Super-BaBar Physics

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Crucial contributions from *Helen Quinn*

- Introduction
  ... Questions / Scenarios
  ... Comparisons with LHCB / BTeV
- Survey of some interesting modes
  ... Consider only with $\lesssim$ few % theory uncertainty
  ... Any "killer application"?
- Summary

Introduction

- Want to make many redundant measurements of observables which in the SM determine CKM elements, but sensitive to different short distance phys.

- Only very few observables are theoretically clean at the few $\%$ level (even in principle):
  $B \to \psi K_S$, $B \to \pi\pi$ w/ isospin analysis (maybe $\rho\pi$)
  $B_s \to D_s K$, $B \to DK$, $K_L \to \pi^0 \nu\bar{\nu}$, ...
  and some observables which vanish in the SM

  Except for $\sin 2\beta$, all are extremely hard to measure

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- If this physics is still interesting at high precision, after LHC turns on, then we only need to consider:
  - SM processes whose theory error is not more than a few percent
  - Measurements sensitive to different short distance phys., as limited by hadronic uncertainties (e.g., $B \to \psi K_s$ vs. ϕK_s; $b \to s/d\,\ell\ell$ vs. $s/d\,\nu\bar{\nu}$)

Assumptions

- Before sBaBar might become reality,
  - $\alpha(B \to \rho\pi)$ known at $\sim 10\%$ (BaBar/Belle)
  - $\gamma(B_s \to D_s K)$ known at $\sim 10\%$ (LHCb/BTeV)
  - $\beta(B \to \psi K_S)$ known at few $(1?)\,\%$ level (all...)
  - Magnitudes of $|V_{ub}/V_{cb}|$ and $|V_{td}/V_{ts}|$ known at $\lesssim 10\,\%$ (maybe $5\,\%$)
  - Some rare decays (e.g., $b \to s\gamma$, $b \to s\ell\ell$, inclusive / exclusive) known at $\sim 10\,\%$

- Won't consider here tau, charm physics, direct CPV — which are all interesting...

Questions

- "Machine":

  Symmetric or asymmetric?
  Is time dependence crucial for the interesting phys.?
  (Probably not for $\pi^0\pi^0$ rate and rare decays)

  Is there a case for $5S$?
  Any B_s physics that can't be done at LHCb / BTeV?

- "Physics":

  Precise SM measurements: what observables can match the accuracy and cleanness of $\sin 2\beta$?

  CKM tests are limited not by THE most precise measurement, but the 2nd, 3rd, etc., best ones!

  Searching for new physics: what are the most interesting processes that can distinguish between various NP scenarios?

  Similar processes involving different generations ($B_{d,s}$ mixing; CPV; $b \to d, s$ rare decays)

Scenarios (1)

- A: New physics found (LHC / B factories) that affects flavor physics sufficiently to learn about some of the new couplings

  $\Rightarrow$ B physics may be important for mapping out new mixing matrices (recall: V_{ts} and V_{td} will be measured in B – not in top – decay)

  We'll want to measure many rare decays and CPV

- B: New physics found at LHC, but no implications for flavor physics

  $\Rightarrow$ B physics will become less interesting

- X: Neither A, nor B

  $\Rightarrow$ B physics remains interesting as precision SM tests — but we all get depressed...

Scenarios (2)

- A: Lattice delivers unquenched form factors at the promised few $\%$ level within next few years

  $\Rightarrow$ Can get $|V_{ub}|$ and $|V_{cb}|$ at this level — large impact (probably cleaner at e^+e^- than at hadron machines). Also good news for many exclusive rare decays, $B \to K^{(*)}\ell\ell$, etc.; and $|V_{td}/V_{ts}|$ from mixing

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- B: Lattice errors decrease slower than promised

  $\Rightarrow$ Inclusive measurements become essential — e^+e^- may have an advantage over hadronic B factories for inclusive decays

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- X: Skeptical view — want many cross-checks

  $\Rightarrow$ Inclusive measurements important, both in their own right and to cross-check exclusive

LHCb highlights

From: T. Nakada, BCP4

http://www.hepl.phys.nagoya-u.ac.jp/public/bcp4/program.html

LHC contributions to CP violation

Improvement in statistics

useful B sample @ LHC in one year $\gtrsim$ Σ all previous B experiments by then

$B_d \to J/\psi\ K_S$ (ATLAS, CMS, LHCb)	$\sigma(\sin 2\beta) < 0.01$
$B_d \to K^*\ \mu^+\mu^-$ (ATLAS, CMS, LHCb)	45k events/year LHCb
$B_d \to \pi^+\pi^-$ (LHCb, ATLAS???)	~5k flavour tagged/year
$B_d \to \rho\pi$ (LHCb)	100 flavour tagged $\rho^0\pi^0$/year ($Br = 10^{-6}$)
$B_d \to D^*\pi$ (LHCb)	340k flavour tagged $D^*\pi$/year
$B_d \to K^\pm\pi^\mp$ (LHCb)	
$B_d \to \phi\ K_S$ (LHCb)	

Up to one π^0 in the final state.

