The Belle II Experiment at SuperKEKB

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(for the Belle II Collaboration)

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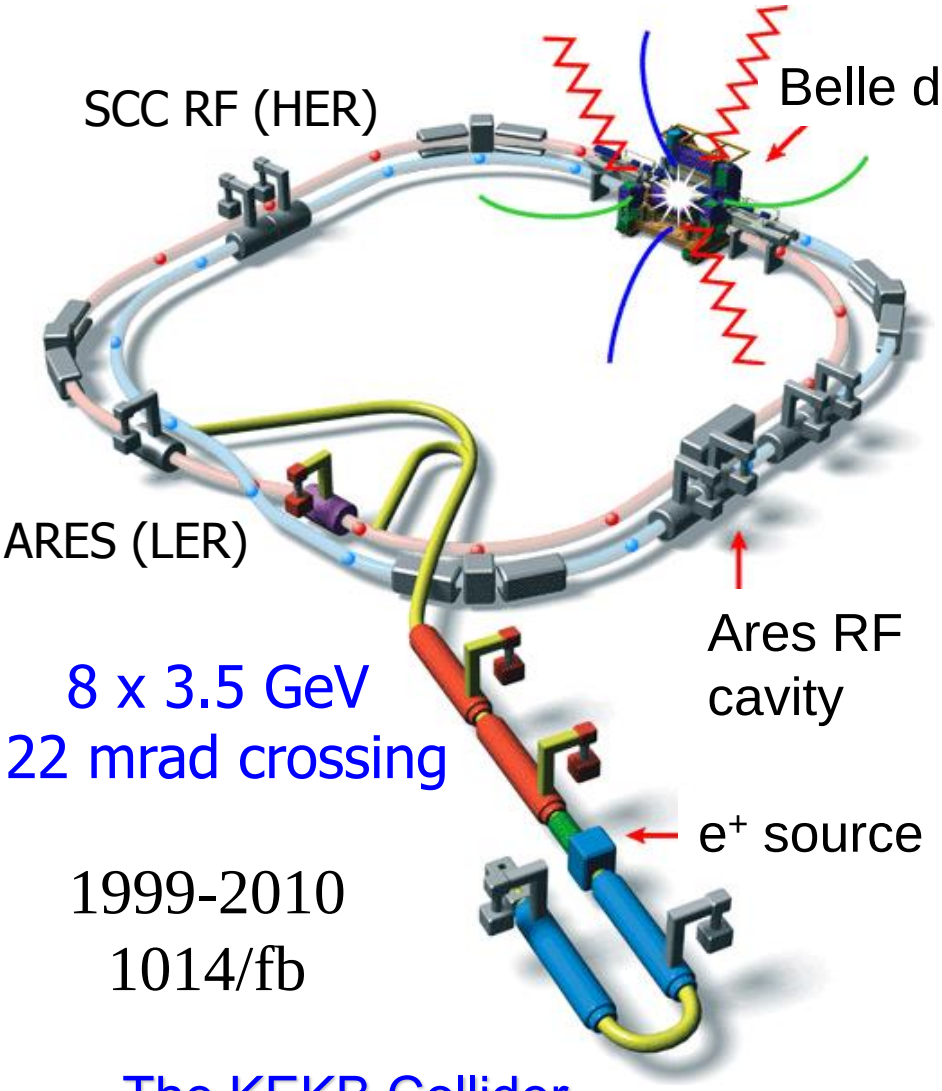
Outline

- Introduction
- Commissioning status and plans
  - SuperKEKB accelerator
  - Belle II detector
- Summary and outlook

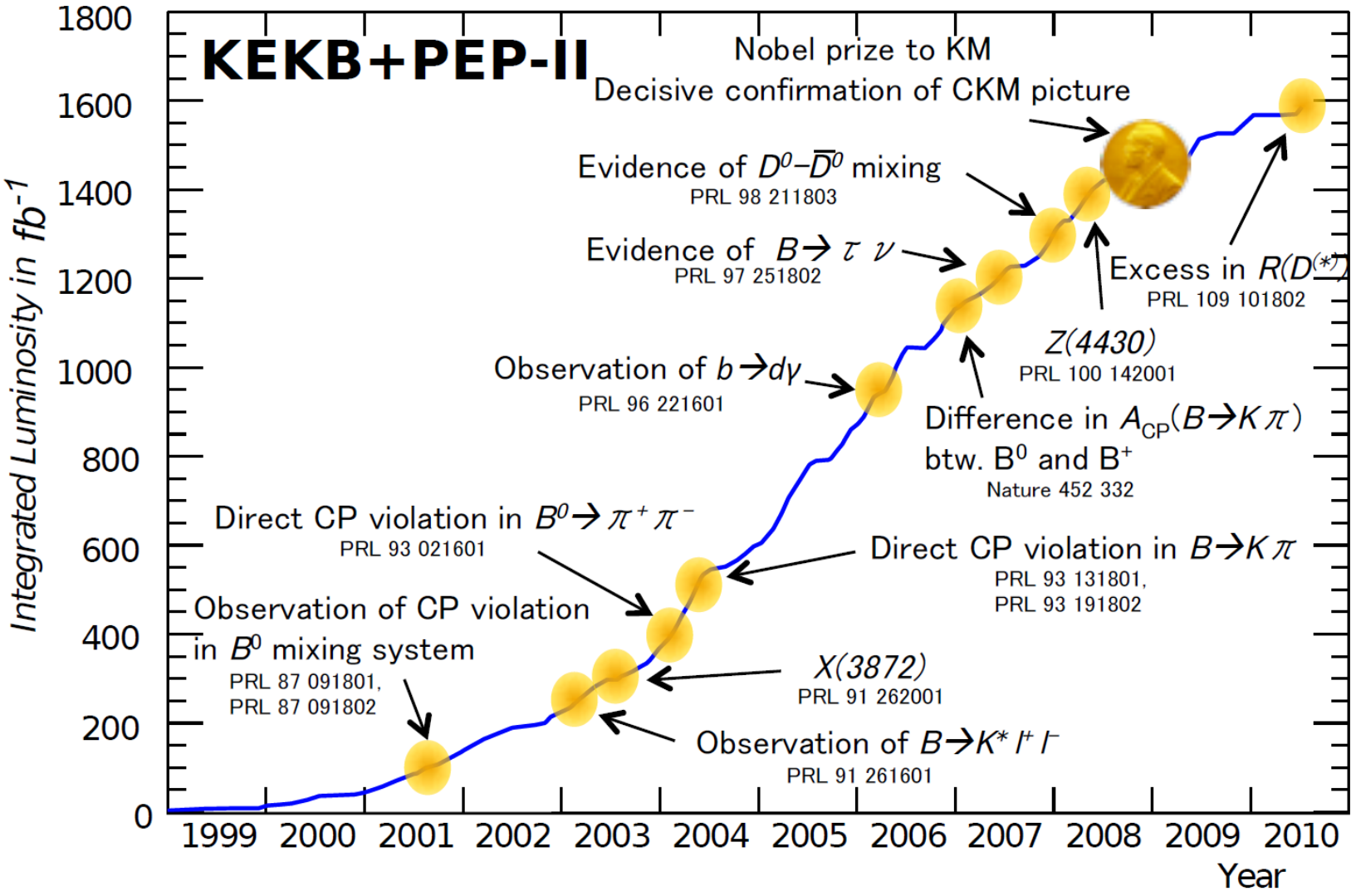
The Belle experiment @ KEKB



World record:

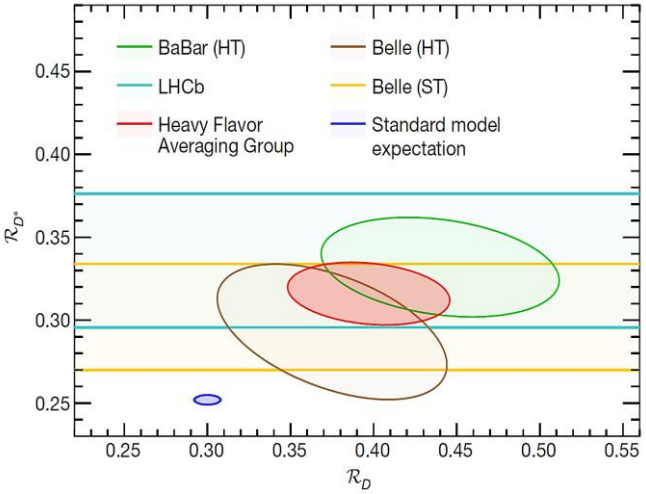
$L = 2.1 \times 10^{34}/cm^2/s$

The B Factory Legacy



- Next Generation SuperKEKB+ Belle II with > 50 ab^{-1}
  - ➔ Discover (or constrain) new physics!

Physics at a Belle II



- Good chance to see/confirm new phenomena:
  - **CPV from the new physics (non KM).**
  - **lepton universality in B decays (R_D, R_{D^*}, R_K)**
  - **B→τν to probe charged Higgs.**
  - **Lepton flavor violations in τ decays.**
- Will help to diagnose (if found) or constrain (if not found) NP.
- **Physics motivation independent of LHC.**
  - If LHC finds NP, precision flavour physics is compulsory.
  - If LHC finds no NP, high statistics B/τ decays would be a unique way to search for the >TeV scale physics.
- Many more topics: CPV in charm, new hadrons, …

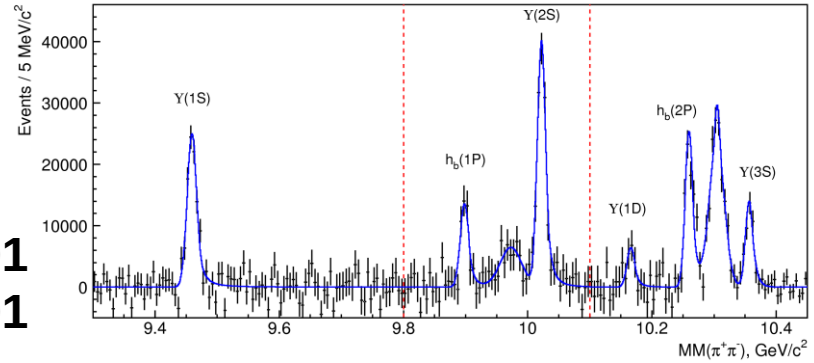
Physics reach with 50 ab^{-1} (75 ab^{-1}):

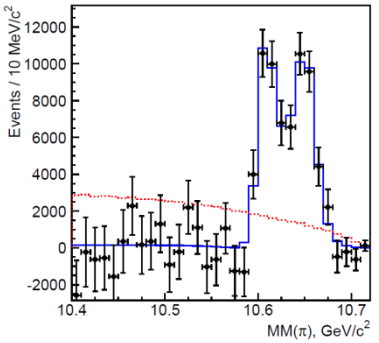
1. Physics at Super B Factory (Belle II authors + guests) > arXiv:1002.5012
2. SuperB Progress Reports: Physics (SuperB authors + guests) > arXiv:1008.1541
3. B2TIP report: confluence.desy.de/display/BI/B2TiP+WebHome: > PTEP soon

