Perspectives on Charm Physics at SuperB

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Outline

- Charm physics at B factories
  - spectroscopy, charm mixing, relevance of D^0 Dalitz plot analyses;
- Charm physics at Super Flavor Factories
  - search for New Physics signatures: CP violation, FCNC, rare decays;
- Discovery potential of SuperB
  - sensitivities for benchmark channels and comparison with other experiments.

Charm Physics at B factories

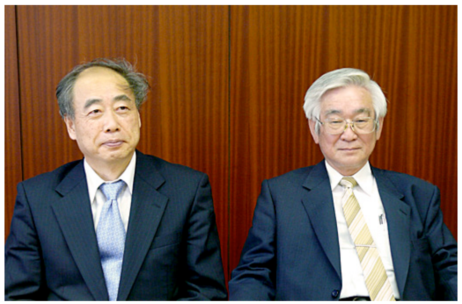
BaBar and Belle purpose

- BaBar and Belle experiments were designed with the main purpose of studying CP violation in the B meson system and verify wether the KM phase is the source of CP violation. Mainly using time-dependent analyses, exploiting the e^+e^- center of mass Lorentz boost.
- Great success of both experiment: the CKM mechanism has been proved to be the dominant source for flavor mixing and CP violation. Mission accomplished!

The CKM mechanism is confirmed

Nicola Cabibbo

Kobayashi and Maskawa awarded of 2008 Nobel Prize



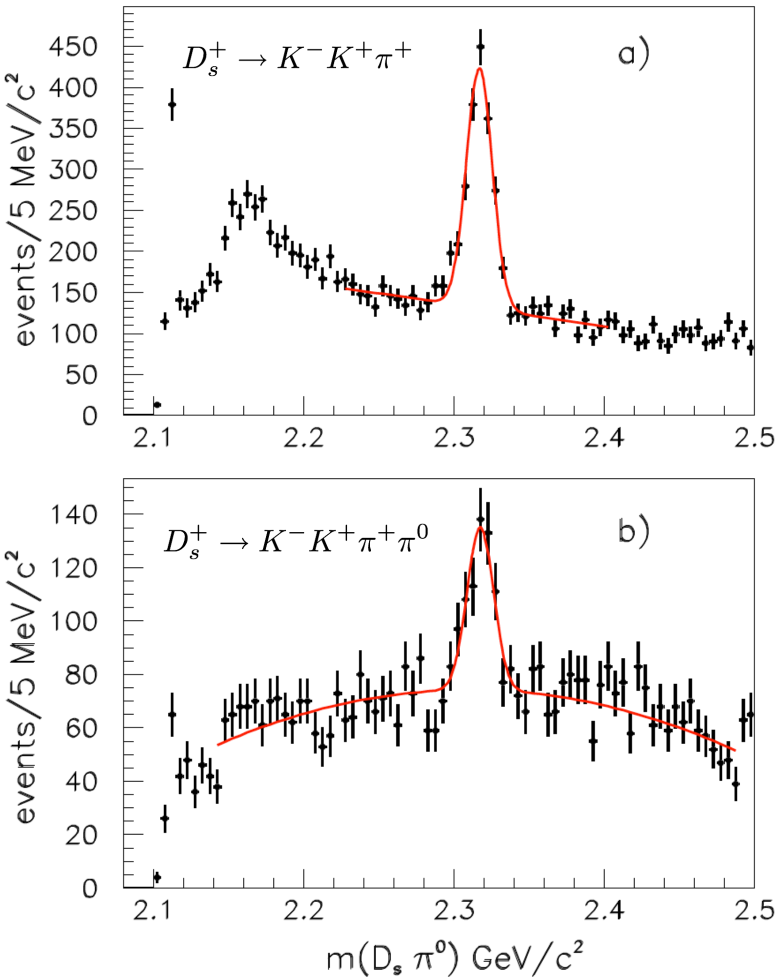
Charm physics

- Although not the main theme at B factories, Charm physics revealed many surprises!
- Few highlights:
  - Found new D_s states not even predicted by theory!
  - Established $D^0 - \overline{D}^0$ oscillations.
  - D^0 Dalitz plot analyses as a crucial tool for measuring the CKM angle γ.
  - Important (and unique) constraints on New Physics models involving up-type FCNC.

Hunting for new charm states

As an example: BaBar discovery of $D_{s0}^{*}(2317)^{+}$

$D^*_{s0}(2317)^+ \rightarrow D_s^+\pi^0$



State not predicted by theory:

- narrow state. Primary decay modes do not conserve isospin;
- a lot of excitement among theorists;
- four-quark state model proposed.

This is the BaBar top cited article!

Phys.Rev.Lett.90:242001, 2003.

D^0 mixing notations

- Flavor mixing occurs when flavor eigenstates differ from mass eigenstates: well established phenomenon in neutral K, B_d, B_s systems.

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

- Mixing parameters are expressed in terms of *x, y* functions of the mass and decay width differences:

$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \qquad \text{where} \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- Three types of CP violation:

$$\langle f|H|D^0\rangle = A_f \qquad \langle f|H|\overline{D}^0\rangle = \overline{A}_f$$

- in the decay (direct): $\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$
- in mixing (indirect): $r_m = \left|\frac{q}{p}\right| \neq 1$
- in the interference between mixing and decay: $\varphi_f \neq 0$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = r_m \left|\frac{\overline{A}_f}{A_f}\right| e^{i(\delta_f + \varphi_f)}$$

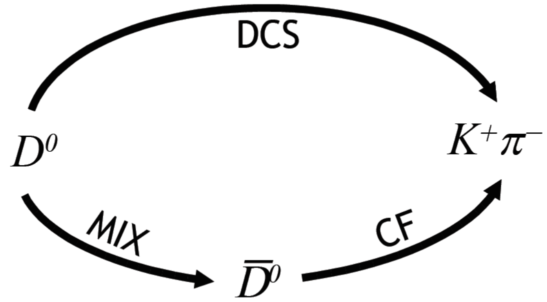
$\varphi_f =$ weak phase
$\delta_f =$ strong phase

First evidence for D^0 mixing in wrong sign $D^0 \to K^+\pi^-$ decays

- Wrong Sign (WS) final states from 2 sources: via double-Cabibbo-suppressed (DCS) decays or via mixing followed by Cabibbo-favored (CF) decays.

Time evolution $(|x| \ll 1, |y| \ll 1)$:

$$\frac{dN_{WS}}{dt} \propto e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y'\sqrt{R_D}(\Gamma t)}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$



$$R_D = \frac{\mathrm{B}(D^0 \to K^+\pi^-)}{\mathrm{B}(D^0 \to K^-\pi^+)} \simeq 3 \cdot 10^{-3}$$

phase between DCS and CF decays not directly measurable at B Factories

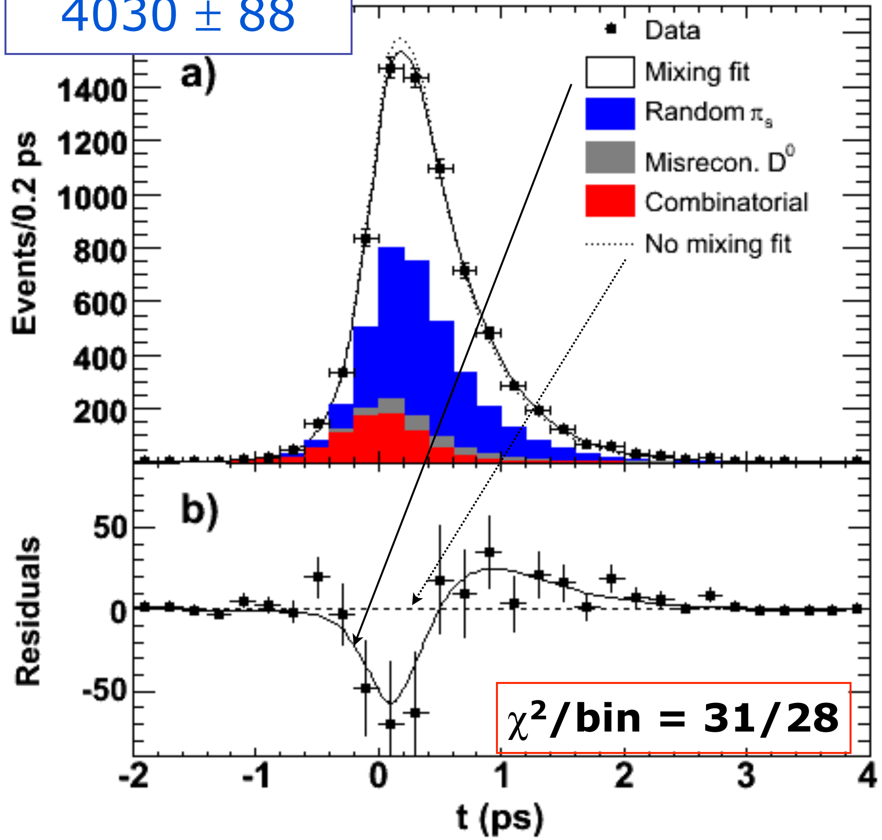
$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \qquad y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

Analysis of the proper time distribution of WS events permits extraction of D^0 mixing parameters y’, x’^{2}

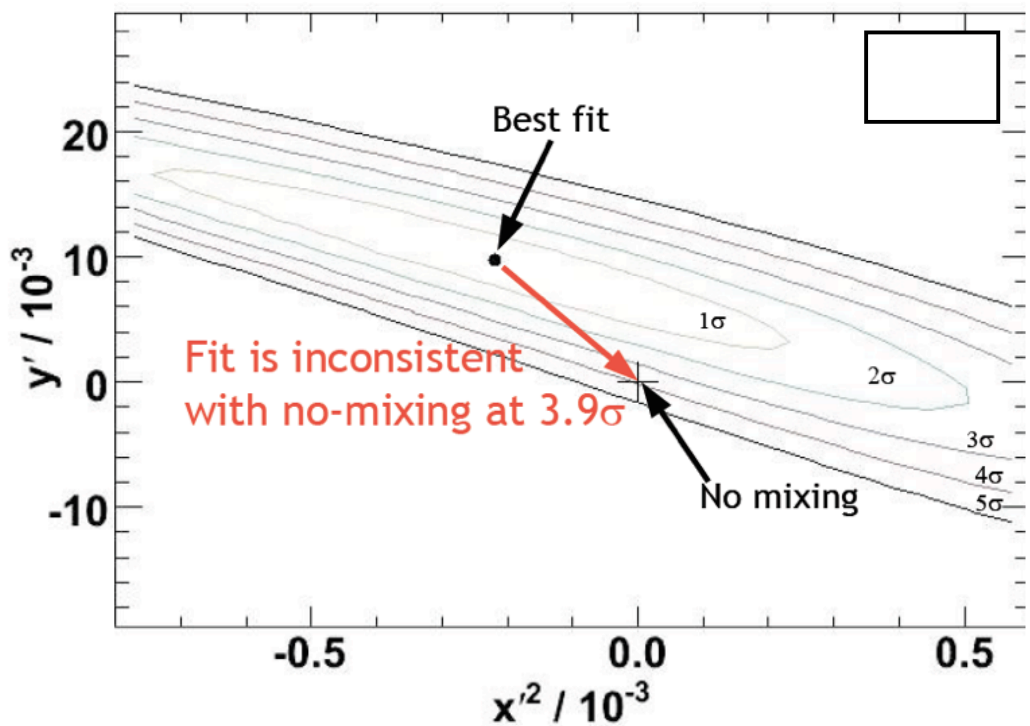
WS time fit: evidence of mixing at 3.9σ

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

Fitted signal
4030 ± 88



WS *mixing* fit projection in signal region
1.843 GeV/c^2<m_D<1.883 GeV/c^2
0.1445 GeV/c^2<Δm< 0.1465 GeV/c^2



R_D: (3.03 ± 0.16 ± 0.10) x 10^{-3}
x'^2: (-0.22 ± 0.30 ± 0.21) x 10^{-3}
y': (9.7 ± 4.4 ± 3.1) x 10^{-3}

No evidence for CP violation fitting separately D^0 and $\overline{D}^0$

D^0 mixing with a time-dependent Dalitz plot (TDDP) analysis

$$\frac{dN_f(s_{12},s_{13},t)}{ds_{12}ds_{13}dt} \propto e^{-\Gamma t}\left\{|A_f|^2 + \left[y\underbrace{\mathrm{Re}(A_f^*\bar{A}_f)} - x\underbrace{\mathrm{Im}(A_f^*\bar{A}_f)}\right](\Gamma t) + \frac{x^2+y^2}{4}(\Gamma t)^2|\bar{A}_f|^2\right\}$$

larger sensitivity in regions populated by Doubly Cabibbo Suppressed and CP eigenstates.

$$A_f = A(s_{12},s_{13}) \quad \bar{A}_f = \bar{A}(s_{12},s_{13}) \text{ and } (s_{12},s_{13}) = \text{Dalitz plot location}$$

-if f and $\bar{f}$ belong to the same Dalitz plot (e.g. $K_S^0\pi^+\pi^-$) by assuming CP conservation in decay $(\bar{A}_f = A_{\bar{f}})$ is possible to extract directly x, y mixing parameters, without relative strong phase uncertainty.

