D Mixing and CP Violation

Boštjan Golob
University of Ljubljana/Jožef Stefan Institute & Belle/Belle II Collaboration

University of Ljubljana
"Jožef Stefan" Institute

Part I

1. Introduction
2. Mixing phenomenology
3. Mixing measurements

Part II

1. CPV phenomenology
2. CPV measurements
3. Constraints on NP
4. Outlook

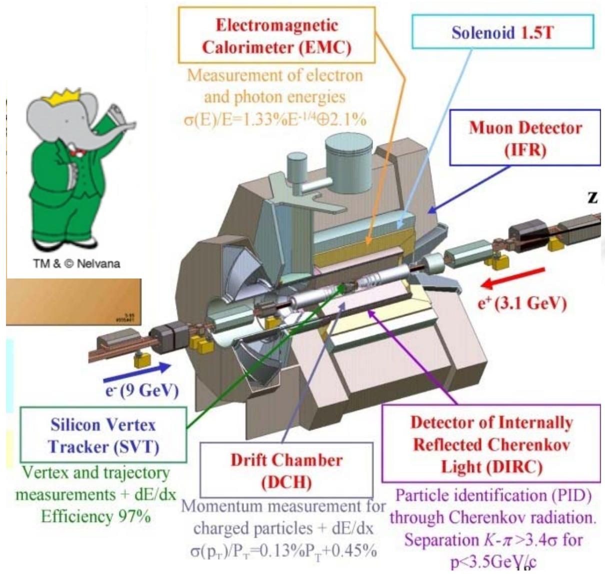
Topical Seminars on Frontier of Particle Physics,
Hu Yu Village, Aug 27 – Aug 31, 2010

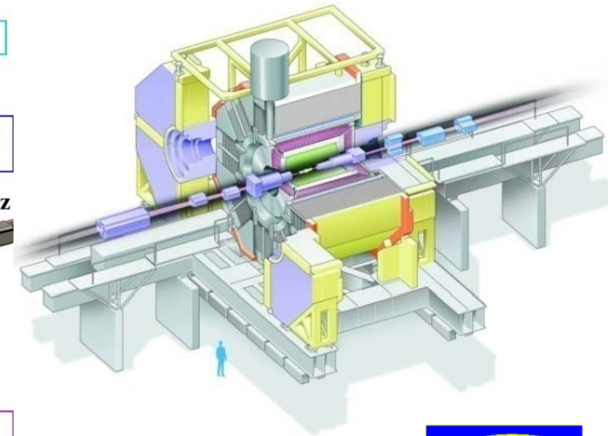
Introduction

Experiments

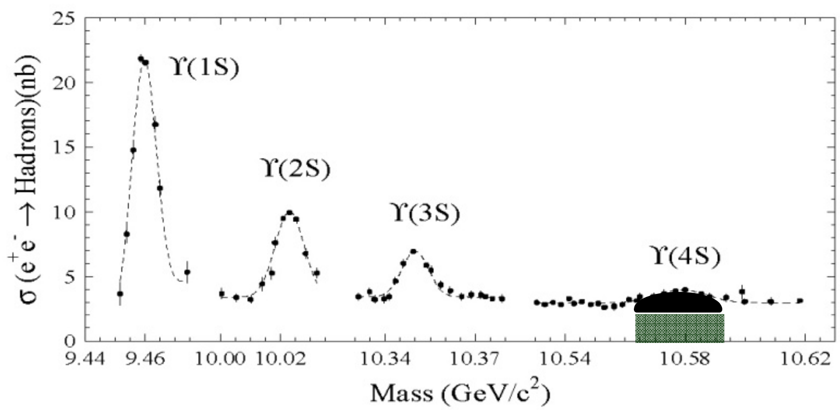
B-Factories

BaBar @ PEPII
SLAC



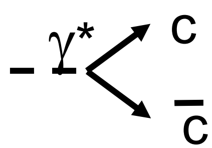


Belle @ KEKB
KEK



on resonance production
$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0, B^+B^-$
$\sigma(B\bar{B}) \approx$ 1.1 nb (~10^9 $B\bar{B}$ pairs)

continuum production
$\sigma(c\bar{c}) \approx$ 1.3 nb (~1.3×10^9 $X_c\bar{Y}_c$ pairs)
$N_{rec}(D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+) \approx 2.5\times10^6$

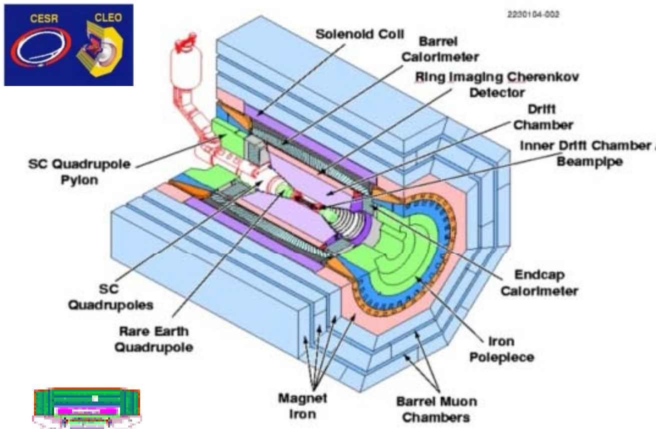


B-factory=
charm factory

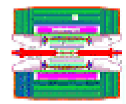
Experiments

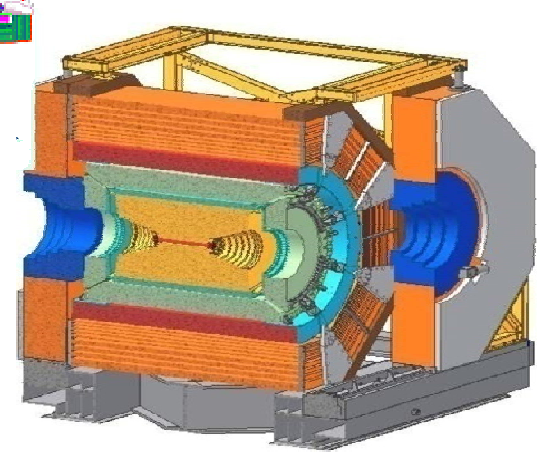
Charm-Factories

Cleo-c @ CESR
Cornell



BESIII @ BEPC-II
IHEP





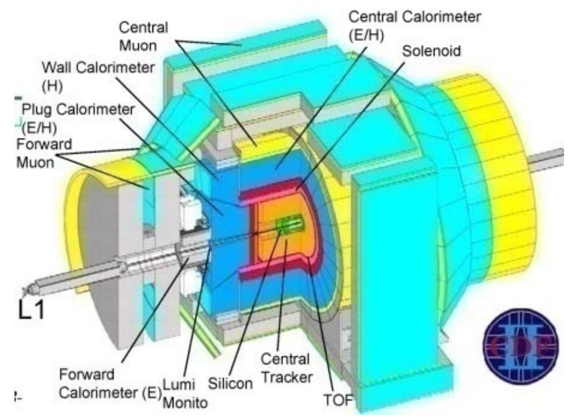
$e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0, D^+D^-$

Cleo-c:
~800 pb^{-1} of data
available at ψ(3770); 2.8x10^6 $D^0\bar{D}^0$
$N_{rec}(D^0 \rightarrow K^- \pi^+) \approx 150\text{x}10^3$ (single tag)

BES-III:
~900 pb^{-1} of data (?)
available at ψ(3770);

$D\bar{D}$ in coherent (C = -1) state

Experiments



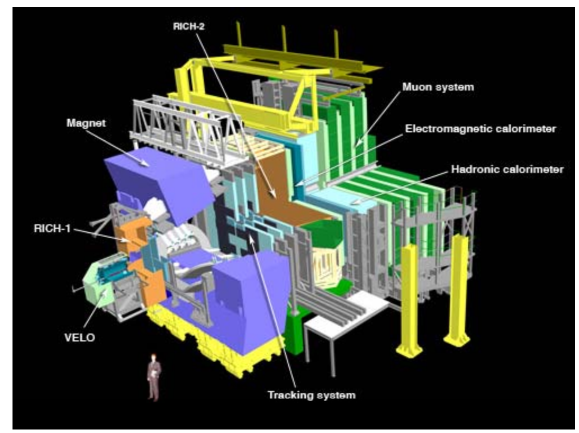
$p\overset{(-)}{p}$ Colliders

D0, CDF @ Tevatron
Fermilab

~ 6 fb^{-1} available

$N_{rec}(D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi^+) \approx 7\text{x}10^6$

LHCb @ LHC
CERN



For 2 fb^{-1} (currently 1 pb^{-1})

$N_{rec}(D^{*+} \to D^0 \pi^+ \to K^- \pi^+ \pi^+) \approx 15\text{x}10^6$

diverse exp. conditions to study charm physics

We all live with the objective of being happy; our lives are all different and yet the same.

Anne Frank (1929 -1945)

huge statistics in more requiring exp. environment

Flavor physics

Questions (to SM)

You always admire what you really don't understand.

B. Pascal (1623 - 1662)

Why are we humans and not anti-humans?

Sakharov, CP violation;
CPV in SM small

Why are some large and some small?

Hierarchy, three generations

Why am I massive?

Origin of EW symmetry breaking;
beyond SM theories may explain,
but at what scale?
Precission needed

Charm physics

Charm is... a way of getting the answer yes without having asked any clear question.

A. Camus (1913 - 1960)

Dual role

- experimental tests of theor. predictions (most notably of (L)QCD); improve precision of CKM measurements (B physics);

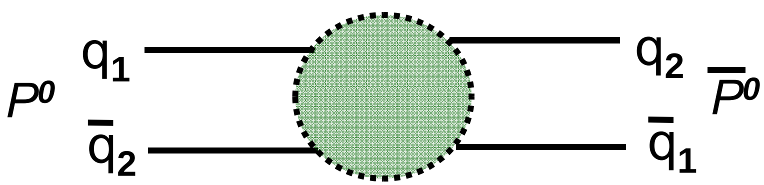
example: leptonic decays of D mesons → decay constants, tests of LQCD;

- standalone field of SM tests and searches for new phenomena (SM and/or NP);

example: mixing and CPV in D^0 system

Mixing of neutral mesons

Phenomena
in course of life neutral meson P^0 can transform into anti-meson $\bar{P}^0$



$P^0 = K^0, B_d^0, B_s^0$ and D^0

History

observation of K^0:
1950 (Caletch)
mixing in K^0:
1956 (Columbia) — 6 years
c quark mass
observation of B_d^0:
1983 (CESR)
mixing in B_d^0:
1987 (Desy) — 4 years
t quark mass
observation of B_s^0:
1992 (LEP)
mixing in B_s^0:
2006 (Fermilab) — 14 years
????
observation of D^0:
1976 (SLAC)
mixing in D^0:
2007 (KEK, SLAC) — 31 years
????
(evidence of)

Time evolution

D. Kirkby, Y. Nir, *CPV in Meson Decays*, in RPP

Schrödinger equation
mixing affects the time evolution → oscillations

state initially produced as

$$\left|\psi(t=0)\right\rangle = a(0)\left|P^0\right\rangle + b(0)\left|\overline{P}^0\right\rangle$$

will evolve in time as

$$\left|\psi(t)\right\rangle = a(t)\left|P^0\right\rangle + b(t)\left|\overline{P}^0\right\rangle + \ldots$$

if interested in *a(t), b(t):*
effective Hamiltonian
H=M-(i/2)Γ (non-Hermitian)
and t-dependent Schrödinger eq.:

$$i\frac{\partial}{\partial t}\begin{bmatrix}\left|P^0(t)\right\rangle \\ \left|\overline{P}^0(t)\right\rangle\end{bmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{bmatrix}\left|P^0(t)\right\rangle \\ \left|\overline{P}^0(t)\right\rangle\end{bmatrix}$$

eigenstates:
(well defined $m_{1,2}$ and $\Gamma_{1,2}$)

$$\left|P_{1,2}\right\rangle = p\left|P^0\right\rangle \pm q\left|\overline{P}^0\right\rangle$$

Time evolution

Schrödinger equation
eigenvalues
diagonal elem.:
$P^0 \leftrightarrow P^0$
non-diagonal elem.:
$P^0 \leftrightarrow \bar{P}^0$

$$\begin{bmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M - i\frac{\Gamma}{2} \end{bmatrix} \begin{bmatrix} p \\ \pm q \end{bmatrix} = \lambda_{1,2} \begin{bmatrix} p \\ \pm q \end{bmatrix}$$

$$\lambda_{1,2} = M - i\frac{\Gamma}{2} \pm \frac{q}{p}\left[M_{12} - i\frac{\Gamma_{12}}{2}\right] \equiv m_{1,2} - i\frac{\Gamma_{1,2}}{2}, \quad \left(\frac{q}{p}\right)^2 = \frac{M_{12}{}^* - i\frac{\Gamma_{12}{}^*}{2}}{M_{12} - i\frac{\Gamma_{12}}{2}}$$

q/p: CPV;
if CPV neglected q/p=1

$P_{1,2}$ evolve in time according to $m_{1,2}$ and $\Gamma_{1,2}$:

$$\left|P_{1,2}(t)\right\rangle = e^{-i\lambda_{1,2}t}\left|P_{1,2}(t=0)\right\rangle$$

Time evolution

$$|P^0(t)\rangle = \frac{1}{2p}\left[|P_1(t)\rangle + |P_2(t)\rangle\right]$$

$$|\overline{P}^0(t)\rangle = \frac{1}{2q}\left[|P_1(t)\rangle - |P_2(t)\rangle\right]$$

