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HADRONIC PRODUCTIONS OF HEAVY $Q\overline{Q}$ BOUND STATES

C.O. Escobar*,[1], A.P.C. Malbouisson[†] ,
A.F.S. Santoro[†], R.C. Shellard*,[1] and
M.H.G. Souza[†]

[†]Centro Brasileiro de Pesquisas Físicas - CBPF/CNPq
Av. Wenceslau Braz, 71 , fundos - Rio de Janeiro -R.J.- Brasil

*Instituto de Física Teórica de São Paulo
Rua Pamplona, 145 - 01405 - São Paulo - S.P. - Brasil

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Abstract

Several mechanisms for the production of heavy $Q\overline{Q}$ bound states are reviewed. A systematic comparison between model predictions and experimental results is presented. The various theoretical and experimental uncertainties are discussed.

1. Introduction

Since their discovery in 1974[1] the new particles have never ceased to be a subject of intensive experimental and theoretical investigation. The reason for the sustained effort devoted to their study is the often expressed hope that the understanding of bound states of heavy quarks may throw light on the dynamics of the colour gauge theory of the strong interactions,i.e.,quantum chromodynamics (QCD)[2], so that the discovery and study of the new particles gave a new life to particle physics.

The natural place to produce them and study the details of the new spectroscopy is in e^+e^- annihilation; however,the hadronic production of the new particles offers the possibility of investigating the gluonic distribution inside hadrons and may even give us information on the short distance dynamics of the strong interactions. Unfortunately the hadronic production of heavy flavours does not stand on firm theoretical grounds, as deep inelastic leptonic processes. For instance,most of the proposed models for the production of $Q\bar{Q}$ bound states are based on the Drell-Yan[3] conjecture, which itself is only justified by its success and simplicity in describing the lepton pair continuum, even though it has been recently amenable to theoretical investigation by pertubative QCD[4]. Even more serious is that for the hadronic production of new flavours one is not sure if it is reasonable to neglect the complications introduced by soft processes,like gluon emission and confinement problems;after all,we should remember that we are concerned with the inclusive spectrum of a definite bound state.

This somehow uncertain theoretical situation invites a detailed phenomenological investigation of the problem, hoping that a systematic comparison with the experiments may select a set of models which could provide a basis for more rigorous theoretical developments.

The several mechanisms proposed in the literature can be classified according to the nature of the hadronic constituents which are supposed to participate in the production of the $Q\bar{Q}$ bound states, be they light quarks, heavy quarks or gluons. They can be further classified according to the nature of the dynamical process by which the bound state is produced: colour singlet production (direct fusion of the constituents into a singlet state), colour non-singlet production or production through an intermediate P-wave state. Of course, no one would pretend to describe the whole kinematical range with a single mechanism, and it is one of the purposes of our article to exhibit the interplay between the several mechanisms as we go through different kinematical regions ; however, as we pretend to show in this article, it is more difficult to establish a clean separation between colour singlet and colour non-singlet processes.

This review is organized as follows. In Section II we present a summary of the main experimental results, including data on the recently found Υ states ($b\bar{b}$ bound states) [5]. Section III is devoted to the presentation of the general aspects of the several existing mechanisms. We leave their detailed predictions and comparison with the experimental data for

Section IV. Finally, critical comments, conclusions and outlook are left for Section V.

II. Experimental Results

Our current theoretical understanding of the new heavy resonances is based on a picture originally suggested by Appelquist and Politzer[6].They considered the J/ψ particle as a bound state of a charmed quark anti-quark pair,bound by a potential whose short-distance part is given by the one gluon exchange (Coulomb potential), due to the property of asymptotic freedom[2]. This model,which resembles the positronium system in quantum electrodynamics,has been called charmonium[7]. Actually, the situation is not as simple as the one originally envisaged by the authors of ref.[6]; the potential binding the charmonium is more complicated than the simple coulombic one, necessitating a long-range component with the property of confinement[7].Even so, the predictions of this model are in astonishing good agreement with the experiments[8]. Just for reference we show in Fig.1 the scheme of the existing levels of the charmonium system below charm threshold. Notice the η_c state at 2983 MeV, recently confirmed by the Crystal Ball Detector at Spear[9].An analogous but richer spectrum exists for the upsilon family ($b\bar{b}$ bound states). Of importance for us (see Section IV)is the existence of the P-wave states (χ-states) which will play an important role in the study of the production mechanisms of the J/ψ.

Next we describe the main experimental results on hadronic production of $Q\bar{Q}$ bound states [10]. We consider the following experimental quantities:

i. Total cross-section - σ_{tot}

ii. Feynman x_F distribution - $d\sigma/dx_F$

iii. Transverse momentum distribution - $d\sigma/dp_t^2$

iv. Angular distribution of the lepton pair: $\frac{d\sigma}{d\cos\theta^*}$

v. Validity of a simple scaling law.

Of course, it is most interesting to have information on all these quantities covering a wide kinematical range,as well as for several particle beams($\pi^\pm$,$K^\pm$,p,$\bar{p}$), for this combination of several beams and different kinematical ranges should enable us, in principle, to distinguish the various phenomenological models (see Section IV).

The significance of the following experimental results and their discussion will be postponed to Section IV.

(i) Total Cross-Section

a) J/ψ

We present in Fig.2 a collection of data on J/ψ production in proton-proton collision at various values of energy.

There are also available data on J/ψ production with $\pi^\pm$, $K^\pm$ and $\bar{p}$ beams, however these do not extend to very high energies, being limited to $\sqrt{s} \leq 23.7$GeV. In Fig.3 we show data for π-nucleon collisions,while Table I displays the ratio of cross-sections for different beams. We see from Table I and Fig.3 that pions are more effective than protons for producing the J/ψ,in qualitative agreement with a fusion model involving light valence quarks.

b) ψ'

For the ψ' data are scarcer with less statistics. We compare J/ψ and ψ' production in Table 2, where it is displayed the ratio $\sigma(\psi')/\sigma(J/\psi)$ at different energies for π^--nucleon collisions.

c) Υ

We show in Fig.4 the cross-section for Υ production in p-p and π-p collisions. We understand by Υ all states belonging to this family which are in the energy interval set up by the experimental resolution.

ii) Feynman x_F-distribution, $d\sigma/dx_F$

a) J/ψ

We present in Fig.5a the data for $d\sigma/dx_F$ in $\pi^\pm$ nucleon collisions at low energy ($\sqrt{s}$ = 8.75 GeV) [10c]. Notice a clear asymmetry in the x_F-distribution, with a peak around $x_F = 0.15$. This asymmetry is not present for pp collisions (see Fig.5b), a result which is in qualitative agreement with the theoretical prejudice that the pion has harder quark and gluon distributions. The data at higher energies do indeed display such asymmetry (see Fig.6), thus confirming our theoretical prejudices.

b) ψ'

The situation is very much the same as for the J/ψ, therefore, we do not comment on this further.

c) Υ

There are fewer data for the x_F-distribution in this case, but the available ones show that for π beams the x_F-distribution still displays an asymmetry, with an average value $\langle x_F \rangle = 0.2$ [26].

iii) p_t-distribution

With respect to the p_t distribution there is an observed rise of $\langle p_t \rangle$ and $\langle p_t^2 \rangle$ with the energy. This is shown clearly in Fig.7, where the average value of p_t is plotted against $\sqrt{s}$, for the ψ and Υ separately. We return to this question in section V.

We stress that it is not so clear how should be the behaviour of $\langle p_t \rangle$ as a function of the scaling variable $M/\sqrt{s}$. We show in Fig.8 the data for $\langle p_t \rangle$ plotted against $M/\sqrt{s}$ for the ψ and Υ. As expected no clear-cut behaviour can be infered from this plot.

iv) Angular Distribution of the Lepton Pair

This is a very interesting quantity from the theoretical point of view since the angular distribution of the lepton pairs is sensitive to the spin of the constituents participating in the formation of the $Q\bar{Q}$ bound state[29].

Thus, for example, a model involving the annihilation of a light $q\bar{q}$ pair directly into the observed $Q\bar{Q}$ bound state of spin 1, predicts a distribution of the form,

$$1 + \cos^2\theta^* \qquad (2.1)$$

where θ^* is the angle of one of the leptons in their centre of mass system, with respect to a given axis (Gottfried-Jackson [30] or Collins-Soper[31]). This quantity could give information on the specific mechanism responsible for resonance production.

The data on resonance is not very precise. The several groups present their results in the form:

$$\frac{d\sigma}{d\cos\theta^*} \sim 1 + \lambda\cos^2\theta^* \tag{2.2}$$

and all of them are consistent with a flat distribution ($\lambda=0$), for the J/ψ, ψ' or Υ[*10c,13,18*].

v) Naive Scaling Law

A first approach to the understanding of $Q\bar{Q}$ production consists in the assumption of a simple scaling behaviour for the cross-section[*32*],which is given by an expression of the form:

$$\sigma_V = \frac{\Gamma_h^V}{m_V^3} F(m_V/\sqrt{s}) \tag{2.3}$$

where σ_V is the total cross-section for the production of a heavy vector meson V, with hadronic width Γ_h^V and mass m_V.$F(m_V/\sqrt{s})$ is assumed to be a universal function describing all the dynamics and kinematics of the production process. Notice that this is a function of only the scaling variable $m_V/\sqrt{s}$.

