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Comparison of the particle flow in $q\bar{q}\gamma$ and $q\bar{q}g$ events from e^+e^- annihilations at PETRA

JADE Collaboration

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Abstract. The particle flow distributions in the event plane of 3-jet ($e^+e^- \to q\bar{q}g$) and of radiative 2-jet ($e^+e^- \to q\bar{q}\gamma$) events are compared at a centre of mass energy of 35 GeV. The number of particles in the angular region opposite to the gluon in $q\bar{q}g$ events is found to be significantly reduced relative to the number of particles in the region opposite to the hard photon in $q\bar{q}\gamma$ events. This depletion is expected from the "string effect" observed in 3-jet events. It can be explained within the framework of QCD as arising from soft gluon interference.

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1 Introduction

Hadronic final states in high energy electron-positron annihilation are usually described by perturbative QCD and fragmentation models. In the majority of events, the hadrons show a clear 2-jet configuration. The jets are due to the materialisation of the virtual quark and anti-quark produced in the hard annihilation process $e^+e^- \to q\bar{q}$. The radiation of a hard gluon by the quark or anti-quark ($e^+e^- \to q\bar{q}g$) is responsible for the 3-jet structure. 4-jet events, which have been seen experimentally, are expected in 2nd order QCD when 2 extra partons (quarks or gluons) are radiated.

Particle flow in 3-jet events has been studied by several groups. The "string effect" was first observed by the JADE Collaboration [1], and later confirmed by the TPC and TASSO collaborations [2]. In agreement with the expectation of the Lund string model [3] where the fragmentation occurs in the boosted systems of the colour flux lines (strings), a depletion of particles in the angular region opposite to the gluon jet, relative to the region between the quark (anti-quark) and gluon jets, was observed. The effect occurs also in parton shower fragmentation models [4] which approximately include the soft gluon interference effect [5] via the angular ordering between partons.

Recent QCD calculations [6] attribute the string effect to coherence of soft gluon emissions from the $q\bar{q}g$ system in 3-jet events. The coherent summation of these contributions leads to destructive interference between the 3 "emitters" (q, $\bar{q}$ and g). In the framework of local parton-hadron duality [7], where non-perturbative effects are reduced to normalizing constants relating hadronic amplitudes to partonic amplitudes, this causes a depletion of particles in the region opposite to the hard gluon in $q\bar{q}g$ events. This effect is not expected to occur in $q\bar{q}\gamma$ events, since the photon carries no colour.

In this paper, we compare the particle flow distributions in the event plane of 3-jet ($e^+e^- \to q\bar{q}g$) and of radiative 2-jet ($e^+e^- \to q\bar{q}\gamma$) events for similar topologies and kinematics. Such an analysis is an elegant way of testing both the prediction of QCD and the phenomenological string picture. Previously the Mark-II collaboration [8] and the TPC collaboration [9] at PEP have presented evidence for a depletion of charged particles between the quark and anti-quark jets in 3-jet events when compared to radiative 2-jet events.

2 Event selection

The analysis was performed on approximately 60000 multi-hadronic annihilation events collected by the JADE detector at the PETRA e^+e^- storage ring in the centre of mass energy range between 30 GeV and 46.7 GeV. The integrated luminosity was about 200 pb^{-1}. A detailed description of the JADE detector, the trigger conditions and the selection of hadronic events are given in [10]. The most important criteria for selecting hadronic annihilation events were:

1. The total lead glass energy had to exceed 3 GeV in the barrel part of the detector or 0.4 GeV in each end-cap.
2. At least four charged particles had to originate from the event vertex, the topology 3 tracks opposite to one track being excluded.
3. Remaining cosmic ray events, τ-pairs and purely leptonic QED events were removed in a visual scan.

Further cuts, in visible energy $E_{\text{vis}} = \sum_i p_i$ and longitudinal momentum balance $p_{\text{bal}} = \sum_i p_i^z / E_{\text{vis}}$, rejected multihadronic events from two-photon processes. The sums run over all particle momenta p_i, p_i^z denoting the momentum components along the beam axis.

4. $E_{\text{vis}} > E_{\text{beam}}$, where E_{beam} is the beam energy.
5. $|p_{\text{bal}}| < 0.4$.

