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# Search for Diffractive Dissociation of a Long-lived $H$ Dibaryon

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## Abstract

We have searched for long-lived $H$ dibaryons (six-quark *uuddss* states) in a neutral beam produced by 24.1 GeV/$c$ $p$-Pt collisions. The signature was exclusive $\Lambda^0\Lambda^0$ production from diffractive dissociation of $H$'s striking plastic scintillator. We observed 40 $\Lambda^0\Lambda^0$ events with a background of 3.2 events, but see no evidence of $H$ dissociation. Using our additional observation of $187\pm39$ $\Lambda^0 K^0_S$ events produced by coherent diffractive dissociation of neutrons from carbon for normalization, we place an upper limit of 1 mb/sr on the production of $H$'s with lifetimes $\gtrsim 10^{-8}$ s.

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In the theory of hadrons composed of colored quarks and anti-quarks, combinations other than the usual $qqq$ and $q\bar{q}$ are allowed as long as they are color singlets. Jaffe [1] found that a six-quark $uuddss$ color singlet state ($H$) might have strong enough color-magnetic binding to be stable against strong decay; that is, the mass $m_H$ could be less than the strong-decay threshold, twice the $\Lambda^0$ ($uds$) mass. Subsequent estimates of $m_H$ have varied widely [2]. Since $m_H$ determines the decay channels and phase space available for decay, the uncertainty in $m_H$ results in a wide range of lifetimes $\tau_H$ to be considered, from $\sim 10^{-10}$ near the $\Lambda^0\Lambda^0$ threshold to $> 10^7$ s for light $H$'s near the $nn$ threshold [4]. The potentially long lifetimes raise the possibility that $H$'s may be present as components of existing neutral beams.

We have searched for the $H$ in a neutral beam [5] at the Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS) accelerator. Our detection technique relied on diffractive dissociation of $H$'s impinging on plastic scintillator, resulting in $\Lambda^0\Lambda^0$ production (Fig. 1):

$$H + A \;\rightarrow\; \Lambda^0\,\Lambda^0\,A \;\rightarrow\; p\pi^-\,p\pi^-\,A. \tag{1}$$

While this method is intrinsically sensitive to the whole $H$ mass range, the dissociation material was placed roughly $10^{-8}$s (proper time at the design momentum of $\sim$ 10 GeV/$c$) downstream of the production target, and, given the lifetime calculations of Ref. [4], is therefore sensitive to bound $H$'s with a mass less than about 2150 MeV/$c^2$.

Neutrons in the beam initiated two other reactions with similar topology,

$$n + A \;\rightarrow\; \Lambda^0\,\Lambda^0\,X \;\rightarrow\; p\pi^-\,p\pi^-\,X, \tag{2}$$

$$n + A \;\rightarrow\; \Lambda^0\,K^0_S\,X \;\rightarrow\; p\pi^-\,\pi^+\pi^-\,X, \tag{3}$$

which provided natural calibration events but also potential background. Reaction (3) includes coherent diffractive dissociation off (3a) hydrogen, $^1$H, or (3b) carbon, C; (3c) incoherent dissociation off C, in which case $X$ is composed of nuclear fragments; and (3d) other reactions, typically resulting in more charged particles.

The data were taken as part of Brookhaven National Laboratory Expt. 888. A 24.1 GeV/$c$ proton beam from the AGS was directed onto a 4.7-in. Pt target at 65-mr with respect to the neutral beam line ($z$-axis), described in Ref. [5]. Lead sheets totaling 108 g/cm$^2$ were placed inside sweeping magnets to materialize and remove photons. The resulting neutral beam exited vacuum 18 m downstream of the target ($z$=0), and after an air gap struck a scintillation counter system, the "dissociator". Roughly equal amounts of data were taken with the dissociator in two positions, $z$ = 20.586 m and $z$ = 21.078 m with respect to the production target.

