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The ARGUS Collaboration

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The ARGUS Collaboration

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Search for charm production in direct decays of the $\Upsilon(1S)$ resonance

Abstract

The production of $D^*(2010)^+$ and J/ψ mesons and of prompt leptons has been investigated in e^+e^- interactions at the $\Upsilon(1S)$ resonance energy. The data were collected at the storage ring DORIS II at DESY with the ARGUS detector. We obtain upper limits of $BR^{dir}(\Upsilon(1S) \to D^*(2010)^\pm + X) < 0.019$ (for $x_p > 0.2$) and $BR^{dir}(\Upsilon(1S) \to J/\psi + X) < 0.68 \times 10^{-3}$, both at the 90% confidence level. From the prompt lepton analysis, a model dependent limit of $BR^{dir}(\Upsilon(1S) \to Y_c + X) < 0.034$ (Y_c denoting a charm-containing particle) is derived.

1 Introduction

While the light quark species u, d and s are abundantly produced in jet fragmentation, the heavier flavours c and b play a more distinguished rôle. In e^+e^- annihilation, they are either created directly by the electromagnetic process, or they originate from the weak decay of a still heavier quark. The large quark mass and the limited energy density of the strong force field inhibit the creation of heavy quark pairs in the "soft" fragmentation step. For the energy region around $\sqrt{s} = 10$ GeV this means that, below the $B\bar{B}$ threshold, charmed particles are commonplace in nonresonant e^+e^- continuum interactions only. It is an interesting question if there are other mechanisms by which charm can be produced.

The $\Upsilon(1S)$ resonance, being the lightest $b\bar{b}$ vector meson, lies well beneath the $B\bar{B}$ threshold. The major fraction of its hadronic decays proceed via the strong interaction. We will refer to these decays as the "direct" decay modes. They proceed mostly through an intermediate state of three gluons, in analogy to the decay of ortho-positronium into three photons, or two gluons and one photon. The gluons then fragment into hadrons which can be observed. The $\Upsilon(1S)$ forms therefore an ideal laboratory to search for uncommon mechanisms of charm production, provided the nonresonant continuum beneath the resonance is correctly subtracted. Another background comes from the electromagnetic transition of the $\Upsilon(1S)$ into a $q\bar{q}$ pair, the so-called vacuum-polarization. Such electromagnetic decays lead to an event structure resembling that of the ordinary continuum background beneath the resonance, including the charm component.

Theoretical ideas for charm production in three-gluon decays of an Υ resonance were developed more than a decade ago. Bigi and Nussinov [1] pointed out the fusion of two gluons into a $c\bar{c}$ pair as a possible charm source, but quoted no value for the branching ratio (Fig. 1a). Fritzsch and Streng [2] gave a rough estimate for the process where one (virtual) gluon splits up into a $c\bar{c}$ pair (Fig. 1b) which was on the level of a few percent.

On the experimental side, the CLEO group has reported an observation of J/ψ mesons on the $\Upsilon(1S)$. It was seen in the $\mu^+\mu^-$ channel and corresponded to a much smaller branching ratio of $(1.1 \pm 0.4) \times 10^{-3}$ [3].

This paper investigates three different signatures of charm production in direct $\Upsilon(1S)$ decays. In chapters 2 and 3 we search for the production of $D^*(2010)^+$ and J/ψ mesons in $\Upsilon(1S)$ decays. In chapter 4, we look for prompt leptons which might come from semileptonic charm decays, and derive a model-dependent upper limit for inclusive charm production.

2 Search for $D^*(2010)^+$ mesons in direct $\Upsilon(1S)$ decays

The data used for this analysis have been obtained with the ARGUS detector at the storage ring DORIS II. A detailed description of the detector can be found elsewhere [4]. The sample corresponds to integrated luminosities of 41.1 pb^{-1} taken on the $\Upsilon(1S)$ resonance and 95.8 pb^{-1} from the nearby continuum. Electrons, muons, pions and kaons have been identified by means of combined likelihoods calculated from the available specific energy loss (dE/dx) and time-of-flight (ToF) measurements for all possible particle hypotheses. A particular hypothesis was accepted for a particle if the corresponding relative likelihood exceeded 5% [4]. For the identification of electrons, the energy deposition and its lateral distribution in the electromagnetic calorimeter was used as well, while muon candidates were required to have at least one hit in the outer muon chambers.

