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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
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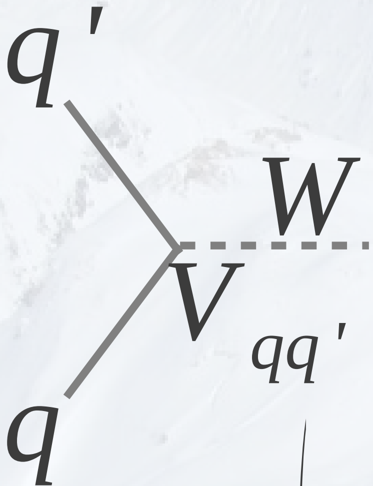
- →Numerical Results

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

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

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

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

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

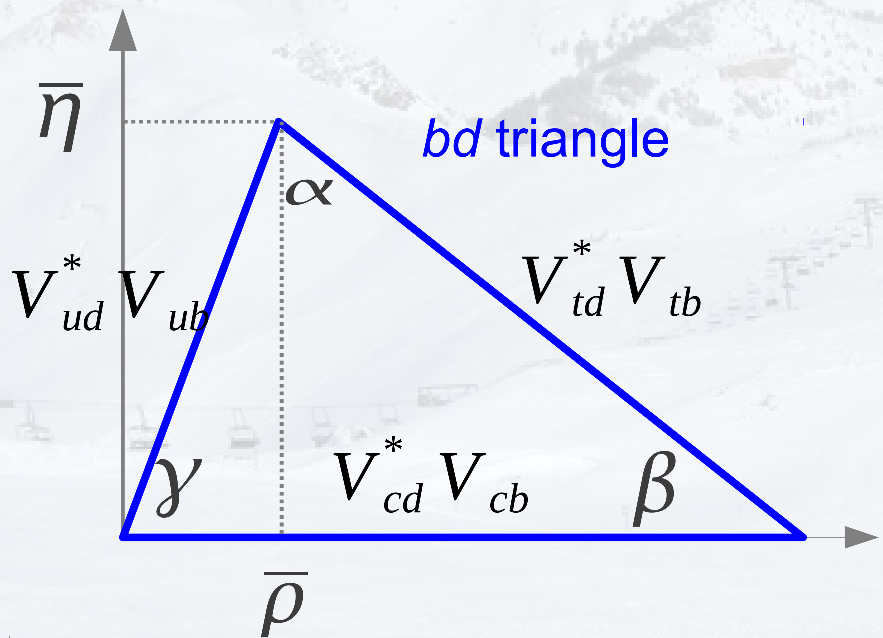
TAB 1

	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.



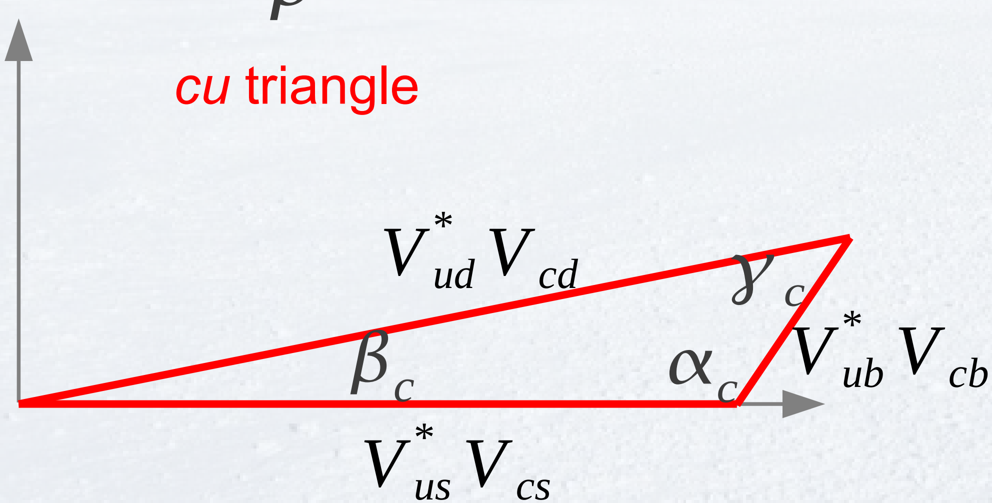
$$V^*_{ud}V_{ub} + V^*_{cd}V_{cb} + V^*_{td}V_{tb} = 0$$