For tracking charged particles produced in the dissociator, an array of drift chambers was positioned further downstream, as shown in Figure 2. Three chamber planes, including one rotated view, preceded a bending magnet of $p_\perp$ = 318 MeV/$c$. The magnet was followed by two more planes of chambers arranged in a double-arm configuration on either side of the neutral beam. Downstream of the chambers were two banks of hodoscope counters surrounding threshold Cherenkov counters. The detector geometry was optimized to accept the two relatively high momentum protons (bending toward beam left) and low momentum negative pions (beam right) which result from the decay of two diffractively produced $\Lambda^0$'s. In addition, the left side Cherenkov counter was filled with freon of index 1.0011 providing a threshold for rejecting pions of $p > 3$ GeV/$c$.

The dissociator (Fig. 1) consisted of eight 5-in. $\times$ 5-in. $\times$ 0.5-in. pieces of BC400 scintillator, each viewed from the side by one photomultiplier tube (PMT). The most downstream segment was followed by a 12-in. $\times$ 12-in. $\times$ 0.125-in. scintillator viewed by two phototubes, called the dissociator veto, which tagged charged particles exiting in the forward direction. In an ideal diffractive process, recoiling protons with $\sim 60$ MeV of kinetic energy produced light in the dissociator while leaving the veto quiet. The light yields were calibrated using high-energy minimum-ionizing particles (mips) from $K_L$ decays.

Signals from the hodoscopes were used to generate two levels of hardware trigger. The first level required at least one charged particle in each arm, and a prescaled sample of this "minimum bias" (m.b.) trigger, which included $K_L^0$ decays, was recorded. The second level required hodoscopes signals to be consistent with at least two charged particles in each arm, allowing for the potential miss of soft $\pi^-$'s or a stiff $p$ in one of the hodoscopes. The second level trigger initiated on-line software processing which required only that hits in the drift chambers were consistent with the passage of four charged particles. Events passing this final criterion were written to tape for later analysis. A total of $4 \times 10^7$ events were recorded over several days at an average intensity of $2 \times 10^{11}$ protons on target.

The offline analysis looked for pairs of fitted trajectories which formed a vertex ($V^0$), and pairs of $V^0$'s which pointed toward a common vertex ($V^0V^0$). Of the many combinations of tracks and $V^0$'s in a given event that could produce a good $V^0V^0$, the best was selected based upon a combination of the chisquares found in each stage of reconstruction and fitting. For each $V^0$ in our sample of $V^0V^0$'s, we calculated invariant masses under $\pi^+\pi^-$ or $p\pi^-$ hypotheses. Events with $m_{p\pi}$ near $m_\Lambda$ for one $V^0$ and $m_{\pi\pi}$ near $m_K$ for the other were candidate $\Lambda^0K_S^0$'s. By studying these events, as well as a prescaled sample (10%) of events whose masses fell within the $\Lambda^0\Lambda^0$ signal mass region, all events outside but near the $\Lambda^0\Lambda^0$ signal mass region, and Monte Carlo simulations, we produced a set of selection criteria ("cuts") which we used to extract the $\Lambda^0K_S^0$ and $\Lambda^0\Lambda^0$ signal samples.

The first set of cuts required the position of each $V^0$ in the best $V^0V^0$ to be 3 standard deviations downstream of the dissociator veto, and the position of the $V^0V^0$ itself to be consistent with the dissociator volume. Figure 3 is a plot of $m_{\pi\pi}$ for one $V^0$ vs $m_{p\pi}$ for the second $V^0$, for all $V^0V^0$'s passing the vertex position cuts. The peak at $m_K$ vs $m_\Lambda$ is due to $\Lambda^0K_S^0$ production by neutrons in the dissociator (Reaction 3). The mass projections were well fitted by Gaussians with $\sigma = 0.8$ MeV for $m_\Lambda$ and $\sigma = 2.64$ MeV for $m_K$. The requirement that $|m_\Lambda - m_{p\pi}| < 2.5$ MeV and $|m_K - m_{\pi\pi}| < 7.5$ MeV left us with 2605 $\Lambda^0K_S^0$ events. From the events outside the mass peak, we estimate 14 of these are background events passing the mass cuts.

