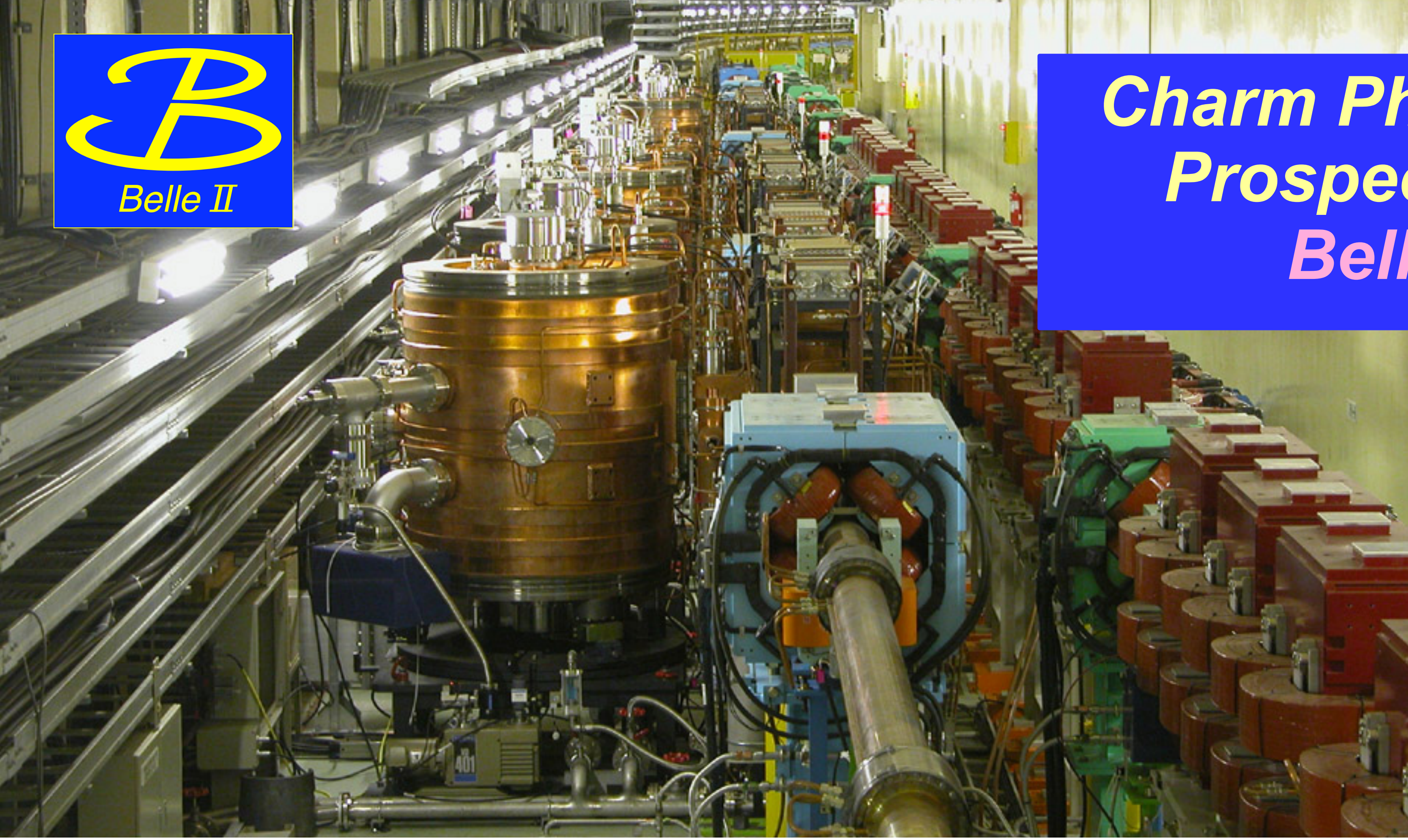

Charm Physics Prospects at Belle II

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University of Cincinnati, USA

VIIIth International Workshop on Charm Physics
Bologna, Italy
9 September 2016

- motivation
- upgrading Belle/KEKB → Super B Factory
- mixing and CPV
- leptonic and rare decays
- detector status and schedule

Motivation

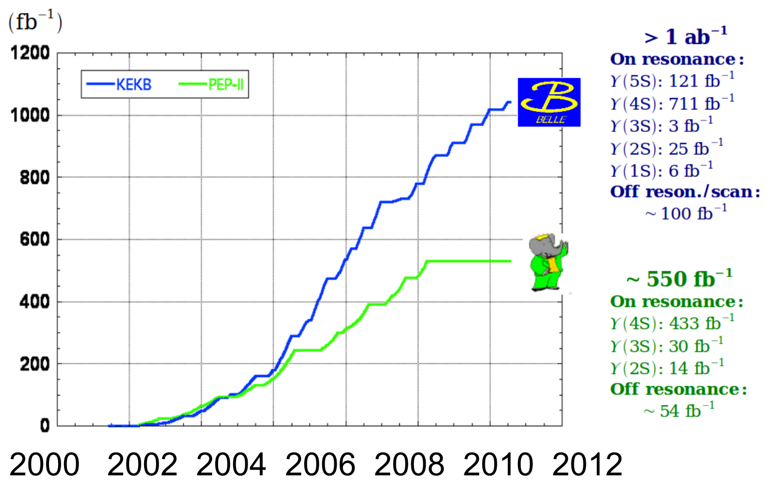
Why an e^+e^- Machine for Charm Physics?

- *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*

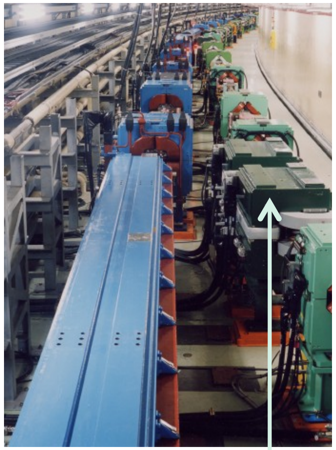
- *Due to low backgrounds, negligible trigger bias, and good kinematic resolutions, Dalitz plots analyses are straightforward. Absolute branching fractions can be measured. Missing energy and missing mass analyses are straightforward.*

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

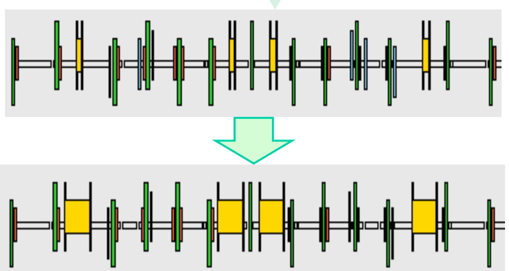
- *Belle II goal: to increase the sampe sizes over what Belle achieved by a factor of 50 (>4 x 10^{10} BB pairs)*



KEKB → SuperKEKB (nano-beam)

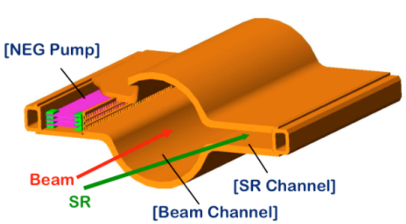


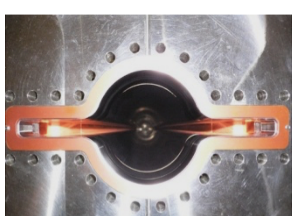
Replace short dipoles with longer ones (LER)