Flavor states

state initially produced as pure P^0 or $\overline{P}^0$

$$|P^0(t)\rangle = \left[|P^0\rangle \cosh\left(\frac{ix+y}{2}\overline{\Gamma}t\right) - \frac{q}{p}|\overline{P}^0\rangle \sinh\left(\frac{ix+y}{2}\overline{\Gamma}t\right)\right] e^{-i\overline{m}t-\frac{\overline{\Gamma}}{2}t}$$

$$|\overline{P}^0(t)\rangle = \left[|\overline{P}^0\rangle \cosh\left(\frac{ix+y}{2}\overline{\Gamma}t\right) - \frac{p}{q}|P^0\rangle \sinh\left(\frac{ix+y}{2}\overline{\Gamma}t\right)\right] e^{-i\overline{m}t-\frac{\overline{\Gamma}}{2}t}$$

can at a later time t be $\overline{P}^0$ or P^0, depending on values of mixing parameters x, y:

$$x \equiv \frac{m_1 - m_2}{\overline{\Gamma}}; y \equiv \frac{\Gamma_1 - \Gamma_2}{2\overline{\Gamma}}; \overline{\Gamma} \equiv \frac{\Gamma_1 + \Gamma_2}{2}; \overline{m} \equiv \frac{m_1 + m_2}{2}$$

Time evolution

M. Gronau et al., PLB508, 37 (2001)

Flavor states

coherent pair production from vector resonance

$e^+e^- \to V \to P^0 \overline{P}^0$

$V=\Upsilon(4S)$ B^0
$V=\Psi(3770)$ D^0
$V=\Phi$ K^0

$$\psi = \frac{1}{\sqrt{2}}\left[\left|P^0(\vec{p}_1)\right\rangle\left|\overline{P}^0(\vec{p}_2)\right\rangle \pm \left|\overline{P}^0(\vec{p}_1)\right\rangle\left|P^0(\vec{p}_2)\right\rangle\right]$$

initial state, C= ±1

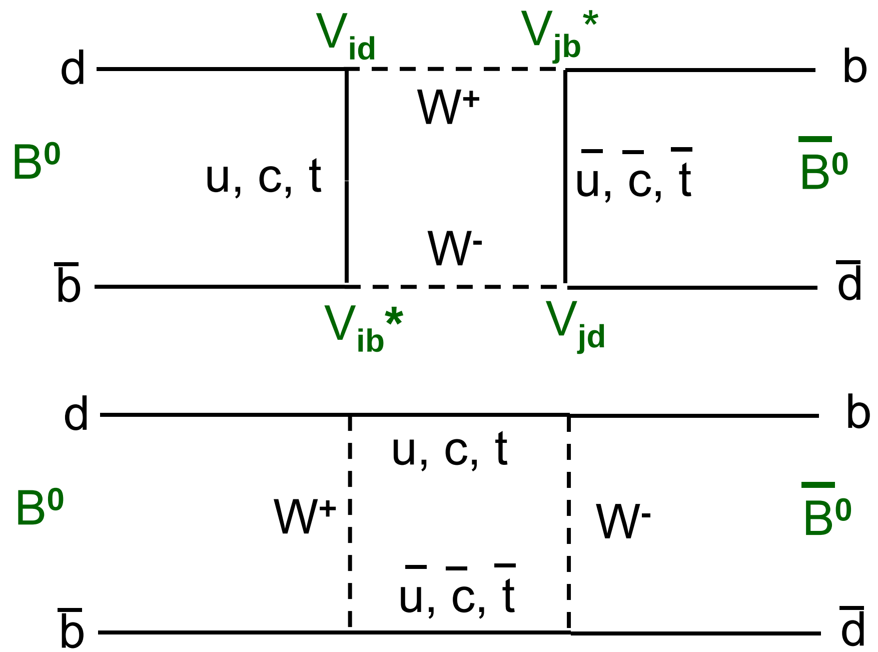
$$\psi(t_1,t_2) = \frac{1}{\sqrt{2}} e^{-(\overline{m}-i\overline{\Gamma}/2)(t_1+t_2)}\left\{\cos\left(\overline{\Gamma}\frac{x-iy}{2}(t_1 \pm t_2)\right)\left[\left|P^0(\vec{p}_1)\right\rangle\left|\overline{P}^0(\vec{p}_2)\right\rangle \pm \left|\overline{P}^0(\vec{p}_1)\right\rangle\left|P^0(\vec{p}_2)\right\rangle\right] \pm \right.$$
$$\left. \pm i\sin\left(\overline{\Gamma}\frac{x-iy}{2}(t_1 \pm t_2)\right)\left[\left|P^0(\vec{p}_1)\right\rangle\left|P^0(\vec{p}_2)\right\rangle - \left|\overline{P}^0(\vec{p}_1)\right\rangle\left|\overline{P}^0(\vec{p}_2)\right\rangle\right]\right\}$$

Mixing rate

Phenomenology

P^0-$\bar{P}^0$ transition → box diagram at quark level

P^0: any pseudo-scalar meson; specific example of B_d^0



$$\left\langle \overline{B}^0 \middle| H_{wk} \middle| B^0 \right\rangle \propto \sum_{i,j=u,c,t} V_{ib}^* V_{id} V_{jd} V_{jb}^* \mathcal{F}(m_W^2, m_i^2, m_j^2)$$

if $m_i = m_j \Rightarrow$ due to CKM unitarity: no mixing

Mixing rate

Phenomenology
simplified treatment
based on dimension:

$$\left\langle \overline{B}^0 \middle| H_{wk} \middle| B^0 \right\rangle \propto \sum_{i,j=u,c,t} V_{ib}^* V_{id} V_{jd} V_{jb}^* \mathcal{F}(m_W^2, m_i^2, m_j^2)$$

O. Nachmtann, Elem. Part. Phys., Springer-Verlag

$$\mathcal{F}(m_W^2, m_i^2, m_j^2) \propto f_0 m_W^2 + f_1 m_i^2 + f_2 m_j^2 + f_3 m_i m_j + O(m_W^{-2})$$

for serious treatment see e.g.: A.J. Buras et al., Nucl.Phys.B245, 369 (1984)

CKM unitarity $\Rightarrow$

$$\left\langle \overline{B}^0 \middle| H_{wk} \middle| B^0 \right\rangle \propto \sum_{i,j=u,c,t} V_{ib}^* V_{id} V_{jd} V_{jb}^* m_i m_j$$

Homework: contribution of which quark is dominant in the above expression?

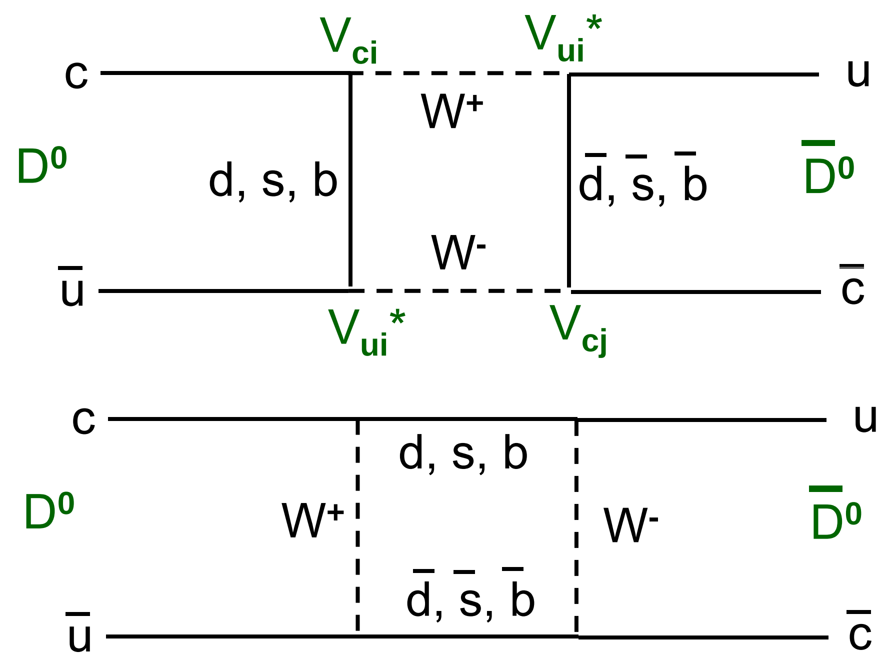
Mixing rate

Phenomenology

D^0 case

the only *P^0* system with uplike q's

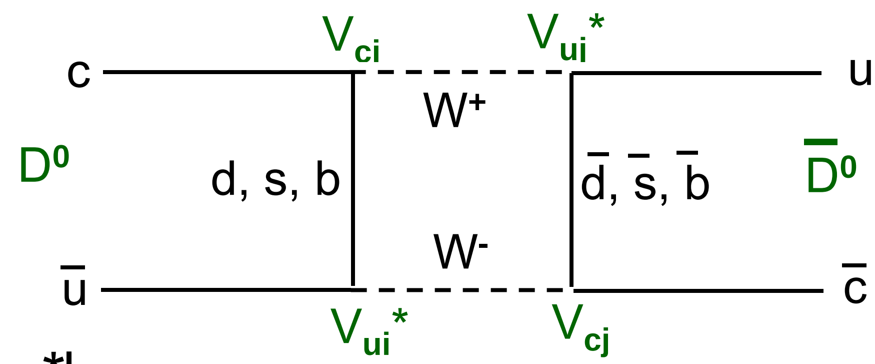
the system resisiting exp. observation for the longest time



$$\left\langle \bar{D}^0 \middle| H_{wk} \middle| D^0 \right\rangle \propto \sum_{i,j=d,s,b} V_{ui}^* V_{ci} V_{cj} V_{uj}^* m_i m_j$$

Mixing phenomenology

Mixing rate



Phenomenology

$|V_{cb}V_{ub}^*| << |V_{cs}V_{us}^*|, |V_{cd}V_{ud}^*|$
assuming unitarity in
2 generations $\Rightarrow$

$$\langle \bar{D}^0 | H_{wk} | D^0 \rangle \propto \underbrace{V_{us}^* V_{cs} V_{cd} V_{ud}^*}_{\text{DCS}} \underbrace{(m_s - m_d)^2}_{\text{SU(3) breaking}}$$

more involved (and correct) calculation:

A.F. Falk et al., PRD65, 054034 (2002)

G. Burdman, I. Shipsey, Ann.Rev.Nucl.Sci. 53, 431 (2003)

$$\langle \bar{D}^0 | H_w^{\Delta C=-2} | D^0 \rangle = \frac{G_F^2}{4\pi^2} \underbrace{V_{cs}^* V_{cd}^* V_{ud} V_{us}}_{\text{DCS}} \underbrace{\frac{(m_s^2 - m_d^2)^2}{m_c^2}}_{\text{SU(3) breaking}} \langle \bar{D}^0 | \bar{u}\gamma^\mu (1-\gamma_5) c \bar{u} \gamma_\mu (1-\gamma_5) c | D^0 \rangle$$

Mixing rate

Phenomenology

2nd order perturb. theory

$$(M - i\frac{\Gamma}{2})_{ij} = \frac{\langle D_i | H_{eff} | D_j \rangle}{2M_D} =$$

$$= M_D \delta_{ij} + \frac{1}{2M_D} \langle \overline{D}^0 | H_w^{\Delta C=-2} | D^0 \rangle +$$

$$+ \frac{1}{2M_D} \sum_n \frac{\langle \overline{D}^0 | H_w^{\Delta C=-1} | n \rangle \langle n | H_w^{\Delta C=-1} | D^0 \rangle}{M_D - E_n + i\varepsilon}$$

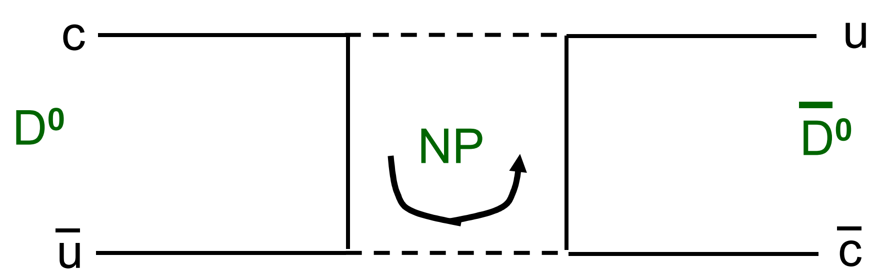
$\Delta m = m_1 - m_2 = f(M_{12}, \Gamma_{12})$

$\Delta\Gamma = \Gamma_1 - \Gamma_2 = g(M_{12}, \Gamma_{12})$

short distance $|x| \sim \mathcal{O}(10^{-5})$

common statement: mixing with large x sign of NP;

more appropriate: measurement of x yields complementary constraints on NP models (because of specific uplike q couplings)



Mixing rate

Phenomenology

2nd order perturb. theory

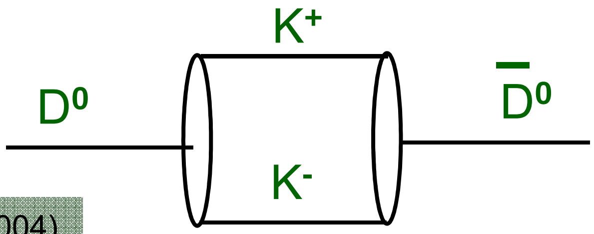
long distance

$$(M - i\frac{\Gamma}{2})_{ij} = \frac{\langle D_i | H_{eff} | D_j \rangle}{2M_D} =$$

$$= M_D \delta_{ij} + \frac{1}{2M_D}\langle \overline{D}^0 | H_w^{\Delta C=-2} | D^0 \rangle +$$

$$+ \frac{1}{2M_D}\sum_n \frac{\langle \overline{D}^0 | H_w^{\Delta C=-1} | n \rangle \langle n | H_w^{\Delta C=-1} | D^0 \rangle}{M_D - E_n + i\varepsilon}$$

difficult to calculate;
contributes to real and imaginary part $\Rightarrow$ affects *x* and *y*;



two approaches:
OPE — I.I. Bigi, N. Uraltsev, Nucl. Phys. B592, 92 (2001)
exclusive approach — A.F. Falk et al., PRD69, 114021 (2004)
(principle can be easy understood, see p. II/26)

$$|x|, |y| \leq \mathcal{O}(10^{-2})$$

$$\frac{1}{M_D - E_n + i\varepsilon} = PV\left(\frac{1}{M_D - E_n}\right) + i\pi\delta(E_n - M_D)$$

