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ESTIMATION OF THE SENSITIVITY TO Δm_s FROM COMBINATION OF VARIOUS B_s^0 DECAY CHANNELS IN CDF RUN I

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1 Introduction

We estimate the CDF sensitivity to measure the $B_s^o \bar{B}_s^o$ oscillation frequency with combination of results from different decay modes. The purpose of this study is to evaluate the expected Δm_s reach using the Run I data samples.

In the Standard Model $B_q^o \bar{B}_q^o$ oscillation, where q indicates d or s, is a direct consequence of second-order weak transitions between quarks through box diagrams (see Fig.1). The mass difference of two B meson eigenstates, Δm_q, determines the frequency of oscillation. The mass difference depends on the complex elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, on the top mass, and on the poorly known strong interaction parameters. Theoretical uncertainties in the determination of the CKM matrix elements are much reduced by considering the ratio:

$$\frac{\Delta m_s}{\Delta m_d} = \frac{(m_{B_s} \eta_{QCD}^{B_s} B_{B_s} f_{B_s}^2)}{(m_{B_d} \eta_{QCD}^{B_d} B_{B_d} f_{B_d}^2)} \frac{|V_{ts}|^2}{|V_{td}|^2}, \tag{1}$$

where m_{B_q} are the meson masses; B_{B_q} are the B meson bag parameters; f_{B_q} are weak B meson decay constants and $\eta_{QCD}^{B_q}$ are QCD corrections of order unity. Thus, the measurement of both Δm_d and Δm_s leads to determination of the ratio between the CKM matrix elements and will serve as a sensitive test of the Standard Model.

The time-dependent $B_d^o \bar{B}_d^o$ mixing was well measured at CDF by using low-p_t electron-muon [1] or dimuon [2] events collected in Run I. Δm_d was also extracted from the inclusive lepton data samples [3, 4]. The CDF average on the value of Δm_d is [5]:

$$\Delta m_d = (0.461 \pm 0.039)\, ps^{-1}. \tag{2}$$

More complicated is the situation with Δm_s measurement and no significant B_s^o oscillations have been seen so far. The lower limit of $\Delta m_s > 5.8\ ps^{-1}$ was obtained recently at CDF from the detailed study of ϕ-lepton correlations in semileptonic B_s^o decays collected with the use of Run I dilepton triggers [6]. Also, the upper limit

$\Delta m_s < 94\ ps^{-1}$ was obtained from the study of $D_s^- l^+$ correlations in the decay $B_s^o \to D_s l \nu X$, where various D_s decay modes are considered [7, 8].

For the Δm_s reach improvement we propose to combine the results expected from the different B_s^o decay modes in the Run I data. Various channels, already investigated by the CDF collaboration or not yet, are considered for the mixing analysis.

2 Method

For estimations we used the Amplitude fit approach [9], which allows an easy combination of mixing results originating from various analyses and experiments. In this method the B_s^o osillation amplitude A is measured at each fixed value of Δm_s, with the use of a maximum likelihood fit based on the functions:

$$\Gamma\frac{e^{-\Gamma t}}{2}(1 \pm \mathbf{A}cos(\Delta m_s t)), \qquad (3)$$

where the minus sign at the amplitude corresponds to the probability of observing mixed events, while the plus sign describes unmixed events. To a very good approximation, the statistical uncertainty on A is Gaussian and equals to [10]:

$$\frac{1}{\sqrt{\frac{N}{2}}f_s(1-2\eta)D(\Delta m_s, \sigma_l, \sigma_p)}, \qquad (4)$$

where N and f_s are the number of candidates and the fraction of the signal in the selected sample, η is the mistag probability and $D(\Delta m_s, \sigma_l, \sigma_p)$ is the damping factor due to the lifetime resolution. For the lifetime resolution we use the following parametrization:

$$\sigma(c\tau) = \sqrt{\sigma_l^2 + (t\sigma_p)^2}, \qquad (5)$$

where σ_l is the decay length resolution and σ_p the error in B_s^o momentum reconstruction. The damping factor can be written as:

$$D(\Delta m_s, \sigma_l, \sigma_p) = exp(-\frac{\sigma_l^2 \Delta m_s^2}{2})r(\sigma_p, \Delta m_s). \qquad (6)$$

