Future prospects for charm physics at Belle II

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Topics

- $D^0 - \overline{D}^0$ mixing and t-dependent CPV
- t-integrated CPV (A_{CP})
- Rare decays (FCNC, LFV, LV)

$D^0 - \overline{D}^0$ mixing

- Mass eigenstates differ from flavor eigenstates

$$|D^0_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

  - $D^0_{1,2}$ with masses m_1, m_2 and partial widths Γ_1, Γ_2
  - CP violation if $q \neq p$

- Mixing parameters:

$$x = \frac{\Delta m}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

- Time dependent decay rates of $D^0 \to f$ (since mixing is small):

$$\frac{dN_{D^0\to f}}{dt} \propto e^{-\Gamma t}\left|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}(\frac{y+ix}{2}\Gamma t)\langle f|\mathcal{H}|\overline{D}^0\rangle\right|^2$$

Measurement strategies

$$\frac{dN_{D^0\to f}}{dt} \propto e^{-\Gamma t}\left|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}\left(\frac{y+ix}{2}\Gamma t\right)\langle f|\mathcal{H}|\overline{D}^0\rangle\right|^2$$

- Wrong-sign semileptonic decays ($D^0 \to K^+\ell^-\nu$)
  - WS only via mixing: $\langle f|\mathcal{H}|D^0\rangle = 0$
  - measures time integrated mixing rate $R_M = \frac{x^2+y^2}{2} = \frac{N_{WS}}{N_{RS}}$
- Wrong-sign hadronic decays ($D^0 \to K^+\pi^-$)
  - WS via doubly Cabibbo suppressed (DCS) decays or mixing
  - interference between DCS and mixing (strong phase δ)
  - measures $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$
- Decays to CP eigenstates ($D^0 \to K^+K^-, \pi^+\pi^-$)
  - if no direct CPV: $\langle f|\mathcal{H}|\overline{D}^0\rangle = -\langle f|\mathcal{H}|D^0\rangle$
  - measures y
- Decays to self-conjugate states ($D^0 \to K_s^0\pi^+\pi^-$)
  - time dependent Dalitz plot analysis
  - measures x and y

CP violation

$$\frac{dN_{D^0\to f}}{dt} \propto e^{-\Gamma t}\left|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}\left(\frac{y+ix}{2}\Gamma t\right)\langle f|\mathcal{H}|\overline{D}^0\rangle\right|^2$$

Two kinds:

- $q/p \neq 1 \;\; \Rightarrow$ indirect CP violation
- $q/p = |q/p| \cdot e^{i\phi}$:
  - $|q/p| \neq 1 \;\; \Rightarrow$ CP violation in mixing
  - $\phi \neq 0(\pi) \;\; \Rightarrow$ CP violation in interference of decays w/ and w/o mixing
- $|\mathcal{A}(D^0 \to f)|^2 \neq |\mathcal{A}(\bar{D}^0 \to \bar{f})|^2 \;\; \Rightarrow$ direct CP violation

Indirect CPV

- D^0 only, common to all decay modes

Direct CPV

- All three species (D^0, D^+, D_s^+), decay mode dependent

CP violation

Experimental techniques

- Time-dependent analysis:
  - difference in proper decay time distributions of $D^0 \to f$ and $\bar{D}^0 \to \bar{f}$
  - we measure indirect CPV
- Time-integrated analysis:
  - difference in time-integrated decay rates of $D^0 \to f$ and $\bar{D}^0 \to \bar{f}$
  - we measure direct+indirect CPV

Time-integrated analysis

- Asymmetry in time-integrated decay rates: $A^f_{CP} = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \bar{f})}$
- Charged D mesons: $A^f_{CP} = a^f_{\mathrm{dir}}$
- Neutral D mesons: $A^f_{CP} = a^f_{\mathrm{dir}} + a_{\mathrm{ind}}$
  - indirect CPV is universal: $a_{\mathrm{ind}} \equiv -A_\Gamma$ (neglecting terms with y_{CP})
  - world average: $A_\Gamma = (-0.014 \pm 0.052)\%$ (HFAG, June-2014)

