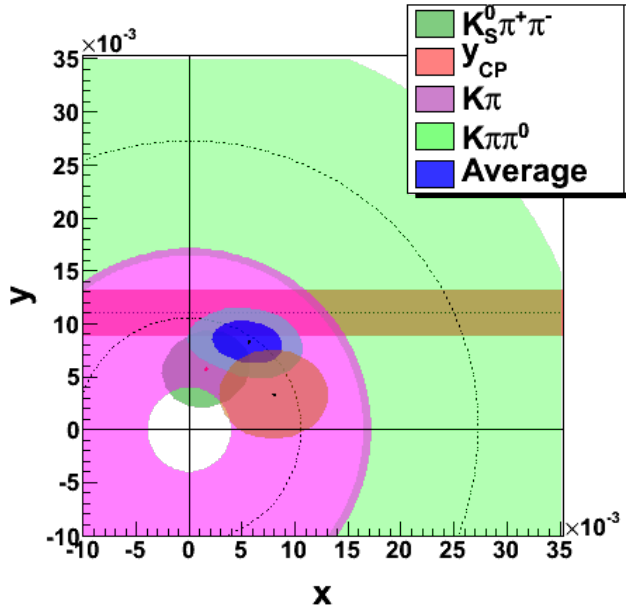
Charm mixing at flavour factories

- $K\pi$, $K\pi\pi^0$: Measure RS/WS ratio as function of time, extract rotated mixing parameters.
- $K^0_S\pi^+\pi^-$: Measure average decay time as function of Dalitz-plot position, get mixing parameters directly.
- $\Delta\Gamma$: Measure ratios of lifetimes of CP and flavour eigenstates, *eg* $\tau_{KK}/\tau_{K\pi}$, to extract y_{CP} - equivalent to y in the absence of CP violation.
- $\cos\delta$: Run at the $D\overline{D}$ threshold energy and produce coherent pairs. Measure the correlation between their respective Dalitz plots to extract the strong phase.
- Current experiments have well established the existence of mixing, but are not sensitive to *CP* violation.



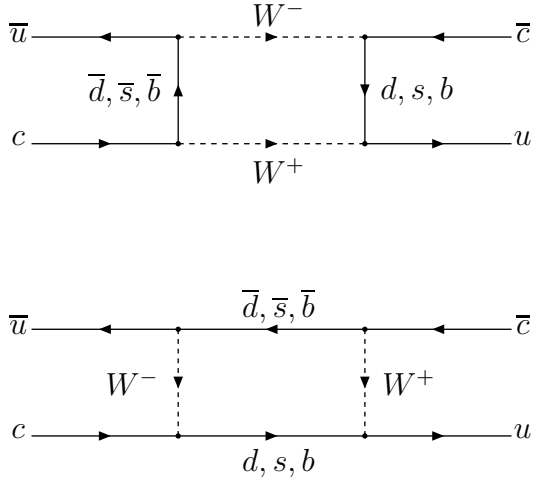
Reminder of mixing formalism

- Mixing is a transition from a particle to its antiparticle.
- It occurs when the flavour eigenstates (D^0, $\overline{D}^0$) produced in decays are not the same as the mass eigenstates (D_1, D_2) which move through space.
- We parametrise mixing by the normalised mass and width differences of the mass eigenstates:

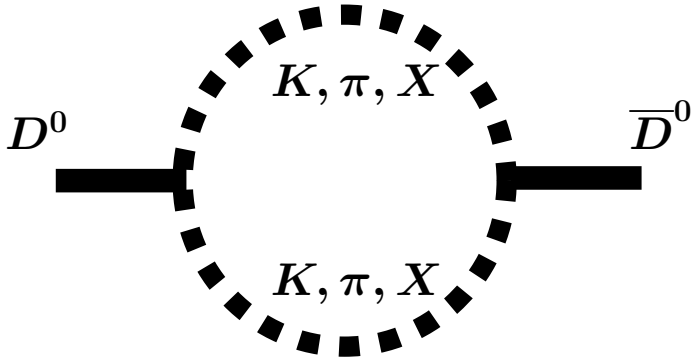
$$\begin{aligned} \Delta M &= m_1 - m_2 \\ \Delta\Gamma &= \Gamma_1 - \Gamma_2 \\ \Gamma &= (\Gamma_1 + \Gamma_2)/2 \\ x &= \Delta M/\Gamma \\ y &= \Delta\Gamma/2\Gamma. \end{aligned}$$

- Mixing is strongly suppressed in charmed mesons; the Standard Model predicts a very tiny ($x, y < 10^{-3}$) effect from calculable short-distance effects.