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

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

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

FROM EXPERIMENTS



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

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

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

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

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:

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

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

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

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

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

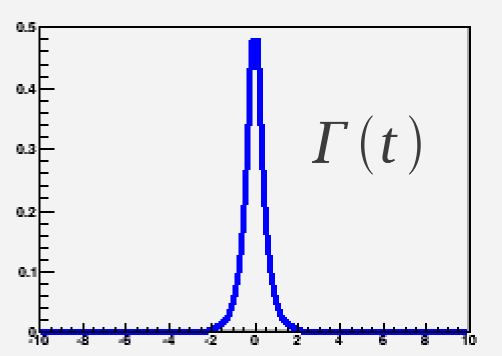
$$H_{eff}=M-\frac{i}{2}\Gamma$$

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

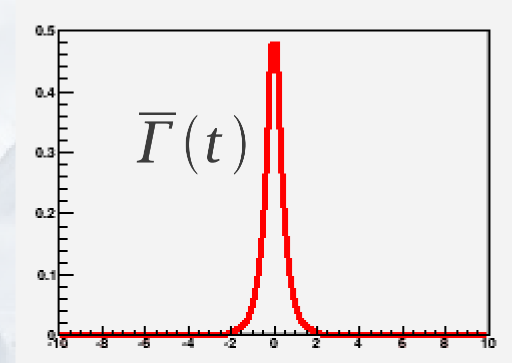
$$M_{11}=M_{22},\Gamma_{11}=\Gamma_{22},\Im[\frac{\Gamma_{12}}{M_{12}}]=0 \quad \leftarrow \quad CP\ \ INVARIANCE$$

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

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



Time-dependent formalism (ii)



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

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

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

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

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 "*ω*" and dilution "*D*".

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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:

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

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

ϕ_{CP} : *overall phase of* $D^0 \to f_{CP}$ *(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

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

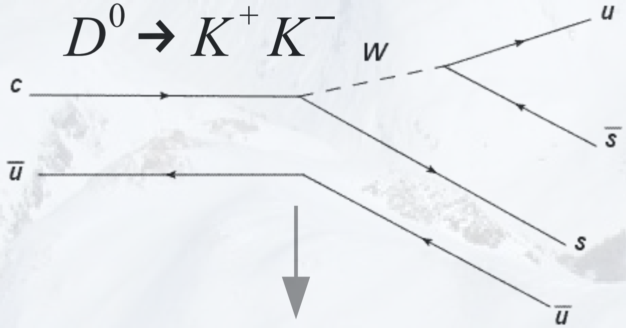
Assuming negligible the contribution due to P/CS/WE amplitudes, then:

