CP Violation Beyond the Standard Model

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Discovery/Diagnostics

Examine CP violation beyond the SM in the context of future hadron colliders. Need to consider the following question: will NP will be discovered directly or not?

- No direct evidence for NP at hadron colliders. Study of B physics: discovery signals for NP. (Model independent)
- NP produced directly at hadron colliders. Study of B physics: diagnostic tests of this NP. (Model dependent)

Both possibilities must be considered. [see Bob Cahn's talk]

New Physics & CP Violation

$\exists$ many models of NP $\Longrightarrow \exists$ many effects on B decays.

- $b \to s$ FCNC: B_s^0–$\bar{B}_s^0$ mixing, $b \to s$ penguin
- $b \to d$ FCNC: B_d^0–$\bar{B}_d^0$ mixing, $b \to d$ penguin
- tree-level decays: $b \to c\bar{q}q'$, $b \to u\bar{q}q'$.

(Of course, any particular NP model may have all types of effects.)

Look for new CP-violating effects in all three areas. Concentrate principally on those measurements which can be made at hadron colliders.

$B_d^0(t) \to \phi K_s$

[Grossman] Hint of discrepancy in $B_d^0(t) \to \phi K_S$ $\Longrightarrow$ NP in $\bar{b} \to \bar{s}s\bar{s}$ penguin amplitude, i.e. NP in $b \to s$ FCNC.

Many NP models proposed: Z- or Z'-mediated FCNC's, nonminimal SUSY, SUSY with R-parity violation, LR symmetric models, anomalous t-quark couplings. G. Hiller; A. Datta; M. Ciuchini, L. Silvestrini; M. Raidal, ...

If effect confirmed, want to distinguish among these models, either through other B-physics measurements, or through direct searches at hadron colliders.

One important question: is only the $\bar{b} \to \bar{s}s\bar{s}$ decay affected, or are all $b \to s$ FCNC amplitudes affected? In particular, is there NP in B_s^0–$\bar{B}_s^0$ mixing? Can check this through other B measurements.

$b \longrightarrow s$ FCNC CP Tests

Important job for hadron colliders: study B_s^0–$\bar{B}_s^0$ mixing. Note: need to be able to resolve oscillations in B_s system. Once shown that can do this, can turn to CP tests involving B_s^0 mesons.

Note: even if NP discovered directly, cannot test the CP nature of the NP couplings to ordinary particles. This is the domain of B physics.

- $B_s^0(t) \to D_s^+ D_s^-$, $J/\psi\phi$. In SM, weak phase of B_s^0–$\bar{B}_s^0$ mixing is $\simeq 0$. Any CP asymmetry in these modes is sign of phase in B_s^0–$\bar{B}_s^0$ mixing $\Longrightarrow$ NP.
- $\mathcal{A}_{CP}^{mix}(B_s^0(t) \to D_s^{\pm} K^{\mp})$ measures γ. Possibly the first direct measurement of γ.

  R. Aleksan, I. Dunietz, B. Kayser

  Compare to measurement of γ at B-factories from $\mathcal{A}_{CP}(B^{\pm} \to DK^{\pm})$. Discrepancy points to NP in B_s^0–$\bar{B}_s^0$ mixing.
- $\mathcal{A}_{CP}^{mix}(B_s^0(t) \to \phi\phi)$: analogous to $B_d^0(t) \to \phi K_S$. (Need angular analysis: more below.) In SM, expect CP asymmetry $\simeq 0$. Measurement of nonzero asymmetry $\Longrightarrow$ NP in B_s^0–$\bar{B}_s^0$ mixing and/or $b \to s$ penguin.

In all cases, the NP must have new phases.

Note: not all models of NP predict new phases. For example, in the MSSM with minimal flavour violation, there are no new phases — the couplings of all SUSY particles track the CKM matrix.