(It seems to me [see: B decays at the LHC, hep-ph/0003238, p.90] that # events for $B_d \to K^*\mu^+\mu^-$ should read 4.5k/year)

BTeV highlights

From: BTeV Proposal, Executive Summary, p.13

http://www-btev.fnal.gov/public_documents/btev_proposal/

Table 3: Summary of physics reach in 10^7s. Pairs of reactions between two lines are used together.

Process	# of Events	S/B	Parameter	Error or (Value)
$B^o \to \pi^+\pi^-$	24,000	3	Asym.	0.024
$B_s \to D_s^{\pm} K^{\mp}$	13,100	7	γ	7°
$B^o \to J/\psi K_S$	80,500	10	$\sin(2\beta)$	0.025
$B_s \to D_s^+ \pi^-$	103,000	3	x_s	(75)
$B^- \to \overline{D}^0(K^+\pi^-)K^-$	300	1	γ	10°
$B^- \to D^0(K^+K^-)K^-$	1,800	>10	γ	10°
$B^- \to K_S\pi^-$	8,000	1	γ	$< 5^\circ$
$B^o \to K^+\pi^-$	108,000	20	γ	$< 5^\circ$
$B^o \to \rho^{\pm}\pi^{\mp}$	9,400	4.1	α	$\sim 10^\circ$
$B^o \to \rho^o\pi^o$	1,350	0.3	α	$\sim 10^\circ$
$B_s \to J/\psi\eta$	1,920	15	$\sin(2\chi)$	0.033
$B_s \to J/\psi\eta'$	7,280	30	$\sin(2\chi)$	0.033
$B^- \to K^-\mu^+\mu^-$	1280	3.2		
$B^o \to K^*\mu^+\mu^-$	2200	10		

A sample comparison

- Consider $B \to K^{(*)}\ell^+\ell^-$, which is relatively "easy" at the hadronic B factories

  Jeff Richman tells me that ~ 100 events expected in $230\,\text{fb}^{-1}$ ($K + K^*$ and $e + \mu$)

  $\Rightarrow 10^{36}$ is not "too high" luminosity — needed to be competitive with LHCb / BTeV

- "Harder" modes not necessarily more favorable for e^+e^- — BTeV claims $S/B = 10$ in above mode; see also LHCB/BTeV numbers for $B \to \rho^0\pi^0$.

- I am guessing that e^+e^- may have advantage in
  - Modes w/o two charged tracks, e.g., $B \to \pi^0\pi^0$
  - Modes with neutrinos: semileptonic, $B \to \ell\nu$, etc.
  - Inclusive rare and semileptonic decays

A (subjective) best buy list

- $B \to \pi\pi, \rho\pi$: pursue isospin analysis and Dalitz plot; Only with data can tell how far these can be pushed
- $B \to D^*\pi$: Is it really hopeless to get $\sin(2\beta+\gamma)$? Very clean; and also helps with discrete ambig's
- $B \to DK$: Hard, but clean way to get "γ"
- $B \to \phi K_S$: β from non-$(b \to c\bar{c}s)$ decay

- $B \to \nu\nu\, K^{(*)}/\rho/\pi$ or $B \to \nu\nu X_{s,d}$: (a dream...)
  Very clean — the B physics analog of $K \to \pi\nu\bar{\nu}$
  Are these really hopeless? (3 3rd family fermions)
- $B \to K^{(*)}\ell\ell$ or $B \to X_s\ell\ell$: bsZ penguins, SUSY, right handed couplings, $|V_{ts}|$, $|V_{td}|$, etc.
  In particular A_{FB} is clean probe of NP
- $B \to \ell\bar{\nu}$: $f_B|V_{ub}|$ – test lattice, sensitive to $H^\pm$
  Must nail: in SM $\mu\nu \sim 3\times 10^{-7}$; also do $B \to \tau\bar{\nu}$)

