χ_c production and search for the B_c meson at LEP.

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The inclusive χ_c production in Z decays has been measured by the L3 experiment at LEP, investigating the decay channel $\chi_c \to J/\psi\,\gamma$ with $J/\psi \to \ell^+\ell^-$. The observed χ_c to J/ψ production ratio is compared to recent quarkonium production models. Searching for $B_c^\pm \to J/\psi \ell^\pm \nu$ and $B_c^\pm \to J/\psi \pi^\pm(\pi^+\pi^-)$ decays, upper limits on B_c production in Z decays have been set by the four LEP Collaborations. New limits on $B \to J/\psi\eta(\pi^\circ)$ and $B \to \ell^+\ell^-$ decays are also reported.

1. Introduction

The study of χ_c production in B decays aims to improve our knowledge of quarkonium production processes. It could reveal the relevance of the so-called "color-octet mechanism" [1,2], recently addressed to explain the rate of "direct" quarkonium measured by CDF and by LEP experiments [3].

According to most optimistic predictions, the integrated luminosity collected by LEP could be sufficient to observe a few $B_c^\pm \to J/\psi\ell^\pm\nu$ or $B_c^\pm \to J/\psi\pi^\pm(\pi^+\pi^-)$ events. Discovery of the B_c meson would confirm potential model and lattice predictions, opening a window towards physics at future hadron machines.

A sizeable rate of $B \to J/\psi\pi^\circ(\eta)$ decays would disclose cracks in the factorisation approach to B decays; the observation of flavour changing neutral currents: $B \to \ell^+\ell^-$ would be evidence for physics beyond the Standard Model.

2. Measurement of $\mathrm{Br}(Z \to \chi_c + X)$.

The dominant mechanism for producing χ_c states at LEP is via the decay of a b hadron in $Z \to b\bar{b}$ events. A minor contribution, between 5% and 10% of the inclusive $\mathrm{Br}(Z \to \chi_c + X)$, can be expected from fragmentation processes [4–6].

In the framework of the color-singlet model [7] it has been calculated [8]: $\mathrm{Br}(b \to \chi_c + X) \simeq (0.5-5)\,10^{-3}$, where large QCD uncertainties are due to the choice of the QCD scale, the quark masses and Λ_{QCD}. A reduced sensitivity to QCD details is expected in the ratio: $R_\chi \equiv \mathrm{Br}(b \to \chi_{c1} + X)/\mathrm{Br}(b \to J/\psi + X)$, which (considering χ_c and ψ' decays to J/ψ) is predicted to be: $R_\chi \simeq 0.2$. When the gluon exchange is neglected, creation of χ_{c2} states is strongly suppressed. If, however, other models for quarkonia production are considered, like the color-evaporation model [7] or the color-octet model, χ_{c2} production is allowed, and an enhanced χ_{c1} yield can be expected.

In the framework of the color-evaporation model comparable χ_{c1} and J/ψ rates are predicted, and the relative yield of χ_{cJ} states mimics the angular-momentum multiplicity: $N(\chi_{c0}) : N(\chi_{c1}) : N(\chi_{c2}) = 1 : 3 : 5$.

According to the color-octet model P-wave charmonium states can arise from collinear $(c\bar{c})$ pairs both in a color singlet P-wave state and in a color-octet S-wave state [9]. Color-singlet and color-octet matrix elements contribute to χ_{c1} creation at the same perturbative order. χ_{c0} and χ_{c2} production is allowed through the color-octet matrix elements.

L3 have measured the inclusive χ_c meson production in Z decays, via $\chi_c \to J/\psi\,\gamma$. In a sample of 3 million hadronic Z decays, collected between 1991 and 1994, J/ψ candidates were reconstructed in their decays into $\mu^+\mu^-$ or e^+e^- pairs. In figure 1 the invariant mass spectra are shown. Performing an unbinned maximum likelihood fit, 205 ± 22 $J/\psi \to \mu^+\mu^-$ and 198 ± 20 $J/\psi \to e^+e^-$

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decays were counted.

