SuperB Physics Meeting, INFN-LNF, 11-12 December 2011

Time-Dependent $\not{CP}$ in Charm: Moving Forward

11/12/2011
Gianluca Inguglia
Particle Physics Research Centre
Queen Mary University of London
g.inguglia@qmul.ac.uk

Time-Dependent CP Violation in Charm

→Time-dependent formalism

→CP eigenstates and flavor tagging

→Numerical Results

Time-Dependent CP Violation in Charm

→Time-dependent formalism

→CP eigenstates and flavor tagging

→Numerical Results

Based on...

UCHEP-11-05

Time-dependent CP asymmetries in D and B decays

A. J. Bevan and G. Inguglia
Queen Mary, University of London, Mile End Road, E1 4NS, United Kingdom

B. Meadows
University of Cincinnati, Cincinnati, Ohio 45221, USA

(Dated: November 7, 2011)

ArXiv:1106.5075
Accepted for publication in *Physical Review D*

We examine measurements of time-dependent CP asymmetries that could be made in new and future flavour facilities. In charm decays, where they can provide a unique insight into the flavor changing structure of the Standard Model, we examine a number of decays to CP eigenstates and describe a framework that can be used to interpret the measurements. Such measurements can provide a precise determination of the charm mixing phase, as well as constraints on the Standard

Strongly motivated by...

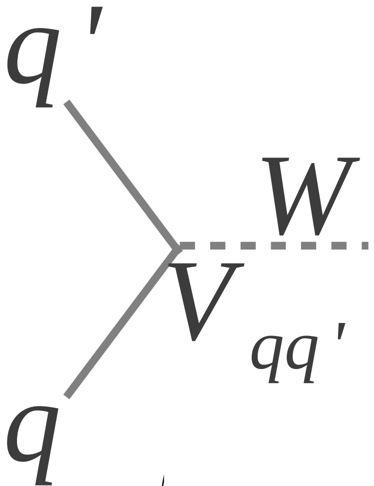
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

ArXiv:1112.0938

LHCb-PAPER-2011-023
CERN-PH-EP-2011-208
December 6, 2011

Evidence for CP violation in time-integrated $D^0 \to h^- h^+$ decay rates

Buras parametrization of the CKM matrix up to λ^5



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

PDG standard parametriazation with

$$s_{12} = \lambda, \quad s_{13}\sin\delta_{13} = A\lambda^3\eta, \quad \bar{\eta} = \eta[1 - \frac{\lambda^2}{2} + O(\lambda^4)]$$

$$s_{23} = A\lambda^{2,} \quad s_{13}\cos\delta_{13} = A\lambda^3\rho, \quad \bar{\rho} = \rho[1 - \frac{\lambda^2}{2} + O(\lambda^4)]$$

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta})+A\lambda^5(\bar{\rho}-i\bar{\eta})/2 \\ -\lambda+A^2\lambda^5[1-2(\bar{\rho}+i\bar{\eta})] & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\lambda^3[1-(\bar{\rho}+i\bar{\eta})] & -A\lambda^2+A\lambda^4[1-2(\bar{\rho}+i\bar{\eta})]/2 & 1-A^2\lambda^4/2 \end{pmatrix} + O(\lambda^6)$$

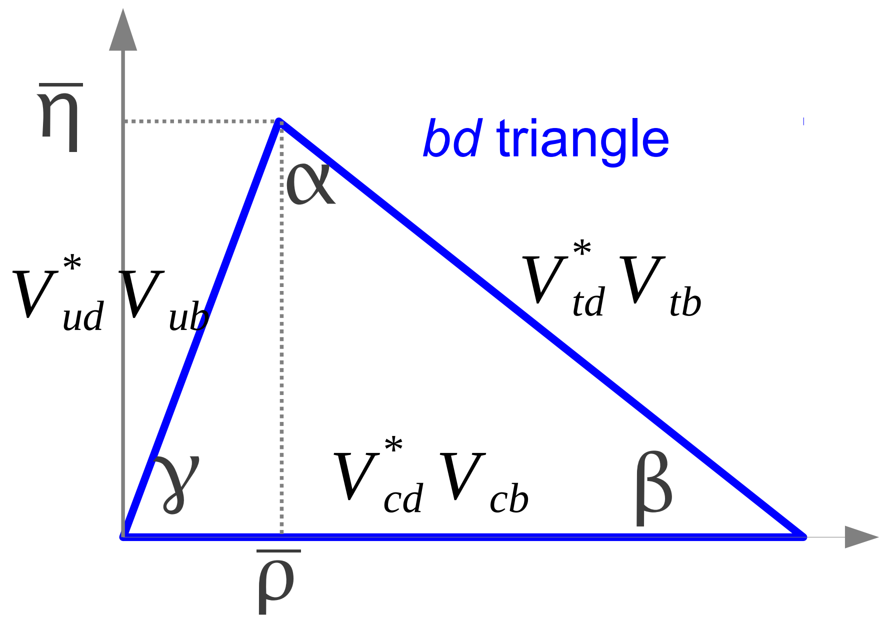
TAB 1

	UTFit	**CKM Fitter**
λ	0.22545 ± 0.00065	0.22543 ± 0.00077
A	0.8095 ± 0.0095	$0.812^{+0.013}_{-0.027}$
ρ	0.135 ± 0.021	————————————
η	0.367 ± 0.013	————————————
$\bar{\rho}$	0.132 ± 0.020	0.144 ± 0.025
$\bar{\eta}$	0.358 ± 0.012	$0.342 + 0.016$

Why do we express the matrix in terms of $\bar{\rho}\,\bar{\eta}$?

