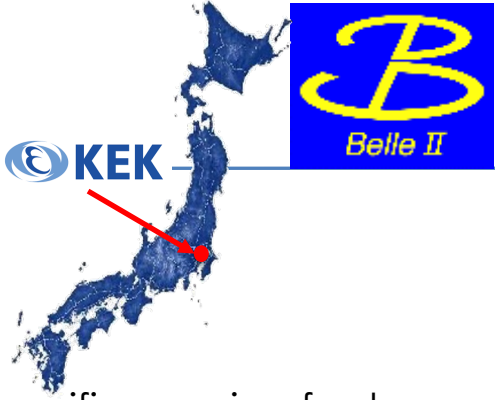
15th Pisa meeting on advanced detectors
22-28 May 2022

The Belle II Upgrade Program

Jerome Baudot
for the Belle II collaboration

- Belle II/SuperKEKB current status & rationale for upgradeS
- Overview of proposed technologies and R&Ds

B,c,τ-factory: SuperKEKB + Belle II



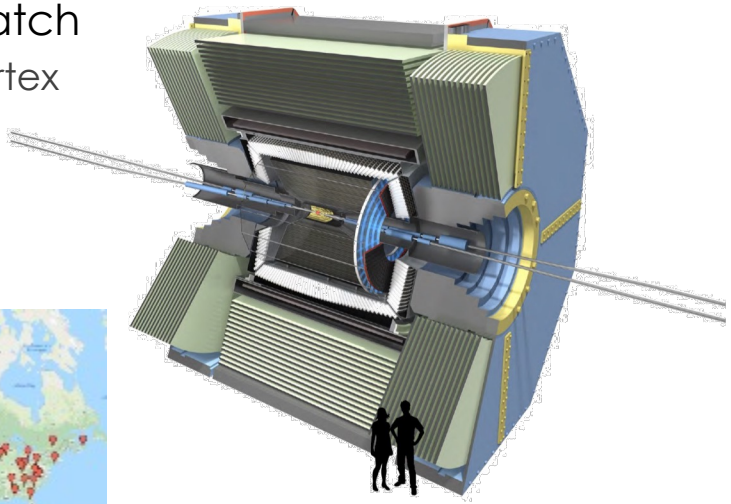
- Initial physics program based on L_{int} = 50 ab^{-1} at $\sqrt{s} = M_{\Upsilon(4S)}$
  ⇒ The Belle II physics book PTEP 12 (2019) 123C01

High luminosity collider:

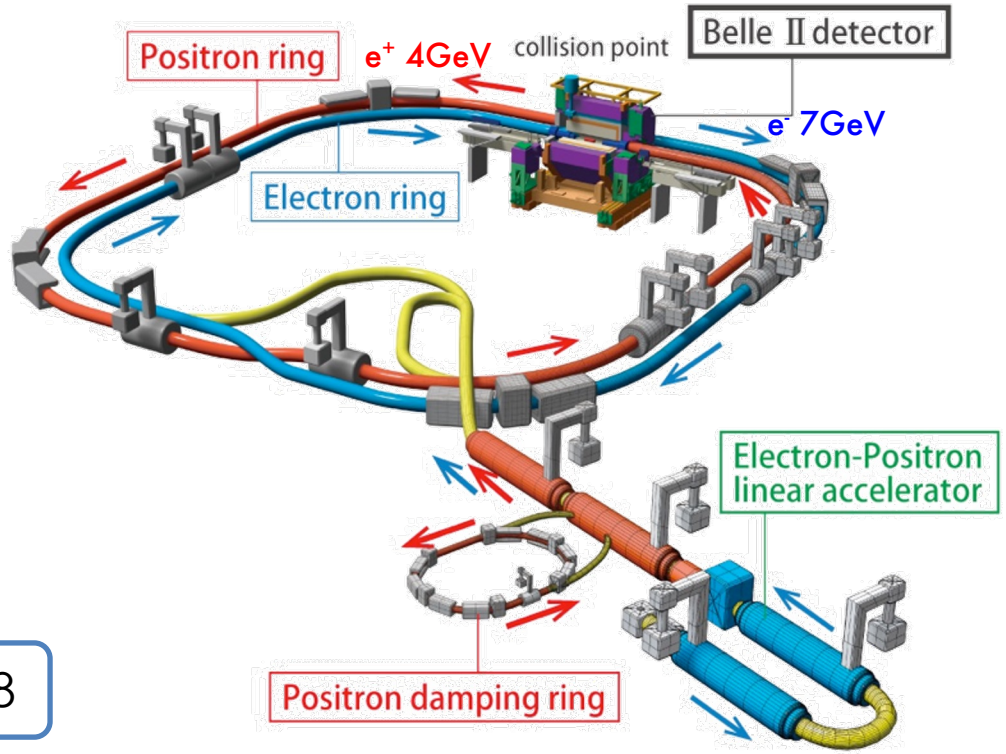
- L_{peak} ~ multi 10^{35} cm^{-2}.s^{-1} range
- High current / nano-beams / specific crossing features
- **Challenging background conditions**
  ⇒ Snowmass contribution: arXiv 2203.05731

Belle II detector:

- Upgraded from Belle to match
  - Lower boost ⇒ improved vertex
  - Higher rates & radiations
    ⇒ faster det. & read-out