In Fig.9 we test the scaling hypothesis (2.3), plotting the data for $J/\psi,\psi'$ and Υ as a function of $m/\sqrt{s}$, conveniently scaled down by m_V^3/Γ_h^V. As we can see from this figure,the scaling behaviour (2.3) is a reasonable first approximation to the description of the data, while a detailed look at this curve shows deviations which should be a matter of theoretical interest (see Section IV).

vi) Production of P-wave states (χ-states)

Several groups have observed the production of J/ψ associated with a photon [33]. These events are usually interpreted as the decay of a charmonium P-state (the χ's) into a J/ψ plus a photon. As a matter of fact, models were proposed [34, 35] which predict a large fraction of the J/ψ's coming from such a decay. These models involve the fusion of two gluons into a C-even state, the χ. They differ however on the amount of χ's that are produced relative to direct production of J/ψ's. It is of great importance to have good experimental data on the precise amount of P-states produced. Also, the identification of which state is being formed is important. At present, there is some incompatibility between the various experiments [10a]. We show the experimental results in Table III noticing that there are now experiments which identify the particular χ-state that is produced - the $\chi(3.510)$ or $^3P_1$ state and the $\chi(3.550)$ or $^3P_2$ state. The fact that the $^3P_1$ state is copiously produced is of some significance since the $^3P_1$ state cannot be formed by two on-shell gluons [36], therefore, this result may be an indication that either higher order QCD corrections are involved, which could put one of the gluons off mass-shell or that the production proceeds via a colour non-singlet state (see Section IV and V).

vii) Comparison with the continuum

In recent years, great theoretical and experimental efforts have been put into the understanding of the production of high-mass lepton pairs in hadron-hadron collisions. The theoretical motivation, as mentioned in the introduction, is to test QCD via Drell-Yan model [4].

While for the continuum there is good agreement between the Drell-Yan model (at least in some of its most naive features) and the experimental data, the situation for resonance production is different and plagued with ambiguities, both theoretical and experimental. However, it should be noticed that some of the features of the continuum are present in the resonance region, like the rise of the average transverse moment with energy (see item (iv)) and the dependence in the atomic number of the nuclear target [10c].

At this stage, we should remark that there is an outstanding result which is not yet completely understood, namely, the question of the global normalization of the Drell-Yan continuum. As pointed out in [37], higher-order QCD corrections could alter the absolute normalization of the cross-section by a factor of about 2. If the higher-order corrections are indeed important for the continuum [38, 13], then there is no reason why they should be absent in the resonance region, thus casting doubt on all theoretical attemps to achieve an absolute normalization for resonance cross-sections.

III. Phenomenological Models: Generalities

As mentioned in the introduction, the mechanisms for the hadronic production of heavy $Q\bar{Q}$ bound states can be classified according to the nature of the hadronic constituents participating in the subprocess of parton fusion. They can be further divided into two categories, one in which the parton fusion produces a colour singlet state[34,35,39-42] and the other in which the partons fuse into a coloured state with subsequent bleaching of colour through the emission of one or more soft gluons [43-46]. Of course,all these mechanisms are inspired on the Drell-Yan model [3]. In the original Drell-Yan model a quark and an anti-quark from each of the hadrons, annihilate in order to form a virtual photon with high mass Q^2. The annihilating quarks are taken near the mass-shell.

The measurement of the lepton pair x_F distribution is used as a way of obtaining information on the quark distribution inside the parent hadrons. It should be pointed out that the quark distribution in the Drell-Yan process is measured at a scale $Q^2>0$ (time-like),as opposed to deep inelastic lepton-hadron interactions where the distributions are measured in the space-like region ($Q^2<0$). There are convincing theoretical arguments (reviewed in ref.[4]) supporting the idea that these parton distributions are indeed universal, independent of the particular hard process being considered,provided they are evaluated at the same scale Q^2. Therefore,the Drell-Yan mechanisms enables us to obtain the quark distribution inside pions and kaons[13,38] , what is impossible in deep inelastic leptonic processes.

It seems that the hadronic production of $Q\bar{Q}$ allows the investigation of the gluon distribution (see Section IV and below).

To establish the main formulae employed in the several models, we naturally divide our discussion into colour-singlet and colour non-singlet mechanisms.

i) Colour-Singlet Production

In this case one has to consider the fusion of two partons from hadrons A and B directly into the state C(heavy $Q\overline{Q}$ bound state). This mechanism is displayed in Fig.10. The partons 1 and 2 can be either quarks ou gluons, near the mass shell. Calling x_+ and x_- the fraction of the parent hadrons momenta carried by partons 1 and 2 respectively, one has:

$$M_C^2 = x_+x_-s$$
$$x_F = 2P_{||}^C/\sqrt{s} = x_+-x_- \qquad (3.1)$$

or,

$$x_\pm = \frac{1}{2}\left[\sqrt{x_F^2+4\tau} \pm x_F\right] \qquad (3.2)$$

where $\tau = M_C^2/s$, M_C beeing the mass of state C.

In the following, unless otherwise stated, we neglect the transverse momentum of the partons, whose intrinsic component is supposed to be limited (∿300 MeV/c). Of course, this implies that we are not able to analyse the transverse momentum distribution of the $Q\overline{Q}$ bound state. As a matter of fact, it is not enterily clear at present how to treat this question. We remark that for the Drell-Yan continuum there are indications that [37,47] QCD corrections beyond the leading logarithm are important for the transverse momentum distribution. We do not consider them in the framework of this paper, since this would be a much finer treatment than what is required by these rough phenomenological models. Notice that the leading logarithm QCD corrections to the Drell-Yan naive parton model are included in the scaling violating structure functions [4].

With these assumptions, the differential cross-section for the process AB→CX is written in the typical parton model form

$$\frac{d\sigma}{dx_F}(AB\to CX) = \frac{4\pi^2}{M_C^3}\frac{(2J_C+1)}{N_c}\left\{\sum_{ij}\Gamma(C\to ij)\,\frac{\tau f_i^A(x_+,M_C^2)\,f_j^B(x_-,M_C^2)}{(x_+ + x_-)} + \right.$$

$$\left. + (i \longleftrightarrow j)\right\} \qquad (3.3)$$

where J_C is total angular momentum of the state C, $\Gamma(C\to ij)$ is the partial width for the decay of C into constituents $\underline{i}$ and $\underline{j}$, $f_i^h(x,M_C^2)$ is the distribution function of constituent $\underline{i}$ in hadron h, evaluated at scale M_C^2. As we are considering colour singlet production, we must include a factor $N_c = 9$ when $\underline{i}$ and $\underline{j}$ are quarks and $N_c = 64$ when $\underline{i}$ and $\underline{j}$ are gluons, remembering that the partial width $\Gamma(C\to ij)$ contains a sum over colour. The widths $\Gamma(C\to ij)$ are usually calculated in potential models for the $Q\bar{Q}$ system [39,48,49,50], we will comment on this in section IV.

Of course, we should make a distinction between models employing light quark fusion (u,d,s) and those using heavy quark fusion (c,b,t...)[40-42,59], in which case we replace the factor $\Gamma(C\to ij)$ by an effective coupling constant $g_{Ci\bar{i}}^2/4\pi$(i = =c,b,t...) times M_C, summing over the three colours of the heavy quarks. The final result for heavy quark fusion is now,

$$\frac{d\sigma}{dx_F}(AB\to CX) = \frac{4\pi^2}{3M_C^2}\frac{g_{Ci\bar{i}}^2}{4\pi}\,\tau\left\{f_i^A(x_+,M_C^2)\;f_{\bar{i}}^B(x_-,M_C^2)/(x_+ + x_-) + (i \longleftrightarrow \bar{i})\right\} \qquad (3.4)$$

From (3.3) we obtain the total cross-section,

$$\sigma_{tot}(AB\to CX) = \frac{4\pi^2}{M_C^3}(2J_C+1)\left\{\sum_{i,j}\Gamma(C\to ij)\,F_{ij}^{AB}(\tau,M_C^2)+(i\longleftrightarrow\bar{i})\right\} \tag{3.5}$$

where the so called excitation function $F_{ij}^{AB}(\tau,M_C^2)$ is given by

$$F_{ij}^{AB}(\tau) = \tau\int_\tau^1 \frac{dx}{x}\,f_i^A(x,M_C^2)f_j^B(\tau/x,M_C^2). \tag{3.6}$$

ii) Colour Non-Singlet Production

Mechanisms of this kind consider the perturbative production of a $Q\bar{Q}$ pair by the incoming partons. As the $Q\bar{Q}$ system is not produced in a colour singlet state all of these models must explain, at some stage, how is the bound state formed. However, the original proposal of duality in this context[43,44], extrapolated from the duality concept introduced in e^+e^- annihilation[51,52], tries to avoid this difficult problem by suggesting that the cross section for producing all $Q\bar{Q}$ states below the heavy flavour Q threshold is equal to the cross section for producing a free $Q\bar{Q}$ pair in this range. When looking for a definite $Q\bar{Q}$ state they assume that all states in the mentioned energy range occur with equal probabilities.

