

# ***IoP Joint HEPP and APP meeting 2012***

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## **The Time-Dependent CPV in Charm**



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# Time-Dependent CP Violation in Charm

- Time-dependent formalism
- CP eigenstates and flavour tagging
- Numerical Results

# Time-Dependent CP Violation in Charm

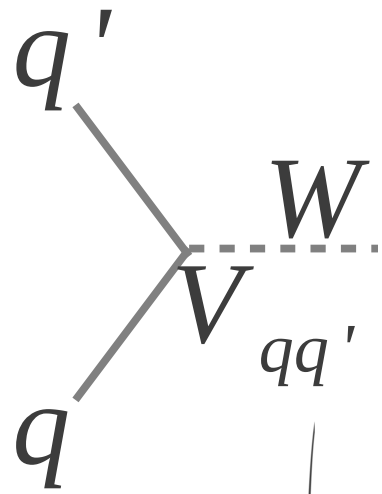
→ Time-dependent formalism

A. Bevan- G. Inguglia- B. Meadows:  
\*) *Phys. Rev. D* 84, 114009, arXiv:1106.5075  
G. Inguglia : *The time-dependent CP violation in charm*, to appear late this week

→ CP eigenstates and flavor tagging

→ Numerical Results

# Buras parametrization of the CKM matrix up to $\lambda^5$



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

PDG standard parametrization with

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

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

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

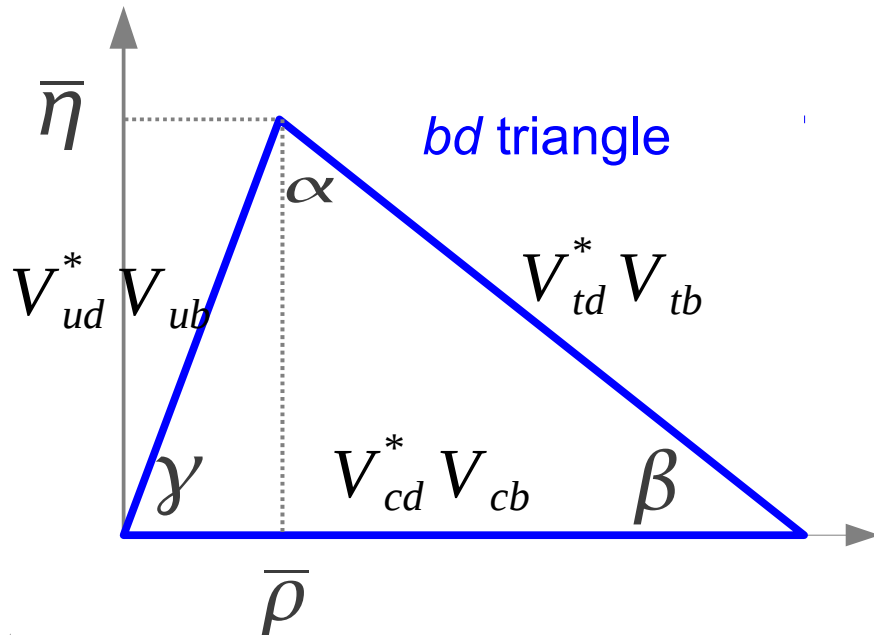
**TAB 1**

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

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

# Unitarity triangles

Unitarity conditions of the CKM matrix give rise to 6 unitarity triangles in the complex plane. We illustrate two here.



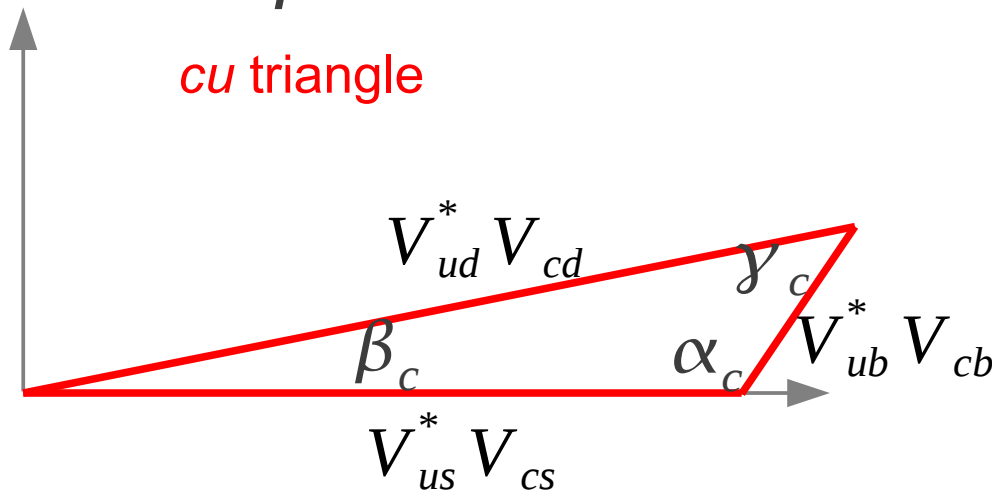
$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$$

