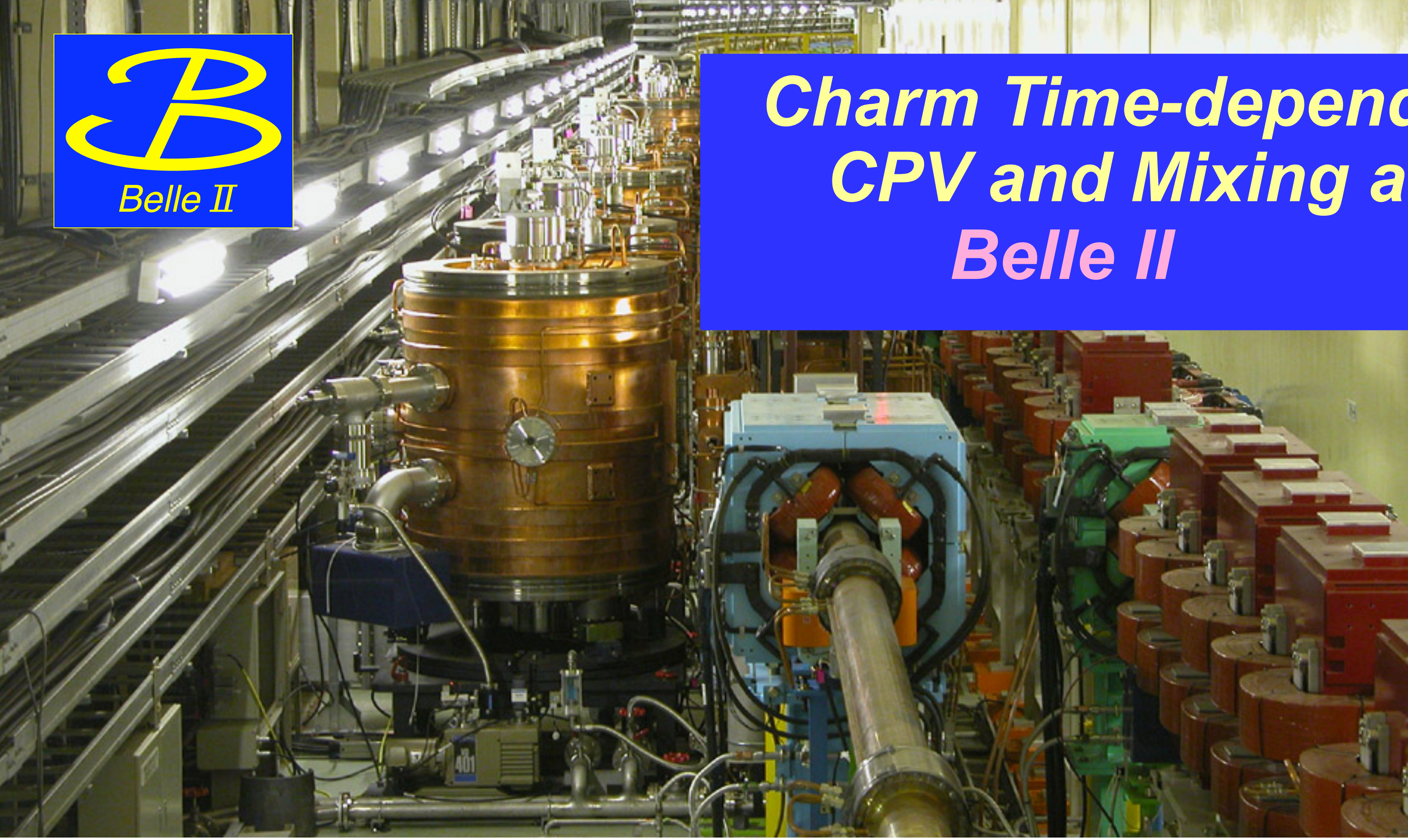
Belle II

Charm Time-dependent CPV and Mixing at Belle II



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Tata Institute of Fundamental Research
Mumbai, India
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- *motivation*
- *upgrading Belle/KEKB → Super B Factory*
- *decay time resolution*
- *2-body decays*
- *multi-body decays*
- *detector status and schedule*

Motivation

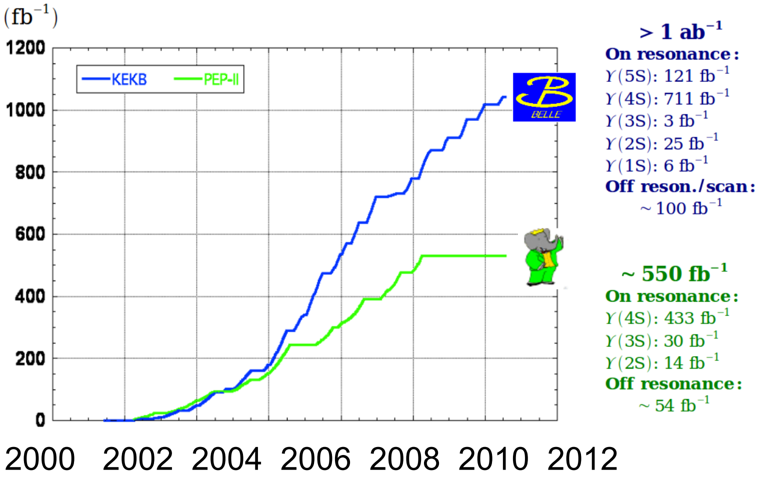
Why an e^+e^- Machine for Charm Physics?

- *Low backgrounds, high trigger efficiency, excellent γ and π^0 recontruction (and thus η, η', ρ^+, etc. reconstruction), high flavor-tagging efficiency with low dilution, many control samples to study systematics*

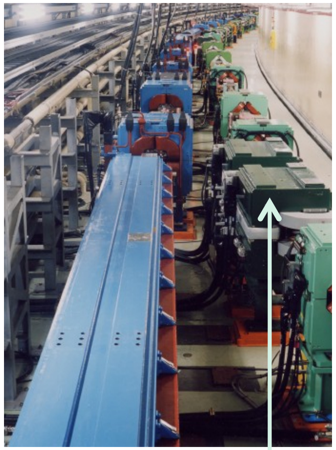
- *Due to low backgrounds, negligible trigger bias, and good kinematic resolutions, Dalitz plots analyses are straightforward. Absolute branching fractions can be measured. Missing energy and missing mass analyses are straightforward.*

- *systematics quite different from those at LHCb. If true NP is seen by one of the experiments, confirmation by the other would be important.*

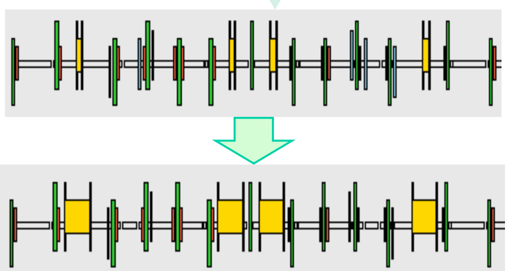
- *Belle II goal: to increase the sampe sizes over what Belle achieved by a factor of 50 (>4 x 10^{10} BB pairs)*



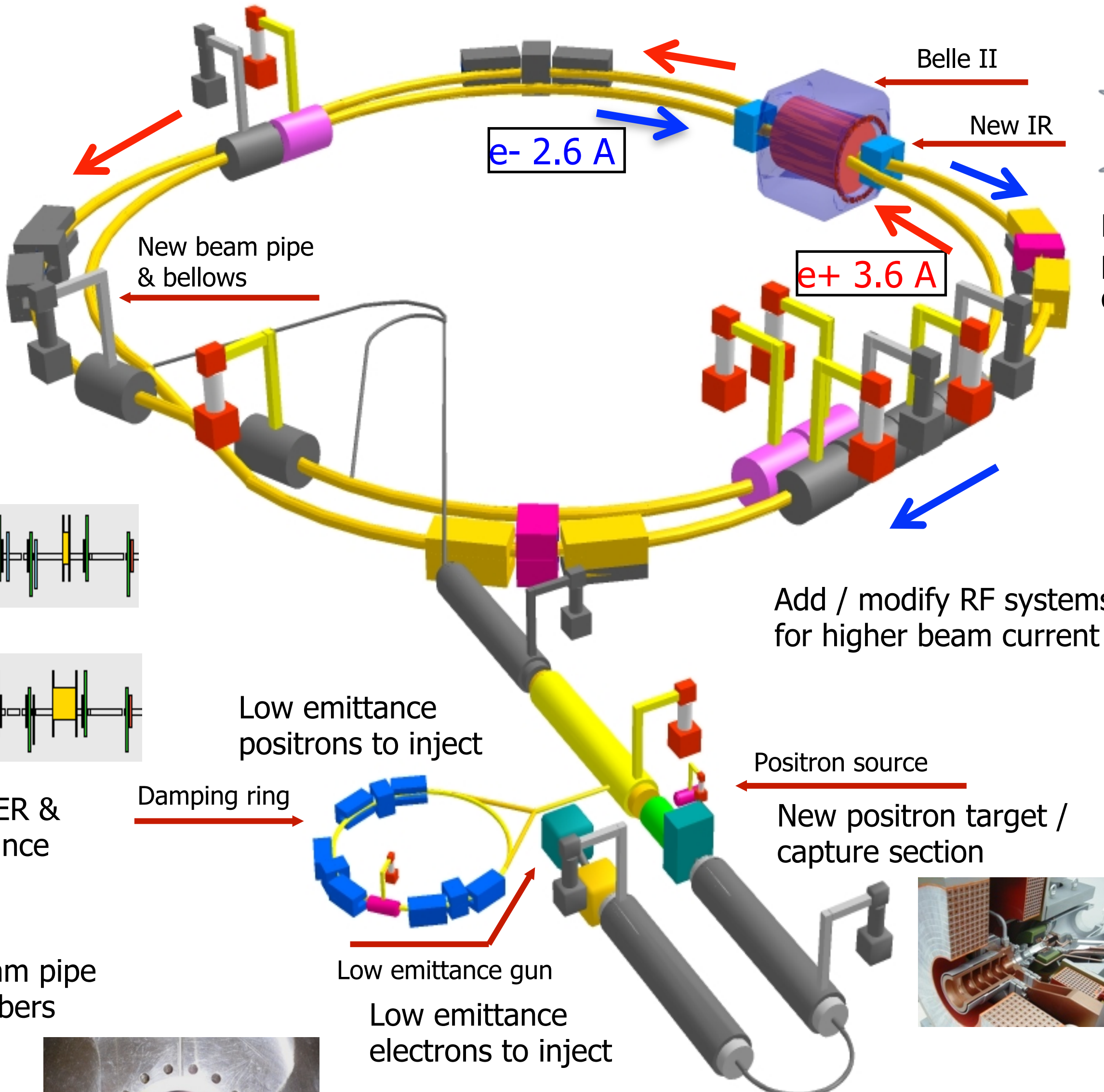
KEKB → SuperKEKB (nano-beam)

