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Prospects of charm mixing and indirect CPV measurements at Belle II

Jitendra Kumar
On behalf of Belle II collaboration

Outline

- **Introduction**
- **Mixing and Indirect CPV in Charm Sector**
  - Brief overview
  - Status so far
  - Prospects with Belle II
- **Summary**

Mixing in neutral mesons

- Mixing in neutral meson
  - Their mass eigenstates do not a priori coincide with flavor eigenstates
  - ..these states are produced, oscillate and then decay

$$|M^0(t)\rangle = f_+(t)|M^0\rangle + \frac{q}{p} f_-(t)|\bar{M}^0\rangle$$

$$|\bar{M}^0(t)\rangle = f_+(t)|\bar{M}^0\rangle + \frac{p}{q} f_-(t)|M^0\rangle$$

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\bar{M}^0\rangle$$

$$f_\pm(t) = \frac{1}{2} e^{-\imath m_1} e^{-\Gamma_1 t/2} \left(1 \pm e^{-\imath \Delta m t} e^{\Delta\Gamma t/2}\right)$$

$$\begin{aligned}
P(M^0(t)\to M^0) = P(\bar{M}^0(t)\to \bar{M}^0) &= |f_+(t)|^2 = \tfrac{1}{2} e^{-\Gamma t}(\cosh(y\Gamma t) + \cos(x\Gamma t)),\\
P(M^0(t)\to \bar{M}^0) &= \left|\tfrac{q}{p}\right|^2 |f_-(t)|^2 = \tfrac{1}{2}\left|\tfrac{q}{p}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))\\
P(\bar{M}^0(t)\to M^0) &= \left|\tfrac{p}{q}\right|^2 |f_-(t)|^2 = \tfrac{1}{2}\left|\tfrac{p}{q}\right|^2 e^{-\Gamma t}(\cosh(y\Gamma t) - \cos(x\Gamma t))
\end{aligned}$$

- Mixing parameters x, and y; characteristic of neutral meson mixing

$$x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma},$$

where Δm = mass differences
and ΔΓ = lifetimes differences

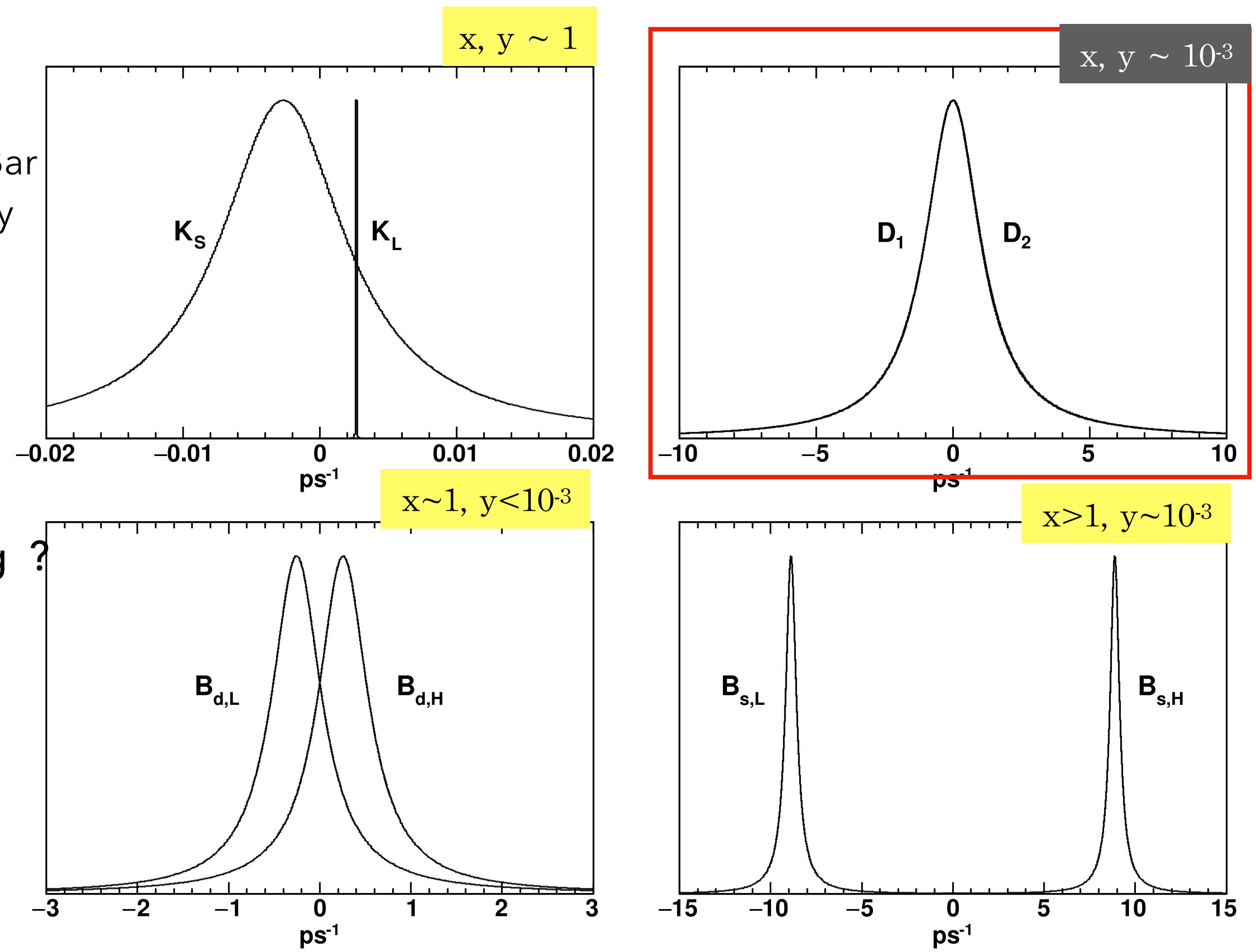
source: Chin.Phys. C38 (2014) 090001.

Mixing in neutral mesons

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

$x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/(2\Gamma)$

- Mixing parameters x, and y;
  - "*x*" → Rate of oscillation between M and MBar
  - "*y*" → Non-oscillating changes in expo-decay

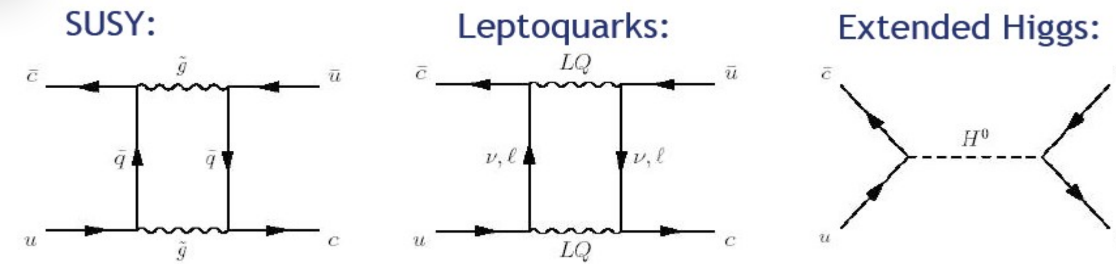


- What variables we can measure for mixing ?
  - Mixing in CP eigenstates ***y_{CP}***
  - Direct measurement of ***x and y***
  - Mixing rate ***R***
  - Through interference: ***x'^2 and y'***

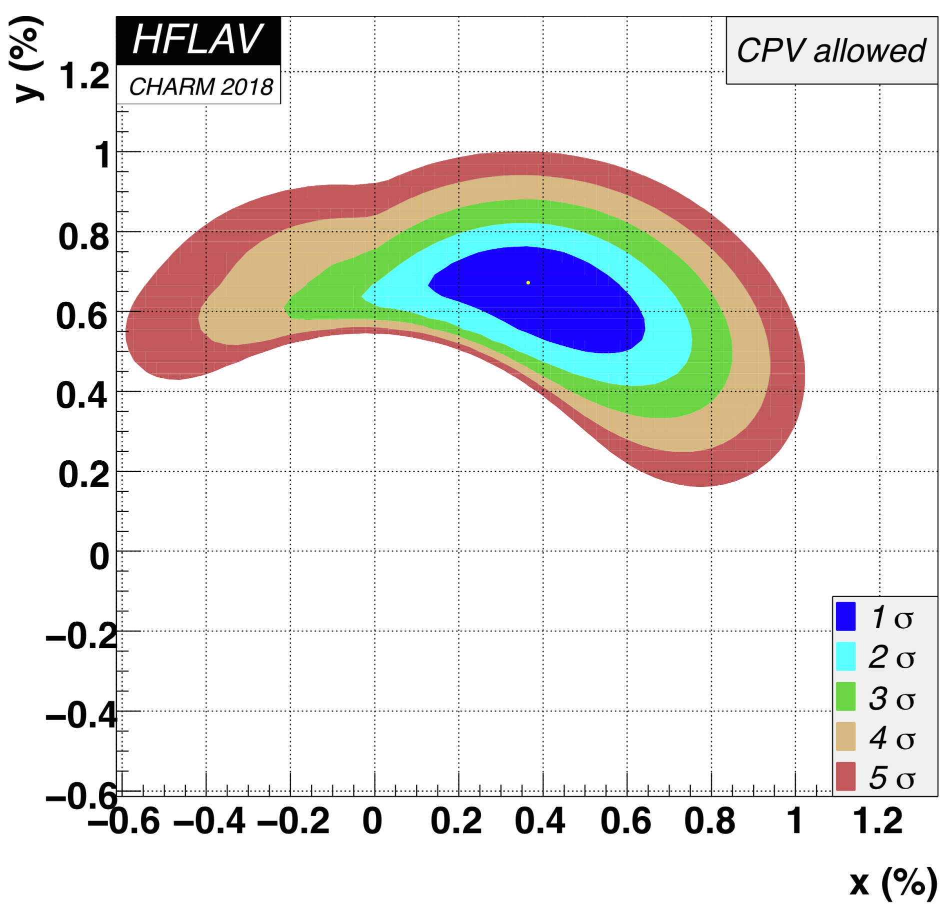
source: Chin.Phys. C38 (2014) 090001.

