Search for narrow resonances below the Υ mesons

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Abstract

We have investigated the invariant mass spectrum of dimuons collected by the CDF experiment during the $1992-1995$ run of the Fermilab Tevatron collider to improve the limit on the existence of narrow resonances set by the experiments at the SPEAR e^+e^- collider. In the mass range $6.3-9.0$ GeV/c^2 we derive an average 90% upper credible limit of 8 eV to the leptonic width of possible resonances. This limit is much worse at the mass of 7.2 GeV/c^2 due to an excess of 250 ± 61 events with a width consistent with the detector resolution.

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I. INTRODUCTION

Supersymmetric theories provide a mechanism to break the electroweak symmetry and to stabilize the large hierarchy between the Planck and the Fermi scales. Supersymmetry requires the existence of scalar partners to each standard model (SM) fermion, and spin$-1/2$ partners to the gauge and Higgs bosons. In particular, supersymmetry predicts the existence of scalar quarks, i.e. particles that carry color, but no spin. Scalar quarks (squarks) have been searched for at current and past colliders, but charge$-1/3$ squarks might have been overlooked for several reasons. Within the minimal supersymmetric standard model (MSSM), Ref. [1] shows that the existence of a yet undetected charge$-1/3$ scalar quark, lighter than the b quark, would require a lot of fine-tuning of the MSSM parameters, but at present cannot be ruled out by the electroweak precision data and the Higgs mass constraints from LEP2. Charge$-1/3$ squarks would give a 2% contribution to the inclusive cross section for $e^+e^- \rightarrow$ hadrons; this contribution is smaller than the experimental error of the present measurements [2]. Searches for narrow resonances at SPEAR have set upper bounds on Γ_l, the leptonic width of possible resonances, of 100 eV in the mass region $5.7 \leq E_{\rm cm} \leq 6.4$ GeV and of approximately 60 eV in the region $7.0 \leq E_{\rm cm} \leq 7.4$ GeV [3]. In Ref. [4], the leptonic width of 1^{--} bound states of such squarks has been evaluated using potential models of ordinary heavy quarks [5]. Because of the p-wave suppression of the fermion contribution to their decay width, the leptonic width is estimated to be approximately 18 (6) eV for a resonance with a 6 (10) GeV/c^2 mass. As noted in Ref. [4], for quarkonium masses above 6 GeV/c^2 the width Γ_l is well below the experimental bounds, and scalar-quark resonances might have been missed. With this study, we investigate the region above 6.3 GeV/c^2 by using muon pairs with invariant mass between the ψ and Υ mesons. The large statistics data set has been collected with the Collider Detector at Fermilab (CDF) during the $1992 - 1995$ Fermilab collider run. Section II describes the detector systems relevant to this analysis. Section III reviews the expectation for bound states of charge $-1/3$ squarks. The data sample is described in Sec. IV, and Section V presents additional selection criteria, tuned with $\Upsilon(1S)$ decays, which reduce the non-resonant background by a factor of three without losing more than 10% of the signal. In Sec. VI, we fit the dimuon invariant mass distribution and derive a 90% Bayesian upper limit on Γ_l as a function of the resonance mass. The shape of the invariant mass distribution is generally quite smooth and we improve the SPEAR limit

by an order of magnitude. An exception is the mass of 7.2 GeV/c^2, at which the data can accommodate a Gaussian bump of 250 ± 61 events. In Sec. VII we explore the possibility of observing a real signal, we estimate its statistical significance, and we study its robustness by using a number of different kinematical selections. Our conclusions are summarized in Sec. VIII.

II.   CDF DETECTOR

CDF is a multipurpose detector, equipped with a charged particle spectrometer and a finely segmented calorimeter. In this section, we recall the detector components that are relevant to this analysis. The description of these subsystems can be found in Ref [6]. Two devices inside the 1.4 T solenoid are used for measuring the momentum of charged particles: the silicon vertex detector (SVX) and the central tracking chambers (CTC). The SVX consists of four concentric layers of silicon microstrip detectors surrounding the beam pipe. The CTC is a cylindrical drift chamber containing 84 sense wire layers grouped into nine alternating superlayers of axial and stereo wires. Electromagnetic (CEM) and hadronic (CHA) calorimeters surround the tracking volume and measure energy deposits over the pseudorapidity region $|\eta| \leq 1$. Muons are reconstructed by matching track segments in the drift chamber systems located outside the CHA (CMU, CMP, and CMX muon detectors, which cover the region $|\eta| \leq 1$) to charged particles reconstructed in the CTC. The dimuon events used in this analysis were collected with a three-level trigger system. The first level required two charged tracks in the muon chambers. The second level trigger required that both muon tracks match a charged particle with transverse momentum $p_T \geq 2.2$ GeV/c as measured by a fast track processor (CFT). The third level software trigger requires that two charged CTC tracks, fully reconstructed in three dimensions, match track segments in the muon chamber and that the dimuon invariant mass is larger than 2.8 GeV/c^2.

