τ-charm factory inputs for measurements of γ and D mixing

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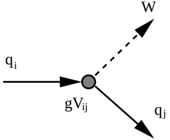
Outline

- Measurement of γ
  - Counting measurements (ADS, GLW). Measurements of charm phase difference and coherence factors
  - Three-body D final states (GGSZ or Dalitz). Measurement of charm phase coefficients
- Charm mixing
  - Effect of charm mixing on γ measurement
  - Charm mixing at LHCb/Belle II and input from D threshold
  - Measurement of charm mixing at threshold
- CP violation in charm
  - CPV in $D \to hh$ and its effect on γ
  - CPV in $D \to K_S^0\pi\pi$ and its effect on γ
  - Measurement of γ allowing for CPV in charm

Cabibbo-Kobayashi-Maskawa mechanism



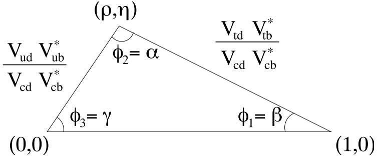
Charged current:

$$\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L) V_{CKM} \gamma^\mu \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W^+_\mu,$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The Unitarity Triangle

Unitarity: $\frac{V^*_{ub}V_{ud}}{V^*_{cb}V_{cd}} + 1 + \frac{V^*_{tb}V_{td}}{V^*_{cb}V_{cd}} = 0$



Sides and angles are observable:

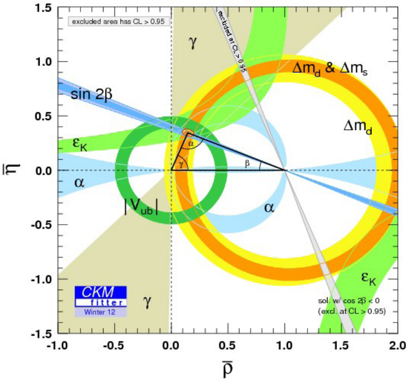
$$\phi_1 \equiv \beta = \arg\left(\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right)$$

$$\phi_2 \equiv \alpha = \arg\left(\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right)$$

$$\phi_3 \equiv \gamma = \arg\left(\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)$$

CKM measurements: current status

Various experimental inputs (sides and angles of the Unitarity Triangle) are combined by averaging groups (CKMfitter and UTfit) to get the general picture. Reasonable consistency so far, although some slight tensions exist.



γ is an important input:

- Indirect constraint: $(68 \pm 4)^\circ$ from decays with loops.
- Direct measurement: Current precision: $10 - 15^\circ$. Tree-level decays.

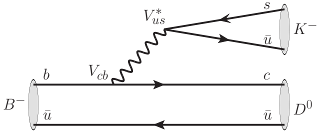
  Theoretical uncertainty: $10^{-6}(!)$.

γ is a high-precision SM reference for other CKM measurements.

The cleanest way to extract γ is from $B \to DK$ decays...

$\mathcal{CP}$ violation in $B \to DK$

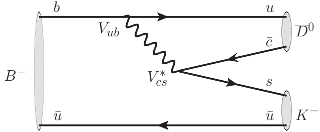
$B^- \to D^0 K^-$:



$A \sim V_{cb} V^*_{us} \sim A\lambda^3$

$+$

$B^- \to \overline{D}^0 K^-$:



$A \sim V_{ub} V^*_{cs} \sim A\lambda^3(\rho - i\eta)$

If D^0 and $\overline{D}^0$ decay into the same final state: $|\tilde{D}\rangle = |D^0\rangle + r_B e^{i\theta} |\overline{D}^0\rangle$

Relative phase for $B^+ \to DK^+$: $\theta = +\gamma + \delta_B$,

$B^- \to DK^-$: $\theta = -\gamma + \delta_B$.

Ratio of two amplitudes: $r_B = \left| \frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right| = \left| \frac{V_{ub} V^*_{cs}}{V_{cb} V^*_{us}} \right| \times$ [Color supp] ~ 0.1

- **Gronau-London-Wyler (GLW)** [PLB 265, 172 (1991)]
  D in $\mathcal{CP}$-eigenstate ($D \to KK$, $\pi\pi$).
- **Atwood-Dunietz-Soni (ADS)** [PRL 78, 3257 (1997)]
  D Cabibbo-allowed ($D^0 \to K^- \pi^+$) and doubly Cabibbo-suppressed ($D^0 \to K^+ \pi^-$) states.
- **Giri-Grossman-Soffer-Zupan, Bondar (GGSZ, Dalitz)**
  D in three-body final state ($K_S \pi^+ \pi^-$). [PRD 68, 054018 (2003)]

So, why am I speaking about this at τ-charm factory workshop?

