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Recent results on B physics at Tevatron

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The measurement of the CP violation in the b-meson system and of b-meson rare decays provides information about the electroweak symmetry breaking in terms of flavour structure of the CKM matrix and flavour changing neutral currents. The deviation of the experimental observations from the Standard Model predictions allows to constrain new physics. In this paper recent results from Tevatron are reported.

1 CDF and D0 experiments at Tevatron

Tevatron is a $p\bar{p}$ collider with a center of mass energy of 1.96 TeV. A total luminosity of 8.8 fb^{-1} was delivered to the experiments and 7.3 fb^{-1} was recorded up to July 2010.

The two experiments at Tevatron, CDF and D0, are suitable for the analysis of b-mesons properties.

The CDF detector relies on an excellent tracking system, with momentum resolution $\sigma_{p_t}/p_t^2 = 0.07\%[\mathrm{GeV/c}]^{-1}$ and impact parameter resolution $\delta D_0 = 40\mu$m. A dedicated trigger allows to provide the track displacement information from the silicon detectors with several 10 kHz rates. The electron identification is performed in the calorimeters and muons are identified in the muon system with a coverage up to $\eta = 1$. The ionization measurement in the drift chambers combined with time of flight measurement in the TOF detector allow an efficient π/K separation used for the identification of kaons from b-quark fragmentation and b-mesons decay.

The key-point of the D0 detector is the excellent coverage of the tracker and of the muon system up to $\eta > 2$. The vertex detector was updated in 2006 with an additional silicon layer L0 near the beam pipe (R=1.6 cm). The momentum resolution is $\sigma_{p_t}/p_t^2 = 0.14\%[\mathrm{GeV/c}]^{-1}$ and the impact parameter resolution is $\delta D_0 = 13\mu\mathrm{m} \oplus 50/\mathrm{p_t}$.

2 New physics in B_s oscillation and CP violation

The $B_s\bar{B}_s$ system is a two states quantum system with flavour eigenstates (b,$\bar{\text{s}}$),($\bar{\text{b}}$,s).

The flavour eigenstates are not CP eigenstates ($\text{CP}\psi_{\text{B}_\text{s}^0} = -\psi_{\bar{\text{B}}_\text{s}^0}$) and mixing between the two states can be mediated by the weak interaction through the flavour-changing transition $b \to s$.

Flavour-changing processes involving quarks are described in the SM by the lagrangian:

$$\mathcal{L} = \frac{g}{\sqrt{2}} \left(\hat{u}, \hat{c}, \hat{t}\right)_L \gamma_\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W_\mu^+ \tag{1}$$

The matrix V_{ij} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1].

The CKM matrix is unitary. The elements of the CKM matrix satisfy the relations $\sum_i V_{ij}V_{ik}^* = \delta_{jk}$ and $\sum_i V_{ij}V_{kj}^* = \delta_{ik}$. The CKM matrix is parameterized by three mixing angles θ_{ij} and one CP violating phase δ. The CP violation is generated in the SM only by the phase δ for flavour changing processes involving quarks. CP violating sources are necessary to explain the matter-antimatter asymmetry observed in nature [4]. Flavour-changing processes in NP models affect the size of the CKM matrix elements and of the CP violating phase.

The $B_s^0\bar{B}_s^0$ mixing is described by the effective Hamiltonian

$$i\frac{\partial}{\partial t}\psi_{B_s^0}(t) = \begin{pmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M - i\frac{\Gamma}{2} \end{pmatrix} \psi_{B_s^0}(t) \tag{2}$$

The off-diagonal terms depend on the elements of the CKM matrix and are sensitive to NP contributions [2]. M_{12} receives contribution from massive internal particles. The main SM contribution is the t-quark and NP models predict highly massive particles which can affect sensitively M_{12}. Γ_{12} receives contribution from light internal particles, as c- or u-quarks. It is not sensitive to NP which has contribution at higher mass scale. The phase $\phi_s = \arg\left(-\frac{\text{M}_{12}}{\Gamma_{12}}\right)$ is also studied. As the SM expectation is $\phi_s = (0.0041 \pm 0.0008)$, ϕ_s is a very sensitive quantity to new physics effects.

Three experimental observables can be constructed after diagonalization of the Hamiltonian 2 and determination of the two $B_{s,L}^0$ and $B_{s,H}^0$ mass eigenstates.

