\[ B_s^0 \rightarrow D_s^- a_1^+(D_s^- \rightarrow \phi \pi^-, \ D_s^- \rightarrow K^{*0}K^-) \] decay channel in the ATLAS \( B_s^0 \)-mixing studies

**Abstract**

It is shown, using a track-level simulation, that the use of the \( D_s^- \rightarrow K^{*0}K^- \) decay channel for \( D_s^- \) reconstruction, in addition with the previously studied \( D_s^- \rightarrow \phi \pi^- \) mode, enables two fold gain in the ATLAS \( B_s^0 \)-mixing signal statistics through \( B_s^0 \rightarrow D_s^- a_1 \ B_s^0 \)-decay channel. A new modification of the amplitude fit method is suggested for the \( x_s \) determination. Some general aspects of the \( B_s^0 \)-mixing phenomenon is illustrated by pictures of Casimir Malevich, Maurits Cornelis Escher and Salvador Dali.

1 Introduction

The main features of the \( B_s \)-mixing studies were explained in previous notes [1, 2] (see also references cited therein), so we don’t need to repeat them here. Instead we will try to give arguments that \( B_s \)-mixing phenomenon is indeed worthy to be studied.

The famous Russian painter Casimir Malevich said a long time ago: ”The object in itself is meaningless ... the ideas of the conscious mind are worthless”. We would like to choose his great painting ”The black square”, which is reproduced below, as a starting point of our introduction.

![Black Square](image)

But from this starting point it is possible to go to the very different directions depending from one’s imagination. So let us imagine the following picture behind the black square [3]:

”A cat is penned up in a steel chamber, along with the following diabolical device: in a Geiger counter there is a tiny bit of radioactive substance, that perhaps in the course

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of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left the entire system to itself for one hour, one would say that the cat still lives if meanwhile no atom has decayed. The state vector $|\Psi>\rangle$ of the entire system would express this by having in it the living and the dead cat mixed or smeared out in equal parts."

But this is of course nonsense, at least from cat’s point of view!

We have reminded Schrödinger’s cat old story here in order to give an impression that although we all became familiar with particle mixing, because the superposition principle lies on a very background of quantum mechanics, this phenomenon is by no means obvious or trivial property of reality.

But what is strange and queer at the macrophysics level can still appear as the most common thing at the microphysics level. It seems that even our existence is based on particle mixing as will be explained below.

One of very important characteristics of elementary particle is its mass. We can get some insight about its origin from the following simple trick. The propagator of a massive fermion can be represented in such a way

$$\frac{1}{\hat{p} - m} = \frac{1}{\hat{p}} + \frac{1}{m^2 \hat{p}} + \frac{1}{m^3 \hat{p}} + \cdots,$$

or graphically

\[
\begin{align*}
\text{m} & \quad + \quad \text{m} \quad + \quad \text{m} \quad + \quad \cdots
\end{align*}
\]

where a single line represents the propagator of a massless particle. So things look like as if the massless particle is propagating through some medium and the mass emerges as a result of friction or interaction with this environment. But what is the medium the particle interacts with? A (massless) fermionic particle can have the following interaction with some scalar field $L_{\text{int}} = g\bar{\psi}\psi \varphi$:

\[
\begin{align*}
g & \quad - \quad - \quad \varphi
\end{align*}
\]

If now the self interactions of this scalar field are such that it doesn’t disappear in a vacuum state and develops a nonzero vacuum expectation value $< \varphi >$, when it is convenient to expand $\varphi = < \varphi > + \varphi'$, where $\varphi'$ corresponds to the physical scalar particles (excitations over the vacuum) and $< \varphi >$ just gives the medium (the vacuum) where all of us are living. Now because of this decomposition of $\varphi$ the fermion-scalar interaction splits into two parts:

\[
\begin{align*}
g & \quad - \quad - \quad \varphi \quad + \quad g < \varphi > \quad + \quad g & \quad - \quad - \quad \varphi'
\end{align*}
\]

The second diagram represents an emission of the real scalar quantum and the first one generates the fermion mass $m = g < \varphi >$. 