Physics related to this workshop

b family
– new states

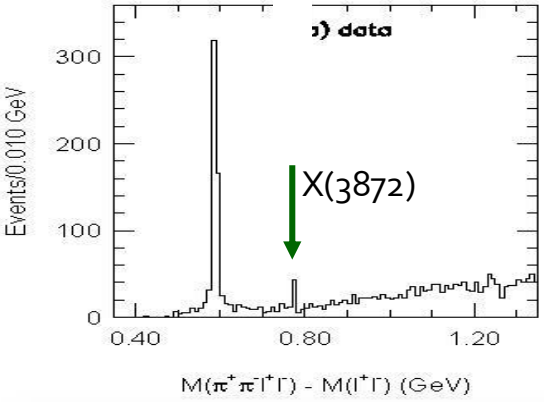
PRL 108, 122001
PRL 108, 032001

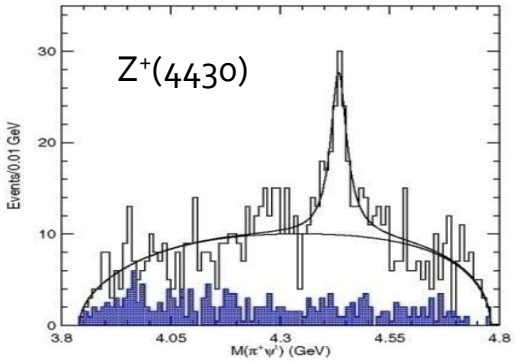




c family
– XYZ states

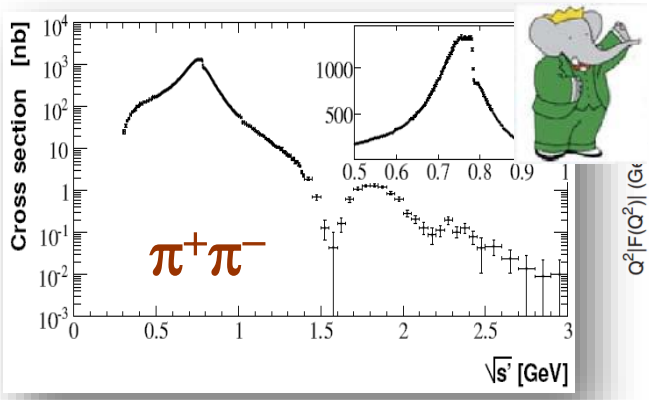
Review in
EPJC71, 1534

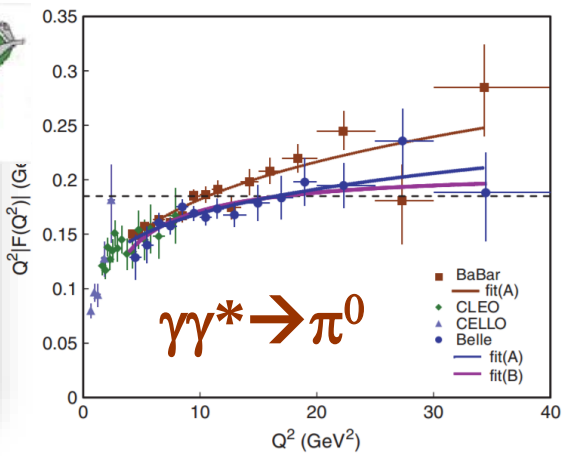




u,d,s families
– via ISR, γγ:
g-2, Δα, …

PRL 103, 231801
PRD 86, 092007



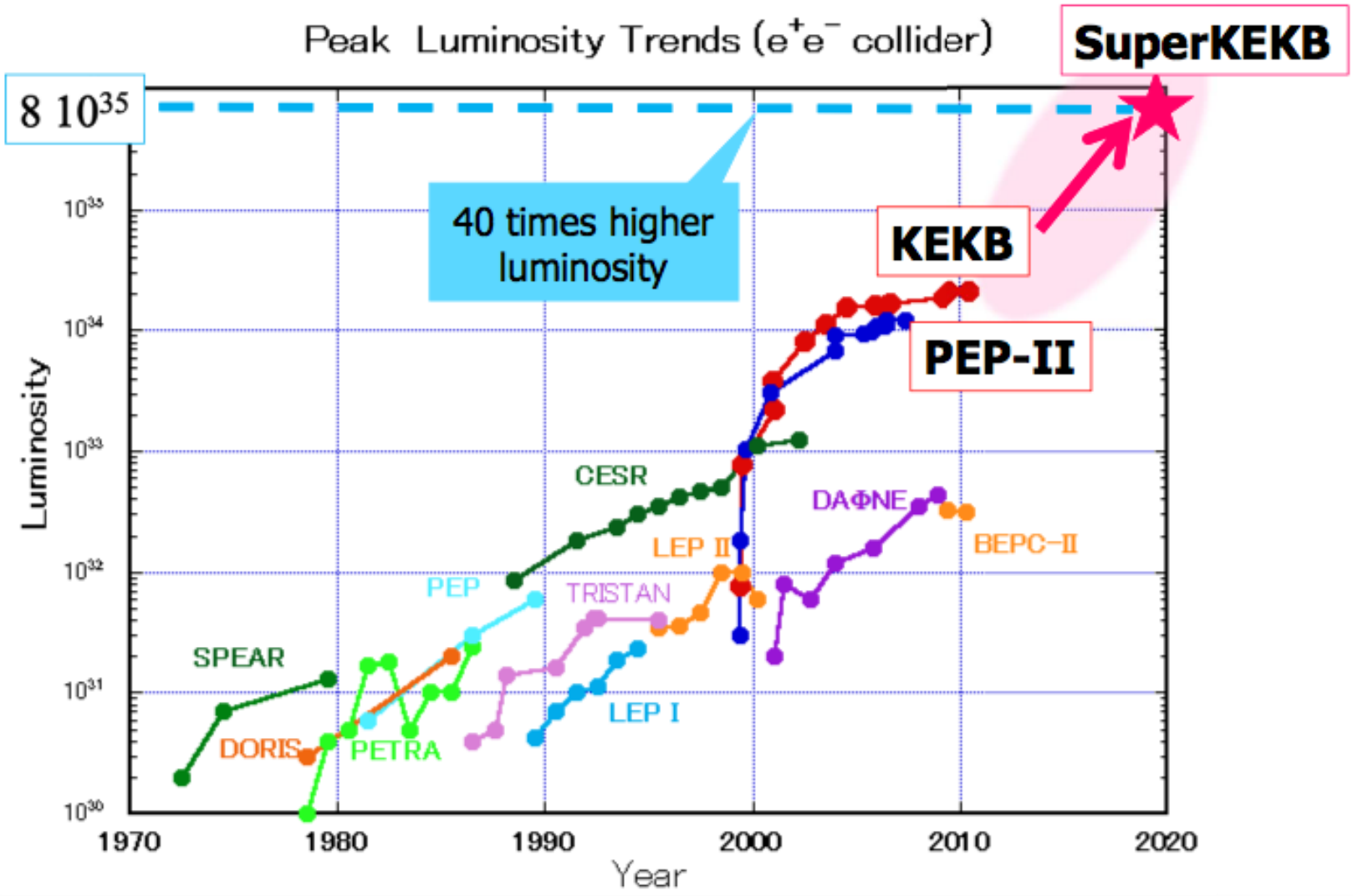


Tau, dark sectors, …

Belle & Belle II talks at this workshop

- Results at Belle and perspectives for ISR physics at Belle II, by Boris Shwartz
- Experimental review of tau lepton studies at the B factories, by Denis Epifanov
- Dark Photon Search at Belle, by Igal Jaegle
- Recent results on XYZ physics from Belle, by Roman Mizuk
- $\gamma\gamma$ physics results from Belle and perspectives for Belle II, by Hideyuki Nakazawa

$\mathscr{L}_{peak} = 2 \cdot 10^{34} \rightarrow 8 \cdot 10^{35} / cm^2 s$



Strategies to increase luminosity

Beam-beam parameter

Lorentz factor

Beam current

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

Lumi. reduction factor (crossing angle)& Tune shift reduction factor (hour glass effect) 0.8 ~ 1 (short bunch)

Classical electron radius

Beam size ratio@IP 1 ~ 2 % (flat beam)

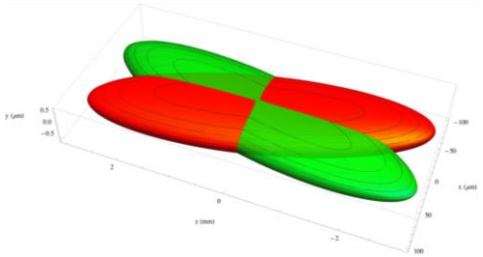
Vertical beta function@IP

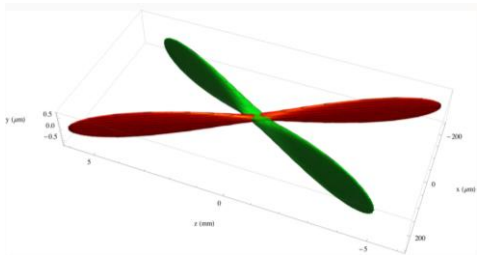
I	↑	x 2
β^*_y	↓	x 1/20

(1) Smaller β_y^*
(2) Increase beam currents
(3) Increase ξ_y

"Nano-Beam" scheme

Collision with very small spot-size beams (P. Raimondi for SuperB)

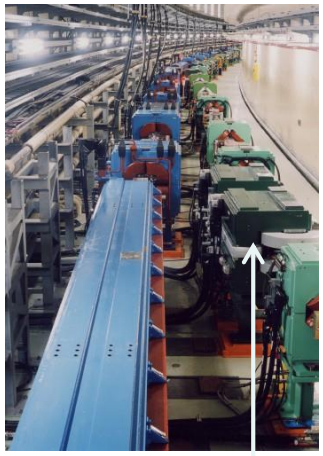




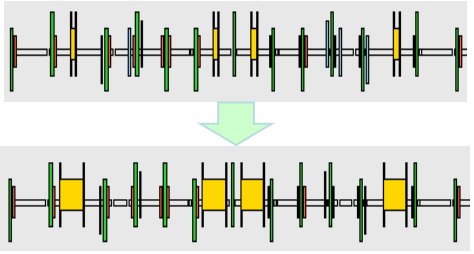
Very focused beams, large crossing angle (83 mrad)

From KEKB to SuperKEKB

Grey is recycled, coloured is new

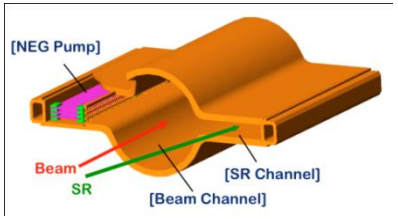


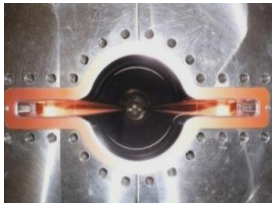
Replace short dipoles with longer ones (LER)

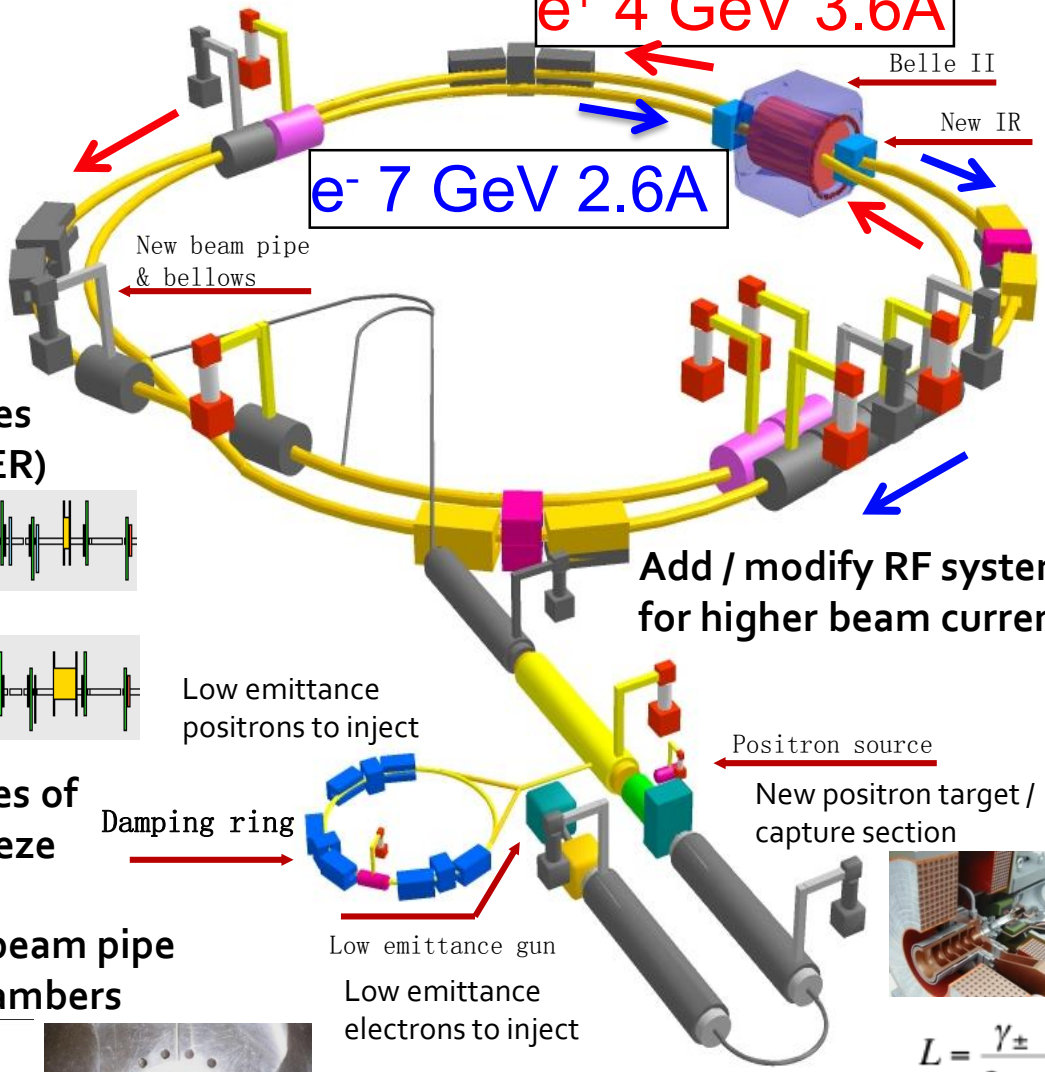


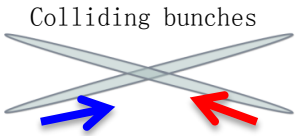
Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers









