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Recent B Physics Results at CDF

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RECENT B PHYSICS RESULTS AT CDF

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Abstract

Three recent B physics results at CDF are presented. The first analysis measures the production polarization of the $\psi(2S)$ from its decay into $\mu^+\mu^-$. The second one determines the χ_b contribution to the $\Upsilon(1S)$ production. Both analyses are important tests of the Color Octet Model. The third analysis related here is a measurement of the full decay amplitudes of $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$. This provides both a test of the factorization model and information relevant to CP violation studies in the B sector.

All of the results are to be considered preliminary.

1 Introduction

The huge $b\bar{b}$ cross section at the Tevatron, of the order of $\sim 100\mu b$, offers such large event rates that it deserves a lot of interest. However, $b-$physics at hadron machines is much more difficult than in e^+e^- machines for many reasons. First of all, the heavy flavor production is only a tiny fraction (of the order of 10^{-3}) of the total $p\bar{p}$ cross section. Second, the transverse momentum spectrum of the produced B's is wide and peaked at low values: this means that the decay products of B's could be confused with particles coming either from spectator or fragmentation processes. Third, possible multiple interactions in the same bunch crossing add further particles in the event. Despite the above difficulties, with dedicated lepton triggers and a powerful silicon vertex detector 1) CDF has been able to obtain significant results in many b physics sectors.

We will discuss here three recent analyses. The first two, the measurement of the $\psi(2S)$ polarization and the measurement of the χ_b contribution to the $\Upsilon(1S)$ production, provide tests of the Color Octet Model of the direct production of quarkonia. The Color Octet Model 2) has been proposed to explain the so call "CDF anomaly" 3): the observed prompt (i.e. not from B decays) direct (i.e. not from χ_c feed-down) production of J/ψ and $\psi(2S)$ is about a factor 50 higher than the perturbative QCD expectation (Color Singlet Model) 4, 5). The Color Octet Model is based on the idea that a relevant contribution (ignored before) to those channels come from gluon fragmentation in color octet $c\bar{c}$ states that evolve non-perturbatively, via emission of soft gluons, into physical color singlet states. This model has successfully explained the CDF measured transverse momentum spectra of direct J/ψ and $\psi(2S)$, but some non-perturbative parameters have been fitted from the data itself 2). A more predictive result of the Color Octet Model, tested for the first time in the measurement presented here, is that the direct J/ψ and $\psi(2S)$ mesons at high transverse momentum should be almost totally polarized 6). This can be understood as follows: at high momentum the fragmenting gluon is effectively on-shell and transverse, hence the $c\bar{c}$ pair inherits the gluon's transverse polarization and so does the ψ (J/ψ or $\psi(2S)$) because the emission of soft gluons during hadronization is not able to flip the spin. Large discrepancies between observations and theoretical expectations from the Color Singlet Model have also been obtained from CDF in the production of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ 7). The Color Octet Model has been successfully applied also in these cases 8), but the test is somewhat limited due to the unknown fractions of Υ's from χ_b feed-down. In the second analysis reported here, this fraction is determined for the $\Upsilon(1S)$.

Finally, the last CDF result reported here is on the full decay amplitudes of $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$. [1] This is useful to test the factorization model, for CP violation studies in the B sector and to improve the sensitivity of a $\Delta\Gamma/\Gamma$ measurement in the B_s^0 system, as discussed later.

All of the results reported in this paper are to be considered preliminary.

2 ψ(2S) polarization in ψ(2S)$\to\mu^+\mu^-$

Let us define the helicity angle θ as the angle of the μ^+ in the $\psi(2S)$ rest frame with respect to the direction of the $\psi(2S)$ in the laboratory frame. The expected angular distribution for $\psi(2S) \to \mu^+\mu^-$ is 9):

$$I(\theta) = \frac{3}{2(\alpha+3)}(1+\alpha\cos^2\theta) \tag{1}$$

where α is the $\psi(2S)$ polarization. Unpolarized $\psi(2S)$ would have $\alpha = 0$ whereas $\alpha = 1$ and -1 correspond to fully transverse and longitudinal polarizations. The goal is to extract the value of α by fitting the decay angular distributions.

