

# Looking for Exotic Multiquark States in Nonleptonic B Decays \*

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## Abstract

Recent data on inclusive  $B$  decays into charmonium states taken by the CLEO collaboration suggest that a sizeable fraction of the nonleptonic decays may consist of the  $J/\psi \Lambda \bar{p}$  three body final state, corresponding to a distinct enhancement in the inclusive  $J/\psi$  momentum distribution. The kinematical boundary of this structure corresponds to the case where the  $J/\psi$  recoils nearly monoenergetically in the  $B$  rest system against a partner having mass of  $\simeq 2$  GeV. This may allow the observation of a  $\Lambda - \bar{p}$  bound state near or just below threshold; *i.e.*, strange baryonium, even if the production rate is small. Using a phase space approach to the  $B$  meson decay, we study the  $J/\psi$  momentum distribution and the effect of baryonium formation. We also discuss the possible observation of pentaquarks and hadronically-bound  $J/\psi$  by the observation of monoenergetic baryons in these decays.

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# 1 Introduction

One of the most important new elements that quantum chromodynamics brings to the strong interactions is the potential existence of new bound states and resonances beyond the conventional mesons, baryons and nuclei. These include exotic states such as gluonium ( $gg$ ,  $ggg$ ), hybrids ( $q\bar{q}g$ ) and dibaryons such as the H ( $udsuds$ ), etc.

A particularly sensitive measure of QCD binding is nuclear-bound quarkonium, *i.e.*, a  $(c - \bar{c})$  or  $(b - \bar{b})$  pair bound to a nucleus. In contrast to the usual strongly interacting few-body systems, the hadrons in the  $(c\bar{c})$  ( $uud$ ) meson-nucleon system have no valence quarks in common. However multiple-gluon exchange (the QCD van der Waals force) may lead to the formation of bound states [1]. Using the fact that the characteristic size of the  $J/\psi$  is much smaller than the typical hadronic scale ( $\Lambda_{QCD}^{-1}$ ), a QCD calculation based on a multipole expansion was performed in [2], leading to nuclear-bound quarkonium binding energies of order  $\simeq 8 - 11$  MeV. In addition, attractive interactions may also arise from the  $J/\psi p \rightarrow D \Lambda_c$  interaction [3]. Long-range exchange interactions may arise in second order perturbation theory if there are significant nonvalence ( $Q\bar{Q}q\bar{q}$ ) Fock states in the quarkonium wavefunction or intrinsic charm ( $uudc\bar{c}$ ) Fock states in the nucleon. There is thus a possibility of a strong  $J/\psi$ -nucleon resonance or bound state.

From the experimental point of view, there is evidence for the state  $B_\phi = |qqqs\bar{s}\rangle$  (where  $q$  are  $u$  or  $d$  quarks), reported by the SPHINX collaboration [4], and there are proposals for a search for the  $B_\psi = |qqqc\bar{c}\rangle$  with the same setup [5] and at Fermilab as well [6].

Another interesting type of exotic state that could arise in QCD are bound states of baryons and antibaryons (baryonia) such as  $p - \bar{p}$  and  $\Lambda - \bar{\Lambda}$ , and pentaquarks,  $P_Q$ , baryons containing five quarks like  $uud\bar{c}s$  or  $uudc\bar{s}$  [6, 7]. Baryonia may have binding energies as small as a few MeV as is characteristic of nuclear interactions, but they are unstable and decay into mesons via  $q - \bar{q}$  annihilation with possibly narrow widths. Such states have been subject of intensive search[8]. In particular, experiments have looked for strange baryonium in hadronic collisions, typically in  $K \bar{p} \rightarrow \Lambda \bar{p} p$  reactions at laboratory energies of 8.25 GeV [9], 18.5 GeV [10] and 50 GeV [11]. The results concerning the width of these states have been somewhat controversial. Some experimental searches [9, 12] found  $\Gamma \simeq 20$  MeV whereas others [11, 10] found  $\Gamma \simeq 150$  MeV. The existence of

narrow structures has never been established or completely ruled out.