New superconducting / permanent final focusing quads near the IP

Add / modify RF systems for higher beam current

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

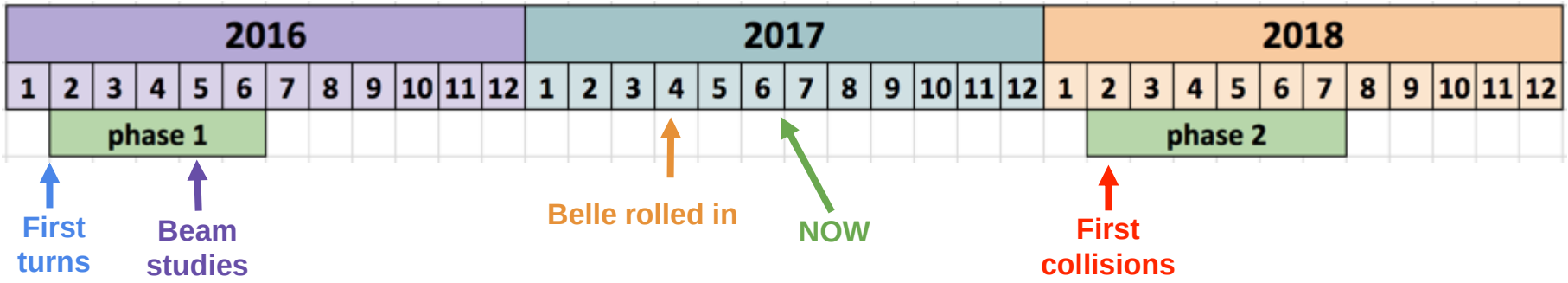
Target: $L = 8\times10^{35}/cm^2/s$

Machine design parameters

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7	GeV
Half crossing angle	ϕ	11		41.5		mrad
Horizontal emittance	ε_x	18	24	3.2	4.3–4.6	nm
Emittance ratio	K	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^*/β_y^*	1200/5.9		32/0.27	25/0.31	mm
Beam currents	I_b	1.64	1.19	3.60	2.60	A
beam-beam parameter	ξ_y	0.129	0.090	0.0886	0.0830	
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

- **Small beam size & high current** to increase luminosity
- **Large crossing angle (83 mrad)**
- **Change beam energies** to solve the problem of LER short lifetime

SuperKEKB Commissioning



Phase I (2016): No Belle II, circulate both beams without collisions

Phase II (2018): With Belle II without vertex detector, first collisions

Commissioning Goals

SuperKEKB

- Clean beam pipe (vacuum scrubbing)
- Real-time monitoring of beam conditions
- Tune accelerator optics, collimators etc.
- Isolate sources of beam loss and collect data for simulations

Belle II

- Guarantee a safe operating environment for Belle II
- Mitigate beam backgrounds around the IP
- Test beam abort system based on diamond sensors
- Collect beam background data to validate background simulations

BEAST II - phase 1

Beam **E**xorcisms for **A** **S**table Belle II Experimen**T**

Goals

- Measure BG levels near IP
  - X-rays, charged tracks, neutrons
  - online feedback to SuperKEKB
  - offline for analysis
- Test and calibration of diamond sensor VXD beam abort
- First measurements of SuperKEKB injection backgrounds
- First comparison of SuperKEKB beam-loss simulation with experimental data

Expected SuperKEKB Backgrounds

Phase 1 (no collisions)

Touschek scattering:

- intra-bunch scattering process
- dominant with highly compressed beams
- 20 times higher

Beam-gas scattering:

- Bremsstrahlung (negligible) & Coulomb interactions (up to 100 times higher) with residual gas atoms & molecules

Synchrotron radiation:

- emission of photons by charged particles (e^+e^-) when deflected in *B*-field

Phase 2 (collisions)

Radiative Bhabha process:

- photon emission prior or after *Bhabha* scattering
- interaction with iron in the magnets leads to neutron background

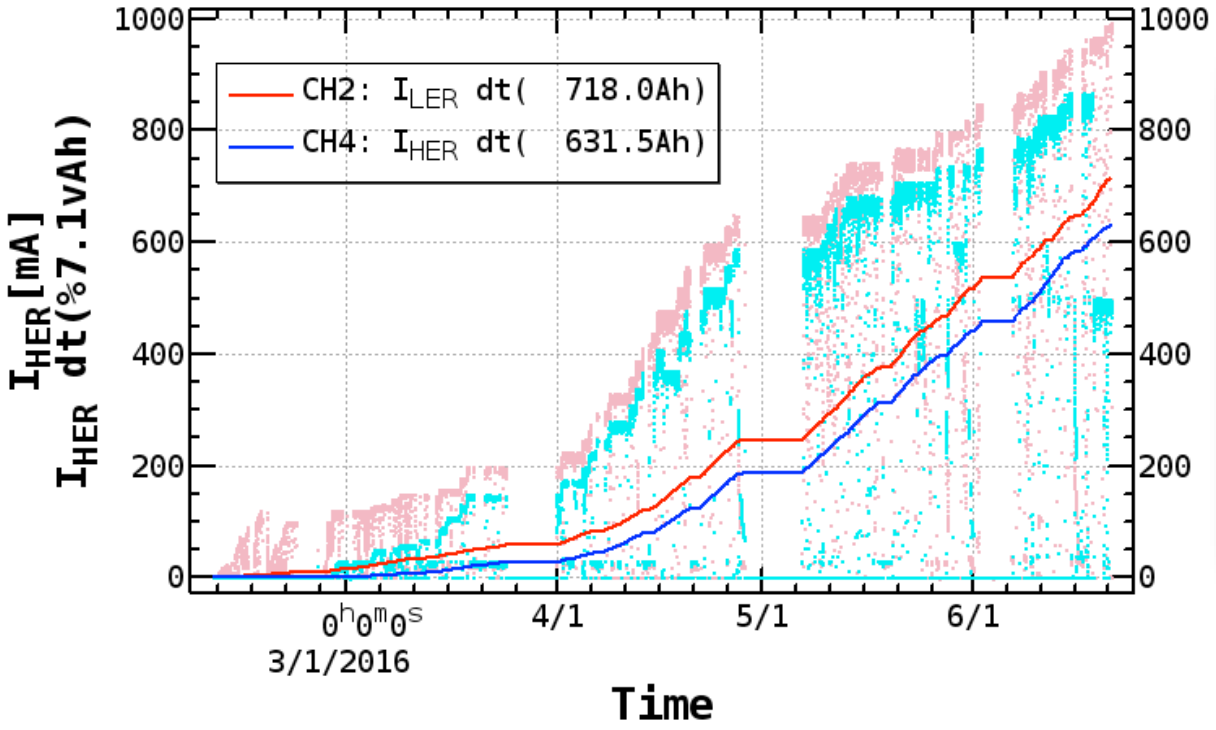
Two photon process:

- very low momentum e^+e^- pairs via $e^+e^- \rightarrow e^+e^-e^+e^-$
- increased hit occupancy in inner detectors

Injection Background:

History of Phase 1 operation

June 21: LER beam current exceeded 1 Ampere



First 4 months of beam commissioning

KEKB

LER: 540 mA

HER: 300 mA

SuperKEKB

LER: 820 mA

HER: 740 mA

- SuperKEKB startup much faster than KEKB
- All upgraded components worked fine!
- KEKB experience was key

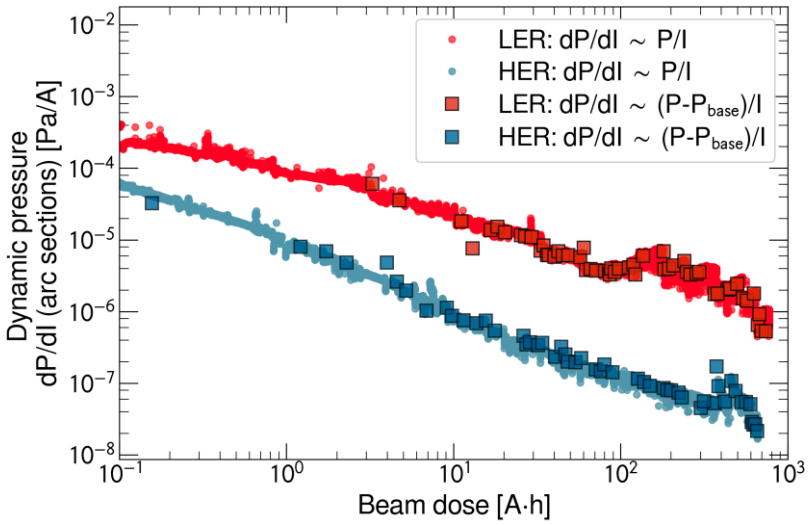
Beam "Scrubbing"

BEAST II - Phase 1

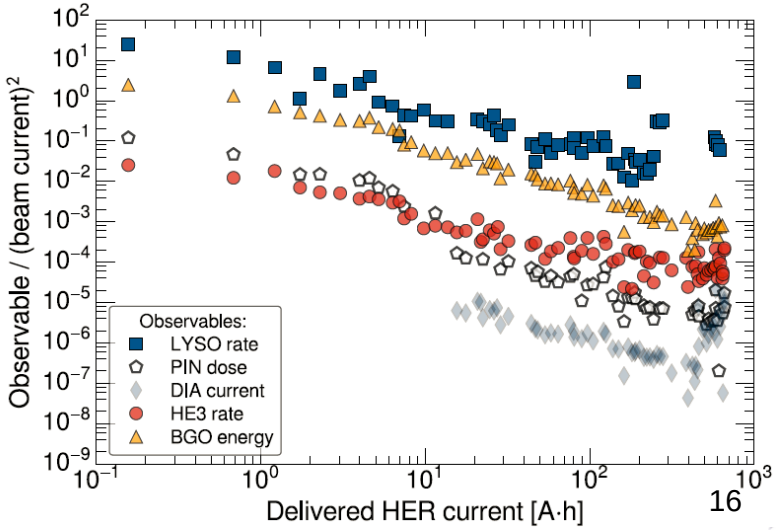
Cleaning a new beam pipe

- A key goal of phase 1 was to "scrub" the beam pipes
  - High currents stimulate desorption of impurities from beam pipe walls
  - Over time, **vacuum improves** lowering beam-gas backgrounds
- BEAST quantified distinct improvements in beam-gas in phase 1