The reconstruction of $D^*(2010)^+$ mesons [1] was performed using the decay channel $D^*(2010)^+ \to D^0\pi^+$, followed by $D^0 \to K^-\pi^+$, $K^-\pi^-\pi^+\pi^+$, or $K^0_S\pi^+\pi^-$. Only D^0 candidates lying within $\pm 80\ MeV$ and ± 2 standard deviations of the nominal mass were accepted. The $D^*(2010)^+$ mass was reconstructed by adding the measured $D^* - D^0$ mass difference to the nominal D^0 mass. The shape of the $D^*(2010)^+$ signal in the various mass spectra was parametrized by a Gaussian; mean values and widths for the various momentum ranges and decay channels were obtained by fits to the continuum data alone. A background description of the form $a_1(m - a_2)^{a_3}$ was used, where a_1, a_2 and a_3 were treated as free parameters in the fit.

Although charm production in three-gluon decays is expected to be a rare process [2,5], charmed mesons are abundantly produced in the continuum below the resonance and by vacuum polarization decays of the $\Upsilon(1S)$. In order to search for a signal from direct $\Upsilon(1S)$ decays, both backgrounds have to be carefully subtracted. This has been achieved using the continuum data taken at nearby energies, after rescaling according to the ratio of integrated luminosities and the energy dependence of the hadronic cross section, including soft and hard radiative corrections. Special care has been taken to account for the slight energy-dependent distortion of the scaled momentum spectra caused by initial-state radiation and kinematic effects. The scaling variable $x_p = p/p_{max}$, with $p_{max} = \sqrt{E^2_{Beam} - m(D^*)^2}$ was used. Since even in this variable the spectra scale only approximately, appropriate transformations were applied to the spectra. These transformations were derived numerically using the Lund model (version 6.3) [5], with the Υ resonances incorporated by appropriate weighting.

Acceptance correction was performed on an event-to-event basis by weighting every $D^*(2010)^+$ candidate with the inverse momentum dependent efficiency as determined using Monte Carlo events which had been passed through a full detector simulation and reconstruction. Figure 2 shows the $D^0\pi^+$ invariant mass spectra on the $\Upsilon(1S)$ resonance after subtraction of the scaled continuum spectra. The number of $D^*(2010)^+$ mesons from direct $\Upsilon(1S)$ decays was obtained by fitting a Gaussian signal with free amplitude, plus a background of the form noted above (solid line in fig. 2), to the continuum-subtracted mass spectra from $\Upsilon(1S)$ decays. The absolute number of $D^*(2010)^+$ mesons has been calculated by using the averaged branching ratios as given by the particle data group [6].

Table 1 shows the number of $D^*(2010)^+$ mesons from direct $\Upsilon(1S)$ decays after acceptance correction for the three D^0 decay modes under study. All figures are compatible with zero. The underlying continuum charm production, together with the vacuum polarization on the resonance, is sufficient to explain the $D^*(2010)^+$ production in the $\Upsilon(1S)$ data sample. Also given in table 1 are the $\Upsilon(1S) \to D^*(2010)^+ + X$ branching ratios obtained for each D^0 decay mode studied, using an effective number of (332800 ± 12300) direct $\Upsilon(1S)$ decays. The combined result from all decay channels leads to a hadronic branching ratio of $BR^{dir}(\Upsilon(1S) \to D^*(2010)^\pm + X) = (4.8 \pm 9.0 \pm 2.9) \times 10^{-3}$ for $x_p > 0.2$, where the systematic error includes uncertainties in the background and signal shape, the continuum scaling, luminosity, efficiency and the D^* and D branching ratios. To avoid ambiguity, we emphasize that this branching ratio includes the charge-conjugate decay mode. The result can be converted into an upper limit of $BR^{dir}(\Upsilon(1S) \to D^*(2010)^\pm + X) < 0.019$ at the 90% confidence level, for $x_p > 0.2$. From the measured inclusive D^* continuum cross section [7], and using the known R value [8], one can estimate that 30% of the charm quarks fragment into a $D^*(2010)^+$ meson. Assuming this ratio to apply also for charm produced in $\Upsilon(1S)$ decays, one obtains an open-charm branching ratio of $BR^{dir}(\Upsilon(1S) \to Y_c Y_{\bar{c}} + X) < 0.032$, not corrected for the D^* fraction in $x_p > 0.2$.

