Belle II Detector Overview and Upgrade plans

Shohei Nishida

KEK

Belle Analysis Workshop 2024 @ IITH

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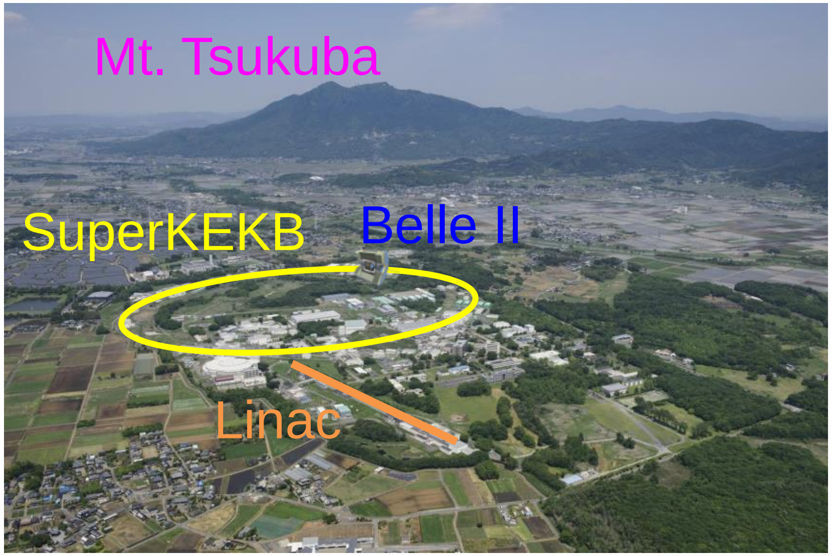
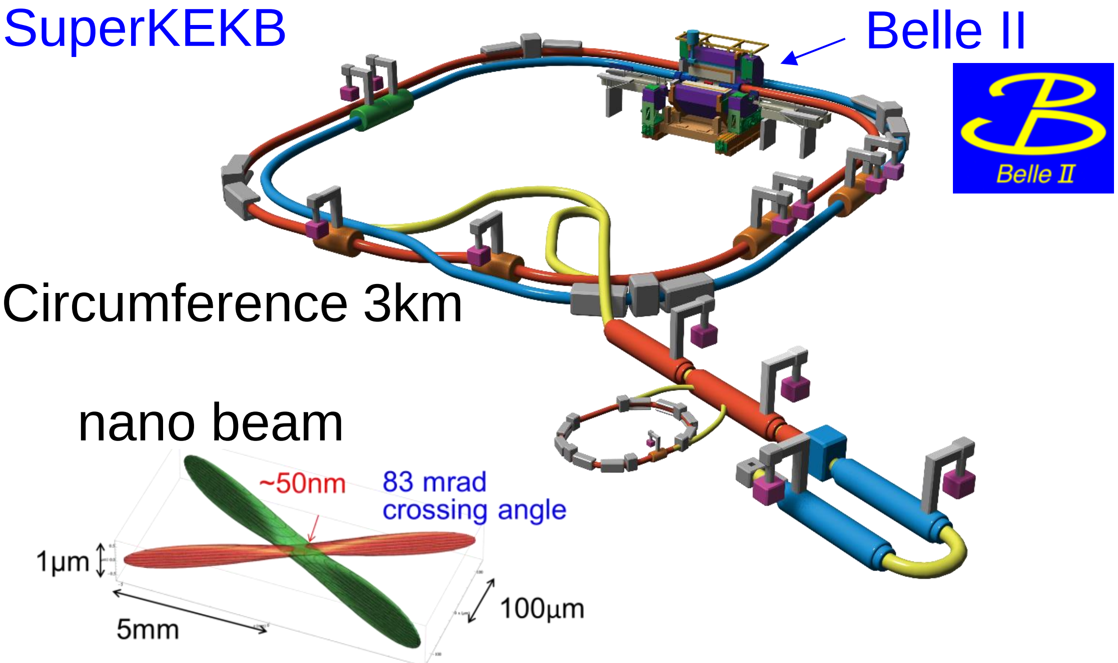
SuperKEK and Belle II





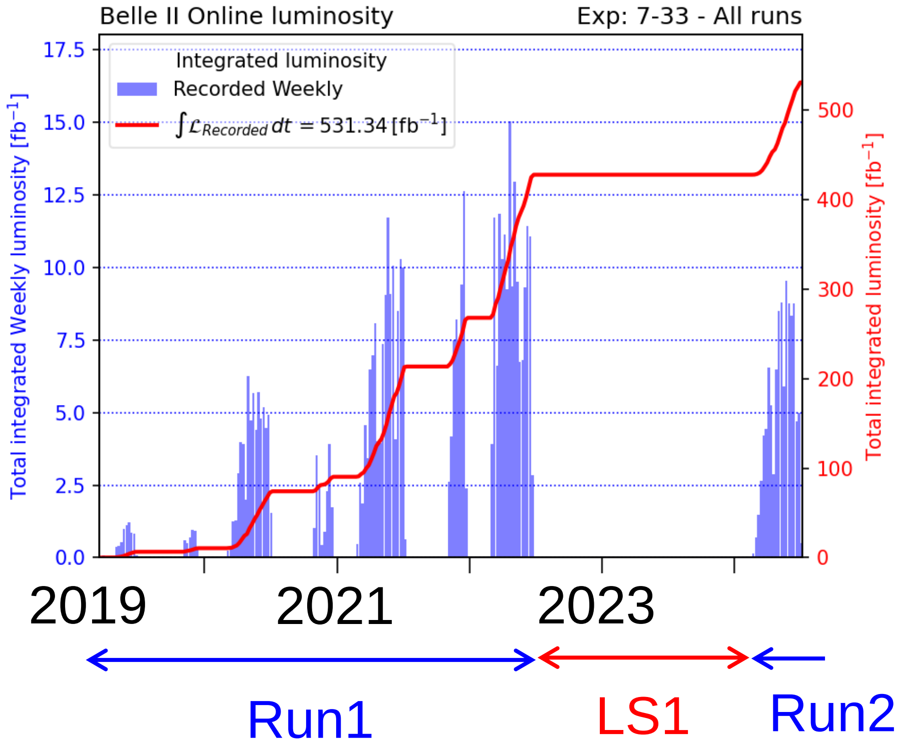
SuperKEKB and Belle II

- Located at KEK, Tsukuba, Japan
- SuperKEKB: asymmetric e^+e^- collider (4 GeV e^+ + 7 GeV e^-)
  - ✓ Nano-beam scheme to achieve high luminosity
- Belle II: flavor physics experiment at SuperKEKB
- Successor of KEKB, Belle in operated in 1999-2010
  - ✓ Verified Kobayashi-Maskawa theory in the study of CP violation in B mesons

Kibayashi, Maskawa
(2008 Nobel Prize)

Luminosity

- Luminosity (~intensity) is a key for the experiment.
  - ✓ Luminosity [cm^{-2} s^{-1}] = (event rate [s^{-1}]) / (cross-section [cm^{-2}])
  - ✓ Integrated luminosity = Luminosity × (operation time) : collected data size



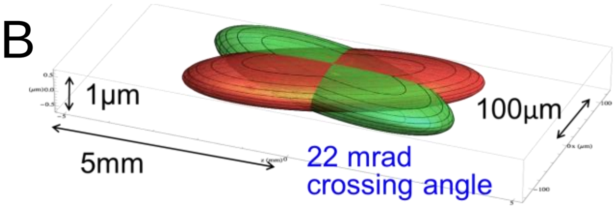
Long shutdown to fully install PXD detector

- Luminosity 4.7 × 10^{34} cm^{-2} s^{-1} achieved (Jun. 2022):
  - ✓ World record (~ ×2 of KEKB)
  - ✓ Aiming one order higher.
- 530 fb^{-1} of data accumulated so far.
  - ✓ Similar to BaBar data set.
  - ✓ Belle: 1 ab^{-1} (=1000 fb^{-1}) in 11 years.
- Belle II target: 50 ab^{-1}
- Run 2 just started.

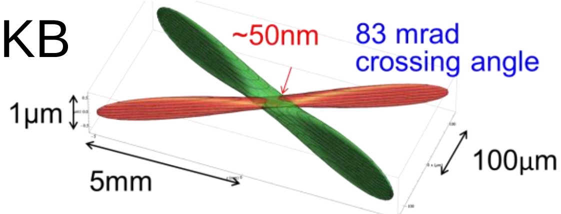
SuperKEKB

nano beam scheme: new technology

KEKB

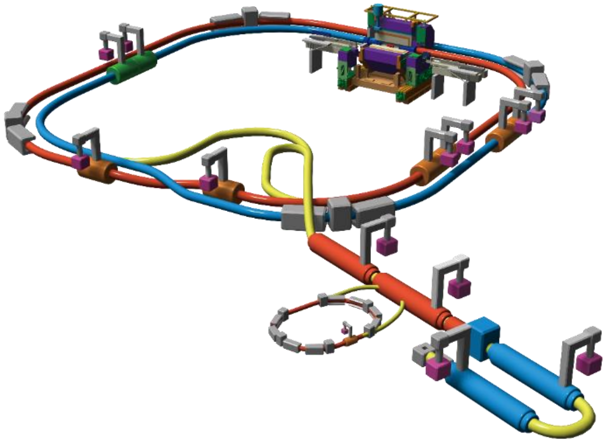


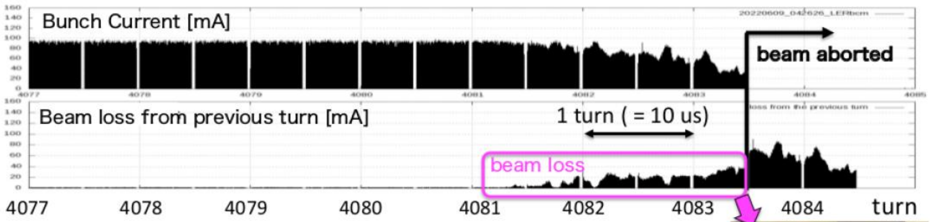
SuperKEKB

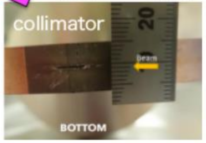


Current issue in SuperKEKB: Sudden Beam Loss (SBL)

- All the beam is lost within a few turns.





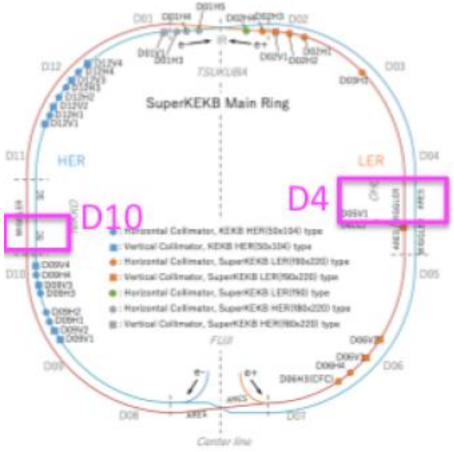


In few cases, damaged Belle II detector and accelerator equipment (QCS quenches)

- The beam current needs to be increased to obtain high luminosity.
- Frequent SBL prevents the operation in high beam current.
- From the investigation in 2024, we find some hints of the source of SBL (dust in some section ?). To be solved in the autumn 2024 run.

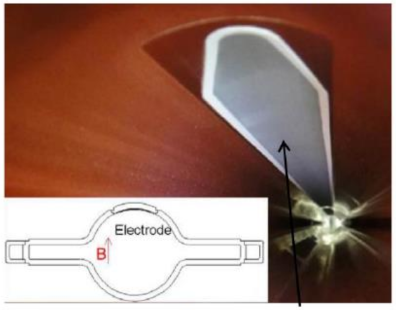
SBL

- The source of LER SBL seems to be dusts in D04 and D10 wiggler section.
  - ✓ The source of HER SBL is still unknown.

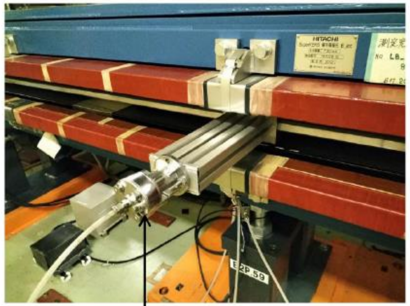


Knocker studies

◦ knocked beam pipes on D10 wiggler with clearing electrodes (with beams at 600-1000 mA)



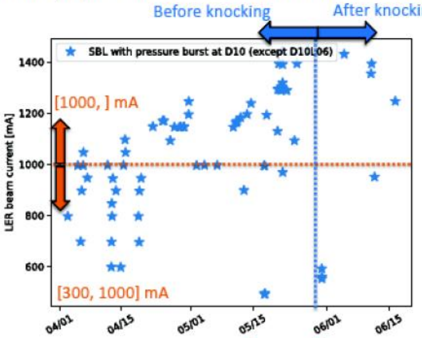
clearing electrode



Knocker machine

⇒ SBL events can be artificially produced by knocking beam pipes !!

◦ knocked beam pipes at D10 several times without beams



I_{LER} [mA]		[300, 1000]	[1000,]
Before knocking	#SBL	24	42
	Operation-time [h]	633.77	350.32
	#SBL/time [1/h]	0.038 ± 0.008	0.12 ± 0.02
After knocking	#SBL	4	4
	Operation-time [h]	98.5	162.3
	#SBL/time [1/h]	0.041 ± 0.020	0.025 ± 0.012

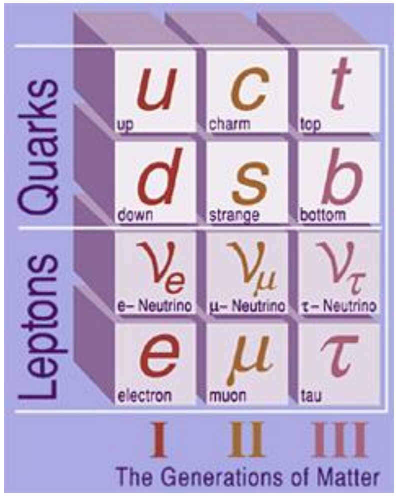
⇒ frequency at $I_{LER} \geq 1$ A is reduced: 0.12±0.02 → 0.025±0.012!! ("knocking effect")

Contributions to the studies from Belle II are very welcome.
MDI (= Machine Detector Interface group

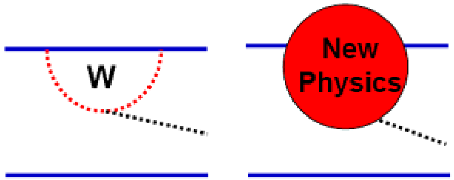
[slides by K.Trabelsi]

Belle II

Belle II: flavor physics experiment

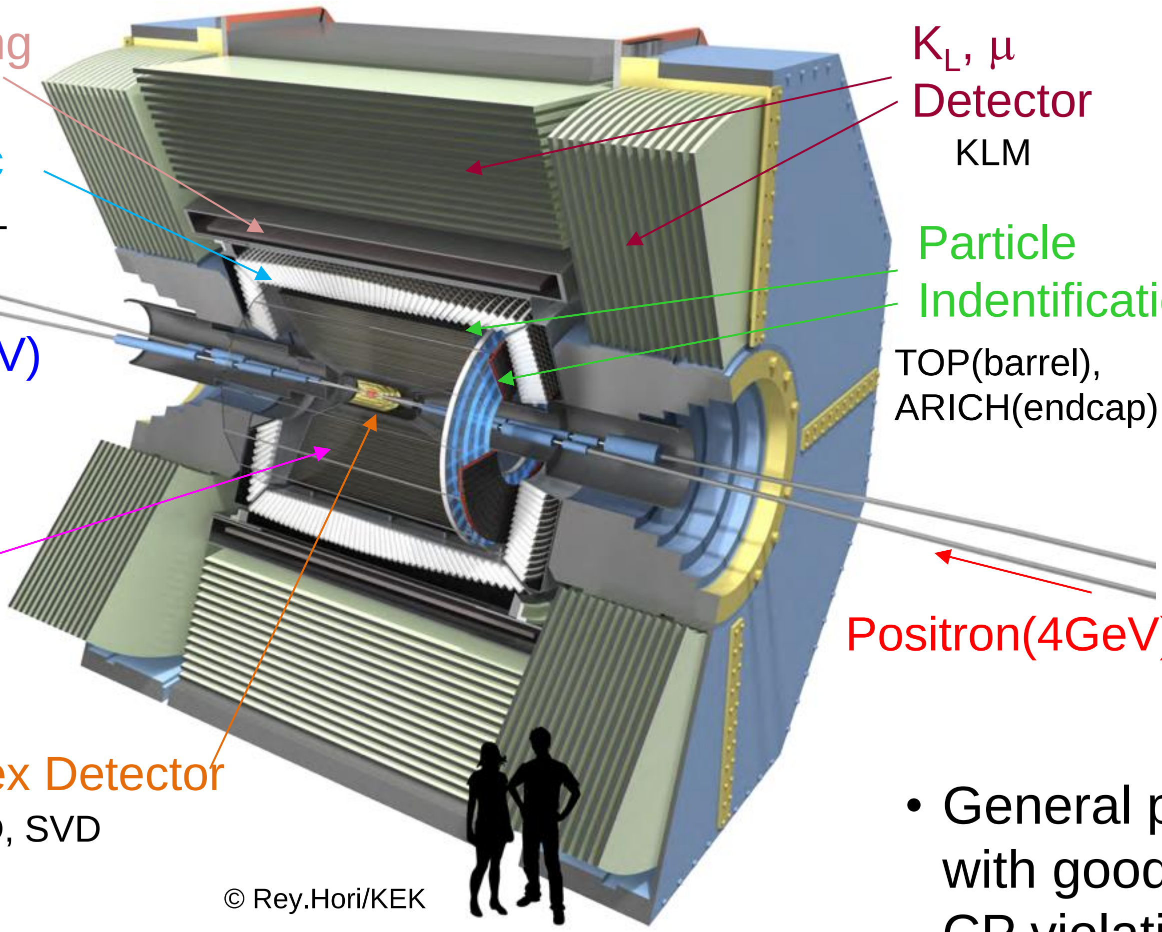


- Flavor = species of the quarks and leptons
  - ✓ Only weak interaction changes the species of the quarks and leptons.
- Produce large number of B mesons, charm, τ at SuperKEKB.
- Precise measurements of the B, c, τ decays provide information of New Physics (NP) Beyond the Standard Model (BSM)
  - ✓ Loop diagrams: BSM particles can virtually contribute to the decays.
  - ✓ Compare with the prediction of the Standard Model (SM)



- Keys
  - ✓ Particle identification (PID): e.g. kaon and pion
  - ✓ Vertex measurement: relatively long lifetime of B, D, τ (←weak decay)

Belle II



Superconducting Solenoid(1.5T)

Electromagnetic Calorimeter ECL

Electron(7GeV)

Central Drift Chamber CDC

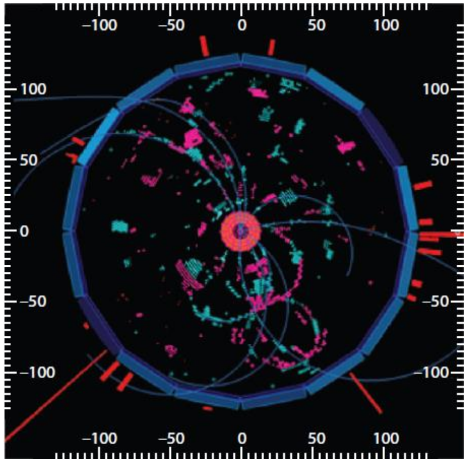
Silicon Vertex Detector PXD, SVD

K_L, μ Detector KLM

Particle Indentification TOP(barrel), ARICH(endcap)

Positron(4GeV)