SuperKEKB measurements of dP/dI vs integrated current



BEAST measurements of Rates/I^2 vs integrated current

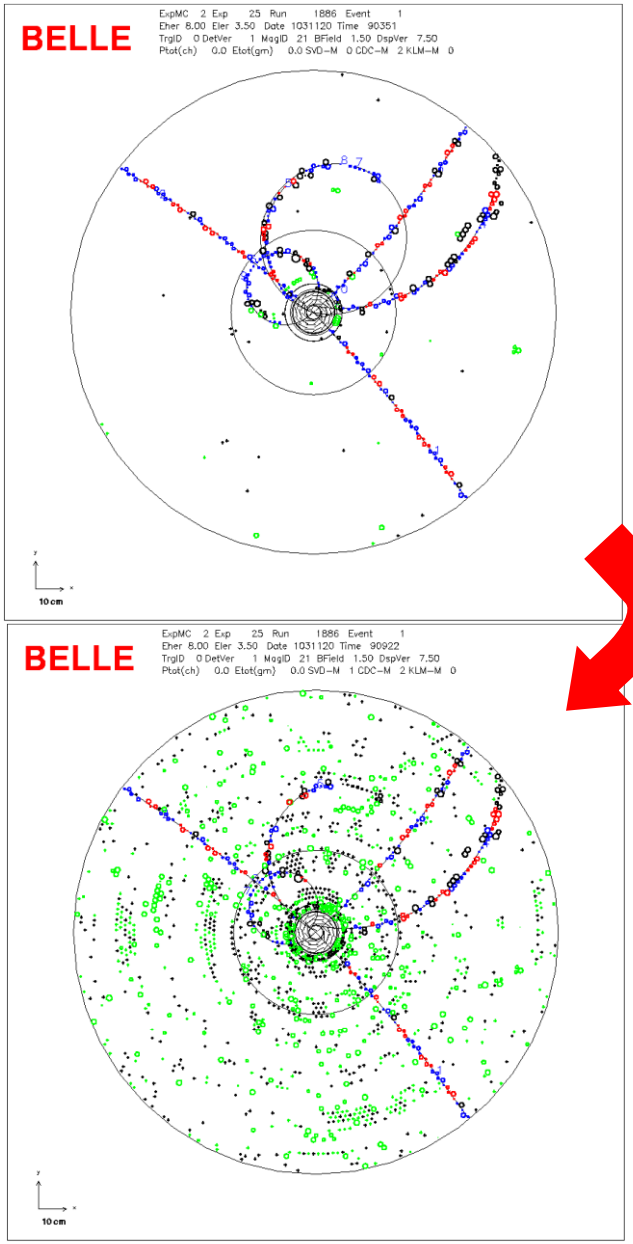


Requirements on the detector

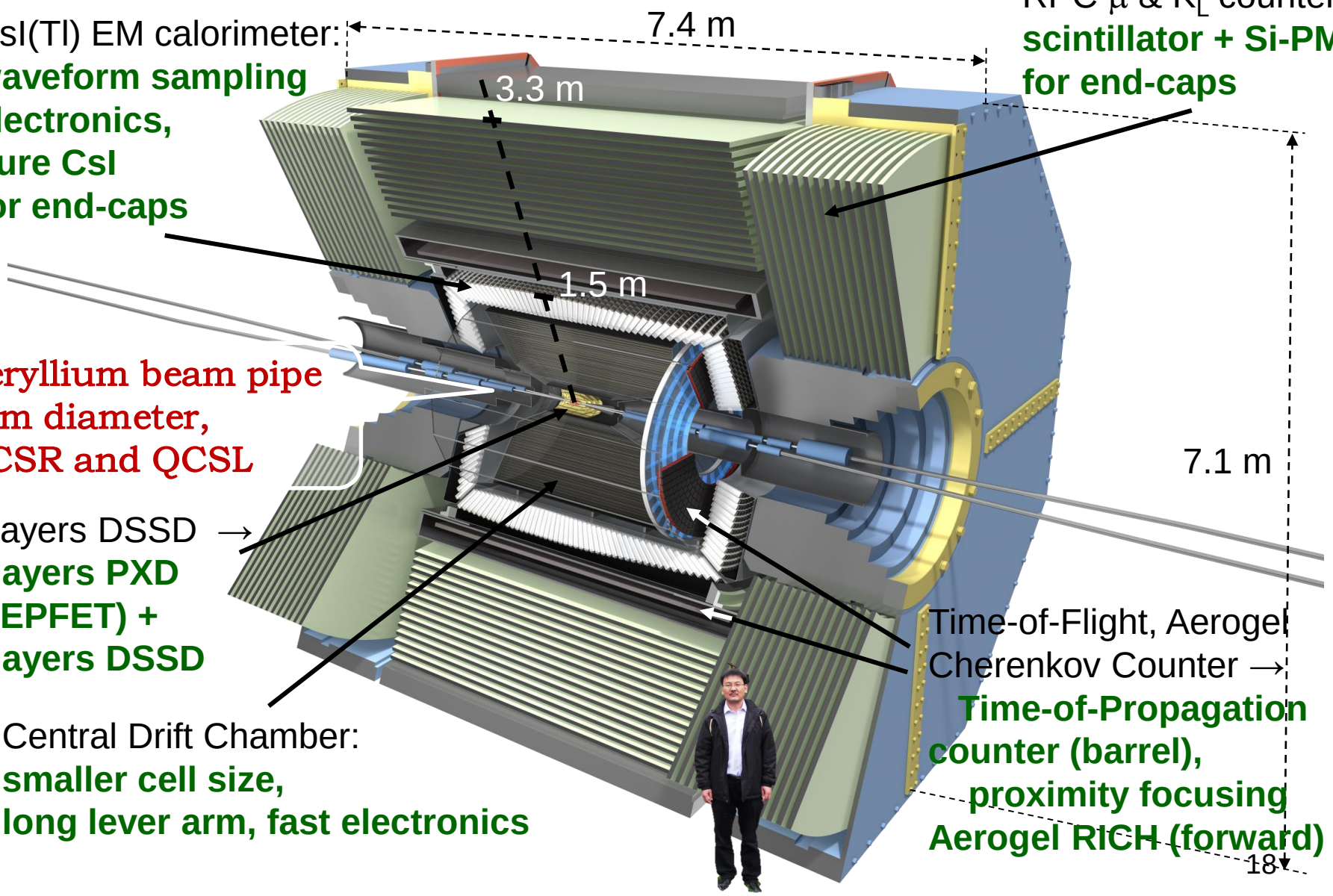
Critical issues at L= 8 x $10^{35}/cm^2/s$

- **Higher background (×10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM Calorimeter
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing
- **Special features required**
  - low momentum μ identification
  - Hermeticity, ν "reconstruction"

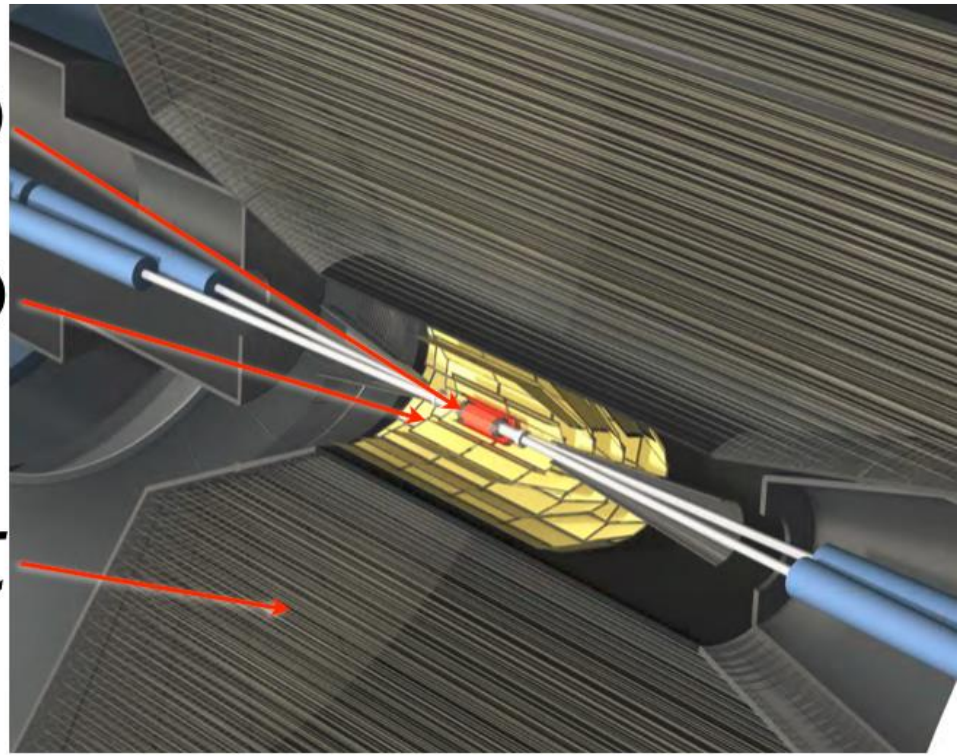
Result: significant upgrade



Belle II detector upgrade

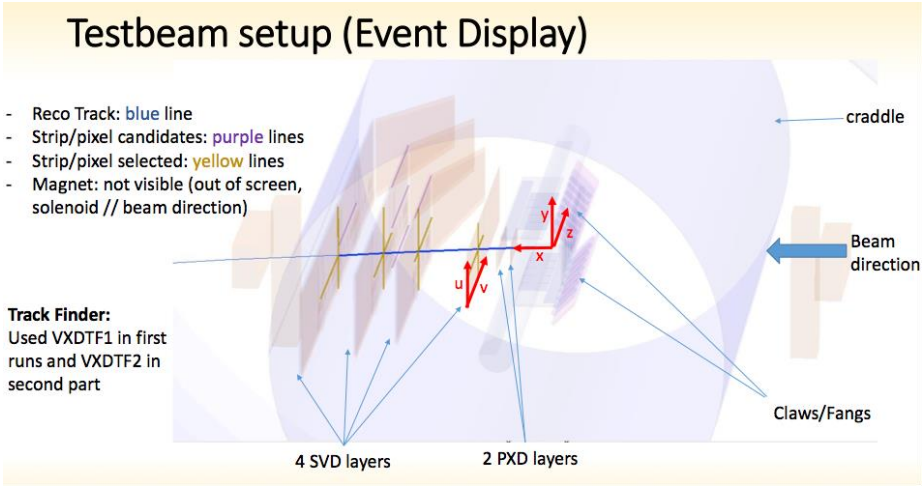


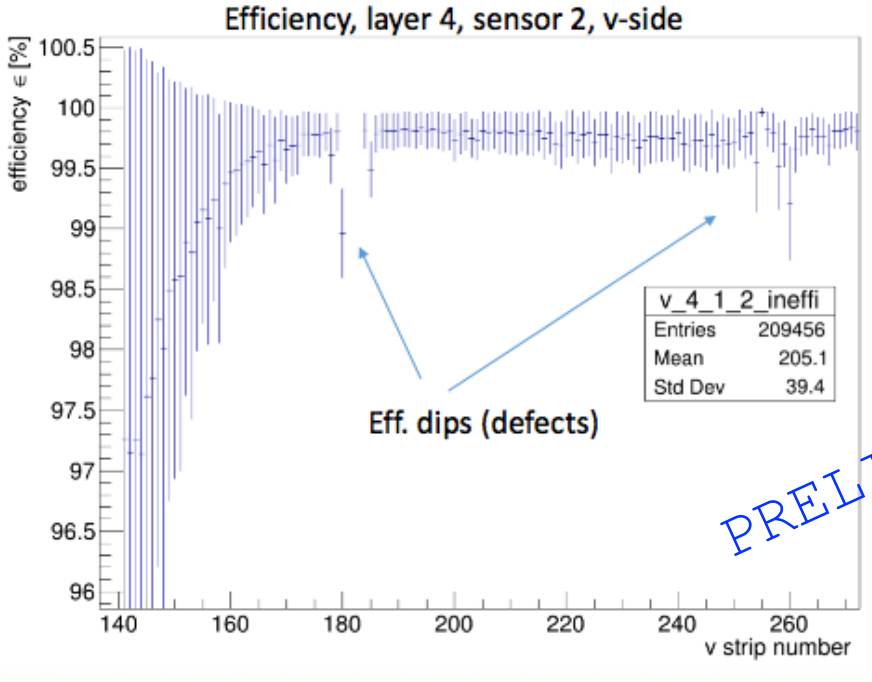
The tracking system

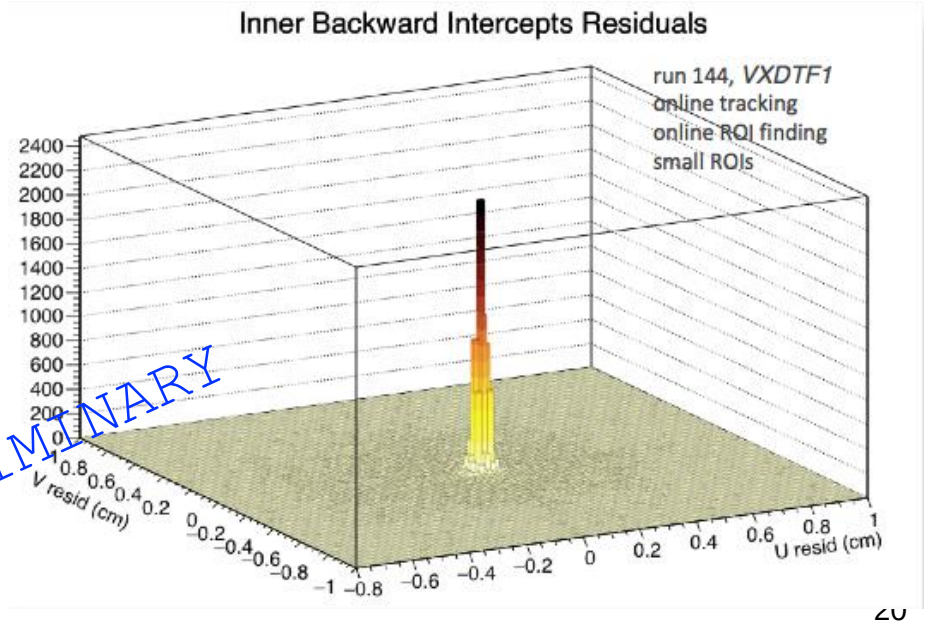


Component	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double-wall	Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be		
PXD	Silicon pixel (DEPFET)	Sensor size: 15×100 (120) mm^2 pixel size: 50×50 (75) μm^2 2 layers: 8 (12) sensors	10 M	impact parameter resolution $\sigma_{z_0} \sim 20$ μm (PXD and SVD)
SVD	Double sided Silicon strip	Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors	245 k	
CDC	Small cell drift chamber	56 layers, 32 axial, 24 stereo r = 16 - 112 cm - 83 $\leq z \leq$ 159 cm	14 k	$\sigma_{r\phi} = 100$ μm, $\sigma_z = 2$ mm $\sigma_{p_t}/p_t = \sqrt{(0.2\% p_t)^2 + (0.3\%/\beta)^2}$ $\sigma_{p_t}/p_t = \sqrt{(0.1\% p_t)^2 + (0.3\%/\beta)^2}$ (with SVD)