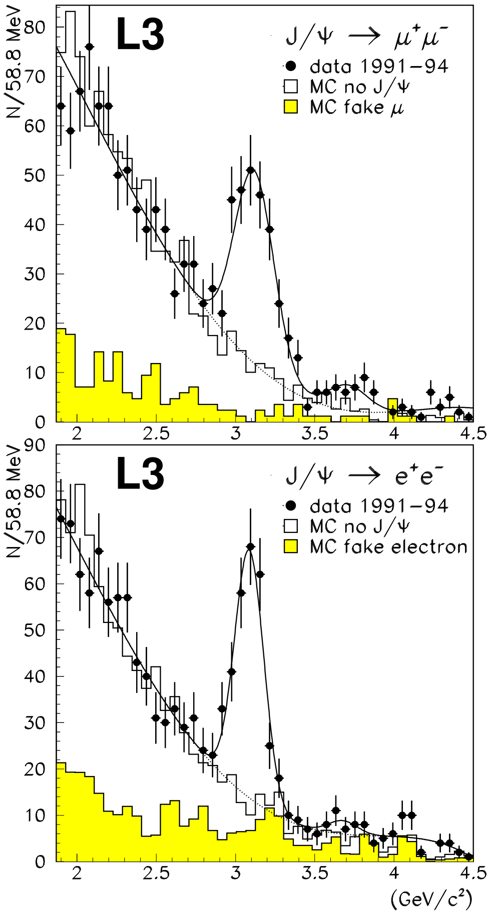

Figure 1. Invariant mass spectra for e^+e^- and $\mu^+\mu^-$ selected pairs both in data (points) and $q\overline{q}$ background Monte Carlo (histogram).

Dilepton pairs inside the 3σ window from the J/ψ mass were combined with photons of more than 1.1 GeV energy found in a cone of less than 40° around the reconstructed J/ψ direction.

The χ_c signal was searched in the $M(J/\psi\,\gamma) - M(J/\psi)$ spectrum inside the (357–470) MeV/c^2 invariant mass window (see figure 2). The background shape was modelled through $b \rightarrow J/\psi + X$ Monte Carlo events, mixed to data events selected from the side bands of the J/ψ mass region and to $e^\pm\mu^\mp$ pairs.

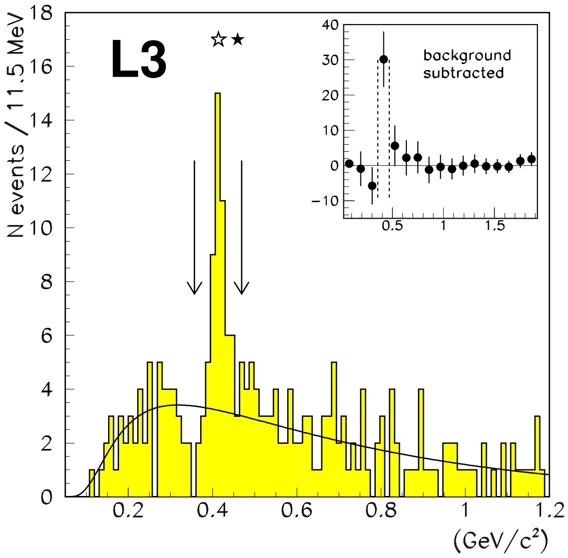

Figure 2. $M(J/\psi\,\gamma) - M(J/\psi)$ spectrum. The arrows delimit the signal region. The empty and the full stars mark the position where (respectively) the χ_{c1} and the χ_{c2} signals can be expected. In the inset the background subtracted distribution is shown.

After background subtraction, 30.2 ± 7.8 χ_c candidates were observed. The signal shape is consistent with $\chi_{c1} \rightarrow J/\psi\,\gamma$ decays from the Monte Carlo. The acceptance (including the J/ψ efficiency) was calculated to be $\varepsilon_{\chi_c} = (8.2 \pm 0.3)\%$. Attributing the signal to χ_{c1} states (and allowing for χ_{c2} contamination in the systematics), the following branching ratio was obtained (preliminary):

$$\mathrm{Br}(Z \rightarrow \chi_{c1} + X) = (2.7 \pm 0.7 \pm 0.6) \times 10^{-3}\,.$$

Assuming that all the observed χ_c states were produced in the decay of a b hadron, the inclusive branching ratio:

$$\mathrm{Br}(b \rightarrow \chi_{c1} + X) = (0.87 \pm 0.23 \pm 0.19)\,\%$$

was calculated, consistent with other current measurements (shown in Table 1). The ratio:

$$R_\chi \equiv \frac{\mathrm{Br}(b \rightarrow \chi_{c1} + X)}{\mathrm{Br}(b \rightarrow J/\psi + X)} = (0.84 \pm 0.22 \pm 0.17)\,\%$$

was obtained, which is in excess with respect to the color-singlet model expectation $R_\chi \simeq 0.2$.

Table 1
Measurements of $Br(b \rightarrow \chi_c + X)$ [10].

