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Searches for new physics in the charm and beauty sector at the Tevatron

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Summary. — We report a few recent results from the CDF and D0 Collaborations in the sector of Heavy Flavors. They include measurements of CP-violating asymmetries in B hadron charmless decays, studies of the kinematical properties of flavor changing neutral current decays characterized by the transition of a quark b to a quark s and a muon pair, a search for B_s decay into a muon pair, and measurements of mixing asymmetries in semi-leptonic decays of B_s mesons. All these measurements are sensitive to the possible presence of new physics.

PACS 13.20.He – Decays of bottom mesons.
PACS 13.30.Eg – Hadronic decays of baryons.
PACS 14.40.Nd – Bottom mesons.
PACS 11.30.Er – Charge conjugation, parity, time reversal, and other discrete symmetries.

1. – Introduction

The Tevatron was shut down for good on September 30, 2011 and both CDF and D0 have now approximately 10 fb^{-1} of recorded data to be analyzed. This contribution will report on a few new results obtained during the last year, since 2012 winter conferences, by the CDF and D0 Collaborations about processes that are particularly sensitive to possible deviations from the Standard Model.

The heavy flavor production rates at the Tevatron were very high, actually higher than at B-factories, with the handicap that interesting events were just a small fraction of the total production rate. But some very important detector features helped overcome the handicap, like excellent mass resolution, precision vertex reconstruction, and a powerful trigger on secondary vertices. Another very important feature was the forward-backward symmetry of the detectors and the CP-symmetric $p\bar{p}$ initial state. These result in an important advantage over the LHC in measuring small CP asymmetries because you are guaranteed to get the same number of particles and antiparticles in the acceptance.

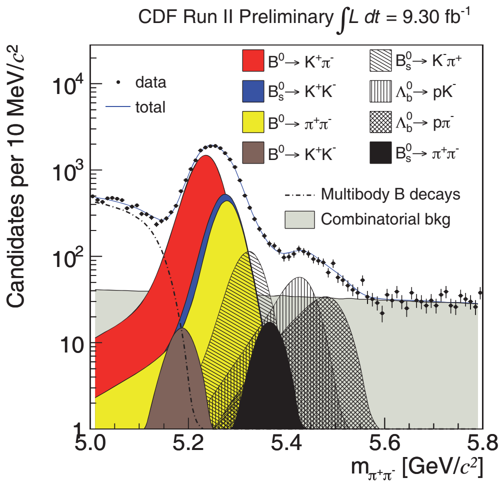

Fig. 1. – Invariant mass distribution of pairs of tracks coming from a secondary vertex. Pion rest mass is assumed for both tracks. Many different processes overlap to form a single broad peak. Individual contributions, as resulting from the fit, are shown with different colors.

2. – A_{CP} in charmless B-hadron decays

Charmless B-hadron decays are particularly interesting because they are more directly connected to the elements of the CKM mixing matrix and their study is important to test its unitarity and detect the possible effects of new physics. Particularly important is the measurement of charge asymmetry (A_{CP}) in this class of decays [1, 2]. A_{CP} is defined as the difference of opposite flavor branching ratios divided by the sum:

$$A_{\mathrm{CP}} = \frac{\mathcal{B}(b \to f) - \mathcal{B}(\bar{b} \to \bar{f})}{\mathcal{B}(b \to f) + \mathcal{B}(\bar{b} \to \bar{f})}\,. \tag{1}$$

A_{CP} can be measured counting the number of opposite flavor decays and correcting for detector efficiencies.

The data sample for this analysis is collected by the trigger on displaced tracks [3, 4]. We search for two tracks coming from a secondary vertex and build the invariant mass assuming the π meson mass for both tracks. Figure 1 shows the mass spectrum on a log scale. Many individual modes overlap in a single broad peak. We use particle ID and kinematics in a multi-dimensional un-binned fit to separate the contributions of different decays (also shown in the figure). The shapes of the individual contributions are obtained from Monte Carlo.