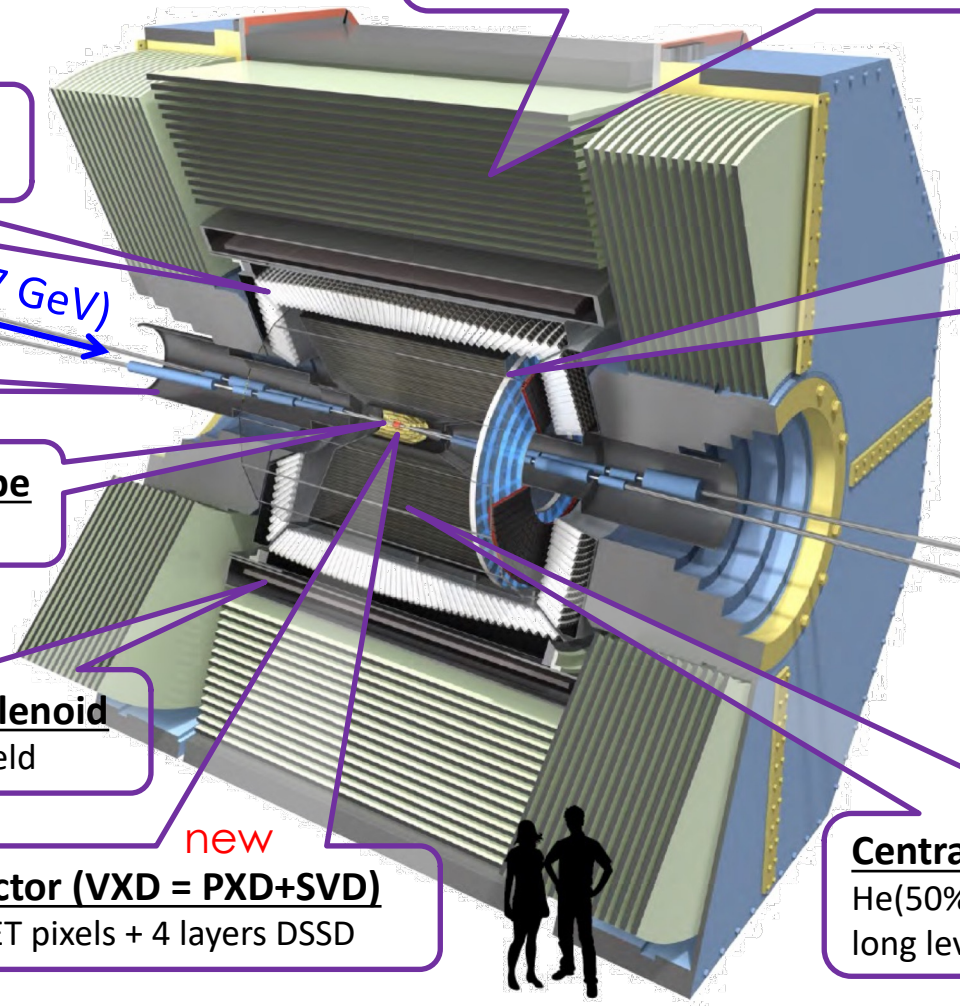


⇒ Started in 2018



Belle II detector

Upgraded or new / Belle



KLong and muon detector (KLM) upgraded
Resistive Plate Chambers (barrel outer layers)
Scintillator + WLSF + SiPM's (end-caps , inner 2 barrel layers)

EM Calorimeter (CDC) upgraded
CsI(Tl), waveform sampling (barrel+ endcap)

electrons (7 GeV)

new
Final focusing magnets

Beryllium beam pipe
2cm diameter new

SuperCond. Solenoid
1.5 T magnetic field

new
Vertex Detector (VXD = PXD+SVD)
2 layers DEPFET pixels + 4 layers DSSD

C.Irmler, SVD
Tuesday AM poster

Particle Identification
TOP detector system (barrel)
Prox. focusing Aerogel RICH (fwd) new

U.Tamponi, PID
Monday PM talk

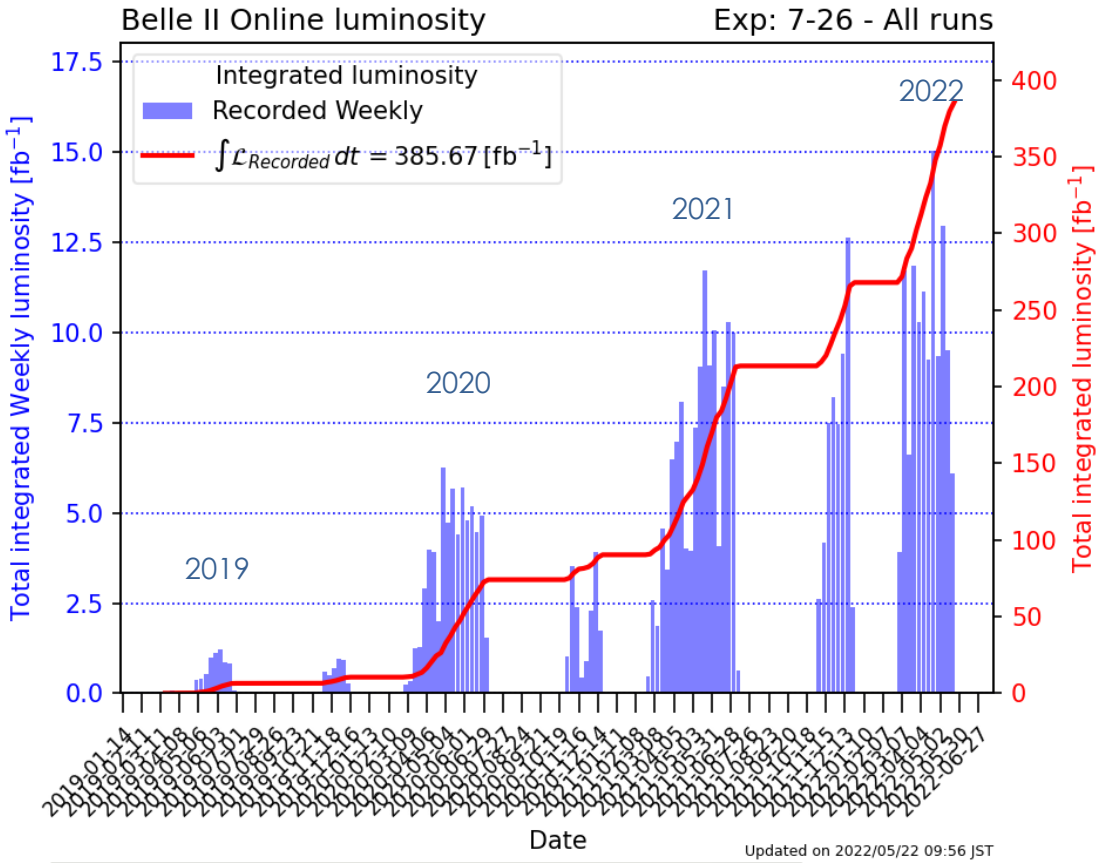
R.Pestonik, ARICH
Monday PM poster

positrons (4 GeV)

