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The Observation of the Radiative Decay $D^{*+} \to D^+\gamma$

CLEO Collaboration

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Abstract

Using approximately 4 fb^{-1} of integrated luminosity (~ 4.8 million $c\bar{c}$ pairs) collected by CLEO II, a statistically significant signal for $D^{*+} \to D^+\gamma$ has been observed. By measuring the branching ratio $\mathcal{B}(D^{*+} \to D^+\gamma)/\mathcal{B}(D^{*+} \to D^+\pi^0)$ and assuming isospin symmetry we are able to determine all the D^{*+} branching fractions. The preliminary result of this analysis is: $\mathcal{B}(D^{*+} \to D^+\gamma) = (1.4 \pm 0.5 \pm 0.6)\%$, where the first uncertainty is statistical and the second is systematic. This branching fraction is consistent with the previous CLEO II upper limit, as well as the theoretical expectations. We also combine this result with the CLEO measurement of $\mathcal{B}(D_s^{*+} \to D_s^+\pi^0)$ in order to test a prediction about the relationship between the two branching fractions.

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I. INTRODUCTION

A great deal of interest in the radiative D^{*+} decay was generated by the previous Particle Data Group average of $\mathcal{B}(D^{*+} \to D^+\gamma) = (18 \pm 4)\%$ [1] which was dominated by a Mark III result [2]; this value was virtually impossible to reconcile with theory without assuming an anomalously large magnetic moment for the charm quark. Such speculation was put to rest when CLEO II found an upper limit of 4.2% (90% C.L.) for this branching fraction [3]. The central value, $\mathcal{B}(D^{*+} \to D^+\gamma) = (1.1 \pm 1.4 \pm 1.5)\%$, was then used (assuming isospin symmetry) to derive all the D^{*+} branching fractions, resulting in significant shifts in many of the B branching ratios as well. That result was based on 780 pb^{-1} of data. This paper will describe the current status of the analysis of the CLEO II data set.

Recently, additional impetus for the measurement was given by a calculation by Peter Cho and Mark Wise [4] which relates the radiative decay of the D^{*+} to the isospin violating decay $D_s^{*+} \to D_s^+\pi^0$ which was recently observed by CLEO [5]. This result implies a D^{*+} radiative branching fraction of 0.8-1.0% or $\sim 0.1\%$. The ambiguity in the predicted branching fraction is the result of an indeterminacy in the coupling g which enters into the chiral Lagrangian in Cho and Wise's calculation; the value of this coupling is of interest in itself.

II. $D^{*+} \to D^+\gamma$ ANALYSIS TECHNIQUE

The approach used in this analysis is to search in the $M(D^{*+}) - M(D^+)$ mass difference plot for $D^{*+} \to D^+\gamma$ and $D^{*+} \to D^+\pi^0$. The D^{*+} candidates are formed by combining either a π^0 or a γ with a D^+ reconstructed from its decay $D^+ \to K^-\pi^+\pi^+$. To reduce combinatorial background the three tracks are required to come from a common vertex and the D^{*+} candidate is required to have $x \equiv p/p_M > 0.7$, where $p_M^2 = E_0^2 - M_{D^{*+}}^2$ and E_0 is the beam energy. A particle ID χ^2 is formed using specific ionization and time-of-flight (where available) measurements for each of the three tracks. We require the χ^2 probability be at least 0.1 under the $K^-\pi^+\pi^+$ hypothesis.

The branching ratio

$$R_\gamma^+ \equiv \frac{\mathcal{B}(D^{*+} \to D^+\gamma)}{\mathcal{B}(D^{*+} \to D^+\pi^0)} = \frac{N(D^+\gamma)}{N(D^+\pi^0)} \times \frac{\epsilon_{\pi^0}}{\epsilon_\gamma} \tag{1}$$

is then determined, where $N(D^+\gamma)/N(D^+\pi^0)$ is the ratio of the number of D^{*+} decays observed in each mode, and $\epsilon_{\pi^0}/\epsilon_\gamma$ is the relative efficiency for finding the π^0 or the γ from the D^{*+} decay.

