B PHYSICS PROSPECTS AT LHC

MARTA CALVI

Dipartimento di Fisica Università di Milano Bicocca and INFN Sezione di Milano

Future experiments at the LHC will have the opportunity to pursue an extensive program on B Physics and CP violation. The expected performances will be presented here.

1 Introduction

First pp collisions are foreseen in the Large Hadron Collider at Cern in summer 2007. At that time several precise measurements will be available from B-Factories and Tevatron experiments to test the CKM paradigm of flavour structure and CP violation. However New Physics could be hidden in B decays, specially those involving box and penguin diagrams. On the other hand, if New Physics will be found at LHC in direct searches, B physics measurements will have to sort out the corresponding flavour structure.

The B Physics program at LHC is rich. It will include precise measurement of $B_s^0\bar{B}_s^0$ mixing (mass difference, width difference and phase), precise measurements of the angle $\gamma$ (including from processes only at tree level), several measurements of other CP phases in different channels for over-constraining the Unitarity Triangles, search for New Physics effects appearing in rare exclusive and inclusive B decays, studies of b-baryons and $B_c$ physics and also studies of b production.

B physics at LHC has the great advantage of a high $b\bar{b}$ cross section ($\sigma_{bb} \sim 500 \mu b$), several orders of magnitude higher than at the $\Upsilon(4S)$, and of the production of all species of $b$-hadrons, including $B_s$, $b$-baryons and $B_c$. The challenge in the analysis is related to the presence of the underlying event, to the high particle multiplicity and to the high rate of background events (the inelastic cross section is $\sim 80 \text{ mb}$). These features demand to the experiments an excellent trigger capability, with good efficiency also on fully hadronic decay modes of $b$-hadrons, excellent tracking and vertexing performance, allowing for high mass resolution and proper time resolution, and excellent particle identification to separate exclusive decays.
2 LHC experiments

The LHC will collide protons at 14 TeV with a bunch crossing rate of 40MHz.

Two experiments, ATLAS and CMS, are omni-purpose and optimized for discovery physics. Their B physics program is mainly pursued in the first years of running, when the LHC luminosity is expected to be $1-2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$. In the subsequent years at high luminosity ($10^{34} \text{cm}^{-2}\text{s}^{-1}$), when several pp collisions per bunch crossing will pile up, only search for very rare B decays with clear signatures will be performed. Reaches in B Physics will depend on the chosen trigger strategy and allocated bandwidth. B events will be mainly triggered by high $p_T$ muons or di-muon triggers. CMS also exploits on-line tracking for the selection of exclusive B events at High Level Trigger (1), while ATLAS foresees a flexible trigger strategy with the progressive addition of other triggers (2).

LHCb is the LHC experiment dedicated to B physics. It will locally tune the luminosity, by de-focusing the beams, to $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$, in order to limit pile up of pp interactions. Taking the nominal year period as $10^7$ s, an integrated luminosity of 2 fb$^{-1}$ per year is expected, corresponding to $10^{12}$ $b\bar{b}$ events/year. LHCb is a single-arm forward detector in the polar region 10-300 mrad, with good acceptance for $b$ events due to the forward peaked production of $b$-hadrons at LHC. A schematic view of the LHCb detector is shown in Figure 1. A description of the detector and its performances can be found in (3). The LHCb trigger is operating in three stages. The Level-0 reduces the rate to 1 MHz requiring the presence of leptons or photons or hadrons with high $p_T$ while the Level-1 selects on high impact parameter, high $p_T$ tracks. The High Level Trigger is a software trigger using the full information on the event. Its output contains 200 Hz of exclusive B candidates and about 1.8 KHz of inclusive channels to be used also for calibration purposes and systematic studies.
3 Prospects on $B^0_s \bar{B}^0_s$ mixing measurements

3.1 Measurements of $\Delta m_s$

The $B^0_s \bar{B}^0_s$ oscillation has been proven to be too fast to be resolved at LEP and SLC experiments. The best limit today is $\Delta m_s > 14.5 \, \text{ps}^{-1}$ at 95\%CL. The Tevatron is at present the only available source of $B^0_s$ mesons and CDF and DØ have the chance to find a mixing signal in the coming years. The measurement requires best performances in the event reconstruction and purity, proper time resolution and flavour tagging.