Central Drift Chamber new
He(50%):C_2H_6(50%), small cells, long lever arm, fast electronics

Luminosity & data taking timeline

- TODAY
  - 386 fb^{-1} accumulated
  - World record peak lumi 4.1 x 10^{34} cm^{-2}.s^{-1}



Follow us: https://confluence.desy.de/display/BI/Belle+II+Luminosity

- Long Shutdown Jul-2022 / Fall 2023
  - Completeness & robustness of present Belle II

⇩

reach 2 x 10^{35} cm^{-2}.s^{-1}

- Long Shutdown ~2026/27
  - Higher luminosity SuperKEKB
    - Change collider interaction region

⇩

reach 6 x 10^{35} cm^{-2}.s^{-1}

- Beyond 2032, ideas for
  - Extended physics program

⇩

Polarized beams
reach 10^{36} cm^{-2}.s^{-1}

Upgrade motivation

- Mitigate impact of beam-induced background
- Increase detector lifetime against radiation
- Improve performance: more physics/ab^{-1}

- **Long Shutdown Jul-2022 / Fall 2023**
  - Completeness & robustness of present Belle II

    ⇩

    reach 2 x 10^{35} cm^{-2}.s^{-1}

- **Long Shutdown ~2026/27**
  - Higher luminosity SuperKEKB
    - Change collider interaction region

    ⇩

    reach 6 x 10^{35} cm^{-2}.s^{-1}

- **Beyond 2032, ideas for**
  - Extended physics program

    ⇩

    Polarized beams
    reach 10^{36} cm^{-2}.s^{-1}

Upgrade plans

- **Short-term:**
  - Vertex: complete 2nd layer for pixel
  - PID: replace PMTs used in TOP
  - Data acquisition: replace boards (PCIe40)

On-going or planned (not covered here)

- **Medium-term:**
  - Vertex detector
  - Parts of main tracker
  - PID with TOP & KLM

To be decided

- **Long-term:**
  - Tracker
  - PID with TOP, ARICH, KLM
  - Calorimetry

- **Long Shutdown Jul-2022 / Fall 2023**
  - Completeness & robustness of present Belle II

  ⇩

  reach 2 x 10^{35} $cm^{-2}.s^{-1}$

- **Long Shutdown ~2026/27**
  - Higher luminosity SuperKEKB
    - Change collider interaction region

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  reach 6 x 10^{35} $cm^{-2}.s^{-1}$

- **Beyond 2032, ideas for**
  - Extended physics program

  ⇩

  Polarized beams
  reach 10^{36} $cm^{-2}.s^{-1}$

⇒ Snowmass contribution: arXiv 2203.11349

Vertex detector: VXD (PXD+SVD)

Rationale

- Be prepared for IR redesign (higher Background conditions)
- Improve performance / IP resolution, low p_T tracks
- Be prepared to cover inner CDC (radii 135-240 mm)
- Triggering: possible contribution to L1

- Target **Medium-term**

Requirements

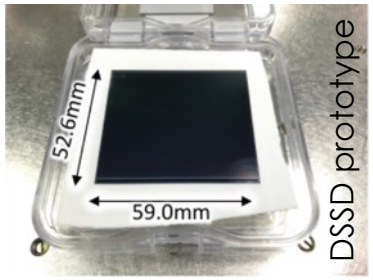
5-6 layers over radii	14-135 mm
Spatial resolution	< 15 µm
Total material budget	< (2x0.2% + 4x0.7%) X_0
Hit rate	120 ↘ 1 MHz/cm^2
Total Ionizing Dose (inner)	100 kGy / year
NIEL fluence (inner)	5x10^{13} n_{eq}/cm^2

⇒ Higher granularity in time and/or space / current VXD

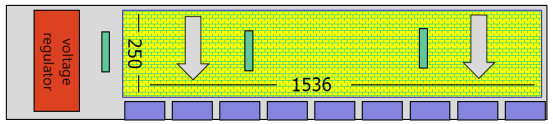
Prototyping & tests on-going

Various proposals

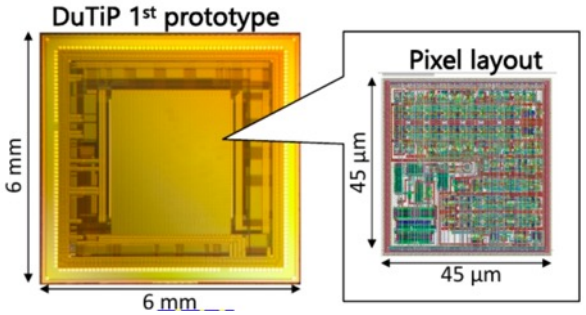
- **Thin and fine-pitch DSSD**
  - Sensor 140 µm thin & z-pitch < 80 µm
  - New ASIC for low noise



- **Upgraded DEPFET**
  - Higher radiation tolerance through higher gain
  - Faster read-out (few µs) with re-orientation and new ASICs



- **SOI pixels**
  - Lapis 200 nm process
  - Dual Time pixel sensor (DuTiP)
  - pitch 45 µm
    2x60 ns integration



