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Abstract

We suggest that direct muon production in proton-proton collisions may be ascribed to familiar hadronic production mechanisms. To this end, we construct a pion exchange multiperipheral model for massive muon pair production. The numerical results are in rough agreement with the cross sections observed at Brookhaven and more recently at FNAL.

Interest in the direct production of muons in proton-proton collisions has been stimulated recently by experiments at Brookhaven[1] and at Fermi National Accelerator Laboratory[2]. In particular, the Drell-Yan mechanism[3] for muon production via parton-antiparton annihilation has proven inadequate to the task of explaining the experimentally observed

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rates[4-7]. One's thoughts then turn naturally to alternative explanations, particularly those involving familiar strong interaction concepts, and in this letter we use the pion exchange multiperipheral model[8] to study muon pair production.

We shall construct an explicit model with essentially no free parameters, and then present the most salient results of a numerical comparison to the experiments at Brookhaven and at FNAL. More detailed comparisons, further theoretical considerations and a derivation of the scaling law implied by the model shall be reserved for a future article[9].

Explicitly, our model is the following: we assume that the μ-pair occurs as the decay product of a massive virtual photon which can appear along with the usual systems of hadrons that are produced in a multiperipheral chain. The inclusive cross section is depicted in Fig. 1. The ingredients which enter into the calculation are the off-shell πp absorptive parts, the pion propagator, and the $\pi\pi\gamma$ and $\gamma\mu\bar{\mu}$ couplings. The $\pi\pi\gamma$ coupling is taken to be proportional to the pion electromagnetic form factor. The $\gamma\mu\bar{\mu}$ coupling is taken to be that of (pointlike) quantum electrodynamics. The on-shell πp absorptive parts are taken from experiment. A similar model has been proposed earlier by Subbarao and by Thacker[10].

There are serious difficulties with a literal use of the multiperipheral model for calculation. First, it is well known that the low energy $\pi\pi$ cross section, when iterated in the familiar way to build the high energy cross section, is too small, producing output Regge poles which are far too low[11]. Second, some form for the off-shell extrapolation of the πp absorptive parts and the $\pi\pi\gamma$ vertex must be chosen. We deal with both difficulties by constructing a model for pion production via rho meson decay. That is, a $\pi\pi\rho$ vertex is attached to the pion chain in Fig. 1, where the coupling is fixed by the rho width. The observed <u>shape</u> and <u>magnitude</u> of the pion transverse momentum distribution at $E_{lab} = 300$ GeV are reproduced by first choosing an appropriate off-shell extrapolation.

Then the $\pi\pi$ cross section is multiplied by the necessary overall constant. This, in effect, assumes that high energy hadronic cross section are built from a large number of multiperipheral "pion-like" processes, and so retains the successful predictions of multiperipheral models.

The pion form factor $F_\pi(Q^2)$ is not well known for large values of Q^2 (photon mass squared). We shalldisplay results for different possible choices of $F_\pi(Q^2)$. Lastly, we will neglect photon emission from the ends of the chain corresponding to a coupling to virtual nucleon (or baryon) lines.

We build a model for pion production by assuming the $\pi\pi$ scattering amplitude is dominated by the rho resonance,

$$A_{\pi^+\pi^-} = \frac{48\pi\ \Gamma_\rho m_\rho^2}{(m_\rho - 4m_\pi^2)^{3/2}} (Q_1 - Q_2)\cdot(p_a - p_b) \frac{1}{s - m_\rho^2 + i\Gamma_\rho m_\rho} \quad (1)$$

where p_a and p_b are the momenta of the produced pions. Then the inclusive pion cross section may be written as

$$\lambda^{\frac{1}{2}}(s, m_p^2, m_p^2)\,d\sigma = Z \frac{4}{(2\pi)^4} \delta^4(Q+Q_1+Q_2)\, d^4Q\, d^4Q_1\, d^4Q_2 \quad (2)$$