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

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

**FROM EXPERIMENTS**

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



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

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

$$\beta_c = \arg\left[\frac{-V_{ud}^* V_{cd}^*}{V_{us}^* V_{cs}^*}\right] = (0.0350 \pm 0.0001)^\circ$$

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

**USE NAIVE AVERAGE OF FITTER GROUPS**

# Time-dependent formalism (i)

Neutral meson systems exhibit *mixing* of mass eigenstates

$|P_{1,2}\rangle$  where:

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

Mixing is often expressed in terms of the two Parameters:

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

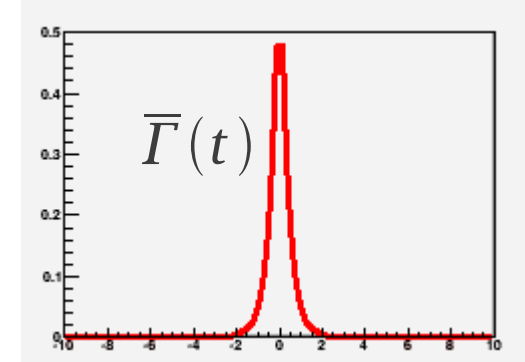
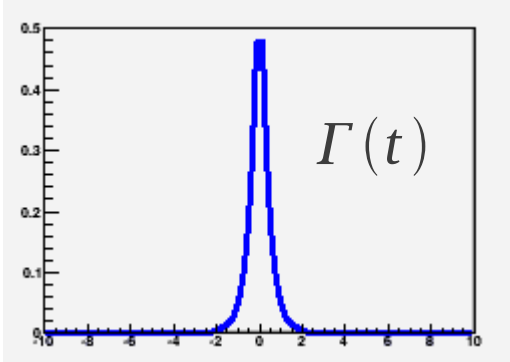
$$y = \frac{\Delta \Gamma}{2\Gamma}$$

$$|P_{1,2}\rangle = p|P^0\rangle \pm q|\bar{P}^0\rangle \quad \begin{matrix} \nearrow q^2 + p^2 = 1 \text{ normalize the wavefunction} \\ \searrow \frac{q}{p} = \sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}} \end{matrix}$$

$$H_{eff} = M - \frac{i}{2}\Gamma \quad \begin{matrix} \nearrow M_{11} = M_{22}, \Gamma_{11} = \Gamma_{22} \leftarrow \text{CPT INVARIANCE} \\ \rightarrow M_{11} = M_{22}, \Gamma_{11} = \Gamma_{22}, \Im\left[\frac{\Gamma_{12}}{M_{12}}\right] = 0 \leftarrow \text{CP INVARIANCE} \\ \searrow \Im\left[\frac{\Gamma_{12}}{M_{12}}\right] = 0 \leftarrow \text{T INVARIANCE} \end{matrix}$$

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

# Time-dependent formalism (ii)



The time-dependence (at charm threshold) of the decays of D mesons to final state  $|f\rangle$  are:

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

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

where:  $h_{+-} = 1 \pm e^{\Delta\Gamma \Delta t}$ ,  $\lambda_f = \frac{q}{p} \frac{\bar{A}}{A}$   **$\lambda_f$  very important!**

We now obtain the time-dependent CP asymmetry

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

Where we include mistag probability " $\omega$ " and dilution " $D$ ".

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A. Bevan- G. Inguglia- B. Meadows:  
\*) *Phys. Rev. D* **84**, 114009, *arXiv:1106.5075*  
G. Inguglia:  
\*) *arXiv:1109.4494*  
\*) *The time-dependent CP violation in charm*,  
to appear late this week



# Analysis of CP eigenstates (i)

When exploring CP violation, ignoring long distance effects, the parameter  $\lambda$  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  $D^0 \bar{D}^0$  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

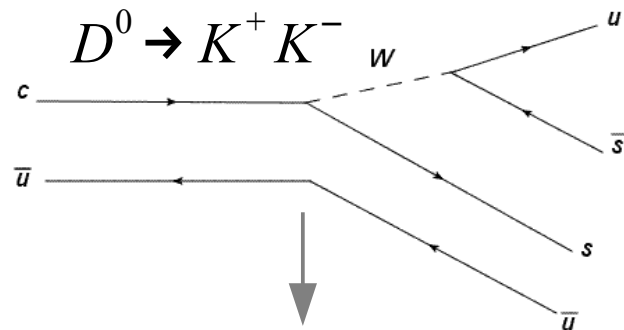
$$D^0 \rightarrow K^+ K^-, \pi^+ \pi^-, K^+ K^- K^0, K^0 \pi^+ \pi^-$$

