CHARM2012 - 5th International Workshop on Charm Physics - 14-17 May 2012, Honolulu, Hawai'i

Rare Decays, Mixing and *CP* violation Potential at Super*B*

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Rare Decays, Mixing and CP Violation: Outline

Rare Decays

Mixing

CP Violation

Rare Decays, Mixing and CP Violation

$\rightarrow$Rare Decays

$D^0 \rightarrow \gamma\gamma$, $D^0 \rightarrow \mu\mu$, $D^0 \rightarrow ull$

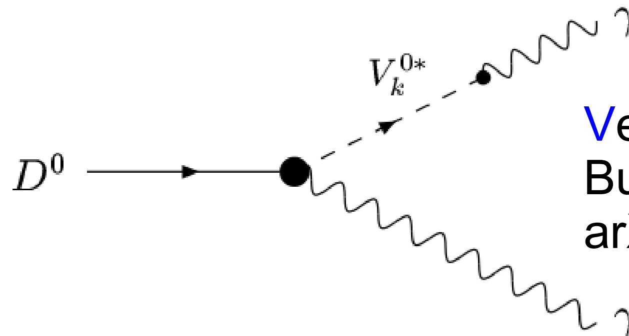
Mixing

CP Violation

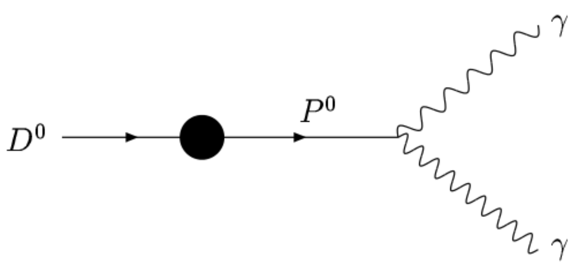
$D^0 \to \gamma\gamma$

Why? FCNC forbidden in the SM at tree level

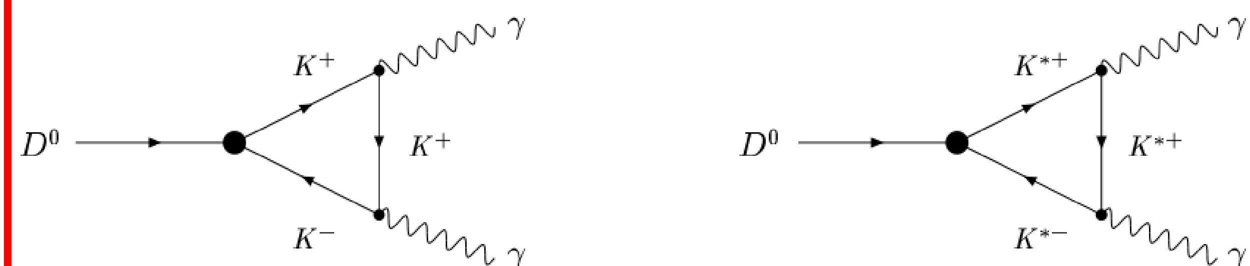
$$B(D^0 \to \gamma\gamma)_{SD} = 3\times10^{-11}$$
$$B(D^0 \to \gamma\gamma)_{LD} = 1\pm0.5\times10^{-8}$$



Vector Meson Dominance
Burdman et al.
arXiv:hep-ph/0112235v2



Weak Mixing Contribution



Unitarity Contributions

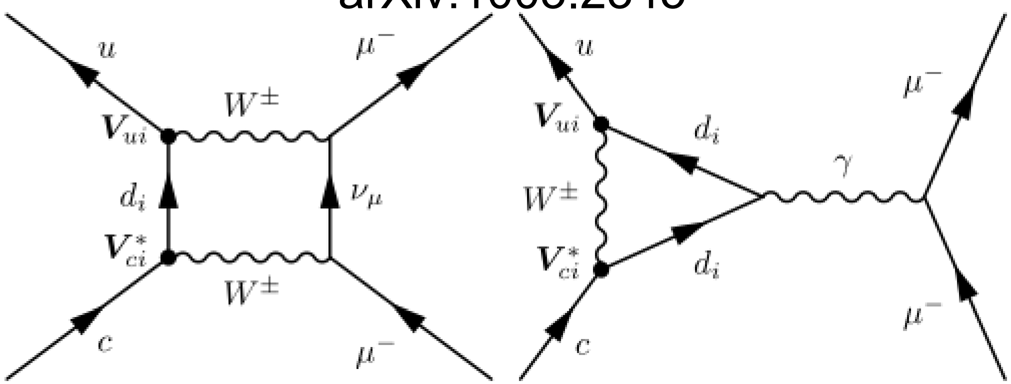
$B(D^0 \to \gamma\gamma) < 2.7\times10^{-5}$	CLEO Collaboration:	PRL **90** 101801 (2003)
$B(D^0 \to \gamma\gamma) < 2.2\times10^{-6}$ $90\%\,CL$	*Ba*B*ar* Collaboration:	arXiv:1110.6480v1 (appr. by PRD)
$B(D^0 \to \gamma\gamma): 0.5\times10^{-7}$ $(20\ fb^{-1})$	BESIII Collaboration:	arXiv:0809.1869v1
$B(D^0 \to \gamma\gamma): 500\ fb^{-1}\ at\ \ \Psi(3770)$	Super*B* Collaboration	under evaluation

$D^0 \to \mu^+ \mu^-$

Why? Test for ΔC=1 weak neutral current

$$B(D^0 \to \mu^+ \mu^-) \simeq B(D^0 \to \mu^+ \mu^-)_{LD} = 3 \times 10^{-5} B(D^0 \to \gamma\gamma)$$

arXiv:1003.2345



BURDMAN & SHIPSEY
ArXiv:hep-ph/0310076

- SD contribution (~10^{-18}) allows for NP enhancements, but LD need to be "under control"
- LD contribution related to the 2-photon channel need to be understood to interpret any signal found

$Precision(D^0 \to \mu\mu): 0.5 \times 10^{-7}$ 20 fb^{-1} (full program)	BESIII Collaboration arXiv:0809.1869v1
$Precision(D^0 \to \mu\mu): 1.0 \times 10^{-8}$ 1 month running at charm threshold	Super*B* Collaboration arXiv:1008.1541v1
$B(D^0 \to \mu\mu): < 1.3 \times 10^{-8}$ 0.9 fb^{-1} (2011 run)	LHCb Collaboration LHCb-CONF-2012-005

Expected sensitivities

$D^0 \to ue^+e^-$

Why? Test for ΔC=1 weak neutral current

arXiv:1008.1541v1

Channel	Sensitivity	BR (th.)	UL (expt.)
$D^0 \to \pi^0 \ell^+ \ell^-$	2×10^{-8}	0.8×10^{-6}	4.5×10^{-5} (CLEO)
$D^+ \to \pi^+ \ell^+ \ell^-$	1×10^{-8}	2×10^{-6}	$< 3.9 \times 10^{-6}$ (D0)
$D^0 \to \pi^0 e^\pm \mu^\mp$	2×10^{-8}	–	
$D^+ \to h^- \ell^+ \ell^+$ $(h = \pi, K)$	1×10^{-8}	–	$< 3.6 \times 10^{-6}$ (CLEO)
$D^+ \to h^- e^\pm \mu^\mp$ $(h = \pi, K)$	1×10^{-8}	–	$< 3.4 \times 10^{-6}$ (CLEO)

