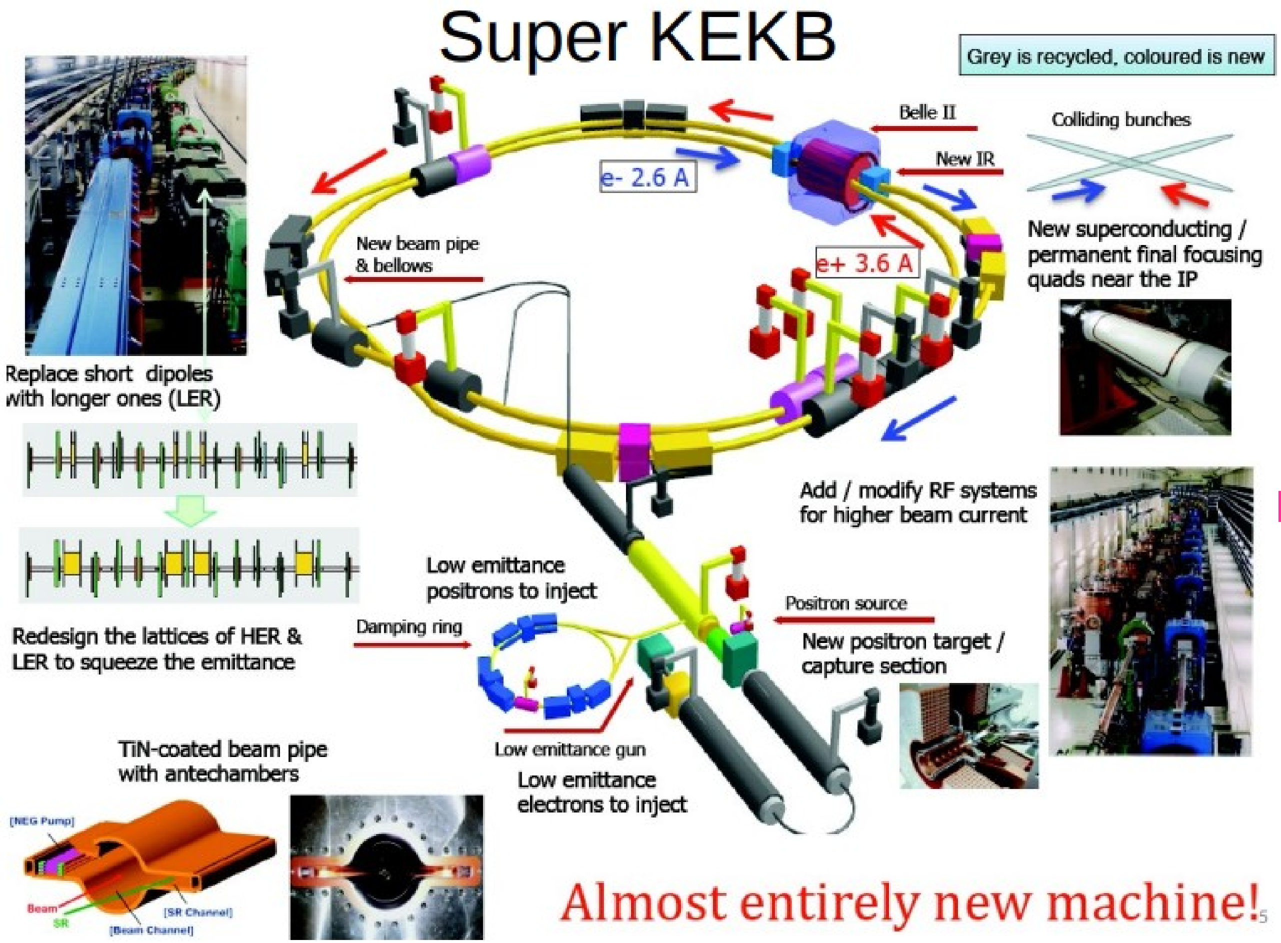
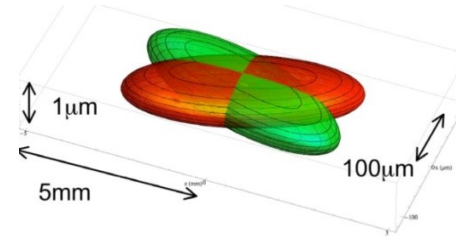
Status and upgrade of BelleII detector

A.Kuzmin, BINP/NSU
(For Belle II collaboration)

- SuperKEKB and Belle II
- Belle II data taking
- Vertex detector
- Central drift chamber (CDC)
- Particle ID
- Calorimeter
- KLM system
- Upgrade plans

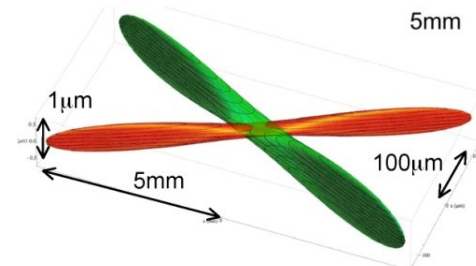


KEKB



σ_x~100μm,σ_y~2μm

Nano-Beam SuperKEKB



σ_x~10μm,σ_y~60nm

- **e^-(7GeV) -e^+(4GeV) collider**
- **Target luminosity 6 10^{35} $cm^{-2}s^{-1}$**
- **Target luminosity integral 50 ab^{-1}**

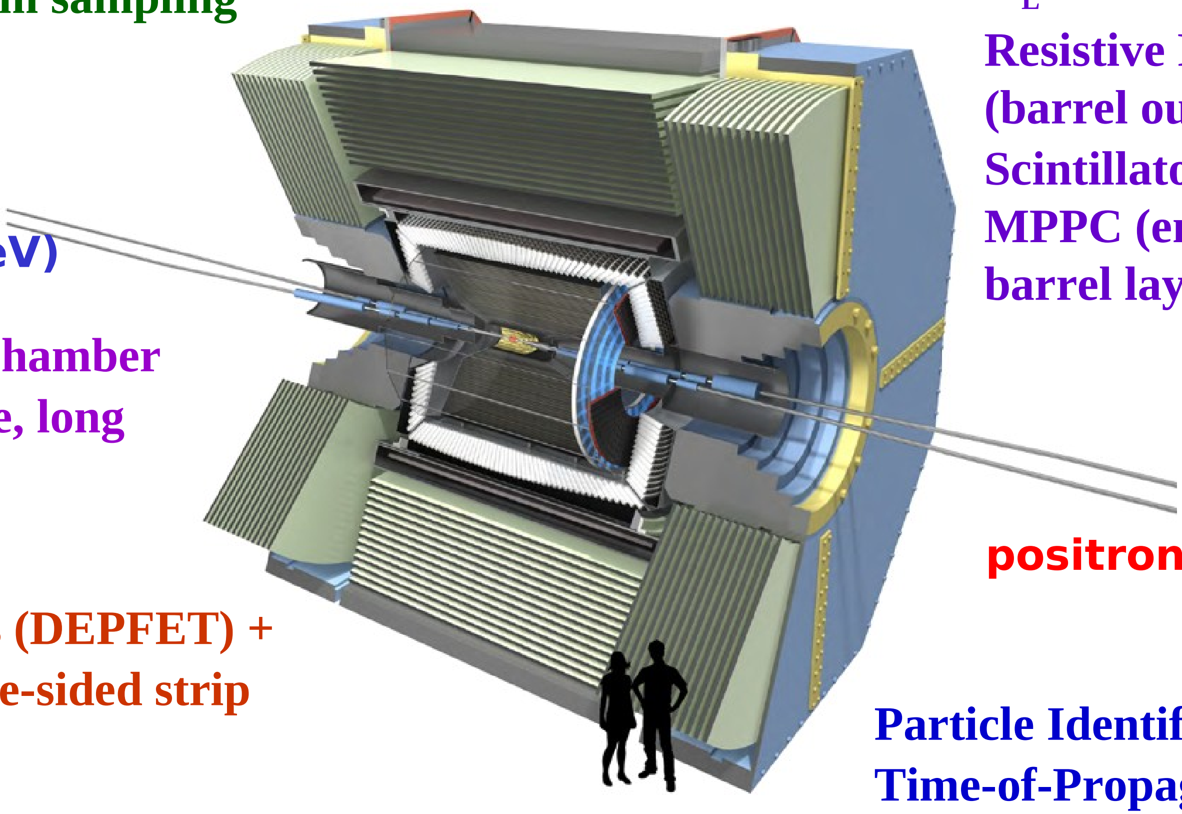
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm\xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_{y\pm}}}\right)$$

Belle II Detector

EM Calorimeter:
CsI(Tl), waveform sampling electronics

K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

electrons (7GeV)



Central Drift Chamber
Smaller cell size, long lever arm

positrons (4GeV)

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double-sided strip DSSD

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

+ New software, improved tracking, ...
+ Optimization for low multiplicity trigger
+ Improved simulation, generators and GRID

The Belle II data taking

First beam in 2016 → first collision in April 2018

Run I: from March 2019 to June 2022; L_{int}= 430 fb^{-1}

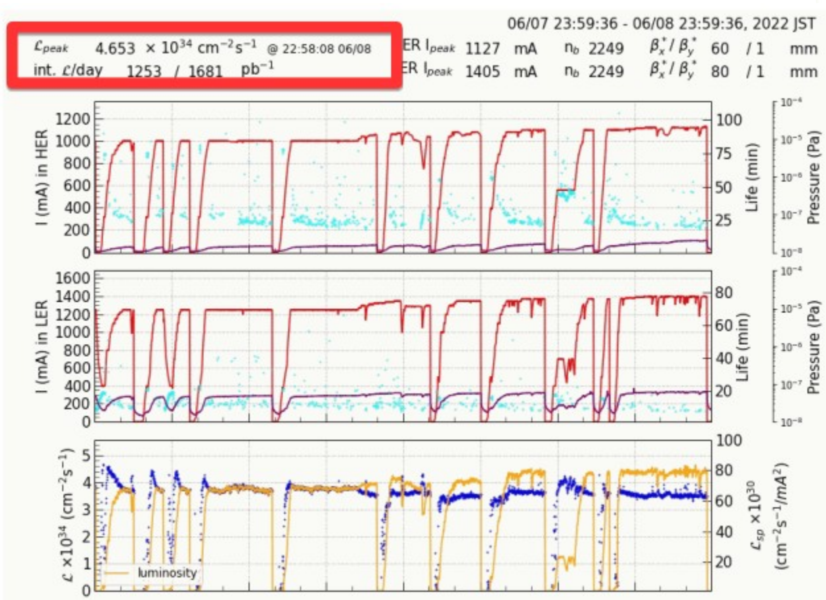
Achived luminosity 4.7 10^{34} $cm^{-2}s^{-1}$ (World Record)

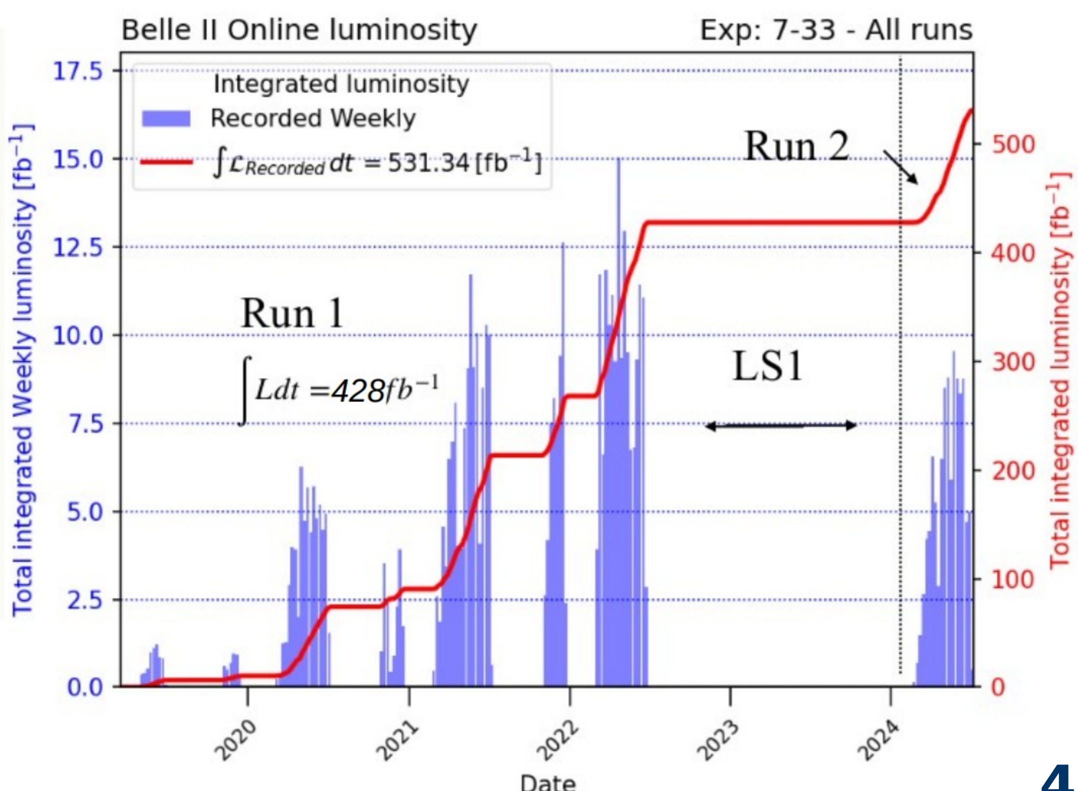
LS1: from July 2022 to February 2024

Run II: from February 2024; L_{int}= 100/fb^{-1}

Run 1

Type	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (fb^{-1})
$\Upsilon(4S)$	10.580	365.37 ± 1.70
off-$\Upsilon(4S)$	10.517	42.74 ± 0.20
$\Upsilon(5S)$ scan	10,657	3.54 ± 0.03
	10.706	1.63 ± 0.02
	10.751	9.88 ± 0.06
	10.810	4.71 ± 0.03
Total	—	427.87 ± 2.01