Method pioneered by CLEO Collaboration: D.Asner *et. al. Phys.Rev.D72:012001,2005*.

Considered as golden channel for D^0 mixing and CPV at future experiments.

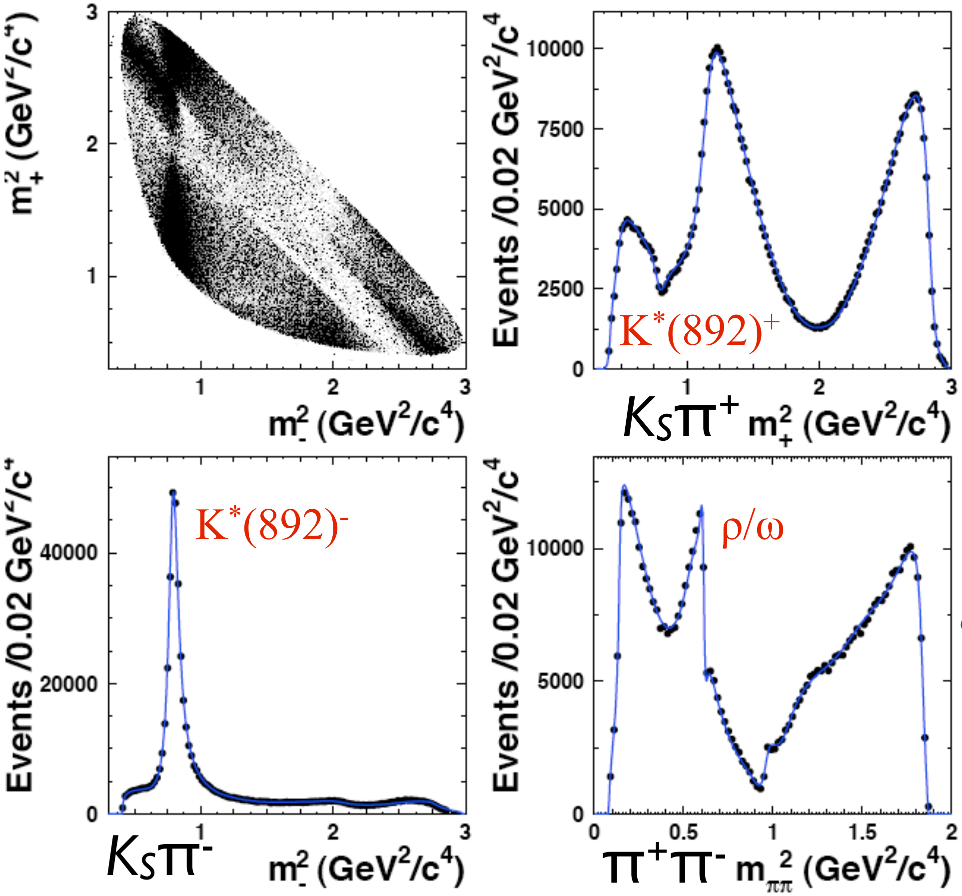
$D^0(t) \to K_S\pi^+\pi^-$ TDDP mixing fit

Phys.Rev.Lett.99:131803,2007

540 fb^{-1} data
N_{sig}= $(534.4\pm0.8)\times10^3$
Purity= 95%

Isobar model fit results

$$\chi^2/ndof = 2.1 \quad \text{with } (3653\text{-}40) \text{ ndof}$$



Resonance	Amplitude	Phase (°)	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	-146.6 ± 0.9	0.0914
σ_2	0.267 ± 0.013	-157 ± 3	0.0088
NR	2.36 ± 0.07	155 ± 2	0.0615

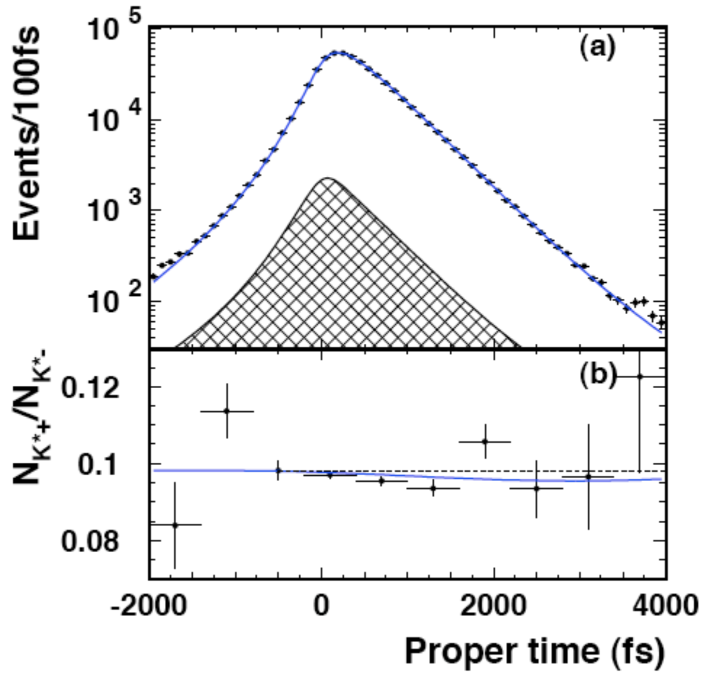
DCS states: $K^*(892)^+$, $K_0^*(1430)^+$, $K_2^*(1430)^+$, $K^*(1410)^+$, $K^*(1680)^+$

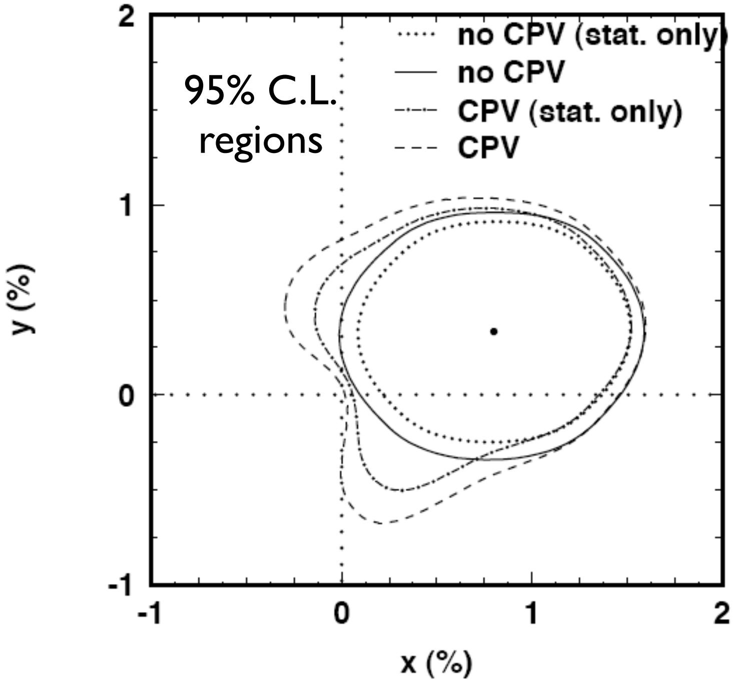
CP eigenstates: $\rho(770)$, $\omega(782)$, $f_0(980)$, $f_0(1370)$, $f_2(1270)$, $\rho(1450)$, σ_1, σ_2

Mixing fit results

Phys.Rev.Lett.99:131803,2007

$\tau = 409.9 \pm 0.9$ fs consistent with PDG





$$x = \left[0.80 \pm 0.29(\text{stat.})^{+0.09}_{-0.07}(\text{syst.})^{+0.10}_{-0.14}(\text{model})\right]\ \%$$

$$y = \left[0.33 \pm 0.24(\text{stat.})^{+0.08}_{-0.12}(\text{syst.})^{+0.06}_{-0.08}(\text{model})\right]\ \%$$

No mixing disfavored at 2.2σ level

$$|q/p| = 0.86^{+0.30}_{-0.29}(\text{stat.})^{+0.10}_{-0.09}(\text{syst.})$$

$$\phi = -0.24^{+0.28}_{-0.30}(\text{stat.}) \pm 0.09(\text{syst.})$$

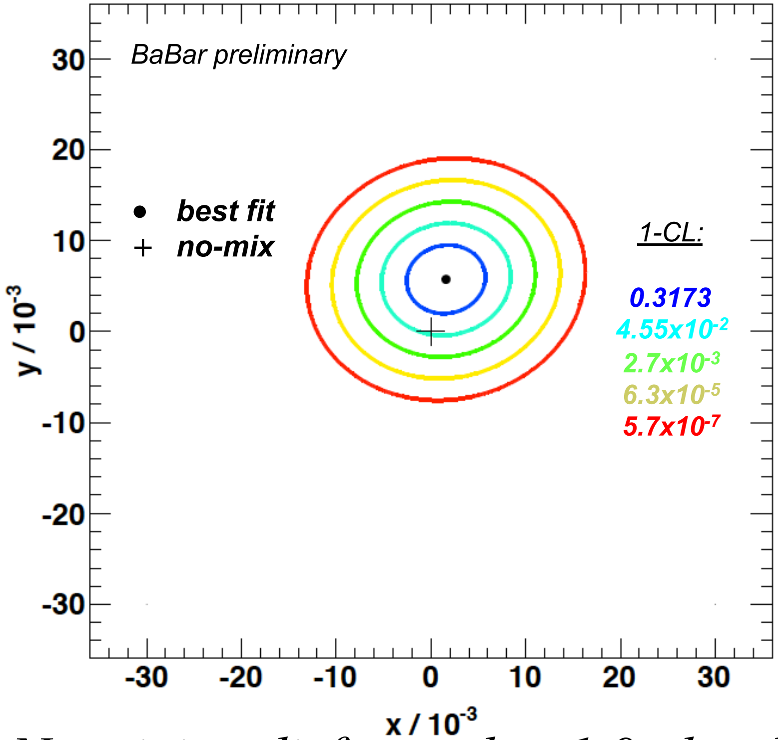
No evidence for CP violation

Mixing fit results

468.5 fb^{-1} data

Phys.Rev.Lett.105:081803,2010.

Combined $K_S\pi^+\pi^- + K_SK^+K^-$ fit



No mixing disfavored at 1.9σ level

Experimental systematics

Source	$x[\%]$	$y[\%]$
SVT misalignment	0.0279	0.0826
Fit bias	0.0745	0.0662
Charge-flavor correlation (mistagging)	0.0487	0.0398
Event selection	0.0395	0.0508
Efficiency map	0.0367	0.0175
Background Dalitz-plot distribution	0.0331	0.0142
D^0 mass window	0.0250	0.0250
Proper lifetime PDF	0.0134	0.0128
Signal and background yields	0.0109	0.0069
Mixing in background	0.0103	0.0082
Dalitz-plot normalization	0.0106	0.0053
Proper lifetime error PDF	0.0058	0.0087
Experimental systematics	0.1177	0.1302

D^0 decay amplitude model systematics

Dominated by uncertainty on K*(892), K-matrix, Kπ Lass parameters	0.0678	0.0532
Total	0.0830	0.0685

Combined $K_S\pi^+\pi^- + K_SK^+K^-$ fit results assuming CP conservation:

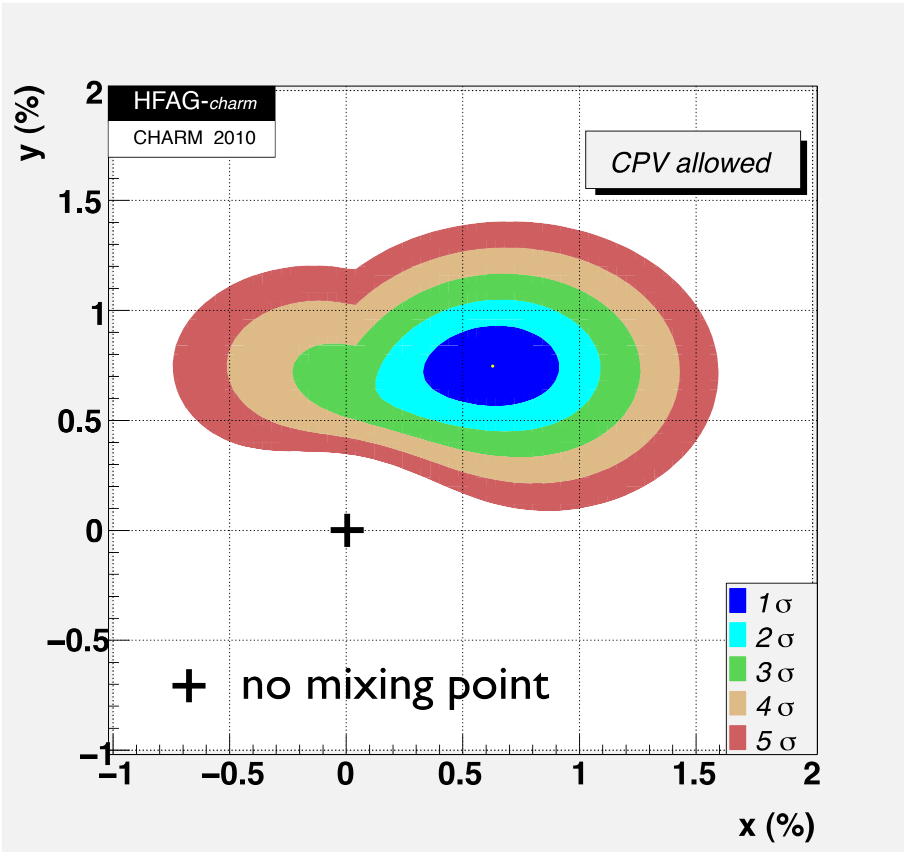
$$x = [0.16 \pm 0.23(\text{stat.}) \pm 0.12(\text{syst.}) \pm 0.08(\text{model})]\,\%$$

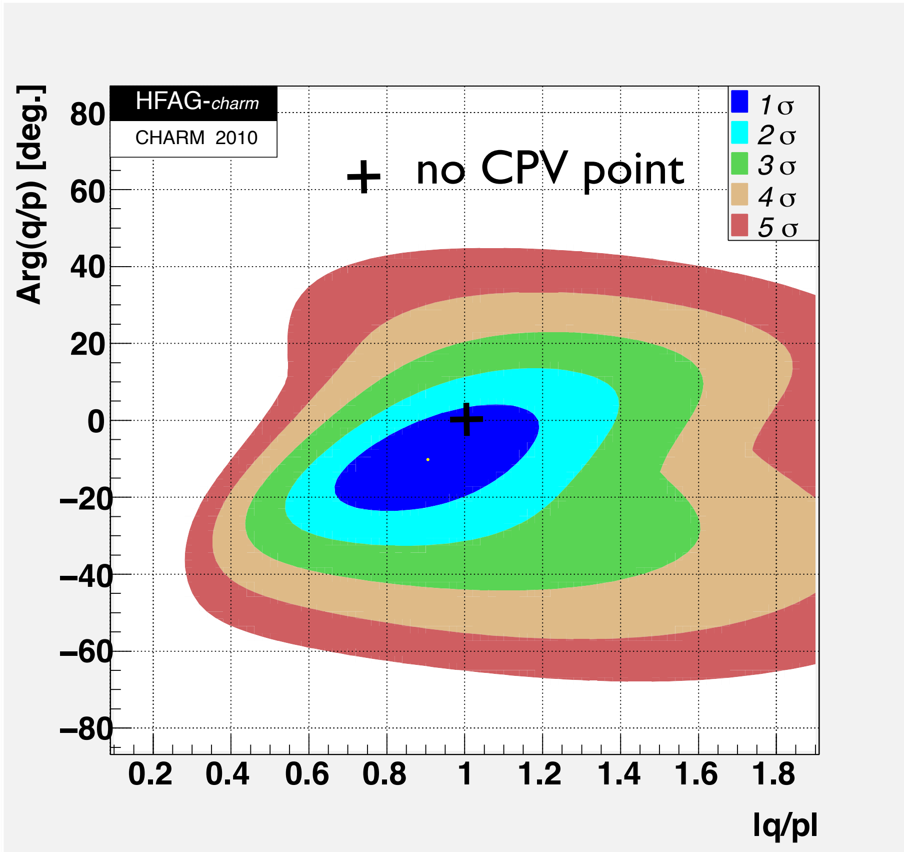
$$y = [0.57 \pm 0.20(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.07(\text{model})]\,\%$$

Best measurement of x parameter so far.

HFAG average for mixing and CPV parameters

Updated averages (CPV allowed) with all available measurements: mostly from B Factories but also CDF and CLEO-c.





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

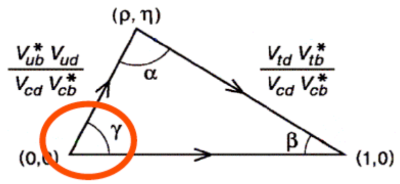
$$y = (0.75 \pm 0.12)\%$$

$$|q/p| = 0.91^{+0.18}_{-0.16}$$

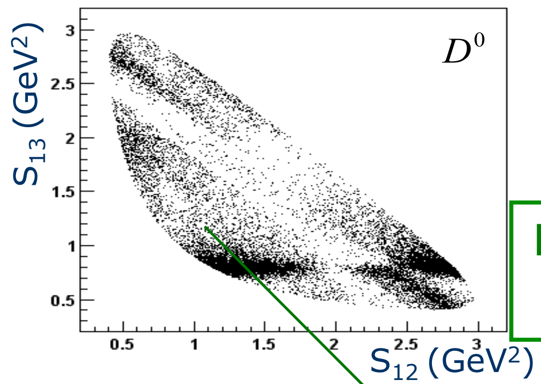
$$\varphi = (-10.2^{+9.4}_{-8.9})^\circ$$

Evidence of D^0 mixing exceeds 10σ combining all experimental results:

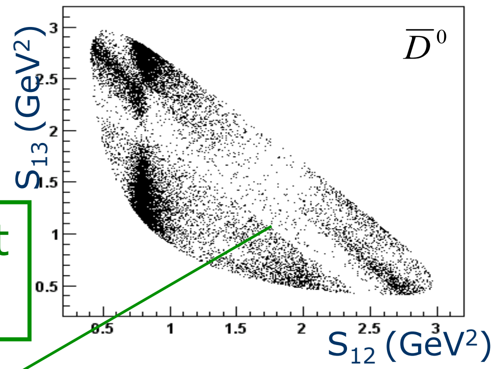
though no single measurement exceeds 5σ.



Dalitz plot analysis of $D^0 \rightarrow K_s h^+ h^-$ decays and extraction of the CKM angle γ



$B^- \rightarrow DK^-$ decays



D^0 3-body decay → Dalitz plot distribution $|A_D(s_{12}, s_{13})|^2$

CP

$A(B^-) = A_D(s_{12}, s_{13}) + r_B\, e^{i(-\gamma+\delta_B)} A_D(s_{13}, s_{12})$

Assuming CP is conserved in D decays

$A(B^+) = A_D(s_{13}, s_{12}) + r_B\, e^{i(\gamma+\delta_B)} A_D(s_{12}, s_{13})$

γ from interference term

$|A(B^-)|^2 = |A_D(s_{12}, s_{13})|^2 + r_B^2\, |A_D(s_{13}, s_{12})|^2 +$

Distribution of events over the D^0 Dalitz plot

$+2r_B \mathrm{Re}[A_D(s_{12}, s_{13})\, A_D(s_{13}, s_{12})^* \, e^{-i(-\gamma+\delta_B)}]$

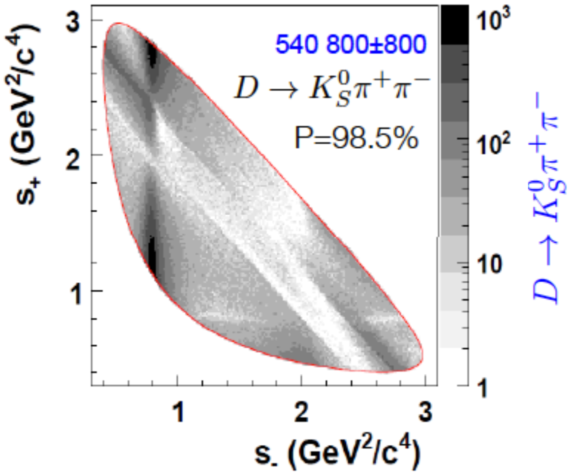
Extraction of γ with a discrete ambiguity: $(\gamma, \delta_B) \rightarrow (\gamma+\pi, \delta_B+\pi)$

Theory: PRD63 (2001)036005
PRD68 (2003) 054018

- Extract D decay amplitude from independent high statistics sample of flavor tagged D^0 mesons ($D^{*+} \rightarrow D^0\pi^+$). The so called “Dalitz model”.

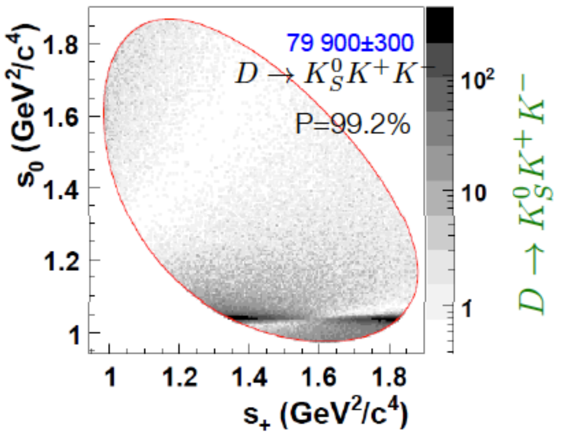
Good fit quality taking into account statistical, experimental and model uncertanties

$\chi^2/ndof = 1.21$ with (8626-41) ndof



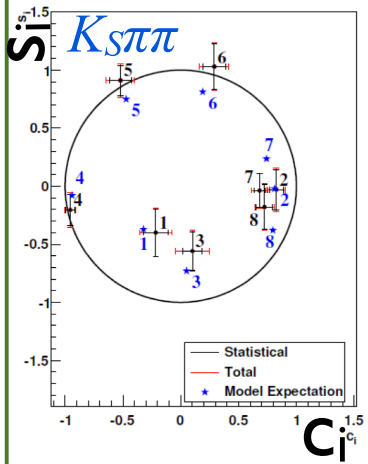
Wave	Parameterization
ππ S-wave	K-matrix
$K_S\pi$ S-wave	K-matrix (LASS)
ππ P-wave	BW: ω(782), G.S. ρ(770)
$K_S\pi$ P-wave	BW: CA and DCS K*(892), CA K*(1680)
ππ D-wave	BW $f_2(1270)^0$
$K_S\pi$ D-wave	BW: CA and DCS K_2*(1430)

$\chi^2/ndof = 1.28$ with (1195-17) ndof



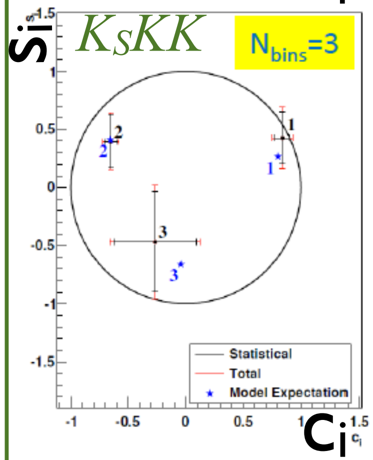
Wave	Parameterization
KK_S S-wave	BW: CA and DCS a_0(980), CA a_0(1450)
KK S-wave	Flatte a_0(980), BW a_0(1450), f_0(1370)
KK P-wave	BW ϕ(1020)
KK D-wave	BW $f_2(1270)^0$

Good agreement between BaBar Dalitz model expectation and CLEO-c model independent determination of D^0-$\overline{D}^0$ relative phases.