Assuming that the three decay modes of the D^{*+} add to unity, isospin symmetry, and p-wave decay widths, one finds [3]

$$\mathcal{B}(D^{*+} \to D^+\gamma) = \frac{R_\gamma^+}{R_\gamma^+ + (3.21 \pm 0.07)} \tag{2}$$

where the uncertainty is dominated by those in the $M_{D^*} - M_D$ mass differences. This method has the advantage of canceling many systematic uncertainties, in particular those associated with the D^+ reconstruction [3].

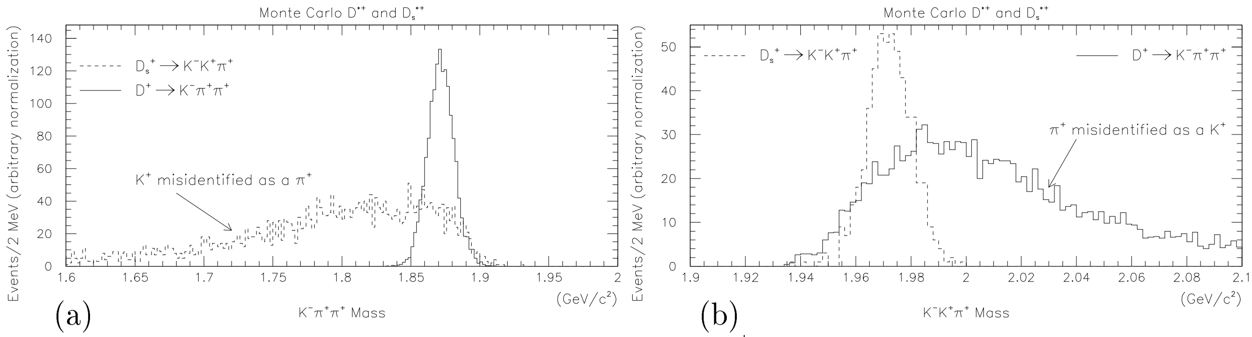

FIG. 1. (a) The $K\pi\pi$ mass distribution found when D^+ are reconstructed correctly (solid) and the distribution found when the K^+ from a D_s^+ decay is misidentified as a π^+ (dashed). Also shown (b) is the $K^-K^+\pi^+$ mass distribution found for the same events. For each $D^+ \to K^-\pi^+\pi^+$ candidate, the π^+ mass is replaced with the K^+ mass; the smaller mass of the two possible combinations is plotted for each candidate.

The analysis was performed using hadronic data accumulated at the Υ(4S) resonance and just below in the continuum by the CLEO II detector which is described in detail elsewhere [6]. The Monte Carlo data used to determine signal shapes and detection efficiencies was passed through a GEANT-based full detector simulation. Also a "generic" continuum Monte Carlo sample (which contains roughly double the statistics of the data) was used to test the analysis code and methods.

A. D_s^{*+} Background

The primary difficulty in this analysis is the size of the signal, due to its small branching fraction, relative to a large combinatoric background and, most importantly, relative to a background due to the D_s^{*+} radiative decay. Unlike the D^{*+}, the D_s^{*+} almost always decays radiatively. This is a major problem because the $M(D_s^{*+}) - M(D_s^+)$ mass difference is 143.97 ± 0.41 MeV [5] and the $M(D^{*+}) - M(D^+)$ mass difference is 140.64 ± 0.09 MeV [7]. These two processes cannot be separated in the mass difference plot because the resolution on the photon in the decay is ~ 6 MeV. Fig. 1(a) shows the mass distribution found when the K^+ from the decay chain $D_s^{*+} \to D_s^+\gamma$, $D_s^+ \to K^-K^+\pi^+$ is misidentified as a π^+, as determined by Monte Carlo simulation. This misidentification can occur because the time-of-flight and specific ionization information used for particle identification fails to separate K's from π's whose momentum is above ~ 1 GeV/c. The two mass distributions partially overlap, and any attempt to estimate the fraction of D_s^+ under the D^+ peak will depend on the resonant substructure of the $D_s^+ \to K^-K^+\pi^+$ decay. The large D_s^+ contribution to the lower D^+ sideband further complicates the analysis by preventing the use of this sideband in a combinatoric background subtraction.

