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# Possible Studies of Parton Distribution Functions at JHF

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# Possible Studies of Parton Distribution Functions at JHF

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Abstract

We discuss possible studies of parton distribution functions (PDFs) in the nucleon and nuclei at the Japan Hadron Facility (JHF). First, the PDFs could be investigated by the 50 GeV primary proton facility. The distributions at medium $x$ are determined, for example, by Drell-Yan measurements. Second, there are feasibility studies to propose a neutrino factory within the 50 GeV proton ring. If such an intensive high-energy neutrino facility is built, neutrino reactions should be able to provide valuable information on the PDFs, whereas the current structure functions have been measured mainly for neutrino-iron reactions.

## 1 Introduction

Structure functions have been investigated since 1970's. We can test both perturbative and non-perturbative aspects of Quantum Chromodynamics (QCD) by their measurements. From measured $Q^2$ dependence of the structure functions, we learned that it agrees with perturbative QCD predictions. From their $x$ dependent measurements, parton distribution functions (PDFs) have been extracted. They are valuable for testing non-perturbative aspects such as predictions by lattice QCD and various phenomenological models. Furthermore, the PDF studies have wide applications to heavy-ion physics, neutrino oscillation experiments, and exotic event searches at extremely large $Q^2$ beyond the current theoretical framework.

Now, the unpolarized PDFs of the nucleon are relatively well established through a variety of experimental measurements. There are three established groups: CTEQ (Coordinated Theoretical/Experimental Project on QCD Phenomenology and Tests of the Standard Model), GRV (Glück, Reya, and Vogt), and MRST (Martin, Roberts, Stirling, and Thorne). All the distributions agree

rather well, which convinces us that the unpolarized PDFs in the nucleon are well determined except for extreme kinematical regions.

On the contrary, polarized PDFs and nuclear PDFs are not reliably determined at this stage. The European Muon Collaboration (EMC) discovery on the proton spin triggered enthusiastic investigations on high-energy spin physics. Even a decade has passed since the EMC finding, we do not understand yet how the proton spin consists of quarks and gluons. Of course, we have rough ideas on the spin carriers mainly through the electron and muon scattering data. However, they are not enough to determine all the polarized PDFs.

Nuclear PDFs are in the similar situation to the polarized. There are available experimental information from the deep inelastic scattering (DIS) and Drell-Yan processes. They enable us to find rough $x$ dependence of valence and antiquark distributions. However, it is still difficult to determine gluon distributions in nuclei. Furthermore, analysis technique has not been well developed for the nuclear parametrization.

Considering these situations, we think that the JHF could contribute to these PDF studies. There are two major possibilities. One is to use the primary 50 GeV proton beam, and the other is to use a neutrino factory. The proton beam will certainly become available in the near future, so that proton reactions could be used for the PDF studies. On the other hand, the possibility of the Japanese neutrino factory is not very clear at this stage. Neutrino factories have been considered in Europe, USA, and Japan, so that we hope that at least one of them will be materialized.

In this paper, we discuss possible PDF studies at JHF. In Sec. 2, primary proton topics are discussed. Then, neutrino-factory possibilities are discussed in Sec. 3. These topics are summarized in Sec. 4.

# 2 Primary proton beam

The JHF is a unique facility to investigate physics associated with secondary beams. Feasibility has been extensively studied in such fields. On the other hand, topics associated with the primary proton beam are not well investigated. One of the possibilities is to use the facility for the PDF studies. Because the beam energy is 50 GeV, we should inevitably focus on the medium and large $x$ regions of the parton distributions.

## 2.1 Drell-Yan processes

In the proton reactions, Drell-Yan processes provide important constraints for the parton distributions. For example, Fermilab-E866/NuSea data made important contribution to the determination of $\bar{u}/\bar{d}$ asymmetry in the nucleon. The

difference between $\bar{u}$ and $\bar{d}$ was first suggested by the New Muon Collaboration (NMC) in the studies of Gottfried-sum-rule violation. However, the NMC data were not sufficient to conclude actual antiquark flavor asymmetry due to the lack of small $x$ data. The Fermilab and CERN Drell-Yan measurements indicated the ratio $\bar{u}/\bar{d}$ directly, and the data enabled us to determine the difference between $\bar{u}$ and $\bar{d}$. In this way, the lepton DIS and the Drell-Yan process are complementary in establishing precise PDFs.