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

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

Tree topology

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

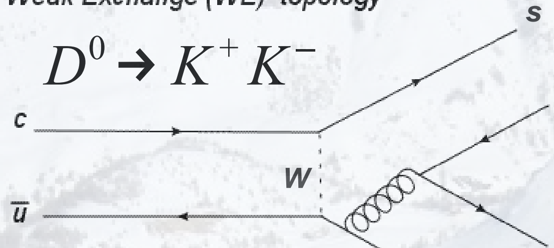


$\boxed{V_{cs} V^*_{us}}$

Real

Weak Exchange (WE) topology

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

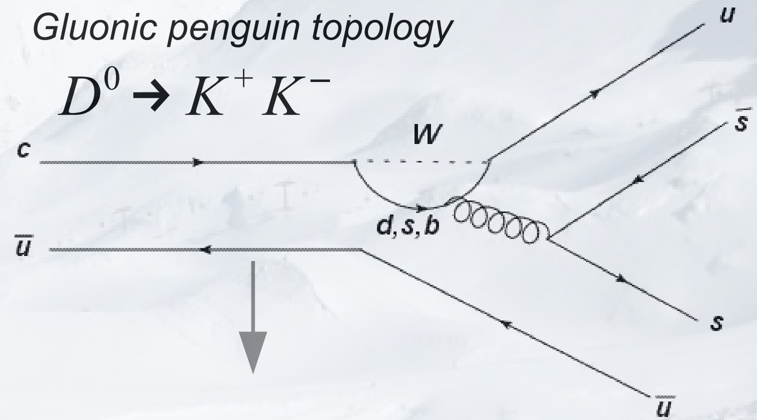


$\boxed{V_{cd} V^*_{ud}}$

Assume WE is small

Gluonic penguin topology

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



$\boxed{V_{cd} V^*_{ud}} + \boxed{V_{cs} V^*_{us}} + \boxed{V_{cb} V^*_{ub}}$

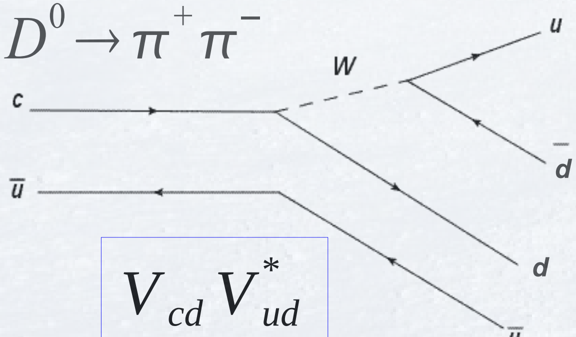
Real **Negligible**

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

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

Tree topology

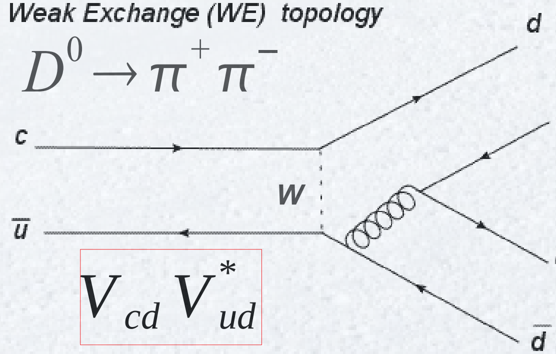
$D^0 \rightarrow \pi^+ \pi^-$



$\boxed{V_{cd} V^*_{ud}}$

Weak Exchange (WE) topology