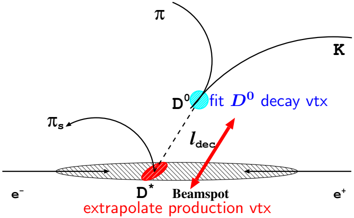
D^0 flavor tag

- Usually using $D^{*+} \to D^0 \pi^+_{\rm slow}$
  - flavor tagging by $\pi_{\rm slow}$ charge
  - provides also considerable background suppression
- Observables:
  - D^0 invariant mass: $M \equiv m(K\pi)$
  - D^{*+} mass difference: $\Delta M \equiv m(K\pi\pi_{\rm slow}) - m(K\pi)$ or $Q \equiv \Delta M - m_\pi$

- Measurements performed mainly at $\Upsilon(4S)$
  - D^{*+} from B decays can be completely rejected with

$$p_{D^{*+}}^{CMS} > 2.5 \ GeV/c$$

  - similar requirement used also when reconstructing charged D mesons
- IP constrained refit of $\pi_{\rm slow}$ to improve ΔM resolution



$$t = \frac{l_{dec}}{c\beta\gamma}, \quad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$

Time-integrated measurements (A_{CP})

- Asymmetry in time-integrated decay rates of $D^0 \to f$ and $\overline{D}^0 \to \overline{f}$

$$A_{CP}^f = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \overline{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \overline{f})}$$

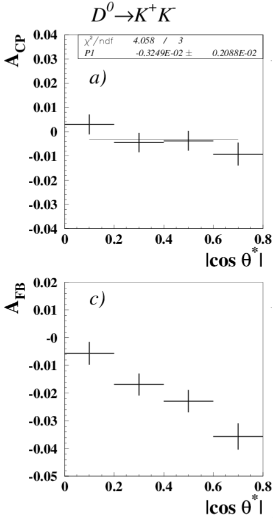
- Raw asymmetry

$$A_{\rm raw} = \frac{N - \overline{N}}{N + \overline{N}} = A_{\rm prod} + A_\epsilon^f + A_{CP}^f$$

  - $A_{\rm prod}$ production asymmetry
  - A_ϵ^f asymmetry in efficiency
- Production asymmetry at B-factory
  - odd function of CMS polar angle
    $A_{\rm prod} \equiv A_{FB}(cos\theta^*)$
  - can easily be disentangled

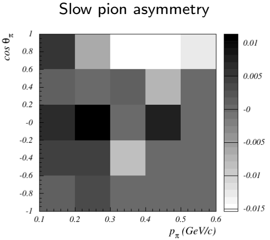
$$A_{CP} = \frac{A_{\rm raw}^{\rm cor}(cos\theta^*) + A_{\rm raw}^{\rm cor}(-cos\theta^*)}{2}$$

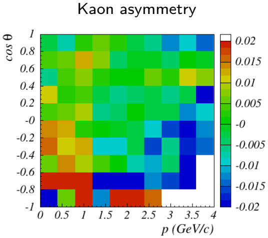
$$A_{FB} = \frac{A_{\rm raw}^{\rm cor}(cos\theta^*) - A_{\rm raw}^{\rm cor}(-cos\theta^*)}{2}$$



Detection asymmetries A_ϵ^f

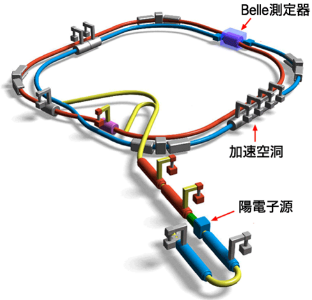
- Asymmetries in detection efficiency can be measured with sufficient precision using CF decays (direct CPV is very unlikely)
  - must be performed in bins of relevant phase-spaces
  - requires production asymmetries to be known
    $\rightarrow$ at B-factory: $A_{\text{prod}} \equiv A_{FB}(cos\theta^*)$
- Slow pions: from tagged and untagged $D^0 \rightarrow K^-\pi^+$ decays
- Kaons: from decays $D^0 \rightarrow K^-\pi^+$ and $D_s^+ \rightarrow \phi\pi^+$
- Pions: from decays $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^0$