Figure 3 compares, after subtraction of nonresonant background, the mass spectrum of direct $\Upsilon(1S)$ decays with the scaled D^* signal from the continuum data, i.e. the natural background. The 'direct' spectrum results by subtracting large numbers from one another. The statistical errors mainly reflect the available number of $\Upsilon(1S)$ events.

3 Search for J/ψ mesons in direct $\Upsilon(1S)$ decays

In contrast to D^* mesons, J/ψ mesons are expected to have at most a small production rate in $e^+e^- \to q\bar{q}$ reactions in the Υ energy region, since the probability for a final state c-quark to pick up a partner $\bar{c}$ from the fragmentation process is extremely small. In the three-gluon decay of the $\Upsilon(1S)$ or $\Upsilon(2S)$ however, J/ψ's might be created by the gluon fusion and gluon split-up processes mentioned above (fig. 1a,b) [1,2]. J/ψ candidates were selected by combining oppositely-charged electron and muon pairs. Only one of the two lepton candidates in a combination had to satisfy strict particle identification criteria, the other one was accepted if there was no contrary information. The momenta of electrons and muons had to be larger than 0.85 GeV/c and their polar angles had to satisfy the conditions $|cos\theta_e| < 0.85$ and $|cos\theta_\mu| < 0.90$. Electron candidates from events with less than five charged tracks were rejected to suppress radiative Bhabha events. Electron candidates were rejected if they could be assigned to a converted photon candidate with $m(e^+e^-) < 0.1$ GeV/c^2. The momentum dependent shape of the J/ψ signal in both decay channels was determined by studying Monte Carlo events and parametrized using Gaussians. In the e^+e^- channel, the signal develops a 'tail' towards lower energy due to the electron energy loss in the traversed material which was accounted for by adding a corresponding term to the Gaussian. The validity of the signal shape parametrization was tested at the $\Upsilon(4S)$ resonance energy, where a substantial J/ψ production from B decays is observed [9].

[1] References to a specific particle state also imply the charge-conjugate state, except in chapter 4.

Figure 4 shows the fits to the e^+e^- and $\mu^+\mu^-$ mass spectra in three momentum ranges for the $\Upsilon(1S)$ data. There is no significant J/ψ signal in any of these intervals. After summation and correction for efficiency, we obtain an inclusive branching ratio of $BR^{dir}(\Upsilon(1S) \to J/\psi + X) = (0.11 \pm 0.45 \pm 0.01) \times 10^{-3}$ from the e^+e^- and $BR^{dir}(\Upsilon(1S) \to J/\psi + X) = (0.24 \pm 0.51 \pm 0.03) \times 10^{-3}$ from the $\mu^+\mu^-$ channel. The leptonic J/ψ branching ratios recently measured by MARK III [10] have been used which are considerably improved in precision compared to the previous world averages [6]. Combining the two J/ψ decay modes, a branching ratio of $BR^{dir}(\Upsilon(1S) \to J/\psi + X) = (0.18 \pm 0.34 \pm 0.02) \times 10^{-3}$ is obtained. This converts to an upper limit of $BR^{dir}(\Upsilon(1S) \to J/\psi + X) < 0.68 \times 10^{-3}$ at the 90% confidence level. The CLEO group has reported a J/ψ signal in their $\Upsilon(1S)$ data which was only seen in the $\mu^+\mu^-$ channel and yields a branching ratio of $(1.1 \pm 0.4) \times 10^{-3}$ [3]. We do not confirm this signal, though within the large error given in [3], the results are not entirely inconsistent.

4 Search for prompt leptons in direct $\Upsilon(1S)$ decays

Another possible signature for charm production in direct $\Upsilon(1S)$ decays is an excess of leptons produced by the semileptonic decays. The study of lepton spectra is of interest in itself because the $\Upsilon(1S)$ data samples are sometimes used to estimate lepton fake rates for various purposes. Here the analysis is restricted to positrons. They contain less background from secondary reactions, like fast delta electrons, than the electron sample.

