Charm mixing study at Belle and prospects at Belle II

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On behalf of the Belle II Collaboration

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Mixing in D^0 system

- Mass eigenstates are superposition of flavour eigenstates:

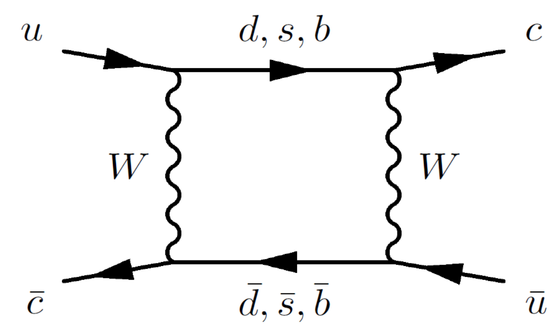
$$|D^0_{1,2}\rangle = \frac{1}{\sqrt{|p|^2+|q|^2}}(p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle)$$

If p ≠ q, CP is violated

- Mixing parameterized by mass/width splittings:

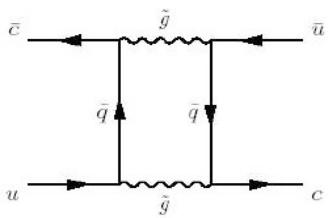
$$x = \frac{m_1 - m_2}{\Gamma},\; y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

- In SM, D-mixing is heavily suppressed (both CKM, and GIM suppressed)

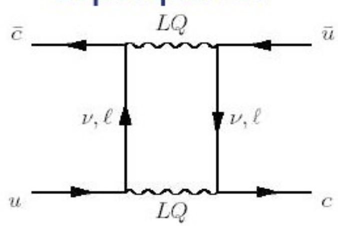


- SM expectation: |x|, |y| ~ $O(10^{-3} - 10^{-2})$.
- NP could significantly affect the measured values

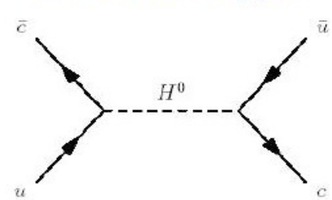
SUSY:



Leptoquarks:



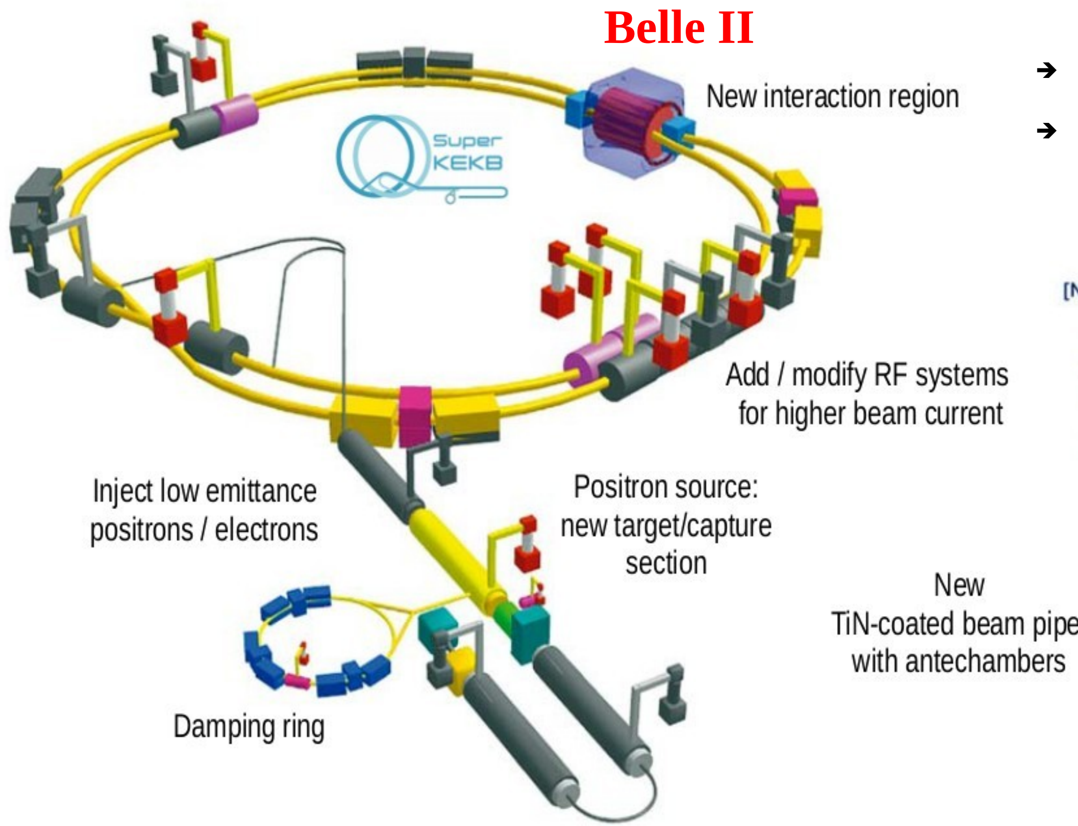
Extended Higgs:



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

SuperKEKB (High luminosity frontier machine!)

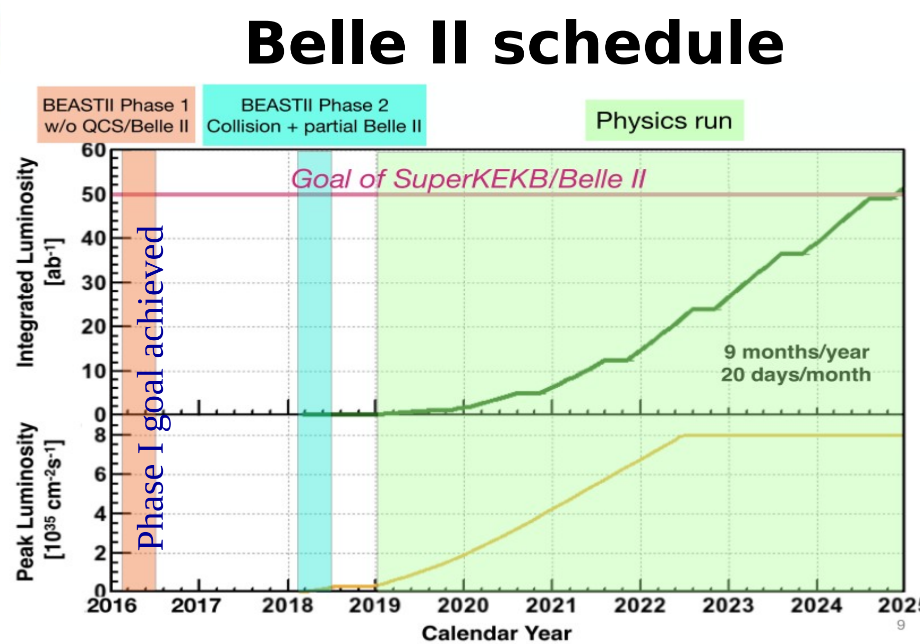
- SuperKEKB – major upgrade of the KEKB factory at KEK
- e^+e^- (**4 GeV** + **7 GeV**) → $B\bar{B}$ mainly at $\sqrt{s}_{cm}$=10.58 GeV (peak of Y(4S) resonance)



To obtain x40 higher instantaneous luminosity:

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

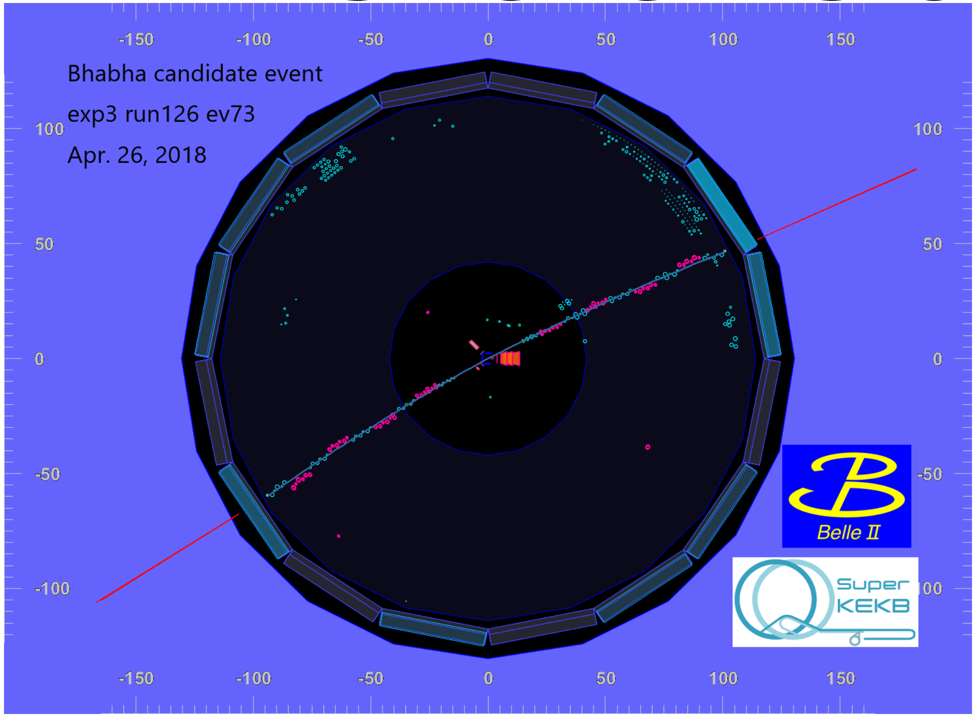
[N



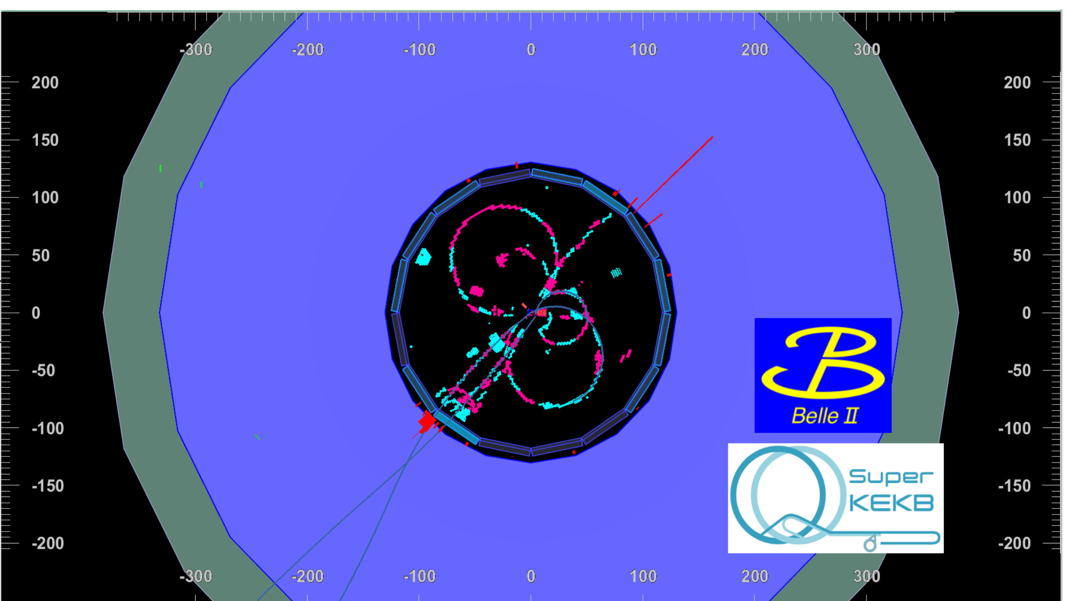
Phase II ends today!