The first term in this expression is due to the error in the decay length reconstruction and the second term comes from the boost resolution. According to the calculations in Ref.[9]:

$$r(\sigma_p, \Delta m_s) \approx \sqrt{\pi} Y exp(Y^2) ERFC(Y), \qquad (7)$$

with $Y = \frac{1}{\sqrt{2}}\frac{\Gamma}{\sigma_p \Delta m_s}$ and $ERFC(Y) = \frac{2}{\sqrt{\pi}}\int_Y^{\infty} e^{-t^2}dt$. It is clear that η, σ_l and σ_p are critical parameters for the mixing analysis.

Since the expected shape of the amplitude $\mathbf{A}(\Delta m_s)$ has a normalized Breit-Wigner form, one expects A=1 at $\Delta m_s = \Delta m_s^{true}$ and A=0 if Δm_s is far from its true value. The procedure of Δm_s search becomes a measurement of the $\mathbf{A}(\Delta m_s)$ amplitude and its Gaussian error $\sigma_{\mathbf{A}}(\Delta m_s)$ at each Δm_s. A value of Δm_s can be excluded at the 95% confidence level (C.L.) if $(\mathbf{A}+1.645\sigma_{\mathbf{A}}) \leq 1$. The lower limit on Δm_s is defined as the highest value below which all values of Δm_s are excluded. If Δm_s^{true} is very large (i.e. A=0), all values of Δm_s such that $1.645\sigma_{\mathbf{A}}(\Delta m_s) < 1$ are expected to be excluded at 95% C.L. Because of the proper time resolution, the quantity $\sigma_{\mathbf{A}}(\Delta m_s)$ is an increasing function of Δm_s and therefore one can exclude Δm_s values up to Δm_s^{sens}, where Δm_s^{sens}, called the sensitivity of the analysis, is defined by $1.645\sigma_{\mathbf{A}}(\Delta m_s^{sens})=1$.

Different measurements of A performed at a given value of Δm_s can be easily averaged. For n independent measurements the average amplitude is [9]:

$$\bar{A} = (\frac{A_1}{\sigma(A)_1^2} + \frac{A_2}{\sigma(A)_2^2} + ... + \frac{A_n}{\sigma(A)_n^2})\sigma(\bar{A})^2, \qquad (8)$$

with the total uncertainty:

$$\sigma(\bar{A}) = (\sigma(A)_1^{-2} + \sigma(A)_2^{-2} + ... + \sigma(A)_n^{-2})^{-1/2}. \qquad (9)$$

3 Estimation of the sensitivity to Δm_s

For our estimation we considered various B_s^o decay modes, already investigated at CDF or not yet, in the dilepton and inclusive lepton trigger samples.

3.1 Combination of already investigated channels

The starting point for our estimations is the already performed search for $B_s^o\bar{B}_s^o$ oscillations in the semileptonic $B_s^o \to \phi X l\nu$ decay with the use of dilepton events [6]. As candidate for use in a mixing study we also considered the Run I $\bar{B}_s^o$ lifetime measurement from $D_s^+ l^-$ correlations in the inclusive lepton trigger sample [7]. In this analysis D_s^+ mesons are reconstructed through the decay modes:

$$D_s^+ \to \phi\pi^+, \tag{10}$$

$$D_s^+ \to \bar{K}^{*o} K^+, \tag{11}$$

$$D_s^+ \to \bar{K}_s^o K^+. \tag{12}$$

Later these investigations were updated in the low mass dilepton sample for the $B_s^o \to D_s^- \mu^+ \nu X$ decay [8], where

$$D_s^- \to \phi\mu^-\nu. \tag{13}$$

Since events from (13) are not included in the study of ϕ-lepton correlations in Ref.[6], this channel will also contribute to the combined Δm_s reach.

The parameters of these channels used for our estimations, the number of events in the B_s^o sample N, the purity of the B_s^o sample f_s, the mistag probability η, the resolutions σ_l and σ_p, are presented in Table 1. The mistag probability $\eta = 0.4$ is expected in the inclusive lepton sample by applying a Same Side Tagging (SST) technique. This assumption is based on the results of Ref.[3], where the tagging

dilution of D=0.18 ($D = 1 - 2\eta$) was obtained for the B^o mesons with the use of an SST method.

