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

K.Trabelsi (KEK)
karim.trabelsi@kek.jp

Flavor Physics & CP Violation 2013
May 19-24, 2013

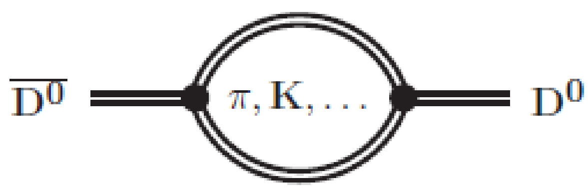
Flavour Mixing in the Charm Sector

Mass eigenstates $\neq$ flavour eigenstates

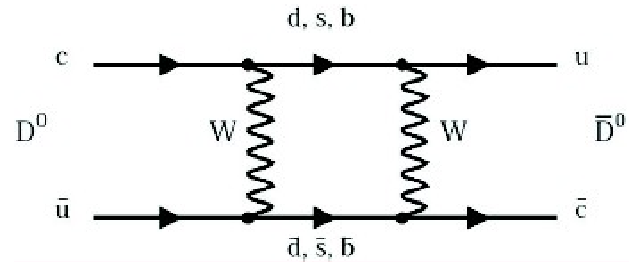
$$|D_{1,2}> = p\,|D^0> \pm q\,|\overline{D}^0>$$

$m_{1,2}$ and $\Gamma_{1,2}$ are mass and width of $|D_{1,2}>$

$p/q \neq 1 \Rightarrow$ CP violation



Long – distance contributions dominant, affected by large theoretical uncertainties



Short – distance contributions, GIM and CKM suppressed in SM

Time evolution of a $D^0 - \overline{D}^0$ system

$$i\frac{d}{dt}\begin{pmatrix}|D(t)\rangle \\ |\bar{D}(t)\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|D(t)\rangle \\ |\bar{D}(t)\rangle\end{pmatrix}$$

with M and Γ being hermitian

Solutions

$$|D^0(t)> = e^{-(\Gamma/2 + im)t}\left[\cosh\left(\frac{y+ix}{2}\Gamma t\right)|D^0> + \frac{q}{p}\sinh\left(\frac{y+ix}{2}\Gamma t\right)|\overline{D}^0>\right]$$

$$|\overline{D}^0(t)> = e^{-(\Gamma/2 + im)t}\left[\frac{p}{q}\sinh\left(\frac{y+ix}{2}\Gamma t\right)|D^0> + \cosh\left(\frac{y+ix}{2}\Gamma t\right)|\overline{D}^0>\right]$$

Mixing parameters

$$x = \frac{m_1 - m_2}{\Gamma_D}, \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}$$

$\Gamma_D = (\Gamma_1 + \Gamma_2)/2$

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

- Since D^0 mixing is small $(|x|, |y| << 1)$:

$$|D^0(t)> = e^{-(\Gamma/2 + im)t}\,[|D^0> + \frac{p}{q}(\frac{y+ix}{2}\Gamma t)|\overline{D}^0>]$$

- Time dependent decay rates of $D^0 \rightarrow f$:

$$\frac{dN_{D^0 \rightarrow f}}{dt} \propto |<f|H|D^0(t)>|^2 = e^{-\Gamma t}|<f|H|D^0> + \frac{q}{p}(\frac{y+ix}{2}\Gamma t)|<f|H|\overline{D}^0>|^2$$

- Exponential decay modulated with x and y

  x and **y** can be obtained from measured time dependence of $\frac{dN_{D^0 \rightarrow f}}{dt}$

- Shape is final state dependent

  different final states sensitive to different combinations of **x** and **y**

D^0 - $\overline{D}^0$ mixing – SM estimates

Can express (Joachim Brod)

$$\mathbf{y} = \frac{1}{2\Gamma_D} \sum_n \rho_n [<D^0|H|n><n|H|\overline{D}^0> + <\overline{D}^0|H|n><n|H|D^0>]$$

$$\mathbf{x} = \frac{1}{\Gamma_D}[<D^0|H|\overline{D}^0> + P \sum_n \frac{<D^0|H|n><n|H|\overline{D}^0> + <\overline{D}^0|H|n><n|H|D^0>}{M_D^2 - E_n^2}]$$

''Inclusive approach'':

- OPE expansion in powers of ''Λ/m_c''
- $x \sim y < 10^{-3}$ [Georgi 1992; Ohl et al 1993; Bigi et al 2000]
- Cannot exclude $y \sim 10^{-2}$ [Bobrowski et al 2010]
- Violation of quark-hadron duality

''Exclusive approach'':

- Sum over on-shell intermediate states
- Mainly $D \to PP$, PV leads to $x \sim y < 10^{-3}$ [Cheng et al 2010]
- $SU(3)_F$ breaking in phase space alone leads to $y \sim 10^{-2}$ [Falk et al 2002]
- Get $x \sim 10^{-2}$ from a dispersion relation [Falk et al 2004]

Experimental status at FPCP 2012

(A.Di Canto)

From HFAG page:

$D^0 \to K^+ \pi^-$ E791

$D^0 \to h^+ h^-$ E791

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

$D^0 \to K^+ \pi^+ 2\pi^-$

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

$D^0 \to K^+ l^- \nu$ E791

$\psi(3770) \to D^0 \overline{D}^0$

★ = mixing probability $> 3\sigma$

Experimental status at FPCP 2012

[http://www.slac.stanford.edu/xorg/hfag/charm/March12]

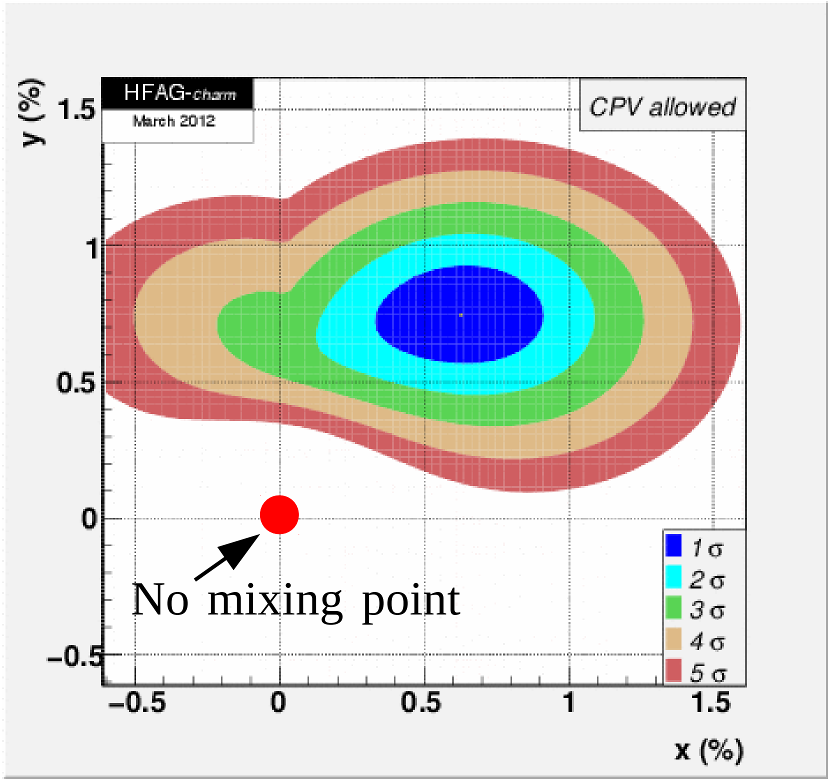
Mixing in the D^0 system is well established: significance $\sim 10\sigma$

$$\mathbf{x = \left(0.63\,^{+0.19}_{-0.20}\right)\%}$$
$$\mathbf{y = \left(0.75 \pm 0.12\right)\%}$$

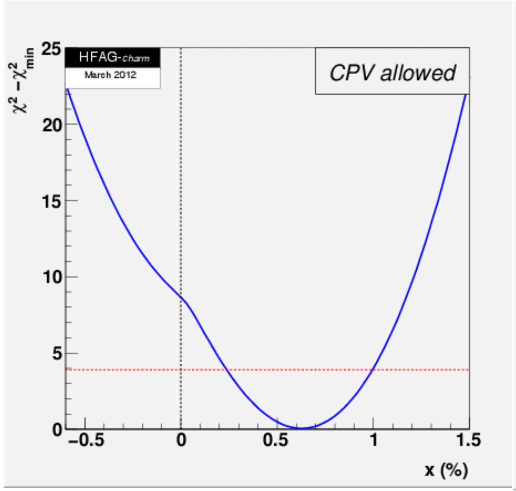
SM predictions affected by large uncertainties:

$$x^{theo}, y^{theo} \sim O\left(10^{-2}\text{-}10^{-7}\right)$$

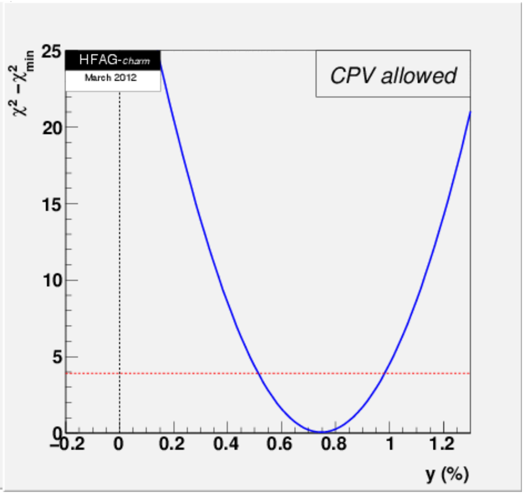
[see Joachim Brod's compilation next slide]



Measurements of x and y are at the upper limits of SM, NP contributions (in short-distance diagrams) could at the 1% level e.g. [Golowich et al]



$x \leq 0$ excluded at 2.7σ



$y \leq 0$ excluded at 6.0σ

Results discussed in this talk...

From HFAG page:

$D^0 \rightarrow K^+ \pi^-$ E791

$D^0 \rightarrow h^+ h^-$ E791

$D^0 \rightarrow K^+ \pi^- \pi^0$

$D^0 \rightarrow K^+ \pi^+ 2\pi^-$

$D^0 \rightarrow K_S^0 h^+ h^-$

$D^0 \rightarrow K^+ l^- \nu$ E791

$\psi(3770) \rightarrow D^0 \overline{D}^0$

★ = mixing probability $> 3\sigma$

Decays to CP-even eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$

Measurement of lifetime difference between $D \to K^-\pi^+$ and $D^0 \to K^+K^-, \pi^+\pi^-$

Timing distributions are exponential (if CP is conserved)

- mixing parameter: $y_{CP} = \dfrac{\tau(K^-\pi^+)}{\tau(h^+h^-)} - 1$
- if CP conserved: $y_{CP} = y$

If CP is violated → difference in lifetimes of $D^0/\overline{D}^0 \to K^+K^-, \pi^+\pi^-$

- lifetime asymmetry: $A_\Gamma = \dfrac{\tau(\overline{D}^0 \to h^-h^+) - \tau(D^0 \to h^-h^+)}{\tau(\overline{D}^0 \to h^-h^+) + \tau(D^0 \to h^-h^+)}$
- $y_{CP} = y\cos\varphi - \frac{1}{2} A_M x \sin\varphi$
- $A_\Gamma = \frac{1}{2} A_M y \cos\varphi - x\sin\varphi$

$\varphi = \arg(q/p)$

$A_M = 1 - |q/p|^2$

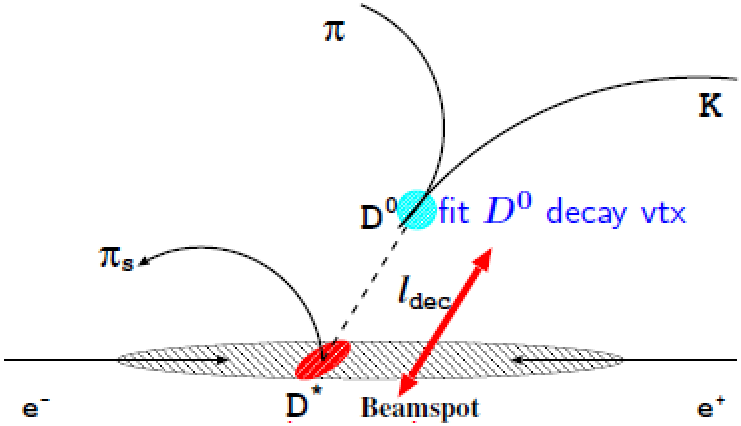
[S.Bergmann et al, PLB 486, 418 (2000)]

Experimental method (update with 976 fb^{-1})

[arXiv:1212.3478; M.Staric et al, PRL98, 211803 (2007)]

using $D^{*+} \to \pi^+ D^0$

- flavor tagging by the charge of π_{slow}
- background suppression



extrapolate production vtx

D^0 proper decay time measurement:

$$t = \frac{l_{dec}}{c\beta\gamma}, \qquad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$

- decay time uncertainty σ_t (calculated from vtx err matrices)

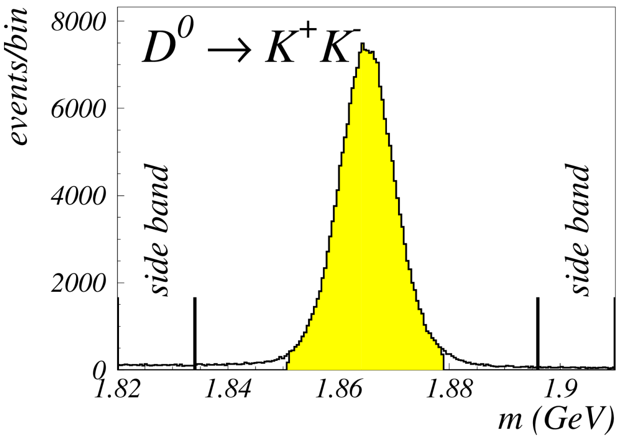
To reject D^{*+} from B decays: $p_{D^{*+}}^{CMS} > 2.5\ (3.1)$ GeV/c $\Upsilon(4S)$ ($\Upsilon(5S)$)

