Charm Physics Opportunities at a Super Flavor Factory

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What is in a name?

- A Super Flavor Factory really is a more appropriate name for the next generation 10 GeV machine
  - $B\bar{B}$ cross section 1.1 nb
  - τ pair cross section 0.89 nb
    - Compares favorably with peak cross section near threshold of 1.2 nb
  - $c\bar{c}$ cross section exceeds $B\bar{B}$
    - and B's mostly decay to charm
- Physics case driven by precision B physics
  - Charm and τ are important components

Purpose of Talk

- Organizers have asked me to describe the charm physics case of a SuperB factory.
- This is more complex than it sounds
  1) In order to care about the charm physics potential of a Super B-factory you have to believe the total physics case is sufficiently compelling so that the facility might actually be built!!
  2) Physics case must be evaluated in the context of results from other experiments with flavor results
     - CLEO-c/BESIII/BABAR/Belle/LHCb/CDF/D0/ATLAS/CMS
  3) Two proposals - not identical
     - SuperBelle at KEKB
     - SuperB at Tor Vergata near Frascati
  4) Finally, there is the charm physics case

My point of view

- I am not an independent observer
  - CLEO
    - member for ~15 years!
  - SuperB (10^{36})- (INFN) “Low emittance”
    - Co-Author of CDR
    - Member of steering committee
    - Most of the “good things” I say about SuperB also apply to SuperKEKB
      - Low emittance machine is being designed to run near charm threshold with L ~ 10^{35}
      - Impacts Charm Physics Program
  - BESIII
    - Contributing to BESIII “Yellow Book”
  - LHCb
    - Just a fan - share Spokes office with Sheldon Stone

Physics Case for SuperB

Abridged!

Physics Case for SuperB

- Primary Goal: Search for New Physics (NP)
  - LHC will look for SM Higgs Boson + NP
  - Precision electroweak data implies NP ~ 1 TeV
  - Two regimes to search for NP
    - Energy Frontier - direct production
    - Precision Frontier - indirect through interference effects
  - Indirect searches have good track record
    - β decay predicted neutrino (Fermi)
    - Absense of $K_L \to \mu\mu$ predicted charm (GIM)
    - ε_K predicted 3rd generation (KM)
    - Δm_K predicted charm mass (GL)
    - Δm_B predicted heavy top
  - Flavor Physics is the BEST candidate for indirect NP searches
    - FCNC, oscillations, CPV all occur at loop level in SM
    - Potentially subject to O(1) NP corrections
    - Generic flavor violating NP violate current data unless NP scale 10-100 TeV
  - NP ~ 1 TeV $\Rightarrow$ non-trivial flavor structure
- Given success of CKM picture we do NOT expect large effects

Why not just drop the whole thing?

- Even when/if NP discovered at LHC still need to discern what it is
  - Direct searches - mass scale
  - Indirect searches - mass scales x couplings
- Direct searches provide “foot prints” but do not provide the full picture
- Need complementary info from flavor physics
  - Exploit high sensitivity of b, D, τ physics program to differentiate between NP models after mass scale is determined at LHC

Dead end without breakthrough in luminosity ~100x

Two Approaches to Achieve 10^{36} Luminosity

SuperKEKB

- Target Lumi 0.8×10^{36}
- Reuse much of KEKB
  - Magnets, klystrons, tunnel, facilities
- Ultra-high beam current
  - High wall plug power
- Low beta function
- Finite cross angle with crab
- Beam related bkgd non-trivial impact on detector design
- \$400M + detector
- Physics as early as 2011
- Strongly endorsed by PAC
- Next milestone : Director statement anticipated in 2007

