6 The DØ Experiment at the Tevatron $p\bar{p}$ Collider: Search for Rare Decays of the B_s^0-Mesons

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The full DØ collaboration consists of 86 institutes from 19 countries:
Argentina (1), Brazil (3), Canada (4), China (1), Czech Republic (3), Colombia (1), Ecuador (1), France (8), Germany (6), India (3), Ireland (1), Korea (1), Mexico (1), Netherlands (3), Russia (5), Sweden (4), United Kingdom (3), United States of America (36) and Vietnam (1)

(DØ Collaboration)

Until LHC turns on in 2007 the Tevatron collider at the Fermi National Accelerator Laboratory, Batavia, USA, will remain the world's highest-energy accelerator with an available center of mass energy of $\sqrt{s} = 2$ TeV. The accelerator is routinely delivering $p\bar{p}$ collisions with a peak luminosity of 1.7×10^{32} cm^{-2}s^{-1}. The two main detectors, CDF and DØ, are taking continuously collision data and have recorded more than 1 fb^{-1} of collision data up to now. The Tevatron physics program is rich and includes direct and indirect searches for as yet unknown particles and forces, including those that are predicted in the Standard Model (SM) like the Higgs boson and those that would come as a surprise. Moreover, numerous measurements of various B meson decay modes have already allowed the investigation of B meson properties that are not accessible at e^+e^- annihilation machines. One of the most recent results highlighting Tevatron's great potential in B physics is the first direct experimental determination (1) of the oscillation frequency Δm_s in the B_s^0 meson system albeit with large uncertainties. The precise value of the oscillation frequency Δm_s is of large importance for the fundamental parameters of the CKM matrix and will be later accurately measured at LHCb. A participation in the Tevatron B physics program is therefore one of the best preparations of a successful contribution in the physics activities at LHCb.

The main physics topic of the DØ group at the Physik Institut is the investigation of flavor-changing neutral current (FCNC) B meson decays. FCNC decays are forbidden in the SM at tree level but proceed through higher order diagrams at low rate. Due to interference effects with new particles in the loops FCNC decays are a good place to probe new physics and to provide severe constraints on several models beyond the SM. For instance, the purely leptonic decay amplitude of $B_s^0 \rightarrow \mu^+\mu^-$ suffers from helicity suppression and has therefore a small branching ratio in the SM. However, it can be significantly enhanced in most extensions of the SM: in type-II two-Higgs-doublet models (2HDM) the branching fraction depends only on the charged Higgs mass M_{H^+} and $\tan\beta$, the ratio of the two neutral Higgs field vacuum expectation values, with the branching fraction growing like $(\tan\beta)^4$ (2). In the minimal supersymmetric standard model (MSSM), however, $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) \propto (\tan\beta)^6$, leading to an enhancement by up to two orders of magnitude (3) compared to the SM value of $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = 3.5 \times 10^{-9}$, even if the MSSM with minimal flavor violation (MFV) is considered, in which case the CKM matrix is the only source of flavor violation.

Since this decay shows such a strong sensitivity to many new models and its amplitude is theoretically very clean, it allows one of the most sensitive (indirect) searches for new physics with the statistics presently available at the Tevatron. Moreover, in a long-term perspective, the LHCb experiment expects to discover this process being one of the most important prospects in the B-physics program at hadron colliders.

In October 2005 Ralf Bernhard completed his PhD thesis on an analysis of rare B_s^0 decays using DØ data (4). As one of his main results he conducted a search for $B_s^0 \to \mu^+\mu^-$ events. The result of this analysis using 300 pb^{-1} of data was published in Ref. (5) and allowed to set an upper bound at a 90% C.L. of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.0 \times 10^{-7}$. This upper limit was then combined (6) with the CDF result taking correlated systematic uncertainties properly into account to obtain the world-best limit on $B_s^0 \to \mu^+\mu^-$. The combined exclusion limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.2 \times 10^{-7}$ at a 90% C.L. is used to constrain supersymmetric models at high $\tan\beta$.

An updated DØ analysis on $B_s^0 \to \mu^+\mu^-$ is presently being performed by Ralf Bernhard and will exploit additional 400 pb^{-1} of DØ data. It is expected to release a new result by summer 2006. The signal region in the analysis is currently kept hidden during the optimization in order to avoid any experimenter's bias. The events next to the region around the B_s^0 invariant mass are used to determine the background and as a normalization mode events from the known decay $B^\pm \to J/\psi(\to \mu^+\mu^-)K^\pm$ are reconstructed. The current sensitivity at a 90% C.L. of the entire DØ data set is given by 1.9×10^{-7}. A new combination with CDF will then allow to further push the branching ratio of this important decay to smaller values.

