Charm Mixing and CPV at BaBar experiment

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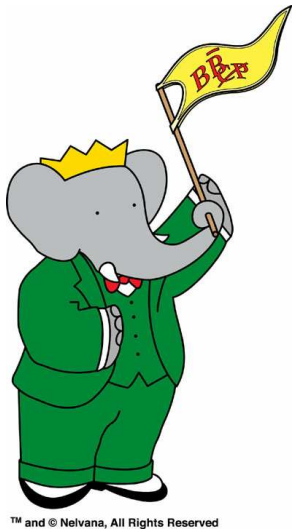
on behalf of BaBar Collaboration



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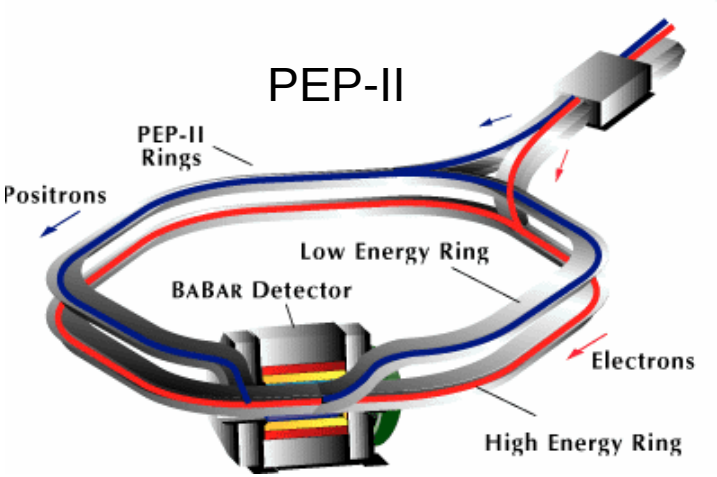
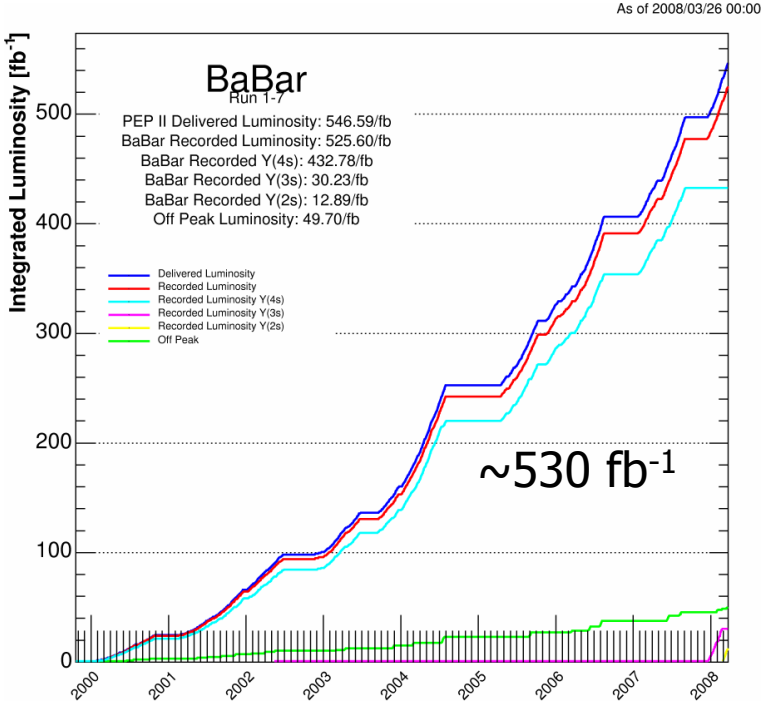
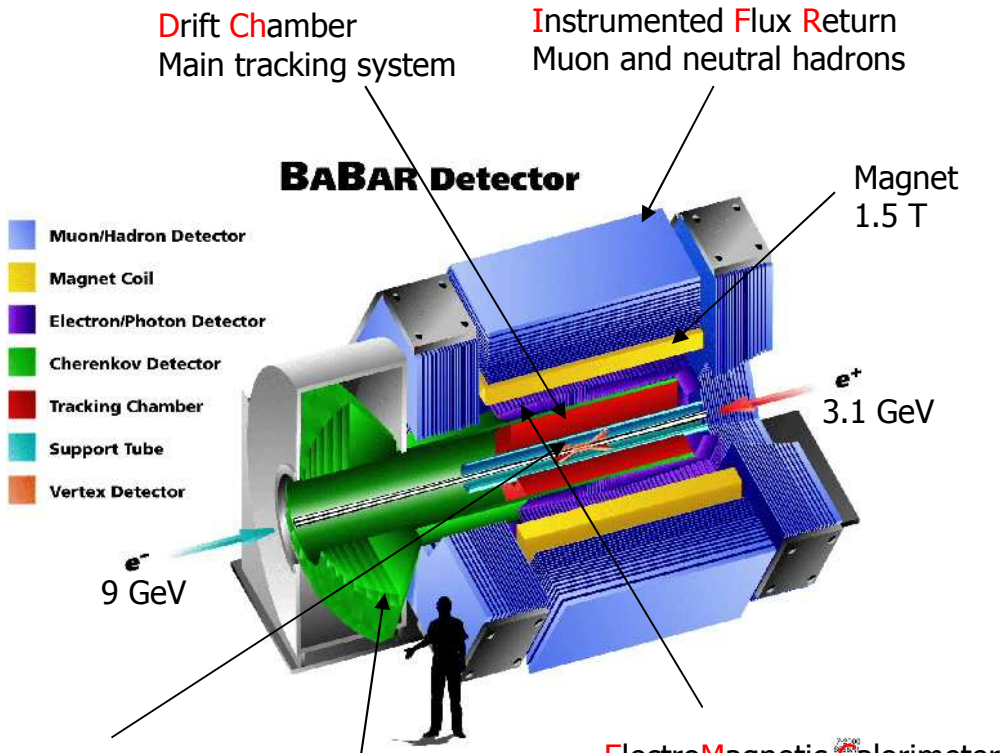
Outline

- BaBar detector
- D^0 production and selection
- Mixing and CPV notation
- Standard Model predictions and new physics
- Charm Mixing results
  - Time dependent wrong-sign hadronic decays
  - Time dependent semileptonic decays
  - Lifetime ratios between states of different CP
- Charm CPV results
  - Time integrated searches
- Summary