But the definitive answer on $B^0_s \bar{B}^0_s$ mixing may come from LHC. The best channel for these studies is $B^0_s \to D_s^- \pi^+$. Results of LHCb full simulation indicate a proper time resolution of $\sigma_\tau \simeq 40 \, \text{fs}$ and an annual yield of 80,000 events with a signal over background ratio of about 3. The effective efficiency for flavour tagging is estimated to be about 7\%. The expected proper time distribution of tagged events is shown in Figure 2 for two different values of $\Delta m_s$. In one year of data-taking a 5\% observation of oscillation is expected if $\Delta m_s < 68 \, \text{ps}^{-1}$. Once observed, the precision to measure $\Delta m_s$ is $\sim 0.01 \, \text{ps}^{-1}$.

ATLAS will also make a 5\% observation of oscillations if $\Delta m_s < 22 \, \text{ps}^{-1}$, in 10 fb$^{-1}$. Most recent expectation of CMS is lower, due to restriction to the trigger bandwidth allocated to this channel.

3.2 $\phi_s$ and $\Delta \Gamma_s/\Gamma_s$ measurements

The phase $\phi_s$ of $B^0_s \bar{B}^0_s$ mixing is expected to be very small in the Standard Model $\phi_s = -2\chi = -2\lambda^2 \eta \simeq -0.04$ resulting in a high sensitivity to possible New Physics contributions in $b \to s$ transitions. Hints of New Physics could also be found in the measurement of the decay width difference between the two CP eigenstates $\Delta \Gamma_s = \Gamma(B_L) - \Gamma(B_H)$. In the Standard Model $\Delta \Gamma_s$ is expected to be of the order of 10\%. Both quantities can be measured using $B^0_s \to J/\psi \phi$ decays ($J/\psi \to \mu \mu, \phi \to KK$). In a decay to two vector mesons three distinct amplitudes contribute:
two CP even and one CP odd. The CP components can be disentangled on a statistical basis taking into account the distribution of the so-called transversity angle $\theta_{tr}$, defined as the angle between the positive lepton and the $\phi$ decay plane, in the $J/\psi$ rest frame. The physics parameters can be extracted from a simultaneous fit to the proper time, $\cos(\theta_{tr})$ and $\Delta m_s$ distributions of tagged events. In one year of data-taking LHCb expects to collect 100,000 $J/\psi(\mu\mu)\phi$ decays and to obtain a precision on $\sin(\phi_s)$ of about 0.06 and precision on $\Delta \Gamma_s/\Gamma_s$ of about 0.018 (for $\Delta m_s=20$ ps$^{-1}$). The sensitivity will be increased adding $B_s^0 \rightarrow J/\psi\eta$ events, which are pure CP eigenstates. About 7000 events per year are expected in this channel.

CMS and ATLAS, with 30 fb$^{-1}$, expect a sensitivity on $\sin(\phi_s)$ of 0.03-0.04 and a sensitivity on $\Delta \Gamma_s/\Gamma_s$ of 0.015-0.012, respectively.

4 Measurements of $\gamma$

4.1 $\gamma$ measurements from $B_s \rightarrow D_s K$ decays

$B_s^0 \rightarrow D_s^+ K^-$ and $\bar{B}_s^0 \rightarrow D_s^- K^+$ decays can proceed through the tree diagrams shown in Figure 3 which can interfere via mixing. From the measurement of the time-dependent decay asymmetries the phase $\gamma + \phi_s$ can be extracted, together with a strong phase. If $\phi_s$ has been determined otherwise, $\gamma$ can be extracted, with little theoretical uncertainty, and insensitive to New Physics.

