UNIVERSITY of HAWAI'I MĀNOA

Belle II Upgrade

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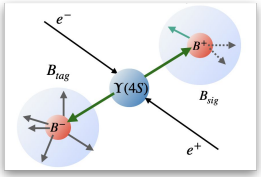
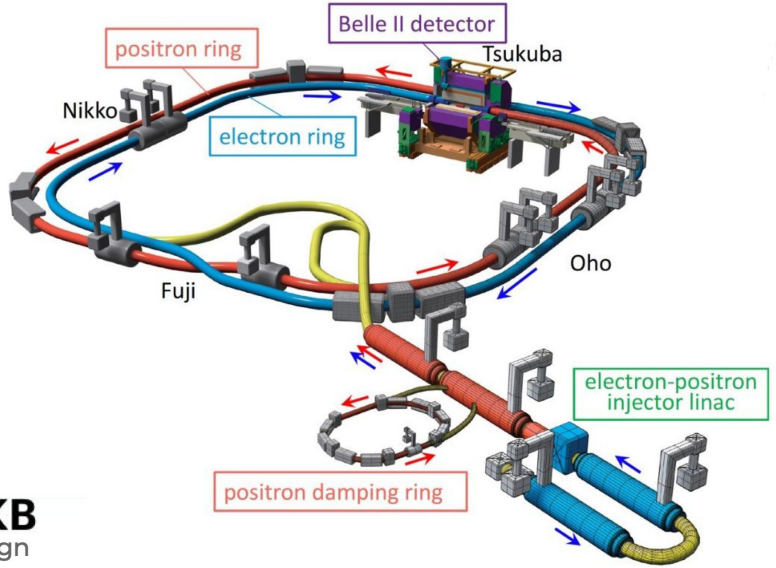
Outline

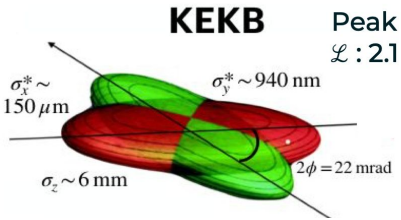
- SuperKEKB and Belle II
- Belle II upgrade:
  - Motivations
  - Upgrade of each sub-system
  - Schedule and milestones
- Summary & outlook

SuperKEKB



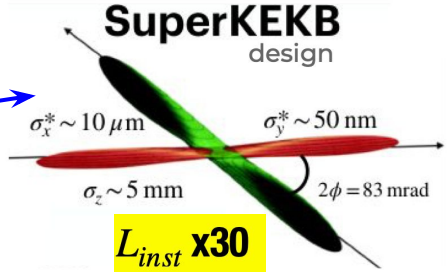


- ***SuperKEKB***
  - Asymmetric e^+(4GeV) e^- (7GeV) collider in Tsukuba, Japan
  - Operating around the *Y(4S)* resonance (√s = 10.58 GeV)