BaBar detector







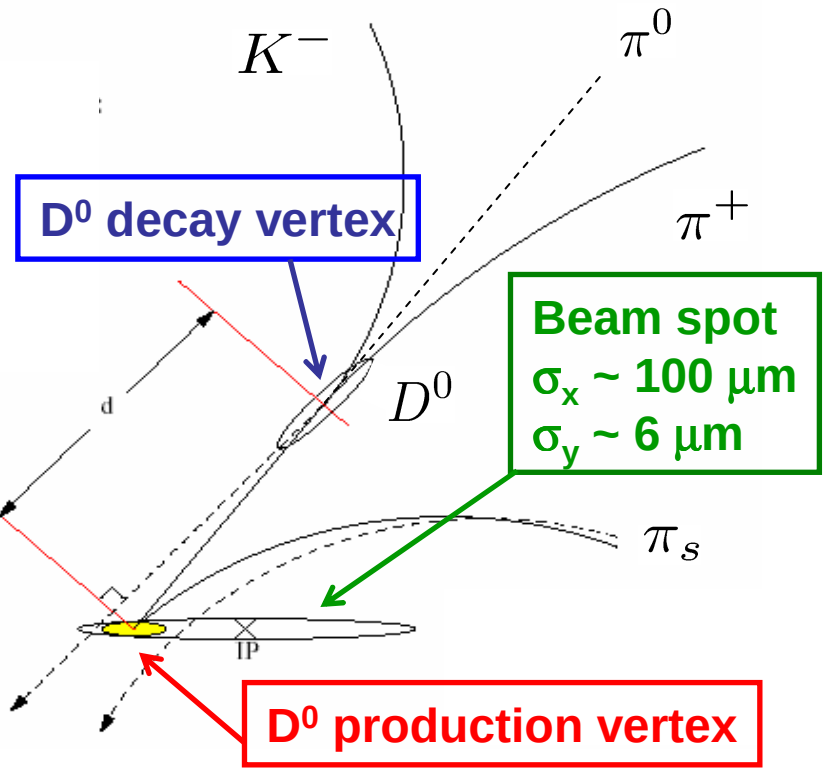
D^0 production and selection

- D^0 tagged at production
  - Inclusive D* production
  - $D^{*+} \rightarrow D^0 \pi_s^+$
  - D^0 flavor determined by the charge of the π_s
  - $e^+e^- \rightarrow c\bar{c}$ events have high D^0 momentum in $\Upsilon(4S)$ CM. Reject $B\bar{B}$ events.

- D^0 tagged at decay
  - WS (wrong sign) and RS (right sign) D^0 decay products determine also its flavor

- Beam spot constraint determines t and σ_t. It improves also the m_D and $\Delta m = m(D^0\pi_s) - m(D^0)$ resolutions

$$\sigma(e^+e^- \rightarrow c\bar{c}) \sim 1.3\text{nb}$$
$$\sigma(e^+e^- \rightarrow b\bar{b}) \sim 1.1\text{nb}$$



Mixing and CPV notation

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

- Flavor mixing occurs when flavor eigenstates differ from mass eigenstates

$$|D^0_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$|p|^2 + |q|^2 = 1$$

- Mixing parameters are given by

$$x = \frac{m_2 - m_1}{\Gamma}$$

$$y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- Mixing has been well determined in K, B_s, B_d systems

CP violation

- The amplitudes of the D^0 meson into a final state *f* can be written as:

$$A_f = \langle f|\mathcal{H}|D^0\rangle, \quad \bar{A}_f = \langle f|\mathcal{H}|\bar{D}^0\rangle$$

- CPV in the decay (direct)

$$\frac{\bar{A}_{\bar{f}}}{A_f} \neq 1$$

- CPV in the mixing (indirect)

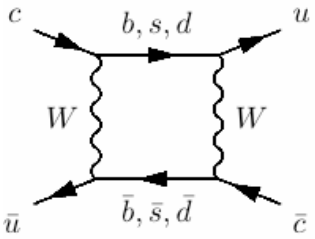
$$\left|\frac{q}{p}\right|^2 \neq 1$$

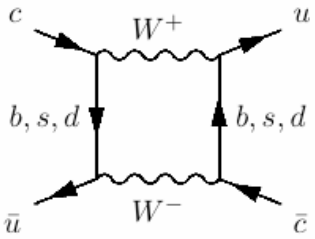
- CPV in the interference between mixing and decay

$$\arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

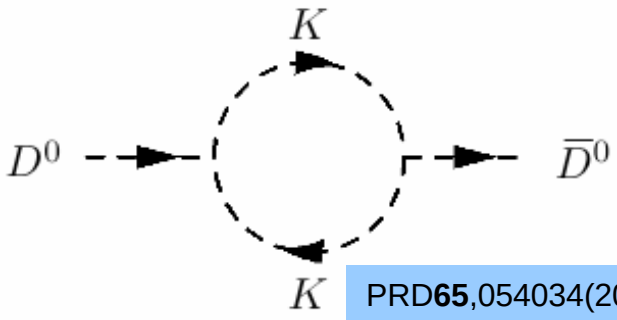
SM predictions and NP

- Short-distance contributions
  - From mixing box diagrams
  - SM predicts mixing to be small
  - *b* quarks are CKM suppressed
  - *s* and *d* quarks are GIM suppressed
  - Contributes mainly to *x*





- Long-distance contributions
  - Via hadronic intermediate states
  - Expected to dominate
  - Still a small effect
  - Non-perturbative and hard to estimate
  - Predictions give *x, y* in (0.001-0.01) and |*x*|<|*y*|



PRD**65**,054034(2002)
PRD**69**,114021(2004)

- NP through new particles in the loops
- If *x*>>*y*, this could be a hint of NP
- No CPV expected in SM with current sensitivity, however it is a "smoking gun" for NP since SM predicts CPV to be $<10^{-3}$.

