The Belle II Upgrade Program

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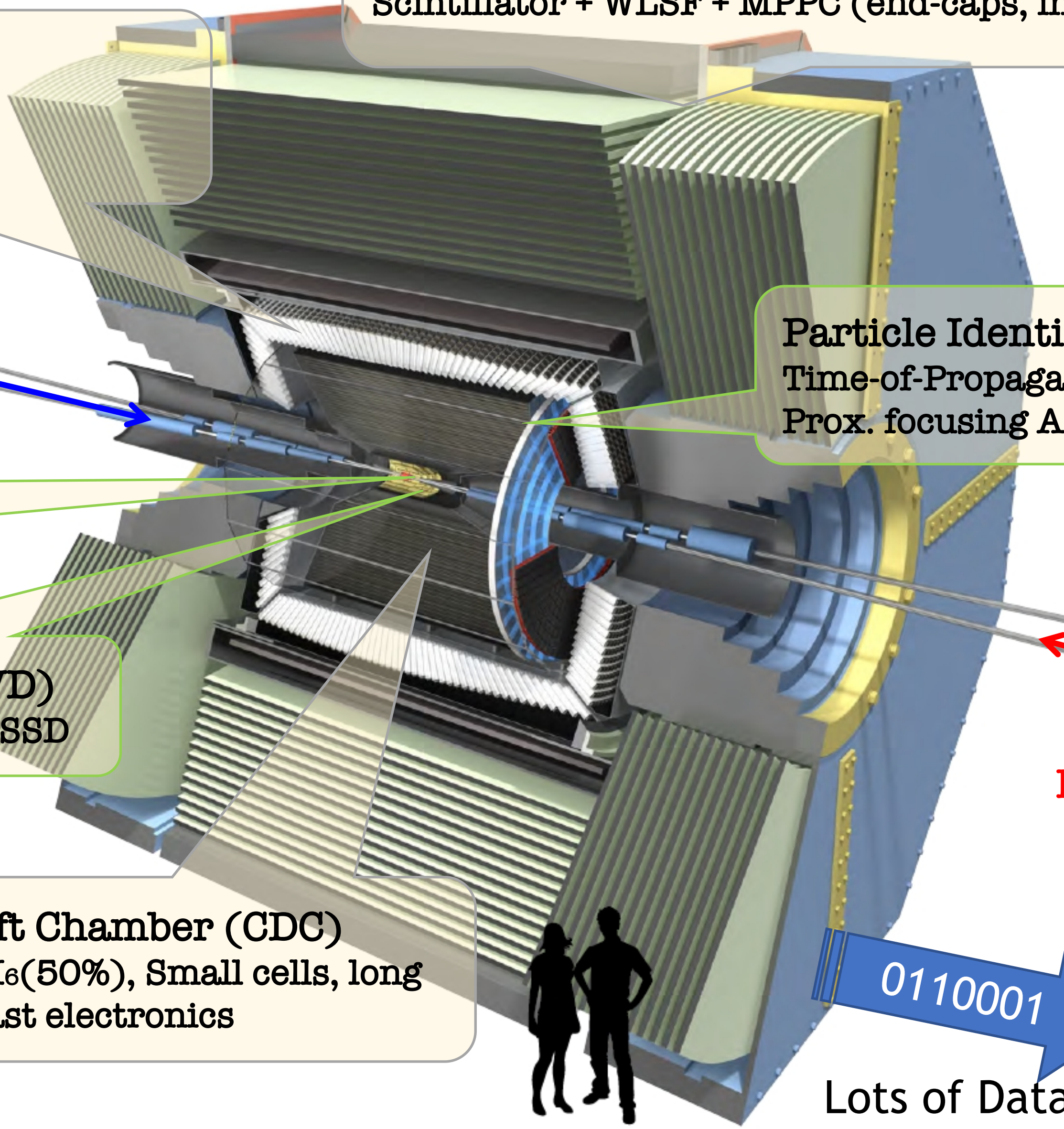
Outline

- The Belle II and SuperKEKB Program
- Timescales for upgrades
- Motivations and opportunities
- Upgrades overview
- Technical description of possible upgrades
- Review process and perspectives

The Belle II Detector



K_L and muon detector: (KLM)
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

EM Calorimeter: (ECL)
CsI(Tl), waveform sampling

TOP: G.Pinna Angioni, #349

Particle Identification (TOP+ARICH)
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

electron (7GeV)

Beryllium beam pipe
2cm diameter

Vertex Detector (PXD+SVD)
2 layers DEPFET + 4 layers DSSD

PXD: B.Spruck, # 225 Tues @ 11.25

SVD: L.Zani, #275 Tues @ 11.50

positron (4GeV)

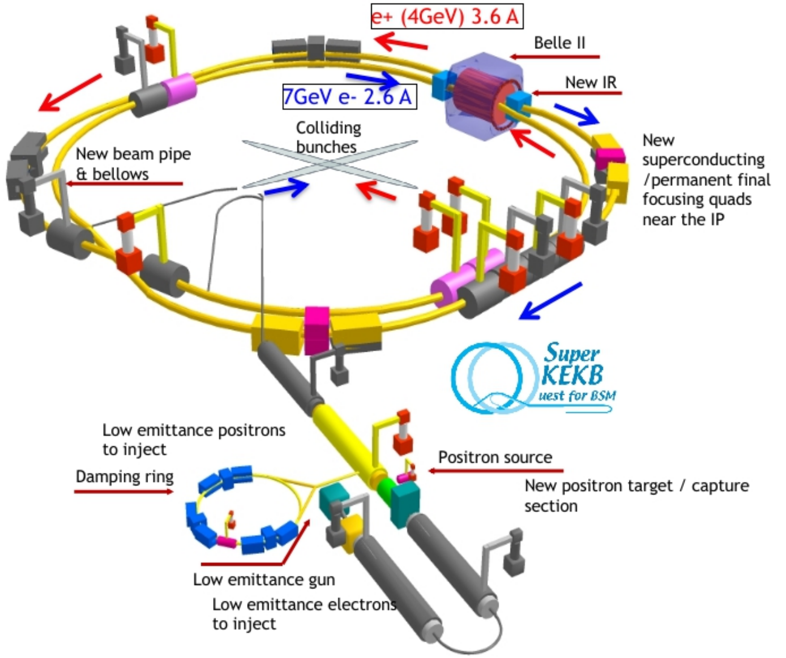
Central Drift Chamber (CDC)
He(50%):C_2H_6(50%), Small cells, long lever arm, fast electronics

