PRODUCTION OF ONIA IN HADRONIC Z^0 DECAYS

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(Preliminary)

Abstract

Direct production mechanisms of heavy quarkonium states in hadronic Z^0 decays are discussed. A search is described for direct production of J/ψ , $\psi(2S)$ and Υ in more than 3 million of the 1991-1994 DELPHI data. In the presence of a small excess ($\sim 1\%$ statistical probability) in the sum of candidate events relative to the estimated background, new upper limits are set in the range $Br(Z^0 \rightarrow (Q\bar{Q}) X)/Br(Z^0 \rightarrow \text{hadrons}) < 0.87 - 8.7 \times 10^{-4}$ (90 % CL) for various strong production mechanisms of J/ψ and $\Upsilon(1S, 2S, 3S)$.

1 INTRODUCTION

Direct production of vector meson states $(Q\bar{Q})$ of heavy quarks $Q = c, b$ in hadronic Z^0 decay is expected to be dominated by two *fragmentation* processes

- (1) heavy quark fragmentation: $Z^0 \rightarrow (Q\bar{Q})Q\bar{Q}$
- (2) gluon fragmentation: $Z^0 \rightarrow q\bar{q}g^*$, $g^* \rightarrow (Q\bar{Q})gg$

where q represents any quark u, d, c, s or b . In perturbative QCD, there is also a *short-distance* process (scale $1/M_{Z^0}$) of hard gluon radiation off the heavy quarks which can then form a bound state

- (3) $Z^0 \rightarrow (Q\bar{Q})gg$

QCD based calculations of Ref. [1] predict branching ratios $Br(Z^0 \rightarrow (Q\bar{Q}) X)/Br(Z^0 \rightarrow \text{hadrons})$ about $25(4) \times 10^{-6}$ for J/ψ (Υ) for each process (1) or (2). The branching ratios of the process (3) are expected to be smaller, 4×10^{-7} (2×10^{-6}) for J/ψ (Υ) [2]. However, preliminary results from the CDF Collaboration have reported on an order of magnitude higher rates of direct $J/\psi, \psi(2S), \Upsilon(1S, 2S)$ production in $p\bar{p}$ collisions [3] compared to initial predictions [1]. In

the LEP data, the upper limit for direct production of J/ψ states through the process (2) is 7×10^{-4} (90% CL) [4]. A primary component of $7.7^{+6.3}_{-5.4}(\text{stat})\%$ has been estimated in the inclusive J/ψ proper time distribution [5].

In the following, a dedicated search is described for promptly produced ψ and Υ mesons decaying to an electron or muon pair in hadronic Z^0 decays at LEP. Such events would signal the presence of direct production processes. The prompt meson states are identified as pairs of leptons with an invariant mass compatible with the meson state and produced at the interaction point. In addition, isolation of leptons with respect to the jet systems and b antitagging of the hadronic jets are useful in eliminating known indirect sources such as J/ψ from intermediate bottom decays, or events with semileptonic decays of other heavy flavour hadrons, possibly with hadrons misidentified as leptons. These observables also allow for distinguishing between various production mechanisms. The results are preliminary ¹.

2 DETECTOR AND DATA

The analysis is based on data collected with the DELPHI detector (Ref. [7]) at LEP in 1991-1994. The data sample of about 3.2×10^6 hadronic events is selected by criteria which have an efficiency more than 98% for hadronic Z^0 decays. The background from $\tau^+\tau^-$ pairs (and $\gamma\gamma$ collisions to smaller extent) is 0.7% in the analyzed sample. The analysis relies mainly on identification of isolated muons and electrons, reconstructed with precise vertex parameters. Charged and neutral particles are included in defining hadronic jets. The data is compared with a large sample of $Z^0 \rightarrow q\bar{q}$ events generated by the JETSET7.3 parton shower Monte Carlo [8] with the DELPHI tuning of b and c decays (B meson lifetime 1.6 ps), followed by the full detector simulation. Specific simulated samples of the $b \rightarrow J/\psi$ channel and four fermion processes $e^+e^- \rightarrow llq\bar{q}$ [9] have been used, too.

2.2 Selection of prompt isolated lepton pairs and light flavour jets

The pairs of identified leptons have been considered when both lepton momenta are greater than 3 GeV/c, the sum of the lepton energies is greater than 10 GeV,

¹The numbers presented at the conference are updated here for an update of data calibration files with improved understanding of systematics. Changes are minor. A more detailed description is in Ref. [6]

the opening angle of the lepton pair less than 90° and the probability for both leptons to come from the same decay vertex in space is greater than 0.1 %. Electrons associated to converted photons are rejected. For each lepton pair being considered, the hadronic system (i.e. the lepton pair removed) is forced to cluster in two jets by using the $y_{\min}$ jet criterion [10] as a free parameter. Only pairs with both jet energies above 10 GeV are considered.

The background is greatly reduced by requiring lepton pair isolation. The sum of energies of charged and neutral particles in cones around the lepton candidates are required to be small and the angles of leptons with respect to the jet axes to be significant. In addition, the missing momentum vector and the lepton pair momentum should not point at the same direction in events with some missing energy.

A lepton pair is considered to be produced in the primary interaction point by the cuts on the absolute difference (and its uncertainty) between the fitted dilepton vertex and the mean beam spot position in the xy plane. The flavour content of the hadronic jets is analyzed with the algorithm which computes probabilities b^{tag} of charged particles to originate from the primary vertex by using impact parameter significances [11]. The efficiency of 70% (60%) to prompt muon (electron) pairs with light flavour jets is found while events of $b \rightarrow J/\psi$ are rejected by more than factor of eleven. The systematic uncertainty due to vertex criteria is $\pm 10\%$ including the uncertainty on the b hadron lifetime. The systematic uncertainty due to all cuts is $\pm 30\%$. The invariant masses of the selected lepton pairs in data and in simulation (hadronic Z^0 decays and four fermion processes added up) are shown in figure 1 a)-d).

