The partial reconstruction of $B^0 \to \chi_{c1} K^0_S$, $B^0 \to \psi' K^0_S$ and $B^0 \to J/\psi K^{\star 0}$ decays at the HERA-B experiment

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Abstract: The possibility of partial reconstruction of additional $\mathcal{CP}$ channels at the HERA-B experiment is considered. The resulting error in $\sin 2\beta$ is estimated.

1 Introduction

The decays $B^0 \to J/\psi K^0_S$ and $B^0 \to \pi^+\pi^-$ determine the $\mathcal{CP}$ reach of the HERA-B experiment [1, 2]. Some more $\mathcal{CP}$ channels are automatically included into the main trigger. The use of these additional $\mathcal{CP}$ channels can effectively enhance the statistics coming from the main channels. Besides, if $\mathcal{CP}$ violation is observed in more than one channel, the reliability of the obtained result becomes larger. Among the additional $\mathcal{CP}$ channels are:

$$\begin{array}{lll} B^0 \to \chi_{c1} K^0_S \to (J/\psi\gamma) K^0_S & & (a) \\ B^0 \to \psi' K^0_S \to (J/\psi X^0) K^0_S & (X^0 \text{ is mainly } \pi^0\pi^0) & (b) \\ B^0 \to J/\psi K^{\star 0} \to J/\psi (K^0_S \pi^0) & & (c) \end{array}$$

The longitudinal polarization has been measured to dominate in the latter decay [3], thus resulting in a $\mathcal{CP}$ eigenstate. This mode is especially important, since the predicted $\mathcal{CP}$ parity of the final state is opposite in sign to that of $J/\psi K^0_S$ mode and possible systematic biases can be revealed. The neutral particles in the final state can not be detected with high efficiency. Another approach is to reconstruct these channels partially as it is described below.

2 Method

In a two-body decay the direction of mother particle and the momentum of one of the daughters determine the kinematics of the decay if masses of all particles are known. This fact is used to reconstruct the kinematics of the decays $B^0 \to J/\psi K^0_S X$, where X – undetected particle(s). The J/ψ and K^0_S are regarded as one daughter particle and undetected particle(s) are regarded as the other one. Measured values are the B^0 meson flight direction (known from the reconstruction of B^0 meson production and decay vertices) and the J/ψ and K^0_S momenta. The method of partial reconstruction is described in more detail in [4]. The found energy-momentum of X can be used

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to calculate the invariant masses of J/ψ X and K^0_S X. The peaks at χ_{c1} and ψ' masses in J/ψ X invariant mass distribution would be the signatures of **(a)** and **(b)** decays correspondingly. The peak at $K^{\star 0}$ mass in K^0_S X invariant mass distribution would be the signature of **(c)** decay.

The mass of X is set to zero, when the invariant mass of J/ψ X is calculated (the error in $m_{J/\psi X}$ due to substitution $m_{\pi^0\pi^0}$ by zero is negligible) and to m_{π^0} when the invariant mass of K^0_SX is calculated.

The decay kinematics is known with two-fold ambiguity (this fact is considered in [1] for the similar partial reconstruction of semileptonic B decays). The invariant masses are calculated for both solutions and their average is taken as a final value.

Simulation shows that the maximal value of θ (where θ is the angle between the B^0 meson flight direction and the $J/\psi\, K^0_S$ momentum): $\theta_{\max} \sim 5 \cdot 10^{-3}$, is comparable with the accuracy in θ due to finite vertex resolution: $\delta\theta \sim 3 \cdot 10^{-3}$. Therefore the measured value of θ is often outside the kinematically allowed region and the solutions exist only in about one half of cases.

3 Monte Carlo Simulation

For simulation we use the `PYTHIA 5.6` [5] event generator for $b\bar{b}$ events and `FRITIOF 7.0` [6] for minimum bias events. To reproduce HERA-*B* experimental conditions we generate 1 $b\bar{b}$ event with 4 Poisson distributed minimum bias events for every interaction of bunch of protons with target. J/ψ vertex is smeared with the nominal detector resolution [2] $\sigma_x = \sigma_y = 25\mu$m, $\sigma_z = 500\mu$m. The B production vertex is smeared with $\sigma_x = \sigma_y = \sigma_z = 10\mu$m.

