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PROSPECTS ON CP VIOLATION IN THE B SECTOR AT HADRON COLLIDERS

Marta Calvi
Dipartimento di Fisica Università di Milano-Bicocca
and INFN Sezione di Milano

Abstract

Hadron Colliders are the most copious source of b hadrons. We present results on B Physics and CP violation from the running experiments CDF and DØ at the Tevatron Run II, and prospects for future measurements by the next generation of experiments: LHCb at LHC and BTeV at Tevatron.

1 Introduction

B decays offer great opportunities to test the Standard Model paradigm of quark mixing and CP violation, but also to discover signal of new couplings and measure their strength and phases. Several B decay modes can be used to measure the sides and the angles of the Unitarity Triangles making possible to over-constraint the Triangles and, comparing different results, eventually show the effects of New Physics.

B physics at Hadron Colliders have the great advantage of the high $b\bar{b}$ cross section, several order of magnitude higher than at e^+e^- Colliders 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 physics analysis is related to the high track multiplicity and to the high rate of background events. This demands to the experiments an excellent trigger capability, with good efficiency also on fully hadronic decay modes of b-hadrons, excellent tracking and vertexing capability, resulting in high mass resolution and proper time resolution, and excellent particle identification capability for separation of exclusive decays.

The feasibility and the good perspectives of this approach have already been demonstrated by the first results obtained at the Tevatron Collider Run II by the CDF and DØ experiments, this program will be further developed and completed in the coming years by the new generation of experiments: LHCb and BTeV.

2 Present and future Experiments

2.1 CDF and DØ

The Tevatron accelerator complex has undergone an extensive upgrade for the Run II phase. The instantaneous luminosity has been growing steadily up to the recent maximum of 7.3×10^{31} sec^{-1} cm^{-2}. Projection for the future are to accumulate from 4.4 to 8.5 fb^{-1} for the year 2009. A description of the major upgrades CDF and DØ Detectors can be found elsewhere [?]. It is relevant to mention here the installation in CDF of a new Silicon Vertex Trigger, selecting on tracks with high impact parameter and high p_T, which is pioneering the hadronic track triggers of the future experiments.

2.2 LHCb and BTeV

A comparison of the future LHC and Tevatron features is given in Table**??**. The higher energy at LHC, with respect to the Tevatron, will give a $b\bar{b}$ cross section about five times larger, with an inelastic cross section which is only a factor 1.6 higher.

The LHCb luminosity will be controlled during the high-luminosity LHC runs by locally de-tuning the beam focus, and will give an average of about 0.4 visible interaction per bunch crossing. Having a single primary vertex have

Table 1: *Expected features of the Tevatron and LHC Colliders*

	LHC (LHCb)	Tevatron (BTeV)
Energy/collision mode	14 TeV pp	2 TeV $p\bar{p}$
$b\bar{b}$ cross section	$\sim 500\mu$b	$\sim 100\mu$b
inelastic cross section	~ 50 mb	~ 80 mb
bunch spacing	25 ns	396 ns
Luminosity (cm^{-2} s^{-1})	2×10^{32}	2×10^{32}
$b\bar{b}$ events per 10^7 s	10^{12}	2×10^{11}
interactions per crossing	~ 0.4	~ 6
σ_z	5 cm	30 cm
expected year of startup	2007	2009

several advantages: reducing confusion to the trigger, reducing particle occupancy and hence improving pattern recognition in the detector components. Low luminosity also ensures less radiation damage.

At the Tevatron, in the present running scheme, the average number of interaction per bunch crossing will be about 6 at the luminosity foreseen for BTeV, however the interactions will be distributed on a long luminous region, and this will allow to reconstruct different interactions.

Both the LHCb and BTeV are single-arm forward detectors. The $b\bar{b}$ production cross section is sharply peaked in the forward (backward) direction, with a strong correlation between the direction of the b and the $\bar{b}$. Therefore the acceptance for the selected B decay and its companion b quark, which is used for tagging purposes, is high. B hadrons produced in the high pseudorapidity region have a larger boost than in the central region, therefore a longer decay length which is an advantage for signal separation. A schematic of the LHCb detector, presently under construction, is shown in Fig. **??**. A description of the detector and its performances can be found in [?]. The BTeV detector [?] has recently undergone first stages of approval and is planned to be installed at the Tevatron Collider during the 2009 summer shutdown. A schematic is shown in Fig. **??**.