2.3 Mass resolution and the resonance hypothesis

By comparing the measured invariant masses with the nominal vector meson masses allowing for experimental resolutions ², eight events are found to be compatible with being decays of J/ψ , $\psi(2S)$ or Υ states. The event rates and the expected background in the mass windows and in the continuum are summarized in table 1. The statistical probabilities for such numbers of events (or more) to appear in the mass windows of J/ψ , $J/\psi + \psi(2S)$, and $J/\psi + \psi(2S) + \Upsilon(1S, 2S, 3S)$

²The mass resolution is about 50 MeV/c² for $J/\psi \rightarrow \mu\mu$, about 120 MeV/c² for $\Upsilon \rightarrow \mu\mu$, and slightly larger for electron pairs allowing for brehmsstrahlung.

windows are 5.4%, 3.1% and 1.1%, respectively. They are computed using the prescription in Ref. [12] (Poisson processes with background, smeared). The probability to have more than seven events in the side band is 15%. The data and simulation agree very well for the $e\mu$ and $l^\pm l^\pm$ pairs. The checks suggest for a small excess which has a tendency to be related to the meson mass windows. There is no significant excess in any individual window, however.

3 RESULTS AND DISCUSSION

As there is no significant excess in any individual mass window, the result of the analysis can be expressed as 90% confidence level upper limits for each production channel, computed from the observed candidates, the background and efficiency estimates (with uncertainties), and the leptonic branching ratios. The efficiencies have been checked by using fully simulated events (see table 2). The efficiency for gluons channels and the process $Z^0 \rightarrow J/\psi cc$ is computed with the decay length cut and b veto, while b tag is required for the channel $Z^0 \rightarrow b\bar{b}\Upsilon$. The upper limits for signal events in the mass windows of J/ψ and $\Upsilon(1S), (2S), (3S)$ are computed analogously to the probability estimates of the previous section. The J/ψ production through process (1) is better estimated by using the inclusive J/ψ proper time distribution of the earlier DELPHI analysis of [5] combined with the world average values [12] relevant branching ratios.

The upper limits are listed in the lower part of table 2. They are either new or improve earlier result at LEP. For convenience, table 2 includes also branching ratio estimates if the events are taken as signal after subtracting the expected background. Among the direct strong production mechanisms studied here, the gluon processes come to the closest in interpreting the data. For example, taking the data as a signal of J/ψ from gluon splitting would suggest rates which are a factor of ten above the early predictions [1].

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in the window of	Real ($\mu + e$)	Sim (μ, e)
J/ψ	$2 + 2 = 4$	1.2 ± 0.1
$\psi(2S)$	$1 + 1 = 2$	1.0 ± 0.09
$\Upsilon(1S, 2S, 3S)$	$2 + 0 = 2$	0.47 ± 0.06
side bands	$6 + 2 = 8$	4.8 ± 0.4

Table 0.1:

Process	Efficiencies (%)	
$J/\psi, \Upsilon \rightarrow \mu^+\mu^-, e^+e^-$	μ / e	
$c\bar{c} \rightarrow J/\psi X$	$0.2 \pm 0.2/0.0 \pm 0.2$	
$g^* \rightarrow J/\psi gg$	$4.1 \pm 0.5/2.5 \pm 0.3$	
$Z^0 \rightarrow gg J/\psi$	$28 \pm 2/17 \pm 2$	
$b\bar{b} \rightarrow \Upsilon X$	$2.8 \pm 1.0/1.7 \pm 0.6$	
$Z^0 \rightarrow gg\Upsilon$	$29 \pm 3/11 \pm 3$	
$\text{Br}(Z^0 \rightarrow (QQ)X) / \text{Br}(Z^0 \rightarrow \text{hadrons})$		
Process	estimate	90% c.l. upper limit
$c\bar{c} \rightarrow J/\psi X$	$3.1^{+2.5}_{-2.1} \times 10^{-4} (*)$	$6.2 \times 10^{-4} (*)$
$g^* \rightarrow J/\psi gg$	$(2.2 \pm 1.6) \times 10^{-4}$	5.9×10^{-4}
$Z^0 \rightarrow gg J/\psi$	$(0.32 \pm 0.24) \times 10^{-4}$	1.1×10^{-4}
$b\bar{b} \rightarrow \Upsilon(1S, 2S, 3S) X$	no candidates	8.7×10^{-4}
$Z^0 \rightarrow gg\Upsilon(1S, 2S, 3S)$	$(0.48 \pm 0.46) \times 10^{-4}$	1.7×10^{-4}

Table 0.2:

TABLE CAPTIONS

Table 1. Summary of real oppositely signed lepton pairs satisfying the selection criteria (with *b veto*), expectation from simulation and the statistical probabilities for observing such a number (or more) events in mass windows and continuum. Predictions from simulation include simulated Z^0 hadronic events and 4-fermion processes. The errors in simulated data are statistical, with the systematic uncertainty of 30%.

Table 2. Efficiencies, rate estimates and 90% c.l. upper limits for the branching ratios for various production mechanisms. (*) value deduced from the life time fit of inclusive J/ψ sample Ref. [5]

FIGURE CAPTIONS

Figure 1. a) Distributions of invariant masses of the isolated $\mu^+\mu^-$ and e^+e^- pairs. b) as a) but for simulated hadronic Z^0 decays and the process $e^+e^- \rightarrow l^+l^-q\bar{q}$. c)-d) as a)-b) but for $e\mu$ and like signed lepton pairs, which satisfy the event selection with cuts on decay lengths and satisfy the *b veto*.