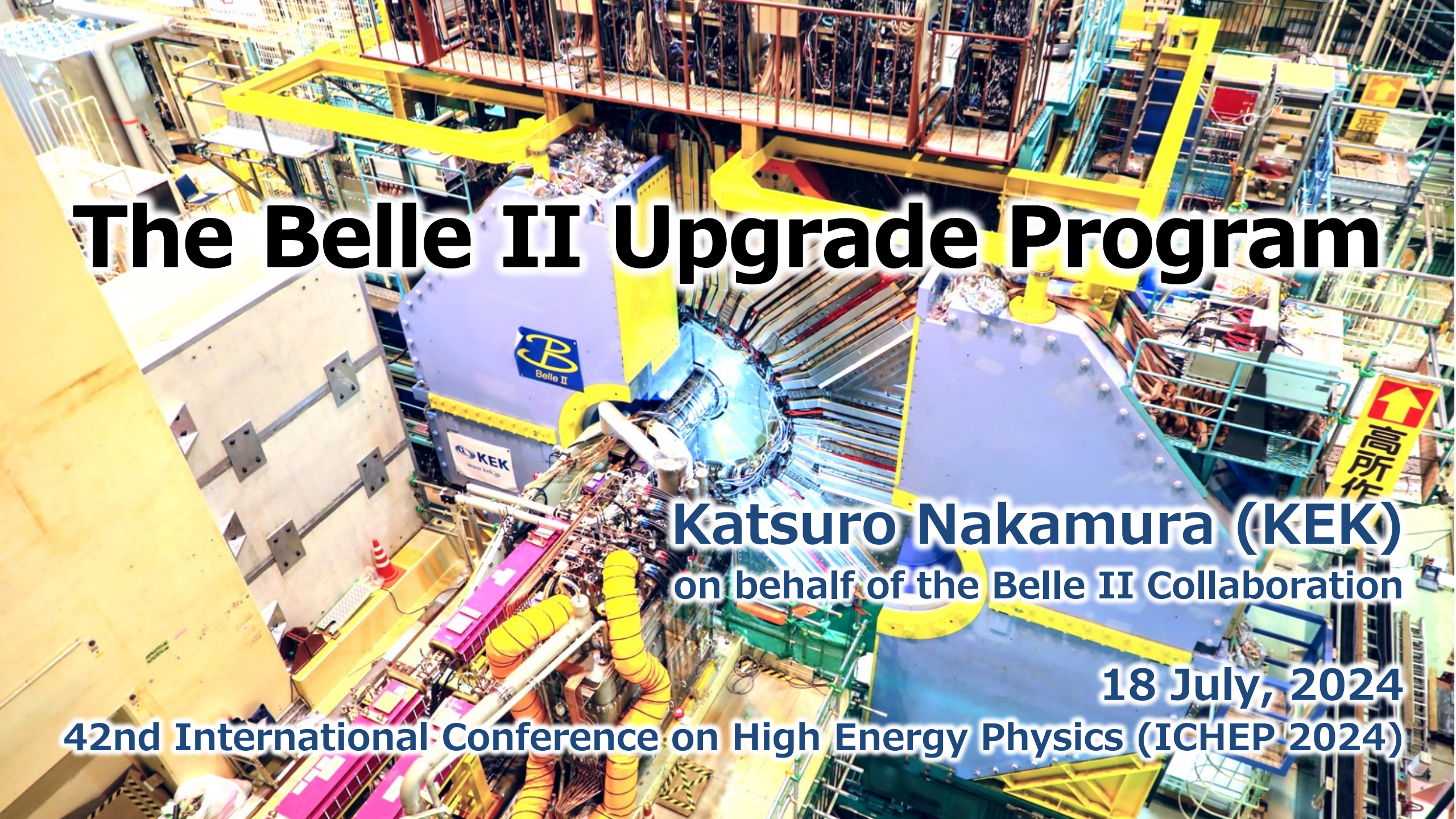


The Belle II Upgrade Program

Katsuro Nakamura (KEK)
on behalf of the Belle II Collaboration

18 July, 2024

42nd International Conference on High Energy Physics (ICHEP 2024)