Mixing of neutral mesons

Observables

(B-factories, hadron machines)

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

$|x|, |y| << 1 \Rightarrow$

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left|A_f + \frac{q}{p}\frac{ix+y}{2}\overline{A}_f\,\overline{\Gamma}t\right|^2$$

$$A_f = \left\langle f \middle| D^0 \right\rangle,\ \overline{A}_f = \left\langle f \middle| \overline{D}^0 \right\rangle$$

$$\frac{dN(\overline{D}^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left|\overline{A}_f + \frac{p}{q}\frac{ix+y}{2}A_f\,\overline{\Gamma}t\right|^2$$

Decay time distribution of experimentally accessible states D^0, $\overline{D}^0$ sensitive to mixing parameters x and y, depending on final state

Mixing of neutral mesons

Observables

(Charm-factories)

coherent production, $V(C= -1) \rightarrow D^0\overline{D}^0$

t-integrated rate

$$\Gamma(V \rightarrow D^0\overline{D}^0 \rightarrow f_1 f_2) = \frac{1}{2}|a_-|^2\left(\frac{1}{1-y^2}+\frac{1}{1+x^2}\right)+\frac{1}{2}|b_-|^2\left(\frac{1}{1-y^2}-\frac{1}{1+x^2}\right)$$

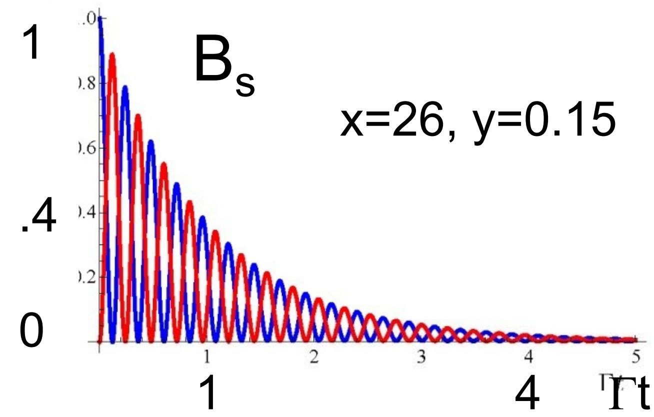
$$a_- = A_{f1}\overline{A}_{f2} - \overline{A}_{f1}A_{f2}; \quad b_- = \frac{p}{q}A_{f1}A_{f2} - \frac{q}{p}\overline{A}_{f1}\overline{A}_{f2}$$

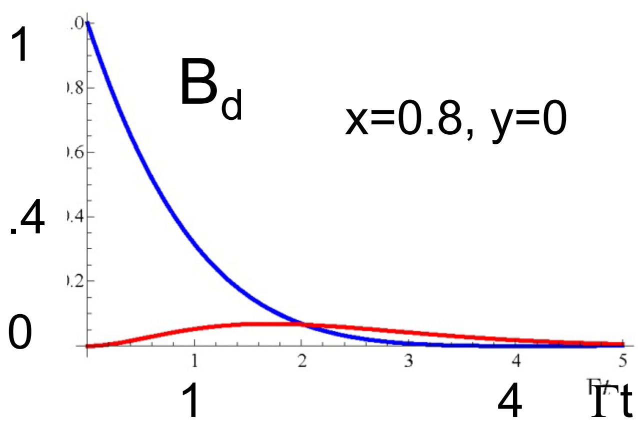
Decay rate of experimentally accessible states D^0, $\overline{D}^0$ sensitive to mixing parameters x and y, depending on final state

Mixing of neutral mesons

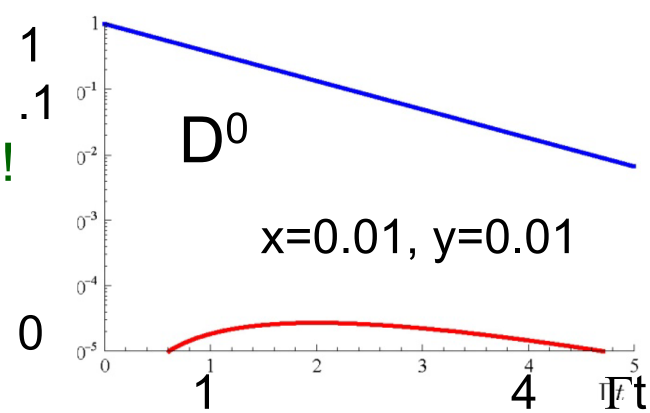
Observables

- $P(P^0 \to P^0)$
- $P(P^0 \to \bar{P}^0)$





log scale!



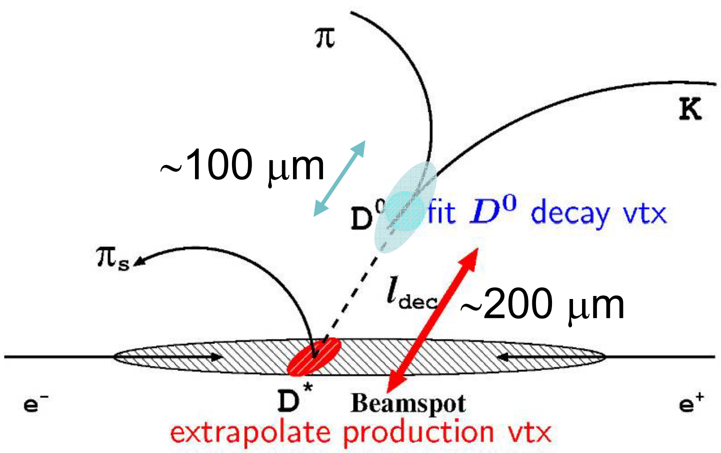
Experimental methods

$$\frac{1}{e^{-t}} \frac{d\Gamma(D^0 \to f)}{dt} = \left| A_f + \frac{q}{p} \frac{ix+y}{2} A_{\bar{f}}\, t \right|^2$$

(for easier notation: $\bar{\Gamma} t \to t$)

Common exp. features

tagging
(B-factories, hadron machines)
$D^{*+} \to D^0 \pi_s^+$
charge of $\pi_s \Rightarrow$ flavor of D^0;
$\Delta M = M(D^0\pi_s) - M(D^0)$
(or $q = \Delta M - m_\pi$) $\Rightarrow$
background reduction



decay time
(B-factories)
D^0 decay products vertex;
D^0 momentum & int. region;

$p^*(D^*) > 2.5$ GeV/c
eliminates D^0 from $b \to c$

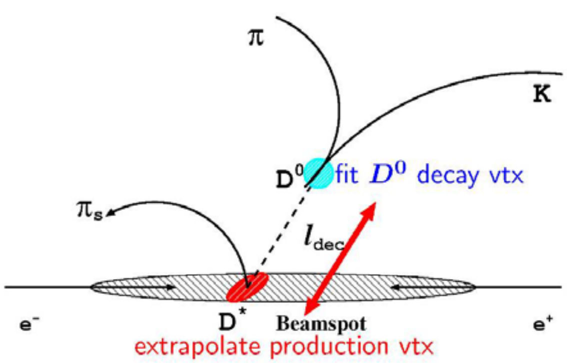
Experimental methods

B-factories

decay time

D^0 decay products vertex;
D^0 momentum & int. region;

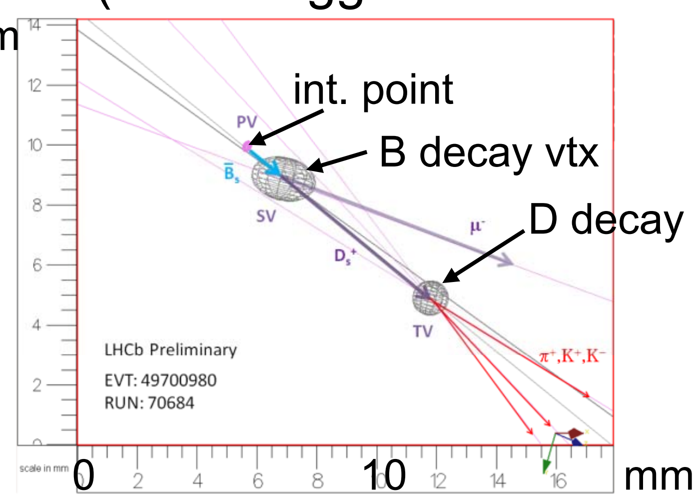
$p^*(D^*)$ > 2.5 GeV/c
eliminates *D^0* from $b \to c$



hadron machines

Tevatron: transverse decay length
LHCb: decay length between *B* (*B*→ *D**X*) and *D^0* vtx

Tevatron: impact param. distribution
LHCb: using *D^0* from *B* (better trigger ε and vtx resol.)



Experimental methods

Decay modes

methods/precision/measured parameters
depend on the decay mode

final states:	example, $D^0 \rightarrow$
semileptonic	$K^+ \ell \nu$
CP states	K^+K^-
WS hadronic 2-body states	$K^+\pi^-$
multi-body self conjugated states	$K_S\pi^-\pi^+$
and some decays which are a combination of those examples	$K^+\pi^-\pi^0$

Semileptonic decays

Principle

$D^{*+} \to D^0 \pi_{slow}^+$
$D^0 \to K^{(*)-} e^+ \nu$ RS
$D^0 \to \overline{D}^0 \to K^{(*)+} e^- \overline{\nu}$ WS

t-integrated rates
$N_{WS}/N_{RS} = R_M = (x^2+y^2)/2$

Belle, PRD77, 112003 (2008), 492 fb^{-1}

Reconstruct ν:
$p_{miss} = p_{CMS} - p_{Ke\pi} - p_{rest}$

to improve resolution
$M(Ke\nu\pi_{slow}) \equiv M(D^{*+}),\ M^2(\nu) \equiv 0$

$f = K^- \ell^+ \nu$

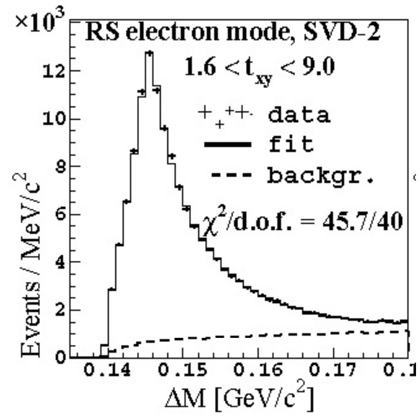
$$\overline{A}_f = A_{\bar{f}} = 0; \quad A_f = \overline{A}_{\bar{f}} \equiv A$$

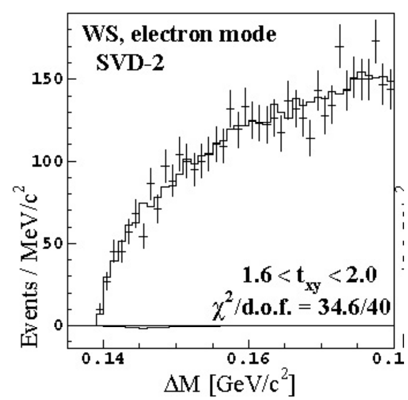
RS $$\frac{\left|\langle f | D^0(t) \rangle\right|^2}{e^{-t}} = |A|^2$$ derived from master formula on p. I/18

WS $$\frac{\left|\langle \bar{f} | D^0(t) \rangle\right|^2}{e^{-t}} = |A|^2 \frac{x^2+y^2}{4} t^2$$

WS $$\frac{\left|\langle f | \overline{D}^0(t) \rangle\right|^2}{e^{-t}} = |A|^2 \frac{x^2+y^2}{4} t^2$$

RS $$\frac{\left|\langle \bar{f} | \overline{D}^0(t) \rangle\right|^2}{e^{-t}} = |A|^2$$





$N_{RS} \approx 330 \cdot 10^3$ $N_{RS} \approx 0$

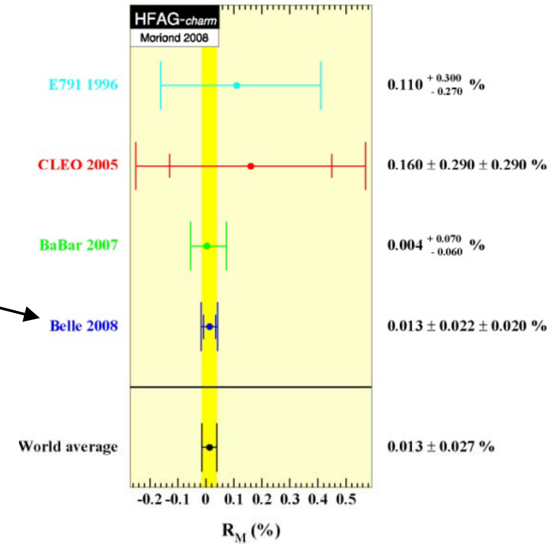
Semileptonic decays

Results

$R_M=(1.3 \pm 2.2 \pm 2.0)\cdot 10^{-4}$

$R_M< 6.1\cdot 10^{-4}$ @ 90% C.L.