To distinguish different particle species we use both kinematics and dE/dx. While looking for small effects, we need to correct for small charge asymmetries in detector acceptance and efficiency. The CDF detector is not charge symmetric due to the particular structure of the wiring of the central chamber [5] which results in an asymmetry in reconstruction efficiency between positive and negative charged tracks of order of a percent. Additionally, the efficiency for detecting K^+ and K^- is slightly different due to the intrinsically different properties of the interactions of opposite sign K mesons with matter. To correct for these detector induced asymmetries CDF has studied a sample

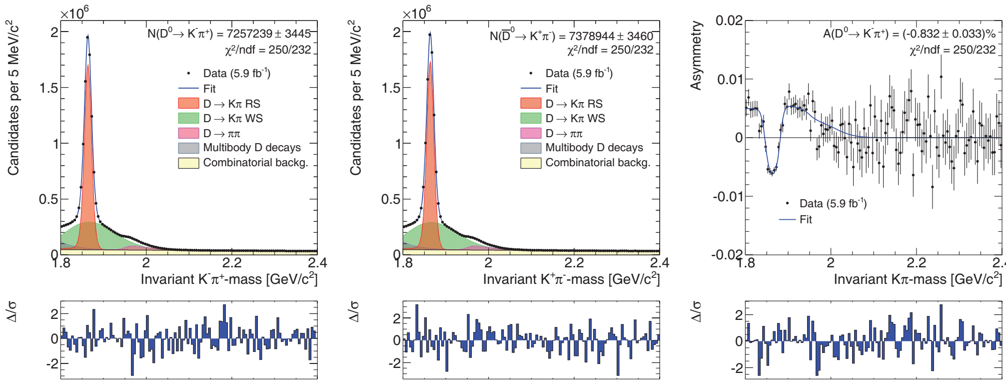

Fig. 2. – Results of the combined fit of the tagged $D^0 \to K^-\pi^+$ samples. Distribution of $D^0\pi_s$ mass for charm (left), and anticharm (center) decays, and asymmetry as a function of the mass (right). Fit results are overlaid.

of about 14 million D^0 and $\bar{D}^0$ meson decays into $K^-\pi^+$ and $K^+\pi^-$. Given the CP-symmetric initial state ($p\bar{p}$) and the forward-backward symmetric detector acceptance, we know that an equal number of D^0 and $\bar{D}^0$ mesons are produced in the CDF detector and, therefore, any measured asymmetry of $K^-\pi^+$ *versus* $K^+\pi^-$, must be artificially produced by detector asymmetries.

Figure 2 shows the raw charge asymmetry as a function of the $K^-\pi^+$ invariant mass. We clearly see the narrow D^0 peak (negative) over a broader $\bar{D}^0$ peak (positive) generated by the wrong mass assignment to the decay products. The number we need, to correct the raw asymmetries, is the height of the narrow negative peak. It represents the charge asymmetry of the detection efficiency for $K^-\pi^+$ *versus* $K^+\pi^-$. It is of the order of 1% or less and is momentum dependent. A sample of $\Lambda \to p\pi$ is used, in a similar way, to correct the measurement of the Λ_b^0 asymmetries.

The CP asymmetry is obtained by taking the difference of the rates of opposite flavor decays divided by their sum. The correction for residual detector asymmetries obtained from the study of D^0 to $K\pi$ decays is applied to the raw rates. This precision measurement is possible because we know that b and $\bar{b}$ are produced equally in the detector acceptance given the CP symmetry of the initial state as are the D^0 and $\bar{D}^0$ mesons used for computing corrections.

Table I shows the latest CDF results on B^0, B_s and Λ_b charmless decays. The result for $A_{CP}(B^0 \to K^-\pi^+)$ has a significance larger than 5.0σ. The updated result for $A_{CP}(B_s^0 \to K^-\pi^+)$ has a significance of 3.0σ and confirms the LHCb evidence for the same decay [6], with the same level of precision. The averaged value of this result and the LHCb measurement is $+0.24 \pm 0.05$ which differs from zero with a significance of 4.8σ and results in a strong evidence of CP violation in the B_s^0 meson system. The observed asymmetries for $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ are consistent with zero.