© Rey.Hori/KEK



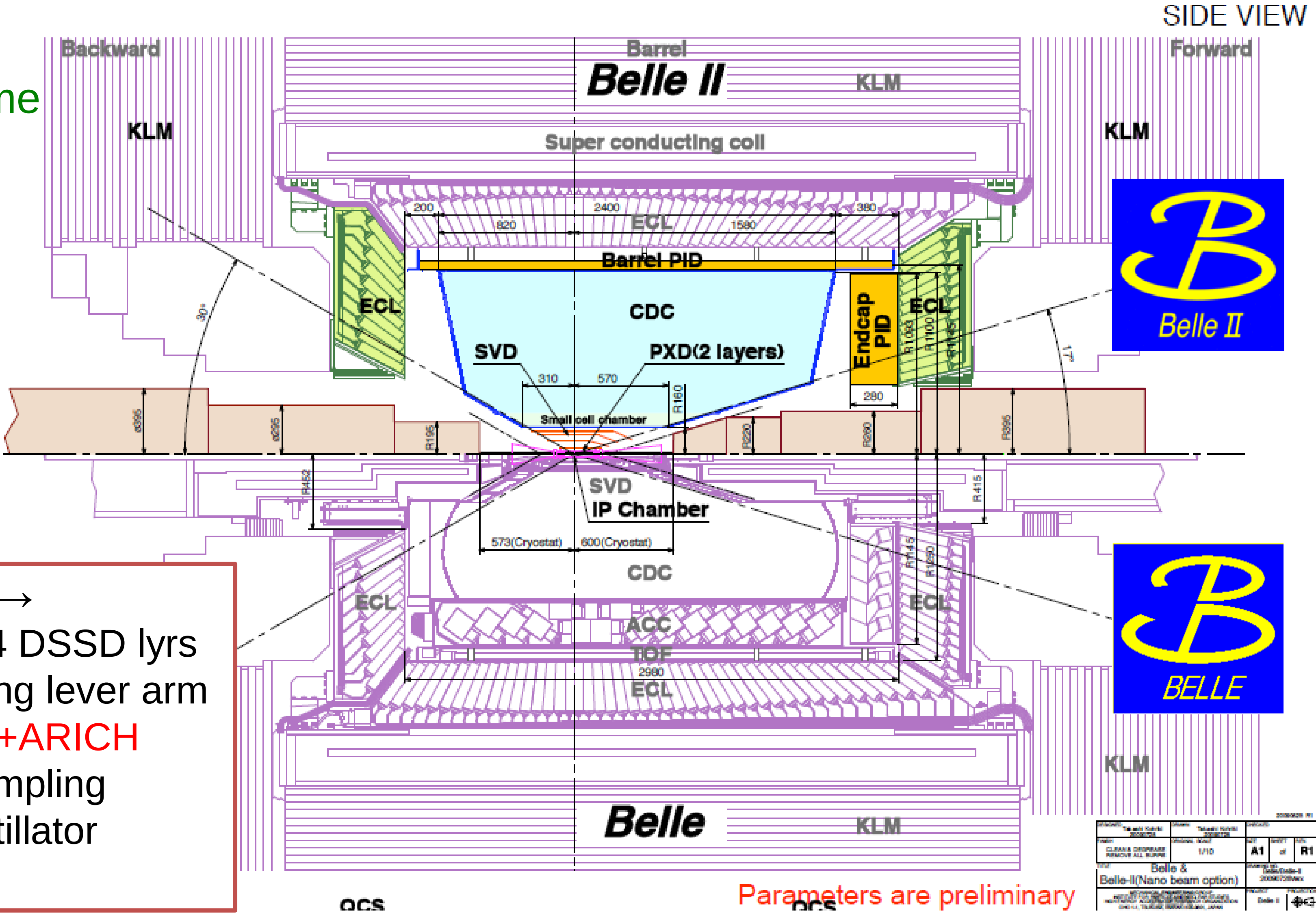
Belle II Detector (8m×8m×8m, 1400t)

- General purpose 4π detector with good vertexing (for time CP violation) and particle identification.

From Belle to Belle II

Belle II

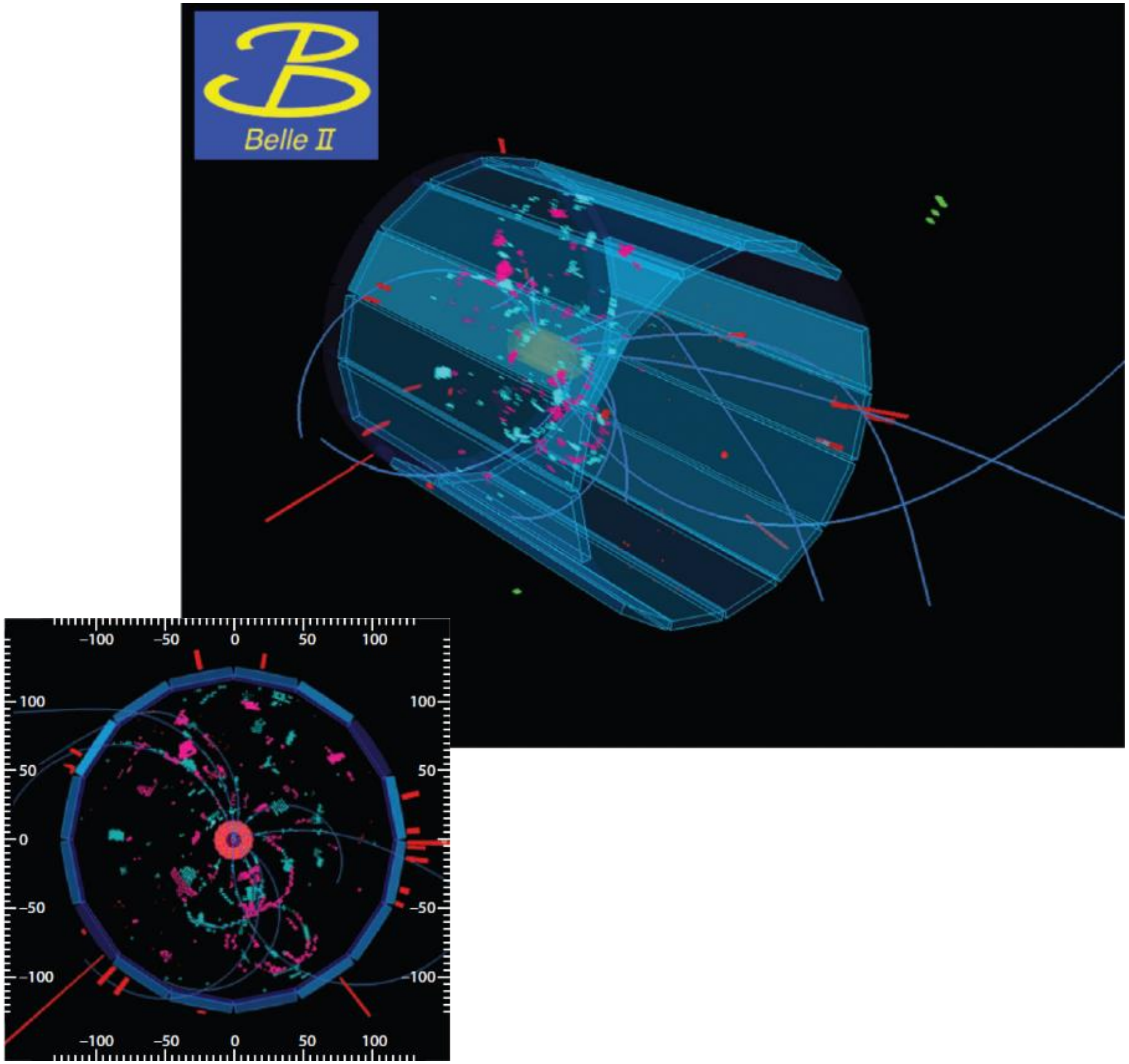
- At least, the same performance as Belle in higher luminosity.
- Better performance if important for physics



Parameters are preliminary

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

Event Display

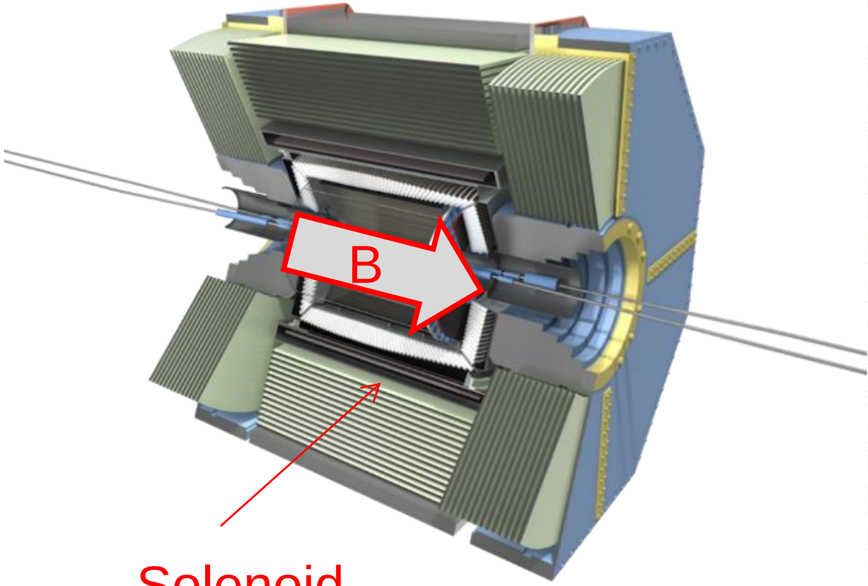


- One event (one collision).
- B meson pair is produced after the collision of e^+ and e^-.
- B meson decays; many charged and neutral particles are produced.
- We detect the particles with Belle II detector.
    - ✓ Need to know 4-momentum of each particle to reconstruct events.

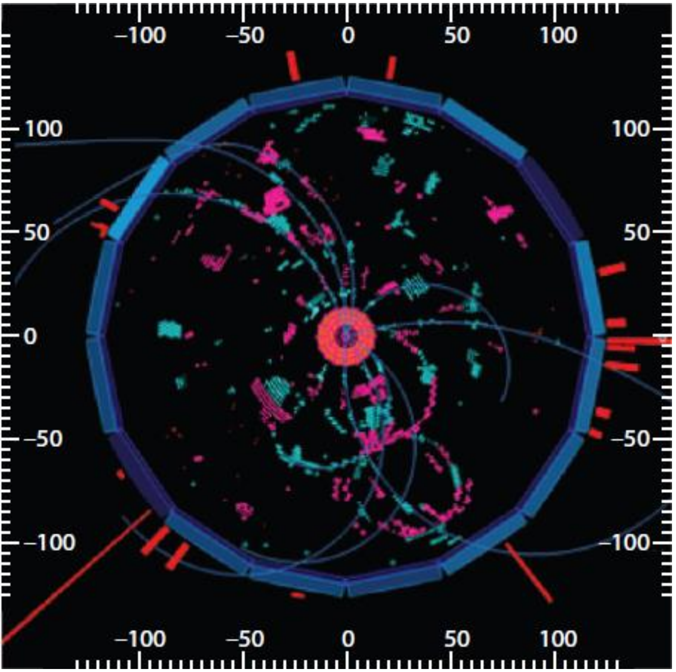
Charged Particles

How to detect charged particles

- Magnetic field (1.5 T at Belle II) is applied in parallel to the beam axis.
  - ✓ Charged particles curls in the plane perpendicular to the beam axis.
- Measure the trajectory of the charged particles at SVD and CDC.
  - ✓ Momentum can be obtained by the relation p [GeV] = 0.3 B [T] R [m].



Solenoid



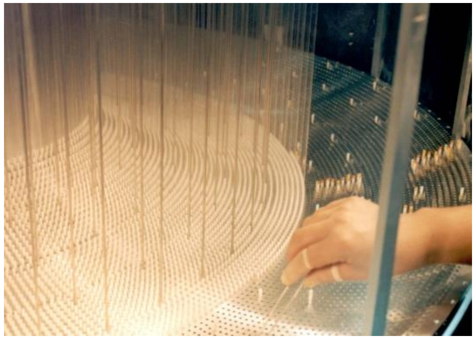
More exactly, only transverse momentum (p_T) can be obtained. But, we also know the direction of the particle. Hence the momentum vector can be calculated.

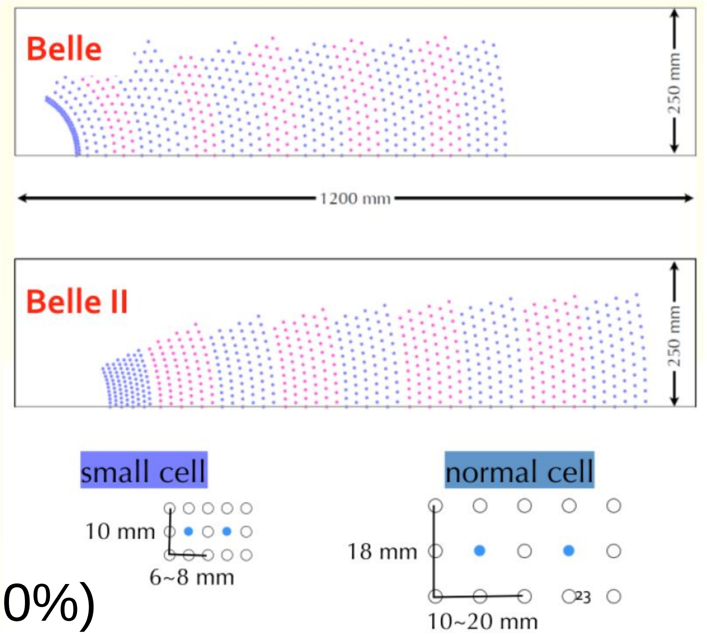
Central Drift Chamber

Central Drift Chamber (CDC)

- Tracking of charged particles.
  - ✓ Momentum measurement.
- Trigger signal
- PID by dE/dx (later)

(next page)





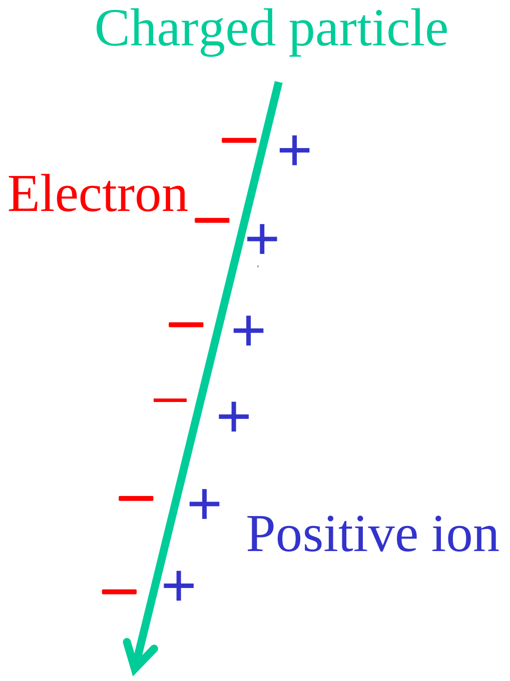
He(50%)+etane(50%)

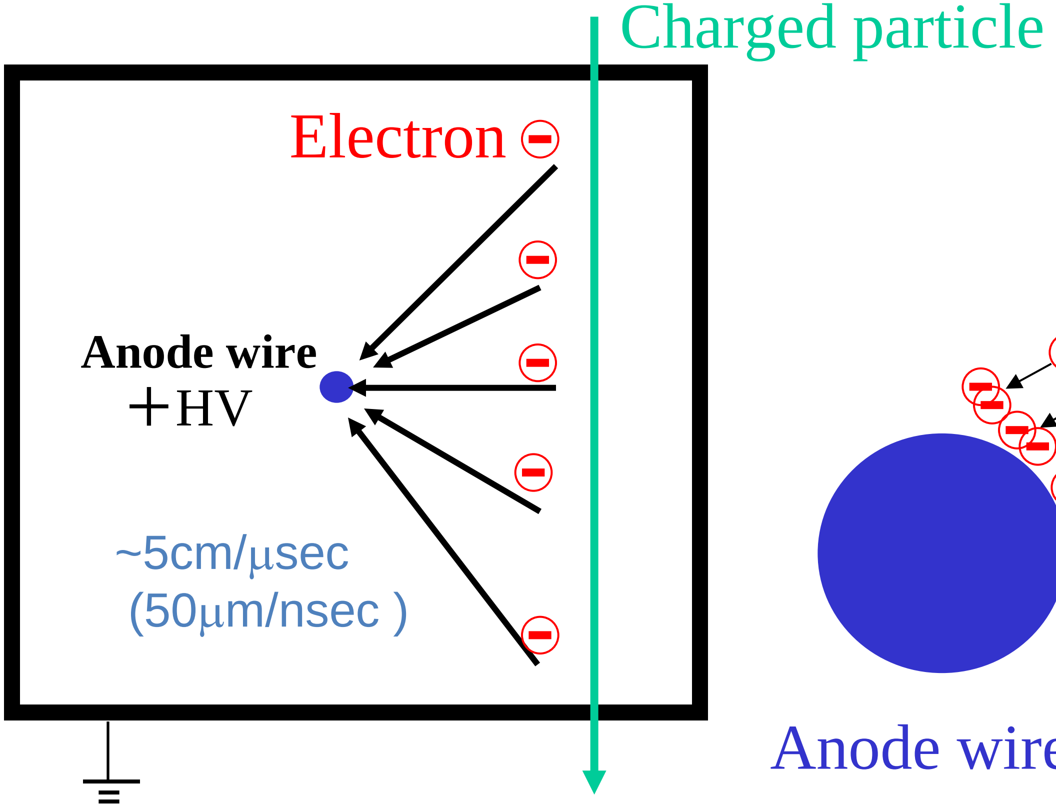
- Extend outer radius (for better momentum resolution)
  - ✓ Inner radius is also larger.
- Small cell in Belle II
  - ✓ Why ?

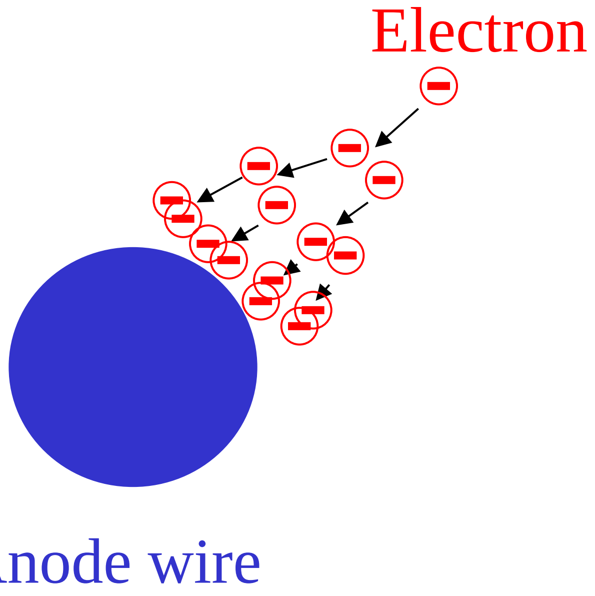
Belle II CDC Belle CDC

Principle of CDC

- Ionization of the gas molecules by charged particle (creation of electrons)
- Transportation of electron（drift）
- Gas amplification near anode wire
- Generation of pulse signal due to electromagnetic induction.

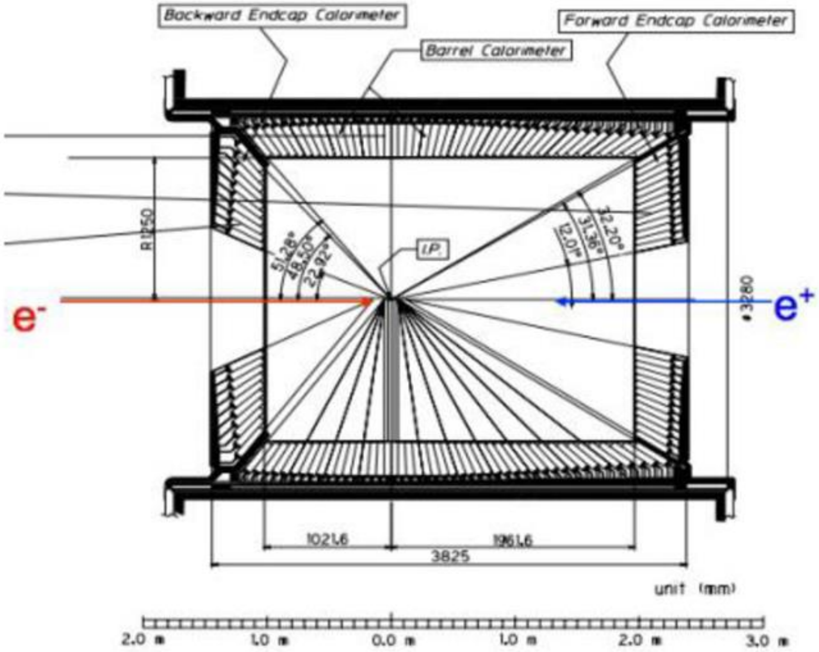






Neutral Particles

- π^0 decays ($\pi^0 \to \gamma\gamma$). $K_S{}^0$ also decays ($K_S{}^0 \to \pi^+\pi^-$, $\pi^0\pi^0$ with $c\tau$ = 2.7cm).
- The most important neutral particle is the photon (γ).
  - ✓ Not detected inside the tracking device (CDC etc.).
  - ✓ Photons lose all the energy in the calorimeter
    - ➢ Energy of a photon is measured in the calorimeter.
  - ✓ Direction is known from the measured position
    ⇒ 4-momentum is measured.