$$\times \quad A_{\pi^- p}(p_1, Q_1)\, S(t_1)\, R(Q, Q_1, Q_2)\, S(t_2)\, A_{\pi^+ p}(p_2, Q_2)$$

where $t_1 = Q_1^2$, $t_2 = Q_2^2$ and $\lambda(x,y,z) \equiv x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$. The squared pion propagator is $S(t) = 1/(t - m_\pi^2)^2$. The $\pi\pi$ kernel is,

$$R(Q, Q_1, Q_2) = \int dp_a\, dp_b\, \delta^4(p_a + p_b - Q) \left| A_{\pi^+\pi^-} \right|^2 \quad (3)$$

using the shorthand notation for the phase space volume: $dp \equiv d^3p/[2E(2\pi)^3]$.

The πp absorptive parts have been paramterized as,

$$A_{\pi p} = \sum_{i=1,2} r_i \left(\frac{p \cdot Q}{s_0}\right)^{\alpha_i} \left(\frac{m^2 - m_\pi^2}{m^2 - Q^2}\right)^{\alpha_i + n} \tag{4}$$

where $s_0 \equiv 1 \text{ GeV}^2$. The on-shell absorptive part corresponds to the total cross section, $A_{\pi p}(Q^2 = m_\pi^2) = s\,\sigma_{\pi p}$. The total cross sections are asymptotically constant: $r_1 = 22.5$ mb GeV^2, $\alpha_1 = 1$. The low energy part is interpolated smoothly for $\pi^+ p$ by $r_2 = 50.5$ mb GeV^2, $\alpha_2 = -.06$; and for $\pi^- p$ by $r_2 = 29.9$ mb GeV^2, $\alpha_2 = .33$.[12]

The off-shell extrapolation is determined by demanding that the model reproduce the shape of the observed[13] pion transverse momentum distribution. We have taken $m^2 = 1 \text{ GeV}^2$ and $n = 2$. Further discussion of the off-shell question will be given in Ref. 9.

The normalization of the observed[13] transverse momentum distribution is then obtained by choosing $Z = 90$. Such large normalizations have been found earlier by Tan and Tow using the same type of model.[14] They conclude that a literal pion exchange model is necessarily unrealistic. We choose to take the point of view that, for the purpose of our calculation, the choice $Z = 90$ is a phenomenological way of including the effect of all possible exchange mechanisms which could lead to pion production.

To build our model for muon pair production, we simply replace the $\pi\pi$ - kernel $R(Q, Q_1, Q_2)$ in Eq. (2) by a new $\pi\pi$-kernel $L(Q, Q_1, Q_2)$ for lepton production via a massive photon,

$$L(Q, Q_1, Q_2) = \frac{(4\pi\alpha)^2}{Q^4} \left[F_\pi(Q^2)\right]^2 (Q_1 - Q_2)_\lambda (Q_1 - Q_2)_\nu \times \int dp_+ \, dp_- \, \delta^4(p_+ + p_- - Q) \, \mathrm{Tr}\left[(\not{p}_- + m_\mu) \gamma^\lambda (\not{p}_+ - m_\mu) \gamma^\nu\right] \tag{5}$$

where p_+ and p_- are the lepton momenta.

We have compared our model to the Brookhaven-Columbia muon pair experiment[1] and to the Chicago-Princeton single muon experiment.[2] Our numerical calculations make no kinematical approximations, and should therefore correctly represent any phase space threshold effects. Due to limitations of space, we present here only a representative sample of results.

The comparison to the Brookhaven-Columbia experiment is shown in Fig. 2. The effect of the experimental aperture is included in the calculation. (Only μ-pairs with longitudinal momentum in the laboratory greater than 12 GeV/c were observed.) The curves (a) and (b) represent different choices for the pion form factor as depicted in Fig. 3. In both cases, $F_\pi(Q^2)$ was taken from $e^+e^- \to \pi^+\pi^-$ storage ring data[15] for $Q^2 < 6\ \mathrm{GeV}^2$. For larger values of Q^2, curve (a) represents the usual extrapolated form factor $F_\pi(Q^2) \sim 1.6/Q^2$, while curve (b) corresponds to an approximately constant cross section for $e^+e^- \to \pi^+\pi^-$ in the region $9\ \mathrm{GeV}^2 < Q^2 < 25\ \mathrm{GeV}^2$. The radical behavior of form (b) for the form factor can probably be ruled out by data from SPEAR, since such a behavior would imply that $\sigma_{\pi^+\pi^-}/\sigma_{\mu^+\mu^-}$ is approximately equal to two for $s = 25\ \mathrm{GeV}^2$.[16]