The production of the $Q\bar{Q}$ pair is calculated in perturbative QCD, from the diagrams in Fig.11. Convoluting the QCD cross-section for the subprocesses in Fig.11 with the parton (quark or gluon) distributions, one obtains for the cross section below Q threshold the expression[43]

$$\frac{d\sigma}{dx_F}(AB\to Q\bar{Q}X) = \int_{4m_Q^2}^{4m'^2} dQ^2 \left\{\sigma_{q\bar{q}\to Q\bar{Q}}(Q^2)\,\frac{1}{Q^2}\,\frac{x_+x_-}{x_++x_-}\left[f_q^A(x_+,Q^2)f_{\bar{q}}^B(x_-,Q^2)+q\leftrightarrow\bar{q}\right]\right.$$

$$\left. +\ \sigma_{gg\to Q\bar{Q}}(Q^2)\,\frac{1}{Q^2}\,\frac{x_+\,x_-}{x_++x_-}\left[f_g^A(x_+,Q^2)f_g^B(x_-,Q^2)\right]\right\} \quad (3.7)$$

where f_g^A is the distribution of gluons in A, 2m' is the threshold for a naked Q state. The cross-sections $\sigma_{q\bar{q}\to Q\bar{Q}}$ and $\sigma_{gg\to Q\bar{Q}}$ calculated from Fig.11 are given by

$$\sigma_{q\bar{q}\to Q\bar{Q}}(Q^2) = \frac{2}{9}\,\frac{4\pi\alpha_s^2}{3Q^2}\,(1+\frac{1}{2}\gamma)(1-\gamma)^{1/2} \quad (3.8)$$

$$\sigma_{gg\to Q\bar{Q}}(Q^2) = \frac{\pi\alpha_s^2}{3Q^2}\left[(1+\gamma+\frac{1}{16}\gamma^2)\ln\frac{1+(1-\gamma)^{1/2}}{1-(1-\gamma)^{1/2}} - (\frac{7}{4}+\frac{31}{16}\gamma)(1-\gamma)^{1/2}\right]$$

where $\gamma = \frac{4m_Q^2}{Q^2}$ and α_s is the running coupling constant of QCD, $\alpha_s = \frac{12\pi}{(33-2N_f)\ln\frac{Q^2}{\Lambda^2}}$ with N_f the number of flavours and Λ the scale parameter of QCD, $\Lambda \simeq 0.5$ GeV.

We postpone the discussion of this model to the next section and would like to conclude by mentioning recent attempts to face the problem of colour bleaching: how a particular, definite state is produced from a $Q\bar{Q}$ colour octet. The authors of reference [46] have tried to scape from the uncertain framework of duality ideas and proposed to calculate the transition from a colour octet $Q\bar{Q}$ state to a final $Q\bar{Q}$ singlet bound state via the emisssion of a single soft gluon. It is not clear that the calculational procedure employed by these authors is entirely valid. For instance they use harmonic oscillator wave functions for the $Q\bar{Q}$ bound state and plane waves for the $Q\bar{Q}$

colour octet state. They start their calculation from a conjecture by Gottfried[53] who attempted to analyze the coupling of heavy-quarks mesons to light hadrons through the observation that the small size of the heavy meson justifies the use of a multipole expansion in the gluonic field, thought to couple to light quarks. The first term in this multipole expansion , the dipole, would correspond to the emission of a single gluon. However, as shown by the authors of reference[54],the multipole expansion which is equivalent in this context to a short-distance expansion,is valid for a bound state of radius a_0, provided the external momentum scale be much less than the Rydberg energy g^2/a_0, associated with the Coulomb potential. Therefore, these results are only applicable for bound states of extremely heavy quarks (m_Q>25GeV), which are to a good degree purely coulombic. It is not clear that this approximation holds for the charmonium or even bottomonium family . Recently,this theoretical result has been applied by Flory[55]to the calculation of charmonium production in heavy $Q\bar{Q}$ decays, showing that the duality prediction [56] is very much suppressed when one performs a proper calculation along the lines indicated in ref.[54]. We expect that the same result will apply to hadronic production of $Q\bar{Q}$ states via colour non-singlet mechanisms. This question clearly deserves further investigation.

IV. Performance of the Models

We consider in this section the detailed comparison of the several mechanisms with the experimental data, a summary of which can be found in Section II.This section will be organized as follows. Firstly we look at the models , paying attention only to the nature of the participating constituents, considering the vertex in Fig.10 as a "black box". We show that several features of the data allow us to discriminate between the mechanisms involving quarks from those using gluons. After a discussion of the "black-box" approach we begin to look at the inside of the vertex. The discussion now is divided into singlet and non-singlet mechanisms. A point of particular importance is the production of P-wave states (χ-states). As we hope to show these states can give us some insight on the delicate question of colour bleaching.

i) Light Quark Fusion and Gluon Fusion

We are going to use throughout this section the following set of structure functions. For the nucleon we use the parametrization of Buras and Gaemers, taking into account scaling breaking effects[*57*], while for pions we shall use the experimental fits of the NA3 collaboration[*21*].

At low energy ($\sqrt{s}$= 8.7 GeV) the experimental data from the Ω spectometer experiment at CERN[*10c*] show that the ratio of proton initiated reactions to antiproton ones is very small, $P/\overline{P}$ = 0.15 ± 0.06. As pointed out by various authors[*39, 42, 43*], this result is readily understood if one assumes a significant contribution of $q\overline{q}$ annihilation, since the antiproton has plenty of valence antiquarks. Any mechanism involving gluons or charmed quarks would predict $P/\overline{P}$=1. As the energy increases it is natural to expect that the ratio $P/\overline{P}$ also increases since from (3.1), $\langle x \rangle = \frac{M\psi}{\sqrt{s}}$ decreases, thus diminishing the importance of valence quark processes and increasing the role of the gluons whose distribution is concentrated at small x.

We show in Fig.2 the contribution of $q\bar{q}$ and gg to the total cross-section at several energies. Even though the relative contribution of the two processes could be altered, the shape of the total cross-section as a function of energy is indicative of the taking over of the gluon-gluon contribution as the energy is increased.

Next we present the x_F-distribution in π-N collisions at low[*10c*]and high[*58*] energies. As we can see from Fig.12,we cannot neglect the $q\bar{q}$ contribution in trying to fit the shape of the experimental distribution, in fact only a combination of a dominant $q\bar{q}$ component together with some contribution gg is able to fit the data[*10c*]. Contrast this with the higher energy data shown in Fig.13, which favours a gluon-gluon mechanism. Notice that even at these energies, which are not very high, the gluon mechanism is already dominating, in agreement with the behaviour of the total cross-section.

As mentioned in section II,it would be helpful to have better data on the angular distribution of the lepton pair.In particular, since there is evidence for a dominant $q\bar{q}$ component in $\bar{P}$ initiated reactions at low energies, it should be interesting to see if $\frac{d\sigma}{d\cos\theta^*}$ in $\bar{P}$ collisions is given by $1+\cos^2\theta$,as expected for spin-1/2 light quarks.

ii) Heavy Quark Fusion [*40-42,59*]

Models based on heavy quark fusion do need as input, quite unusual sea distributions. As a matter of fact, the authors of reference[42,59] use a heavy quark distribution behaving as $(1-x)^5$ for large x. So, it seems to us that the above mentioned authors are indeed using a gluon distribution for the heavy quark without recognizing it as such. Support to our interpetation of their results can be found if one adopts a two-component fit to the low-energy data of reference[10c]. As noticed by Romana[10c] a combination of $q\bar{q}+c\bar{c}$ leads to the same fit for the $q\bar{q}$ component as the combination $q\bar{q}+gg$. What is more, since the J/ψ is a non-relativistic bound state of $c\bar{c}$, the c quarks must be moving slowly in order to form the J/ψ. Obviously, this condition is not met in the Drell-Yan mechanism, so that we are not surprised if $c\bar{c}$ fusion is supressed for this reason. Lastly remember that in the $c\bar{c}$ mechanism one expects the production of associated charmed particles which are not found experimentally[60], even though we are aware that the proponents of this model suggest mechanisms for the supression of the associated production of charm.

iii) Looking at the inside of the "black box"

We now turn our attention to the finer details of the proposed mechanisms, in order to increase the predictive power of the models, hoping to achieve the absolute normalization for each competing mechanism.

Unfortunately this is not an easy task since the details of the several processes are subjected to considerable theoretical uncertainties.

iii) Colour Singlet Production

Direct production of colour singlet states is of course possible with $q\bar{q}$ as well as with gluon-gluon fusion. In this case the analysis can be performed using expressions (3.3) and (3.5). We restrict ourselves to the discussion of the total cross-section. As we can see from (3.5), the normalization of the total cross-section is determined by the partial width $\Gamma(C\to ij)$, therefore, we should compare the widths obtained from a fit to the cross-sections with those expected in quarkonium models or with their experimental values determined in e^+e^- annihilation.

With respect to light quark fusion we remark that both C-even and C-odd states can be produced, while with gluon-gluon only C-even states (the χ's) are produced directly as colour singlets.

The authors of Ref. [61] considered the singlet production of the $\psi'(3.685)$. In this case, since there are no C-even states above the ψ', which radiatively decay into this state, there is no need to consider the gluon-gluon contribution. Therefore, they only take the $q\bar{q}$ component to ψ' production. Fitting the data for the cross-section at $\sqrt{s}=20.6$ GeV [13], they found widths $\Gamma(\psi'\to q\bar{q})$ of the order of a few MeV (for example, for PP collisions their fit gives $\Gamma(\psi'\to q\bar{q})=3.54$ MeV). This should be compared to the total width of the ψ' which is $\Gamma_{tot}(\psi') = 0.215 \pm 0.040$ Mev [62]. The conclusion is that singlet production can only be a small part of the ψ' cross-section.

The situation for the J/ψ is somewhat more difficult, since now the J/ψ can be produced via the decay of the C-even states χ. We have seen in tableIII that at $\sqrt{s}$=19Gev,approximately 36% of the J/ψ's are produced from χ-decays, so that about 64% of the observed cross-section has to be accounted by direct production. Fitting the 64% of the cross-section at these energies we find $\Gamma(\psi\to q\bar{q}) = 0.15$ MeV, which should be compared with $\Gamma_{tot}(\psi) = 0.063 \pm 0.009$ MeV[62]. So, we see that for the J/ψ a colour singlet mechanism is not able to account for even half of the 64% of the J/ψ's which are not produced via $\chi\to J/\psi + \gamma$.