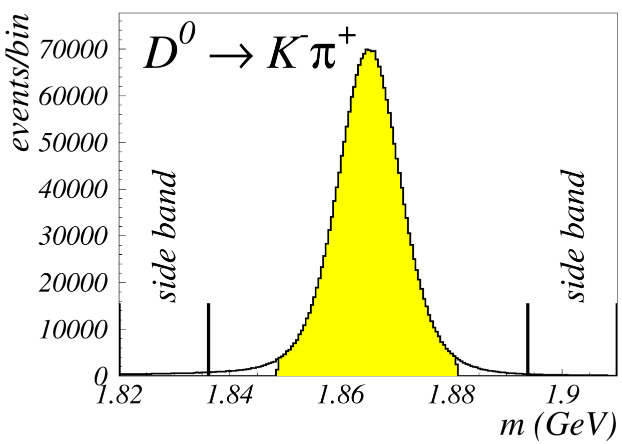
Observables:

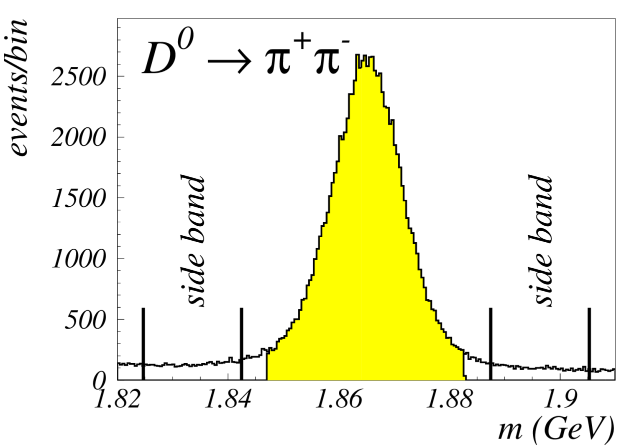
- $m = m(K\pi)$
- $q = m(K\pi\pi_s) - m(K\pi) - m_\pi$

Decays to CP-even eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$

[arXiv:1212.3478]







- Analysis cuts: m, q, σ_t
  optimized on tuned Monte Carlo
  figure of merit: statistical error on y_{CP}
- Background estimated from sidebands in m
  sideband position optimized
- Signal yields (purities) entering the measurement:

channel	KK	Kπ	ππ
Yield	242k	2.61 M	114k
Purity	98.0 %	99.7 %	92.9 %

Decays to CP-even eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$

[arXiv:1212.3478]

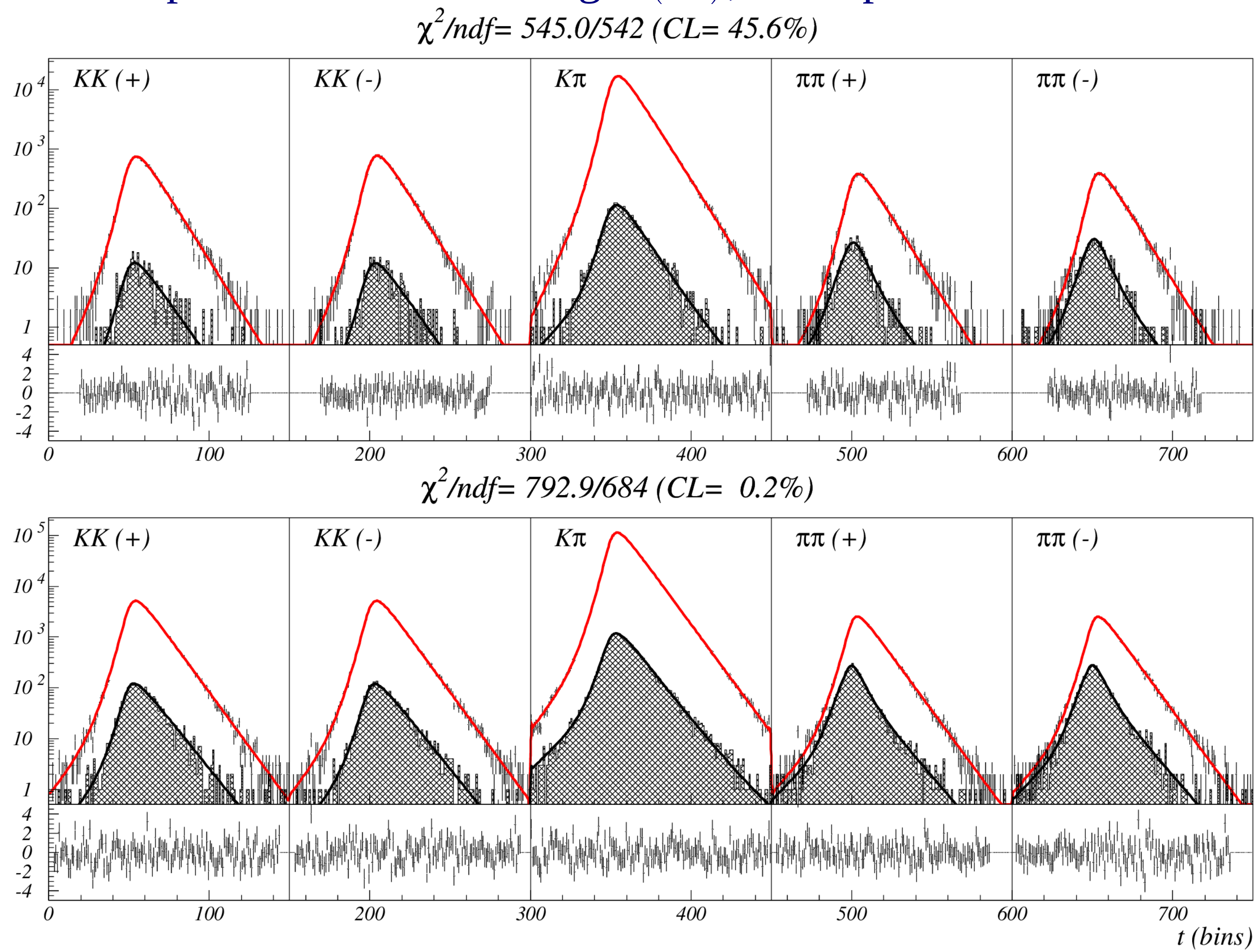
simultaneous binned fit to K^+K^-, $K^+\pi^-$, $\pi^+\pi^-$ samples

sum of histograms and fitted function over $\cos\theta^*$

[as resolution function depends on D^0 CMS angle (θ^*), fit is performed in bins of $\cos\theta^*$]

SVD1
3-layer SVD
153 fb^{-1}

SVD2
4-layer SVD
823 fb^{-1}

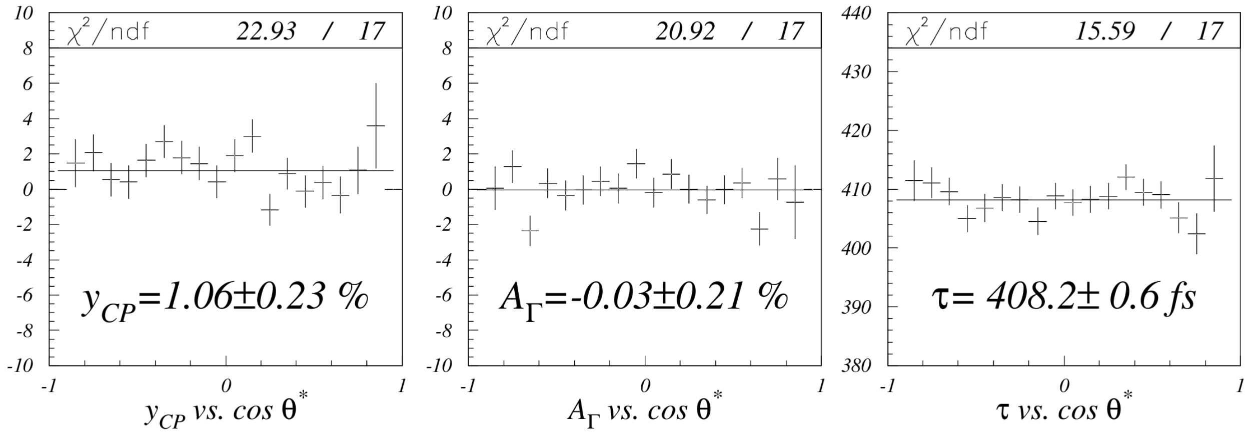


Decays to CP-even eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$

[arXiv:1212.3478]

[as resolution function depends on D^0 CMS angle (θ^*), fit is performed in bins of $\cos\theta^*$]

SVD2
4-layer SVD
823 fb^{-1}



Results (preliminary) with 976 fb^{-1}

$$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\,\%$$

$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\,\%$$

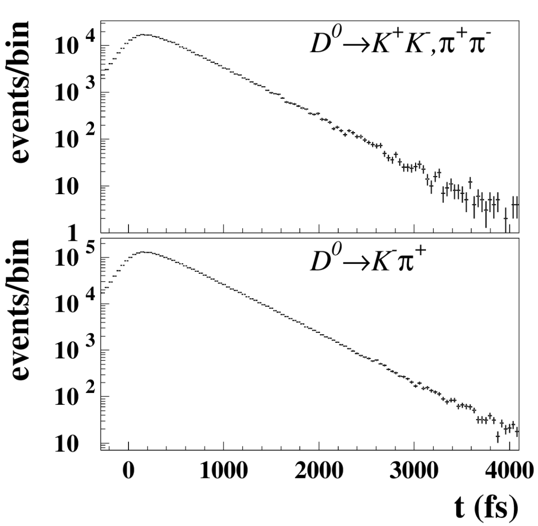
$$\tau = 408.56 \pm 0.54_{stat}$$

Belle, 540 fb^{-1}

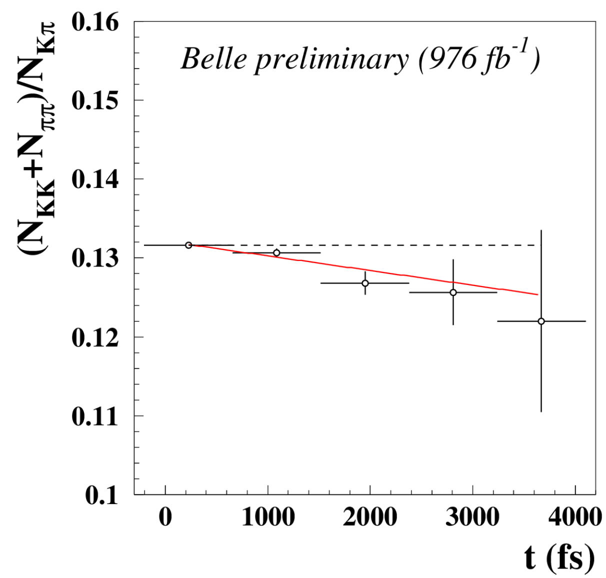
$$y_{CP} = (+1.31 \pm 0.32 \pm 0.25)\%$$

$$A_\Gamma = (+0.01 \pm 0.30 \pm 0.15)\%$$

- y_{CP} is at 4.5σ when both errors are combined in quadrature and at 5.1σ if only statistical error is considered
- A_Γ is consistent with no indirect CP violation



divide distributions



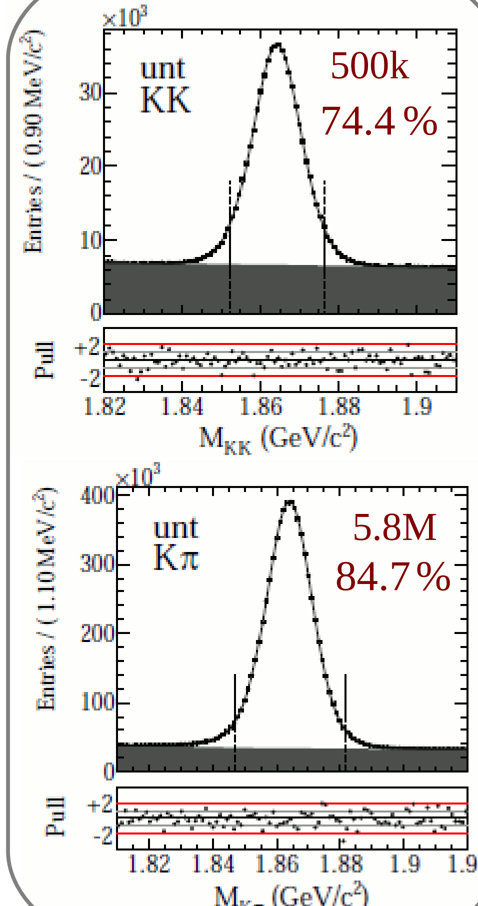
Decays to CP-even eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$

[J.P. Lees et al, PRD87, 012004 (2013), arXiv:1209.3896]