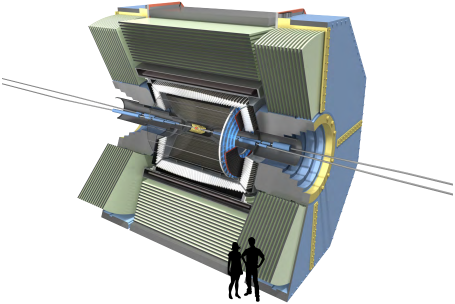




Belle II experiment

- Successor of Belle experiment (KEK, Tsukuba, Japan)





SuperKEKB accelerator

- upgraded KEKB
- luminosity 40 $\times$ KEKB $(8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1})$
- nano-beam optics

Belle II detector

- upgraded Belle detector
- majority of components replaced

Belle II environment

Critical issues at $\mathcal{L} = 8 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Higher background ($\times$10 - 20)
  - radiation damage and occupancy
  - fake hits and pile-up noise in EM calorimeter
- Higher event rate ($\times$40)
  - affects trigger, DAQ and computing

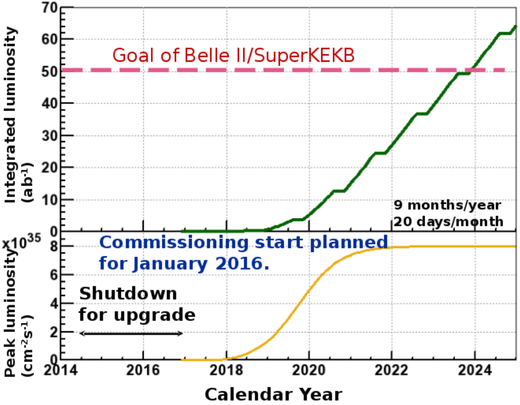
Have to employ and develop new technologies to make such an apparatus work efficiently.

Belle II detector upgrade

- Vertex detector
  - 4-layer DSSD replaced with 2 DEPFET layers + 4 DSSD layers
  - smaller inner radius, larger outer radius
    → better vertex resolution
    → improved efficiency for slow pions and K_S
- Central drift chamber
  - smaller cells, larger outer radius
    → improved momentum resolution and dEdx
- Hadron ID
  - ACC + TOF replaced with TOP (barrel) and aerogel RICH (forward)
    → less material in front of calorimeter
    → improved hadron ID
- Electromagnetic calorimeter
  - waveform sampling technique to cope with increased background
- K-long and muon detector
  - RPC's in endcaps and first two layers of barrel replaced with scintillator counters to cope with increased neutron background

Belle II schedule

- 2018: start to increase luminosity
- collect $\sim$ 10 ab^{-1} by mid 2020
- collect 50 ab^{-1} by 2024



Prospects for charm at Belle II

- Belle measurements extrapolated to 50 ab^{-1}
- Systematic uncertainties primarily scale with integrated luminosity, with two exceptions:
  - t-dependent Dalitz: model related systematics (resonance parameters - masses, widths, form factors, angular dependence etc.)
  - A_{CP} of modes with K_s^0: asymmetry of $K^0/\overline{K}^0$ interactions in material (PRD 84, 111501 (2011)), $\sigma_{\rm ired} \approx 0.02\%$
- Extrapolation:

$$\sigma_{BelleII} = \sqrt{(\sigma_{stat}^2 + \sigma_{sys}^2)\frac{\mathcal{L}_{Belle}}{50\ \mathrm{ab}^{-1}} + \sigma_{\rm ired}^2}$$