Unitarity triangles

Unitarity conditions of the CKM matrix are translated into 6 possible unitary triangles in the complex plane. We illustrate two here.



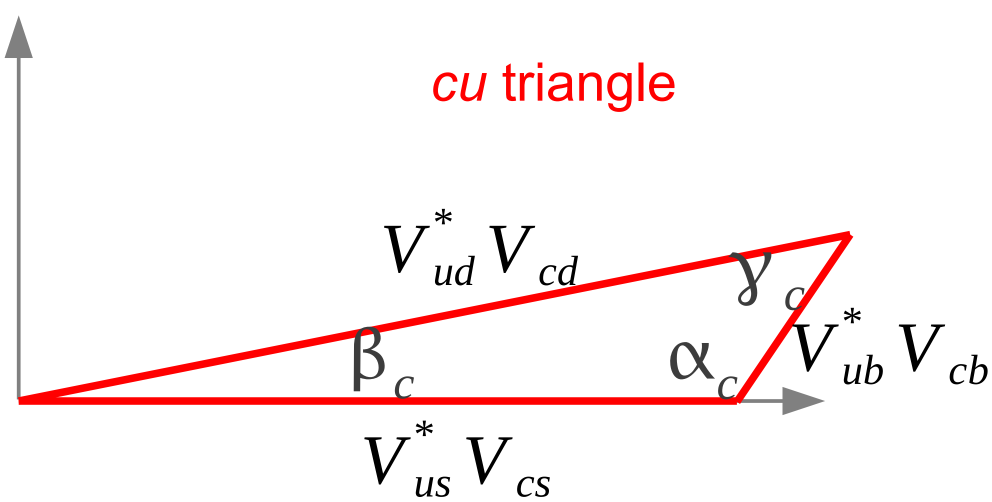
$$V^*_{ud} V_{ub} + V^*_{cd} V_{cb} + V^*_{td} V_{tb} = 0$$

$$\alpha = arg\left[\frac{-V_{td} V^*_{tb}}{V_{ud} V^*_{ub}}\right] = (91.4 \pm 6.1)^o$$

$$\beta = arg\left[\frac{-V_{cd} V^*_{cb}}{V_{td} V^*_{tb}}\right] = (21.1 \pm 0.9)^o$$

$$\gamma = arg\left[\frac{-V_{ud} V^*_{ub}}{V_{cd} V^*_{cb}}\right] = (74 \pm 11)^o$$

FROM EXPERIMENTS



$$V^*_{ud} V_{cd} + V^*_{us} V_{cs} + V^*_{ub} V_{cb} = 0$$

$$\alpha_c = arg\left[\frac{-V^*_{ub} V_{cb}}{V^*_{us} V_{cs}}\right] = (111.5 \pm 4.2)^o$$

$$\beta_c = arg\left[\frac{-V^*_{ud} V_{cd}}{V^*_{us} V_{cs}}\right] = (0.035 \pm 0.0001)^o$$

$$\gamma_c = arg\left[\frac{-V^*_{ub} V_{cb}}{V^*_{ud} V_{cd}}\right] = (68.4 \pm 0.1)^o$$

USED AVERAGE OF VALUES IN TAB 1

Time-dependent formalism (i)

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

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

Mixing is often expressed in terms of the two Parameters:

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

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

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

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

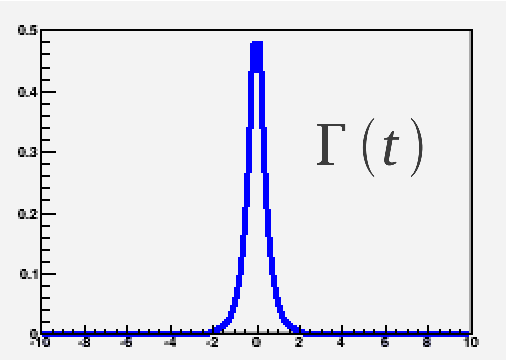
$$H_{eff}=M-\frac{i}{2}\Gamma$$

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

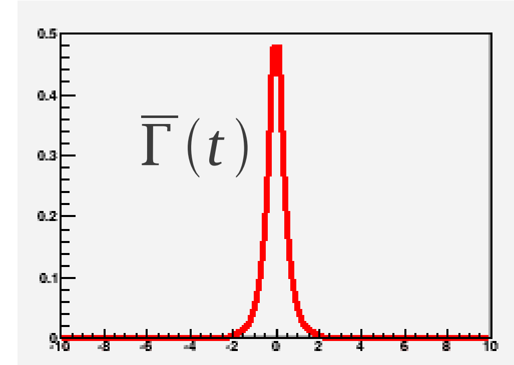
$$M_{11}=M_{22},\Gamma_{11}=\Gamma_{22},\Im[\frac{\Gamma_{12}}{M_{12}}]=0 \quad \leftarrow \quad \textit{CP INVARIANCE}$$

