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PRODUCTION OF HEAVY LEPTONS IN PROTON-PROTON COLLISIONS AND THE PARTON MODEL*

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ABSTRACT

Searches for leptons heavier than the muon may be conducted in hadron-hadron collisions: $p + p \to L^+ + L^- +$ hadrons. We apply the parton model to this process and calculate the correlations between the decay products of the heavy leptons.

I. INTRODUCTION

The electron and muon are the only two massive leptons which have been observed in nature. Since the properties of the two particles are identical except for their masses, physicists have long wondered at this apparently needless duplication. And given duplication, why not multiplication? Are there any other, more massive leptons?

The recent development of the unified gauge theories of the weak and electromagnetic interactions[1] has lent a new immediacy to the question of heavy leptons. It appears that in theories of this type, renormalizability is tied to the postulated existence of either neutral currents, or heavy leptons, or both. In the context of the gauge theories, the possible heavy leptons are E^+ and E^0 (M^+ and M^0), $J = \frac{1}{2}$ fermions, with the same lepton number as the e^- (μ^-).

Searches for heavy leptons may be made in:

(a) electron-positron colliding beams ($e^+ + e^- \to L^+ + L^-$ or $e^+ + e^- \to L^0 + \nu_L$),

(b) photoproduction experiments ($\gamma + N \to L^+ + L^- +$ hadrons),

(c) neutrino beams ($\nu_e + N \to L^+ +$ hadrons),

(d) charged lepton beams ($e^- + N \to L^0 +$ hadrons) and

(e) proton-proton collisions ($p + p \to L^+ + \nu_L +$ hadrons or $p + p \to L^+ + L^- +$ hadrons).

In this paper, we shall concern ourselves with the final possibility: the production of charged heavy leptons in pairs from proton-proton collisions where substantial advantages in beam intensity may make detection more tractable. We shall assume that the lepton pair is produced via the two step process involving a single virtual photon:

$$p + p \rightarrow \gamma + \text{hadrons}$$
$$\hookrightarrow L^+ + L^- .$$

This paper is divided into five sections. Section I is the introduction which the reader is presently being subjected to. Section II concerns itself with a short review of the detection problems peculiar to heavy leptons. In particular, the leptons probably have too short a lifetime to be observed directly, and therefore must be identified by their decay products. Section III deals with kinematics and the application of the parton model to lepton pair production. Section IV describes how one may obtain the correlations and angular distributions of the heavy lepton decay products. Section V is the conclusion.

II. HOW TO DETECT HEAVY LEPTONS

The lifetime of a heavy lepton is expected to be far too short for it to be directly observed in the laboratory. Colliding beam experiments at Frascati have established a lower limit on the mass of 1 GeV.[2] In fact, neutrino experiments at NAL[3] have improved the lower limit to 8.4 GeV for heavy muon-like leptons M^+ (with the same lepton number as the μ^-). It has been estimated that the lifetime of the heavy lepton must be less than 10^{-11} sec. if its mass is greater than 1 GeV.[4,5]

Therefore, any observation of heavy leptons must be made indirectly via their decay products. For charged heavy leptons, typically important decay modes are,

$$\begin{aligned} L^+ \rightarrow\ & \bar{\nu}_L\, e^+ \nu_e \\ & \bar{\nu}_L\, \mu^+ \nu_\mu \\ & \bar{\nu}_L\, \pi^+ \\ & \bar{\nu}_L\, \rho^+ \\ & \bar{\nu}_L + \text{hadrons}. \end{aligned} \qquad \text{(II.1)}$$

Estimates for the branching ratios as a function of M_L are given by Tsai[4] and by Bjorken and Llewellyn-Smith.[5] In p-p collisions, where the heavy leptons are expected to be produced in pairs, it would be feasible to identify them by detecting oppositely charged decay products in coincidence: e.g., $\mu^+ e^-$, $\pi^+\pi^-$, or $\pi^+ e^-$.

The flux of such pairs may be estimated by using the branching ratios of Refs. 4 and 5 and noting that the production of heavy lepton pairs is simply related to μ-pair production,

$$\frac{d\sigma/dQ^2(pp \rightarrow L^+L^- + \text{hadrons})}{d\sigma/dQ^2(pp \rightarrow \mu^+\mu^- + \text{hadrons})} = \left(1 - \frac{4M_L^2}{Q^2}\right)^{\frac{1}{2}} \left(1 + \frac{2M_L^2}{Q^2}\right) \qquad \text{(II.2)}$$

where Q^2 is the mass squared of the lepton pair, and we have neglected the muon mass.

One may calculate the decay of the heavy leptons by assuming eμL universality. In the case of the purely leptonic decay mode,

$$L^+ \rightarrow \bar{\nu}_L \bar{\nu}_e e^+ \qquad \text{or} \qquad L^- \rightarrow \nu_L \bar{\nu}_e e^-$$

the energy and angular distribution of the electron from a lepton of polarization $\vec{s}$ can be written in the rest frame of L as,[6]

$$\Gamma \begin{pmatrix} L^+ \to \bar{\nu}_L \, \nu_e \, e^+ \\ L^- \to \nu_L \, \bar{\nu}_e \, e^- \end{pmatrix} = \frac{G^2 M_L^5}{3 \quad 2^7 \pi^4} \int d\Omega_e \int_0^1 dx \, x^2 [3 - 2x \pm (\vec{s}\cdot\hat{p}_e)(2x-1)] \qquad \text{(II.3)}$$

where $G = 1.02 \times 10^{-5}/M_p^2$, $x = E/E_{max}$ of the electron, with $E_{max} = \frac{1}{2} M_L$, and $\hat{p}_e$ is the unit vector of the electron momentum.

