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Search for Two-Body Radiative $\Upsilon(1S)$ Decays

CLEO Collaboration

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Abstract

We report on a study of exclusive radiative decays of the $\Upsilon(1S)$ resonance in a sample of 1.78 million $\Upsilon(1S)$ decays collected with the CLEOII detector. We present the first observation of the radiative decay $\Upsilon(1S) \rightarrow \gamma\pi^+\pi^-$, based on an excess of events in the $\Upsilon(1S)$ data over background. The excess is observed in the dipion mass interval 1.2 - 1.4 GeV/c^2. If we fit the enhancement in this region to a single Breit-Wigner function, we find 38.9 ± 11.3 events, with a fitted mass of $M_{\pi\pi} = (1.28 \pm 0.03)$ GeV/c^2 and width of $\Gamma_{\pi\pi} = (163 \pm 73)$ MeV/c^2. If we interpret this as a single enhancement X, we determine the product of branching fractions: $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma X) \times \mathcal{B}(X \rightarrow \pi^+\pi^-) = (0.96 \pm 0.25) \times 10^{-4}$ (statistical error only); the relative systematic error is estimated to be 25%. The observed properties of the enhancement find a consistent, although not conclusive, interpretation as the $f_2(1270)$.

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I. INTRODUCTION

Although several modes of radiative and hadronic $\Upsilon(1S)$ decays with multiparticle final states have been previously observed, no two-body radiative decays of the $\Upsilon(1S)$ have yet been reported. Such two-body J/ψ decays have been seen at the 10^{-4} level [1]. Simple scaling arguments predict a suppression of the order $[(q_b/q_c)(m_c/m_b)]^2$ for the relative branching ratios for such decays between the $\Upsilon(1S)$ and the J/ψ. More sophisticated calculations can also be found in the literature [2]. The radiative decays of the $\Upsilon(1S)$ can provide a door to a host of exotica, including higgs, cosmions[1] [3] and other non-interacting particles, glueballs and axions. For the "standard" axion, the axion-heavy quark couplings are prescribed by a single parameter x, the ratio of the the vacuum expectation values of the Higgs fields. For $q\bar{q}$ decaying radiatively into γ+axion, the dependence of branching ratio on x is proportional to $x^2(x^{-2})$ for charge 2/3(-1/3) quarks. Hence, the product of branching fractions $B(J/\psi \to \gamma + a) \times B(\Upsilon \to \gamma + a)$ is independent of x [4,5].

The observation of resonances in the invariant mass spectrum opposite photons is also one of the ways of establishing possible glueball candidates both in J/ψ and $\Upsilon(1S)$ radiative decays. Previous studies of charmonium have provided a detailed list of two-body radiative J/ψ decays [1]. Although, in many cases, the particles recoiling against the photon are "ordinary" (η and η', e.g.), in some cases, the particles are "exotic" ($\eta(1440)$, e.g.), or familiar particles ($f_2(1270)$, e.g.) with masses close to that expected by lattice calculations for glueballs with specified quantum numbers. Combined with information from quarkonium decays where an ω or a ϕ replaces the photon, one is able to determine the quark composition of a particular recoil state, and, by inference, its glue fraction as well. Alternately, particles believed to have large gg and correspondingly small $q\bar{q}$ content should have relatively small production cross-sections in two-photon collision events. To date, although exclusive multi-body radiative Υ decays have been seen [6], there have been no convincing signals observed for two-body radiative $\Upsilon(1S)$ decays, and the efforts to observe the glueball candidates seen in radiative J/ψ decay have so far been unsuccessful.