Note that measurements of B-baryon asymmetries are still unique to CDF. They are all based on the assumption of symmetric production which is very good at the Tevatron given the $p\bar{p}$ initial state.

TABLE I. – *Direct CP-violating asymmetries results. The first quoted uncertainty is statistical, the second is systematic. $\mathcal{N}$ is the number of events determined by the fit for each decay mode.*

Mode	$\mathcal{N}_{b\to f}$	$\mathcal{N}_{\bar{b}\to\bar{f}}$	$A_{CP}(b\to f)(\%)$
$B^0 \to K^+\pi^-$	5313 ± 109	6348 ± 117	$-8.3 \pm 1.3 \pm 0.4$
$B_s^0 \to K^-\pi^+$	560 ± 51	354 ± 46	$+22 \pm 7 \pm 2$
$\Lambda_b^0 \to p\pi^-$	242 ± 24	206 ± 23	$+6 \pm 7 \pm 3$
$\Lambda_b^0 \to pK^-$	271 ± 30	324 ± 31	$-10 \pm 8 \pm 4$

3. – $b \to s\mu^+\mu^-$ decays

The transition of a b quark to an s quark is another golden probe for new physics. This is because it's a flavor changing neutral current process (FCNC), very much suppressed in the Standard Model and sensitive to the presence of new objects in the loops. The corresponding decay modes are three-body or more and they provide a number of kinematical variables whose distributions can be studied in search for deviations from predictions based on the Standard Model.

Figure 3 shows the mass spectra of the processes that were studied at CDF. All six processes are characterized by a transition b to s plus the production of a $\mu^+\mu^-$ pair. They are the following:

$$
\begin{aligned}
B^+ &\to K^+\ \mu^+\mu^-,\\
B^0 &\to K^{*0}(892)\ \mu^+\mu^-,\\
B^0 &\to K_s^0\ \mu^+\mu^-,\\
B^+ &\to K^{*+}(892)\ \mu^+\mu^-,\\
B_s^0 &\to \phi\ \mu^+\mu^-,\\
\Lambda_b^0 &\to \Lambda\ \mu^+\mu^-.
\end{aligned}
$$

By binning signal events in invariant mass squared of the muon pair (q^2), we obtain differential branching fraction distributions. They are shown in fig. 4 for four of the six processes, with the whole statistics available to CDF and compared to a prediction based on the Standard Model. No significant deviation from the predictions is observed.

Figure 5 shows isospin asymmetries calculated as the difference divided by the sum of the rates for B^0 to $K^0\mu^+\mu^-$ and B^+ to $K^+\mu^+\mu^-$:

$$
A_{\rm I}^{(*)} = \frac{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) - \mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{(*)0}\mu^+\mu^-) + \mathcal{B}(B^+ \to K^{(*)+}\mu^+\mu^-)}\,. \qquad (2)
$$

This is shown both for $A_{\rm I}$ (in blue) and $A_{\rm I}^*$ (in red). The plot is again binned in q^2. The SM prediction for this quantity is zero for all q^2. LHCb observed a three sigma effect in the highest q^2 bin [7] which is not confirmed, nor can be excluded, by this measurement.