Searches for the pentaquarks are in progress at Fermilab. Data from the collaboration E-791 are currently being analyzed, and another experiment, the E-781, is accumulating events with charmed baryons, which may determine the existence of certain pentaquarks [13].

In this paper we will show how to look for QCD exotic states in a B-factory. In particular, we will show how the  $B^- \rightarrow J/\psi \Lambda \bar{p}$  decay channel can be used to search for the  $(J/\psi - \bar{p})$ ,  $(J/\psi - \Lambda)$  and  $(\Lambda - \bar{p})$  bound states. Also the appearance of two-body structures in the momentum distribution of the  $\bar{\Lambda}_c$  near  $p = 0.47$  GeV/c in the  $B^+ \rightarrow \bar{\Lambda}_c + X$  decay channel may provide a signature for the  $u u d c \bar{s}$  pentaquark.

## 2 $B^- \rightarrow J/\psi \Lambda \bar{p}$ decay mode

Among the numerous decay modes of the  $B$  mesons, the  $B \rightarrow$  charmonium +  $X$  channels have drawn particular attention. Recent measurements of these decays performed by the CLEO collaboration [14] have found the following inclusive branching fractions:  $(1.12 \pm 0.04 \pm 0.06)\%$  for  $B \rightarrow J/\psi X$ ,  $(0.34 \pm 0.04 \pm 0.03)\%$  for  $B \rightarrow \psi' X$  and  $(0.40 \pm 0.06 \pm 0.04)\%$  for  $B \rightarrow \chi_{c1} X$ . Crossing this information with the measured [15] branching fraction  $(2.5 \pm 0.4)\%$  for  $B \rightarrow \Lambda \bar{p} X$ , one can infer that a significant fraction of the charmonium decays correspond to the three-body decay:

$$B^- \rightarrow J/\psi \Lambda \bar{p} \quad (1)$$

This process, ideal for our purposes, is depicted in Fig. 1a. In first place, the  $e^- e^+ \rightarrow B \bar{B}$  environment is much cleaner than in hadronic collisions, and the four momentum of the  $B$  is precisely determined. Moreover these decay products are very massive and only a small amount ( $\simeq 128$  MeV) of the initial energy is converted into kinetic energy. The decay particles move slowly in the  $B$  rest frame, interact strongly and can thus form bound states just below threshold or resonances just above threshold.

The CLEO collaboration has already provided a measurement of the inclusive momentum distributions of the  $J/\psi$  and  $\psi'$  in  $B$  decays [14]. If the  $\Lambda - \bar{p}$  is formed as a bound state, the  $J/\psi$  will be produced with a momentum just above 0.56 GeV/c (in the  $B$  rest frame). Similarly, if the  $J/\psi - \Lambda$  is bound, the  $\bar{p}$  will be produced at a momentum above 0.45 GeV/c. Finally, if the  $J/\psi - \bar{p}$  is formed, the  $\Lambda$  will have momentum slightly

larger than 0.48 GeV/c. If the  $B_\psi$  state is below the  $J/\psi - p$  mass threshold it may be observed in the  $B^+$  decay as a narrow peak in the  $\bar{\Lambda}$  momentum distribution at 0.48 GeV/c. Another interesting decay channel is shown in Fig. 1b, where the proton and the  $D_s^+$  meson may be bound forming the  $u u d c \bar{s}$  pentaquark. The conjugate process is shown in Fig. 1c. In Fig. 1d we illustrate the  $B^- \rightarrow D_s^- p \bar{p}$  decay. Here the proton and the  $D_s^-$  meson may be bound forming the  $u u d \bar{c} s$  pentaquark. This state, although CKM suppressed, is interesting because it is more strongly bound than  $u u d c \bar{s}$  [6, 7]. It thus seems possible, with high enough statistics, to identify two-body structures in these spectra, direct signatures for the formation of exotic QCD bound states.

