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PHYS

LHCb Sensitivity to γ with $B_s \to D_s K$ [1]

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Abstract

The decay channels $B_s^0 \to D_s^{\pm} K^{\mp}$ and $B_s^0 \to D_s^- \pi^+$ can be used to extract the CKM-matrix γ angle, a parameter of the Standard Model not yet directly measured. The strategy of the LHCb experiment for such a measurement is described. We also outline the event selection criteria, the expected annual yields and background-over-signal B/S ratii, and the expected precision on the CKM γ measurement.

[1] Proceedings of the conference "Physics at LHC", 13-17 July 2004, Vienna, Austria

1 Introduction

The CP violation phenomena and mixing are described within the framework of the Standard Model (SM) via the CKM matrix. Of particular importance is the determination of the CKM angles α, β and γ.

Several methods exist in the literature to extract the γ angle. This paper focuses on a direct determination of γ with the LHCb detector [1] using $\mathrm{B_s^0} \to \mathrm{D_s^{\pm}K^{\mp}}$ decays. Other B-decay channels will also be studied in LHCb to extract the γ angle; they are detailed elsewhere [2], [3]. Compared to the other methods, the approach based on $\mathrm{B_s^0} \to \mathrm{D_s^{\pm}K^{\mp}}$ has the advantage to be theoretically clean and not sensitive to extra CP-contributions coming from new Physics beyond the SM.

The $\mathrm{B_s^0} \to \mathrm{D_s^{\pm}K^{\mp}}$ decay allows in fact the extraction of the quantity $\gamma - 2\chi$, the mixing angle χ arising from the B_s-mixing. In LHCb this angle will be measured by means of the decay mode $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ [4]. A statistical error on $\sin 2\chi$ of 0.06 is expected to be obtained with LHCb after one year of data taking.

In addition basic parameters such as the mixing parameter Δm_s and the lifetime difference $\Delta\Gamma_s$ of the two $\mathrm{B_s^0}$ mass eigenstates will be determined with high precision using the flavour-specific $\mathrm{B_s^0} \to \mathrm{D_s^-}\pi^+$ decay. In fact, this input is needed for the method of extraction of γ presented here.

At present no direct measurement of γ has been possible, the production of $\mathrm{B_s^0}$ mesons being unfeasible at the SLAC and KEK B-factories. The expectation $50° < \gamma < 80°$ comes from global fits [5].

2 Event reconstruction and selection with LHCb

The LHCb experiment at the LHC collider of CERN has been designed to focus on the study of CP violation and rare decays of the B-meson system. With a luminosity of 2×10^{32} cm^{-2}s^{-1}, a collision rate of 40 MHz, and a $b\bar{b}$ cross-section at $\sqrt{14}$ TeV of ≈ 0.5 mb, the LHC will provide in 2007 a sample of B-mesons far larger that those available or being produced today - one expects 10^{12} $b\bar{b}$ pairs produced per year.

The LHCb forward spectrometer comprises a high-precision silicon vertex locator (VELO), a tracking system and dipole magnet, two ring imaging Cherenkov detectors (RICH1 and RICH2), electromagnetic and hadronic calorimeters, and a muon system. A detailed description can be found in [1] and references therein.

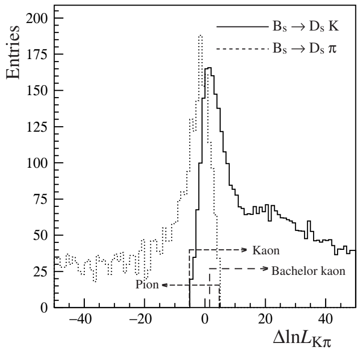

Figure 1: Kaon-pion separation for the bachelor particles from $\mathrm{B_s^0} \to \mathrm{D_s h}$ decays.

