Charmonium and Bottomonium Production in the L3 detector

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The production of quarkonium states at high energy provides quite stringent test of our understanding of both short-distance and long-distance aspects of quantum choromodynamics. In this article we review the status of charmonium and bottomonium production at LEP.

1. Charmonium Production

The dominant production mechanism of charmonium at LEP is predicted to be the decay of a b hadron in $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ events followed by the decay of $\mathrm{b} \rightarrow \mathrm{J}/\psi(\psi', \chi_\mathrm{c}) + \mathrm{X}$. This decay probes the color suppressed spectator diagram as shown in figure 1, where c and $\bar{c}$ have to match in color. A minor contribution is expected to be prompt,

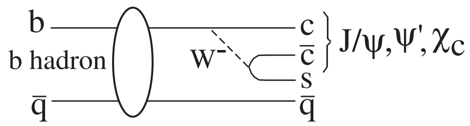

Figure 1. *First order contribution to Charmonium production in decay of b-hadron* $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ *events.*

deriving from the fragmentation of a gluon or a c-quark in $\mathrm{Z} \rightarrow \mathrm{q\bar{q}}$ decays. The calculation of $\mathrm{Br}(\mathrm{b} \rightarrow \mathrm{J}/\psi + \mathrm{X})$ suffers from large QCD uncertainties; the results range from 0.2% to 2% [1–4]. Estimates for the rate of prompt J/ψ production $\mathrm{Br}(\mathrm{Z} \rightarrow \mathrm{J}/\psi + \mathrm{X})_\mathrm{p}$ vary from 1×10^{-4} to 4×10^{-4} [5–11].

The interest on quarkonium production has been recently renewed by measurements at the TEVATRON collider [12,13], which give prompt quarkonium cross sections much higher than predicted by first order color singlet model calculations [14–16]. It has been shown in references [17–19] that the inclusion of color-octet contribution [20–22] is able to reproduce both the rate and the observed p_t spectrum of $\mathrm{c\bar{c}}$ bound states. Features distinctive of the color-octet contribution could show up in the decays of b hadrons into χ_c states, where both color-singlet and color-octet matrix elements contribute at first order [20]. The production of χ_{c1} states could be significantly enhanced, as would be revealed by the value of: $\mathrm{R}^\mathrm{b}_{\chi_{c1}} = \mathrm{Br}(\mathrm{b} \rightarrow \chi_{c1} + \mathrm{X})/\mathrm{Br}(\mathrm{b} \rightarrow \mathrm{J}/\psi + \mathrm{X})$, where most of QCD uncertainties cancel out, which in the color singlet model is computed to be $\mathrm{R}^\mathrm{b}_{\chi_{c1}} \simeq 0.2$ [2]. The production of χ_{c0} and χ_{c2} states, which is strongly suppressed in the color singlet model framework [1], would proceed at first order through the color-octet matrix elements. Since the χ_{c2} has a non-negligible branching fraction into $\mathrm{J}/\psi\,\gamma$, its production could result in a visible signal close to the χ_{c1} peak. Moreover, the observation of a large χ_{c2} signal would validate another model of charmonium production,the color evaporation model [23].

An update of our previous analysis [24] has been performed on 3.2 million hadronic events collected by the L3 detector in the years from 1991 through 1994. The J/ψ mesons are reconstructed through their decays into lepton pairs. The invariant mass spectra of the selected $\mu^+\mu^-$ and $\mathrm{e^+e^-}$ pairs are shown in the figure 2. Fitting these spectra with an unbinned maximum-likelihood; we obtain 241±25 $\mathrm{J}/\psi \rightarrow \mu^+\mu^-$ and 200±18 $\mathrm{J}/\psi \rightarrow \mathrm{e^+e^-}$ decays, together with 27±10 $\psi' \rightarrow \mu^+\mu^-$ and 12±7 $\psi' \rightarrow \mathrm{e^+e^-}$ candidates. The resulting mass values and resolutions for the J/ψ signal are in agreement with

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[2]as can be derived from [1] after accounting for the feed-down from χ_c and ψ' decays into J/ψ.

the expectations from the Monte Carlo.