In Fig. 2 we reproduce the  $B \rightarrow J/\psi X$  spectrum presented in [14], in which the feed-down modes  $B \rightarrow \psi' X$  and  $B \rightarrow \chi_{c1} X$  have been subtracted. This procedure eliminates the  $J/\psi$ 's coming from decays of excited charmonium states. The number of remaining points is not large, but we can nevertheless clearly see a distinct secondary bump in the lower momentum region corresponding to the  $B \rightarrow J/\psi \bar{p} \Lambda$  decay.

A baryonium state such as  $\Lambda - \bar{p}$  has the same quantum numbers as an excited kaon. We can distinguish a nuclear-type  $\Lambda - \bar{p}$  bound state by the fact that its mass should be within 10's of MeV of the threshold. Thus  $B$  decays offer not only the possibility of observing baryonium resonances [8, 9, 10, 11, 12], but also bound-state baryonia such as the  $\Lambda - \bar{p}$  with mass below the threshold ( 2.05 GeV). The  $(\Lambda - \bar{p})$  state recoils against the  $J/\psi$  with momentum (in the  $B^-$  c.m.s.) slightly beyond the upper limit (0.56 GeV/c) of the phase space for the three body decay  $B \rightarrow J/\psi \Lambda \bar{p}$ .

If there is a narrow peak at  $p_{J/\psi} \simeq 0.56$  GeV/c, the mass  $M_X$  of the  $J/\psi$  decay partner can be immediately inferred from the simple two body phase space formula:

$$p_{J/\psi} = \frac{M_B}{2} \lambda^{1/2} \left( 1, \frac{M_X^2}{M_B^2}, \frac{m_{J/\psi}^2}{M_B^2} \right) \quad (2)$$

with

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz \quad (3)$$

In the above expression  $M_B$  is the B meson mass (= 5.279 GeV) and  $m_{J/\psi} = 3.097$  GeV. This simple equation can be solved for  $M_X$  giving  $M_X \simeq 2.05$  GeV, which is exactly equal to the sum of the  $\Lambda$  and  $\bar{p}$  masses. A peak above 0.56 GeV would be an indication of a  $\Lambda \bar{p}$  bound-state formation. If the binding energy of the  $\Lambda - \bar{p}$  system is  $\Delta m_{\Lambda \bar{p}} \simeq 10$

MeV then

$$\Delta p_{J/\psi}^2 = \Delta m_{\Lambda\bar{p}}^2 \cdot \frac{m_{J/\psi}}{M_B} \quad (4)$$

giving  $\Delta p_{J/\psi} = 21 \text{ MeV}/c$  beyond the upper limit of the allowed kinematical region for  $B \rightarrow J/\psi \Lambda\bar{p}$ . Given that the estimated experimental resolution is of  $\Delta p = 1.7 \text{ MeV}$  [16], it seems possible to detect such peak.

In Ref. [14] the  $\psi'$  spectrum is also presented. The statistics are still small, and there is no evidence of any structure. This is in agreement with our phase-space based considerations: because of its larger mass ( $\simeq 3.686 \text{ GeV}$ ), the  $\psi'$  decay partners can have masses of at most  $1.593 \text{ GeV}$ . This is not enough to produce two baryons and therefore a near-threshold decay is excluded.

### 3 Modified phase-space analysis of $B$ -decay

Quantitative predictions for exclusive decay amplitudes such as  $B \rightarrow J/\psi \Lambda\bar{p}$  or strange baryonium formations  $B \rightarrow J/\psi[\Lambda\bar{p}]$  involve all of the complexities and uncertainties of QCD hadronization at the amplitude level and at low relative momentum where the gauge interactions are strongest. Nonrelativistic QCD (NRQCD) has brought significant progress to this field. The underlying weak decay  $b \rightarrow c\bar{c}s$  provides a guide to the flow of the heavy quarks. Very recently [17] the  $J/\psi$  momentum distribution in the decay  $B \rightarrow J/\psi + X$  was calculated for the first time and compared to data. It is interesting to observe that the obtained spectra agree with data, but fail in the low momentum region, exactly where we may expect some enhancement due to the exclusive channel considered here.