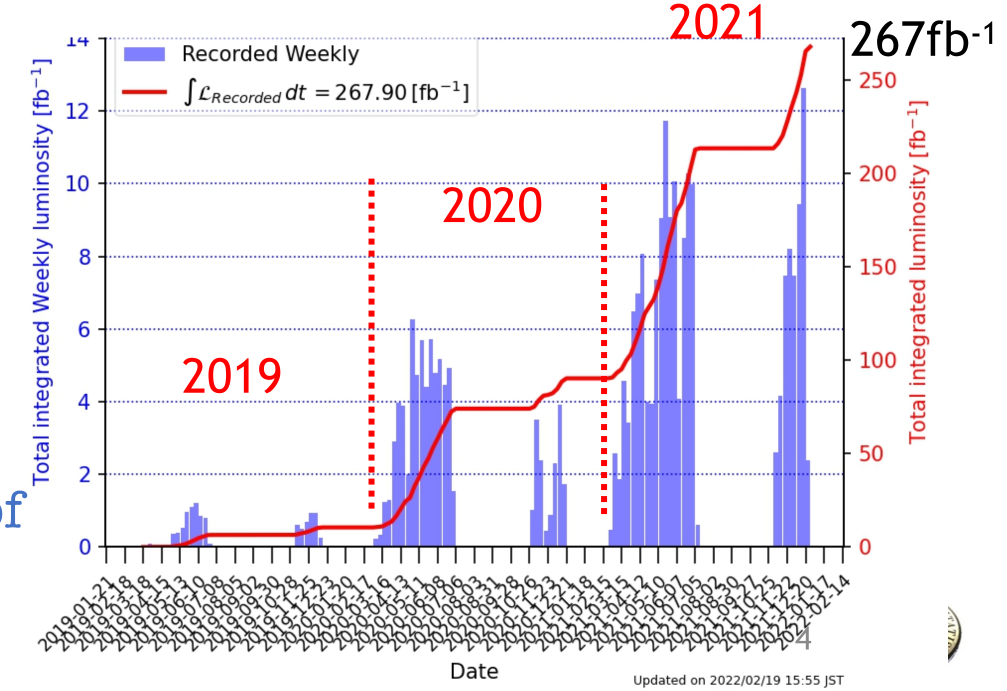
Computing

Lots of Data

The SKB/Belle II program

- Phase 1(2016): no detector, no collision, test the rings
- Phase 2 (2018): first collisions with complete accelerator
  - Incomplete detector: Vertex detector replaced by dedicated background detector (Beast 2)
- Phase 3 (2019-): luminosity run with complete detector
  - Pixel Detector (PXD): layer 1 + only 2 ladders in layer 2
  - Full 4-layers strip detector (SVD)
  - First physics paper appeared in January 2020
- New and difficult accelerator. Additional operational complexity during the pandemic.
- Record peak luminosity $3.81 \times 10^{34} cm^{-2}s^{-1}$.
- Path to reach $2 \times 10^{35} cm^{-2}s^{-1}$ identified.
- Still large factors to reach the target peak luminosity of $6.5 \times 10^{35} cm^{-2}s^{-1}$.





Path to the future

Steep path to higher luminosity

- A. Machine performance and stability
  - Beam blow up due to beam-beam effects
  - Lower than expected beam lifetime
  - Transverse mode coupling instabilities
  - Low machine stability
  - Injector capability
  - Aging infrastructure
- B. Backgrounds in the detector
  - Single beam: Beam-gas, Touchek,
  - Luminosity: Radiative Bhabha, Two photons
  - Injection backgrounds

Mitigation measures

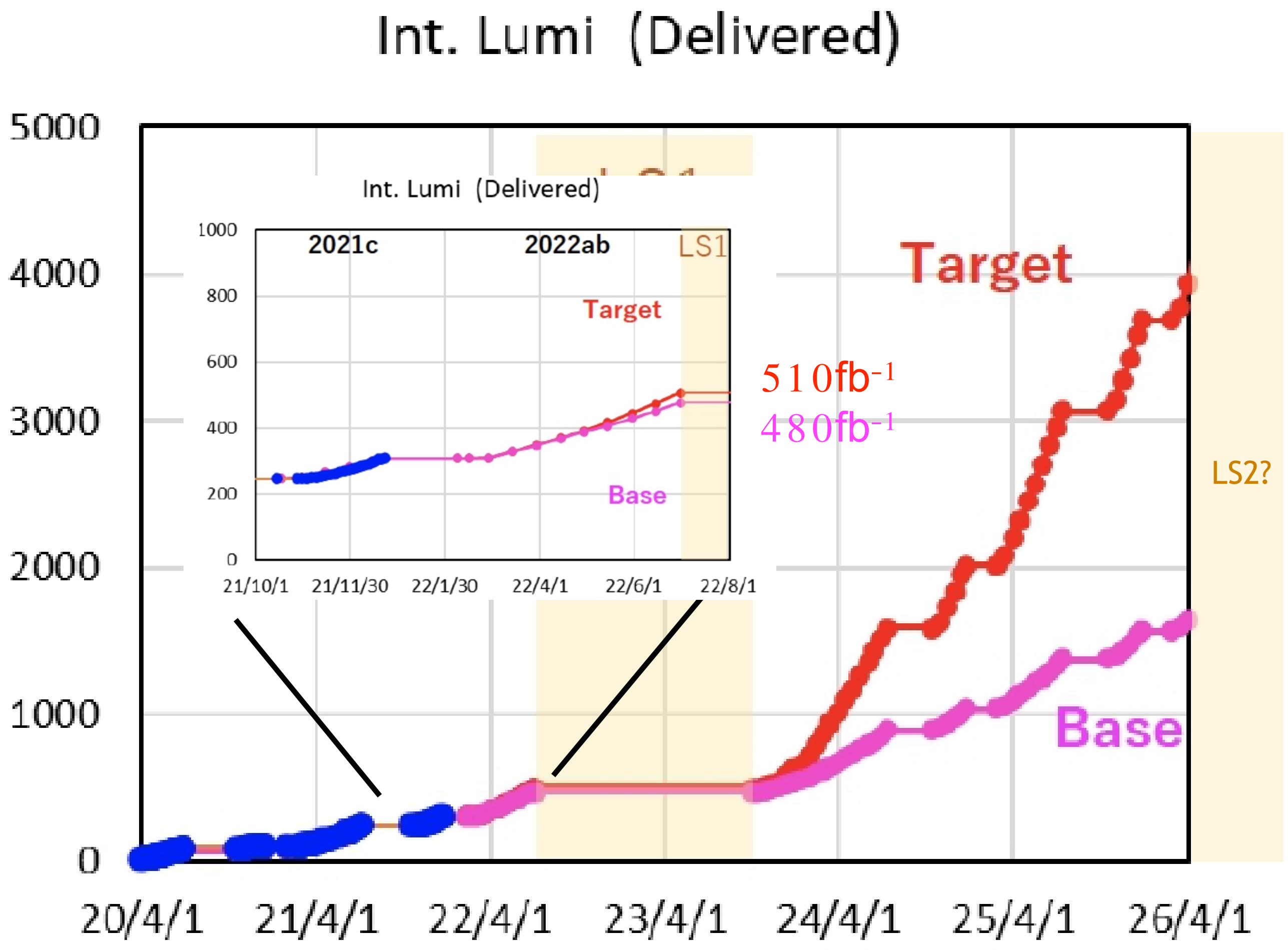
- A. Consolidate machine
  - International task force at work to help
  - Many countermeasures under development
  - A major redesign of the Interaction Region may be required to go beyond $\sim 2 \times 10^{35} cm^{-2}s^{-1}$.
- B. Consolidate the detector
  - Install a complete PXD
  - Complete installation of more robust TOP PMTs
- C. Improve detector
  - Upgrade program to make the detector more robust against backgrounds and with improved performance