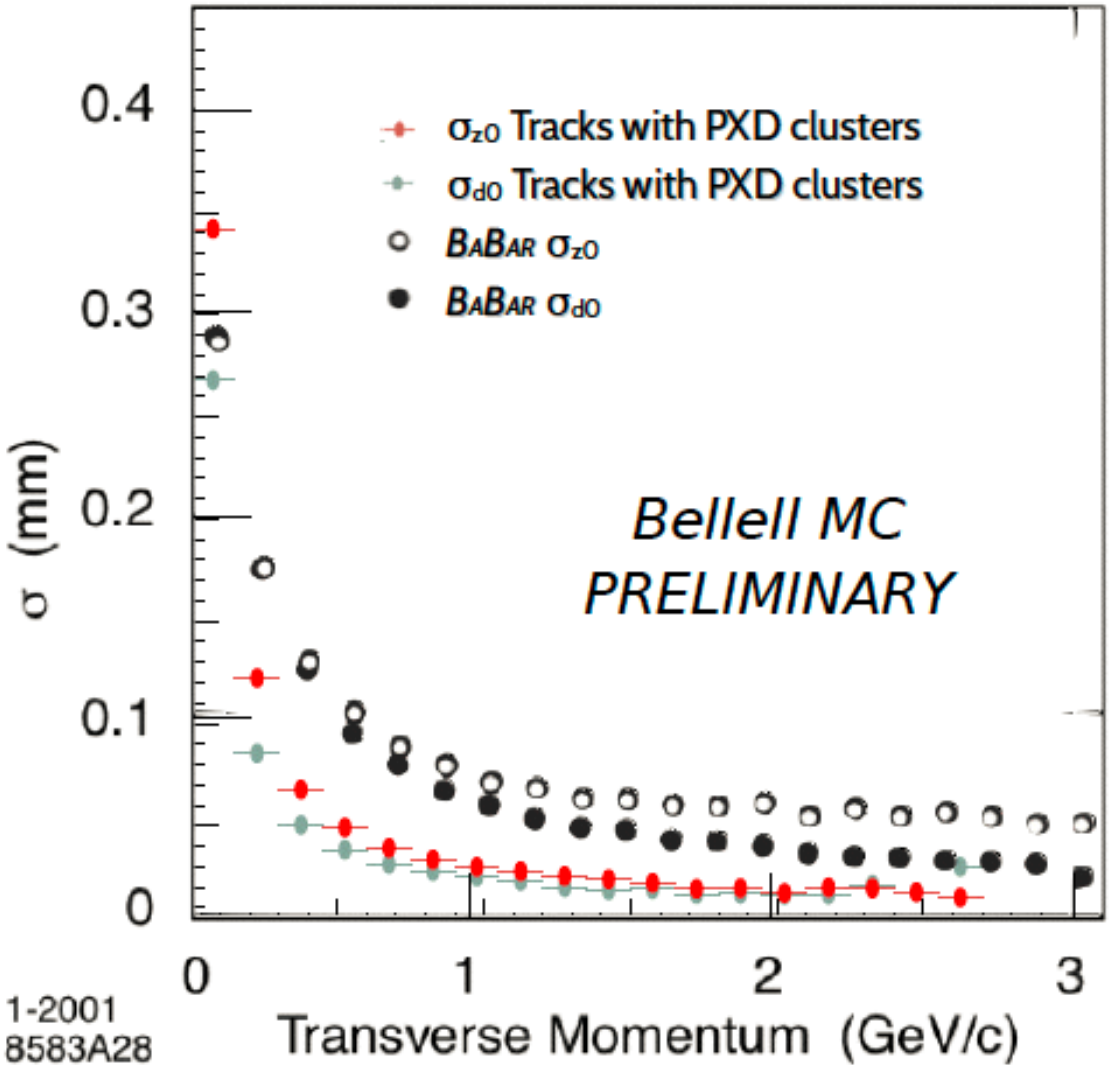
Combined PXD+SVD beam test at DESY







Improvements of vertex detector

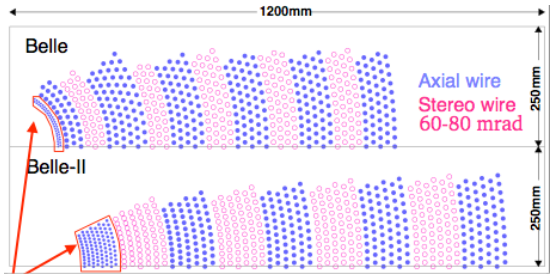


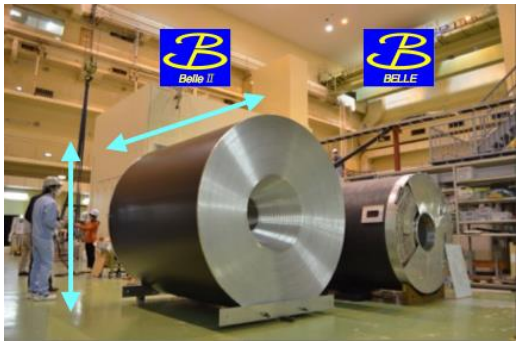
- Extrapolations of detector performance confirmed after beam-test results, and realistic software implementation
- Currently, in spite of

$$\langle\beta\gamma\rangle^{\text{Belle II}} = 28/44 \cdot \langle\beta\gamma\rangle^{\text{Belle}}$$

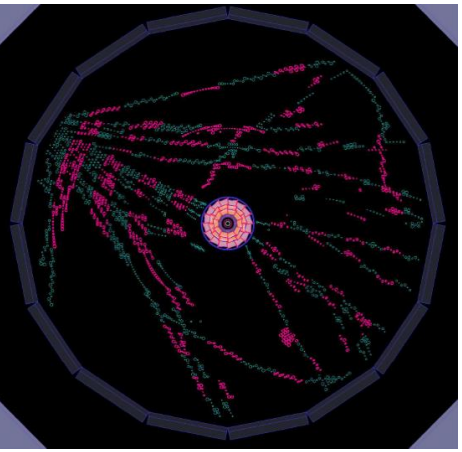
$$\sigma_{\Delta_t}^{\text{Belle II}} \sim \frac{3}{4}\sigma_{\Delta t}^{\text{Belle}}$$

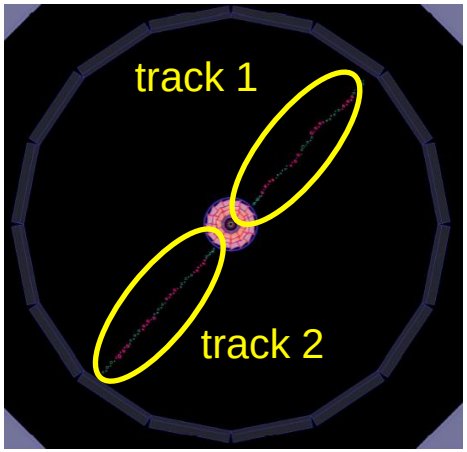
The Central Drift Chamber (CDC)

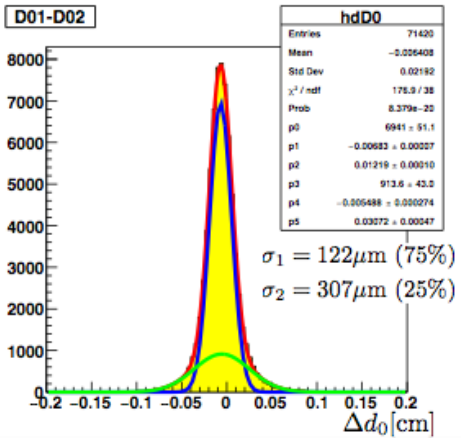


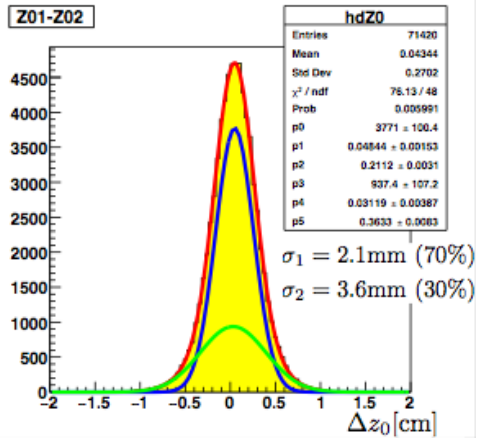


- Installed on Oct, 2016
- Commissioning with cosmic ray tracks is ongoing







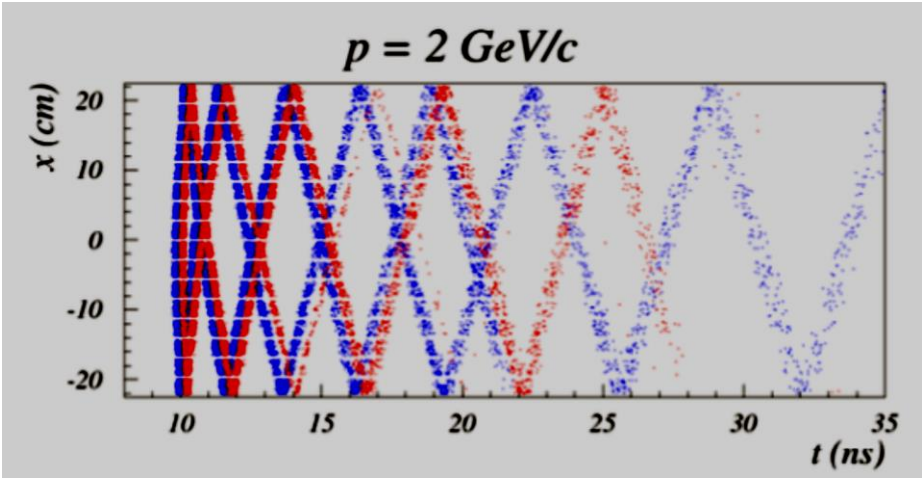


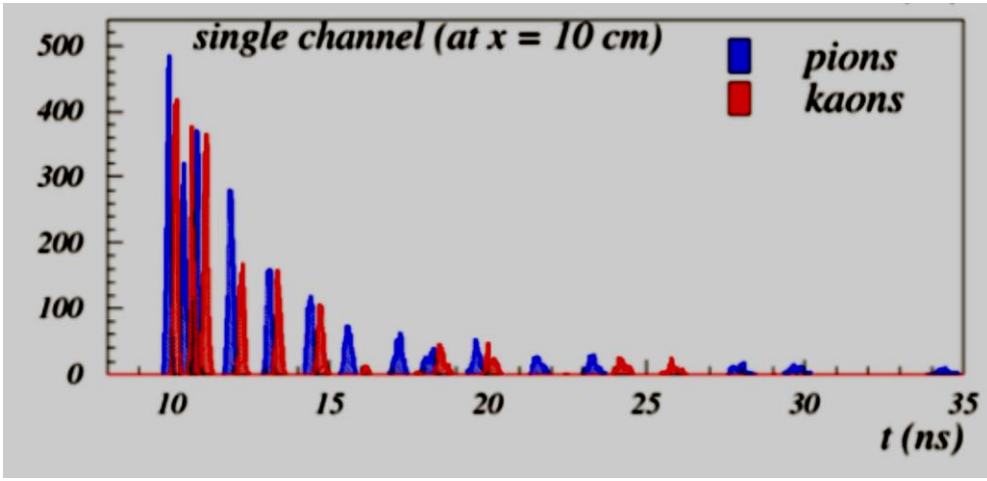
Barrel PID: Time Of Propagation (TOP)

