Flavor Physics in the LHC Era

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Introduction

Flavor physics is the study of processes involving the heavy quarks c, b, t. The idea is to look for indications of NP via its virtual contributions to these processes. The quarks b and c are found in B and D mesons. The t quark is very massive, so it decays before forming a meson.

For a number of years, “flavor physics” largely meant B physics. A great deal of work was done in the context of the B factories: finding methods for measuring the SM parameters, examining ways of looking for NP, analysing the results, etc. Unfortunately, most of the measurements agreed with the SM. Although there were several hints of NP, mostly in $\bar{b} \to \bar{s}$ transitions, there were no statistically-significant signals. Now, with the LHC, much attention is also paid to D and t physics. In this talk, I review a variety of B, D and t processes susceptible to revealing the presence of NP.

B_s^0-$\bar{B}_s^0$ Mixing

Formalism: mass eigenstates B_L and B_H (L, H: light and heavy states) are admixtures of the flavor eigenstates B_s^0 and $\bar{B}_s^0$:

$$\begin{aligned} |B_L\rangle &= p\left|B_s^0\right\rangle + q\left|\bar{B}_s^0\right\rangle \ , \\ |B_H\rangle &= p\left|B_s^0\right\rangle - q\left|\bar{B}_s^0\right\rangle \ , \end{aligned}$$

with $|p|^2 + |q|^2 = 1$. Initial flavor eigenstates oscillate into one another according to the Schrödinger equation with $H = M^s - i\Gamma^s/2$ (M^s and Γ^s are the dispersive and absorptive parts of the mass matrix). The off-diagonal elements M_{12}^s and Γ_{12}^s are generated by B_s^0-$\bar{B}_s^0$ mixing.

Defining $\Delta M_s \equiv M_H - M_L$ and $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$, we have

$$\Delta M_s = 2|M_{12}^s| \ , \ \ \Delta\Gamma_s = 2|\Gamma_{12}^s| \cos\phi_s \ , \ \ \frac{q}{p} = e^{-2i\beta_s} \ ,$$

where $\phi_s \equiv \arg(-M_{12}^s/\Gamma_{12}^s)$ is the CP phase in $\Delta B = 2$ transitions.

The weak phases ϕ_s and $2\beta_s$ are independent – the SM predicts ϕ_s and $2\beta_s \simeq 0$ (but $\phi_s \neq -2\beta_s$!). Points: $\Delta\Gamma_s$ is sizeable and is > 0 in SM; in presence of NP, can have $2\beta_s \neq 0$ and $\Delta\Gamma_s < 0$.

$J/\psi\phi$: In 2008 the CDF and DØ collaborations measured the CP asymmetry in $B_s^0 \to J/\psi\phi$, and found a hint for indirect CP violation. The 2011 update gives (at 68% C.L.)

$$\begin{aligned} 2\beta_s^{\psi\phi} &\in [2.3^\circ, 59.6^\circ] \cup [123.8^\circ, 177.6^\circ] \ , \qquad \text{CDF} \ , \\ &\in [9.7^\circ, 52.1^\circ] \cup [127.9^\circ, 170.3^\circ] \ , \qquad \text{DØ} \ . \end{aligned}$$

Note that the measurement is insensitive to the transformation $(2\beta_s^{\psi\phi}, \Delta\Gamma_s) \leftrightarrow (\pi - 2\beta_s^{\psi\phi}, -\Delta\Gamma_s)$, so that $2\beta_s^{\psi\phi}$ is obtained with a twofold ambiguity.

LHCb has greatly improved this result. First, they remove the twofold ambiguity by measuring $\Delta\Gamma_s > 0$ [R. Aaij$+$, 1202.4717]. Second, they find $2\beta_s^{J/\psi\phi} = (-0.06 \pm 5.77 \ (\mathrm{stat}) \pm 1.54 \ (\mathrm{syst}))^\circ$ [LHCb Collaboration, CERN-LHCb-CONF-2012-002], in agreement with the SM.