Belle, PRD77, 112003 (2008), 492 fb^{-1}



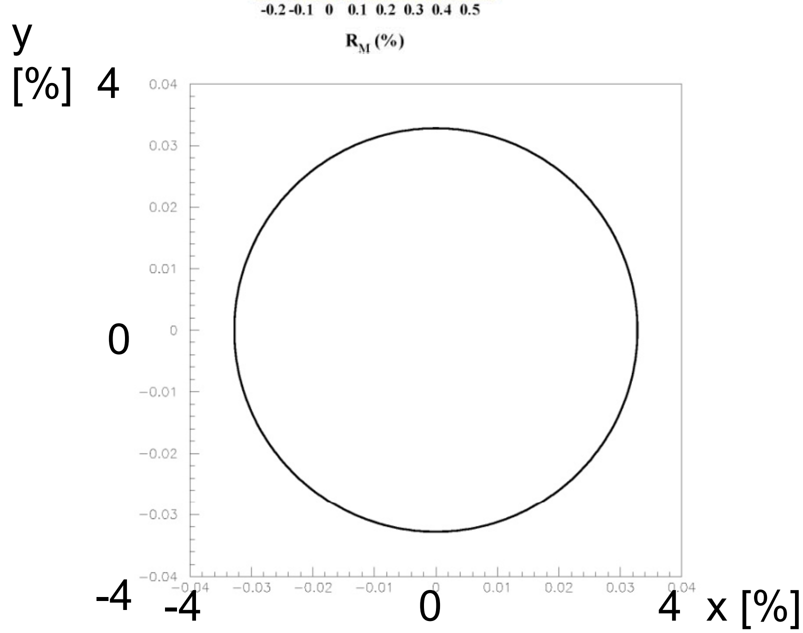
main syst.: WS bkg. Br's
WS bkg. ΔM shape

average of various measurements:
Heavy Flavor Averaging Group

HFAG, http://www.slac.stanford.edu/xorg/hfag/

$R_M=(1.3 \pm 2.7)\cdot 10^{-4}$

$R_M =(x^2+y^2)/2$



Decays to CP eigenstates

Principle

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

CP even final state;

if no CPV:

$CP|D_1\rangle = |D_1\rangle$

$|D_1\rangle$ is CP even state; only this component of $D^0/\bar{D}^0$ decays to $K^+K^- / \pi^+\pi^-$;

measuring lifetime in these decays $\Rightarrow \tau = 1/\Gamma_1$;

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

$K^-\pi^+$: mixture of CP states $\Rightarrow$ $\tau = f(1/\Gamma_1, 1/\Gamma_2)$

$$f = \bar{f};\quad A_f = A_{\bar{f}};\quad \bar{A}_f = \bar{A}_{\bar{f}};\quad \left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| = 1$$

$$\frac{\left|\langle f | P^0(t)\rangle\right|^2}{e^{-t}} = \left|A_f\right|^2\left[1 - y\,t + \frac{x^2+y^2}{4}t^2\right]$$

$$\frac{\left|\langle f | \bar{P}^0(t)\rangle\right|^2}{e^{-t}} = \left|A_f\right|^2\left[1 - y\,t + \frac{x^2+y^2}{4}t^2\right]$$

to linear order:

derived from master formula on p. I/18

$$\frac{\left|\langle f | P^0(t)\rangle\right|^2}{e^{-t}} + \frac{\left|\langle f | \bar{P}^0(t)\rangle\right|^2}{e^{-t}} = \left|A_f\right|^2\left[1 - y\,t\right]$$

$$\left|\langle f | P^0(t)\rangle\right|^2 + \left|\langle f | \bar{P}^0(t)\rangle\right|^2 \propto e^{-t}(1 - yt)$$

$$\approx e^{-t}e^{-yt} = e^{-(1+y)t}$$

when considering CPV expression is modified $\Rightarrow$ y in this mode called y_{CP}

Decays to CP eigenstates

Principle

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

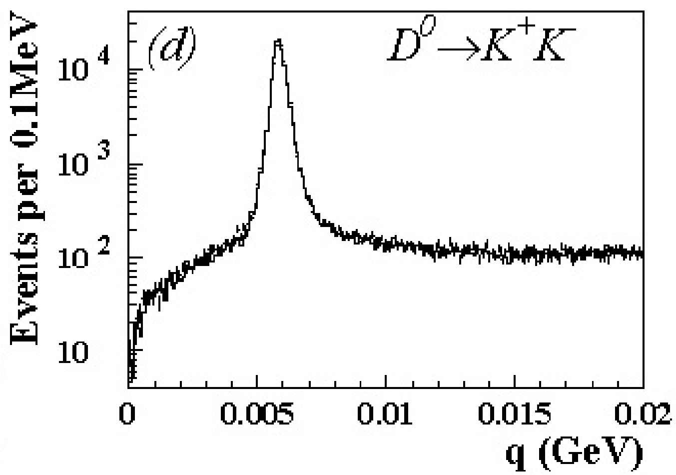
$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 \underset{no\ CPV}{=} y$$

Results

$M(K^+K^-)$,
$q=M(K^+K^-\pi_s)- M(K^+K^-)- M(\pi)$,
σ_t,
selection optimized on MC

	K^+K^-	$K^-\pi^+$	$\pi^+\pi^-$
N_{sig}	111×10^3	1.22×10^6	49×10^3
P	98%	99%	92%

Belle, PRL 98, 211803 (2007), 540fb[-1]



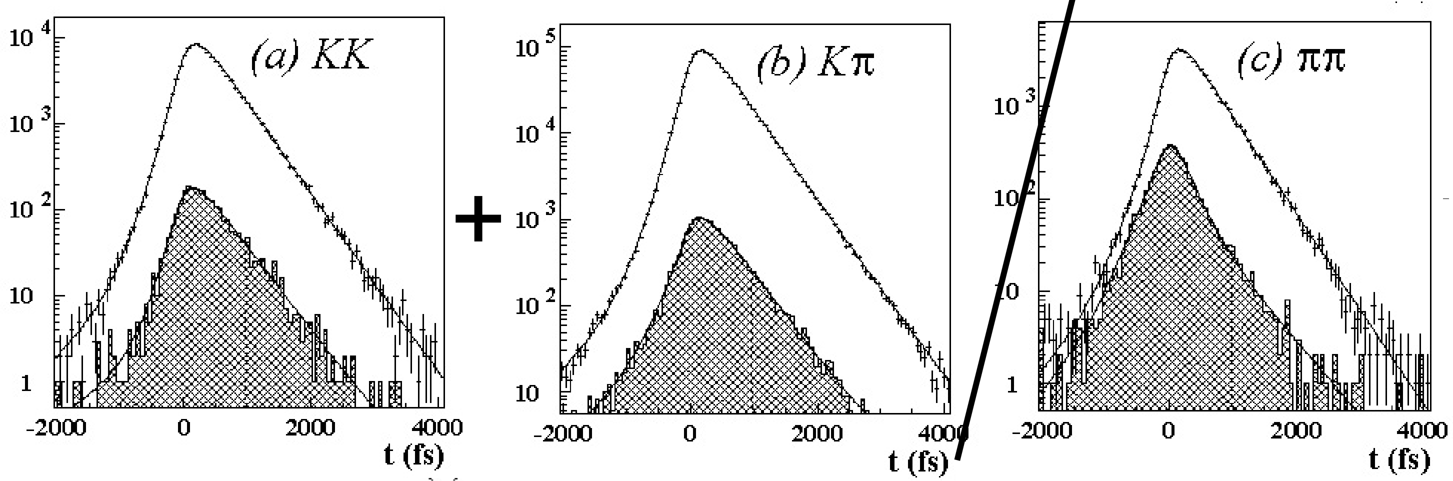
Belle, PRL 98, 211803 (2007), 540fb^{-1}

Decays to CP eigenstates

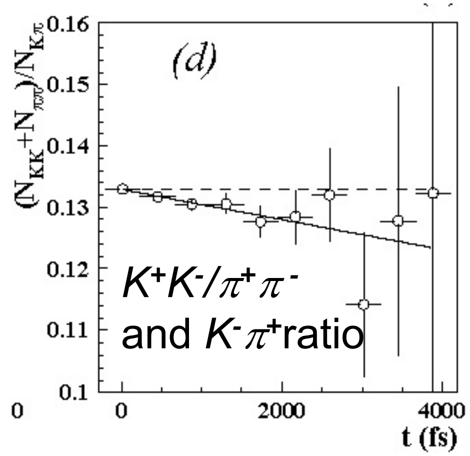
Results

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

simultaneous binned likelihood fit to decay-t, common free y_{CP}



χ^2/ndf= 1.084 (ndf=289)



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

first evidence (one of ...) for D^0 mixing

dominant syst.: t acceptance linearity; small residual bias in τ;

Decays to CP eigenstates

Principle

$D^0 \to (K^+K^-)K_S$
$(D^0 \to \phi K_S, a_0(980) K_S, ...)$
mixture of CP= ±1 states

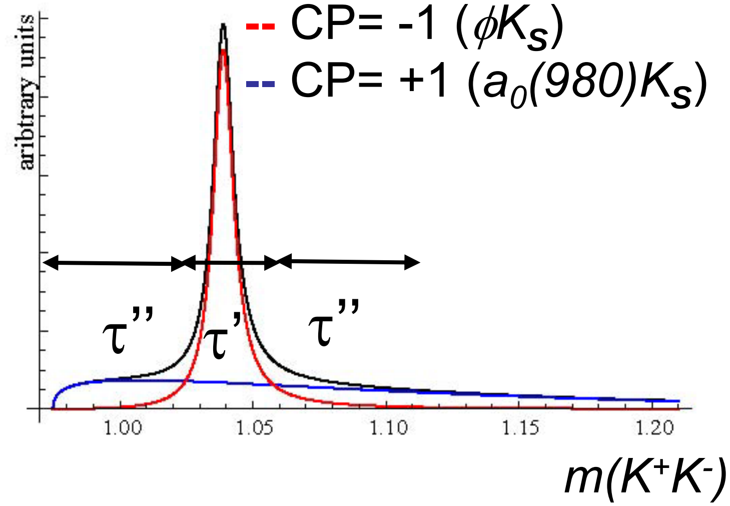
$\tau(\phi K_S) = 1/\Gamma_2 > 1/\Gamma_1 = \tau(K^+K^-)$

$D^0 \to (K^+K^-)K_S$ is topologically different than $D^0 \to K^-\pi^+$;

small biases in the τ measurement would not cancel in the ratio $\tau(K^-\pi^+)/\tau(K^+K^- K_S)$

measure τ for $K^+K^- K_S$ only in different $m(K^+K^-)$ regions

$$\tau' = f_{CP=+1}\frac{\tau}{1+y_{CP}} + (1-f_{CP=+1})\frac{\tau}{1-y_{CP}}$$



$$\Delta\tau = \frac{\tau' - \tau''}{\tau' + \tau''} \approx y_{CP}(f'_{CP=+1} - f''_{CP=+1})$$

Decays to CP eigenstates

Results

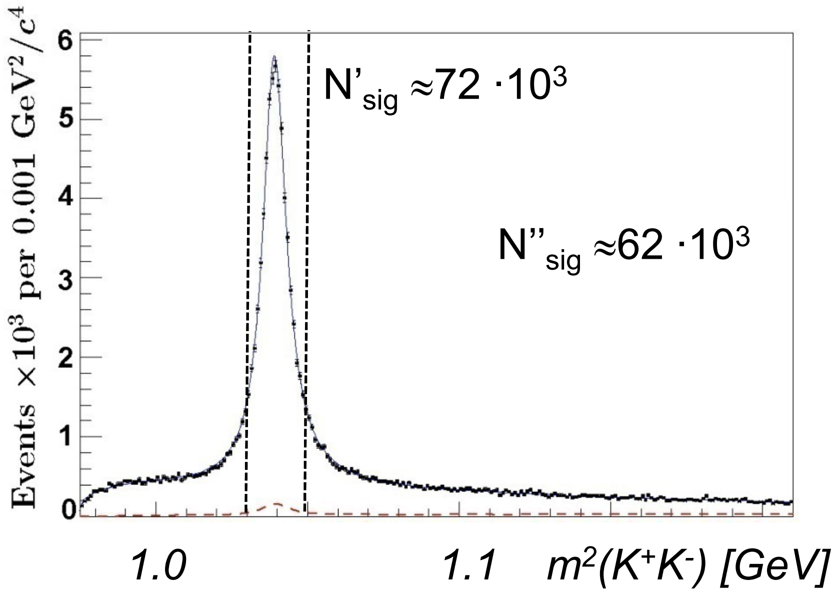
$D^0 \rightarrow (K^+K^-) K_S$

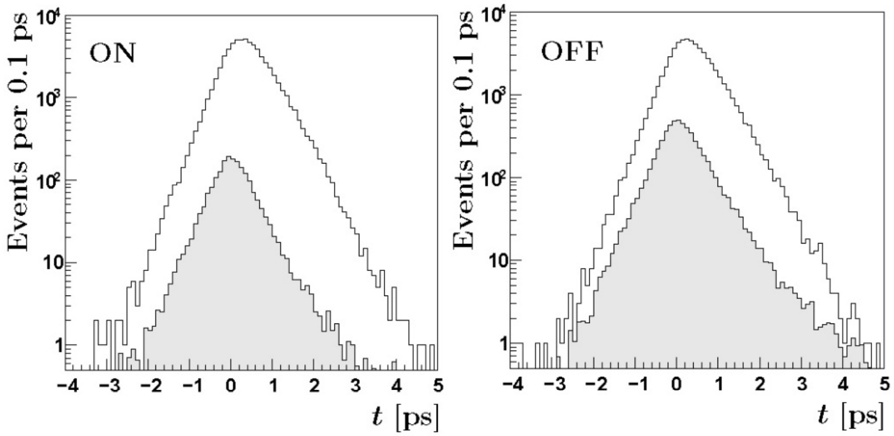
$(D^0 \rightarrow \phi K_S, a_0(980) K_S, ...)$

