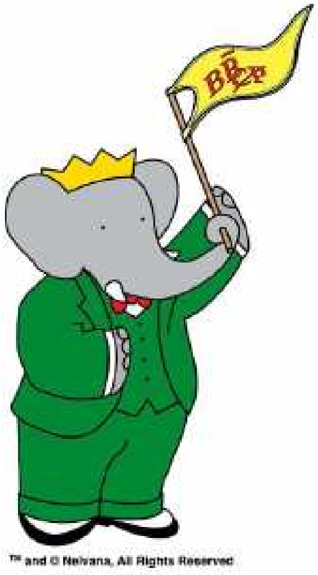
Charm Physics at BaBar and Belle



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Florence, Italy
19th - 23rd April 2010

Outline

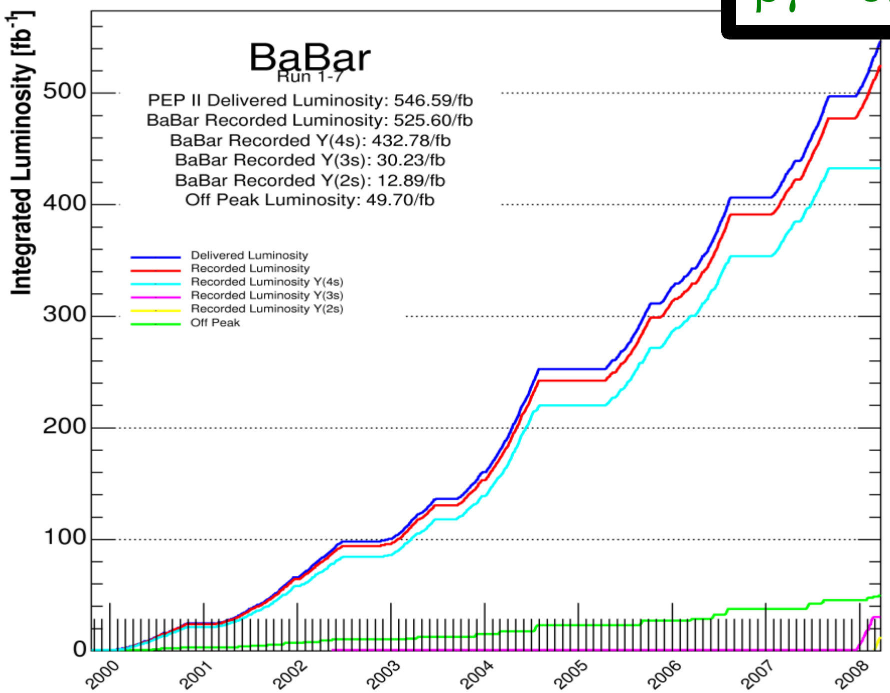
- Asymmetric B-factories
- Extraction of the decay constant f_{Ds}
- Charm mixing and CPV: SM predictions and NP
- D^0 Mixing searches
- CPV searches
- Conclusions

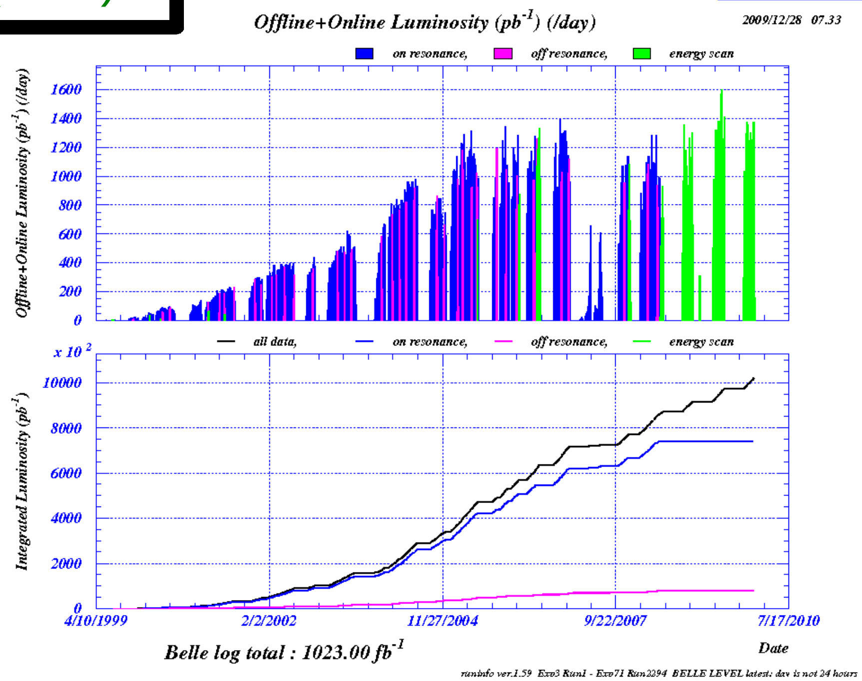
Asymmetric B-factories

BaBar detector

$\Upsilon(4S)$ 10.58 GeV
$\beta\gamma = 0.55$ (PEP-II)
$\beta\gamma = 0.425$ (KEK)

Belle detector



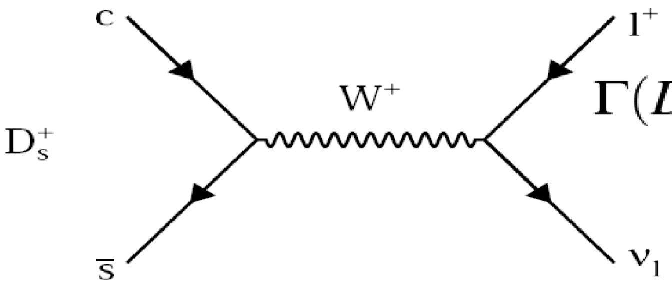


1999 - 2008
~ 530 fb^{-1}
> 600M $c\bar{c}$ events

1999 - 2009
~ 1.02 ab^{-1}
> 925M $c\bar{c}$ events

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

Extraction of the decay constant f_{D_s}



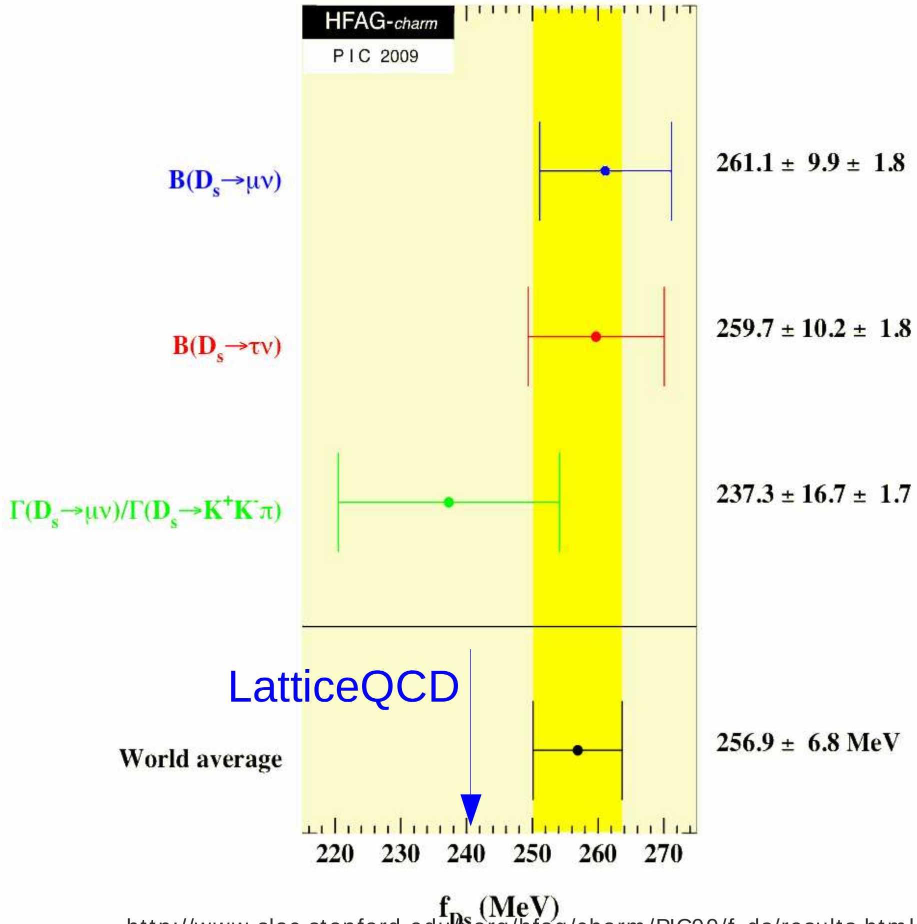
$$\Gamma(D_s^+ \to l^+ \nu_l) = \frac{G_F^2}{8\pi} M_{D_s^+}^3 \left(\frac{m_l}{M_{D_s^+}}\right)^2 \left(1 - \frac{m_l^2}{M_{D_s^+}^2}\right)^2 |V_{cs}|^2 f_{D_s^+}^2$$

Helicity suppression — Phase-space

- The decay constant contains the information on the probability for the quarks to have no separation (overlap of the wave functions for the light and heavy quarks)
- To be compared with Lattice QCD expectations. Currently 2.1σ discrepancy

  f_{Ds} = 241 ± 3 MeV. Follana et.al. PRL100,062002(2008)

  - Any difference can be a hint for NP, i.e. Charged Higgs, leptoquarks, SUSY, W', ...



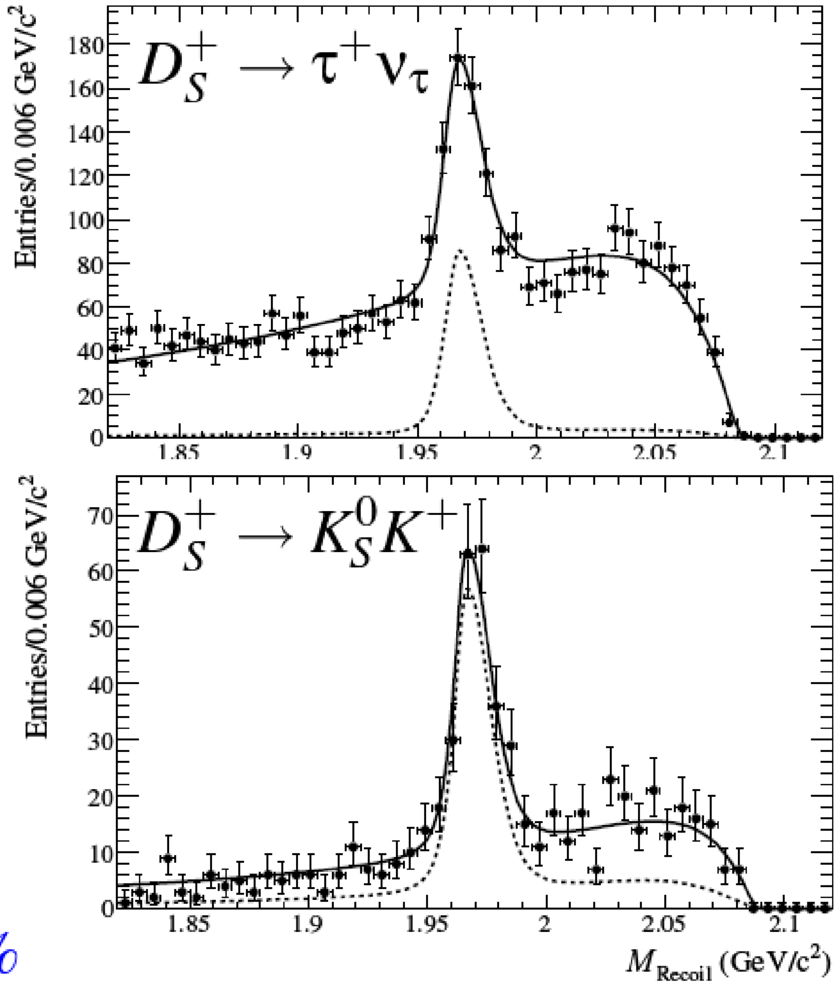
http://www.slac.stanford.edu/xorg/hfag/charm/PIC09/f_ds/results.html

NEW f_{D_s} from $D_S^+ \to \tau^+ \nu_\tau, \quad \tau^+ \to e^+ \nu_e \bar{\nu}_\tau$

L = 427fb[-1]
arXiv:1003.306v2

$$e^+ e^- \to c\bar{c} \to D_s^{*+} \bar{D}_{\mathrm{TAG}} \bar{K} X$$
$$D_s^{*+} \to D_s^+ \gamma$$
$$D_s^+ \to l^+ \nu_l$$

- $\bar{D}_{\mathrm{TAG}}$ reconstruction in several hadronic modes, to suppress large background from non-charm continuum
- $\bar{K}$ is a single meson required to assure final state strangeness balance
- Branching fraction extracted from the yields ratio with the normalization decay $D_s^+ \to K_S^0 K^+$



$$\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (4.5 \pm 0.5 \pm 0.4 \pm 0.3)\,\%$$

$$f_{D_s} = (233 \pm 13 \pm 10 \pm 7)\,\mathrm{MeV}$$

Uncertainties from theoretical inputs

Charm mixing and CPV

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

Physical states are a linear combination of flavor eigenstates. Mixing can occur because flavor and mass eigenstates differ.

