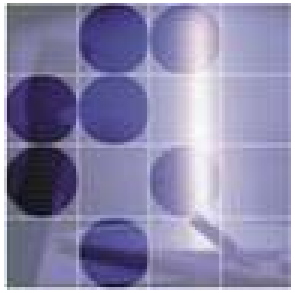
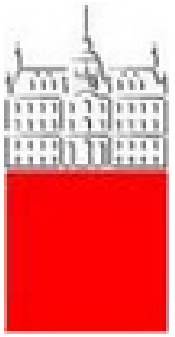


"Jožef Stefan" Institute

D^0 Mixing

B. Golob
University of Ljubljana,
Jožef Stefan Institute
&
Belle Collaboration



University
of Ljubljana

Outline

1. Phenomenology
2. Measurements
   - A) Experiments
   - B) CP states
   - C) Wrong sign (non-CP)
   - D) t-dependent Dalitz
   - E) $\psi(3770)$
3. Prospects & Summary
   - A) constraints on NP
   - B) expected sensitivity

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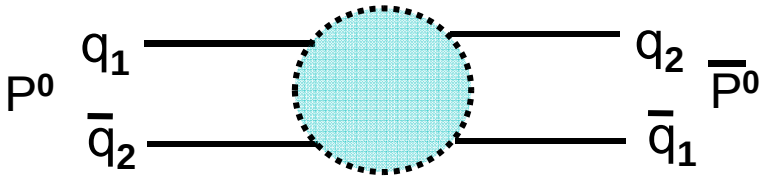

$P^0 = K^0, B_d^0, B_s^0$ and D^0

Time evolution

flavor states ≠ H_{eff} eigenstates:
(defined flavour) (defined $m_{1,2}$ and $\Gamma_{1,2}$)

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

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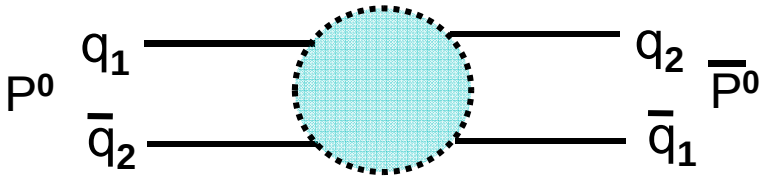

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$$\left|D^0(t)\right\rangle = \left[\left|D^0\right\rangle \cosh\left(\frac{ix+y}{2}\overline{\Gamma}t\right) - \frac{q}{p}\left|\overline{D}^0\right\rangle \sinh\left(\frac{ix+y}{2}\overline{\Gamma}t\right)\right] e^{-i\overline{m}t - \frac{\overline{\Gamma}}{2}t}$$

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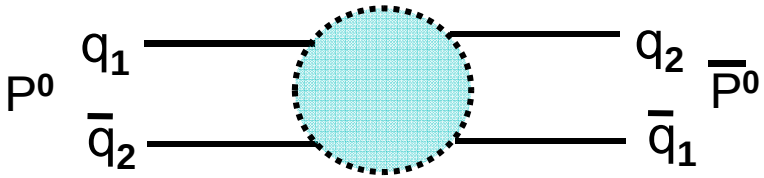

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$|x|, |y| << 1 \Rightarrow$

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

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

Contributions to x and y

$$\frac{\langle D_i | H_{eff} | D_j \rangle}{2M_D} = M_D \delta_{ij} + \frac{1}{2M_D} \langle \bar{D}^0 | H_w^{\Delta C=-2} | D^0 \rangle + \frac{1}{2M_D} \sum_n \frac{\langle \bar{D}^0 | H_w^{\Delta C=-1} | n \rangle \langle n | H_w^{\Delta C=-1} | D^0 \rangle}{M_D - E_n + i\varepsilon}$$

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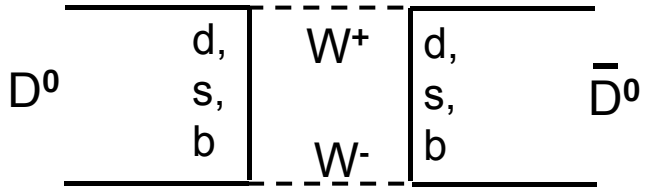

$$\propto V_{us}^* V_{cs} V_{cd} V_{ud}^* (m_s^2 - m_d^2)^2$$

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

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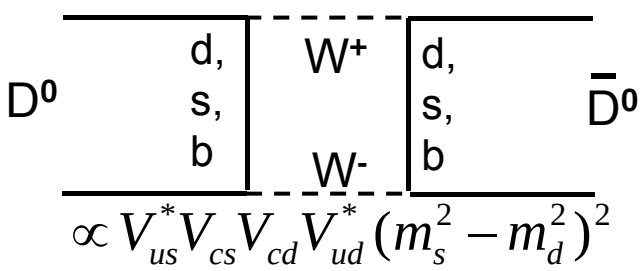

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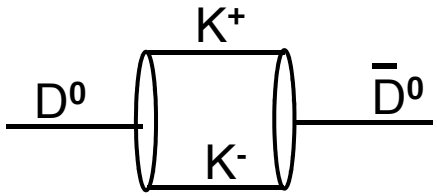

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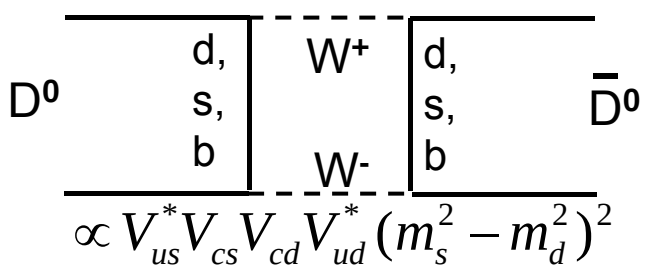

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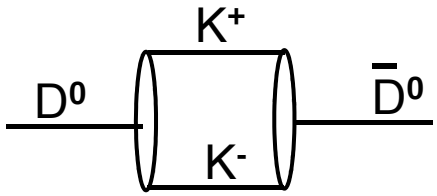

|x| ~ $\mathcal{O}(10^{-5})$

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unique for D^0's: down q's loop;
mixing: 30 years after discovery

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

The duration of passion is proportionate with the original resistance of the woman.

H. de Balzac (1799 -1850)

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CP violation

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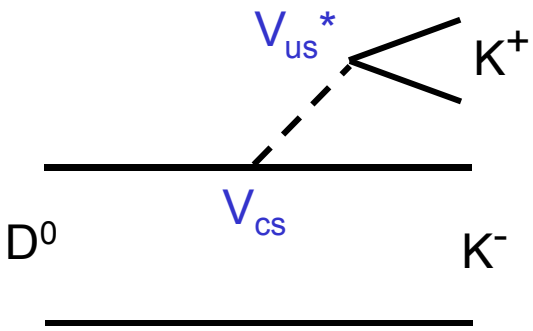

using CKM unitarity:

$$\arg\left(\frac{\langle \bar{f} | \overline{D}^0 \rangle}{\langle f | D^0 \rangle}\right) \approx \Im \frac{V_{cb}^* V_{ub}}{V_{cs} V_{us}^*} \sim \mathcal{O}(10^{-3})$$

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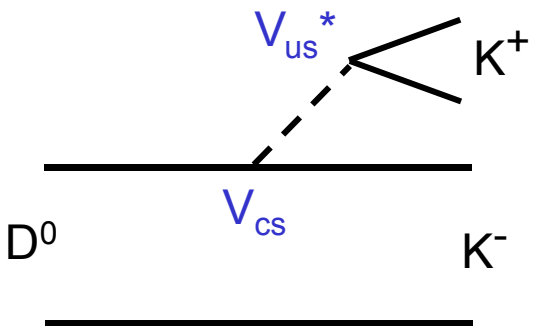

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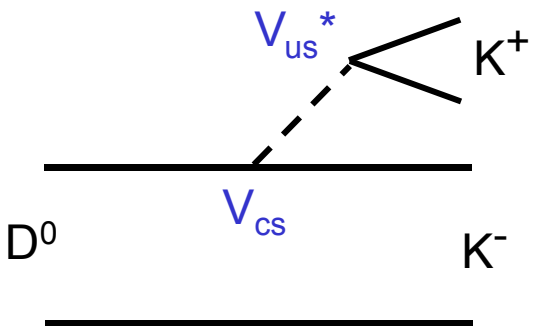

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parameterization:

$R_D \neq 1$: Cabbibo suppression

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

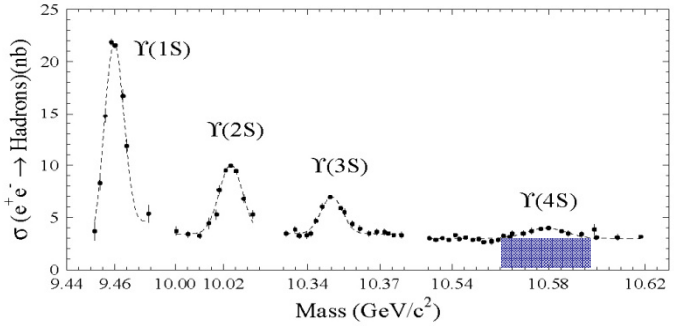
$$\left|\frac{\langle \bar{f}|D^0\rangle}{\langle f|D^0\rangle}\right| \equiv \sqrt{R_D},$$

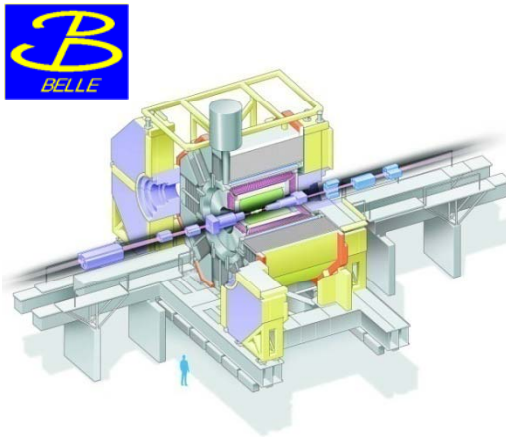
$$\left|\frac{\langle f|D^0\rangle}{\langle \bar{f}|\overline{D}^0\rangle}\right| \equiv 1+\frac{A_D}{2}, \quad \left|\frac{q}{p}\right| \equiv (1+\frac{A_M}{2}),$$

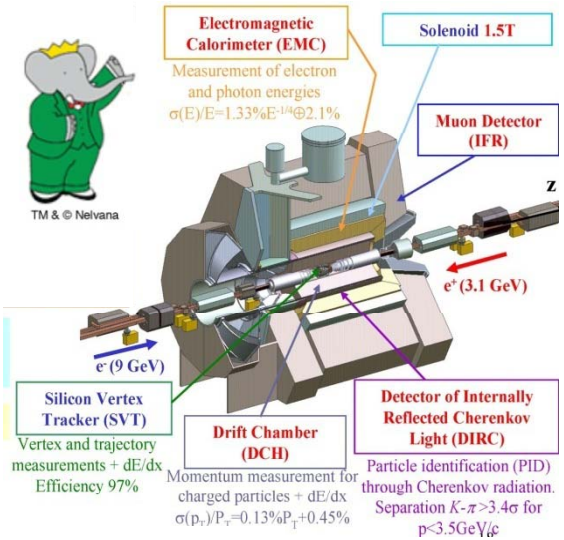
$$\frac{q}{p}\frac{\langle f|\overline{D}^0\rangle}{\langle f|D^0\rangle} \equiv -\frac{(1+A_M/2)\sqrt{R_D}}{1+A_D/2}e^{-i(\delta_f-\varphi)}$$