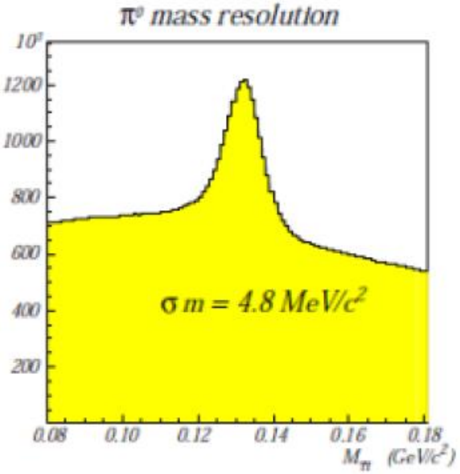
Long-lived neutral particles (neutrons, $K_L{}^0$ …) are not easy to measure (hadronic interaction). Neutrino is impossible to detect.

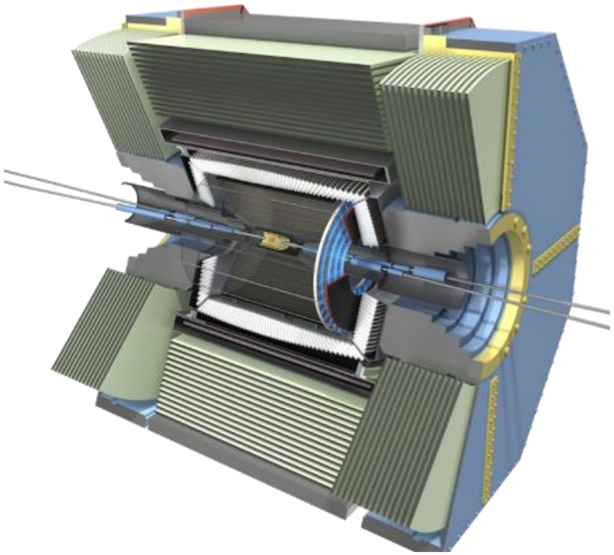
Electromagnetic Calorimeter (ECL)

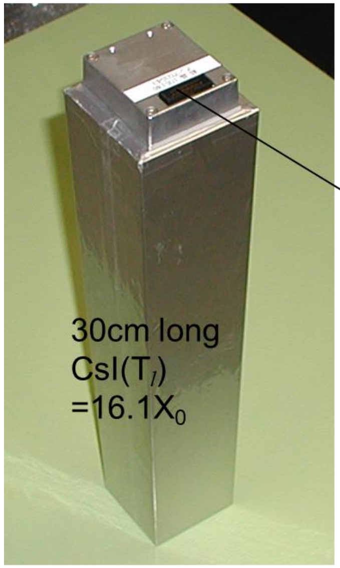
Electricmagnetic Calorimeter (ECL)

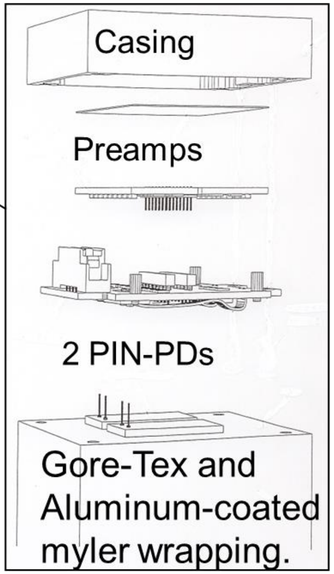
- 8736 CsI(Tl) crystals
- Measure the total energy of γ.
  - ✓ Radiation length: 16.1 X_0
- Electron identification (e also looses all the energy)
- Trigger information (energy, #(clusters))
- Luminosity measurement (Bhabha events).

$\pi^0 \rightarrow \gamma\gamma$





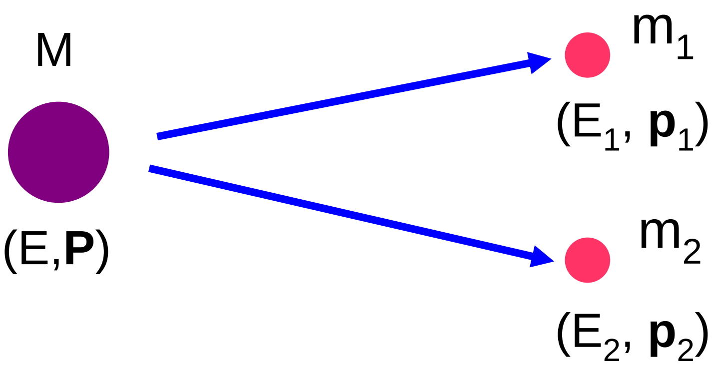


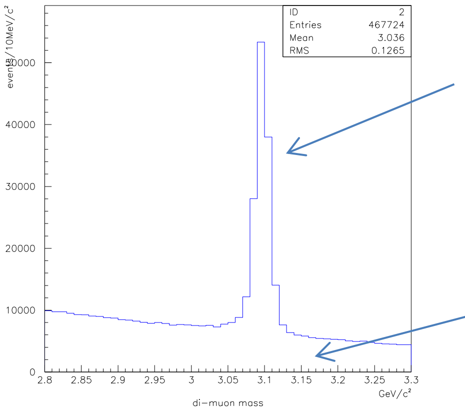


How to Detect Particles

Most short-lived particles generated by the collision (in which we are interested) decay inside the detector, but we can reconstruct them if we know the 4-momentum of decay products.

Simple case: 2-body decay.





reconstructed particle

random combination

energy and momentum conservation

$$E = E_1 + E_2$$

$$\mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2$$

$$M^2 = E^2 - |\mathbf{P}|^2 = (E_1+E_2)^2 - |\mathbf{p}_1+\mathbf{p}_2|^2$$

In reality, there are many particles in a final state; we don’t know which is the correct combination.

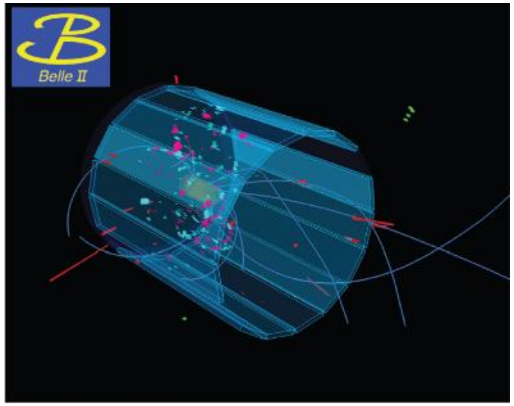
How to Detect Particles

- From the tracking device, we can tell the 3-momentum of a charged particle.
  - ✓ (p_x, p_y, p_z)
- However, we need to know the 4-momentum of a particle for reconstruction.
  - ✓ (E, p_x, p_y, p_z)
- For this purpose, we will need to measure the mass of a charged particle, i.e., the particle species (if we cannot measure the energy itself).

$$E^2 = m^2+|\mathbf{p}|^2$$

⇨ Particle identification

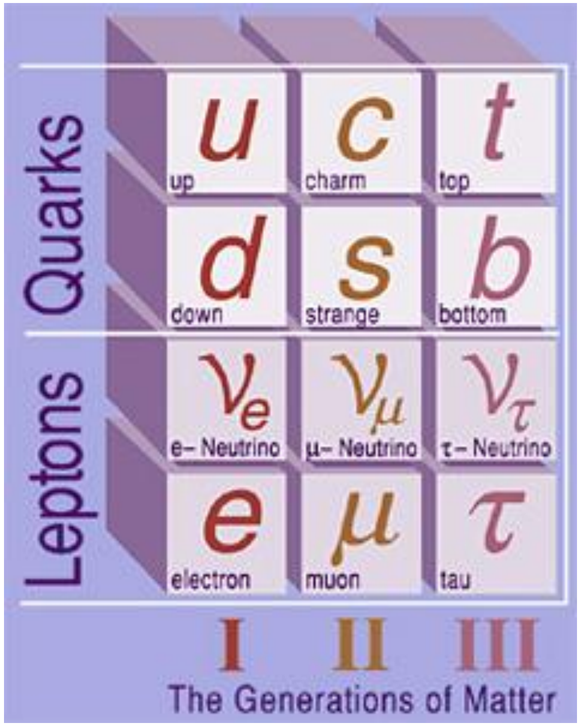
By the way, what are the charged particles that are directly detected at Belle II?



only stable particles and particles with long lifetime can reach the detector.

How to Detect Particles

- electron (positron) : $e^{\pm}$
- muon : $\mu^{\pm}$
- pion : $\pi^{\pm}$
- kaon : $K^{\pm}$
- proton, anti-proton : p, $\bar{p}$
- deuteron…



We need to separate these particles
(Particle Identification = PID).

PID at Belle II

Charged particles that need identification

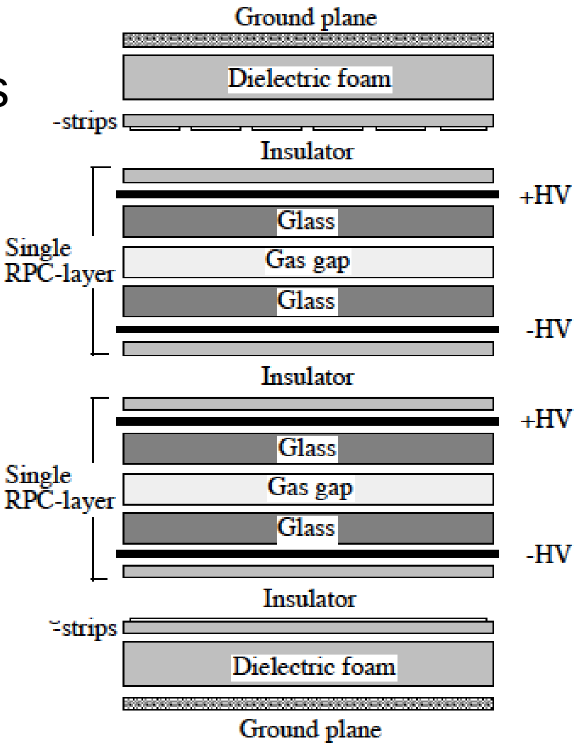
electron ($e^\pm$), muon ($\mu^\pm$), pion ($\pi^\pm$), kaon ($K^\pm$), proton (p, $\bar{p}$), deuteron (d, $\bar{d}$)

PID can be done using…

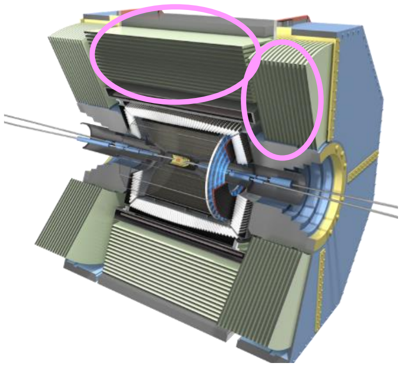
- Difference of interaction
  - ✓ Energy Loss (interaction with electrons inside matter): all charged particles.
  - ✓ Cherenkov radiation: all charged particles
  - ✓ Bremsstrahlung: electrons
  - ✓ Hadron interaction: hadrons
- Difference of mass
  - ✓ Momentum and charge of a particle are measured by CDC (drift chamber). From $p = mv\gamma$, if we measure the velocity, independently from the momentum, we can tell the mass.

Muon Identification

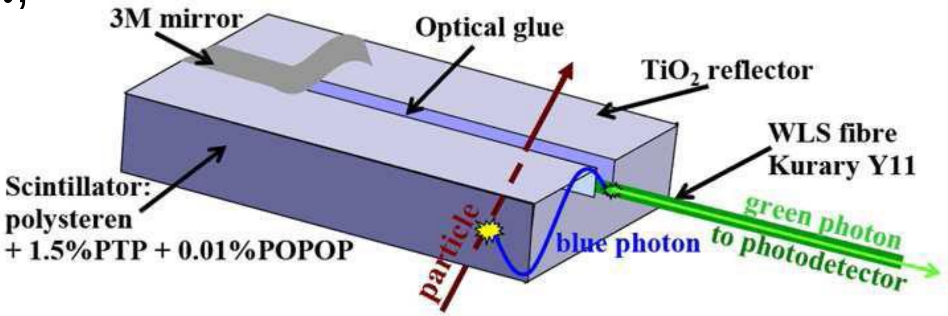
- Muon identification is simple: high penetration.
  - ✓ No strong interaction, i.e., no interaction with hadrons
  - ✓ No bremsstrahlung like electrons.
- Muons penetrates the calorimeter and KLM detector.
  - ✓ Belle KLM: sandwich of iron and RPC (Resistive Plate Chamber)
  - ✓ Belle II KLM: layer 1-2 of barrel KLM and all the endcap KLM are replaced by Scintillator + SiPM to cope with higher hit rate.



KLM = K_L and μ

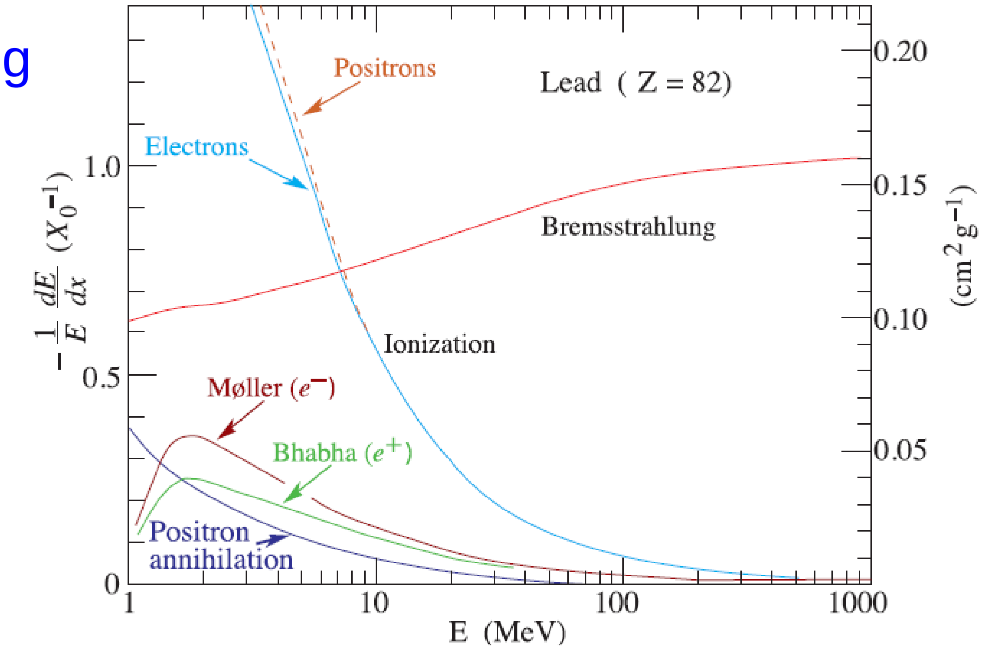


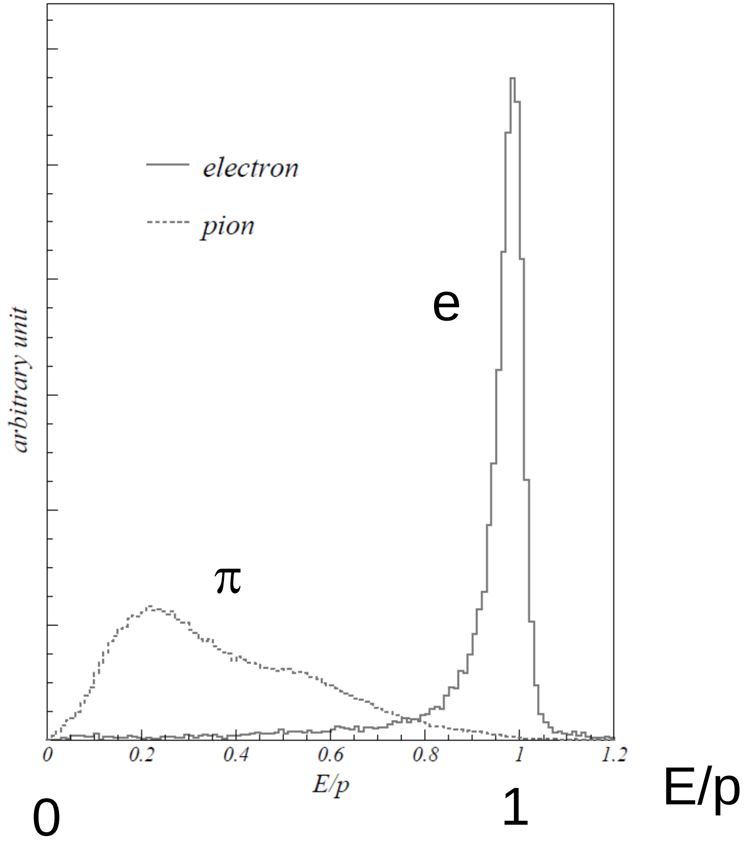
- Identification becomes difficult when the momentum is small.
- Misidentification with π, because the mass is close.



Electron Identification

- Electrons lose energy by Bremsstrahlung
  - ✓ It loses all the energy in the calorimeter.