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

$$\frac{d}{dt}\langle\Psi(t)|\Psi(t)\rangle=-\langle\Psi(t)|\Gamma|\Psi(t)\rangle$$



Time-dependent formalism



The time-dependence of decays of P^0 ($\overline{P^0}$) to final state |f > are:

$$\Gamma(P^0 \rightarrow f) \propto e^{-\Gamma_1|\Delta t|}\left[\frac{h_+}{2} + \frac{\Re(\lambda_f)}{1+|\lambda_f|^2} h_- + e^{[\Delta\Gamma \Delta t/2]}\left(\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\Delta M \Delta t - \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}\sin\Delta M \Delta t\right)\right]$$

$$\overline{\Gamma}(\overline{P^0} \rightarrow f) \propto e^{-\Gamma_1|\Delta t|}\left[\frac{h_+}{2} + \frac{\Re(\lambda_f)}{1+|\lambda_f|^2} h_- - e^{[\Delta\Gamma \Delta t/2]}\left(\frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\Delta M \Delta t - \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}\sin\Delta M \Delta t\right)\right]$$

$$where: \quad h_{+-} = 1 \pm e^{\Delta\Gamma \Delta t}, \quad \lambda_f = \frac{q}{p}\frac{\overline{A}}{A}$$

λ_f very important!

We now obtain the time-dependent CP asymmetry

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

Where we included mistag probability effects

Time-Dependent CP Violation in Charm

→Time-dependent formalism

→CP eigenstates and flavor tagging

→Numerical Results

Analysis of CP eigenstates (i)

When exploring CP violation, ignoring long distance effects, the parameter λ may be written as:

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

$$\phi_{MIX} : phase\ of\ D^0 \overline{D^0} mixing$$

$$\phi_{CP} : overall\ phase\ of\ D^0 \rightarrow f_{CP}(eigenstate)$$

$$A = |T|\ e^{i(\phi_T + \delta_T)} + |CS|\ e^{i(\phi_{CS} + \delta_{CS})} + |W|\ e^{i(\phi_W + \delta_W)} + \sum_{q=d,s,b} |P_q|\ e^{(i\phi_q + \delta_q)}$$

The following processes, as we will see, are tree dominated

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

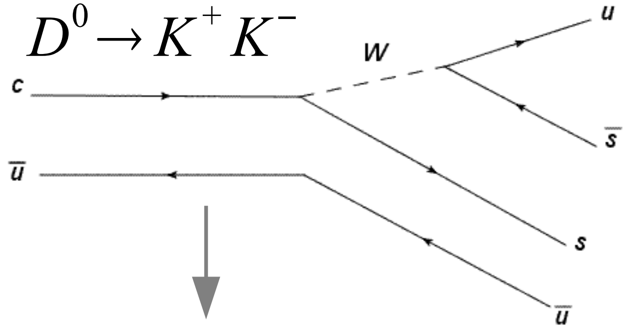
Assuming negligible the contribution due to P/CS/W amplitudes, then:

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

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

Tree topology

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



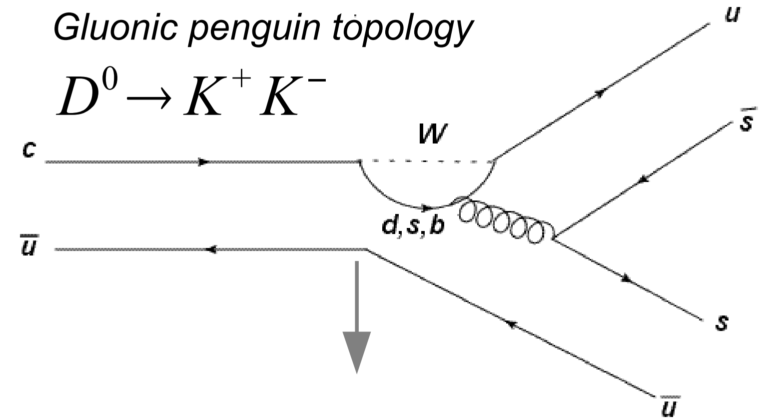
$V_{cs} V_{us}^*$

Real

$$V_{cs} V_{us}^* = -\lambda + \frac{\lambda^3}{2} - \left(\frac{1}{8} + \frac{A^2}{2}\right)\lambda^5$$

Gluonic penguin topology

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



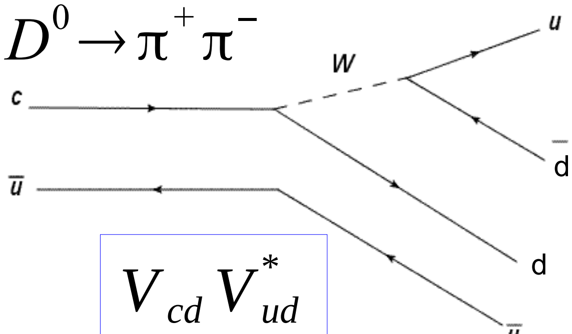
$V_{cd} V_{ud}^* + V_{cs} V_{us}^* + V_{cb} V_{ub}^*$

Real **Negligible**

$$V_{cd} V_{ud}^* = -\lambda + \frac{\lambda^3}{2} + \frac{\lambda^5}{8} + \frac{A^2 \lambda^5}{2}\left[1 - 2(\bar{\rho} + i\bar{\eta})\right]$$

