Extraction of the first transverse moments of Sivers and $g_{1T}^{\perp}$ PDFs from COMPASS SIDIS data

T. Nechaeva[1]
Supervisor: B. Parsamyan[2,3]
[1] *Theoretical Physics Department, Belorussian State University and Institute for Nuclear Problems, Minsk, Belarus*
[2] *CERN, 1211 Geneva 23, Switzerland*
[3] *INFN, Sezione di Torino, 10125 Torino, Italy*

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Abstract

According to QCD the quark structure of the nucleon spin within the *twist-2* approximation is parameterized by eight transverse-momentum-dependent (TMD) parton distribution functions (PDFs). The PDFs describe the distributions of longitudinal and transverse momenta of partons and their correlations with nucleon and quark polarizations and can be accessed through measurement of spin (in)dependent azimuthal asymmetries in semi-inclusive DIS (SIDIS). The COMPASS experiment at CERN, as part of its programme, addresses the exploration of the spin structure of the nucleon by measuring spin (in)dependent azimuthal asymmetries in SIDIS.

Using the high-statistics data collected by the COMPASS Collaboration in 2010 with naturally polarized μ^{+}-beam and a transversely polarized proton (NH_3) target the first transverse moments of the Sivers PDF $f_{1T}^{\perp}$ for u and d quarks were obtained from the P_T-weighted Sivers asymmetries $A_{UT}^{\sin(\phi_h-\phi_s)}$. Then, using the same formalism, the first moments of the $g_{1T}^{\perp}$ PDF were extracted for the P_T-weighted double spin asymmetries $A_{LT}^{\cos(\phi_h-\phi_s)}$. The latter results have not yet been released by the collaboration and are not for public use at this stage.

1 Introduction

Current knowledge of the spin structure of the nucleon is based on experimental data on hadron-hadron collisions and on semi-inclusive hadron measurements in deep-inelastic lepton-nucleon scattering (hereafter referred to as semi-inclusive DIS or SIDIS). Common DIS experiments are making a use of high-energy lepton beam impinging on a longitudinally or transversely polarized nucleon at large momentum transfer Q^2 (the virtuality of the exchanged photon). In past years a number of inclusive measurements, where only the scattered lepton is observed in the final state, and semi-inclusive measurements, where one tags on at least one final-state hadron in coincidence with the scattered lepton, were performed [1]. Measurements with longitudinally polarized targets and beams tell us about the helicity distributions of quarks and gluons in the nucleon, which can be interpreted as a difference in probability of finding a parton with longitudinal polarization parallel or antiparallel to that of the nucleon. Measurements with transversely polarized targets are particularly sensitive to transverse degrees of freedom of partons inside a nucleon, such as intrinsic transverse momentum of partons k_T and their orbital motion. Studies of transverse degrees of freedom in the nucleon and in hadronization processes are a subject of extensive experimental and phenomenological investigations.

Within QCD-improved parton model approach, quark transverse-momentum-dependent (TMD) parton distribution functions (PDFs) provide a three-dimensional picture of a fast moving nucleon in momentum space and play an important role in the theoretical description of high energy reactions. At leading order (LO) of QCD parton model the spin and quark-transverse-momentum structure of the nucleon is fully described by six time reversal even and two time reversal odd *twist-2* TMD PDFs [2]. The TMD PDFs are universal, process-independent functions describing longitudinal and transverse momenta distributions of partons and their correlations with nucleon and quark spins [3]. Such correlations induce azimuthal modulations (asymmetries) in the cross sections of SIDIS ($lN \to l'hX$, semi-inclusive hadron production in deep-inelastic lepton-nucleon scattering) and of Drell-Yan (DY) ($hN \to l\bar{l}X$, massive lepton-pair production in hadron-nucleon collisions) processes. Applying the TMD factorization theorems [3] allows one to express the asymmetries raising in DY and SIDIS cross sections in terms of convolutions of perturbatively calculable hard-scattering parton cross sections, hard-scale dependent TMD PDFs and (for SIDIS) parton fragmentation functions (FFs). In this paper the Sivers asymmetry, arising from the asymmetric distributions of partons in the transversely polarized nucleon [4] and the Kotzinian-Mulders double spin asymmetry (longitudinally polarized lepton and transversely polarized target nucleon), arising from the longitudinal polarization of an active quark [5] are considered.

