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The measurements of the anomalous like-sign dimuon charge asymmetry in $p\bar{p}$ collisions by the DØ Collaboration

B. Hoeneisen
Universidad San Francisco de Quito, Ecuador

In this short review we present the history, an overview of the analysis, and some personal comments on the anomalous like-sign dimuon charge asymmetry measurements by the DØ Collaboration.

I. INTRODUCTION

The DØ Collaboration has published three measurements of the like-sign dimuon charge asymmetry in proton-antiproton collisions: in 2006 with 1.0 fb^{-1} of data [1], in 2010 with 6.1 fb^{-1} [2], and in 2011 with 9.0 fb^{-1} [3]. The results differ from the Standard Model prediction by 1.7, 3.2 and 3.9 standard deviations respectively, so have attracted much attention. Is this, at long last, the first hint of new physics beyond the Standard Model of quarks and leptons? Are we seeing a new source of CP violation that could explain why the Universe has matter? If so, is this asymmetry due to $B^0_d\bar{B}^0_d$ mixing, $B^0_s\bar{B}^0_s$ mixing, both or none? The experimental situation is changing rapidly. The Tevatron has been turned off for the last time and we are now doing the final analysis with the full data set of about 10.0 fb^{-1}. On the other side of the pond, the LHC is collecting data at a rate exceeding all estimates of the preceding year. The LHCb Collaboration is showing results on B-physics with unprecedented low backgrounds and high precision, and the results on $B^0_s(\bar{B}^0_s) \to J/\psi\phi$ presented at the Lepton Photon conference in September of 2011 have been unexpected.

In this short review we present the history, an overview of the analysis, and some personal comments on the like-sign dimuon charge asymmetry. We do not enter into any of the technical details, because they would fill a book and are readily available: full descriptions of the measurements can be found in [1–3], the Proceedings of the DPF-2011 Conference are in [4], and the theory of CP-, T- and CPT-violation in the mixing, decay, and interference of mixing and decay of B^0_q ($q = d$ or s) mesons can be found in [5].

II. HISTORY

At the Fermilab Tevatron collider, b quarks are produced mainly in $b\bar{b}$ pairs. Therefore, to observe an event with two like-sign muons from semi-leptonic b-hadron decay, one of the hadrons must be a B^0_d or B^0_s meson that oscillates and decays to a muon of charge opposite of that of the original b quark. The oscillation $B^0_q \leftrightarrow \bar{B}^0_q$ is described by "box" Feynman diagrams. To calculate these diagrams it is necessary to integrate over the 4-momentum running around the loop. These integrals can pick up new virtual particles of high mass not directly accessible at the Tevatron. New particles add new Feynman box diagrams, changing the Standard Model matrix element $M^{q,\mathrm{SM}}_{12}$, that induces $B^0_q\bar{B}^0_q$ mixing, to $M^{q,\mathrm{SM}}_{12}|\Delta_q|e^{i\phi^{\Delta}_q}$. A non-zero phase ϕ^{Δ}_q would be a new source of CP violation. For example, a 4th generation of quarks and leptons would contribute new box diagrams with a t' in the loop. The CKM matrix would become 4×4, and have 3 observable CP violating phases, compared with 1 in the 3×3 matrix of the Standard Model. A second example is a new, perhaps right handed, SU_2 symmetry, with a new CKM matrix and a new CP violating phase, with the W' contributing new box diagrams. A third example are charged higgs bosons in the loop.

The like-sign dimuon charge asymmetry from semi-leptonic decay of b-hadrons,

$$A^b_{\mathrm{sl}} \equiv \frac{N^{++}_b - N^{--}_b}{N^{++}_b + N^{--}_b}, \tag{1}$$

has contributions from the semi-leptonic charge asymmetries a^d_{sl} and a^s_{sl} of B^0_d and B^0_s mesons:

$$A^b_{\mathrm{sl}} \;=\; C_d a^d_{\mathrm{sl}} + C_s a^s_{\mathrm{sl}}. \tag{2}$$

Our first attempt to measure the like-sign dimuon charge asymmetry in Run I of the DØ detector (1992 to 1996) did not succeed mainly because of the background from the Main Ring accelerator that went right through our calorimeter! The DØ detector was shut down and upgraded from 1996 to 2002. The Main Ring was removed; a superconducting solenoid was installed around the collision point; the tracking wire chambers were replaced by a silicon micro vertex detector and a scintillating fiber tracker; the forward muon system was

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replaced by mini-drift chambers; and the DØ detector was fully covered by scintillating trigger counters that reduced the cosmic ray and halo backgrounds.