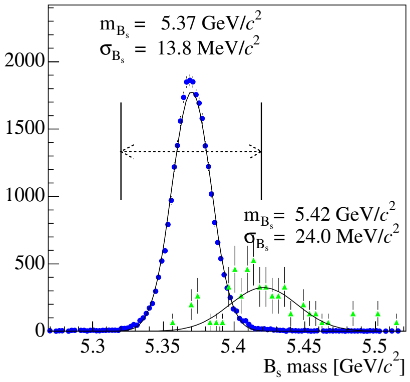

Figure 2: $\mathrm{B_s^0} \to \mathrm{D_s^{\pm} K^{\mp}}$ mass resolution plot as obtained from the simulation. The mass resolution is ≈ 14 MeV/c^2. The second lower peak corresponds to the mass distribution of $\mathrm{B_s^0} \to \mathrm{D_s^{-}} \pi^{+}$ decays reconstructed as $\mathrm{B_s^0} \to \mathrm{D_s^{\pm} K^{\mp}}$ events.

2.1 Event selection

Both the $\mathrm{B_s^0} \to \mathrm{D_s^{\pm} K^{\mp}}$ and $\mathrm{B_s^0} \to \mathrm{D_s^{-}} \pi^{+}$ decays being very similar, a common set of selection criteria was derived. Small differences in the selection have only to do with the selection of the bachelor pion or kaon (the bachelor particle is the one that accompanies the D_s); the bachelor pion/kaon separation makes use of the log-likelihood particle identification hypothesis as provided by the RICH system (see figure 1).

The event selection can be sub-divided in three main parts: the selection of the tracks, and the reconstruction of the $\mathrm{B_s}$ and $\mathrm{D_s}$ decay vertices.

Quality and transverse momentum cuts are applied to the tracks. This ensures that only well reconstructed tracks are used for the reconstruction of the $\mathrm{B_s^0}$ decay. The transverse momentum cuts translate the fact that $\mathrm{B_s^0}$ decay products tend to have a relatively large transverse momentum.

The particular event topology resulting from the relatively long lifetimes of the B_s and D_s mesons is exploited – their respective lifetimes are around 1.5 and 0.5 ps. The mean decay lengths are of the order of a few centimeters, so that the detached secondary vertices can be observed. The $\mathrm{D_s}$ is reconstructed in the high branching ratio $D_s^- \to K^+K^-\pi^-$ mode, applying quality, impact parameter (with respect to the primary vertex) and mass window cuts. The D_s vertex z-resolution is $\approx 440\mu$m, to be "compared" to the primary vertex z-resolution of $\approx 47\mu$m. The B_s vertex is obtained from the reconstructed D_s vertex and the bachelor particle also imposing quality and mass window cuts; its z-resolution is $\approx 144\mu$m.

As can be seen from figure 2, a $B_s^0 \to D_s^\pm K^\mp$ mass resolution of $\approx 14\text{MeV}/c^2$ is expected. The secondary small peak comes from the 10% pollution from $B_s^0 \to D_s^-\pi^+$ events misidentified as $B_s^0 \to D_s^\pm K^\mp$ events – most likely because of the misidentification of the bachelor pion.

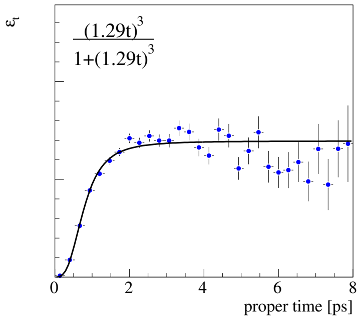

Figure 3: Time-dependent reconstruction+selection+trigger efficiency of $B_s^0 \to D_s h$ events (arbitrary units). The data were fitted with the equation shown in the figure.

Figure 3 presents the time dependent reconstruction+selection+trigger efficiency of $B_s^0 \to D_s h$ ($h = K, \pi$) events. The effect of demanding detached secondary vertices can clearly be seen.

The proper time resolution for the reconstructed (triggered and selected) B_s^0 mesons is of the order of 33 fs, see figure 4.

