Charm Physics:

after the recent charm mixing results & implications for SuperB

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Introduction

- Charm physics in the era of the LHC falls into two broad categories

1) Precision CKM physics

2) Rare Charm Processes

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1) Precision CKM physics
   - Direct determination: V_{cd}, V_{cs} & unitarity tests
   - Precision tests of (Lattice) QCD calculations - V_{ub}, V_{cd}, V_{td}, V_{td}/V_{ts}

Enables precision Unitarity Triangle measurements (New Physics searches)

2) Rare Charm Processes

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2) Rare Charm Processes
   - Oscillations
   - CP violation
   - Rare decays

Search for New Physics signatures in Charm

Experiments

- Current experiments
  - CLEO-c (0.75 fb^{-1} @3.77 GeV, 0.75 fb^{-1} @4.17 GeV)
  - BABAR, Belle (combined 2 ab^{-1})
  - CDF, D0 (combined 16 fb^{-1})
- Approved experiments
  - BESIII (20 fb-1 @3.77 GeV, 12 fb^{-1} @4.17 GeV)
  - LHCb (10 fb^{-1})
  - PANDA
- Proposed experiments
  - LHCb upgrade (100 fb^{-1}),
  - Super B-factory (50 ab^{-1} ~10 GeV, 350 fb^{-1} ~4 GeV)

Outline

- For Overview of Charm Physics at SuperB - see my talk at SuperB IV
- Today's talk concentrates on mixing
  - Formalism
  - Expectations
  - Results
    - Emphasis on recent BaBar & Belle results
  - Implications for SuperB
    - Benefits of additional charm threshold data

$D^0-\bar{D}^0$ Mixing

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(M - i\Gamma/2\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

Two state system

Mass Eigenstates≠Flavor Eigenstates

$$R\left(D^0(t) \to f\right) = \left|A_f\right|^2 e^{-\Gamma t}\left[1 + \left[y\,\mathrm{Re}(\lambda) - x\,\mathrm{Im}(\lambda)\right](\Gamma t) + |\lambda|^2 \frac{x^2+y^2}{4}(\Gamma t)^2\right]$$

Oscillations “slow”

Parameter definitions

Mixing parameters: $x=\Delta m/\Gamma$, $y=\Delta\Gamma/2\Gamma$

Mixing Rate: $R_M = (x^2+y^2)/2$

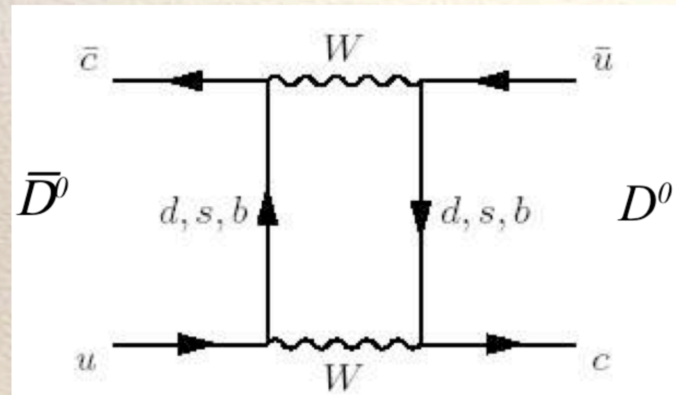
$D^0/\bar{D}^0$ relative strong phase δ

Effective parameters: $y` = y\cos\delta - x\sin\delta$; $x` = y\sin\delta + x\cos\delta$

CP violation: $\lambda \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$ $A_M=|q/p|-1$