$$y_{CP} = (0.11 \pm 0.61 \pm 0.52)\%$$

Belle, PRD 80, 052006 (2009), 673fb^{-1}

main syst.: residual biases in τ





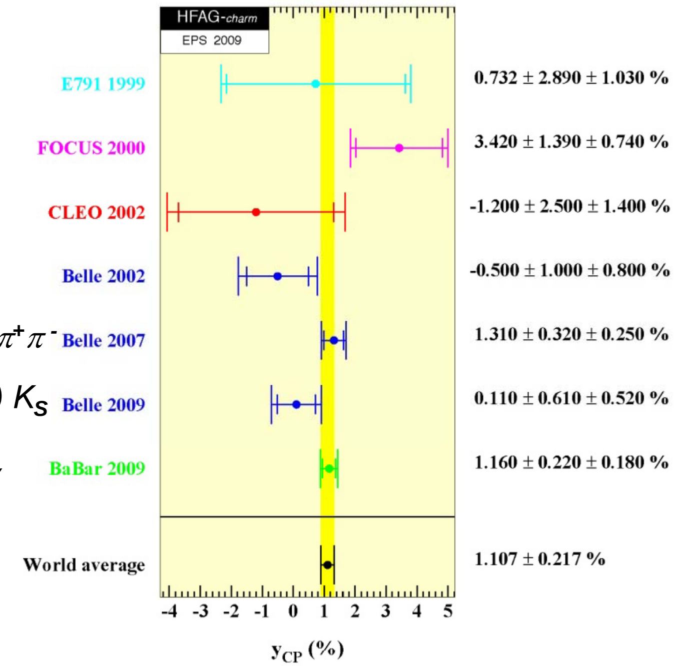
Decays to CP eigenstates

Results

average y_{CP}

$$y_{CP} = (1.107 \pm 0.217)\%$$

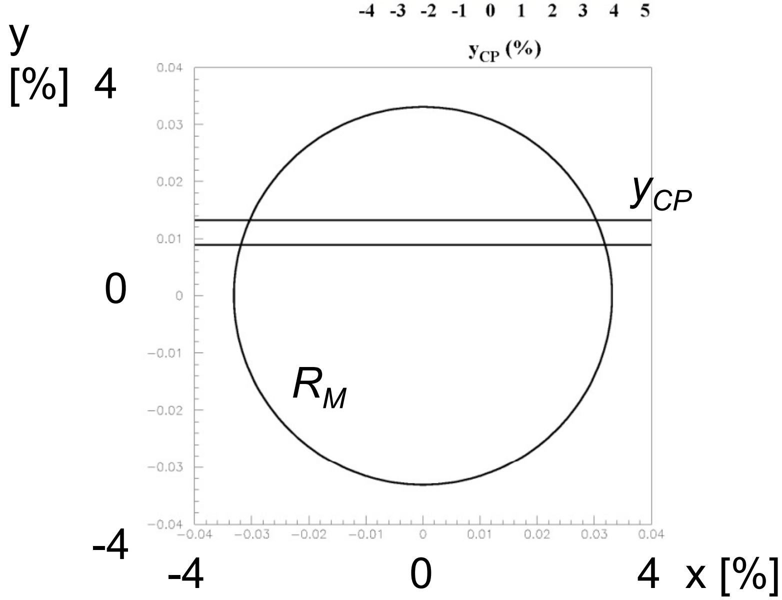
HFAG, http://www.slac.stanford.edu/xorg/hfag/



meas. can be performed with un-tagged (no $D^{*+} \to D^0\pi^+$) decays (larger stat., larger bkg.)

BaBar, PRD 80, 071103 (2009), 384fb^{-1}

$y_{CP} = y$



WS 2-body decays

Principle

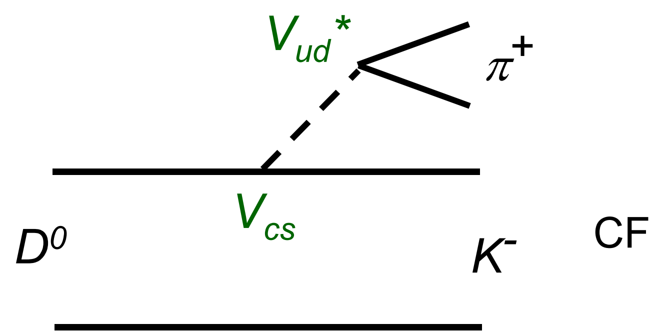
$D^{*+} \to D^0 \; \pi_{slow}^+$

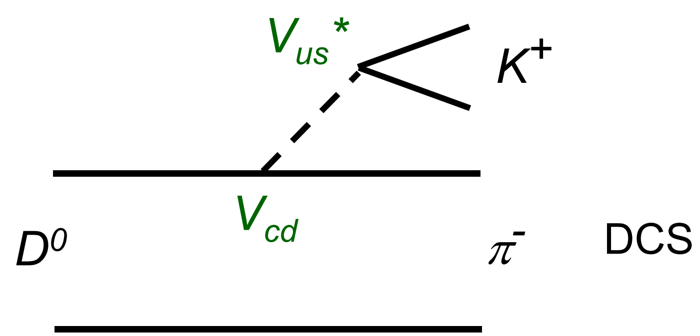
RS: $D^0 \to K^- \pi^+$

WS: $D^0 \to \bar{D}^0 \to K^+ \pi^-$

or

WS: $D^0 \to K^+ \pi^-$ (DCS)





interference between mixing and DCS for WS decays

$f=K^-\pi^+$

$$\frac{\bar{A}_f}{A_f} \equiv -\sqrt{R_D}e^{-i\delta}; \left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| = 1$$

- sign due to relative sign of V_{us} and V_{cd}

$$\frac{\bar{A}_f}{A_f} \propto \frac{V_{cd}^* V_{us}}{V_{ud}^* V_{cs}} = \frac{-\lambda\,\lambda}{(1-\lambda^2)(1-\lambda^2)} = -\frac{\lambda^2}{(1-\lambda^2)^2}$$

WS 2-body decays

Principle

$D^{*+} \to D^0 \ \pi_{slow}^+$

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

WS: $D^0 \to \bar{D}^0 \to K^+ \pi^-$

t-dependence to separate DCS/mixed

δ: unknown strong phase DCS/CF;
not directly measurable at B-factories;
directly accesible at charm-factories

$$x' \equiv x\cos\delta + y\sin\delta; \quad y' \equiv y\cos\delta - x\sin\delta$$

$$y'' \equiv y\cos\delta + x\sin\delta$$

derived from master formula on p. 18

$$\frac{\left|\langle f|P^0(t)\rangle\right|^2}{e^{-t}} = \left|A_f\right|^2\left[1-\sqrt{R_D}\,y''t + R_D\frac{x^2+y^2}{4}t^2\right] \approx \left|A_f\right|^2$$

$$\frac{\left|\langle \bar{f}|\bar{P}^0(t)\rangle\right|^2}{e^{-t}} \approx \left|\bar{A}_{\bar{f}}\right|^2$$

$$\frac{\left|\langle \bar{f}|P^0(t)\rangle\right|^2}{e^{-t}} = \left|\bar{A}_{\bar{f}}\right|^2\left[R_D + \sqrt{R_D}\,y't + \frac{x^2+y^2}{4}t^2\right]$$

$$\frac{\left|\langle f|\bar{P}^0(t)\rangle\right|^2}{e^{-t}} = \left|A_f\right|^2\left[R_D + \sqrt{R_D}\,y't + \frac{x^2+y^2}{4}t^2\right]$$

$$\left|\langle K^+\pi^-|D^0(t)\rangle\right|^2 \propto \left[\underbrace{R_D}_{DCS} + \underbrace{\sqrt{R_D}\,y't}_{interf.} + \underbrace{\frac{x'^2+y'^2}{4}t^2}_{mix}\right]e^{-t}$$

n.b.: $x'^2+y'^2 = x^2+y^2$

WS 2-body decays

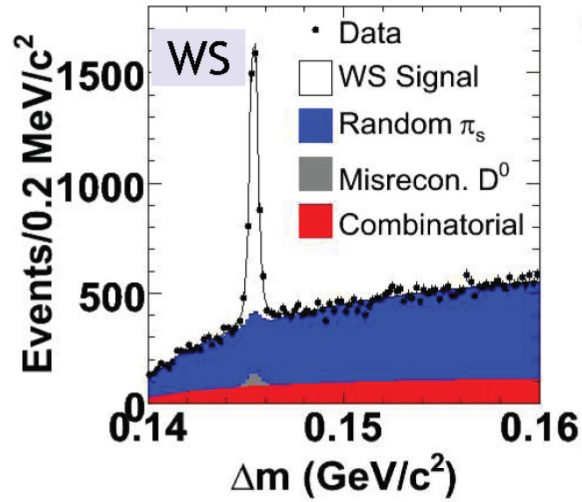
Results

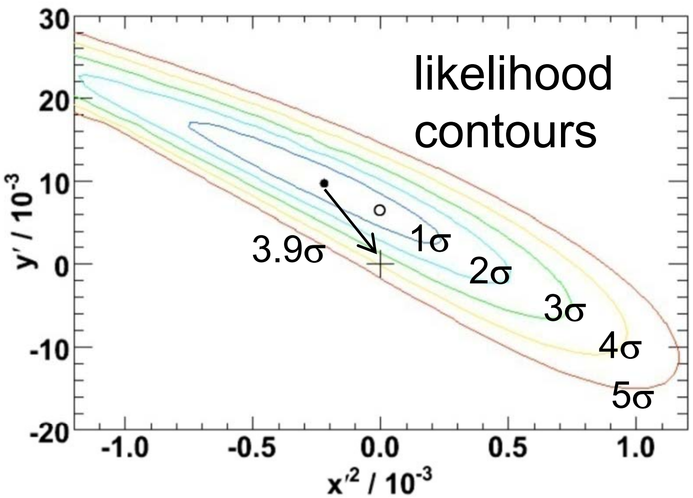
$D^0 \rightarrow K^{+} \pi^{-}$

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

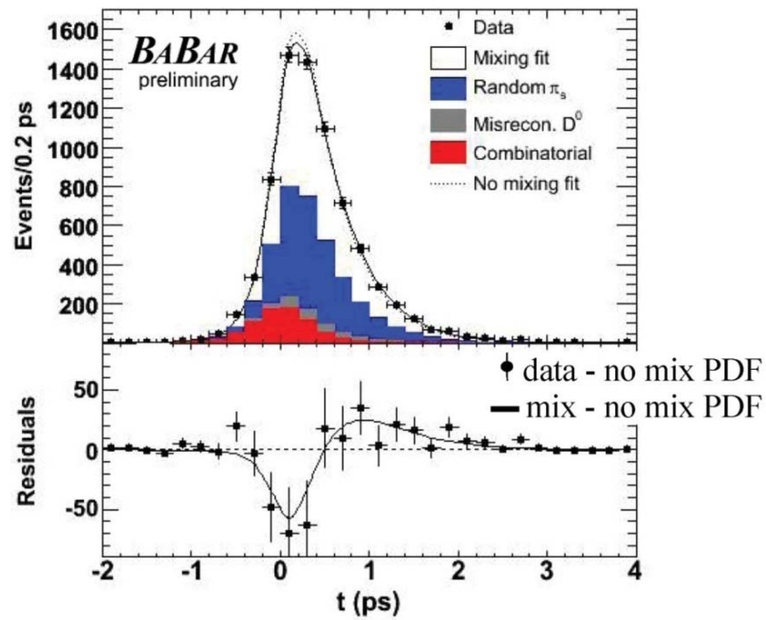
BaBar, PRL 98, 211802 (2007), 384fb[-1]

$N_{WS} \approx 4000$;
(note: P worse than for K^+K^-)





first evidence (2nd of ....) for D^0 mixing



WS 2-body decays

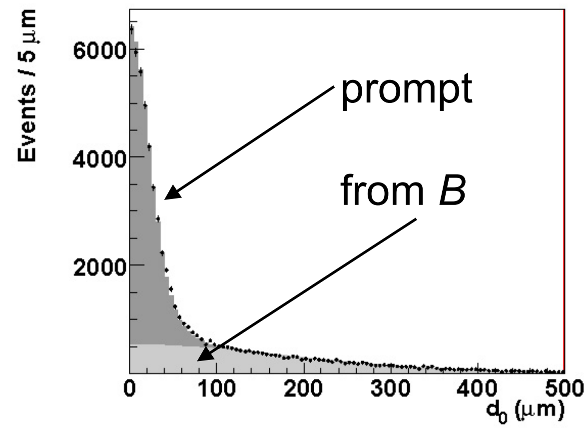
CDF, PRL 100, 121802 (2008), 1.5fb^{-1}

Results

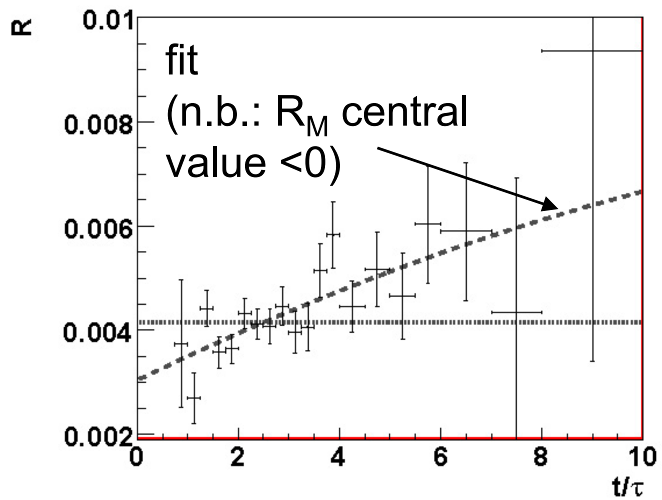
$D^0 \to K^+ \pi^-$

CDF: divide data into 20 *t* bins;

in each bin determine yield of prompt (not from *B*) RS and WS events, based on imp. parameter distr.;



plot WS/RS ratio in bins of *t*;



fit the distribution;

$$\frac{\left|\left\langle K^+\pi^- \middle| D^0(t)\right\rangle\right|^2}{\left|\left\langle K^-\pi^+ \middle| D^0(t)\right\rangle\right|^2} = R_D + \sqrt{R_D}\,y' t + \frac{x'^2 + y'^2}{4} t^2$$

