Why Super-B?

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P5 Meeting, Feb 21 2008, SLAC

- Flavor as a probe of new physics
- Sizable NP contributions possible
- Some key processes
- Conclusions

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Professor Charles Baltay
Chair, P5 Subpanel
Department of Physics
Yale University
P.O. Box 208120
New Haven, CT 06520

Dear Professor Baltay,

We are writing to encourage the P5 committee to recommend funding US experimentalists to participate in an offshore super B factory.

As you know, the main focus of the high energy community is directed towards the study of the physics of the origin of electroweak symmetry breaking. There are very good reasons for this. The single Higgs doublet is the simplest way to break the electroweak symmetry, however, there is no direct experimental evidence that it is the correct one. Furthermore, the standard model with a single Higgs doublet requires an awkward fine tuning, and this unpleasant feature is usually called the hierarchy puzzle. Many extensions of the standard model have been proposed in the literature, the most well studied of which is low energy supersymmetry. However, it is possible that none of the proposed theoretical ideas is correct, and the LHC results will lead the physics community in a new direction.

Before the impressive results from the B factories, the simple picture of Kobayashi and Maskawa for the origin of the CP violation observed in weak K decays had not been tested experimentally. The BaBar and Belle experiments have shown that the standard model description of the flavor sector is correct at leading order, and corrections to it are constrained to be around or below the 10% level. In fact, some extensions of the standard model that were proposed to solve the hierarchy puzzle are likely to give rise to changes in flavor physics that can be observable at a super B factory.

Equally importantly is the fact that flavor physics can teach us something about the TeV scale new physics, which cannot be learned from the direct production of new particles at the LHC. The pattern of possible small deviations from the standard model may discriminate between different new physics

scenarios. Direct measurements of the subleading couplings of the new heavy particles may be impossible. However, one can probe them via loop processes in B, D, K meson and lepton decays. Therefore, the precision of the tests of the standard model flavor sector should be improved as much as possible.

For example, consider the magnitude of $B\bar{B}$ mixing in low energy supersymmetry. In the standard model this arises predominantly from a box diagram with W bosons and top quarks in the loop. In a supersymmetric extension of the standard model there is also a box diagram with winos and stops in the loop. The precise size of this contribution depends crucially on the mechanism of SUSY breaking that we would like to probe. In order to detect a new physics contribution to $B\bar{B}$ mixing at the percent level, it is not enough to measure the mixing amplitude itself, but it is the combination of many measurements that can reveal such an effect. A super B factory can also make sensitive tests of lepton flavor and lepton number conservation (e.g., $\tau \to \mu\gamma$ and $\tau \to 3e$), which may not be available at other facilities. Furthermore, even in the absence of new beyond the standard model discoveries, a super B factory can provide important constraints similar to what the LEP program has done.

For these reasons we think that it is extremely important to carry out the super B factory program. The experience of US physicists interested in working on this project is crucial for its success. Thus, we think the US should take a major role in this project, and we encourage you to recommend supporting it.

Sincerely,

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Benjamin Grinstein, UCSD
Yuval Grossman, Cornell
Zoltan Ligeti, LBNL
Aneesh V. Manohar, UCSD
Ira Z. Rothstein, Carnegie Mellon
Iain W. Stewart, MIT
Mark B. Wise, Caltech

Why is flavor physics interesting?

- SM flavor problem: hierarchy of masses and mixing angles; why ν's are different
- NP flavor problem: TeV scale (hierarchy problem) $\ll$ flavor & CPV scale

$$\epsilon_K\!: \frac{(s\bar d)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\text{TeV}, \quad \Delta m_B\!: \frac{(b\bar d)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3\,\text{TeV}, \quad \Delta m_{B_s}\!: \frac{(b\bar s)^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2\,\text{TeV}$$

  - Almost all extensions of the SM have new sources of CPV & flavor conversion
  - A major constraint for model building
  - The observed baryon asymmetry of the Universe requires CPV beyond the SM
    Not necessarily in flavor changing processes, nor necessarily in quark sector
    Flavor suppression destroys KM baryogenesis; flavor matters for leptogenesis

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- Flavor sector has only been tested at the 10% level; can be done a lot better, and many NP models proposed to solve the hierarchy puzzle have observable effects