Branching ratios of B decays to charmonium for signal and background processes are listed in Table 1. Only a few decay modes are measured experimentally (shown in **bold**) [7]. For

	J/ψ	ψ'	χ_{c1}	χ_{c2}
K^0	**0.94 (+)**	0.69 (+)	1.0 (+)	0.29 (−)
$K^{\star 0}$	**1.6 (−)**	1.18 (−)	1.7 (−)	0.49
$K^0\pi^0$	1.0	0.27	0.23	0.31
$K^+\pi^-$	**1.0**	0.27	0.23	0.31
$K^0\pi^0\pi^0$	1.2	0.33	0.29	0.37
$K^0\pi^+\pi^-$	1.2	0.33	0.29	0.37
$K^+\pi^-\pi^0$	1.2	0.33	0.29	0.37
anything	**8.0**	**3.4**	**4.0**	**2.5**

Table 1: *Branching ratios of* B^0 *decays to charmonium (in* 10^{-3}*). Measured values are shown in* **bold**. *The channels, which result in* $J/\psi K^0_S X$ *final states with positive* $\mathcal{CP}$ *parity are marked with* (+)*, with negative* − (−).

some channels isotopic relations can be used:

$$\begin{aligned}
\mathcal{B}(B^0 \to \chi_{c1} K^0) &= \mathcal{B}(B^+ \to \chi_{c1} K^+) \\
\mathcal{B}(B^0 \to \psi' K^0) &= \mathcal{B}(B^+ \to \psi' K^+) \\
\mathcal{B}(B^0 \to J/\psi K^0 \pi^0) &= \mathcal{B}(B^0 \to J/\psi K^+ \pi^-) \\
\mathcal{B}(B^0 \to J/\psi K \pi\pi) &= \mathcal{B}(B^+ \to J/\psi K^+ \pi^+ \pi^-)
\end{aligned} \quad .$$

In order to compare with $B^0 \to J/\psi K^0_S$ decay, the trigger and reconstruction efficiencies determined for this decay were used.

The J/ψ X mass peaks of $\chi_{c1}K^0_S$ and $\psi' K^0_S$ decay modes overlap (see Figure 1). However the final states are predicted to have the same $\mathcal{CP}$ parity and both channels can be combined for $\mathcal{CP}$ violation studies.

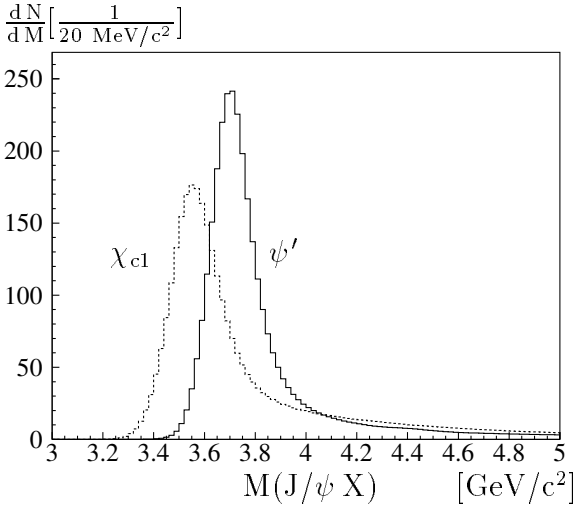

Figure 1: J/ψ X *mass distribution of* $\chi_{c1}K^0_S$ *and* $\psi' K^0_S$ *decay modes.*

The main sources of background both for the decays **(a)**, **(b)** and **(c)** are:
1) J/ψ and K^0_S from $B^0 \to J/\psi K^0_S X$ decays, in which the final states have a $\mathcal{CP}$ parity opposite in sign to that of signal. This source of background dilutes strongly the observable $\mathcal{CP}$ asymmetry. For $(\chi_{c1}, \psi')K^0_S$ signal such background modes are $(J/\psi, \chi_{c1}, \psi')K^{\star 0}$ (we assume, that in $(\chi_{c1}, \psi')K^{\star 0}$ modes longitudinally polarized helicity state dominates, like in $J/\psi K^{\star 0}$ mode). For the $J/\psi K^{\star 0}$ signal such background modes are $(\chi_{c1}, \psi')K^0_S$.
2) J/ψ and K^0_S from $B^0 \to J/\psi K^0_S X$ decays, in which the final states have the same $\mathcal{CP}$ parity as the signal. For $J/\psi K^{\star 0}$ signal such background modes are $(\chi_{c1}, \psi')K^{\star 0}$.
3) J/ψ and K^0_S from $B \to J/\psi K^0_S X$ decays, which does not result in a $\mathcal{CP}$ eigenstate.
4) J/ψ and accidental K^0_S. It is considered, that only J/ψ and K^0_S originating from the same target wire contribute to this source of background.
The background from direct J/ψ and accidental K^0_S is strongly suppressed by the cut on minimal B meson flight distance of 4 mm.

