Charm CPV in decays with neutrals

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Towards the Ultimate Precision in Flavour Physics

Outline

I will purely focus on time-integrated measurements because in many decays with neutrals the decay vertex is not possible to reconstruct. I will also limit my presentation to prospects for Belle II measurements.

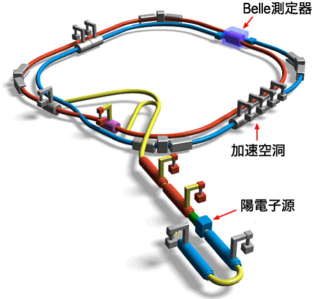
- The Belle II experiment
- Flavor tagging
- How the systematics is controlled
- Prospects at Belle II
    - $D^0 \to K_s^0 K_s^0$
    - $D^+ \to \pi^+ \pi^0$
    - $D^0 \to \phi\gamma, \rho^0\gamma$
    - other decays modes

More details

E. Kou, P. Urquijo eds., The Belle II Physics Book, to be published in Prog. Theor. Exp. Phys.

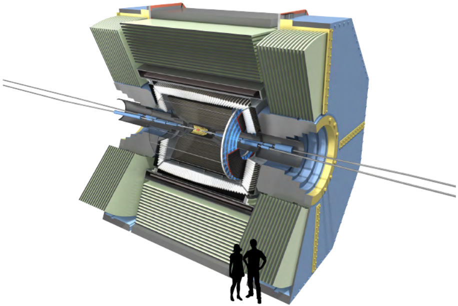
The Belle II experiment

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



SuperKEKB accelerator

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



Belle II detector

- upgraded Belle detector
- majority of components replaced

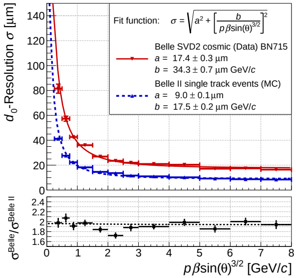
The Belle II detector

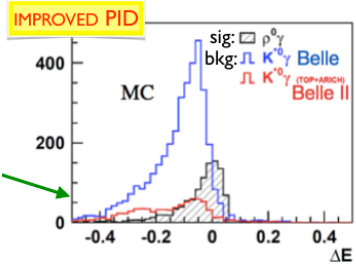
- Vertex detector (replaced completely)
  - 2 DEPFET layers + 4 DSSD layers
  - smaller inner radius, larger outer radius
    → two-times better vertex resolution
    → improved efficiency for slow pions and K_S
- Central drift chamber (replaced completely)
  - smaller cells, larger outer radius
   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

Belle II performance improvements

Improvements w.r.t Belle

- primary and secondary vertex resolution
- K_S and π^0 reconstruction efficiency
- hadron and muon ID in the end caps
- K/π separation



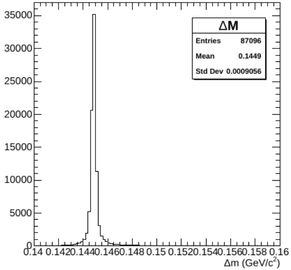


Flavor tagging: golden method

Golden method

- selecting D^0 from $D^{*+} \rightarrow D^0\pi^+_{\rm slow}$
  - flavor is tagged with the charge of $\pi_{\rm slow}$
  - observables:
    - D^0 invariant mass
    - D^{*+} mass difference: $\Delta M \equiv m(D^{*+}) - m(D^0)$
- to select D^0 from $c\overline{c}$ events: $p^{CMS}_{D^{*+}} > 2.5\ GeV/c$

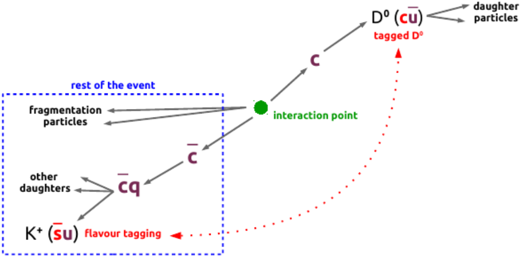
- provides good background rejection power because of small energy release
  - ΔM resolution at Belle II: $\sim 180\ \mathrm{keV/c^2}$
  - a factor of two better than at Belle or BaBar
- typical reconstruction efficiency: 80%
- typical mistagging rate: 0.2%