2
But if, for example $d$-quark can emit a scalar particle without changing its flavour, why can’t it do this with changing the flavour? We know that the flavour is not always conserved, so the following interaction is not excluded:

$$
\begin{align*}
    g & \quad \varphi \quad g < \varphi > \quad + \quad g \quad \varphi' \\
    d & \quad \quad s \\
    s & \quad \quad d \\
\end{align*}
$$

But now the first term gives $d-s$ mixing! As a result our initial $d$ and $s$ fields are no longer mass eigenstates (the states with definite mass), instead their time development in the rest frame is described by the matrix Schrödinger’s equation ($\hbar = 1$):

$$
\begin{align*}
    i \frac{\partial}{\partial t} \begin{pmatrix} d \\ s \end{pmatrix} &= \begin{pmatrix} m_d & m_{ds} \\ m_{ds} & m_s \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} \\
    \begin{pmatrix} \cos \theta_c & \sin \theta_c \\ -\sin \theta_c & \cos \theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} &= \begin{pmatrix} \bar{m}_d & 0 \\ 0 & \bar{m}_s \end{pmatrix} \begin{pmatrix} \cos \theta_c & -\sin \theta_c \\ \sin \theta_c & \cos \theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix},
\end{align*}
$$

where $\tan 2 \theta_c = \frac{2m_{ds}}{m_d - m_s}$ and $\bar{m}_d, \bar{m}_s$ mass eigenvalues are defined from the equations $m_d = \bar{m}_d \cos^2 \theta_c + \bar{m}_s \sin^2 \theta_c$, $m_s = \bar{m}_d \sin^2 \theta_c + \bar{m}_s \cos^2 \theta_c$. It is obvious that the corresponding eigenvectors (the physical $d$ and $s$ quarks) are

$$
\begin{align*}
    \begin{pmatrix} \bar{d} \\ \bar{s} \end{pmatrix} &= \begin{pmatrix} \cos \theta_c & -\sin \theta_c \\ \sin \theta_c & \cos \theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} \rightarrow \bar{d} = \cos \theta_c \ d - \sin \theta_c \ s \\
    \bar{s} &= \sin \theta_c \ d + \cos \theta_c \ s
\end{align*}
$$

This particle mixing has one important observable consequence. If initially the weak transitions were possible only within the $(u,d)$ or $(c,s)$ pairs, now the intergeneration transitions $\bar{u} \leftrightarrow \bar{s}$ and $\bar{c} \leftrightarrow \bar{d}$ are also possible because, for example, the physical $s$-quark contains both $d$ and $s$ bare fields $\bar{s} = \sin \theta_c d + \cos \theta_c s$. Thus $\bar{u} \rightarrow \bar{s}$ transition is proportional to $\sin \theta_c$ - sine of the so called Cabibo angle.

But we have three quark-lepton generations. So after the mixing the weak transitions are possible between any up and any down quarks. The amplitudes of these weak transitions are convenient to express as a $3 \times 3$ unitary matrix. This Kobayashi-Maskawa matrix is a generalization of the Cabibo angle and reveals a remarkable hierarchical structure.

$$
\begin{align*}
    \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} & \approx \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 & \lambda & A \lambda^3 (\rho - i \eta) \\ -\lambda & 1 - \frac{1}{2} \lambda^2 & A \lambda^2 \\ A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1 \end{pmatrix}.
\end{align*}
$$

(1)

Here $\lambda = \sin \theta_c \approx 0.22$ is a small quantity. So the intergeneration weak transitions are suppressed and this suppression is more strong for not neighboring generations.

If $\eta \neq 0$, the Kobayashi-Maskawa matrix is complex and violates $CP$. It is commonly believed today that this $CP$-violation is an important ingredient in baryon-antibaryon asymmetry generation in the universe and so the source of our very existence.

So far we were talking about particle mixing at quark level. But quarks are confined into hadrons and we can study quark-mixing only indirectly via hadron-mixing. $B$-meson system is very promising in this respect: because of a large mass of the $b$-quark we
can enjoy an asymptotic freedom advantage of QCD and calculate strong interaction corrections, unlike, for example, $K$-meson system.

