# $D^0$ Mixing and CP Violation

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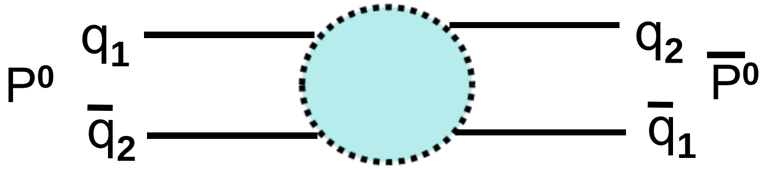
1. Phenomenology
2. Measurements
    3. Decays to CP eigenstates
    4. Hadronic WS decays
    5. t-dependent Dalitz analyses
6. Average
7. Constraints
8. Outlook

# 1. Phenomenology



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

### $D^0$ mixing is FCNC of u-type quarks

### Time evolution

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

flavor states ≠ $H_{eff}$ eigenstates:

(defined flavor) (defined $m_{1,2}$ and $\Gamma_{1,2}$)

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

---

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

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

---

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

$$|x|, |y| << 1 \Rightarrow \frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left|\left\langle f\middle|D^0\right\rangle + \frac{q}{p}\frac{ix+y}{2}\left\langle f\middle|\overline{D}^0\right\rangle\right|^2$$

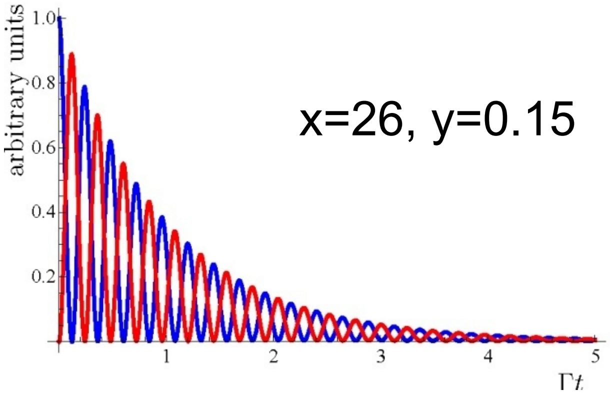
Decay time distribution of experimentally accessible states $D^0$, $\overline{D}^0$ sensitive to mixing parameters x and y, depending on final state

# 1. Phenomenology

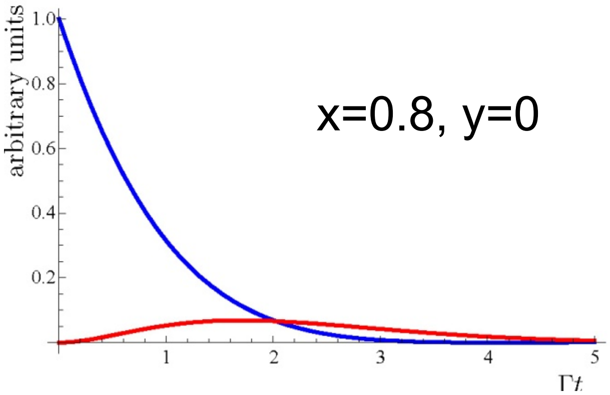
## Oscillation frequency

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

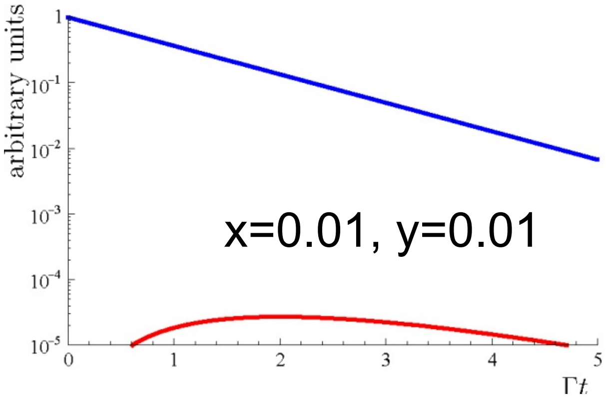
$B_s$



$B_d$



$D^0$

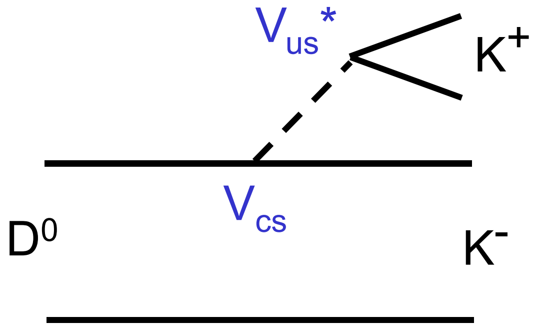


*Thus the system of the world only oscillates around a mean state from which it never departs except by a **very small quantity***

Marquis de Laplace (1749 -1827)

# 1. Phenomenology

## CP violation



$D^0$: first two quark generations;
CKM elements ≈ real;

using CKM unitarity:

$$\arg(V_{cs}^*V_{us}) \approx \mathrm{Im}\left[\frac{V_{cb}^*V_{ub}}{V_{cd}^*V_{ud}}\right] \sim \mathcal{O}(10^{-3})$$

below current exp. sensitivity;
signals New Physics

parameterization:

$R_D \neq 1$: Cabibbo suppression

$A_D \neq 0$: CPV in decay
$A_M \neq 0$: CPV in mixing
$\phi \neq 0$ : CPV in interference

$$\left|\frac{\langle \bar{f} | D^0 \rangle}{\langle f | D^0 \rangle}\right| \equiv \sqrt{R_D},$$

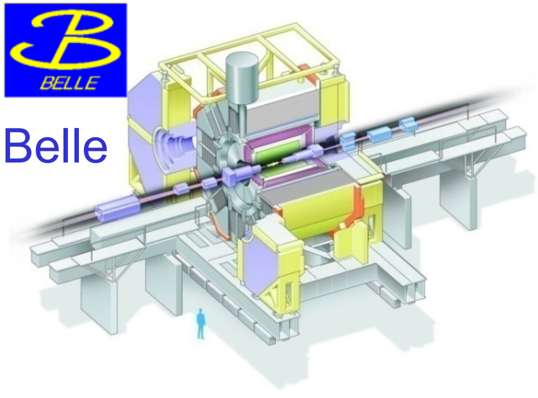
$$\left|\frac{\langle f | D^0 \rangle}{\langle \bar{f} | \bar{D}^0 \rangle}\right| \equiv 1+\frac{A_D}{2}, \quad \left|\frac{q}{p}\right| \equiv (1+\frac{A_M}{2}),$$

$$\frac{q}{p}\frac{\langle f | \bar{D}^0 \rangle}{\langle f | D^0 \rangle} \equiv -\frac{(1+A_M/2)\sqrt{R_D}}{1+A_D/2}e^{-i(\delta_f-\varphi)}$$

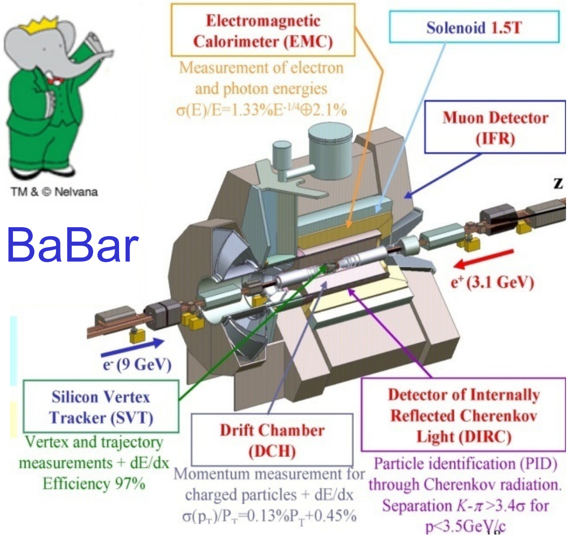
# 2. Measurements - general

## Experiments

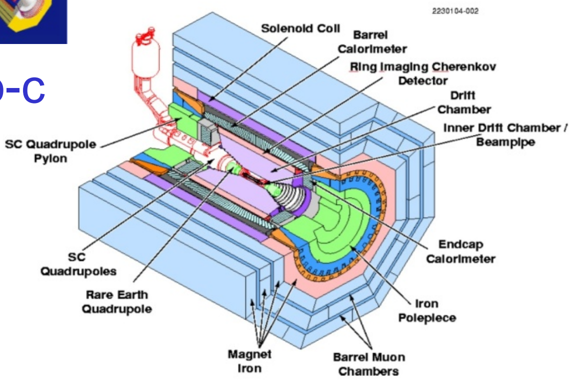
Belle



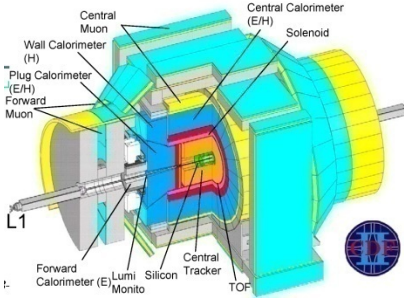
BaBar



Cleo-c



CDF II



## Common methods

$D^{*+} \to D^0 \pi_s^+$

charge of $\pi_s \Rightarrow$ flavor of $D^0$;

$\delta M = M(D^0\pi_s) - M(D^0) \Rightarrow$

background reduction

$p^*(D^*) > 2.5$ GeV/c

(or impact parameter)

eliminates $D^0$ from $b \to c$

# 3. Decays to CP eigenstates

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

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

CP even final state;
no CPV:
$CP|D_1\rangle = |D_1\rangle \Rightarrow \tau = 1/\Gamma_1$;
$K^-\pi^+$: mixture of CP states $\Rightarrow$
$\tau = f(1/\Gamma_1, 1/\Gamma_2)$