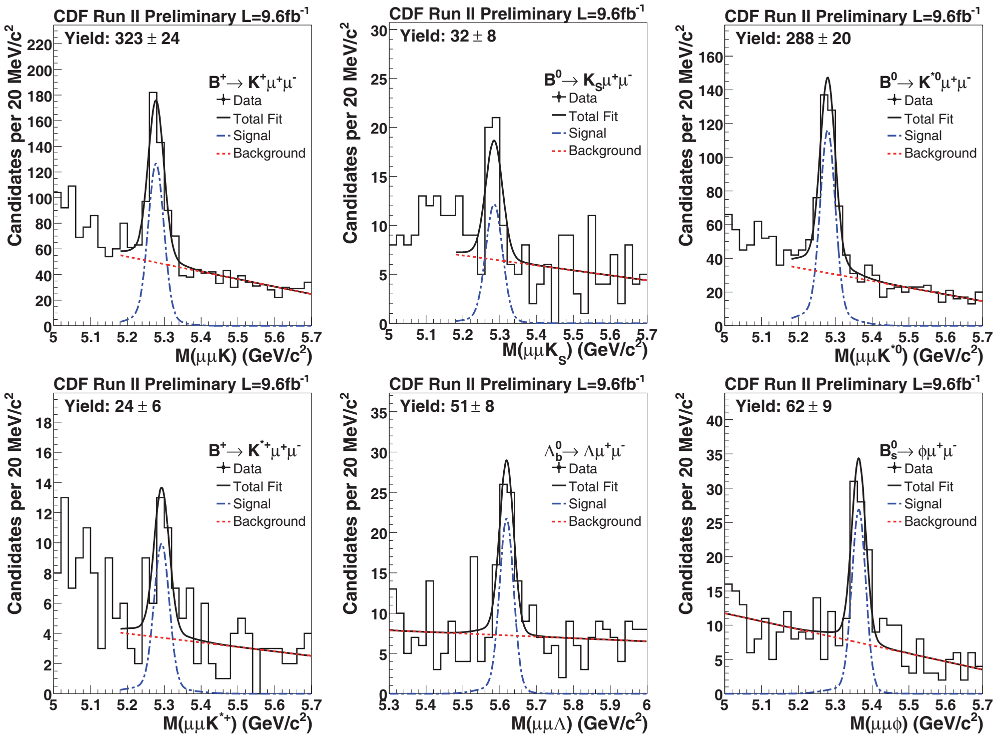

Fig. 3. – Invariant mass distributions for the six decay modes analyzed.

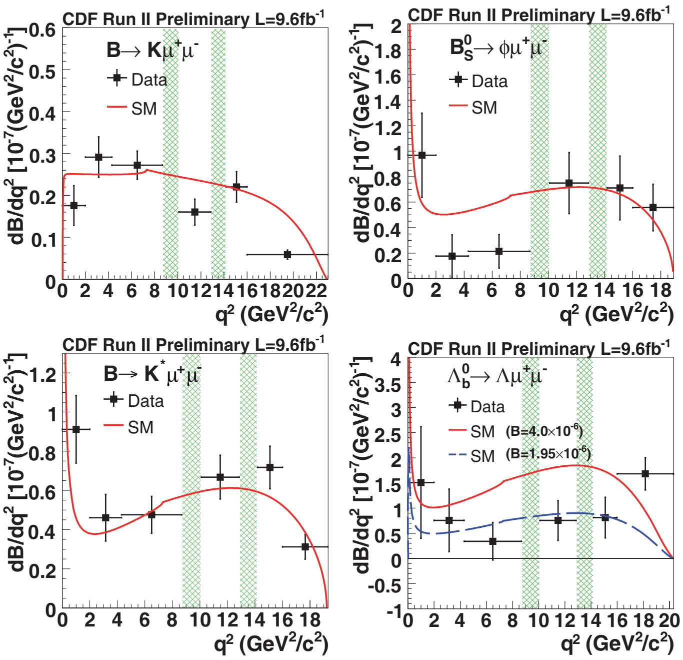

Fig. 4. – Differential branching ratio distributions for four of the decay modes.

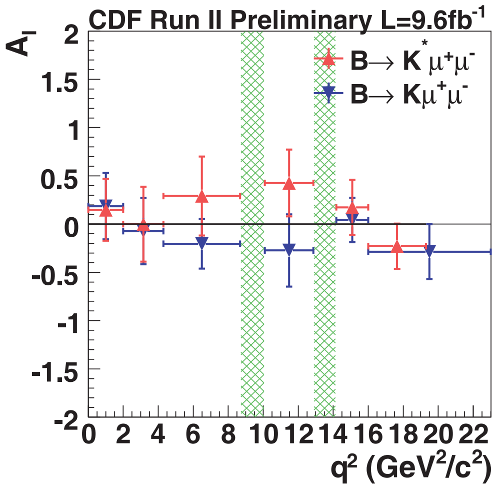

Fig. 5. – Isospin asymmetries as defined in eq. (2) binned in the invariant mass of the $\mu^+\mu^-$ pair (q^2), shown both for A_I (blue) and A_I^* (red).