Figure 4 is a plot of $m_{p\pi}$ for the first $V^0$ found vs $m_{p\pi}$ for the second, with the additional constraints that no signal appeared in the left-side Cherenkov counter (to reject positively charged pions), and that all pairs of opposite sign tracks in an event had $|m_K - m_{\pi\pi}| >$ 10.0 MeV (to prevent $K_S^0$'s from faking $\Lambda^0$'s). The peak contains 40 events that satisfy the $\Lambda^0\Lambda^0$ mass cuts, including 3.2 background events estimated from the population outside the mass peak. Our tight chisquare cuts on the quality of the reconstructed $V^0$'s and $V^0V^0$'s, as well as our millimeter resolution in the $x$ and $y$ positions of the vertices ensure that the $\Lambda^0\Lambda^0$

events are not caused by multiple neutron or $K^0$ interactions in the dissociator. Analyses with the $V^0V^0$ cuts removed allowed us to eliminate this possibility as source of $\Lambda^0\Lambda^0$'s at the 0.1 event level. The events in Figure 4 can therefore be attributed at this stage to either inelastic production of $\Lambda^0\Lambda^0$ by neutrons or $H$ dissociation.

We first discuss the $\Lambda^0 K_S^0$ events of Figure 3. The sample can be divided into three categories, based upon the signals in the dissociator and veto counters. In the first category we place all events in which there are signals in at least one dissociator counter and the veto. These events we consider primarily to be those where $\Lambda^0 K_S^0$ pairs are produced along with additional charged particles, as in Reaction (3d).

In the second category we place events where there is a signal in at least one dissociator segment but no veto signal above a threshold of 1/4 mip. These 527 events we attribute primarily to elastic (diffractive) production of $\Lambda^0 K_S^0$ from either the hydrogen in the dissociator or from nucleons in dissociator carbon. Of course, the sample also includes events similar to those in the first category but where the extra particles are undetected neutrals.

The third category contains events in which there is no signal in either the dissociator or the veto counter. These 292 events are of special interest, as they correspond to events where the recoil was a nucleon which escaped detection or where the production has been coherent off the carbon nuclei in the dissociator. Figure 5 is a histogram of $t' = |t - t_{\rm min}|$, where $t$ is the 4-momentum transfer squared [7], and $t_{\rm min}$ is its minimum value. Coherent production from carbon is clearly evident in the steep forward peak of the distribution. The histogram is well fit by $dN/dt = A_1 \exp(b_1 t') + A_2 \exp(b_2 t')$, with $b_1 = -68 \pm 11 {\rm GeV}^{-2}$, characteristic of coherent diffraction off carbon, and $b_2 = -11 \pm 2{\rm GeV}^{-2}$, characteristic of diffraction off of nucleons. With $A_1 = 102 \pm 13$, we attribute $187 \pm 39$ events to the coherent process [8].

It is reasonable to expect $H$ diffractive dissociation from C or $^1$H to have a $t'$ dependence similar to that of our observed analogous $\Lambda^0 K_S^0$ production reactions. For reaction (1), we require no signal in the dissociator veto and $t' \approx p_T^2 < 0.330$ (GeV/$c$)$^2$ for the $\Lambda^0\Lambda^0$ system. Of the 40 peak events in Fig. 4, 38 have a veto signal. As shown in Figure 6 , they have a relatively flat distribution in $p_T^2$, inconsistent with diffractive dissociation of $H$'s. Of the two events with no veto, one survives the $p_T^2$ cut with $p_T^2 = 0.235$ GeV$^2$, marginally consistent with both a real $H$ and residual background from (2). The average invariant mass of the 40 $\Lambda^0\Lambda^0$'s is 2.33 GeV/$c^2$; we see no evidence of a narrow resonance and with our limited statistics a broad resonance cannot be distinguished. Therefore we also do not see evidence for an $H$ *above* the $\Lambda^0\Lambda^0$ threshold.