Experiment	$Br(b \rightarrow \chi_c + X)$
L3 (prelim.)	$(0.87 \pm 0.23 \pm 0.19)\%$
ARGUS	$(1.23 \pm 0.41 \pm 0.29\%)$
CLEO	$(0.40 \pm 0.06 \pm 0.04\%$
DELPHI	$(1.4 \pm 0.6^{+0.4}_{-0.2})\%$
L3	$(2.4 \pm 0.9 \pm 0.2\%)$

3. Search for the B_c meson.

B_c^+ mesons are the bound state of a c quark and a $\overline{b}$ quark. A rich spectrum of $(c\overline{b})$ bound states has been predicted through potential models and lattice calculations [11]. The mass of the ground state is $m_{B_c(1S)} = (6.258 \pm 0.020)$ GeV/c^2 and its lifetime between 0.2 and 1.5 ps. It has been computed that more than 460 $B_c(1S)$ mesons can be produced every million hadronic Z decays, when the production of $B_c^*(1S)$, $B_c(2S)$ and $B_c^*(2S)$ states decaying to the 1S state is considered [12].

The four LEP collaborations have performed searches looking at the exclusive decay modes: $B_c^\pm \rightarrow J/\psi\pi^\pm$ and $B_c^\pm \rightarrow J/\psi\pi^\pm\pi^+\pi^-$ (whose branching ratios are expected between 0.2% and 0.4%) and $B_c^\pm \rightarrow J/\psi\ell^\pm\nu$ (with a branching predicted around 3%) [13–16]. The first two channels allow the direct measurement of the B_c mass, while the second one has more chances as a discovery channel.

Defining: $F^h_{B_c} = \Gamma(Z \rightarrow B_c + X)/\Gamma(Z \rightarrow q\overline{q})$ and considering predictions which can be found in literature for both the production and the decay rates [17], the following theoretical range can be inferred:

$$1.6\,10^{-6} \leq F^h_{B_c}\, Br(B_c^\pm \rightarrow J/\psi\ell^\pm\nu) \leq 2.5\,10^{-5}.$$

The signature is a $J/\psi \rightarrow \ell^+\ell^-$ decay with a third "hard" lepton (or $\pi^\pm$) coming from the same vertex. Main background processes are "fake" J/ψ from $b \rightarrow c\ell^-\nu; c \rightarrow \ell^+\nu X$ cascade decays, $B \rightarrow J/\psi K(\pi^+\pi^-)$, $B \rightarrow J/\psi K^*$ exclusive decays, and random $J/\psi\,\ell^\pm$, $(J/\psi\,\pi^\pm)$ combinations.

Selection strategies rely on kinematical cuts, tight lepton identification requirements, vertexing of the J/ψ and the lepton (or the $\pi^\pm$). The displacement between the primary event vertex and the B_c candidate decay vertex can be used to constraint the B_c direction and improve (in the $B_c^\pm \rightarrow J/\psi\ell^\pm\nu$ channel) the reconstruction of the B_c mass. When cuts on the B_c decay length are applied, limits dependent on the supposed B_c lifetime are obtained.

3.1. $B_c^\pm \rightarrow J/\psi\ell^\pm\nu$.

In a sample of 3.9 million hadronic Z decays collected in 1991-95, ALEPH selected around 700 $J/\psi \rightarrow \ell^+\ell^-$ candidates. These were combined to leptons forming a common vertex with the J/ψ and with a total $(J/\psi\,\ell)$ momentum exceeding 10 GeV/c. The mass of the B_c candidate was estimated assigning the measured missing energy in the J/ψ hemisphere to the neutrino and averaging over a neutrino flat angular distribution in the B_c rest frame; $M^{rec}_{B_c} > 4.8$ GeV/c^2 was required. With 0.36 and 0.28 expected background events respectively in the electron and in the muon channel, and 10% efficiency in both channels, two candidate events were observed and the $F^h_{B_c} Br(B_c^\pm \rightarrow J/\psi\ell^\pm\nu) < 5\,10^{-5}$ 90%c.l. limit was derived by combining the two channels and conservatively making no background subtraction.

Both candidates were found to be consistent with being background events. A separate study selected an interesting $B_c \rightarrow J/\psi\,\mu^+\nu_\mu$ candidate (which fails the standard selection, due to the muon escaping the muon chambers acceptance), which presents a three-jet topology and a well displaced secondary vertex, with a reconstructed B_c mass of $5.96^{+0.25}_{-0.19}$ GeV/c^2.