Modified optimal BABAR 2008

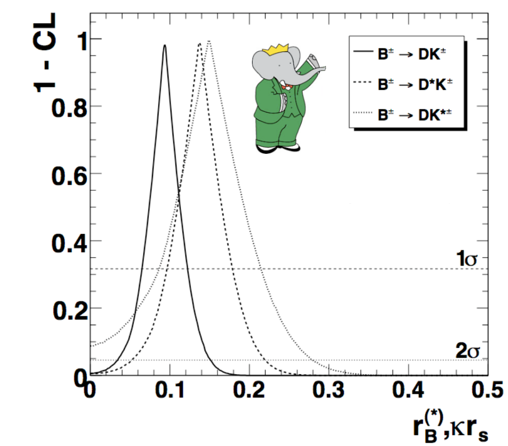
χ^2/DOF = 13.8/16

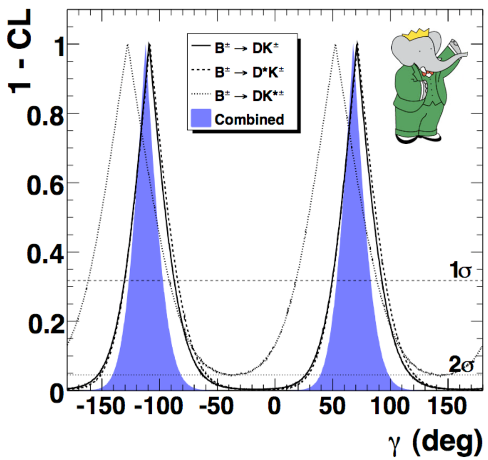


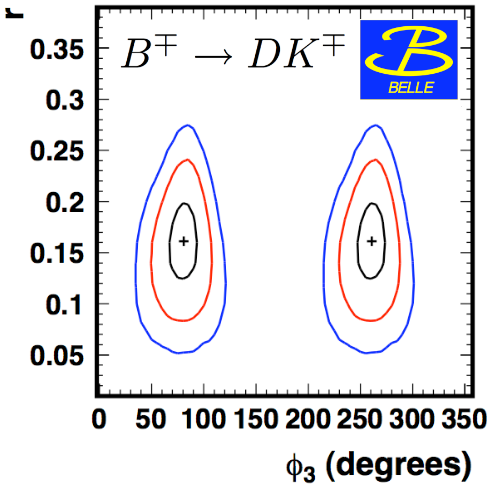
from Stefania Ricciardi talk at CKM 2010.

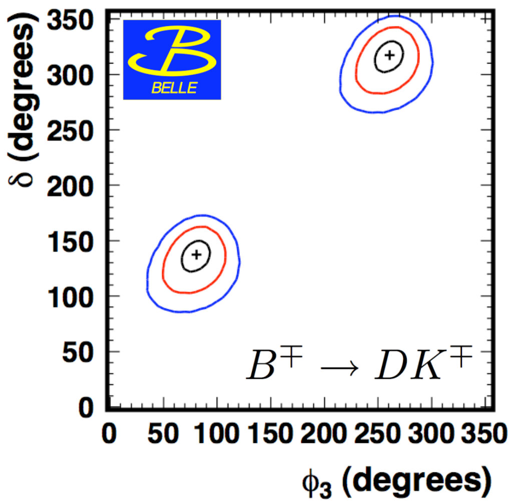
- c_i and s_i are weighted averages of the cosine and sine of the phase-difference between D^0 and $\overline{D}^0$ in bin i

$B^{\pm} \rightarrow D^{(*)}K^{(*)\pm}$ combined results: interpretation









B decay mode	***BELLE*** ($K_s\pi^+\pi^-$) **657 MB$\bar{B}$**	***BaBar*** ($K_s\pi^+\pi^-$) **468 MB$\bar{B}$**	***BaBar*** ($K_sK^+K^-$) **468 MB$\bar{B}$**
$B^{\pm} \rightarrow DK^{\pm}$	757 ± 30	920 ± 35	142 ± 14
$B^{\pm} \rightarrow D^*(D\pi^0)K^{\pm}$	168 ± 15	246 ± 22	53 ± 11
$B^{\pm} \rightarrow D^*(D\gamma)K^{\pm}$	83 ± 10	191 ± 19	31 ± 7
$B^{\pm} \rightarrow DK^{*\pm}$	*(not updated to 657 MB$\bar{B}$)*	163 ± 17	28 ± 6

Phys.Rev.Lett.105:121801 (2010)

BaBar 425 fb^{-1} (468 MB$\bar{B}$)

BaBar

$\gamma = (68 \pm 14 \pm 4 \pm 3)^{o}$

(*value* ± *stat.* ± *sys.* ± *model*)^{o}

Excludes γ =0 at 3.5 std.dev.

$r_B(DK) = (9.4\ ^{+2.8}_{-2.9})\%$

(*value* ± *total error*)%

Error breakdown (±0.5 *expt.*, ±0.4 *model*)%

Phys. Rev. D 81, 112002 (2010)

BELLE 605 fb^{-1} (657 MB$\bar{B}$)

BELLE

$\gamma = (78.4\ ^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^{o}$

(*value* ± *stat.* ± *sys.* ± *model*)^{o}

*B→DK and B→D*K only, 657 MB$\bar{B}$*

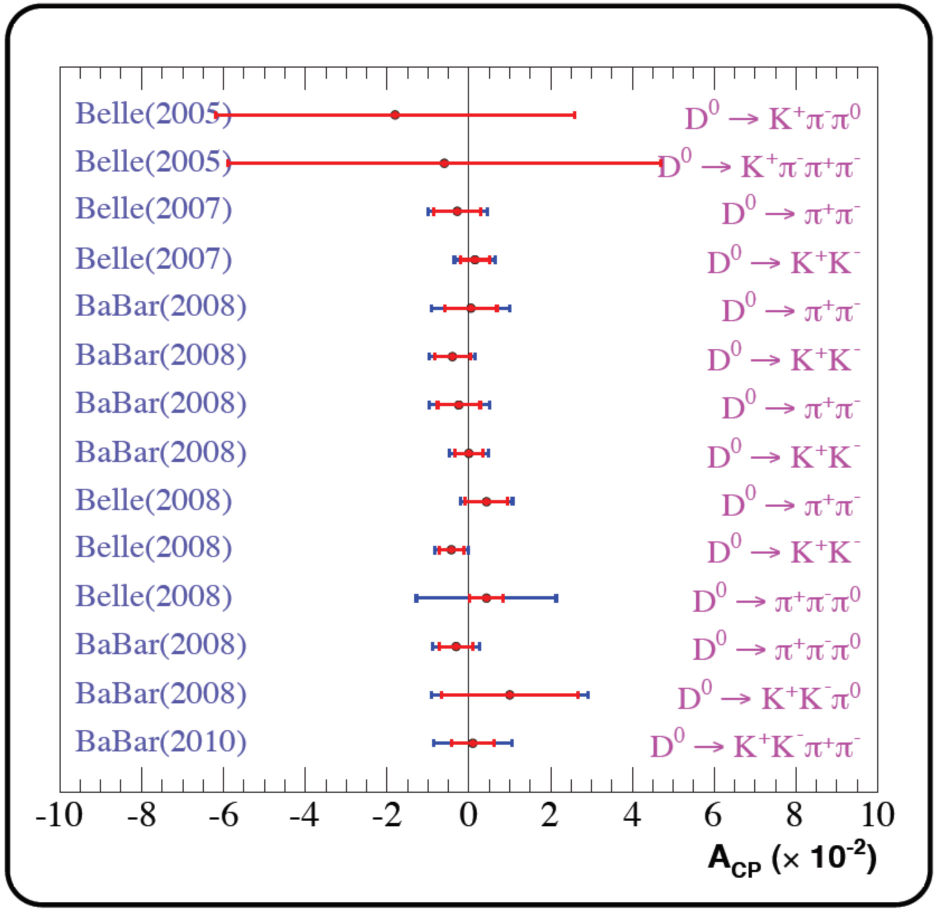
Excludes γ =0 at 3.5 std.dev.

$r_B(DK) = (16.0\ ^{+4.0}_{-3.8} \pm 0.011\ ^{+5.0}_{-1.0})\%$

(*value* ± *stat.* ± *sys.* ± *model*)%

Search for CP violation in D^0 decays

CP violation in D^0 decays is highly suppressed in the SM ($<10^{-3}$), hence it is sensitive to New Physics effects.



- Experimental sensitivity not yet at the level of SM predictions.
- Statistical error is dominant.

Which are the sources of flavour symmetry breaking accessible at low energies?

limits from CPV in D^0 mixing

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \sum \frac{c_{ij}}{\Lambda^2} O_{ij}^{(6)}$$

Isidori, Nir & GP, Ann. Rev. Nucl. Part. Sci. (10)

Operator	Bounds on Λ (TeV) ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

New flavor-breaking sources of O(1) at the TeV scale are definitely excluded

Charm physics at Super Flavor Factories

Charm physics has a great past!

- Quark proposed as an elementary particle and a fundamental constituent of the matter (M. Gell-Mann; G. Zweig 1964);
- prediction of the existence of the charm quark. GIM mechanism (S. Glashow, J. Iliopoulus, L. Maiani 1970);
- discovery of the J/Ψ meson, the first excited state of a $(c\overline{c})$ bound state. Discovery at SLAC and at Brookhaven Lab (1974);
- Goldhaber, *et al.* detected the neutral D meson at SLAC, (Mark I experiment 1976);
- first speculations on charm mixing and CP violation (A. Pais, S. B. Treiman 1977); A. Pais and S. B. Treiman, Phys. Rev. D 12, 2744 (1975) [Erratum-ibid. D 16, 2390 (1977)]
- after 30 years, first evidence for $D^0 - \overline{D}^0$ mixing. BaBar and Belle experiments (2007), quickly confirmed by CDF.

Why should we still study Charm Physics at SuperB?

From I. Bigi's talk at Valencia Workshop 7-15 Jan 2008

Prologue: New Physics Scenarios & Uniqueness of Charm

- New Physics in general induces FCNC
  - their couplings could be substantially stronger for Up-type than for Down-type quarks

(actually happens in some models which `brush the dirt of FCNC in the down-type sector under rug of the up-type sector)

- SM `background' much smaller for FCNC of *Up*-type quarks
  - ➥ cleaner -- albeit smaller -- signal!

Charm signatures for New Physics

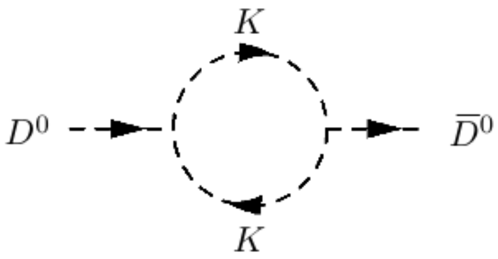
- The real certainty in charm physics is that $\not{CP}$, either in decay or in mixing or in interference, is the way to search for New Physics.
- At SuperB precision measurements of mixing should be considered as a tool for searches for $\not{CP}$.

- CP violation in charm decays:
  - in D^0 decays: indirect CPV, in mixing or in the interference between mixing and decay.
  - in D^0 and $D_{(s)}^+$ decays: direct CPV.
- Search for very rare charm decays:
  - FCNC decays: $D^0 \rightarrow \mu^+\mu^-$, $D^0 \rightarrow \gamma\gamma$, $D \rightarrow l^+l^-X$, etc.

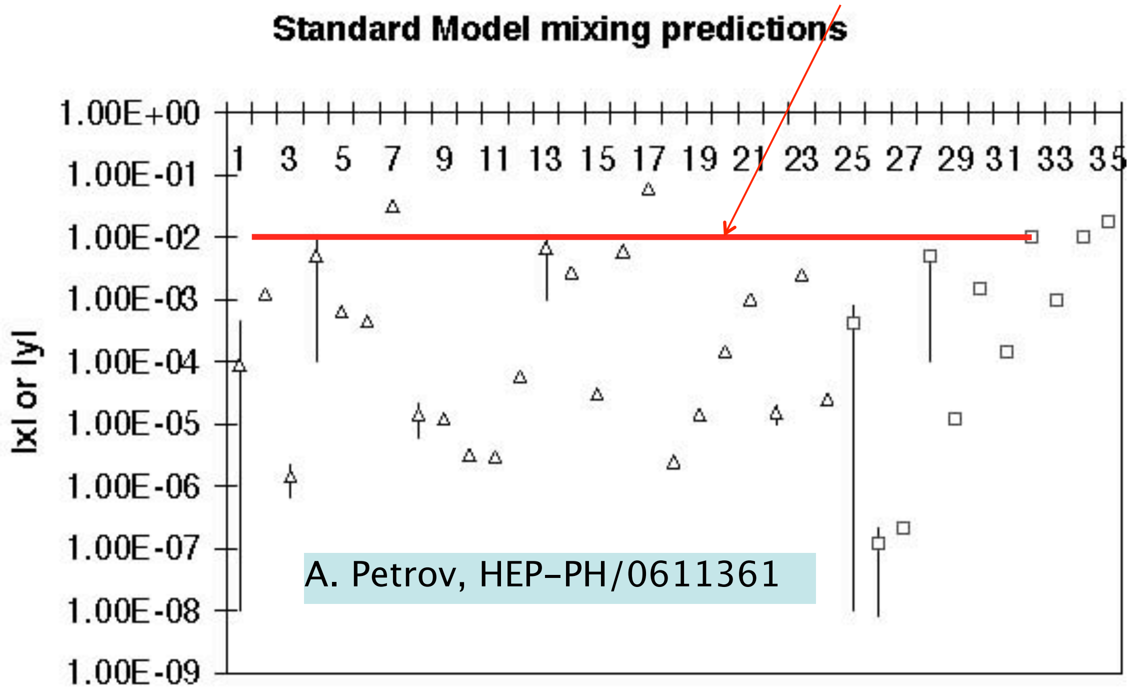
D0 mixing: SM predictions

- Short-distance contributions from mixing box diagrams in the Standard Model are expected to be small :
  - *b* quark is CKM-suppressed
  - *s* and *d* quarks are GIM suppressed