Charm Mixing

SM Charm Mixing has down-type quarks in the loop



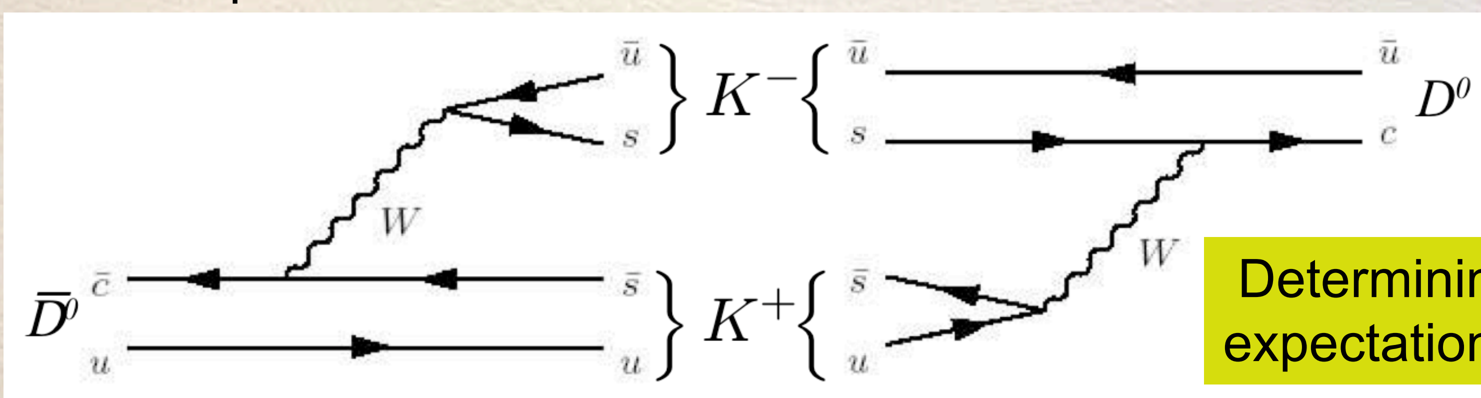
Double Cabibbo Suppressed

GIM Suppressed

SM: Short distance 10^{-6} - 10^{-3}

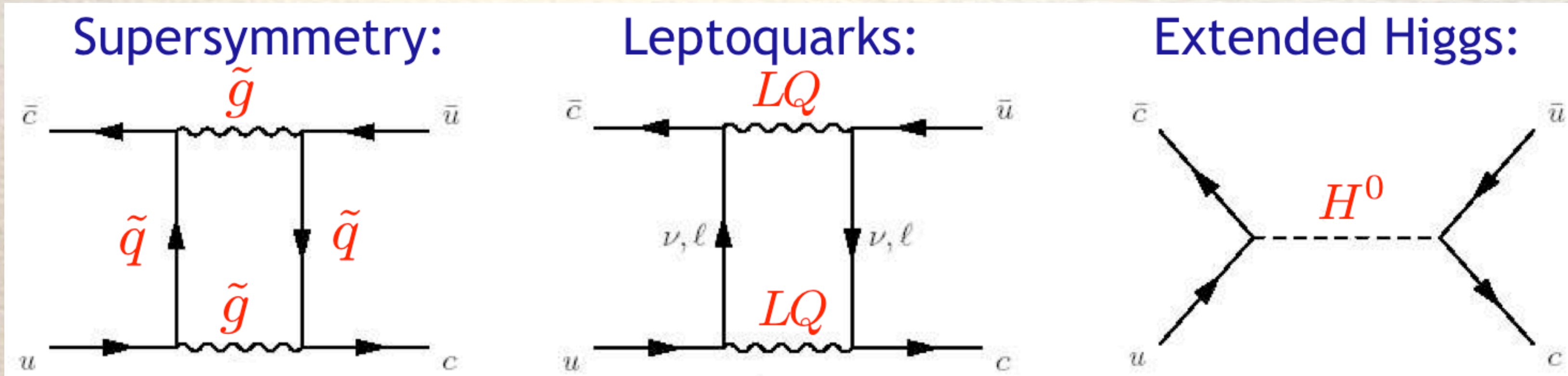
Long distance 10^{-3} - 10^{-2}

Expect hadronic intermediate states to dominate



Determining SM expectation difficult

New Physics: Charm Mixing



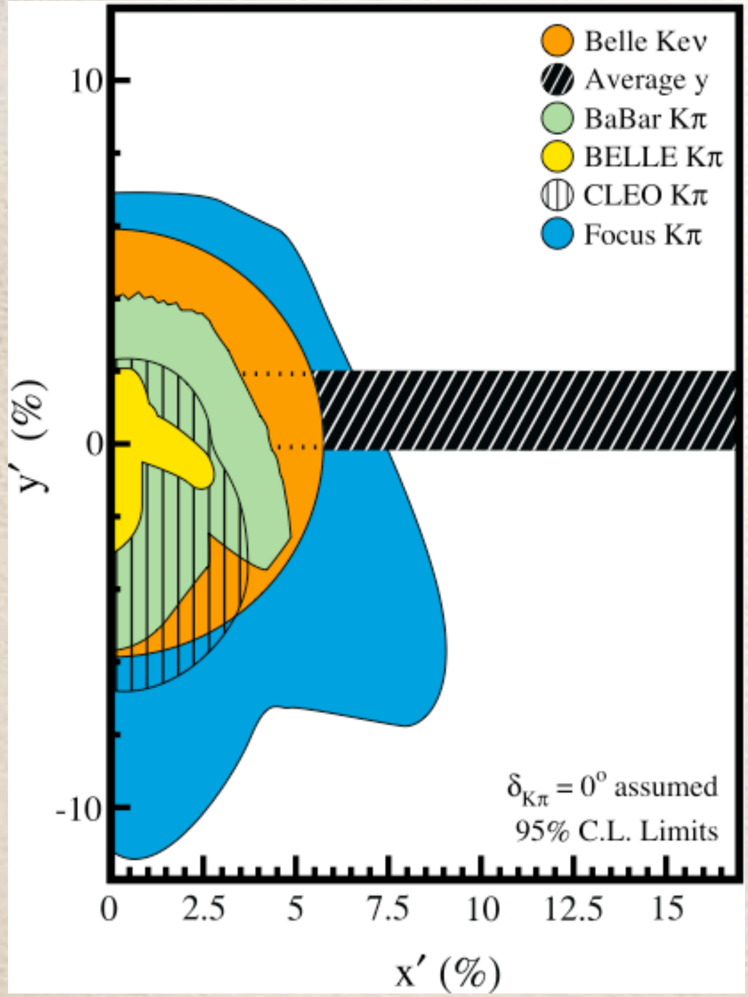
- Both loop and tree level NP contributions
- Some models avoid large FCNC in B & K sectors by having large mixing in charm
- New physics (NP) in loops implies
  - $x \equiv \Delta m/\Gamma >> y \equiv \Delta\Gamma/2\Gamma$;
  - but long range effects complicate predictions.
- Large CPV in mixing indicates New Physics

