PROSPECTS OF CHARM PHYSICS WITH Belle II

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on behalf of the Belle II Collaboration

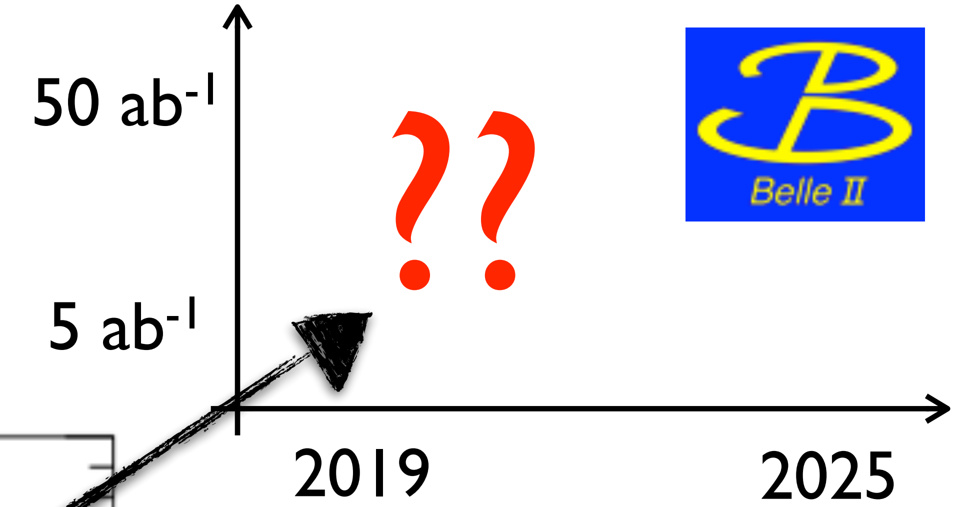
Belle II

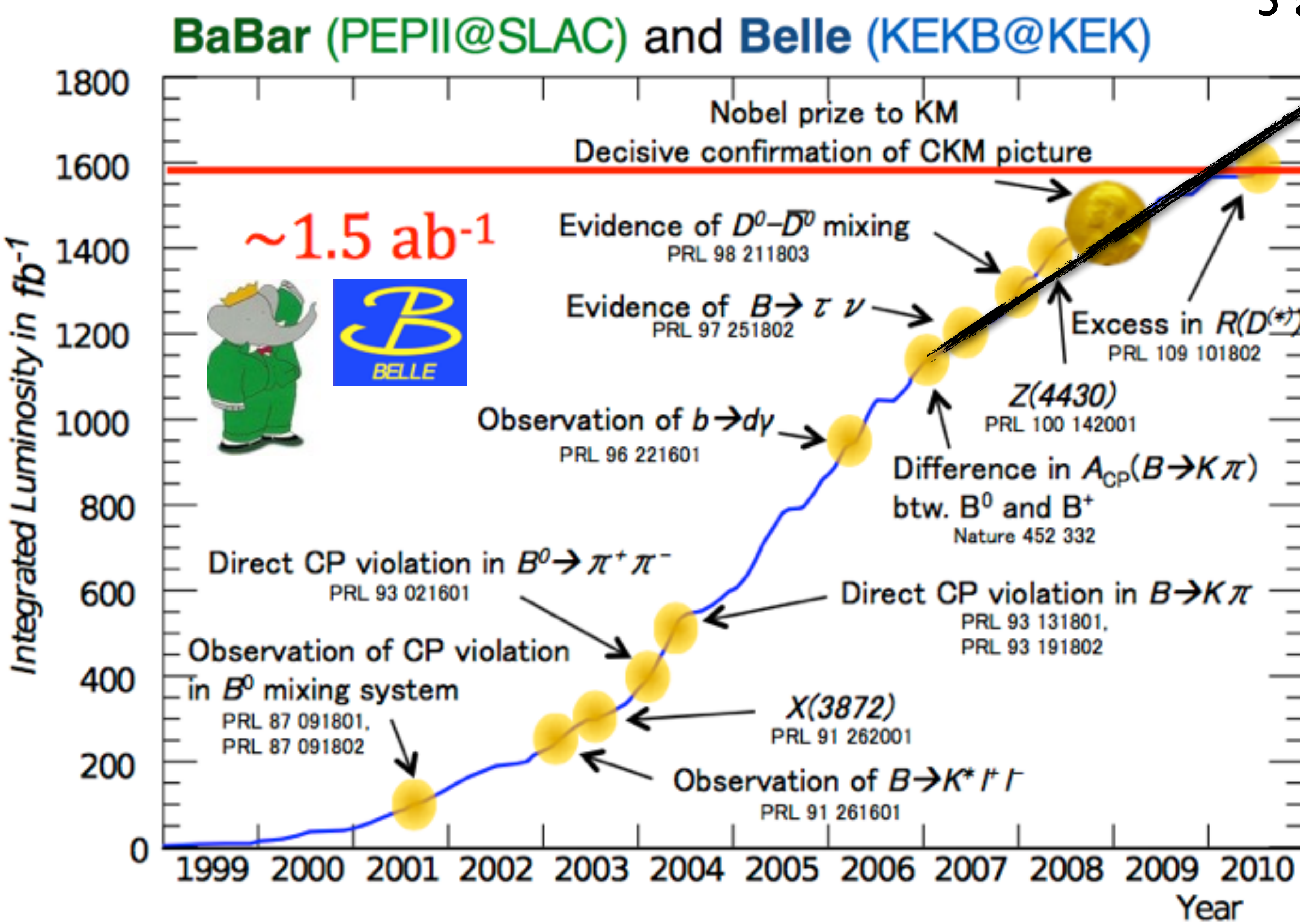
9th International Workshop on Charm Physics, Budker INP ~ May 21st, 2018

Outline

- ☑ *SuperKEKB and Belle II*
- ☑ *Today: Status of the Detector and the Accelerator*
- ☑ *Selection of Belle II Prospects on Charm*

Flavour Physics @ B Factory

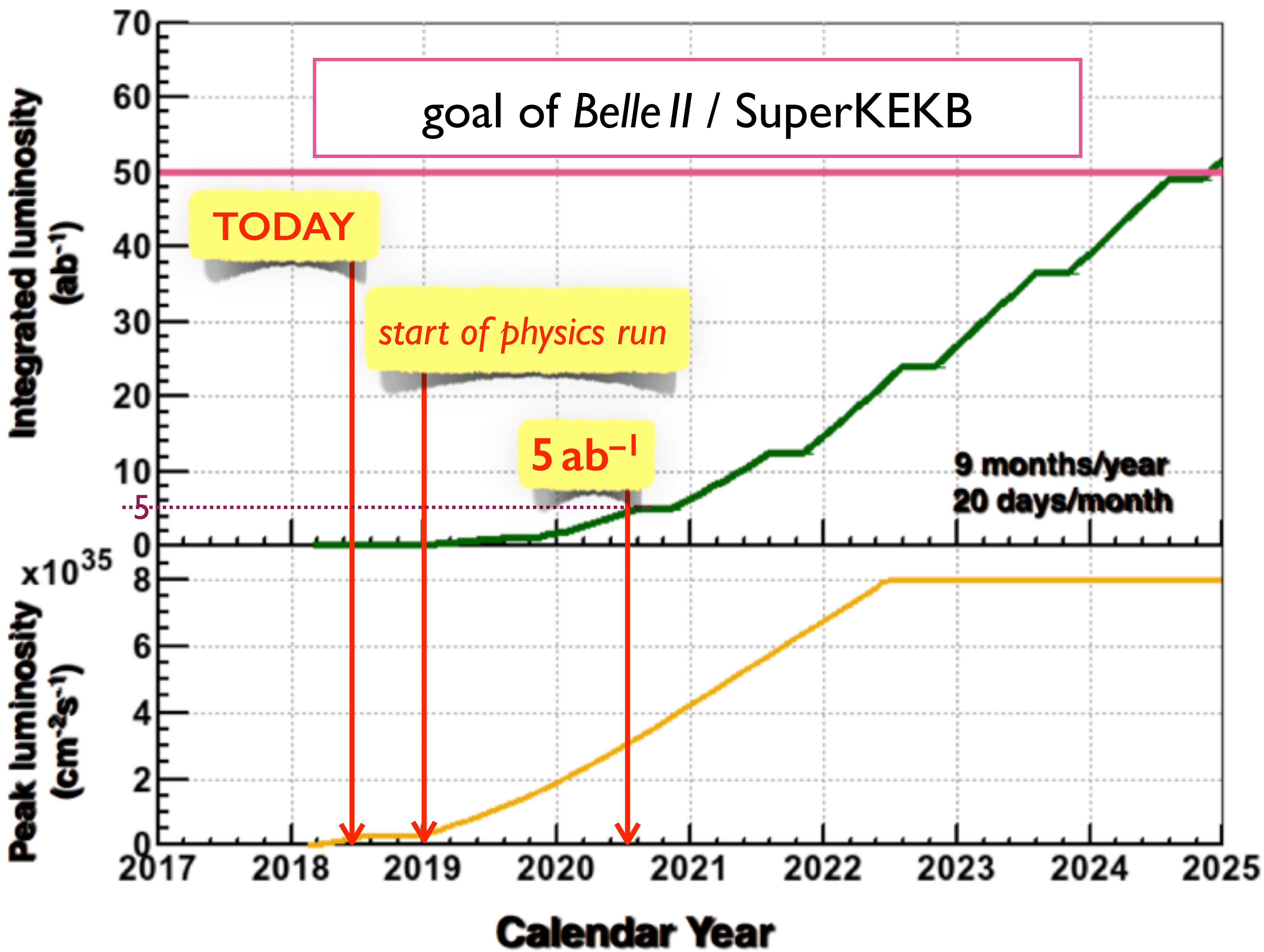




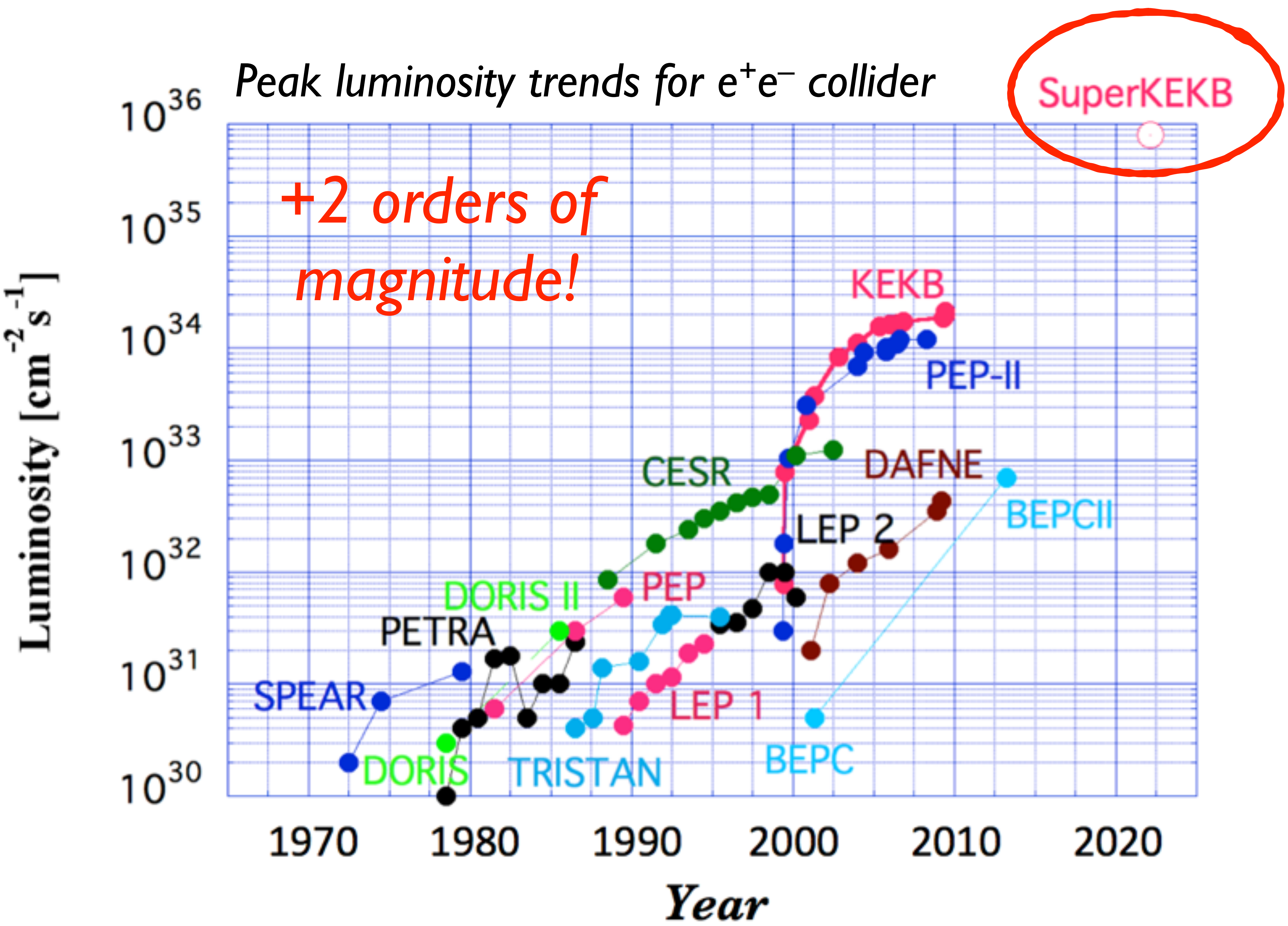
- Belle and BABAR have a produced a large number of important results, since the beginning of their data taking
- Competition between the two experiments has helped in pulling out the best from the two datasets
- First Results of *combined* analysis are coming out

Belle II will provide a significantly larger data sample (x50 Belle) that will allow to continue the investigation with a much more powerful instrument

Road to 50 ab^{-1}…



…on the leading edge of Luminosity



High-Luminosity Asymmetric B Factory

- ➡ Target luminosity is $\mathscr{L} = 8\text{x}10^{35}\ \text{cm}^{-2}\text{s}^{-1}$ (x40 w.r.t. KEKB)
- ➡ Achievable in the *nano-beam scheme* (P. Raimondi for SuperB)
  - double beam currents
  - squeeze beams @ IP by 1/20

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

- Lorentz factor
- beam current
- beam-beam parameter
- geometrical reduction factors
- beam aspect ratio at the IP
- vertical beta-function at the IP

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
beam energy	E_b	3.5	8	4	7	GeV
CM boost	$\beta\gamma$	0.425		0.28		
half crossing angle	φ	11		41.5		mrad
horizontal emittance	ε_x	18	24	3.2	4.6	nm
emittance ratio	κ	0.88	0.66	0.37	0.40	%
beta-function at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.30	mm
beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam parameter	ξ_y	129	90	0.0881	0.0807	
beam size at IP	σ_x^*/σ_y^*	100/2		10/0.059		μm
Luminosity	$\mathscr{L}$	$2.1\text{x}10^{34}$		$8\text{x}10^{35}$		$\text{cm}^{-2}\text{s}^{-1}$

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Lorentz factor

beam

beam-beam

$L = \frac{\gamma}{2e r_e} \ldots$

beam aspect … at the IP

vertical beta-function at the IP

reduced CM boost

- reduced vertex separation, Δt resolution
- increased detector hermeticity

squeezed beams @ IP

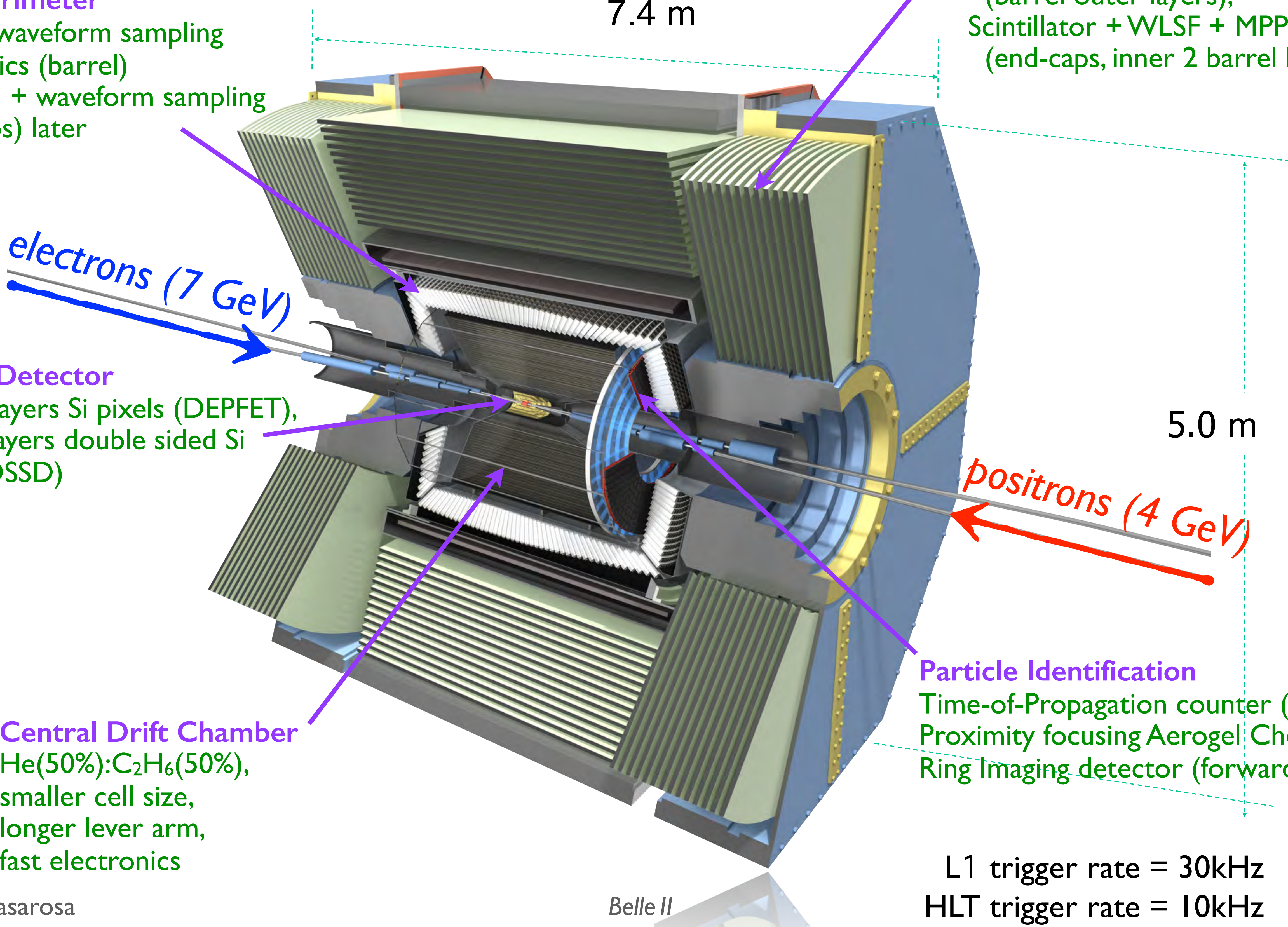
- greatly improved constraint for decay chain vertex fitting

parameters		KEKB LER	KEKB HER	SuperKEKB LER	SuperKEKB HER	units
beam energy		3.5	8	4	7	GeV
CM boost		0.425		0.28		
h…				41.5		mrad
ho…			24	3.2	4.6	nm
			0.66	0.37	0.40	%
b…			5.9	32/0.27	25/0.30	mm
			1.19	3.6	2.6	A
bea…			90	0.0881	0.0807	
			2	10/0.059		μm
			…0^{34}	8×10^{35}		$cm^{-2}s^{-1}$

x40 luminosity

- higher background rates (~10-20x)
  - detector occupancy, radiation damage, fake hits, pile-up noise in the calorimeter
- higher event rate
  - higher trigger rate, DAQ, computing
- x40 produced signal events