The mass difference between the two mass eigenstates $\Delta M_s = (M_H - M_L) \approx 2\,|M_{12}|$ is sensitive to NP due to the proportionality to M_{12}. It was measured by CDF and

D0 collaboration using 1 fb^{-1} of data [3]. The CDF and D0 experiment report respectively $\Delta M_s = 17.77 \pm 0.10$ (stat) ± 0.07 (syst) ps^{-1} and $\Delta M_s = 18.53 \pm 0.93$ $(stat) \pm 0.30$ $(syst)$ ps^{-1}. The experimental value of ΔM_s and of ΔM_d [5] are combined to determine the CKM matrix element V_{td}, which is used to prove the unitarity condition $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$. The experimental result was found in agreement with the SM expectation [6].

The width difference between the two mass eigenstates $\Delta\Gamma_s = (\Gamma_L - \Gamma_H) \approx 2\,|\Gamma_{12}|\cos\phi_s$ is very sensitive to NP due to the correlation with ϕ_s. The golden mode to study this observable is the measurement of the CP violation in the interference between mixing and decay in $B_s^0 \to J/\psi\phi$. In this decay the relation $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$ is studied from which the angle β_s is defined as $2\beta_s = 2arg\left[-\frac{(V_{ts}V_{tb}^*)^2}{(V_{cs}V_{cb}^*)^2}\right]$. The SM expectation is $\beta_s = 0.04 \pm 0.01$ rad. It is hence very sensitive to effects of NP[1] (section 2.1).

The flavour specific or semi-leptonic CP asymmetries are also sensitive probe of NP. In case $\bar{B}_s^0 \to f$ and $B_s^0 \to \bar{f}$ are forbidden the asymmetry is defined as $a_{sl}^s = \frac{\Gamma(\bar{B}_s\to f)-\Gamma(B_s\to\bar{f})}{\Gamma(\bar{B}_s\to f)+\Gamma(B_s\to\bar{f})} = \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi_s$. The same relation yields for B_d^0 mesons: $a_{sl}^d \equiv \frac{\Gamma(\bar{B}_d\to f)-\Gamma(B_d\to\bar{f})}{\Gamma(\bar{B}_d\to f)+\Gamma(B_d\to\bar{f})} = \frac{\Delta\Gamma_s}{\Delta M_d}\tan\phi_d$. The relation to ϕ_q makes this observables sensitive to NP. These observables are studied in the measurement of the di-muon charge asymmetry[2] $A_{sl}^b \equiv \frac{N_b^{++}-N_b^{--}}{N_b^{++}+N_b^{--}}$. A_{sl}^b receives contribution from both B_s and B_d mesons: $A_{sl}^b = (0.506 \pm 0.043)\,a_{sl}^d + (0.494 \pm 0.043)\,a_{sl}^s$. The SM expectation is $A_{sl}^b = \left(-2.3^{+0.5}_{-0.6}\right) \times 10^{-4}$. NP contributions to the Feynman box diagrams responsible for B_q^0 mesons mixing affect significantly the value of A_{sl}^b (section 2.2).

2.1 CP violation in $B_s \to J/\psi\,(\mu\mu)\,\phi\,(KK)$

The analysis is performed on the decay $B_s^0 \to J/\psi\phi$ with the subsequent two body decays $\phi \to KK$ and $J/\psi \to \mu\mu$.

The final state of the decay $B_s \to J/\psi\phi$ is composed of a mixture of CP eigenstates. As the J/ψ and ϕ are spin-1 particles, the allowed CP states are defined by the relation $CP\psi_{J/\psi\phi} = \eta_{Jpsi}\eta_\phi\,(-1)^L$, with $L = 0, 1, 2$ and η intrinsic CP of the two particles. Two

[1] A relation exists between the angle β_s and the parameter ϕ_s. NP alters the phase $2\beta_s$ to $\phi_s^\Delta - 2\beta_s$ and the phase ϕ_s to $\phi_s + \phi_s^\Delta$. As both ϕ_s and $2\beta_s$ are expected to be very small in the SM, the effects of NP are dominant and of the same size ϕ_s^Δ for both parameters.

[2] N_b^{++} and N_b^{--} are the number of events in which two selected muons in the final state have the same charge

CP-even (L=0,2) and one CP-odd (L=1) states are formed. The total decay amplitude is described in the transversity base [7] and is decomposed in the polarization amplitudes A_0, $A_\parallel$ and $A_\perp$.

Five parameters defined in QCD are used to describe the polarization amplitudes [8]. They are the strong phase and the amplitude of $A_\parallel$, the strong phase and the amplitude of $A_\perp$ and the real-valued amplitude A_0.