Detector performance improvements are not included in the extrapolation (detailed MC studies are on the way)

Mixing and indirect CPV

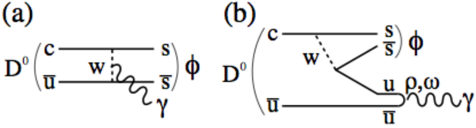
$D^0 \to K^{(*)-}\ell^+\nu$	492 fb^{-1}	50 ab^{-1}
R_M	$(1.3 \pm 2.2 \pm 2.0) \times 10^{-4}$	$\pm 0.3 \times 10^{-4}$
$D^0 \to K^+K^-, \pi^+\pi^-$	976 fb^{-1}	50 ab^{-1}
y_{CP}	$(1.11 \pm 0.22 \pm 0.11)\%$	$\pm 0.04\%$
A_Γ	$(-0.03 \pm 0.20 \pm 0.08)\%$	$\pm 0.03\%$
$D^0 \to K^+\pi^-$	400 fb^{-1}	50 ab^{-1}
x'^2	$(1.8 \pm 2.2 \pm 1.1) \times 10^{-4}$	$\pm 0.22 \times 10^{-4}$
y'	$(0.06 \pm 0.40 \pm 0.20)\%$	$\pm 0.04\%$
A_M	0.67 ± 1.20	± 0.11
$\|\phi\|$	0.16 ± 0.44	± 0.04
$D^0 \to K_s^0\pi^+\pi^-$	921 fb^{-1}	50 ab^{-1}
x	$(0.56 \pm 0.19 \pm 0.06 \pm 0.08)\%$	$\pm 0.08\%$
y	$(0.30 \pm 0.15 \pm 0.06 \pm 0.04)\%$	$\pm 0.05\%$
$\|q/p\|$	$0.90 \pm 0.16 \pm 0.04 \pm 0.06$	± 0.06
ϕ	$-0.10 \pm 0.19 \pm 0.04 \pm 0.07$	± 0.07

$$|q/p| = 1 + \tfrac{1}{2}A_M \Rightarrow \delta|q/p| = \tfrac{1}{2}\delta A_M$$

Time-integrated measurements (A_{CP})

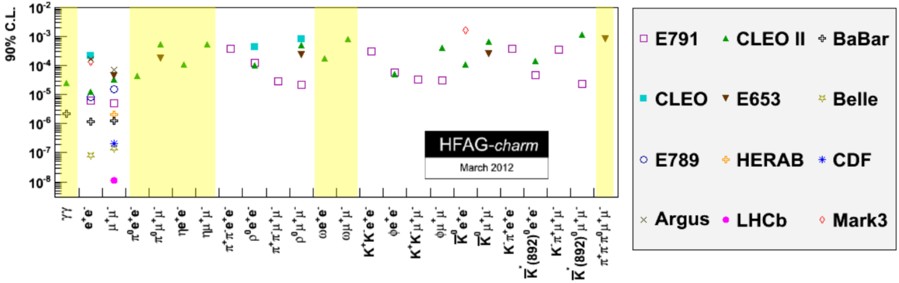
mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K_s^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.03
$D^0 \to K_s^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K_s^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K_s^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \to K_s^0K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D_s^+ \to K_s^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_s^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

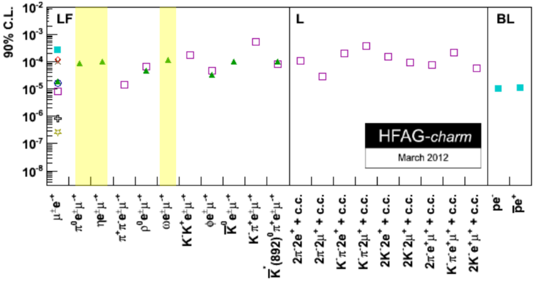
Direct CPV in $D^0 \to \phi\gamma, \rho^0\gamma$