To completely search for NP, LHCb has to measure B_s^0-$\bar{B}_s^0$ mixing in as many different decays as possible.

$J/\psi f_0(980)$: LHCb measures $\beta_s^{J/\psi f_0} = (-25.2 \pm 25.2 \pm 1.1)^\circ$ [R. Aaij+, PLB707, 497 (2012)]. Advantage of decay: because $f_0(980)$ is a scalar, no angular analysis is needed. Disadvantage: $f_0(980)$ not a pure $s\bar{s}$ state, so there are possibly other contributions to the decay, and this leads to hadronic uncertainties [R. Fleischer+, EPJ C71, 1832 (2011)].

$K^0\bar{K}^0$: Like $B_d^0 \to \phi K_S$, $B_s^0 \to K^0\bar{K}^0$ is a pure $\bar{b} \to \bar{s}$ penguin decay. There are two decay amplitudes, $P'_{tc} \sim V_{tb}^* V_{ts}$ and $P'_{uc} \sim V_{ub}^* V_{us}$. $|P'_{uc}| \ll |P'_{tc}|$, so that $B_s^0 \to K^0\bar{K}^0$ is approximately governed by a single decay amplitude, and the measurement of indirect CP violation then probes $\beta_s^{K^0\bar{K}^0}$. The decay modes in which one or both of the final-state particles are vectors can also be used.

Other decays which are potentially of interest are $B_s^0(\bar{B}_s^0) \to D_s^\pm K^\mp$, $B_s^0 \to D_s^+ D_s^-$ [R. Fleischer, NPB671, 459 (2003), EPJ C10, 299 (1999), EPJ C51, 849 (2007)], $B_s^0(\bar{B}_s^0) \to D_{CP}^0 K\bar{K}$ [S. Nandi+, 1108.5769], and certain 3-body decays.

Like-sign Dimuon Asymmetry

The DØ Collaboration has reported an anomalously large CP-violating like-sign dimuon charge asymmetry in the B system. The updated measurement is [V. M. Abazov$+$, PRD84, 052007 (2011)]

$$A^b_{\rm sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} = -(7.87 \pm 1.72 \pm 0.93) \times 10^{-3} ~,$$

a 3.9σ deviation from the SM prediction, $A^{b,{\rm SM}}_{\rm sl} = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$.

Now, it has been shown that, if this anomaly is real, it implies NP in B_s^0-$\bar B_s^0$ mixing. Such NP effects can appear in M^s_{12} and/or Γ^s_{12}. In fact, it has been argued that NP in Γ^s_{12} should be considered as the main explanation for the above result [C. Bobeth$+$, 1109.1826].

In the SM, the dominant contribution to Γ^s_{12} comes from $\bar b \to \bar s c \bar c$. Significant NP contributions, i.e. comparable to the SM, can come mainly from $\bar b \to \bar s \tau^+ \tau^-$. This is straightforward to detect. For example, if $\mathcal{B}(B_s^0 \to \tau^+\tau^-)$ is observed to be at the percent level, this will be a clear indication of NP (in the SM, $\mathcal{B}(B_s^0 \to \tau^+\tau^-) = 7.9 \times 10^{-7}$). Thus, this is one decay that LHCb should try to measure.

$B_s^0 \to VV$ Decays

$B_s^0 \to V_1 V_2$: 3 decays. V_1 and V_2 can have relative orbital angular momentum $l = 0$ (s wave), $l = 1$ (p wave), or $l = 2$ (d wave). Equivalently, one decomposes the decay amplitude into components in which the polarizations of the final-state vector mesons are either longitudinal (A_0), or transverse to their directions of motion and parallel ($A_{\|}$) or perpendicular ($A_{\perp}$) to one another.