The Belle II physics

- B-physics, CP-violation
- tau, charm physics
- Clean environment for spectroscopy and dark sector
- Study processes in Initial state radiation(ISR)

Variety of analysis:

- Life time, time-dependent analysis
- Missing energy and missing mass

Recent results:

EW-radiative penguins:

- BR, A_{CP} and Δ_{+0} of $B \to K^* \gamma$
- search for $B^0 \to \gamma\gamma$
- $b \to d\, ll$
- Evidence of $B^+ \to K^+ \nu\nu$

Semileptonic decays:

- Vub untagged $B \to \pi/\rho l \nu$
- Update of $B \to D^* l \nu$

low multiplicity and τ

- $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$
- LFU in τ decays
- $\tau \to \mu\mu\mu$

Dark sector

- Search $Z' \to \mu\mu$

b, c hadronic decays:

- BR of $B^- \to D^0\rho^-$
- BR and A_{CP} of $B0 \to \pi^0\pi^0$
- BR of $\Xi^0_c \to \Xi^0\pi^0, \Xi^0\eta, \Xi^0\eta'$
- γ angle Belle+Belle II determination

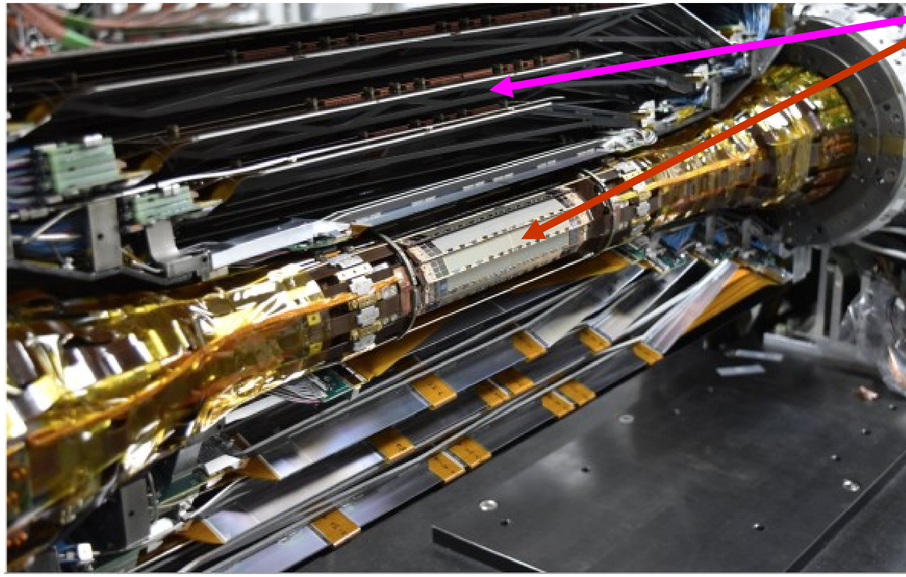
Time dependent CPV:

- $B^0 \to \eta' K_S$
- $B^0 \to K_S \pi^0 \gamma$

Quarkonia and spectroscopy:

- Υ(10753) rediscovery
- Search $\Upsilon(10753) \to \omega\, \eta_b(1S)/\chi_b^0(1P)$
- Energy dependence of e+e- $\to B^{(*)}B^{(*)}$

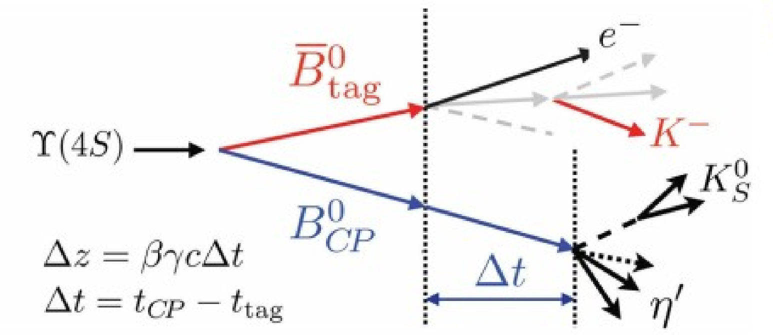
Vertex detector PXD+SVD

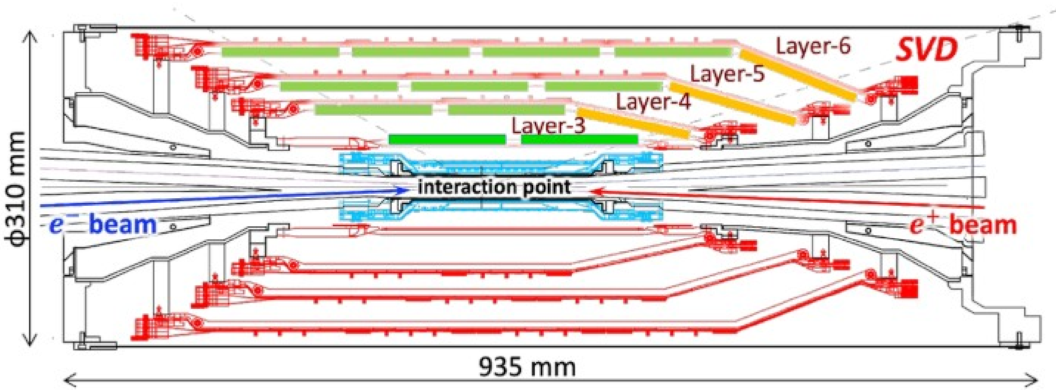


Vertex measurement:

-CP violation study

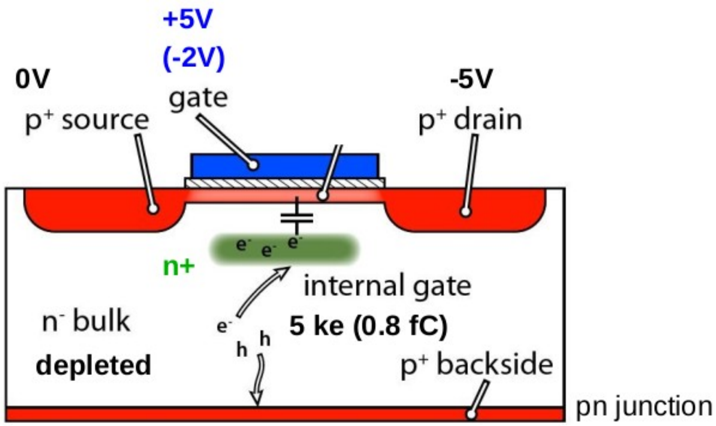
-decay time measurement



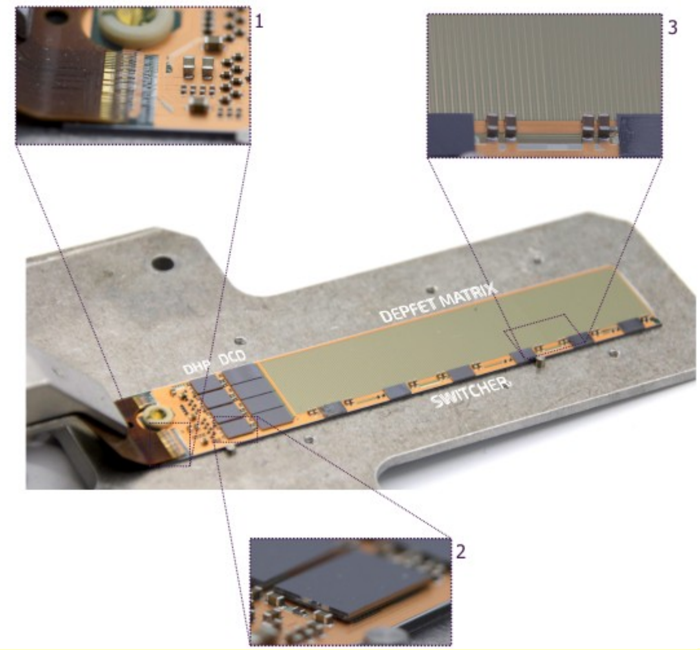


	Belle II	Belle
Beam pipe	10 mm	15 mm
DEPFET		
layer 1	14 mm	
layer 2	22 mm	
DSSDD		
layer 3	39 mm	20 mm
layer 4	80 mm	43.5 mm
layer 5	104 mm	70 mm
layer 6	135 mm	88 mm

PXD



-60V bias (top surface punch through)



-pixel detector: depleted FET

-ionized charge collected by drift at an internal gate (small deep implant)

-DEPFET is off for 19.9/20 μs: gate at +5V

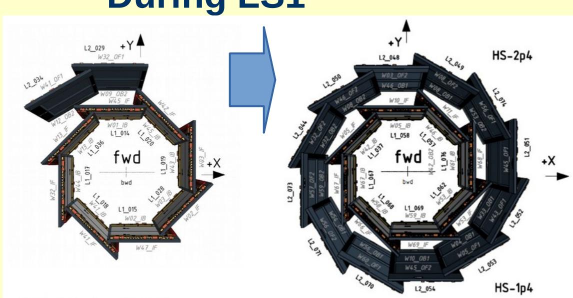
-“readout”: modulated drain current: gate at -2V

-reset after readout: Clear at +15V (punch through)

Each module is 15.4 × 85.0(68.0)mm² single-die silicon structure with 768 × 250 pixels of varying sizes from 50 μm × 55 μm to 50 μm × 85 μm.
2 modules are joined end-to-end with glue and ceramic stiffeners to form a ladder.
The ladders are cooled by evaporating CO_2 -20°C– 30°C

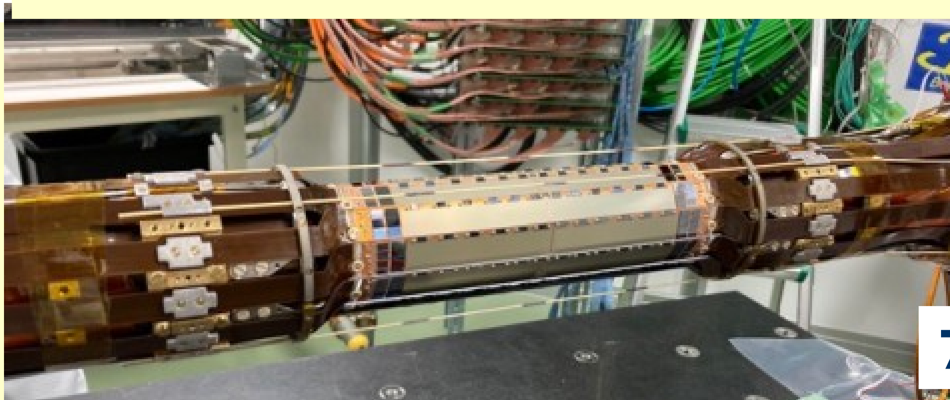
L1: 8 ladders; L2: 12 ladders

During LS1

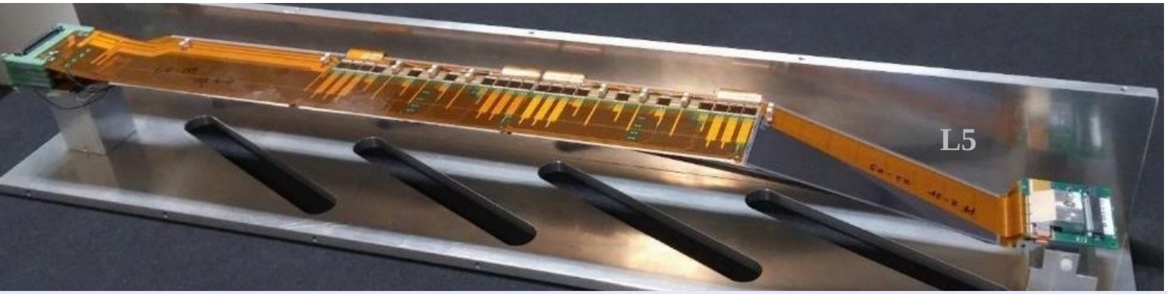


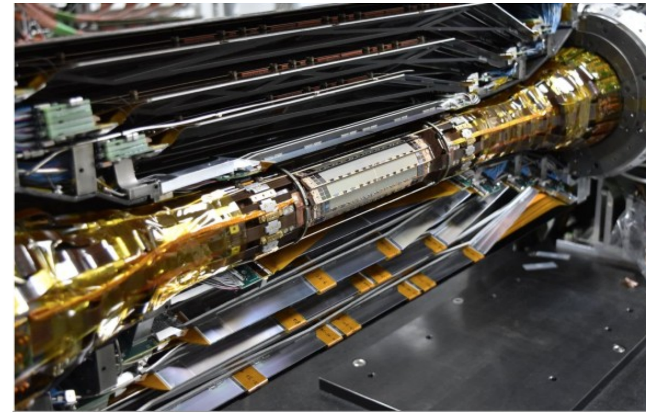
2018: lack of quality ladders (in-house production)