First, let us discuss the kinematical region to be probed by the possible JHF Drell-Yan measurements. In the Drell-Yan process, an antiquark (quark) with momentum fraction $x_1$ in the projectile interacts with a quark (antiquark) with $x_2$ to produce a dimuon pair with mass $m_{\mu\mu}$. If the center-of-mass (c.m.) energy is $\sqrt{s}$, they are related by

$$x_1 x_2 = \frac{m_{\mu\mu}^2}{s} \,. \tag{1}$$

The dimuon-mass square $m_{\mu\mu}^2$ is equal to $Q^2$ of the virtual photon, and it should be larger than a few GeV$^2$ in order to apply perturbative QCD picture. Considering the c.m. energy $\sqrt{s}$=10 GeV, we estimate that the target momentum fraction $x_2$ should be limited by $x_2 > 0.1$. This means that the medium and large $x$ regions could be investigated by the primary proton beam.

The feasibility of such Drell-Yan measurements has been investigated in detail by J. C. Peng *el al.* [1] for the JHF project. For example, the facility could contribute to the topic of the antiquark flavor asymmetry [2]. The present experimental situation is shown in Fig. 1. Experimentally, the Drell-Yan cross sections for the proton-proton and proton-deuteron reactions have been measured. Then, the cross-section difference is converted to the antiquark flavor asymmetry in Fig. 1. The experimental data are taken by the E866/NuSea [3] and NA51 [4] collaborations. It is clear from the figure that $\bar{d}$ is larger than $\bar{u}$ in the $x$ region, $x = 0.04 \sim 0.2$. Possible JHF experiments could extend the measured region to larger $x$, where current data are not accurate enough or even not available.

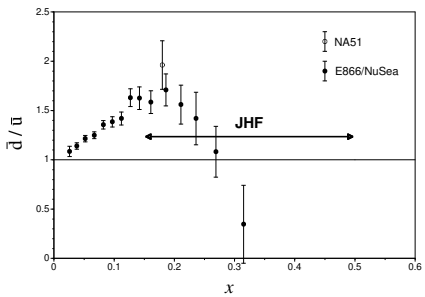


Figure 1: Measured $\bar{d}/\bar{u}$ ratios by the E866/NuSea and NA51 collaborations [3, 4].

Next, the Drell-Yan experiments could be used for determining nuclear antiquark distributions in the medium $x$ region. The situation of determining nuclear PDFs is much worse than the one for the nucleon in the sense that a variety of experimental data are not available and that analysis technique has not been well developed. For example, although the nuclear antiquark distributions could be

roughly determined by the measurements of the $F_2$ structure functions at small $x$, their determination is not possible at medium $x$ due to the lack of data. The present situation is typically shown in Fig. 2, where E772 data are shown for the cross-section ratios, $\sigma^{pCa}/\sigma^{pD}$ and $\sigma^{pFe}/\sigma^{pD}$ [5]. We should note that the cross-section ratios are almost equal to the antiquark ratios, $\bar{q}^{Ca}/\bar{q}^{D}$ and $\bar{q}^{Fe}/\bar{q}^{D}$ in the region, $x < 0.1$. The data indicate small nuclear corrections in the antiquark distributions at $x \sim 0.1$. However, they are not accurate enough at larger $x$, so that the determination is almost impossible in the medium $x$ region. This fact makes a nuclear $\chi^2$ analysis difficult for fitting various experimental data [6]. In the parametrization of the nuclear PDFs [6, 7], nuclear $F_2$ data are used together with the Drell-Yan data to produce the optimum distributions. If the medium $x$ data are taken at JHF as indicated in Fig. 2, the antiquark distributions are easily constrained at medium $x$, and the $\chi^2$ analysis becomes much reliable.

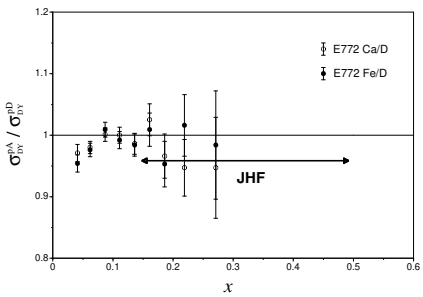


Figure 2: Nuclear Drell-Yan cross section ratios [5].

