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STUDIES OF THE TOP QUARK WITH THE DØ DETECTOR

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ABSTRACT: The observation of the top quark by the DØ experiment, at Fermilab's Tevatron proton-antiproton collider, is briefly reviewed. The analysis of the top quark mass in the lepton plus jets decay channels, resulting in $m_t \approx 200$ GeV/c^2 is reviewed; and a preliminary mass analysis from the dilepton decay channels resulting in $m_t = 145 \pm 25$ (statistical) $\pm$ 20 (systematic) GeV/c^2 is presented. These mass measurements are compared with Standard Model limits from CERN's LEP experiments and the published CDF measurement. Preliminary observation of top quark-W boson correlation is shown.

1. Introduction

The Standard Model predicts that quarks and leptons exist in electroweak doublets, hence the existence of the $q = -1/3$ bottom quark requires the $q = +2/3$ top quark. But the Standard Model does not predict the top quark's mass. Searches for the top quark have been proceeding at ever higher energies for more than fifteen years. Finally, the unambiguous observation of the top quark was announced in February of 1995 by the CDF[1] and DØ[2] experiments at Fermilab. With the sensation which accompanied this observation behind us, it is appropriate to begin serious study of the dynamic properties of the top quark.

In this presentation, we consider the production of top quarks, t, through the interaction of partons produced in collisions of protons and anti-protons at a center of mass energy, $\sqrt{s}$ = 1.8 TeV. We assume that t and $\bar{t}$ quarks are produced in pairs and decay with 100% branching fraction to a W boson and a b quark. This presentation looks at the three separate categories of t quark decays depicted in Fig.1: (a) the dilepton channel where both W bosons decay to $l\nu$ pairs – accounting for about 11% of the total top quark branching fraction; (b) the single lepton channel where one of the W bosons decays to a $l\nu$ pair and the other decays to an electroweak quark doublet, $q\bar{q}'$ – 45% of the branching fraction; and, (c) the all jets channel where both of the W bosons decay to $q\bar{q}'$ pairs – 44% of the branching fraction (wherever a bare quark, q or b, is noted the fragmented hadronic jet is implied). Since we do not present results here which include reconstructed τ leptons, our current results cover about 81% of the total top decay branching fraction.

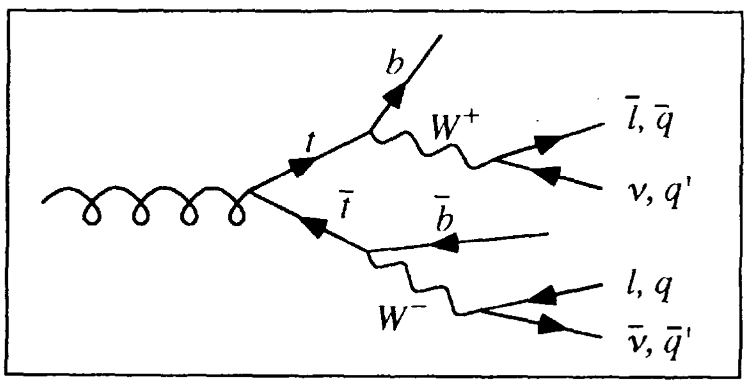

Figure 1. Top production and decay.

The data studied for the analyses presented here correspond to subsets of 100 pb^{-1} recorded by the detector to date. The DØ Collaboration consists of about 450 physicists from some 46 institutions in nine countries on four continents. The DØ detector features non-magnetic tracking with vertex detection, central and forward drift chambers surrounded by transition radiation detectors, all encapsulated by liquid argon electromagnetic and hadronic calorimetry with pseudorapidity/azimuthal angle segmentation of $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ extending out to $\eta < 4$. Electrons are identified by their longitudinal and transverse shower profile in the calorimeter with a matching track in the tracking chambers. Muons are identified by their ability to penetrate the calorimeter and are momentum analyzed with an iron toroid spectrometer outside the calorimeter cryostats. The existence of neutrinos in an event are indicated by unbalanced transverse momentum, or missing E_T. Hadronic jets are reconstructed from streams of hadrons detected in the calorimetry using a cone algorithm with various cone sizes. The DØ detector, particle identification, and trigger techniques are described in detail in references 2, 3 and 4.