"α" modes

- $B \to \pi\pi$: Penguin only contributes to $\Delta I = 1/2$ amplitude $\Rightarrow$ To get clean information, need $B \to \pi^0\pi^0$ to isolate asymmetry in the $\Delta I = 3/2$ channel

  Expect $\mathcal{B}(\pi^0\pi^0) \sim$ few $\times\, 10^{-7}$ — very tough

  Isospin violation claimed to be sizable (Gardner)

  — need to check / reanalize

- $B \to \rho\pi$: Isospin analysis is still possible (Dalitz plot), and $\pi^+\pi^-\pi^0$ final state has two charged tracks

$\mathcal{B} \times 10^5$	CLEO	BaBar
$\rho^0\pi^+$	1.0 ± 0.4	< 3.9
$\rho^\pm\pi^\mp$	2.8 ± 0.9	4.9 ± 1.4

  Good news if: 1) nonresonant $\pi^+\pi^-\pi^0$ rate small; 2) higher resonance contributions (ρ', ...) small

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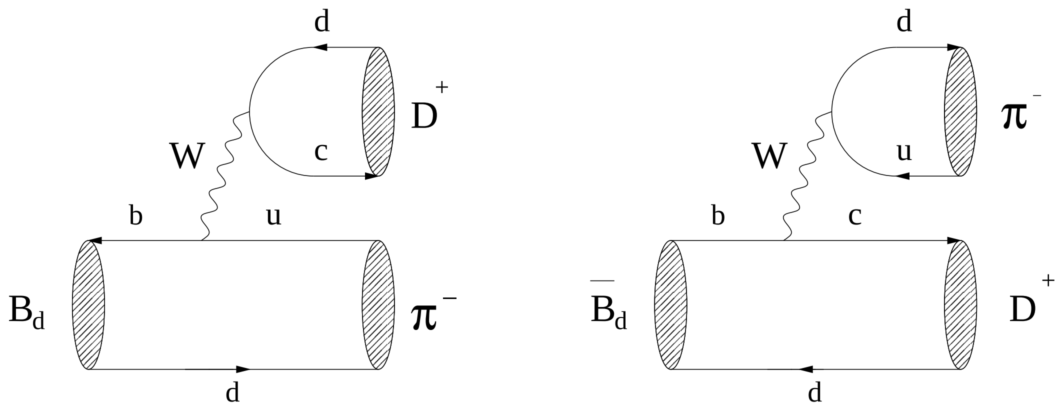
Unclear whether theory uncertainty can be pushed down to few $\%$ in either case — need both more data and some theoretical work to know

$B \to D^*\pi$

- Interference between $b\bar{d} \to c\bar{u}d\bar{d}$ and $\bar{b}d \to \bar{u}c\bar{d}d$

  Four time dependent rates, $B, \bar{B} \to D^{*\pm}\pi^{\mp}$, determine A_1/A_2 and $\sin(2\beta+\gamma)$ free of theory errors



  Problem: $A(\bar{b} \to \bar{u}c\bar{d})/A(b \to c\bar{u}d) \sim \lambda^2$

  I was told at the collaboration meeting to forget it. Still, this is a very clean mode, to be kept in mind...!

  Belle study obtains 0.2 error from $1/2\,\mathrm{ab}^{-1}$ (BCP4)

Even crude measurement could help with discrete ambiguities (different from 2β or $2\alpha = 2\pi - 2\beta - 2\gamma$)

“γ” modes

Direct CPV: $b \to u\bar{u}d,\ u\bar{c}d$ — requires strong phase, which must be extracted from the analysis

- $B^\pm \to (D^0, \bar{D}^0)K^\pm \to f_i\, K^\pm \qquad (i = 1, 2)$

  Triangle construction from rates $\Rightarrow \quad \sin(\gamma \pm \delta)$

  Total Br's $\sim 10^{-7}$ — statistics?

