b Physics at Hadron Colliders: Some Recent Ideas

David London
Université de Montréal

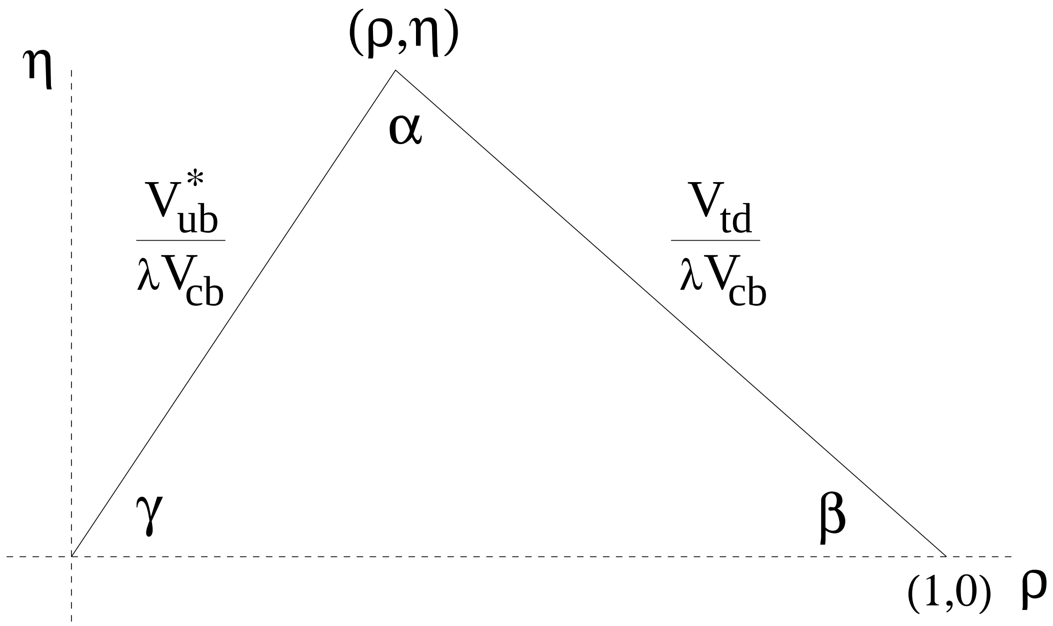
Nov. 22, 2002
Fermilab

Introduction

B physics: studied at B-factories and hadron colliders (complementary).

Raison d'être: test SM explanation of CP violation.

$\Rightarrow$ Unitarity Triangle:



Measure α, β and γ in as many independent ways as possible $\Longrightarrow$ find New Physics.

To see New Physics, need to know SM predictions. *All* predictions have theoretical input. Most promising signals have small theoretical uncertainty. A partial list (B: B-factories; H: hadron colliders) is

- $\mathcal{A}_{CP}^{mix}(B_d^0(t) \to \Psi K_S) = \mathcal{A}_{CP}^{mix}(B_d^0(t) \to \phi K_S)$. B
- $\mathcal{A}_{CP}^{dir}(B \to \Psi K) = \Lambda_{\perp i}(B \to \Psi K^*) = 0$. B
- $\mathcal{A}_{CP}(B^\pm \to D K^\pm) = \mathcal{A}_{CP}^{mix}(B_s^0(t) \to D_s^\pm K^\mp)$. B,H
- $\mathcal{A}_{CP}^{mix}(B_s^0(t) \to \Psi\phi) \simeq 0$. H
- Suppose one measures $\mathcal{A}_{CP}^{mix}(B_s^0(t) \to \Psi\phi) \Longrightarrow$ extract CKM phase χ ($\sim 2-5\%$). Within SM,

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

Another aim of studying B physics: improve our understanding of the hadronic physics describing B decays (e.g. B_s–$\bar{B}_s$ mixing, exclusive hadronic decays, etc.). Distinguish among various theoretical frameworks on market (e.g. QCD factorization, PQCD, etc.).

Outline

In this talk, I will describe some recent work on B physics. Topics applicable to hadron colliders, and involve CP violation, hadronic physics, and searches for new physics.