Cherenkov ring imaging with precision time measurement (better than 100ps)

Installation completed! 2016, May 11

Quartz Property	Requirement
Flatness	<6.3μm
Perpendicularity	<20 arcsec
Parallelism	<4 arcsec
Roughness	< 0.5nm (RMS)
Bulk transmittance	> 98%/m
Surface reflectance	>99.9%/reflection

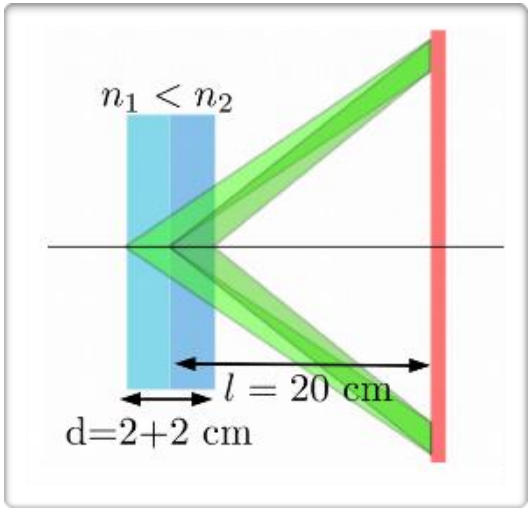




Forward PID: the Aerogel RICH

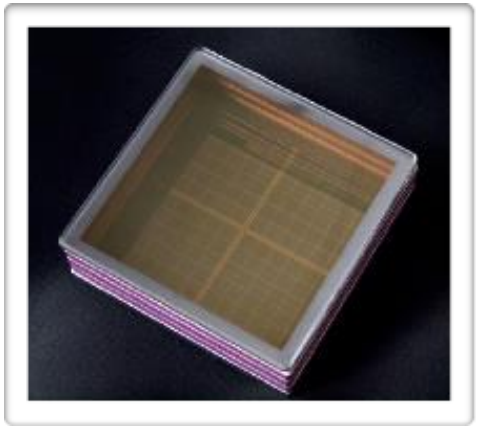
Use two aerogel layers in focusing configuration to increase n. of photons without resolution degradation

n1=1.045, n2=1.055



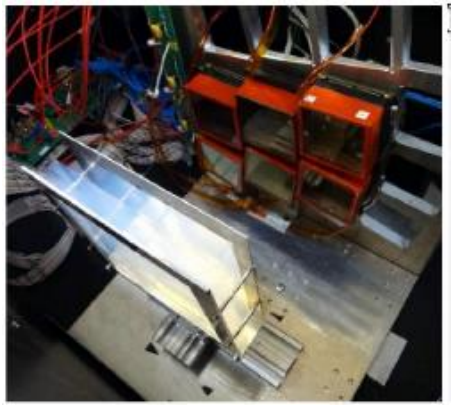
HAPD – Hybrid Avalanche Photo-Detector

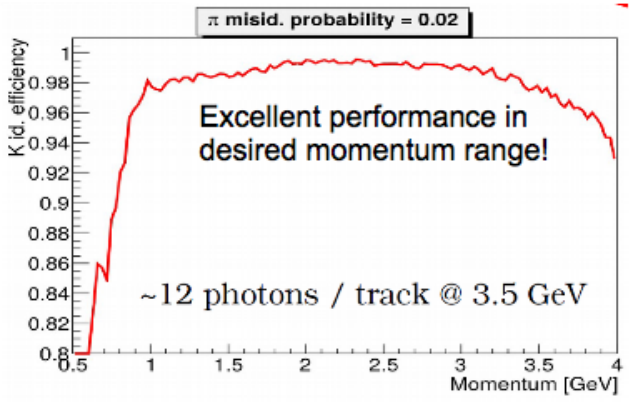
- Developed in collaboration with Hamamatsu photonics
- Basic requirements: - 1.5 T - n,γ tolerance (10^{12} n/cm^2)



- position resolution
- large coverage (3.5 m^2)

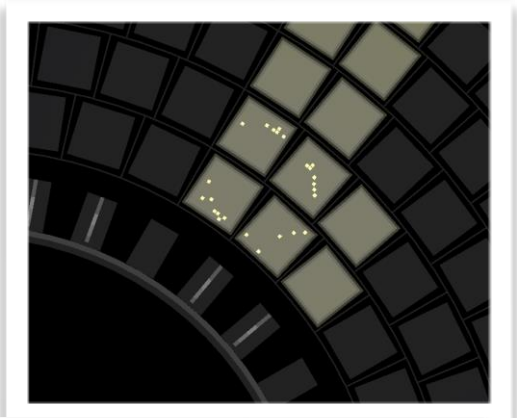
Beam test measurements

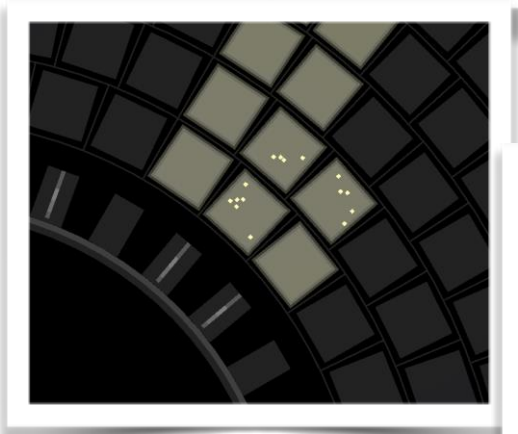


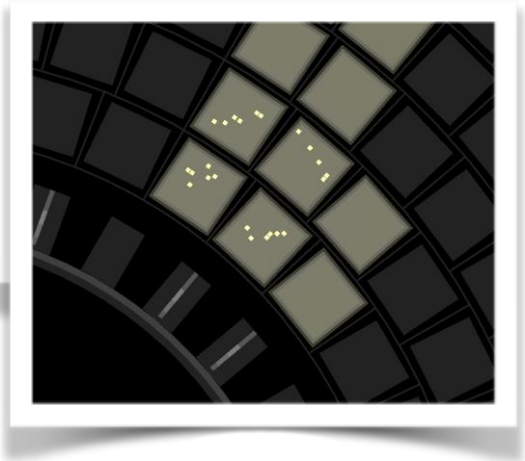


ARICH Rings from cosmic ray muons

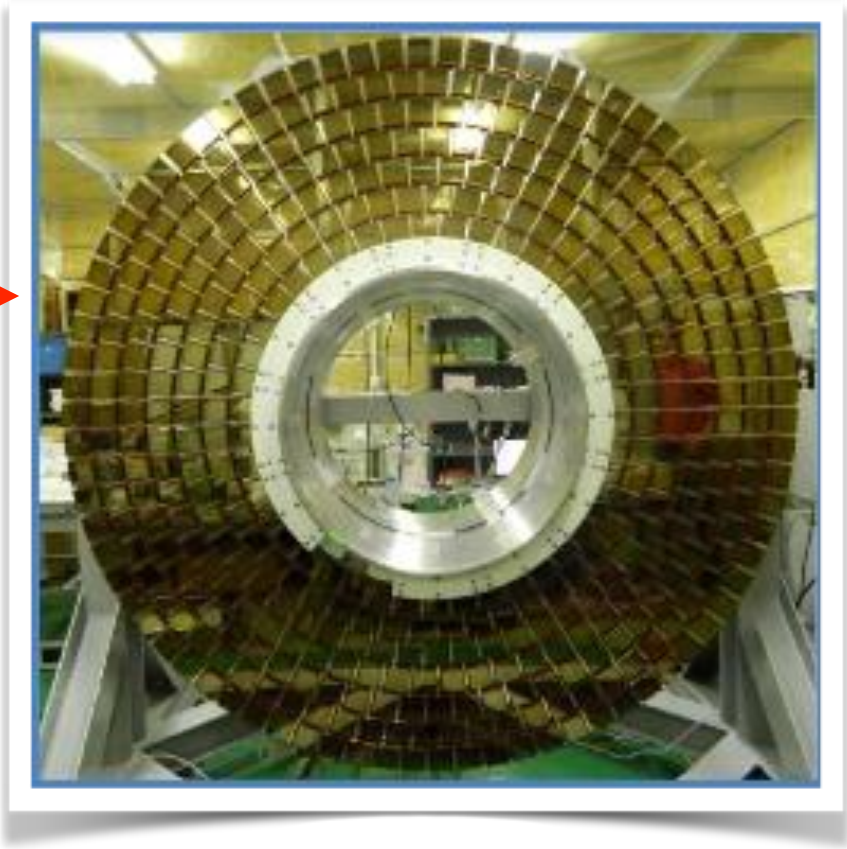
- First events from CR tracks recorded in a partially instrumented sector of the ARICH



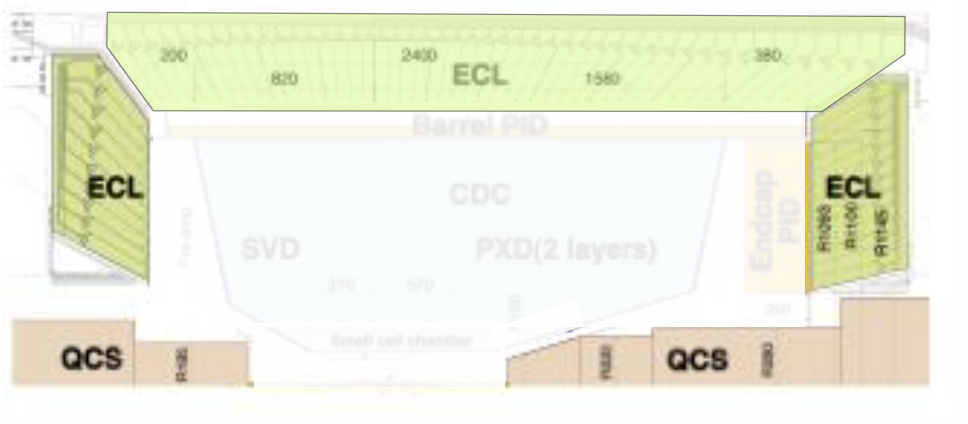




- Production of aerogel tiles and HAPDs is finished.
- Installation on the structure complete!
- Install in Belle II in September.



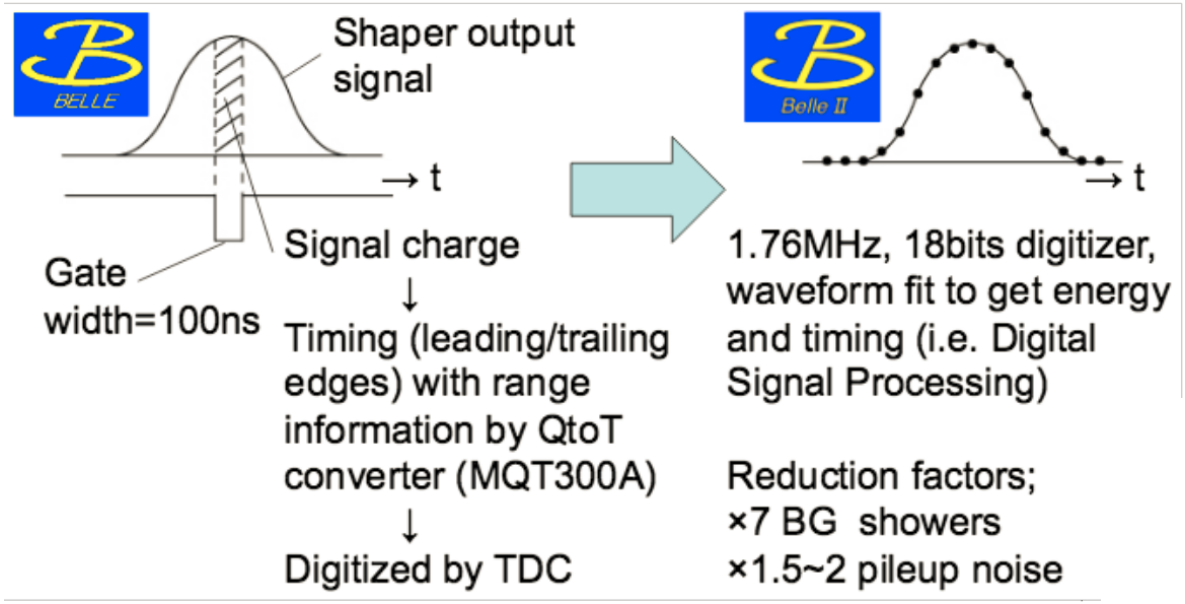
E.M. Calorimeter (ECL)