The results of our estimations for the above-considered channels and the combined result are shown in Fig.2. The smooth curve in this figure shows the 95% confidence level contour around the expectation for no oscillations, and the **A**=1 line is the peak position for oscillations at each value of Δm_s.

As a test of our estimation method, we used the semileptonic $B_s^o \to \phi X l\nu$ decay channel in the dilepton sample. Our estimation gives the Δm_s search sensitivity of 5.1 ps^{-1} at 95% confidence level (see Fig.2, a). This result is in reasonable agreement with the lower limit $\Delta m_s > 5.8\ ps^{-1}$ obtained in Ref.[6].

Combination of results from different channels gives the sensitivity to the mixing parameter Δm_s up to 5.6 ps^{-1} (Fig.2, f).

3.2 Consideration of additional channels in inclusive lepton sample

Trying to find the possibility for further Δm_s improvement we considered additional decay channels contributing to the combined mixing analysis. For the inclusive lepton sample these additional channels are the D_s^+ decay modes

$$D_s^+ \to \phi\pi^+\pi^+\pi^-, \tag{14}$$

$$D_s^+ \to K^+\pi^+\pi^-, \tag{15}$$

$$D_s^+ \to f_o(980)\pi^+. \tag{16}$$

The advantage of these channels is the similarity to the decay modes already investigated in references [7, 8].

Assuming the same reconstruction efficiency for decay channels (14) and (10) in the inclusive lepton sample we estimated the expected event yield for channel (14):

$$N_{D_s^+\to\phi\pi^+\pi^+\pi^-} = N_{D_s^+\to\phi\pi^+} \frac{Br(D_s^+ \to \phi\pi^+\pi^+\pi^-)}{Br(D_s^+ \to \phi\pi^+)}. \quad (17)$$

Using the branching ratios from the Review of Particle Physics [11] and the measured number of events $N_{D_s^+\to\phi\pi^+}$= 395 from the Ref.[7] we obtained $N_{D_s^+\to\phi\pi^+\pi^+\pi^-}$= 198. The expected event yield for channels (15) and (16) are obtained in the similar way. The purity of the B_s^o sample, the mistag probability, the resolutions σ_l and σ_p are the same as in Ref.[7] (see Table 1).

Averaging all channels considered in the inclusive lepton sample leads to the Δm_s^{sens}=4.2 ps^{-1} (see Fig.3).

For the further Δm_s reach improvement we also considered full inclusive lepton sample from Ref.[4]. However the obtained sensitivity (see details in Appendix A) is less than what is achieved above from the combination of decay channels (10)-(12) and (14)-(16) in the inclusive lepton sample enriched with B_s mesons [7].

Channel	*Data sample*	*N*	f_s	η	σ_l [μm]	σ_p	*Ref.*
$B_s^o \to \phi X l \nu$	high mass dilepton	3132	0.21	0.25	60	0.14	[6]
$D_s^+ \to \phi\pi^+$	inclusive lepton	395	0.64	0.40	70	0.12	[7]
$D_s^+ \to \bar{K}^{*o}K^+$	inclusive lepton	277	0.65	0.40	70	0.12	[7]
	high mass dilepton	128	0.61	0.25	60	0.14	–
$D_s^+ \to \bar{K}_s^o K^+$	inclusive lepton	59	0.69	0.40	70	0.12	[7]
	high mass dilepton	30	0.61	0.25	60	0.14	–
$D_s^- \to \phi\mu^-\nu$	low mass dilepton	610	0.34	0.40	70	0.12	[8]
$D_s^+ \to K^+\pi^+\pi^-$	inclusive lepton	110	0.65	0.40	70	0.12	–
	high mass dilepton	51	0.61	0.25	60	0.14	–
$D_s^+ \to f_o(980)\pi^+$	inclusive lepton	132	0.64	0.40	70	0.12	–
	high mass dilepton	61	0.61	0.25	60	0.14	–
$D_s^+ \to \phi\pi^+\pi^+\pi^-$	inclusive lepton	198	0.64	0.40	70	0.12	–

Table 1: Parameters of decay channels considered for the estimations of the Δm_s search sensitivity.