A means to veto D_s^+ events, which is independent of the decay's resonant substructure, is to require that the invariant mass of the three tracks reconstructed under the $K^-K^+\pi^+$ hypothesis be greater than a cut which removes all the D_s^+ events. An unwanted side effect of vetoing D_s^+ events by this method is that a cut in the $KK\pi$ mass distribution greatly

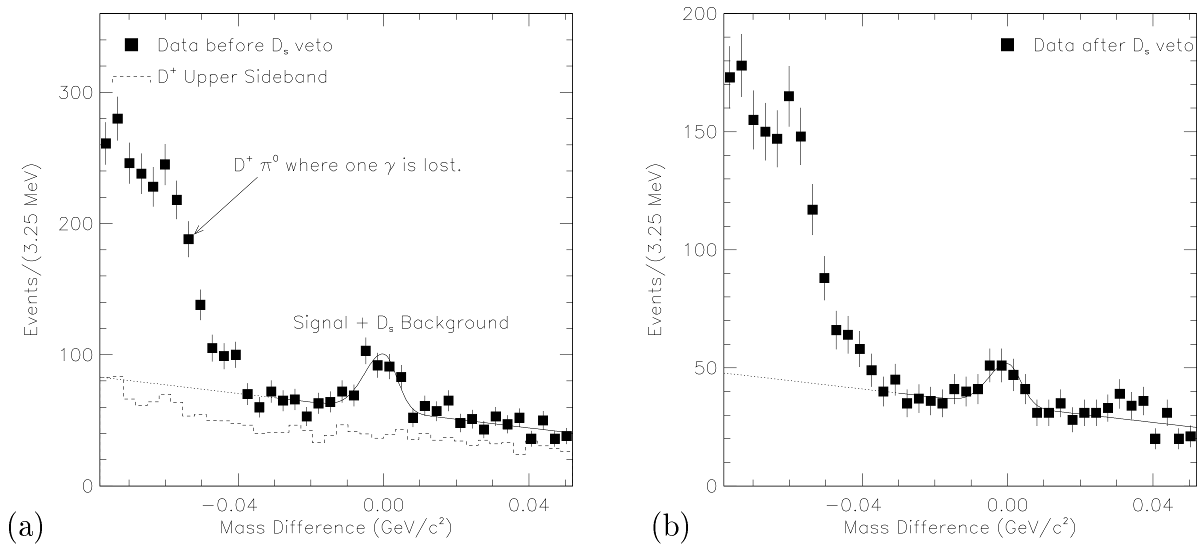

FIG. 2. (a) The mass difference $[M(K\pi\pi\gamma) - M(K\pi\pi) - (M_{D^{*+}} - M_{D^+})]$ for the data with a loose decay angle cut and **no** D_s^+ veto applied. The large peak on the left side of the plot is due to $D^{*+} \to D^+\pi^0$ where one of the photons is lost. This process has been studied and found not to contribute the signal peak. The fit is to a bifurcated Gaussian plus a first order polynomial. The parameters for the signal shape are taken from a Monte Carlo simulation of $e^+e^- \to D^{*+}X \to D^+\gamma X$ followed by the full detector simulation. Also shown (dashed histogram) are the data taken from the D^+ mass upper sideband. (b) The mass difference obtained after requiring the D_s^+ hypothesis to yield an invariant mass greater than 1.9905 GeV/c^2.

distorts the $K\pi\pi$ mass distribution, making the relative normalization between the D^+ upper sideband and the signal region uncertain. Thus the use of a sideband subtraction to remove the combinatoric background from the mass difference plot is impossible if this method of D_s^+ veto is used. Fig. 1(b) shows the $K^-K^+\pi^+$ mass distribution found in D_s^+ decays and that found in D^+ decays when one of the π^+'s is misidentified as a K^+. Since there are two possible tracks to assign the K^+ mass, both combinations are tried, and the one yielding the smaller mass is plotted. Again there is a sizable amount of overlap in the two distributions, so any attempt to remove all the D_s^+ contamination will invariably greatly reduce the already small $D^+\gamma$ signal.

