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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 flavor tagging

→Numerical Results

Time-Dependent CP Violation in Charm

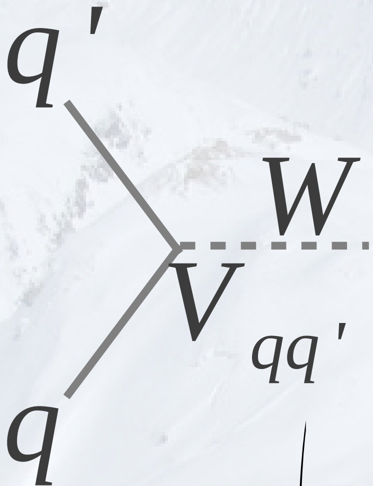
→Time-dependent formalism

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

→CP eigenstates and flavor tagging

→Numerical Results

Buras parametrization of the CKM matrix up to λ⁵



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

PDG standard parametriazation with

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

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

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

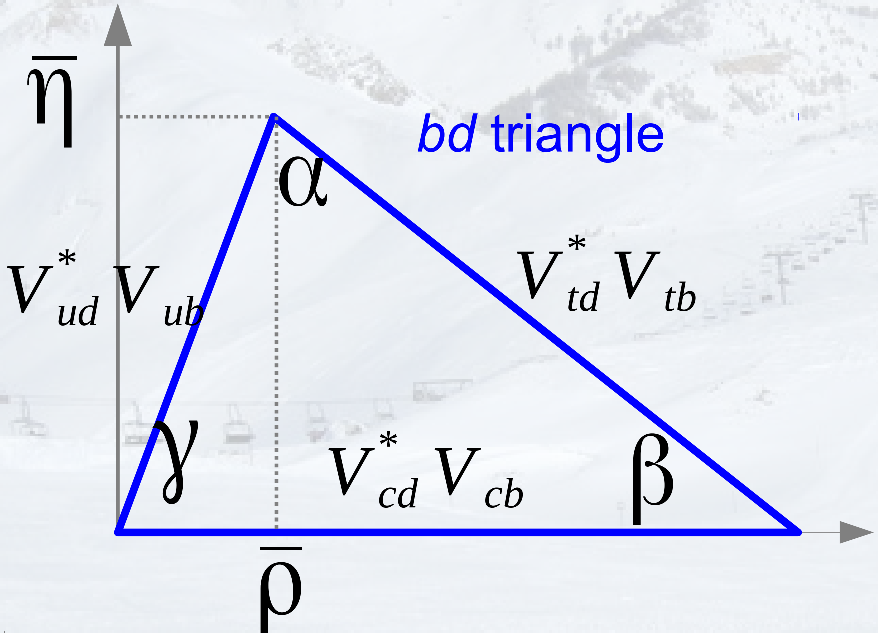
TAB 1

	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 give rise to 6 unitarity triangles in the complex plane. We illustrate two here.



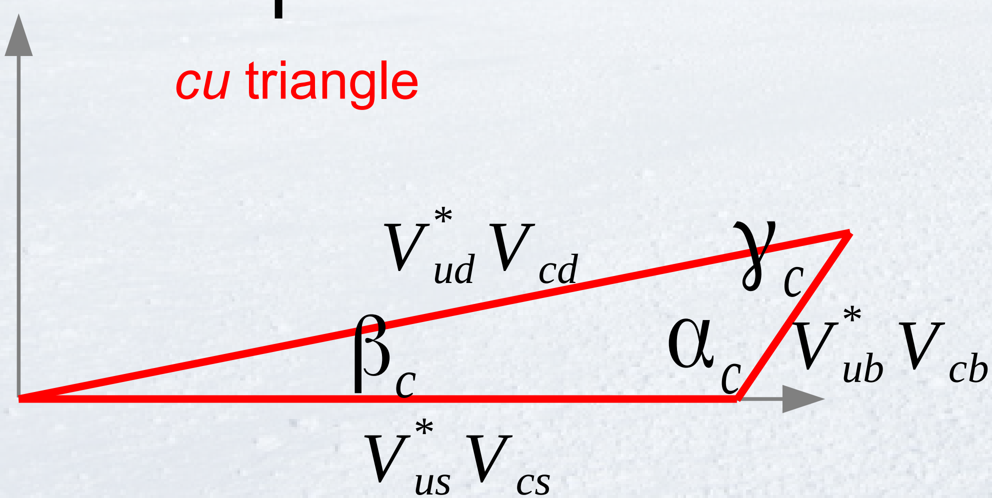
$$V^*_{ud}V_{ub}+V^*_{cd}V_{cb}+V^*_{td}V_{tb}=0$$

$$\alpha=arg[\frac{-V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}]=(91.4\pm6.1)^o$$

$$\beta=arg[\frac{-V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}]=(21.1\pm0.9)^o$$

$$\gamma=arg[\frac{-V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}]=(74\pm11)^o$$