2023: 40 (all new) modules, same design (same in-house production)



SVD



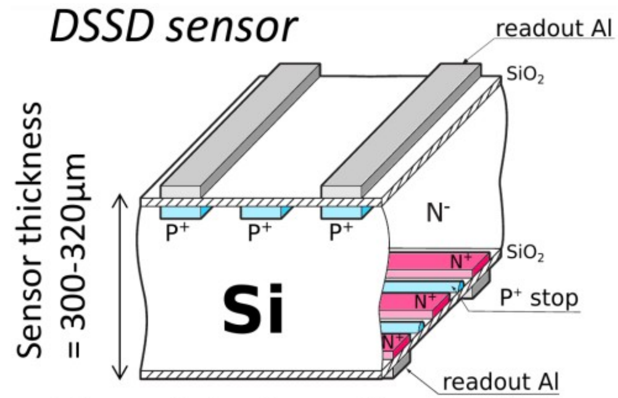


Ladder: 3 to 6 Double-Sided Si strip sensors along z

- **AC coupling: block leakage current and bias potential**
- **intermediate floating strips improve resolution**
- **readout and power distribution on flexible Kapton prints**

- work for 10 Mrad and 3×10^{13} n_{eq}/cm^2

- Thickness 0.75%X_0/layer (SVD) 0.25%X_0/layer(PXD)
total thickness: 3.5%X_0



AC-coupled strips on N-type substrate
Full depletion voltage: 20-60V
Operation voltage: 100V

	Small rectangular	Large rectangular	Trapezoidal
Readout strips P-side	768	768	768
Readout strips N-side	768	512	512
Readout pitch P-side (μm)	50	75	50 – 75
Readout pitch N-side (μm)	160	240	240
Sensor active area (mm^2)	122.90×38.55	122.90×57.72	$122.76\times(38.42-57.59)$
Sensor thickness (μm)	320	320	300
	L3	L4-6	L4-6

Vertex detector performance

PXD:

Excellent spatial granularity (σ~15 μm)

Low material (layer 1 is $0.16X_0$)

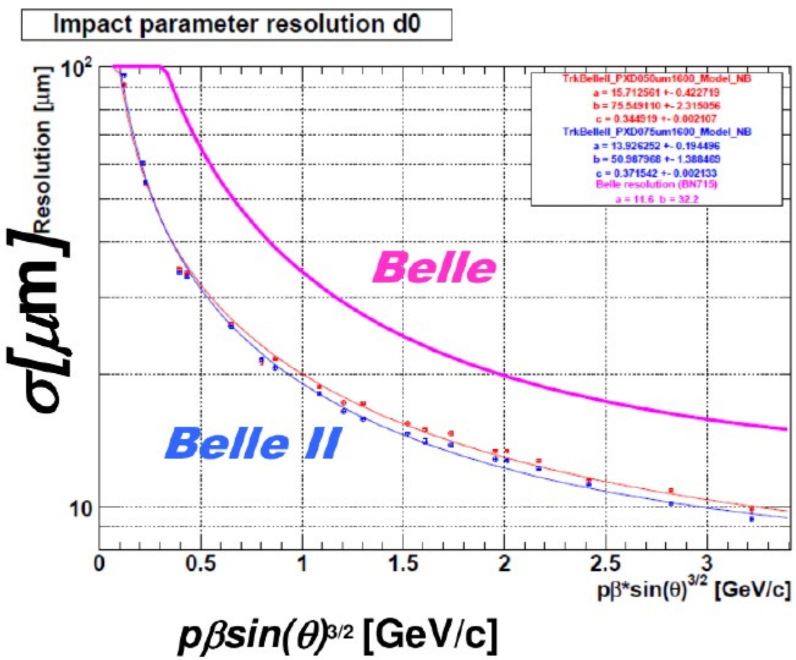
Significant amount of background, high data rate

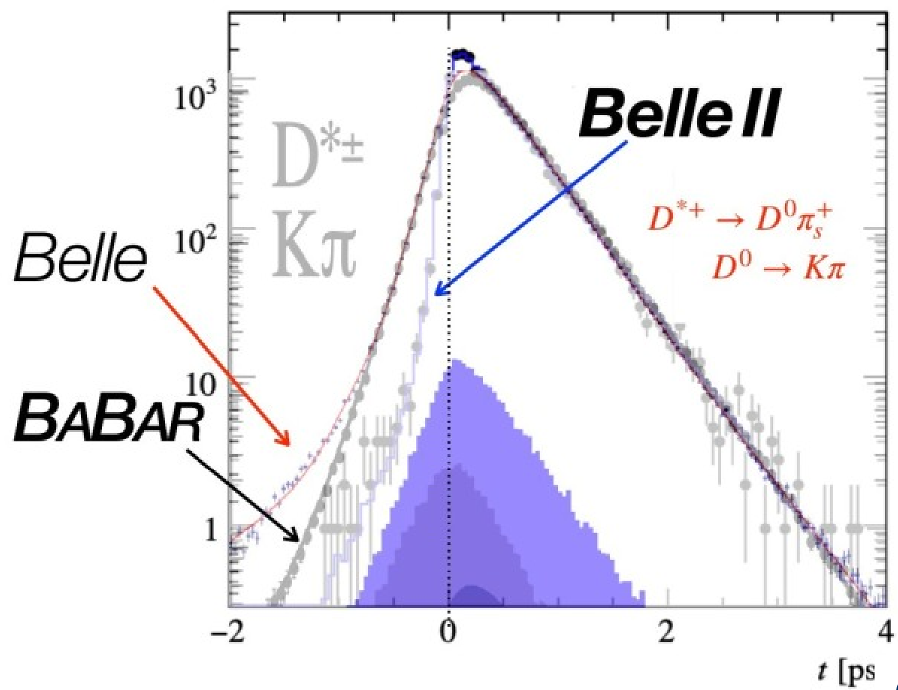
SVD:

Excellent time resolution (σ~2-3 ns)

Has ambiguities in space

Their combination of two detectors provides exelent performance





Central Drift Chamber(CDC)

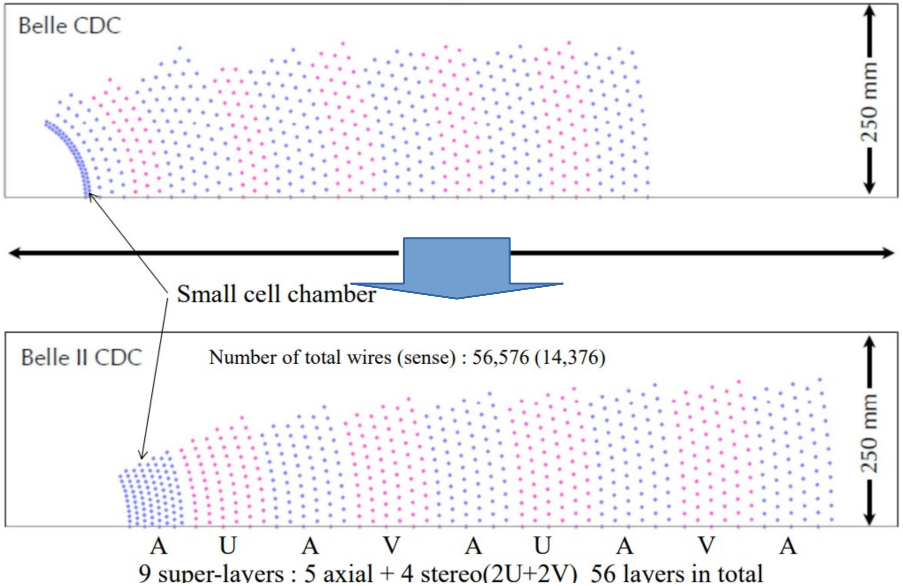
Charged tracks reconstruction:

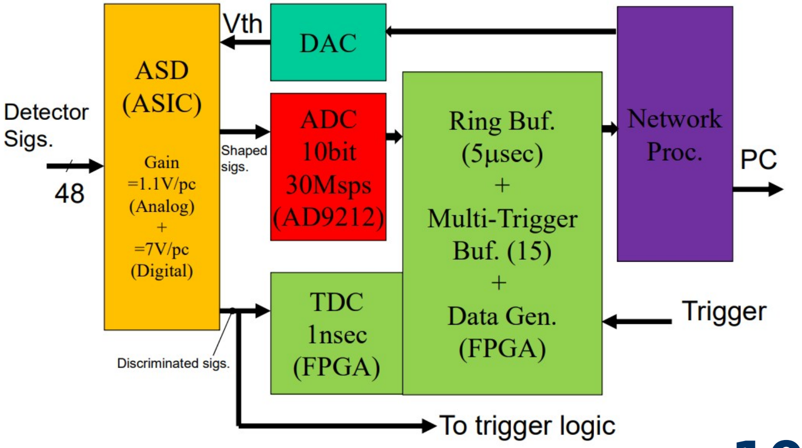
- Measurement of track momentum precisely under magnetic field (1.5 T): position resolution : ~0.1mm
- Particle identification
- Providing the trigger signal

Radius 160 mm – 1130 mm
14 376 Sense wires: Au-W 30μm ~0.072% X_0
56 576 Field wires :Al 126 μm ~0.147% X_0
Chamber Gas He(50%)-C_2H_6(50%) ~0.139% X_0

4 stereo layers with angle of 45.5 mrad to 74 mrad to measure Z-coordinate.

Wire configuration



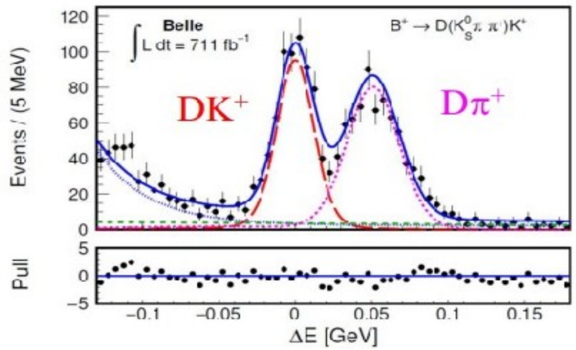


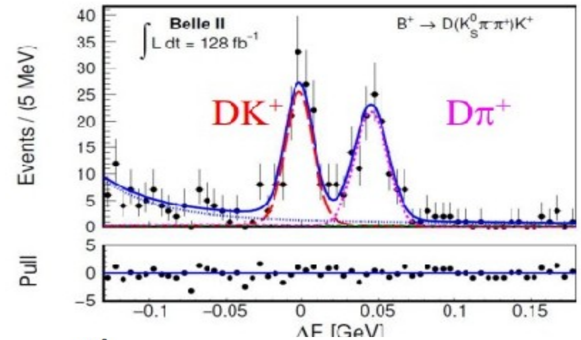
CDC detector performance

-Good P_t resolution better

than for Belle

-Good dE/dx resolution for PID



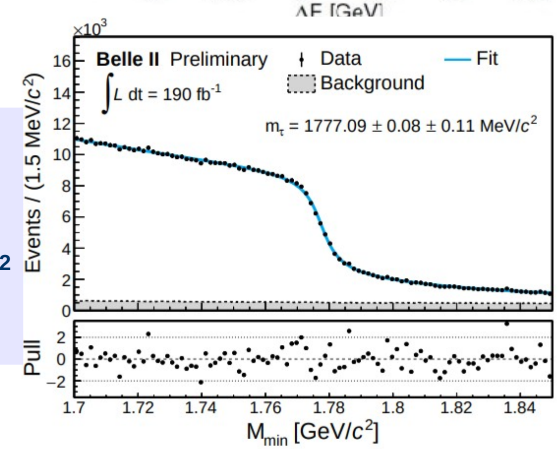


$$\Delta E = \sum \sqrt{p_i^2 + m_i^2} - E_{beam}$$

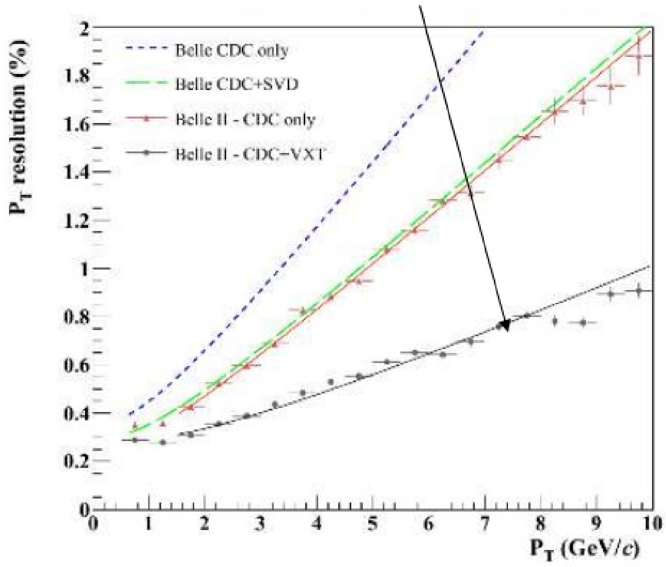
m_τ (τ→ 3π)