3 B Flavour Tagging

The identification of the flavour of the B hadron at its production is necessary for oscillation measurements and most CP violation measurements. This

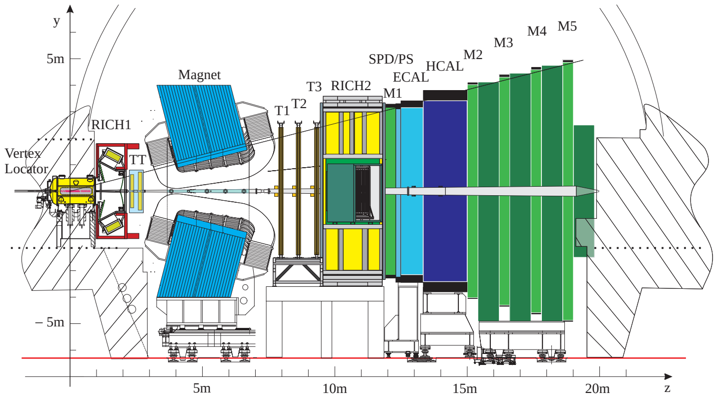

Figure 1: *A schematic of the LHCb detector.*

is usually obtained at the B-Factories by the exclusive reconstruction of the opposite B meson. At Hadron Colliders several inclusive tagging methods are used, which are designed either to identify directly the flavour of the $\bar{b}$ (b) quark in the signal B ($\bar{B}$) meson (same side tag) or that of its companion b ($\bar{b}$) (opposite side tag). Same side tags exploit the correlation between a B_d^0 and a positively charged pion originating in the fragmentation chain, or pions produced in the decay of an excited B^{**} state. The same correlation is present between B_s^0 and K^+ and can be exploited if kaon/pion identification is possible in the detector. Opposite side tags are based on the identification of leptons from the semileptonic decay of the b-hadrons, of kaons from the $b \to c \to s$ decay chain or on the reconstruction of the jet charge or of the charge of an inclusive secondary vertex. The flavour tagging optimization is still in progress in both CDF and DØ experiments, Table **??** shows preliminary results on the tagging power ϵD^2 obtained with different algorithms.

Expectation for LHCb and BTeV flavour tagging performance are also shown in Table **??**. They get substantial improvement from kaon tagging, due to the ID capability.

4 Perspectives on $B_s^0 - \bar{B}_s^0$ mixing measurements

4.1 Δm_s measurements

The $B_s^0 - \bar{B}_s^0$ oscillation frequency is too fast to be resolved at LEP and SLC, despite the relevant statistics of B_s^0 decays collected there. Tevatron is at

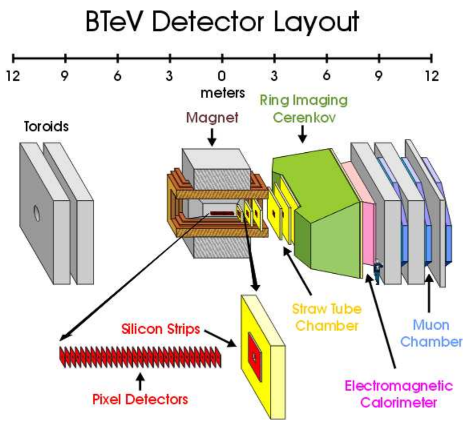

Figure 2: *A schematic of the BTeV detector.*

present the unique available source of B_s^0 mesons and CDF and DØ have the chance to find a mixing signal in the next coming years. The measurement requires best performances in the event reconstruction, purity, proper time resolution and flavour tagging.