- Identification can be done using E/p information.
- In addition, Shower Shape（E9/E25 @ belle）and dE/dx (described later) can be also used.

dE/dx

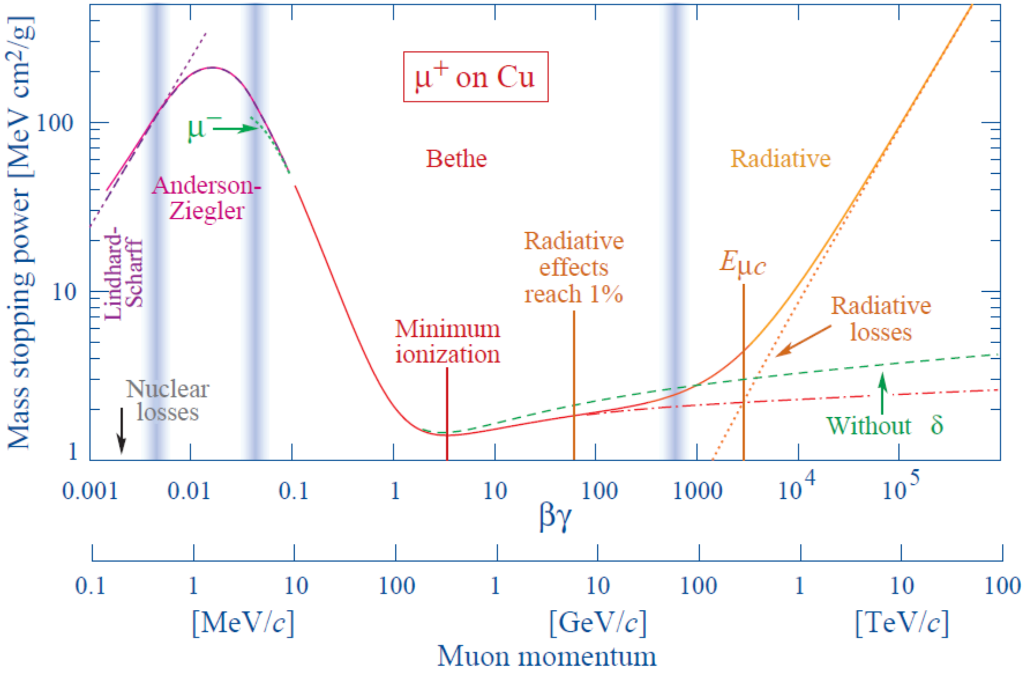
Bethe equation (used to be called as Bethe-Bloch equation)

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

W	energy transfer to an electron in a single collision	MeV
k	bremsstrahlung photon energy	MeV
z	charge number of incident particle	
Z	atomic number of absorber	
A	atomic mass of absorber	g mol^{-1}
K	$4\pi N_A r_e^2 m_e c^2$	0.307 075 MeV mol^{-1} cm
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	

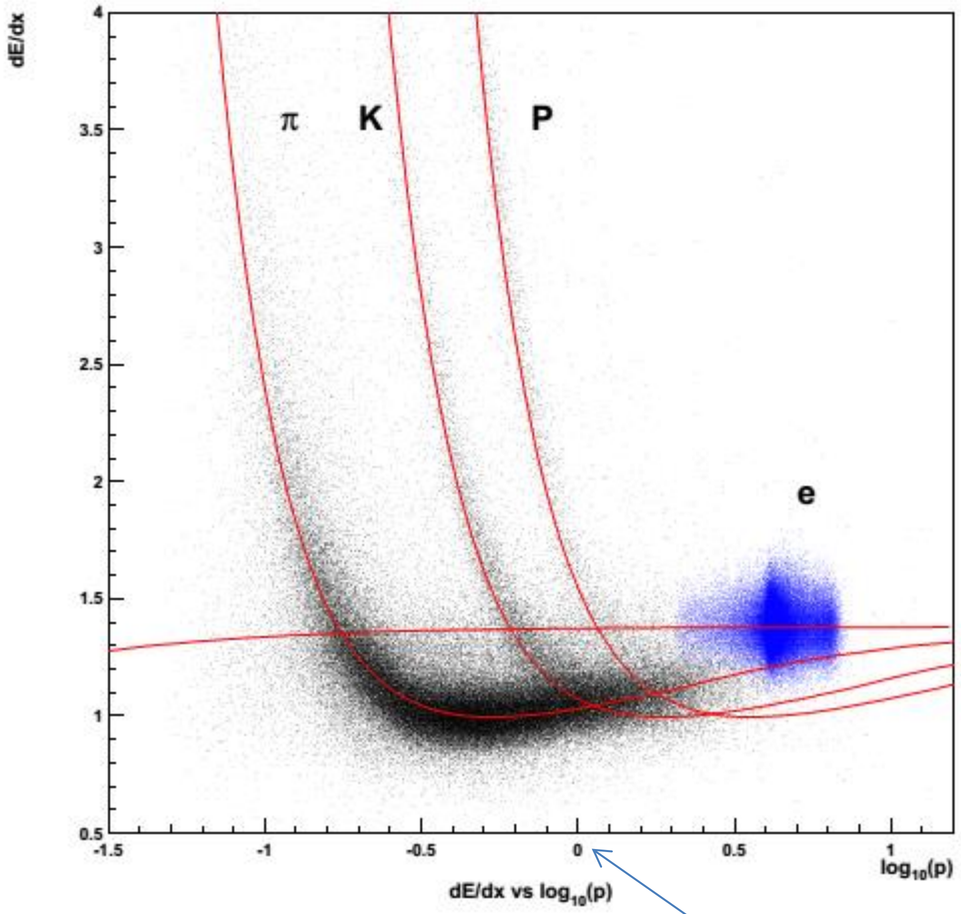
Energy loss of heavy charged particles (except electrons)

Basically, energy loss depends on the velocity of the particle



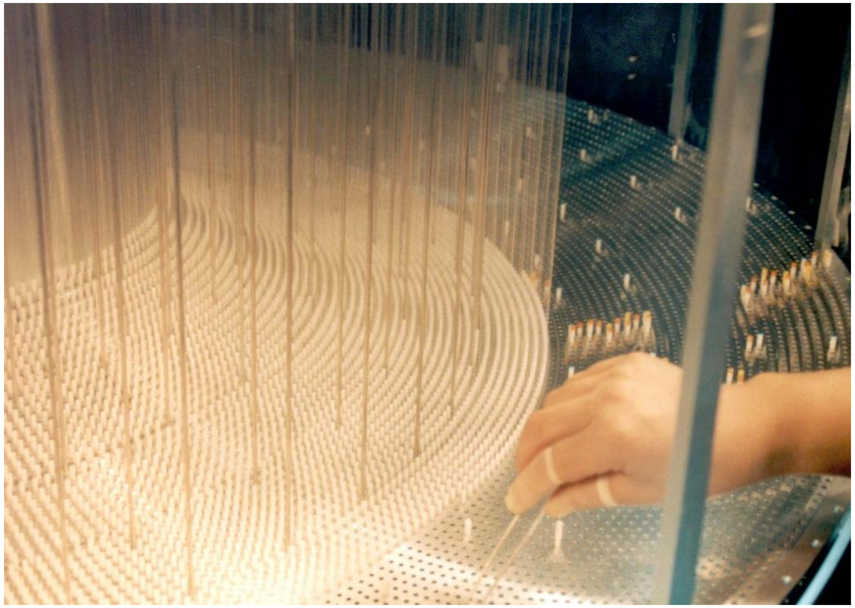
dE/dx

Energy deposit (dE/dx) inside CDC



(GeV)

1GeV



Central Drift Chamber

dE/dx covers low momentum region (below 0.7 GeV for K/π separation)

Cherenkov Light

- Cherenkov Light is produced when a charged track that passes inside a material is faster than the speed of light inside the material.

Sonic boom

P.Cherenkov

Cherenkov light from reactor

TRIGA reactor at JSI (Slovenia)

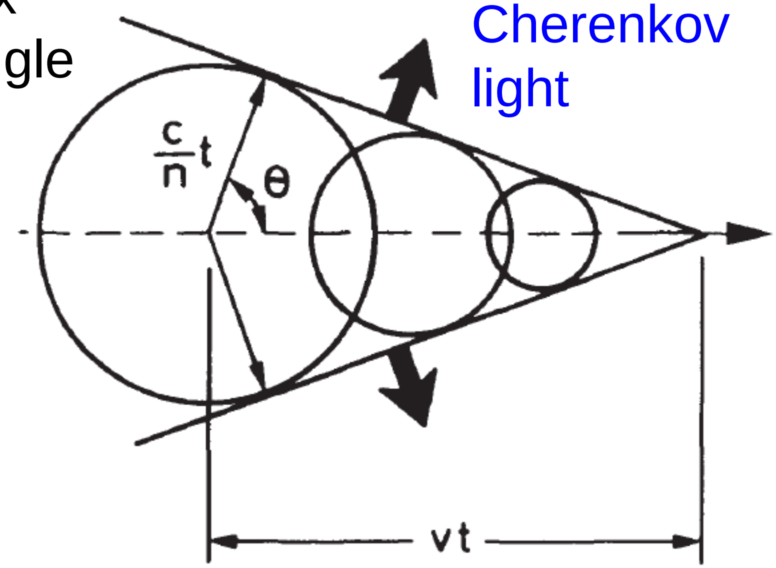
Cherenkov Light

Condition : β > 1/n

n : refractive index
θ_c : Cherenkov angle

Angle

$$\cos\theta_c = \frac{1}{\beta n}$$



Number of photon

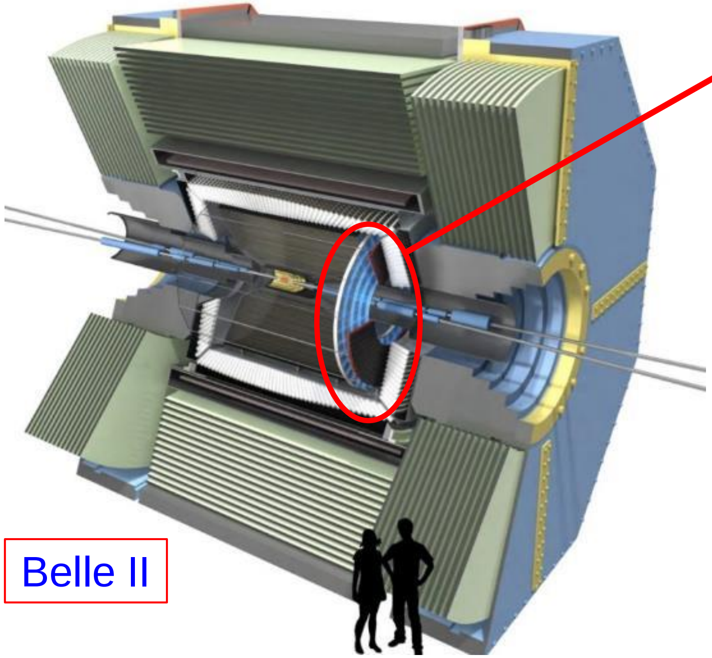
$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$
$$\approx 370 \sin^2\theta_c(E)\ \mathrm{eV}^{-1}\mathrm{cm}^{-1} \qquad (z = 1)\ ,$$

Larger number of photons for larger θ_c

For PID

- Threshold type
  - ✓ Measure whether Cherenkov light is emitted. Then, we can tell if the charged particle is faster than a certain velocity.
- Ring Imaging CHerenkov (RICH) Counter
  - ✓ Measure the Cherenkov angle → velocity of the charged particle.

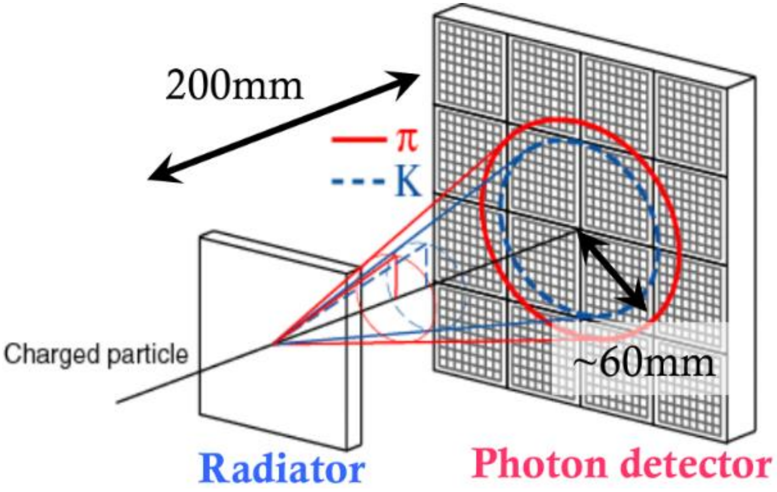
Aerogel RICH



Belle II

PID device at the endcap

Concept of Aerogel RICH



$$\cos\theta_c = \frac{1}{\beta n} = \frac{\sqrt{(m/p)^2 + 1}}{n}$$

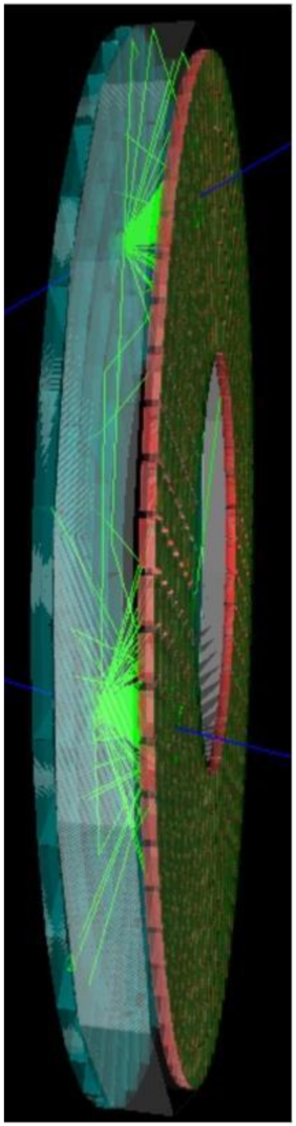
$$\theta_C(\pi) - \theta_C(K) \simeq 23\ \mathrm{mrad}$$

(@ 4 GeV; n = 1.05)

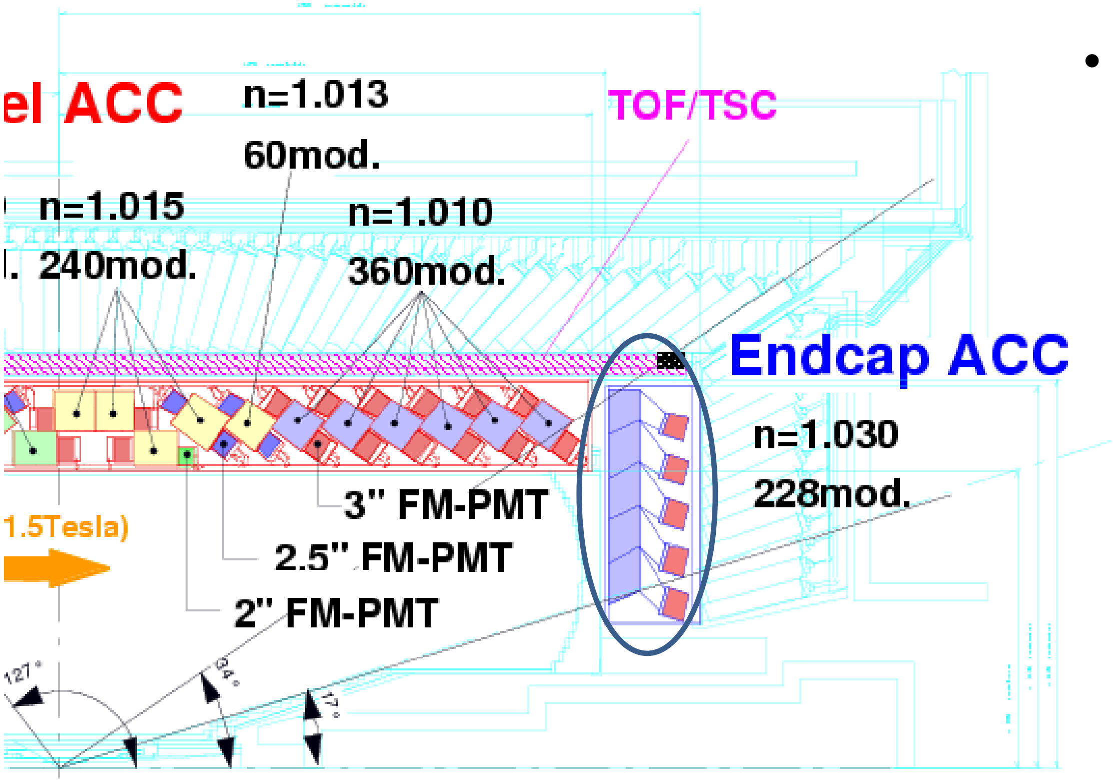
Target:

K/π Separation up to 4 GeV.

e.g.) B → ργ v.s. K*γ

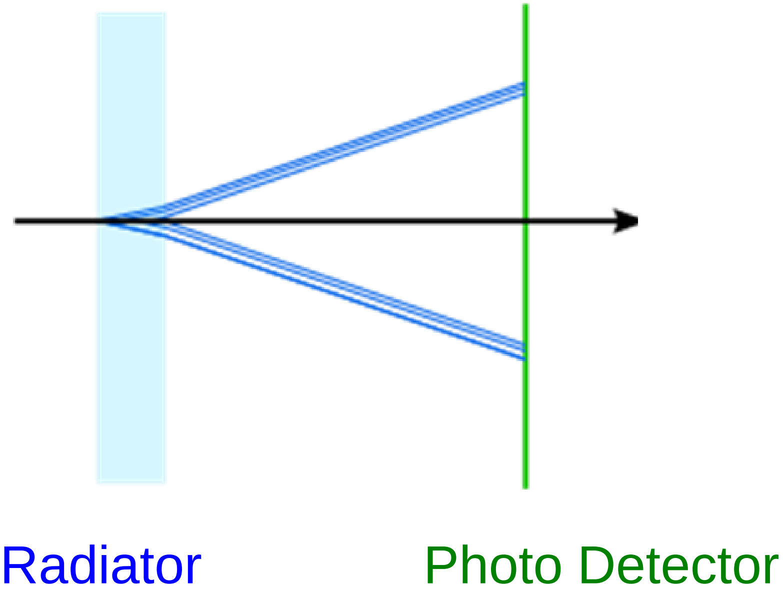


Aerogel RICH



- Replace endcap ACC
  → space is limited.
  → Proximity type RICH

(usually called “Proximity focusing RICH”, though it’s not focusing….)

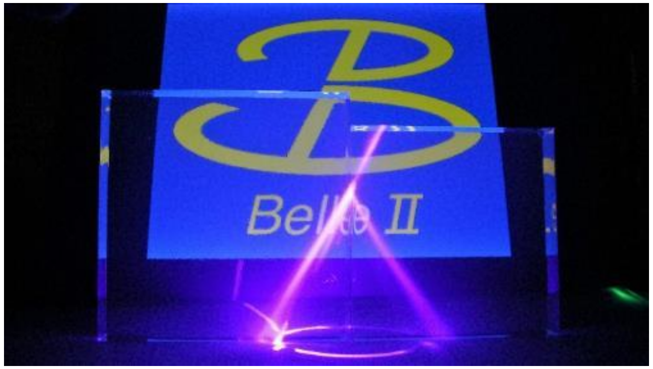


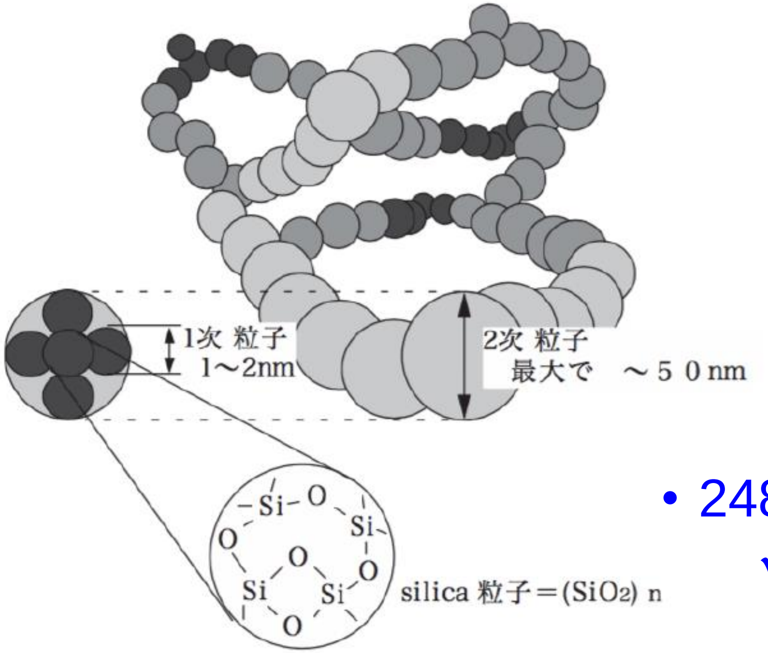
- No PID for particles above 2 GeV at Belle endcap ACC.
- Replace to RICH, targeting high K/π separation up to 4 GeV/

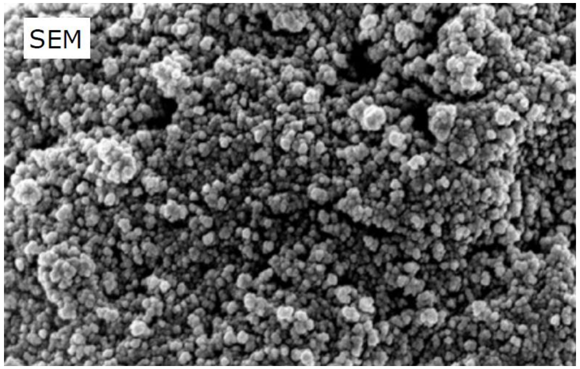
Aerogel

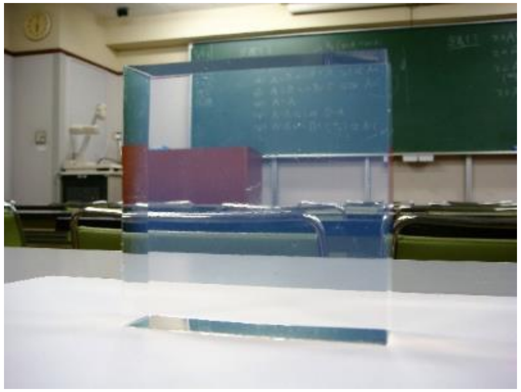
Silica aerogel is used as the radiator.

- Composition:SiO_2 .
- Very light. Sparse structure (>90% air).
- Refractive index is around 1.01-1.1 (between gas and liquid/solid) and can be adjusted.