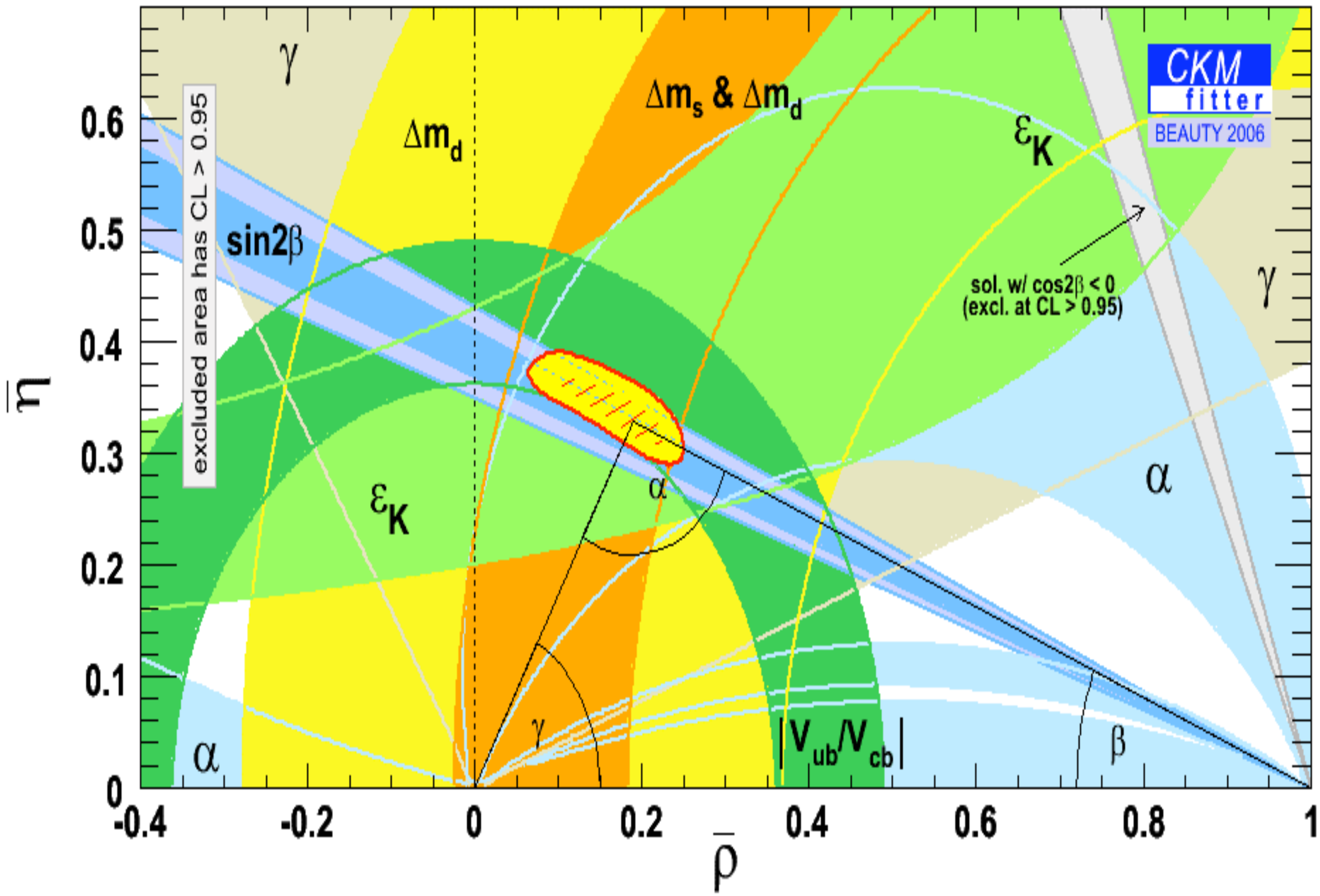
SuperB (ILC DR, FF, e^+ source)

- Target Lumi > 10^{36} (10^{35} ~ 4 GeV)
- Reuse much of PEP-II
  - Magnets, Power supplies, RF system
  - Also BABAR EMC, DIRC
- Low beam current
  - Lower wall plug power
  - Ultra-low emittance, beta
- Lower beam related bkgds
  - Luminosity bkgds large?
- \$500M(machine+site+detector)
  - 1/3 in kind from PEP-II/BABAR
- Physics 5 years after t_0
- Under review by International Committee - Report due fall '07
- Presented to ECFA as "opportunity for Europe" at Tor Vergata site
- Next milestone: ECFA endorsement
  - Lead to CERN review ⇒ funding

SuperB Physics Program

- The principle goal of the heavy flavor program is evolving/has evolved from precision determination of CKM parameters (sin2β, V_{ub} etc.) to a search for New Physics!
  - Inconsistency in various CKM determinations
    - Requires precision theory
    - Precision theory benefits from precision charm
  - Also rare B decays
  - Precision charm measurements
  - Rare charm processes
    - Oscillations
    - CP Violation
    - Rare decays
  - Precision τ