Figure 6 shows the definition of some kinematical variables in the B to $K^*\mu^+\mu^-$ decay. Particularly interesting are the muon forward backward asymmetry, based on the angle θ_μ between the positive muon and the B meson in the di-muon rest frame and K^* polarization, based on the angle θ_K between the kaon and the B meson in the $K\pi$ rest frame. Both quantities are shown as a function of q^2 in fig. 7. Contributions from B^0 and B^+ are averaged. No significant deviation from the Standard model is observed.

4. – B_s to $\mu^+\mu^-$

The decay of B_s to $\mu^+\mu^-$ is another very important channel to search for possible effects of new physics. The branching ratio is predicted to be very small by the Standard Model ($\approx 3 \times 10^{-9}$) [8, 9] because it is a flavor changing neutral current process and is

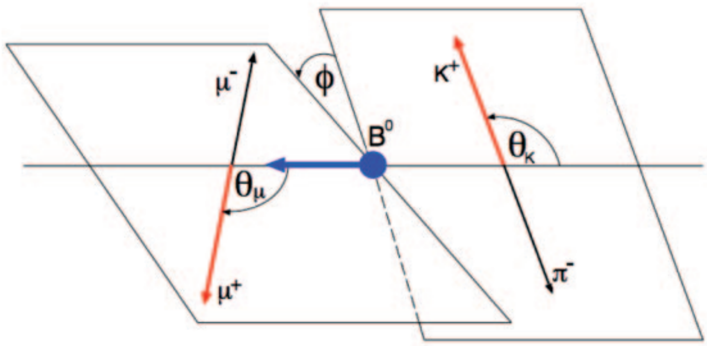

Fig. 6. – Definition of geometrical variables θ_μ and θ_K used in the definition of the muon forward-backward asymmetry and K^* polarization, respectively.

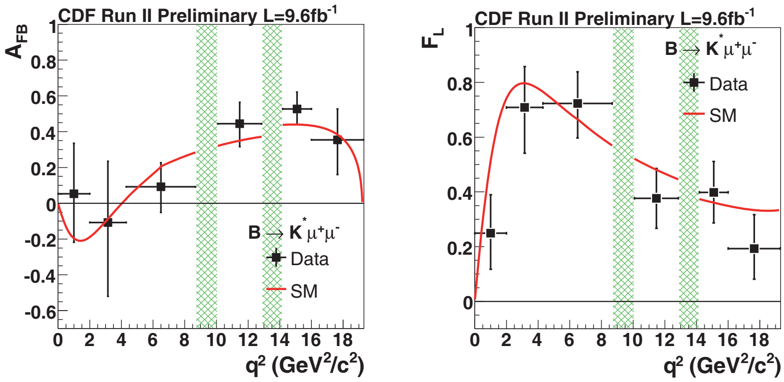

Fig. 7. – Forward-backward muon asymmetry (left) and K^* polarization (right) in $B \to K^* \to \mu^+\mu^-$ decays as a function of q^2. Charged and neutral B's are averaged.

helicity suppressed. The decay rate can therefore be significantly enhanced even by small contributions due to the presence of new particles in the diagrams.

The measurement of the B_s to $\mu^+\mu^-$ branching ratio has been recently updated by the D0 Collaboration [10]. The analysis uses a multivariate technique based on a boosted decision tree to suppress backgrounds. The branching ratio is normalized to B^+ to $J/\psi\ K$. A blind analysis is performed in the di-muon mass range between 4.0 and 7.0 GeV/c^2 with a blinded region from 4.9 to 5.8 GeV/c^2 (fig. 8).