Spectacular track record

- Flavor and CP violation are excellent probes of New Physics
  - β-decay predicted neutrino (Pauli)
  - Absence of $K_L \to \mu\mu$ predicted charm (GIM)
  - ϵ_K predicted 3rd generation (KM)
  - Δm_K predicted m_c (GL)
  - Δm_B predicted large m_t
- If there is NP at the TEV scale, it must have a very special flavor & CP structure
- A super B factory will increase the sensitivity to a large number of interesting processes in B, D, and τ decays by over an order of magnitude

SUSY contributions to $K^0 - \overline{K}^0$ mixing

- $$\frac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm exp}} \sim 10^4 \left(\frac{1\,\mathrm{TeV}}{\tilde m}\right)^2 \left(\frac{\Delta\tilde m^2_{12}}{\tilde m^2}\right)^2 \mathrm{Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$$

  $K^d_{L(R)}$: mixing in gluino couplings to left-(right-)handed down quarks and squarks

  Constraint from ϵ_K: $10^4\,\mathrm{Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big] \;\Rightarrow\; 10^6\,\mathrm{Im}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$

- Classes of models to suppress each factors

  (i) Heavy squarks: $\tilde m \gg 1\,\mathrm{TeV}$ (e.g., split SUSY)

  (ii) Universality: $\Delta m^2_{\tilde Q,\tilde D} \ll \tilde m^2$ (e.g., gauge mediation)

  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (e.g., horizontal symmetries)

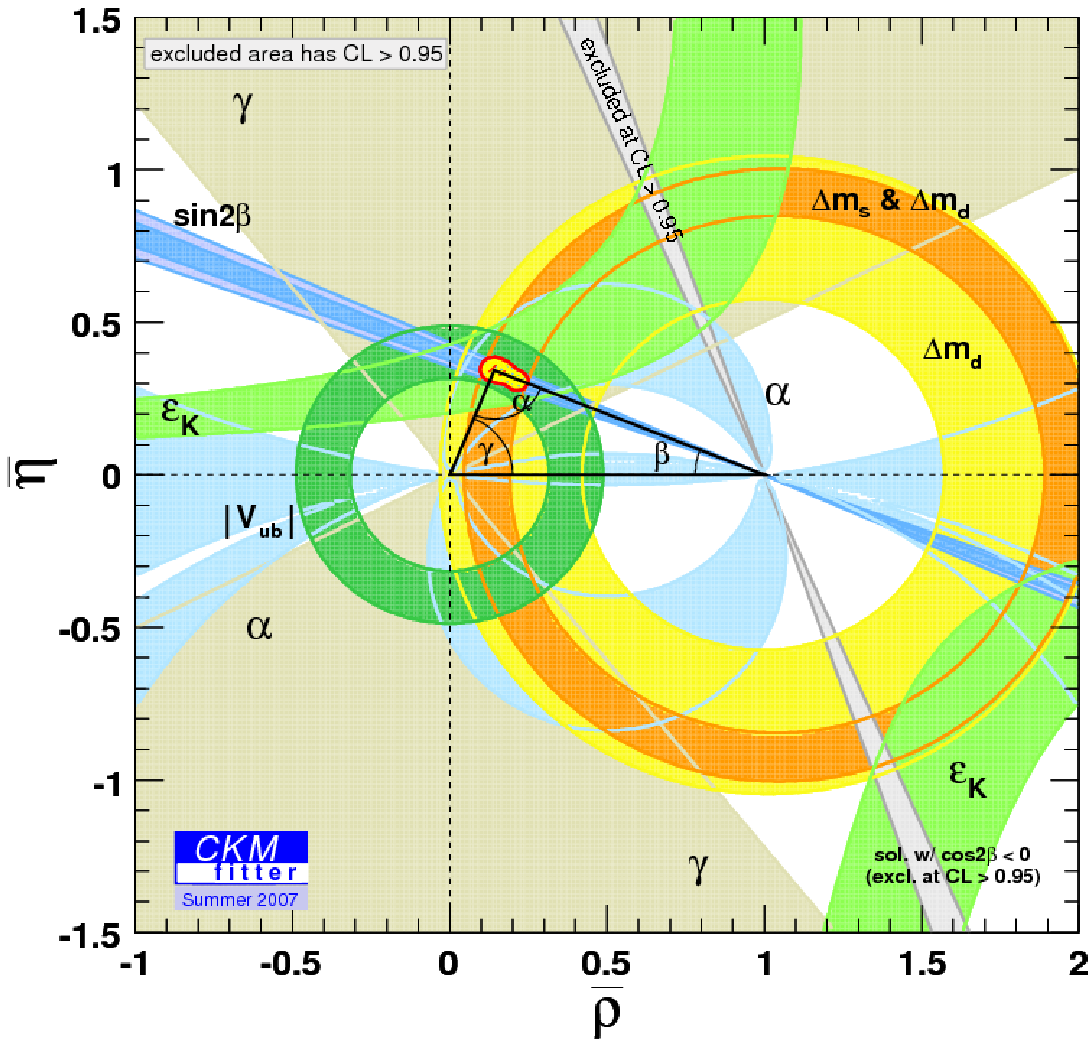
- Has driven SUSY model building — all models incorporate some of the above