In this paper, due both to the author's preference and space limitations, we prefer to concentrate on the more salient features of the individual analyses while leaving many of the details (e.g., event selection, detector efficiency, background calculations, and what have you) to the previously published articles, Ref.'s 2 and 4.

2. The Dilepton Channel

The dilepton decays are characterized by the detection of two leptons, two hadronic jets from the b quark fragmentation, and considerable missing E_T from neutrinos escaping detection. Backgrounds to this signal consist of *W/Z* boson production with jets and QCD multijet events where a jet is mistaken for a lepton (i.e., a *fake* lepton) accompanied by mismeasured E_T. In Ref. 2 we published results from the dilepton analyses, $ee/e\mu/\mu\mu$, based on about 50 pb^{-1} resulting in 0/2/1 candidate events with estimated backgrounds of 0.12 ± 0.03/0.28 ± 0.14/0.25 ± 0.04 respectively, resulting in a total of three candidate events on a background of 0.65 ± 0.15 yielding the cross section, $\sigma(p\bar{p} \rightarrow t\bar{t}X) = 7.6 \pm 5.8$ pb, for $m_t = 200$ GeV/c^2.

Since publishing Ref. 2, we have expanded the dilepton analysis to include 72 pb^{-1} of data yielding a total of five candidate events. We have performed a preliminary mass analysis on this sample.

In the dilepton channel we have 12 measured kinematic variables: $\vec{p}_l$, $\vec{p}_{\bar{l}}$, $\vec{p}_b$, and $\vec{p}_{\bar{b}}$ and 6 unmeasured: $\vec{p}_\nu$, and $\vec{p}_{\bar{\nu}}$. Since we also measure the total transverse momentum of the event we have an equation of constraint: $\vec{p}_T^{\,event} = -\vec{p}_{T\nu} - \vec{p}_{T\bar{\nu}}$. This leaves 4 unknowns. We can build two more equations by constraining the $l\nu$ masses to $M_W^2 = \left(E_l + E_{\bar{\nu}}\right)^2 - \left(\vec{p}_l + \vec{p}_{\bar{\nu}}\right)^2$. We can build another two equations by constraining the $l\nu b$ combination to the top mass – but at the expense of introducing another unknown, m_t. This leaves four equations in five unknowns. We can then build likelihoods for a spectrum of assumed top masses[5] .There are still ambiguities in this algorithm. First, to assign jets the role of b-jet we take the two highest p_T jets; this assumption grows in accuracy with m_t.from 15% accuracy at $m_t = 100$ GeV/c^2 to 54% accuracy at $m_t = 140$ GeV/c^2 Next, for each m_t.there are 0, 2, or 4 possible solutions of the four equations for various combinations of $l, \bar{l}$, $\nu, \bar{\nu}$, b, and $\bar{b}$ Thus weights are assigned to each consistent solution, w_i:

$$w_i = f(x_i)f(\bar{x}_i)p(E_l^{(i)}|m_t)p(E_{\bar{l}}^{(i)}|m_t) \quad (1)$$

where $f(x_i)$ are structure functions and $p(E_l^{(i)}|m_t)$ are parton distribution functions for the lepton energy, E_l, in the top quark's rest frame. The weights are then integrated over the experimental resolution and initial and final state radiation is included by calibrating the weights with Monte Carlo simulations. Then, finally, the peak of the w_i distribution gives the most consistent estimate of m_t for each event. Two such weight distributions are presented in Fig. 2. With a mass spectrum in hand we perform a maximum likelihood fit of signal and background distributions, Fig. 3, to obtain the preliminary mass measurement in the dilepton channel m_t=145 ± 25 ± 20 GeV/c^2 where the statistical error is derived from different ensemble tests and the systematic errors include uncertainties in the Monte Carlo event generator, the jet energy scale, the background parameterization, and the choice of the weight function.