If the true value of Δm_s is only slightly above the current world average limit ($\Delta m_s > 14.5$ ps^{-1} at 95% CL) it can be reached using semileptonic decays $B_s^0 \rightarrow D_s \ell \nu X$, ($D_s \rightarrow \phi\pi$, $\phi \rightarrow KK$) since the large statistics compensates the limited proper time resolution caused by the missing momentum of the neutrino. Thanks to the large acceptance on muons, DØ currently has a specific yield in the muon channel of about 31 pb, and expects to reach a 1.5 σ sensitivity up to $\Delta m_s = 15$ ps $^{-1}$ with 0.5 fb^{-1} of data. CDF has a lower efficiency in this channel, but is favored in the selection of exclusive hadronic decays with better purity and proper time resolution. Some improvements are expected in the event yield from the addition of other decay modes like $B_s^0 \rightarrow D_s\pi\pi\pi$ and $D_s \rightarrow K^*K, K_s^0 K$, in the proper time resolution up to $\sigma_\tau = 50$ fs and in the flavour tagging performances to reach ϵD^2=5%. In this condition CDF expects to reach a 5 σ sensitivity up to $\Delta m_s = 18$ ps^{-1} with 1.7 fb^{-1} and up to $\Delta m_s = 24$ ps^{-1} with 3.2 fb^{-1}.

But the definitive answer on $B_s^0 - \bar{B}_s^0$ mixing may come from the next generation of B experiments. Results of LHCb full simulation indicate a proper time resolution for $B_s^0 \rightarrow D_s\pi$ events of $\sigma_\tau = 33$ fs and an annual yield of 80.000 events with a background over signal ratio of 0.32. The expected proper time

Table 2: *Tagging powers ϵD^2 (in%) obtained by the CDF and DØ experiments (preliminary), and expected in the LHCb and BTeV experiments. In the last line combined results are shown, after removing the overlaps between different tagging algorithms.*

	CDF	DØ	LHCb		BTeV	
			B_d^0	B_s^0	B_d^0	B_s^0
Opposite μ	0.7 ± 0.1	1.6 ± 1.1	1.0	1.0	1.2	1.3
Opposite e	in progress	in progress	0.4	0.4	0.8	0.9
Opposite K	in progress	-	2.4	2.4	6.0	5.8
Jet charge	0.42 ± 0.02	3.3 ± 1.7	1.0	1.0	4.8	4.5
Same side π	2.4 ± 1.2	5.5 ± 2.0	0.7		1.8	
Same side K	in progress	-		2.1		5.7
Combined			4.7	6.0	10.0	13.0

distribution of tagged events is shown in Fig. **??** for two different values of Δm_s. In one year of data taking a 5 σ sensitivity up to $\Delta m_s = 68$ ps^{-1} is expected, and a precision on the measurement $\sigma(\Delta m_s) \sim 0.01$ ps^{-1}. Similar performances are expected in BTeV with a 5 σ observation of B_s^0 oscillations up to 51 ps^{-1} in one year.

4.2 ϕ_s and $\Delta\Gamma_s/\Gamma_s$ measurements

The phase ϕ_s of $B_s^0\bar{B}_s^0$ mixing has high sensitivity to possible New Physics contributions in $b \to s$ transition because it is expected to be very small in the Standard Model $\phi_s = -2\chi = -2\lambda^2\eta \simeq -0.04$. Hint of New Physics could also be found in the measurement of the decay width difference between the two B_s CP eigenstates $\Delta\Gamma_s = \Gamma(B_L) - \Gamma(B_H)$ which is expected in the Standard Model to be of the order of 10%. Both quantities can be measured using $B_s^0 \to J/\psi\phi$ decays. CDF and DØ have observed the exclusive decays $B_s^0 \to J/\psi\phi$ ($J/\psi \to \mu\mu, \phi \to KK$). The mass distribution is shown in Fig. **??**.

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. The two CP components can be disentangled on a statistical basis 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.