The *Belle II* Detector



K_L & μ Detector
Resistive Plate Counter (barrel outer layers),
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM calorimeter
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) later

Vertex Detector
PXD: 2 layers Si pixels (DEPFET),
SVD: 4 layers double sided Si strips (DSSD)

Particle Identification
Time-of-Propagation counter (barrel),
Proximity focusing Aerogel Cherenkov Ring Imaging detector (forward)

Central Drift Chamber
$He(50\%):C_2H_6(50\%)$,
smaller cell size,
longer lever arm,
fast electronics

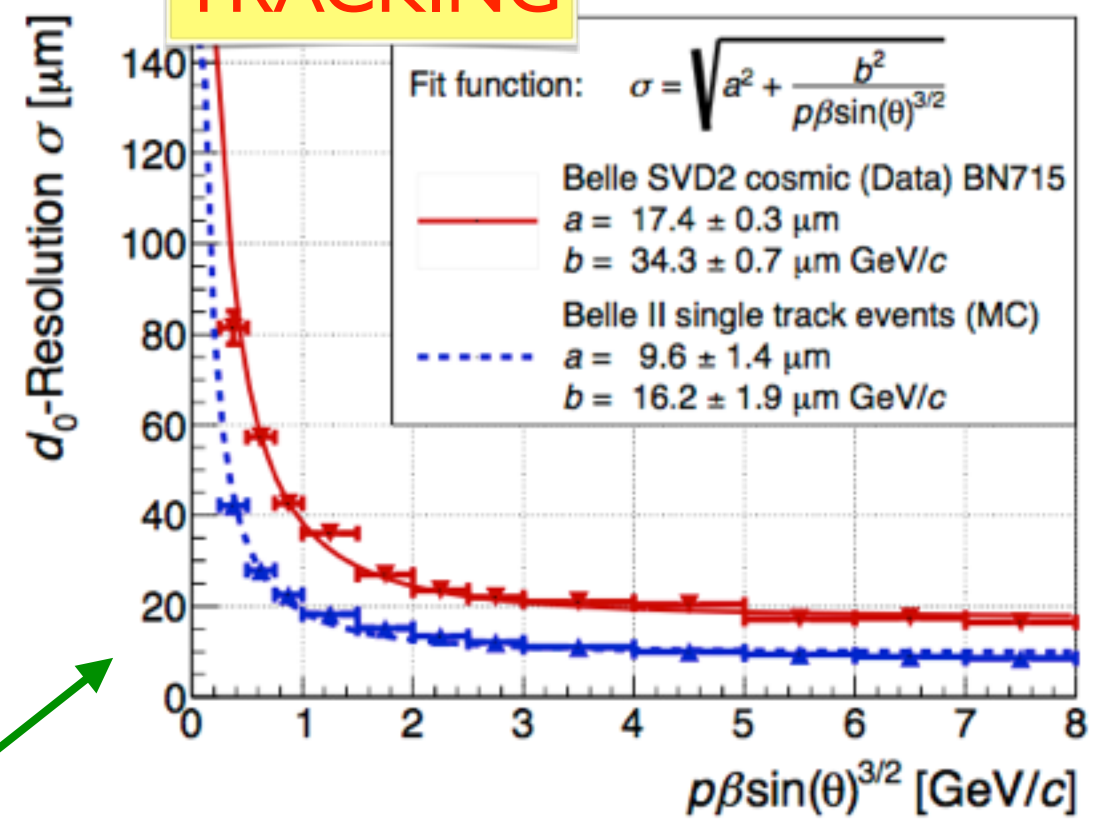
L1 trigger rate = 30kHz
HLT trigger rate = 10kHz

Belle II Perfomance Improvements

➡ B-Factory advantages over hadron collider detectors:

- clean event environment
- high trigger efficiency
- high-efficiency detection of neutrals (γ, π^0, η, η', …)
- many control samples to study systematics
- good kinematic resolution (Dalitz plots analysis)
- missing energy and missing mass analysis are straightforward (for B physics)

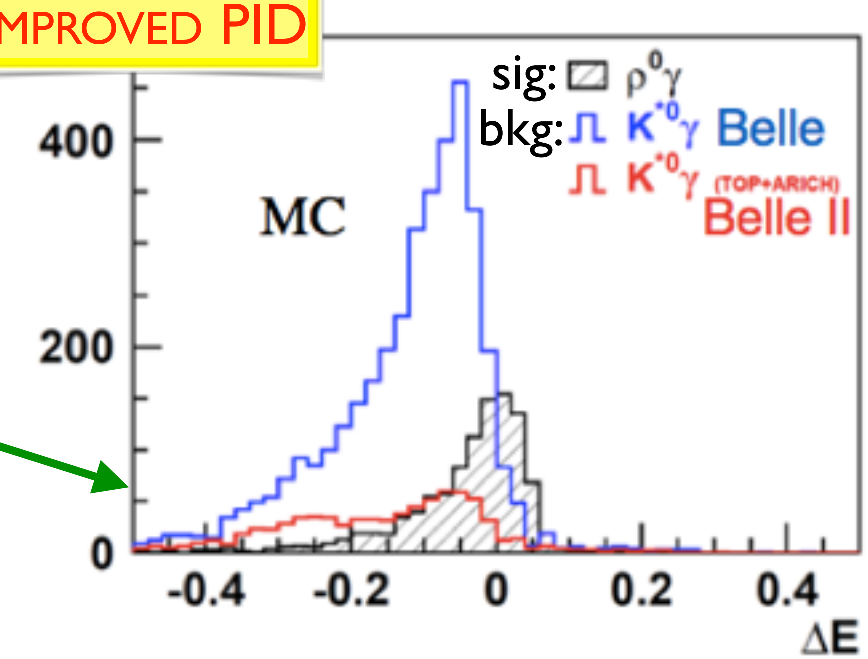
TRACKING



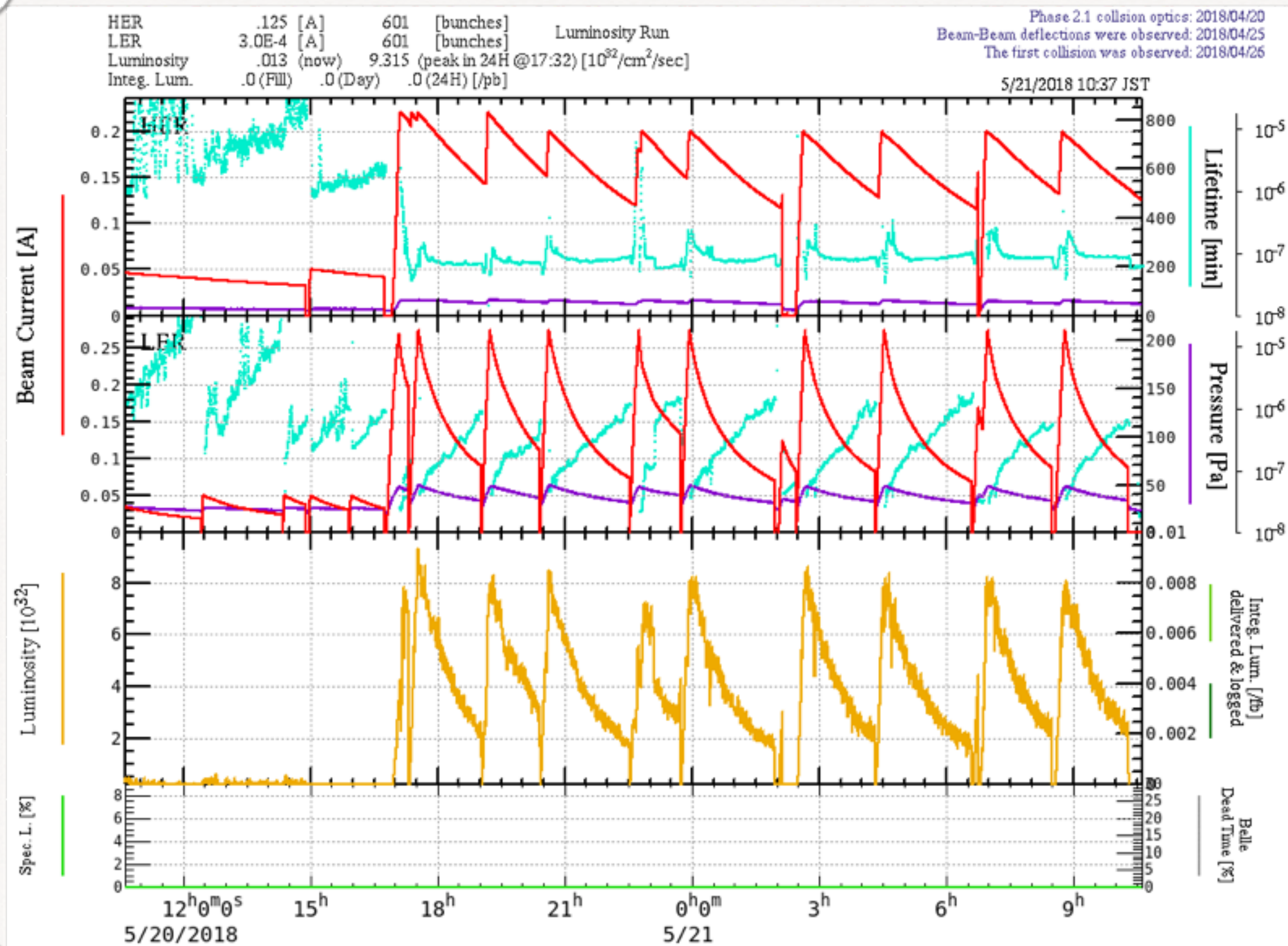
IMPROVEMENTS wrt Belle

- primary and secondary vertex resolution
- K_S and π^0 reconstruction
- K/π separation
- PID and μ ID in the end caps

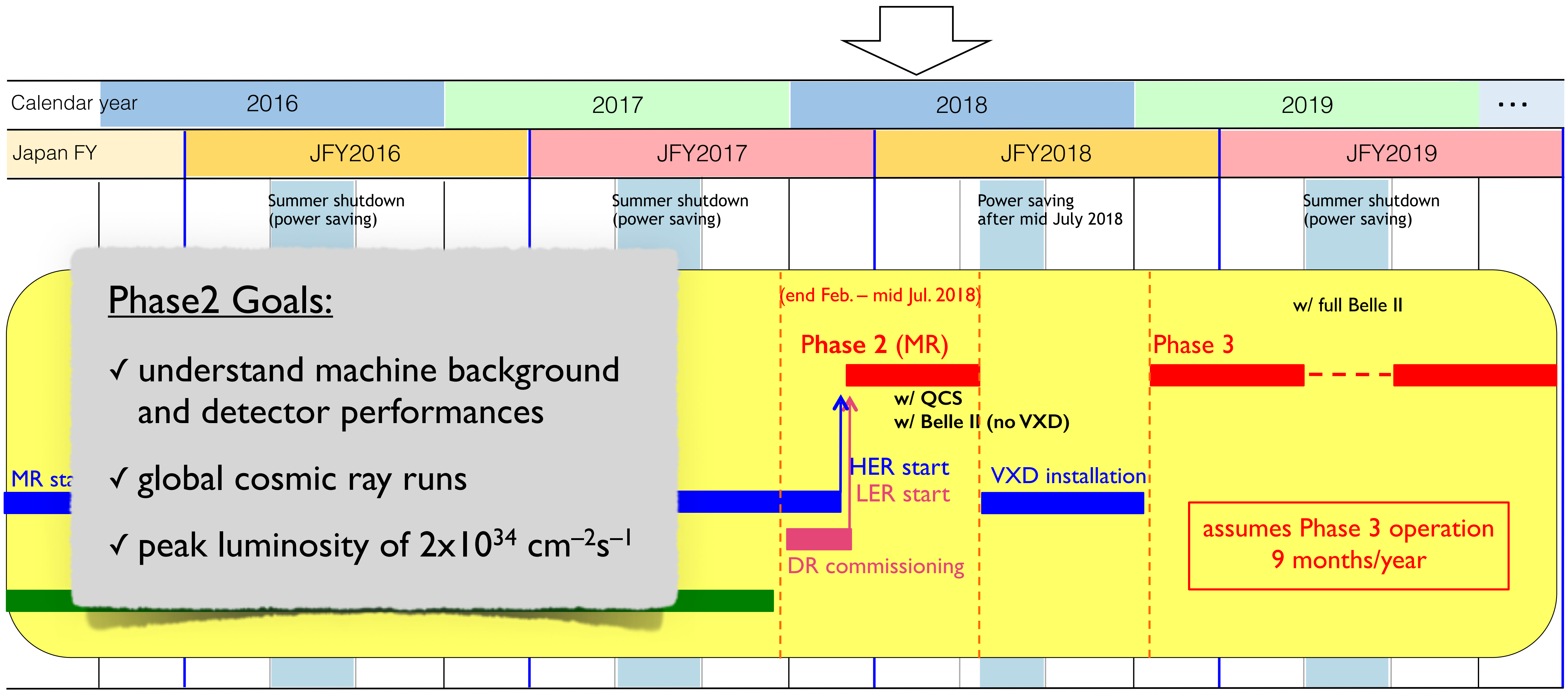
IMPROVED PID



Today: Current Status of Detector and Accelerator

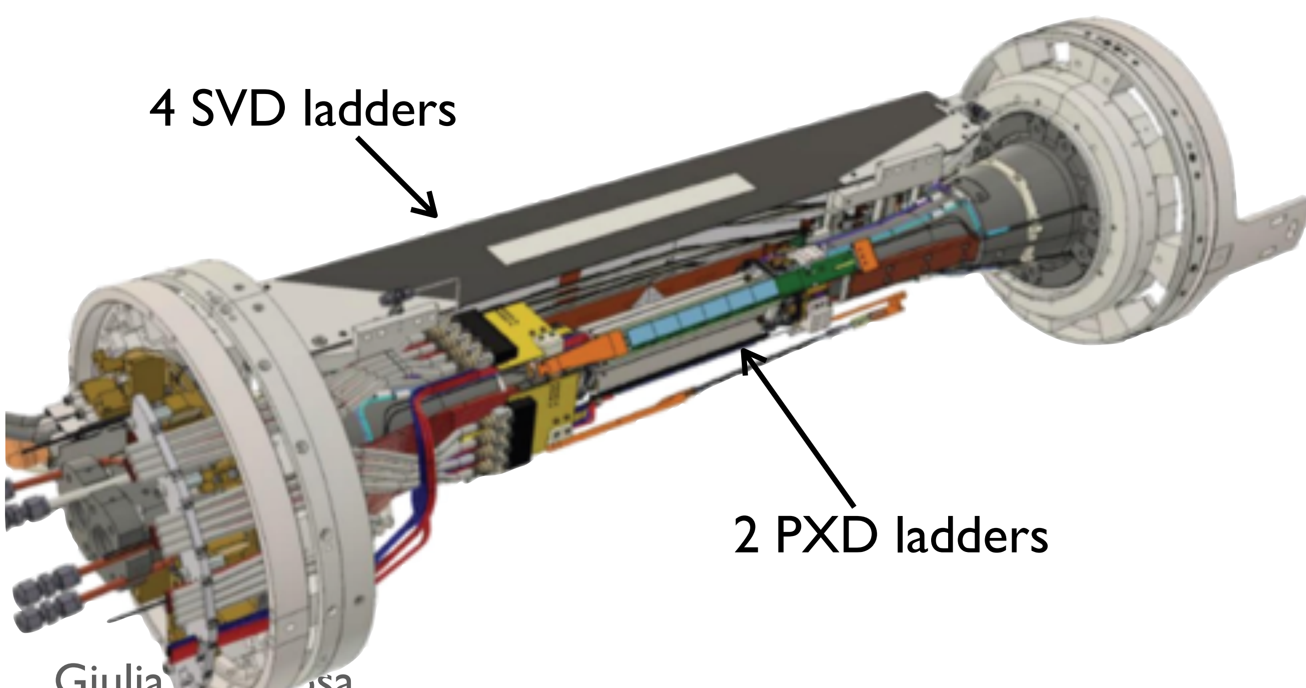


SuperKEKB and *Belle II* Schedule



Phase2 Goals:

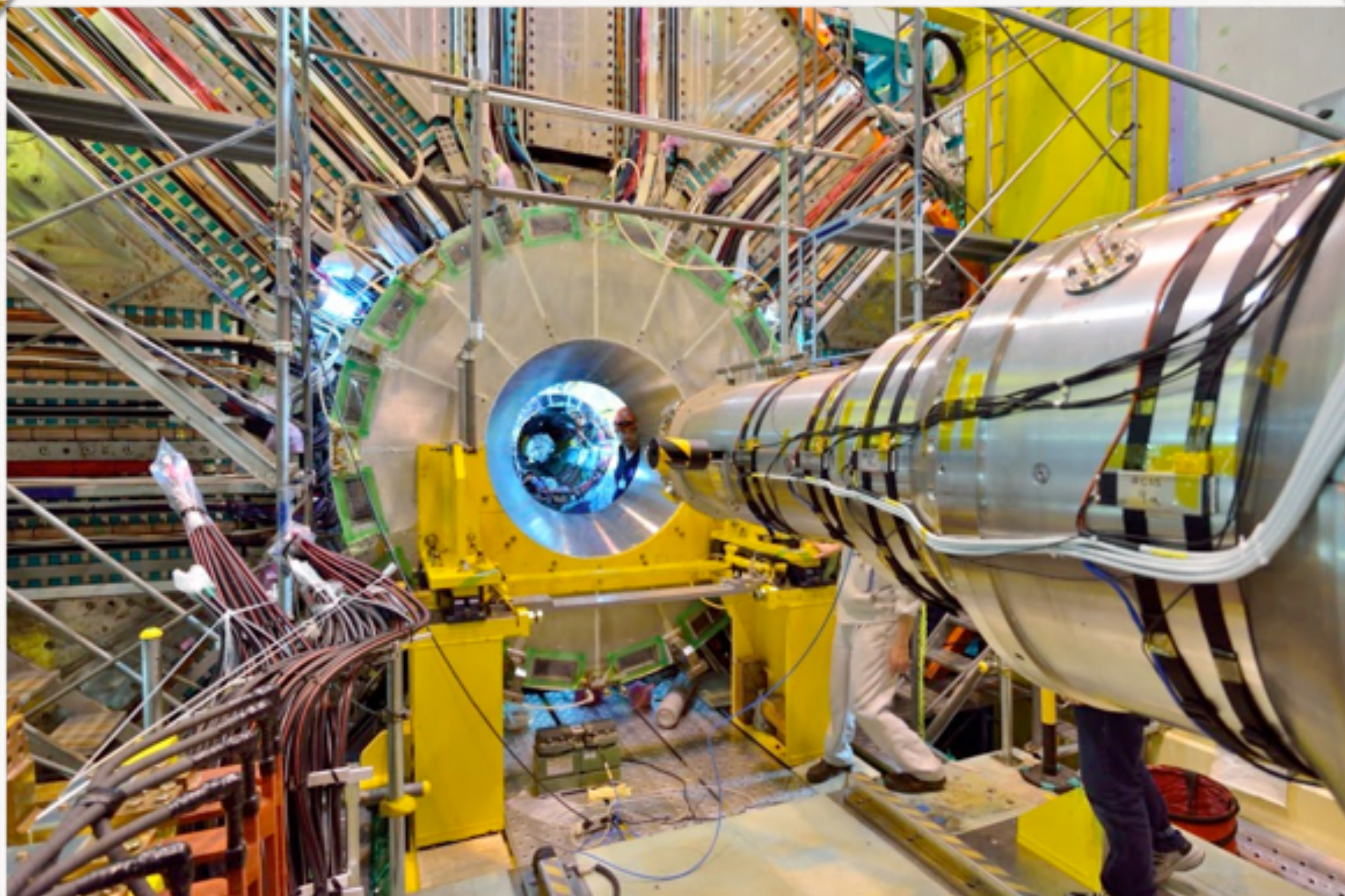
- ✓ understand machine background and detector performances
- ✓ global cosmic ray runs
- ✓ peak luminosity of 2×10^{34} cm^{-2}s^{-1}



➡ **Phase2 detector**: *Belle II* with no VXD but the Beast2 detector = one VXD ladder per layer installed on the horizontal plane + dedicated beam-background detectors

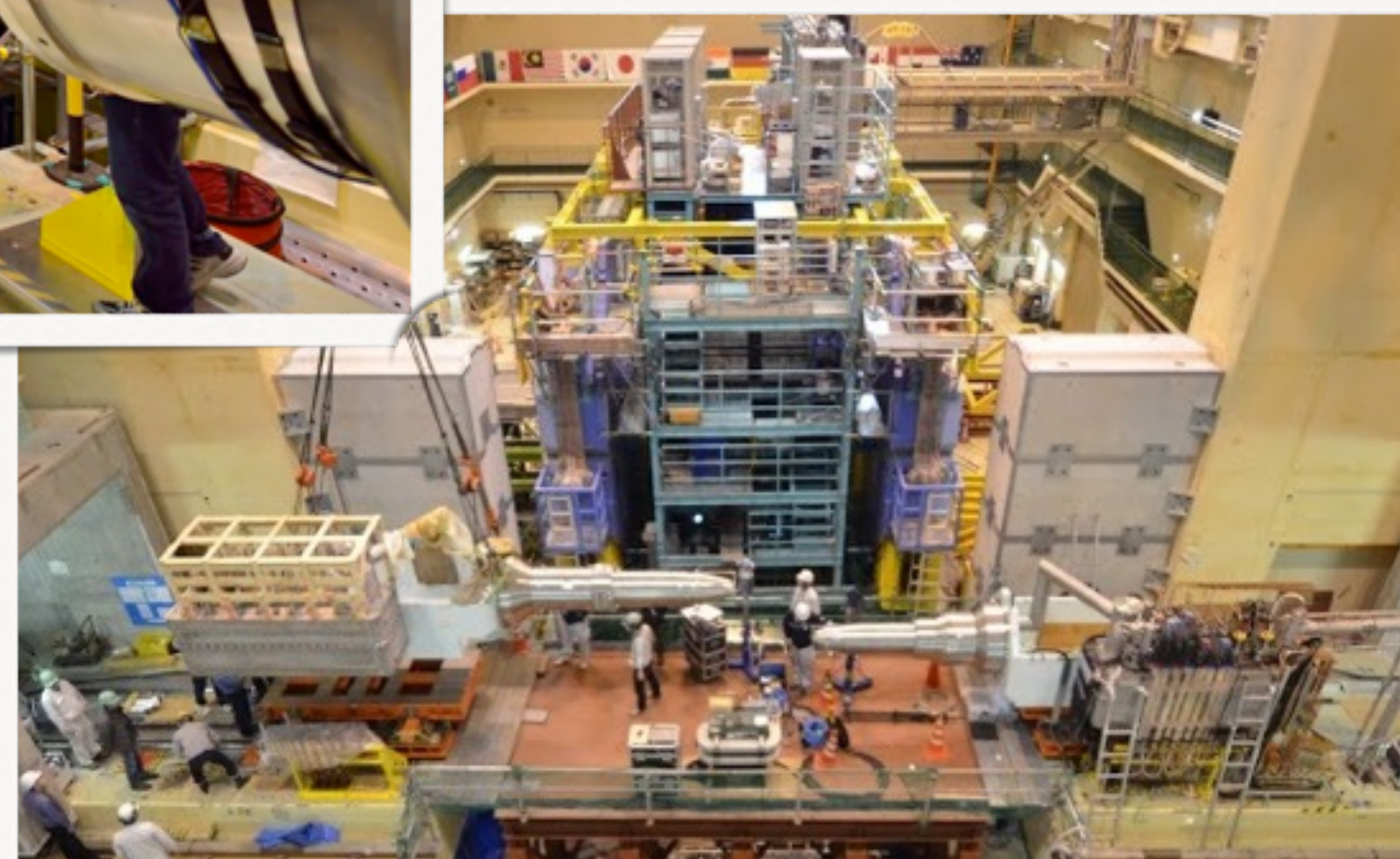
➡ **First collisions recorded on April 25th 2018!!**

SuperKEKB Final Focus



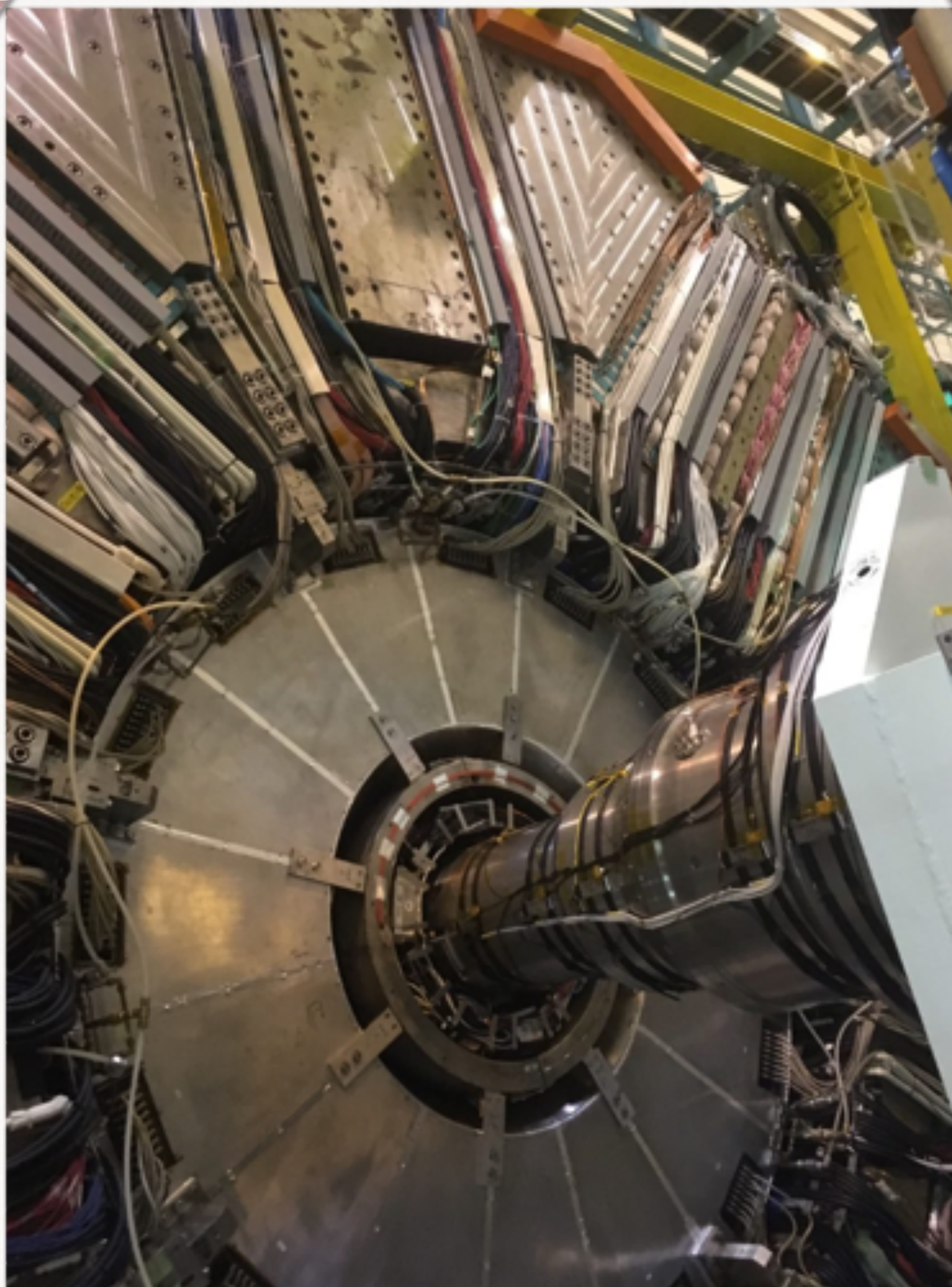
Superconducting final focus QCSL being prepared for final integration, January 2018

Final Focus installation, February 2017

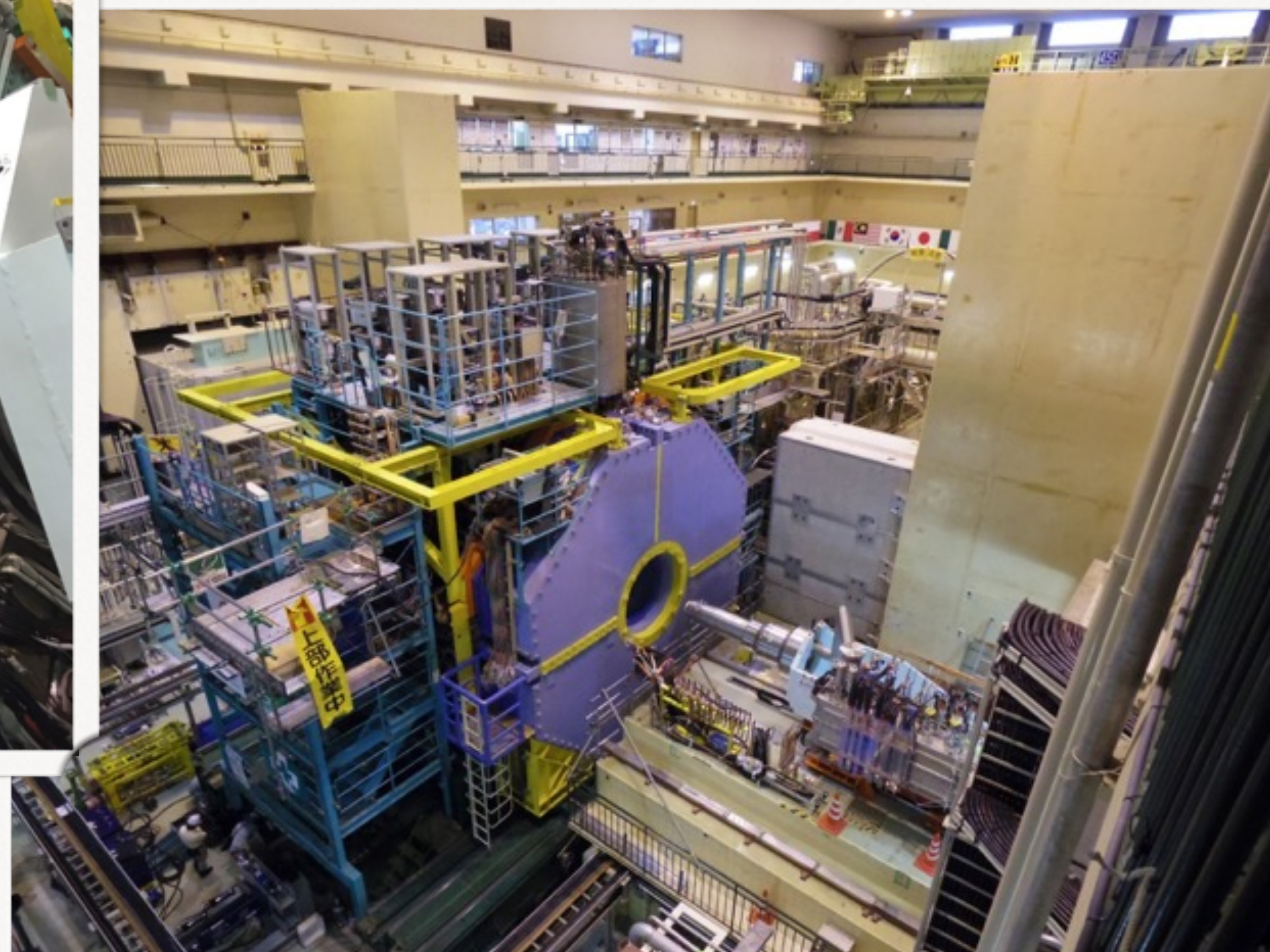


The –almost– *Belle II* Detector

- *Belle II* without the vertex detector: CDC, TOP, ARICH, ECL, KLM, plus
- Beast2: one VXD ladder per layer, plus beam-background dedicated detectors