Tsai uses pion decay to calculate the decay mode into a single pion,[4]

$$\Gamma \begin{pmatrix} L^+ \to \bar{\nu}_L \, \pi^+ \\ L^- \to \nu_L \, \pi^- \end{pmatrix} = \frac{G^2 f_\pi^2 \cos^2 \theta_c}{16\pi} M_L^3 \left(1 - \frac{M_\pi^2}{M_L^2}\right)^2 \int \frac{d\Omega}{4\pi} (1 \mp \vec{s}\cdot\hat{p}_\pi) \qquad \text{(II.4)}$$

where $\theta_c \sim 15^\circ$ is the Cabibbo angle and the pion decay constant $f_\pi = 0.137 \, M_p$.

III. KINEMATICS AND APPLICATION OF THE PARTON MODEL

The invariant cross section for the production of a heavy lepton pair (Fig. 1) may be written as,

$$d\sigma = \frac{1}{2\left\{\lambda(s, M_1^2, M_2^2)\right\}^{\frac{1}{2}}} \frac{(4\pi\alpha)^2}{Q^4} \frac{d^4Q}{(2\pi)^4} W^{\mu\nu}(p_1, p_2, Q) \frac{d^3p_+}{(2\pi)^3 2E_+} \frac{d^3p_-}{(2\pi)^3 2E_-}$$

$$\times L_{\mu\nu}(p_+, p_-) \, (2\pi)^4 \, \delta(p_+ + p_- - Q) \qquad \text{(III.1)}$$

where p_1 and p_2 are the initial proton momenta, p_+ and p_- are the final lepton momenta, and Q is the momentum of the lepton pair. For leptons of a given spin,

$$L_{\mu\nu}(p_+, p_-) = \mathrm{Tr}\left[\frac{(1 + \gamma_5 \not{s}_-)}{2} (\not{p}_- + M_L)\gamma_\mu \frac{(1 + \gamma_5 \not{s}_+)}{2} (-\not{p}_+ + M_L)\gamma_\nu\right]. \qquad \text{(III.2)}$$

The operator $(1 + \gamma_5 \not{s})/2$ is the spin projection of a lepton with spin $\vec{s}$ in its rest frame. The structure function $W^{\mu\nu}$ contains the dynamics of the process and is written in terms of the electromagnetic current as,

$$W^{\mu\nu}(p_1, p_2, Q) = (2\pi)^6 \, 2E_1 \, 2E_2 \int d^4x \; e^{-iQ\cdot x} \langle p_1 p_2 | j^\mu(x) \, j^\nu(0) | p_1 p_2 \rangle . \qquad \text{(III.3)}$$

Before any prediction for the decay correlation of the heavy leptons can be made, there must be some way of determining the hadronic structure function $W^{\mu\nu}$. Experimental evidence from μ-pair production experiments can, in principle, provide all the needed information. But practical problems arising from aperature limitations and other experimental uncertainties can make such an analysis difficult, if not impossible. Therefore, we shall use the parton model as a tool for predicting the decay correlations. Our analysis will not be completely dependent on the success of the model for its validity. To the extent that we can demonstrate that the model, in some form, can explain the published μ-pair production data, we would expect it to be a useful means of predicting heavy lepton production.

We assume with Drell and Yan[7] that the heavy photon is produced via parton-antiparton annihilation (Fig. 2). Thus, we have the usual expression,

$$W^{\mu\nu}(p_1,p_2,Q) = (p_1{}^{\mu} p_2{}^{\nu} + p_2{}^{\mu} p_1{}^{\nu} - g^{\mu\nu} p_1\cdot p_2) \sum_a \lambda_a{}^2$$

$$\times \int dx_1 dx_2\, d^2\vec{k}_{1\perp}\, d^2\vec{k}_{2\perp}\, f_a(x_1,\vec{k}_{1\perp}) f_{\bar{a}}(x_2,\vec{k}_{2\perp})(2\pi)^4\, \delta(k_1 + k_2 - Q) \quad \text{(III.4)}$$

where k_1 and k_2 are the parton momenta. The summation is over all species a of partons and antipartons, and the index $\bar{a}$ refers to the antiparticle of a. The parton charge is $\lambda_a e$. We have shown in an earlier paper[8] that this expression for the structure function is valid to $O(s^{\frac{1}{2}})$ in an appropriately chosen frame. The parton distribution function $f_a(x_1,\vec{k}_{1\perp})$ is related to the structure function in electroproduction by,

$$\nu W_2(x = \frac{1}{\omega}) = \sum_a \lambda_a{}^2 x \int d^2\vec{k}_\perp\, f_a(x,\vec{k}_\perp) \equiv \sum_a \lambda_a{}^2 x\, f_a(x) \, . \quad \text{(III.5)}$$