2. Measurements

A) Experiments

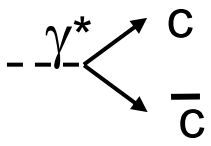






continuum production

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



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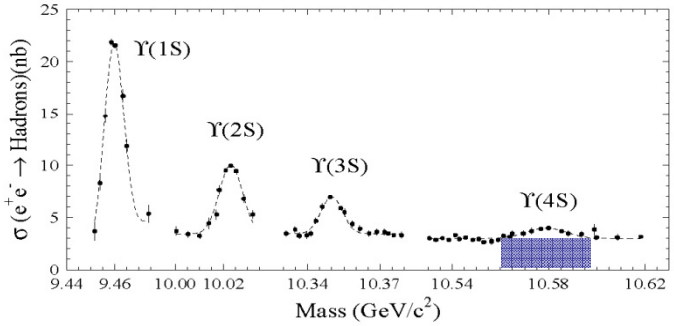

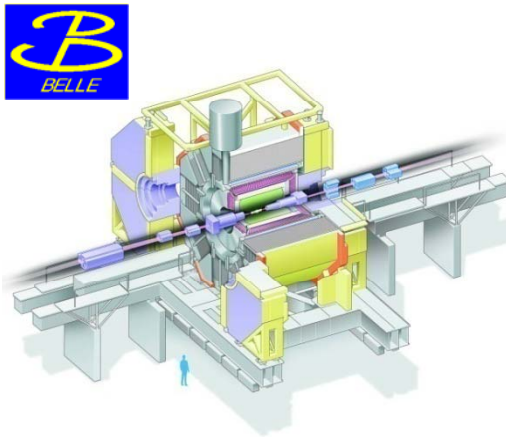

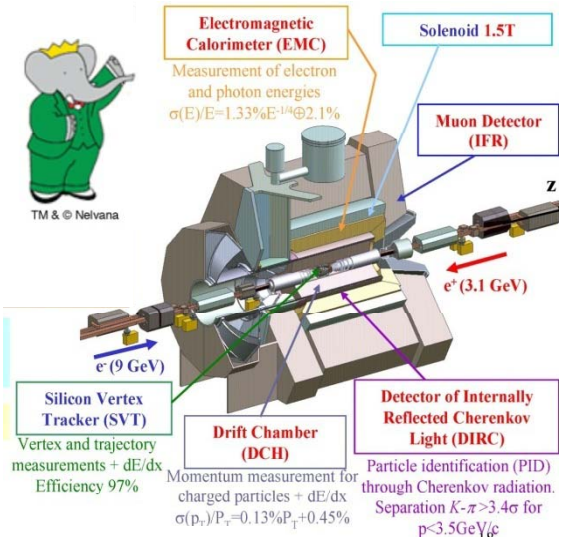

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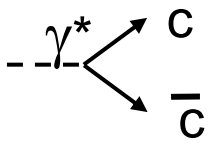

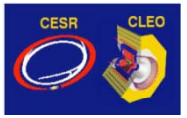

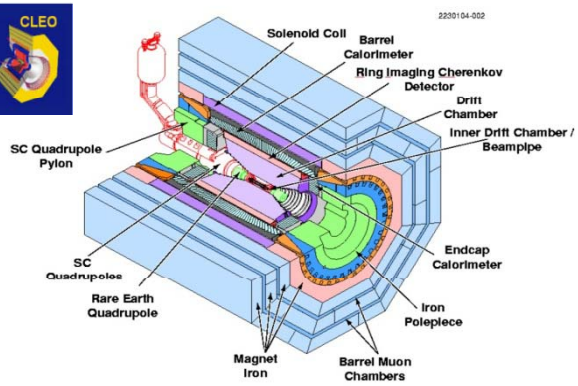

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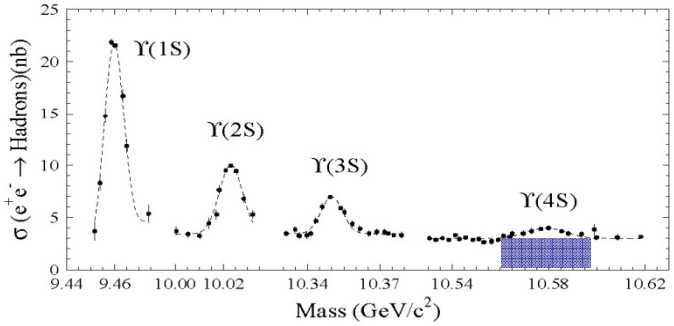

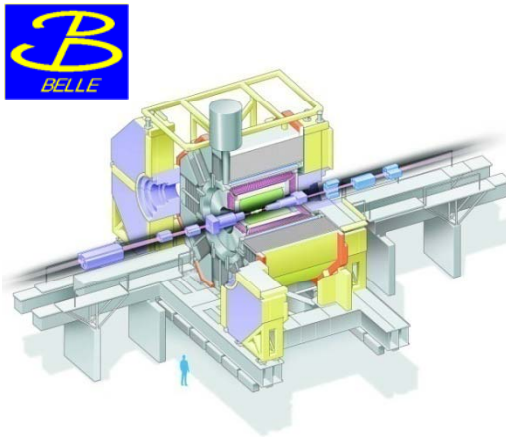

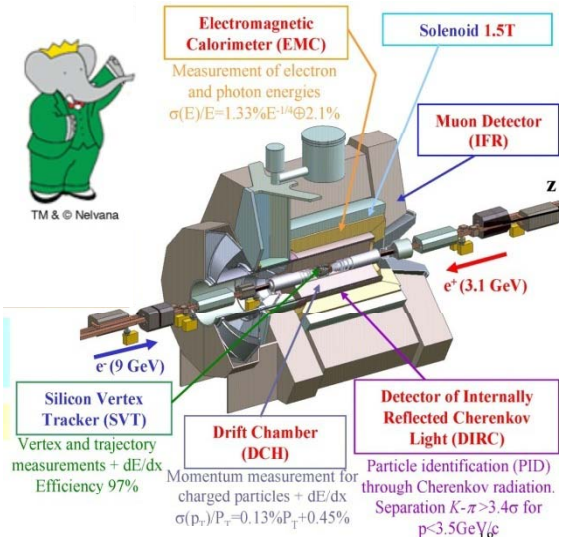

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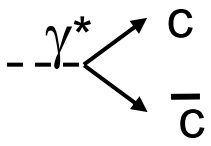

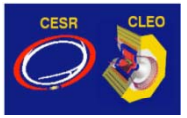

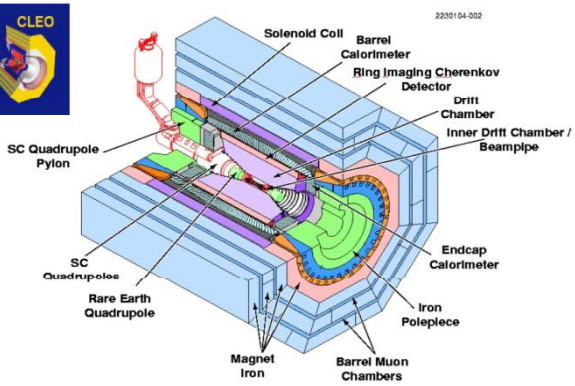

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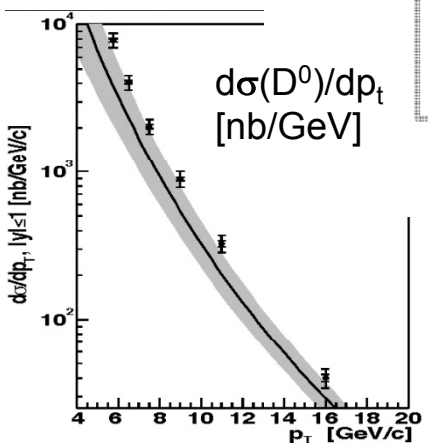
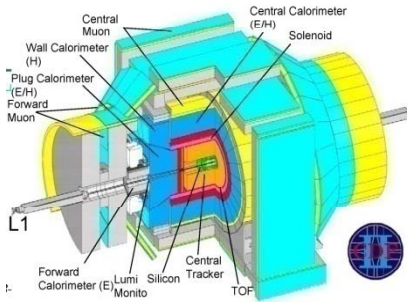


3.5 fb^{-1} on tape
$\sigma(D^0; p_t>5.5$ GeV,$|y|<1)\approx13$ μb
50×10^9 D^0's

very diverse exp. conditions



2. Measurements

General

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

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

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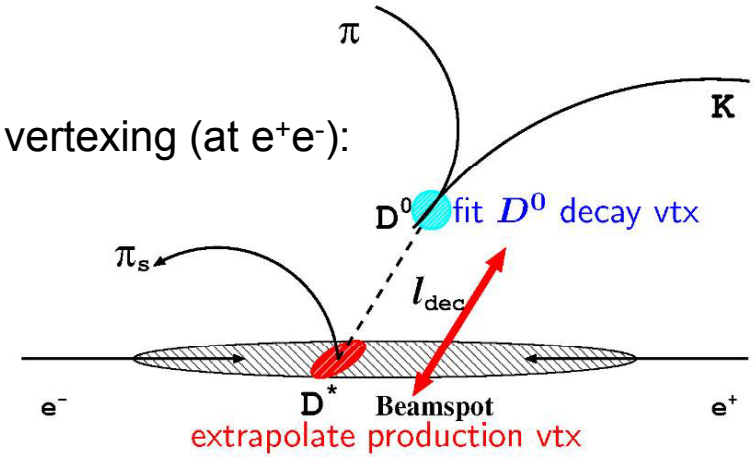
vertexing (at e^+e^-):



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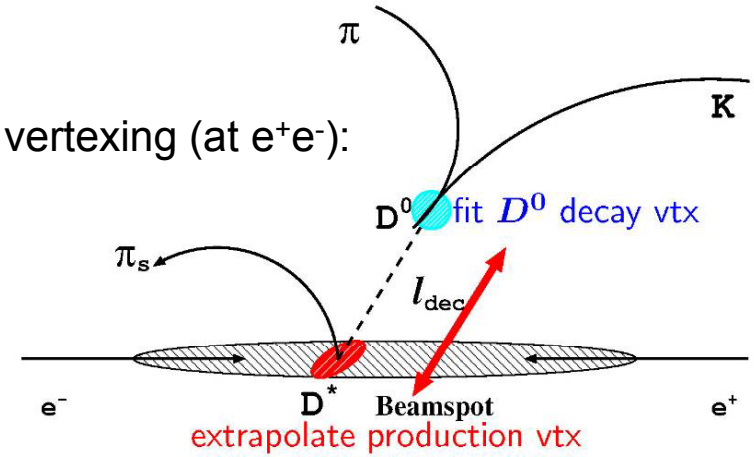