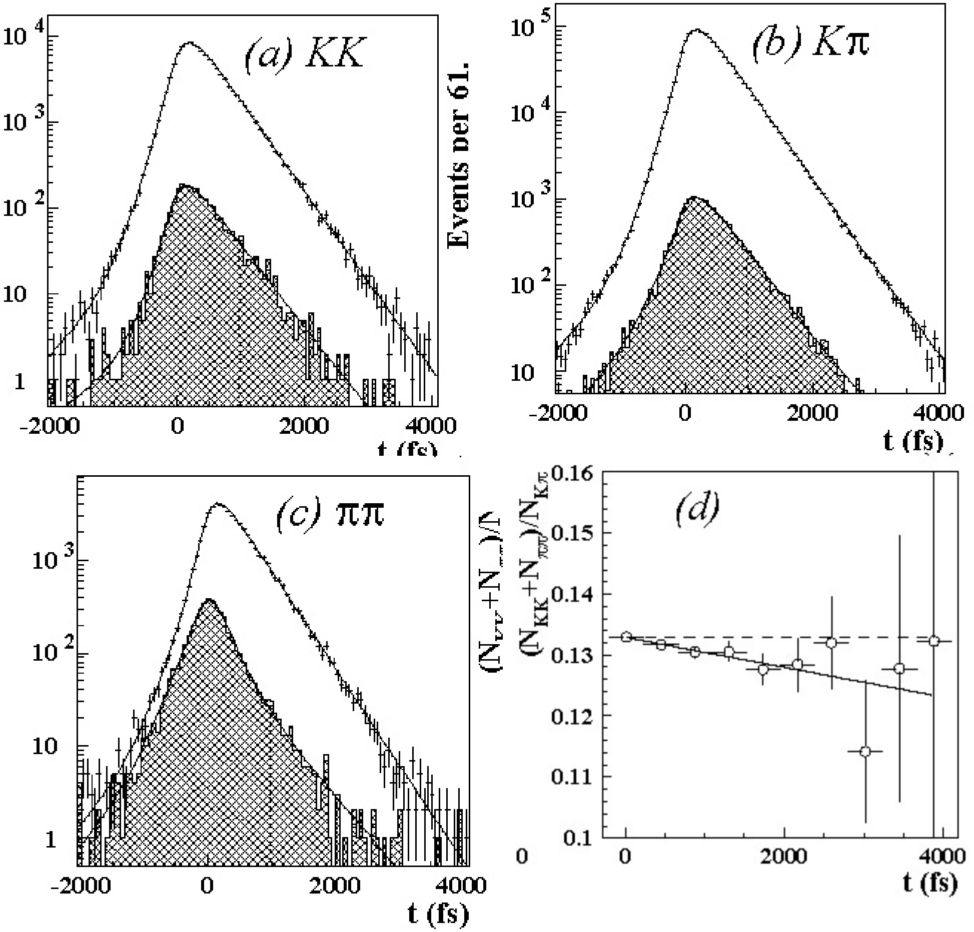
$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 \approx$$

$$y\cos\varphi - \frac{A_M}{2} x \sin\varphi \underset{no\ CPV}{=} y$$

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

$A_M$, $\varphi$: CPV in mixing and interference

exp. issues:
- good S/N (tagged decays)
- precise modeling of decay-t resolution needed



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

BaBar, PRD78, 011105 (2008), 384fb$^{-1}$

$y_{CP} = (1.24 \pm 0.39 \pm 0.13)\%$

⑪

# 3. Decays to CP eigenstates

## CPV

t-dependent

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

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

BaBar, PRD78, 011105 (2008), 384fb$^{-1}$

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

t-dependent:

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)} \approx$$

$$\approx \frac{A_M}{2} y \cos\varphi - x \sin\varphi \underbrace{=}_{no\,CPV} 0$$

t-integrated:

$$A_{CP}^f = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)} =$$

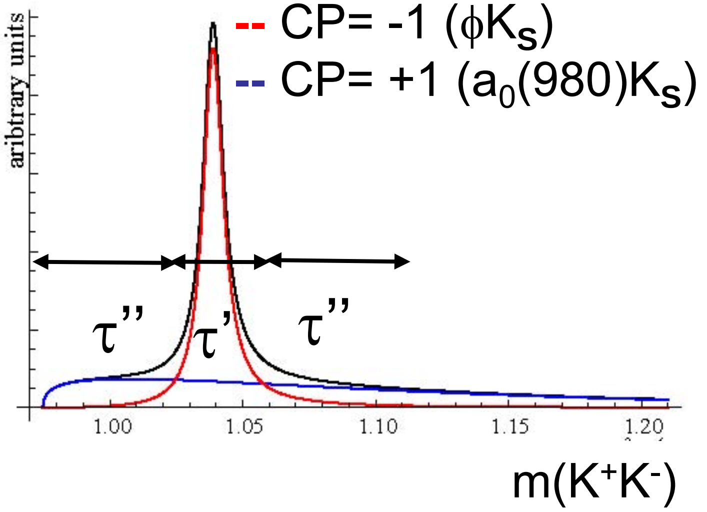
$$= a_{dec}^f + a_{mix} + a_{int}$$

## related meas.

$D^0 \to \phi K_S$

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

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



exp. issues:

un-tagged decays; worse $\sigma_t$ due to K$_s$ ; comparison of topologically equal decays → reduced effects of resolution in <t>

# 4. WS decays

$D^{*+} \to D^0 \, \pi_{\mathbf{slow}}^+ \qquad D^0 \to \bar{D}^0 \to K^+ \pi^-$

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

DCS decays ⇒ interference;

t-dependence to separate DCS/mixed

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

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

δ: unknown strong phase DCS/CF

## CPV allowed:

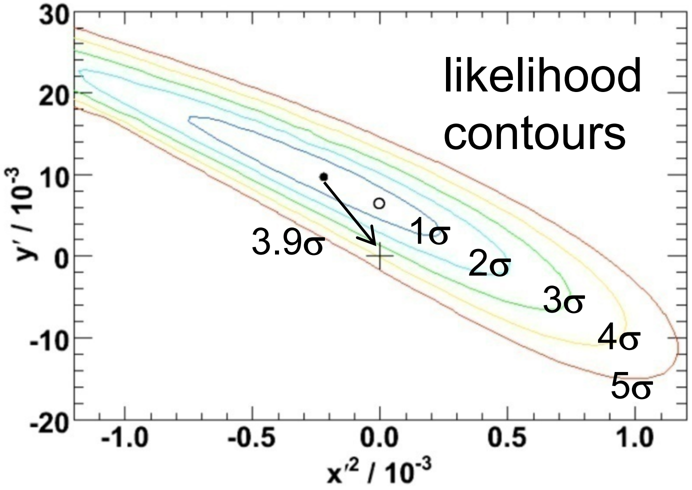
separate $D^0$ and $\bar{D}^0$ tags

$(x'^2, y', R_D) \to (x'^{\pm 2}, y'^{\pm}, R_D^{\pm})$

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

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

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



likelihood contours

exp. issues:

- signif. background in WS;
- accurate resol. f. param.;
- stat. issues for $x'^2<0$;

results of similar accuracy

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

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

# 5. t-dependent Dalitz

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

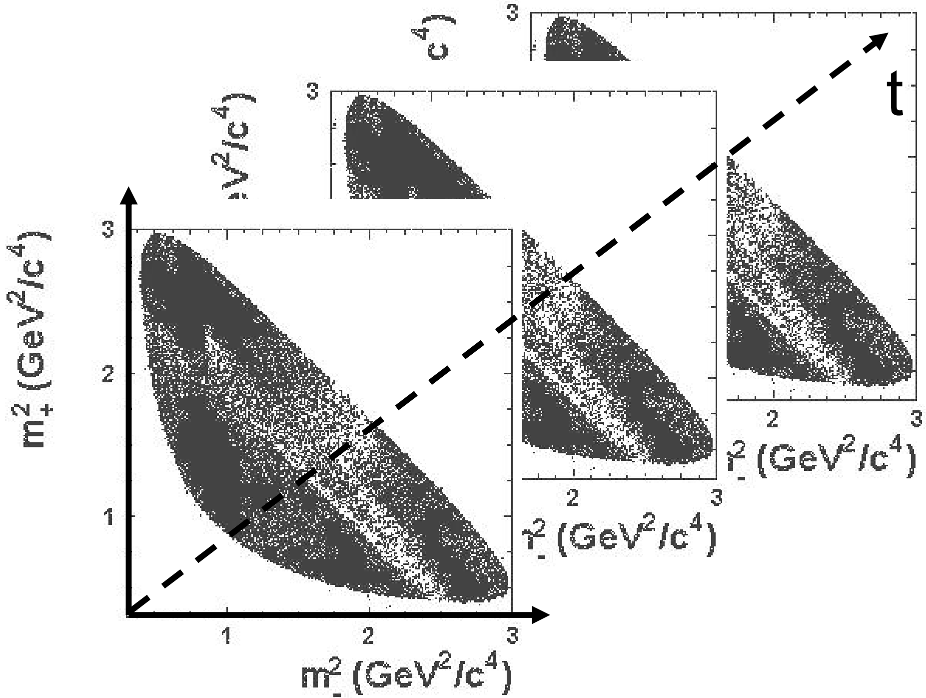
different types of interm. states;

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

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

if $f = \overline{f} \Rightarrow$ relative phases determined

(unlike $D^0 \to K^+\pi^-$);



t-dependence:

regions of Dalitz plane →

specific t dependence f(x, y);

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

$$= \frac{1}{2} \overset{D^0 \to f}{\mathcal{A}(m_-^2, m_+^2)} \left[ e^{-i\lambda_1 t} + e^{-i\lambda_2 t} \right] +$$

$$+ \frac{1}{2} \frac{q}{p} \overset{\overline{D}^0 \to f}{\overline{\mathcal{A}}(m_-^2, m_+^2)} \left[ e^{-i\lambda_1 t} - e^{-i\lambda_2 t} \right]$$

exp. issues:

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

- model system.;
- direct meas. x, y;
- any $f = \overline{f}$: sensitivity to x depending on a priori unknown strong phase variation

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

$\lambda_{1,2} = f(x,y)$;

n.b.: $K^+\pi^-$: $x'^2$, $y'$

$$x = (0.80 \pm 0.29 \pm^{0.13}_{0.16})\%, \quad y = (0.33 \pm 0.24 \pm^{0.10}_{0.14})\%$$

$$|q/p| = 0.86 \pm^{0.30}_{0.29} \pm^{0.10}_{0.09}, \quad \varphi = (-0.24 \pm^{0.28}_{0.30} \pm 0.09)\ rad$$

access directly x, y ①

# 6. Average

## Average of results

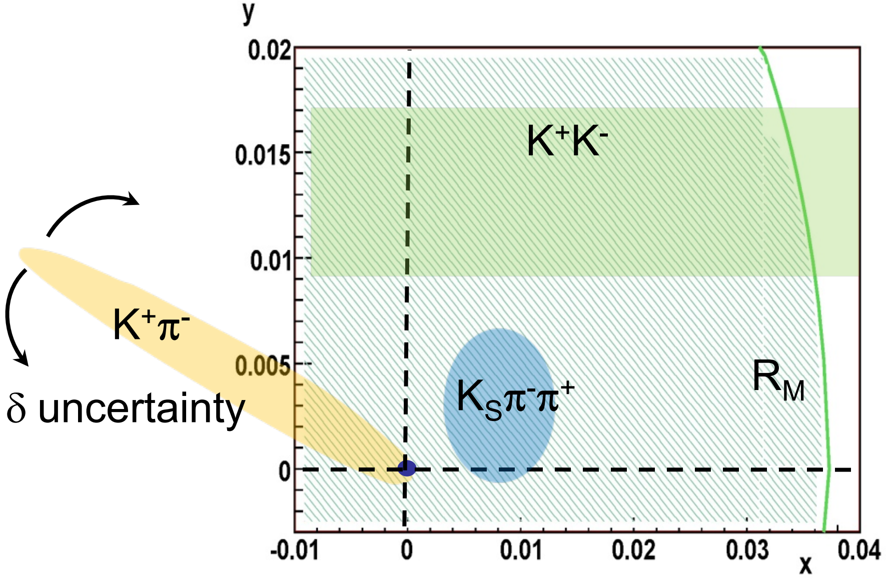
$\chi^2$ fit including correlations among measured quantities