Mixing parameters

$$x = \frac{m_1 - m_2}{\Gamma}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

The decay amplitudes at *t=0* are

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

CPV in decay

$$\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$$

CPV in mixing

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

CPV in interference

$$\phi_f = \arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq 0, \pi$$

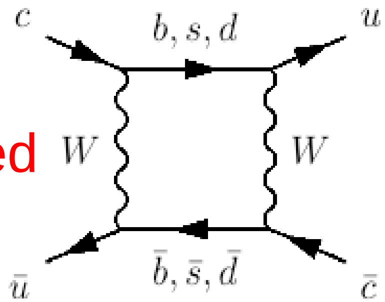
Predicted to be small in SM. NP?

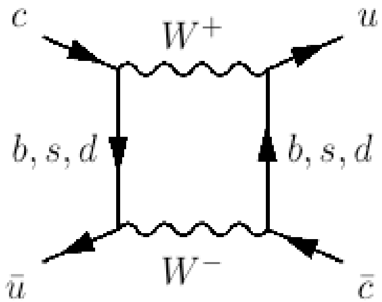
Squared time-dependent amplitude, allowing for mixing and CPV

$$|A_f(t)|^2 = \frac{1}{2}e^{-\Gamma t}\left\{\left(|A_f|^2 + \left|\frac{q}{p}\right|^2 |\bar{A}_f|^2\right)\cosh(-\Gamma y t) + 2\mathcal{R}e\left(A_f^*\bar{A}_f\frac{q}{p}\right)\sinh(-\Gamma y t)\right.$$
$$\left. + \left(|A_f^2| - \left|\frac{q}{p}\right|^2 |\bar{A}_f|^2\right)\cos(\Gamma x t) + 2\mathcal{I}m\left(A_f^*\bar{A}_f\frac{q}{p}\right)\sin(\Gamma x t)\right\}$$

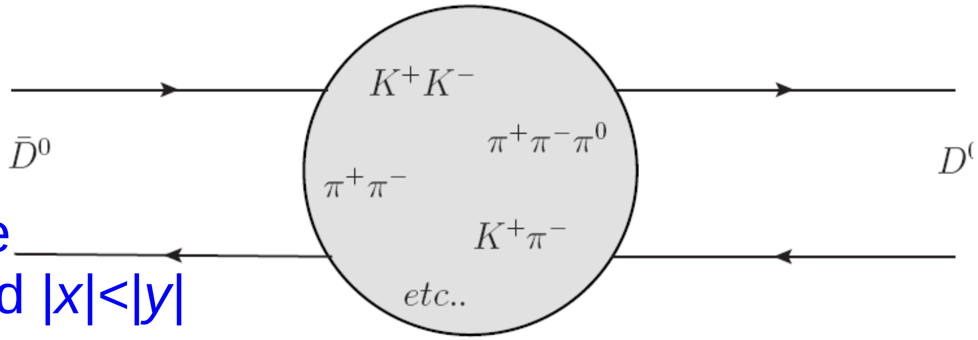
SM predictions and NP

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





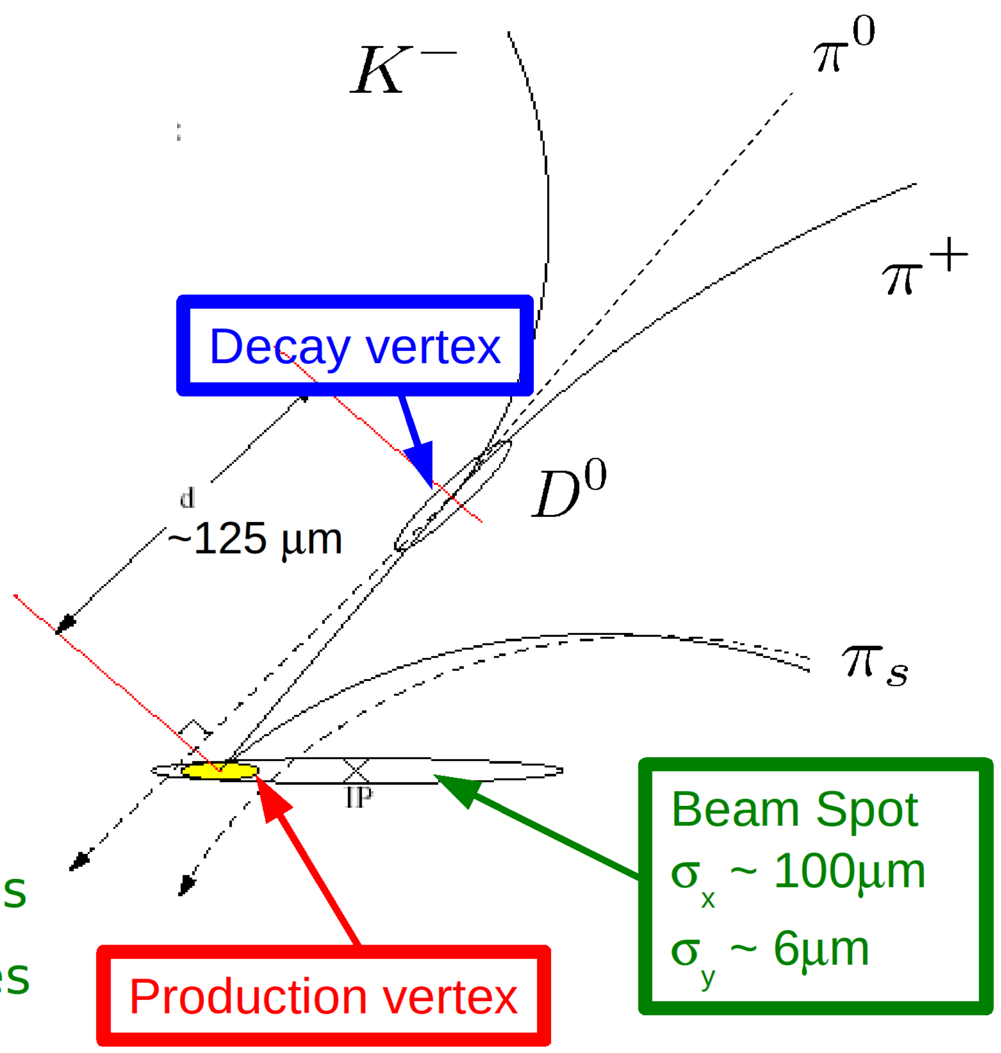
- Long-distance contributions
  - Via hadronic intermediate states
  - Expected to dominate
  - Non-perturbative and hard to calculate
  - Predictions for *x,y* range (10^{-4}-10^{-2}) and |*x*|<|*y*|
  - Still a small effect



- New Physics
  - NP through new particles in the loops
  - If |x|>>|y| this colud be a hint of NP
  - 2HDM, Heavy Down Quark, Tree level FCNC,SUSY, ...

D^0 production and selection

- D^0 production
  - $e^+e^- \to D^{*+}X$
    $D^{*+} \to D^0\pi_s^+$
  - Charge of π_s determines the D^0 flavor
  - $p^*_{D^0} > 2.5\mathrm{GeV}$ rejects $B\bar{B}$ bkg
- D^0 decay
  - Cabibbo favored (CF), e.g. $K^-\pi^+\pi^0$ and Doubly Cabibbo suppressed (DCS), e.g. $K^+\pi^-\pi^0$ decay products
- Beam spot constraint determines proper time and σ_t, and improves resolution in m_D and Δm



Charm mixing and CPV searches

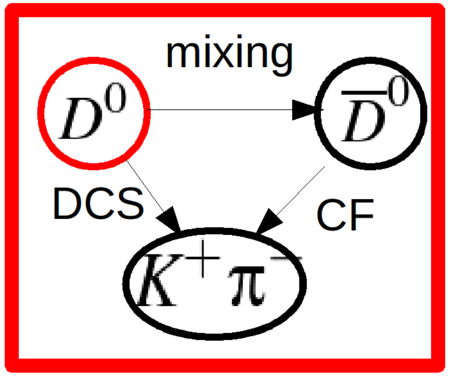
Mixing

$D^0 \to K^+\pi^-$	WS decay	PRL**98**:211802,2007. L = 384 fb^{-1} PRL**96**:151801,2006. L = 400 fb^{-1} PRL**100**:121802,2008. L = 1.5 fb^{-1}
$D^0 \to K^+\pi^-\pi^0$	WS decay	PRL**103**:211801,2009. L = 384 fb^{-1}
$D^0 \to K^+K^-, \pi^+\pi^-$	Lifetime ratio tagged	PRD**78**,011105(R),2008. L = 384fb^{-1} PRL**98**,211803,2007. L = 540 fb^{-1}
$D^0 \to K^+K^-, \pi^+\pi^-$	Lifetime ratio untagged	PRD**80**,071103(R),2009. L = 384 fb^{-1} RECENT
$D^0 \to K^{(*)-} l^+ \nu$	Semileptonic	PRD**77**:112003,2008. L = 492 fb^{-1} PRD**76**:014018,2007. L = 344 fb^{-1}
$D^0 \to K^0_S K^+ K^-$	Lifetime ratio	PRD**80**:052006,2009. L = 673 fb^{-1}
$D^0 \to K^0_S \pi^+\pi^-$	Dalitz-Plot analysis	PRL**98**:211803,2007. L = 540 fb^{-1}
$D^0 \to K^0_S h^+ h^-$	Dalitz-Plot analysis	Preliminary. L = 468 fb^{-1} NEW

CPV

$D^0 \to K^+K^-, \pi^+\pi^-$	Time Integrated	PRL**100**:061803,2008. L = 385fb^{-1} PLB**670**:190-195,2008. L = 540 fb^{-1}
$D^0 \to \pi^0 h^+ h^-$	Time Integrated	PRD**78**:051102,2008. L = 385 fb^{-1}
$D^0 \to \pi^+\pi^-\pi^0$	Time Integrated	PLB**662**:102-110,2008. L = 532 fb^{-1}
$D^0 \to K^+K^-\pi^+\pi^-$	T-odd correlations	arXiv:1003.3397. L = 470fb^{-1} NEW

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

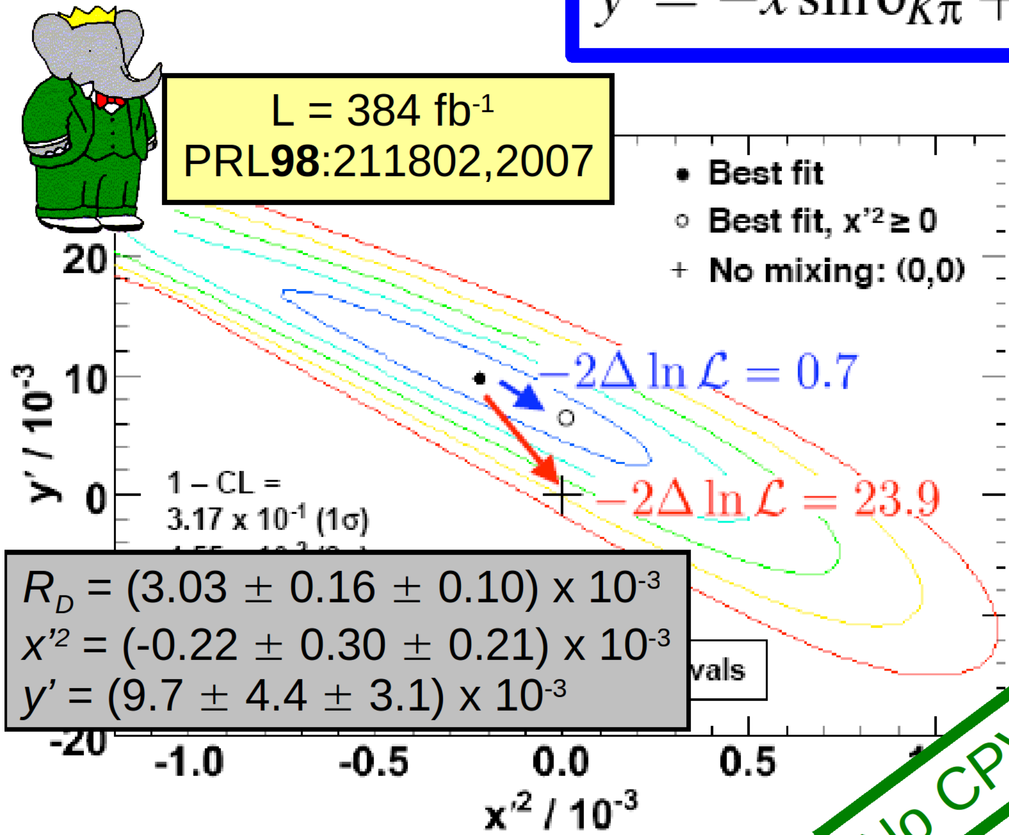


$$\Gamma_{WS}(t) = e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y'\sqrt{R_D}(\Gamma t)}_{\text{Interference}} + \underbrace{\frac{x'^2+y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