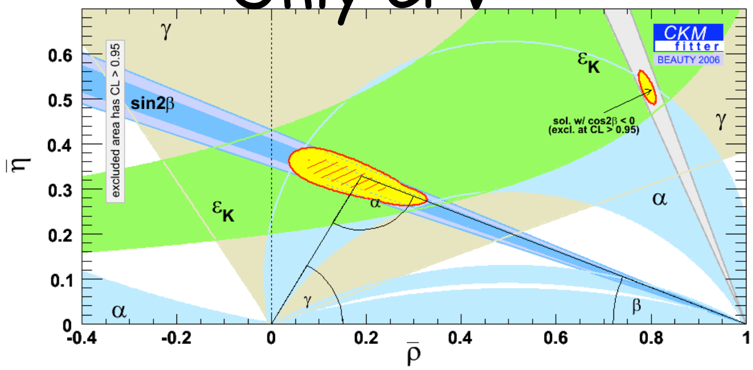
CKM Constraints



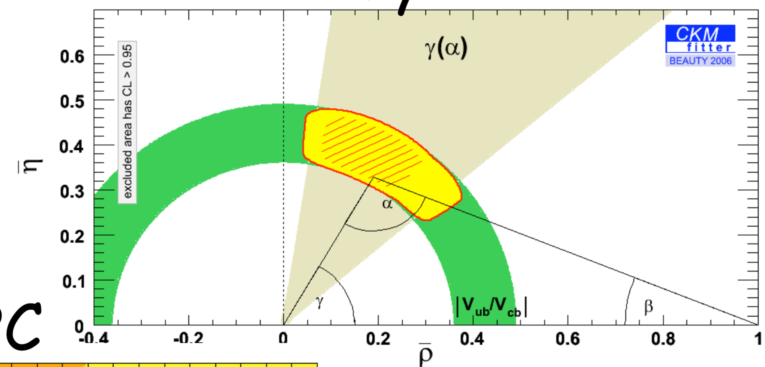
- The apex (ρ,η) of the unitarity triangle can be determined in independent ways
  - Only tree processes (no new physics)
  - Only loop processes (new physics window)
  - Only CP violating processes
  - Only CP conserving processes
  - Only CKM angles
- Inconsistency would indicate New Physics
- More to the study of heavy flavor than precision determination of CKM parameters

