Evidence for D^0 mixing at Belle

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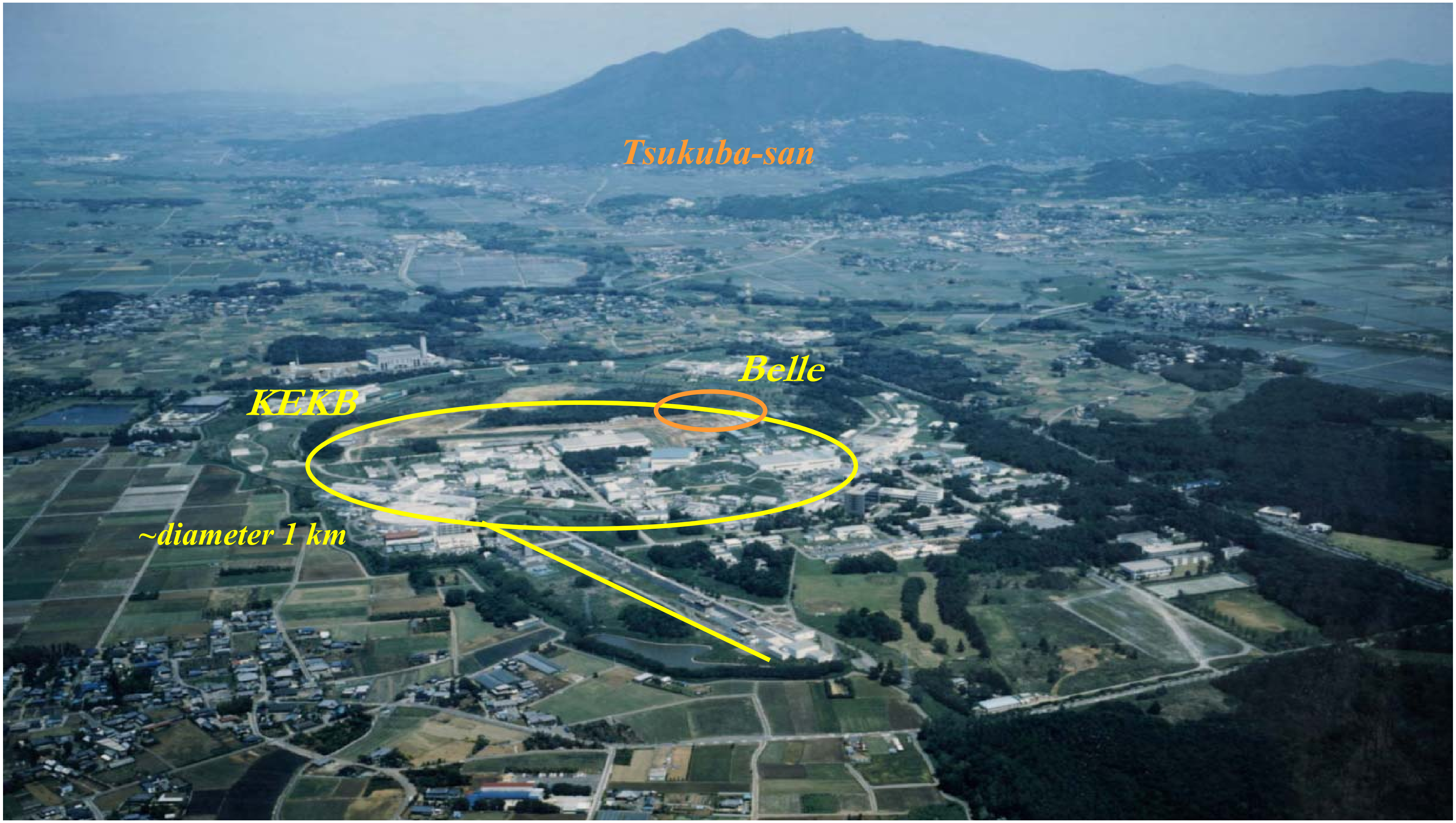
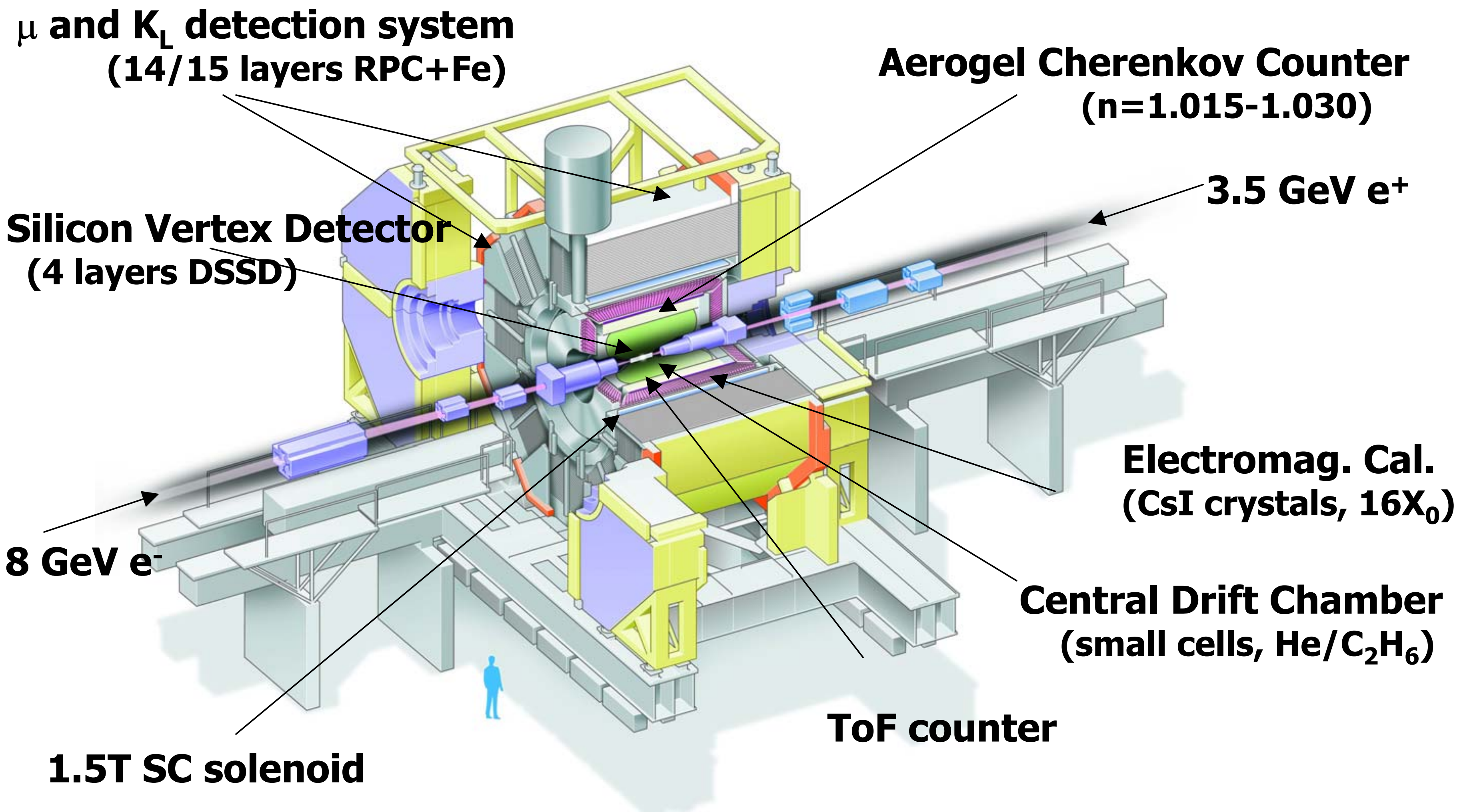
Belle @ KEK-B in Tsukuba



Peak luminosity: 1.7 x 10^{34} $cm^{-2}s^{-1}$

Belle spectrometer at KEK-B



Data sample >750M BB-pairs, >850M cc pairs

Contents

Motivation →M. Sokoloff's talk

Belle@KEK-B

Search for D^0 mixing in $D^0 \rightarrow K^+\pi^-$ and semileptonic decays

$D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$: apparent lifetime of a CP eigenstate

$D^0 \rightarrow K_S{}^0\pi^+\pi^-$: time-dependent Dalitz plot analysis

CP violation searches in D mixing

Summary and prospects

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

An arbitrary linear combination of the neutral D-meson flavor eigenstates

$$a\left|D^0\right\rangle + b\left|\overline{D}^0\right\rangle$$

is governed by a time-dependent Schroedinger equation

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = H\begin{pmatrix} a \\ b \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} a \\ b \end{pmatrix}$$

M and Γ are 2x2 Hermitian matrices.

The light D_1 and heavy D_2 mass eigenstates are:

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

Time evolution in the B system

Time evolution is governed by the parameters x, y, $\overline{\Gamma}$

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

A D^0 at t=0 evolves as:

$$\left|D^0(t)\right\rangle = \left[\left|D^0\right\rangle \cosh\left(\frac{ix+y}{2}t\right) + \frac{q}{p}\left|\overline{D}^0\right\rangle \sinh\left(\frac{ix+y}{2}t\right)\right] e^{-(\frac{1}{2}+i\frac{m}{\overline{\Gamma}})t}$$

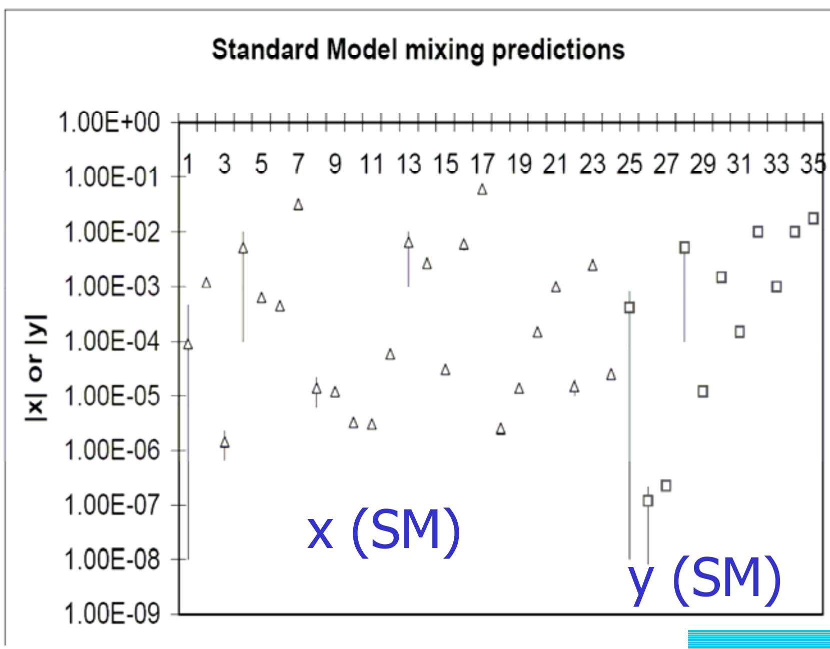
Decay time distribution of different final states of D^0, $\overline{D}^0$, and D_{CP} : sensitive to different combinations of mixing parameters.