5 Mixing in neutral mesons

$$|D_{1,2}\rangle = p\,|D^0\rangle \mp q\,|\bar{D}^0\rangle$$



- Mixing in charm mesons
  - Heavily suppressed (both CKM, and GIM suppressed)
  - Small x, y parameters ~ 10^{-3}-10^{-2}
  - Non-SM particles contributing to the box diagram could significantly affect the measured values : **Towards NP**
- Why mixing measurement need to be improved
  - For non-CPV mixing, the theory is limited by "long-distance effects" –> low-energy QCD.
  - For fits allowing for CPV (hope to see more than expected –> **towards NP**)



Experiment	Year	$\sqrt{s}$	$\sigma_{acc}(D^0)$	L	$n(D^0)$
CLEO-c	2003-2008	3.77 GeV	8 nb	0.5 fb^{-1}	4.0×10^6
BESIII	2010-2011	3.77 GeV	8 nb	3 fb^{-1}	2.4×10^7
BaBar	1999-2008	10.6 GeV	1.45 nb	500 fb^{-1}	7.3×10^8
Belle	1999-2010	10.6 – 10.9 GeV	1.45 nb	1000 fb^{-1}	1.5×10^9
CDF	2001-2011	2 TeV	13 μb	10 fb^{-1}	1.3×10^{11}
LHCb	2011	7 TeV	1.4 mb	1 fb^{-1}	1.4×10^{12}
LHCb	2012	8 TeV	1.6 mb*	2 fb^{-1}	3.2×10^{12}

Belle II 2017-2022, L=50 ab^{-1}, and more charm will arrive

source: arXiv:1503.00032v2

Indirect CPV

Direct CPV (Decay)

$$\left|\frac{\overline{A}}{A}\right| \neq 1$$

Indirect CPV (Mixing)

$$\left|\frac{q}{p}\right| \neq 1$$

Interference of Mixing and Decay

$$\left(\frac{q}{p}\frac{\overline{A}}{A}\right) \neq 0$$

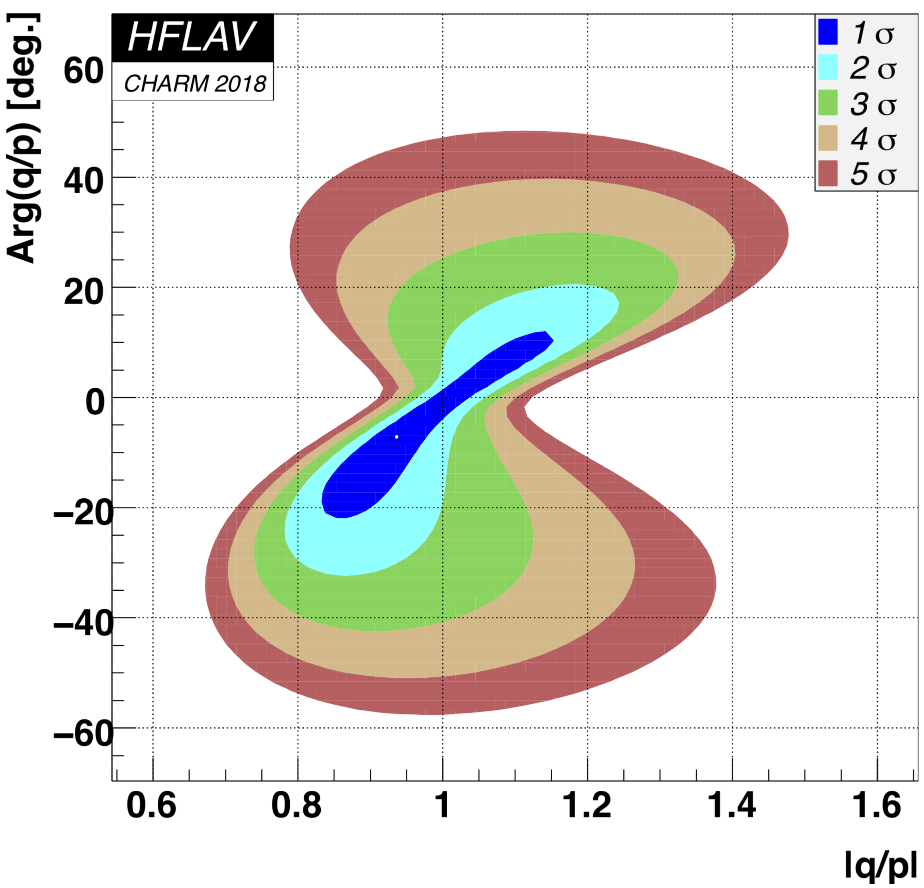
$$|D_{1,2}\rangle = p\,|D^0\rangle \mp q\,|\overline{D}^0\rangle$$

$$-\eta_{CP}\left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$$

- What variables we can measure for indirect CPV ?
  - Direct measurement of |q/p| or ϕ
  - ACP for interference between mixing and decay

Indirect CPV in charm

- CP violation in charm sector is special !
  - Charm, after strange and beauty (in B^0), where CP violation *remains to be discovered !*
  - Only up-type quark family, where mixing and CPV (may) occur
  - Mixing is heavily suppressed (both CKM, and GIM suppressed)
    - Small x, y parameters ~10^{-3}-10^{-2}
    - Non-SM particles contributing to the box diagram could significantly affect x, y *(NP?)*
  - Study of their oscillations in time can provide insights into CPV in mixing



Belle II and SuperKEKB

Powerful **SuperKEKB**

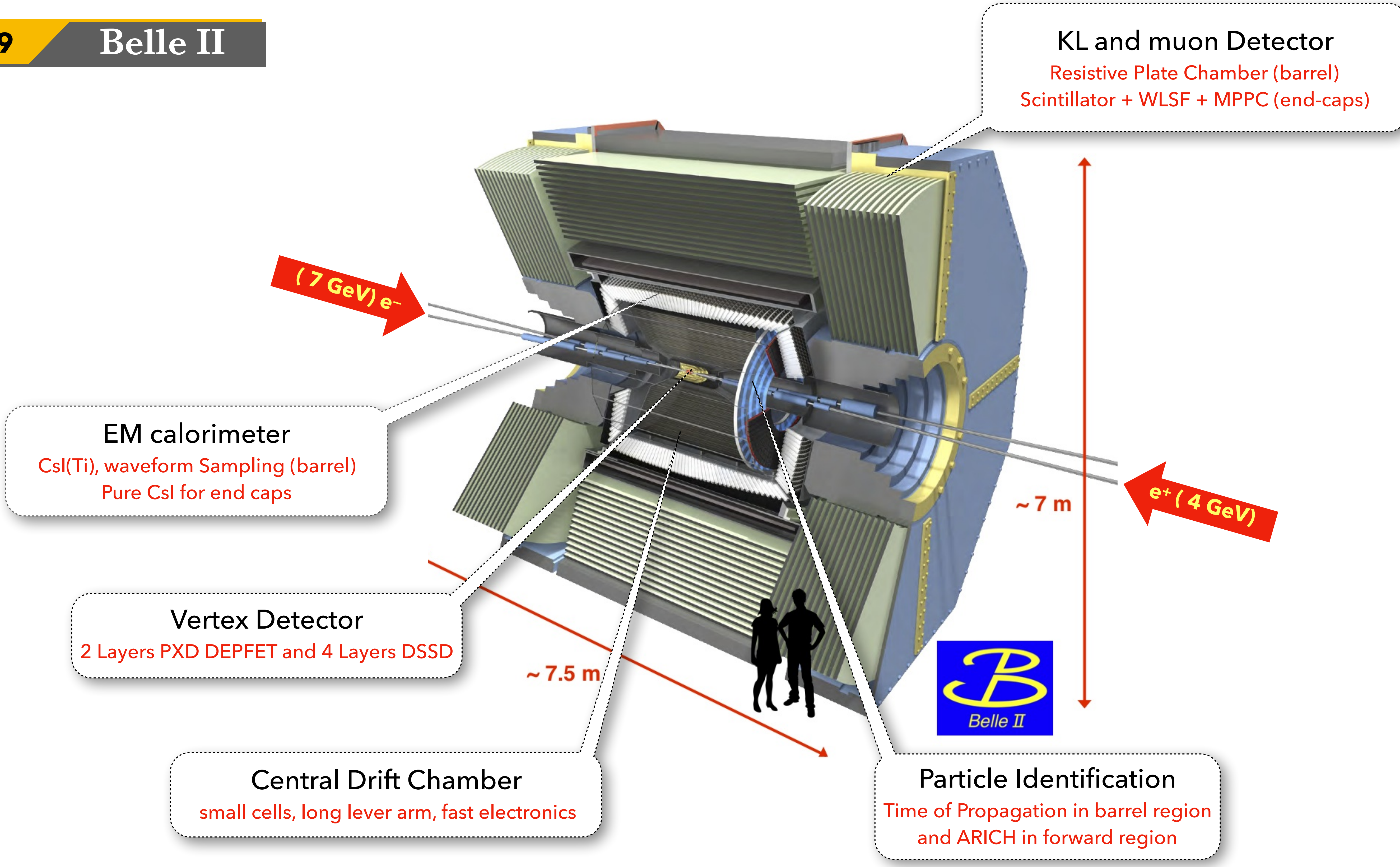
- Provide clean signal of $B\bar{B}$ pairs; low background with respect to hadron colliders
- Large samples of B and D decays (5×10^{10} pairs of b and c over planned operation)
- Lorentz boost (asymmetric energy) allows precision measurement mixing parameters, and CP violations.
  - Better reconstruction of final states containing photons from particle decays such as π^0, η etc
  - Straight forward Dalitz plot analyses with low background
  - Many control samples to study systematics

