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PHENOMENOLOGY OF LEPTON PRODUCTION

F.M. RENARD

Département de Physique Mathématique*

Université des Sciences et Techniques du Languedoc

34060 MONTPELLIER CEDEX, France

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* Physique Mathématique et Théorique, Equipe de Recherche associée au CNRS

I - Introduction, historics and motivations

The subject we want to review concerns the leptons production in hadronic collisions. The experimental processes are $h+h' \to \ell^{+}+\ell^{-}$ + anything or $h+h' \to \ell^{\pm}$ + anything where the beams (h) are mesonic or baryonic, the targets (h') is a proton or a nucleus, the leptons (electrons or muons) are detected in pairs or individually.

The first motivation in the years 64/65 was the search [1] for heavy intermediate bosons $W^{\pm}$ decaying into $\mu+\nu$ so producing large transverse momentum muons. Such an experiment requiring a good knowledge of the background processes motivated the study of the leptons pairs first carefully done [2] in 68 with p+U collisions.

Needless to say the search for $W^{\pm}$ bosons being always negative, experiments detecting single leptons at large ℓ_T were pursued at higher and higher energies. During the last few years, Serpukhov, BNL, FNAL, Cern PS and Cern ISR accumulated results with an interest culminating at the London Conference [3] in July 74 due to the famous and unexpected result for the ratio $\ell/\pi \simeq 10^{-4}$ in the range $0.2 \lesssim \ell_T \lesssim 5$ GeV/c.

Such a value is effectively muchlarger than what was expected theoritically for a continuous production, for example with the Drell-Yan [4] mechanism for the decay a massive photon into $\ell^{+}\ell^{-}$. Of course the trivial sources of single leptons, especially the long-lived particles and the internal conversion of photons into pairs were subtracted but there are still some uncertainties in these processes and discussions are running in particular about a possible high contribution of photon bremstrahlung [53]. The contribution of the known vector mesons, ρ, ω and φ was expected to be 10 times smaller even if these were produced copiously at large q_T so one begun to imagin new mechanisms or particles.

At the same time the $e^{+}e^{-}$ annihilation into hadrons was shown [5] to have an anomalously large total cross-section and many processes were proposed in order to explain both reactions (modifications of the parton model, generalized vector dominance, charmed particles, heavy leptons and many other exotic states) ; specific models for the production of large transverse momentum particles (hadrons or leptons) were also suggested [6] (parton subprocesses, cluster models, real or virtual photon bremstrahlung...).

Soon after, the discovery of the ψ particles [7] offer the hope of explaining anything due to their large $\ell^+\ell^-$ branching ratio. It is however now almost sure that they are not sufficient in order to explain both the $\ell^+\ell^-$ mass spectra and the single $\ell^\pm$ transverse momentum spectra. There are also now some evidences for the existence of heavy leptons [8] and charmed particles [9] in e^+e^- annihilation and neutrino scattering ; but in this case also the weakness of their production rate in hadronic collisions whatever could be their leptonic branching ratio makes doubtful their importance for our problem.

On the experimental side there are still many questions to answer which are strongly connected to the possible production mechanisms. What is really the behaviour of ℓ/π at low ℓ_T, is it really increasing when $\ell_T \to 0$ or roughly constant ? What is the behaviour of ℓ/π with the total energy $\sqrt{s}$, is there a threshold effect or is this ratio also roughly constant down to the low energies ? Do we have an equal production of ℓ^+ and ℓ^- and an equal production of electrons and muons for all ℓ_T ? Does the single lepton production correspond completely (after substraction of the trivial background) to a $\ell^+\ell^-$ pair production and in this case what is the dominant range of mass (continuous low or high mass or new objects)?

Most of the experimental material quoted in this lecture has been reviewed by Lederman [10] at the Slac Conference (Aug 75). We have added the observation of high mass (5.5 - 10. GeV) e^+e^- pairs at FNAL in p+Be interactions by D.C. Hom et al [22] with a clustering of events between 5.8 and

6.1 GeV already called the Υ(5.97) resonance. On another hand, also with 400 GeV protons at FNAL, L.B. Leipuner et al [48] claim evidence for pair origin of the muon production at large ℓ_T with a dominant mass range of 0.6 to 1.0 GeV ; the muons are not polarized (which is in favor of an electromagnetic process) but the level of the cross-section is about 10 times larger than the one predicted by ρ and ω production. Concerning the single lepton spectra we have the results of E.W. Beier et al [49] obtained at BNL who confirm the rise of the ratio e/π up to 2.10^{-4} for ℓ_T decreasing down to 0.5 GeV/c but give values of the order of 0.1 to 0.5 $\times 10^{-4}$ for $\ell_T > 1$ GeV/c which could be consistent with vector meson decays. Such results are in contradiction with the CCRS results [50] obtained with the ISR (however in a different energy range) which have an e/π ratio of the order of $1.\times 10^{-4}$ constant or decreasing for low ℓ_T. We quote finally results by Buchholz et al [51] with 300 GeV p+Cu collisions at FNAL who detected forward muons ($|\vec{\ell}|$ = 90 and 150 GeV/c with $\ell_T < 0.4$ GeV/c) still with a high μ/π ratio ($3.8 \pm 2.1\times 10^{-5}$ for 150 GeV/c and $1.56 \pm 0.40\times 10^{-4}$ for 90 GeV/c) which is also about 10 times larger than what is expected from forward ρ^0 production.

We thank D^{rs} J-M Gaillard and J.P. Pansart for having let us know these last experimental informations.

In the next chapters we develop the following subjects :

Sect.II : the Drell-Yan model for continuous $\ell^+\ell^-$ production

1. The parton-antiparton annihilation mechanism
2. Scaling forms ; relation with Deep Inelastic Scattering (DIS)
3. Model calculations
4. Results
5. Modifications of the model and additionnal contributions.

Sect. III : Vector mesons and clusters

1. Vector mesons contributions
2. Vector mesons production mechanisms
3. Experimental informations on vector mesons production
4. Lepton spectra from vector meson decays
5. The parent-child relation
6. Discussion of the ℓ/π ratio
7. Higher vector mesons
8. Cluster models

Sect. IV : Other sources of direct leptons

1. Charmed particles
2. Heavy leptons
3. Weak bosons

II - The Drell-Yan model for continuous $\ell^+\ell^-$ production

1. The parton-antiparton annihilation mechanism

The process $h+h' \rightarrow \ell^+\ell^- + X$ is supposed to be due to a virtual massive photon production, this one decaying then into lepton pairs (fig. 1)

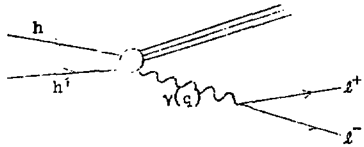

Fig.1

The cross-section takes the general form [4]:

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3Q^2} \sqrt{1 - \frac{4m^2}{Q^2}} \left(1 + \frac{2m^2}{Q^2}\right) \frac{W(Q^2,s)}{\sqrt{(s-(M+M')^2)(s-(M-M')^2)}}$$

where m is the lepton mass, M and M' the hadron masses and q^μ is the photon 4-momentum of mass $q^2 = Q^2$. The first part of this expression comes from the usual $\gamma\ell^+\ell^-$ vertex and the function W is given in term of the electromagnetic current :

$$W(Q^2,s) = -16\,\pi^2\, EE' \int d_4q\; \delta(q^2-Q^2) \int d_4y\; e^{-iq.y}\, \frac{1}{4} \sum_{spins} \langle PP'|J^\mu(y)\, J_\mu(0)|pp'\rangle$$

p and p' are the hadrons 4-momenta ; $s = (p+p')^2$.
This form has some similarity with the one [11] occuring in Deep Inelastic Scattering ; however it does not possess the light cone dominance. The reasons are first because $Q^2/s < 1$ by kinematical conditions (whereas one would need $Q^2/s \rightarrow \infty$) and secondly because we deal with a product of currents instead of a commutator vanishing for space-like y^2 separations.

Nevertheless Drell and Yan showed [4] that if the photon is coupled to a parton-antiparton pair in order to produce a high mass Q the parton and the antiparton must be issued separately from h and h' (diag. 2A).

Then $Q^2 = (k+k')^2 = sxx'$, if the masses and transverse momenta of the partons inside each hadron are neglected ($k^\mu = x\ p^\mu$, $k'^\mu = x'\ p'^\mu$). A high mass lepton pair can be produced by the annihilation of a pair of hard parton ($0 < x,x' < 1$).

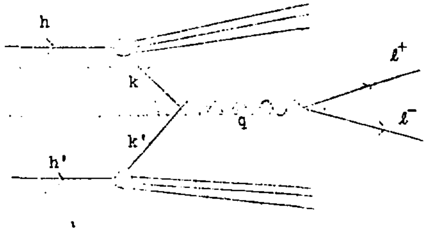

Fig. 2A

This diagram was opposed to the one (diag. 2B) where the pair issues from a single hadron ; in this case a high mass requires a high momentum transfer between the two hadrons :

$$K = \frac{\sqrt{s}}{2}\left[\sqrt{x^2 + \frac{4(q_\perp^2+Q^2)}{s}} - x\right]$$

if $q^\mu = xp^\mu + q_\perp^\mu$.