FROM EXPERIMENTS



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

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

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

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

USE NAIVE AVERAGE OF FITTER GROUPS

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:

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

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

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

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

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

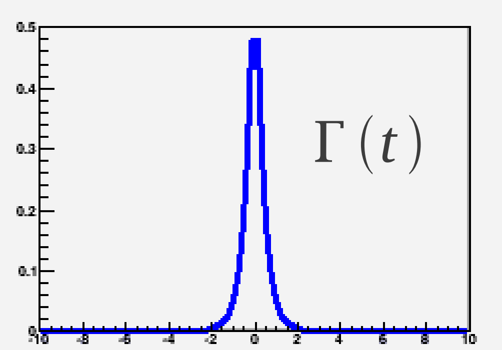
$$H_{eff}=M-\frac{i}{2}\Gamma$$

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

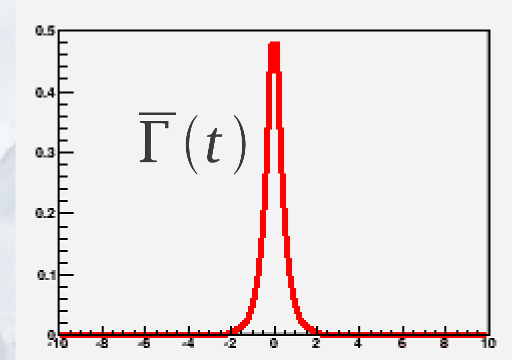
$$M_{11}=M_{22},\Gamma_{11}=\Gamma_{22},\Im\left[\frac{\Gamma_{12}}{M_{12}}\right]=0 \quad \leftarrow \quad \textit{CP INVARIANCE}$$

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

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



Time-dependent formalism (ii)



The time-dependence of decays of P^0 (P^0) to final state |f > are:

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

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

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

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 include mistag probability

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) Phys. Rev.* ***D* *84, 114009, arXiv:1106.5075*
G. Inguglia:
**) arXiv:1109.4494*

→Numerical Results

Analysis of CP eigenstates (i)

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

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

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

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

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

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

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

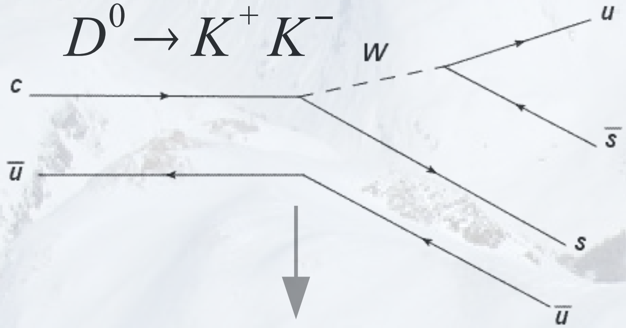
Assuming negligible the contribution due to P/CS/WE amplitudes, then:

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

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

Tree topology

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

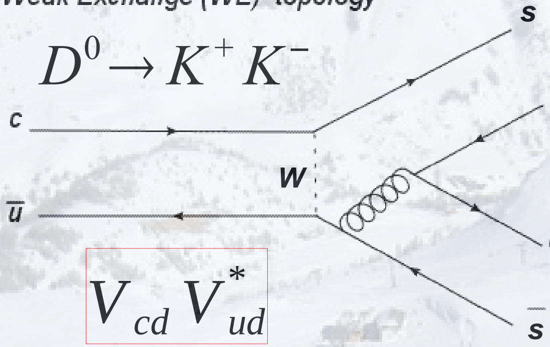


$V_{cs}V_{us}^*$

Real

Weak Exchange (WE) topology

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

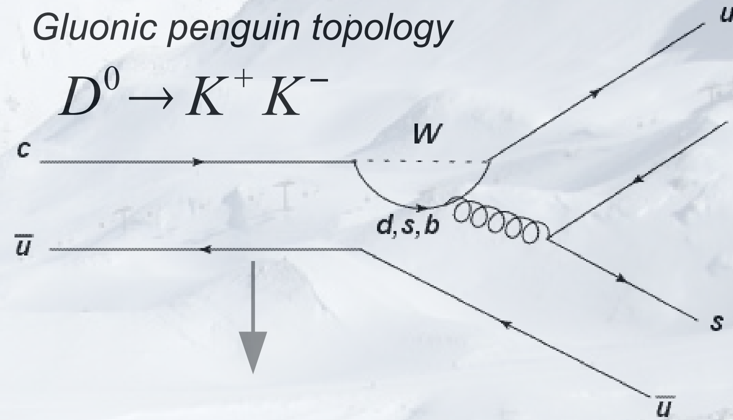


$V_{cd}V_{ud}^*$

Assume WE is small

Gluonic penguin topology

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



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

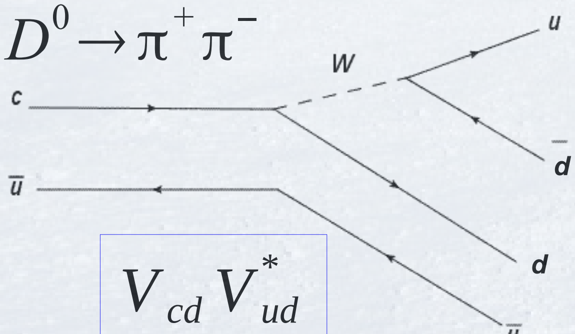
Real **Negligible**

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

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

Tree topology

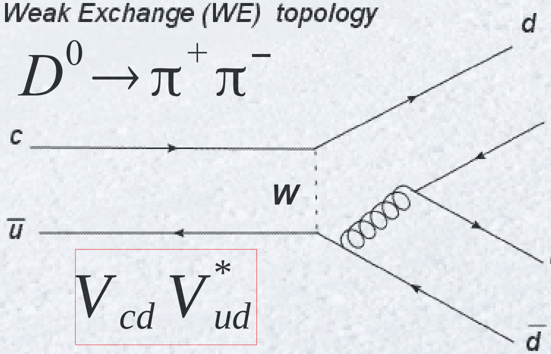
$D^0 \to \pi^+ \pi^-$



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

Weak Exchange (WE) topology

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