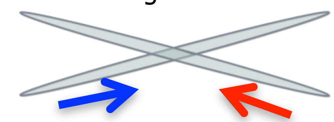


Replace short dipoles with longer ones (LER)

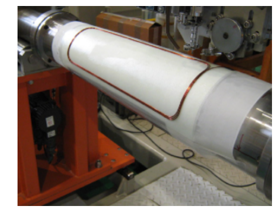


Redesign the lattices of HER & LER to squeeze the emittance





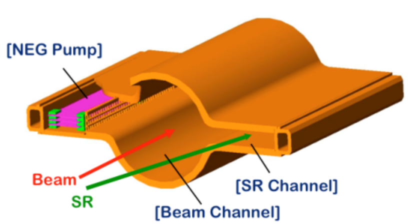
New superconducting / permanent final focusing quads near the IP

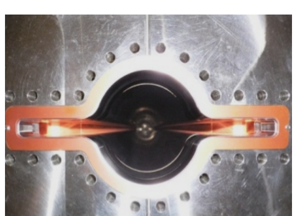


Add / modify RF systems for higher beam current

New positron target / capture section

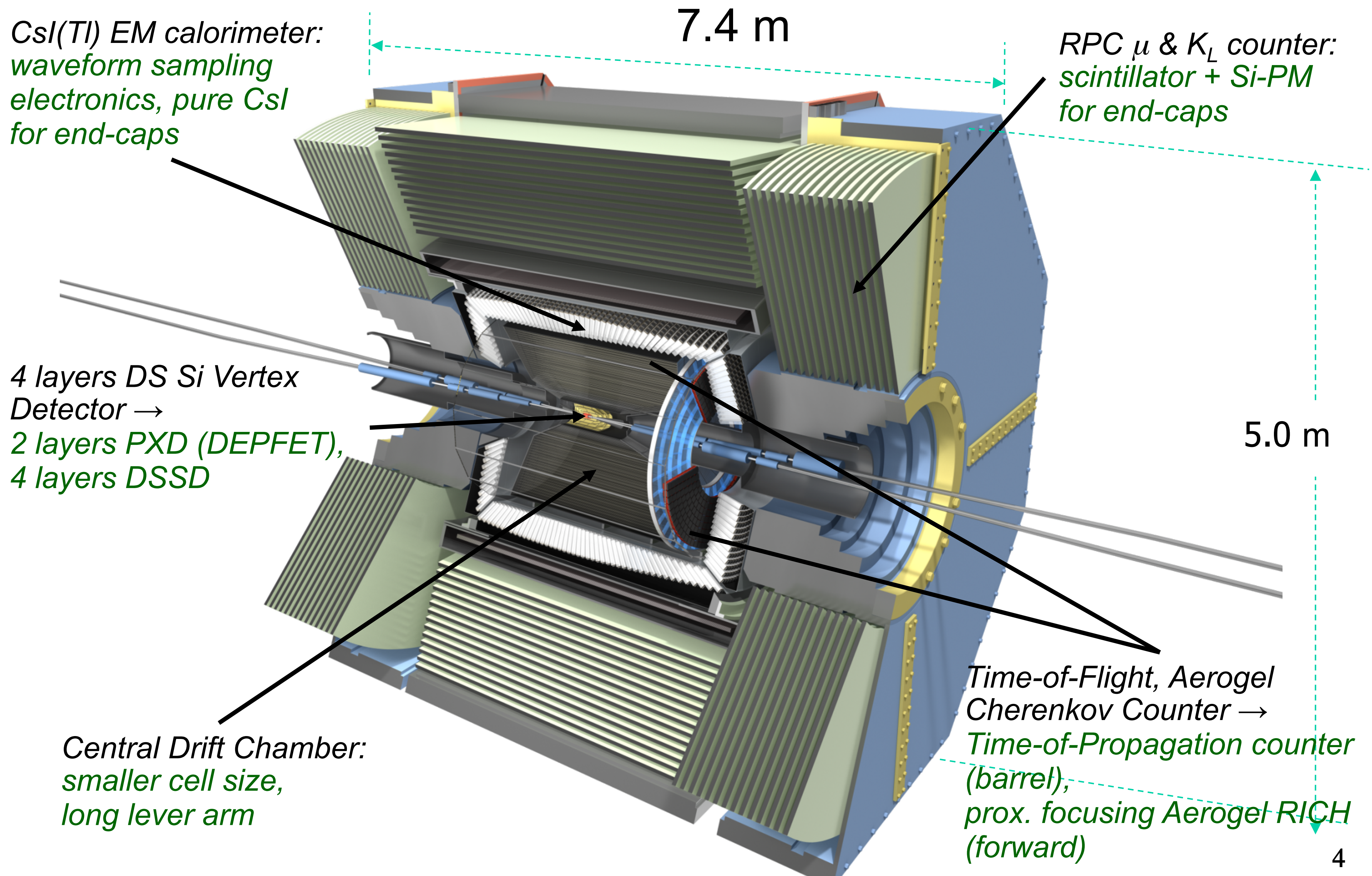
TiN-coated beam pipe with antechambers





To get 40x higher luminosity

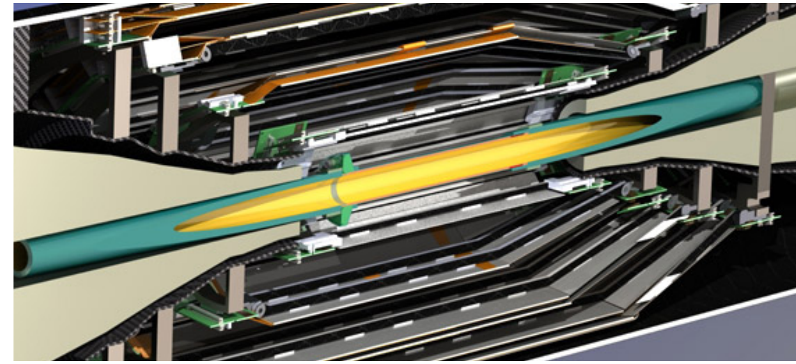
The Belle II Detector

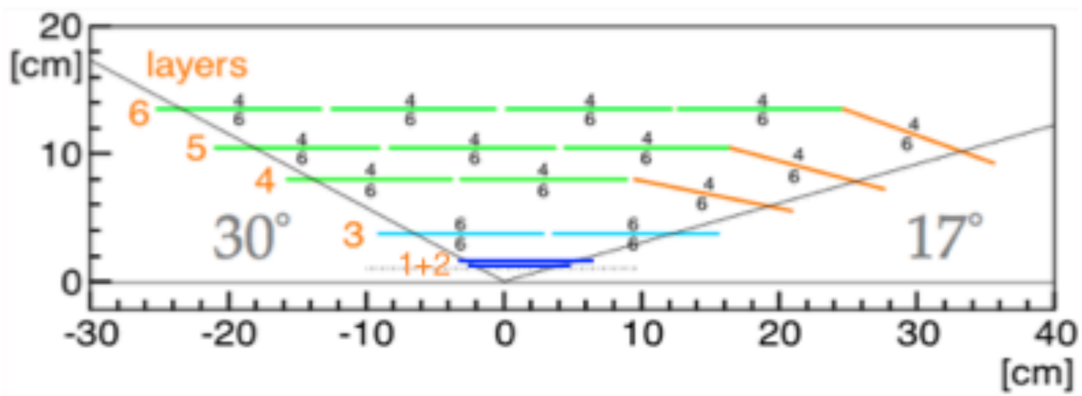


The Belle II Vertex Detector

Two detectors for vertexing:

- *2 layers of DEPFET pixels*
- *4 layer of silicon strips*





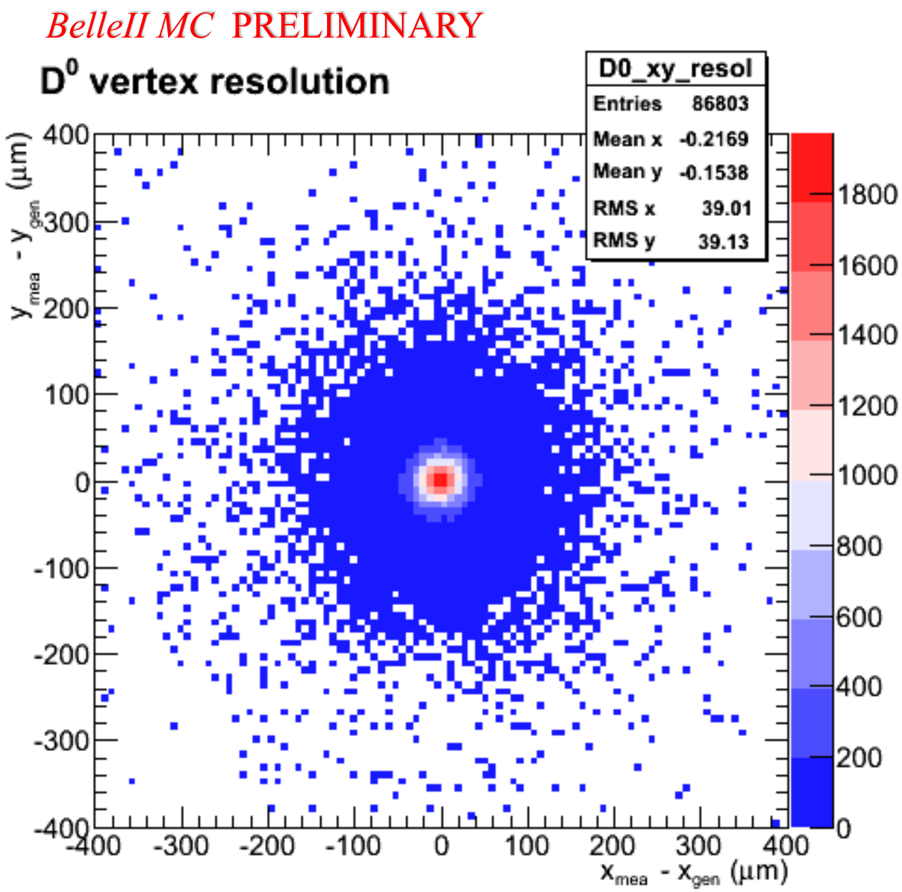
Pixel detector:

	Inner layer (L1)	Outer layer (L2)
# modules	2 x 8	2 x 12
distance from IP (cm)	1.4	2.2
thickness (μm)	75	75
total # pixels	3.072×10^6	4.608×10^6
pixel size (μm^2)	55, 60 x 50	70, 85 x 50
sensitive area (mm^2)	44.8 x 12.5	61.44 x 12.5