2.2 Annual yields and background estimates

According to the latest simulation studies [6] LHCb is expected to collect per year of data taking a total of (82 ± 26)k $B_s^0 \to D_s^-\pi^+$ and (5.4 ± 2.2)k $B_s^0 \to D_s^\pm K^\mp$ events, after triggering, reconstruction and event selection.

The main source of (combinatorial) background for the $B_s^0 \to D_s^-\pi^+$ decay comes from the so-called $b\bar{b}$ inclusive background, i.e. $pp \to b\bar{b}X$ events (where at least one of the B-particles was produced within a cone of 400 mrad around the beam axis [2], giving a background-over-signal ratio of $B/S = 0.32 \pm 0.10$. In the case of the $B_s^0 \to D_s^\pm K^\mp$ decays also the $B_s^0 \to D_s^-\pi^+$ events are a non-negligible (extra) source of contamination,

[2]The LHCb acceptance is ≈ 300 mrad

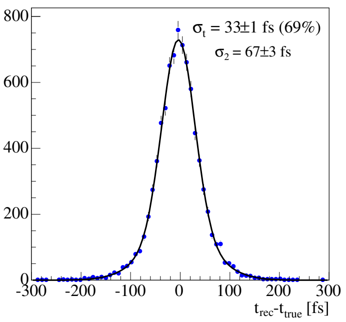

Figure 4: Proper time resolution distribution for the reconstructed B_s^0 mesons.

Decay	Annual yields	B/S (90% C.L.)
$B_s \to D_s K$	$\approx 5.4k$	< 1.0
$B_s \to D_s \pi$	$\approx 82k$	0.32 ± 0.10

Table 1: Annual yields and background-over-signal B/S ratii for $\mathrm{B}_s^0 \to \mathrm{D_s h}$ events.

since the ratio of branching ratii $Br(B_s \to D_s\pi)/Br(B_s \to D_sK) \approx 12$. As a result, the latest simulations give $B/S < 1.0$ at a 90% confidence level (90% C.L.). All these numbers are collected in table 1.

3 Extraction of the CP-violation parameters

This paragraph summarises the formalism and strategy used by LHCb for the extraction of γ. See [7] for full details.

3.1 General formalism

The two eigenstates of the B_s^0 are the heavy(B_{sH}) and light(B_{sL}) mass eigenstates

$$|B_{sH(L)}\rangle = \frac{1}{\sqrt{p^2+q^2}}[p|B_s\rangle + (-)q|\bar{B}_s\rangle]. \tag{1}$$

The time evolution of the $|B_s\rangle$ and $|\bar{B}_s\rangle$ flavour eigenstates can be expressed as

$$\Gamma_{B_s\to f}(t) = \frac{|A_f|^2}{2} e^{-\Gamma_s t}[I_+(t) + I_-(t)]$$
$$\Gamma_{\bar{B}_s\to f}(t) = \frac{|A_f|^2}{2} \left|\frac{p}{q}\right|^2 e^{-\Gamma_s t}[I_+(t) - I_-(t)]$$
$$\Gamma_{\bar{B}_s\to \bar{f}}(t) = \frac{|\bar{A}_{\bar{f}}|^2}{2} e^{-\Gamma_s t}[\bar{I}_+(t) + \bar{I}_-(t)]$$

$$\Gamma_{B_s \to \bar{f}}(t) = \frac{|\bar{A}_{\bar{f}}|^2}{2} \left|\frac{q}{p}\right|^2 e^{-\Gamma_s t}[\bar{I}_+(t) - \bar{I}_-(t)] \tag{2}$$

where A_f is the instantaneous decay amplitude for a B_s-meson into a final state f, and mutatis mutandis for the $A_{\bar{f}}$, etc. Here

$$\begin{aligned} I_+(t) &= (1 + |\lambda|^2)\cosh(\frac{\Delta\Gamma_s}{2}t) - 2\Re\lambda \sinh(\frac{\Delta\Gamma_s}{2}t), \\ I_-(t) &= (1 - |\lambda|^2)\cos(\Delta m_s t) - 2\Im\lambda \sin(\Delta m_s t), \end{aligned} \tag{3}$$