- Last year, BaBar & Belle Δm_D results ruled out alignment as the sole explanation

Sizable NP contributions possible

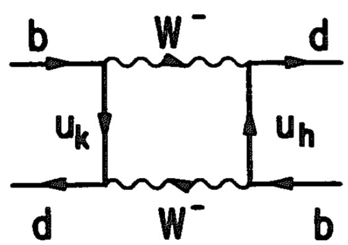
The standard model CKM fit

- Impressive accomplishments
- The level of agreement between the various measurements is often misinterpreted
- Plausible TeV scale NP scenarios, consistent with all low energy data, without minimal flavor violation
- CKM is inevitable; the question is not if it's correct, but is it sufficient?



New Physics in FCNC processes

- Mixing



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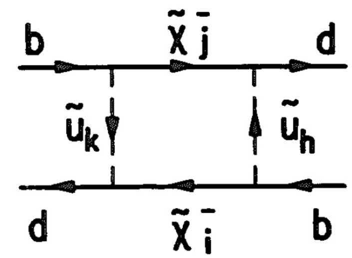
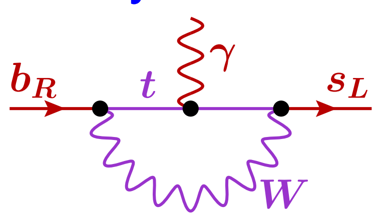
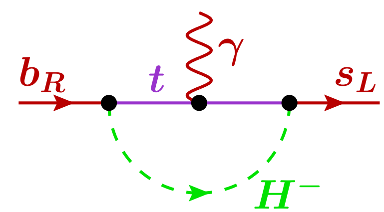


Simple parameterization for each neutral meson: $M_{12} = M_{12}^{\rm SM}\,(1 + h e^{2i\sigma})$

- Penguin decays



~~OR~~ $\Rightarrow$ AND?