The upgraded DØ detector was uniquely well suited for the precision measurement of the like-sign dimuon charge asymmetry for the following reasons: (i) the initial $p\bar{p}$ state was symmetric with respect to CP conjugation; (ii) the solenoid and toroid magnetic fields were reversed periodically, thereby canceling first order detector asymmetries; (iii) the shielding between the central tracker and the outer muon spectrometer was sufficient to reduce the background from hadron punch-through to the 1% level; and (iv) the muon track parameters were measured twice, once by the central tracker, and once by the outer muon system, thereby reducing fake muon tracks and kaon and pion decay backgrounds, and allowing the detector asymmetries and backgrounds to be studied in more detail.

The pioneering measurement published in 2006 [1] had to establish which issues were important, and which could be neglected. How should we parametrize the detector charge asymmetries? How could we measure these parameters with data? Do positive and negative muons have the same energy loss in the calorimeter and iron toroids to one part in 10^4? Is the efficiency of detecting, triggering and tracking positive and negative muons the same? What is the fraction and charge asymmetry of fake muon tracks, of cosmic rays detected once, of cosmic rays detected twice (once entering the DØ detector, and once exiting it), and of the kaon decay background? What is the fraction of tracks that have a wrong charge measurement? Is the toroid magnetic field the same for both polarities to one part in 10^4? Is there any charge bias in the track reconstruction software? Is muon production forward-backward symmetric? And on and on. Submitting Monte Carlo jobs daily for six months resulted in only 21 dimuon events, which was barely sufficient for this analysis.

The measurement of 2010 was greatly improved. The kaon, pion and punch-trough backgrounds were measured by reconstructing exclusive decays in the same inclusive muon and like-sign dimuon data sets, with minimal use of Monte Carlo simulation. The residual muon spectrometer charge asymmetry was measured by reconstructing J/ψ's using only the central detector tracks. The residual charge asymmetry of the central tracker was measured by counting positive and negative particles and correcting for kaon decay. All of these measurements were done as a function of the momentum p_T of the particles transverse to the proton-antiproton beams. The main cross-check was the measurement of the charge asymmetry of inclusive muons. There were about 300 inclusive muons per like-sign dimuon event. The charge asymmetry of the inclusive muons was dominated by the residual detector asymmetry (after averaging over the 4 solenoid-toroid magnet polarities) and by the kaon decay background, because in this data set any asymmetry from $B_q^0\bar{B}_q^0$ mixing was diluted by decays without mixing. The inclusive muon charge asymmetry provided an indispensable "closure test". This closure test was also done separately for each bin of p_T. These improvements were necessary to keep the systematic uncertainty below the statistical one.

Let us now describe in more detail the measurement of 2011.

III. OVERVIEW OF THE MEASUREMENT WITH 9 FB^{-1}

Two data sets were used for this measurement: the *inclusive muon set*, collected with single muon triggers, had $n^+ + n^- = 2.04 \times 10^9$ muon candidates passing strict quality selections; and the *like-sign dimuon set*, collected with dimuon triggers, had $N^{++} + N^{--} = 6.02 \times 10^6$ dimuon events with each muon passing the same quality selections, and in addition the following dimuon requirements: same charge sign, same associated vertex, and a dimuon invariant mass greater than 2.8 GeV to suppress events with the two muons coming from the same B-hadron decay cascade. Counting inclusive muons, and like-sign dimuons, we obtained the "raw" asymmetries

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = (+0.688 \pm 0.002)\%, \text{ and} \tag{3}$$

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (+0.126 \pm 0.041)\%. \tag{4}$$

These "raw" asymmetries were corrected for kaon, pion and proton decay or punch-through, and for the residual muon detector asymmetry after averaging over the 4 solenoid-toroid magnet polarity combinations. These corrections were measured, as a function of p_T, with the same data sets, by reconstructing exclusive decays, with minimal use of simulation. As far as possible, measurements were redundant using two independent channels. The main background asymmetry was due to kaon decay. Positive kaons had a longer inelastic interaction length in the calorimeter than negative kaons, and hence had more time to decay. The resulting positive charge asymmetry contributions from kaon decay were measured to be $(+0.776 \pm 0.021)\%$ for a, and

