Υ Production in hadronic Z decays

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Abstract. We have searched for evidence of Υ production in 3.5 million hadronic Z decays collected by the L3 detector at LEP in 1991-1995. No signals are observed for the decay chain $\mathrm{Z} \to \Upsilon\mathrm{X}$; $\Upsilon \to \ell^+\ell^-$ ($\ell = \mathrm{e}, \mu$), therefore upper limits at the 95% confidence level are set on the following Z branching fractions: $\mathrm{Br}\,(\mathrm{Z} \to \Upsilon(1\mathrm{S})\mathrm{X}) < 5.5 \times 10^{-5}$, $\mathrm{Br}\,(\mathrm{Z} \to \Upsilon(2\mathrm{S})\mathrm{X}) < 13.9 \times 10^{-5}$, $\mathrm{Br}\,(\mathrm{Z} \to \Upsilon(3\mathrm{S})\mathrm{X}) < 9.4 \times 10^{-5}$.

Introduction

Recent theoretical predictions for Υ production [2] in Z decays [4] suggest that each LEP experiment should be able to observe a few Υ events using the decay mode $\Upsilon \to \ell^+\ell^-$, where $\ell = e, \mu$. Such an observation would strongly favour the colour-octet models which have been invoked to explain the anomalously high Υ production rates observed by the CDF Collaboration [2].

We describe here the search for Υ production [1] at LEP using the L3 detector [3]. The analysis uses a sample of approximately 3.5 million hadronic Z events acquired during 1991-1995 at $\sqrt{s} \approx M_{\mathrm{Z}}$.

Event Selection

In a set of 3 453 780 selected hadronic events, we search for events containing either two electrons or two muons. Candidate electrons with energies of more than 4 GeV are selected within $|\cos\theta| < 0.97$, where θ is the polar angle. Muon candidates, with momenta of more than 3 GeV, are required to be within $|\cos\theta| < 0.8$. Each candidate electron (muon) must be isolated by at least 10° (15°) from the closest jet. The lepton pairs are required to have opposite charges and to have an opening angle of less than 90°.

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1) Representing the L3 collaboration
2) Throughout this paper, we use Υ to denote the three states $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(3\mathrm{S})$.

Υ production mechanism		Br ($Z \to \Upsilon X$) $\times 10^5$		ε ($Z \to \Upsilon X; \Upsilon \to \ell^+\ell^-$) [%]	
				e^+e^- channel	$\mu^+\mu^-$ channel
1. $Z \to \Upsilon bb$	(b-quark fragmentation)	1.6	[5,7]	$37.4 \pm 0.6 \pm 5.0$	$21.2 \pm 0.5 \pm 2.6$
2. $Z \to \Upsilon q\bar{q}gg$	(gluon fragmentation)	0.07	[6,8]	$25.5 \pm 0.6 \pm 3.4$	$14.3 \pm 0.5 \pm 1.7$
3. $Z \to \Upsilon gg$	(gluon radiation)	0.05	[9–11]	$32.1 \pm 0.6 \pm 4.3$	$19.6 \pm 0.5 \pm 2.4$
4. $Z \to \Upsilon q\bar{q}$	(gluon fragmentation)	4.1	[4]	$33.2 \pm 0.6 \pm 4.4$	$21.2 \pm 0.5 \pm 2.6$
5. $Z \to \Upsilon g$	(gluon radiation)	0.1	[4]	$41.5 \pm 0.6 \pm 5.5$	$33.3 \pm 0.6 \pm 4.1$
Combined model		5.9			

TABLE 1. Υ production mechanisms in Z decays and their predicted branching ratios and reconstruction efficiencies for the process $Z \to \Upsilon X; \Upsilon \to \ell^+\ell^-$. The first error in each case is statistical and the second is systematic.

To study the sensitivity of this analysis to events containing $\Upsilon \to \ell^+\ell^-$ decays, five distinct mechanisms for the production of (unpolarised) Υ's in Z decays, as listed in Table 1, were considered. Table 1 also shows the predicted branching ratios, Br ($Z \to \Upsilon X$), for the colour-singlet (1–3) and colour-octet (4–5) processes. Samples of 5000 $e^+e^- \to \Upsilon X$ events were generated for each of these production mechanisms. The Υ's were required to decay via the chain $\Upsilon \to \ell^+\ell^-$. The PDG [17] values for the masses and leptonic branching ratios of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ were assumed. A "combined model" sample was also used, which is the sum of the five distinct samples weighted according to the production rates predicted by the theory.

Figure 1 shows the expected dilepton invariant mass distributions for the "combined model" Monte Carlo sample after application of the described selection procedure for a) $\Upsilon \to e^+e^-$, and b) $\Upsilon \to \mu^+\mu^-$. The average dilepton invariant mass resolutions are 100 MeV for $\Upsilon \to e^+e^-$ decays and 235 MeV for $\Upsilon \to \mu^+\mu^-$ decays. Table 1 shows the efficiencies for each Υ production mechanism and decay mode, as determined from the Υ Monte Carlo samples.