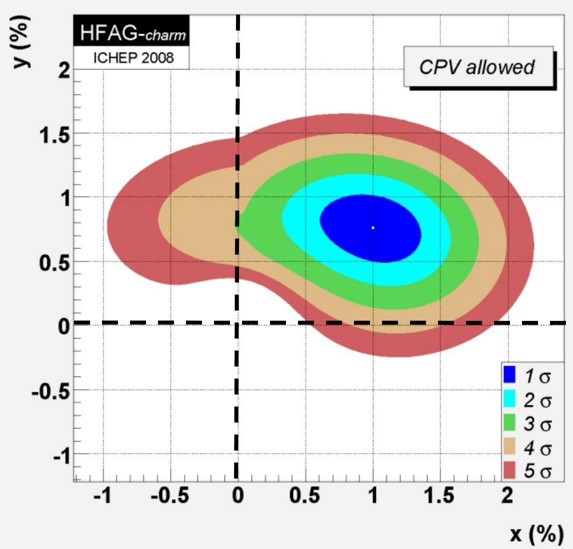
| | |
|---|---|
| x | $(1.00\ ^{+0.24}_{-0.26})\%$ |
| y | $(0.76\ ^{+0.17}_{-0.18})\%$ |
| $\delta$ | $(22.5\ ^{+10.4}_{-11.0})°$ |
| $\delta_{K\pi\pi}$ | $(11.2\ ^{+20.6}_{-22.5})°$ |
| $R_D$ | $(0.336 \pm 0.009)\%$ |
| $A_D$ | $(-2.1 \pm 2.4)\%$ |
| $\lvert q/p \rvert$ | $0.86\ ^{+0.17}_{-0.15}$ |
| $\varphi$ | $(-8.8\ ^{+7.6}_{-7.2})°$ |

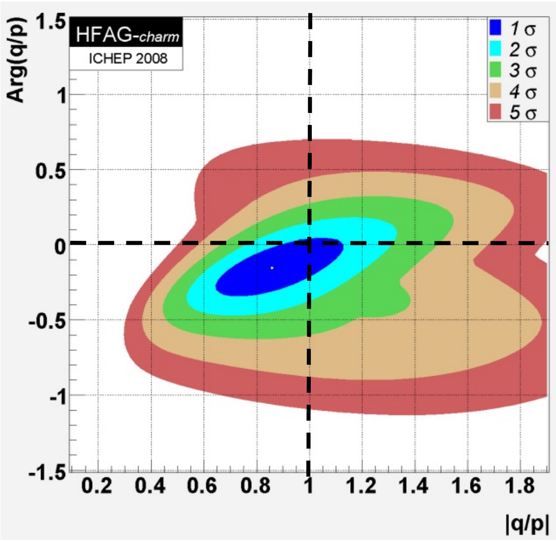
CPV

http://www.slac.stanford.edu/xorg/hfag/charm/

$\chi^2$/n.d.f.= 25.3/20







(x,y)≠(0,0): 9.8 σ;
CP even state heavier and shorter lived;
no CPV within 1σ

# 8. Outlook

## expected sensitivity

only KK/ππ, Kπ and $K_s\pi\pi$ projected sensitivities included

## HFAG $\chi^2$ fit

50 $ab^{-1}$

$$x = (0.793 \pm 0.087)\%$$

$$y = (0.798 \pm 0.062)\%$$

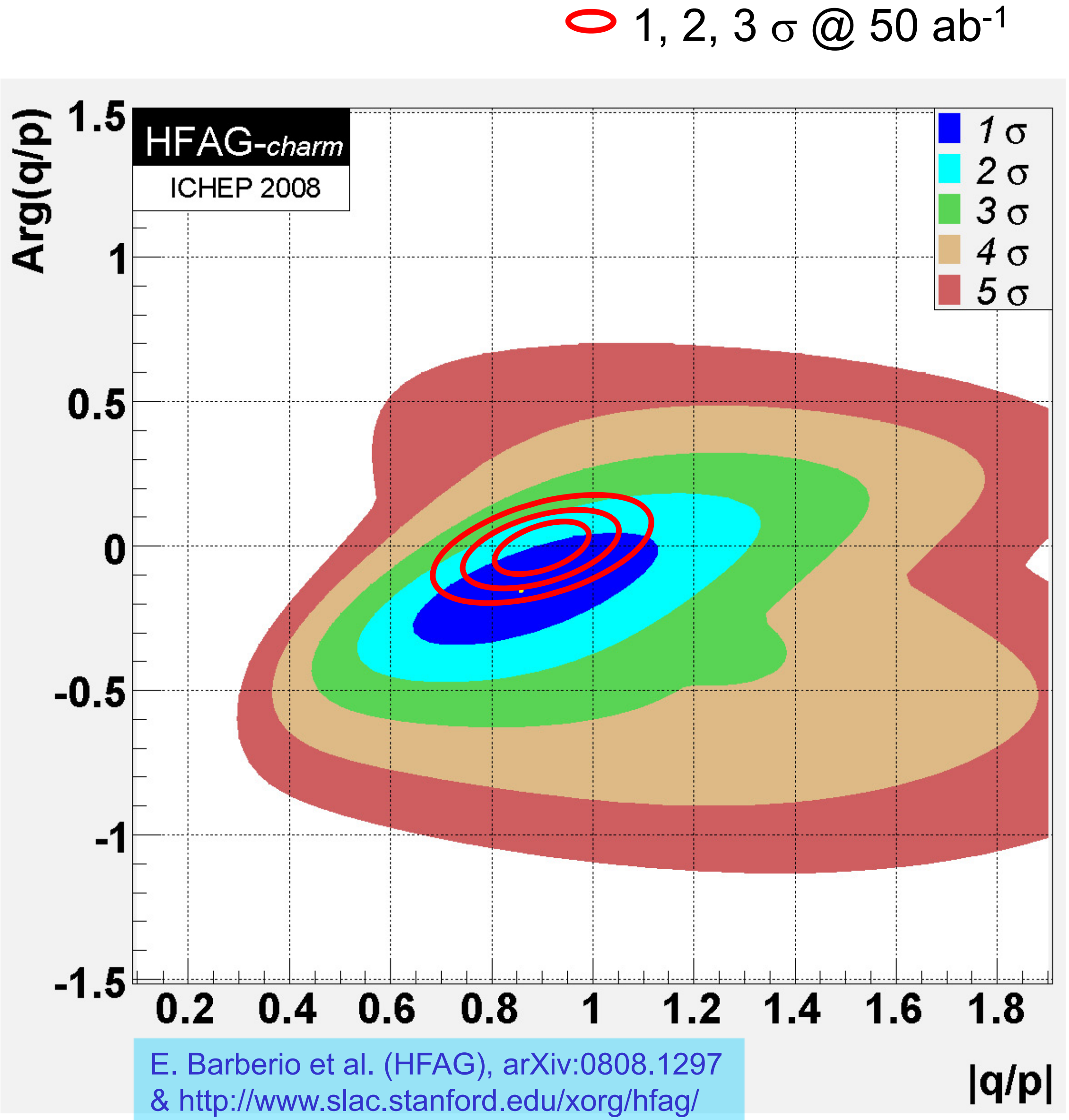
$$\delta_{K\pi} = 24.5° \pm 4.6°$$

$$R_D = (0.336 \pm 0.001)\%$$

$$\frac{|q|}{|p|} = 0.919 \pm 0.055$$

$$\varphi = -0.01 \pm 0.049\ rad$$

$$A_D = (-0.1 \pm 0.3)\%$$



E. Barberio et al. (HFAG), arXiv:0808.1297
& http://www.slac.stanford.edu/xorg/hfag/

# 7. Constraints on NP

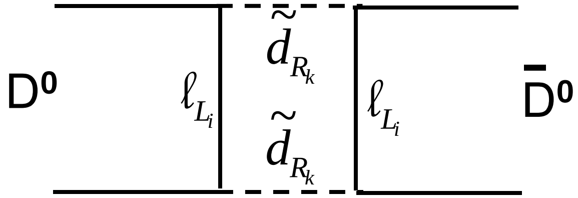
## constraints from mixing

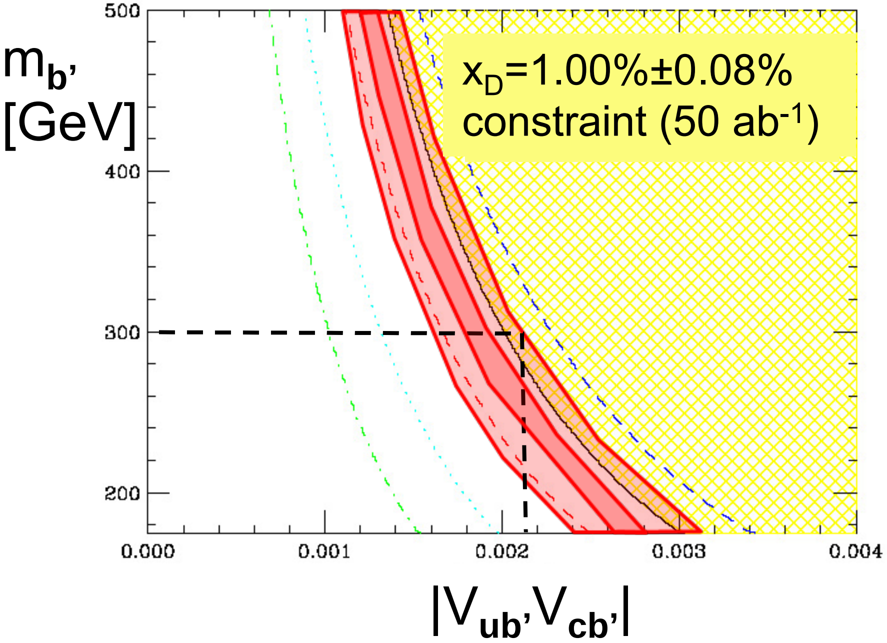
E. Golowich et al., PRD76, 095009 (2007)

