# Prospects for charm mixing at Belle II

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On behalf of the Belle II Collaboration

Lake Louise Winter Institute 2018

February 18-24, 2018

# Mixing in $D^0$ system

- Mass and weak eigenstates are expressed as

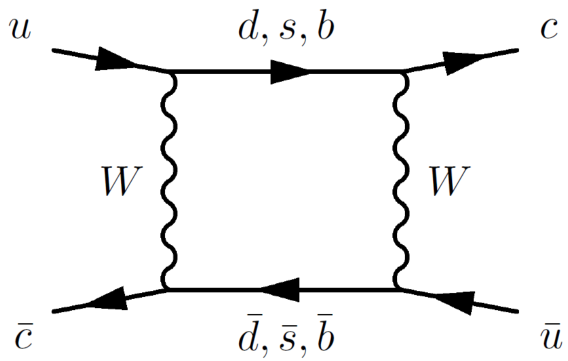
$$|D^0_{1,2}\rangle = \frac{1}{\sqrt{|p|^2+|q|^2}}\left(p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle\right)$$

If p ≠ q, CP is violated

- Mixing parameterized by mass/width splittings:

$$x = \frac{m_1 - m_2}{\Gamma},\ y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

- In SM, D-mixing is heavily suppressed
  - CKM suppressed
  - GIM suppressed



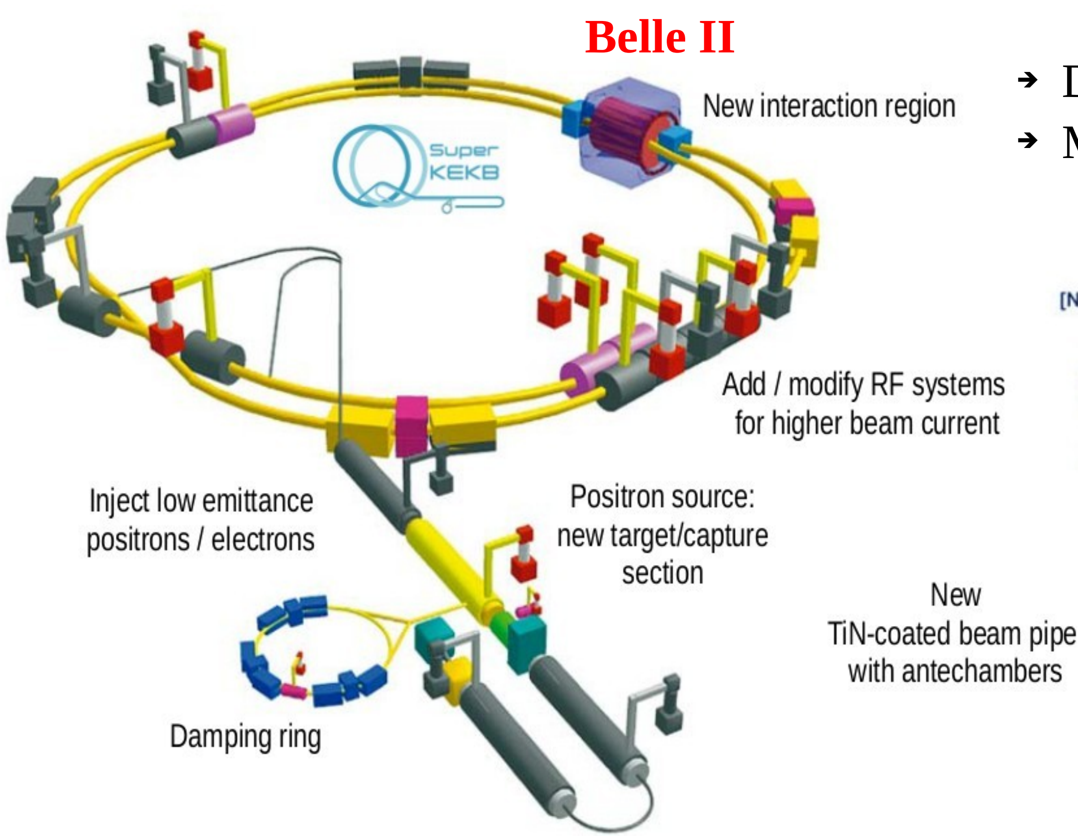

- SM expectation: $|x|, |y| \sim O(10^{-3} – 10^{-2})$.

- Non-SM particles contributing to the box diagram (NP) could significantly affect the measured values

- Precision measures need huge satistics (KEKB → SuperKEKB) and clean, accurate signals (Belle → Belle II)

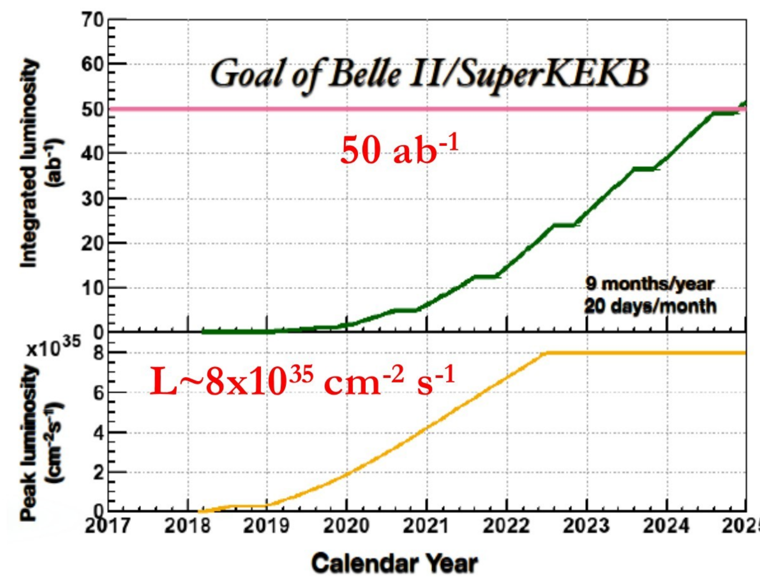
# SuperKEKB (High luminosity frontier machine!)