3.3 Consideration of additional channels in high mass dilepton sample

Since the yield of $D_s l$ events is greatly reduced by the effective tagging efficiency, looking for its correlation in dilepton data might be useful. The second lepton in these events will serve as a flavor tag at production of B_s^o mesons providing lower mistag probability. Applying the branching ratio from [11]:

$$\frac{Br(D_s^\pm \to \phi\pi^\pm)}{Br(D_s^\pm \to \phi X)} \approx 0.17 \quad (18)$$

and using reference [6] we evaluated the yield of $\phi\pi$ events in the high mass dilepton sample. Exploiting this knowledge we estimated the expected yield of events from decay channels (11), (12), (15) and (16) in this sample of data. The parameters for these channels used for our estimations are listed in Table 1. The combined result for all channels considered in the high mass dilepton trigger sample is shown in Fig.4. The sensitivity up to 5.5 ps^{-1} is obtained at 95% C.L.

3.4 Combined results

Averaging results from all decay channels considered in the inclusive lepton and high or low mass dilepton samples we have estimated the Δm_s search sensitivity as 5.7 ps^{-1} at 95% C.L. (see Fig.5). We can improve this result by considering different ways of flavor tagging in the inclusive lepton sample. Application of the Jet charge and Soft lepton tagging methods with lower mistag probability of about η=0.3 [4] leads to the Δm_s^{sens}=6.5 ps^{-1} at 95% C.L. (see Fig.6).

4 Conclusion

The sensitivity to the Δm_s mixing parameter has been estimated with the combination of the results from various B_s^o decay channels in CDF Run I. We considered various channels, already investigated by the CDF collaboration or not yet, in the dilepton and single lepton trigger samples. The combination of the results expected from all B_s^o decay channels discussed leads to the Δm_s^{sens}=6.5 ps^{-1} at 95% C.L. The comparison of the Δm_s search sensitivity in CDF Run I with the LEP results [5] are listed in Table 2.

Experiment	*Lower limit* ps^{-1}	*Sensitivity* ps^{-1}	*Ref.*
ALEPH combined	10.4	11.7	[5]
DELPHI combined	8.4	8.1	[5]
OPAL	6.7	4.8	[5]
CDF Run I, combined	-	6.5	this note

Table 2: Lower limits for Δm_s and sensitivities of various B_s mixing analyses at 95% C.L.

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Appendix A

We have estimated the CDF sensitivity to Δm_s for the full inclusive lepton data sample selected as described in ref.[4]. This sample is not optimized for measuring B_s oscillations and the fraction of B_s mesons is less than 11%. Most of the selected events (90%) are tagged with the use of the Jet Charge (JC) tagging method with rather high mistag probability.

We were surprised with low decay length resolution of about σ_l=1.1 mm obtained from the $L_{xy}^{meas} - L_{xy}^{true}$ distributions in Ref.[4]. For our estimations we have used more optimistic value $\sigma_l = 150\ \mu m$ (the FWHM/2.36 from the above mentioned distributions in Ref.[4]). Error in the B_s momentum reconstruction σ_p=0.18 is derived from the K-factor distribution. This value is bigger than 0.12 which we have used for the decay channels considered in the inclusive lepton sample (see Table 1). The parameters of the full inclusive lepton sample from Ref.[4] used for the sensitivity estimations are presented in Table 3.

The result of our estimation is shown in Fig.7. The Δm_s search sensitivity up to 2.6 ps^{-1} is obtained.

Trigger	*Tagging method*	N	f_s	η	σ_l [μm]	σ_p
e	SLT	4482	0.11	0.27	150	0.18
e	JC	39692	0.11	0.43	150	0.18
μ	SLT	4110	0.11	0.28	150	0.18
μ	JC	40437	0.11	0.42	150	0.18

Table 3: Parameters used for the estimation of the sensitivity to Δm_s in the inclusive lepton sample from Ref.[4].