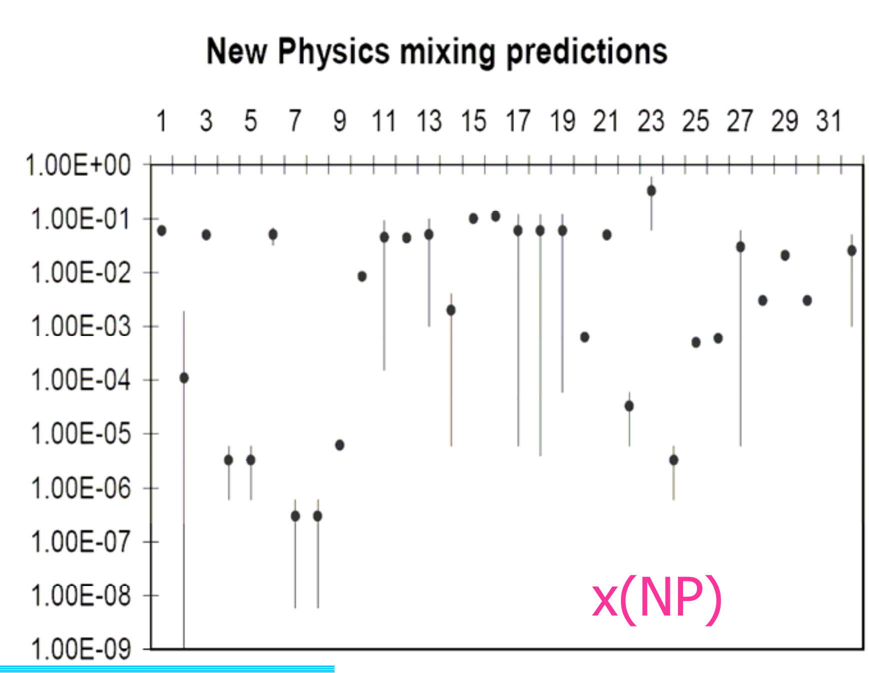
D^0 - $\bar{D}^0$ mixing

Mixing in the neutral D system: highly suppressed due to GIM mechanism ($m_s \sim m_d$). → A place to search for new physics (in principle).

Mixing in SM: completely dominated by long-range contributions.

New physics: x>>y, CPV → E. Golowich et al., arXiv:0705.3650





A. Petrov, hep-ph/0311371

Experimental methods in D^0 mixing searches

The method: investigate D decays in the decay sequence:

$D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow$ specific final states

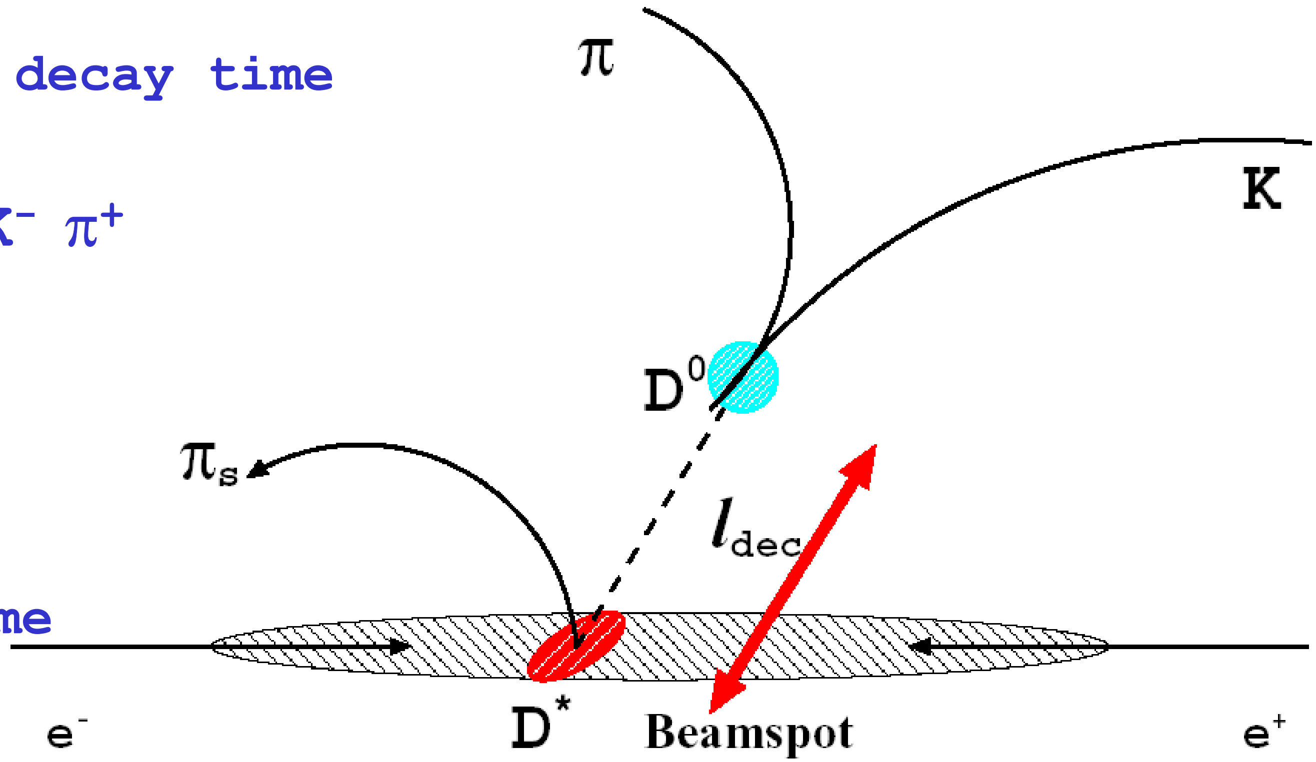
Used for tagging the initial flavour and for background reduction

$\bar{D}^0$ or D^0 at decay time

$K^- \pi^+$

$D^{*+} \rightarrow D^0 \pi^+$

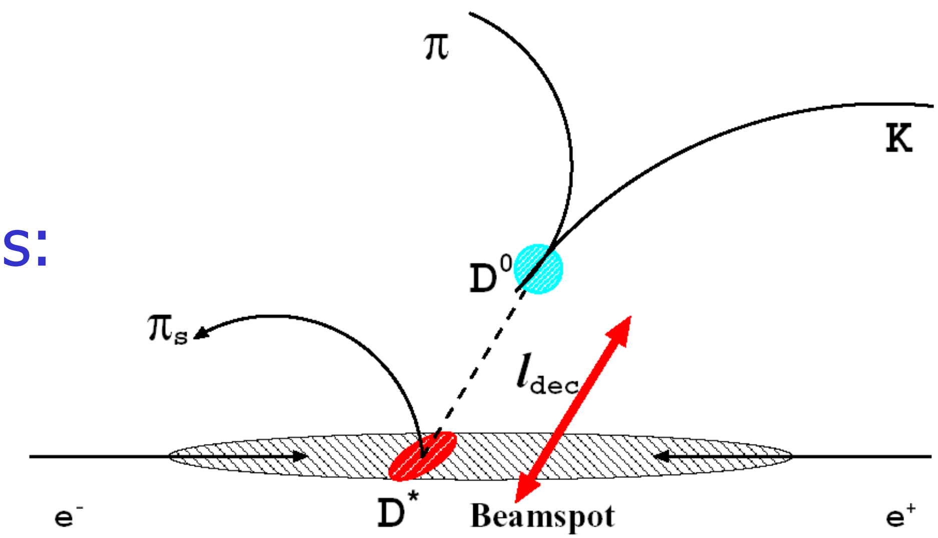
$\bar{D}^0$ or D^0 at production time



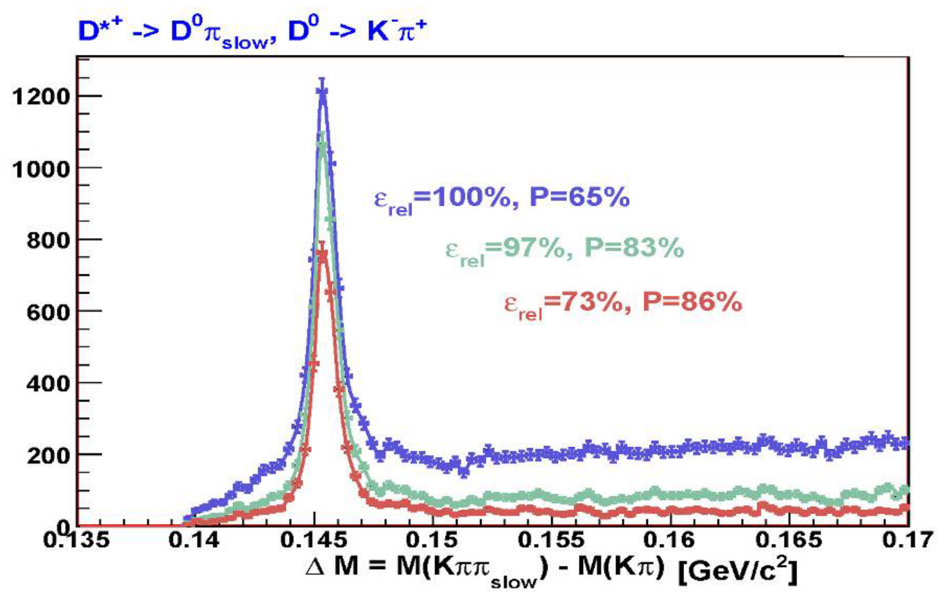
$p_{cms}(D^*) > 2.5$ GeV/c eliminates D meson production from $b \rightarrow c$

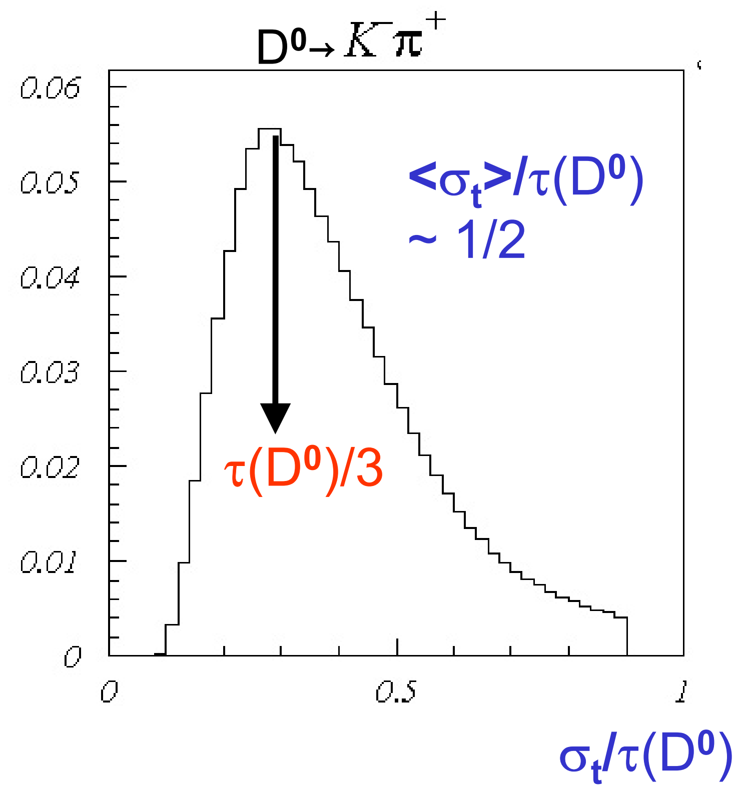
Experimental methods

Performance of the apparatus:
-PID performance
-vertex resolution



$\varepsilon(K^{\pm}) \sim 85\%$
$\varepsilon(\pi^{\pm} \rightarrow K^{\pm}) \leq 10\%$
for p < 3.5 GeV/c





D^0 mixing in $D^0 \to K\pi$ and $Ke\nu$ decays

The method: search for D mixing in the decay sequence: $D^{*+} \to D^0\pi^+$, $D^0 \to$flavour specific final state.