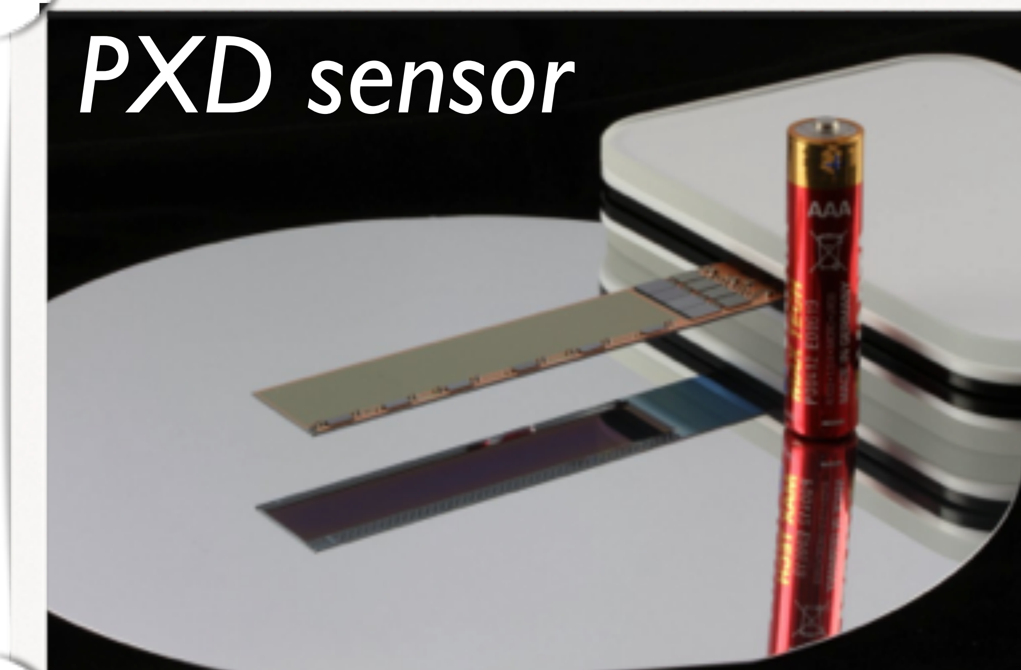


QCSR & backward side of *Belle II*, Feb 9, 2018

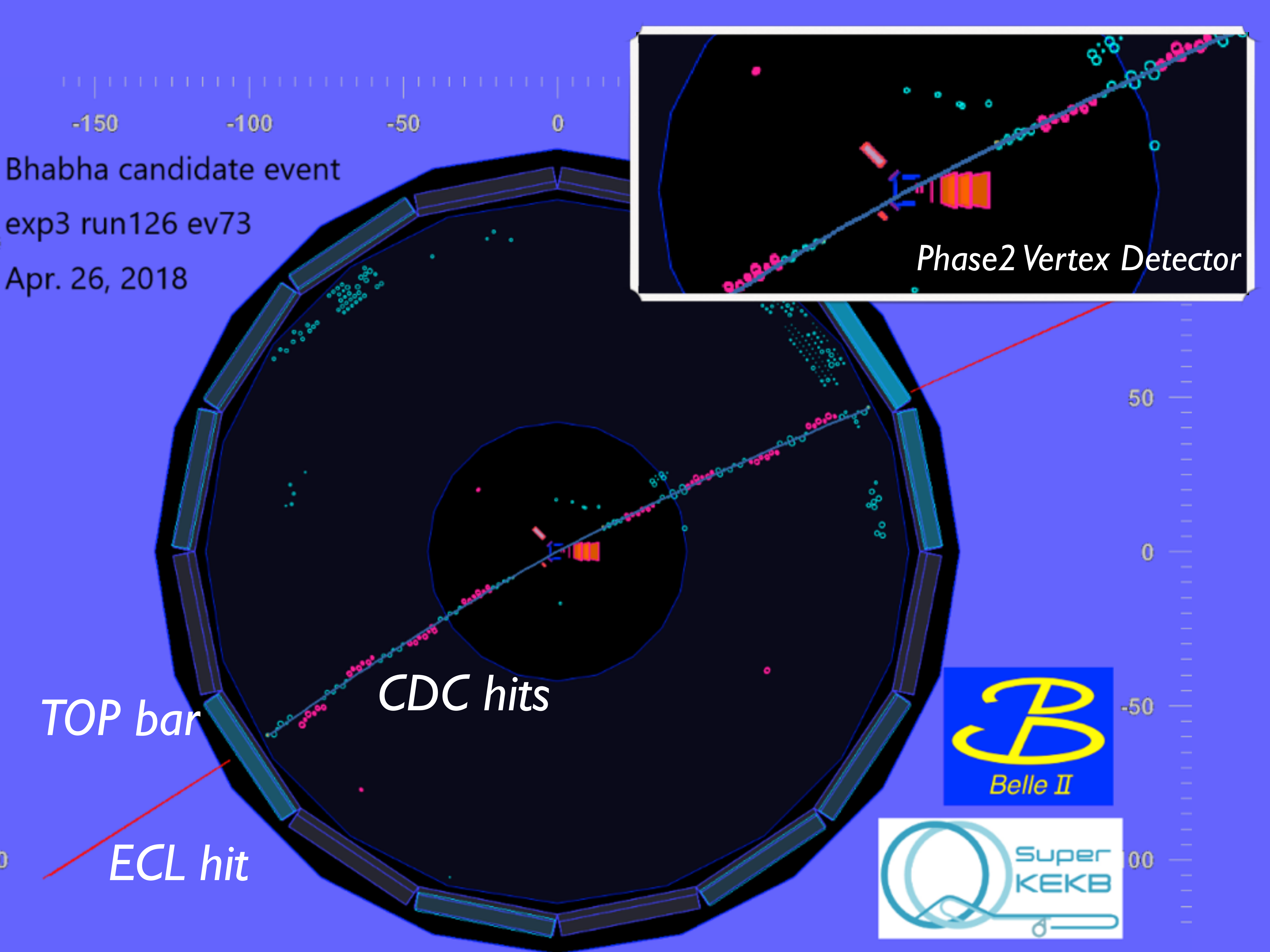


Belle II rolled-in on beam line on Apr 11, 2017

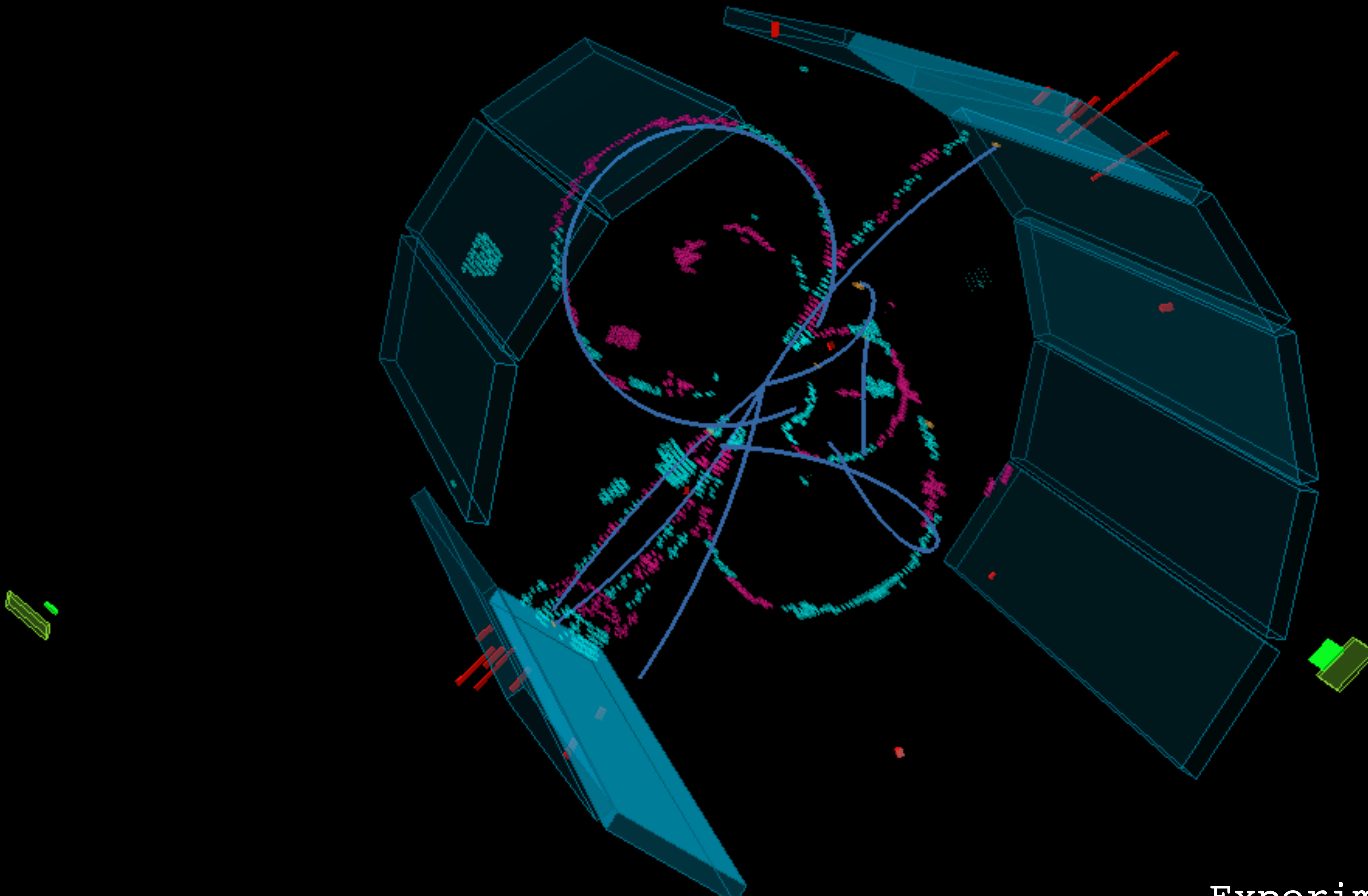
…and the missing part, the VXD!



PXD ladders


-150
-100
-50
0
Bhabha candidate event
exp3 run126 ev73
Apr. 26, 2018
Phase2 Vertex Detector
50
0
-50
CDC hits
TOP bar
ECL hit
Belle II
Super
KEKB

Luminosity Run, 26th April 2018 First Hadronic Event

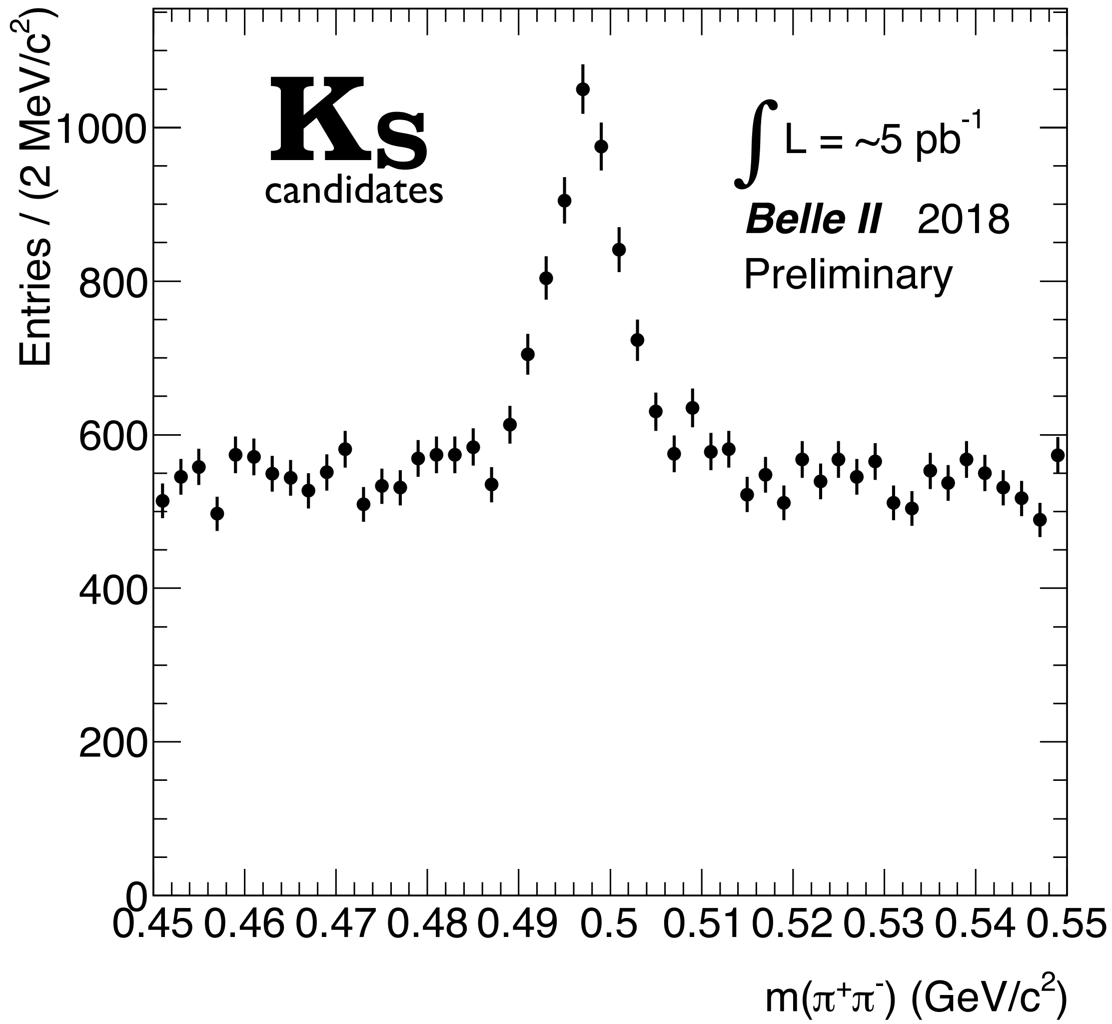


Experiment 3
Run 125
Event 223

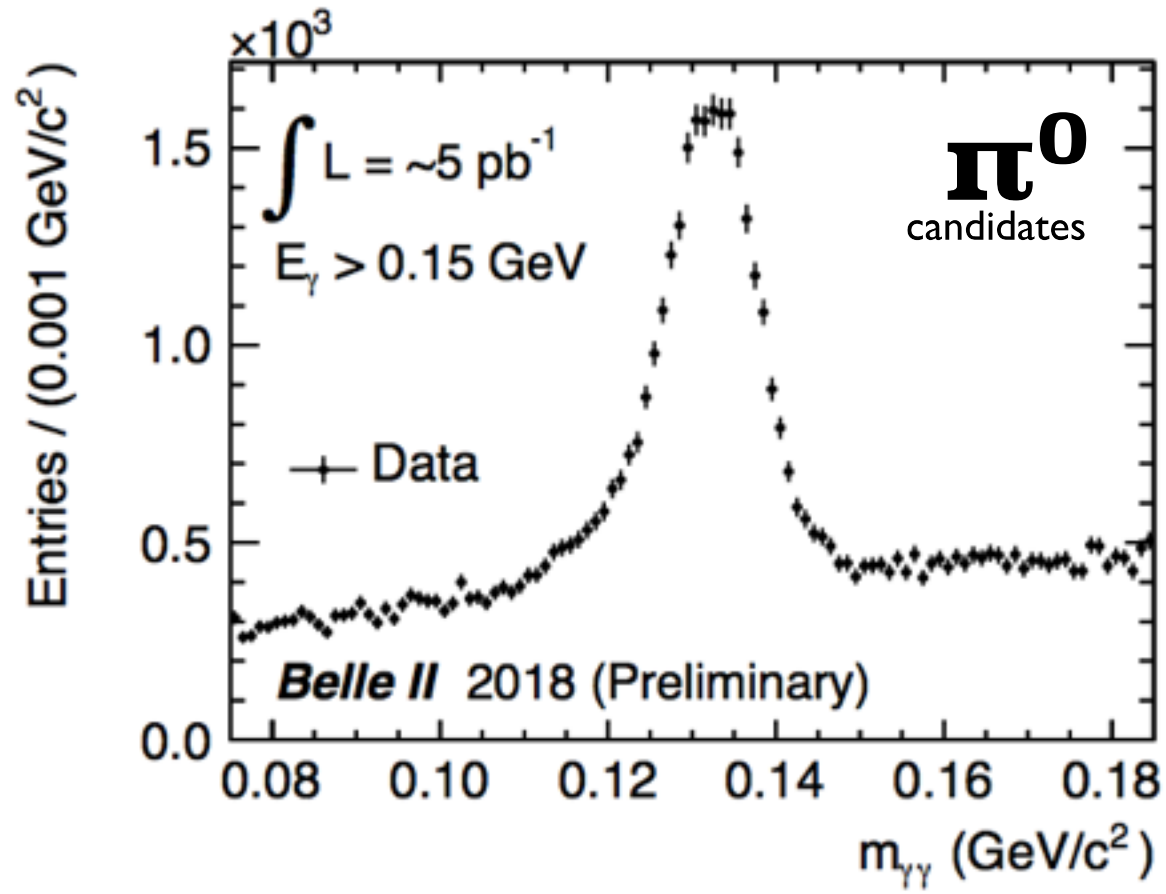
note: vertex detector not shown

…first bumps observed!

ππ invariant mass



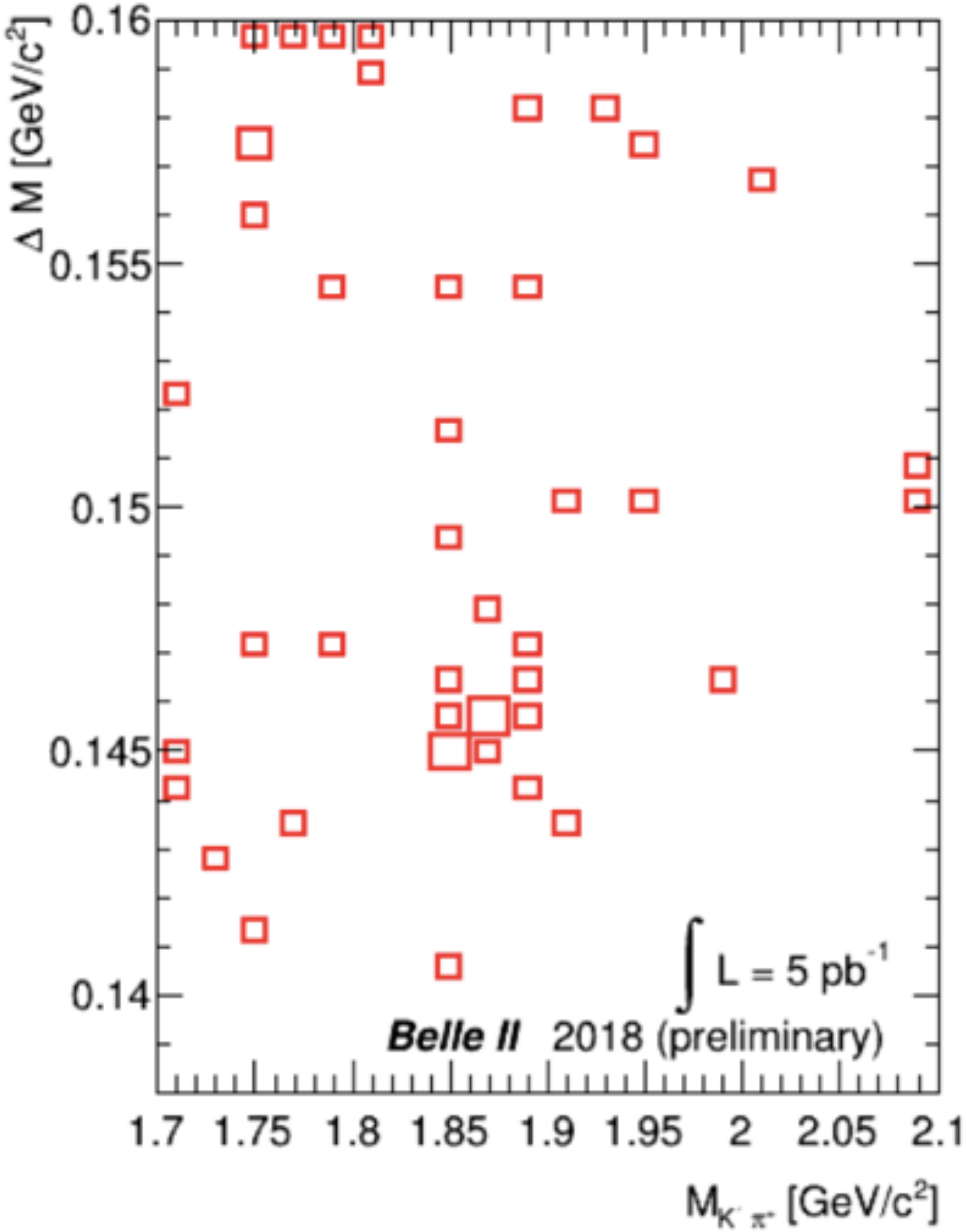
γγ invariant mass

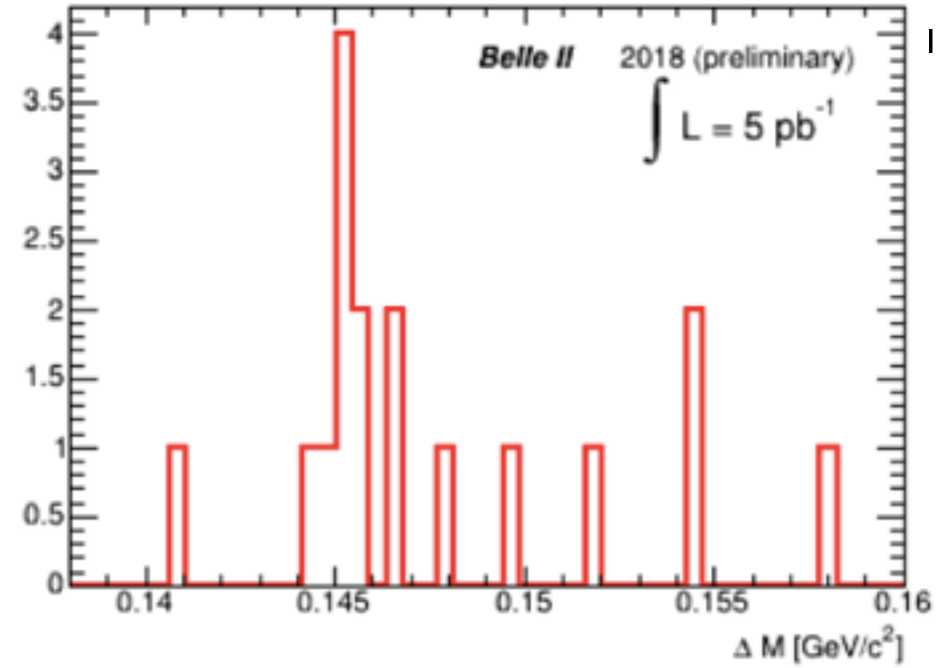


- ➡ Evidence of K_S and π^0 in the collected data sample of 5/pb
- ➡ First preliminary plots, calibrations at a very early stage, no PID cuts applied