III.   SEARCH FOR NARROW RESONANCES

In this study, we search for narrow resonances $\mathcal{E}$, bound states of scalar quarks, in the dimuon invariant mass distribution between the 6.3 GeV/c^2 and the Υ mesons. For a charge$-1/3$ squark, the muonic width, $\Gamma_\mu(\mathcal{E} \rightarrow \mu^+ \mu^-)$, of 2P resonances in this mass range

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has been evaluated in Ref. [4] to be approximately 15 eV. In contrast, the $\Upsilon(1S)$ meson has a larger leptonic width Γ_μ of 1.32 keV. In analogy with the $\Upsilon(1S)$ meson, the annihilation of a $\mathcal{E}$ state into hadrons is believed to proceed through gluons [4], the dominant contribution coming from the minimum number of intermediate gluons (one-gluon is excluded by color conservation and two-gluons by C-conservation). In $p\bar{p}$ collisions quarkonia states are directly produced through subprocesses such as $gg \to g\Upsilon(1S)$ or $gg \to g\,\mathcal{E}$. As the production subprocesses are directly related by crossing to the corresponding decay processes, the production cross section σ is determined by the decay widths [7], and approximately reads:

$$
\sigma_{\mathcal{E}}\, B(\mathcal{E} \to \mu\mu) \simeq \left(\frac{m_{\Upsilon(1S)}}{m_{\mathcal{E}}} \right)^3 \frac{\Gamma_\mu^{\mathcal{E}}}{\Gamma_\mu^{\Upsilon(1S)}} \, \sigma_{\Upsilon(1S)} \, B(\Upsilon(1S) \to \mu\mu) = R \, \sigma_{\Upsilon(1S)} \, B(\Upsilon(1S) \to \mu\mu) \quad (1)
$$

where B is the branching ratio of the muonic decay and $R = \left(\frac{m_{\Upsilon(1S)}}{m_{\mathcal{E}}} \right)^3 \frac{\Gamma_\mu^{\mathcal{E}}}{\Gamma_\mu^{\Upsilon(1S)}}$.

We check the validity of equation (1) by replacing the $\mathcal{E}$ with the $\psi(1S)$ meson. In this case $R = 113$. For $|\eta^\Upsilon| \leq 0.6$ and $p_T^\Upsilon = 5.5$ GeV/c CDF measures $d\sigma/dp_T \times B(\Upsilon(1S) \to \mu\mu) = 89.1 \pm 17.3$ pb/(GeV/c) [8]. Using $R = 113$, equation (1) predicts that the differential cross section times the muonic branching ratio for prompt $\psi(1S)$ mesons is $d\sigma/dp_T \times B(\psi(1S) \to \mu\mu) = 10 \pm 2$ nb/(GeV/c) for $|\eta^\psi| \leq 0.6$ and $p_T^\psi = 5.5$ GeV/c, in agreement with the value 8 ± 1 nb/(GeV/c) reported by CDF [9].

For an $\mathcal{E}$ particle in the mass region investigated by this study, R is approximately 2% when the width $\Gamma_\mu^{\mathcal{E}}$ is evaluated using the standard potential of heavy-quark spectroscopy [4]. Using a different potential model and one-loop corrections to the static potential of the scalar quark-anti-quark system, Reference [10] predicts leptonic widths that are a factor of three larger. In conclusion, R is expected to be between 2 and 6%. Since CDF has collected approximately 10^4 $\Upsilon(1S)$ mesons, the data could contain at least 200 events contributed by a hypothetical $\mathcal{E}$ meson on top of the smooth background due to Drell-Yan production, double semileptonic decays of $c\bar{c}$ and $b\bar{b}$ pairs, and fake muons produced by hadrons that mimic their signal.

IV.   DIMUON DATA SAMPLE

The dimuon sample used in this analysis corresponds to approximately 110 pb^{-1} of data collected with the CDF detector during the 1992−1995 collider run. This data set has been used in several CDF analyses and is described in more detail in Ref. [11]. The muon