The comparison to the Chicago-Princeton experiment is shown in Fig. 4. The data is taken at $E_{lab} = 300$ GeV with the detectors fixed at 90° in the center of mass. The curves are generated by the model. The solid line indicates the predicted cross sections for μ^+. The shape and normalization are consistent with experiment for $p_\perp < 3$ GeV/c, while the damping becomes significantly weaker than experiment for $p_\perp > 3$ GeV/c. It is worth noting that the parton model prediction using the quark-parton distributions of Ref. 4 falls considerably below the data everywhere, and almost two orders of magnitude for $p_\perp \sim 1.5$ GeV.

The cross sections for π^+ and ρ^o are also shown for reference. Recall that the shape and normalization of the π^+ distribution were adjusted to agree with the data.[13] The damping in the ρ^o distribution is significantly weaker than the π^+ damping for kinematical reasons: the decay pions must share the rho momentum and have the angular distribution for $J = 1$.[17]

If, indeed, spin 0 exchange is responsible for μ-pair production, one would expect a well-defined angular distribution for the muons in the pair rest frame. For example, if the exchanged pions are close to the mass shell, the distribution should be $\sin^2\theta$, where θ is the angle between one of the muons and one of the pions. Since there is a strong damping for off-mass-shell pions, and since the exchanged pions are strongly aligned along the beam axis, we expect that the distribution should be approximately $\sin^2\theta'$ (at large Q^2), where θ' is the Gottfried-Jackson angle. This is in contrast to the parton model expectation of $1 + \cos^2\theta'$.

To provide a balanced appraisal of our results, we must include a caveat. Our multiperipheral model can not be regarded as a fully consistent and realistic model of particle production. For example, while we have assumed that all produced pions originate from ρ decay, present data indicate that most pions (approximately $\frac{4}{5}$ at E_{lab} = 205 GeV) are generated by other mechanisms.[18] If our normalization were adjusted to the actual ρ cross section, the predicted μ-pair cross section would decrease by a factor of five. On the other hand, we have omitted the contribution of the ω and ϕ mesons and, more generally, isoscalar photons. Their inclusion would increase our prediction. Rather than catalog compensating effects, we prefer the point of view that the model represents an average over possible multiperipheral production mechanisms, and it is then natural to normalize to pion inclusive data. Of course this introduces an approximation, but probably not a gross error. Note that if this point of view is correct, then the μ-pair angular distribution could depart from $\sin^2\theta'$, since various production mechanisms could lead to μ-pairs with different angular distributions.

We conclude by suggesting that familiar hadronic processes may be responsible for the observed muon cross sections in proton-proton collisions. Certainly, before one appeals to exotic ideas (e.g., charmed particles or heavy leptons) such a possibility must be fully explored.

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Figure Captions:

Figure A: A rare bubble chamber photograph of a massive mute pair.

Figure 1: The cross section for inclusive μ-pair production in the multiperipheral model. The blobs labelled A denote off-shell $\pi - p$ absorptive parts.

Figure 2: The invariant mass distribution of μ-pairs. The data is from the Brookhaven-Columbia experiment.[1] The two curves are the result of two possible choices for the pion form factor.

Figure 3: The pion form factor. The data is from Ref. 15 . The two curves correspond to those in Fig. 2 . At large s , curve (a) represents the "standard" behavior $F_\pi \sim 1.6/s$, and curve (b) represents an approximately constant total cross section for $e^+e^- \to \pi^+\pi^-$.