Belle II Experiment

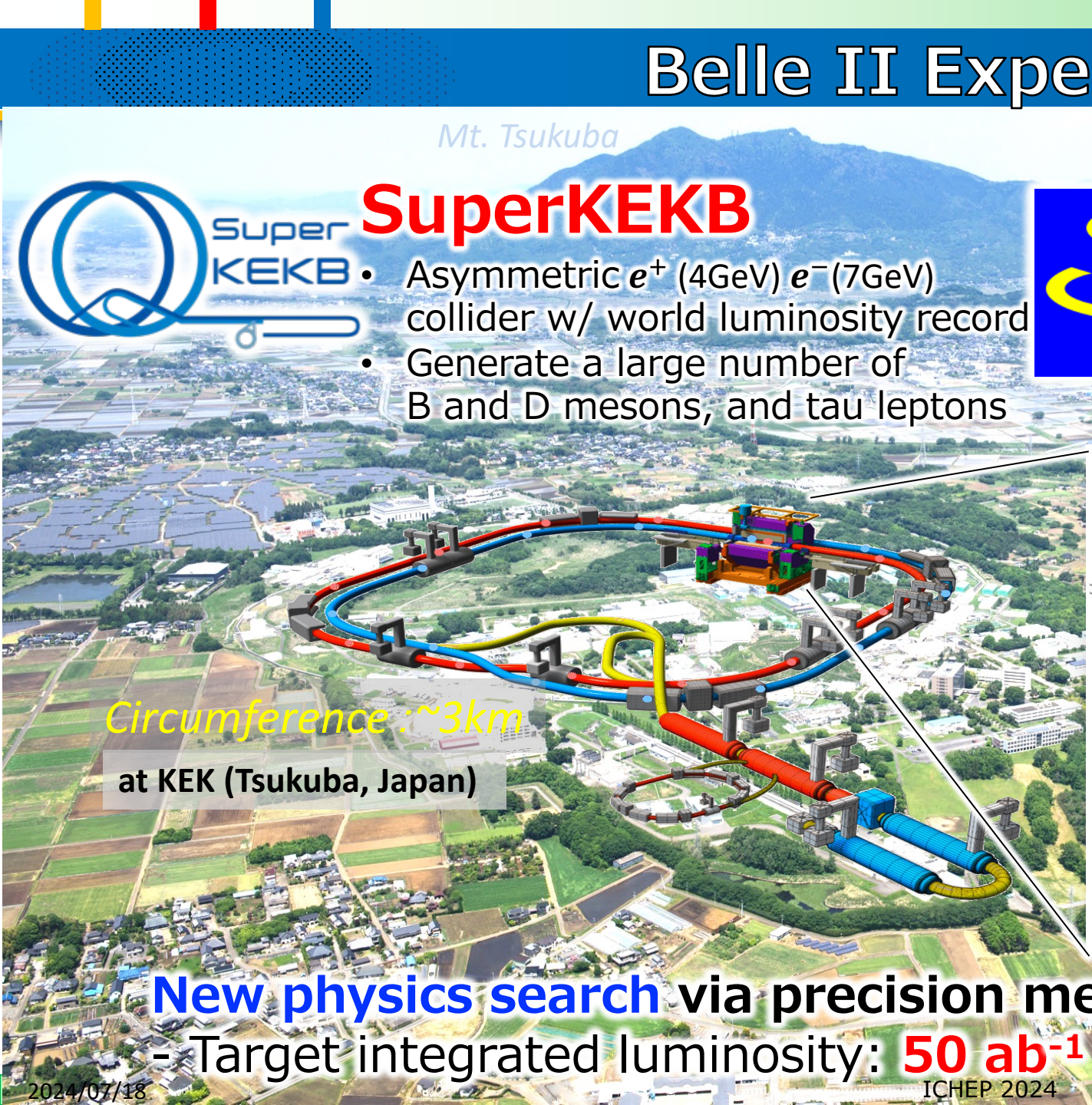
Mt. Tsukuba

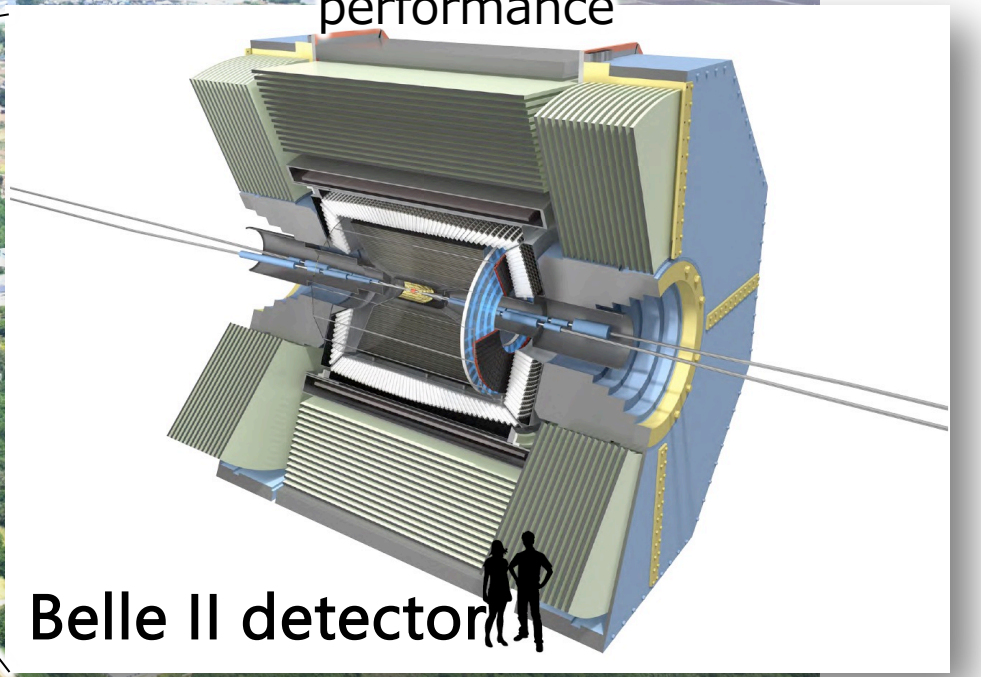
SuperKEKB

- Asymmetric e^+ (4GeV) e^-(7GeV) collider w/ world luminosity record
- Generate a large number of B and D mesons, and tau leptons

Belle II detector

- Hermetic detector: full event reconstruction to exploit kinematic constraint
- Excellent tracking, PID, and vertex performance

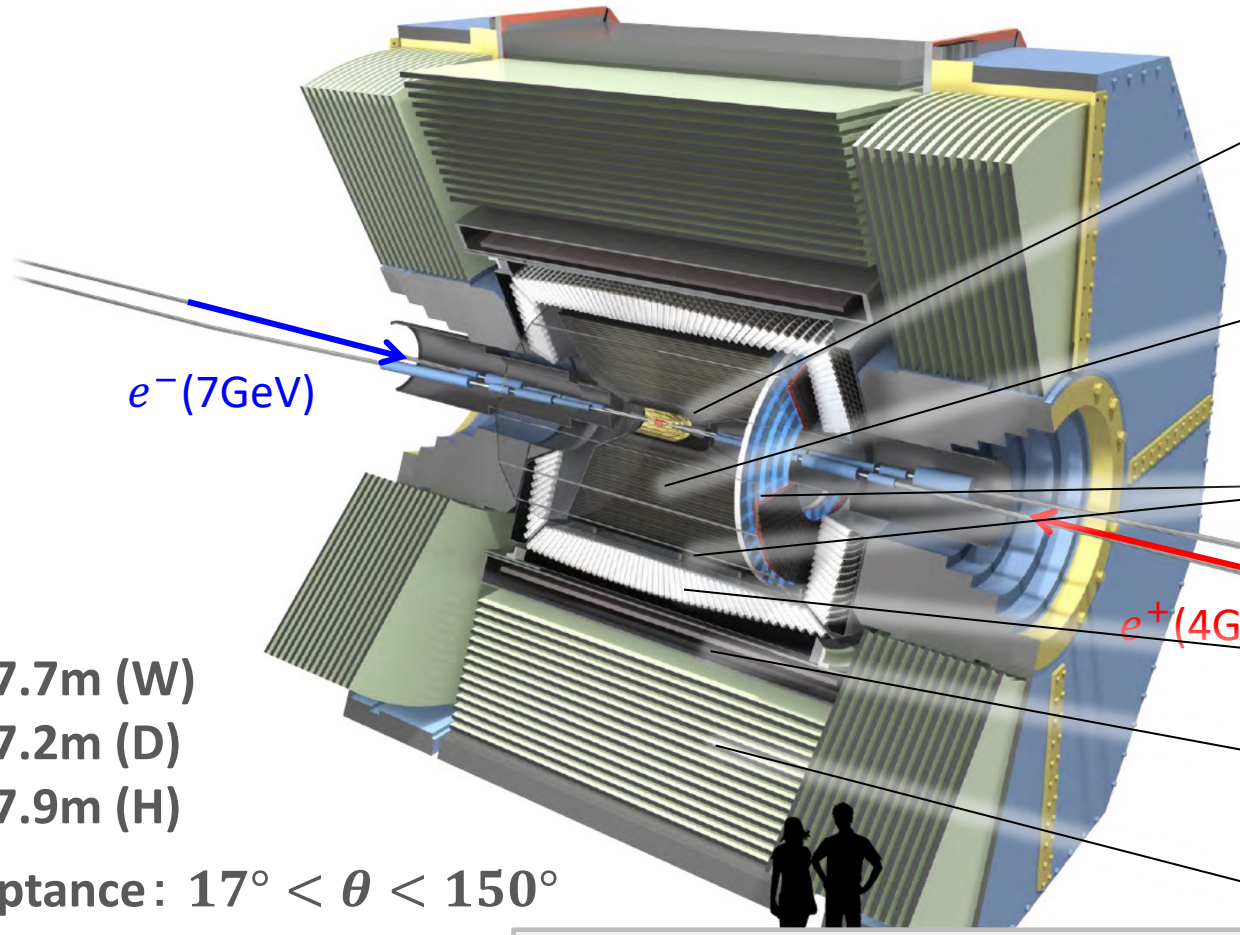



Belle II detector

New physics search via precision measurement of particle decays

- Target integrated luminosity: **50 ab^{-1}**

Belle II Detector



7.7m (W)
7.2m (D)
7.9m (H)

Acceptance: $17° < \theta < 150°$

Vertex detector
- Inner 2 layers w/ DEPFET (pixel): PXD
- Outer 4 layer w/ DSSD (strip): SVD

talk at 15:21 on Jul 18 by L. Corona

Central Drift Chamber (CDC)
- He + C_2H_6 gas (1:1)
- Smaller cell size than Belle

PID detectors (TOP + ARICH)
- Barrel: Time-Of-Propagation counters
- Forward endcap: Aerogel RICH

