Belle II perspectives on charm

(in the light of recent LHCb results)

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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

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

- $q/p \neq 1 \;\Rightarrow$ 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

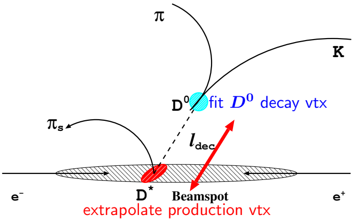
Experimental techniques

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

Experimental method at B-factories

- $D^{*+} \to D^0 \pi^+_{\rm slow}$
  - flavor tagging by $\pi_{\rm slow}$ charge
  - background suppression
- D^0 proper decay time measurement:

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



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

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

t-integrated measurements (A_{CP})

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

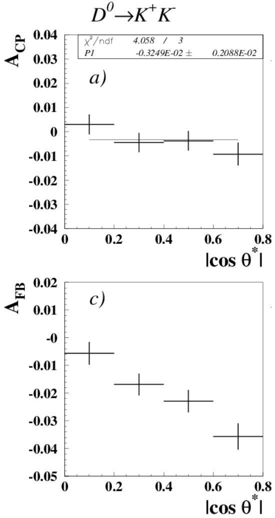
$$A^f_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \overline{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \overline{f})}$$

- Raw asymmetry

$$A_{\mathrm{raw}} = \frac{N - \overline{N}}{N + \overline{N}} = A_D + A^f_\epsilon + A^f_{CP}$$

  - A_D production asymmetry
  - A^f_ϵ asymmetry in efficiencies
- Production at B-factory is symmetric
  - huge benefit vs. LHC
  - however: odd function of CMS polar angle
    $A_D \equiv A_{FB}(cos\theta^*)$
  - can easily be disentangled

$$A_{CP} = \frac{A^{\mathrm{cor}}_{\mathrm{raw}}(cos\theta^*) + A^{\mathrm{cor}}_{\mathrm{raw}}(-cos\theta^*)}{2}$$
$$A_{FB} = \frac{A^{\mathrm{cor}}_{\mathrm{raw}}(cos\theta^*) - A^{\mathrm{cor}}_{\mathrm{raw}}(-cos\theta^*)}{2}$$



Detection asymmetries

- Asymmetries in detection efficiencies can be measured with sufficient precision using CF decays (CPV is very unlikely)
  - must be performed in bins of relevant phase-spaces
  - requires production asymmetries to be known
    $\rightarrow$ at B-factory: $A_D \equiv A_{FB}(cos\theta^*)$
- 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 $D^0 \rightarrow K^-\pi^+\pi^0$

Recent LHCb results

- A_Γ (1 fb^{-1} @ 7 TeV) PRL 112, 041801 (2014)
  - no evidence for CPV
  - $4\times$ better sensitivity compared to Belle result at 1 ab^{-1}
- $D^0 \to K^+\pi^-$ (3 fb^{-1} @ 7-8 TeV) PRL 111, 251801 (2013)
  - observation of mixing
  - no evidence for CPV
- $\Delta A_{CP} = A_{CP}^{KK} - A_{CP}^{\pi\pi}$ (1 fb^{-1} @ 7 TeV)
  - update of prompt D^* sample LHCb-CONF-2013-003
  - $B \to D^0\mu X$ sample ($2\times$ less sensitive) PLB 723 (2013) 33
  - no evidence for CPV
- A_{CP} for $D^+ \to \phi\pi^+$ (1 fb^{-1} @ 7 TeV) JHEP 06 (2013) 112
  - equal systematic and statistic uncertainties
  - no evidence for CPV
- y_{CP} (0.03 fb^{-1}) JHEP 04 (2012) 129
  - on very small (low luminosity) sample - no update available yet

Recent LHCb results compared to Belle

- Uncertainty is statistics and systematics added in quadrature
- Naive average of the two LHCb results in case of A_Γ and ΔA_{CP}

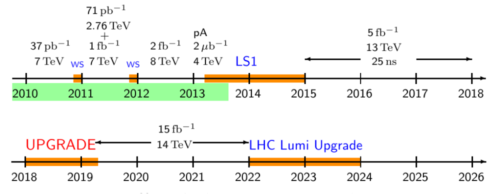
	LHCb	lumin. fb^{-1}	Belle	lumin. ab^{-1}	
A_Γ	$(-0.017 \pm 0.054)\%$	1	$(-0.03 \pm 0.22)\%$	1	naive av.
ΔA_{CP}	$(-0.15 \pm 0.16)\%$	1	$(-0.87 \pm 0.41)\%$	1	naive av.
x'^2	$(5.5 \pm 4.9) \times 10^{-5}$	3	$(18 \pm 22) \times 10^{-5}$	0.4	no CPV
y'	$(4.8 \pm 1.0) \times 10^{-3}$	3	$(0.6 \pm 4.0) \times 10^{-3}$	0.4	no CPV
y_{CP}	$(0.55 \pm 0.75)\%$	0.03	$(1.11 \pm 0.25)\%$	1	
$A_{CP}^{\phi\pi^+}$	$(-0.04 \pm 0.20)\%$	1	$(0.51 \pm 0.28)\%$	1	