The time evolution of each polarization amplitude is calculated from the Schrödinger equation 2. The angular distribution of the particles in the final states is calculated through the decomposition of the $J/\psi \to \mu\mu$ and $\phi \to KK$ decay amplitudes in partial amplitudes [9].

The analysis consists of a likelihood fit to the angular and time distributions in order to extract the value of $\Delta\Gamma$ and β_s. This report refers to the recent CDF update with a data sample of 5.2 fb^{-1} [10]. The analysis relies on:

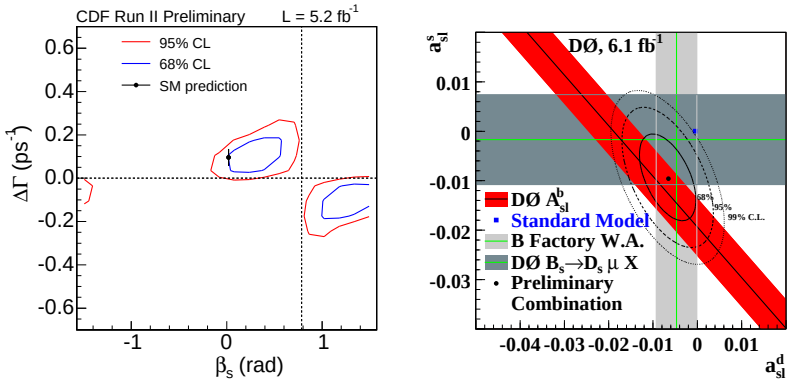
- The event reconstruction and event selection which yield 6504 ± 85 $B_s^0 \to J/\psi\phi$ signal events.
- Two b-tagging methods. The opposite side tagging combines the information of jet charge and lepton identification to reconstruct the flavour of the b quark at the moment of production. It was calibrated using $B^+ \to \Psi K^+$ decay and has an efficiency of 94.2 % and dilution 11.5%. The same side tagging identifies a $K^\pm$ from fragmentation of the b-quark. It was calibrated with a simultaneous measurement of ΔM_s and of a dilution scale factor A. It has a total tagging power of 3.2%.
- Angular efficiency function used to take into account the detector angular acceptance.

The resulting value of $\Delta\Gamma_s$ and β_s (Fig. 1a) is found in agreement with the SM prediction at 0.8 σ. The possibility of the extension of this analysis including data collected with a two displaced tracks trigger is being studied.

2.2 CP violation in di-muon charge asymmetry measurement

The analysis consists of the reconstruction of events with two same charge muons in the final state.

In this paper the results are reported from the D0 experiment obtained with a total data set of 6.1 fb^{-1} [11].



(a) (b)

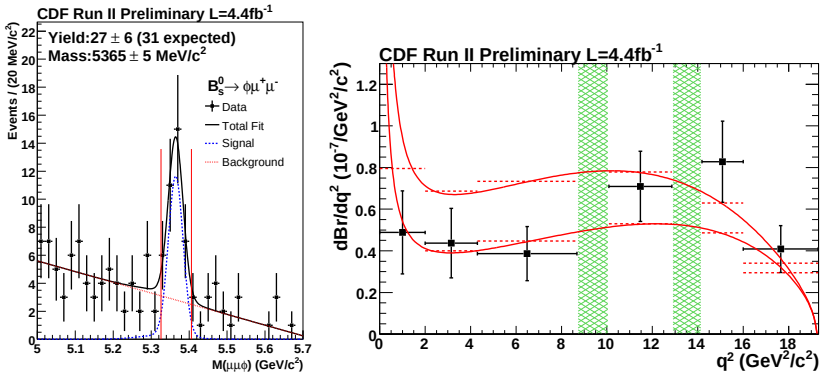
Figure 1: Measurement of CP violation in B meson mixing. In (a) the 68% and 95% CL contours in the $\beta_s - -\Delta\Gamma_s$ plane are shown, from the CDF analysis of $B_s^0 \to J/\psi\phi$ decay. A deviation from the standard model expectation (black point) of 0.8σ is measured. In (b) the comparison of the like-sign dimuon charge asymmetry A_{sl}^b measured by D0 and the SM is shown. Also shown are the existing measurements of a_{sl}^d and a_{sl}^s. A_{sl}^b is found with a deviation of 3.2σ from the SM.

The analysis is performed on two data samples. The inclusive muon sample is composed of events with at least one single muon candidate passing the muon selection and at least one single muon trigger. The like-sign di-muon sample consists of all events with at least two muons candidates of the same charge that pass the dimuon selection and at least one dimuon trigger. This analysis relies on:

- Reversing of the polarity of the toroidal ad solenoidal magnet every two weeks, in order to cancel first order effects related with the instrumental asymmetry.