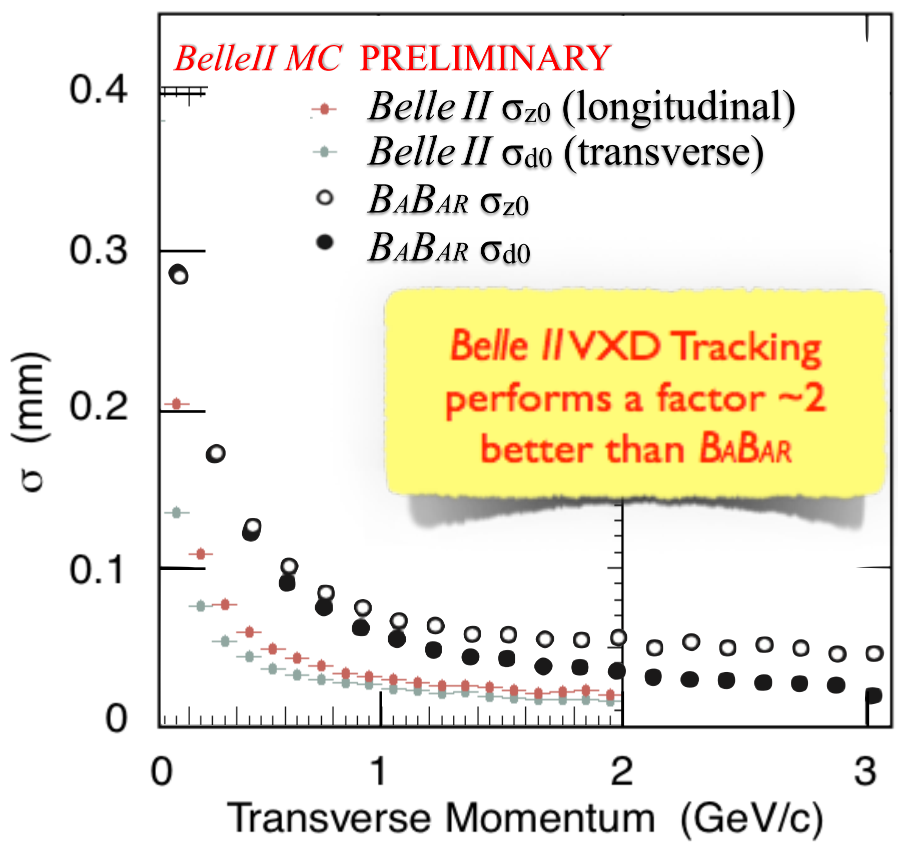
Silicon strip detector:

layer	type	readout strip(p/r-ϕ)	readout strip(n/z)	strip pitch (p/r-ϕ)	strip pitch (n/z)
4,5,6	Large	768	512	75 μm	240 μm
4,5,6 forward	Trapezoidal	768	512	50-75 μm	240 μm
3	Small	768	768	50 μm	160 μm

Belle II Vertex Detector Upgrade



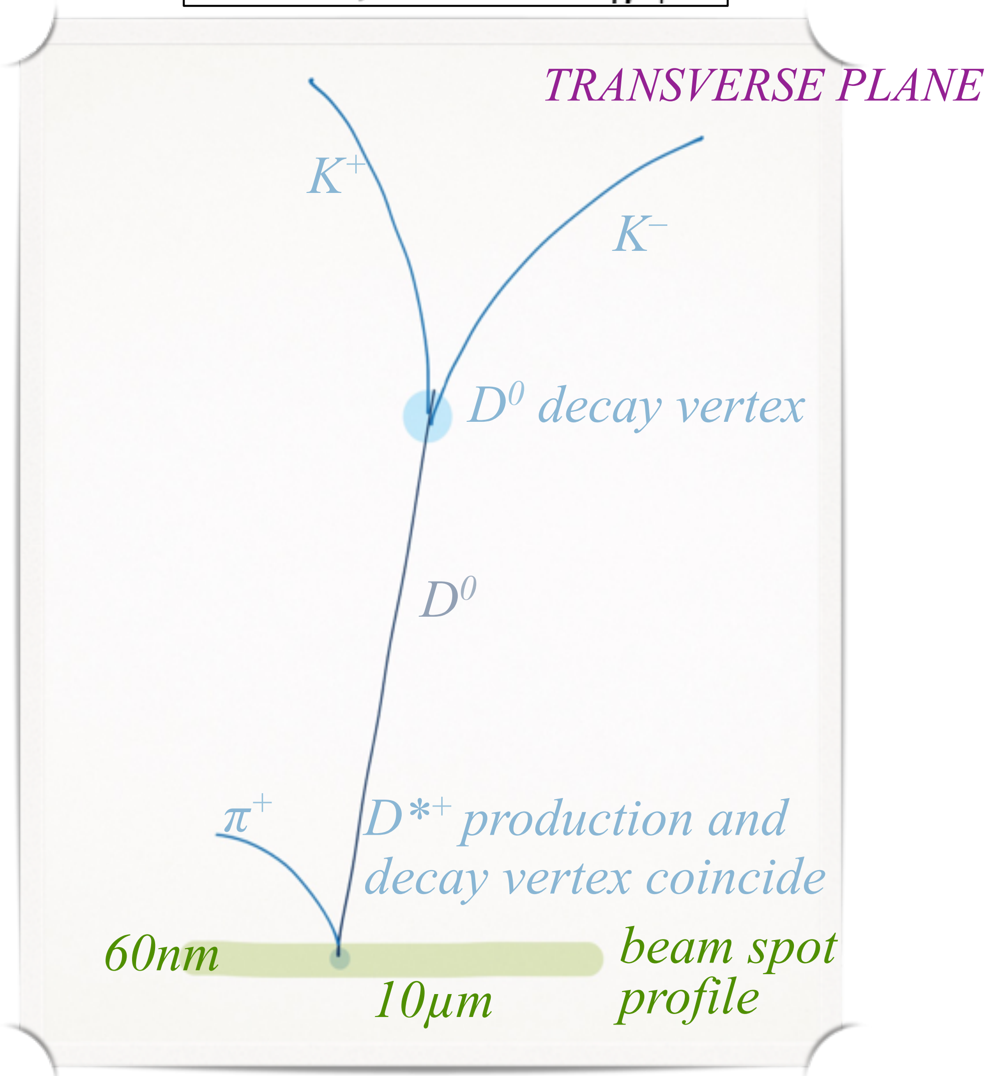
Resolution on track impact parameter w/r/t interaction point (IP):



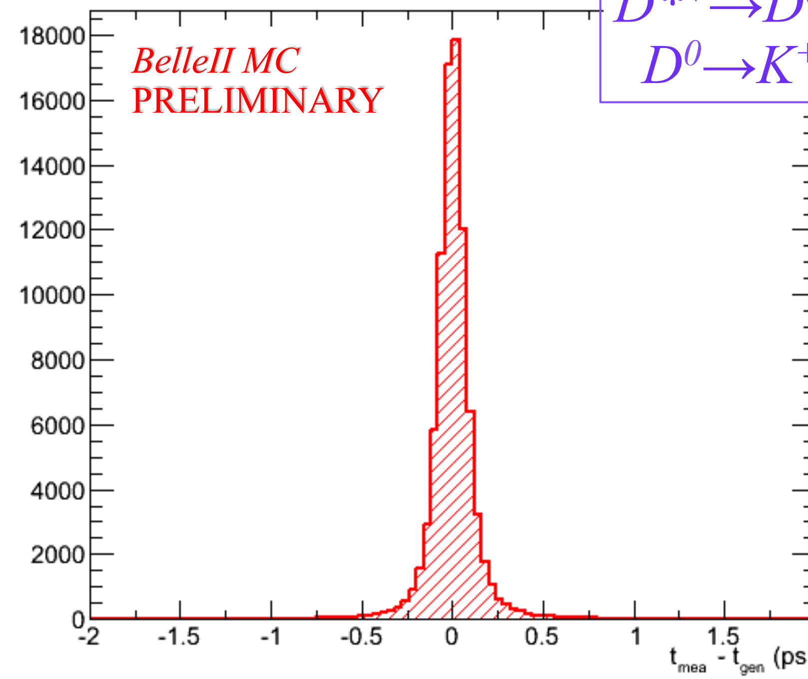
Belle II:
$\sigma \approx 40\ \mu m$

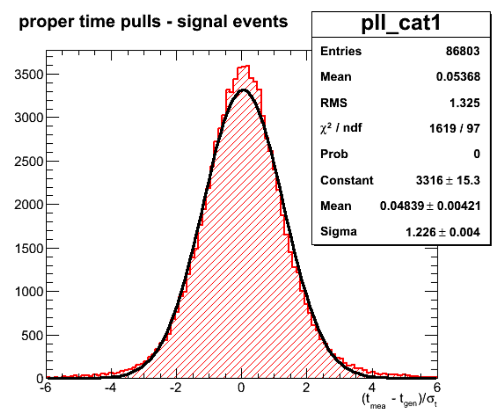
$D^0 \to K^+K^-$ Decay Time Resolution (D^* tag)

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



$D^{*+} \to D^0\pi^+$, $D^0 \to K^+K^-$





⇒

resolution = 0.14 ps
(2x better than Belle/ BaBar (0.27 ps)