- SuperKEKB – major upgrade of the KEKB B factory at KEK
- $e^+e^-$ (**4 GeV** + **7 GeV**) → BB mainly at $\sqrt{s}_{cm}$=10.58 GeV (peak of Υ(4S) resonance)




To obtain x40 higher instantaneous luminosity:

- Double beam current
- Major increase by small beam size "nano-beam" (vertical spot size ~50nm !!)

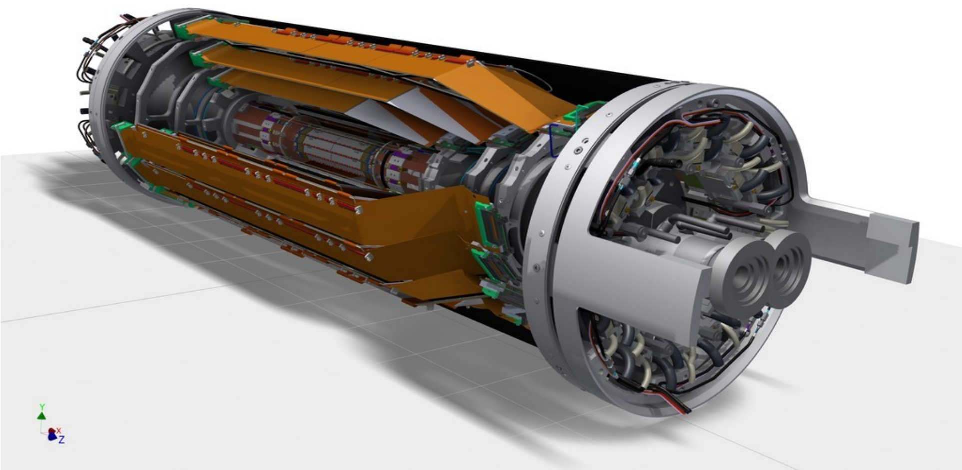


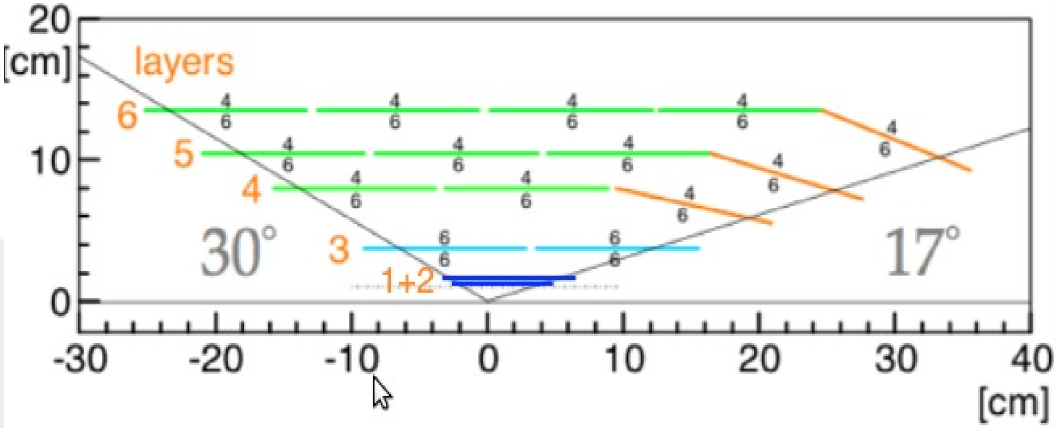

Covered by Alexei Sibidanov on
Belle II readiness for Phase II collisions

# Belle II Vertex detector (main player for D-mixing sensitivity measurement)

Belle II detector covered by Alexei

- VXD = silicon vertex detector (SVD) + pixel detector (PXD)
- Precise measurement of the primary and secondary vertices of short-lived particles





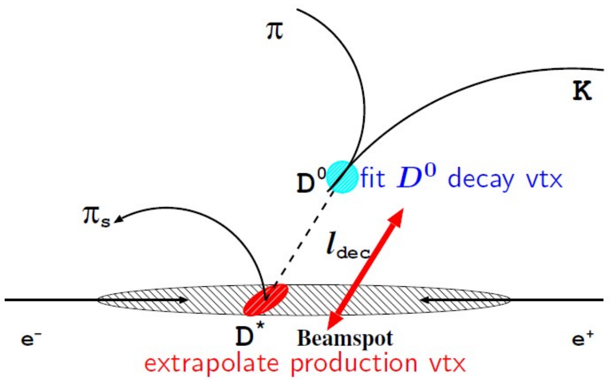

PXD:
- 2 layers of DEPFET pixels
- Very thin (50 μm) pixel sensor
- Inner most layer very close to IP (r = 1.4cm)
- Very low material budget
- Excellent spatial granularity ($\sigma \leq 15\mu m$)