- **CMOS-MAPS**
  - Tower 180 nm process
  - Extension of TJ-MONOPIX2 ⟶ OBELIX sensor
  - Pitch <40 µm with 100 ns integration
  - Fully pixelated VXD concept = **VTX**
    with all-Si modules or ALICE-ITS-like ladders

Vertex detector: VXD (PXD+SVD)

Rationale

- Be prepared for IR redesign (higher Background conditions) @ medium-term
- Be prepared to cover inner CDC (radii 135-240 mm)
- Improve performance / IP resolution, low p_T tracks
- Triggering: possible contribution to L1

- Target **Medium-term**

Requirements

5-6 layers over radii	14-135 mm
Spatial resolution	< 15 μm
Total material budget	< (2x0.2% + 4x0.7%) X_0
Hit rate	120 ↘ 1 MHz/cm^2
Total Ionizing Dose (inner)	100
NIEL fluence (inner)	5x1

⇒ Higher granularity in

prototyping & tests on-going

C.Wessel, MAPS uprgade
Tuesday AM talk

L.Massaccesi, VTX perf. simulation
Tuesday AM poster

Various proposals

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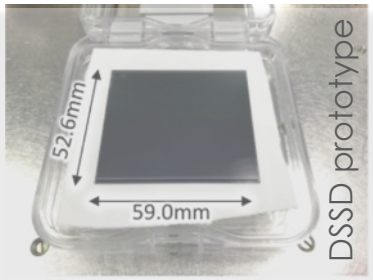
  - New ASIC for low noise



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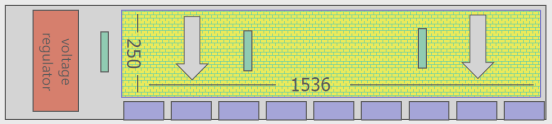

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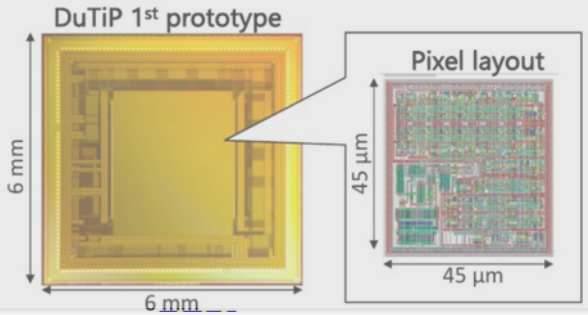

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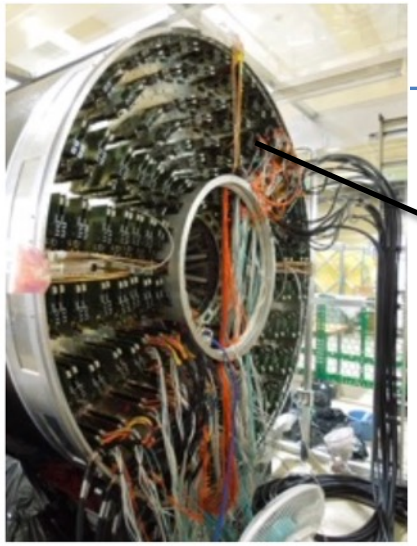
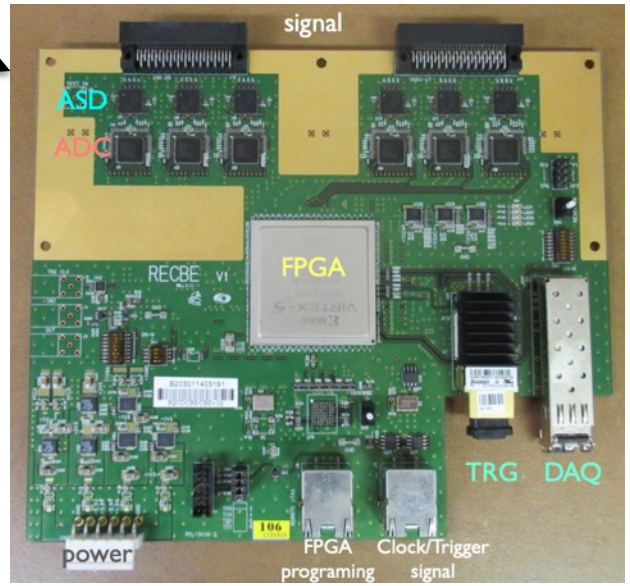
Main tracker: CDC



Current read-out board



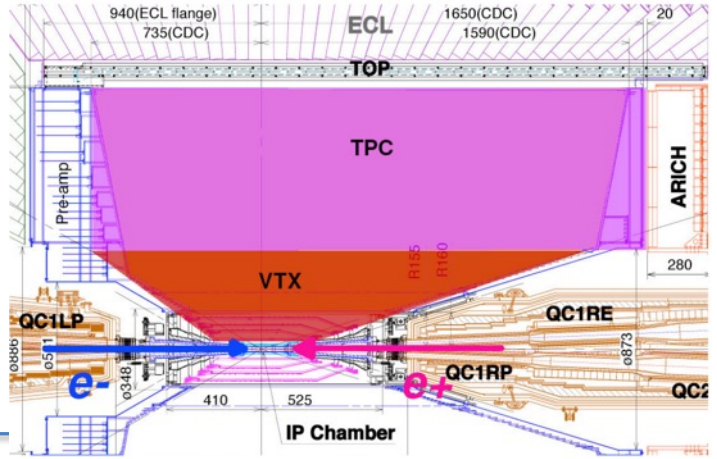
- [Short-/Medium-term](#)
  - Robustness against radiation-damage
  - Mitigate cross-talk between read-out channels