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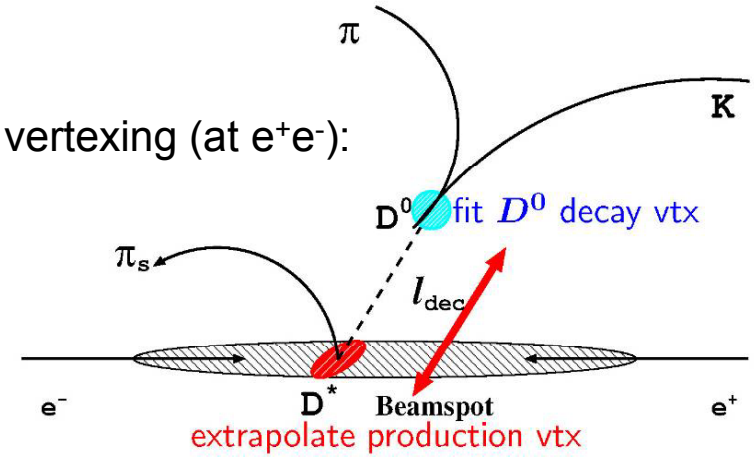

B) Decays to CP eigenstates

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

CP even final state;

no CPV:

$CP|D_1\rangle = |D_1\rangle \Rightarrow \tau = 1/\Gamma_1$;

$K^-\pi^+$: mixture of CP states $\Rightarrow$

$\tau = f(1/\Gamma_1, 1/\Gamma_2)$

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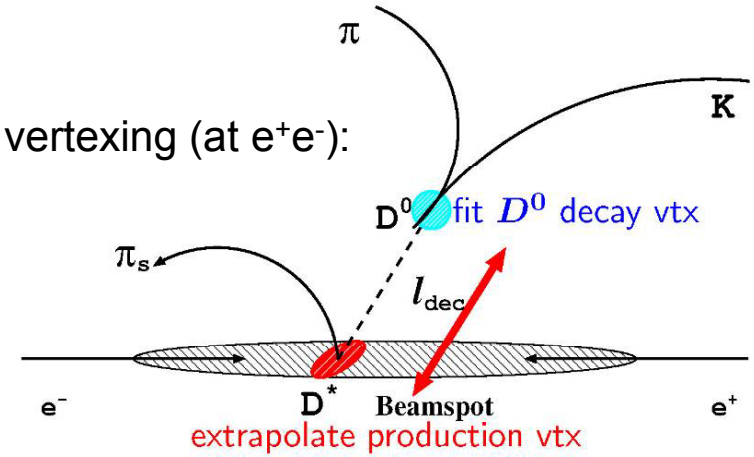

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CP even final state;

no CPV:

$CP|D_1\rangle = |D_1\rangle \Rightarrow \tau = 1/\Gamma_1$;

$K^-\pi^+$: mixture of CP states $\Rightarrow$

$\tau = f(1/\Gamma_1, 1/\Gamma_2)$

A_M, φ: CPV in mixing and interference

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

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

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

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

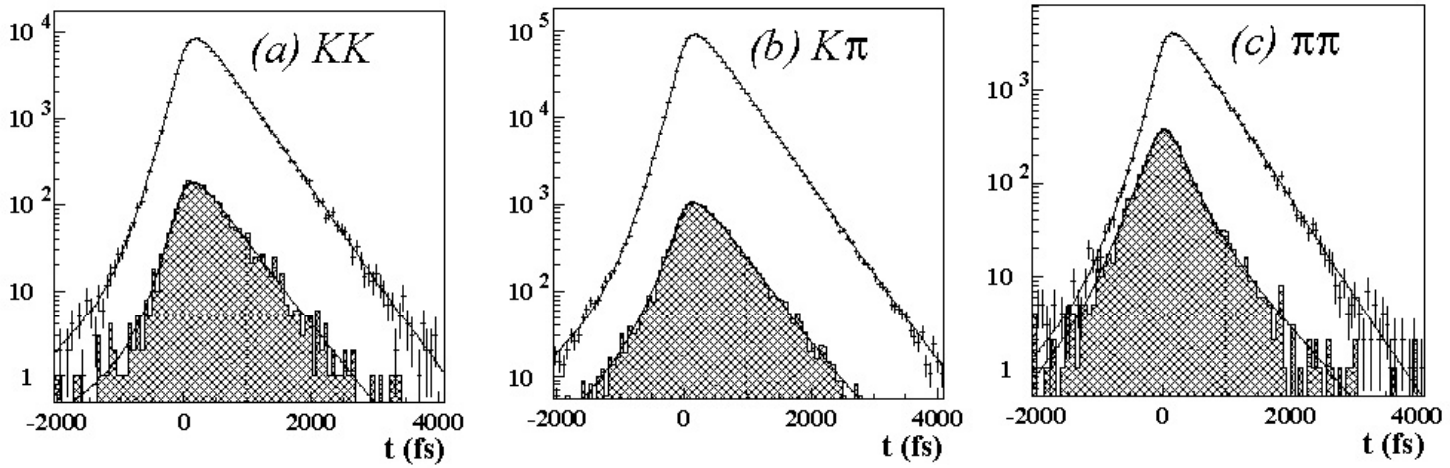
$N_{sig}(K^+K^-) \approx 110 \times 10^3$, P≈98%

2. Measurements

B) Decays to CP eigenstates

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

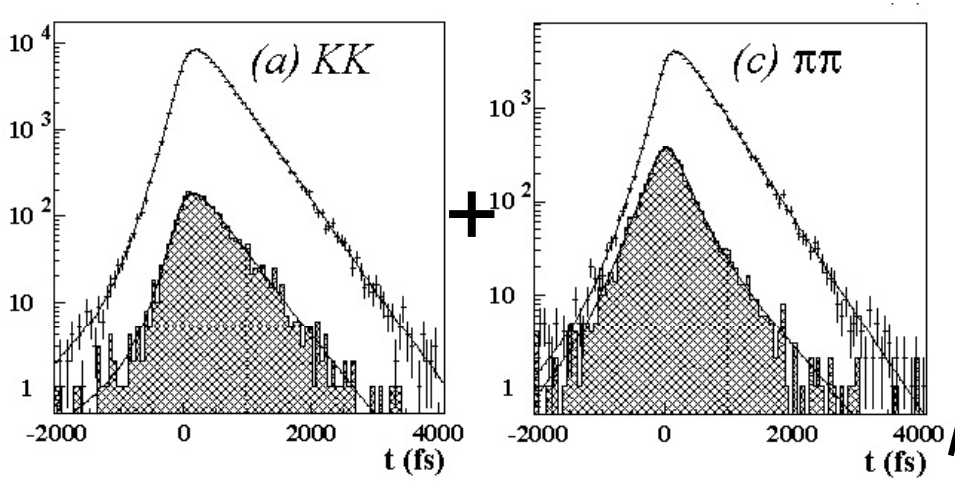
χ^2/ndf=1.084 (ndf=289)

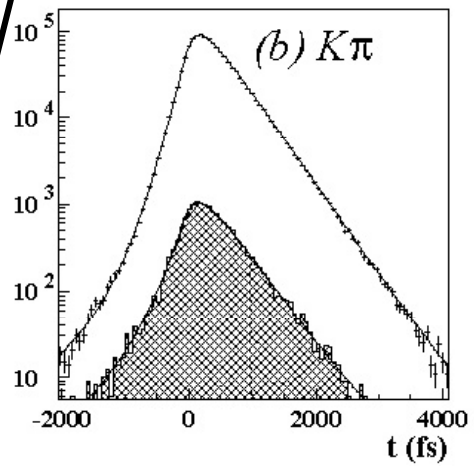


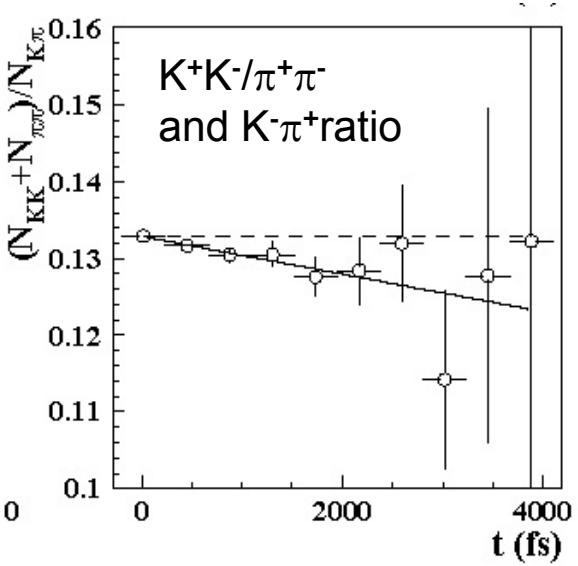
2. Measurements

B) Decays to CP eigenstates

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







2. Measurements

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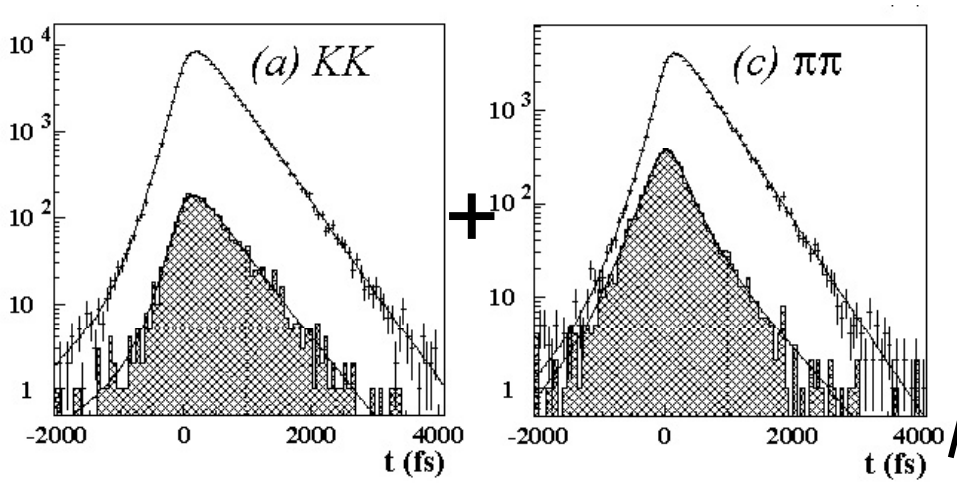
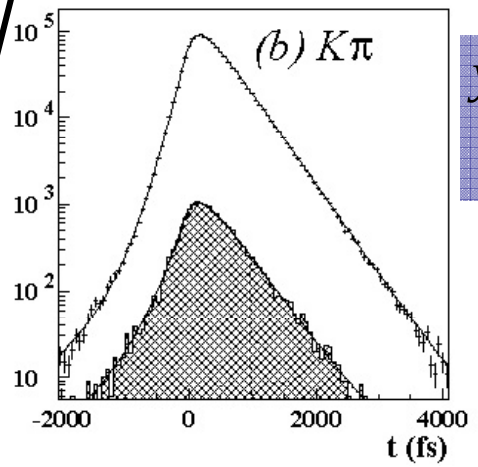
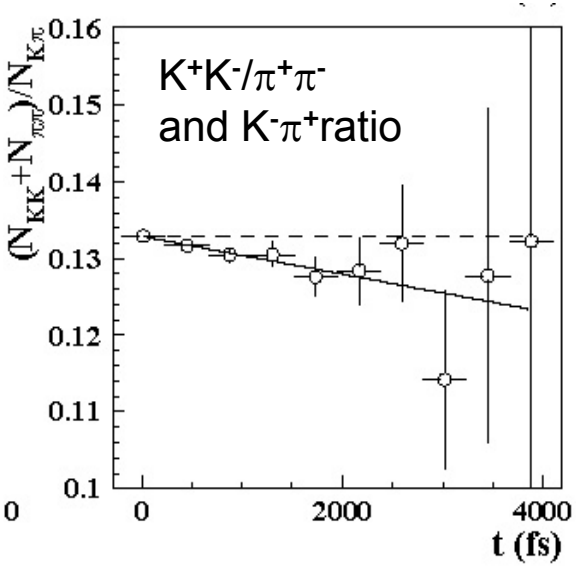
Belle, PRL 98, 211803 (2007), 540fb^{-1}