B. Observation of $D^{*+} \to D^+\gamma$

To first establish the existence of a $D^+\gamma$ signal, a cut on $\cos\theta_\gamma$, where θ_γ is the angle of the γ in the D^* rest frame with respect to the D^* direction in the laboratory frame, was tuned to maximize S^2/B using the "generic" Monte Carlo data sample. Since we just need to see a significant signal, the absolute efficiency of this cut is not important at this point. This procedure for setting the decay angle cut cannot be used when determining $\mathcal{B}(D^{*+} \to D^+\gamma)$ because the polarization of the D^{*+}'s is not well known (it is assumed to

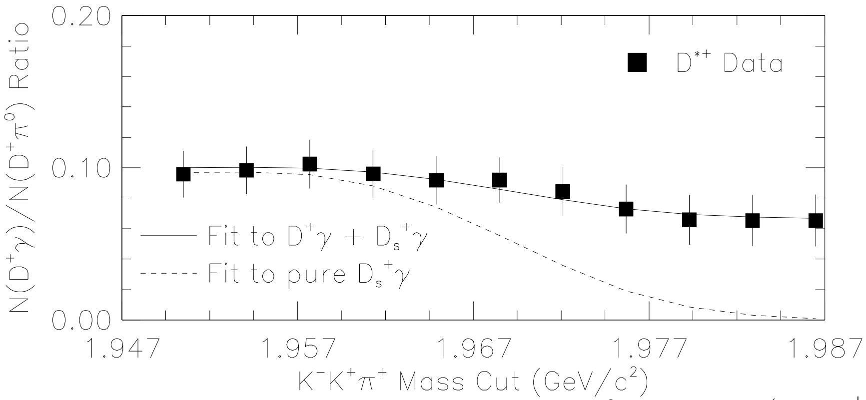

FIG. 3. Each point shows the ratio determined using data for which $M(K^-K^+\pi^+)$ invariant mass was greater than the cut value shown on the x-axis. The dashed curve shows the behavior expected if the "signal" in the data were due solely to D_s^{*+} radiative decays. The cut range shown covers approximately $\pm 2.5\ \sigma$ in D_s^+ mass. It should be noted that the errors are highly correlated bin-to-bin.

be unpolarized in the Monte Carlo). So when measuring $\mathcal{B}(D^{*+} \to D^+\gamma)$ this cut will be tightened to $\cos\theta_\gamma > 0$, since regardless of the D^* polarization, the $\cos\theta_\gamma$ distribution is symmetric about 0.

Fig. 2 shows the mass difference (for the data passing the loose decay angle cut, $\cos\theta_\gamma > -0.35$) after the known difference has been subtracted out. Also shown is the distribution from the combinatoric background taken from the D^+ mass upper sideband. The sideband distribution is quite flat under the signal region, justifying the use of a first order polynomial in fitting this background. No D_s^+ veto has been applied to the data in Fig.2(a), so we can expect that a fair fraction of the events in this "signal" are D_s^{*+} background.

Using Monte Carlo $D_s^{*+} \to K^-K^+\pi^+$ events to determine the fraction of D_s^+ which would pass a cut of $M(K^-K^+\pi^+) > 1.9905$ GeV/c^2 and assuming that the entire "signal" yield in Fig. 2(a) is due to D_s^{*+}, one expects 3.4 ± 3.4 events in Fig. 2(b). After subtracting out the 3.4 expected events, we find 56.7 ± 17.4 events (where the error is only the statistical uncertainty from the fits). Various methods were employed to assess the significance of the signal, but all yield a signal with **greater than 3σ significance**.

To demonstrate evidence that this peak is not solely due to D_s^{*+} events, Fig. 3 shows the effect of applying increasingly tighter D_s^+ vetoes on the ratio $N(D^+\gamma)/N(D^+\pi^0)$. By dividing the $D^+\gamma$ yield by the $D^+\pi^0$ yield obtained using the same veto, each point is essentially efficiency corrected; for pure $D^+\gamma$ one expects a flat line at some non-zero value. What we find is that, as the veto is tightened, the distribution indeed approaches a value which is **not** consistent with pure D_s^{*+} and is consistent with pure D^{*+}.