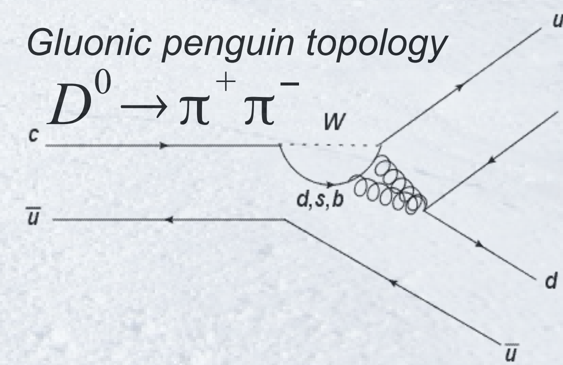


$V_{cd}V_{ud}^*$

WE- same phase as T

Gluonic penguin topology

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



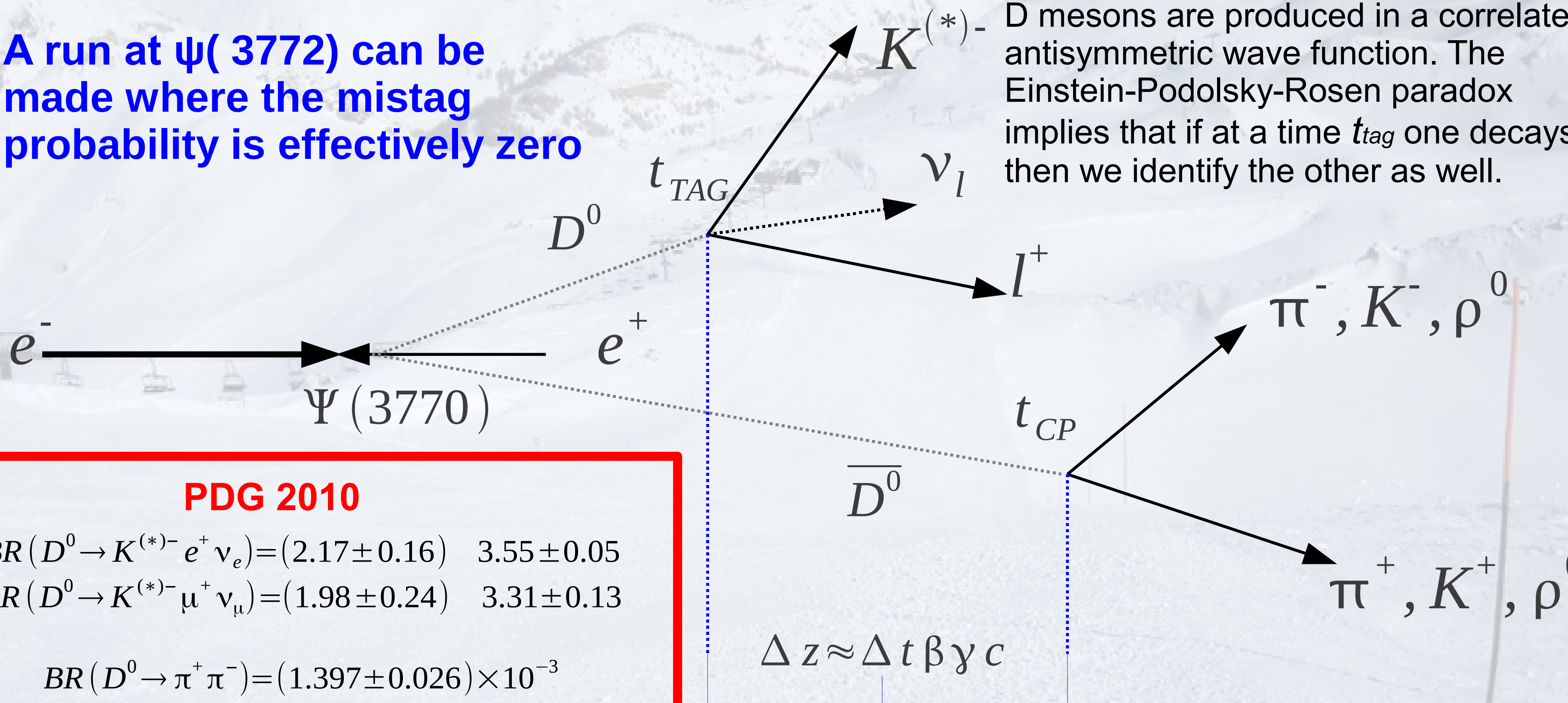
Real **Negligible**

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

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

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

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

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

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

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

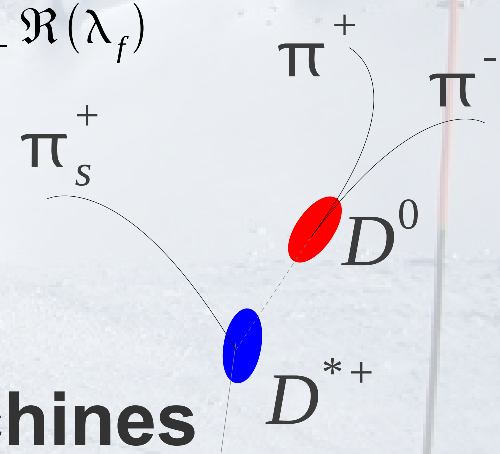
$$A(t)=\frac{\overline{\Gamma}(t)-\Gamma(t)}{\overline{\Gamma}(t)+\Gamma(t)}=2e^{\Delta\Gamma t/2}\frac{(|\lambda_f|^2-1)\cos\Delta M\,t+2\Im(\lambda_f)\sin\Delta M\,t}{(1+|\lambda_f|^2)(1+e^{\Delta\Gamma t})+2\Re(\lambda_f)(1-e^{\Delta\Gamma t})}$$

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.