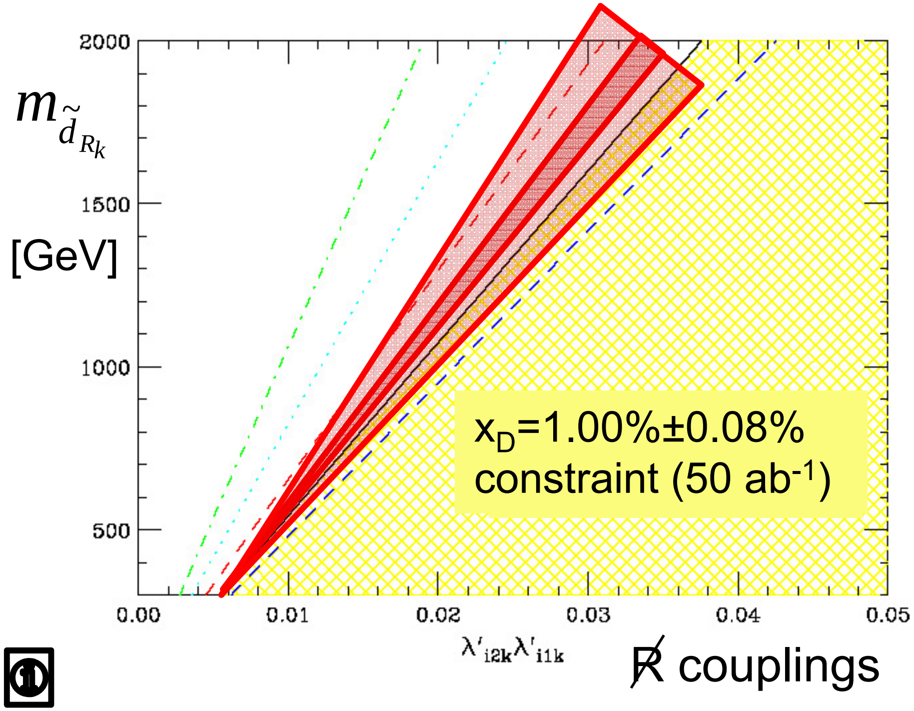
21 NP models considered →17 with useful constraints;
improved existing constraints;
examples:

4th generation fermion

$\not{R}$ SUSY:







# 8. Outlook

## unexploited possibilities with B-factory data

T-odd moments:

D →KKππ

α: ∠(KK, ππ plane);

$$\frac{d\Gamma}{d\alpha} = \Gamma_1 \cos^2\alpha + \Gamma_2 \sin^2\alpha + \Gamma_3 \cos\alpha \sin\alpha$$

$$\frac{d\overline{\Gamma}}{d\alpha} = \overline{\Gamma}_1 \cos^2\alpha + \overline{\Gamma}_2 \sin^2\alpha + \overline{\Gamma}_3 \cos\alpha \sin\alpha$$

$$\cos\alpha \sin\alpha \xrightarrow{CP,T} -\cos\alpha \sin\alpha$$

$\Gamma_{1,2} \neq \overline{\Gamma}_{1,2}$ : DCPV

$\Gamma_3, \overline{\Gamma}_3 \neq 0$ : can be induced by FSI

$\Gamma_3 \neq \overline{\Gamma}_3$ : CPV

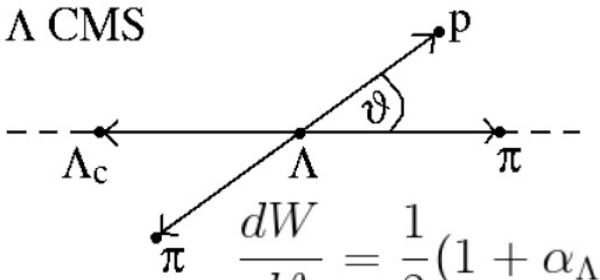
exp. issues:

-Br(D →KKππ) ~1/2 Br(D →KK);

- angular analysis

charmed baryon decays:

$\Lambda_c \to \Lambda\pi$, $\Lambda \to p\pi$



$$\frac{dW}{d\vartheta} = \frac{1}{2}(1 + \alpha_{\Lambda_c}\alpha_\Lambda \cos\vartheta)$$

$$A = \frac{\alpha_{\Lambda_c} + \alpha_{\overline{\Lambda_c}}}{\alpha_{\Lambda_c} - \alpha_{\overline{\Lambda_c}}}$$

exp. issues:

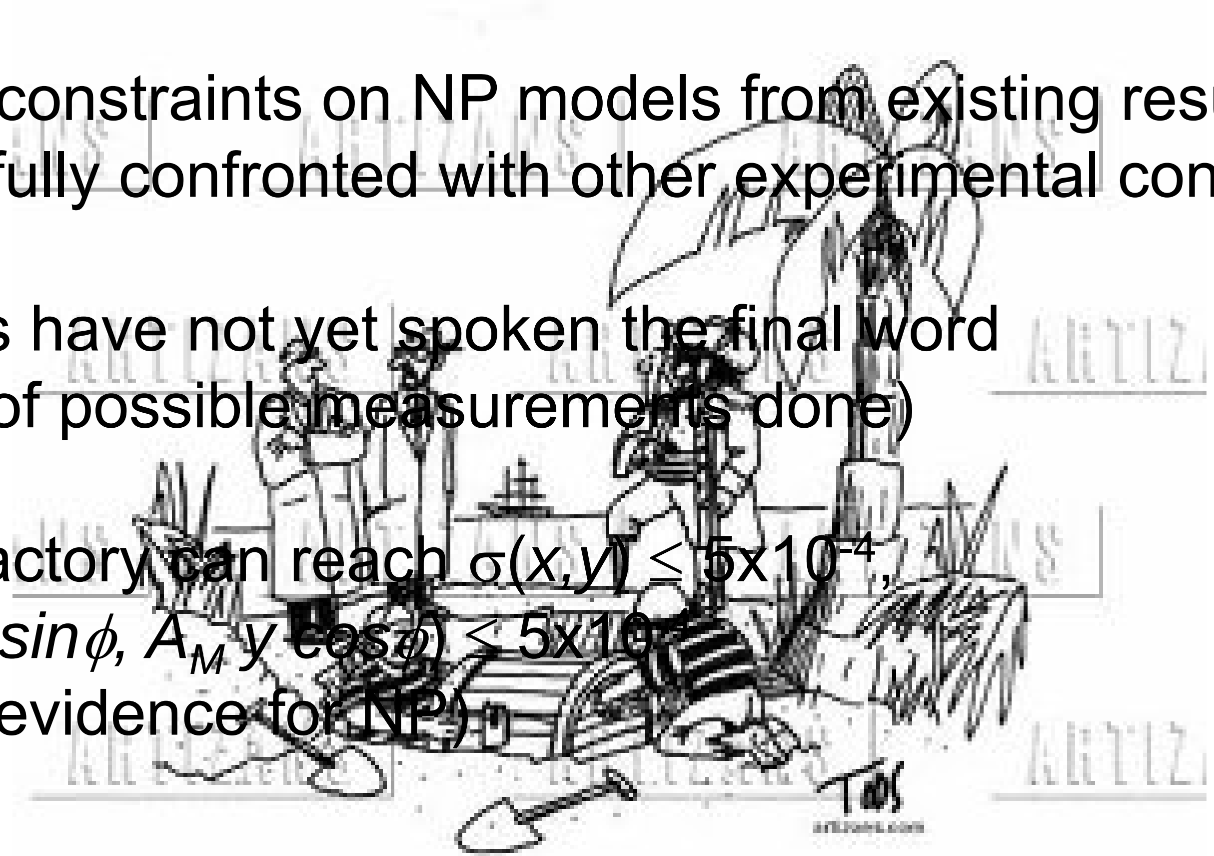
- unpolarized $\Lambda_c$;
- p, $\overline{\text{p}}$ detector asymmetry

# Conclusion

- D mixing and CPV are a unique handle to test FCNC of u-like quarks

there may be hidden treasures in charm physics…

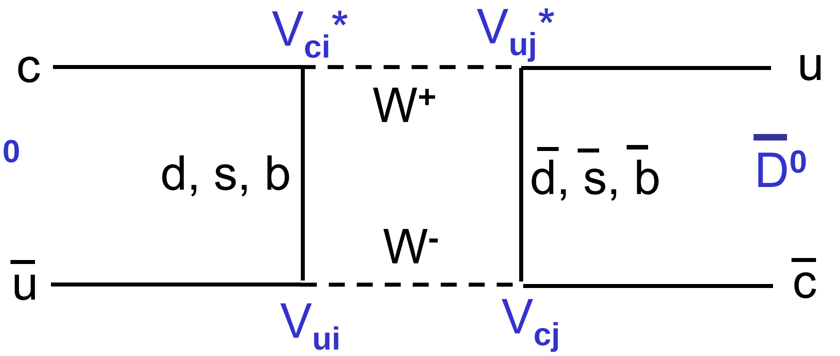
- Important constraints on NP models from existing results (yet to be fully confronted with other experimental constraints)
- B-factories have not yet spoken the final word (only part of possible measurements done)
- Super-B factory can reach $\sigma(x,y) \leq 5\text{x}10^{-4}$, $\sigma(A_{CP} \sim x \sin\phi, A_M\ y \cos\phi) \leq 5\text{x}10^{-4}$ (possible evidence for NP)



"No one is happier than us that you found the treasure ... now, about that grant ..."