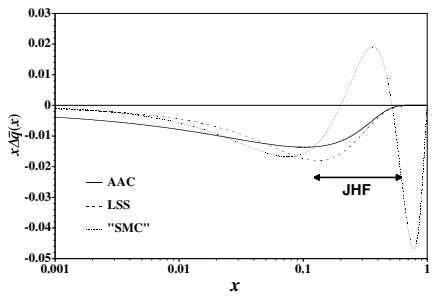


Figure 3: Antiquark distributions by LSS, SMC, and AAC [8].

Another application is for polarized PDFs. The polarized distributions in the nucleon have been obtained by using polarized electron and muon DIS experimental data. They are taken mainly for the structure function $g_1$, but there are also available semi-inclusive data. Several parametrizations have been proposed for explaining the polarized experimental data. However, the data are still taken in a limited kinematical range, and a variety of data are not available yet. This situation makes accurate determination of polarized antiquark distributions difficult. It is clearly illustrated in Fig. 3 [8]. Three antiquark distributions are shown in the figure, and they are obtained by Leader-Sidrov-Stamenov (LSS), Spin Muon Collaboration (SMC), and Asymmetry Analysis Collaboration (AAC). It is obvious from the figure that the antiquark distributions at medium $x$ are much different depending on the analysis methods. The JHF project probes the medium $x$ range as shown in Fig. 3 if the proton is polarized, so that its data are also valuable for the high-energy spin physics, especially for the determination of $\Delta\bar{q}$ at medium $x$.

## 2.2 Drell-Yan processes with polarized deuteron target

Using a polarized deuteron target, we could investigate polarized proton-deuteron processes. The reactions have never been investigated experimentally, whereas there are a few theoretical studies. There are two major purposes. One is to investigate new tensor structure functions, which do not exist for the spin-1/2 nucleon, and the other is to find flavor asymmetry for the polarized antiquark distributions.

First, we discuss the tensor structure functions. The polarized proton-proton ($pp$) reactions have been extensively investigated theoretically, and experimental studies are in progress as the Relativistic Heavy Ion Collider (RHIC) Spin project. We expect that nucleon spin structure will be partially clarified in the near future. However, it is important that different aspects of spin physics should be also investigated in order to test our knowledge of high-energy spin. One of such quantities is the tensor structure of the deuteron, and it could be studied by the tensor structure functions [9]. In the electron and muon scattering, there are leading-twist structure functions $b_1$ and $b_2$, which are related by the Callan-Gross type relation $2xb_1 = b_2$. The antiquark part of the tensor structure could be investigated by polarized proton-deuteron ($pd$) Drell-Yan processes in the same way as the unpolarized Drell-Yan reactions in Sec. 2.1.

A theoretical formalism of the polarized $pd$ Drell-Yan was investigated in Ref. [10]. In comparison with the $pp$ Drell-Yan processes, there are additional structure functions associated with the tensor structure of the deuteron. Among them, a quadrupole spin asymmetry $A_{UQ_0}$ is sensitive to the $b_1$ distributions:

$$A_{UQ_0} = \frac{\sum_a e_a^2 \left[ f_1(x_1)\, \bar{b}_1(x_2) + \bar{f}_1(x_1)\, b_1(x_2) \right]}{\sum_a e_a^2 \left[ f_1(x_1)\, \bar{f}_1(x_2) + \bar{f}_1(x_1)\, f_1(x_2) \right]} \,. \tag{2}$$

The notation $UQ_0$ indicates that the proton is unpolarized and a tensor spin combination is taken for the deuteron. The functions $f_1(x)$ and $\bar{f}_1(x)$ are unpolarized quark and antiquark distributions, and $b_1(x)$ and $\bar{b}_1(x)$ are tensor-polarized distributions. In the large $x_F$ region, the spin asymmetry becomes

$$A_{UQ_0}(\text{large } x_F) \approx \frac{\sum_a e_a^2\, f_1(x_1)\, \bar{b}_1(x_2)}{\sum_a e_a^2\, f_1(x_1)\, \bar{f}_1(x_2)} \quad \text{at large } x_F \,. \tag{3}$$

It indicates that the tensor polarized antiquark distributions can be obtained by the spin asymmetry measurements in the polarized $pd$ reactions. This is complementary to the studies of the tensor structure in the electron and muon scattering, where the antiquark distributions cannot be determined in the medium $x$ region.