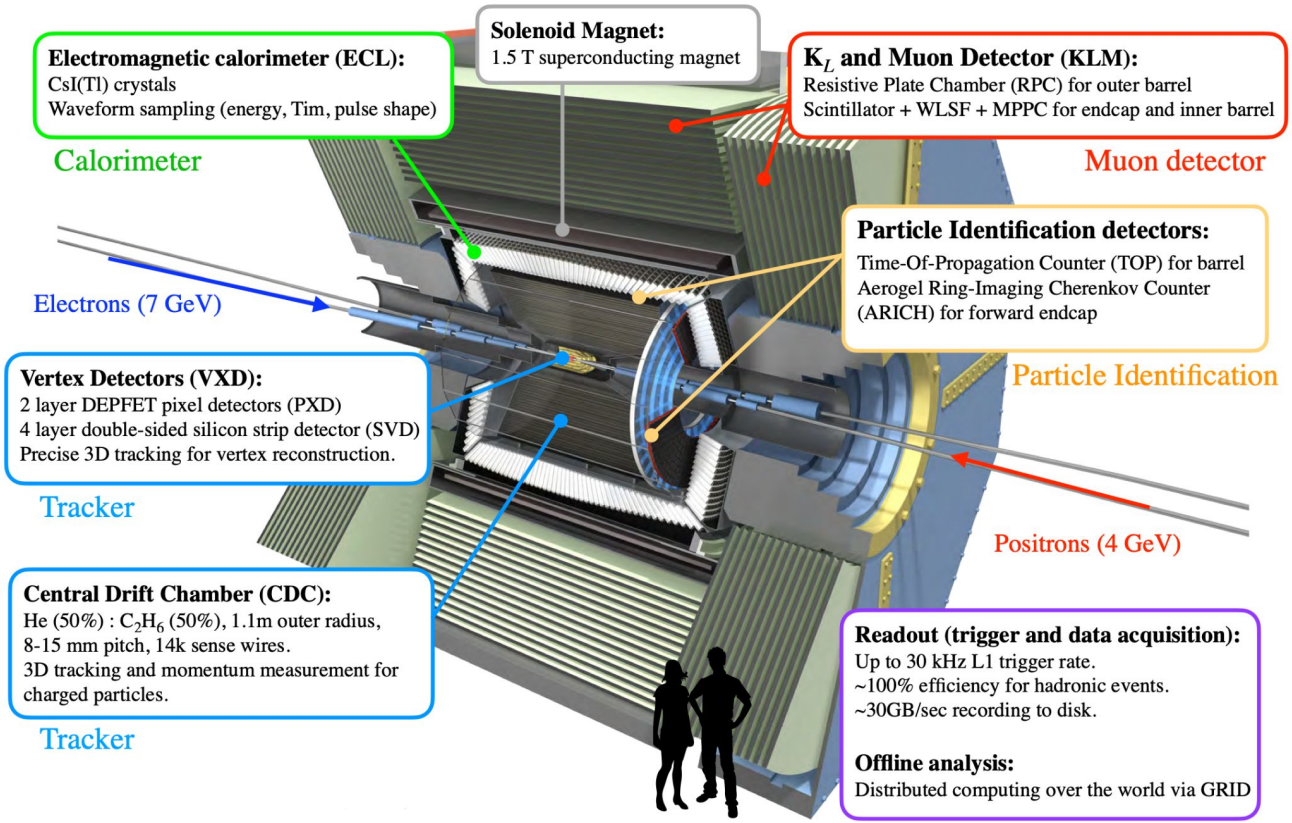
Nano-beam scheme

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



Belle II experiment

- ***Belle II:***
  - A hermetic detector with known initial-state



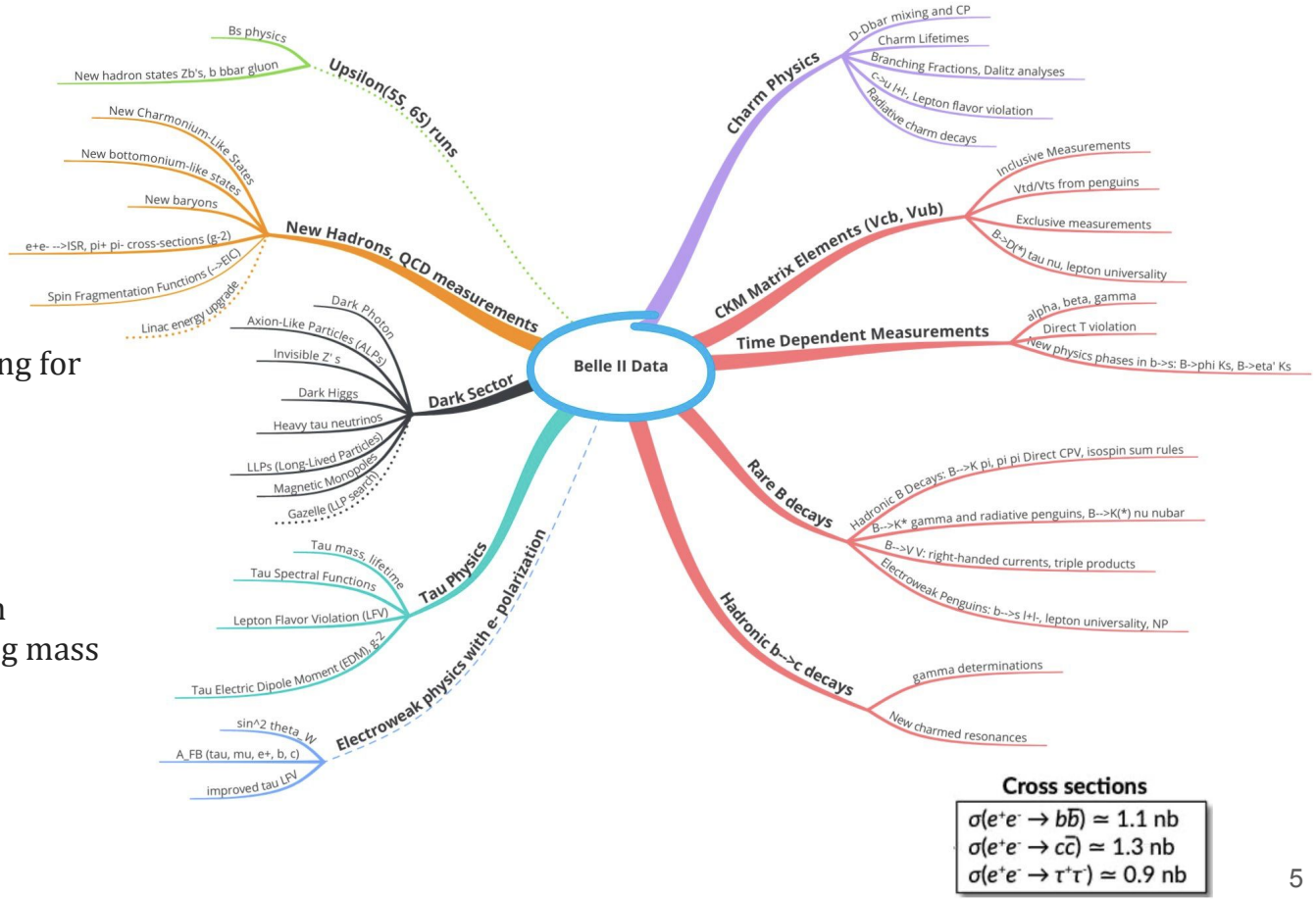
Belle II Physics

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

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

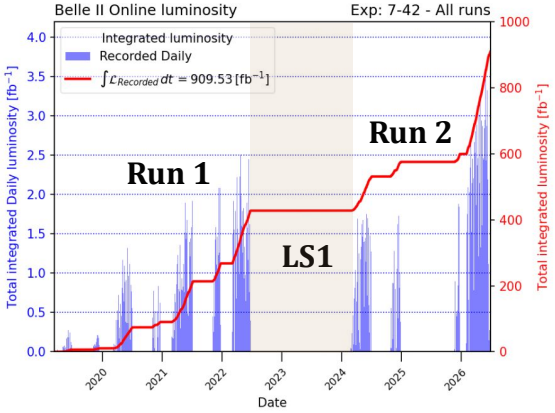
Various type of analyses:

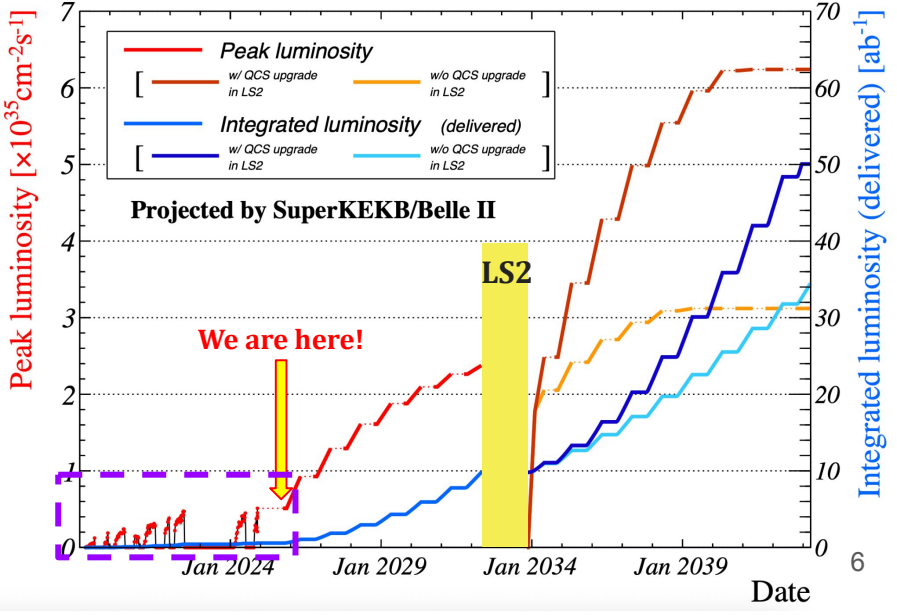
- Lifetime, time-dependent measurement
- well-suited for decays with missing energy and missing mass



Status and prospect

- **914 fb^{-1} data collected so far:**
  - **2019:** **Run 1** data collection started
  - **2022.06:** first world record L_{inst} : **4.7×10^{34} cm^{-2} s^{-1}**
  - **~2023.12 LS1,** 2-layer PXD, TOP PMT replacement etc
  - **2024:** Start of **Run 2**
  - **2026.03.19** : **new highest L_{inst} 5.28×10^{34} cm^{-2} s^{-1}**
  - **2026.05.17:** Surpass Belle data size
  - 2026.07.01: end of 2026 data taking
- Plenty of physics results with the data collected so far
- **Long-term operation till 2043:**
  - Targeting higher L_{inst}: 6×10^{35} cm^{-2} s^{-1}
  - Ultimate goal: ~ 50 ab^{-1}
- **LS2 planned for a major upgrade: 2032**
  - Upgrade & Redesign of the **Interaction Region (IR)**
  - Window for upgrades of the Belle II detector

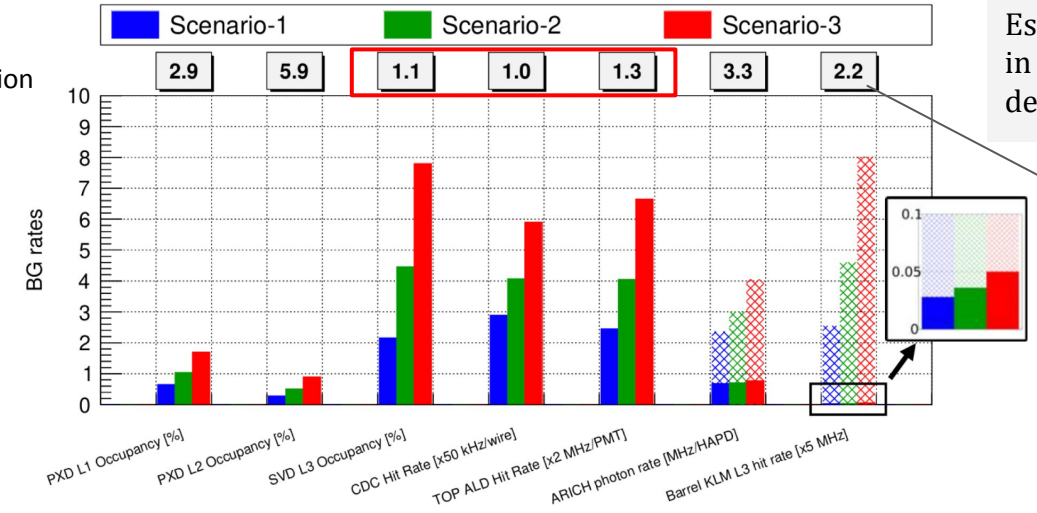




Motivations-1

- 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 of scenario-2)
  - Beam background reaching the limits of several sub-detectors: SVD, CDC, TOP

Ratio of the limits/estimation



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

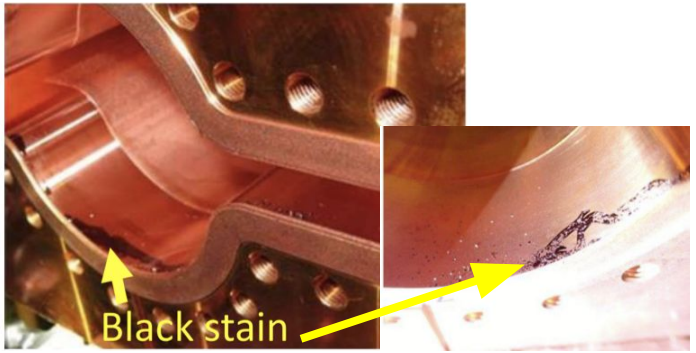
Safety margin using scenario-2: Ratio of the limits/estimation

Framework Conceptual Design report (FCDR) https://arxiv.org/html/2406.19421v2

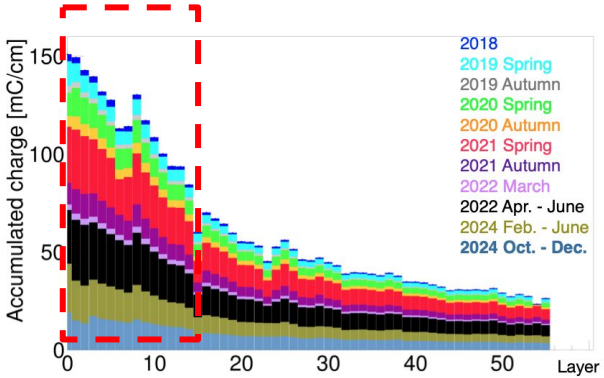
Motivations-2

Main issues during Run1/2:

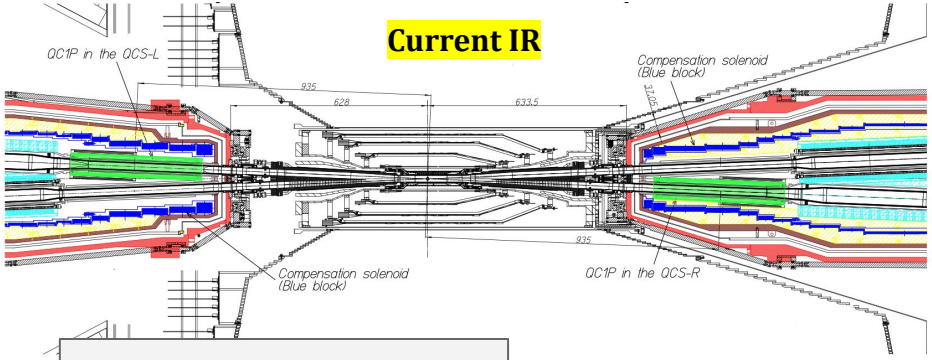
- **Sudden Beam Loss (SBL): significant beam charge loss**
  - PXD2 was switched off for that (~2% damaged area by SBL), occasionally leading to quenching of Superconducting magnets
  - Attempts to understand the issue:
    - *Installed Knockers => SBL events decreased*
    - *Flipped clearing electrodes => 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:**
  - Gain drop of 10-15% observed in the inner super layers
  - Various studies ongoing to understand the issue and evaluate the impact on performance



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

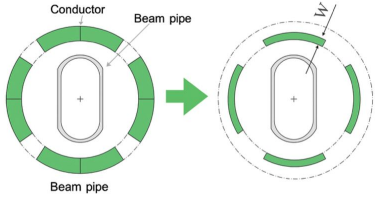


Upgrade of the IR

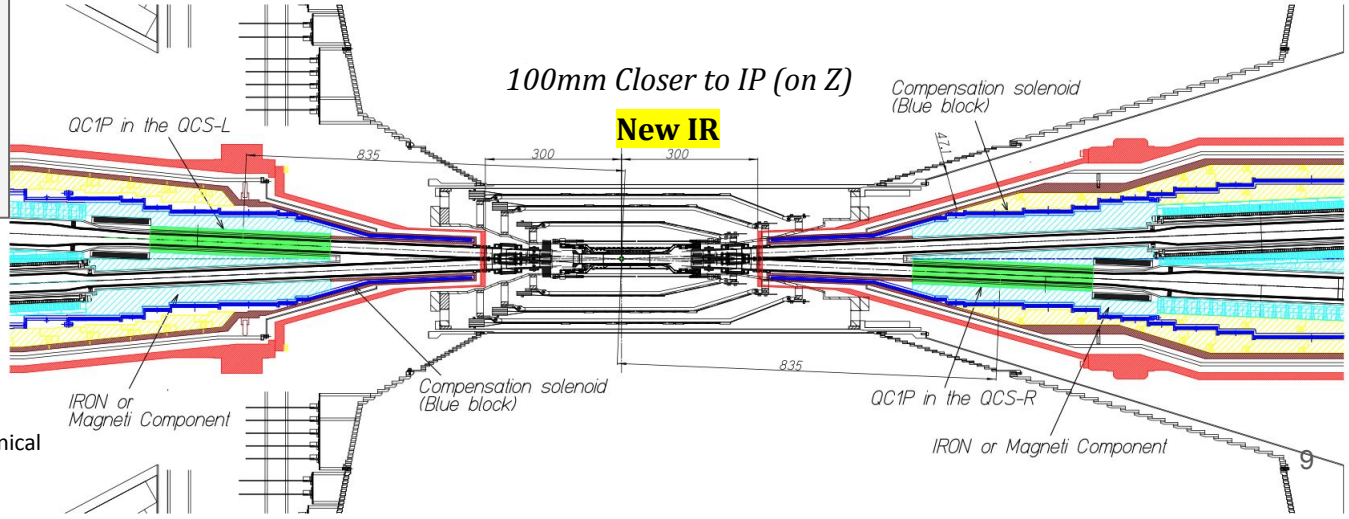


- New QCS to squeeze beams for higher L_{inst}
- IR region needs to adapt to the new QCS
- Potential new beampipe and innermost detector

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



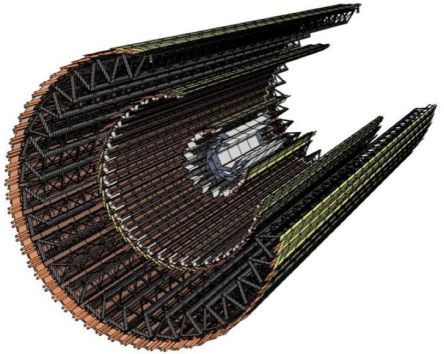
Thinner conductors will be needed to avoid mechanical interference between the two beam lines



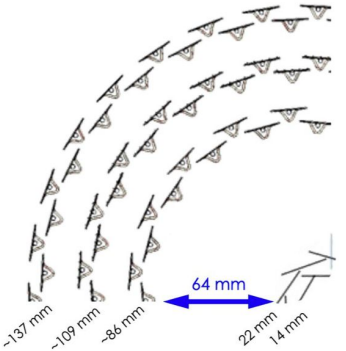
Vertex detector upgrade: VTX

- PXD + SVD ⇒ **new VTX**

- A **5-layer** depleted monolithic active pixel sensors (DMAPS)
  - Radius: 14 mm ~ 170 mm
  - Improve low-momentum tracking and impact parameter resolution
  - Use TJ-Monopix2 as starting point



- 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

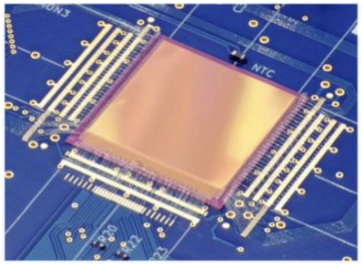


Vertex detector upgrade: the OBELIX sensor

OBELIX sensor: Optimized BELLE II monolithic active pixel sensor

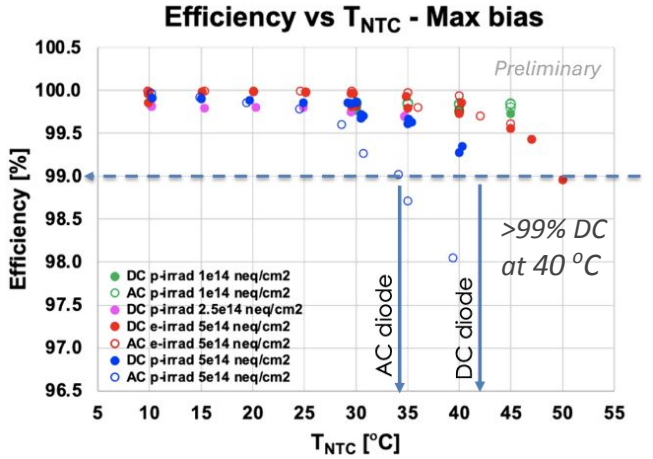
1. Derived from TJ-monopix2 (developed for the ATLAS inner Tracker upgrade)
   a. TJ 180 nm technology
   b. Pitch size: 33 um
   c. Time-stamping capability with 50ns resolution
   d. New digital periphery designed to be compatible with the Belle II trigger&DAQ system
2. Laboratory tests and test beam 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

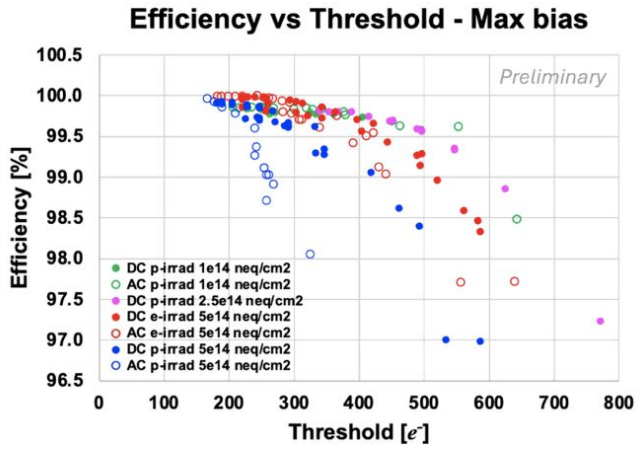
The DMAPS upgrade of the Belle II Vertex Detector

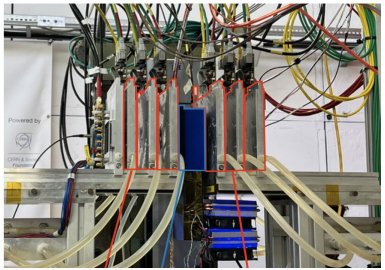


TJM2 sensor bonded on a test board

Triggerless readout with no memories in periphery



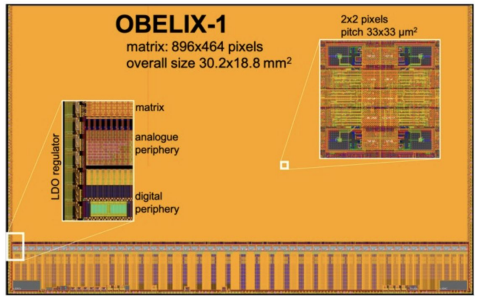




DESY, EUDET telescope. 4.2 GeV electron beam

Vertex detector upgrade: VTX

- 2nd dedicated VTX workshop: Apr 20-22 2026@DESY
- Schedule :
  - **OBELIX-1:**
    - Design frozen and submitted in Apr 2026
    - Expected to be returned in Sep 2026
  - **OBELIX-2:**
    - Design kick-off ~Mar 2026
    - Submission planned beginning of 2028