The data set is the Run I data sample, corresponding to an integrated luminosity of $110\,\mathrm{pb}^{-1}$. Events are selected by triggering on a dimuon signature. The muons are required to be seen in the Silicon Tracker and have transverse momentum above 2 GeV/c. From a fit of the dimuon invariant mass we get about 1780 $\psi(2S)$ signal events. This sample is split into three transverse momentum ranges ($5.5-7$, $7-9$ and $9-20$ GeV/c), to study the p_T dependence of the polarization. Each of these subsamples is further divided into two classes according to the reconstructed proper decay length, *ct*, of the $\psi(2S)$: the low *ct* ($< 100\mu m$) region is prompt enriched whereas the high *ct* ($> 100\mu m$) region is dominated by B decays. The $\cos\theta$ distribution is fitted simultaneously for the six subsamples. The value of $\cos\theta$ for each candidate is calculated from the momentum vectors of the muons and the mass and momentum of the reconstructed $\psi(2S)$. Since the angular distribution is symmetric, the absolute value of $\cos\theta$ is used, and subdivided into ten bins. The mass distribution in each $\cos\theta$ bin is fitted to determine the number of observed signal events. An essential ingredient in the fit is the distribution of the signal acceptance as a function of $\cos\theta$. The acceptance is depleted at large $|\cos\theta|$, but extends to higher values as the $\psi(2S)$ transverse momentum increases. Such acceptance is obtained from Monte Carlo, where the $\psi(2S)$ p_T spectrum has been tuned to match the data. The fit result and the comparison with the Color Octet Model prediction 6) are shown for the prompt sample in Fig.1. Given the large error bars

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[1] Throughout this paper, charge conjugate modes are always implied.

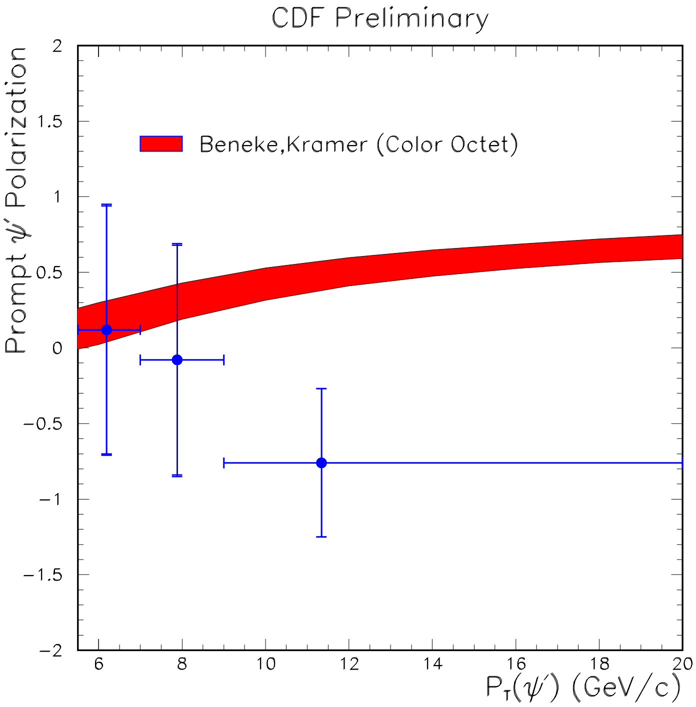

Figure 1: *Prompt* $\psi(2S)$ *polarization versus* p_T*. The theory band is from Color Octet Model calculation* $^{6)}$.

(dominated by the statistical error), it is not possible to draw any strong conclusion about the Color Octet Model. However, the predicted shape does not seem to follow the data. It will be very interesting to see the results of other polarization measurements, such as $J/\psi \to \mu^+\mu^-$, $\psi(2S) \to J/\psi\pi^+\pi^-$ and $\Upsilon \to \mu^+\mu^-$, all in progress at CDF. Note that the polarization measurements in quarkonia are also important to improve the cross section measurements, since the unknown polarizations are the dominant sources of error.

