Flavor Physics and CP Violation at LHC

A. Schopper
CERN, PH-Department, 1211 Geneva 23, Switzerland

Flavor Physics at LHC will contribute significantly to the search for New Physics via precise and complementary measurements of CKM angles and the study of loop decays. Here we present the expected experimental sensitivity and physics performance of the LHC experiments that will to B-physics.

1. Introduction

The B-factories are extremely successful in constraining the Unitarity Triangles within the Standard Model and experiments at the Tevatron have demonstrated their $\mathrm{B_s^0}$-physics capability. Starting from summer 2007, the Large Hadron Collider (LHC) at CERN shall contribute to further improve the CKM consistency test and look for deviations from the Standard Model rare processes. LHC will not only give access to a new high energy frontier, but will also act as a new generation b-factory with large b-quark production rates including $\mathrm{B_s^0}$. New Physics can be hidden in B-decays, since New Physics models can introduce new particles, dynamics and symmetries at higher energy scales with virtual particles that appear e.g. in loop processes, such as box and penguin diagrams. Therefore, B-physics measurements are complementary to direct searches and will allow to understand the nature and flavor structure of possible New Physics.

The B-physics program at LHC is vast. It will include a precise measurement of $\mathrm{B_s^0}$-$\mathrm{\overline{B}_s^0}$ mixing via e.g. $\mathrm{B_s^0} \to \mathrm{D_s^-}\pi^+$, $\mathrm{B_s^0} \to \mathrm{J}/\psi\phi$ and $\mathrm{B_s^0} \to \mathrm{J}/\psi\eta$, to extract Δm_s, $\Delta\Gamma_\mathrm{s}$ and the weak phase ϕ_s. Possible effects of New Physics appearing in suppressed and rare exclusive and inclusive B-decays will be searched for in $\mathrm{B^0_{(s)}} \to X\gamma$, $\mathrm{B^0} \to \mathrm{K^{*0}}l^+l^-$, $\mathrm{b} \to sl^+l^-$ and $\mathrm{B_s^0} \to \mu^+\mu^-$. In order to disentangle possible New Physics contributions, the CKM angle γ shall be determined precisely from tree-level only decays like $\mathrm{B_s^0} \to \mathrm{D_s^\mp K^\pm}$, $\mathrm{B^0} \to \mathrm{D^0K^{*0}}$, $\mathrm{B^\pm} \to \mathrm{D^0}K^\pm$ and be compared with the value extracted from those decays that include loop diagrams, like $\mathrm{B^0} \to \pi^+\pi^-$and $\mathrm{B_s^0} \to \mathrm{K^+K^-}$. Measurements of other CP phases in various channels like $\mathrm{B^0} \to \phi\mathrm{K_S^0}$, $\mathrm{B_s^0} \to \phi\phi$, $\mathrm{B^0} \to \rho\pi$ and $\mathrm{B^0} \to \rho\rho$ will further allow to over-constrain the Unitarity Triangles.

2. B-physics experiments at LHC

The LHC machine will collide protons at 14 TeV center of mass energy with a bunch crossing rate of 40 Mhz. At this energy the $\mathrm{b\overline{b}}$ production cross section is huge and will be of the order of 500 μb, producing on average b-hadrons with about 40% of $\mathrm{B^0}$&$\mathrm{\overline{B}^0}$, 40% of $\mathrm{B^+}$&$\mathrm{B^-}$, 10% of $\mathrm{B_s^0}$&$\mathrm{\overline{B}_s^0}$ and 10% of b-baryons. The ratio of $\mathrm{b\overline{b}}$ production cross section over inelastic cross section is of the order of 0.6%, which requires top-performing triggers to select the useful B-decays.

The sensitivity of the experiments that will do B-physics at LHC will depend on their detector acceptance for the relevant B-decays, their trigger performance including fully hadronic decays, their capability in rejecting background which requires a good mass resolution and particle identification, their decay-time resolution for reconstructing time-dependent $\mathrm{B_s^0}$-decays, and their flavor tagging capability. Three experiments at LHC intend to do B-physics.