BURDMAN & SHIPSEY
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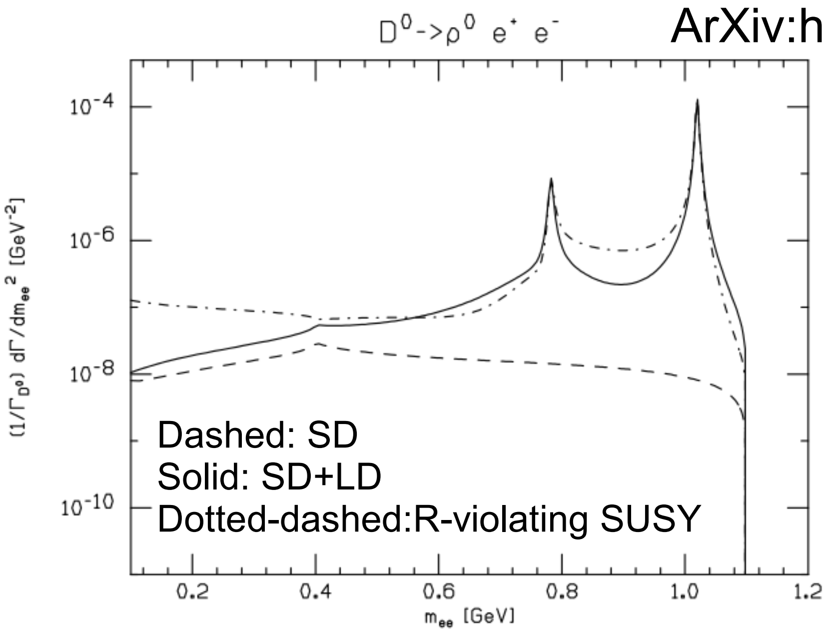

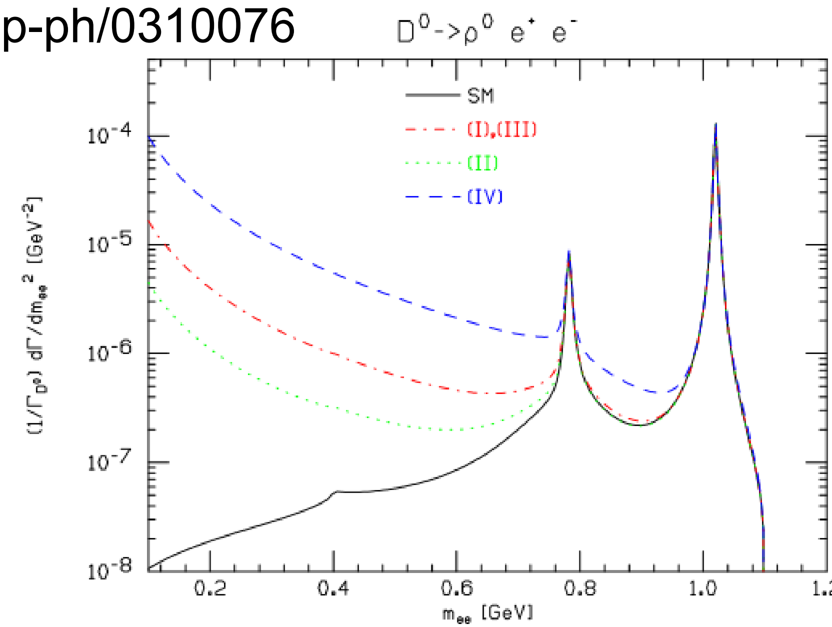

$M_{\tilde{g}} = M_{\tilde{q}} = 250\,GeV$

$M_{\tilde{g}} = 2M_{\tilde{q}} = 500\,GeV$

$M_{\tilde{g}} = M_{\tilde{q}} = 1000\,\text{GeV}$

$M_{\tilde{g}} = \frac{1}{2} M_{\tilde{q}} = 250\,\text{GeV}$

$D^+ \to u e^+ e^-$

Why? Test for ΔC=1 weak neutral current

arXiv:1008.1541v1

Channel	Sensitivity	BR (th.)	UL (expt.)
$D^0 \to \pi^0 \ell^+ \ell^-$	2×10^{-8}	0.8×10^{-6}	4.5×10^{-5} (CLEO)
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BURDMAN & SHIPSEY
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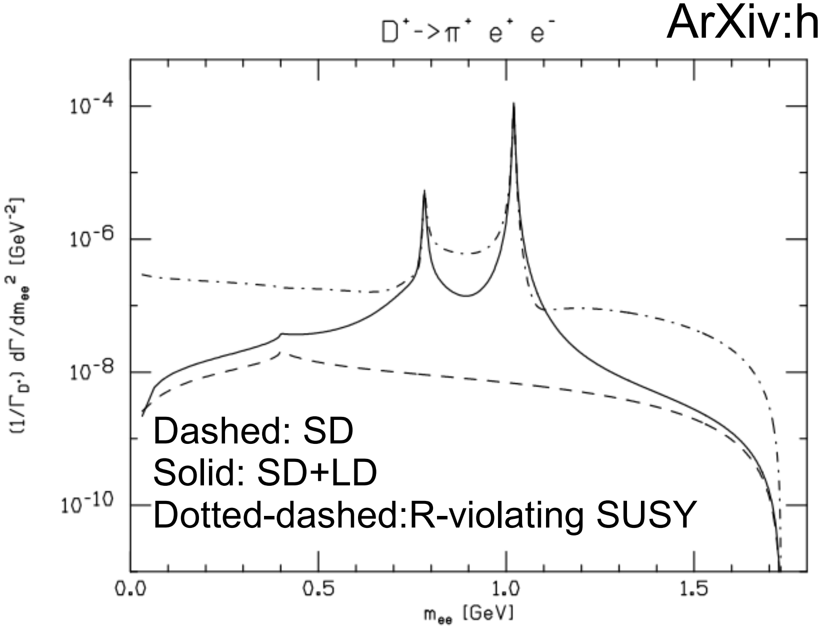

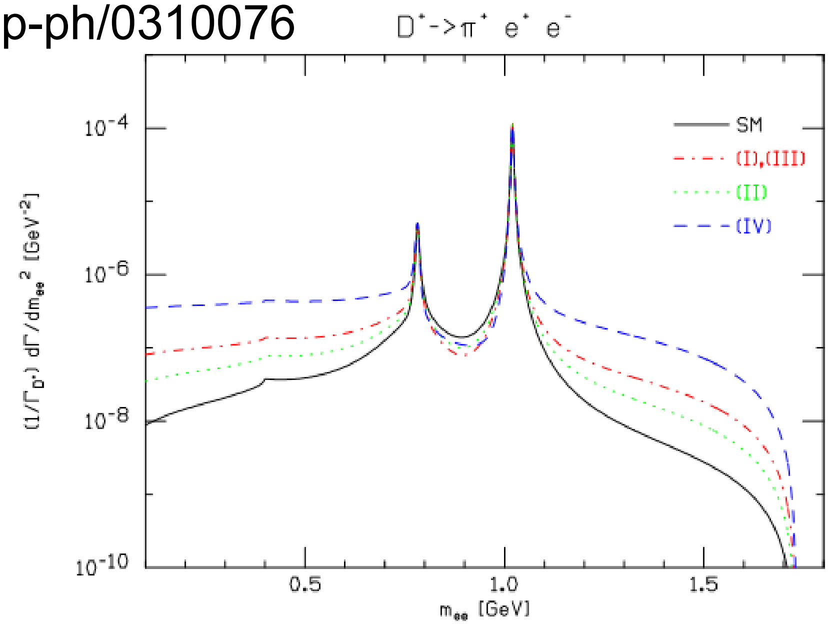

$M_{\tilde{g}} = M_{\tilde{q}} = 250\,GeV$

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$M_{\tilde{g}} = M_{\tilde{q}} = 1000\text{GeV}$