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

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

# $D^0 \rightarrow K^+ K^-$ vs $D^0 \rightarrow \pi^+ \pi^-$

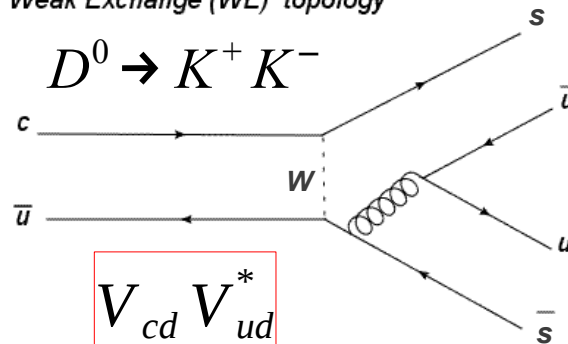
Tree topology



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

**Real**

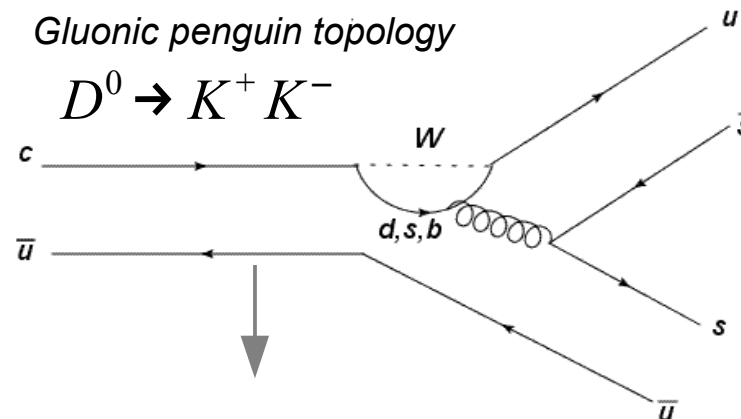
Weak Exchange (WE) topology



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

**Assume WE is small**

Gluonic penguin topology



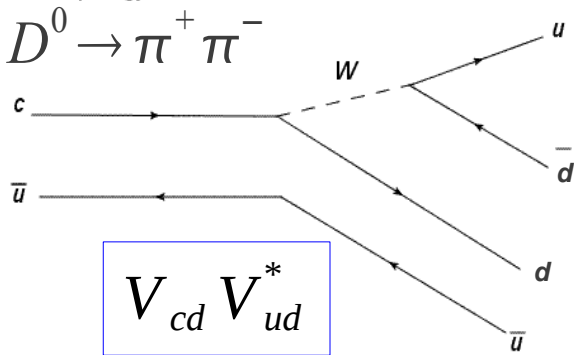
$$V_{cd} V_{ud}^* + V_{cs} V_{us}^* + V_{cb} V_{ub}^*$$

**Real Negligible**

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

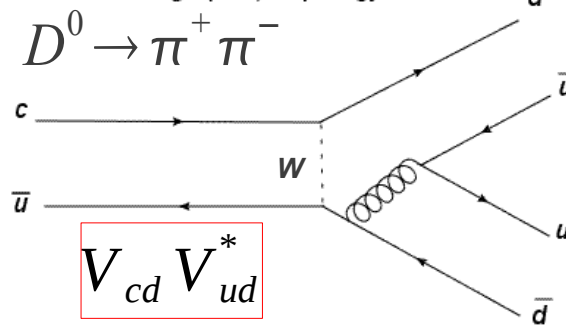
$$V_{cd} V_{ud}^* = -\lambda + \frac{\lambda^3}{2} + \frac{\lambda^5}{8} + \frac{A^2 \lambda^5}{2} [1 - 2(\bar{\rho} + i\bar{\eta})]$$