EM calorimeter
- CsI(Tl) + waveform sampling

Superconducting solenoid: 1.5 T B-field

K_L/μ counter
- Outer barrel: RPC (streamer)
- Endcap/inner barrel: Sci. + MPPC

Level-1 trigger system
- CDC-tracking + EM-cal + μ
- L1 trigger latency: 5 μsec

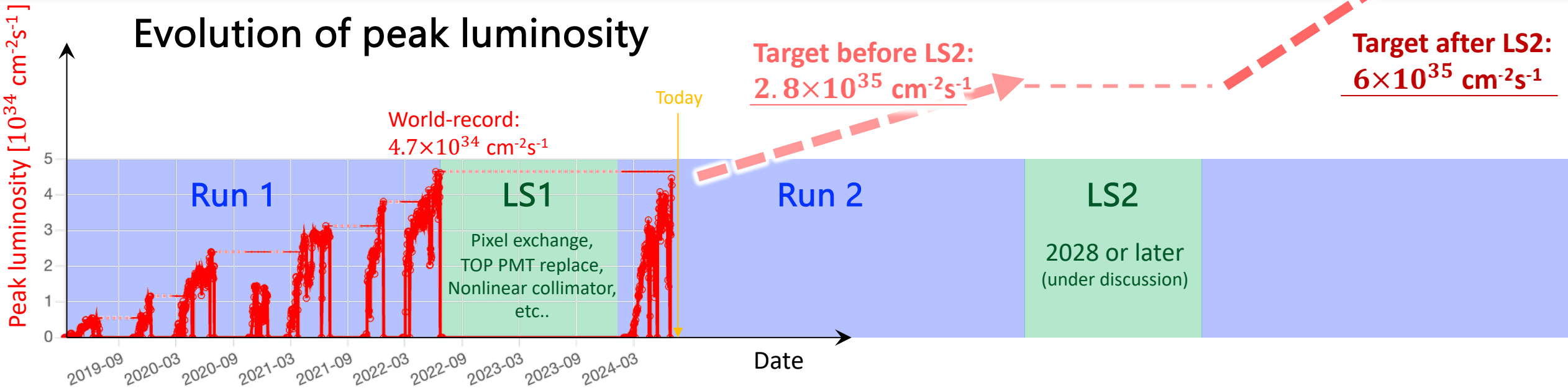
Inner

Outer

High-rate DAQ
- Maximum Level-1 rate: **30kHz**
- Typical data size: 1MB/event

Data analysis w/ GRID computing

SuperKEKB luminosity status and prospect

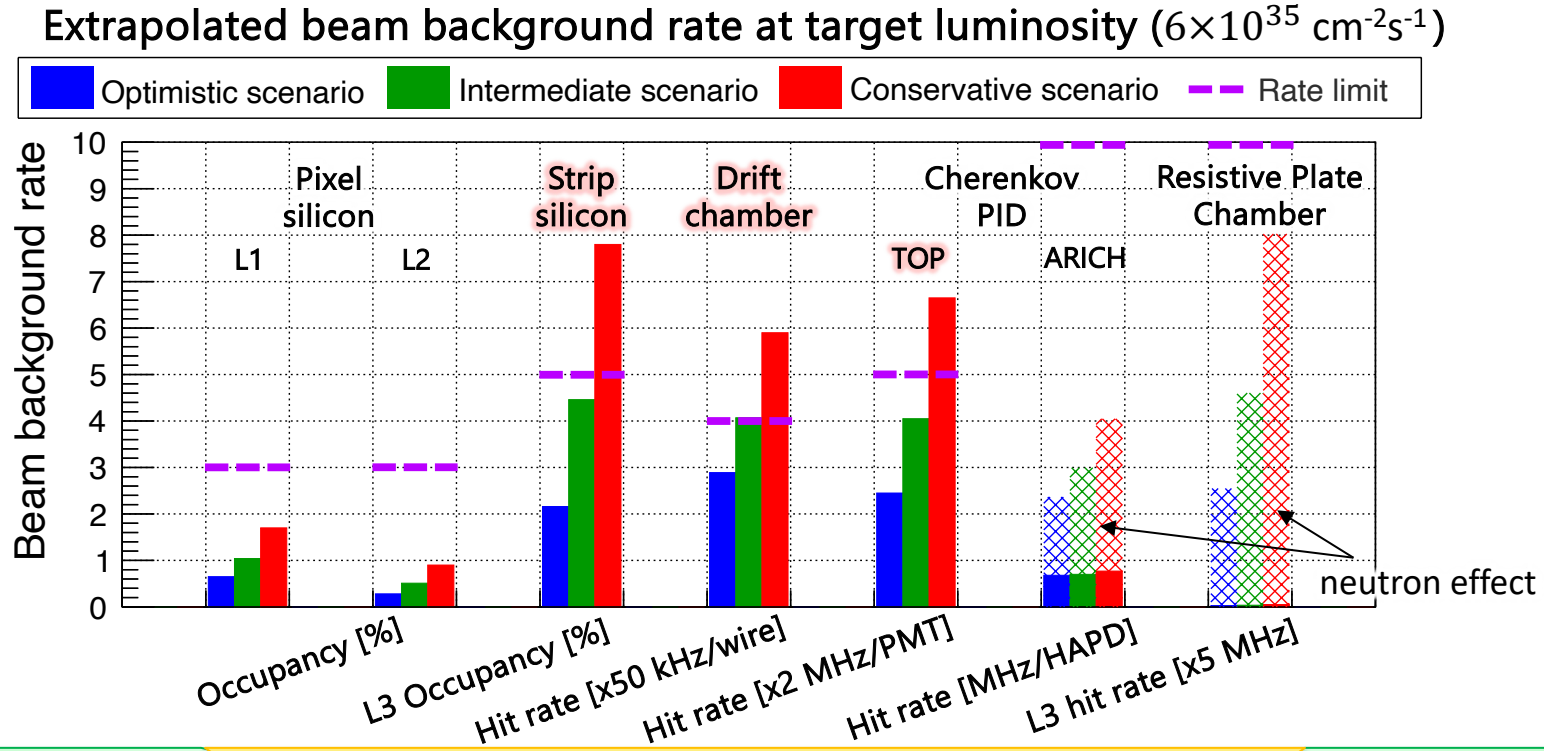


- Achievements as of July 2024
  - World record luminosity: 4.7×10^{34} cm^{-2}s^{-1}
  - Integrated luminosity: ~530 fb^{-1} (recorded)
- Targets
  - **~10-fold** in luminosity: 6×10^{35} cm^{-2}s^{-1}
  - **~100-fold** in integrated luminosity: 50 ab^{-1}

- **Additional long shutdown(s) under discussion to improve the SuperKEKB luminosity.**
  - LS2 in 2028 or later
  - Possible SuperKEKB upgrade: Redesign of Interaction Region (IR), emmittance reduction in injector, etc…

Beam-induced Background

- **Severe beam-induced background at high luminosity**
  - Secondary particles from beam-halo and radiative photon scattering in the IR material
  - Very low-momentum particles from beam collisions through two-photon process ($e^+e^- \to eeee$)
- **In future operation, background rates getting closer or reaching system limits.**
  - Tracking system (Strip Si + drift chamber CDC) and central PID (TOP) are main concerns.
- **Also, pixel Si detector is damaged due to sudden beam loss. Resulting in ~2% dead area.**
  - The cause and the measures are being understood, such that frequency could be reduced in future.



Belle II detector upgrade

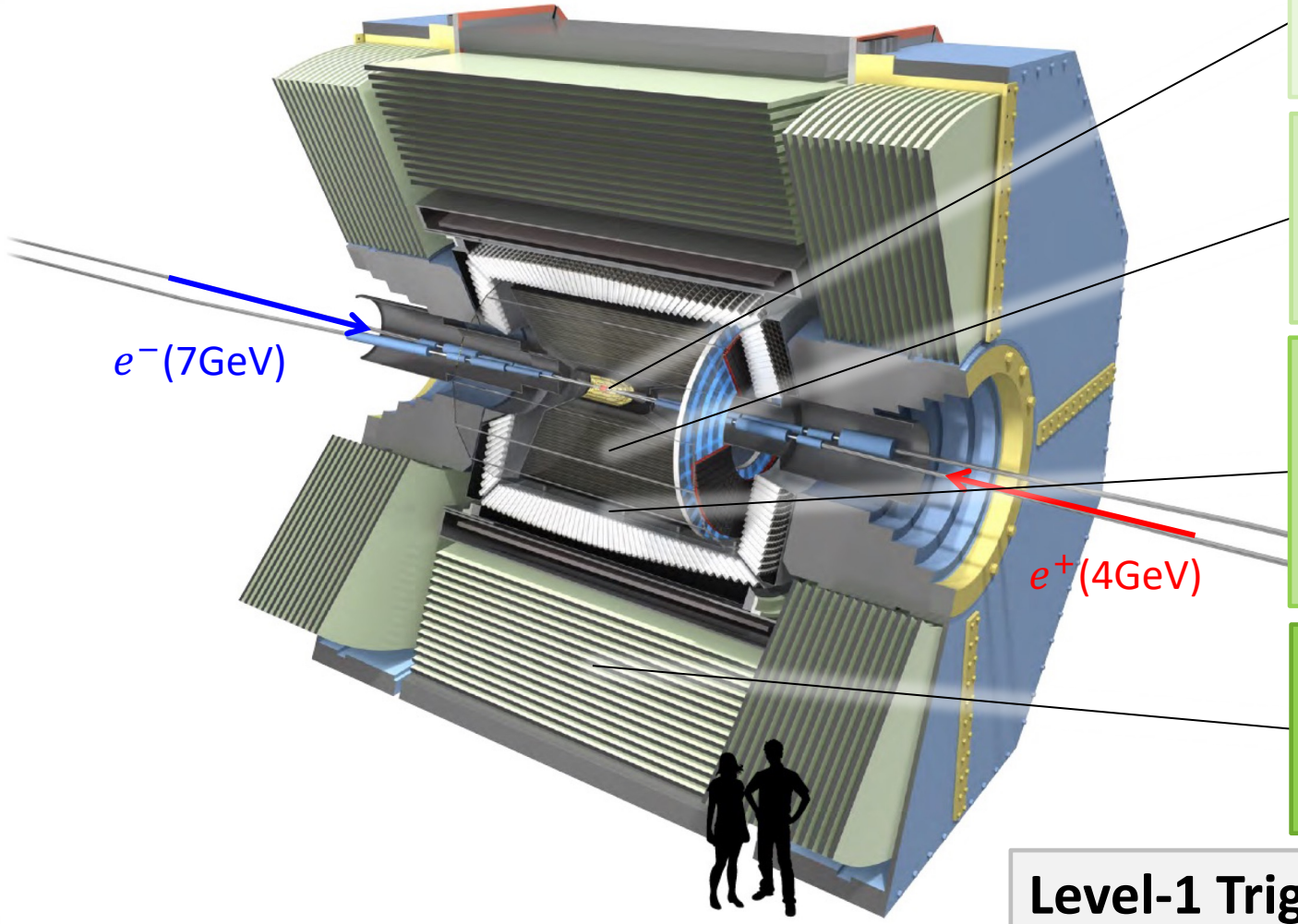
- **Motivations for the detector upgrade**
  - Improve detector robustness and tolerance against beam-induced backgrounds
    - for stable operation with sufficient performance at higher luminosity operation
  - Improve physics performance
    - get more physics per luminosity → effectively increase luminosity

- **Framework Conceptual Design Report (FCDR) is published.** [arXiv:2406.19421]
  - Summarizes various possible detector upgrade plans