Radiative decays of the $\Upsilon(1S)$ have been investigated by many experimental groups, including CLEO [6], ARGUS [7], and MD-1 [8]. In the CLEO analysis, the decay modes $\Upsilon(1S)\to \gamma X$; $X \to \pi^+\pi^-$, $X \to K^+K^-$ and $X \to p\bar{p}$ were investigated. After applying a subtraction of non-$\Upsilon(1S)$ data, limits on branching fractions for exclusive radiative decays of the $\Upsilon(1S)$ into a photon plus another particle decaying into two charged tracks were obtained [6]. As noted in that paper, the only region of the dipion invariant mass plot suggestive of an excess above background appeared at $m_{\pi\pi} \sim 1.4$ GeV/c^2, where 10 events were counted in the interval 1.2 GeV/c^2 $< m_{\pi\pi} <$ 1.6 GeV/c^2; the scaled background count in the same region corresponded to 2 events. In this paper, we extend the previous CLEO analysis, using an enlarged data set and exploiting the excellent photon detection capabilities of the CLEO-II detector.

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[1] "Cosmion" is a generic term referring to a particle residing in the solar interior which can act as a heat sink, thus lowering the solar interior sufficiently so as to have a measurable lowering of the expected rate of ^8B neutrinos.

II. DATA SAMPLE AND EVENT SELECTION

The signal data used in this analysis were collected on the $\Upsilon(1S)$ resonance at a center-of-mass energy $E_{cm} = 9.46$ GeV, corresponding to an integrated luminosity of 78.9 pb^{-1} acquired during three different running periods. Non-$\Upsilon(1S)$ background data were taken at a center-of-mass energy $E_{cm} \sim 10.55$ GeV. The non-1S data is used to subtract the $e^+e^- \to \gamma X$ events not associated with the 1S, which constitute the largest background for this analysis. The sample of non-$\Upsilon(1S)$ events chosen for our background studies corresponds to an integrated luminosity of 500.4 pb^{-1}.

These data were collected with the CLEO-II detector [9] at the Cornell Electron Storage Ring. The CLEO II detector is a general purpose solenoidal magnet spectrometer and calorimeter. The detector was designed for efficient triggering and reconstruction of two-photon, tau-pair, and hadronic events. Measurements of charged particle momenta are made with three nested coaxial drift chambers consisting of 6, 10, and 51 layers, respectively. These chambers fill the volume from r=3 cm to r=1 m, with r the radial coordinate relative to the beam ($\hat{z}$) axis. This system is very efficient ($\epsilon \geq$98%) for detecting tracks that have transverse momenta (p_T) relative to the beam axis greater than 200 MeV/c, and that are contained within the good fiducial volume of the drift chamber ($|\cos\theta| <$0.94, with θ defined as the polar angle relative to the beam axis). This system achieves a momentum resolution of $(\delta p/p)^2 = (0.0015p)^2 + (0.005)^2$ (p is the momentum, measured in GeV/c). Pulse height measurements in the main drift chamber provide specific ionization resolution of 5.5% for Bhabha events, giving good K/π separation for tracks with momenta up to 700 MeV/c and separation of order 2σ in the relativistic rise region above 2 GeV/c. Outside the central tracking chambers are plastic scintillation counters, which are used as a fast element in the trigger system and also provide particle identification information from time of flight measurements.

Beyond the time of flight system is the electromagnetic calorimeter, consisting of 7800 thallium doped CsI crystals. The central "barrel" region of the calorimeter covers about 75% of the solid angle and has an energy resolution which is empirically found to follow:

$$\frac{\sigma_{\mathrm{E}}}{E}(\%) = \frac{0.35}{E^{0.75}} + 1.9 - 0.1E; \tag{1}$$

E is the shower energy in GeV. This parameterization includes effects such as noise, and translates to an energy resolution of about 4% at 100 MeV and 1.2% at 5 GeV. Two end-cap regions of the crystal calorimeter extend solid angle coverage to about 95% of 4π, although energy resolution is not as good as that of the barrel region. The tracking system, time of flight counters, and calorimeter are all contained within a 1.5 Tesla superconducting coil. Flux return and tracking chambers used for muon detection are located immediately outside the coil and in the two end-cap regions.

Our event selection criteria are optimized for high efficiency and low backgrounds. We search for events in both our $\Upsilon(1S)$ (signal) and non-$\Upsilon(1S)$ (background) datasets compatible with the kinematics for the two-body process $\Upsilon(1S) \to \gamma + X$; $X \to \pi^+\pi^-$. Candidate events must satisfy the following criteria:

1. There must be exactly two oppositely signed, good quality, charged tracks observed in the detector. Neither track can be identified as a lepton.