Figure 1 shows the dilepton invariant mass spectra obtained from the data (solid line) for c) e^+e^-, and d) $\mu^+\mu^-$. No evidence is seen for Υ production. The dashed line represents the background contribution, which was estimated using a sample of approximately seven million hadronic events generated with JETSET [14–16], not including the production of Υ's, and samples of 1000 four-fermion events, generated with the FERMISV [13] Monte Carlo program, for each of the processes $e^+e^- \to \ell^+\ell^- q\bar{q}$, where $\ell = e, \mu$ and $q = u, d, s, c, b$.

The average number of background events expected in the mass window from 7 to 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 is five and three for the e^+e^- and $\mu^+\mu^-$ samples respectively, which is consistent with the background.

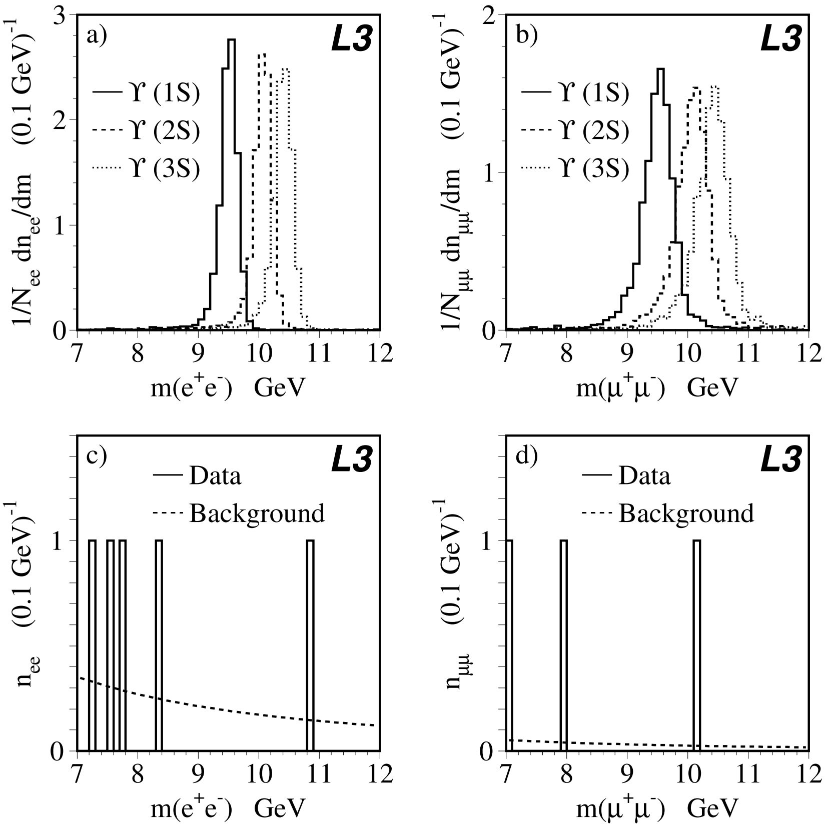

FIGURE 1. Predictions for the dilepton invariant mass distributions for a) $\Upsilon \to e^+e^-$, and b) $\Upsilon \to \mu^+\mu^-$ decays. Invariant mass spectra obtained from the data (solid line) for c) e^+e^-, and d) $\mu^+\mu^-$; the dashed lines show the background predicted by the Monte Carlo. 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.

Determination of Upper Limits on $\mathrm{Br}\,(Z \to \Upsilon X)$

Given the absence of a signal, upper limits on the branching fractions $\mathrm{Br}\,(Z \to \Upsilon X)$ are obtained from binned maximum-likelihood fits to the $\ell^+\ell^-$ invariant mass distributions. Separate limits are derived for each of the five production mechanisms considered and for each Υ state. Limits are also determined using the "combined model" sample. We also derive limits for the production of an "average Υ" which is a mixture of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$. The systematic errors include contributions from uncertainties in the detector resolution, the background, the Υ reconstruction efficiency and the Υ branching ratios. Further sources of systematic errors come from the uncertainties in the theoretical modelling of Υ production: Υ polarisation, feed-down decays from higher-mass Υ and χ_b states and relative fractions of $\Upsilon(1S)$, $\Upsilon(2S)$, and

$\Upsilon(3S)$ states.

Table 2 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 $Br(Z \to \Upsilon X) = 5.9 \times 10^{-5}$, shown in Table 1.

Υ production mechanism	Upper limit on $Br(Z \to \Upsilon X) \times 10^5$ at the 95% C.L.			
	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	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 2. Upper limits on the branching ratios for the process $Z \to \Upsilon X$, at the 95% confidence level.

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