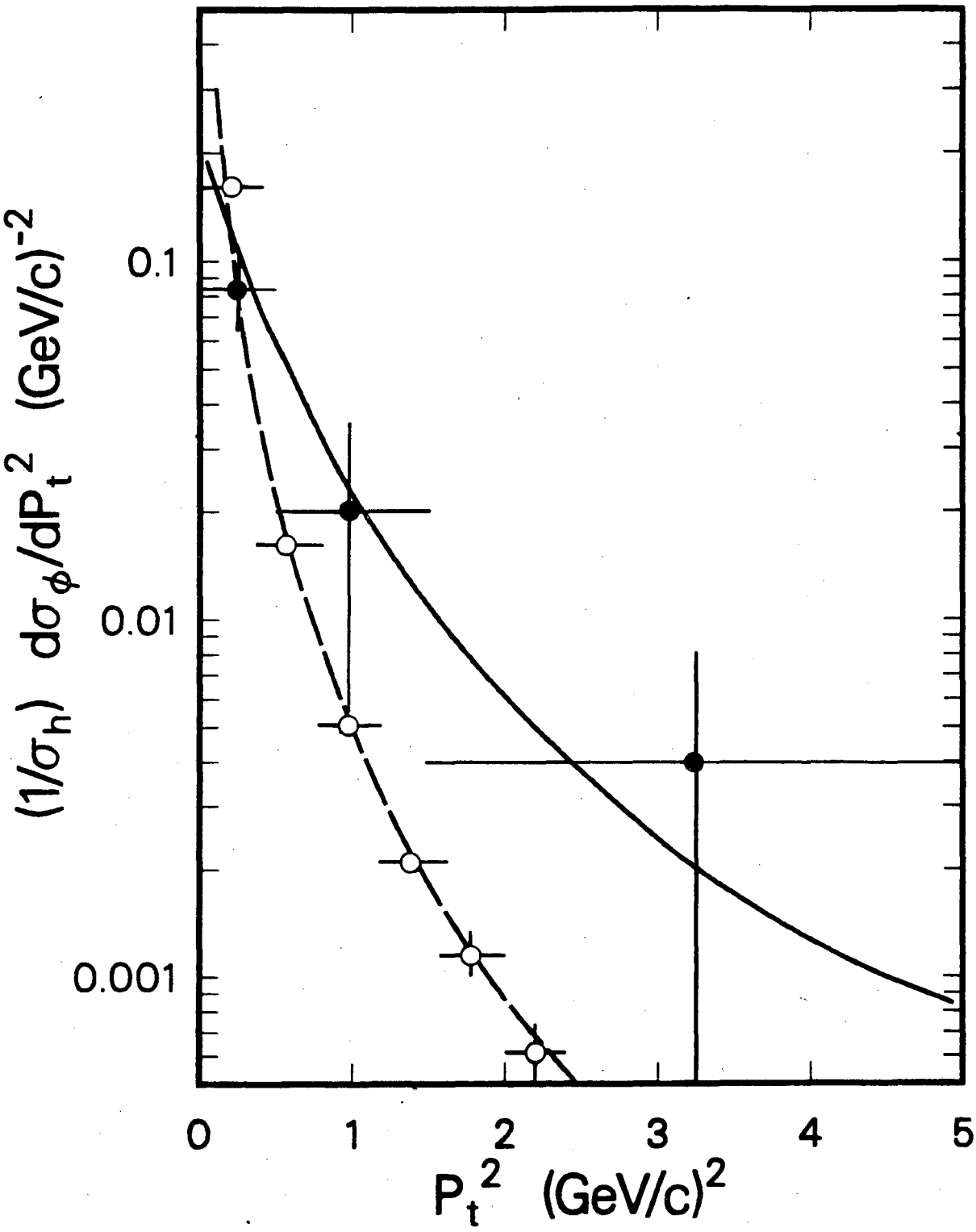

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