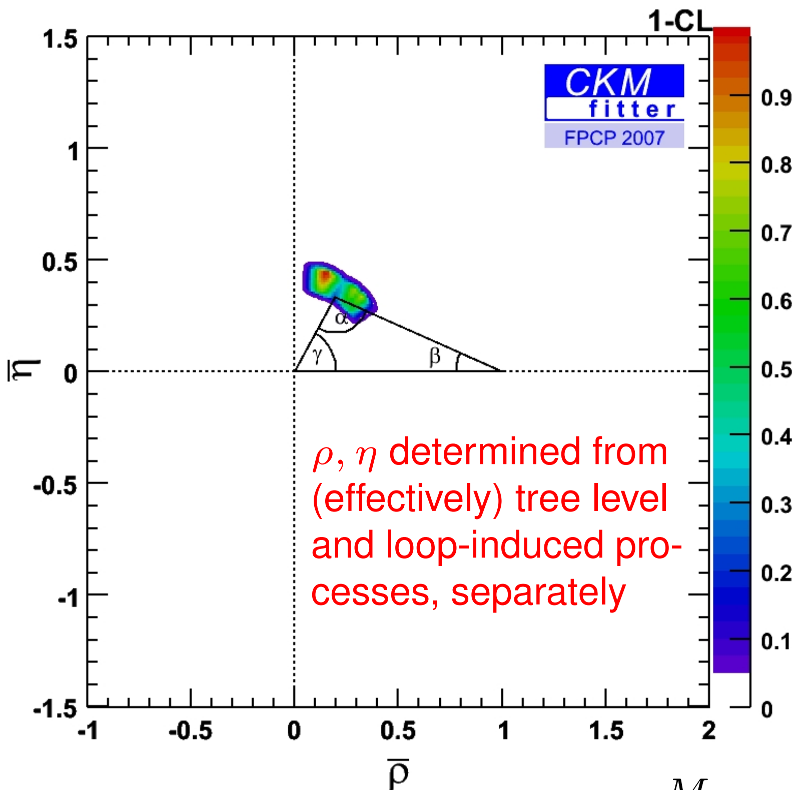


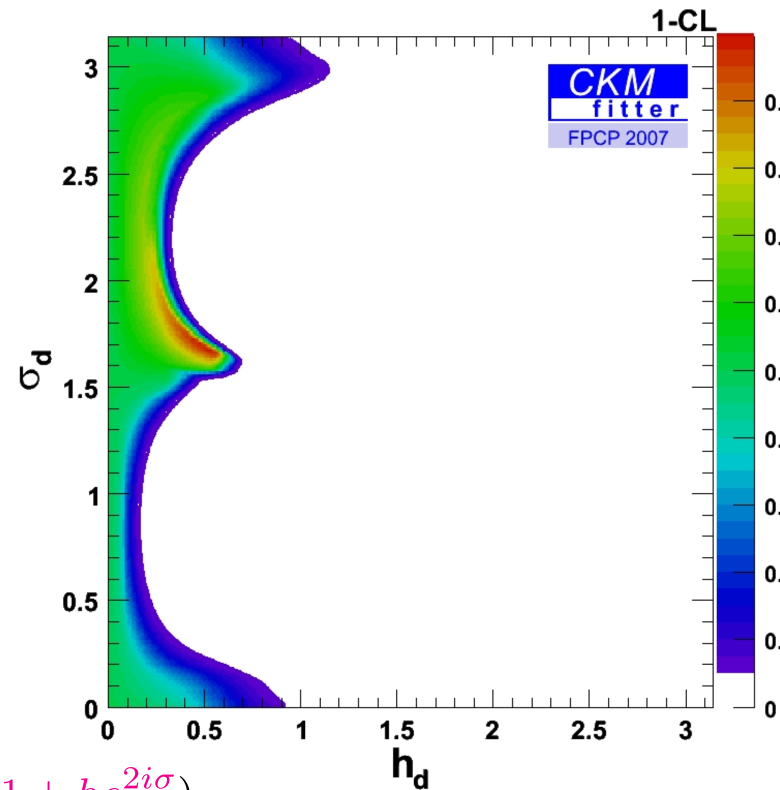
Many operators for $b \to s$ transitions — no simple parameterization of NP

- $V_{td,\,ts}$ only measurable in loops; likely also subleading couplings of new particles

- Isolating modest NP contributions requires many measurements — compare NP-independent (tree-level) with NP-dependent (loop-dominated) processes

Constraints on NP in mixing





$$M_{12} = M_{12}^{\mathrm{SM}}\,(1 + h e^{2i\sigma})$$

Only the SM-like region is allowed, even in the presence of NP in mixing

NP $\sim$ SM is still allowed; Think "MFV": $h \sim (4\pi v/\Lambda_{\text{flav.}})^2$; is $\Lambda_{\text{flav.}} \gg \Lambda_{\text{EWSB}}$?

- 10–20% non-SM contributions to most loop-mediated transitions are possible

B_s^0 and D^0 mixing and CP violation

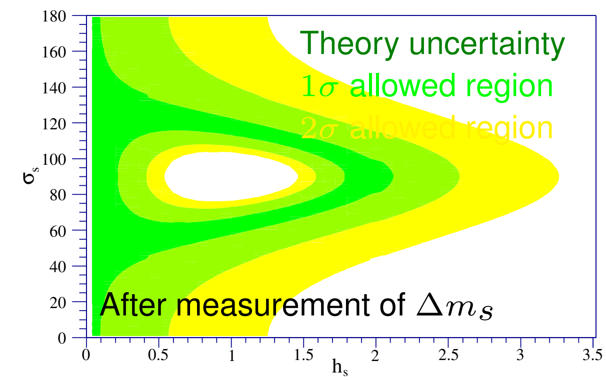
- Even after the measurement of Δm_s, large NP contribution to B_s–$\overline{B}{}_s^0$ mixing is allowed