LHCb in one year of data taking expects to collect 100.000 $J/\psi\phi$ decays

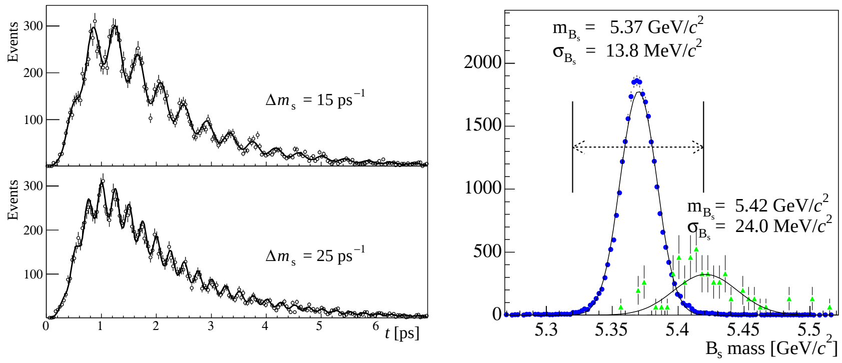

Figure 3: *Left: LHCb Expected proper time distribution of simulated $B_s^0 \to D_s\pi$ candidates that have been flavour tagged as having not oscillated, for two different values of Δm_s. The statistics corresponds to one year of data taking. Right: The B_s^0 mass distribution of $B_s^0 \to D_sK$ decays, as determined from the full LHCb MC. Also shown is the mass distribution of $B_s^0 \to D_s\pi$ decays that have been reconstructed as $B_s^0 \to D_sK$ decays. The histograms are correctly normalized to compensate for the different branching ratios.*

with $J/\psi \to \mu\mu$ and 20.000 decays with $J/\psi \to ee$, with proper time resolution of 38 fs. The values of the physics parameters can be extracted from a simultaneous fit to the proper time, $cos(\theta_{tr})$ and m_s distributions, reaching in one year a precision on the phase ϕ_s of about 3.6 degrees and precision on $\Delta\Gamma_s/\Gamma_s$ of about 0.018, if Δm_s=20 ps^{-1}.

BTeV intends to use $B_s^0 \to J/\psi\eta^{(')}$ events, which allow for the measurements of ϕ_s with a simpler analysis, since they are pure CP eigenstates. Thanks to the excellent resolution of BTeV calorimeter, the expected annual yield in these channels is of 10.000 for $J/\psi\eta$ and 3.000 events for $J/\psi\eta'$, with a B/S ratio of 0.07 and 0.03, respectively. The expected sensitivity on the phase ϕ_s is of about 2.8 degrees in one year.

5 Two body charmless B_d^0 and B_s^0 decays

Several strategies have been proposed [?] to extract informations on the CKM angle γ from two body charmless decays of B mesons, some of them make use of assumptions on dynamics or on U-spin symmetry.

A first sample of $B_{d,s}^0 \to h^+h^{'-}$ events has been collected by the CDF experiment, the invariant mass spectrum is shown in Fig. ??. Different channels contribute to the mass peak: $B_d^0 \to \pi^+\pi^-, K^+\pi^-$; $B_s^0 \to K^+K^-, \pi^+K^-$. A statistical separation has been performed combining PID from specific ionization and kinematic variables. With a subsample of 65 pb^{-1} CDF gets the first evidence of $B_s^0 \to K^+K^-$ decays with a relative branching ratio $[f_s \times BR(B_s^0 \to K^+K^-)]/[f_d \times BR(B_d^0 \to K^+\pi^-)] = 0.74 \pm 0.20(stat) \pm 0.22(syst)$ and the direct CP asymmetry $A_{CP}(B_d^0 \to K^+\pi^-) = 0.02 \pm 0.15(stat) \pm 0.02(syst)$. The next step is the measurement of time dependent asymmetries in flavour tagged samples. In an integrated luminosity of 3.5 fb^{-1}, about 11.700 $B_d^0 \to K^+\pi^-$, 3.500 $B_d^0 \to \pi^+\pi^-$ and 7.100 $B_s^0 \to K^+K^-$ events are expected, with which the uncertainties on the time dependent asymmetries are of the order of 20-30%.

Future experiments will have RICH detectors to separate the K/π channels with high efficiency and purity. LHCb in one year of data taking expects to collect 135.000 $B_d^0 \to K^+\pi^-$, 26.000 $B_d^0 \to \pi^+\pi^-$ and 37.000 $B_s^0 \to K^+K^-$ decays, with mass resolution $\sigma(M_B) = 17$ MeV and a proper time resolution of $\sigma_\tau = 33$ 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 for the four CP asymmetries, giving a precision of about 5-6%. Following the method suggested in [?], exploiting U-spin flavour symmetry and assuming the knowledge of the mixing phases ϕ_d and ϕ_s from previous measurements, the γ angle can be extracted with a precision of $\sigma_\gamma = 4 - 6$ degrees in one year.

BTeV in one year expect to collect 15.000 $B_d^0 \to \pi^+\pi^-$ and 62.000 $B_s^0 \to K^+\pi^-$ decays, with a precision of about 3% on the CP asymmetries.