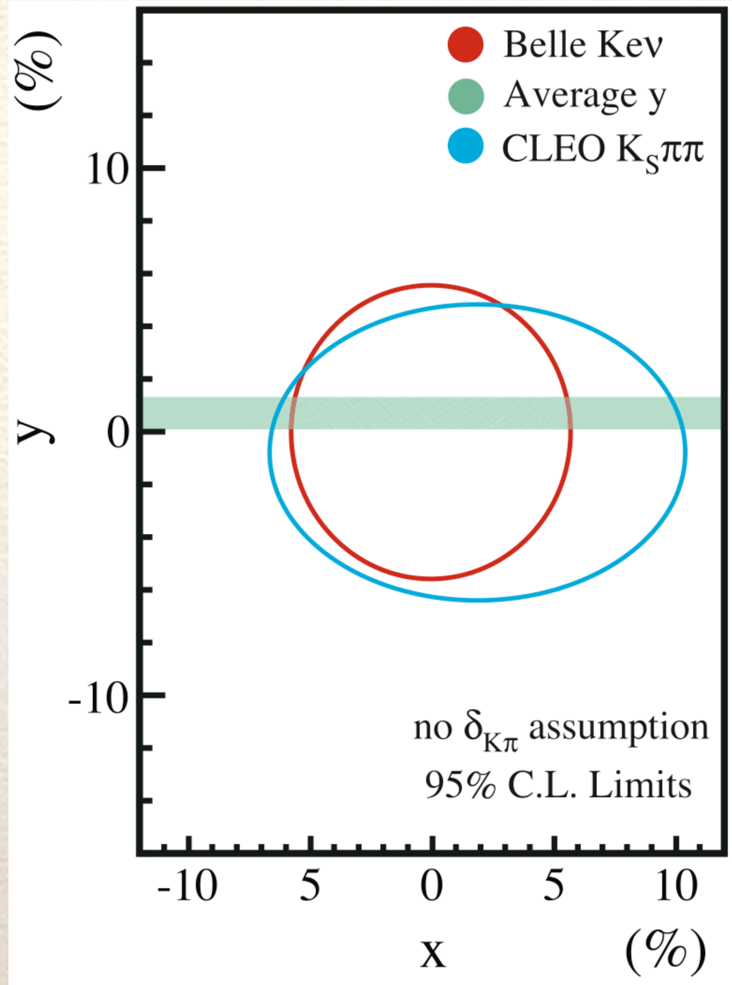
Charm Mixing: Several Probes

Experimental probes

- Semileptonic Decay: Sensitive to R_M , No DCS process
  - Search for $\Gamma(D^0 \rightarrow K^{(*)+} l^- \nu)$ (E791, CLEO, BABAR, Belle)
- CP Eigenstate: Sensitive to y
  - $D^0(t) \rightarrow$ CP Eigenstate (E791,CLEO,FOCUS,BABAR,Belle)
- Wrong-sign $K^+\pi^-$: Sensitive to $x`^2$, $y`$
  - $D^0(t) \rightarrow K^+\pi^-$: (CLEO,FOCUS,BABAR,Belle)
- Wrong-sign multibody $K^+\pi^-\pi^0$, $K^+3\pi$: Sensitive to R_M
  - $D^0(t) \rightarrow K^+\pi^-\pi^0$, $K^+3\pi$ (CLEO, BABAR, Belle)
- Dalitz plot: Sensitive to x, y
  - $D^0\ (t) \rightarrow K_s\pi^+\pi^-$: (CLEO, Belle)
- Quantum Correlations: Primarily sensitive to y, cos δ
  - e+e- $\rightarrow D^0\bar{D}^0(n)\gamma(m)\pi^0$: (CLEO-c)