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identification is based on the three-dimensional matching of the track segment in the muon chambers with the track reconstructed in the CTC and on the energy deposited in the calorimeter tower in the muon path [11, 12]. In this study, we search for muons with $p_T \geq 3$ GeV/c as in Ref. [12]; we select muons with $2 \leq p_T \leq 3$ GeV/c using the stricter cuts of the SLT algorithm [13, 14] in order to reduce the misidentification background. We require that at least one of the muons has been detected in both the CMP and CMU muon chambers. We retain events which contain two and only two muons. The muon momentum is evaluated with a fit which constrains the track to originate from the beam line. The dimuon invariant mass is calculated using these momenta. This study uses opposite charge dimuon pairs; however, distributions for same charge dimuon pairs are also shown as a cross-check.
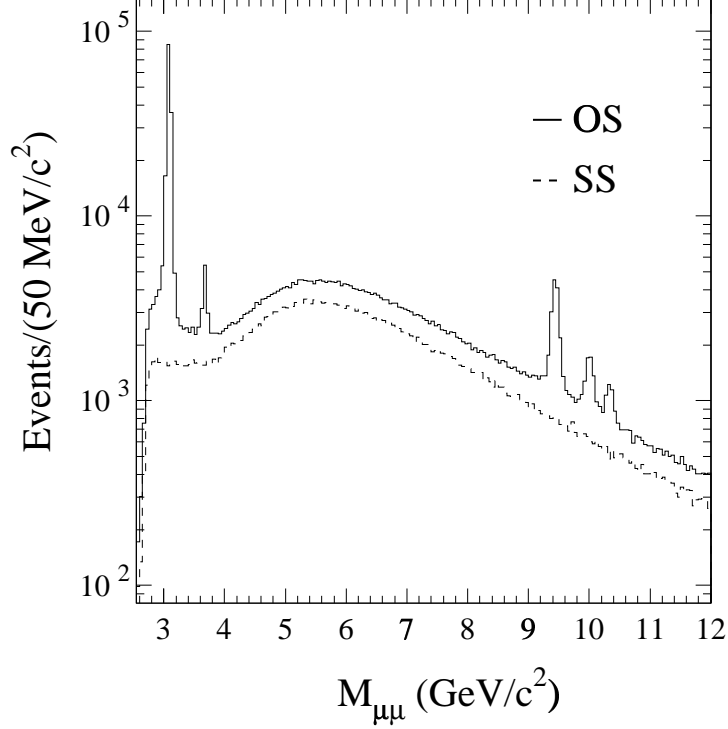
FIG. 1: Invariant mass distribution of all muon pairs. OS indicate dimuons with opposite charge used in this analysis. Dimuons with same sign charge (SS) are shown as an indication of the background level.

The dimuon invariant mass distribution is shown in Fig. 1. The yield of ψ mesons is much suppressed with respect to that of Υ mesons because, for invariant masses below 6.3 GeV/c^2, the kinematical acceptance decreases steeply due to the transverse momentum cut used to select muons; for masses larger than 6.3 GeV/c^2, the acceptance is flat and corresponds to the detector geometrical acceptance. Because of the uncertainty in modeling an acceptance that depends on the kinematics, we limit our study to the region above 6.3 GeV/c^2. The mass distributions at the $\Upsilon(1S)$ and in the region of interest for this study are shown in Fig. 2.

The number of $\Upsilon(1S)$ mesons in the data is derived by fitting with a binned maximum likelihood method the invariant mass distribution in Fig. 2(a) with a first order polynomial

and a Gaussian function. The best fit returns 9838 ± 141 $\Upsilon(1S)$ mesons over a background of 5769 events in the region $9.3 \leq M_{\mu^+\mu^-} \leq 9.55$ GeV/c^2. The fit also returns $M_{\Upsilon(1S)} = 9439\pm1$ MeV/c^2 and a mass resolution $\sigma_M = 57 \pm 1$ MeV/c^2. This mass resolution is well modeled by a simulation of the process $p\bar{p} \rightarrow \Upsilon(1S)X$, in which $\Upsilon(1S)$ mesons are produced with the transverse momentum distribution measured in the data and with a flat rapidity distribution. The same simulation predicts a mass resolution of 40 MeV/c^2 for $\mathcal{E}$ states with a mass around 7.5 GeV/c^2.
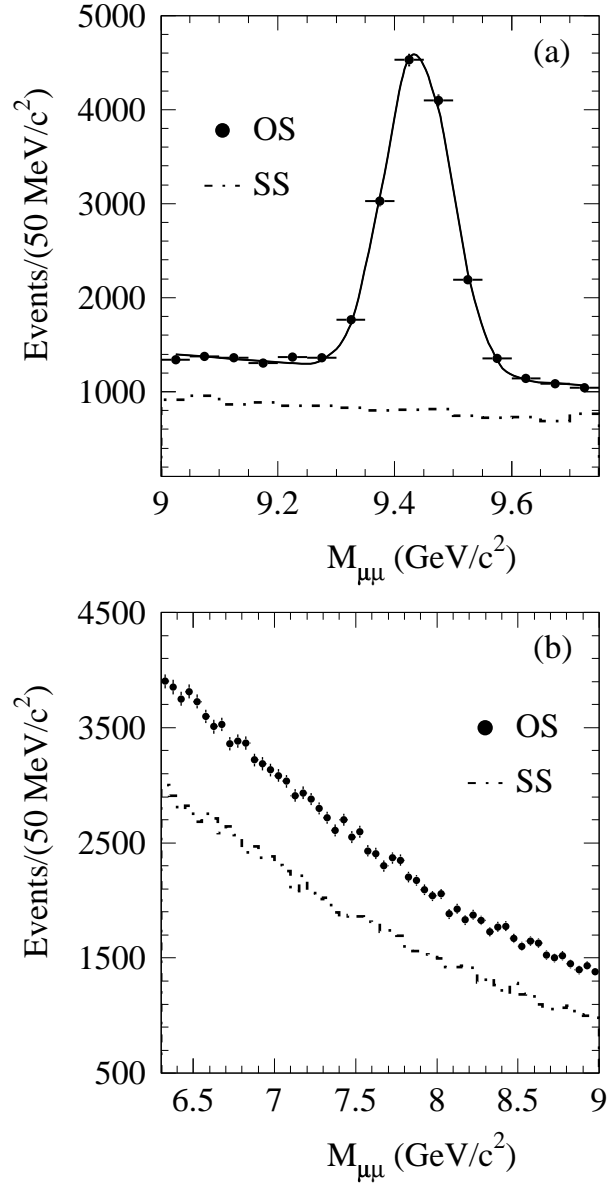
FIG. 2: Invariant mass distributions of muon pairs at the $\Upsilon(1S)$ (a) and in the region of interest for this study (b). The solid line represents the fit used to estimate the number of $\Upsilon(1S)$ mesons.

