Belle II Upgrade

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On behalf of the Belle II collaboration
FTCF2025, Huangshan
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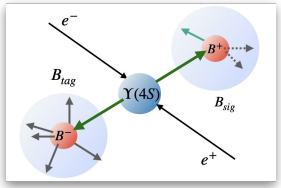
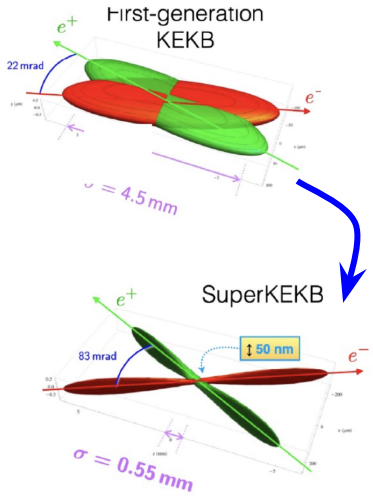
Outline

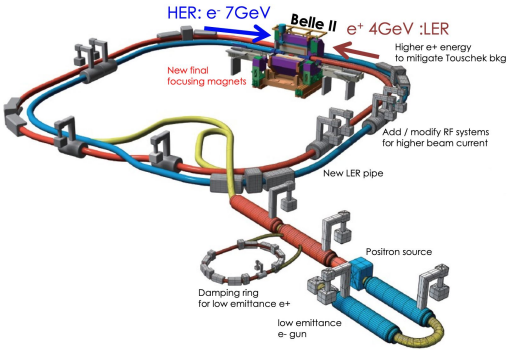
- SuperKEKB and Belle II
- Belle II upgrade:
  - Motivations
  - Upgrade of each sub-detector
    - VTX, CDC, ECL, KLM, TOP
  - Schedule and milestones
- Summary & outlook

The experiment

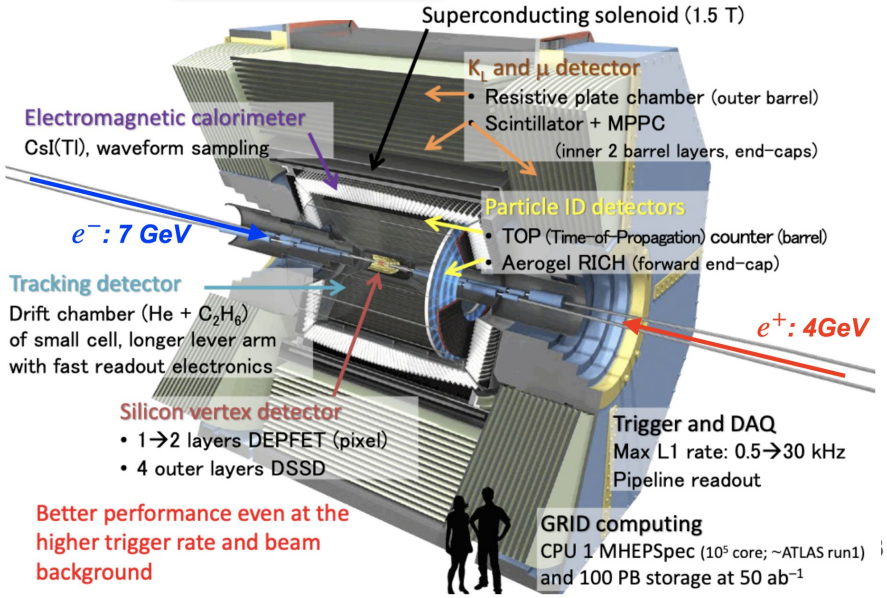
- ***SuperKEKB***
  - Asymmetric e^+(4GeV) e^- (7GeV) collider in Tsukuba, Japan
  - Operating around the *Y(4S)* resonance (√s = 10.58 GeV)
- ***Belle II***
  - A hermetic detector with known initial-state
  - (Production of BB at threshold) Low-physics background
  - Excellent tracking, PID and vertexing performance







New final focus magnets for **Nano-beam scheme**



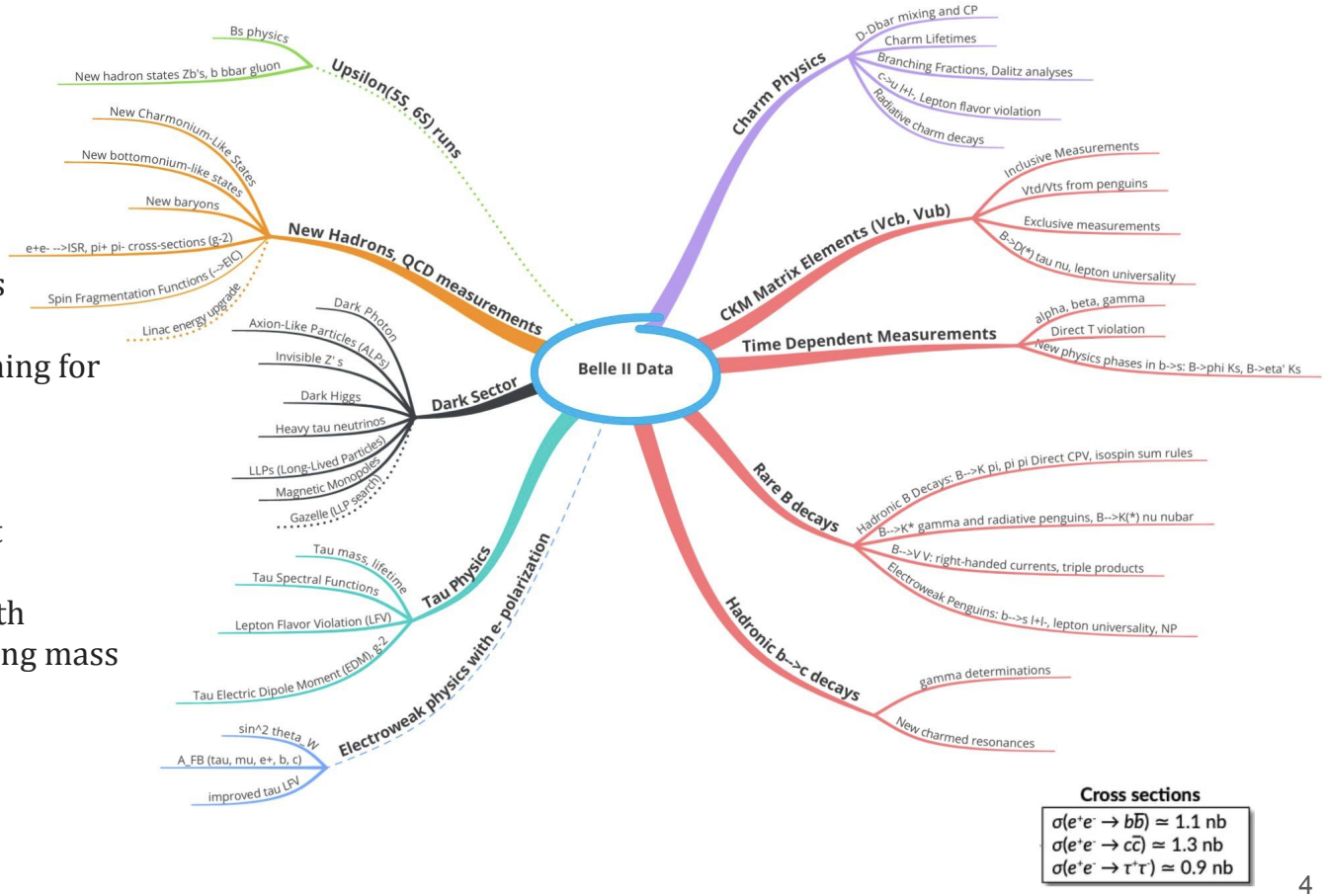
Belle II Physics

Primarily a **B factory**
But not only B physics!