Tree topology



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

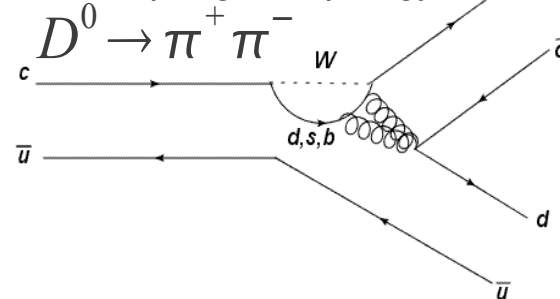
Weak Exchange (WE) topology



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

**WE- same phase as T**

Gluonic penguin topology

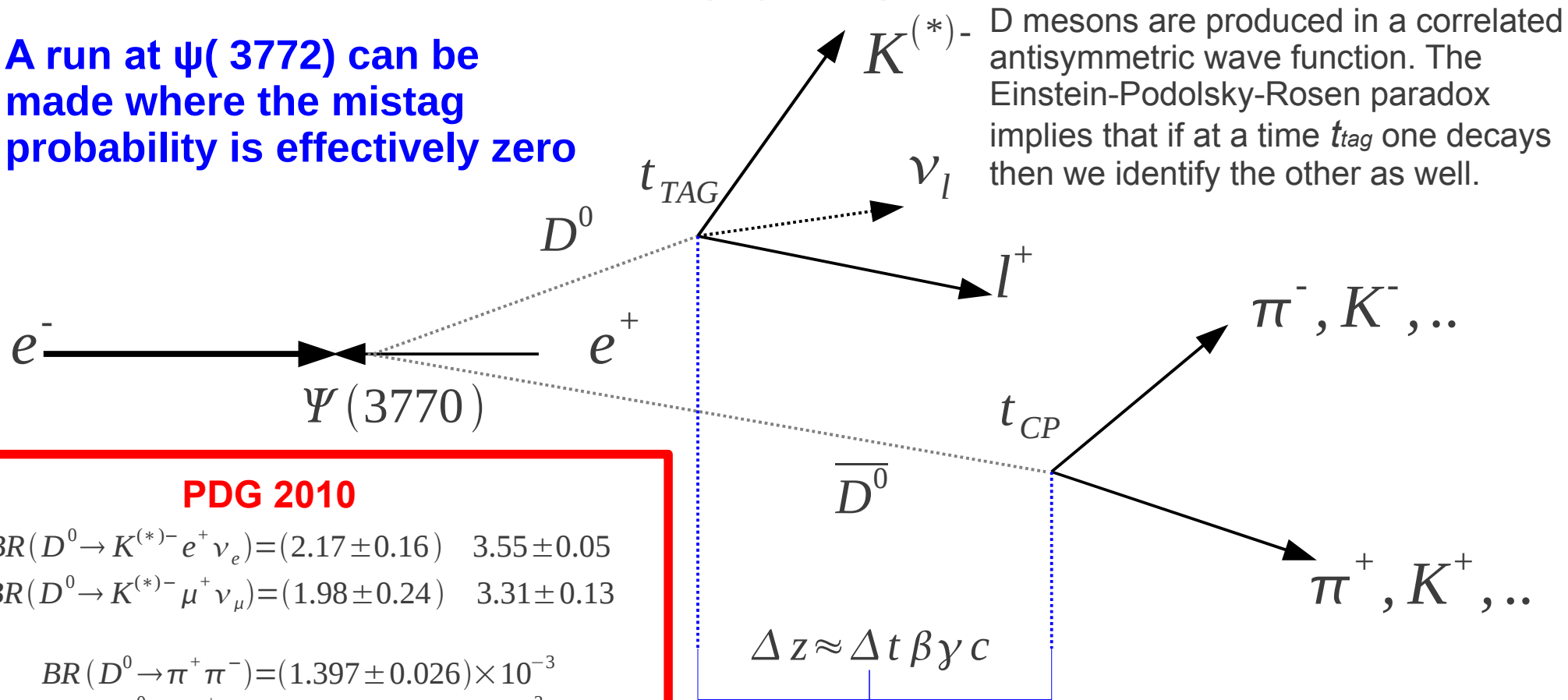


$$V_{cd} V_{ud}^* + V_{cs} V_{us}^* + V_{cb} V_{ub}^*$$

**Real Negligible**

# Correlated mesons: semi-leptonic tagging

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



## PDG 2010

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

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

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

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

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

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

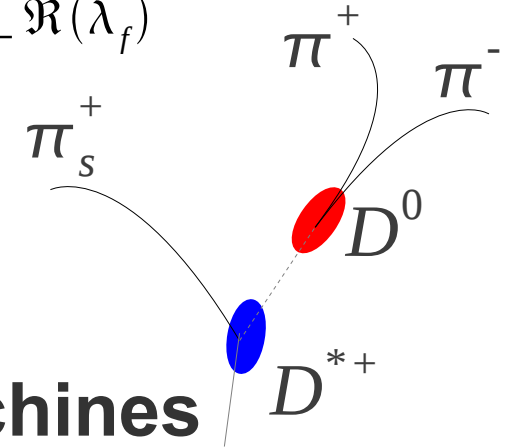
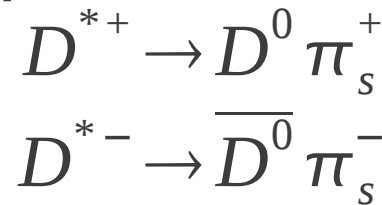
# Uncorrelated $D^0$ mesons

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

Mistag probability and dilution become important

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

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



$e^+e^-$  machines at  $\Upsilon(4S)$  and hadron machines

$D^*$  from  $e^+e^- \rightarrow c\bar{c}$  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

A. Bevan- G. Inguglia- B. Meadows:

\*) *Phys. Rev. D* 84, 114009, [arXiv:1106.5075](https://arxiv.org/abs/1106.5075)

\*) *Issues on TDCPV in Charm (to appear soon..)*

G. Inguglia :

\*) *The time-dependent CP violation in charm*, to appear late this week

# Expected number of (tagged) events

LHCb $5.0 \text{ fb}^{-1}$	$4.9 \times 10^6$	$D^0 \rightarrow \pi^+ \pi^-$	
Estimated from arXiv:1112.0938 [hep-ex]	$1.9 \times 10^7$	$D^0 \rightarrow K^+ K^-$	$\pi$ -T

Belle II $50.0 \text{ ab}^{-1}$	$4.4 \times 10^6$	$D^0 \rightarrow \pi^+ \pi^-$	
$\Upsilon(4S)$	$1.0 \times 10^7$	$D^0 \rightarrow K^+ K^-$	$\pi$ -T
Estimated from Phys. Rev. D 78, 011105 (2008)			