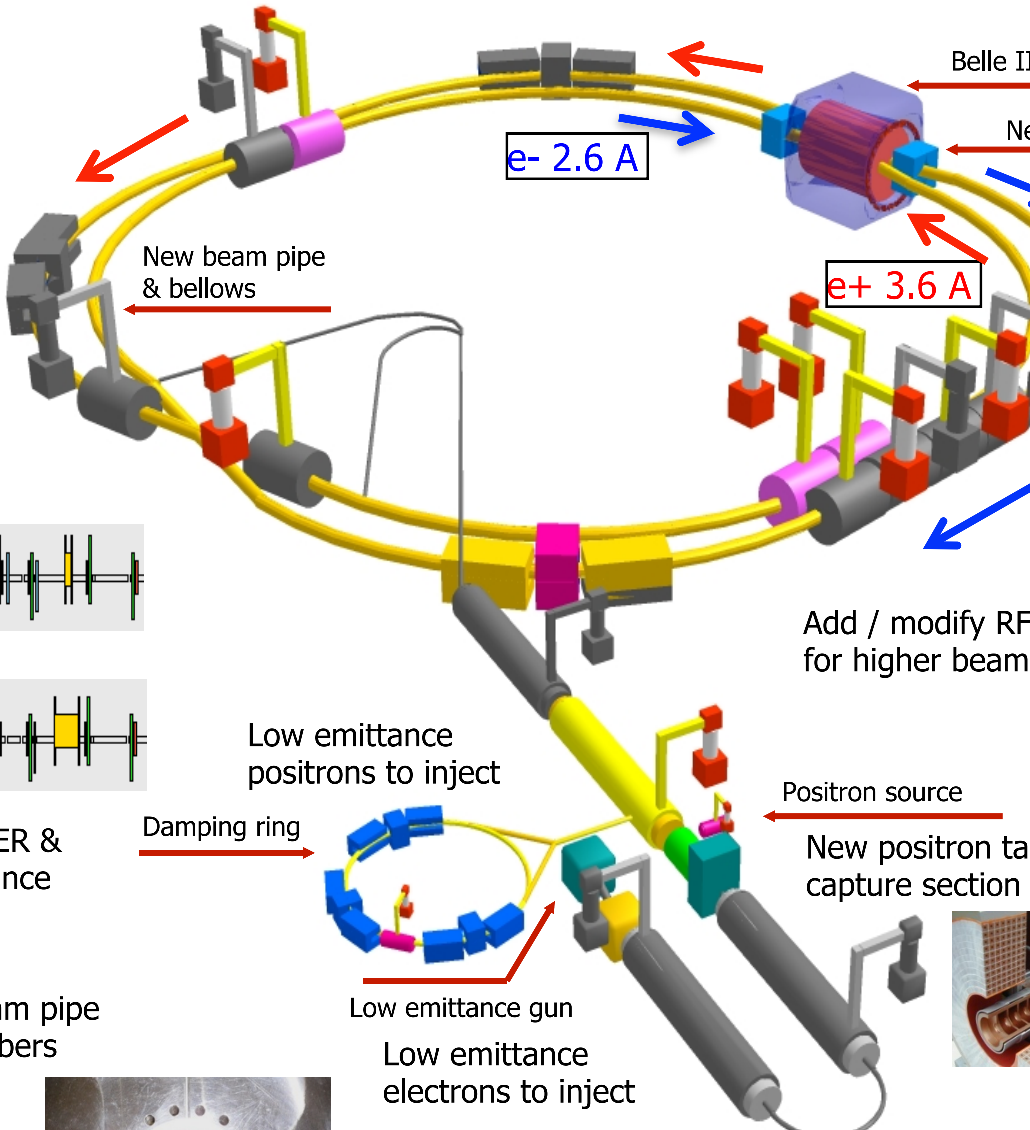


Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers







Belle II

New IR

New beam pipe & bellows

Low emittance positrons to inject

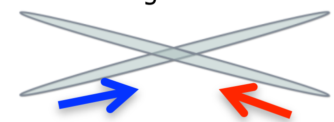
Damping ring

Low emittance gun

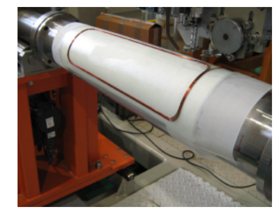
Low emittance electrons to inject

Positron source

Colliding bunches

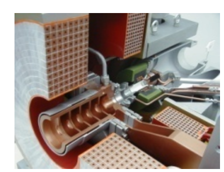


New superconducting / permanent final focusing quads near the IP



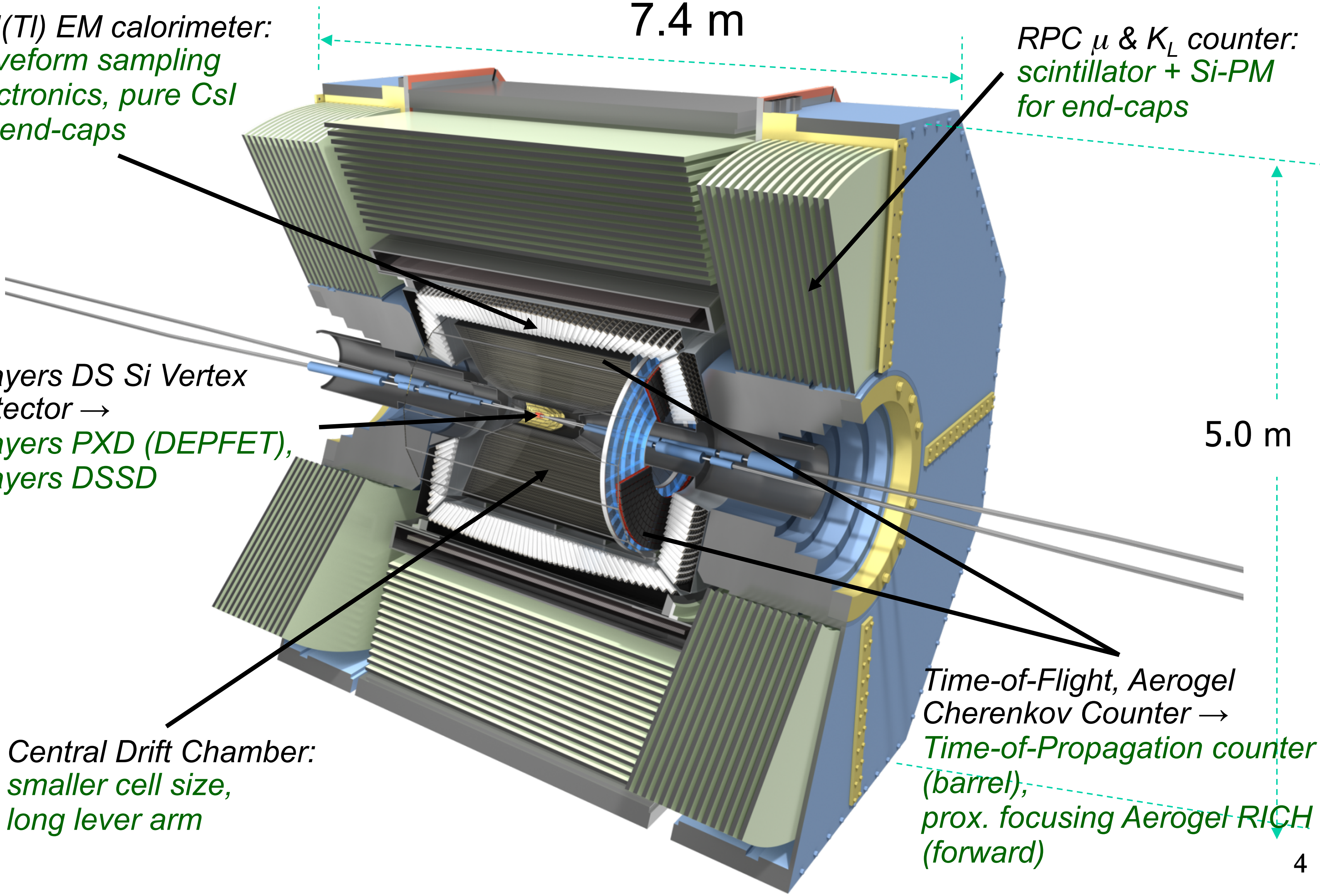
Add / modify RF systems for higher beam current

New positron target / capture section



To get 40x higher luminosity

The Belle II Detector



CsI(Tl) EM calorimeter:
waveform sampling electronics, pure CsI for end-caps

RPC μ & K_L counter:
scintillator + Si-PM for end-caps

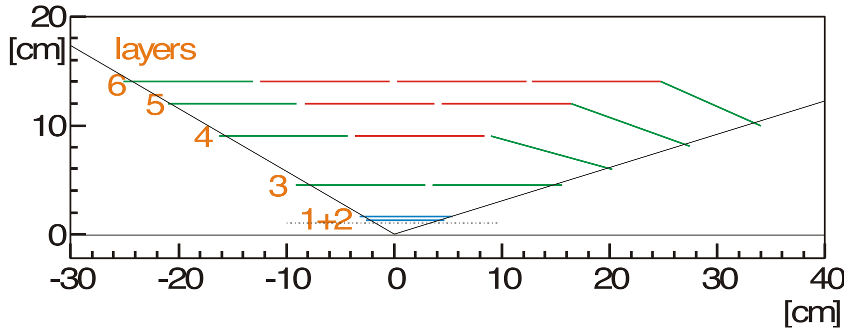
4 layers DS Si Vertex Detector →
2 layers PXD (DEPFET), 4 layers DSSD

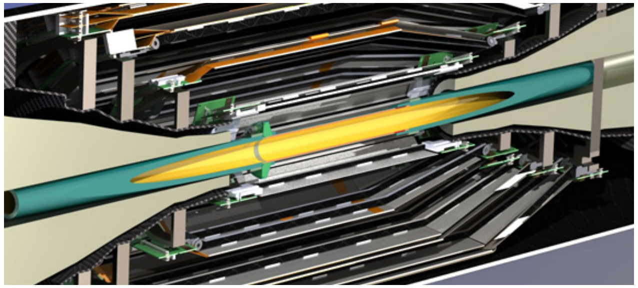
Central Drift Chamber:
smaller cell size, long lever arm

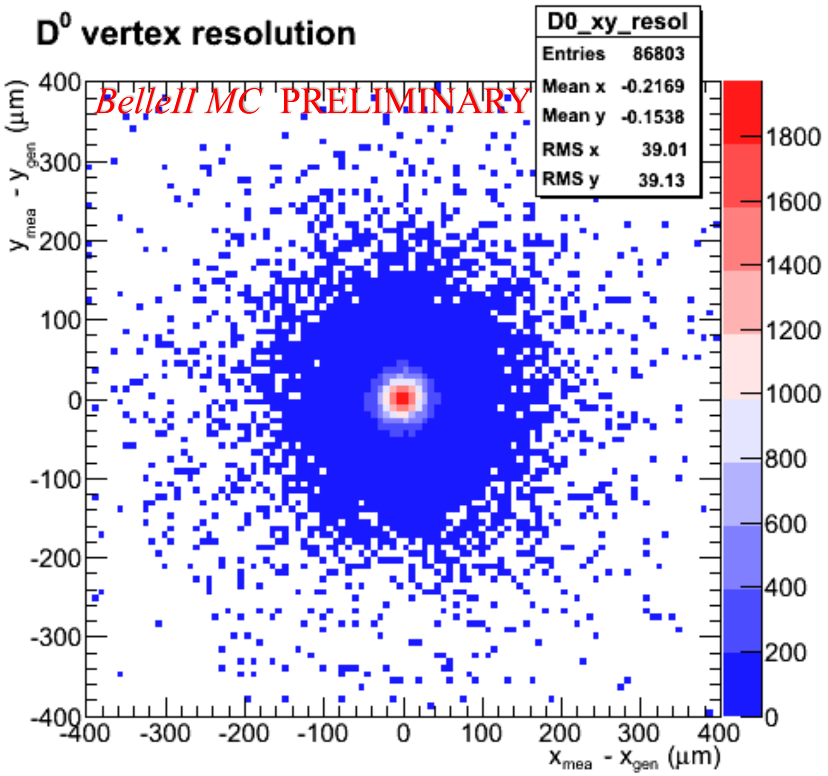
Time-of-Flight, Aerogel Cherenkov Counter →
Time-of-Propagation counter (barrel),
prox. focusing Aerogel RICH (forward)