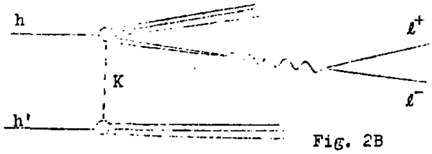

Fig. 2B

This process is therefore much less probable for high Q^2 than process (A). We shall consider its possible contribution in Sect. III 2.

Coming back to process (A), with an incoherent sum of parton amplitudes, the cross-section can be written :

$$\sigma(h+h' \to \ell^+\ell^-+X) = \iint dx\ dx' \sum_a f_a^h(x)\ f_{\bar{a}}^{h'}(x')\ \sigma(a+\bar{a} \to \ell^+\ell^-)\ \delta(Q^2-(k+k')^2)\ dQ^2$$

where $\sum_a$ extends over all kinds of partons and antipartons one can find inside h and h' ; $f_a^h(x)$ is the normalized probability of finding such a parton or antiparton "a" with a momentum $k^\mu = xp^\mu$ inside h.

With a point-like $\gamma a \bar{a}$ coupling (like in e^+e^- annihilation) one gets directly the following spectra :

The mass spectrum

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3Q^4} \sum_a \lambda_a^2 \iint dx\ dx'\ \delta(xx'-\tau)\ x\ f_a^h(x)\ x'\ f_{\bar{a}}^{h'}(x')$$

where λ_a is the charge (in unit of e) of the parton a and $\tau = Q^2/s$, the longitudinal spectrum (in the Feynman variable $\xi = \frac{2Q_L}{\sqrt{s}} = x-x'$)

$$\frac{d\sigma}{dQ^2 d\xi} = \frac{4\pi\alpha^2}{3Q^4} \sum_a \lambda_a^2 \frac{x_1 x_2}{\sqrt{\xi^2+4\tau}} f_a^h(x_1) f_{\bar{a}}^{h'}(x_2)$$

$$\text{with } x_{1,2} = \frac{\pm\xi + \sqrt{\xi^2+4\tau}}{2} .$$

In this simplified version of the parton model with no transverse momenta, the angular distribution of the photon (i.e. the pair of leptons) with respect to the beam is completely peaked longitudinally ; we shall discuss in Sect. III 5 attempts to take into account the possible partons transverse momenta.

The *angular distribution of the leptons in the photon rest system is specific* of the parton model : $1 + \cos^2\theta$ for spin - ½ partons (like in e^+e^- annihilation). Finally one can get [12] the single lepton ($\ell^\pm$) spectrum :

$$\frac{\ell^0 \, d\sigma}{d_3\ell} = \frac{2\alpha^2}{\ell_T^4} \int_{z_1}^{z_2} dy \, y(1-y) \, [1-2y\,(1-y)] \sum_a \lambda_a^2 \frac{z_1 z_2}{y(1-y)} f_a^h\left(\frac{z_1}{y}\right) f_{\bar{a}}^{h'}\left(\frac{z_2}{1-y}\right)$$

with $z_{1,2} = \frac{\ell^0 \pm \ell_L}{\sqrt{s}}$, ℓ_L and ℓ_T being the longitudinal and transverse components of the single lepton momentum with respect to the beam. The integration variable y is related to the mass of the pair :

$$y(1-y) = \frac{z_1 z_2}{xx'} = \frac{\ell_T^2}{Q^2} ;$$

notice also $\ell_T^2 = s\, z_1 z_2$ and that for leptons detected at 90° ($\ell_L = 0$) one has $z_1 = z_2 = \frac{\ell_T}{\sqrt{s}} < \frac{1}{2}$.

2. Scaling forms ; relations with D.I.S.

The above spectra possess the following scaling properties :

$$\frac{d\sigma}{dQ^2} \propto \frac{1}{Q^4} \mathcal{F}(Q^2/s)$$

$$\frac{d\sigma}{dQ^2 d\xi} \propto \frac{1}{Q^4} G\,(\xi,\, Q^2/s)$$

$$\frac{\ell^0 d\sigma}{d_3\ell} \propto \frac{1}{\ell_T^4} \mathcal{H}\left(\frac{\ell^0}{\sqrt{s}},\, \frac{\ell_L}{\sqrt{s}}\right) \text{ and only } \frac{1}{\ell_T^4} \mathcal{K}\left(\frac{\ell^0}{\sqrt{s}}\right) \text{ at } 90°.$$

These are already severe consequences of the parton model ;but in addition the probability distribution $f_a^h(x)$ are exactly those which occur [11] in DIS of leptons on hadrons h :

$$\nu W_2^h \equiv F^h(x) = \sum_a \lambda_a^2 \, x \, f_a^h(x)$$

and can be in principle extracted from experiments with e, ν and $\bar{\nu}$ scattering [13]. The method is the following. Any parton distribution is written as the sum of a valence and a sea distribution :

$$f_a(x) = V_a(x) + S_a(x)$$

The valence term is constrained by the normalization condition :

$\int_0^1 V_a(x)\, dx = n_a$, the number of quarks of type a in the valence configuration of the hadron.

The sea distribution is taken as SU_3 (or SU_4,...) symmetric, corresponding to the singlet formation of pairs $p\bar{p} + n\bar{n} + \lambda\bar{\lambda} + c\bar{c} + \ldots$:

$$S_a(x) \equiv S(x).$$

The total distribution is colour ($\widetilde{SU}_3$) symmetric :

$$f_{q_i}(x) = \frac{1}{3}\ f_q(x) = \frac{1}{3} \sum_{i=R,W,B} f_{q_i}(x)$$

This way we get the hadron structure function of table I, examples :

$$F^{P}(x) = \frac{x}{9}\,[4\,V_{p}(x) + V_{n}(x) + 20\,S(x)]$$

$$F^{\pi^{+}}(x) = \frac{x}{9}\,[5\,V'(x) + 20\,X'(x)]$$

$V'(x)$ and $S'(x)$ for mesons can be different from $V_{p}(x) \neq V_{n}(x)$ and $S(x)$ for baryons.

Notice the effect of Gell-Mann colour which is exactly a reduction by a factor 3 of the cross-section for lepton pair production with respect to the uncolored case :

$$\sum_{q_i} f_{q_i}(x)\, f_{\bar{q}_i}(x) = 3 \sum_{q} \frac{1}{3} f_{q}(x) \frac{1}{3} f_{\bar{q}}(x) = \frac{1}{3} \sum_{q} f_{q}(x)\, f_{\bar{q}}(x).$$

Other cases like Han Nambu's integer charges would lead to different modification :

$$\frac{1}{3} \times \frac{1}{3} \times \sum_{i} \lambda_{i}^{2} = \frac{4}{9} \quad \text{instead of} \quad \sum_{q} \lambda_{q}^{2} = \frac{6}{9} \quad \text{for ordinary quarks.}$$

The effect of new flavors (i.e. new quarks like charmed ones) appears with additionnal terms in the sea contribution :

$$S(x) \sum_{f} \lambda_{f}^{2} \,.$$

However in practice the sea contribution inside the nucleons is globally constrained by the experimental measurements [13] of DIS, such that any addition of new flavor will result in a corresponding reduction of the factor $S(x)$ and the global contribution of the sea to the lepton pair production will be practically unchanged.

Upper bounds of the cross-section $\frac{d\sigma}{dQ^2}$ has been established by Savit and Einhorn [14] using positivity conditions $f_{a}(x) \geq 0$ and the DIS structure functions measured [13] at Slac and with neutrino scattering in gargamelle. The results are given only for the conditions of the BNL experiment but appear to be already very stringent. It must be however noticed that they are very sensitive to the antiquark distributions constrained by the gargamelle datas which are perhaps not yet in the scaling region.

3. Model calculations

They use well defined expressions for the functions $V(x)$ and $S(x)$. First their behaviours for $x \to 0$ and $x \to 1$ are generally fixed according to counting rules.

Regge duality [15] suggest that for $x \to 0$ (the Regge limit $\nu \gg q^2$) :

$$\nu W_2^{sea}(x) \propto \operatorname{Im} T^{\mathbb{P}}_{\gamma N \to \gamma N}(t=o) \propto \nu^{\alpha(o)-1} \propto x^{1-\alpha(o)}$$ with $\alpha(o) = 1$ for the Pomeron. This means $S(x) \propto \frac{1}{x}$.

And $\nu W_2^{val}(x) \propto \operatorname{Im} T^{Regge}_{\gamma p \to \gamma p} \propto x^{1-\alpha(o)}$ with $\alpha(o) = \frac{1}{2}$ for the Regge trajectories, means $V(x) \propto \frac{1}{\sqrt{x}}$.