Few of Phase II achievements are in next slide

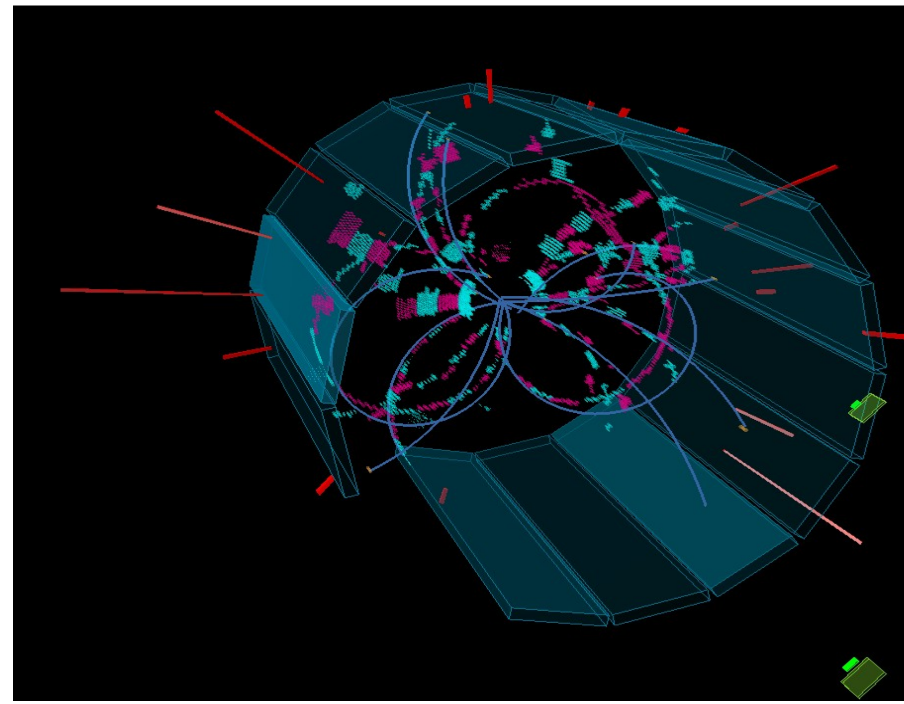
First events on April 26, 2018



Bhabha event



Hadronic event

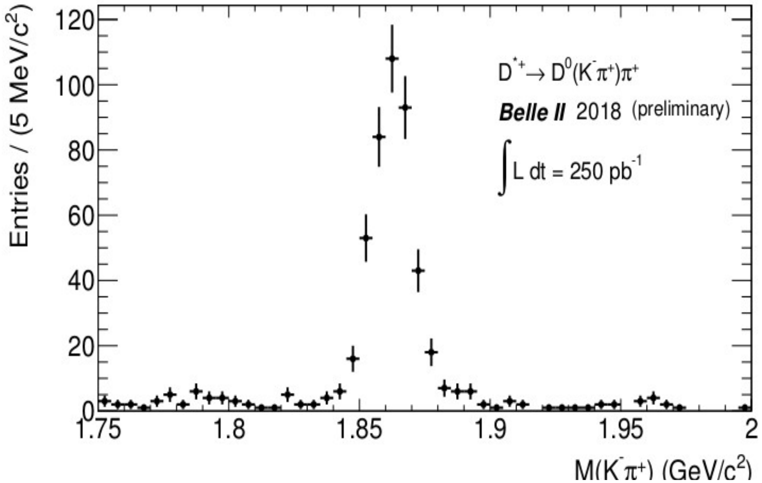


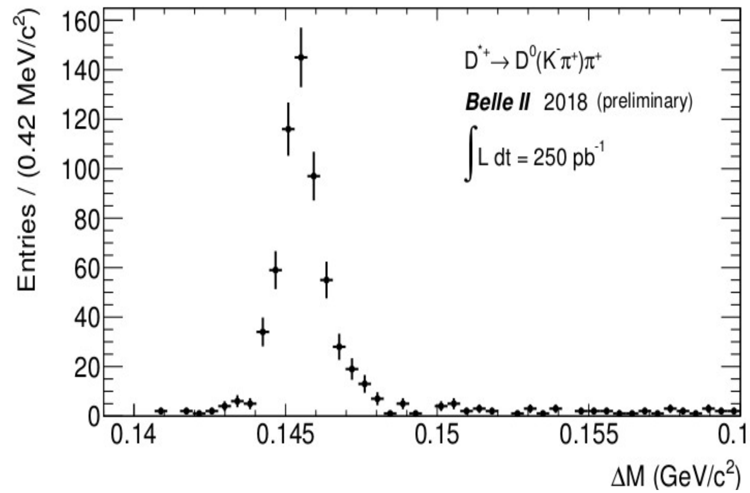
$B\bar{B}$ like event

Rediscovery of charm mesons in phase II data

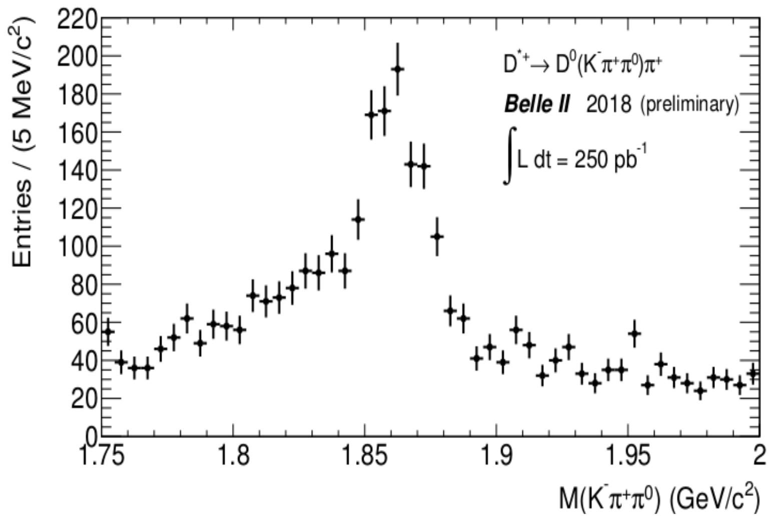
Remark: Full Belle II without VXD

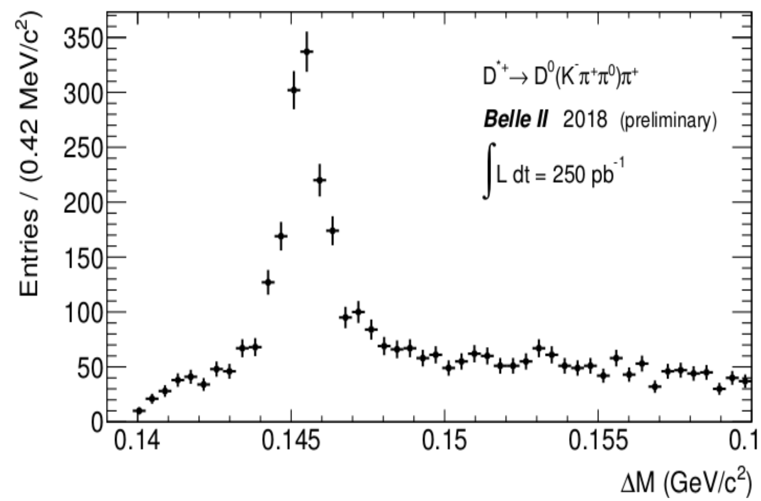
$D^{*\pm} \rightarrow D(K^{-}\pi^{+})\pi^{\pm}$



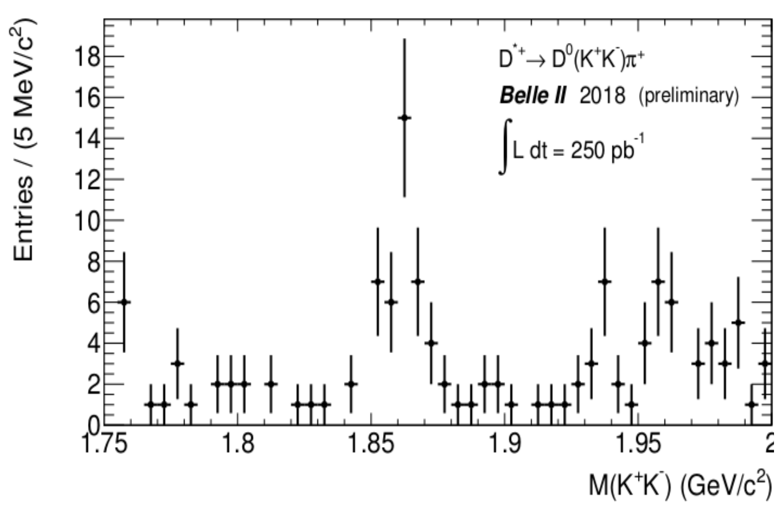


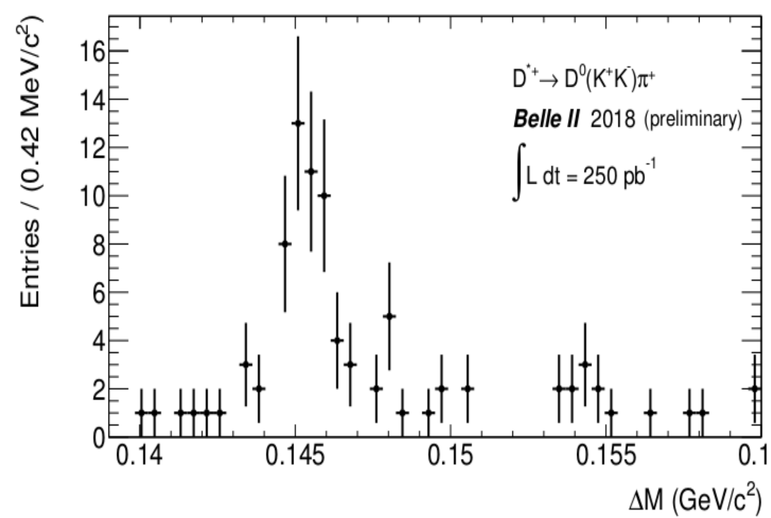
$D^{*\pm} \rightarrow D(K^{-}\pi^{+}\pi^{0})\pi^{\pm}$



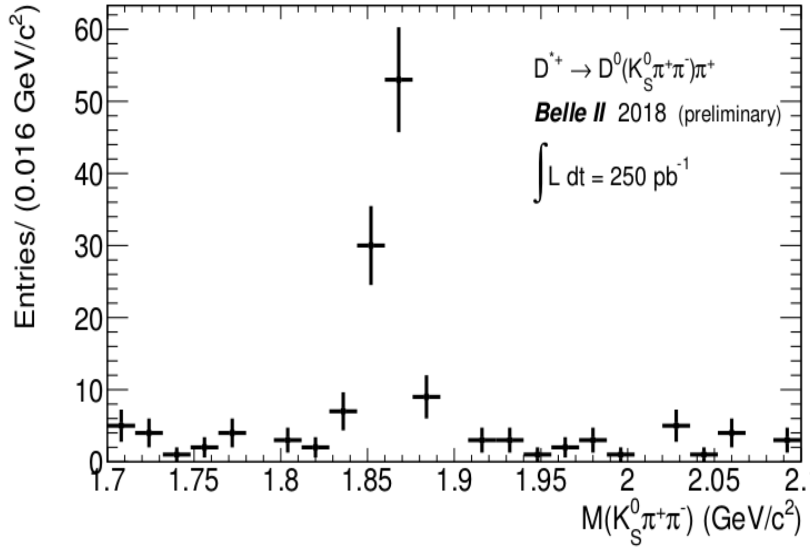


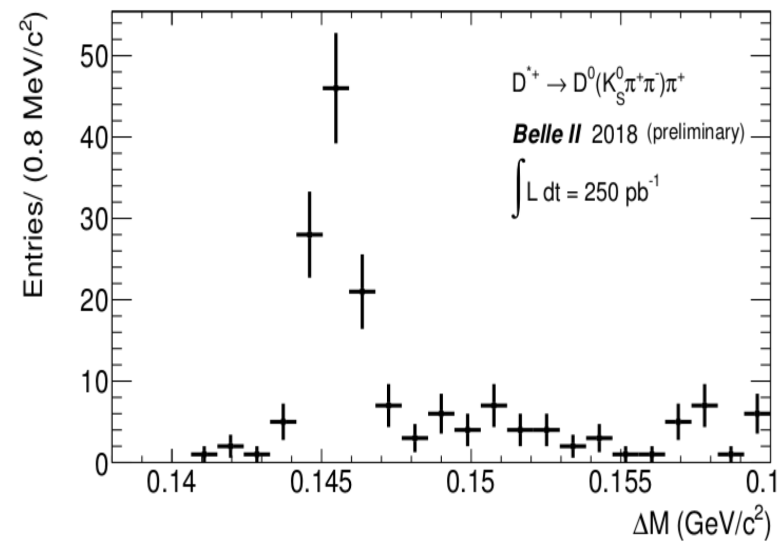
$D^{*\pm} \rightarrow D(K^{-}K^{+})\pi^{\pm}$