Several measures were taken to suppress positrons of non-charm origins, such as Dalitz-decays of π^0 and η mesons, photon conversions and misidentified pions and kaons. A total charged multiplicity of more than four was required to suppress radiative Bhabha events. The positron candidate had to point to the main vertex with a $\chi^2 < 18$, a radial distance $\delta_r < 0.4$ *cm* and an axial distance $\delta_z < 0.5$ *cm*. The relative pion likelihood for a positron candidate had to be less than 0.01. For every pair of electron-positron candidates with an invariant mass of $m(e^+e^-) < 0.1$ GeV/c^2, the positron was discarded from further analysis. The influence of these cuts was tested with a standard $q\bar{q}$ Monte Carlo model; above a momentum of 1.5 GeV/c, more than 75% of the accepted positron candidates were from charm decays. Figure 5a shows the x_p dependence of positron candidates passing these cuts from the $\Upsilon(1S)$ energy, together with the properly scaled spectrum from continuum events. Above $x_p = 0.35$ the spectra are clearly similar, while below this value the rate from the $\Upsilon(1S)$ energy is enhanced. Figure 5b shows the subtracted spectrum ($\Upsilon(1S)$ minus scaled continuum). The smooth line is the expected rate of positrons from non-charm sources in three-gluon decays which pass the cuts at low momenta. This contribution has been obtained by a fit to the distribution from three-gluon Monte Carlo events without charm, properly scaled to the number of direct $\Upsilon(1S)$ decays in the data. The agreement is excellent. There is no evidence for additional leptons from the $\Upsilon(1S)$ decays to charm.

In order to deduce a limit for charm production from the lepton yield, assumptions concerning the charmed particle momentum spectra are needed. We have studied the positron spectrum using a model in which the charmed mesons have a softer momentum spectrum than in normal continuum reactions, motivated by the fact that in processes like the gluon fusion mechanism (fig. 1a), the charm quarks are not given the full beam energy, as in the ordinary $e^+e^- \to c\bar{c}$ process. A soft spectrum was obtained by generating $\Upsilon(1S)$ three-gluon decays with a modified Lund model in which a non-zero probability for charm pair production in the fragmentation was introduced. (For a harder real spectrum, the leptons would be still easier to detect.) The resulting x_p spectrum for D^* mesons in this model is shown in fig. 6. The positron spectrum from this model was again scaled to the number of direct $\Upsilon(1S)$ decays in the data sample, and parametrized. This function and the one for ordinary charmless $\Upsilon(1S)$ decays were combined to the total spectrum

$$f(x_p) = \alpha \cdot \frac{dN}{dx_p}[\Upsilon(1S) \to ggg \to c\bar{c}X] + (1-\alpha) \cdot \frac{dN}{dx_p}[\Upsilon(1S) \to ggg \to X]$$

with unknown weighting factors parametrized by a free parameter α. The fit to the observed spectrum found a value for α compatible with zero. Using an average number of 0.108 ± 0.02 e^+ per charm quark decay, motivated by a recent inclusive measurement in tagged $e^+e^- \to c\bar{c}$ events [11] and the leptonic J/ψ branching ratios from MARK III [10], the fit to the data gives $BR^{dir}(\Upsilon(1S) \to Y_{c(\bar{c})} + X) < 0.034$ at the 90% confidence level. This limit is model dependent and less restrictive than those from the direct D^* and J/ψ measurements. However, it does provide information through a different decay channel and probes the production of all charmed particles. Moreover, this study particularly excludes charmed particle production with a harder spectrum which would be detectable in the lepton spectra at large momenta.

5 Summary

A search for charm production in $\Upsilon(1S)$ decays beyond the yield expected from vacuum polarization has been performed. We obtain upper limits for the decays into $D^*(2010)^+$ and J/ψ mesons of $BR^{dir}(\Upsilon(1S) \to D^*(2010)^\pm + X) < 0.019$ ($x_p > 0.2$) and $BR^{dir}(\Upsilon(1S) \to J/\psi + X) < 0.68 \times 10^{-3}$, both at 90% confidence level. We find no excess leptons on the $\Upsilon(1S)$ resonance which might stem from semileptonic decays of directly produced charmed particles.