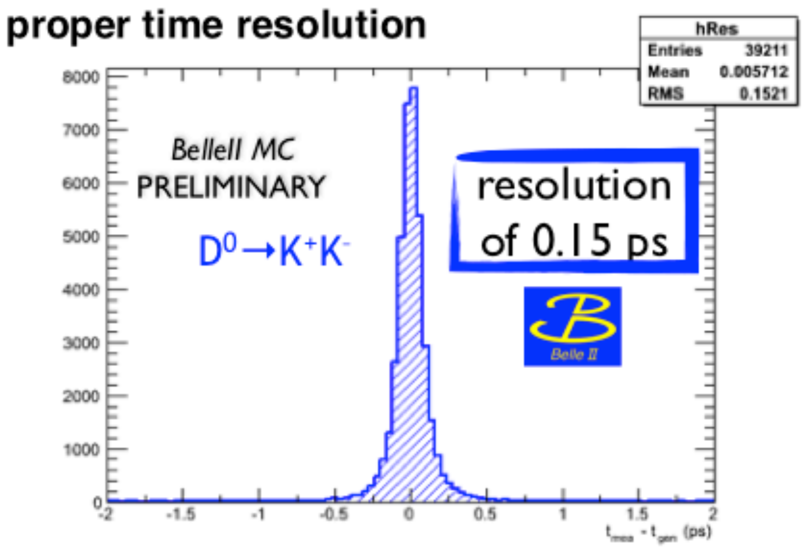
pulls distribution ok

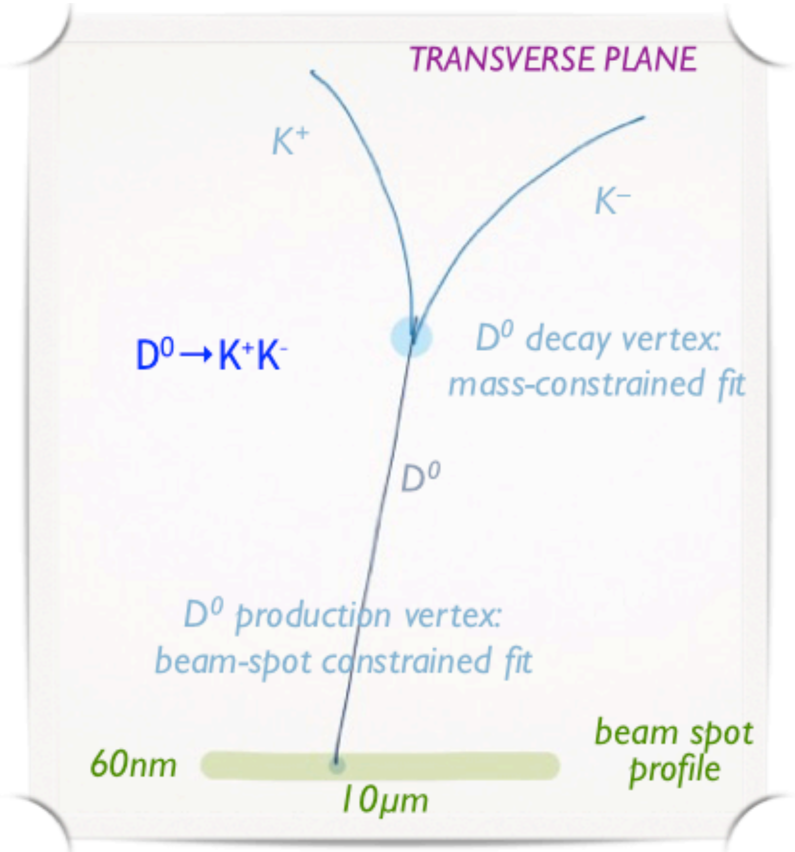
$K\pi$, $\pi\pi$ results similar

$D^0 \to K^+K^-$ Decay Time Resolution (prompt)

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

$e^+e^- \to \bar{D}^0 D^0$,
$D^0 \to K^+K^-$



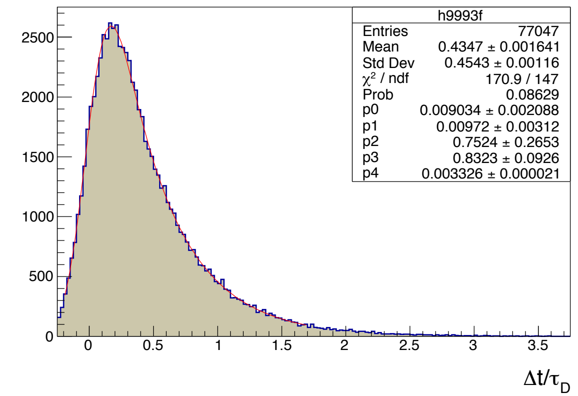


⇒ decay time resolution of prompt D^0 = 0.15 ps
(also excellent)

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

Preliminary

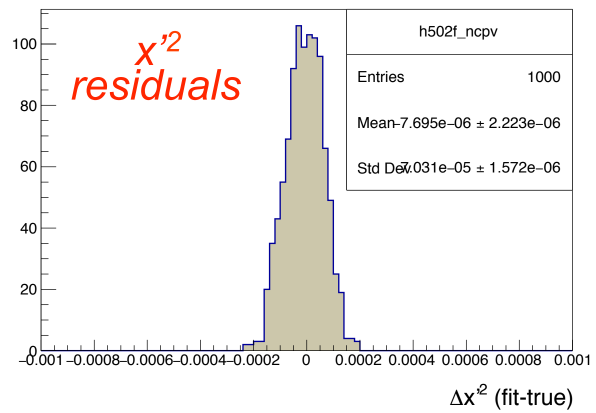
- generate $D^0 \to K^+\pi^-$ decays with mixing (study II: + CPV)
- smear decay time according to resolution $\sigma = 0.14\ ps$
- generate and fit ensembles of 1000 experiments corresponding to 5, 20, 50 ab^{-1} of data)



Toy MC study #1: no CPV

- fit decay time distribution for R_D, x'^2, y'
- use same PDF for D^0 and D^0bar (convolved with Gaussian resolution function)

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

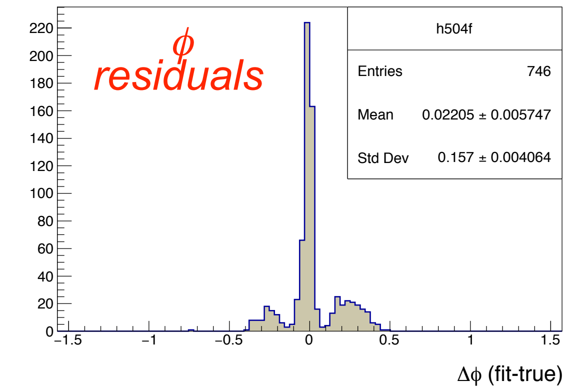


Toy MC study #2: include CPV

- fit decay time distribution for R_D, x', y', $|q/p|$, ϕ
  (note: sensitive to sign of x)
- use different PDFs for D^0 and D^0bar (convolved with the same Gaussian resolution function)

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

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



Effect upon Mixing and CPV Precision

***Toy MC no CPV results** (preliminary):*

	5 ab^{-1}	20 ab^{-1}	50 ab^{-1}
x'^2 (x 10^{-5}) x' (%)	14.4 0.72	7.0 0.35	4.4 0.22
y' (%)	0.156	0.075	0.047

LHCb 3 fb^{-1}

4.3

0.08

competitive for y'?

***Toy MC allowing for CPV results** (preliminary):*

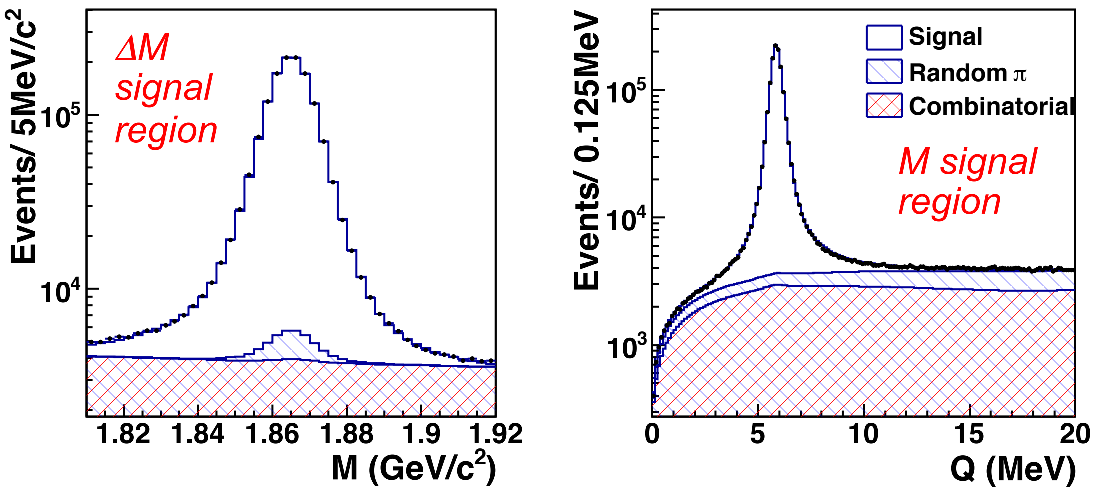
	5 ab^{-1}	20 ab^{-1}	50 ab^{-1}
x' (%)	0.37	0.23	0.15
y' (%)	0.26	0.17	0.10
$\|q/p\|$	0.197	0.089	0.051
ϕ (deg)	15.5	9.2	5.7

Time-dependent $D^0(t) \to K_S \pi^+\pi^-$

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

Fitting the time-dependent Dalitz plot yields x, y, |q/p| and ϕ = Arg(q/p)

- *976 fb^{-1}, full data set*
- *Signal yield determined from 2-dim. fit to $M_{K\pi\pi}$ and $\Delta M = M_{K\pi\pi\pi} - M_{K\pi\pi}$. Yield is 1.2 x 10^6 events with a purity of 96%.*
- *Select events in signal region $|M_{K\pi\pi} - M_D| < 15$ MeV/c^2 and ΔM = (5.75, 5.95) MeV.*
- *For events in signal region, do unbinned ML fit to $m^+ = M(K\pi^+)^2$, $m^- = M(K\pi^-)^2$, and decay time t. Fit parameters are x, y, τ, resolution function parameters (2-3 Gaussians), and decay model: magnitudes and phases of 13 intermediate resonances.*
- *Do fit separately (+ simultaneously) for D^0 and D^0bar samples to obtain |q/p|, ϕ parameters.*



$$R_{D^0} = \frac{e^{-\Gamma t}}{2}\left\{\left(|\mathcal{A}_f|^2 + \left|\frac{q}{p}\right|^2 |\overline{\mathcal{A}}_f|^2\right)\cosh(yt) + \left(|\mathcal{A}_f|^2 - \left|\frac{q}{p}\right|^2 |\overline{\mathcal{A}}_f|^2\right)\cos(xt) + 2\mathrm{Re}\left(\frac{q}{p}\overline{\mathcal{A}}_f\mathcal{A}_f^*\right)\sinh(yt) - 2\mathrm{Im}\left(\frac{q}{p}\overline{\mathcal{A}}_f\mathcal{A}_f^*\right)\sin(xt)\right\}$$

$$R_{\overline{D}^0} = \frac{e^{-\Gamma t}}{2}\left\{\left(|\overline{\mathcal{A}}_f|^2 + \left|\frac{p}{q}\right|^2 |\mathcal{A}_f|^2\right)\cosh(yt) + \left(|\overline{\mathcal{A}}_f|^2 - \left|\frac{p}{q}\right|^2 |\mathcal{A}_f|^2\right)\cos(xt) + 2\mathrm{Re}\left(\frac{p}{q}\mathcal{A}_f\overline{\mathcal{A}}_f^*\right)\sinh(yt) - 2\mathrm{Im}\left(\frac{p}{q}\mathcal{A}_f\overline{\mathcal{A}}_f^*\right)\sin(xt)\right\}$$