Charm inputs for γ measurements

- Unique feature of $B \to DK$ decays which allows extraction of γ without theory uncertainties is a combination of interference and factorisation [Grossman, CKM2012]:
  - Interference (between $B \to D^0 K$ and $B \to \overline{D}^0 K$) provides CP violation.
  - Factorisation of B and D amplitudes allows for clean measurement.

  Because of factorisation, the number of unknown hadronic parameters is smaller than the number of observables, and they can all be obtained from data.
- Hadronic parameters in D decays can also be obtained from the other system with $D - \overline{D}$ interference, thus increasing the precision of γ.
  - The system where this interference (and thus the sensitivity to hadronic parameters) is maximal is $\psi(3770) \to D^0\overline{D}^0$ (only at CLEO-c so far). $\psi(3770)$ is a vector, thus two D-mesons in $\psi(3770) \to D^0\overline{D}^0$ are produced in a P-wave. Quantum-entangled state with antisymmetric wave function:

$$|A(D_1 D_2)|^2 = |A(D_1)\overline{A}(D_2) - \overline{A}(D_1)A(D_2)|^2$$

Now let's consider each of the methods (ADS, GLW, GGSZ) and see how τ-charm factory can help.

ADS and GLW measurements

Observables for $D \to hh$ (GLW) and $D \to K\pi$ (ADS) modes:

$$\mathcal{R}_{GLW} = \frac{\Gamma(B \to D_{CP} K)}{\Gamma(B \to D_{fav} K)} = 1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma$$

$$\mathcal{A}_{GLW} = \frac{\Gamma(B^+ \to D_{CP} K) - \Gamma(B^- \to D_{CP} K)}{\Gamma(B^+ \to D_{CP} K) + \Gamma(B^- \to D_{CP} K)} = 2 r_B \sin\delta_B \sin\gamma / R_{GLW}$$

$$\mathcal{R}_{ADS} = \frac{\Gamma(B \to D_{sup} K)}{\Gamma(B \to D_{fav} K)} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\gamma$$

$$\mathcal{A}_{ADS} = \frac{\Gamma(B^+ \to D_{sup} K) - \Gamma(B^- \to D_{sup} K)}{\Gamma(B^+ \to D_{sup} K) + \Gamma(B^- \to D_{sup} K)} = 2 r_B r_D \sin(\delta_B + \delta_D) \sin\gamma / R_{ADS}$$

γ is what we are mainly interested in.

r_B and δ_B are strong parameters (ampl. ratio and strong phase) related to B decay. Free parameters.

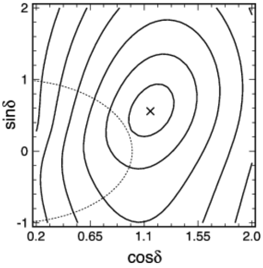
δ_D is the strong phase between $D^0 \to K^+\pi^-$ and $\overline{D}^0 \to K^+\pi^-$. Can be measured at threshold.

Measurements with multibody modes can be done in a similar fashion, but the interference terms are diluted by coherence factor R $(0 < R < 1)$ to account for overlap of the amplitudes. Can be measured at threshold, too.

CLEO measurements in ADS modes

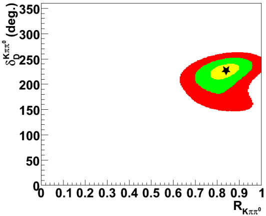
CLEO measurements of strong phase differences and coherence factors done with 0.8 fb^{-1} at $\psi(3770)$. [CLEO, PRD 86 (2012) 112001; PRD 80 (2009) 031105]

$D \to K\pi$



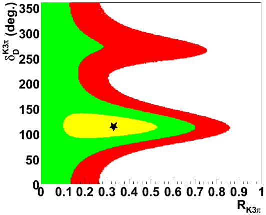
$\delta_{K\pi} = (18^{+11}_{-17})^\circ$