In a search performed by the L3 experiment, J/ψ selected in a sample of 3 million hadronic Z decays, collected between 1991 and 1994, were combined to leptons inside a cone of 40° from the J/ψ direction. Strong lepton identification criteria were applied, and the transverse momentum with respect to the jet the J/ψ belongs to had to exceed 0.75 GeV/c. Requiring the J/ψ - lepton invariant mass to be inside the (4-6.5) GeV/c^2 window, one candidate event was observed (consistent with background expectations, but well inside the acceptance cuts), and the $F^h_{B_c}$ Br($B_c^\pm \to J/\psi\ell^\pm\nu$) $<$ 6.6 10^{-5} 90% c.l. limit was derived.

Table 2
Upper limits at the 90% confidence level on $F^h_{B_c}$ Br($B_c^\pm \to J/\psi\ell^\pm\nu$), $F^h_{B_c}$ Br($B_c^\pm \to J/\psi\pi^\pm$) and $F^h_{B_c}$ Br($B_c^\pm \to J/\psi\pi^\pm\pi^+\pi^-$). In the rightmost column the number of the observed candidates is reported. DELPHI result is related to a B_c meson lifetime in the (0.4 − 1.4) ps range.

Experiment		limit	cand.
		$F^h_{B_c}$ ($B_c^\pm \to J/\psi\ell^\pm\nu$)	
ALEPH	(91 − 95)	5 10^{-5}	2
DELPHI	(91 − 94)	(8.3 − 7.1) 10^{-5}	–
L3	(91 − 94)	6.6 10^{-5}	1
		$F^h_{B_c}$ ($B_c^\pm \to J/\psi\pi^\pm$)	
ALEPH	(91 − 95)	3 10^{-5}	–
DELPHI	(91 − 94)	(1.5 − 1.2) 10^{-4}	1
OPAL	(90 − 94)	9 10^{-5}	1
		$F^h_{B_c}$ ($B_c^\pm \to J/\psi\pi^\pm\pi^+\pi^-$)	
DELPHI	(91 − 94)	2.5 10^{-4}	1

3.2. $B_c^\pm \to J/\psi\pi^\pm(\pi^+\pi^-)$.

Over a sample of 3 million hadronic Z decays collected between 1991 and 1994, DELPHI selected around 270 $J/\psi \to \ell^+\ell^-$candidates with the $\ell^+\ell^-$vertex displaced from the primary event vertex with a significance of at least 2σ in the azimuthal plane. Charged particles consistent with the $\pi^\pm$ hypothesis and associated to the $\ell^+\ell^-$vertex were combined to the J/ψ. $J/\psi\,\pi^\pm(\pi^+\pi^-)$ combinations in the M[$J/\psi\pi^\pm(\pi^+\pi^-)$] $\in$ (6.0, 6.5) GeV/c^2 (for $J/\psi \to \mu^+\mu^-$) and M[$J/\psi\pi^\pm(\pi^+\pi^-)$] $\in$ (5.8, 6.7) GeV/c^2 (for $J/\psi \to e^+e^-$) invariant mass region were accepted as B_c candidates if the angle in the azimuthal plane between the line joining the primary and the J/ψ vertices and the reconstructed B_c momentum vector was less than 10°. Events consistent with $B \to J/\psi K\,(n\,\pi)$ decays were rejected.

Two candidates were found. One in the $B_c \to \mu^+\mu^-\pi^-$ channel, with a reconstructed invariant mass of (6340.6 ± 26.8) MeV/c^2 and a proper decay time of (0.38 ± 0.06) ps. The other in the $B_c \to \mu^+\mu^-\pi^-\pi^+\pi^-$ channel, with M($J/\psi\,\pi^-\pi^+\pi^-$) = (6119.2 ± 22.2) MeV/c^2 and a proper decay time of (0.41 ± 0.07) ps. They were consistent with being background events, and 90% confidence level upper limits were set, as reported in table 2.

Another $B_c \to J/\psi\pi^\pm$ candidate has been observed by OPAL, with a mass of (6.31 ± 0.17 ± 0.01) GeV/c^2. It is consistent with the expected background and, allowing for the 19% systematical error on the efficiency (mainly due to knowledge of the B_c momentum distribution), the $F^h_{B_c}$ Br($B_c^\pm \to J/\psi\,\pi^\pm$) $<$ 9 10^{-5} 90% c.l. limit was set.