$M_{\tilde{g}} = \frac{1}{2} M_{\tilde{q}} = 250\text{GeV}$

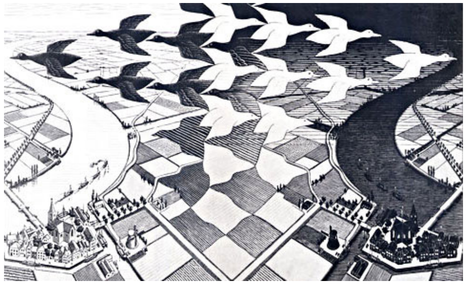
Rare Decays, Mixing and CP Violation

Rare Decays

→Mixing

x_D, y_D: *BaBar, SuperB at* $\Upsilon(4S)$,

SuperB+BESIII, SuperB at $\Psi(3770)$



CP Violation

Charm Mixing: an introduction

Neutral meson systems exhibit *mixing* of mass eigenstates $|P_{1,2}>$ where:

$$i\frac{d}{dt}\begin{pmatrix}|P_1>\\|P_2>\end{pmatrix}=\begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12}\\ M_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*} & M_{22}^{*}-\frac{i}{2}\Gamma_{22}^{*}\end{pmatrix}\begin{pmatrix}|P^0>\\|\overline{P^0}>\end{pmatrix}=H_{eff}\begin{pmatrix}|P^0>\\|\overline{P^0}>\end{pmatrix}$$

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

$$q^2+p^2=1 \quad \textit{normalize the wavefunction}$$

$$\frac{q}{p}=\sqrt{\frac{M_{12}^{*}-i\Gamma_{12}^{*}/2}{M_{12}-i\Gamma_{12}/2}}$$

$$H_{eff}=M-\frac{i}{2}\Gamma$$

$$M_{11}=M_{22},\Gamma_{11}=\Gamma_{22} \quad \leftarrow \quad \textit{CPT INVARIANCE}$$

$$M_{11}=M_{22},\Gamma_{11}=\Gamma_{22},\Im[\frac{\Gamma_{12}}{M_{12}}]=0 \quad \leftarrow \quad \textit{CP INVARIANCE}$$

$$\Im[\frac{\Gamma_{12}}{M_{12}}]=0 \quad \leftarrow \quad \textit{T INVARIANCE}$$

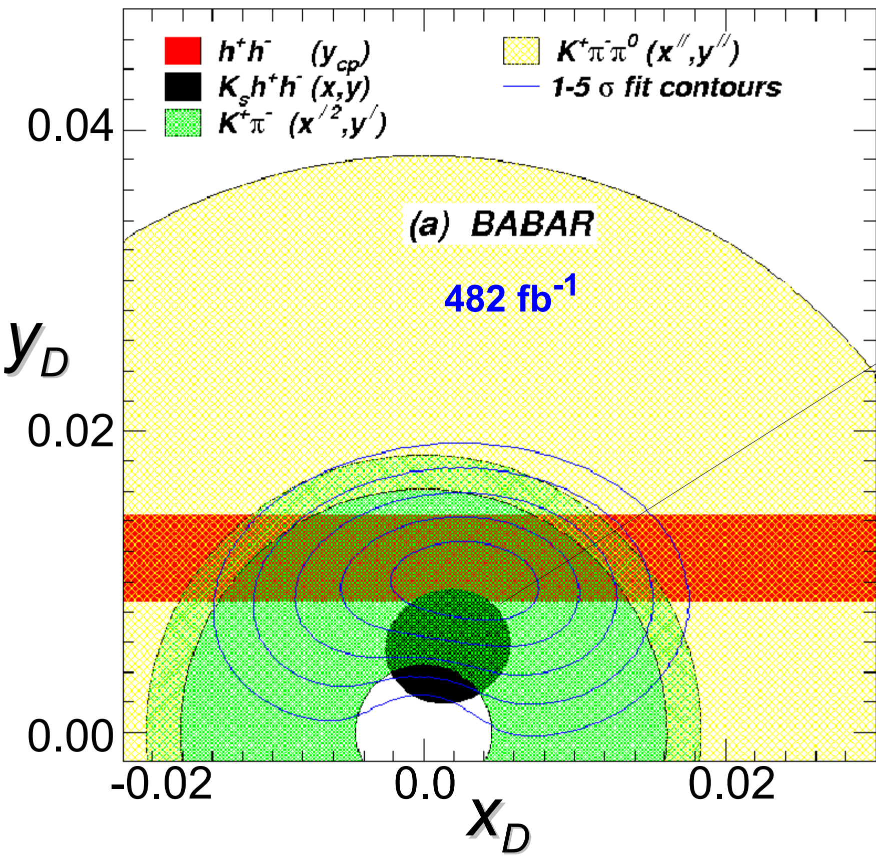
Mixing is often expressed in terms of the two parameters:

$$x_D=x=\frac{\Delta M}{\Gamma}$$

$$y_D=y=\frac{\Delta\Gamma}{2\Gamma}$$

Charm Mixing: x_D and y_D from BaBar

arXiv:1008.1541v1



$$x_D \times 10^3 = 3.10^{+3.12}_{-3.39}$$
$$y_D \times 10^3 = 10.10^{+1.69}_{-1.72}$$

"Golden Channels"

$$D^0 \rightarrow K^0_S h^+ h^- \qquad h = \pi, K$$

- Self-conjugate multi-body states
- Combination of CP odd and even eigenstates
- δ_f =0 (or π)

x_D and y_D directly measurable with TDDP

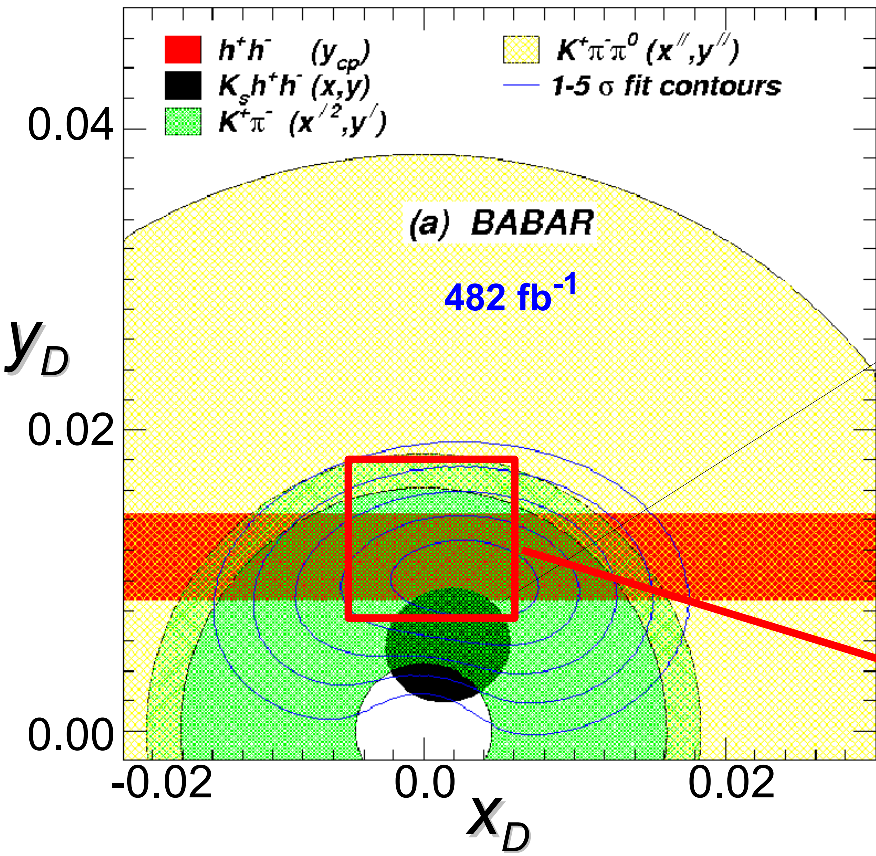
BaBar main charm mixing results combined into average values for x_D and y_D

