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Heavy flavor at the Tevatron

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Summary. — The CDF and D0 experiments at the Tevatron proton-antiproton collider have pioneered and established the role of hadron collisions in exploring flavor physics through a broad program that continues to offer competitive results. I report on latest results in the flavor sector obtained using the whole CDF and D0 data sets corresponding to $\sim 10\,\mathrm{fb}^{-1}$ of integrated luminosity; including B-mesons spectroscopy and production asymmetries, flavor specific decay bottom-strange mesons lifetime. I also present measurements of direct and indirect CP violation in bottom and charm meson decays.

PACS 13.25.Hw – Decays of bottom mesons.
PACS 13.30.-a – Decays of baryons.
PACS 11.30.Er – Charge conjugation, parity, time reversal, and other discrete symmetries.
PACS 14.40.Nd – Bottom mesons ($|B| > 0$).

1. – Introduction

The standard model (SM) has a highly distinctive flavor structure, with no tree-level flavor changing neutral currents (FCNC), and quark mixing described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] involving only a single source of CP violation. The Tevatron $p\bar{p}$ collider, which exploited collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$, is a privileged environment to test the SM, potentially revealing new physics effects in the flavor sector. At the Tevatron, b and c quarks are pair-produced with large cross section [1] and generate all sorts of heavy flavor hadrons. Studies of production and spectroscopy of heavy hadrons help refining our understanding of QCD. The boundaries of weak decays and hadronic physics effects are probed by lifetime and branching fraction measurements. The size of CP violation present in the SM is not sufficient to explain a dynamical generation of the observed matter-antimatter asymmetry of the universe. We are therefore constantly searching for additional sources of CP violation due to physics beyond the standard model. In this paper some of the latest heavy flavor results from the CDF and D0 Collaborations are discussed.

TABLE I. – Ξ_c *and b-baryon mass results. The first uncertainty listed is statistical and the second is systematic.*

Baryon	Mass (MeV/c^2)
Ξ_c^0	$2470.85 \pm 0.24 \pm 0.55$
Ξ_c^+	$2468.00 \pm 0.18 \pm 0.51$
Λ_b	$5620.15 \pm 0.31 \pm 0.47$
Ξ_b^-	$5793.4 \pm 1.8 \pm 0.7$
Ξ_b^0	$5788.7 \pm 4.3 \pm 1.4$
Ω_b^-	$6047.5 \pm 3.8 \pm 0.6$
$M(\Xi_c^0) - M(\Xi_c^+)$	$2.85 \pm 0.30 \pm 0.04$
$M(\Xi_b^-) - M(\Xi_b^0)$	$4.7 \pm 4.7 \pm 0.7$