Timeline of upgrade work

- Long Shutdown 1 (LS1) planned for 2022-23
  - Motivated by the installation of a complete PXD.
  - Start of LS1 used to be in Dec 22. Advanced to July 22 because of reduction in 2022 running time caused by soaring electricity costs.
- Long Shutdown 2 (LS2): end of 2026 or 2027
  - Motivated by a (still to be defined) redesign of the IR, with superconducting quadrupole replacement.
  - Window of opportunity for significant detector updgrades, but large uncertainties
  - Prepare technology choice for a full VXD replacement
- Longer term upgrades: >2032
  - Not clear at this time how to realize a significant luminosity increase
  - Study the physics case and start technology R&D for an extreme-luminosity detector
  - Interesting possibility of beam polarization under active study; maybe possible on a more rapid timescale

Short term luminosity projections

- Base scenario: conservative extrapolation of SKB parameters from 2021
- Target scenario: extrapolation including possible improvement during LS1
- LS1 starts in summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement work on machine and detector.
- We resume machine operation from fall 2023.
- An International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.



Motivation and for Belle II upgrades

- Improve detector robustness against backgrounds
  - Provide larger safety factors for running at higher luminosity
- Increase longer term subdetector radiation resistance
- Develop the technology to cope with different future paths
  - For instance if a major IR redesign is required to reach the target luminosity
- Improve physics performance: get more physics per ab-1.

- A number of ideas are being developed and reviewed internally for the different time scales

Belle II Upgrades

KLM: Replacement of barrel RPC with scintillators, upgrade of readout electronics, possible use as TOF

ECL: Crystal replacement with pure CsI and APD; pre-shower; replace PIN-diodes with APD photosensors.

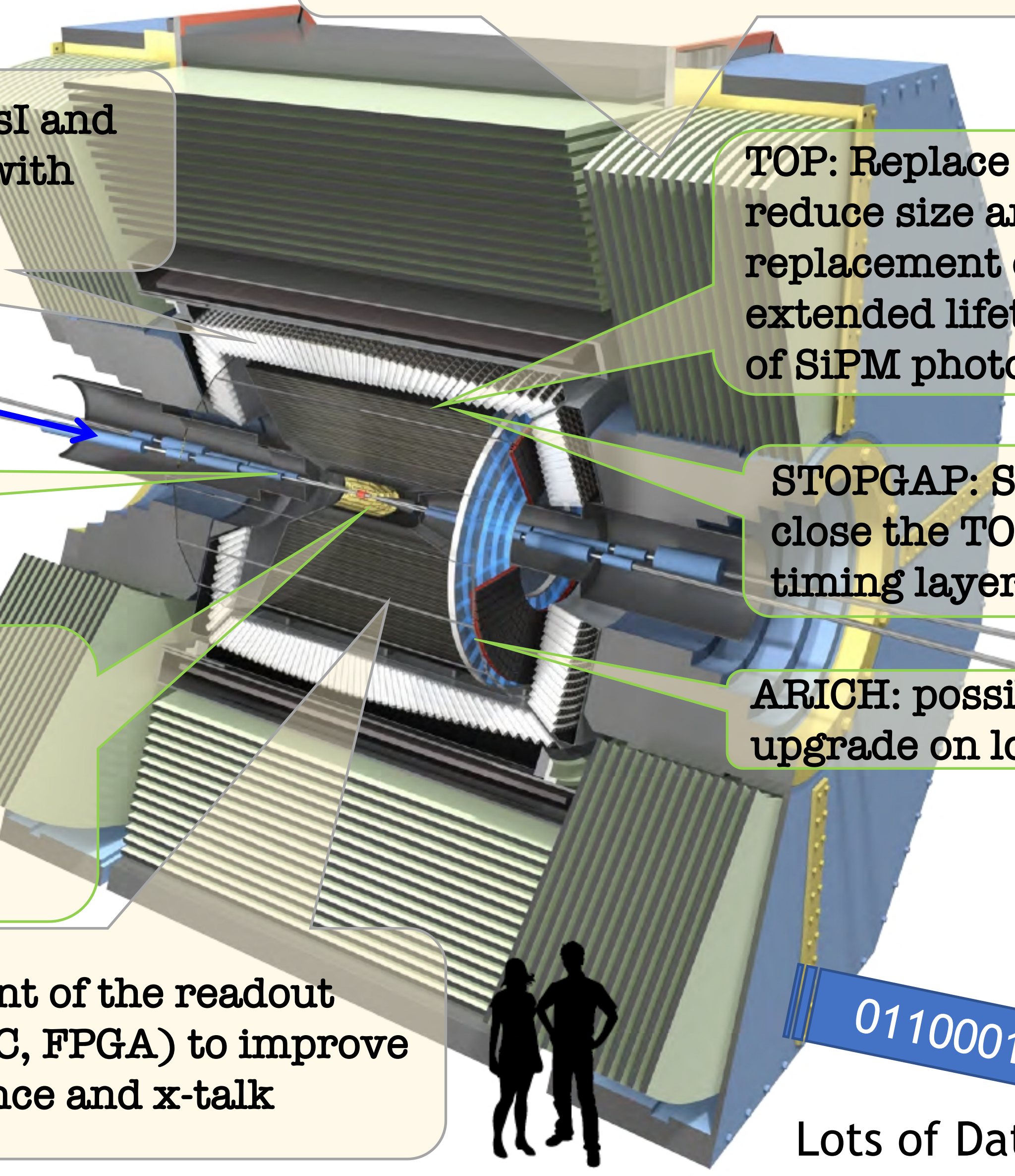
VXD: C.Bespin #151, Thurs@12.15

Trigger: K.Unger #201

TOP: Replace readout electronics to reduce size and power, replacement of MCP-PMT with extended lifetime ALD PMT, study of SiPM photosensor option

QCS replacement and IR redesign

STOPGAP: Study of fast CMOS to close the TOP gaps and/or provide timing layers for track trigger

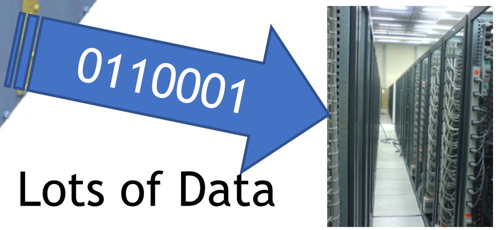


VXD: options
- DEPFET
- Thin Strips
- SOI-DUTIP
- DMAPS

ARICH: possible photosensor upgrade on longer term

TRIGGER: Take advantage of electronics technology development. Increase bandwidth, open possibility of new trigger primitives