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Tables

D^0 decay mode	N^{dir} $(\Upsilon(1S) \to D^*(2010)^+ + X)$	BR^{dir} $(\Upsilon(1S) \to D^*(2010)^+ + X)$
$D^0 \to K^-\pi^+$	2680 ± 3700	$(8.06 \pm 12.15) \times 10^{-3}$
$D^0 \to K^-\pi^-\pi^+\pi^+$	-1760 ± 5580	$(-5.29 \pm 17.06) \times 10^{-3}$
$D^0 \to K_S^0\pi^+\pi^-$	6740 ± 13570	$(20.24 \pm 42.60) \times 10^{-3}$

Table 1: Acceptance corrected number of $D^*(2010)^+$ mesons, and corresponding $\Upsilon(1S)$ branching ratios (systematic errors included), separate for the three D^0 decay modes under study

Figure Captions

Figure 1 Mechanisms through which charm might be created in the three-gluon decay of an Υ resonance: (a) by fusion of two gluons [1] or (b) by split-up of one (virtual) gluon [2].

Figure 2 Acceptance corrected $D^0\pi^+$ invariant mass spectra for $x_p > 0.2$ after subtraction of continuum and vacuum polarization for three different D^0 decay channels: (a) $D^0 \rightarrow K^-\pi^+$, (b) $D^0 \rightarrow K^-\pi^-\pi^+\pi^+$, (c) $D^0 \rightarrow K^0_S\pi^+\pi^-$.

Figure 3 Acceptance corrected $D^0\pi^+$ invariant mass spectra for $x_p > 0.2$ after subtraction of nonresonant background, left column (a-c) shows continuum scaled to the continuum plus vacuum polarization cross section times luminosity on the $\Upsilon(1S)$ resonance, i.e. the natural background to the direct component; right column (d-f) shows the direct component, i.e. the total $\Upsilon(1S)$ contribution minus the left column histograms. The spectra are shown for three different D^0 decay channels: (a,d) $D^0 \rightarrow K^-\pi^+$, (b,e) $D^0 \rightarrow K^-\pi^-\pi^+\pi^+$, (c,f) $D^0 \rightarrow K^0_S\pi^+\pi^-$. The line corresponds to the $D^*(2010)^+$ signal fit.

Figure 4 Invariant mass spectra of e^+e^- (a,c,e) and $\mu^+\mu^-$ (b,d,f) combinations at the $\Upsilon(1S)$ energy for three different momentum regions: 0-1 GeV (a,b), 1-2 GeV (c,d), 2 GeV-∞ (e,f). The continuum spectrum has not been subtracted. The solid line represents the fit of a J/ψ signal shape plus a parametrization of the background. The hatched histogram shows the continuum data scaled to the $\Upsilon(1S)$ energy.

Figure 5 Scaled momentum spectra of electrons as seen by the detector after applying the cuts described in the text: (a) filled circles for the $\Upsilon(1S)$ data, the solid line for the scaled continuum data. (b) open circles for the continuum subtracted $\Upsilon(1S)$ data, the solid curve is a properly scaled parametrization of the spectrum from a charmless $\Upsilon(1S)$ decay Monte Carlo simulation.

Figure 6 Scaled momentum spectrum of D^* mesons in a modified Lund model for the decay $\Upsilon(1S) \rightarrow ggg$, where charm has been introduced by setting a small probability $\gamma_c \neq 0$ for $c\bar{c}$ production in the fragmentation chain. The purpose is to obtain a model with a soft charm production with the kinematic features of the three-gluon decay, in contrast to the hard charm production in $e^+e^- \rightarrow c\bar{c}$.