The standard notation for DIS variables is used: l and l' are the momenta of the initial and final lepton, $q = l - l'$ is the exchanged virtual photon momentum, P is the target nucleon momentum, P^h is the final hadron momentum; $Q^2 = -q^2$, the Bjorken variable $x = Q^2/2P \cdot q$, $z = P^h \cdot P/P \cdot q$ [6].

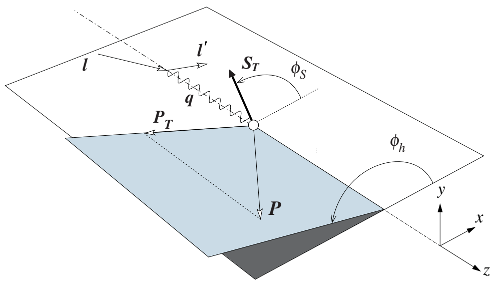

Figure 1: The SIDIS framework.

The data used in this analysis were collected in 2010 by COMPASS experiment using a 160 GeV μ^+ beam impinging on a transversely polarized proton (NH_3) three-cell target [7]. The data were collected at a mean beam intensity of 3.5 $\times 10^8$ μ/spill, for a spill length of about 10 s every 40 s. About 37 $\times 10^9$ DIS events, corresponding to 1.9 PB of data, were collected in 12 separate periods. In order to minimize systematic uncertainties related to possible acceptance variations, during each period of data taking the orientation of the polarization of free protons in the three target cells was either up-down-up or down-up-down in the first sub-period, and reversed in the second one.

The weighted asymmetries extracted by COMPASS were measured separately for positive and negative hadrons as a function of x or z. For each bin in x or z and for each period of data taking, the asymmetries were extracted from the number of hadrons produced in each cell for the two directions of the target polarization, and the mean of the results from the twelve periods was taken as final result.

In this paper, the values of the weighted asymmetries for charged hadrons with a fraction of available energy $z > 0.2$ as functions of x are used to extract the first transverse moments of Sivers ($f_{1T}^{\perp}$) and $g_{1T}^{\perp}$ PDFs for u_V and d_V quarks.

2 The weighted asymmetries

Throughout the paper, the asymmetries are denoted as A_{XY}^{w}, where w is the corresponding azimuthal modulation, $w = \sin\Phi \equiv \sin(\phi_h - \phi_s)$ for the Sivers asymmetry or $w = \cos\Phi \equiv \cos(\phi_h - \phi_s)$ for the Kotzinian-Mulders double spin asymmetry, X indicates the state of the lepton polarization (U - unpolarized, L - longitudinal), Y – the state of the target polarization (U - unpolarized, L - longitudinal, T - transverse).

Within the QCD parton model approach two asymmetries mentioned earlier have pure *twist-2* interpretations in terms of convolutions of TMD PDFs and FFs [2], [5],

$$A_{UT}^{\sin(\phi_h - \phi_s)} \sim f_{1T}^{\perp q} \otimes D_{1q}^{h}; \tag{1}$$

$$A_{LT}^{\cos(\phi_h - \phi_s)} \sim g_{1T}^{q} \otimes D_{1q}^{h}. \tag{2}$$

Angle ϕ_h (ϕ_S) defines the azimuthal orientation of the hadron momentum (target spin) with respect to the lepton scattering plane and is calculated about the virtual-photon momentum direction. The corresponding right-handed coordinate system is defined by the lepton transverse momentum direction (x axis), virtual photon direction (z axis) and respective normal vector (y axis).

The part of the fully differential SIDIS cross section relevant to the Sivers asymmetry can be presented as follows:

$$d\sigma = d\sigma_U + S_T d\sigma_S \sin\Phi, \tag{3}$$

where S_T is the target nucleon polarization, $\Phi = \phi_h - \phi_s$, $d\sigma_U$ and $d\sigma_S$ are the spin-independent and spin-dependent parts of the cross section [7].