In the Standard Model the $B_d - \bar{B}_d$ mixing originates from the following diagram (and from the second one there intermediate up-quark and $W$ lines are interchanged)

$u_i$ stands for any up quark. So

$$B_d - \text{mixing} \sim \sum_{i,j} \lambda_i \lambda_j I(m_i, m_j)$$

where $\lambda_i = V_{ub} V_{ud}^*$ and $I(m_i, m_j)$ represents the loop integral. This integral diverges quadratically. But this divergence is harmless because the unitarity of the Kobayashi-Maskawa matrix ensures its cancellation in the sum: the unitarity means $\sum \lambda_i = 0$, therefore

$$\sum_{i,j} \lambda_i \lambda_j I(m_i, m_j) = \sum_{i,j} \lambda_i \lambda_j [I(m_i, m_j) - I(0, m_j) - I(m_i, 0) + I(0, 0)]$$

and these subtractions greatly improve the convergence. For example, in case of $t$-quark contribution, these subtractions lead to the replacement

$$\frac{1}{(k^2 - m_t^2)^2} \rightarrow \frac{1}{(k^2 - m_t^2)^2} - \frac{2}{k^2(k^2 - m_t^2)} + \frac{1}{k^2k^2} = \frac{m_t^4}{k^2k^2(k^2 - m_t^2)}.$$

From this expression it is also clear that in fact just $t$-quark contribution is dominant for $B$-mixing, because of its extraordinary large mass.

When ARGUS made his measurement of the $B_d$-mixing [3], nobody thought that $t$-quark is so massive. So the result of this measurement appeared as a big surprise. We can even say that $t$-quark was discovered by ARGUS, because the large $B_d$-mixing, observed by ARGUS, is very difficult to explain without the existence of the $t$-quark with mass $> 100 GeV$.

We can infer from the above given diagram that even larger mixing is expected in $B_s$-system:

$$\frac{B_s - \text{mixing}}{B_d - \text{mixing}} \sim \frac{V_{ts}}{V_{td}}^2 \sim \lambda^2 \left[(1 - \rho)^2 + \eta^2\right] \sim \frac{1}{\lambda^2} \sim 25$$

We see also that the relative magnitude of $B_s$ and $B_d$ mixings measures $(1 - \rho)^2 + \eta^2$ - one side of the notorious unitarity triangle [4]. It is worthwhile to mention that this ratio is, to a great extent, free from hadronic uncertainties, which arise when we ask how quark and antiquark from the above given $B$-mixing diagram really form $B$-meson.
To summarize, the $B_s$-mixing studies are interesting, because they reveal a very fundamental underlying phenomenon - the generation of particle masses and mixing angles via the Higgs mechanism, the least understood thing in the Standard Model. Because of heaviness of the $b$-quark and asymptotic freedom of QCD, the theory gives very definite predictions about expected $B_s$-mixing, hampered only from uncertainties due to our inability to solve QCD in the confinement region. But these uncertainties are also, to a certain extent, under control [7]. The theoretical predictions involve such a fundamental property as the unitarity of the Kobayashi-Maskawa matrix (the existence of only three generations). Any deviation between the theory and experiment can lead to significant change of our present day picture of the elementary particle world (recall the $B_d$-mixing story). The forthcoming ATLAS experiment sensitivity to the $B_s$-mixing covers the Standard Model prediction range [8]. So it will either give one more confirmation of the theory or will open a window into a physics beyond the Standard Model.

2 Black Square view on the $B_s$-mixing

We hope the above given considerations convinced the reader that the Black Square can hide a very reach content behind it. For example, reflecting about the Schrödinger’s cat we can end with the following picture of $B_d$-oscillations (experimentally confirmed by ARGUS [6])

![escher1.jpg](escher1.jpg)
As we have already mentioned, more rapid oscillations are expected in the $B_s$ system. So if man eagerly stares on the Black Square he will at last distinguish the picture of $B_s$-mixing:

The most impressive people can remark even a symbolization of the $CP$-violation on this illustration: the nature for some reason makes an absolute difference between particle and antiparticle, not just the conventional difference between black and white.