In table 2 results of B_c searches at LEP are summarised. A few interesting events have been reported, but no definite evidence for signal. In the $B_c^\pm \to J/\psi\ell^\pm\nu$ channel, the limits are close to most optimistic theoretical predictions.

4. Search for the exclusive B decays: $B^\circ \to J/\psi\,\eta$ and $B^\circ \to J/\psi\,\pi^\circ$

B decays to a J/ψ plus a pseudo-scalar meson provide a clean environment to the study of factorization and color suppression in B decays. Predictions for the branching ratios range from (1.0 ± 0.4) 10^{-3} for $B_s \to J/\psi\,\eta$ down to (1.0 ± 0.4) 10^{-5} for $B_d \to J/\psi\,\eta$ [18,19], but (as explained in [20]) significantly enhanced values could derive from non-factorized terms. L3 has performed a search for these decays over a data sample of around 3.5 million hadronic Z decays collected between 1991 and 1995 [16,21]. η and π° were detected through their decays into photon pairs and combined to $J/\psi \to \ell^+\ell^-$ candidates when the total $J/\psi\eta$ (π°) energy exceeded 20 GeV. In Figure 3 the invariant mass spectra for the data and the Gaussian fits to the simulated

signal are shown. No candidate event was found for any of the final configurations and upper limits at 90% confidence level have been set as:
$\mathrm{Br}(\mathrm{B_d^0} \to \mathrm{J}/\psi\,\pi^\circ) < 3.2\,10^{-4}$
(consistent with the more stringent limit set by CLEO [22]) and:
$\mathrm{Br}(\mathrm{B_d^0} \to \mathrm{J}/\psi\,\eta) \;< 1.2\,10^{-3}$,
$\mathrm{Br}(\mathrm{B_s^0} \to \mathrm{J}/\psi\,\eta) \;< 3.8\,10^{-3}$,
$\mathrm{Br}(\mathrm{B_s^0} \to \mathrm{J}/\psi\,\pi^\circ) < 1.2\,10^{-3}$,
which are the first experimental limits.

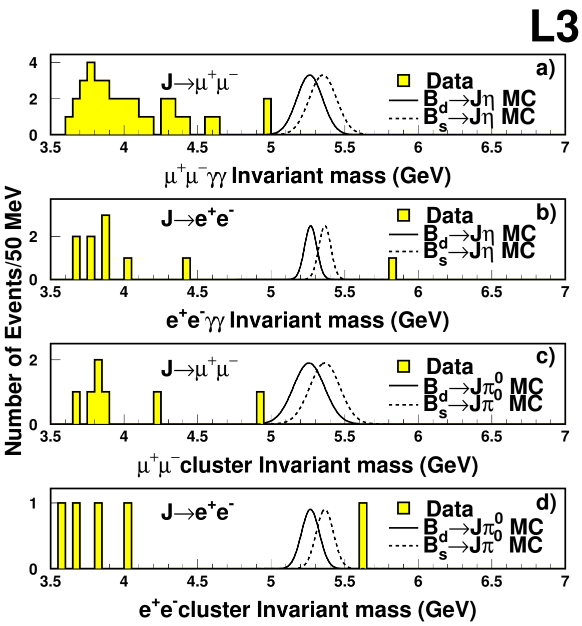

Figure 3. Invariant mass spectra for data (histogram) and Gaussian fits to the simulated signal (arbitrary units). a) $\mathrm{B}^\circ \to \mathrm{J}/\psi\eta \to \mu^+\,\mu^-\gamma\gamma$. b) $\mathrm{B}^\circ \to \mathrm{J}/\psi\eta \to e^+\,e^-\gamma\gamma$. c) $\mathrm{B}^\circ \to \mathrm{J}/\psi\pi^\circ \to \mu^+\,\mu^-$cluster. d) $\mathrm{B}^\circ \to \mathrm{J}/\psi\pi^\circ \to e^+\,e^-$cluster.