More studies not covered today:

- Performance validation and comparison with current Belle II
  - Improved detection efficiency and ks efficiency
- DAQ development
- Cooling strategy and support method heavily studied
- Outer layer of VTX (oVTX) also potential input to the trigger
- More can be found in this slides

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

Slides

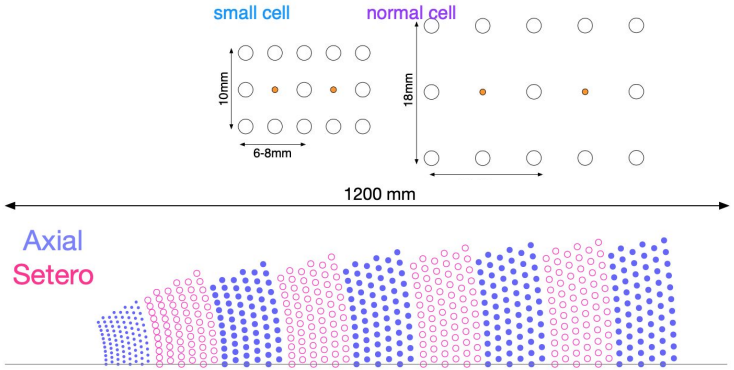
CDC upgrade

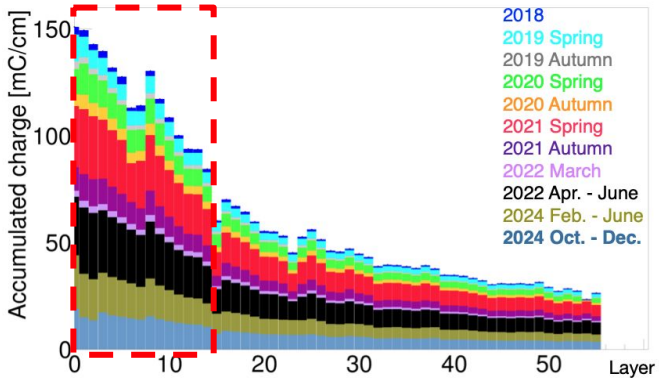
- Main tracking detector, also contributes to PID and Trigger
  - Covering radius from 160 -1130 mm
  - 56 layers in total, grouped into 9 super-layers
  - Gas: He:ethane = 50:50
  - Gas system improved for better monitoring/control of H_2O during LS1

- 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 taken with lower HV for testing
  - One of the critical issue to be understood for current operation and future upgrade

⇒ **CDC upgrade scenarios :**

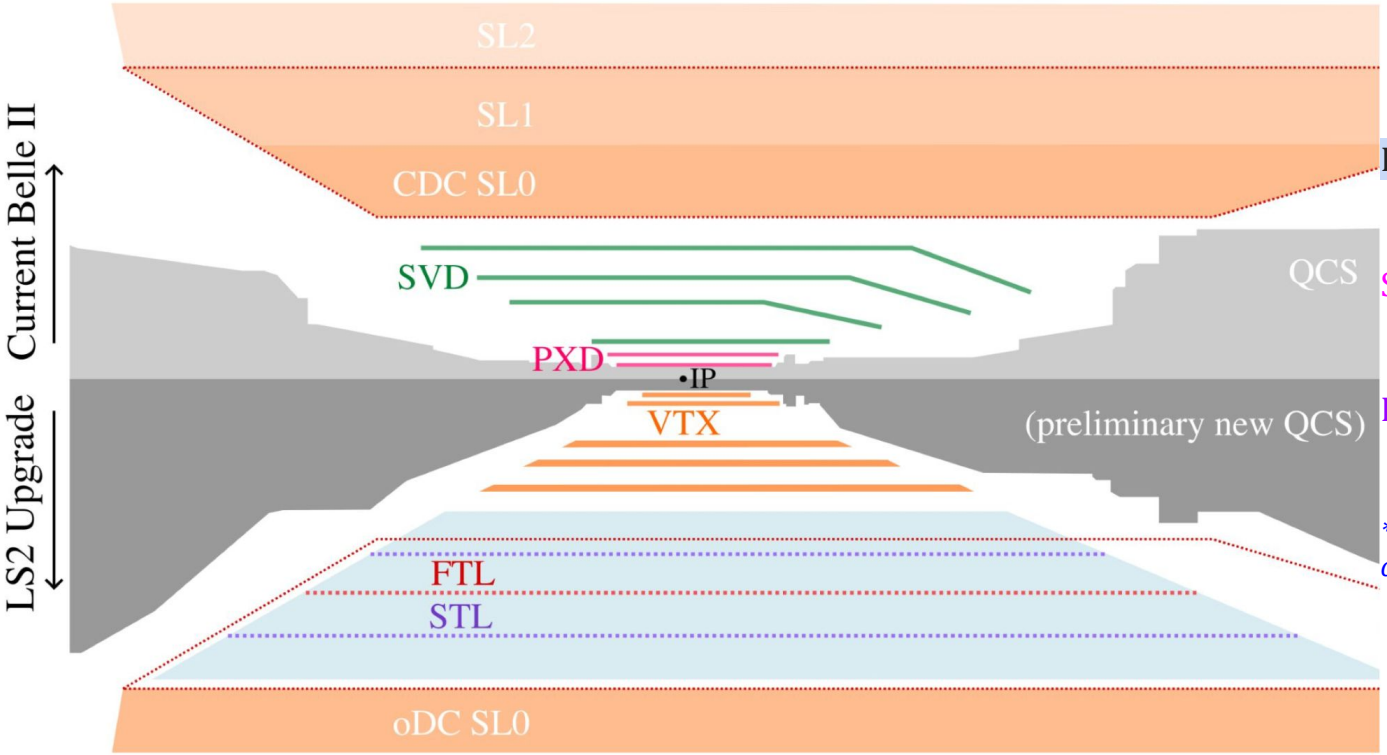
- **iDC+oDC:** two separated parts
- **ITT+oDC:** silicon-based Inner Timing Tracker
- Others: New front-end board with better cross-talk tolerance, power consumption, and radiation hardness





Proposal for ITT

If the ITT +oDC scenario was chosen:



Proposal for ITT:

- STL/FTL or STL+FTL

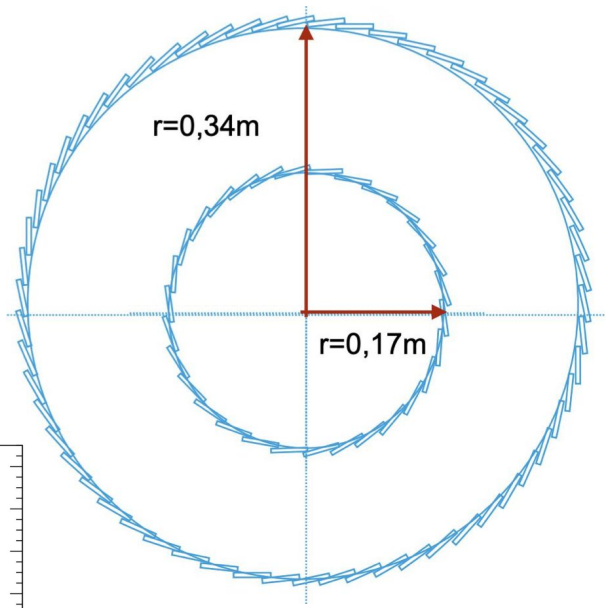
STL: Silicon Translation Layer
Pure tracking solution

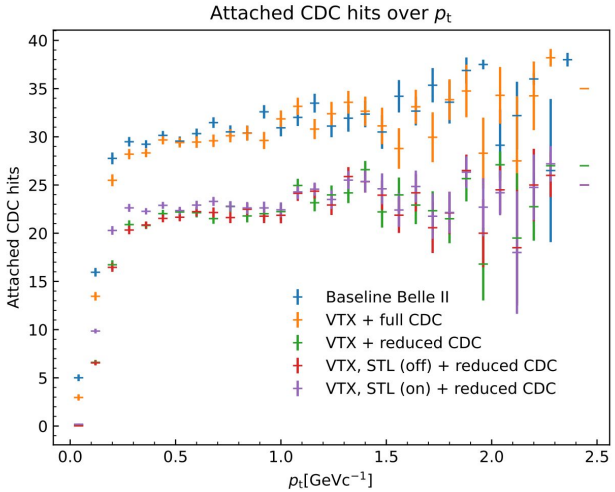
FTL: Fast Timing Layer
New TOF-PID information