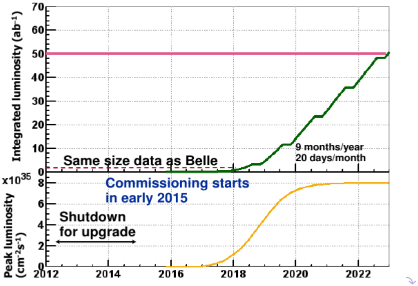
- Equivalent Belle II luminosity to obtain the sensitivity of LHCb measurements at 1 fb^{-1} can be roughly estimated with

$$\mathcal{L}_{\mathrm{BelleII}}^{\mathrm{equiv}} = \left(\frac{\sigma_{\mathrm{Belle}}}{\sigma_{\mathrm{LHCb}}}\right)^2 \frac{\mathcal{L}_{\mathrm{Belle}}}{\mathcal{L}_{\mathrm{LHCb}}}$$

LHCb/Belle II schedules

- LHCb (A. Contu, Charm 2013)
  - expect $\sim$ 8 fb^{-1} by 2018
  - 2018 - mid 2019 upgrade (3 - 4$\times$increase in D meson yields)
  - then additional 15 fb^{-1} by 2022
- Belle II
  - 2017: start to increase luminosity
  - collect $\sim$ 10 ab^{-1} by mid 2019
  - collect 50 ab^{-1} by 2023





Equivalent Belle II integrated luminosity

A_Γ	1 fb^{-1} (LHCb)	$\sim$	16 ab^{-1}	(Belle II)
ΔA_{CP}	1 fb^{-1} (LHCb)	$\sim$	7 ab^{-1}	(Belle II)
$x'^2,\ y'$	1 fb^{-1} (LHCb)	$\sim$	2.5 ab^{-1}	(Belle II)
y_{CP}	1 fb^{-1} (LHCb)	$\sim$	4 ab^{-1}	(Belle II)
$A_{CP}^{\phi\pi^+}$	1 fb^{-1} (LHCb)	$\sim$	2 ab^{-1}	(Belle II)

- Will not be competitive in A_Γ and ΔA_{CP}
  - but Belle II can measure A_{CP}^{KK} and $A_{CP}^{\pi\pi}$ separately
- Maybe still competitive in $x'^2,\ y'$ and y_{CP}
  - y_{CP} comparison based on initial low luminosity LHCb data (0.03 fb^{-1}) $\rightarrow$ extrapolation to 1 fb^{-1} might be too optimistic
- t-dependent Dalitz ?
- A_{CP} measurements: Belle II in favor because of symmetric production

Prospects at Belle II for mixing and CPV

- Belle measurements extrapolated to 50 ab^{-1}
- Systematics primarily scales 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)), $\sigma_{\text{ired}} \approx 0.02\%$
- Extrapolation:

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

Mixing and indirect CPV

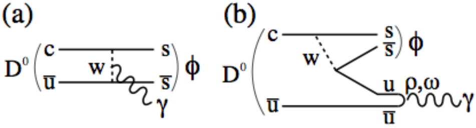
$D^0 \to K^{(*)-}\ell^+\nu$	492 fb^{-1}	50 ab^{-1}
R_M	$(1.3 \pm 2.2 \pm 2.0) \times 10^{-4}$	$\pm 0.3 \times 10^{-4}$
$D^0 \to K^+K^-, \pi^+\pi^-$	976 fb^{-1}	50 ab^{-1}
y_{CP}	$(1.11 \pm 0.22 \pm 0.11)\%$	$\pm 0.04\%$
A_Γ	$(-0.03 \pm 0.20 \pm 0.08)\%$	$\pm 0.03\%$
$D^0 \to K^+\pi^-$	400 fb^{-1}	50 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

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

Direct CPV

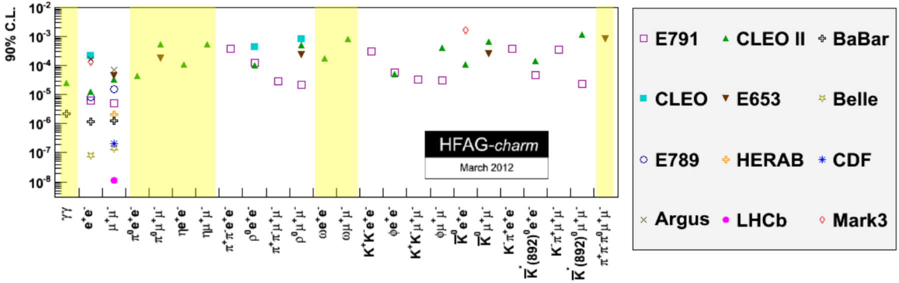
mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	976	$\sim \pm 0.60$	± 0.08
$D^0 \to K_s^0\pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	± 0.03
$D^0 \to K_s^0\eta$	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 $D^0 \to \phi\gamma, \rho^0\gamma$