2. – Spectroscopy

Heavy flavor spectroscopy provides the opportunity to test the theory of QCD bound states in the simplest systems. In the framework of HQET [1] heavy-quark hadrons can be considered the hydrogen atom of QCD, and b hadrons offer the heaviest quarks in bound systems. Mass measurements of bottom baryons Λ_b, Ξ_b^- and Ω_b^- and of charm baryons Ξ_c^0, Ξ_c^+ have been reported by CDF [2] using the decay processes $\Lambda_b \to J/\psi\,\Lambda$, $\Xi_b^- \to J/\psi\,\Xi^-$, and $\Omega_b^- \to J/\psi\,\Omega^-$. The measurements of Ξ_c^0, Ξ_c^+, Ξ_b^-, and Ξ_b^0 mass are made by reconstructing the processes $\Xi_c^0 \to \Xi^-\,\pi^+$, $\Xi_c^+ \to \Xi^-\,\pi^+\,\pi^+$, $\Xi_b^- \to \Xi_c^0\,\pi^-$, and $\Xi_b^0 \to \Xi_c^+\,\pi^-$. In addition to masses, lifetime measurements are also reported. Candidate selection starts with well reconstructed $J/\psi \to \mu^+\,\mu^-$ candidates. Charged particles associated to reconstructed tracks of $p_T > 0.4\,\mathrm{GeV}/c$ (not corresponding to the J/ψ muon candidates) are used to form all the intermediate hadronic and baryonic states. The invariant mass of intermediate particles is used as discriminant and vertex fits of the reconstructed tracks are performed in order to reduce the background when possible (*i.e.* in the case of $\Xi^- \to \Lambda\pi^-; \Omega^- \to \Lambda K^-$). A maximum likelihood fit is used to first extract the mass and signal yield of the baryons in exam. The lifetime is then extracted maximizing a likelihood function with an additional lifetime term free to float while the mass and signal yield terms are fixed. The analysis is tested using $B^+ \to J/\psi\,K^+$, $B^0 \to J/\psi\,K^*(892)^0$, $K^*(892)^0 \to K^+\pi^-$, and $B^0 \to J/\psi\,K_S^0$, $K_S^0 \to \pi^+\,\pi^-$ decay channels. Results of measured baryon masses along with the isospin splitting of the $\Xi_b^{-,0}$ and $\Xi_c^{0,+}$ are reported in table I, while lifetime results are $\tau(\Lambda_b) = 1.565 \pm 0.035(\mathrm{stat}) \pm 0.020(\mathrm{syst})\mathrm{ps}$, $\tau(\Xi_b^-) = 1.32 \pm 0.14(\mathrm{stat}) \pm 0.02(\mathrm{syst})\mathrm{ps}$, and $\tau(\Omega_b^-) = 1.66^{+0.53}_{-0.40}(\mathrm{stat}) \pm 0.02(\mathrm{syst})\mathrm{ps}$. In addition, the analysis reports first evidence for the process $\Omega_b^- \to \Omega_c^0\,\pi^-$, $\Omega_c^0 \to \Omega^-\,\pi^+$ with a significance of 3.3σ as shown in fig. 1, left.

CDF also conducted studies of orbitally excited $B_{(s)}$ mesons using the full CDF Run II data sample [2]. In analogy with the hydrogen atom, the B meson system shows four states defined by the value of the orbital angular momentum combined with the spin of the light quark ($j = 1/2, 3/2$) and the total angular momenta ($J = 0, 1, 2$), fig. 1, right. These states, collectively named $B_{(s)}^{**}$, correspond to fine and hyperfine splitting. Because of experimental sensitivity and parity conservation only states with $j = 3/2$ and $J = 2$ (called B_2^*) are ultimately studied. B_2^* decays include $B\pi$ and $B^*\pi$

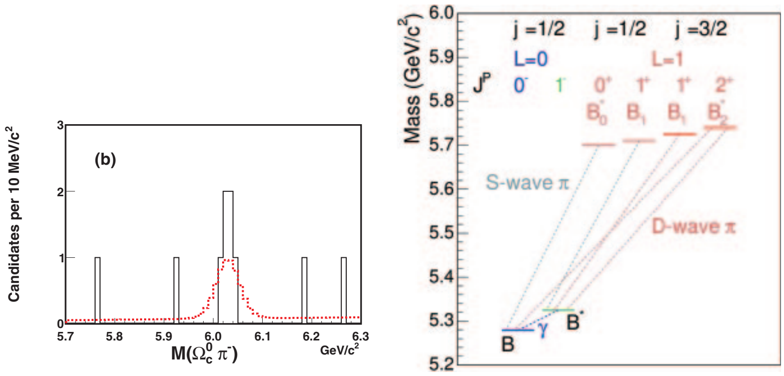

Fig. 1. – Left: Distribution of $\Omega_c^0\,\pi^-$ mass used for the Ω_b^- mass measurement with fit overlaid. Right: Spectrum and allowed decays for the lowest orbitally excited states $B^{**0,+}$.

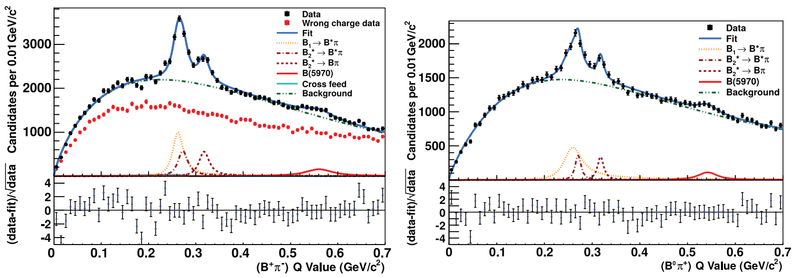

Fig. 2. – Left: B^{**0} candidates with fit results overlaid. Right: B^{**+} candidates with fit results overlaid.