- Long-distance contributions expected to dominate, still small effect, hard to estimate precisely



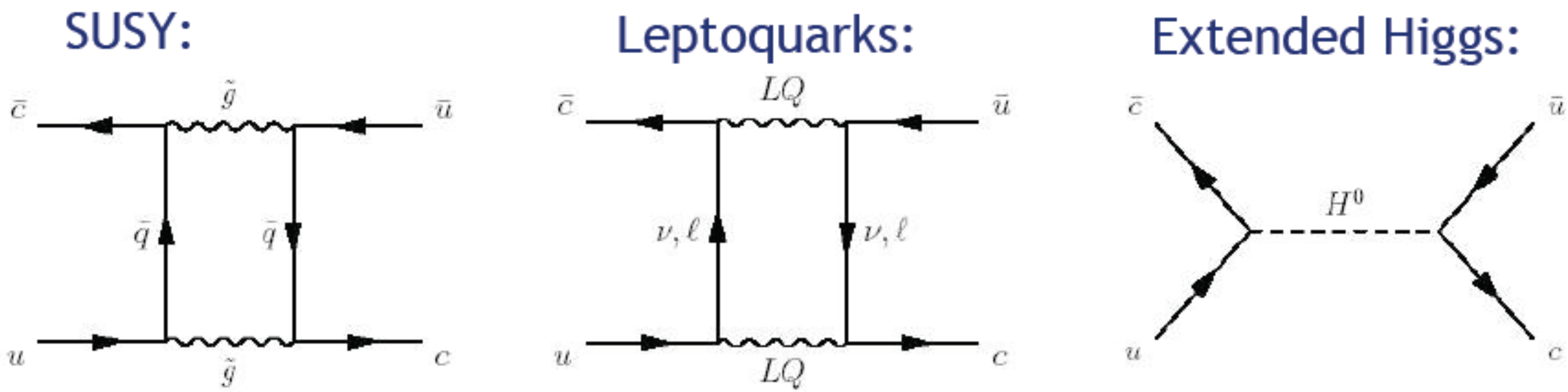
Reasonable to expect $|x| \leq 10^{-2}$, $|y| \leq 10^{-2}$



- New Physics could introduce new particles in loops.
- No direct or indirect CP violation expected in SM at 10^{-2}-10^{-3} level.

Possible New Physics in Charm Mixing

Charm mixing can be affected by possible new physics



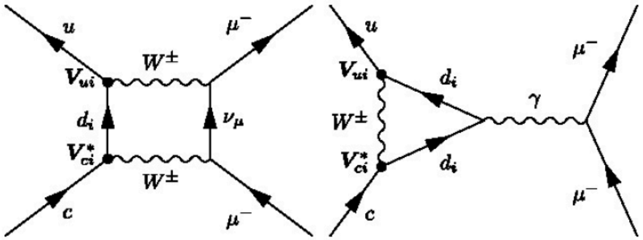
- new physics can increase *x* value, while *y* mostly unaffected: e.g. |x| >> |y| could be hint of New Physics;
- new physics contributions can generate CP violation up to few % level, more then one order of magnitude with respect to Standard Model expectations.

From Gilad Peres'z talk at Charm2010

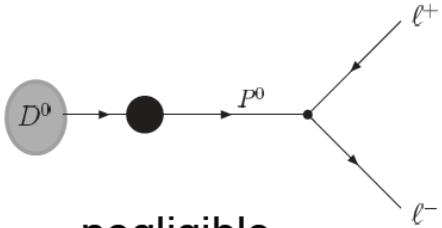
On the potential power of $D^0 \to \ell^+\ell^-$

Practically no SM short distance:

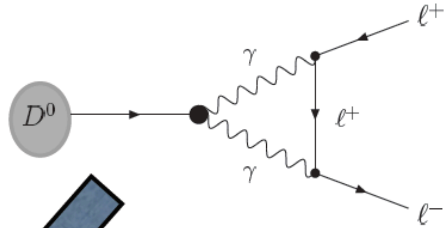
Burdman, Golowich, Hewett & Pakvasa PRD (02).



short distance, $\mathcal{B}$~10^{-18}



negligible



$$\mathcal{B}r^{(\gamma\gamma)}_{D^0\to\mu^+\mu^-} \simeq 2.7\times 10^{-5}\mathcal{B}r_{D^0\to\gamma\gamma} \sim 10^{-13}$$

Motivation

FCNC of *D* mesons
- FCNC of uplike (*c*) quarks;
- $\Rightarrow$ complementary constraints to *B* (and *K*) rare decays;

NP: enhancement of
- $\mathcal{B}(D^0 \to \mu^+\mu^-)$, $\mathcal{B}(D^0 \to e^+e^-)$, by orders of magnitude;
- possibility of LFV $\mathcal{B}(D^0 \to e^+\mu^-)$;

example $\not{R}$ SUSY:
- $\mathcal{B}(D^0 \to \mu^+\mu^-)$~$4\cdot 10^{-6}$
- $\mathcal{B}(D^0 \to e^+e^-)$~$10^{-10}$
- $\mathcal{B}(D^0 \to e^+\mu^-)$~$10^{-6}$

Discovery potential of SuperB

SuperB design and goals

- *Run at Υ(4S):* $\mathcal{L} = 10^{36}\ \ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1};\ \ \int \mathcal{L}\,dt = 75\ \mathrm{ab}^{-1}\ \ \text{at the } \Upsilon(4S)$

✓ Large improvement in D^0 mixing and CPV: factor 12 improvement in statistical error wrt BaBar (0.5 ab^{-1});
✓ Time-dependent measurements will benefit also of an improved (2x) D^0 proper-time resolution.

Unique feature of SuperB

- *Run at ψ(3770):* $\mathcal{L} = 10^{35}\ \ \mathrm{cm}^{-2}\,\mathrm{sec}^{-1};\ \ \int \mathcal{L}\,dt = 500\ \mathrm{fb}^{-1}\ \ \text{at the } \Psi(3770)$

✓ $D\bar{D}$ coherent production with 100x BESIII data and center-of-mass boost βγ=0.24;
✓ almost zero background environment: search for rare/forbidden decays, precise measurement of relative $D^0\bar{D}^0$ strong phases, search for CPV in wrong sign (WS) semileptonic (SL) D^0 decay modes.

Mixing and ~~CP~~ violation observables

$D^0 \to l^- \nu X$

$$R_M = \frac{1}{2}(x^2 + y^2) \qquad A_{sl} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4}$$

$D^0 \to CP$

$$2y_{CP} = \big(|q/p| + |p/q|\big) y\cos\phi - \big(|q/p| - |p/q|\big) x\sin\phi$$
$$2A_\Gamma = \big(|q/p| - |p/q|\big) y\cos\phi - \big(|q/p| + |p/q|\big) x\sin\phi$$

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

$$x_{K^0\pi\pi} = x$$
$$y_{K^0\pi\pi} = y$$

$$|q/p|_{K^0\pi\pi} = |q/p|$$
$$\mathrm{Arg}\,(q/p)_{K^0\pi\pi} = \phi$$

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

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x'\cos\phi \pm y'\sin\phi) \qquad A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$
$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y'\cos\phi \mp x'\sin\phi) \qquad \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\frac{1}{2}\left[R(D^0 \to K^+\pi^-) + \overline{R}(\overline{D}^0 \to K^-\pi^+)\right] = R_D$$

$$\frac{R(D^0 \to K^+\pi^-) - \overline{R}(\overline{D}^0 \to K^-\pi^+)}{R(D^0 \to K^+\pi^-) + \overline{R}(\overline{D}^0 \to K^-\pi^+)} = A_D$$

Sensitivity projections for mixing

✓ Realistic estimates using BaBar's results with 482 fb^{-1} of data at $\Upsilon(4S)$ and projecting to 75 ab^{-1}.

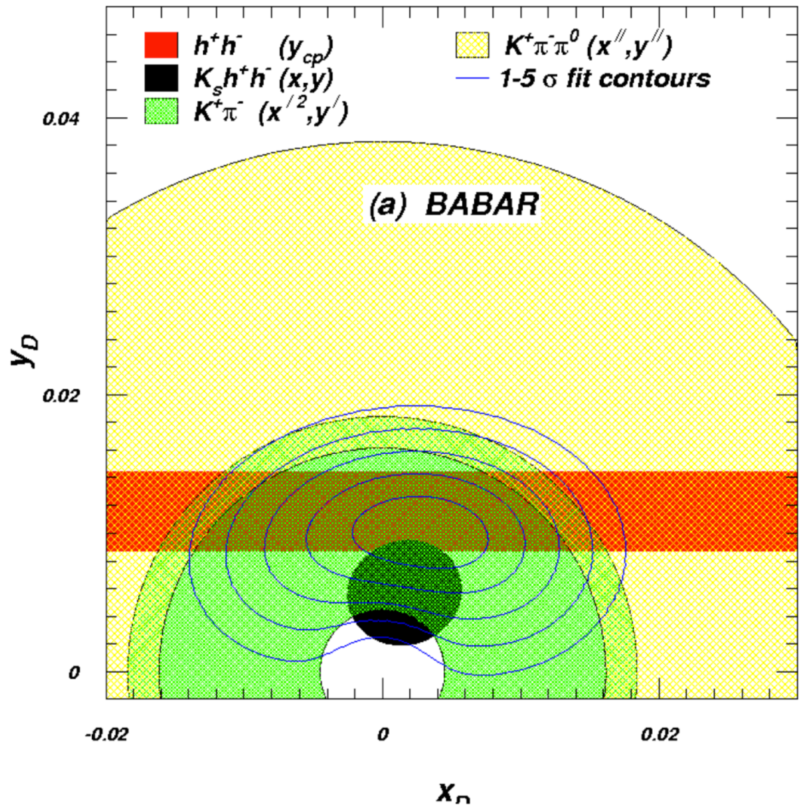
✓ Statistical error scales as $\sqrt{\text{integrated luminosity}}$.

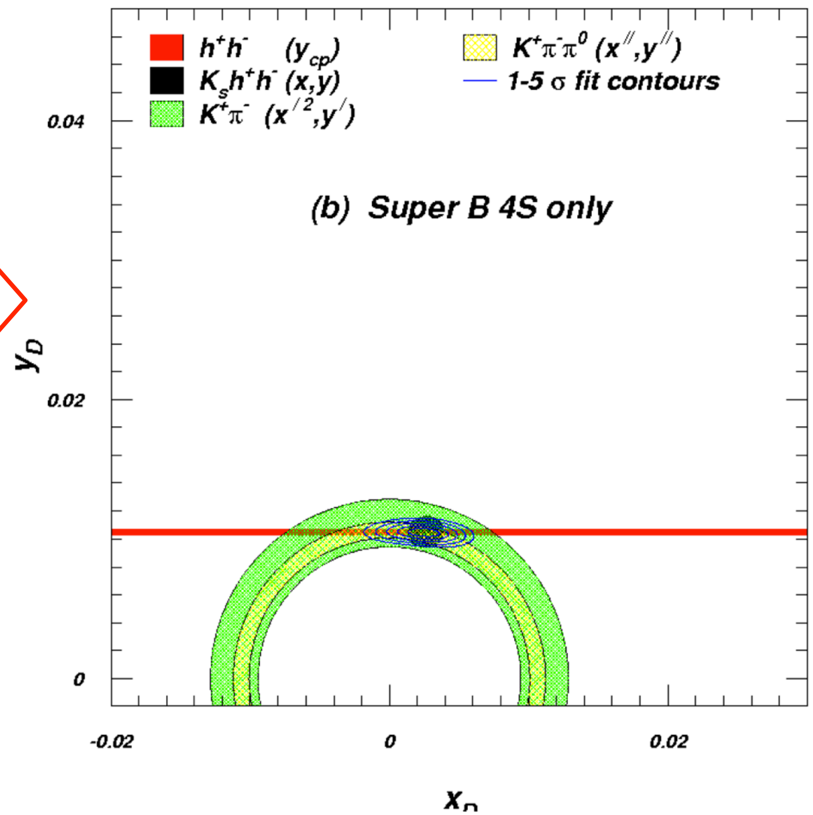
✓ Same for systematic errors:

- mostly determined directly from data and control samples.
- Except for:

$D^0 \to K_S\pi^+\pi^-$ analysis has "irreducible" uncertainty in x_D and in y_D of order 1×10^{-3} due to uncertainty in Dalitz model.