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

$$R_D = \left|\frac{A(D^0 \to K^+\pi^-)}{A(\overline{D}^0 \to K^+\pi^-)}\right|^2$$

L = 384 fb^{-1}
PRL**98**:211802,2007

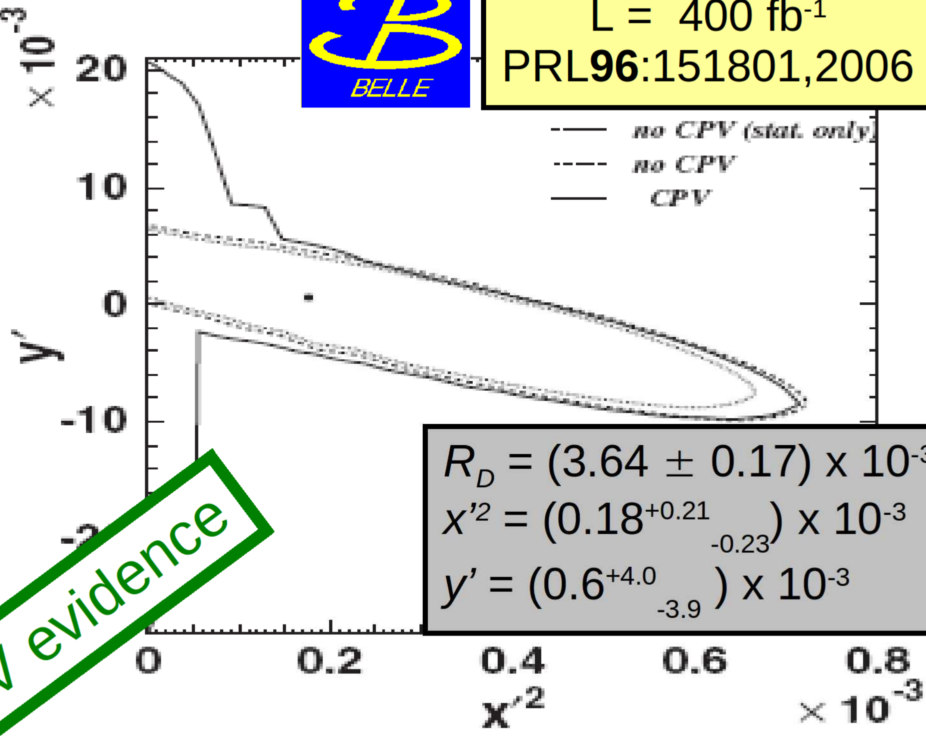


$R_D = (3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$
$x'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
$y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

Mixing @ 3.9σ

No CPV evidence

L = 400 fb^{-1}
PRL**96**:151801,2006



$R_D = (3.64 \pm 0.17) \times 10^{-3}$
$x'^2 = (0.18^{+0.21}_{-0.23}) \times 10^{-3}$
$y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$

Mixing @ 2σ

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

- Mixing and CPV alter decay time distributions of CP eigenstates.
- ~ exponential distributions with effective lifetimes $\tau^{\pm}_{hh}$

Mixing and CP observables

$$y_{CP} = y\cos\phi_f = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle} - 1$$

$$\Delta Y = -A_\Gamma = x\sin\phi_f = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle}A_\tau$$

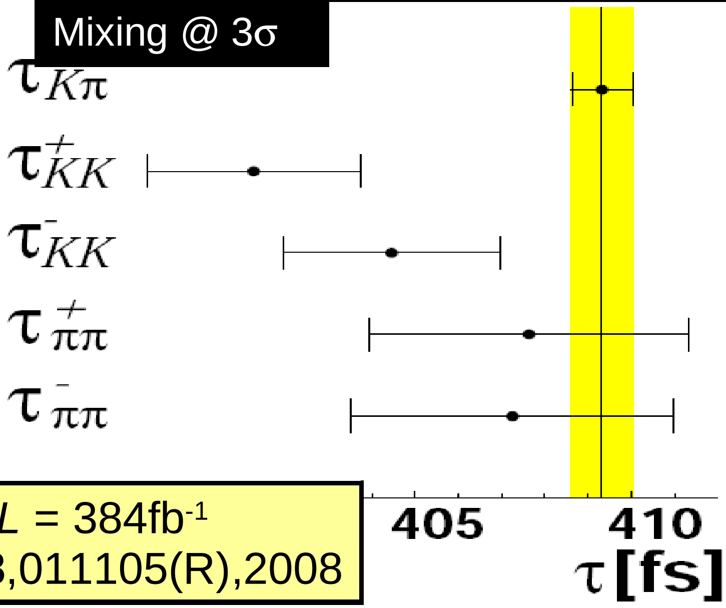
$$\langle\tau_{hh}\rangle = \frac{\tau^+_{hh} + \tau^-_{hh}}{2}$$

$$A_\tau = \frac{\tau^+_{hh} - \tau^-_{hh}}{\tau^+_{hh} + \tau^-_{hh}}$$

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

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

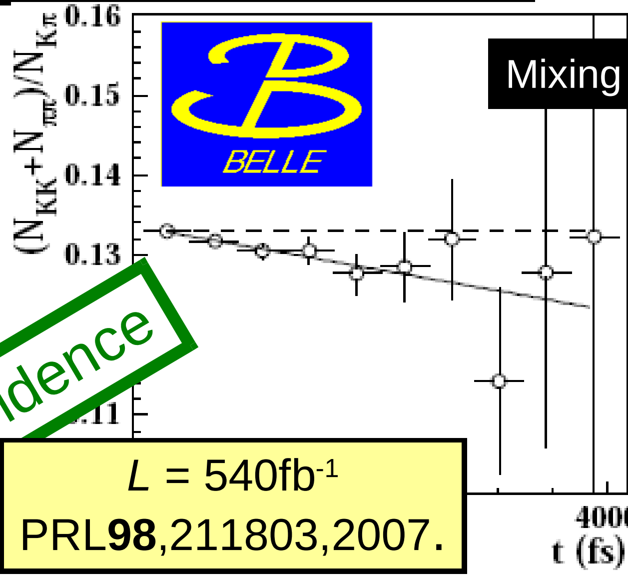
Mixing @ 3σ



L = 384fb^{-1}
PRD**78**,011105(R),2008

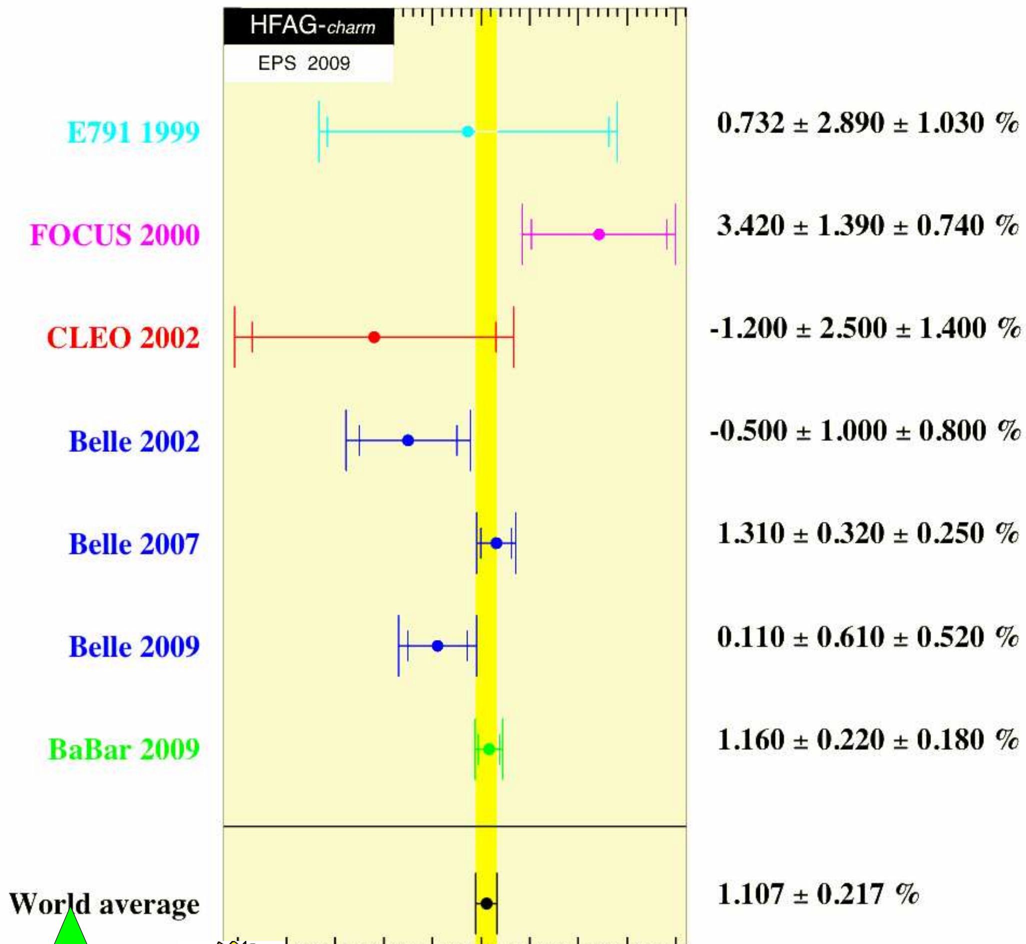
No CPV evidence

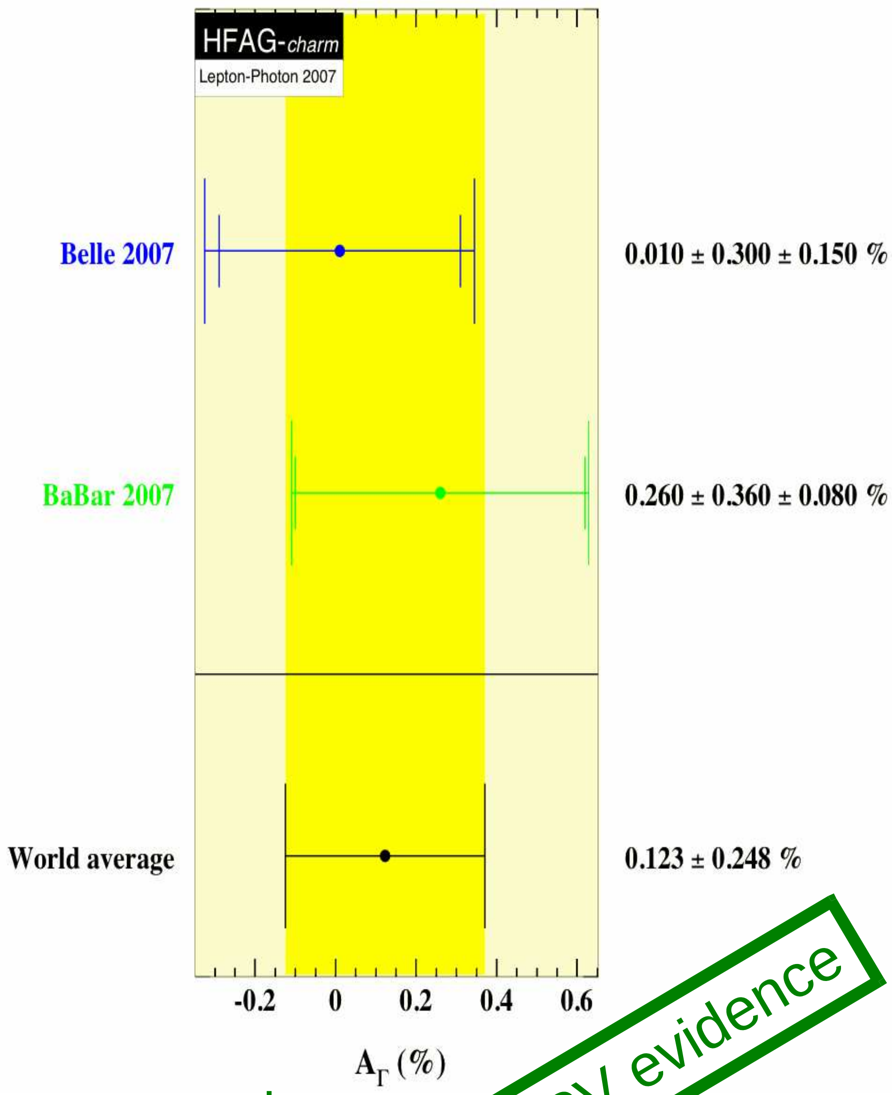
Mixing @ 3.2σ

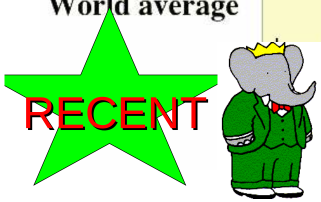


L = 540fb^{-1}
PRL**98**,211803,2007.