Now,we consider colour singlet production via gluon-gluon. In this case,the two gluons will not couple to the C-odd state directly, but can instead couple to the C-even states χ. As mentioned in Section II, there are now available data from the WA11 collaboration [33e] who found the following cross-sections for χ production in π^- nucleon collisions at $\sqrt{s}$ = 19.2 GeV,

$$\begin{aligned} B(\chi_1\to\psi\gamma)\sigma(\pi^- N\to\chi_1 X) &= 21 \pm 7 \text{ nb} \\ B(\chi_2\to\psi\gamma)\sigma(\pi^- N\to\chi_2 X) &= 13 \pm 5 \text{ nb} \end{aligned} \qquad (4.1)$$

where the branching ratios for radiative decays are[62],

$$B(\chi_1\to\psi\gamma) = (31.5 \pm 4.6)\%$$

$$B(\chi_2\to\psi\gamma) = (15.4 \pm 2.7)\%$$

Using (3.5) to evaluate the cross-section for χ production, we see that the normalization is given by the widths.The problem now is to compare the values obtained from a fit to (4.1)with the values given by the charmonium model, since there are no data on the total width of the χ's.

There are estimates for the total width of the χ-states using the charmonium model [50, 39], the results are subject to large uncertainties [63, 64] but they generally give widths around, $\Gamma(\chi_1 \to q\bar{q}) \simeq 0.2$ MeV and $\Gamma(\chi_2 \to gg) \simeq 0.8$ MeV.

Using these values for the widths, we are not able to account for the experimental results (4.1). As a matter of fact we would miss the data by a factor of approximately 4! The experimental cross-section could have been fitted using $\Gamma(\chi_1 \to q\bar{q}) = 1.40$ MeV and $\Gamma(\chi_2 \to gg) = 3$ MeV, which are in disagreement with the charmonium predictions. This difficulty had been already noticed by the authors of ref. [61].

The overall conclusion on colour-singlet production is that contrariwise to the initial hopes [34, 39] gluon-gluon fusion directly into a C even state <u>is not</u> the dominant mechanism for J/ψ production! The experimental data is now quite conclusive, only about 30% of the J/ψ's, are due to intermediate χ-states and additionally, by what we have shown above, it is doubtful that one can account for this 30% of the J/ψ's by colour-singlet production alone.

To conclude these comments on colour-singlet production, we would like to call attention to a problem that is frequently ignored in the literature. The identification of the 1^{++} state [33e] in hadronic collisions, does exclude its production by two on-shell gluons, thanks to Yang's theorem [36]. This fact combined with the lack of a significant $q\bar{q}$ component already at not so high energies (see item (i) above) is indicative of either higher-order QCD corrections, which could put one of the gluons far off-shell or a significant colour non-singlet χ_1-production (see below). In the first hypothesis one clearly would expect a rather broad P_t-distribution for the χ_1(in this respect see ref.[47]).

iv) Colour Non-Singlet Production

Now that we have gathered plenty of evidence for a significant colour non-singlet component in $Q\bar{Q}$ production,we turn our attention to the discussion of these mechanisms,stressing their most uncertain features.

The first step in analysing colour non-singlet production is to approach the problem within the duality framework outlined in Section III. The starting point is the cross-section given in (3.8). It is well known that using (3.8) as it stands,gives a cross-section for the J/ψ that is too large when compared with the data[65]. The usual explanation for this discrepancy is that one has to divide this result by the number of charmonium levels below charm threshold. Of course,in this approach one gives up the hope of predicting the absolute normalization for the production of each of these states.

The other important uncertainty in this approach, is the pronounced sensitivity of the results on the heavy quark mass. As shown by many authors [45,65], changing the charmed quark mass by small amounts in the lower limit of integration of (3.8), easily changes the absolute normalization by large factors. The authors of ref.[65] have observed that changing

m_c from 1.5 GeV to 0.6 GeV will increase the cross-section by a factor of 5 to 10. Of course, given the knowledge we have from charm production at threshold in e^+e^- annihilation, a mass $m_c \simeq 1.5$ GeV is favoured.

The next step in improving the predicability for colour non-singlet production is to attempt the calculation of the absolute normalization for each specific quarkonium state produced[46].

We have already commented about this approach in Section III, here we only stress the fact that the mentioned authors do need, in order to fit the data, a low value for the charmed and bottom quark masses (m_c=1.2 GeV and m_b=4 GeV). Such a low value for the heavy quark mass does not justify the use of a simple dipole approximation (one gluon emission) along the lines of reference[54,55].

Our conclusion is that all the attempts to achieve an absolute normalization for heavy $Q\bar{Q}$ bound states cross-sections are subject to large uncertainties coming from our ignorance of higher-order QCD corrections and lack of understanding of the colour bleaching mechanism.

V. Conclusions and Outlook

In this final section we comment on what we consider are important points for future experimental and theoretical developments. There are at the present stage of knowledge several points which remain obscure both experimentally and theoretically, some of them are listed below.

i) Angular Distribution

As remarked in Section II, it would be very useful to have better experimental data on $\frac{d\sigma}{d\cos\theta}$ for all of the $Q\overline{Q}$ states, at several energies. In particular, an effort should be made to distinguish between the Gottfried-Jackson (G.J.) and Collins-Soper (C.S.) choices of axes. The importance of this last comment is made evident from a look at Fig.14, taken from Ref.*1b*, showing $\frac{d\sigma}{d\cos\theta}$ for the two chices of axes. As we see, it is impossible to distinguish between G.J. and C.S. If such a distinction were possible experimentally it could throw light on the question of the transverse momentum of the constituents participating in the mechanism for $Q\overline{Q}$ production. For an extensive discussion of this and related matter, see the paper by Argyres and Lam [*29*].

ii) χ-states

As we have repeatedly stressed, it is very important to have information on these states at various energies and with different beams. As we hope has become clear from the discussion in Section IV, the precise determination of the relative fraction of production for each of these states throws light on the question of colour singlet versus colour non-singlet production

iii) The Υ Family

It would be important to have experiments with improved mass resolution, so as to be able to identify the particular member of the Υ family which is being produced. This would put the charmonium and bottomonium families on equal footing, thus allowing extrapolations from the results valid for one family to the other. All of the preceding remarks that were made for the charmonium family are valid for the bottomonium system (angular distribution, P-states etc.). An important aspect of Υ production is the possibility of studying the relevance of scaling violations in the structure functions. Thanks also to its large mass the Υ family could provide useful information on the question of the transverse momentum distribution (rise of $<P_t>$ with mass).

iv) x_F-distribution

The x_F-distribution being so sensitive to the behaviour of the structure functions of the colliding hadrons, is a very useful information in trying to distinguish between the several models. In particular, it would be helpful to extend the kinematical range in x_F, covering both positive and negative values.

For the Υ there are at present few data on its x_F-distribution. These data would be welcome, since a comparison with the J/ψ corresponding distribution, could furnish us indication of sizeable scaling violations when going from M^2_ψ for M^2_Υ in the structure functions.

A final remark concerns the x_F-distribution for J/ψ production with a $\bar{p}$ beam[*10c*]. The existing data has low statistics and cover a limited kinematical range (both in $\sqrt{s}$ and x_F). An improvement on this distribution could help us understand the relative contribution of the $q\bar{q}$ and gg mechanism for J/ψ production.

v) Event Structure

Finally we should not forget that experimental information on the event structure of heavy $Q\overline{Q}$ production can be sensitive to the particular mechanism producing these states. For instance, a mechanism involving the fusion of two gluons should produce a leading charged particle spectrum very similar to a normal hadronic event without the $Q\overline{Q}$ bound state.

We give here an example of how the leading particle spectrum is sensitive to the production mechanism of the $Q\overline{Q}$ bound state. Take for instance $Q\overline{Q}$ production in proton-proton collisions, we have two u-valence quarks in the proton, a process involving gluons leave these two quarks unaltered and ready to form a rapidly moving π^+. On the other hand, if a valence quark is used for producing the $Q\overline{Q}$ state one is left with less quarks for forming a rapidly moving π^+. Grossly speaking,one would expect twice as much π^+ for the mechanism using gluons than for the one employing $q\overline{q}$ fusion. Therefore,it is possible to examine the relative contribution of each mechanism as we change the energy, by looking at the spectrum $\frac{dN}{dx_F}$ of π^+ associated with the $Q\overline{Q}$ bound state. Given this event structure on resonance, a natural thing to do, and a useful one in this respect, is to compare it with the event structure obtained in the continuum.

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FIGURE CAPTIONS

Fig.1 - Energy levels of the charmonium family below charm threshold. The spectroscopic notation is used ($n^{2s+1}L_J$, L stands for the orbital angular momentum, S for spin, J for the total angular momentum, and n for the radial quantum number).

Fig.2 - Collection of data for the total cross-section for J/ψ production in pp-collision(Whenever the only information available was for $d\sigma/dx_F|_{x_F=0}$, we made the approximation $d\sigma/dx_F|_{x_F=0} \simeq \sigma_{tot}$). For comparison we have plotted the theoretical curves for $q\bar{q}$ and gg fusion(black-box approach-SectionIV) normalized at $\sqrt{s}$=30 GeV.

Fig.3 - The total cross-section for J/ψ in π^--Nucleon collisions.

Fig.4 - Total cross-section $B\sigma$ for the Υ production in pp and π^-N reactions. B is the Υ leptonic branching ratio.

Fig.5 - (a) Differential cross-section $d\sigma/dx_F$ for $\pi^-N \to J/\psi + X$ at $\sqrt{s}$ = 8.7 (Gev). x_F is defined as $x_F=2p_L^*/\sqrt{s}$, where p_L^* is the longitudinal momentum of J/ψ in the C.M.system. This figure has been taken from Ref.[*10c*]

(b) Same as in Fig.5a but for p beam.

Fig.6 - x_F distribution for the J/ψ in π^-N scattering at 150(GeV/c)[*20*]

Fig.7 - Average transverse momentum of J/ψ and Υ as a function of $\sqrt{s}$

Fig.8 - $<P_t>$ for J/ψ and Υ as function of $M/\sqrt{s}$.

