Charm Physics Prospects at the Belle II experiment

Yeqi Chen (On behalf of the Belle II Collaboration)
State Key of Particle Detection and Electronics
University of Science and Technology of China
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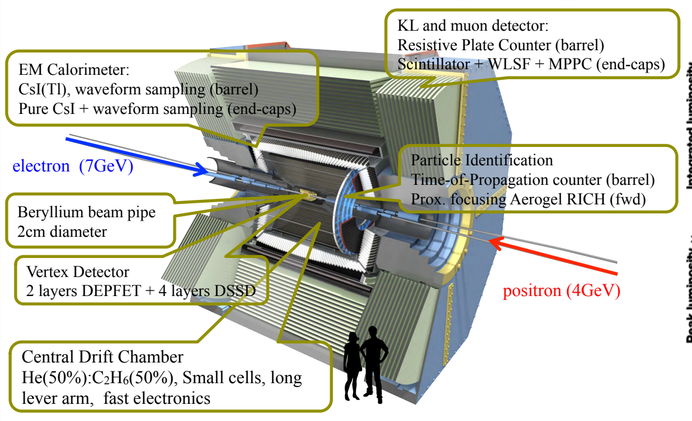
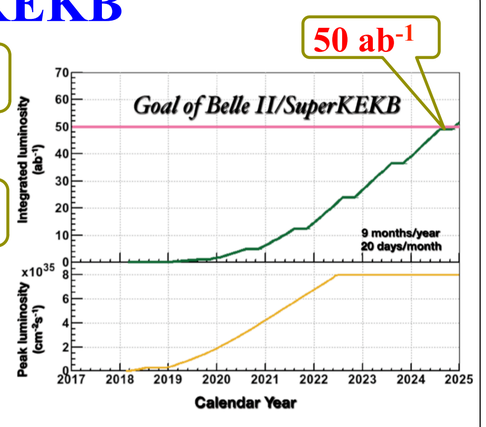
LEPTON PHOTON 2017

Belle II Detector @ SuperKEKB

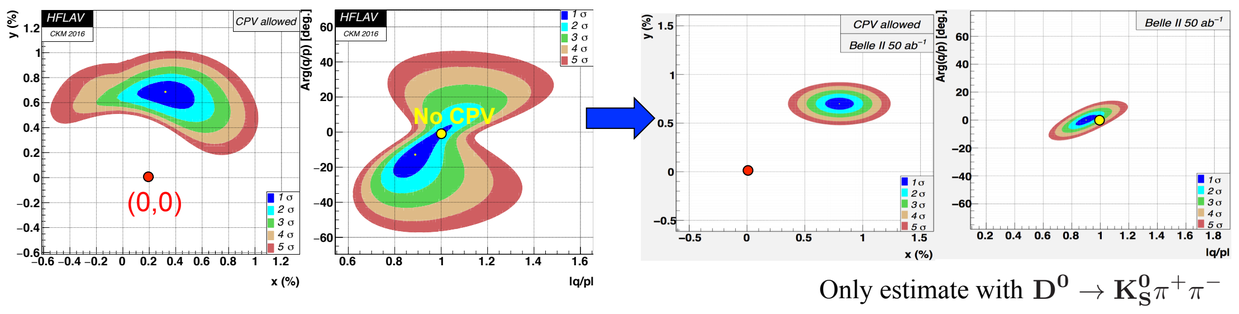




- Great performances expected in the reconstruction of final states with neutrals and missing energies (e.g. K^0_S, π^0, η)
- First data taking (without vertex detector) will start in 2018

Status of $D^0 - \bar{D}^0$ Mixing and *CP* Violation

- **Status from HFAG 2016**
- **Prospects at Belle II**



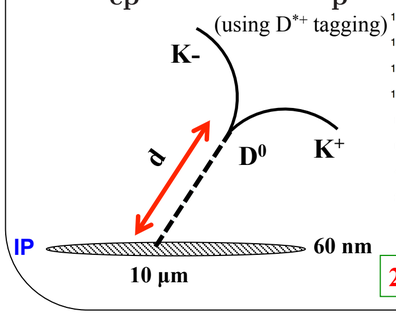
Only estimate with $D^0 \to K^0_S\pi^+\pi^-$