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







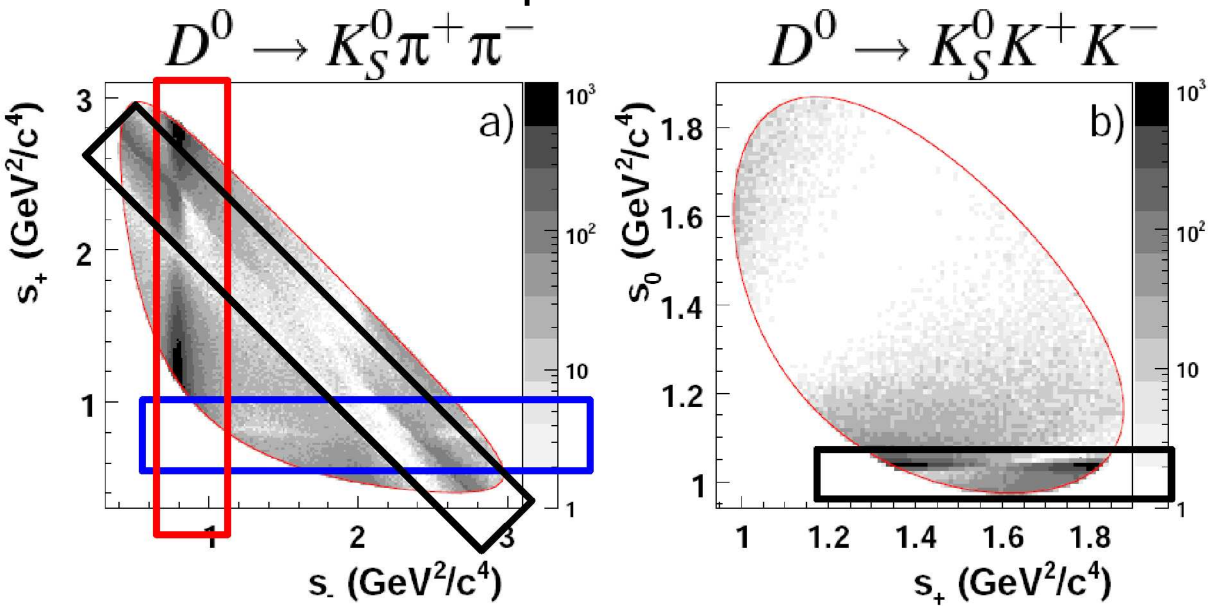
L = 384fb^{-1}
PRD**80**,071103(R),2009.

Combined tagged + untagged, mixing significance of 4.1σ

No CPV evidence

Dalitz-Plot analysis of $D^0 \to K_S h^+ h^-$ (h=K,π)

- Sensitivity to mixing arises from variation of the Dalitz Plot distribution with the proper time.
- Gives acces to *x* and *y* directly without ambiguities
  - Sensitivity comes from the interference between CF and DCS, and CP eigenstates
  - D^0 and $\overline{D}^0$ decays fall into the same Dalitz plot (assuming CP conserved in the decay) $\overline{A}(m^2_{K^0_S h^+}, m^2_{K^0_S h^-}) = A(m^2_{K^0_S h^+}, m^2_{K^0_S h^+})$
- D^0 decay amplitudes depend on the Dalitz Plot position
- A detailed study of the Dalitz model is needed
- Extraction of the mixing parameters along with proper time parameters and the D^0 Dalitz-Plot amplitude



Cabibbo Favored

Doubly Cabibbo Suppressed

CP eigenstates

Dalitz-Plot analysis of $D^0 \to K_S h^+ h^-$ ($h=K,\pi$)

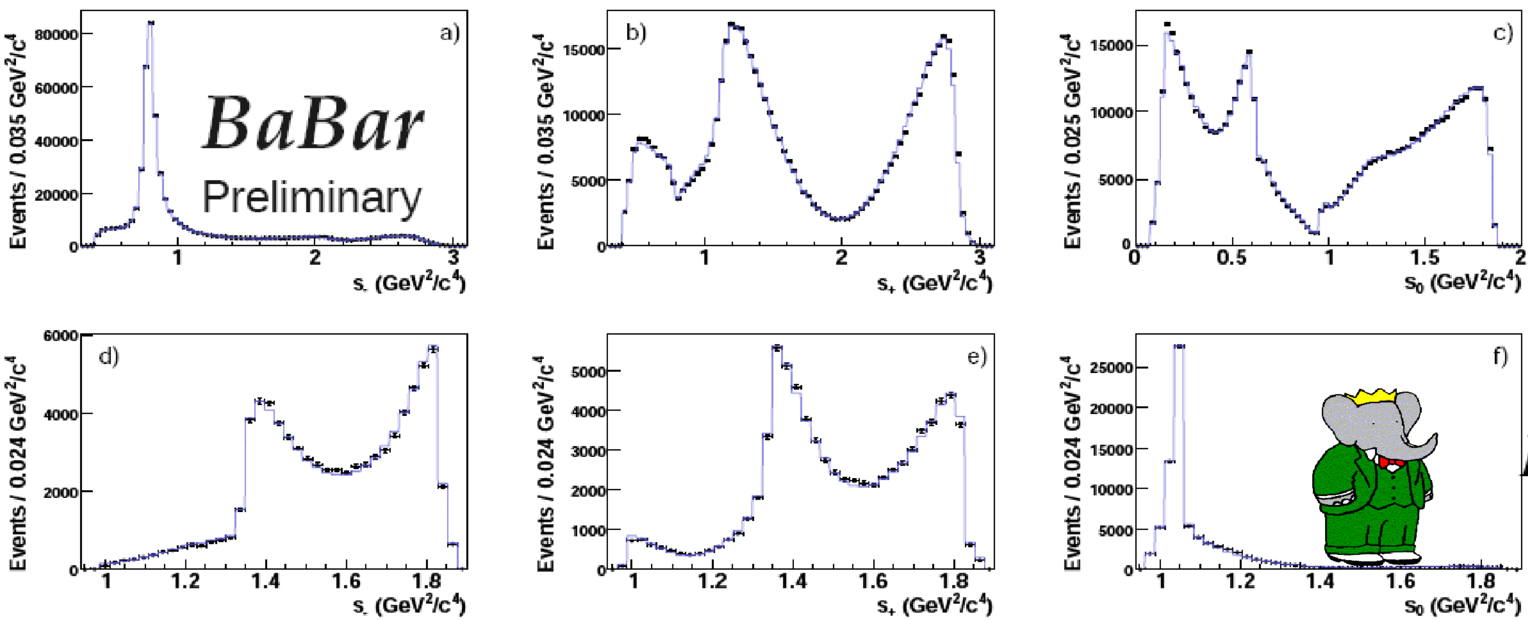
L = 540fb^{-1}
PRL98:211803(2007)

- $K_s\pi^+\pi^-$ only
- All resonances parametrized using BW-like distributions plus a NR term.
- Mixing fit in the CP conserving case and allowing for CPV

NEW

L = 468fb^{-1}
Preliminary

- Combined $K_S\pi^+\pi^-$ and $K_SK^+K^-$
- K-matrix formalism implemented to describe ππ and Kπ S-waves PRD**78**:034023(2008).
- Assumes CP conservation (CPV test against mixing has been done w/o CPV evidence)



$D^0 \to K_S^0\pi^+\pi^-$

$D^0 \to K_S^0K^+K^-$

Dalitz-Plot analysis of $D^0 \to K_S h^+ h^-$ ($h=K,\pi$)

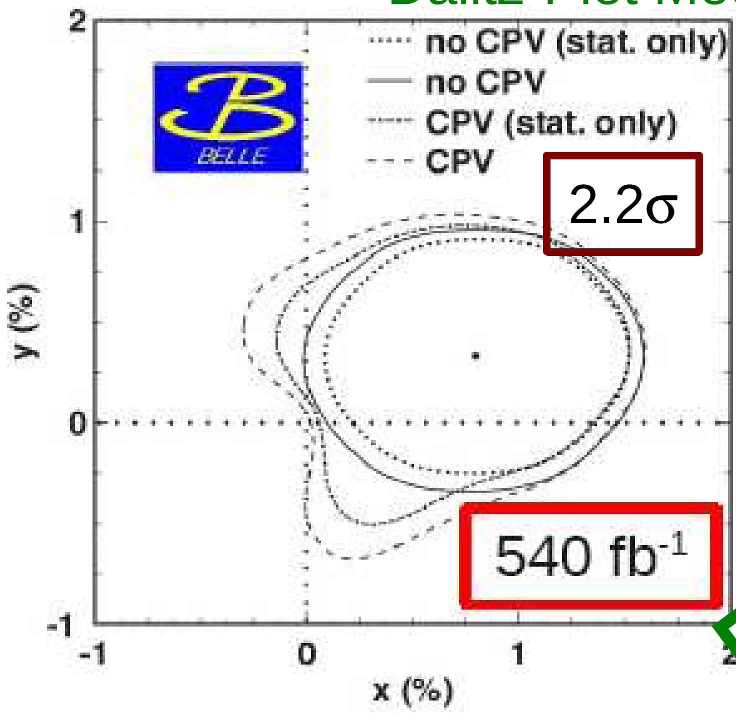
$$x = (0.80 \pm 0.29^{+0.09+0.10}_{-0.07-0.14}) \cdot 10^{-2}$$

$$y = (0.33 \pm 0.24^{+0.08+0.06}_{-0.12-0.08}) \cdot 10^{-2}$$

$$|q/p| = 0.86^{+0.30+0.06}_{-0.29-0.03} \pm 0.08$$

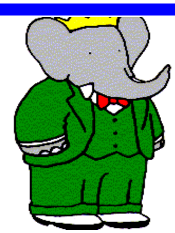
$$\phi_f = -14^{+16+6+2}_{-18-3-4}\,{}^\circ$$

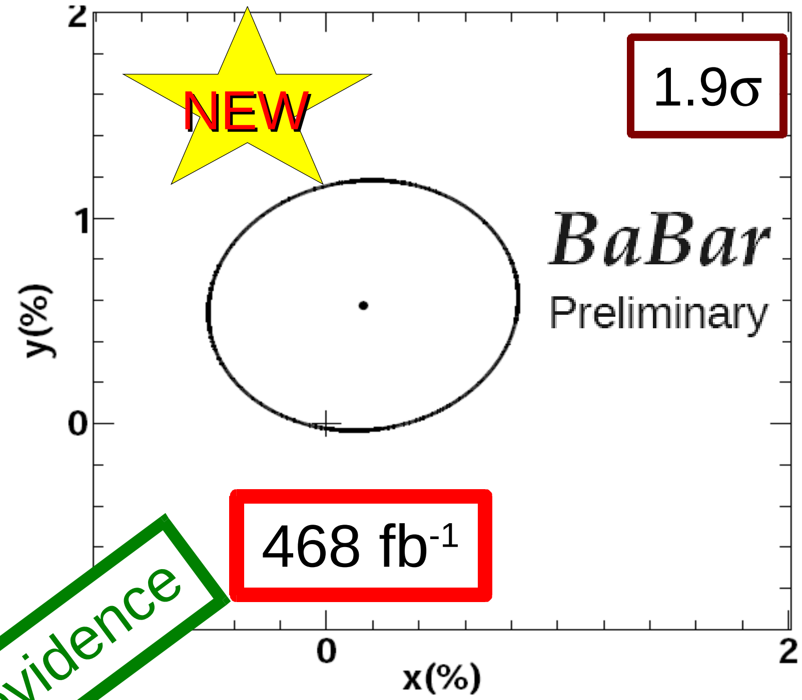
Dalitz-Plot Model



x = (0.16 ± 0.23 (stat) ± 0.12 (exp) ± 0.08 (mod)) 10^{-2} *BaBar*
y = (0.57 ± 0.20 (stat) ± 0.13 (exp) ± 0.07 (mod)) 10^{-2} Preliminary