- Direct CPV in radiative decays can be enhanced to exceed 1% (G. Isidori and J. F. Kamenik, PRL 109, 171801 (2012))
  - $D^0 \to \phi\gamma$: A_{CP} up to 2%
  - $D^0 \to \rho^0\gamma$: A_{CP} up to 10%
- $D^0 \to \phi\gamma$: first observation by Belle with 78 fb^{-1} (PRL 92, 101803 (2004))
  - measured yield: $27.6^{+7.4+0.5}_{-6.5-1.0}$
    $\Rightarrow$ relative error on yield 25% (as would be the error on A_{CP})
- A_{CP} sensitivity at 50 ab^{-1}: $\approx 1\%$

Rare and forbidden decays

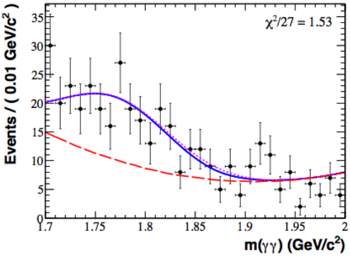




- Shaded regions indicate the decays with γ or π^0
- Mostly done by CLEO
- Belle II can improve these UL by several orders of magnitude

$D^0 \to \gamma\gamma$

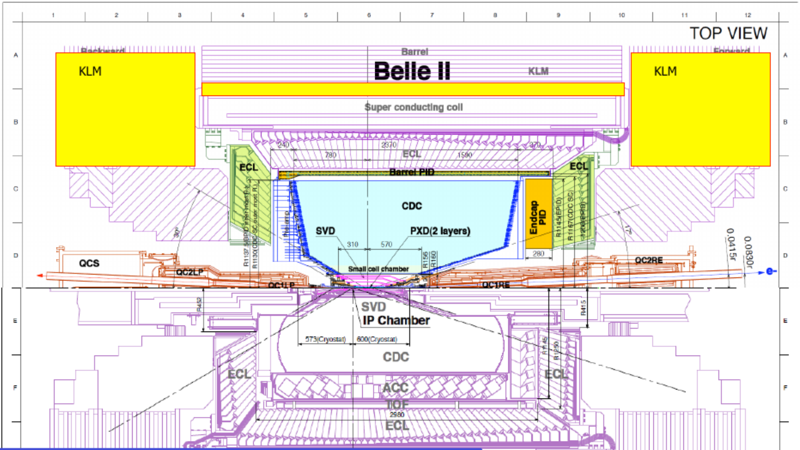
- SM predictions: long distance effects dominate
  $Br \sim \text{few} \times 10^{-8}$
- BaBar, 470 fb^{-1} PRD 85 (2012) 091107
  $Br < 2.2 \times 10^{-6}$ @ 90% CL
- Belle II at 50 fb^{-1}:
  $\to$ depends how background behaves
  - if UL would scale with $\mathcal{L}$:
    UL $\sim 2 \times 10^{-8}$
  - if UL would scale with $\sqrt{\mathcal{L}}$:
    UL $\sim 2 \times 10^{-7}$



Conclusions

- Perspectives for charm measurements at Belle II have been discussed.
- We focused on D-mixing and CPV.
- Using Belle results and a rough extrapolation to 50 ab^{-1} we found:
  - Sensitivities of most measurements will still be statistically limited.
  - In t-dependent Dalitz analysis of $D^0 \to K_s^0 \pi^+ \pi^-$ the model dependent systematics will probably dominate and saturate the sensitivity.
  - Belle II is in favor (compared to LHCb) in A_{CP} measurements because of equal D and $\overline{D}$ production; the sensitivity would reach in some cases a 0.03% level.
- Belle II can also be competitive in searches of rare and forbidden decays of D-mesons with γ or π^0 in the final state.