- [Replacement of read-out board](#)
  - New ASIC
    - all-in-one ASD+ADC, lower cross-talk (100 ↘ 10 mV/7pC)
  - Components with higher radiation tolerance
    - Optical transceiver (sensitive to γ and neutrons)
    - FPGA (sensitive to SEU)

- Tests in 2022
- Mass production 2023

- [Long-term studies](#)
  - Sustaining higher rates & backgrounds

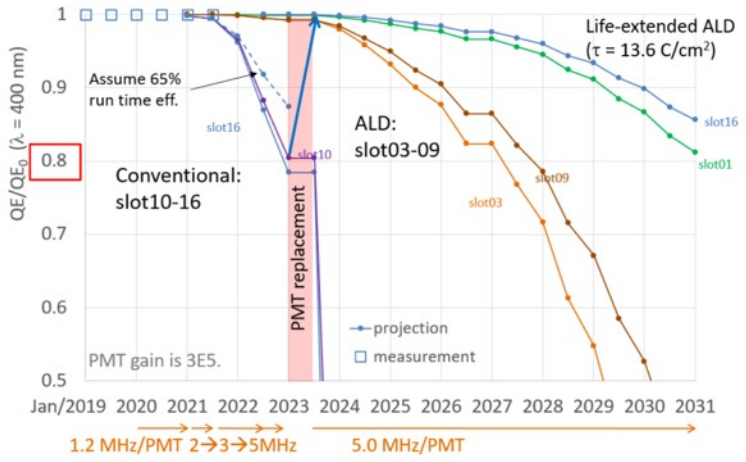
- [Exploration](#)
  - Extended VTX
  - TPC tracker with pixel read-out Gridpix-like 200^2 μm^2



Particle Identification: TOP & ARICH

Time Of Propagation (TOP)

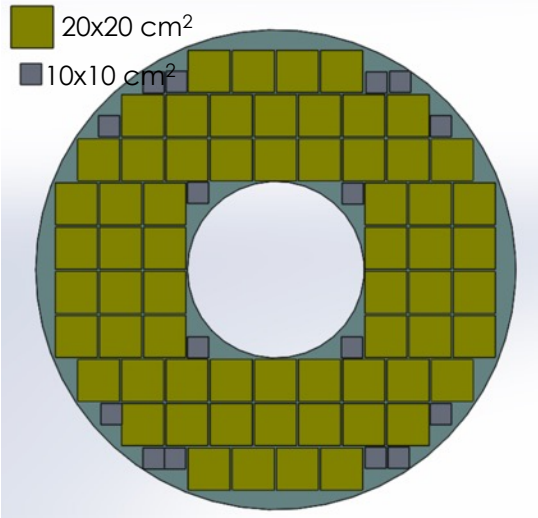
- Maintain efficiency against ever higher background
  - Needed already at **short/medium-term**
- Photon detection devices
  - 2022: move to Atomic Layer Deposited ALD-MCP-PMT
  - 2026: move to life extended ALD-MCP-PMT possibly to SiPM



- Read-out electronics to accommodate SiPM
  - Better compactness using SiPM dedicated ASICs
  - Allows extra cooling required by SiPM

Aerogel RICH

- target **long term**
  - Current Hybrid-APD not adapted beyond $8x10^{35}$ $cm^{-2}.s^{-1}$
- 1st option: SiPM
  - On-going evaluation of various device
    - Single photon detection, Dark count rate, Neutron sensitivity ($5x10^{12}$ n_{eq}/cm^2), Cooling required
- 2nd option: Large Area Picosecond photodetectors
- Read-out
  - Upgrade of current ASIC
  - Or new ASIC



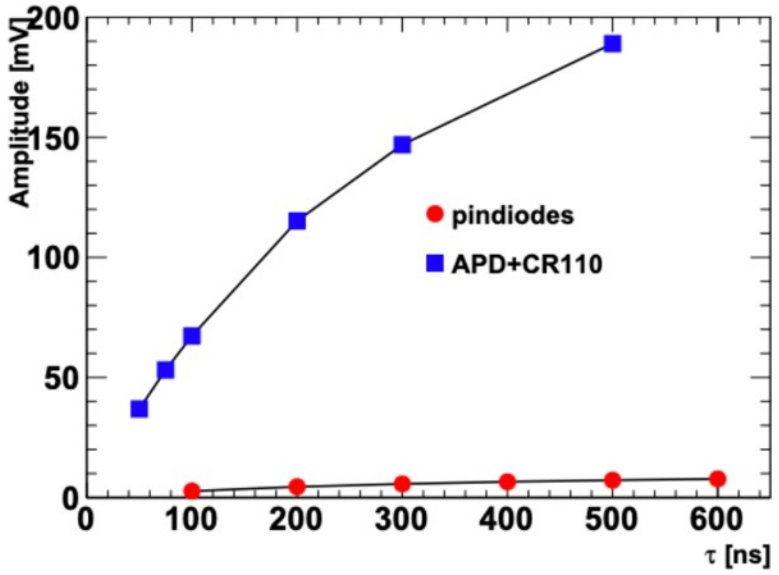
STOPGAP proposal

- target **long term**
- Fill-in gaps between TOP quartz bar
- CMOS-MAPS with 50 ps timing

Calorimetry: ECL

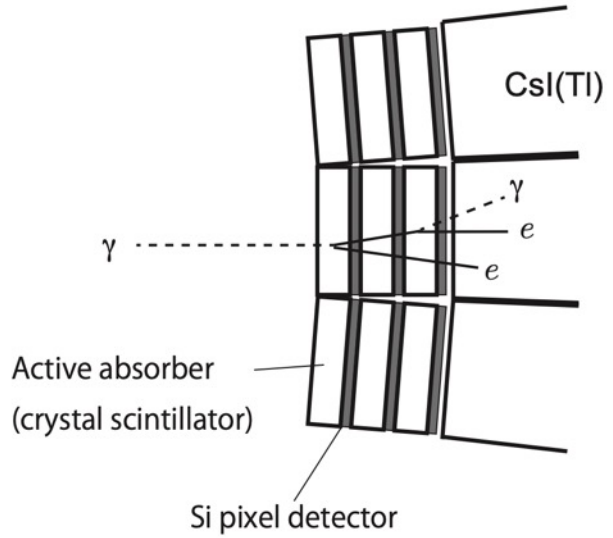
- Rationale
  - Target **long-term**
  - Reduce pile-up from beam-induced background
  - Sensitivity to photon incident angle