Flavor tagging: ROE method

Rest-of-event (ROE) method

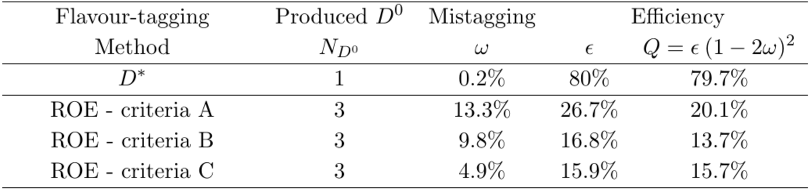
- New method with the goal of increasing tagged sample size by adding D^0 mesons not reconstructed in D^{*+} decays



- reconstruct D^0 and look at the rest-of-event
    - the events with only one $K^{\pm}$ are selected
    - flavor is tagged with the charge of a kaon
- to select D^0 from $c\bar{c}$ events: $p_{D^0}^{CMS} > 2.5\ GeV/c$

Flavor tagging: method comparison

comparison of tagging methods



Flavour-tagging Method	Produced D^0 N_{D^0}	Mistagging ω	ϵ	Efficiency $Q = \epsilon\,(1-2\omega)^2$
D^*	1	0.2%	80%	79.7%
ROE - criteria A	3	13.3%	26.7%	20.1%
ROE - criteria B	3	9.8%	16.8%	13.7%
ROE - criteria C	3	4.9%	15.9%	15.7%

- About 4 times lower tagging efficiency of ROE method is compensated by 3 times higher non-D^{*+} production rate
- Combining both we can almost double the tagged samples
  - however, mistagging rate is higher and also sample purity is lower

Impact on precision of time-integrated measurements

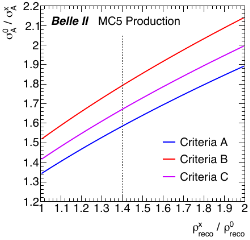
- The ratio of A_{CP} statistical uncertainties can be written as

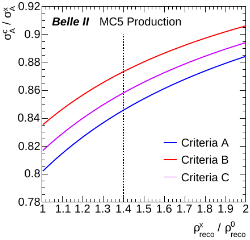
$$\frac{\sigma^{ROE}_{A_{CP}}}{\sigma^{D^*}_{A_{CP}}} = \sqrt{\frac{1}{3} \cdot \frac{Q^{D^*}}{Q^{ROE}} \cdot \frac{\rho^{D^*}_{reco}}{\rho^{ROE}_{reco}}} \equiv \alpha$$

● production ratio ● effective tagging efficiency ● sample purity

  - ratio of sample purities ~1.4 BaBar, PRD 87(1), 012004 (2013)

- both methods combined: $\sigma_{A_{CP}} = \frac{\alpha}{\sqrt{1+\alpha^2}} \cdot \sigma^{D^*}_{A_{CP}}$





→ expect to increase sensitivity by 15% if combining both methods

Time-integrated measurements (A_{CP})

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

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

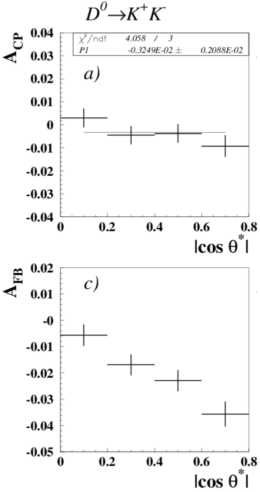
- Raw asymmetry

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

  - A_D production asymmetry
  - A^f_ϵ asymmetry in efficiencies
- Production asymmetry at B-factory
  - odd function of CMS polar angle
    $A_D \equiv A_{FB}(cos\theta^*)$
  - can easily be disentangled

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

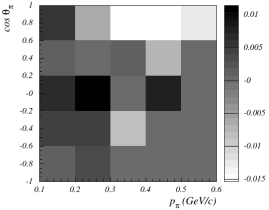
$$A_{FB} = \frac{A^{\mathrm{cor}}_{\mathrm{raw}}(cos\theta^*) - A^{\mathrm{cor}}_{\mathrm{raw}}(-cos\theta^*)}{2}$$