C. Measurement of $\mathcal{B}(D^{*+} \to D^+\gamma)$

As mentioned earlier, the cut on $\cos\theta_\gamma$ must be $\cos\theta_\gamma > 0$ in order not to introduce a direct dependence on the D^{*+} polarization into the measurement. This of course means the

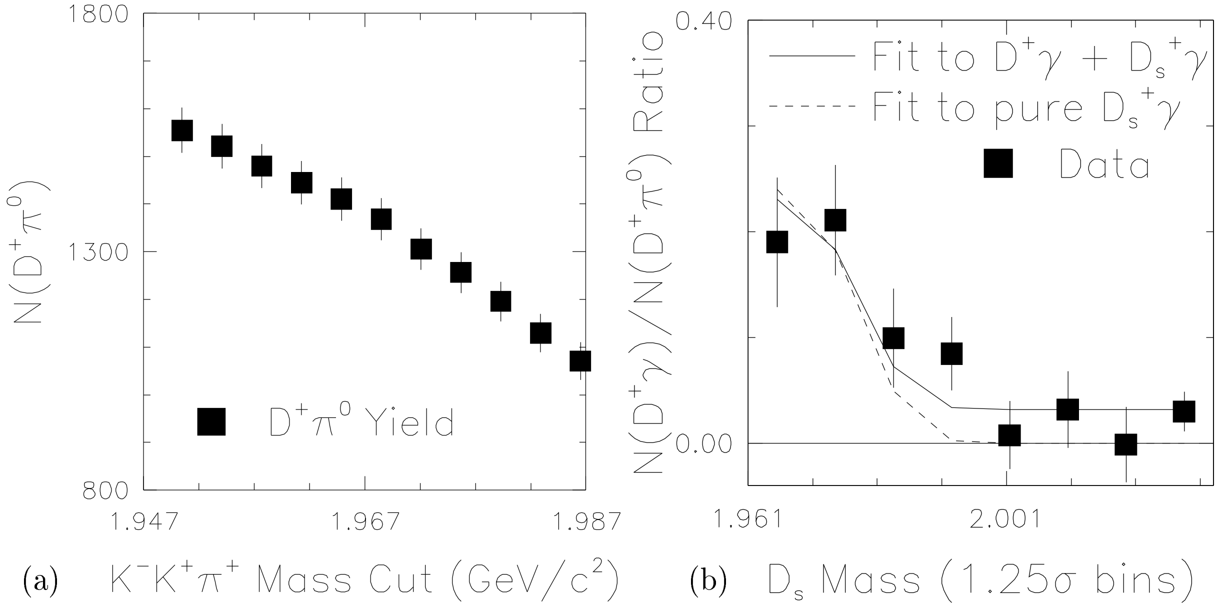

FIG. 4. (a) The $D^{*+} \to D^+\pi^0$ yield as a function of the D_s^+ veto. (b) The differential distribution of the data with the unbiased (tight) decay angle cut applied. The $D^+\gamma$ and the $D^+\pi^0$ data are binned by D_s^+ mass (the last bin contains all the data above the previous D_s^+ mass bin), and the resulting ratio of number of events is plotted. As in the integral plot, one expects to see the data approach a flat nonzero value if $N(D^+\gamma) \neq 0$.

already small signal will be further reduced. So it is necessary to balance removal of the D_s^+ contamination with the loss of signal efficiency. Fig. 4(a) shows the $D^+\pi^0$ yield obtained by fitting the $M(D^{*+}) - M(D^+)$ mass difference plot as a function of the $M(KK\pi)$ mass cut used to reject the D_s^+ background. If a cut were to be applied at 1.99 GeV/c^2 (as was done when establishing a $D^+\gamma$ signal) on top of a tight $\cos\theta_\gamma$ cut, the signal would be lost in the combinatoric background.

In order to make use of the information contained in the shape of Fig. 3, the equivalent differential plot is fit under the assumption that the data contain both D^{*+} and D_s^{*+} events. The result is shown in Fig. 4(b). The statistics are clearly marginal at this point, but the errors are now uncorrelated so a reliable value of $N(D^+\gamma)/N(D^+\pi^0)$ can be extracted. Correcting this ratio for the relative efficiency, $\epsilon_{\pi^0}/\epsilon_\gamma$, to obtain R_γ^+ and using relation (2) we find:

$$\mathcal{B}(D^{*+} \to D^+\gamma) = (1.4 \pm 0.5)\%$$

(statistical uncertainty only) which is in good agreement with the previous CLEO upper limit as well as its central value. Currently the primary systematic uncertainty in this measurement is due to the fitting procedures and the D_s^+ background shape.