Semileptonic decay:

- $K^- \ e^+ \ \nu$: no mixing (RS, Right Sign)
- $K^+ \ e^- \ \nu$: mixing (WS, Wrong Sign)

→ measure WS rate

Hadronic decay:

- $K^- \ \pi^+$: no mixing
- $K^+ \ \pi^-$: mixing or doubly Cabbibo suppressed (DCSD)

→ measure WS time evolution

D^0 mixing in $D^0 \to K\pi$ decays

$D^0 \to K\pi$ time evolution

for x,y << 1

$$dN/dt \;\alpha\; \{R_D + R_D^{1/2}\, y'\, t + (x'^2 + y'^2)\;\; t^2/4\}\, e^{-t}$$

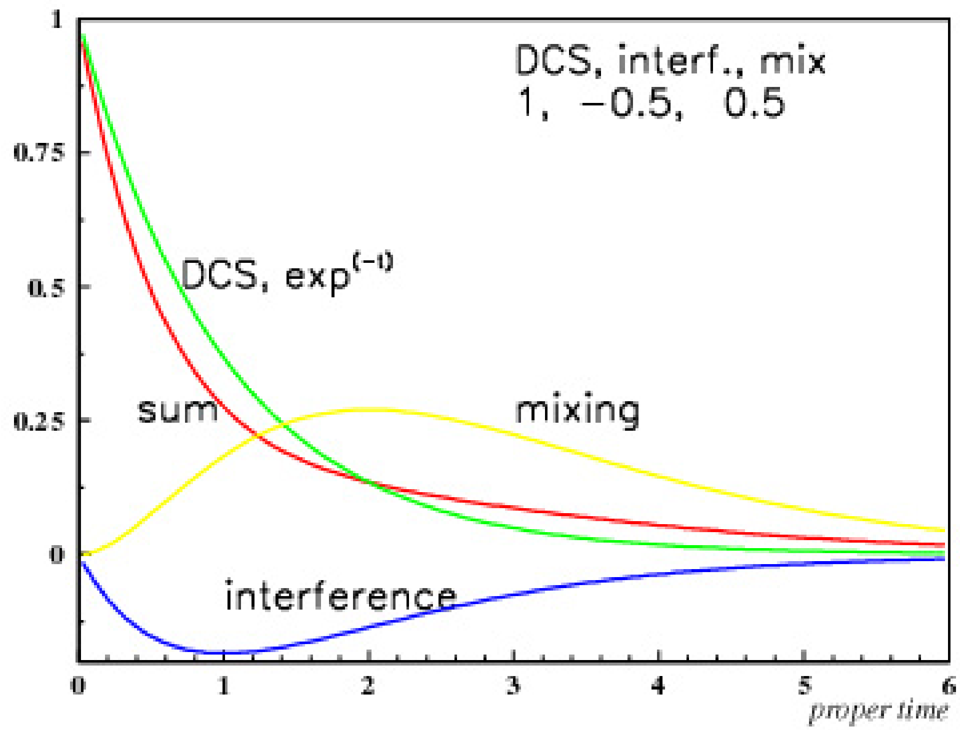
DCS interference mixing

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

$y' = y \cos\delta - x \sin\delta$

$x = \Delta M/\Gamma \qquad y = \Delta\Gamma/2\Gamma$

δ= strong phase difference

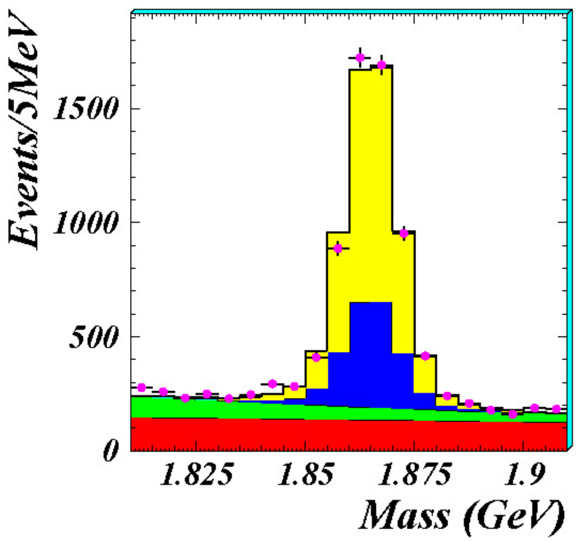


D^0 mixing in $D^0 \to K\pi$ decays

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

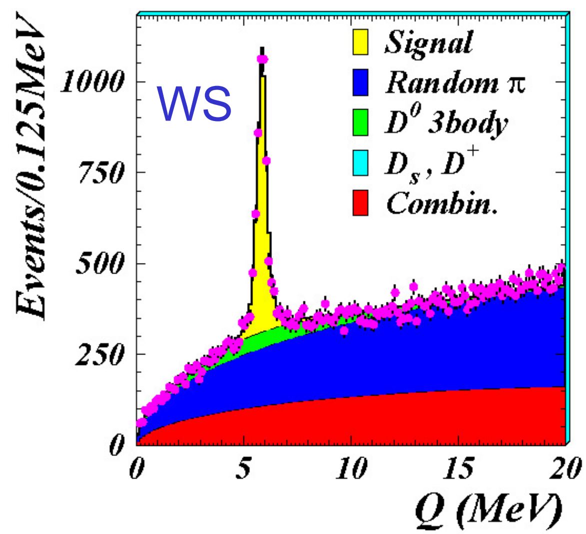
Signal extraction

3σ Q interval



$M = m(K\pi)$

3σ M interval



$Q = m(\pi_s K\pi) - m(K\pi) - m(\pi)$

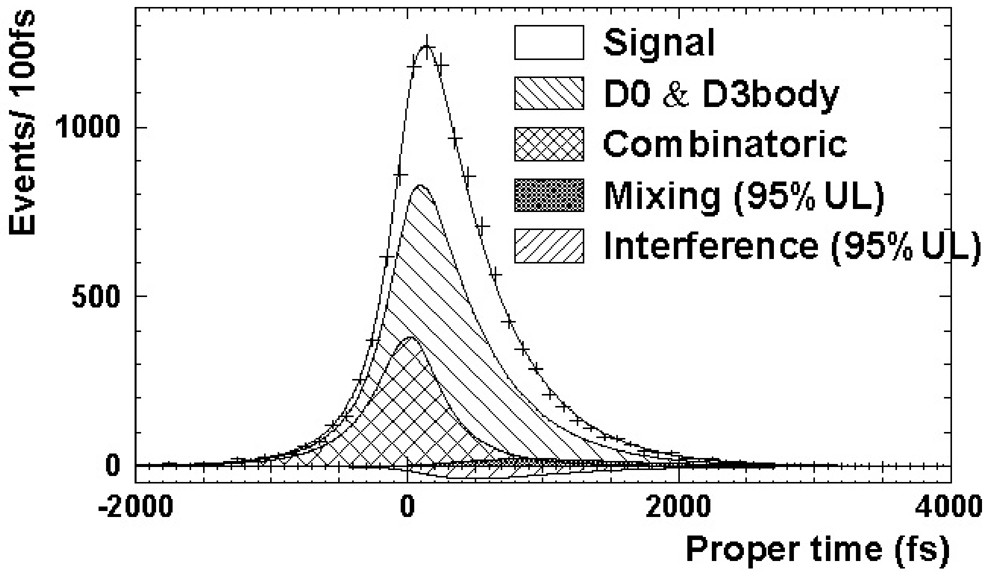
Wrong sign combinations: $D^0 \to K^+ \pi^-$

D^0 mixing in $D^0 \to K\pi$ decays

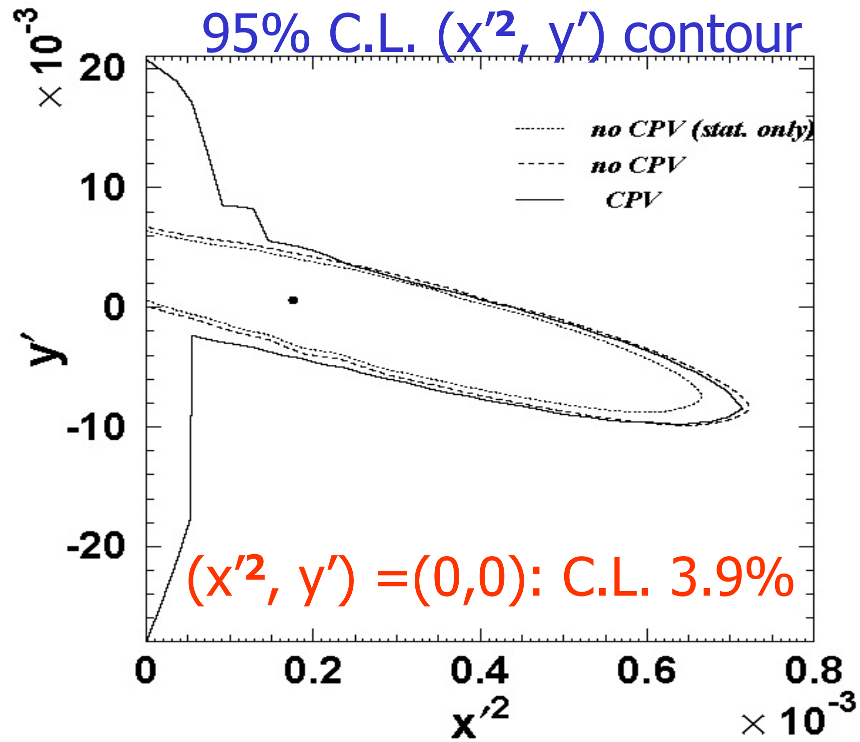
Results

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

Wrong sign time evolution



95% C.L. (x'^2, y') contour



(x'^2, y') =(0,0): C.L. 3.9%

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

BaBar result consistent → previous talk

BaBar: PRL 98, 211803 (2007), 384fb^{-1}

PRD72, 071101 (2005), 253 fb^{-1}

D^0 mixing in $D^0 \to K e \nu$ decays

Wrong charge combination → mixing (no DCS decays)

Again tag with D^{*+} charge: $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- e^+ \nu$

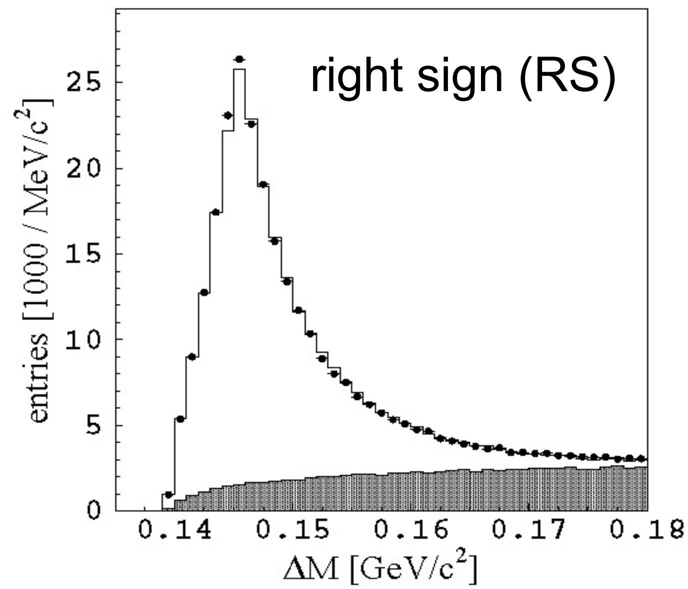
Selection criteria:

- c.m.s. momentum of the Ke system > 2 GeV (rejects bb, combinatorial background)
- Inv. mass of $e^- e^+$ ($e^+ \to \pi^+$) > 0.15GeV (rejects γ conversions)
- Cut on decay time (signal: $t^2 e^{-t}$)

Neutrino reconstruction: hermiticity, kinematic constraints.