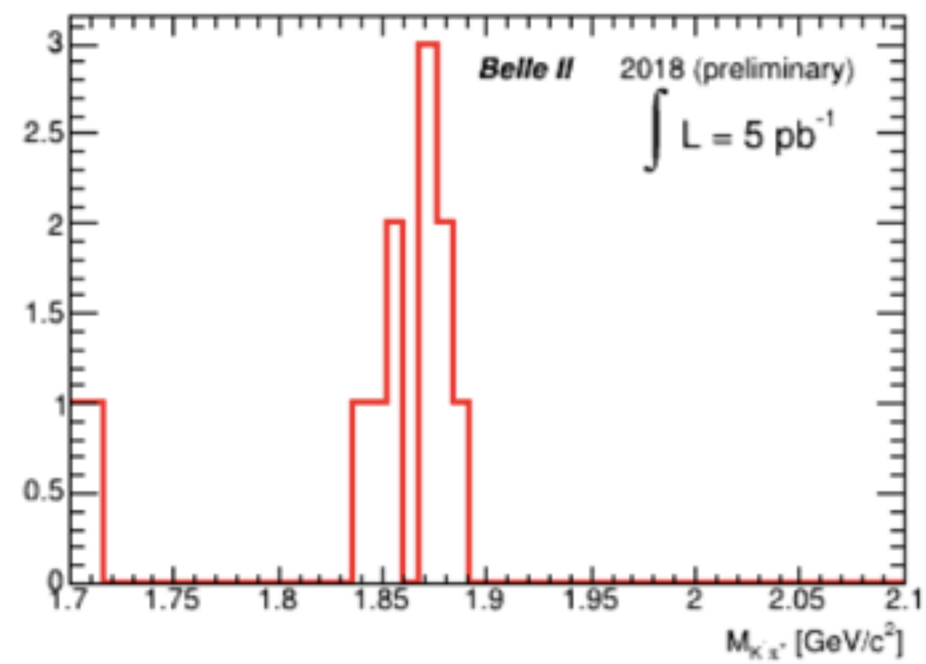
We got Charm :)

$D^* \rightarrow D^0(\rightarrow K^- \pi^+)\, \pi$





$1.845 < M(K\pi) < 1.885$ (GeV/c^2)



$0.144 < \Delta M < 0.146$ (GeV/c^2)

- ➡ Evidence of D^* and D^0 in the collected data sample of 5/pb
- ➡ First preliminary plots, calibrations at a very early stage, no PID cuts applied

Selection of Belle II Prospects on Charm

- The following projections are extrapolated from Belle measurements

$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{sys})\frac{\mathcal{L}_{Belle}}{50\ \mathrm{ab}^{-1}} + \sigma^2_{\mathrm{ired}}}$$

- we assumed that most of the systematics scale with statistics
- There maybe (other) sources of systematic errors that do not scale with statistics, that show up only in very high statistics samples
  - *Belle II* will have high statistics control samples to keep them under control
- The *detector improvements* w.r.t. Belle will be helpful, but their effect is *not included* in these extrapolations unless otherwise stated

Prospects for CP Asymmetries

M. Staric @ KEK FF 2014

$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{sys})\frac{\mathcal{L}_{Belle}}{50 \text{ ab}^{-1}} + \sigma^2_{\text{ired}}}$$

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
$D^+ \to \phi\pi^+$	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
$D^+ \to K^0_sK^+$	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
$D^+_s \to K^0_sK^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

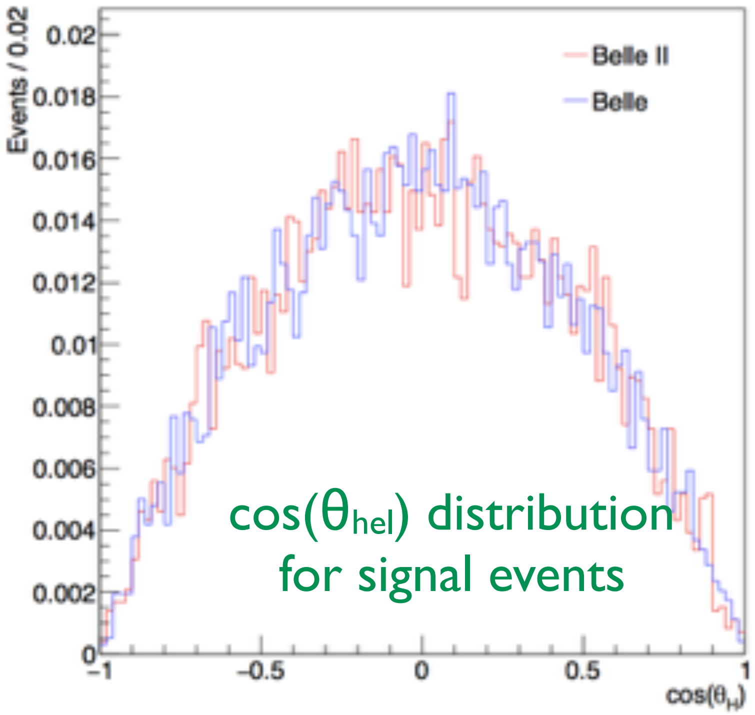
- A_{CP} precision will reach o(10^{-4}), also in channels with neutrals in the final state
- *Belle II* is favoured on measurements with neutrals in the final state
- Other interesting channels not included in this table: $D^+ \to \pi^+\pi^0$, $D^0 \to K_SK_S$, 3-body final states (DP analysis), radiative decays (in the next slide)

Radiative Decays $D^0 \to V\gamma$

1. <u>CP Violation</u>: SM expectations on the order of 10^{-3}, NP contributions can enhance it up to an order of magnitude
2. <u>tests of QCD</u>: transitions dominated by long-range diagrams

- ➡ A_{CP} and BR measurements of decays $D^0 \to V\gamma$ completed at Belle
- ➡ dominant error for A_{CP} is statistical, *BelleII* can significantly improve the precision

  - *Studies on BelleII official MC have shown that $m(D^0)$ and $\cos(\theta_{hel})$ distributions have resolutions similar Belle, allowing an extrapolation based on luminosity*



A_{CP} estimated error on	*Belle*	*Belle II statistical error*		
	1/ab	5/ab	15/ab	50/ab
$D^0 \to \rho^0 \gamma$	± 0.152 ± 0.006	± 0.07	± 0.04	± 0.02
$D^0 \to \Phi \gamma$	± 0.066 ± 0.001	± 0.03	± 0.02	± 0.01
$D^0 \to \overline{K^{*0}} \gamma$	± 0.020 ± 0.000	± 0.01	± 0.005	± 0.003

Mixing & Indirect CPV Prospects

$$\sigma_{BelleII} = \sqrt{(\sigma^2_{stat} + \sigma^2_{sys})\frac{\mathcal{L}_{Belle}}{50\ \mathrm{ab}^{-1}} + \sigma^2_{\mathrm{ired}}}$$

M. Staric @ KEK FF 2014

channel	observable	Belle $\sim 1\ ab^{-1}$	Belle II $50\ ab^{-1}$
$D^0 \to K^+\pi^-$	x'^2 (%)	± 0.022	± 0.003
	y' (%)	± 0.34	± 0.04
	$\lvert q/p \rvert$	± 0.6	± 0.06
	ϕ	± 25°	± 2.3°
$D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$	y_{CP} (%)	± 0.22	± 0.04
	A_Γ (%)	± 0.20	± 0.03
$D^0 \to K_S\pi^+\pi^-$	x (%)	± 0.19	± 0.08
	x (%)	± 0.15	± 0.05
	$\lvert q/p \rvert$	± 0.16	± 0.06
	ϕ	± 11°	± 4°

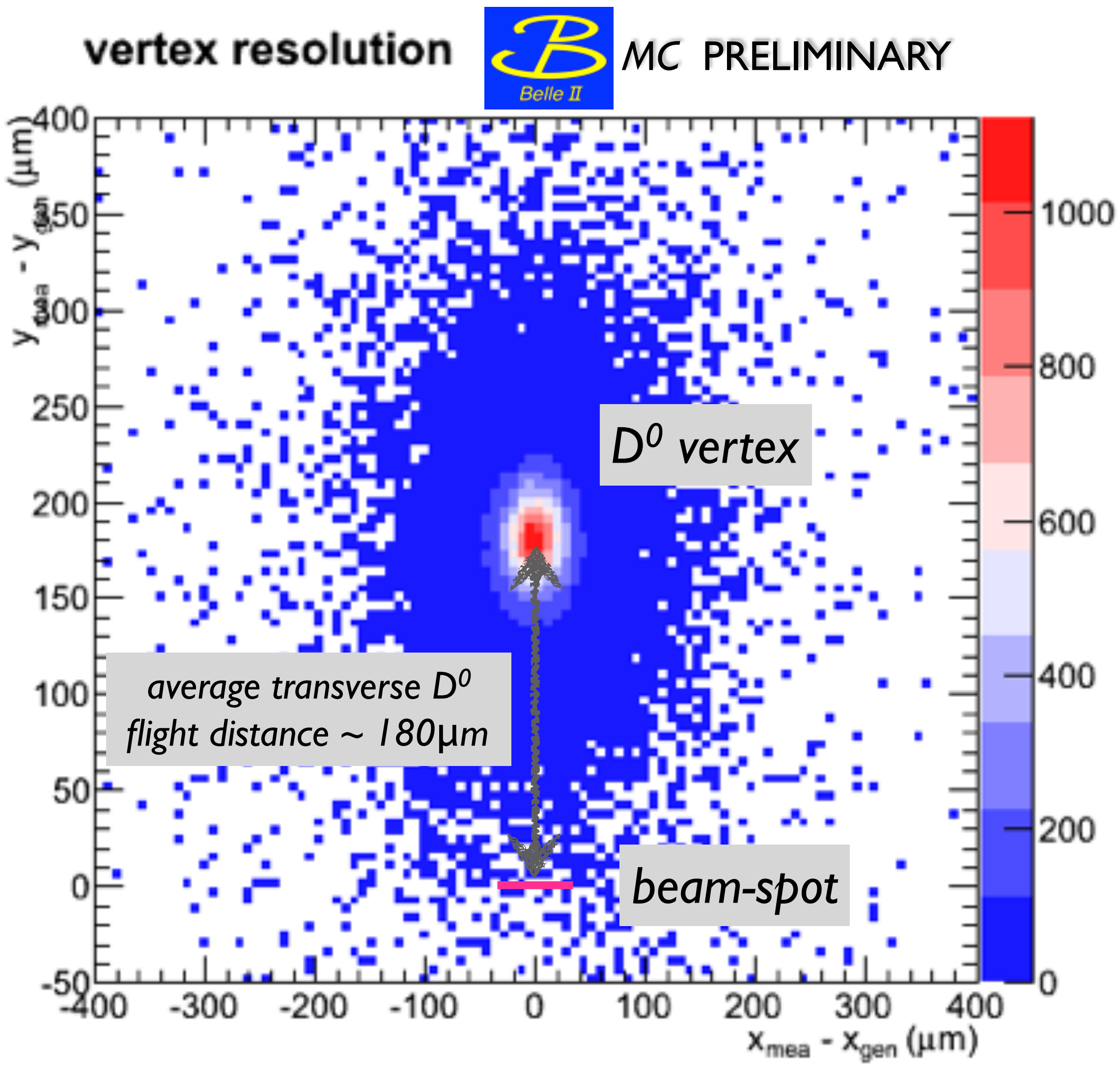
~ *factor 8-10 better* — systematics free measurement

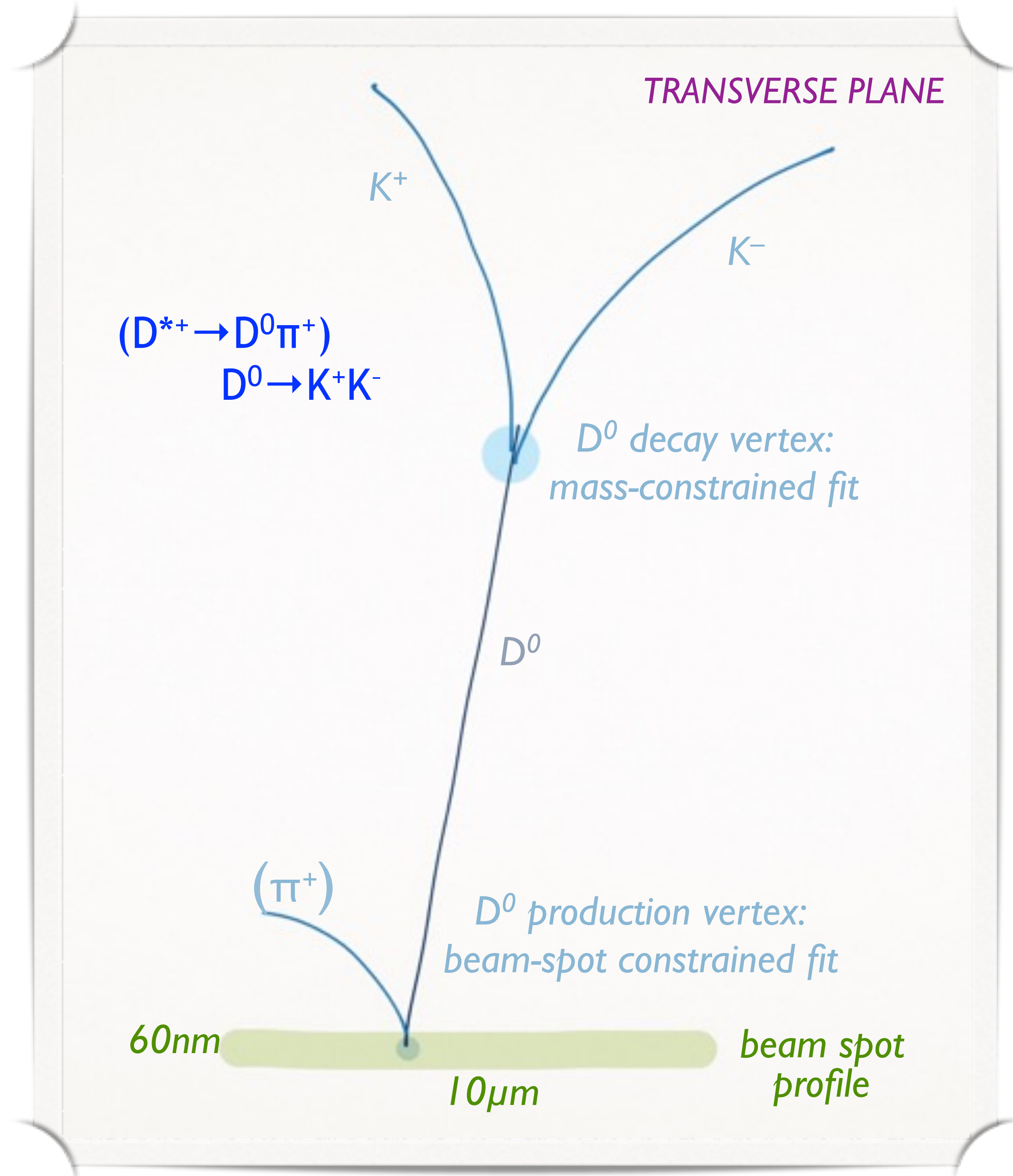
~ *factor 6 better* — comparable contributions from statistical and systematic errors

~ *factor 3 better* — limited by systematics related to DP Model

can be improved using a model-independent approach to reduce the systematics!