Cottage Industry

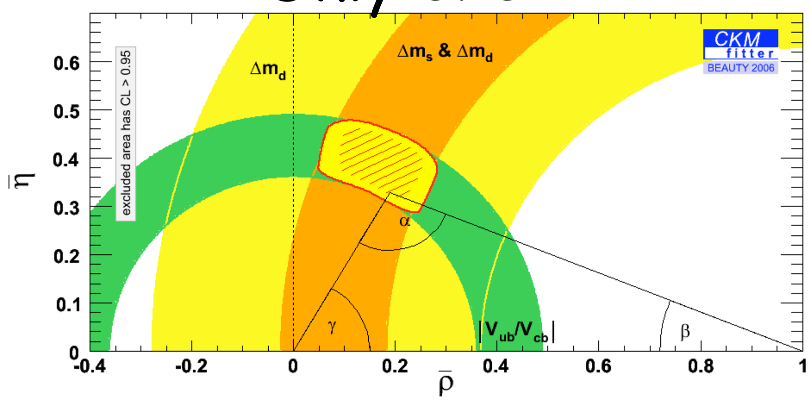
Only CPV



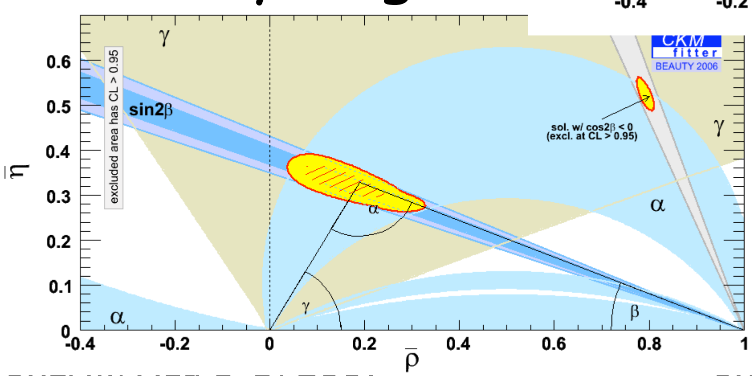
Only Tree



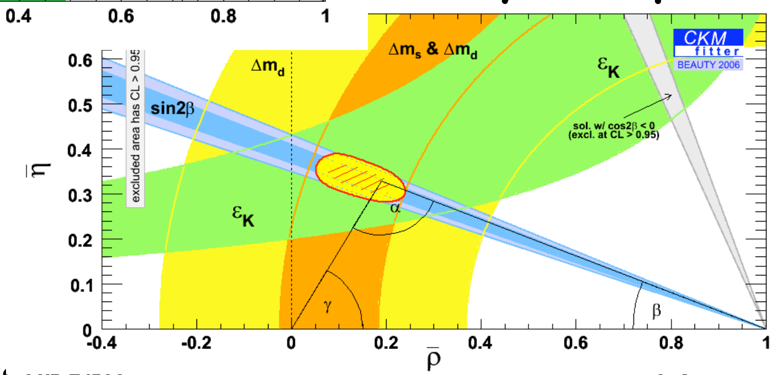
Only CPC



Only Angles



Only Loop

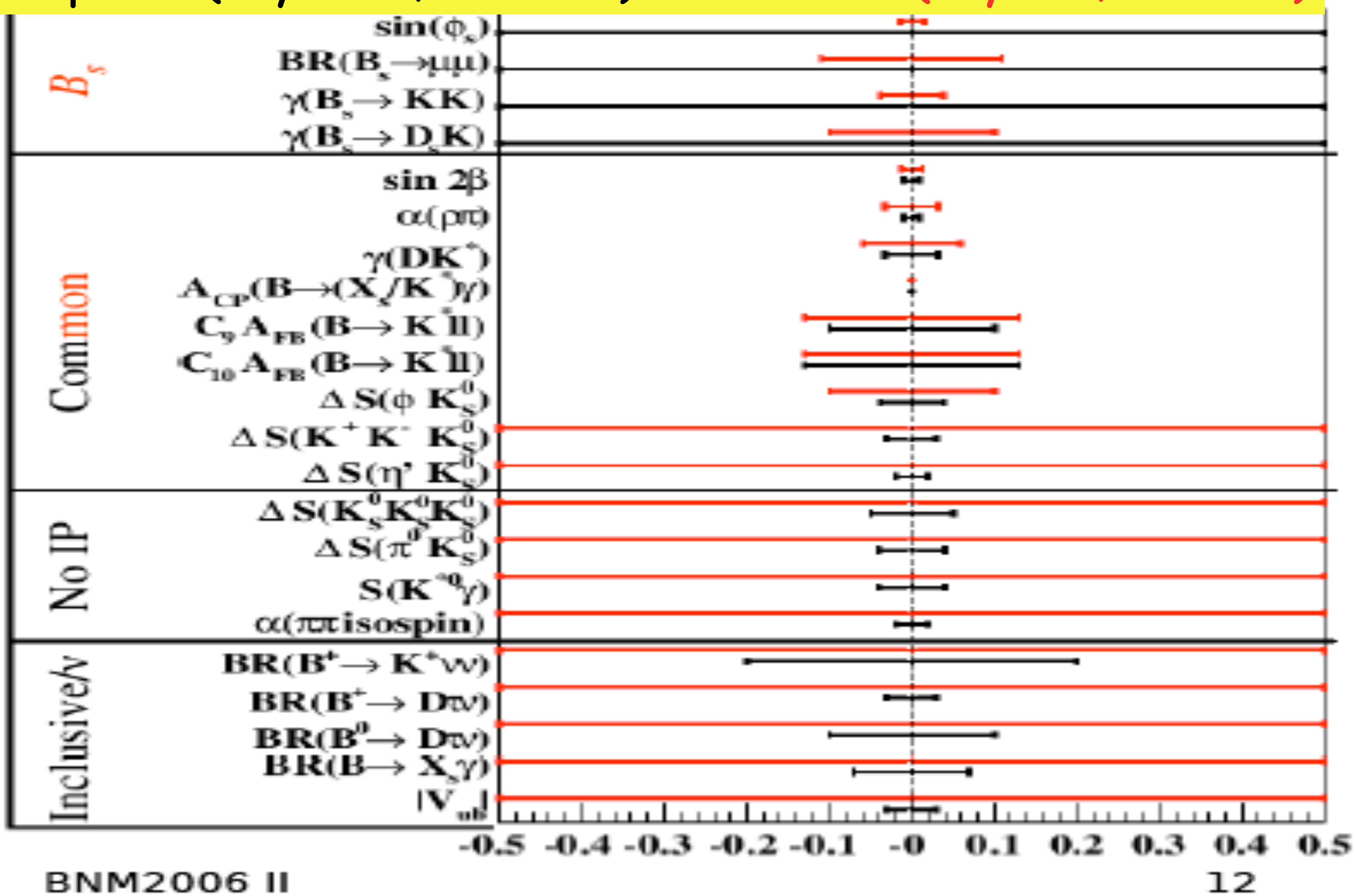


Beyond Precision CKM

- Electroweak FCNC
  - Rates, spectra, asymmetries, Wilson coeff
    - $b \to s\gamma$, $b \to d\gamma$
    - $b \to s\nu\underline{\nu}$, $b \to d\nu\underline{\nu}$
    - $b \to s\ell^+\ell^-$, $b \to d\ell^+\ell^-$
    - $B \to ee, \mu\mu, \tau\tau$
- Search for LFV, LNV processes
- With 10^{36} luminosity pattern of deviation with SM predictions (or lack thereof) tells us something about NP observed (or not) at the energy frontier
- Generic NP ~1 TeV has "large" effect in flavor physics
- Not seeing effect or see small effect tells us something
- Absence of NP signal in precision flavor results to date implies NP scale ~ 10-100 TeV

SuperB/LHCb Complementarity

SuperB (3 years, 50 ab^{-1}) and LHCb (5 year, 10 fb^{-1})



Status of Charm Physics in 2013

Results from

CLEO-c,BESIII,BABAR,Belle,
LHCb,CDF,D0,ATLAS,CMS

Impact of Charm Physics - I

- Precision CKM
    - Over constrain CKM with results from B-sector
    - Inconsistencies indicate New Physics
    - Precision charm required for precision CKM results in B sector
  - Leptonic Charm Decays $D \to \ell^+ \nu$: Check QCD calculations
    - Measure decay constants fD, fDs
    - Improved f_B possible from f_D measurement + LQCD
    - Important for $|V_{td}|$, $|V_{ts}|$ and $|V_{ts}|/|V_{td}|$
  - Semileptonic decay rates & form-factors: Check QCD calculations
    - Measurements of $|V_{cs}|$ and $|V_{cd}|$