To check the result obtained by fitting the differential $N(D^+\gamma)/N(D^+\pi^0)$ distribution, the identical method was used as described in the prior CLEO II analysis [3]. This method relies on identifying the D_s^+ through its decay to K^*K or $\phi\pi$ and then estimating what

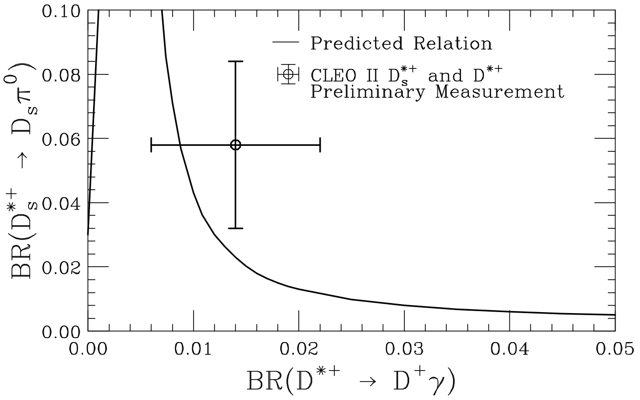

FIG. 5. The relation predicted between the branching fractions for $D_s^{*+} \to D_s^+\pi^0$ and $D^{*+} \to D^+\gamma$ along with the CLEO measurements.

fraction of D_s^+ events are missed. The primary drawback is uncertainty in the branching fractions of the D_s^+. The result, $\mathcal{B}(D^{*+} \to D^+\gamma) = (1.4 \pm 0.6)\%$, agrees with that found using the $K^-K^+\pi^+$ mass veto. This comparison is of particular relevance because the two methods used have significantly different sources of systematic uncertainty.

Using chiral perturbation theory, Peter Cho and Mark Wise [4] predict a relationship between the radiative decay of the D^{*+} and the decay $D_s^{*+} \to D_s^+\pi^0$. CLEO recently published the first observation of this decay [5] and measured $\mathcal{B}(D_s^{*+} \to D_s^+\pi^0) = 0.058^{+0.018}_{-0.016} \pm 0.020$. This decay is explained as resulting from the decay of the D_s^{*+} via emission of a virtual η, which neither violates isospin nor is OZI suppressed, followed by isospin violating $\pi^0 - \eta$ mixing. Fig. 5 shows the predicted relationship between the two branching fractions and CLEO's measurements; good agreement is found.

III. CONCLUSIONS AND PROSPECTS

We have observed, with greater than 3σ significance, the radiative decay of the D^{*+} and measured $\mathcal{B}(D^{*+} \to D^+\gamma) = (1.4 \pm 0.5 \pm 0.6)\%$. This value is in good agreement with theoretical expectations. Assuming isospin symmetry and that the branching fractions of the D^{*+} to $D^+\pi^0$, $D^0\pi^+$ and $D^+\gamma$ add to unity, we find $\mathcal{B}(D^{*+} \to D^+\pi^0) = 67.9\%$ and $\mathcal{B}(D^{*+} \to D^0\pi^+) = 30.7\%$. Currently the best numbers for these two branching fractions, derived from the previous CLEO II upper limit on $\mathcal{B}(D^{*+} \to D^+\gamma)$, are $(68.1 \pm 1.6)\%$ and $(30.8 \pm 0.9)\%$ respectively. The uncertainties on these numbers will not improve appreciably with the new analysis because they are dominated by the 2% uncertainty (due to uncertainties in the $M_{D^*} - M_D$ mass differences) in the isospin and p-wave decay width assumptions used in the derivation. However, it is good to know that we do not need to adjust any results based on the previous central values of the D^{*+} branching fractions. In the months to come improvements in the analysis, primarily the measurement of the D^{*+} alignment, and adding the remaining CLEO II data are expected to lead to significant reductions in the systematic as well as statistical uncertainty in the measurement of $\mathcal{B}(D^{*+} \to D^+\gamma)$.

This new measurement of $\mathcal{B}(D^{*+} \to D^+\gamma)$ and the recent measurement of $\mathcal{B}(D_s^{*+} \to$

$D_s^+\pi^0$) [5] support the chiral perturbative calculation of Cho and Wise and will help to constrain the value of the coupling constant g.

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