- Also **tau, charm** factories
- Clean background for **spectroscopy** and searching for dark sector

Various type of analyses:

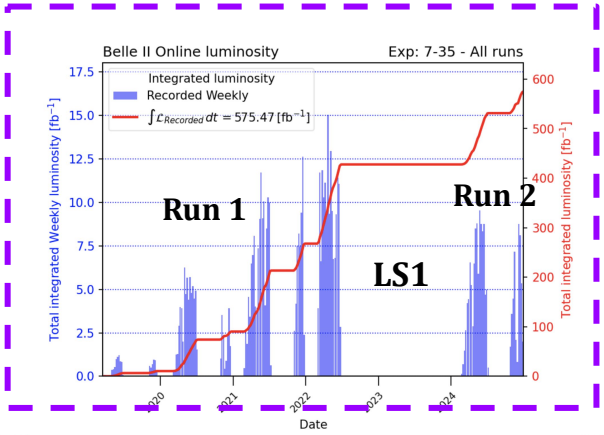
- Lifetime, time-dependent measurement
- well-suited for decays with missing energy and missing mass

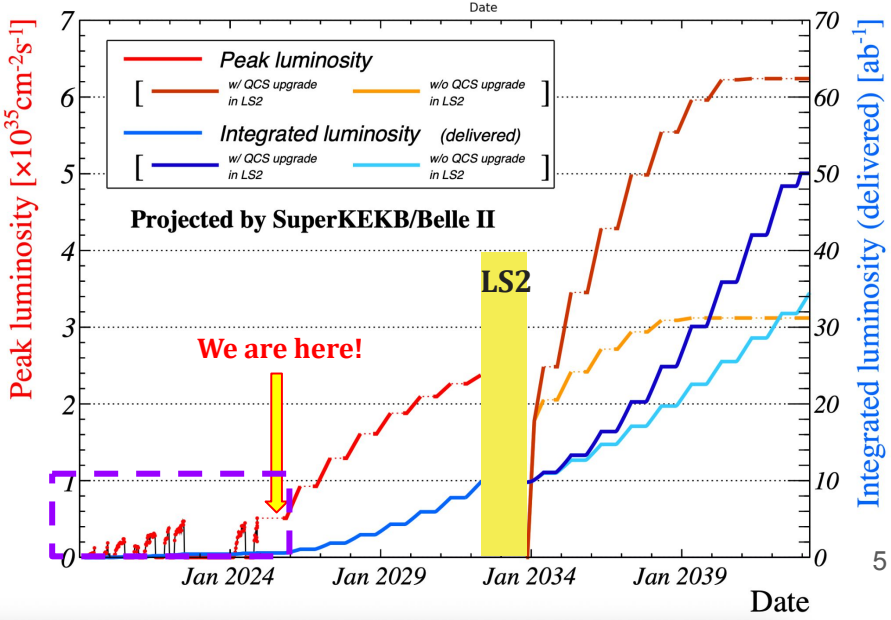


Status and prospect

- **575 fb^{-1} data collected so far:**
  - 2019: **Run 1** data collection started (365 fb^{-1})
  - 2022.06: world record L_{inst}: **4.7×10^{34} cm^{-2} s^{-1}**
  - ~2023.12 **LS1,** New Collimator, 2-layer PXD, etc
  - 2024: start of **Run 2**
  - 2024.12.27 : new L_{inst} record (Belle II off) 5.2×10^{34} cm^{-2} s^{-1}
- Plenty of physics results with the data collected so far

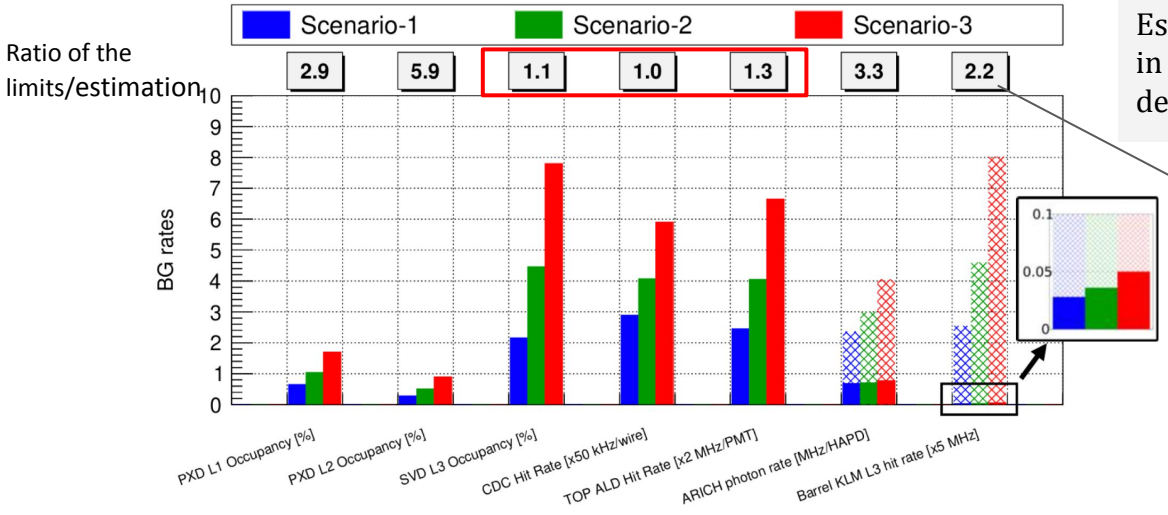
- **LS2 planned for a major upgrade: 2032**
  - Targeting higher L_{inst}: 6×10^{35} cm^{-2} s^{-1}
  - Ultimate goal: ~ 50 ab^{-1}
  - Upgrade & Redesign of the **Interaction Region (IR)**
  - Window for upgrades of the Belle II detector





Motivations

- New final focus quadrupole magnet system (QCS) to achieve the ambitious goal: $L_{inst} = 6 \times 10^{35}\ cm^{-2}\ s^{-1}$
- **Mechanical:**
  - Inner Region (IR) need to adapt to new QCS; New beampipe and innermost detector are required
- Severe beam background level:
  - Both single-beam and luminosity backgrounds will significantly increase (x5 for scenario-2)
  - Beam background reaching the limits of several sub-detectors: SVD, CDC, TOP



Estimation of expected beam background in 2032 with different scenarios for all the detectors (larger uncertainties):

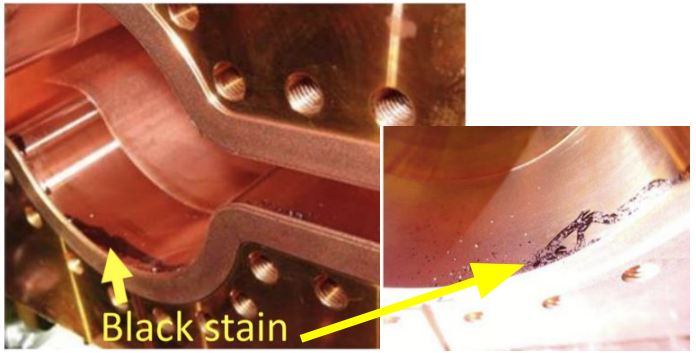
Safety margin using scenario-2: Ratio of the limits/estimation

amework Conceptual Design report (FCDR)
ttps://arxiv.org/html/2406.19421v2

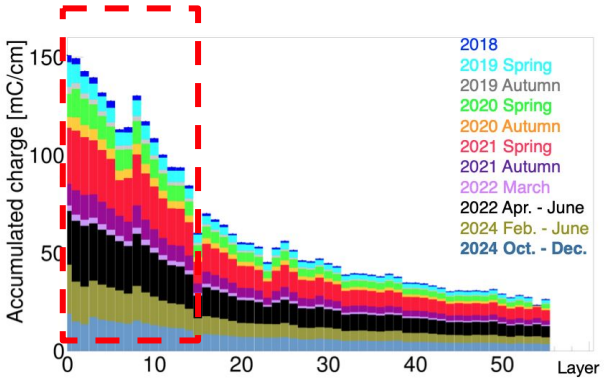
Motivations

Main issues during Run1/2:

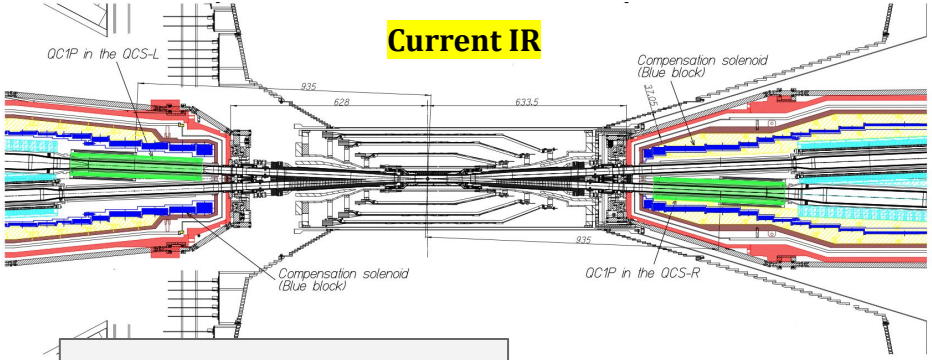
- **Sudden Beam Los (SBL): significant beam charge loss**
  - PXD2 was switched off for that (~2% damaged area by SBL), occasionally leading to quenching of Superconducting magnets
  - Attempts to understand the issue:
    - *Installed Knockers => SBL events decreased*
    - *Flipped clearing electrodes => no improvement*
    - Cleaned the black stains near flanges ***=> no more SBL from that location***
  - Faster beam loss detection and emergency shutdown implemented to protect detector
- **CDC aging issue:** (Carsten's talk on Tuesday)
  - Gain drop of 10-15% observed in the inner super layers
  - Various studies ongoing to understand the issue and evaluate the impact on performance
- **Beam-beam interaction** (short beam lifetime)
  - Upgrade of the IR



Identified as burnt silicon, most likely from the degradation of vacuum sealant (VACSEAL)