Signal yield (purity > 98%)
$K_S\pi^+\pi^-$ 540789 evts
$K_SK^+K^-$ 79908 evts

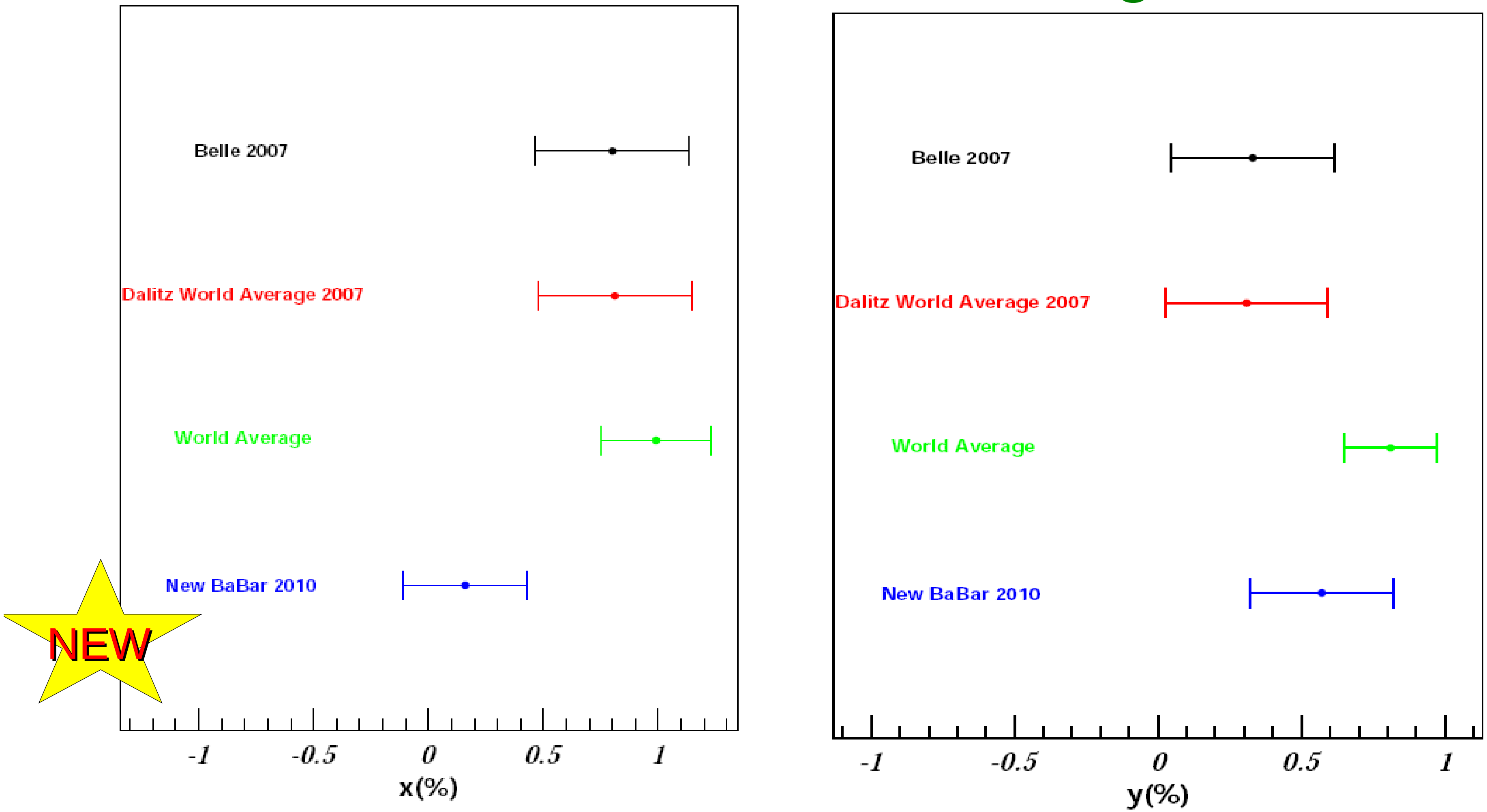




No CPV evidence

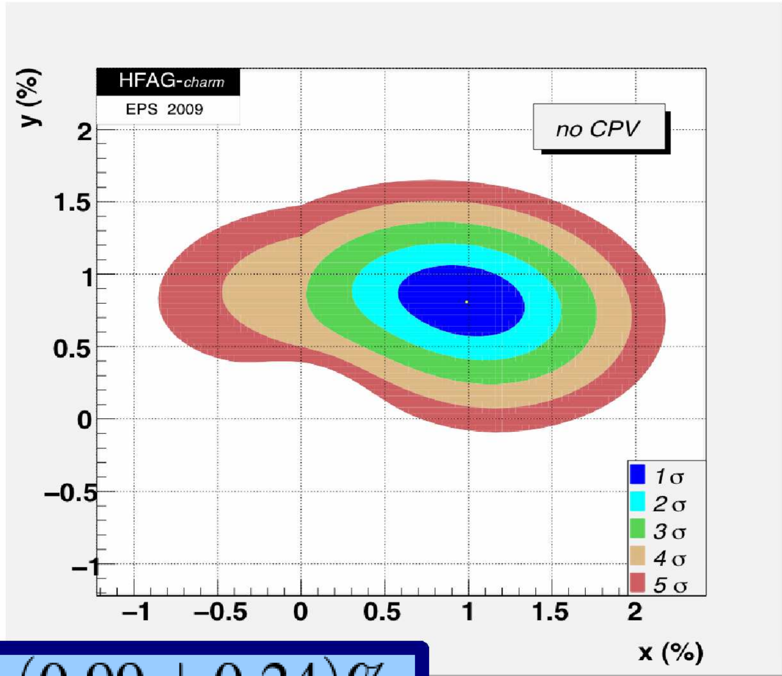
Most precise single direct measurement of *x* and *y*

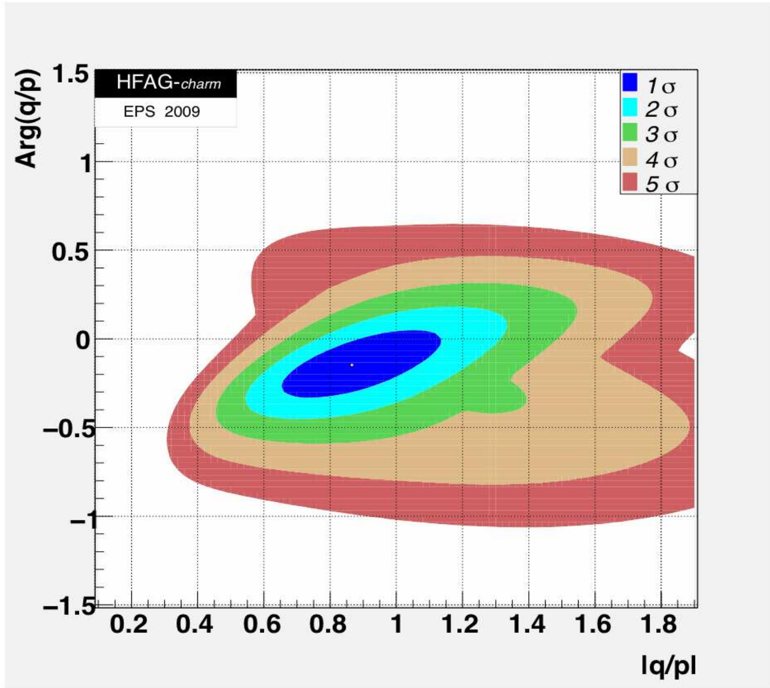
Dalitz-Plot analysis of $D^0 \to K_S h^+ h^-$ (h=K,π)



- Preliminary BaBar result favors lower value for *x* than for *y* and the central values move toward SM range

HFAG global average





$$x = (0.99 \pm 0.24)\%$$
$$y = (0.81 \pm 0.16)\%$$

- Preliminary BaBar Dalitz-Plot result not included yet
- All available mixing and CPV results are compatible
- No single mixing measurement exceeds 5σ. A quest for future experiments like LHCb and the Super B-factories
- Combined HFAG mixing significance 10.2σ.
- No CPV evidence (time-dependent analysis) in decay, mixing or interference

Time-Integrated CPV $D^0 \to K^+K^-(\pi^0)$, $\pi^+\pi^-(\pi^0)$

- CP-even final states. Single-Cabibbo-suppressed (SCS) modes.
- CPV in these modes is predicted to be ~10^{-4}-10^{-5} in SM.
- Measurement of the asymmetries of the partial decay widths.
- Asymmetry includes the 3 possible CP violation sources: mixing, decay and interference

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

Data sample 385fb^{-1}
PRL**100**:061803(2008)

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

Data sample 385fb^{-1}
PRD**78**:051102(2008)

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

Data sample 532 fb^{-1}
PLB**662**:102-110,2008

$$a_{CP}^{\pi\pi\pi^0} = (+0.43 \pm 1.30)\%$$

Data sample 540 fb^{-1}
PLB**670**:190-195,2008

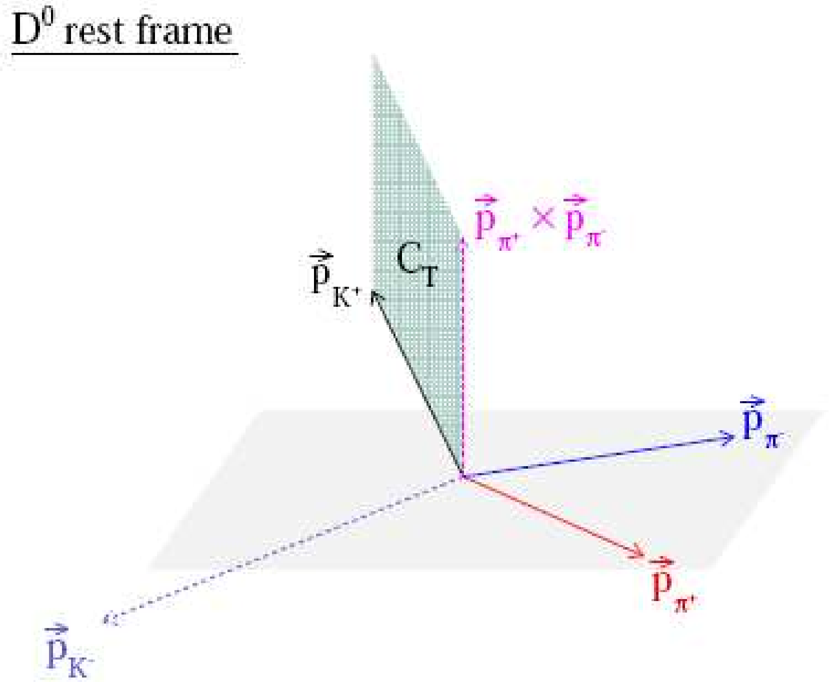
$$a_{CP}^{KK} = (-0.43 \pm 0.30 \pm 0.11)\%$$
$$a_{CP}^{\pi\pi} = (+0.43 \pm 0.52 \pm 0.12)\%$$

No CPV evidence at the level of 10^{-2}

I.Bigi, hep-ph/0107102

CPV using T-odd correlations in $D^0 \to K^+K^-\pi^+\pi^-$

Assuming CPT theorem, T-violation is a signal of CPV



T-odd triple product

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$

$$A_T \equiv \frac{\Gamma(D^0, C_T>0) - \Gamma(D^0, C_T<0)}{\Gamma(D^0, C_T>0) + \Gamma(D^0, C_T<0)};$$

$$\bar{A}_T \equiv \frac{\Gamma(\bar{D}^0, -\bar{C}_T>0) - \Gamma(\bar{D}^0, -\bar{C}_T<0)}{\Gamma(\bar{D}^0, -\bar{C}_T>0) + \Gamma(\bar{D}^0, -\bar{C}_T<0)}.$$

T-violation if

$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A}_T) \neq 0$$

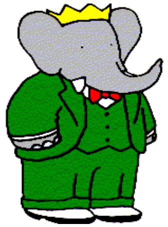
FOCUS E831

882 $D^0 \to K^+K^-\pi^+\pi^-$ events
PLB**622**:239(2005)