Signal yield: $\Delta m = m(\pi_s K e \nu) - m(K e \nu)$

$$N_{RS} = (229.45 \pm 0.69) \cdot 10^3$$



D^0 mixing in $D^0 \to Ke\nu$ decays

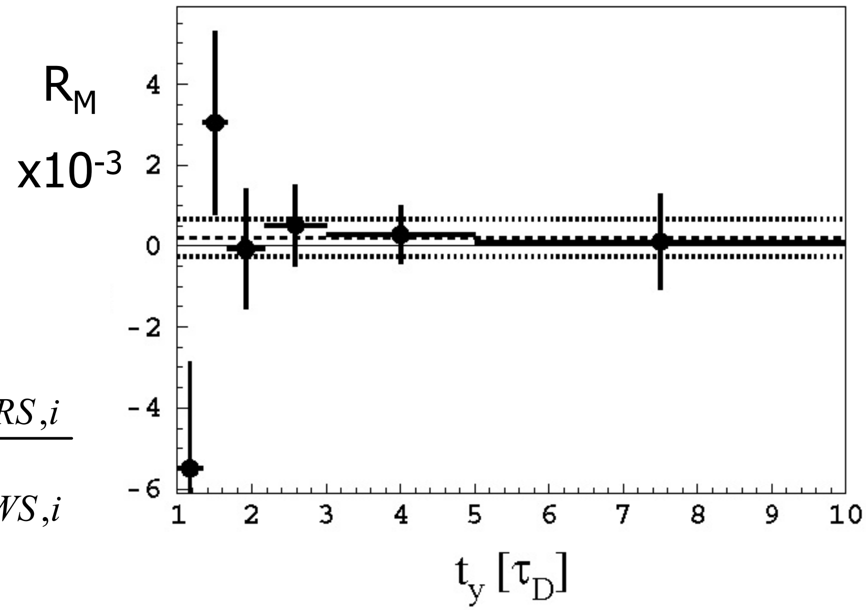
PRD72, 071101 (2005), 253 fb^{-1}

Decay time:

reduce bkg., increase sensitivity;
$\langle t \rangle$(bkg., RS) < $\langle t \rangle$(mix. signal)

6 bins in 1 < t < 10

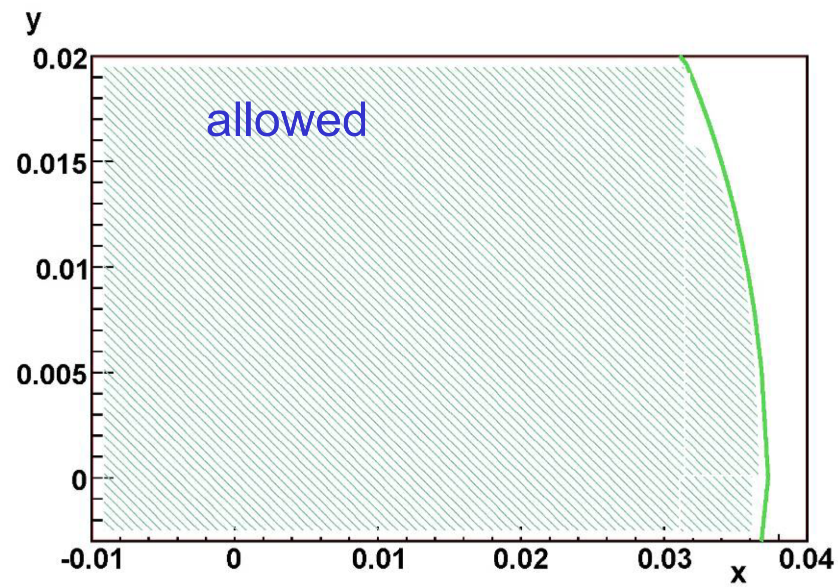
$$R_{M,i} = \frac{N_{WS,i}}{N_{RS,i}} \cdot \frac{\varepsilon_{RS,i}}{\varepsilon_{WS,i}}$$



Result:

$$R_M = \frac{N_{WS}}{N_{RS}} \approx \frac{x^2 + y^2}{2}$$

$R_M = (0.20 \pm 0.47 \pm 0.14) \cdot 10^{-3}$
$R_M < 1.2 \cdot 10^{-3}$ 95% C.L.



Update this summer with 4x statistics

D^0 mixing in K^+K^-, $\pi^+\pi^-$

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

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

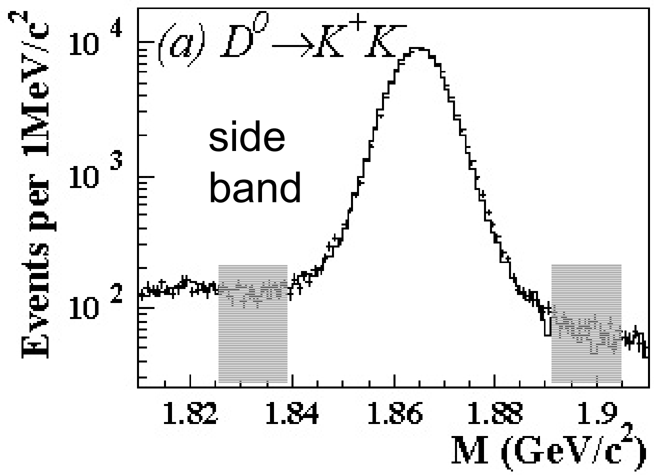
CP even final state;
in the limit of no CPV: $CP|D_1\rangle = |D_1\rangle$
$\Rightarrow$ measure $1/\Gamma_1$

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

$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = y\cos\varphi - \frac{1}{2}A_M x \sin\varphi \underset{no\ CPV}{=} y$$

S. Bergman et al., PLB486, 418 (2000)

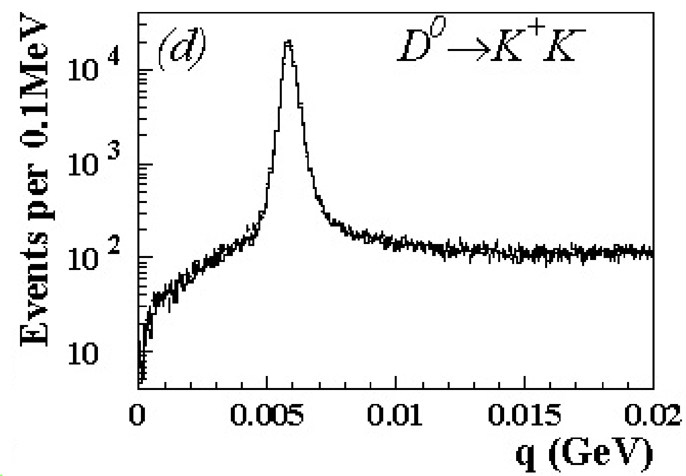
A_M, ϕ: CPV in mixing and interference



Signal: $D^0 \to K^+K^- / \pi^+\pi^-$ from D^*

M, Q, σ_t selection optimized in MC

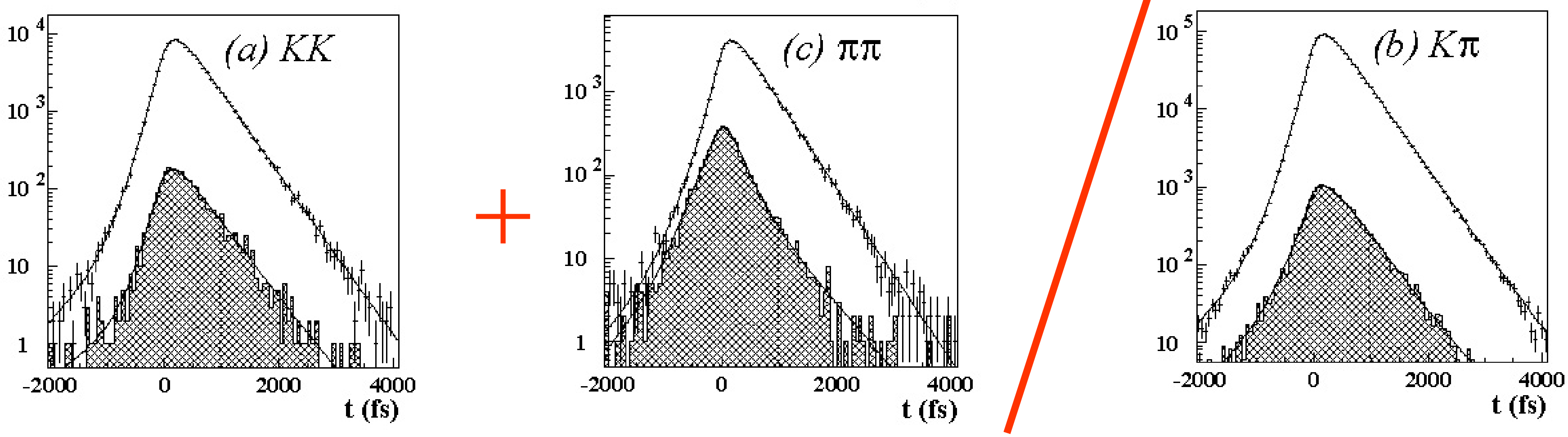
	K^+K^-	$K^-\pi^+$	$\pi^+\pi^-$
N_{sig}	111×10^3	1.22×10^6	49×10^3
purity	98%	99%	92%



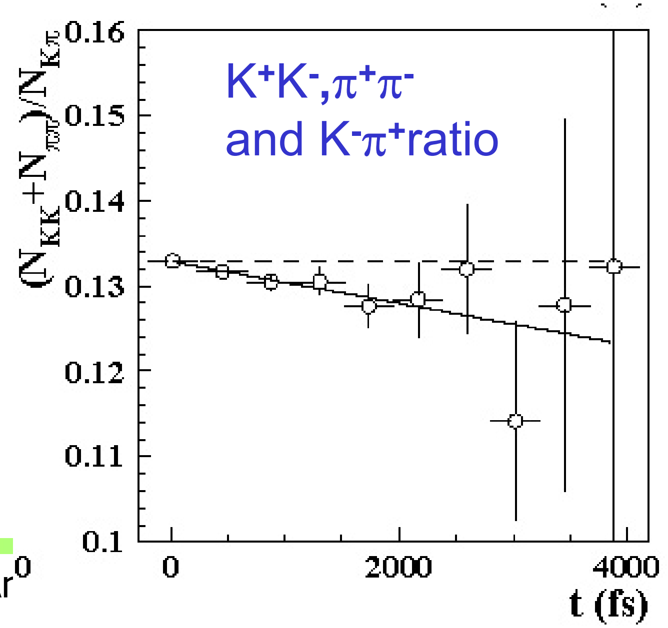
D^0 mixing in K^+K^-, $\pi^+\pi^-$

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

Decay time distributions for KK, ππ, Kπ



Difference of lifetimes visually observable in the ratio of the distributions →



D^0 mixing in K^+K^-, $\pi^+\pi^-$

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

Fit

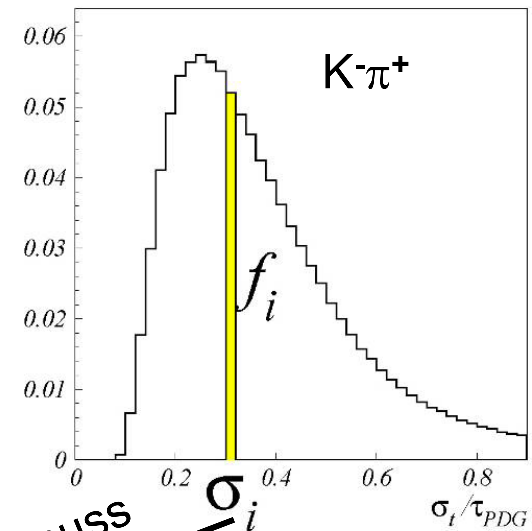
simultaneous binned likelihood fit to
K^+K^- / $K^-\pi^+$ / $\pi^+\pi^-$ decay-t → y_{CP}

$$\frac{dN}{dt} = \frac{N}{\tau}\int e^{-t'/\tau}\mathcal{R}(t-t')dt' + B(t)$$

(M sideband)