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

3.2 σ
(4.1 σ
stat. only)



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

2. Measurements

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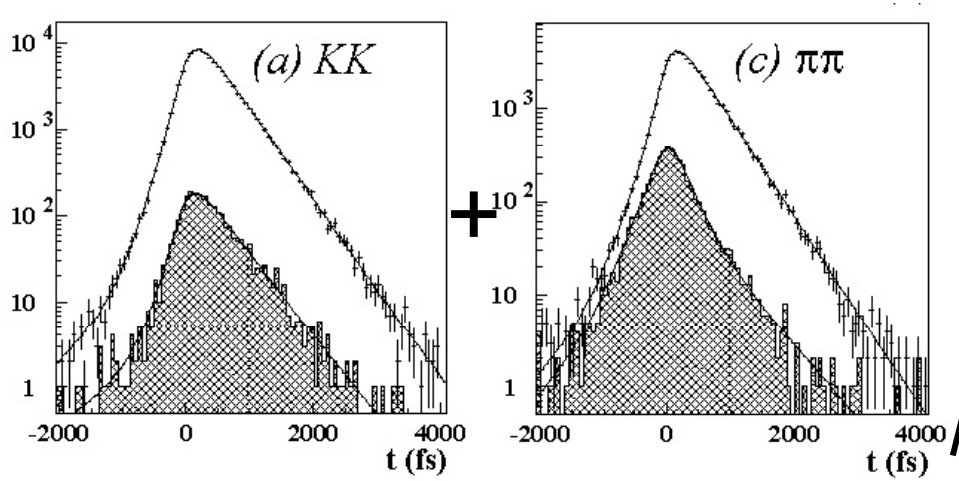
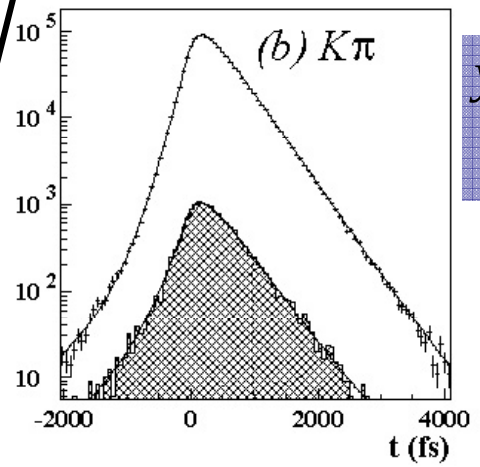
Belle, PRL 98, 211803 (2007), 540fb^{-1}





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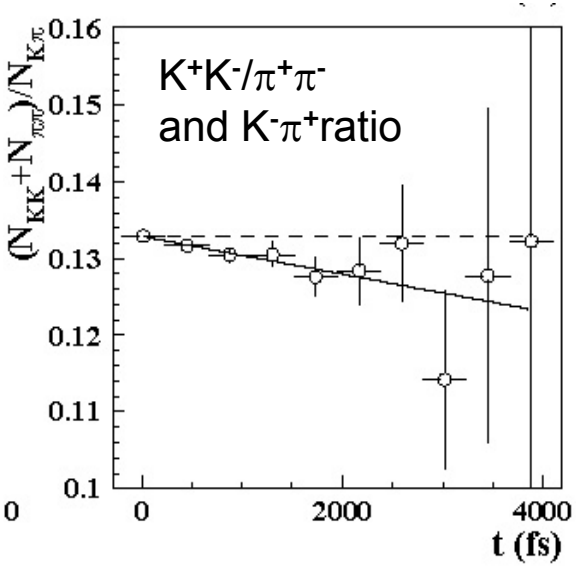
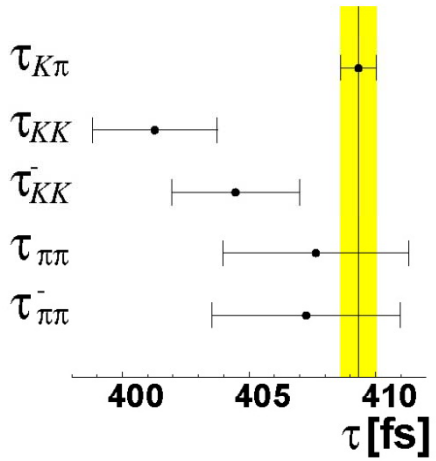


evidence
for D⁰ mixing
(regardless of
possible CPV)

confirmation:

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



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

y_{CP} currently most precisely measured param.

2. Measurements

B) Decays to CP eigenstates

CPV

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

$$= a_{dec}^{f} + a_{mix} + a_{int}$$ with a_{dec}<<1:

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

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

2. Measurements

B) Decays to CP eigenstates

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t-dependent

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

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

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

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

2. Measurements

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t-integrated

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

A_ε^π : comparison of tagged/untagged ($D^{*+} \to D^0\pi^+$),$D^0 \to K^-\pi^+$

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

2. Measurements

B) Decays to CP eigenstates

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

with $a_{dec} \ll 1$:

CPV

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

t-dependent

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

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)} \approx \frac{A_M}{2} y\cos\varphi - x\sin\varphi \underset{no\ CPV}{=} 0$$

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

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

t-integrated

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

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

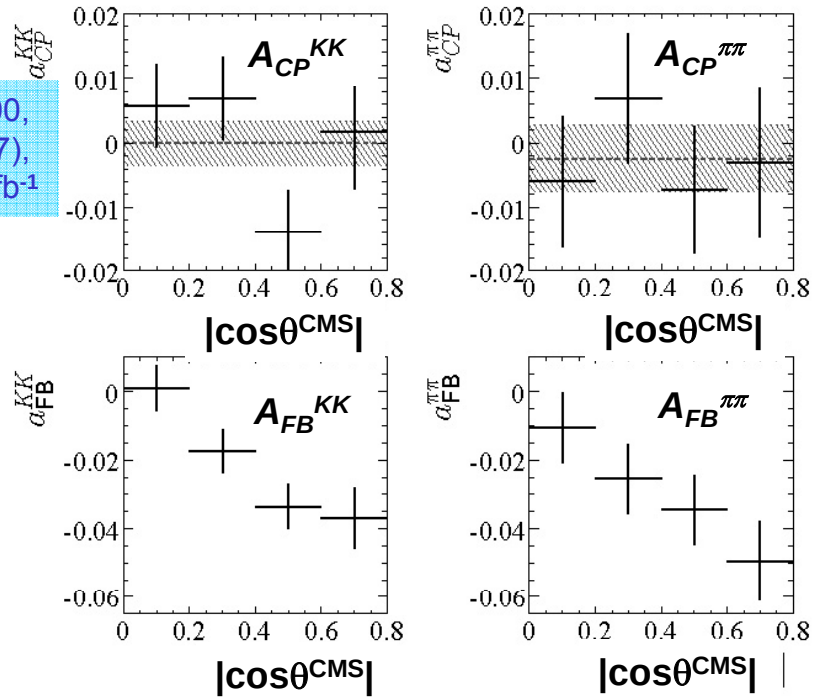
A_ε^{π} : comparison of tagged/untagged $(D^{*+} \to D^0\pi^+), D^0 \to K^-\pi^+$

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

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

Belle, preliminary, 540fb^{-1}

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



2. Measurements

C) WS decays (non-CP)

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

DCS decays $\Rightarrow$ interference;

t-dependence to separate DCS/mixed

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$$\left|\left\langle K^+\pi^- \middle| D^0(t)\right\rangle\right|^2 \propto$$

$$\left[\underbrace{R_D}_{DCS} + \underbrace{\sqrt{R_D}\,y't}_{interf.} + \underbrace{\frac{x'^2+y'^2}{4}t^2}_{mix}\right]e^{-t}$$

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

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

δ: unknown strong phase DCS/CF

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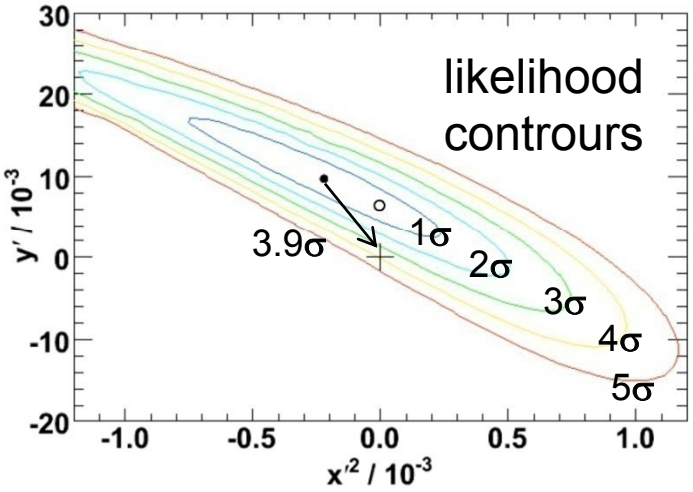