D^0 Decay Vertex Resolution





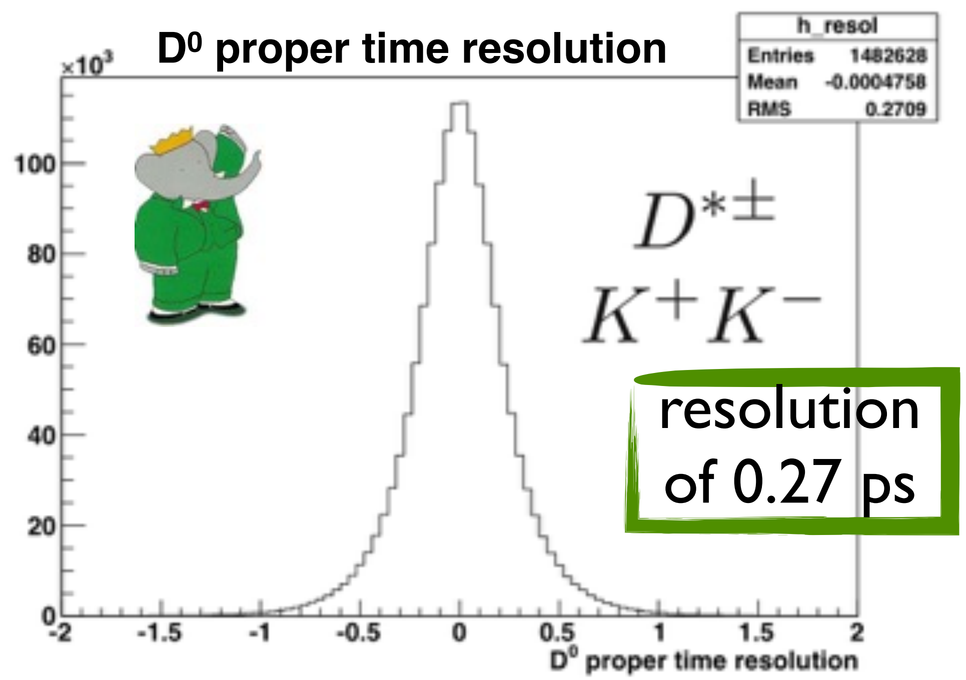
NOTE: the cartoon is not to scale

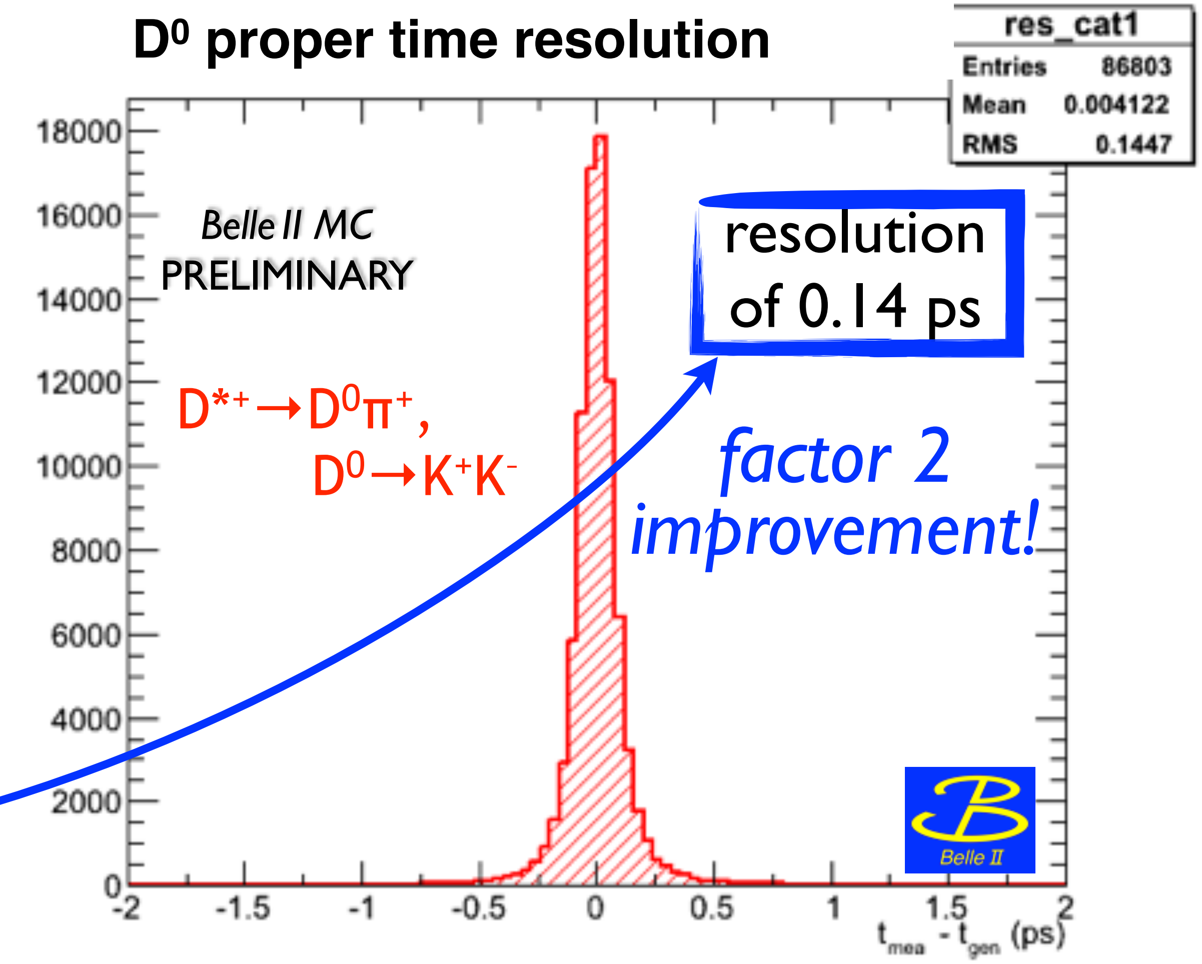
- D^0 *mass–constrained* vertex fit yields a resolution of the vertex position of ~40µm in transverse plane and also in the longitudinal direction
- $D^{*+} \to D^0\pi^+$ beam-spot constrained fit yields an *unprecedented* precision of the determination of the D^0 decay vertex

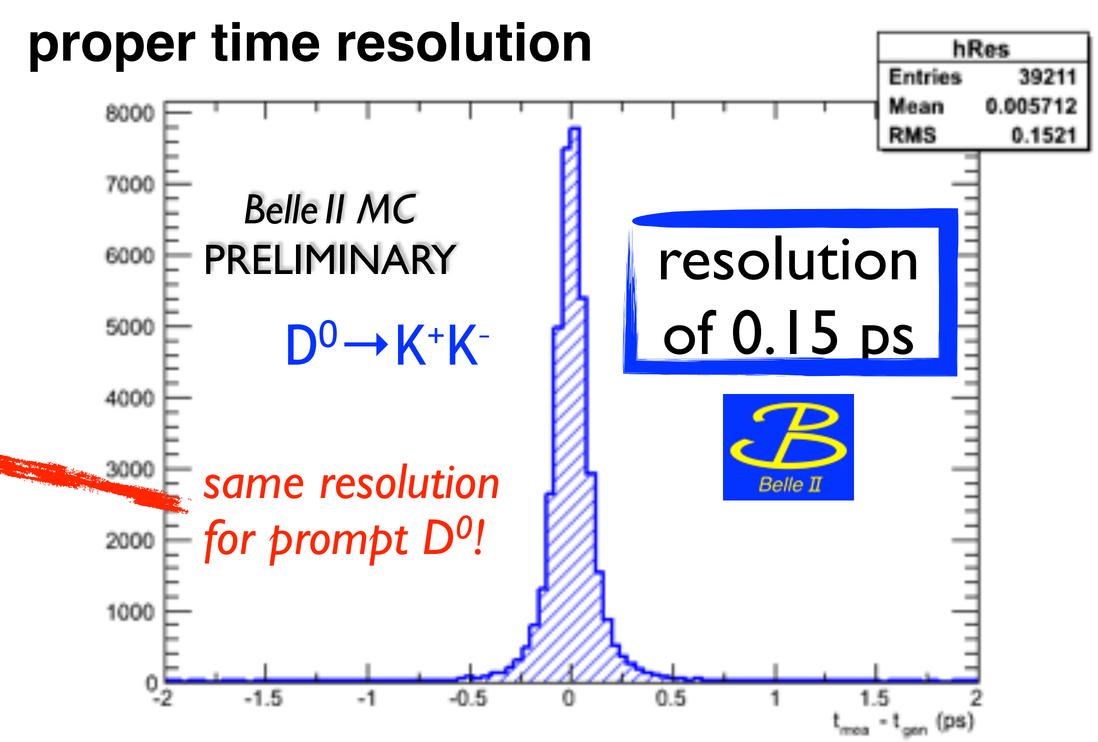
BaBar *beam-spot:* 6µm x 110 µm

D^0 Proper Time Resolution

➡ The factor 2 improvement on the track impact parameters directly reflects on charm reconstruction







Is there a way to determine the flavour of the prompt D^0, i.e. not coming from a charged D decay?*

… work in progress …

Impact on WS $D^0 \to K^+\pi^-$

The WS $D^0 \to K^+\pi^-$ mixing and CPV analysis is almost systematic-free, perfect candidate to evaluate the impact of an improved resolution of the proper time.

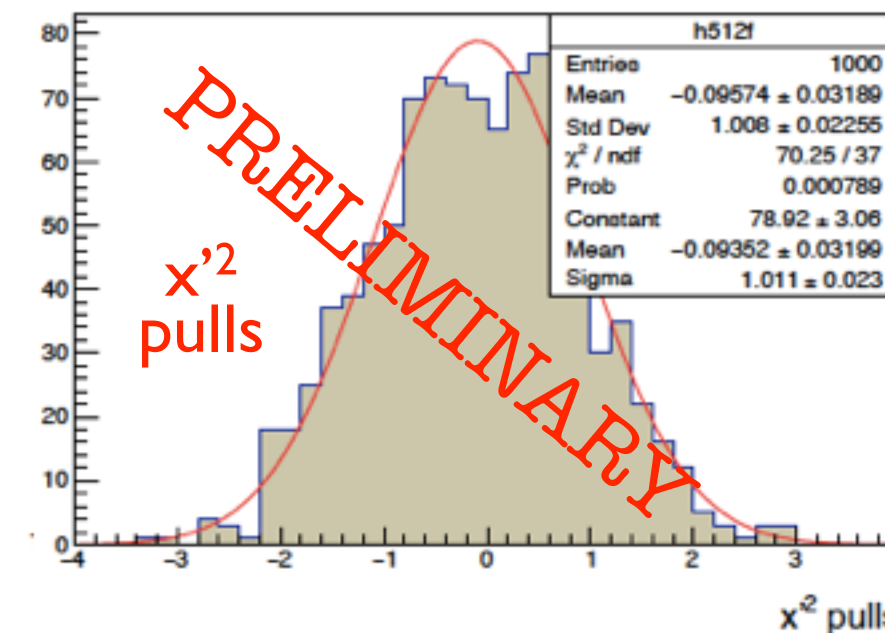
➡ ToyMC studies: w/o CPV allowed

- fit decay time distribution for mixing and CPV parameters R_D, x', y', |q/p|, ϕ (*sensitive to the sign of x'!*)
- use different PDFs for D^0 and $\overline{D}^0$ (both convolved with a Gaussian resolution function)

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

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

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



estimated error on	current HFAG	Belle + BaBar 1.5/ab	scaled 50/ab	Toy MC with improved σ_t 50/ab, no CPV	Toy MC with improved σ_t 50/ab, CPV
x' (%)	–	(*) 0.98	(*) 0.45	(*) 0.22	0.15
x'^{2} (%)	–	0.0195	0.009	0.0044	–
y' (%)	–	0.321	0.16	0.047	0.10
|q/p|	0.1				0.051
Φ (deg)	10	–	–	–	5.7

Improved sensitivity, *beyond* increase of luminosity!

Full Charm Event Reconstruction

➡ use the **recoil method** successfully exploited for D_s decays:

$$e^+e^- \to c\bar{c} \to D_{\text{tag}} X_{\text{frag}} D_{\text{sig}}$$

- X_{frag} → light mesons (K, π, …)
- D_{tag} → reconstructed in several channels (D^0, D^*, D_s, …)
- D_{sig} → signal channel

➡ use energy and momentum conservation to search for the desired final state:

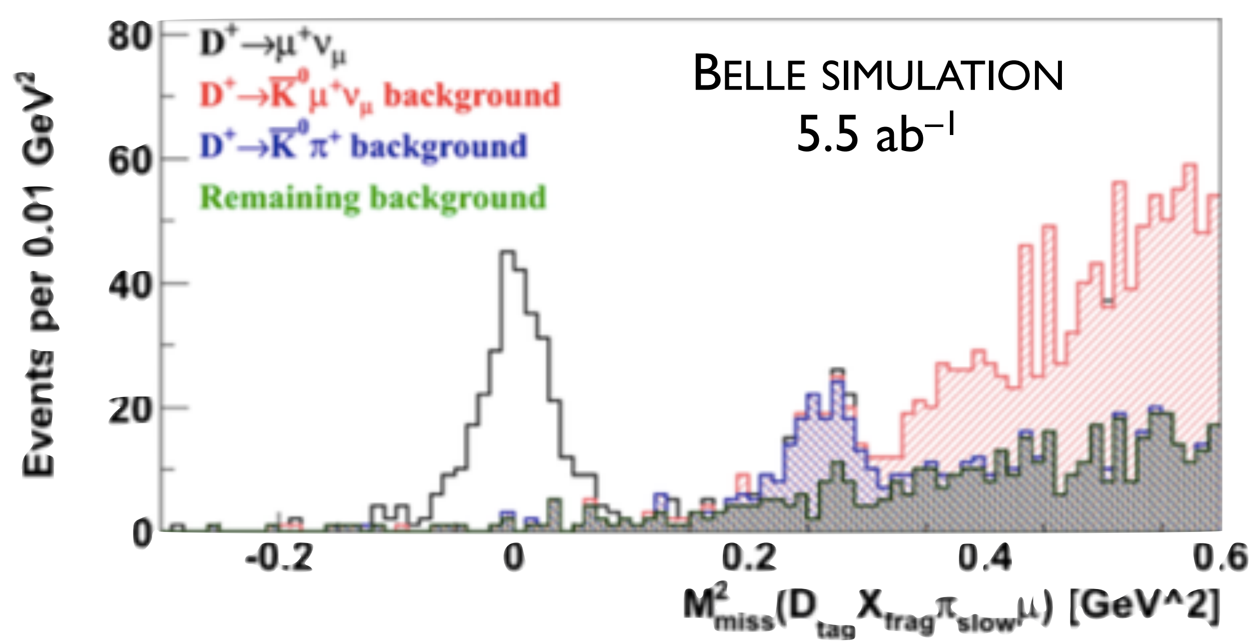
- *example*:

$$D_{\text{sig}} = D^{*+} \to D^+ \pi_{\text{slow}};\ \boxed{D^+ \to \mu^+ \nu}$$

- "miss" quantities computed for the system:

$$D_{\text{tag}} + X_{\text{frag}} + \pi_{\text{slow}} + \mu^+$$

$$M^2_{miss}(\nu\ ) = (E_{\text{miss}} - |\vec{p}|_{\text{miss}})(E_{\text{miss}} + |\vec{p}|_{\text{miss}})$$



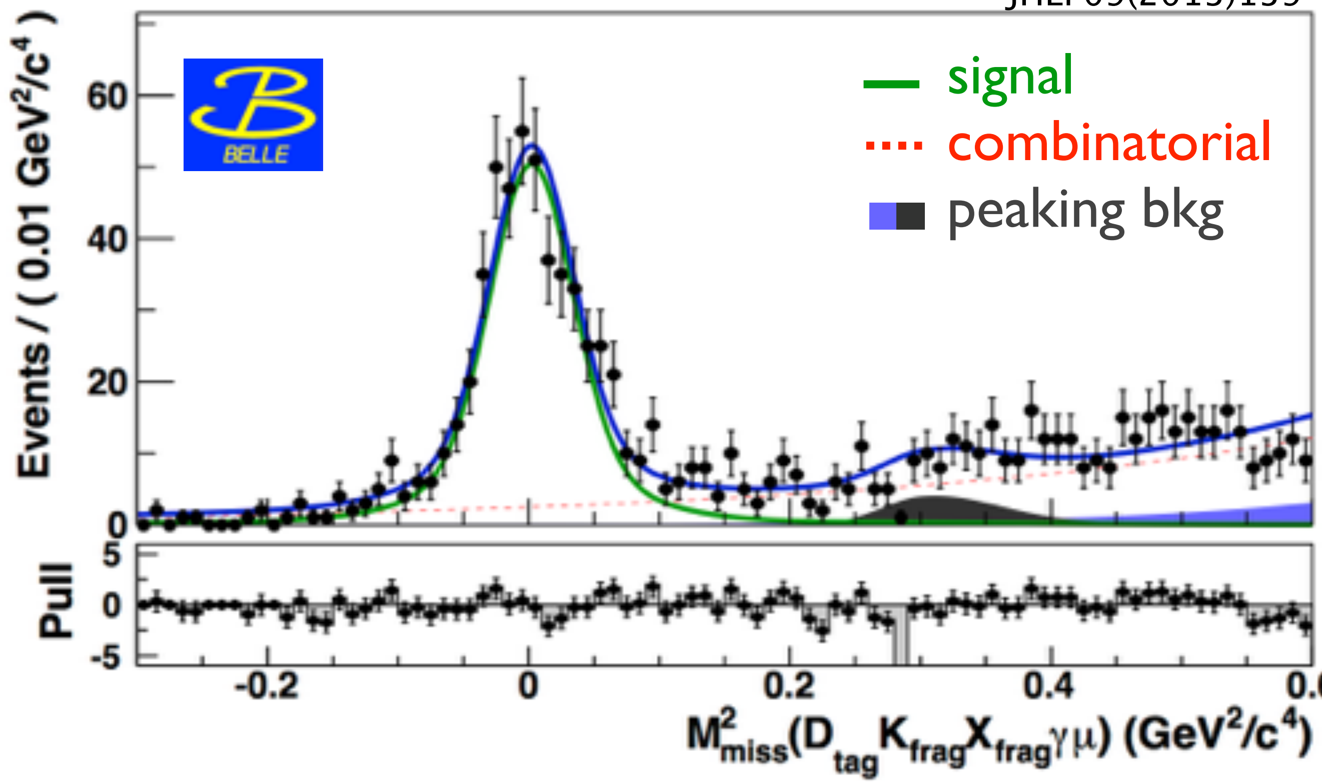
Leptonic Decays: $D_{(s)}^{-} \to \mu^{-} \nu$

➡ $D_s^+ \to \mu^+ \nu$ Belle Analysis:

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

- require one charged track passing muon-ID pointing the IP
- fit the missing mass distribution.