Mixing measurements

WS 2-body decays

Results

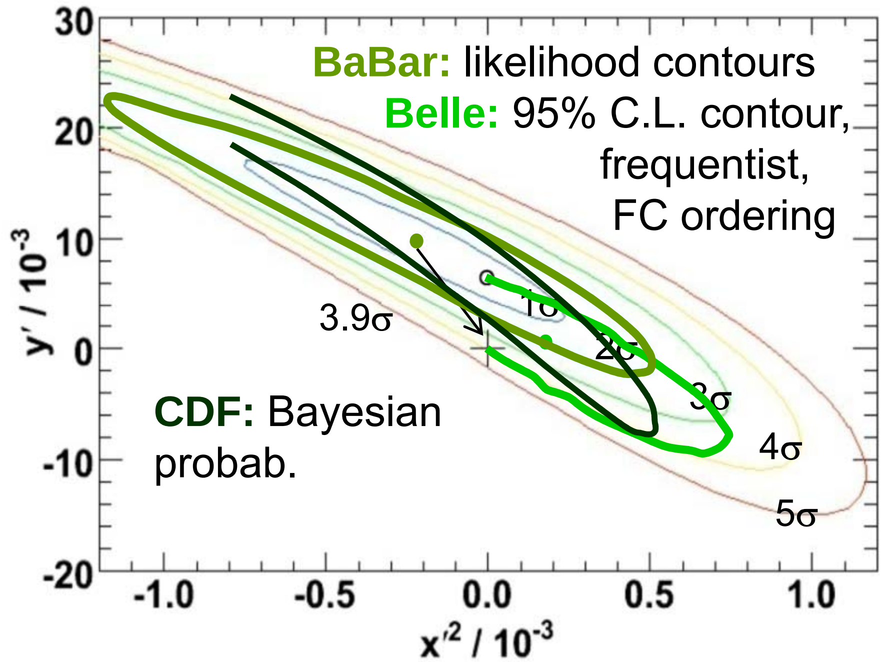
$D^0 \to K^+ \pi^-$

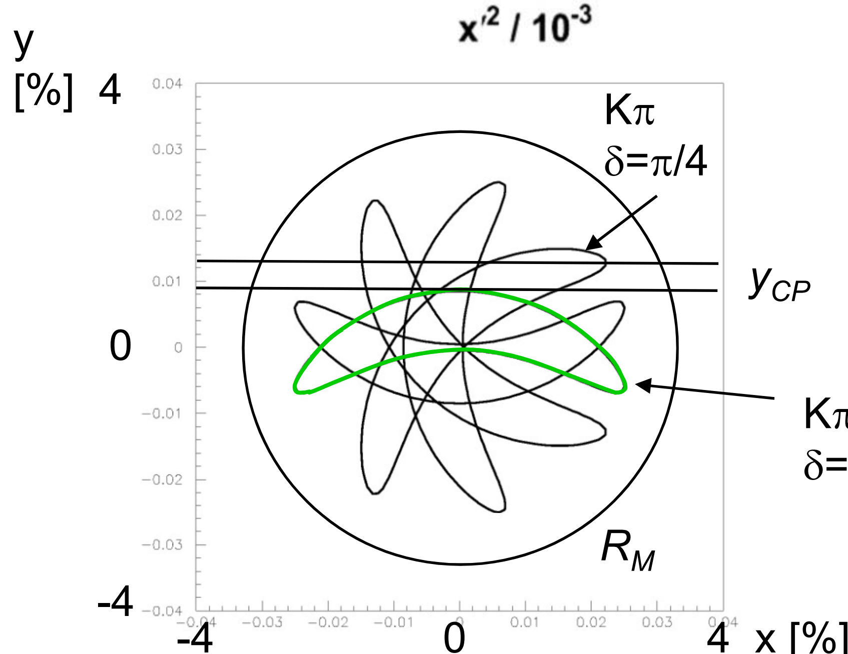
Belle, PRL 96, 151801 (2006), 400fb^{-1}

BaBar, PRL 98, 211802 (2007), 384fb^{-1}

CDF, PRL 100, 121802 (2008), 1.5fb^{-1}

$x'^2 = (x \cos\delta + y \sin\delta)^2$
$y' = -x \sin\delta + y \cos\delta$





Charm-factories

derived from master formula on p. 19

$$\Gamma(V \to D^0\overline{D}^0 \to f_1 f_2) =$$
$$= \frac{1}{2}|a_-|^2\left(\frac{1}{1-y^2}+\frac{1}{1+x^2}\right)+\frac{1}{2}|b_-|^2\left(\frac{1}{1-y^2}-\frac{1}{1+x^2}\right)$$

Principle

coherence of $D^0\overline{D}^0$ pair affects t-integrated rates;
example: $f_1 = K^-\pi^+$, $f_2 = e^-X$

$$A_{f1} \equiv A,\ \overline{A}_{f2} \equiv A_e;\quad \overline{A}_{f1} = -\sqrt{R_D}e^{-i\delta}A,\ A_{f2} = 0$$
$$a_- = AA_e;\quad b_- = \frac{q}{p}\sqrt{R_D}e^{-i\delta}AA_e \approx \sqrt{R_D}e^{-i\delta}AA_e$$
$$\Gamma(V \to D^0\overline{D}^0 \to K^-\pi^+, e^-X) =$$
$$= \frac{1}{2}|AA_e|^2\left\{2+x^2(1+R_D)-y^2(1-R_D)\right\}$$

for $D^0 \to f_1$ and $\overline{D}^0 \to f_2$ ("double tagged", DT events);
sensititiviy to x, y is in 2nd order only

$$\Gamma(V \to D^0\overline{D}^0 \to K^-\pi^+, e^-X) = |AA_e|^2\left\{1+\frac{x^2-y^2}{2}\right\}$$

Charm-factories

Principle

one can also reconstruct only single final state, e.g. $K^-\pi^+$ ("single tagged", ST events);

each event contains D^0 and $\overline{D}^0$, inclusive singe tag rate equals the rate of non-coherent decays;

sensitivity of ST events to $\sqrt{(R_D)}\, y \cos\delta$ is in 1st order;

DT/ST ratio
(ST provides sensitivity to mixing parameters, DT normalization)

$f = K^-\pi^+$

derived from master formula on p. 18

$$\frac{1}{2e^{-t}}\left(\left|\left\langle f\left|P^0(t)\right.\right\rangle\right|^2+\left|\left\langle f\left|\overline{P}^0(t)\right.\right\rangle\right|^2\right)\approx$$

$$\approx\frac{1}{2}|A|^2\left[1+\sqrt{R_D}y''t\right]+\frac{1}{2}|A|^2\left[R_D+\sqrt{R_D}y't\right]$$

$$\Gamma(V\to D^0\overline{D}^0\to K^-\pi^+X)=$$

$$=\frac{1}{2}\int\left[\left|\left\langle f\left|P^0(t)\right.\right\rangle\right|^2+\left|\left\langle f\left|\overline{P}^0(t)\right.\right\rangle\right|^2\right]dt\approx$$

$$=|A|^2\left[1+R_D+2\sqrt{R_D}\,y\cos\delta\right]$$

$f = e^- X$

$$\frac{1}{2e^{-t}}\left(\left|\left\langle f\left|P^0(t)\right.\right\rangle\right|^2+\left|\left\langle f\left|\overline{P}^0(t)\right.\right\rangle\right|^2\right)=|A_e|^2$$

$$\frac{\Gamma(K^-\pi^+,e^-X)}{\Gamma(K^-\pi^+)\Gamma(e^-X)}\approx 1-R_D-2\sqrt{R_D}\,y\cos\delta$$

see also formula on p. 37

Charm-factories

Principle

various decay modes,
effective rates;
$S_{\pm}$: CP= ±1 eigenstate
e^- : semileptonic state
r : $\sqrt{R_D}$

Cleo, PRD 78, 012001 (2008), 281pb^{-1}

Mode	Correlated
$K^-\pi^+$	$1+R_{WS}$
S_+	2
S_-	2
$K^-\pi^+, K^-\pi^+$	R_M
$K^-\pi^+, K^+\pi^-$	$(1+R_{WS})^2 - 4r\cos\delta(r\cos\delta+y)$
$K^-\pi^+, S_+$	$1+R_{WS}+2r\cos\delta+y$
$K^-\pi^+, S_-$	$1+R_{WS}-2r\cos\delta-y$
$K^-\pi^+, e^-$	$1-ry\cos\delta-rx\sin\delta$
S_+, S_+	0
S_-, S_-	0
S_+, S_-	4
S_+, e^-	$1+y$
S_-, e^-	$1-y$

ST;
$$\frac{\Gamma(f)}{\Gamma^{uncorr}(f)}$$

DT;
$$\frac{\Gamma(f_1,f_2)}{\Gamma^{uncorr}(f_1)\,\Gamma^{uncorr}(f_2)}$$

Mixing measurements

Charm-factories

Principle

carefull when reading the table:

→ $\frac{\Gamma(K^-\pi^+)}{\Gamma^{uncorr}(K^-\pi^+)}$ $1+R_{WS}$

→ $\frac{\Gamma(\Gamma(K^-\pi^+, e^-X)}{\Gamma^{uncorr}(K^-\pi^+)\,\Gamma^{uncorr}(e^-X)}$ $1-\sqrt{R_D}\, x\sin\delta - \sqrt{R_D}\, y\cos\delta$

ST rates

$$\Gamma(V \to D^0\overline{D}^0 \to K^-\pi^+X) =$$
$$= \frac{1}{2}\left(\Gamma(D^0 \to K^-\pi^+) + \Gamma(\overline{D}^0 \to K^-\pi^+)\right)$$

uncorrelated

$$\Gamma^{uncorr}(D^0 \to K^-\pi^+) =$$
$$= \frac{1}{2}\left(\Gamma(D^0 \to K^-\pi^+) + \Gamma(\overline{D}^0 \to K^+\pi^-)\right)$$

→ $$\Gamma(V \to D^0\overline{D}^0 \to K^-\pi^+X) = (1+R_{WS})\Gamma^{uncorr}(D^0 \to K^-\pi^+) =$$
$$= (1+R_{WS})\frac{1}{2}\left(\Gamma(D^0 \to K^-\pi^+) + \Gamma(\overline{D}^0 \to K^+\pi^-)\right) =$$
$$= \underbrace{(1+R_D+\sqrt{R_D}\,y'+R_M)}_{1+R_{WS}}|A|^2(1+\sqrt{R_D}\,y'') \approx |A|^2\left[1+R_D+2\sqrt{R_D}\,y\cos\delta\right]$$

→ $$\frac{\Gamma(V \to D^0\overline{D}^0 \to K^-\pi^+, e^-X)}{\Gamma^{uncorr}(D^0 \to K^-\pi^+)\Gamma^{uncorr}(D^0 \to e^-X)} = \frac{|AA_e|^2\left(1+(x^2-y^2)/2\right)}{|A|^2\left(1+\sqrt{R_D}\,y''\right)|A_e|^2} \approx$$
$$\approx 1-\sqrt{R_D}\,y'' = 1-\sqrt{R_D}\,y\cos\delta - \sqrt{R_D}\,x\sin\delta$$

derived from equations on p. I/37, 38

Mixing measurements

Charm-factories

Results

examples of DT, $\overline{M} = (M_{f1}+M_{f2})/2$

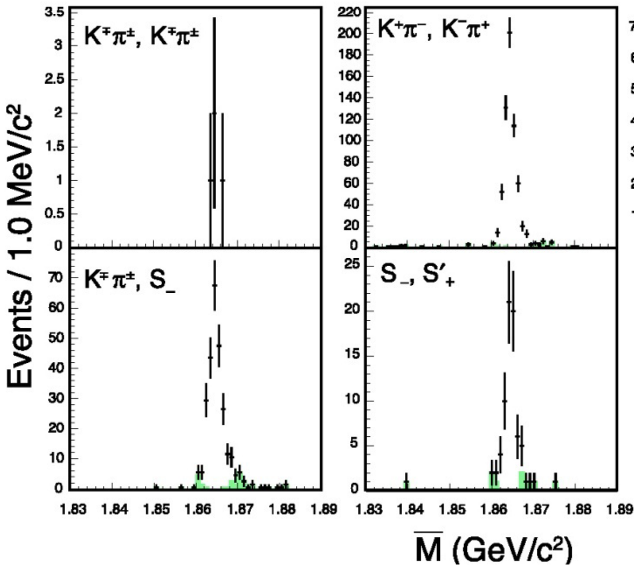
$N_{ST}(K^-\pi^+ + K^+\pi^-) \sim 51\cdot 10^3$
$N_{DT}(K^-\pi^+ , K^+\pi^-) \sim 600$