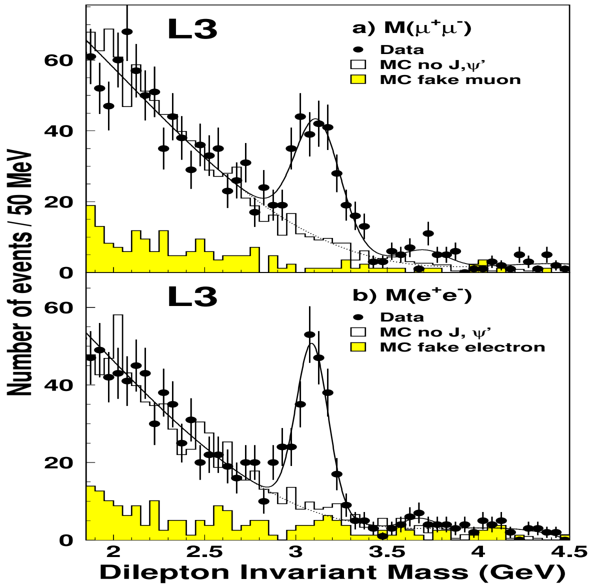

Figure 2. *(a) Invariant mass spectrum of $\mu^+\mu^-$ and (b) $\mathrm{e^+e^-}$ selected pairs. The line represents the result of the unbinned maximum-likelihood fit.*

From the number of reconstructed $\mathrm{J}/\psi \to \ell^+\ell^-$ and $\psi^{'} \to \ell\ell$ decays we measure

$$\boxed{\begin{array}{ll}\mathrm{Br(Z \to J/\psi + X)} &= (3.40 \pm 0.23 \pm 0.27) \times 10^{-3} \\ \mathrm{Br(Z} \to \psi^{'} + \mathrm{X)} &= (1.60 \pm 0.50 \pm 0.30) \times 10^{-3}\end{array}}$$

The first error is due to statistics and second is systematic. The details of the systematic error can be found in [25]. The branching fractions $\mathrm{Br(b \to J/\psi + X)}$ and $\mathrm{Br(b} \to \psi^{'} + \mathrm{X)}$ can be evaluated, taking into account the J/ψ and $\psi^{'}$ not produced in b-decays. We use: $\mathrm{Br(b \to J/\psi + X)_{prompt}} = (2 \pm 2) \times 10^{-4}$ and $\mathrm{Br(b} \to \psi^{'} + \mathrm{X)_{prompt}} = (1 \pm 1) \times 10^{-4}$,we derive:

$$\boxed{\begin{array}{ll}\mathrm{Br(b \to J/\psi + X)} &= (1.06 \pm 0.08 \pm 0.11) \times 10^{-2} \\ \mathrm{Br(b} \to \psi^{'} + \mathrm{X)} &= (0.46 \pm 0.16 \pm 0.08) \times 10^{-2}\end{array}}$$

These results are consistent with other LEP measurements and $\Upsilon(4S)$ as shown in figure 3.

Inclusive χ_c are reconstructed via the decay mode $\chi_\mathrm{c} \to \mathrm{J}/\psi + \gamma$. Dilepton pairs inside the 3σ window from the J/ψ mass were combined with photons of more than 1.1 GeV energy found in the

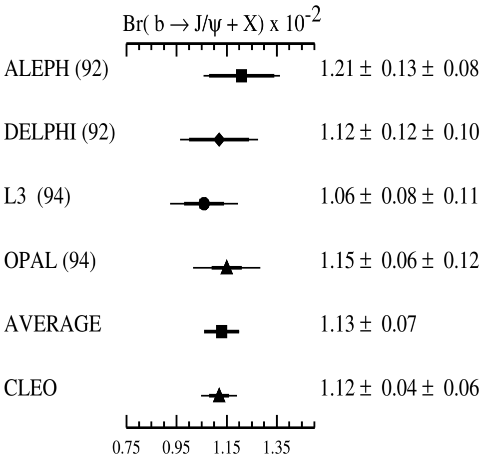

Figure 3. *Measurements of* $\mathrm{Br(b \to J/\psi + X)}$ *at LEP and* $\Upsilon(4\mathrm{s})$*. The* χ^2 *of the average is 2.52 for 3 d.o.f. The errors are added in quadrature and assumed to be uncorrelated.*

cone of less than 40° around the reconstructed J/ψ direction. The χ_{c1} candidates are selected in the $\mathrm{M}(\ell^+\ell^-\gamma) - \mathrm{M}(\ell^+\ell^-) = (414 \pm 56)$ MeV mass difference window, which is centred around the $\mathrm{M}(\chi_{\mathrm{c1}}) - \mathrm{M(J}/\psi)$ expected value. Figure 4 shows the measured $\mathrm{M}(\ell^+\ell^-\gamma) - \mathrm{M}(\ell^+\ell^-)$ spectrum. After background subtraction, the number of observed χ_{c1} candidates is 32.8 ± 8.0. The signal shape is consistent with the Monte Carlo prediction. The acceptance was calculated to be $(8.1 \pm 0.3)\%$.