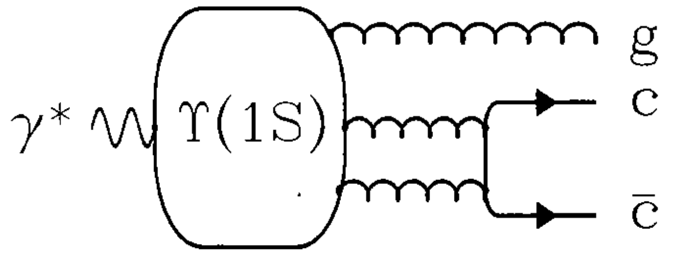


Fig. 1a

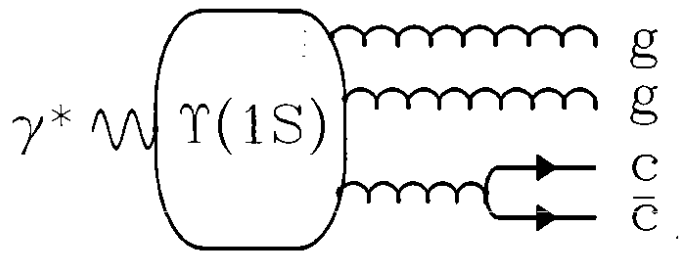
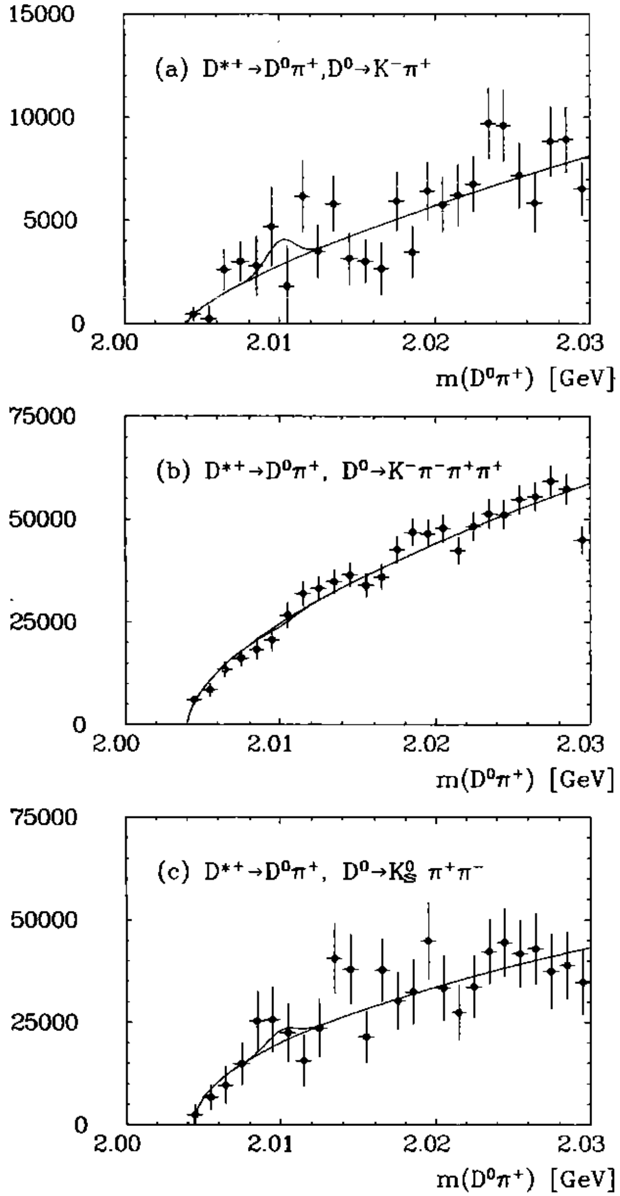
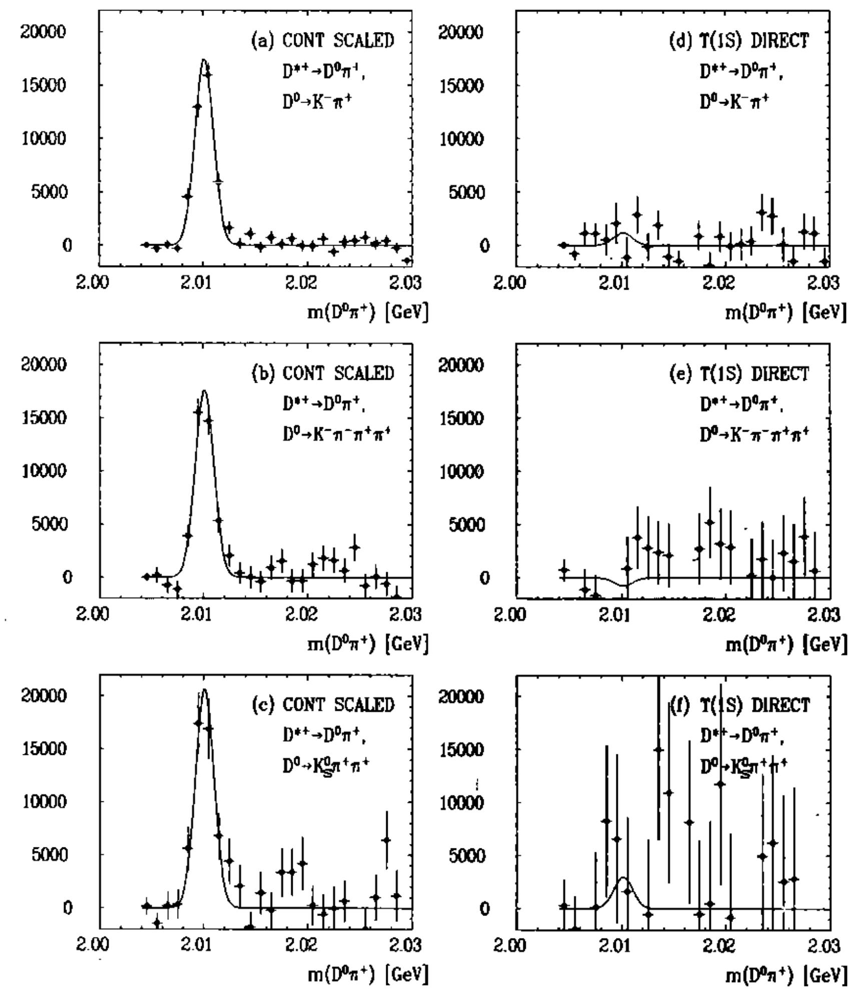