$\Gamma_s = (\Gamma_{sH} + \Gamma_{sL})/2$, $\Delta\Gamma_s$ is the decay width difference between the heavy and light B_s-meson eigenstates (for $\bar{I}_+$ and $\bar{I}_-$ replace λ by $\bar{\lambda}$), and

$$\lambda \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f} \quad , \quad \bar{\lambda} \equiv \frac{p}{q}\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}} \quad . \tag{4}$$

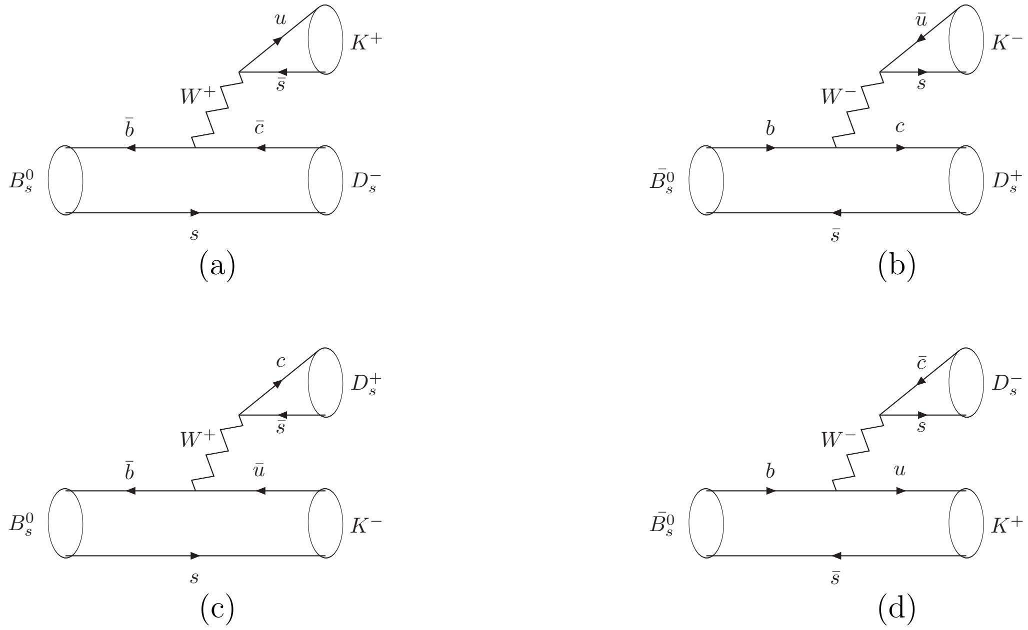

Figure 5: The tree diagrams for the $\mathrm{B_s^0} \to \mathrm{D_s^-K^+}$ and $\mathrm{B_s^0} \to \mathrm{D_s^+K^-}$ decays. (a) The instantaneous decay amplitude A_f (or $T1$), (b) $\bar{A}_{\bar{f}}$, (c) $A_{\bar{f}}$, and (d) $\bar{A}_f$ (or $T2$).

3.2 Case of $\mathrm{B_s^0} \to \mathrm{D_s^\pm K^\mp}$

In the case of the $\mathrm{B_s^0} \to \mathrm{D_s^\pm K^\mp}$ decay, both the $\mathrm{B_s^0}$ and the $\mathrm{\bar{B}_s^0}$ can decay into a same final state f (figure 5 shows the relevant tree-level Feynman diagrams). CP violation then arises from the interference between the 2 tree diagrams via mixing, i.e. from the interference between the $\mathrm{B_s^0}$-mesons that have and have not decayed.