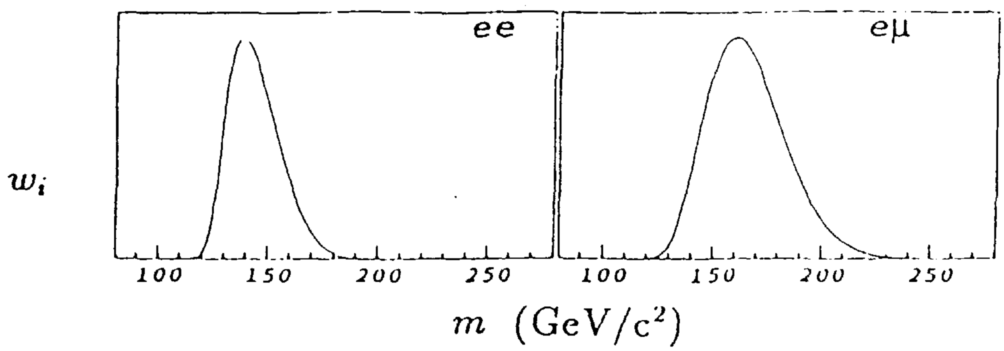

Figure 2. The weight distributions of two dilepton events.

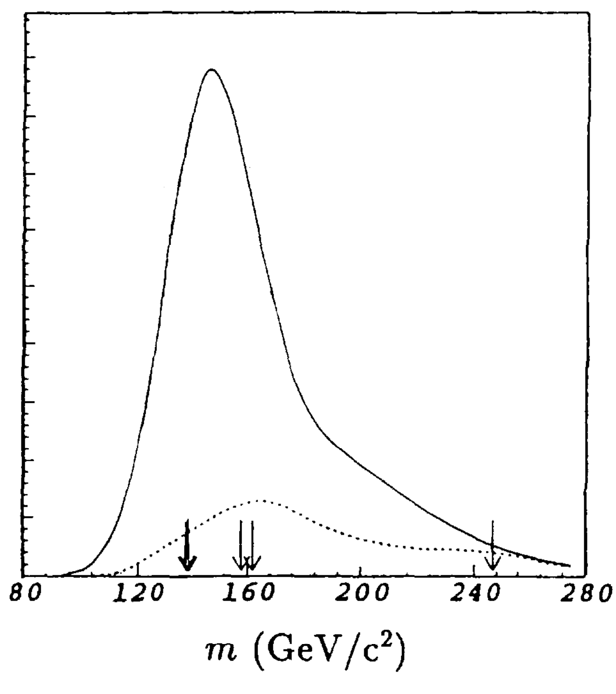

Figure 3. The top quark signal (solid) and background (dashed) fit contributions to the five dilepton candidate events. The arrows indicate the individual event masses (two overlap near 140 GeV/c^2).

3. The Lepton Plus Jets Channel

The lepton plus jets top decay signature includes one hard isolated lepton, missing E_T, two jets from fragmented b quark, and an additional two jets from the $W \rightarrow q\bar{q}'$ decay. In this channel we utilize the increase in the number of candidate events and use the fact that 44% of the b quark jets decay through $b \rightarrow \mu\bar{\nu}c$ providing a 'μ-tag' for some events. Since there are at least four uncorrelated jets associated with these events they tend to have an aplanar topology. Thus a soft aplanarity cut can also be employed. The backgrounds of this signal consist of W/Z plus jet events and QCD multijet events with a fake lepton and mismeasured E_T. Four analyses are performed which include an aplanarity cut and a cut on the sum of the scalar E_Ts of the jets and leading electron (if there is one), H_T, (standard cuts) or not (loose cuts) and/or a μ-tag. Events with and without μ-tags are mutually exclusive. Combining the lepton plus jets analyses with standard cuts and the results from the dilepton analysis yields Fig. 4, which for $m_t = 200\,\mathrm{GeV/c^2}$ gives $\sigma(p\bar{p} \rightarrow t\bar{t}X) = 6.3 \pm 2.2$ pb. This analysis is described in detail in Ref. 2.