$D \to K\pi\pi^0$



$\delta_{K\pi\pi^0} = (227^{+14}_{-17})^\circ$
$R_{K\pi\pi^0} = 0.84 \pm 0.07$

$D \to K\pi\pi\pi$



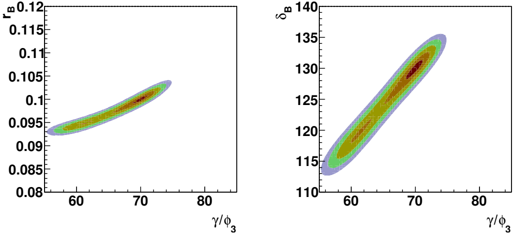
$\delta_{K3\pi} = (114^{+26}_{-23})^\circ$
$R_{K3\pi} = 0.33^{+0.20}_{-0.23}$

Scaling to 10 fb^{-1} (BES III sample): $\sigma(\delta_D) \sim 5^\circ$

1 ab^{-1} (1 year of τ-charm factory at $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1}): $\sigma(\delta_D) \sim 2^\circ$

Prospects for future measurements with ADS/GLW

- Expected sensitivity using ADS/GLW modes ($D \to hh$) alone is:
  - Belle II: $\sigma(\gamma) = 5^\circ$ [CKM2010]
  - Upgraded LHCb: $\sigma(\gamma) = 1.3^\circ$ [EPJ C (2013) 73:2373]
- This precision critically depends on the precision of δ_D. Strong correlation btw. γ and strong phase, precision required for δ_D is of the order $\sigma(\gamma)$.



No δ_D constraint.

- Precision can be improved by adding other D modes (e.g. $D \to K\pi\pi^0$) with different strong phases.
- Systematic uncertainties are not discussed here. Critical uncertainty is detector charge asymmetry (for LHCb, also production asymmetry). Assume it can be controlled with data.

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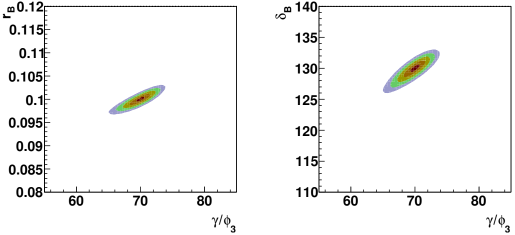


$\sigma(\delta_D) = 1^\circ$

- Precision can be improved by adding other D modes (e.g. $D \to K\pi\pi^0$) with different strong phases.
- Systematic uncertainties are not discussed here. Critical uncertainty is detector charge asymmetry (for LHCb, also production asymmetry). Assume it can be controlled with data.

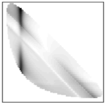
$B^+ \to DK^+$, $D \to K_S^0\pi^+\pi^-$ Dalitz plot analysis

Giri, Grossman, Soffer, Zupan, PRD 68, 054018 (2003)
Bondar, Belle Dalitz analysis meeting (2002)

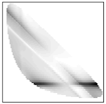
$D \to K_S^0\pi^+\pi^-$ Dalitz distribution:
$d\sigma(m_+^2, m_-^2) \sim |A|^2 dm_+^2 dm_-^2$
where $m_\pm^2 = m_{K_S\pi^\pm}^2$

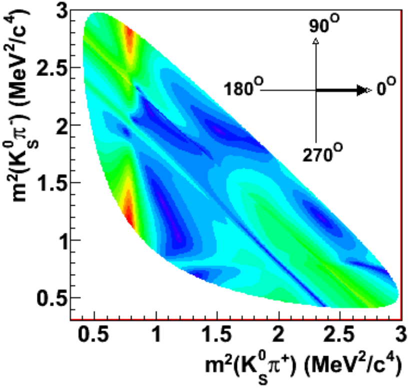
$\mathcal{CP}$ conservation in D decays:
$\overline{A}_D(m_+^2, m_-^2) = A_D(m_-^2, m_+^2)$

D decay amplitude from $B^+ \to DK^+$:
$A_B(m_+^2, m_-^2) =$



$+ r_B e^{i\delta_B \pm i\gamma}$

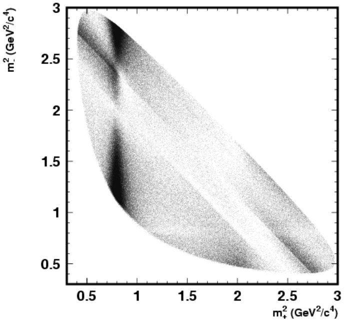




Rotation of phase $\delta_B + \gamma$
$r_B = 0.1$

$D \to K_S^0\pi^+\pi^-$ amplitude is obtained from $D^{*\pm} \to D\pi^\pm$, parametrized by the isobar model.