Tree topology

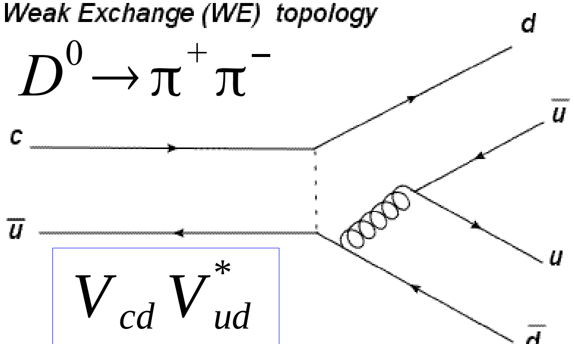
$D^0 \to \pi^+ \pi^-$



$V_{cd} V_{ud}^*$

Weak Exchange (WE) topology

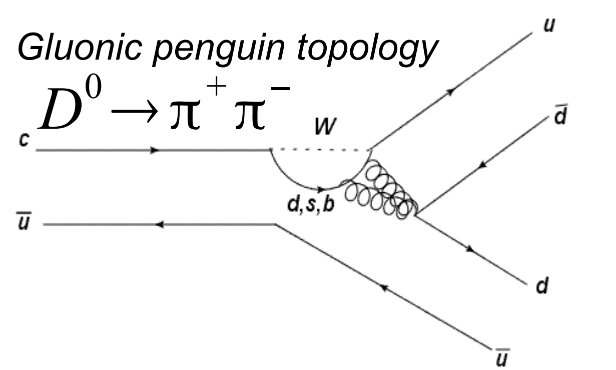
$D^0 \to \pi^+ \pi^-$



$V_{cd} V_{ud}^*$

Gluonic penguin topology

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



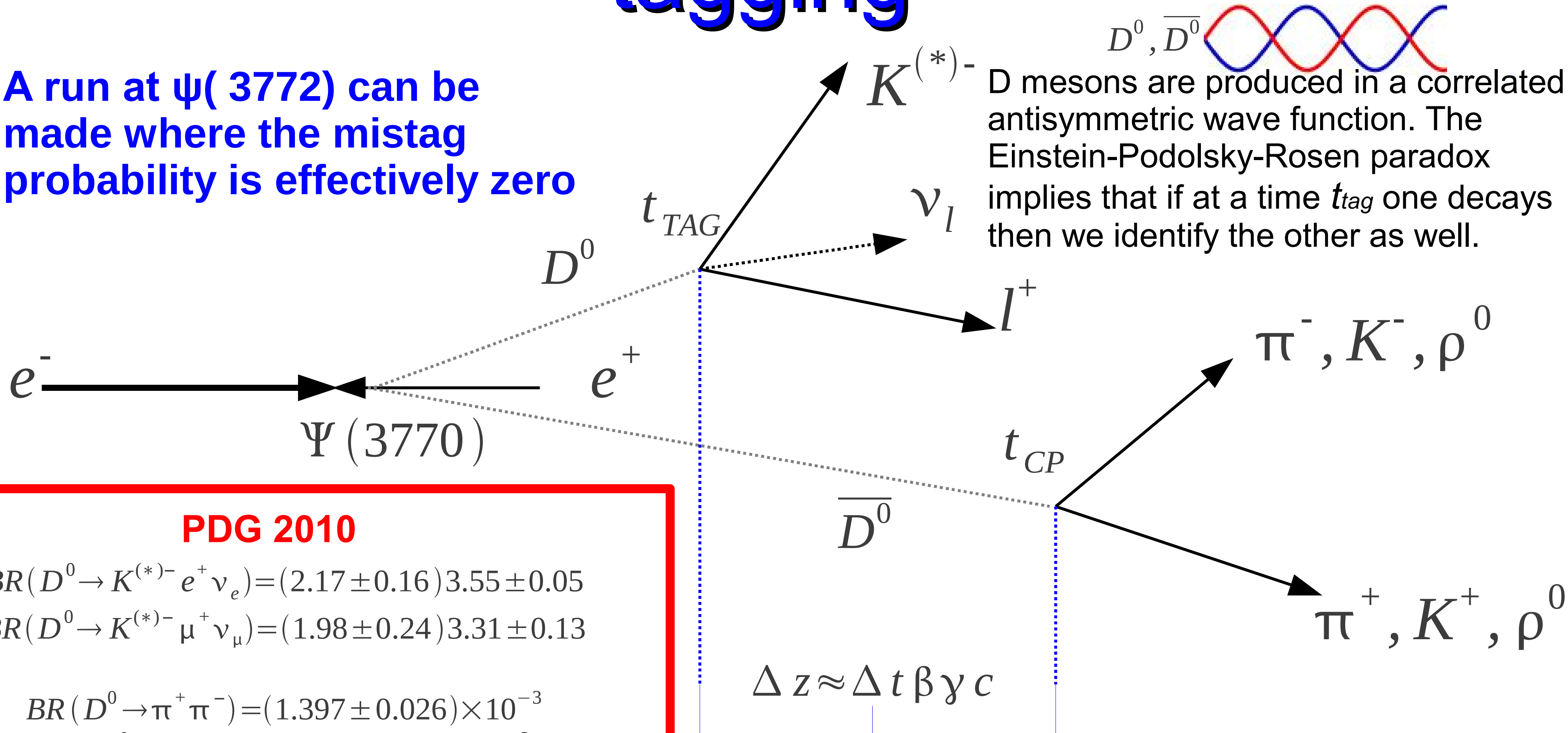
Real **Negligible**

$V_{cd} V_{ud}^* + V_{cs} V_{us}^* + V_{cb} V_{ub}^*$

Correlated mesons: semi-leptonic tagging

A run at ψ(3772) can be made where the mistag probability is effectively zero

D mesons are produced in a correlated antisymmetric wave function. The Einstein-Podolsky-Rosen paradox implies that if at a time t_{tag} one decays then we identify the other as well.