3 $D_s^- \rightarrow K^{*0}K^-$ decay channel for $D_s$ reconstruction

To observe the $B_s^0$-mixing in a real experiment like ATLAS and extract the corresponding $x_s$ parameter, which characterizes the $B_s - \bar{B}_s$ oscillation frequency, you need to reconstruct $B_s$ meson and determine its decay vertex with great precision. Two of the $B_s$ decay channels were considered for this goal up to now: $B_s^0 \rightarrow D_s^- \pi^+$ [1] and $B_s^0 \rightarrow D_s^- a_1^+$ [2]. For the second channel $D_s^- \rightarrow \phi \pi^-$, $\phi \rightarrow K^+K^-$ decay mode was used for the $D_s^-$ reconstruction. It was mentioned in [1, 2] that other decay channels of $D_s^-$ can be also used to increase signal statistics. In the present note we consider $D_s^- \rightarrow K^{*0}K^-$, $K^{*0} \rightarrow K^+\pi^-$ decay mode as one of the possibilities:
As it is clear from the Table 1 below, this decay channel is quite promising if compared to the previously used $D_s^- \to \phi\pi^-$. 

**Table 1.**
Branching ratios and signal statistics for $B_s^0 \to D_s^- a_1^+(1260)$.

| Parameter | Value | Comment |
|-----------|-------|---------|
| $L$ [$cm^{-2}s^{-1}$] | $10^{33}$ | |
| $t$ [s] | $10^7$ | |
| $\sigma(\bar{b}b \to \mu X)$ [$\mu b$] | 2.3 | $p_{\mu}^t > 6$ GeV/c $|\eta_{\mu}| < 2.2$ |
| $N(b \to \mu X)$ | $2.3 \times 10^{10}$ | |
| $Br(b \to B_s^0)$ | 0.112 | |
| $Br(B_s^0 \to D_s^- a_1^+, \rho^0
ds \to a_1^+,$ $\pi^+\pi^-$) | 0.006 | |
| $Br(a_1^+ \to \rho^0\pi^+)$ | $\sim 0.5$ | |
| $Br(\rho^0 \to \pi^-\pi^+)$ | $\sim 1$ | |
| $Br(D_s^- \to \phi\pi^-)$ | 0.036 | |
| $Br(\phi \to K^+K^-)$ | 0.491 | |
| $Br(D_s^* \to K^{*0}K^-)$ | 0.034 | |
| $Br(K^{*0} \to K^+\pi^-)$ | $\sim 0.65$ | |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$ | 136600 | $D_s^- \to \phi\pi^-$ |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$ | 170800 | $D_s^- \to K^{*0}K^-$ |
Event generation and reconstruction procedures are similar to ones considered in \[2\]. All other general parameters, like impact parameter resolution for smearing and transverse momentum resolution, are also the same as in \[2\] and can be found there.

Contrary to the $D_s^- \to \phi\pi^-$ case, where $D_s^-$ peak was clearly seen in the invariant mass distribution of the three properly charged particles, assuming that two of them are $K$-mesons and one is pion, now $D_s^-$ peak is not seen (Fig. 1), perhaps because $K^{*0}$ is too wide as compared to $\phi$. Thus the combinatorial background from the signal events alone is already able to hide the $D_s^-$ and the reader is left with the sentence [9] “if you should see the word "buffalo" written on a cage containing an elephant, don’t believe your eyes”. Although when $D_s^-$ meson is reconstructed from its true decay products the resulting invariant mass resolution, shown on Fig. 2, is almost the same as for the $D_s^- \to \phi\pi^-$ mode. The another picture on Fig. 2 shows $K^{*0}$, reconstructed from its true decay products.

The resolution in the $B_s$-decay proper time (Fig. 3a) $\sigma_\tau \approx 0.061\text{ps}$ is practically the same as for the $D_s^- \to \phi\pi^-$ mode. The corresponding $B_s$-decay length resolution in the transverse plane is $\approx 100\mu m$ and the relevant distribution is shown on Fig. 3b.

We expect that signal to background situation when using $D_s^- \to K^{*0}K^-$ mode will be similar to what was considered in \[2\]. Compare for example Fig. 4 from \[2\] and from this work, which describes a possible background from the $B^0_s \to D^- a_1^+$ decay when $D_s^-$ is reconstructed via $D_s^\to \phi\pi^-$ or $D_s^- \to K^{*0}K^-$ modes respectively.