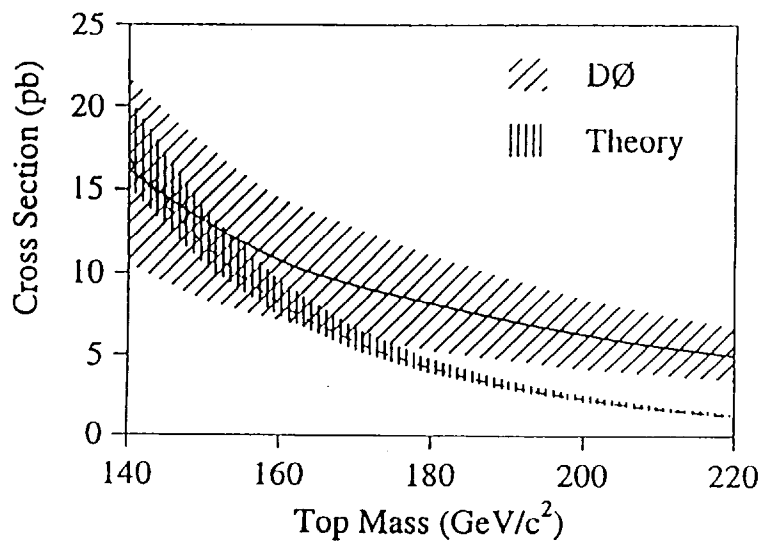

Figure 4. The DØ cross section (solid), with one standard deviation error band, as a function of the top quark mass. The theoretical cross section is shown as the dashed curve[6].

Mass analyses are performed separately on the lepton plus jets candidates with loose and standard cuts. Here, we have 15 measured kinematic variables $\vec{p}_l$, $\vec{p}_q$, $\vec{p}_{\bar{q}'}$, $\vec{p}_b$, and $\vec{p}_{\bar{b}}$, three unmeasured, $\vec{p}_\nu$, and two measured constraints: $\vec{p}_T^{\,event} = -p_{T\nu}$ leaving one unknown. We also have three equations of constraint: two from requiring the invariant masses of the $l\nu$ and $q\bar{q}'$ combinations to the W-boson invariant mass; and one from requiring that the t and $\bar{t}$ quark masses be the same, $M_{l\nu b} = M_{q\bar{q}'b}$. We're left with three equations and one unknown. Thus we perform two constraint fits on the possible combinations. A priori, we cannot distinguish the four q, $\bar{q}'$, b, and $\bar{b}$ jets (unless either the b or $\bar{b}$ jet has a μ-tag) yielding 12 possible (t, $\bar{t}$) combinations (6 with a μ-tag). Each possible solution is subject to the fit. To obtain the best estimate of the top quark mass for a given event, a weighted average of the combinations which pass a $\chi^2 < 7$ cut (24 of 29 candidate events pass) is performed. The weights for each combination are given by $\exp(-\chi^2)$. This approach prevents fluctuations in the kinematic variables of a given combination from dominating the mass estimate. Finally, we obtain fitted mass spectra on which we perform Poisson statistics fits with the top quark mass and the numbers of signal and background events as floating parameters. These spectra, with fits, are given in Fig. 5. For the standard cuts we get $m_t = 199^{+31}_{-25}\mathrm{GeV/c}^2$; and for the loose cuts, $m_t = 199^{+19}_{-21}\mathrm{GeV/c}^2$, in both cases the systematic error is $^{+14}_{-21}$ GeV/c^2. Since these are our most accurate current measurements of m_t, the cross sections quoted throughout this paper, save Fig. 4, are for $m_t = 200$ GeV/c^2.

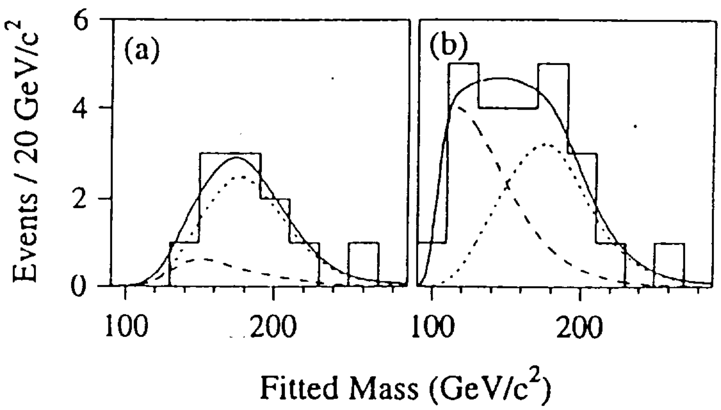

Figure 5. The lepton plus jets top quark candidate mass spectrum (histogram) with fitted signal (dotted curve) and background (dashed curve) contributions for (a) standard and (b) loose event selection.