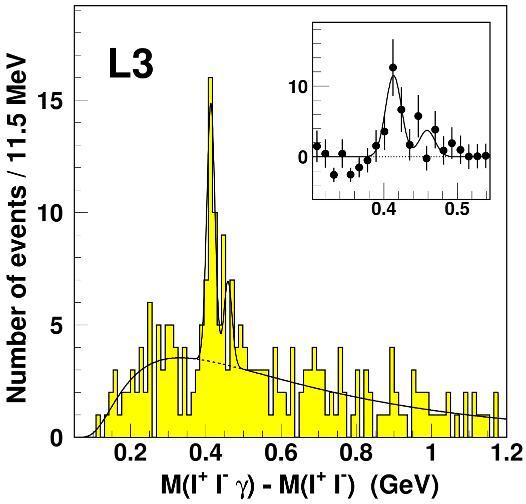

Figure 4. *Maximum likelihood fit to the* $M(\ell^+\ell^-\gamma) - M(\ell^+\ell^-)$ *mass difference spectrum. In the insert the background-subtracted distribution of the signal region is shown.*

From the observed number of χ_{c1} candidates, we drive:

$$\boxed{\begin{array}{ll}\mathrm{Br}(\mathrm{Z} \rightarrow \chi_{c1} + \mathrm{X}) & = (2.7 \pm 0.6 \pm 0.5) \times 10^{-3} \\ \mathrm{Br}(\mathrm{b} \rightarrow \chi_{c1} + \mathrm{X}) & = (0.84 \pm 0.20 \pm 0.16) \times 10^{-2} \\ \mathrm{R}^{\mathrm{b}}_{\chi_{c1}} & = 0.80 \pm 0.19 \pm 0.14\end{array}}$$

The $\mathrm{R}^{\mathrm{b}}_{\chi_{c1}}$ ratio is higher than expected from first order color singlet calculations and probably suggests the existence of additional mechanisms of quarkonium production. We also search for the possibility of a χ_{c2} signal, performing unbinned maximum likelihood fit to the $\mathrm{M}(\ell^+\ell^-\gamma) - \mathrm{M}(\ell^+\ell^-)$ distribution with two gaussian shapes for the χ_{c1} and χ_{c2} signal. The number of χ_{c1} and χ_{c2} candidates found by the fit are $30.1^{+7.7}_{-7.0}$ and $8.8^{+5.4}_{-4.6}$ respectively. The number of χ_{c1} candidates found by the fit are in agreement with the earlier method. For non observation of excess for χ_{c2} state, an upper limit at 90% CL has been set

$$\boxed{\mathrm{Br}(\mathrm{Z} \rightarrow \chi_{c2} + \mathrm{X}) < 3.2 \times 10^{-3}}$$

A comparison of our results with other measurements is shown in Figure 5.

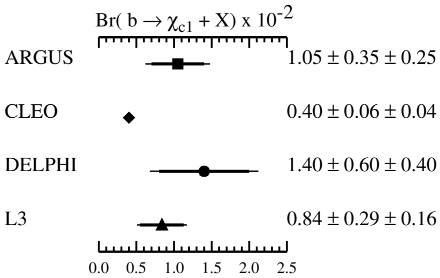

Figure 5. *Measurements of* $\mathrm{Br}(\mathrm{b} \rightarrow \chi_{c1} + \mathrm{X})$ *at LEP and* $\Upsilon(4\mathrm{S})$.