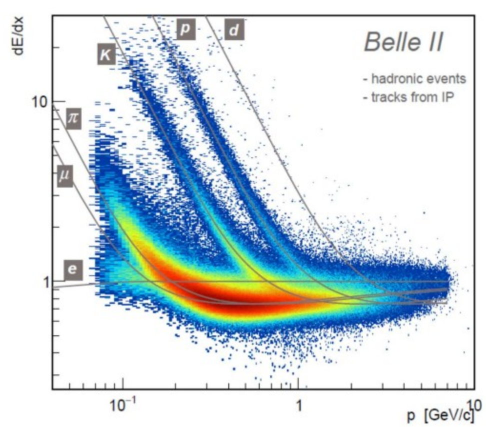
Belle : 1776.61±0.13±0.35 MeV/c²

Belle II: 1777.09±0.08± 0.11 MeV/c²



$$\sigma p_t = \sqrt{(0.098 p_t)^2 + (0.27)^2}\%$$





Bhabha events

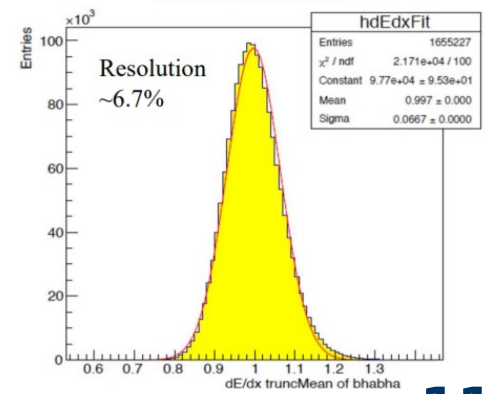
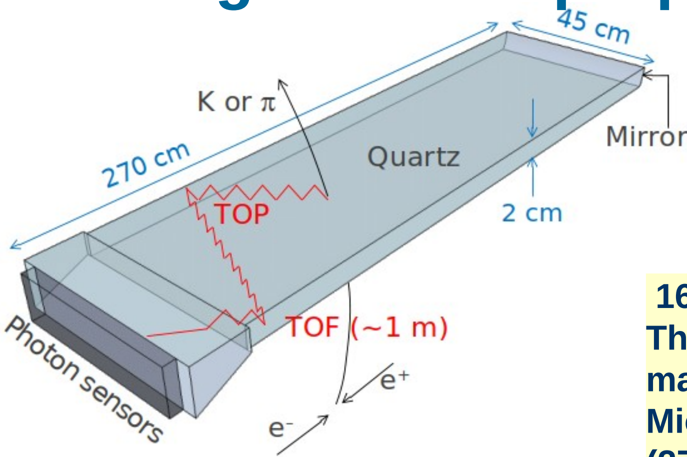
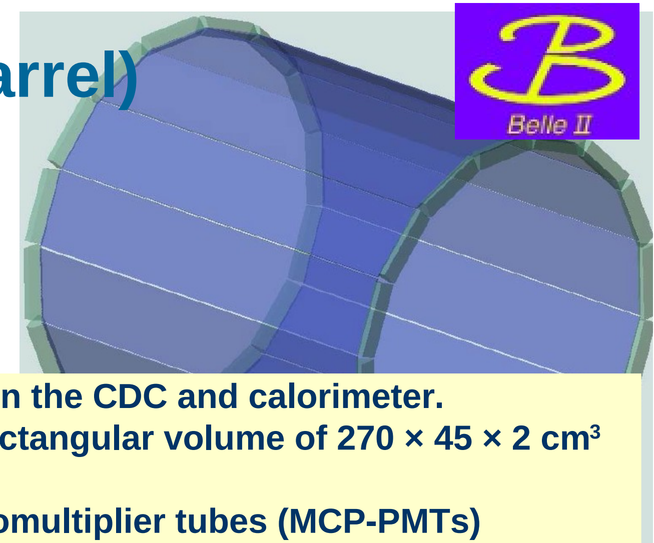
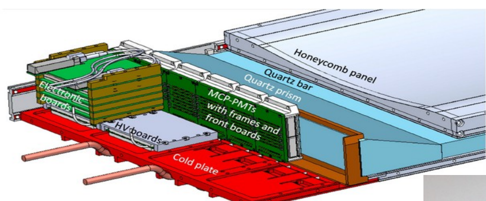


Image Time of propagation counter(Barrel)





16 identical modules, located between the CDC and calorimeter.
The Cherenkov light is emitted in a rectangular volume of 270 × 45 × 2 cm^3 made of fused silica.
Micro-channel-plate multianode photomultiplier tubes (MCP-PMTs) (27.6×27.6)mm^2. The average QE at λ = 360 nm is 29.3%.
The TTS is 34.3 ps. Anode 5.3x5.3 mm^2.
Four MCP-PMTs are assembled into a PMT module.

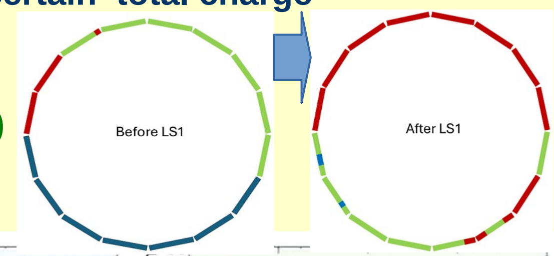


MCP-PMTs photocathode degrades after certain total charge

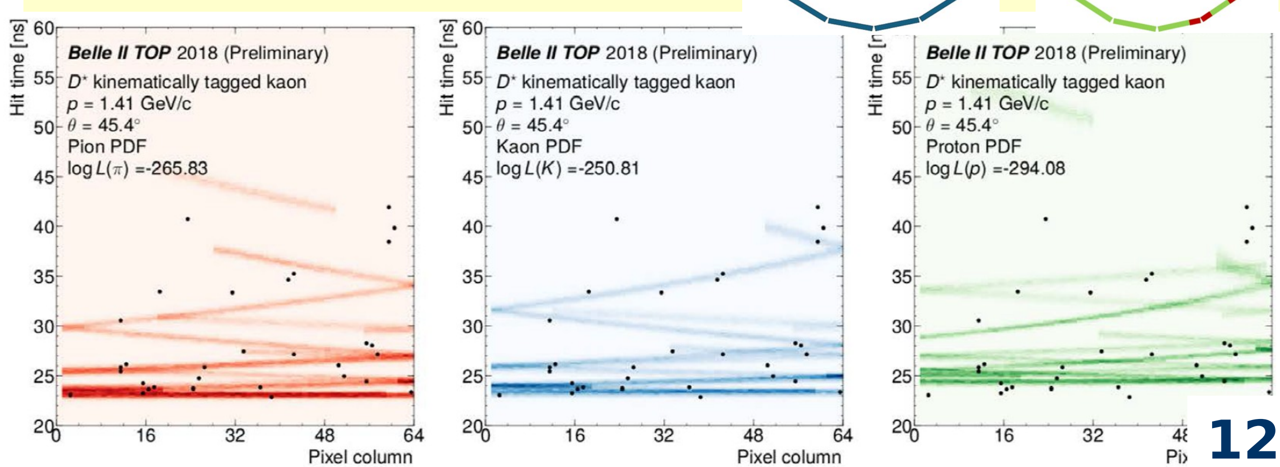
Conventional MCP-PMTs (1.1 C/cm^2)

Atomic Layer Deposition (ALD) (~10 C/cm^2)

life-extended-ALD (>15 C/cm^2)



The geometrical distribution of the detected light and the time required by each photon to travel form the emission point to the detection plane are functions of the emission angle.

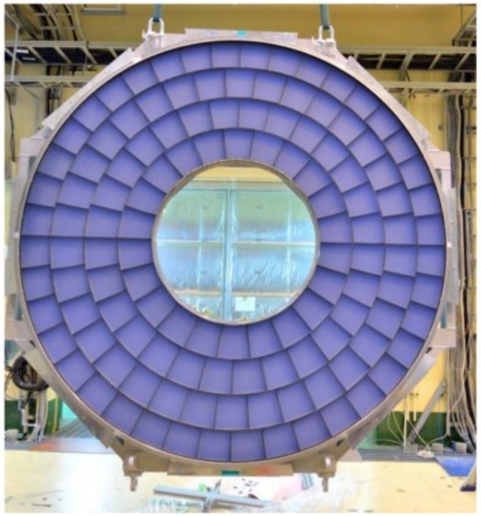


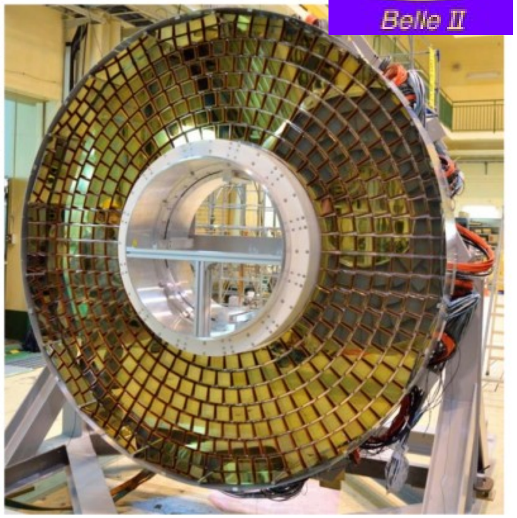
Aerogel Ring Imaging Cherenkov counters ARICH(FWD)

-ARICH detector allows to separate kaons from pions and protons over most of their momentum spectrum in the forward end-cap measuring Cherenkov light angle.

The radiator plane is comprised of two layers of hydrophobic aerogel blocks.

The refractive indices are n = 1.045 in the first and n = 1.055 in the second layer.