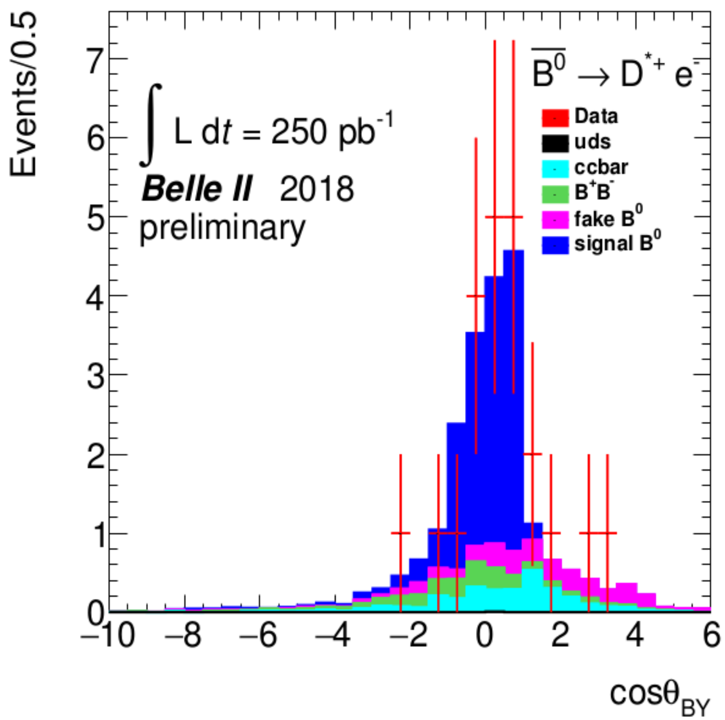


$D^{*\pm} \rightarrow D(K_S\pi^+\pi^-)\pi^\pm$

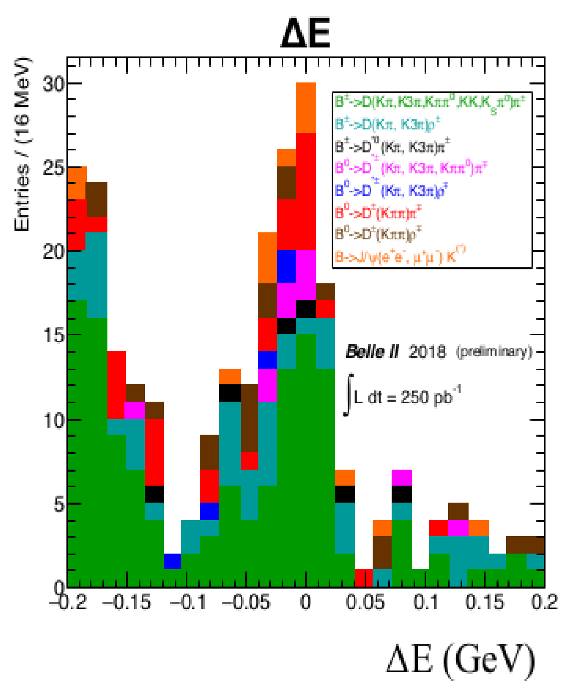


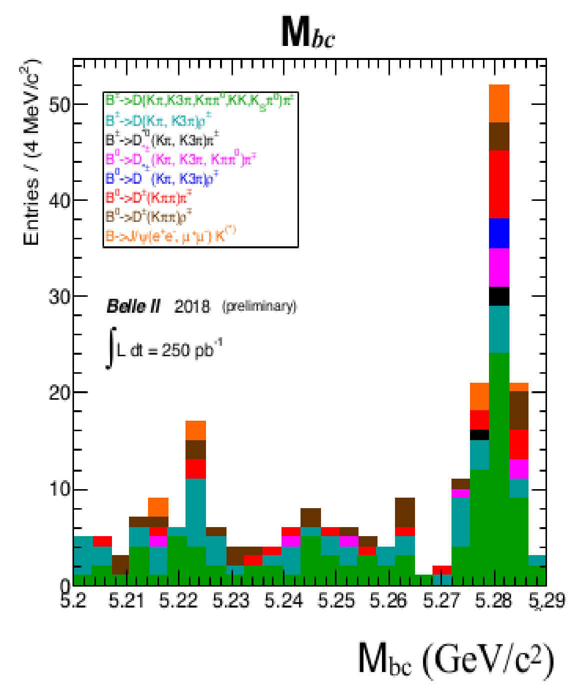


Semileptonic B Decays to Charm



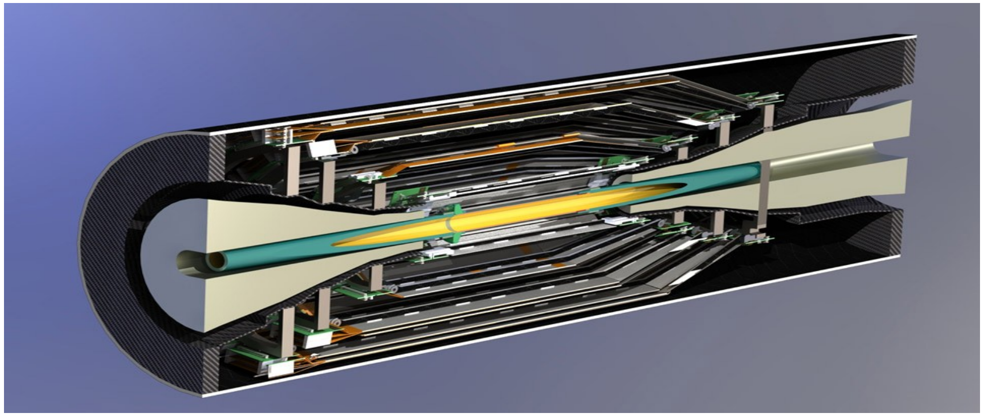
Hadronic B Decays to Charm

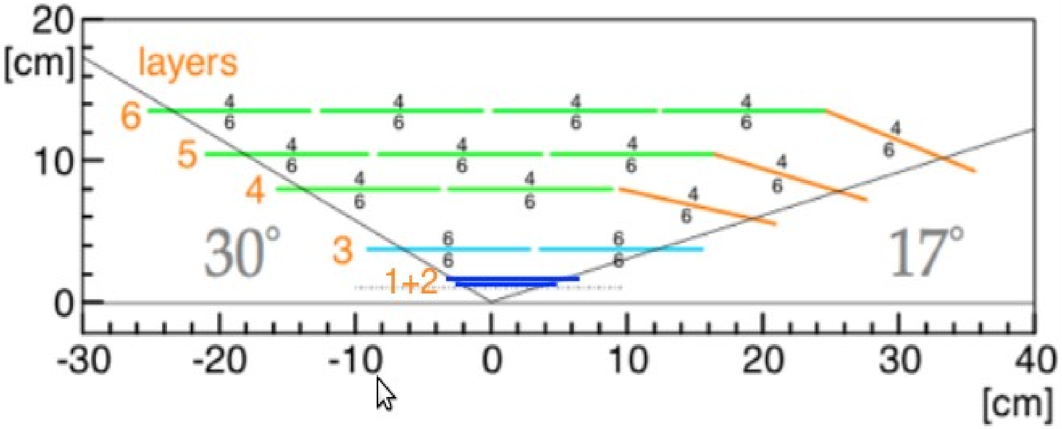




Belle II Vertex detector (main player for D-mixing sensitivity measurement)

- Precise measurement of PV and SV of short-lived particles





4 layers DS Si strips (SVD) + 2 layers of DEPFET pixels (PXD)
(Will be in place during phase III)

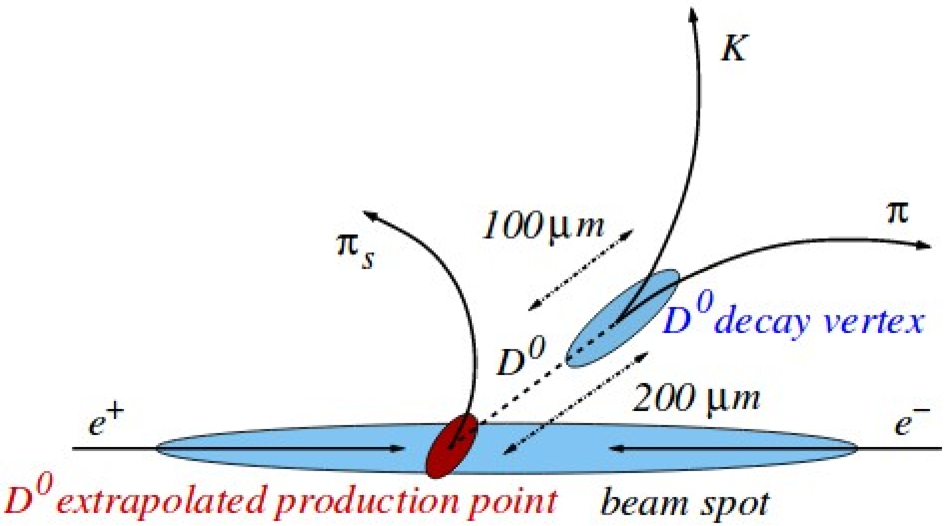
PXD:
- Very thin (50 μm) pixel sensor
- Inner most layer very close to IP (r = 1.4cm)
- Very low material budget
- Excellent spatial granularity ($\sigma \leq 15 \mu m$)