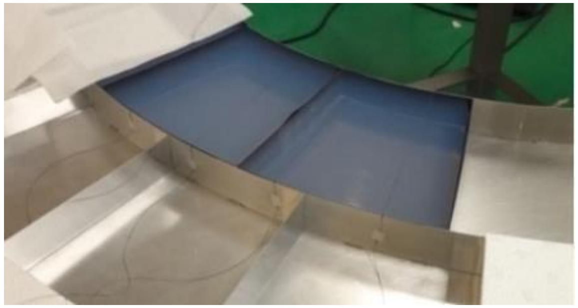




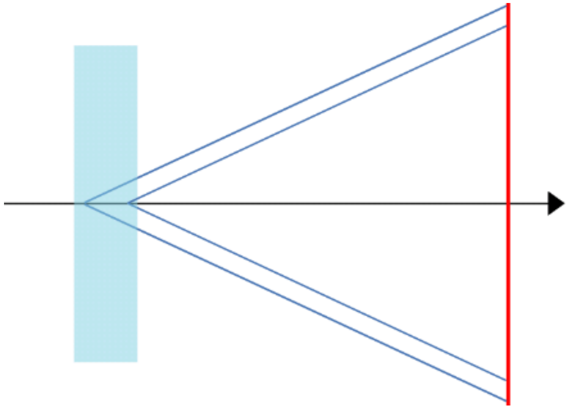




- 248 tiles in total
  - ✓ Cut with water jet from 18cm × 18cm tiles.



Proximity type RICH



PID performance is determined by the Cherenkov angle resolution per track:

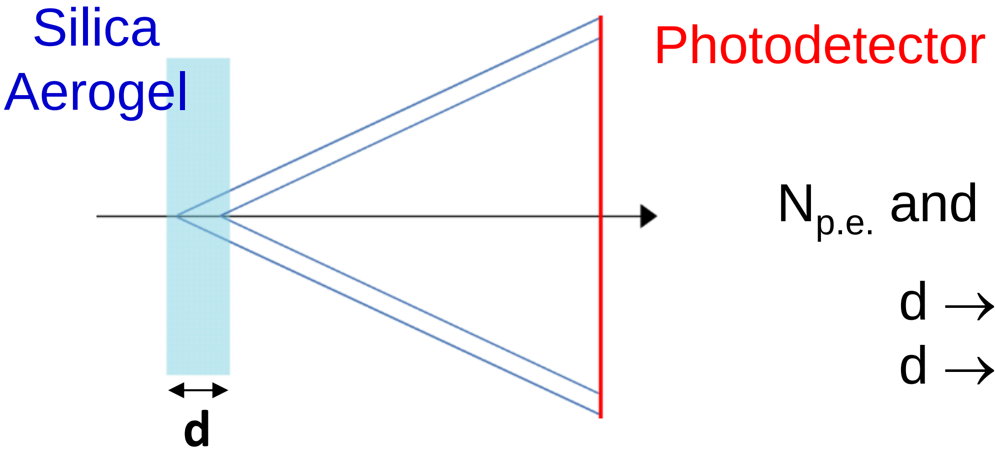
$$\sigma_{\text{track}} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

σ_θ : Cherenkov angle resolution per photon (how precise we can measure the angle).

Main contribution to σ_θ

- Position resolution of the photon detector
- Thickness of the radiator
- Tracking resolution of the charged particle (position, angle)
- Multiple scattering of track (low momentum)
- Wave length dependence of the refractive index (Chromatic dispersion)

Proximity Focusing RICH

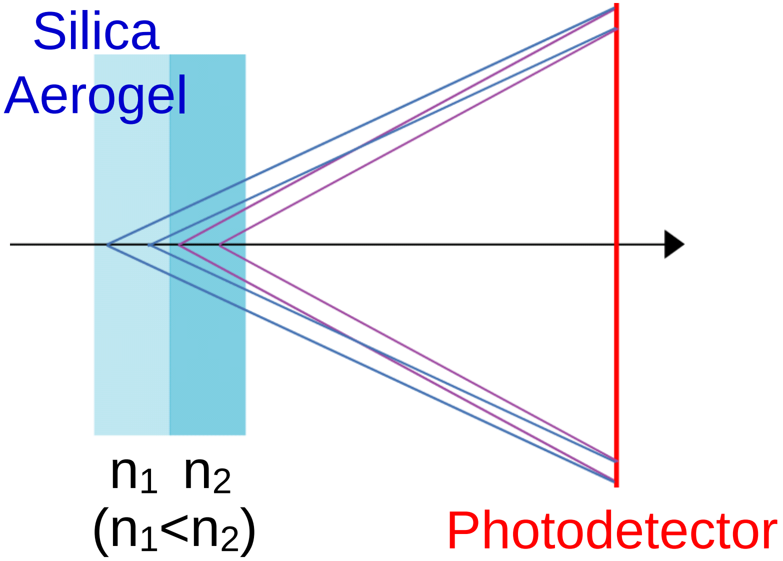


$$\sigma_{\text{track}} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$

$N_{p.e.}$ and σ_θ is proportional to d (radiator thickness)

d → large ⇒ $N_{p.e.}$ → large, σ_θ → bad
d → small ⇒ $N_{p.e.}$ → small, σ_θ → good

Belle II Aerogel RICH: dual radiator RICH



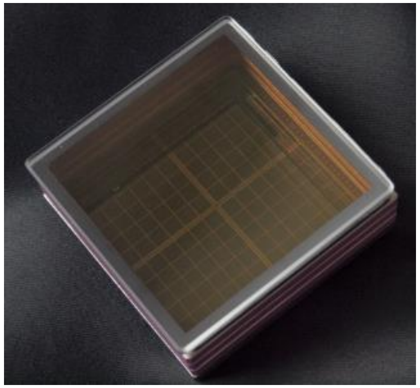
- Use two layer of aerogels with different refractive index.
  - ✓ Ring image overlap at the photodetector.
  - ✓ Possible only with aerogels: we can adjust the index of aerogels.
  - ✓ $n_1 = 1.045$, $n_2 = 1.055$

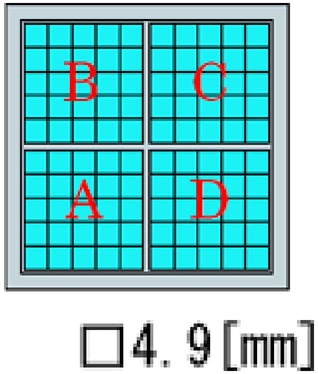
Photo Detector

Photo-detector

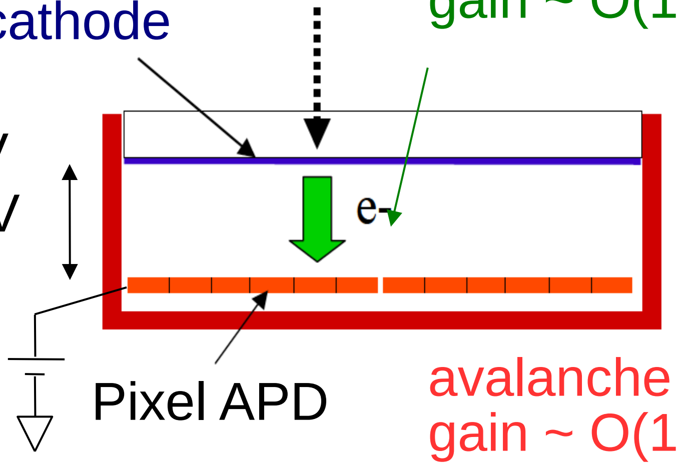
- ~5mm pixel size. Large coverage.
- Immune to 1.5T magnetic field.
- Radiation tolerance (neutron, gamma).

⇨ HAPD (Hybrid Avalanche Photo-Detector)





Hybrid: Vacuum tube + semi-conductor



bi-alkali photocathode

photon

bombardment gain ~ O(1000)

HV −8kV

e-

300V bias

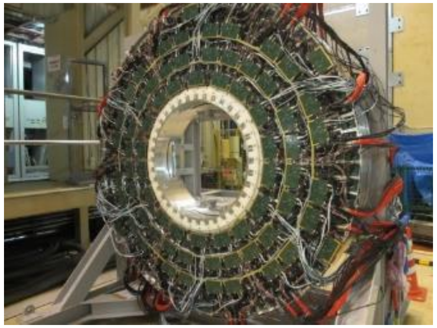
Pixel APD

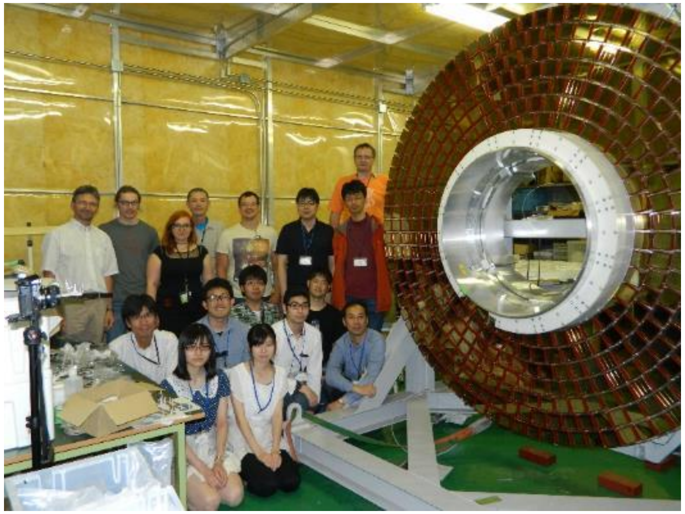
avalanche gain ~ O(10)

- Developed with Hamamatsu Photonics.
- 144 channels (36-ch APD chip × 4).
- Gain ≥45000.
- Peak QE ~28%
- Size 73mm × 73mm.
- Effective area 63mm×63mm (65%).

Total 420 HAPDs

ARICH Status

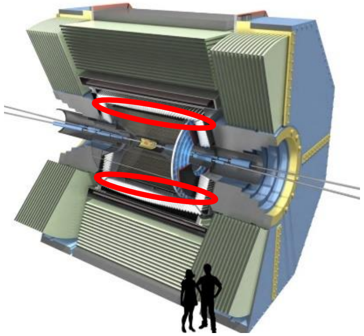


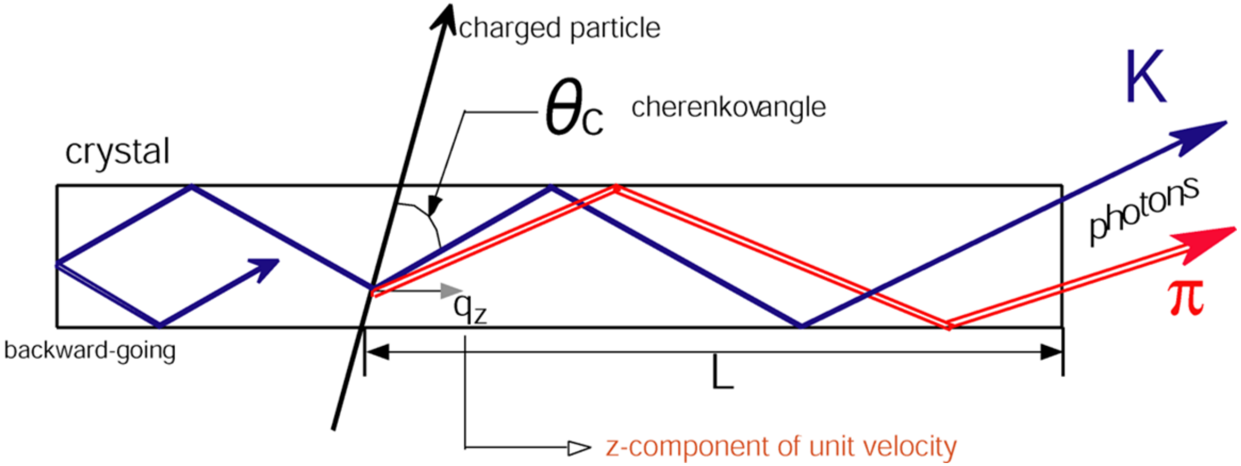


- 2017: ARICH installation to Belle II detector.
- 2018 Feb-Jun: Belle II commissioning without inner vertex detector (Phase 2).
- 2018 Sep-: ARICH hardware modification
- 2019-2022 Jun: Belle II operation with full detector (except PXD 2nd layer)
- 2022 Summer- 2023 : Long Shutdown1 LS1 (for PXD 2nd layer installation).
- 2024-: Resume operation.

TOP

Measurement principle of TOP (Time of Propagation) Detector

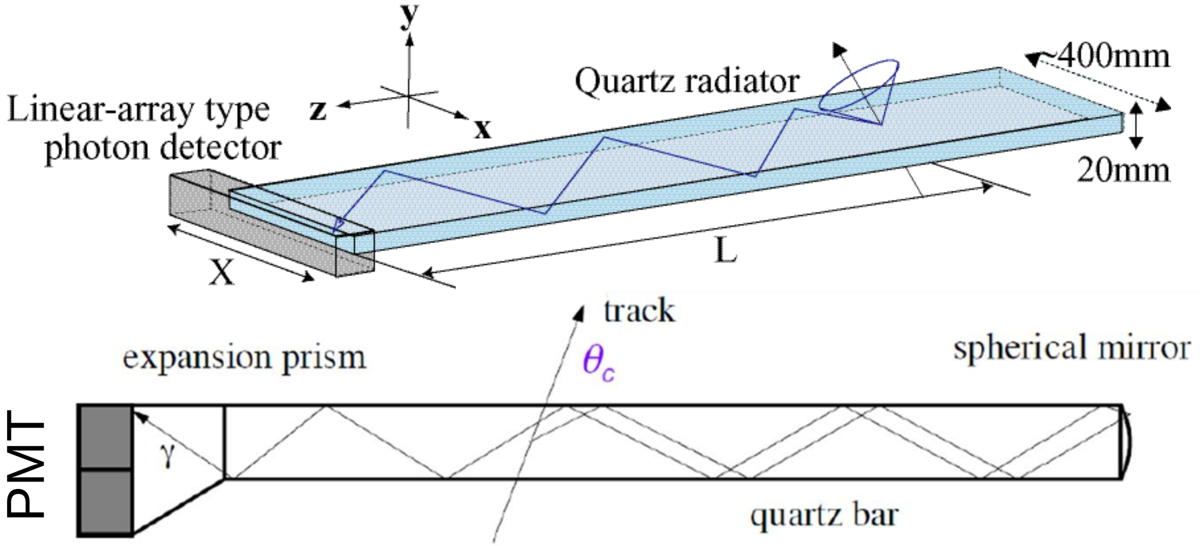


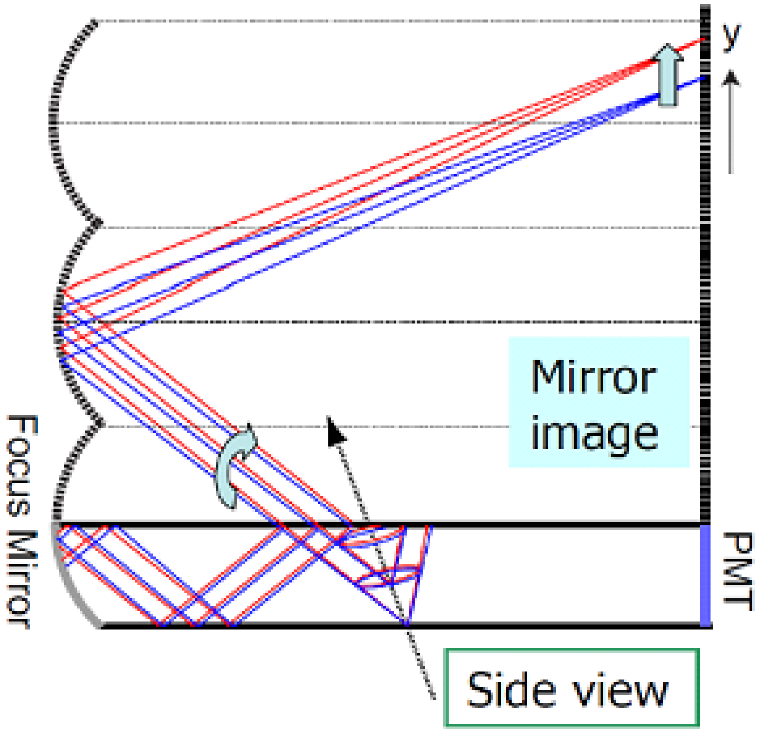


Different Cherenkov angle
→ Different photon path
→ Different time of propagation.

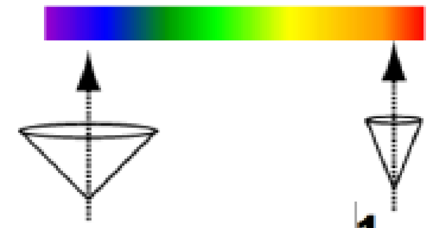
- Measure the time of propagation of K and π: need ~ 50 ps timing resolution
- Measure the position of photons, too.
- Also works as a TOF (Time of Flight) detector for low momentum particles.
  - ✓ Combination of TOF and RICH with a single device

TOP





- Very flat quartz bar
- Photo-detector with good timing resolution.
- Focus Mirror
  - ✓ Parallel photons are focused: remove the uncertainty from the bar thickness.
  - ✓ y actually differs with different θ_c (when wavelength is different).
    → Correction of chromatic dispersion (look at the relation of y and t)



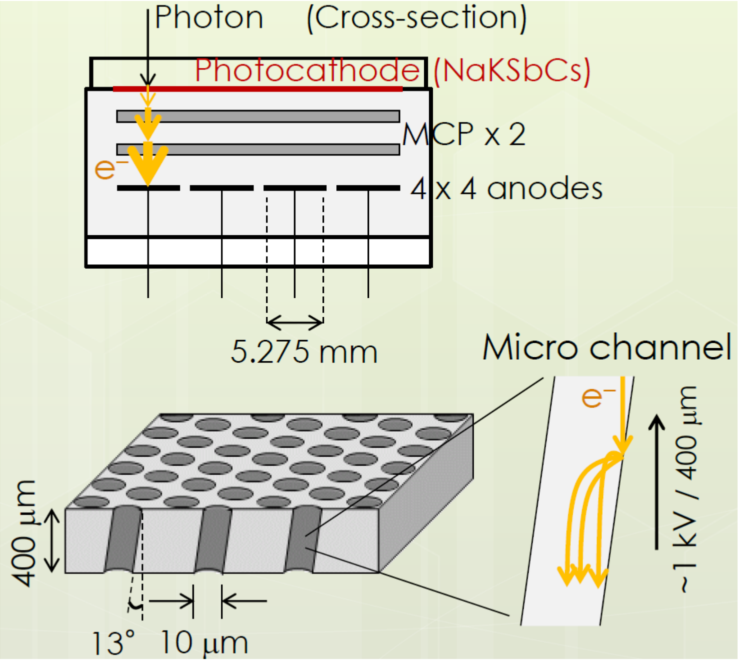
$$\theta_c(\lambda) = \cos^{-1}\left(\frac{1}{n(\lambda)\beta}\right)$$

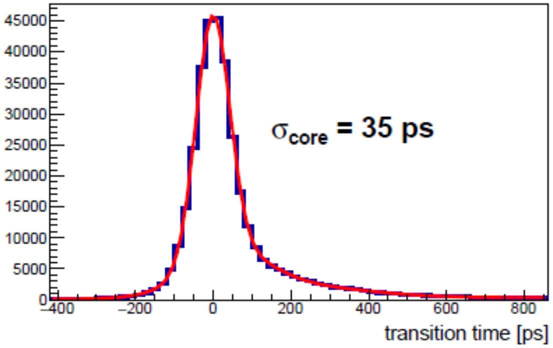
MCP-PMT

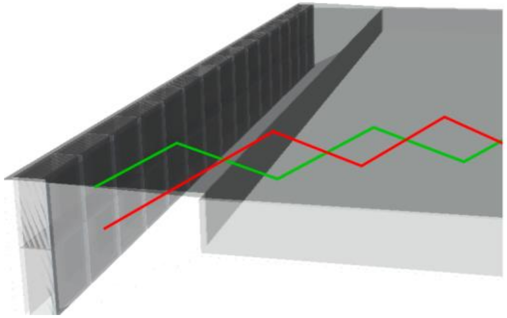
MCP (Micro Channel Plate) -PMT

- 4 × 4 channels, 5.5 mm pixel size
- NaKSbCs photo cathode; QE>24%
- Photodetector with the best time resolution
    - ✓ TTS (Transit Time Spread)* < 40ps
- single photon sensitivity
- works in the magnetic field.

* = Fluctuation of the signal timing for single photon input.