It is theoretically expected that $A_f \approx \bar{A}_f$, hence $|\lambda| = |\bar{\lambda}|$. Since the ratio

$$\left|\frac{A_f}{\bar{A}_f}\right| = \left|\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}}\right| = \left|\frac{V_{ub}V_{cs}}{V_{cb}V_{us}}\right| \approx 0.5, \tag{5}$$

the interference effects are large. As mentioned earlier, this interference gives a sensitivity to $\gamma - 2\chi$ and the use of all decay combinations resolves the strong phase difference between $T1$ and $T2$ (i.e. A_f and $\bar{A}_f$), denoted $\Delta_{T1/T2}$.

For $\mathrm{B_s^0 \rightarrow D_s^{\pm} K^{\mp}}$ the strong phase difference $\Delta_{T1/T2}$ and the CP angle $\gamma - 2\chi$ follow then from

$$\gamma - 2\chi = \frac{1}{2}[\arg(\lambda) - \arg(\bar{\lambda})] \tag{6}$$

$$\Delta_{T1/T2} = \frac{1}{2}[\arg(\lambda) + \arg(\bar{\lambda})]. \tag{7}$$

Since χ is obtained independently – for example from $J/\psi\phi$ decays [4]) – this first relation determines the angle γ.

3.3 Case of $\mathrm{B_s^0 \rightarrow D_s^- \pi^+}$

The case of the $\mathrm{B_s^0 \rightarrow D_s^- \pi^+}$ decay is somewhat simpler, as a single tree diagram exists. A $\mathrm{B_s^0}$ decays instantaneously as $\mathrm{D_s^- \pi^+}$ and a $\mathrm{\bar{B}_s^0}$ as $\mathrm{D_s^+ \pi^-}$. The $\mathrm{B_s^0 \rightarrow D_s^- \pi^+}$ decay is therefore flavour-specific and $A_{\bar{f}} = \bar{A}_f = 0$, thus $\lambda = \bar{\lambda} = 0$. With the approximation $\left|\frac{p}{q}\right| = 1$ a flavour asymmetry can be defined as

$$\mathcal{A}^{flav} = \frac{\Gamma_{\bar{B}_s \rightarrow f} - \Gamma_{B_s \rightarrow f}}{\Gamma_{\bar{B}_s \rightarrow f} + \Gamma_{B_s \rightarrow f}} = -D \cdot \frac{\cos(\Delta m_s t)}{\cosh(\Delta \Gamma_s t)}, \tag{8}$$

where D is a dilution factor with contributions from a wrong tagging (1-2w, with w the wrong tag fraction) and experimental resolutions.

This asymmetry $\mathcal{A}^{flav}$ allows the extraction of Δm_s, w, and $\Delta\Gamma_s$ from the decay rates $\Gamma_{B_s \rightarrow f}$ and $\Gamma_{\bar{B} \rightarrow f}$, and similarly from $\Gamma_{B_s \rightarrow \bar{f}}$ and $\Gamma_{\bar{B}_s \rightarrow \bar{f}}$.

3.4 Likelihood fit and results

The extraction of γ is done with a log-likelihood fit to the combined set of $\mathrm{B_s^0 \rightarrow D_s^{\pm} K^{\mp}}$ and $\mathrm{B_s^0 \rightarrow D_s^- \pi^+}$ events. Both the $\mathrm{B_s^0 \rightarrow D_s^{\pm} K^{\mp}}$ and the $\mathrm{B_s^0 \rightarrow D_s^- \pi^+}$ events are fitted together to correctly take into account the correlations between parameters.