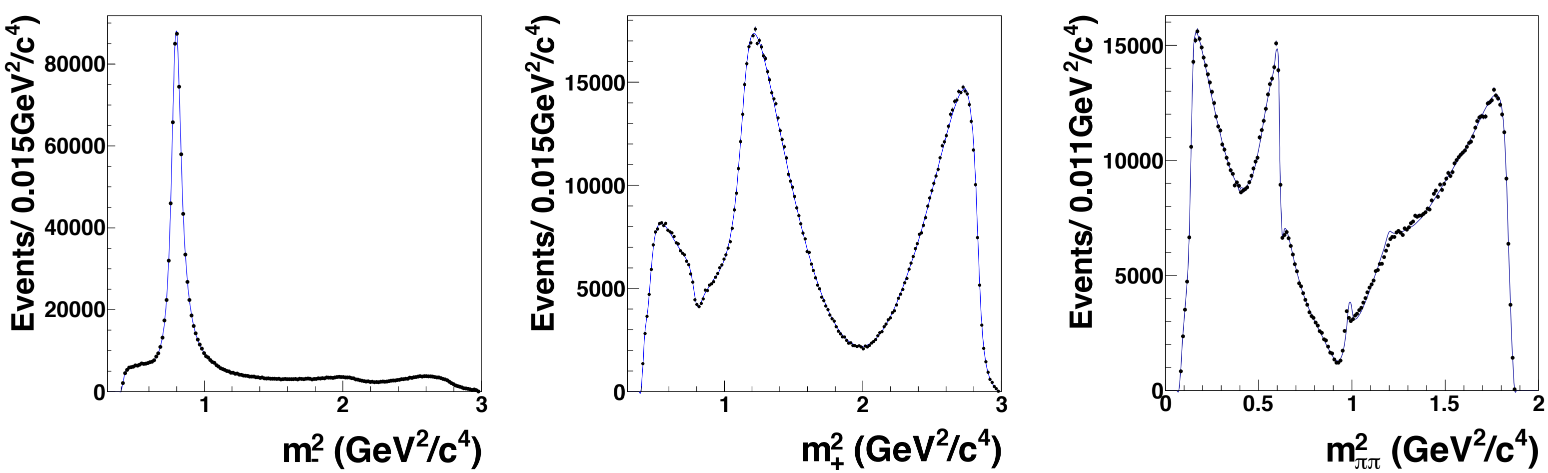
$$\text{If no } CPV: \quad \mathcal{A}_f(m_+^2, m_-^2) = \overline{\mathcal{A}}_f(m_-^2, m_+^2)$$

$D^0(t) \to K_S \pi^+ \pi^-$: time-dependent Dalitz plot fit

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K_0^*(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702
$K_2^*(1430)^-$	1.150 ± 0.009	-41.5 ± 0.4	0.0221
$K^*(1410)^-$	0.496 ± 0.011	83.4 ± 0.9	0.0026
$K^*(1680)^-$	1.556 ± 0.097	-83.2 ± 1.2	0.0016
$K^*(892)^+$	0.139 ± 0.002	-42.1 ± 0.7	0.0046
$K_0^*(1430)^+$	0.176 ± 0.007	-102.3 ± 2.1	0.0005
$K_2^*(1430)^+$	0.077 ± 0.007	-32.2 ± 4.7	0.0001
$K^*(1410)^+$	0.248 ± 0.010	-145.7 ± 2.9	0.0007
$K^*(1680)^+$	1.407 ± 0.053	86.1 ± 2.7	0.0013
$\rho(770)$	1 (fixed)	0 (fixed)	0.2000
$\omega(782)$	0.0370 ± 0.0004	114.9 ± 0.6	0.0057
$f_2(1270)$	1.300 ± 0.013	-31.6 ± 0.5	0.0141
$\rho(1450)$	0.532 ± 0.027	80.8 ± 2.1	0.0012

Resonance	Amplitude	Phase (deg
$\pi\pi$ S-wave		
β_1	4.23 ± 0.02	$164.0 \pm 0.$
β_2	10.90 ± 0.02	15.6 ± 0.2
β_3	37.4 ± 0.3	3.3 ± 0.4
β_4	14.7 ± 0.1	-8.9 ± 0.3
f_{11}^{prod}	12.76 ± 0.05	$-161.1 \pm 0.$
f_{12}^{prod}	14.2 ± 0.2	$-176.2 \pm 0.$
f_{13}^{prod}	10.0 ± 0.5	$-124.7 \pm 2.$
$K\pi$ S-wave	**Parameters**	
$M(MeV/c^2)$	1461.7 ± 0.8	
$\Gamma(MeV/c^2)$	268.3 ± 1.1	
F	0.4524 ± 0.005	
$\phi_F(rad)$	0.248 ± 0.003	
R	1(fixed)	

Fit projections:
(fitted function describes the data well)



Mixing/CPV Precision for $D^0 \to K_S \pi^+\pi^-$

	Observable	Statistical	Systematic red.	Systematic irred.	Total	LHCb 3 fb^{-1} (arXiv:1208.3355)	LHCb 1 fb^{-1} (JHEP 1604, 033)
x	$x^{K_S\pi^+\pi^-}$ $[10^{-2}]$						
	976 fb^{-1}	0.19	0.06	0.11	0.20		
	50 ab^{-1}	0.03	0.01	0.11	0.11	0.2	0.6
$\|q/p\|$	$\|q/p\|^{K_S\pi^+\pi^-}$ $[10^{-2}]$						
	976 fb^{-1}	15.5	5.2-5.6	7.0-6.7	17.8		
	50 ab^{-1}	2.2	0.7-0.8	7.0-6.7	7.0-7.4	20	-
y	$y^{K_S\pi^+\pi^-}$ $[10^{-2}]$						
	976 fb^{-1}	0.15	0.06	0.04	0.16		
	50 ab^{-1}	0.02	0.01	0.04	0.05	0.2	0.5
ϕ	$\phi^{K_S\pi^+\pi^-}$ $[°]$						
	976 fb^{-1}	10.7	4.4-4.5	3.8-3.7	12.2		
	50 ab^{-1}	1.5	0.6	3.8-3.7	4.0-4.2	15	-

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

- *irreducible systematics related to Dalitz plot model; this will improve with model-independent approach (using BESIII binned phases)*
- *improvement in proper time resolution not included here*

D^0-$\bar{D}^0$ mixing and CPV

Earlier Estimated Uncertaintes *(M. Staric, KEK FFW14)*:

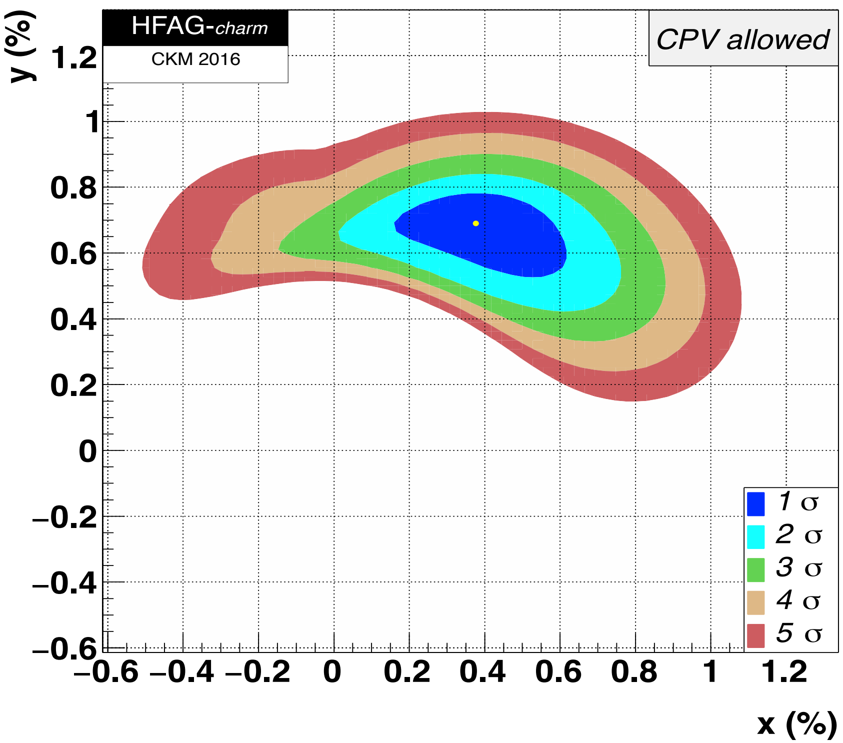
Analysis	Observable	Uncertainty (%)	
		Now ($\sim$1 ab^{-1})	$\mathcal{L}$ = 50 ab^{-1}
$K_S^0\pi^+\pi^-$	x	0.21	0.08
	y	0.17	0.05
	$\lvert q/p\rvert$	18	6
	ϕ	0.21 rad	*(4°)* 0.07 rad
$\pi^+\pi^-$, K^+K^-	y_{CP}	0.25	0.04
	A_Γ	0.22	0.03
$K^+\pi^-$	x'^2	0.025	0.003
	y'	0.45	0.04
	$\lvert q/p\rvert$	0.6	0.06
	ϕ	0.44	*(2.2°)* 0.04 rad

NOTE: *does not include improvement in decay time resolution*

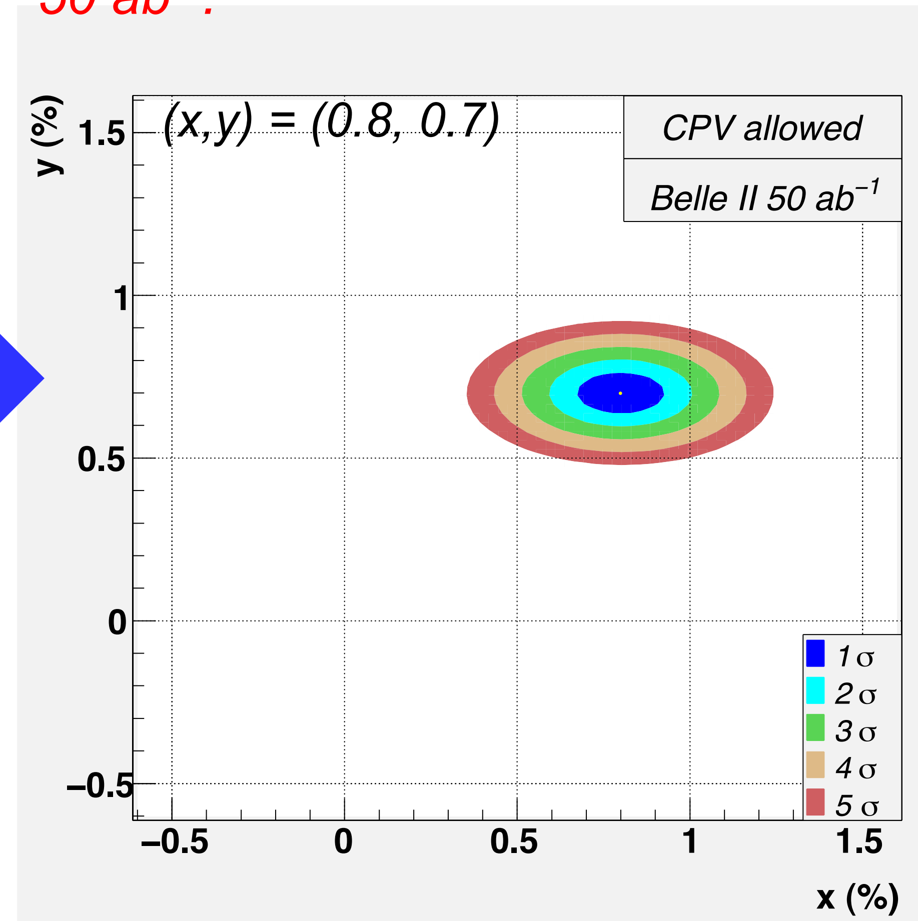
Note: *statistical error and some systematics scale by luminosity, but other systematics do not.*