- **The upgrade plans are categorized into two different timescales, based on the progress of each R&D and its urgency.**
  - Middle-term upgrade → during LS2 (2028 or later)
  - Longer-term upgrade → beyond LS2 (~mid-2030s)

Possible Belle II detector upgrade in LS2

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



Vertex detector

- Fully-pixelated CMOS DMAPS detector

Drift chamber (CDC)

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

Particle identification

Barrel: Time-Of-Propagation counters (TOP)

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

K_L/μ detector (RPC + scintillator)

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

Level-1 Trigger

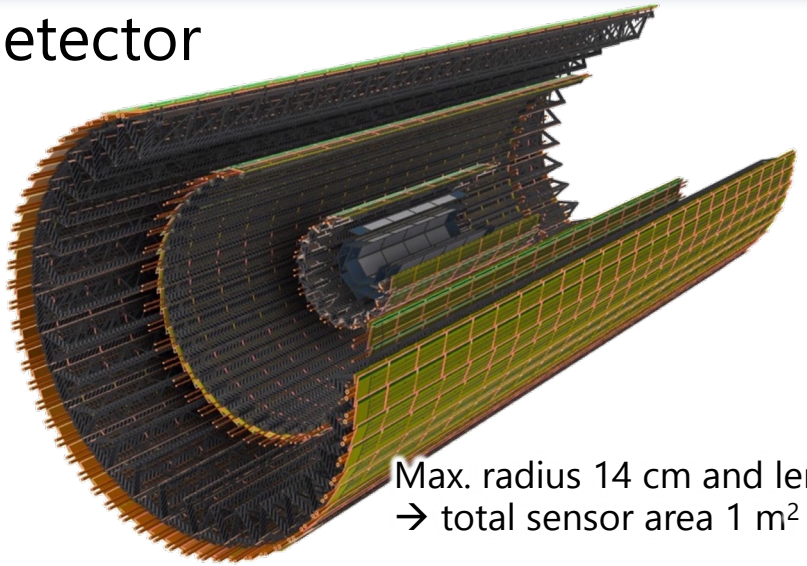
- Replace electronics with latest technology to allow more sophisticated ML algorithm and more data bandwidth

Upgraded vertex detector: VTX

talk at 15:57 on Jul 18 by A. Kumar

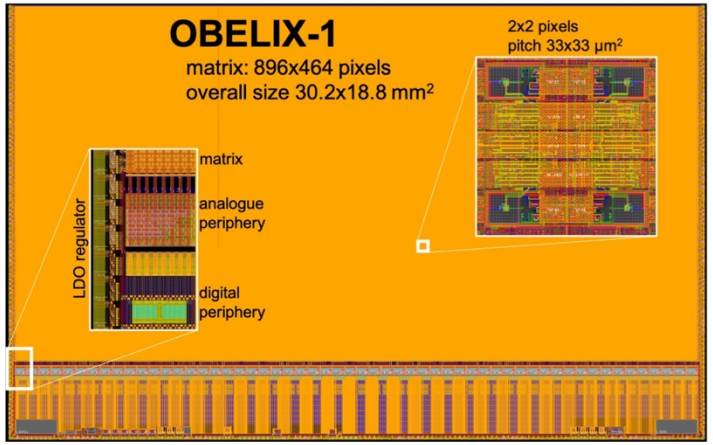
- **Fully-pixelated CMOS MAPS detector with simple design and light support**
  - Cope with more significant background rates
  - Improve low-momentum tracking and impact parameter resolution
- **5 layers with straight ladders**
  - inner 2 layers: self-supported, cooling method under study
  - outer 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.

VTX detector



Max. radius 14 cm and length 70 cm
→ total sensor area 1 m^2

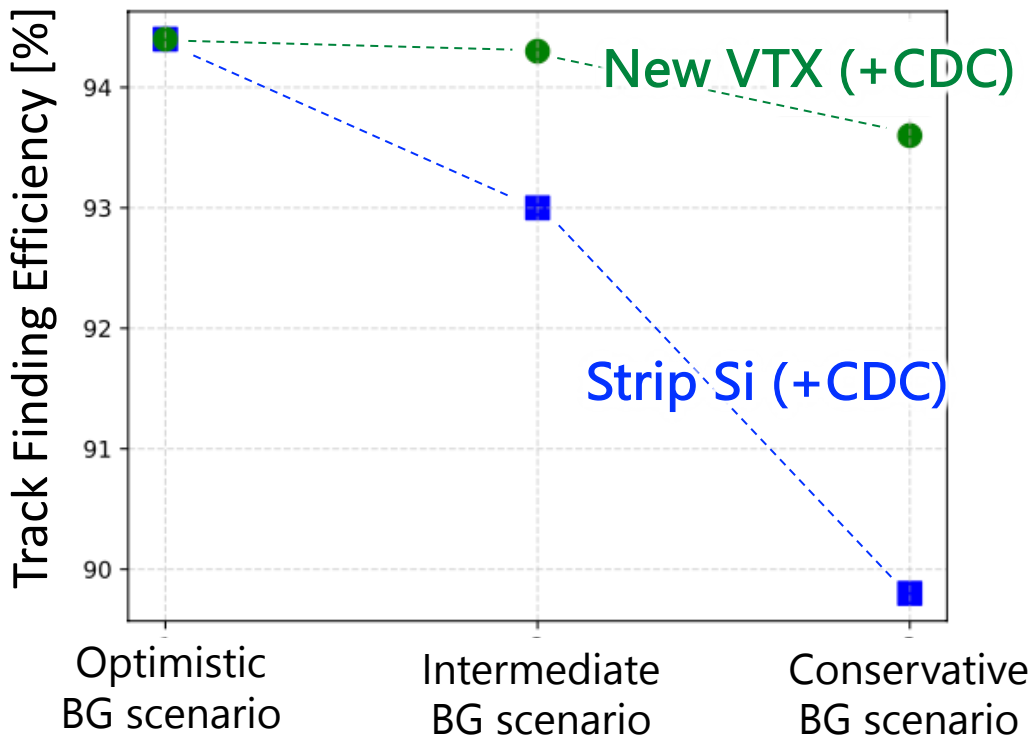
OBELIX prototype sensor



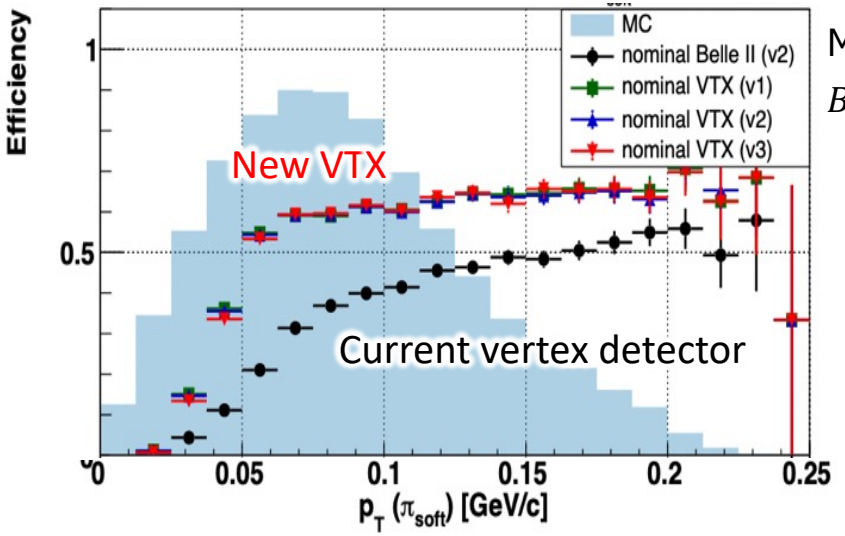
	Design/Target
Pixel pitch	33 µm
Sens. area	~30x16 mm^2
Sens. thickness	< 50 µm (sensitive layer < 30um)
ToT	7-bit
Integration	50 to 100 ns
Power	< 200 mW/cm^2
Radiation tolerance	1 MGy 5×10^{14} n_{eq}/cm^2

Improvement in Tracking Performance with VTX

Track Efficiency [%]



Slow-pion tracking efficiency



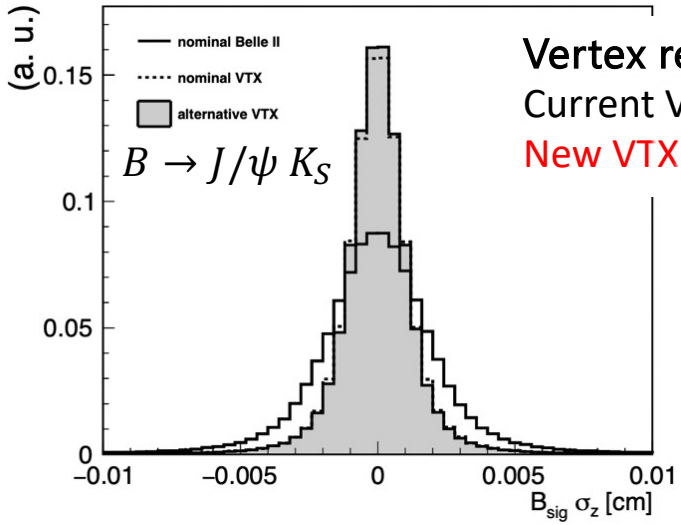
MC samples:

$B^0 \to D^{*-} l^+ \upsilon$

↳ $\bar{D}^0 \pi^-_{soft}$

↳ $K^+ \pi^-$

Residual of B decay vertex



Vertex resolution

Current VXD: ~23um

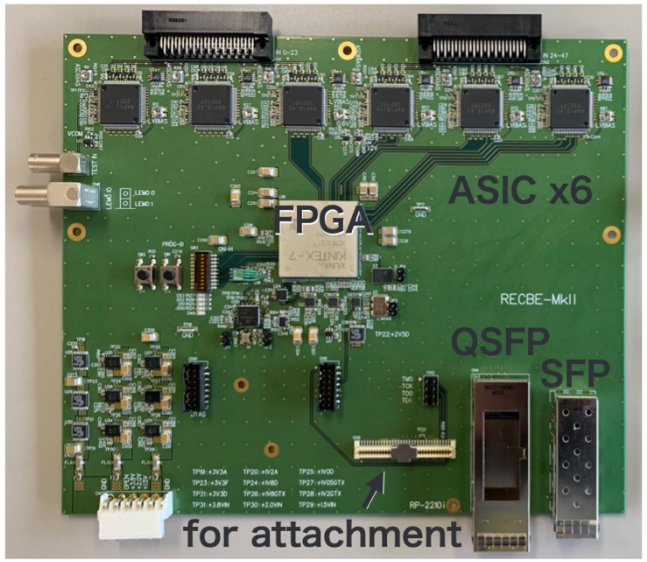
New VTX: ~14um

- Recover the tracking efficiency degradation under a high background environment
- ~70% improvement in efficiency for low-momentum pions
  - Slow-pion is essential for D* reconstruction required in many "bread-and-butter" modes of Belle II (e.g $B \to D^* l\upsilon$, $D^* \tau\upsilon$)
- ~35% better B decay-vertex resolution in $B \to J/\psi\, K_S$

Central Drift Chamber (CDC)

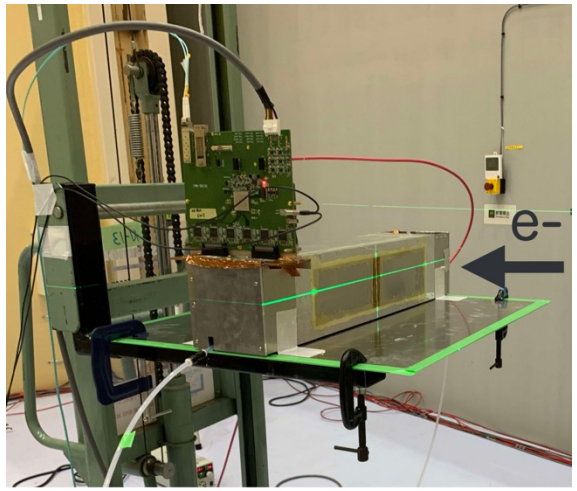
- **New front-end board with better cross-talk tolerance, power consumption, and radiation hardness**
  - New 8-channel 65nm front-end ASIC (TDC+flash-ADC)
    - 6 ASICs per board
  - Rad-hard optical module QSFP (for data transmission to trigger/DAQ)
    - Total dose: ~1kGy, total neutron fluence: 1.0×10^{12} n/cm^2
    - Candidates of QSFP are selected through γ and n radiation hardness tests

Prototype new front-end module

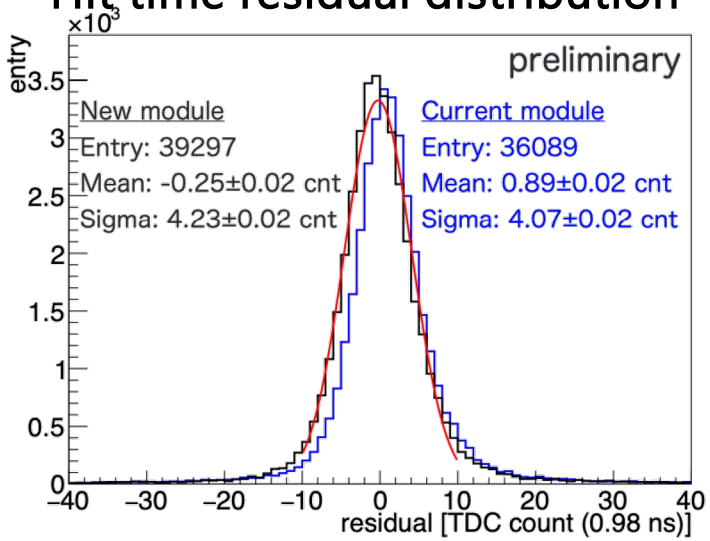


- **Performance characterization with 3-GeV electron beam**
  - Observed comparable performance to the existing front-end.
  - But, slightly worse time resolution. Further investigations are ongoing.