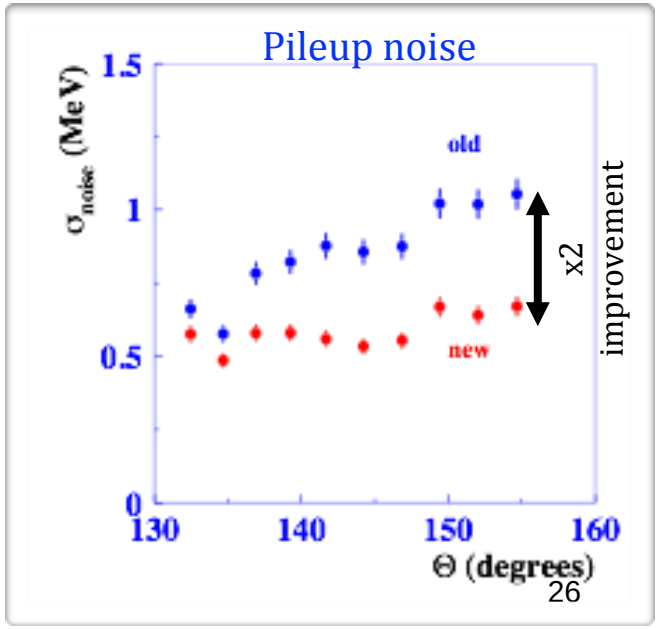
Belle calorimeter

- 8736 CsI(Tl) crystals
- 6624 Barrel
- 1152 Fwd Endcap
- 960 Bwd Endcap

- High rates (machine+physics) ⇒ upgrade of electronics
  - shorter signal shaping
  - waveform fit to extract signal time and amplitude



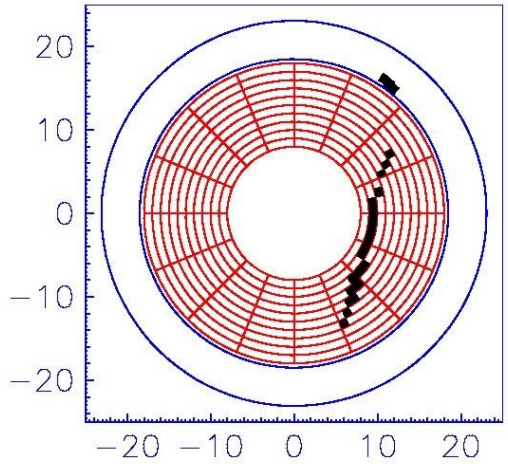
Early prototype tested at Belle

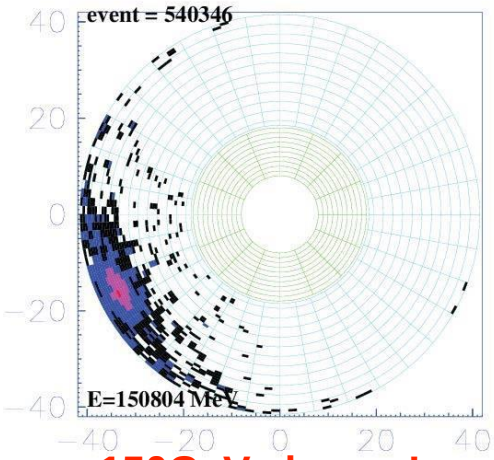


ECL commissioning

BWD endcap installation
January 2017

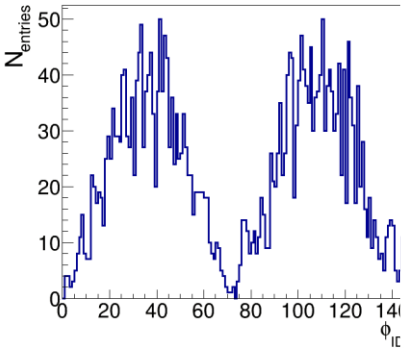
- Barrel ECL under CR test since 2015
- Endcap calorimeter CR test ongoing

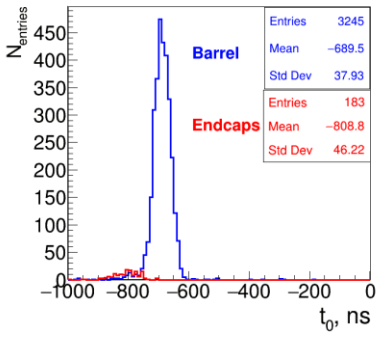


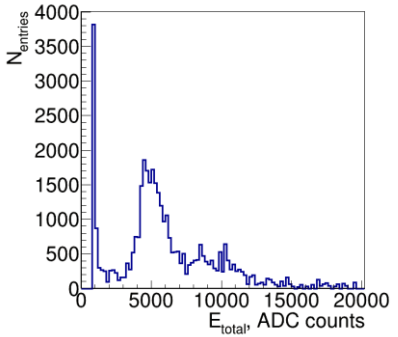


150GeV shower!

Combined CDC-ECL cosmic ray test

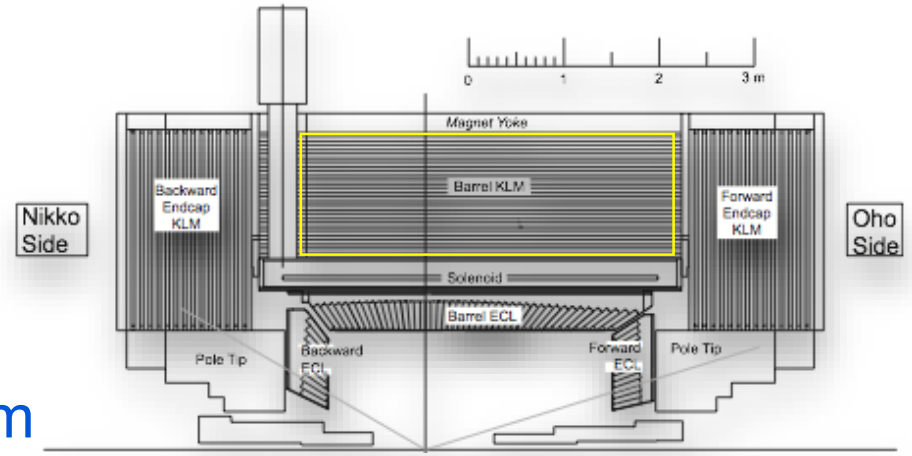


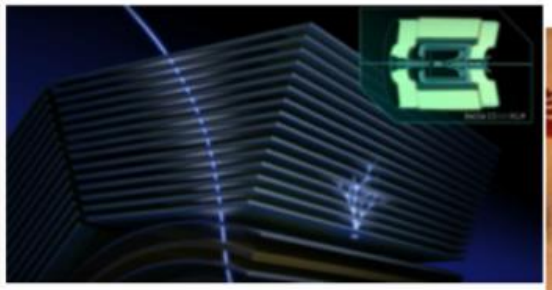


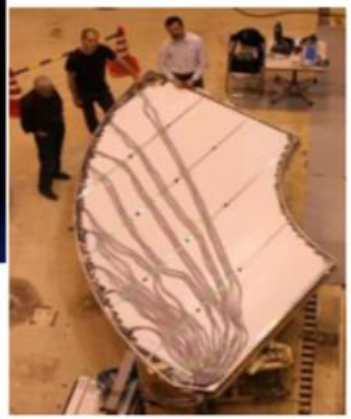


The KLong and Muon detector KLM

- 14 iron layers 4.7cm thick
- 15 barrel active layers
  - ✓2 x [scintillator strips + WLS + SiPM] ⇐ NEW
  - ✓13 x [double glass RPC + 5 cm orthogonal phi, z strips]
- 14 endcap active layers
  - ✓14 x [scintillator strips + WLS + SiPM] ⇐ NEW





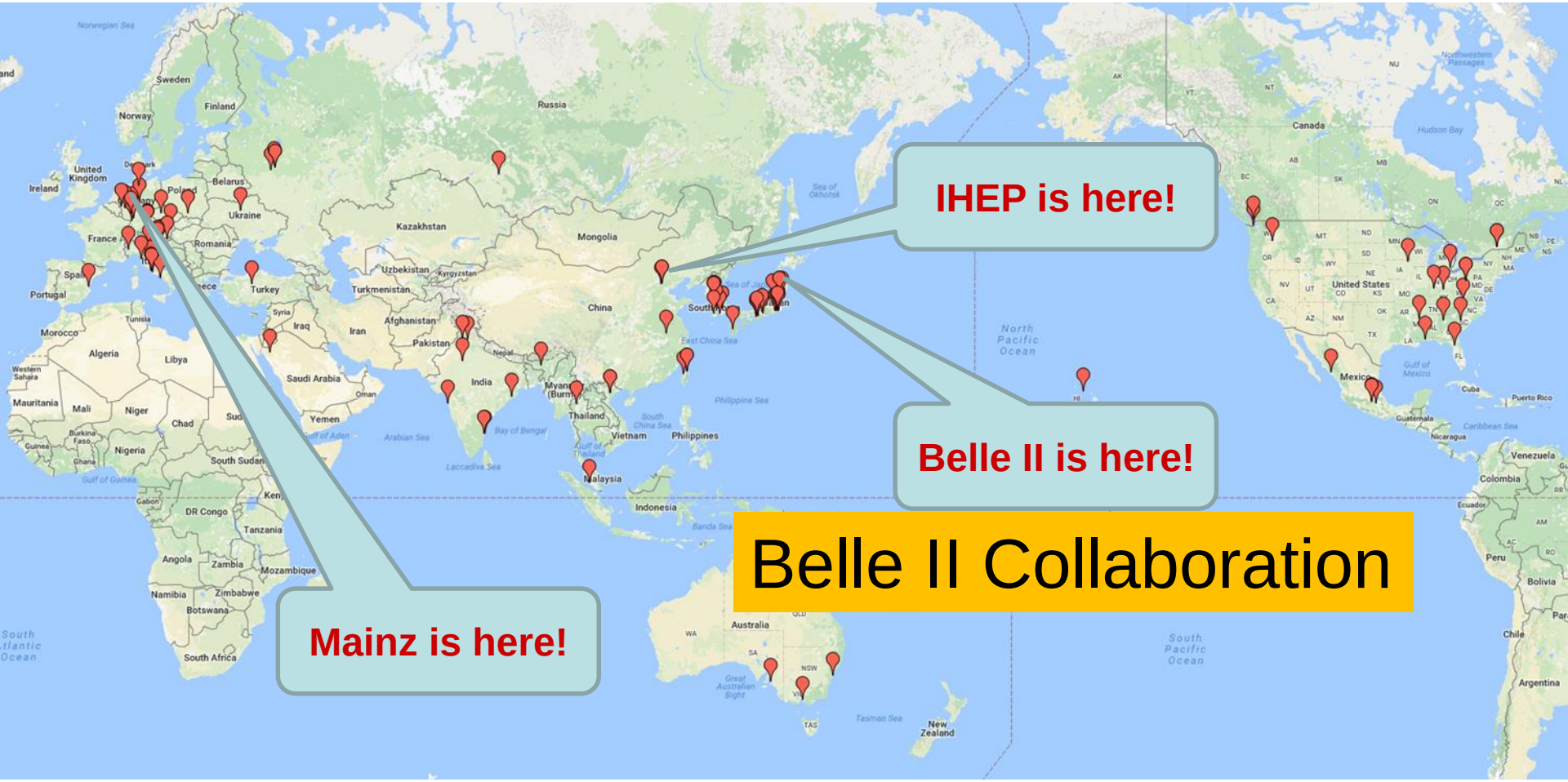


- All endcap glass RPC + 2 in the innermost layers of the barrel replaced with scintillator strips to resist higher backgrounds
- Installation is complete
- Commissioning with cosmic rays ongoing

Belle II Roll In

April 11th, 2017, Belle II Milestone!

Who are working on these?