Belle II improvements in view of charm measurement

- New VXD of Belle II provides better vertex resolution (for D^0 its around 40 μm → **next slide**)
- IP resolution is improved by PXD being at radius of 1.4 cm (better D^0 proper time resolution: **next slide**)
- Better particle identification w/ upgraded SVD, CDC, TOP and ARICH; better K/π separation **($D^0 \to K^-\pi^+$)**
- Better reconstruction efficiency with improved tracking efficiency: eg: **$D^* \to D^0\pi^+$** etc
- More tracking volume from upgraded CDC and SVD provides higher K_s efficiency ~ 30%

see more at Belle II TDR: arXiv: 1011.0352

Belle II



see more at Belle II TDR: arXiv: 1011.0352

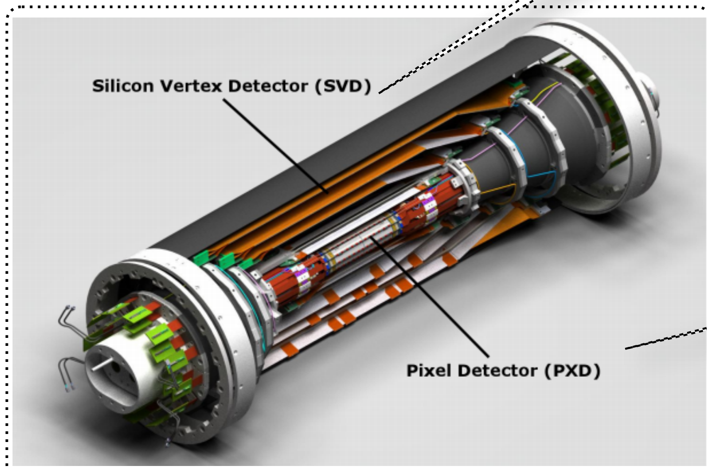
Belle II

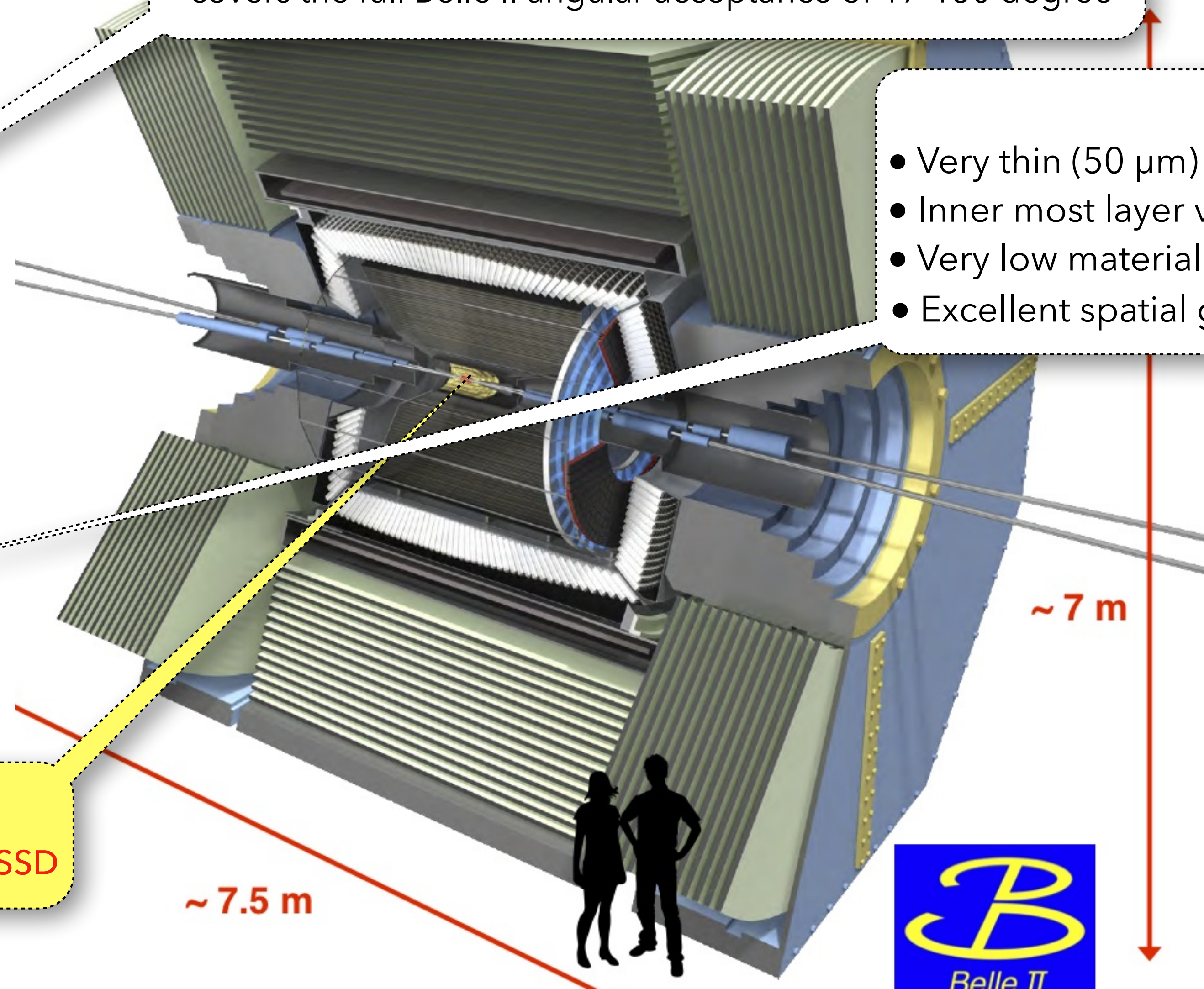
SVD

- Excellent timing resolution (σ ~ 2-3 ns)
- Low material budget
- Larger outer radius (6.05 cm → 14 cm)
- Inner radius: 3.8 cm
- covers the full Belle II angular acceptance of 17-150 degree

PXD

- Very thin (50 μm) pixel sensor
- Inner most layer very close to IP (r = 1.4 cm)
- Very low material budget
- Excellent spatial granularity (σ ≤15 μm)





Vertex Detector

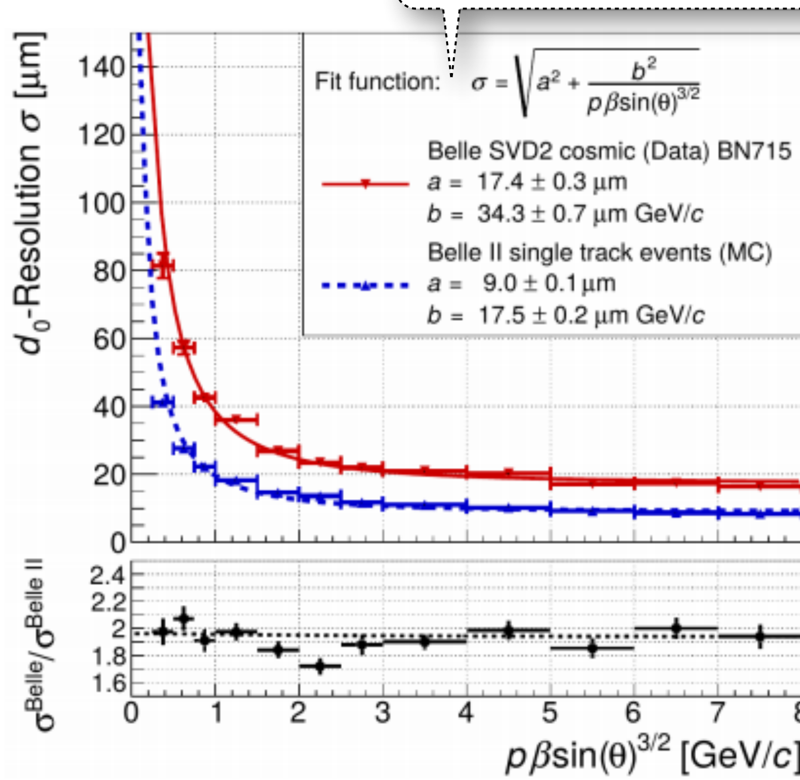
2 Layers PXD DEPFET and 4 Layers DSSD

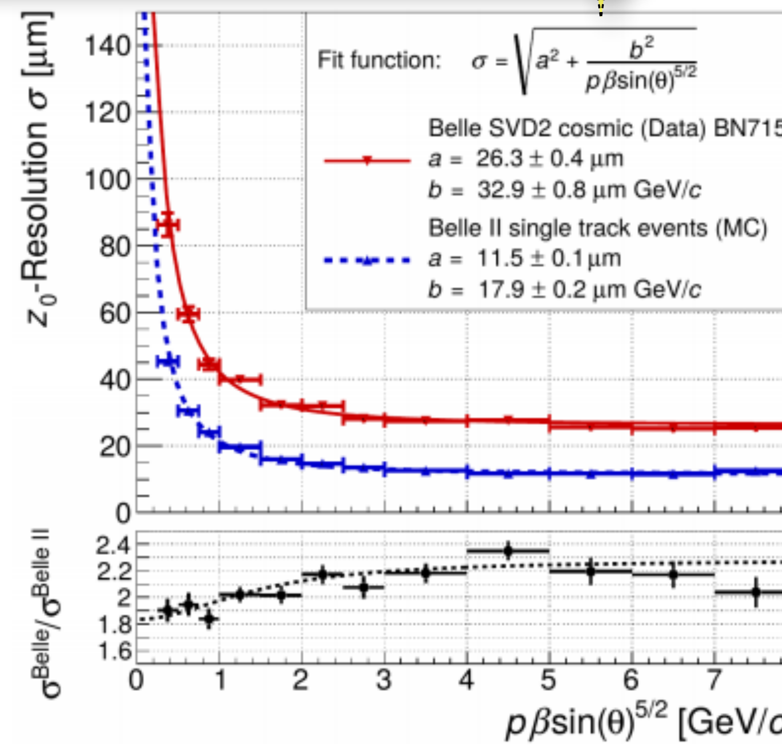
- First run with full vertex detector in early 2019 (Phase 3 of Belle II)
- Key player for D-mixing sensitivity measurements !
  - Highly granular pixel sensors provide most accurate 2D position information
  - Reconstruction of primary and secondary vertices of short-lived particles (<100 μm from IP)

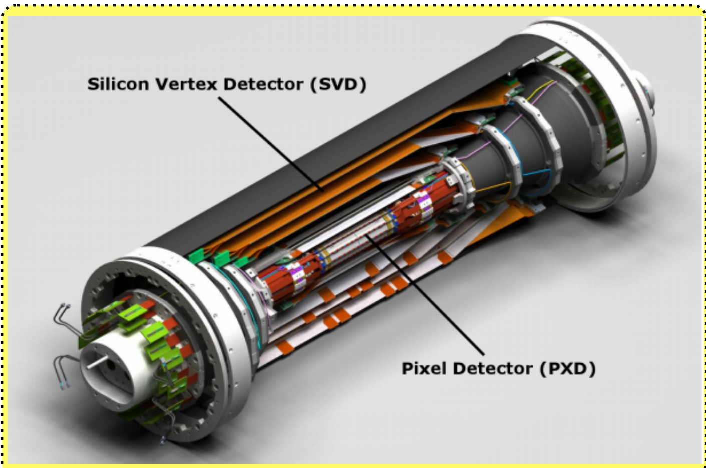
see more at Belle II TDR: arXiv: 1011.0352