Aside: Suppose one measures $\mathcal{A}_{CP}^{mix}(B_s^0(t) \to \Psi\phi)$ $\Longrightarrow$ extract CKM phase χ ($\sim 2-5\%$). Within SM,

$$\sin\chi = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{\sin\beta\sin(\gamma-\chi)}{\sin(\beta+\gamma)} \ .$$

A discrepancy points to the presence of NP (though we don't know where). R. Aleksan, B. Kayser, D.L.

Direct CP Asymmetries

Other tests for NP: direct CP asymmetries. There are several decays which have a single amplitude in SM. Many examples: $B \to J/\psi K$, ϕK; $B_d^0 \to D_s^+ D^-$; $B_s^0 \to D_s^+ D_s^-$; $B_c^+ \to J/\psi \pi^+$, etc. If find direct CP violation, implies the presence of a NP decay amplitude (penguin or tree).

One particularly useful decay: $B^+ \to \pi^+ K^0$. In SM, expect $|A(B^+ \to \pi^+ K^0)| = |A(B^- \to \pi^- \bar{K}^0)|$. Discrepancy in BR's points to NP, specifically in $b \to s$ penguin. In this case the transition $\bar{b} \to \bar{s} d \bar{d}$ is affected. (Note: there is also a hint of NP in $B \to K\pi$ [Grossman]. This is a good way of testing for this NP.)

Many models of NP affect $b \to s$ or $b \to d$ penguin amplitudes; fewer affect tree amplitudes. A complete study of direct CP asymmetries will probe various NP models. If NP has already been found, good way to study the new couplings.

Potential problem with direct CP asymmetries:

$$\mathcal{A}_{CP}^{dir} \propto \sin\phi \sin\delta \ ,$$

where δ is the strong phase difference between the SM and NP amplitudes. If $\delta = 0$, $\mathcal{A}_{CP}^{dir} = 0$, even if $\exists$ a NP contribution.

Triple Products

Even if $\mathcal{A}_{CP}^{dir} = 0$, can find NP by measuring the triple-product correlation $\vec{\varepsilon}_1^{\,*T} \times \vec{\varepsilon}_2^{\,*T} \cdot \hat{p}$ in the corresponding $B \to V_1 V_2$ decays (V_1 and V_2 are vector mesons). TP's complementary to direct CP asymmetries:

$$\mathcal{A}_T \propto \sin\phi \cos\delta \ .$$

Unlike $\mathcal{A}_{CP}^{dir}$, triple product doesn't vanish if $\delta = 0$.

TP's are odd under time reversal (T), can be faked by strong phases. To obtain true CP-violating signal: compare TP in $B \to V_1 V_2$ with that in $\bar{B} \to \bar{V}_1 \bar{V}_2$. The CP-violating TP is found by adding the two T-odd asymmetries:

$$\mathcal{A}_T \equiv \frac{1}{2}(A_T + \bar{A}_T) \ .$$

Thus, neither tagging nor time dependence is necessary to measure TP's – can in principle combine measurements of charged and neutral B decays.

Can obtain TP's by performing an angular analysis of the $B \to V_1 V_2$ decay. Note: a full angular analysis not necessary.

Triple Products in SM

Which $B \to V_1 V_2$ decays are expected to yield large TP's in the SM? Answer: None! G. Valencia; G. Kramer, W. Palmer; D. Atwood, A. Soni; A. Datta, D.L., ...

1. Decays with a single weak amplitude: e.g. $B \to J/\psi K^*$, $B_s^0 \to \phi\phi$, $B_s^0 \to D_s^* D_s^*$, $B_c^+ \to J/\psi \rho^+$, etc. No TP's expected. Model-independent.
2. Color-allowed decays with two weak amplitudes: e.g. $\bar{B}_d^0 \to D^{*+} D^{*-}$, $\bar{B}_s^0 \to D_s^{*+} D^{*-}$, $\bar{B}_s^0 \to K^{*+} K^{*-}$, $B_c^- \to \bar{D}^{*0} \rho^-$, $B_c^- \to \bar{D}^{*0} K^{*-}$, etc. Within (naive) factorization, TP's expected to vanish (even though there are two decay amplitudes with a relative weak phase). Nonfactorizable corrections expected to be very small for such decays. Predictions of tiny TP's robust.
3. Color-suppressed decays with two weak amplitudes: e.g. $B^- \to \rho^0 K^{*-}$, $\bar{B}_s^0 \to \phi K^*$, $B_c^- \to J/\psi D^{*-}$, etc. Nonfactorizable effects may be large. We have tried to be conservative in our estimates of such effects, and still find tiny TP's for such decays. Clearly model-dependent. Note: in any case BR's for such decays are very small.