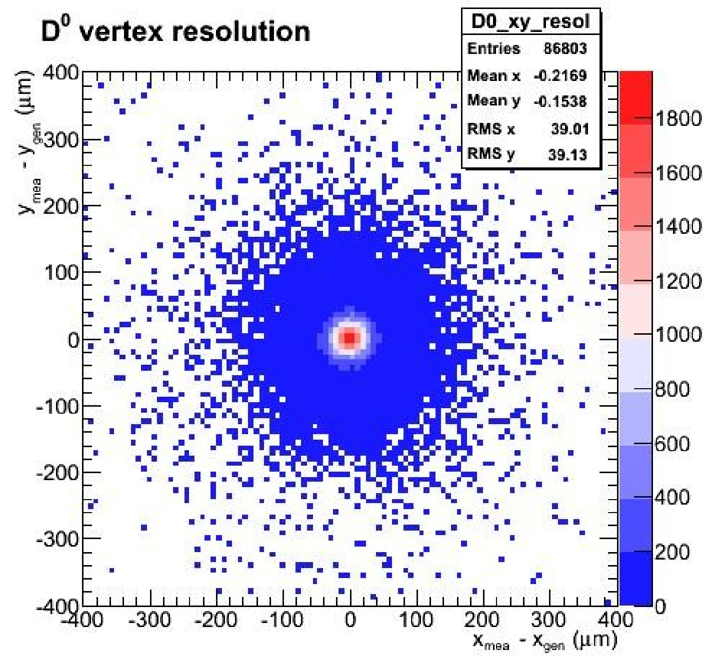
SVD:
- Excellent timing resolution ($\sigma \sim$ 2-3 ns)
- Low material budget
- Larger outer radius (6.05 cm → 14 cm)
- Inner radius: 3.8cm
- covers the full Belle II angular acceptance of $17^o < \theta < 150^o$

Motivation to SuperKEKB and Belle II for charm mixing analysis

- Low backgrounds, high trigger efficiency, excellent γ and π^0 recontruction
- Excellent Dalitz plot analysis with low background
- With Belle II VXD: D^0 decay vertex resolution precision ~ 40μm, large improvement w.r.t B-Factories and 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 : > $6x10^{10}$ charm events (Belle: 10^9 charm events)

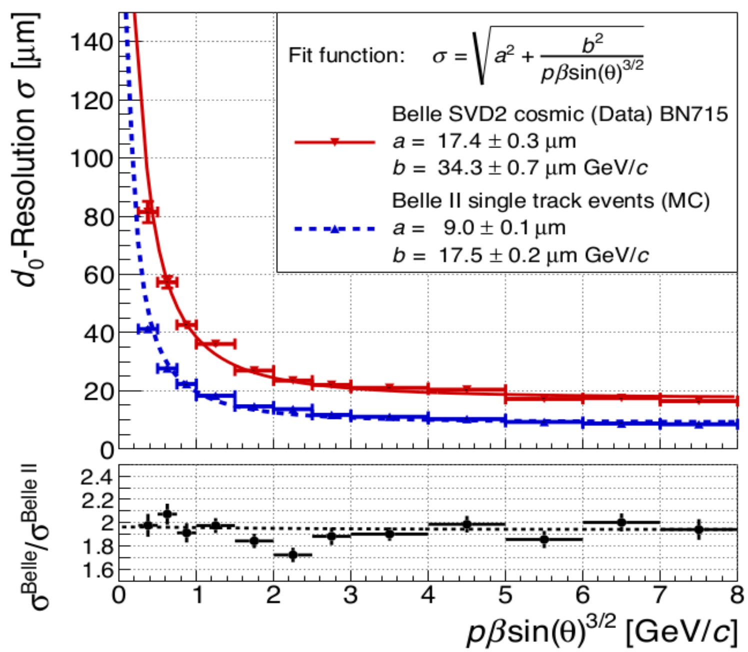
D0 decay vertex resolution





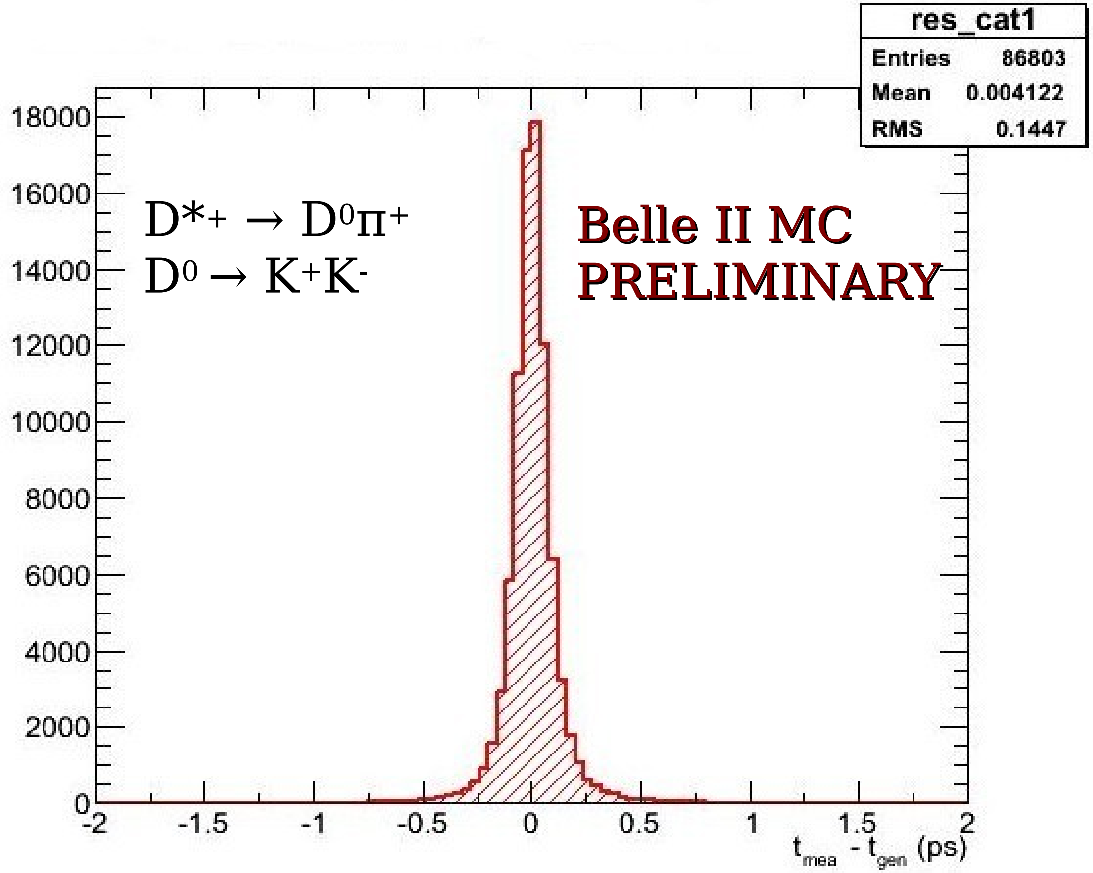
Belle II: σ ≈ 40 µm

- Belle, **- Belle II** Factor of 2 improvement !



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

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



Lifetime of D^0 = 0.41 ps

Decay time resolution of 0.14 ps

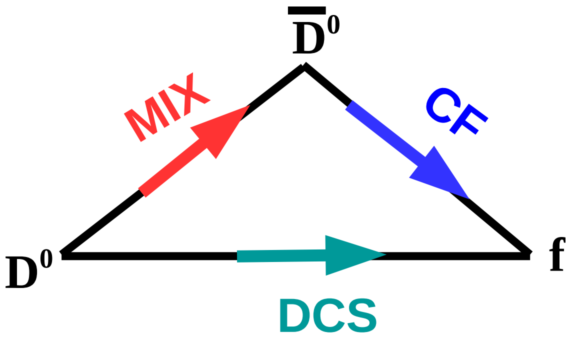
2 x better than Belle and Babar (0.27 ps)

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 $\overline{D}^0$, 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

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

D^0-mixing precision at Belle and expected precision at Belle II using few golden modes

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

- $D^0 \to K^+\pi^-$ 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'

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

with CPV assumption:

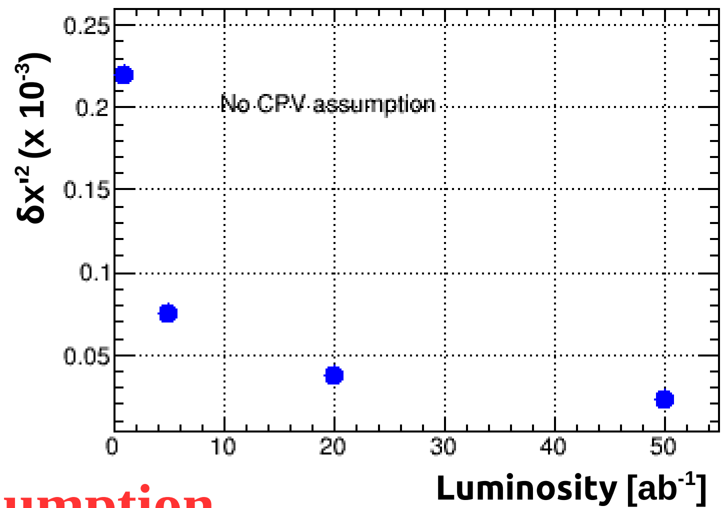
fit decay time distribution with additional parameters: $|q/p|$, φ