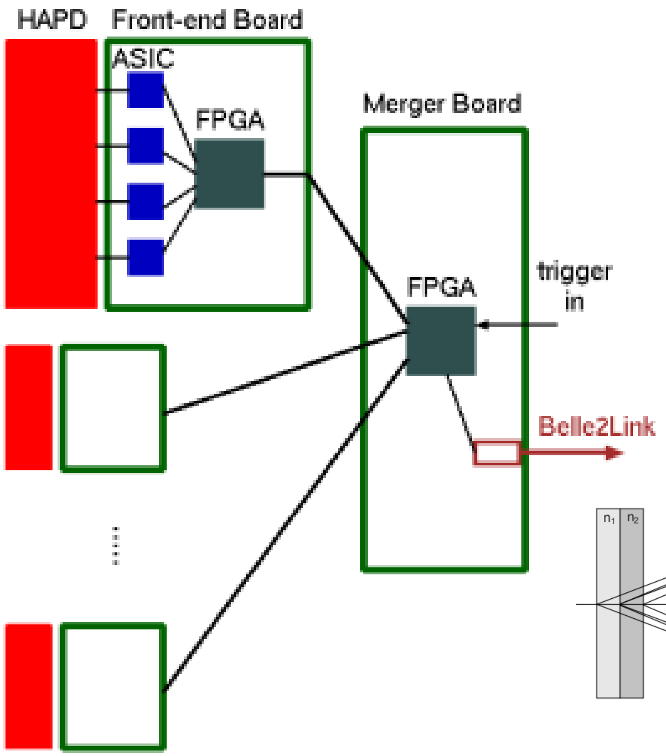


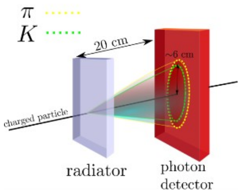


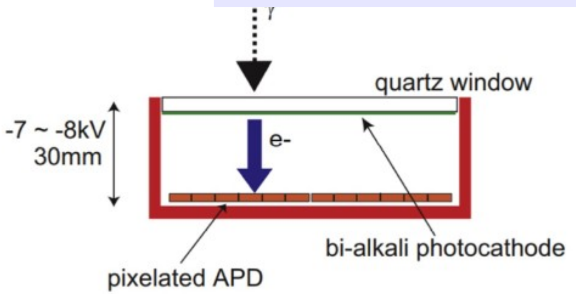
-124 aerogel modules

$180 \times 180 \times 20\ \mathrm{mm}^3$

-420 hybrid avalange photodetectors

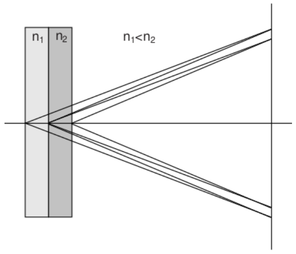




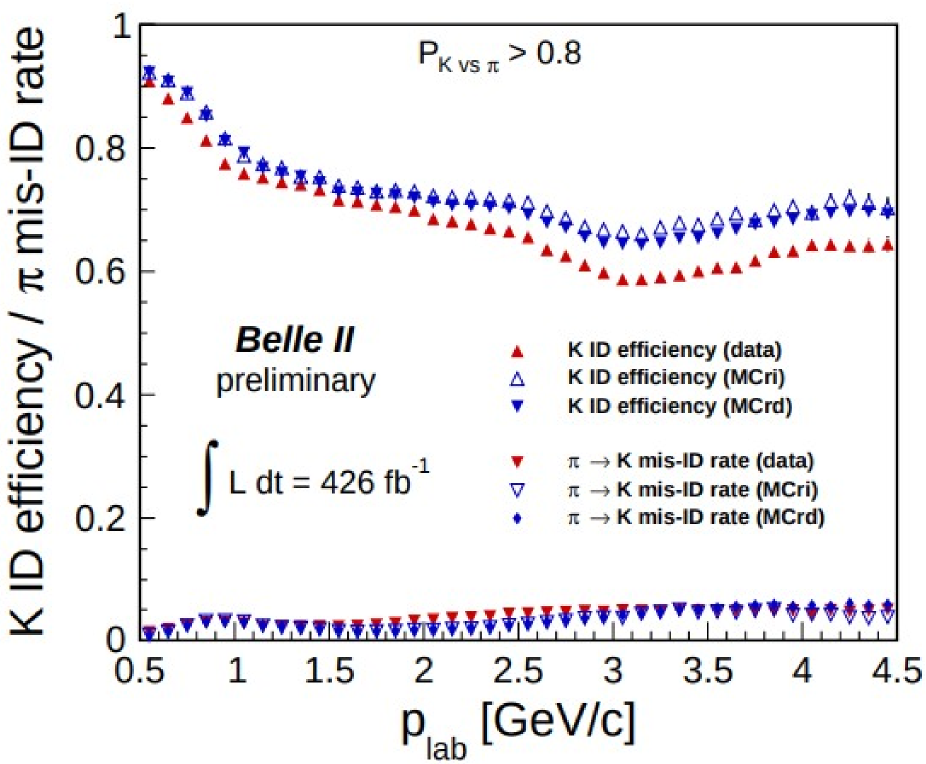


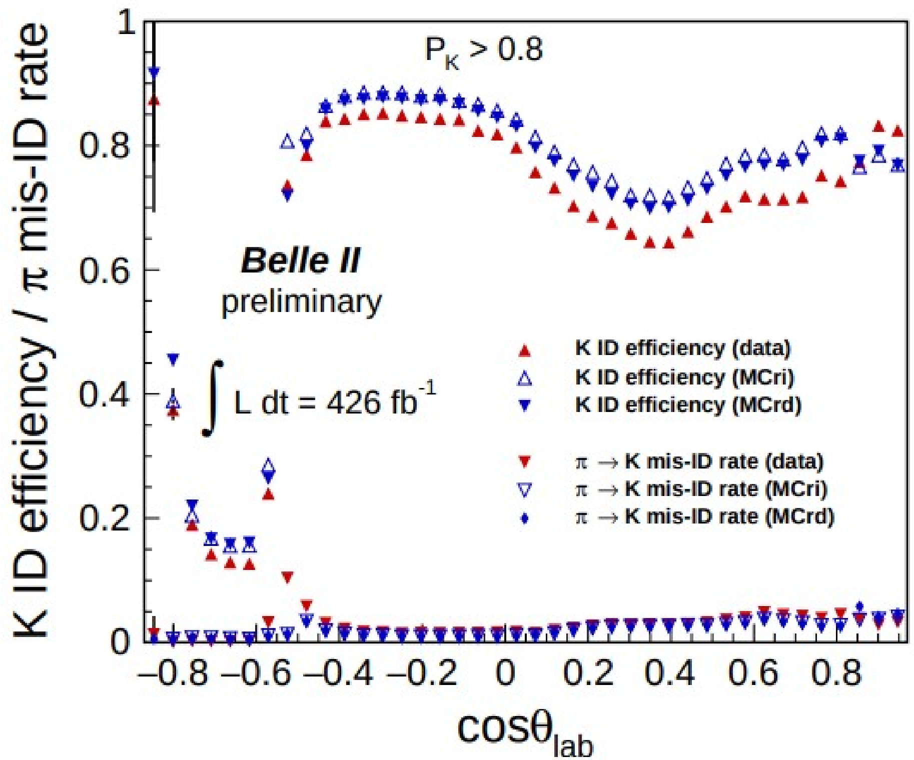
-The quantum efficiency of the photocathode is ≈ 30% at the wavelength of 400 nm The photo-electron detection efficiency is around 90%.

The radiation tolerance of the device was tested in the preparatory phase; the tested samples retained the required performance at the neutron fluence of 10^{12} 1 MeV neq cm^{-2}



PID performance





-Good kaon identification, currently slightly underperforming wrt Belle.

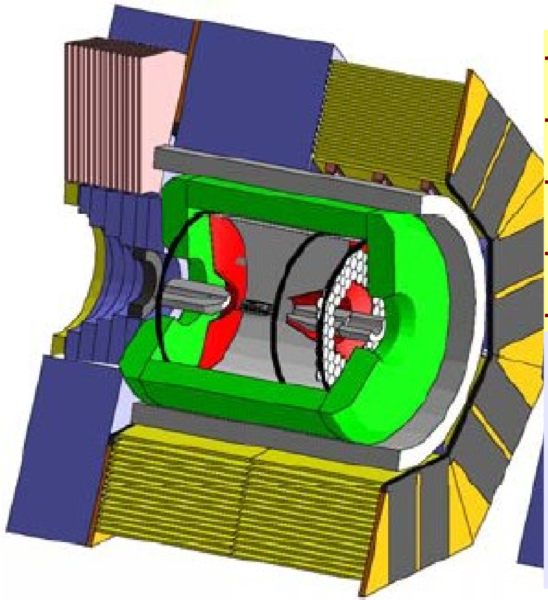
-Big efforts underway that will improve this

-ML for TOP

-Taking into account correlations

-Systematics associated to Data/MC correction factors currently at 0.8-1% level (0.8% at Belle).

Electromagnetic Calorimeter



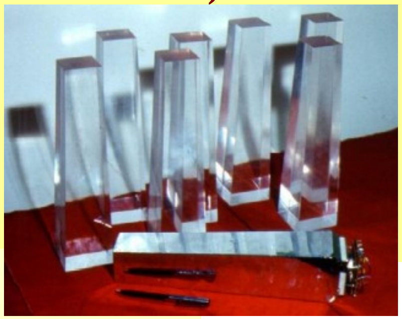
-Measurement energy, time and angles of the photons (30 MeV -7 GeV)

-Electron identifcation

-K_L identification

-Neutral trigger

-On-line luminosity measurement



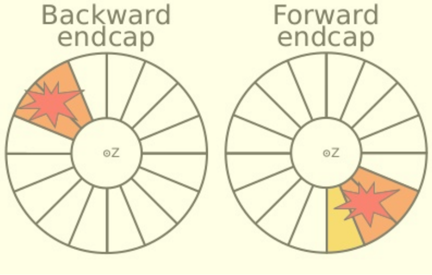
- Total 8736 counters.
- Barrel 6624
- Forward end cap 1152
- Backward end cap 960

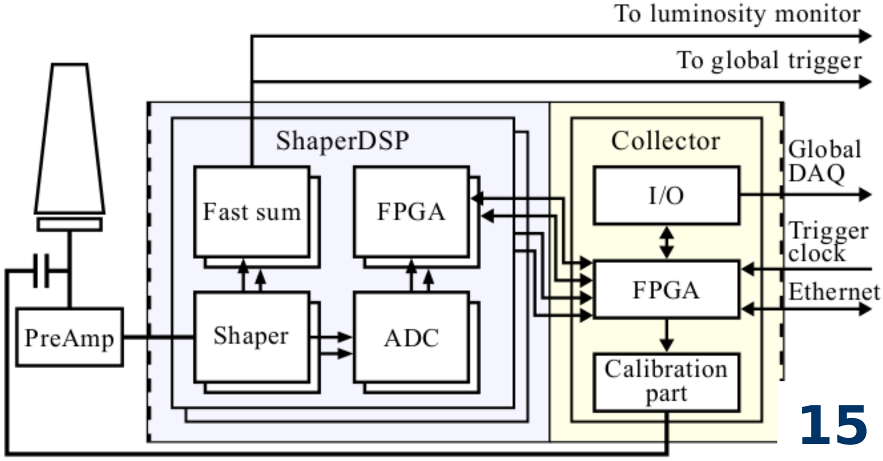
Counter:

- 30cm long CsI(Tl) (16.1 X_0)
- 2x 2cm^2 PIN diodes
- 2 preamplifiers

- Belle calorimeter worked for ten years – all counters are alive!
- Crystals, PINs and preamplifiers are kept from Belle
- Shaping and digitizing electronics have been upgraded

-Counting rate of the coincidence two endcaps sectors provides luminosity measurement





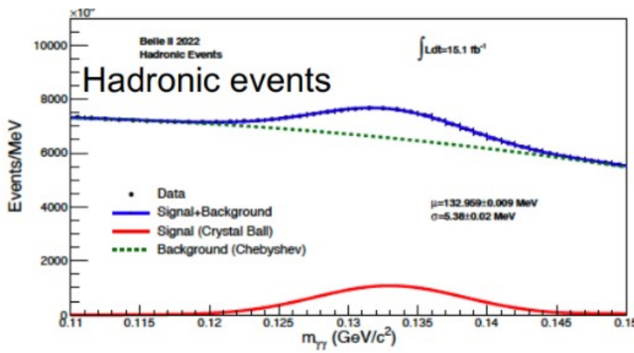
Calorimeter performance

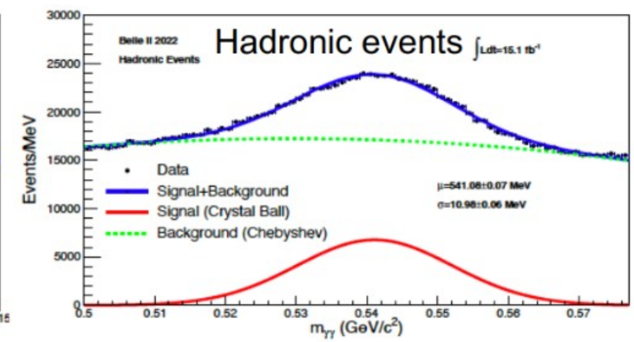
Energy resolution was studied for $e^+e^- \to \mu^+\mu^-\gamma$ events

For 1 GeV $\sigma E/E$=2.2% $\sigma\tau$ ~1.5 ns

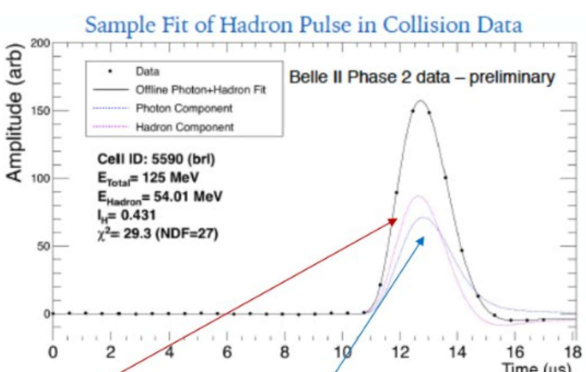
For Hadronic events:

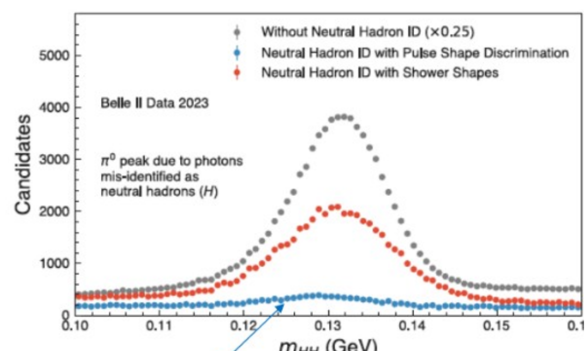
$\pi^0 \to \gamma\gamma$ ($E\gamma$>25 MeV) $\sigma m_{\gamma\gamma}$=5.4 MeV/c^2 $\eta \to \gamma\gamma$ ($E\gamma$>400 MeV) $\sigma m_{\gamma\gamma}$=11 MeV/c^2





There is a difference in pulse shape for MIP and High density ionization.For hadron interactins we have p, nuclear fragments etc. Fitting the response by sum of high ionizing(Eh) and MIP(Ep) component, Eh/Ep can be used for PID h/e and K_L/γ.