- χ^2 minimization technique
- Correlation effects included in calculations
- Results based on no *CPV* assumption

- (x'^2,y') from WS $D^0 \rightarrow K^+ \pi^-$ decays
- (x'',y'') from TDDP analysis of $D^0 \rightarrow K^+ \pi^- \pi^0$
- y_{CP} from tagged/untagged $D^0 \rightarrow h^+h^-$ decays
- (x_D , y_D) from the combined golden channels

Charm Mixing: x_D and y_D from BaBar

arXiv:1008.1541v1



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- $\delta_f = 0$ (or π)

x_D and y_D directly measurable with TDDP

$$x_D \times 10^3 = 3.10^{+3.12}_{-3.39}$$
$$y_D \times 10^3 = 10.10^{+1.69}_{-1.72}$$

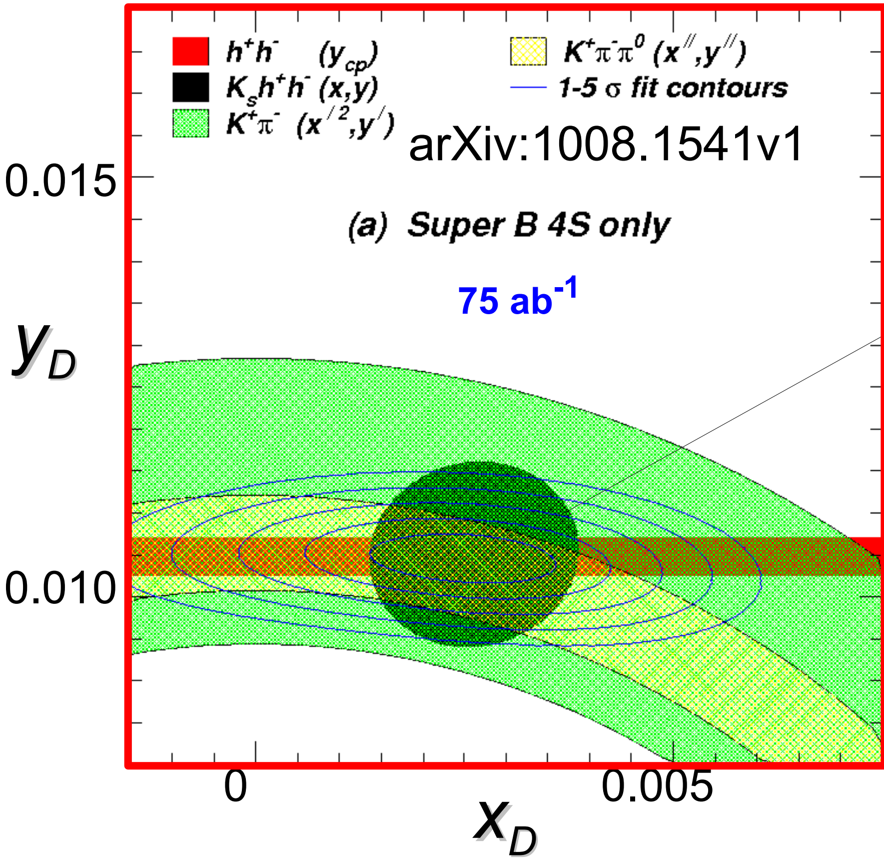
Super*B* region

*Ba*Bar main charm mixing results combined into average values for x_D and y_D

- χ^2 minimization technique
- Correlation effects included in calculations
- Results based on no *CP*V assumption

- (x'^2, y') from WS $D^0 \to K^+ \pi^-$ decays
- (x'', y'') from TDDP analysis of $D^0 \to K^+ \pi^- \pi^0$
- y_{CP} from tagged/untagged $D^0 \to h^+ h^-$ decays
- (x_D, y_D) from the combined golden channels

Charm Mixing: x_D and y_D from SuperB Running at the $Y(4S)$



"Golden Channels"

$D^0 \to K_S^0 h^+ h^- \quad h = \pi, K$

- Self-conjugate multi-body states
- Combination of CP odd and even eigenstates
- $\delta_f = 0$ (or π)

$$x_D \times 10^3 = xxx^{+0.72}_{-0.75}$$
$$y_D \times 10^3 = yyy \pm 0.19$$

x_D and y_D directly measurable with TDDP

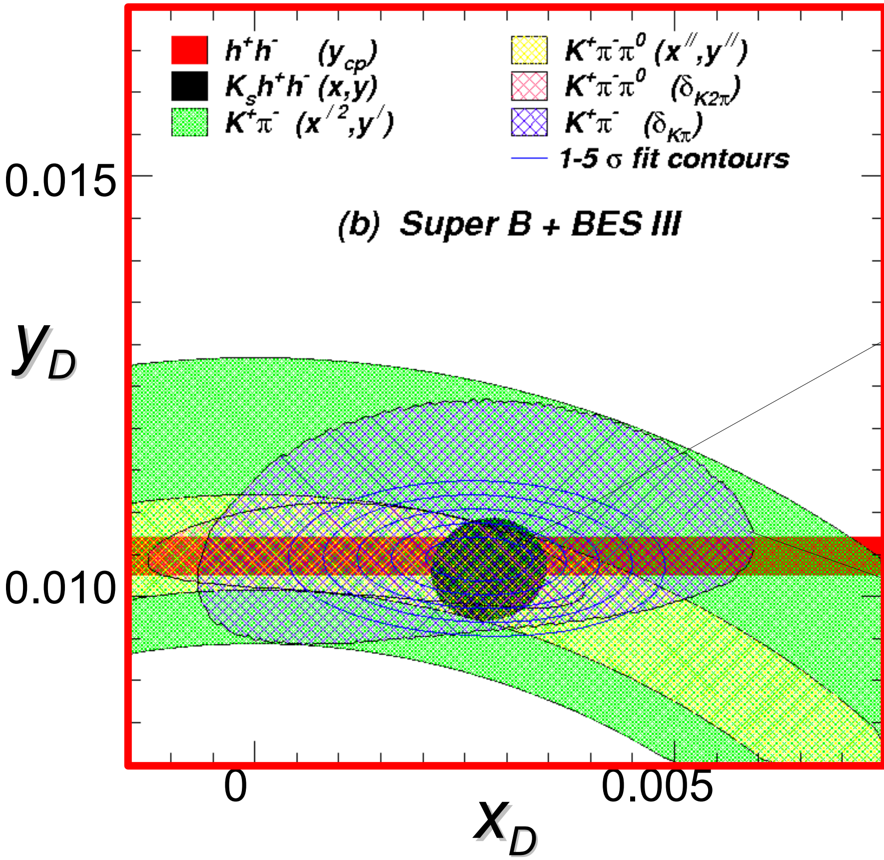
SuperB (4S only) projection of BaBar main charm mixing results combined into average values for x_D and y_D

- χ^2 minimization technique
- Correlation effects included in calculations
- Results based on no CPV assumption

- (x'^2,y') from WS $D^0 \to K^+ \pi^-$ decays
- (x'',y'') from TDDP analysis of $D^0 \to K^+ \pi^- \pi^0$
- y_{CP} from tagged/untagged $D^0 \to h^+h^-$ decays
- (x_D , y_D) from the combined golden channels