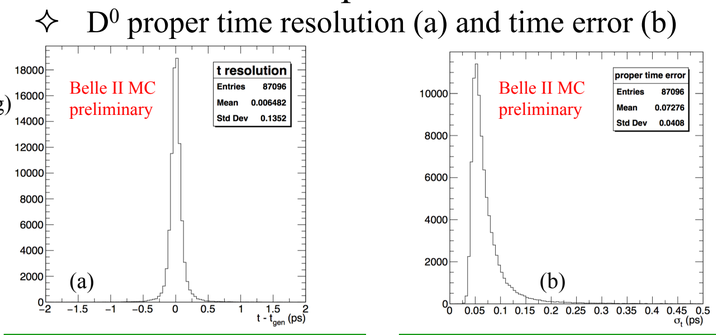
✧ Unique system to study mixing and *CP* Violation (CPV) in the up-quark sector
✧ It is difficult to calculate $D^0 - \bar{D}^0$ mixing via non-perturbative theory
✧ $D^0 - \bar{D}^0$ mixing has been observed with >> 11.5σ confidence level[1]

D^0 Proper Time Resolution

- **D^0 proper time resolution** is improved by a factor of two, mainly benifiting from[2]
  - ✧ 6 layers vertex detector: **4 layers SVD + 2 layers PXD**; and the innermost layer is 2 times **closer to** interaction point(IP)
  - ✧ squeezed beams at the IP, two orders of magnitude smaller w.r.t Belle
- **Time resolution** is essential in time-dependent measurements
  - ✧ D^0 proper time resolution (a) and time error (b)

$$t = \frac{m_{D^0}}{cp}(\vec{r}_{dec} - \vec{r}_{IP})\frac{\vec{p}}{p}$$





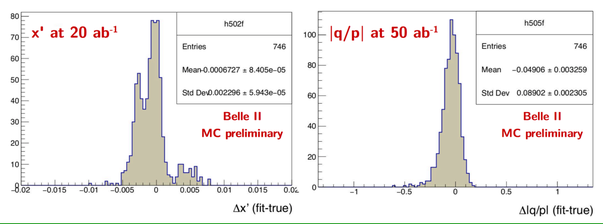
2x better w.r.t BaBar: 140 fs

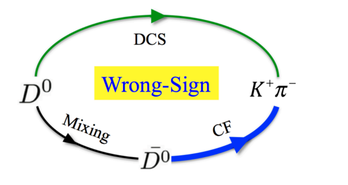
3x smaller w.r.t BaBar: 73 fs

Impact on $D^0 - \bar{D}^0$ Mixing and CPV

- Toy MC study for WS decay $D^0 \to K^+\pi^-$
  (using D^{*+} tagging, almost background free at B-factories)

$$D^0(t) = e^{-\Gamma t}\left[R_D + \left|\frac{q}{p}\right|\sqrt{R_D}(y'\cos\phi - x'\sin\phi)(\Gamma t) + \left|\frac{q}{p}\right|^2\frac{x'^2+y'^2}{4}(\Gamma t)^2\right]$$





CPV parameters: |q/p| and ϕ=Arg(q/p)

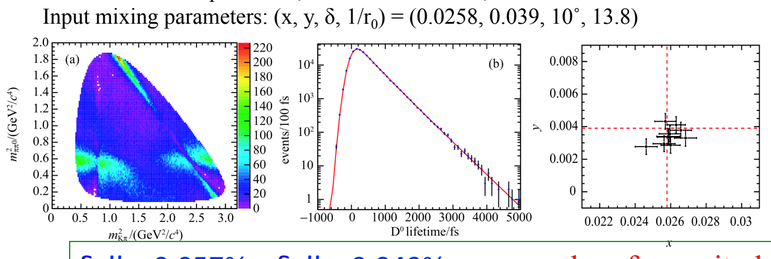
$$x' = x\cos\delta + y\sin\delta$$
$$y' = -x\sin\delta + y\cos\delta$$