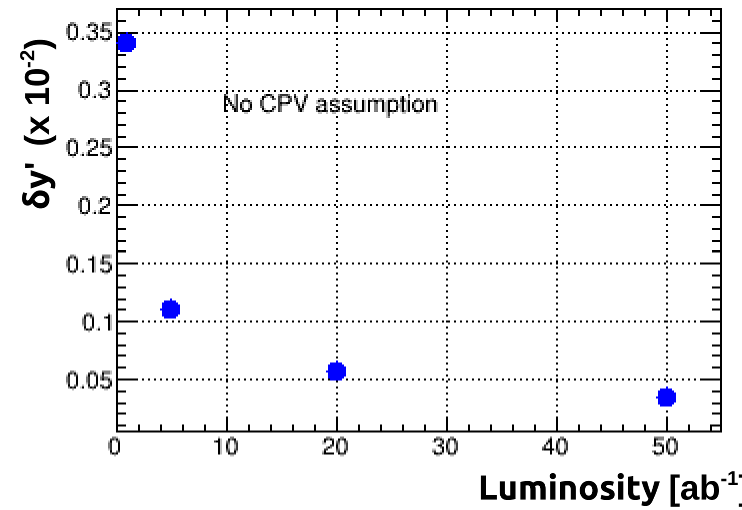
$$D^0(t) = e^{-\bar{\Gamma}t}\left\{R_D + \left|\frac{q}{p}\right|\sqrt{R_D}(y'\cos\phi - x'\sin\phi)(\bar{\Gamma}t) + \left|\frac{q}{p}\right|^2\frac{(x'^2+y'^2)}{4}(\bar{\Gamma}t)^2\right\}$$

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

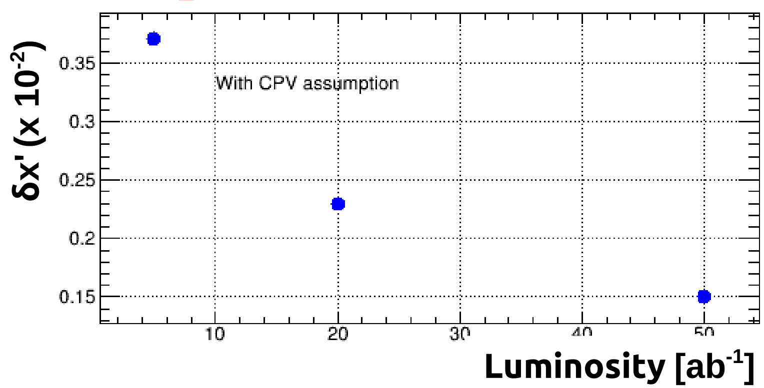
Estimated Mixing precision at Belle II for $D^0 \to K^+\pi^-$ decay

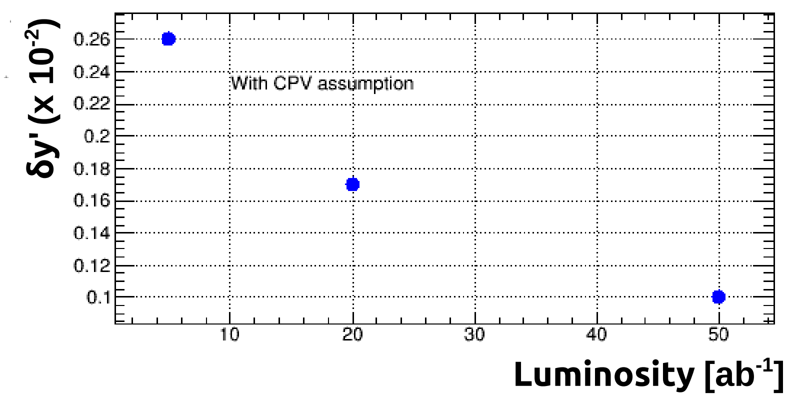
No CPV assumption

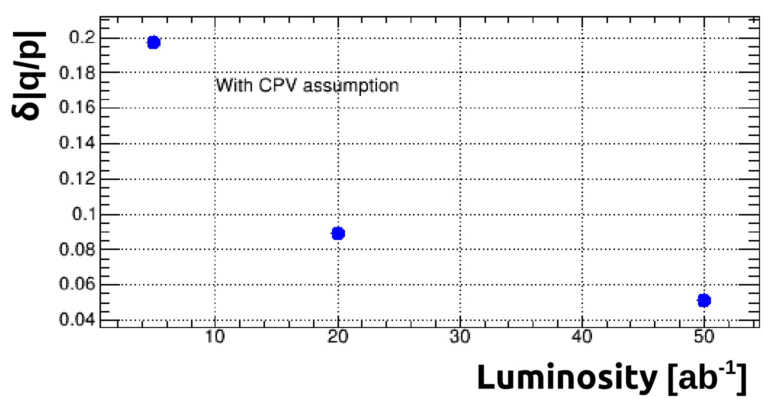


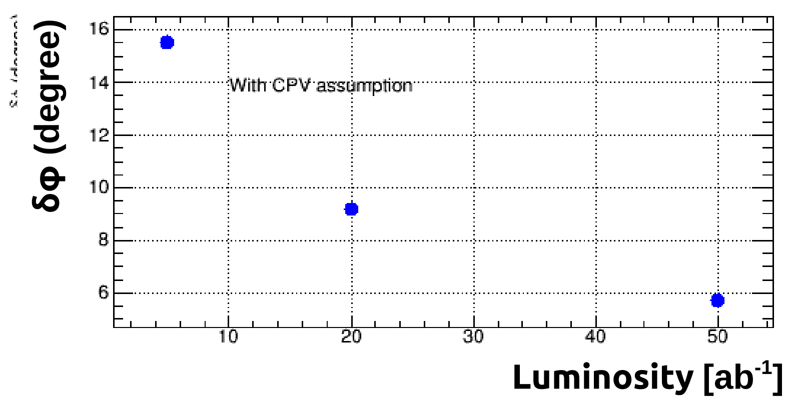


With CPV assumption



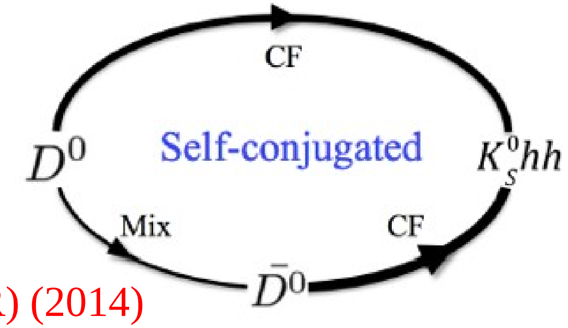






Golden mode: $D^0 \rightarrow K_S\pi^+\pi^-$ decay

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

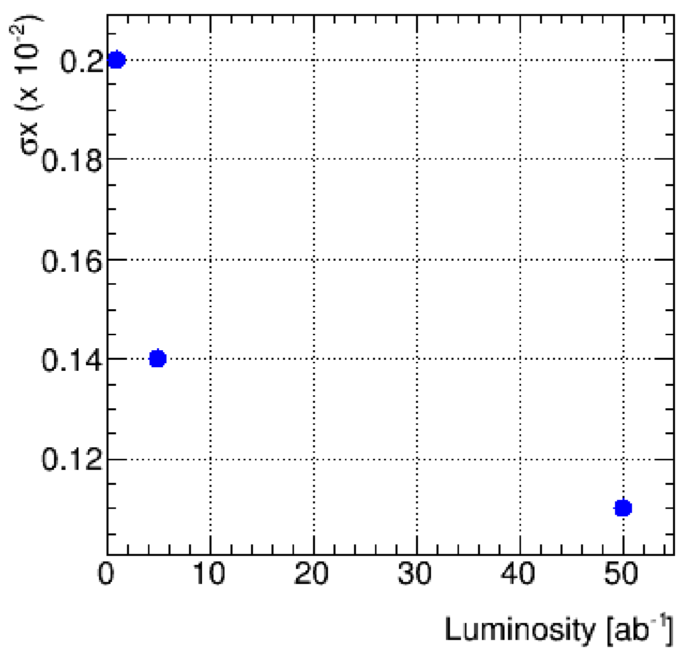


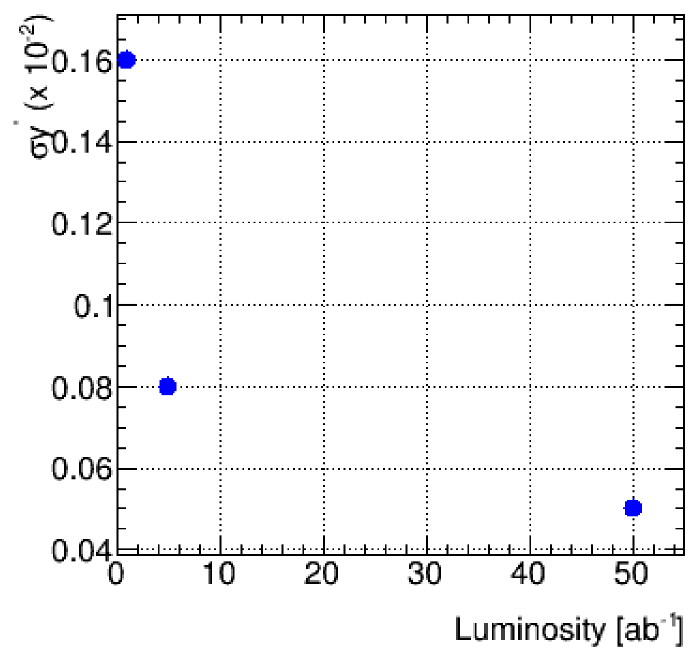
Peng et al., PRD 89, 091103(R) (2014)