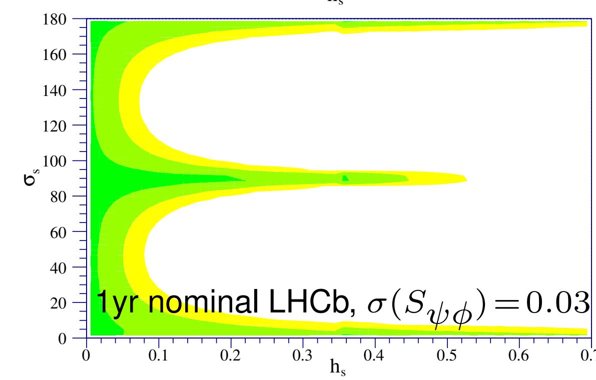
  Next key measurement: CP asymmetry in $B_s \to \psi\phi$
  The analog of $S_{\psi K}$ $(\sin 2\beta)$, and similarly clean

  In SM: $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = 0.0365 \pm 0.0020$

- LHCb will probe B_s sector at a level comparable to B_d

- A super B factory taking some data on the $\Upsilon(5S)$ can make important contributions





- First evidence for D–$\overline{D}{}^0$ mixing from BaBar and Belle (2007, $\sim 5\sigma$ combined)

  A super B factory is important to refine Δm, $\Delta\Gamma$ and search for CP violation, which are crucial for the interpretation

Some important processes

Questions super B can give insights on

- The 3rd generation may differ from the 1st and 2nd by more than we know so far

  Heavy m_t, large Yukawa, maybe non-universal coupling to EWSB and NP sector

  Want to compare 3rd–1st and 3rd–2nd generation data with precision kaon data

  $|V_{cb}|$ crucial to interpret $K \to \pi\nu\bar{\nu}$, $|V_{ub}|$ to compare trees vs. loops — e^+e^- only

- Many processes have different sensitivities to various NP scenarios

  In SM: CPV only in flavor changing, charged current interactions of quarks

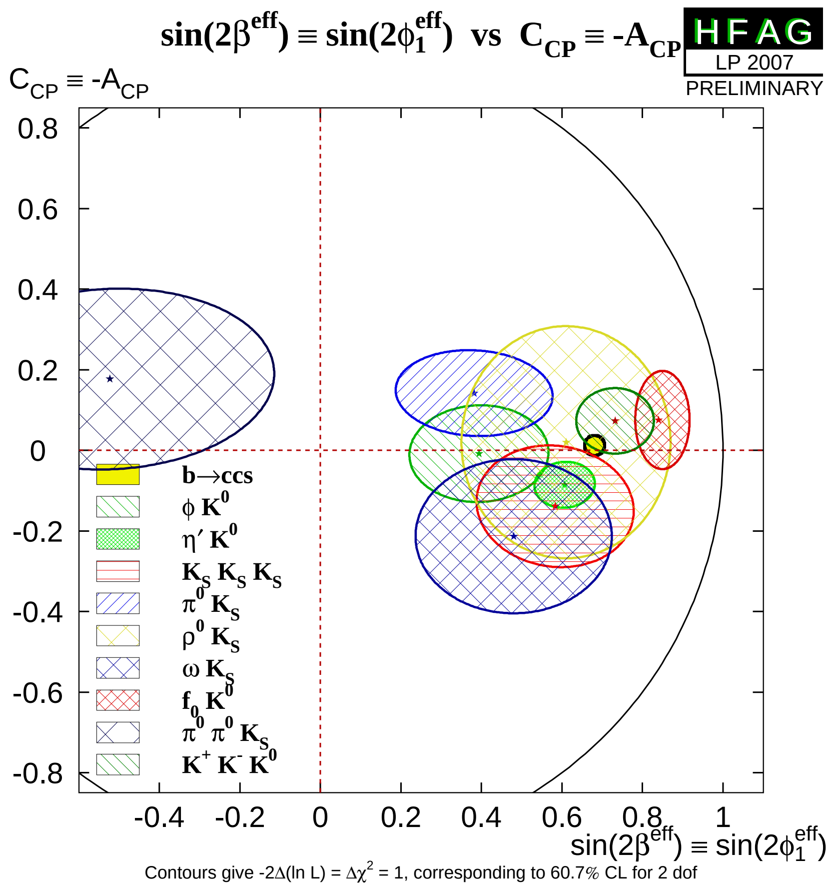
  With NP: possible in flavor diagonal processes, neutral currents, in lepton sector