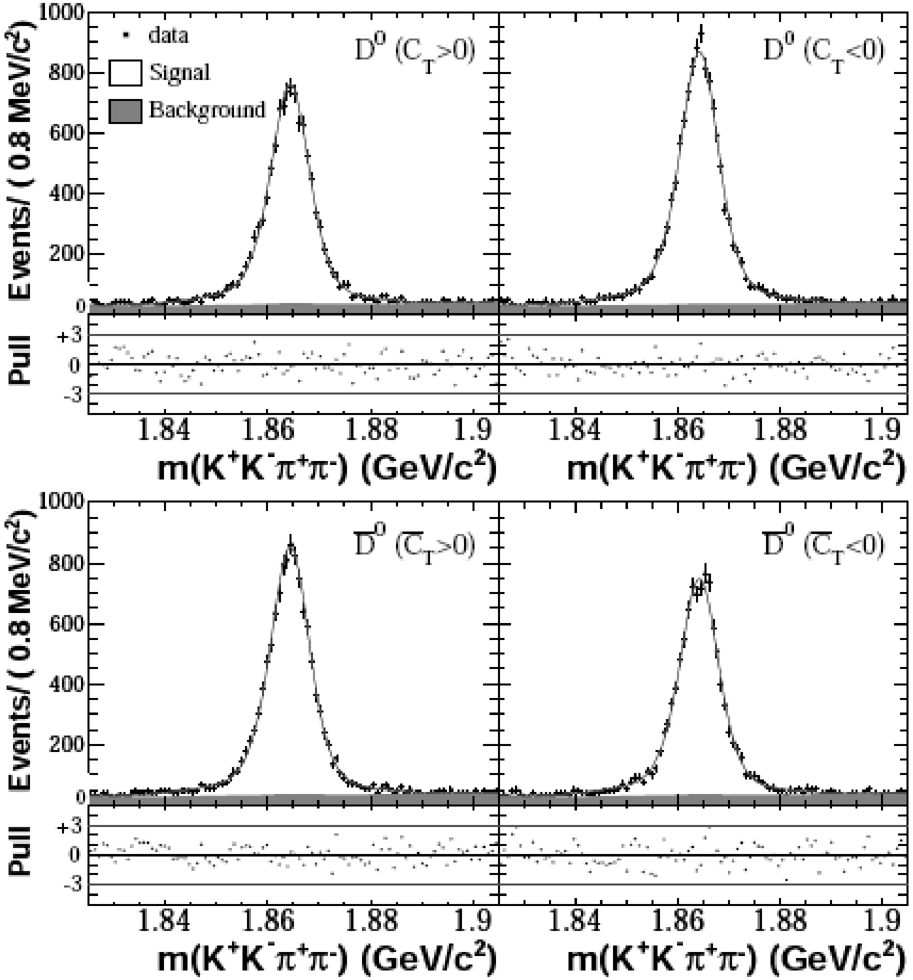
$$\mathcal{A}_T = 0.010 \pm 0.057(stat) \pm 0.037(syst)$$

CPV using T-odd correlations in $D^0 \to K^+K^-\pi^+\pi^-$

NEW



Data sample 470 fb^{-1}
arXiv:1003.3397



Subsample	Events
(a) D^0, $C_T > 0$	10974 ± 117
(b) D^0, $C_T < 0$	12587 ± 125
(c) $\overline{D}^0$, $\overline{C}_T > 0$	10749 ± 116
(d) $\overline{D}^0$, $\overline{C}_T < 0$	12380 ± 124

$$A_T = (-68.5 \pm 7.3_{\rm stat} \pm 4.5_{\rm syst}) \times 10^{-3},$$

$$\overline{A}_T = (-70.5 \pm 7.3_{\rm stat} \pm 3.9_{\rm syst}) \times 10^{-3}.$$

$$\mathcal{A}_T = (1.0 \pm 5.1_{\rm stat} \pm 4.4_{\rm syst}) \times 10^{-3}$$

Particle ID, the largest systematic effect

Improves the precision in one order of magnitude compared with previous FOCUS result

No T-violation evidence

Conclusions

- New measurements from BaBar help to disentangle the f_{Ds} puzzle. Other analyses with increased sensitivity are ongoing.

- D-mixing well-established from combination of measurements. No evidence for CPV.

- Recent BaBar lifetime ratio result using tagged and untagged events gives mixing significance of 4.1σ.

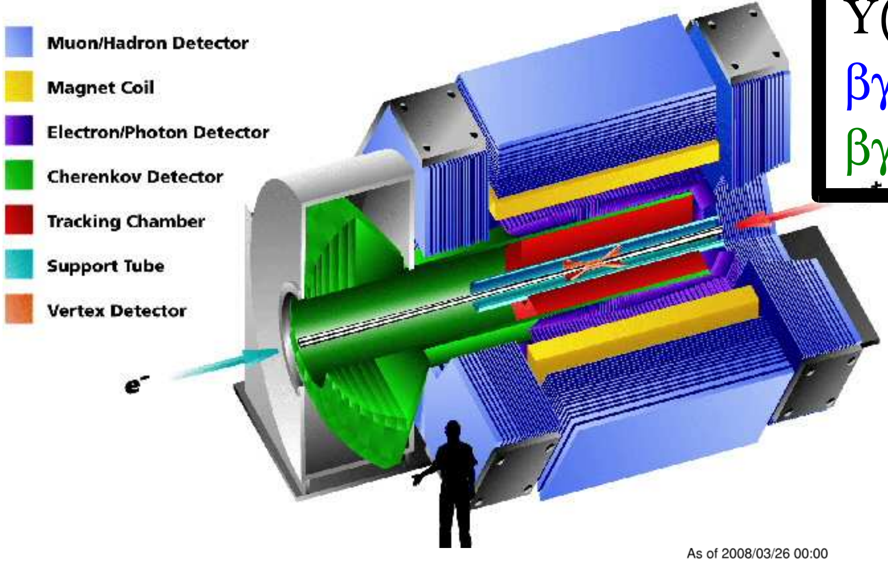
- New BaBar $D^0 \rightarrow K_S \pi^+ \pi^-$ and $D^0 \rightarrow K_S K^+ K^-$ combined analysis gives most precise direct measurement of *x* and *y* mixing parameters.
  - Favors lower values for *x* (and *y*)
  - It gives a mixing significance of 1.9σ
  - Good agreement with $D^0 \rightarrow K_S \pi^+ \pi^-$ Belle result.

- CPV searches in BaBar using T-odd correlated asymmetries with $D^0 \rightarrow \pi^+ \pi^- K^+ K^-$, improve the resolution by one order of magnitude with respect to the FOCUS measurement. No signal for T-violation has been found.

BACK UP SLIDES

Asymmetric B-factories

BaBar detector

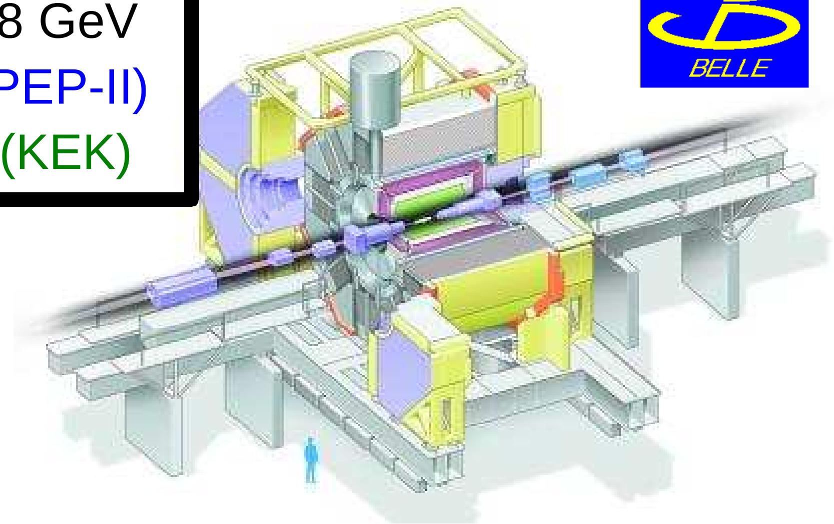


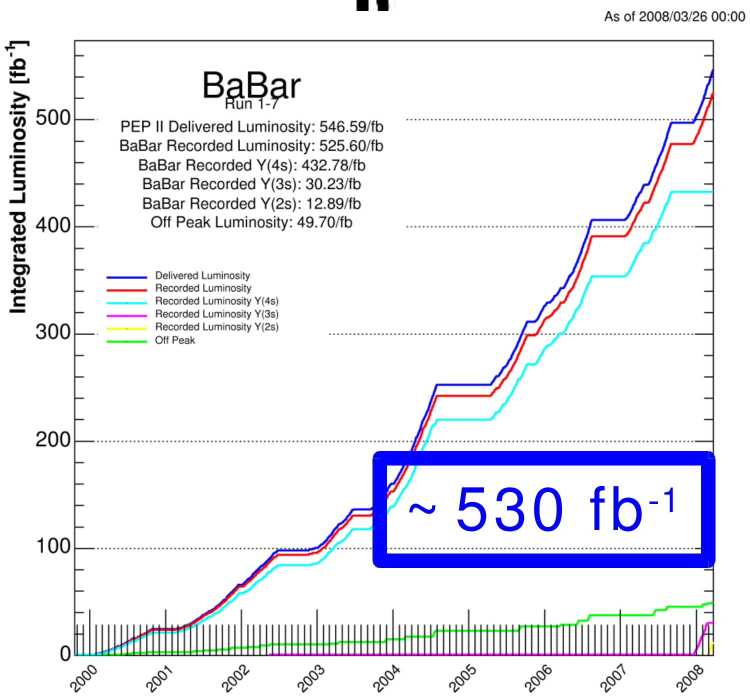
$\Upsilon(4S)$ 10.58 GeV

$\beta\gamma = 0.55$ (PEP-II)

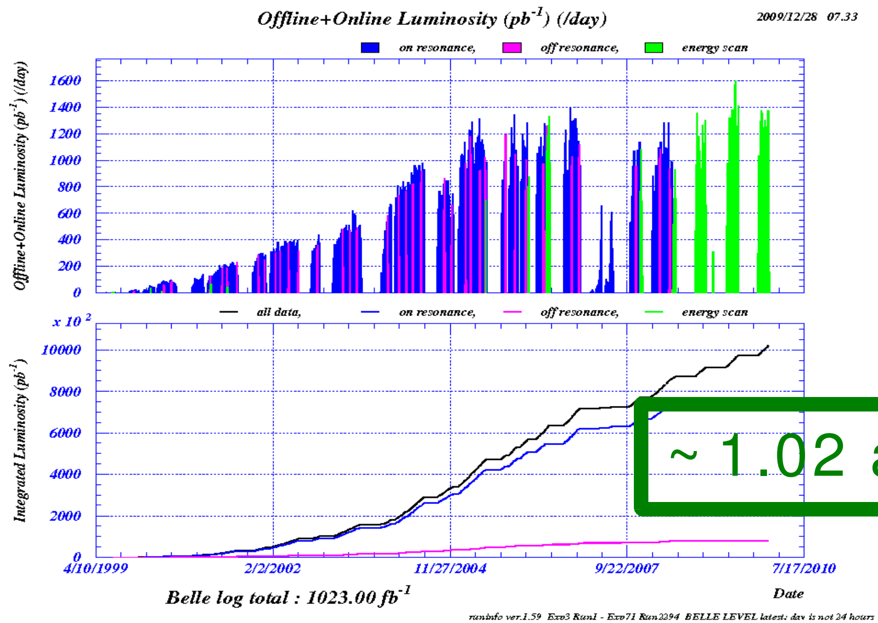
$\beta\gamma = 0.425$ (KEK)

Belle detector





~ 530 fb^{-1}



~ 1.02 ab^{-1}

Charm mixing and CPV

Schrödinger's equation
Effective Hamiltonian which
mediates time evolution

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

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

Physical states are a linear combination of flavor eigenstates. Mixing can occur because flavor and mass eigenstates differ.

Time evolution of physical states

$$|D_{1,2}(t)\rangle = \exp\left\{-i\left(m_{1,2} - i\frac{\Gamma_{1,2}}{2}\right)\right\}|D_{1,2}\rangle$$

Mixing parameters $x = \frac{m_1 - m_2}{\Gamma}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma},$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2} = \frac{1}{\tau}$$

Charm mixing and CPV

Squared time dependent amplitude, allowing for mixing and CPV

$$|A_f(t)|^2 = \frac{1}{2}e^{-\Gamma t}\left\{\left(|A_f|^2 + \left|\frac{q}{p}\right|^2 |\bar{A}_f|^2\right)\cosh\left(-\Gamma y t\right) + 2\mathcal{R}e\left(A_f^* \bar{A}_f \frac{q}{p}\right)\sinh\left(-\Gamma y t\right)\right.$$
$$\left. + \left(|A_f^2| - \left|\frac{q}{p}\right|^2 |\bar{A}_f|^2\right)\cos\left(\Gamma x t\right) + 2\mathcal{I}m\left(A_f^* \bar{A}_f \frac{q}{p}\right)\sin\left(\Gamma x t\right)\right\}$$

The amplitudes at *t=0* are $A_f = \langle f|\mathcal{H}|D^0\rangle, \quad \bar{A}_f = \langle f|\mathcal{H}|\overline{D}^0\rangle$

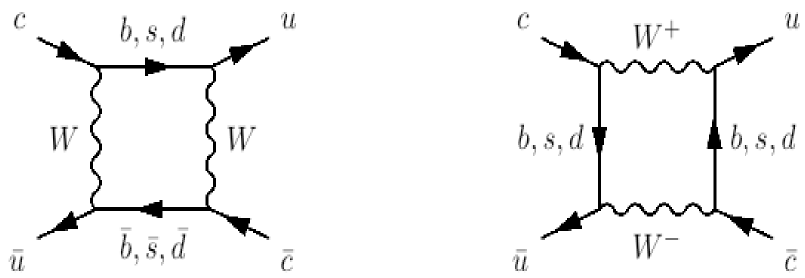
CPV in the decay $\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$