Mixing Constraints in the D^0-$\bar{D}^0$ system

Inserting these errors for y_{CP}, A_Γ, x'^2, y', and $K_S\pi^+\pi^-$ observables into the HFAG global fit:



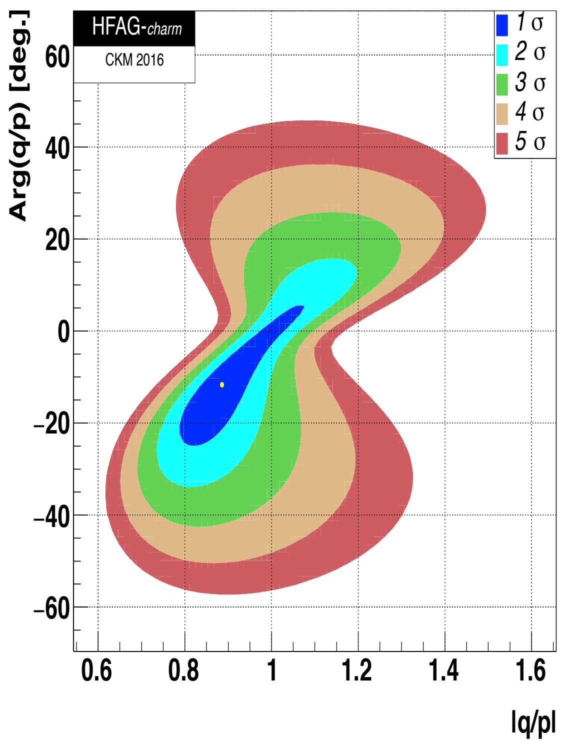
50 ab^{-1}:



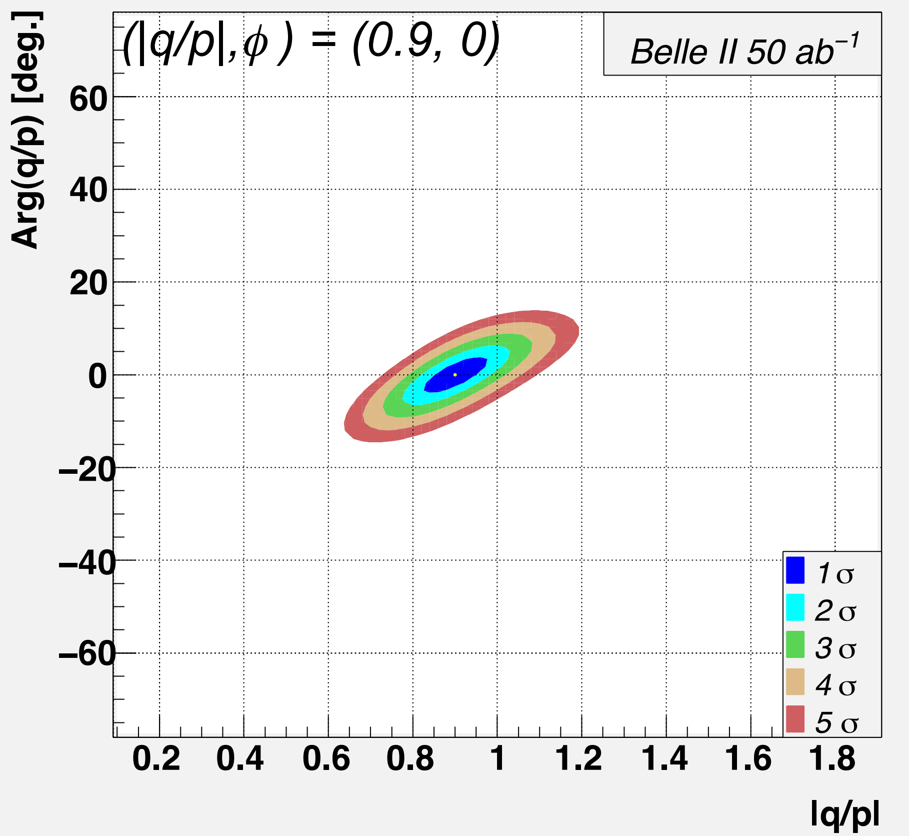
Current measurements of x, y give many constraints on NP models
[see Golowich et al., PRD76, 095009 (2007); 21 models considered, e.g., 2-Higgs doublets, left-right models, little Higgs, extra dimensions, of which 17 give constraints]

CPV Constraints in the D^0-$\bar{D}^0$ system

Now:



50 ab^{-1}:



Note: LHCb will dominate most of these measurements, but Belle II should be competitive in y_{CP} and possibly in x'^2, y', $|q/p|$, ϕ (see Staric, KEK FFW14). *If LHCb sees new physics, it would be important for Belle II to independently confirm.*

Mixing/CPV Precision for $D^0 \to K^+ \pi^- \pi^0$

[Longki Li, USTC]

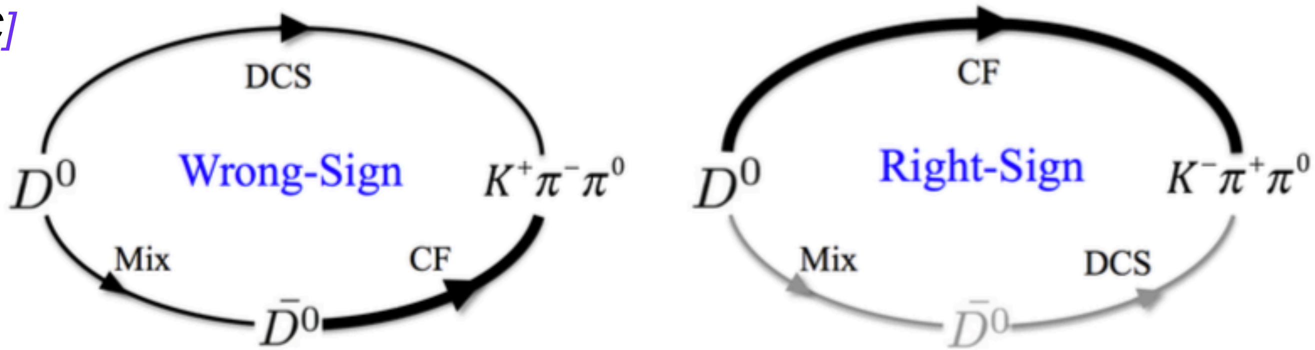


Fig. 1. WS decay(left) through the DCS process and the mixing followed by CF process, and RS decay(right) through the CF process and the mixing followed by DCS process.

$$x'' = x\cdot\cos\delta_{K\pi\pi^0} + y\cdot\sin\delta_{K\pi\pi^0}, \qquad \mathcal{A}_{\bar{f}}(m^2_{K^+\pi^-}, m^2_{\pi^-\pi^0}) = r_0\cdot\mathcal{A}^{DCS}_{\bar{f}}(m^2_{K^+\pi^-}, m^2_{\pi^-\pi^0}),$$

$$y'' = y\cdot\cos\delta_{K\pi\pi^0} - x\cdot\sin\delta_{K\pi\pi^0} \qquad \bar{\mathcal{A}}_{\bar{f}}(m^2_{K^+\pi^-}, m^2_{\pi^-\pi^0}) = \bar{\mathcal{A}}^{CF}_{\bar{f}}(m^2_{K^+\pi^-}, m^2_{\pi^-\pi^0}).$$

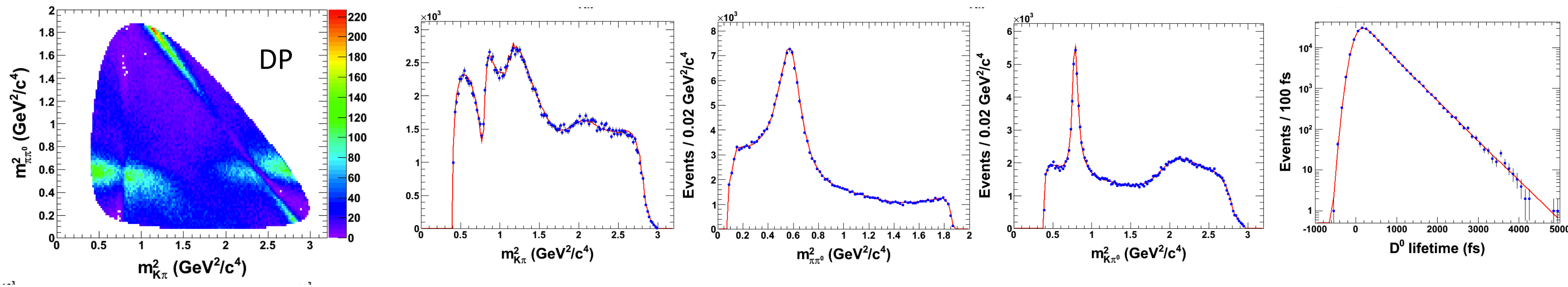
$$|\mathcal{M}(\bar{f},t)|^2 = e^{-\Gamma t}\left\{r_0^2\cdot|\mathcal{A}^{DCS}_{\bar{f}}|^2 + \frac{x''^2+y''^2}{4}|\bar{\mathcal{A}}^{CF}_{\bar{f}}|^2(\Gamma t)^2 - r_0\cdot[y''\,\mathrm{Re}(\mathcal{A}^{DCS}_{\bar{f}}\bar{\mathcal{A}}^{*CF}_{\bar{f}}) + x''\,\mathrm{Im}(\mathcal{A}^{DCS}_{\bar{f}}\bar{\mathcal{A}}^{*CF}_{\bar{f}})]\cdot\Gamma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

$$|\mathcal{M}(\bar{f},t)|^2 = |\mathcal{M}^{DCS}_{\bar{f}}|^2\, e^{-\Gamma t}\otimes_t Res(t) + \frac{x''^2+y''^2}{4}|\bar{\mathcal{M}}^{CF}_{\bar{f}}|^2\frac{1}{r_0^2}\cdot(\Gamma^2t^2\cdot e^{-\Gamma t})\otimes_t Res(t)$$
$$-\frac{1}{r_0}\cdot(y''\cdot\Re[\mathcal{M}^{DCS}_{\bar{f}}\bar{\mathcal{M}}^{*CF}_{\bar{f}}] - x''\cdot\Im[\mathcal{M}^{DCS}_{\bar{f}}\bar{\mathcal{M}}^{*CF}_{\bar{f}}])(\Gamma t\cdot e^{-\Gamma t})\otimes_t Res(t)$$