11 Vertex performance

A factor of 2 improvement in "track impact parameter" with respect to Belle





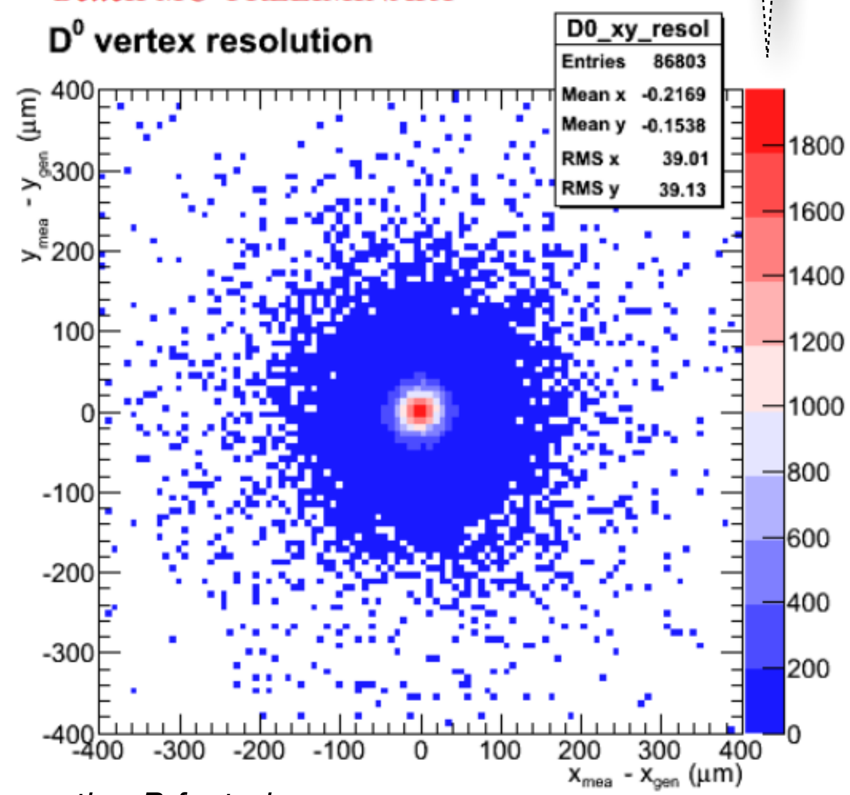


Vertex Detector

2 Layers PXD DEPFET and 4 Layers DSSD

Better vertex resolution ~ 40 µm

BelleII MC PRELIMINARY

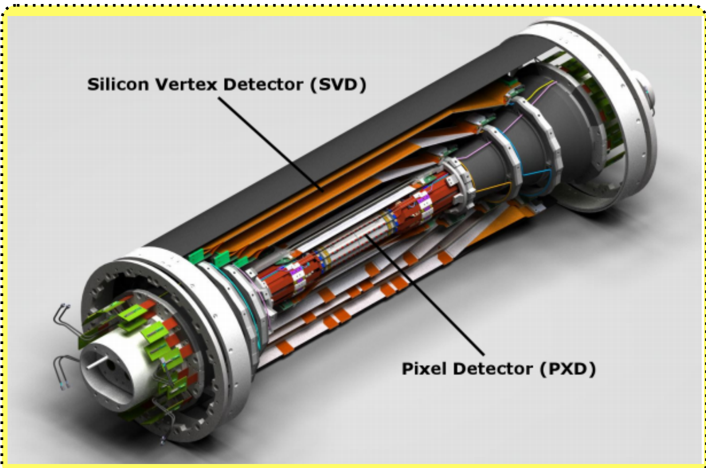


*with respect to previous generation B factories.

see more at Belle II TDR: arXiv: 1011.0352

12 Time resolution

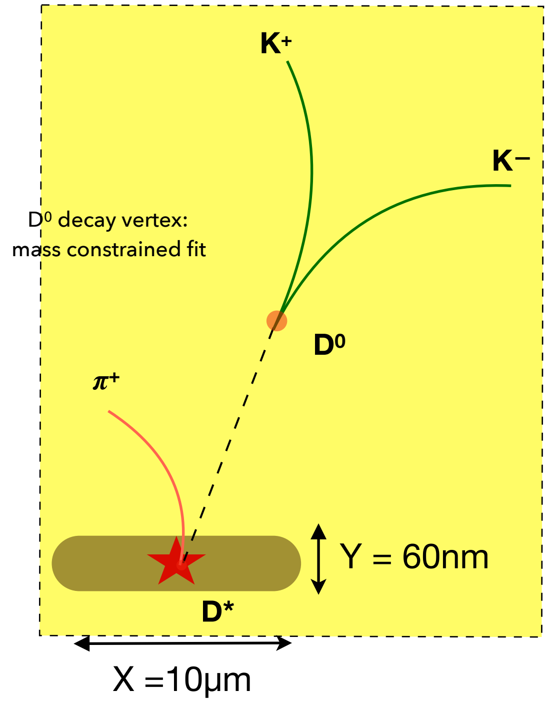
$$t = \frac{\ell}{\beta\gamma c} = \frac{\ell}{c}\frac{m_D}{|\vec{p}|}$$

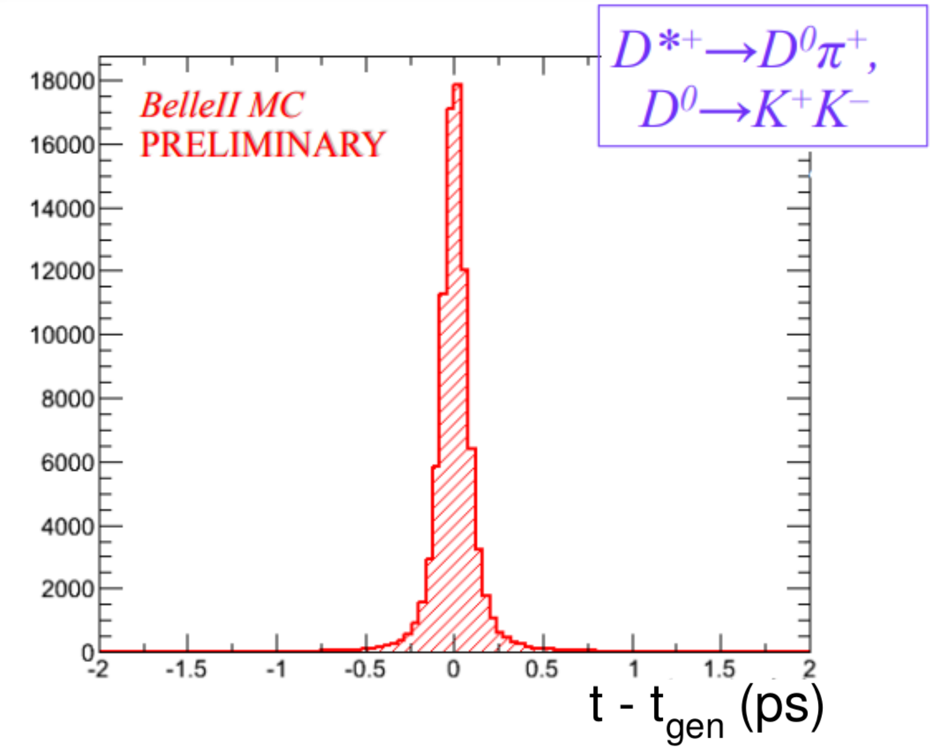


Vertex Detector

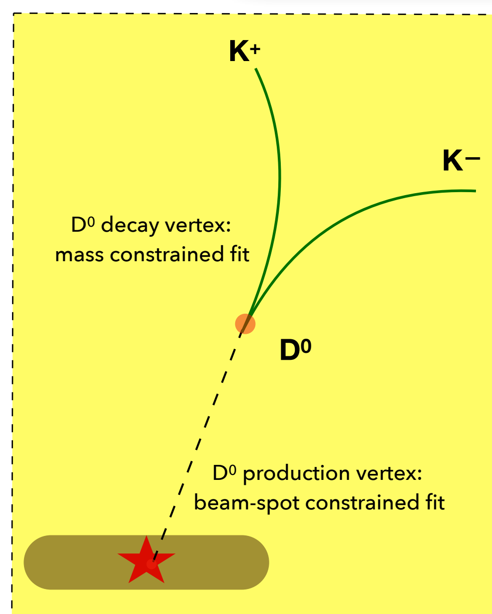
2 Layers PXD DEPFET and 4 Layers DSSD

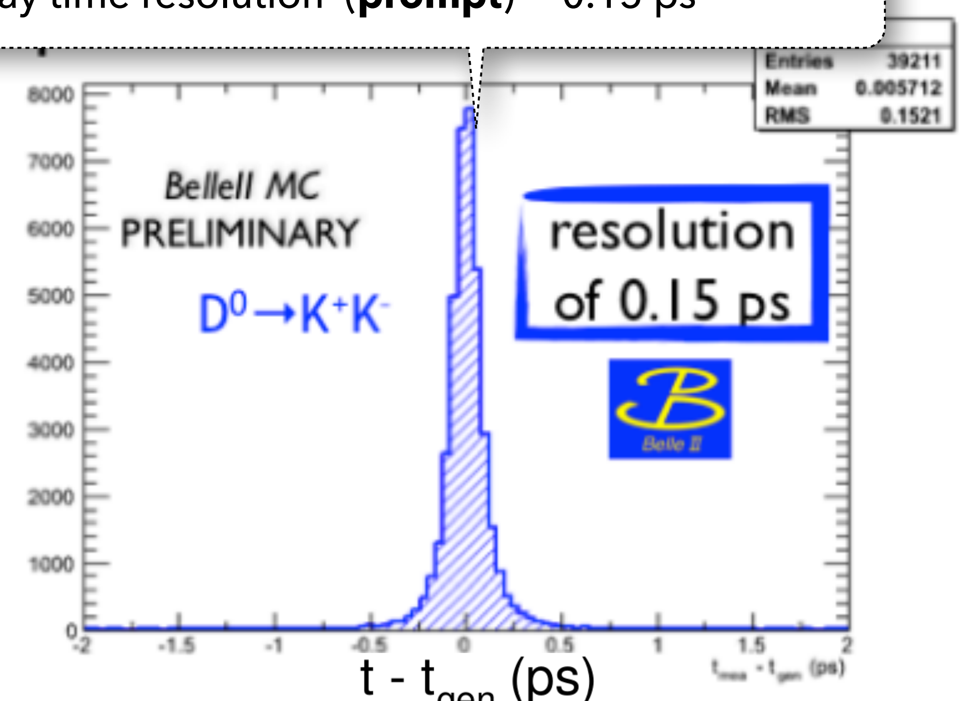
D→hh decay time resolution **(D* tag)** ~ 0.14 ps
-- 2× better than belle and BaBar





D→hh decay time resolution (**prompt**) ~ 0.15 ps





Belle II Physics Book: *https://arxiv.org/pdf/1808.10567.pdf)*

Charm Mixing and Indirect CPV prospects at Belle II

The experimental status of $D^0\overline{D}^0$ mixing and CP violation in different decays.