- Read-out of current CsI(Tl)
  - From PiN diodes to APD



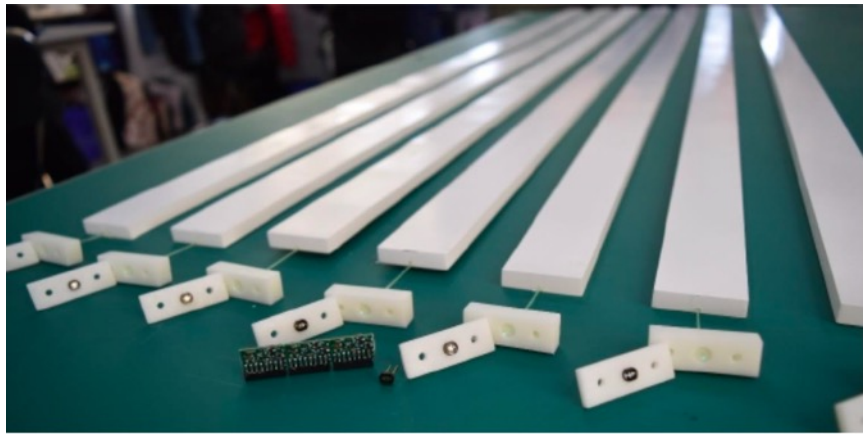
- Faster cristals
  - Full replacement: CsI(Tl) ⟶ pure CsI
    - From 1 μs to 30 ns light decay tile
  - Photon detection: WLS + APD

- New preshower
  - BGO/LYSO + 1mm^2 Si pixel
    - Angle = 0.08 rad expected @ normal incidence



Klong & Muon identification: KLM

- Target **medium to long term**

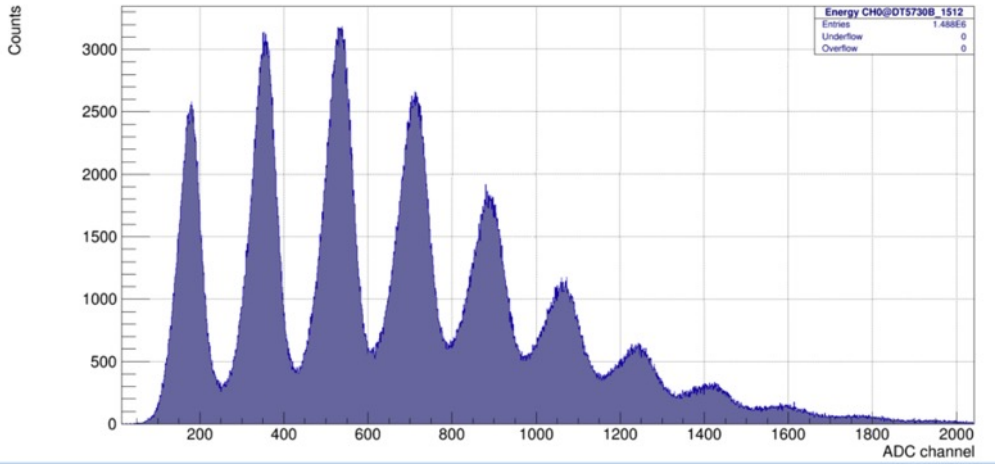


Complete replacement of RPCs with Scintillators

- Rationale: increased rate & robustness of read-out chain
- New system = scint. bars + wave-length shifter fibers + SiPM
  - Already used in first layer & end-cap
- More compact read-out
  - Allowing waveform sampling (time resol.) & improved data push to trigger

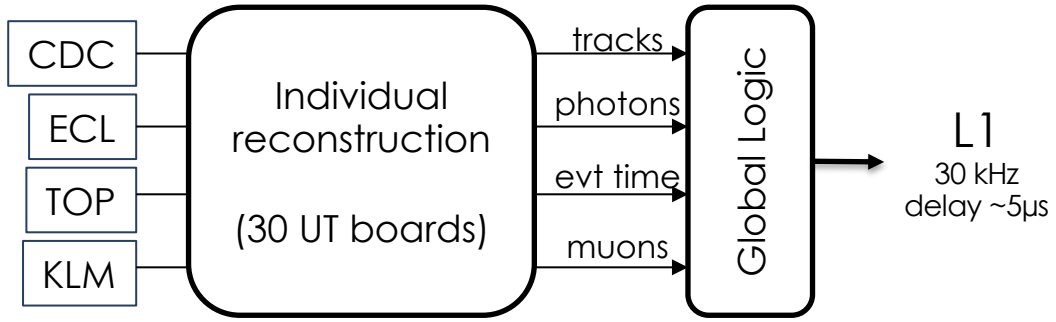
Investigating TOF-like performance

- Rationale: K_L energy & background neutron rejection
- Required time resolution ~30 ps
- R&D on-going with large MPPC + new pre-amp



Trigger

- Rationale
  - Keep high-efficiency on hadronic events
  - Improve efficiency on low-multiplicity events (τ, dark sector)
  - **Continuous improvements**



- Hardware
  - Deployment of most recent UT4 boards
    - Xilinx Ultrascale with 200k gates, 25 Gbps, DDR4
    - Target 2026
  - New UT5
    - Xilinx Ultrascale+ with 8000k gates, 32 Gbps, UltraRAM
    - Lower #boards needed
    - 2024-32