Fig. 1b



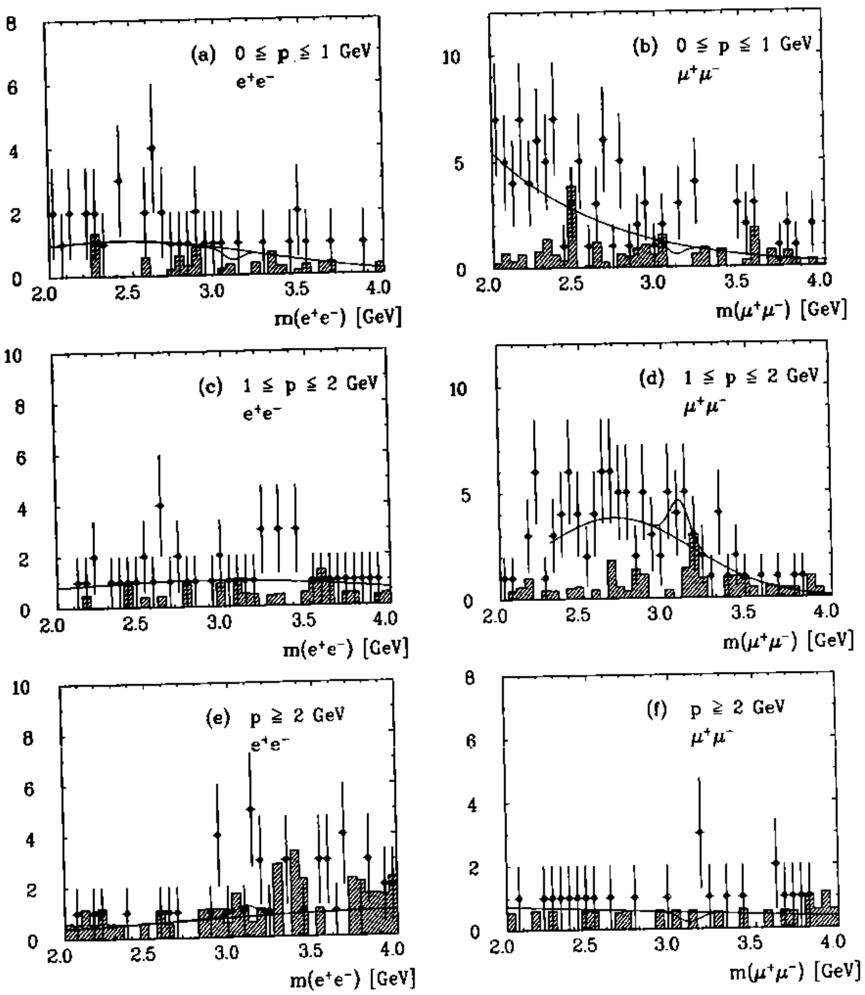
(a) $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$
(b) $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^-\pi^+\pi^+$
(c) $D^{*+} \to D^0\pi^+,\ D^0 \to K^0_S\ \pi^+\pi^-$
$m(D^0\pi^+)$ [GeV]

Fig. 2



(a) CONT SCALED
(b) CONT SCALED
(c) CONT SCALED
(d) Υ(1S) DIRECT
(e) Υ(1S) DIRECT
(f) Υ(1S) DIRECT
$m(D^0\pi^+)$ [GeV]