BaBar, PRL 98, 211802 (2007), 384fb^{-1}

evidence for D^0 mixing

$$\left|\left\langle K^+\pi^- \middle| D^0(t)\right\rangle\right|^2 \propto$$

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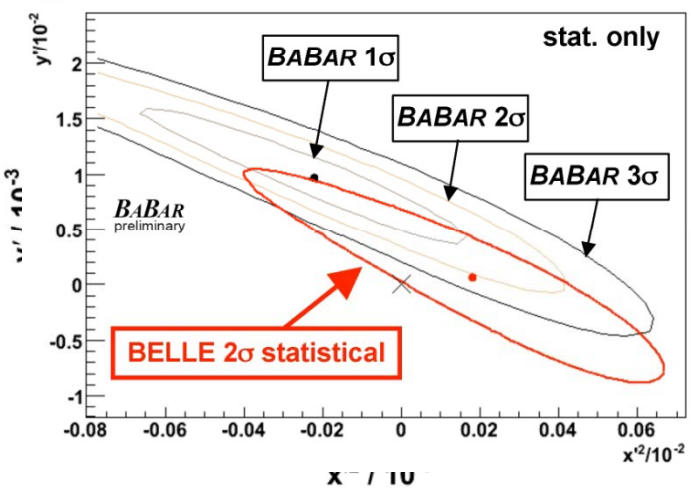

BaBar, PRL 98, 211802 (2007), 384fb^{-1}

evidence for D^0 mixing

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

$$\left|\left\langle K^+\pi^- \middle| D^0(t)\right\rangle\right|^2 \propto$$

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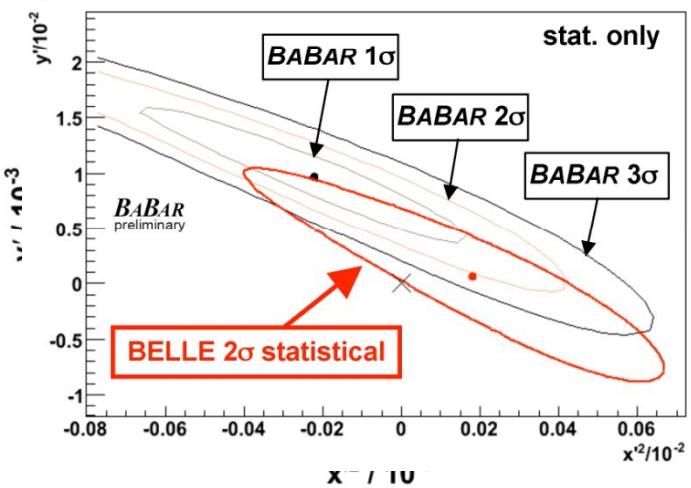
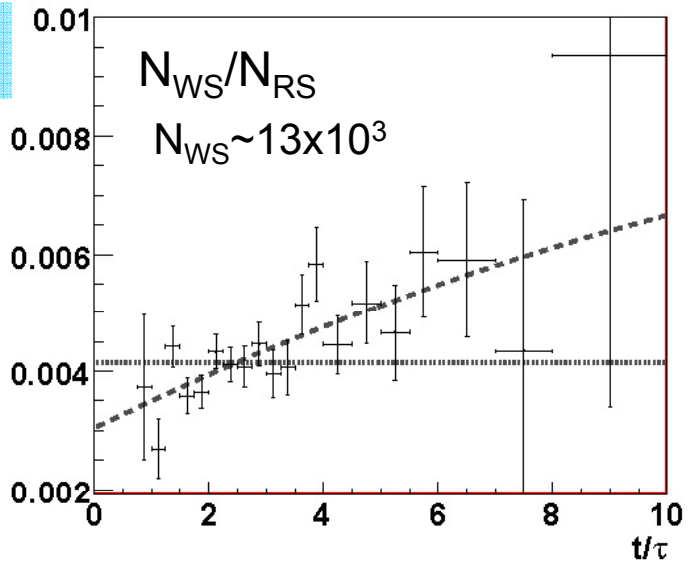


BaBar, PRL 98, 211802 (2007), 384fb^{-1}

evidence for D^0 mixing

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.;

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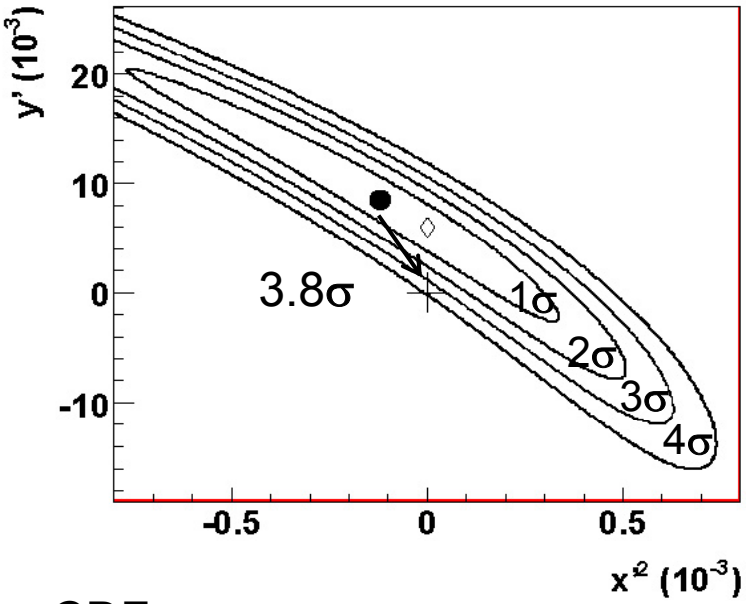

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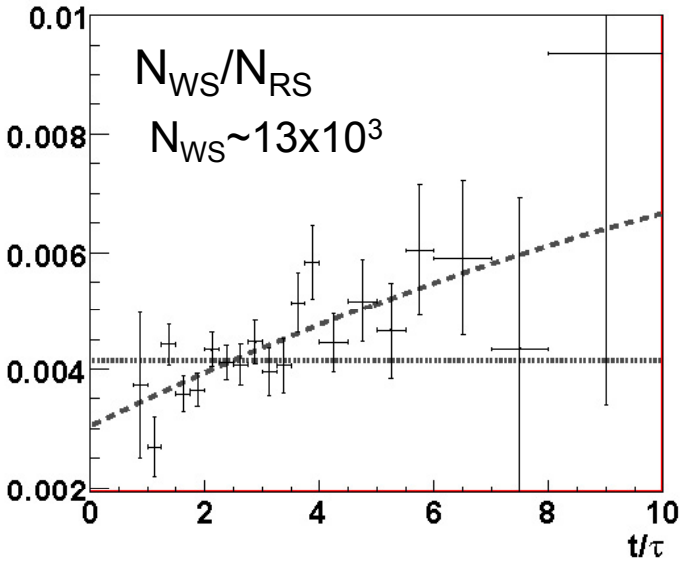
CDF, PRL 100, 121802 (2008), 1.5fb^{-1}



2. Measurements

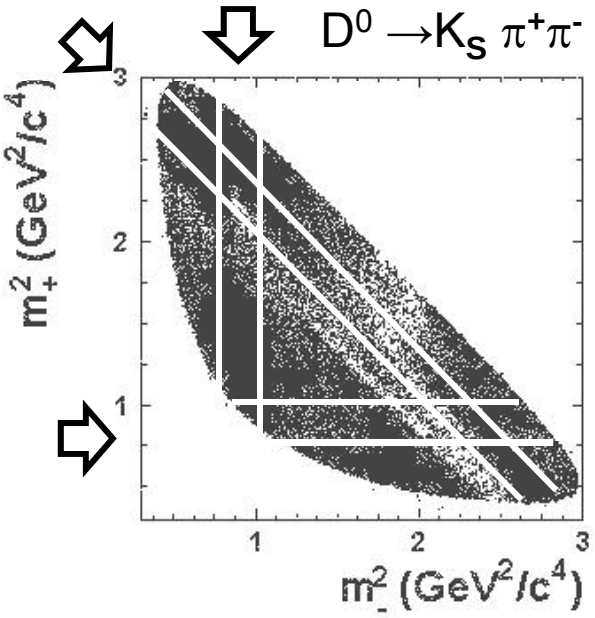
D) t-dependent Dalitz analyses

different types of interm. states;

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

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

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



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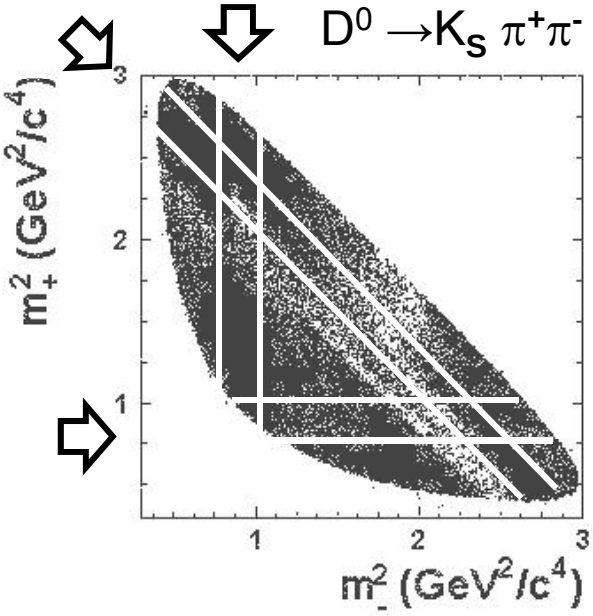
if $f = \overline{f} \Rightarrow$ populate same Dalitz plot;
relative phases determined
(unlike $D^0 \to K^+\pi^-$);



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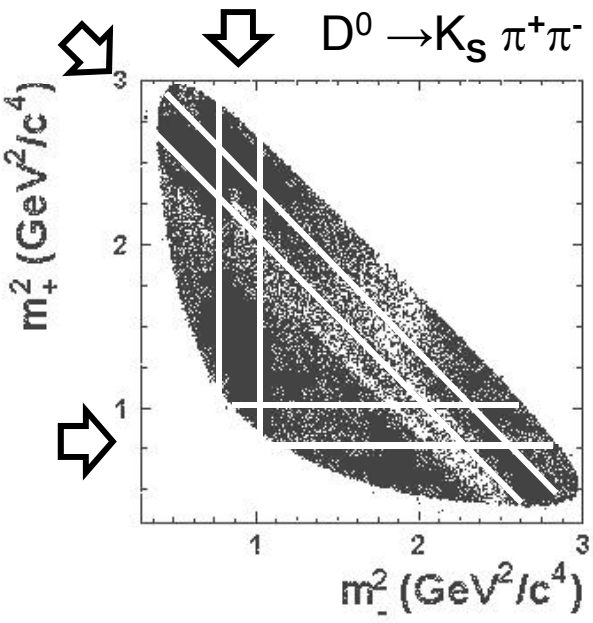

t-dependence:

regions of Dalitz plane →
specific t dependence f(x, y);
$m_\pm^2 = m^2(K_S\pi^\pm)$, $\lambda_{1,2} = f(x,y)$;
n.b.: $K^+\pi^-$: x'^2, y'