1. Measuring α using $B \to K^{(*)}\bar{K}^{(*)}$ Decays
2. T-Violating Triple-Product Correlations in Charmless Λ_b Decays
3. Triple Products in $B \to VV$ Decays (in progress)

Talk based on work done in collaboration with Alakabha Datta and Wafia Bensalem

A. Datta and D.L., PLB 533, 65, 2002

W. Bensalem, A. Datta and D.L., PLB 538, 309, 2002

W. Bensalem, A. Datta and D.L., hep-ph/0208054, to be published in PRD.

Signals for new physics: in general, probe new physics in the $b \to s$ FCNC (B_s^0–$\bar{B}_s^0$ mixing or the $b \to s$ penguin). No hadronic uncertainties.

Question: are there clean probes of new physics in the $b \to d$ FCNC?

NO.

Consider $b \to d$ penguin:

$$A = P_u V_{ub}^* V_{ud} + P_c V_{cb}^* V_{cd} + P_t V_{tb}^* V_{td}$$

Can eliminate any one CKM combination in terms of the other two:

$$\begin{array}{ll} (P_u - P_c) V_{ub}^* V_{ud} + (P_t - P_c) V_{tb}^* V_{td} & (\alpha) \\ (P_c - P_u) V_{cb}^* V_{cd} + (P_t - P_u) V_{tb}^* V_{td} & (\beta) \\ (P_u - P_t) V_{ub}^* V_{ud} + (P_c - P_t) V_{cb}^* V_{cd} & (\gamma) \end{array}$$

There is a "CKM ambiguity": don't know the relative weak phase.

In order to test for new physics in the $b \to d$ FCNC, need a theoretical assumption to break the CKM ambiguity.

(D.L., N. Sinha, R. Sinha)

$B_d^0 \to K^0 \bar{K}^0$

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 parameters: $\mathcal{P}_{uc}$, $\mathcal{P}_{tc}$, $\Delta \equiv \delta_{uc} - \delta_{tc}$, α

Recall:

$$\Gamma(B_d^0(t) \to f) \sim X + Y \cos \Delta m t - Z_I \sin \Delta m t$$

where

$$X \equiv \frac{|A|^2 + |\bar{A}|^2}{2} \quad , \quad Y \equiv \frac{|A|^2 - |\bar{A}|^2}{2} \; ,$$
$$Z_I \equiv \mathrm{Im}\left(e^{-2i\beta} A^* \bar{A}\right) \quad , \quad Z_R \equiv \mathrm{Re}\left(e^{-2i\beta} A^* \bar{A}\right) \; .$$

$(Z_R^2 = X^2 - Y^2 - Z_I^2.)$

3 OBSERVABLES, 4 UNKNOWNS.

Can express 3 theoretical parameters in terms of 4^{th}:

$$\mathcal{P}_{tc}^2 = \frac{Z_R \cos 2\alpha + Z_I \sin 2\alpha - X}{\cos 2\alpha - 1} \; .$$

$B_d^0 \to K^* \bar{K}^*$

K^* is $K^*(892)$, $K_1(1270)$, ...

Similar analysis as for $B_d^0 \to K^0 \bar{K}^0$:

$$\mathcal{P}'^{\,2}_{tc} = \frac{Z'_R \cos 2\alpha + Z'_I \sin 2\alpha - X'}{\cos 2\alpha - 1} \ .$$

Therefore

$$\frac{\mathcal{P}^2_{tc}}{\mathcal{P}'^{\,2}_{tc}} = \frac{Z_I \sin 2\alpha + Z_R \cos 2\alpha - X}{Z'_I \sin 2\alpha + Z'_R \cos 2\alpha - X'} \ .$$

Note: CKM info in $\mathcal{P}_{tc}$ and $\mathcal{P}'_{tc}$ cancels in the ratio.

If we knew the value of $\mathcal{P}^2_{tc}/\mathcal{P}'^{\,2}_{tc}$, we could extract α.