Decay Type	Final State	LHCb	Belle	BaBar	CDF	CLEO	BES III
DCS 2-body(WS)	$K^+\pi^-$	★	★	●	★	✓	
DCS 3-body(WS)	$K^+\pi^-\pi^0$		✓ A_{CP}	●		✓ A_{CP}	
CP-eigenstate	K^+K^-, $\pi^+\pi^-$	● (a) A_{CP}	●	●	✓ A_{CP}	✓	
Self-conjugated 3-body decay	$K^0_S\pi^+\pi^-$	✓	✓	✓ A_{CP}	✓		
	$K^0_SK^+K^-$		✓ (b)	✓			
Self-conjugated SCS 3-body decay	$\pi^+\pi^-\pi^0$	✓ A_{CP}	✓ A_{CP}	✓ $mixing$ A_{CP}			
	$K^+K^-\pi^0$			✓ A_{CP}			
SCS 3-body	$K^0_SK^\pm\pi^\mp$	✓ $\delta^{K^0_SK\pi}$				✓ $\delta^{K^0_SK\pi}$	
Semileptonic decay	$K^+\ell^-\nu_\ell$		✓	✓		✓	
Multi-body(n≥4)	$\pi^+\pi^-\pi^+\pi^-$	✓ A_{CP}					
	$K^+\pi^-\pi^+\pi^-$	★	✓ A_{CP}	✓			
	$K^+K^-\pi^+\pi^-$	✓ (c) A_{CP}		✓ A_T		✓ A_{CP}	
$\psi(3770) \to D^0\overline{D}$ via correlations						✓ $\delta^{K\pi}$	✓ y_{CP}

★ for observation ($> 5\sigma$); ● for evidence ($> 3\sigma$); ✓ for measurement.

(a) LHCb measured the indirect CP asymmetry in Phys. Rev. Lett. **112**, 041801 (2014).

(b) Belle measured y_{CP} in $D^0 \to K^0_S\phi$ in Phys. Rev. D **80**, 052006 (2009).

(c) LHCb searched for CP violation using T-odd correlations in JHEP **10** (2014) 005.

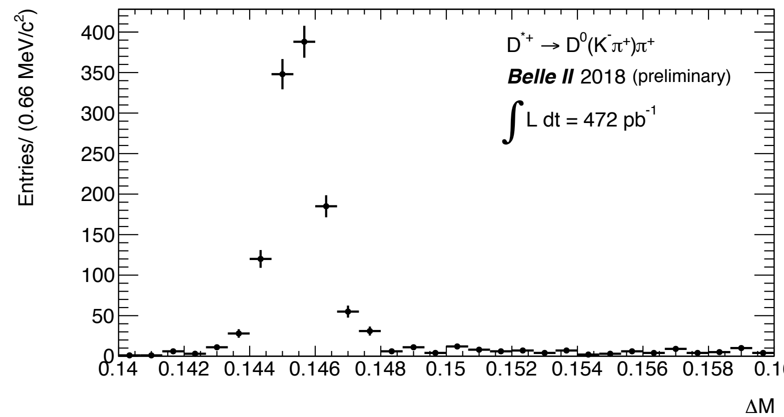
Challenging: higher event rate and radiation damage to detectors from machine background processes

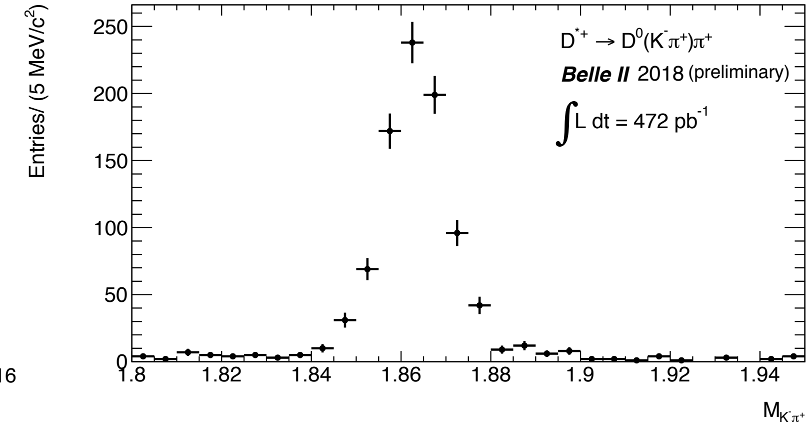
source: Belle II Physics Book: arXiv: 1808.10567

First Belle II collision data

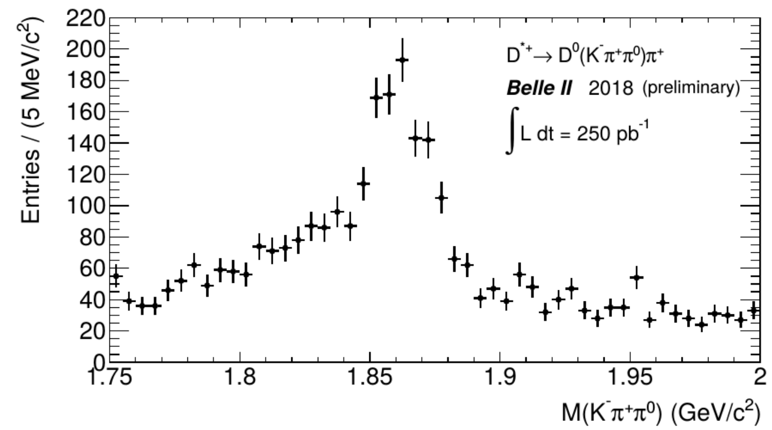
Re-discoveries of D meson decays

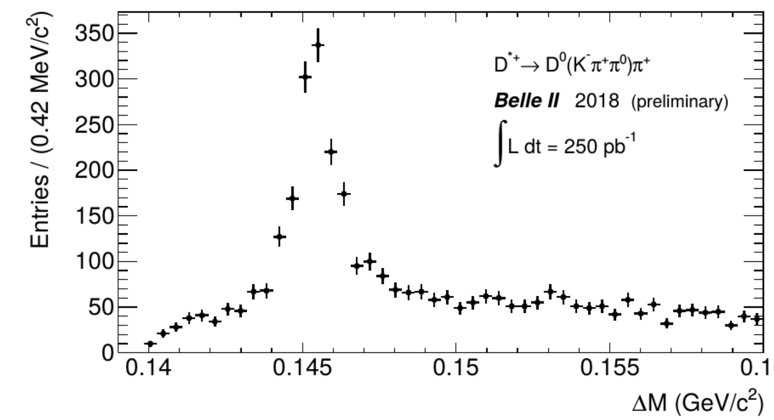
$D^0 \to K^-\pi^+$



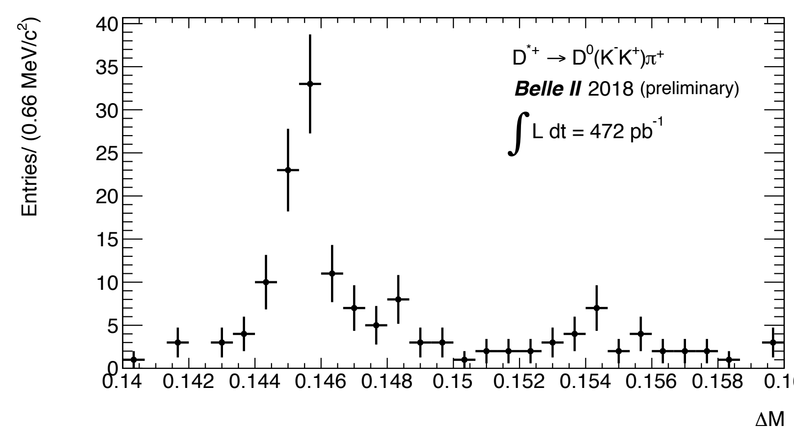


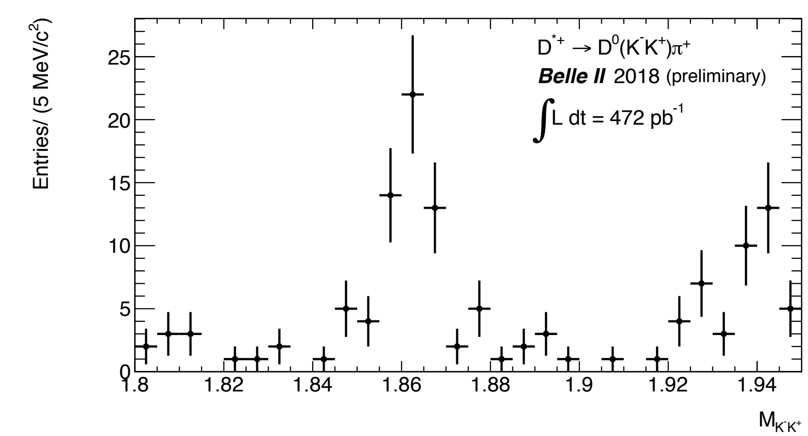
$D^0 \to K^-\pi^+\pi^0$



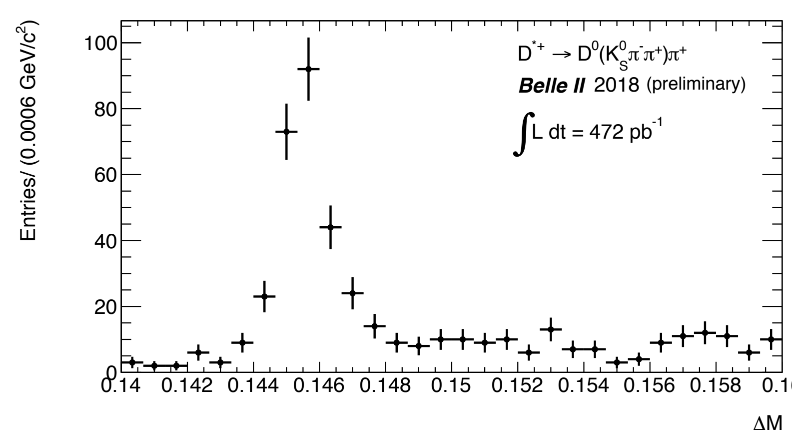


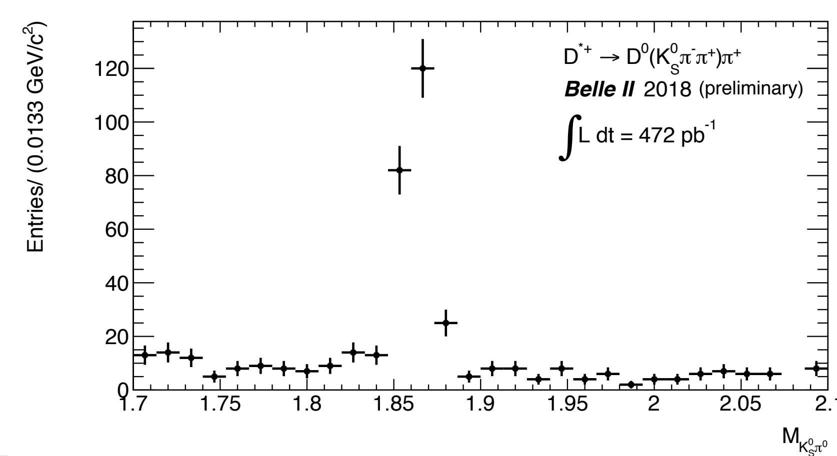
$D^0 \to K^+K^-$





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





Mixing measurements

So far...