Measurement of weighted by the transverse momentum of the produced hadron $w = P_T/zM$ asymmetries provides an unbiased way to access the first transverse moments of the corresponding TMD PDFs [7]. The weighted Sivers asymmetries are defined as:

$$A_{UT}^{\sin(\phi_h - \phi_s)} = \frac{\int d\Phi \sin\Phi \int d^2\mathbf{P}_T \left(\frac{P_T}{zM}\right) d\sigma}{\int d\Phi \int d^2\mathbf{P}_T d\sigma} \tag{4}$$

In terms of quark distribution and fragmentation functions, the asymmetries are interpreted as follows:

$$A_{UT}^{\sin(\phi_h - \phi_s)}(x, z) = \frac{\sum_q e_q^2 x \int d^2\mathbf{P}_T \frac{P_T}{zM} \mathcal{C}\left[\frac{\mathbf{P}_T \cdot \mathbf{k}_T}{MP_T} f_{1T}^{\perp q}(x, k_T^2) D_1^q(z, p_T^2)\right]}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)}. \tag{5}$$

Using the delta function to integrate the convolution over $\mathbf{P}_T$ the integral in the numerator gives:

$$\begin{aligned}&\int d^2\mathbf{P}_T \frac{P_T}{zM}\mathcal{C}\Big[\frac{\mathbf{P}_T\cdot\mathbf{k}_T}{MP_T} f_{1T}^{\perp q} D_1^q = \\ &= \int d^2\mathbf{k}_T \frac{1}{zM^2}\int d^2\mathbf{p}_T (zk_T^2 + \mathbf{k}_T\cdot\mathbf{p}_T) f_{1T}^{\perp q}(x,k_T^2) D_1^q(z,p_T^2) = \\ &= \int d^2\mathbf{k}_T \frac{k_T^2}{M^2} f_{1T}^{\perp q}(x,k_T^2)\int d^2\mathbf{p}_T D_1^q(z,p_T^2) = \\ &= 2 f_{1T}^{\perp(1)q}(x) D_1^q(z)\end{aligned} \tag{6}$$

finally for the weighted Sivers asymmetry we get:

$$A_{UT}^{\sin(\phi_h-\phi_s)}(x,z) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)}. \tag{7}$$

Similarly we obtain the expression for the Kotzinian-Mulders asymmetry $A_{LT}^{\cos(\phi_h-\phi_s)}$:

$$A_{LT}^{\cos(\phi_h-\phi_s)}(x,z) = 2\frac{\sum_q e_q^2 x g_{1T}^{\perp(1)q}(x) D_1^q(z)}{\sum_q e_q^2 x f_1^q(x) D_1^q(z)}. \tag{8}$$

The results for the Sivers and Kotzinian-Mulders asymmetries for nine x bins and $z > 0.2$ are shown in the figures below.

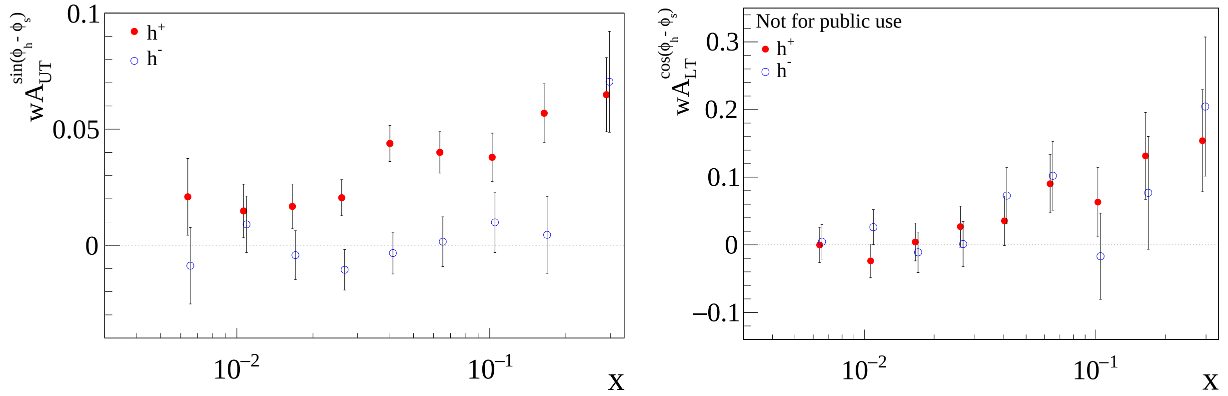

Figure 2: *Left panel:* Weighted $A_{UT}^{\sin(\phi_h-\phi_s)}$ for positive (full points) and negative(open points) hadrons; *Right panel:* Weighted $A_{LT}^{\cos(\phi_h-\phi_s)}$ for positive (full points) and negative (open points) hadrons. All the points for negative hadrons are slightly shifted towards bigger x values for clarity.