In the $J/\psi K^{\star 0}$ mode the expected distribution in $\theta_{K^{\star 0}}$ (where $\theta_{K^{\star 0}}$ is the angle between $K^{\star 0}$ direction in B^0 meson rest frame and K^0_S direction in $K^{\star 0}$ rest frame) is $d\Gamma_L/d\cos\theta_{K^\star} = \frac{3}{2}\cos^2\theta_{K^\star}$ [3]. The background with positive sign of $\mathcal{CP}$ parity is concentrated in the region of negative $\cos\theta_{K^{\star 0}}$ (see Figure 2). Therefore, the cut $\cos\theta_{K^{\star 0}} > 0.4$ is applied.

In the signal decay modes no hadron tracks originate from the B^0 decay vertex. The background from B decays with additional hadrons from the B decay vertex can be suppressed. The event is rejected if there is at least one track near the B decay vertex and far from interaction vertices. The cut in distance from a track to vertices is at the level $2.5\,\sigma_{\mathrm{imp.par.}}$ ($\sigma_{\mathrm{imp.par.}} = 25\mu\mathrm{m} \oplus 30\mu\mathrm{m}/\mathrm{p_t}$ – nominal impact parameter resolution for a given track). Only tracks with transverse momentum $\mathrm{p_t} > 0.3\mathrm{GeV/c}$ are regarded. The efficiency of this cut is 85%, while the background is suppressed by a factor of three.

The J/ψ X and K^0_S X mass distributions expected after one year of HERA-B operation, are shown in Figure 3. The accuracy in $\sin 2\beta$ using the combined $B^0 \to \chi_{c1}K^0_S \to (J/\psi\gamma)K^0_S$ and

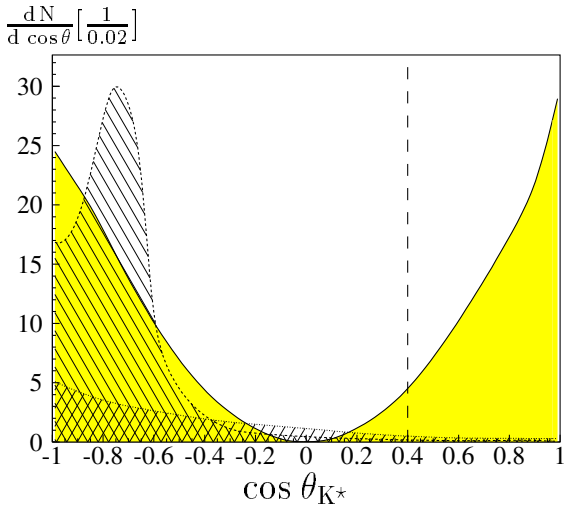

Figure 2: $\cos\theta_{K^\star}$ *distributions. The contribution of* $J/\psi K^{\star 0}$ *signal is represented by the grey area. The contribution of background with positive sign of* $\mathcal{CP}$ *parity – by the area, hatched with the slope to the left, the contribution of background with negative sign of* $\mathcal{CP}$ *parity – by the area, hatched with the slope to the right.*