3 Production of $\Upsilon(1S)$ from χ_b decays

In this analysis, the radiative decay $\chi_b \to \Upsilon(1S)\gamma$, where $\Upsilon(1S) \to \mu^+\mu^-$, has been used. A similar analysis was already published by CDF for the decay $\chi_c \to J/\psi\gamma$ $^{10)}$. In the case of the bottomonium system there is no contribution from B decays; however, everything else is more difficult because of the smaller cross section (and therefore smaller event sample) and the kinematics of the radiative decay, which results in photons too soft to be detected unless the p_T of the χ_b is relatively large.

The mass differences $\Delta M = M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ associated with $\chi_b(1P) \to \Upsilon(1S)\gamma$ and $\chi_b(2P) \to \Upsilon(1S)\gamma$ are respectively $443\,\mathrm{MeV/c^2}$ and $802\,\mathrm{MeV/c^2}$ $^{11)}$. These mass differences, after a proper kinematical selection of photons and χ_b's, are sufficiently large to be detected at CDF and also separated enough to allow observation of a double peak in the ΔM spectrum (whereas, as for the χ_c, the different J=1,2 states cannot be resolved except with the use of $\gamma \to e^+e^-$ conversion pair events).[2]

The data set is the Run Ib data sample, corresponding to an integrated luminosity of about $90\,\text{pb}^{-1}$. From a fit of the dimuon invariant mass we get 1462±50 $\Upsilon(1S)$ signal events, with a ratio S/N of about 2. Fig.2 shows the fit result of the ΔM spectrum after requiring $p_T(\Upsilon) > 8\,\text{GeV/c}$ and an isolated photon, inside a 90° cone around the $\Upsilon(1S)$, with $E_T(\gamma) > 700\,\text{MeV}$. The background shape is determined from a Monte Carlo method based on data. From this result, and using the CDF measured differential cross section for Υ production 7), the fraction of *directly* produced $\Upsilon(1S)$ turns out to be:

$$F_{\text{direct }\Upsilon(1S)} = (51.8 \pm 8.2\ ^{+9.0}_{-6.7})\%$$

Although we are not able to single out all of the transitions in the bottomonium system, such as the feed-down of χ_b to $\Upsilon(2S)$ and $\Upsilon(3S)$, this measurement should help the understanding of the importance of Color Octet contributions in bottomonium production.

4 Polarization in B→VV

The total amplitude of the decay $B \to VV$ of a pseudoscalar (B^0 or B^0_s) to two vectors ($J/\psi K^{*0}$ or $J/\psi\phi$) consists of three partial amplitudes labelled by the angular momentum numbers of the daughter particles (V,V). These amplitudes can be described in many bases, the most interesting of which is the so called transversity basis $\{A_0,\, A_\parallel,\, A_\perp\}$ 12). The basis states in this representation isolate the longitudinal polarization state and are eigenstates of parity. This simplifies extracting the longitudinal polarization fraction $\frac{\Gamma_L}{\Gamma} = \frac{|A_0|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$ which is important for testing the factorization ansatz 13), and the P-odd fraction $\frac{|A_\perp|^2}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$ which is relevant for CP violation studies (where charge conjugate final state particles are considered). In fact, both $B^0 \to J/\psi K^{*0}$ and $B^0_s \to J/\psi\phi$ decays can receive contributions from the two P-states (although the P-even one is expected to be dominant): hence it is necessary to know their relative branching fractions in order to use these channels for CP violation measurements.[3] Another interesting potential

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[2] The energy threshold for photon detection at CDF is about 500 MeV, with a resolution of the order of 60 MeV.

[3] This will be important in the Run II for $B^0_s \to J/\psi\phi$. For $B^0 \to J/\psi K^{*0}$ the neutral mode $K^{*0} \to K^0\pi^0$ must be used: this limits the application only to e^+e^- machines, being very difficult