$$y_{CP} \equiv \frac{\Gamma_{CP\pm}}{\Gamma} - 1$$

1 CP eigenstates, $D^0 \to K^+K^-/\pi^+\pi^-$ and decays to CP mixed state, $D^0 \to K^-\pi^+$

	y_{CP} in 10^{-3}
LHCb	$5.5 \pm 6.3 \pm 4.1$
BaBar	$7.2 \pm 1.8 \pm 1.2$
Belle	$11.1 \pm 2.2 \pm 1.1$

BaBar: Phys.Rev. D87 (2013) 012004
LHCb: JHEP 1204 (2012) 129
Belle: arXiv:1212.3478

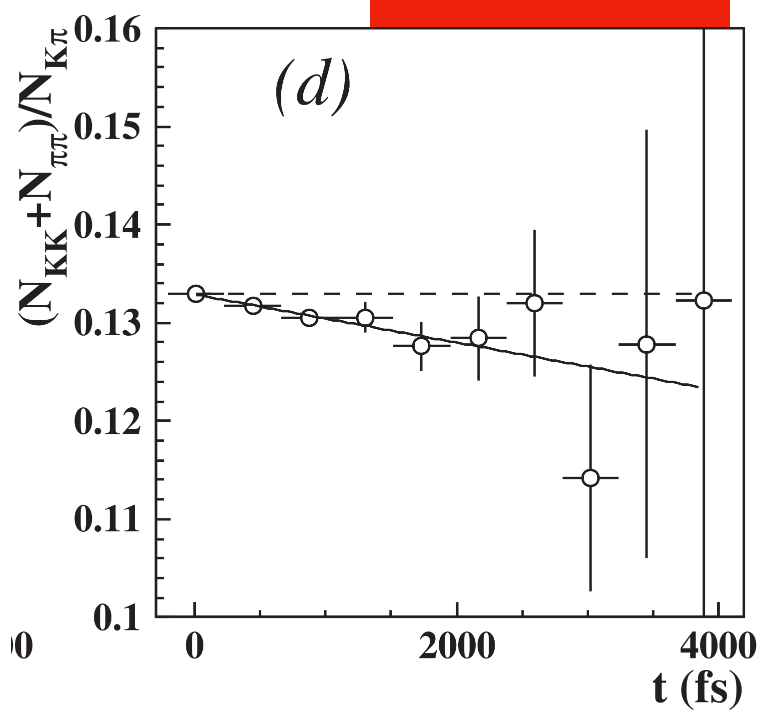
2 CP eigenstates, $D^0 \to K_sK^+K^-$ via Dalitz model

	y_{CP} in 10^{-3}
Belle	$1.1 \pm 6.1 \pm 5.2$

Category 1. Mixing in CP eigenstates

- Compare effective lifetime of CP eigenstates with flavor ones
- y_{CP} is most powerful parameter that can constraint **"y"**

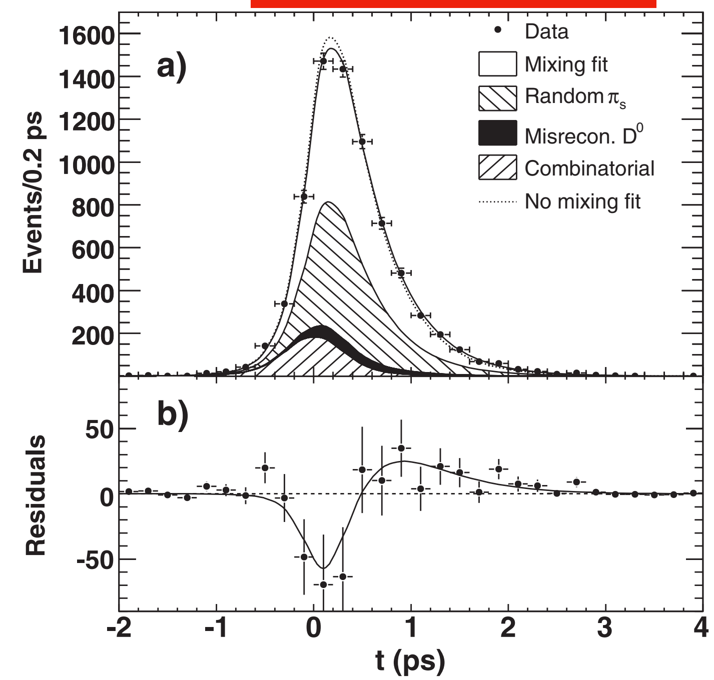
Belle collaboration



Phys. Rev. Lett. 98 (2007) 211803

w/ $D^0 \to K^-\pi^+$ (RS) and $D^0 \to K^+\pi^-$ (WS)

BaBar collaboration



Phys. Rev. Lett. 98 (2007) 211802

Belle II predictions

1

Observable	Statistical	Systematic red.	Systematic irred.	Total
y_{CP} $[10^{-2}]$				
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

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

$D^0 \to \pi^-\pi^+\pi^-\pi^+$?
$D^0 \to K_s\pi^+\pi^-\pi^0$?

?

Source Belle II Physics Book: arXiv: 1808.10567

Mixing measurements

Category 2. Measurement of x and y variables

-- Simultaneous measurement of decay-time evolution and resonance amplitudes

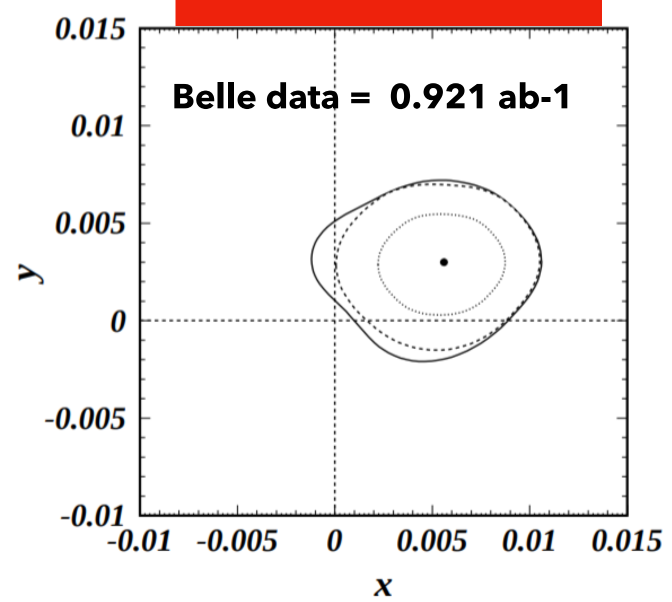
-- $D^0 \to K_s K^- K^+$ for study which also allow to probe indirect CPV

So far…

	x in 10^{-3}	y in 10^{-3}
BaBar	$1.6 \pm 2.3 \pm 1.2 \pm 0.8$	$5.7 \pm 2.0 \pm 1.3 \pm 0.7$
Belle	$5.6 \pm 1.9^{+0.3+0.6}_{-0.9-0.9}$	$3.0 \pm 1.5^{+0.4+0.3}_{-0.5-0.6}$