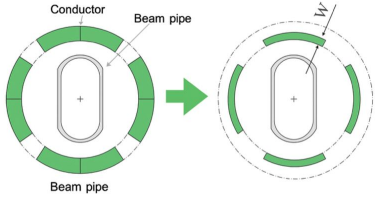
Upgrade of the IR



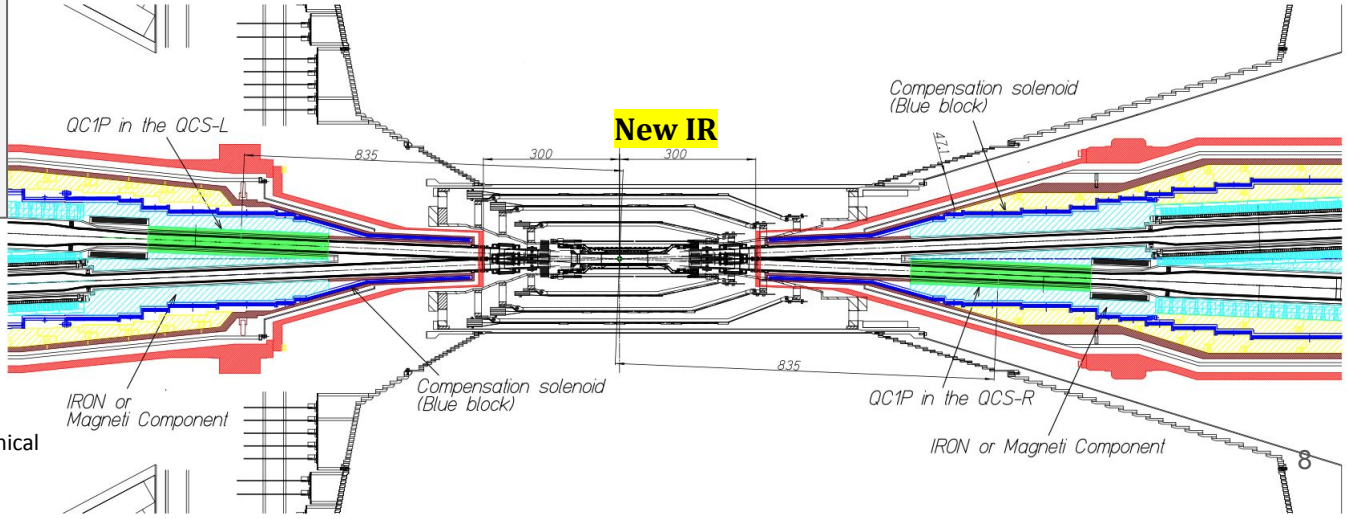
Cope with machine upgrade:

- Redesigned QCS to squeeze beams for higher L_{inst}
  - 100mm Closer to IP (on Z)
- IR region needs to adapt to the new QCS
- Potential new beampipe and innermost detector

Vacuum vessels of the cryostat
Liquid helium vessels
Tungsten radiation shields
Anti-solenoid coils
Magnetic yokes/shields
QC1P magnets

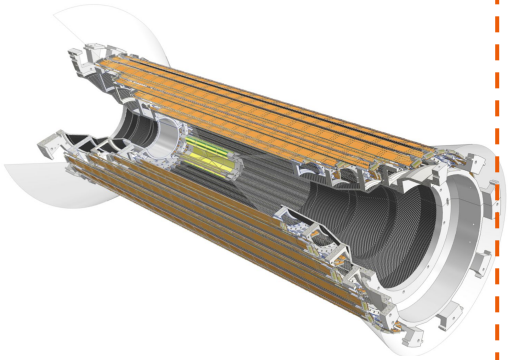


Thinner conductors will be needed to avoid mechanical interference between the two beam lines



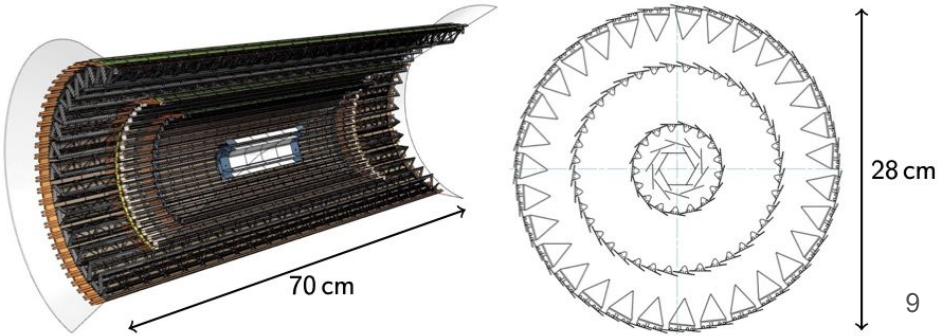
Vertex detector upgrade: VTX

- PXD + SVD ⇒ **new VTX**
- Key performance requirements for the upgrade:
  - Higher spatial and time granularity to cope with the harsh background condition
  - Spatial resolution: < 15 um
  - Low Material budget: 0.2% - 0.8% X/X_0 per layer for the inner and outer layers
  - Hit rates capability: up to 120 MHz/cm^2
  - Fast timestamping: capabilities in 50-100 ns
  - Power dissipation: < 200 mW/cm^2
  - Radiation tolerance (inner layer over 10 years operation): TID up to 1 MGy and NIEL of $5x10^{14}$ n_{eq}/cm^2



5-layer VTX Baseline

- A **5- or 6-layer** depleted monolithic active pixel sensors (DMAPS)
  - Radius: 14 mm ~ 140 mm
  - Improve low-momentum tracking and impact parameter resolution
  - TJ-Monopix2 is a good starting point

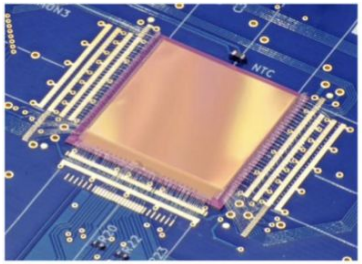


Vertex detector upgrade: VTX sensor

OBELIX sensor: Optimized BELLE II monolithic active pixel sensor

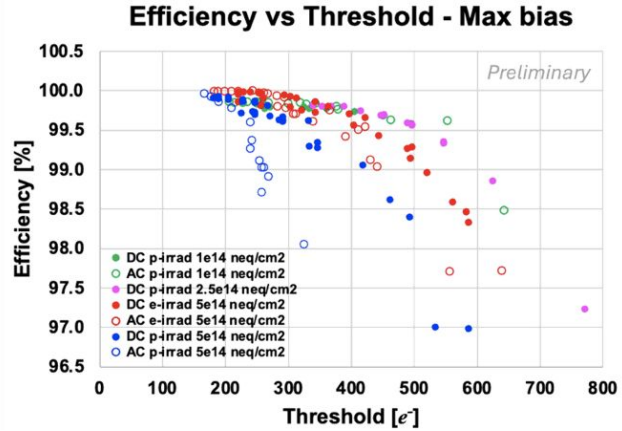
1. Derived from TJ-monopix2 (developed for the ATLAS inner Tracker upgrade)
   a. TJ 180 nm technology
   b. Pitch size: 33 um
   c. Time-stamping capability with 50ns resolution
   d. New digital periphery designed to be compatible with the Belle II trigger&DAQ system
2. Laboratory tests and test beam studies been performed (on TJ-Monopix2 as a reference)
   E.g. Irradiated TJ-Monopix2 beam test @March 2025
   -> operation temperature should < 40 °C; DC diode chosen for higher operation range

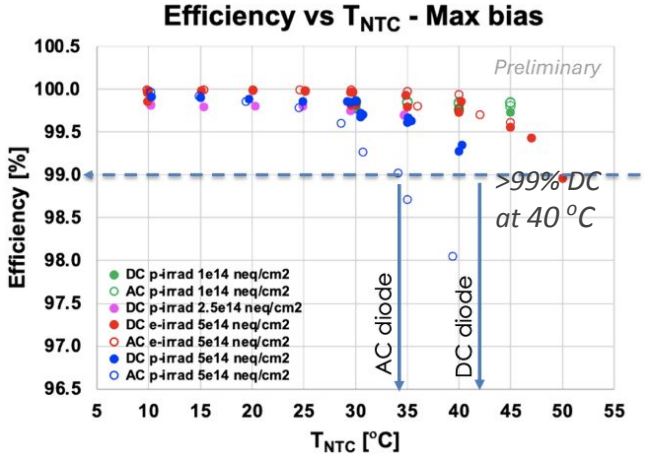
The DMAPS upgrade of the Belle II Vertex Detector