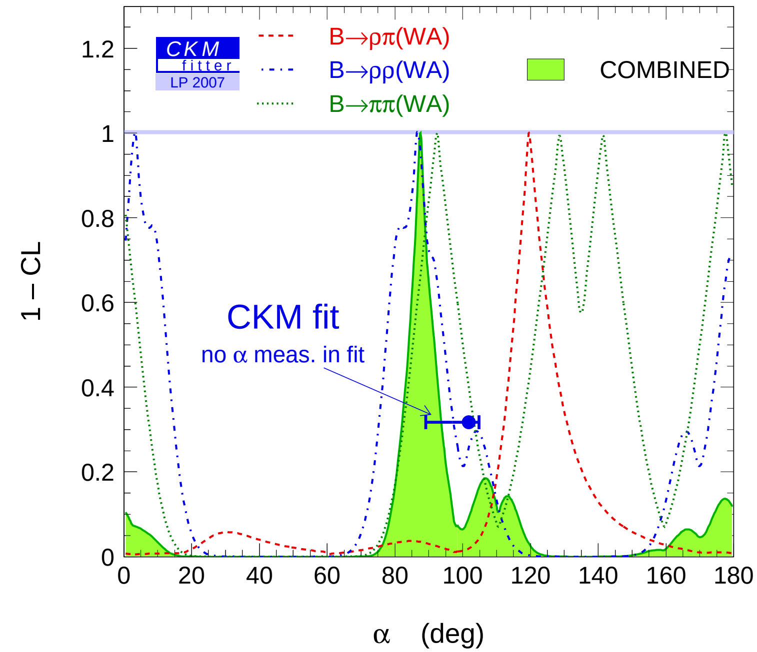
  Does new physics give rise to operators forbidden (highly suppressed) in the SM?

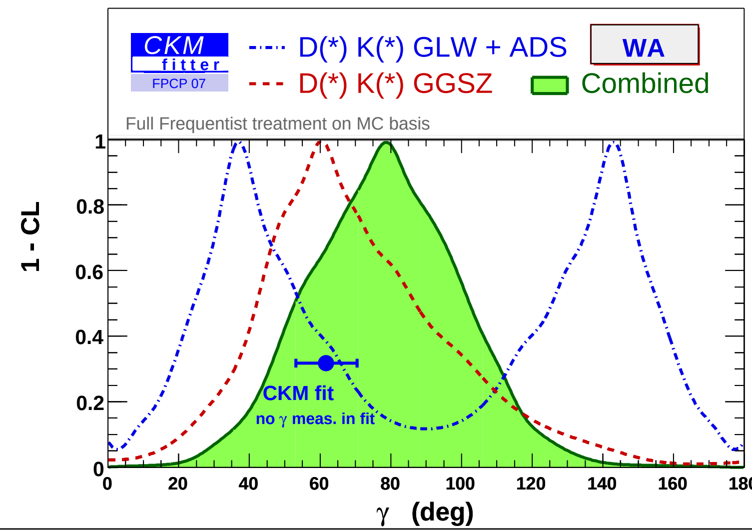
  E.g., $O_7 = \bar{s}\,\sigma^{\mu\nu} F_{\mu\nu} P_R\, b$ vs. $O_7' = \bar{s}\,\sigma^{\mu\nu} F_{\mu\nu} P_L\, b \Rightarrow$ measure $S_{K^*\gamma}$ — e^+e^- only

- Try to distinguish NP scenarios: One / many sources of CPV? Only in CC interactions? Couples to up / down sector? 3rd / all generations? $\Delta F = 2$ and / or 1?

$\sin 2\beta_{\rm eff}$, α, γ — large improvements possible





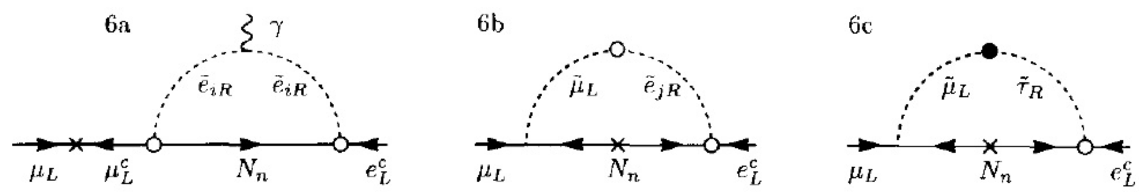


- E.g., $S_{\psi K} - S_{\phi K} = 0.29 \pm 0.17$; also for α & γ: want $\sim 10\times$ smaller error $\Rightarrow \sim 100\times$ more data
- Many of these only possible at a super B factory