- **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:**





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)

$$y_{CP} = \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x\sin\phi \quad , \varphi = \arg(q/p)$$

$$\approx y\cos\phi - A_M x \sin\phi \ .$$

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

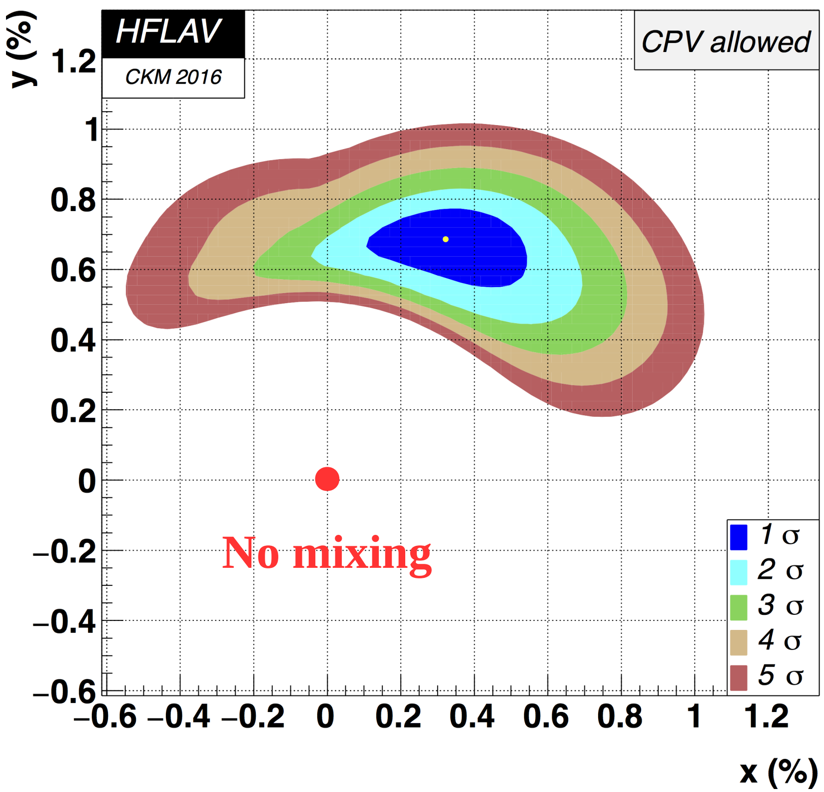
Expected Belle II sensitivity

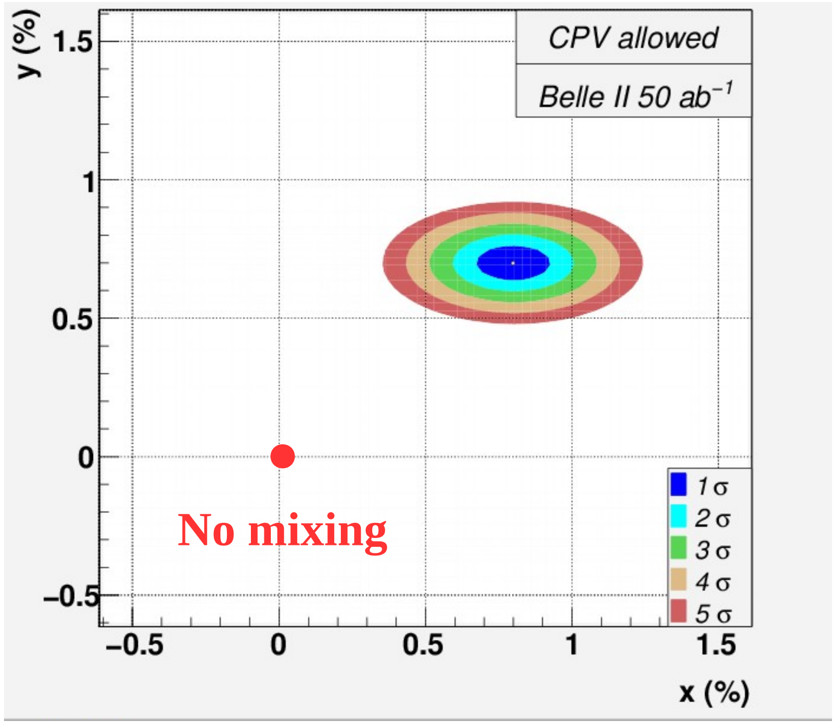
Observable	Statistical	Systematic red.	Systematic irred.	Total
$y_{CP}(\%)$				
976 fb^{-1}	0.22	0.07	0.07	0.24
5 ab^{-1}	0.10	0.03-0.04	0.07-0.04	0.11-0.12
50 ab^{-1}	0.03	0.01	0.07-0.04	0.05-0.08

Sources of Systematic for Belle

Source	Δy_{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

Expected Belle II precision vs. Current WA





World average (mixing):

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

Belle II (50 ab^{-1})

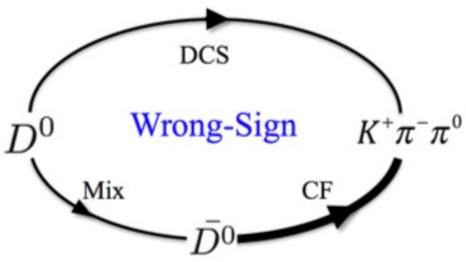
x = 0.8 ± 0.09%, y = 0.7 ± 0.04%

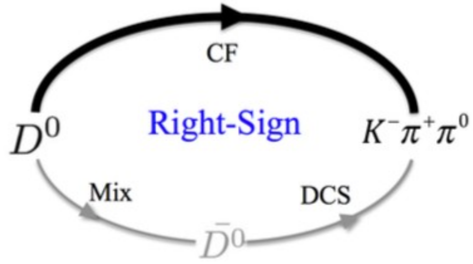
(result is conservative, does not include modes: $K^+\pi^-\pi^0$, $K_SK^+K^-$ etc.)

- The experimental data consistently indicate that the D^0 and $\overline{D}^0$ 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)]

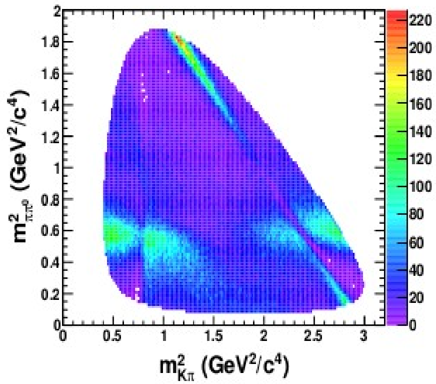
Time dependent Dalitz analysis of $D^0 \to K^-\pi^+\pi^0$ to measure mixing

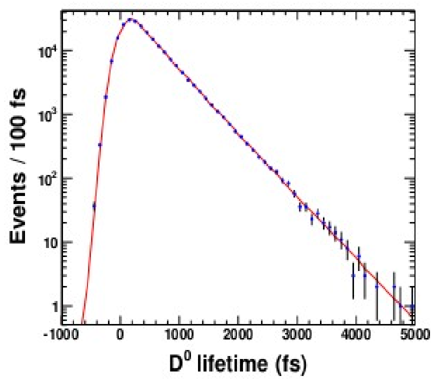




$$x'' = x \cdot \cos\delta_{K\pi\pi^0} + y \cdot \sin\delta_{K\pi\pi^0},$$
$$y'' = y \cdot \cos\delta_{K\pi\pi^0} - x \cdot \sin\delta_{K\pi\pi^0}$$

Measurement of effective mixing parameters from the time-dependent fit to the ($m^2_{K+\pi-}$, $m^2_{K+\pi0}$) Dalitz plot