Substituting into Eq. (III.1), the differential cross section is, for asymptotic energies,

$$\frac{d\sigma}{dQ^2} = \frac{1}{2(2\pi)^2} \frac{(4\pi\alpha)^2}{Q^4 s} \tau W(\tau)\, \delta(p_+ + p_- - Q) \frac{d^3p_-}{2E_+} \frac{d^3p_-}{2E_-}$$

$$\times (p_1{}^{\mu} p_2{}^{\nu} + p_2{}^{\mu} p_1{}^{\nu} - g^{\mu\nu} p_1\cdot p_2) L_{\mu\nu}(p_+,p_-) \quad \text{(III.6)}$$

where $\tau \equiv Q^2/s$ is the usual scaling variable, and has the range $0 < \tau < 1$.

$$W(\tau) = \sum_a \lambda_a{}^2 \int_0^1 dx_1 \int_0^1 dx_2\, \delta(x_1 x_2 - \tau)\, f_a(x_1)\, f_{\bar{a}}(x_2) \, . \quad \text{(III.7)}$$

We note here, that integration over the lepton variables yields the familiar result for the differential cross section

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3Q^4} \left(1 - \frac{4M_L{}^2}{Q^2}\right)^{\frac{1}{2}} \left(1 + \frac{2M_L{}^2}{Q^2}\right) \tau W(\tau) \, . \quad \text{(III.8)}$$

At subasymptotic energies, the expression for $W(\tau)$ in (III.7) must be modified to account for the kinematic limitations on τ (or, equivalently, on Q^2). In particular, $Q^2_{max} = (s^{\frac{1}{2}} - 2M)^2$; and at Brookhaven energies such limitations become important. The accommodation of these effects is discussed in Ref. 8.

We may express (III.4) in terms of the variables $\tau = Q^2/s$, $\vec{Q}_\perp$, and y, the fractional longitudinal momentum of the lepton pair relative to p_1 in the center of mass of the colliding hadrons.

$$x_1 = \frac{+y + (y^2 + 4\tau + 4Q_\perp{}^2/s)^{\frac{1}{2}}}{2} \, ,$$

$$x_2 = \frac{-y + (y^2 + 4\tau + 4Q_\perp{}^2/s)^{\frac{1}{2}}}{2} \quad \text{(III.9)}$$

with $-(1 - \tau) < y < (1 - \tau)$, and $0 < x_1 x_2 < 1$.

Substituting (III.4) into (III.1) then gives,

$$\frac{d\sigma}{dy\, d^2Q_\perp\, dQ^2} = 4\alpha^2 \frac{1}{s^2 Q^4} \frac{1}{(y^2 + 4\tau + 4Q_\perp{}^2/s)^{\frac{1}{2}}} \sum_a \lambda_a{}^2$$

$$\times \int d^2k_\perp\, f_a(x_1,\vec{k}_\perp)\, f_{\bar{a}}(x_2, \vec{Q}_\perp - \vec{k}_\perp)$$

$$\times \delta(p_+ + p_- - Q) \frac{d^3p_+}{2E_+} \frac{d^3p_-}{2E_-} (p_1{}^{\mu} p_2{}^{\nu} + p_2{}^{\mu} p_1{}^{\nu} - g^{\mu\nu} p_1\cdot p_2) L_{\mu\nu}(p_+,p_-) . \quad \text{(III.10)}$$

This determines the full distribution of the heavy photon momentum Q, and will be the fundamental equation for calculating the decay correlations of the heavy leptons. The dynamics is contained in the parton distribution functions $f_a(x,k_\perp)$. The subsequent calculation of the correlations of the decay products is essentially kinematic in nature.

We have shown[8] that reasonable choices for the parton distribution functions cannot fit the Brookhaven experimental data for μ-pair production,[9] once constraints from electroproduction, deep inelastic neutrino scattering, and large angle scattering are imposed. However, the shape of the experimental longitudinal momentum distribution in the lab, $d\sigma/dp_{\parallel}$, is accurately reproduced, and if the partons are given a form factor and magnetic moment, as suggested by West[10] to explain the e^+e^- annihilation data, then the shape of the experimental invariant mass distribution, $d\sigma/dQ^2$, may be approximately reproduced as well. Therefore, if we renormalize the distribution functions by a constant factor and include a factor arising from parton structure, then we will have a reliable tool for estimating lepton pair production, at least at Brookhaven energies.

Thus, one may use the quark distribution functions of Ref. 8

$$\begin{aligned} u_p(x) &= \hat{u}_p(x) + r_p(x) + s(x) \\ u_n(x) &= \hat{u}_n(x) + r_n(x) + s(x) \\ u_{\bar{p}}(x) &= u_{\bar{n}}(x) = u_{\bar{\lambda}}(x) = s(x) \end{aligned} \qquad \text{(III.11)}$$

with the particular choices,

$$\begin{aligned} s(x) &= 0.15(1-x)^7/x + 75x^4(1-x)^7 \\ r_p(x) &= 2.420(1-x)^7/x^{\frac{1}{2}} \\ r_n(x) &= 1.555(1-x)^7/x^{\frac{1}{2}} \end{aligned} \qquad \text{(III.12)}$$

and where $\hat{u}_p(x)$ and $\hat{u}_n(x)$ are shown in Fig. 7 of Ref. 8. The transverse momentum dependences for $f_a(x,k_\perp)$ may be taken to be those suggested in Ref. 8. The usual quark charge assignments are,

$$\lambda_p^2 = \frac{4}{9}, \qquad \lambda_n^2 = \lambda_\lambda^2 = \frac{1}{9} \qquad \text{(III.13)}$$