CDC: Replacement of the readout electronics (ASIC, FPGA) to improve radiation tolerance and x-talk



Upgrades main ideas and time scale

EOI	Upgrade ideas scope and technology	Time scale
DEPFETs	Adiabatically improved replacement of existing PXD system	LS2
DMAPS	Fully pixelated Depleted CMOS tracker, replacing the current VXD. Evolution from ALICE ITS developed for ATLAS ITK.	LS2
SOI-DUTIP	Fully pixelated system replacing the current VXD based on Dual Timer Pixel concept on SOI	LS2
Thin Strips	Thin and fine-pitch double-sided silicon strip detector system replacing the current SVD and potentially the inner part of the CDC	LS2
CDC	Replacement of the readout electronics (ASIC, FPGA) to improve radiation tolerance and x-talk	< LS2
TOP	Replace readout electronics to reduce size and power, replacement of MCP-PMT with extended lifetime ALD PMT, study of SiPM photosensor option	LS2 and later
ECL	Crystal replacement with pure CsI and APD; pre-shower; replace PIN-diodes with APD photosensors.	> LS2
KLM	Replacement of barrel RPC with scintillators, upgrade of readout electronics, possible use as TOF	LS2 and later
Trigger	Take advantage of electronics technology development. Increase bandwidth, open possibility of new trigger primitives	< LS2 and later
STOPGAP	Study of fast CMOS to close the TOP gaps and/or provide timing layers for track trigger	> LS2
TPC	TPC option under study for longer term upgrade	> LS2

Belle II Upgrades Description

A very quick tour through the technical description of the upgrades

VXD Upgrade -Requirements

Radius range: R	14 – 135 mm (**)
Tracking & Vertexing performance at least as good as current VXD	
Single point resolution(*)	< 15 um
Total material budget	< (2x 0.2% + 4x 0.7%) X_0
Robustness against radiation environment	
Hit rate(*)	~ 120 MHz/cm^2
Total Ionizing Dose(*)	~ 10 Mrad/year
NIEL fluence(*)	~ 5.0×10^{13} $n_{eq}/cm^2/year$

(*) requirement for the innermost layer (R=14mm)
(**) Optionally, we may include also the CDC inner region (135<R<240mm)

- Be prepared for a major interaction region redesign
  - Allow large safety factors against backgrounds
- Take advantage of technology development
- Possible performance improvements
  - Impact parameter and vertexing resolution
  - Tracking performance for low pT tracks
  - Lower trigger latency
  - L1 trigger capabilities

Thin DSSD option - replace SVD

Thin/fine-pitch SVD (TFP-SVD) concept

Targets

- Outer layers
- Handle higher hit-rate
  - O(1MHz/cm²) R>4cm
- Improve tracking/K_S vertexing performance

Thin DSSD sensor (Micron)

Thinner sensor: 140um

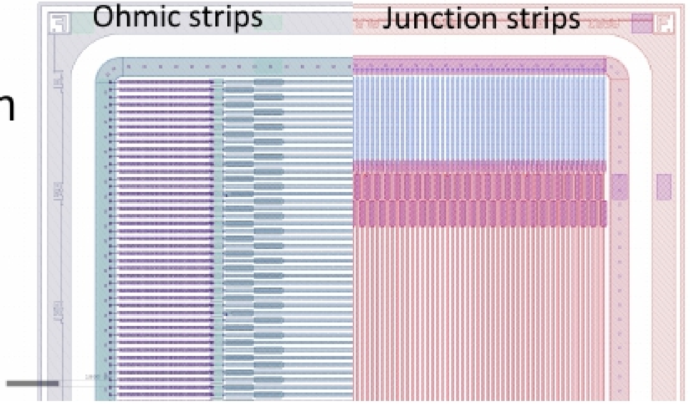
Finer N-side strip pitches than SVD: ~85um

Develop new front-end ASIC (SNAP128A)

→ **R&D challenges in front-end**

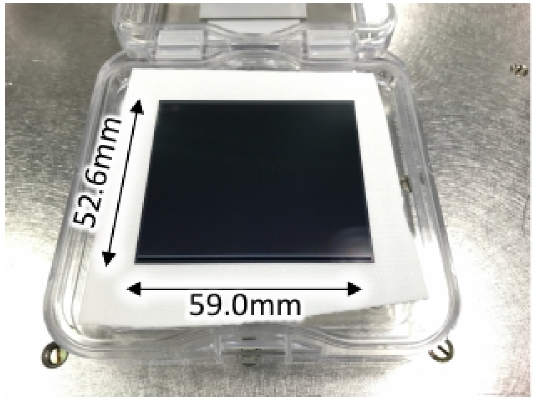
- Small noise : ~640e⁻ @ C_{det}=12pF (simulation)
- Small heat dissipation: ~330mW
- Short signal pulse width : ~60us

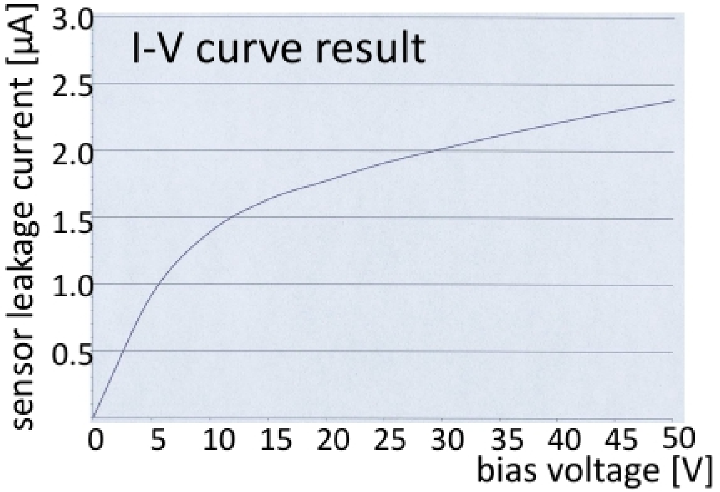
TFP-SVD DSSD layout



- Basic characterization of prototype sensors
  - Reasonable I-V and C-V curves
  - Thickness: 148±5um
  - Full depletion voltage: 14±1 V
- Performance evaluation of prototype ASIC on going