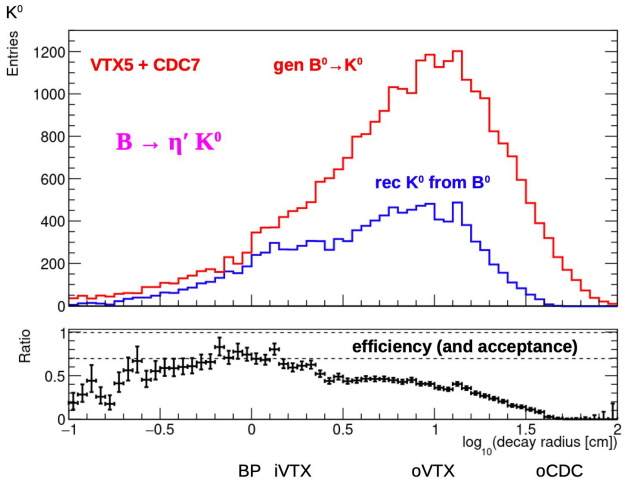
**Prefer mutual technique due to time constraints.*

ITT - STL

- WG been was formed very recently ~3 months ago
- Starting point: adding a two-layer CMOS strip @ 17cm and 34cm
- Led by DESY, with contribution from DESY ATLAS group
- Preliminary study been carried out with simulation:
  - Impact to tracking: number of CDC hits been found with truth VTX+STL tracks
  - Ks efficiency: on-going



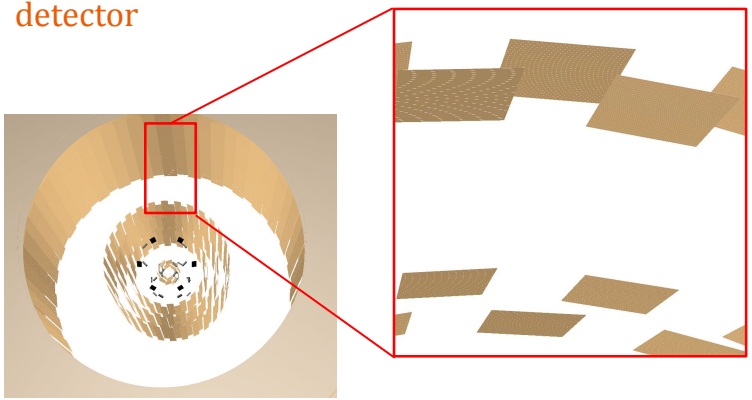


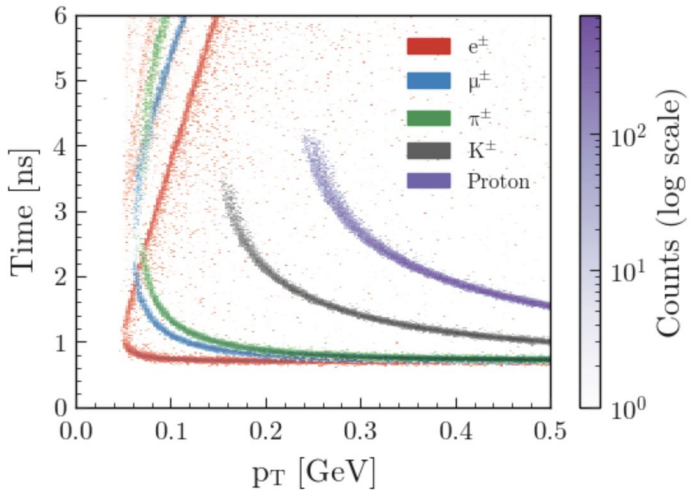


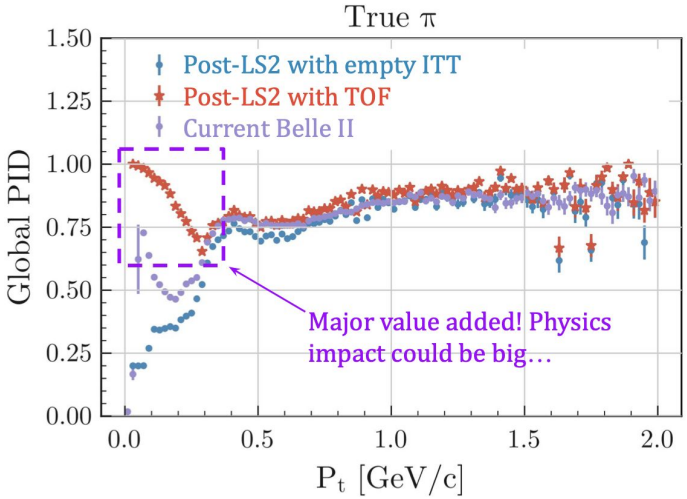
ITT - FTL

- Led by University of Hawaii so far
- Potential candidate: AC-LGAD (excellent timing performance and well-established technology)

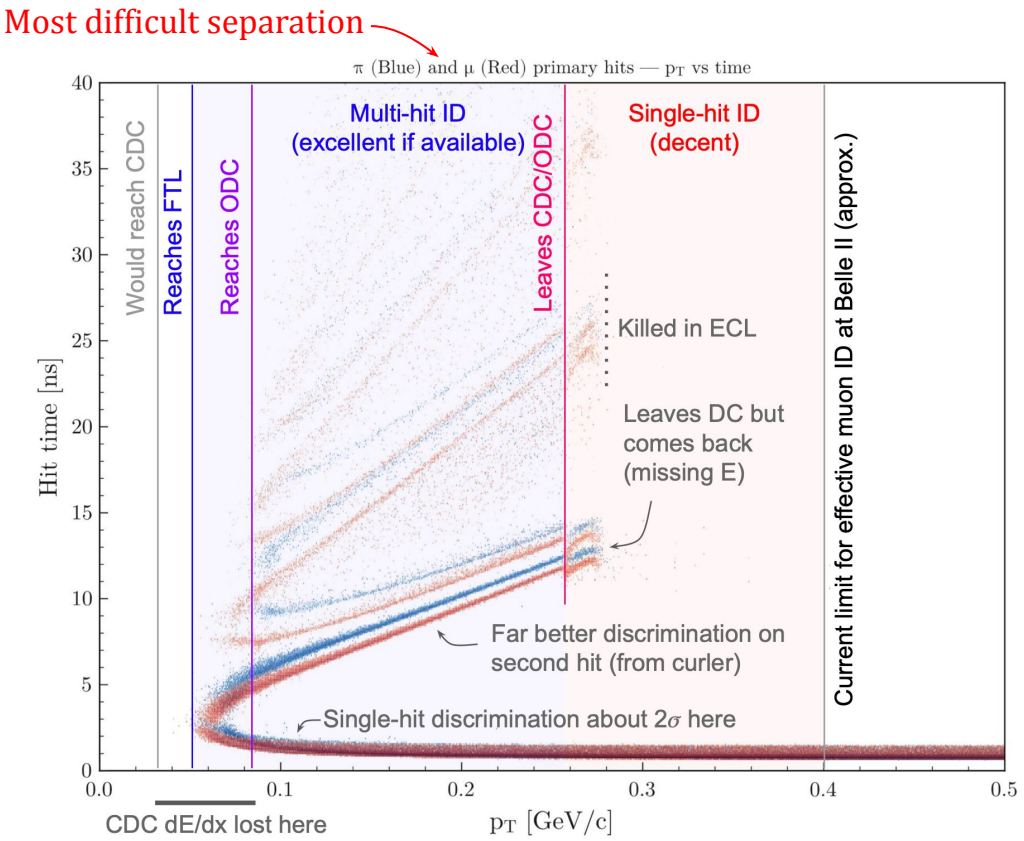
- Implemented into Belle official soft (basf2):
  - Promising PID improvement;
  - Potential source to EventT0, Trigger
  - Small impact to Tracking -> doesn't have to be a tracking detector







FTL- multi-hit ID concept



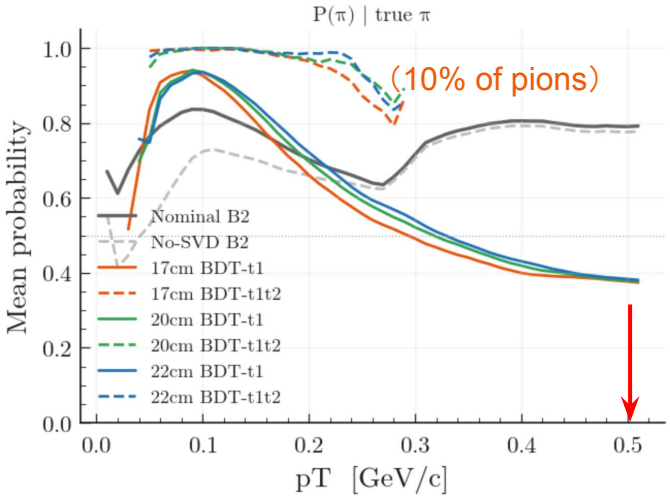
- Time vs Pt (Truth info) for pi and mu (FTL@22cm)
  - Several structures observed
- Multi-hits from loopers:
  - (small radius of FTL + large CDC volume)
  - Low-pt (<0.25 GeV/c) tracks curling inside CDC
  - Entering FTL multiple times
  - Provide extra timing information with much larger flight length -> New opportunities with multi-hit ID!
- Tested with different methods to get the PID performance
  - BDT-based PID will be shown in the next slides