# Supplementary slides

# Phenomenology more



## x and y in SM

2nd order perturb.:

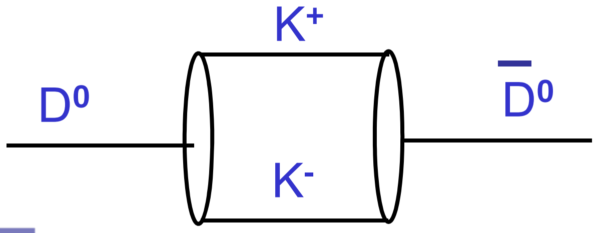
$$(M - i\frac{\Gamma}{2})_{12} = \frac{1}{2M_D}\langle \overline{D}^0 | H_w^{\Delta C=-2} | D^0\rangle + \frac{1}{2M_D}\sum_n \frac{\langle \overline{D}^0|H_w^{\Delta C=-1}|n\rangle\langle n|H_w^{\Delta C=-1}|D^0\rangle}{M_D - E_n + i\varepsilon}$$

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

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

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

absorptive part (real interm. states) ⇒ y
dispersive part (off-shell interm. states) ⇒ x



long distance:

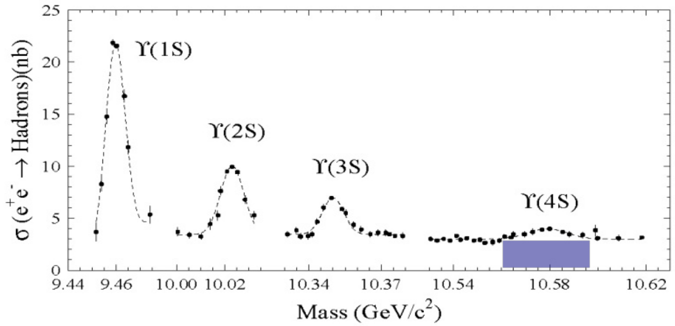
$|x|, |y| \sim \mathcal{O}(10^{-2})$

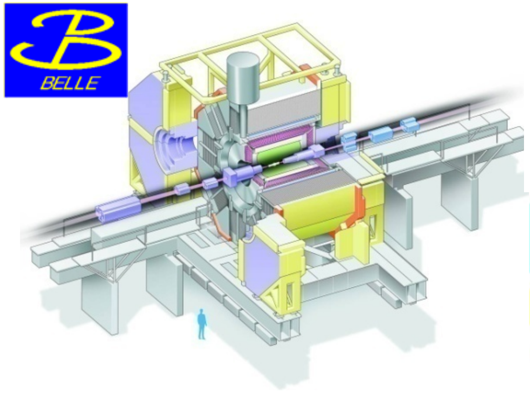
I.I. Bigi, N. Uraltsev,
Nucl. Phys. B592, 92 (2001);
A.F. Falk et al., PRD69, 114021 (2004)

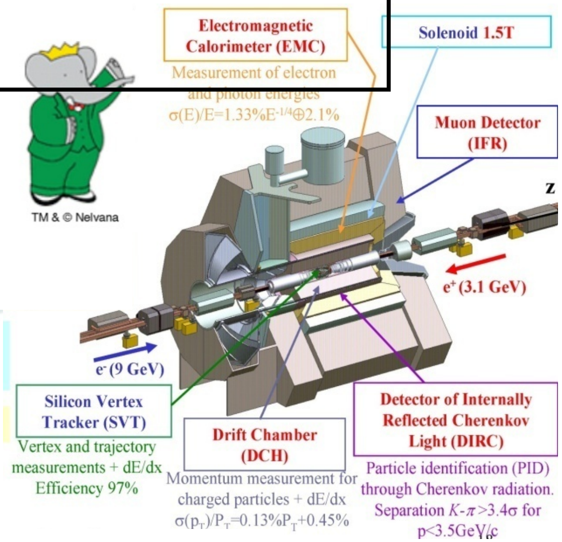
$D^0$ mixing: rare process in SM;
possible contrib. from NP

# Measurements – experim. more

## A) Experiments







Measurement of electron and photon energies $\sigma(E)/E=1.33\%E^{-1/4}\oplus2.1\%$

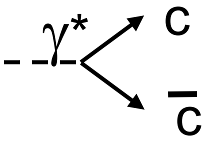
Vertex and trajectory measurements + dE/dx Efficiency 97%

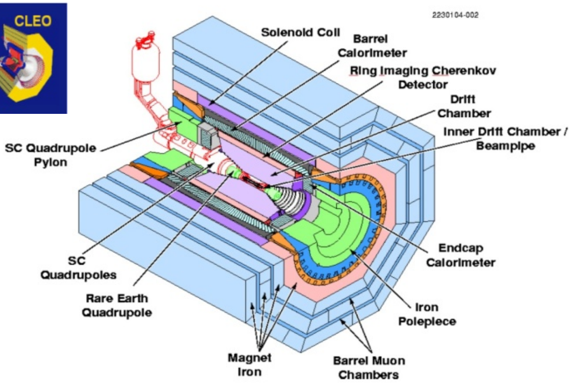
Momentum measurement for charged particles + dE/dx $\sigma(p_T)/P_T=0.13\%P_T+0.45\%$

Particle identification (PID) through Cherenkov radiation. Separation $K$-$\pi>3.4\sigma$ for $p<3.5$GeV/c

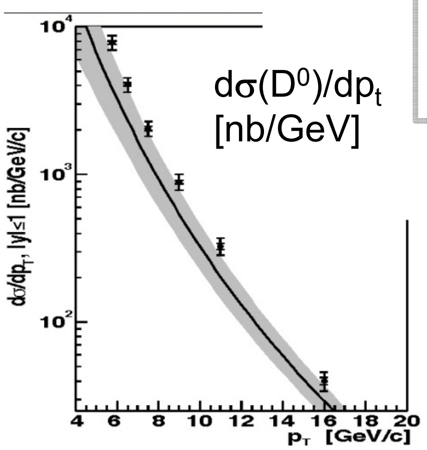
continuum production

$\sigma(c\bar{c}) \approx 1.3$ nb (~$10^9$ $X_c\bar{Y}_c$ pairs)



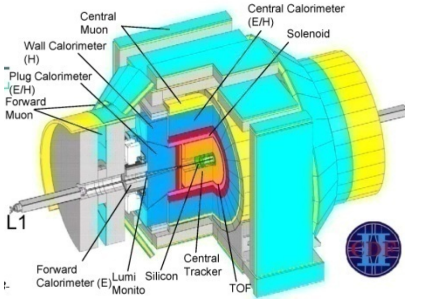


$e^+e^- \to \psi(3770) \to D^0\bar{D}^0, D^+D^-$
(coherent C=-1 state);
~800 $pb^{-1}$ of data available at $\psi(3770)$
$2.8\times10^6$ $D^0\bar{D}^0$



$d\sigma(D^0)/dp_t$ [nb/GeV]

3.5 $fb^{-1}$ on tape
$\sigma(D^0; p_t>5.5$ GeV$,|y|<1)\approx13$ μb
$50\times10^9$ $D^0$'s



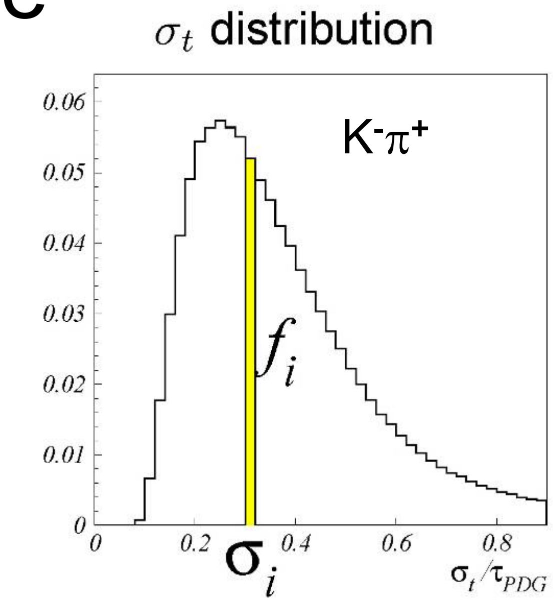
very diverse exp. conditions

# Decays to CP eigenstates more

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

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

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

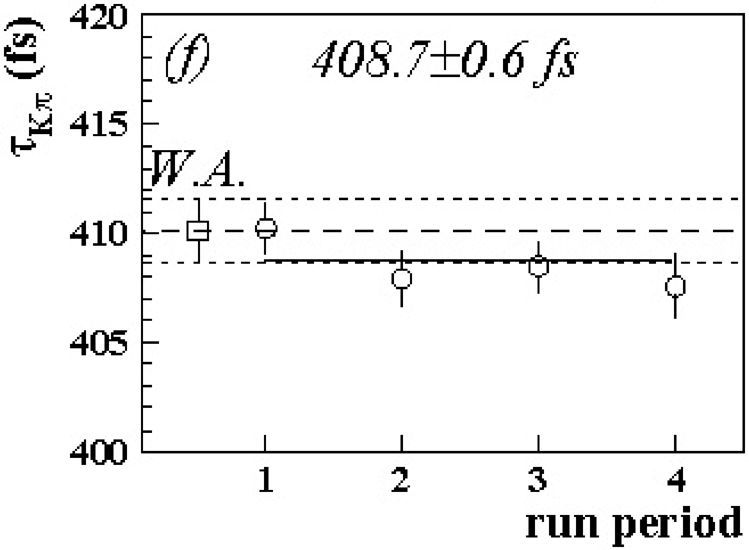


$\mathcal{R}$: ideally each $\sigma_i$ Gaussian resol. term with fraction $f_i$;

event-by-event $\sigma_t$

$t_{rec}$-$t_{gen}$/$\sigma_t$ : described by 3 Gaussians ⇒

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



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

$\tau$ = 408.7±0.6 fs

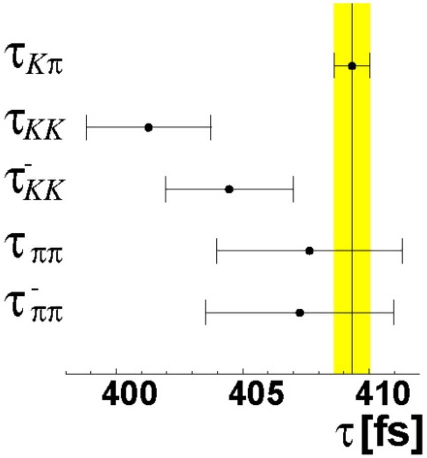
# Decays to CP eigenstates more

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

$$\tau_f = \tau\left[1 + (1 + A_M - A_D)(x\sin\varphi - y\cos\varphi)\right],\ \bar{\tau}_f = \tau\left[1 - (1 - A_M - A_D)(x\sin\varphi + y\cos\varphi)\right]$$

$$A_\Gamma \equiv \frac{\bar{\tau}_f - \tau_f}{\bar{\tau}_f + \tau_f} = A_M y\cos\varphi - (1 - A_D)x\sin\varphi \approx A_M y\cos\varphi - x\sin\varphi$$

confirmation: BaBar, arXiv:0712.2249, 384fb$^{-1}$



$y_{CP}$=(1.24± 0.39±0.13)%

$y_{CP}$ currently most precisely measured param.