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

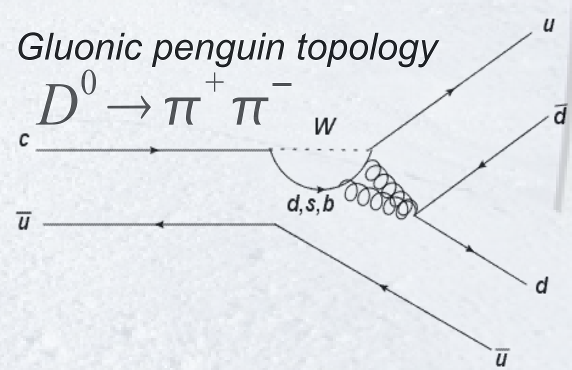


$\boxed{V_{cd} V^*_{ud}}$

WE- same phase as T

Gluonic penguin topology

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



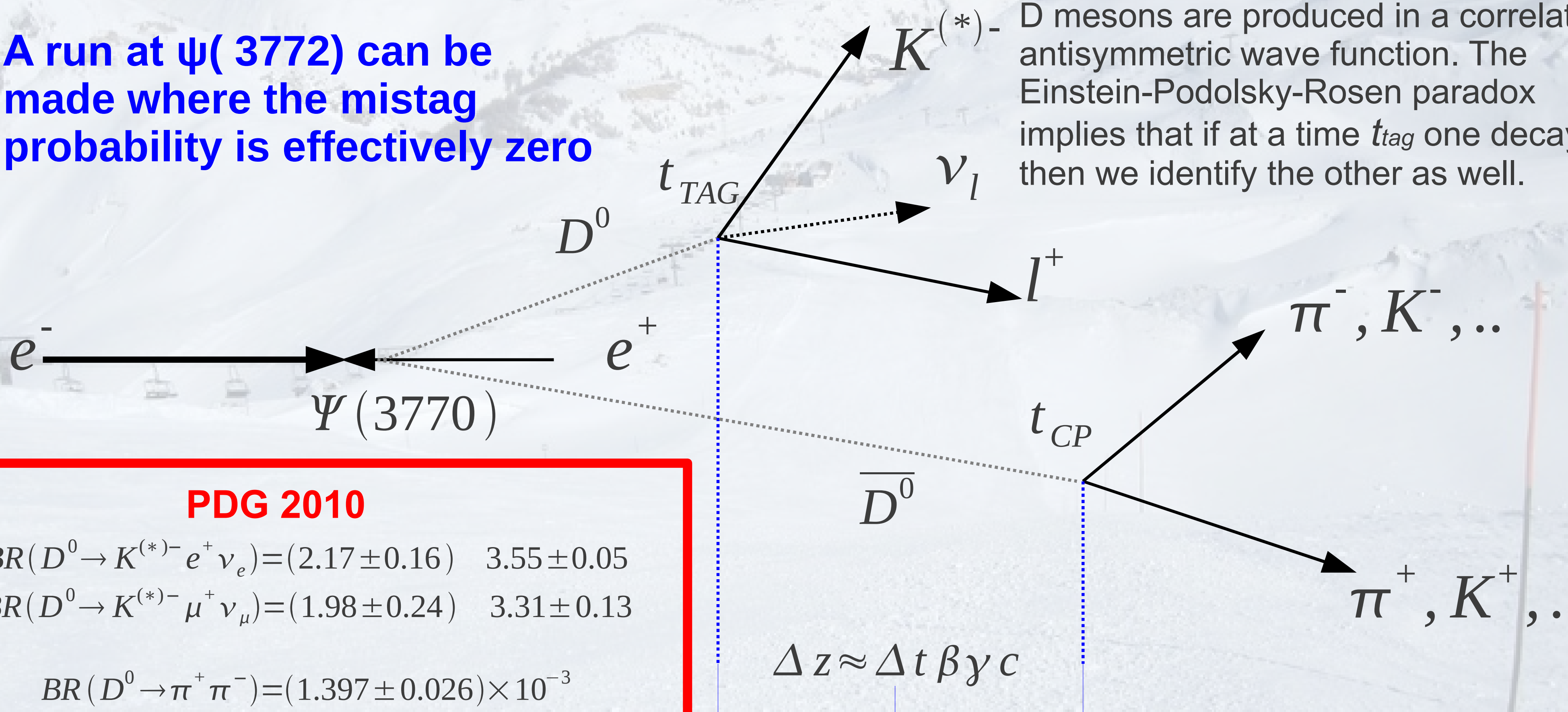
Real **Negligible**

$\boxed{V_{cd} V^*_{ud}} + \boxed{V_{cs} V^*_{us}} + \boxed{V_{cb} V^*_{ub}}$

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

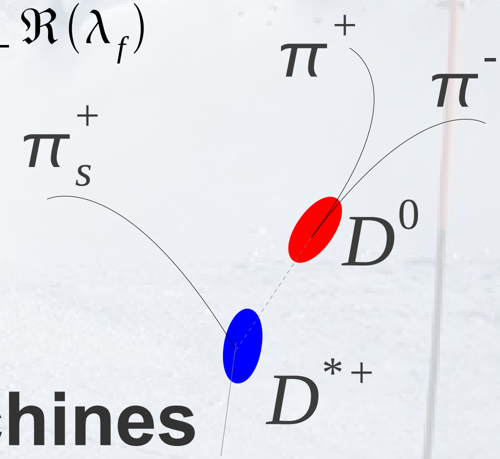
$$A(t)=\frac{\overline{\Gamma}(t)-\Gamma(t)}{\overline{\Gamma}(t)+\Gamma(t)}=2e^{\Delta\Gamma t/2}\frac{(|\lambda_f|^2-1)\cos\Delta M\,t+2\Im(\lambda_f)\sin\Delta M\,t}{(1+|\lambda_f|^2)(1+e^{\Delta\Gamma t})+2\Re(\lambda_f)(1-e^{\Delta\Gamma t})}$$

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 $e^+e^-\rightarrow c\bar{c}$ 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.

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A. Bevan- G. Inguglia- B. Meadows:
*)*Phys. Rev.* ***D*** *84, 114009, arXiv:1106.5075*
*)*Numerical Issues on TDCPV in Charm (to appear soon..)*

Expected number of (tagged) events

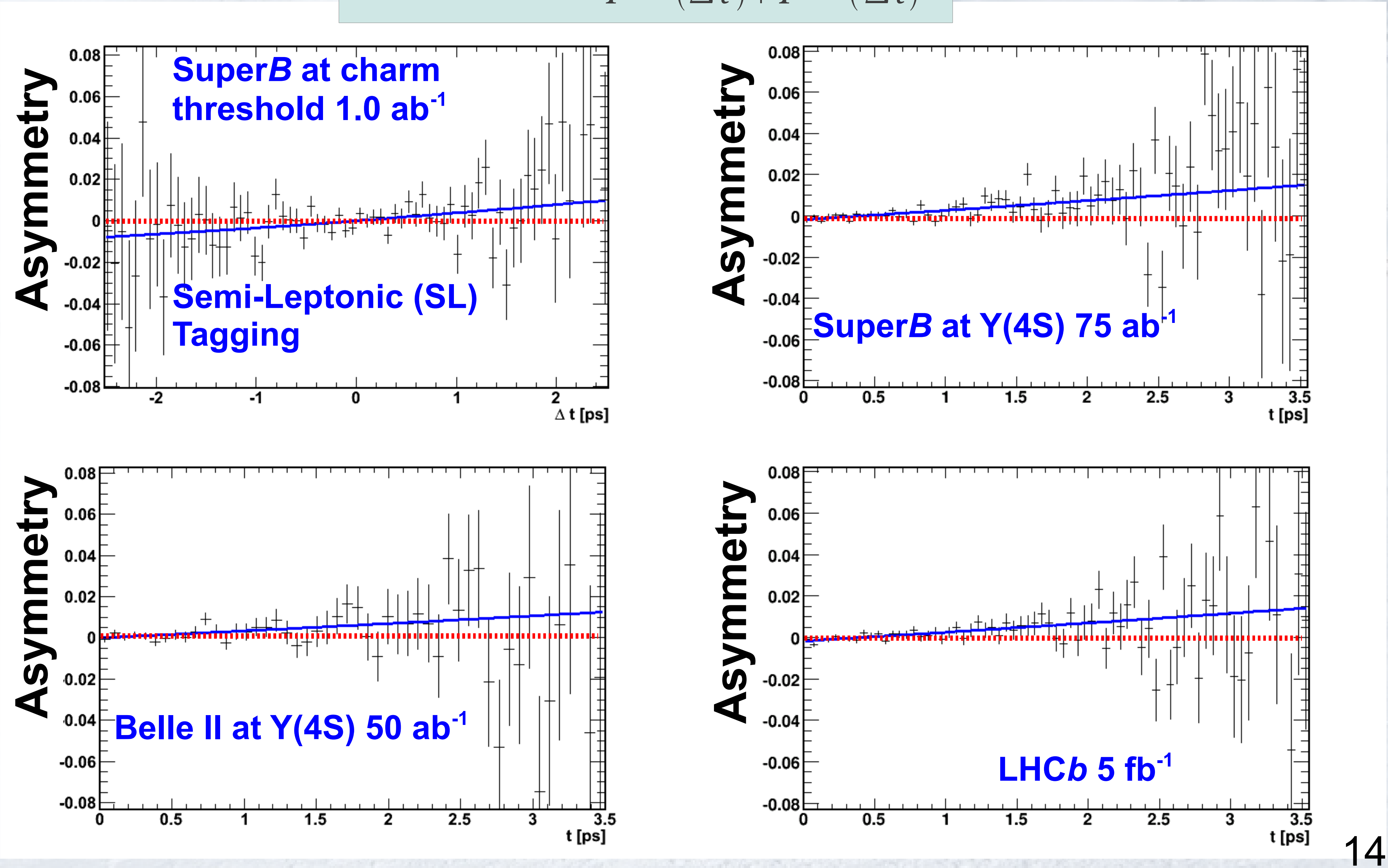
LHC*b* *5.0 fb*$^{-1}$ Estimated from arXiv:1112.0938 [hep-ex]	4.9×10^{6} 1.9×10^{7}	$D^0\to\pi^+\pi^-$ $D^0\to K^+K^-$	**π-T**
Belle II 50.0 *ab*$^{-1}$ $\Upsilon(4S)$ Estimated from Phys. Rev. D 78, 011105 (2008)	4.4×10^{6} 1.0×10^{7}	$D^0\to\pi^+\pi^-$ $D^0\to K^+K^-$	**π-T**
Super*B* *1.0 ab*$^{-1}$ $\Psi(3770)$ Estimated from Phys. Rev. D 78, 012001 (2008)	9.8×10^{5} 4.8×10^{6} 2.8×10^{6} 1.2×10^{7}	$D^0\to\pi^+\pi^-$ $D^0\to\pi^+\pi^-$ $D^0\to K^+K^-$ $D^0\to K^+K^-$	**SL-T** **K-T** **SL-T** **K-T**
Super*B* 75.0 *ab*$^{-1}$ $\Upsilon(4S)$ Estimated from Phys. Rev. D 78, 011105 (2008)	6.6×10^{6} 1.5×10^{7}	$D^0\to\pi^+\pi^-$ $D^0\to K^+K^-$	**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*)