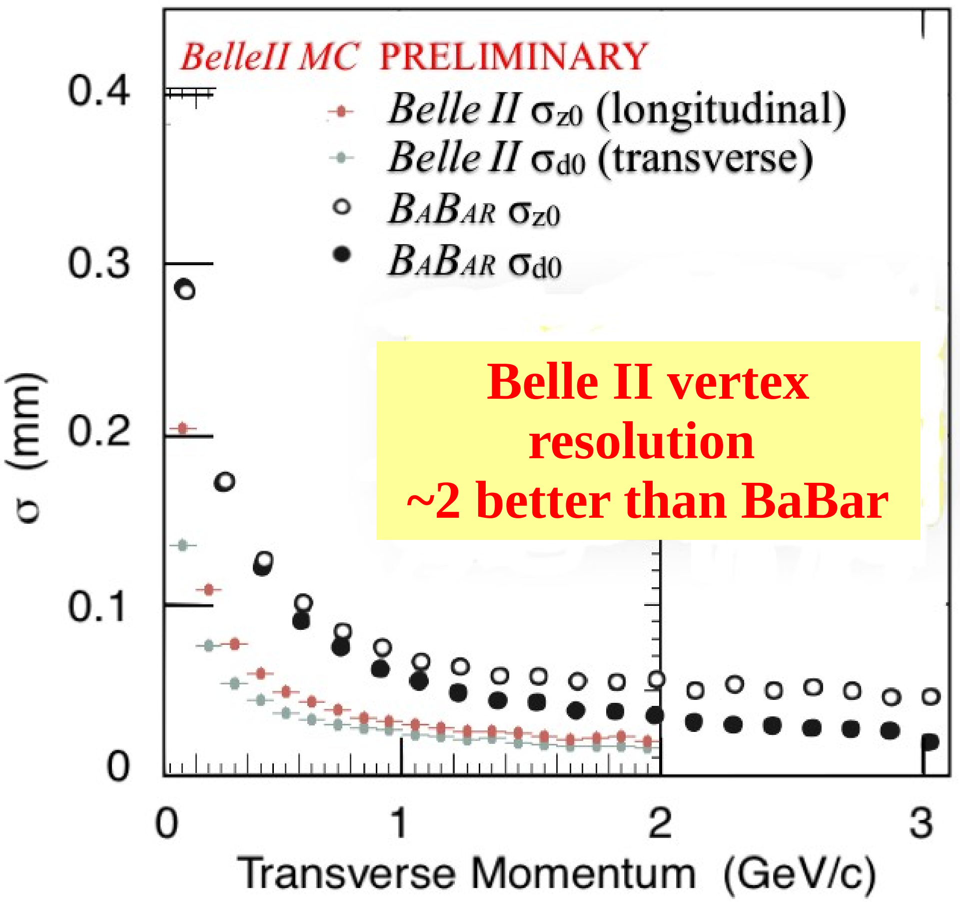
SVD:
- 4 layers of DSSD detectors
- Excellent timing resolution ($\sigma \sim$ 2-3 ns)
- Low material budget
- Larger outer radius (6.05 cm → 14 cm)
- Inner radius: 3.8cm
- covers the full Belle II angular acceptance of $17^o < \theta < 150^o$

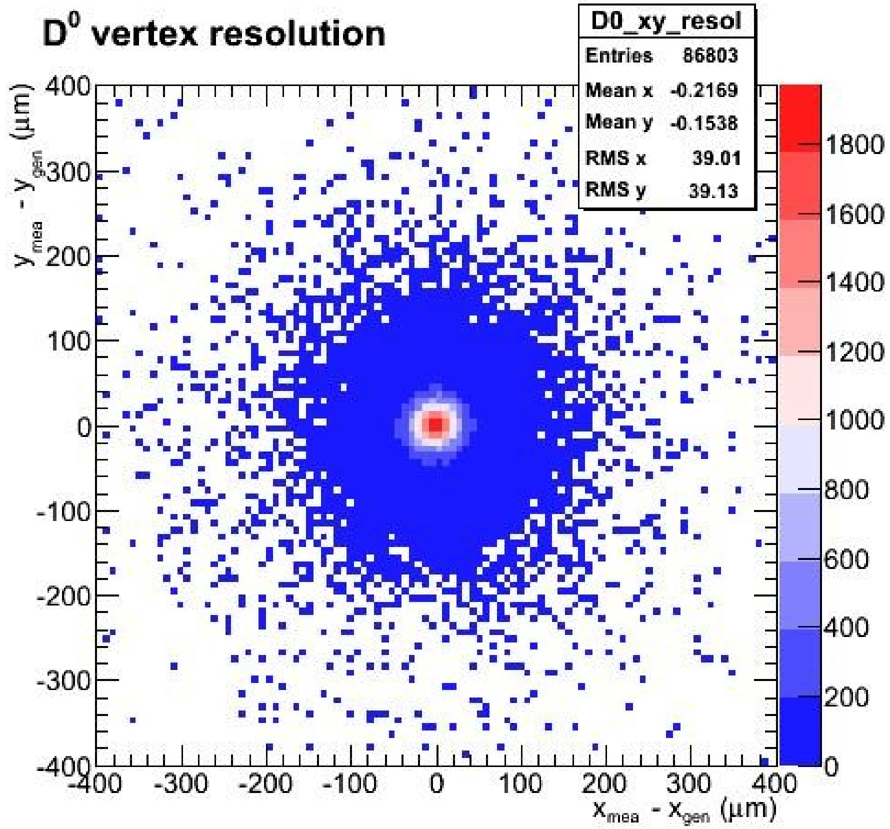
# Motivation to SuperKEKB and Belle II for charm mixing analysis