Both charged and neutral particles, with momenta exceeding 100 and 150 MeV/c respectively, were used. In order to avoid a possible bias due to particles lost in the beampipe a cut on the polar angle θ_T of the thrust axis $|\cos\theta_T| < 0.8$ was applied.

3-jet and 2-jet events were defined by a cluster algorithm which was developed in [11]. In each event, two particles i and j with the smallest scaled invariant mass $y = M_{ij}^2 / E_{\text{vis}}^2$ were combined to form one "cluster" by adding the two 4-vectors if y is smaller than a fixed cutoff y_{cut}. This procedure was repeated until all possible combinations of the remaining particles or clusters satisfied the relation $y \geqq y_{\text{cut}}$ and the resulting number of clusters was called the jet multiplicity of an event. For calculating the invariant mass M_{ij}^2 we used the expression

$$M_{ij}^2 = 2 \cdot E_i \cdot E_j \cdot (1 - \cos\Theta_{ij}).$$

The above expression for M_{ij}^2 was chosen in order to obtain the closest agreement between the definition of massive clusters and massless partons at comparable y-values as we have checked by complete second order QCD calculations using the Lund string fragmentation model [3]. The resulting cluster-multiplicities for data and model calculations at $E_{\text{cm}} = 34$ GeV with $y_{\text{cut}} = 0.040$, which corresponds to minimum invariant jet mass of 6.8 GeV, show that this value of y_{cut} is a reasonable choice for the definition of experimentally resolvable jets [11].

2.1 $q\bar{q}g$ candidates

Planar 3-jet events were selected by requiring

$$|\mathbf{k}_1 \cdot (\mathbf{k}_2 \times \mathbf{k}_3)| \leqq 0 \cdot 25$$

$\mathbf{k}_i$ being the normalised direction of jet i given by the vector sum of the particle momenta within the jet.

The jet directions were then projected onto the event plane defined by ($\mathbf{q}_2$, $\mathbf{q}_3$), two of the three principal axes of the normalised sphericity tensor*:

$$T_{\alpha\beta} = \frac{\sum p_{i\alpha} p_{i\beta}}{\sum p_i^2} \qquad (\alpha, \beta = x, y, z).$$

* The eigenvalues Q_1, Q_2, Q_3 of the tensor $T_{\alpha\beta}$ corresponding to the eigenvectors $\mathbf{q}_1, \mathbf{q}_2, \mathbf{q}_3$ were normalised such that $Q_1 < Q_2 < Q_3$ and $Q_1 + Q_2 + Q_3 = 1$

Because jet directions are better measured than jet energies, the jet energies were calculated from the angles between the projected jet directions:

$$E_j = E_{\text{vis}} \frac{\beta_k \beta_l \sin\theta_{kl}}{\beta_1 \beta_2 \sin\theta_{12} + \beta_2 \beta_3 \sin\theta_{23} + \beta_3 \beta_1 \sin\theta_{31}}$$
j, k, l cyclic

where θ_{kl} is the angle between jets k and l projected onto the event plane $(\mathbf{q}_2, \mathbf{q}_3)$ and β_k is the velocity of jet k.

In the case of 3-jet events we assumed the velocities of the jets to be equal ($\beta_1 = \beta_2 = \beta_3$). The formula above then reduces to its usual form. The jets were ordered according to their energies: $E_1 > E_2 > E_3$. Events with jets containing less than 4 particles, or with a jet energy less than 3 GeV, were rejected. To reduce the 2-parton contribution we demanded that $E_1 < 0.98 \cdot E_{\text{vis}}/2$. After these cuts we were left with 8.619 $q\bar{q}g$ events.

In a Monte Carlo simulation of e^+e^- annihilation into hadrons the four momenta of final state particles were calculated, including bremsstrahlung from the initial leptons. A description of the different model calculations used and of the fitted parameters can be found in references 1 and 11. In a second step, the generated events were passed through a simulation of the detector with all known imperfections and processed by the same chain of computer programs and cuts as the real data.

For the Monte Carlo assignment of jets to partons, we used the smallest angle between the parton momentum and the reconstructed jet directions. The probabilities that jets #1, #2, and #3 are closest to the gluon direction are 8%, 22% and 64% respectively*. The sum of these probabilities does not add up to 100%, the remaining 3-jet structures being due to 2-parton and 4-parton background.