$B_s^0 \to K^{(*)}\bar{K}^{(*)}$

$B_s^0 \to K^0\bar{K}^0$: pure $b \to s$ penguin:

$$\begin{aligned} A &= P_u^{(s)}\,V_{ub}^*V_{us} + P_c^{(s)}\,V_{cb}^*V_{cs} + P_t^{(s)}\,V_{tb}^*V_{ts} \\ &= \mathcal{P}_{uc}^{(s)}\,e^{i\gamma}\,e^{i\delta_{uc}^{(s)}} + \mathcal{P}_{tc}^{(s)}\,e^{i\delta_{tc}^{(s)}} \end{aligned}$$

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

CLAIM:

$$\frac{{\mathcal{P}_{tc}^{(s)}}^2}{{\mathcal{P}_{tc}^{\prime(s)}}^2} = \frac{\mathcal{P}_{tc}^2}{{\mathcal{P}'_{tc}}^2} \ .$$

Note: CKM matrix elements cancel in ratios, so this is a statement about hadronic parameters.

A similar method applies to non-CP-conjugate decays of the form $K^0\bar{K}^*$, $K^*\bar{K}^0$.

IN ALL CASES, THE THEORETICAL ERROR IS SMALL, AT MOST 5% (AND MAY WELL BE EVEN SMALLER).

(Reason: theoretical uncertainties largely cancel in the double ratio.)

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.

Discrete ambiguities:

Potentially a serious drawback: method allows extraction of α with a 16-fold (!) ambiguity.

- Can be reduced to 4-fold by considering two different pairs of $K^{(*)}\bar{K}^{(*)}$ final states (e.g. $K^0\bar{K}^0$ and $K^*\bar{K}^*$; $K^0\bar{K}^*$ and $K^*\bar{K}^0$).
- We expect P_u, P_c in $b \to d$ penguins to be at most 50% of $P_t \Longrightarrow \mathcal{P}_{uc}/\mathcal{P}_{tc} < 0.5$ for all decays. This reduces the ambiguity to 2-fold: α, $\alpha + \pi$.

Other methods for measuring α: $B_d^0(t) \to \pi^+\pi^-$ (+ isospin analysis), $B \to \rho\pi$ (+ Dalitz-plot analysis). These methods have their difficulties. Could the $B \to K^{(*)}\bar{K}^{(*)}$ method be first? Perhaps. Regardless: a discrepancy between the values of α would point to new physics in the $b \to d$ penguin.

Triple Products

Triple-product correlation: $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, where each v_i is a spin or momentum.

TP correlations are odd under T $\Longrightarrow$ odd under CP.

Measure a nonzero value of

$$A_T \equiv \frac{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) - \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) + \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)} .$$

Complication: strong phases can produce a nonzero value of A_T, even if there is no CP violation (i.e. if the weak phases are zero).

True T-violating signal: nonzero value of

$$\mathcal{A}_T \equiv \frac{1}{2}(A_T - \bar{A}_T) \ ,$$

where $\bar{A}_T$ is the T-odd asymmetry measured in the CP-conjugate decay process.

$\mathcal{A}_T \sim \sin\phi \cos\delta \Longrightarrow$ remains even if strong phases vanish.

$b \to s\bar{u}u$ Decays

Inclusive $b \to s\bar{u}u$ decays get contributions from tree and penguin operators $\Longrightarrow$ looked at triple-product correlations.

(W. Bensalem, D.L.)

Ignored final-state masses (i.e. heavy-quark limit), did not consider triple products involving 3 spins (difficult).

Found: 2 nonzero TP's. In the rest frame of the b quark, they are:

1. $\vec{p}_u \cdot (\vec{s}_u \times \vec{s}_{\bar{u}})$ or $\vec{p}_{\bar{u}} \cdot (\vec{s}_u \times \vec{s}_{\bar{u}})$.
   These can be probed in $B \to V_1 V_2$ decays, where V_1 and V_2 are vector mesons.
2. $\vec{s}_b \cdot (\vec{p}_u \times \vec{p}_s)$.
   This can only be measured in Λ_b decays, since the spin of the b quark is involved.

TP's in Λ_b Decays (SM)

Idea: use $b \to s\bar{u}u$ effective hamiltonian, apply it to Λ_b decays using factorization.

Look at colour-allowed decays $\Lambda_b \to pK^-$, pK^{*-}.

a) $\Lambda_b \to pK^-$: one TP possible: $\vec{p}_p \cdot (\vec{s}_p \times \vec{s}_{\Lambda_b})$.