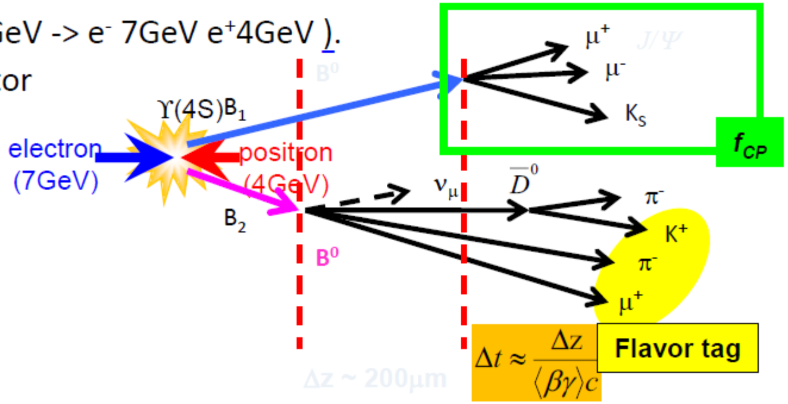
2 × 16 PMTs per module (512 pixels)

Vertex Detector

VXD(Vertex Detector : PXD+SVD) for Belle II

Beam energy is changed from Belle (e$^-$ 8GeV e$^+$ 3.5GeV -> e$^-$ 7GeV e$^+$4GeV).

- Boost factor is smaller : 67% of Belle's boost factor
  - Vertex resolution needs to be improved.

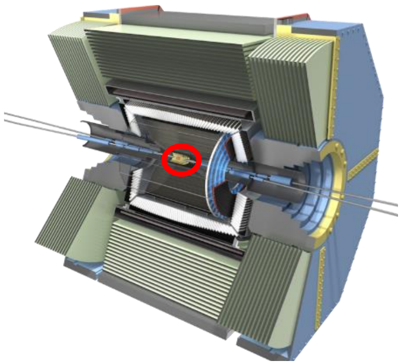


To avoid multiple scatterings in sensors

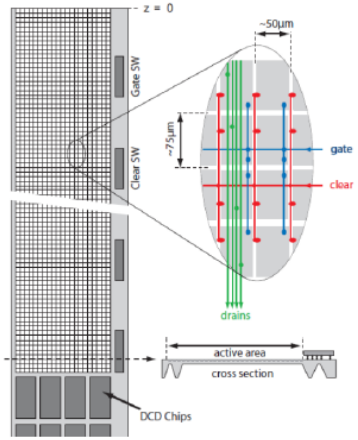
- Amount of material needs to be reduced.
  - Pixel detector(PXD) : width 75 μm
  - Silicon vertex detector(SVD) : width 300 μm

Higher luminosity

- Large occupancy, pileup
- High granularity -> smaller pixel size
- Fast data transfer

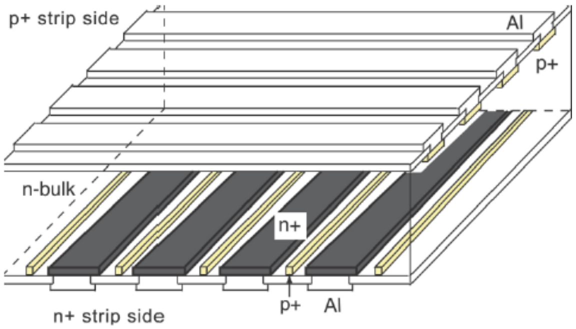


PXD(Pixel detector)

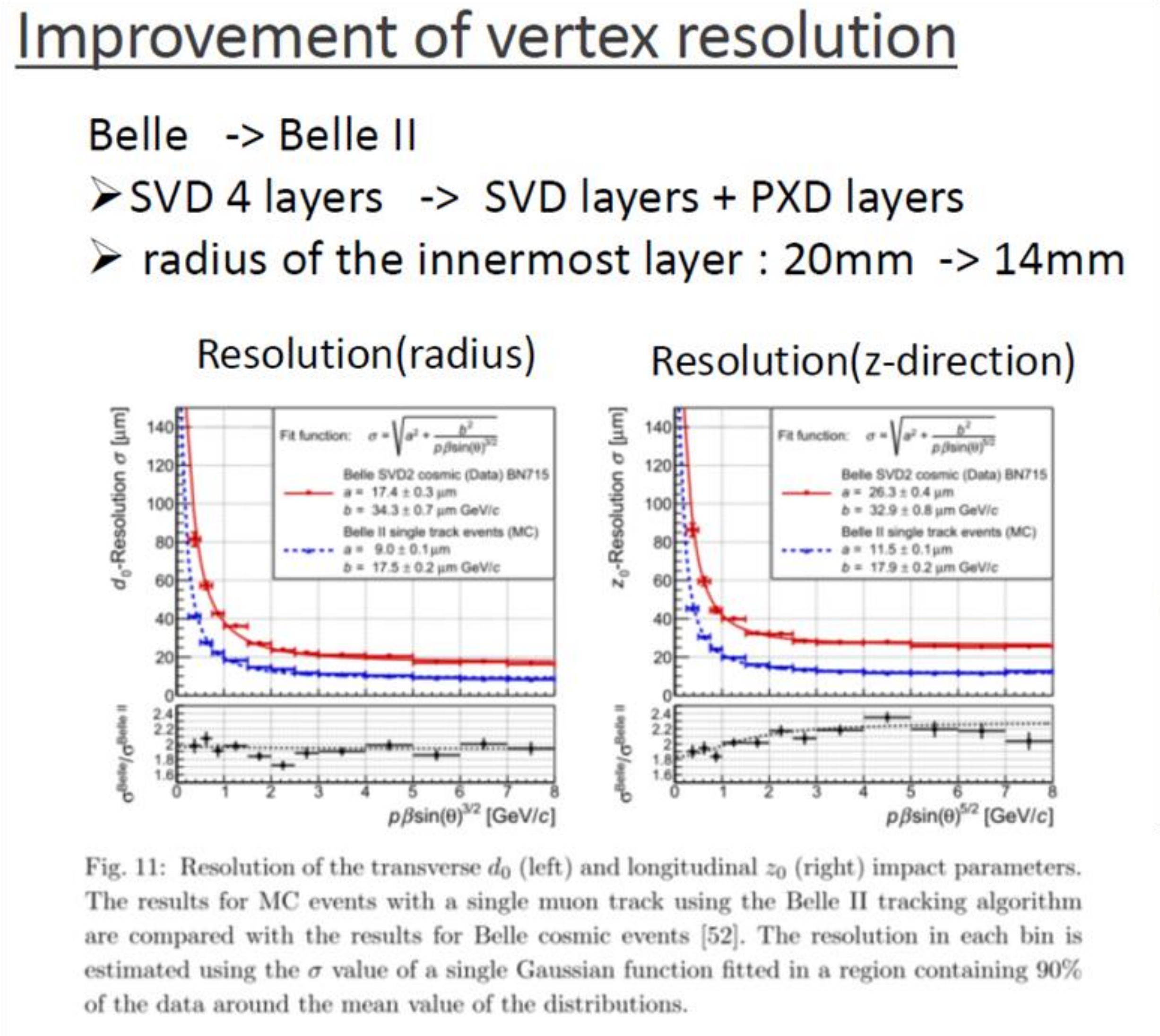


SVD(Silicon Vertex detector)

Double Sided Silicon Strip detector (DSSD)



Vertex Detector



Improvement of vertex resolution

Belle -> Belle II

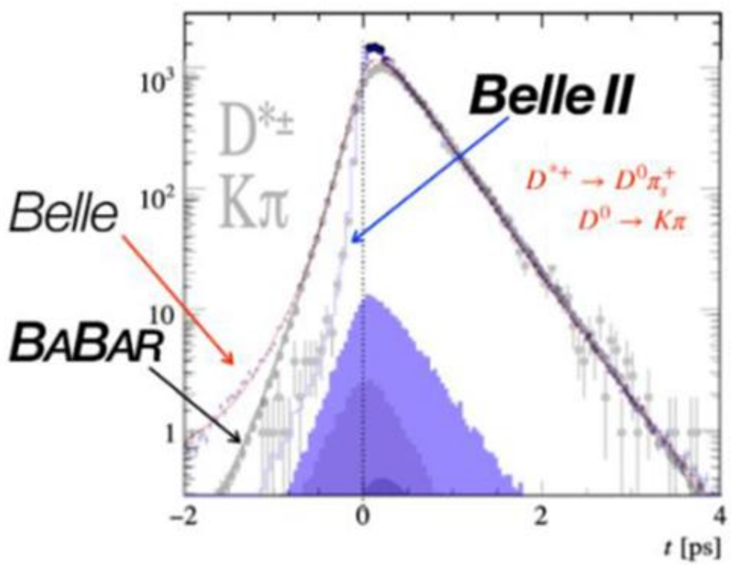
- SVD 4 layers -> SVD layers + PXD layers
- radius of the innermost layer : 20mm -> 14mm

Resolution(radius)

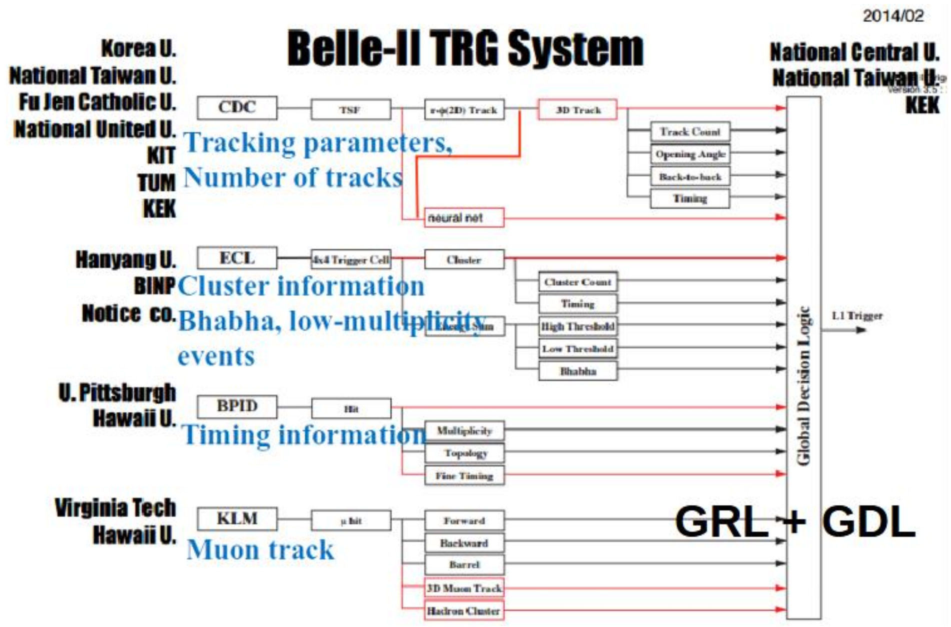
Resolution(z-direction)

Fig. 11: Resolution of the transverse d_0 (left) and longitudinal z_0 (right) impact parameters. The results for MC events with a single muon track using the Belle II tracking algorithm are compared with the results for Belle cosmic events [52]. The resolution in each bin is estimated using the σ value of a single Gaussian function fitted in a region containing 90% of the data around the mean value of the distributions.

Lifetime measurement of D meson



Trigger and DAQ



- In Belle II, we should trigger all the hadronic events.

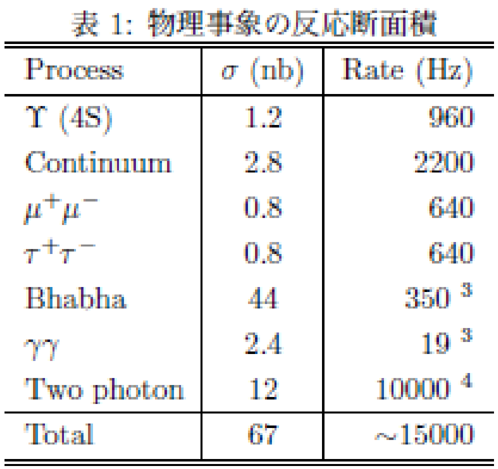
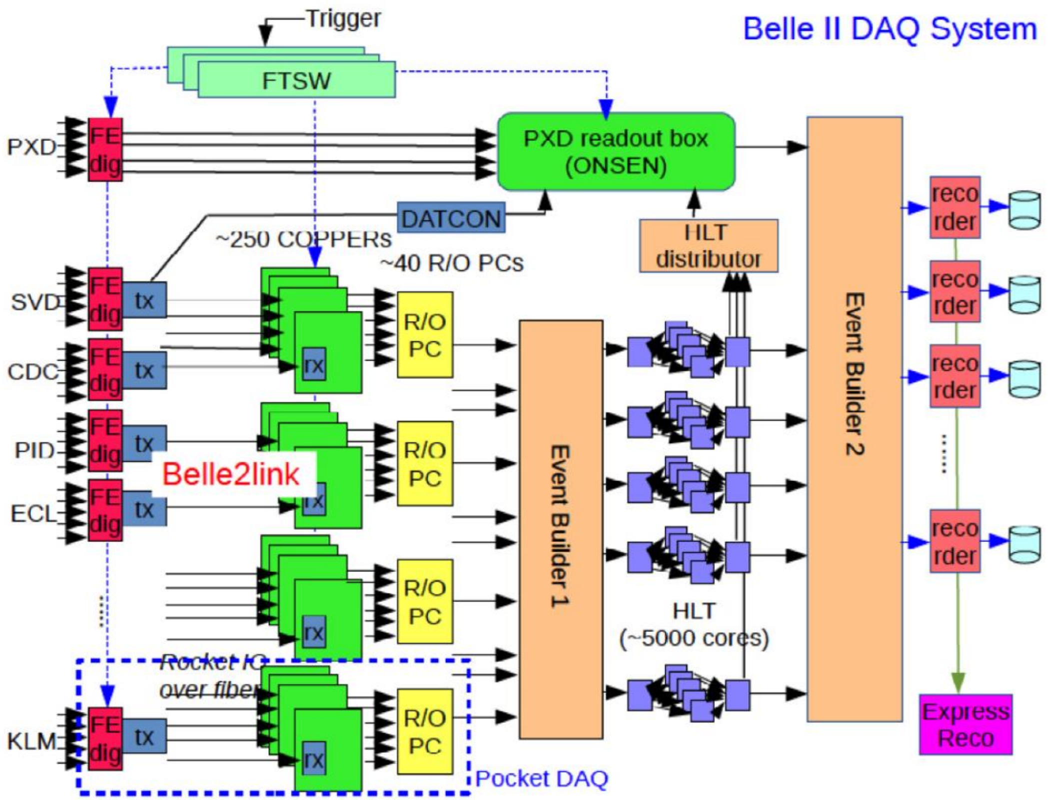


表 1: 物理事象の反応断面積

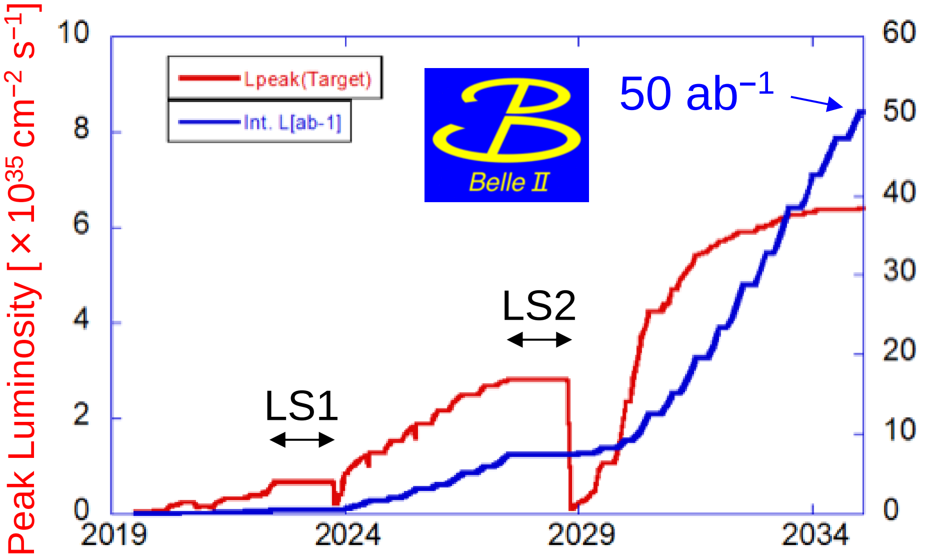
Process	σ (nb)	Rate (Hz)
Υ (4S)	1.2	960
Continuum	2.8	2200
$\mu^+\mu^-$	0.8	640
$\tau^+\tau^-$	0.8	640
Bhabha	44	350[3]
$\gamma\gamma$	2.4	19[3]
Two photon	12	10000[4]
Total	67	$\sim$15000

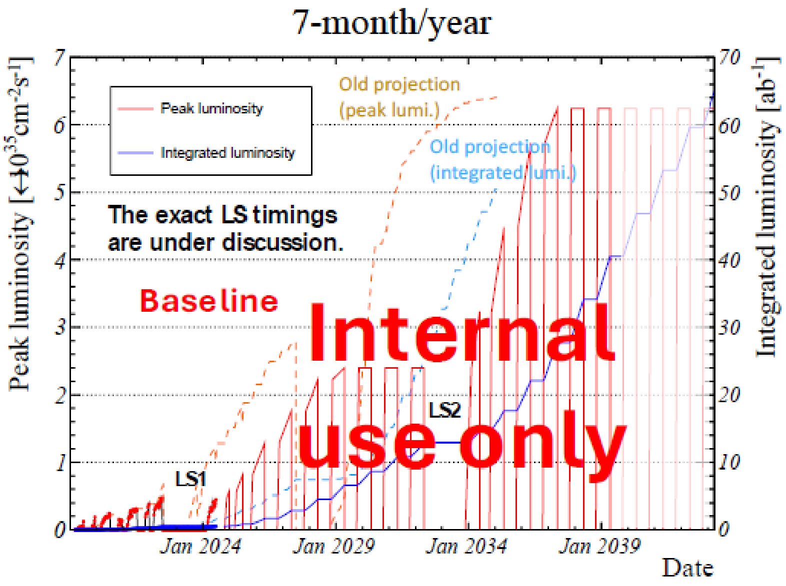
Maximum trigger rate 30 kHz (designed value)



Upgrades

Belle II Upgrade



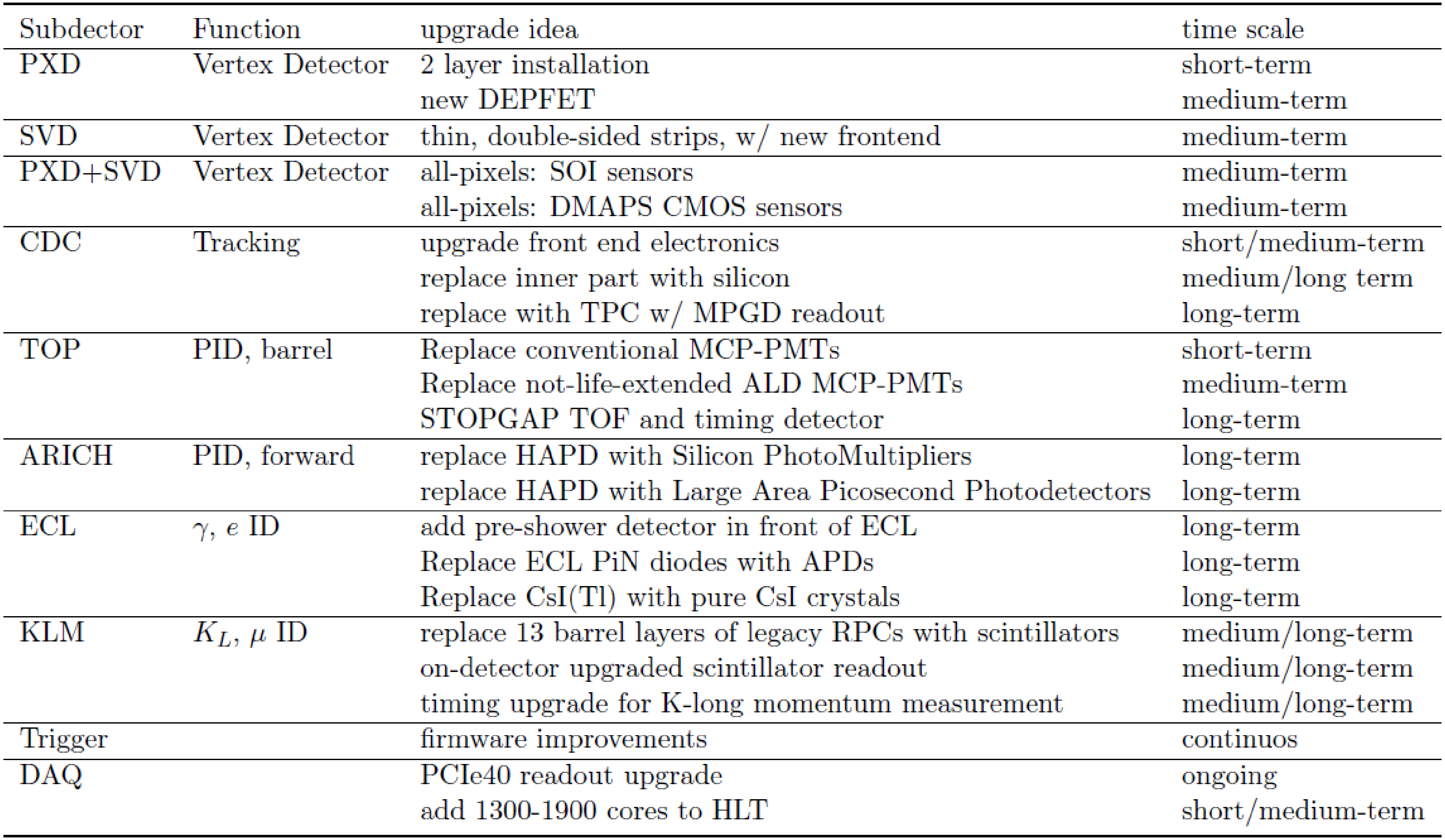


We needs an upgrade of Belle II detector.