Figure 4: The transverse momentum distribution of μ^+ . The data is from the Chicago-Princeton experiment.[2] The curves are generated by the model.

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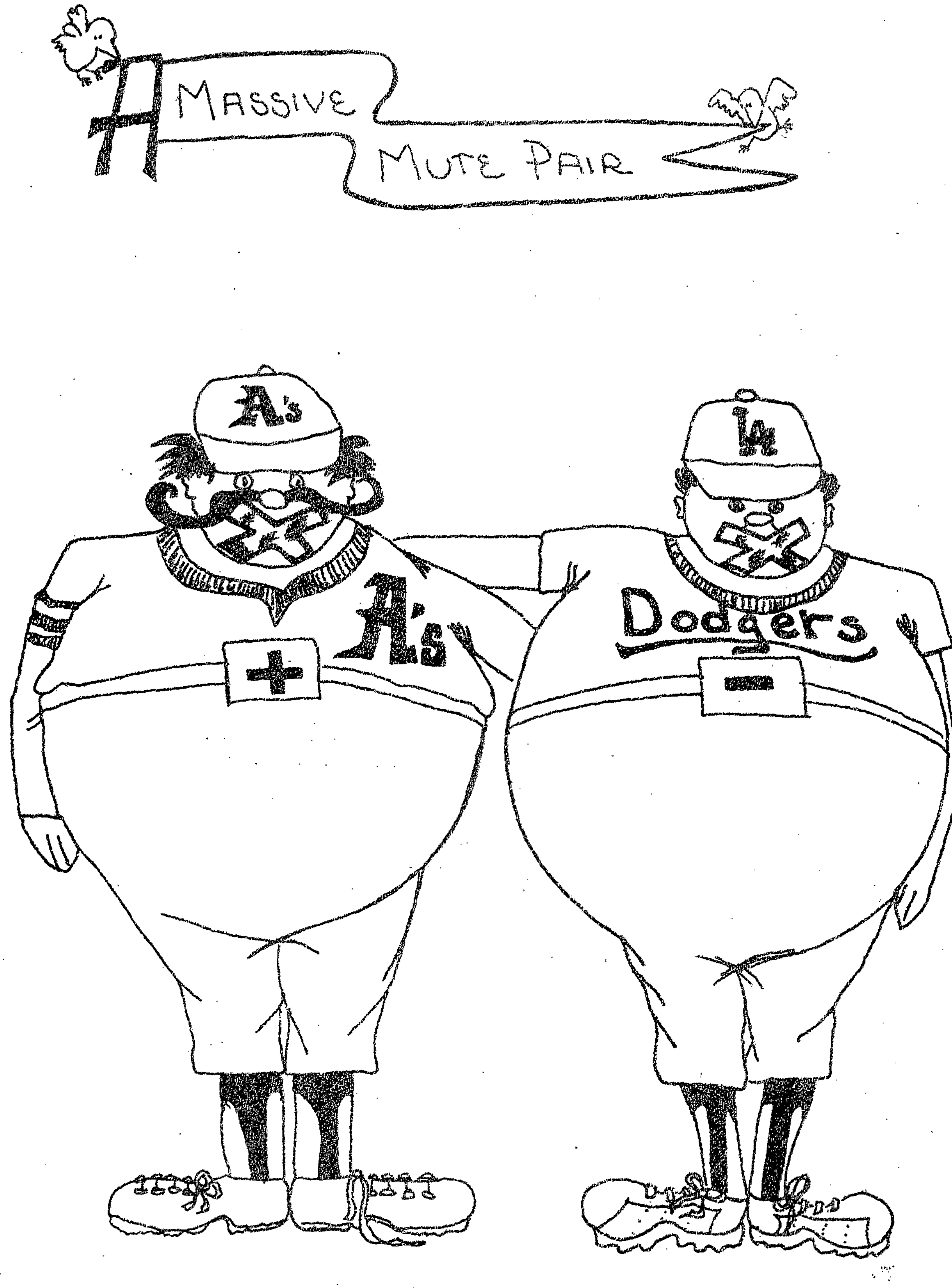