JHEP09(2013)139



➡ Same analysis method for the D^+ channel

- Belle simulation with 5.5 ab^{-1}, scaled to 50 ab^{-1}, yields:

yields	$D_s^+ \to \mu^+\nu$		$D^+ \to \mu^+\nu$	
	inclusive	exclusive	inclusive	exclusive
Belle, 913 fb^{-1}	94400	490	–	–
BelleII, 50 ab^{-1}	5.2×10^6	27×10^3	3.5×10^6	1250

$\delta(|V_{cs}|) = 0.004$, $\delta(|f_{Ds}|) = 0.9$

statistical error ~1/3 of the theory error

$\delta(f_d|V_{cd}|) = 1.3$

competitive with CLEOc and BESIII

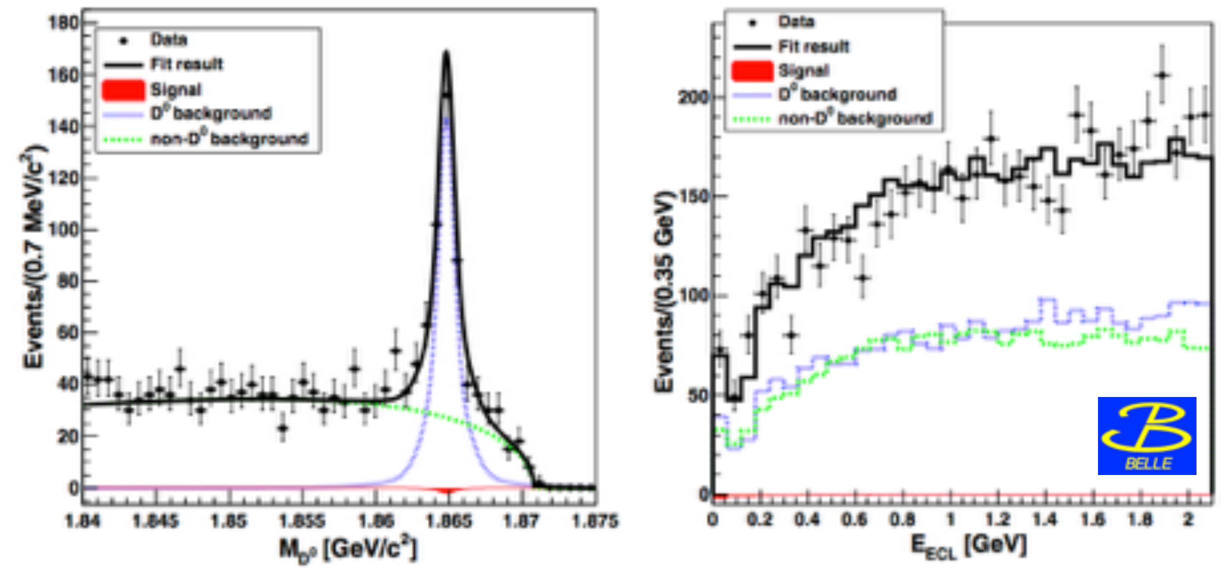
D^0 Decays to Invisible: $D^0 \to \nu\nu$

➡ $D^0 \to \nu\nu$ Belle Analysis:

$$e^+e^- \to D_{\text{tag}} X_{\text{frag}} D^{*+}$$

$$D^{*+} \to D^0 \pi_s^+$$

- require no extra-charged tracks of photons, π^0, …
- fit the missing mass and ECL energy distributions.



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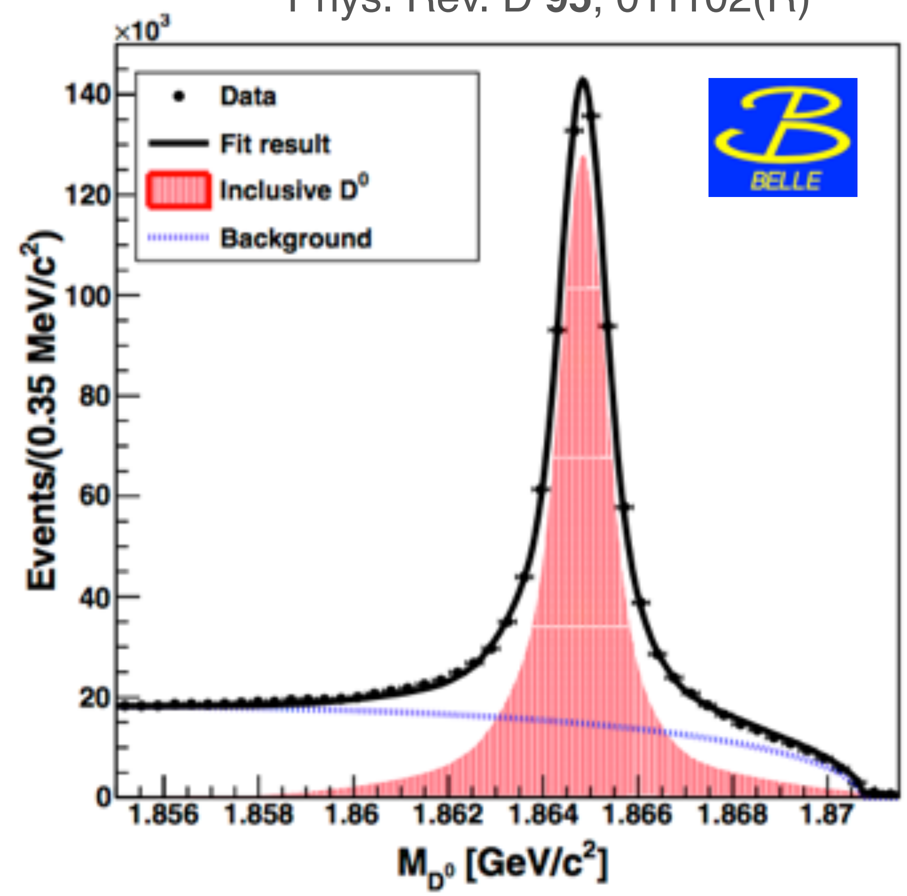


yields	inclusive D^0
Belle, 924 fb^{-1}	695000
BelleII, 50 ab^{-1}	38×10^6

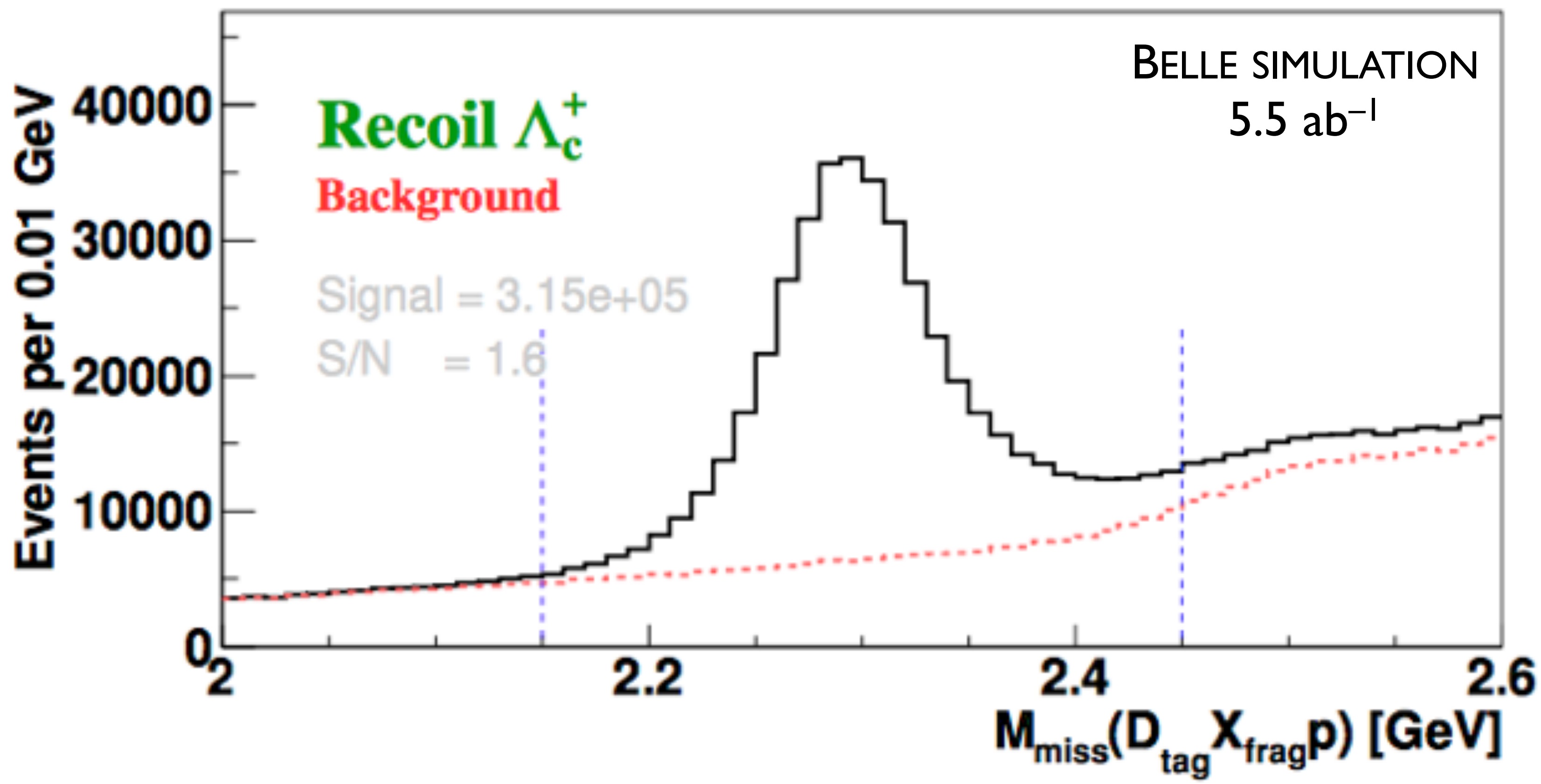
nearly 40M inclusive D^0 decays to search for forbidden/rare decays

Inclusive Λ_c^+ Sample

Extension of the Full Charm Event Reconstruction with:

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

- in this case $M_{miss} = \Lambda_c^+$ mass

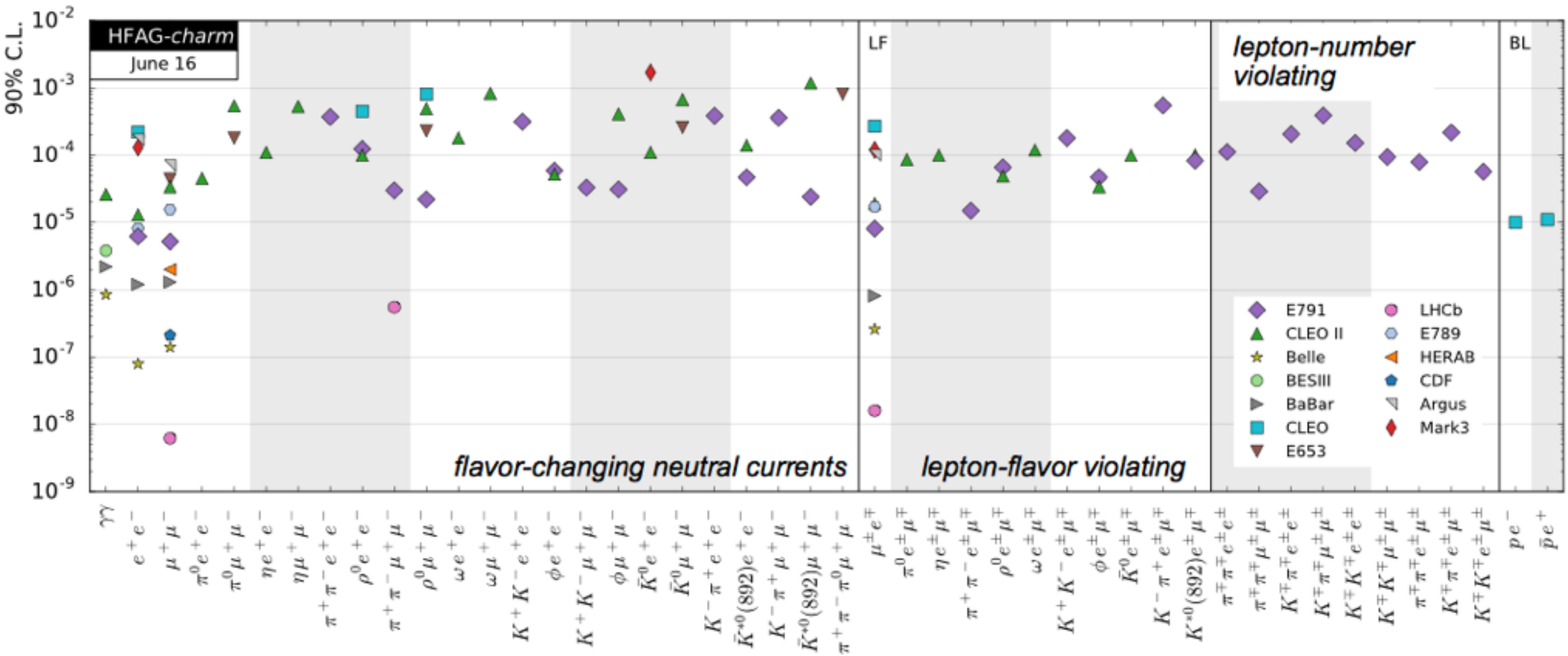


➡ *BelleII* simulation scaled to 50 ab^{-1} yields **2.8×10^6 inclusive Λ_c^+**

➡ **Unique** sample that allows to:

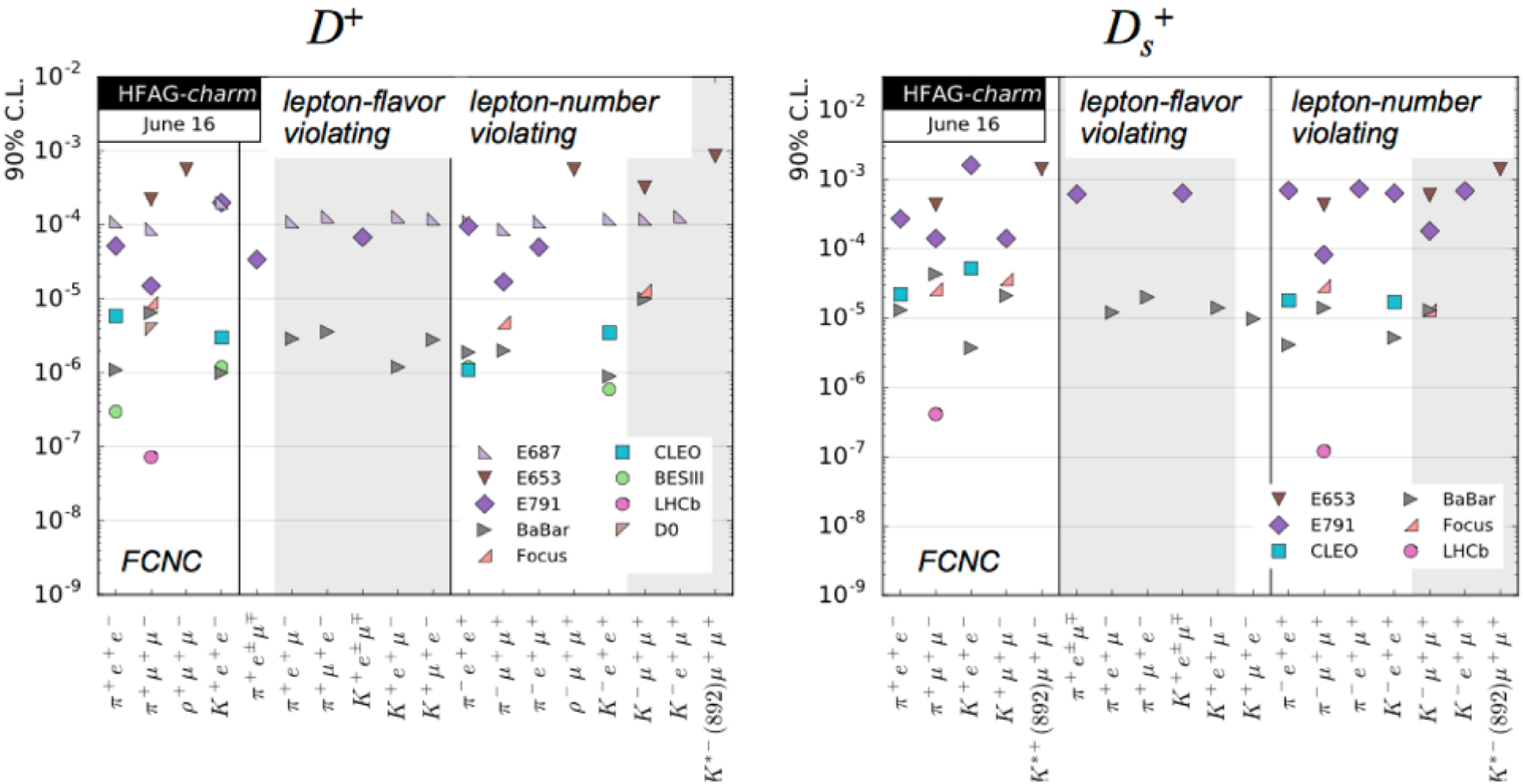
- measure absolute branching fractions
- measure semileptonic decays
- search for rare decays with missing energy

Rare/Forbidden D^0 Decays



➡ *BelleII* can improve on many of these channels up to one order of magnitude at 50 ab^{-1}, having largest impact on the modes with π^0s (and electrons) in the final state.