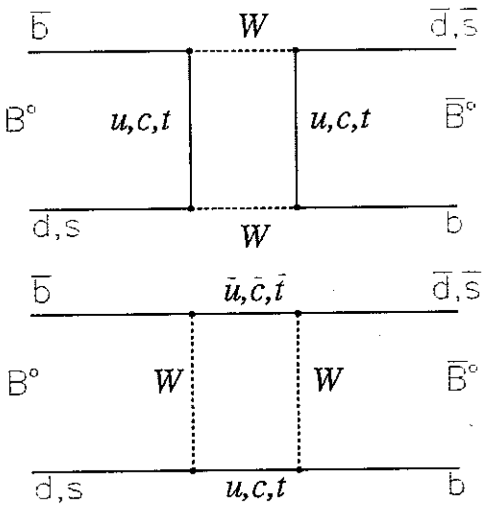

Figure 1: Box diagrams describing $B^o\bar{B}^o$ mixing.

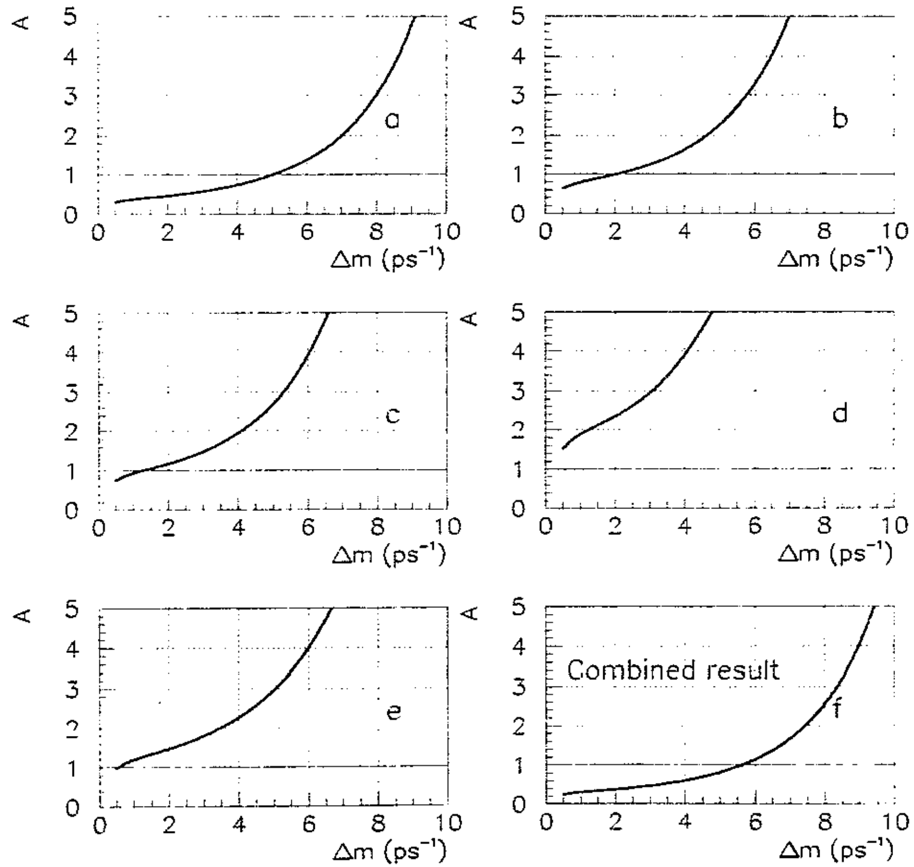

Figure 2: Estimation of the sensitivity to the Δm_s: a) from the study of ϕ-l correlations in the $B_s^o \to \phi l \nu X$ decay in the high mass dilepton sample [6], b) from the $D_s^+ \to \phi\pi^+$ channel in the $\bar{B}_s^o \to D_s^+ l^- \nu X$ decay in the inclusive lepton sample [7], c) from the $D_s^+ \to \bar{K}^{*o}K^+$ [7] and d) $D_s^+ \to \bar{K}_s^o K^+$ channels in the same data sample [7], e) from the $D_s^- \to \phi\mu^-\nu$ channel in the $B_s^o \to D_s^-\mu^+\nu X$ decay in the low mass dilepton sample [8], f) from the combination of all above channels.