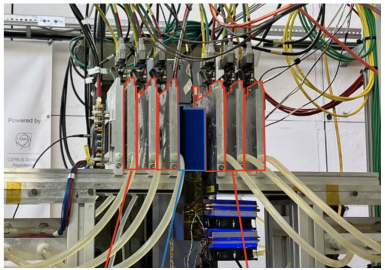


TJM2 sensor bonded on a test board

Triggerless readout with no memories in periphery



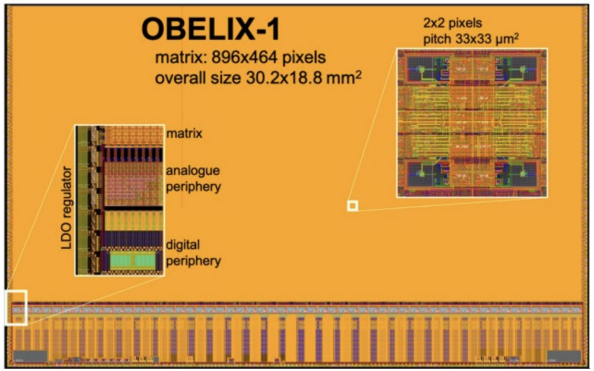




DESY, EUDET telescope. 4.2 GeV electron beam

Vertex detector upgrade: VTX

- Schedule :
  - **OBELIX-1:** New version in preparation
    - First review of OBELIX-1 design completed, addressing feedback in progress
    - Submission targeted for December 2025
    - First test starting in summer 2026
  - **OBELIX-2:** design starts in early 2026



More studies not covered today:

- Performance validation and comparison with current Belle II
  - Improved detection efficiency, impact parameter resolution and vertexing resolution *(more in backup slides)*
- DAQ development
- Cooling strategy and support method heavily studied
- Outer layer of VTX (oVTX) also potential input to the trigger

VTX upgrade is in good organization and had good progress already!

Slides

CDC upgrade

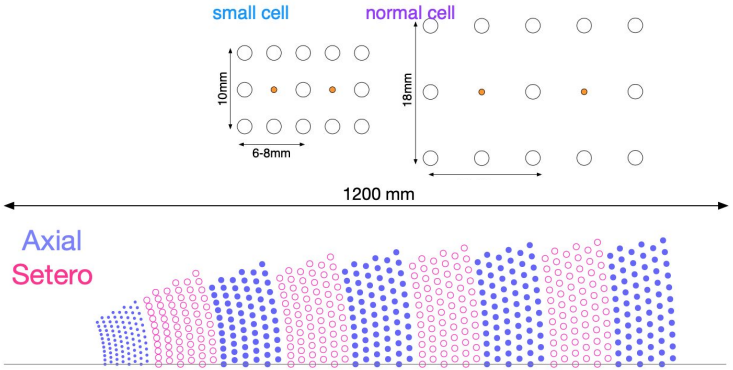
- Main tracking detector, also contributes to PID and Trigger
  - Covering radius from 160 -1130 mm
  - 56 layers in total, grouped into 9 super-layers
  - Gas: He:ethane = 50:50
  - Gas system improved for better monitoring/control of H_2O during LS1

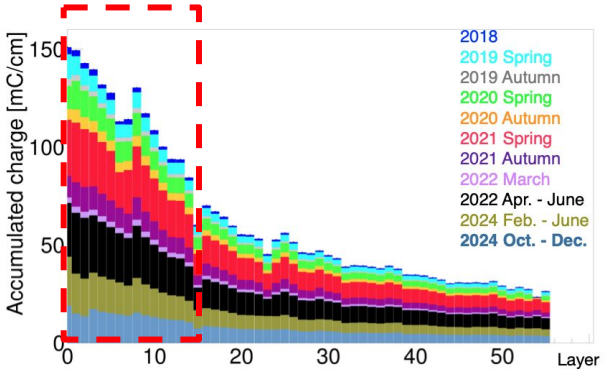
- Main issues during Run1/2: Aging issue
  - Active studies being done, with more planned in the future
  - Tests with e- beam line are scheduled
  - Collaborations established with detector experts work on this issue
  - Special dataset will be taken with lower HV for testing
  - One of the critical issue to be understood

⇒ CDC upgrade scenarios :

- Use of current CDC: ***IF*** the aging issue was understood
- New CDC with larger inner radius = current CDC without SL0 and SL1

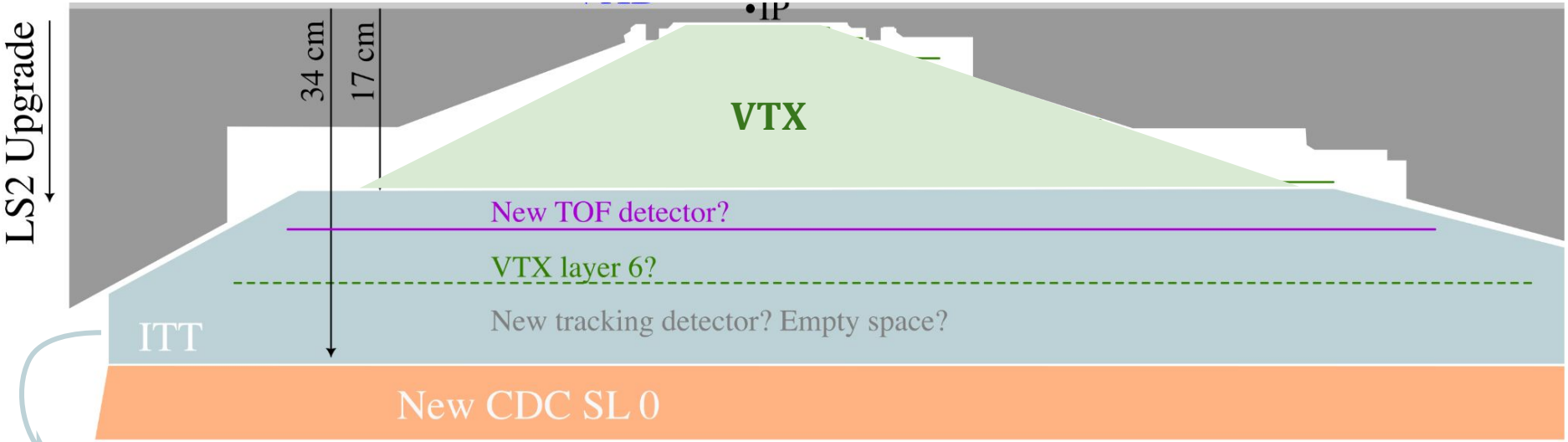
Others: New front-end board with better cross-talk tolerance, power consumption, and radiation hardness





Potential space for a Inner Timing Tracker (ITT)

If the new CDC scenario was chosen:



A Gap between VTX and new CDC => leaving tracks in this region uncovered
-low pt tracks

Proposal: Add a detector here!

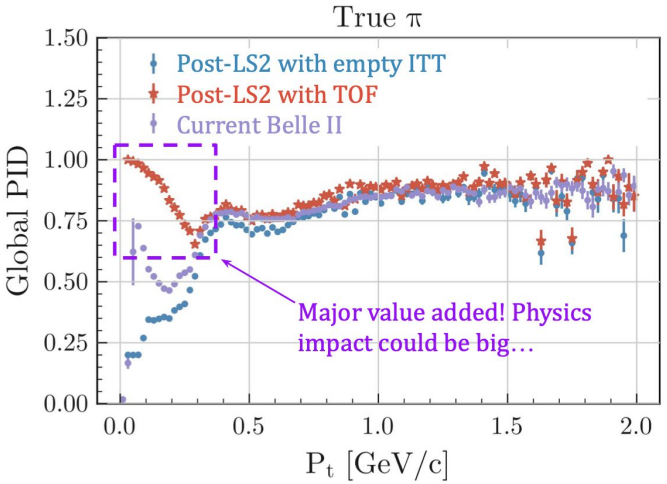
- Fast timing detector (PID based on TOF) -> ITT region (Inner Timing Tracker)

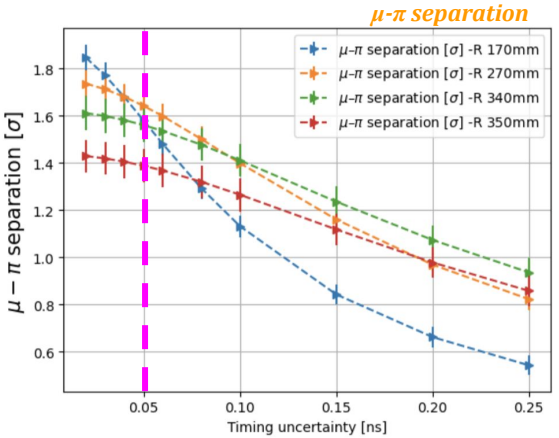
↪ Identify a fast timing , practical solution with acceptable material.