The two general-purpose experiments, ATLAS and CMS, are optimized for discovery physics and will complete most of their B physics program within the first few years [1][2], when the LHC luminosity is expected to be below $2{\times}10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. In the following years of high luminosity running with order $10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$, several pp collisions will pile-up per bunch crossing, which will limit the B-physics studies to the search of very rare B-decays with clear signatures, like e.g. $\mathrm{B^0_{(s)}} \to \mu\mu$. The reach in B-physics will very much depend on the trigger strategy and bandwidth allocation. B-events will mainly be selected by high p_T single muon and dimuon triggers. At low luminosity, ATLAS foresees a flexible trigger strategy in which both, a muon signal and either an electromagnetic cluster in a region of interest can be identified to select e.g. $\mathrm{B^0} \to \mathrm{K^{*0}}\gamma$, or hadronic b-decay products in a jet region of interest can be identified to select e.g. $\mathrm{B_s^0} \to \mathrm{D_s^-}\pi^+$. CMS exploits the possibility of online tracking with a reduced number of hits per track at the High Level Trigger to select exclusive B-events like e.g. $\mathrm{B_s^0} \to \mathrm{D_s^-}\pi^+$.

LHCb is the experiment dedicated to B-physics at the LHC [3]. The detector is a single arm forward spectrometer covering a pseudo-rapidity range of $1.9 \leq \eta \leq 4.9$, which maximizes the acceptance for B-events, since at LHC $\mathrm{b\overline{b}}$ events are produced correlated in space and are forward peaked. In order to minimize pile-up of pp collisions per bunch crossing, LHCb will be running at a nominal luminosity of $2{\times}10^{32}\,\mathrm{cm^{-2}\,s^{-1}}$, which can be tuned locally at the LHCb interaction point by adjusting the beam focus. Since this luminosity is expected to be available at LHC very soon after the start-up, LHCb shall be fully efficient staring with the first physics run. In a nominal year with 10^7 s/year of data taking an integrated luminosity of 2 fb$^-1$/year is expected, translating into 10^{12} $b\bar{b}$ events/year. The LHCb trigger is optimized for selecting efficiently many different B-decays and operates in two stages. A fully synchronized hardware trigger based on custom electronics boards reduces the 10 MHz visible bunch crossing rate to 1 MHz, requiring the presence of high p_T leptons or photons or hadrons with a typical p_T cut of e.g. 1.3 GeV/c for muons. A software trigger running on a computer farm of about 2000 CPU's is then reducing the output rate further to 2 kHz using the full detector information. First it selects events with high impact parameter and high p_T tracks on which it then provides full event reconstruction. The final data stream will consist of typically 200 Hz exclusive B-events and 1.8 kHz of inclusive channels that will also be used for calibration purposes and systematic studies.

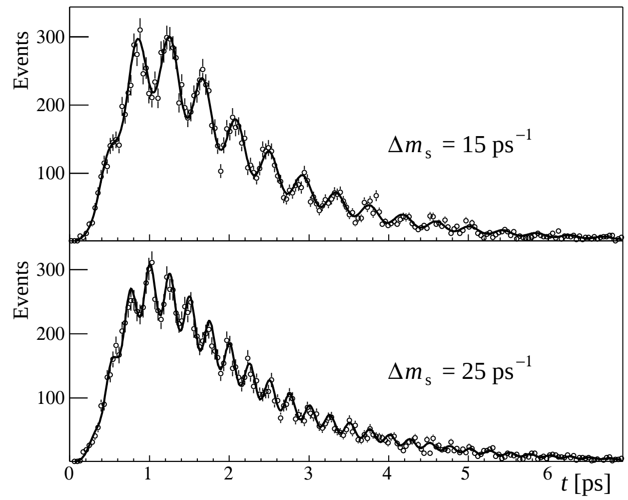

Figure 1: Proper-time distribution of simulated $B_s^0 \to D_s^- \pi^+$ candidates in LHCb that have been flavour-tagged as having not oscillated, for two different values of Δm_s. The data points represent one year of data, while the curves correspond to the maximized likelihood.

3. Prospects for $B_s^0 - \overline{B}_s^0$ mixing

3.1. Determination of Δm_s from $B_s^0 \to D_s^- \pi^+$

A first measurement of the $B_s^0\overline{B}_s^0$ oscillation frequency $\Delta m_s = 17.33^{+0.42}_{-0.21}(stat.) \pm 0.07(syst.)$ ps^{-1} has been reported in this conference by CDF, following the upper and lower bound that was announced previously by D0.