modes, with the low energy photon emitted by the excited B undetected. Therefore the invariant mass spectrum of the $B\pi$ system yields two different structures. To account for the undetected photon a fit to the Q value $(= m(Bh) - m(B) - m_h)$ of the process is performed instead. Candidates are reconstructed using the collection of data from triggers on displaced tracks and $J/\psi \to \mu^+\mu^-$ candidates. Figure 2 shows the Q-values distribution for the B^{**0} and B^{**+} candidates. Evidence for a new resonance, both in the $B^{**0} \to B^+\pi^-$ ($\sim$1400 signal events) and $B^{**+} \to B^0\pi^+$ ($\sim$2600 signal events) decays is found with a significance of 4.4 standard deviations. The masses of the new resonances, named as $B(5970)$, are $5978 \pm 5(\text{stat}) \pm 12(\text{syst})\,\text{MeV}/c^2$ for the neutral state and $5961 \pm 5(\text{stat}) \pm 12(\text{syst})\,\text{MeV}/c^2$ for the charged state. The properties of the orbitally excited and the new $B(5970)^{0,+}$ states are compatible with isospin symmetry.

Additionally masses and widths of fully reconstructed B^{**0}, B^{**+}, and B_s^{**0} states are reported in table II.

3. – Production asymmetry

Forward-backward production asymmetries of heavy quarks gained significant attention over the past few years because of top-quark experimental results in tension with theoretical predictions [3]. The D0 collaboration presented a measurement of the forward-backward asymmetry in the production of $B^\pm$ mesons, $A_{\text{FB}}(B^\pm)$, using fully

TABLE II. – *Measured masses and widths of $B^{**(s)}$ mesons. The first contribution to the uncertainties is statistical; the second is systematic.*

	Q (MeV/c^2)	Γ (MeV/c^2)
B_1^0	$262.7 \pm 0.9\ ^{+1.1}_{-1.2}$	$23 \pm 3 \pm 4$
B_2^{*0}	$317.9 \pm 1.2\ ^{+0.8}_{-0.9}$	$22\ ^{+3}_{-2}\ ^{+4}_{-5}$
B_1^+	$262 \pm 3\ ^{+1}_{-3}$	$49\ ^{+12}_{-10}\ ^{+2}_{-13}$
B_2^{*+}	$317.7 \pm 1.2\ ^{+0.3}_{-0.9}$	$11\ ^{+4}_{-3}\ ^{+3}_{-4}$
B_{s1}^0	$10.35 \pm 0.12 \pm 0.15$	$0.5 \pm 0.3 \pm 0.3$
B_{s2}^{*0}	$66.73 \pm 0.13 \pm 0.14$	$1.4 \pm 0.4 \pm 0.2$

reconstructed $B^\pm \to J/\psi(\to \mu^+\mu^-)K^\pm$ decays [4]. $A_{\mathrm{FB}}(B^\pm)$ is sensitive to the same production asymmetries as $A_{\mathrm{FB}}^{b\bar{b}}$. It is defined as $A_{\mathrm{FB}}(B^\pm) = \frac{N(q_{\mathrm{FB}}>0)-N(q_{\mathrm{FB}}<0)}{N(q_{\mathrm{FB}}>0)+N(q_{\mathrm{FB}}<0)}$, where $q_{\mathrm{FB}} = -q_B\,\mathrm{sgn}(\eta_B)$, and q_B is the $B^\pm$ meson electric charge, $\mathrm{sgn}(x)$ is the sign function, and η_B is the $B^\pm$ meson pseudorapidity. The charge of the kaon in the decay directly identifies the quark flavor (*i.e.*, b or $\bar{b}$). Candidates reconstruction identifies pairs of oppositely charged muons having transverse momentum $p_T > 1.5\,\mathrm{GeV}/c$ and consistent with J/ψ meson decay. An additional charged track with $p_T > 0.7\,\mathrm{GeV}/c$ associated to $K^\pm$ candidate is required to come from the same J/ψ vertex displaced from the $p\bar{p}$ interaction vertex. The J/ψ candidates mass is used for background reduction. Candidates with $B^\pm$ mass in the range 5.05–5.65 GeV/c^2 are retained for analysis. $A_{\mathrm{FB}}(B^\pm)$ is extracted from a maximum-likelihood fit which uses reconstructed $B^\pm$ mass $m_{J/\psi K}$ and the kaon energy E_K as inputs. Detector induced asymmetries on events reconstructed in opposite halves of the detector ($\eta < 0$ *vs.* $\eta > 0$) are accounted for in data samples with no expected production asymmetries. Figure 3 shows measurements of $A_{\mathrm{FB}}(B^\pm)$ and $A_{\mathrm{FB}}^{\mathrm{SM}}(B^\pm)$ *vs.* p_T and $|\eta|$. The measured asymmetry is found to be consistent with zero, $A_{\mathrm{FB}}(B^\pm) = [-0.24 \pm 0.41\,(\mathrm{stat}) \pm 0.19\,(\mathrm{syst})]\%$.