2. There must be exactly one electromagnetic shower in the barrel calorimeter which has energy more than $0.8\times E_{beam}$ and does not match (within 15 degrees) the position of any charged track extrapolated into the barrel. Additional showers, presumed to be noise, are allowed provided their measured energies are each less than 500 MeV.

3. The sum of the energy of the highest energy photon candidate plus the energies of the drift chamber tracks must, under the $\pi^+\pi^-$ hypothesis, lie within 3 standard deviations in energy resolution σ_E (typically $\sigma_E \approx 100$ MeV/c^2 based on the known photon energy and charged track resolutions) of the total event center of mass energy. Designating ΔE as the difference between $E_{\gamma\pi^+\pi^-}$ and the total center of mass energy, this requirement can therefore be written as: $|\Delta E| < 3\sigma_E$. We note that Υ(1S)$\rightarrow \gamma K^+K^-$ and Υ(1S)$\rightarrow$ $\gamma p\overline{p}$ events will, if misinterpreted as Υ(1S)$\rightarrow \gamma\pi^+\pi^-$, have a calculated event energy which is generally smaller than the known center of mass energy. Such events are therefore more likely to fail this energy conservation requirement than true Υ(1S)$\rightarrow$ $\gamma\pi^+\pi^-$ events.

4. The net momentum of the event, taking into account the two tracks and photon, must lie within 3 standard deviations in momentum resolution σ_p (typically, $\sigma_p \approx$ 100 MeV/c) of zero.

5. We require that the opening angle ϕ between the two charged tracks satisfy the condition cosϕ >-0.95. This condition is very effective at removing QED backgrounds, where the two leptons often emerge approximately anticollinear from the interaction point.

The momentum of the charged tracks recoiling against the high energy photon is typically $\sim$2 GeV/c, beyond the momentum range for which the CLEO detector can effectively discriminate pions from kaons (or protons). In order to maximize efficiency, we therefore do not require that the candidate pions be positively identified as pions, although we do require that the available particle identification information be consistent with the pion hypothesis.[2]

We use a GEANT-based [10], full CLEO-II Monte Carlo simulation to determine the efficiency for reconstructing a radiative Υ(1S) event, as a function of dipion mass, for each separate data sample. This Monte Carlo simulation also includes trigger efficiencies which have been tuned using CLEO-II data itself. For the bulk of the data used for this analysis, the overall event selection efficiency (including all trigger effects) varies smoothly from $\epsilon \sim$40% at threshold ($m_{\pi\pi} = 2m_\pi$) to a maximum of $\epsilon \sim$50% at $m_{\pi\pi} \sim$2 GeV.

The invariant mass of hadrons recoiling against high energy photon for events satisfying the above requirements is presented in Figure 1, for both the Υ(1S) resonance data and the non-1S data, under the assumption that the recoil tracks are pions. The non-Υ(1S) data have been properly scaled to the Υ(1S) data, taking into account: a) differences in the luminosity of our signal and background event samples, b) the expected $1/E^2$ energy dependence of

[2]We have, nevertheless, performed dedicated searches for Υ(1S)$\rightarrow \gamma K^+K^-$ and Υ(1S)$\rightarrow \gamma p\overline{p}$. In both cases, the yields from the resonance data were found to be fully consistent with the yields from the non-Υ(1S) data.

the QED cross section, and c) the relative event selection efficiency for the $\Upsilon(1S)$ and the non-1S data.