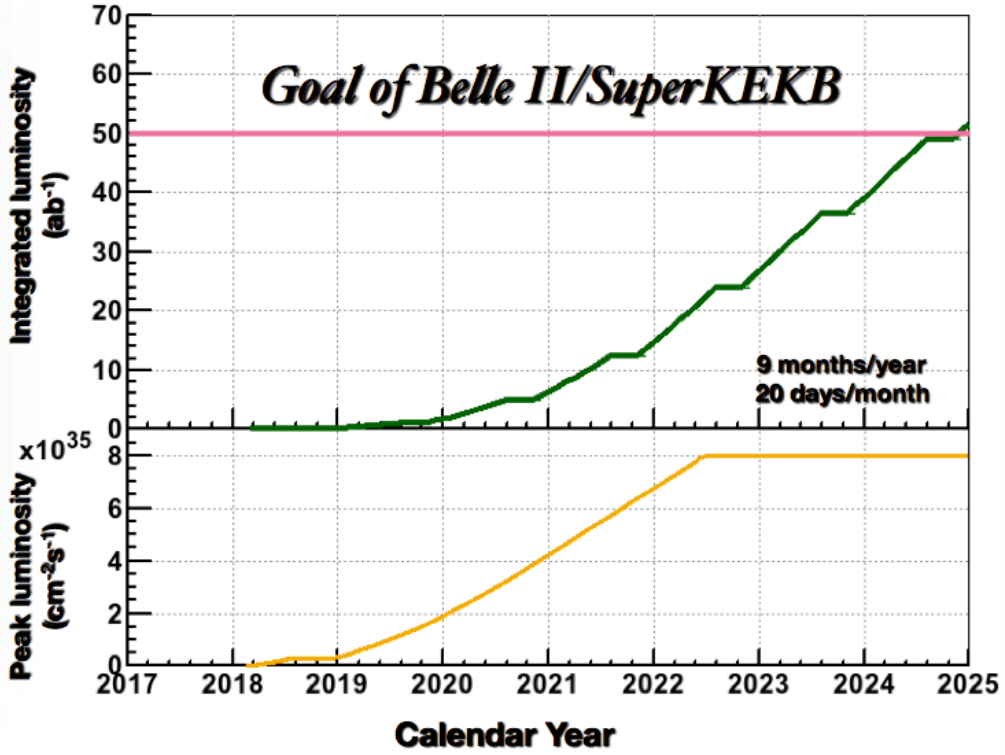
~ 700 members from 104 institutes in 24 countries

➔ Distributed collaboration ➔ distributed computing

When do we start Belle II?

- Phase II Operation: *Starts in Nov. 2017*
  - Begin with damping ring commissioning
  - Main ring (Feb. 2018): first collisions!
  - Two main goals:
    - SuperKEKB luminosity with nano-beams - reach KEKB maximum luminosity at the end of phase 2.
    - Ensure background levels are compatible with the operation of the vertex detector
  - Limited physics without vertex detectors
- Phase III: *Starts late 2018*
  - Belle II Physics Running (with vertex detectors in)

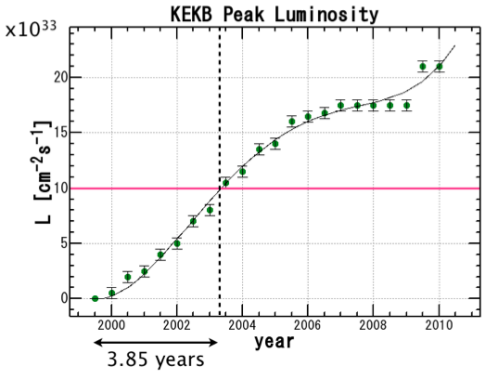
Luminosity profile of SuperKEKB



Expected data sample @ full luminosity

Channel	Belle	BaBar	Belle II (per year)*
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

* assuming 100% running at each energy



- Assumptions:
  - same commission time to reach design lum. as KEKB
  - 9 months/year running
  - 20 days/month

Summary and Outlook

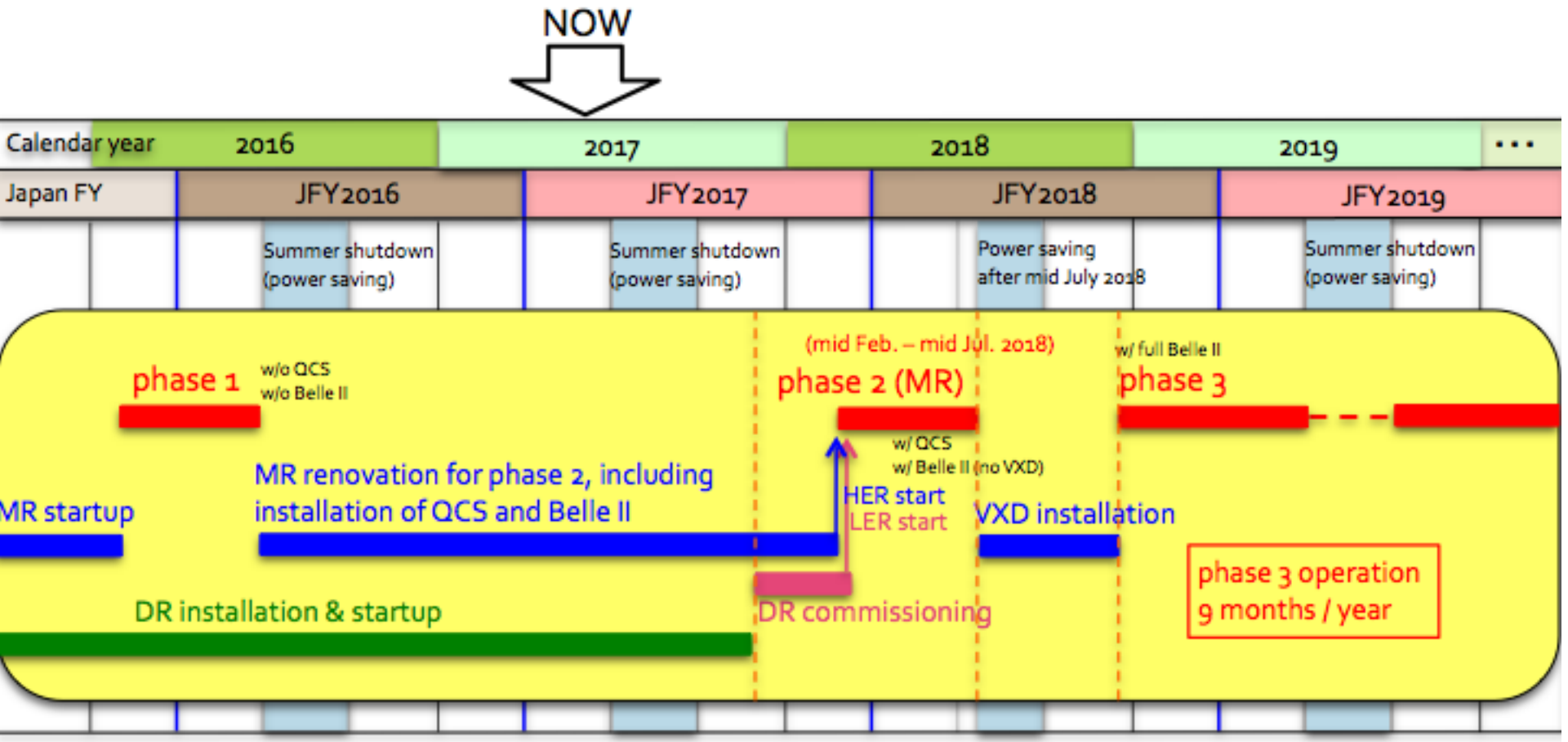
- Phase 1 of the SuperKEKB commissioning successfully completed in 2016, with BEAST II commissioning detector on the beam line
- Belle II rolled in on April 11, 2017!
- June 2017 - B-field measurement, start global cosmic ray run
- Sept. 2017- Installation of A-RICH and forward ECL
- Nov. 2017 - Spring 2018: Phase 2 commissioning

  (+ first Physics runs, without vertex detector)
- Summer 2018 - Install vertex detectors
- Late 2018 - full detector operation - Start of Physics runs

Thank you!

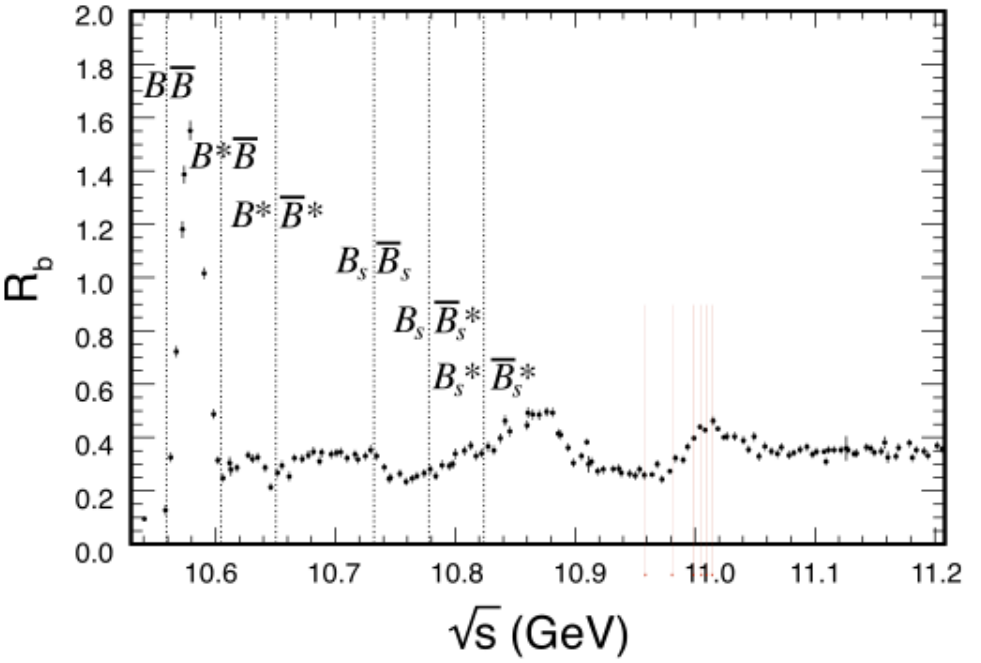
More slides

SuperKEKB/Belle II schedule



Phase II Unique data sets

- **Only ~20-40 fb^{-1} in Phase II**
  - Unique E_{CM} , e.g. Y(6S) for bottomonium - strong interaction studies
  - New trigger menu to greatly enhance low multiplicity & dark sector physics

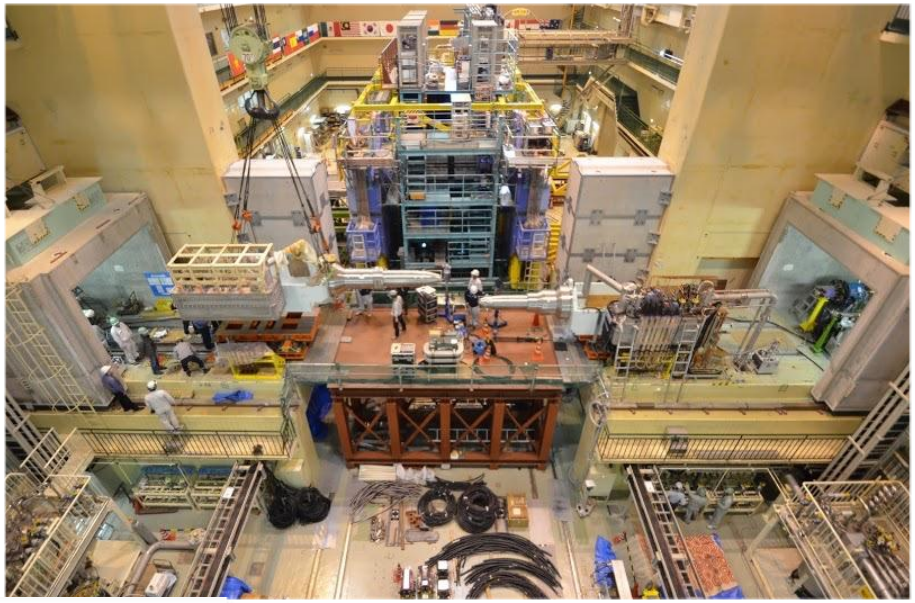


Experiment	Scans Off. Res.	$\Upsilon(6S)$ fb^{-1}	$\Upsilon(5S)$ fb^{-1}	$\Upsilon(5S)$ 10^6	$\Upsilon(4S)$ fb^{-1}	$\Upsilon(4S)$ 10^6	$\Upsilon(3S)$ fb^{-1}	$\Upsilon(3S)$ 10^6	$\Upsilon(2S)$ fb^{-1}	$\Upsilon(2S)$ 10^6	$\Upsilon(1S)$ fb^{-1}	$\Upsilon(1S)$ 10^6
CLEO	17.1	-	0.1	0.4	16	17.1	1.2	5	1.2	10	1.2	21
BaBar	54	R_b scan			433	471	30	122	14	99	–	
Belle	100	~ 5.5	36	121	711	772	3	12	25	158	6	102

Final focus magnets

Superconducting quadrupole magnets with 30+25 coils

The second one delivered on Feb 13



World's most complex SC final focus!