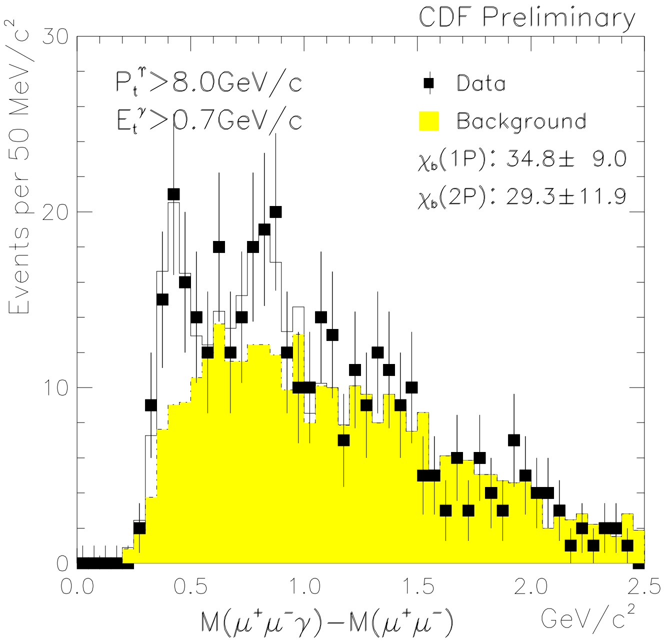

Figure 2: *ΔM distribution. The points show the data histogram, the shaded histogram represents the background. The solid line is the fit result. The two peaks are in the right positions where we expect the $\chi_b(1P)$ and $\chi_b(2P)$ signals.*

application of the angular analysis of $B_s^0 \to J/\psi\phi$, feasible in Run II, is to improve the sensitivity of a $\Delta\Gamma/\Gamma$ measurement in the B_s^0 system. The two mass eigenstates are almost CP eigenstates, so the decay angular distribution as a function of proper decay time allows to separate the light (short-lived and almost CP-even) and heavy (long-lived and almost CP-odd) states. 12, 14)

The two vectors in the final state are reconstructed via their two body decays: $J/\psi \to \mu^+\mu^-$ and $K^{*0} \to K^+\pi^-$, for B^0; $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$, for B_s^0. The kinematics of these four final particles, coming from the decays of two vectors mesons, can be described by three angles. The transversity matrix elements favor using the transversity angles 12): $(\Theta_{K^*},\ \Theta_T,\ \Phi_T)$[4] which give the decay angular distribution a relatively simple form. Without going into details of the derivation of the decay angular distribution, or the exact definition of the decay angles, we note that there are terms which change sign depending on whether a B or $\bar{B}$ decays 12):

$$\Omega_{transv} \quad \propto \quad 2\cos^2\Theta_{K^*}(1-\sin^2\Theta_T\cos^2\Phi_T)|A_0|^2$$

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to reconstruct π^0's in a hadron collider environment.

[4] From now on, although the angle Θ_{K^*} refers to the $B^0 \to J/\psi K^{*0}$ decay, it is understood that for the $B_s^0 \to J/\psi\phi$ decay such angle should be replaced by Θ_ϕ.

$$\begin{aligned}
&+ \quad \sin^2\Theta_{K^*}(1-\sin^2\Theta_T\sin^2\Phi_T)|A_{||}|^2 \\
&+ \quad \sin^2\Theta_{K^*}\sin^2\Theta_T|A_\perp|^2 \\
&+ \quad \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin^2\Theta_T\sin 2\Phi_T\mathrm{Re}(A_0^*A_{||}) \\
&\mp \quad \sin^2\Theta_{K^*}\sin 2\Theta_T\sin\Phi_T\mathrm{Im}(A_{||}^*A_\perp) \\
&\pm \quad \frac{1}{\sqrt{2}}\sin 2\Theta_{K^*}\sin 2\Theta_T\cos\Phi_T\mathrm{Im}(A_0^*A_\perp) \qquad (2)
\end{aligned}$$

The B^0 decay mode is self tagging (i.e. from the sign of the kaon we know the flavor of the B^0) but the B_s^0 decay is not: this implies that for B_s^0 decays the last two terms in Eq.2 cancel statistically, and we lose all information about the phase of $A_\perp$.