We derive an upper limit on production of long-lived $H$'s by normalizing both to the coherent production of $\Lambda K_S$ from C in the dissociator (3b) and the neutral-beam $K_L^0$ decays found in the m.b. data. Reaction (3b) is our primary normalization since it has the advantage that detector and pattern recognition efficiencies are similar to those of (1). We write the limit on $H$ production in terms of the cross section for neutron production by 24.1 GeV/$c$ $p$'s incident on Pt:

$$\frac{d\sigma_H}{d\Omega}\Big|_{65\,\rm mr} < \left(\frac{N^H_{\Lambda\Lambda} A_{\Lambda K_S} \sigma^c_{\Lambda K_S}}{N^c_{\Lambda K_S} A_{\Lambda\Lambda} \sigma_{\Lambda\Lambda}}\right) \frac{d\sigma_n}{d\Omega}\Big|_{65\,\rm mr}. \qquad (4)$$

$N^c_{\Lambda K_S}$ is the number of coherently produced $\Lambda^0 K_S^0$; $A_{\Lambda\Lambda}$ and $A_{\Lambda K_S}$ are the acceptances and efficiencies for (1) and (3b), resp.; $\sigma_{\Lambda\Lambda}$ and $\sigma^c_{\Lambda K_S}$ are their cross sections; and $N^H_{\Lambda\Lambda}$ is the

Poisson mean for which the probability of observing 0 or 1 events is less than 10%. The term in parentheses in Eqn. 4 is the ratio of $H$'s in our beam to neutrons yielding $\Lambda^0 K_S$ above our 8 GeV/$c$ detection threshold.

There is theoretical uncertainty in Eqn. 4 due to the unknown values of $\sigma^c_{\Lambda K_S}$ and $\sigma_{\Lambda\Lambda}$. For the former, we use an optical model [3,9] to scale the cross section off of free protons [10], and and find $\sigma^c_{\Lambda K_S} = (1.4 \pm 0.35)\sigma_{\Lambda K_S} = 5.9 \pm 1.8$ $\mu$b. We estimate $\sigma_{\Lambda\Lambda}$ for (1) off $^1$H in several ways, including a model [11] for $p$-deuteron scattering and a fit scaled from high energy, high mass inclusive proton diffraction dissociation [12]. We find values for $\sigma_{\Lambda\Lambda}$ in the range 0.2–1.0 mb after dividing by 8 to account for the flavor decomposition of the $H$ found in Ref. [4]. For lack of more information, we use a value for $\sigma_{\Lambda\Lambda}$ in the middle of the range, 0.5 mb. For the coherent dissociation of $H$'s from C, we assume the same scaling holds as for coherent production of $\Lambda^0 K_S$. In addition, we increase the effective cross sections for both $\Lambda^0 K_S$ and $\Lambda^0\Lambda^0$ production by a factor of two due to our inability to distinguish $\Sigma^0$'s from $\Lambda^0$'s.

We have used M.C. simulations to estimate both $A_{\Lambda K_S}$ and $A_{\Lambda\Lambda}$. By varying the mass and momentum spectra input to the M.C. within limits compatible with the data, we estimate 16% uncertainty in $A_{\Lambda K_S}$. For $H$ dissociation, we used several input momentum spectra based upon simple models such as coalescence and central production. For mass spectra of the $\Lambda^0\Lambda^0$ pair we tried both resonance-based shapes and a $1/M^2$ distribution modified by phase space. The result is a large uncertainty, $\sim$ 80%, in $A_{\Lambda\Lambda}$.

With these systematic uncertainties, we increase the Poisson upper limit of $N^H_{\Lambda\Lambda} < 3.9$ to $N^H_{\Lambda\Lambda} < 7.3$. [13]. Combining the acceptance estimates and $N^c_{\Lambda K_S}$ both the downstream and upstream data sets yields

$$\left.\frac{d\sigma_H}{d\Omega}\right|_{65\,\mathrm{mr}} < 2.3 \times 10^{-4} \times \left.\frac{d\sigma_n}{d\Omega}\right|_{65\,\mathrm{mr}} (90\%\ \mathrm{C.L.}). \quad (5)$$

Assuming central production of $H$'s so that the mean momentum is 7-8 GeV/$c$, the limit is valid for $\tau_H \gtrsim 10^{-8}$ s. Eqn. 5 scales linearly with the ratio $\sigma^c_{\Lambda K_S}/\sigma_{\Lambda\Lambda}$, and we have not included the large uncertainty in $\sigma_{\Lambda\Lambda}$. Using $d\sigma_n/d\Omega = 4.26$ b/sr for $n$ production [6], we obtain, for 24.1-GeV/$c$ $p$-Pt collisions at 65 mr, $d\sigma_H/d\Omega < 1$ mb/sr (90% C.L.).