Figure A

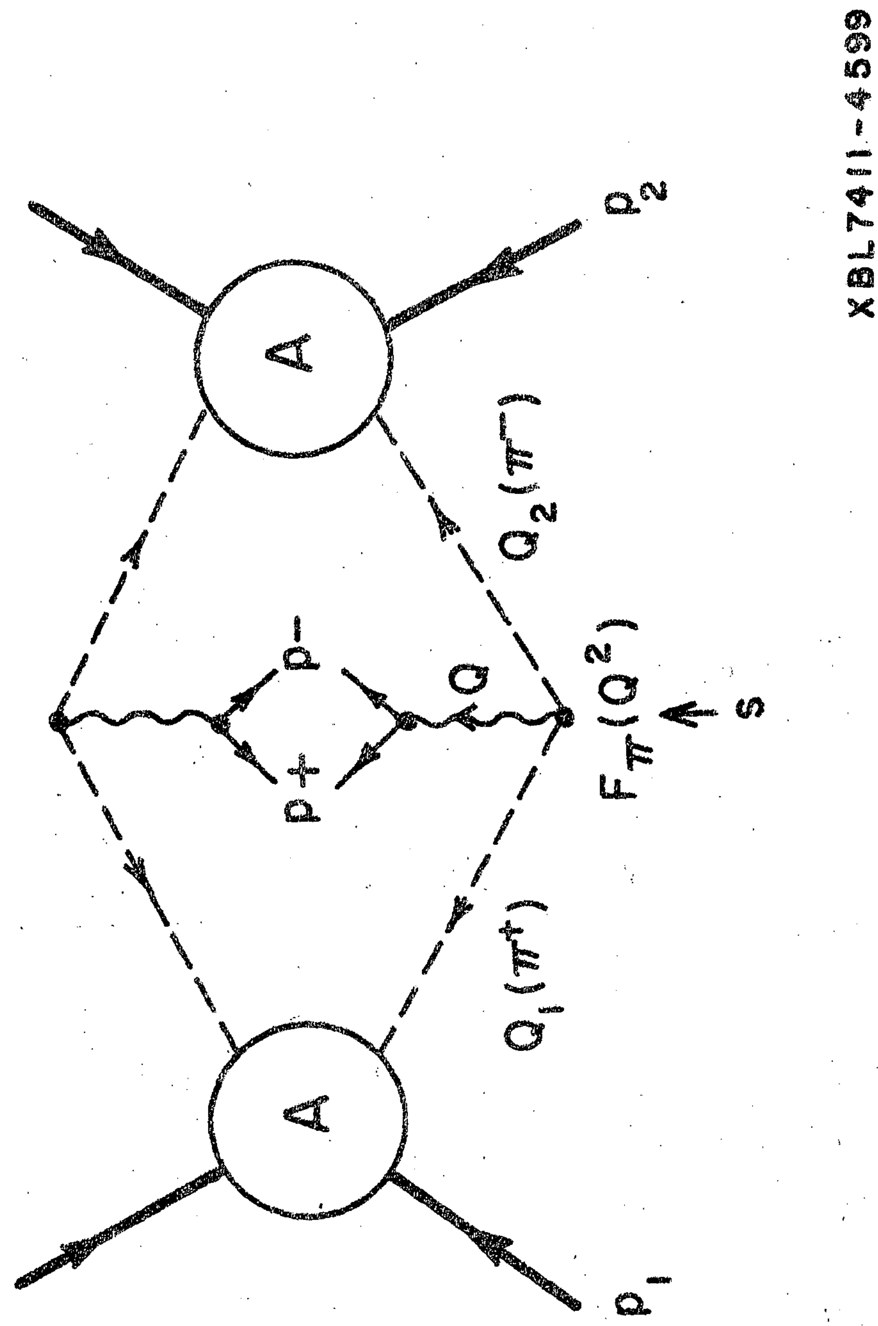

Figure 1

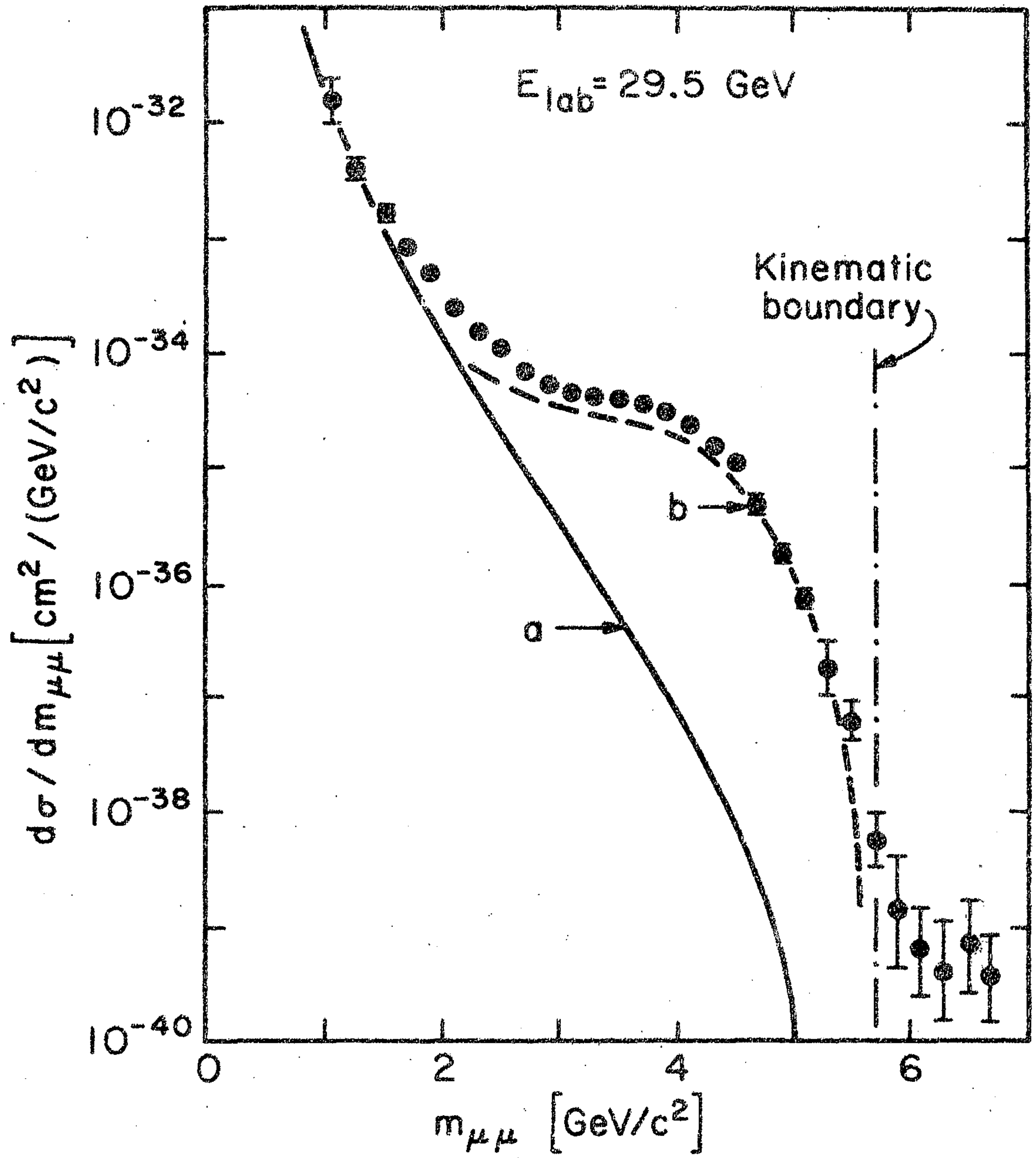