2.2 $q\bar{q}\gamma$ candidates

We first selected an isolated photon with an energy $E_\gamma > 2.5$ GeV, such that there was no charged particle with a momentum $p > 0.5$ GeV within a cone of half opening angle 30° around the photon direction. In events where more than one photon was found, the most energetic one was chosen. Photons detected in both the barrel lead glass ($|\cos\theta_\gamma| < 0.84$) and in the end caps ($0.89 < |\cos\theta_\gamma| < 0.98$) were used. The same cluster algorithm described above was then used to select 2-jet events. In this case, all particles were used except the candidate photon which was treated as a third "jet"**. Some of the radiative 2-jet events which were also accepted as 3-jet events when all particles were used were removed from our 3-jet sample.

* For jet energies of at least 6 GeV, these probabilities change to 9%, 28% and 56% for jet #1, #2 and #3, respectively

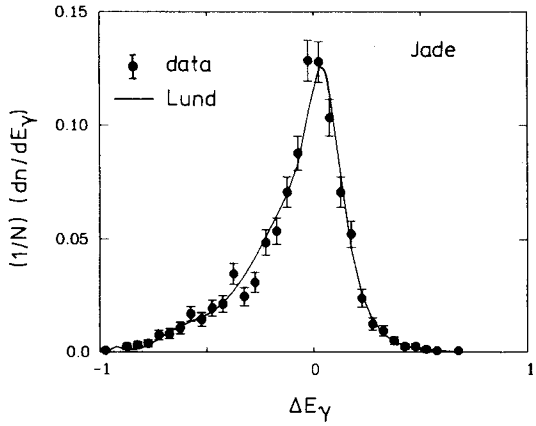

Fig. 1. Difference between measured and calculated photon energies for $q\bar{q}\gamma$ events. The ratio ΔE_γ is defined as $(E_\gamma^{LG} - E_\gamma^{\text{calc}})/E_{\text{beam}}$. The curve shows the prediction of the Lund model

In the following, the photon of the radiative 2-jet events was treated as a third jet, and the events underwent the same analysis steps as the 3-jet events. Nonplanar events were rejected ($|\mathbf{k}_1 \cdot (\mathbf{k}_2 \times \mathbf{k}_3)| \leq 0 \cdot 25$) and the "jet" directions were projected onto the event plane defined by $(\mathbf{q}_2, \mathbf{q}_3)$. The "jet" energies were calculated from the angles using the same formula as for the 3-jet events. The velocity of the photon β_γ was taken to be one. The velocities of the two quark jets were obtained assuming the mass of the jet to be proportional to its energy: $M = \kappa \cdot E_{\text{jet}}$ which gives $\beta_{\text{jet}} = \sqrt{1-\kappa^2}$. The parameter κ was fixed such that the photon energy calculated from the angles (E_γ^{calc}) was compatible with its energy measured in the lead glass counters (E_γ^{LG}). Figure 1 shows the ratio

$$\Delta E_\gamma = \frac{E_\gamma^{LG} - E_\gamma^{\text{calc}}}{E_{\text{beam}}}$$

for $\kappa = 0.35$ (corresponding to $\beta_{\text{jet}} = 0.94$) which gives the best agreement. The solid line shows how well the Lund Monte Carlo reproduces the data. To avoid the tail of the distribution a cut $|\Delta E_\gamma| < 0.3$ was applied.

After an ordering of the "jets" according to their energies ($E_1 > E_2 > E_3$), the same cuts as in the 3-jet selection were applied ($E_1 < 0.98 \cdot E_{\text{vis}}/2$ and $E_3 > 3$ GeV) in order to have a similar configuration

** To check that no bias was introduced by this procedure it has been verified that applying the cluster algorithm using all particles and then searching for isolated photons produced essentially the same event sample in both sets of events. We were then left with 490 $q\bar{q}\gamma$ events, including background. The $q\bar{q}\gamma$ events of interest were however those in which the photon had an energy lower than that of jet #1 and jet #2. In this case a probability of 65% that the photon corresponds to the least energetic "jet" was found using the selected radiative 2-jet events*. Six events in which a charged track faked the hard photon candidate were rejected in a visual scan. After these requirements, a final sample of 310 $q\bar{q}\gamma$ events remained. The main source of contamination was from "faked" radiative events in which the photon came from a π^0 decay. Using Monte Carlo methods** this background was estimated to be around 12%. Other sources of background were negligible.