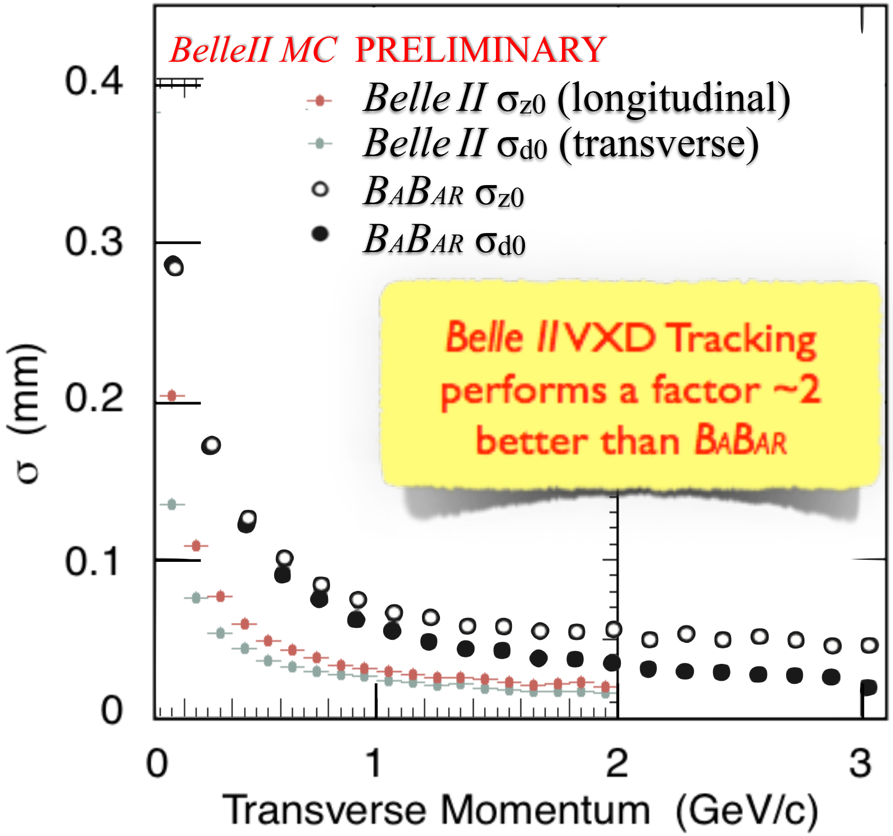
Belle II Vertex Detector Upgrade

Vertex detector:
double layer of DEPFET pixels + 4 layers DS Si strips





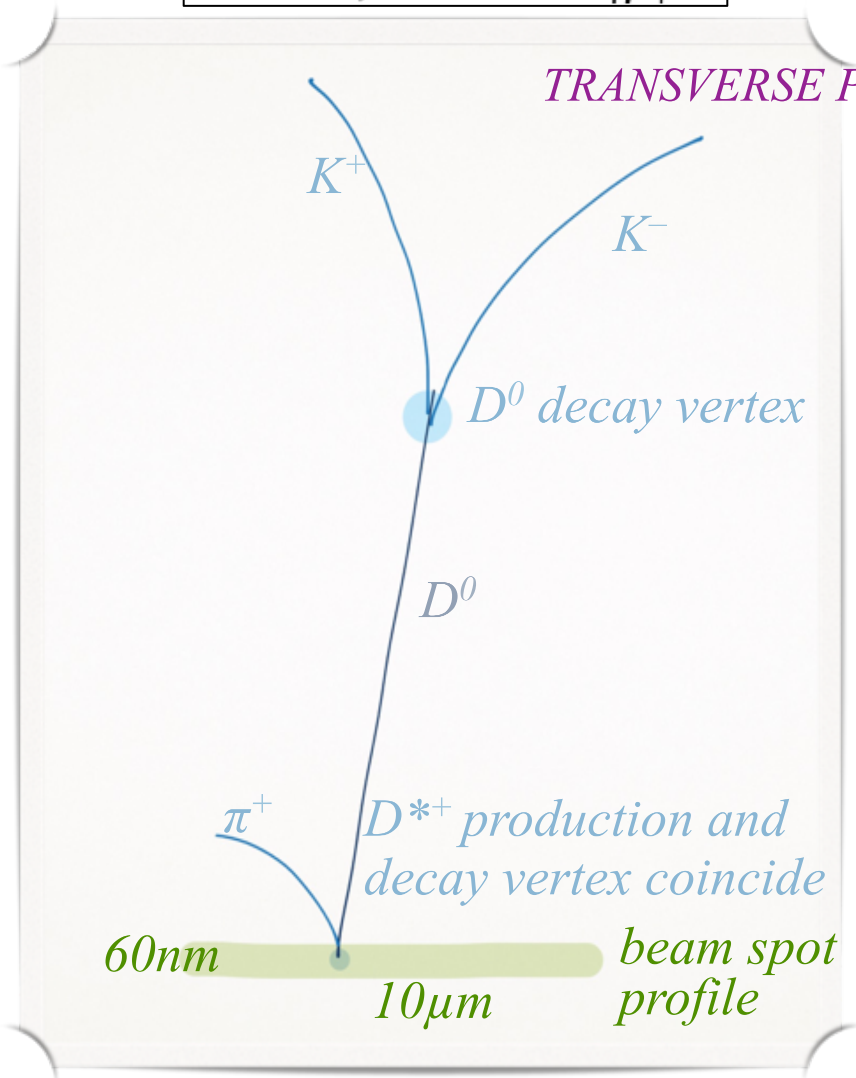




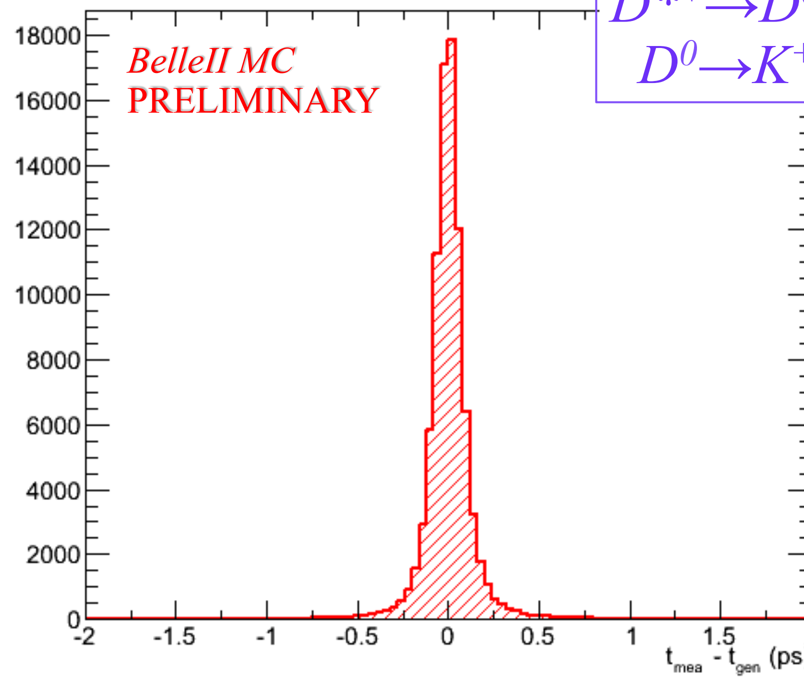
Belle II: $\sigma \approx 40\ \mu m$

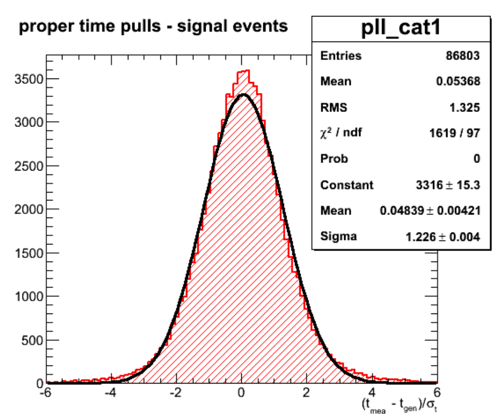
$D^0 \to K^+K^-$ Decay Time Resolution

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



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





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

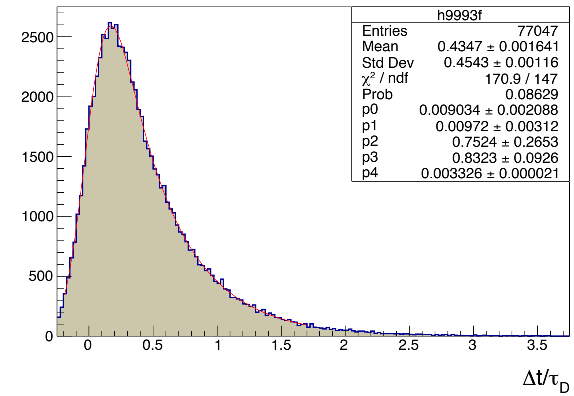
pulls distribution ok

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

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

- *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)*

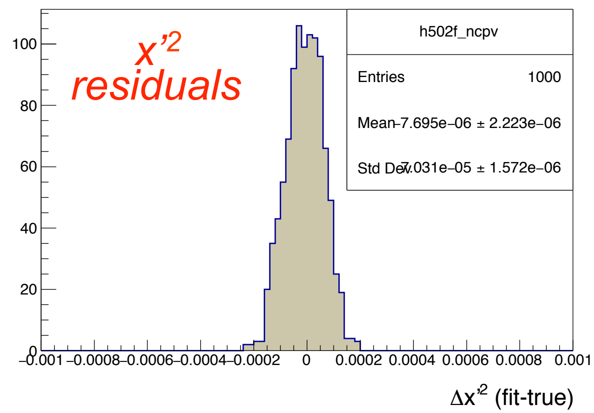
Preliminary



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)*

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

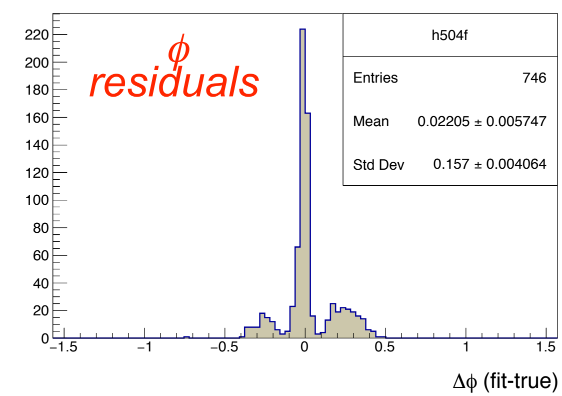


Toy MC study #2: include CPV

- *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 ($\times 10^{-5}$) 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
$\lvert q/p \rvert$	0.197	0.089	0.051
ϕ (deg)	15.5	9.2	5.7

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

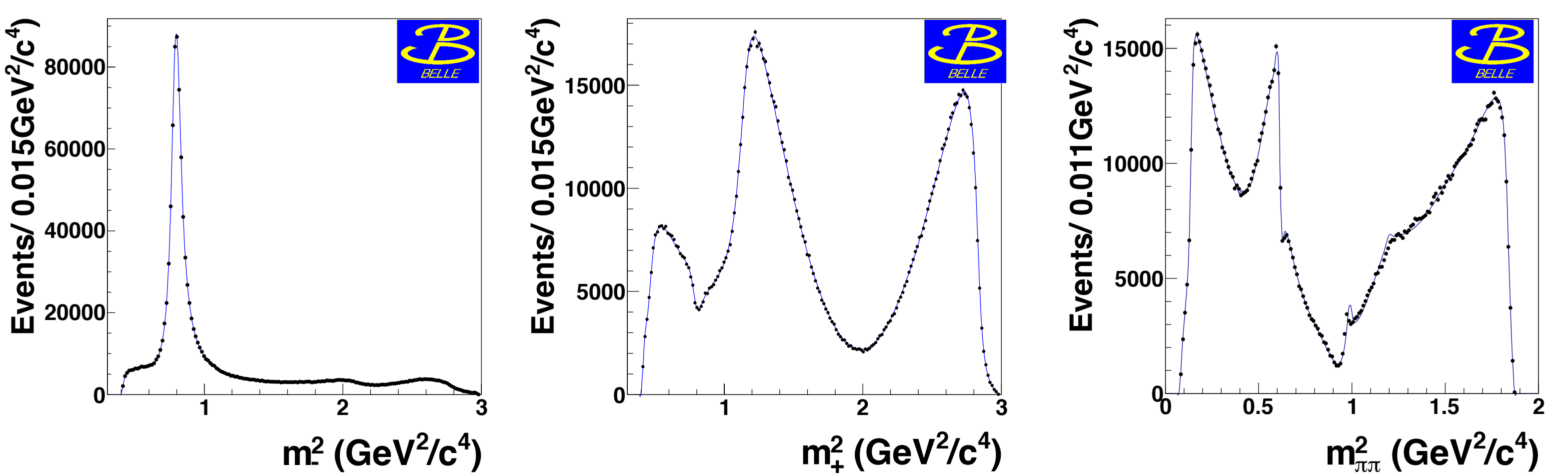
PRD 89, 091103(R) (2014)

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

- *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 1.2×10^6 events with a purity of 96%.*
- *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.*

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

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)
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
$\lvert q/p\rvert$	$\lvert q/p\rvert^{K_S\pi^+\pi^-}$ $[10^{-2}]$					
	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
ϕ	$\phi^{K_S\pi^+\pi^-}$ $[^\circ]$					
	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

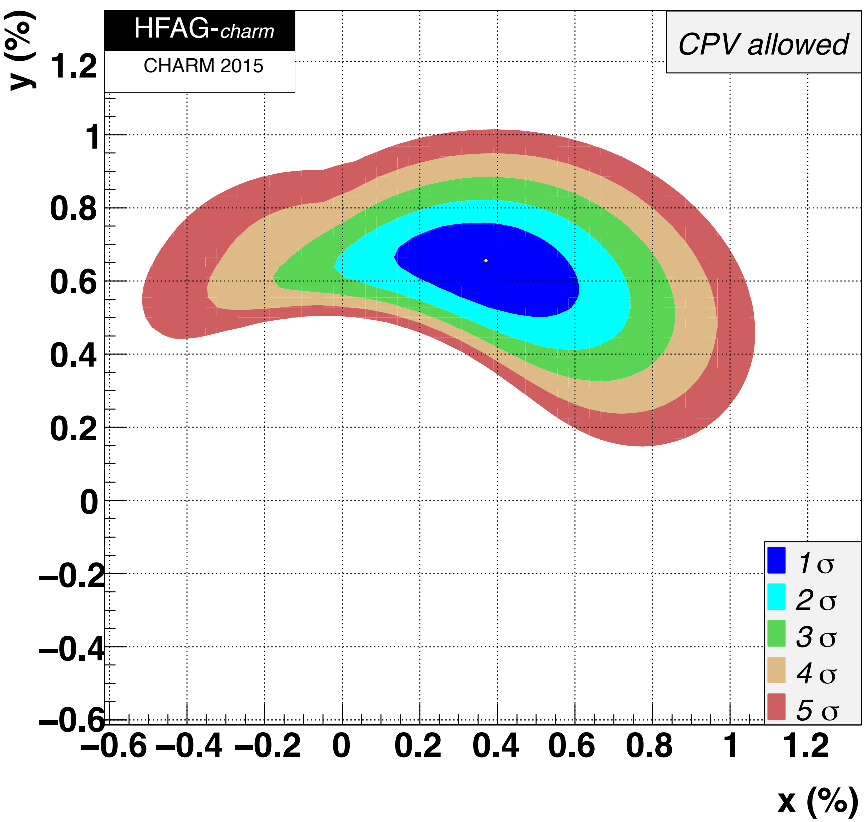
Earlier Estimated Uncertaintes *(M. Staric, KEK FFW14)*:

Analysis	Observable	Uncertainty (%)	
		Now ($\sim$1 ab^{-1})	$\mathcal{L} = 50$ ab^{-1}
$K^0_S\pi^+\pi^-$	x	0.21	0.08
	y	0.17	0.05
	$\|q/p\|$	18	6
	ϕ	0.21 rad	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
	$\|q/p\|$	0.6	0.06
	ϕ	0.44	0.04 rad

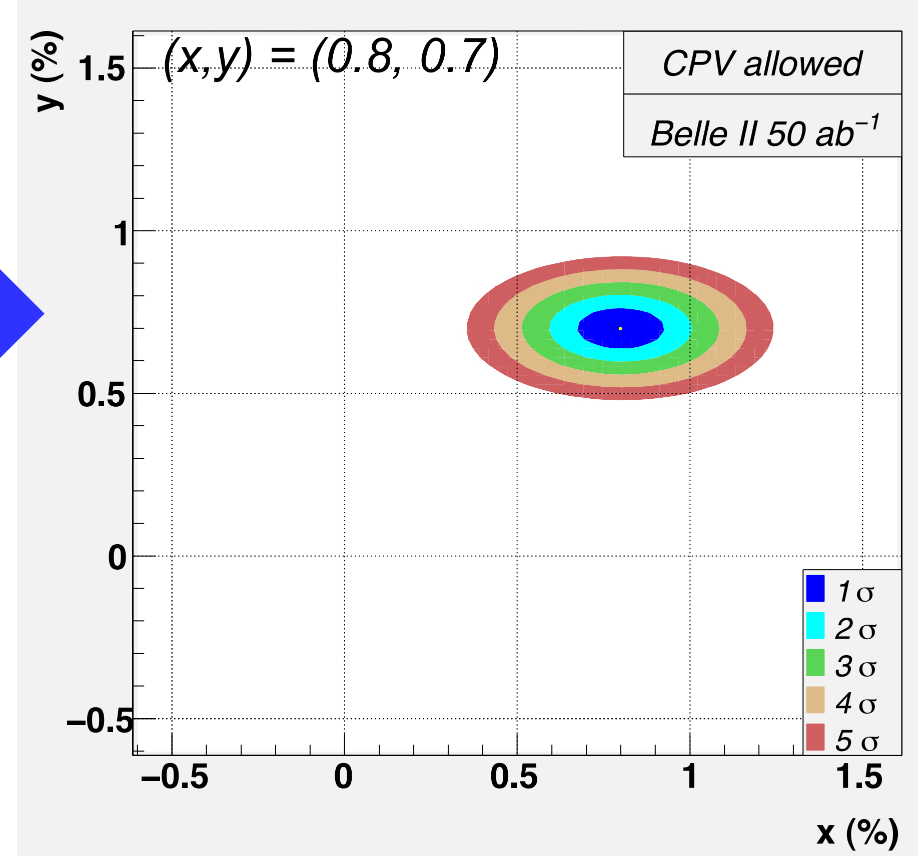
Note: *statistical error and some systematics scale by luminosity, but other systematics do not.*

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

Now:



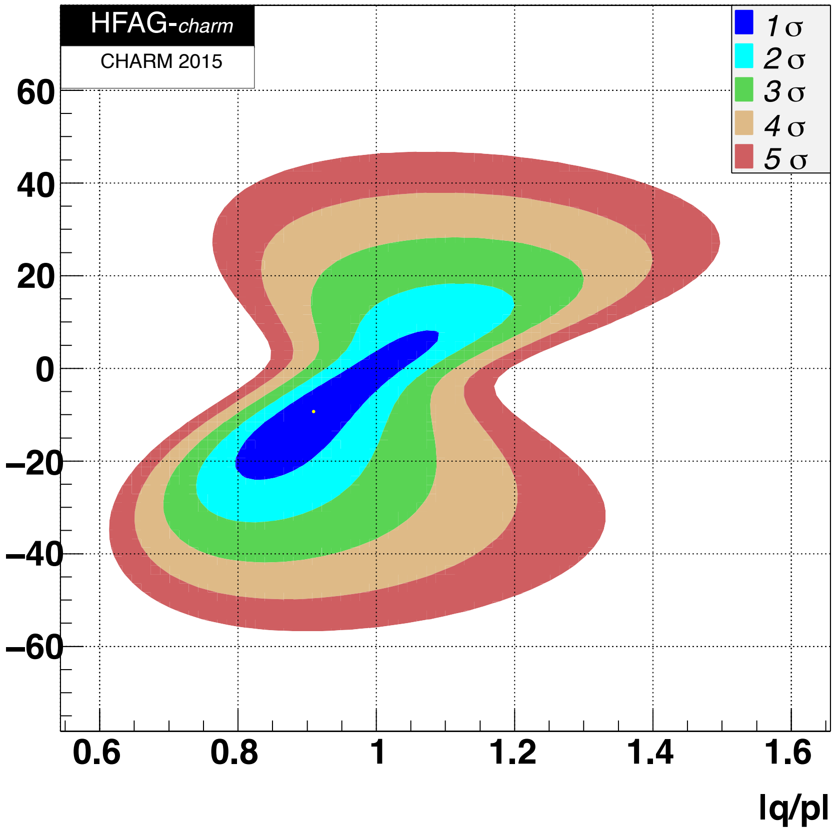
50 ab⁻¹:



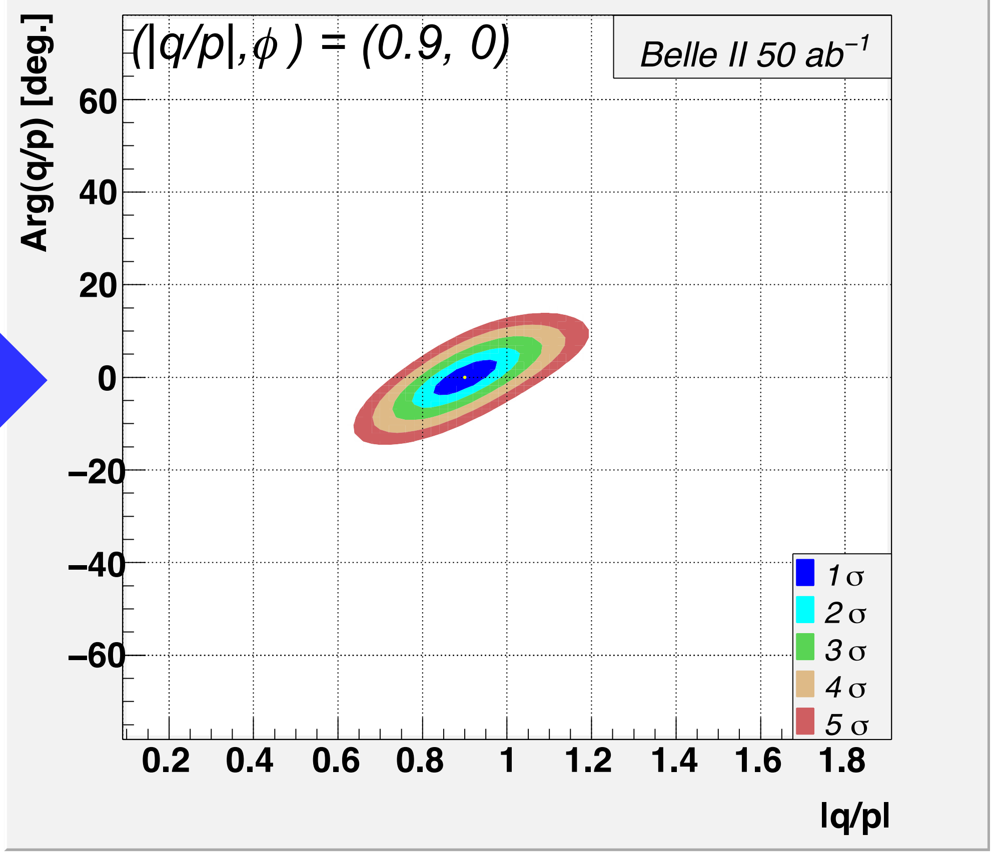
Current measurements of x, y give many constraints on NP models
[see Golowich et al., PRD76, 095009 (2007); 21 models considered, e.g., 2-Higgs doublets, left-right models, little Higgs, extra dimensions, of which 17 give constraints]

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

Now:



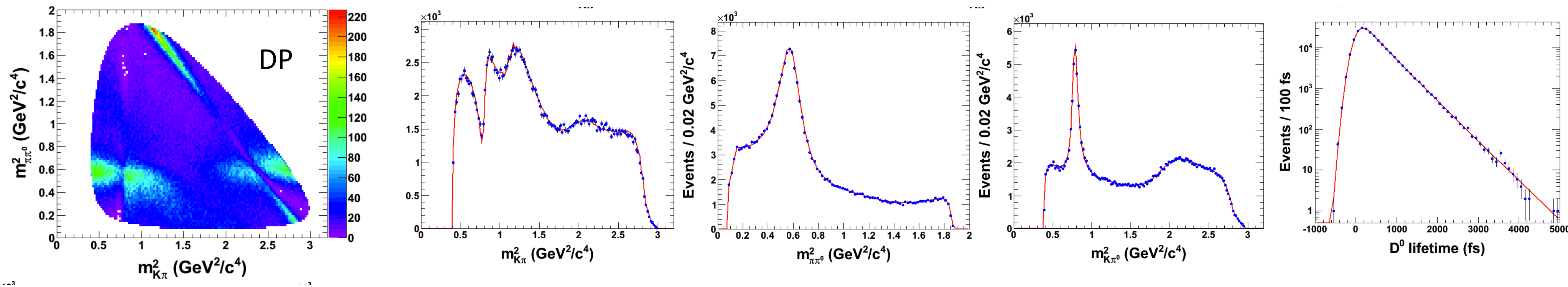
50 ab^{-1}:



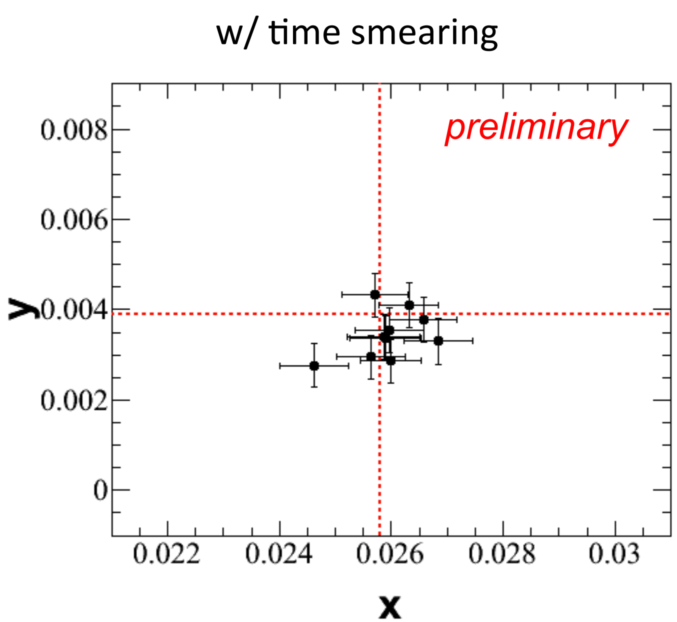
Note: *LHCb will dominate most of these measurements, but Belle II should be competitive in y_{CP} and possibly in x'^2, y', $|q/p|$, ϕ (see Staric, KEK FFW14). If LHCb sees new physics, it would be important for Belle II to independently confirm.*