V.   BACKGROUND REDUCTION

As outlined in Sec. III, the hypothetical signal of an ε resonance of mass $\simeq 7.5$ GeV/c^2 is expected to be at least 2% of the $\Upsilon(1S)$ yield, i.e. about 200 events. Given the detector mass resolution, the 200 events have to be integrated in a region of 150 MeV/c^2 ($\pm 2\sigma_M$). As

shown in Fig. 2(b), three 50 MeV/c^2 bins centered around this mass contain approximately 8000 events. This background can be largely suppressed because it is mostly contributed by $b\bar{b}$ and $c\bar{c}$ production. The measurement of the time-integrated $B^0 - \bar{B}^0$ mixing probability, reported in Ref. [15], also makes use of this data sample. From that study we estimate that approximately 75% of the muon pairs arise from heavy flavor production. We use two intuitive criteria to reject dimuons arising from the decay of hadrons with heavy flavor:

1. An isolation requirement. The isolation, I, is defined as the scalar sum of the transverse momenta of all the tracks in a cone of radius 0.4 around a muon. We require that both muons have isolation $I \leq 4$ GeV/c.

2. A promptness requirement. In contrast to b and c-hadrons, the $\Upsilon(1S)$ and $\mathcal{E}$ mesons have negligible lifetime. We select prompt muons by requiring the sum of the impact parameter significance of both muons, s_{ip}, to be less than 4 [1]. The impact parameter significance is estimated for muons with tracks reconstructed in the microvertex silicon detector (SVX), otherwise is set to zero in order not to lose events.

The values of these cuts have been determined at the $\Upsilon(1S)$ mass (see Fig. 3). As shown in Table I, these cuts reduce the background by more than a factor of three while retaining more than 90% of the $\Upsilon(1S)$ signal.

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[1] The track impact parameter d is the distance of closest approach to the event primary vertex in the plane transverse to the beam line. The significance is defined as d/σ_d. The event primary vertex is determined as in the study in Ref. [15].
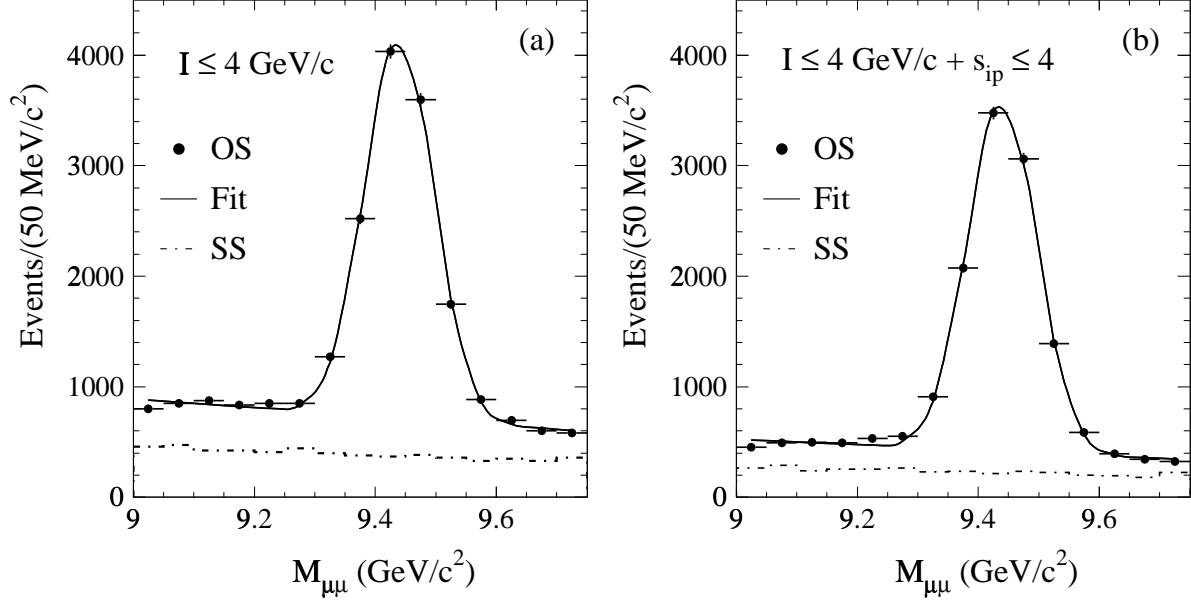
FIG. 3: Invariant mass distributions of opposite (•) and same sign charge (dot-dashed) muon pairs in the Υ (1S) mass range after the isolation (a) and impact parameter cuts (b). The solid line is a fit using a Gaussian plus a first order polynomial functions.