For $x \to 1$ inclusive-exclusive connections [16] relate the behaviour [17] of the elastic or quasi-elastic form factors $F(t) \sim \frac{1}{t^{n-1}}$ (for $t \to \infty$) for a system with n non-wee constituents to the one of the structure functions :

$$\nu W_2(x) \to (1-x)^{2n-3} .$$

For example :

the valence part of a baryon (qqq), $n=3$, $F(t) \sim \frac{1}{t^2}$, $V(x) \simeq (1-x)^3$

the sea part of a baryon $(qqqq\bar{q})$, $n = 5$, $F(t) \sim \frac{1}{t^4}$, $S(x) \simeq (1-x)^7$

the valence part of a meson $(q\bar{q})$, $n=2$, $F(t) \sim \frac{1}{t}$, $V'(x) \simeq (1-x)$

the sea part of a meson $(q\bar{q}q\bar{q})$, $n=4$, $F(t) \sim \frac{1}{t^3}$, $S'(x) \simeq (1-x)^5$.

The Slac and Gargamelle datad (for nucleons) suggest [13] then the shapes of the distributions and can be fitted [18] with :

$$\sum_{\bar{q}} f_{\bar{q}}(x) \simeq \frac{0.3\,(1-x)^7}{x}$$

(this quantity being equal to 4 S(x) in an SU_q description, q=p,n,λ,c), and with the valence part :

$$V_p(x) = \frac{Z_1}{\sqrt{x}} (1-x)^3 (1+ax) \qquad Z_1=1.79 \text{ , } a = 2.3$$

$$V_n(x) = \frac{Z_2}{\sqrt{x}} (1-x)^{3+\beta} (1+bx) \qquad Z_2 = 1.107 \text{ , } b \simeq 0 \text{ , } \beta \simeq 0.1$$

Meson structure functions are of course more speculative. On the basis of the above counting rules and by analogy with the nucleon structure functions one can try the gess :

$$\sum_{\bar{q}} f'_{\bar{q}} (x) \simeq \frac{0.3 (1-x)^5}{x}$$

and

$$V'(x) \simeq \frac{3}{4\sqrt{x}} (1-x) \text{ .}$$

4. Results

Independantly ofthe details of the x dependance of the structure functions, from the preceding sea and valence properties of mesons and baryons, one expects first that antibaryons and mesons beams will lead to much higher cross-sections than nucleon beams because of the possibility of finding large antiquark distributions in the valence part ; secondly from the quark charges one expects [19 a,b] the following equalities and inequalities :

$$\sigma(\bar{p}p) > \sigma(\bar{n}p) > \sigma(pp) > \sigma(np)$$

$$\sigma(\pi^- p) = \sigma(K^- p) > \sigma(\pi^+ p) = \sigma(\bar{K}^{0} p) > \sigma(K^+ p) = \sigma(K^0 p)$$

$$\sigma(\pi^- p) - \sigma(K^+ p) = 4 \; (\sigma(\pi^+ n) - \sigma(K^+ n))$$

$$\sigma(\pi^- n) - \sigma(K^+ n) = 4 \; (\sigma(\pi^+ p) - \sigma(K^+ p))$$

the last two equalities gives a relation for deuterium targets.

With the explicit forms choosen for the structure functions, one can then compute [18,19a,b] exactly the various spectra ; the results are shown on fig. 3,4,5.

The fall-off of $\frac{d\sigma}{dQ}$ for large Q $(\tau \to 1)$ and of $\frac{\ell^0 d\sigma}{d_3\ell}$ for large ℓ_T $(\ell_T \to \frac{\sqrt{s}}{2})$ reflect directly the behaviour of the parton and antiparton distributions $f_a(x)$ for $x \to 1$. Notice that this behaviour is not so well established experimentally [13] by DIS of electrons and neutrinos.

The shape of $\frac{d\sigma}{d\xi}$ at fixed s and Q^2 is the most stringent test of the model and of the parton distributions to which it is directly proportionnal. If this Drell-Yan process was the dominant one, it would be the best way for extracting from experiment the antipartons distributions and also the meson structure functions which are not directly accessible experimentally.

Comparison with experiments can be done first for the pairs detection. The discrepancy quoted [20] since a longtime ago with the BNL experiment $(p+U \to \mu^+\mu^- + X$ at 29.5 GeV) is much reduced after subtraction [10] of the nuclear effects and the ψ resonance.
For higher energies (for ex $n+N \to \mu^+\mu^- + X$ at FNAL) a comparison can be done [21] for $m < m_\psi$; the Drell-Yan prediction is still a little too weak. For $m > m_\psi$ $(p+Be \to e^+e^- + X$ at FNAL) one encounters the problem of the Υ bump [22].

Concerning the single lepton detection [6,10] at Serpukhov, FNAL and ISR, the ℓ_T dependance between 1 and 6 GeV/C is much more steeper than the one predicted by the Drell-Yan model ; also the magnitude is much different with a factor 100 at $\ell_T \simeq 1$ GeV/C and still a factor 5 at $\ell_T \simeq 5$ GeV/C.

5. Modifications of the model and additionnal contributions

a) Initial and final state interactions among hadrons

It was shown [23] that these ones can only modify the distributions of the hadrons but not the inclusive properties of the leptons.

b) Wee parton effects

Drell-Yan[4] had already noticed the possibility (diag. 2B) of bremstrahlung of small masses Q. This was taken again by Bjorken and Weisberg [24]; on the basis of the pion production supposed to be of this type, they estimated an additionnal contribution concentrated at low Q^2 (and therefore low ℓ_T for single leptons) and which could be 25 times larger than the Drell-Yan one. This goes in the right way but it is difficult to estimate precisely and to separate from the vector meson production which has also a large bremstrahlung contribution and which will be discussed in the next section.

c) Effect of the transverse momenta of the partons

We have seen that for partons with zero transverse momenta the single lepton transverse momentum ℓ_T and the mass Q of the pair are intimately connected. If one now allows a k_T spread of the parton momentum, it is possible to reach the same value of ℓ_T with a smaller mass Q ; as the Q^2 distribution is falling with Q^2 one gets finally a displacement of the ℓ_T spectrum towards the large values. This goes also in the right way. In order to obtain [25] a shape close to experiment

i.e. $\frac{\ell^0 d\sigma}{d_3} \sim (\frac{Ed\sigma}{d_3p})_\pi \sim \frac{1}{(m^2+\ell_T^2)^4}$, one needs a distribution for the photon

like $\frac{1}{(m^2+q_T^2)^4}$. It can be obtained just with structure functions

like $\frac{(1-x)^3}{(m^2+k_T^2)^4}$ for valence partons and $\frac{(1-x)^7}{(m^2+(q_T-k_T)^2)^8}$ for sea partons

which correspond to the generalized counting rules [52].

d) Charge clustering effects : modifications of the $q\bar{q}\gamma$ coupling

Many proposals had been done for this problem as well as for the one [5] of the e^+e^- annihilation into hadrons before the discovery of the ψ particles. Some modifications of the $q\bar{q}\gamma$ coupling (magnetic moments, form factors ...) would occur similarly in both reactions and maintain totally or partly the following relation [26] :

$$\frac{d\sigma}{dQ^2} = \sum_a \sigma(e^+e^- \to a\bar{a})\; G_a(Q^2) = \sigma^{e^+e^- \to had}(Q^2)\; G(Q^2)$$

$$\text{with } G_a(Q^2) = \int dx\, dx'\, \delta(Q^2 - xx's)\; f_a^h(x)\; f_{\bar{a}}^{h'}(x')$$

$$\text{and } G(Q^2) = \sum_a \frac{\lambda_a^2\, G_a(Q^2)}{\sum_a \lambda_b^2} \;.$$

An independent enhancement of the lepton pair production could [24] come from the clustering of partons into integrally charged "proto-hadrons" before annihilation into one photon ; the corresponding mean squared charge $\langle\lambda_a^2\rangle$ would be much larger.

e) gluon effects

It is known [13] from DIS that the charged partons carry only half of the momentum of the hadron, the other half being attributed to the gluons. On can then imagin that these ones could also play a role in lepton pair production. For example [27] supposing that a time-like photon is like a real hadron a superposition of partons and gluons and requiring the extraction of these configurations from the initial hadrons h and h', leads to cross-sections differing from the Drell-Yan ones by the factor :

$$K = (1 + gg')\; e^{g'(g-1)}$$

where g and g' are the coupling constants of the gluons inside the hadrons and inside the photon. It is easy to see that this factor can strongly modify the results and even the shape of the distributions if one allows the percentage of gluons with respect to partons to vary with x.

f) Other parton subprocesses

Within the framework of the constituent interchange model [28] first proposed for the description of the hadronic production at large p_T;

the massive lepton pair production has also been studied. An interesting subprocess is for example [29] meson + quark → massive photon + quark. We shall come back to such processes when discussing the vector meson production ; the interesting features are a steeper Q^2 dependance than Drell-Yan and an explicit treatment of the q_T dependance for the massive photon.