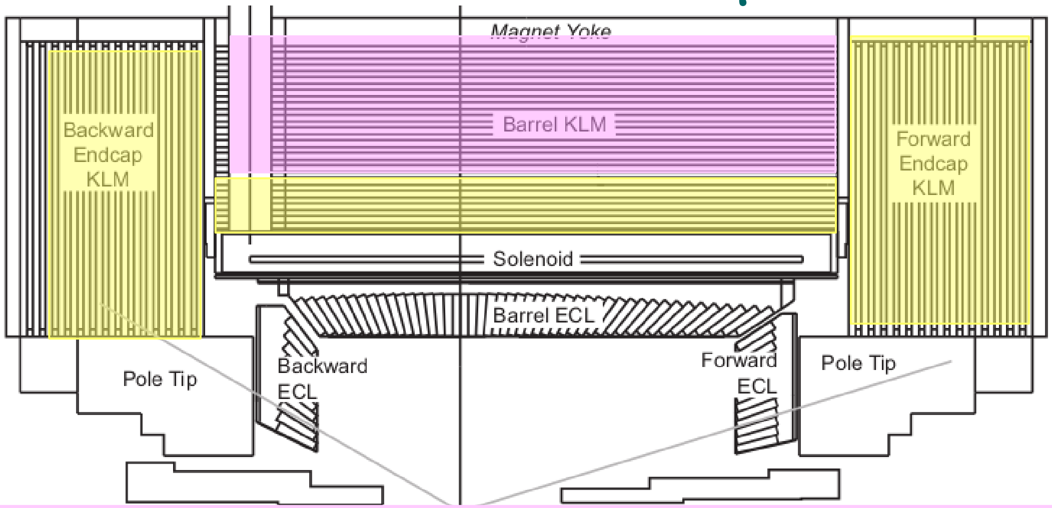




Hadron and photon components exhibit different pulse shape

By rejecting photon-like clusters, π^0 mass peak disappears.

K_L/μ detector



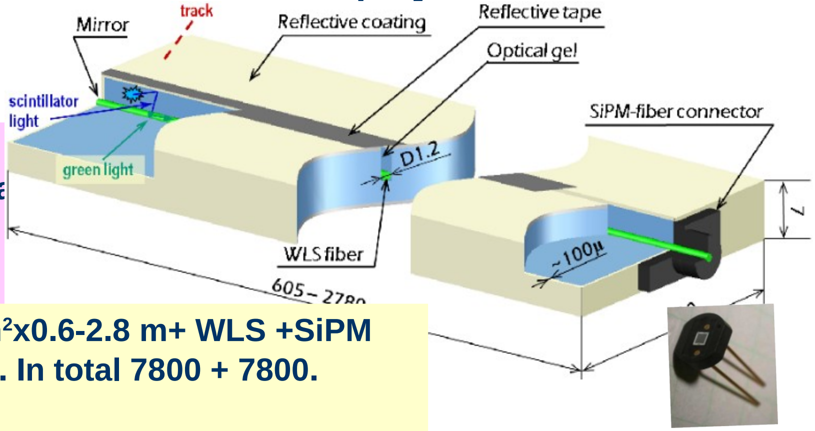
in the barrel: 15 detector layers+14 iron plates

L1-2: Scintilators; L3-15: RPC

14 detector layers +14 iron plates in forward.

12 detector layers +14 iron plates in backward.

In endcap scintilators, 2 outer layers of backward filled with polyethelen



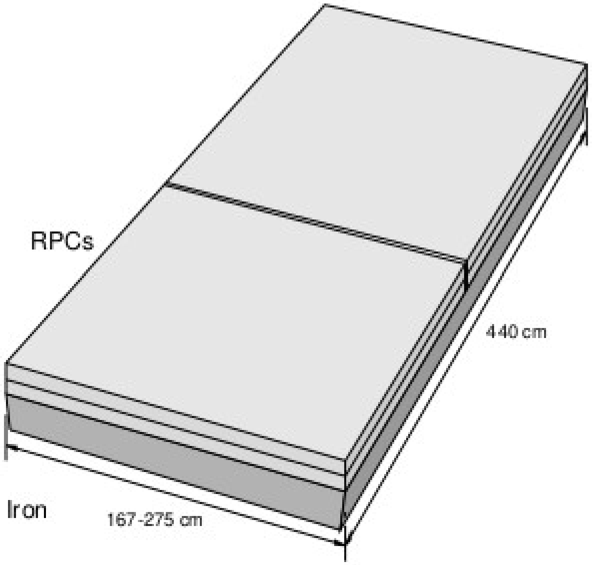
One RPC layer: two independent counters assembled is enclosed in an aluminum box 3.7 cm thick x 2.2×1.8 m^2 to 2.2×2.7 m^2 in surface area

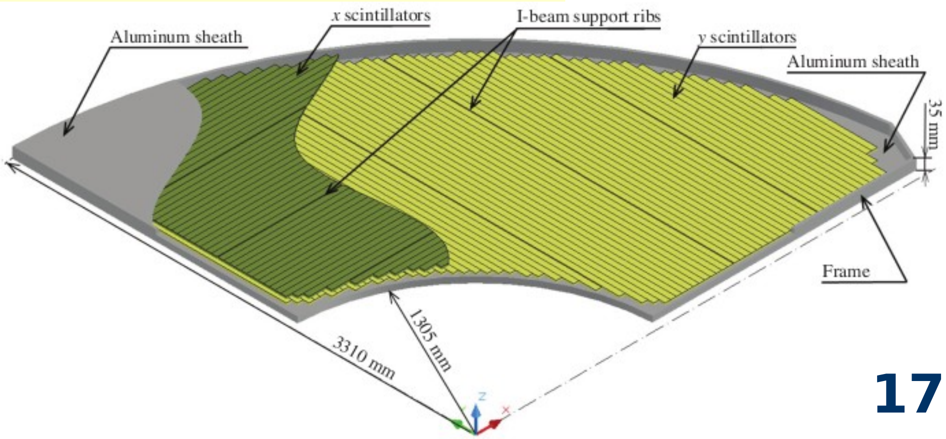
Gas: Ar(30%)+C_4H_{10}(8%)+CH_2 FCF_3(62%); HV: +4.7 kV and –3.5 kV;

Strip width ~5 cm: 9116 strips in ϕ+ 9206 strips iz Z

Scintilator: 40x7mm^2x0.6-2.8 m+ WLS +SiPM

75 ϕ + 75 Z per octant. In total 7800 + 7800.

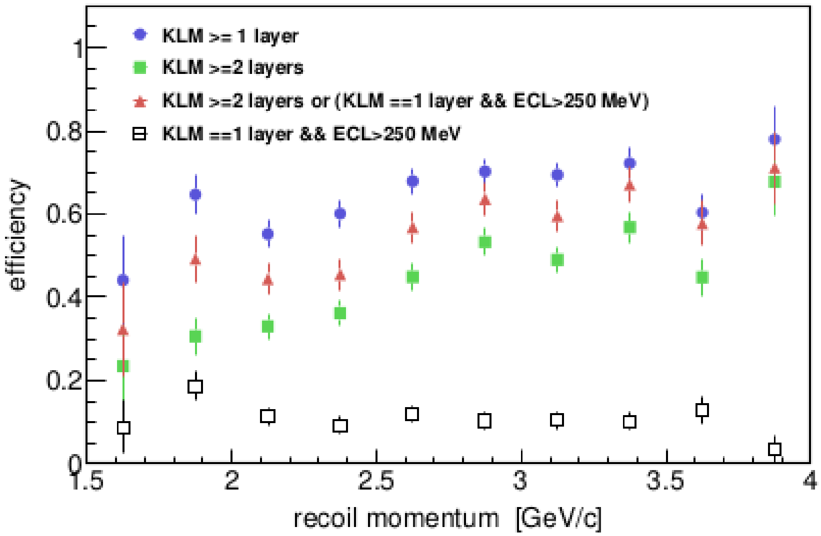


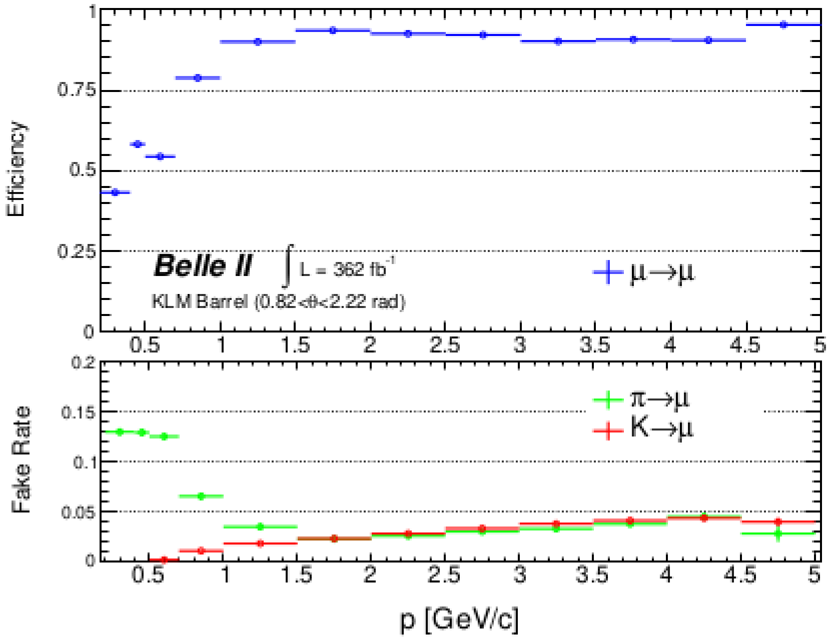


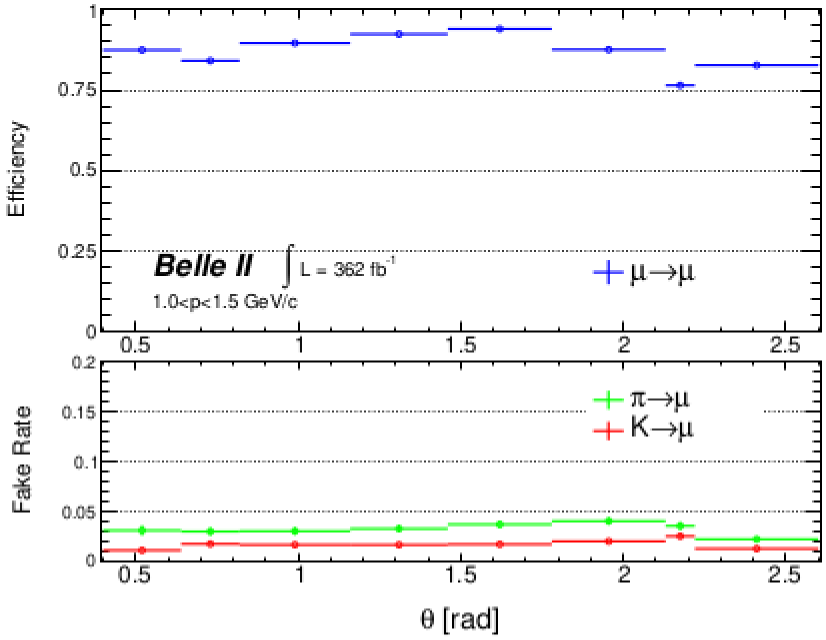
KLM performance

-K_L are detected with efficiency > 50% in KLM

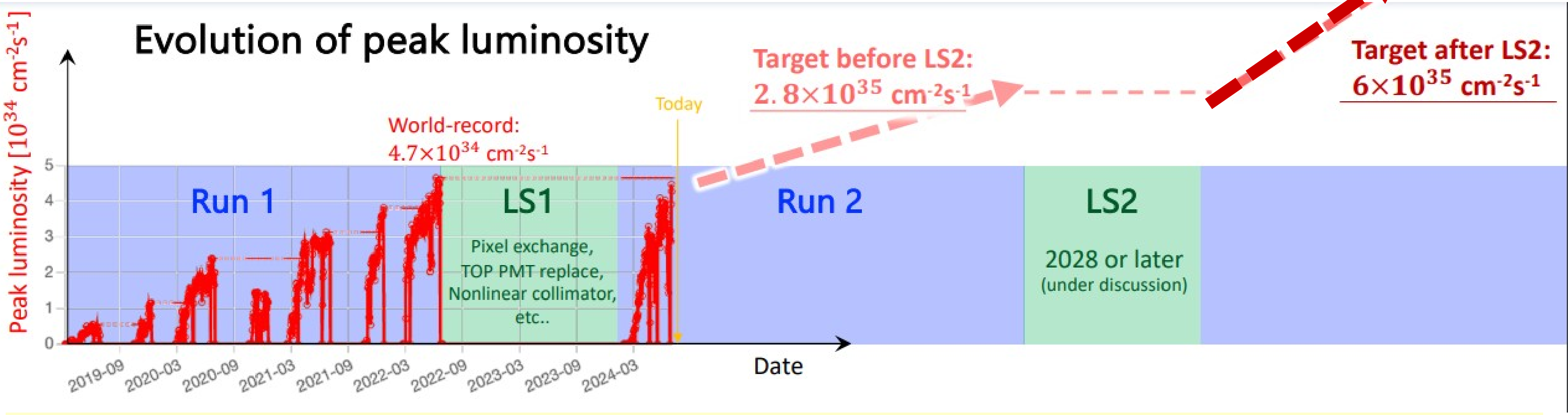
-KLM provides π/μ separation for p>1 GeV/c







Belle II upgrade



-Severe beam-induced background at high luminosity.