Triple Products: New Physics

All TP's in SM expected to vanish or be very small in SM $\Longrightarrow$ excellent place to search for new physics!

Within factorization, if large TP found, indicates new physics with large couplings to the right-handed b-quark. Many new-physics models, though not all, have such couplings.

D. Atwood, A. Soni; A. Kagan; A. Datta, D.L.

Example: $A_{CP}(J/\psi K_S) \neq A_{CP}(\phi K_S)$. One explanation: contributions to $B \to \phi K_S$ from SUSY with R-parity violation. If so, will also contribute to $B \to \phi K^* \Longrightarrow$ TP's. In SM, TP's vanish; in this model of new physics, can get very large TP asymmetries: 15–20%!

Triple products are excellent diagnostic tests for new physics. Some NP models predict large TP's $\Longrightarrow$ null measurements can strongly constrain (or eliminate) such models.

Time-Dependent Angular Analysis

Consider $V_1 V_2$ state to which both B and $\bar{B}$ can decay (e.g. $B_s^0(t) \to \phi\phi$). Can get much more information if a time-dependent angular analysis of the decay $B^0(t) \to V_1 V_2$ can be performed.

D.L, N. Sinha, R. Sinha

In this case there are many more NP signals than just direct CP violation and TP's. In fact, there are a total of 12 such signals. If the NP conspires to make direct CP violation and TP's small, can still find it through one of the other signals.

Furthermore: if a signal for NP is found, there is enough information to obtain a lower bound on the NP parameters. Extremely useful: get direct information on the NP through measurements in the B system.

$B^0_{d,s} \to K^{(*)}\bar{K}^{(*)}$

Consider $B^0_d \to K^0\bar{K}^0$: pure $b \to d$ penguin:

$$\begin{aligned} A &= P_u\, V^*_{ub}V_{ud} + P_c\, V^*_{cb}V_{cd} + P_t\, V^*_{tb}V_{td} \\ &= \mathcal{P}_{uc}\, e^{i\gamma}\, e^{i\delta_{uc}} + \mathcal{P}_{tc}\, e^{-i\beta}\, e^{i\delta_{tc}} \ . \end{aligned}$$

Note: $\mathcal{P}_{uc}$ and $\mathcal{P}_{tc}$ include CKM info.

4 unknowns: $\mathcal{P}_{uc}$, $\mathcal{P}_{tc}$, $\Delta \equiv \delta_{uc} - \delta_{tc}$, α. But there are only 3 observables in $B^0_d(t) \to K^0\bar{K}^0$.

Now consider $B^0_s \to K^0\bar{K}^0$: pure $b \to s$ penguin:

$$\begin{aligned} A &= P^{(s)}_u\, V^*_{ub}V_{us} + P^{(s)}_c\, V^*_{cb}V_{cs} + P^{(s)}_t\, V^*_{tb}V_{ts} \\ &= \mathcal{P}^{(s)}_{uc}\, e^{i\gamma}\, e^{i\delta^{(s)}_{uc}} + \mathcal{P}^{(s)}_{tc}\, e^{i\delta^{(s)}_{tc}} \ . \end{aligned}$$

Note: $\mathcal{P}^{(s)}_{uc}$ is negligible compared to $\mathcal{P}^{(s)}_{tc}$. Therefore the measurement of $B(B^0_s \to K^0\bar{K}^0)$ gives $|\mathcal{P}^{(s)}_{tc}|$.