Short-distance

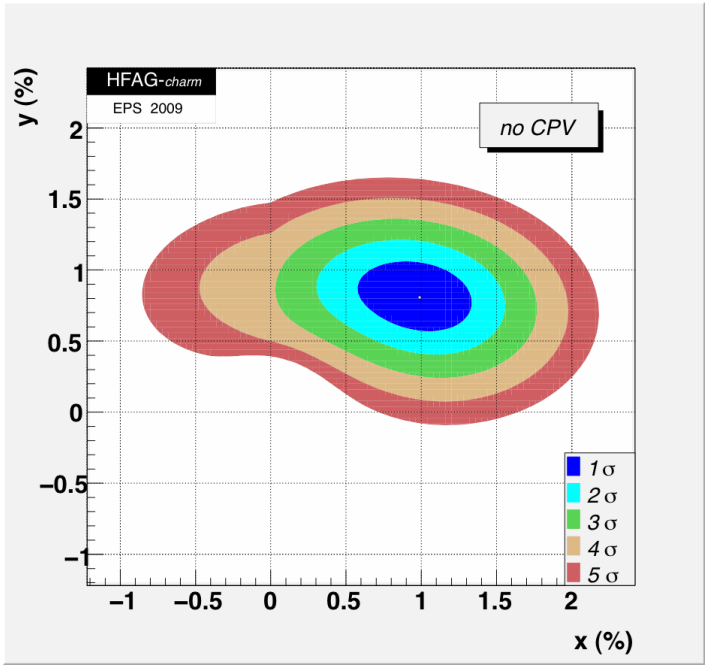


Long-distance



New Physics possibilities

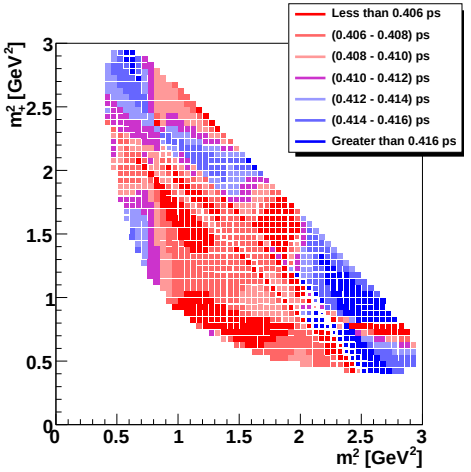
- Long-distance effects are hard to calculate, but from considerations of phase-space SU(3) symmetry breaking we can get an upper bound of $y \sim 1\%$.
- Possible New Physics signatures:
  - *CP* violation (eg $(x, y)_{D^0} \neq (x, y)_{\bar{D}^0}$).
  - Large mixing - $x, y > 1\%$.
  - 'Upside down' mixing, $|x| > |y|$.
- 'Main' measurement using $D^0 \to K\pi$ is not sensitive to the sign of x.

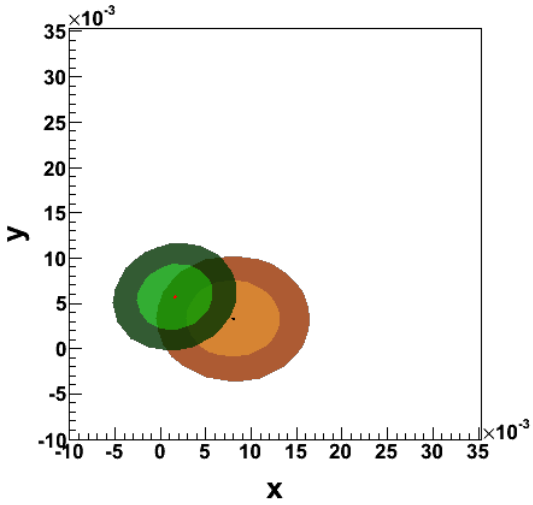


Falk *et. al.*, hep-ph/0110317
Falk *et. al.*, hep-ph/0402204

$D^0 \to K^0_S h^+ h^-$: x, y

- Intermediate state $K^0_S \rho$ with well-defined CP allows us to extract strong phase at each point in the Dalitz plot.
- Variation in average decay time depends on mixing parameters - fit extracts Dalitz-plot model and mixing parameters simultaneously.
- Results from Belle and *BABAR* :