(1) f_T, f_L: naively, one expects $f_T \ll f_L$, where f_T (f_L) is the fraction of transverse (longitudinal) decays. However, it was observed that $f_T/f_L \simeq 1$ in $B \to \phi K^*$. One explanation of this "polarization puzzle" is that penguin annihilation (PA) contributions are important [A. L. Kagan, PLB601, 151 (2004)]. Normally such contributions are expected to be small, but they can be sizeable within QCDf.

$\exists$ two penguin decay pairs whose amplitudes are the same under flavor SU(3), and for which QCDf makes a precise estimate of SU(3) breaking: ($B_s^0 \to \phi\phi, B_d^0 \to \phi K^{0*}$) and ($B_s^0 \to \phi \bar{K}^{0*}, B_d^0 \to \bar{K}^{0*} K^{0*}$) [A. Datta$+$, EPJ C60, 279 (2009)]. Given the polarization in the B_d^0 decay (already measured), can predict the polarization in the B_s^0 decay (to be measured by LHCb) $\Longrightarrow$ test PA.

(2) Triple Product (TP): In the B rest frame, the TP takes the form $\vec{q} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2)$, where $\vec{q}$ is the difference of the two final momenta, and $\vec{\varepsilon}_1$ and $\vec{\varepsilon}_2$ are the polarizations of V_1 and V_2. The TP is odd under both P and T, and thus constitutes a potential signal of CPV. In $B_s^0 \to V_1 V_2$, there are two TP's: $A_T^{(1)} \propto \mathrm{Im}(A_\perp A_0^*)$ and $A_T^{(2)} \propto \mathrm{Im}(A_\perp A_\|^*)$.

"TP's are a signal of CP violation:" not quite accurate. In general the A_i ($i = 0, \|, \perp$) possess both weak (CP-odd) and strong (CP-even) phases. Thus, $\mathrm{Im}(A_\perp A_0^*)$ and $\mathrm{Im}(A_\perp A_\|^*)$ can both be nonzero even if the weak phases vanish. In order to obtain a true signal of CP violation, one has to compare the B and $\bar{B}$ decays.

The TP's for the $\bar{B}$ decay are $-\mathrm{Im}(\bar{A}_\perp \bar{A}_0^*)$ and $-\mathrm{Im}(\bar{A}_\perp \bar{A}_\|^*)$. The true (CP-violating) TP's are then given by $\frac{1}{2}[\mathrm{Im}(A_\perp A_0^*) + \mathrm{Im}(\bar{A}_\perp \bar{A}_0^*)]$ and $\frac{1}{2}[\mathrm{Im}(A_\perp A_\|^*) + \mathrm{Im}(\bar{A}_\perp \bar{A}_\|^*)]$. But there are also fake (CP-conserving) TP's, due only to strong phases of the the A_i's. These are given by $\frac{1}{2}[\mathrm{Im}(A_\perp A_0^*) - \mathrm{Im}(\bar{A}_\perp \bar{A}_0^*)]$ and $\frac{1}{2}[\mathrm{Im}(A_\perp A_\|^*) - \mathrm{Im}(\bar{A}_\perp \bar{A}_\|^*)]$. Thus, for the fake TP's, it is necessary to distinguish B and $\bar{B}$.

(a) CPV due to interference of two amplitudes. Common way to look for CPV – non-zero rate difference between the decay and its CP-conjugate decay (direct CPV). The direct CP asymmetry is proportional to $\sin\phi\sin\delta$, where ϕ and δ are the relative weak and strong phases of the two amplitudes. IOW, direct CPV requires a non-zero strong-phase difference. OTOH, the true (CP-violating) TP is proportional to $\sin\phi\cos\delta$, so no strong-phase difference is necessary. Helps in search for NP. Also, in SM, true TP's are generally small (or zero) [A. Datta+, IJMP A19, 2505 (2004)] $\Longrightarrow$ good way to find NP.