Point: can relate $|\mathcal{P}^{(s)}_{tc}|$ to $\mathcal{P}_{tc}$. Gives 4 measurements, 4 unknowns $\Longrightarrow$ can extract α from $B^0_{d,s} \to K^{(*)}\bar{K}^{(*)}$. Method more accurate if we use several final $K\bar{K}$ states – theoretical error is small, at most 5% and may well be even smaller. A. Datta, D.L.

Compare this value of α with that obtained elsewhere (e.g. $\pi\pi$, $\rho\pi$). A discrepancy would point to NP in the $b \to d$ or $b \to s$ penguin.

Experimental considerations:

- Branching ratios $\sim 10^{-6}$.
- K^*, $\bar{K}^*$ detected through their decays to charged π's and K's only $\Longrightarrow$ good K/π separation.
- No π^0 detection needed.

Method appropriate for hadron colliders.

Triple Products in Λ_b Decays

Look at decays $\Lambda_b \to F_1 P$ and $F_1 V$, where F_1 is a fermion (p, Λ, ...), P is a pseudoscalar (K^-, η, ...), V is a vector (K^{*-}, ϕ, ...).

W. Bensalem, A. Datta, D.L.

$\Lambda_b \to F_1 P$: one TP possible: $\vec{p}_{F_1} \cdot (\vec{s}_{F_1} \times \vec{s}_{\Lambda_b})$.

$\Lambda_b \to F_1 V$: 3 spins, 1 momentum $\Longrightarrow$ 4 possible TP's.

Within factorization, require right-handed coupling to b-quark to obtain TP. For certain $F_1 P$ final states, one can "grow" a sizeable RH current due to Fierzing certain operators. However, for $F_1 V$ final states, there are no such RH currents $\Longrightarrow$ all TP's expected to vanish in SM for $\Lambda_b \to F_1 V$ decays.

Find: $\mathcal{A}_T^{pK} = -18\%$, but TP's for all other decays (pK^{*-}, $\Lambda\eta$, $\Lambda\eta'$, $\Lambda\phi$) are expected to be small, at most $O(1\%)$ $\Longrightarrow$ good place to look for NP. Can use such TP's as a diagnostic tool for NP.

$b \to s\gamma$, $b \to d\gamma$

Inclusive partial rate asymmetries can be calculated reliably in the SM:

$$\begin{aligned} \mathcal{A}_{CP}^{dir}(b \to s\gamma) &= 0.6\% \, , \\ \mathcal{A}_{CP}^{dir}(b \to d\gamma) &= -16\% \, . \end{aligned}$$

If these are found to differ from their SM values $\Longrightarrow$ NP. Large deviations possible in several models of NP. A. Kagan, M. Neubert; K. Kiers, A. Soni, G.-H. Wu

Exclusive partial rate asymmetries $B \to K^*\gamma$, $B \to \rho\gamma$ not known as well — there are important bound-state corrections. However, if significant deviations from above values found for exclusive decays $\Longrightarrow$ NP. In particular, expect tiny asymmetry in $B \to K^*\gamma$. C. Greub, H. Simma, D. Wyler

Can also consider mixing-induced CP asymmetries (e.g. $B_d^0(t) \to \rho\gamma$, $B_s^0(t) \to \phi\gamma$). In the SM the photon polarization is opposite for B and $\bar{B}$ decays $\Longrightarrow$ no interference. That is, $\mathcal{A}_{CP}^{mix}(b \to s\gamma, b \to d\gamma) \simeq 0$ in SM. However, can get significant $\mathcal{A}_{CP}^{mix}$ in certain models of NP (e.g. LRSM, SUSY, exotic fermions).

D. Atwood, M. Gronau, A. Soni

Conclusions

There are many, many signals of NP in B/Λ_b processes.

There are many ways of determining which types of NP might be responsible for these signals. It is quite likely that we will have a fairly good idea of what kind of NP is present in these decays.

Hadron colliders have a significant role to play in the discovery of NP, as well as in its identification. Direct searches are complementary to the study of B processes.