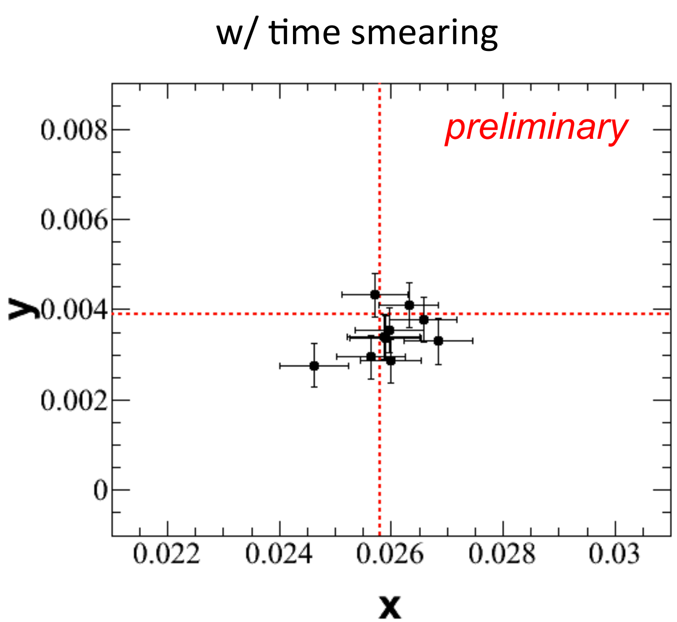
Mixing/CPV Precision for $D^0 \to K^+ \pi^- \pi^0$

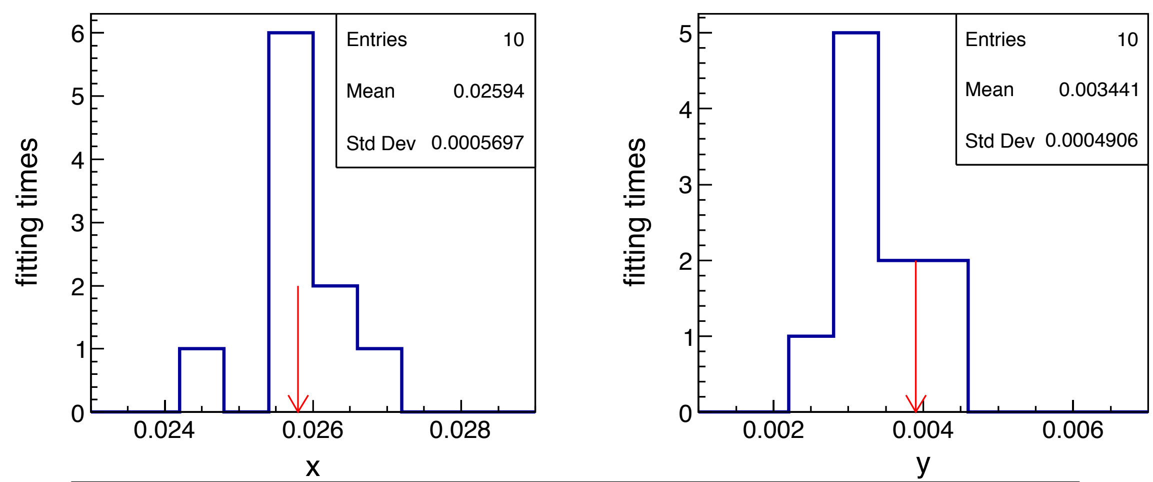
Belle II

[Longki Li, USTC] *Monte Carlo study with 140 fs decay time resolution:*



Ensemble of 10 experiments, decay time resolution =140 fs, x_{in} = 2.5%, y_{in} = 0.4% :





$\Rightarrow$ $\delta x''$ = 0.057% $\delta y''$ = 0.049%
(1 order of magnitude more precise than BaBar)

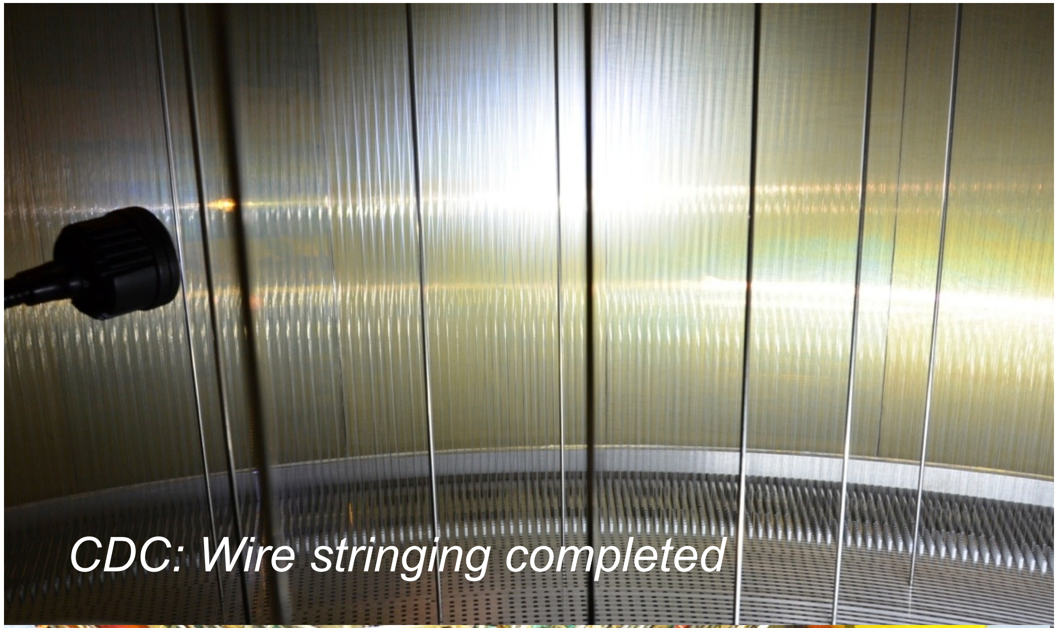
SuperKEKB construction status

Accelerator completed, now circulating beams:

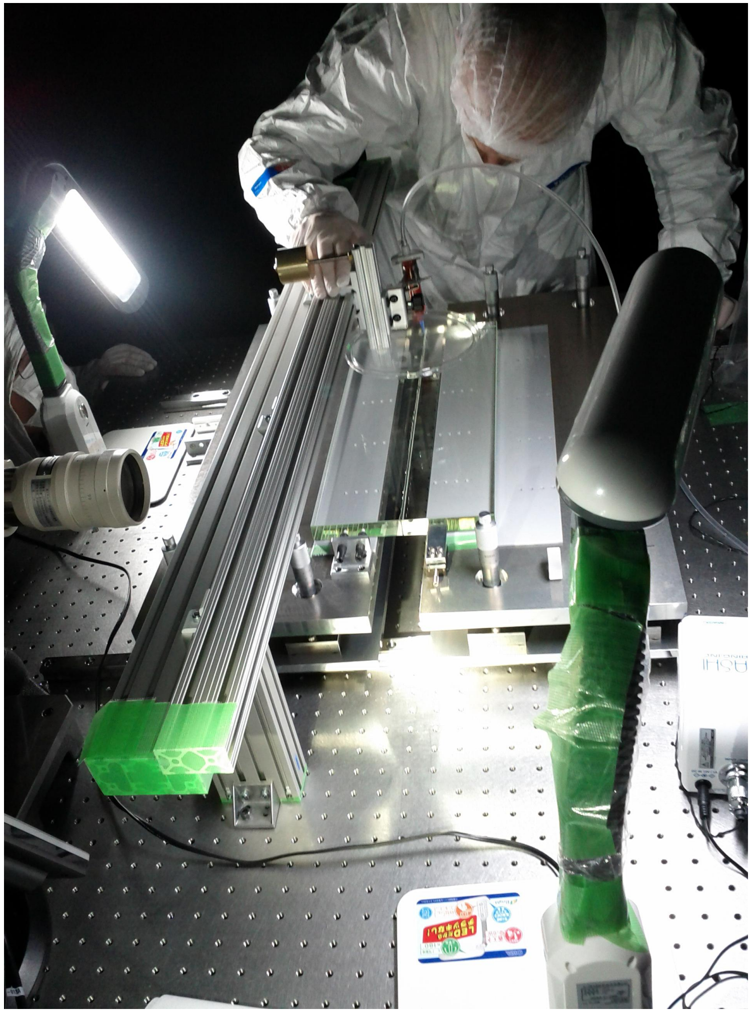
D2(Oho-side)

D1(Nikko-side)

Belle II construction status

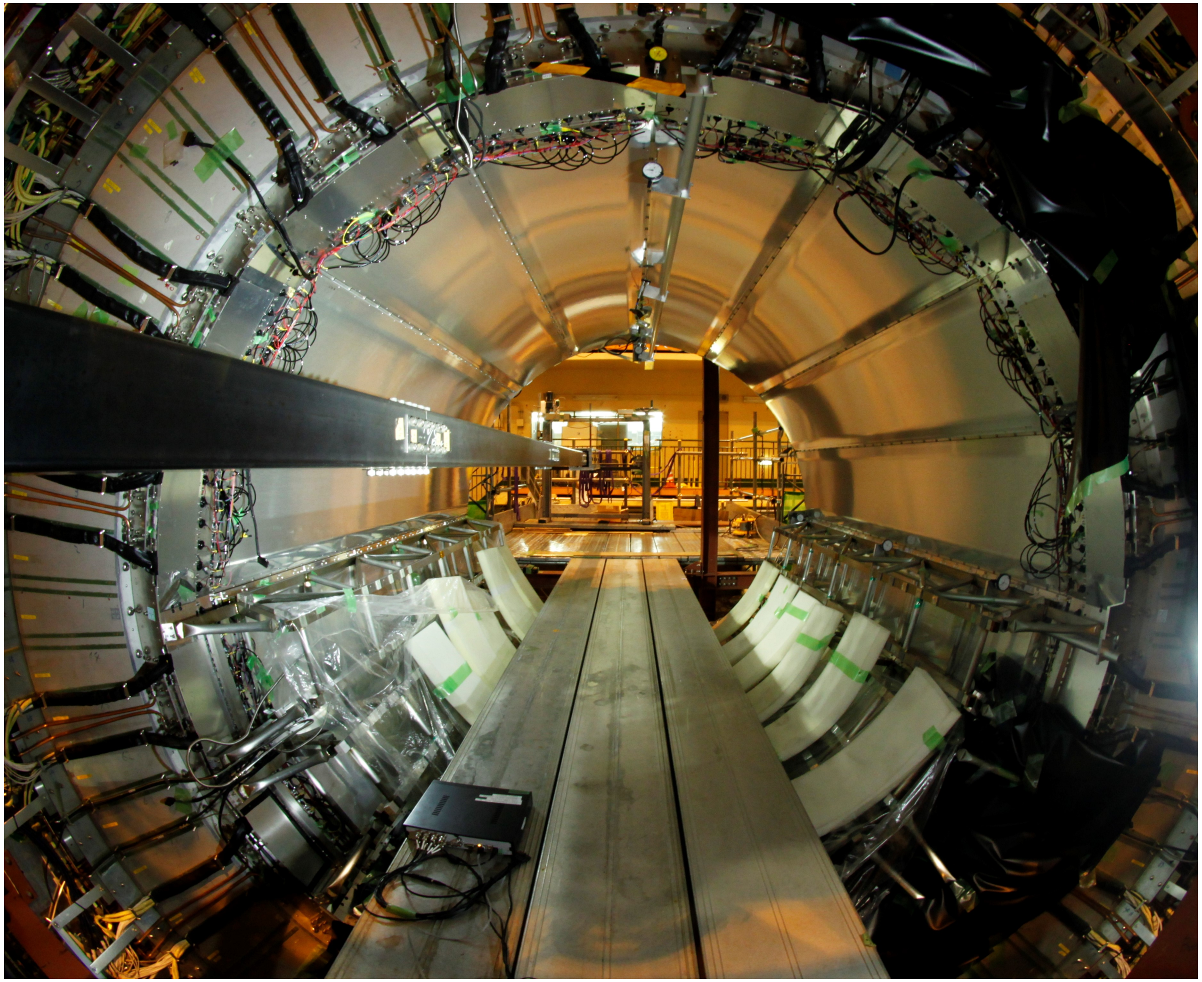


iTOP optics assembly and installation completed



Belle II construction status

iTOP optics assembly and installation completed: (16 modules)