Experiment	Sample	x [%]	y [%]
CLEO	9 fb^{-1}	$1.9^{+3.2}_{-3.3} \pm 0.4 \pm 0.4$	$-1.4 \pm 2.4 \pm 0.8 \pm 0.4$
Belle 2007	540 fb^{-1}	$0.80 \pm 0.29 \pm 0.17$	$0.33 \pm 0.24 \pm 0.15$
BABAR 2010	469 fb^{-1}	$0.16 \pm 0.23 \pm 0.12 \pm 0.08$	$0.57 \pm 0.20 \pm 0.13 \pm 0.07$

$D^0 \to K\pi$: x'^2, y'

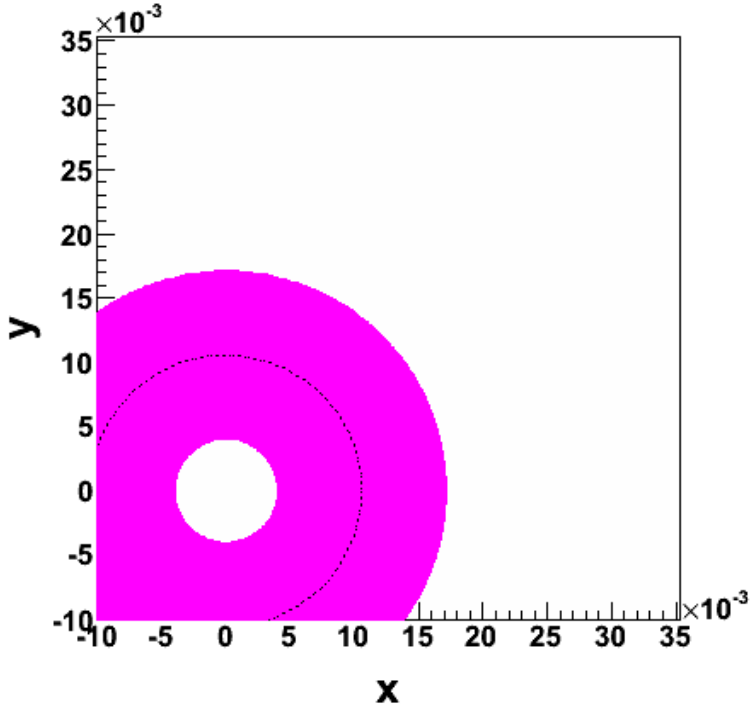
- Unknown strong phase $\delta_{K\pi}$ between mixed and DCS decays prevents us measuring x, y directly:

$$x' = x\cos(\delta_{K\pi}) - y\sin(\delta_{K\pi})$$
$$y' = y\cos(\delta_{K\pi}) + x\sin(\delta_{K\pi}).$$

- WS amount as a function of time is given by

$$T_{\rm WS}(t)e^{\Gamma t} \propto R_D + y'\sqrt{R_D}(\Gamma t) + 0.25(x'^2 + y'^2)(\Gamma t)^2$$

and we fit for x'^2 and y'.