Second, the polarized $pd$ Drell-Yan could be used for investigating the polarized antiquark flavor asymmetry $\Delta\bar{u}/\Delta\bar{d}$ [11]. As shown in Sec. 2.1, the difference

between the $pp$ and $pd$ cross sections is attributed to the difference between $\bar{u}$ and $\bar{d}$. In the same way, the difference between the polarized $pp$ and $pd$ cross sections should be associated with the difference between $\Delta\bar{u}$ and $\Delta\bar{d}$. Another important point is that it enables us to determine $\Delta_T\bar{u}/\Delta_T\bar{d}$ for the transversity distributions, because the transversity cannot be measured by the $W$ production process. The cross-section ratio for the $pp$ and $pd$ reactions is

$$R_{pd} \equiv \frac{\Delta_{(T)}\sigma_{pd}}{2\,\Delta_{(T)}\sigma_{pp}} = \frac{\sum_a e_a^2 \left[\,\Delta_{(T)}q_a(x_1)\,\Delta_{(T)}\bar{q}_a^{\,d}(x_2) + \Delta_{(T)}\bar{q}_a(x_1)\,\Delta_{(T)}q_a^d(x_2)\,\right]}{2\,\sum_a e_a^2 \left[\,\Delta_{(T)}q_a(x_1)\,\Delta_{(T)}\bar{q}_a(x_2) + \Delta_{(T)}\bar{q}_a(x_1)\,\Delta_{(T)}q_a(x_2)\,\right]}\,, \quad (4)$$

where $\Delta_{(T)}q$ denotes a polarized distribution $\Delta q$ or $\Delta_T q$ depending on the longitudinal or transverse polarization. If the large $x_F$ $(= x_1 - x_2)$ region is considered, the ratio becomes

$$R_{pd}(x_F \to 1) = \frac{1}{2}\left[1 + \frac{\Delta_{(T)}\bar{d}(x_2)}{\Delta_{(T)}\bar{u}(x_2)}\right]_{x_2\to 0}\,, \quad (5)$$

which is directly proportional to the flavor asymmetry ratio. It indicates that the flavor asymmetry could be measured especially at large $x_F$.

### 2.3 Comments on other processes

We have discussed the PDF studies by the Drell-Yan processes; however, there are other possibilities. For example, $J/\psi$ production could be used for investigating the antiquark flavor asymmetry [1]. Furthermore, the process is known to be sensitive to the gluon distribution, so that the production measurements could impose constraints on the unpolarized and polarized gluon distributions.

On the other hand, the feasibility of direct photon measurements has not been studied for the JHF project. Since the beam energy is not high, direct photons from perturbative processes could be mixed with other background contributions. However, if the measurements are possible, the JHF contributes to the gluon determination at medium $x$. Several years ago, the CDF (Collider Detector at Fermilab) group reported anomalous events in their jet cross sections for the $p+\bar{p}$ reaction at $\sqrt{s} = 1.8$ TeV. Because they cannot be explained by the next-to-leading-order (NLO) QCD, the events were considered to be a signature beyond the current theoretical framework [12]. However, it was revealed that the gluon distribution at large $x$ could be the reason for the discrepancy from the QCD prediction. In fact, according to Ref. [13], the events could be explained by a gluon enhancement at large $x$. We think that unexpected events for new physics should be found at extremely large $Q^2$, which inevitably means large $x$. As shown by the anomalous CDF events and also similar ones at HERA, the PDFs at large $x$ should be known precisely in order to find any exotic signatures. In this sense, the JHF has potential to contribute to such a large $x$ determination.