Factorization gives:

$$A(\Lambda_b \to pK^-) = \sum_{\mathcal{O},\mathcal{O}'} \langle K^- | \mathcal{O} | 0 \rangle \langle p | \mathcal{O}' | \Lambda_b \rangle \ .$$

This leads to

$$\begin{aligned} \mathcal{M}_P &= i f_K p_K^\mu \langle p | \, \bar{u} \gamma_\mu (1 - \gamma_5) b \, | \Lambda_b \rangle \, X_P \\ &\quad + i f_K p_K^\mu \langle p | \, \bar{u} \gamma_\mu (1 + \gamma_5) b \, | \Lambda_b \rangle \, Y_P \ , \end{aligned}$$

where X_P, Y_P are functions of CKM matrix elements, Wilson coefficients and masses.

Point: in order to have a nonzero TP, need interference of two different kinematical decay amplitudes $\Longrightarrow$ need X_P, Y_P nonzero.

Also, coefficient of $\vec{p}_p \cdot (\vec{s}_p \times \vec{s}_{\Lambda_b})$ is $\mathrm{Im}(X_P Y_P^*)$, so there must be a relative weak phase.

In SM, $X_P \neq 0$: all operators in effective hamiltonian involve a left-handed b. X_P contains pieces proportional to $V_{ub}V_{us}^*$ (tree) and $V_{tb}V_{ts}^*$ (penguin).

What about Y_P, which involves right-handed b?

One operator in H_{eff} is

$$\begin{aligned}\mathcal{O}_6 &\sim \bar{s}\gamma_\mu(1-\gamma_5)b\,\bar{u}\gamma^\mu(1+\gamma_5)u \\ &= -\frac{1}{2}\bar{s}(1+\gamma_5)u\,\bar{u}(1-\gamma_5)b\end{aligned}$$

But: factorization:

$$\langle p|\bar{u}(1-\gamma_5)b|\Lambda_b\rangle = \frac{p_K^\mu}{m_b}\langle p|\bar{u}\gamma_\mu(1+\gamma_5)b|\Lambda_b\rangle \ .$$

Therefore, using a Fierz transformation, one can generate a right-handed current due to operators such as $\mathcal{O}_6$.

But note: Y_P is suppressed by $1/m_b \Longrightarrow$ vanishes in heavy-quark limit. Small effect?

No: Y_P is proportional to

$$\chi_K = \frac{2m_K^2}{(m_s + m_u)m_b} \simeq 1 \ .$$

That is, Y_P is formally suppressed by $1/m_b$, but is not small due to chiral enhancement factor χ_K.

Result: X_P, $Y_P \neq 0$, and they have different weak phases. Expect sizeable TP. We find:

$$\mathcal{A}_T^{pK} = -18\% \ .$$

b) $\Lambda_b \to pK^{*-}$: 3 spins, 1 momentum $\Longrightarrow$ 4 possible TP's.

Like $\Lambda_b \to pK^-$, use factorization to write

$$\begin{aligned}\mathcal{M}_V &= m_{K^*} g_{K^*} \varepsilon_{K^*}^{*\mu} \langle p|\, \bar{u}\gamma_\mu(1-\gamma_5)b\,|\Lambda_b\rangle\, X_V \\ &\quad + m_{K^*} g_{K^*} \varepsilon_{K^*}^{*\mu} \langle p|\, \bar{u}\gamma_\mu(1+\gamma_5)b\,|\Lambda_b\rangle\, Y_V \ .\end{aligned}$$

Only two amplitudes $\Longrightarrow$ coefficients of 4 TP's are all proportional to $\mathrm{Im}(X_V Y_V^*)$.

Again, in order to have nonzero TP's, need two interfering kinematical decay amplitudes $\Longrightarrow$ need X_V, Y_V nonzero.

As before, $X_V \neq 0$, and it contains pieces proportional to $V_{ub}V_{us}^*$ (tree) and $V_{tb}V_{ts}^*$ (penguin).

And Y_V? Recall: for $\Lambda_b \to pK^-$, we generated a matrix element $\langle p|\bar{u}\gamma_\mu(1+\gamma_5)b|\Lambda_b\rangle$ due to the operator $\mathcal{O}_6 \sim \bar{s}(1+\gamma_5)u\,\bar{u}(1-\gamma_5)b$.

But here: $\langle K^{*-}|\bar{s}(1\pm\gamma_5)u|0\rangle = 0$!