- Most recent results:

Experiment	Sample	x'^2 [%]	y' [%]
Belle 2006	400 fb^{-1}	$0.018^{+0.021}_{-0.023}$	$0.06^{+0.40}_{-0.39}$
BABAR 2007	384 fb^{-1}	$-0.022 \pm 0.030 \pm 0.021$	$0.97 \pm 0.44 \pm 0.31$
CDF 2007	1.5 fb^{-1}	-0.012 ± 0.35	0.85 ± 0.76

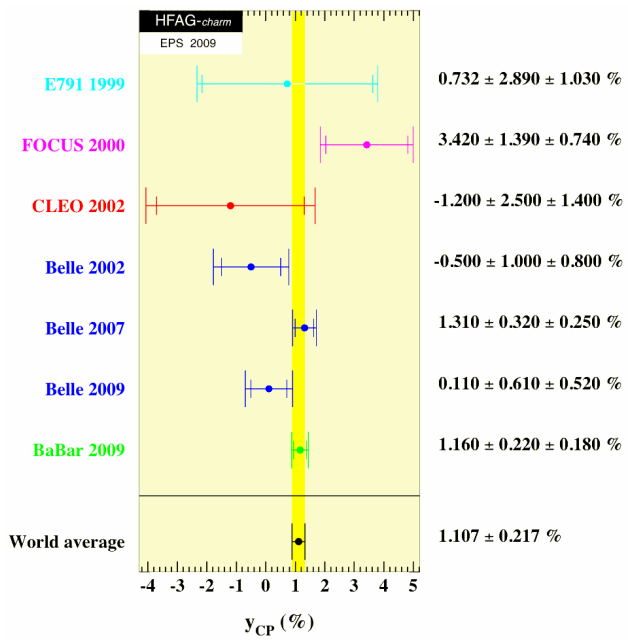
$D^0 \to K^+K^-/D^0 \to K\pi$: y_{CP}

- Look at ratio of decay rates between CP and flavour eigenstates, eg $\tau_{KK}/\tau_{K\pi}$:

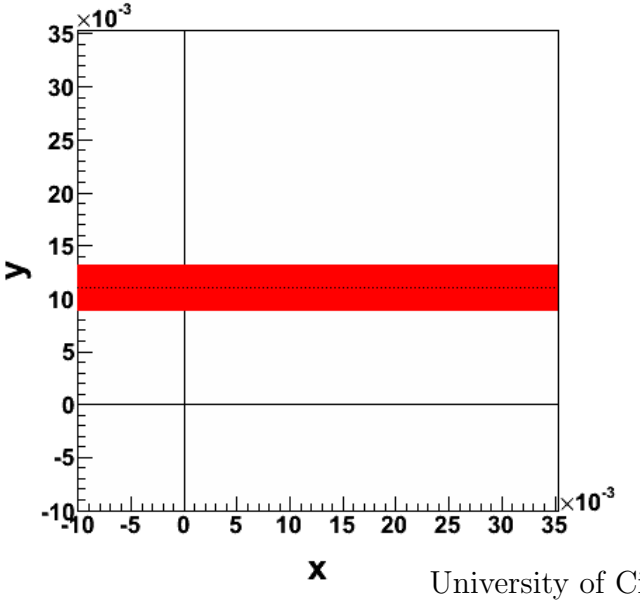
$$\tau^+_{CP} = \tau_{K\pi}\left[1 + \left|\frac{q}{p}\right|(y\cos\phi_f - x\sin\phi_f)\right]^{-1}$$

$$\tau^-_{CP} = \tau_{K\pi}\left[1 + \left|\frac{p}{q}\right|(y\cos\phi_f + x\sin\phi_f)\right]^{-1}$$

$$y_{CP} = \frac{2\tau_{K\pi}}{\tau^+_{CP} + \tau^-_{CP}}$$



- KK is a CP eigenstate - strong phase is zero.
- In the absence of CP violation, $\phi_f = 0$ and $q = p$, so $y_{CP} = y$.