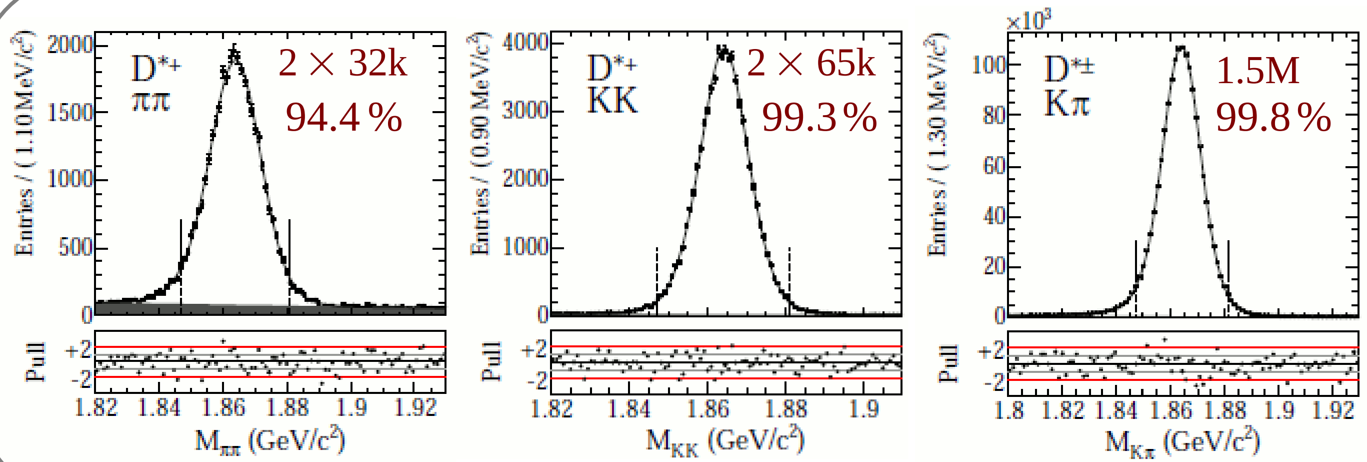
Simultaneous fit to 7 signal channels:

- flavour tagged: $D^{*+} \to D^0\pi^+$, $D^0 \to K^+K^-$; $D^{*-} \to \overline{D}^0\pi^-$, $D^0 \to K^+K^-$; $D^{*+} \to D^0\pi^+$, $D^0 \to \pi^+\pi^-$; $D^{*-} \to \overline{D}^0\pi^-$, $D^0 \to \pi^+\pi^-$; $D^* \to D\pi$, $D \to K^\pm\pi^\mp$
- flavour untagged: $D \to K^+K^-$, $D \to K^\pm\pi^\mp$

flavour untagged



flavour tagged



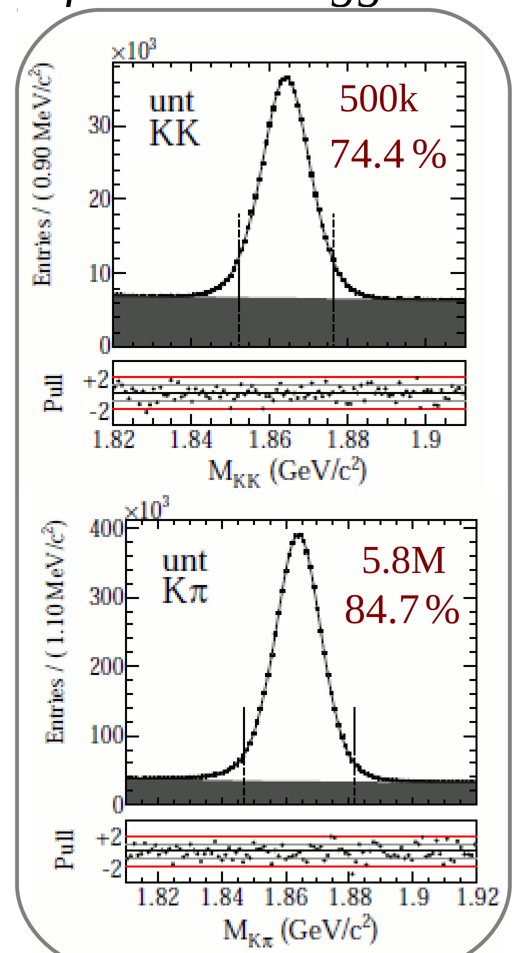
Decays to CP-even eigenstates $D^0 \rightarrow K^+K^-, \pi^+\pi^-$

[J.P. Lees et al, PRD87, 012004 (2013), arXiv:1209.3896]

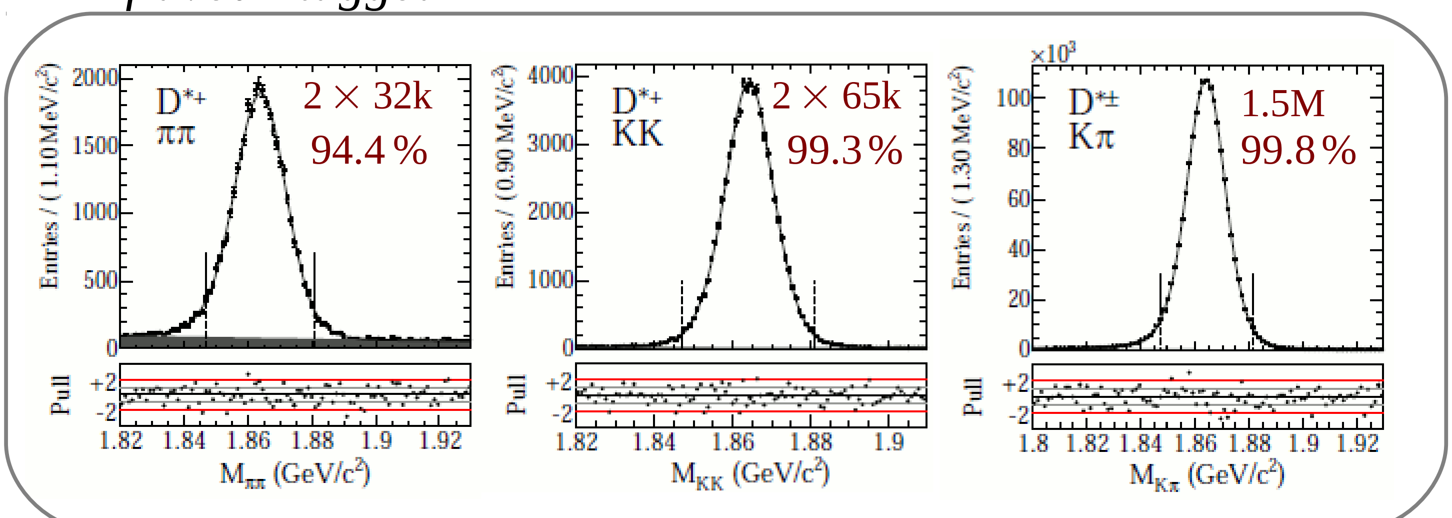
- **Charm background:**
  Small component (< 0.7%), misreconstructed charm decays, not separated in the mass fit
  Lifetime fit PDFs and yields extracted from MC in the signal region

- **Combinatorial background:**
  Main component, random tracks
  Lifetime fit PDFs extracted from data outside the signal region
  Lifetime fit yields (not for untagged K^+K^-) are extracted from data in the signal region (integral of bkg PDF minus the charm bkg yields from MC)

flavour untagged



flavour tagged

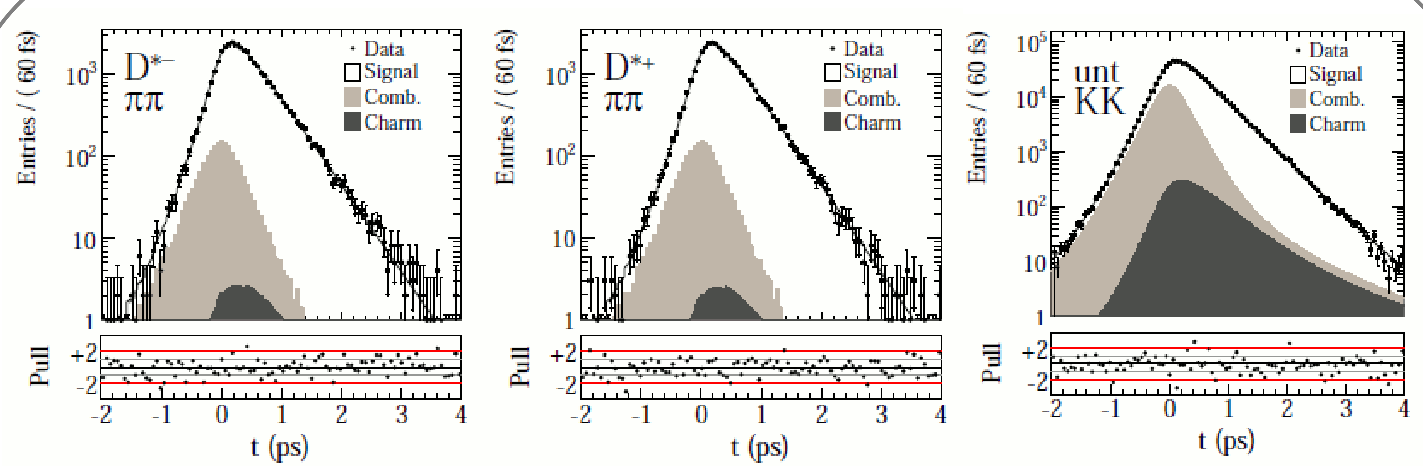


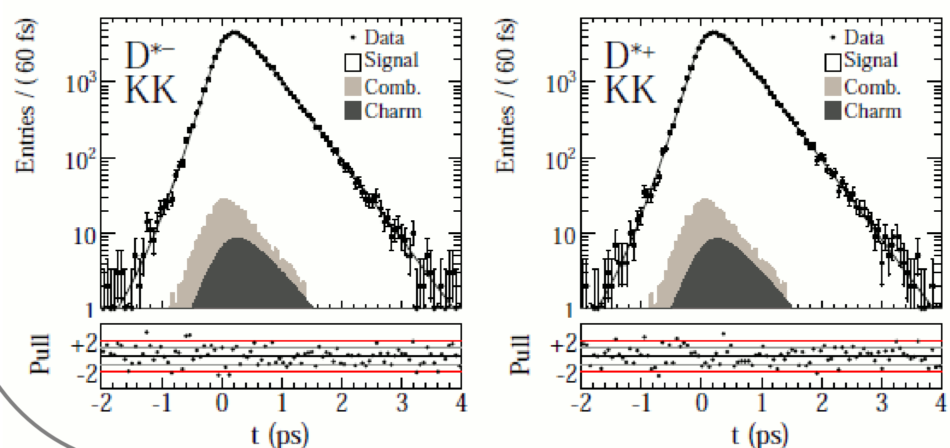
Decays to CP-even eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$

[J.P. Lees et al, PRD87, 012004 (2013), arXiv:1209.3896]

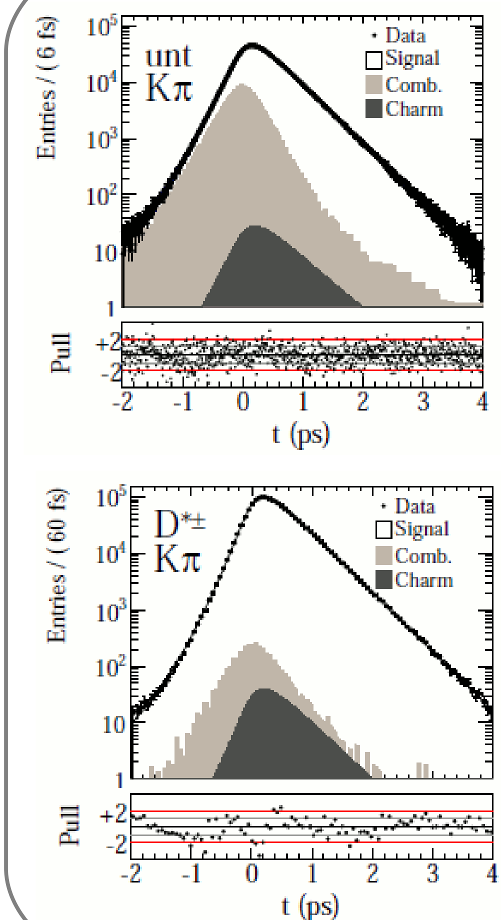
- Signal: properly normalized 2d conditional PDF (t, σ_t)
- Lifetime 2d fit in the signal region only

CP+ eigenstates





CP mixed states



CP+ lifetimes

$\tau^+ = (405.69 \pm 1.25)$ fs

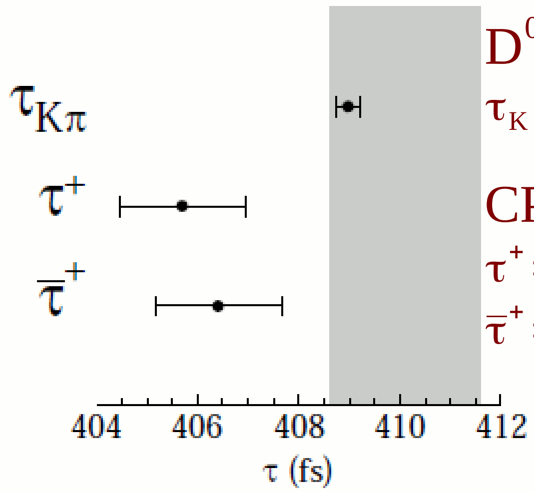
$\bar{\tau}^+ = (406.40 \pm 1.25)$ fs

D^0 lifetime

$\tau_{K\pi} = (408.97 \pm 0.24)$ fs

Decays to CP-even eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$

[J.P. Lees et al, PRD87, 012004 (2013), arXiv:1209.3896]