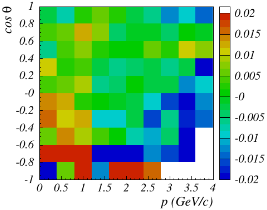
Detection asymmetries A_{ϵ}^{f}

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

Slow pion asymmetry



Kaon asymmetry



Prospects for A_{CP} at Belle II

- Belle measurements extrapolated to 50 ab^{-1}
- Systematic uncertainties primarily scale with integrated luminosity, with an exception of modes with K_s^0
  - asymmetry of $K^0/\overline{K}^0$ interactions in the material: $\sigma_{\mathrm{ired}} \approx 0.02\%$ PRD 84, 111501 (2011)
- Extrapolation:

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

Detector performance improvements are not included in the extrapolation as well as possible sensitivity increase obtained with additional ROE tagging.

$D^0 \to K_s^0 K_s^0$

- Promising channel since CPV can be as large as 1% in SM
- Belle measurement (921 fb^{-1}), PRL 119, 171801 (2017)

$$A_{CP}(D^0 \to K_s^0 K_s^0) = (-0.02 \pm 1.53 \pm 0.17)\%$$

  - significantly more precise than LHCb at 3 fb^{-1}
- Since final state includes two K_s^0 the only detection asymmetry comes from tagging: $A_{\mathrm{raw}} = A_{CP} + A_{FB} + A_{\epsilon}^{\pi slow}$
  - can be corrected for by using tagged and untagged $D^0 \to K^-\pi^+$ decays
- Other option (used in Belle measurement): normalize to $D^0 \to K_s^0\pi^0$:

$$A_{CP}(K_s^0 K_s^0) = A_{\mathrm{raw}}(K_s^0 K_s^0) - A_{\mathrm{raw}}(K_s^0\pi^0) + A_{CP}(K_s^0\pi^0)$$

  - CPV due to K^0 mixing (-0.34%) must be subtracted from $A_{CP}(K_s^0\pi^0)$
  - $\sigma_{\mathrm{ired}} \approx 0.02\%$ due to $K^0/\overline{K}^0$ material interactions comes in
- Extrapolating Belle sensitivity to 50 ab^{-1}

$$\sigma_{A_{CP}} \sim 0.21\%$$

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

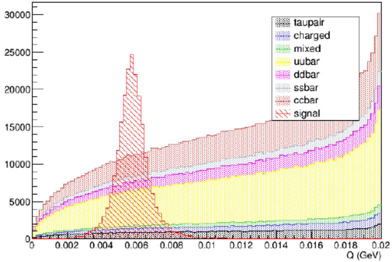
- Smoking gun for NP since CPV in SM is tiny in this mode
- Belle measurement (921 fb^{-1}), PRD 97, 011101(R) (2018)

$$A_{CP}(D^0 \to \pi^+\pi^0) = (2.31 \pm 1.24 \pm 0.23)\%$$

- a MC study performed in order to estimate Belle II precision
  - with MC sample corresponding to 50 ab^{-1}
  - using D^+ from $D^{*+} \to D^+\pi^0$ to reduce background
  - selection efficiency and background rejection found similar to Belle

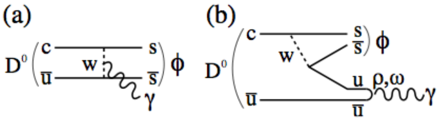
Extrapolating Belle sensitivity to 50 ab^{-1}

$$\sigma_{A_{CP}} \sim 0.17\%$$



signal peak is multiplied by 10

$D^0 \to \phi\gamma, \rho^0\gamma$

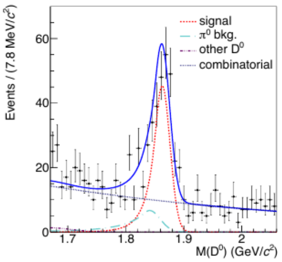


- Direct CPV in radiative decays can be enhanced by chromomagnetic dipole operators, G. Isidori and J. F. Kamenik, PRL 109, 171801 (2012)
  - $D^0 \to \phi\gamma$: A_{CP} up to 2%
  - $D^0 \to \rho^0\gamma$: A_{CP} up to 10%