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*)*Phys. Rev.* ***D*** *84, 114009, arXiv:1106.5075*
*)*Numerical Issues on TDCPV in Charm (to appear soon..)*

Expected number of (tagged) events

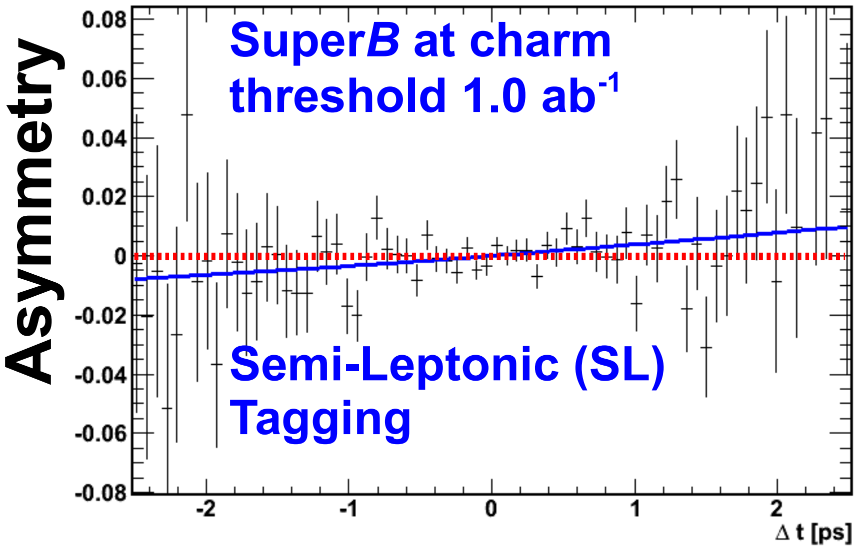
LHC*b* *5.0 fb^{-1}* Estimated from arXiv:1112.0938 [hep-ex]	4.9×10^6	$D^0\rightarrow\pi^+\pi^-$	**π-T**
	1.9×10^7	$D^0\rightarrow K^+K^-$	**π-T**
Belle II *50.0 ab^{-1}* Estimated from Phys. Rev. D 78, 011105 (2008)	4.4×10^6	$D^0\rightarrow\pi^+\pi^-$	**π-T**
	1.0×10^7	$D^0\rightarrow K^+K^-$	**π-T**
Super*B* *1.0 ab^{-1}* $\Psi(3770)$ Estimated from Phys. Rev. D 78, 012001 (2008)	9.8×10^5	$D^0\rightarrow\pi^+\pi^-$	**SL-T**
	4.8×10^6	$D^0\rightarrow\pi^+\pi^-$	**K-T**
	2.5×10^6	$D^0\rightarrow K^+K^-$	**SL-T**
	1.2×10^7	$D^0\rightarrow K^+K^-$	**K-T**
Super*B* *75.0 ab^{-1}* $\Upsilon(4S)$ Estimated from Phys. Rev. D 78, 011105 (2008)	6.6×10^6	$D^0\rightarrow\pi^+\pi^-$	**π-T**
	1.5×10^7	$D^0\rightarrow K^+K^-$	**π-T**

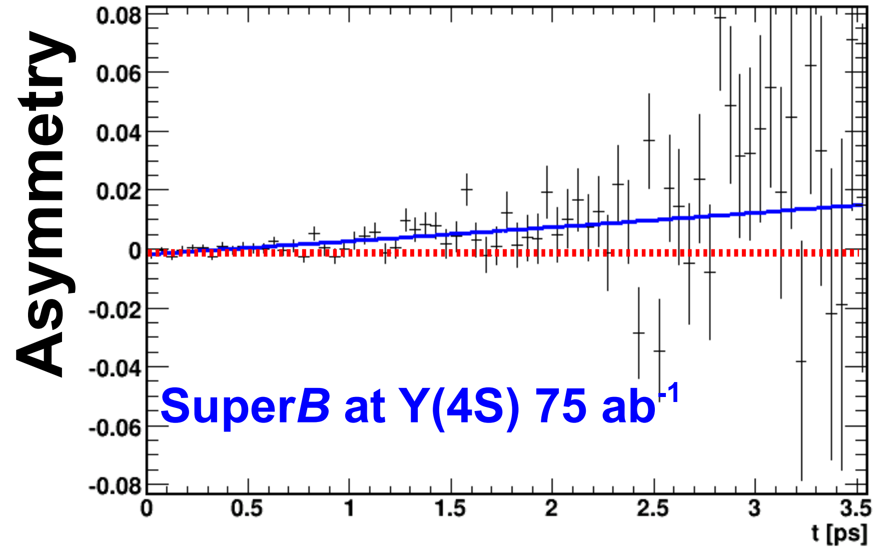
π-T indicates that the D^0 mesons are tagged using the electrical charge of the associated short pion (LHC*b*/Belle/Super*B*)