PDG 2010

$BR(D^0 \to K^{(*)-} e^+ \nu_e) = (2.17 \pm 0.16) 3.55 \pm 0.05$

$BR(D^0 \to K^{(*)-} \mu^+ \nu_\mu) = (1.98 \pm 0.24) 3.31 \pm 0.13$

$BR(D^0 \to \pi^+ \pi^-) = (1.397 \pm 0.026) \times 10^{-3}$

$BR(D^0 \to K^+ K^-) = (3.94 \pm 0.07) \times 10^{-3}$

At time t_{TAG} *the decays* $D \to K^{-(+)} l^{+(-)} \nu_l$ *account for* 11 % *of all D decays* and *unambiguously assigns the flavour* : D^0 *is associated* to *a* l^+, $\overline{D^0}$ *is associated* to *a* l^-

One may consider $D^0 \to K^- X$ (X=anything) to flavor-tag a D^0 meson with a mistag probability ~3% and a total BR~54%

Uncorrelated D^0 mesons

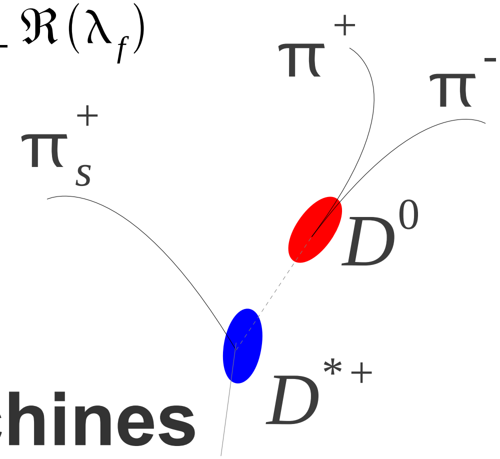
$$A(t)=\frac{\overline{\Gamma}(t)-\Gamma(t)}{\overline{\Gamma}(t)+\Gamma(t)}=2e^{\Delta\Gamma t/2}\frac{(|\lambda_f|^2-1)\cos\Delta M\, t+2\Im(\lambda_f)\sin\Delta M\, t}{(1+|\lambda_f|^2)(1+e^{\Delta\Gamma t})+2\Re(\lambda_f)(1-e^{\Delta\Gamma t})}$$

Mistag probability and dilution become important

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

The flavour tagging is accomplished by identifying a "slow" pion in the processes (CP and CP conjugated):

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



e^+e^- machines at Υ(4S) and hadron machines

D^* from $e^+e^-\rightarrow c\overline{c}$ can be separated from those coming from B's by applying a momentum cut.
Clean environment.
More easier to separate prompt D* from B cascade than LHCb

D^* mesons are produced both promptly or as secondary particles from primary decay of a B meson.
High background level to keep under control.
Trigger efficiency.

Time-Dependent CP Violation in Charm

→Time-dependent formalism

→CP eigenstates and flavor tagging

→Numerical Results

Expected number of (tagged) events

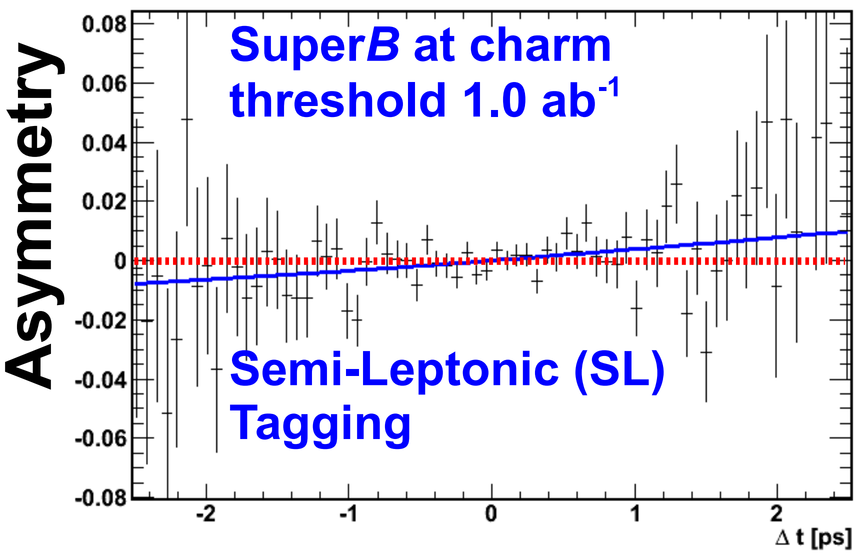
LHC*b*	7.8×10^{6}	$D^0\to\pi^+\pi^-$	**π-T**
	2.2×10^{7}	$D^0\to K^+K^-$	
Belle II	7.8×10^{6}	$D^0\to\pi^+\pi^-$	**π-T**
	2.2×10^{7}	$D^0\to K^+K^-$	
Super*B* $\Psi(3770)$	9.8×10^{5}	$D^0\to\pi^+\pi^-$	**SL-T**
	4.8×10^{6}	$D^0\to\pi^+\pi^-$	**K-T**
	2.8×10^{6}	$D^0\to K^+K^-$	**SL-T**
	1.2×10^{7}	$D^0\to K^+K^-$	**K-T**
Super*B* $\Upsilon(4S)$	6.6×10^{6}	$D^0\to\pi^+\pi^-$	**π-T**
	1.9×10^{7}	$D^0\to K^+K^-$	