SuperB $1.0 \text{ ab}^{-1}$	$9.8 \times 10^5$	$D^0 \rightarrow \pi^+ \pi^-$	SL-T
$\Psi(3770)$	$4.8 \times 10^6$	$D^0 \rightarrow \pi^+ \pi^-$	K-T
Estimated from Phys. Rev. D 78, 012001 (2008)	$2.8 \times 10^6$	$D^0 \rightarrow K^+ K^-$	SL-T
	$1.2 \times 10^7$	$D^0 \rightarrow K^+ K^-$	K-T

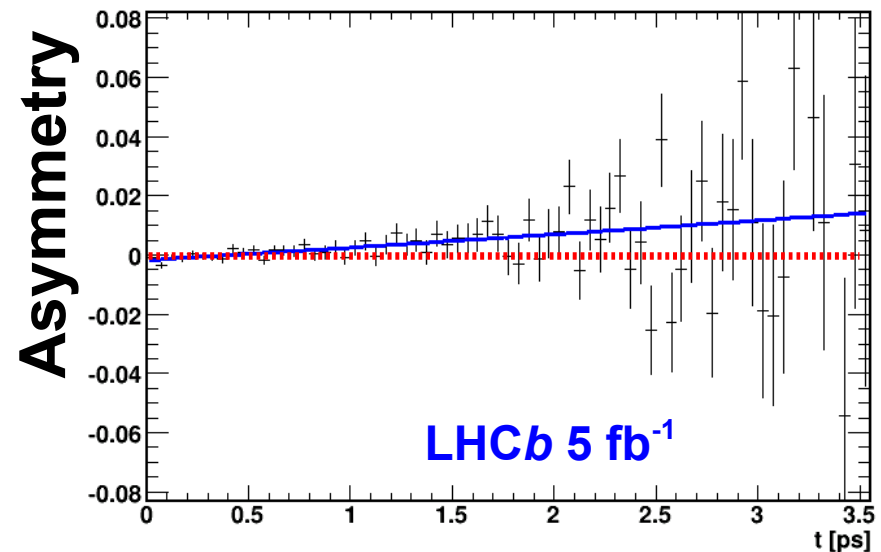
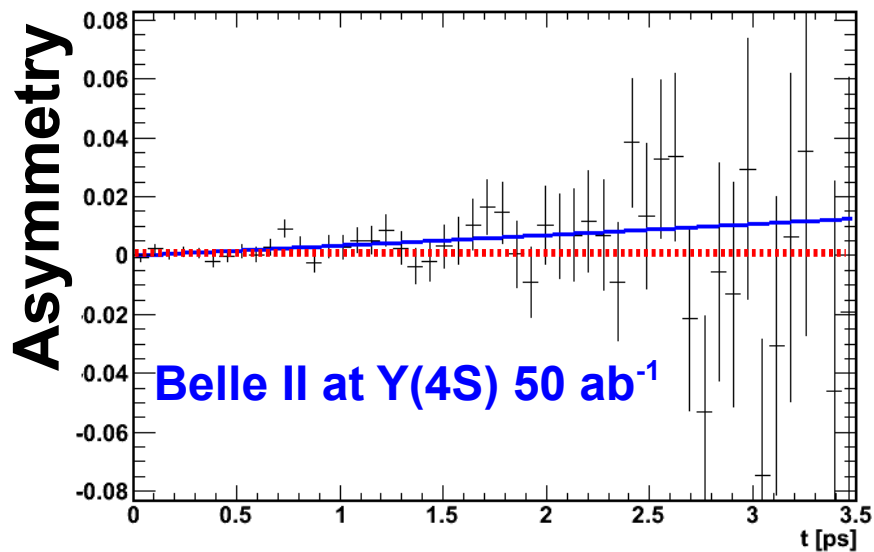
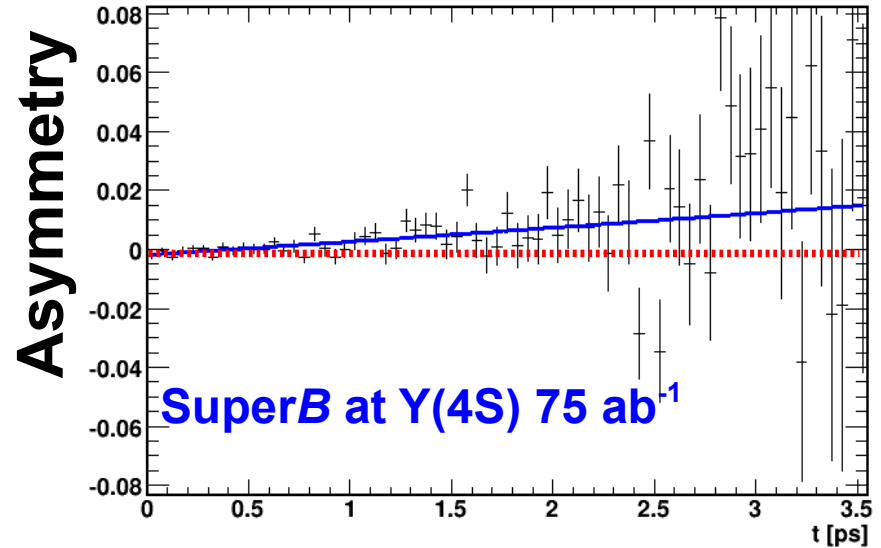
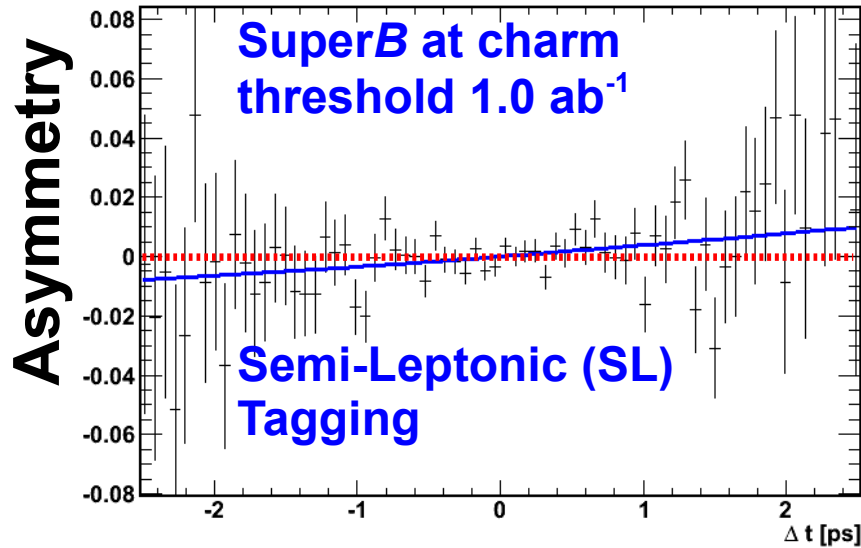
SuperB $75.0 \text{ ab}^{-1}$	$6.6 \times 10^6$	$D^0 \rightarrow \pi^+ \pi^-$	
$\Upsilon(4S)$	$1.5 \times 10^7$	$D^0 \rightarrow K^+ K^-$	$\pi$ -T
Estimated from Phys. Rev. D 78, 011105 (2008)			