2. Bottomonium Production

Recent theoretical predictions for Υ^3 production in hadronic Z decays (see Table 1) suggest that each LEP experiment should be able to observe a few Υ events using the decay modes $\Upsilon \rightarrow \ell^+\ell^-$, where $\ell^+\ell^-$ denotes either $\mathrm{e^+e^-}$ or $\mu^+\mu^-$. Such an observation would support the novel color-octet contribution which have been invoked to explain the anomalously high Υ production rates observed by the CDF Collaboration[26]. The search for Υ production has been performed with a sample of approximately 3.5 million hadronic Z events acquired during 1991-1995 at $\sqrt{s} \approx M_{\mathrm{Z}}$. We have considered five distinct mechanisms for the production of (unpolarised) Υ's in Z decays. Table 1 shows the predicted branching ratios, $\mathrm{Br}(\mathrm{Z} \rightarrow \Upsilon\mathrm{X})$, for the color-singlet (1–3) and color-octet (4–5) processes.

[3] Throughout this report, we use Υ to denote the three states $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(3\mathrm{S})$.

Υ production mechanism	$\mathrm{Br}(\mathrm{Z} \rightarrow \Upsilon\mathrm{X}) \times 10^5$	
1. $\mathrm{Z} \rightarrow \Upsilon\mathrm{bb}$	1.6	[7,6,11]
2. $\mathrm{Z} \rightarrow \Upsilon\mathrm{q\bar{q}gg}$	0.07	[27,5]
3. $\mathrm{Z} \rightarrow \Upsilon\mathrm{gg}$	0.05	[28–30]
4. $\mathrm{Z} \rightarrow \Upsilon\mathrm{q\bar{q}}$	4.1	[9,11]
5. $\mathrm{Z} \rightarrow \Upsilon\mathrm{g}$	0.1	[9,11]
Combined model	5.9	

Table 1: Υ *production mechanisms in Z decays and their predicted branching ratios.*

Figure 6 shows the expected dilepton invariant mass distributions for the "combined model" Monte Carlo sample after application of the selection procedure described above for a) $\Upsilon \rightarrow \mathrm{e^+e^-}$, and b) $\Upsilon \rightarrow \mu^+\mu^-$. The shapes of the distributions for each individual Υ sample are similar. The average dilepton invariant mass resolutions are 100 MeV for electrons from $\Upsilon \rightarrow \mathrm{e^+e^-}$ decays and 235 MeV for muons from $\Upsilon \rightarrow \mu^+\mu^-$ decays. Table 2 shows the efficiencies for each Υ production mechanism and decay mode, as determined from the Υ Monte Carlo samples. The efficiencies for the three Υ states differ, for a given model, by typically 0.5% for the $\mathrm{e^+e^-}$ channel and 0.2% for the $\mu^+\mu^-$ channel. This variation is accounted for in the analysis.

Υ production mechanism	$\varepsilon\,(\mathrm{Z} \rightarrow \Upsilon\mathrm{X}; \Upsilon \rightarrow \ell^+\ell^-)$ [%]	
	$\mathrm{e^+e^-}$ channel	$\mu^+\mu^-$ channel
1. $\mathrm{Z} \rightarrow \Upsilon\mathrm{b\bar{b}}$	$37.4 \pm 0.6 \pm 5.0$	$21.2 \pm 0.5 \pm 2.6$
2. $\mathrm{Z} \rightarrow \Upsilon\mathrm{q\bar{q}gg}$	$25.5 \pm 0.6 \pm 3.4$	$14.3 \pm 0.5 \pm 1.7$
3. $\mathrm{Z} \rightarrow \Upsilon\mathrm{gg}$	$32.1 \pm 0.6 \pm 4.3$	$19.6 \pm 0.5 \pm 2.4$
4. $\mathrm{Z} \rightarrow \Upsilon\mathrm{q\bar{q}}$	$33.2 \pm 0.6 \pm 4.4$	$21.2 \pm 0.5 \pm 2.6$
5. $\mathrm{Z} \rightarrow \Upsilon\mathrm{g}$	$41.5 \pm 0.6 \pm 5.5$	$33.3 \pm 0.6 \pm 4.1$

Table 2: Efficiencies for the process $\mathrm{Z} \rightarrow \Upsilon\mathrm{X}; \Upsilon \rightarrow \ell^+\ell^-$. *The first error in each case is statistical and the second is systematic.*

Figure 6 shows the dilepton invariant mass spectra obtained from the data (solid line) for c) e^+e^-, and d) $\mu^+\mu^-$ channels. No evidence is seen for Υ production in either of the decay modes considered. The dashed line represents the background contribution which is estimated from the Monte Carlo sample of hadronic Z and four-fermion events. The average number of background events expected in the mass window of 7–12 GeV is $10.3 \pm 2.0 \pm 1.1$ for the e^+e^- sample and $1.5 \pm 0.1 \pm 0.1$ events for the $\mu^+\mu^-$ sample, where the first error is due to the Monte Carlo statistics and the second is systematic. The number of events observed in the data are five and three for the e^+e^- and $\mu^+\mu^-$ samples respectively, which is consistent with the background.