D^0 lifetime

$\tau_{K\pi} = (408.97 \pm 0.24)$ fs

CP+ lifetimes

$\tau^+ = (405.69 \pm 1.25)$ fs

$\bar{\tau}^+ = (406.40 \pm 1.25)$ fs

Results with 468 fb^{-1}

$y_{CP} = (+0.72 \pm 0.18 \pm 0.12)\%$

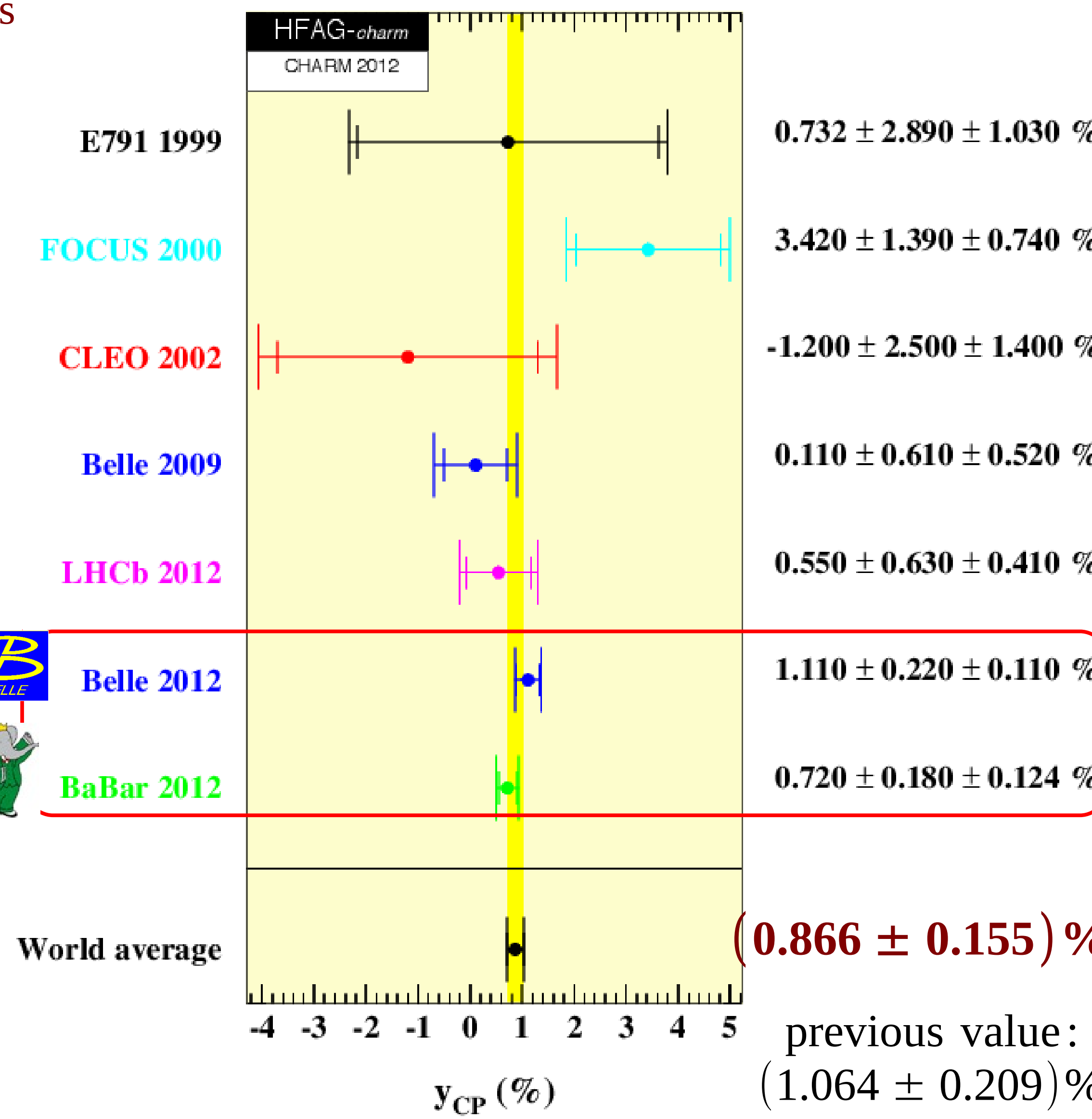
$A_\Gamma = (+0.09 \pm 0.26 \pm 0.06)\%$

Exclude no mixing at 3.3σ

BaBar, 384 fb^{-1}

$y_{CP} = (+1.16 \pm 0.22 \pm 0.18)\%$

$A_\Gamma = (+0.26 \pm 0.36 \pm 0.08)\%$



(0.866 ± 0.155)%

previous value: (1.064 ± 0.209)%

$D \to K^0_S \pi^+ \pi^-$ time-dependent Daliz analysis

- For D^0 3 body self-conjugated decays, Dalitz analysis can be performed:

  e.g. in $D^0 \to K^0_S \pi^+ \pi^-$, decay amplitude $A(m^2_-, m^2_+)$
  where $m^2_- \equiv m_{K^0_S \pi^-}$, $m^2_+ \equiv m_{K^0_S \pi^+}$

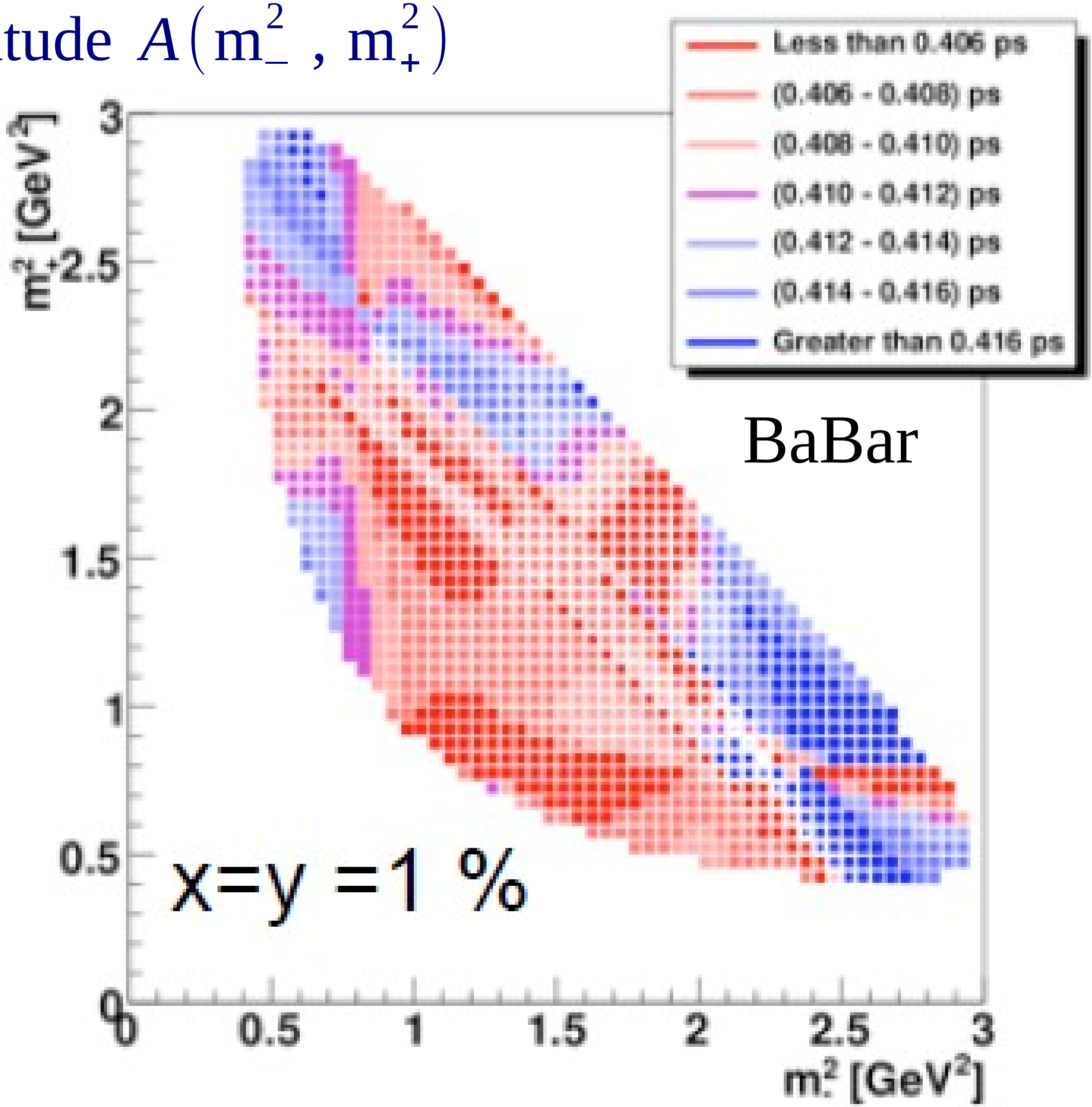
- In CP conservation assumption,
  $A = \overline{A}$ and $q/p = 1$

Distribution of events across Dalitz space vs $t(D^0)$

Variation → signature of mixing

sensitivity to x and y comes mainly from regions with:

- interferences of CF and DCS
- CP eigenstates



Simultaneous determination of x and y

Example of mean lifetime in different regions of the DP

$D \to K_S^0 \pi^+ \pi^-$ time-dependent Dalitz analysis

- $D^{*+} \to D^0 \pi_s^+$, $D^0 \to K_S^0 \pi^+ \pi^-$ Results (preliminary) with **920 fb^{-1}**

  $K_S^0 \to \pi^+ \pi^-$ selection:

  common vertex separated from the interaction region

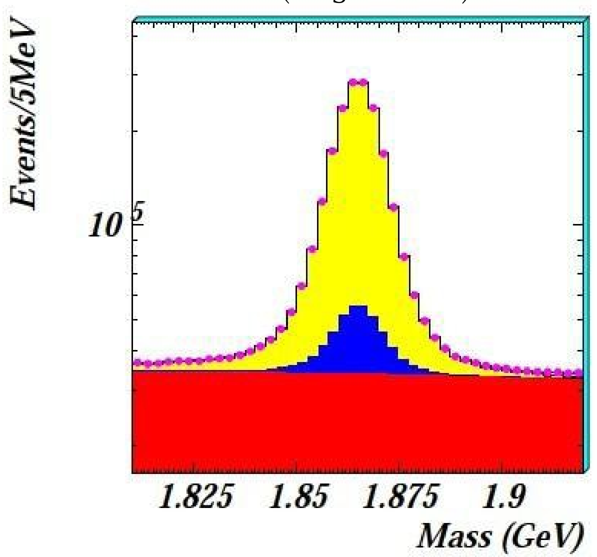
  $|M(\pi^+\pi^-)| < 10\ \text{MeV}/c^2$

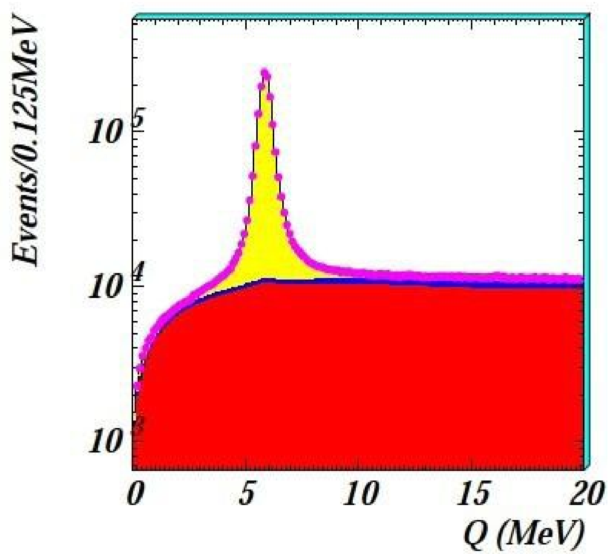
  Decay vertex:

  reconstructed with charged π tracks only (at least 4 SVD hits per track)

  $\sum \chi^2 < 100$ (vertex fit constraint), $\sigma_t < 1000\,\text{fs}$

$M = M(K_S^0 \pi^+ \pi^-)$ $Q = M(K_S^0 \pi^+ \pi^- \pi_s) - M(K_S^0 \pi^+ \pi^-) - m_{\pi^+}$





signal

random π background

combinatorial background

$\Upsilon(4S)$, $\Upsilon(5S)$ full dataset (**920 fb^{-1}**)

signal region: $|Q - 5.85| < 1.0$ GeV

$|M - 1.865| < 0.015\ \text{GeV}/c^2$

channel	$K_S^0 \pi\pi$
Yield	1.23M
Purity	95.6%

	Belle (2007)	New	Ratio
Lumi (fb^{-1})	540	920	1.7
Signal yield	534k	1.23M	2.3

$\Rightarrow$ significant gain from reprocessing

$D \to K^0_S \pi^+ \pi^-$ time-dependent Dalitz analysis

Dalitz model (signal):

$$A(m^2_-, m^2_+) = B_{res \neq S\text{-}wave} + K_{\pi\pi\ S\text{-}wave} + L_{K\pi\ S\text{-}wave}$$