(b) In SM, certain fake TP's are very small [A. Datta+, PLB701, 357 (2011)] $\Longrightarrow$ it is possible to partially distinguish the SM from NP through the measurement of the fake $A_T^{(2)}$ TP. This applies to $B \to \phi K^*$ and $B_s^0 \to \phi\phi$.

(c) If the time-dependent angular analysis of a pure-penguin $\bar{b} \to \bar{s}$ $B_s^0 \to VV$ decay, such as $B_s^0 \to \phi\phi$ or $B_s^0 \to K^{*0}\bar{K}^{*0}$, can be performed, there are many tests of NP in the decay, see D. London+, Europhys. Lett. 67, 579 (2004), PRD69, 114013 (2004).

Measuring U-spin/SU(3) breaking

Consider charmless $\bar{b} \to \bar{d}$ and $\bar{b} \to \bar{s}$ decays whose amplitudes are equal under U spin ($d \leftrightarrow s$). In general, there are four observables in these processes: the CP-averaged $\bar{b} \to \bar{d}$ and $\bar{b} \to \bar{s}$ decay rates B_d and B_s, and the direct CP asymmetries A_d and A_s. In the U-spin limit, $X = 1$, where $X \equiv -(A_s/A_d)(B_s/B_d)$. Thus, by measuring the four observables, and computing the deviation of X from 1, one can *measure* U-spin breaking [M. Imbeault$+$, PRD84, 056002 (2011)].

This can be applied to decay pairs involving B_s^0 decays:

1. $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$,
2. $B_s^0 \to \pi^+K^-$ and $B_d^0 \to \pi^-K^+$,
3. $B_d^0 \to K^0\bar{K}^0$ and $B_s^0 \to \bar{K}^0K^0$,
4. $B_d^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$.

The first (second) decay is $\bar{b} \to \bar{d}$ ($\bar{b} \to \bar{s}$).

If one neglects annihilation- and exchange-type diagrams, there are 12 additional pairs of decays to which this analysis can be applied. These are not related by U spin, but are instead related by SU(3).

D^0-$\bar{D}^0$ Mixing

$|\Delta C = 2|$ interactions $\Longrightarrow$ D^0-$\bar{D}^0$ mixing $\Longrightarrow$ mass eigenstates D_1 and D_2 are linear combinations of D^0 and $\bar{D}^0$. Define $\Delta M_D \equiv M_1 - M_2$, $\Delta\Gamma_D \equiv \Gamma_1 - \Gamma_2$, and $\Gamma_D = (\Gamma_1 + \Gamma_2)/2$. One tracks mixing by defining the following quantities:

$$x_D \equiv \frac{\Delta M_D}{\Gamma_D} \quad , \quad y_D \equiv \frac{\Delta\Gamma_D}{2\Gamma_D} \; .$$

Two additional measured quantities are $y_D^{(CP)}$ and y'_D, which take into account properties of the particular final state in the decay.

Non-zero mixing has been measured in various decays: $D^0 \to K^+ l^- \nu$, K^+K^-, $\pi^+\pi^-$, $K^+\pi^-$, etc. This mixing is much larger than the quark-level (short-distance) SM predictions. But it is in qualitative agreement with the hadron-level (long-distance) SM expectations due to the significant hadronic uncertainties in the LD calculations. It has been established that a large variety of NP models can reproduce the measured mixing [E. Golowich$+$, PRD76, 095009 (2007)], but because of the SM hadronic uncertainties, it is not clear whether or not NP is actually required.

CPV in $D^0 \to K^+K^-, \pi^+\pi^-$

In SM, CPV is strongest in the down-type quark sector (K, B mesons). But: it is plausible that NP affects mostly the up-type quark sector (e.g. large t mass) $\Longrightarrow$ CPV in D decays is particularly interesting.

Recently, LHCb found the difference between the time-integrated CP asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ to be

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = -(0.82 \pm 0.21 \pm 11)\% \;.$$

Combined with previous measurements, one finds

$$\Delta A_{CP} = -(0.65 \pm 18)\% \;,$$

which is non-zero at 3.6σ. Now, it is expected that CPV in D decays is only $O(10^{-3})$ in the SM. So, is the measured ΔA_{CP} a sign of NP?