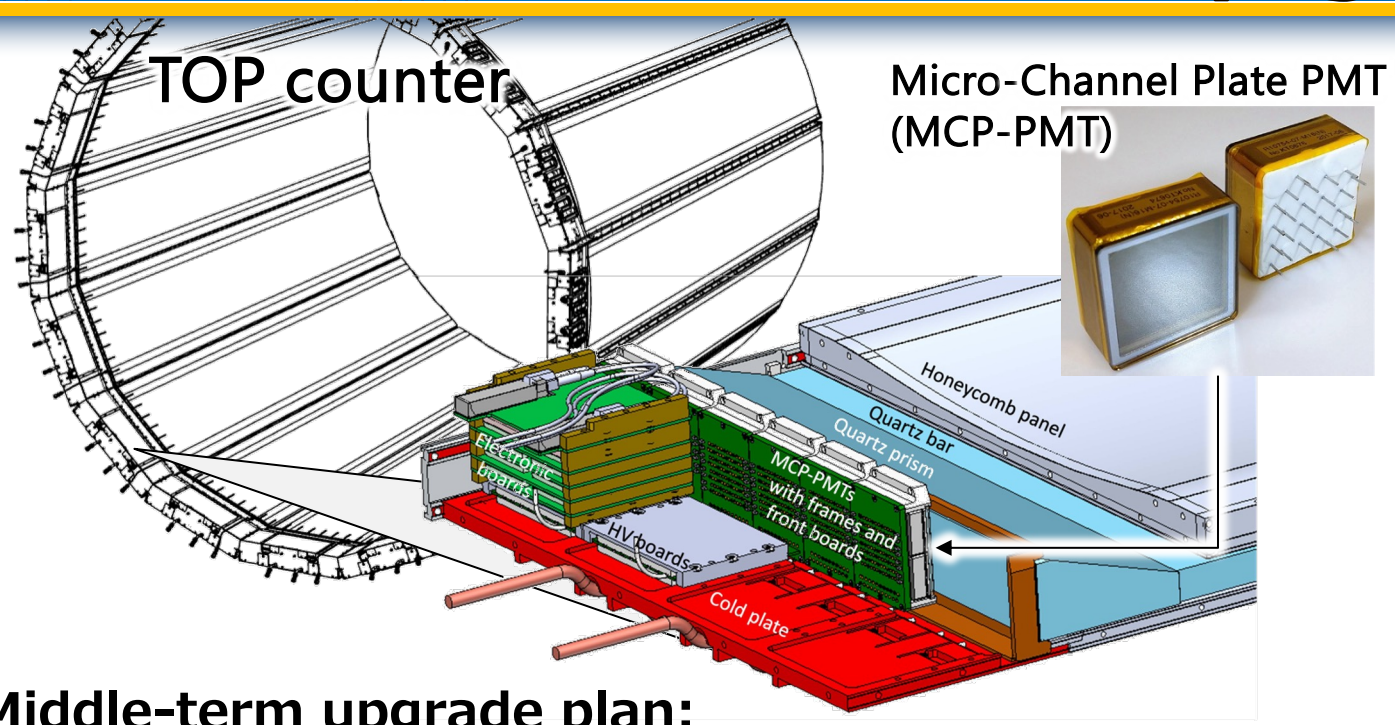
Electron beam test at KEK

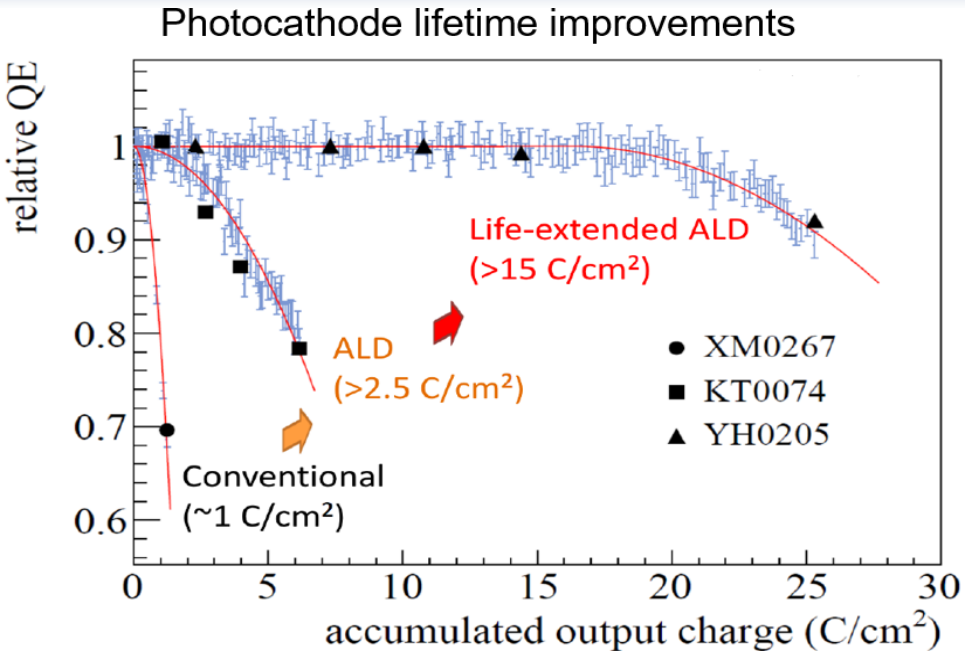


Hit time residual distribution



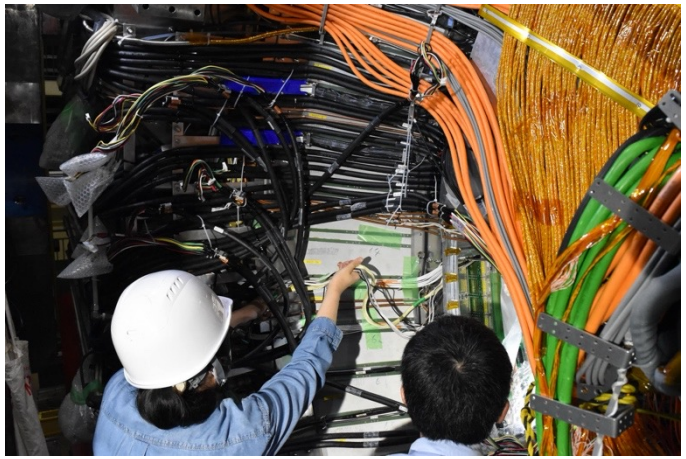
Central PID: Time of Propagation counter (TOP)





Middle-term upgrade plan:

- Complete replacement of MCP-PMTs with lifetime-extended ALD type
  - Better accumulated-charge tolerance, necessary to survive until the end of Belle II
  - At the moment, ~50% of PMTs are still ALD type with a shorter lifetime.
- New compact front-end boards
  - Waveform Digitizer ASoC: No need for high-end FPGA w/ complex process
  - → Less power consumption (lower T for smaller QE degradation of PMT) and fewer SEU



Level-1 Trigger

Next-generation Universal Trigger (UT) board: UT5

UT3
Xilinx Virtex-6
GTX, GTH

UT4
Xilinx UltraScale
GTH, GTY

UT5
Xilinx Versal
(SoC FPGA)
GTY, GTM

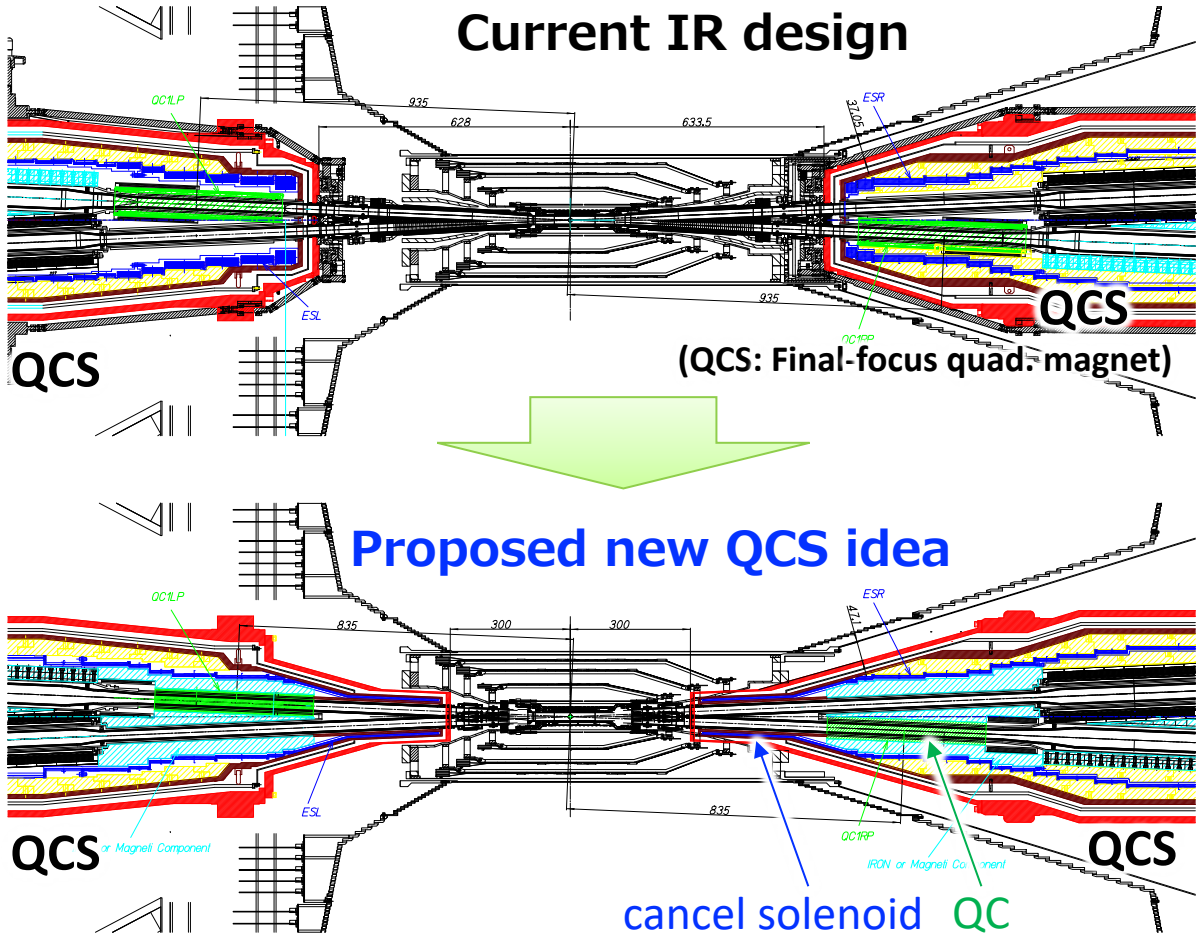
UT generation	UT3	UT4	UT5
Main FPGA (Xilinx)	Virtex6 XC6VHX380-565	Virtex Ultrascale XCVU080-190	Versal
Sub FPGA (Xilinx)	––	Artex7	Artex7, Zynq
# Logic gate	500k	2000k	8000k
Optical transmission rate	8 Gbps	25 Gbps	58 Gbps
RAM	––	DDR4	DDR4, UltraRAM
# UT boards	30	30	10
Cost per a board (k$)	15	30	50
Time schedule	2014-	2019-2026	2024-2032

- Offers improved background rejection with more sophisticated trigger algorithms
  - Large DSP and AI engine: machine-learning-based trigger logic
  - High data-rate bandwidth: broader hit information from detectors available
    - Central-drift-chamber trigger: More TDC and ADC information from all wires
    - EM calorimeter trigger: Higher granularity hit information for cluster shape reconstruction and mitigation of pile-up
  - New vertex-detector trigger: Additional background suppression in track trigger.
    Also, offers possible detection of long-lived particles.

Possible longer-term upgrade (~mid-2030)

- **New superconductive final-focus quad. magnets (QCS) to improve luminosity**
  - Nb_3Sn wire for compact magnet with sufficient field strength
    - Current density: ~3000A/mm^2
    - Filament size: < 5um (c.f. LHC filament ~ 50um)
    - R&D ongoing
  - Vertex detector has to be also replaced with a modified design.