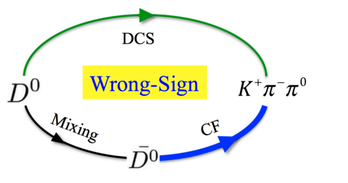
σ(x') = 0.015% σ(y') = 0.010% σ(|q/p|) = 0.05% σ(φ) = 5.7°
~ one order of magnitude better than that of Belle ~ 1.6 times better than the world average

- Toy MC study for time-dependent Dalitz analysis of WS decay $D^0 \to K^+\pi^-\pi^0$[3]
  (using D^{*+} tagging, without including the backgrounds)

$$|\mathcal{M}(\bar{f},t)|^2 = e^{-\bar{\Gamma}t}\left\{r_0^2|\mathcal{A}_{\bar{f}}^{DCS}|^2 - r_0\left[Ay'' + Bx''\right](\bar{\Gamma}t) + \frac{x''^2+y''^2}{4}|\bar{\mathcal{A}}_{\bar{f}}^{CF}|^2(\bar{\Gamma}t)^2\right\}$$

Ensemble of 10 experiments, t resolution =140 fs,
Input mixing parameters: (x, y, δ, 1/r_0) = (0.0258, 0.039, 10°, 13.8)





CPV neglected

$$x'' = x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0}$$
$$y'' = y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0}$$
$$A = \Re(\mathcal{A}_{\bar{f}}^{DCS}\bar{\mathcal{A}}^{*CF}_{\bar{f}})$$
$$B = \Im(\mathcal{A}_{\bar{f}}^{DCS}\bar{\mathcal{A}}^{*CF}_{\bar{f}})$$

δx'' = 0.057% δy'' = 0.049% ~ one order of magnitude more precise than BaBar

Impact on Time-integrated (direct) CPV

- *CP* asymmetry parameter

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

- No clear evidence of direct CPV, no hints of indirect CPV
- Typical golden channels at Belle II, e.g.

$D^0 \to K^0_S K^0_S$
- ✧ CPV enhanced in SM predictions
- ✧ limited by statistic at Belle
- ✧ Belle II expects a precision of ~0.2%

$D^+ \to \pi^0\pi^+$
- ✧ No CPV in the isospin limit
- ✧ possible enhancement from NP
- ✧ Belle II expects a precision of ~0.4%

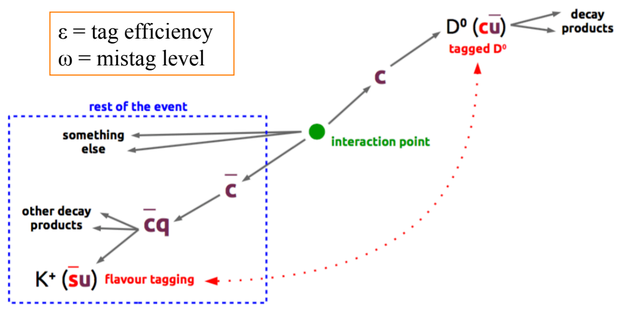
Expected A_{CP} uncertainty @ Belle II of 50 ab^{-1} (D^{*+} tagging)