III - Vector mesons and clusters

1. Vector mesons contributions

Vector mesons with a large branching ratio into $\ell^+\ell^-$ are an obvious possible source of lepton pair production. The corresponding cross-sections can be written [19a, 30]:

$$\frac{d\sigma}{dQ^2} = \sum_V \frac{1}{\pi} \cdot \frac{\sigma^V\, m\,\Gamma_{V\to\ell^+\ell^-}}{D_V^2\,(Q^2)}$$

$$\frac{d\sigma}{dQ^2\,d\xi} = \sum_V \frac{1}{\pi} \cdot \frac{d\sigma^V}{d\xi} \cdot \frac{m\Gamma_{V\to\ell^+\ell^-}}{D_V^2(Q^2)}$$

$$\frac{\ell^0 d\sigma}{d_3\ell} = \int_{4m_\ell^2}^{(\sqrt{s}-M-M')^2} dQ^2 \int \frac{d_3 q}{q^0} \cdot \frac{\delta(q^0-\ell^0-\ell'^0)}{\ell'^0} \left(\frac{q^0 d\sigma^V}{d_3 q}\right) \frac{m_V}{2\pi^2\sqrt{m_V^2-4m_\ell^2}} \cdot \frac{m\Gamma_{V\to\ell^+\ell^-}}{D_V^2(Q^2)}$$

where σ^V is the production cross-section $(h+h' \to V+X)$ of a vector meson V with momentum q ; $D_V(Q^2) = m_V^2 - Q^2 - im\Gamma_V$ is its propagator and its partial decay width into lepton pair is given in terms of the vector meson-photon coupling :

$$m\Gamma_{V\to\ell^+\ell^-} = \frac{4\pi\alpha^2}{3m_V^2} \cdot g_{V\gamma}^2$$

These partial width are well-known (from e^+e^- experiments) for ρ, ω, φ, ψ and ψ'. It is however not the same for their production cross-section in hadronic collisions and this is a major source of discussions in the interpretations of the experimental results.

2. Vector meson production mechanisms

As the vector mesons and the photons have the same quantum numbers the same processes can be in principle used for their interactions. In particular the arguments given [4] by Drell and Yan for the separation of the annihilation (A) and bremstrahlung (B) processes can be applied here too.

With the annihilation mechanism (6A)

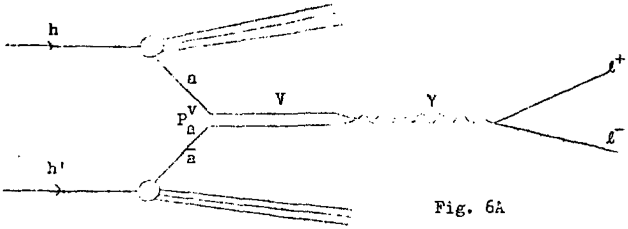

Fig. 6A

the production cross-sections are again calculable [19a,31] in terms of the quark distributions :

$$\sigma^V = \frac{\pi}{m_V^2} \sum_a P_a^V \iint dx\, dx'\, \delta(xx'-\tau)x\, f_a^h(x)\, x'\, f_{\bar{a}}^{h'}(x')$$

$$\frac{d\sigma^V}{d\xi} = \frac{\pi}{m_V^2} \cdot \frac{x_1 x_2}{\sqrt{\xi^2+4\tau}} \sum_a P_a^V f_a^h(x_1)\, f_{\bar{a}}^{h'}(x_2)$$

$$\frac{q^o d\sigma^V}{d_3 q} = \frac{2q^o}{\sqrt{s}} \cdot \frac{d\sigma^V}{d\xi} f(\vec{q})$$

P_a^V is the coupling constant squared of the a $\bar{a}$ pair to the vector meson V ; in the simplest version one can try $P_p^\rho = P_p^\omega = P_n^\rho = P_n^\omega = \frac{1}{2}$, $P_\lambda^\varphi = 1$, $P_c^\psi = 1$. $f(\vec{q}_\perp) \equiv \delta(\vec{q}_\perp)$ for purely longitudinal partons. Any other normalized function can be used for an extended version ; for example an exponential fall-off :

$$f(\vec{q}_\perp) = \frac{\beta}{\pi} e^{-\beta q_\perp^2} \quad \text{for which} \quad \langle q_\perp^2 \rangle = \frac{1}{\beta} .$$

This process should be important for high masses m_V (i.e. high Q^2 and ℓ_T), perhaps already for the ψ's and the higher vector mesons as discussed later on.

For light vector mesons the peripheral bremstrahlung mechanism (6B) is surely dominant. As for any other peripheral production, one can try [19a] the parametrisation :

$$\frac{q^o d\sigma^V}{d_3 q} = A(s,q_L)\, e^{-B\sqrt{m_V^2+q_\perp^2}}$$

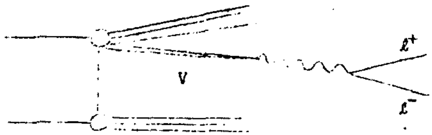

Fig. 6B

with $B \simeq 6\ GeV^{-1}$ (by similarity with pions), this term would be influent essentially for $m_V \lesssim 1.5$ GeV and $q_\perp \lesssim 1.5$ GeV/C.

For large $q_\perp$ various mechanisms already proposed [28,29,32] for pion production have been considered and could compete with the above ones. Let us quote for example :

jets

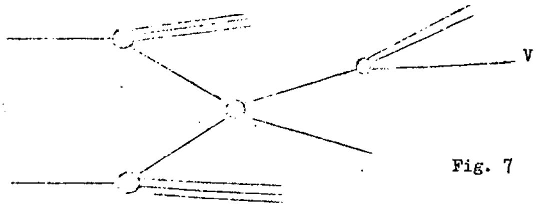

Fig. 7

meson bremsstrahlung

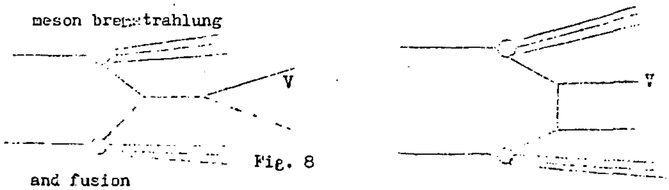

Fig. 8

and fusion

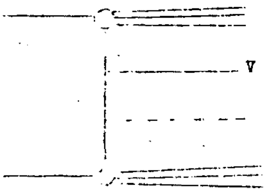

Fig . 9

3. <u>Experimental informations on vector mesons production</u>

They concern mainly ρ and ψ production, but even in this case, the experimental results are restricted to a very limited range of transverse momenta. This is the reason for the variety of conclusions which has been stated about the contributions of vector mesons to lepton production.

The ρ production[33] seems to be peripheral at low $q_\perp$ (i.e. $\frac{d\sigma}{dq_T^2} \simeq e^{-6q_T^2}$ for $q_\perp^2 < 1\ GeV^2/c^2$) with a tail for larger

$q_\perp \; (\frac{d\sigma}{dq_T^2} \simeq e^{-2q_T^2}$ for $1. \lesssim q_T^2 \lesssim 2.5 \;\; GeV^2/c^2$). The average transverse momentum is $\langle q_T^\rho \rangle \simeq 0.5$ GeV/c to be compared with $\langle p_T^\pi \rangle \simeq 0.34$ GeV/c. The magnitude of the ρ production versus π production seem to increase with q_T with a maximum around 1 for $q_\perp \gtrsim 1$ GeV/c in the case of $\pi^+ p$ interactions. The results depend in fact upon the incident beam and the ratio ρ^o/π is generally larger for incident pion beams than for nucleon beams.

The ω production [34] seems to be less than or equal to the ρ production. In most of the phenomenological models they are assumed to be equal.

The φ production [34] is surely much weaker ; an upper limit of $\varphi/\pi < 0.055$ at $q_T \simeq 2.5$ GeV/c has been obtained.

The ψ production has been intensively studied[35] recently. Its transverse momentum dependance is comparable to the long tail of the ρ one ; the average transverse momentum in pp collision $\langle q_T^\psi \rangle \simeq 0.7$ GeV/C . The magnitude is roughly $\psi/\pi \simeq 10^{-5}$. The shape of the distributions depend also upon the nature of the beams ; for ex :

$$\frac{d\sigma}{dx_{11}\, dq_T^2} \simeq \exp\left[-a x_{11} - b q_T\right] , \quad x_{//} = 2q_{//}/\sqrt{s}$$

with $\quad a = 6.2 \pm 0.8 \quad b = 1.6 \pm 0.2 \; GeV^{-1}$ for π^-

$\qquad a = 9.7 \pm 1.6 \quad b = 2.2 \pm 0.5 \; GeV^{-1}$ for p .

On this basis several phenomenological [19a,36] for the vector meson production cross-sections have been proposed, generally of the type

$$\frac{q^o d\sigma}{d_3 q} \;(h+h' \to V+X) = f(q_{//})\; g(q_T) \quad \text{at each value of } s.$$

for examples : $f(q_{//}) \sim \exp(-a\, x_{//}) \quad x_{//} = 2q_{//}/\sqrt{s}$

and $g(q_T) = \exp(-b q_T)$ or $\exp(-b q_T^2)$ or $\exp(-b\sqrt{q_T^2+m_V^2})$ or $(q_T^2+m_V^2)^{-n}$.