3 Step by step extraction of the first moments of the Sivers and $g_{1T}^{\perp}$ PDFs

The weighted asymmetries are used for the extraction of the first moments of the Sivers and $g_{1T}^{\perp}$ PDFs. Thus we consider the asymmetries integrated over z (restore the Q^2 dependence) [7]:

$$A_{UT}^{\sin(\phi_h-\phi_s)}(x,Q^2) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x,Q^2)\tilde{D}_1^q(Q^2)}{\sum_q e_q^2 x f_1^q(x,Q^2)\tilde{D}_1^q(Q^2)}, \tag{9}$$

$$A_{LT}^{\cos(\phi_h-\phi_s)}(x,Q^2) = 2\frac{\sum_q e_q^2 x g_{1T}^{\perp(1)q}(x,Q^2)\tilde{D}_1^q(Q^2)}{\sum_q e_q^2 x f_1^q(x,Q^2)\tilde{D}_1^q(Q^2)}, \tag{10}$$

where

$$\tilde{D}_1^q(Q^2) = \int_{z_{min}}^{z_{max}} dz D_1^q(z,Q^2). \tag{11}$$

The integrated over z ($z_{min} = 0.2, z_{max} = 1.0$) fragmentation functions (DSS parametrization [8] used) for charged hadrons and all quark flavors q are shown on the next figures.

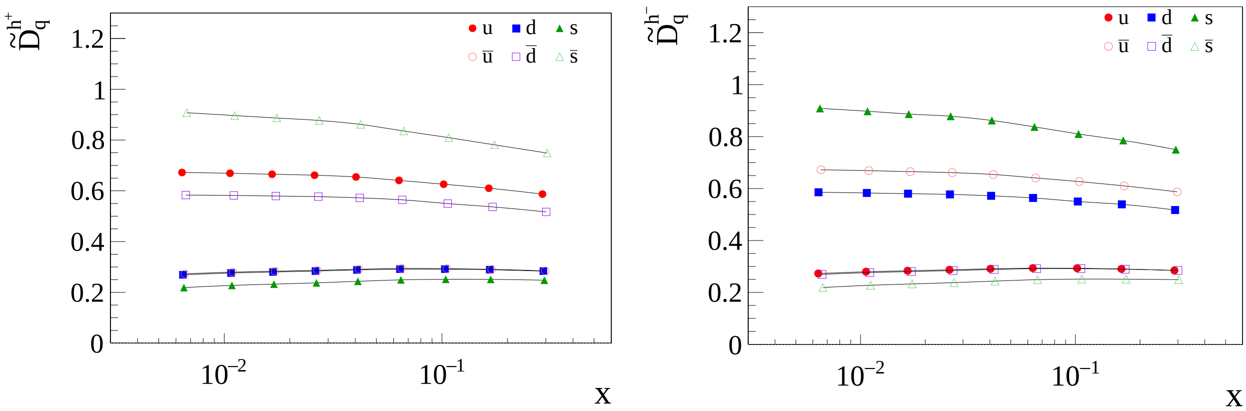

Figure 3: *Left panel:* Integrated DSS-07 (LO) FFs for positive hadrons; *Right panel:* Integrated DSS-07 (LO) FFs for negative hadrons; the values differ insignificantly for Sivers and Kotzinian-Mulders asymmetries.

For the obtaining of the distribution functions f_1^q for all quark flavors CTEQ5D parametrization [9] and the LHAPDF 6.2.1 software [10] were used.