At LHC, the determination of Δm_s from $B_s^0 \to D_s^- \pi^+$ with better than five sigma significance is one of the first goals of LHCb. This requires very good proper-time resolution, flavor tagging and background discrimination. LHCb expects an annual event yield of 80'000 events with a signal over background ratio of about 3. With its very good proper time resolution of $\sigma_\tau \sim 40$ fs and a tagging power for B_s^0 of $\sim 7\%$, a five sigma significance can be reached with the statistics of one month of data taking. The expected proper-time distribution for simulated $B_s^0 \to D_s^- \pi^+$ events is shown in Fig. 1.

ATLAS will have a 5σ observation of oscillations after 3 years of low luminosity running, whilst the expectations for CMS are somewhat lower due to limitations in the allocated trigger bandwidth for $B_s^0 \to D_s^- \pi^+$.

3.2. Determination of ϕ_s and $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\phi$

The channel $B_s^0 \to J/\psi\phi$ is the SU(3) analogue of $B^0 \to J/\psi K_S^0$ and can as such be used to determine the phase ϕ_s due to B_s^0-$\overline{B}_s^0$ oscillations. In the Standard Model, the CKM picture predicts that this phase difference should be small, $\phi_s = -2\chi = -2\eta\lambda^2$, of the order of -0.04. The observation of a large CP asymmetry in this channel would therefore be a striking signal for physics beyond the Standard Model. Due to the fact that both J/ψ and ϕ are vector mesons, there are three distinct amplitudes contributing to this decay: two CP even, and one CP odd. Fortunately, the two CP components can be disentangled on a statistical basis by taking into account the distribution of the so-called transversity angle, θ_{tr}, defined as the angle between the positive lepton and the ϕ decay plane in the J/ψ rest frame (see Fig. 2). The CP-even and CP-odd components are expected to have a non-negligible relative decay-width difference $\Delta\Gamma_s/\Gamma_s$ of the order of 10%.

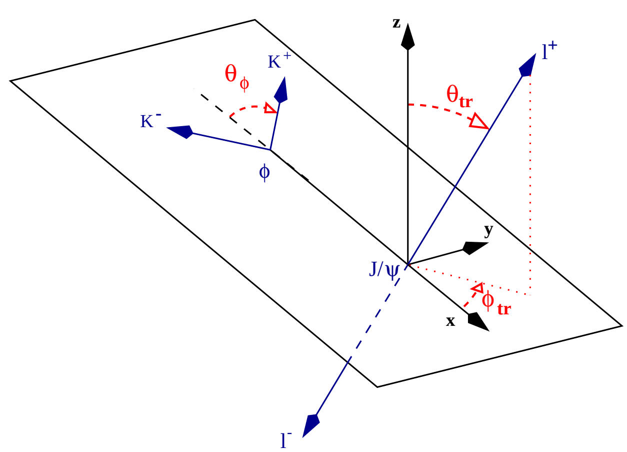

Figure 2: Definition of the transversity angle θ_{tr} in the $B_s^0 \to J/\psi(\ell^+\ell^-)\phi(K^+K^-)$ decay.

LHCb expects in one year of data taking to collect

125'000 $B^0_s \to J/\psi\phi$ decays and to obtain (for Δm_s= 20 ps^{-1}) a precision on $\sin(\phi_s)$ of 0.031 and on $\Delta\Gamma_s/\Gamma_s$ of about 0.011. By adding pure CP modes like $B^0_s \to J/\psi\eta$ and $B^0_s \to J/\psi\eta'$, which are expected to contribute with about 7000 events/year, this sensitivity can be somewhat improved. ATLAS expects a similar event rate as LHCb per year of low luminosity running, but has a reduced sensitivity of about 0.08 on $\sin(\phi_s)$.

4. Prospects for the measurement of suppressed and rare decays

4.1. Measurement of exclusive $b \to s\mu\mu$

Exclusive $b \to s\mu\mu$ decays like e.g. $B^0 \to K^{*0}\mu^+\mu^-$ are suppressed decays with branching fractions of the order of 10^{-6} with a clear experimental signature. The forward-backward asymmetry is defined as

$$A_{FB}(\hat{s}) = (\int_0^1 dcos\theta - \int_{-1}^0 dcos\theta)\frac{d\Gamma^2}{d\hat{s}dcos\theta}$$

where θ is the angle between the μ^+ and the K^{*0} in the di-muon rest frame, and $\hat{s}$=$(m_{\mu^+\mu^-}/m_B)^2$. The forward-backward asymmetry is a sensitive probe of New Physics. In the Standard Model the value of $\hat{s}$ for which $A_{FB}(\hat{s})$ is zero can be calculated with a 5% precision. Models with non-standard values of Wilson coefficients C_7, C_9, C_{10} predict $A_{FB}(\hat{s})$ of opposite sign or without zero point.