$\pi$ -T indicates that the  $D^0$  mesons are tagged using the electrical charge of the associated short pion (LHCb/Belle/SuperB)

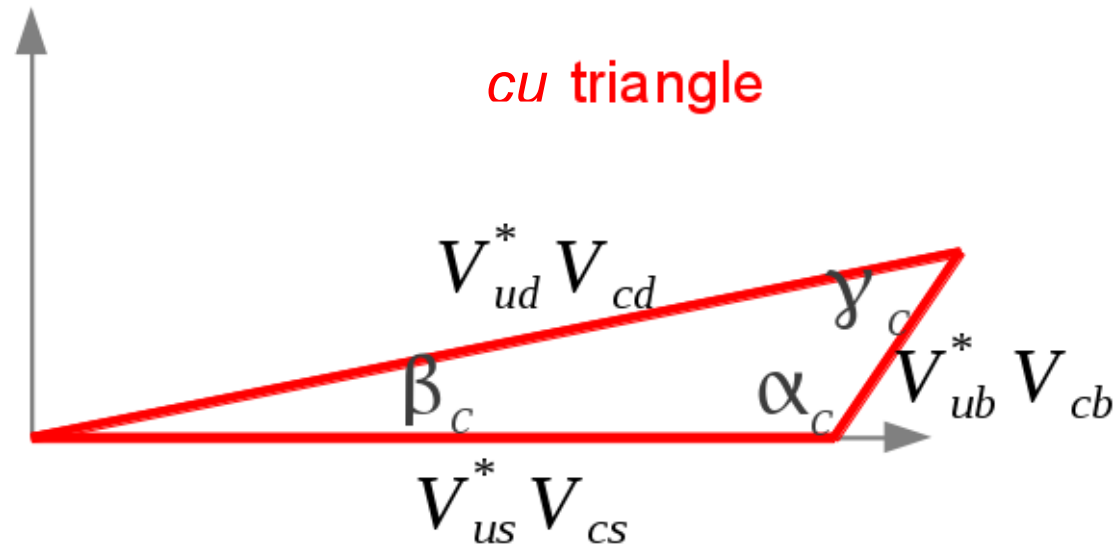
SL-T refers to semi-leptonic tag at charm threshold and K-T to the Kaon tag at charm threshold (SuperB only)

# TDCPV in charm: numerical analysis

$$A_{D^0 \rightarrow \pi^+ \pi^-}^{Phys}(\Delta t) = \frac{\overline{\Gamma^{Phys}}(\Delta t) - \Gamma^{Phys}(\Delta t)}{\overline{\Gamma^{Phys}}(\Delta t) + \Gamma^{Phys}(\Delta t)}$$