- Current Belle II detectors are designed to run for ~10 years, and are not guaranteed to work till the end of experiment.
  - ✓ Some components do not have spares…
- Cooperation with the instrument community
  - ✓ SuperKEKB, Belle II are considered as an demonstrator for Higgs factory (ILC, FCC-ee, CEPC)

Belle II Upgrade

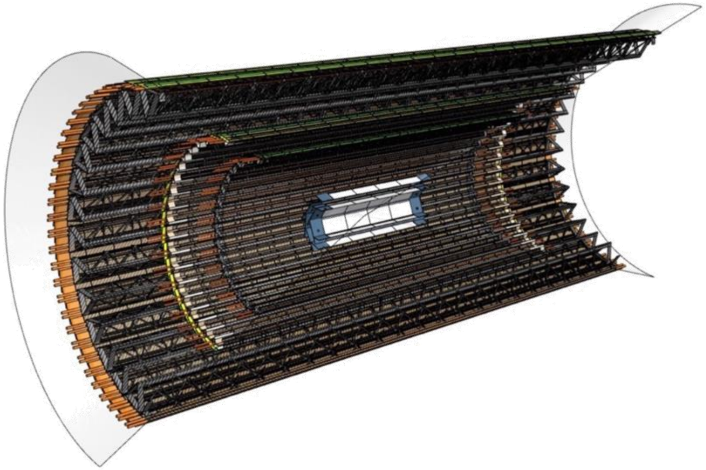
Snowmass white paper in 2022 https://arxiv.org/abs/2203.11349



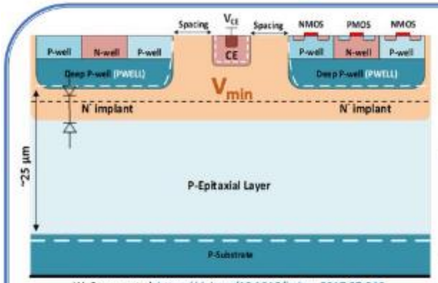
Subdector	Function	upgrade idea	time scale
PXD	Vertex Detector	2 layer installation	short-term
		new DEPFET	medium-term
SVD	Vertex Detector	thin, double-sided strips, w/ new frontend	medium-term
PXD+SVD	Vertex Detector	all-pixels: SOI sensors	medium-term
		all-pixels: DMAPS CMOS sensors	medium-term
CDC	Tracking	upgrade front end electronics	short/medium-term
		replace inner part with silicon	medium/long term
		replace with TPC w/ MPGD readout	long-term
TOP	PID, barrel	Replace conventional MCP-PMTs	short-term
		Replace not-life-extended ALD MCP-PMTs	medium-term
		STOPGAP TOF and timing detector	long-term
ARICH	PID, forward	replace HAPD with Silicon PhotoMultipliers	long-term
		replace HAPD with Large Area Picosecond Photodetectors	long-term
ECL	γ, e ID	add pre-shower detector in front of ECL	long-term
		Replace ECL PiN diodes with APDs	long-term
		Replace CsI(Tl) with pure CsI crystals	long-term
KLM	K_L, μ ID	replace 13 barrel layers of legacy RPCs with scintillators	medium/long-term
		on-detector upgraded scintillator readout	medium/long-term
		timing upgrade for K-long momentum measurement	medium/long-term
Trigger		firmware improvements	continuos
DAQ		PCIe40 readout upgrade	ongoing
		add 1300-1900 cores to HLT	short/medium-term

PXD + SVD

PXD2+SVD



DMAPS pixel technology



W. Snoeys et al. https://doi.org/10.1016/j.nima.2017.07.046

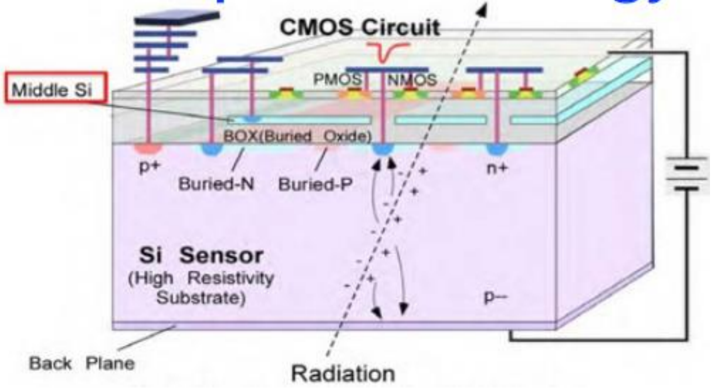
$C_d \leq 3fF$

$P \approx \frac{S}{N} \approx \frac{Q}{C_d}$

DMAPS in TJ 180 nm: Concept

- Small sensor capacitance (Cd)
  - Key for low power/low noise
- Radiation tolerance challenges
  - Modified process
  - Small pixel size
- Design challenges
  - Compact, low power FE
  - Compact, efficient R/O

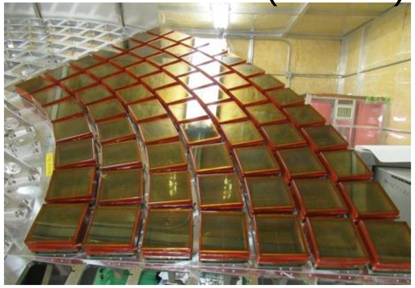
SOI pixel technology

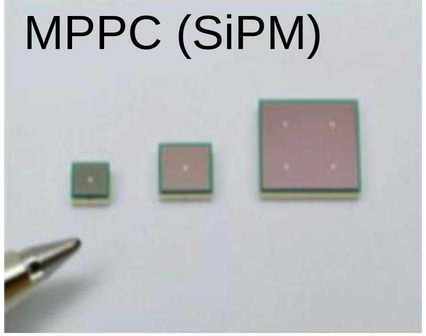


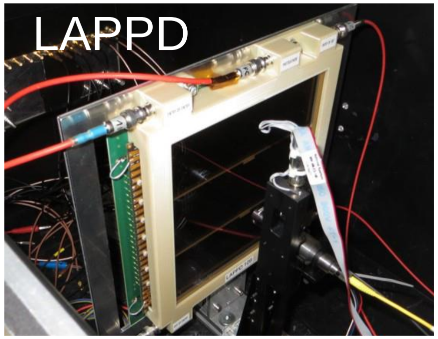
Upgrade to pixel devices (study is going on)

TOP, ARICH (photodetector)


MCP-PMT (TOP)


HAPD (ARICH)


MPPC (SiPM)


LAPPD

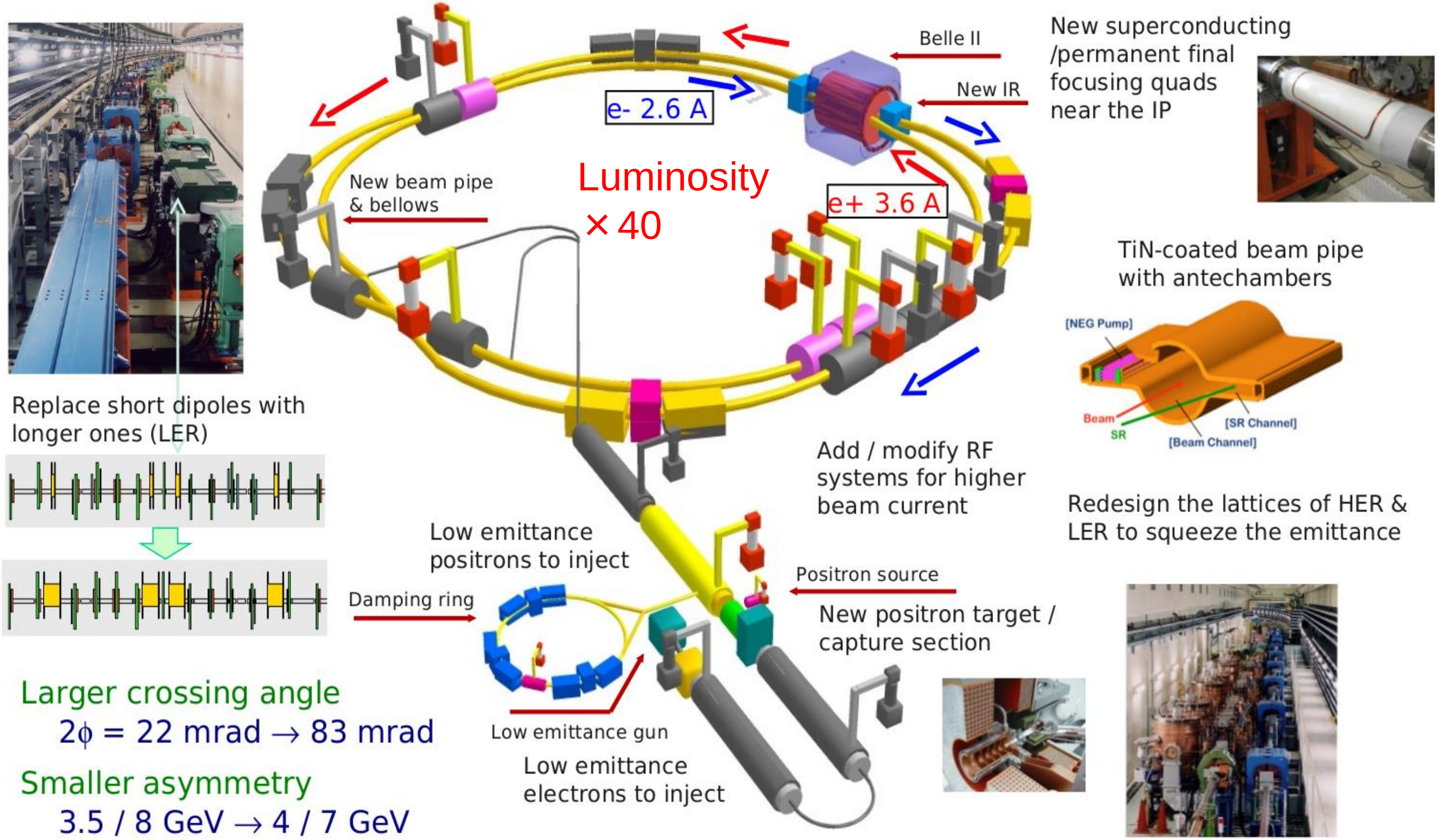
Replacement of photodetectors are under consideration (long-time project)

For ARICH:

- HAPDs are discontinued (no more production).
- MPPC (SiPM) has better performance (PDE) but has large concern on the dark count and radiation damage (>10^{12} n / cm^2 @ 1 MeV equiv. is expected.)
  - ✓ Cooling (~ −40°C ?) is necessary.
  - ✓ Readout electronics with fast timing capability (fastIC chip developed for LHCb ARICH is a candidate)
- LAPPD looks a promising option, but it is still at development.

Backup

SuperKEKB



Luminosity × 40

New superconducting /permanent final focusing quads near the IP

New beam pipe & bellows

TiN-coated beam pipe with antechambers

Replace short dipoles with longer ones (LER)

Add / modify RF systems for higher beam current

Redesign the lattices of HER & LER to squeeze the emittance

Low emittance positrons to inject

Damping ring

Positron source

New positron target / capture section

Low emittance gun

Low emittance electrons to inject

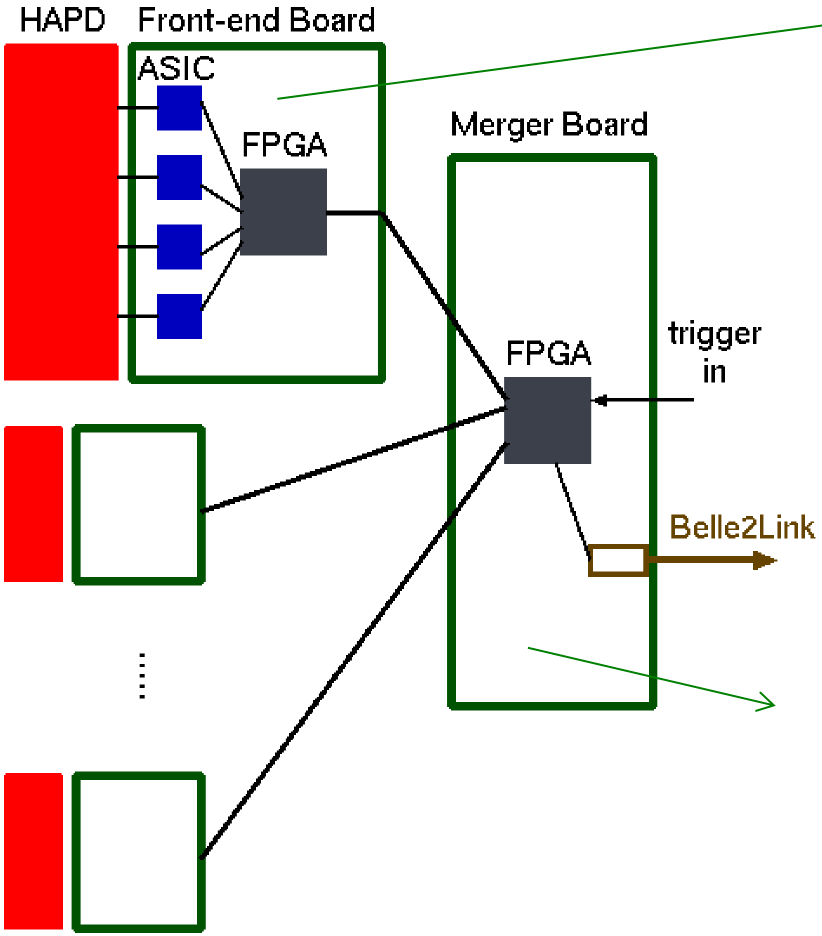
Larger crossing angle

2ϕ = 22 mrad → 83 mrad

Smaller asymmetry

3.5 / 8 GeV → 4 / 7 GeV

Electronics



Front-end Board

- 4 ASIC + Xilinx FPGA (Spartan6).
- ASIC : preamp + shaper + discriminator.

- Total 60480 channels.
  - ✓ 1-bit ON/OFF information is enough.

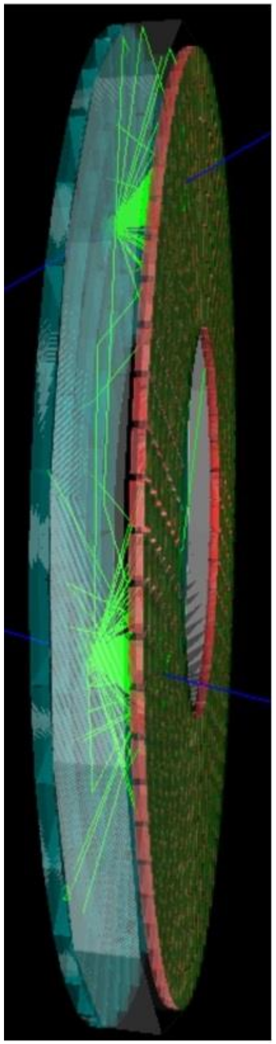
Merger

- Receive hitdata from 5-6 front-end boards.
- Zero suppression.
- Send to DAQ.

420 HAPDs + Front-end Boards
72 Merger Boards

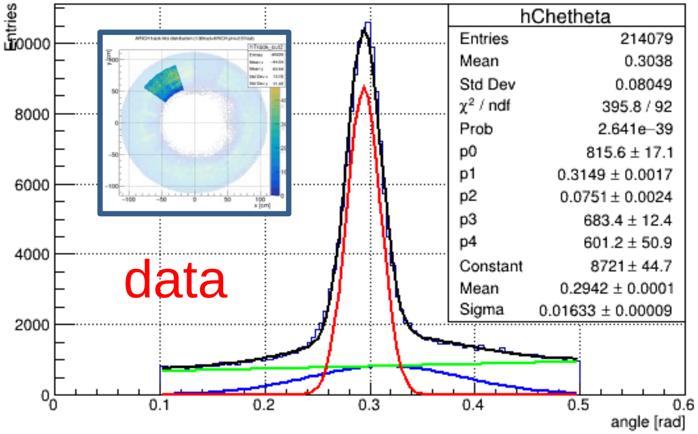
Cherenkov Angle

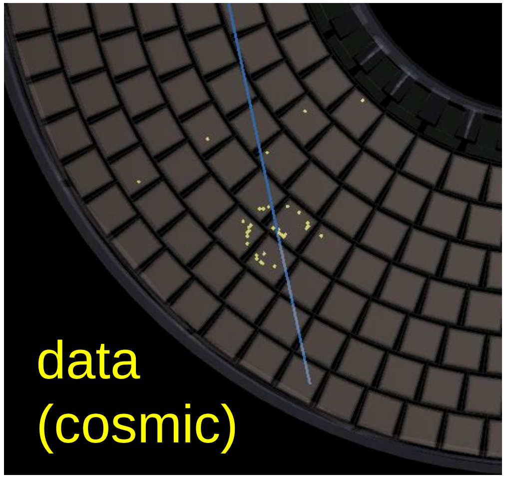
MC



- Rough performance can be obtained Cherenkov angle (σ_θ) and Number of photons per track ($N_{p.e.}$)
- Distribution with Bhabha sample from the commissioning run (2018).
  - ✓ $N_{p.e.}$ = 9.5 (10.4), σ_θ = 16.3 (14.7) mrad in data (MC)
  - ✓ corresponding to 4.3 σ K/π separation at 4 GeV.

Cherenkov Angle distribution (Bhabha, 2018)

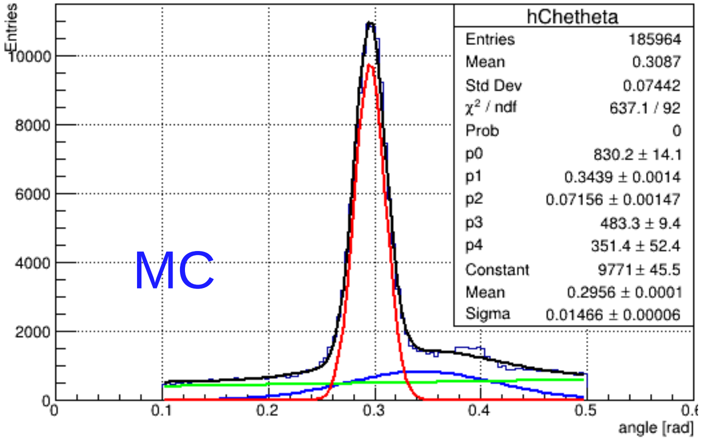




ARICH is working well

performance:

$$\sigma_{\text{track}} = \frac{\sigma_\theta}{\sqrt{N_{p.e.}}}$$



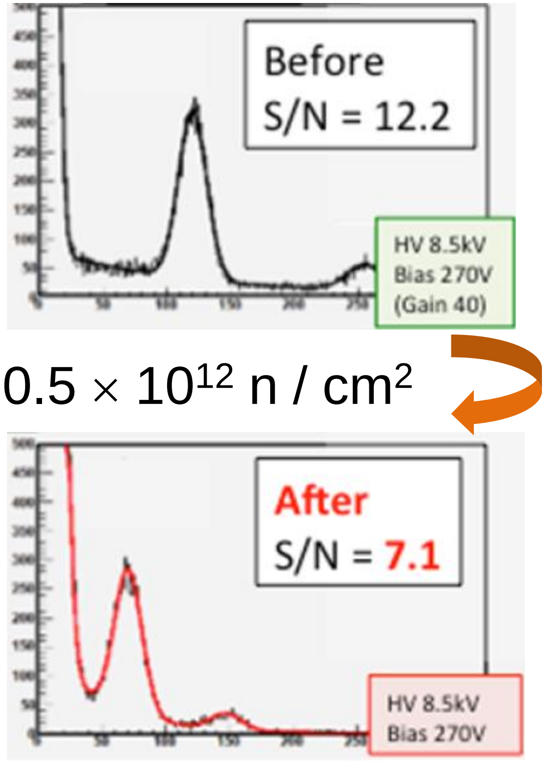
Radiation

- ARICH operation has been stable. No major problem happened in ARICH.