- Preliminary simulation to understand the performance

ITT

- Preliminary studies have been done to understand the potential benefits and requirements to the actual technology:
  - Promising PID improvement: TOF-base PID with 50ps timing resolution
  - Further studies to be done to understand the contribution to tracking and trigger





- Potential scenarios:
  - TOF: LGAD is an attractive option for its timing performance and well-established technology
  - Pure tracking layer

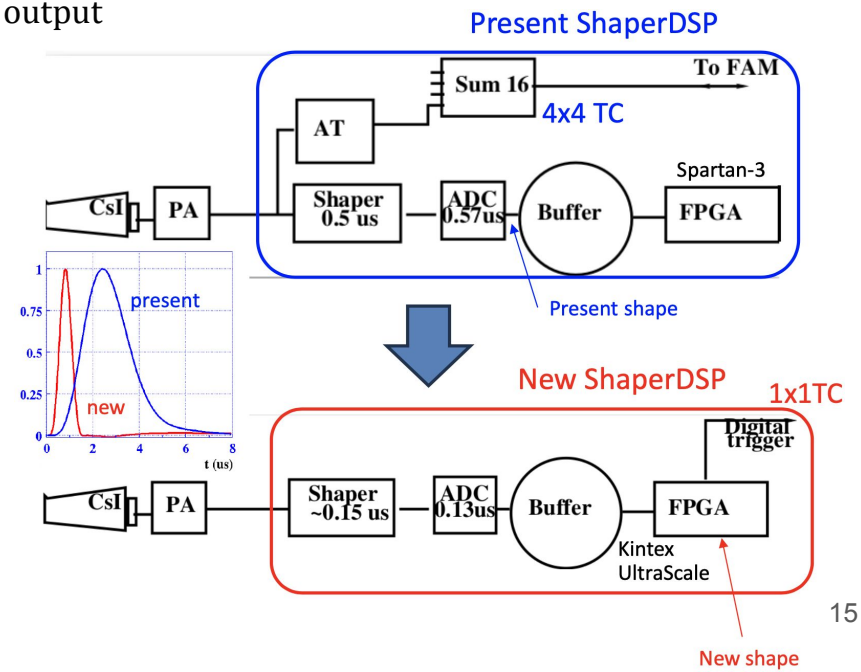
ECL upgrade

- Degraded energy and time resolution is expected with higher pileup noise (fluctuation of the beam background events overlapping the signal)
  - Efforts on benchmarking the impact with physics performance (ongoing): π^0 mass resolution, more channel to be explored
- New ShaperDSP(digitizer board): with faster shaping, higher sample-rate ADC, higher-granularity trigger cell, new FPGA and new optical trigger links and fully digital trigger output

- New electronics chain: new Trigger and DAQ chain for the new shaper
- Upgrade of the simulation to emulate the response of the new ShaperDSP

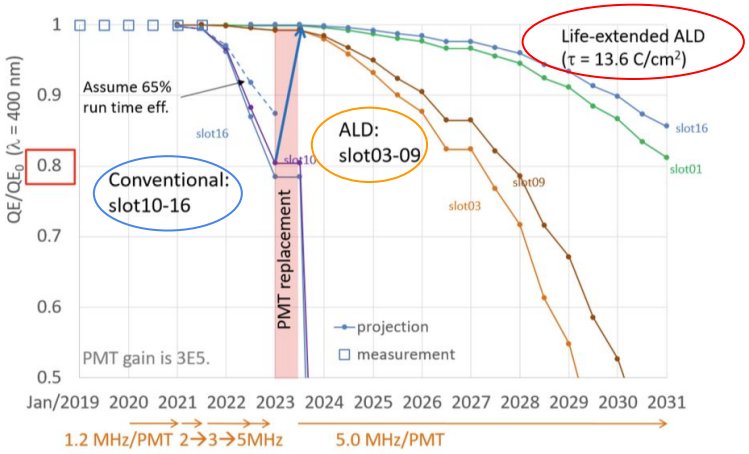
Status: Design of the first prototype of new ShaperDSP in progress

ECL upgrade talk



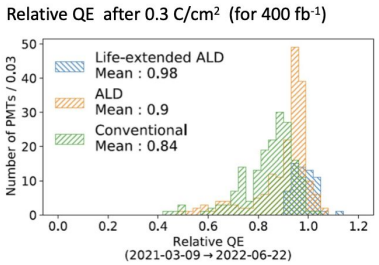
Time of Propagation counter (TOP)

- TOP Belle II main PID detector in the barrel region:
  - Operating smoothly and performing well without major issues
  - Evidence of accelerated aging of PMTs under high hit rate
    - Photocathodes are damaged by ions or residual gas in the tube
    - Atomic layer deposition (ALD) to mitigate this
  - Replacement of the Microchannel Plate photomultiplier Tubes (MCP-PMTs) has started to ensure stable operation throughout the entire experiment

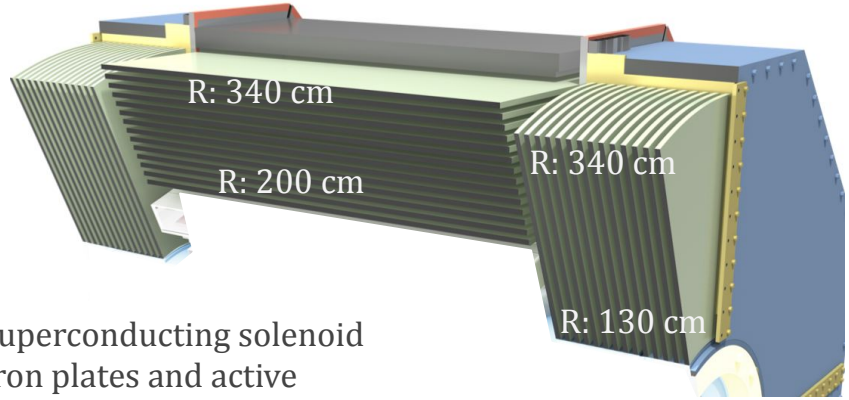


Middle-term upgrade plan:

- (primary)Complete replacement of MCP-PMTs with lifetime-extended ALD type: end of 2026
  - At the moment, ~50% of PMTs are still ALD type with a shorter lifetime
  - 220 new MCP-PMTs needed => production started already
  - Studies ongoing to understand the ageing differences
- (alternative) Further R&D to explore replacing MCP-PMTs with SiPMs



Upgrade of KLM

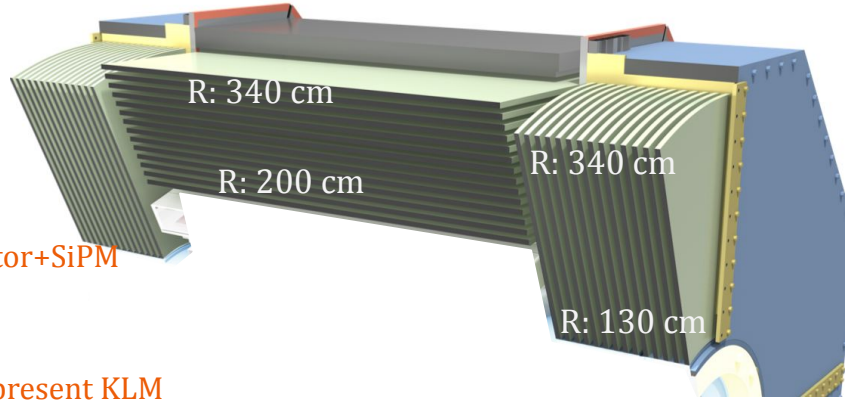


- Detection of K_L and μ:
  - Large-surface-area, thin planar detectors outside the superconducting solenoid
  - Consisting of an alternating sandwich of 4.7 cm thick iron plates and active detector elements
  - K_L detection had been essential for decays with missing mass

Two independent upgrade options under study:

- Option-1: Rebuild detector panels and replace all RPCs with scintillator+SiPM
- Option-2: Change the RPC operation mode from streamer to proportional mode

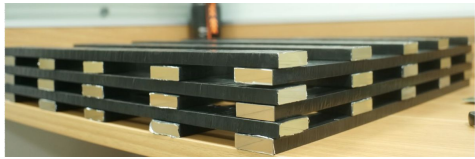
Upgrade of KLM



Two independent upgrade options under study:

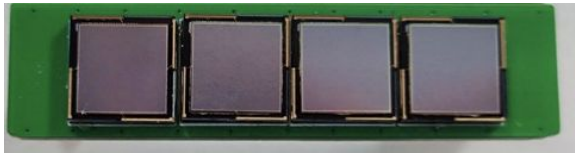
- Option-1: rebuild detector panels and replace all RPCs with scintillator+SiPM
  - Allow fast timing (~100ps):
    - Rejects out-of-time hits from the ambient neutron flux
    - Access to K_L momentum via TOF => not possible with present KLM
      - *2m flight length -> momentum resolution of ~13% for 1.5 GeV/c K_L*
  - Mechanically complicated: Requires roll-out of Belle II and opening of the forward and backward endcap doors
    - Access of all the panels will be challenging: beamline-supporting concrete shield blocks the bottom 3 sectors
    - Need to coordinate with other subsystems for installation
  - Status: A small prototype been built with 60 scintillators and will be ready for testing soon

Shiming's talk on Belle II KLM upgrade



30 scintillator strips. Array size: 50ccmm × 50ccmm × 6ccmm

- Option-2: Change the RPC operation mode from streamer to proportional mode
  - Keep the existing KLM detector panels untouched
  - New preamplifier required to operate in proportional mode