CPV in the mixing $\left|\frac{q}{p}\right|^2 \neq 1$

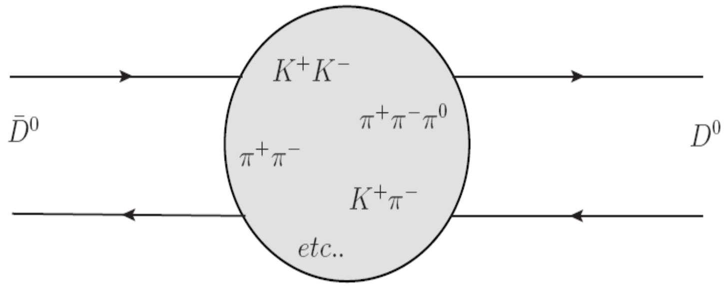
CPV in the interference $\arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq 0, \pi$

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*

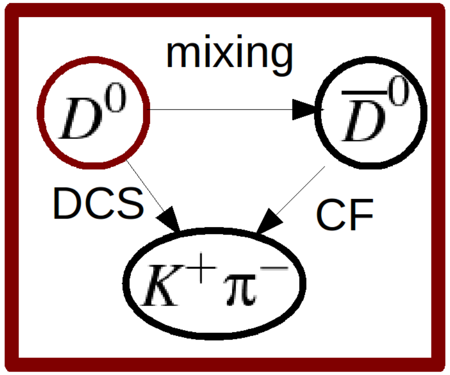


- Long-distance contributions
  - Via hadronic intermediate states
  - Expected to dominate
  - Still a small effect
  - Non-perturbative and hard to estimate
  - Predictions give *x*, *y* in (0.001-0.01) and |*x*|<|*y*|



- 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 would be a sign of NP since SM predicts CPV to be <0.001

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



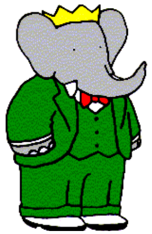
- Three main contributions
- DCS decay
- Mixing + CF decay
- Interference
- Contributions are disentangled thanks to different behaviour with time evolution in the *x*, *y*<<1 limit

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

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

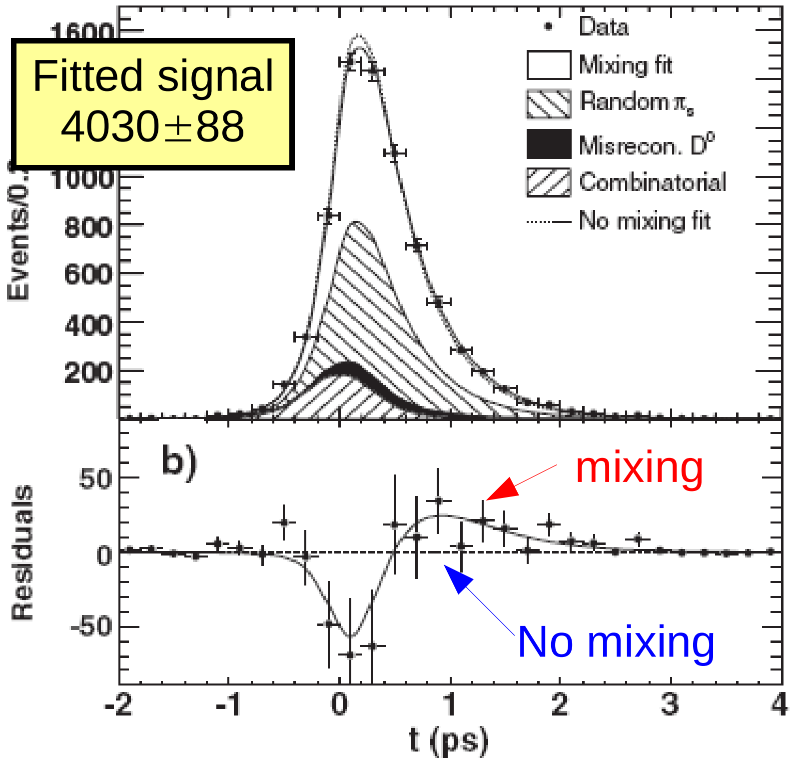
$$R_D = \left|\frac{A(D^0 \to K^+\pi^-)}{A(\overline{D}^0 \to K^+\pi^-)}\right|^2 = \left|\frac{A_f}{\overline{A}_f}\right|^2$$

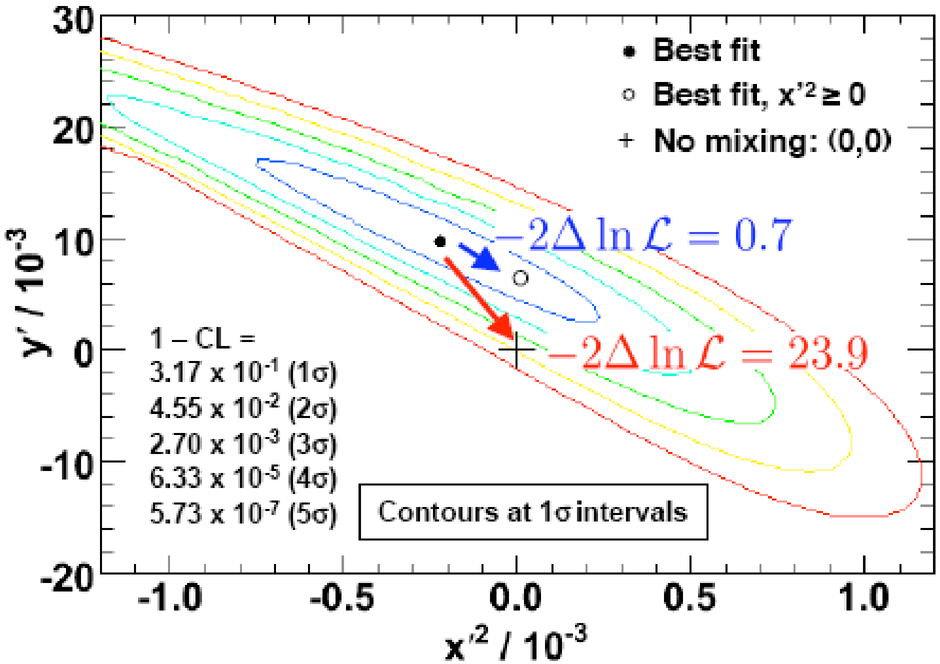
WS hadronic decay $D^0 \to K^+\pi^-$



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

Fitted signal
4030±88



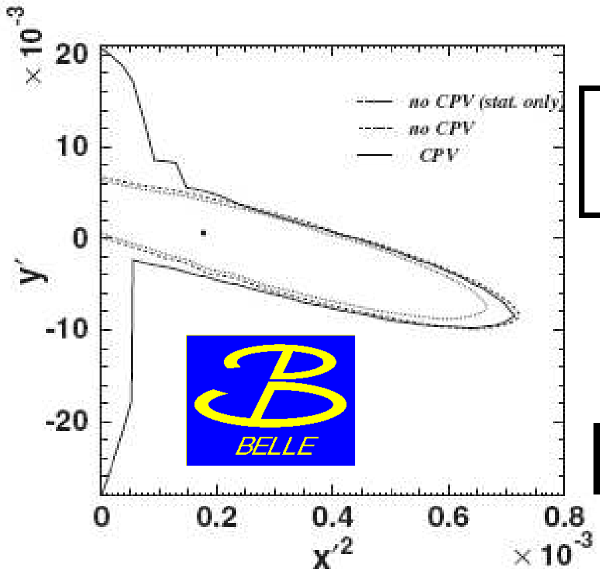


R_D = (3.03 ± 0.16 ± 0.10) x 10^{-3}
x'^2 = (-0.22 ± 0.30 ± 0.21) x 10^{-3}
y' = (9.7 ± 4.4 ± 3.1) x 10^{-3}

- 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

No CPV evidence

WS hadronic decay $D^0 \to K^+\pi^-$

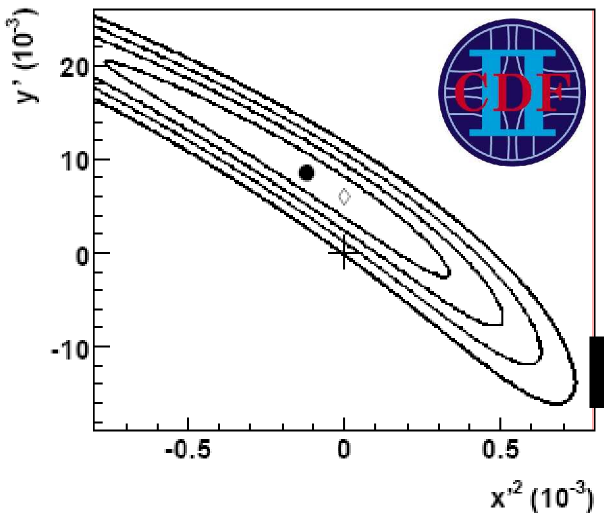


Data sample 400 fb^{-1}
PRL**96**:151801,2006

Fitted signal
4024±88

Mixing @ 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	···	$(0.63 \times 10^{-5}, 0.40)$
CPV	A_D	23 ± 47	(−76, 107)
	A_M	670 ± 1200	(−995, 1000)
	x'^2	···	<0.72
	y'	···	(−28, 21)
	R_M	···	<0.40
No mixing	R_D	3.77 ± 0.08(stat.) ± 0.05(syst.)	



Data sample 1.5 fb^{-1}
PRL**100**:121802,2008

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

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

Mixing and CPV alter decay time distributions of CP eigenstates. A good approximation are exponential distributions with effective lifetimes $\tau^{\pm}_{hh}$

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

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

$$\phi_f = \arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right)$$

Measured quantities

$$\tau^+_{hh} = \tau(D^0 \to h^+h^-)$$

$$\tau^-_{hh} = \tau(\overline{D}^0 \to h^+h^-)$$

$$\tau_{K\pi} = \tau(D^0 \to K^-\pi^+)$$

The mixing and CP observables are:

$$y_{CP} = y\cos\phi_f = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle} - 1$$

$$\Delta Y = x\sin\phi_f = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle}A_\tau$$

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

$$A_\tau = \frac{\tau^+_{hh} - \tau^-_{hh}}{\tau^+_{hh} + \tau^-_{hh}}$$

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

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

PRD 78, 011105(R) (2008)

Tagged:
$y_{CP} = (\ 1.03 \pm 0.33\ (stat) \pm 0.19\ (syst)\ ) \cdot 10^{-2}$
$\Delta y = (\ -0.26 \pm 0.36\ (stat) \pm 0.08\ (syst)\ ) \cdot 10^{-2}$

Mixing evidence at 3σ

PRD 80, 071103(R) (2009)

Combined tagged + untagged:
$y_{CP} = (\ 1.13 \pm 0.22\ (stat) \pm 0.18\ (syst)\ ) \cdot 10^{-2}$

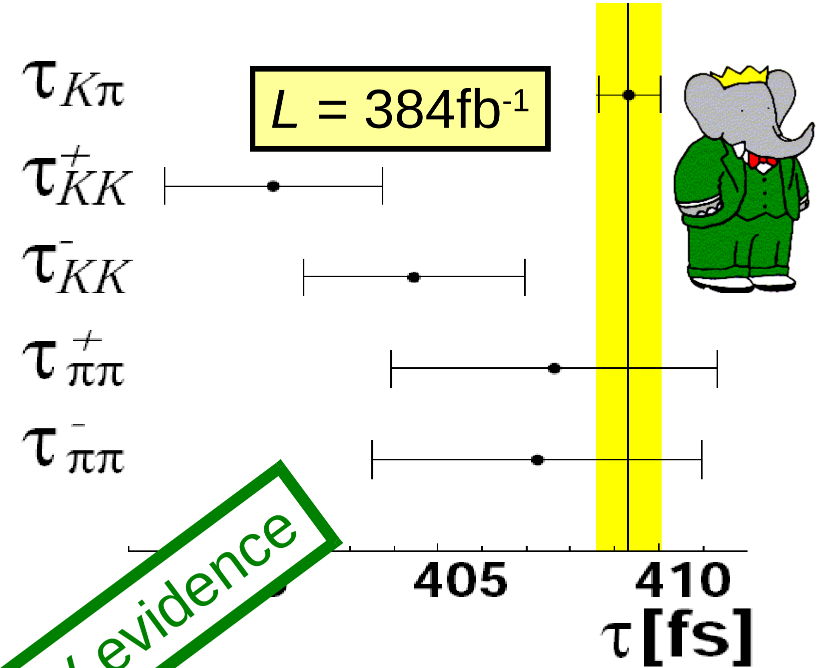
NEW

Mixing evidence at 4.1σ

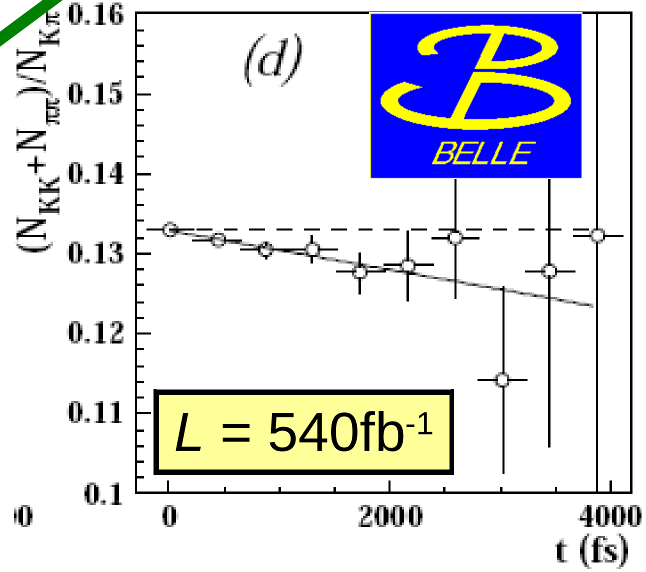
PRL 98, 211803 (2007)