and we make the modification, as calculated in Ref. 8,

$$\lambda_a^2 \to \lambda_a^2 R \left(\frac{1}{1 - Q^2/\Lambda^2}\right)^2 \left(1 + \frac{\mu^2 Q^2}{4}\right) \qquad \text{(III.14)}$$

which accounts for the form factor and magnetic moment, and the overall renormalization R necessary to fit to the Brookhaven data. The parameters are

$$\begin{aligned} R &= 5.4 \\ \Lambda &= 8 \text{ GeV} \\ \mu &= 0.2 \text{ GeV}^{-1} \end{aligned} \qquad \text{(III.15)}$$

where Λ and μ are determined by fitting the electroproduction and annihilation data,[10] and where R is the renormalization required to fit the data at $E_{lab} = 29.5$ GeV.[8]

The choice of distribution functions and parameters in Equations (III.11) through (III.15) yield an excellent fit to the μ-pair production data at $E_{lab} = 29.5$ GeV. Comparisons to the experimental points in $d\sigma/dQ^2$ and $d\sigma/dp_{\parallel}$ can be seen in Figs. 3 and 4.

IV. DECAY CORRELATIONS

It is now possible to calculate the angular distribution of the decay products of the heavy leptons. The expression for the differential cross section (III.10) together with our choices for the parton distributions and charges (III.11 through III.15) gives the spin and momentum distributions of the outgoing leptons. Then, the appropriate Lorentz transformations and the equations for the subsequent lepton decay (II.3 and II.4) may be used to determine the distributions for $\pi\pi$, πe, or μe coincidental detection. Such a calculation may be performed by a Monte Carlo computer program, although we shall not attempt any such project in this paper.

It may prove useful, however, to write down an approximate analytical expression for the decay correlations. It is convenient to choose a coordinate system in the center of mass of the two leptons, where the z-axis is defined by the lepton momentum $\vec{p}_-$. (See Fig. 5.) We shall make the usual parton model approximation that $\vec{Q}_\perp^{\,2} \ll Q^2$. In any reasonable model, one would expect a sharp peaking at low values of the transverse momentum; in fact, a distribution of $e^{-2.5Q_\perp}$ has been reported for μ-pair production at Brookhaven energies.[9] The longitudinal momentum fraction y of the lepton pair will be unrestricted, of course.

The lepton pair is created with momentum fraction y, and invariant mass squared Q^2. Define $\vec{s}$ and $\vec{s}\,'$ to be the spin polarizations of L^- and L^+ in their respective rest frames. In our chosen frame of reference, the covariant spins may be obtained by a Lorentz transformation,

$$s_- = (\beta\gamma s_z,\ s_x,\ s_y,\ \gamma s_z)$$

$$s_+ = (-\beta\gamma s_z',\ s_x',\ s_y',\ \gamma s_z') \qquad \text{(IV.1)}$$

where $\beta = (1 - 4M_L^2/Q^2)^{\frac{1}{2}}$ and $\gamma = \frac{1}{2}(Q^2/M_L^2)^{\frac{1}{2}}$. We use the metric $g^{\mu\nu} = (1, -1, -1, -1)$, giving $s_\pm \cdot s_\pm = -1$. The lepton and proton momenta are,

$$p_- = \left((Q^2)^{\frac{1}{2}}/2,\ 0,\ 0,\ \beta(Q^2)^{\frac{1}{2}}/2\right)$$

$$p_+ = \left((Q^2)^{\frac{1}{2}}/2,\ 0,\ 0,\ -\beta(Q^2)^{\frac{1}{2}}/2\right)$$

$$p_1 = \left(\tilde{\gamma}(1+\tilde{\beta})P,\ -\tilde{\gamma}(1+\tilde{\beta})P\sin\theta,\ 0,\ \tilde{\gamma}(1+\tilde{\beta})P\cos\theta\right)$$

$$p_2 = \left(\tilde{\gamma}(1-\tilde{\beta})P,\ \tilde{\gamma}(1-\tilde{\beta})P\sin\theta,\ 0,\ -\tilde{\gamma}(1-\tilde{\beta})P\cos\theta\right) \qquad \text{(IV.2)}$$

where

$$P \approx s^{\frac{1}{2}}/2, \qquad \tilde{\beta} = -y/(4\tau + y^2)^{\frac{1}{2}}, \qquad \tilde{\gamma} = (1 + y^2/4\tau)^{\frac{1}{2}},$$

and θ is the angle between the negative lepton and the incident hadron (1).