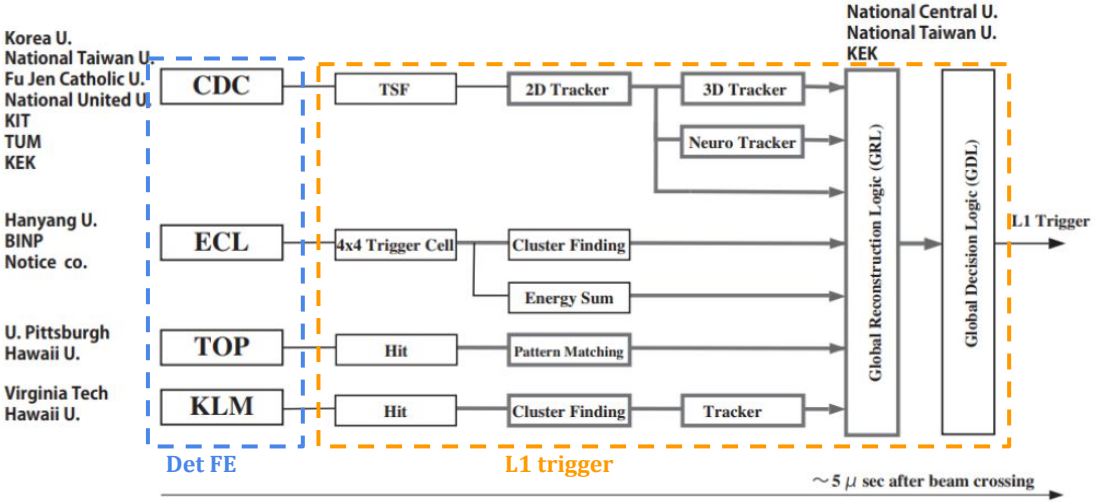


SiPM array

Trigger

- Current Hardware trigger: (L1 trigger)
  - CDC and ECL are taking a major role to trigger charged particles
  - KLM for muons and TOP for precise event time measurement
  - Matching of sub-triggers (GRL); final trigger decision
  - UT, universal trigger board, used by different sub-trigger commonly
- Further upgrades are needed to satisfy the high lumi environment:
  - Next-generation universal Trigger board: UT5 for ML and AI engine
  - Upgrade on both hardware and firmware

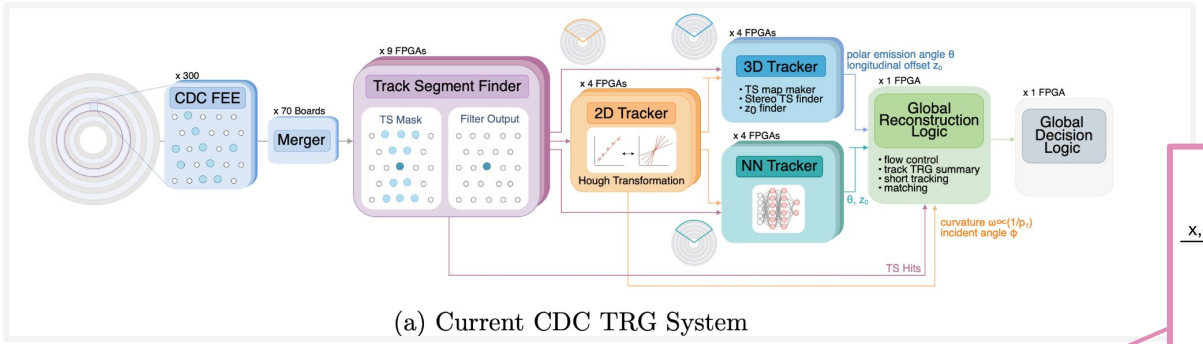
UT generation	UT3	UT4	UT5
Main FPGA (Xilinx)	Virtex6 XC6VHX380-565	Virtex Ultrascale XCVU080-190	Versal
Sub FPGA (Xilinx)	––	Artex7	Artex7, Zynq
# Logic gate	500k	2000k	8000k
Optical transmission rate	8 Gbps	25 Gbps	58 Gbps
# UT boards	30	30	10
Cost per a board (k$)	15	30	50
Time schedule	2014-	2019-2026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



Potential new inputs to L1-trigger:

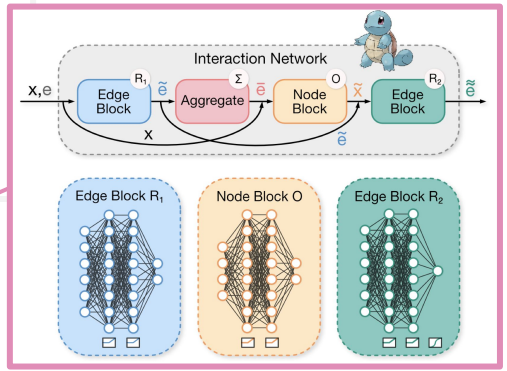
- New VTX and ITT as the input to L1 trigger