$y_{CP} = (\ 1.31 \pm 0.32\ (stat) \pm 0.25\ (syst)\ ) \cdot 10^{-2}$
$A_\tau = (\ 0.01 \pm 0.30\ (stat) \pm 0.15\ (syst)\ ) \cdot 10^{-2}$

Mixing evidence at 3.2σ



No CPV evidence



Dalitz Plot analysis of $D^0 \to K_S h^+ h^-$ (h=K,π)

$x = (\,0.16 \pm 0.23\,(stat) \pm 0.12\,(exp) \pm 0.08\,(mod)\,)\,10^{-2}$ *BaBar*
$y = (\,0.57 \pm 0.20\,(stat) \pm 0.13\,(exp) \pm 0.07\,(mod)\,)\,10^{-2}$ Preliminary

BELLE

$x = (0.80 \pm 0.29^{+0.09+0.10}_{-0.07-0.14}) \cdot 10^{-2}$

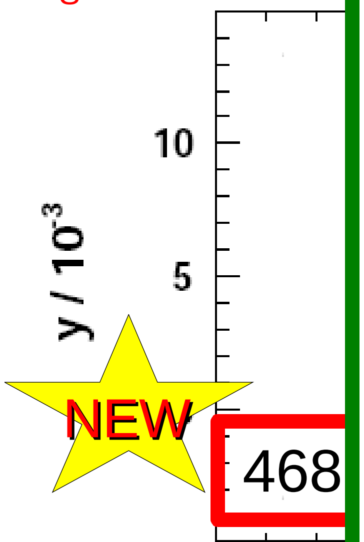
$\ldots.24^{+0.08+0.06}_{-0.12-0.08}) \cdot 10^{-2}$

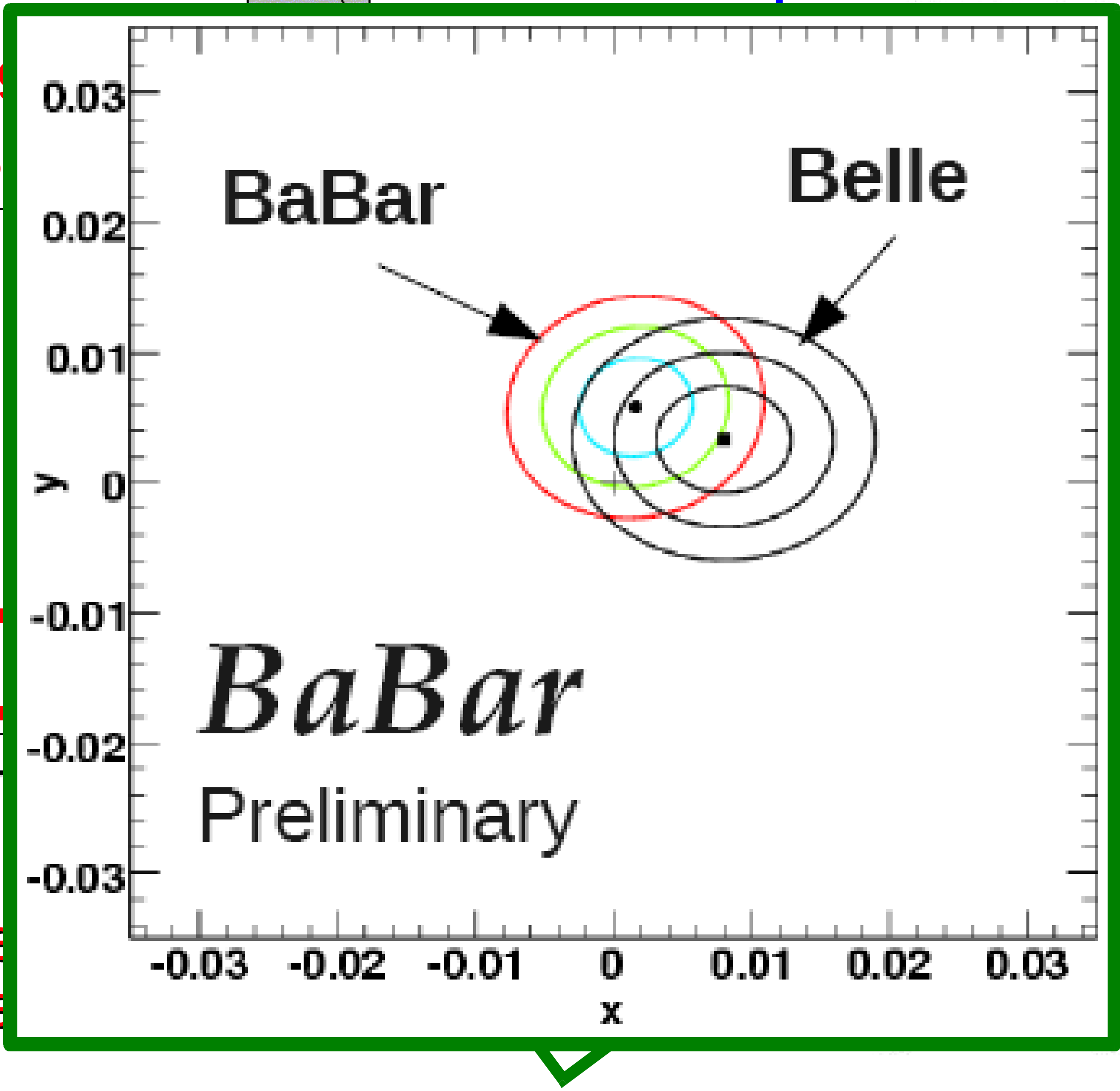
$^{+0.30+0.06}_{-0.29-0.03} \pm 0.08$

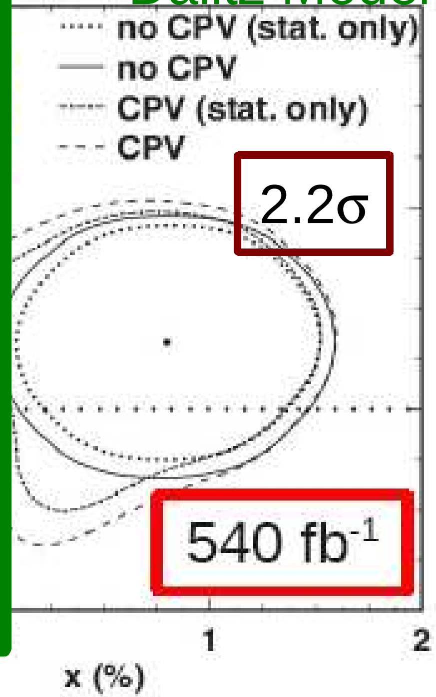
$^{+16+6+2}_{-18-3-4}\,{}^{\circ}$

Dalitz Model

Signal yield
$K_S\pi^+\pi^-$ 540789 [partly hidden]
$K_SK^+K^-$ 79908 [partly hidden]







Most pre[partly hidden]
measure[partly hidden]

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

- CP-even final states. Single-Cabibbo-suppressed (SCS) modes
- CPV in these modes is predicted to be $\sim 10^{-4}$-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

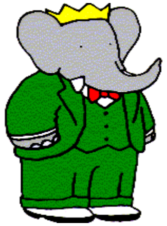
$$a_{CP}^{hh} = \frac{\Gamma\left(D^0 \to h^- h^+\right) - \Gamma\left(\bar{D}^0 \to h^+ h^-\right)}{\Gamma\left(D^0 \to h^- h^+\right) + \Gamma\left(\bar{D}^0 \to h^+ h^-\right)}$$

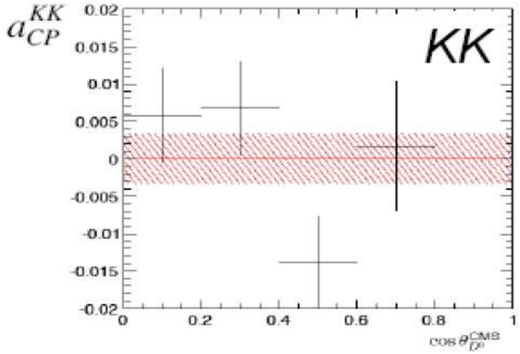
- Precise D^0 flavor tag is the main experimental concern.
  - $D^0 \to K^-\pi^+$ is used for this purpose
- Forward-Backward asymmetry in charm pairs production ~few%.

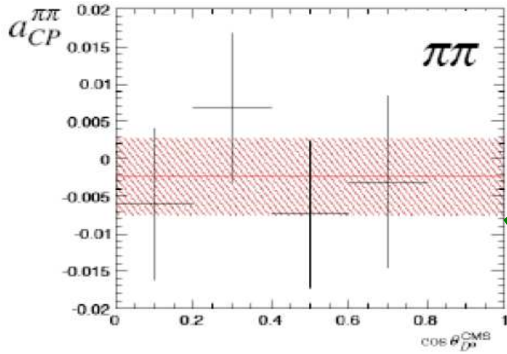
Time-Integrated CPV $D^0 \to K^+K^-(\pi^0), \pi^+\pi^-(\pi^0)$

Data sample 385fb^{-1}
PRL**100**:061803(2008)

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



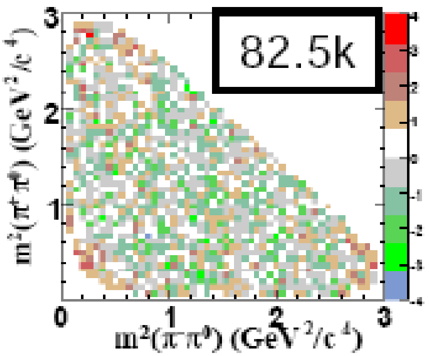




No CPV evidence at the level of 10^{-2}

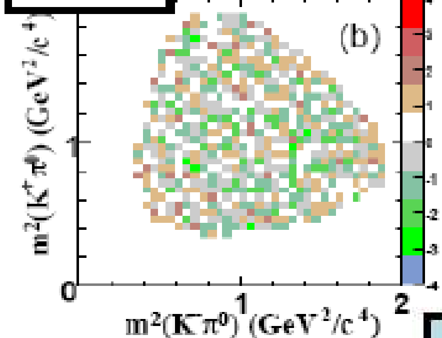
πππ

82.5k

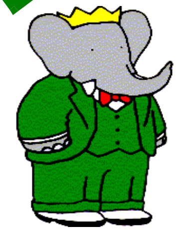


11.3k

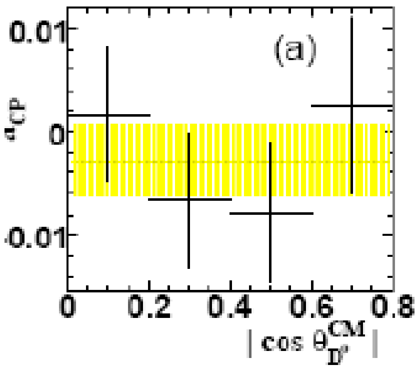
KKπ

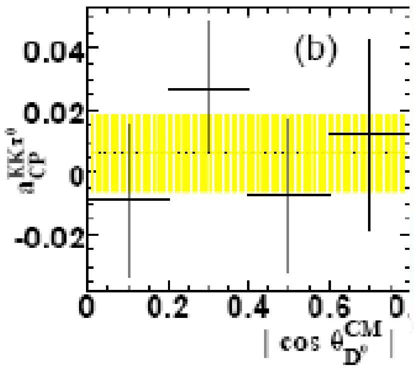


Data sample 385fb^{-1}
PRD**78**:051102(2008)



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





BELLE

Data sample 532fb^{-1}
PLB**662**:102-110(2008)

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