# 3. Decays to CP eigenstates

## CPV

t-dependent

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

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

BaBar, PRD78, 011105 (2008), 384fb$^{-1}$

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

t-integrated

$A_{CP}^{meas} = A_\varepsilon^\pi + A_{FB} + A_{CP}^f$

$A_\varepsilon^\pi$ : comparison of tagged/untagged ($D^{*+} \rightarrow D^0\pi^+$),$D^0 \rightarrow K^-\pi^+$

$A_{FB}$: asymmetric $f(\cos\theta^{CMS})$

exp. issues:

- meas. in bins of $p_D$, $\cos\theta_D$ due to $A_\varepsilon^\pi$ ($\sigma$ determined by $N_{K\pi}^{tag}$);
- $A_\varepsilon^\pi$ can be used in other meas.;

t-dependent:

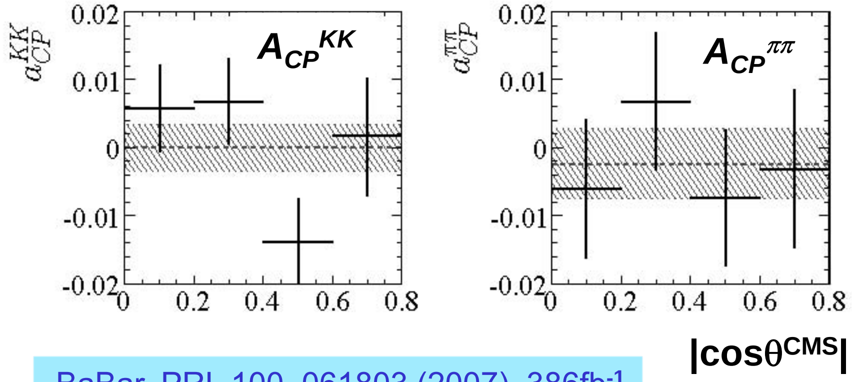
$$A_\Gamma = \frac{\tau(\overline{D}^0 \rightarrow K^+K^-) - \tau(D^0 \rightarrow K^+K^-)}{\tau(\overline{D}^0 \rightarrow K^+K^-) + \tau(D^0 \rightarrow K^+K^-)} \approx$$

$$\approx \frac{A_M}{2} y\cos\varphi - x\sin\varphi \underbrace{=}_{no\ CPV} 0$$

t-integrated:

$$A_{CP}^f = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\overline{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\overline{D}^0 \rightarrow f)} =$$

$$= a_{dec}^f + a_{mix} + a_{int}$$



BaBar, PRL 100, 061803 (2007), 386fb$^{-1}$

$$A_{CP}^{KK} = (0.00 \pm 0.34 \pm 0.13)\%$$

Belle, PLB 670, 190 (2008), 540fb$^{-1}$

$$A_{CP}^{KK} = (-0.43 \pm 0.30 \pm 0.11)\%$$

# 3. Decays to CP eigenstates

## related meas.

$D^0 \rightarrow \phi K_S$

CP odd final state;

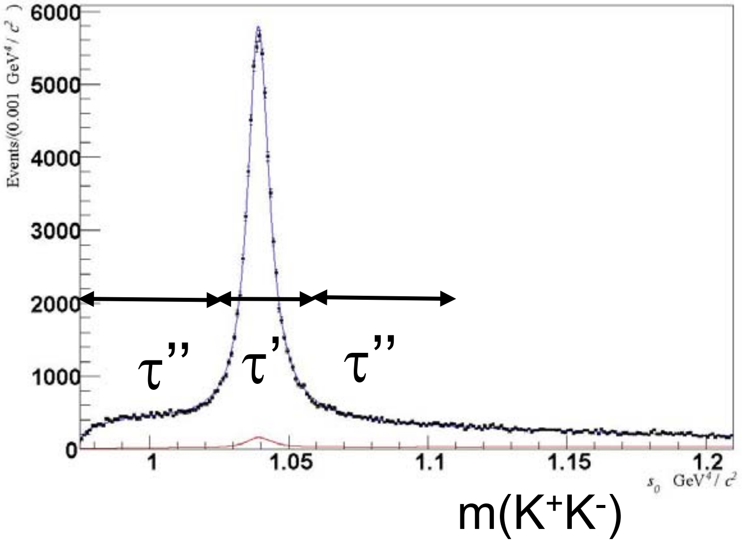
$\tau(\phi K_S) = 1/\Gamma_2 > 1/\Gamma_1 = \tau(K^+K^-)$

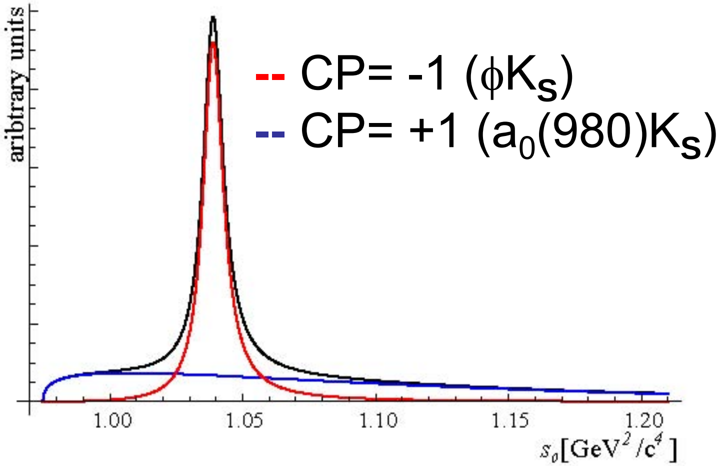
$$\tau' = f_{CP=+1}\frac{\tau}{1+y_{CP}} + (1-f_{CP=+1})\frac{\tau}{1-y_{CP}}$$

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

exp. issues:

- un-tagged decays;
- worse $\sigma_t$ due to $K_s$
- comparison of topologically equal decays → reduced effects of resol. in <t>





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

Belle, preliminary, $600 fb^{-1}$

⑪

# Decays to CP eigenstates more

## $D^0 \to \phi K_s$

method

$$\tau + t_0 = \frac{\langle t\rangle - (1-p)\langle t\rangle_b}{p}$$

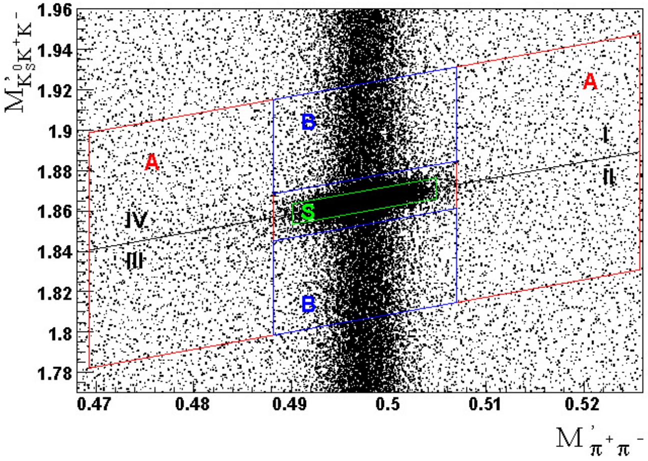
$$\langle t\rangle^A = p^A_{tKs}\langle t\rangle_{tKs} + p^A_{rest}\langle t\rangle_{rest}$$

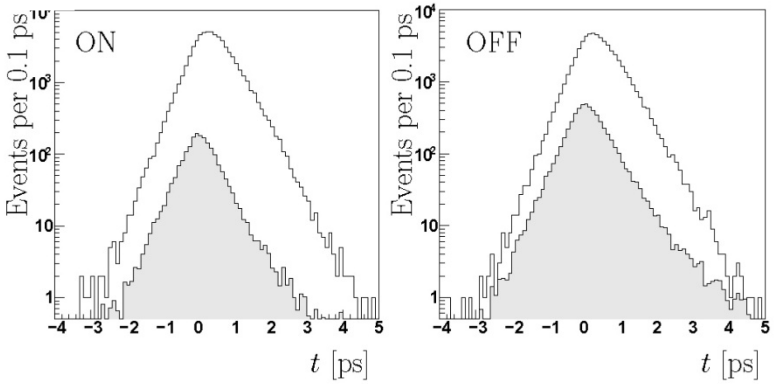
$$\langle t\rangle^B = p^B_{tKs}\langle t\rangle_{tKs} + p^B_{rest}\langle t\rangle_{rest}$$

$$\langle t\rangle_b = p^S_{tKs}\langle t\rangle_{tKs} + p^S_{rest}\langle t\rangle_{rest}$$

$$\langle t\rangle_b = \frac{P^S\left(\langle t\rangle^A - \langle t\rangle^B\right) + P^A\langle t\rangle^B - P^B\langle t\rangle^A}{P^A - P^B}$$

Belle, preliminary, 600fb$^{-1}$





①

# Decays to CP eigenstates more

## $D^0 \rightarrow \phi K_s$

Belle, preliminary, $600 fb^{-1}$

Dalitz model
- CP=-1
  - $\phi K_s$
- CP=+1
  - $a_0(980)K_s$
  - $a_0(1450)K_s$
  - $f_0(980)K_s$
  - $f_0(1370)K_s$
  - $f_2(1270)K_s$
- flavour spec.
  - $K^- a_0(980)^+$
  - $K^+ a_0(980)^-$
  - $K^- a_0(1450)^+$

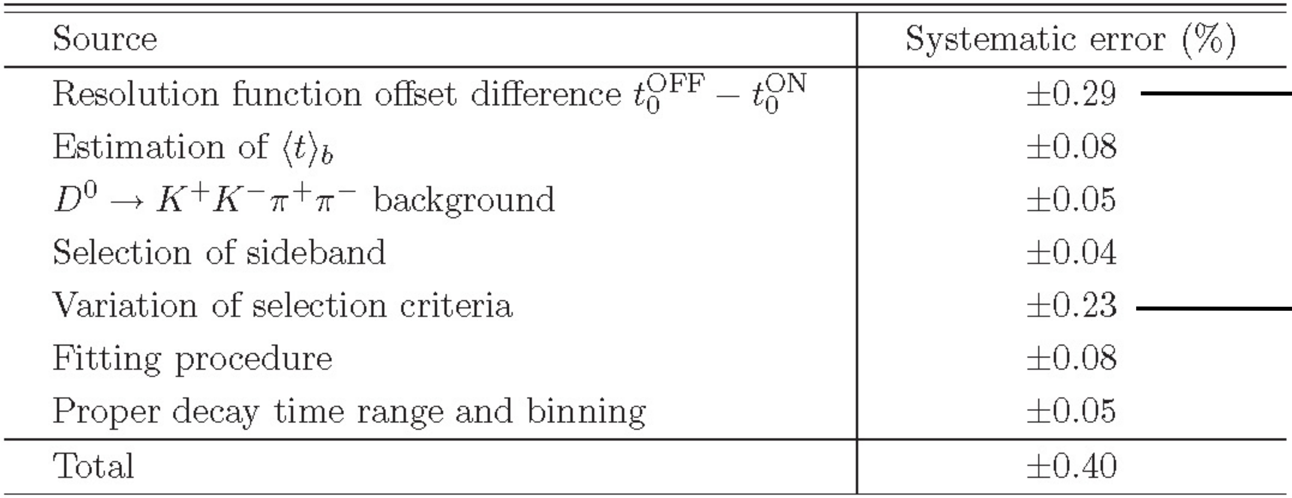
model affects only fraction of CP=+1 states in individual mass interval; small model syst. uncertainty