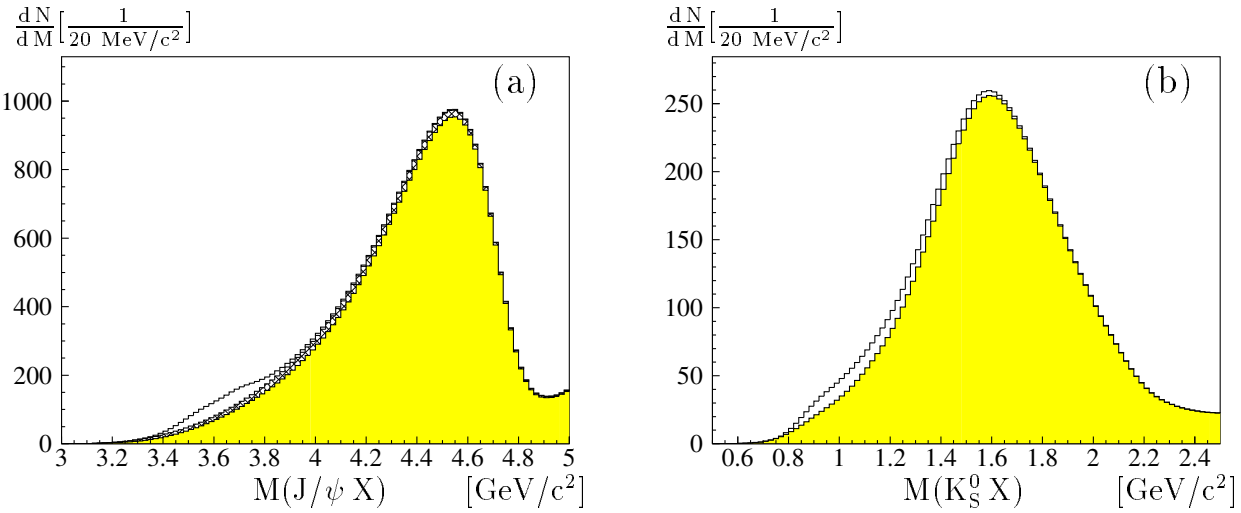

Figure 3: *Invariant mass distribution of* J/ψ X (a) *and* K^0_S X (b) *expected after one year of operation of HERA-B. The open histogram represents the contribution of the signal. The hatched histogram* (a) *represents the contribution of the background with negative* $\mathcal{CP}$ *parity. Gray histogram represents contribution of background of B decays which do not lead to a* $\mathcal{CP}$ *eigenstate. In the case of* K^0_S X *mass the background from* $\mathcal{CP}$ *eigenstates is strongly suppressed by the cut on* $\cos\theta_{K^{\star 0}}$.

$B^0 \to \psi' K^0_S \to (J/\psi X^0) K^0_S$ channels is $\delta \sin 2\beta \sim 0.5$, using $B^0 \to J/\psi K^{\star 0} \to J/\psi(K^0_S \pi^0)$ channel – $\delta \sin 2\beta \sim 0.6$ (the $J/\psi K^0_S$ mode is used for normalization - $\delta \sin 2\beta = 0.13$ for about 1400 signal events without a background; the event numbers and background conditions for the decays under analysis are taken into account). The error of background subtraction is not included here. The values of errors depend strongly on the accuracy in the measurement of vertex coordinates. 10% improvement in vertex resolution gives 5% improvement in $\delta \sin 2\beta$.

The simulation can be checked with data sample. We expect about 800 fully reconstructed $B^+ \to \psi' K^+ \to (J/\psi \pi^+ \pi^-) K^+$ decays per year, 3000 $B^0 \to J/\psi K^+ \pi^-$ decays and 3000

$B^+ \to J/\psi K^+\pi^+\pi^-$ decays. Comparison of partially reconstructed events $B^0 \to \psi' K^0_S$ followed by $\psi' \to J/\psi\pi^+\pi^-$ with full reconstruction allows the determination of the systematic errors coming from the method described. Thus after normalization of any decay under study to the $\psi' \to J/\psi X$ the systematic errors due to method uncertainties mainly cancel. The shape, normalization and efficiency are determined directly from the data.

4 Summary

The accuracy in $\sin 2\beta$ using combined $B^0 \to \chi_{c1} K^0_S \to (J/\psi\gamma)K^0_S$ and $B^0 \to \psi' K^0_S \to (J/\psi X^0)K^0_S$ channels is $\delta \sin 2\beta \sim 0.5$, and using $B^0 \to J/\psi K^{\star 0} \to J/\psi(K^0_S\pi^0)$ channel is $\delta \sin 2\beta \sim 0.6$. The latter channel is especially important, since it is predicted to carry $\mathcal{CP}$ parity opposite in sign to that of "gold-plated" $J/\psi K^0_S$ mode and possible systematic biases can be revealed. About 10% effective enhancement of $J/\psi K^0_S$ mode statistics can be expected. The errors can be reduced by the improvements in vertex resolution.

The statistics of all three additional channels can be combined and then the error is $\delta \sin 2\beta \sim 0.4$. Since $\sin 2\beta$ is expected to be about 0.6, an independent measurement of $\mathcal{CP}$ violation with these modes seems to be possible after 4 years of HERA-B operation.

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