# Precision I



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

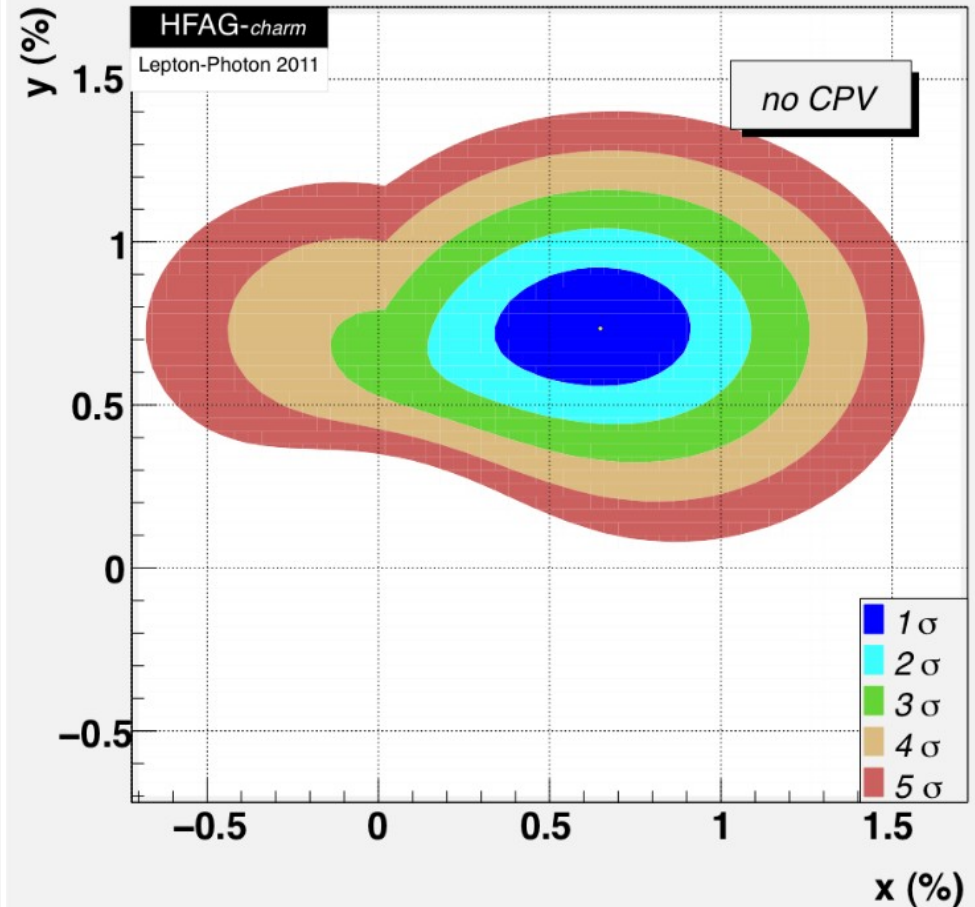


# Precision II

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

*no CPV assumption*

Experiment/HFAG	$\sigma_x(\phi = \pm 10^\circ)$	$\sigma_x(\phi = \pm 20^\circ)$
SuperB [ $\Upsilon(4S)$ ]		
$D^0 \rightarrow \pi^+\pi^-$	0.12%	0.06%
$D^0 \rightarrow K^+K^-$	0.08%	0.04%
SuperB [ $\Psi(3770)$ ]		
$D^0 \rightarrow \pi^+\pi^- (SL)$	0.30%	0.15%
$D^0 \rightarrow \pi^+\pi^- (SL + K)$	0.13%	0.06%
$D^0 \rightarrow K^+K^- (SL)$	0.19%	0.10%
$D^0 \rightarrow K^+K^- (SL + K)$	0.08%	0.04%
LHCb		
$D^0 \rightarrow \pi^+\pi^- (1.1 \text{ fb}^{-1})$	0.40%	0.20%
$D^0 \rightarrow K^+K^- (1.1 \text{ fb}^{-1})$	0.22%	0.11%
$D^0 \rightarrow \pi^+\pi^- (5.0 \text{ fb}^{-1})$	0.15%	0.08%
$D^0 \rightarrow K^+K^- (5.0 \text{ fb}^{-1})$	0.09%	0.04%
Belle II		
$D^0 \rightarrow \pi^+\pi^-$	0.14%	0.07%
$D^0 \rightarrow K^+K^-$	0.10%	0.04%
HFAG	0.18%	