TABLE I: Numbers of $\Upsilon(1S)$ mesons and underlying-background events for different analysis cuts. Rates are evaluated by fitting the data with a Gaussian plus a first order polynomial function. The background is integrated over the mass region between 9.3 and 9.55 GeV/c^2. The last cut, QC, is used in the $\mathcal{E}$ search. Efficiencies are calculated with respect to the number of $\Upsilon(1S)$ candidates in the first row.

Cut	$\Upsilon(1S)$ candidates	Background	Efficiency(%)
None	9838 ± 141	5769	
I	9821 ± 129	3345	99.8
$QC = I + s_{ip}$	9064 ± 118	1842	92.1

VI. ESTIMATE OF THE UPPER LIMIT ON $\Gamma_l^{\mathcal{E}}$

Figure 4 shows the invariant mass distribution of muon pairs in the region between 6.3 and 9.0 GeV/c^2 after the isolation and impact parameter significance cuts.

We use a binned maximum likelihood method to fit the mass spectrum in Fig. 4 with a fourth order polynomial, which serves the purpose of modeling a smooth background, plus a Gaussian function, which searches for narrow resonances. We perform 54 fits, in which we constrain the Gaussian peak to the center of each of the 54 mass bins of Fig. 4; in each fit, we force the Gaussian width to the simulated resolution of the detector for that mass. For each mass bin, we use the integral of the Gaussian function and its error returned by the best fit to derive N_{ul}, the 90% credibility upper limit to the number of events contributed by a narrow resonance centered in that mass bin [2]. We evaluate the acceptance for a narrow resonance of a given mass relative to the $\Upsilon(1S)$ meson with a simulation in which an unpolarized resonance is produced with a flat rapidity distribution and with a transverse momentum distribution which has the same shape of the $\Upsilon(1S)$ meson (the average transverse momentum is reduced by the ratio of the masses). The ratio of N_{ul}, corrected for the detector acceptance, to the number of observed $\Upsilon(1S)$ mesons provides the 90% credibility upper limit to $\sigma_{\mathcal{E}} \; B(\mathcal{E} \to \mu\mu)/\sigma_{\Upsilon(1S)} \; B(\Upsilon(1S) \to \mu\mu)$ shown in Fig. 5. Figure 6 shows the 90% credibility upper limit to $\Gamma_l^{\mathcal{E}}$ derived using equation (1).