- Belle, 943 fb^{-1}, PRL 118, 051801 (2017)
  - $A_{CP}(D^0 \to \phi\gamma) = (-9.4 \pm 6.6 \pm 0.1)\%$
  - $A_{CP}(D^0 \to \rho^0\gamma) = (5.6 \pm 15.2 \pm 0.6)\%$

    → consistent with no CPV

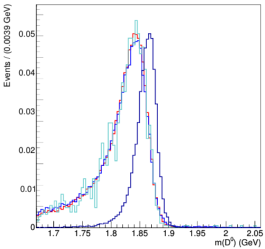
$D^0 \to \phi\gamma$

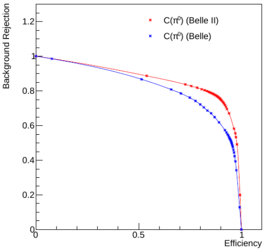


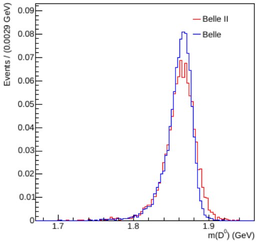
$D^0 \to \phi\gamma, \rho^0\gamma$: sensitivity at Belle II

- Background rejection and mass resolution studied by MC
- The dominant background arises from $D^0 \to V\pi^0$ ($V \equiv \phi, \rho^0$)
  - Belle developed a dedicated π^0 veto employing a neural network
  - MC indicates that this veto would perform similarly at Belle II
- Invariant mass resolution also found similar

  → can extrapolate Belle measurements by luminosity scaling only
- Sensitivity at 50 ab^{-1}
  - $A_{CP}(D^0 \to \phi\gamma)$: 0.9% (NP: up to 2%)
  - $A_{CP}(D^0 \to \rho^0\gamma)$: 2.1% (NP: up to 10%)







A_{CP} sensitivities at Belle II (decays with neutrals)

mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K_S^0 K_S^0$	921	$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$	± 0.21
$D^0 \to K_s^0 \pi^0$	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
$D^0 \to \phi\gamma$	943	$-9.4 \pm 6.6 \pm 0.1$	± 0.90
$D^0 \to \rho^0\gamma$	943	$+5.6 \pm 15.2 \pm 0.6$	± 2.10
$D^0 \to \overline{K}^{*0}\gamma$	943	$-0.3 \pm 2.0 \pm 0.04$	± 0.27
$D^+ \to \eta\pi^+$	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
$D^+ \to K_s^0 K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D^+ \to \pi^+\pi^0$	921	$+2.31 \pm 1.24 \pm 0.23$	± 0.17
$D_s^+ \to K_s^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_s^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

Conclusions

- Perspectives for CPV in decays with neutrals have been discussed.
- We focused on the time-integrated measurements at Belle II.
- Initial MC studies have indicated that the performance at Belle II will stay similar to Belle, therefore a straightforward extrapolation by luminosity scaling could already give reasonable sensitivity estimates.
- The sensitivities in singly Cabibbo suppressed decays are found typically between 0.1% and 0.2%.
- Most measurements will still be dominated by statistics uncertainties.

Backup: purely charged modes

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
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04

Backup: Sum rules (sensitivitis at Belle II)

Sum rule I

mode	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$	$D^0 \to \pi^0\pi^0$
$\sigma_{A_{CP}}$	0.03%	0.05%	0.09%

Sum rule II

mode	$D^+ \to K_s^0 K^+$	$D_s^+ \to K_s^0\pi^+$	$D_s^+ \to K^+\pi^0$
$\sigma_{A_{CP}}$	0.05%	0.29%	(*)

(*) not measured at Belle

- $D_s^+ \to K^+\pi^0$ not measured at Belle
  - simple scaling by Br ratio of $D_s^+ \to K_s^0\pi^+$ and $D_s^+ \to K^+\pi^0$, and assuming similar detection efficiencies gives $\sigma_{A_{CP}} \sim 0.4\%$