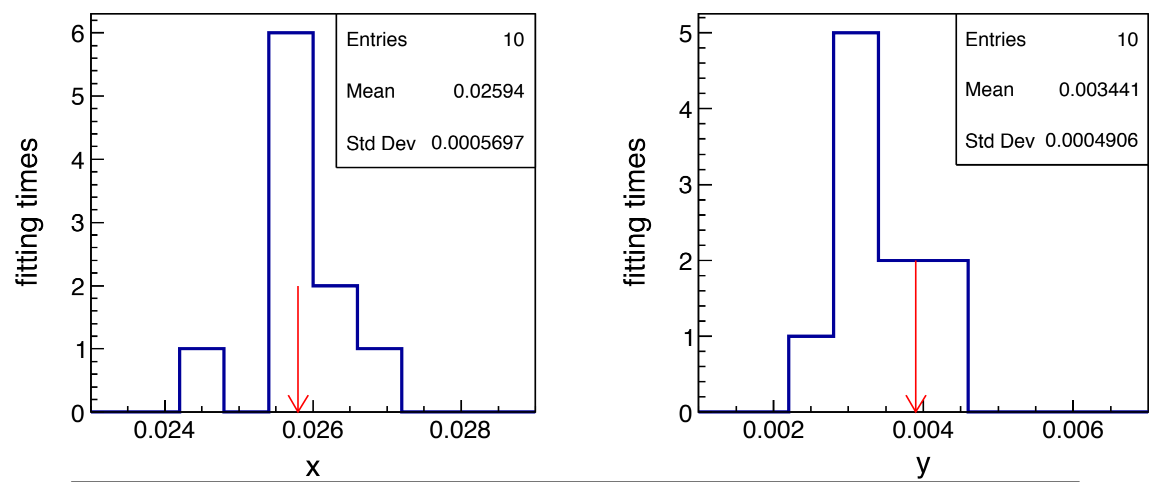
Mixing/CPV Precision for $D^0 \to K^+ \pi^- \pi^0$

[Longki Li, USTC] *time-dependent Dalitz plot fit:*



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





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

Direct CP Asymmetries

Marko Staric, CKM 2014:

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

mainly due to K^0-K^0bar interaction asymmetry

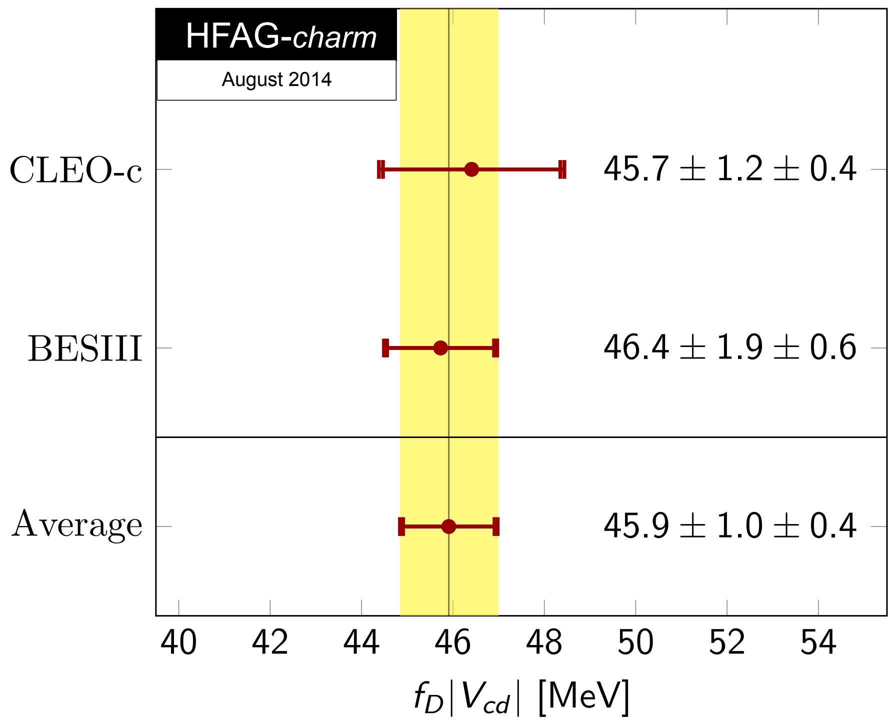
mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K^0_s\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.03
$D^0 \to K^0_s\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K^0_s\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 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
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K^0_s\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \to K^0_s K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D^+_s \to K^0_s\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D^+_s \to K^0_s K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

modes with π^0's are easier @ e^+e^-

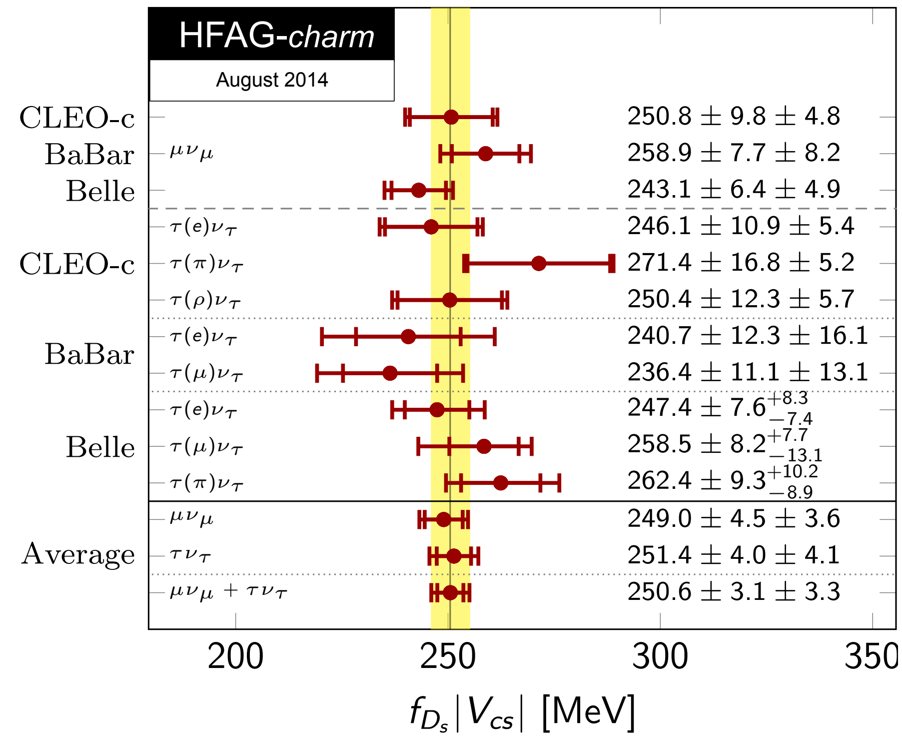
Leptonic Decays $D_{(s)}^{+} \to \ell^{+} \nu$

Anze Zupanc, B2TIP Workshop, 2014:

$D^{+} \to \mu^{+} \nu_{l}$



$D_{s}^{+} \to \ell^{+} \nu_{\ell}$



Agreement between experiments and different decay modes.

Taking $f_D = 209 \pm 3.3$ MeV and $f_{D_s} = 248.6 \pm 2.7$ MeV from FLAG2:

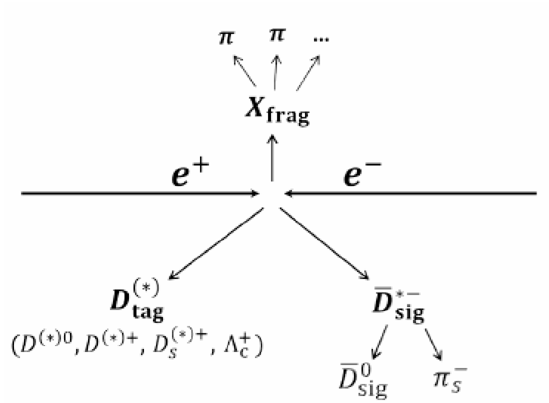
$$V_{cd} = 0.219 \pm 0.005(\mathrm{exp.}) \pm 0.003(\mathrm{LQCD})$$
$$V_{cs} = 1.008 \pm 0.018(\mathrm{exp.}) \pm 0.011(\mathrm{LQCD})$$

Leptonic Decays $D_{(s)}^+ \to \ell^+\nu$

Method: *use energy/momentum conservation to search for rare $D^+ \to \ell^+\nu$, $D^+ \to \nu\nu$, etc.*

$e^+e^- \to D_{tag}\, X_{frag}\, D_{signal}$

Charm tagging



D_{tag} decay modes

D^0 decay	D^+ decay	Λ_c^+ decay	D_s^+ decay
$K^-\pi^+$	$K^-\pi^+\pi^+$	$pK^-\pi^+$	$K^+K^-\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	$pK^-\pi^+\pi^+\pi^0$	$K^0_SK^+$
$K^-\pi^-\pi^+\pi^+$	$K^0_S\pi^+$	pK^0_S	$K^0_SK^0_S\pi^0$
$K^-\pi^-\pi^+\pi^+\pi^0$	$K^0_S\pi^+\pi^0$	$\Lambda\pi^+$	$K^+K^-\pi^+\pi^0$
$K^0_S\pi^+\pi^-$	$K^0_S\pi^+\pi^+\pi^-$	$\Lambda\pi^+\pi^0$	$K^0_SK^-\pi^+\pi^+$
$K^0_S\pi^+\pi^-\pi^0$	$K^+K^-\pi^+$	$\Lambda\pi^+\pi^+\pi^-$	

X_{frag} for $D_{tag}^{(*)}$

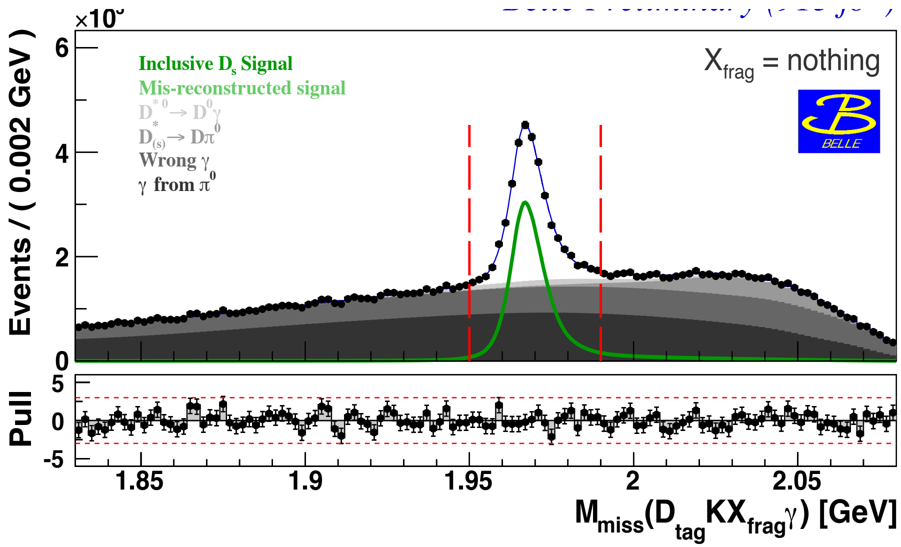
$D^{(*)+}$	$D^{(*)0}$	Λ_c^+	$D_s^{(*)+}$	
nothing(K^+K^-)	$\pi^+(K^+K^-)$	$\pi^+\bar{p}$	K^0_S,	$\pi^0K^0_S$
$\pi^0(K^+K^-)$	$\pi^+\pi^0(K^+K^-)$	$\pi^+\pi^0\bar{p}$	π^+K^-,	$\pi^+\pi^0K^-$
$\pi^+\pi^-(K^+K^-)$	$\pi^+\pi^-\pi^+(K^+K^-)$	$\pi^+\pi^-\pi^+\bar{p}$	$\pi^+\pi^-K^0_S$,	$\pi^+\pi^-\pi^0K^0_S$
$\pi^+\pi^-\pi^0(K^+K^-)$			$\pi^+\pi^-\pi^+K^-$	