In general, hadronization will distort the “bare” quark momentum distribution given by the weak matrix element. Another source of uncertainty is the momentum distribution of the initial quarks inside the  $B$  meson, which was shown in [17] to strongly affect the spectrum of final particles. In order to keep our approach simple, we shall assume that the  $J/\psi$  spectrum measured over the whole available phase space gives a good indication of how the complicated underlying dynamics modifies the pure phase space picture ( $|\mathcal{M}|^2 = \text{const}$ ), thus providing a good representation of the squared matrix element.

In what follows we describe our modified phase space analysis of  $B$  decay. Following

the standard description of the kinematics[18] the decay rate, at the hadronic level, is given by:

$$d\Gamma = \frac{1}{2\sqrt{s}} \frac{1}{2} \sum |\mathcal{M}|^2 (2\pi)^{4-9} \prod_{i=1}^3 \frac{d^3 p_i}{2E_i} \delta^3(\vec{p} - \vec{p}_1 - \vec{p}_2 - \vec{p}_3) \delta(\sqrt{s} - E_1 - E_2 - E_3) \quad (5)$$

In the above expression the indexes 1,2 and 3 refer to the  $J/\psi$ ,  $\Lambda$  and  $\bar{p}$  respectively.  $E_i$  is the energy of the  $i^{th}$  particle and  $\sqrt{s}$  is the center of mass energy. We take  $|\mathcal{M}|^2$  as

$$|\mathcal{M}|^2 \longrightarrow \text{const} \cdot f(p_1) \quad (6)$$

where the function  $f$  is given by

$$f(x) = x \cdot \exp\left(-\frac{(x - x_0)^2}{\sigma_0^2}\right) \cdot (1 - x) \quad (7)$$

where  $x = p_1 / p_{\max}$ ,  $x_0 = 2.0 / p_{\max}$ ,  $\sigma_0 = 0.92 / p_{\max}$  and  $p_{\max}$  is the maximum momentum allowed for the  $J/\psi$ . In our case  $p_{\max} = 1.95$  GeV and the function  $f$  reproduces the data presented in [14]. The normalization of  $f$  is absorbed in the constant in eq. (6).

In the rest frame of the decaying particle ( $\vec{p} = 0$  and  $\sqrt{s} = M_B$ ) the integration over the variables 2 and 3 can be then easily done and we obtain the  $J/\psi$  momentum spectrum:

$$\frac{d\Gamma}{dp_1} = \frac{p_1}{E_1} f(p_1) \frac{1}{s_2} \lambda^{1/2}(M_B^2, s_2, m_1^2) \lambda^{1/2}(s_2, m_2^2, m_3^2) \quad (8)$$

where we have omitted all constant factors (since the normalization is free) and  $s_2 = M_B^2 + m_1^2 - 2M_B E_1$ . Inserting in eq. (8) the values of the masses, we obtain a spectrum which is adjusted to data and plotted in Fig. 2 as a solid line. As can be seen, the position of the maximum given by the simple modified phase space model coincides with the maximum of the bump. In Fig. 2 we also show (with a dotted line) the fit of data with eq.(7). In the region  $p_{J/\psi} \leq 0.56$  GeV/c this curve is an estimate of the background, *i.e.*, all processes other than eq. (1) in which a  $J/\psi$  is produced. Subtracting the integral of the dotted curve (over  $0 \leq p_{J/\psi} \leq 0.56$  GeV/c) from the integral of the solid line we can obtain an estimate for the branching fraction for eq. (1)  $\simeq 0.04\%$ .

For a baryonium binding energy of  $\Delta m_{\Lambda\bar{p}} = 10$  MeV, the exact position of the peak in the  $J/\psi$  distribution is given by eq. (2) with  $M_X = m_\Lambda + m_{\bar{p}} - \Delta m_{\Lambda\bar{p}}$ . We assume that the width of this state is equal to its binding energy. A final condition must be

satisfied by this bound state: it will be observed only if the strength of the peak is much larger than the background. For illustration we have estimated this strength to be 10% of the whole distribution. This produces a clear signal, which is shown in Fig. 2 with a dashed line. More details are given in the next section.