Sensitivity projections with 75 ab^{-1} at $\Upsilon(4S)$





Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(a)	$3.01^{+3.12}_{-3.39}$	$10.10^{+1.69}_{-1.72}$	$41.3^{+22.0}_{-24.0}$	43.8 ± 26.4
Stat.	(2.76)	(1.36)	(18.8)	(22.4)

Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(b)	$xxx^{+0.72}_{-0.75}$	$xxx \pm 0.19$	$xxx^{+3.7}_{-3.4}$	$xxx^{+4.6}_{-4.5}$
Stat.	(0.18)	(0.11)	(1.3)	(2.9)

Uncertainties shrink:

$x_D \rightarrow x_D/4$; $y_D \rightarrow y_D/10$

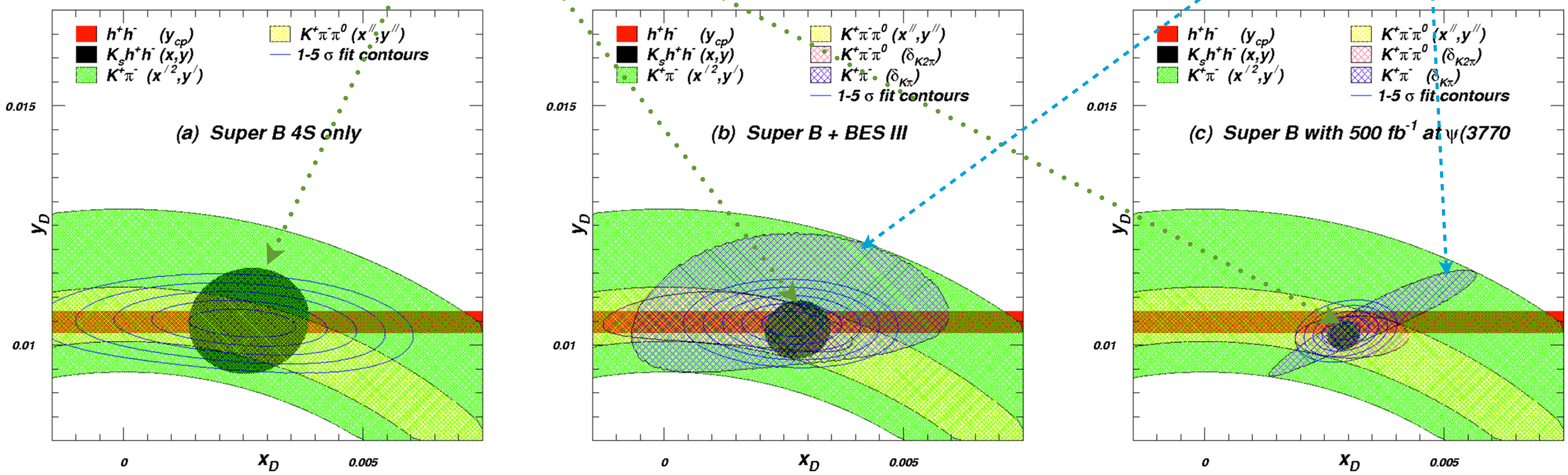
Precision in x_D is limited by Dalitz plot model.

Using $D\bar{D}$ threshold data

- ✓ Data taken at $D\bar{D}$ threshold provide measurements of strong phases $\delta_{K\pi}$ and $\delta_{K\pi\pi0}$.
- ✓ Also provide measurement of δ as a function of Dalitz plot position:
  - this can be used to significantly reduce the Dalitz model uncertainties for the three-body decay modes $Ksh^{+}h^{-}$.
- ✓ As a basis for projection, we take results from CLEO-c:
  - N. Lowrey et al, PRD80, 031105 (2009), 0903.4853
- ✓ We assume that new data from threshold will reduce the uncertainties in model uncertainty:
  - BES III – ~factor 3 improvement in model uncertainty
  - Super B 500 fb^{-1} $D\bar{D}$ threshold run – ~factor 10 improvement.

Two improvements in mixing precision come from threshold data:

- Dalitz plot model uncertainty shrinks
- Information on overall strong phase is added



Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(b)	$xxx^{+0.72}_{-0.75}$	$xxx \pm 0.19$	$xxx^{+3.7}_{-3.4}$	$xxx^{+4.6}_{-4.5}$
Stat.	(0.18)	(0.11)	(1.3)	(2.9)

Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(c)	$xxx \pm 0.42$	$xxx \pm 0.17$	$xxx \pm 2.2$	$xxx^{+3.3}_{-3.4}$
Stat.	(0.18)	(0.11)	(1.3)	(2.7)

Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(d)	$xxx \pm 0.20$	$xxx \pm 0.12$	$xxx \pm 1.0$	$xxx \pm 1.1$
Stat.	(0.17)	(0.10)	(0.9)	(1.1)

Uncertainty in x_D improves more than that of y_D

Comparison with LHCb 10 fb^{-1} approx. 5 years running

Decay Mode	*BABAR*	Super*B* *	LHCB**
$\boldsymbol{K^+K^-}$ **($\boldsymbol{D^*}$-tag):**			
N (Events)	88×10^3	13.7×10^6	8×10^6
Δy_{CP} (stat)	$\pm 3.9 \times 10^{-3}$	0.28×10^{-3}	0.5×10^{-3}
$\boldsymbol{K^+K^-}$ **(no tag):**			
N (Events)	330×10^3	51.4×10^6	–
Δy_{CP} (stat)	$\pm 2.3 \times 10^{-3}$	0.19×10^{-3}	–
$\boldsymbol{K^+\pi^-}$ **(WS):**			
N (Events)	5.1×10^3	0.79×10^6	0.23×10^6
$\Delta y'$ (stat)	$\pm 4.4 \times 10^{-3}$	0.31×10^{-3}	0.87×10^{-3}
$\Delta x'^2$ (stat)	$\pm 3.0 \times 10^{-4}$	0.21×10^{-4}	0.64×10^{-4}

No LHCb projections available for golden modes $D^0 \to K_S h^+ h^-$

* SuperB with 75 ab^{-1} data at $\Upsilon(4S)$

** P. M. Spradlin (2007), 0711.1661. See also CERN-lhcb-2007-049.

Sensitivity projections for CP violation from mixing measurements

CPV Reach in Mixing (Strategy I)

- Search for asymmetries for x_D^+, y_D^+ values x_D^-, y_D^- obtained from separate samples of D^0 or $\overline{D}^0$, respectively.
- To a good approximation:
- $$a_z = (z^+ - z^-) / (z^+ + z^-) = |q|^2 - |p|^2$$
- where z can be x_D, y_D, y_{CP}, y', x'' or y''
- Not all modes allow measurement of x_D, y_D so
  - asymmetries a_Z can be compared for a variety of channels.
  - Differences would indicate *CPV* was in decay rather than in mixing.
- Systematic uncertainties in z^+, z^- are likely to be cancelled in these asymmetries, so statistical uncertainties will dominate.

CPV Reach in Mixing (Strategy II)

- Golden channels provide a direct way to obtain values for $|q/p|$ and $\mathrm{Arg}\{q/p\}$.
- We project to 75 ab^{-1} at $\Upsilon(4S)$ the statistical and systematic uncertainties found by Belle in their Time Dependent Dalitz Plot (TDDP) analysis of the $K_s h^+ h^-$ mode.
- Uncertainties from the Dalitz plot model will be important, and the CPV reach will be much improved with data from threshold.

CPV Reach in Mixing (Strategy III)

- Wrong Sign (WS) lepton asymmetry measures CPV in mixing:

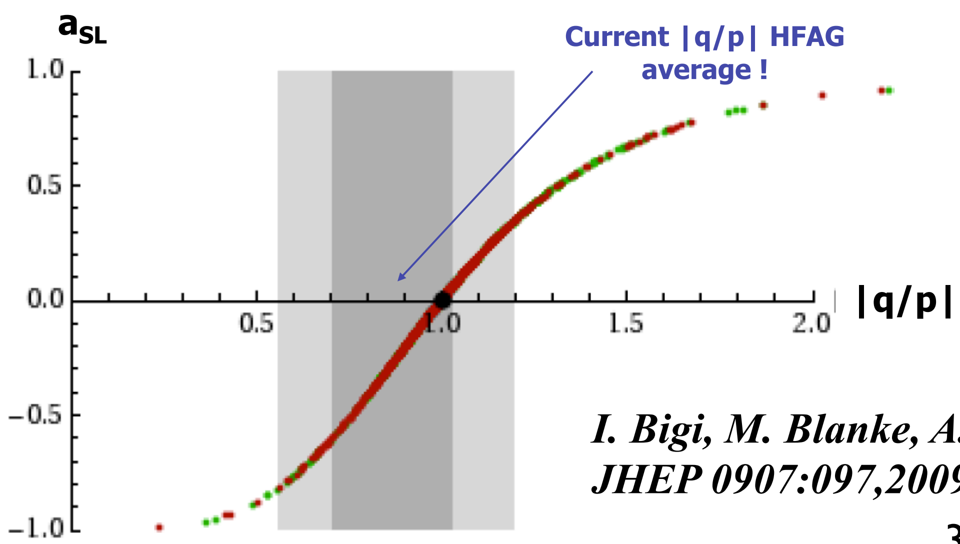
$$a_{SL} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4}$$

$$\left[\begin{array}{lll} D^0 & = & \text{"}-\text{"},\ \bar{D}^0 = \text{"}+\text{"},\ \ell^{\pm} = \text{"}\pm\text{"} \\ N^{++} & = & \bar{D}^0 \to \ell^+ \nu K^-,\ N^{--} = D^0 \to \ell^- \bar{\nu} K^+ \end{array}\right]$$

WS semi-leptonic decays $D^0 \to X^+ \ell^- \bar{\nu}_\ell$ *only from* mixing $(D^0 \to \overline{D}^0)$ followed by decay

$rate \sim (x^2 + y^2)/4 \sim 5{\times}10^{-5}$ *very rare, only upper limit at present*

a_{SL} in Little Higgs Model with T-parity



✓Asymmetry can be large:

$$-0.8 \lesssim a_{\rm SL}(D^0) \lesssim +0.3$$

in 2σ range of |q/p| experimental values

✓Clear signal of New Physics

I. Bigi, M. Blanke, A. Buras, S. Recksiegel
JHEP 0907:097,2009.

Summary of CPV Sensitivity from mixing

Strategy	Decay	$\sigma(\lvert q_D/p_D\rvert)\times 10^2$	$\sigma(\phi_M)^\circ$
HFAG (direct *CPV* allowed):			
Global χ^2 fit	<All modes>	± 18	± 9
Asymmetries a_z:			
x_D	<All modes>	± 1.8	–
y_D	<All modes>	± 1.1	–
y_{CP}	K^+K^-	± 3.8	–
y'	$K^+\pi^-$	± 4.9	–
x'^2	$K^+\pi^-$	± 4.9	–
x''	$K^+\pi^-\pi^0$	± 5.4	–
y''	$K^+\pi^-\pi^0$	± 5.0	–
TDDP (*CPV* allowed):			
Model-dependent	$K^0_S h^+h^-$	± 8.4	± 3.3
BES III DP model	$K^0_S h^+h^-$	± 3.7	± 1.9
Super*B* DP model	$K^0_S h^+h^-$	± 2.7	± 1.4
SL Asymmetries a_{SL}:			
75 ab^{-1} at $\Upsilon(4S)$	$X\ell\nu_\ell$	± 10	
500 fb^{-1} at $\psi(3770)$	$K\pi$	± 10	
500 fb^{-1} at $\psi(3770)$	$X\ell\nu_\ell$	TBD	

Sensitivity projections for CP violation in time-integrated measurements

Search for CPV in $D^0 \to K^+K^-(\pi^0), \pi^+\pi^-(\pi^0)$

SCS = Single Cabibbo Suppressed

- CP violation in these modes is predicted to be $\mathcal{O}(10^{-5} - 10^{-4})$ in SM. *Evidence of CP violation with present experimental sensitivity would be sign of New Physics*.