As a check, we have similarly calculated a limit using $K^0_L$'s from the m.b. trigger, with added uncertainty due to different efficiencies. We find $d\sigma_H/d\Omega < 3.8 \times 10^{-4} d\sigma_{K_L}/d\Omega$ (90% C.L.). Scaling measurements of inclusive $K^0$ production [14], this method leads to an upper limit of $\sim$ 0.5 mb/sr.

In conclusion, we have observed the production of $\Lambda^0\Lambda^0$ pairs in a neutral beam, but in comparing them to our observed $\Lambda^0 K^0_S$ events, we find no evidence of $H$ diffractive dissociation. Our limits on $H$ production indicate that long-lived $H$'s can contaminate neutral beams only at a level thousands of times less than the primary components, neutrons and $K_L$'s. The only other experiment with sensitivity to neutral beam $H$'s was that of Gustafson et al. [15], who set limits on the invariant cross section at 300 GeV/$c$ for the production of neutrals with lifetimes $\tau > 10^{-7}$s and masses higher than those searched for here.

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[7] $t$ is calculated assuming incoming $n$ and recoiling C; this degrades the estimate slightly for the incoherent events.

[8] $p + C \to (YK^0) + C$ reactions were recently seen by Golovkin *et al.* (SPHINX Collaboration), in preprint IHEP 94-78, but with a much shallower slope ($b \sim 30\mathrm{GeV}^2$).

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FIGURES

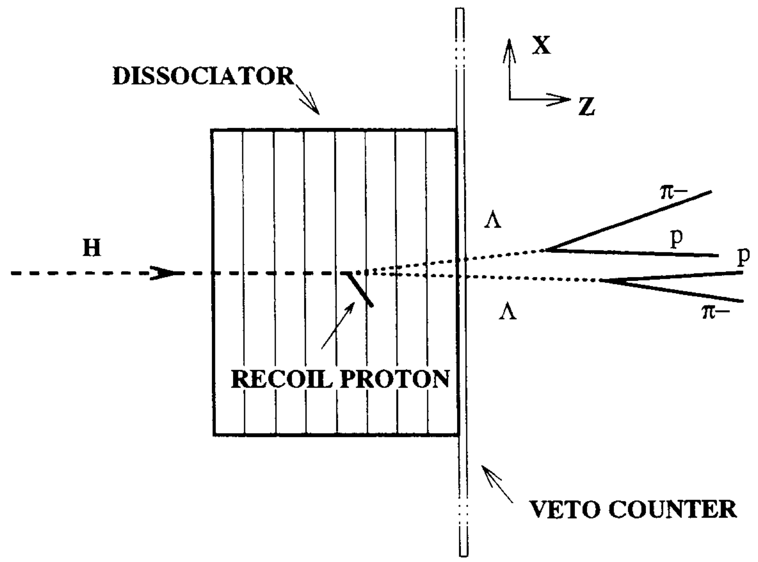


FIG. 1. $H$ diffractive dissociation off proton in dissociator.

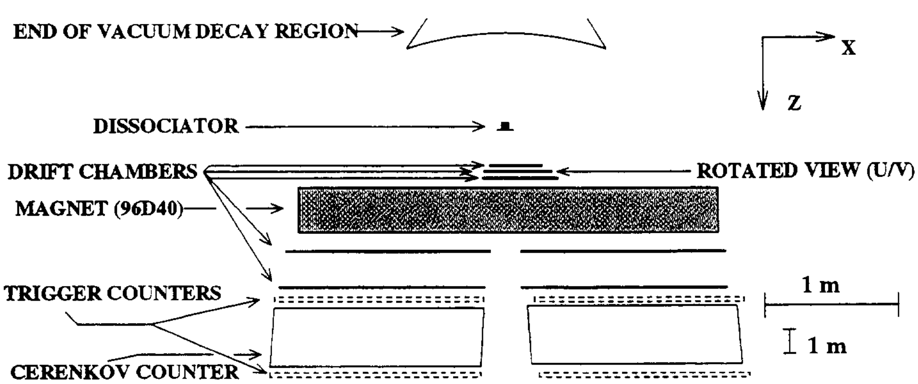


FIG. 2. Plan view of the detection apparatus.