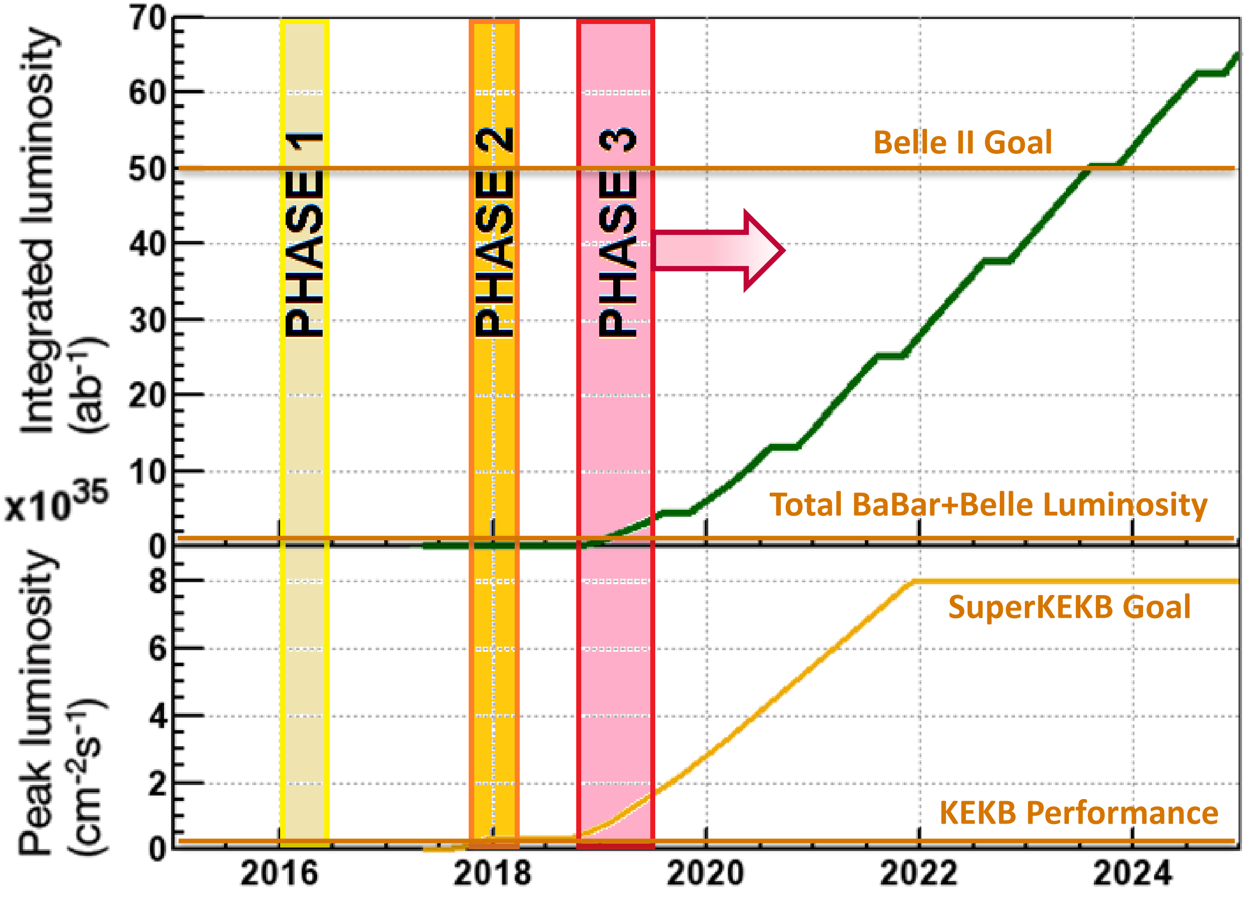


Schedule

Phase 1:
- *accelerator commissioning (now complete)*
- *no detector (under assembly)*

Phase 2 (late 2017):
- *first collisions*
- *partial detector*
- *background study*

Phase 3 (late 2018):
- *full detector (pixels in)*
- *first physics data run*



Summary

- *B factories have proven to be an excellent tool for charm physics, producing a wealth of physics results, having reliable long-term operation, and having constant improvement of performance.*
- *Major upgrade at KEK in 2010-16 → Super B factory: $\mathcal{L}$ x 40 ⇒ 50 ab^{-1}. Essentially a new experiment, most detector components and electronics are replaced.*
- *Belle II will have a rich charm physics program: it should improve precision of mixing/CPV parameters, direct CP asymmetries, precision of V_{cd}, V_{cs} from semileptonic decays, decay constants f_D, f_{Ds}, measurements of charm baryons, much lower limits on rare and forbidden decays, etc. Many final states studied (e.g., those with lepton-ν, π^0, η, η', etc.) will be complementary to those studied at LHCb.*
- *Due to upgraded vertex detector (with pixels), charm decay time resolution is ~half of Belle/Babar value. This notably improves the precision of mixing/CPV parameters.*
- *Detector is now mostly installed, will be completed and fully commissioned in 2017, with first data in 2018.*

How to achieve L~10^{36}? Super-KEKB

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lorentz factor

Beam current

Beam-Beam parameter

Geometrical reduction factors (crossing angle, hourglass effect) ***(0.8-1.0)***

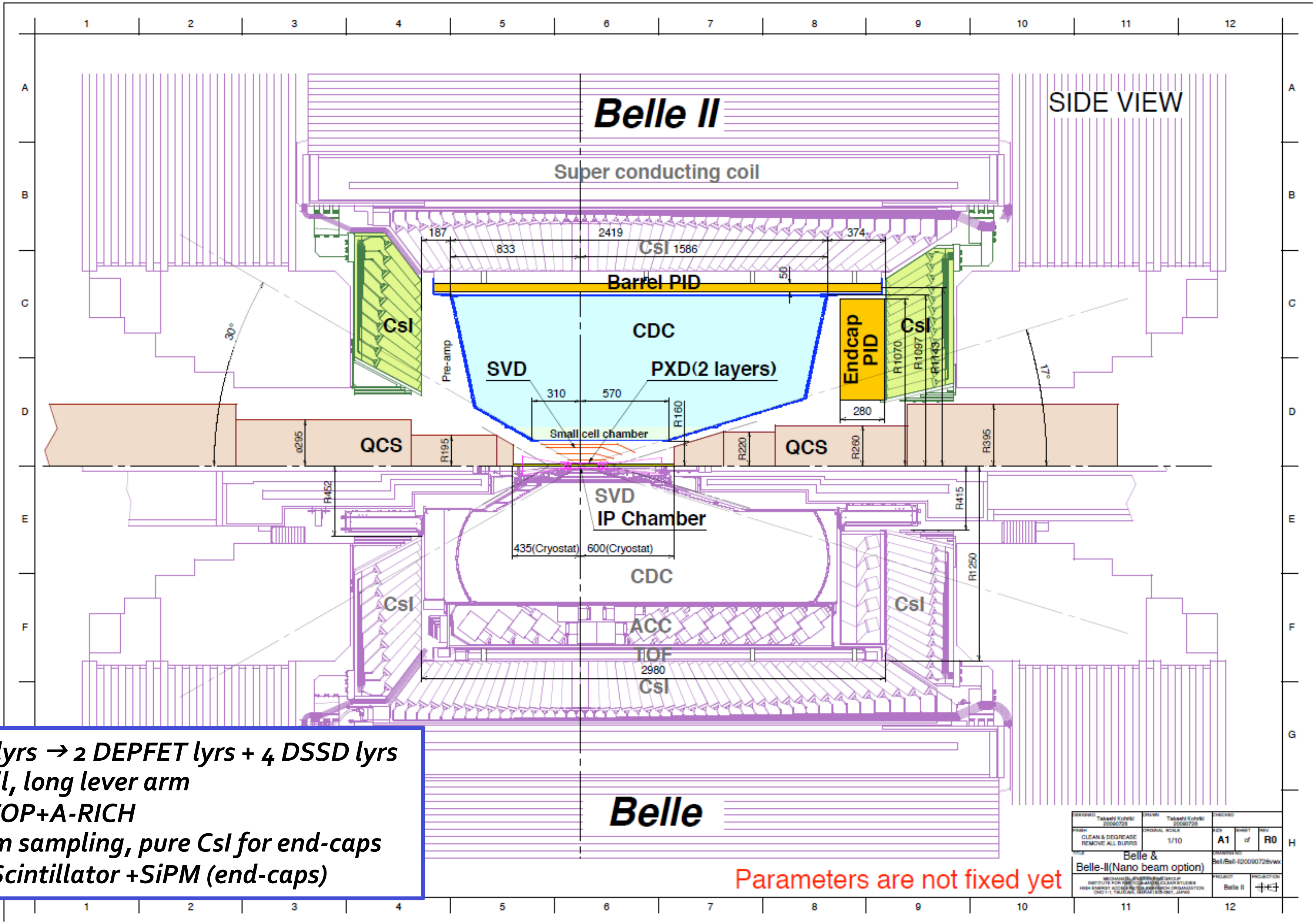
Vertical beta function at IP

Beam aspect ratio at IP ***(0.01-0.02)***

Two options considered:	***I (current) (amps)***	***β_y (mm)***	***ξ***
KEKB achieved	***1.8/1.45***	***6.5/5.9***	***0.11/0.06***
High current	***9.4/4.1***	***3/6***	***0.3/0.51***
Nano-beam ***(Raimondi for SuperB)*** ← chosen	***3.6/2.6***	***0.27/0.30***	***0.09/0.08***

beam size: *100 μm(H) x 2 μm(V) → 10 μm(H) x 59 nm(V)*

Belle II detector compared to Belle



SVD: *4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs*
CDC: *small cell, long lever arm*
ACC+TOF → *TOP+A-RICH*
ECL: *waveform sampling, pure CsI for end-caps*
KLM: RPC → *Scintillator +SiPM (end-caps)*