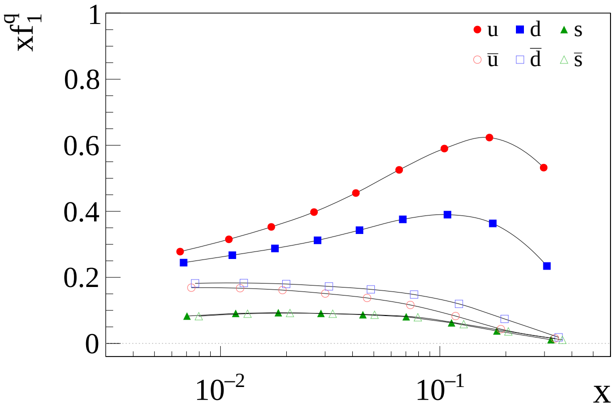

Figure 4: Parton distribution functions f_1^q for positive and negative hadrons; their values differ insignificantly for Sivers and Kotzinian-Mulders asymmetries.

As it was mentioned before, there are two sets of asymmetries, for positively (superscript +) and negatively (superscript –) charged hadrons. Sea quark contribution can be omitted, as in the number of studies it was shown to be negligible [1], [11]. Then the asymmetries read:

$$A_{UT}^{\sin(\phi_h-\phi_s),\pm} = 2\frac{4xf_{1T}^{\perp(1)u_V}\tilde{D}_1^{u,\pm} + xf_{1T}^{\perp(1)d_V}\tilde{D}_1^{d,\pm}}{9\sum_q e_q^2 xf_1^q\tilde{D}_1^{q,\pm}}, \tag{12}$$

$$A_{LT}^{\cos(\phi_h-\phi_s),\pm} = 2\frac{4xg_{1T}^{\perp(1)u_V}\tilde{D}_1^{u,\pm} + xg_{1T}^{\perp(1)d_V}\tilde{D}_1^{d,\pm}}{9\sum_q e_q^2 xf_1^q\tilde{D}_1^{q,\pm}}. \tag{13}$$

Denoting the denominator by $\delta^{\pm}$,

$$\delta^{\pm} \equiv 9\sum_q e_q^2 xf_1^q\tilde{D}_1^{q,\pm}, \tag{14}$$

the valence Sivers first moments can be extracted from the asymmetries as follows:

$$xf_{1T}^{\perp(1)u_V} = \frac{1}{8}\frac{\delta^+ A_{UT}^{\sin(\phi_h-\phi_s),+}\tilde{D}_1^{d,-} - \delta^- A_{UT}^{\sin(\phi_h-\phi_s),-}\tilde{D}_1^{d,+}}{\tilde{D}_1^{u,+}\tilde{D}_1^{d,-} - \tilde{D}_1^{d,+}\tilde{D}_1^{u,-}}, \tag{15}$$

$$xf_{1T}^{\perp(1)d_V} = \frac{1}{2}\frac{\delta^- A_{UT}^{\sin(\phi_h-\phi_s),-}\tilde{D}_1^{u,+} - \delta^+ A_{UT}^{\sin(\phi_h-\phi_s),+}\tilde{D}_1^{u,-}}{\tilde{D}_1^{u,+}\tilde{D}_1^{d,-} - \tilde{D}_1^{d,+}\tilde{D}_1^{u,-}}. \tag{16}$$

The same method can be applied to extract the valence first moments of $g_{1T}^{\perp}$ from the corresponding sets of asymmetries:

$$xg_{1T}^{\perp(1)u_V} = \frac{1}{8}\frac{\delta^+ A_{LT}^{\cos(\phi_h-\phi_s),+}\tilde{D}_1^{d,-} - \delta^- A_{LT}^{\cos(\phi_h-\phi_s),-}\tilde{D}_1^{d,+}}{\tilde{D}_1^{u,+}\tilde{D}_1^{d,-} - \tilde{D}_1^{d,+}\tilde{D}_1^{u,-}}, \tag{17}$$

$$xg_{1T}^{\perp(1)d_V} = \frac{1}{2}\frac{\delta^- A_{LT}^{\cos(\phi_h-\phi_s),-}\tilde{D}_1^{u,+} - \delta^+ A_{LT}^{\cos(\phi_h-\phi_s),+}\tilde{D}_1^{u,-}}{\tilde{D}_1^{u,+}\tilde{D}_1^{d,-} - \tilde{D}_1^{d,+}\tilde{D}_1^{u,-}}. \tag{18}$$

The results are displayed on the figures below.