Note: any explanation – SM or NP – has to deal with two issues:
(i) reproduce the measured BR's, which give $|A(D^0 \to \pi^+\pi^-)| = 4.70 \pm 0.08$ and $|A(D^0 \to K^+K^-)| = 8.49 \pm 0.10$,
(ii) reproduce ΔA_{CP}.

SM: $\exists$ a number of papers. They differ in the details, but the general idea is as follows. The decay amplitudes can be written as follows:

$$
\begin{aligned}
A(D^0 \to \pi^+\pi^-) &= \lambda_d T_{\pi\pi} + (\lambda_d P_d + \lambda_s P_s + \lambda_b P_b) \; , \\
A(D^0 \to K^+K^-) &= \lambda_s T_{KK} + (\lambda_d P_d + \lambda_s P_s + \lambda_b P_b) \; ,
\end{aligned}
$$

where $\lambda_q \equiv V^*_{cq} V_{uq}$. Tree diagrams $T_{\pi\pi}$, T_{KK} differ only by SU(3)-breaking effects (decay constants, form factors).

At the quark level (short distance), the size of the penguin diagrams $P_{d,s,b}$ is small(ish). However, the P_d and P_s hadronic matrix elements can be enhanced due to long-distance rescattering contributions from the tree diagrams [M. Golden+, PLB222, 501 (1989); J. Brod+, 1111.5000] $\Longrightarrow$ with the inclusion of SU(3) breaking ($P_d \neq P_s$) and enhanced hadronic matrix elements, the BR and ΔA_{CP} data can be reproduced by the SM (according to some analyses, only marginally).

$\exists$ a number of NP explanations for ΔA_{CP}. These include model-independent analyses as well as examinations of particular NP models.

$t\bar{t}$ Forward-Backward Asymmetry

SM: the $t\bar{t}$ quark pair is produced at hadron colliders almost entirely through QCD processes, which are FB symmetric at tree level. The interference of tree-level and higher-order QCD processes leads to $A_{FB} \sim 7\%$. In their 2011 updates, the CDF and DØ Collaborations reported measurements of A_{FB} of $(20.1 \pm 6.7)\%$ (CDF) and $(19.6 \pm 6.5)\%$ (DØ). Thus, there is a discrepancy with the prediction of the SM, which provides a hint of NP.

The NP explanations can be divided roughly into 3 classes:
(i) t-channel vector exchange, such as a Z' contribution to $u\bar{u} \to t\bar{t}$ via a $t\bar{u}Z'$ FCNC coupling [S. Jung$+$, PRD81, 015004 (2010)], or a W' contribution to $d\bar{d} \to t\bar{t}$ via a $t\bar{d}W'$ coupling [K. Cheung$+$, PLB682, 287 (2009)], (ii) t-channel flavor-changing scalar exchange [J. Shu$+$, PRD81, 034012 (2010); A. Arhrib$+$, PRD82, 034034 (2010); J. Cao$+$, PRD 81, 014016 (2010)], (iii) s-channel axigluon exchange [P. H. Frampton$+$, PLB683, 294 (2010)].

One can generally distinguish these three classes by measuring the top polarization asymmetry [D. Choudhury$+$, PRD84, 014023 (2011)]. Although difficult, this can be done at the LHC. Other ways of distinguishing the various explanations are explored in Q. -H. Cao$+$, PRD81, 114004 (2010).

t Decays

The t decays almost exclusively via $t \to bW \Longrightarrow$ NP can be seen only in rare decays of the t. Fortunately, the LHC will produce 10^7-10^8 $t\bar{t}$ pairs per year, so that decays with BR's $\sim 10^{-5}$-10^{-6} can be probed. In this way, it may be possible to detect the presence of NP.