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



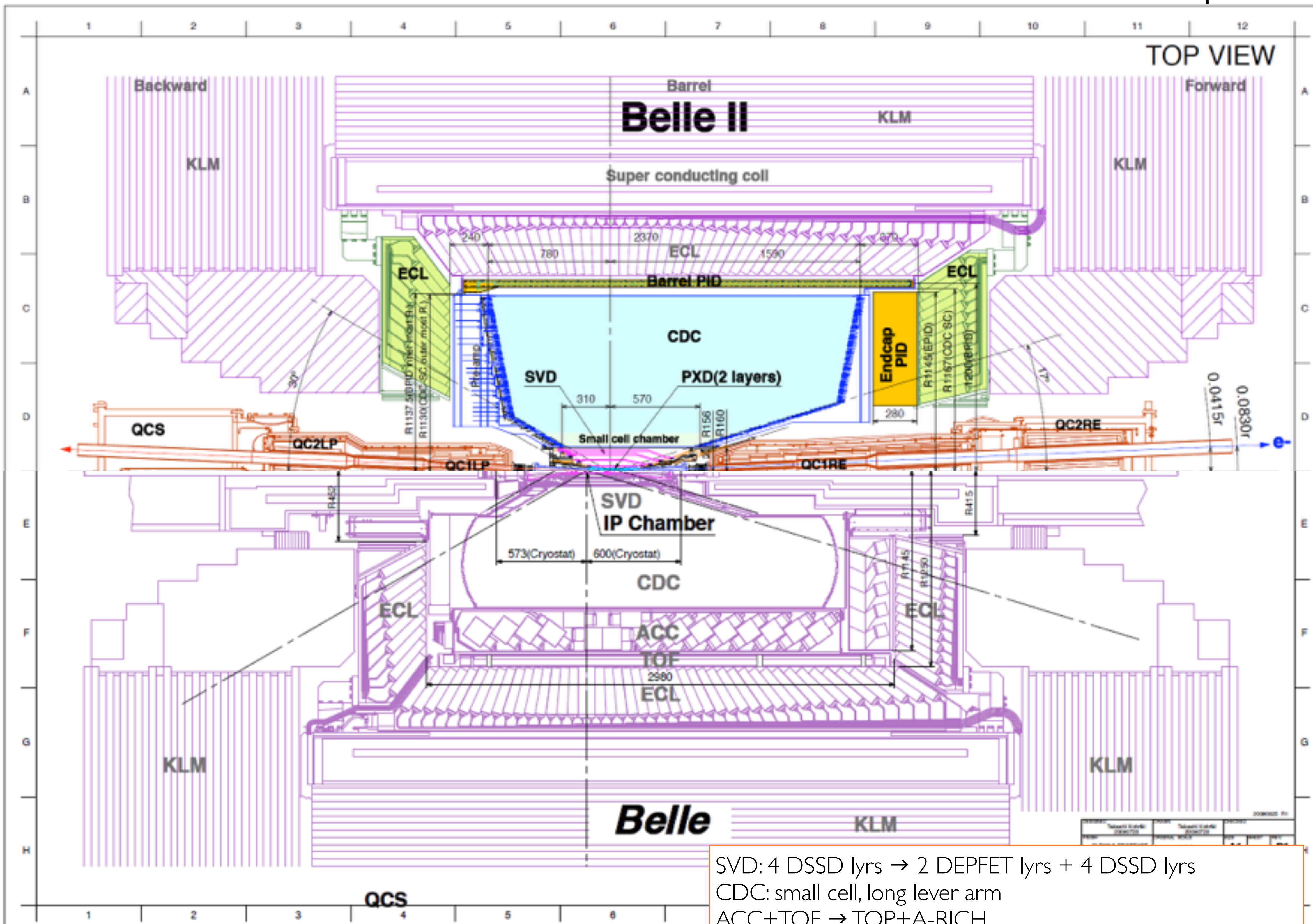
➡ *BelleII* can improve on many of these channels up to one order of magnitude at 50 ab^{-1}

Conclusions

- *SuperKEKB is completing commissioning phase, first collisions achieved one month ago!*
- *Phase2 data taking started:*
  - *understand the machine and the backgrounds, detector and software checkout, possible initial physics studies*
  - *all efforts to ensure rapid luminosity ramp up and a 9 months per year running period*
- *Physics Run will start in less than a year, at the beginning of 2019*
- *A rich charm physics program ahead, ready to improve precision on:*
  - *direct CP asymmetries, mixing and CPV parameters*
  - V_{cd} *and* V_{cs} *from semileptonic decays, decay constants* f_D, f_{Ds}
  - *measurements of charm baryons*
  - *limits on rare and forbidden decays*

BelleII VS Belle

in colours the new components



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 endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

Charm Physics @ a High-Luminosity B-Factory

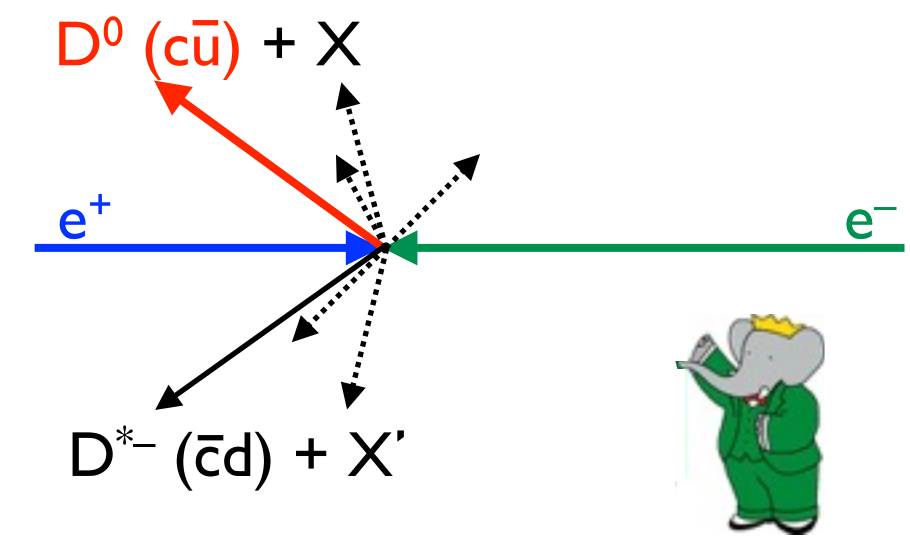
- No coherent production of the $D^0 - \bar{D}^0$ state:
  - no access to strong phases
  - D^0 flavour tagging with D^{*+} decays (lower efficiency, higher purity w.r.t. untagged D^0)

    + tagged prompt D^0 + D from B decays
- Time-dependent analysis are possible assuming that D are produced at the interaction point

$$t = \ell/(\beta\gamma c)$$

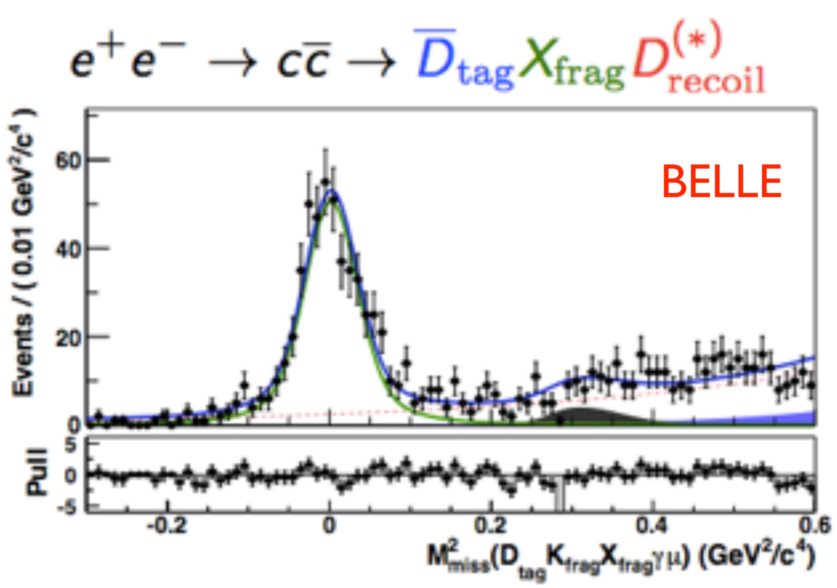
+ benefits from the improved tracking

- D full reconstruction for neutrinos and inclusive analyses (precise test of LQCD and NP searches in (semi)leptonic decays)



- average D^0 flight length $\ell \approx 200$ μm
- average proper time error ≈ ~~0.28~~ 0.15 ps
- p*(D^0) > 2.5GeV/c removes 98% of D from B decays

may remove this cut depending on the D reconstruction technique



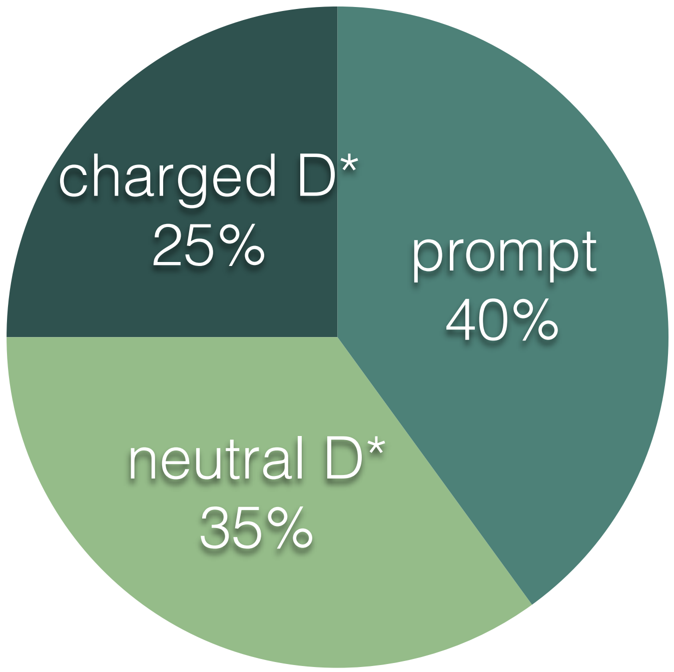
BelleII expected perfomance

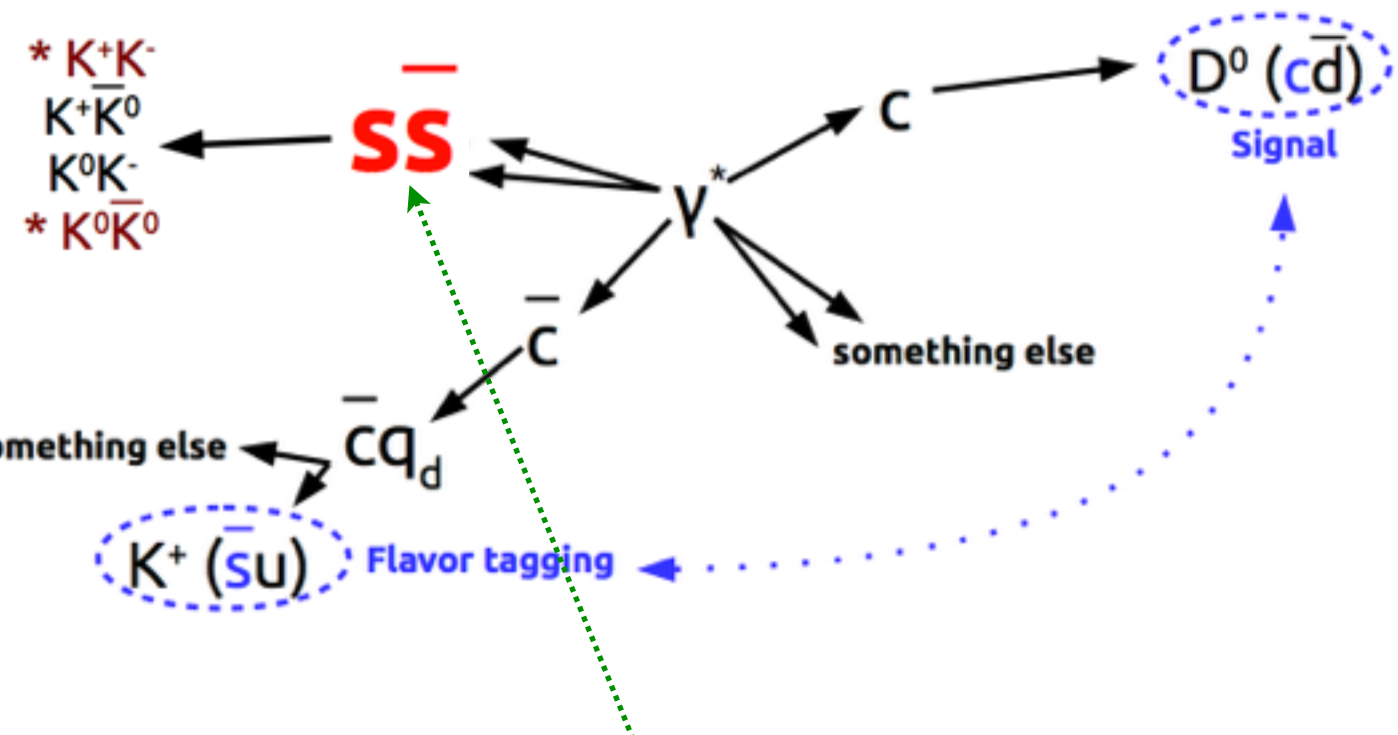
- The *Belle II* expected performances allow to develop reconstruction algorithms and experimental techniques that were not feasible at the B-Factories

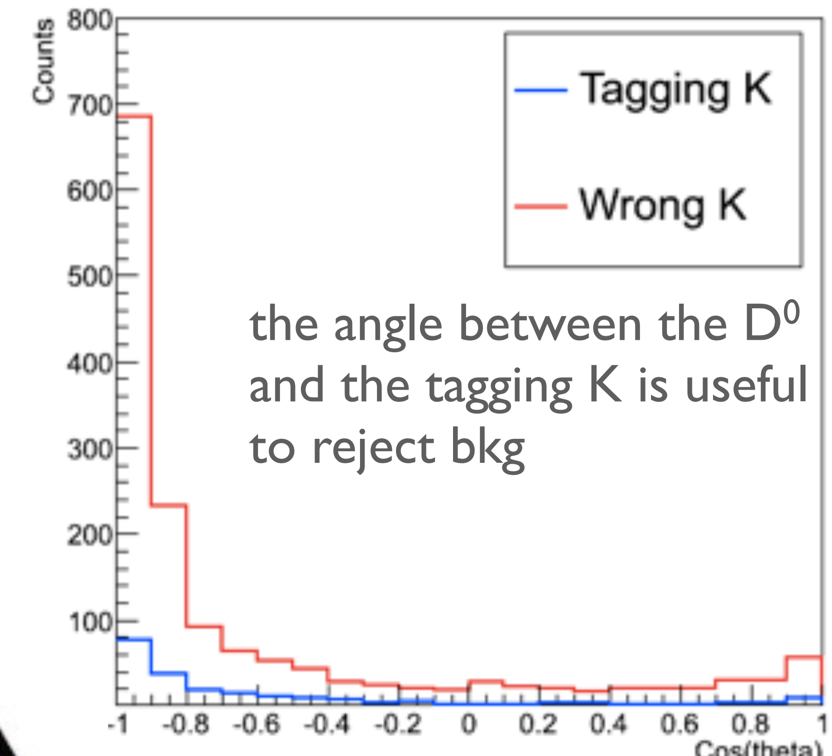
Prompt D^0 Flavour Tagging

- ➡ Only 1/4 of the D^0 produced in the $e^+e^- \rightarrow c\bar{c}$ events are flavour tagged with $D^{*+} \rightarrow D^0\pi^+$ and used for CP violation measurements
- ➡ Implement a reconstruction technique that allows to tag the flavour the rest 75% of produced D^0 looking at the rest of the event
  - select events with one single D^0 and one single charged K in the rest of the event

D^0 mothers in $c\bar{c}$ events







- ➡ flavour mis-tagging due to $c\bar{c}s\bar{s}$ events that introduce un-correlated charged kaons into the rest of the event
- ➡ irreducible bkg due to DCS decays
- ➡ First studies on generated events (no reconstruction) are encouraging: 20% reconstruction efficiency

Heavy Flavour Averaging Group Summary Tables

Parameter	No CPV	No direct CPV in DCS decays	CPV-allowed	CPV-allowed 95% CL Interval
x (%)	$0.46\,^{+0.14}_{-0.15}$	$0.41\,^{+0.14}_{-0.15}$	0.32 ± 0.14	[0.04, 0.62]
y (%)	0.62 ± 0.08	0.61 ± 0.07	$0.69\,^{+0.06}_{-0.07}$	[0.50, 0.80]
$\delta_{K\pi}$ (°)	$8.0\,^{+9.7}_{-11.2}$	$4.8\,^{+10.4}_{-12.3}$	$15.2\,^{+7.6}_{-10.0}$	[−16.8, 30.1]
R_D (%)	$0.348\,^{+0.004}_{-0.003}$	$0.347\,^{+0.004}_{-0.003}$	$0.349\,^{+0.004}_{-0.003}$	[0.342, 0.356]
A_D (%)	–	–	-0.88 ± 0.99	[−2.8, 1.0]
$\lvert q/p\rvert$	–	0.999 ± 0.014	$0.89\,^{+0.08}_{-0.07}$	[0.77, 1.12]
ϕ (°)	–	$0.05\,^{+0.54}_{-0.53}$	$-12.9\,^{+9.9}_{-8.7}$	[−30.2, 10.6]
$\delta_{K\pi\pi}$ (°)	$20.4\,^{+23.3}_{-23.8}$	$22.6\,^{+24.1}_{-24.4}$	$31.7\,^{+23.5}_{-24.2}$	[−16.4, 77.7]
A_π(%)	–	0.02 ± 0.13	0.01 ± 0.14	[−0.25, 0.28]
A_K(%)	–	-0.11 ± 0.13	-0.11 ± 0.13	[−0.37, 0.14]
x_{12} (%)	–	$0.41\,^{+0.14}_{-0.15}$		[0.10, 0.67]
y_{12} (%)	–	0.61 ± 0.07		[0.47, 0.75]
ϕ_{12}(°)	–	-0.17 ± 1.8		[−5.3, 4.4]