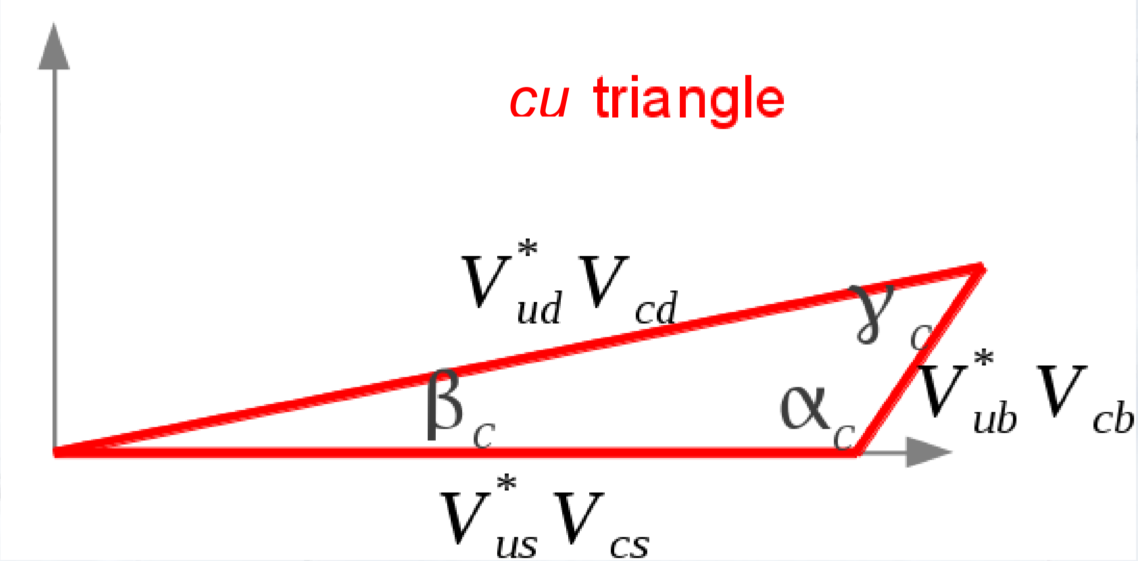
SL-T refers to semi-leptonic tag at charm threshold and **K-T** to the Kaon tag at charm thereshold (Super*B* only)