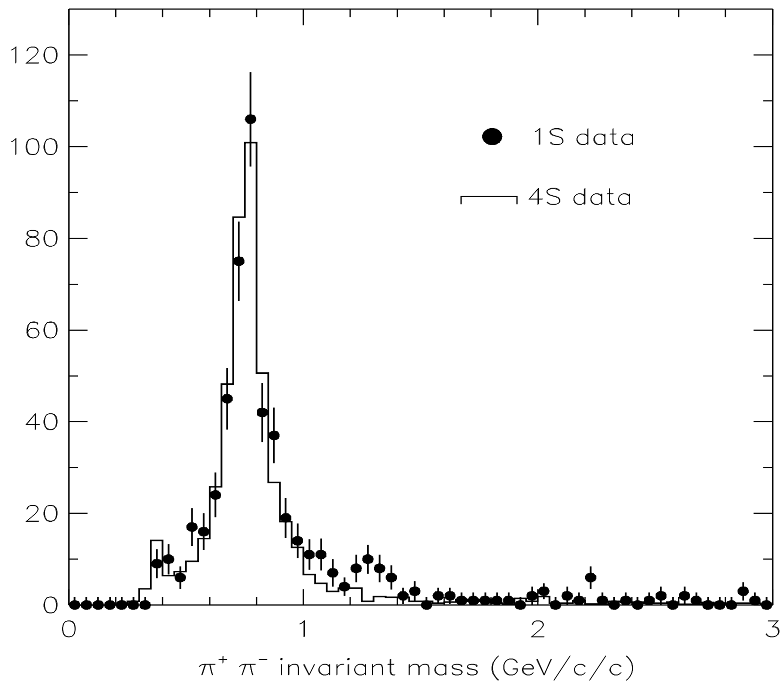

FIG. 1. Dipion ivariant mass for the 1S data, with non-1S data overlaid. The non-1S data have been scaled to equivalent luminosity taking into account the energy dependence of the cross section and efficiency effects.

Prominent in this invariant mass plot is the presence of a large ρ^0 signal, as is expected theoretically and verified experimentally [6–8] by other analyses. This is consistent with our expectation that backgrounds due to QED processes (e.g., $e^+e^- \to \rho^0\gamma$, $\rho^0 \to \pi^+\pi^-$) will be dominant in this analysis. Comparing the acceptance and luminosity corrected signals observed in both the $\Upsilon(1S)$ and non-1S data, we note that the $\gamma\rho^0$ rate observed on the $\Upsilon(1S)$ is consistent with the yield from the non-$\Upsilon(1S)$ data. Also evident in both plots is a small enhancement near threshold (at $m_{\pi\pi}$ ~350 MeV/c^2); this peak results largely from misidentified $e^+e^- \to \gamma\phi$; $\phi \to K^+K^-$ events. As with $e^+e^- \to \gamma\rho^0$, this enhancement shows approximately the same observed cross-section for both the 1S and the non-1S data samples, as expected.

We note an apparent excess of events in the $\Upsilon(1S)$ data sample over background in the region $m_{\pi\pi}$ ≈1.3 GeV. To further investigate this peak, we fit the recoil dipion invariant mass spectra to Breit-Wigner functions, one corresponding to the ρ^0 resonance and the second corresponding to a possible resonance in the region $m_{\pi\pi}$ ≈1.3 GeV, as follows:

- The non-$\Upsilon(1S)$ data are fit to a relativistic, spin-1 Breit-Wigner in the region $m_{\pi\pi} >$ 600 MeV/c^2 (Figure 2; we exclude the region $m_{\pi\pi} <$ 600 MeV/c^2 from this fit, as this mass region is subject to background from $e^+e^- \to \gamma\phi$; $\phi \to K^+K^-$, as well as contamination from QED processes, particularly $e^+e^- \to e^+e^-\gamma$).

- Using the parameters for the ρ^0 taken from the previous fit to the non-1S data, we now fit the Υ(1S) data to a sum of the ρ^0 signal plus a second relativistic spin-1 Breit-Wigner. Performing a free fit for the mass and width of this second Breit-Wigner, we find that the second Breit-Wigner corresponds to an excess of 38.9 ± 11.3 events with mean equal to (1.28 ± 0.03) GeV/c^2, and fitted width equal to (163 ± 73)MeV/c^2 (Figure 3). For both data samples, we note that the ρ^0 Breit-Wigner is observed to saturate the dipion mass spectra in the region $m_{\pi\pi}$ >1.6 GeV/c^2.