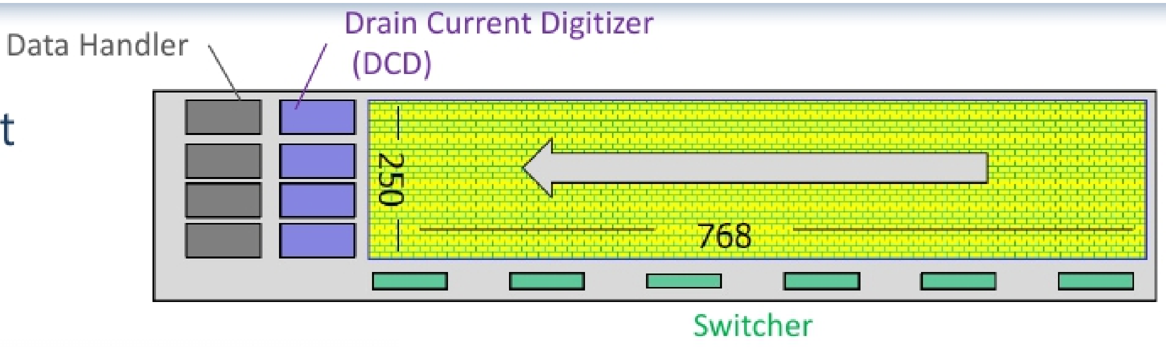
DSSD prototype





DEPFET Option - Replace PXD

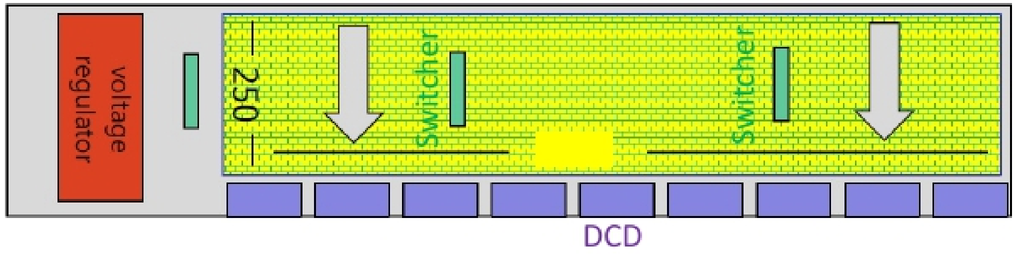
- **Current Belle II PXD**
  - First use of the technology in HEP experiment
  - Current integration time: 20 µs



- **Sensor R&D**
  - Gain increase with shorter FET length L
    - higher amplification in pixel → thinner oxide → improved radiation tolerance
  - Extend Cu interconnection layer into pixel array
    - improve the signal integrity of fast signals (e.g. "clear" and "gate")

$$g = \frac{dI_{drain}}{dQ} \propto \sqrt{\frac{t_{ox}}{L^3}}$$

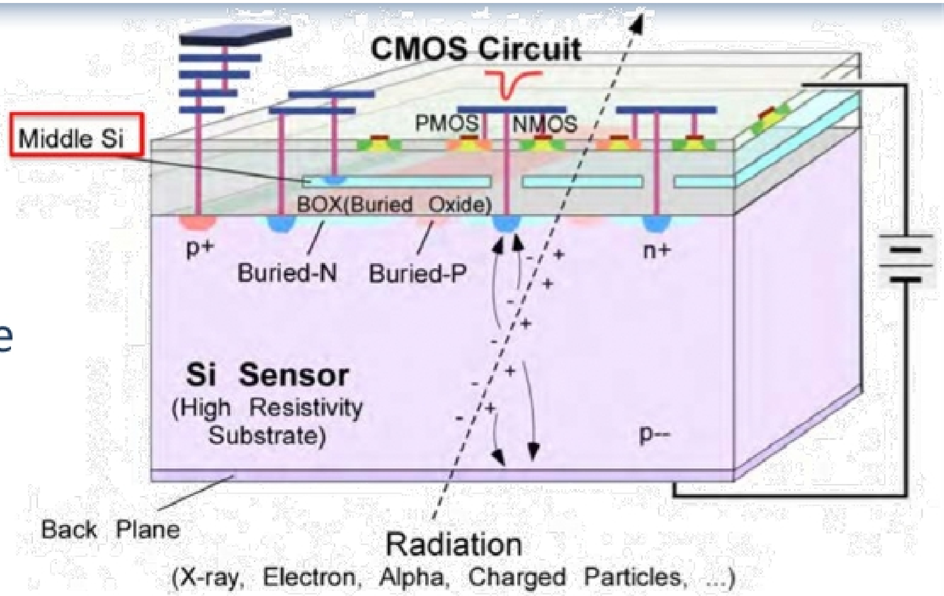
- **ASIC R&D**
  - Faster driving and readout circuit
    - Integration speed x2
- **More aggressive option**
  - Rotate readout direction of pixel array by 90°
    - Additional improve on integration speed x3



SOI Option - Fully pixelated VXD

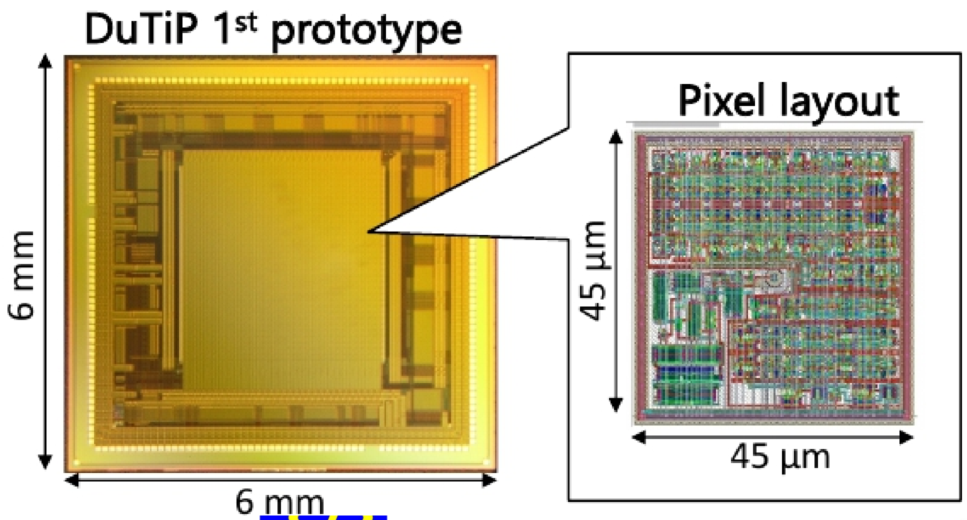
Silicon-On-Insulator pixel (SOIPIX)

- CMOS circuit produced on silicon wafer isolated by a buried oxide (BOX) layer
  - Full depleted sensor: Fast signal, good S/N
  - Logics w/o well structure: High density, small capacitance
  - Complex circuit can be implemented in each pixel
- Produced by LAPIS semiconductor