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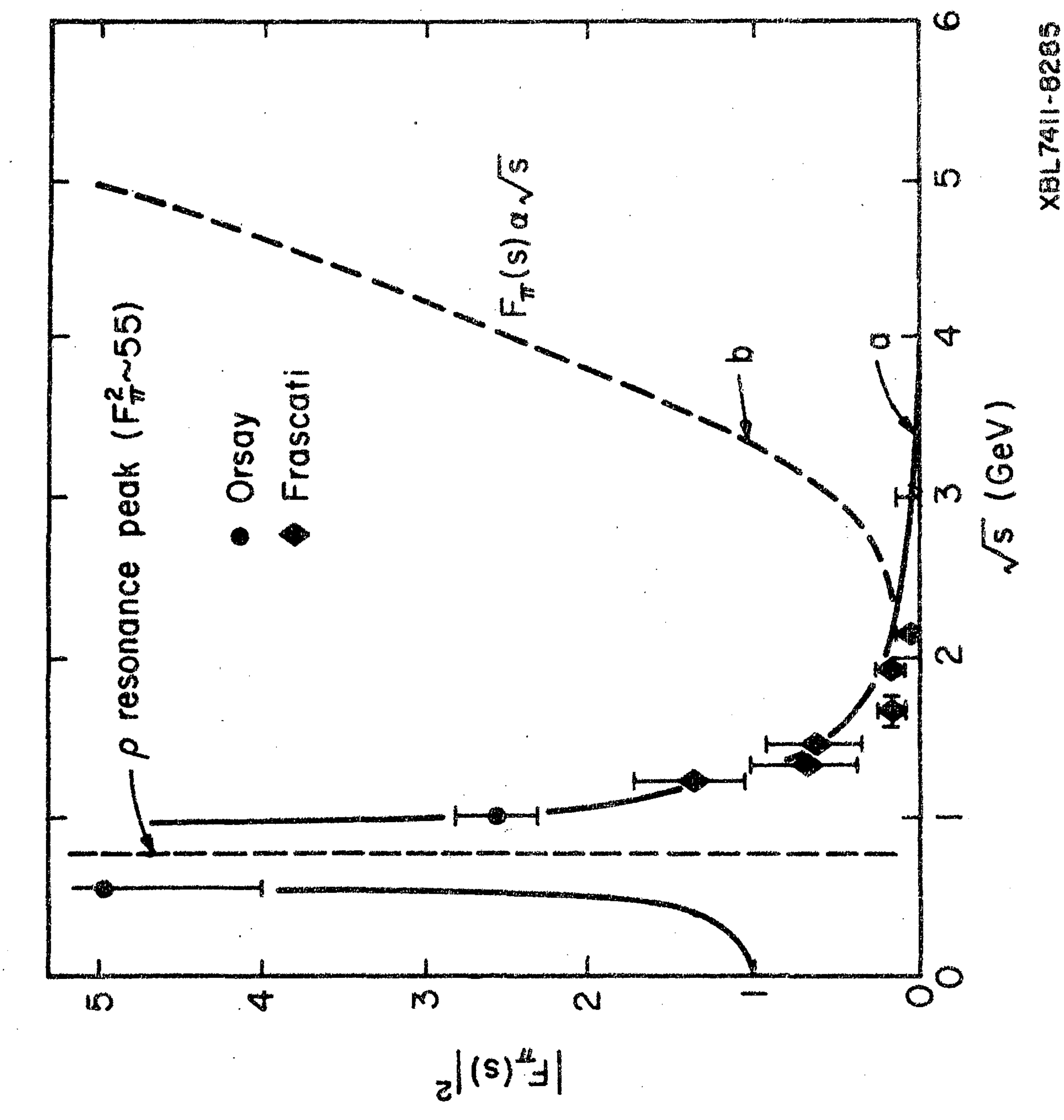
Figure 2



ρ resonance peak ($F_\pi^2 \sim 55$)
Orsay
Frascati
$F_\pi(s) \alpha \sqrt{s}$
b
a
$|F_\pi(s)|^2$
$\sqrt{s}$ (GeV)
0
1
2
3
4
5
6
XBL 7411-8285