# Decays to CP eigenstates more

## $D^0 \rightarrow \phi K_s$

Belle, preliminary, 600fb$^{-1}$

syst. uncertainty on $\Delta\tau$



| Source | Systematic error (%) |
|---|---|
| Resolution function offset difference $t_0^{\mathrm{OFF}} - t_0^{\mathrm{ON}}$ | ±0.29 |
| Estimation of $\langle t \rangle_b$ | ±0.08 |
| $D^0 \rightarrow K^+K^-\pi^+\pi^-$ background | ±0.05 |
| Selection of sideband | ±0.04 |
| Variation of selection criteria | ±0.23 |
| Fitting procedure | ±0.08 |
| Proper decay time range and binning | ±0.05 |
| Total | ±0.40 |

$\pm 0.29 \longrightarrow$ from MC (stat.)

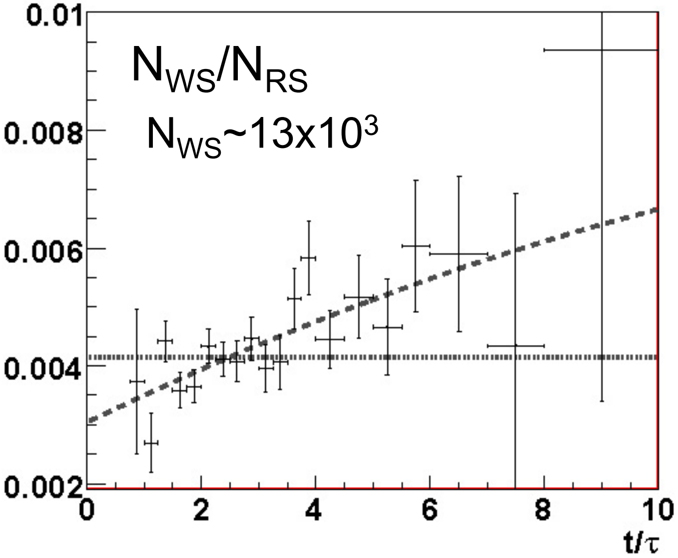
$\pm 0.23 \longrightarrow$ data fluctuations

# WS decays more

## C) WS decays (non-CP)

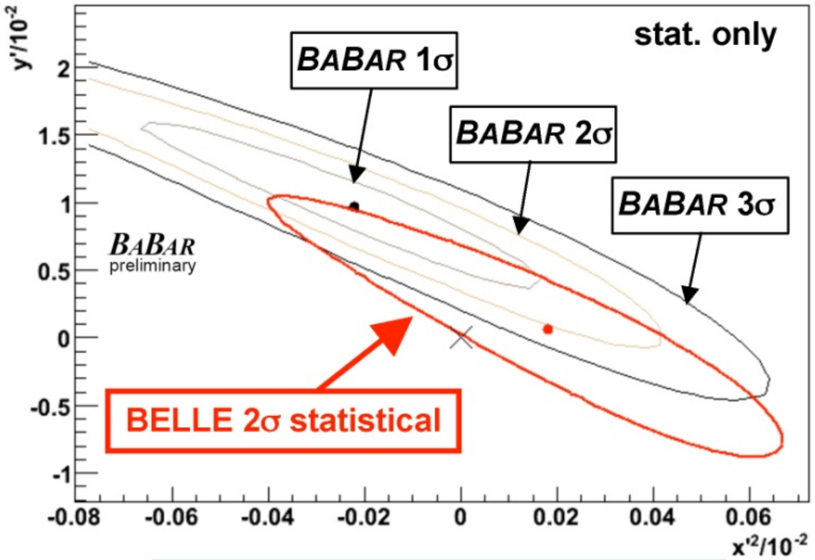
$$D^{*+} \to D^0 \; \pi_{slow}^+ \qquad D^0 \to \overline{D}^0 \to K^+ \pi^-$$

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

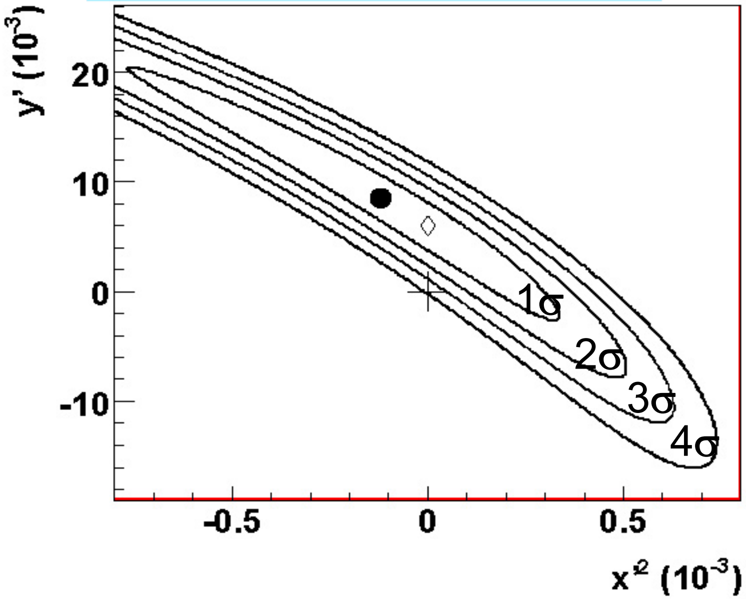


BaBar, PRL 98, 211802 (2007), 384fb$^{-1}$

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



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



CDF:

trigger: $h^+h^-$ from second. vtx;

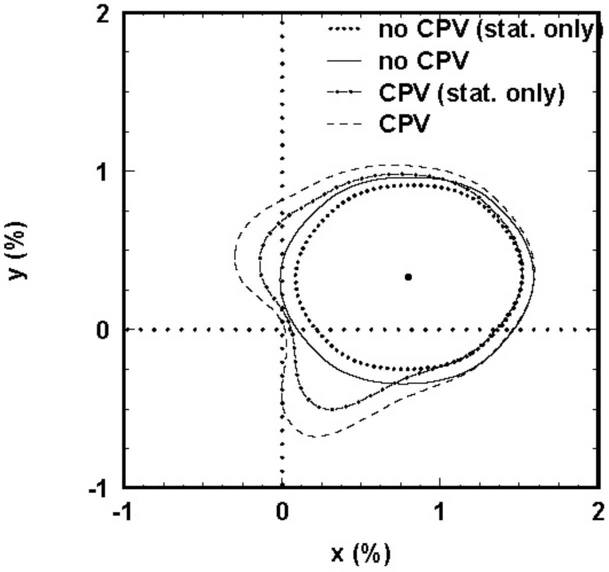
$N_{WS}/N_{RS}$ vs. t/τ from M, δM, imp. param.;