    - Test theoretical form factor models in D meson decays
    - Impacts prediction of form factors for B meson decays
    - Important for $|V_{ub}|$ and $|V_{cb}|$
  - Hadronic Charm Decays - $B \to$ Charm is dominant
    - Important for $|V_{cb}|$ and γ/ϕ_3
    - Engineering numbers useful for other studies
      - absolute $\mathcal{B}$'s, resonant substructure, phases on Dalitz plots, especially versus CP eigenstates, final state interactions

Impact of Charm Physics - II

- Search for New Physics in Charm Sector
  - Very low SM rates for loop processes provide unique window to observe NP in rare charm processes (rare decays, CPV & mixing)
    - NP can introduce new particles into loop
  - Different sensitivity to NP than B and K sectors
    - Particles & couplings in rare charm processes NOT the same as rare B, K
  - Rare Charm Decays (Heavily GIM suppressed: BF($c \rightarrow ull$)~10^{-8})
    - FCNC decays only occur in loop diagrams in SM:
  - Charm Mixing (Large CPV in mixing indicates New Physics)
    - Mixing is Double Cabibbo suppressed & GIM mechanism suppressed
    - SM $x \equiv \Delta m/\Gamma \lesssim y \equiv \Delta\Gamma/2\Gamma$ short distance 10^{-6}-10^{-3}, long distance 10^{-3}-10^{-2}
    - NP in loops implies $x >> y$; long range effects complicate predictions.
  - CP Violation - Direct (New Physics could be ~%)
    - CF & DCS decay: Direct CPV requires New Physics
      - Exception: interference between CF & DCS amplitudes to $D^{\pm} \rightarrow K_{S,L}\pi^{\pm}$
      - SM contribution due to K^0 mixing is $A_S=[+]_S-[-]_S \sim -3.3\times10^{-3}$; $A_S = -A_L$
    - SCS decay
      - expect $O(\lambda^4) \sim 10^{-3}$ from CKM matrix