# 3 Neutrino factory

In addition to the primary proton beam, there is another passibility for the PDF studies at JHF by using neutrinos from accelerated muons. It is called a neutrino factory. Its feasibility studies are still at the early stage. However, we hope that at least one of the neutrino factory plans in Europe, USA, and Japan will be realized. At this stage, a 30 GeV neutrino factory is considered as a possibility within the 50 GeV proton ring. In neutrino-nucleon scattering, the Bjorken scaling variable is given by $x = Q^2/(2M_N\nu)$, where $M_N$ is the nucleon mass and $\nu$ is the energy transfer. In order to be considered as DIS data, $Q^2$ should be larger than at least 1 GeV$^2$, and $\nu$ should be smaller than the neutrino beam energy. Therefore, the minium $x$ is $x_{min} = 1/(2 \cdot 1 \cdot 30) \approx 0.017$. In the following, we discuss nucleon and nuclear PDF studies at such a neutrino facility.

## 3.1 Comments on unpolarized structure functions in the nucleon

There have been already measurements of neutrino DIS. In fact, the data have been included in the unpolarized PDF parametrizations. Especially, the opposite sign dimuon events are crucial for the determination of the strange quark distribution, and $F_3$ structure functions are valuable for the valence-quark distributions. In the recent parametrization, the CCFR (Columbia-Chicago-Fermilab-Rochester) data have been used. It should be, however, noticed that the target is iron instead of the proton. Although some nuclear corrections, which are suggested by nuclear $F_2$ modification, are applied, it is not obvious that proper PDFs in the "nucleon" have been extracted from the CCFR iron data. A future neutrino factory could clarify the distributions in the nucleon if the proton and deuteron targets could be used with an intense neutrino beam.

## 3.2 Polarized structure functions

Polarized structure functions $g_1$ and $g_2$ have been measured by electron and muon DIS. In the neutrino scattering, there are additional ones, $g_3$, $g_4$, and $g_5$, due to a parity-violation nature of the reaction. These additional structure functions have not been measured experimentally, and there are not sufficient theoretical studies. It is typically reflected in confusing definitions of $g_3$, $g_4$, and $g_5$. Various definitions are summarized in Ref. [14], where we notice that someone's $g_3$ structure function could be $g_5$ for some others and vice versa. In reading the papers on these structure functions, one should be careful about their definitions. In the following, the conventions of Ref. [15] are used. In the leading

order (LO), they are related to the polarized parton distributions as

$$
\begin{aligned}
(g_4^{\nu p} + g_5^{\nu p})/2x = g_3^{\nu p} &= -(\Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c}), \\
(g_4^{\bar{\nu} p} + g_5^{\bar{\nu} p})/2x = g_3^{\bar{\nu} p} &= -(\Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}).
\end{aligned} \tag{6}
$$

Combining these structure functions, we have

$$
\begin{aligned}
g_3^{\nu p} + g_3^{\bar{\nu} p} =& -(\Delta u_v + \Delta d_v) - (\Delta s - \Delta\bar{s}) - (\Delta c - \Delta\bar{c}), \\
\frac{1}{2}\,[\, g_3^{\bar{\nu}(p+n)} - g_3^{\nu(p+n)} \,] =& (\Delta s + \Delta\bar{s}) - (\Delta c + \Delta\bar{c}).
\end{aligned} \tag{7}
$$

The differences $\Delta s - \Delta\bar{s}$ and $\Delta c - \Delta\bar{c}$ are expected to be small, so that the first combination $g_3^{\nu p} + g_3^{\bar{\nu} p}$ could be used for determining the polarized valence-quark distributions. The second combination $g_3^{\bar{\nu}(p+n)} - g_3^{\nu(p+n)}$ is sensitive to the strange and charm distributions.

There is additional importance in the neutrino scattering. The quark spin content of the nucleon has been controversial for a decade. The EMC finding initiated many theoretical and experimental investigations. Despite such efforts, the spin content $\Delta\Sigma$ is not still clear. As shown in Fig. 3, the obtained antiquark distributions have different $x$ dependence in the small $x$ region due to the lack of small $x$ data. It makes the determination of $\Delta\Sigma$ rather difficult. In fact, the obtained $\Delta\Sigma$ ranges from 5% to 30% depending on the models in Fig. 3. In order to clarify $\Delta\Sigma$, the neutrino reactions are very useful. The $g_1$ structure functions are expressed in the parton model as

$$
\begin{aligned}
g_1^{\nu p} =& \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{c}, \\
g_1^{\bar{\nu} p} =& \Delta u + \Delta c + \Delta\bar{d} + \Delta\bar{s}.
\end{aligned} \tag{8}
$$

Combining these expressions, we find

$$
\int dx\, (g_1^{\nu p} + g_1^{\bar{\nu} p}) = \Delta\Sigma, \tag{9}
$$

in the LO. Although there are NLO and higher-order corrections, the spin content could be obtained directly without resorting to low-energy semi-leptonic data for fixing the first moments of the valence-quark distributions.