Charm Mixing: x_D and y_D from Super*B* + BESIII

arXiv:1008.1541v1



BESIII can measure strong phase in "golden channels"

"Golden Channels"

$D^0 \to K^0_S h^+ h^- \qquad h = \pi, K$

- Self-conjugate multi-body states
- Combination of CP odd and even eigenstates
- δ_f =0 (or π)

$x_D \times 10^3 = xxx \pm 0.42$

$y_D \times 10^3 = yyy \pm 0.17$

x_D and y_D directly measurable with TDDP

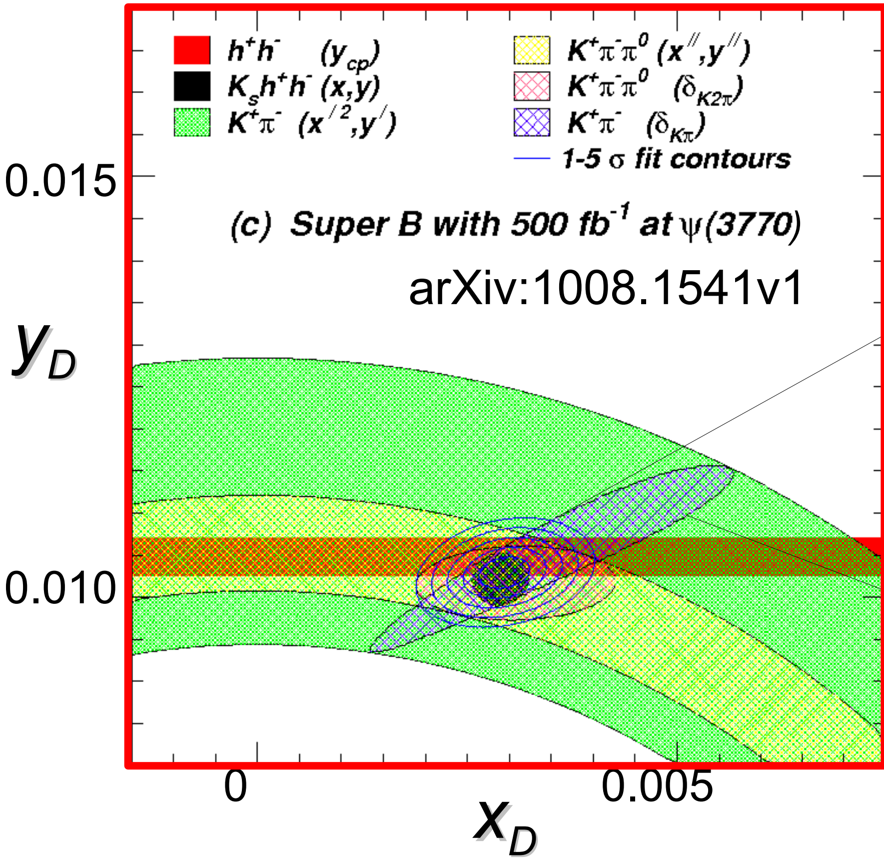
"Strong phase $\delta_{K\pi}$" From BESIII

Super*B* (4S only) projection of *BaB*ar main charm mixing results combined into average values for x_D and y_D combined with expectation from BESIII strong phase measurements

- χ^2 minimization technique
- Correlation effects included in calculations
- Results based on no *CPV* assumption

- (x'^2,y') from WS $D^0 \to K^+\pi^-$ decays
- (x'',y'') from TDDP analysis of $D^0 \to K^+\pi^-\pi^0$
- y_{CP} from tagged/untagged $D^0 \to h^+h^-$ decays
- (x_D , y_D) from the combined golden channels

Charm Mixing: x_D and y_D from SuperB Running at the $\Psi(3770)$



SuperB can measure strong phase in "golden channels"

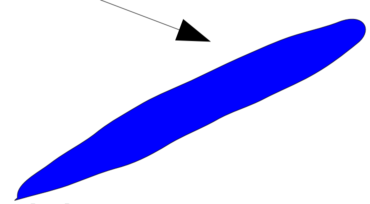
"Golden Channels"

$$D^0 \rightarrow K^0_S h^+ h^- \qquad h = \pi, K$$

- Self-conjugate multi-body states
- Combination of CP odd and even eigenstates
- δ_f =0 (or π)

$$x_D \times 10^3 = xxx \pm 0.20$$
$$y_D \times 10^3 = yyy \pm 0.12$$

x_D and y_D directly measurable with TDDP



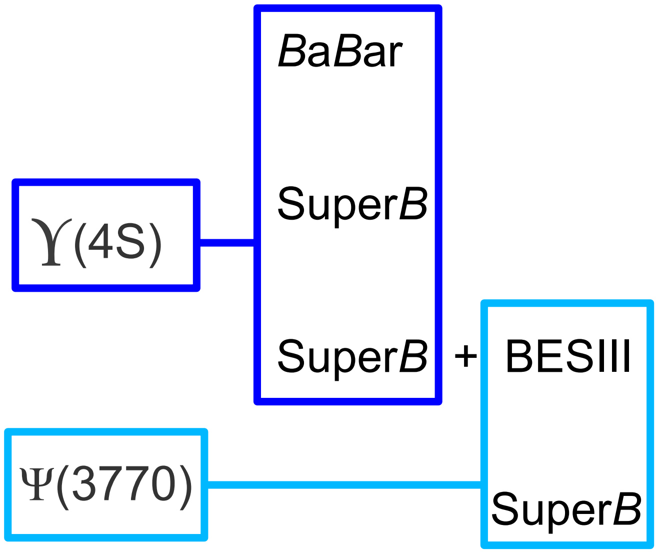
"Strong phase $\delta_{K\pi}$"
From SuperB at $\Psi(3770)$

SuperB (Ψ(3770)) expectation of main charm mixing measurement combined into average values for x_D and y_D end expectation of strong phase measurements

- χ^2 minimization technique
- Correlation effects included in calculations
- Results based on no *CPV* assumption

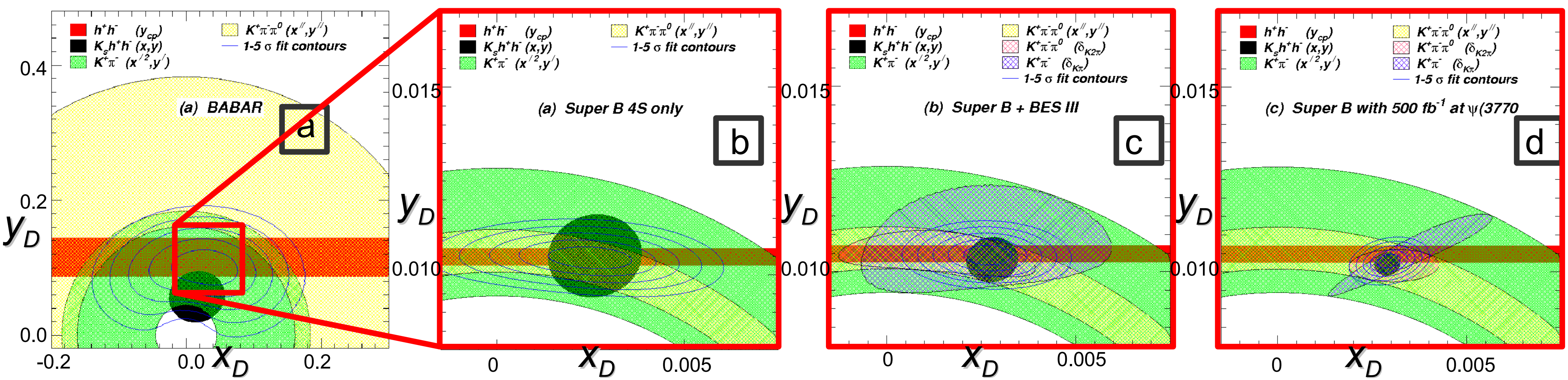
- (x'^2,y') from WS $D^0 \rightarrow K^+ \pi^-$ decays
- (x'',y'') from TDDP analysis of $D^0 \rightarrow K^+ \pi^- \pi^0$
- y_{CP} from tagged/untagged $D^0 \rightarrow h^+h^-$ decays
- (x_D , y_D) from the combined golden channels