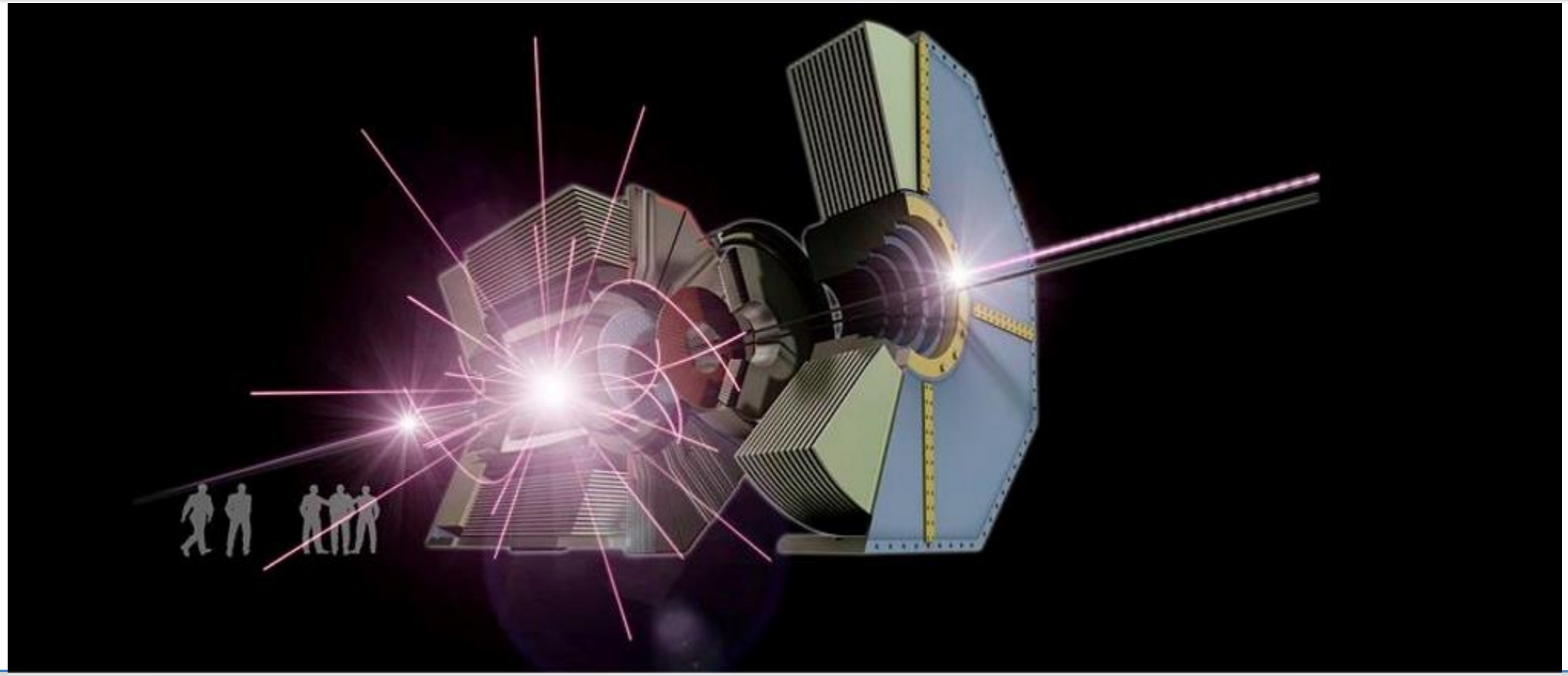
- Firmware

Component	Improvement	Time	#UT
CDC cluster finder	beamBG rejection	2026	10
CDC 2Dtrack finder	increase occupancy limit	2022	4
CDC 3Dtrack finder	enlarge θ angle acceptance	2022	4
CDC 3Dtrack fitter (1)	beamBG rejection	2025	4
CDC 3Dtrack fitter (2)	beamBG rejection	2025	4
Displaced vertex finder	LLP search	2025	1
ECL waveform fitter	resolution	2026	–
ECL cluster finder	beamBG rejection	2026	1
KLM track finder	beamBG rejection	2024	–
VXD trigger	BG rejection	2032	–
GRL event identification	signal efficiency	2025	1
GDL injection veto	DAQ efficiency	2024	–

Summary & Outlook

- Belle II physics goals has steered and is steering a rich instrumental program
- Belle II operates efficiently at peak luminosities just below 10^{35} $cm^{-2}.s^{-1}$
- Short-term: **consolidation of existing technologies**
  - entering the L_{inst} = **1-2 10^{35} $cm^{-2}.s^{-1}$** regime in the next years
- Medium- to Long-term: **introducing new technologies/concepts**
  - running safely at **6x10^{35} $cm^{-2}.s^{-1}$** after 2026 and beyond after 2032
  - with enhanced performances
- **To come**
  - International Task Force on SuperKEKB luminosity ⟶ conclusion THIS summer
  - Conceptual Design Report for medium-term upgrades ⟶ early 2023