Charm Physics Circa 2013

- Hadronic Branching Ratios
  - D^0 & D^+ branching ratios syst. limited at (1-2)% CLEO-c
  - D_s^+ BR stat. limited at 6% CLEO-c
    - CLEO-c will improve to ~4%
    - BESIII will improve to (1-2)%
- Decay constants: statistics limited
  - f_{D+} 7.5% (281pb^{-1}) at 3770. CLEO-c
    - CLEO-c will improve to (4-5)%
    - BESIII will improve to (1-2)%
  - f_{Ds} 4.1% (200pb^{-1}) at 4170. CLEO-c
    - CLEO-c will improve to (2-3)%
    - BESIII can improve
  - $\sigma(f_D/f_{Ds})$ ~ 2% at BESIII (20 fb^{-1})
- Semileptonic Decays
  - BR of Cabibbo suppressed $D^0 \to \pi e \nu$ known to 4% CLEO-c
    - CLEO-c will improve to (2-3)%
    - BESIII can improve
  - Vcs ~ 2%, Vcd ~ 4% CLEO-c
    - CLEO-c will improve Vcd~2%
  - Precision form-factors to improve V_{ub} benefits from more 4 GeV data
- CP tagged Dalitz plot analyses e.g. $D^0 \to CP$ vs. $D^0 \to K_{S,L}\pi^+\pi^-$
  - Important for γ
  - Statistics limited
  - CLEO-c can limit sys err on γ ~ 3°
- Rare Decays
  - CLEO-c sensitivity 10^{-5}-10^{-6}
  - BESIII sensitivity 10^{-6}-10^{-7}
  - Standard Model rates ~10^{-8}
  - LHCb sensitivity?
  - SuperB @ ~4 GeV ~SM sensitivity
- Charm Mixing
  - Exploiting quantum coherent initial state CLEO-c will measure $\cos\delta$~±0.1
  - BESIII sensitivity to y ~few x 10^{-3}
  - Need LHCb (Upgrade) or SuperB to cover full range of SM expectations
- CP Violation
  - BESIII sensitive to ~SM asymmetry in $D^+ \to K_{S,L}\pi^+$ ~few x10^{-3} .
  - Need LHCb (Upgrade) or SuperB to reach SM expectation in SCS decay.

Finally

Charm Physics Program at SuperB

SuperB CDR

- http://www.pi.infn.it/SuperB/?q=CDR
  - Charm chapter of CDR is only a highlight reel
    - 13 pages, 4 tables, 1 figure
- http://mlm.home.cern.ch/mlm/FlavLHC.html
  - CERN Yellowbook on Flavor Physics in the Era of the LHC - to be released later this year
  - more detailed document on charm
    - 31 pages, 10 tables, 8 figures
    - Much smaller font, wider margins
    - Some more detail on LHCb capability

Table 2-16. *Expected 90% confidence level upper limits that may be obtained on various important rare D decays, from 1 month of SuperB running at the* $\psi(3770)$.

Channel	Sensitivity
$D^0 \to e^+e^-$, $D^0 \to \mu^+\mu^-$	1×10^{-8}
$D^0 \to \pi^0 e^+e^-$, $D^0 \to \pi^0\mu^+\mu^-$	2×10^{-8}
$D^0 \to \eta e^+e^-$, $D^0 \to \eta\mu^+\mu^-$	3×10^{-8}
$D^0 \to K^0_S e^+e^-$, $D^0 \to K^0_S\mu^+\mu^-$	3×10^{-8}
$D^+ \to \pi^+ e^+e^-$, $D^+ \to \pi^+\mu^+\mu^-$	1×10^{-8}
$D^0 \to e^\pm\mu^\mp$	1×10^{-8}
$D^+ \to \pi^+ e^\pm\mu^\mp$	1×10^{-8}
$D^0 \to \pi^0 e^\pm\mu^\mp$	2×10^{-8}
$D^0 \to \eta e^\pm\mu^\mp$	3×10^{-8}
$D^0 \to K^0_S e^\pm\mu^\mp$	3×10^{-8}
$D^+ \to \pi^- e^+e^+$, $D^+ \to K^- e^+e^+$	1×10^{-8}
$D^+ \to \pi^-\mu^+\mu^+$, $D^+ \to K^-\mu^+\mu^+$	1×10^{-8}
$D^+ \to \pi^- e^\pm\mu^\mp$, $D^+ \to K^- e^\pm\mu^\mp$	1×10^{-8}