Lepton flavor violation — largest τ samples

- $\tau \to \mu\gamma$ (few $\times 10^{-9}$) vs. $\mu \to e\gamma$

  Simplest $SU(5)$ expectation is $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 3 \times 10^3$



  In many models best bet is $\mu \to e\gamma$, but this is model dependent, many exceptions

- $\tau^- \to \ell_1^- \ell_2^- \ell_3^+$ (few $\times 10^{-10}$) vs. $\tau \to \mu\gamma$

  Consider operators: $\bar\tau_R \sigma_{\alpha\beta} F^{\alpha\beta} \mu_L$, $(\bar\tau_L \gamma^\alpha \mu_L)(\bar\mu_L \gamma_\alpha \mu_L)$

  Suppression by $\alpha_{\rm em}$ opposite in two cases $\Rightarrow$ model dependent which process gives the best sensitivity

Super B sensitivity with $75\,\mathrm{ab}^{-1}$

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}

- $\mu \to e\gamma$ and $(g-2)_\mu$ operators are very similar: $\dfrac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} e\,, \quad \dfrac{m_\mu}{\Lambda^2}\, \bar\mu \sigma_{\alpha\beta} F^{\alpha\beta} \mu$

  If coefficients comparable, $\mu \to e\gamma$ gives much stronger bound

  If $(g-2)_\mu$ is due to NP, large hierarchy of coefficients ($\Rightarrow$ model building lessons)

Rare (semi)leptonic FCNC B decays

- Important probes of new physics
  - $B \to X_s\gamma$: Best $m_{H^\pm}$ limits in 2HDM — in SUSY many parameters
  - $B \to X_s\ell^+\ell^-$ or $K^{(*)}\ell^+\ell^-$: bsZ penguins, SUSY, right handed couplings

A crude guide ($\ell = e$ or μ)

Decay	$\sim$ SM rate	physics examples
$B \to s\gamma$	3×10^{-4}	$\lvert V_{ts}\rvert$, $H^\pm$, SUSY
$B \to \tau\nu$	1×10^{-4}	$f_B\lvert V_{ub}\rvert$, $H^\pm$
$B \to s\nu\nu$	4×10^{-5}	new physics
$B \to s\ell^+\ell^-$	6×10^{-6}	new physics
$B_s \to \tau^+\tau^-$	1×10^{-6}	$\Downarrow$
$B \to s\tau^+\tau^-$	5×10^{-7}	
$B \to \mu\nu$	5×10^{-7}	
$B_s \to \mu^+\mu^-$	4×10^{-9}	
$B \to \mu^+\mu^-$	2×10^{-10}	

Replacing $b \to s$ by $b \to d$ costs a factor ~ 20 (in SM); interesting to test in both: rates, CP asymmetries, etc.

In $B \to q\, l_1\, l_2$ decays expect 10–20% K^*/ρ, and 5–10% K/π (model dept)

Many interesting modes can first be seen at a super B factory

Some of the theoretically cleanest (ν, τ, inclusive) only possible at e^+e^-

Final comments

Theoretical limitations (continuum methods)

- Many important measurements are not theory limited even with $100\times$ current data

Measurement (in SM)	Theoretical limit	Present error
$B\to\psi K\ \ (\beta)$	$\sim 0.2^\circ$	1.3°
$B\to\eta' K,\ \phi K\ (\beta)$	$\sim 2^\circ$	$5,\ 10^\circ$
$B\to\rho\rho,\ \rho\pi,\ \pi\pi\ \ (\alpha)$	$\sim 1^\circ$	$\sim 10^\circ$
$B\to DK\ \ (\gamma)$	$\ll 1^\circ$	$\sim 30^\circ$
$\lvert V_{cb}\rvert$	$\sim 1\%$	$\sim 2\%$
$\lvert V_{ub}\rvert$	$\sim 5\%$	$\sim 10\%$
$B\to X_s\gamma$	$\sim 5\%$	$\sim 10\%$
$B\to X_s\ell^+\ell^-$	$\sim 5\%$	$\sim 25\%$
$B\to K^{(*)}\nu\bar\nu$	$\sim 5\%$	—
Many more, plus D and τ decays sensitive to new physics		

For some entries, the above theoretical limits require more complicated analyses

Theory will also improve — past breakthroughs motivated by data; lattice will help