Fig.9 - Test of the scaling law (2.3) from reference [18]. Notice that the J/ψ data has been re-scaled by an extra factor of 0.53, to account for the amount of J/ψ's coming from P-states (see Section II-vi)

Fig.10 - Drell-Yan type mechanism for the production of a heavy particle C.

Fig.11 - Diagrams for the production of a $Q\bar{Q}$ pair, from (a) light quarks, (b) gluons.

Fig.12 - x_F distributions at $\sqrt{s}$ = 8.7 (GeV) compared with $q\bar{q}$ and gg contribution. The theoretical curves are arbitrarily normalized.

Fig.13 - Same as fig.12 at $\sqrt{s}$ = 17 (GeV)

Fig.14 - Angular distribution for the J/ψ decay in $\pi^- N$ scattering at $\sqrt{s}$ = 8.7 GeV (from Ref. [10c]).

TABLE I

$R(H/\pi)$ \ H	π^+	K^+	K^-	$\bar{p}$	P
FNAL $\sqrt{s} = 20.5$ [GeV] REF. [13]	0.93 ± 0.19	0.56 ± 0.19	—	0.97 ± 0.48	0.60 ± 0.11
NA3 $\sqrt{s} = 19.4$ [GeV] REF [21,22]	1.01 ± 0.02	0.78 ± 0.08	1.10 ± 0.10	0.83 ± 0.12	0.59 ± 0.10
CERN OMEGA $\sqrt{s} = 8.7$ [GeV] REF. [10c]	1.00 ± 0.06	0.26 ± 0.05	0.89 ± 0.12	0.81 ± 0.12	0.10 ± 0.02

Ratios of J/ψ cross-sections for different beams and energies

TABLE II

$\sqrt{s}$ [GeV]	$\sigma(\psi')/\sigma(J/\psi)_{\pi\text{-}N}$	REF.
8.7	0.40 ± 0.13	[10c]
17	0.16 ± 0.03	[20]
20.5	0.18 ± 0.05	[13]

Ratio of the total cross-sections for $(\psi')/(J/\psi)$ in π-N collisions at different energies

TABLE III

EXP.	COLLISION	$\sqrt{s}$ [GeV]	FRACTION OF X (%)	STATE (J^{PC})
REF. [33a]	PP	62.	47 ± 8	NOT IDEN-TIFIED.
REF. [33b]	PP	62.	$15 \pm {}^{10}_{15}$	
REF. [33c]	$\pi^- P$	20.	70 ± 28	
REF. [33d]	$\pi^- P$	18.	11 ± 3.6	1^{++}
REF. [33c]	$\pi^- P$	19.	36 ± 5.0	1^{++}, 19 ± 4 2^{++}, 12 ± 4

Fractions of X - states relative to the J/ψ produced in hadronic collisions

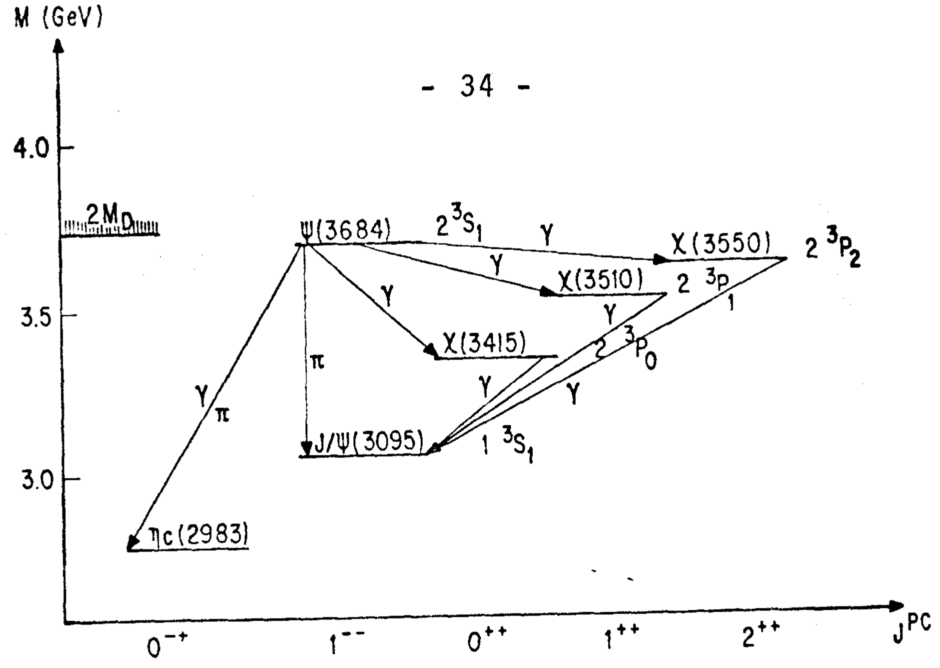

M (GeV)
4.0
3.5
3.0
2M_D
ψ(3684)
2 ³S₁
γ
χ(3550)
2 ³P₂
γ
χ(3510)
2 ³P₁
γ
χ(3415)
2 ³P₀
γ
π
γ
γ
γ
π
J/ψ(3095)
1 ³S₁
ηc(2983)
0⁻⁺
1⁻⁻
0⁺⁺
1⁺⁺
2⁺⁺
J^PC

Fig. 1

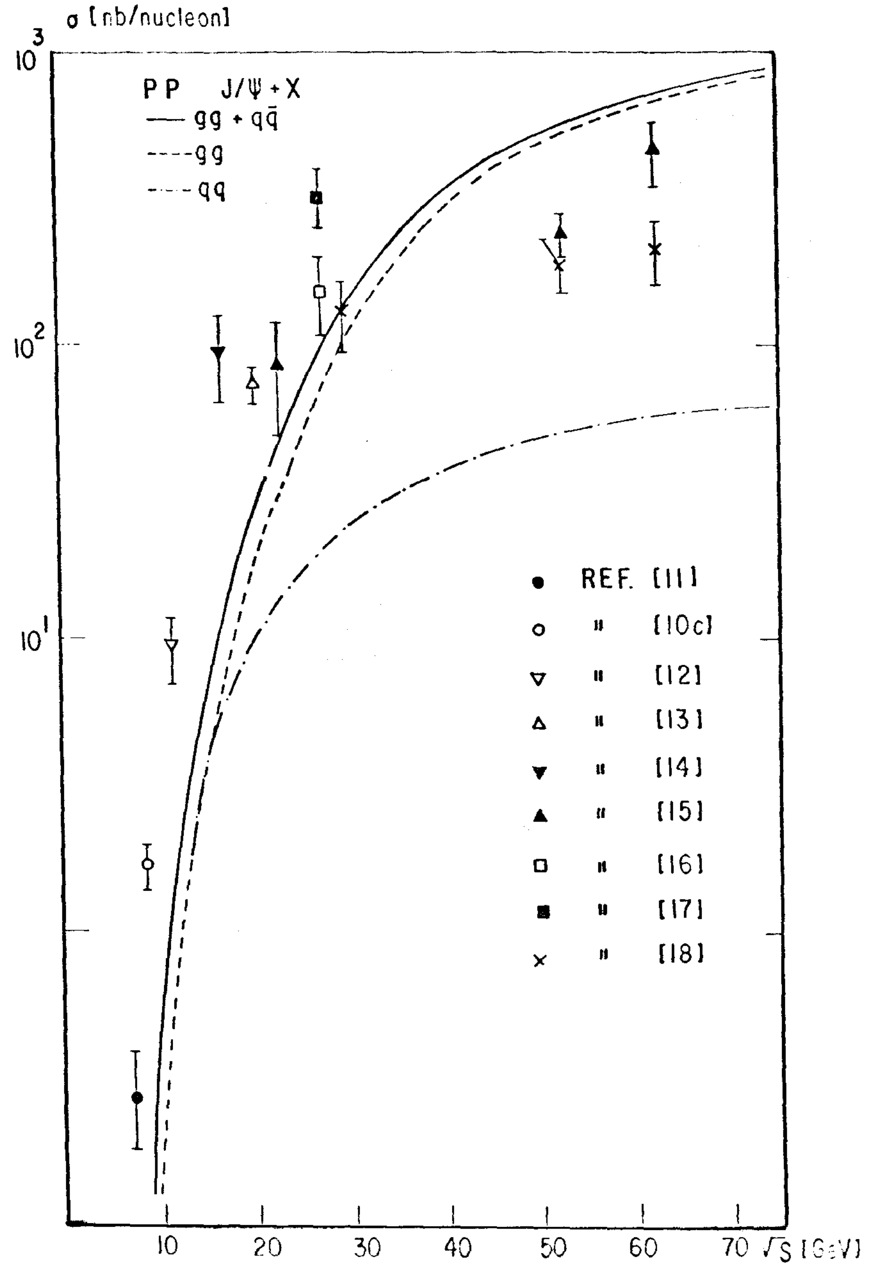

σ [nb/nucleon]
10³
10²
10¹
PP J/ψ + X
gg + qq̄
gg
qq
● REF. [11]
○ " [10c]
▽ " [12]
△ " [13]
▼ " [14]
▲ " [15]
□ " [16]
■ " [17]
× " [18]
10
20
30
40
50
60
70
√S [GeV]