Table 2-14. *Statistics required to obtain 0.5% statistical uncertainties on corresponding branching fractions (column 2) or one million signal events (column 3) using double tagged events, when running at threshold.*

Channel	Integrated luminosity (fb^{-1})	Integrated luminosity (fb^{-1})
$D^0 \to K^- e^+\nu_e$	1.3	33
$D^0 \to K^{*-} e^+\nu_e$	17	425
$D^0 \to \pi^- e^+\nu_e$	20	500
$D^0 \to \rho^- e^+\nu_e$	45	1125
$D^+ \to K^0_S e^+\nu_e$	9	225
$D^+ \to \bar{K}^{*0} e^+\nu_e$	9	225
$D^+ \to \pi^0 e^+\nu_e$	75	1900
$D^+ \to \rho^0 e^+\nu_e$	110	2750
$D_s^+ \to \phi e^+\nu_e$	85	2200
$D_s^+ \to K^0_S e^+\nu_e$	1300	33000
$D_s^+ \to K^{*0} e^+\nu_e$	1300	33000

Table 42: Approximate expected precision (σ) on the measured quantities using methods described in the text for the integrated luminosity of 10 fb^{-1} at LHCb, 2 ab^{-1} at the B-factories at 10 GeV, and 20 fb^{-1} at BESIII running at charm threshold. The LHCb numbers do not include the effect of systematic errors, but neglect the contribution of events from prompt charm production. Entries marked '/' in the LHCb column are where expected performance numbers are not yet available.

Mode	Observable	LHCb (10 fb^{-1})	B-factories (2 ab^{-1})	$\psi(3770)$ (20 fb^{-1})
$D^0 \to K^{(*)-}\ell^+\overline{\nu}$	R_M	/	0.2×10^{-3}	
$D^0 \to K^+\pi^-$	x'^2	0.6×10^{-4}	1.5×10^{-4}	
	y'	0.9×10^{-3}	2.5×10^{-3}	
$D^0 \to K^+K^-$	y_{CP}	0.5×10^{-3}	3×10^{-3}	
$D^0 \to K^0_S\pi^+\pi^-$	x	/	2×10^{-3}	
	y	/	2×10^{-3}	
$\psi(3770) \to D^0\overline{D}^0$	x^2			3×10^{-4}
	y			4×10^{-3}
	$\cos\delta$			0.05

Table 43: Approximate expected precision (σ) on the measured quantities using methods described in the text for the integrated luminosity of 100 fb^{-1} at an upgraded LHCb, 75 ab^{-1} at a Super B-factory at 10 GeV, and 200 fb^{-1} at a Super B-factory running at charm threshold. The upgraded LHCb numbers are merely the results from Table 42 scaled to the new integrated luminosity.

Mode	Observable	LHCb (100 fb^{-1})	Super B (75 ab^{-1})	$\psi(3770)$ (200 fb^{-1})
$D^0 \to K^+\pi^-$	x'^2	2.0×10^{-5}	3×10^{-5}	
	y'	2.8×10^{-4}	7×10^{-4}	
$D^0 \to K^+K^-$	y_{CP}	1.5×10^{-4}	5×10^{-4}	
$D^0 \to K^0_S\pi^+\pi^-$	x	/	5×10^{-4}	
	y	/	5×10^{-4}	
$\psi(3770) \to D^0\overline{D}^0$	x^2			$< 0.2 \times 10^{-4}$
	y			$(1-2) \times 10^{-3}$
	$\cos\delta$			< 0.05

Table 2-13. *Statistics required to obtain 0.5% statistical uncertainties on corresponding branching fractions using double-tagged events, when running at threshold.*