## 4 The strength of the peak

In this section we explain how to estimate the strength of the quasi-two-body decays corresponding to the area below the (dashed line) peak in the  $J/\psi$  momentum distribution. The process

$$B^- \longrightarrow J/\psi \Lambda \bar{p} \quad (9)$$

can be understood, at the quark level, as the reaction

$$b + \bar{u} \longrightarrow c \bar{c} u d s \bar{u} \bar{u} \bar{d} \quad (10)$$

characterized by a cross section,  $\sigma$ , which cannot be rigorously calculated. Since we are always treating the case where we have a  $J/\psi$ , we can coalesce the two charmed quarks into one particle and say that the effective reaction is

$$b + \bar{u} \longrightarrow J/\psi + u d s \bar{u} \bar{u} \bar{d} \quad (11)$$

where the six quarks system has invariant mass  $m_6$ . Following the spirit of the approximations made in the last section, the differential cross section  $\sigma$  can be written as

$$d\sigma = \text{const} \cdot dR_7 \quad (12)$$

where the constant factor represents the matrix element squared and  $R_7$  is the phase space factor for the seven final particles ( $J/\psi u d s \bar{u} \bar{u} \bar{d}$ ), which, with the help of a recursion relation [18], can be written as a function of  $m_6$ :

$$dR_7 = \frac{d^3 p_{J/\psi}}{2E_{J/\psi}} R_6(m_6) \quad (13)$$

In the center of mass system, from energy momentum conservation we have

$$M_B = \sqrt{p_{J/\psi}^2 + m_{J/\psi}^2} + \sqrt{p_{J/\psi}^2 + m_6^2} \quad (14)$$

Solving this relation for  $p_{J/\psi}$ , differentiating with respect to  $m_6$ , substituting in eq. (13) and inserting eq. (13) into eq. (12) we obtain

$$\frac{d\sigma}{dm_6} \simeq \sqrt{M_B - m_{J/\psi} - m_6} \left( \frac{m_6}{m_{J/\psi} + m_6} \right)^{3/2} R_6(m_6) \quad (15)$$

where a nonrelativistic approximation is made and some immaterial constants are dropped. With the additional assumption that the six body phase space is approximately one-dimensional and taking constituent masses for the quarks ( $\simeq 300$  MeV) we can evaluate  $R_6$  (almost) analytically. As expected the curve Eq. (15) has a bell shape.  $R_6$  starts from zero when  $m_6$  is just the sum of the quark masses and then increases monotonically. The multiplying factor in Eq. (15) is a decreasing function of  $m_6$  and goes to zero when it is equal to  $M_B - m_{J/\psi}$ . This cross section can be integrated over different  $m_6$  intervals. The bound-state region corresponds to  $m_6$  smaller than the  $\Lambda - \bar{p}$  threshold, *i.e.*,

$$m_p + m_\Lambda - \varepsilon \leq m_6 \leq m_p + m_\Lambda \quad (16)$$

where  $\varepsilon$  is the binding energy. The continuum region is given by

$$m_p + m_\Lambda \leq m_6 \leq M_B - m_{J/\psi} \quad (17)$$

The region

$$m_6 \leq m_p + m_\Lambda - \varepsilon \quad (18)$$

refers to processes in which the  $B$  mesons decays into pions and a kaon with too small invariant mass. Such events do not come from the baryonium decay and are thus uninteresting. This part of the phase space will be ignored.

The probability of forming a bound state is then given by

$$p = \frac{\int_{m_p + m_\Lambda - \varepsilon}^{m_p + m_\Lambda} dm_6 \frac{d\sigma}{dm_6}}{\int_{m_p + m_\Lambda - \varepsilon}^{M_B - m_{J/\psi}} dm_6 \frac{d\sigma}{dm_6}} \quad (19)$$

We use  $\varepsilon = 10$  MeV. Performing the calculations we find that  $p = 10\%$ .