Channel	Current measurement $\mathcal{L}$(fb^{-1})	value(%)	Scaled 50 ab^{-1}
$D^0 \to K^+K^-$	976	-0.32 ± 0.21 ± 0.09	±0.03
$D^0 \to \pi^+\pi^-$	976	+0.55 ± 0.36 ± 0.09	±0.05
$D^0 \to \pi^0\pi^0$	966	-0.03 ± 0.64 ± 0.10	±0.09
$D^0 \to K^0_S\pi^0$	966	-0.21 ± 0.16 ± 0.07	±0.03
$D^0 \to K^0_S\eta$	791	+0.54 ± 0.51 ± 0.16	±0.07
$D^0 \to K^0_S\eta'$	791	+0.98 ± 0.67 ± 0.14	±0.09
$D^0 \to K^0_S K^0_S$	921	-0.02 ± 1.53 ± 0.17	±0.20
$D^0 \to \pi^+\pi^-\pi^0$	532	+0.43 ± 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
$D^0 \to \rho^0\gamma$	976	+0.056 ± 0.152 ± 0.006	±0.02
$D^0 \to \phi\gamma$	976	-0.094 ± 0.066 ± 0.001	±0.01
$D^0 \to \bar{K}^{*0}\gamma$	976	-0.003 ± 0.020 ± 0.000	±0.003
$D^+ \to \pi^0\pi^+$	921	+0.89 ± 1.98 ± 0.22	±0.40
$D^+ \to \phi\pi^+$	955	+0.51 ± 0.28 ± 0.05	±0.04
$D^+ \to \eta\pi^+$	791	+1.74 ± 1.13 ± 0.19	±0.14
$D^+ \to \eta'\pi^+$	791	-0.12 ± 1.12 ± 0.17	±0.14
$D^+ \to K^0_S\pi^+$	977	-0.36 ± 0.09 ± 0.07	±0.03
$D^+ \to K^0_S K^+$	977	-0.25 ± 0.28 ± 0.14	±0.05
$D^+_s \to K^0_S\pi^+$	673	+5.45 ± 2.50 ± 0.33	±0.29
$D^+_s \to K^0_S K^+$	673	+0.12 ± 0.36± 0.22	±0.05

$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{syst})\cdot(\mathcal{L}_{Belle}/50\ ab^{-1}) + \sigma^2_{irred}}$$

Flavour tagging: ROE method (new)

- B-factories usual flavour tagging:
  - ✧ D^0 flavour tagged by the charge of π_{slow} from D^*
  - ✧ Lose 75% of in $c\bar{c}$ events
- ROE: selecting events with only one $K^\pm$ in the rest of event to tag D^0 flavour



✧ Examples of Signal Events

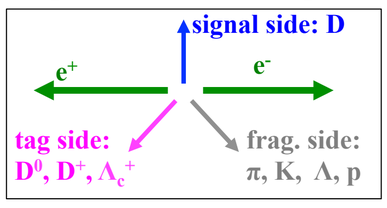
$c\bar{c} \to D^0D^-X; D^0 \to X; D^- \to K^+\pi^-e^-\nu_e$
$D^- \to K^{*0}e^-\bar{\nu}_e; K^{*0} \to K^+\pi^-$
$c\bar{c} \to D^0\Lambda_c^-X; D^0 \to X; \Lambda_c^- \to \Delta^-K^{*+}; K^{*+} \to K^+\pi^0$

- ✦ Expected performances:
  ε ~ 27% ω ~13%
  ⟹ efficiency $Q^0 = \varepsilon\cdot(1-2\omega)^2 \sim 20\%$
- ✦ Performances for D^{*+} tagging:
  ε ~ 27% ω ~13%
  ⟹ efficiency $Q^* = 0.8\cdot(1-2\cdot 20\%)^2 \sim 80\%$
  (but only 25% of D^0 are from D^{*+})

A reduction ~ 15% of stat. uncertainty on A_{CP} mesurement

(semi)Leptonic decays and Rare charm decays

- Leptonic and semileptonic decays

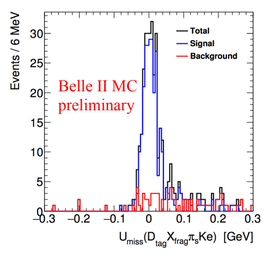


✧ leptonic decay $D_{(s)}^+ \to \ell^+\nu$
- ✦ improve uncertainty measurement of $|V_{cs}|$
- ✦ measure $|V_{cd}|$ with < 2% of precision