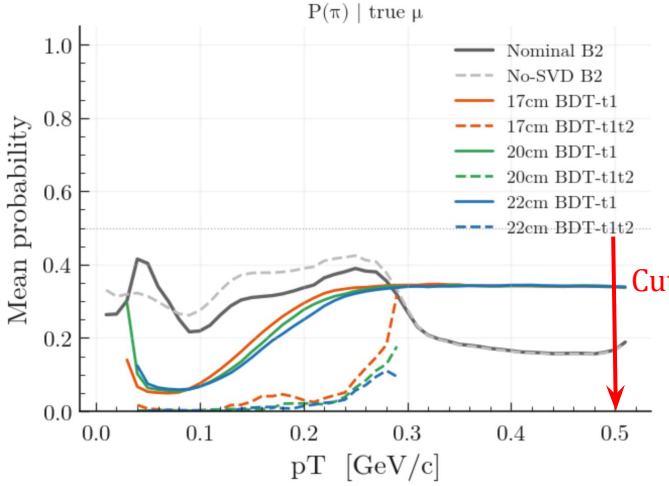
FTL - multi-hit ID concept

BDT-based FTL PID:

BDT-t1: training using the time information from the first crossing

BDT-t1t2: add time information from the second crossing





- Promising improvement with BDTt1 and BDT-t1t2
- With FTL and mult-hits method it's possible to have a lower cuts on Pt
- Still at pre-CDR stage with major effort from University of Hawaii, open for more contribution on this!

ECL and TOP

ECL upgrade:

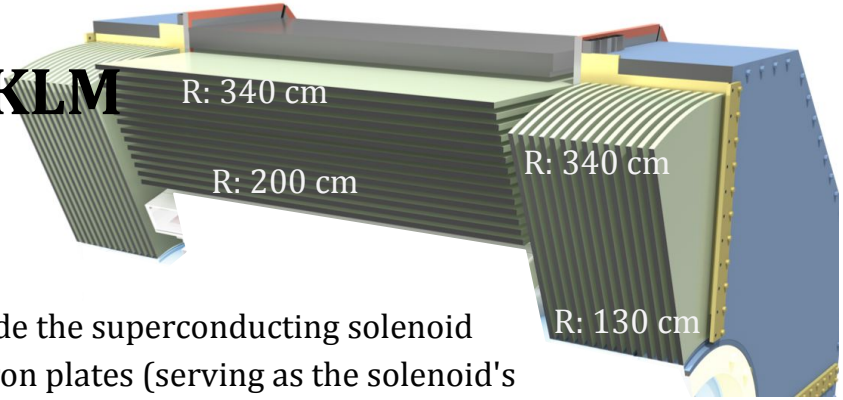
- Primarily for trigger, photon detection and lumi measurement
- Degraded energy and time resolution is expected with higher pileup noise (fluctuation of the beam background events overlapping the signal)
- New ShaperDSP(digitizer board): with faster shaping, higher sample-rate ADC, higher-granularity 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

ECL upgrade talk

TOP upgrade:

- Dedicated Belle II 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
  - Front end electronics upgrade for lower gain operation and MCP-PMT lifetime extension

Upgrade of KLM

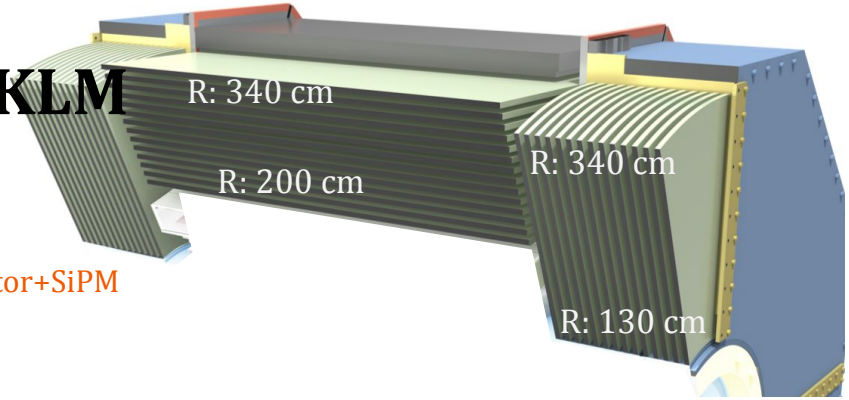


- Detection of K_L and μ:
  - Large-surface-area, thin planar detectors located outside the superconducting solenoid
  - Consisting of an alternating sandwich of 4.7 cm thick iron plates (serving as the solenoid's flux return yoke) and active detector elements
  - K_L detection is essential for decays with missing energy/neutral final states
  - In the Belle -> Belle II upgrade, all replaced with scintillator except 13 RPC layers remaining in the barrel
  - The remaining 13 RPCs' efficiency significantly decreases with increasing background rate (limited rate capability of streamer-mode operation)

Two independent upgrade options under study:

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

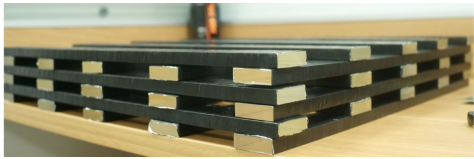
Upgrade of KLM



Two independent upgrade options under study:

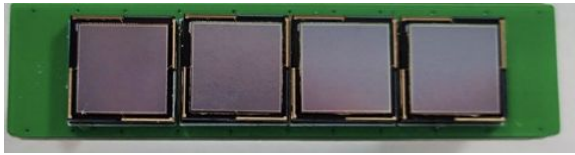
- Option-1: rebuild detector panels and replace all RPCs with scintillator+SiPM
  - Allow fast timing (~100ps):
    - Rejects out-of-time hits from the ambient neutron flux
    - Access to K_L momentum via TOF => not possible with present KLM
      - *2m flight length -> momentum resolution of ~13% for 1.5 GeV/c K_L*
  - Mechanically complicated: Requires roll-out of Belle II and opening of the forward and backward endcap doors
  - Status: A small prototype been built with 60 scintillators and is ready for testing
  - -> also useful as one prototype for forward tagger!

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

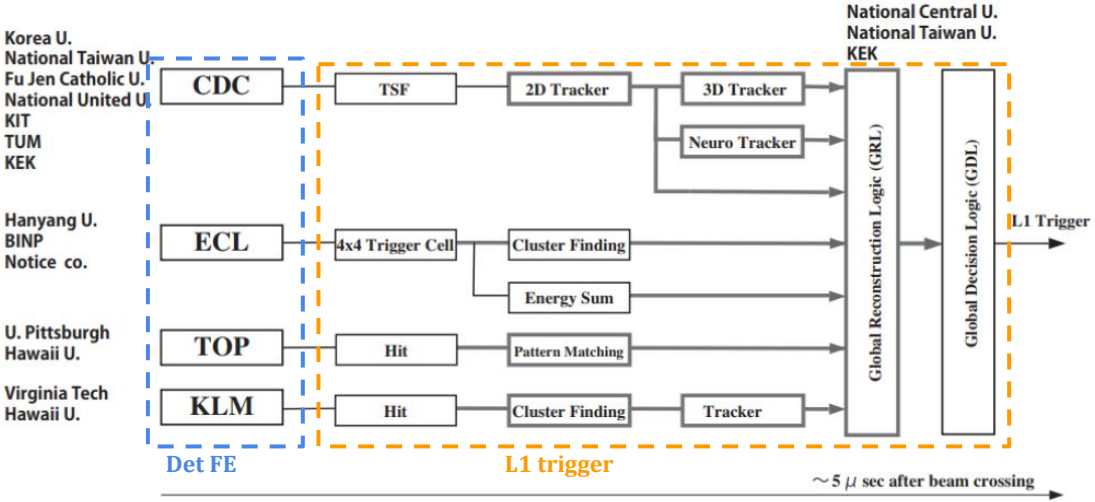


SiPM array

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(X) for ML and AI engine
  - Upgrade on both hardware and firmware