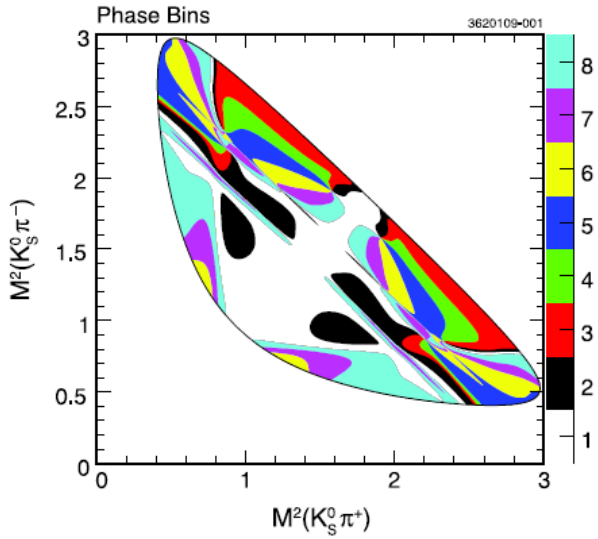


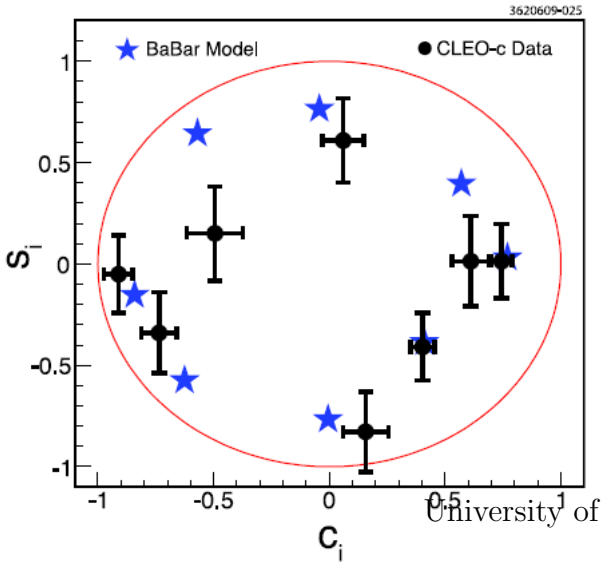
Threshold production: $\cos\delta$

- If we had a constraint in $\delta_{K\pi}$, the doughnut from $D^0 \to K\pi$ analyses could be reduced to a much smaller part of (x, y) space.
- Running at the $D\overline{D}$ threshold allows us to extract the strong phase by looking at correlated decays.
- CLEO 2008, 281 pb^{-1}:

$$\cos\delta_{K\pi} = 1.03^{+0.31}_{-0.17} \pm 0.06.$$

- Another possibility: Measure strong phase in sections of the $K_S\pi^+\pi^-$ Dalitz plot, and do several $K\pi$-like analyses. Reduce dependence on amplitude model.

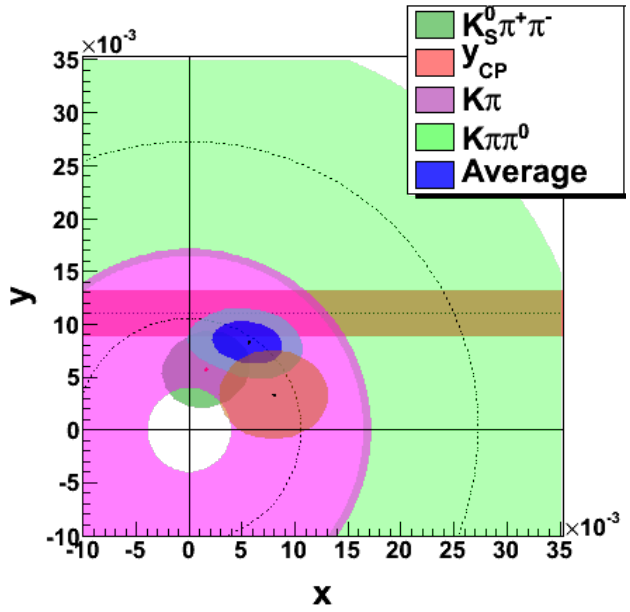




Current situation

- (x, y) seems to be in first quadrant, less than 1% mixing overall, $x < y$. Nothing very surprising.
- CKM-like combination of many results gives

$$\begin{aligned} x &= (0.56 \pm 0.21)\% \\ y &= (0.83 \pm 0.13)\% \\ \delta_{K\pi} &= 1.53 \pm 0.36 \\ \delta_{K\pi\pi^0} &= -0.44 \pm 0.40 \end{aligned}$$