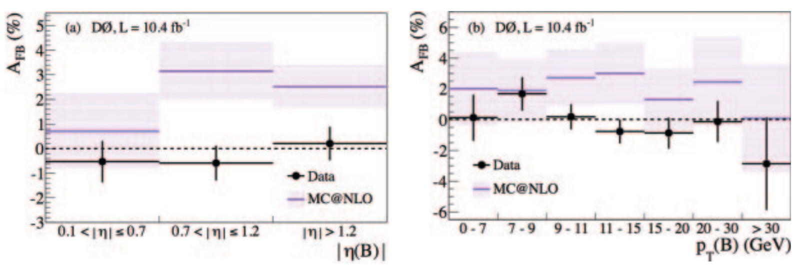

Fig. 3. – Left: Comparison of $A_{\mathrm{FB}}(B^\pm)$ and $A_{\mathrm{FB}}^{\mathrm{SM}}(B^\pm)$ in bins of $|\eta_B|$. Right: Same comparison as in left panel, but in $p_T(B)$ bins.

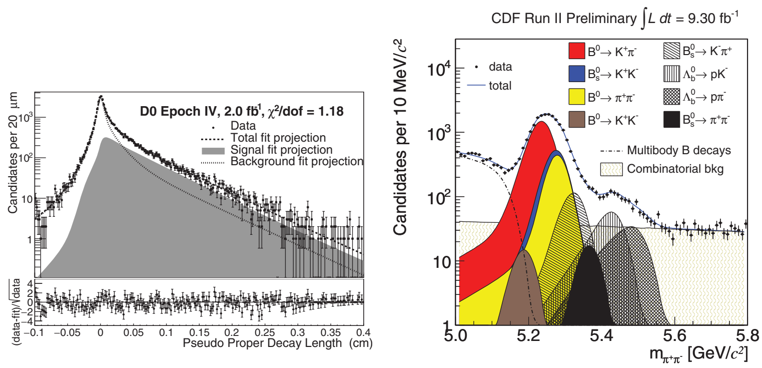

Fig. 4. – Left: PPDL distribution for $D_s^-\mu^+$ candidates in the signal sample for one of the five data periods of the D0 dataset. Fit projections are superimposed and residuals are shown in the bottom panel. Right: Mass distribution of reconstructed $B \to hh'$ candidates using CDF data. Total fit projection overlaid on the data distribution.