$D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot



The amplitude contains $O(10)$ resonant contributions in $K\pi$ (K^*, K_0^*, K_2^*) and $\pi\pi$ (ρ, ω, f_0, f_2 etc.) channels

$D \to K_S^0\pi^+\pi^-$ decay is unique to combine the following properties:

- High branching fraction.
- Rich resonance structure $\Rightarrow$ significant phase variations across the phase space.

Can be used to effectively measure the properties of $D^0 - \overline{D}^0$ admixture which appears in a few measurements:

- γ measurement in $B^+ \to DK^+$
- D^0 mixing and $\mathcal{CP}$ violation
- β measurement in $B^0 \to D\pi^0$.

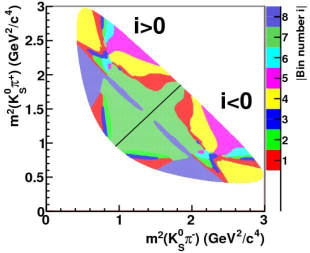
In flavour-tagged $D^* \to D\pi$ decays used to obtain the $D \to K_S^0\pi^+\pi^-$ amplitude, only $|f_D|^2$ is observable $\Rightarrow$ Model uncertainty.

γ: Binned Dalitz plot analysis

Solution: use binned Dalitz plot and deal with numbers of events in bins.

[A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD **68**, 054018 (2003)]

[A. Bondar, A. P. EPJ C **47**, 347 (2006); EPJ C **55**, 51 (2008)]



System of equations:

$$M_i^{\pm} = h\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_{\pm} c_i + y_{\pm} s_i)\}$$

with free parameters

$$x_{\pm} = r_B \cos(\delta_B \pm \gamma) \quad y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

$M_i^{\pm}$: numbers of events in $D \to K_S^0 \pi^+ \pi^-$ bins from $B^{\pm} \to DK^{\pm}$
K_i: numbers of events in bins of flavour $D \to K_S^0 \pi^+ \pi^-$ from $D^* \to D\pi$.
c_i, s_i contain information about strong phase difference between symmetric Dalitz plot points (m_+^2, m_-^2) and (m_-^2, m_+^2):

$$c_i = \langle \cos \Delta\delta_D \rangle, \quad s_i = \langle \sin \Delta\delta_D \rangle$$

If CP is conserved in D, $c_i = -c_i$, $s_i = -s_{-i}$, so independent only for $i > 0$.
Why is it better than model description of the amplitude?

γ: Obtaining c_i, s_i

Coefficients c_i, s_i can be obtained in $\psi(3770) \to D^0\overline{D}^0$ decays.
Use quantum correlations between D^0 and $\overline{D}^0$.

- If both D decay to $K_S^0\pi^+\pi^-$, the number of events in i-th bin of $D_1 \to K_S^0\pi^+\pi^-$ and j-th bin of $D_2 \to K_S^0\pi^+\pi^-$ is

$$M_{ij} = K_i K_{-j} + K_{-i} K_j - 2\sqrt{K_i K_{-i} K_j K_{-j}}(c_i c_j + s_i s_j).$$

  $\Rightarrow$ constrain c_i and s_i.

- If one D decays to a CP eigenstate, the number of events in i-th bin of another $D \to K_S^0\pi^+\pi^-$ is

$$M_i = K_i + K_{-i} \pm 2\sqrt{K_i K_{-i}} c_i.$$

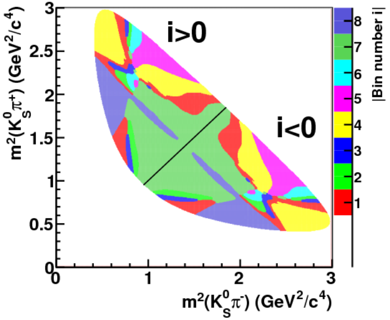
  $\Rightarrow$ constrain c_i.

c_i, s_i measurement has been done by CLEO and can be done in future at BES-III (and hopefully at τ-charm factory!).