Charm mixing and CPV analyses

- Mixing

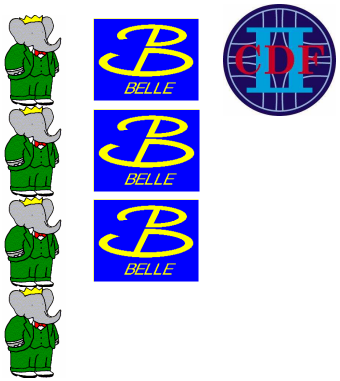
$\Rightarrow \quad D^0 \to K^+\pi^-$

$\Rightarrow \quad D^0 \to K^+K^-, \pi^+\pi^-$

$\Rightarrow \quad D^0 \to K^{(*)-}l^+\nu$

$\Rightarrow \quad D^0 \to K^+\pi^-\pi^0$

$\Rightarrow \quad D^0 \to K^0_S\pi^+\pi^-$



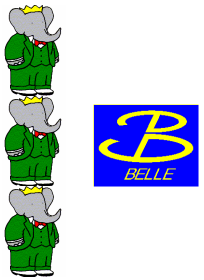
Not presented

- CPV

$\Rightarrow \quad D^0 \to K^+K^-, \pi^+\pi^-$

$\Rightarrow \quad D^0 \to \pi^+\pi^-\pi^0$

$\Rightarrow \quad D^0 \to K^+K^-\pi^0$



Charm Mixing Analyses

Time Dependent (TD) WS hadronic decays. $D^0 \to K^+\pi^-$

- Reconstruction of wrong signal decay chain: $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^+\pi^-$
- Contributions
  - Doubly-Cabibbo-supressed (DCS) decay: $D^0 \to K^+\pi^-$
  - Mixing & Cabibbo-favoured (CF) decay : $D^0 \to \bar{D}^0 \to K^+\pi^-$
  - Interference
- Distiguish contributions using the different time dependences, $x,y \ll 1$

$$\Gamma_{WS}(t) = e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y'\sqrt{R_D}}_{\text{Interference}}(\Gamma t) + \underbrace{\frac{x'^2+y'^2}{4}}_{\text{Mixing}}(\Gamma t)^2\right)$$

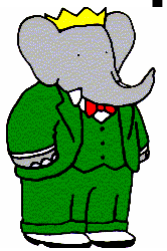
$$\begin{aligned} x' &= x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \\ y' &= -x\sin\delta_{K\pi} + y\cos\delta_{K\pi} \end{aligned}$$

$$R_D = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} \sim 3\times 10^{-3}$$

D^0-$\bar{D}^0$ relative strong phase.
Phase depends on D^0 decay channel

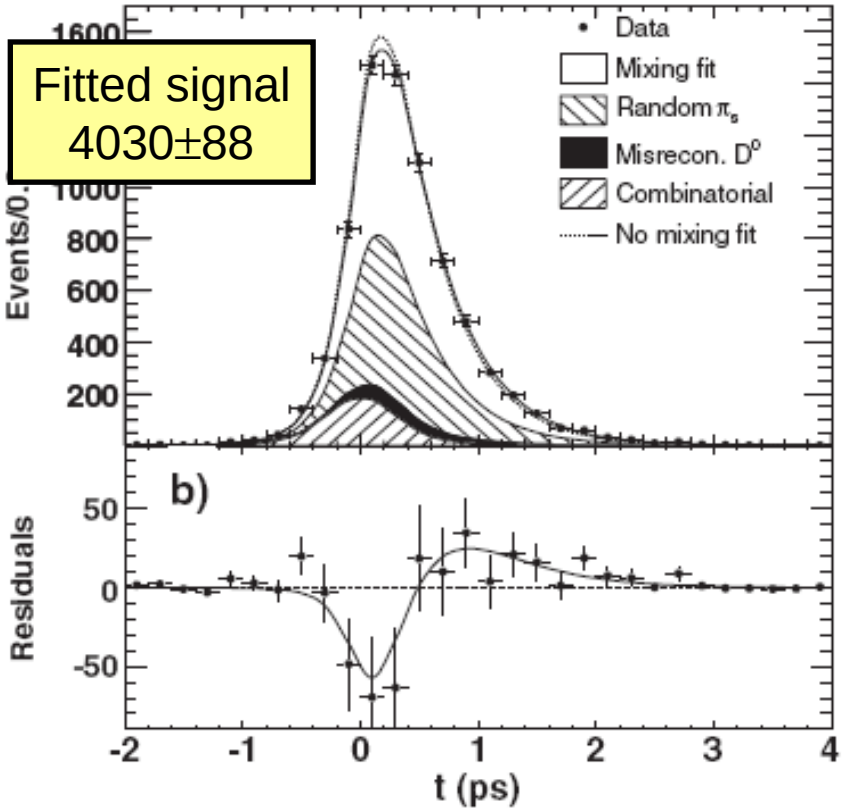
Analysis of the proper time distribution of WS events permits extraction of D^0 mixing parameters y' and x'^2

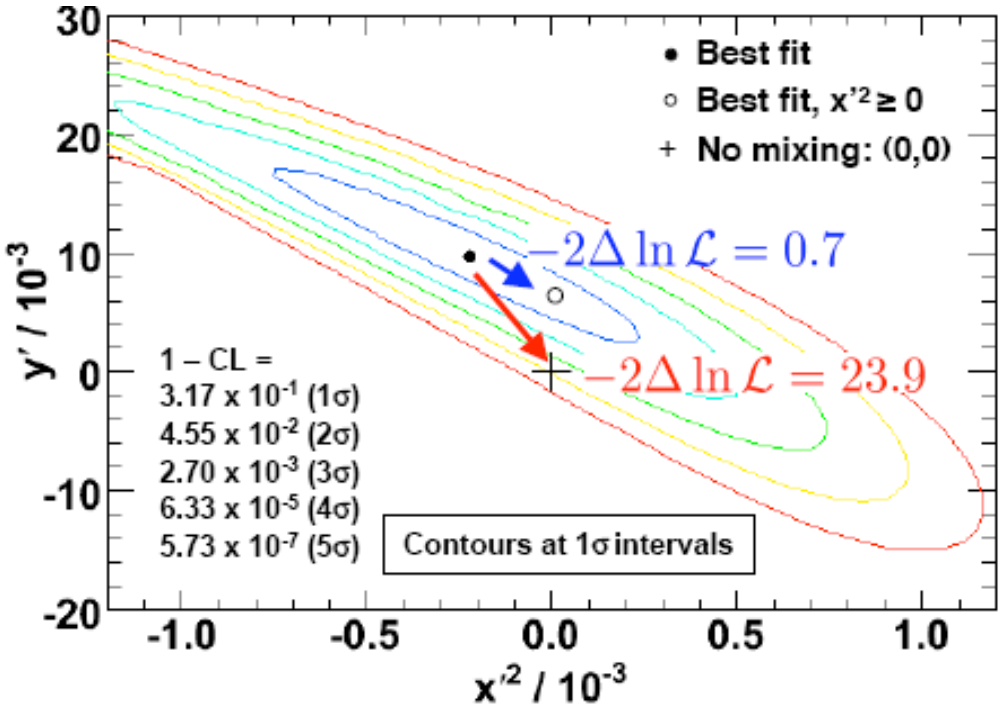
TD WS hadronic decays. $D^0 \to K^+\pi^-$