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[2] The integral of the fit likelihood from N_{ul} to infinity is 10% of the integral of the fit likelihood from 0 to infinity. The justification for this procedure is Bayesian with a prior that is zero for negative resonance cross sections and flat for positive ones.
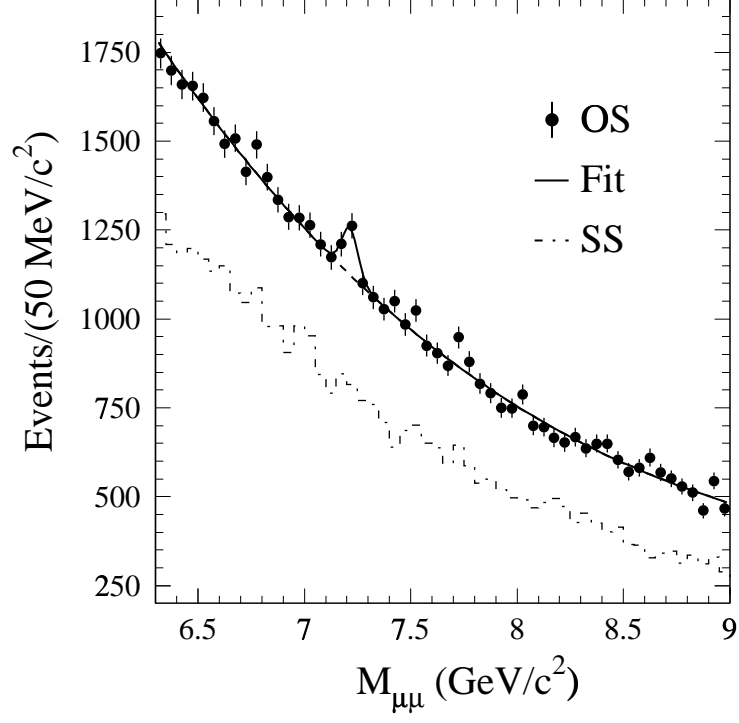
FIG. 4: Invariant mass distribution of opposite (•) and same sign charge (dot-dashed) muon pairs which pass the isolation and impact parameter cuts. The solid line represents the fit described in Sec. VII.
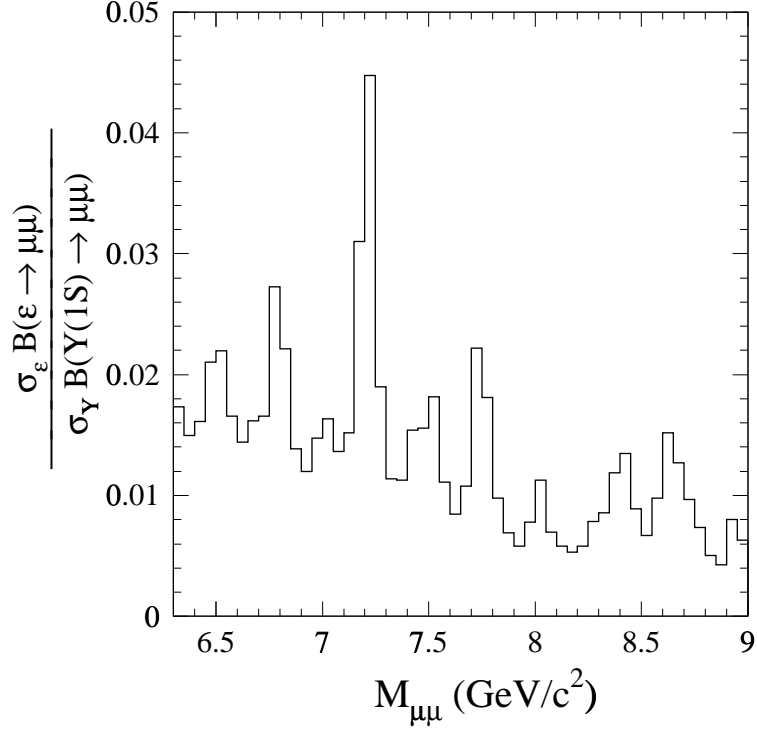
FIG. 5: Bayesian 90% upper limit to $\frac{\sigma_{\mathcal{E}}}{\sigma_{\Upsilon(1S)}} \frac{B(\mathcal{E} \to \mu\mu)}{B(\Upsilon(1S) \to \mu\mu)}$ as a function of the $\mathcal{E}$ mass.
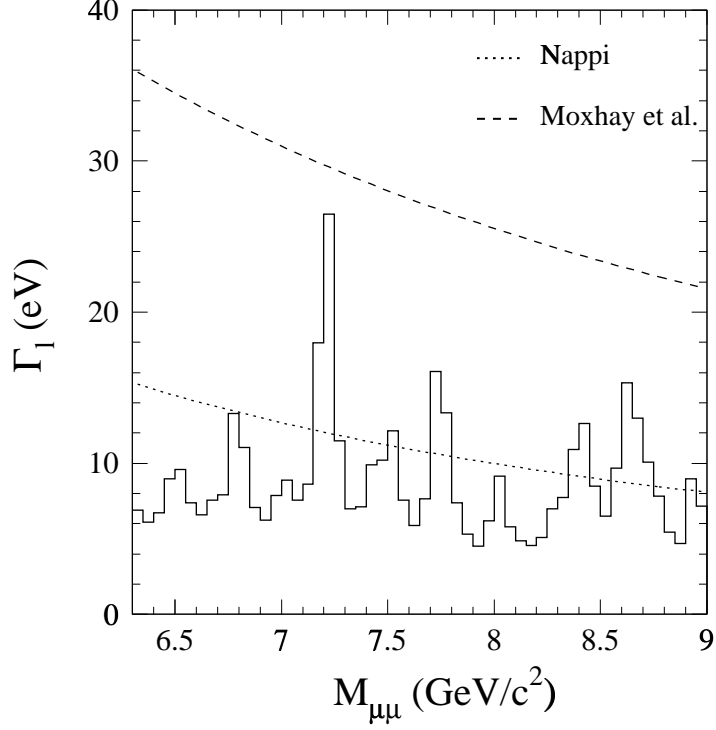
FIG. 6: Bayesian 90% upper limit to $\Gamma_l^{\mathcal{E}}$ (histogram). The dashed and dotted lines represent the leptonic widths of 1^{--} bound states of scalar quark predicted in Refs. [4] and [10], respectively.