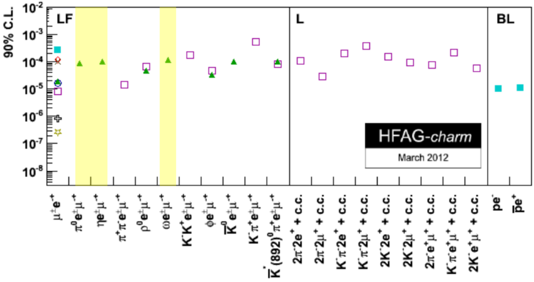


- Direct CPV in radiative decays can be enhanced to exceed 1% (G. Isidori and J. F. Kamenik, PRL 109, 171801 (2012))
  - $D^0 \to \phi\gamma$: A_{CP} up to 2%
  - $D^0 \to \rho^0\gamma$: A_{CP} up to 10%
- $D^0 \to \phi\gamma$: first observation by Belle with 78 fb^{-1} (PRL 92, 101803 (2004))
  - measured 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



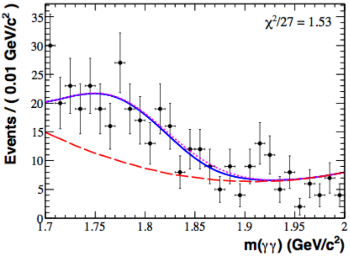
- Shaded regions indicate the decays with γ or π^0
- Mostly done by CLEO
- Belle II can improve these UL by several orders of magnitude



$D^0 \to \gamma\gamma$

- 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



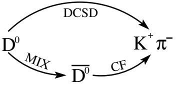
- Belle II at 50 fb^{-1}:
  $\to$ depends how background behaves
  - if UL would scale with $\mathcal{L}$:
    UL $\sim 2 \times 10^{-8}$
  - if UL would scale with $\sqrt{\mathcal{L}}$:
    UL $\sim 2 \times 10^{-7}$

Conclusions

- Perspectives for charm measurements at Belle II have been discussed in the light of recent LHCb results.
- We focused on D-mixing and CPV.
- Using Belle results and a rough extrapolation to 50 ab^{-1} we found:
  - Belle II cannot compete with LHCb in measurements of A_Γ and ΔA_{CP}, but might still be competitive in x'^2, y' and y_{CP} measurements.
  - 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 in A_{CP} measurements because of symmetric D-meson 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.

t-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

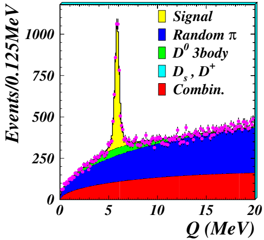
R_D ratio of DCS/CF decay rates

$x' = x\cos\delta + y\sin\delta$

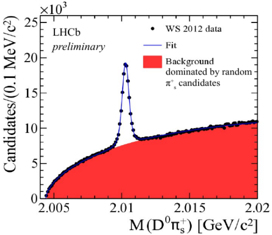
$y' = y\cos\delta - x\sin\delta$

δ strong phase between DCS and CF

WS events (Belle)



WS events (LHCb)



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

CP violation

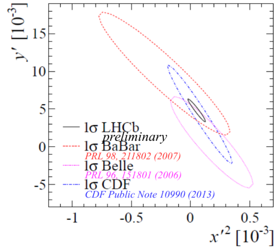
- D^0 and $\bar{D}^0$ samples analyzed separately
  $\Rightarrow R_D^{\pm},\ x'^{2\pm},\ y'^{\pm}$
- direct CPV in DCS decays:

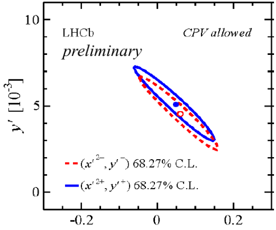
$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

- CPV in mixing and interference $\to$ by solving 4 equations for 4 unknowns:

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

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





t-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: $\boxed{y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1}$
  - $y_{CP} = y$, if CP conserved
- If CP violated $\to$ difference in lifetimes of $D^0/\overline{D^0} \to K^+K^-, \pi^+\pi^-$
  - asymmetry in lifetimes: $\boxed{A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}}$
- If direct CPV negligible:
  - $y_{CP} = y \cos\phi - \frac{1}{2} A_M x \sin\phi$
  - $A_\Gamma = \frac{1}{2} A_M y \cos\phi - x \sin\phi$

t-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