On the other hand, looking at Fig. 2, we observe that the probability of forming a bound state may be identified with the ratio between the area below the (dashed line) peak and the total area (solid plus dashed lines), *i.e.*, the differential branching fraction integrated over  $p_{J/\psi}$  :

$$p = \frac{\int_{p_{\max}}^{p_{\max} + \Delta p_{J/\psi}} \frac{dB}{dp_{J/\psi}} dp_{J/\psi}}{\int_0^{p_{\max} + \Delta p_{J/\psi}} \frac{dB}{dp_{J/\psi}} dp_{J/\psi}} \quad (20)$$



where  $\Delta p_{J/\psi}$  given by Eq. (4). Knowing  $p$  from eq. (19), we replace it in the above expression and determine the right hand side, *i.e.*, the strength of the peak, which, with the parameters stated above, is 10%.

The same procedure can be applied to the other interesting bound states in the decay mode (1) as mentioned at the end of the introduction. The  $(J/\psi - \bar{p})$  and  $(J/\psi - \Lambda)$  may be observed as peaks in the momentum distribution of the  $\Lambda$  and  $\bar{p}$  respectively. These spectra are computed with the help of eq. (8). Now,  $p_1$  refers to  $\bar{p}$  or to  $\Lambda$  and  $f(p_1) = 1$ , since we do not know how to modify the phase space in these cases where no data are available. The strengths of the bound state peaks are computed in the way described above (with  $\varepsilon = 10$  MeV and  $\Delta m_{J/\psi \bar{p}} = \Delta m_{J/\psi \Lambda} = 10$  MeV), and the results are  $p = 10.7\%$  and  $p = 11\%$  for the  $\Lambda$  and  $\bar{p}$  spectra respectively. These spectra (with corresponding peaks) are shown in Fig. 3 in arbitrary units.

## 5 Conclusions

The high luminosity of the CESR storage ring and the  $B$ -factories now under construction will provide a high statistic sample of  $B$  decays. As we have discussed in this paper, the decay of the  $B$  may lead to the production of exotic QCD states such as quarkonium-baryonium bound states, pentaquarks, and strange baryonium. The nearly monoenergetic production of the recoil hadron in the rest system of the  $B$  could provide a sensitive and clean signal for these states.

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## Figure Captions

**Fig. 1** Exclusive hadronic  $B$  decays which may lead to the formation of bound states. 1a) hadronically bound  $J/\psi$  or strange baryonium; 1b)  $u u d c \bar{s}$  pentaquark; 1c)  $\bar{u} \bar{u} \bar{d} \bar{c} s$  pentaquark; 1d)  $u u d \bar{c} s$  pentaquark.

**Fig. 2** The  $J/\psi$  momentum spectrum measured by the CLEO Collaboration [14] after the subtraction of the feed-down modes. The solid line is the result of a modified phase space calculation for the  $B \rightarrow J\psi \Lambda \bar{p}$  three-body decay, eq.(8). The dotted line shows the fit of data, eq.(7), used to estimate background contributions. The dashed line represents the expected peak if there is a narrow strange baryonium with binding energy of 10 MeV and width 10 MeV.

**Fig. 3** The momentum distribution of the  $\bar{p}$  (solid line) and  $\Lambda$  (dashed line) produced in the  $B$  decay eq.(1). The broad curves show the three-body decay spectra of the  $\bar{p}$  and  $\Lambda$  calculated with eq.(8). Just beyond the kinematical limits of these two curves we show the peaks which would be signatures of the below-threshold  $(J/\psi - \Lambda)$  (solid line) and  $(J/\psi - \bar{p})$  (dashed line) bound states. Their binding energies and widths are assumed to be  $\varepsilon = 10$  MeV. These numbers determine the position and width of the bound state peaks. Their strengths are given by eqs. (19) and (20).