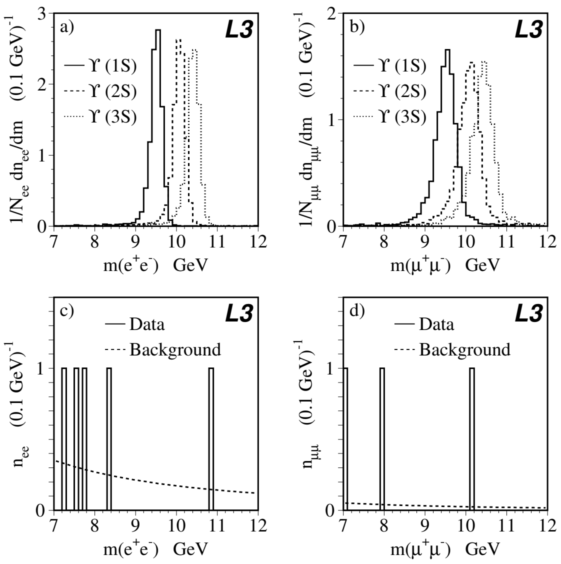

Figure 6. *Predictions for the dilepton invariant mass distributions for a)* $\Upsilon \to e^+e^-$, *and b)* $\Upsilon \to \mu^+\mu^-$ *decays. Invariant mass spectra obtained from the data (solid line) for c)* e^+e^-, *and d)* $\mu^+\mu^-$*; the dashed lines show the background predicted by the Monte Carlo. The number of selected dilepton candidates in a given bin is denoted by* $n_{\ell\ell}$ *(*$\ell = e, \mu$*) while* $N_{\ell\ell}$ *denotes the total number in the sample.*

Table 3 summarises the upper limits obtained at the 95% confidence level (C.L.). The upper limit of $Br(Z \to \Upsilon X) < 7.6 \times 10^{-5}$ is consistent with the theoretical prediction of $Br(Z \to \Upsilon X) = 5.9 \times 10^{-5}$ and previous less stringent upper limits from LEP[31,32]. Consistency with the OPAL measurement of $Br(Z \to \Upsilon X) = (10 \pm 4 \pm 1) \times 10^{-5}$[33] is marginal.

Υ production mechanism	Limits on $Br(Z \to \Upsilon X) \times 10^5$			
	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	Average Υ
1. $Z \to \Upsilon b\bar{b}$	5.4	13.5	9.0	7.4
2. $Z \to \Upsilon q\bar{q}gg$	7.8	16.3	13.0	10.5
3. $Z \to \Upsilon gg$	6.0	14.1	9.9	8.0
4. $Z \to \Upsilon q\bar{q}$	5.5	14.0	9.5	7.6
5. $Z \to \Upsilon g$	3.9	10.3	6.9	5.4
Combined model	5.5	13.9	9.4	7.6

Table 3: Upper limits on the branching ratios for the process $Z \to \Upsilon X$, *at the 95% confidence level. The "Average* Υ*" is an admixture of* $\Upsilon(1S)$, $\Upsilon(2S)$, *and* $\Upsilon(3S)$. *The "combined model" corresponds to the sum of the five* Υ *production mechanisms, weighted according to their predicted rates and reconstruction efficiencies.*

3. Conclusions

The results of $Br(b \to J/\psi + X)$ are in good agreement with the other LEP and CLEO measurements. Where as χ_c production at LEP is higher than expected from color singlet contribution but consistentency with CLEO result is within 1.5 σ. For the bottomonium sector, results from LEP experiments (ALEPH, DELPHI, L3) are consistent with the theoretical prediction but consistency with the OPAL measurement is marginal.

I would like to point out that the situation at LEP is quite confusing. We not only need improvements in the theoretical understanding of perturbative and non-perturbative contribution to QCD but also need to look more carefully the LEP data in details.

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