The angular distribution of the lepton pair may be calculated by integrating (III.10), where we have made the usual parton model assumption that the transverse momentum of the lepton pair is small compared to Q^2.

$$\frac{d\sigma}{d\Omega_L\, dy\, dQ^2} \cong \frac{\alpha^2}{2sQ^2}\,\frac{1}{(y^2+4\tau)^{\frac{1}{2}}}\sum_a \lambda_a^2\, f_a(x_1)\, f_{\bar{a}}(x_2)$$

$$\times\, \beta\Big[1 + \cos^2\theta + \frac{\sin^2\theta}{\gamma^2} + s_z s_z'\big(1 + \cos^2\theta - \frac{\sin^2\theta}{\gamma^2}\big)$$

$$+ s_x s_x'\big(1 + \frac{1}{\gamma^2}\big)\sin^2\theta - s_y s_y'\beta^2\sin^2\theta + (s_x s_z' + s_x' s_z)\frac{1}{\gamma}\sin 2\theta\Big] \qquad \text{(IV.3)}$$

where

$$x_1 \cong \frac{+y + (y^2 + 4\tau)^{\frac{1}{2}}}{2} \quad \text{and} \quad x_2 \cong \frac{-y + (y^2 + 4\tau)^{\frac{1}{2}}}{2} .$$

It is worth noting that we have obtained a result identical in form to that obtained by Tsai for $e^+e^- \to L^+L^-$.[4] The reason is quite simple. Both proton momenta, p_1 and p_2, occur linearly in the cross section (III.10). Thus, the Lorentz transformation $(\tilde{\gamma}, \tilde{\beta})$ must cancel out of the calculation in our particular choice of reference frame since

$$\tilde{\gamma}(1 + \tilde{\beta}) \times \tilde{\gamma}(1 - \tilde{\beta}) = 1.$$

We are then left with a calculation exactly like that of Eq. (4.10) in Tsai's paper, Ref. 4. Therefore, the remarks made by Tsai regarding the spin correlations in $e^+e^- \to L^+L^-$ apply equally well to $pp \to L^+L^-$ + anything. We therefore refer the reader to Ref. 4 for a complete discussion.

The results Tsai obtains for the combined angular distribution of the decay products $L^- \to x$ and $L^+ \to x'$ for a fixed production angle also hold. For completeness, we transcribe the results for p-p collisions. Define

$$G(y, Q^2) \equiv \frac{\alpha^2}{2s\, Q^2} \frac{\beta}{(y^2 + 4\tau)^{\frac{1}{2}}} \sum_a \lambda_a^2 f_a(x_1) f_{\bar{a}}(x_2) \tag{IV.4}$$

with $\tau = Q^2/s$ and $x_{1,2} = (\pm y + (y^2 + 4\tau)^{\frac{1}{2}})/2$. Then the combined distribution may be written as

$$\frac{d\sigma}{d\Omega_L\, d\Omega\, d\Omega'\, dy\, dQ^2} = \frac{1}{\Gamma^2_{tot}} G(y,Q^2)\left[A(Q^2,\theta) + B(Q^2,\theta)\right] \tag{IV.5}$$

where Γ_{tot} is the total width of $L^\pm$, $d\Omega$ and $d\Omega'$ are solid angles for the decay products of L^- and L^+ in their respective rest frames, and the functions A and B depend on the decay products observed.

For the decay channel, $L^- \to \nu_L + \bar{\nu}_\mu + \mu^-$, $L^+ \to \bar{\nu}_L + \nu_e + e^+$ with μ^- and e^+ detected in coincidence,

$$A(Q^2, \theta) = F\left(1 + \cos^2\theta + \frac{\sin^2\theta}{\gamma^2}\right) \int_0^1 x^2 dx(3 - 2x) \int_0^1 x'^2 dx'(3 - 2x')$$

$$B(Q^2,\theta) = -F\int_0^1 x^2 dx \int_0^1 x'^2 dx'(1 - 2x)(1 - 2x')$$

$$\times \frac{1}{qq'}\left[q_z q_z'\left(1 + \cos^2\theta - \frac{\sin^2\theta}{\gamma^2}\right) + q_x q_x'\left(1 + \frac{1}{\gamma^2}\right)\sin^2\theta - q_y q_y'\,\beta^2 \sin^2\theta + (q_x q_z' + q_x' q_z)\frac{1}{\gamma}\sin 2\theta\right] \tag{IV.6}$$

where

$$F = \left(\frac{G^2 M_L^5}{3\; 2^7 \pi^4}\right)^2, \quad x = q/q_{max}, \quad x' = q'/q'_{max}, \text{ and}$$

$q_{max} = q'_{max} = \frac{1}{2} M_L$, and q and q' are defined in the L^- and L^+ rest frames respectively. Similar results hold for $\pi^+\pi^-$ and $\pi^-\mu^+$ coincidence. The reader is referred to Ref. 4 where the formulas for A and B may be obtained and where a complete discussion of the correlations occurs.

V. SUMMARY AND CONCLUSIONS

Unlike the colliding beam process, $e^+e^- \to L^+L^-$, the expectations for heavy lepton production in proton-proton collisions depend on the parton model: i.e., one must adopt the picture that the lepton pair is created via parton-antiparton annihilation, and then employ explicit distributions for the partons.

In an earlier paper,[8] we have shown that by including parton structure (one possible explanation for the behavior of the cross section for $e^+e^- \to$ hadrons) and renormalizing the parton charges, it is possible to describe the Brookhaven data for $pp \to \mu^+\mu^-$ + anything using an otherwise attractive parton model. One may hope that our calculation of the hadronic, parton sensitive structure function, describing $pp \to$ massive photon, is at least phenomenologically satisfactory. Thus our predictions for $pp \to L^+L^-$ + anything should be reasonably reliable and should serve as an adequate guide in the search for heavy leptons at Brookhaven energies ($s \sim 60\ GeV^2$). Hopefully the extrapolation to ISR energies ($s \sim 2500\ GeV^2$) would also be valid. This could be directly checked by performing the μ-pair experiment, an important goal in itself.