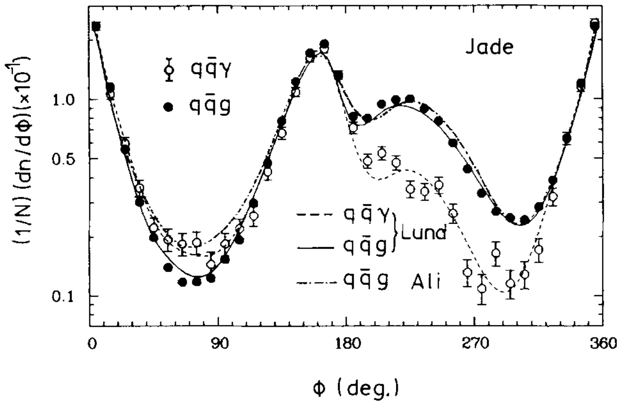

Fig. 2. Particle flow in the event plane of $q\bar{q}g$ and of $q\bar{q}\gamma$ events for all particles. The expectations of the Lund and Ali et al. models are indicated

3 Results and discussion

Figure 2 shows the particle flow of the selected 3-jet events compared to the particle flow in the event plane of the radiative 2-jet events. These distributions were obtained by projecting all particle momenta of an event onto the event plane $(\mathbf{q}_2, \mathbf{q}_3)$. Φ is the angle, within the event plane, between the particle momentum and the axis of jet #1, and runs via jets #2 and #3 back to jet #1. Thus the axis of jet #1 coincides with $\Phi=0°$, whereas the axes of jets #2 and #3 are distributed around 155° and 230° respectively. In the case of radiative 2-jet events jet #3 is of course missing (only one particle, namely the hard photon candidate, was counted in this region). All distributions are normalised to the relevant numbers of events.

Near the cores of jet #1 and jet #2, the distributions agree with each other. In the region between jet #1 and jet #2, however, the $q\bar{q}g$ distribution shows a deficit in the particle density when compared to the $q\bar{q}\gamma$ distribution. The predictions of the Lund string model (solid curve for $q\bar{q}g$ and dashed curve for $q\bar{q}\gamma$) are consistent with the data, particularly in the region between jet #1 and jet #2. The Lund result concerning the $q\bar{q}g$ density of particles is lower in this region since there is no string stretching from the quark directly to the antiquark. The independent fragmentation model expectation of Ali et al. [13] (dashed-dotted curve) is also indicated. A similar depletion of particles was observed when taking into account only charged particles (Fig. 3). The hard photon is then omitted from the plot and the results may

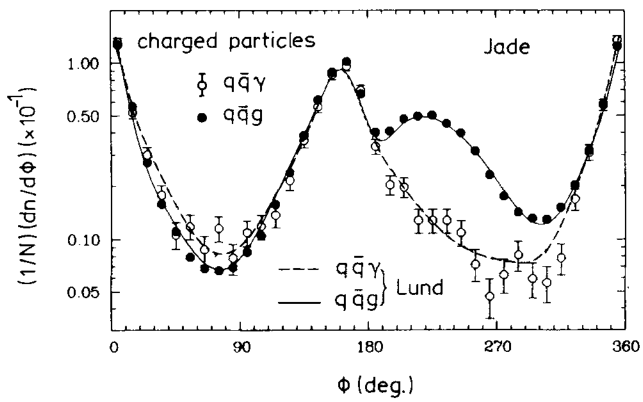

Fig. 3. Particle flow in the event plane of $q\bar{q}g$ and of $q\bar{q}\gamma$ events for charged particles. The expectations of the Lund model are indicated

be compared directly with those of the Mark-II collaboration which carried out the analysis using only charged particles. Figure 3 agrees nicely with the corresponding one from [8].

According to the Lund string model, the observed depletion ought to become more pronounced for particles with larger values of the transverse mass

$$\sqrt{m^2 + (p_\perp^{\text{out}})^2}$$

where $p_\perp^{\text{out}}$ is the momentum vector normal to the event plane. Such an enhancement is observed in Fig. 4, where the particle flow distribution is plotted for particles with $p_\perp^{\text{out}} > 0.3$ GeV/c.