384 fb^{-1} ~ 500M $c\bar{c}$ events
PRL**98**:211802,2007

Fitted signal
4030±88

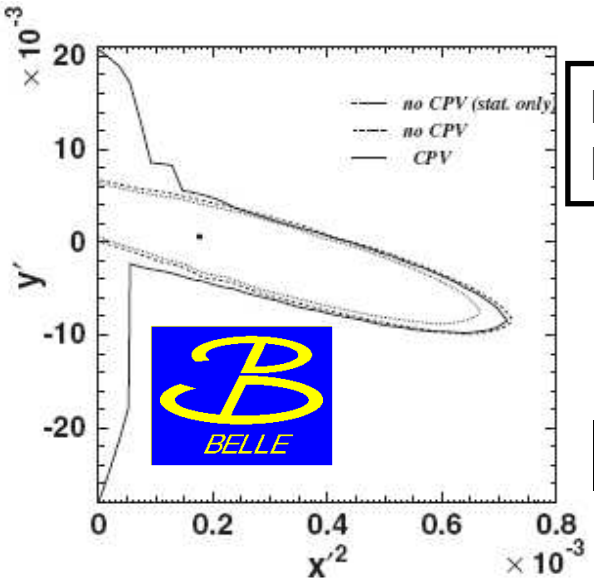




$R_D = (3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$
$x'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
$y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

- Principal systematic modeling long decay time component in the signal region
- Difference between no mixing and mixing fits is observed in the residual
- Best fit point is in the non physical region $x'^2<0$
- Mixing evidence @ 3.9σ
- CP conserving case

TD WS hadronic decays. $D^0 \to K^+\pi^-$

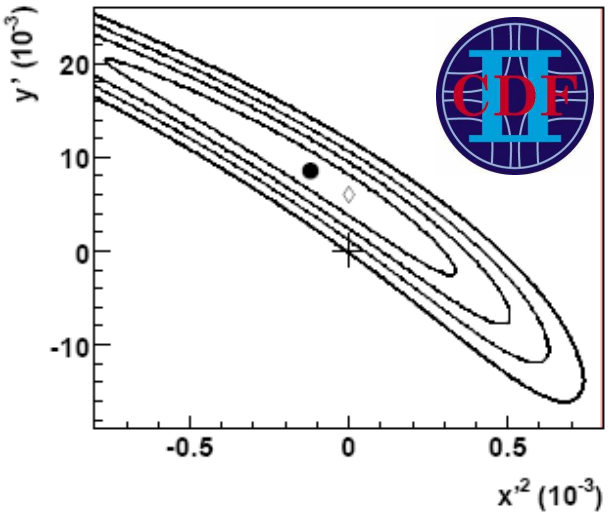


Data sample 400 fb^{-1}
PRL**96**:151801,2006

Fitted signal
4024±88

Mixing evidence @ 2σ

Fit case	Parameter	Fit result ($\times 10^{-3}$)	95% C.L. interval ($\times 10^{-3}$)
No *CPV*	R_D	3.64 ± 0.17	$(3.3, 4.0)$
	x'^2	$0.18^{+0.21}_{-0.23}$	<0.72
	y'	$0.6^{+4.0}_{-3.9}$	$(-9.9, 6.8)$
	R_M	$\cdots$	$(0.63 \times 10^{-5}, 0.40)$
CPV	A_D	23 ± 47	$(-76, 107)$
	A_M	670 ± 1200	$(-995, 1000)$
	x'^2	$\cdots$	<0.72
	y'	$\cdots$	$(-28, 21)$
	R_M	$\cdots$	<0.40
No mixing	R_D	$3.77 \pm 0.08(\text{stat.}) \pm 0.05(\text{syst.})$	



Data sample 1.5 fb^{-1}
arXiv:0712.1567 (preliminary)

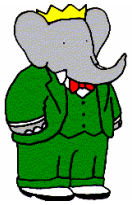
Fitted signal
(12.7±0.3)K

Mixing evidence @ 3.8σ

Fit type	$R_D(10^{-3})$	$y'(10^{-3})$	$x'^2(10^{-3})$	χ^2 / d.o.f.
Unconstrained	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	19.2 / 17
Physically allowed	3.22 ± 0.23	6.0 ± 1.4	0	19.3 / 18
No mixing	4.15 ± 0.10	0	0	36.8 / 19

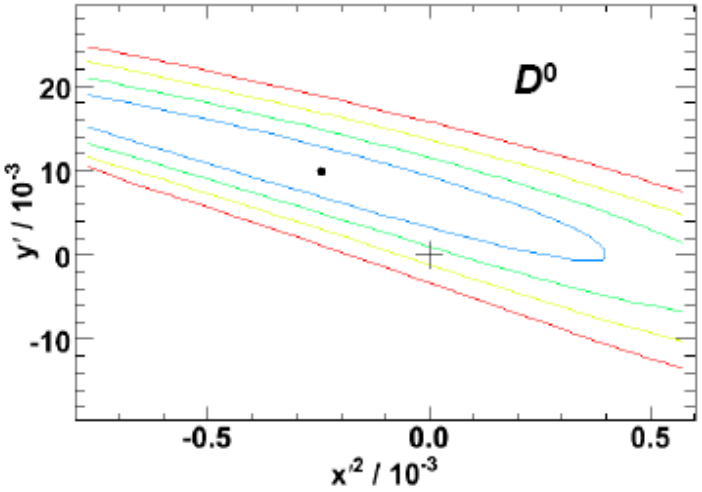
TD WS hadronic decays. $D^0 \to K^+\pi^-$

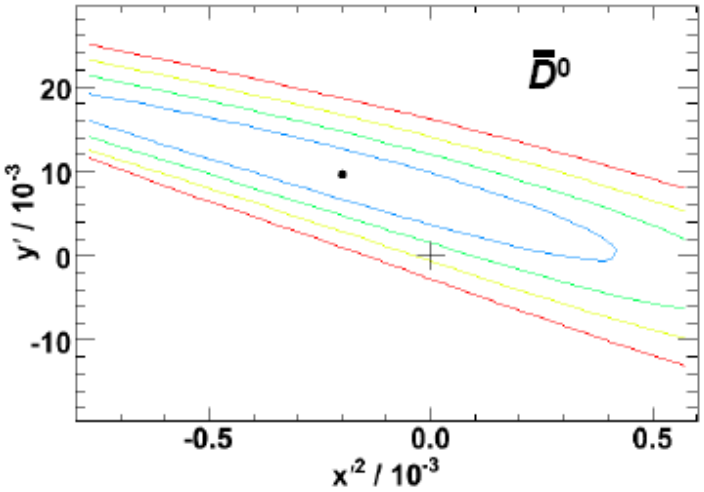
Fit to D^0 and $\bar{D}^0$ independently