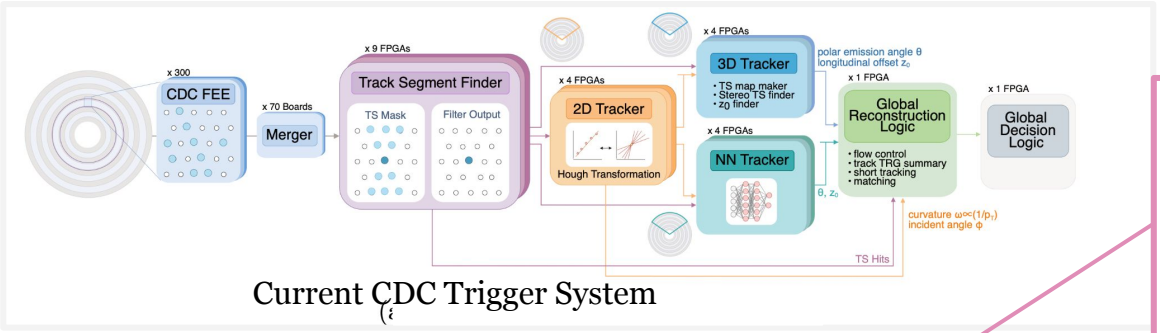
UT generation	UT3	UT4	UT5
Main FPGA (Xilinx)	Virtex6 XC6VHX380-565	Virtex Ultrascale XCVU080-190	Versal
Sub FPGA (Xilinx)	––	Artex7	Artex7, Zynq
# Logic gate	500k	2000k	8000k
Optical transmission rate	8 Gbps	25 Gbps	58 Gbps
# UT boards	30	30	10
Cost per a board (k$)	15	30	50
Time schedule	2014-	2019-2026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



Potential new inputs to L1-trigger:

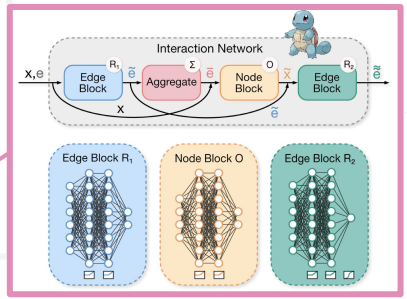
- New VTX and ITT as the input to L1 trigger

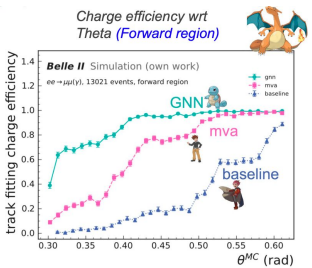
Trigger: ML for FE

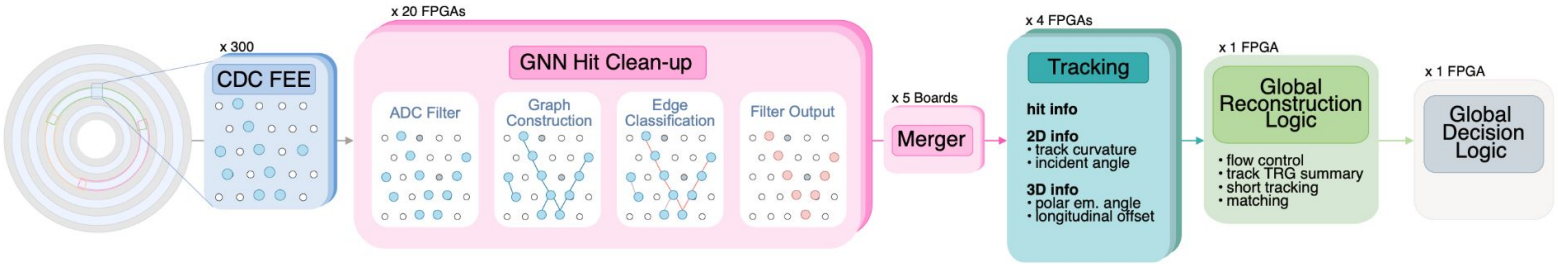


Current CDC Trigger System

GNN based hit clean-up for CDC

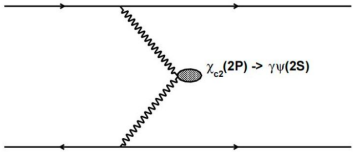






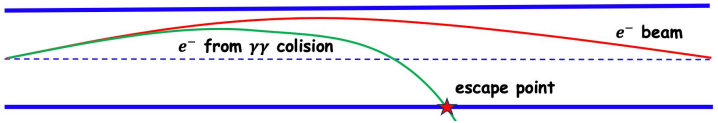
(b) Future Upgrade Concept for the CDC Trigger System

New Opportunities



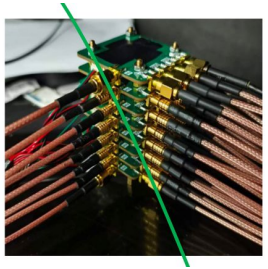
Forward taggers: (led by Fudan University)

- **Motivation:** $\gamma\gamma$ processes are a clean probe of C-even resonances, but ISR is a major, irreducible background
- **Key point:** In $\gamma\gamma$ events the scattered e^+e^- are emitted at very small angles and intercepted by the beam pipe(a distinctive signature wrt ISR)



- **Simulation:** tagging shows significant improvement in sensitivity (e.g. Z(3930): $3.14\sigma \rightarrow 5.72\sigma$)
- **Prototypes @ KEK** (two technologies under test):
  - 8-layer position-sensitive silicon sensor (PSS) → track information
  - Scintillator strips, ~70 ps time resolution → precise timing to suppress beam background (same technology as the Belle II KLM upgrade)

Prototype 1



Study using Belle Z(3930)