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

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

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

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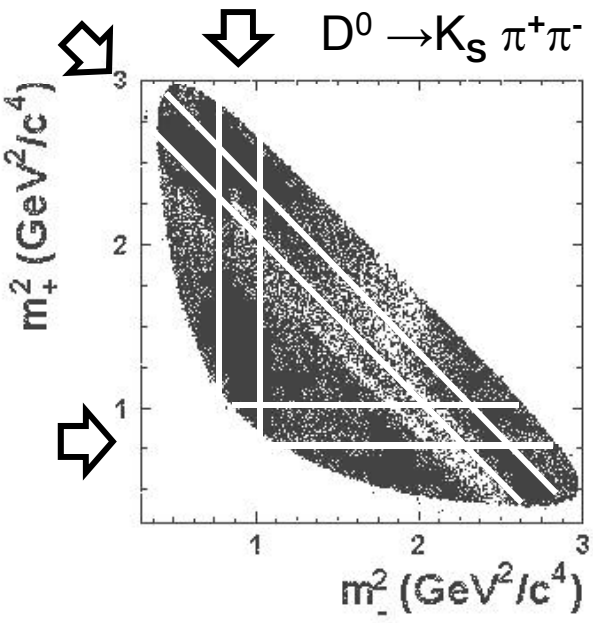

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sum of intermediate states: $\mathcal{A}(m_-^2, m_+^2) = \sum a_r\, e^{i\Phi_r} B(m_-^2, m_+^2) + a_{NR}\, e^{i\Phi_{NR}}$

2. Measurements

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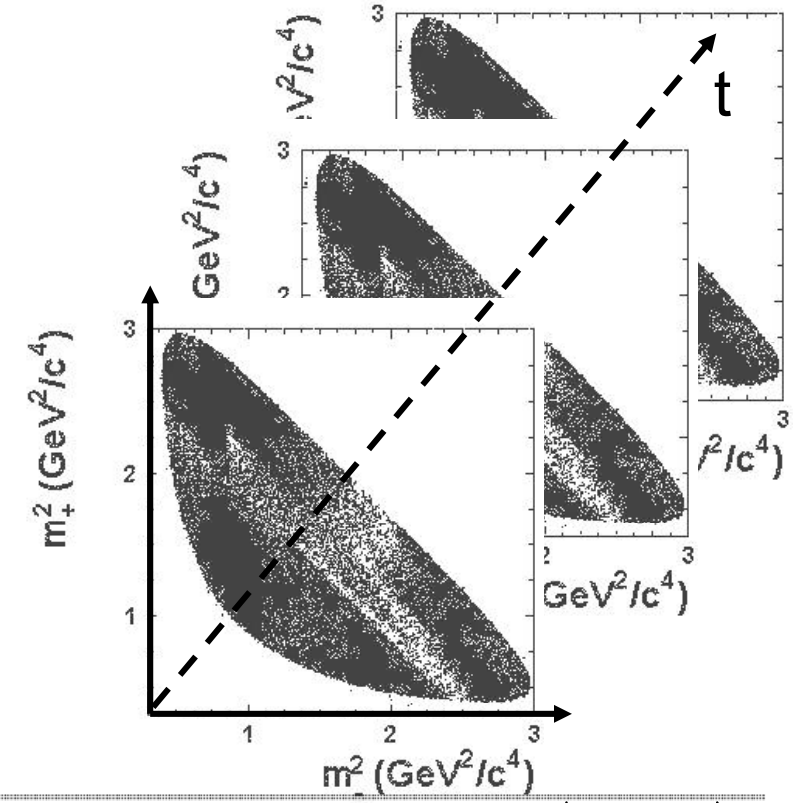

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n.b.: $K^+\pi^-$: x'^2, y'

access directly x, y

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

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

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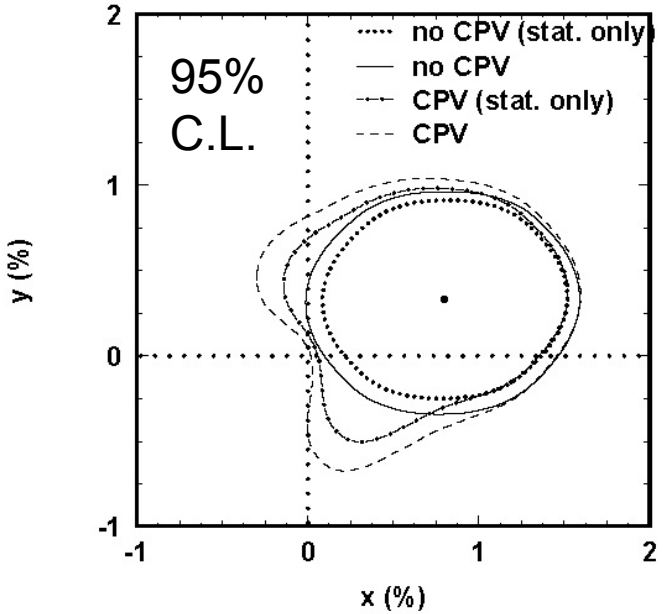
2. Measurements

D) t-dependent Dalitz analyses

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

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



2. Measurements

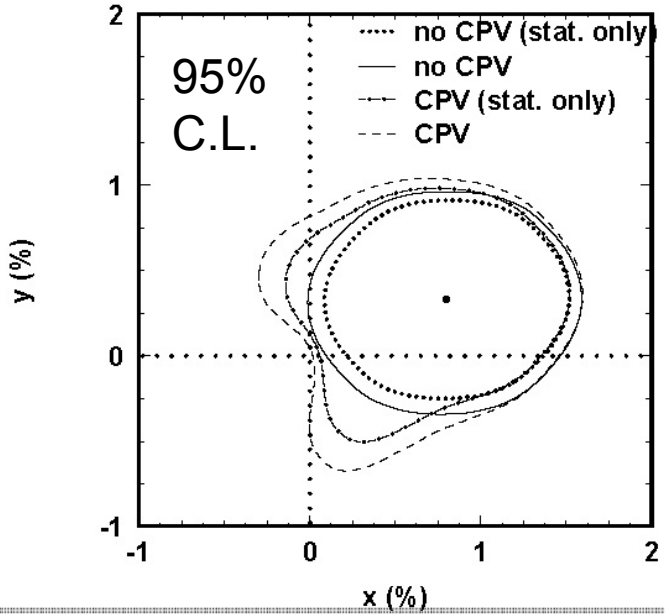
D) t-dependent Dalitz analyses

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

most accurate x;
model systematics;

$$x = (0.80 \pm 0.29 \pm {}^{0.13}_{0.16})\%$$
$$y = (0.33 \pm 0.24 \pm {}^{0.10}_{0.14})\%$$
$$|q/p| = 0.86 \pm {}^{0.30}_{0.29} \pm {}^{0.10}_{0.09}$$
$$\varphi = (-0.24 \pm {}^{0.28}_{0.30} \pm 0.09)\ rad$$

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



2. Measurements

D) t-dependent Dalitz analyses

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

most accurate x;
model systematics;

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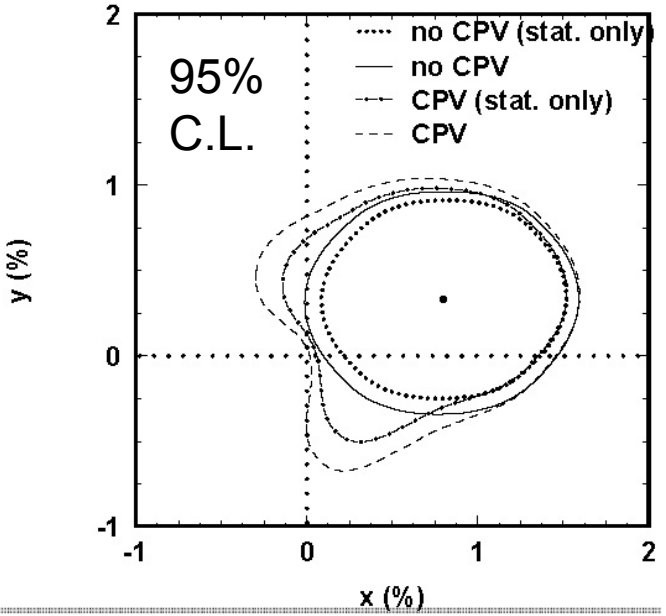

$D^0 \to K^+ \pi^-\pi^0$

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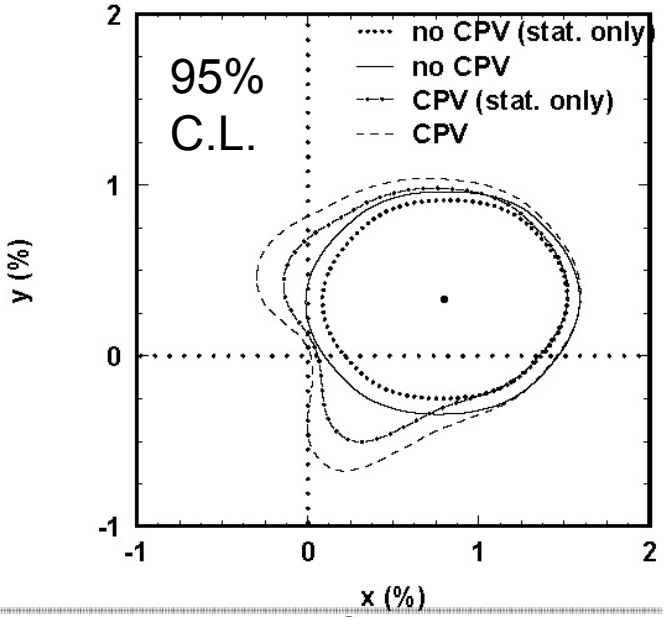

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$$\left|\left\langle K^+\pi^-\pi^0 \left| D^0(t)\right\rangle\right|^2 \propto [\underbrace{|A_{\bar f}|^2}_{DCS} +$$
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$$x'' = x\cos\delta_{K\pi\pi} + y\sin\delta_{K\pi\pi}$$
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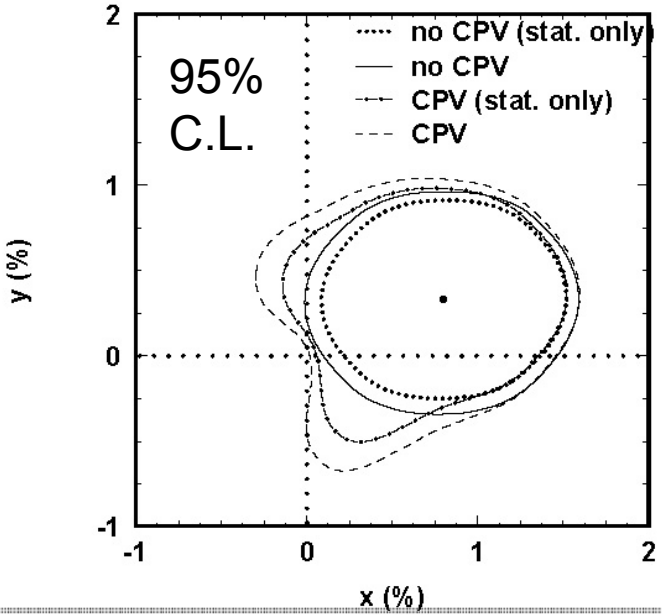