Mixing Limit Plots: PDG06





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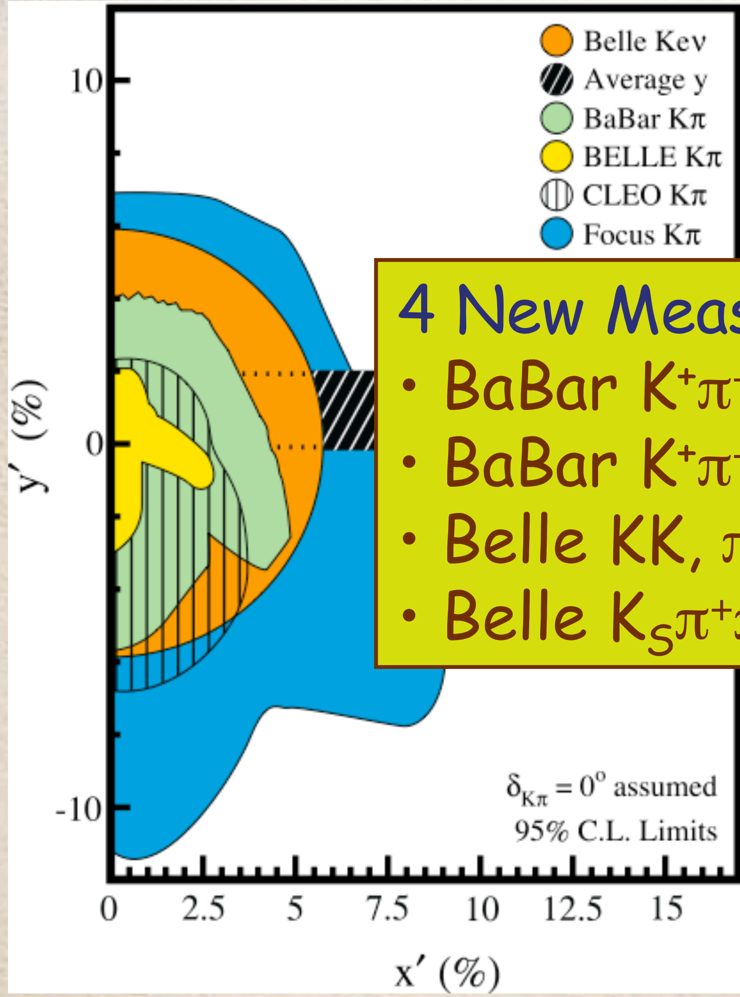
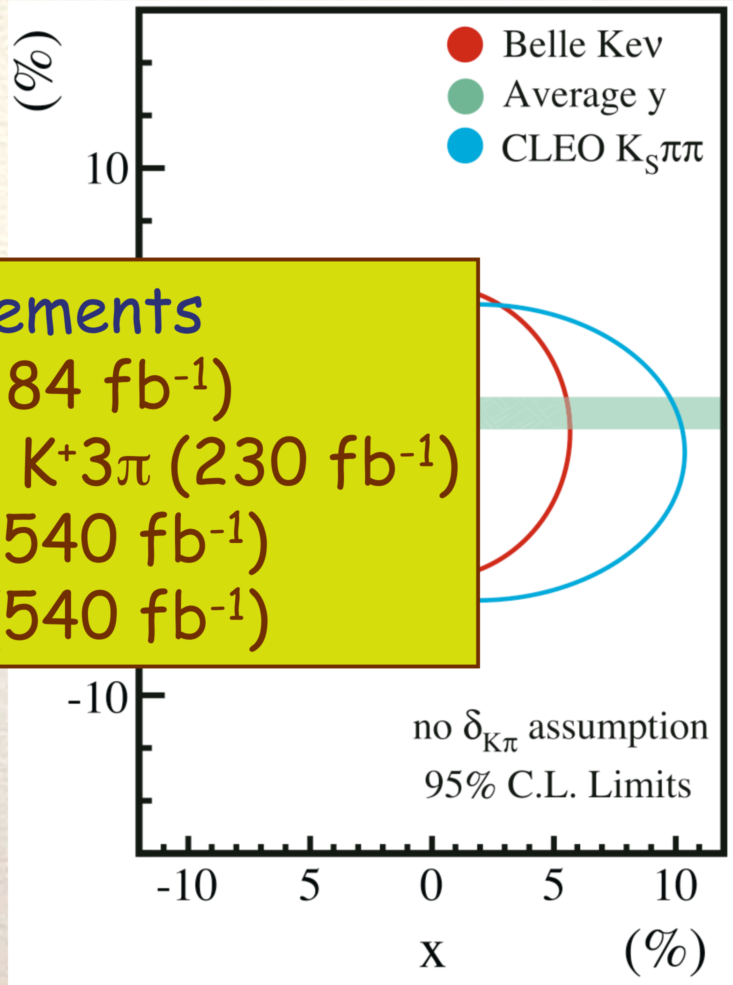




4 New Measurements

- BaBar $K^+\pi^-$ (384 fb^{-1})
- BaBar $K^+\pi^-\pi^0$, $K^+3\pi$ (230 fb^{-1})
- Belle KK, ππ (540 fb^{-1})
- Belle $K_S\pi^+\pi^-$ (540 fb^{-1})

"Evidence" for D Mixing: Only 2 results > 3σ

- Babar (384 fb^{-1}) $D^0 \to K\pi$
  - c.w. Belle (400 fb^{-1})

    $x'^2 = (0.18^{+0.21}_{-0.23}) \times 10^{-3}$ $y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$

$$x'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$$
$$y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$$

- Belle (540 fb^{-1}) $D^0 \to KK, \pi\pi$
  - c.w. W.A. (includes Belle '03)

    $y_{CP} = (0.90 \pm 0.42)\%$

$$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$$

- Belle (540 fb^{-1}) $D^0 \to K_S\pi\pi$
  - c.w. CLEO (9 fb-1)