We determine the product of branching fractions: $\mathcal{B}(\Upsilon(1S) \to \gamma X) \times \mathcal{B}(X \to \pi^+\pi^-) = (0.96 \pm 0.25) \times 10^{-4}$ (statistical error only).

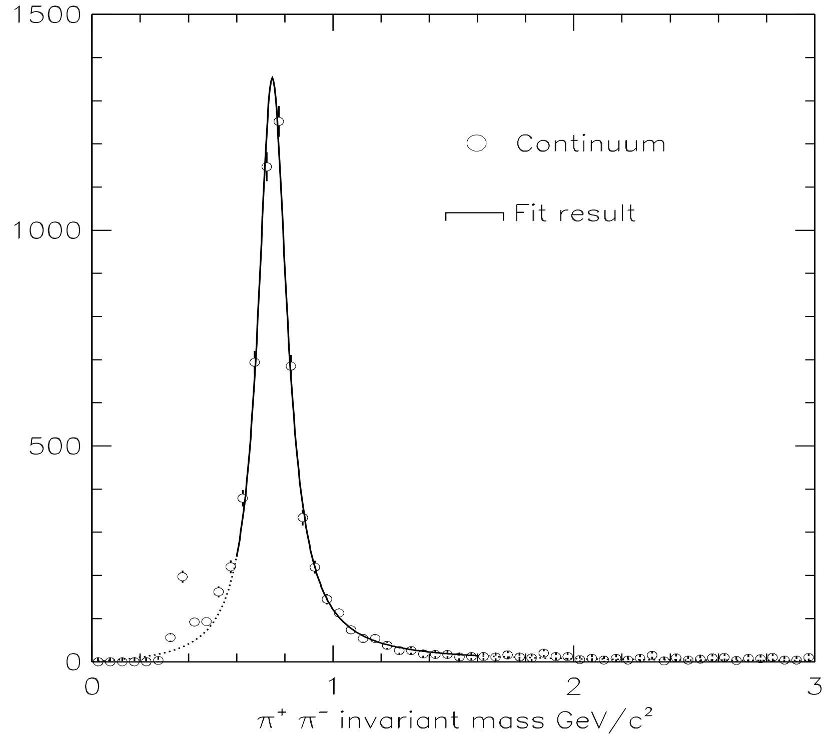

FIG. 2. Fit of the dipion invariant mass spectrum for $\gamma\pi^+\pi^-$ events taken from the non-Υ(1S) data sample to the ρ^0 Breit-Wigner function. (50 MeV/c^2 per bin)

The most prominent resonance in this mass range observed in radiative J/ψ decays is the $f_2(1270)$, for which $\mathcal{B}(J/\psi \to \gamma f_2(1270)) = (1.38 \pm 0.14) \times 10^{-3}$. Under the assumption that the 1.3 GeV/c^2 peak we observe comes exclusively from the process: Υ(1S)$\to \gamma f_2(1270)$; $f_2 \to \pi^+\pi^-$, and neglecting any possible interference effects with other processes producing the $\gamma\pi^+\pi^-$ final state, we fitted the on-resonance recoil dipion invariant mass data (after background subtraction) to a spin-2 Breit-Wigner function with the mean and width parameters fixed to the Particle Data Group $f_2(1270)$ values. Such a fit yields (43.3 ± 11.4) events consistent with the $f_2(1270)$ interpretation.