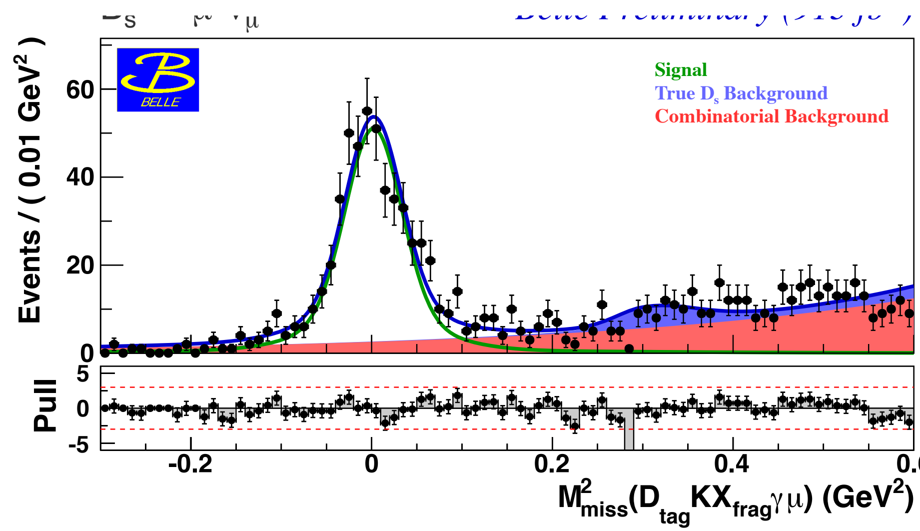
For D_{signal} require 1 lepton track ($D^+ \to \ell^+\nu$), no additional tracks ($D^+ \to \nu\nu$) etc. (depending on signal mode)

Leptonic Decay $D_s^+ \to \mu^+ \nu$

$e^+e^- \to D_{tag}\, X_{frag}\, K\, D_s^{*+} \to D_s^+ \gamma$

- *Require 1 charged track passing μ ID and pointing to IP*
- *Fit to $D_{tag}\, X_{frag}\, K\, \mu^+ \gamma$ missing mass*





Belle yield: 94400 inclusive
489 exclusive $D_s^+ \to \mu^+ \nu$ } *913 fb^{-1}*

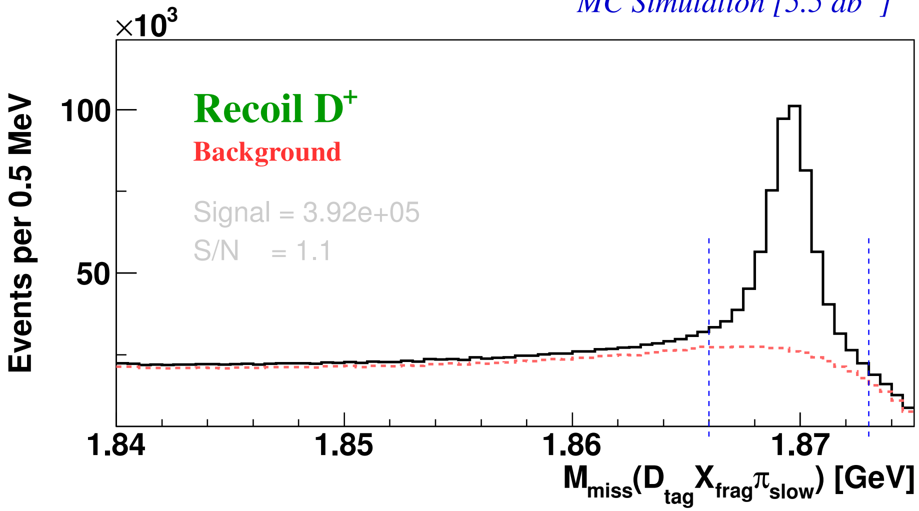
⇒ *Belle II yield in 50 ab^{-1}:* ***5.2 x 10^6 inclusive***
27k exclusive $D_s^+ \to \mu^+ \nu$

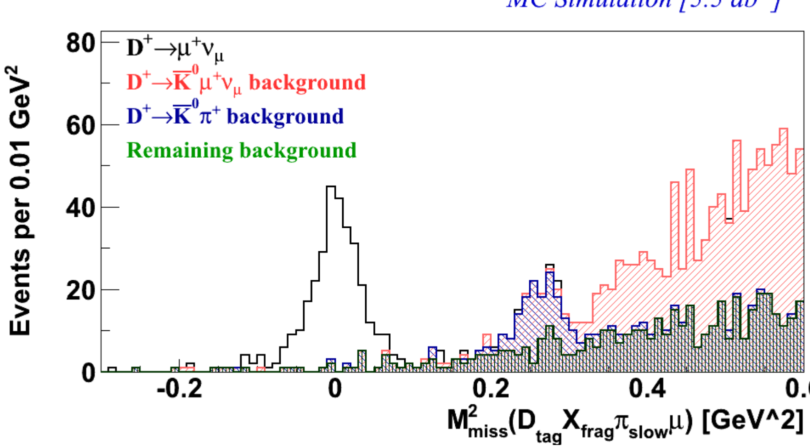
⇒ *$\Delta |V_{cs}|$ = 0.004 (stat), well below theory error (LQCD) of 0.011*
Δf_{Ds} = 0.9 (stat), well below theory error (FLAG2) error of 2.7

Leptonic Decay $D^+ \to \mu^+\nu$

$e^+e^- \to D_{tag}\, X_{frag}\, K\, D^{*+} \to D^+\pi^0$

- Require 1 charged track passing μ ID and pointing to IP
- Fit to $D_{tag}\, X_{frag}\, \mu^+\pi^0$ missing mass





$\Rightarrow$ Belle II yield in 50 ab^{-1}: **3.5 x 10^6 inclusive**

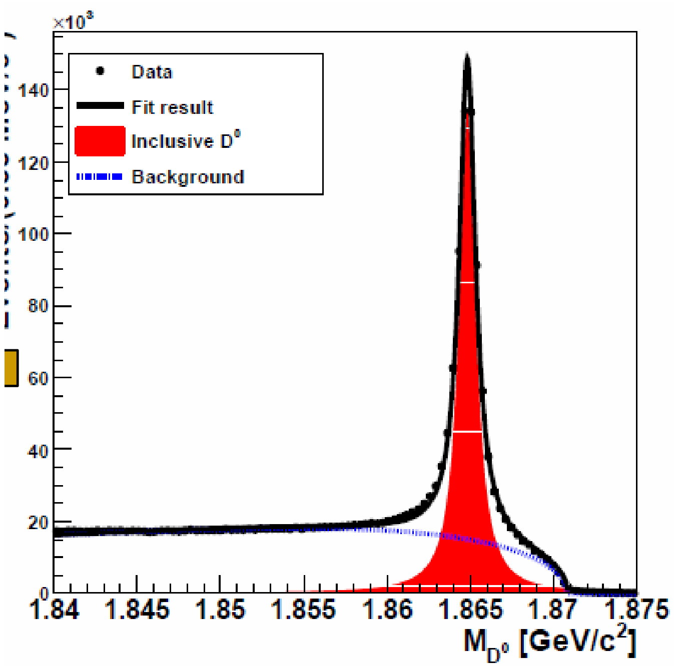
1250 exclusive $D^+ \to \mu^+\nu$

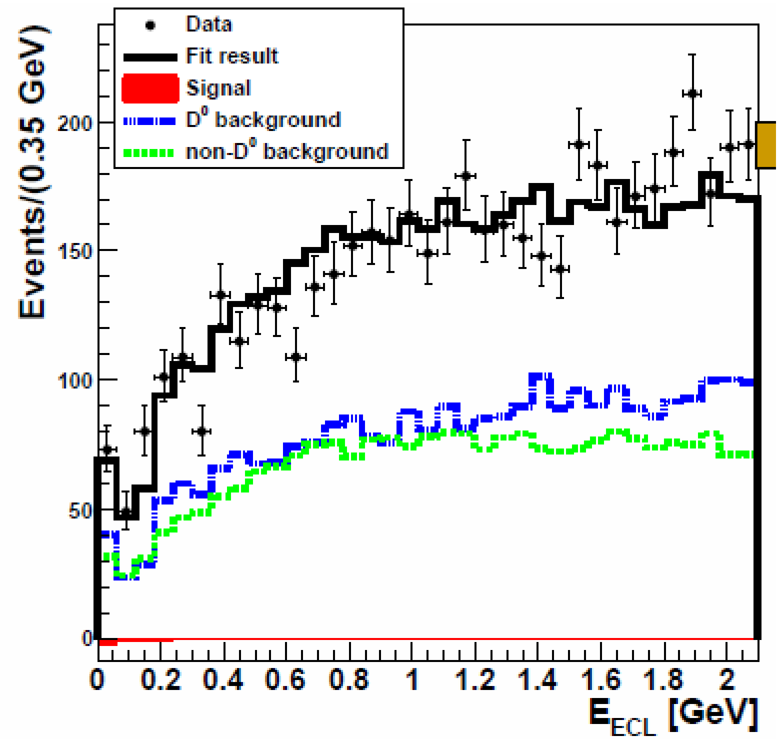
$\Rightarrow \Delta f_D|V_{cd}|$ = 1.3, competitive with CLEOc (1.2) and BESIII (1.9)

Leptonic Decay $D^0 \to \nu\nu$ (nothing)

$e^+e^- \to D_{tag}\, X_{frag}\quad D^{*+} \to D^0 \pi_s^+$

- *Require no extra charged tracks, γ, π^0, etc.*
- *Fit to $D_{tag}\, X_{frag}\, \pi_s$ missing mass and ECL isolated energy distribution:*





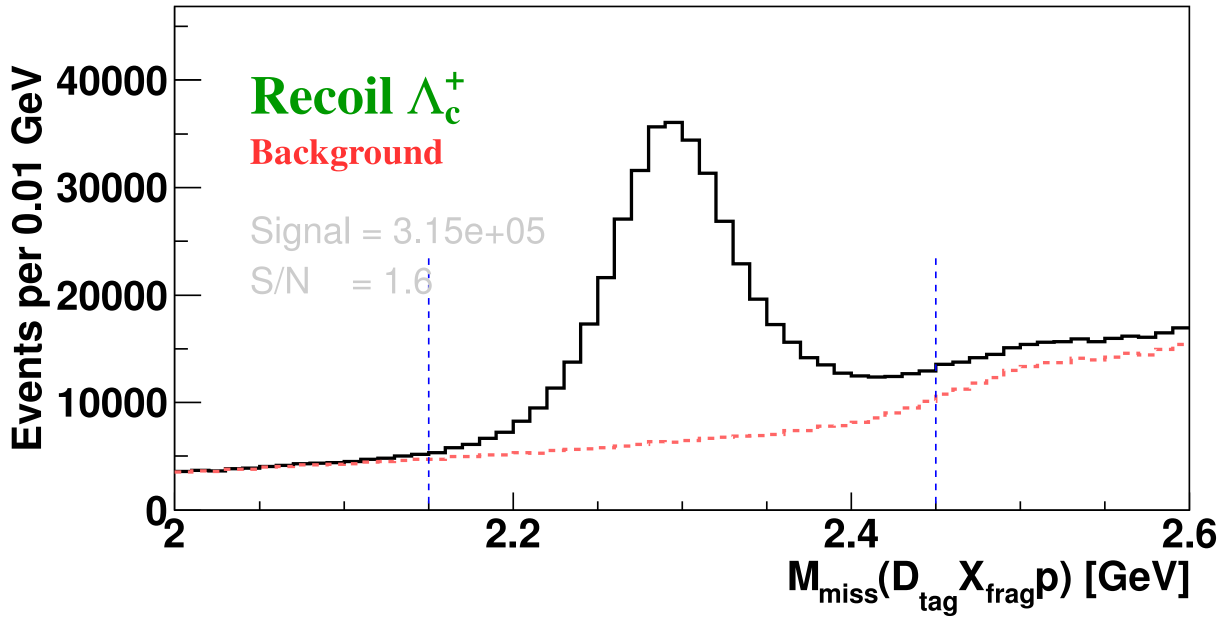
Belle yield: 694505 inclusive
no signal for $D^0 \to \nu\nu$ } *924 fb^{-1}*

$\Rightarrow$ *Belle II yield in 50 ab^{-1}:* ***38 x 10^6 inclusive D^0 decays***