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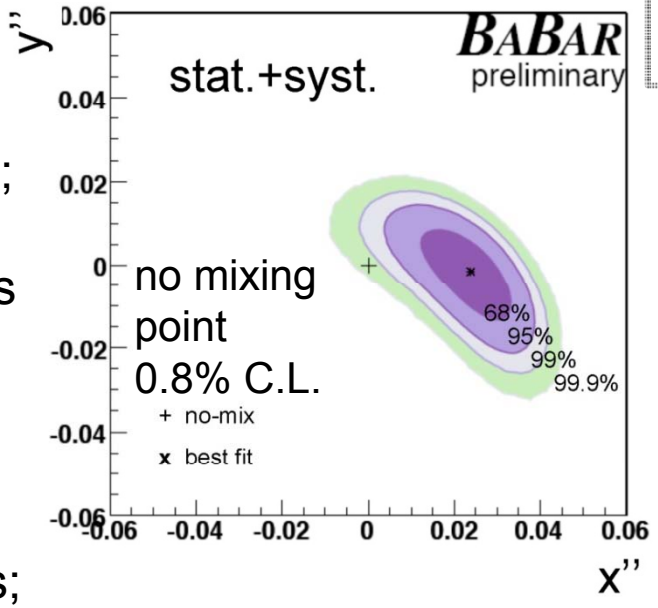

BaBar, Lepton Photon 07, 384fb^{-1}

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at threshold $D^0\bar{D}^0$ in C=-1 state $\Rightarrow$
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$S_\pm$: CP eigenstates

e^-: $Xe\nu$

Cleo-c, arXiv:0802.2268, 281pb^{-1}

$$\frac{Br(D^0\bar{D}^0 \to f_i X)}{Br(D^0 \to f_i)}$$

Mode		C-odd
$K^-\pi^+$	single D^0 reconstr.	$1+R_{WS}$
S_+		2
S_-		2
$K^-\pi^+/K^-\pi^+$	both D^0 reconstr.	R_M
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S_+/S_+		0
S_-/S_-		0
S_+/S_-		4
S_+/e^-		$1+y$
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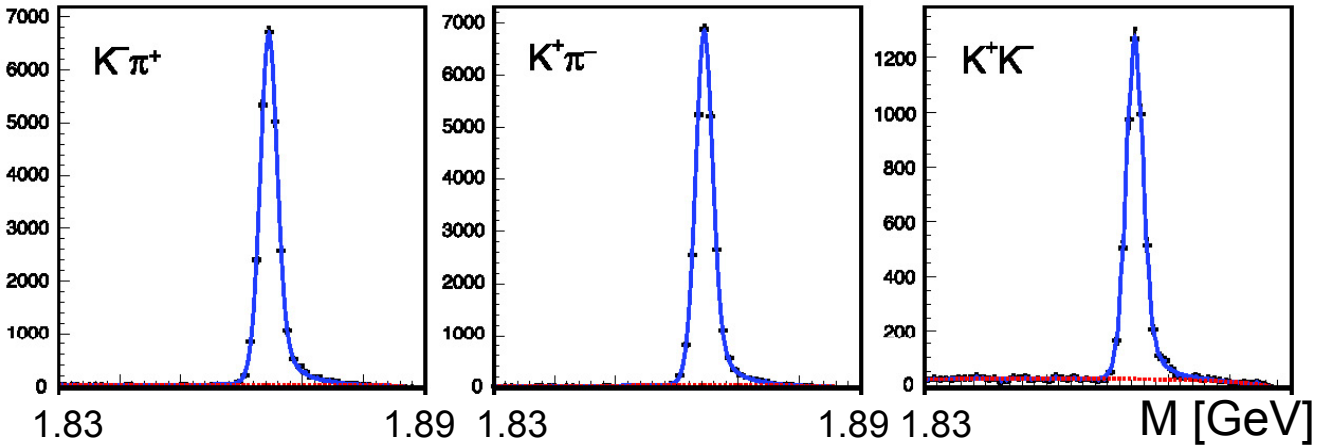

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$$\sqrt{R_{WS}}\cos\delta = 0.089 \pm 0.036 \pm 0.009$$

δ measurement

$$y = (-5.2 \pm 6.0 \pm 1.7)\%$$
$$R_{WS} = (-2.4 \pm 1.6 \pm 1.2)\%$$
$$R_M = (0.20 \pm 0.12 \pm 0.12)\%$$

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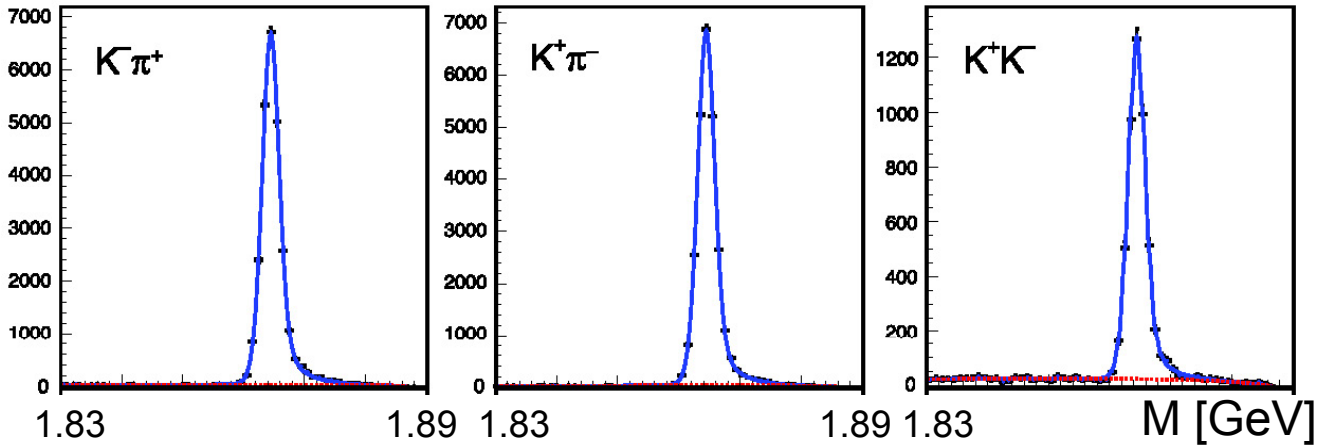

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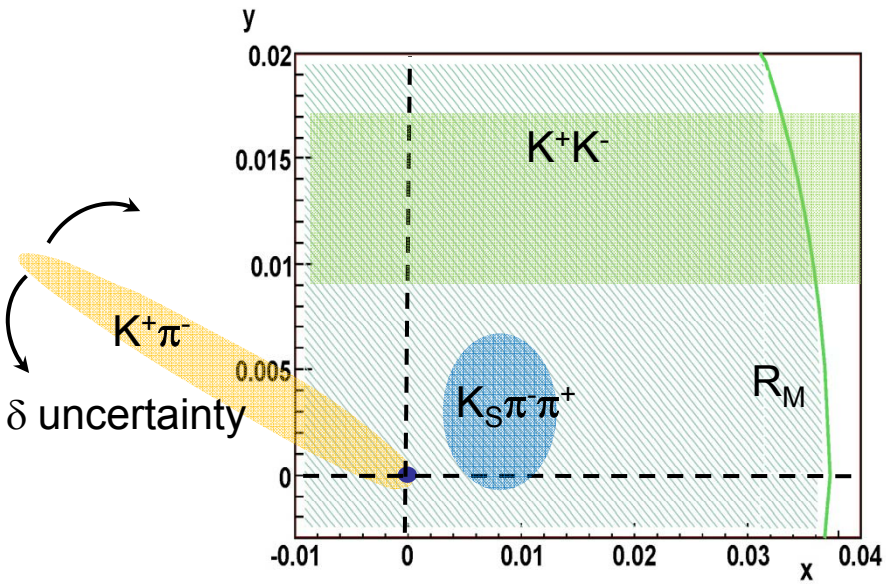
Average of results

χ^2 fit including correlations among measured quantities



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Parameter	CPV-allowed
x (%)	$0.89\ ^{+0.26}_{-0.27}$
y (%)	$0.75\ ^{+0.17}_{-0.18}$
δ (°)	$21.9\ ^{+11.3}_{-12.4}$
R_D (%)	0.3348 ± 0.0086
CPV: A_D (%)	-2.0 ± 2.4
CPV: $\lvert q/p \rvert$	$0.87\ ^{+0.18}_{-0.15}$
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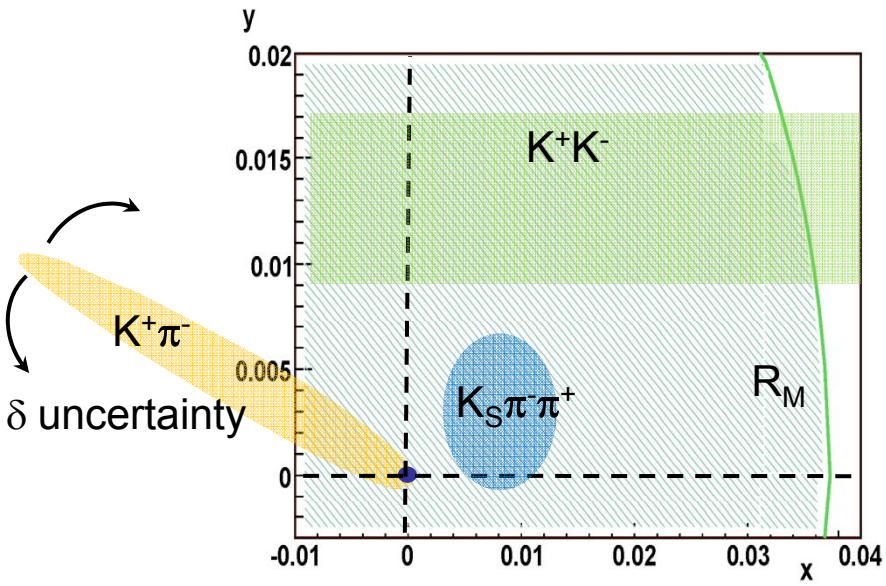
http://www.slac.stanford.edu/xorg/hfag/charm/

χ^2/n.d.f.= 23.5/18



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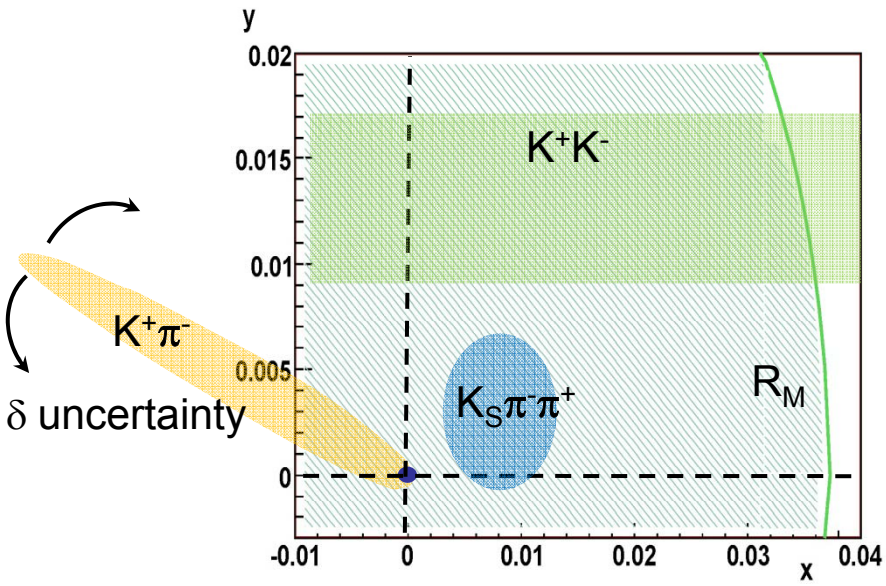