β from non-$(b \to c\bar{c}s)$ decay

$\sin 2\beta$ from $B \to \psi K_S$ is very clean theoretically (Have to be reconsidered at the ~ 0.01 level)

- In the SM both $\begin{cases} B \to \psi\, K_S & b \to c\bar{c}s \text{ tree} \\ B \to \phi\, K_S & b \to s\bar{s}s \text{ penguin} \end{cases}$

  measure $\sin 2\beta$ — NP can easily modify $b \to s\bar{s}s$ decay amplitude Grossman, Worah

  Important to measure same angle in several modes

The decay rate is:
$\mathcal{B}(B \to \phi\, K_S) = (8.1^{+3.1}_{-2.5}) \times 10^{-6}$ (BaBar)

Constrain rescattering ($b \to u\bar{u}s, s\bar{d}d \to s\bar{s}s$), by measuring $B^+ \to \phi\pi^+, K^*K^+$ Grossman, Isidori, Worah

- Interesting to push until ~ 0.04 error — requires of order 5 ab^{-1} (BaBar book p.315)

  But hadronic B factories can probably also do this

Rare decays

- A crude guide... ($\ell = e$ or μ)

Decay	SM rate	physics examples
$B \to c\ell\nu$	$10.5\,\%$	reference, $\lvert V_{cb}\rvert$
$B \to c\tau\nu$	$2.3\,\%$	mass effects
$B \to u\ell\nu$	1×10^{-3}	$\lvert V_{ub}\rvert$
$B \to s\gamma$	3×10^{-4}	$\lvert V_{ts}\rvert$, $H^{\pm}$, SUSY
$B \to s\nu\nu$	4×10^{-5}	new physics
$B \to \tau\nu$	4×10^{-5}	$f_B \lvert V_{ub}\rvert$, $H^{\pm}$
$B \to s\ell^+\ell^-$	7×10^{-6}	new physics
$B_s \to \tau^+\tau^-$	1×10^{-6}	
$B \to s\tau^+\tau^-$	5×10^{-7}	
$B \to \mu\nu$	3×10^{-7}	
$B_s \to \mu^+\mu^-$	4×10^{-9}	
$B \to \mu^+\mu^-$	1×10^{-10}	

- Replacing $b \to s$ by $b \to d$ costs factor ~ 20 (in SM)

  Would e^+e^- have an advantage to study rare $b \to d$ decays under large $b \to s$ backgrounds?

- In $B \to q\, l_1 l_2$ decay expect $\sim 10 - 20\%$ K^*/ρ, and $\sim 5 - 10\%$ K/π

Brainstorming

Recent ideas requiring “ridiculous” number of B’s:

- Extracting $\cos\alpha$ from $B^{\pm} \to \pi^{\pm} e^{+} e^{-}$
  Grinstein, Nolte, Rothstein, PRL 84 (2000) 4545

  Need rough q^2 dependence of a $\sim 10^{-8}$ rate

- Gamma with CP-tagged B_s and B_d decays
  Falk & Petrov, PRL 85 (2000) 252

  Cannot be done at hadron machines, but no asymmetry needed. They estimate that 10^{35} on the $5S$ may be enough.

Should search for lepton number/flavor violation at accessible ($10^{-(9-10)}$?) level, $B \to e\mu, \tau\mu$, etc., but...

Summary

If NP is discovered then many couplings may only be measurable in B decays

If results consistent with SM, then program is interesting as long as sensitivity to NP can be improved

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- The 10^{36} luminosity seems about right to be competitive with hadronic B factories, e.g., on rare decays

  Still, $\Upsilon(4S) \to B_{u,d}$ only, and there are many exciting processes involving B_s decays

  I think only NP searches or precision SM tests could justify such machine; not hadronic physics by itself

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- Is there an advantage for an asymmetric over a symmetric machine for this physics?

  Can I imagine a scenario in which either is crucial?

Gold-plated modes?

- What could be a "killer application"?
  - $\mathcal{B}(B \to \pi^0\pi^0)$ and isospin analysis in $B \to \pi\pi$
  - Decays with ν's, e.g., $B \to \mu\nu$ & semileptonic
    Will $10\,$ab^{-1}/yr mean few $\times\, 10^7$ fully reco'd B's?
    ... then do $B \to \tau\nu$ and try $B \to K^{(*)}/X_s\,\nu\nu$...!?
  - Angle γ from $B \to DK$ (maybe $B \to D^*\pi$)
  - Many inclusive rare / semileptonic decays
    How well can one get $|V_{td}/V_{ts}|$ without mixing?
    (ultimately it's a lattice issue whether $|V_{ub}/V_{cb}|$ and $|V_{td}/V_{ts}|$ can be measured at the $\%$ level)

- Many interesting and maybe even unique measurements, but cannot seem to find anything terribly compelling beyond $\sim 1\,$ab^{-1} and LHCb / BTeV

  This may well change depending on where the physics leads us... and/or with more imagination...