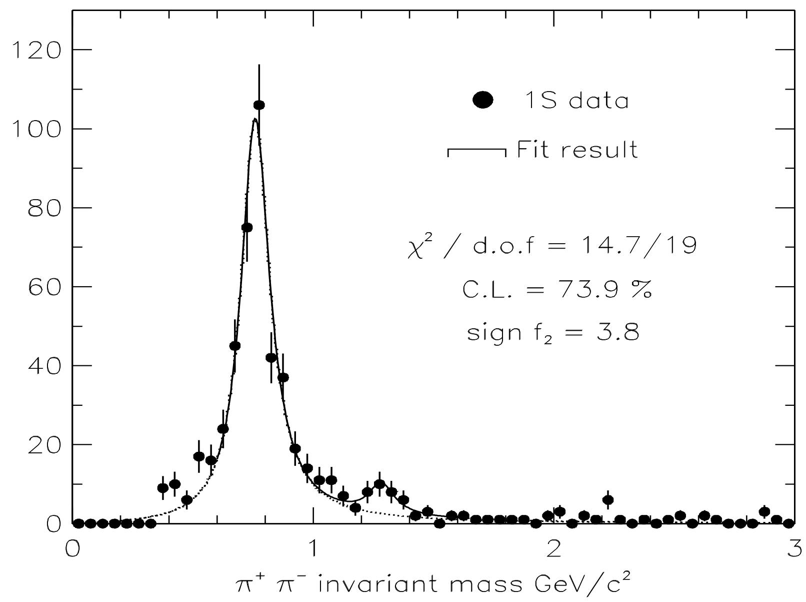

FIG. 3. Fit of the dipion invariant mass spectrum for $\gamma\pi^+\pi^-$ events taken from the Υ(1S) data sample to the sum of the ρ^0 Breit-Wigner functions, plus a second Breit-Wigner with floating mean and width. (50 MeV/c^2 per bin)

In principle, decays of the type $\Upsilon(1S)\rightarrow \pi^0 X$, although not yet observed, could produce background in the case where the π^0 decays either very asymmetrically, or produces a 'merged' π^0. In the former case, we expect the mean of the difference between the Υ candidate energy and the known e^+e^- center of mass energy to be shifted off-center (to negative values), since the high energy photon will always have less than the full π^0 energy. Figure 4 shows that the observed ΔE distribution for our signal candidates (i.e., for events in the interval 1.2 GeV/c^2 $< m_{\pi\pi} <$ 1.4 GeV/c^2) fits well to a Gaussian with zero mean and unit width, as expected for a true signal. We have additionally attempted to establish whether an

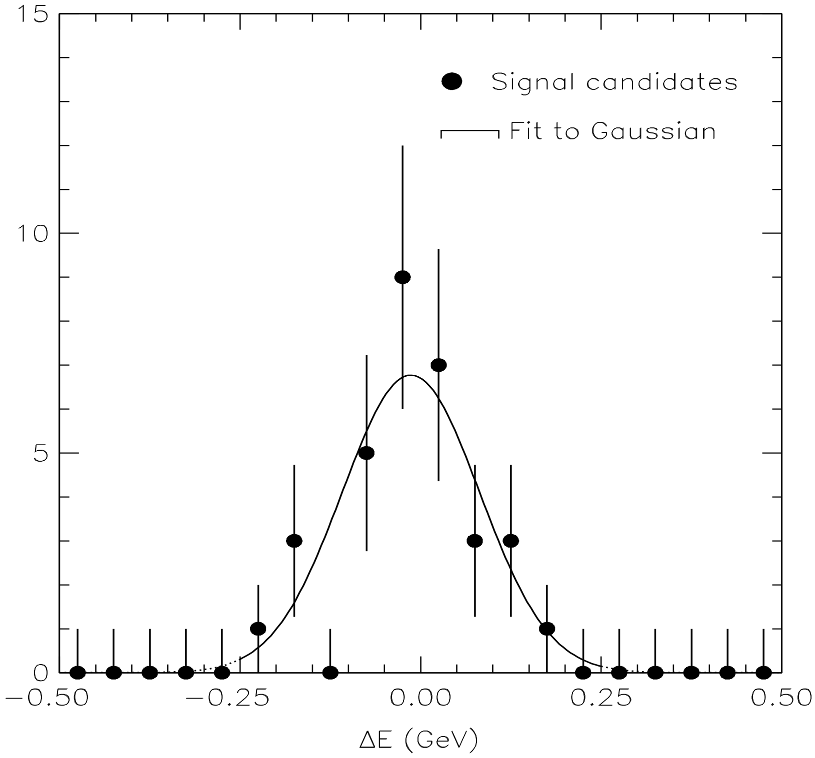

FIG. 4. Fit to ΔE distribution for signal candidates.