Fig. 3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e+e−
(b) 0 ≦ p ≦ 1 GeV
μ+μ−
(c) 1 ≦ p ≦ 2 GeV
e+e−
(d) 1 ≦ p ≦ 2 GeV
μ+μ−
(e) p ≧ 2 GeV
e+e−
(f) p ≧ 2 GeV
μ+μ−
m(e+e−) [GeV]
m(μ+μ−) [GeV]

Fig. 4

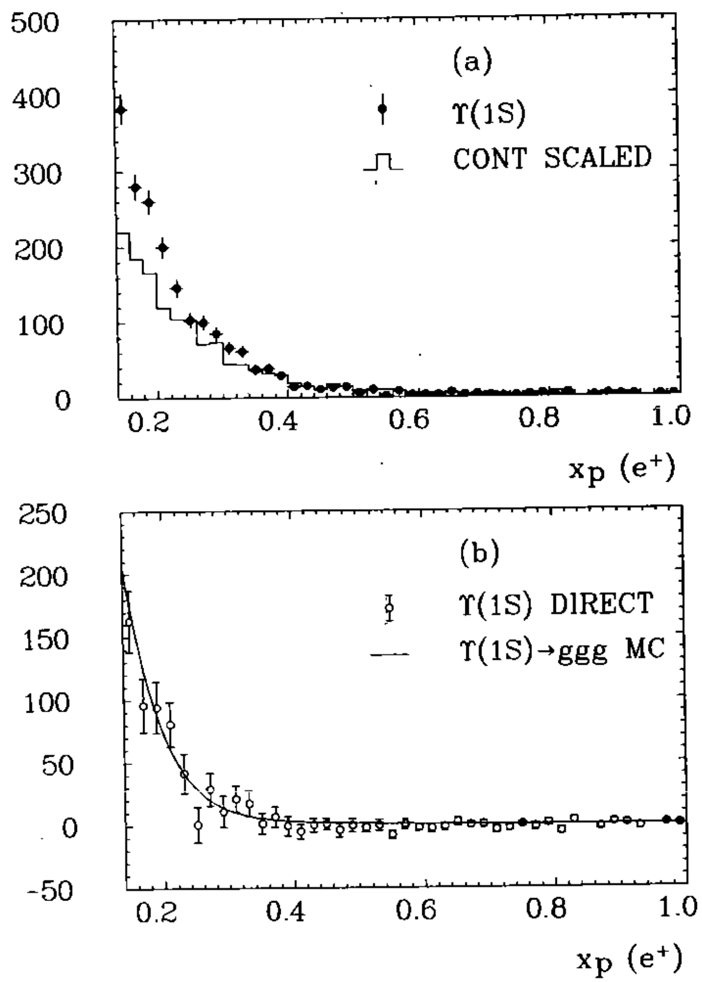
(a)
ϒ(1S)
CONT SCALED
xp (e+)
(b)
ϒ(1S) DIRECT
ϒ(1S)→ggg MC
xp (e+)

Fig. 5

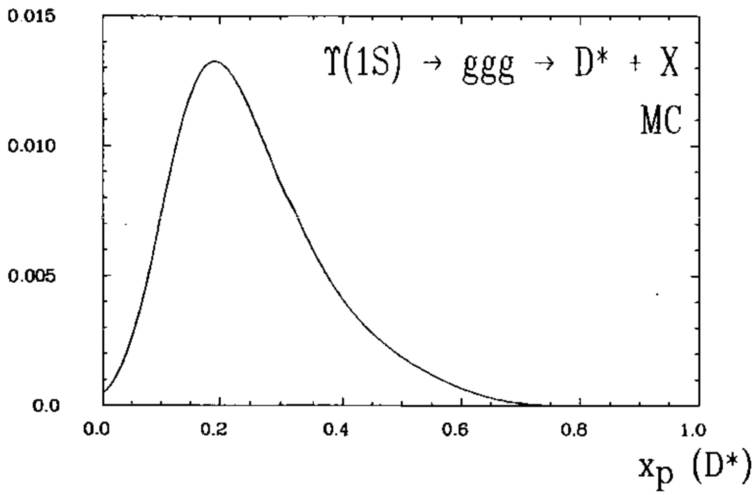

Fig. 6