Events are generated with a parameterized toy Monte Carlo (MC) program, for different settings of the CP parameters $\gamma - 2\chi$, $\Delta_{T1/T2}$ Δm_s, $\Delta\Gamma_s/\Gamma_s$. But the information

Δm_s	15	20	25	30
$\sigma(\gamma-2\chi)$	12.1	14.2	16.2	18.3

$\Delta\Gamma_s/\Gamma_s$	0	0.1	0.2
$\sigma(\gamma-2\chi)$	14.7	14.2	12.9

$\gamma-2\chi$	55	65	75	85	95	105
$\sigma(\gamma-2\chi)$	14.5	14.2	15.0	15.0	15.1	15.2

$\Delta_{T1/T2}$	-20	-10	0	$+10$	$+20$
$\sigma(\gamma-2\chi)$	13.9	14.1	14.2	14.5	14.6

Table 2: Expected statistical uncertainty on $\gamma-2\chi$ for one year of LHCb data. Unless otherwise specified, Δm_s=20 ps^{-1}, $\Delta\Gamma_s/\Gamma_s$=0.1, $\gamma-2\chi=65°$ and $\Delta_{T1/T2}=0°$. All values are given in degrees, except Δm_s (ps^{-1}) and $\Delta\Gamma_s/\Gamma_s$.

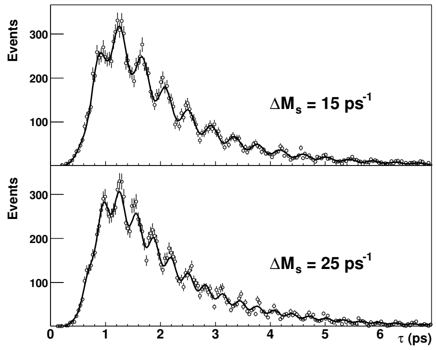

Figure 6: Simulated $\mathrm{B_s^0} \rightarrow \mathrm{D_s^-}\pi^+$ decay rate for two different values of Δm_s. Only B_s decays which have been tagged as not having oscillated are included. The data represents one year of LHCb data. The curve represents the probability as obtained with the likelihood maximization.

of the full simulation is used for the acceptance function, the decay time uncertainty distribution, the fraction of background events, etc. The background events are simulated with half the lifetime of the $\mathrm{B_s^0}$ and with a mass distribution observed in the full MC simulation. The w values are assumed to be equal for the two decays (fact confirmed in the full detector simulation), since their selection criteria is identical except for the selection of the bachelor meson, and the event topologies are very similar. An experimental uncertainty on the reconstructed decay time, $\Delta\tau_{rec}$, is assigned to each generated event.

The extraction of all the parameters uses a likelihood (maximization) fit of the combined function

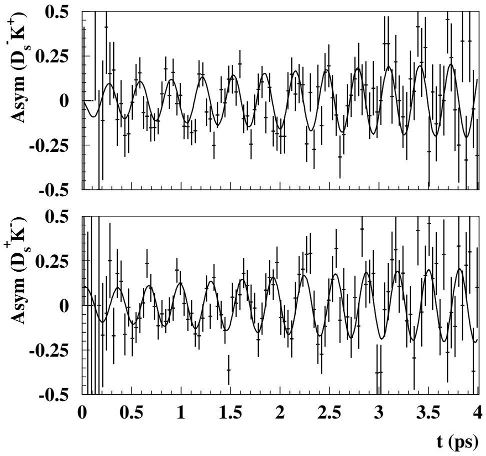

Figure 7: The $B_s^0 \to D_s^{\pm} K^{\mp}$ asymmetries for 5 years of LHCb data.

$$\mathcal{L}_{B_s \to f}(\overrightarrow{\alpha}) = \prod_i^{B_s \to D_s K} \mathrm{Prob}(\tau_{rec}, \Delta\tau_{rec}|\overrightarrow{\alpha}, w) \cdot \prod_i^{B_s \to D_s \pi} \mathrm{Prob}(\tau_{rec}, \Delta\tau_{rec}|\overrightarrow{\alpha}, w) \tag{9}$$

with $\overrightarrow{\alpha}$=(Γ_s, Δm_s, $\Delta\Gamma_s$, λ, $\bar{\lambda}$, w) being the set of parameters used for the event generation, and $\Delta\tau_{rec}$ the per event decay time resolution.

$\mathrm{Prob}(\tau_{rec}, \Delta\tau_{rec}|\overrightarrow{\alpha}, w)$ incorporates the knowledge about the time evolution of both signal and background (equations 2 for the signal) taking into account the background fraction, the time-dependent acceptance function depicted in figure 3, etc.