The main reason which allowed a good signal to background separation in \[2\] was the fact that $D^-$ and $B^0_d$ masses are shifted from the $D_s^-$ and $B^0_s$ masses by about 100 $MeV$. But this equally applies to the $D_s^- \to K^{*0}K^-$ case also, because our cut on the $D_s^-$ invariant mass doesn’t change very much. The only problem which can arise is a large $K^{*0}$ width (as compared to the $\phi$-meson width) and therefore the cut on the invariant mass of $K^{*0}$ should be considerably loose. At present we are not aware of a background for which this circumstance will play a crucial role.

Acceptance and analysis cuts are summarized in Table 2. As it is known [10], a second level trigger is necessary to reduce an event rate, which is still too high after the first level trigger (the tag-muon). For the $B_s \to D_s^- \pi^+$, $D_s^- \to \phi\pi^-$ mode the problem was studied in [10] and it was shown that some loose cuts on the invariant masses of $\phi$ and $D_s$ candidates can be used for this purpose. The resulting trigger efficiency appeared to be [8] about 0.54. For the $B_s \to D_s^- a_1^+$, $D_s^- \to K^{*0}K^-$ channel, discussed in this note, the second level trigger should be specially investigated, of course. However we expect that the similar mass cuts on $D_s$ and $K^{*0}$ candidates will work in this case also and a 50% trigger efficiency should be a safe estimate.
Table 2.
Number of signal events from $B_s^0 \rightarrow D_s^- a_1^+$ (1260) channel expected in ATLAS after 1 year ($10^7 s$) of operation at $10^{33} cm^{-2} s^{-1}$.

| Parameter                                                                 | Value   | Comment          |
|---------------------------------------------------------------------------|---------|------------------|
| $N(K^+K^-\pi^+\pi^-\pi^+)$                                              | 136600  | $D_s^- \rightarrow \phi\pi^-$ |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$                                        | 170800  | $D_s^- \rightarrow K^{*0}K^-$ |
| **Cuts:**                                                                                     |
| $p_T > 1 GeV/c$                                                             |         |                  |
| $|\eta| < 2.5$                                                                |         |                  |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$                                        | 9015 (6.6%) | $D_s^- \rightarrow \phi\pi^-$ |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$                                        | 9910 (5.8%) | $D_s^- \rightarrow K^{*0}K^-$ |
| $\Delta \varphi_{\pi\pi} < 35^\circ$                                      |         |                  |
| $\Delta \theta_{\pi\pi} < 15^\circ$                                      |         |                  |
| $|M_{\pi\pi} - M_{\rho}| < 192 MeV/c^2$ (±3$\sigma$)                     |         |                  |
| $|M_{\pi\pi\pi} - M_{a_1^+}| < 300 MeV/c^2$                              |         |                  |
| $\Delta \varphi_{KK} < 10^\circ$                                         |         | $D_s^- \rightarrow \phi\pi^-$ |
| $\Delta \theta_{KK} < 10^\circ$                                          |         |                  |
| $|M_{KK} - M_{\phi}| < 20 MeV/c^2$                                         |         |                  |
| $|M_{KK\pi} - M_{D^-_s}| < 15 MeV/c^2$                                    |         |                  |
| $\Delta \varphi_{K\pi} < 20^\circ$                                       |         | $D_s^- \rightarrow K^{*0}K^-$ |
| $\Delta \theta_{K\pi} < 10^\circ$                                         |         |                  |
| $|M_{K\pi} - M_{K^{*0}}| < 80 MeV/c^2$                                    |         |                  |
| $|M_{K\pi\pi} - M_{D^-_s}| < 20 MeV/c^2$                                  |         |                  |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$                                        | 6830 (5.0%) | $D_s^- \rightarrow \phi\pi^-$ |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$                                        | 6830 (4.0%) | $D_s^- \rightarrow K^{*0}K^-$ |
| $D_s^- \text{ vertex fit } \chi^2 < 12.0$                                 |         |                  |
| $a_1^+ \text{ vertex fit } \chi^2 < 12.0$                                 |         |                  |
| $B_s^0 \text{ proper decay time } > 0.4 ps$                               |         |                  |
| $B_s^0 \text{ impact parameter } < 55 \mu m$                              |         |                  |
| $B_s^0 \text{ } p_T > 10.0 GeV/c$                                         |         |                  |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$ after cuts                              | 4100 (3.0%) | $D_s^- \rightarrow \phi\pi^-$ |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$ after cuts                              | 4780 (2.8%) | $D_s^- \rightarrow K^{*0}K^-$ |
| Lepton identification                                                     | 0.8     |                  |
| Hadron identification                                                     | (0.95)$^6$ |                  |
| Trigger efficiency                                                        | 0.5     |                  |
| Mass cut ±2$\sigma$                                                       | 0.95    |                  |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$ reconstructed                           | 1240 (0.9%) | $D_s^- \rightarrow \phi\pi^-$ |
| $N(K^+K^-\pi^+\pi^-\pi^+\pi^-)$ reconstructed                           | 1330 (0.8%) | $D_s^- \rightarrow K^{*0}K^-$ |
As we see, about 2570 reconstructed \( B_0^s \) mesons are expected for \( 10^4 pb^{-1} \) integrated luminosity from \( B_0^s \rightarrow D^- a_i^+ \) channel when both of \( D^- \rightarrow \phi \pi^- \) and \( D^- \rightarrow K^*0K^- \) modes are used for \( D^- \) reconstruction. To them we should add 3640 \( B_0^s \) mesons from \( B_0^s \rightarrow D^- \pi^+ \) channel [8]. So in total we expect 6210 reconstructed \( B_0^s \) mesons per \( 10^4 pb^{-1} \) integrated luminosity when all as yet considered decay modes are used.