For the FCNC decays $t \to c\gamma, g, Z$ we have $BR(t \to c\gamma, Z) \sim 10^{-13}$ and $BR(t \to cg) \sim 10^{-11}$. With ATLAS, assuming no signal, one can constrain $BR(t \to c\gamma) \leq 1.2 \times 10^{-5}$, $BR(t \to cZ) \leq 5.5 \times 10^{-5}$ and $BR(t \to cg) \leq 4.2 \times 10^{-4}$ [J. Carvalho+, EPJ C52, 999 (2007)]. For certain NP models, it is found that the BR for a FCNC decay can be enhanced to a level where it is observable at the LHC.

In the SM, the FCNC decay $t \to cH$ has $BR(t \to cH) \sim 10^{-15}$. Assuming no signal, ATLAS can constrain $BR(t \to cH) \leq 2 \times 10^{-3}$ [L. Chikovani+, hep-ex/0505079]. It is found that, even with NP, $BR(t \to cH)$ can be increased only to the level of $\lesssim 10^{-4}$-10^{-5}, which is insufficient for observation. Other rare t decay modes include $t \to cVV$ [J. L. Diaz-Cruz+, PRD60, 115014 (1999)] and $t \to cl\bar{l}$ [M. Frank+, PRD74, 073014 (2006); J. L. Diaz-Cruz+, 1203.6889]. The SM BR's are tiny so their study could reveal the presence of NP.

t Decays: CP Violation

CPV requires two amplitudes with a relative weak phase. In the SM, t-quark processes are dominated by a single amplitude $\Longrightarrow$ the observation of a CP-violating effect involving the t would be a smoking-gun signal of NP.

There has been little discussion of CPV in t decays. One needs to add (at least) one NP amplitude. Furthermore, for a sizeable effect, the two amplitudes must be of comparable size. This requires a process which, though subdominant, is not negligible in the SM. One such decay is $t \to c\bar{b}b$. In the SM, this arises via $t \to bW(\to c\bar{b})$. The BR is $|V_{cb}|^2/3 = 5.6 \times 10^{-4}$, which is accessible at the LHC.

In K. Kiers+, PRD84, 074018 (2011), a NP effective Lagrangian is added to $t \to c\bar{b}b$ decays. First, there is a CP-violating partial rate asymmetry (PRA), which is proportional to the difference of rates between $t \to c\bar{b}b$ and its CP-conjugate decay. The PRA is due only to SM-NP interference, and its maximum possible value is 18%. Second, one has a triple-product asymmetry (TPA) involving the top quark's spin and two of the final-state momenta. It is found that the TPA is due to NP-NP interference, and can be of order 10's of percent.

Conclusions

In this talk, I have presented several measurements that can be made in the context of flavor physics – B and D mesons, t quarks – with the aim of finding signals of NP. Note that this is only a subset of possible measurements – there are many others that I haven't mentioned.

In the past, there were a number of hints of NP. Many of these have gone away – e.g. the discrepancy in the value of the B_d^0-$\bar{B}_d^0$ mixing phase β in $B_d^0 \to J/\psi K_S$ and $\bar{b} \to \bar{s}$ B_d^0 penguin decays, $B_s^0 \to \mu^+\mu^-$, $B_d^0 \to \bar{K}^*\mu^+\mu^-$, etc. However, there are still some that remain. For example, (i) there has been an argument that the measured value of β is in some tension with other, independent measurements, (ii) in $B \to \pi K$ decays, it is difficult to account for all the experimental measurements within the SM, (iii) several that I mentioned in the talk – the CP-violating like-sign dimuon charge asymmetry in the B system, the CPV asymmetry in $D^0 \to K^+K^-$ and $\pi^+\pi^-$, the $t\bar{t}$ forward-backward asymmetry. Hopefully there will be further signs of NP when these measurements are repeated with greater precision, when related processes are measured, and/or when other measurements are made.