Therefore: $Y_V = 0$, so all triple-product asymmetries in $\Lambda_b \to pK^{*-}$ vanish in the SM.

Nonfactorizable effects:

- All calculations suggest these are small.
- Look for $\Lambda_b \to \Delta^+ K^- (\pi^-)$, $\Lambda_b \to \Sigma\eta(\eta')$, or $\Lambda_b \to \Sigma\phi$. Observation of any of these decays indicates sizeable nonfactorizable effects.

Λ_b Triple Product Summary:

- $\Lambda_b \to pK^-$: -18%,
- $\Lambda_b \to p\pi^-$: $+6\%$,
- $\Lambda_b \to \Lambda\phi$: 0 (single weak decay amplitude),
- $\Lambda_b \to \Lambda\eta$, $\Lambda\eta'$, pK^{*-}, $p\rho^-$: $< 1\%$.

Note: many TP asymmetries in Λ_b decays are expected to be very small in the SM $\Longrightarrow$ *good place to look for new physics*.

TP's in Λ_b Decays (NP)

Look for new-physics effects in triple products. Model-independent analysis: consider all NP $\bar{s}\mathcal{O}b\,\bar{u}\mathcal{O}'u$ operators, calculate their effects on TP's.

For example, which NP operators can lead to large TP asymmetries in $\Lambda_b \to pK^{*-}$?

Answer: need operators which contribute to the $\langle p|\,\bar{u}\gamma_\mu(1+\gamma_5)b\,|\Lambda_b\rangle$ matrix element. They are:

$$\bar{s}(1+\gamma_5)b\,\bar{u}(1-\gamma_5)u$$

and

$$\bar{s}\gamma^\mu(1+\gamma_5)b\,\bar{u}\gamma_\mu(1+\gamma_5)u\ .$$

First operator corresponds to scalar exchange. Can occur, for example, in multi-Higgs models without Natural Flavour Conservation or in SUSY models with R-parity violation.

Second operator can occur in models with Z- or Z'-mediated FCNC's.

Point: a significant triple-product signal in $\Lambda_b \to pK^{*-}$ would

- tell us that new physics is present, and
- indicate which new-physics operators can contribute.

That is: TP asymmetries in Λ_b decays can serve as a diagnostic tool for new physics.

Can apply same procedure to other decays such as $\Lambda_b \to \Lambda\eta$, $\Lambda_b \to \Lambda\phi$, etc. Can get a complete picture of which new-physics operators are or are not present.

TP's in $B \to V_1 V_2$ Decays

(Originally examined by G. Valencia, PRD 39, 3339, 1989.)

Look at decays $B(p) \to V_1(k_1, \varepsilon_1) + V_2(k_2, \varepsilon_2)$: one TP possible: $\vec{q} \cdot (\varepsilon_1 \times \varepsilon_2)$, where $q \equiv k_1 - k_2$.

Within factorization,

$$\begin{aligned} \mathcal{A}(B \to V_1 V_2) &= \sum_{\mathcal{O},\mathcal{O}'} \{ \langle V_1 | \mathcal{O} | 0 \rangle \langle V_2 | \mathcal{O}' | B \rangle \\ &\qquad + \langle V_2 | \mathcal{O} | 0 \rangle \langle V_1 | \mathcal{O}' | B \rangle \} \ . \end{aligned}$$

Point: both kinematical amplitudes must be present to produce a triple product!

Example: consider $B_d^0 \to D^{*+} D^{*-}$. There is a tree ($V_{cb}^* V_{cd}$) and a penguin ($V_{tb}^* V_{td}$) contribution. Two amplitudes, a relative weak phase $\Longrightarrow$ there is a CP-violating triple product, right?

No: both amplitudes contribute to $\langle D^{*+} | \mathcal{O} | 0 \rangle \langle D^{*-} | \mathcal{O}' | B \rangle$; there is no $\langle D^{*-} | \mathcal{O} | 0 \rangle \langle D^{*+} | \mathcal{O}' | B \rangle$. (I.e. in the SM one has only $\bar{b} \to \bar{c}$; $\bar{b} \not\to c$.) Thus, there is no triple product.

Which $B \to V_1 V_2$ decays are expected to yield triple products in the SM?

In the quark-level decay $b \to q\bar{q}'q'$, the spectator quark $\bar{q}_s$ must be the same as $\bar{q}'$.