LHCb will select 4400 decays per year with an expected S/B> 0.4, which allows a determination of the branching fractions and CP asymmetries with a precision of a few percent. Using a toy Monte Carlo to determine the sensitivity in the forward-backward asymmetry measurement, including background subtraction, an uncertainty of 0.06 on the location of $\hat{s}_0$ is found, in 1 year of data-taking. ATLAS will collect about 1000 $B^0_d \to K^{*0}\mu^+\mu^-$ decays per year of low luminosity running, with an expected S/B> 1.

Other $b \to s\mu\mu$ decays like $\Lambda_b \to \Lambda\mu^+\mu^-$ are being investigated. The expected forward-backward asymmetry after 3 years of low luminosity data taking by ATLAS is shown in Fig. 3 and compared with the expected asymmetries from the Standard Model and from the Minimal Supersymmetric Standard Model.

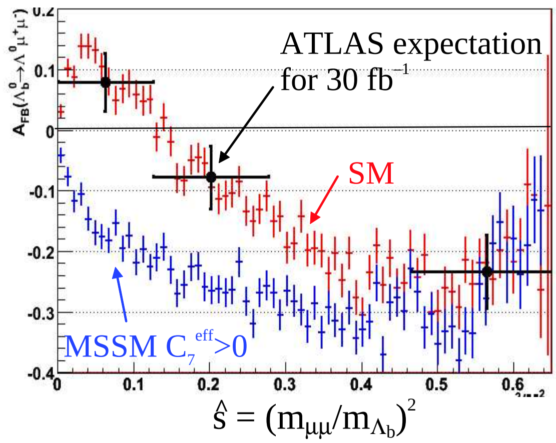

Figure 3: Expected forward-backward asymmetry for $\Lambda_b \to \Lambda\mu^+\mu^-$ after 3 years of low luminosity data taking by ATLAS (black data points), to be compared with the expected asymmetries from the Standard Model (SM) (red) and from the Minimal Supersymmetric Standard Model (MSSM) (blue).

4.2. Measurement of $B^0_s \to \mu^+\mu^-$

$B^0_s \to \mu^+\mu^-$ is a rare decay involving flavor changing neutral currents. In the Standard Model the branching ratio is estimated to be $BR(B_s \to \mu^+\mu^-) = (3.5 \pm 0.1) \times 10^{-9}$ [4]. In various supersymmetric extensions of the Standard model it can be enhanced by one to three orders of magnitude with $BR \sim (tan\beta)^6$, for large $tan\beta$. The best upper limit on the branching ratio comes at present from CDF and is 10^{-7} at 95% CL.

Within the Standard Model context, LHCb expects to select 30 signal events per year, with a resolution on the B^0_s mass of 18 MeV/c^2. The background determination requires a huge Monte Carlo statistics and is still under study. Following a full detector simulation, no background events were selected in the two samples of 10^7 $b\bar{b}$ and 10^7 $b \to \mu$, $b \to \mu$ events that have been used so far. The background estimations by CMS and ATLAS rely on simulation studies with generator cuts and assuming cut factorization. With a mass resolution of 46 MeV/c^2 CMS is expecting 7 signal events with less than 1 background event per year of low luminosity running. ATLAS will reconstruct the B^0_s mass with a resolution of 80 MeV/c^2 and expects 7 signal events with less than 20 background events. Both general purpose experiments also exploit the possibility of selecting $B^0_s \to \mu^+\mu^-$ decays during high luminosity runs with 30 fb^{-1}/year at 10^{34} cm^{-2} s^{-1}.

In conclusion there are good prospects of significant measurement in this channel, even for the Standard Model value of the branching ratios.