    $x = (1.8 \pm 3.4 \pm 0.6)\%$ $y = (-1.4 \pm 2.5 \pm 0.9)\%$

$$x = (0.80 \pm 0.29 \pm 0.17)\%$$
$$y = (0.33 \pm 0.24 \pm 0.15)\%$$

- CLEO-c (281 pb^{-1}) - new results expected soon
  - y, x^2 and cosδ

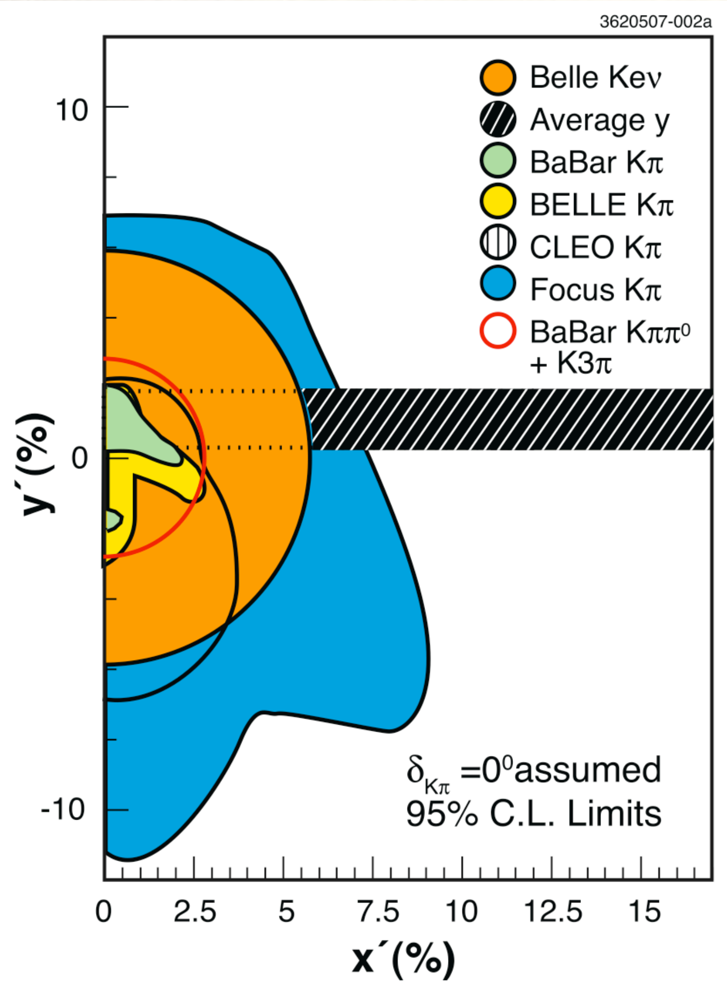
Before Moriond '07

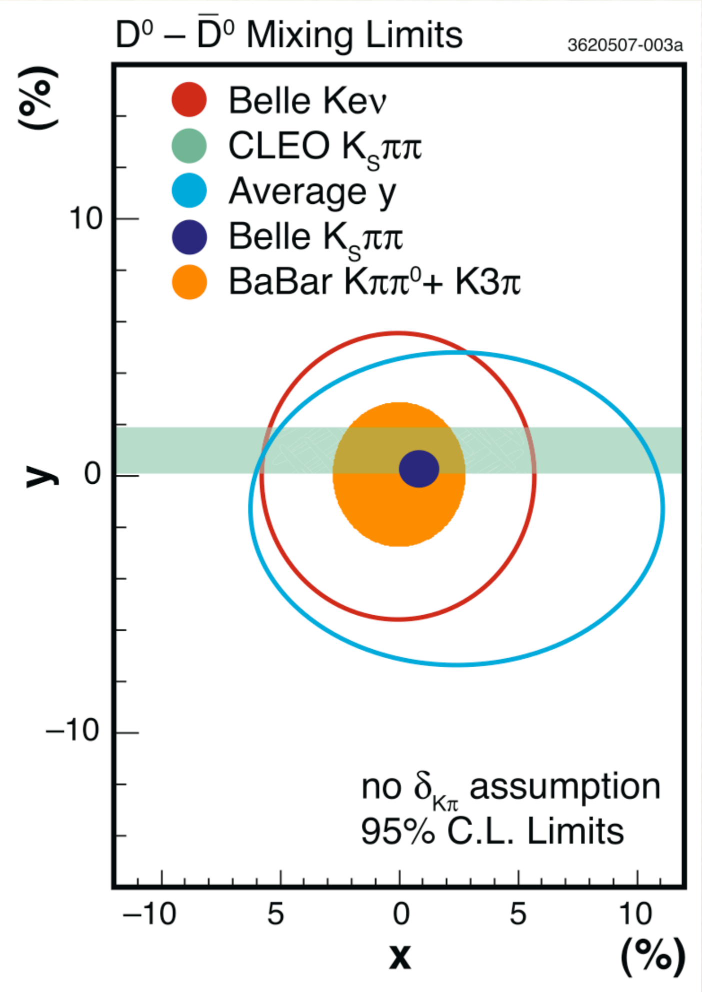
NO MIXING (x,y)=(0,0) excluded:
- ✓ ~2.1 σ Belle $D^0 \to K\pi$ (no CPV)
- ✓ ~2.3 σ BaBar $D^0 \to K2\pi/K3\pi$
- ✓ ~2.2 σ Average y_{CP}

After Moriond '07

NO MIXING (x,y)=(0,0) excluded:
- ✓ 3.9 σ BABAR $D^0 \to K\pi$ (no CPV)
- ✓ ~2.4 σ Belle $D^0 \to K_S\pi\pi$
- ✓ ~3.5 σ New Average y_{CP}=1.12±0.32