4. – Lifetime

Measurements of b-hadron lifetimes play an important role to further our understanding of quark dynamics in heavy hadrons and to refine the models that are important for increasing the knowledge of CKM observables. The D0 experiment performed an updated measurement of the B_s^0 lifetime using the semileptonic decays $B_s^0 \to D_s^-\mu^+\nu X$, with $D_s^- \to \phi\pi^-$ and $\phi \to K^+K^-$ with the full available dataset [5]. The charge of the decay products directly disentangle initially produced B_s^0 or $\bar{B}_s^0$. Selected candidates come from data collected with a single muon trigger requiring muon candidates to have transverse momentum $p_T > 2.0\,\mathrm{GeV}/c$ and a total momentum of $p > 3.0\,\mathrm{GeV}/c$. A pair of oppositely charged particle tracks of $p_T > 1.0\,\mathrm{GeV}/c$ consistent with a ϕ meson ($1.008 < M(K^+K^-) < 1.032\,\mathrm{GeV}/c^2$) is then combined with a third track of $p_T > 0.7\,\mathrm{GeV}/c$ to form a $D_s^- \to \phi\pi^-$ candidate. To reduce combinatorial background the three tracks associated to $\phi\pi^-$ candidates are required to have a common vertex and invariant mass consistent with the D_s^- mass window $1.73 < M(\phi\pi^-) < 2.18\,\mathrm{GeV}/c^2$. $B_s^0 \to D_s^-\mu^+\nu X$ decays are thus finally reconstructed combining D_s^- meson candidate with the muon. All four tracks must be associated with the same $p\bar{p}$ interaction vertex (PV) and the invariant mass must be $3 < M(D_s^-\mu^+) < 5\,\mathrm{GeV}/c^2$. However, due to the missing energy of the neutrino, the B_s^0 meson kinematics cannot be fully reconstructed. Therefore the so called pseudoproper decay length, PPDL $= L_{xy}M/p_T(D_s^-\mu^+)$, is used instead to perform the measurement. In order to account for time- and luminosity- dependent effects the dataset is partitioned into five data-collection periods, each comprising 1–3 fb^{-1} of integrated luminosity. Figure 4, left, shows the PPDL distribution in one of the five data period. Lifetimes are extracted separately for each period using a single exponential fit function which is valid with good approximation [5]. The final flavor-specific lifetime is measured to be $\tau_{\mathrm{fs}}(B_s^0) = 1.479 \pm 0.010\,(\mathrm{stat}) \pm 0.021\,(\mathrm{syst})\,\mathrm{ps}$. Additionally, the method is validated by simultaneous extraction of B^0 lifetime using $B^0 \to D^-\mu^+\nu X$ decays. The B^0 measured lifetime is $\tau(B^0) = 1.534 \pm 0.019\,(\mathrm{stat}) \pm 0.021\,(\mathrm{syst})\,\mathrm{ps}$ and the lifetime ratio is $\tau_{\mathrm{fs}}(B_s^0)/\tau(B^0) = 0.964 \pm 0.013\,(\mathrm{stat}) \pm 0.007\,(\mathrm{syst})$.

5. – CP violation

Non-leptonic two-body charmless decays of neutral B mesons ($B \to hh'$, where h is a charged pion or kaon) allow for constraints on the parameters of the CKM matrix, providing also sensitivity to NP. Asymmetries up to about 10% are predicted for $\Lambda_b^0 \to pK^-$ and $\Lambda_b^0 \to p\pi^-$ decays in the SM [6], and are accessible with the current CDF data set [6]. CDF selects pairs of oppositely-charged particles with $p_T > 2\,\mathrm{GeV}/c$ and $p_T(1) + p_T(2) > 5.5\,\mathrm{GeV}/c$, that form B candidates. The trigger requires also a transverse opening angle $20° < \Delta\phi < 135°$ between the two tracks for background rejection. In addition, both charged particles are required to originate from a displaced vertex with a large impact parameter ($0.1 < d_0(1,2) < 1\,\mathrm{mm}$), while the b-hadron candidate is required to be produced in the primary $\bar{p}p$ interaction ($d_0 < 140\,\mu\mathrm{m}$) and to have travelled a transverse distance $L_T > 200\,\mu\mathrm{m}$. A maximum-likelihood fit, including kinematic and PID information, is performed to disentangle the different compontents of the resulting mass peak (fig. 4, right) and extract signal yields. To determine the physical asymmetries these yields are corrected for detector-induced charge asymmetries extracted from control samples in data. The result $\mathcal{A}_{CP}(B^0 \to K^+\pi^-) = -0.083 \pm 0.013 \pm 0.003$, is consistent with current results from asymmetric e^+e^- colliders and LHCb [6]. The result $\mathcal{A}_{CP}(B_s^0 \to K^-\pi^+) = 0.22 \pm 0.07 \pm 0.02$ confirms the LHCb observation [6]. The observed asymmetries in $\Lambda_b^0 \to pK^-$ decays, $\mathcal{A}_{CP}(\Lambda_b^0 \to p\pi^-) = 0.07 \pm 0.07 \pm 0.03$, and in $\Lambda_b^0 \to p\pi^-$ decays, $\mathcal{A}_{CP}(\Lambda_b^0 \to pK^-) = -0.09 \pm 0.08 \pm 0.04$, are consistent with zero.