$K\pi$ S-wave: LASS model

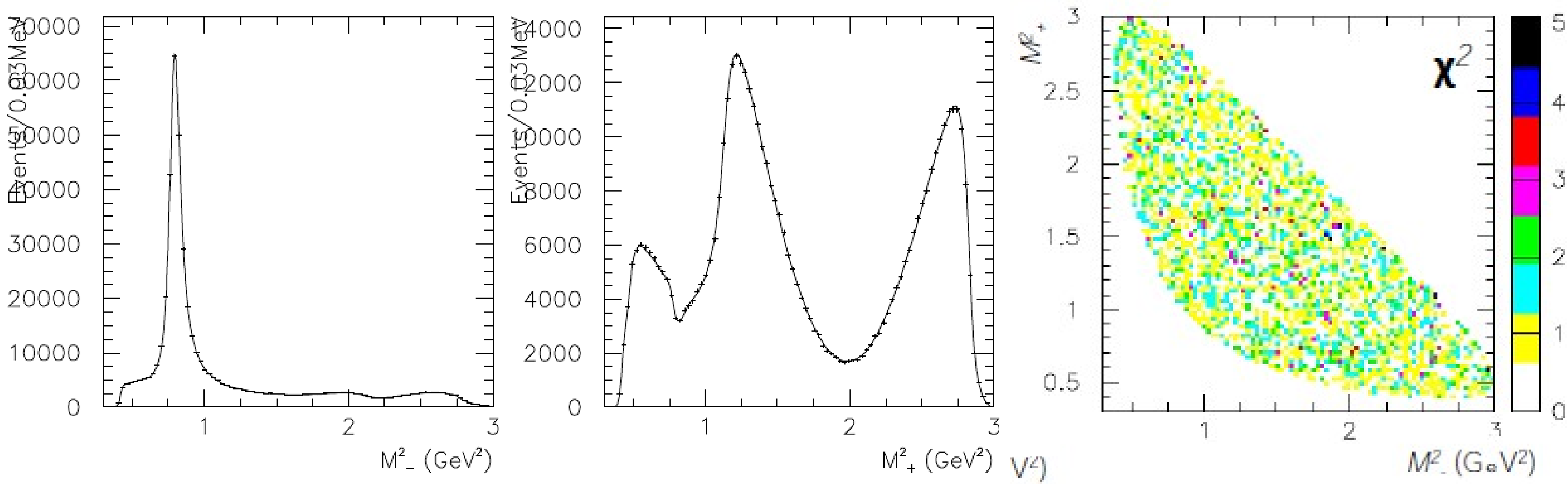
$\pi^+\pi^-$ S-wave: K-matrix model

Breit-Wigner (12 resonances) $B_{res \neq S-wave} = \sum_{res \neq S-wave} a_r e^{i\varphi_r} A_r(m^2_-, m^2_+)$

Dalitz PDF for combinatorial background: sideband region
$(0.03 < |M - 1.865| < 0.05\ \mathrm{GeV}/c^2$ and $|Q - 5.85| < 5\ \mathrm{MeV})$

DP projections of $D^0 \to K^0_S \pi^+ \pi^-$ time-integrated Dalitz fit

$\chi^2/\mathrm{ndf} = 1.246$ for $(3653 - 49)$ ndf

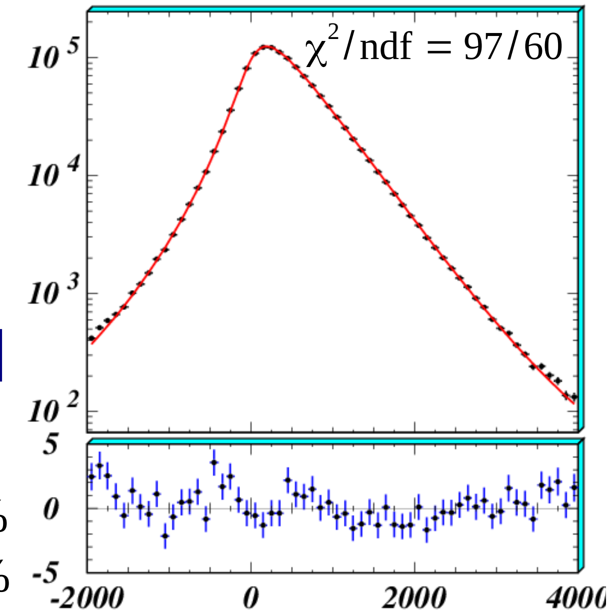


$D \to K_S^0 \pi^+ \pi^-$ time-dependent Dalitz analysis

Results (preliminary) with **920 fb^{-1}**, assuming CP conservation

$$x = (+0.56 \pm 0.19\ {}^{+0.03}_{-0.09}\ {}^{+0.06}_{-0.09})\%$$
$$y = (+0.30 \pm 0.15\ {}^{+0.04}_{-0.05}\ {}^{+0.03}_{-0.06})\%$$
(syst) (model)

$\tau = (410.3 \pm 0.4)$ fs
[$\tau_{PDG} = (410.1 \pm 1.5)$ fs]



Belle (2007) @ 540 fb^{-1}

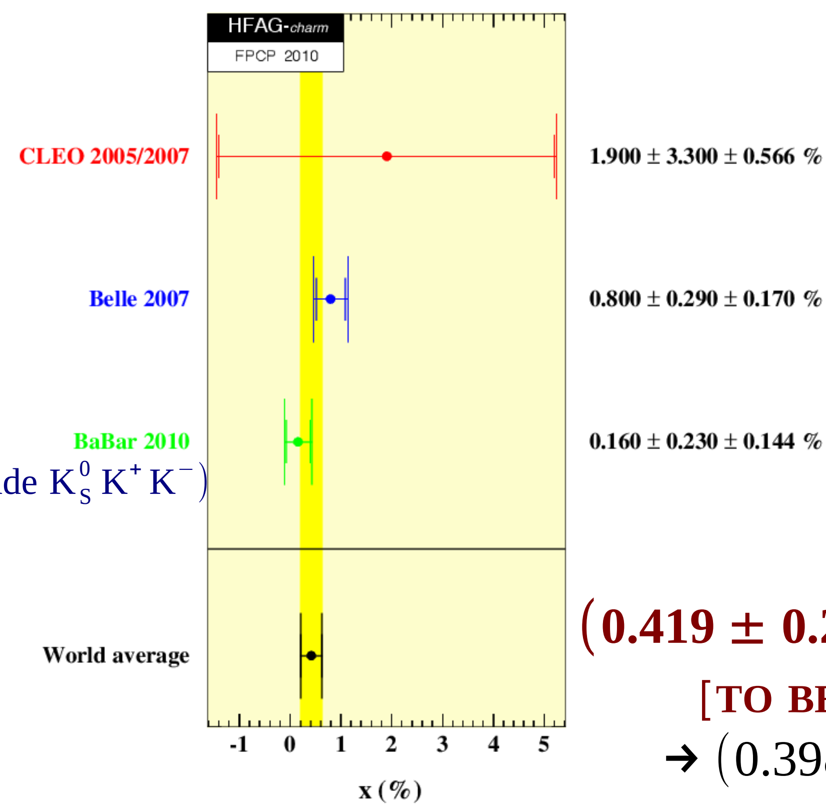
$x = (+0.80 \pm 0.29\ {}^{+0.09}_{-0.07}\ {}^{+0.10}_{-0.14})\%$

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

BaBar (2010)

$x = (+0.16 \pm 0.23 \pm 0.12 \pm 0.08)\%$

$y = (+0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%$

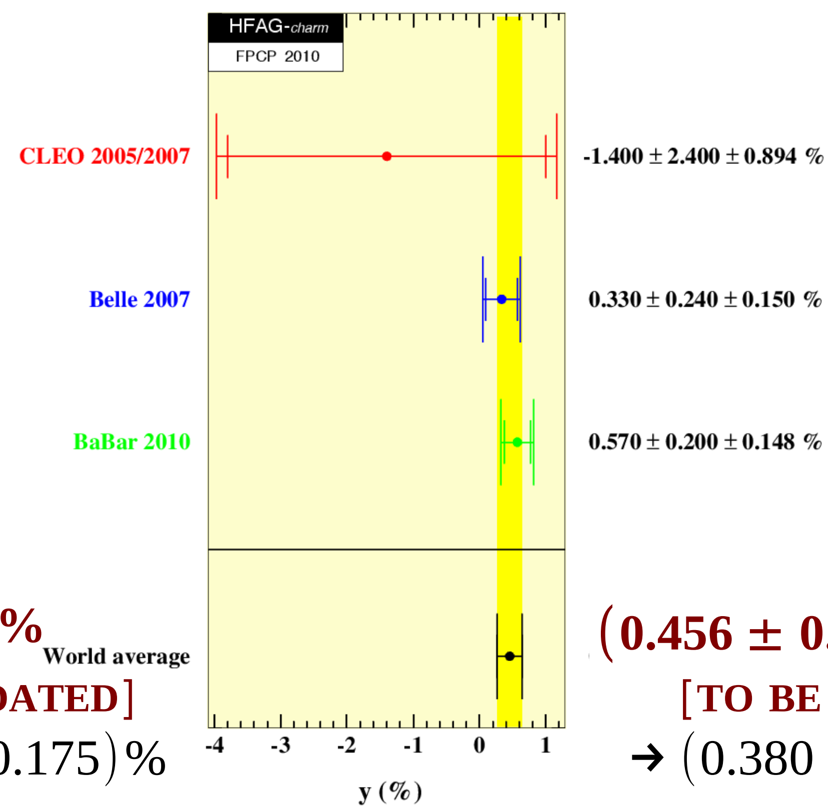


(include $K_S^0 K^+ K^-$)

(0.419 ± 0.211) %

[TO BE UPDATED]

→ (0.398 ± 0.175)%

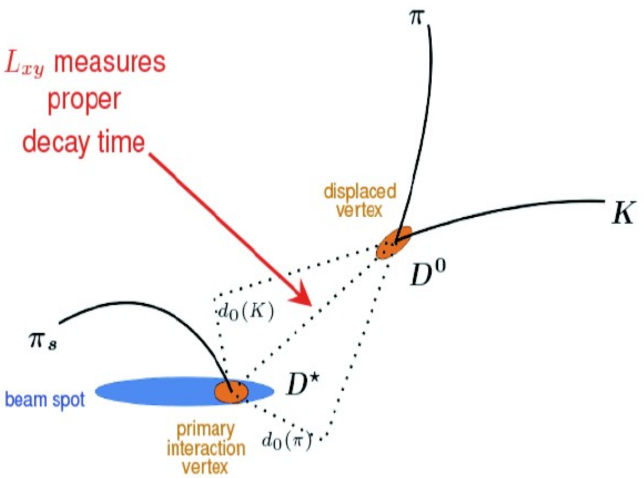


(0.456 ± 0.186) %

[TO BE UPDATED]

→ (0.380 ± 0.140)%

Charm mixing in $D^0 \to K^+ \pi^-$



D^0 is tagged by $D^{*+} \to D^0 \pi^+_s$ decay

$D^{*+} \to \pi^+ D^0$: mixing $\to \overline{D}^0$, DCS $\to K^- \pi^+$; CF $\to K^- \pi^+$

Right-Sign (RS) decay (π with the same charge)

$D^{*+} \to \pi^+ D^0$: mixing $\to \overline{D}^0$, CF $\to K^+ \pi^-$; DCS $\to K^+ \pi^-$

Wrong-Sign (WS) decay (π with the opposite charge)

The ratio $R(t)$ of WS $D^{*+} \to D^0 \pi^+_s \to K^+ \pi^- \pi^+_s$ to RS $D^{*+} \to D^0 \pi^+_s \to K^- \pi^+ \pi^+_s$ decay rates can be approximated (assuming $|x|, |y| << 1$ and no CPV) by:

DCS to CF ratio — mixing rate

$$R(t) = R_D + \sqrt{R_D}\, y' t + \frac{x'^2 + y'^2}{4} t^2$$

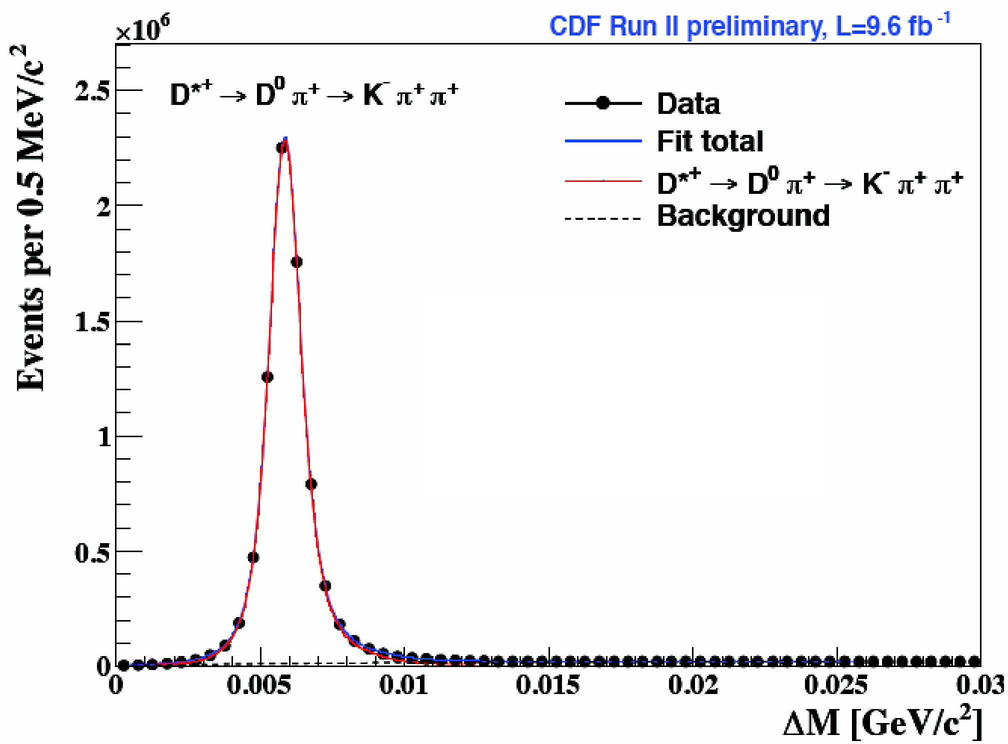
$$x' = x \cos\delta_{K\pi} + y \sin\delta_{K\pi}$$
$$y' = y \cos\delta_{K\pi} - x \sin\delta_{K\pi}$$