$\mathcal{R}$: ideally each σ_i Gaussian resol. term with fraction f_i;

σ_t distribution



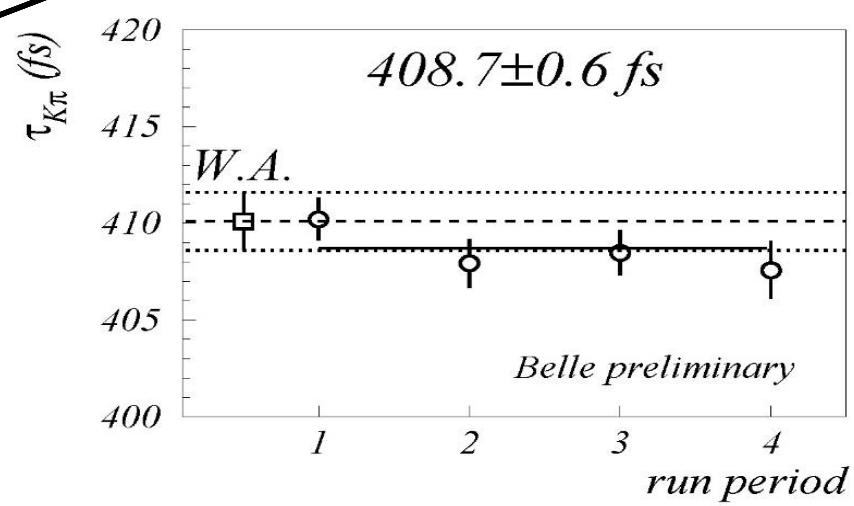
event-by-event σ_t

$(t_{rec}-t_{gen})/\sigma_t$: described by 3 Gaussians ⇒ each σ_i → 3 Gauss

↓ MC

$$\mathcal{R}(t-t') = \sum_{i=1}^{N} f_i \sum_{k=1}^{3} w_k G(t-t', s_k\sigma_i, t_0)$$

parameters of $\mathcal{R}$ depend slightly on data taking conditions



τ = 408.7±0.6 fs

D^0 mixing in K^+K^-, $\pi^+\pi^-$

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

Expected statistical precision in $\tau(K^+K^-/\pi^+\pi^-)$: ~0.3%

→Cross-checks:

MC: y_{CP}(out) - y_{CP}(input) < 0.04% for a large range of input values

y_{CP} independent of resolution function parameterization:
R(t) = single Gaussian → $\Delta\tau$ = 3.9%, but Δy_{CP} = 0.01%

Exchanging data side band with signal window background from tuned MC: Δy_{CP} = -0.04%

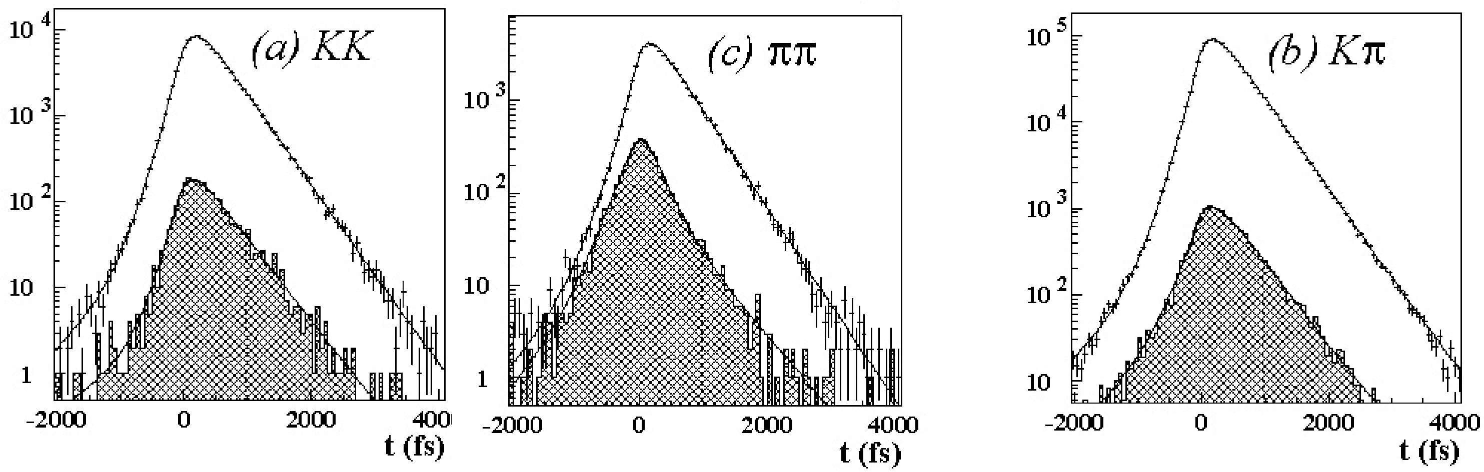
Measure y_{CP} with subsamples (run periods, $K^+K^-/\pi^+\pi^-$, separate free offset t_0) → all consistent

→Systematic error: conservative estimates: equal t_0 0.14%, acceptance 0.12%, selection variation 0.11%, signal band/sideband background differences 0.09%, background distribution B(t) 0.07%, M window position 0.04% → 0.25%

D^0 mixing in K^+K^-, $\pi^+\pi^-$

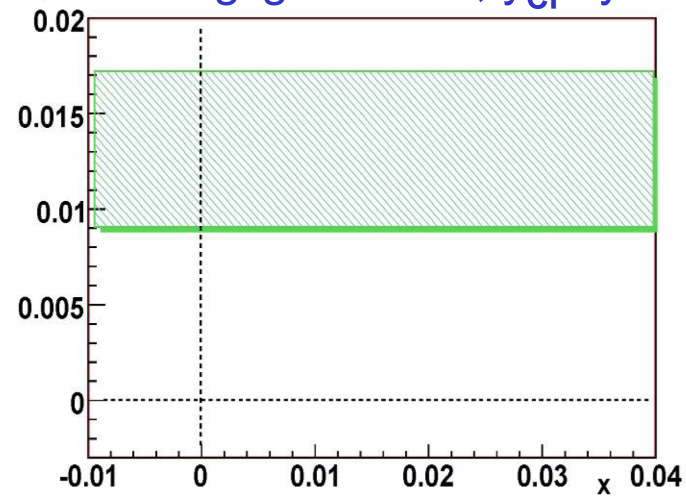
PRL 98, 211803 (2007), 540fb^{-1}

Result



simultaneous binned likelihood fit to
K^+K^- / $K^-\pi^+$ / $\pi^+\pi^-$ decay-t →

negligible CPV, y_{CP}=y



y_{CP} = (1.31 ± 0.32 ± 0.25) %

3.2 σ from zero (4.1 σ stat. only)

evidence for D^0 mixing
(regardless of possible CPV)

D^0 mixing in $K_S\,\pi^+\pi^-$

arXiv: 0704.1000, 540 fb^{-1}
submitted to PRL

BELLE

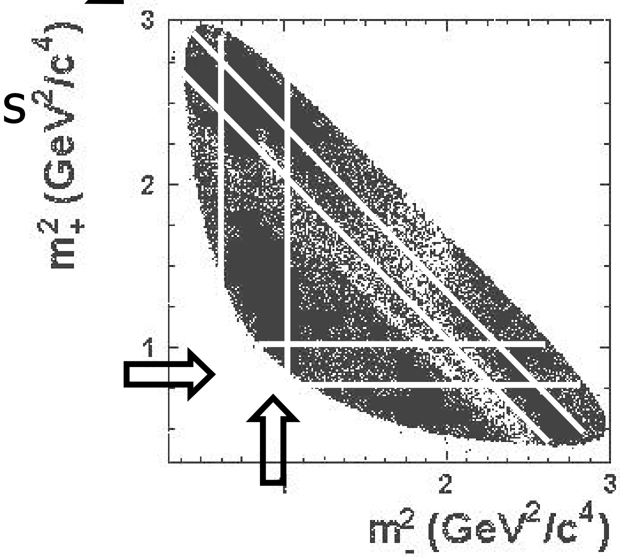
time-dependent Dalitz plot analysis

different decays identified through Dalitz plot analysis

CF: $D^0 \to K^{*-}\pi^+$

DCS: $D^0 \to K^{*+}\pi^-$

CP: $D^0 \to \rho^0 K_S$



$m_\pm^2 = m^2(K_S\,\pi^\pm)$: Dalitz variables

time-dependence:

$$\mathcal{M}(m_-^2, m_+^2, t) \equiv \left\langle K_S \pi^+ \pi^- \middle| D^0(t) \right\rangle =$$

$$= \frac{1}{2}\mathcal{A}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} + e^{-i\lambda_2 t}\right] + \frac{1}{2}\frac{q}{p}\overline{\mathcal{A}}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} - e^{-i\lambda_2 t}\right]$$

$< f \mid D^0 >$ $\qquad$ $< f \mid \overline{D}^0 >$

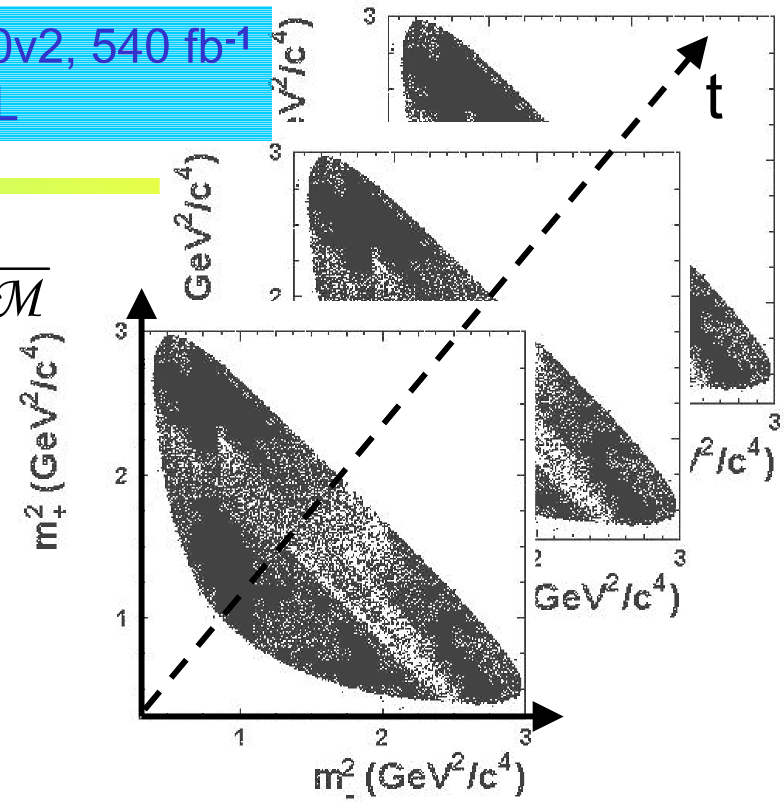
analogous for $\overline{\mathcal{M}} = < f \mid \overline{D}^0(t) >$