We shall see how these various types of q_T tails influence the lepton production.

4. Lepton spectra from vector meson decays

They can now be calculated with the help of equ.III.1

They possess however very interesting properties to discuss.

The mass distribution $\frac{d\sigma}{dQ^2}$ reflects directly the vector meson Breit-Wigner propagator but also the m_V dependance of the production cross-section σ^V. In particular for broad resonances like the ρ, it could be possible to see the tail of the peripheral mechanism which peaks strongly [19a,37] towards low Q^2.

The ξ distribution of the pair of leptons is directly proportionnal to the one of the vector meson and provide a good test of the production mechanism, for example of the quark distributions inside the hadrons.

The single lepton spectrum has more specific properties. First for a given mass $Q^2 = m_V^2$ and a purely longitudinal vector meson, the transverse momentum of a lepton ℓ_T is obviously strictly limited to $\ell_T < \frac{m_V}{2}$.
The spectrum would have the shape (fig. 10) controlled by the kinematical factor $\frac{1}{\sqrt{1 - 4\ell_T^2/Q^2}}$:

$$\frac{\ell^0 d\sigma}{d_3\ell} = \frac{2e^2}{\ell_T^4} \sum_a F_a^V \frac{z_1 z_2}{y_0(1-y_0)} f_a^h\left(\frac{z_1}{y_0}\right) f_{\bar{a}}^{h'}\left(\frac{z_2}{1-y_0}\right) \cdot \frac{\pi}{m_V \Gamma_V} \cdot \frac{\ell_T^2}{Q^4\sqrt{1-4\ell_T^2/Q^2}}$$

where $m_V^2 = \frac{z_1 z_2 s}{y_0(1-y_0)}$.

With a transverse momentum extension q_T for the vector meson, the peak at $\frac{m_V}{2}$ is broaden by a tail for high ℓ_T whose steepness is the image of the q_T one and which is one of the purpose of the present discussions.

Now concerning the intensity of these vector meson contributions to the single lepton spectra, it is not simply (as can already be seen in the purely longitudinal case above) the product of the vector meson q_T spectrum by the lepton pair branching ratio $B_V \to \ell^+\ell^-$. The integration over d_3q produces an additionnal reduction effect which is known [38] as the "parent-child relation" and which we want to discuss now.

5. The parent-child relation

Suppose a parent particle is produced with momentum p and a cross-section $\frac{Ed\sigma}{d_3p}$ in some reaction. It decays then into a child with momentum ℓ plus anything ($p \to \ell+X$). The child spectrum is given by :

$$\frac{\ell^0 d\sigma}{d_3\ell} = \int\left(\frac{Ed\sigma}{d_3p}\right) \cdot \frac{d_3p}{E} \cdot \frac{|D|^2}{m\Gamma}$$

if m and Γ are the mass and width of the parent and Γ_ℓ its partial decay width into $\ell+X$ given in term of the decay amplitude D by :

$$m\,\Gamma_\ell = \int |D|^2 \frac{d_3\ell}{\ell^0} .$$

When the parent isproduced at sufficently high energy, its decay products are boosted in the direction of $\vec{p}$ such that $\vec{\ell} \simeq x\,\vec{p}$ and one can define a decay distribution :

$$g(x) = \frac{1}{m\Gamma_\ell} \cdot \frac{dm\Gamma_\ell}{dx} = \frac{|D|^2}{m\Gamma_\ell} \cdot \frac{\ell}{x\ell^0}$$

Using $\frac{d_3\ell}{\ell^0} = \frac{\ell}{\ell^0} \cdot d_2\ell_T \frac{dx}{x}$ and $\frac{d_3p}{p} = \frac{dx}{x^3} d_2\ell_T$ in the high energy limit,

$$\frac{\ell^0 d\sigma}{d_3\ell} = B_\ell \int\left(\frac{Ed\sigma}{d_3p}\right) \frac{g(x)dx}{x^2}$$

with B_ℓ the branching ratio $m\Gamma_\ell/m\Gamma$ of the parent into $\ell+X$.

Now suppose that in some range of p_T one can write :

$$\frac{Ed\sigma}{d_3p} \simeq \frac{A}{p_T^n} \simeq A\frac{x^n}{\ell_T^n}$$

then,

$$\frac{\ell^0 d\sigma}{d_3\ell} \simeq \frac{1}{\ell_T^n} B_\ell \int_0^1 x^{n-2} g(x)\,dx.$$

The child distribution has the same shape in ℓ_T but with a magnitude reduced by the factor

$$r = B_\ell \int_0^1 x^{n-2} g(x)\,dx .$$

Notice the normalization $\int_0^1 g(x)\,dx = 1$.

The magnitude of r depends upon the shape of $g(x)$ for large values of x which in principle depends first upon the number of particles associated with ℓ in the decay of the parent. Suppose (always in the high energy approximation) a jet of N particles (including ℓ) with a uniform repartition

$$f_N(x_1,\ldots,x_N) = C_N .$$

The one particle spectrum is :

$$f_N(x) = C_N \int dX_1\ldots dX_N\ \delta(\Sigma x_j - 1)\ \delta(x_i - x) = (N-1)\ (1-x)^{N-2}$$

It peaks stronger and stronger for $x \to 0$ as N is larger ; consequently r will be weaker and weaker.

$$r = B_\ell \int_0^1 x^{n-2}\ (N-1)\ !\ (1-x)^{N-2}\ dx = B_\ell \frac{(n-2)\ !\ (N-1)\ !}{(n+N-3)\ !}$$

examples :

for $n = 12$, $N = 2$ $r = \frac{B_\ell}{11}$

$N = 3$ $r = \frac{B_\ell}{66}$

In our case ($V \to \ell^+\ell^-$, $N = 2$) we have an additionnal reduction by a factor 1/10 with respect to B_ℓ.

6. Discussion of the ℓ/π ratio

From the preceding properties it appears that the ψ contribution is surely limited to the vicinity of $\ell_T \simeq \frac{m_\psi}{2} \simeq 1.5$ GeV/C. Its tail for higher ℓ_T depends directly upon the q_T dependanceof the ψ production ; with $\langle q_T^\psi \rangle \simeq 0.7$ GeV/C there is no hope to fit the datas on ℓ/π . Even at $\ell_T \simeq 1.5$ GeV/C there is a factor 5 missing in the magnitude [19a, 36, 10] (fig. 11, 12, 13).

Below $k_T = \frac{m_\psi}{2}$, even if one had $\rho/\pi \simeq 1$ for all q_T, from the parent-child relation one would get

$$\ell/\pi \simeq (\ell/\rho^o) \simeq \frac{B_\ell}{11} \simeq 0.4\ 10^{-5} .$$

In any case the upper limit supposing that all pions come from ρ decay would be [10] $\ell/\pi^o = (\ell/\rho^o)\ (\rho^o/\pi^o) = \frac{B_\ell}{11} \cdot (\frac{B_{\rho^+\to\pi^+\pi^o}+B_{\rho^-\to\pi^-\pi^o}}{11})^{-1} \simeq 2.10^{-5}$.

The ω contribution (with $B_\ell \simeq 7.6\ 10^{-5}$) is surely no more than the ρ one. The φ contribution (with $B_\ell \simeq 3.10^{-4}$ but $\varphi/\pi < 0.05$) is also limited to $\ell/\pi < 0.15\ 10^{-5}$.

So there is no hope to reach 10^{-4} in this range of transverse momenta with ρ, ω, φ and ψ alone.

7. Higher vector mesons

The existence of series of higher vector mesons is suggested at low energy by the possible states $\rho'(1.3)$ and $\rho''(1.6)$ and at higher energies by the $\psi'(3.7)$ and the peaks in the 3.9 – 4.5 GeV region. The extension of the preceding calculations to higher vector mesons can be easily done as soon as one knows or postulates rules for the vector mesons production and decay. Such properties had been already used for the description of the Deep Inelastic lepton Scattering on nucleons and of the e^+e^- annihilation into hadrons under the names of Generalized or Extended Vector dominance model [39]. Calculations have been carried with series of vector meson states, for example [19a] with equal squared mass spacing $m^2_{V_n} = m^2_{V_o} + n$ ($n = 1,2,\ldots$ .. in GeV^2), or with continuous spectra [30] with a density $dN = a(m^2)\ dm^2$ of states. The scaling properties of DIS and e^+e^- annihilation suggest the following behaviours :

$$m\Gamma_{V_n} \simeq \frac{m^2_{V_n}}{m^2_{V_o}}\ m\Gamma_{V_o}\ ,\ m\ \Gamma_{V_n \to \ell^+\ell^-} \to C^{te}\ (\text{or } g_{V_n\gamma} / g_{V_o\gamma} \simeq m_{V_n}/m_{V_o})$$

and a production cross-section

$$\sigma(h+h' \to V_n+X) \;/\; \sigma(h+h' \to V_o+X) \simeq \frac{m^2 V_o}{m^2 V_n}$$

With such inputs the resulting leptons pair production appear to be rather similar to the one predicted by the Drell-Yan quark-antiquark annihilation. This is not surprising since it is known that such a GVDM description can be in a sense "dual" to a parton model description. Also in both cases the leptons pair production is closely related to the behaviour of the e^+e^- annihilation total cross-section [26,40].