SUPPLEMENTARY SLIDES

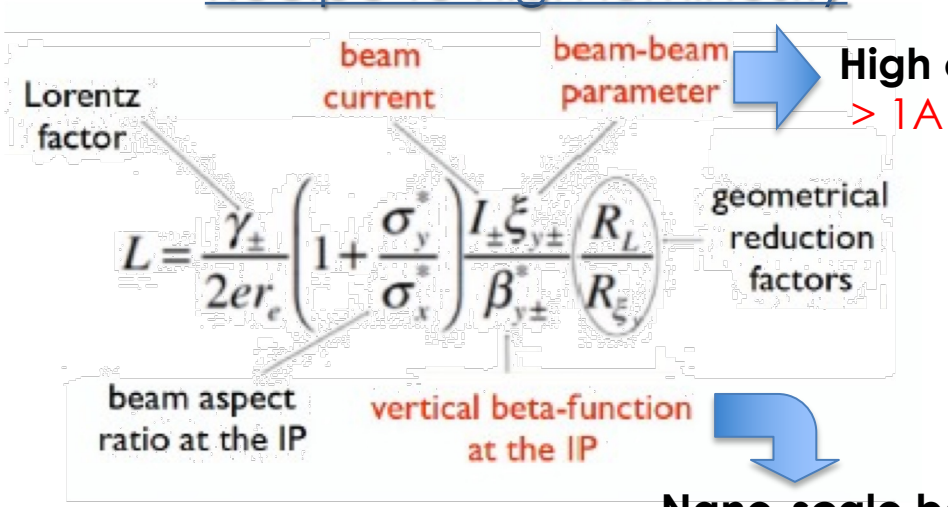


Belle II @ Pisa meeting on advanced det.

- Christian Wessel, MAPS upgrade, Tuesday AM https://agenda.infn.it/event/22092/contributions/167366/
- Umberto Tamponi, PID system, Monday PM https://agenda.infn.it/event/22092/contributions/167677/
- Rok Pestonik, ARICH, Monday posters https://agenda.infn.it/event/22092/contributions/167676/
- Ludovico Massacesi, MAPS simulation, Tuesday poster, https://agenda.infn.it/event/22092/contributions/166670/
- Chrstian Irmler, SVD, Tuesday poster, https://agenda.infn.it/event/22092/contributions/166726/
- Alice Gabriella, Diamond calibration, Tuesday poster, https://agenda.infn.it/event/22092/contributions/166769/

SuperKEKB collider

Recipe to high luminosity



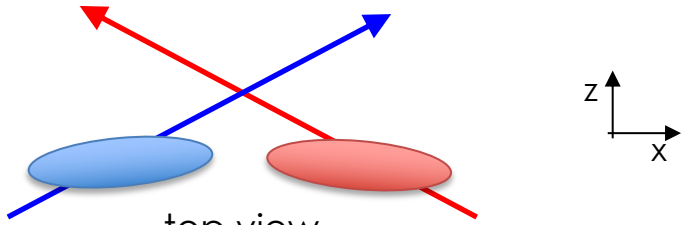
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$

High currents:
> 1A

Nano-scale beam size:
$\sigma_x \times \sigma_y \sim 10\mu m \times \sim 60\ nm$
$B_y^* < 1\ mm$

& specific beam crossing features

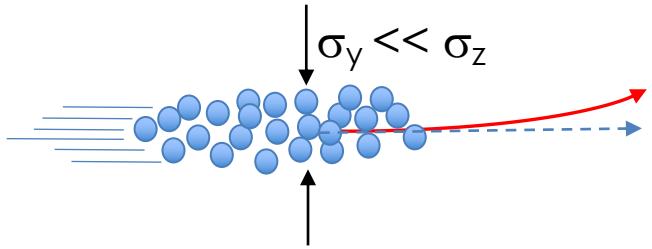
Crossing angle (83 mrad) + crab waist (80%)



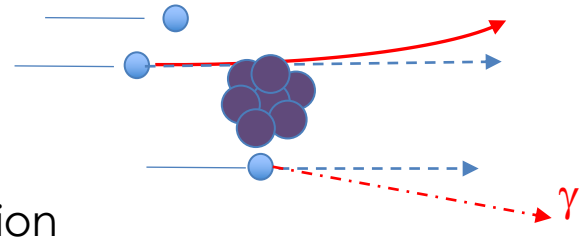
top view

Beam-induced backgrounds

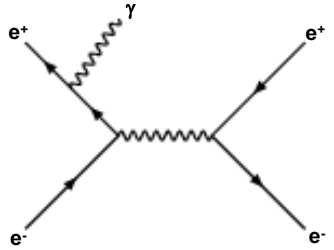
- Intra-beam scattering



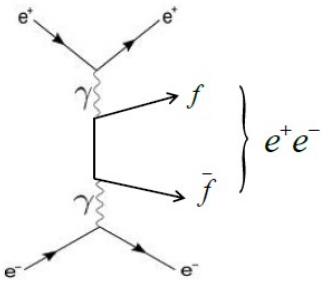
- Beam-gas interaction



- Synchrotron radiation
- Luminosity driven



Radiative Bhabha scattering



2-photon interaction

Overview of the Upgrade program

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

Impact on performance & physics

=> Snowmass Belle II : arXiv 2203.11349

Topic	VXD	CDC	PID	ECL	KLM
Low momentum track finding	✓	✓			
Track p, M resolution		✓			
IP/Vertex resolution	✓				
Hadron ID		✓	✓		
K_L^0 ID				✓	✓
Lepton ID		✓		✓	✓
π^0, γ				✓	
Trigger	✓	✓			

Topic	VXD	CDC (incl. Trigger)	PID	PID(Ω coverage)	ECL	KLM
$\mathcal{B}(B \to \tau\nu, B \to K^{(*)}\nu\bar{\nu})$	✓			✓	✓	✓
$\mathcal{B}(B \to X_u\ell\nu)$	✓		✓	✓		✓
R, Polarisation$(B \to D^{(*)}\tau\nu)$	✓				✓	
FEI	✓	✓		✓		
$S_{CP}, C_{CP}(B \to \pi^0\pi^0, K_S^0\pi^0)$	✓	✓			✓	
$S_{CP}, C_{CP}(B \to \rho\gamma)$		✓	✓		✓	
$S_{CP}, C_{CP}(B \to J/\psi K_S^0, \eta' K_S^0)$	✓	✓				
Flavour tagger	✓		✓			
τ LFV		✓			✓	
Dark sector searches		✓			✓	✓

Belle II, another view