Inclusive $\Lambda_c^+ \to X$

$e^+e^- \to D_{tag}\, X_{frag}\, p\, \Lambda_c^+$

MC Simulation [5.5 ab^{-1}]



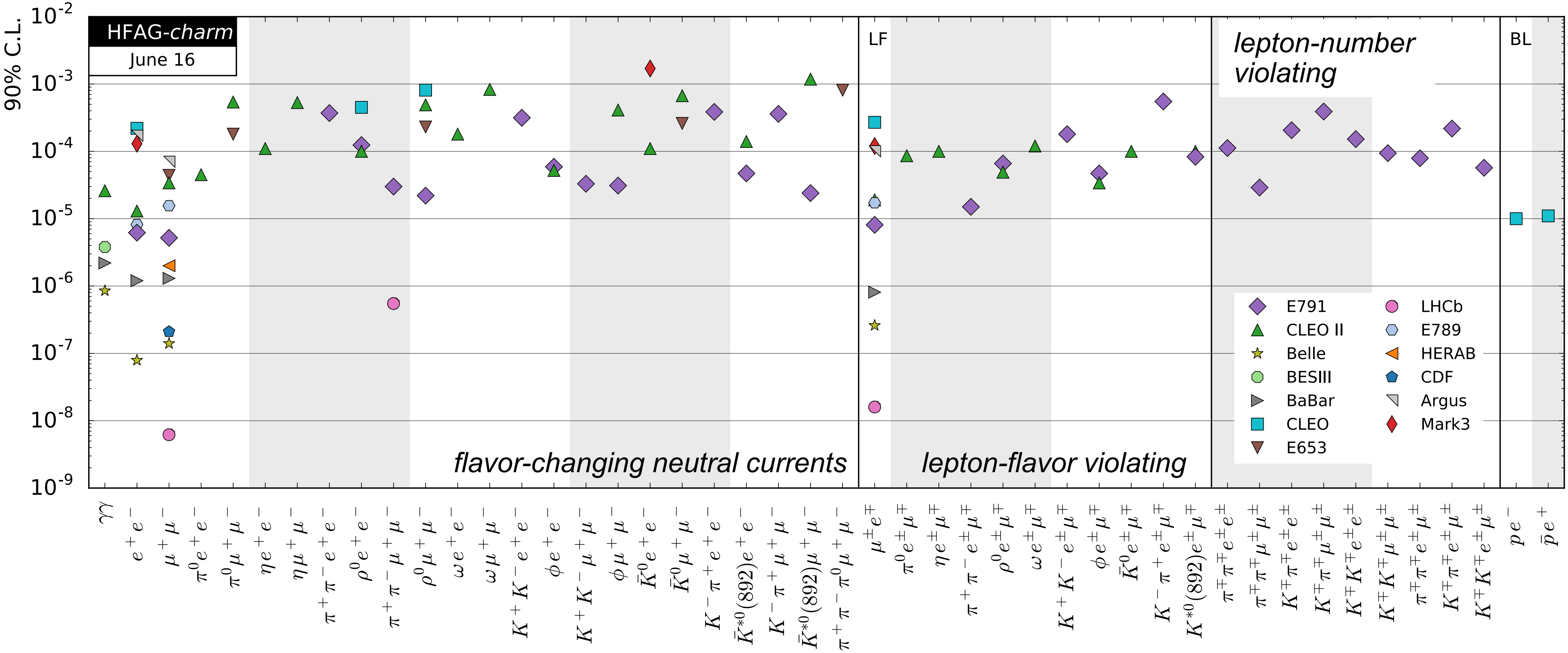
⇒ *Belle II yield in 50 ab^{-1}:* ***2.8 x 10^6 inclusive***

Unique sample:

- *allows measurement of Λ_c absolute branching fractions*
- *allows measurement of semileptonic Λ_c decays*
- *allows searches for Λ_c rare decays with missing energy*

Rare/Forbidden D^0 Decays

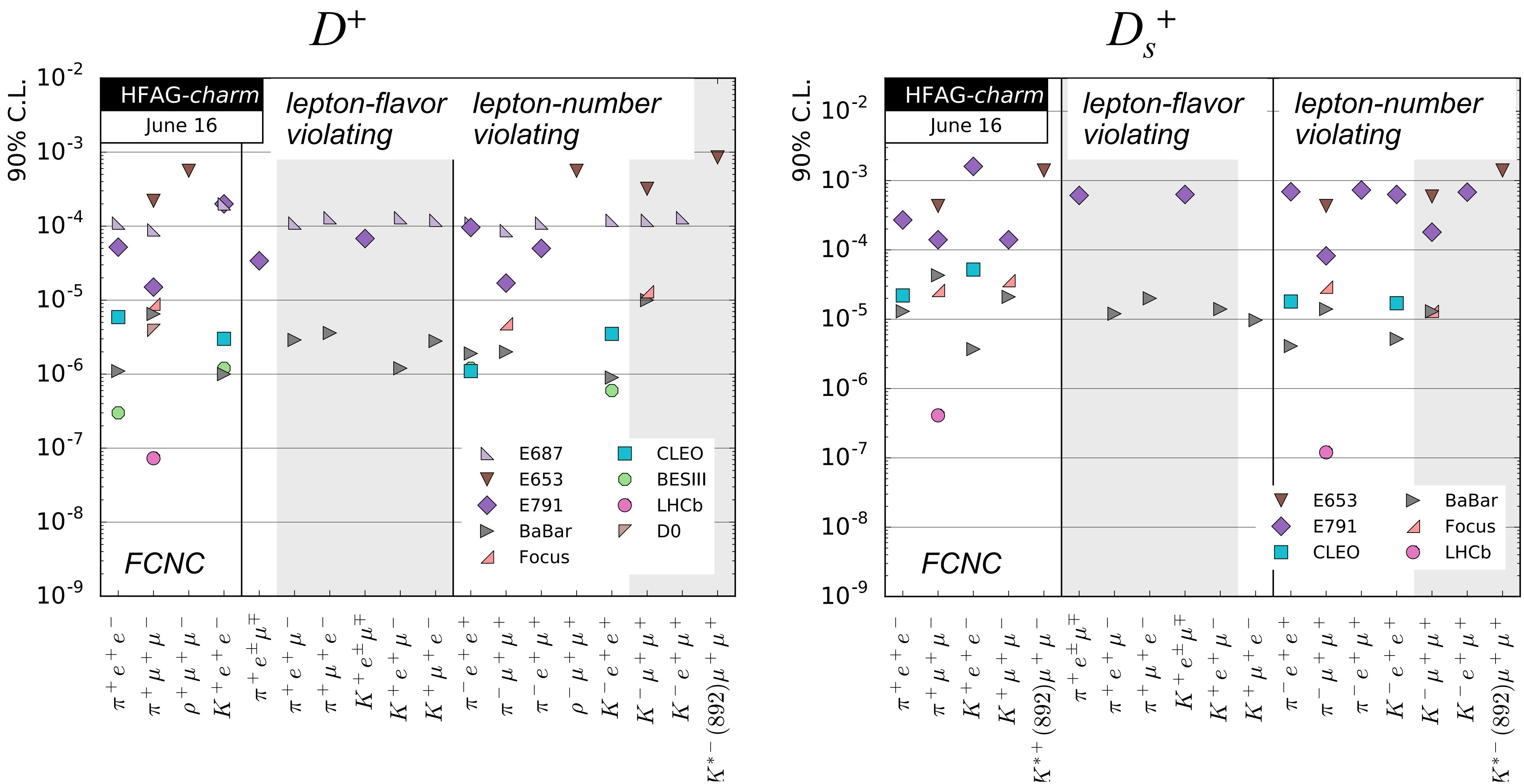
www.slac.stanford.edu/xorg/hfag/charm/



NOTE: modes with π^0's are easier @ e^+e^-

Rare/Forbidden $D_{(s)}^{+}$ Decays

www.slac.stanford.edu/xorg/hfag/charm/



NOTE: BaBar limits can improve by factor of 10 at Belle II

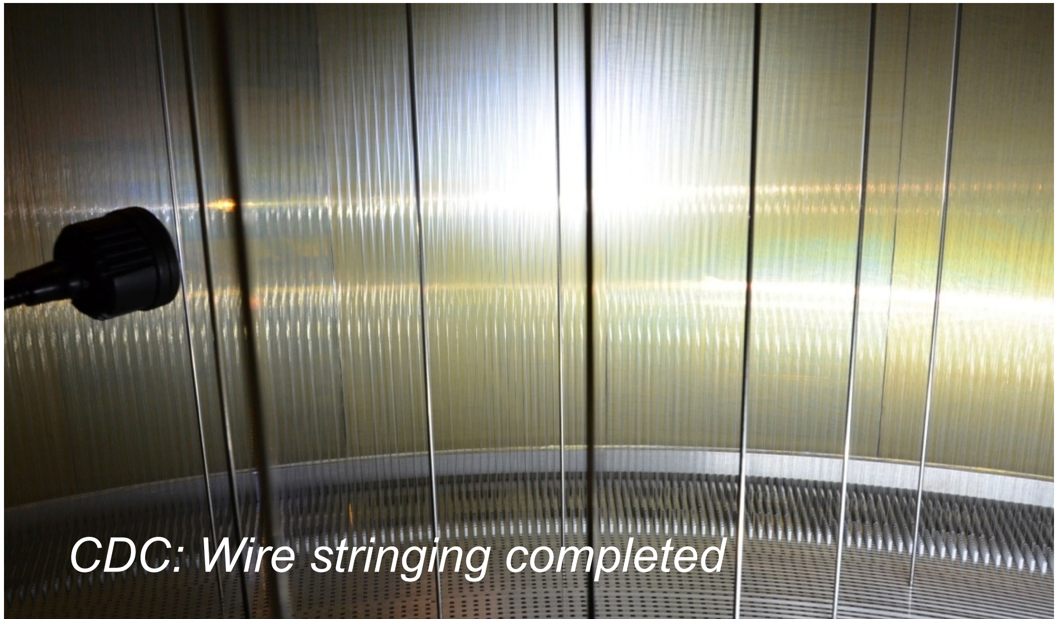
SuperKEKB construction status

Accelerator completed, now circulating beams:

D2(Oho-side)

D1(Nikko-side)