- Low backgrounds, high trigger efficiency, excellent $\gamma$ and $\pi^0$ recontruction, high flavor-tagging efficiency with low dilution
- Excellent Dalitz plot analysis with low background
- With Belle II VXD: $D^0$ decay vertex resolution precision of ~ 40μm, large improvement w.r.t B-Factories
- IP resolution improved by PXD being at radius of 1.4 cm
- Increased tracking volume in both SVD and CDC ⇒ ~30% higher $K_S$ efficiency
- Improved PID with better K/π separation relative to Belle.
- Belle II by 2025: 50ab$^{-1}$ data : > $6\times10^{10}$ charm events (Belle had $10^9$ charm events)

# D0 decay vertex resolution



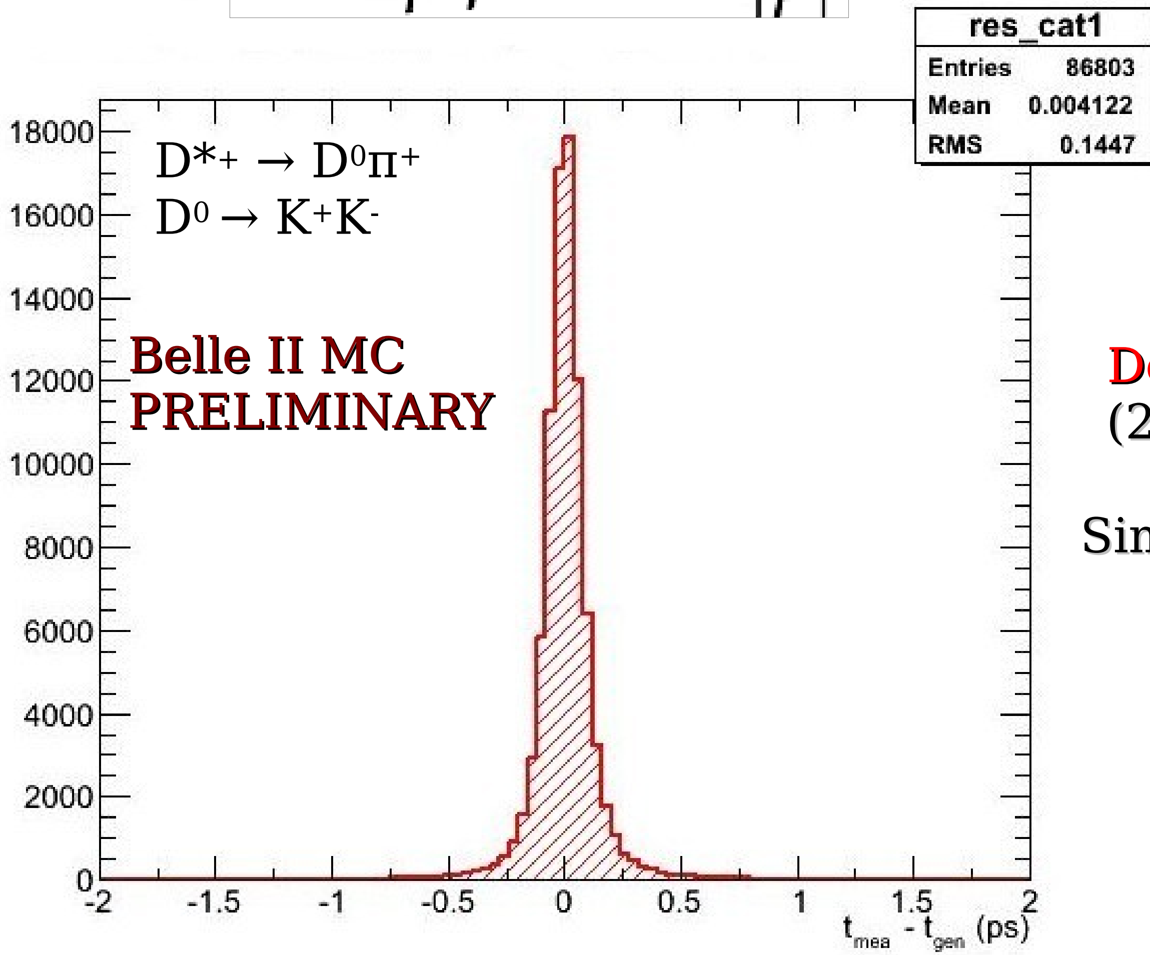




**Belle II: σ ≈ 40 μm**

# $D^0 \to h^+h^-$ decay time resolution ($D^*$ tag)

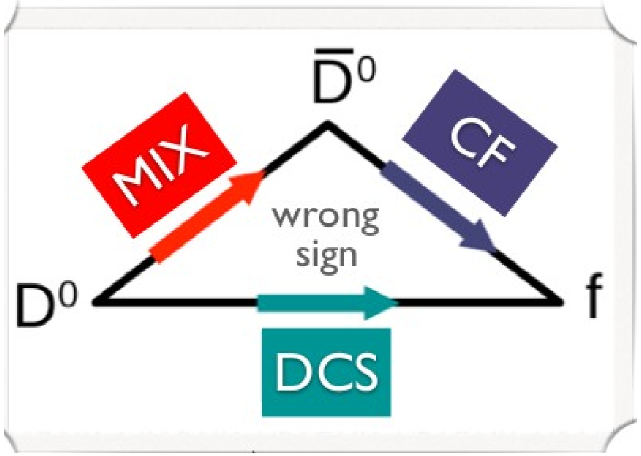
$$t = \frac{\ell}{\beta\gamma c} = \frac{\ell}{c}\frac{m_D}{|\vec{p}|}$$