Charm Mixing, x_D and y_D: improving the picture



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)
(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)
(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)
(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)

ArXiv: 1008.1541v1



Is it possible to further reduce the systematic uncertainties from Dalitz plots analysis? Maybe, using a model-independent approach: Bondar et al. Phys. Rev. **D** 82, 034033 (2010)

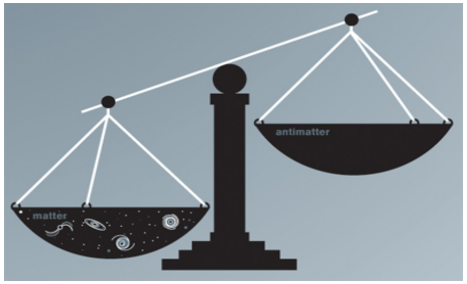
Rare Decays, Mixing and CP Violation

Rare Decays

Mixing

→CP Violation

Indirect , direct, Δa_{cp}, Time-Dependent CPV



Indirect CP Violation in charm

Effective values:

$$D^0 \rightarrow (x_D^+, y_D^+)$$
$$\overline{D^0} \rightarrow (x_D^-, y_D^-)$$

Super*B* will be sensitive at 3σ level to a difference

$$x_D^+ - x_D^- \quad (y_D^+ - y_D^-)$$

of 5(3) x 10^{-4} in the average *x* (*y*) value.

If observed and if they were due to *CPV* in mixing they would provide a measurement of

$$x_D^+ \simeq |q_D / p_D| x_D$$
$$x_D^- \simeq |p_D / q_D| x_D$$
$$a_z = \frac{z^+ - z^-}{(z^+ + z^-)} \approx \frac{1 - |q_D / p_D|^2}{1 + |q_D / p_D|^2}$$

$a_Z \neq 0 \rightarrow$ *CP* is violated in mixing

Super*B* estimates for uncertainties in *CP* violation mixing parameters

arXiv:1008.1541v1

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	$K_S^0 h^+ h^-$	± 8.4	± 3.3
BES III DP model	$K_S^0 h^+ h^-$	± 3.7	± 1.9
Super*B* DP model	$K_S^0 h^+ h^-$	± 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	

Direct CP Violation in charm

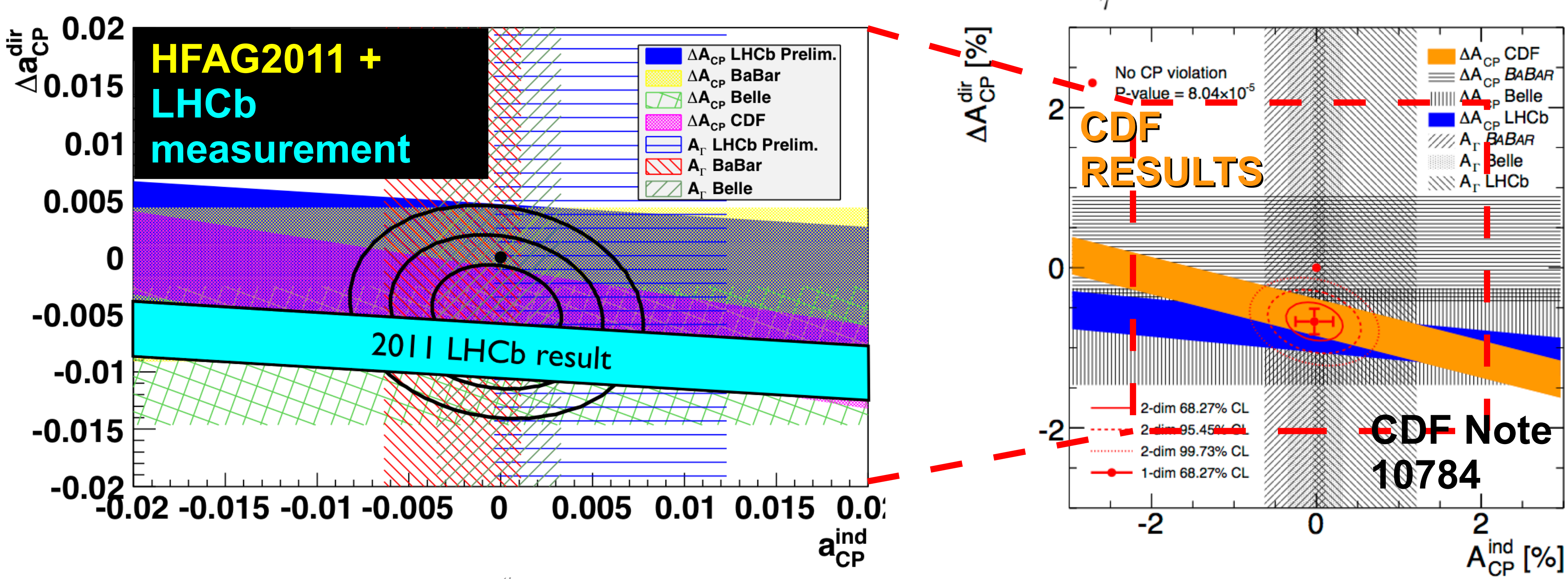
$$a_{CP}^{f} = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \bar{f})} \qquad f = \bar{f} = K^+K^-(K^0), \pi^+\pi^-(\pi^0)$$