- ARICH is relatively tolerant to the beam background.
  - ✓ In general, large beam background is an issue to Belle II detector.
- One concern is the neutron radiation.

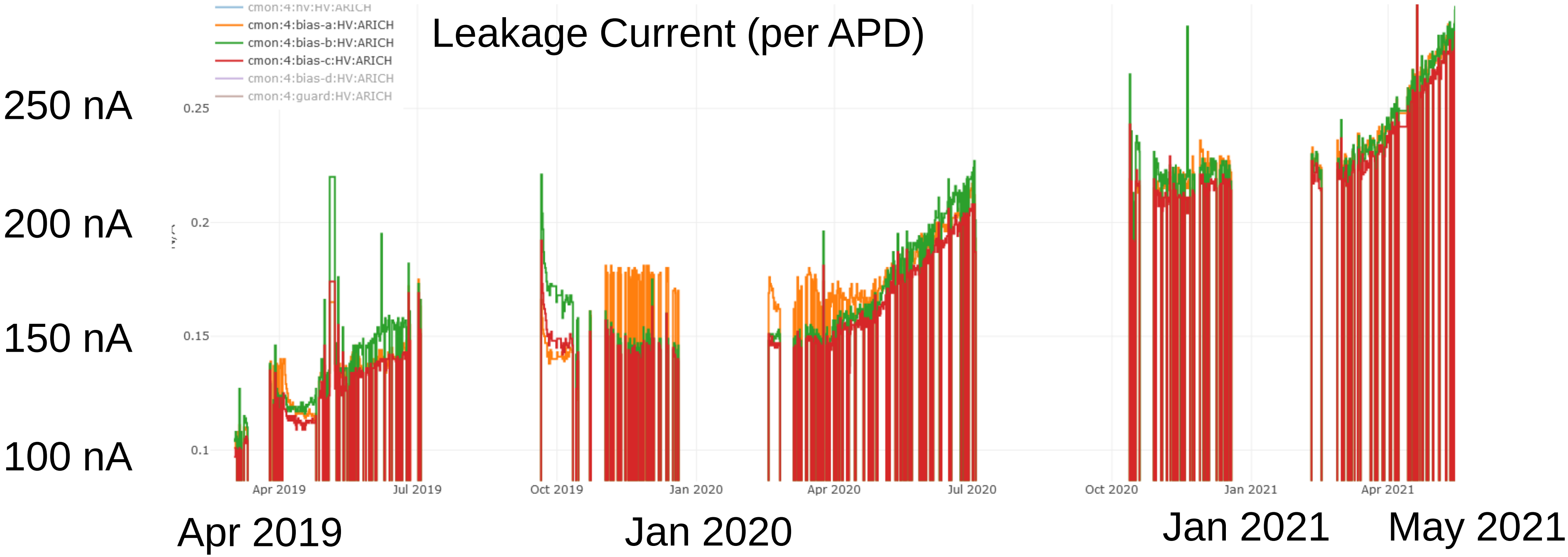
- Deterioration of HAPDs (increase of the leakage current, larger noise) due to silicon bulk damage by neutrons.
  - ✓ Tolerant to 10^{12} neutrons / cm^2 @ 1MeV equiv., assumed for to 10 years' operation.
  - ✓ Sensor performance will be gradually degraded, with a very modest effect on the PID performance.
- Single event upset in the FPGAs electronics.

neutron irradiation test of HAPD



0.5×10^{12} n / cm^2

HAPD Leakage Current

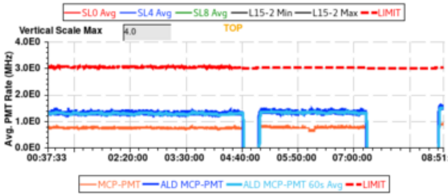


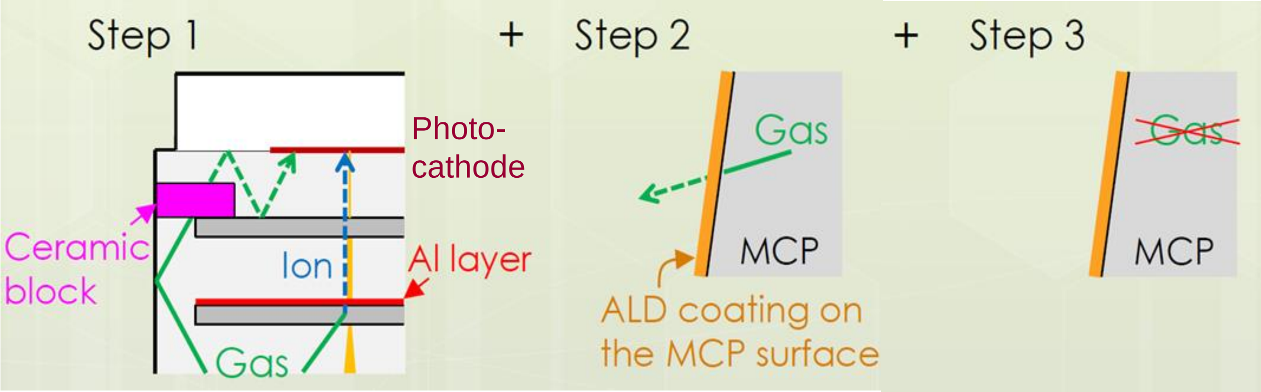
- Leakage current of APD (bias) increases at ~ 10-30 nA / months.
- Estimated neutrons ~ (0.3-1) × 10^9 n / cm^2 / month; 6 × 10^9 n / cm^2 till now.
- Below the original expectation (10^{11} n / cm^2 / year or 10^{12} n / cm^2 in 10 years' operation)

MCP-PMT

Aging problem of MCP

- QE drops as a function of accumulated charge.
  - ✓ The gas and ion from MCP damage the photo-cathode.
- ALD (Atomic Layer Deposition) and life-extended ALD type were developed during mass production.
- The MCP-PMT rate (~accumulate charge) is now limited to 3 MHz so that MCP-PMTs survive till the replacement.
- Replacement work was done during.

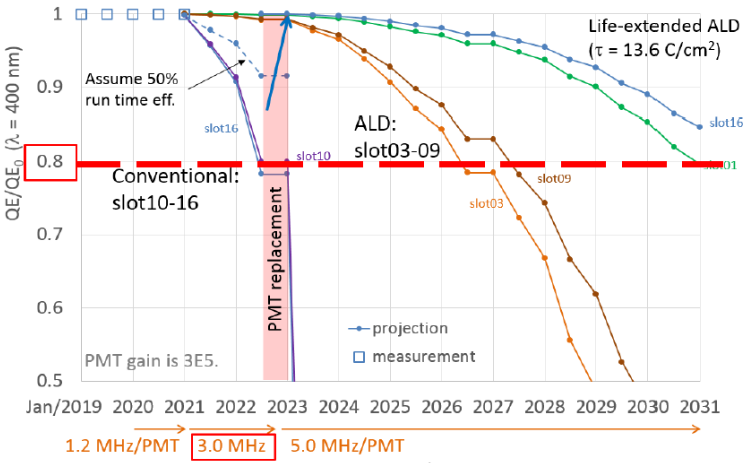




Conventional

ALD

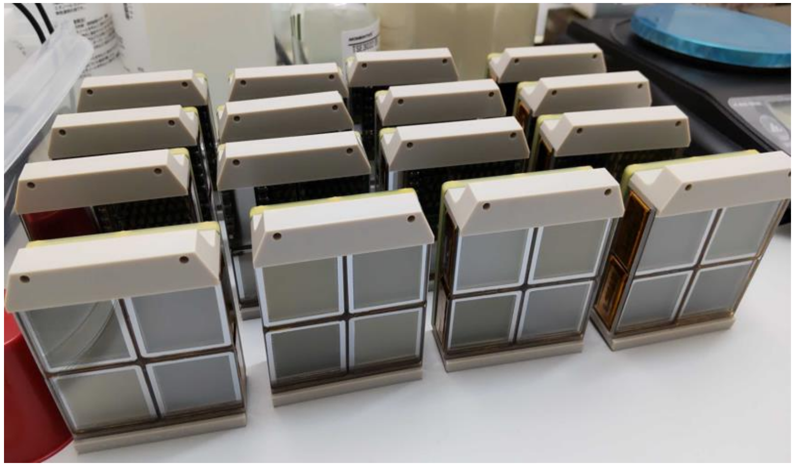
Life-extended ALD

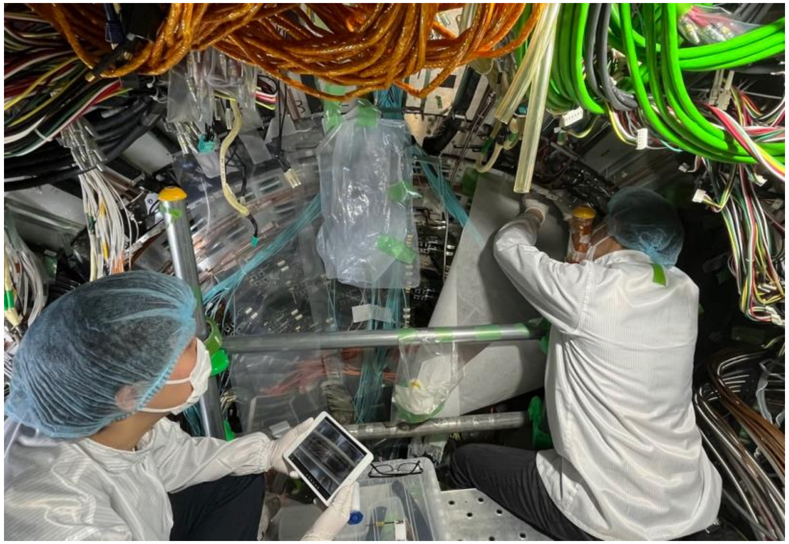


Assumption: The luminosity background follows 17th MC, scaling to the peak luminosity.
IntL~870fb^{-1}, Lp~5.7x10^{34} at 2022/June and 5months operation in 2022ab.

MCP-PMT Replacement

- Replaced 224 MCP-PMTs by new life-extended ALD PMTs
  - ✓ Installed to upper half of TOP modules
- Relocate lower half by best ALD and conventional PMTs
- Exchanged/repaired frontend electronics → >99.5% active channels

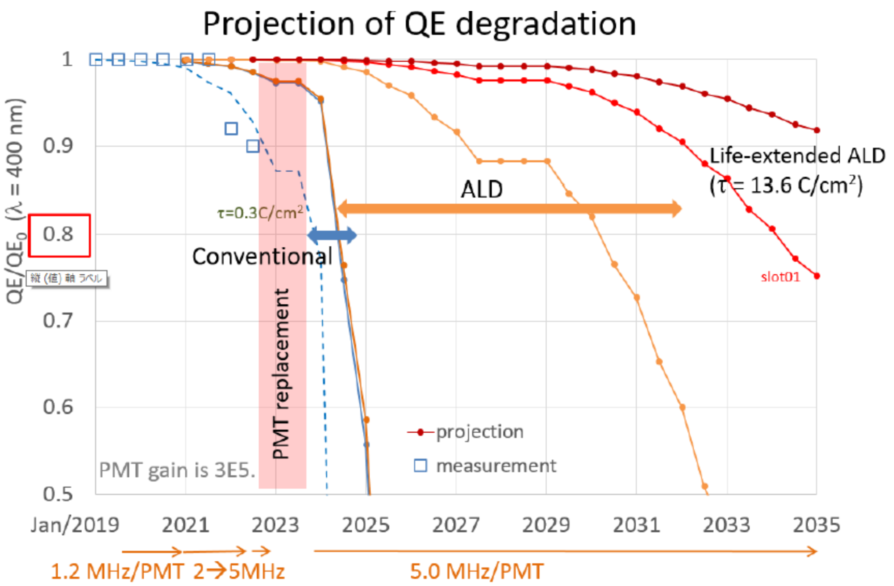


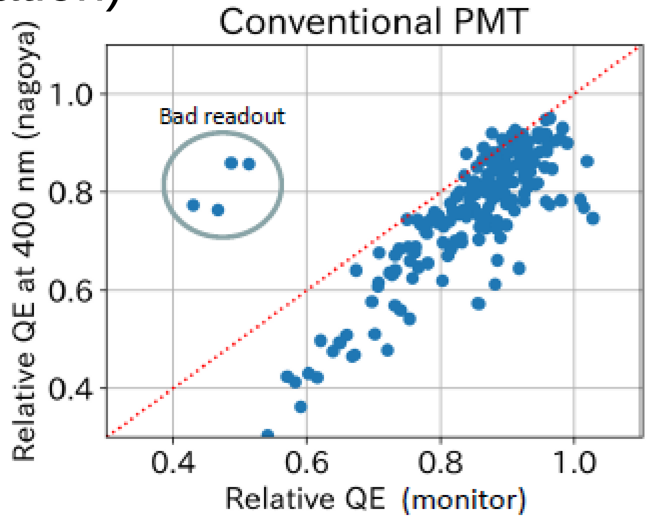


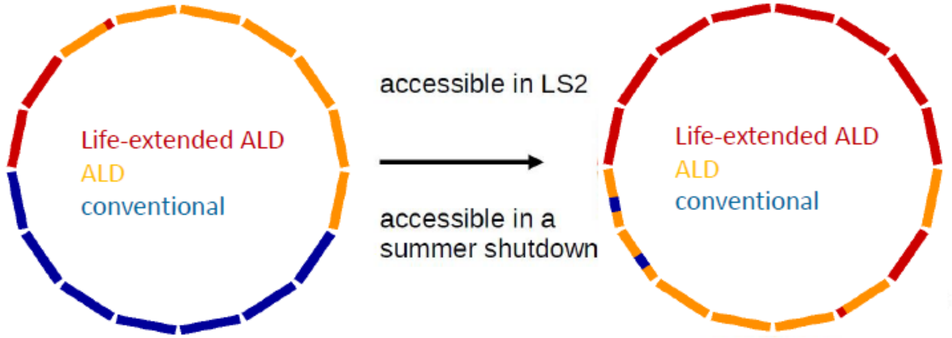
TOP MCP-PMT Replacement

QE degradation of MCP-PMT due to accumulated charge is an issue.

- (Try to avoid unnecessary accumulation during operation)







- QEs for removed PMTs are measured. Confirmed that the QE drop is real.
- Replacement is done considering future access.
- Plan to prepare spare PMTs for next possible replacement before LS2.

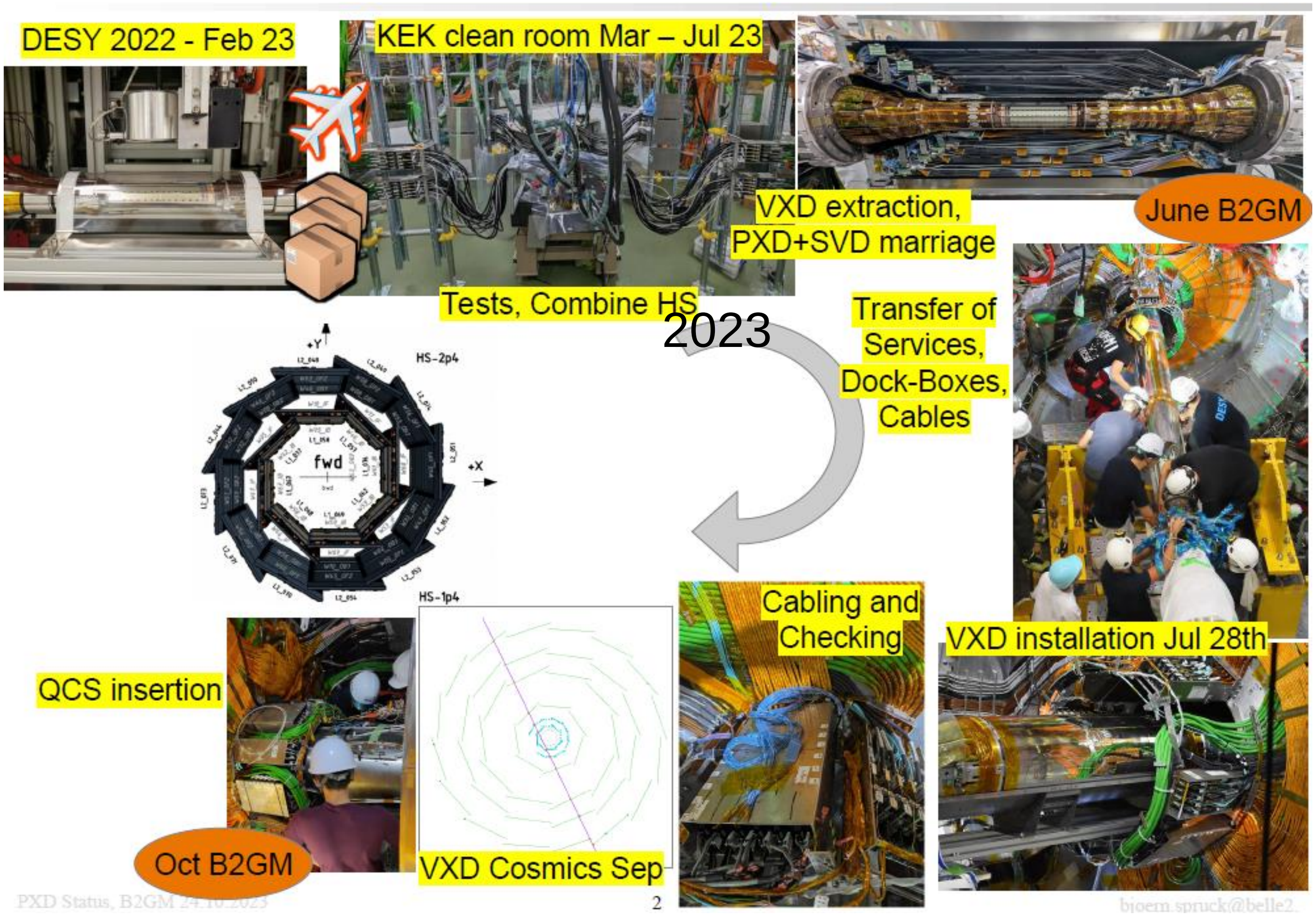
Belle II Upgrade during LS1

VXD (PXD)	PXD 2nd layers installation (VXD reinstallation); New IP beam pipe
TOP	MCP-PMTs replacement
KLM	Study for efficiency recovery; monitoring
DAQ	Complete migration to PCIe40 (SVD, CDC, ECL, TRG); More HLT unit (higher L1 trigger); New monitoring and alarm system, scheme.
Background	Additional background shield
MDI	Additional loss monitor and faster beam abort signal
…	…

Belle II control room, Feb. 20, 2024

PXD

2nd layer of PXD was missing; installed during LS1



DESY 2022 - Feb 23

KEK clean room Mar – Jul 23

Tests, Combine HS

VXD extraction, PXD+SVD marriage

June B2GM

2023

Transfer of Services, Dock-Boxes, Cables

VXD installation Jul 28th

Cabling and Checking

VXD Cosmics Sep

QCS insertion

Oct B2GM

PXD Status, B2GM 24.10.2023

2

bjoern.spruck@belle2.

- Bowing (transformation) of ladders were found during preparation, but finally the detector is installed.
- After PXD installation, QCS insertion was not successful (conflict in remote vacuum connection (RVC)). Solved by a modification of RVC. Minimum delay of the schedule.