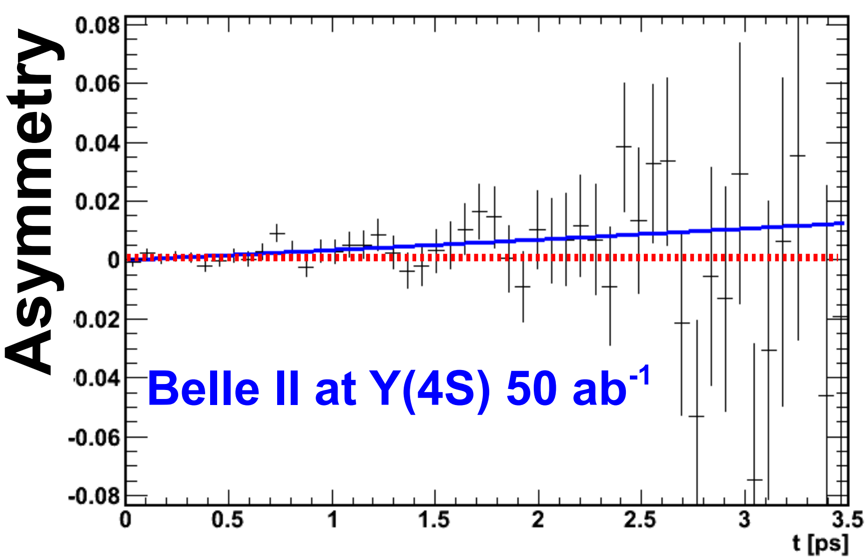
SL-T refers to semi-leptonic tag at charm threshold and **K-T** to the Kaon tag at charm thereshold (Super*B* only)