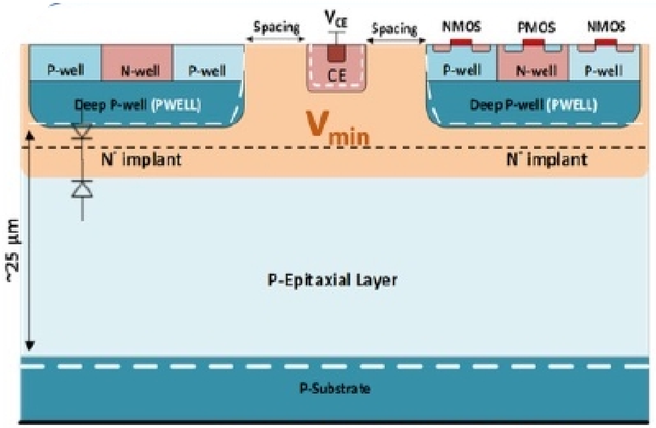
Dual Timer Pixel (DuTiP) sensor

- Alternative operation of two timers allows the next hit before the trigger arrival for the previous hit.
- Target thickness: 50um
- Prototype sensor produced
  - Modified ALPIDE (low power) analog circuit
  - Basic in-pixel digital circuit
  - Performance evaluation is on going



CMOS DMAPS Option - Fully pixelated VXD

DMAPS in TJ 180nm



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

$$C_d \leq 3fF$$

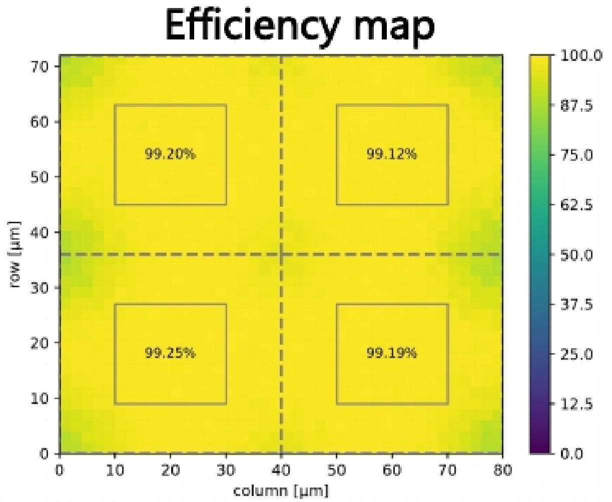
$$P \approx \frac{S}{N} \approx \frac{Q}{C_d}$$

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

TJ-Monopix1

Characterization started in 2018

- Noise, threshold, gain, hit efficiency, and radiation hardness



300 µm Cz: 98.6% @ 490 e⁻ (with 10^{15} n_{eq}/cm^2 irradiation)

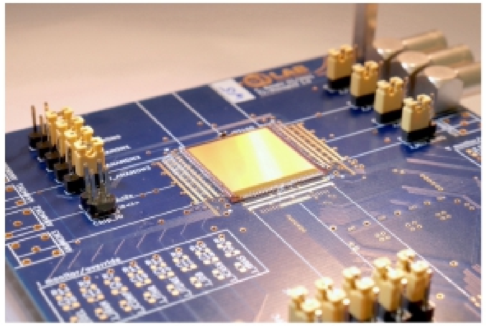
TJ-Monopix2

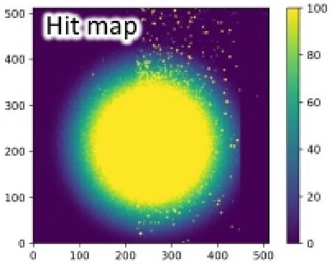
Chip size: 2x2 cm^2

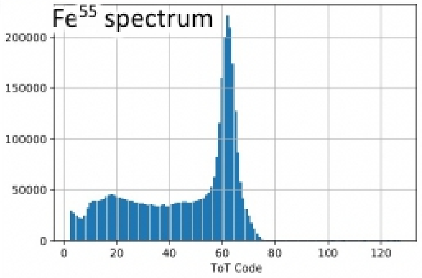
Chip is alive and working

- Synchronization, configuration, DACs
- Analog pixels respond to injection
- Chip detects radiation

Analysis of beam test data on-going





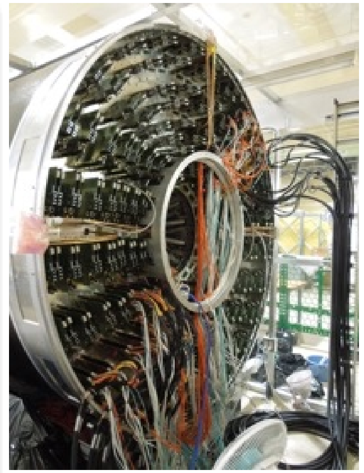


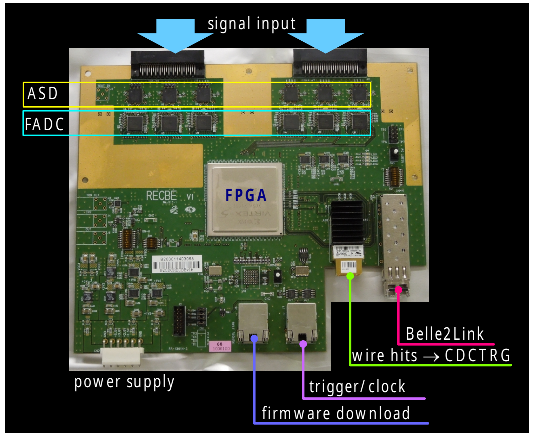
Proof-of-principle prototype

CDC Electronics

- Improve radiation tolerance,
- Reduce cross-talk and power consumption
- New ASIC, new FPGA, optical modules
- First prototypes in Apr 2022
- Installation in LS2

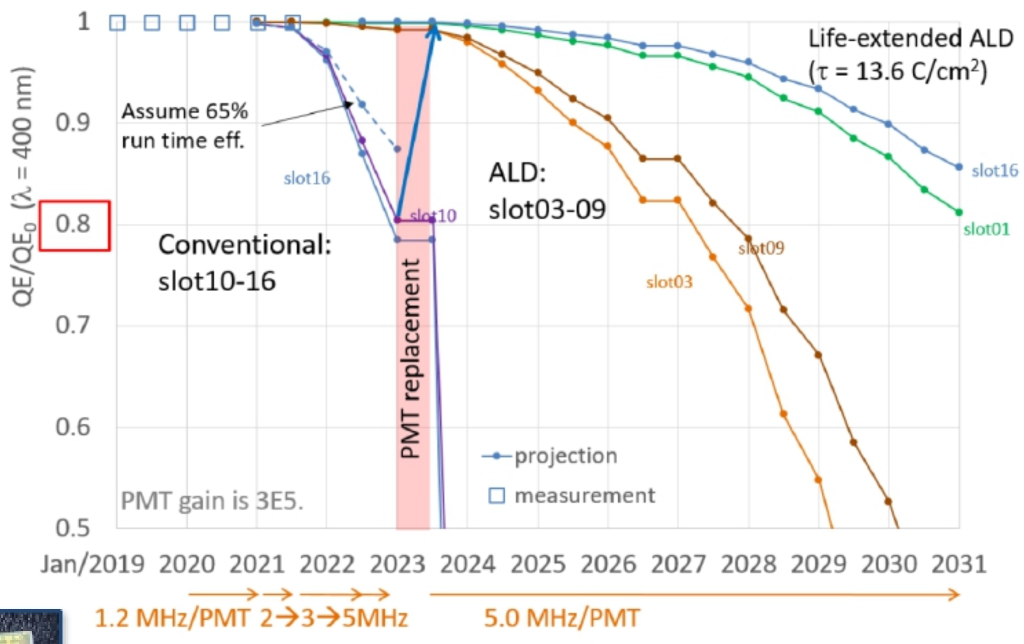
	the present board	upgrade	status
power consumption (ASIC of ASD)	separated chips, ASD and FADC	functions of ASD and FADC are in one chip. ~60% reduction is expected in ASD+FADC	design is almost finalized (M. Miyahara, KEK Esys) mass production from 2023
cross talk (ASIC of ASD)	~100mV pulse height induced in neighbor ch with 7pC input	~10mV pulse height induced in neighbor ch with 7pC input + double thresholds	
FPGA soft error	Virtex-5	Kintex-7	purchased and fabricated on the prototype board. irradiation test is planed in 2022.
radiation tolerance of optical transceiver	SFP for DAQ (1kGY) Avago HFBR-7934WZ for TRG (300-400Gy)	QSFP	purchased several QSFPs to be tested with irradiation
bandwidth of optical transceiver	SFP for DAQ Avago HFBR-7934WZ for TRG (3.125Mb/s)	one QSFP in stead of two different optical transceivers	basic test is done with TRG system