5. Search for $\mathrm{B_d^\circ}/\mathrm{B_s^\circ} \to \mathrm{e^+e^-}/\mu^+\mu^-/\mathrm{e}^\pm\mu^\mp$ decays

In the Standard Model the flavour-changing neutral current decays: $\mathrm{B}^\circ \to \mu^+\mu^-$ and $\mathrm{B}^\circ \to \mathrm{e^+e^-}$ can occur only through processes beyond the tree-level, with branching fractions of less than $\mathcal{O}(10^{-9})$ [23]. The lepton number violating $\mathrm{B}^\circ \to \mathrm{e}^\pm\mu^\mp$ decay is forbidden. Observation of any of these decays at LEP would be indication for physics beyond the Standard Model. L3 has performed a search for these decay modes [16,24] selecting hadronic decays of the Z with two oppositely-charged leptons with opening angle of less than 90° and a combined energy of more than 20 GeV. In Figure 4 the expected invariant mass distributions for the signal and the mass spectra obtained from the data are shown. No clear signal is seen for $\mathrm{B^0_{d,s}} \to \mathrm{e^+e^-}$, $\mathrm{B^0_{d,s}} \to \mu^+\mu^-$, or $\mathrm{B^0_{d,s}} \to \mathrm{e}^\pm\mu^\mp$ decays. Performing a binned maximum likelihood fit to the $\ell^+\ell^-$ invariant mass distributions the following upper limits at the 90% (95%) c.l. (allowing for systematic errors) have been obtained:
$\mathrm{Br}(\mathrm{B_d^0} \to \mathrm{e^+e^-}\,) \;< 1.4\,(1.8)\,10^{-5}$,
$\mathrm{Br}(\mathrm{B_d^0} \to \mu^+\mu^-\,) < 1.0\,(1.4)\,10^{-5}$,
$\mathrm{Br}(\mathrm{B_d^0} \to \mathrm{e}^\pm\mu^\mp\,) < 1.6\,(2.0)\,10^{-5}$,
$\mathrm{Br}(\mathrm{B_s^0} \to \mu^+\mu^-\,) < 3.8\,(5.1)\,10^{-5}$,
which are consistent with the slightly more stringent limits from CLEO and CDF [25], and:
$\mathrm{Br}(\mathrm{B_s^0} \to \mathrm{e^+e^-}\,) \;< 5.4\,(7.0)\,10^{-5}$,
$\mathrm{Br}(\mathrm{B_s^0} \to \mathrm{e}^\pm\mu^\mp\,) < 4.1\,(5.3)\,10^{-5}$,
which are the first limits set on these decay modes.

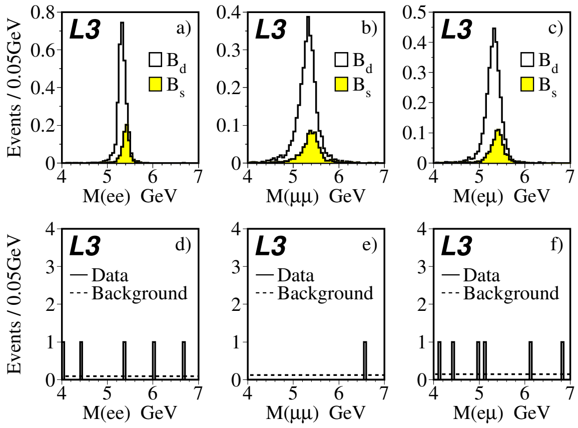

Figure 4. Predictions for a) $\mathrm{e^+e^-}$, b) $\mu^+\mu^-$, and c) $\mathrm{e}^\pm\mu^\mp$, invariant mass simulated distributions. Mass spectra obtained from the data (solid line) for d) $\mathrm{e^+e^-}$, e) $\mu^+\mu^-$, and f) $\mathrm{e}^\pm\mu^\mp$; the dashed lines show the background predicted by Monte Carlo.

6. Conclusions

The inclusive production of χ_c meson in Z decays has been measured by L3; the observed χ_c to J/ψ production ratio is higher than the color-singlet model expectation.

Exploiting the $B_c^\pm \rightarrow J/\psi\, \pi^\pm\, (\pi^+\pi^-)$ and $B_c^\pm \rightarrow J/\psi \ell^\pm \nu$ decay channels, the four LEP collaborations have searched for the B_c meson production in Z decays. Consistent results have been obtained, and few candidate events (consistent with background expectations) are observed. In the $B_c^\pm \rightarrow J/\psi \ell^\pm \nu$ channel, limits close to the theoretical threshold are set.

Searching for $B^\circ \rightarrow J/\psi\eta\, , B^\circ \rightarrow J/\psi\pi^\circ$ and $B^\circ \rightarrow \ell^+\,\ell^-$ exclusive decays, no signal has been observed by L3, and the first limits on $B_d^0 \rightarrow J/\psi\eta$, $B_s^0 \rightarrow J/\psi\eta$, $B_s^0 \rightarrow J/\psi\pi^\circ$, $B_s^0 \rightarrow e^+e^-$ and $B_s^0 \rightarrow e^\pm\mu^\mp$ decays have been set.

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