The data are also compared to the prediction of QCD shower models based on the leading log approximation. As shown in Fig. 5, the Webber model also describes the data. In this model, the QCD coher-

* This probability is compatible with that obtained using Monte Carlo. The probability obtained using data is, however, affected by the π^0 contamination

** In this case final state radiation was included by adapting the Monte Carlo generator for $\mu\mu\gamma$ [12] for fractionally charged quarks

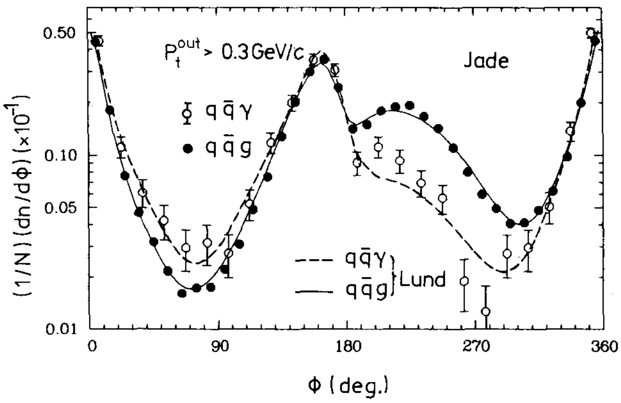

Fig. 4. Particle flow in the event plane of $q\bar{q}g$ and of $q\bar{q}\gamma$ events for particles with $P_{T_{out}} \geq 0.3$ GeV/c. The expectations of the Lund model are indicated

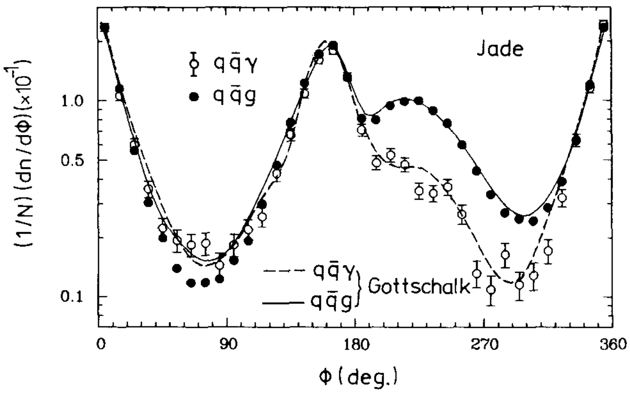

Fig. 6. Particle flow in the event plane of $q\bar{q}g$ and of $q\bar{q}\gamma$ events compared to the Gottschalk model

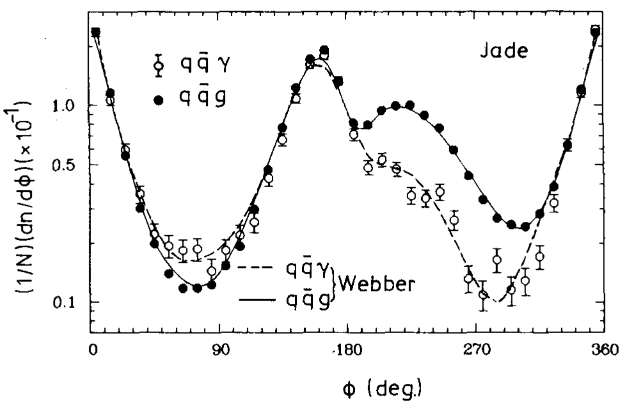

Fig. 5. Particle flow in the event plane of $q\bar{q}g$ and of $q\bar{q}\gamma$ events compared to the Webber model

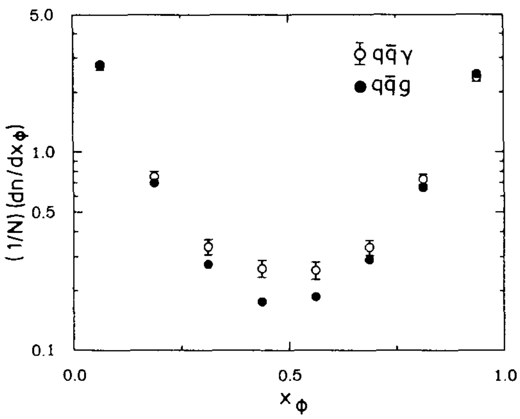

Fig. 7. Particle flow in the event plane of $q\bar{q}g$ and of $q\bar{q}\gamma$ events, as a function of the normalised angle x_Φ

ence effect is approximately taken into account through the angular ordering between partons which leads to a suppression of large angle emission of soft gluons. On the other hand, the Gottschalk model [14] (without QCD interference effect) does not reproduce the data (Fig. 6).