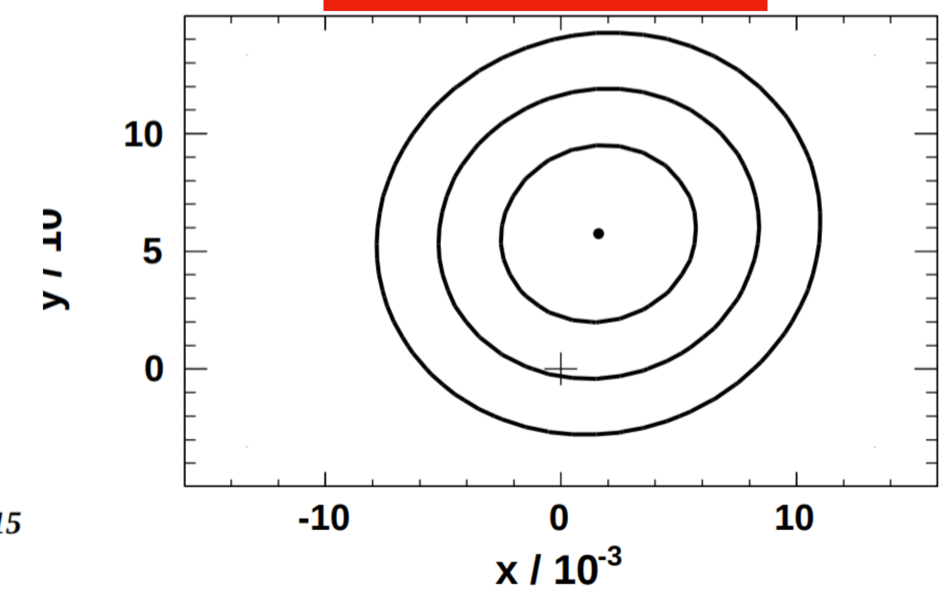
*Under no CPV

Belle collaboration



Phys.Rev. D89, (2014) 091103

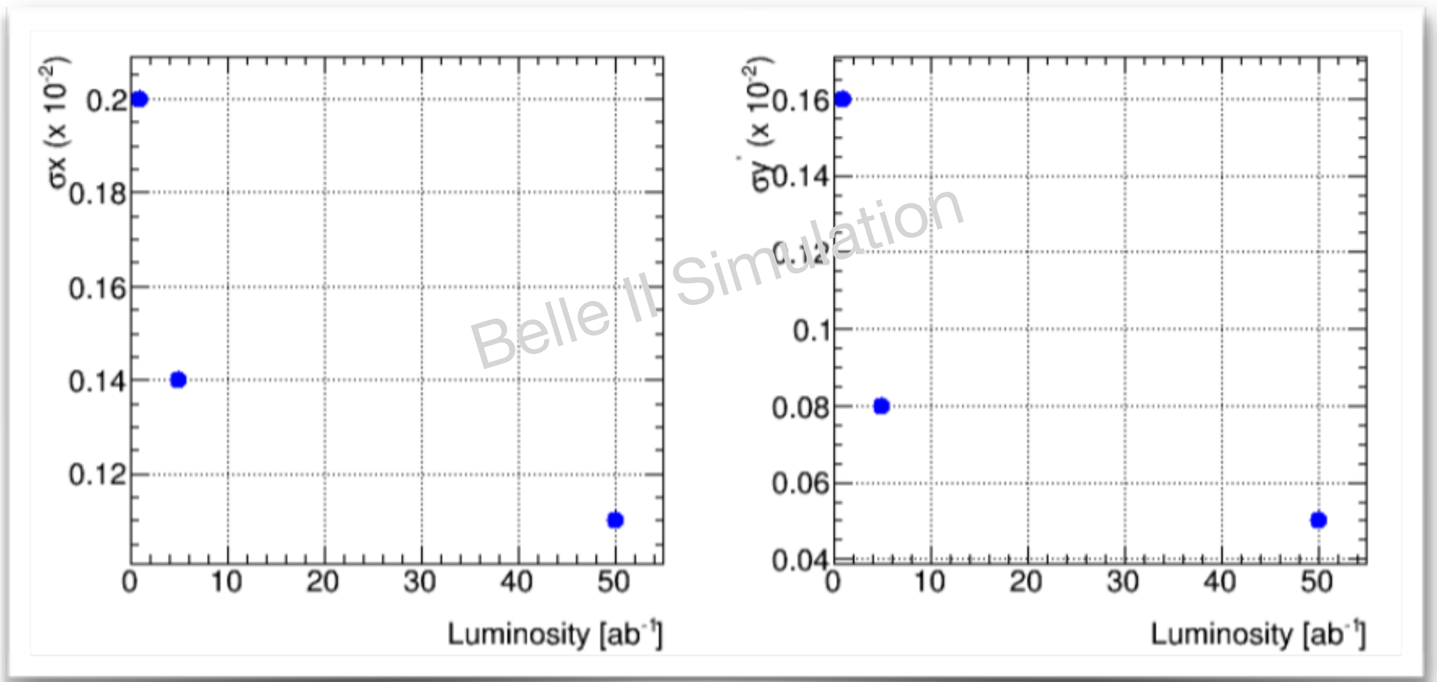
BaBar collaboration



Phys. Rev. Lett. 105 (2010) 081803,

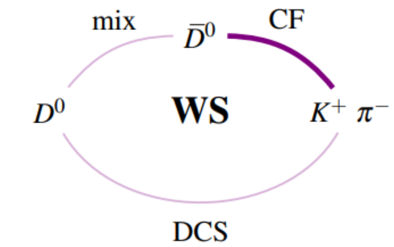
Belle II predictions

- better precision is expected
  -- by factor of 3 for x, y resolutions
- even more..
  --w/ improved decay time resolution

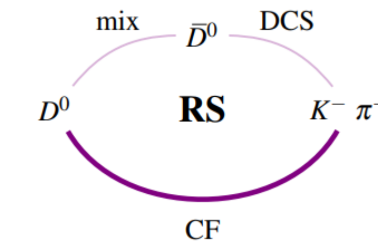


Mixing measurements

Category 3. Mixing via interference



- Golden channel is $\mathbf{D^0 \to K^+\pi^-}$ (many syst auto-cancelled)

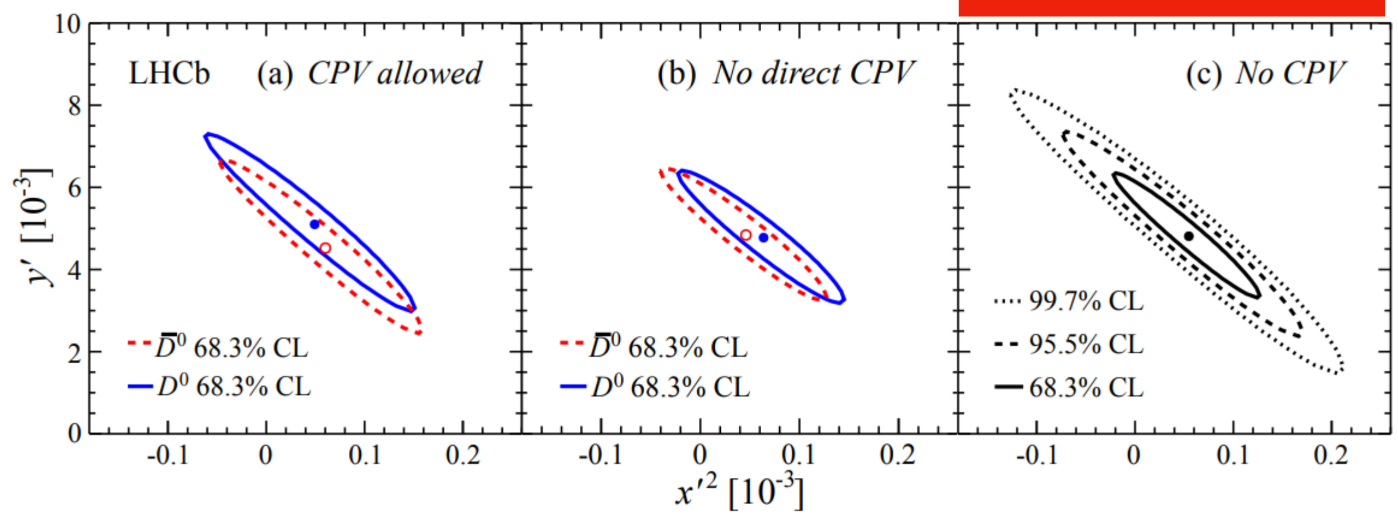


So far...

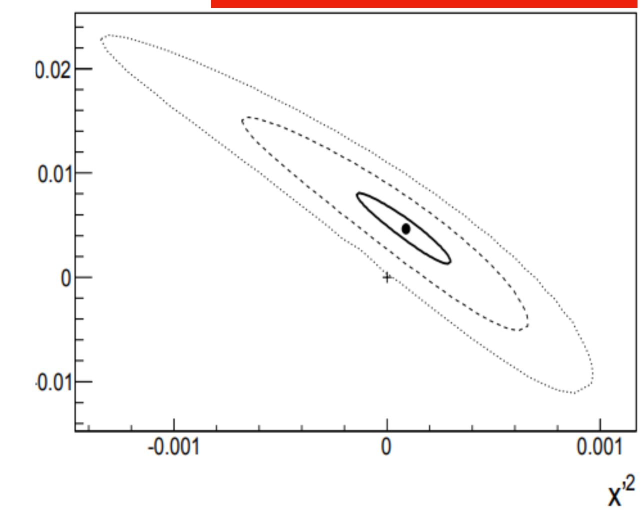
	x'^2 in 10^{-3}	y' in 10^{-3}
CDF	0.08 ± 0.18	4.3 ± 4.3
LHCb	0.06 ± 0.05	4.8 ± 1.0
Belle	0.09 ± 0.22	4.6 ± 3.4

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

LHCb collaboration



Belle collaboration



LHCb: Phys. Rev. Lett. 110 (2013) 101802,
CDF: Phys. Rev. Lett. 100 (2008) 121802
CDF : Phys.Rev.Lett. 111, (2013) 231802
LHCb: Phys. Rev. Lett. 111 (2013) 251801
Belle : Phys. Rev. Lett. 112, (2014) 111801

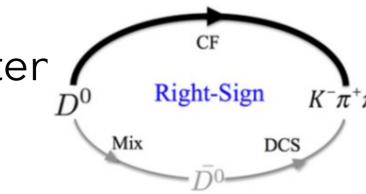
Belle II predictions

Parameter	5 ab^{-1}	20 ab^{-1}	50 ab^{-1}
$\delta x'^2$ (10^{-5})	7.5	3.7	2.3
$\delta y'$ (%)	0.11	0.056	0.035

Luminosity (ab^{-1})	Belle	Belle II
0.400	4 024	
0.976	11 478	
5.0		58 800
20		235 200
50		588 010

Mixing measurements

Category 3. Mixing via interference



- CF and DCS can also lead to exited states of same quark conter
- Channel is **$D^0 \to K^+\pi^-\pi^0$** (resonance $K^+\rho^-$ and $K^{*+}\pi^-$)

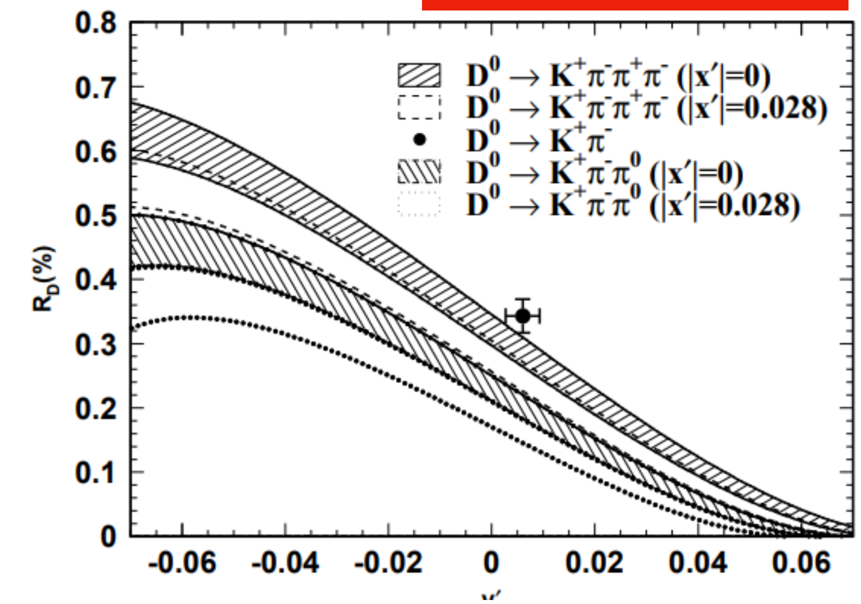
$$x'' = x\cos\delta_{K^+\pi^-\pi^0} + y\sin\delta_{K^+\pi^-\pi^0}$$
$$y'' = y\cos\delta_{K^+\pi^-\pi^0} - x\sin\delta_{K^+\pi^-\pi^0}$$