$(+0.633 \pm 0.031)\%$ for A. The residual muon detector asymmetries were measured (reconstructing J/ψ's from central detector tracks) to be $(-0.047 \pm 0.012)\%$ for a, and $(-0.212 \pm 0.030)\%$ for A. Corrections due to pion decay and proton punch-through were smaller. The charge asymmetries, corrected for background and detector effects, are

$$a - a_{\rm bkg} \equiv (-0.034 \pm 0.042 \text{ (stat)})\%, \text{ and} \tag{5}$$
$$A - A_{\rm bkg} \equiv (-0.276 \pm 0.067 \text{ (stat)})\%. \tag{6}$$

We interpreted these charge asymmetries as arising from CP violation in the mixing of B_d^0 and B_s^0 mesons. To obtain $A^b_{\rm sl}$, we divided the corrected asymmetries $a - a_{\rm bkg}$ and $A - A_{\rm bkg}$ by "dilution factors"

$$c_b = +0.061 \pm 0.007, \text{ and} \tag{7}$$
$$C_b = +0.474 \pm 0.032, \tag{8}$$

respectively. These "dilutions factors", obtained from simulation, are due to prompt decays that are not direct semi-leptonic $b \to \mu X$, i.e. sequential decays $b \to c \to \mu X$, decays with $b \to c\bar{c}q$ with $c \to \mu X$ or $\bar{c} \to \mu X$, decays of light mesons, events with $c\bar{c}$, and events with $b\bar{b}c\bar{c}$. The results are

$$A^b_{\rm sl} = (-1.04 \pm 1.30 \text{ (stat)} \pm 2.31 \text{ (syst)})\%, \text{ and} \tag{9}$$
$$A^b_{\rm sl} = (-0.808 \pm 0.202 \text{ (stat)} \pm 0.222 \text{ (syst)})\%, \tag{10}$$

respectively. The asymmetries a and A have correlated backgrounds. Therefore, a more precise measurement of $A^b_{\rm sl}$ can be obtained from $A - \alpha a$. The parameter $\alpha = 0.89$ was chosen to minimize the total uncertainty of $A^b_{\rm sl}$. The resulting final measurement is

$$A^b_{\rm sl} = (-0.787 \pm 0.172 \text{ (stat)} \pm 0.093 \text{ (syst)})\%. \tag{11}$$

This result differs from the Standard Model prediction [3],

$$A^b_{\rm sl} = (-0.028^{+0.005}_{-0.006})\%, \tag{12}$$

by 3.9 standard deviations. Equation (2) with the result (11) is show in Figure 1.

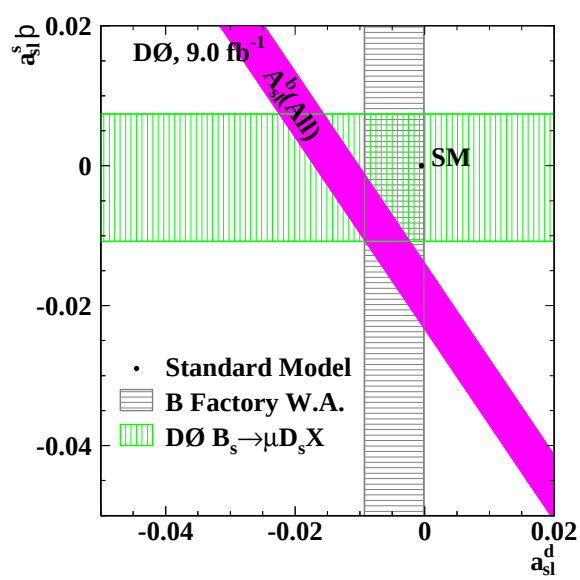

FIG. 1: Comparison of $A^b_{\rm sl}$ in data with the Standard Model prediction for $a^d_{\rm sl}$ and $a^s_{\rm sl}$. Also shown are the measurements of $a^d_{\rm sl}$ [6] and $a^s_{\rm sl}$ [7]. The bands represent the ± 1 standard deviation uncertainties on each individual measurement.