Standard Model expectation: $a_{CP} \approx O(10^{-5} - 10^{-4})$

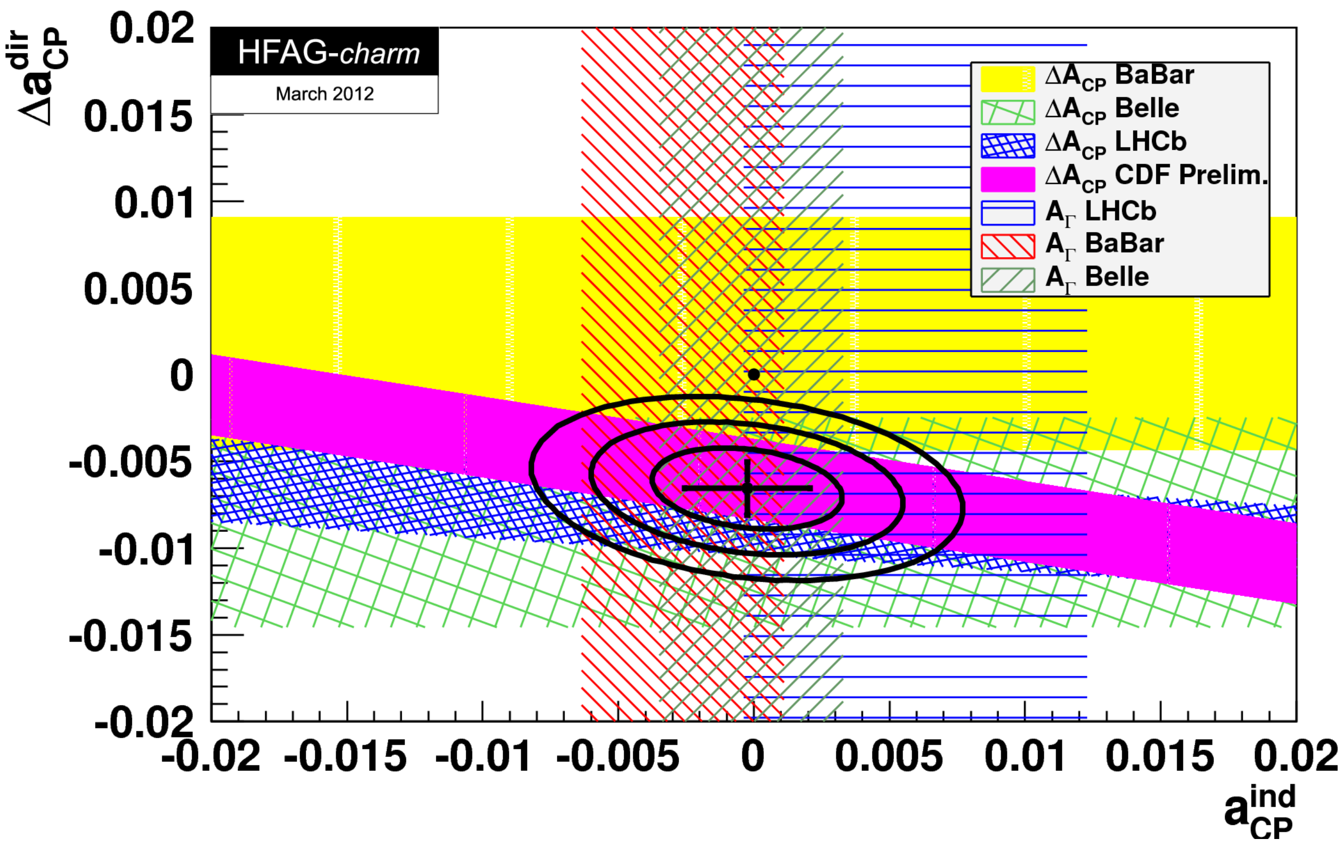
Super*B* sensitivity to *CPV* : $\sigma = 3 \times 10^{-4}$

The same decay channels have already shown hints for *CPV* in charm

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \Delta A_{CP}^{dir} + \frac{\Delta\langle t\rangle}{\tau} A_{CP}^{ind}$$



CP Violation in charm, the closest picture



Data consistent with no *CP* violation at 0.006% CL

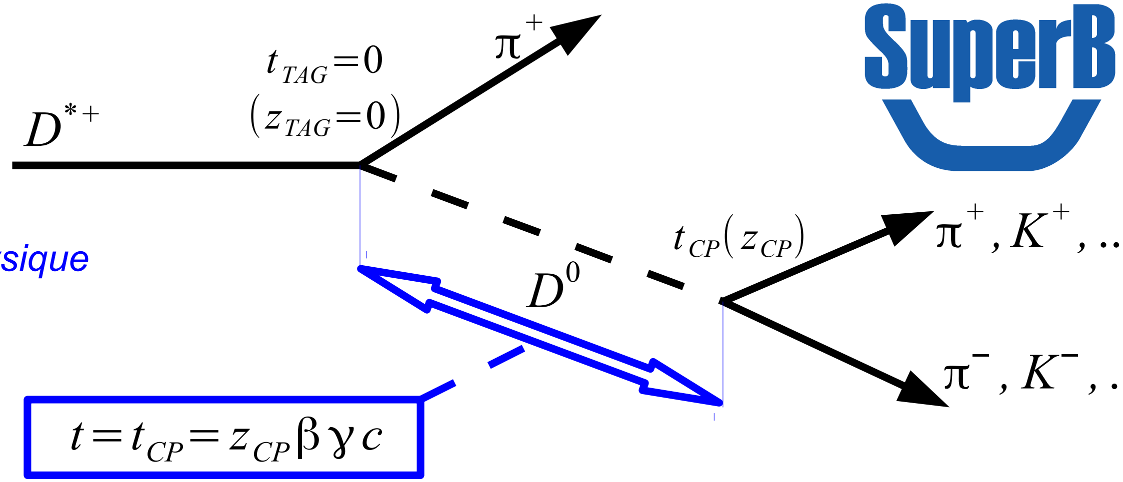
***) Are we really observing *CP* violation in charm?**
***) Could SM account for this asymmetry or NP is showing up?**
***) Is it possible to go beyond this picture?**

- Theorists are suggesting to double check these results by measuring final states including neutrals (see J. Brod, A. L. Kagan, J. Zupan- ArXiv: 1111.5000)

TDCPV in Charm

A. Bevan- G. Inguglia- B. Meadows:
*)Phys. Rev. **D** 84, 114009, arXiv:1106.5075

*)"The Time-Dependent CP Violation in Charm"
G. Inguglia, Proceedings of "Les Rencontres de physique de la vallee d'aoste" arXiv:1204.2303



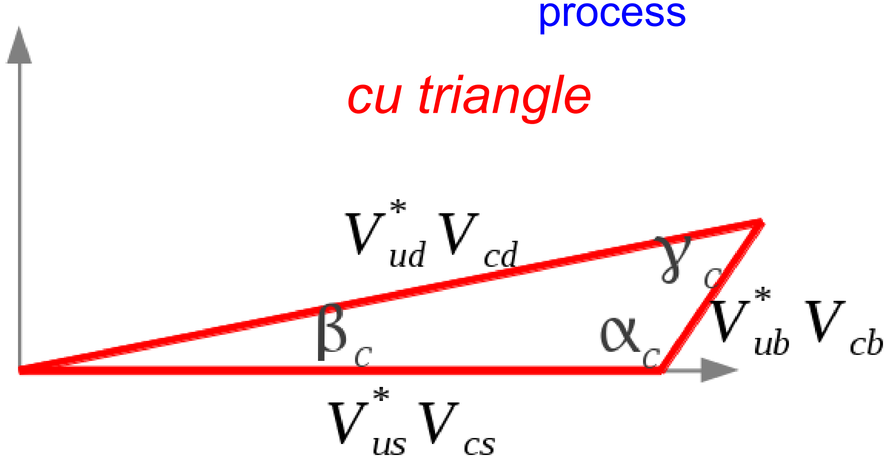
$$A_{CP}^{Phys}(t)=\frac{\overline{\Gamma^{Phys}}(t)-\Gamma^{Phys}(t)}{\overline{\Gamma^{Phys}}(t)+\Gamma^{Phys}(t)}=-\Delta\omega+\frac{(D+\Delta\omega)e^{\Delta\Gamma t/2}(|\lambda_f|^2-1)\cos\Delta M t+2\Im(\lambda_f)\sin\Delta M t}{(1+|\lambda_f|^2)h_+/2+h_-\Re(\lambda_f)}$$

$$\lambda_f=\left|\frac{q}{p}\right|e^{i\phi_{MIX}}\left|\frac{\bar{A}}{A}\right|e^{i\phi_{CP}} = \left|\frac{q}{p}\right|e^{i\phi_{MIX}}e^{-2i\phi_T^W}$$