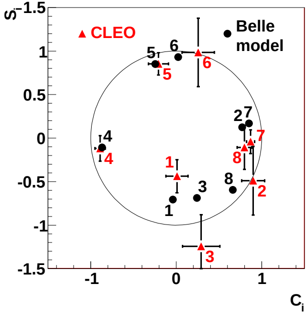
γ: Optimal binning and CLEO measurement of c_i, s_i

Binned analysis reduces stat. precision.

Can improve this by choosing a binning inspired by $D \to K_S^0\pi^+\pi^-$ model. Only $10-15\%$ loss in precision. [A. Bondar, A.P., EPJ C 55, 51 (2008)]



Optimised $D \to K_S^0\pi^+\pi^-$ binning using BaBar 2008 measurement.



Measured c_i, s_i values and predictions by Belle model

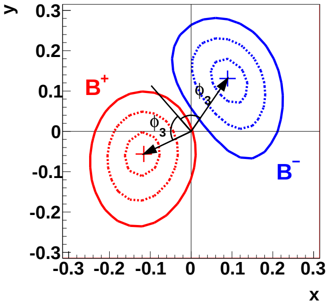
[CLEO collaboration, PRD **82**, 112006 (2010)]

Optimal binning depends on model, but γ does not.

Bad model $\Rightarrow$ worse precision, but no bias!

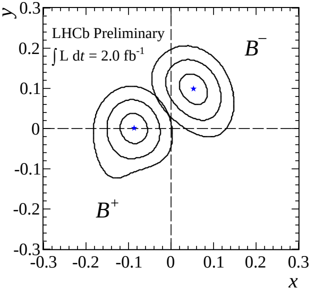
This technique has been successfully employed by Belle and LHCb

[Belle, PRD 85, 112014 (2012)]



$$x_+ = -0.110 \pm 0.043 \pm 0.014 \pm 0.016$$
$$y_+ = -0.050^{+0.052}_{-0.055} \pm 0.011 \pm 0.021$$
$$x_- = +0.095 \pm 0.045 \pm 0.014 \pm 0.017$$
$$x_- = +0.137^{+0.053}_{-0.057} \pm 0.019 \pm 0.029$$
$$\gamma = (77 \pm 15 \pm 4 \pm 4)^\circ$$

[LHCb, LHCb-CONF-2013-004]



$$x_+ = -0.087 \pm 0.031 \pm 0.016 \pm 0.006$$
$$y_+ = -0.001 \pm 0.036 \pm 0.014 \pm 0.019$$
$$x_- = +0.053 \pm 0.032 \pm 0.009 \pm 0.009$$
$$x_- = +0.099 \pm 0.036 \pm 0.022 \pm 0.016$$

$\gamma = (57 \pm 16)^\circ$ (combined 2011+2012 data, 3 fb^{-1})

Common systematics (third error) due to CLEO c_i, s_i measurement.

Prospects for Belle II/upgraded LHCb

- Precision on γ expected at Belle II (~ 50 ab^{-1}) and upgraded LHCb (~ 50 fb^{-1}) is of order 2° (for $B \to DK$, $D \to K_S^0\pi^+\pi^-$ only).
- Other channels can use $D \to K_S^0\pi^+\pi^-$ (such as $B^0 \to DK^*$, $B \to DK\pi\pi$ etc.) and provide more constraints on γ.
- If recalculated to γ, the current uncertainty due to CLEO measurement of c_i, s_i is $\sim 4^\circ$ (Belle). The way this uncertainty is calculated, it is dependent on B sample. According to MC, it flattens at $\sim (2-3)^\circ$ for large B sample.
- Uncertainty of BES III sample (10 fb^{-1}) would be $\sim 1^\circ$. so similar or somewhat less than stat. error due to B sample.
  Looking forward to BES III measurement
- τ-charm factory sample (1 ab^{-1}) would reduce the contribution of c_i, s_i precision to a comfortable level of $\sim 0.1^\circ$.

Reaching sub-degree precision on γ will require some subtle effects to be accounted for. More in the following slides...