The data set is the Run Ib data sample, corresponding to an integrated luminosity of about $90\,\mathrm{pb}^{-1}$. Our candidate selection starts seeking first the J/ψ and then adding other charged tracks to reconstruct the decay from the final state particles. To suppress the background we rely on the long lifetime of the B mesons: for the B^0 we require proper decay length above $100\,\mu m$, and for the B_s^0 above $50\,\mu m$. From the fit of the mass peaks for B^0 and B_s^0 candidates we get respectively 194 ± 17 and 40 ± 10 signal events. After accounting for detector and selection sculpting of the angular distribution and background contaminations, a four dimensional (the three transversity angles plus the reconstructed B mass) unbinned maximum likelihood fit yields the following matrix elements:

$$\begin{aligned}
A_0 &= 0.770\pm0.039\pm0.012 \\
A_{||} &= (0.530\pm0.106\pm0.034)e^{i\,(2.16\pm0.46\pm0.10)} \\
A_\perp &= (0.355\pm0.156\pm0.039)e^{i\,(-0.56\pm0.53\pm0.12)} \qquad (3)
\end{aligned}$$

for $B^0\to J/\psi K^{*0}$;

$$\begin{aligned}
A_0 &= 0.778\pm0.090\pm0.012 \\
A_{||} &= (0.407\pm0.232\pm0.034)e^{i\,(1.12\pm1.29\pm0.11)} \\
|A_\perp| &= (0.478\pm0.202\pm0.040) \qquad (4)
\end{aligned}$$

for $B_s^0\to J/\psi\phi$. One sigma contours are shown in Fig.3. Notice that, since there is an arbitrary common phase to the three matrix elements, we are free to choose A_0 on the positive real axis; furthermore, because we are not interested here in the full decay width, we normalize the quadratic sum of the moduli of the three amplitudes to one. The result in Eq.3 has similar precision to the latest CLEO mesurement [15]