The expected number of background events in the signal window is 4.3 ± 1.6 with a Standard Model signal yield of 1.23 ± 0.13. Opening the box revealed three events in the signal window as shown in fig. 8. This translates to an upper limit for the branching ratio of 15×10^{-9} at 95% CL, a significant improvement from the previous D0 result [11].

5. – CP violation in semi-leptonic decays

Neutral B mesons mix, so they oscillate into their antiparticles. The rate of a B oscillating into a $\bar{B}$ may be different from the opposite process where a $\bar{B}$ oscillates into a B. We can define a semi-leptonic mixing asymmetry as a_{sl} equal to the difference divided by the sum of the rates of a B and a $\bar{B}$ oscillating into their antiparticles and decaying into a final state containing a lepton:

$$a^q_{sl} = \frac{\Gamma(\bar{B}^0_q \to B^0_q \to \ell^+ X) - \Gamma(B^0_q \to \bar{B}^0_q \to \ell^- X)}{\Gamma(\bar{B}^0_q \to B^0_q \to \ell^+ X) + \Gamma(B^0_q \to \bar{B}^0_q \to \ell^- X)}, \tag{3}$$

where q can be d or s according to the flavor of the B mesons.

These mixing asymmetries are predicted by the Standard Model to be of the order of 10^{-4} to 10^{-5} and, therefore, too small to be measured by current experiments [12]. Any significant deviation from zero would be unequivocal proof of the existence of new physics.

A surprising result was obtained by the D0 Collaboration in 2011 in a study of the charge asymmetry of the production rate of pairs of muons of the same sign [13] which showed a significant deviation from zero and therefore a disagreement with the Stan-

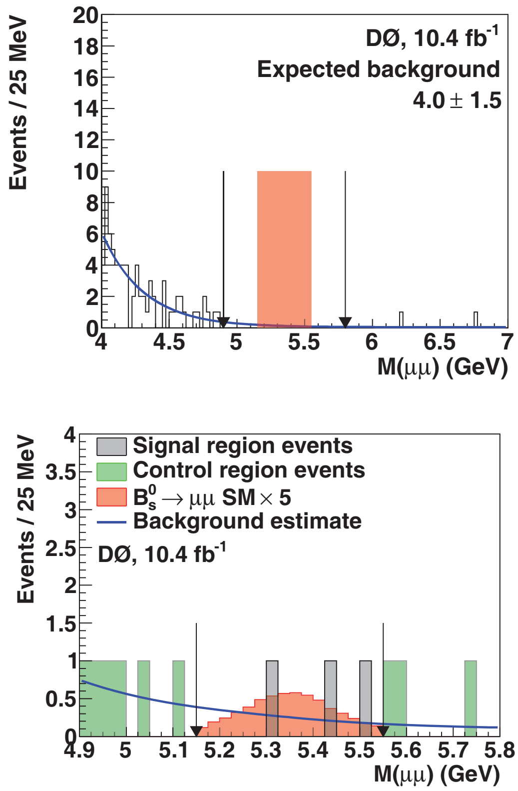

Fig. 8. – Blinded region (arrows) and signal window (shaded) in the invariant mass distribution for the $B_s \to \mu^+\mu^-$ search (top). Three events fall in the signal window (bottom).

dard Model prediction. The significance of the discrepancy was more than 3σ and was interpreted as arising from CP violation in B mixing.