Effect of charm mixing on γ

A few papers considered effect of charm mixing on γ measurement:

- If charm mixing is ignored in $B \to DK$ decays but D amplitudes are taken w/o mixing contribution, effect is of the first order: $\mathcal{O}(x, y) \sim 1\%$.
  [Silva et al., PRD 61 (2000) 112001]
- If charm mixing is consistently ignored in both $B \to DK$ and D decays, only second-order corrections: $\mathcal{O}(x^2, y^2)$, thus can be ignored.
  [Grossman et al., PRD 72 (2005) 031501]
- However, if quantum-correlated $\psi(3770) \to D\overline{D}$ data are used, things are more complicated. In $\psi(3770) \to D\overline{D}$, charm mixing contribution cancels in the first order in x, y.

$$M_{ij} = K_i K_{-j} + K_{-i} K_j - 2\sqrt{K_i K_{-i} K_j K_{-j}}(c_i c_j + s_i s_j) + \mathcal{O}(x^2, y^2).$$

  Thus if (uncorrected) c_i, s_i are used, the correction to γ is $\mathcal{O}(x, y)$. There is, however, an additional suppression by $r_B \simeq 0.1$, thus the bias is of the order $\Delta\gamma = 0.2^\circ$. [Bondar et al., PRD 82 (2010) 034033]

  As x, y are measured, this effect can be corrected for, so is not a problem.

Time-dependent measurement of charm mixing

Measurement of charm mixing is interesting *per se*, but also is an important input for γ measurement.

Time-dependent measurements of charm mixing can be performed with boosted D mesons (Belle II, LHCb), but need the same strong phases as γ measurement.

- Time-dependent $D^0 \to K\pi$ analysis: phase difference δ_D to relate y' with x, y.
- Time-dependent $D^0 \to K^0_S\pi^+\pi^-$ analysis

$$|A_D(t)|^2 \simeq |A_D + (x+iy)t\overline{A}_D|^2$$

Measures both x and y independently. Can be done in the similar model-independent binned fashion as γ. [Bondar et al., PRD 82 (2010) 034033]

upgraded LHCb, Belle II: expect ~100M decays. Stat. precision:

$\sigma(x,y) \sim 0.2\times 10^{-3}$, $\sigma(r_{CP}) \sim 1\%, \sigma(\alpha_{CP}) \sim 0.7^\circ$

[G. Wilkinson, C. Thomas, arXiv:1209.0172]

Current precision of c_i, s_i would dominate the precision of x, y and CP violation parameters already for ~10M $D \to K^0_S\pi^+\pi^-$ samples $\Rightarrow$

need 100 fb^{-1} at $D\overline{D}$ threshold to reduce it to the level of stat. error.

Measurement of charm mixing at threshold

Time-integrated $\psi(3770) \to D\overline{D}$ decays are insensitive to mixing in the first order. $D\overline{D}^*$ is a different case. Consider $e^+e^- \to \psi(4040) \to D^0\overline{D}^{*0}$ production.

- $D^0\overline{D}^0\pi^0$: $\mathcal{C} = -1$, nothing changes wrt. $D\overline{D}$.
- $D^0\overline{D}^0\gamma$: $\mathcal{C} = +1$, now the wave function is symmetric:

$$|A(D_1D_2)|^2 = |A(D_1)\overline{A}(D_2) + \overline{A}(D_1)A(D_2)|^2$$

  Charm mixing contribution is *doubled* compared to time-dependent (uncorrelated) case.

Analysis should involve reconstruction of both $D^0\overline{D}^0\gamma$ (mixing-sensitive) and $D^0\overline{D}^0\pi^0$ (w/o mixing contribution) [Bondar et al., PRD 82, 034033 (2010)].
Sensitivity simulation studies with 1 year at $E = 4040$ MeV with $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} (1 ab^{-1}):

Mixing parameters $\sigma(x, y) \sim 1 \times 10^{-3}$,

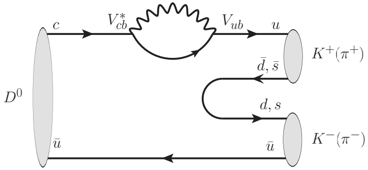
CP violation parameters $\sigma(r_{CP}) \sim 4\%, \sigma(\alpha_{CP}) \sim 3^\circ$.