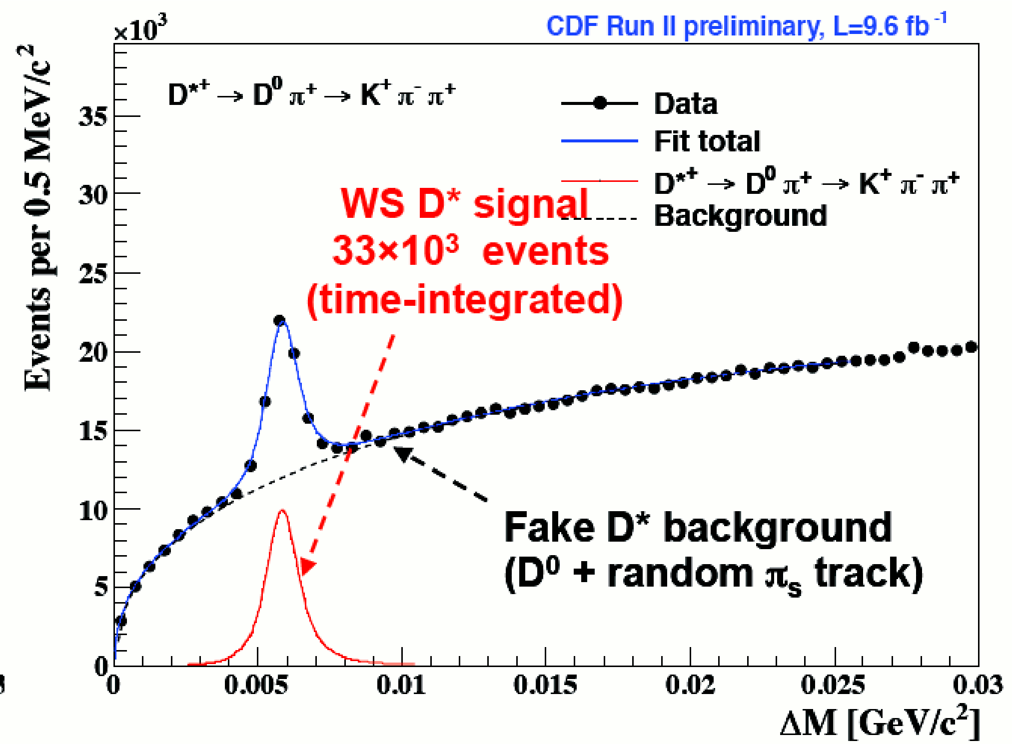
$\delta_{K\pi}$: strong phase difference btw DCS and CF amplitudes

Charm mixing in $D^0 \to K^+ \pi^-$

http://www-cdf.fnal.gov/physics/new/bottom/130408.blessed-DMix_9.6fb/public_note_CDF_D_mix.pdf

Time-integrated yields $(9.6\ fb^{-1})$





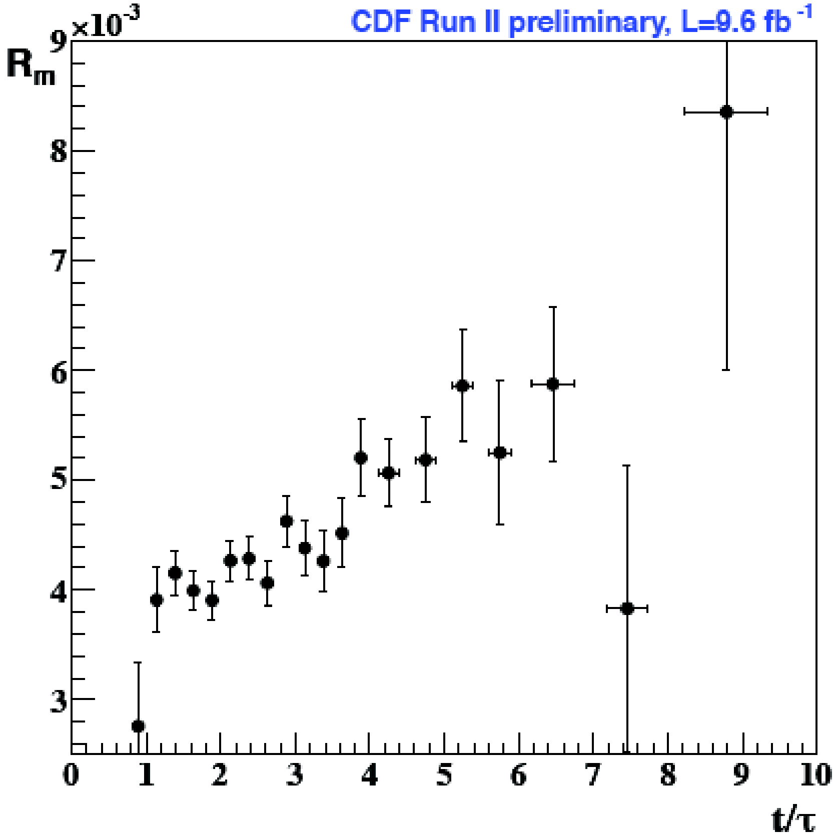
RS: $D^0 \to K^- \pi^+$
7.6M decays

WS: $D^0 \to K^+ \pi^-$
33k decays

Charm mixing in $D^0 \rightarrow K^+\pi^-$

http://www-cdf.fnal.gov/physics/new/bottom/130408.blessed-DMix_9.6fb/public_note_CDF_D_mix.pdf

Time-dependent fit strategy



In each decay-time bin

fit RS sample to determine signal shape's parameters

fit WS sample with signal shape fixed to RS

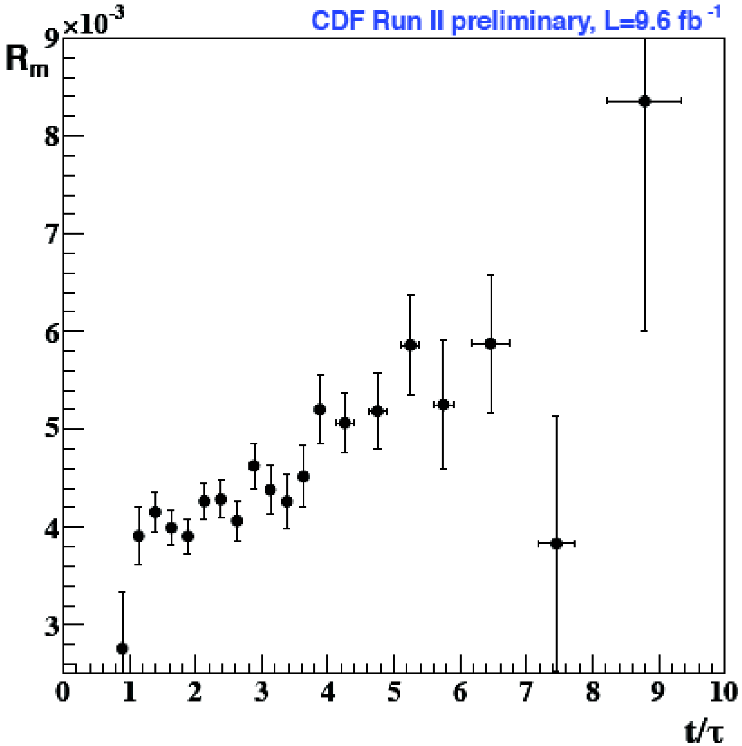
Calculate WS/RS ratio from measured yields

- ○ charm mesons from b-hadron decays
- ○ backgrounds from mis-identified charm decays peaking in $M(D^0\pi_s)$

⇒ accounted for in the time-dependent fit

Charm mixing in $D^0 \rightarrow K^+\pi^-$

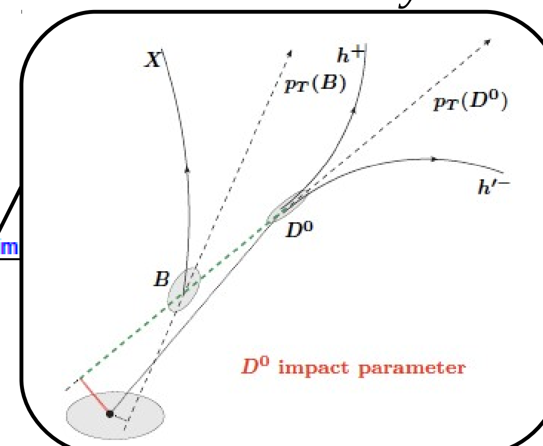
http://www-cdf.fnal.gov/physics/new/bottom/130408.blessed-DMix_9.6fb/public_note_CDF_D_mix.pdf



Calculate the WS/RS ratio from measured D^* yields in each decay time bin (20 bins)

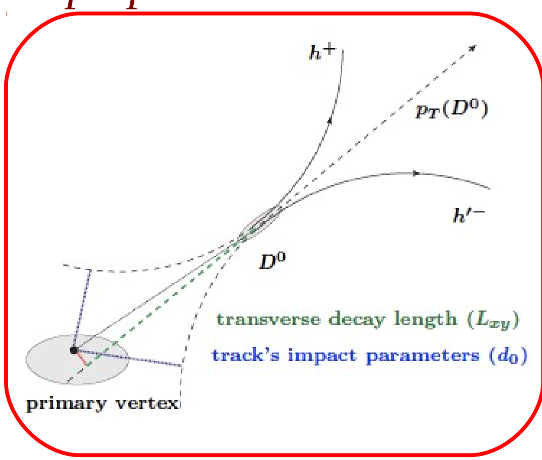
$$R_m(t) = \frac{N^{WS}(t) + N_B^{WS}(t)}{N^{RS}(t) + N_B^{RS}(t)}$$

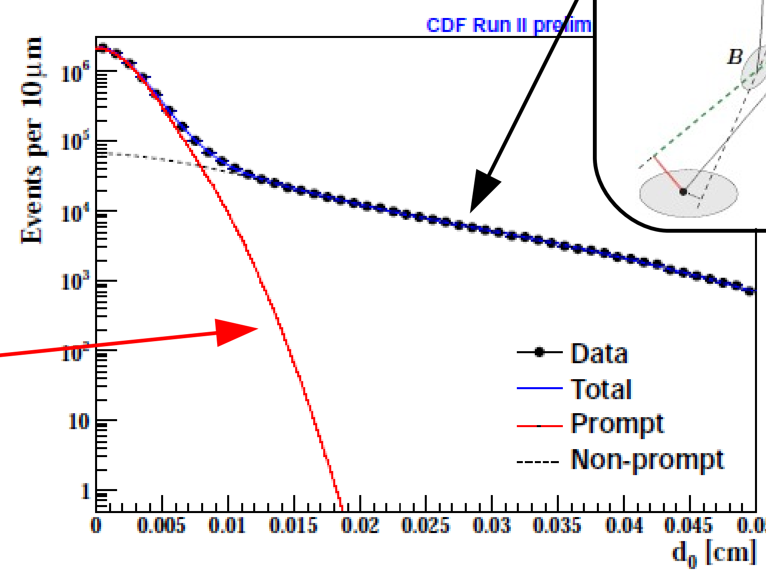
Secondary production D^0 from *B decay*



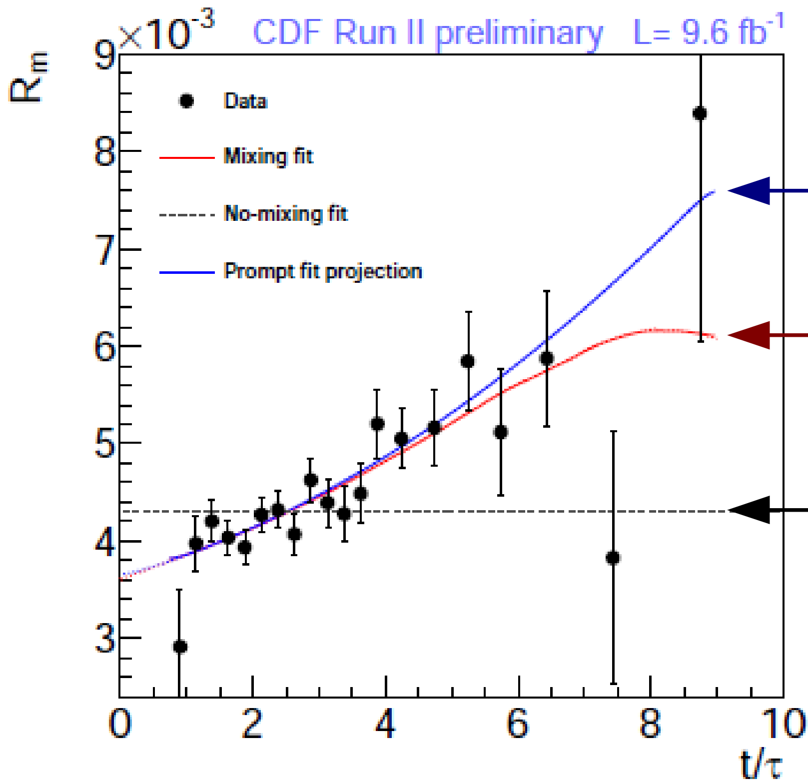
Apply $d_0(D^0) < 60\,\mu m$ to *reduce secondary D*