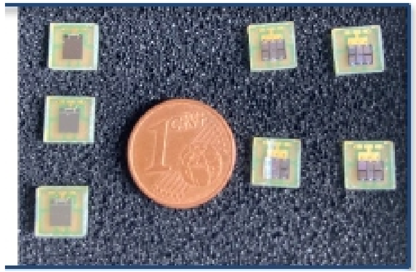


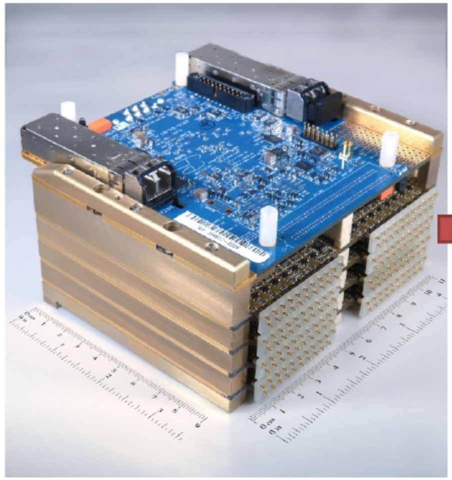


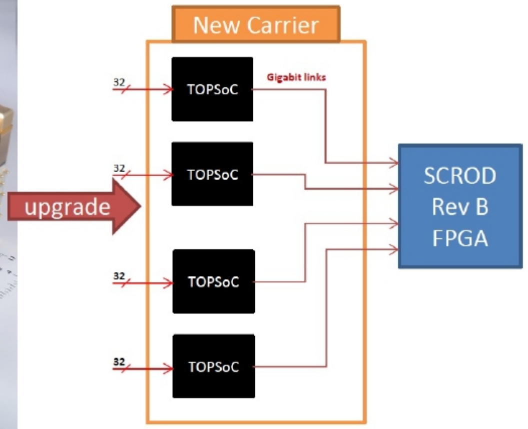
TOP

- Install Life-extended Atomic Layer Deposition PMTs
  - in 2022 for standard PMTs
  - possibly in LS2 for ALD PMTs
- Study of SiPM as possible PMT replacement
  - Require cooling system
  - Longer time scale
- Electronics upgrade
  - IRSX ASIC 8-channel 250 µm CMOS -> TOPSoC ASIC 32-channel 130 µm CMOS
  - Feature extraction inside ASIC
  - Reduced power consumption