5. Prospects for the determination of γ

5.1. γ from $B^0_s \to D^{\mp}_s K^{\pm}$ decays

A theoretically clean way to extract γ is to mix the two tree diagrams, $\bar{b} \to \bar{u} + W^+$ and $\bar{b} \to \bar{c} + W^+$. This can be done by studying the time-dependent rates of B^0_s decaying into $D^+_s K^-$ and $D^-_s K^+$ and their CP-conjugated processes. The measurement of two time-dependent decay asymmetries from the four decay rates $B_s^0 \to D_s^{\pm}K^{\mp}$ and $\overline{B}_s^0 \to D_s^{\mp}K^{\pm}$ allow to extract the phase $\gamma + \phi_s$ together with a strong phase. Assuming that ϕ_s has been determined from previous measurements, γ can be determined with little theoretical uncertainty and is insensitive to New Physics.

The strong particle identification capability of LHCb is essential to separate $B_s \to D_sK$ decays from the $B_s \to D_s\pi$ background that has a ∼12 times larger branching fraction. Fig. 4 shows the mass resolution for the reconstructed signal events and the expected background contribution. Monte Carlo studies have shown that 5400 $D_s^{\mp}K^{\pm}$ events will be collected in one year of data taking with a S/B ratio, estimated from $b\bar{b}$ events, larger than 1. The $D_s^{\mp}K^{\pm}$ asymmetries are shown in Fig. 5. A sensitivity of $\sigma_\gamma = 14$ degrees is obtained for Δm_s=20 ps^{-1}.

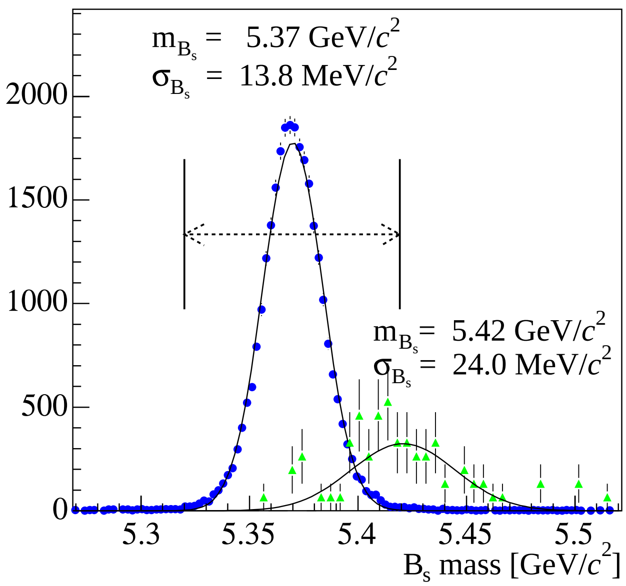

Figure 4: B_s^0 mass distribution for selected $B_s^0 \to D_s^{\mp}K^{\pm}$ candidates in LHCb. The Gaussian fit gives a resolution of 14 MeV/c^2 for the signal. Also shown are the misidentified $B_s^0 \to D_s^-\pi^+$ background events. Their mass is shifted up due to the misidentification of the bachelor π as a K.

5.2. γ from $B^0 \to D^0K^{*0}$ decays

The simultaneous measurement of the rates for the decays $B^0 \to \overline{D}^0(K^+\pi^-)K^{*0}$, $B^0 \to D^0_{CP}(K^+K^-)K^{*0}$, $B^0 \to D^0(\pi^+K^-)K^{*0}$ and their CP conjugates, where $K^{*0} \to K^+\pi^-$, allows the CKM angle γ to be extracted, without the need of flavor tagging or proper-time determination.

The method described in [5] is based on the measurement of six time-integrated decay rates for $B^0 \to D^0K^{*0}, \bar{D}^0K^{*0}, D_{CP}K^{*0}$ and their CP conjugates. The decays are self-tagged through $K^{*0} \to K^+\pi^-$ while the CP self-conjugate states D^0_{CP} can be reconstructed