One question we can ask, in the lepton plus jets channel is: can we reconstruct $W \rightarrow q\bar{q}'$? If so, then can we calibrate m_t against M_W? Are the top quark and W boson mass peaks correlated?

To pick out the W boson daughters we need to consider $(\bar{t},t) = (\bar{b}\bar{l}\bar{\nu}, bq\bar{q}')$ and focus our interest on the $bq\bar{q}'$ system. Envisioning the t quark decay in its rest frame, it is obvious that the jet from the b quark will have the largest energy of the three jets (if there is an ambiguity we can consider two combinations) and plot m_t vs $M_{q\bar{q}'}$. We use the lepton plus jets data selected with the loose cuts and calculate the weighted average, $m_t^{event} = \langle M_{q\bar{q}'b} \rangle$, with weights proportional to $\exp\left(-\ln^2(M_{\bar{b}\bar{l}\bar{\nu}} / M_{q\bar{q}'b}\right)$. This technique means that each event contributes a total of one entry to the m_t vs $M_{q\bar{q}'}$ plot possibly distributed over more than one bin. Fig. 6(a)-(c) give preliminary results in the form of a lego plot of a pure top signal (for m_t = 200 GeV/c^2), the background, and the data sample. The data qualitatively indicate a mix of signal and background. Performing a binned Poisson statistics maximum likelihood fit of the signal and background to the data gives the fraction of data from signal: $f_{top} = 0.43^{+0.23}_{-0.20}$ (PRELIMINARY) which is consistent with what we measure in the standard analysis: $f_{top} = 0.38 \pm 0.21$.