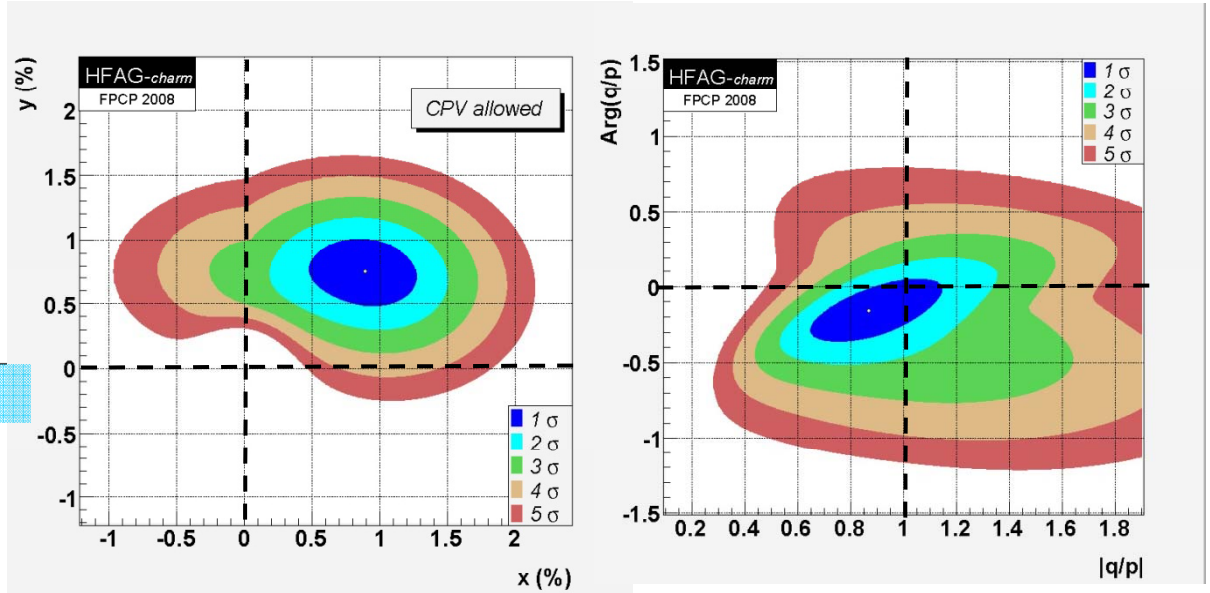

(x,y)≠(0,0): 6.7σ;
CP even state heavier and shorter lived;
no CPV within 1σ

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A) Constraints on NP

uncertain SM predictions for x, y;
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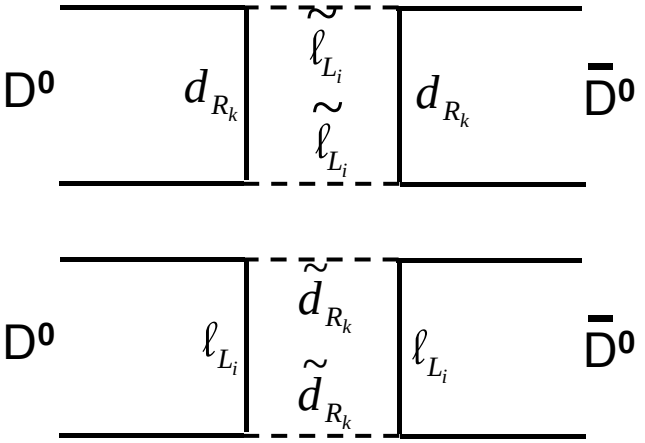

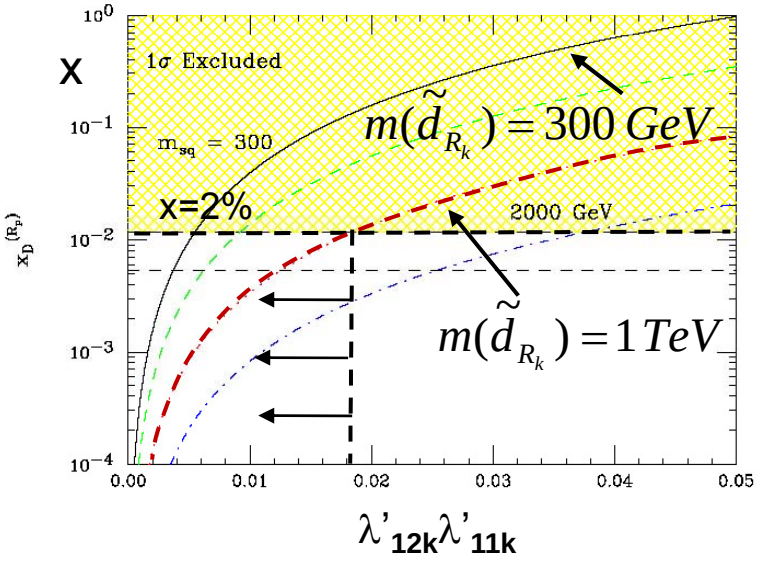

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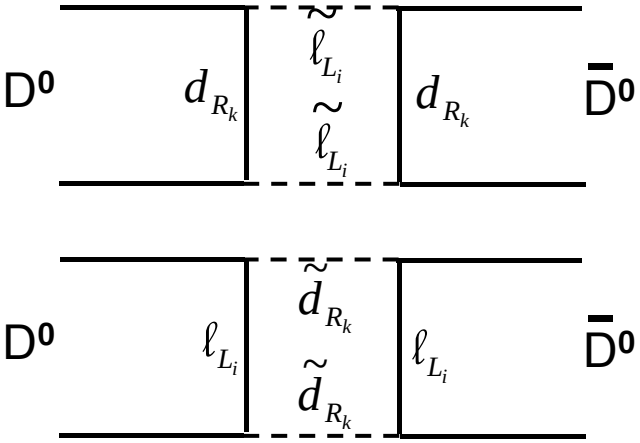

B) Approximate sensitivity

Super-B

		σ(x)	σ(y)	σ(|q/p|)	σ(ϕ)
initial→	5 ab^{-1}	0.15%	0.08%	0.09	0.10
	50 ab^{-1}	0.10%	0.06%	0.06	0.05

LHCb

	σ(x'^{2})	σ(y')
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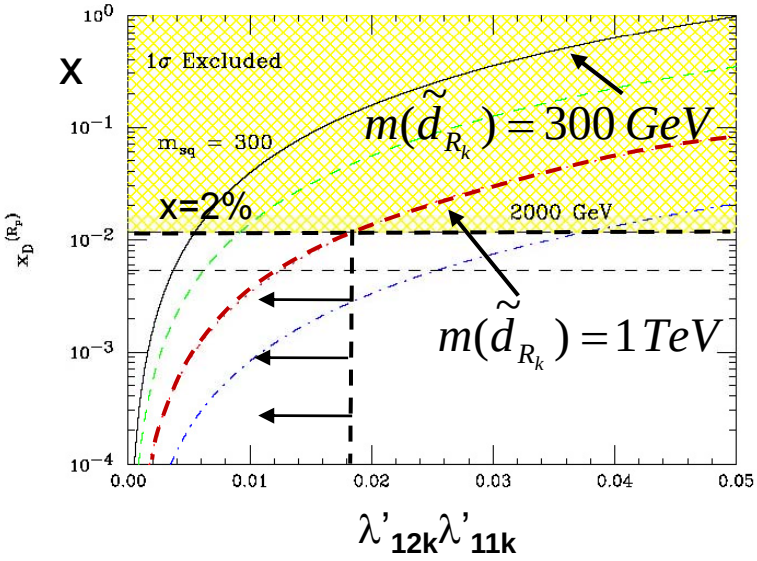

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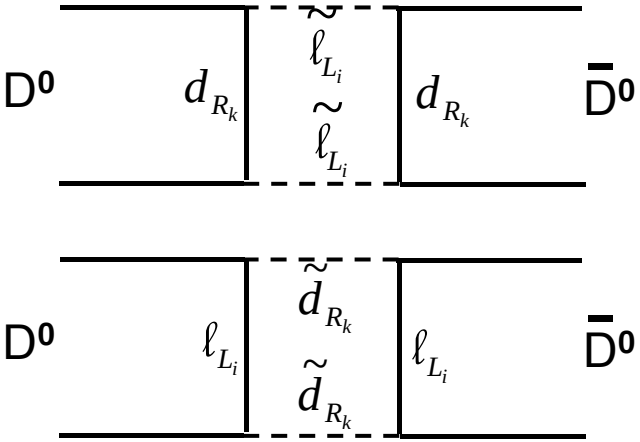

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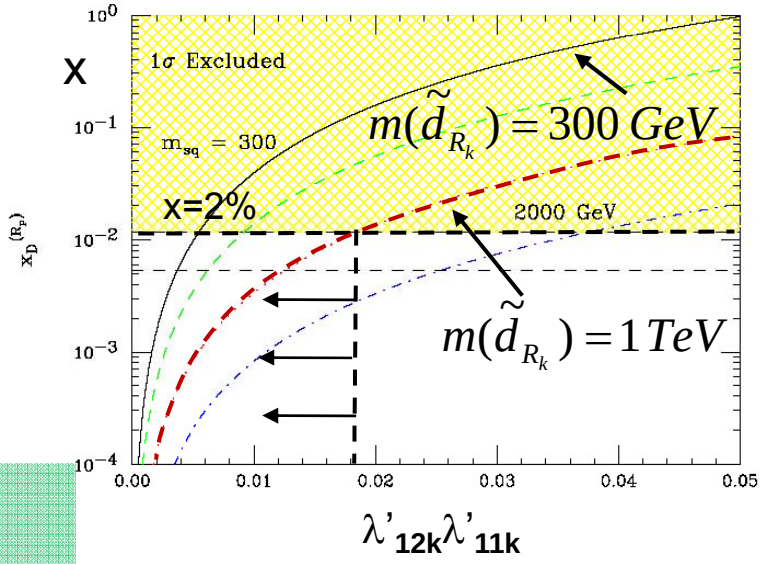
initial stage of Super-B, LHCb:
x, y ~3x better than WA;
sensitivity to CPV ə range of SM predictions



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mid-term future: sensitivity to test full range of SM expectations;