Decay time resolution of 0.14 ps
(2 x better than Belle and Babar)

Similar result for $D^0 \to h^+h^-$ prompt decay (0.15 ps)

# Time dependent $D^0$ mixing studies




- Final state accessed both by $D^0$ or $D^0$bar, the two paths interfer in the amplitude as:

$$|\mathcal{M}(\bar{f},t)|^2 = e^{-\Gamma t}\left(|\mathcal{A}_{\bar{f}}|^2 + \frac{x^2+y^2}{4}|\bar{\mathcal{A}}_{\bar{f}}|^2(\Gamma t)^2 - \Re(\mathcal{A}_{\bar{f}}\bar{\mathcal{A}}^*_{\bar{f}})\cdot y\Gamma t - \Im(\mathcal{A}_{\bar{f}}\bar{\mathcal{A}}^*_{\bar{f}})\cdot x\Gamma t\right)$$

- Measuring the decay rate as a function of the $D^0$ proper time gives access to be sensitive to mixing

- With multibody final state, the Dalitz analysis allows to access to more than one channel at the same time

## Belle II sensitivity extrapolation

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

- Estimation for Belle II: scaling by the ratio of luminosities, and assuming the same reconstruction efficiency as Belle
- we assumed that most of the systematics scale with statistics
- irred. syst. those do not scale with luminosity. e.g. decay time resolution due to detector misalignment

# Mixing precision for $D^0 \to K^+\pi^-$ decay

- Two body final state $D^0 \to K^+\pi^-$ is an ideal channel for mixing study, almost systematic free
- Belle measurement using full statistics:

$$x'^2 = (0.09 \pm 0.22) \times 10^{-3} \text{ and } y' = (4.6 \pm 3.4) \times 10^{-3}$$

PRL 112, 111801 (2014)

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

**no CPV assumption:**

fit decay time distribution for mixing parameters $R_D$, $x'^2$, $y'$

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\overline{\Gamma}t}\left\{R_D + \sqrt{R_D}\,y'(\overline{\Gamma}t) + \frac{(x'^2+y'^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

**with CPV assumption:**

fit decay time distribution with additional parameters: |q/p|, φ

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

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

# Estimated Mixing precision for $D^0 \rightarrow K^+\pi^-$ decay

## *No CPV assumption*

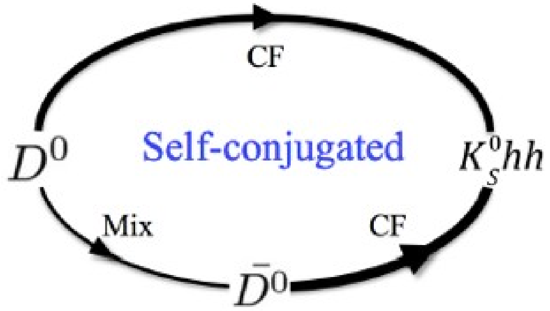
| | $976\ fb^{-1}$ (Belle measurement) | $5\ ab^{-1}$ | $20\ ab^{-1}$ | $50\ ab^{-1}$ |
|---|---|---|---|---|
| $\delta x'^2$ (x $10^{-5}$) | 22 | 7.5 | 3.7 | 2.3 |
| $\delta y'$ (%) | 0.34 | 0.11 | 0.056 | 0.035 |

## *with CPV assumption*

| | $5\ ab^{-1}$ | $20\ ab^{-1}$ | $50\ ab^{-1}$ |
|---|---|---|---|
| $\delta x'$ (%) | 0.37 | 0.23 | 0.15 |
| $\delta y'$ (%) | 0.26 | 0.17 | 0.10 |
| $\delta\lvert q/p\rvert$ | 0.197 | 0.089 | 0.051 |
| $\delta\Phi$ (deg) | 15.5 | 9.2 | 5.7 |

# Mixing precision for $D^0 \rightarrow K_S\pi^+\pi^-$ decay

- Belle II sensitivity to x, y from $D^0 \rightarrow K_S \pi^+ \pi^-$ decay is estimated by scaling from the Belle measurement




Peng et al., PRD 89, 091103(R) (2014)

- Using 0.921 $ab^{-1}$ data, Belle measurements of x and y:

$$x = (0.56 \pm 0.19^{+0.03}_{-0.09}{}^{+0.06}_{-0.09})\% \quad y = (0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.06})\%$$

- Expected Belle II sensitivity:

| Data | stat. | syst. red. | syst. irred. | Total | stat. | syst. red. | syst. irred. | Total |
|---|---|---|---|---|---|---|---|---|
| | $\sigma_x(\%)$ | | | | $\sigma_y(\%)$ | | | |
| 976 $fb^{-1}$ | 0.19 | 0.06 | 0.11 | 0.20 | 0.15 | 0.06 | 0.04 | 0.16 |
| 5 $ab^{-1}$ | 0.08 | 0.03 | 0.11 | 0.14 | 0.06 | 0.03 | 0.04 | 0.08 |
| 50 $ab^{-1}$ | 0.03 | 0.01 | 0.11 | 0.11 | 0.02 | 0.01 | 0.04 | 0.05 |

- At high statistics, the irreducable uncertainty is due to the $D^0$ decay model. This will be improved with model independent approach
- Improvement in decay time resolution is not included here.