8. Cluster models

The fact that the lepton/hadron ratio appears to be roughly constant in a large range of transverse momentum has led some authors [41] to conclude that both come from the decay of clusters produced in h+h' collisions. Pokorski and Stodolsky [42] supposed in addition that the decay properties of such a cluster are just the ones observed in e^+e^- annihilation into hadrons. Using a mass spectrum $\frac{d\sigma}{dM} \propto \frac{1}{M^\gamma}$ in the production of the cluster, the inclusive distribution in $e^+e^- \to h+X$, $\frac{s\,d\sigma}{dx} = C\,\frac{(1-x)^p}{x}$ and the ratio $R = \frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)}$ they predict a lepton/pion ratio :

$$\ell/\pi = \frac{8\pi\alpha^4 R^2}{27} \cdot \frac{\gamma(\gamma-1)}{C}$$

which is independant of ℓ_T and varies between $(2.4-18.)\ 10^{-4}$ when γ varies between 3-7 . This is even more than demanded by experiments but this number can be reduced by taking into account clusters with different charges and spins.

Independantly of the numerical results the important point in this model is the relation between the production of high p_T hadrons and leptons in hadronic collisions and the e^+e^- annihilation into high momentum ($x \simeq 1$) hadrons (for example with formation of jets).

IV - Other sources of direct leptons

1. Charmed particles

The possible production of a pair of charmed particles $h+h' \to M_c + \bar{M}_c + X$ was in fact one of the first suggestion for explaining the large number of direct leptons. The very short-lived charmed mesons $D, D^*, F, F^*, \ldots$ candecay weakly with leptonic ($\ell+\nu$), semi-leptonic ($\ell+\nu$+had) or non-leptonic modes. Quantitatively this seems presently unlikely because of the rather low limits for charmed particle production in hadronic collisions [43].

First notice that for a charmed particle of mass $m \simeq 2$ GeV, in a two-body decay the lepton spectrum (see IV.4) would be peaked at $\ell_T \simeq \frac{m}{2} \simeq 1$ GeV/c, whereas in a 3-body decay it would be peaked at the origin. Secondly the parent child relation gives for high transverse momenta :

$$\ell/M_c \simeq B_\ell/11 \quad \text{or} \quad B_\ell/66 \quad \text{for 2 or 3 body decays.}$$

Now $\ell/\pi \simeq 10^{-4}$ requires $M_c/\pi \simeq \dfrac{10^{-4} \times (11 \text{ or } 66)}{B_\ell}$.

$B_\ell < 1$ implies $M_c/\pi > 10^{-2}$ to 10^{-3} which is very doubtful even for large p_T.

2. Heavy leptons

The anomalous $e\mu$ events found by the Slac-LBL collaboration [8] at Spear are more likely interpreted as due to 3 body decays of a pair of heavy leptons ($e^+e^- \to L^+L^-$; $L^\pm \to e^\pm + \ldots$ or $\mu^\pm + \ldots$) with a mass close to 1.8 GeV and a leptonic branching ratio of the order of 10 to 20 % ; a point-like QED γL^+L^- coupling is consistent with experiment.

In hadronic collisions the production of heavy leptons would then be similar to the one of ordinary pairs of leptons apart from kinematical mass effects. Chu and Gunion [44] and Bhattacharya et al [45] have used once more the Drell-Yan mechanism ; the production cross-section has the same expression as before, keeping the exact kinematics, one can write :

$$\frac{d\sigma}{dQ^2}\,(h+h' \to L^+L^- +X) = \left(1-\frac{4\,M_L^2}{Q^2}\right)^{\frac{1}{2}} \left(1+\frac{2M_L^2}{Q^2}\right) \frac{d\sigma}{dQ^2}\,(h+h' \to e^+e^- +X)$$

In the limit $m_L^2/s \to 0$, using standard parton distributions of Sect. II.3, one obtains a total cross-section :

$$\sigma(p+p \to L^+L^-+X) \to 8\times10^{-35}\ \log\left(\frac{s}{m_L^2}\right)\ \ cm^2 .$$

Using a branching ratio of $L^\pm$ into $\ell^\pm + \nu + \bar\nu$ of 10% the spectra of lepton pairs $\ell^+\ell^-$ and of single leptons $\ell^\pm$ have been calculated numerically. Both spectra appear to be flatter in $m_{\ell^+\ell^-}$ and in ℓ_T than the direct $\ell^+\ell^-$ production but also much smaller (about 100 times) in absolute magnitude for the present range of energies.

3. Weak bosons

Finally we come back to the first motivations for these studies, the weak bosons search.

The production of $W^{\pm,0}$ vector bosons has been reconsidered recently by Palmer et al [46]. Using once more the Drell-Yan mechanism with the invariant $\bar{q}qW$ coupling, the get a rather high cross-section $\sigma(pp \to W+X) \simeq 10^{-33}$ to 10^{-32} cm^2 for $s/m_W^2 \simeq 10$ to 100. However the masses expected to be in the range $m_W \simeq 50$ to 100 GeV force us to wait for the next generation of accelerators. With a total width of the order of 1 GeV and a leptonic branching ratio into lepton pairs $(\ell^\pm\nu,\ \ell^+\ell^-)$ of the order of $\frac{1}{R} = \frac{\sigma(e^+e^- \to \mu^+\mu^-)}{\sigma(e^+e^- \to had)}$, the single lepton spectrum has been calculated and lies around $\frac{d\sigma}{d\ell_T d\Omega} \simeq 10^{-35}$ $cm^2/GeV - sr$ for $\ell_T \simeq 50$ GeV/C.

Another possibility would be the production of scalar Higgs mesons also weakly coupled to hadrons and lepton pairs ; however their masses and couplings are either not specified or very model dependent. Ellis et al [47] have discussed these properties. Higgs mesons could have a mass arbitrarily small (even less than $2m_\mu$) or arbitrarily high (comparable or higher than W masses) ; would one of them exist between 1.5 and 4 GeV, the cross-section $\sigma(pp \to H_{\to\mu^+\mu^-} + X)$ would be 10^{-2} to 10^{-5} times the direct $\sigma(pp \to \mu^+\mu^- + X)$, which is practically unobservable even if the H is very narrow.

Table I : Structure functions for baryons and mesons

hadrons \ quarks	p	n	λ	c	$\bar{p}$	$\bar{n}$	$\bar{\lambda}$	$\bar{c}$
P	$2V_p+S$	V_n+S	S	S	S	S	S	S
N	V_n+S	$2V_p+S$	S	S	S	S	S	S
$\bar{P}$	S	S	S	S	$2V_p+S$	V_n+S	S	S
$\bar{N}$	S	S	S	S	V_n+S	$2V_p+S$	S	S
π^+	V'+S'	S'	S'	S'	S'	V'+S'	S'	S'
π^-	S	V'+S'	S'	S'	V'+S'	S'	S'	S'
K^+	V'+S'	S'	S'	S'	S'	S'	V'+S'	S'
K^-	S'	S'	V'+S'	S'	V'+S'	S'	S'	S'
K^0	S'	V'+S'	S'	S'	S'	S'	V'+S'	S'
$\bar{K}^0$	S'	S'	V'+S'	S'	S'	V'+S'	S'	S'

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Figure Captions

Fig. 3 Mass distribution of the pair in the Drell-Yan model for various energies ;

——— proton beam ; - - - - - π^- beam

Fig. 4 Longitudinal-momentum distribution of the pair in the Drell-Yan model at $\sqrt{s}$ = 25 GeV ;

——— proton beam ; - - - - - π^- beam

Fig. 5 Single lepton transverse momentum distribution in the Drell-Yan model for various energies ;

——— proton beam ; - - - - - π^- beam

Fig. 10 Shape of the single lepton transverse momentum distribution due to the decay of a vector meson of mass m_V ;

- - - - - when the vector meson is produced longitudinally

——— when the vector meson has a transverse momentum extension.

Fig. 11 Single lepton transverse momentum distribution due to series of vector mesons from ref [19a].

Fig. 12 Single lepton transverse momentum distribution due to ρ, ω, φ and ψ from ref [36], Bourquin and Gaillard.

Fig. 13 Comparison of expected electrons from ψ decay for various production models with the CCRS results at $\sqrt{s}$ = 52.7 GeV.