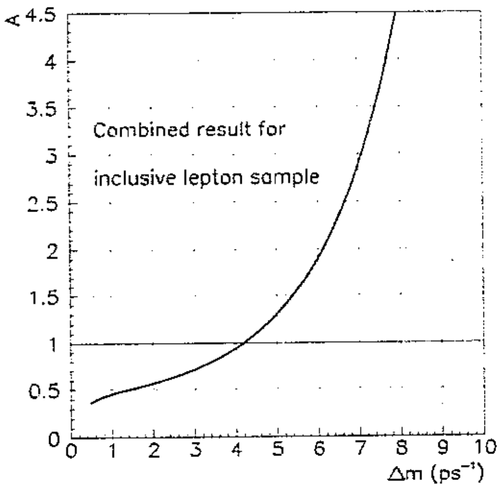

Figure 3: The combined result for all channels considered in the inclusive lepton sample.

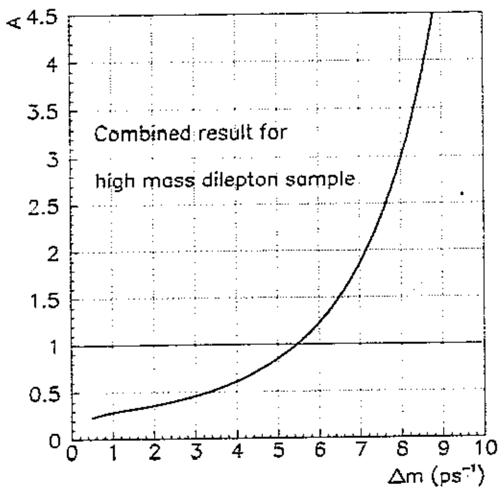

Figure 4: The combined result for all channels considered in the high mass dilepton sample.

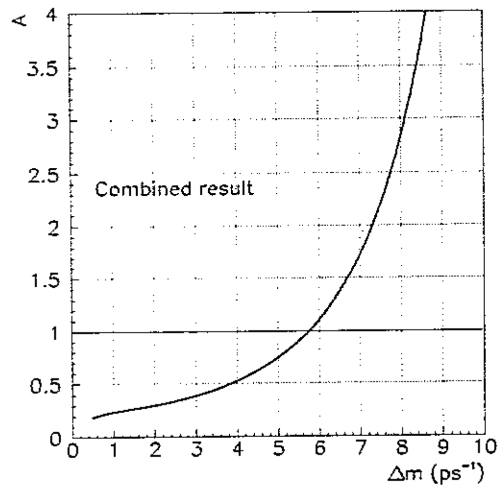

Figure 5: The combined result for all channels considered in the inclusive and high or low mass dilepton samples.

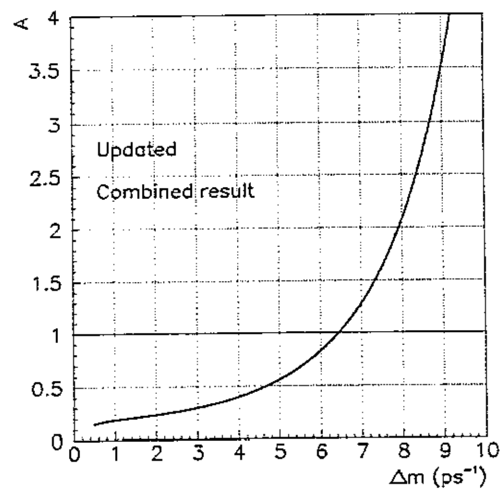

Figure 6: The updated combined result assuming the mistag probability η=0.3 for the inclusive lepton sample.

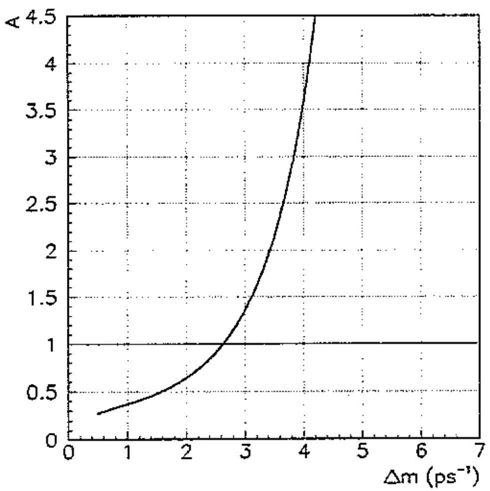

Figure 7: The sensitivity estimation for the full inclusive lepton sample from Ref.[4].

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