The "residual" like-sign dimuon charge asymmetry, obtained from $A - \alpha a$, corrected for detector and background effects, but without any interpretation, i.e. without dividing by a dilution factor, is

$$A_{\rm res} = (-0.246 \pm 0.052 \text{ (stat)} \pm 0.021 \text{ (syst)})\%, \tag{13}$$

and differs from the Standard Model prediction by 4.2 standard deviations.

These results are in good agreement with the previous measurements: the publication of 2010 with 6.1 fb^{-1} reported a like-sign dimuon charge asymmetry from semi-leptonic decay [2]

$$A^b_{\rm sl} \;=\; (-0.957 \pm 0.251\ (\text{stat}) \pm 0.146\ (\text{syst}))\%; \tag{14}$$

and the measurement of 2006 with 1.0 fb^{-1} [1] reported a "residual" charge asymmetry, corrected for detector and background effects,

$$A_{\rm res} = (-0.28 \pm 0.13\ (\text{stat}) \pm 0.09\ (\text{syst}))\%. \tag{15}$$

To explore the origin of the charge asymmetry, we performed measurements with muon impact parameter IP $> 120\mu$m and IP $< 120\mu$m (for like-sign dimuons each muon is required to pass the IP cut). IP is the distance of closest approach of the muon track to the primary vertex projected onto the plane transverse to the $p\bar{p}$ beams. The coefficients C_d and C_s in (2) depend on the IP cut, since for IP $> 120\mu$m the B^0_d-meson has a longer lifetime on average, and hence a greater probability to oscillate. The results of these measurements are consistent with the hypothesis of CP violation in the mixing of B^0_d and B^0_s mesons with semi-leptonic decay asymmetries

$$a^d_{\rm sl} \;=\; (-0.12 \pm 0.51)\%,\ \text{and} \tag{16}$$
$$a^s_{\rm sl} \;=\; (-1.81 \pm 1.04)\%. \tag{17}$$

These two asymmetries are correlated as shown in Figure 2.

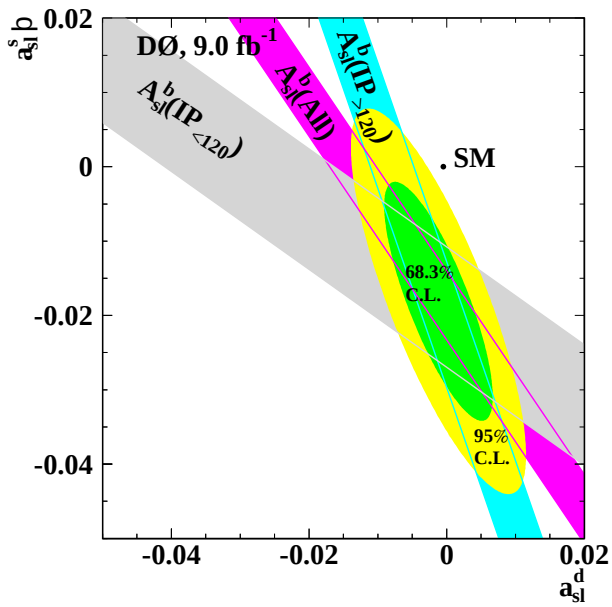

FIG. 2: Measurements of $A^b_{\rm sl}$ with different muon impact parameter selections in the $(a^d_{\rm sl}, a^s_{\rm sl})$ plane. The bands represent the ± 1 standard deviation uncertainties on each individual measurement. The ellipses represents the 68.3% and 95% confidence-level contours of $a^d_{\rm sl}$ and $a^s_{\rm sl}$ values obtained from the measurements with IP selections.

IV. COMMENTS

As data was collected over the years, more and more statistically significant cross-checks became possible. Each of these tests could have revealed inconsistencies, but none have been observed so far.

The "raw" inclusive muon charge asymmetry a is dominated by background and detector asymmetries due to the small value of the dilution factor c_b. Therefore, the corrected inclusive muon charge asymmetry (5) serves as a "closure test" of the measurements of the backgrounds and detector asymmetries. Equation (5) indicates that the sum of uncertainties of all background and detector asymmetries (those that have been explicitly considered,

and even those that have not been imagined!) is less than approximately $\pm 0.042\%$, which is smaller than the statistical uncertainty of $A - A_{\rm bkg}$ in (6). The "closure test" has been presented in [3] as a function of transverse momentum p_T, and pseudo-rapidity η, and good agreement is found.