$x'^{2+} = (-0.24 \pm 0.43 \pm 0.30) \times 10^{-3}$
$y'^{+} = (9.8 \pm 6.4 \pm 4.5) \times 10^{-3}$

$x'^{2-} = (-0.20 \pm 0.41 \pm 0.29) \times 10^{-3}$
$y'^{-} = (9.6 \pm 6.1 \pm 4.3) \times 10^{-3}$





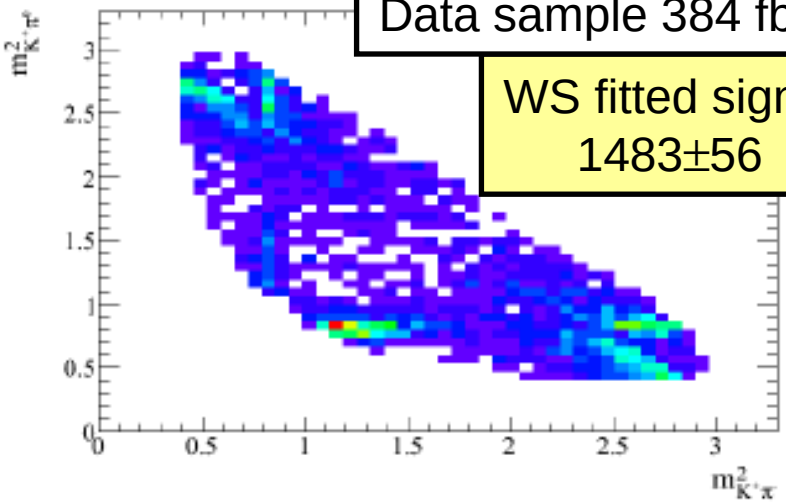
$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

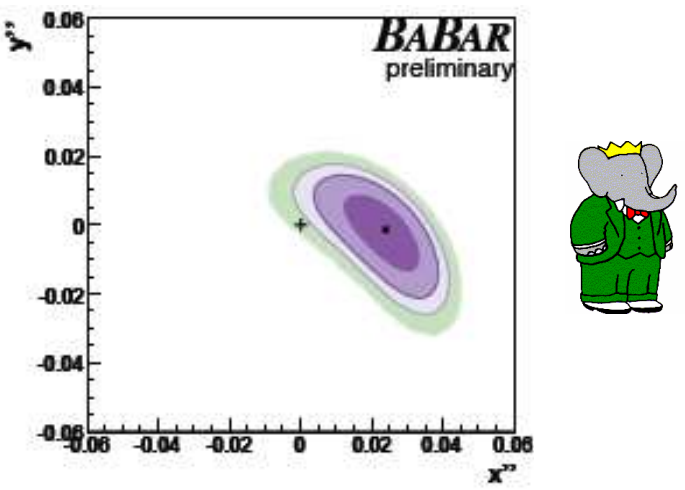
$A_D = (-21 \pm 52 \pm 15) \times 10^{-3}$

Results compatible with no CPV

TD WS hadronic decays. $D^0 \to K^+\pi^-\pi^0$

- As in Kπ case, D^0 flavor at decay is tagged with the charge of the kaon
- Amplitudes and phases of the DCS and CF vary across the Dalitz plot
- Time dependence is function of the Dalitz plot
- Uses time dependent analysis to separate DCS from mixing events





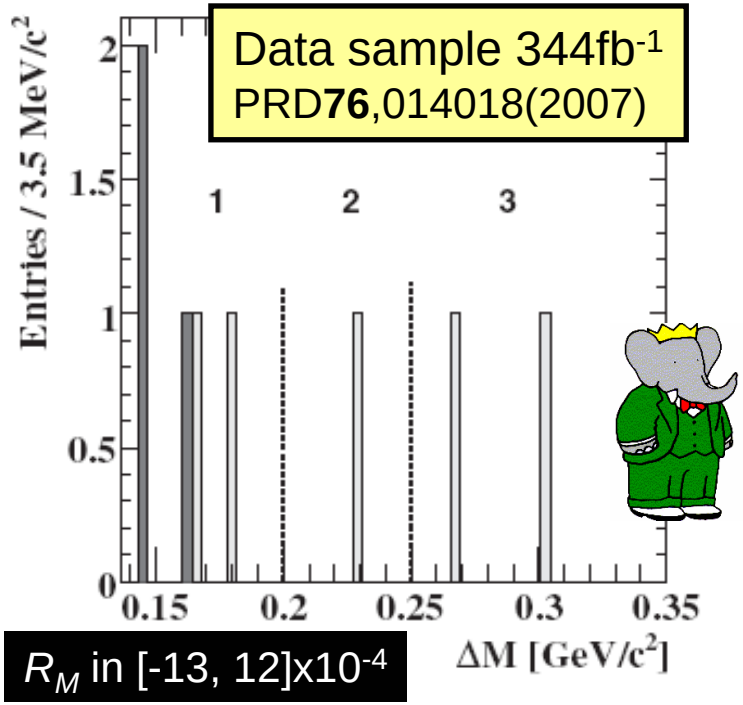
$$x'' = x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0}$$
$$y'' = -x\sin\delta_{K\pi\pi^0} + y\cos\delta_{K\pi\pi^0}$$
$$R_M = \frac{x''^2 + y''^2}{2}$$

$R_M = (2.9 \pm 1.6) \times 10^{-4}$
$x'' = (2.39 \pm 0.61 \pm 0.32)\%$
$y'' = (-0.14 \pm 0.60 \pm 0.40)\%$