### 4 Peak amplifier

To extract the oscillation frequency, from M.C. or experimental asymmetry distributions, the so called amplitude fit method is useful [11]. Here we describe some refinements of this method.

In the amplitude fit method an asymmetry distribution \( A(t) \) is fitted with the cosine function \( A_{fit} \cos(x_s t/\tau) \) in which \( x_s \) is fixed and \( A_{fit} \) is the only free parameter. Repeating the fit for different values of \( x_s \), we get \( A_{fit}(x_s) \) distribution. This distribution is peaked at \( x_s \) which corresponds to the true value of the oscillation frequency.

The peak position in the \( A_{fit}(x_s) \) distribution can be found with the help of the recently suggested "quantum" peak finding algorithm [12]. The idea of this algorithm is based on the property of small quantum balls to penetrate narrow enough obstacles. So if such a ball is placed on the edge of some potential wall it will find its way down to the potential wall bottom even if the potential wall is distorted by statistical fluctuations.

Let us introduce instead of continuous \( x_s \) some discrete parameter \( i \), say through \( N_i = A_{fit}(i/2) \). The transformation \( A_{fit}(x_s) \rightarrow u(x_s) \), which we call peak amplifier, is defined for selected discrete values of \( x_s \) as follows

\[
    u(i/2) \equiv u_i , \quad u_{i+1} = \frac{P_{i,i+1}}{P_{i+1,i}} u_i , \quad \sum u_i = 1 . \tag{2}
\]

And \( P_{i,i\pm1} \) transition probabilities are determined by the initial \( N_i \) spectrum [12]

\[
    P_{i,i\pm1} = A_i \sum_{k=1}^{2} \exp \left[ \frac{N_{i\pm1} - N_i}{\sigma_{i\pm1}^2 + \sigma_i^2} \right] , \tag{3}
\]

\( A_i \) normalization constant being defined from the \( P_{i,i-1} + P_{i,i+1} = 1 \) condition. \( \sigma_i \) is a standard deviation (error) of \( N_i \) as determined by the cosine fit.

If now we apply this peak amplifier to the data after the amplitude fit we get the probability distributions shown on Fig. 5 (for \( x_s = 30 \)) and on Fig. 6 (for \( x_s = 45 \)). As we see, the peak amplifier enables a clear determination of \( x_s \) from the amplitude fit spectrum.

### 5 \( x_s \) sensitivity range

To estimate the ATLAS sensitivity range for the \( x_s \) measurement, the analogous procedure was used as in [8].

Amplitude fit is applied to the asymmetry distribution generated by Monte-Carlo program. The input parameters of this program, such as signal to background ratio,
$B^0_s$ lifetime, proper-time resolution and dilution factors are the same as in [8], with the exception of the number of signal events, which was taken to be 62\,10.