So far...

$$x'' = (2.61^{+0.57}_{-0.68} \pm 0.39)\%$$
$$y'' = (-0.06^{+0.55}_{-0.64} \pm 0.34)\%$$

BaBar, Phys. Rev. Lett., 103, 211801 (2009)

$R_{WS} = (0.229 \pm 0.015)\%$ *Belle collaboration*

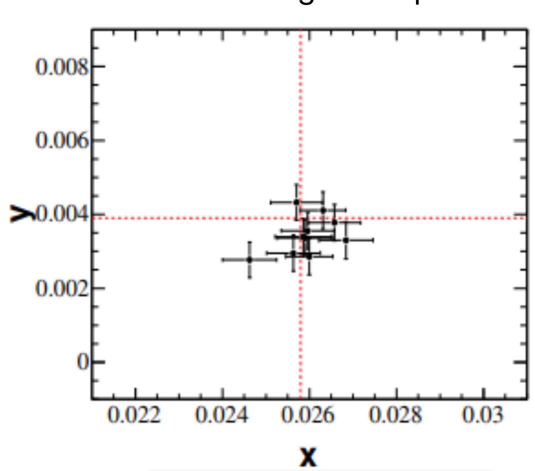


Belle, Phys. Rev. Lett., 95, 231801 (2005)

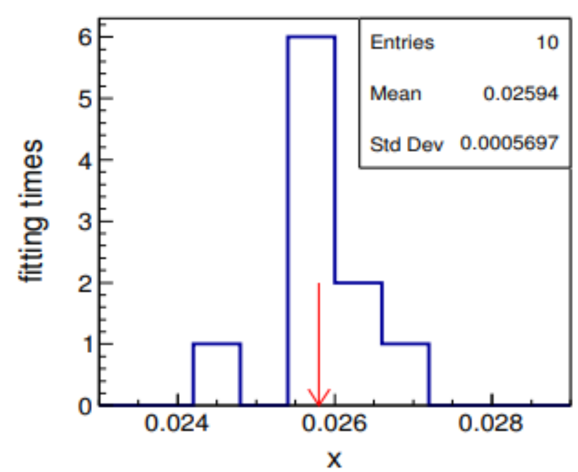
Belle II predictions

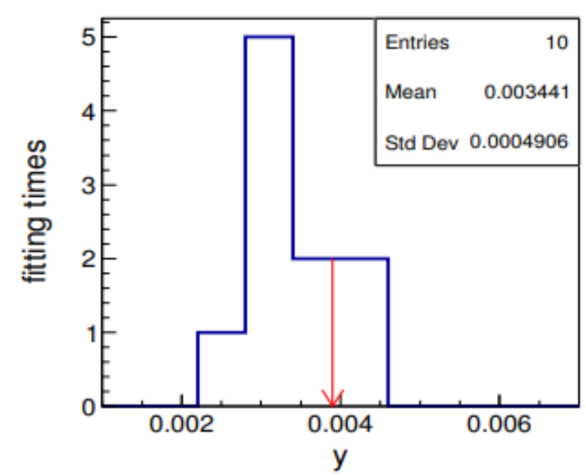
$$\sigma_{x''} = 0.057\%$$
$$\sigma_{y''} = 0.049\%$$

*assuming Belle II reconstruction efficiency is same as Belle
* one order of magnitude precise than BaBar



assuming no CP violation





Mixing measurements

So far...

Belle II impact on the World Average

- So far no single measurement has been able to measure precisely
- Combined results by Heavy-Flavour Averaging group (HFA) : **World Average**

w/o CPV in mixing and decay

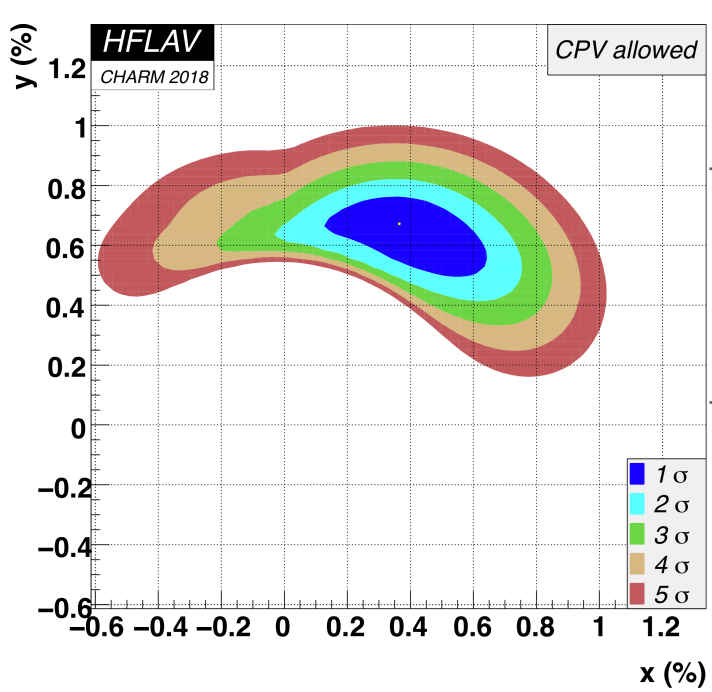
$$x = (4.9^{+1.4}_{-1.5}) \times 10^{-3} \qquad y = (6.2 \pm 0.8) \times 10^{-3}$$

- .. but hint of D^0 and $\bar{D}^0$ mixing by many measurements

w/ CPV in mixing and decay

World Average	Belle II (50 ab^{-1})
$x = 3.2 \pm 1.4 \times 10^{-3}$, $y = 6.9 \pm 0.6 \times 10^{-3}$	$x = 8.0 \pm 0.9 \times 10^{-3}$, $y = 7.0 \pm 0.4 \times 10^{-3}$

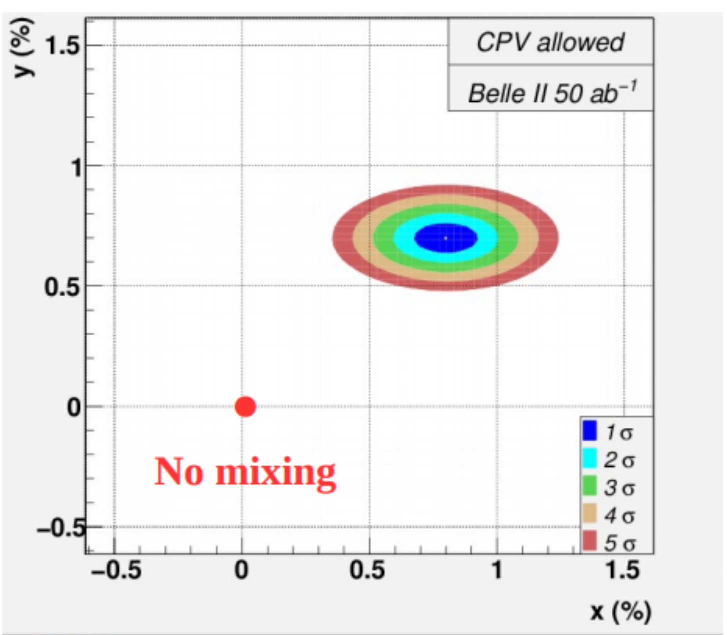
Belle II predictions



mixing parameters

$$x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma},$$

where Δm = mass differences and ΔΓ = lifetimes differences



Measuring indirect CPV

NO sign of CPV so far ..

So far...

1. Direct measurement of |p/q| and ϕ

- Golden channel are : $D^0 \to K_s K^- K^+$ or $D^0 \to K_s \pi^+ \pi^-$
- Provide most precise mixing parameters
- To avoid systematic limitation > reduce model limitation OR improve model independent strong phase difference (at BESIII)

Belle collaboration

Fit type	Parameter	Fit result
No *CPV*	$x(\%)$	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$
	$\|q/p\|$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg(q/p)(°)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

Phys. Rev. D 89, 091103 (2014)

2. CP asymmetries in WS decay: $D^0 \to K^+\pi^-$

- Measurement of R_D, x'^2 and y'^2
- Small phase (ϕ) gives direct access to |q/p|

$$x'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1}(x'\cos\phi \pm y'\sin\phi)$$

$$y'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1}(y'\cos\phi \mp x'\sin\phi)$$

Belle: Phys.Rev.Lett. 96 151801,2006
BaBar: Phys. Rev. Lett. 98 (2007) 211802

Belle II predictions

Assuming no CPV

Data	stat.	syst. red.	syst. irred.	Total	stat.	syst. red.	syst. irred.	Total
	σ_x (10^{-2})				σ_y (10^{-2})			
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
	$\|q/p\|$ (10^{-2})				ϕ (°)			
976 fb^{-1}	15.5	5.2-5.6	7.0-6.7	17.8	10.7	4.4-4.5	3.8-3.7	12.2
5 ab^{-1}	6.9	2.3-2.5	7.0-6.7	9.9-10.1	4.7	1.9-2.0	3.8-3.7	6.3-6.4
50 ab^{-1}	2.2	0.7-0.8	7.0-6.7	7.0-7.4	1.5	0.6	3.8-3.7	4.0-4.2

Parameter	5 ab^{-1}	20 ab^{-1}	50 ab^{-1}
$\delta x'^2$ (10^{-5})	7.5	3.7	2.3
$\delta y'$ (%)	0.11	0.056	0.035
$\delta x'$ (%)	0.37	0.23	0.15
$\delta y'$ (%)	0.26	0.17	0.10
$\delta\|q/p\|$	0.197	0.089	0.051
$\delta\phi$ (°)	15.5	9.2	5.7

Summary

- SuperKEKB and Belle II will be an excellent platform for charm measurements
  - SuperKEKB Will record 50 x larger data sample than KEKB / Belle (by 2025).
  - Upgraded VXD will provide factor two better D0 decay time resolution than Belle/BaBar.
  - First collision data successfully recorded this year.
  - First data with full vertex detector early 2019.
- Better precision on x and y variables ≤ 0.1 % is expected.
- Error extrapolations from Belle measurements is predicted as;

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

σ_{stat}: *Scaling Belle statistical error by the ratio of integrated luminosities*

σ_{syst}: *Only those who scale with luminosity such as background shapes measured with control samples*

σ_{irred}: *Those who do not scale with luminosity such as decay time resolution due to detector misalignment*

Source Belle II Physics Book: arXiv: 1808.10567

Stay tuned.. for new and precise measurements..