Of course, if one is able to completely determine the angular distribution of the μ-pair at any given energy, then the results could be used directly to predict the decay product correlations of the heavy leptons.

For further information on the expected properties of the heavy leptons and other mechanisms for their production, the reader is urged to consult the earlier works by Tsai,[4] and Bjorken and Llewellyn-Smith,[5] and the references contained therein.

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FOOTNOTES AND REFERENCES

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1. For references, see the review article by E. Abers and B. W. Lee, Phys. Reports 9C (1973).
2. V. Alles-Borelli, et al., Lett. Nuovo Cimento 4, 1156 (1970); A. K. Mann, ibid 1, 486 (1971).
3. B. Barish, et al., "Gauge Theory Heavy Muons: An Experimental Search," Cal Tech preprint CALT-68-430 (1974).
4. Y.-S. Tsai, Phys. Rev. D4, 2821 (1971).
5. J. D. Bjorken and C. H. Llewellyn-Smith, Phys. Rev. D7, 887 (1973).
6. T. Kinoshita and A. Sirlin, Phys. Rev. 107, 593 (1957).
7. S. D. Drell and T.-M. Yan, Ann. Phys. 66, 578 (1971).
8. G. Chu and J. Gunion, "Probing Parton Distribution Functions in Massive Lepton Pair Production," Berkeley-Pittsburgh preprint PITT-122, LBL-3021 (1974).
9. J. H. Christenson, et al., Phys. Rev. D8, 3698 (1973).
10. G. West, "Evidence for Quark Substructure from Electron-Positron Colliding Beam Experiments?," Stanford University preprint ITP-454 (1974).

FIGURE CAPTIONS

Fig. 1. Kinematics for $pp \to L^+L^-$ + anything.

Fig. 2. Parton-antiparton annihilation diagram.

Fig. 3. Invariant mass distribution of μ-pairs. The dashed curve (a) is the renormalized prediction for point-like partons; the solid curve (b) is the renormalized prediction for partons with structure, a form factor and an anomalous magnetic moment. The kinematic boundary is defined by the requirement that $m_{\mu\mu} < s^{\frac{1}{2}} - 2M$, and the theoretical curves are calculated taking this limitation into account using the method described in Ref. 8.

Fig. 4. Longitudinal momentum distribution of μ-pairs in the laboratory. The data is from the Brookhaven-Columbia experiment,[9] and the curve is the prediction of the parton model with an overall renormalization. The experimental aperature allowed the detection only of μ-pairs with longitudinal momentum in the lab greater than 12 GeV/c.

Fig. 5. Center-of-mass frame of the lepton pair used to calculate decay correlations.

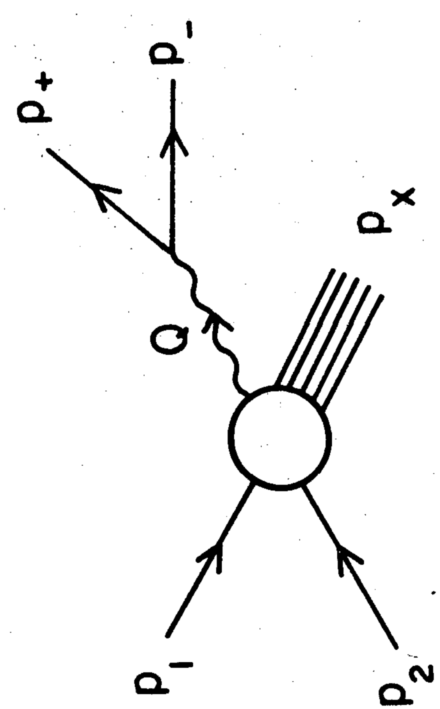

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Fig. 1.

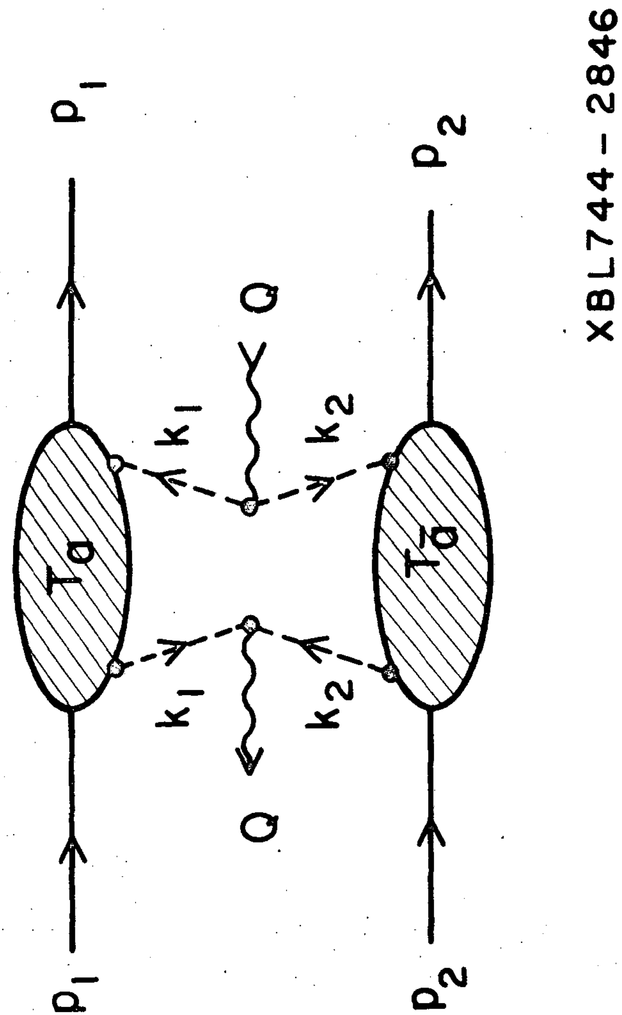

Fig. 2.