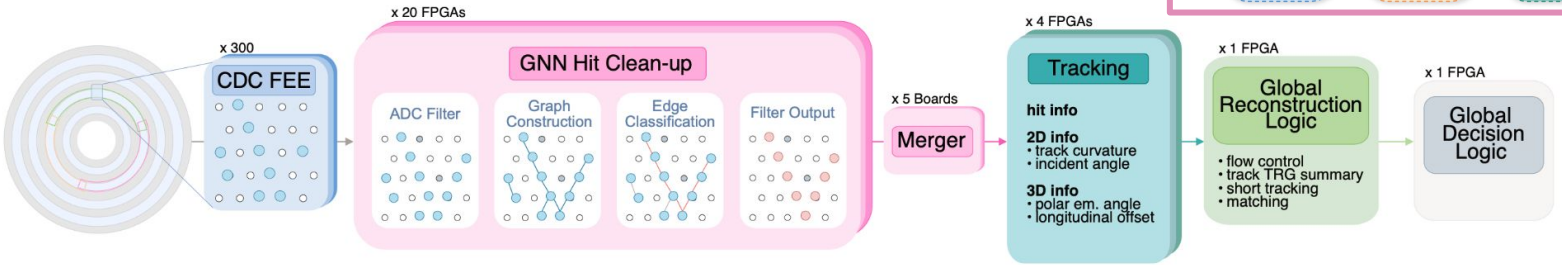
Trigger: ML for FE



(a) Current CDC TRG System

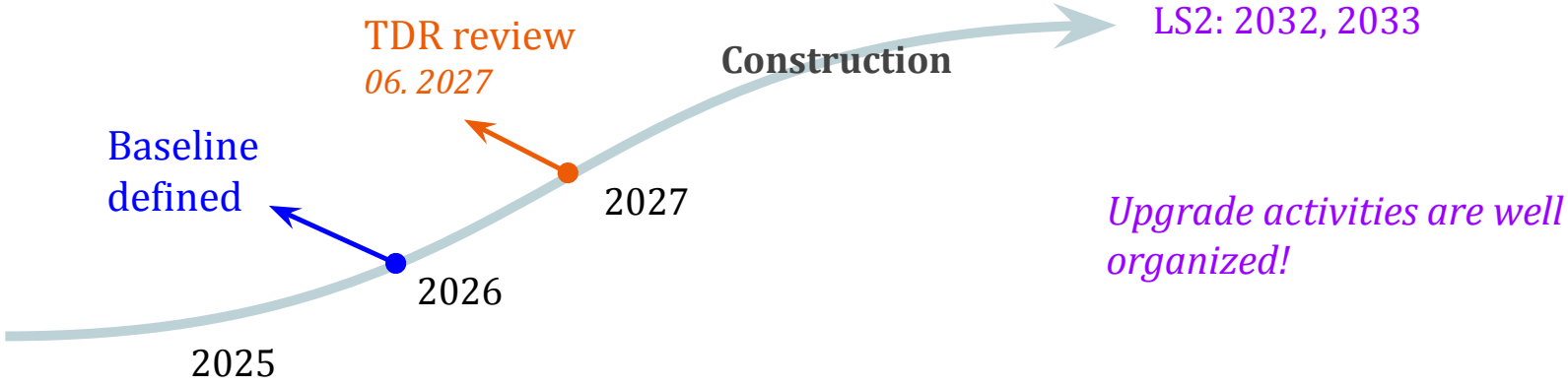
GNN based hit clean-up for CDC





(b) Future Upgrade Concept for the CDC Trigger System

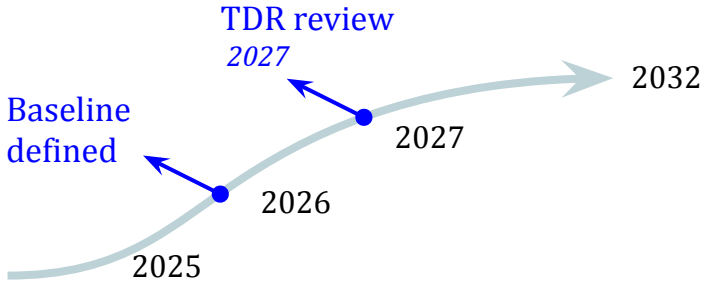
Upgrade timeline

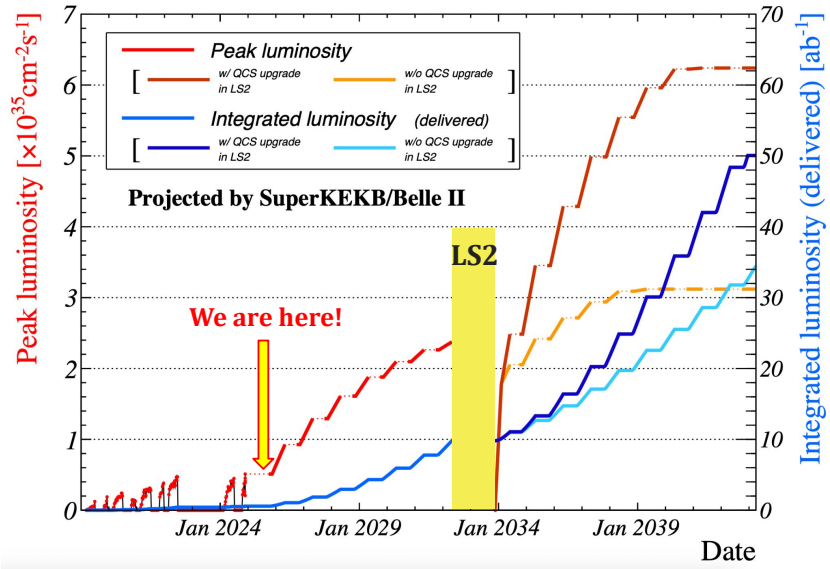


- A lot more R&D activities going on but not covered today!
- Various options are still being studied in parallel and they are all on the table
- Major timeline towards LS2:
  - Early 2026: converge on a baseline upgrade scenario
    - QCS envelope geometry
    - Understand more about the CDC aging issue
    - ITT scenario if there will be an ITT volume
    - Post-LS2 Beam Background estimation
  - TDR review planned in 2027

Summary & outlook

- Belle II has been operating and collecting data successfully in the past several years
- Ambitious plans targeting much higher L_{inst} have been made
- LS2 planned: Upgrade of Belle II detector to operate under higher luminosity with improved performance:
  - Large number of ongoing R&D studies
  - Huge amount of work to be done in the next few years
- Targeting TDR review in 2027
- Stay tuned!

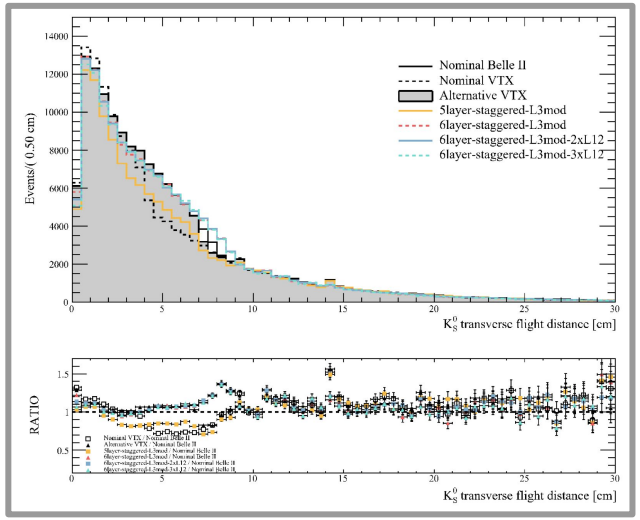


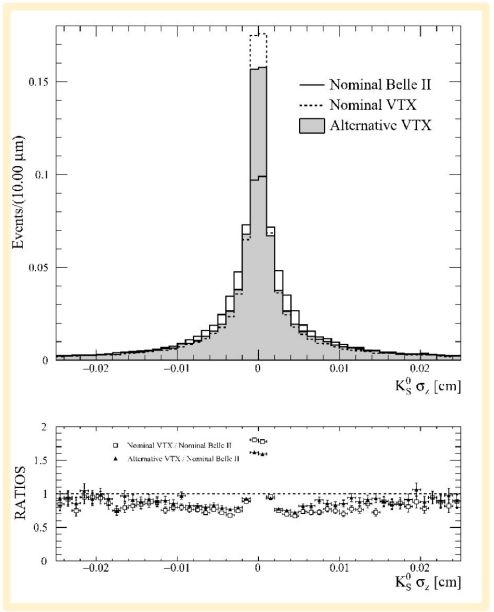


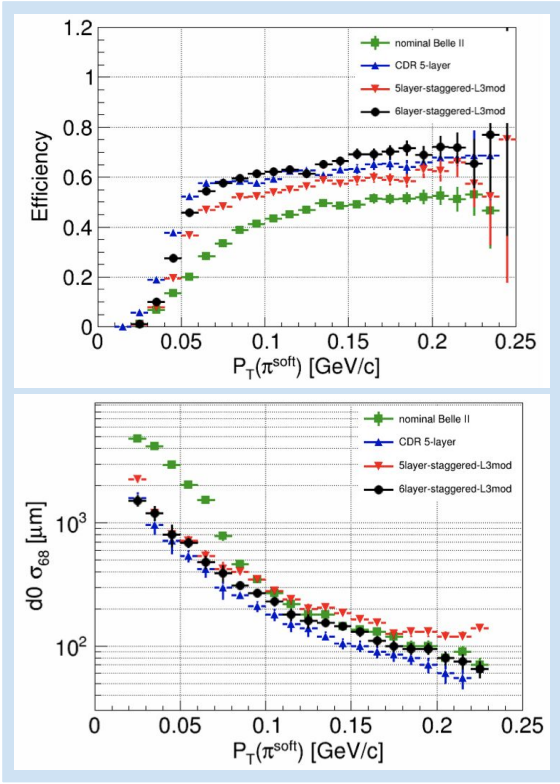
backup

VTX performance and geometry optimization based on simulation

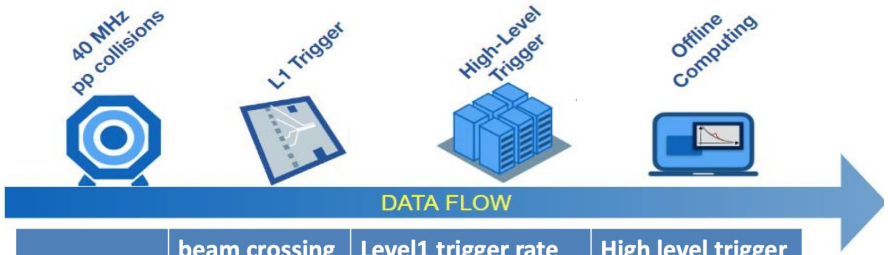
- Improved detection efficiency and improved impact parameter resolution for π_s
  - $B^0 \to D^{*-}(\to D^0 \pi_s^-)\,\mu^+\nu_\mu$
- Better vertex resolution
  - $B^0 \to J/\psi\, K_S^0$
- Material budget: less material for inner layer







➔ More studies in the future (Move this slide to backup)



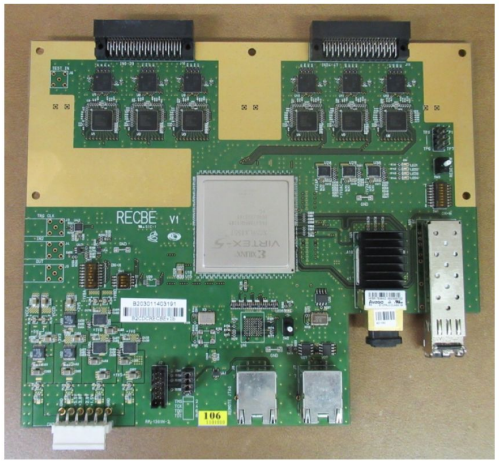
	beam crossing rate	Level1 trigger rate (FPGA)	High level trigger rate (CPU/GPU)
ATLAS	40MHz	100kHz	1kHz
LHCb	40MHz	1MHz	12.5kHz, 0.6GB/s
LHCb upgrade	30MHz	no Level1 !	2-5 GB/s
Belle II	250MHz	30kHz	5~10kHz, 1.8GB/s

CDC upgrade

Others: New front-end board with better cross-talk tolerance, power consumption, and radiation hardness