Belle II detector in comparison to Belle

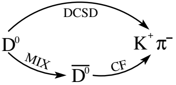


SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colour: new or upgraded components

Time-dependent measurements: $D^0 \to K^+\pi^-$

- Wrong sign (WS) final state: via DCS decays or via mixing



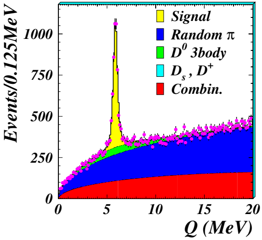
- Proper decay time distribution

$$\frac{dN}{dt} \propto [R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2]e^{-\Gamma t}$$

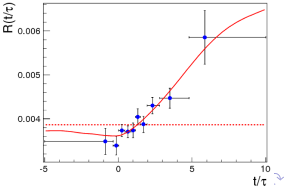
DCS interference mixing

R_D ratio of DCS/CF decay rates
$x' = x\cos\delta + y\sin\delta$
$y' = y\cos\delta - x\sin\delta$
δ strong phase between DCS and CF

WS events (400 fb^{-1})
PRL 96, 151801 (2006)



WS/RS ratio (976 fb^{-1})
PRL 112, 111801 (2014)



CP violation

- D^0 and $\bar{D}^0$ samples analyzed separately
  $\Rightarrow R_D^{\pm},\ x'^{2\pm},\ y'^{\pm}$
- direct CPV in DCS decays:

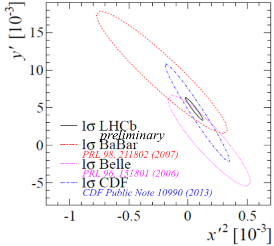
$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

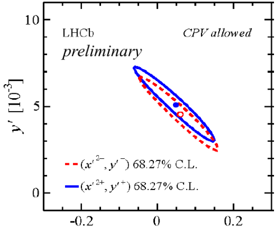
- CPV in mixing and interference → by solving 4 equations for 4 unknowns:

$$x'^{\pm} = (1 \pm \frac{1}{2}A_M) \cdot (x' \cos\phi \pm y' \sin\phi)$$

$$y'^{\pm} = (1 \pm \frac{1}{2}A_M) \cdot (y' \cos\phi \mp x' \sin\phi)$$

$\to x',\ y',\ \phi,\ |q/p| = 1 + \frac{1}{2}A_M$





Time-dependent measurements: $D^0 \to K^+K^-, \pi^+\pi^-$

- Measurement of lifetime difference between flavor specific and decays into CP final states
  - choice of flavor specific: kinematically similar $D^0 \to K^-\pi^+$
- Timing distributions are exponential
  - mixing parameter: $$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$$
  - $y_{CP} = y$, if CP conserved
- If CP violated $\to$ difference in lifetimes of $D^0/\overline{D^0} \to K^+K^-, \pi^+\pi^-$
  - asymmetry in lifetimes: $$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}$$
- If direct CPV negligible:
  - $y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$
  - $A_\Gamma = \frac{1}{2}A_M y \cos\phi - x\sin\phi$

Time-dependent measurements: $D^0 \to K_s^0\ \pi^+\pi^-$

- This three body decay proceeds via many intermediate states, like

  CF: $D^0 \to K^{*-}\pi^+$

  DCS: $D^0 \to K^{*+}\pi^-$

  CP: $D^0 \to \rho^0 K_s^0$
- Matrix element is Dalitz space dependent, so also time distribution is

$$\frac{dN_{D^0\to f}}{dt} \propto e^{-\Gamma t}\left|\mathcal{A}(m_-^2, m_+^2) + \frac{q}{p}(\frac{y+ix}{2}\Gamma t)\overline{\mathcal{A}}(m_-^2, m_+^2)\right|^2$$

- Total amplitude $\mathcal{A}$ parametrized as a sum of quasy-two-body amplitudes of resonances $\mathcal{A}_r$

$$\mathcal{A}(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r}\mathcal{A}_r(m_-^2, m_+^2)$$

- Both mixing parameters, x and y as well as CPV parameters ϕ and $|q/p|$ can be measured
- 3D fit in (m_-^2, m_+^2, t); many free parameters