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



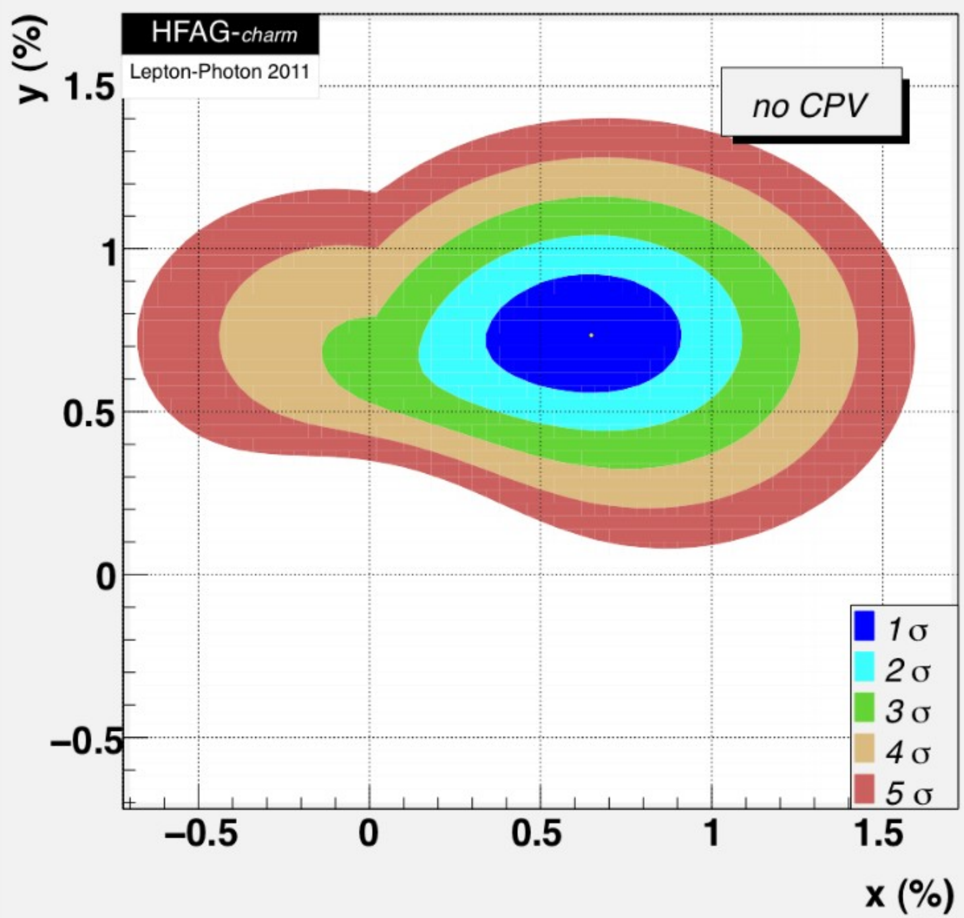
Parameter	Super$B$ $\Psi(3770)$ SL	Super$B$ $\Psi(3770)$ SL+K	Super$B$ $\Upsilon(4S)$ $\pi_s^\pm$	LHCb $\pi_s^\pm$	Belle II $\pi_s^\pm$
$\sigma_{\phi_{\pi\pi}} = \sigma_{arg(\lambda_{\pi\pi})}$	5.7°	2.4°	2.2°	3.0°	2.8°
$\sigma_{\phi_{KK}} = \sigma_{arg(\lambda_{KK})}$	3.5°	1.4°	1.6°	1.8°	1.8°
$\sigma_{\beta_{c,eff}}$	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 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	0.18%	