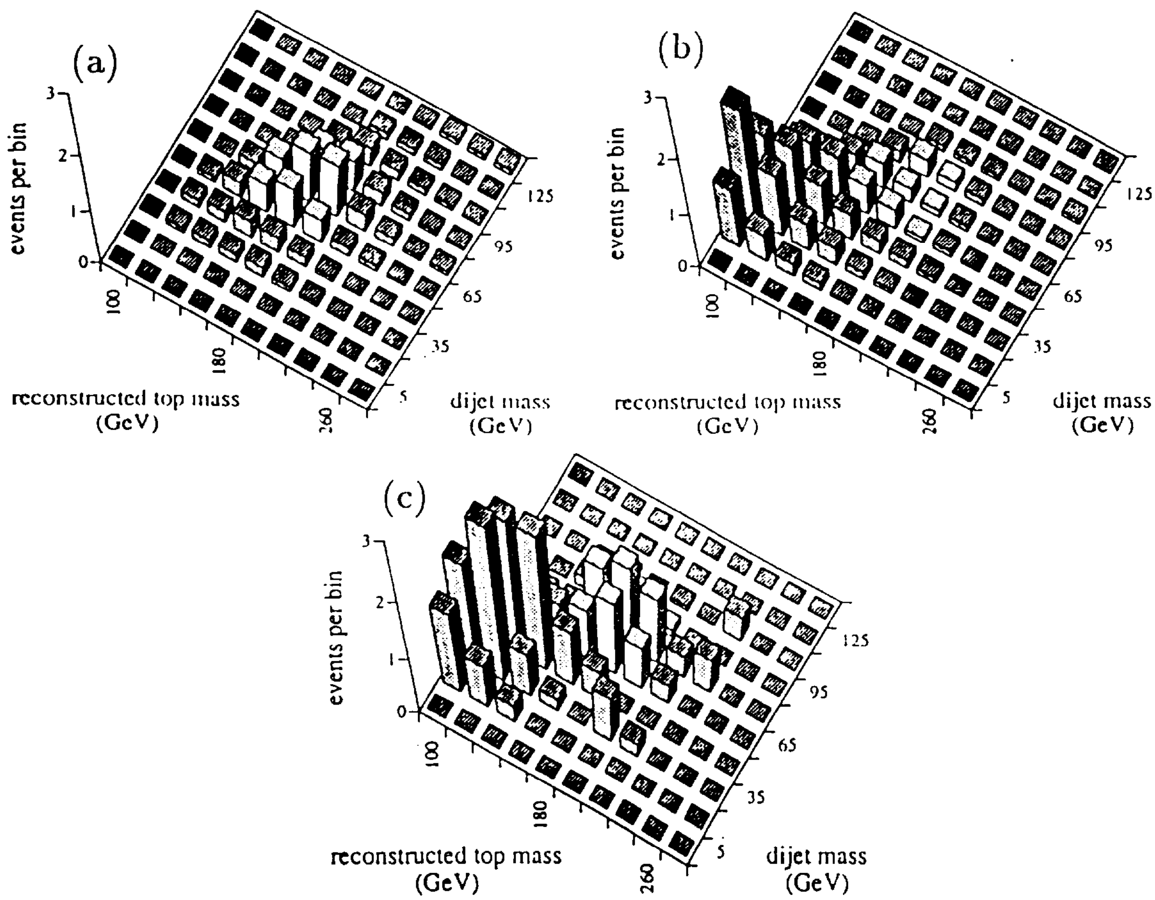

Figure 6. PRELIMINARY lego plots of the reconstructed top quark mass vs the dijet invariant mass for (a) a Monte Carlo simulation of the signal with m_t = 200 GeV/c^2; (b) a background consisting of a combination of simulated *W/Z* boson plus jets and QCD multijet data; and (c) the data.

4. The All Jets Channel

The case where each *W* boson decays to a quark doublet consists of at least six hadronic jets, two of which (the b or $\bar{b}$) may be μ-tagged. This channel is very difficult to pull out of the huge QCD multijet background: there are no hard isolated leptons and one expects low missing E_T. However, we have the possibility of μ-tagging b quark jets. The large number of uncorrelated jets will be aplanar. The jets will have large center of mass energy, implying large centrality (the ratio of transverse to the sum of total jet energies) and large H_T. With these levers we expect to be able to separate the top quark signal from the seemingly formidable background. Our preliminary results using these criteria with separate analyses for zero, single, and double μ-tagged samples give signal to background ratios that are roughly one to one[8]. Further, the $t\bar{t}$ signal we expect from the dilepton and lepton plus jets analyses is consistent with the number of events we observe minus the backgrounds we calculate.

4. Conclusion

The DØ experiment observes consistent top quark signals in all three decay categories (dilepton, lepton plus jets, and all jets) convering some 80% of the total branching fraction. Mass analyses were presented from the dilepton and lepton plus jets decay channels and are summarized in Fig. 7 which includes the published CDF lepton plus jets analysis and limits set by the LEP experiments through Standard Model fits to the Z peak cross section and asymmetries[9]. We also gave preliminary results of evidence for top quark W boson correlations in the lepton plus jets channels.

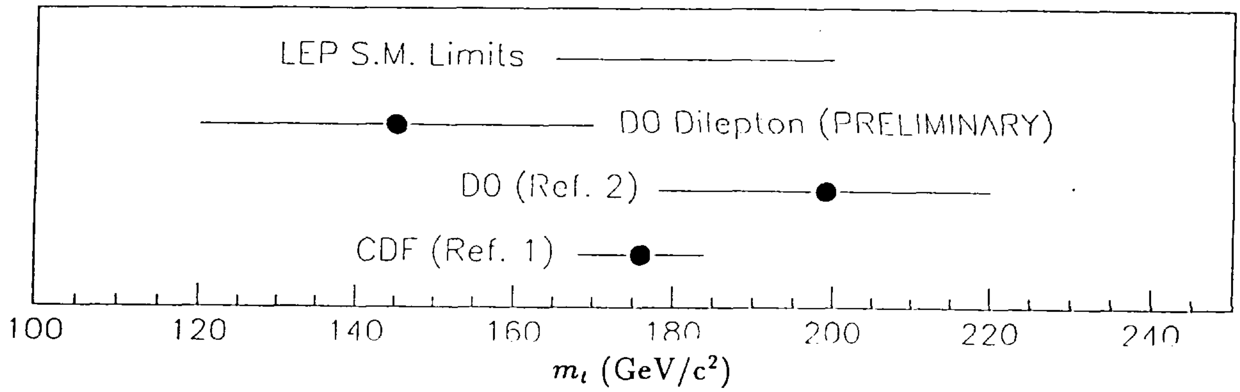

Figure 7. Comparison of top quark mass measurements with limits set by the LEP experiments through standard model parameters assuming $50 < m_{Higgs} < 1000$ GeV/c^2.

5. References

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