Figure 7 shows the distribution of $N_{\mathcal{E}}$, the number of events attributed to a narrow resonance, divided by the error σ_N returned by the best fit for the 54 considered mass bins. With the exception of a point at 4.1 σ, this distribution is consistent with a Gaussian function of unit width, and it seems fair to assume that the distribution of the 90% upper limits in Fig. 6 is statistically consistent with the average upper limit $\Gamma_l^{\mathcal{E}} = 8$ eV. The 4.1 σ fluctuation occurs at the mass of 7.25 GeV/c^2.
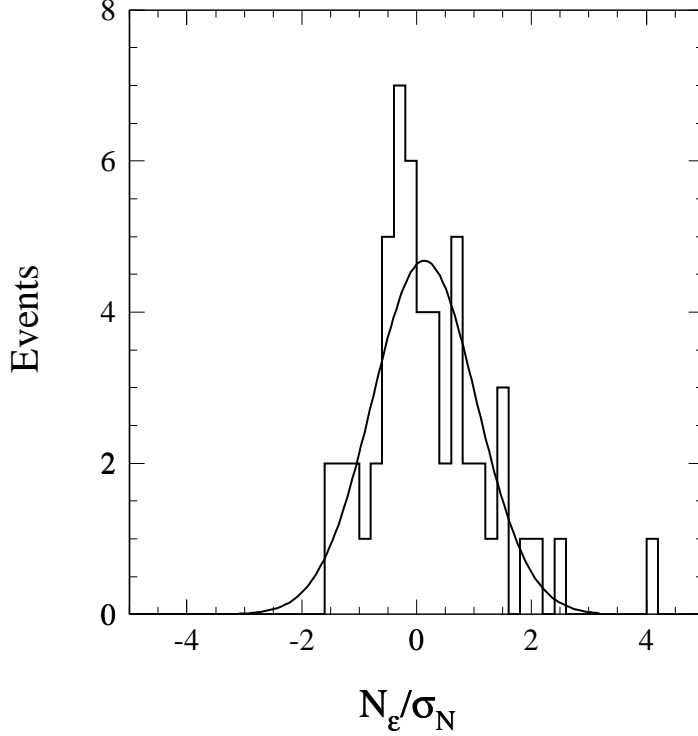
FIG. 7: Distribution of $N_{\mathcal{E}}/\sigma_N$ (see text). The solid line is a Gaussian function with unit width.

VII. STUDY OF THE 7.25 GeV/c^2 FLUCTUATION

In this section we explore the possibility that the anomalously large upper limit at 7.25 GeV/c^2 is due to a real signal. A fit, which uses a Gaussian function with a fixed 38 MeV/c^2 resolution, returns $M_{\mathcal{E}} = 7.22 \pm 0.01$ GeV/c^2 and a signal of 250 ± 61 events over a smooth background of 3355 events, extrapolated in the 150 MeV/c^2 region between 7.15 and 7.3 GeV/c^2 (see Fig. 4). The probability that 3355 background events fluctuate to no less than 3605 is 8×10^{-6} (4.3 σ). Since the mass range examined in Fig. 4 includes 52 almost independent combinations of three consecutive 50 MeV/c^2 bins, the probability of obtaining an equal or larger statistical fluctuation in the inspected mass window is approximately 4.1×10^{-4} (3.5 σ).

According to the simulation the acceptance for a 7.2 GeV/c^2 resonance relative to the

$\Upsilon(1S)$ meson is $A_{\mathcal{E}} = 0.78 \times A_{\Upsilon(1S)}$. It follows that

$$\sigma_{\mathcal{E}} \; B(\mathcal{E} \to \mu\mu) = (3.6 \pm 0.9) \times 10^{-2} \times \sigma_{\Upsilon(1S)} \; B(\Upsilon(1S) \to \mu\mu)$$

We note that this value is in agreement with the theoretical expectation for a bound state of charge$-1/3$ squarks.

We have investigated three additional selection cuts that reduce the number of events by more than a factor of two and compare the effect of these cuts on the number of $\mathcal{E}$ and $\Upsilon(1S)$ candidates:

1. $|\cos(\theta^*)| \leq 0.4$, where θ^* is the polar angle between the μ^+ and $\mathcal{E}$ directions in the $\mathcal{E}$ center-of-mass system. This cut reduces the number of events by simply selecting a particular sector of the phase space.

2. $\sum_i p_T \leq 40$ GeV/c and $\sum_j s_{ip}^j \leq 30$, where $\sum_i p_T^i$ is the scalar sum of the transverse momentum of all tracks i originating from the same vertex as the muon pair and $\sum_j s_{ip}^j$ is the sum of the impact parameter significance of all tracks j not used to define the primary vertex of the event [16]. This cut is intended to further suppress the heavy flavor background by rejecting events in which the muon pair carries a small fraction of the total transverse momentum or is produced in association with additional long-lived particles.