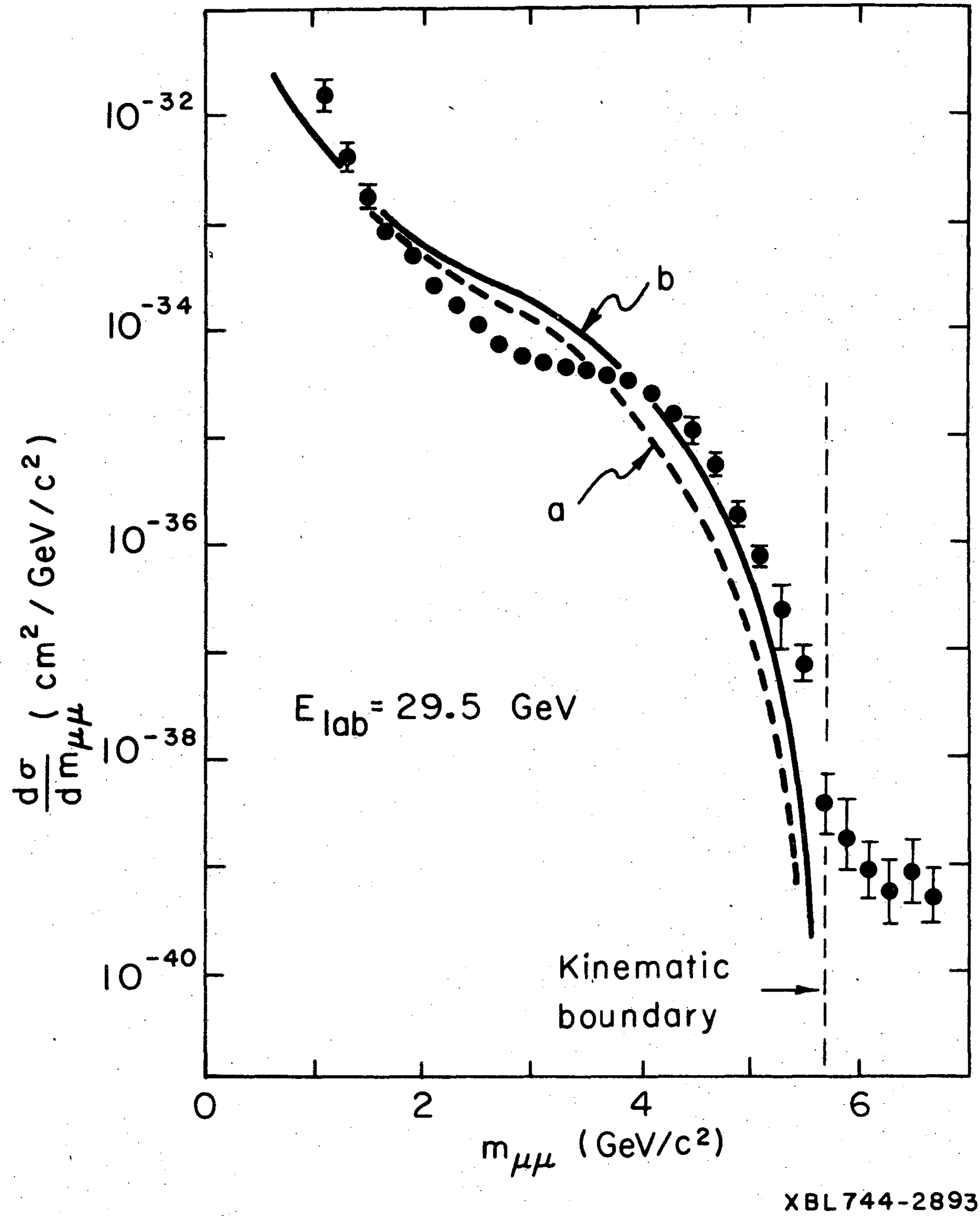
10^{-32}
10^{-34}
10^{-36}
10^{-38}
10^{-40}
$\frac{d\sigma}{dm_{\mu\mu}}$ (cm^2/GeV/c^2)
b
a
E_{lab} = 29.5 GeV
Kinematic boundary
0
2
4
6
$m_{\mu\mu}$ (GeV/c^2)
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Fig. 3.