Conclusions

- Flavor sector has been tested at the 10% level; can be done a lot better, and many models proposed to solve the hierarchy puzzle have observable effects
- Despite tremendous progress, new physics in neutral meson mixings may be comparable to the SM contributions (sensitive to scales $\gg$ LHC)
- Measuring $S_{\psi\phi}$, etc., at LHCb will constrain B_s sector much better, similar to B_d
  Super B factory program is crucial for this as well (and for K, D, and τ physics)
- If new physics shows up in the flavor sector, pursuing this program is a no-brainer

  If no signal of NP is found in the flavor sector, constraints will give important clues to model building in the LHC era (similar to tests of the gauge sector at LEP)
- The full exploration of the influence of NP in the flavor sector requires very large e^+e^- data sets ($\sim 100\times$ current), achievable only at a super B factory

Backup slides

Exciting theoretical developments

- B physics has been and continues to be fertile ground for theory developments
- HQET & OPE — model independent description of certain exclusive and inclusive decays; nonperturbative matrix elements of higher dimensional operators are being extracted from the data, and used for precision measurements
- SCET — developed to address complicated kinematic regions in B decays, new and simplified proofs of factorization theorems, some new results for power suppressed processes; may have important applications for jets at the LHC as well
- Lattice QCD — in principle, fully model independent nonperturbative information No longer need model dependent assumptions for practical applications

  Large investment worldwide, flavor physics provides some of the most important applications and testing grounds

Parameterization of NP in mixing

- Assume: (i) 3×3 CKM matrix is unitary; (ii) Tree-level decays dominated by SM

  Concentrate on NP in mixing amplitude; two new param's for each neutral meson:

$$M_{12} = \underbrace{M_{12}^{\rm SM}\, r_q^2\, e^{2i\theta_q}}_{\text{easy to relate to data}} \equiv \underbrace{M_{12}^{\rm SM}(1 + h_q\, e^{2i\sigma_q})}_{\text{easy to relate to models}}$$

- Tree-level constraints unaffected: $|V_{ub}/V_{cb}|$ and γ (or $\pi - \beta - \alpha$)

- Observables sensitive to $\Delta F = 2$ new physics:

$$\Delta m_{B_q} = r_q^2\, \Delta m_{B_q}^{\rm SM} = |1 + h_q e^{2i\sigma_q}|\Delta m_q^{\rm SM}$$

$$S_{\psi K} = \sin(2\beta + 2\theta_d) = \sin[2\beta + \arg(1 + h_d e^{2i\sigma_d})] \qquad S_{\rho\rho} = \sin(2\alpha - 2\theta_d)$$

$$S_{\psi\phi} = \sin(2\beta_s - 2\theta_s) = \sin[2\beta_s - \arg(1 + h_s e^{2i\sigma_s})]$$

$$A_{\rm SL}^q = {\rm Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q r_q^2\, e^{2i\theta_q}}\right) = {\rm Im}\left[\frac{\Gamma_{12}^q}{M_{12}^q(1 + h_q e^{2i\sigma_q})}\right] \qquad \Delta\Gamma_s = \Delta\Gamma_s^{\rm SM} \cos^2 2\theta_s$$

Some of the key CPV measurements

- β: $S_{\psi K_S} = -\sin[(B\text{-mix} = -2\beta) + (\text{decay} = 0) + (K\text{-mix} = 0)] = \sin 2\beta$

  World average: $\sin 2\beta = 0.681 \pm 0.025$ — 4% precision (theory uncertainty $<1\%$)

- $S_{b\to s}$ “penguin” dominated modes: NP can enter in mixing (as $S_{\psi K}$), also in decay

  Earlier hints of deviations reduced: $S_{\psi K} - S_{\phi K_S} = 0.29 \pm 0.17$

- α: $S_{\pi^+\pi^-} = \sin[(B\text{-mix} = 2\beta) + (\overline{A}/A = 2\gamma + \ldots)] = \sin[2\alpha + \mathcal{O}(P/T)]$

  CLEO 1997: $K\pi$ large, $\pi\pi$ small $\Rightarrow P_{\pi\pi}/T_{\pi\pi}$ large $\Rightarrow$ pursue all $\rho\rho$, $\rho\pi$, $\pi\pi$ modes

- γ: interference of tree level $b \to c\bar{u}s$ $(B^- \to D^0 K^-)$ and $b \to u\bar{c}s$ $(B^- \to \overline{D}^0 K^-)$

  Several difficult measurements ($D \to K_S\pi^+\pi^-$, D_{CP}, CF vs. DCS)

- Need a lot more data to approach irreducible theoretical limitations