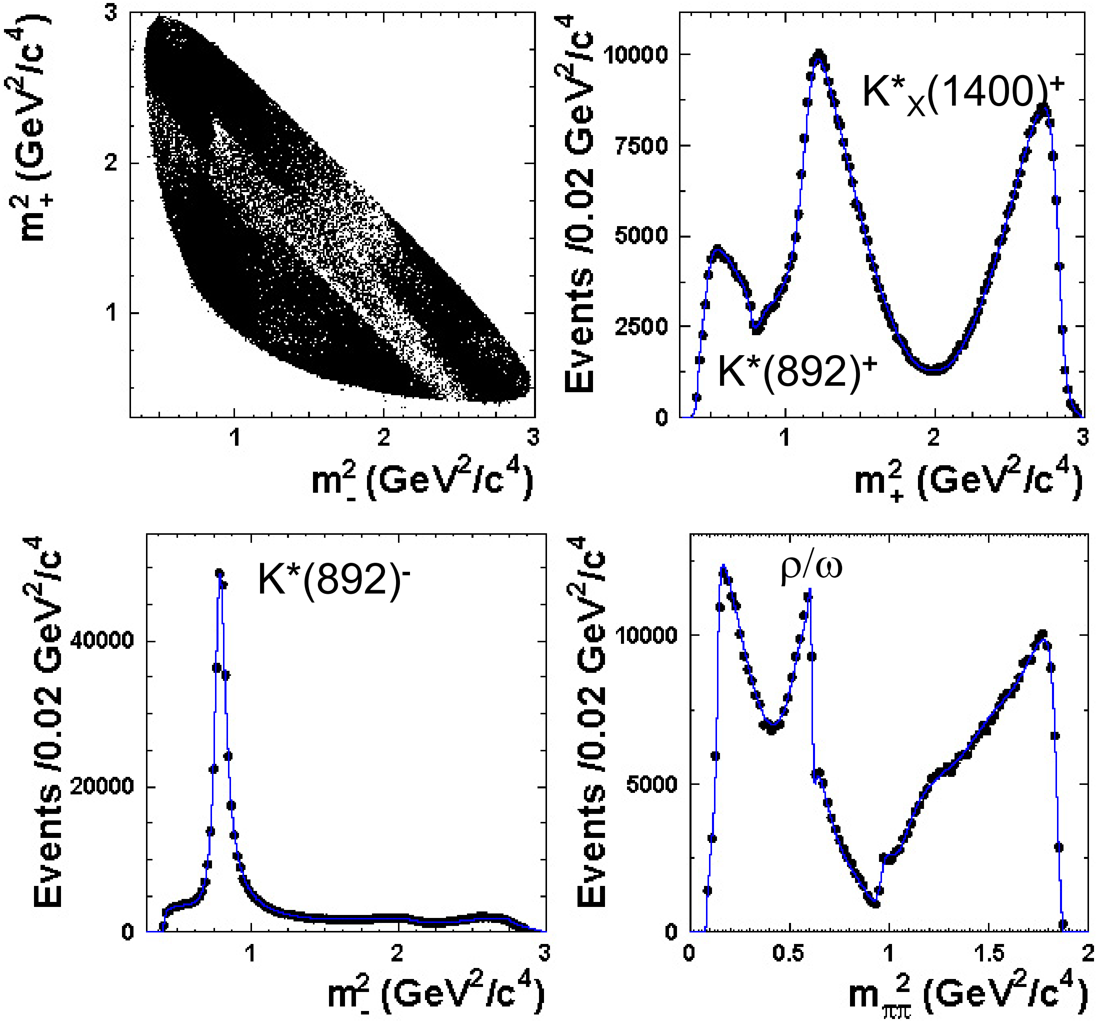
# t-dependent Dalitz more

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

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

most accurate x





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

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

$$\left| q/p \right| = 0.86 \pm {}^{0.30}_{0.29} \pm {}^{0.10}_{0.09}$$

$$\varphi = (-0.24 \pm {}^{0.28}_{0.30} \pm 0.09)\ rad$$

①

# t-dependent Dalitz more

BaBar, Lepton Photon 07, 384fb$^{-1}$

$D^0 \rightarrow K_S \pi \pi^0$

BaBar, PRL97, 221803 (2006), 384fb$^{-1}$

$$\frac{\left|\left\langle \bar{f} \middle| P^0(t) \right\rangle\right|^2}{e^{-\bar{\Gamma} t}} = \left|A_{\bar{f}}\right|^2 + \Im\left(\bar{A}_{\bar{f}} A^*_{\bar{f}}\right) xt - \Re\left(\bar{A}_{\bar{f}} A^*_{\bar{f}}\right) yt + \left|\bar{A}_{\bar{f}}\right|^2 \frac{x^2+y^2}{4} t^2$$

$$\mathcal{A}_{\bar{f}}(m_1^2, m_2^2) = a_1\, e^{i\Phi_1}\left(1 + \sum_{r \neq 1} a_r(m_1^2, m_2^2)\, e^{i\Phi_r}\right) \equiv a_1\, e^{i\Phi_1}\, |\mathcal{M}_{\bar{f}}(m_1^2, m_2^2)|\, e^{i\delta(m_1^2, m_2^2)}$$

$$\bar{\mathcal{A}}_{\bar{f}}(m_1^2, m_2^2) = \bar{a}_1\, e^{i\bar{\Phi}_1}\left(1 + \sum_{r \neq 1} \bar{a}_r(m_1^2, m_2^2)\, e^{i\bar{\Phi}_r}\right) \equiv \bar{a}_1\, e^{i\bar{\Phi}_1}\, |\bar{\mathcal{M}}_{\bar{f}}(m_1^2, m_2^2)|\, e^{i\bar{\delta}(m_1^2, m_2^2)}$$

$$\Im\left(\bar{A}_{\bar{f}} A^*_{\bar{f}}\right) xt = a_1 \bar{a}_1\, |\mathcal{M}_{\bar{f}}(m_1^2, m_2^2)|\, |\bar{\mathcal{M}}_{\bar{f}}(m_1^2, m_2^2)|\, \Im\left(e^{i(\bar{\Phi}_1 - \Phi_1)} e^{i(\bar{\delta}(m_1^2, m_2^2) - \delta(m_1^2, m_2^2))}\right) xt$$

$$\bar{\Phi}_1 - \Phi_1 \equiv \delta_{K\pi\pi}$$

# 5. t-dependent Dalitz

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

## D$^0$ →K$_S$ $\pi^+\pi^-$

$$x=(0.80\pm0.29\pm^{0.13}_{0.16})\%,\quad y=(0.33\pm0.24\pm^{0.10}_{0.14})\%$$

$$|q/p|=0.86\pm^{0.30}_{0.29}\pm^{0.10}_{0.09},\quad \varphi=(-0.24\pm^{0.28}_{0.30}\pm0.09)\,rad$$

exp. issues:
- model system.;
- direct meas. x, y;
- any f = $\bar{f}$: sensitivity to x depending on apriori unknow strong phase variation

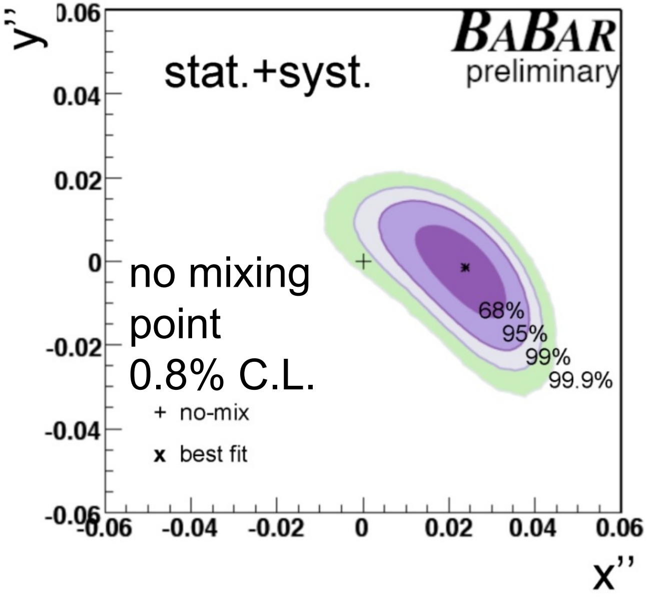
## related meas.

### D$^0$ →K$^+$ $\pi^-\pi^0$

separate WS/RS Dalitz distributions;

t-distrib. analogous to D$^0$ →K$^+$ $\pi^-$;

RS t-integrated Dalitz analysis;
WS Dalitz analysis;



BaBar, PRL97, 221803 (2006), 384fb$^{-1}$

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

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

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

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

$\delta_{K\pi\pi}$: unknown strong phase shift DCS/CF

# Average more

## Expected sensitivities from individual meas.

| | $\mathcal{L}$ = 5 ab$^{-1}$ | $\mathcal{L}$ = 50 ab$^{-1}$ | $\mathcal{L}$ = 5 ab$^{-1}$ | $\mathcal{L}$ = 50 ab$^{-1}$ |
|---|---|---|---|---|
| $\sigma(x)$ | 0.14% | 0.10% | 0.08% | 0.05% |
| | | | $K_sKK$, $\pi\pi\pi^0$ | total error :√3 |
| $\sigma(y)$ | 0.11% | 0.08% | 0.06% | 0.04% |
| | | | $K_sKK$, $\pi\pi\pi^0$ | total error :√3 |
| $\sigma(y_{CP})$ | 0.16% | 0.11% | | |
| $\sigma(A_\Gamma)$ | 0.12% | 0.07% | | |
| $\sigma(A_{CP})$ | 0.12% | 0.07% | | |
| $\sigma(x'^2)$ | 0.11x10$^{-3}$ | 0.09x10$^{-3}$ | 0.13x10$^{-3}$ | 0.10x10$^{-3}$ |
| | | | $x'^{2\pm}$ | stat. error •√2 |
| $\sigma(y')$ | 0.20% | 0.16% | 0.23% | 0.17% |
| | | | $y'^{\pm}$ | stat. error •√2 |
| $\sigma(A_D)$ | 2.1% | 1.7% | | |
| $\sigma(R_D)$ | 5x10$^{-5}$ | 1.5x10$^{-5}$ | 7x10$^{-5}$ | 2x10$^{-5}$ |
| | | | $R_D^{\pm}$ | stat. error •√2 |
| $\sigma(\lvert q/p\rvert)$ | 0.13 | 0.09 | 0.08 | 0.05 |
| | | | $K_sKK$, $\pi\pi\pi^0$ | total error :√3 |
| $\sigma(\phi)$ | 0.12 rad | 0.07 rad | 0.07 rad | 0.04 rad |
| | | | $K_sKK$, $\pi\pi\pi^0$ | total error :√3 |

→ i.e. assuming sens. same as in $K_s\pi\pi$

→ for CPV allowed fit

→ total error scaled

⑪

# Average more

## Projected sensitivities from average

| 5 $ab^{-1}$ | 5 $ab^{-1}$, $K_sKK$, $\pi\pi\pi^0$ | 50 $ab^{-1}$ | 50 $ab^{-1}$, $K_sKK$, $\pi\pi\pi^0$ |
|---|---|---|---|
| $x=(0.80\pm0.12)\%$ | $x=(0.80\pm0.07)\%$ | $x=(0.793\pm0.087)\%$ | $x=(0.793\pm0.055)\%$ |
| $y=(0.80\pm0.09)\%$ | $y=(0.80\pm0.06)\%$ | $y=(0.798\pm0.062)\%$ | $y=(0.800\pm0.045)\%$ |
| $\delta_{K\pi}=24.4°\pm6.4°$ | $\delta_{K\pi}=24.5°\pm4.7°$ | $\delta_{K\pi}=24.5°\pm4.6°$ | $\delta_{K\pi}=24.6°\pm3.7°$ |
| $R_D=(0.336\pm0.004)\%$ | $R_D=(0.336\pm0.003)\%$ | $R_D=(0.336\pm0.001)\%$ | $R_D=(0.336\pm0.001)\%$ |
| $\frac{\lvert q\rvert}{\lvert p\rvert}=0.91\pm0.08$ | $\frac{\lvert q\rvert}{\lvert p\rvert}=0.910\pm0.055$ | $\frac{\lvert q\rvert}{\lvert p\rvert}=0.919\pm0.055$ | $\frac{\lvert q\rvert}{\lvert p\rvert}=0.914\pm0.036$ |
| $\varphi=-0.01\pm0.08\,rad$ | $\varphi=-0.01\pm0.051\,rad$ | $\varphi=-0.01\pm0.049\,rad$ | $\varphi=-0.01\pm0.03\,rad$ |
| $A_D=(-0.2\pm1.0)\%$ | $A_D=(-0.2\pm1.0)\%$ | $A_D=(-0.1\pm0.3)\%$ | $A_D=(-0.1\pm0.26)\%$ |

+ assuming $A_{CP}=A_D \Rightarrow \sigma(A_D)$ ~ 0.1%

LHCb, 10 $fb^{-1}$ (5 y): $\sigma(x'^2)$~$6x10^{-5}$, $\sigma(y')$~$0.9x10^{-3}$
$\sigma(y_{CP})$~0.05%

main sensitivity on *x*, *|q/p|*, $\phi$ from t-dependent Dalitz analyses of $K_s\pi\pi$, $\pi\pi\pi^0$, $K_sKK$

# Average more

$\psi(3770) \to D^0 D^0$

$\delta$ constraints

- average
- direct meas.
  (fit w/o external input)