-In future operation, background rates getting closer or reaching system limits.

-PXD detector is damaged due to sudden beam loss. Resulting in ~2% dead area.

Upgrade motivation:

-Improve detector robustness and tolerance against beam-induced background;
-Provide larger safety factors for running at higher luminosity;
-Improve overall physics performance.

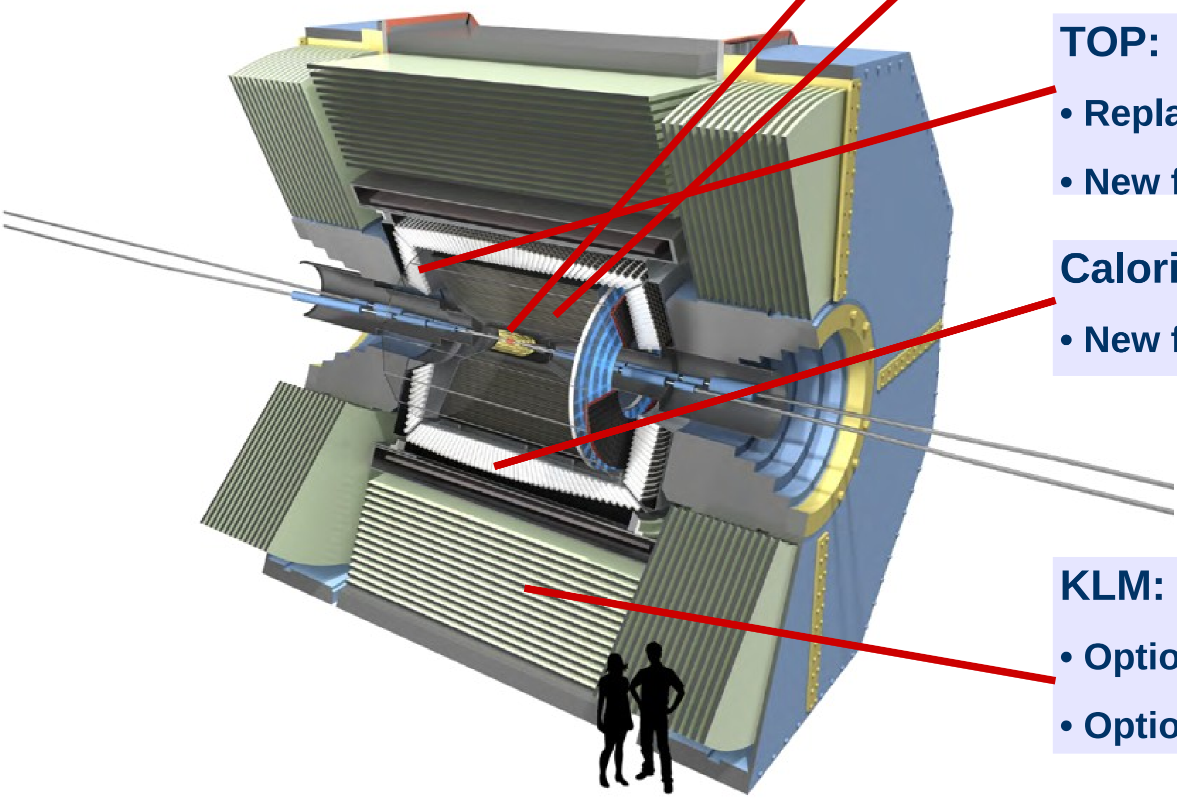
The upgrade plans are categorized into two different timescales:

– Middle-term upgrade -- during LS2 (2028 or later)

– Longer-term upgrade -- beyond LS2 (~mid-2030s)

Belle II upgrade

– Middle-term upgrade during LS2 (2028 or later)



VXD:

- Fully-pixelated CMOS DMAPS detector

CDC:

- New front-end electronics (less cross-talk, better radiation hardness, and less power)

TOP:

- Replace w/ life-extended PMTs
- New front-end electronics (less power)

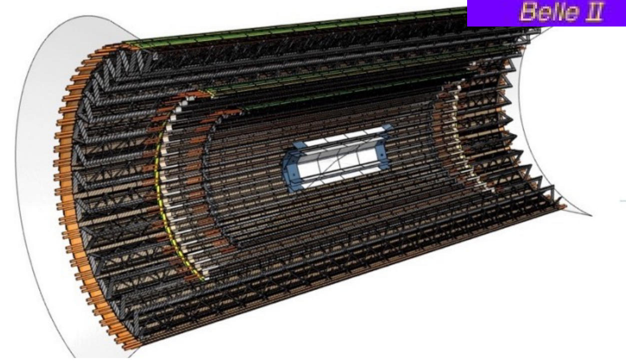
Calorimeter:

- New faster electronics

KLM:

- Option 1: Replace RPC w/ scintillator
- Option 2: RPC avalanche mode operation

VXD upgrade



Fully-pixelated CMOS MAPS detector with simple design and light support

– Cope with more significant background rates
– Improve low-momentum tracking and impact parameter resolution

5 layers with straight ladder

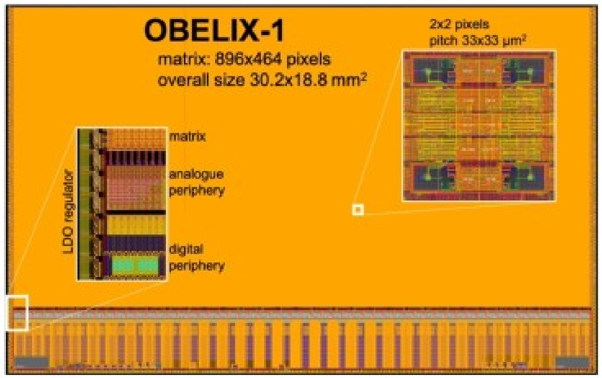
– inner 2 layers: self-supported, cooling method under study
– outer 3 layers: CF structure, water cooling

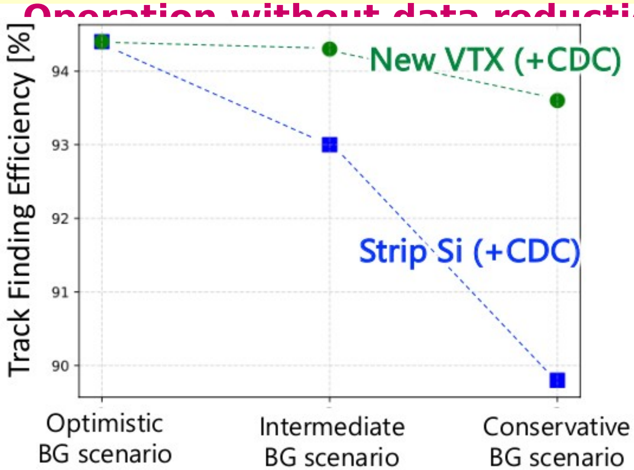
OBELIX sensor: DMAPS for Belle II vertex detector

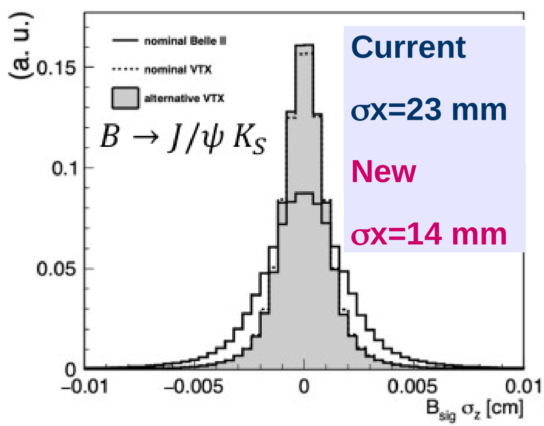
– Design based on TJ-Monopix2 (prototype for HL-LHC ATLAS), implementing new digital periphery and trigger logic
– 1st prototype submission will be in late 2024.

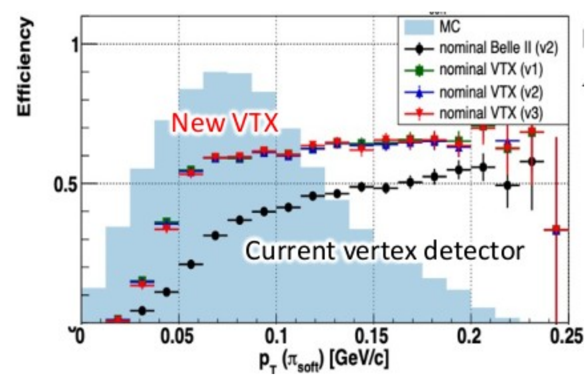
- **Improved tracking and vertex resolution**
- **Simplify vertex system (pixels + strips →pixels)**
- **Handle high background rates**
- **Contribute to L1 trigger**
- **Operation without data reduction**

OBELIX prototype sensor









Slow p from D* decay

CDC upgrade

Upgrade front-end board with better cross-talk tolerance, power consumption, and radiation hardness

– New 8-channel 65nm front-end ASIC (TDC+flash-ADC)

- ASICs per board

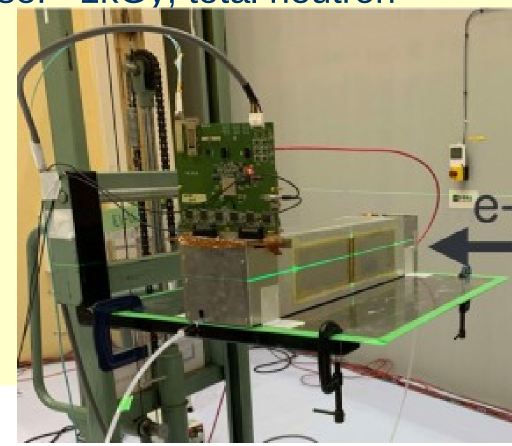
– Rad-hard optical module QSFP (for data transmission to trigger/DAQ) Total dose: ~1kGy, total neutron fluence: 1.0×10^{12} n/cm2

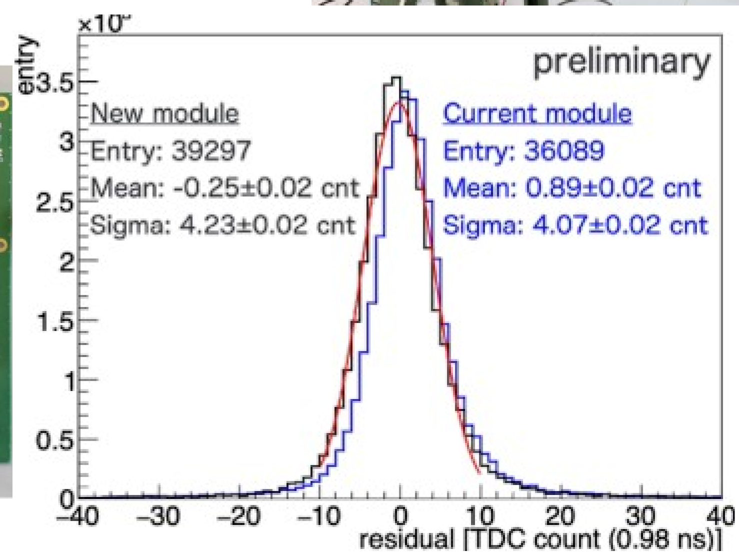
- Candidates of QSFP are selected through γ and n radiation hardness tests

Performance was tested with 3-GeV electron beam

– Observed comparable performance to the existing front-end.

– But, slightly worse time resolution. Further investigations are ongoing.