# Expected $y_{CP}$ precision for $D^0 \to K^+K^- / \pi^+\pi^-$ decay (CP even modes)

$$y_{CP} = \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x\sin\phi$$
$$\approx y\cos\phi - A_M x\sin\phi\ .$$

- Belle: $y_{CP} = (1.11 \pm 0.22 \pm 0.09)\%$ (M. Staric et al., Phys. Lett. B 753, 412 (2016).)
- BaBar: $y_{CP} = (0.72 \pm 0.18 \pm 0.12)\%$ (B. Aubertet al., Phys. Rev. D87, 012004 (2013).)

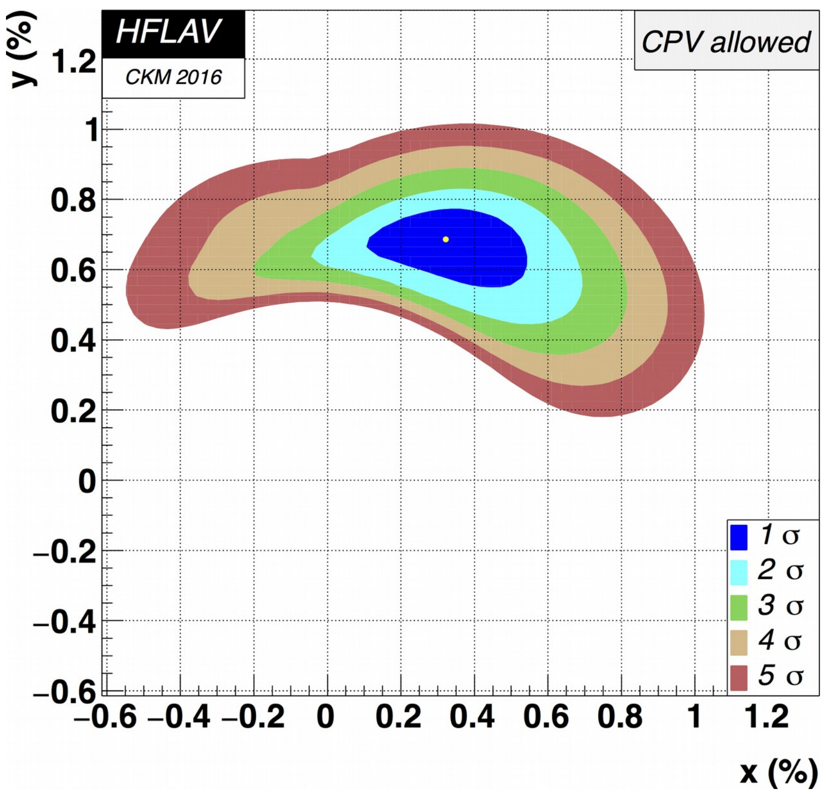
Expected Belle II sensitivity

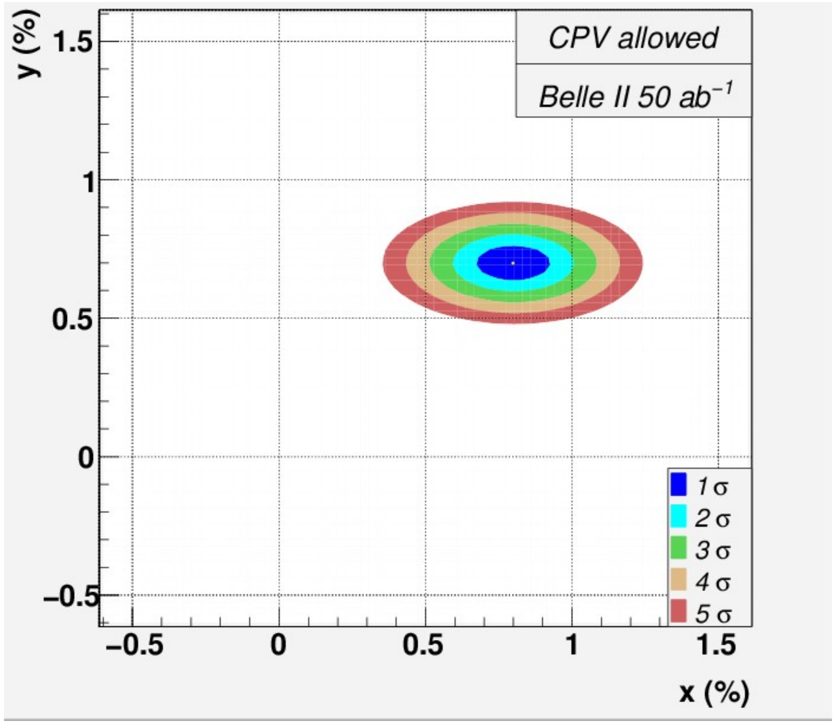
| Observable | Statistical | Systematic red. | Systematic irred. | Total |
|---|---|---|---|---|
| $y_{CP}(\%)$ | | | | |
| 976 $\mathrm{fb}^{-1}$ | 0.22 | 0.07 | 0.07 | 0.24 |
| 5 $\mathrm{ab}^{-1}$ | 0.10 | 0.03-0.04 | 0.07-0.04 | 0.11-0.12 |
| 50 $\mathrm{ab}^{-1}$ | 0.03 | 0.01 | 0.07-0.04 | 0.05-0.08 |

Using full Belle data

| Source | $\Delta y_{CP}$ $[10^{-2}]$ |
|---|---|
| acceptance | 0.050 |
| SVD misalignments | 0.060 |
| mass window position | 0.007 |
| background | 0.059 |
| resolution function | 0.030 |
| binning | 0.021 |
| total syst. error | 0.105 |
| stat. error | 0.220 |