Results exclude no mixing @ 99.2%

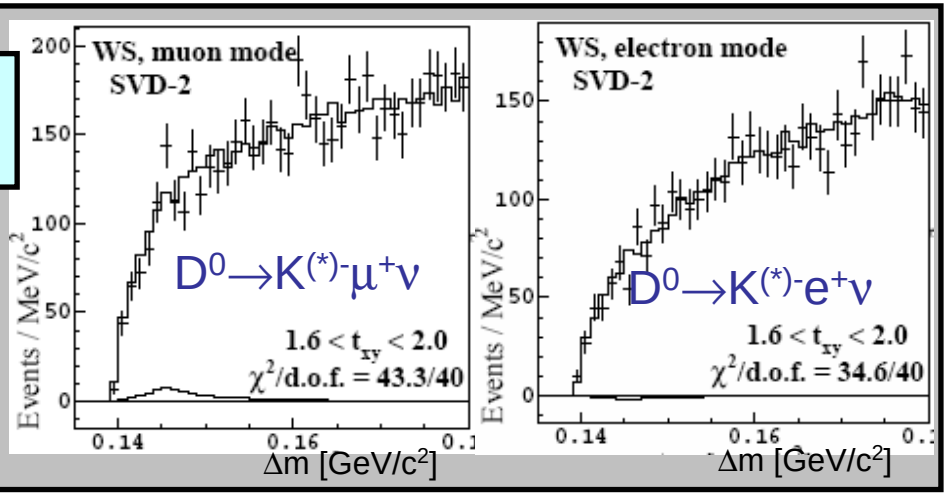
TD semileptonic decays. $D^0 \to K^{(*)-} e^+ \nu$

- Similar to WS TD hadron decays, but…
  - No DCS decay allowed
  - Any WS observation will be interpreted as mixing
- Missing ν makes selection and reconstruction hard
  - WS/mixing reconstruction implies a very challenging rejection of bkg events
- Exclusive reconstruction of the recoil D meson
  - Kinematical constraints and bkg suppression (fake WS soft pions). Double tag at production.
- D^0 flavor tagged at decay using the charge of the kaon and tagged also in production



Data sample 492fb^{-1}
arXiv:0802.2952

R_M <6.1x10^{-4}



- 3 sig evts
- 2.8 expected bkg evts
- Net WS signal yield 0.15 events

No mixing evidence

Lifetime ratio, $D^0 \to h^+h^-$ vs. $D^0 \to K^-\pi^+$

- D^0-$\bar{D}^0$ mixing and CPV alter decay time distributions of CP eigenstates. A good approximation are exponential distributions with effective lifetimes, $\tau^{\pm}_{hh}$

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

$$\phi_f = \arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right), \quad h = K,\pi$$

Measured quantities

$$\tau^{+}_{hh} = \tau\left(D^0 \to h^+h^-\right)$$
$$\tau^{-}_{hh} = \tau\left(\bar{D}^0 \to h^+h^-\right)$$
$$\tau_{K\pi} = \tau\left(D^0 \to K^-\pi^+\right)$$

- The mixing and CPV observables are:

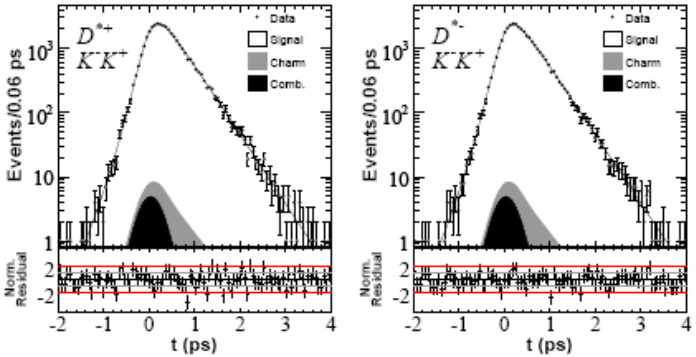
$$y_{CP} = y\cos\phi_f = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle} - 1$$
$$\Delta Y = x\sin\phi_f = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle}A_\tau$$

$\langle\tau_{hh}\rangle = \frac{\tau^{+}_{hh}+\tau^{-}_{hh}}{2}$, $A_\tau = \frac{\tau^{+}_{hh}-\tau^{-}_{hh}}{\tau^{+}_{hh}+\tau^{-}_{hh}}$

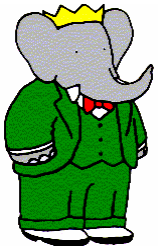
Lifetime average and asymmetry

- *$y_{CP}=y$ and $\Delta Y=0$ if CP conserved, $y_{CP}=0$ and $\Delta Y=0$ if no mixing*

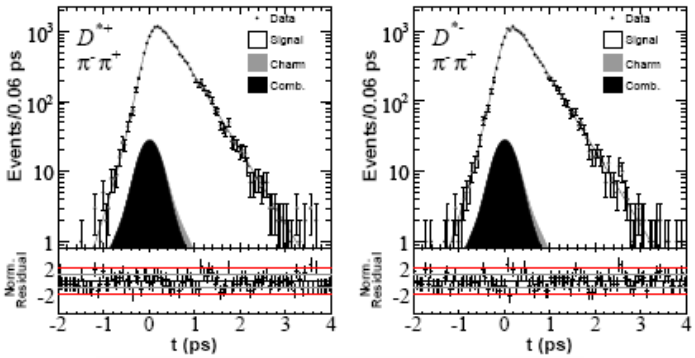
Lifetime ratio, $D^0 \to h^+h^-$ vs. $D^0 \to K^-\pi^+$