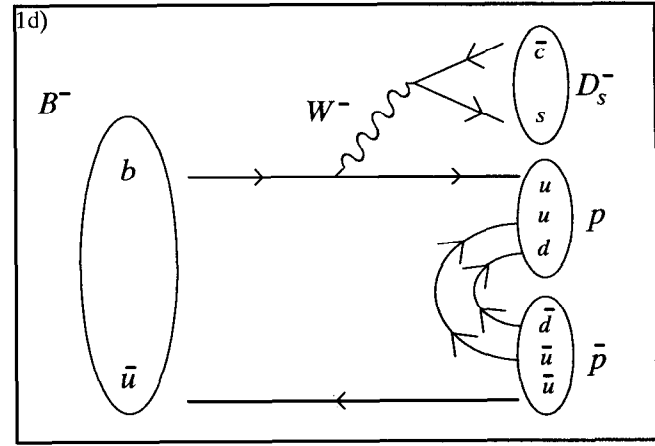
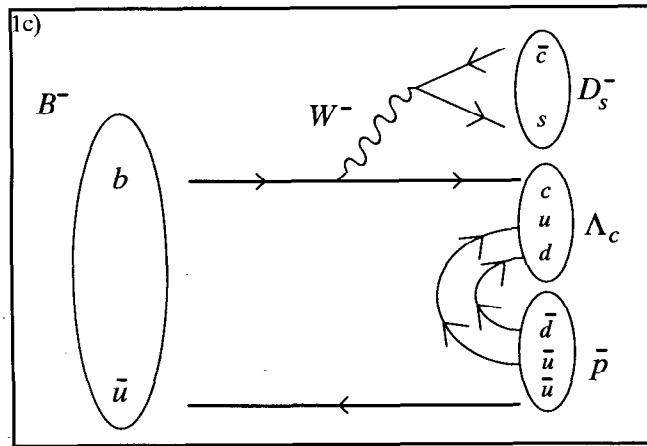
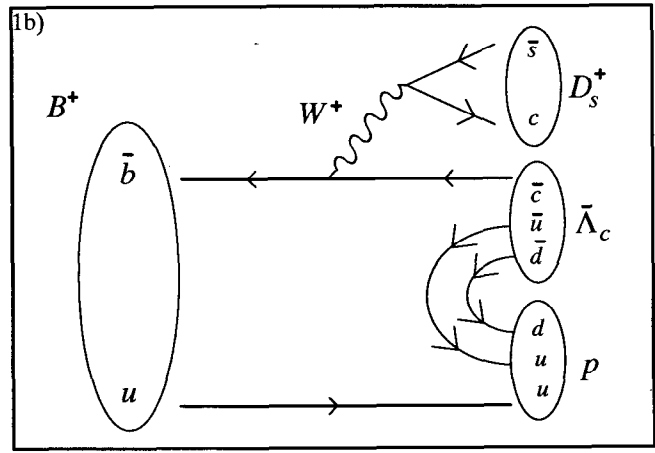
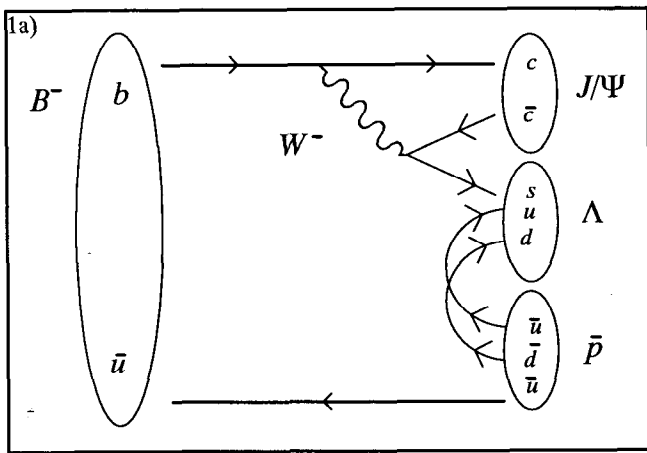