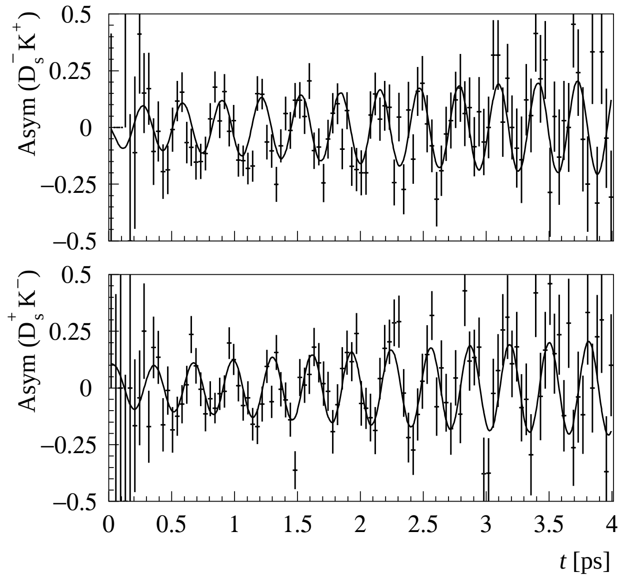

Figure 5: Time-dependent $B_s^0\overline{B}_s^0$ asymmetries of simulated $D_s^-K^+$ (top) and $D_s^+K^-$ (bottom) candidates in LHCb, for $\Delta m_s = 20$ ps^{-1}. The errors correspond to 5 years of data-taking.

in K^+K^- and $\pi^+\pi^-$ modes. This method makes use of two color-suppressed diagrams that are interfering via D^0 mixing, with an expected amplitude ration $r = |A(B^0 \to D^0K^{*0})|/|A(B^0 \to \overline{D}^0K^{*0})| \sim 0.4$.

LHCb expects to collect 3400 $B^0 \to \overline{D}^0K^{*0}$, 500 $B^0 \to D^0K^{*0}$ and 600 $B^0 \to D^0_{CP}K^{*0}$ signal events per year of data taking, which leads to a sensitivity for γ of $\sigma_\gamma \sim 8$ degrees.

5.3. γ from $B^{\pm} \to D^0K^{\pm}$ decays

Another approach to measure γ, closely corresponding to the method suggested in [6], exploits the interference between favored and doubly Cabibbo suppressed decays of D mesons decaying to states such as $K\pi$ and $K\pi\pi\pi$.

A B^- may decay color allowed into D^0K^- or color suppressed into $\overline{D}^0K^-$, with the weak phase γ and a possible strong phase difference δ_B between the two amplitudes. The ratio of magnitude r_B between the two amplitudes is small and expected to be of the order of 0.15. The neutral D meson decaying into $K^+\pi^-$ may arise from either a favored D^0 decay or a doubly Cabibbo suppressed $\overline{D}^0$ decay. The ratio of magnitude between the two D decay amplitudes $r_D^{K\pi}$ is experimentally determined to be of order 0.06 [7]. Taking into account a possible strong phase difference $\delta_D^{K\pi}$ between the two D decay amplitudes, one can measure the relative rates of the four $B^{\pm} \to D^0K^{\pm}$ decays, resulting in three observables that depend on four unknown parameters γ, δ_B, $\delta_D^{K\pi}$ and r_B, and one already known parameter $r_D^{K\pi}$. In order to constrain the problem it is necessary to further include D decays into a different final state, such as $K\pi\pi\pi$. This adds four new rates and two new parameters, $r_D^{K3\pi}$ and $\delta_D^{K3\pi}$, of which the later is again experimentally determined [7]. Thus there are now six observables and five unknowns, which allows to determine γ.

This method of extracting γ from the relevant $B^\pm \rightarrow D^0K^\pm$ decay rate asymmetries is the candidate for LHCb's statistically most precise determination of γ, with an expected sensitivity of $\sigma_\gamma \sim 5$ degrees.

5.4. γ from $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$ decays

Extracting information on the angle γ from two body charmless decays of B mesons by making assumptions on U-spin flavor symmetry has been suggested in [8]. Both decays, $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$ have large penguin contributions and are therefore sensitive to New Physics.

Measuring for both decay modes the time-dependent CP asymmetries:

$$\begin{aligned} A_{CP}(B^0 \rightarrow \pi^+\pi^-)(t) &= A_{CP}^{dir,\pi\pi} cos(\Delta m_d t) \\ &\quad + A_{CP}^{mix,\pi\pi} sin(\Delta m_d t) \\ A_{CP}(B^0_s \rightarrow K^+K^-)(t) &= A_{CP}^{dir,KK} cos(\Delta m_s t) \\ &\quad + A_{CP}^{mix,KK} sin(\Delta m_s t), \end{aligned} \tag{1}$$

allows to fit the four CP asymmetry coefficients. These coefficients depend on the hadronic parameters d (d') and ϑ (ϑ') that are the magnitude and phase of the penguin-to-tree amplitude ratio of the decay transitions for $B^0 \rightarrow \pi^+\pi^-$ ($B^0_s \rightarrow K^+K^-$). In the limit of exact U-spin symmetry of the strong interactions, the relations $d = d'$ and $\vartheta = \vartheta'$ hold, and the measurements of the four asymmetry coefficients allow the simultaneous determination of ϕ_d and γ, provided that ϕ_s is determined previously from $B^0_s \rightarrow J/\psi\phi$. Moreover, ϕ_d will be accurately known by the $B^0 \rightarrow J/\psi K^0_S$ measurement, thus allowing a more precise determination of γ.