KK
70k evts
99.6% purity

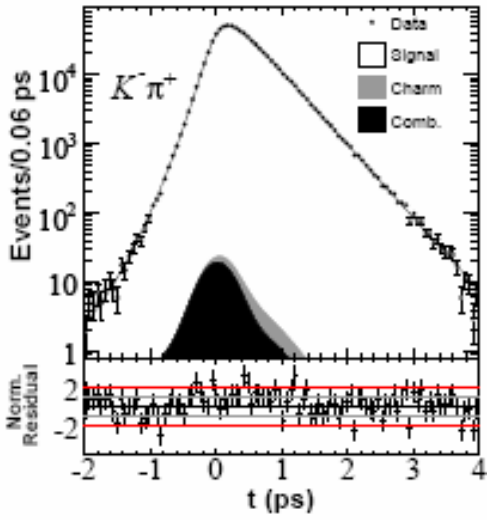


L = 384fb^{-1}
arXiv:0712.2249

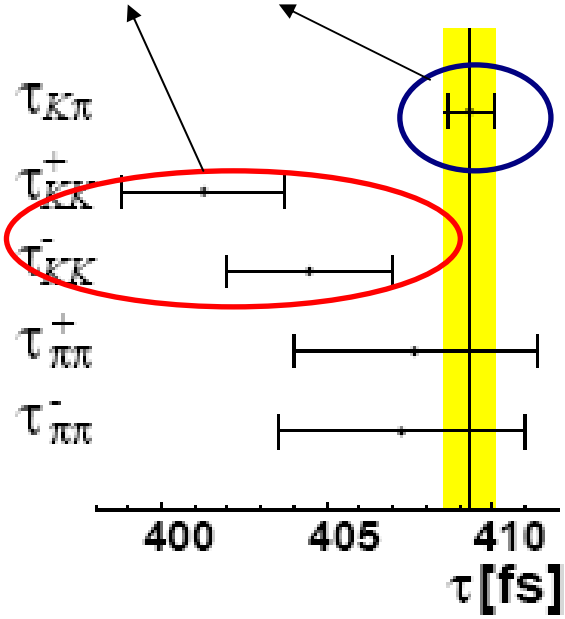


$\pi\pi$
30k evts
98.0% purity

$K\pi$ and KK lifetimes differ !!!
$y_{CP} \neq 0$



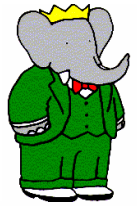
$K\pi$
730k evts
99.9% purity



Lifetime ratio, $D^0 \to h^+h^-$ vs. $D^0 \to K^-\pi^+$

- Most signal systematic error is cancelled in the ratio.
- Systematic error contribution mostly due to bkg

L = 384fb^{-1}
arXiv:0712.2249



Sample	y_{CP}	ΔY
K^-K^+	$(1.60 \pm 0.46 \pm 0.17)\%$	$(-0.40 \pm 0.44 \pm 0.12)\%$
$\pi^-\pi^+$	$(0.46 \pm 0.65 \pm 0.25)\%$	$(\ 0.05 \pm 0.64 \pm 0.32)\%$
Combined	$(1.24 \pm 0.39 \pm 0.13)\%$	$(-0.26 \pm 0.36 \pm 0.08)\%$

Evidence of mixing @ 3σ

L = 540fb^{-1}
PRL98:211803(2007)

BELLE

	y_{CP} (%)	A_Γ (%)
KK	1.25±0.39±0.28	0.15±0.34±0.16
$\pi\pi$	1.44±0.57±0.42	−0.28±0.52±0.30
$KK+\pi\pi$	1.31±0.32±0.25	0.01±0.30±0.15

Evidence of mixing @ 3.2σ

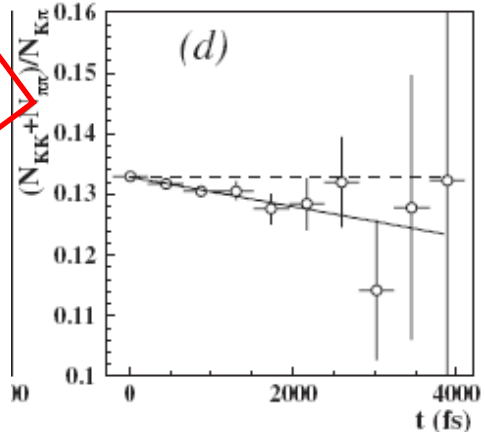
Ratio D^0_{CP}/D^0 varies in time due to lifetime difference

Combinning results with PRL91,162001(2001), an untagged statistically independent sample

$$y_{CP} = (1.03 \pm 0.33 \pm 0.19) \times 10^{-2}$$

arXiv:0712.2249
Submitted to PRD-RC

No CPV evidence



Time Integrated CPV Analyses

Time Integrated (TI) CPV searches.

$D^0 \to K^+K^-, \pi^+\pi^-$

- CP-even final states. Single-Cabibbo-suppressed (SCS) modes
- CPV in these modes is predicted to be ~10^{-4}-10^{-5} in SM. Evidence of CPV with current experimental sensitivity is sign of physics beyond SM

F. Bucella et al., Phys. Rev. **D51**, 3478 (1995)
S. Bianco et al., Riv. Nuovo Cim. 26N7, 1(2003)
Y. Grossman et al., Phys. Rev. **D75**, 036008 (2007)

- Measurement of the asymmetries of the partial decay widths.
- Asymmetry includes the 3 posible CP violation sources: mixing, decay and interference

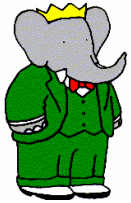
$$a_{CP}^{hh} = \frac{\Gamma\left(D^0 \to h^- h^+\right) - \Gamma\left(\bar{D}^0 \to h^+ h^-\right)}{\Gamma\left(D^0 \to h^- h^+\right) + \Gamma\left(\bar{D}^0 \to h^+ h^-\right)}$$

- Precise D^0 flavor tag is the main experimental concern.
  - $D^0 \to K^-\pi^+$ is used for this purpose
- Forward-Backward asymmetry in $c\bar{c}$ production ~few%.

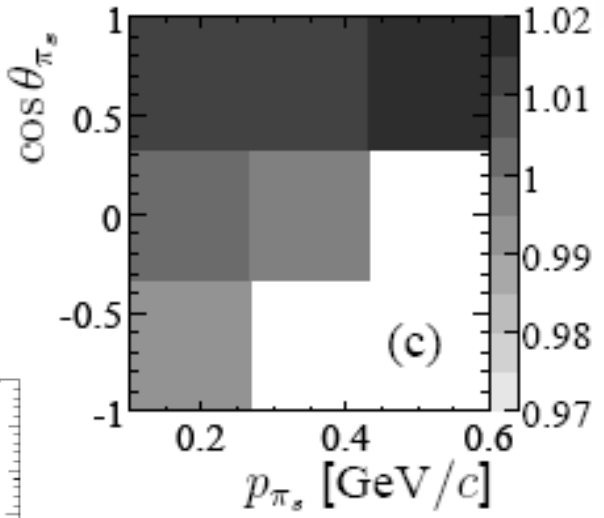
TI CPV searches. $D^0 \to K^+K^-, \pi^+\pi^-$