F. Buccella et al., Phys. Rev. **D51**, 3478 (1995)
S. Bianco et al., Riv. Nuovo Cim. 26N7, 1(2003)
Y. Grossman et al., Phys. Rev. **D75**, 036008 (2007)

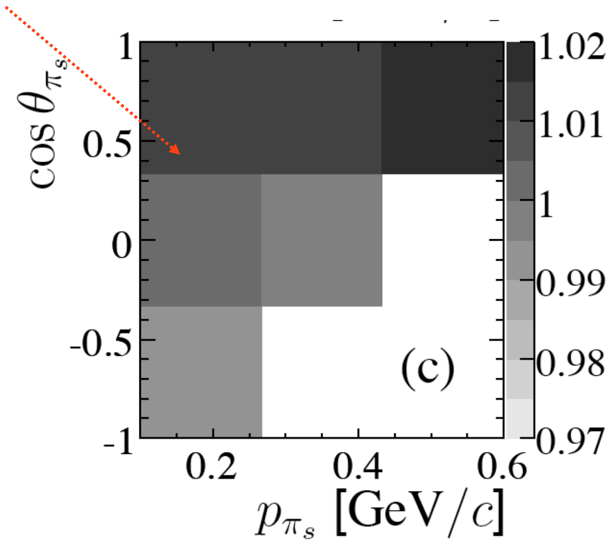
- Time-integrated CP asymmetry get contributions from the 3 different CP violation sources: decay, mixing, interference between mixing and decay.

$$a^f_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \overline{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \overline{f})} \qquad f = K^+K^-(\pi^0), \pi^+\pi^-(\pi^0)$$

- Experimental difficulties:
  - precise determination of detector D^0 tagging asymmetry (accurate estimate of π^+ reconstruction efficiency in $D^{*+} \to D^0\pi^+$ decays)
  - forward-backward (FB) asymmetry in $e^+e^- \to c\bar{c}$ production, asymmetric detector acceptance

Experimental procedure

- Determine relative $D^0/\bar{D}^0$ -soft pion- tagging efficiency using $D^0 \to K^-\pi^+$ tagged + untagged data



Define yield asymmetry vs $\cos\theta^*$:

$$a^{\pm}(\cos\theta^*) = \frac{n_{D^0}(\pm|\cos\theta^*|) - n_{\bar{D}^0}(\pm|\cos\theta^*|)}{n_{D^0}(\pm|\cos\theta^*|) + n_{\bar{D}^0}(\pm|\cos\theta^*|)}$$

$$a_{CP} \simeq \frac{a^+(\cos\theta^*) + a^-(\cos\theta^*)}{2}$$

$$a_{FB} \simeq \frac{a^+(\cos\theta^*) - a^-(\cos\theta^*)}{2}$$

- Correct for FB production asymmetry:
  - choose symmetric region in the center of mass frame $|\cos\theta^*| < 0.8\ (0.9)$
  - A_{FB} originated in $C\bar{C}$ production: Z^0/γ mediated diagrams interference, high order QED diagrams interference. Effects are anti-symmetric in $\cos\theta^*$

Estimates from BaBar analysis to 75 ab^{-1}: $\sigma(A_{CP}) \sim 3\times10^{-4}$

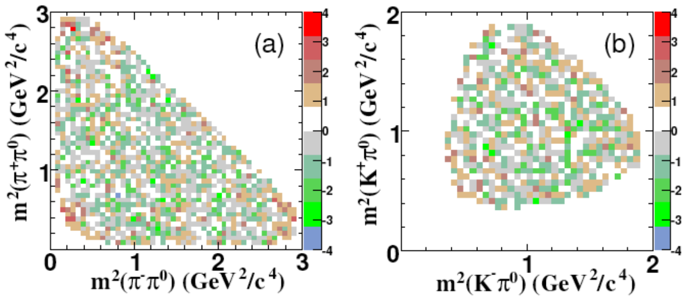
Search for CPV in 3-body $D^0 \rightarrow K^+K^-\pi^0, \pi^+\pi^-\pi^0$ decays

CP asymmetry evaluated with 4 different methods. 3 methods are model independent (MI):

- Difference between D^0 and $\overline{D}^0$ Dalitz plot in 2 dimensions (MI)
- Difference in the angular moments of D^0 and $\overline{D}^0$ (MI)
- Difference in Dalitz plot fit results for amplitude-phases for D^0 and $\overline{D}^0$
- Difference in phase space integrated asymmetry (MI)

Last method is insensitive to Dalitz plot shapes, so complements the other methods.

$\pi^+\pi^-\pi^0$ $\quad\quad$ $K^+K^-\pi^0$



$$\Delta = (n_{\overline{D}^0} - R \cdot n_{D^0}) \,/\, \sqrt{\sigma^2_{n_{\overline{D}^0}} + R^2 \cdot \sigma^2_{n_{D^0}}}$$

Normalized residuals. R efficiency corrected ratio of D^0 wrt $\overline{D}^0$ events

Estimates from BaBar analysis to 75 ab^{-1}: sensitivity to CPV at 10^{-3} level

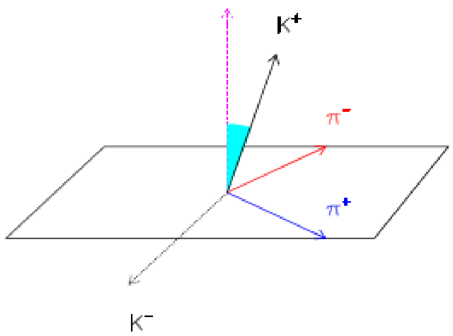
Search for T-odd correlations.

☐ Consider the Cabibbo Suppressed D^0 decay: *I. Bigi, arXiv:hep-ph/0107102.*

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

☐ T-odd correlations can be formed using the momenta of the particles:

$$C_T = p_{K^+} \cdot (p_{\pi^+} \times p_{\pi^-})$$



☐ Under time reversal T, we have $C_T \to -C_T$.

☐ $C_T \neq 0$ does not necessarily established T violation.

☐ Consider also:

$$\overline{D^0} \to K^+ K^- \pi^+ \pi^-$$

where we can compute:

$$\overline{C_T} = p_{K^-} \cdot (p_{\pi^-} \times p_{\pi^+})$$

☐ Finding:

$$C_T \neq -\overline{C_T}$$

establishes CP violation.

- Focus – obtained $A_T = 1.0 \pm 5.7$ (stat) $\pm$ 3.7 (syst) %
- BaBar – obtained $A_T = 1.0 \pm 6.7$ %

SuperB – projected A_T = x.x $\pm$ 0.05 (stat) $\pm$ 0.2 (syst) %

(with conservative assumption on PID systematic error)

Rare Decays

$$D^0 \rightarrow \mu^+\mu^-,\ D^0 \rightarrow \gamma\gamma$$

Interest in $D^0 \rightarrow \mu^+\mu^-$

- *The SM estimates a lower limit* BF > 4 x 10^{-13}
- *Estimates would be improved by measurement of* $D^0 \rightarrow \gamma\gamma$
  - *Only estimate so far - BF[*$D^0 \rightarrow \gamma\gamma$*] < 1.5 x* 10^{-5}

Belle 660 fb^{-1} arXiv:1003.2345v2 $\mathcal{B}\left(D^0 \rightarrow \mu^+\mu^-\right) < 1.4 \times 10^{-7}$

- *Ikaros Bigi: "*10^{-8} *would be an interesting goal"*

Collaboration	90% C.L.	Sample
BESIII	1.7×10^{-6}	per fb^{-1}
LHCb	5×10^{-8}	$2fb^{-1}$
SuperB	$\leq 1 \times 10^{-8}$	$500fb^{-1}$(@threshold)
SuperB	1×10^{-8}	$75ab^{-1}(@\Upsilon(4S))$

- *At D threshold, the* $\mu^+\mu^-$ *(or* $\gamma\gamma$*) are "back-to-back" in transverse momentum and should present an excellent signal-to-noise ratio: kinematics useful to reject bkg from* $D^0 \rightarrow \pi^+\pi^-$ *with pion decaying in flight.*

Interest in $D^0 \to \gamma\gamma$

- In SM dominated by Long-Distance (LD) forces:

$$\mathrm{BR}(D^0 \to \gamma\gamma)_{\mathrm{SM}} \simeq \mathrm{BR}(D^0 \to \gamma\gamma)_{\mathrm{LD}} \sim (1 \pm 0.5) \cdot 10^{-8}$$

provides useful information for a proper interpretation of rare D^0 decays

$$\begin{aligned} \mathrm{BR}(D^0 \to \mu^+\mu^-)_{\mathrm{SM}} &\simeq \mathrm{BR}(D^0 \to \mu^+\mu^-)_{\mathrm{LD}} \\ &\simeq 3 \cdot 10^{-5} \times \mathrm{BR}(D^0 \to \gamma\gamma)_{\mathrm{SM}} \end{aligned}$$

- BaBar should publish a limit close to 2.5×10^{-6} in the near future using 481 fb^{-1}.

Extrapolation at SuperB is 10^{-7}, both at $\Upsilon(4S)$ and at $D\bar{D}$ threshold.

Conclusions

Charm physics provides a unique opportunity to search for New Physics at SuperB:

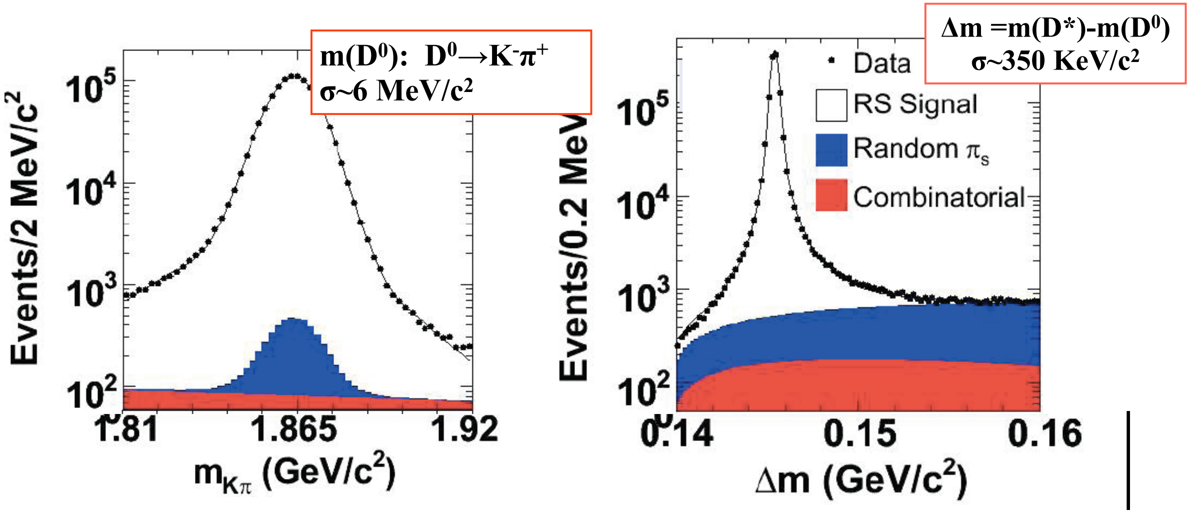
- Recent measurement of sizable charm mixing has started the renaissance of charm physics.
- Together with 500 fb^{-1} from $\psi(3770)$ run, 75 ab^{-1} at $\Upsilon(4S)$ will result in measurements of x_D and y_D with precision $\sim 10^{-4}$.
- This will provide a sensitivity to CPV in mixing $\sigma(|q/p|)$ of order a few %.
- TDDP analysis of golden channels can measure q/p with precision 3-4%.
- Time-integrated measurements of CPV asymmetries at the level of 0.03% and testing of SM limits will be possible.
- Search for $D^0 \rightarrow \mu^+\mu^-$ decays will reach a limit near or below 10^{-8}.

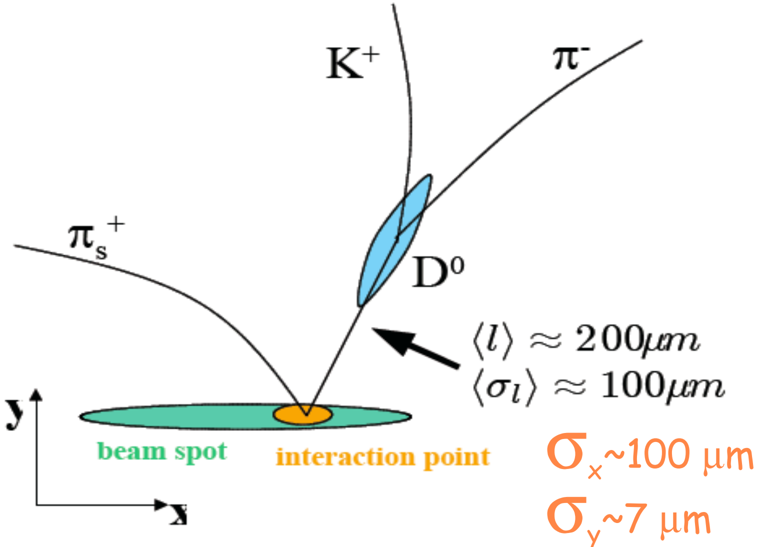
More information on SuperB project

- CDR (2007) arXiv:0709.0451v2
- SuperB Progress Reports
  - Detector (July 2010) arXiv:1007.4241v1
  - Physics (August 2010) arXiv:1008.1541v1
  - Accelerator (Sept 2010) arXiv:1009.6178v1

Backup slides

Selection of D^0 mesons





Select D^0 mesons via $D^{*+} \rightarrow D^0\pi^+$ decay:

- charge of slow pion identifies the flavor of D^0 at production;

- exploit $m(D^0)$, D^0 reco invariant mass and $\Delta m = m(D^*) - m(D)$, D^{*+}-D^0 mass difference for bkg rejection;

Cut on D^0 momentum in center of mass frame, $p^* > 2.5\text{-}3.0$ GeV/c rejects D^0 from B decays and combinatorial bkg.