✧ semileptonic decay $D^+ \to h\ell\nu$
- ✦ **signal:** ℓ = μ, e; h= K, π (D^{*+} tagging)
- ✦ predicts for Belle II 7.0×10^5 πeν

Missing energy from neutrino in $D_{tag}X_{frag}\pi_s^-\ell$ and $D_{tag}X_{frag}\pi_s^-h\ell$ system:

$$P_{miss} = P_{e^+} + P_{e^-} - P_{D_{tag}} - P_{X_{frag}} - P_l$$
$$P_{miss} = P_{e^+} + P_{e^-} - P_{D_{tag}} - P_{X_{frag}} - P_h - P_l$$
$$U_{miss} = E_{miss} - |\vec{p}_{miss}| \text{ peaks at 0 for signal}$$



MC with 1 ab^{-1}
Tag: $D^0 \to K^-\pi^+$
Frag.: π^-

- Rare charm decay: search for New Physics

✧ Radiative decays D → Vγ

$$A_{CP}(D^0\to\rho^0\gamma) = +0.056 \pm 0.152 \pm 0.006$$
$$A_{CP}(D^0\to\phi\gamma) = -0.094 \pm 0.066 \pm 0.001$$
$$A_{CP}(D^0\to\bar{K}^{*0}\gamma) = -0.003 \pm 0.020 \pm 0.000$$

- ✦ results limited by statistical magnitude[4]
- ✦ A_{CP}(D →Vγ) first measurement, no CPV observed
- ✦ an order of increase in sensitivity of Belle II data

$$\begin{cases}\sigma(A_{CP}(D^0\to\rho\gamma)) = 0.02,\\ \sigma(A_{CP}(D^0\to\phi\gamma)) = 0.01,\\ \sigma(A_{CP}(D^0\to K^*\gamma)) = 0.003\end{cases}$$

✧ D → γγ
- ✦ The upper-limit on branch ratio[5]: $B^{90\%}_{UL}(D^0\to\gamma\gamma) < 8.5\times10^{-7}$
  ⟹ approaching SM prediction
- ✦ This decay will be probed futher at Belle II

Conclusions

- Belle II will have a rich charm physics program
- Considering the impact of the improved tracking at Belle II, which will allow
  - ✧ **improved precision of $D^0 - \bar{D}^0$ mixing/CPV parameters**
  - ✧ **more precise direct *CP* asymmetries measurements**
  - ✧ **(semi)leptonic decay study to improve measurement of $|V_{cs}|$, $|V_{cd}|$ and possible to search for $D^0 \to$ invisibles**
  - ✧ **much lower limits on rare and forbidden decays**
- A new flavour-tagging ROE has been developed, which will provide larger statistical data

References
[1] HFAG: Global Fit for $D^0 - \bar{D}^0$ Mixing, http://www.slac.stanford.edu/xorg/hflav/charm/CKM16/results_mix_cpv.html
[2] Belle II Collaboration & B2TiP Theory Community, The Belle II Physics Book (to be published on PTEP)
[3] L. K. Li *et al.*, $D^0 - \bar{D}^0$ mixing sensitivity estimation at Belle II in wrong-sign decays $D^0\to K^+\pi^-\pi^0$ via time-dependent amplitude analysis, Chin. Phys. C **41**, 023001 (2017)
[4] T. Nanut *et al.* (Belle Collaboration), Observation of $D^0\to\rho^0\gamma$ and Search for *CP* Violation in Radiative Charm Decays Phys. Rev. Lett. **118**, 051801 (2017)
[5] N. K. Nisar *et al.* (Belle Collaboration), Search for rare decay $D^0 \to \gamma\gamma$ at Belle, Phys. Rev. D **93**, 051102(R) (2016)