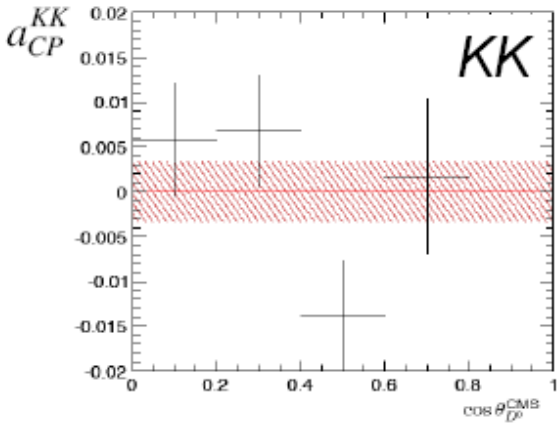
- Determine relative $D^0/\bar{D}^0$ soft pion tagging efficiency using $D^0 \to K^-\pi^+$ sample.
  - Reduces systematic uncertainties

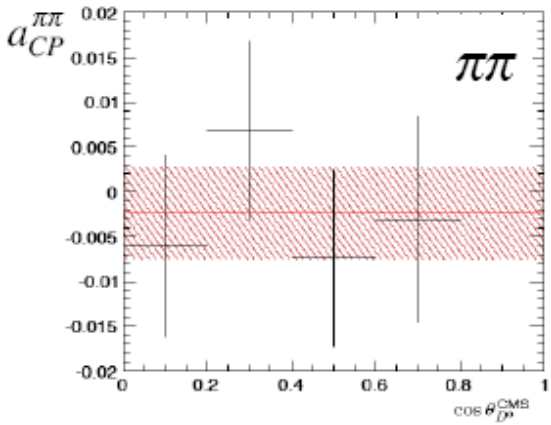
Data sample 385fb^{-1}
arXiv:0709.2715



Category	Δa_{CP}^{KK}	$\Delta a_{CP}^{\pi\pi}$
2-Dim. PDF shapes	$\pm 0.04\%$	$\pm 0.05\%$
π_s correction	$\pm 0.08\%$	$\pm 0.08\%$
a_{CP} extraction	$\pm 0.09\%$	$\pm 0.20\%$
Quadrature sum	$\pm 0.13\%$	$\pm 0.22\%$





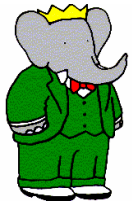


$$a_{CP}^{KK} = (\ 0.00 \pm 0.34\ (\text{stat.}) \pm 0.13\ (\text{syst.}))\%$$
$$a_{CP}^{\pi\pi} = (-0.24 \pm 0.52\ (\text{stat.}) \pm 0.22\ (\text{syst.}))\%$$

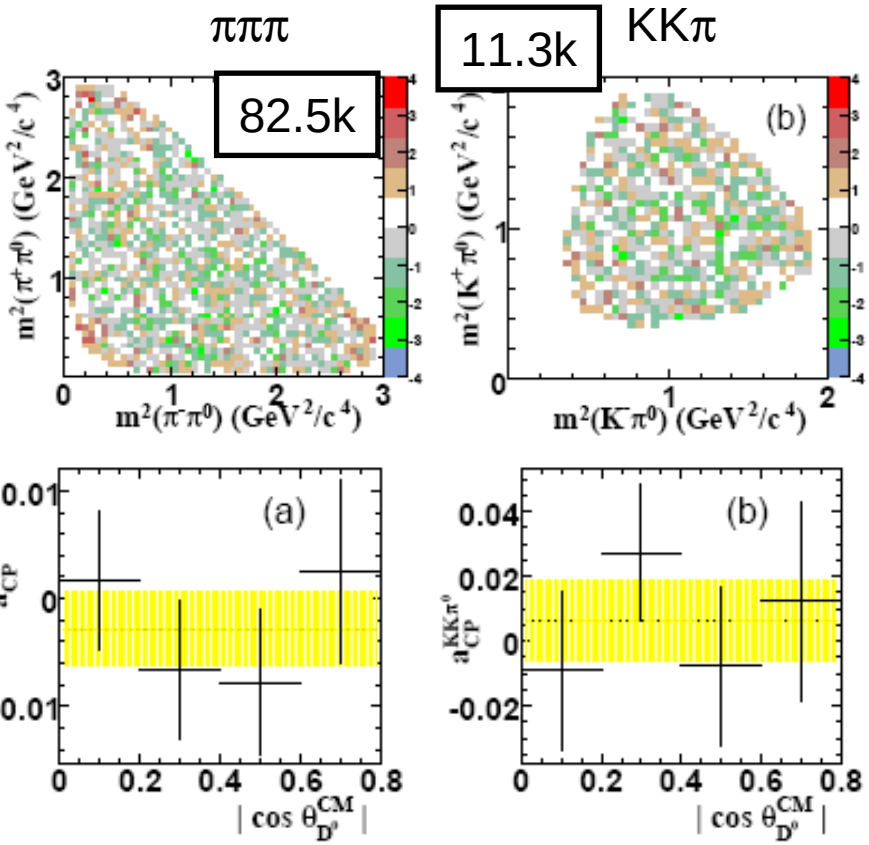
No CPV evidence

TI CPV searches. $D^0 \to K^+K^-\pi^0, \pi^+\pi^-\pi^0$

- Difference between D^0 and $\bar{D}^0$ Dalitz plot in 2D
- Difference in the angular moments of D^0 and $\bar{D}^0$
- Difference in Dalitz plot fit. Amplitudes and phases
- Difference in phase space integrated asymmetry



Data sample 385fb^{-1}
arXiv:0802.4035



$$\Delta = \frac{n_{\bar{D}^0} - R n_{D^0}}{\sqrt{\sigma^2_{n\bar{D}^0} + R^2 \sigma^2_{nD^0}}}$$

Phase space integrated asymmetry a_{CP}

$$a_{CP}^{\pi^+\pi^-\pi^0} = (-0.31 \pm 0.41 \pm 0.17)\,\%$$
$$a_{CP}^{K^+K^-\pi^0} = (1.00 \pm 1.67 \pm 0.25)\,\%$$

BELLE

Data sample 532fb^{-1}
arXiv:0801.2439

$$A_{CP}(D^0 \to \pi^+\pi^-\pi^0) = (0.43 \pm 1.30)\%$$
$$\frac{\mathcal{B}(D^0 \to \pi^+\pi^-\pi^0)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^0)} = 0.1012 \pm 0.0004 \pm 0.0018$$

Summary

- Mixing and CPV results in BaBar are compatible with results found in other experiments
- No single mixing measurement exceeds 5σ
- Combined significance of oscillating effects exceeds 5σ, charm oscillations are established
- Not clear yet if oscillation is due to $x \neq 0$ or $y \neq 0$.
- No CPV evidence in decay, mixing and interference