Strong particle identification capabilities are required to separate $B_s \rightarrow D_s K$ decays from $B_s \rightarrow D_s \pi$ background having $\sim$12 times larger branching fraction. The performance of the LHCb RICH detectors will be fully adequate, as it is shown in Figure 4. Monte Carlo studies have shown that 5400 $D_s^\mp K^\pm$ events will be collected in one year of data-taking, with S/B ratio, estimated from $b\bar{b}$ events, larger than 1. Hereafter only limits on S/B are quoted, due to the limited statistics with which the value of B has been determined. The $D_s^\mp K^\pm$ asymmetries are shown in Figure 4. A sensitivity of $\sigma_\gamma = 14$ degrees can be obtained if $\Delta m_s=20$ ps$^{-1}$. 

![Tree diagram for $B_s \rightarrow D_s K$ decays](image1.png)

![Time-dependent $B_s^0 \bar{B}_s^0$ asymmetry of simulated $D_s^+ K^-$ (top) and $D_s^- K^+$ (bottom) candidates, for $\Delta m_s = 20$ ps$^{-1}$.](image2.png)
4.2 $\gamma$ measurements from $B^0 \to D^0 K^{*0}$ decays

A theoretically clean determination of the angle $\gamma$ can be performed using $B^0 \to D^0 K^{*0}$ decays. The tree diagrams of the decay are shown in Figure 5. The method, described in (1), is based on the measurement of six time-integrated decay rates for $B_d^0 \to D^0 K^{*0}, D^0 K^{*0}, D_{CP} K^{*0}$ and their CP conjugates; the decays are self-tagged through $K^{*0} \to K^\pm \pi^\mp$, while the CP auto-states $D_{CP}$ can be reconstructed in $K^\pm K^\mp$ and $\pi^+ \pi^-$ modes. This method is similar to the analysis of $B^\pm \to D^0 K^\pm$ decays, already performed at the B-Factories, but has the advantage of using two colour-suppressed diagrams with an expected ratio of amplitudes $r = |A(B^0 \to D^0 K^{*0})|/|A(B^0 \to D^0 K^{*0})| \sim 0.4$.

LHCb in one year of data taking expects to collect a total of about 4.000 signal events leading to a sensitivity on $\gamma$ of $\sigma_{\gamma} \sim 8$ degrees.

4.3 $\gamma$ measurements from $B_d^0 \to \pi^+ \pi^-$ and $B_s^0 \to K^+ K^-$ decays

Several strategies have been proposed (5) to extract informations on the angle $\gamma$ from two body charmless decays of $B$ mesons, some of them make use of assumptions on dynamics or on U-spin flavour symmetry.

RICH detectors allow to separate the $K/\pi$ channels with high efficiency and purity, as shown in Figure 6. LHCb in one year of data taking expects to collect 26,000 $B_d^0 \to \pi^+ \pi^-$, 37,000 $B_d^0 \to K^+ K^-$ and 135,000 $B_s^0 \to K^+ \pi^-$ decays, with mass resolution $\sigma(M_B) \sim 17$ MeV and a proper time resolution of $\sigma_t \sim 30$ fs. The two time dependent CP asymmetries

$$A_{CP}(B_d^0 \to \pi^+ \pi^-)(t) = A_{CP}^{dir,\pi\pi} \cos(\Delta m_d t) + A_{CP}^{mix,\pi\pi} \sin(\Delta m_d t)$$

$$A_{CP}(B_s^0 \to K^+ K^-)(t) = A_{CP}^{dir,KK} \cos(\Delta m_s t) + A_{CP}^{mix,KK} \sin(\Delta m_s t)$$

will be used to fit the four CP asymmetries, which will be extracted with a precision of about 6%. Following the method suggested in (5), U-spin symmetry can be exploited to constrain the penguin to tree ratios in the two decays to be the same. Assuming the knowledge of the mixing
phases $\phi_d$ and $\phi_s$ from previous measurements, the $\gamma$ angle can be extracted with a precision $\sigma_\gamma \sim 5$ degrees in one year of data-taking. Additional measurements can be used to test the uncertainty related to the U-spin assumptions.