- **Longer-term upgrade ideas in detector**
  - New tracking chamber w/ pixel Si and/or gas
  - PID counters: photosensor upgrade
  - EM calorimeter: replace CsI(Tl) crystals with pure CsI, APD readout, add pre-shower detector



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

Chiral Belle proposal

talk at 16:00 on Jul 18 by M. Roney
("Quark and Lepton Flavour" session)

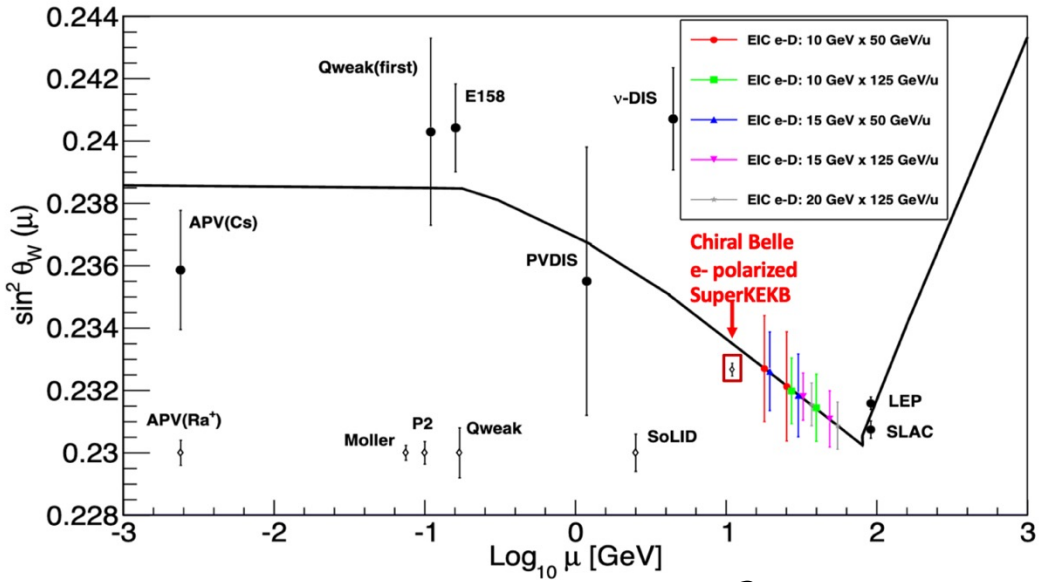
Chiral Belle:

SuperKEKB e^-e^+ collisions **with polarized e^- beam**

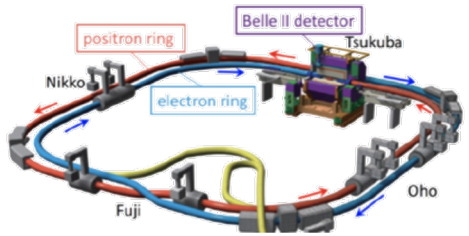
Open new and unique precision physics programs:

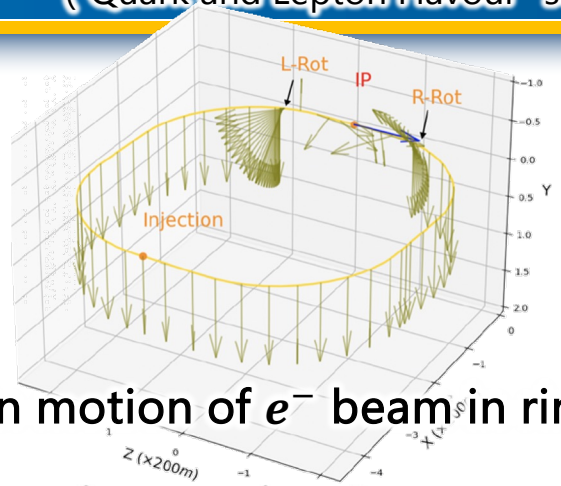
- Precision measurement in EW neutral current coupling sensitive to new physics e.g. light Z_{dark}
- Tau g-2 (precision at ~10^{-5} level)

Adapted from Zhao et al., "*Neutral Weak Interactions at an EIC*" *Eur.Phys.J.A* 53 (2017) 3, 55

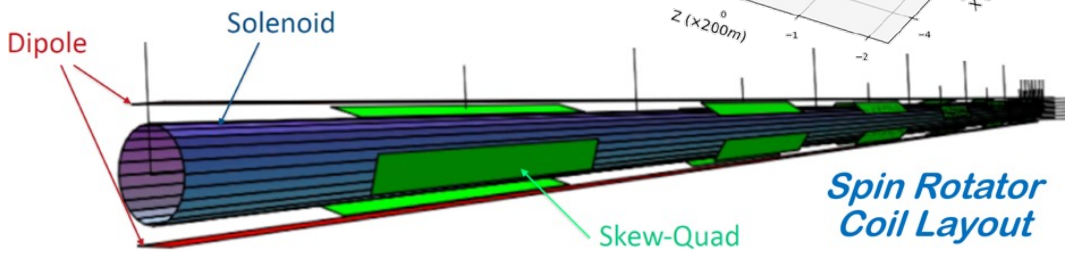


Precision weak mixing angle $\sin^2\theta_W$ to ±0.0002 with 40 ab^{-1} and 70% e$^-$ beam polarization





Spin motion of e^- beam in ring



- **Required upgrades**
  - Low-emittance polarized electron source
  - Spin rotator magnets
    - to rotate the spin before and after IP
  - Compton polarimeter
    - for online beam polarization measurement
- Tests for the polarized e^- source and polarization measurement are investigated.

Summary

- **Belle II detector upgrades are essential for the future high luminosity operation**
  - Improve the detector robustness and tolerance against beam-induced backgrounds
  - Improve the physics performance

- **The framework of the Belle II detector upgrade in middle-term and long-term are summarized in Framework Conceptual Design Report (FCDR), which is now published.** [arXiv:2406.19421]
  - Candidates of upgrades during LS2:
    Vertex detector, drift chamber (electronics), Time-of-Projection counter (PMT, electronics), Resistive Plate Chamber, and Level-1 trigger electronics
  - Longer-term plan: new QCS and larger-scale detector upgrade
  - Chiral Belle: extends the Belle II physics reach

- **Detailed LS2 plan is under discussion and will be decided soon for maximizing the physics production.**

backup

Belle II Collaboration

Asia	473
Saudi Arabia	7
Australia	34
China	109
India	61
Israel	9
Japan	182

South Korea	36
Malaysia	1
Vietnam	5
Taiwan	30
Thailand	4
Turkey	5

America	174
Canada	43
Mexico	11
USA	120

28 countries/regions
122 institutions
1193 members

As of July 2024

Europe	546
Armenia	5
Austria	24
Czechia	7
France	59
Germany	236
Italy	112

Poland	8
Russia	36
Slovenia	25
Spain	7
Sweden	5
Ukraine	7
UK	4

K_L/μ detector: Resistive Plate Chamber (RPC)

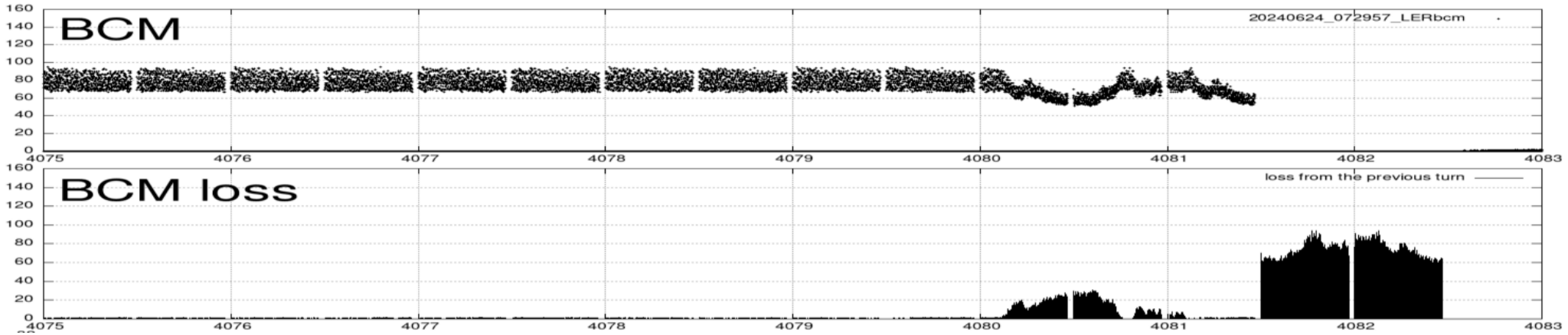
- **Option-1: Replace RPCs with scintillator+SiPM**
  - Better hit rate capability
  - Fast timing (~100ps) gives K_L momentum resolution via TOF (13% p resolution at 1.5 GeV)
    - Physics impact still under study
  - 6x6mm^2 SiPM combined with a high-speed and low-noise preamplifier
  - Cosmic-ray test confirmed 90ps resolution of the test module with 1m long scintillator.