The amplitude fit spectrum is further transformed using the peak amplifier transformation as described above. In the resulting $u(x_s)$ spectrum the mean value of $x_s$ and its standard deviation is calculated considering $u(x_s)$ as a probability density. The “experiment” is considered as successful if the measured $x_s$ value (mean value of $x_s$ according to the $u(x_s)$ distribution) is within two standard deviations from the true $x_s$-value defined in the Monte-Carlo program.

For each $x_s$ point 1000 such ”experiments” were generated and the fraction of the successful ”experiments” was calculated. The highest value of $x_s$, for which this fraction is above 95\%, is considered as a sensitivity limit for the ATLAS experiment. This limit was found to be about $x_s^{\text{max}} = 42.5$. This is almost the same number as found in [8]. In fact the peak amplifier method doesn’t give a significant increase for the sensitivity limit, but it allows a more accurate $x_s$ determination, as is indicated by Fig. 6, because the probability peak is much more narrow.

Fig. 7 shows the distribution of the $x_s$ values, found by the peak amplifier method, for 1000 ”experiments”, generated with the ”true” $x_s = 42.5$.

6 "Where is the beginning of the end that comes at the end of the beginning?"

So we are at the end of our investigation. Our main conclusions are:

- $D^- \rightarrow K^*0 K^-$ mode enables a two fold increase in the signal statistics for the $B^0_s \rightarrow D^- a_1$ decay channel.

- the ATLAS experiment can reach a sensitivity limit for $x_s$ as high as $x_s^{\text{max}} = 42.5$ with the certainty.

- $D^- \rightarrow K^*0 K^-$ mode can be used also for the $B_s \rightarrow D^\pi^-\pi^+$ channel. If the same increase in signal statistics is assumed, the total number of reconstructed $B_s$ events can reach $10^4$ per $10^4 pb^{-1}$ integrated luminosity. According to estimates from [8] this will mean a sensitivity limit for $x_s$ about 46.

We began our story with the Black Square. Here is one more Black Square image which illustrates the continues progress in the $B_s$-mixing studies.
This picture leads to a question about a meaning of the scientific progress, or even to a more general question \( \text{[13]} \) “What profit hath a man of all his labour which he taketh under the sun?”. We refrain to give any other comment about this things because \( \text{[14]} \) "Wo alle Worte zu wenig wären, dort ist jedes Wort zu viel”.

Nevertheless we don’t want to end with only black and white images of the \( B_s \)-mixing related stuff. With the very great imagination you can catch sight of the glorious full colour artist’s view on the particle mixing behind the Black Square (note the role of vertexing in emergence of this dream):
tigers.jpg here
Acknowledgments

The authors are grateful to Paula Eerola and Szymon Gadomski for valuable comments. These comments were used in the text.

Farewell

When we began this investigation our intention was to write a vivid and joyful story about $B_s$-mixing, some mixture of science and art. Only scientific framework appeared to us as too narrow to embrace the beauty of life, because [15] "All things are full of labour; man cannot utter it: the eye is not satisfied with seeing, nor the ear filled with hearing.”.

Unfortunately Sasha Bannikov suddenly died at the end of last year and we are forced to end this project without him.

Farewell Sasha! Let this article be a small thing that remains after you in this world as your memory.
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Figure 1: Invariant mass distributions of three charged particle combinations in signal events, assuming $2K + \pi$ (a) or $3\pi$ combination (b).
Figure 2: Invariant mass distributions of reconstructed $K^{*0}$ and $D_s^-$ events.
Figure 3: Proper time (a) and transverse radius (b) resolutions for the reconstructed $B_s^0$ decay vertex.
Figure 4: Six particle invariant mass distribution corresponding to the $B_s^0$ meson. Dashed line - expected upper limit for background from $B^0$ decay.
Figure 5: amplitude $A(x_s)$ and probability $u(x_s)$ for $x_s = 30$. 
Figure 6: amplitude $A(x_s)$ and probability $u(x_s)$ for $x_s = 45$. 
Figure 7: The distribution of the $x_s$ values, found by the peak amplifier method, for 1000 "experiments", generated with the $x_s = 42.5$. 

\[ N \]

\[ x_{s\;\text{found}} \quad x_s \]

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \]
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