$\lambda_{1,2} = m_{1,2} - i\Gamma_{1,2}/2 = f(x,y)$

Rate: terms with $\cos(x\Gamma t)\exp(-\Gamma t)$, $\sin(x\Gamma t)\exp(-\Gamma t)$, $\exp(-(1+-y)\Gamma t)$ → sensitive to x and y $\quad$ (n.b. for $K^+\pi^-$: x'^2, y')

D^0 mixing in $K_S \pi^+\pi^-$

arXiv: 0704.1000v2, 540 fb^{-1}
submitted to PRL



Fit

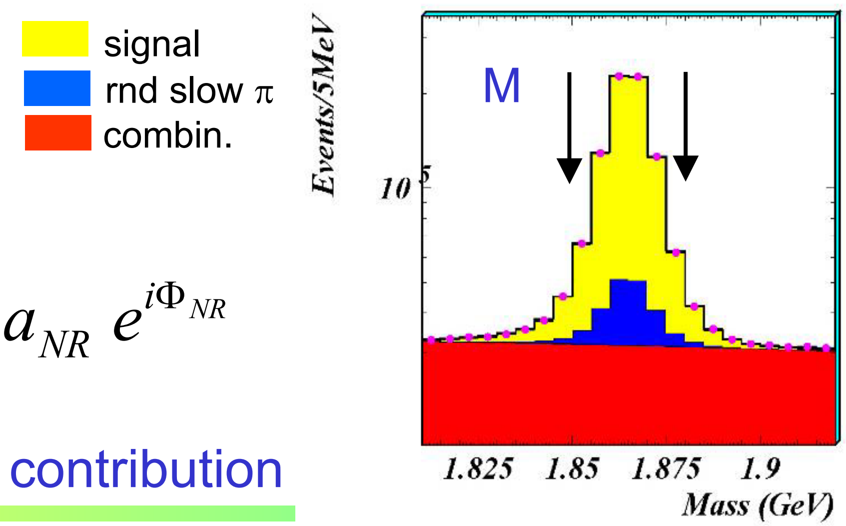
assume no CPV: $\frac{q}{p} = 1, \mathcal{A} = \overline{\mathcal{A}} \Rightarrow \mathcal{M} = \overline{\mathcal{M}}$

fit $\mathcal{M}(m_-^2, m_+^2, t)$ to data distribution $\Rightarrow$ x, y

Signal

$M(K_S \pi^+\pi^-)$ and
$Q = M(K_S \pi^+\pi^-\pi_s) - M(K_S \pi^+\pi^-) - M(\pi)$;
3 σ signal region in M, Q

$N_{sig} = (534.4 \pm 0.8) \times 10^3$
$P \approx 95\%$



Dalitz model

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

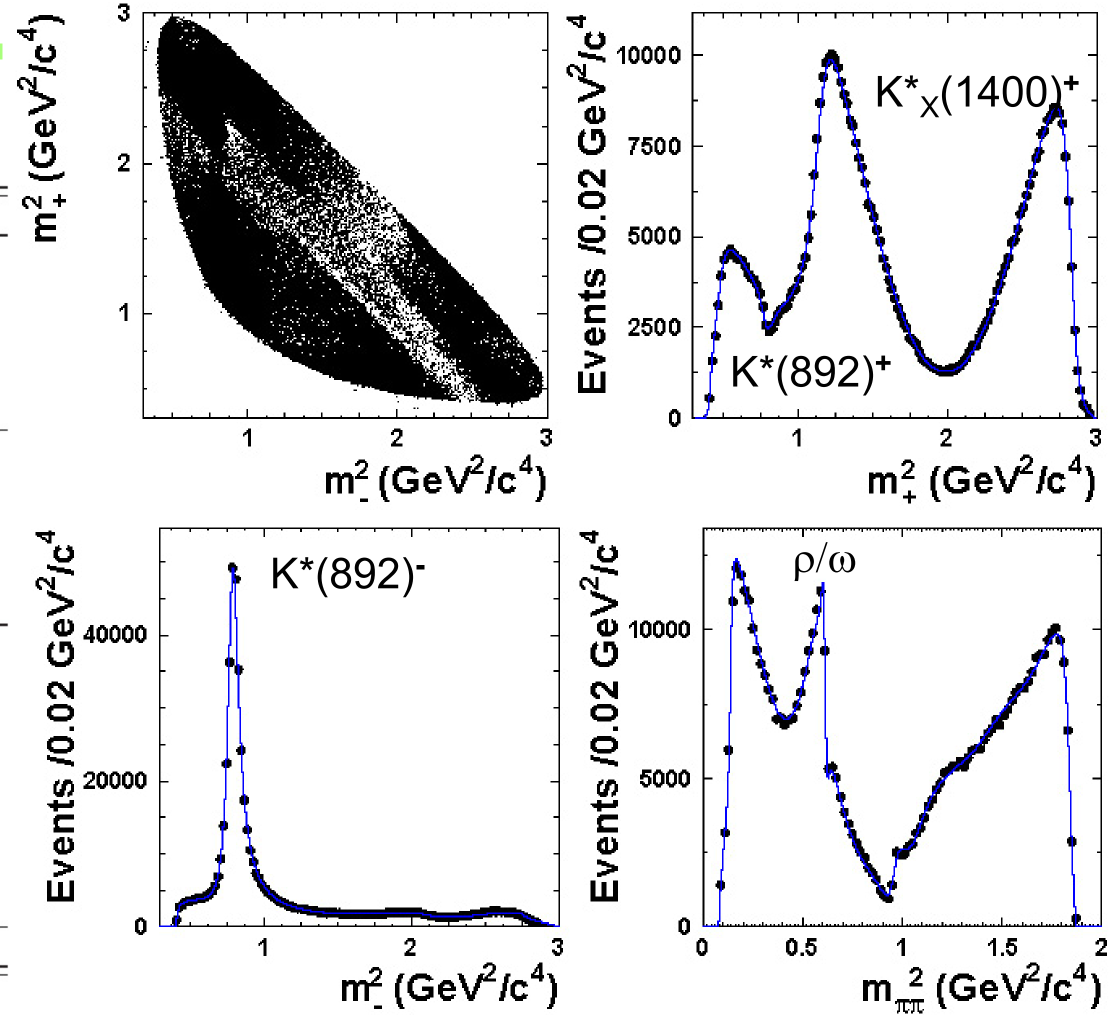
18 resonant BW terms + non-resonant contribution

D^0 mixing in $K_S\,\pi^+\pi^-$

arXiv: 0704.1000v2, 540 fb^{-1}

Dalitz projection of fit

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.006	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.8	0.0724
$K_2^*(1430)^-$	0.87 ± 0.02	-47.3 ± 1.2	0.0133
$K^*(1410)^-$	0.65 ± 0.03	111 ± 4	0.0048
$K^*(1680)^-$	0.60 ± 0.25	147 ± 29	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 1.3	0.0054
$K_0^*(1430)^+$	0.541 ± 0.019	91.8 ± 2.1	0.0047
$K_2^*(1430)^+$	0.276 ± 0.013	-106 ± 3	0.0013
$K^*(1410)^+$	0.33 ± 0.02	-102 ± 4	0.0013
$K^*(1680)^+$	0.73 ± 0.16	103 ± 11	0.0004
$\rho(770)$	1 (fixed)	0 (fixed)	0.2111
$\omega(782)$	0.0380 ± 0.0007	115.1 ± 1.1	0.0063
$f_0(980)$	0.380 ± 0.004	-147.1 ± 1.1	0.0452
$f_0(1370)$	1.46 ± 0.05	98.6 ± 1.8	0.0162
$f_2(1270)$	1.43 ± 0.02	-13.6 ± 1.2	0.0180
$\rho(1450)$	0.72 ± 0.04	41 ± 7	0.0024
σ_1	1.39 ± 0.02	-147 ± 1	0.0914
σ_2	0.267 ± 0.013	-157 ± 3	0.0088
NR	2.36 ± 0.07	155 ± 2	0.0615



Results (fit fractions, phases) in agreement with (measurement of $\phi_3(\gamma)$)

PRD73, 112009 (2006)

D^0 mixing in $K_S\pi^+\pi^-$

arXiv: 0704.1000v2, 540 fb^{-1}
submitted to PRL

Decay-t projection of fit

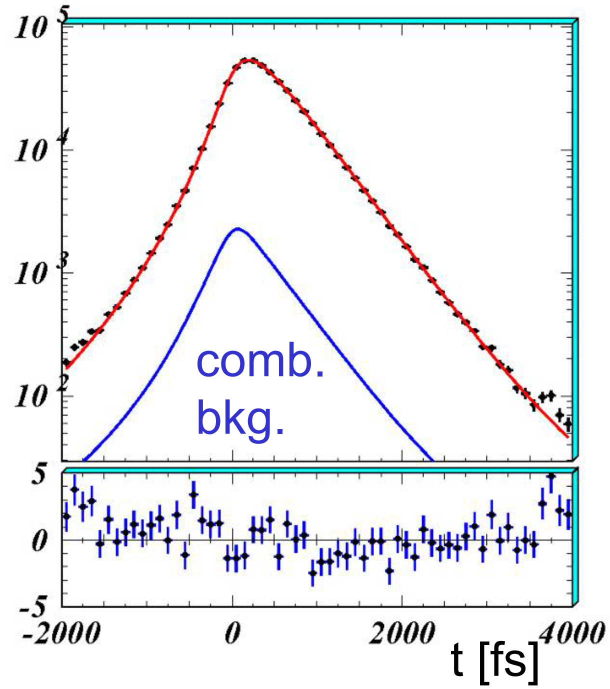
$$x = (0.80 \pm 0.29 \pm {}^{0.09}_{0.07} \pm {}^{0.10}_{0.14})\%$$
$$y = (0.33 \pm 0.24 \pm {}^{0.08}_{0.12} \pm {}^{0.06}_{0.08})\%$$

± stat. ± exp.syst. ± decay model syst.