The reconstruction of $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$decays requires K/π separation with very good efficiency and purity. This is achieved by the particle identification system of LHCb, as shown in Fig. 6. In one year of data taking, LHCb expects to reconstruct 26'000 $B^0 \rightarrow \pi^+\pi^-$, 37'000 $B^0_s \rightarrow K^+K^-$ and 135'000 $B^0 \rightarrow K^+\pi^-$ decays, with a sensitivity for the determination of γ of $\sigma_\gamma \sim 5$ degrees.

6. Conclusion

In the coming years experiments at LHC will pursue an extensive program on B-physics, complementary to the one of B-factories, with high statistics and access to B^0_s-decays. ATLAS and CMS will contribute significantly for rare decay modes including muons, in particular during the first years of low luminosity running. With its dedicated flexible and robust trigger, LHCb can fully exploit the large B-meson yields from the LHC start-up, with excellent mass and decay-time resolution and particle identification. With the statistics of five years of data taking one expects a precision in the determination of γ of ~ 2 degrees in decays involving tree only, and decays involving tree and loop diagrams. Comparing these complementary measurements will allow to disentangle possible New Physics effects. The measurement of rare decays and of the weak $B^0_s\overline{B}^0_s$ mixing phase down to a precision better or comparable with the Standard Model predictions will also contribute to the search for New Physics.

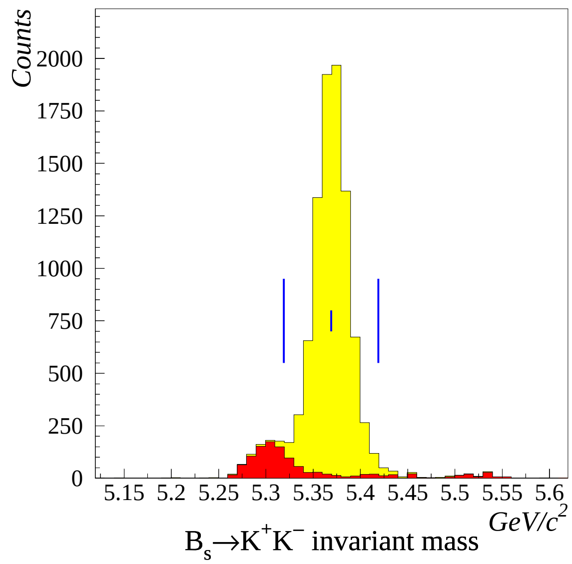

Figure 6: Invariant mass distribution of selected $B^0_s \rightarrow K^+K^-$ candidates. The light-shaded (yellow) histogram is the signal and the dark (red) one represents the background from $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow K^+\pi^-$, $B^0_s \rightarrow \pi^+K^-$, $\Lambda_b \rightarrow pK^-$ and $\Lambda_b \rightarrow p\pi^-$ decays.

Acknowledgments

I would like to thank Olivier Schneider for the help in providing many detailed information on the LHC B-physics program in general, and to Maria Smizanska and Thomas Speer for discussion on the ATLAS and CMS performances in particular.

References

[1] Technical Design Report, CERN/LHCC 99-014/015, (1999).
[2] Technical Proposal, CERN/LHCC 94-38, LHCC/P1, (1994).
[3] Technical Design Report, CERN/LHCC 2003-030, (2003).
[4] A. Ali, Nucl. Phys. Proc. Suppl. **59** , 86, (1997).
[5] M. Gronau and D. Wyler, Phys. Lett. **B 265**, 172 (1991); I. Dunietz, Phys.Lett. **B 270**, 75 (1991).
[6] D. Atwood, I. Dunietz an A. Soni, Phys. Rev. Lett. **78**, 3257 (1997).
[7] http://pdg.lbl.gov/2005/listings/contents_listings.html
[8] R. Fleischer, Phys. Lett. **B 459**, 306, (1999).