- Measurement of background contribution to the asymmetry. Muons are considered from the decay of charged kaons and pions and punch-through kaons, pions and protons. The contribution of these backgrounds to the asymmetry a and A are extracted directly from data.

The quantities $a \equiv \frac{n^+ - n^-}{n^+ + n^-}$, where $n^\pm$ is the number of positive and negative identified muons, and $A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$ are extracted respectively from the inclusive and like-sign



(a) (b)

Figure 2: Rare decays. In (a) the invariant mass is shown of the B_s in the first observation of $B_s \to \phi\mu\mu$. In (b) the measurement is shown of the differential branching ratio of $B^0 \to K^{*0}\mu^+\mu^-$, where the solid lines are the SM expectation, the black dots are the data points.

sample. The value of A^b_{sl} is extracted independently from A and a according to the relations $a = k \times A^b_{sl} + a_{bkg}$ and $A = K \times A^b_{sl} + A_{bkg}$ where a_{bkg} and A_{bkg} are the background contributions extracted from data and k and K are scale factors estimated in MC. It was found that $a_{bg} \sim A_{bg}$ so that a subtraction of the two relations reduces the systematic error on A^b_{sl}.

The measured like-sign dimuon asymmetry is $A^b_{sl} = -0.00957 \pm 0.00251(\text{stat}) \pm 0.00146(\text{syst})$ (Fig. 1b). This asymmetry is in disagreement with the prediction of the SM by 3.2σ deviation. This is the first evidence of anomalous CP-violation in the mixing of neutral B-mesons.

3 New physics in rare B meson decays

3.1 $B^0_s \to \mu^+\mu^-$

The decay $B_s \to \mu\mu$ is a Flavour Changing Neutral Current (FCNC) process forbidden at tree level. It occurs through GIM suppressed box or penguin diagrams. The expected branching ratio of this decay in the SM is $BR\,(B_s \to \mu\mu) = (3.42 \pm 0.54) \times 10^{-9}$. Decay amplitudes can be enhanced of few orders of magnitude in extensions of the SM. This

rare decay is hence very sensitive to effects of new physics.

The analysis is performed on a data sample composed of two identified muons, satisfying the di-muon trigger and the di-muon selection criteria. The number of events passing the selection is normalized to the yield of the well studied normalization channel $B^+ \to J/\psi K^+$.

The upper limit on $BR\,(B_s \to \mu\mu)$ measured by the two experiments is 4.3×10^{-8} (CDF [12]) and 5.1×10^{-8} (D0 [13]) at 95% C.L. obtained analysing respectively a data sample of 3.2 fb^{-1} (CDF) and 6.1 fb^{-1} (D0). The result is in agreement with the SM.

3.2 $B_q^0 \to h\mu\mu$

The $B \to h\mu\mu$ decay is a FCNC process, mediated by the quark transition $b \to sll$. It is described by three dominant Wilson coefficients $C_7^{eff}, C_9^{eff}, C_{10}^{eff}$, where C_7^{eff} gets contribution from the photon penguins, C_9^{eff} comes from the vector and C_{10}^{eff} form the axial component of the weak diagrams [14]. The BR and the front-backward asymmetry A_{FB} depend on the Wilson coefficients, which indicate if the underlying dynamics is described by SM or NP physics like supersymmetry, Technicolor or fourth generation.

In the CDF analysis performed on a data sample of about 4.4 fb^{-1} [15] the decay modes $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$ are searched and fully reconstructed. The branching ratio is calculated respect to the normalization channel $B \to J/\psi h$. Both BR and A_{FB} for the $B^+ \to K^+\mu^+\mu^-$, $B^0 \to K^0\mu^+\mu^-$ are measured in agreement with the SM and with the current best results at BaBar and Belle (Fig. 2b).

A first observation with 6.3σ evidence of the decay mode $B_s \to \phi\mu\mu$ is performed in the CDF experiment on a data sample of about 4.4 fb^{-1} (Fig. 2a). The measured BR is $BR\,(B_s \to \phi\mu\mu) = (1.44 \pm 0.33(\text{stat}) \pm 0.03(\text{syst})) \times 10^{-6}$ [15].

4 Conclusions

The high luminosity reached at Tevatron and the interplay between CDF and D0 experiments allow high accuracy in the measurement of CP violation in the b-mesons mixing and of rare b-meson decays. Both measurements are important for the constrain of new physics processes and for the understanding of the Standard Model.

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