- **Option-2: Change RPC operation from streamer to proportional mode**
  - Avoid blinding from localized discharge by streamer to mitigate possible efficiency drop due to high background neutron flux in future.
  - Require new in-line preamplifiers at the detector-panel faces to cope with smaller charge.
  - R&D tasks
    - Find a suitable gas mixture and operating point for HV for high efficiency and low streamer probability. Introduction of SF6 is being studied.
    - Amplification front-end R&D. Using a method similar to one applied for ATLAS RPC using a new SiGe preamp, we expect a rate capability of approximately 10Hz/cm2 , which is adequate for the expected future background rate.

DOI: 10.1088/1748-0221/8/01/P01003

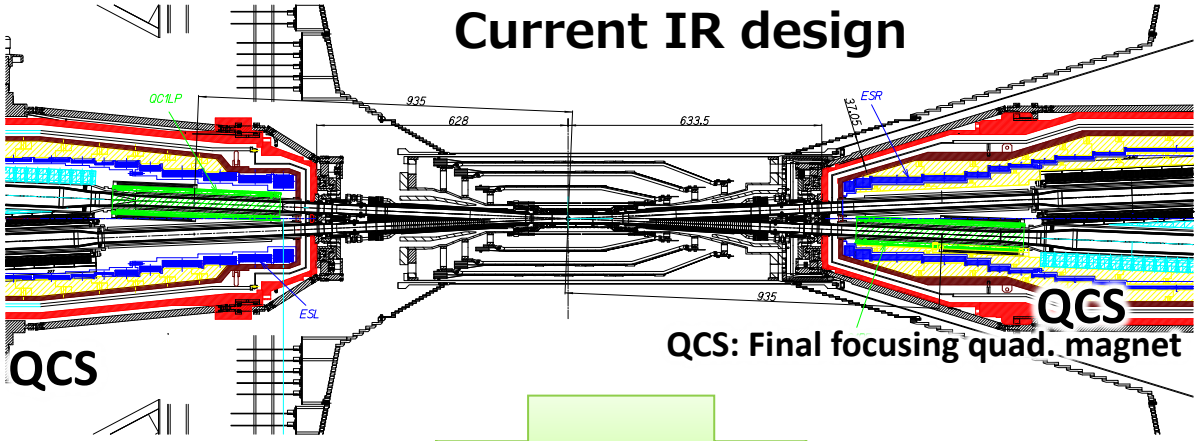
Sudden Beam Loss

- **What is "Sudden Beam Loss"**
  - Significant beam charge loss (> a few %) that occurs suddenly within only a few turns without any precursory phenomena.
- **Such large beam loss damages the pixel detector and the collimator, and causes the quench of the superconductive magnets.**
- **The cause of SBL is being understood.**
  - From the observations of the vacuum burst, the study of beam-pipe knocking and the measurement of bunch-by-bunch orbit, a strong suspect is that disturbance of the beam started in specific beam pipes with electrodes for the electron cloud mitigation. Dust or discharge in the beam pipe.
  - Measures for the SBL will be applied during the summer shutdown.



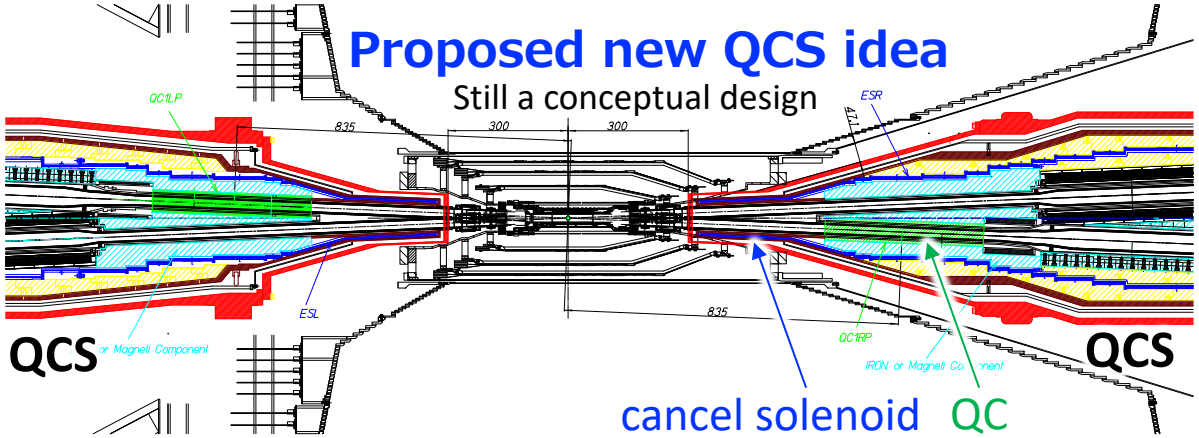
Machine upgrade option: Interaction Region

Current IR design



Proposed new QCS idea

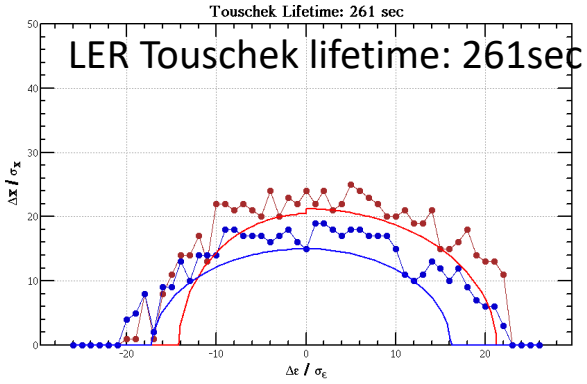
Still a conceptual design



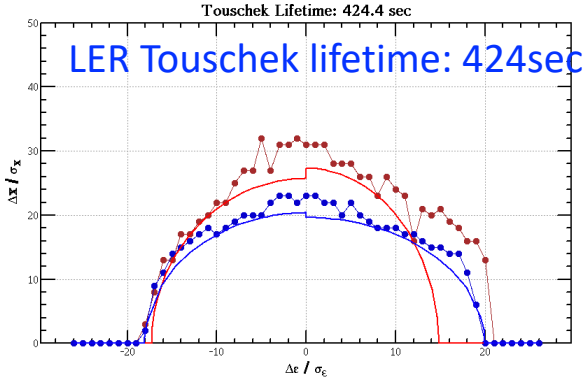
- Longer LER Touschek lifetime
- Reduction of chromatic X-Y coupling in IR
- Straightened beam orbit in IR

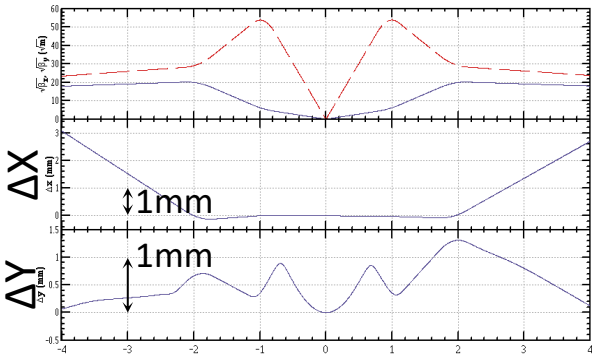
Gain in luminosity is to be estimated.

Beam orbit in IR

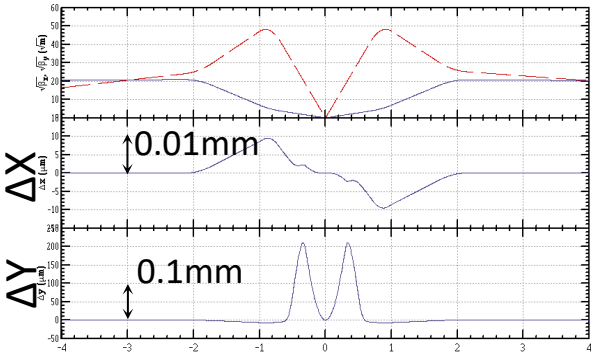


improve lifetime





straightened orbit



s [m]

Improved chromatic X-Y coupling in IR

$\partial R1/\partial\delta$	$\partial R2/\partial\delta$	$\partial R3/\partial\delta$	$\partial R4/\partial\delta$
-8.9×10^{-3}	$+4.0\times10^{-3}$	$-5.0\times10^{+1}$	$+2.9\times10^{+1}$
$+2.3\times10^{-5}$	-6.0×10^{-6}	-4.4×10^{-2}	$+5.5\times10^{-3}$

Aging effect in drift chamber (CDC)

- **~6% gain drop with an accumulated charge in a wire of 1 C/cm is expected from extrapolation of test chamber measurement for Belle CDC.**
  - The study was done up to 0.16 C/cm and observed ~1% gain drop.
- **Accumulated charge in wires of drift chamber during Run 1**
  - Inner layer: ~0.1 C/cm
  - Outer layer: ~0.02 mC/cm
- **No siginificant gain drop is seen yet in Belle II.**