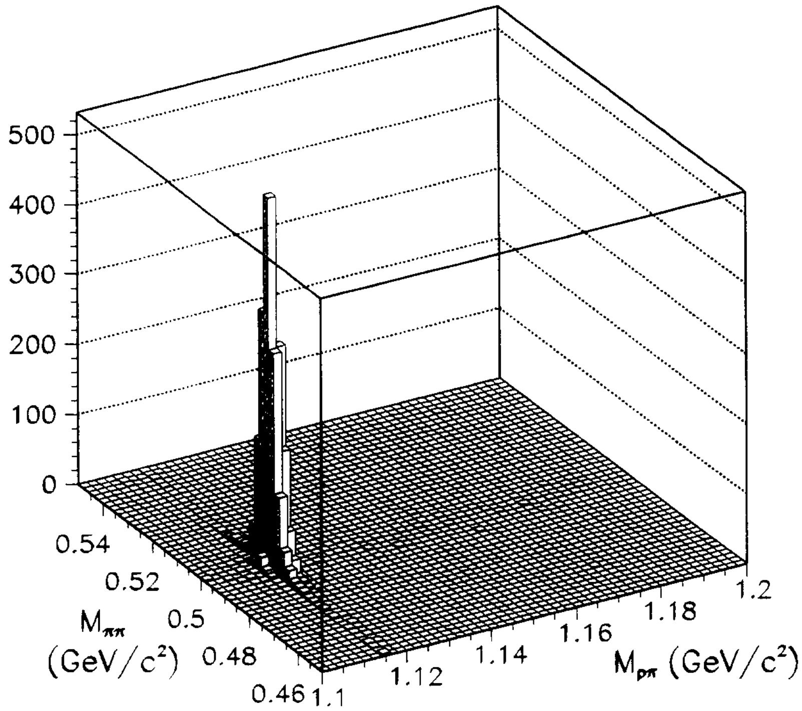


FIG. 3. Plot of $m_{\pi\pi}$ of one $V^0$ vs $m_{p\pi}$ of the other

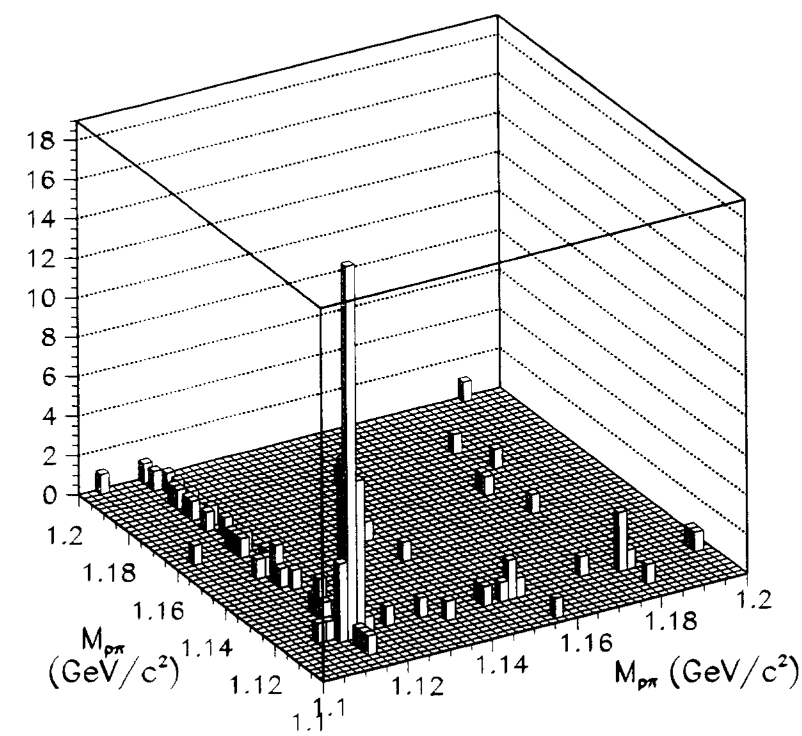


FIG. 4. Plot of $m_{p\pi}$ of one $V^0$ vs $m_{p\pi}$ of the other.

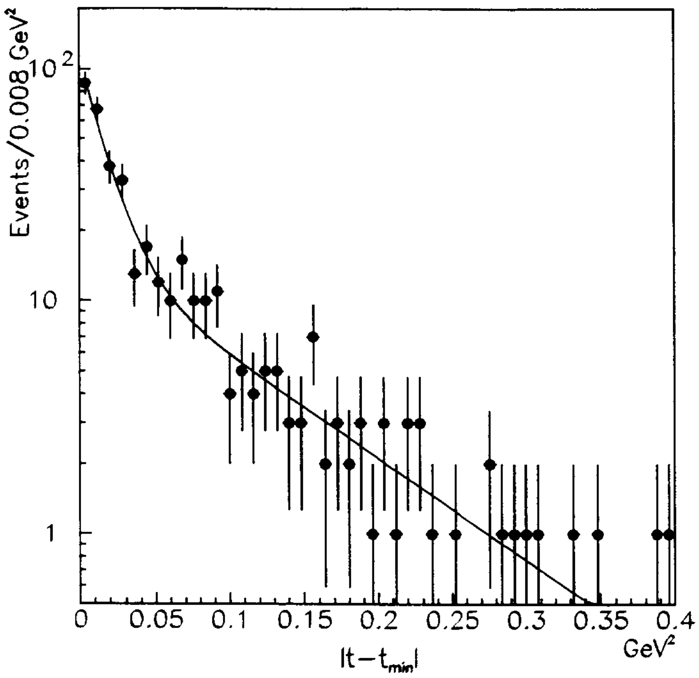