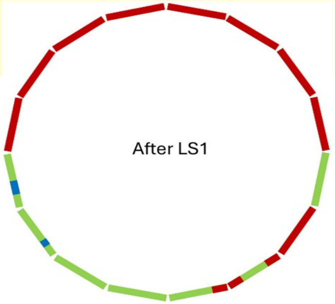


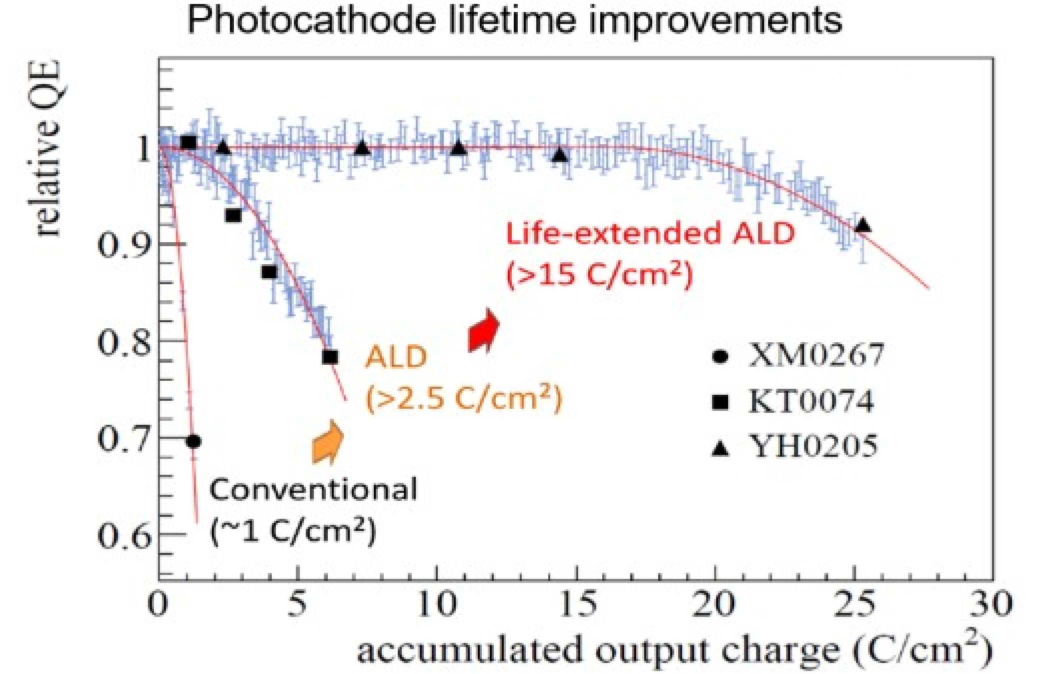


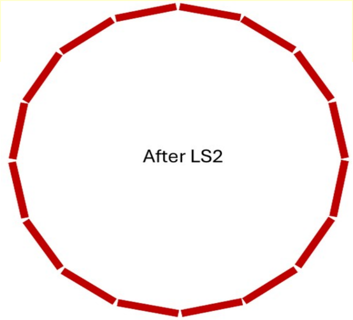
TOP upgrade

Photosensor and readout upgrades in iTOP

- **MCP-PMTs degrading under higher-than-expected backgrounds**
- **Complete residual ~50% MCP-PMT upgrade with life-extended ALD type**
- **Potential replacement of MCP-PMTs with SiPMs**
- **Frontend board: reduce size and power (to accommodate potential SiPM's)**
- **ASoC on ASIC boards with Gpbs to FPGA**







Long term upgrade upgrade

-Make new superconductive final-focus quadrupol magnets (QCS) to improve luminosity

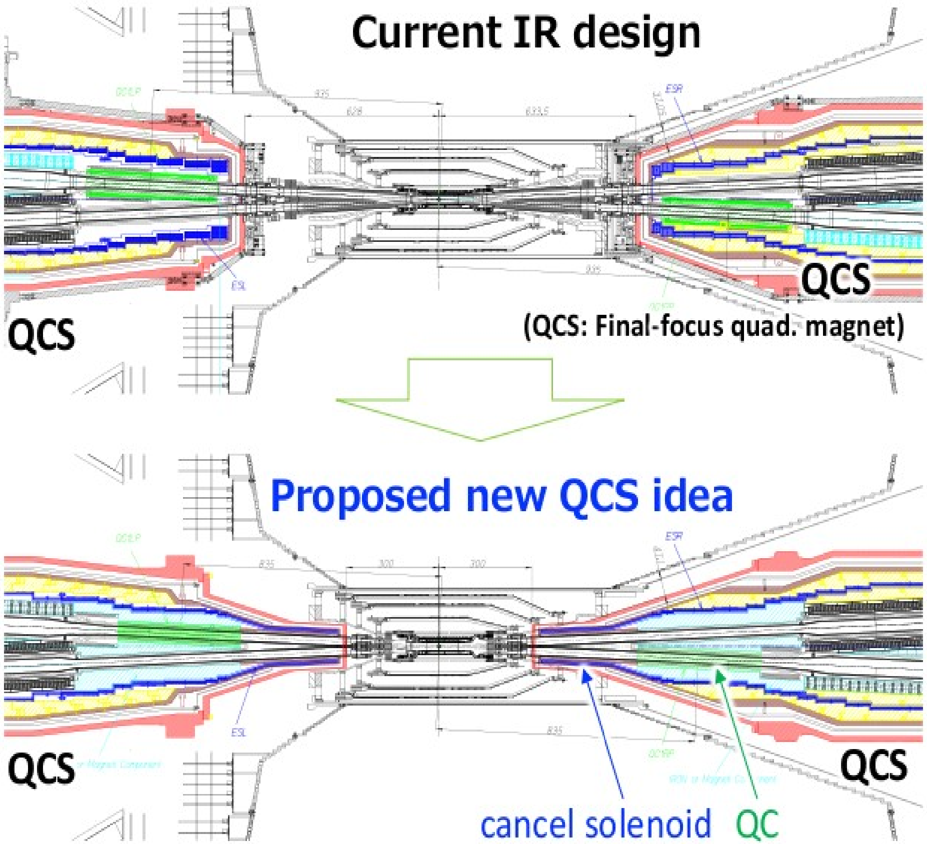
Move the magnets close to the IP and make the orbits in IR straight.

-New vertex detector

-New tracking chamber (pixel Si and/or gas)

– Endcap PID counters: upgrare photosensors.

– EM calorimeter: (preshower, APD/SiPM readout, pure CsI)



Summary

-Belle II is a general purpose detector, providing detection both charged and

neutral particles with good PID system.

-Belle II started operation in 2019 and got the highest world luminosity.

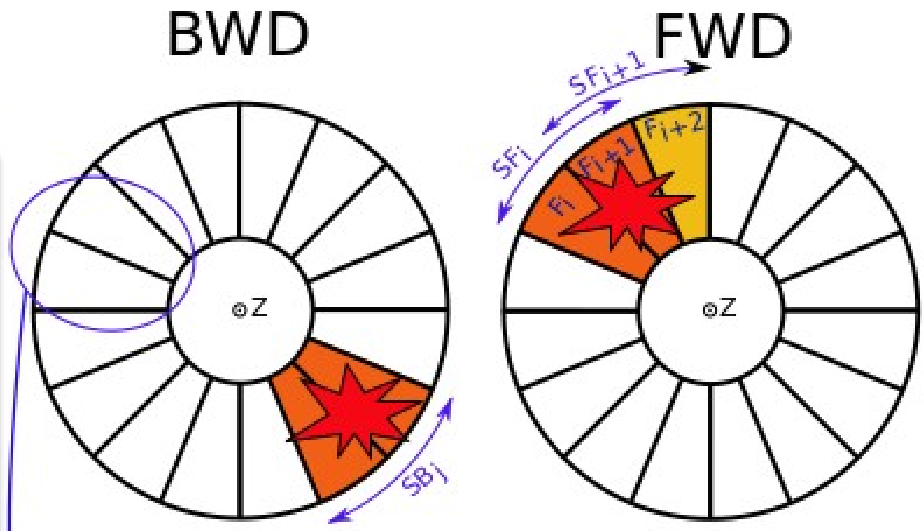
-After 18 months of LS1, SuperKEKB has resumed data taking

-R&D works for Belle II upgrade are going on

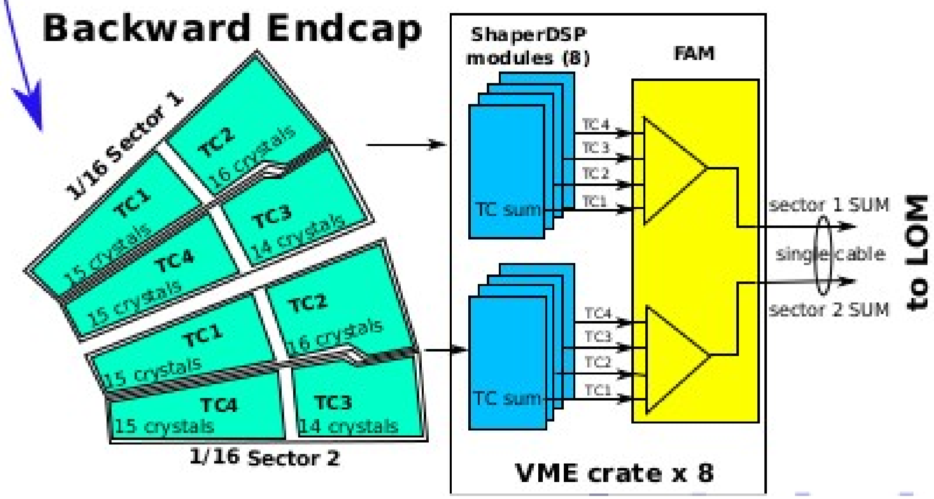
Backup

ECL luminosity monitor

- One endcap 1/16 sector (4 Trigger Cells)
- Each FAM module processes signals from 8 ShaperDSP boards (8 TC) signals and provides analog signals from two endcap sectors to LOM module
- Inner Forward Endcap sector is excluded (may be included)
- Coincidence rate of the signals in opposite sectors is counted and luminosity is calculated

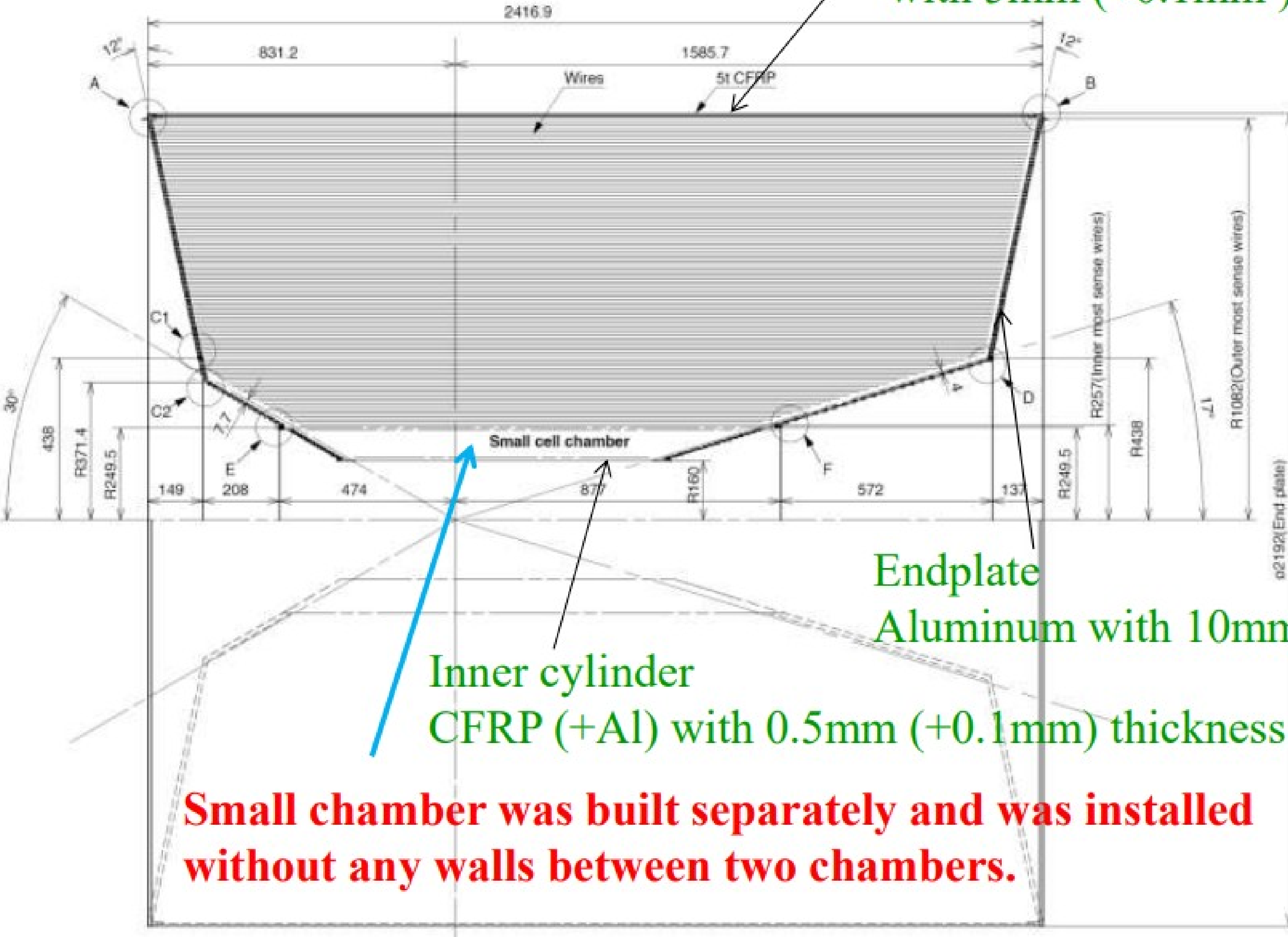


$$C_i = (SF_i > T_f) \& (SB_{i+8} > T_b)$$



CDC Structure

Outer cylinder
CFRP (+Al)
with 5mm (+0.1mm) thickness



Endplate
Aluminum with 10mm thickness

Inner cylinder
CFRP (+Al) with 0.5mm (+0.1mm) thickness

Small chamber was built separately and was installed without any walls between two chambers.