In order to make the discussion more quantitative, only the region between jets #1 and #2 is considered by defining the normalised projected angle:

$$x_\Phi = \frac{\Phi_i}{\Phi_{12}}$$

where Φ_i is the angle between the momentum of particle i and the axis of jet #1, and Φ_{12} is the angle between jet #1 and jet #2. Thus the axes of jets #1 and #2 correspond to $x_\Phi = 0$ and 1 respectively. In Fig. 7 the particle density relative to x_Φ is plotted.

In order to further reduce possible systematic errors, the ratio of the particle densities between $q\bar{q}g$ and $q\bar{q}\gamma$ is shown as a function of the normalised angle x_Φ (Fig. 8):

$$r(x_\Phi) = \left(\frac{1}{N_g}\frac{dn_g}{dx_\Phi}\right) \Big/ \left(\frac{1}{N_\gamma}\frac{dn_\gamma}{dx_\Phi}\right)$$

where N_g is the number of 3-jet events and N_γ the number of radiative 2-jet events.

There is a clear departure from a ratio of one (the expected value without QCD interference effects). Azimov et al. predicted a depletion effect of around 50% in the ideal case where the gluon is always detected as the less energetic jet. In reality the probability that the gluon is the third jet is only 65%; one then expects a depletion of about 35% which is in good agreement with our result and the results of

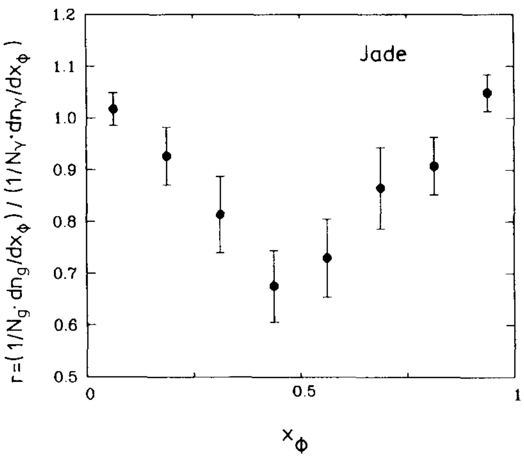

Fig. 8. Ratio $r(x_{\Phi})$ of the particle flow in $q\bar{q}g$ and $q\bar{q}\gamma$ events, in the region between jets #1 and #2, as a function of the normalised angle x_{Φ}

[8, 9]. The expectation of the independent fragmentation model of Ali et al. (not shown) agrees with a ratio of one.

Possible systematic effects were studied by varying some of our cuts (jet and photon energies, velocity of the jets (through the parameter κ), y_{cut}, etc.). The analysis was carried out using only photons in the barrel part of the detector ($|\cos\theta_{\gamma}|<0.8$) and using only charged particles (Fig. 3). Within statistical errors, the distributions remain the same. Taking into account the radiative events where the candidate photon has more energy than jets #1 and #2 (35% of the total) slightly reduces the effect.

4 Summary

In a model independent analysis, the particle flow distributions in the event plane of 3-jet ($e^+e^- \to q\bar{q}g$) and of radiative 2-jet ($e^+e^- \to q\bar{q}\gamma$) events were studied at $\sqrt{s}=35$ GeV using the JADE detector. In comparison to the region opposite the hard photon in the $q\bar{q}\gamma$ events, the region opposite to the hard gluon in the $q\bar{q}g$ events showed a significant reduction of particle density. The results agree with the predictions of QCD concerning soft gluon coherence and support the concept of local parton-hadron duality. The data were also compared to the expectations of different fragmentation models. Both the string model of the Lund group and the QCD shower model of Webber reproduced the effect.

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