Time-Depedent Studies
x(%)= x ± 0.08 (Φ=±10º)
x(%)= x ± 0.04 ((Φ=±20º)

HFAG
x(%)= 0.65 ± 0.18

Precision III

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

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%
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$D^0 \to \pi^+\pi^-$ (1.1 fb^{-1})	0.40%	0.20%
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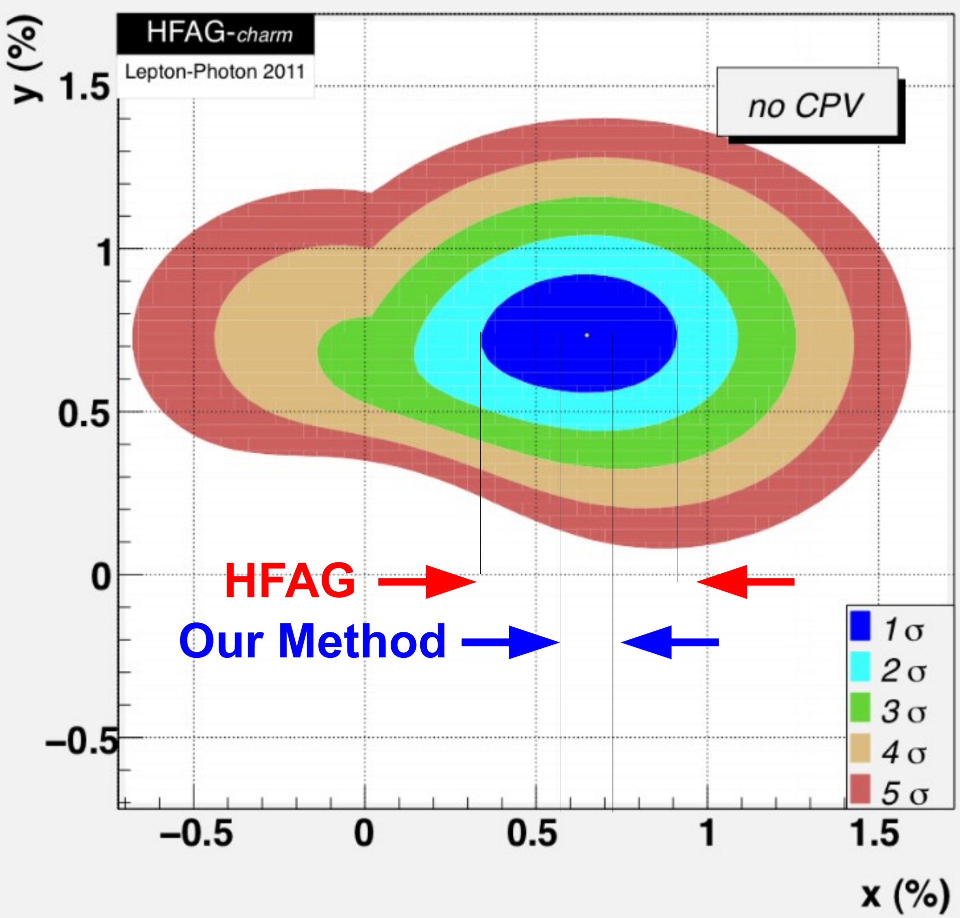
$D^0 \to K^+K^-$	0.10%	0.04%
HFAG	0.18%	



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 $\not{CP}$ 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, 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 ~2.

- Future e^+e^- experiments like Super*B* and Belle II will be competitive with the LHC.


...Many Thanks...