# D⁰ Mixing Parameters – World Average and Expected Belle II precision




**World average (mixing):**

**$x = (0.32 \pm 0.14)\%$, $y = (0.69^{+0.06}_{-0.07})\%$**

**Belle II (50 ab$^{-1}$)**

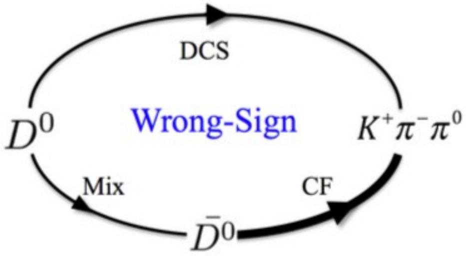
**$x = 0.8 \pm 0.09\%$, $y = 0.7 \pm 0.04\%$**

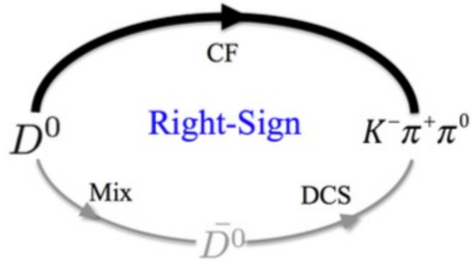
**(result is conservative, does not include modes: $K^+\pi^-\pi^0$, $K_SK^+K^-$ etc.)**

- The experimental data consistently indicate that the $D^0$ and $D^0$bar do mix.
- Current measurement provides constraints on many NP models like fourth generation, extra gauge bosons, left right symmetric models...

  Golowich, Hewett, Pakvasa, Petrov [PRD 76, 095009 (2007)]

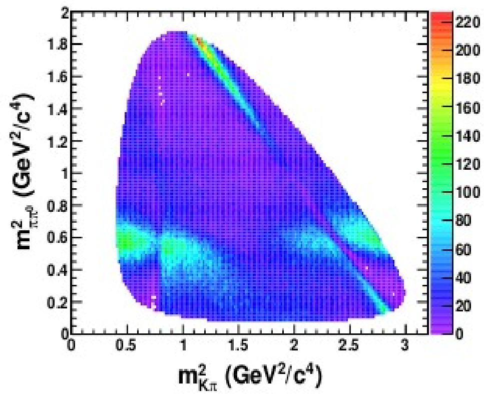
# Time dependent Dalitz analysis of $D^0 \to K^-\pi^+\pi^0$ to measure mixing

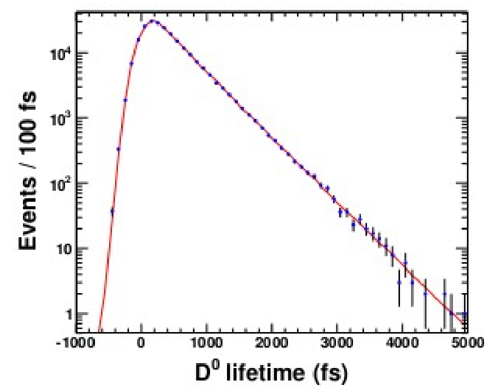


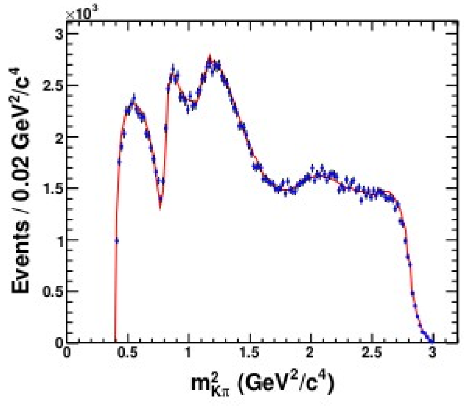



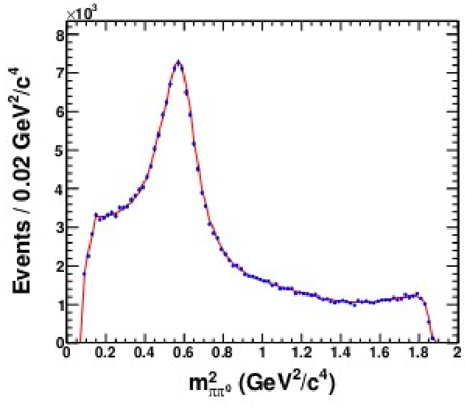

$$
\begin{aligned}
x'' &= x\cdot\cos\delta_{K\pi\pi^0} + y\cdot\sin\delta_{K\pi\pi^0},\\
y'' &= y\cdot\cos\delta_{K\pi\pi^0} - x\cdot\sin\delta_{K\pi\pi^0}
\end{aligned}
$$

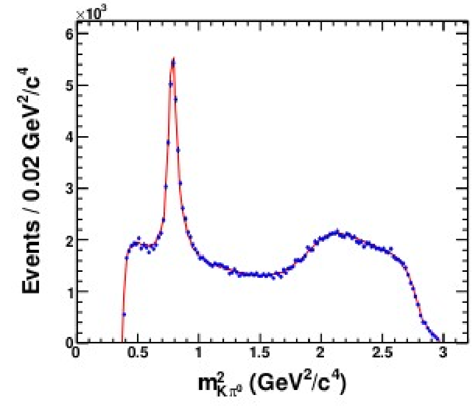
time-dependent fit to the ($m^2_{K+\pi-}$ , $m^2_{K+\pi 0}$ ) Dalitz plot to measure the effective mixing parameters



# Precision results for $D^0 \rightarrow K^-\pi^+\pi^0$ mixing

- Simulation study using an ensemble of 10 experiments of 225,000 WS events (estimated signal yield at 50 $ab^{-1}$ of data) with decay time resolution = 140 fs
- The mixing parameters used for event generation are x" = 2.58%, y" = 0.39%