The total likelihood is

$$\mathcal{L}(\overrightarrow{\alpha}) = \mathcal{L}_{B_s \to f}(\overrightarrow{\alpha}) \cdot \mathcal{L}_{\bar{B}_s \to f}(\overrightarrow{\alpha}) \cdot \mathcal{L}_{B \to \bar{f}}(\overrightarrow{\alpha}) \cdot \mathcal{L}_{\bar{B}_s \to \bar{f}}(\overrightarrow{\alpha}). \tag{10}$$

The results of the likelihood maximization for the uncertainty on $\gamma - 2\chi$ for one year of $B_s^0 \to D_s^{\pm} K^{\mp}$ data are given in table 2. The numbers quoted are the average results obtained with the toy MC for 100 "experiments".

The $B_s^0 \to D_s^- \pi^+$ decay rate after one year of LHCb data for two different values of $\Delta m_s$is presented in figure 6. The curve represents the probability as obtained with the likelihood maximization. The $B_s^0 \to D_s^{\pm} K^{\mp}$ asymmetry for 5 year LHCb data is shown in figure 7. The sensitivity for $\gamma - 2\chi$ was additionally studied as a function of the B/S ratio and the decay time resolution; these dependencies are shown in figures 8 and 9, respectively.

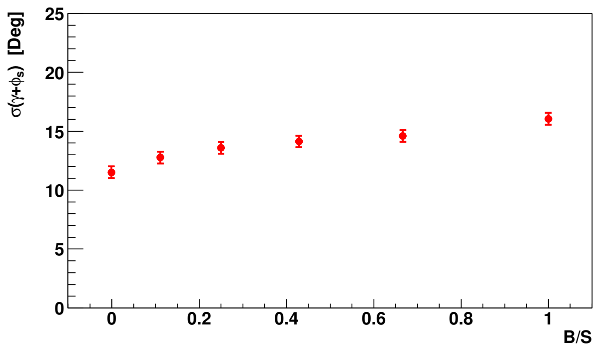

Figure 8: The uncertainty on $\gamma - 2\chi$ ($\phi_s = -2\chi$ in the Standard Model) as a function of the B/S ratio, and for Δm_s= 20 ps^{-1}. The data represents one year of LHCb data. For a B/S ratio that is equal to 0.5 the uncertainty on $\gamma - 2\chi$ is 14.2^0.

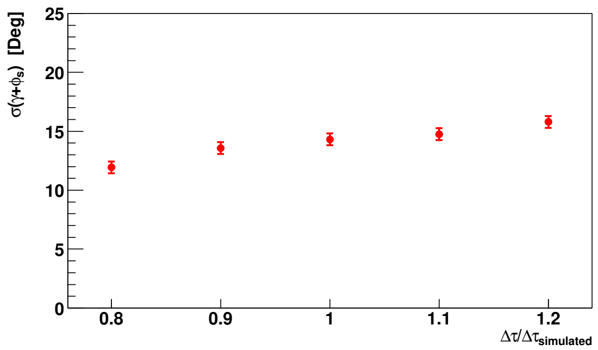

Figure 9: The uncertainty on $\gamma - 2\chi$ as a function of the decay time resolution, and for Δm_s= 20 ps^{-1}. Shown are the sensitivities for the cases where the decay time resolution would be better and worse by 10% and 20%, that is wrong, with respect to the full MC simulation result. The data represents one year of LHCb data.

4 Conclusion

The LHCb experiment will be able to exploit several methods of extraction of the CKM matrix γ angle, allowing cross-checks to be done between different methods with different sensitivity to Physics beyond the Standard Model. A particular method using $\mathrm{B_s^0} \to \mathrm{D_s h}$ decays was described here. It exploits the large sample of $\mathrm{B_s^0}$ mesons that will be produced at the LHC collider.

Acknowledgements:
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