A second analysis of Ralf Bernhard focused on the search for rare $B_s^0 \to \mu^+\mu^-\phi$ events, which is an exclusive FCNC process mediated by $b \to s\,l^+l^-$ quark transitions. Since the decay has a hadronic final state, the SM calculation of the branching ratio has larger theoretical uncertainties than $B_s^0 \to \mu^+\mu^-$. In addition, the decay $B_s^0 \to \mu^+\mu^-\phi$ is not helicity suppressed showing therefore less sensitivity to new physics. The analysis using 450 pb^{-1} of data was just recently concluded and submitted to Phys. Rev. Lett. (7). In the analysis the search for the non-resonant decay is normalized to the known resonant decay $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$ since the final event signature is the same and many systematic uncertainties tend to cancel in the ratio. For the search of the rare candidate events we have used discriminating variables to best exploit the properties of the signal decay and the multi-variate technique of a random-grid search to optimize the analysis. After all cuts zero events were found in the signal box with an expected background of 1.6 ± 0.4. The upper limit on the decay $B_s^0 \to \mu^+\mu^-\phi$ is then calculated to be 3.2×10^{-6} at a 90% C.L improving the only existing published limit (8) by CDF by a factor of ten. The new result is only a factor of two above the SM and an updated analysis may well yield to the first observation of a FCNC decay in the B_s^0 meson system. The future refinement of this search using more available data from DØ will be one of the contents of the PhD thesis of Andreas Wenger. Moreover, he will extend the search to $B_d^0 \to K^*\mu^+\mu^-$ events as well.

The anticipated luminosity at Tevatron will accumulate to about 4 fb^{-1} in fall 2007, the time when LHC turns on. In case of no signal, an expected upper limit on the branching fraction of $B_s^0 \to \mu^+\mu^-$ of 2×10^{-8} at a 90% C.L. is possible if both experiments, CDF and DØ are combined. Although such a limit will be sufficient to exclude large regions of very large $\tan\beta$ in the framework of supersymmetric models, the expected sensitivity is still about $10\times$ worse than the SM prediction. Thus, an experimental observation of the decay at a SM rate is clearly out of reach at Tevatron, but will be possible at the LHC. The LHCb experiment, for instance, expects an annual yield of 17 reconstructed $B_s^0 \to \mu^+\mu^-$ decays and is very likely to discover this rare decay at the first time if no significant enhancements due to new physics exist. After all the DØ analysis activities on rare B_s^0 decays represent an important ingredient for the preparation of physics analysis at the upcoming LHCb.

The DØ detector is presently being upgraded in the Tevatron shutdown lasting from March to June 2006 by installing a new silicon detector layer. This additional layer is very close to the beam pipe and its insertion into the existing detector becomes necessary to compensate for the radiation induced damage of the silicon device. We have contributed to the production of this new layer and developed together with the Swiss based company Dyconex long flexible fine-pitch cables, which transmit the analog signals from the silicon sensors to the front-end electronics situated at the module's end. Christophe Salzmann who has just started his master thesis on the analysis of $B_s^0 \to \psi(2)\phi$ decays has helped to install the detector at Fermilab in March 2006. Andreas Wenger is presently spending a eight-month research period at Fermilab to work on alignment improvement and calibration tasks of the silicon detector. For that reason he will exploit a new detector alignment method that was pioneered (9) by the H1 experiment at DESY.

[1] V. Abazov *et al.*, [DØ Collab.], hep-ex/0603029, submitted to PRL; For CDF result see http://www-cdf.fnal.gov/physics/new/bottom/060406.blessed-Bsmix/

[2] H. E. Logan and U. Nierste, Nucl. Phys. B **586**, 39 (2000).

[3] K. S. Babu and C. F. Kolda, Phys. Rev. Lett. **84**, 228 (2000); A. Dedes *et al.*, FERMILAB-PUB-02-129-T (2002); S. R. Choudhury and N. Gaur, Phys. Lett. B **451**, 86 (1999).

[4] Ralf Bernhard, Search for Rare Decays of the B_s^0 Meson with the DØ Experiment, PhD Thesis U Zurich, 2005.

[5] V. Abazov *et al.* [DØ Collab.], Phys. Rev. Lett. **94**, 071802 (2005); A preliminary result using 300 pb^{-1} is described in DØ note 4733-CONF (2005).

[6] R. Bernhard *et al.*, hep-ex/0508058.

[7] V. Abazov *et al.* [DØ Collab.], hep-ex/0604015, submitted to Phys.Rev.Lett.

[8] T. Affolder *et al.* [CDF Collaboration], Phys. Rev. Lett. **83**, 3378 (1999).

[9] V. Blobel, Software Alignment for Tracking Detectors, invited talk given at the Workshop on Tracking in High Multiplicity Environments, TIME'05, Zurich, October 2005. Submitted to NIM.