τ-charm reach of charm mixing is comparable to Belle II/pre-upgrade LHCb

Time-integrated measurement, so systematic errors are probably much less critical. Precision of upgraded LHCb (time-dep. analysis) is a few times better.

CP violation in charm decays

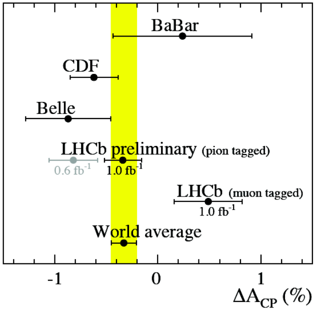
- CP violation in charm is possible in the SM through the contribution of $c \to u$ penguin (only for singly Cabibbo-suppressed modes).
- No CPV at first order in CF and DCS decays, but we have to be prepared for NP to appear.
- In the decays with K_S^0, CPV should appear at the level 10^{-3} due to CPV in K^0.



At degree and sub-degree level of precision, we have to be prepared for CPV in charm.

Experimental CP violation results in $D \to hh$

- LHCb, CDF and Belle measurements of $\Delta A_{CP} = A_{CP}(D \to KK) - A_{CP}(D \to \pi\pi)$ suggested CP violation of the order 0.7%.
- Several papers estimating effect of CPV in charm on γ.
- More recent measurements by LHCb do not support evidence of CPV. Still, SM expects CPV of the order 10^{-3}, so has to be accounted for in the precision γ measurement



HFAG world-average:

$\Delta A_{CP} = (-0.33 \pm 0.12)\%$

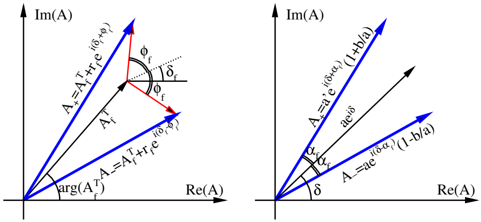
Measurements of the individual asymmetries:

- $A_{KK} = -0.16 \pm 0.20$
- $A_{\pi\pi} = +0.16 \pm 0.21$

Consider $B \to f_D K$ decay. The D decay amplitudes to CP eigenstate f are

$$A_f = A_f^T[1 + r_f e^{i(\delta_f+\phi_f)}]$$
$$\overline{A}_f = A_f^T[1 + r_f e^{i(\delta_f-\phi_f)}]$$

This results in
CP asymmetry $A_f \neq \overline{A}_f$ and
phase difference $\alpha_f = \arg A_f/\overline{A}_f$



Effect on γ: $\mathcal{O}(r_f/r_B)$

- For $B \to DK$, $\Delta\gamma \sim 1^\circ$ (after updated LHCb result), so has to be corrected at the degree-level precision.
- For $B \to D\pi$, the sizes of CP asymmetries due to CPV in charm and in B are comparable, so charm CPV has to be considered from the beginning.

[W. Weng, PRL 110 (2013) 061802]
[M. Martone, J. Zupan, PRD 87 (2013) 034005]

Corrections due to CPV in $D \to hh$

- Knowledge of CP asymmetry in $D \to hh$ is not enough to take it into account in γ measurement.
  - $A_{CP}(B \to f_D K) = 2r_B \sin\delta_B \sin\gamma + a_f$
  - But $R_{CP}(B \to f_D K) = 1 + 2r_B \cos\delta_B \delta\gamma + a_f \cot\delta_f$

  so δ_f has to be known.
- Phase difference $\alpha_f = \arg(A_f/\overline{A}_f)$ (and thus δ_f) can be extracted from $D\overline{D}$ threshold data using $(hh)_D(K^0_S\pi\pi)_D$ final state.
- Alternatively, one can use another B decay (e.g. $B \to D\pi$) where the term $a_f \cot\delta_f$ is the same and thus can be cancelled.

All this requires that there is a decay mode without CP asymmetry in charm ($D \to K\pi$ and $D \to K^0_S\pi^+\pi^-$ are good approximations).
It is not possible in principle to separate common CP violating phases in B (γ) and in charm (α_f, if it exists) using only $B \to DK$ and $\psi(3770) \to D\overline{D}$ (because in $D\overline{D}$ we are sensitive only to the phase difference).