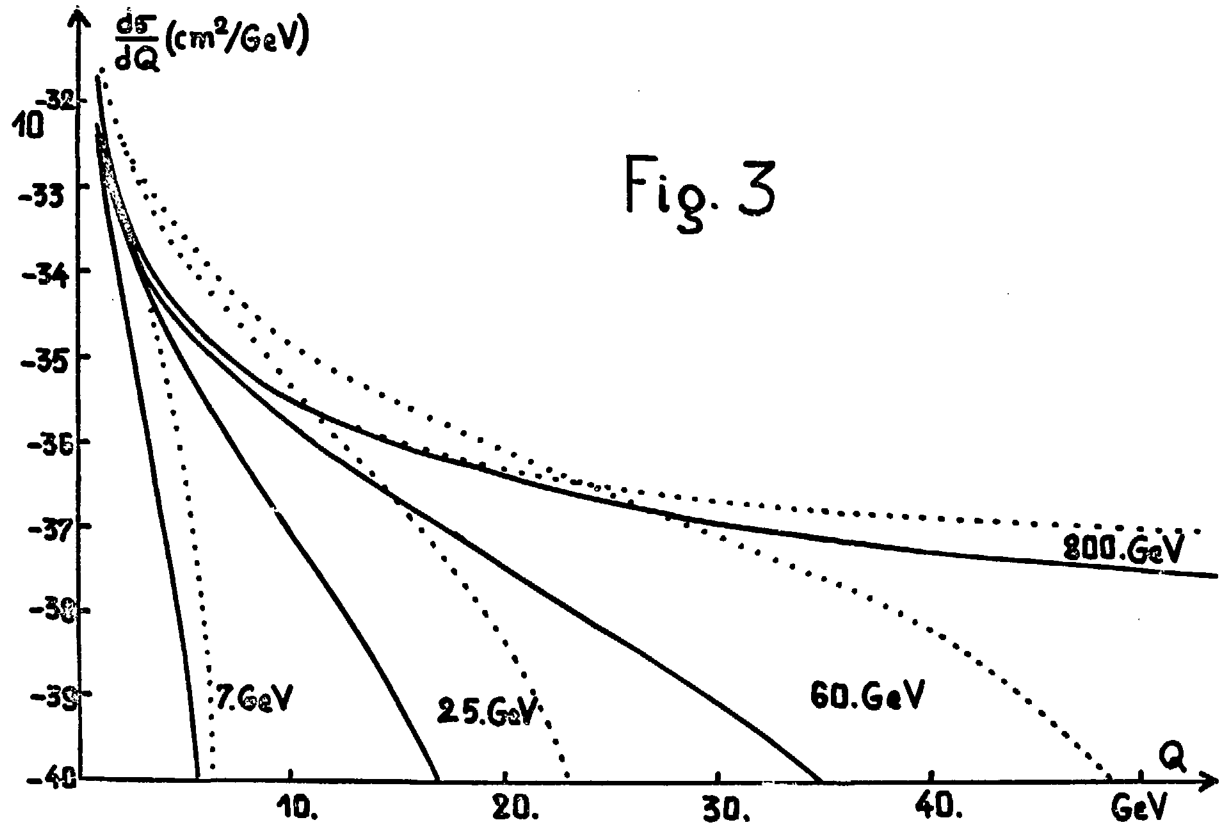

dσ/dQ (cm²/GeV)
10⁻³²
-33
-34
-35
-36
-37
-38
-39
-40
800.GeV
7.GeV
25.GeV
60.GeV
Q
10.
20.
30.
40.
GeV

Fig. 3

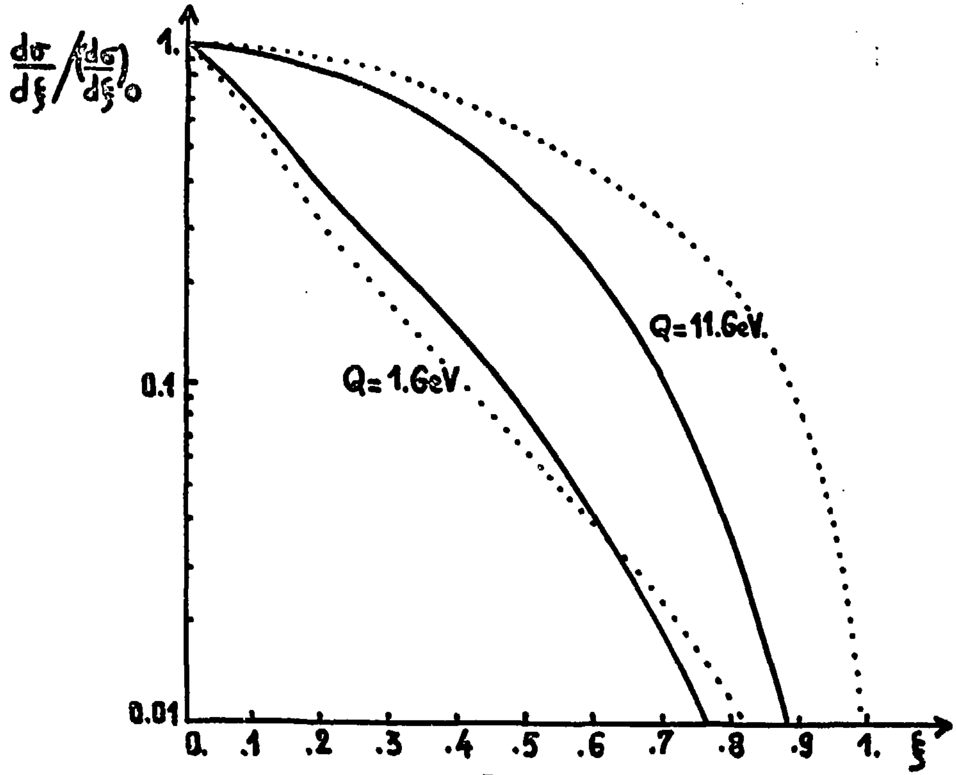
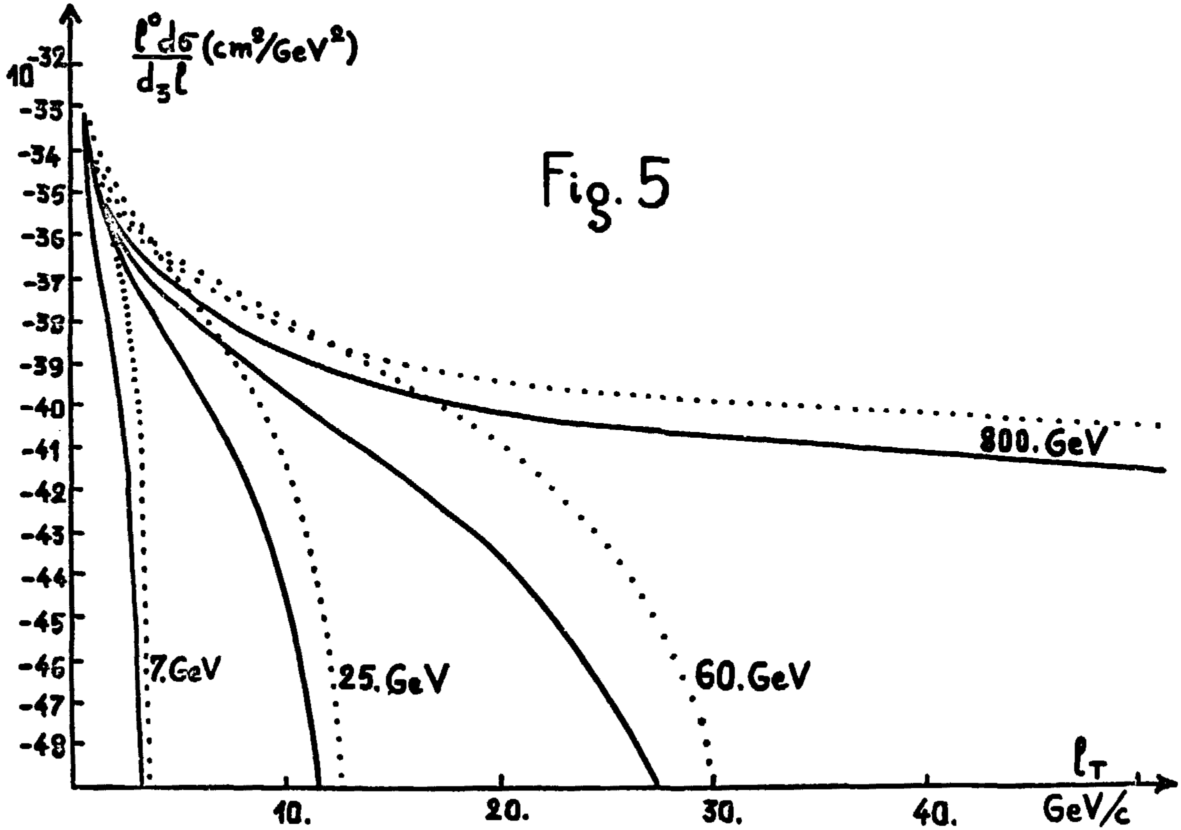