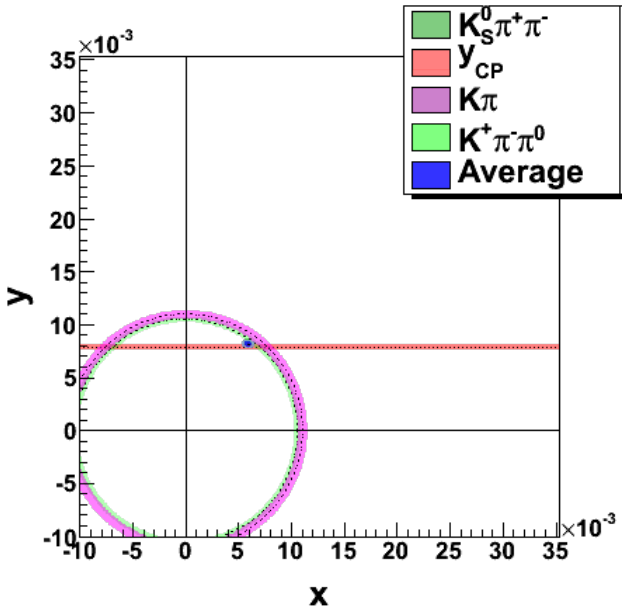


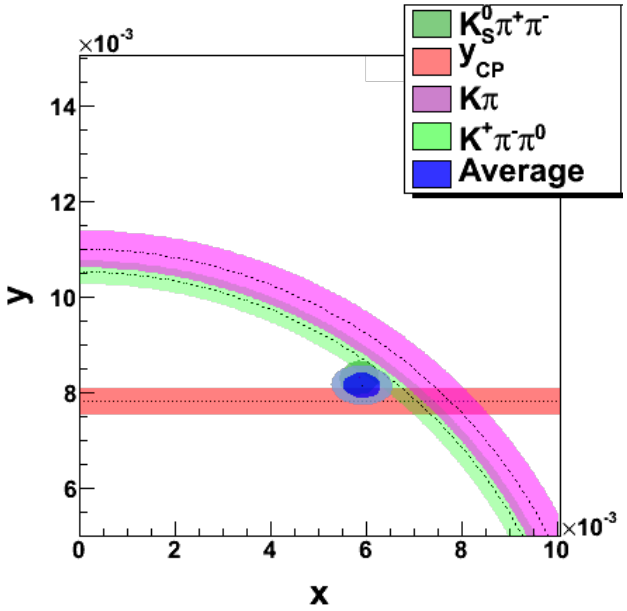
- Input values:

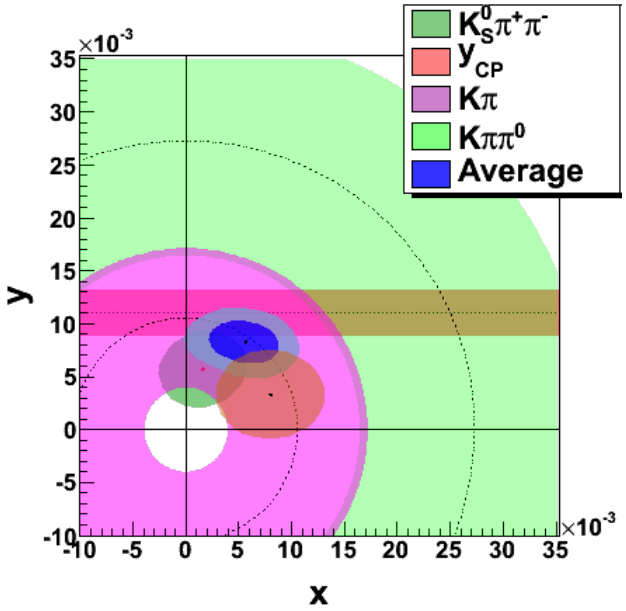
Experiment	Channel	Result [%]
Belle 2007	$K^0_S\pi\pi$	$(x, y) = (0.80 \pm 0.34, 0.33 \pm 0.28)$
BABAR 2010	$K^0_S h^+h^-$	$(x, y) = (0.16 \pm 0.28, 0.57 \pm 0.24)$
HFAG 2009	$KK, \pi\pi, K^+K^-K^0$	$y_{CP} = 1.10 \pm 0.21$
Belle 2006	$K\pi$	$(x'^2, y') = (0.018 \pm 0.022, 0.60 \pm 0.40)$
BABAR 2007	$K\pi$	$(x'^2, y') = (-0.022 \pm 0.036, 0.97 \pm 0.54)$
CDF 2007	$K\pi$	$(x'^2, y') = (-0.012 \pm 0.035, 0.85 \pm 0.76)$
BABAR 2008	$K\pi\pi^0$	$(x'', y'') = (2.61 \pm 0.73, -0.06 \pm 0.69)$

SuperB: 100 times the data!