6 γ measurements from $B \to DK$ decays

$B_s^0 \to D_s^\mp K^\pm$ decays can proceed through two tree diagrams which interference gives access to the phase $\gamma + \phi_s$. If ϕ_s has been determined otherwise, γ can be extracted, from the measurement of the time-dependent decay asymmetries, without theoretical uncertainties, and independently on New Physics.

Strong particle identification capabilities are required to separate the small $B_s^0 \to D_s K$ channel from the ~12 times larger $B_s^0 \to D_s\pi$ one. The performances of the LHCb RICH detectors will be fully adequate, as it is shown in Fig. ??. Montecarlo studies have shown that 5400 $D_s^\mp K^\pm$ events will

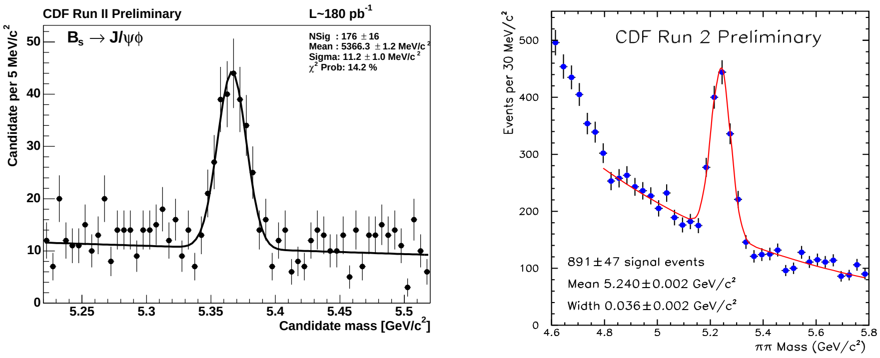

Figure 4: *Left: CDF. Mass distribution of $B_s^0 \to J/\psi\phi (J/\psi \to \mu\mu, \phi \to KK)$ decays. Right: CDF. Invariant mass distribution of $B_{d,s}^0 \to h^+ h^{'-}$ candidates with π mass assumed for both tracks.*

be collected in one year of data taking and a sensitivity of $\sigma_\gamma = 14$ degrees can be obtained, if Δm_s=20 ps^{-1}. Similar performances are expected by the BTeV experiment.

Another theoretically clean determination of the angle γ can come from $B^0 \to D^0 K^{*0}$ decays. The method in ?) is similar to the analysis of $B^\pm \to D^0 K^\pm$ decays, currently under study at the B-Factories, but has the advantage of using B decay amplitudes of more comparable values. It is based on the measurement of six time-integrated decay rates: $B_d^0 \to D^0 K^{*0}, \bar{D}^0 K^{*0}, D_{CP} K^{*0}$ and CP conjugates. The $D^0 K^{*0}$ decays are self-tagged through $K^{*0} \to K^+ \pi^-$, while the CP auto-states D_{CP} can be reconstructed in K^+K^- and $\pi^+\pi^-$ decays. LHCb in one year of data taking expects to collect a total of about 4.000 decays leading to a sensitivity on γ of $\sigma_\gamma = 7 - 8$ degrees.

7 $b \to s$ penguin dominated decays

The discrepancy between $sin(2\beta)$ measured in $B_d^0 \to J/\psi K_S$ and $B_d^0 \to \phi K_S$ channels at the B-Factories has still to be understood and points to a possible New Physics contribution. The $B_d^0 \to \phi K_S$ channel is dominated by a $b \to s$ penguin diagram and similar diagrams are involved in several other B meson decays which can be measured in Hadron Collider experiments. As an example CDF has a first signal of 12 $B_s^0 \to \phi\phi$ events, in a sample of 180 pb^{-1}, from which a preliminary branching fraction of $BR = 1.4 \pm 0.6(stat) \pm 0.2(syst) \pm 0.5(BRs)) \times 10^{-5}$ is obtained.

LHCb will collect about 1200 $B_s^0 \to \phi\phi$ events in one year of data taking (B/S$<$ 0.4) and will also perform studies of channels like $B_d^0 \to \phi K_S, \phi K^{*0}$, $B^+ \to \phi K^+$ and $B_s^0 \to \phi\phi$, $\phi K, \phi\gamma$.

8 Conclusion

CP asymmetries will be measured at Hadron Colliders in the coming years in many channels of B_d^0, B_s^0 mesons and b-baryons decays. In particular, very rare decays will 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 their results.

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