Fig. 4



$\frac{l^0 d\sigma}{d_3 l}$ (cm²/GeV²)
10^-32
-33
-34
-35
-36
-37
-38
-39
-40
-41
-42
-43
-44
-45
-46
-47
-48
7.GeV
25.GeV
60.GeV
800.GeV
10.
20.
30.
40.
l_T
GeV/c

Fig. 5

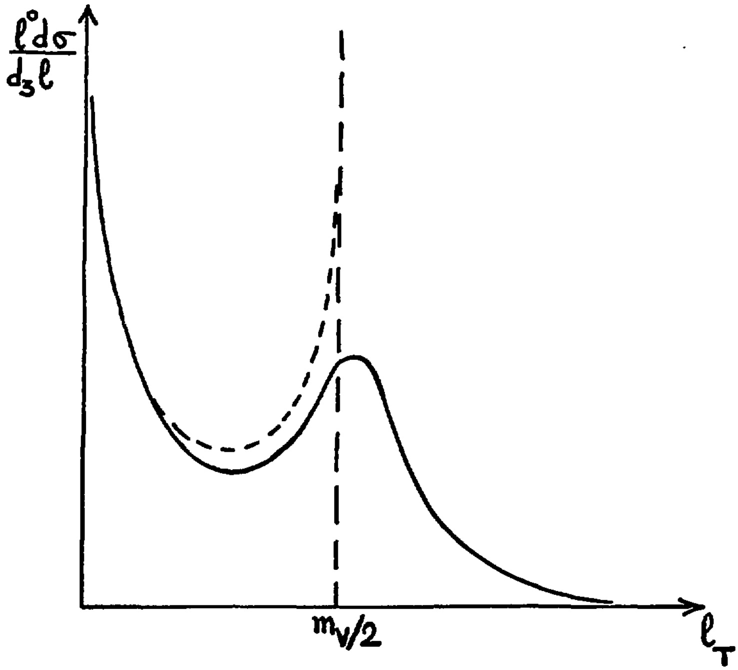
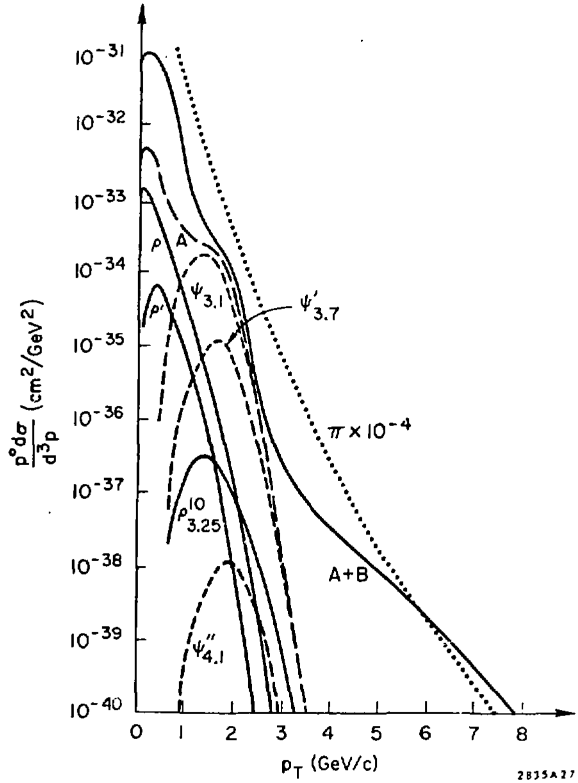


Fig. 10



10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
$\frac{p^0 d\sigma}{d^3p}$ (cm^2/GeV^2)
ρ
A
ρ'
$\psi_{3.1}$
$\psi'_{3.7}$
$\pi \times 10^{-4}$
$\rho^{10}_{3.25}$
A+B
$\psi''_{4.1}$
0
1
2
3
4
5
6
7
8
p_T (GeV/c)
2835A27

Fig. 11

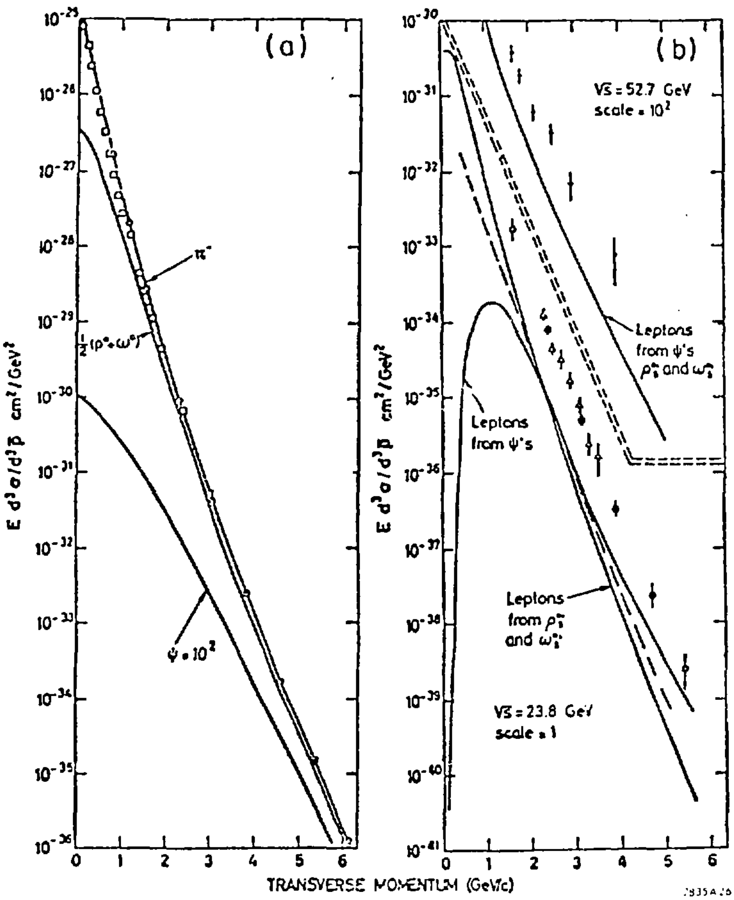
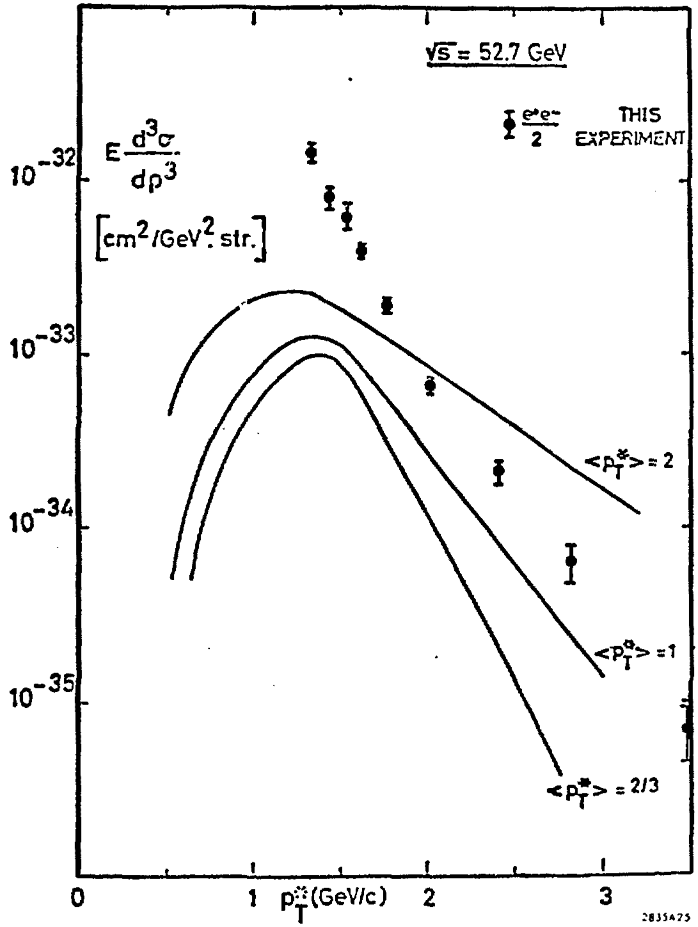

(a)
(b)
$\sqrt{s}$ = 52.7 GeV
scale = 10^2
π^o
$\frac{1}{2}(\rho^o + \omega^o)$
$\psi \times 10^2$
Leptons from ψ's ρ^o_s and ω^o_s
Leptons from ψ's
Leptons from ρ^o_s and ω^o_s
$\sqrt{s}$ = 23.8 GeV
scale = 1
$E\, d^3\sigma/d^3p$ cm^2/GeV^2
TRANSVERSE MOMENTUM (GeV/c)

Fig. 12



√s = 52.7 GeV
e+e−/2 THIS EXPERIMENT
E d³σ/dp³
[cm²/GeV².str.]
10⁻³²
10⁻³³
10⁻³⁴
10⁻³⁵
<pT*> = 2
<pT*> = 1
<pT*> = 2/3
0
1
2
3
pT* (GeV/c)
2835A25

Fig. 13