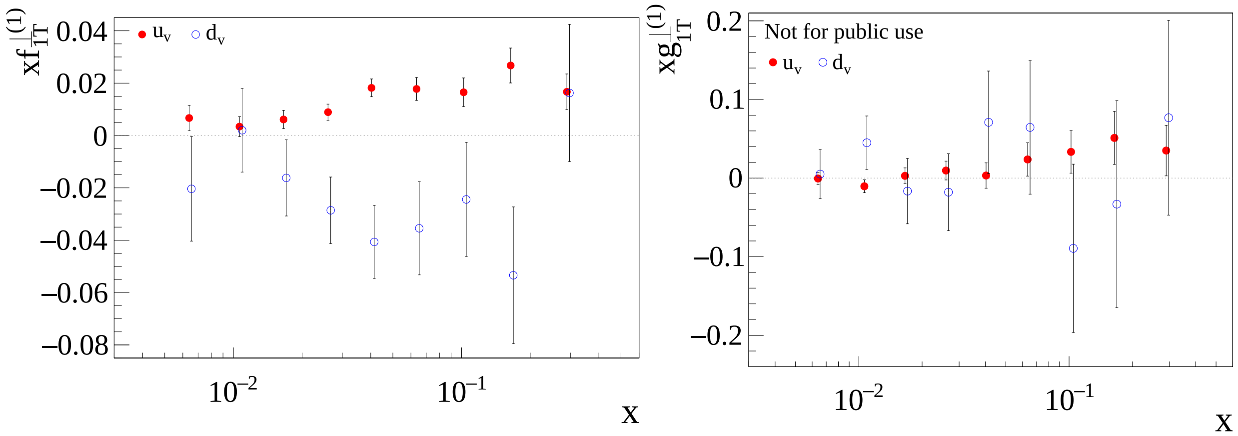

Figure 5: *Left panel:* Values of the first moments of the Sivers PDF for u (closed dots) and d (open dots) quarks from the $A_{UT}^{\sin(\phi_h-\phi_s)}$ for charged hadrons with $z > 0.2$;
Right panel: Values of the first moments of the $g_{1T}^{\perp}$ PDF for u (closed dots) and d (open dots) quarks from the $A_{LT}^{\cos(\phi_h-\phi_s)}$ for charged hadrons with $z > 0.2$.

The uncertainties are calculated from the statistical errors of the measured asymmetries; they are much larger for the d_V Sivers and $g_{1T}^{\perp}$ first moments than for the u_V ones. The u_V and d_V Sivers and $g_{1T}^{\perp}$ first moments are linear combinations of the corresponding asymmetries for positive and negative hadrons in the proton, this is in principle sufficient for their determination, but since the coefficient of proportionality is four times larger for the d quark, the uncertainties for the $f_{1T}^{\perp(1)d_V}$ ($g_{1T}^{\perp(1)d_V}$) are about four times larger than those of $f_{1T}^{\perp(1)u_V}$ ($g_{1T}^{\perp(1)u_V}$).

4 Conclusion

COMPASS has measured the P_T/zM-weighted asymmetries $A_{UT}^{\sin(\phi_h-\phi_s),\pm}$ and $A_{LT}^{\cos(\phi_h-\phi_s),\pm}$ in SIDIS (making use of 160 GeV μ^+ beam and transversely polarized proton target) for positive and negative hadrons. In case of the Sivers asymmetry the values were found to be positive for positive hadrons and compatible with zero within the uncertainties for negative hadrons in the given x range and with $z > 0.2$. As for the Kotzinian-Mulders asymmetry, the values are positive and negative with the predominance of positive ones for both positive and negative hadrons under the same conditions.

From the measured asymmetries the first transverse moments of Sivers and $g_{1T}^{\perp}$ PDFs were extracted for u_V and d_V quarks. Obtained values are model independent, since the weighted asymmetries were used to do the extractions. As in all previous extractions of these moments the $f_{1T}^{\perp(1)d_V}$ ($g_{1T}^{\perp(1)d_V}$) for the d quark are rather poorly determined and strongly dependent on the assumption of the negligible sea quarks contribution mentioned earlier. To overcome this problem more asymmetry data for a transversely polarized deuteron (neutron) target is needed.

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