= if tree-dominated process

Remember from the mixing Part of this talk:

$$x=\frac{\Delta M}{\Gamma}$$
$$y=\frac{\Delta\Gamma}{2\Gamma}$$



$$\alpha_c=arg[\frac{-V_{ub}^*V_{cb}}{V_{us}^*V_{cs}}]=(111.5\pm4.2)^o$$

$$\beta_c=arg[\frac{-V_{ud}^*V_{cd}}{V_{us}^*V_{cs}}]=(0.0350\pm0.0001)^o$$

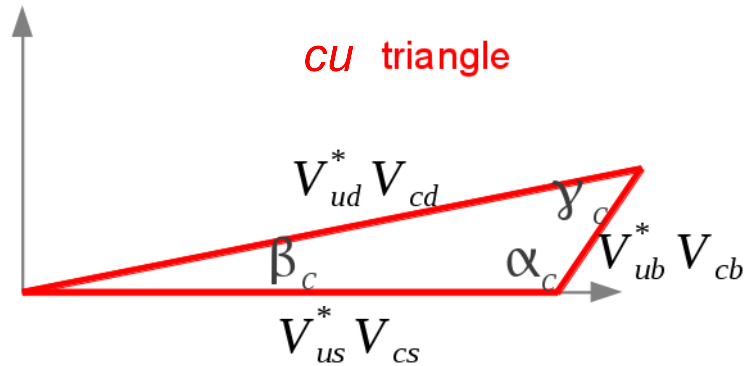
$$\gamma_c=arg[\frac{-V_{ub}^*V_{cb}}{V_{ud}^*V_{cd}}]=(68.4\pm0.1)^o$$

Numerical Results

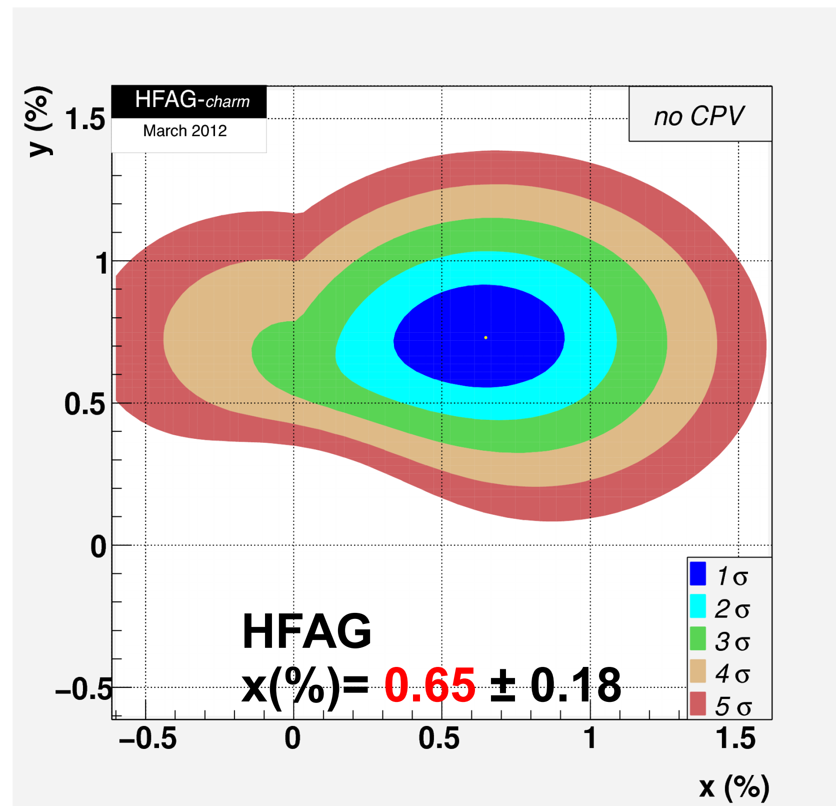
ϕ_{MIX} $\beta_{c,\,eff}$ x

Parameter	Super$B$ $\Psi(3770)$ SL	Super$B$ $\Psi(3770)$ SL+K	Super$B$ $\Upsilon(4S)$ $\pi_s^\pm$	LHCb $\pi_s^\pm$	Belle II $\pi_s^\pm$
$\sigma_{\phi_{\pi\pi}} = \sigma_{arg(\lambda_{\pi\pi})}$	5.7°	2.4°	2.2°	3.0°	2.8°
$\sigma_{\phi_{KK}} = \sigma_{arg(\lambda_{KK})}$	3.5°	1.4°	1.6°	1.8°	1.8°
$\sigma_{\beta_{c,eff}}$	3.3°	1.4°	1.4°	1.9°	1.7°

$$\sigma_{\phi_{KK}} = \sigma_{arg(\lambda_{KK})} = \sigma_{\phi_{MIX}}$$



Experiment/HFAG	$\sigma_x(\phi = \pm 10^o)$	$\sigma_x(\phi = \pm 20^o)$
Super$B$ $[\Upsilon(4S)]$		
$D^0 \to \pi^+\pi^-$	0.12%	0.06%
$D^0 \to K^+K^-$	0.08%	0.04%
Super$B$ $[\Psi(3770)]$		
$D^0 \to \pi^+\pi^-(SL)$	0.30%	0.15%
$D^0 \to \pi^+\pi^-(SL+K)$	0.13%	0.06%
$D^0 \to K^+K^-(SL)$	0.19%	0.10%
$D^0 \to K^+K^-(SL+K)$	0.08%	0.04%
LHCb		
$D^0 \to \pi^+\pi^-$ (1.1 fb^{-1})	0.40%	0.20%
$D^0 \to K^+K^-$ (1.1 fb^{-1})	0.22%	0.11%
$D^0 \to \pi^+\pi^-$ (5.0 fb^{-1})	0.15%	0.08%
$D^0 \to K^+K^-$ (5.0 fb^{-1})	0.09%	0.04%
Belle II		
$D^0 \to \pi^+\pi^-$	0.14%	0.07%
$D^0 \to K^+K^-$	0.10%	0.04%
HFAG	0.20%	



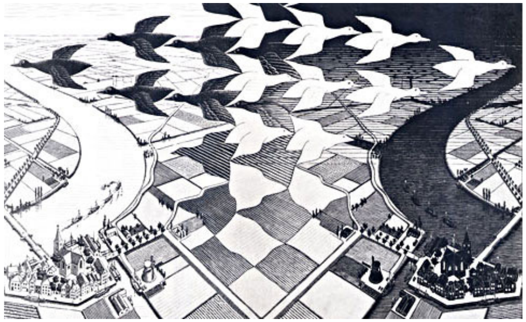
Summary

Rare Decays

- Rare decays provide information on new physics.
- LD contribution play an important role in $D^0 \to \gamma\gamma$ and $D^0 \to \mu^+\mu^-$ and need to be understood in order to interpret any new physics signal.
- $D^0 \to ue^+e^-$ transitions may help to discriminate between SUSY models, however measurements could be challenging in hadron machines.

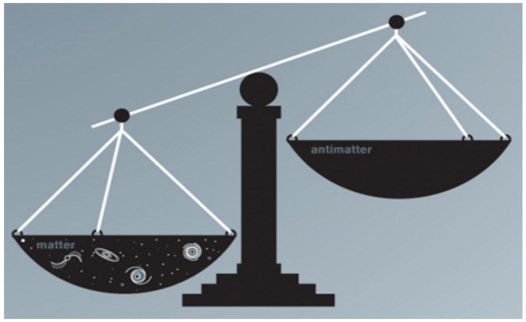
Mixing

- B-factories have provided proof of charm mixing.
- Current limits will be largely improved in the next decade.
- At charm threshold (Super*B*+BESIII) the strong phase can be measured, adding more “strong” constraints on the mixing parameters.



CP Violation

- LHCb+CDF: is it really *CPV*? More work is needed to understand the origin of the observed asymmetry.
- SuperB can measure the effective values of the mixing parameters.
- A time-dependent analysis is a tool to look for *CPV* in charm and will open the door to measurements of the properties of the charm unitarity triangle.



...Many Thanks...