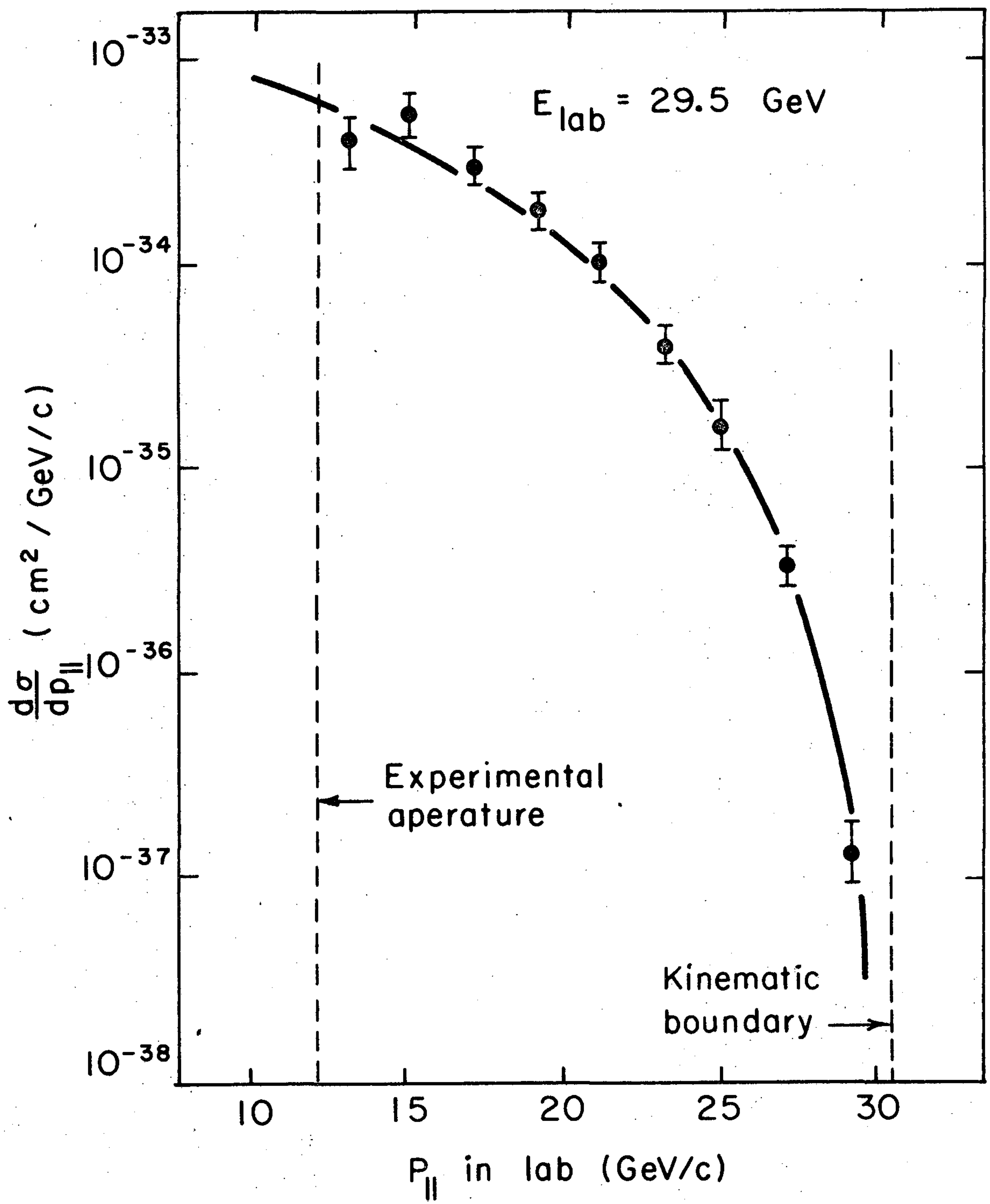
E_{lab} = 29.5 GeV
Experimental aperature
Kinematic boundary
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
$\frac{d\sigma}{dp_{\parallel}}$ (cm² / GeV/c)
10
15
20
25
30
$P_{\parallel}$ in lab (GeV/c)
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Fig. 4.

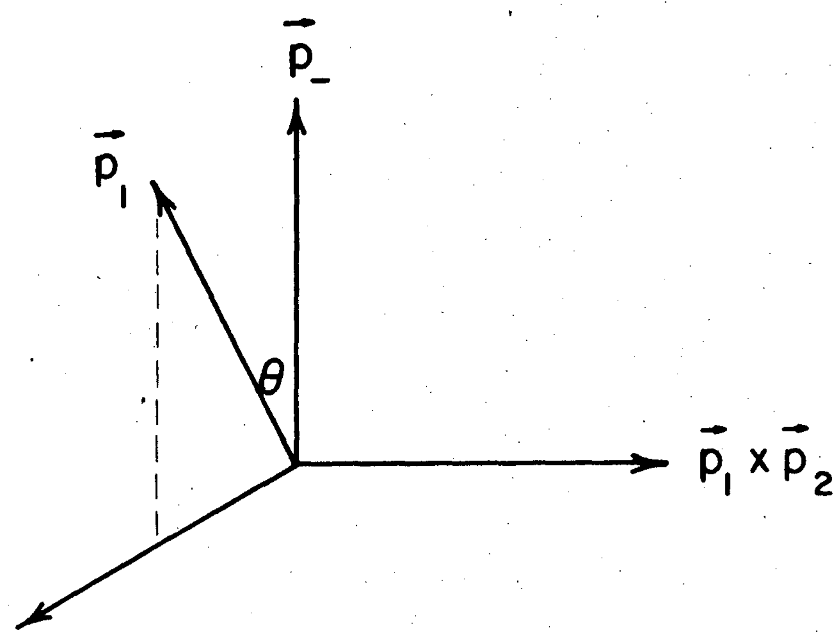

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Fig. 5.

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