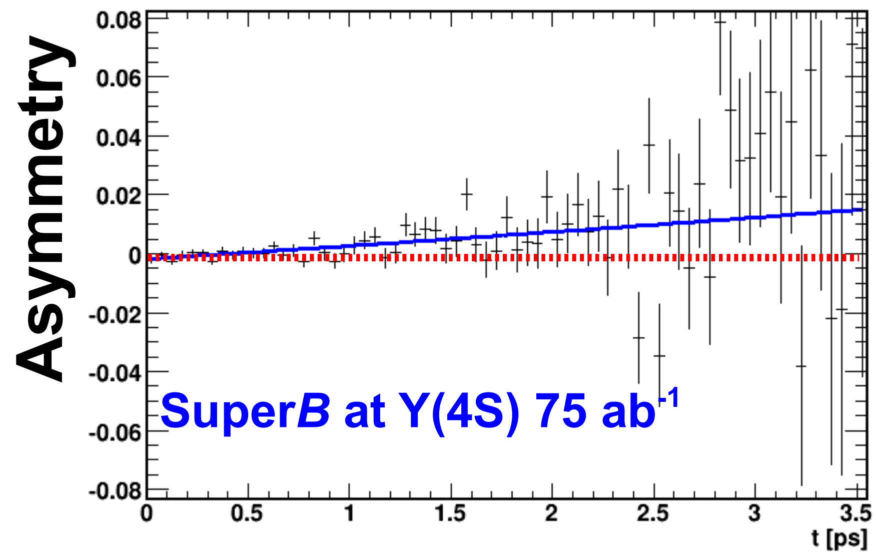
π-T indicates that the D^0 mesons are tagged using the electrical charge of the associated short pion (LHC*b*/Belle/Super*B*)

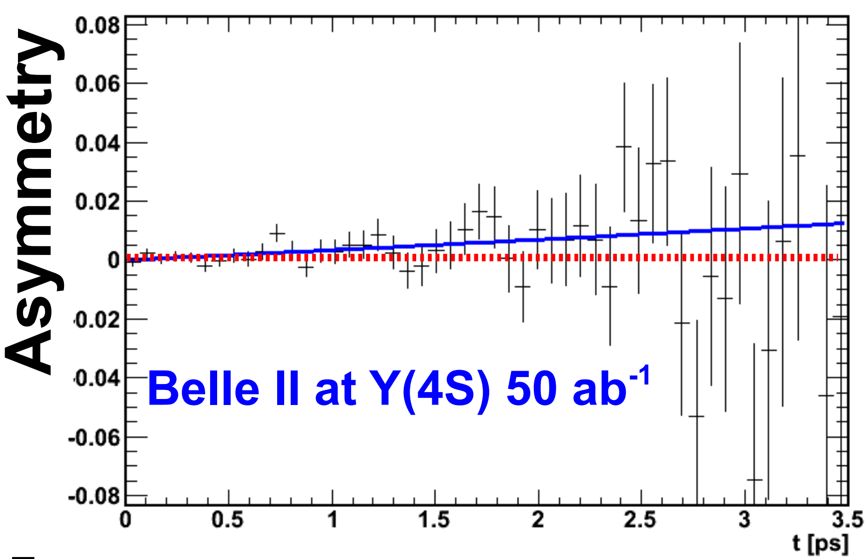
SL-T refers to semi-leptonic tag at charm threshold and **K-T** to the Kaon tag at charm thereshold (Super*B* only)