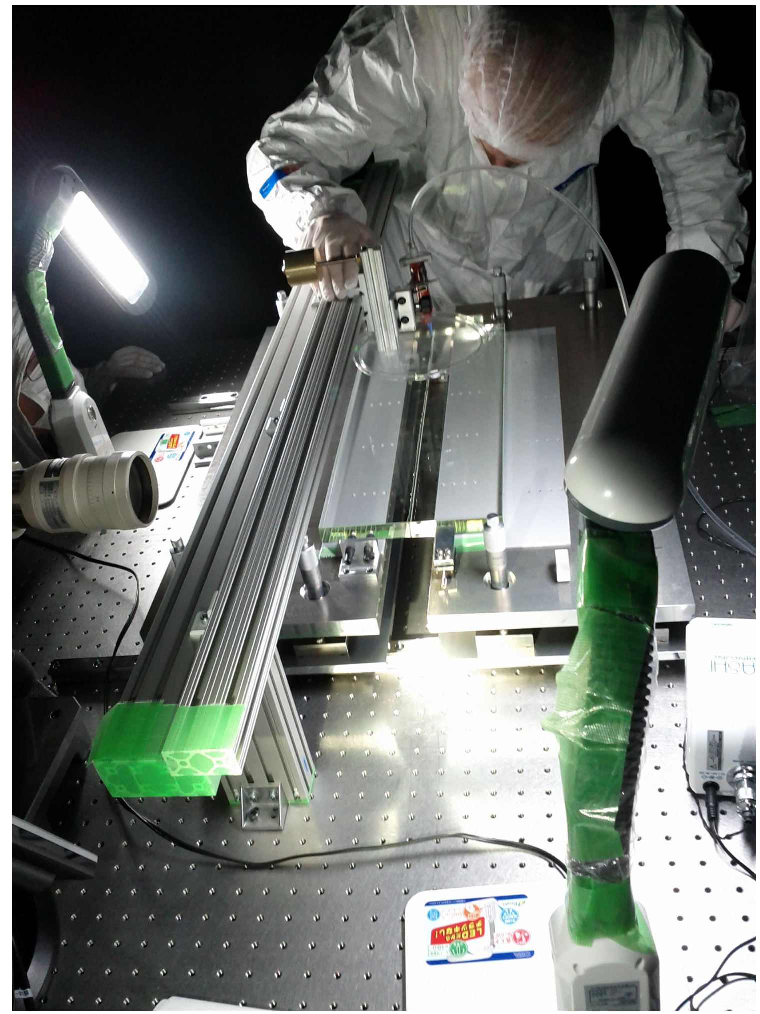
Belle II construction status



CDC: Wire stringing completed

KLM: Barrel installation completed

iTOP optics assembly and installation completed

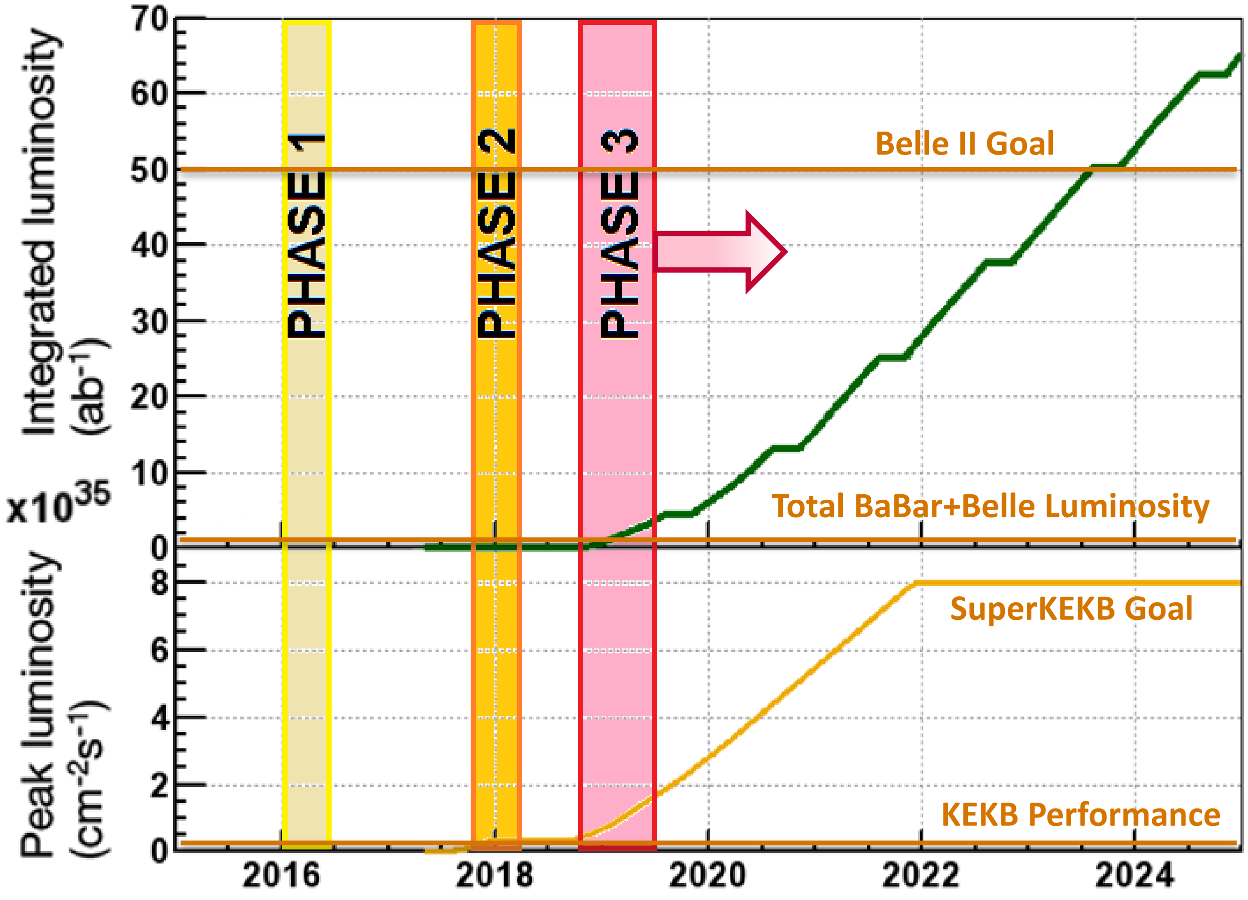


Schedule

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

Phase 2:
- *first collisions*
- *partial detector*
- *background study*

Phase 3:
- *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.
- 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

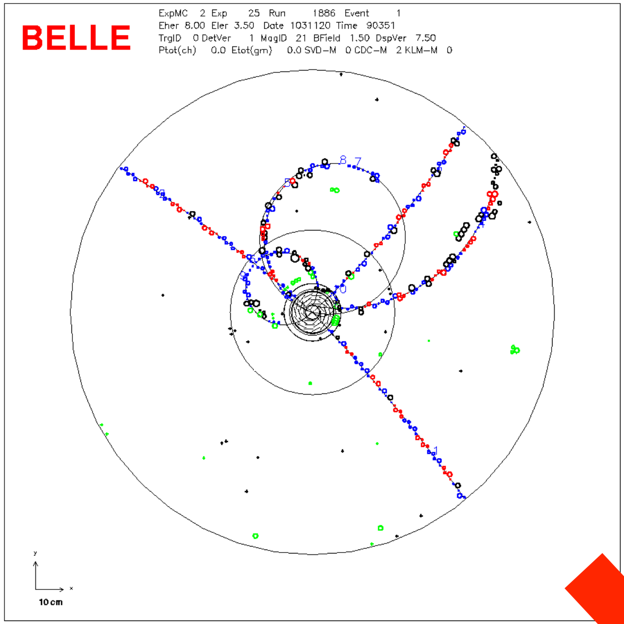
$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\left(\frac{R_L}{R_{\xi_y}}\right)$$

- 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***
chosen → ***Nano-beam*** ***(Raimondi for SuperB)***	***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)*

Detector Upgrade



Challenges:

Higher background (×20), higher event rate (×10)

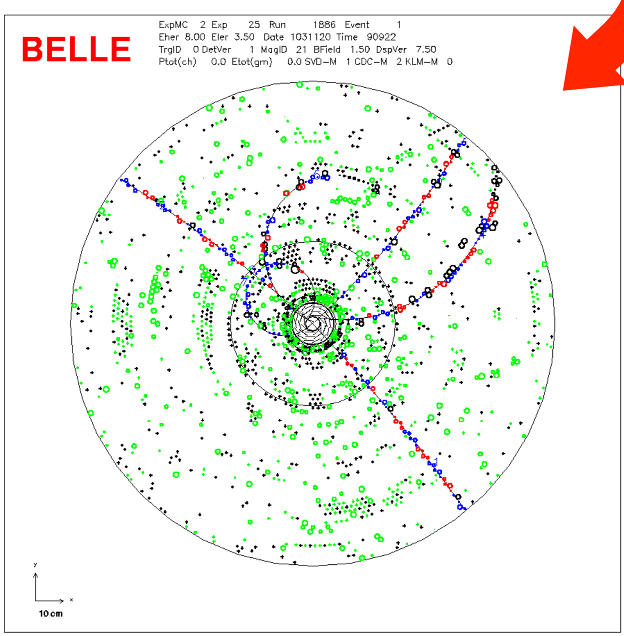
- *radiation damage and occupancy*
- *fake hits and pile-up noise in the EM*

Targeted improvements:

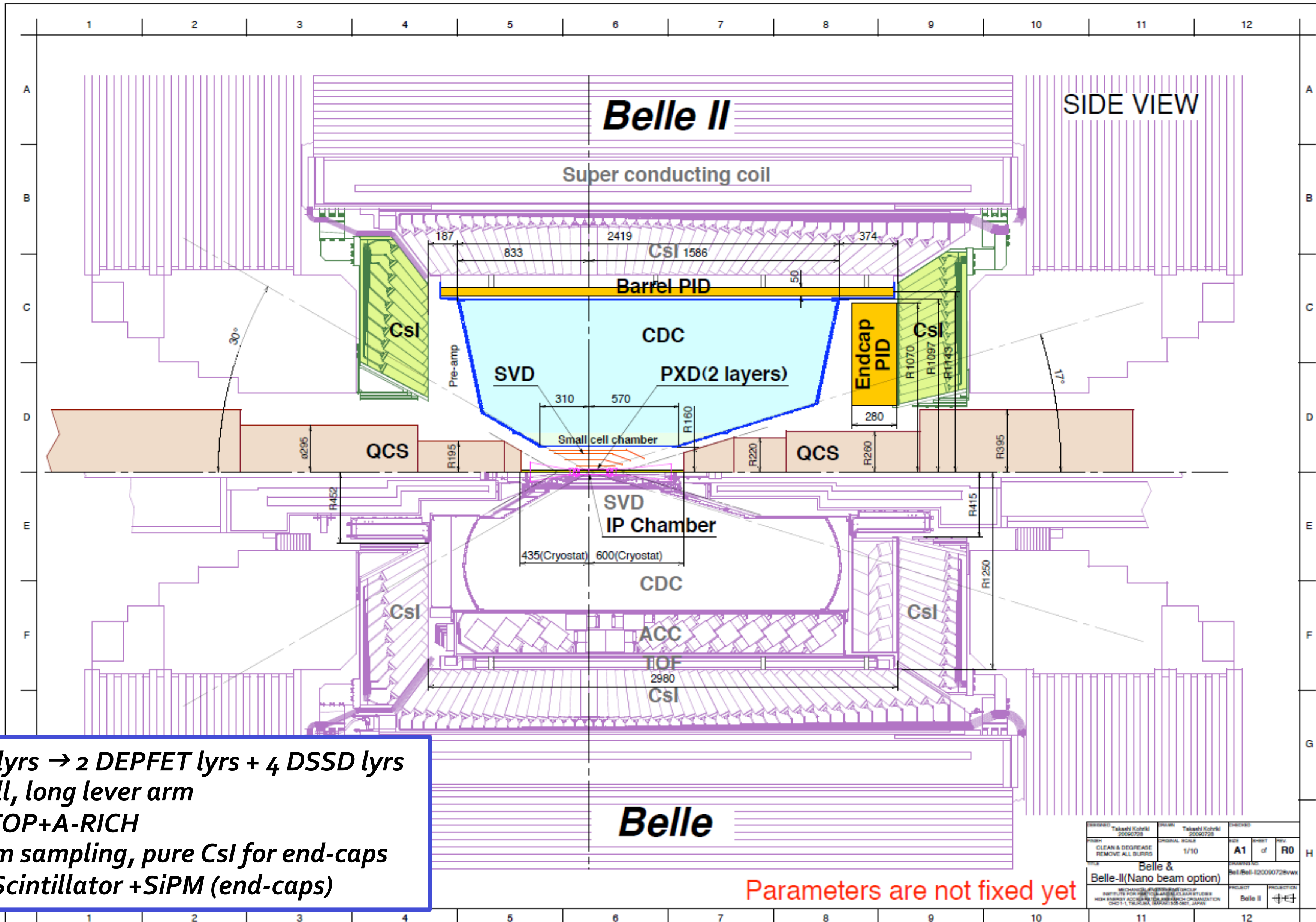
- *Increase hermiticity*
- *Increase K_S efficiency*
- *Improve IP and secondary vertex resolution*
- *Improve π/K separation*
- *Improve π^0 efficiency*
- *Add PID in endcaps*
- *Add μ ID in endcaps*

Detector Choices:

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



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)*