**Time-Dependent Studies**  
 $x(\%) = x \pm 0.08 (\Phi = \pm 10^\circ)$   
 $x(\%) = x \pm 0.04 (\Phi = \pm 20^\circ)$

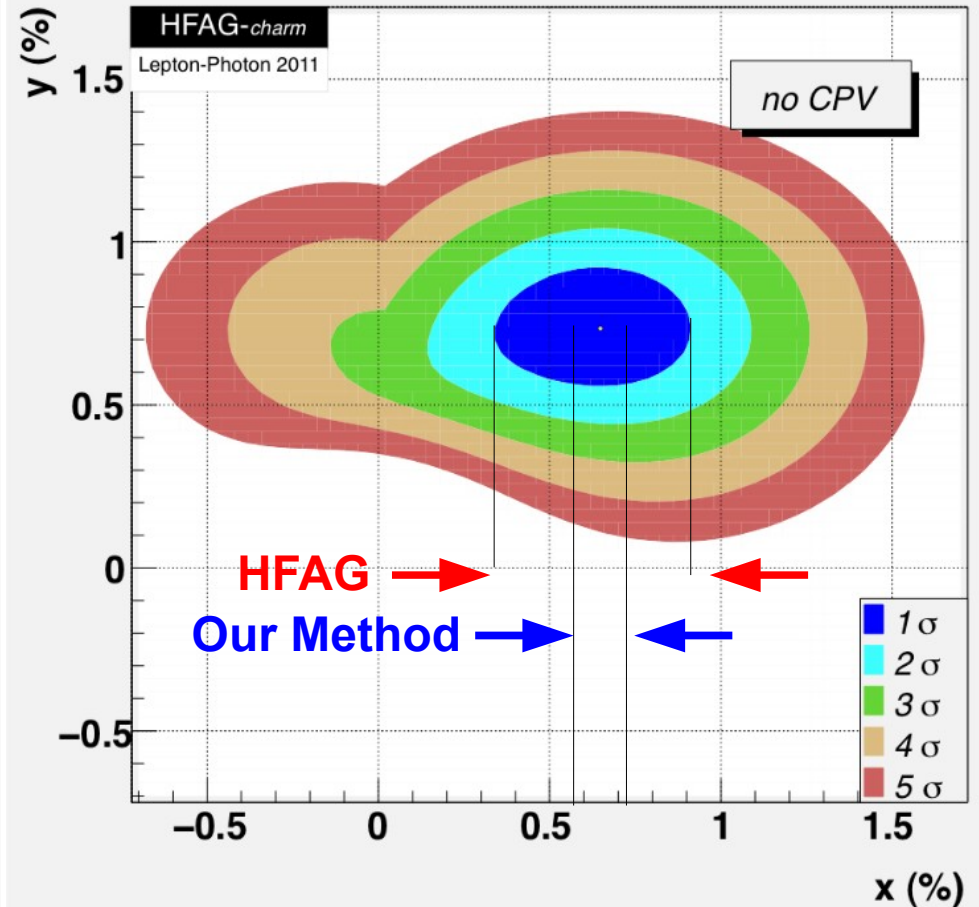
**HFAG**  
 $x(\%) = 0.65 \pm 0.18$

# Precision III

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

*no CPV assumption*

Experiment/HFAG	$\sigma_x(\phi = \pm 10^\circ)$	$\sigma_x(\phi = \pm 20^\circ)$
SuperB [ $\Upsilon(4S)$ ]		
$D^0 \rightarrow \pi^+\pi^-$	0.12%	0.06%
$D^0 \rightarrow K^+K^-$	0.08%	0.04%
SuperB [ $\Psi(3770)$ ]		
$D^0 \rightarrow \pi^+\pi^- (SL)$	0.30%	0.15%
$D^0 \rightarrow \pi^+\pi^- (SL + K)$	0.13%	0.06%
$D^0 \rightarrow K^+K^- (SL)$	0.19%	0.10%
$D^0 \rightarrow K^+K^- (SL + K)$	0.08%	0.04%
LHCb		
$D^0 \rightarrow \pi^+\pi^- (1.1 \text{ fb}^{-1})$	0.40%	0.20%
$D^0 \rightarrow K^+K^- (1.1 \text{ fb}^{-1})$	0.22%	0.11%
$D^0 \rightarrow \pi^+\pi^- (5.0 \text{ fb}^{-1})$	0.15%	0.08%
$D^0 \rightarrow K^+K^- (5.0 \text{ fb}^{-1})$	0.09%	0.04%
Belle II		
$D^0 \rightarrow \pi^+\pi^-$	0.14%	0.07%
$D^0 \rightarrow K^+K^-$	0.10%	0.04%
HFAG	0.18%	



With the time-dependent analysis it is possible to add information on mixing of  $D^0$  meson and improve the current limits

# Conclusions

- Discussed the time-dependent formalism to search for  $\mathcal{CP}$  in the charm sector.
- Method is general (cf.  $B_d^0$  &  $B_s^0$  TDCPV) and may be considered for the analysis in different experimental environments, especially after the latest results from LHCb.
- We have shown that with the time-dependent analysis a first measurement of  $\beta_{c,eff}$  in the charm triangle may be performed and that SuperB may reach a precision of  $\sim 1.4^\circ$  (need to clarify hadronic uncertainties).
- With this same analysis, the asymmetry can be expressed in terms of the parameters  $x$  and  $y$  which define the mixing, this allows to improve the precision on the determination of  $x$  with respect to the most recent HFAG value by a factor  $\sim 2$ .
- Future  $e^+e^-$  experiments like SuperB and Belle II will be competitive with the LHC.

*...Many Thanks...*