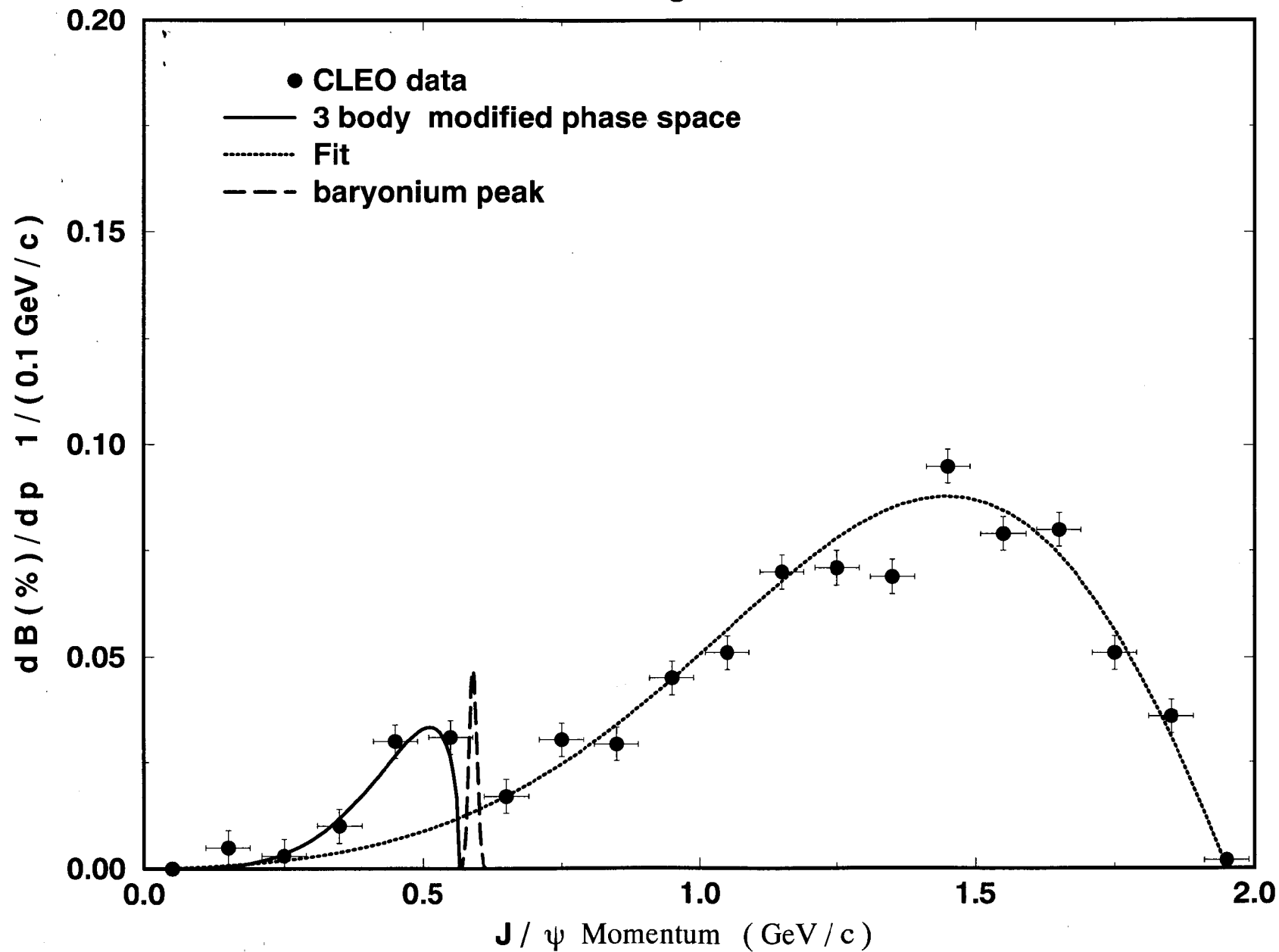


Figure 1

# $J/\psi$ Momentum Distribution

Figure 2



# Momentum Distributions

Figure 3