3D flight path reconstruction

proper time $$t = \frac{\vec{L} \cdot \vec{p}}{p} \frac{m_{D^0}}{p}$$

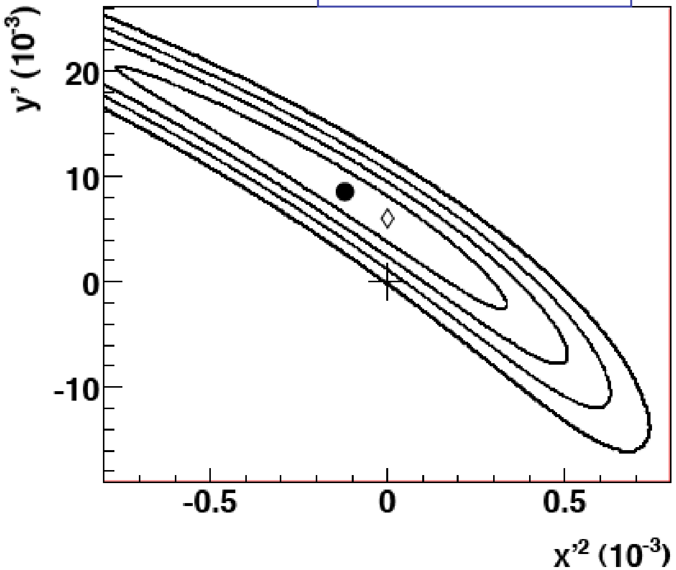
- D^0 vertex with beam spot (interaction region size) constraint applied. Determining decay time, t, and decay time error, σ_t , for each each event.

Typical resolution on proper-time: $\langle \sigma_t \rangle \simeq 0.5\tau_D = 0.2$ ps
thanks to the excellent performance of the Silicon Vertex Tracker.

Belle & CDF measurements

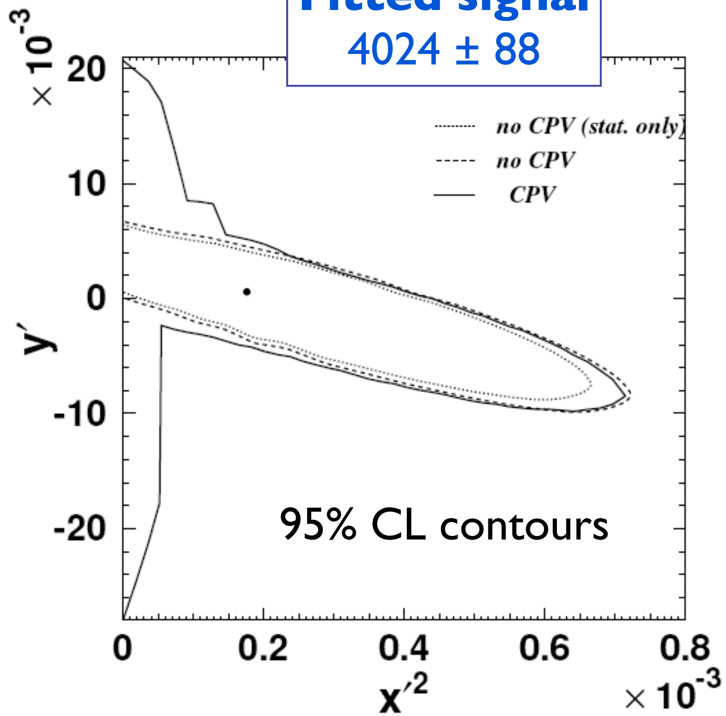
CDF: PRL 100:121802,2008 (1.5 fb^{-1})

Fitted signal
(12.7 ± 0.3)K



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

Fitted signal
4024 ± 88



Experiment	$R_D (10^{-3})$	$y' (10^{-3})$	$x'^2 (10^{-3})$	Mixing Signif.
CDF	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	3.8
BABAR [8]	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9
Belle [9]	3.64 ± 0.17	$0.6\ ^{+4.0}_{-3.9}$	$0.18\ ^{+0.21}_{-0.23}$	2.0

$$x'^2 = (0.18^{+0.21}_{-0.23}) \times 10^{-3}$$

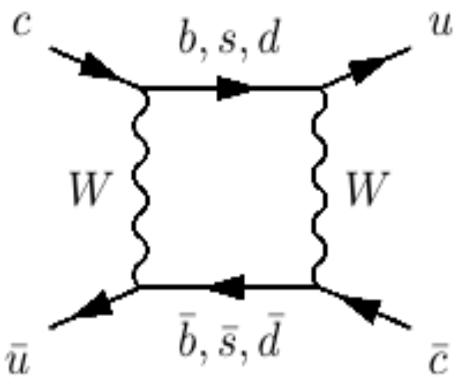
$$y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$$

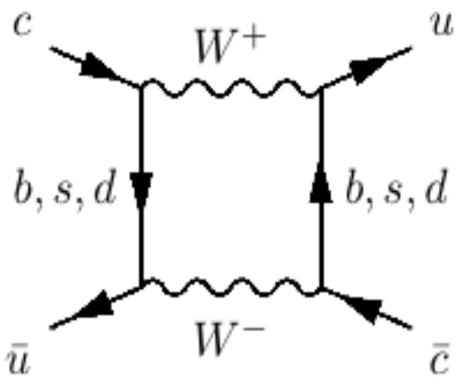
Evidence of mixing at 3.8σ

No mixing point at 2σ

Standard Model predictions

SM mixing loops has down type quarks in the loops:





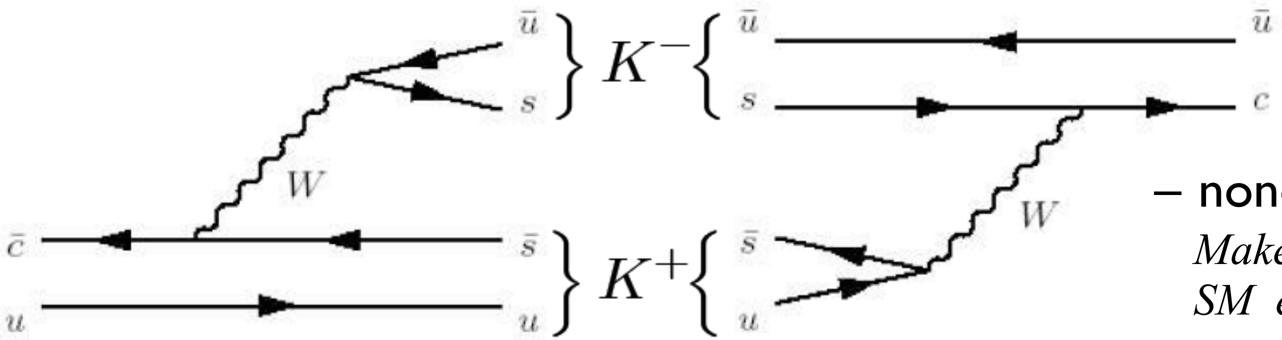
– *b* quark is CKM-suppressed

– *s, d* quark GIM suppressed

$$\Delta m \propto G_F^2 \frac{(m_s^2 - m_d^2)^2}{m_c^2}$$

→ $\Delta m_{\rm box} \sim 10^{-5} {\rm ps}^{-1}$ Tiny!

Expect hadronic intermediate states to dominate:



– non-perturbative contributions

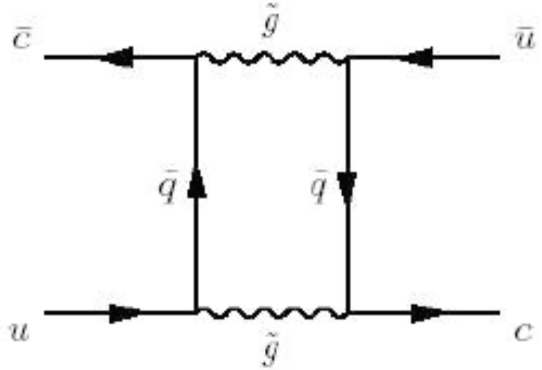
Makes it difficult to precisely predict SM expectations

In SM expected |x|<10^{-2}, |y|<10^{-2} and CP violation below the per mil level. New Physics contributions could enhance mixing rate and/or generate CP violation up to percent level.

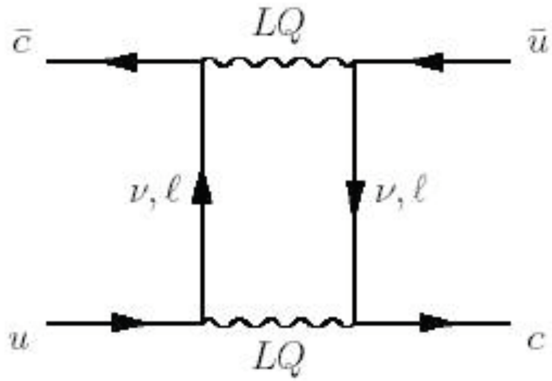
Possible New Physics in Charm Mixing

Charm mixing can be affected by possible new physics

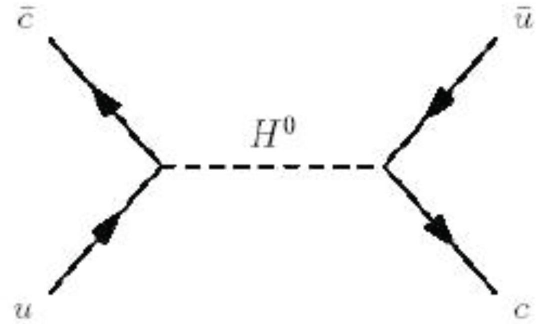
SUSY:



Leptoquarks:



Extended Higgs:



- new physics can increase *x* value, while *y* mostly unaffected: e.g. |x| >> |y| could be hint of New Physics;
- new physics contributions can generate CP violation up to few % level, more then one order of magnitude with respect to Standard Model expectations.

Why should we still study Charm Physics at SuperB?

- *"The prospects for finding New Physics in charm transitions have received a major boost through the strong evidence of* $D^0 - \overline{D}^0$ *oscillations by BaBar and Belle in spring 2007."*
- *"Charm is the only up-type quark allowing the full range of probes for flavour-changing neutral currents and New Physics in general."*
- *"Charm dynamics offer unique phenomenological possibilities for manifestations of New Physics, ... only very recently have experiments reached a range of sensitivity, when one can realistically expect the sought-after effects to show up."*

From "CP violation", Cambridge University Press, second edition -
I. I. Bigi and A. I. Sanda

Three types of CP violation:

1.in the decay (direct):

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

$$\langle f|H|D^0\rangle = A_f \qquad \langle f|H|\overline{D}^0\rangle = \overline{A}_f$$

$$a_{CP}^{f} \neq 0 \Longrightarrow \left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1 \Longrightarrow \text{CPV}$$

2.in mixing (indirect):

$$r_m = \left|\frac{q}{p}\right| \neq 1 \Longrightarrow \text{CPV}$$

3.in the interference between mixing and decay:

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = r_m \left|\frac{\overline{A}_f}{A_f}\right| e^{i(\delta_f + \varphi_f)} \qquad \varphi_f \neq 0 \Longrightarrow \text{CPV}$$

strong phase (δ_f) weak phase (φ_f)

Mixing analyses: time dependent

- $D^0 \to K^+\pi^-$
- $D^0 \to K^+K^-, \pi^+\pi^-$
- $D^0 \to \phi K^0_S$
- $D^0 \to K^+\pi^-\pi^0$
- $D^0 \to K^0_S\pi^+\pi^-$
- $D^0 \to K^0_S K^+K^-$
- $D^0 \to K^{(*)}l\nu$ (time integrated)

Search for CP violation: time integrated

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

BaBar and Belle select events from

$e^+e^- \to c\bar{c}$ process

$$\sigma\left(e^+e^- \to c\bar{c}\right) \simeq 1.3 \text{ nb}$$

Legend: ★ = mixing evidence $> 3\sigma$