Since background muons are mainly produced by decays of kaons and pions, their track parameters independently measured by the central tracker and by the outer muon spectrometer can differ. The background fractions therefore depend strongly on the χ^2 of the difference between these two measurements. In test C of Table XV of [3] the χ^2 cut is changed from 12 to 4 (for 4 degrees of freedom). The "raw" charge asymmetry a (A) changes from +0.688% to +0.325% (+0.126% to -0.361%), yet the measured value of $A^b_{\rm sl}$ does not change significantly (see [3] for details). Note that A changes sign with this reduction of background.

In Tables XV and XVI of [3] are presented 18 tests by varying the muon p_T, η and ϕ ranges, the muon quality selections, the triggers, the maximum impact parameter, the instantaneous luminosity, using only one pair of solenoid-toroid magnet polarities, and different data running periods. The χ^2 of these $18+1$ measurements of $A^b_{\rm sl}$, taking account of common events, is 17.1 for 18 degrees of freedom. These tests prove that the total uncertainty of $A^b_{\rm sl}$ is correct.

In cross-check K of [3] we repeat the measurement of $A^b_{\rm sl}$ using only central muons with pseudo-rapidity $|\eta| < 1.6$. The result does not change significantly. This cross-check is important because the central and forward regions have independent detectors: the central muon detector uses large proportional drift chambers, while the forward muon detector uses mini drift tubes. These two muon systems have independent reconstruction software. The tracking system has silicon barrels and a scintillating fiber tracker in the central region, while silicon discs are used in the forward region. Even the magnetized iron toroids are different in the central and forward regions.

Applying the impact parameter cut IP $> 120\mu$m reduces the kaon and pion decay backgrounds by the large factors 3 to 5, the "raw" charge asymmetry a (A) changes from +0.688% to -0.014% (+0.126% to -0.529%), yet the results are again consistent. Note that both asymmetries a and A change sign with this reduction of the backgrounds, and the measured $A^b_{\rm sl}$ from a ($A^b_{\rm sl} = (-0.422 \pm 0.240\ (\text{stat}) \pm 0.121\ (\text{syst}))\%$) and A ($A^b_{\rm sl} = (-0.818 \pm 0.342\ (\text{stat}) \pm 0.067\ (\text{syst}))\%$) are compatible in spite of the very different dilution factors c_b and C_b.

It is a challenge to imagine a background or detector effect that can make both corrected charge asymmetries (5) and (6), which are so different, zero simultaneously. Finally, we note in Eq. (11) that the uncertainty of $A^b_{\rm sl}$ is still dominated by statistics.

V. ANOMALIES IN B^0_d AND B^0_s MIXING AND DECAY

New physics in the mixing of B^0_q mesons, assuming CPT invariance, can be parametrized by 4 complex numbers Δ_q and $\tilde{\Delta}_q$ as follows [8]:

$$M^q_{12} \equiv M^{q,\rm SM}_{12} \cdot \Delta_q = M^{q,\rm SM}_{12} \cdot |\Delta_q|\, e^{i\phi^\Delta_q}, \text{ and} \tag{18}$$

$$\Gamma^q_{12} \equiv \Gamma^{q,\rm SM}_{12} \cdot \tilde{\Delta}_q = \Gamma^{q,\rm SM}_{12} \cdot \left|\tilde{\Delta}_q\right| e^{-i\tilde{\phi}^\Delta_q}, \tag{19}$$

with $q = d, s$. In the presence of new physics, the semi-leptonic charge asymmetries, and the differences in mass and decay rates of the eigenstates are

$$a^q_{\rm sl} = \left|\frac{\Gamma^{q,SM}_{12}}{M^{q,SM}_{12}}\right| \cdot \frac{|\tilde{\Delta}_q|}{|\Delta_q|} \sin(\phi^{\rm SM}_q + \phi^\Delta_q + \tilde{\phi}^\Delta_q)(1 + 2\delta^q_A), \tag{20}$$