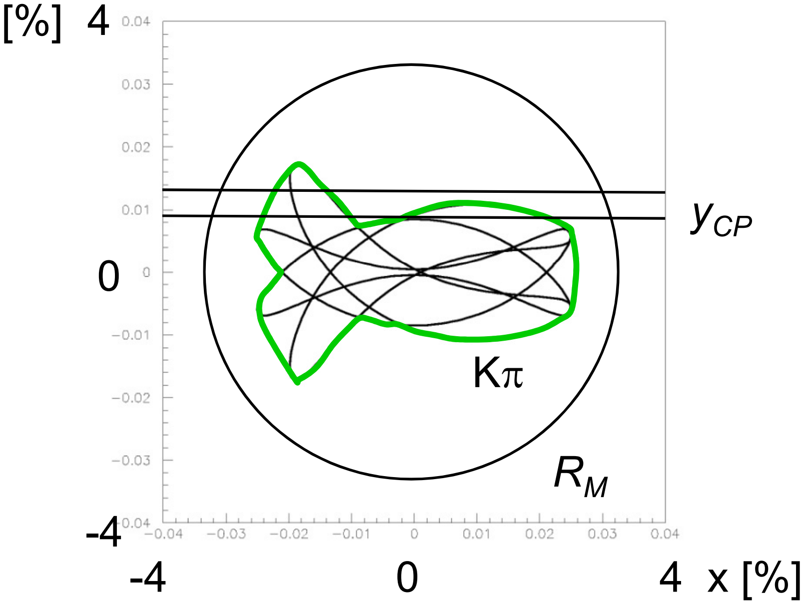
fit to several measured
ST and DT rates

$y=(-5.207 \pm 5.571 \pm 2.737)\%$
$\sqrt{(R_D)}\cos\delta = (8.878 \pm 3.369 \pm 1.579)\%$

using WA value of R_D:
$\cos\delta = (1.54 \pm 0.65)$;
naively: $\delta \in [0^o,27^o]$ & $[153^o, 180^o]$

Cleo, PRD 78, 012001 (2008), 281pb-1

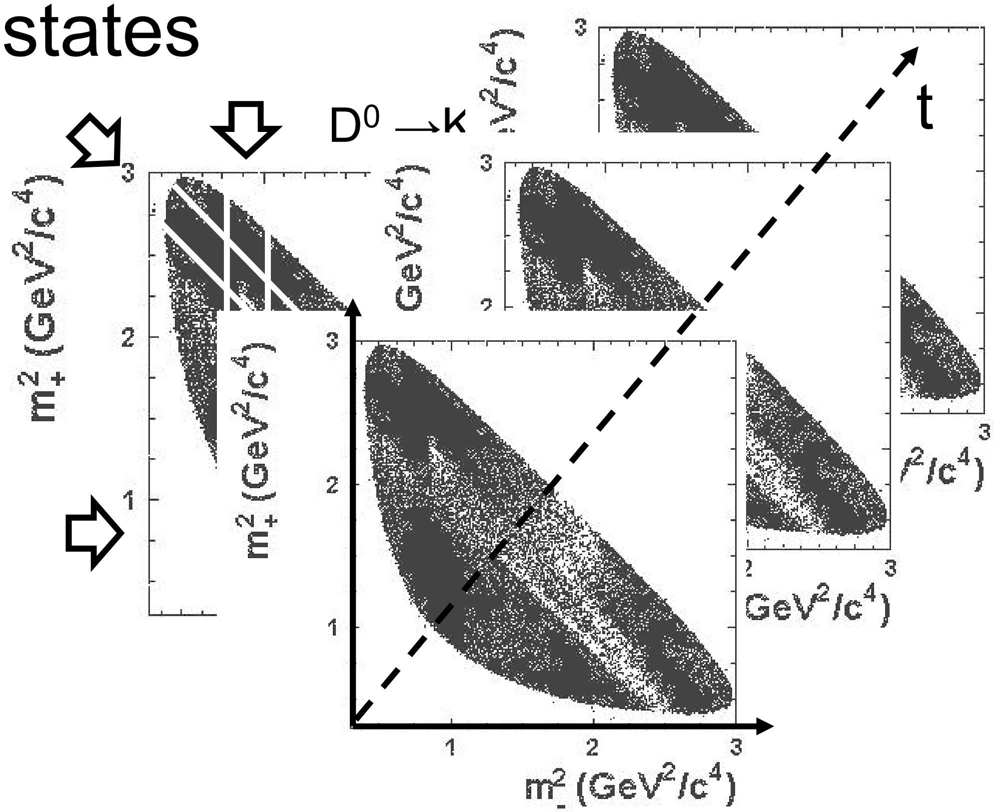




Multi-body self conjugated states

Principle

example $D^0 \to K_S \pi^+ \pi^-$
different types of interm. states;
CF: $D^0 \to K^{*-}\pi^+$
DCS: $D^0 \to K^{*+}\pi^-$
CP: $D^0 \to \rho^0 K_S$



if $f = \overline{f} \Rightarrow$ populate same Dalitz plot;
relative phases determined (unlike $D^0 \to K^+\pi^-$);

specific regions of Dalitz plane →
specific admixture of interm. states →
specific t dependence $f(x, y)$;

by studying the decay time evolution of Dalitz plane → access directly x, y

"t-dependent Dalitz analyses"

Multi-body self conjugated states

Principle

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

t-dependent decay ampl.
depends on Dalitz variables
$m_\pm^2 = m^2(K_S \pi^\pm)$;
contains D^0 and $\overline{D}^0$ part
(due to mixing)
that propagate differently in time
$\lambda_{1,2} = f(x,y)$; see equations on p. I/9
(n.b.: $K^+\pi^-$: dependence on x'^2, y')

$$\mathcal{M}(m_-^2, m_+^2, t) \equiv \left\langle K_S \pi^+ \pi^- \middle| D^0(t) \right\rangle =$$
$$= \frac{1}{2} \underbrace{\mathcal{A}(m_-^2, m_+^2)}_{D^0 \to f} \left[e^{-i\lambda_1 t} + e^{-i\lambda_2 t} \right] +$$
$$+ \frac{1}{2} \underbrace{\overline{\mathcal{A}}(m_-^2, m_+^2)}_{\overline{D}^0 \to f} \left[e^{-i\lambda_1 t} - e^{-i\lambda_2 t} \right]$$

instantaneous amplitude:
sum of intermediate states

$$\mathcal{A}(m_-^2, m_+^2) = $$
$$= \sum a_r \, e^{i\Phi_r} B(m_-^2, m_+^2) + a_{NR} \, e^{i\Phi_{NR}}$$
$$\overline{\mathcal{A}}(m_-^2, m_+^2) =$$
$$= \sum a_r \, e^{i\Phi_r} B(m_+^2, m_-^2) + a_{NR} \, e^{i\Phi_{NR}}$$

Breit-Wigner

Multi-body self conjugated states

Belle, PRL 99, 131803 (2007), 540fb^{-1}

Results

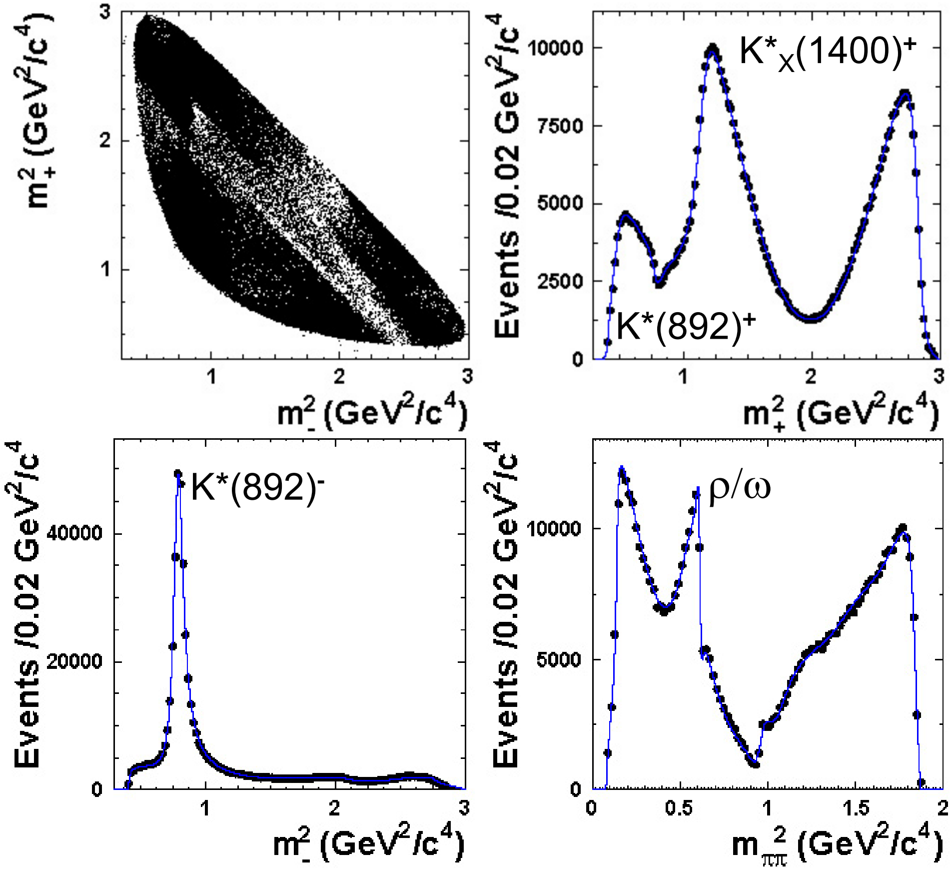
$D^0 \to K_S \pi^+ \pi^-$

$N_{sig} = 530 \cdot 10^3$
$P \approx 95\%$

3-dim fit (m_+^2, m_-^2, t);
complicated, ~40 free param.;
possibility of multiple solutions

usually fit to t-integrated
Dalitz first to establish
the appropriate model
$(\mathcal{A}(m_+^2, m_-^2))$;

projection of fit
in Dalitz plane



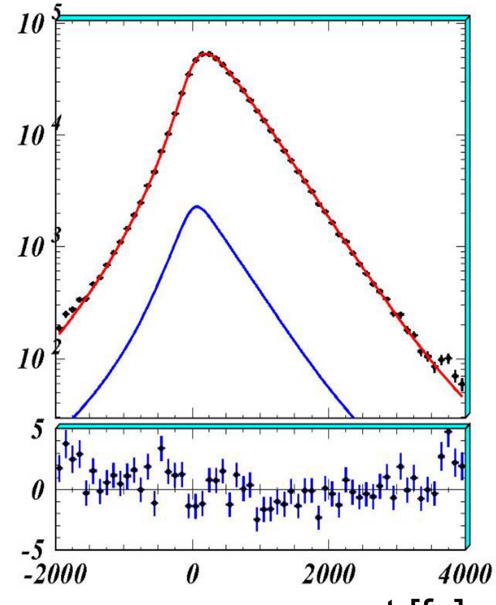
Multi-body self conjugated states

Results

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

Belle, PRL 99, 131803 (2007), 540fb^{-1}

projection of fit in *t* distrib.



$$x = (0.80 \pm 0.29 \pm ^{0.13}_{0.16})\%$$

$$y = (0.33 \pm 0.24 \pm ^{0.10}_{0.14})\%$$

dominant syst.: model dependency (param. of resonances); Dalitz model for bkg.;

Results

other analogous modes: $D^0 \to K_S K^+ K^-$, $\pi^0 \pi^+ \pi^-$

sensitivity to *x, y* depends on relative phases of interm. states (interference); difficult to predict

Multi-body self conjugated states

BaBar, arXiv:1004.5053, 470 fb^{-1}

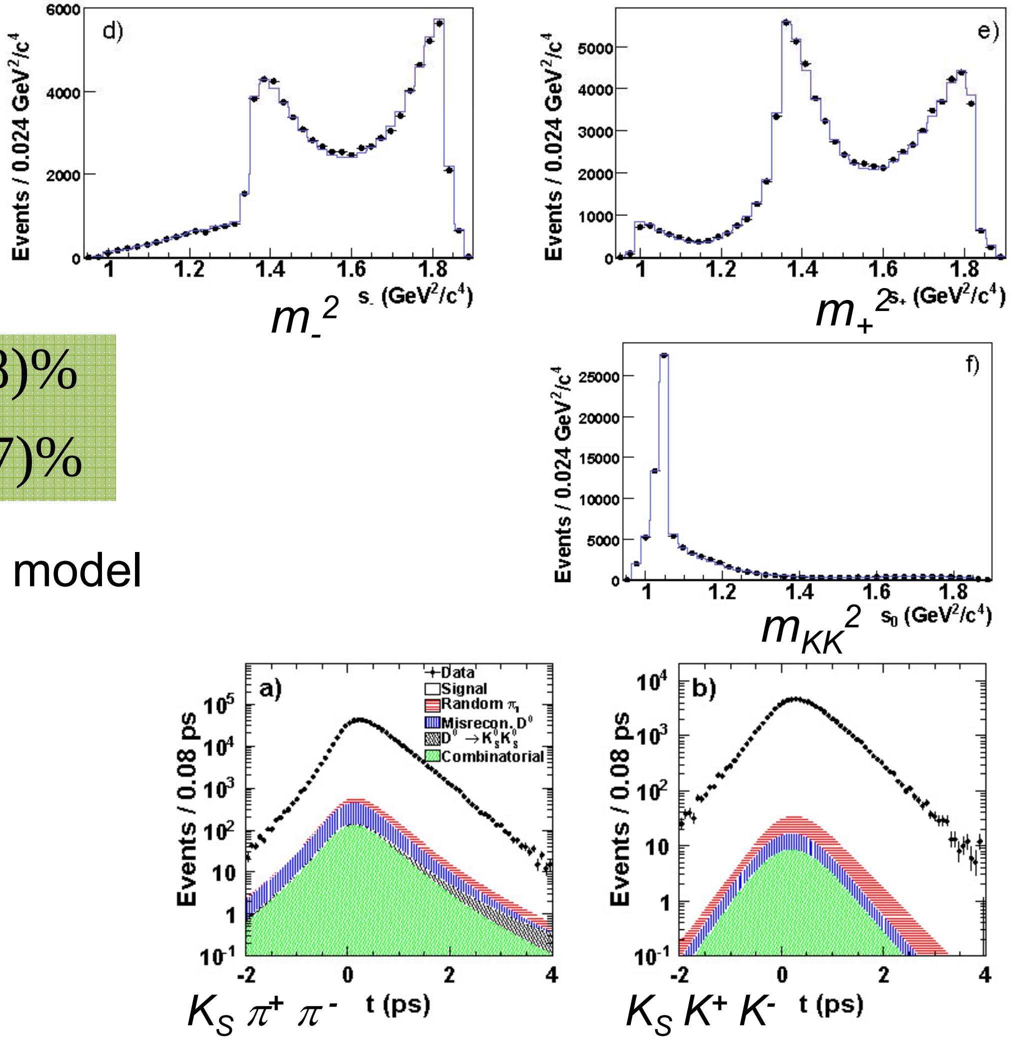
Results

simultaneous:
$D^0 \to K_S \pi^+ \pi^- / K_S K^+ K^-$
profit from resonances that are present in both final states, e.g. $a_0(980)$