- Statistical errors reduced by factor 10.
- Systematic errors assumed to scale with statistics.
- Note: SuperB resolution in D^0 decay time is better than at *BABAR* - this is not taken into account.
- $K^0_S\pi^+\pi^-$ measurement dominates.





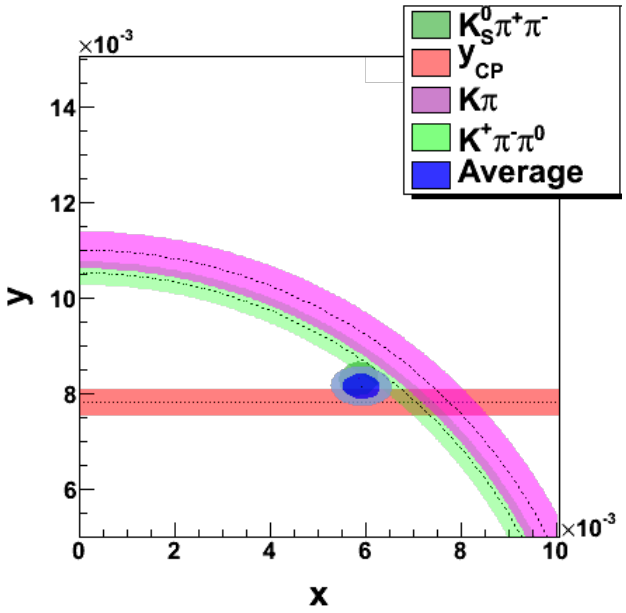


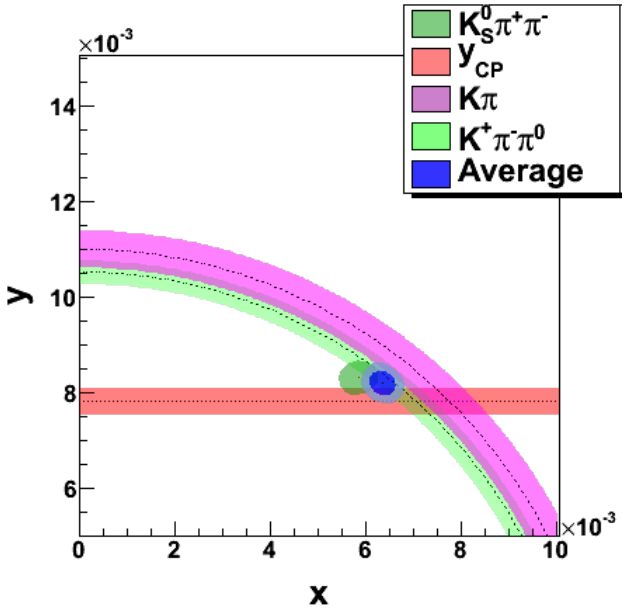
SuperB with a year at threshold

- With 500 fb^{-1} of threshold running, we could improve the CLEO $\delta_{K\pi}$ measurement quite a bit.
- Current CLEO result ($\sim$ 1fb^{-1}):

$$\delta_{K\pi} = 0.87 \pm 0.58.$$

- Scaling to 500 fb^{-1} gives error of 0.026.
- In this case the $K\pi$ mixing measurement begins to dominate.





Outlook

- **These are exciting times for charm mixing studies!**
- **The existence of mixing is now well established.**
- **Studies in more channels are on the way, but...**
- **...the *BABAR* and Belle datasets are probably not sensitive to New Physics.**
- **We need more luminosity, especially to measure *CP* violation.**
- **$\Psi(3770)$ threshold running would be very interesting.**