→most sensitive meas. of x

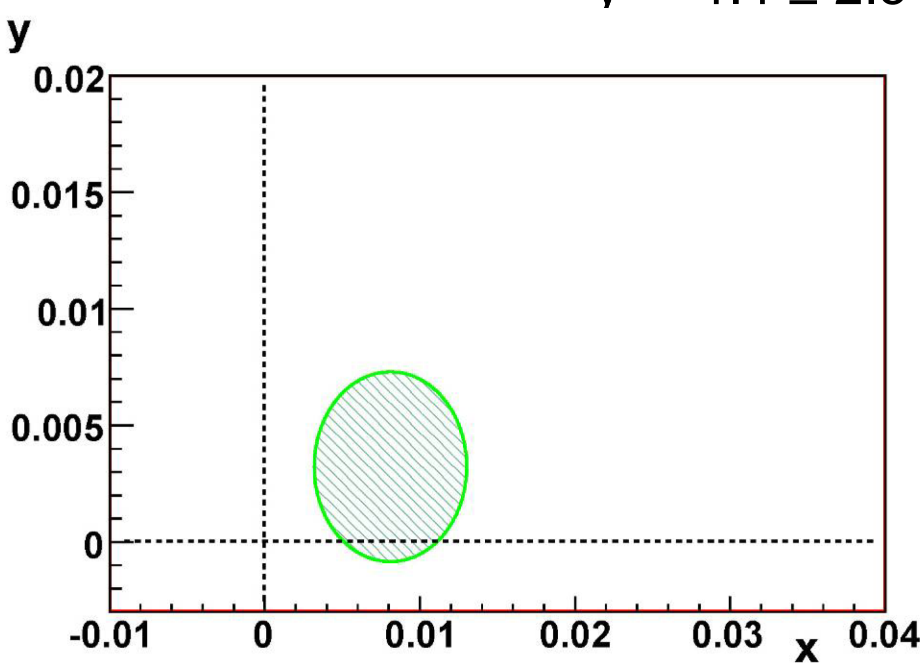
Cleo, PRD72, 012001 (2005)

x = 1.8 ± 3.4 ± 0.6%
y = -1.4 ± 2.5 ± 0.9 %



τ = 409.9±0.9 fs

τ_{PDG}=410.1±1.5 fs



- (x,y)=(0,0) has C.L. 2.6% (2.2 σ)
- x>0: 2.4 σ significance

D^0 mixing: results from $K_S\pi^+\pi^-$ and $K^+K^-/\pi^+\pi^-$

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

arXiv: 0704.1000v2, 540 fb^{-1}
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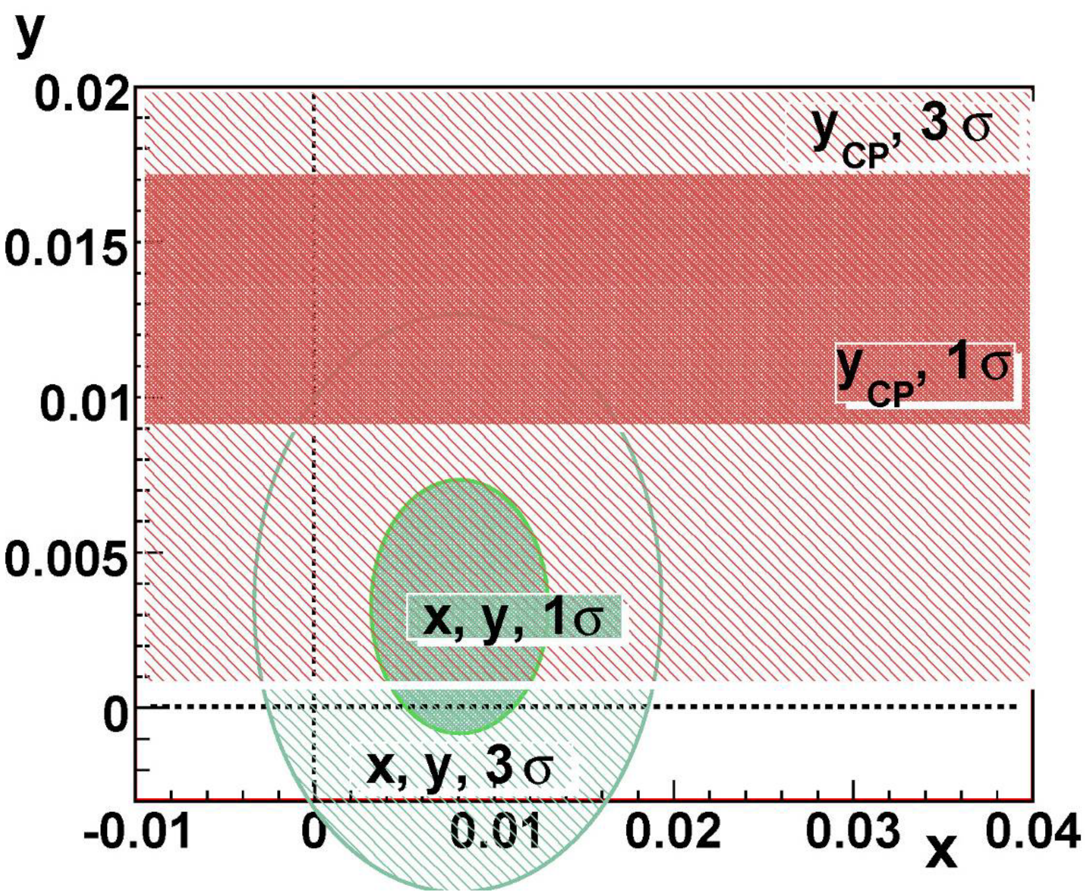
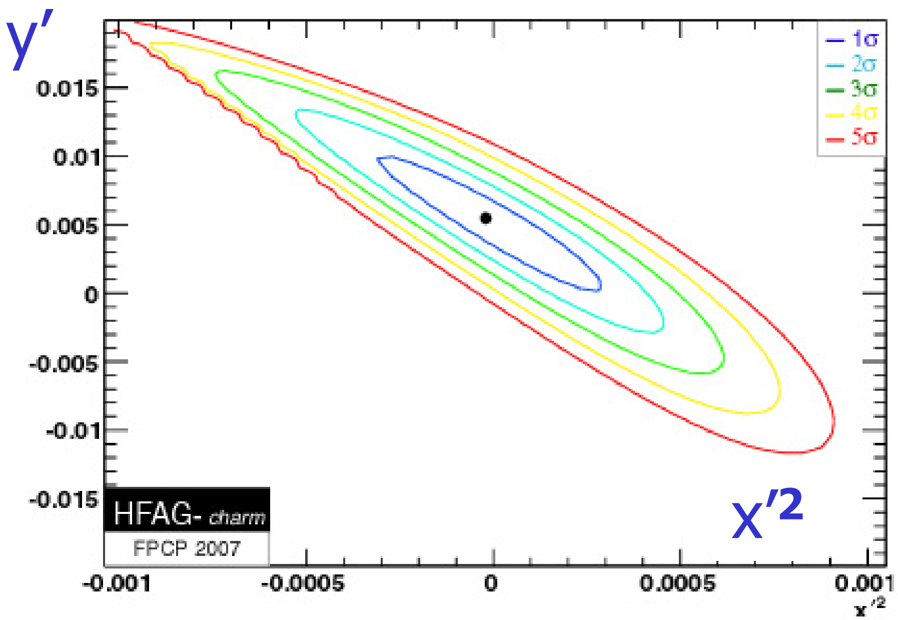
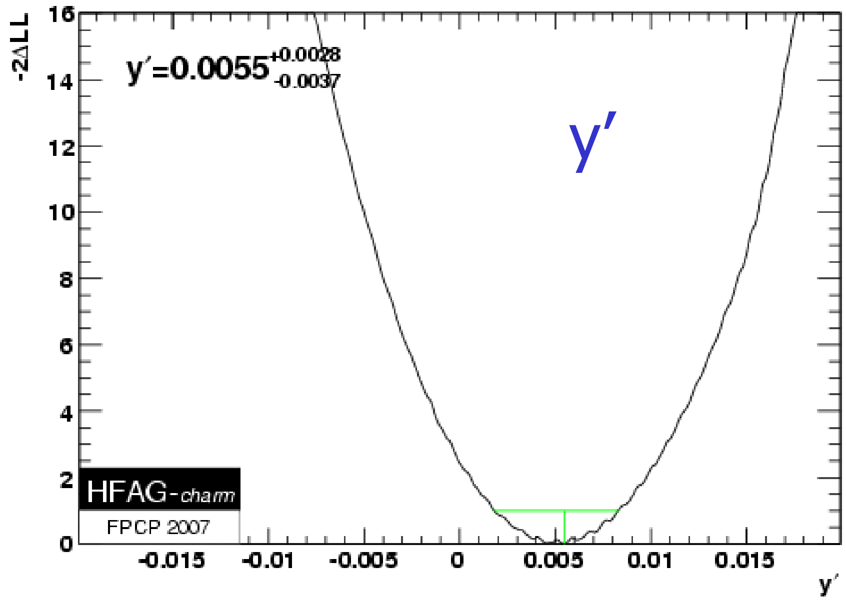
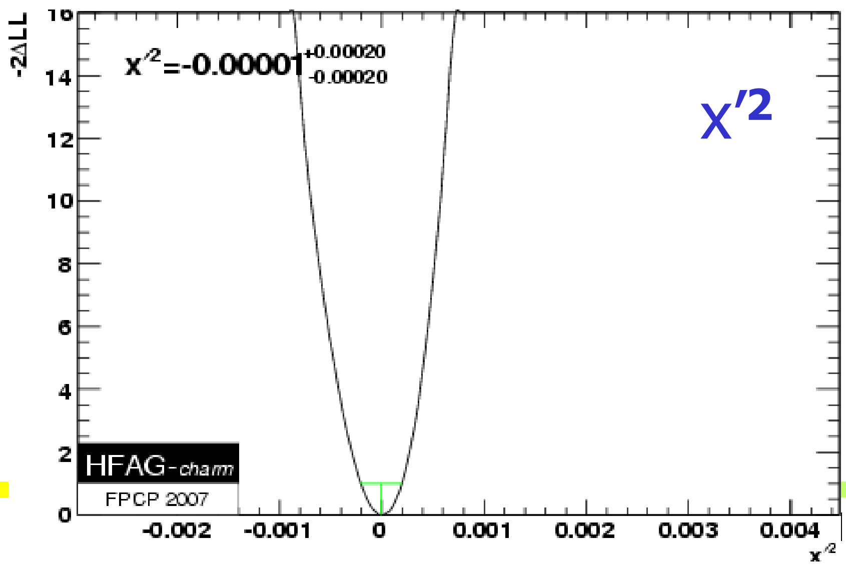


- K^+K^- / $\pi^+\pi^-$: y=0 has C.L. 6×10^{-4}
- K_S $\pi^+\pi^-$: (x,y)=(0,0) has C.L. 2.6%