Channel	Integrated luminosity (fb^{-1})
$D^+ \to \mu^+\nu_\mu$	500
$D_s^+ \to \mu^+\nu_\mu$	100

(Charm) Physics Summary

- Search for NP using precision CKM in B-sector require precision theory (LQCD)
- Precision theory benefits from precision charm
  - Measuring (f_{Ds}/f_D) <1% requires 100's fb^{-1} near 4 GeV
  - Form factor analyses doable at BESIII, SuperB (10 GeV), LHCb? - better with 500 fb^{-1} near 4 GeV
- D-mixing – LHCb will improve on B-factories, SuperB better than LHCb
- CP Violation – more results from B-factories helpful
  - SuperB (10 GeV & 4 GeV) will improve on LHCb constraints
- 10^{-8} sensitivity to rare charm decays
  - probe different New Physics than rare B decays
  - As in rare B, systematic deviation (or not) from SM expectation tells us something about NP

Proposed SuperB cite near Frascati

SM Suppressed Processes

- D mixing
  - Many new results - "Evidence" of D mixing
  - Most precise technique is t-dep analysis of $D^0 \rightarrow K_S\pi^+\pi^-$ (CLEO II.V,Belle)
  - Outlook for Quantum Correlated analysis with BESIII promising
  - First measurement of cos δ (CLEO-c)
  - ~Equivalent sensitivity 2 ab^{-1}@10 GeV ,20 fb^{-1}@4 GeV
  - Very different systematic uncertainties

Outlook for LHCb promising
Benefit from SuperB data at both 4 GeV and 10 GeV

- CP Violation - **much more work needed!**
  - No meaningful constraints on CPV in D mixing
  - Decays to final states with more than two pseudoscalars or one pseudoscalar & one vector meson contain more dynamical info than given by their widths.
  - Distribution on Dalitz plots or T odd moments can exhibit CP asymmetries considerably larger than those for the width
  - Standard Model CPV in charm is as large as 10^{-3} in particular decay channels & should be observable with current B-factories
  - BESIII should have comparable sensitivity

LHCb CPV studies required.
Improved CP constraints from SuperB (10 or 4 GeV)

- Rare Decays
  - Lots of results from FOCUS/CLEO-c/BaBar/D0/CDF
  - ~Equivalent sensitivity 1 fb^{-1} @ 2 TeV, 100 fb^{-1} @ 10 GeV 100 pb^{-1} @ 4 GeV
  - CLEO-c limits statistics limited. Others background limited
  - Clear advantage to threshold - BESIII (20 fb-1) statistics limited

SuperB data near 4 GeV will improve sensitivity

SuperB: Decay Constants

- f_{Bs}/f_B is key ingredient in V_{ts}/V_{td}
- Lattice calculates $\frac{f_{B_s}\sqrt{B_{B_s}}}{f_B\sqrt{B_B}} = 1.210^{+0.047}_{-0.035}$
- Expect $f_{Bs}/f_B = f_{Ds}/f_D$ within a few %
  - From lattice still need $B_{Bs}/B_B \sim 1$
- Precision f_{Ds}/f_D enables precision V_{ts}/V_{td}
- f_D, f_{Ds} & f_{Ds}/f_D statistics limited after CLEO-c

Exp't	3.77 GeV	4.17 GeV	$\sigma(f_{Ds}/f_D)$
CLEO-c	281 pb^{-1}	310 pb^{-1}	9%
CLEO-c	750 pb^{-1}	750 pb^{-1}	5%
BESIII	20 fb^{-1}	12 fb-1	<2%
SuperB	~150 fb^{-1}	~200 fb^{-1}	<1%

Precision Form Factors

- Extrapolating from K sector form factor analyses of NA48/2 & E685 desire $O(10^6)$ to extract precise dynamical information
  - Way beyond the reach of BESIII
  - SuperB (500 fb^{-1}) @4 GeV yields 10^6 tagged $D^0 \rightarrow \pi e \nu$

- Noteworthy that fully reconstructed $e^+e^- \rightarrow c\underline{c}$ obtains q^2 resolution and S/B comparable to threshold running
  - Comparable statistics: BESIII (20 fb^{-1}) & SuperB (140 ab^{-1})
  - LHCb?