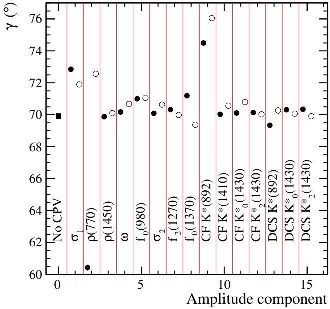
[M. Martone, J. Zupan, PRD 87 (2013) 034005]

CP violation in $D \to K_S^0 \pi^+ \pi^-$

What if we consider CP violation in $D \to K_S^0 \pi\pi$? [Bondar et al., arXiv:1303.6305]

CP violation can occur in any of the quasi two-body amplitudes.

Toy MC: Introduce 10% CPV to each amplitude component.
Check how this affects γ fit. $\longrightarrow$



Current limits on CPV in $D \to K_S^0 \pi^+ \pi^-$ come from CDF [PRD 86, 032007 (2012)].

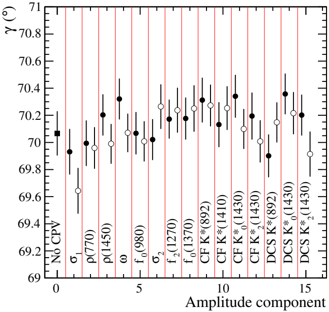
Recalculated γ uncertainty using CDF limits is $\sim 3^\circ$.

CP violation in $D \to K_S^0 \pi^+ \pi^-$

[Bondar et al., arXiv:1303.6305]

Suppose we found disagreement between UT measurements from loops and trees. How can we check it is from loops in B and not from CPV in charm?

We can modify the model-independent procedure to take CP violation in charm into account (double the number of c_i, s_i parameters, no symmetry relations $c_i = -c_{-i}, s_i = -s_{-i}$ anymore).



System of equations is still solvable and γ can be extracted. Reduction of stat. precision due to larger number of parameters is only $< 10\%$.

But. There is one ambiguity in this modified procedure: rotation of c_i, s_i by the angle α_f, with the simultaneous $\gamma \to \gamma + \alpha_f$. Remember?
"It is not possible in principle to separate common CP violating phases in B (γ) and in charm (α_f, if it exists) using only $B \to DK$ and $\psi(3770) \to D\overline{D}$"
[M. Martone, J. Zupan, PRD 87 (2013) 034005]

Accessing the common CPV phase in charm

- We have replaced the large number of possible CP-violating phases in $D \to K_S^0\pi^+\pi^-$ by a single CP-violating phase, but where do we get it from?
- Can check against other CF decays (e.g. $D^0 \to K_S^0\pi^0$). It is unlikely that the nature is so inventive that CP violating phase is the same in all charm decays (and CPV does not manifest itself in any other way, e.g. CP asymmetries). At least can get the systematics due to it from $\psi(3770) \to (K_S^0\pi^0)_D(K_S^0\pi^+\pi^-)_D$.
- Alternatively: obtain this phase from the process which involves $D^0 - \overline{D}^0$ interference with the known phase difference. Example:
  Compare the phase β from $B \to J/\psi K_S^0$ ("golden mode" at B factories) and $B \to D^0(K_S^0\pi^+\pi^-)\pi^0$. [A. Bondar et al. PLB 624, 1 (2005)]
  The difference in β in these decays can be due to weak phase in D^0 (or due to corrections in $B \to J/\psi K_S^0$ but believe they are $< 1°$).
  Experimental precision at Belle II: $\sim 2°$. Can use other similar decays ($B \to D^0\pi\pi$, feasible also at LHCb). At this level of precision, we are *completely* model-independent wrt. charm processes.

Summary

- Input from charm threshold measurements is important for all methods of γ measurement. Going to precisions of 1 degree and below will require accounting for some subtle effects (charm mixing, direct CPV in charm) that will require close collaboration of B and charm analysis groups.
  All the subtleties considered so far can be accounted for in a way free from theoretical ambiguities, so sub-degree precision is feasible.
- Threshold measurements employing quantum correlations can be used to study charm mixing and CPV in mixing. Ability to run the machine at $E = 4040$ MeV (DD^* production) is essential. Precision in x, y and CPV parameters is comparable to pre-upgrade LHCb/Belle II. Time-integrated measurement$\Rightarrow$ complementary (and probebly much lower) systematic errors wrt. time-dep. measurements.