D^0 mixing: Belle + Babar $D^0 \to K\pi$ results combined



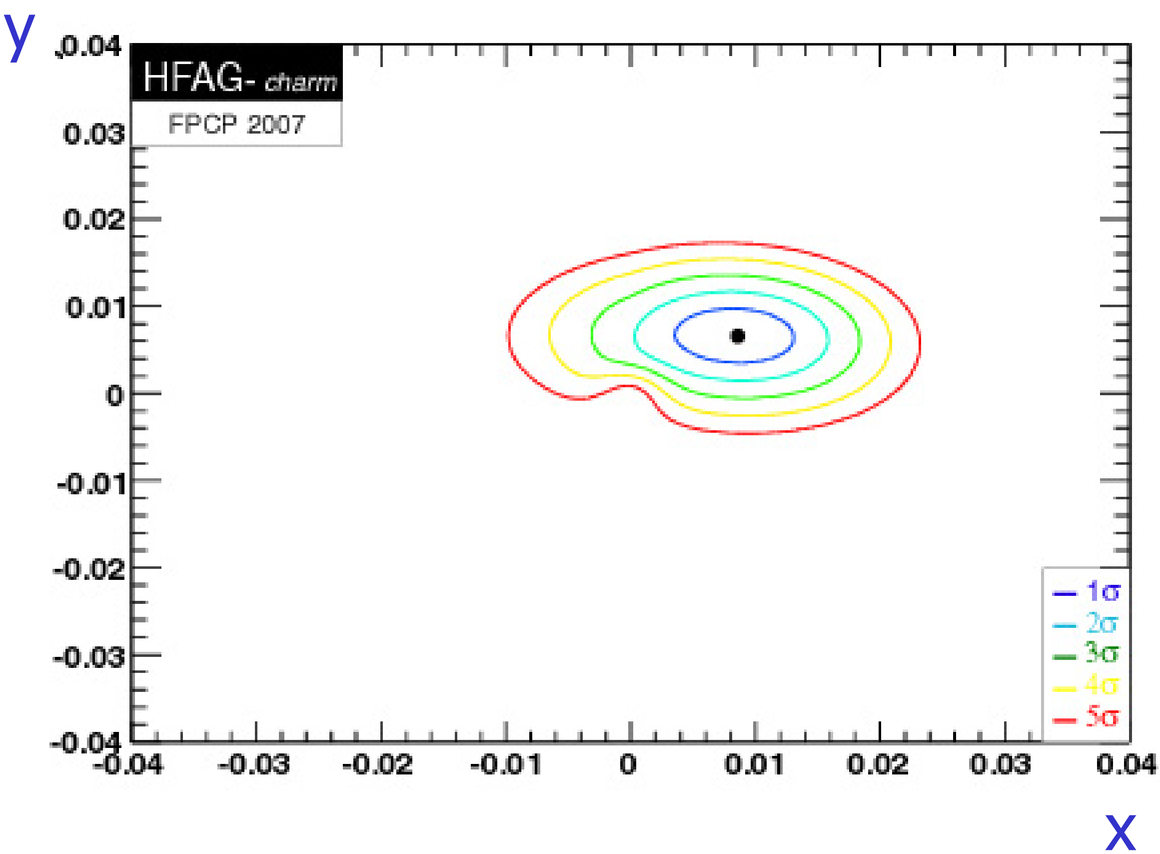




$x'^2 = (0.001 \pm 0.020)\ \%$

$y' = (0.55 \pm {}^{0.28}_{0.37})\%$

D^0 mixing: all results combined



Assuming no CPV

$x = (0.87 \pm ^{0.30}_{0.34})\ \%$

$y = (0.66 \pm ^{0.21}_{0.20})\%$

$\delta = 0.33 \pm ^{0.26}_{0.29}$

(x,y)=(0,0) excluded by >5σ

Search for CP violation

CPV in D^0 system

Relevant CKM elements of the 2x2 submatrix:

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

phase: $\sim \frac{2\eta A^2\lambda^5}{\lambda} \sim O(10^{-3})$

CPV in D^0 very small, $\leq 10^{-3}$;
parameterization:

$$\frac{q}{p} \neq 1;\ \frac{q}{p} \equiv (1+\frac{A_M}{2})e^{i\varphi};\ A_M, \varphi \neq 0$$

$D^0 \rightarrow K^+\pi^-, K^+K^- / \pi^+\pi^-, K_S\pi^+\pi^-$
t evolution depends also on CPV parameters

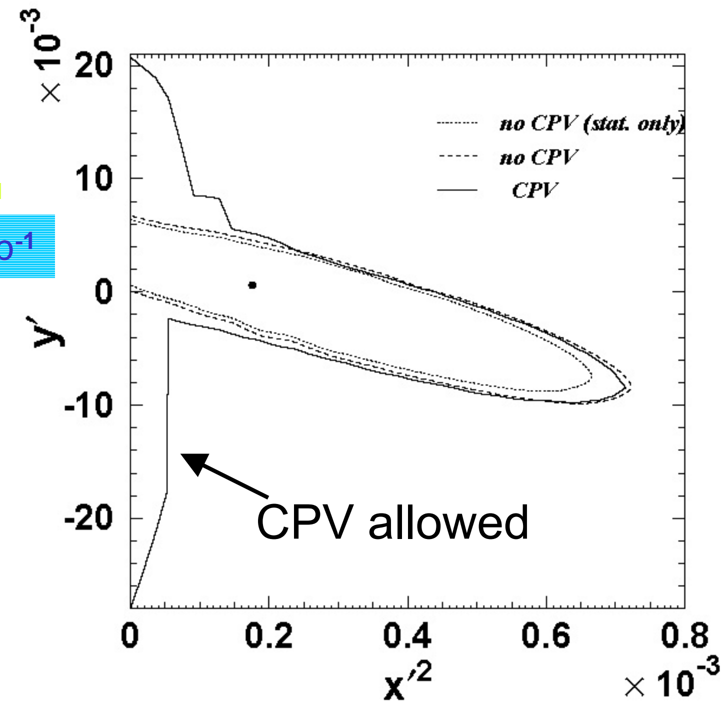
- x, y at upper limit of SM expectation → search for CPV
- at current level of sensitivity: positive signal clear indication of NP

Search for CP violation

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

PRL96, 151801 (2006), 400 fb^{-1}

CPV allowed fit:
separate D^0 and $\overline{D}^0$ tags
$(x'^2, y', R_D) \rightarrow (x'^{\pm 2}, y'^{\pm}, R_D^{\pm})$



$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-} \qquad A_M = \frac{R_M^+ - R_M^-}{R_M^+ + R_M^-}$$

$A_D = (23 \pm 47) \cdot 10^{-3}$ direct CPV
$A_M = (670 \pm 1200) \cdot 10^{-3}$ indirect CPV

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

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

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

indirect CPV

$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = y\cos\varphi - \frac{1}{2} A_M x \sin\varphi$$

$$A_\Gamma = \frac{\tau(\overline{D}^0 \rightarrow K^-K^+) - \tau(D^0 \rightarrow K^-K^+)}{\tau(\overline{D}^0 \rightarrow K^-K^+) + \tau(D^0 \rightarrow K^-K^+)} = \frac{1}{2} A_M y \cos\varphi - x \sin\varphi$$

Search for CP violation - continued

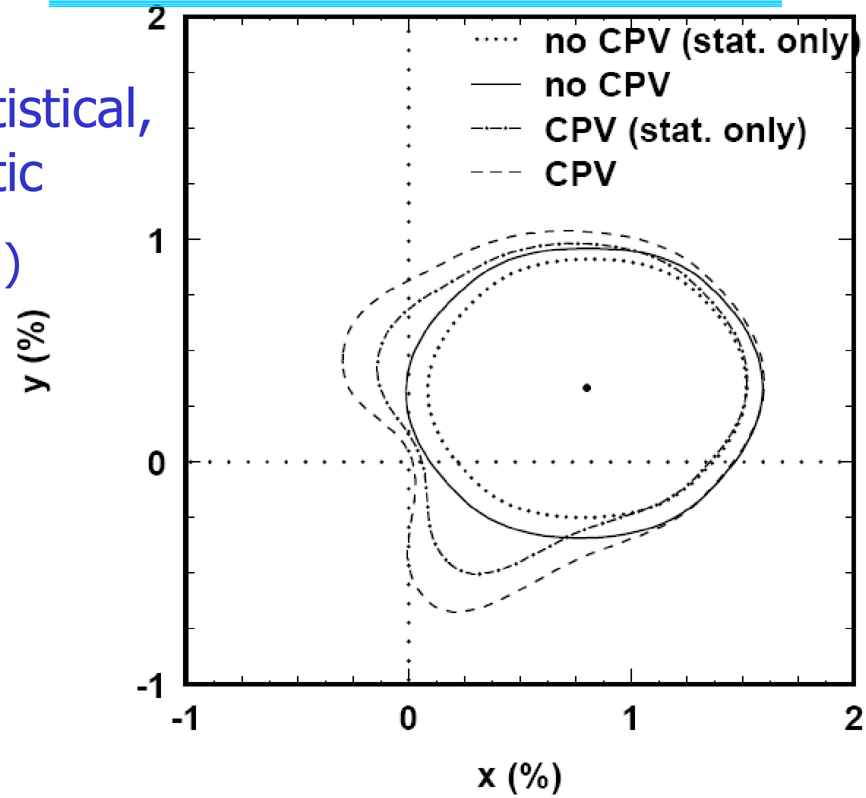
CPV in $D^0 \rightarrow K_S \pi^+\pi^-$

arXiv: 0704.1000v2, 540 fb^{-1}
submitted to PRL

95% C.L. contours for (x, y):

•CPV allowed: dash-dotted: statistical, dashed: statistical and systematic

(No CPV assumed: dotted and solid)



Dalitz plot fit separately for D^0 and $\bar{D}^0$:

•Fit parameters consistent for both samples → no direct CPV

•Parameters $|q/p|$ and $\phi = \arg(q/p)$ consistent with CP conservation

Fit assuming no direct CPV → Parameters of CPV in mixing and interf. in mixing and decay:

$|q/p| = 0.95 \pm ^{0.22}_{0.20}$

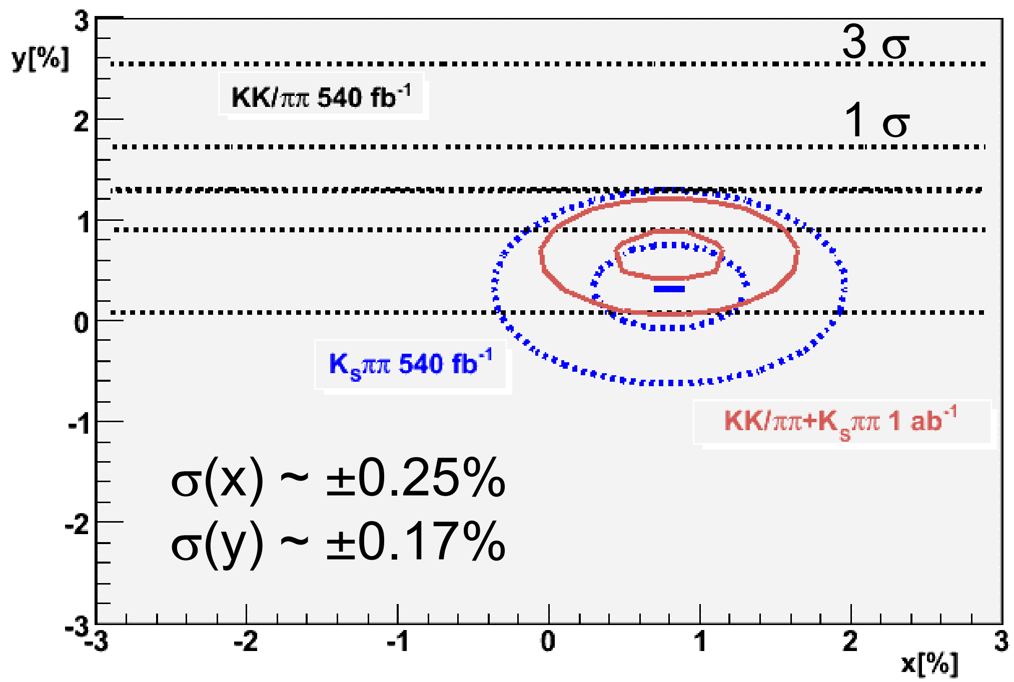
$\phi = \arg(q/p) = (-2 \pm ^{10}_{11})^0$

Prospects: near future

B-factories

near future: 1 ab^{-1}

Contours for combined $K_S\pi^+\pi^-$ and $KK/\pi^+\pi^-$ (assuming present mean)



CLEO and BESIII

new measurements of the phase δ

→ needed to interpret the measurements of x' and y' in terms of x and y in the $K^+\pi^-$ decays

Prospects

Super-B factory: rough expectations at 5 ab^{-1}

combination of results from $K\pi$, $KK/\pi\pi$, $K_S\pi\pi$

$\sigma(x) \sim \sigma(y) \sim 0.10\%$ → mixing

$\sigma(|q/p|) \sim 0.09$, $\sigma(\phi) \sim 0.1$ → CPV

possible CPV - New Physics – would be tested with ~ O(5) better sensitivity at ~50 ab^{-1} (several extensions of SM predict CPV ~ O(1%))

Y. Grossman et al., hep-ph/0609178