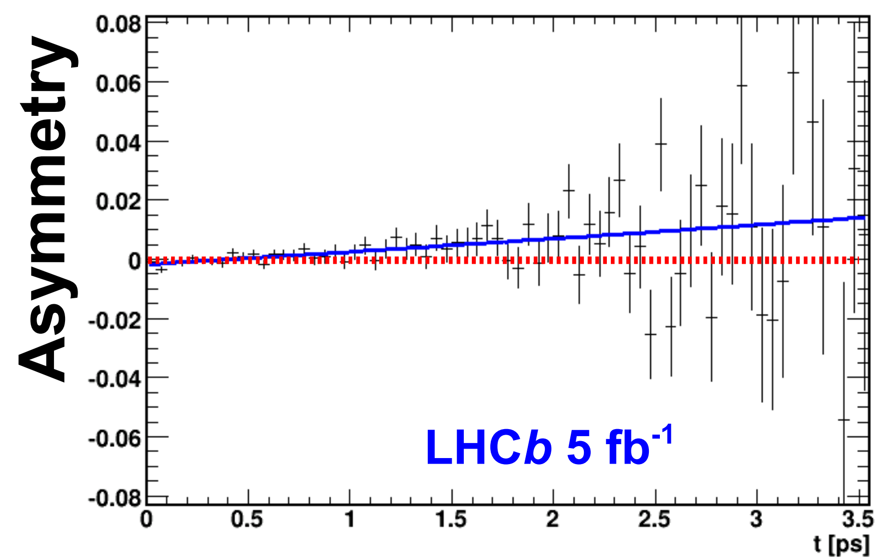
TDCPV in charm: numerical analysis

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

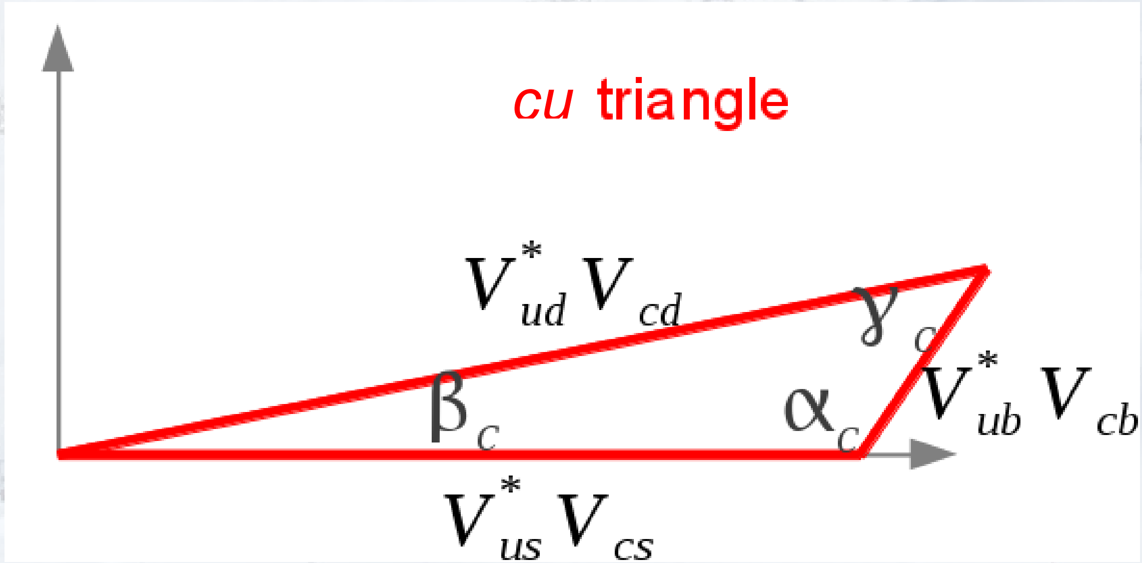








Precision I



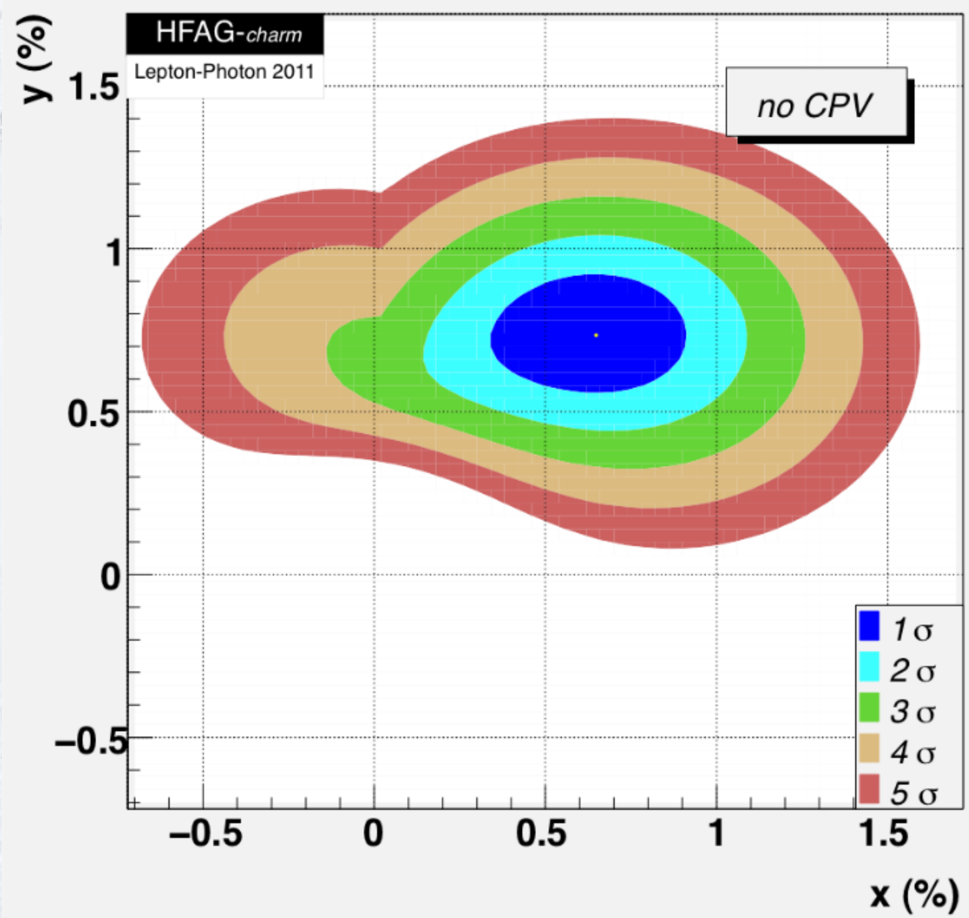
Parameter	Super$B$ $\Psi(3770)$ SL	Super$B$ $\Psi(3770)$ SL+K	Super$B$ $\Upsilon(4S)$ $\pi_s^{\pm}$	LHCb $\pi_s^{\pm}$	Belle II $\pi_s^{\pm}$
$\sigma_{\phi_{\pi\pi}} = \sigma_{arg(\lambda_{\pi\pi})}$	5.7°	2.4°	2.2°	3.0°	2.8°
$\sigma_{\phi_{KK}} = \sigma_{arg(\lambda_{KK})}$	3.5°	1.4°	1.6°	1.8°	1.8°
$\sigma_{\beta_{c,eff}}$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