Selection efficiencies

Method	Eff_{sig} [%]	Eff_{ISR} [%]
Traditional	57.97	2.17
e-tagging	55.04	0.30

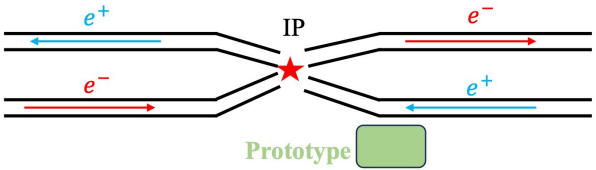
Projected significance

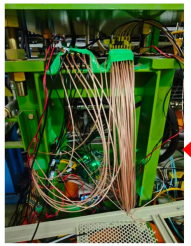
0.89 → 3.14

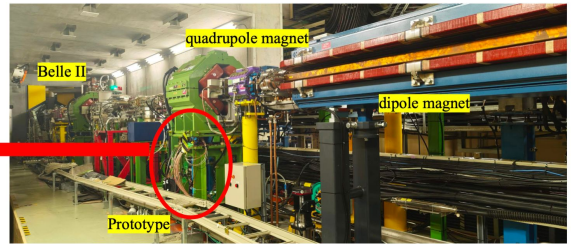
baseline → ISR cuts

0.89 → 5.72

baseline → *e*-tagging

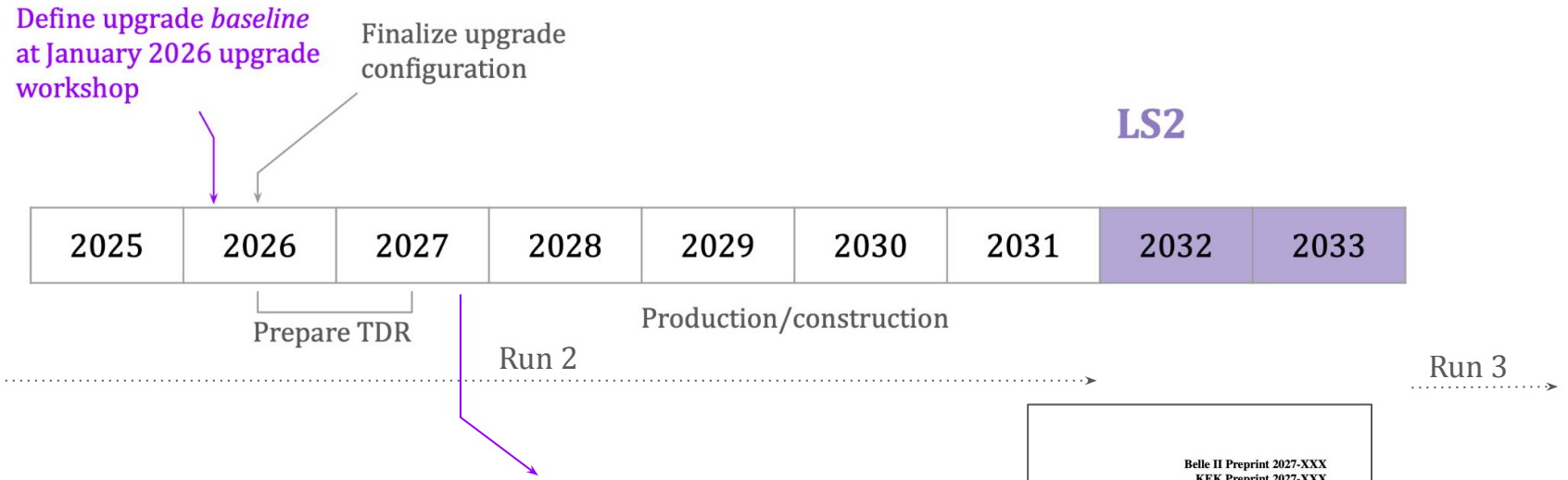






Prototype 2

Upgrade timeline



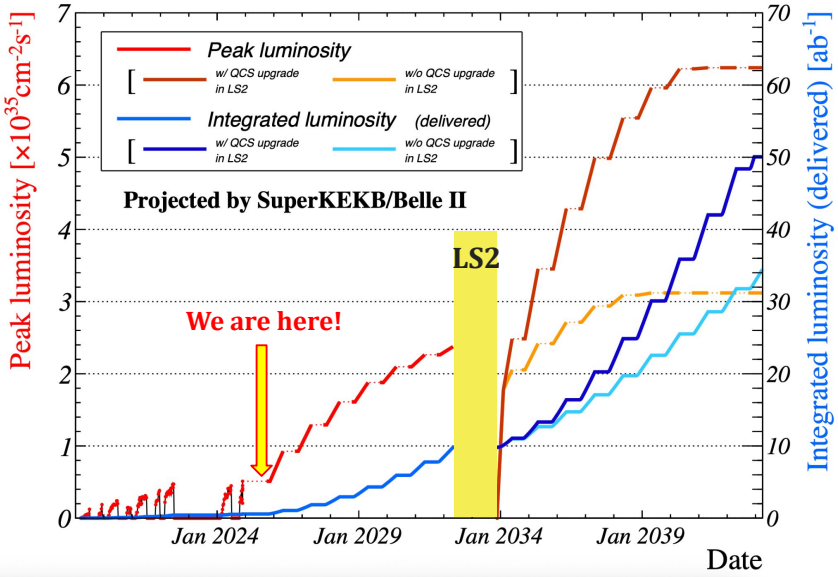
- A lot more R&D activities going on but not covered today!
- Various options are still being studied in parallel and they are all on the table

- Major timeline towards LS2: TDR review planned in 2027

Summary & outlook

- Belle II has been operating and collecting data successfully in the past several years (914 fb^{-1})
- 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
- Aim to have a baseline design very soon! (B2GM next week)
- Targeting TDR review in 2027
- Stay tuned!

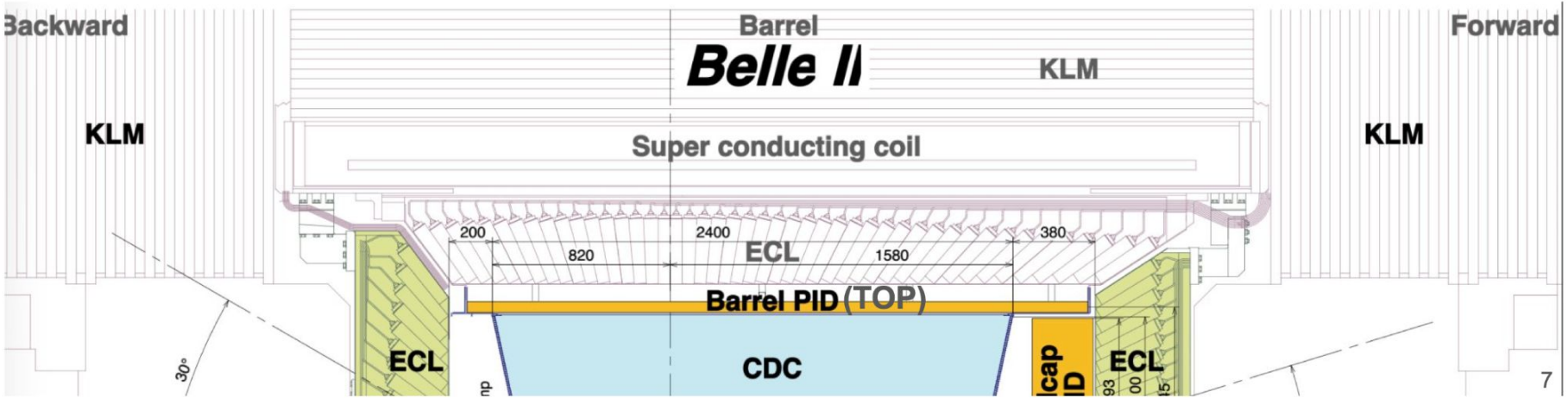
Thanks!



backup

Outer detector upgrade – baseline

- TOP – front end electronics upgrade for lower gain operation and MCP-PMT lifetime extension
- ECL – front end electronics upgrade (ShaperDSP board) for reduction of pileup noise and background
- KLM – move to proportional readout (avalanche mode) for barrel resistive plate chambers (RPCs) to avoid efficiency drop with increasing hit rate
- Study the addition of a forward tagger based on plastic scintillators for new physics searches
- Polarized electron beam upgrade for precision neutral current physics

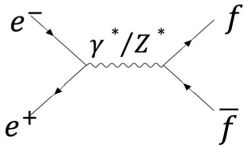


New Opportunities

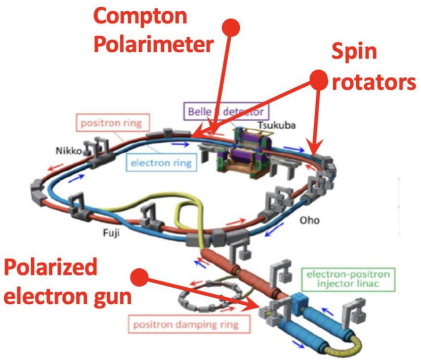
Chiral Belle: e-beam polarization

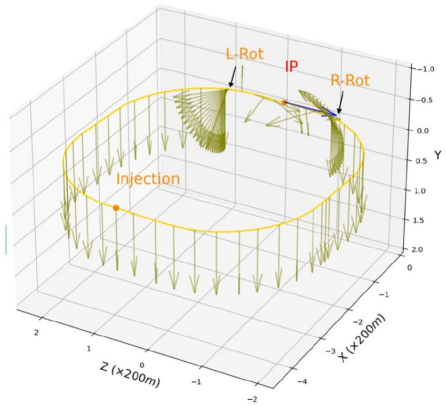
Chiral Belle involves provision of:

- Polarized source – 70% polarization at IP
- Spin rotators to provide longitudinal polarization at IP
- Compton polarimeter for real-time sub-% measurements



$$A_{LR}^f(\mathrm{SM}) = \frac{\sigma_{\mathbf{L}}^f - \sigma_{\mathbf{R}}^f}{\sigma_{\mathbf{L}}^f + \sigma_{\mathbf{R}}^f} = \frac{sG_F}{\sqrt{2}\pi\alpha Q_f} g_A^e g_V^f$$

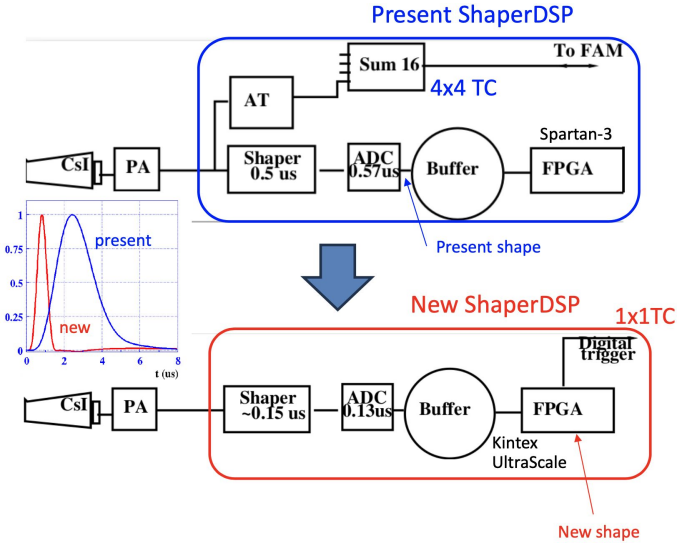




Fermion f	g_V^f (Standard Model)	g_V^f (World Average)	$\sigma(g_V^f)$ Chiral Belle 0.5ab^{-1}	$\sigma(g_V^f)$ Chiral Belle 1ab^{-1}	$\sigma(g_V^f)$ Chiral Belle 5ab^{-1}	$\sigma(g_V^f)$ Chiral Belle 20ab^{-1}
b-quark	-0.3437 ± 0.0001	-0.3220 ±0.0077 (2.8σ off SM)	0.0026 3x better than World Ave σ	0.0022 >3x better than World Ave σ	0.0018 >4x better than World Ave σ	0.0017 >4x better than World Ave σ
c-quark	0.1920 ± 0.0002	0.1873 ± 0.0070	0.005	0.0036 2x better than World Ave σ	0.0018 4x better than World Ave σ	0.0011 >6x better than World Ave σ

ECL upgrade

- Degraded energy and time resolution is expected with higher pileup noise (fluctuation of the beam background events overlapping the signal)
- 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



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
  - Front end electronics upgrade for lower gain operation and MCP-PMT lifetime extension

Middle-term upgrade plan:

- (primary)Complete replacement of MCP-PMTs with lifetime-extended ALD type: end of 2026
- Further R&D to mitigate PMT aging with new electronic