5 $\alpha$ measurements from $B^0 \rightarrow \rho\pi$ decays

A time dependent Dalitz plot analysis of the three body decay $B^0 \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0$ allows a clean extraction of the angle $\alpha = \pi - \beta - \gamma$, as suggested in (2). LHCb expects to reconstruct 14000 decays per year (with S/B > 1.3) in this channel. The Dalitz distribution is shown in Figure 6. An 11-parameter fit has been used to get an independent measurement of tree and penguin parameters, taking into account resonant and non resonant background sources. A sensitivity $\sigma_{\alpha} < 10$ degrees can be obtained in one year of data-taking.
$B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ is a rare decay with branching fraction of the order of $10^{-6}$ which has a clear experimental signature. The forward-backward asymmetry is defined as

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

where $\theta$ is the angle between the $\mu^+$ 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 S/B > 0.4), this allows a determination of branching fractions and CP asymmetries with a precision of 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 also collect about 2000 events of $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$, with S/B > 7 in 30 fb$^{-1}$.

$B_s \rightarrow \mu^+ \mu^-$ is a rare decay involving flavour changing neutral currents whose branching ratio is estimated to be $BR(B_s \rightarrow \mu^+ \mu^-) = (3.5 \pm 0.1) \times 10^{-9}$ in the Standard Model (8). In various supersymmetric extensions of the Standard model it can be enhanced by one to three orders of magnitude, being $BR \sim (\tan\beta)^6$, for large $\tan\beta$. The best upper limit on the branching ratio at present come from experiments at Tevatron, and reaches few $\times 10^{-7}$ at 95% CL.

In the SM context, LHCb expects to select 17 events per year, with a resolution on the $B_s$ mass of 18 MeV/c$^2$. The background determination is still incomplete and require additional Monte Carlo statistics. No events were selected in the $10^7 b\bar{b}$ event sample used so far.

CMS has studied a selection at the High Level Trigger, giving $B_s \rightarrow \mu^+ \mu^-$ candidates with a rate smaller than 1.7 Hz, and a resolution on the $B_s$ mass of 74 MeV/c$^2$. In 10 fb$^{-1}$ 47 signal events are selected. With a refined selection at the offline level 7 signal events are expected to be retained, with less than 1 background event.

For this search ATLAS and CMS will also exploit the high luminosity runs. In 100 fb$^{-1}$ (1 year at 10$^{34}$) 92 signal events are expected (with 660 of background) and 26 signal events (with $\sim$ 6 of background) respectively. The different levels of background can be attributed to different vertex reconstruction and selection, however an update on these estimations is expected.

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

8 Conclusion

In the coming years CP asymmetries will be measured at LHC using several $B_d^0$ and $B_s^0$ mesons and $b$-baryons decay channels. Very rare decays will also be studied, thanks to the high $b\bar{b}$ cross section available. This program is complementary to the B-Factories one and will allow to complete and improve the available results and possibly to reveal first signals of new Physics.

References

1. V. Ciulli, Eur. Phys. J. C 34, s01, s379-s384 (2004);
2. M. Smizanska, Eur. Phys. J. C 34, s01, s385-s392 (2004);
3. R. Antunes et al, LHCb Collaboration; CERN/LHCC 2003-030 (2003)
4. M. Gronau and D. Wyler, Phys. Lett. B 265, 172 (1991); I. Dunietz, Phys.Lett. B 270, 75 (1991).
5. See for example M. Battaglia, A.J. Buras, P. Gambino and A. Stocchi, eds. CERN-2003-002 and references therein.
6. R. Fleisher, Phys. Lett. B 459, 306 (1999); R. Fleisher and J. Matias, Phys. Rev. D 66, 054009 (2002).
7. A. Snyder, H. Quinn, Phys. Rev.D 48 2139 (1993);
8. A.Ali, Nucl.Phys.Proc.Suppl. 59 (1997) 86-100