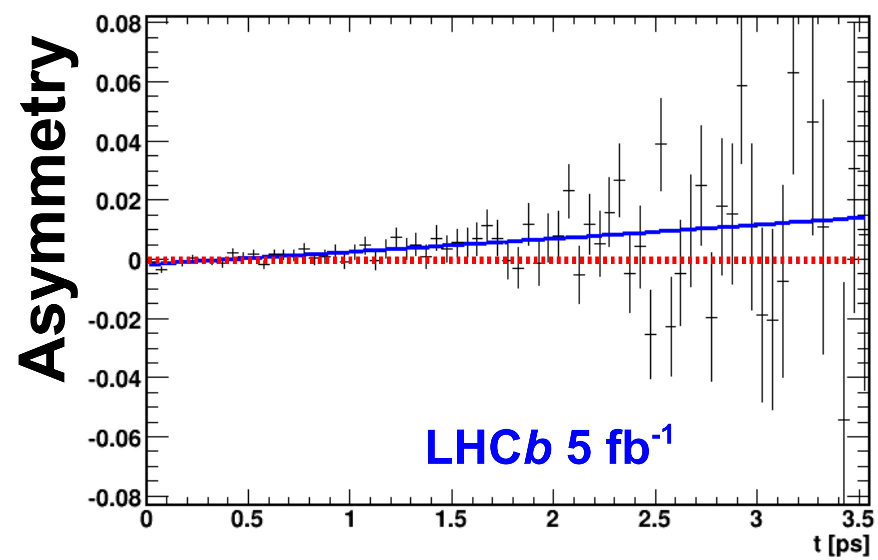
TDCPV in charm: numerical analysis

$$A^{Phys}_{D^0\to\pi^+\pi^-}(\Delta t)=\frac{\overline{\Gamma^{Phys}}(\Delta t)-\Gamma^{Phys}(\Delta t)}{\overline{\Gamma^{Phys}}(\Delta t)+\Gamma^{Phys}(\Delta t)}$$

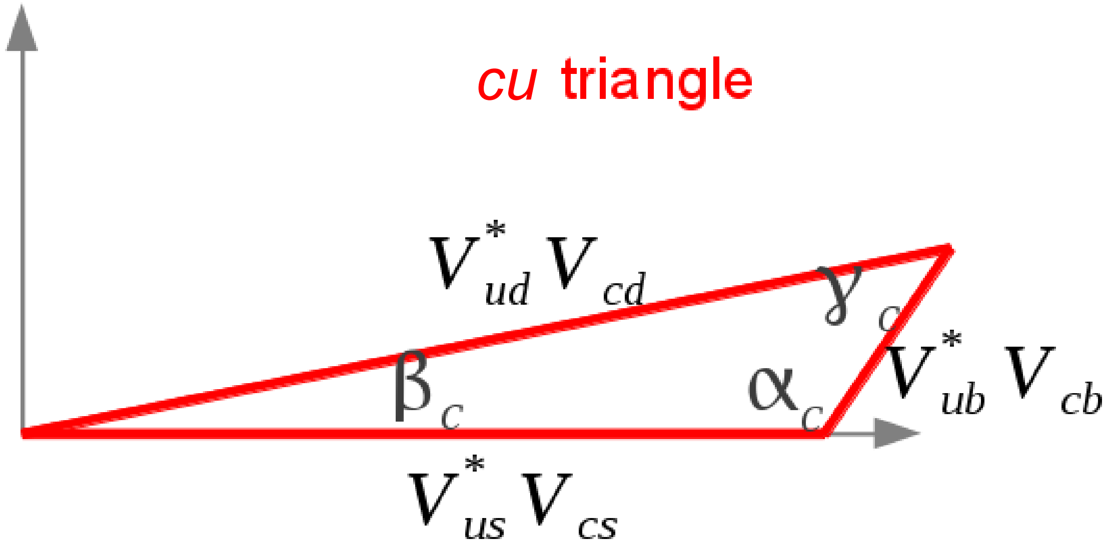








Precision I



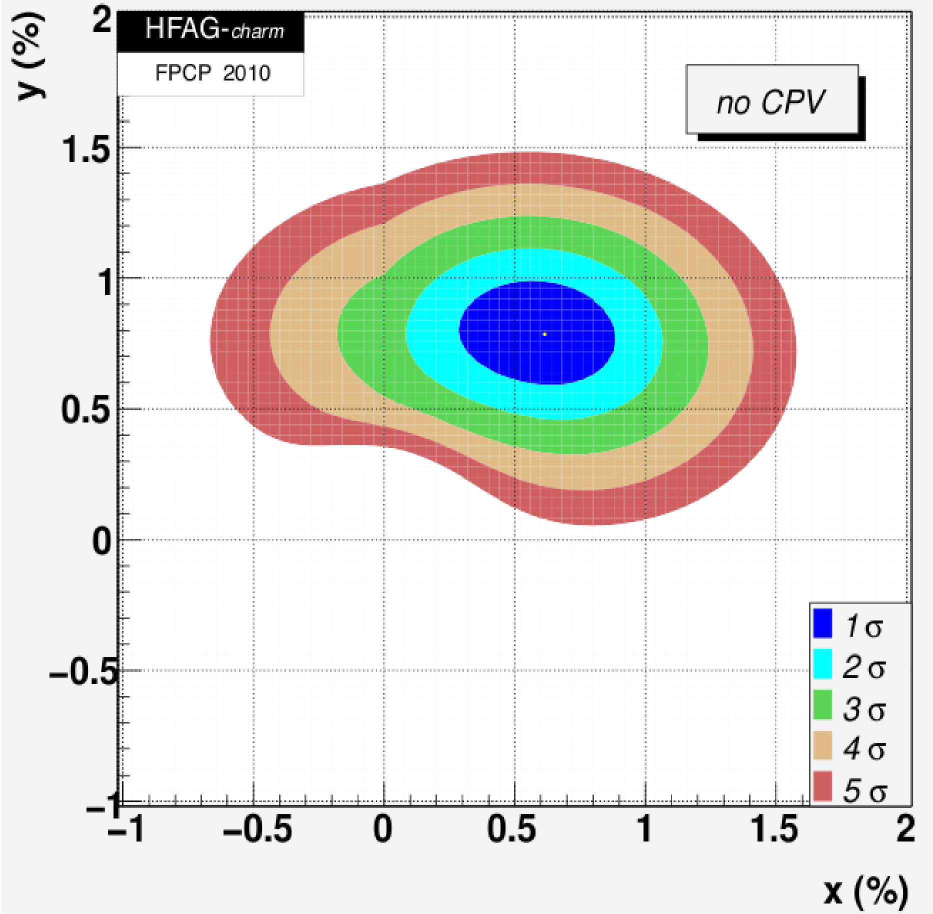
Parameter	$\Psi(3770)$ SL	$\Psi(3770)$ SL+K	$\Upsilon(4S)$ $\pi_s^\pm$	LHCb $\pi_s^\pm$	Belle II $\pi_s^\pm$
$\delta_{\phi_{\pi\pi}} = \delta_{arg(\lambda_{\pi\pi})}$	5.7°	2.4°	2.2°	2.3°	2.8°
$\delta_{\phi_{KK}} = \delta_{arg(\lambda_{KK})}$	3.5°	1.4°	1.3°	1.4°	1.7°
$\delta_{\phi_{CP}} = \delta_{\phi_{KK}-\phi_{\pi\pi}}$	6.6°	2.8°	2.6°	2.7°	3.2°
$\delta_{\beta_{c,eff}}$	3.3°	1.4°	1.3°	1.4°	1.6°