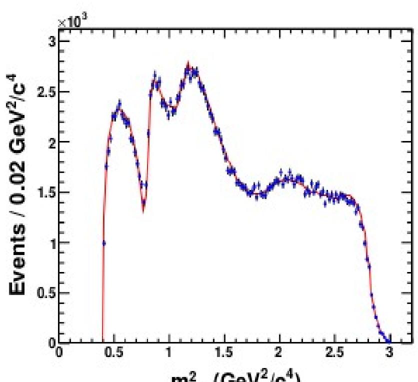


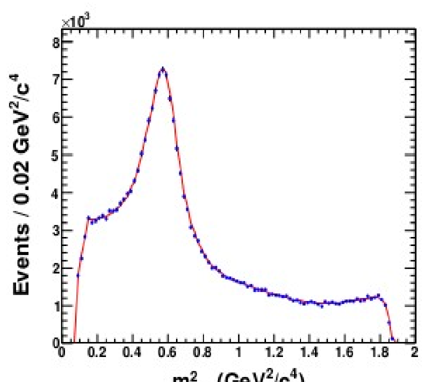


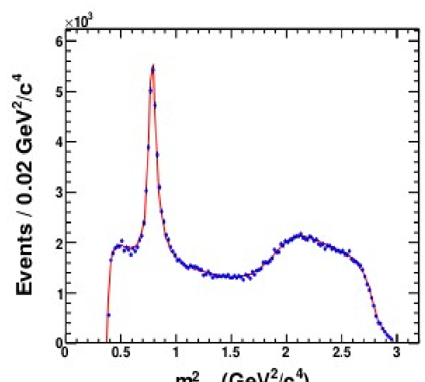
Expected Belle II precision for these parameters:

$$\sigma_{x''} = 0.057\%$$
$$\sigma_{y''} = 0.049\%$$

an order of magnitude better than BaBar (**Phys. Rev. Lett. 103, 211801 (2009)**), if no background

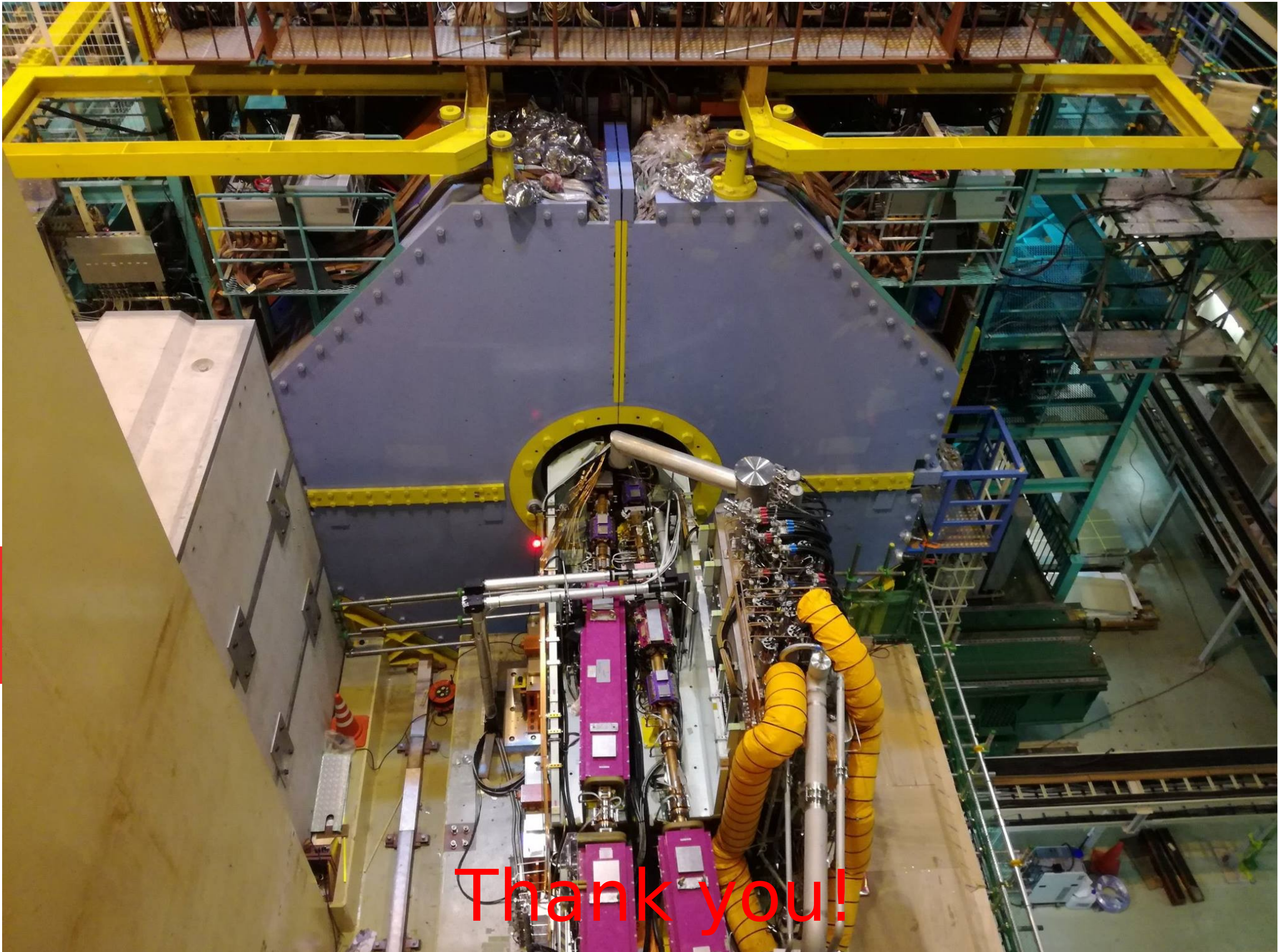






Summary

- B factories have proven to be an excellent tool for charm mixing study
- SuperKEKB will provide L = 40 x Belle ⇒ 50 ab^{-1} (by 2025)
- Due to upgraded VXD, D^0 decay time resolution will improve 2 x 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 x and y.
- Excellent performance of Belle II. Phase 2 data taking is about to end. phase 3 with full Belle II detector early next year.
- Era of precession measurements is approaching. Stay tuned!


Thank you!

Belle II sub-detector performances

Component	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double-wall	Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be		impact parameter resolution $\sigma_{z_0} \sim 20\ \mu$m (PXD and SVD)
PXD	Silicon pixel (DEPFET)	Sensor size: 15×100 (120) mm^2 pixel size: 50×50 (75) μm^2 2 layers: 8 (12) sensors	10 M	
SVD	Double sided Silicon strip	Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors	245 k	
CDC	Small cell drift chamber	56 layers, 32 axial, 24 stereo $r = 16$ - 112 cm $-83 \leq z \leq 159$ cm	14 k	$\sigma_{r\phi} = 100\ \mu$m, $\sigma_z = 2$ mm $\sigma_{p_t}/p_t = \sqrt{(0.2\% p_t)^2 + (0.3\%/\beta)^2}$ $\sigma_{p_t}/p_t = \sqrt{(0.1\% p_t)^2 + (0.3\%/\beta)^2}$ (with SVD) $\sigma_{dE/dx} = 5\%$
TOP	RICH with quartz radiator	16 segments in ϕ at $r \sim 120$ cm 275 cm long, 2 cm thick quartz bars with 4x4 channel MCP PMTs	8 k	$N_{p.e.} \sim 20$, $\sigma_t = 40$ ps K/π separation : efficiency $> 99\%$ at $< 0.5\%$ pion fake prob. for $B \to \rho\gamma$ decays
ARICH	RICH with aerogel radiator	4 cm thick focusing radiator and HAPD photodetectors for the forward end-cap	78 k	$N_{p.e.} \sim 13$ K/π separation at 4 GeV/c: efficiency 96% at 1% pion fake prob.
ECL	CsI(Tl) (Towered structure)	Barrel: $r = 125$ - 162 cm End-cap: $z =$ -102 cm and +196 cm	6624 1152 (F) 960 (B)	$\frac{\sigma E}{E} = \frac{0.2\%}{E} \oplus \frac{1.6\%}{\sqrt[4]{E}} \oplus 1.2\%$ $\sigma_{pos} = 0.5$ cm$/\sqrt{E}$ (E in GeV)
KLM	barrel: RPCs	14 layers (5 cm Fe + 4 cm gap) 2 RPCs in each gap	θ: 16 k, ϕ: 16 k	$\Delta\phi = \Delta\theta = 20$ mradian for K_L ~ 1 % hadron fake for muons
	end-caps: scintillator strips	14 layers of $(7-10)\times 40$ mm^2 strips read out with WLS and G-APDs	17 k	$\Delta\phi = \Delta\theta = 10$ mradian for K_L $\sigma_p/p = 18\%$ for 1 GeV/c K_L