observed shower is due to one photon or two overlapping photons coming from π^0 decays by determining the shower 'mass' of our photon candidates. The shower mass is determined by forming a four-vector for each individual CsI crystal in a shower, based on the energy deposition in that particular crystal. An invariant mass is then calculated from all the four-vectors which comprise the shower. For showers caused by 'merged' π^0's, the shower mass (or the 'connected region' mass) is peaked at a value of approximately m_{π^0}. For true photons, the shower mass peaks at values lower than m_{π^0}. We find, as shown in Fig 5, that the average value of this parameter for Monte Carlo produced merged photons from π^0 decay is well separated from the values obtained for photons from data radiative Bhabha events. Showers selected from our candidate exclusive $\Upsilon(1S)$ decay sample, for which $m_{\pi\pi}$ ~1.3 GeV, are also consistent with the single photon interpretation. The distribution in this shower-mass parameter therefore favors the single photon interpretation for our exclusive radiative decay event candidates.

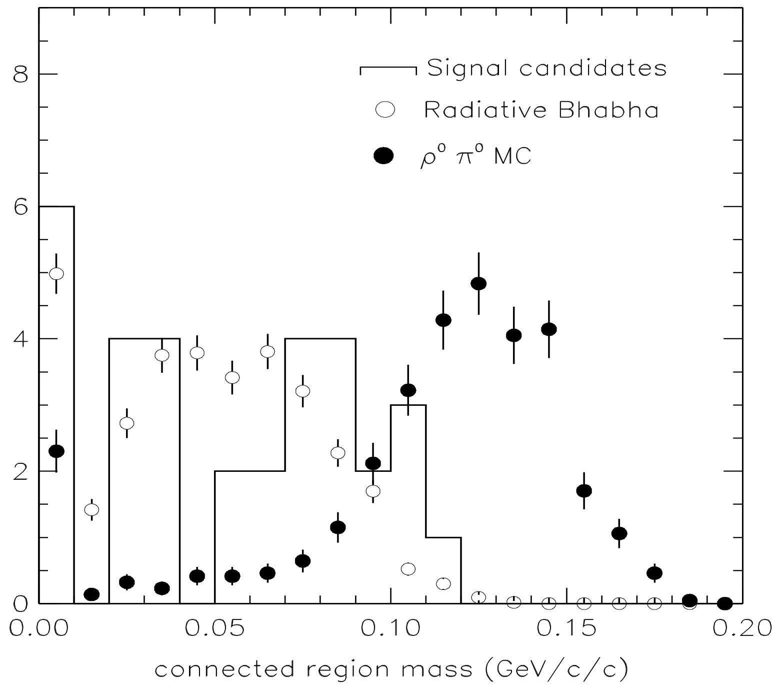

FIG. 5. Shower mass of photon candidates in the calorimeter for single photons and Monte Carlo merged π^0's.

For the measurement $\Upsilon(1S) \rightarrow \gamma X$; $X \rightarrow \pi^+\pi^-$, systematic uncertainties are due primarily to the fitting procedure used to extract the significance of the excess (20% relative error), uncertainties in our total efficiency (5%), and our uncertainty in the total number of $\Upsilon(1S)$ events (4%).

In summary, we have conducted a search for radiative decays: $\Upsilon(1S) \rightarrow \gamma X$; $X \rightarrow \pi^+\pi^-$. We observe an excess over background in the $\gamma\pi^+\pi^-$ final state, in the dipion mass region $m_{\pi\pi} \approx 1.3$ GeV. We have fit this enhancement to a single Breit-Wigner, assuming there is no interference with other possible $\Upsilon(1S) \rightarrow \gamma\pi^+\pi^-$ final states or non-1S production of $\gamma\pi^+\pi^-$. The fit to this enhancement gives a mass equal to 1.28 ± 0.03 GeV/c^2 and width equal to (163 ± 73) MeV/c^2. The efficiency corrected product of branching fractions of this enhancement is $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma X) \times \mathcal{B}(X \rightarrow \pi^+\pi^-) = (0.96 \pm 0.25) \times 10^{-4}$ (statistical errors only).

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