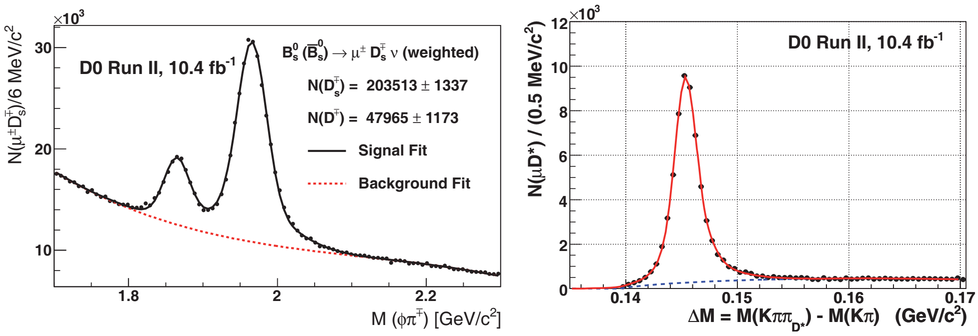

Fig. 9. – $\phi\pi$ invariant mass distribution showing D^+'s and D_s^+'s produced in association with a muon and due respectively to B^0 and B_s^0 decays (left). The D^{*+} peak (right) is due to B^0 decay.

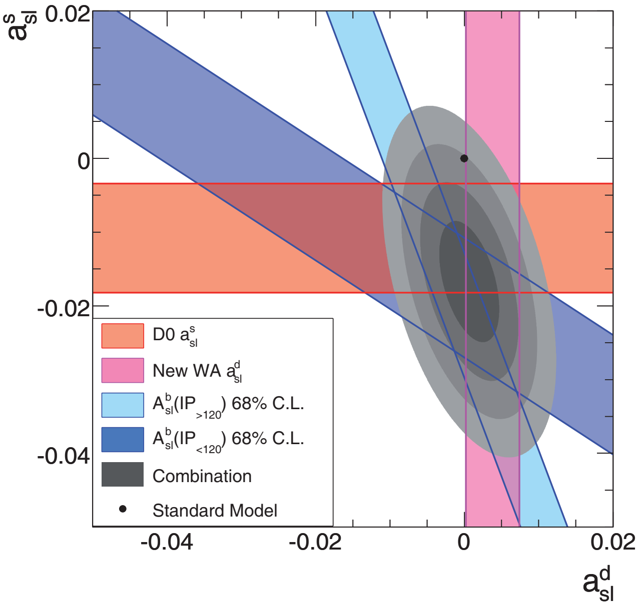

Fig. 10. – Current status of mixing asymmetry measurements shown as bands in the (a^d_{sl}, a^s_{sl})-plane. The different slopes of the bands are due to a different estimated content of B_d and B_s decays in the corresponding samples.

The dimuon asymmetry is sensitive to asymmetries from both B^0_d and B^0_s meson mixing, with approximately equal contributions from each. Given the significance of this result, it is important to try to separate the possible contributions of B^0_d and B^0_s to the mixing asymmetry. This was done studying the three decay modes shown in fig. 9 where a B meson decays into a D meson and a muon plus anything [14, 15]. Raw yields are obtained by fitting the D^+, D^{*+} and D_s mass peaks separately for positive and negative charge. A $D^+(D^-)$ or a $D^{*+}(D^{*-})$ corresponds to the decay of a $B_d(\bar{B}_d)$ while a $D^+_s(D^-_s)$ corresponds to the decay of a $B_s(\bar{B}_s)$. The raw asymmetry is corrected for detector effects and divided by the fraction of decays from oscillated B mesons obtained from Monte Carlo simulation. Other signal sources are assumed to be charge symmetric.

The results are

$$a^d_{sl} = [+0.68 \pm 0.45(\text{stat.}) \pm 0.14(\text{syst.})]\%,$$
$$a^s_{sl} = [-1.12 \pm 0.74(\text{stat.}) \pm 0.17(\text{syst.})]\%.$$

These numbers are both consistent with zero and with the previous result [13]. The overall combination is pictured in fig. 10 as the superposition of bands in the (a^d_{sl}, a^s_{sl}) plane and is still about three sigma away from the Standard Model.

6. – Conclusion

Recent results from the analysis of CDF and D0 data show that some important precision measurements in flavor physics can still be done at the Tevatron and can still be competitive and complementary to similar studies at dedicated facilities (B-factories) or at the LHC. Data taking has ended but analysis continues and more interesting results in flavor physics will be coming in the near future from the Tevatron.

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