Precision II

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

no CPV assumption

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		
$D^0 \to \pi^+\pi^-$ $(1.1\ \text{fb}^{-1})$	0.40%	0.20%
$D^0 \to K^+K^-$ $(1.1\ \text{fb}^{-1})$	0.22%	0.11%
$D^0 \to \pi^+\pi^-$ $(5.0\ \text{fb}^{-1})$	0.15%	0.08%
$D^0 \to K^+K^-$ $(5.0\ \text{fb}^{-1})$	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	0.18%	



Super*B*
x(%)= x ± 0.08 (Φ=±10º)
x(%)= x ± 0.04 ((Φ=±20º)

HFAG
x(%)= 0.65 ± 0.18

Precision II

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

no CPV assumption

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%
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$D^0 \to \pi^+\pi^-(SL+K)$	0.13%	0.06%
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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%
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Belle II		
$D^0 \to \pi^+\pi^-$	0.14%	0.07%
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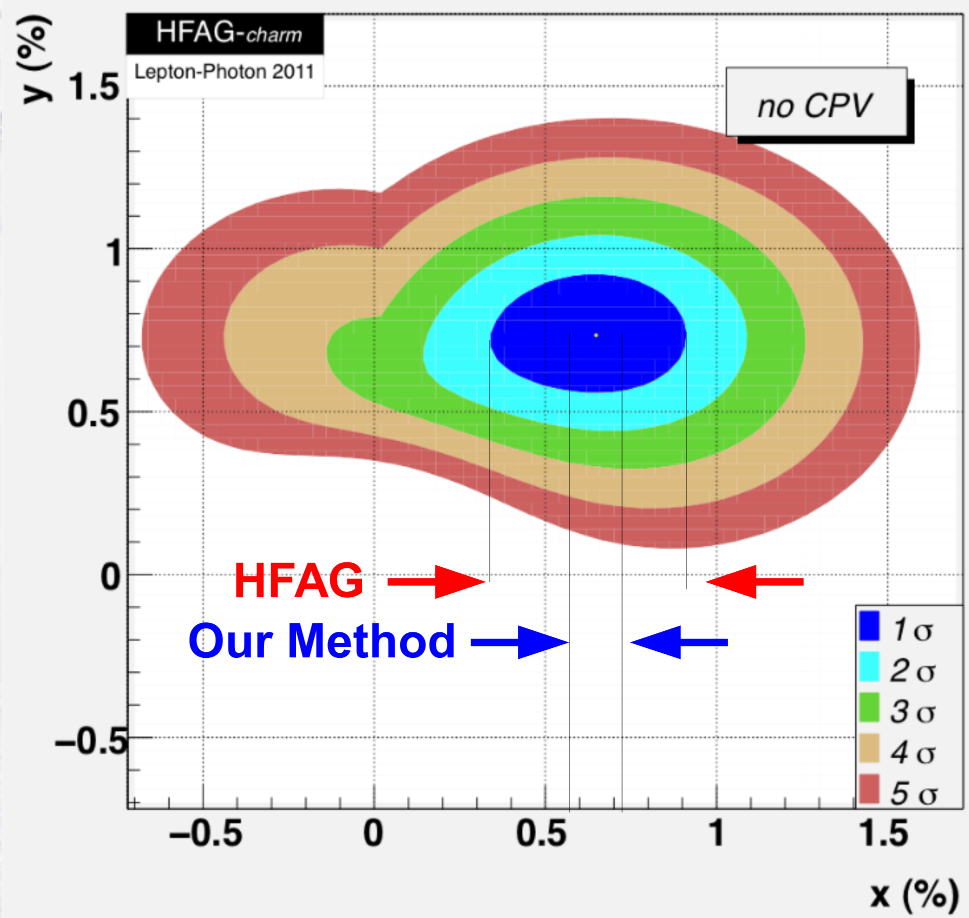
HFAG	0.18%	



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 $\not{CP}$ 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 LHC*b*.
- 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 Super*B* may reach a precision of ~1.4° (need to clarify hadronic uncertainties).
- 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 ~2.
- Future e^+e^- experiments like Super*B* will be competitive with the LHC.


...Many Thanks...