FIG. 5. Histogram of $t'$ for $\Lambda^0 K_S^0$ events with no signals in dissociator, with fit to sum of two exponentials.

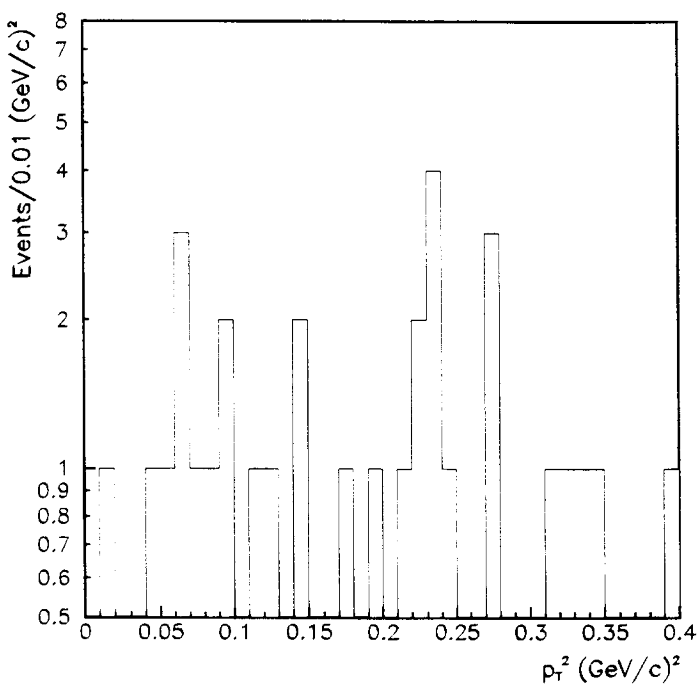


FIG. 6. Histogram of $p_t^2 \approx t'$ for $\Lambda^0\Lambda^0$ events, with no cuts on dissociator signals made.