3. cut #1 + cut #2

The effect of these cuts is shown in Figs. 8 and 9, and is compared to the result for the $\Upsilon(1S)$ meson in Table II.
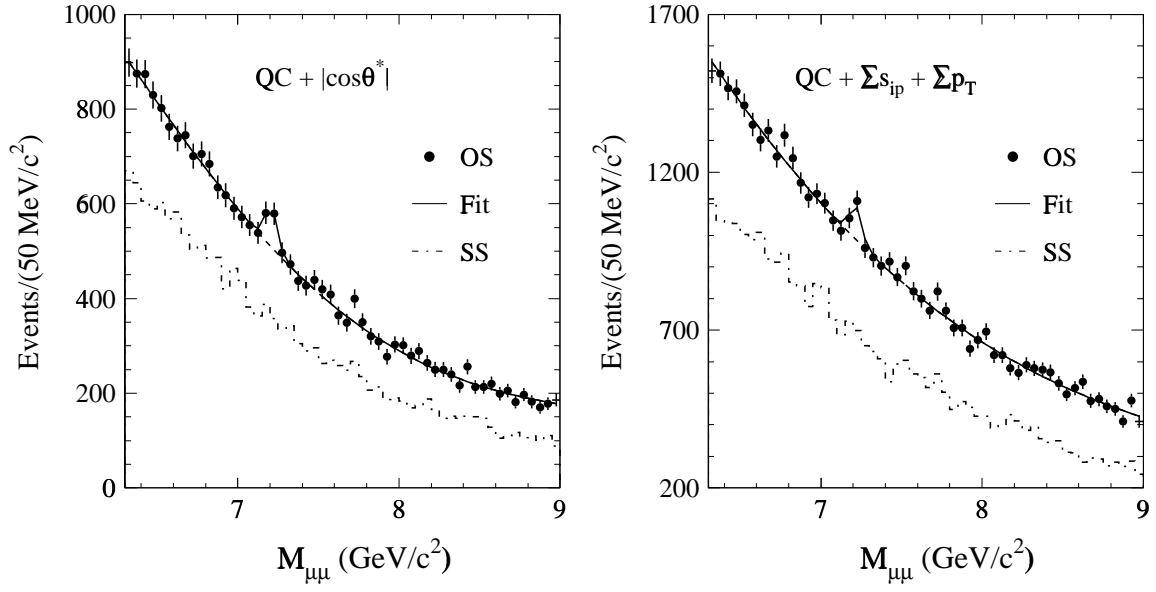
FIG. 8: Invariant mass distributions of muon pairs after applying the first and second cuts described in Table II. The solid line is a fit to the data described in the text.
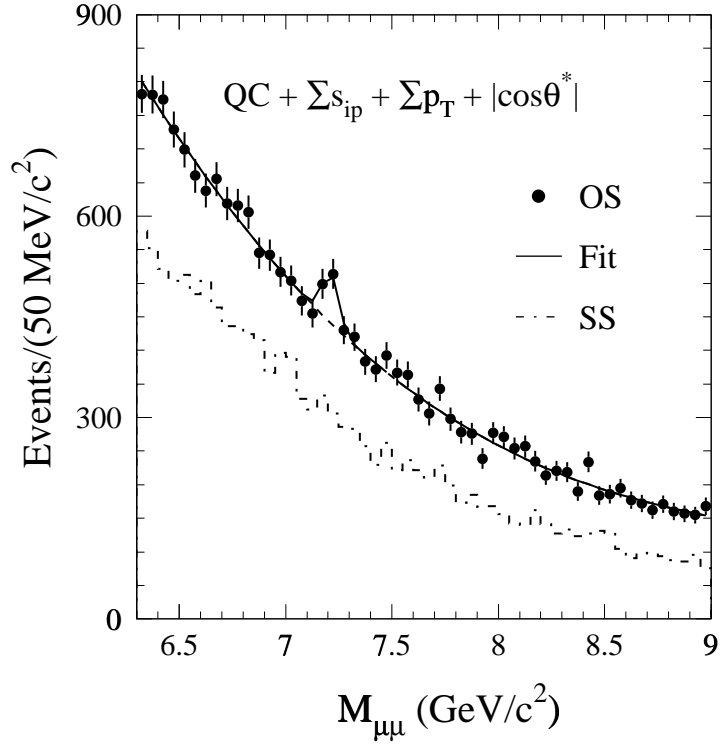

FIG. 9: Invariant mass distributions of opposite sign charge muon pairs after applying the third cut described in Table II.

TABLE II: Yield of $\mathcal{E}$ and $\Upsilon(1S)$ candidates for different analysis cuts. The underlying backgrounds are fitted with polynomial functions and integrated over the mass ranges $7.15 - 7.3$ and $9.3 - 9.55$ GeV/c^2.

Cut	$\mathcal{E}$	Background	$\Upsilon(1S)$	Background
QC	249.7 ± 60.9	3355.0	9064 ± 118	1842
# 1	160.5 ± 41.8	1508.0	3910 ± 90	611
# 2	206.2 ± 57.0	2948.0	8667 ± 136	1587
# 3	144.5 ± 39.0	1311.0	3699 ± 87	561

VIII. CONCLUSIONS

We have investigated the invariant mass spectrum of dimuons collected by the CDF experiment at the Tevatron collider to improve the limit to the existence of narrow resonances set by the experiments at the SPEAR e^+e^- collider. In the mass range $6.3 - 9.0$ GeV/c^2 we derive an average 90% upper credible limit of 8 eV to the leptonic width of possible resonances. An exception is the mass region around 7.2 GeV/c^2 where we observe a bump of 250 ± 61 events with a width consistent with the detector resolution. When attributing these events to a $\mathcal{E}$ meson, bound state of charge$-1/3$ scalar quark, the measured ratio

$$\frac{\sigma_\mathcal{E}}{\sigma_{\Upsilon(1S)}} \frac{B(\mathcal{E} \to \mu\mu)}{B(\Upsilon(1S) \to \mu\mu)} = (3.6 \pm 0.9)\%$$

is in agreement with the theoretical expectation for the production of a 1^{--} p-wave resonance. The statistical significance of this signal ($3.5\ \sigma$) is not sufficient to claim the discovery of a new particle.

IX. ACKNOWLEDGMENTS

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