In charm transitions, the standard model (SM) predicts CP-violating effects not exceeding $\mathcal{O}(10^{-2})$ [7]. Indeed, no CP-violating effects have been firmly established yet in charm dynamics [7]. A measurement of the asymmetry between the effective lifetimes $\hat{\tau}$ of D^0 and $\overline{D}^0$, $A_\Gamma = \frac{\hat{\tau}(\overline{D}^0 \to h^+h^-) - \hat{\tau}(D^0 \to h^+h^-)}{\hat{\tau}(\overline{D}^0 \to h^+h^-) + \hat{\tau}(D^0 \to h^+h^-)}$, yields a measurement of indirect CP violation. The CDF experiment measured A_Γ using fully reconstructed $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays using the full data set [8]. Data collected by a trigger on displaced tracks are used to reconstruct D candidate. Two oppositely charged tracks are fit to a common decay vertex. A charged particle with $p_T > 400\,\mathrm{MeV}/c$ (soft pion candidate, π_s) is associated with each D candidate to form $D^{*\pm}$ candidates. The charge of π_s identifies the initial flavor of the D^0 candidate. The $D^{*\pm}$ candidate decay vertex is required to lie on the beam-line. To separate $D \to K^+K^-$ and $D \to \pi^+\pi^-$ samples, the h^+h^- mass of selected candidates is required to be within $24\,\mathrm{MeV}/c^2$ of the known D^0 mass, m_{D^0} [7]. Final selected samples contain 6.1×10^5 $D^0 \to K^+K^-$, 6.3×10^5 $\overline{D}^0 \to K^+K^-$, 2.9×10^5 $D^0 \to \pi^+\pi^-$, and 3.0×10^5 $\overline{D}^0 \to \pi^+\pi^-$ signal events. D^0 or $\overline{D}^0$ subsamples are thus divided in equally populated 30 bins of decay time between 0.15τ and 20τ. Signal and background yields in the signal region are determined in each decay-time bin, and for each flavor, through χ^2 fits of the $D\pi_s^\pm$ mass distribution. The resulting signal-to-background proportions are used to construct signal-only distributions of the D impact parameter (IP). A χ^2 fit of these signal-only IP distributions identifies $D^{*\pm}$ mesons from b-hadron decays (*secondary*) and determines the yields of charm (N_{D^0}) and anticharm ($N_{\overline{D}^0}$) mesons directly produced in the $p\bar{p}$ collision (*primary*). The yields are then combined into the asymmetry $A = (N_{D^0} - N_{\overline{D}^0})/(N_{D^0} + N_{\overline{D}^0})$, which is fit with the linear function. The slope of the function, which yields A_Γ, is extracted using a χ^2 fit. The fit shown in fig. 5 yields $A_\Gamma(K^+K^-) = (-1.9 \pm 1.5\ (\mathrm{stat})) \times 10^{-3}$ and $A_\Gamma(\pi^+\pi^-) = (-0.1 \pm 1.8\ (\mathrm{stat})) \times 10^{-3}$ which are consistent with zero. The independence of instrumental asymmetries from decay time is demonstrated by the analysis of

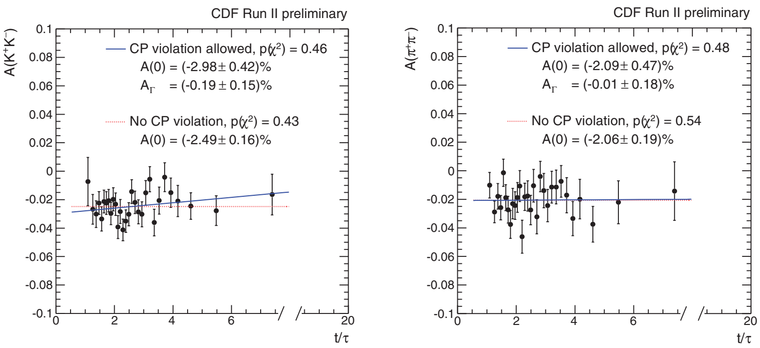

Fig. 5. – Left: Effective lifetime asymmetries as functions of decay time for the $D \to K^+K^-$ sample. Right: $D \to \pi^+\pi^-$ sample. Results of fits not allowing for (red dotted line) and allowing for (blue solid line) CP violation are overlaid.