Fig. 2

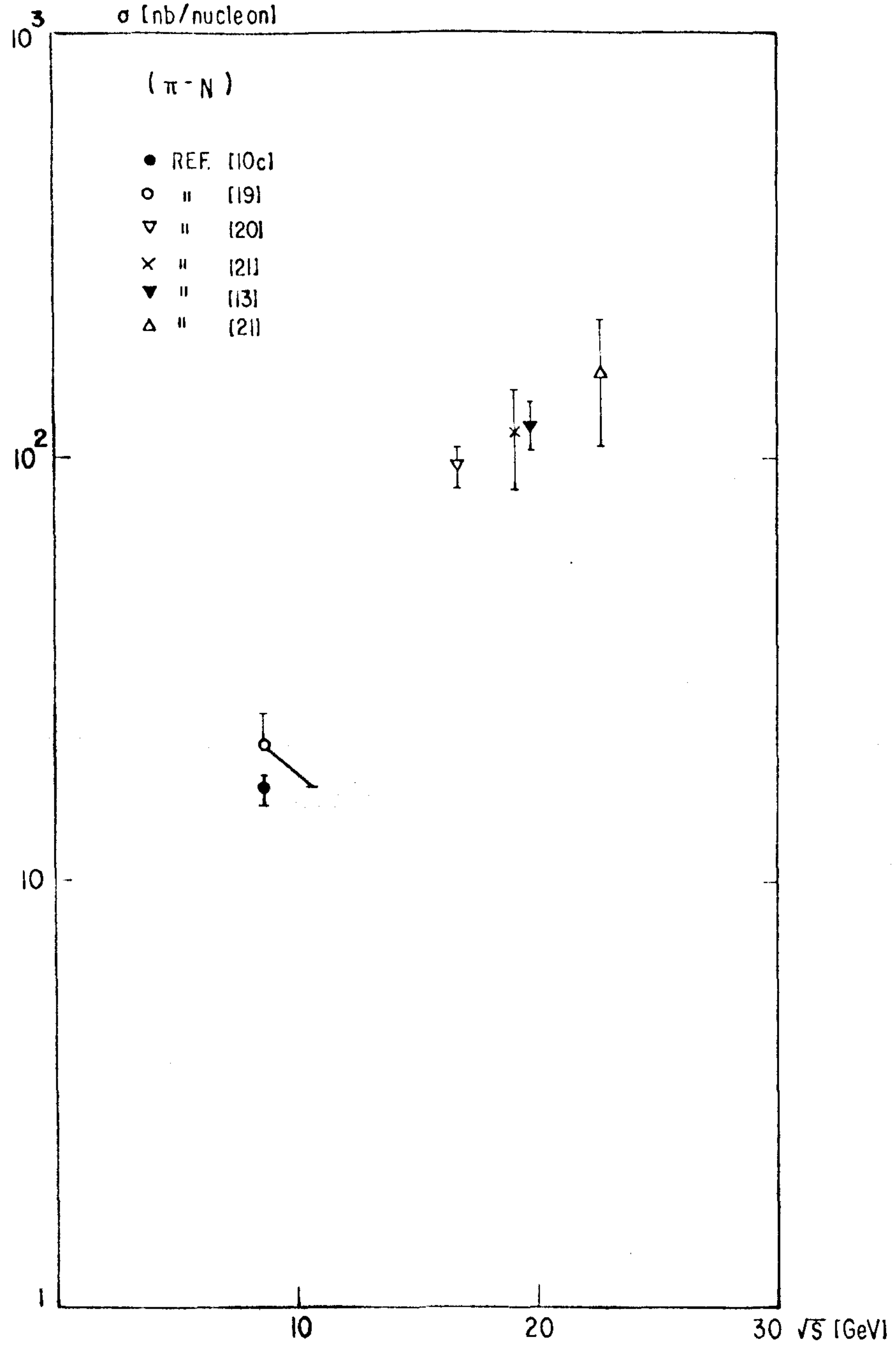

σ [nb/nucleon]
10^3
10^2
10
1
(π-N)
● REF. [10c]
○ " [19]
▽ " [20]
× " [21]
▼ " [13]
△ " [21]
10
20
30
√S [GeV]

Fig. 3

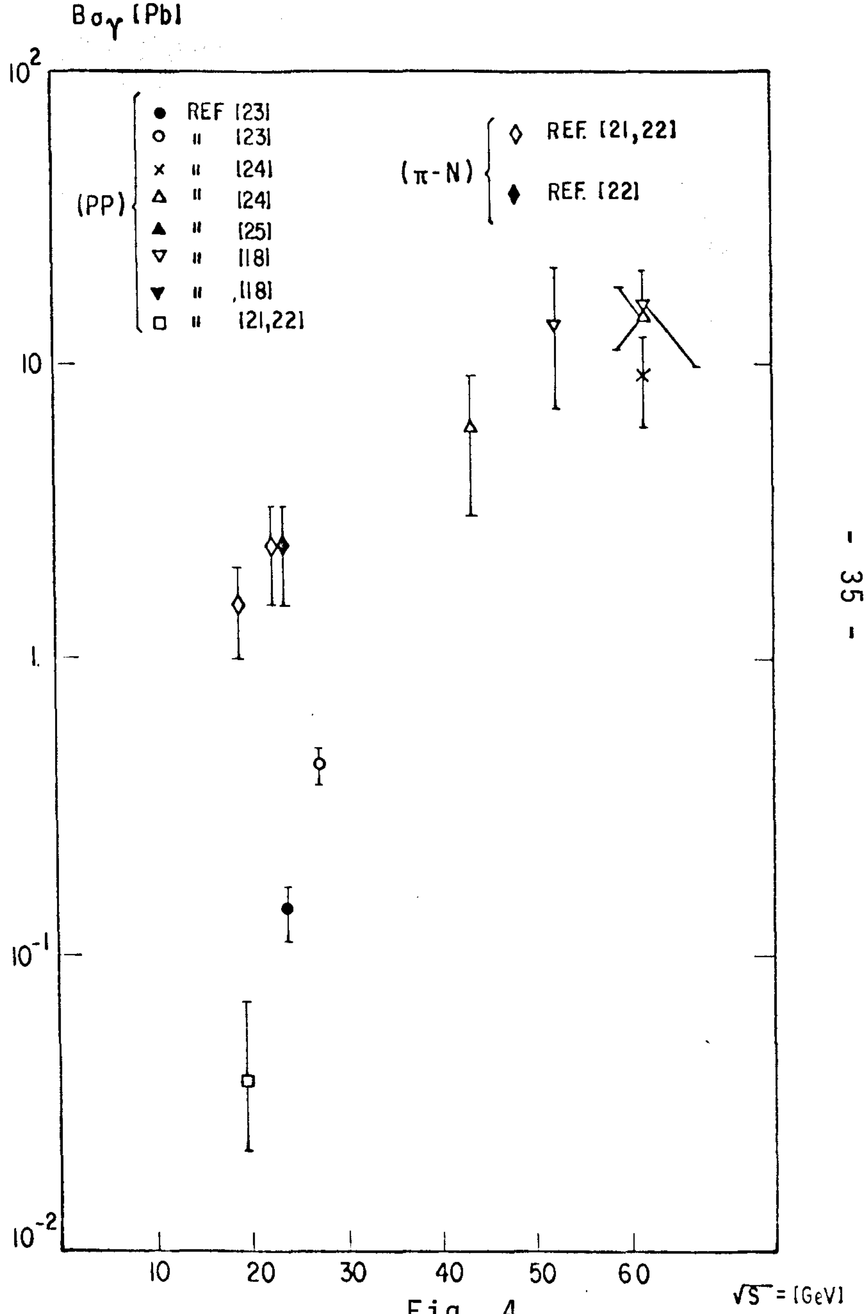

Bσγ [Pb]
10^2
10
1.
10^-1
10^-2
(PP)
● REF [23]
○ " [23]
× " [24]
△ " [24]
▲ " [25]
▽ " [18]
▼ " [18]
□ " [21,22]
(π-N)
◇ REF. [21,22]
◆ REF. [22]
10
20
30
40
50
60
√S = [GeV]