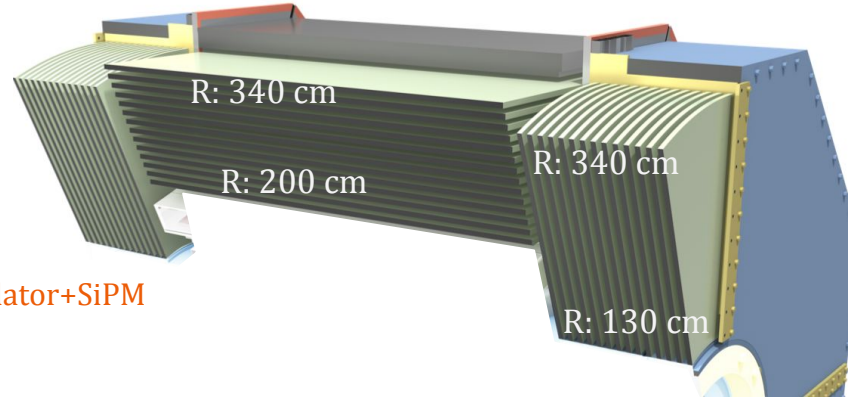
- New 8-channel 65nm front-end ASIC (TDC+flash-ADC)
  - 6 ASICs per board
- Rad-hard optical module QSFP (for data transmission to trigger/DAQ)
  - Total dose: ~1kGy
  - Candidates of QSFP are selected through γ and n radiation hardness tests

Status: electronics design is close to completion => review is planned soon



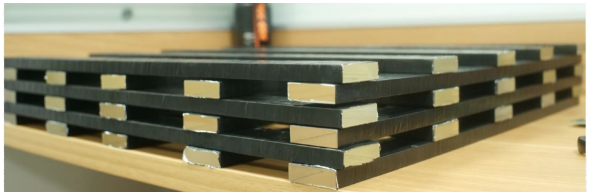
New

Upgrade of KLM

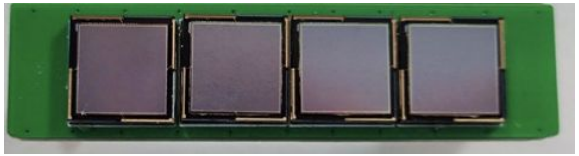


Two independent upgrade options under study:

- Option-1: rebuild detector panel and replace all RPCs with scintillator+SiPM
- Allow fast timing (100ps):
  - Reject out-of-time hits from the ambient neutron flux
  - Access to K_L momentum via TOF => not possible with present KLM
    - *100 ps, 2m flight length -> momentum resolution of ~13% for 1.5GeV/c K_L*
    - *Critical for decays with missing mass and CPV*
- Mechanically complicated: Requires roll-out of Belle II and opening of the forward and backward endcap doors
  - Access of all the panels will be challenging: beamline-supporting concrete shield blocks the bottom 3 sectors
  - Need to coordinate with other subsystems for installation => challenging and requires ~1 year to accomplish the installation steps
- Status: A small prototype been built with 60 scintillators and will be ready for testing soon

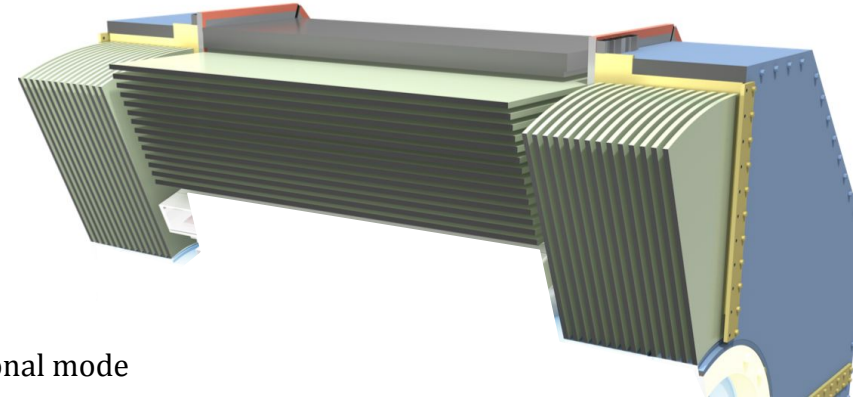


30 scintillator strips. Array size: 50ccmm × 50ccmm × 6ccmm



SiPM array

Upgrade of KLM



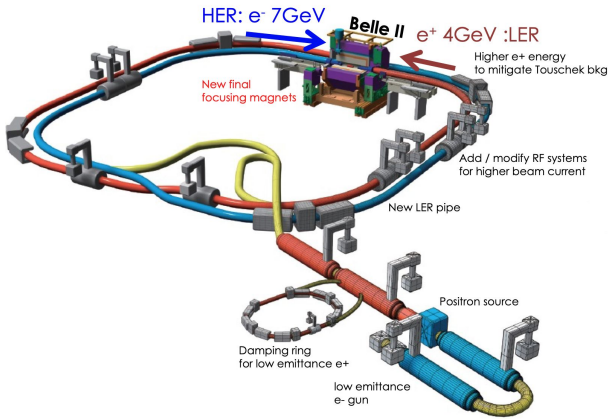
Two independent upgrade options under study:

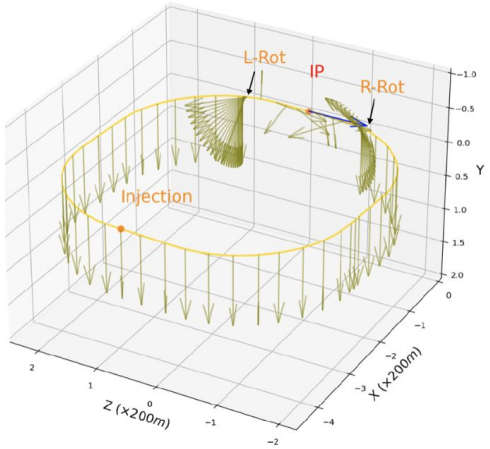
Option-2: Change the RPC operation mode from streamer to proportional mode

- Keep the existing KLM detector panels untouched
- Maintaining present KLM performance in high background condition
- New preamplifier required to work with the proportional mode

Chiral Belle

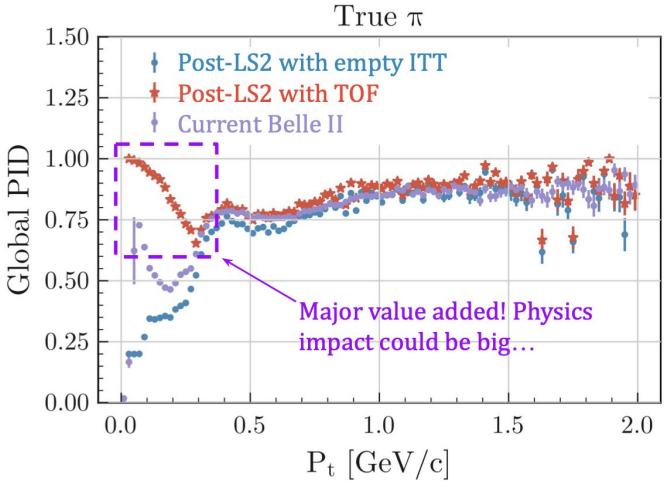
- Polarized electron beams in HER -> enable unique and powerful sensitivities to new physics and precision neutral current measurement at 10 GeV:
  - Neutral current universality between c and b quarks and all three generation leptons at energy below Z^0

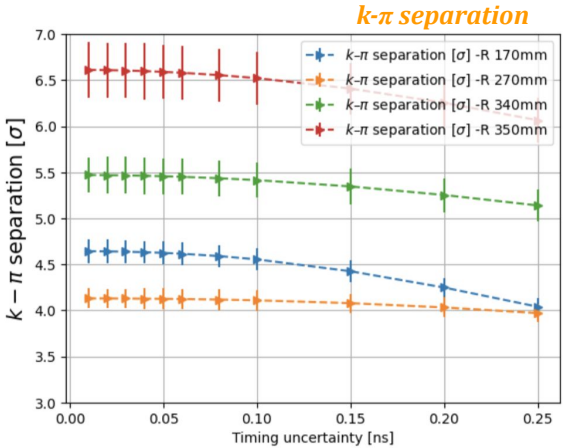


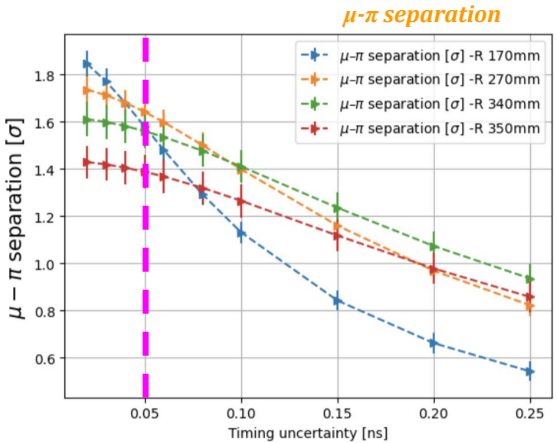


ITT

- Preliminary studies been done to understand the potential benefit and requirements to the actual technology:
  - Promising PID improvement: TOF-base PID with 50ps timing resolution
  - Further study to be done to understand the contribution to tracking and trigger







  - TOF: LGAD is an attractive option for its timing performance and well-established technology
  - Other option: evaluation of a pure tracking layer method based on CMOS-strip in parallel