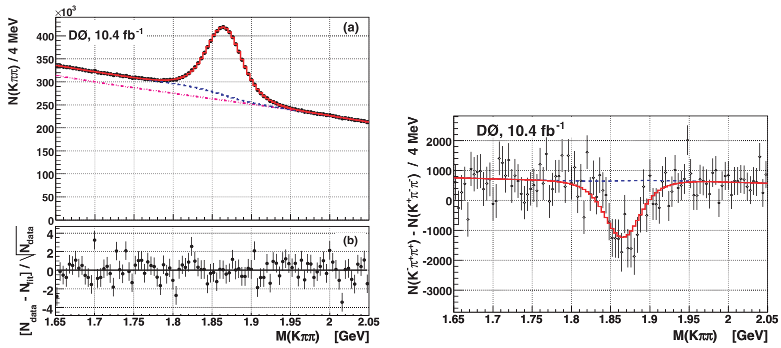

Fig. 6. – Left: Invariant mass distribution $M(K\pi\pi)$ and result of the fit to the data. Fit residuals are reported in the bottom panel. Right: Invariant mass distribution $M(K\pi\pi)$ for the difference $N(D^+) - N(D^-)$. Also shown are the result of the fit to the data.

$D \to K^\mp\pi^\pm$ decays, where no indirect CP violation occurs and instrumental asymmetries are larger; an asymmetry compatible with zero is found, $(-0.5 \pm 0.3) \times 10^{-3}$.

Another reference measurement for future studies on CP violation is the measurement of direct CP violation parameter in the Cabibbo-favored decay $D^+ \to K^-\pi^+\pi^+$ performed using the full set of data collected by the D0 experiment [9]. For these decays the SM predicts negligible CP-violating effects the Cabibbo-favored amplitude is strongly dominant [9]. Experimentally, the asymmetry in the number of D^+ *vs.* D^- mesons (A) is measured by simultaneously fitting the $M(K\pi\pi)$ invariant mass distributions for the sum of all candidates and for the difference $N(D^+) - N(D^-)$. The quantity A includes detector effects (A_{det}) and asymmetries in the production rates of D^+ and D^- mesons (A_{phys}). These effects are all taken into account by using control samples of data and simulations. The detector correction is found to be significant while A_{phys} is negligible compared to the experimental precision. The data used in this analysis are collected by an ensemble of single muon and dimuon triggers. Data selection requires muons with momentum $p(\mu) > 3\,\mathrm{GeV}/c$ and transverse momentum $p_T(\mu) > 2\,\mathrm{GeV}/c$. D candidates are thus reconstructed from all possible three-track combinations, each track with $p_T > 0.7\,\mathrm{GeV}/c$, that have total charge $q = \pm 1$ and a common vertex. The resulting invariant mass of the D candidate must lie within $1.65 < M(K\pi\pi) < 2.05\,\mathrm{GeV}/c^2$. The transverse decay length of the D candidate must exceed three times its uncertainty, $L_{xy}(D)/\sigma[L_{xy}(D)] > 3$. The selection is finally refined using a log-likelihood ratio (LLR) method to combine a suite of variables describing the kinematics of the process. A total of ~ 31 million candidates are left after all the selection criteria are applied (fig. 6, left). The raw asymmetry A is extracted through a simultaneous binned minimum-χ^2 fit of the sum distribution and the difference distribution $[N(D^+) - N(D^-)]$(fig. 6, right). After including all the known detector and physics asymmetry effects, the final direct CP parameter is measured in $A_{CP} = [-0.16 \pm 0.15 \text{ (stat)} \pm 0.09 \text{ (syst)}]\%$. It is consistent with zero, as expected from the standard model prediction of CP conservation.

6. – Conclusions

Latest CDF and D0 results in the flavor sector have been discussed. They are all competitive and among the world' best determinations.

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