Figure 3

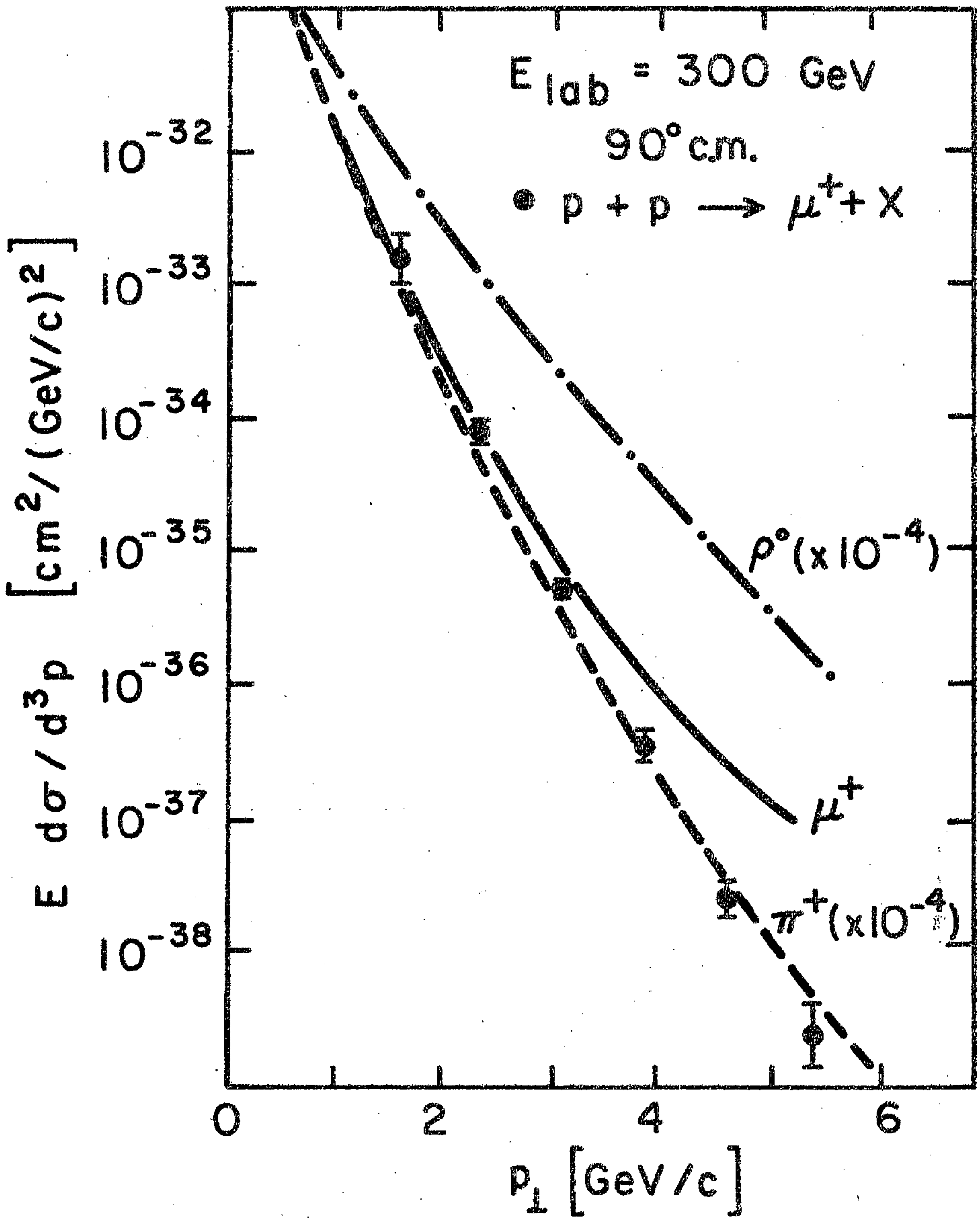


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Figure 4

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