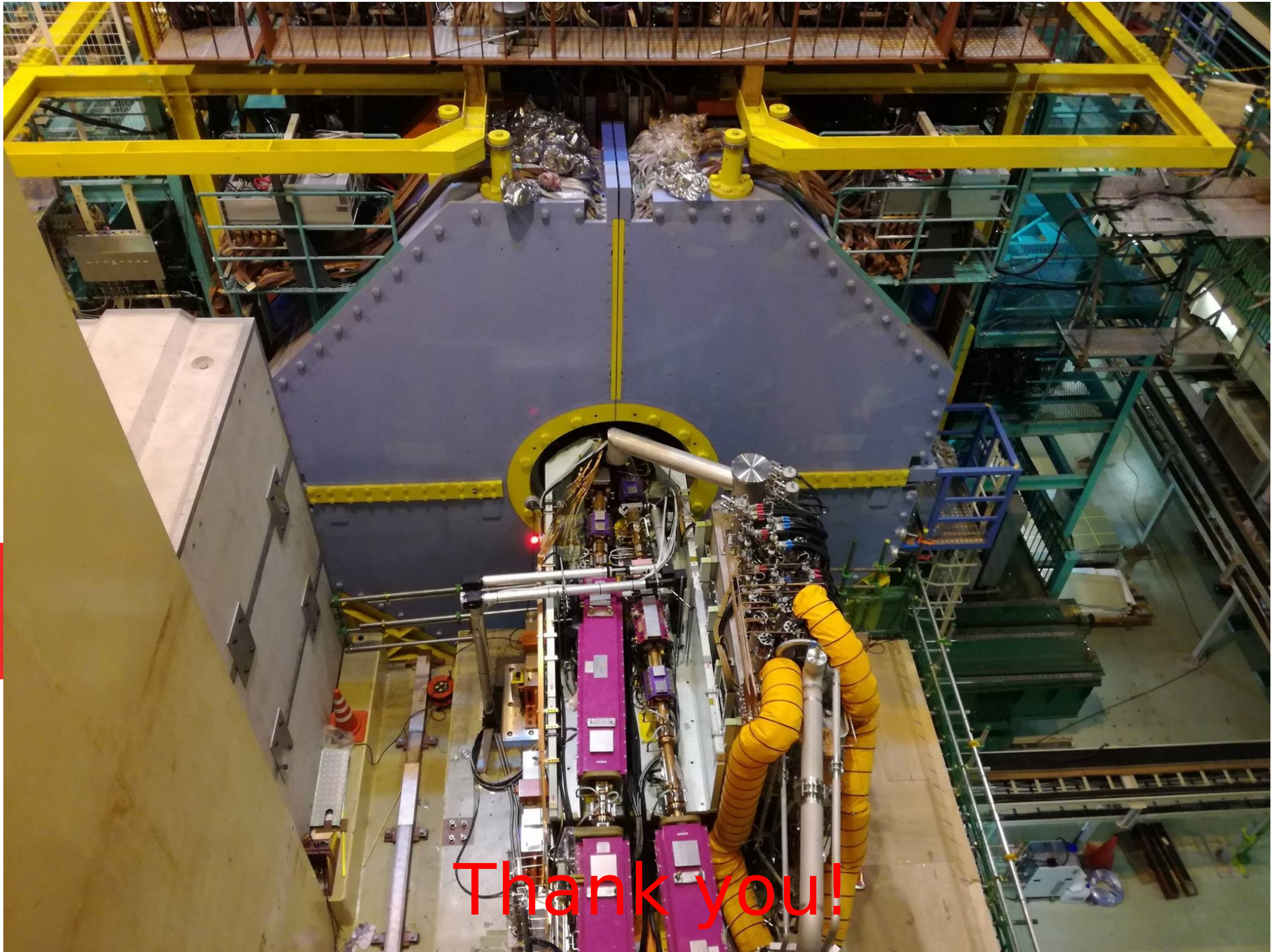
The expected precision of Belle II for these parameters:

$$\begin{aligned} \sigma_{x''} &= 0.057\% \\ \sigma_{y''} &= 0.049\% \end{aligned}$$

- an order of magnitude better than BaBar (**Phys. Rev. Lett. 103, 211801 (2009)**), if no background
- Estimation of background effects from Belle analysis: increase of stat error by 40%.
- conservative, as backgrounds smaller at Belle II than at Belle due to improved vertex resolution, mass resolution, particle identification.
- 20% estimated reduction of systematics at 50$ab^{-1}$

# Summary

- B factories have proven to be an excellent tool for charm mixing study
- Super B factory will provide L = 40 x Belle ⇒ 50 $ab^{-1}$ (by 2025)
- Due to upgraded vertex detector, $D^0$ decay time resolution will improve twice than Belle/Babar which subsequently improves the precision of mixing/CPV parameters.
- Belle D-mixing measurements extrapolated at 50 $ab^{-1}$ show expected precision ≤ 0.1% on mixing parameters x and y.
- Phase 2 without vertex detector will be commissioned in few days, and phase 3 with full Belle II detector early next year.
- Era of precession measurements is approaching. Stay tuned!


Thank you!

# Belle ➡ Belle II

- High luminosity ➡ higher event rate and radiation damage to detectors from **machine background processes**
- Upgrade Belle to have better performances in higher radiation environment

Covered by Alexei Sibidanov on
Belle II readiness for Phase II collisions