Fig. 4

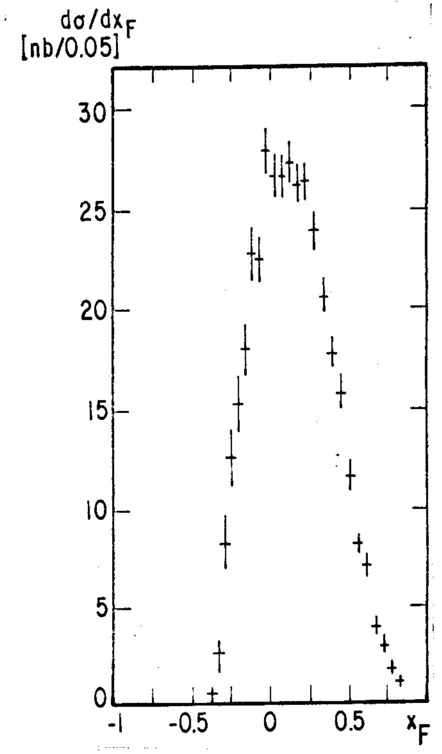


Fig. 5a

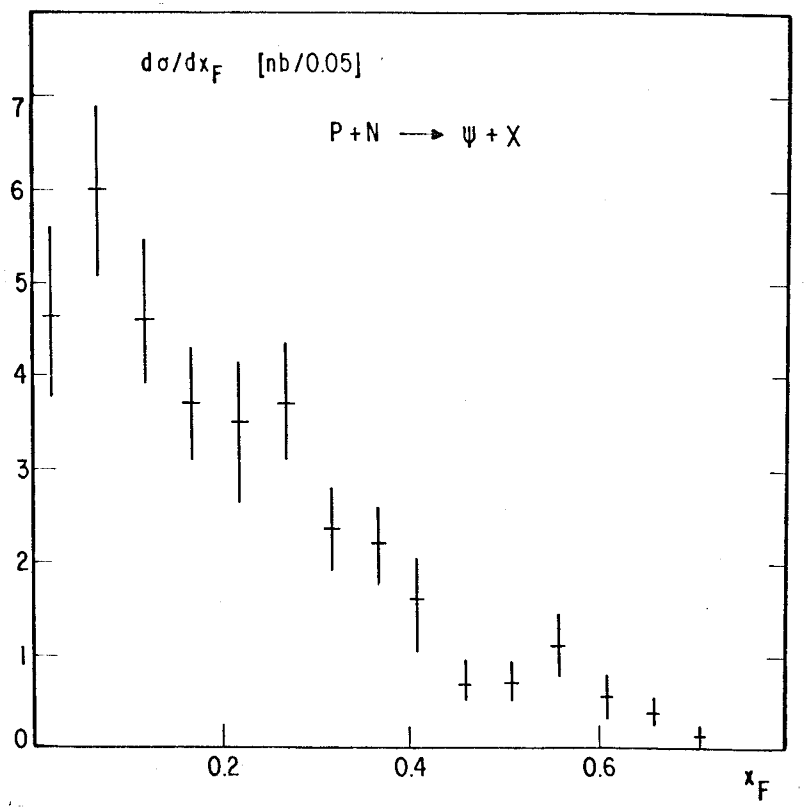


Fig. 5b

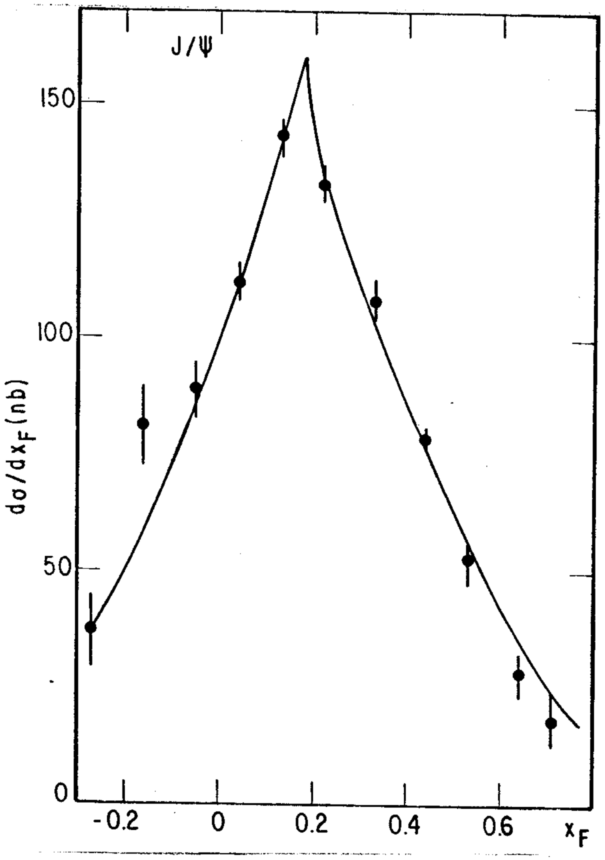
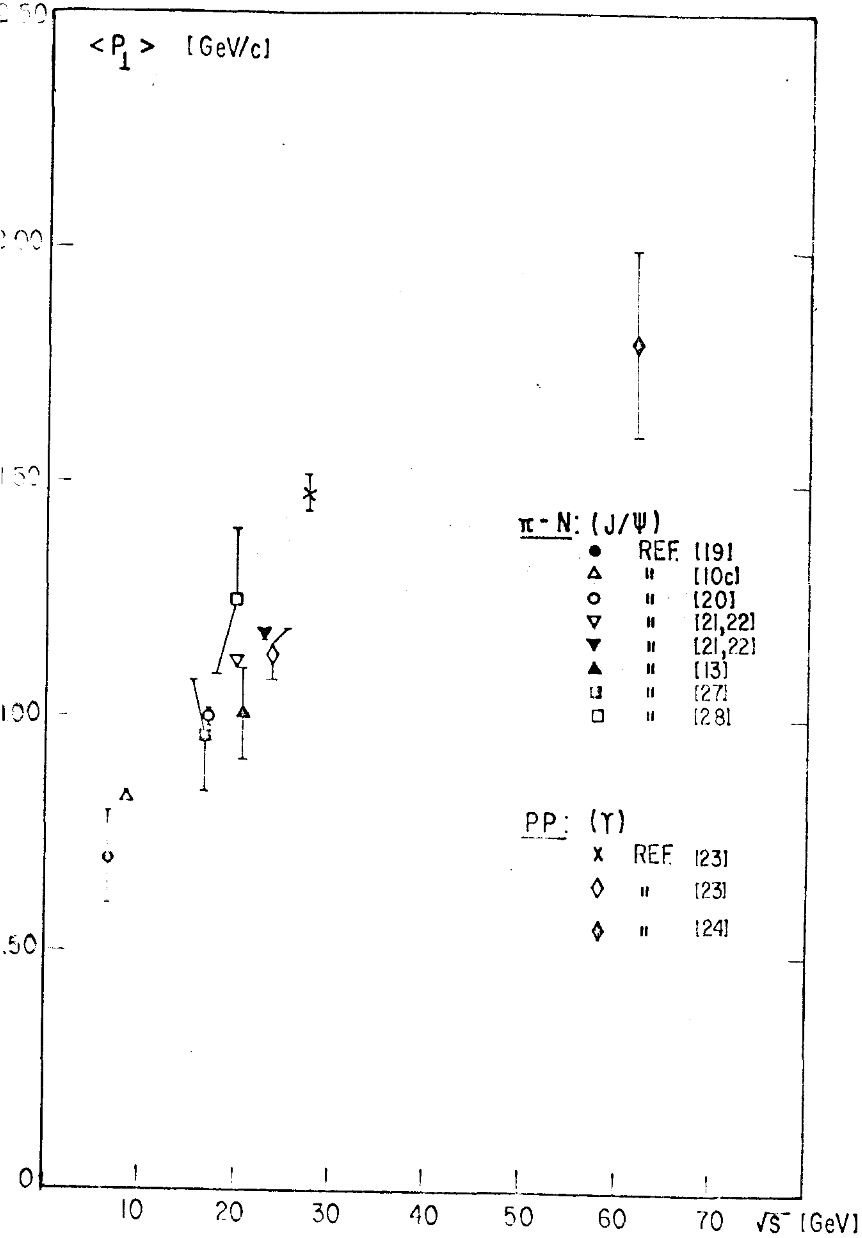
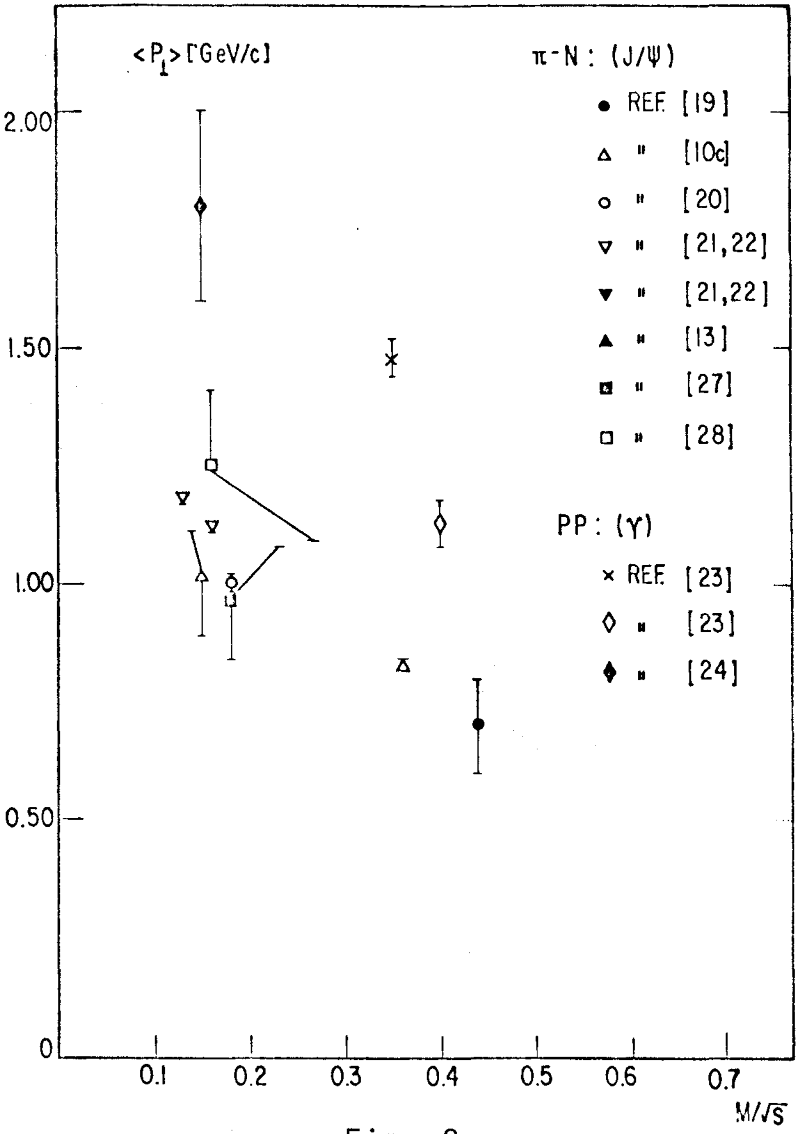


Fig. 6



<P⊥> [GeV/c]
0
.50
1.00
1.50
2.00
2.50
10
20
30
40
50
60
70
√S [GeV]
π - N: (J/Ψ)
● REF. [19]
△ " [10c]
○ " [20]
▽ " [21,22]
▼ " [21,22]
▲ " [13]
⊡ " [27]
□ " [28]
PP: (Υ)
× REF. [23]
◊ " [23]
◊ " [24]