Precision II

$$x(\%) = x + \delta_x$$

no CPV assumption

Experiment/HFAG	$\delta_x(\phi = \pm 10^o)$	$\delta_x(\phi = \pm 20^o)$
Super$B$ $[\Upsilon(4S)]$		
$D^0 \to \pi^+\pi^-$	0.12%	0.06%
$D^0 \to K^+K^-$	0.07%	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		
$D^0 \to \pi^+\pi^-$ $(1.1\ \text{fb}^{-1})$	0.26%	0.13%
$D^0 \to K^+K^-$ $(1.1\ \text{fb}^{-1})$	0.15%	0.08%
$D^0 \to \pi^+\pi^-$ $(5.0\ \text{fb}^{-1})$	0.12%	0.06%
$D^0 \to K^+K^-$ $(5.0\ \text{fb}^{-1})$	0.07%	0.04%
Belle II		
$D^0 \to \pi^+\pi^-$	0.14%	0.07%
$D^0 \to K^+K^-$	0.09%	0.04%
HFAG	0.20%	



Super*B*
x(%)= x ± 0.07 (Φ=±10°)
x(%)= x ± 0.04 ((Φ=±20°)

HFAG
x(%)= 0.59 ± 0.20

Systematic uncertainties

HFAG

y(%)= 0.79 ± 0.13 → no CPV
y(%)= 0.81 ± 0.13 → no direct CPV

May the limited knowledge on the parameter *y* affect our time-dependent measurement?

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

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

Parameter	$\Psi(3770)$ SL	$\Psi(3770)$ SL+K	$\Upsilon(4S)$ $\pi_s^{\pm}$
$\delta_{\phi_{\pi\pi}}(sys.)$	0.5°	0.2°	0.05°
$\delta_{\phi_{KK}}(sys.)$	0.2°	0.1°	0.02°
$\delta_{\phi_{CP}}(sys.)$	0.54°	0.22°	0.05°
$\delta_{\beta_{c,eff}}(sys.)$	0.27°	0.11°	0.03°

Super*B*: Combined results

Since we are also interested in the sensitivity achievable with the full Super*B* program, we have combined the results obtained for the different center-of-mass energy.

$$\sigma_{tot} = \sqrt{\frac{\sigma_{\Psi(3770)} \times \sigma_{\Upsilon(4S)}}{\sigma_{\Psi(3770)} + \sigma_{\Upsilon(4S)}}}$$

Parameter	Statistical sensitivity	Systematic sensitivity
$\delta_x \ (D^0 \to \pi^+\pi^-)$	0.09%	-
$\delta_x \ (D^0 \to K^+K^-)$	0.05%	-
$\delta_{\phi_{\pi\pi}}$	1.62^o	0.14^o
$\delta_{\phi_{KK}}$	0.95^o	0.02^o
$\delta_{\phi_{CP}}$	1.91^o	0.05^o
$\delta_{\beta_{c,eff}}$	0.95^o	0.03^o

Super*B* will be able to perform a measurement of the mixing phase and of the β_c angle with a precision of ~1° and systematic uncertainties coming from the error on the parameter y will not be very relevant.

Conclusions

- We propose the time-dependent formalism to search for $\not{CP}$ in the charm sector.

- Our method is general and may be considered for the analysis in different experimental environments, especially after the latest results from LHC*b*.

- We have shown that with the time-dependent analysis a first measurement of the β_c angle in the charm triangle may be performed and that Super*B* may reach a precision of ~1° (including systematic from y).

- With this same analysis, if one express the asymmetry in terms of the parameters x and y which define the mixing, one may improve the precision on the determination of x with respect to the most recent HFAG value by a factor ~3-5.

- Super*B* will be very competitive with all the other facilities when looking for $\not{CP}$ and related issues in charm: **Super*D*?**

...Many Thanks...