In this way, if the neutrino factory is realized in future at JHF, it could contribute to the high-energy spin physics significantly.

### 3.3 Nuclear structure functions

We mentioned that many of the actual neutrino data are taken for the iron target, so that neutrino-nucleus DIS data already exist. However, experimental nuclear

modification has not been discussed seriously for the neutrino reactions because accurate deuteron data are not obtained yet. At the neutrino factory, accurate deuteron data are expected. It is especially interesting to investigate nuclear $F_3$ structure functions which are specific for parity-violating neutrino scattering. For example, combining functions of different reactions, we obtain

$$\frac{1}{4}\,[\,F_3^{\nu(p+n)} + F_3^{\bar{\nu}(p+n)}\,] = u_v + d_v + (s-\bar{s}) + (c-\bar{c}) \approx u_v + d_v \ , \tag{10}$$

for investigating the valence-quark distributions.

The nuclear PDFs can be determined by analyzing nuclear DIS data together with the Drell-Yan data [6, 7]. The obtained valence-quark distributions are shown in Fig. 4, where the curves indicate $q_v^{Ca}/q_v^D$. The dashed curve is obtained by removing the Drell-Yan data from the analysis data set. The neutrino factory should provide strong constraints on the $x$ dependence in the region $x > 0.02$. In addition, if the beam energy is large enough, the shadowing region could be probed. In the $F_2$ structure functions for the electron and muon DIS, the shadowing phenomenon is well known. However, there is no experimental information on the $F_3$ shadowing. Although the valence-quark distributions are constrained by the baryon number and charge, there is no strong restriction on the small $x$ behavior. In principle, anti-shadowing is not completely ruled out in the present situation. Experimental measurements of the $F_3$ shadowing or anti-shadowing phenomenon are important for understanding high-energy nuclear reactions precisely [16].

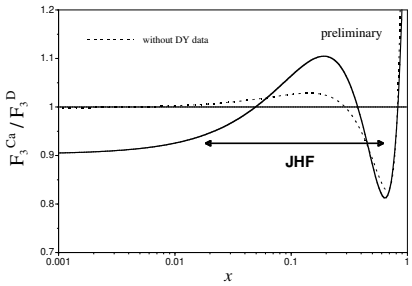


Figure 4: Nuclear modification of the $F_3$ structure function [6].

# 4 Summary

We have explained possible measurements of structure functions and parton distribution functions in the nucleon and nuclei at JHF. There are two possibilities. On is to use the primary proton beam, and the other is to use the neutrino factory. These facilities should provide important data, which cannot be obtained by other laboratories. The Drell-Yan measurements should clarify the antiquark distributions at medium $x$, especially the flavor asymmetry ratios $\bar{u}/\bar{d}$, $\Delta\bar{u}/\Delta\bar{d}$, and $\Delta_T\bar{u}/\Delta_T\bar{d}$. Furthermore, nuclear antiquark distributions should be determined in the medium $x$ region. We hope that feasibility of other processes, such as the charmonium and direct-photon productions, will be seriously studied in the near future.

The Japanese neutrino factory has been considered at JHF. Although long baseline physics (neutrino oscillation) has been rather well studied in the Japanese particle physics community, short baseline physics (hadron structure) has not been well discussed. The facility could be important for finding the details of the polarized PDFs especially in connection with the quark spin content. There are also new structure functions $g_3$, $g_4$, and $g_5$ which do not exit in the electron and muon scattering. Furthermore, the nuclear valence-quark distributions should be clarified by the $F_3$ structure functions in nuclei. It is particularly interesting to find whether the $F_3$ shadowing is similar to the observed $F_2$ shadowing.

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