Fig. 7



<P⊥> [GeV/c]
0
0.50
1.00
1.50
2.00
0.1
0.2
0.3
0.4
0.5
0.6
0.7
M/√S
π - N : (J/Ψ)
● REF. [19]
△ " [10c]
○ " [20]
▽ " [21,22]
▼ " [21,22]
▲ " [13]
⊡ " [27]
□ " [28]
PP : (Υ)
× REF. [23]
◊ " [23]
◊ " [24]

Fig. 8

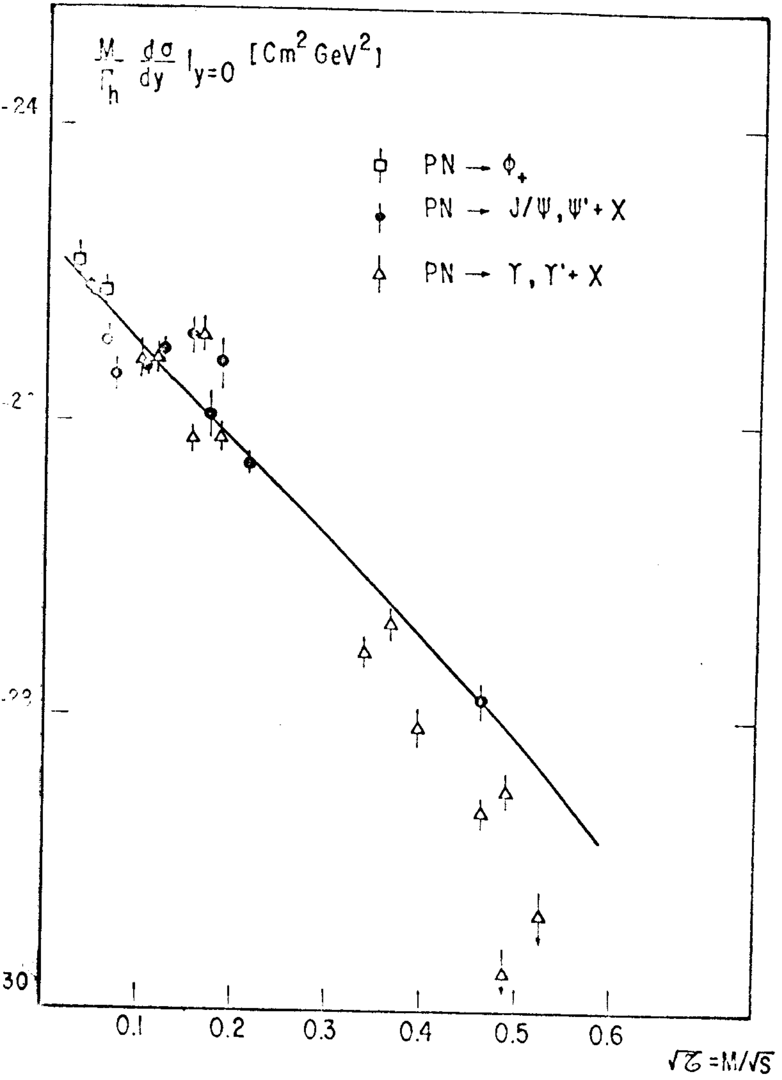


Fig. 9

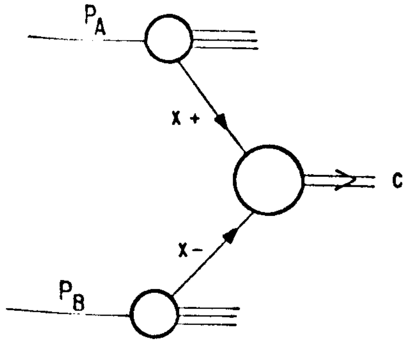


Fig. 10

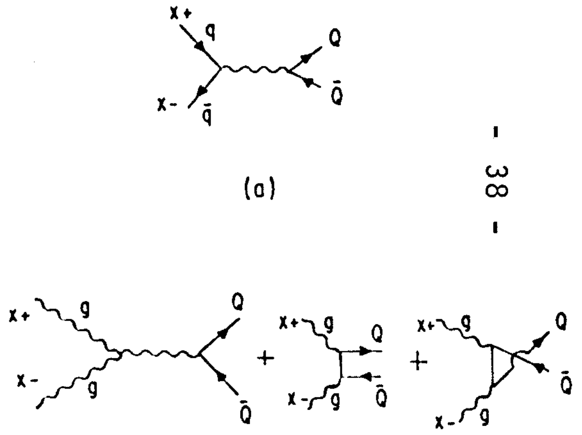


Fig. 11

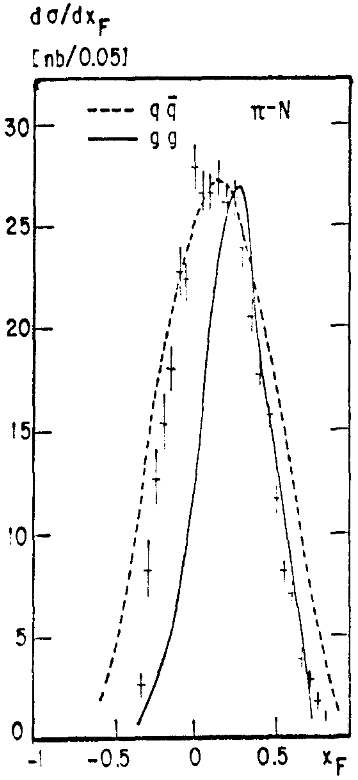


Fig. 12

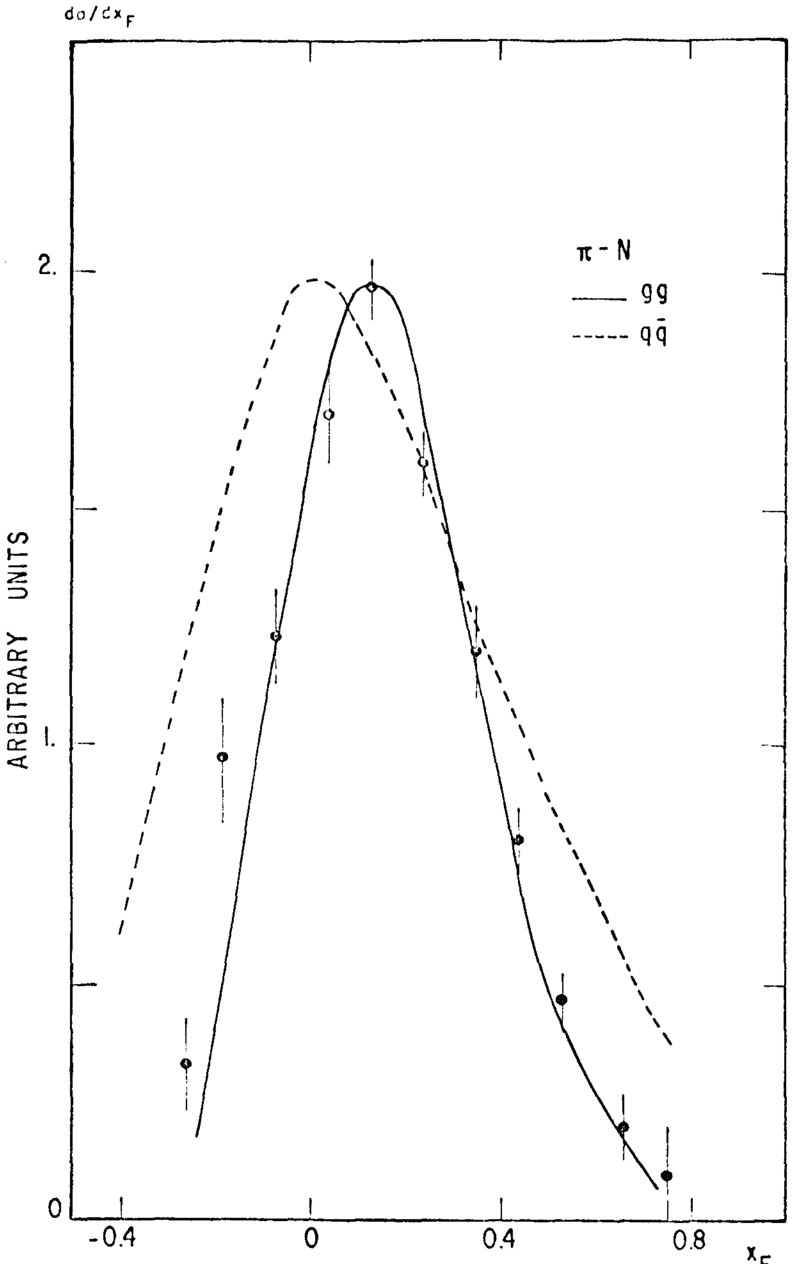


Fig. 13

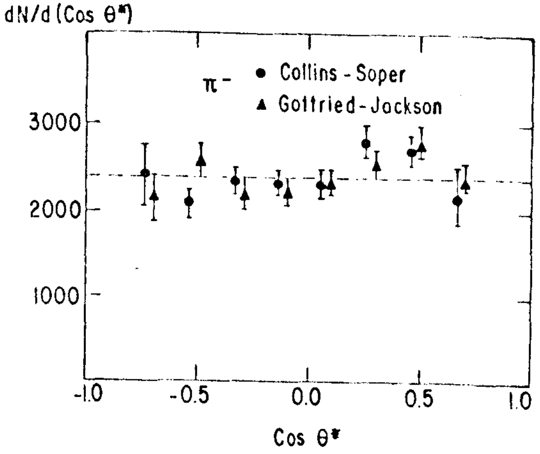


Fig. 14