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

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

first error stat., second syst., third model

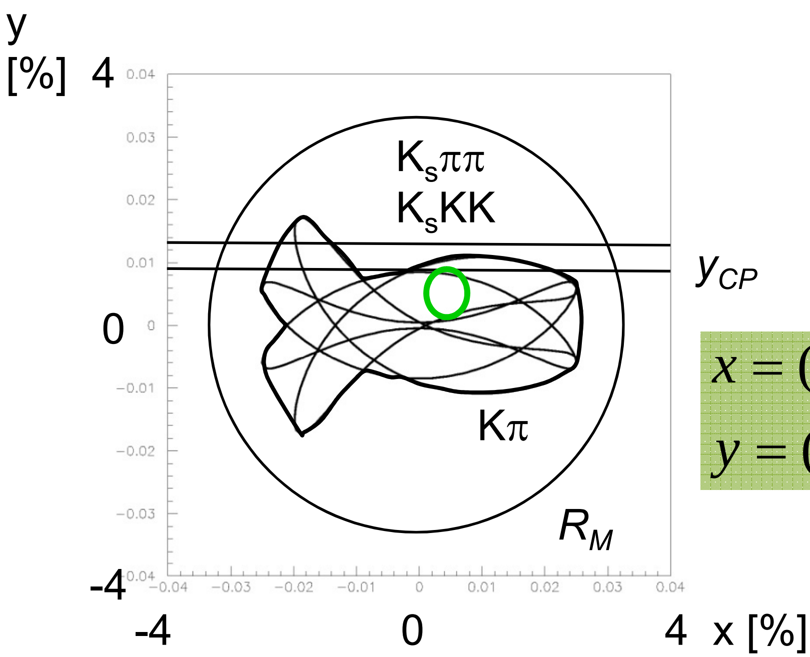


Multi-body self conjugated states

Results

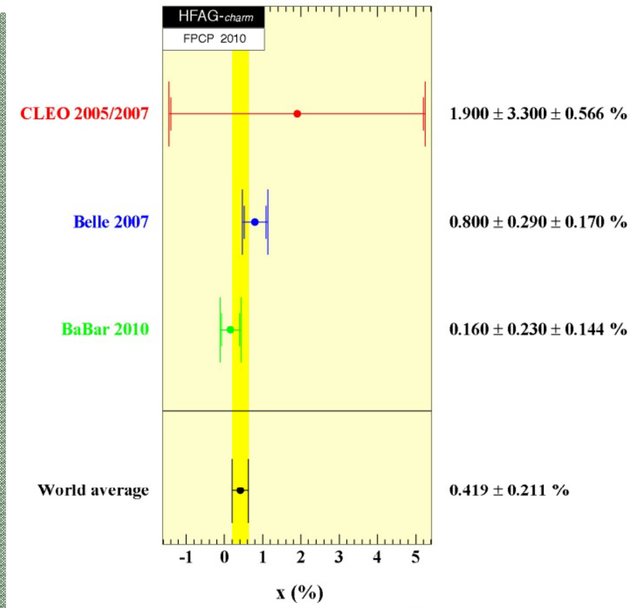
$D^0 \rightarrow K_S \pi^+ \pi^- / K_S K^+ K^-$

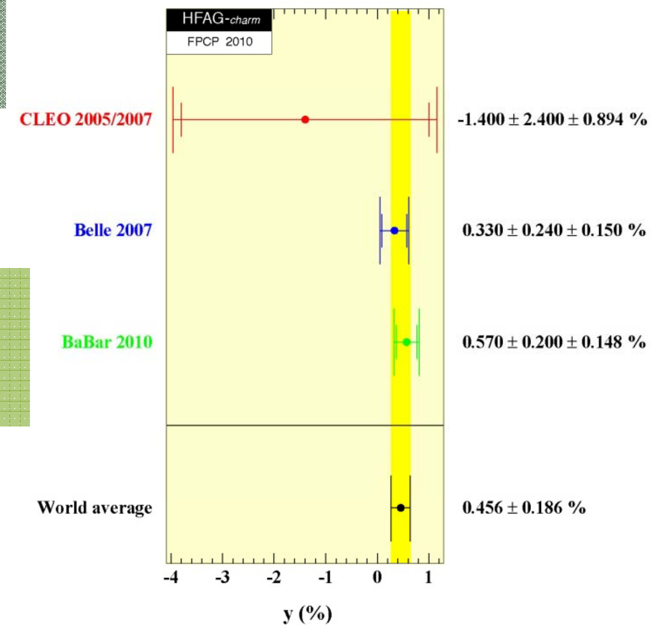
t-dependent Dalitz analyses: most precise determination of mixing parameters



$$x = (0.42 \pm 0.21)\%$$
$$y = (0.46 \pm 0.19)\%$$

HFAG, http://www.slac.stanford.edu/xorg/hfag/





Multi-body flavor specific states

Principle

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

properties: mixture of 2-body WS ($K\pi$) and t-dependent Dalitz ($K_S\pi\pi$);

WS: interference mixing/DCS; t-dependence similar as for $K\pi$;

WS and RS Dalitz distribution; in each relative phases determined; one unknown relative phase between chosen point in RS and WS Dalitz plane;

$f = K^- \pi^+ \pi^0$

$$\left|\left\langle K^+\pi^-\pi^0 \middle| D^0(t)\right\rangle\right|^2 \propto [\underbrace{|A_{\bar{f}}|^2}_{DCS} +$$

$$+\underbrace{|A_{\bar{f}}||\bar{A}_{\bar{f}}|(y'_{K\pi\pi}\cos\delta_f - x'_{K\pi\pi}\sin\delta_f)t}_{interf.} +$$

$$+\underbrace{|\bar{A}_{\bar{f}}|^2 \frac{x'^2_{K\pi\pi} + y'^2_{K\pi\pi}}{4} t^2}_{mix}]e^{-t}$$

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

$A_{\bar{f}}, \bar{A}_{\bar{f}}$ and $\delta_f = \bar{\delta} - \delta$ functions of $m_{K\pi}^2$, $m_{\pi\pi}^2$

$\delta_{K\pi\pi}$: unknown strong phase DCS/CF; not directly measurable at B-factories; directly accesible at charm-factories

Multi-body flavor specific states

Principle

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

$$|\langle K^+\pi^-\pi^0 | D^0(t)\rangle|^2 \propto [\underbrace{|A_{\bar{f}}|^2}_{DCS} +$$

$$+\underbrace{|A_{\bar{f}}||\bar{A}_{\bar{f}}|(y'_{K\pi\pi}\cos\delta_f - x'_{K\pi\pi}\sin\delta_f)t}_{interf.} +$$

$$+\underbrace{|\bar{A}_{\bar{f}}|^2 \frac{x'^2_{K\pi\pi} + y'^2_{K\pi\pi}}{4} t^2}_{mix}]e^{-t}$$

$A_{\bar{f}}, \bar{A}_{\bar{f}}, \delta_f$ determined from RS t-integrated Dalitz distrib.;

mixing parameters from WS t-dependent Dalit distrib.

Results

$x'_{K\pi\pi} = (2.61\ ^{+0.57}_{-0.68} \pm 0.39)\%$
$y'_{K\pi\pi} = (-0.06\ ^{+0.55}_{-0.64} \pm 0.34)\%$

BaBar, PRL 103, 211801 (2009), 384 fb^{-1}

Resonance	a_j^{DCS}	δ_j^{DCS} (degrees)	f_j (%)
$\rho(770)$	1 (fixed)	0 (fixed)	39.8 ± 6.5
$K_2^{*0}(1430)$	0.088 ± 0.017	-17.2 ± 12.9	2.0 ± 0.7
$K_0^{*+}(1430)$	6.78 ± 1.00	69.1 ± 10.9	13.1 ± 3.3
$K^{*+}(892)$	0.899 ± 0.005	-171.0 ± 5.9	35.6 ± 5.5
$K_0^{*0}(1430)$	1.65 ± 0.59	-44.4 ± 18.5	2.8 ± 1.5
$K^{*0}(892)$	0.398 ± 0.038	24.1 ± 9.8	6.5 ± 1.4
$\rho(1700)$	5.4 ± 1.6	157.4 ± 20.3	2.0 ± 1.1

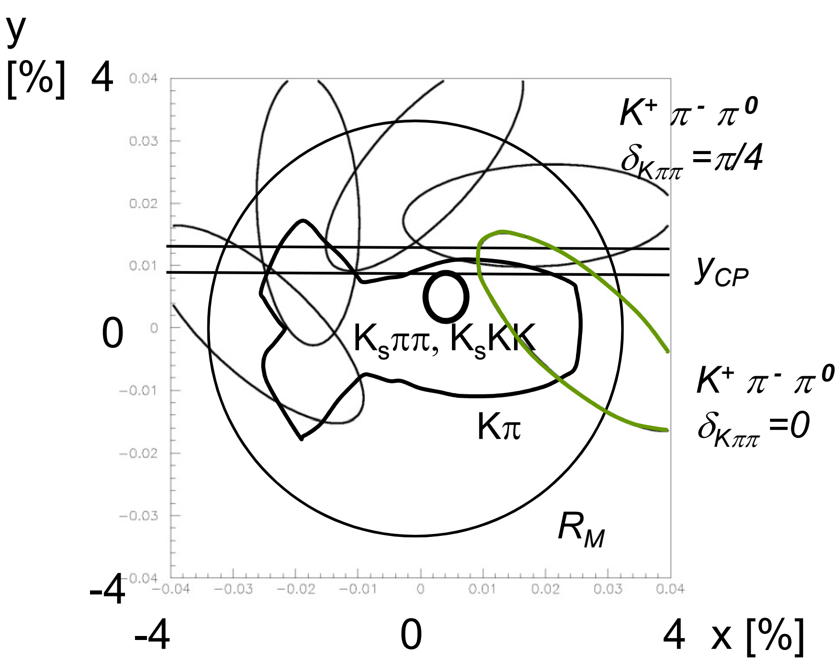
results of Dalitz fit for WS decays

Multi-body flavor specific states

Results

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

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



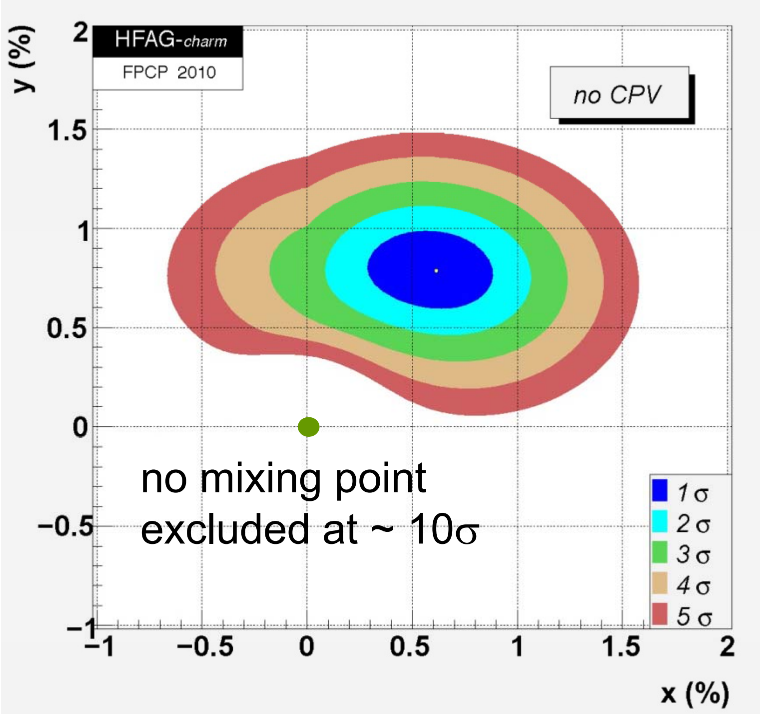
Averages

Results

HFAG, http://www.slac.stanford.edu/xorg/hfag/

χ^2 fit including correlations among measured quantities

Parameter	No CPV
x (%)	$0.61^{+0.19}_{-0.20}$
y (%)	0.79 ± 0.13
δ (°)	$26.6^{+11.2}_{-12.1}$
R_D (%)	$0.3317^{+0.0080}_{-0.0081}$
A_D (%)	–
$\lvert q/p \rvert$	–
ϕ (°)	–
$\delta_{K\pi\pi}$ (°)	$21.6^{+22.1}_{-23.2}$



n.b.: $x(D^0) \approx 0.01$; $x(K^0) \approx 1$; $x(B_d) \approx 0.8$; $x(B_s) \approx 25$;

$(x,y) \neq (0,0)$: 10 σ;

$x \propto m_1 - m_2$, $y \propto \Gamma_1 - \Gamma_2$; D_1: CP=+1;

x, y >0$\Rightarrow$ CP even state heavier and shorter lived;

(unlike K^0 system)