$$\Delta m_q = 2|M^{q,SM}_{12}| \cdot |\Delta_q|, \text{ and} \tag{21}$$

$$\Delta\Gamma_q = 2|\Gamma^{q,SM}_{12}| \cdot |\tilde{\Delta}_q| \cos(\phi^{\rm SM}_q + \phi^\Delta_q + \tilde{\phi}^\Delta_q), \tag{22}$$

where $\phi^{SM}_q \equiv \arg(-M^{q,SM}_{12}/\Gamma^{q,SM}_{12})$, $\phi^{SM}_s = 0.22^o \pm 0.06^o$, and $\phi^{SM}_d = -4.3^o \pm 1.4^o$ [8]. Fits to decays $B^0_s(\bar{B}^0_s) \to J/\psi\phi$ and $B^0_s(\bar{B}^0_s) \to J/\psi f_0$ determine, in particular, Δm_s, $\Delta\Gamma_s$, and the angle [8]

$$-2\beta_s + \delta^{\rm peng,\ SM}_s + \delta^{\rm peng,\ NP}_s + \phi^\Delta_s. \tag{23}$$

If there is no CP-violation in the semileptonic decay of B^0_q mesons, then $\delta^q_A = 0$. The angles $\delta^{\rm peng,\ SM}_s$ and $\delta^{\rm peng,\ NP}_s$ are due to penguin contributions in the Standard Model and beyond.

In November of 2010, A. Lenz, U. Nierste and the CKMfitter Group [9] presented detailed global fits to the Standard Model and to extensions of the Standard Model (with $\delta_A^q = 0$, $\delta_s^{\text{peng, SM}} = 0$ and $\delta_s^{\text{peng, NP}} = 0$). The global fit to the Standard Model finds 4 anomalies (i.e. parameters with "pulls", defined in [9], between 2 and 3 standard deviations): $2\beta_d$, $-2\beta_s$, A_{sl}^b, and the branching ratio of $B \to \tau\nu$. The pulls were 2.8, 2.3, 2.9 and 2.9 standard deviations respectively. The fits including the two independent complex numbers Δ_d and Δ_s (with $\tilde{\Delta}_d = \tilde{\Delta}_s = 1$) resolved all anomalies: the pulls became 0.8, 0.5, 1.2 and 0.7 standard deviations respectively. The fit obtained $|\Delta_d| = 0.747^{+0.195}_{-0.079}$, $|\Delta_s| = 0.887^{+0.143}_{-0.064}$, $\phi_d^\Delta = -12.9^{+3.8}_{-2.7}$ deg, and $\phi_s^\Delta = -130^{+13}_{-12}$ or $-51.6^{+14.2}_{-9.7}$ deg. It is noteworthy to mention that all 4 anomalies were corrected by new physics in only the matrix elements M_{12}^d and M_{12}^s.

Since that review, there have been the following developments: (i) the DØ Collaboration published the measurement with 9.0 fb^{-1} [3]; (ii) the CDF and DØ Collaborations [10, 11] have presented new results on $B_s^0 \to J/\psi\phi$ in agreement with the Standard Model; and (iii) the LHCb Collaboration has presented preliminary results, at the Lepton Photon Conference in September of 2011, on the decays $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi f_0$ with smaller uncertainties, and in good agreement with the Standard Model.

A detailed global fit including these new measurements is not yet available. Let us here mention that these new measurements will add to Figures 1 and 2 a horizontal band that includes $a_{\text{sl}}^s = 0$, and are therefore not in disagreement with the like-sign dimuon charge asymmetry, but shift the burden of CP-violation towards the B_d^0 meson.

Finally, we should mention that new heavy particles, that could contribute to the Feynman box diagrams of M_{12}^q, have been excluded up to higher energies by the Tevatron, and especially, by the LHC (see summer conferences of 2011).

VI. CONCLUSIONS

The DØ Collaboration has measured an anomalous like-sign dimuon charge asymmetry that differs from the Standard Model prediction by 3.9 standard deviations. At present we do not understand the origin of this discrepancy. The situation should become clearer in the near future when the following analysis become available: (i) a new global fit to the Standard Model and beyond; (ii) the measurements of A_{sl}^b, a_{sl}^d and a_{sl}^s with the final data sets of the Tevatron; and (iii) the new results from the LHC in both B-physics, and at the energy fronteer. Or perhaps we will have new surprises? We will work and see.

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