Updated Limit Plots: PDG07



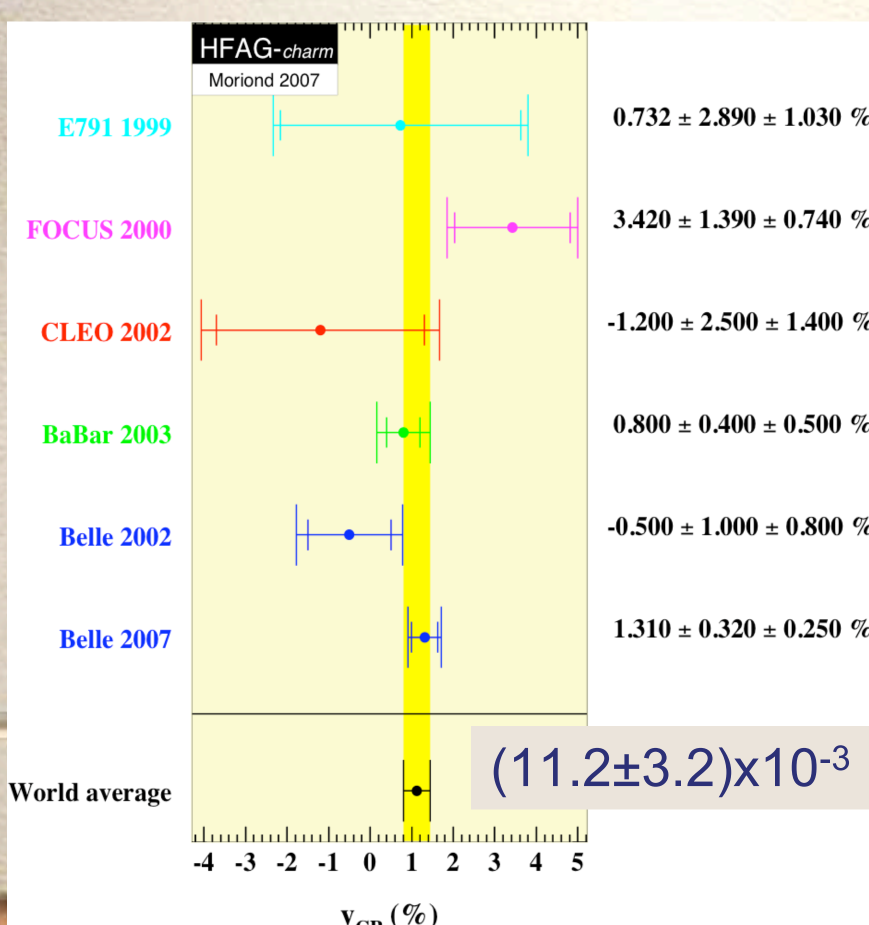


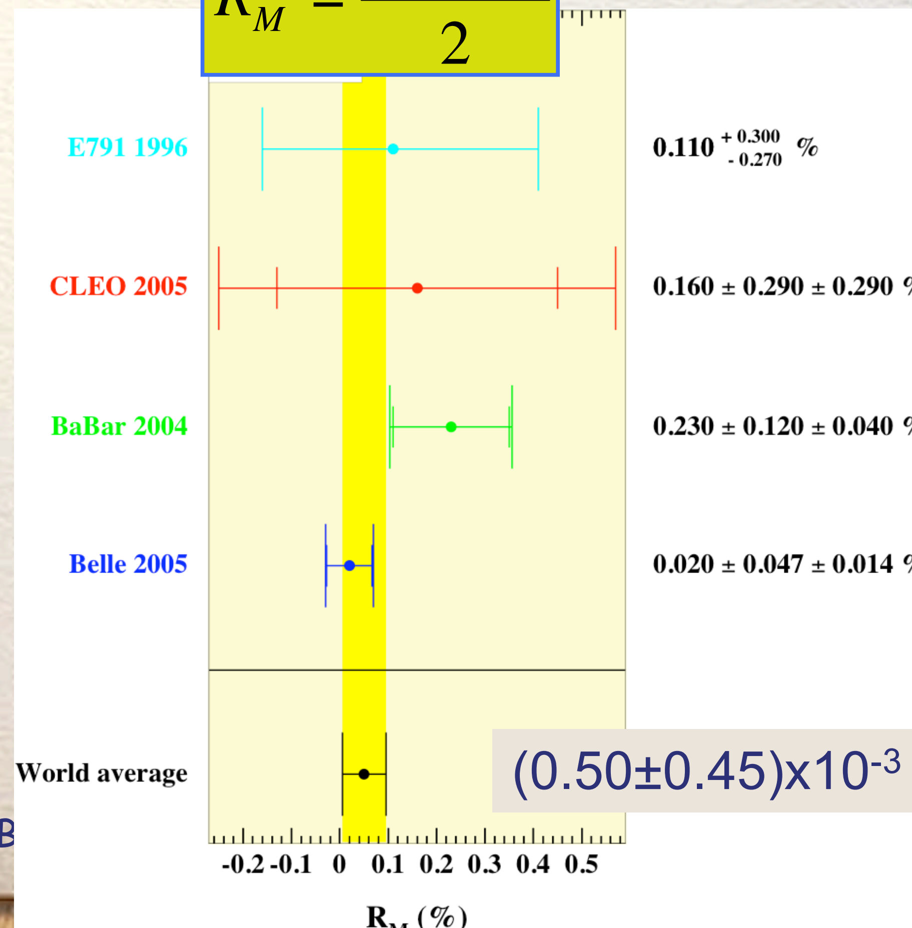
Combining Mixing Results

HFAG has preliminary averages for some measurements

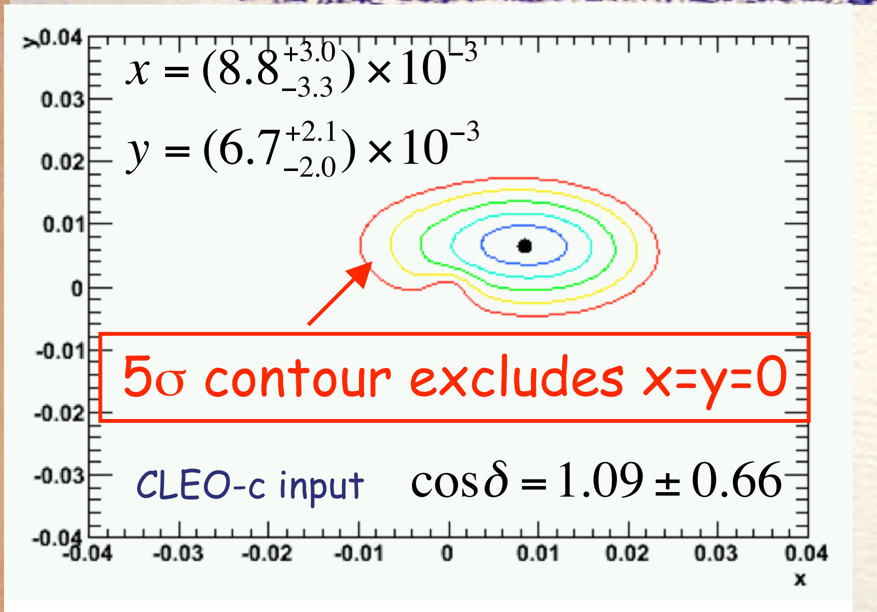
$$y_{cp} = y\cos\varphi$$

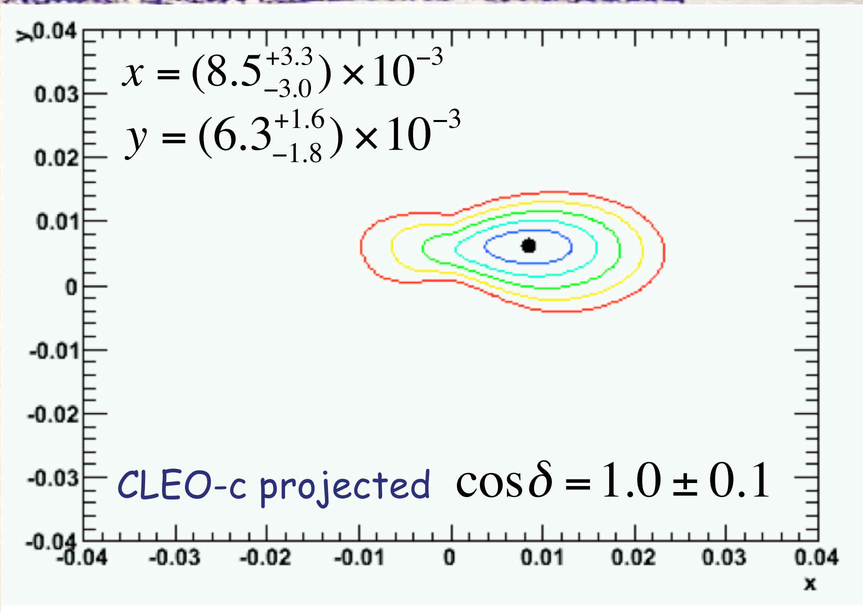
$$R_M = \frac{x^2 + y^2}{2}$$





HFAG - VERY Preliminary





- With great trepidation average all results
  - Use likelihood contours where appropriate
- Consider two scenarios
  - Current results - with CLEO-c $\cos\delta = 1.09 \pm 0.66$
  - Current results + anticipating $\cos\delta = 1.0 \pm 0.1$

Projected Sensitivity

Exp't / 1 σ	y_{CP} (10^{-3})	y' (10^{-3})	x'^2 (10^{-4})	$\cos\delta$
B-factories ($2ab^{-1}$)	2-3	2-3	1-2	-
SuperB ($50\ ab^{-1}$)	0.5	0.7	0.3	-
LHCb ($10\ fb^{-1}$) Only B->D*	?	0.7	0.7	-
LHCb ($100\ fb^{-1}$) Prompt D*	?	?	?	-
CLEO-c ($750\ pb^{-1}$)	10	-	2-3	0.1-0.2
BESIII ($20\ fb^{-1}$)	4	-	0.5-1	0.05
SuperB - 4 GeV ($0.2\ ab^{-1}$)	1-2	-	<0.2	<0.05

- 5σ signal in both y_{CP} & $D^0 \rightarrow K\pi$ possible with $2ab^{-1}$ @$\Upsilon(4S)$
- LHCb can confirm signal in $D^0 \rightarrow K\pi$ - y_{cp} study in progress
- 5σ time independent signal in y not likely @ BESIII
  - Requires ~1 month run at SuperB (4 GeV)

CPV in D Mixing

In Standard Model $x \lesssim y$ Short distance 10^{-6} - 10^{-3}
Long distance 10^{-3} - 10^{-2}

"Evidence" on high side of SM LD expectation

Could this be due (in part) to New Physics?