Prompt production D^0 from *PV*





Charm mixing in $D^0 \to K^+ \pi^-$

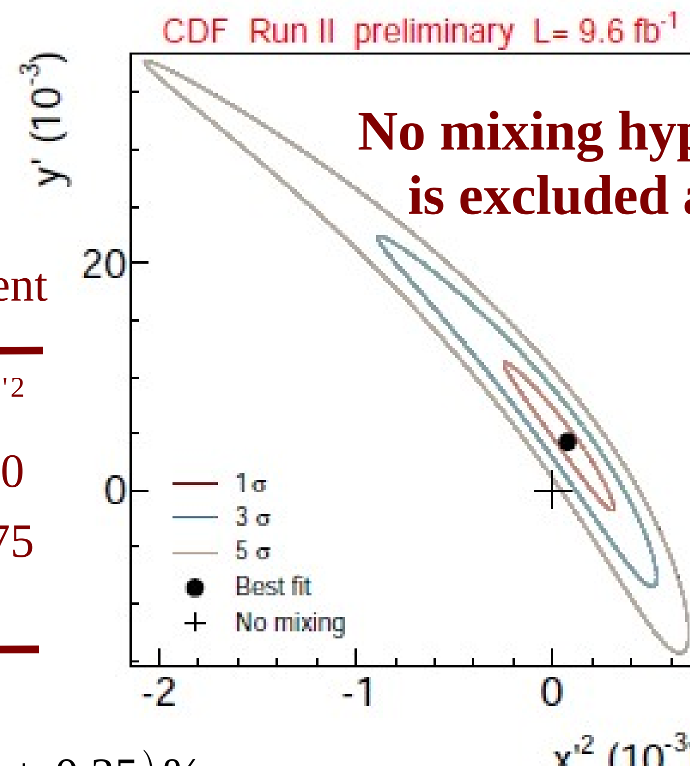


contribution from *B hadron decays is included* in *the WS/RS ratio fit*:

Projection of the prompt component of the fit, i.e. $R(t)$

Best fit, including the effect of D^* from B decays

No-mixing fit ($x'^2 = y' = 0$)



No mixing hypothesis is excluded at 6σ

Fit type	Parameter	Fit result	Correlation coefficient		
(χ^2/ndf)		(10^{-3})	R_D	y'	x'^2
Mixing	R_D	3.51 ± 0.35	1	-0.967	0.900
(16.9/17)	y'	4.3 ± 4.3		1	-0.975
	x'^2	$+0.08 \pm 0.18$			1

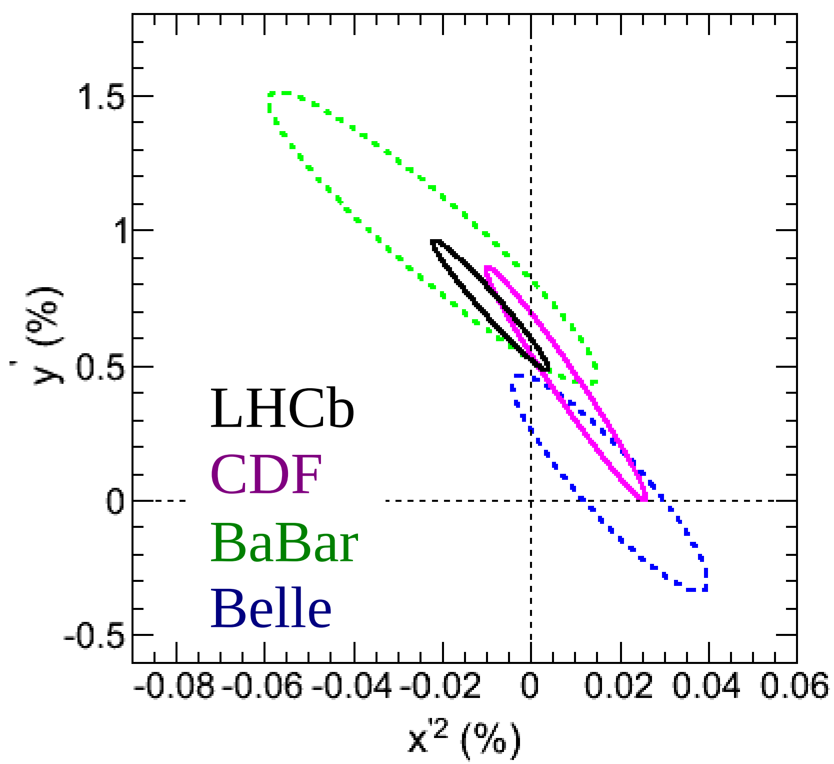
CDF (2007) $R_D = (3.04 \pm 0.55) \times 10^{-3}$

PRL 100 (2008) 121802 $y' = (8.5 \pm 7.6)\%$, $x'^2 = (-0.12 \pm 0.35)\%$

Charm mixing in $D^0 \to K^+ \pi^-$

Experiment	R_D (10^{-3})	y' (10^{-3})	x'^2 (10^{-3})	No-mixing exclusion significance
Belle PRL 96 (2006) 151801	3.64 ± 0.17	$0.6^{+4.0}_{-3.9}$	$+0.18^{+0.21}_{-0.23}$	2.0
BaBar PRL 98 (2007) 211802	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9
LHCb PRL 110 (2013) 101802	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13	9.1
CDF preliminary (2013)	3.51 ± 0.35	4.3 ± 4.3	$+0.08 \pm 0.18$	6.1

See Alberto dos Reis's talk



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

HFAG charm: A.Schwartz, B.Golob, M.Gersabeck

FPCP 2013

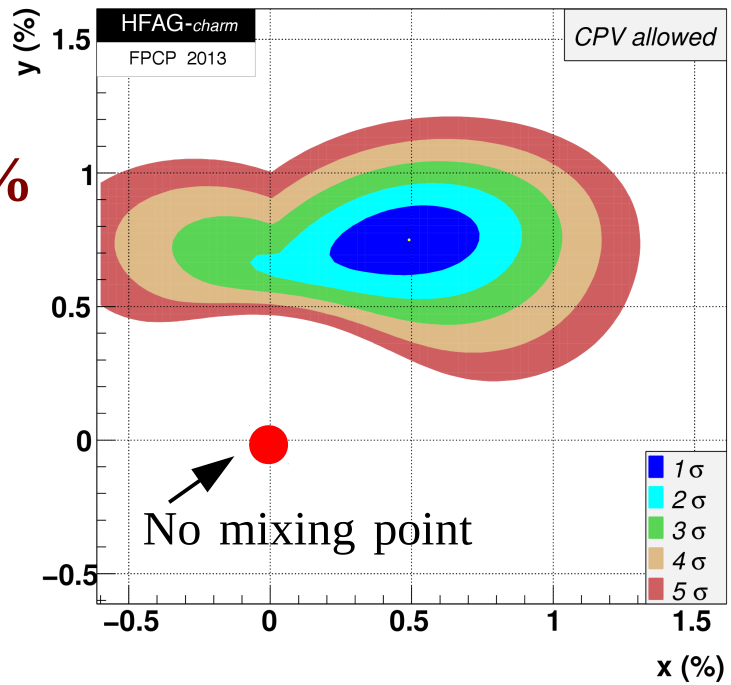
$$x = \left(0.49\,^{+0.17}_{-0.18}\right)\%$$

$$y = \left(0.75 \pm 0.09\right)\%$$

FPCP 2012:

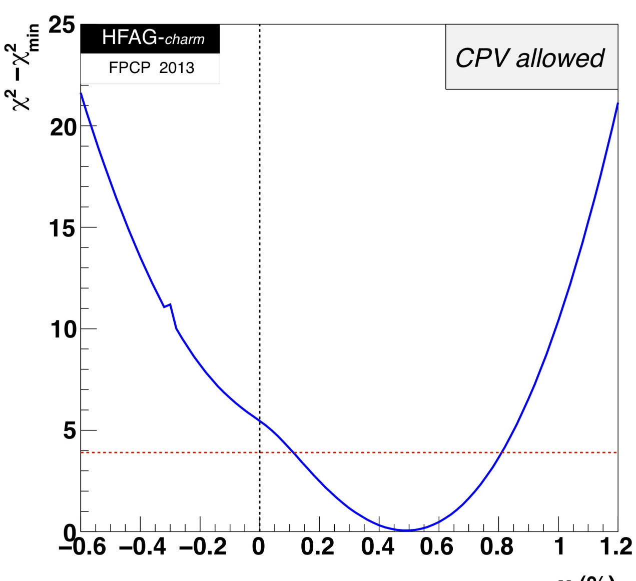
$$x = \left(0.63\,^{+0.19}_{-0.20}\right)\%$$

$$y = \left(0.75 \pm 0.12\right)\%$$

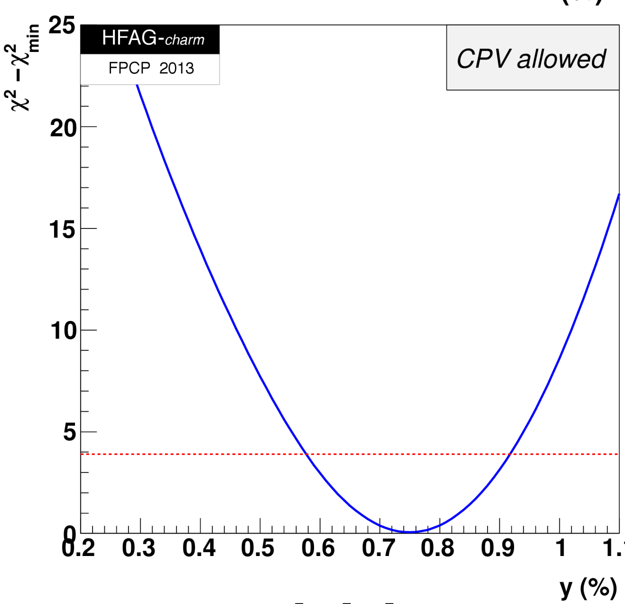


$\chi^2/\mathrm{ndf} = 66.8/41$

Observable	χ^2	$\sum\chi^2$
y_{CP}	2.94	2.94
A_Γ	0.03	2.97
$x_{K^0\pi^+\pi^-}$ Belle	0.85	3.82
$y_{K^0\pi^+\pi^-}$ Belle	1.68	5.50
$\lvert q/p\rvert_{K^0\pi^+\pi^-}$ Belle	0.34	5.84
$\phi_{K^0\pi^+\pi^-}$ Belle	1.04	6.88
$x_{K^0h^+h^-}$ BaBar	1.48	8.37
$y_{K^0h^+h^-}$ BaBar	0.42	8.79
$R_M(K^+\ell^-\nu)$	0.11	8.90
$x_{K^+\pi^-\pi^0}$ BaBar	6.22	15.12
$y_{K^+\pi^-\pi^0}$ BaBar	2.77	17.89
CLEOc		
$(x/y/R_D/\cos\delta/\sin\delta)$	10.83	28.72
$R_D^+/x'^{2+}/y'^+$ BaBar	7.95	36.67
$R_D^-/x'^{2-}/y'^-$ BaBar	5.82	42.49
$R_D^+/x'^{2+}/y'^+$ Belle	1.72	44.20
$R_D^-/x'^{2-}/y'^-$ Belle	0.66	44.87
$R_D/x'^2/y'$ CDF	3.41	48.28
$R_D/x'^2/y'$ LHCb	8.51	56.78
$A_{KK}/A_{\pi\pi}$ BaBar	0.72	57.50
$A_{KK}/A_{\pi\pi}$ Belle	1.55	59.05
$A_{KK} - A_{\pi\pi}$ CDF	1.66	60.70
$A_{KK} - A_{\pi\pi}$ LHCb (D^* tag)	0.00	60.71
$A_{KK} - A_{\pi\pi}$ LHCb ($B^0 \to D^0\mu X$ tag)	6.11	66.82



$x \leq 0$ excluded at 2.1σ



$y \leq 0$ excluded at 7.2σ

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

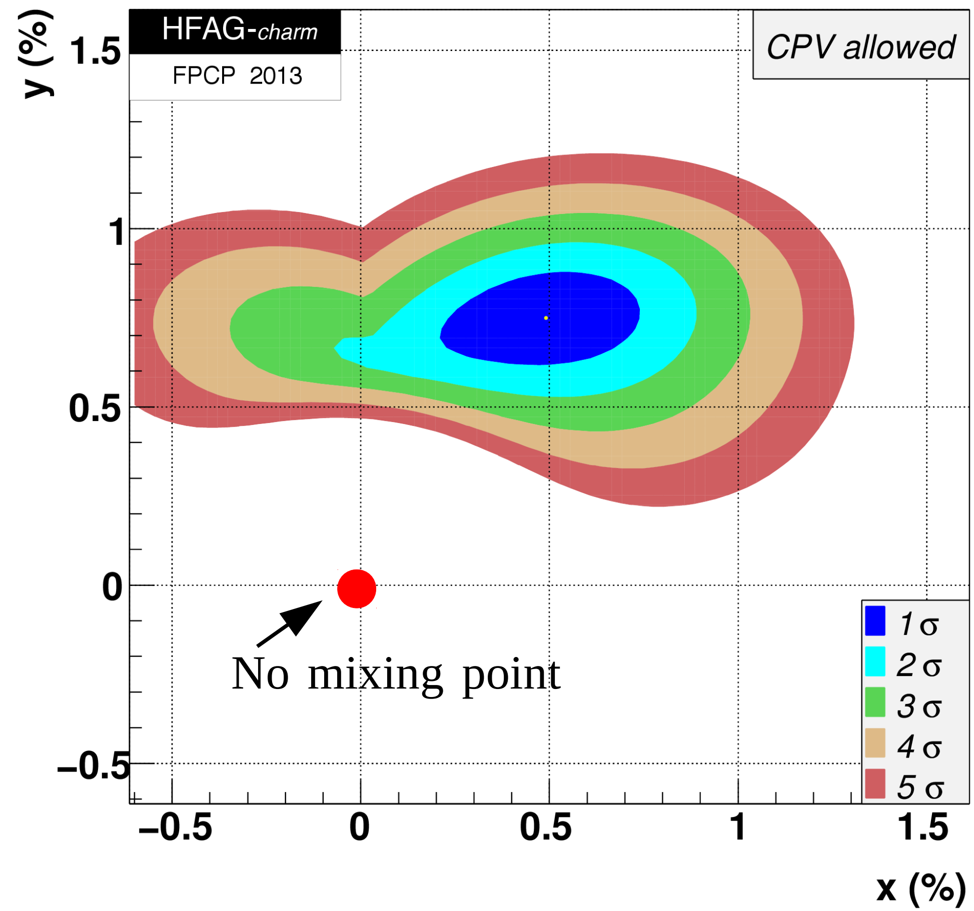
New results since FPCP2012:

- KK, $\pi\pi$: updates with full stat of Belle (tagged) and BaBar (tagged+untagged)
- $K_S\pi\pi$: update of Belle with full stat
- $K\pi$ WS: mixing observations from LHCb and CDF

FPCP 2013

$$x = \left(0.49\,^{+0.17}_{-0.18}\right)\%$$

$$y = \left(0.75 \pm 0.09\right)\%$$

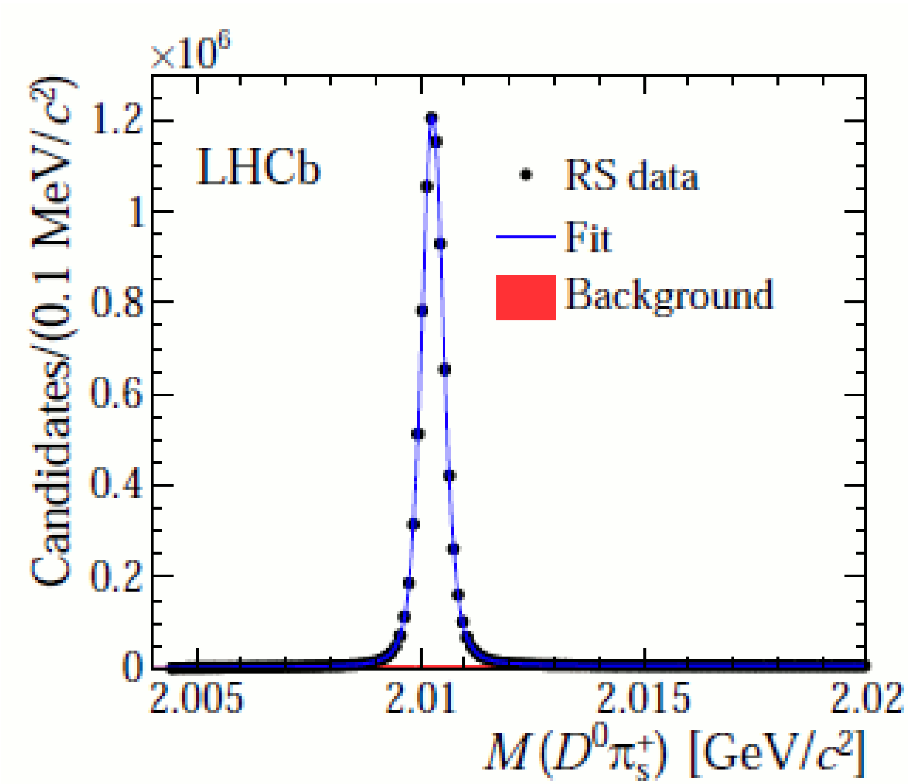


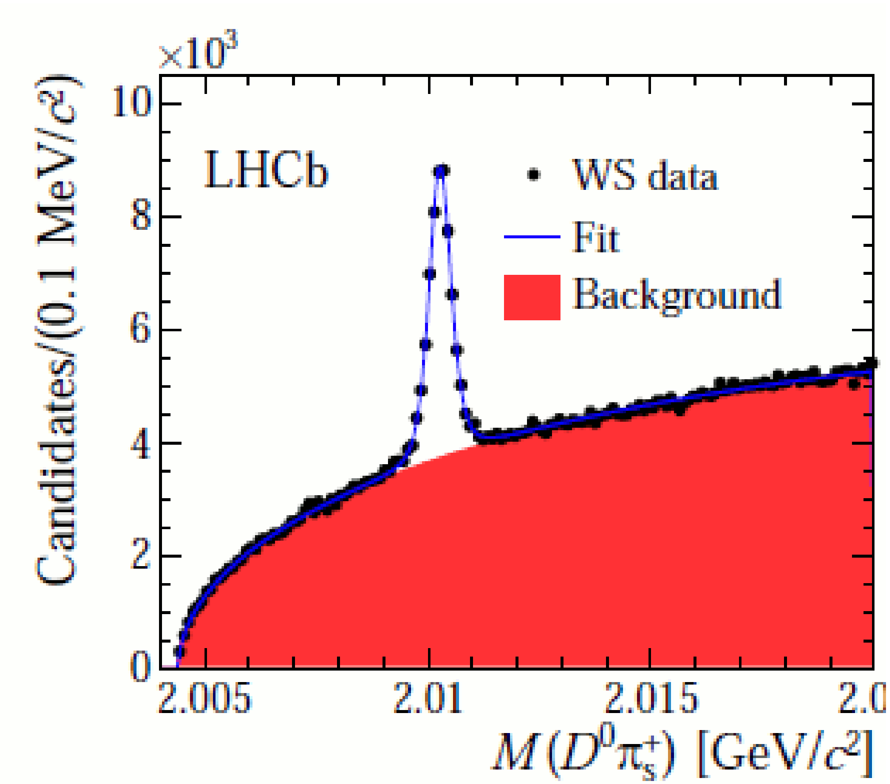
but still much work needed for precise measurements (especially for x), LHCb, Belle II, LHCb upgrade

Charm mixing in $D^0 \to K^+\pi^-$

[PRL 110, 101802 (2013), arXiv:1211.1230]

Time-integrated yields ($1\ fb^{-1}$)





RS: $D^0 \to K^-\pi^+$
8.4M decays

WS: $D^0 \to K^+\pi^-$
36k decays

Charm mixing in $D^0 \to K^+\pi^-$

[PRL 110, 101802 (2013), arXiv:1211.1230]

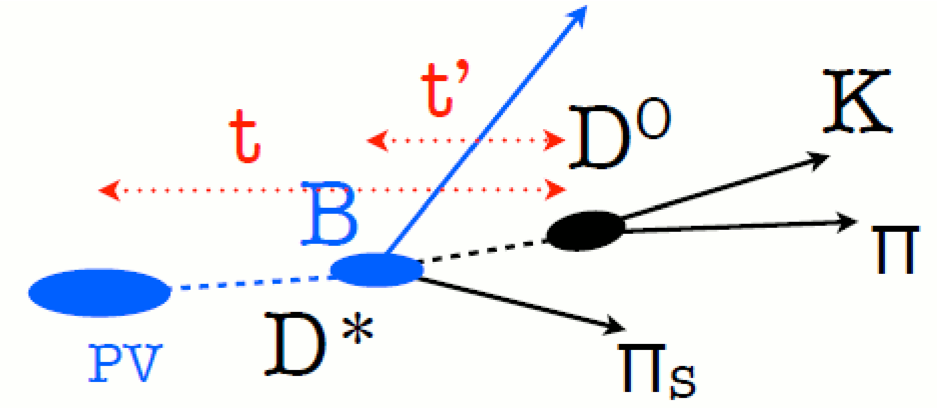
measured WS/RS ratio:

$$R^m(t) = \frac{N^{WS}(t) + N_B^{WS}(t)}{N^{RS}(t) + N_B^{RS}(t)} = R(t)\left\{1 - \underbrace{f_B^{RS}(t)\left[1 - \frac{R_B(t)}{R(t)}\right]}_{\text{bias from secondary D decays}}\right\}$$

where:

$$f_B^{RS}(t) = \frac{N_B^{RS}(t)}{N^{RS}(t) + N_B^{RS}(t)}$$

$$R_B(t) = \frac{N_B^{WS}(t)}{N_B^{RS}(t)}$$



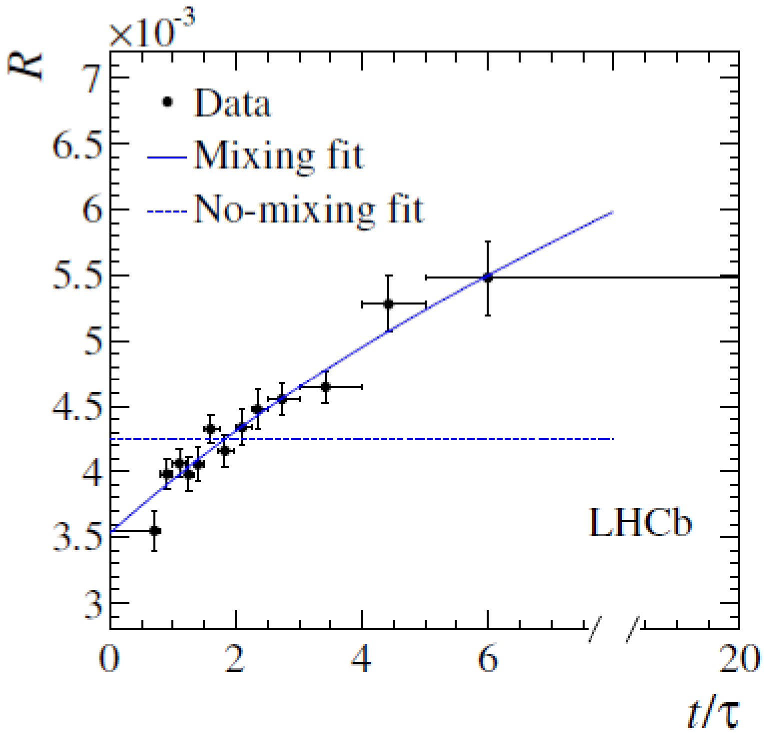
$c\tau(B) \approx 450\ \mu m$, D from B have non-zero impact parameter

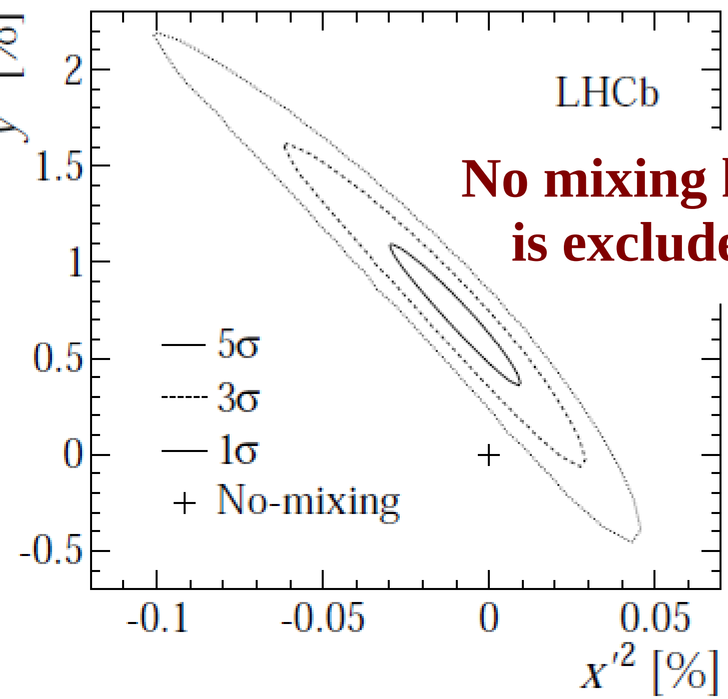
cut on $\chi^2(IP)$, remaining (3%): included in the fit, shape estimated from evts reconstructed as $B \to D^*(3)\pi$, $B \to D^*\mu X$, $D^0\mu X$

Charm mixing in $D^0 \to K^+\pi^-$ ($1\ fb^{-1}$)

[PRL 110, 101802 (2013), arXiv:1211.1230]

See A.C. dos Reis talk





No mixing hypothesis is excluded at 9 σ

1st observation of charm mixing from a single expt

Fit type	Parameter	Fit result	Correlation coefficient		
(χ^2/ndf)		(10^{-3})	R_D	y'	x'^2
Mixing	R_D	3.52 ± 0.15	1	-0.954	0.882
(9.5/10)	y'	7.2 ± 2.4		1	-0.973
	x'^2	-0.09 ± 0.13			1

$D \to K^0_S \pi^+ \pi^-$ time-dependent Daliz analysis

- For D^0 3 body self-conjugated decays, Dalitz analysis can be performed:

  e.g. in $D^0 \to K^0_S \pi^+ \pi^-$, decay amplitude $\mathcal{A}(m^2_-, m^2_+)$

  where $m^2_- \equiv m_{K^0_S \pi^-}$, $m^2_+ \equiv m_{K^0_S \pi^+}$

- In CP conservation assumption, $\mathcal{A} = \overline{\mathcal{A}}$ and $q/p = 1$

- Time-dependent decay amplitude for a D^0 or a $\overline{D}^0$ tagged at $t = 0$:

$$|\mathcal{M}(m^2_-, m^2_+, t)|^2 = (|A_1|^2 e^{-\mathbf{y}t} + |A_2|^2 e^{-\mathbf{y}t} + 2\,\Re[A_1 A_2^*] \cos(\mathbf{x}t) + 2\,\Im[A_1 A_2^*] \sin(\mathbf{x}t))\, e^{-t}$$

$$|\overline{\mathcal{M}}(m^2_-, m^2_+, t)|^2 = (|\overline{A}_1|^2 e^{-\mathbf{y}t} + |\overline{A}_2|^2 e^{-\mathbf{y}t} + 2\,\Re[\overline{A}_1 \overline{A}_2^*] \cos(\mathbf{x}t) + 2\,\Im[\overline{A}_1 \overline{A}_2^*] \sin(\mathbf{x}t))\, e^{-t}$$

t in unit of D^0 lifetime, **y** modifies the lifetime of certain contributions to the DP,
x introduces a sinusoidal rate variation

Simultaneous determination of x and y