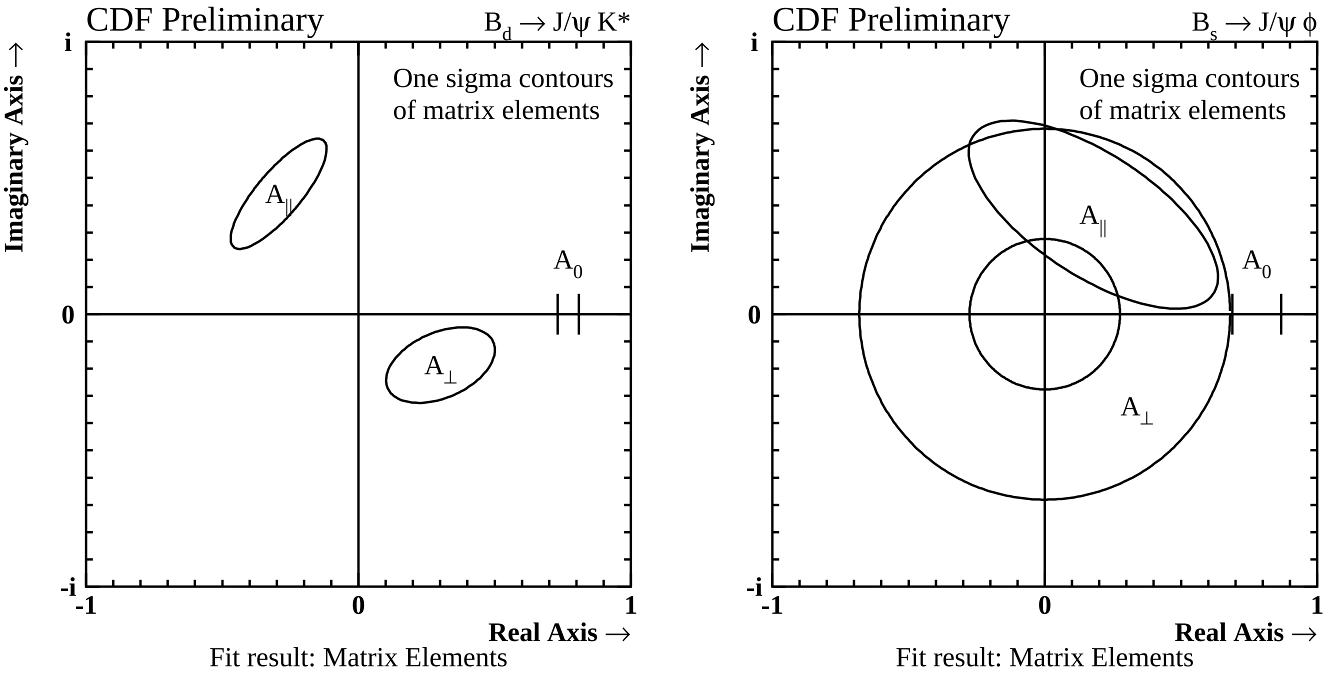

Figure 3: *One sigma contours of fitted matrix elements for decay* $B^0 \rightarrow J/\psi K^{*0}$ *(left) and* $B_s^0 \rightarrow J/\psi\phi$ *(right). Since there is an arbitrary common phase to the three matrix elements we are free to choose* A_0 *on the positive real axis. Notice that, in the right plot, the phase of* $A_\perp$ *is not measured.*

and is also in agreement with it and the previous CDF measurement 16). For the B_s^0, Eq.4 is the first determination of the full decay amplitude. For the CP violation implications, the errors are still large for a reliable determination of the P-odd component contamination, which could be negligible. Finally, a common test of the factorization hypothesis is provided by comparison of measurements of both the longitudinal polarization fractions and the ratios of branching ratios $\mathcal{B}(B \rightarrow J/\psi K^*)/\mathcal{B}(B \rightarrow J/\psi K)$ with theoretical predictions. Earlier results have shown a discrepancy. With new results and better calculations 13) agreement has improved, but the models still do not predict nontrivial matrix element phases.

5 Conclusion

The three measurements reported here are part of CDF's broad program studying b physics in the difficult environment of a hadron collider. We look forward to an even more exciting and rich b physics program in Run II.

References

1. F. Abe *et al*, Nucl. Instrum. Methods **A 271**, 387 (1988); D. Amidei *et al*, Nucl. Instrum. Methods **A 350**, 73 (1994); P. Azzi *et al*, Nucl. Instrum. Methods **A 360**, 137 (1995).
2. E. Braaten, S. Fleming, Phys. Rev. Lett. **74**, 3327 (1995); P. Cho, M. Wise, Phys. Lett. **B346**, 129 (1995); M. Cacciari, M. Greco, M.L. Mangano, A. Petrelli, Phys. Lett. **B356**, 553 (1995); P. Cho, A.K. Leibovich, Phys. Rev. **D 53**, 150 (1996); P. Cho, A.K. Leibovich, Phys. Rev. **D 53**, 6203 (1996).
3. F. Abe *et al*, Phys. Rev. Lett. **79**, 572 (1997).
4. P. Nason, S. Dawson, R.K. Ellis, Nucl. Phys. **B327**, 49 (1988).
5. E. Braaten, M.A. Doncheski, S. Fleming, M.L. Mangano, Phys. Lett. **B333**, 548 (1994); M. Cacciari, M. Greco, Phys. Rev. Lett. **73**, 1586 (1994).
6. P. Cho, M. Wise, Phys. Lett. **B346**, 129 (1995); M. Beneke, M. Kramer, Phys. Rev. **D 55**, 5269 (1997).
7. F. Abe *et al*, Phys. Rev. Lett. **75**, 4358 (1995).
8. P. Cho, A.K. Leibovich, Phys. Rev. **D 53**, 150 (1996); P. Cho, A.K. Leibovich, Phys. Rev. **D 53**, 6203 (1996).
9. S.U. Chung, Spin Formalisms, CERN 71-8.
10. F. Abe *et al*, Phys. Rev. Lett. **79**, 578 (1997).
11. Particle Data Group, C. Caso *et al*, Eur. Jour. Phys. **C 3**, 1 (1998).
12. A.S. Dighe, I. Dunietz, H.J. Lipkin, J.L. Rosner, Phys. Lett. **B369**, 144 (1996).
13. M. Gourdin, A.N. Kamal, X.Y. Pham, Phys. Rev. Lett. **73**, 3355 (1994); H.Y. Cheng, hep-ph/9610283.
14. A.S. Dighe, S. Sen, Phys. Rev. **D59**, 074002 (1999).
15. C.P. Jessop *et al*, Phys. Rev. Lett. **79**, 4533 (1997).
16. F. Abe *et al*, Phys. Rev. Lett. **75**, 3068 (1995).