CP asymmetries involving D oscillations $O(10^{-6})$ in SM

Large CPV in mixing indicates NP

Current results consistent with no CP violation

- $D^0 \to K^+\pi^-$ constrain $-99.5\% < A_M < +100\%$ @95% C.L. (Belle)
- $D^0 \to K^+K^-, \pi^+\pi^-$ $A_\Gamma \cong A_M y\cos\phi - x\sin\phi = (0.01 \pm 0.30 \pm 0.15)\%$ (Belle)
  - Consistent with both $A_M = \pm 1$ and $\sin\phi = \pm 1$

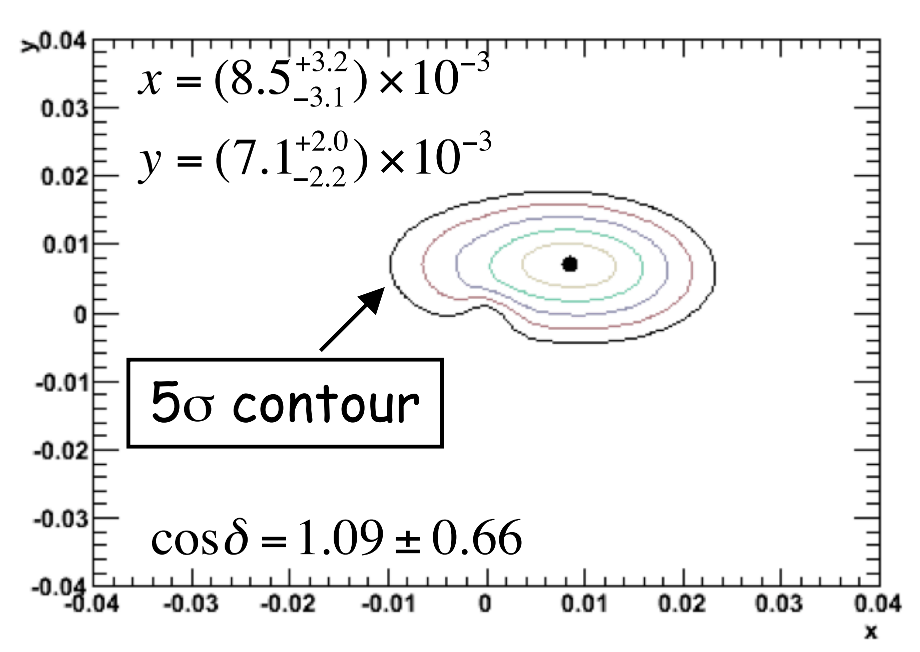
Systematic Uncertainties

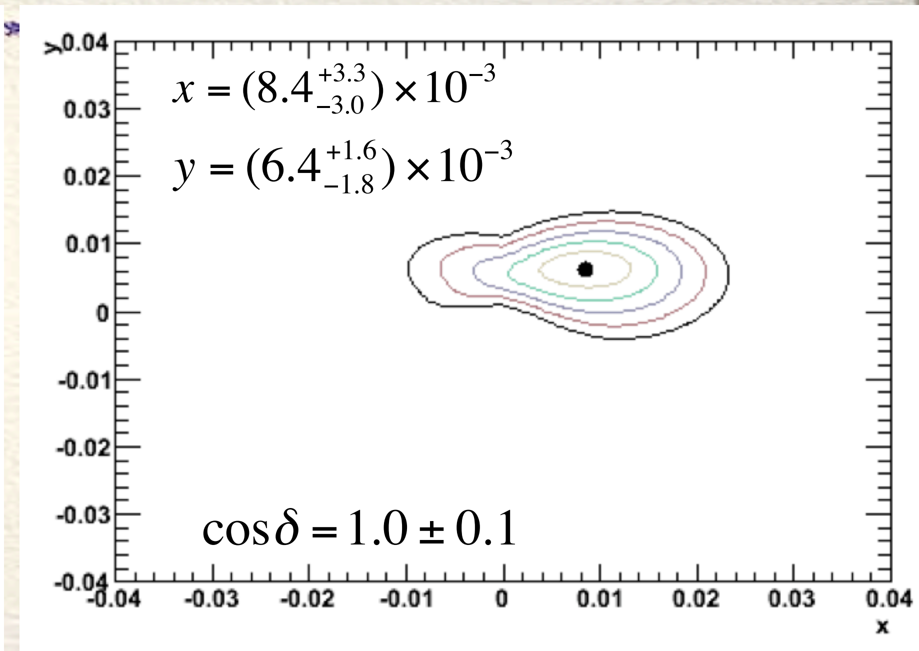
- Systematics should remain under control for mixing and even more so for CP violation measurements
- Due to canceling in ratios, ratios of ratios, differences, ratios of differences etc.
- Dominant Systematic Uncertainty
  - R_M from semileptonic (# of unphysical sign combinations)
  - Ycp (description of background)
  - $D^0 \rightarrow K\pi$ (description of bkgd, decay time resolution)
  - $D^0 \rightarrow K_S\pi\pi$ (bkgd t dep - Dalitz correlation, Dalitz model)
  - Quantum-Correlated (description of bkgds, QC bkgds)
- Measurement/Limit on CP violation in charm mixing at SuperB likely to be statistics limited

Summary

- Sensitivity studies for LHCb (mixing & CPV) and SuperB (CPV) are not complete
- Individual measurements show
  - Evidence (3σ) for Charm Mixing
  - No sign of CP violation in Charm Mixing
- HFAG Preliminary indicate 5σ signal
- Full B-factory data samples could attain 5σ results for each of y_{cp} and $D^0 \to K\pi$
- Precision measurments of charm mixing at SuperB
  - 4 GeV data - measure cos δ directly
  - 5σ crosscheck with different systematic uncertainties
- SuperB will constrain CPV in charm mixing
  - 1σ ~ (5-10)% stat. only for CPV in x, y_{cp}, y' (Recall SM~10^{-6})

HFAG -VERY Preliminary: 30March07 missing untagged Belle ycp result





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