Decays:

- $B_c^- \to \Psi D^{*-}$ ($b \to c\bar{c}d$).
- $B^- \to \rho^0 K^{*-}$ ($b \to u\bar{u}s$).
- $\bar{B}_d^0 \to K^{*0}\rho^0$ ($b \to d\bar{d}s$ and $b \to u\bar{u}s$).
- $B^- \to \rho^- \rho^0$ ($b \to u\bar{u}d$ and $b \to d\bar{d}d$).
- $\bar{B}_s^0 \to \phi K^{*0}$ ($b \to s\bar{s}d$).

Some can be studied at B-factories, while others require hadron colliders.

A second class of decays:

- $B^- \to D^{*0} K^{*-}$ $(b \to c\bar{u}s)$ and $B^- \to \bar{D}^{*0} K^{*-}$ $(b \to u\bar{c}s)$.
- $B_c^- \to D^{*0} D_s^{*-}$ $(b \to c\bar{u}s)$ and $B_c^- \to \bar{D}^{*0} D_s^{*-}$ $(b \to u\bar{c}s)$.
- $B^- \to D^{*0} \rho^-$ $(b \to c\bar{u}d)$ and $B^- \to \bar{D}^{*0} \rho^-$ $(b \to u\bar{c}d)$.
- $B_c^- \to D^{*0} D^{*-}$ $(b \to c\bar{u}d)$ and $B_c^- \to \bar{D}^{*0} D^{*-}$ $(b \to u\bar{c}d)$.

In all cases, we require that the D^{*0} and $\bar{D}^{*0}$ decay to the same final state.

The triple products for all other decays are expected to vanish in the SM $\Longrightarrow$ *a good place to look for new physics*. As in Λ_b decays, by studying TP asymmetries in $B \to V_1 V_2$, can get a good idea of which new-physics operators are or are not present.

In progress: estimates of sizes of nonzero triple products within the SM.

Note: $\vec{q} \cdot (\varepsilon_1 \times \varepsilon_2) = 0$ for longitudinal polarization ($\varepsilon_1 \sim k_1$ and $\varepsilon_2 \sim k_2$). Thus, triple products arise only for transversely-polarized final-state vector mesons.

However,

$$\frac{M_T}{M_L} \sim \frac{m}{E} ,$$

where $m \sim m_{1,2}$ and $E \sim M_B/2$.

Thus, the branching ratio for producing transversely-polarized V's is suppressed relative to that for producing longitudinally-polarized V's by $(m/E)^2$.

Therefore: best to use heaviest final-state vector mesons possible. (E.g. radially excited states of ρ, K^* or ϕ.)

Conclusions

I presented several recent results in B physics which might be useful for experiments at hadron colliders.

1. New method for measuring α: $B^0_{d,s}(t) \to K^{(*)}\bar{K}^{(*)}$ decays
   - Good for hadron colliders: branching ratios $\sim 10^{-6}$; K^*, $\bar{K}^*$ detected through their decays to charged particles; no π^0 detection needed.
   - Compare with α as obtained in $B \to \pi\pi$ or $B \to \rho\pi$. Can find new physics in $b \to d$ FCNC.
   - Requires theoretical input. But model calculations suggest that the error is at most 5%, and could well be quite a bit less. Can be tested experimentally. So the method is quite clean.
2. Triple-product asymmetries in Λ_b decays
   - Using factorization, we find that the triple product in $\Lambda_b \to pK^-$ ($\Lambda_b \to p\pi^-$) is expected to be -18% ($+6\%$) in the SM.
   - All other TP's are $< 1\%$. The measurement of a sizeable TP in any of these decays would indicate the presence of new physics.
   - By measuring TP's in a variety of Λ_b decays, one can establish which new-physics operators are or are not present. This will help in determining the identity of the new physics.

3. Triple-product asymmetries in $B \to V_1 V_2$ decays (in progress)

- The triple product vanishes for longitudinally-polarized V's $\Longrightarrow$ best to use heaviest final-state vector mesons possible
- Most $B \to V_1 V_2$ decay modes are not expected to yield triple products. Thus, by searching for triple products in these modes, one can probe for new physics.
- For those decay modes which do have triple products in the SM, we are in the process of calculating their expected values.