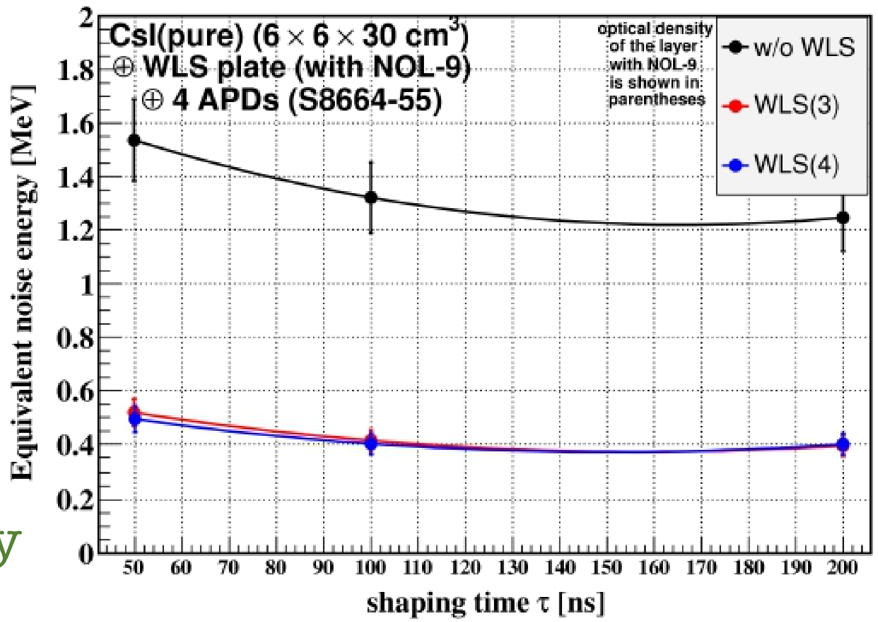


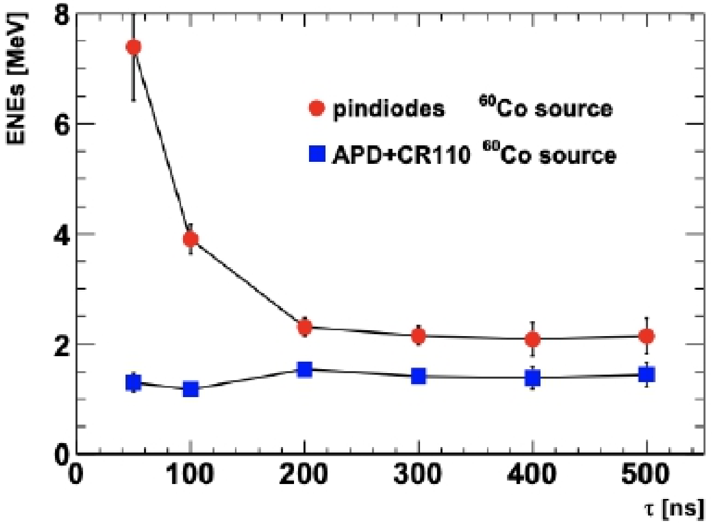


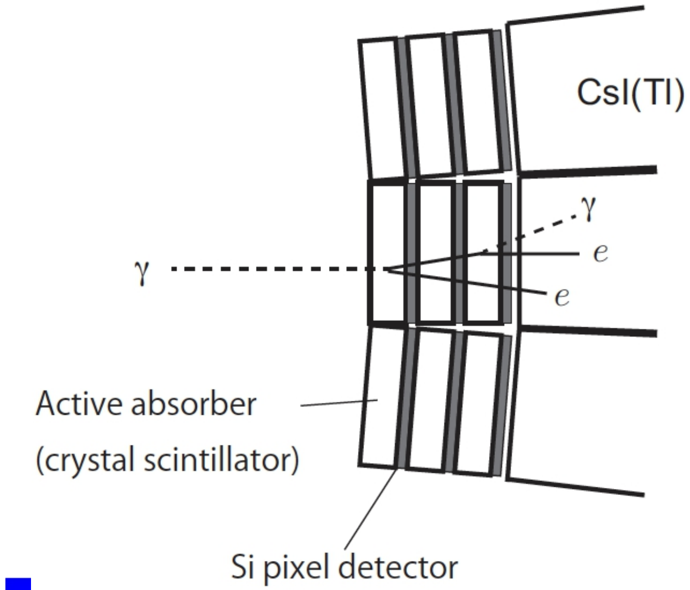
ECL

Hypotheses for long term upgrades

- CsI(Tl) --> pure CsI
  - Improves pile-up
  - WLS employed to improve Equivalent Noise Energy
- Preshower detector
  - Help reduce background and pileup
- PiN diodes --> APDs
  - Reduce ENE and improve resolution
- All complex and expensive options
  - Longer time scale

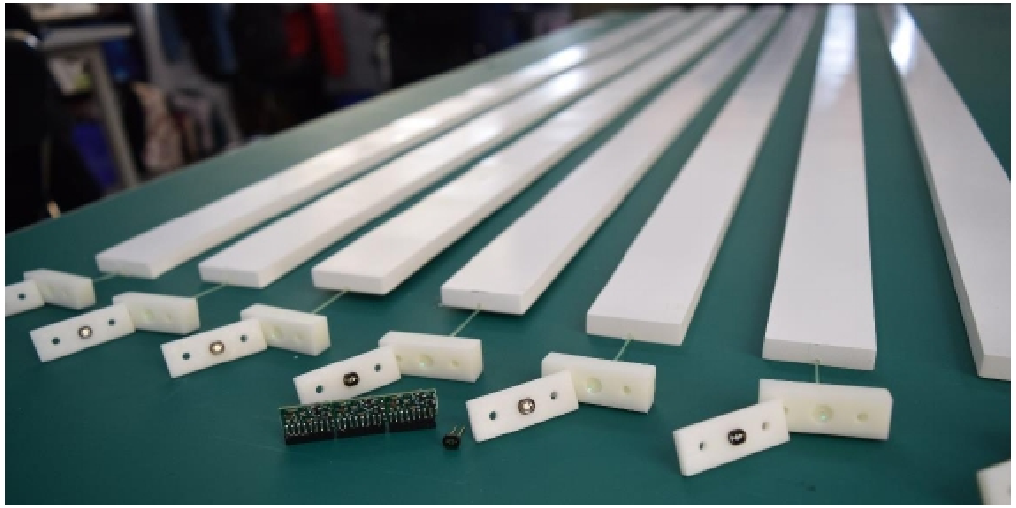


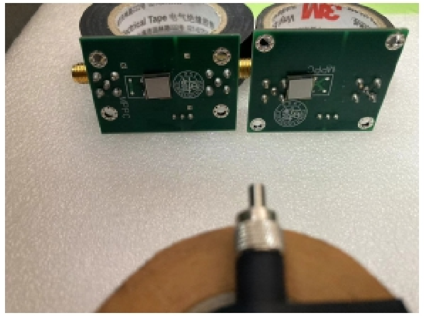




KLM

- RPCs -> scintillator bars + WLS fiber + SiPM
  - Already done in first layers and endcap
  - Increase rate capability
- Readout electronics upgrade
  - More compact readout
  - Data push architecture possible
- Possible use as TOF detector
  - Required time resolution around 30ps
  - Improve KL identification
  - Ongoing studies of scintitllators and SiPM readout arrangement for high time resolution





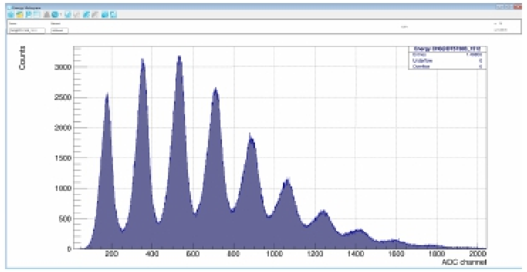
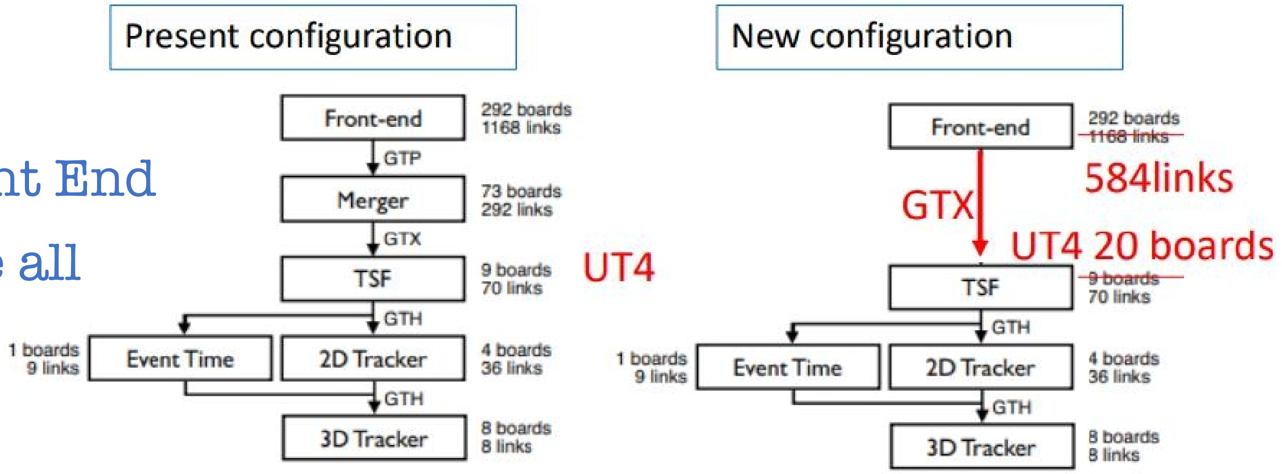


Figure 11: *Left: two sets of new photosensors with newly designed preamplifier and a laser source. Right: the ADC distribution shows clear peaks of p.e.*

Trigger

- More powerful UT4 board for new CDC Front End
- Avoid merger boards, more bandwidth, use all CDC TDC and ADC information
- Many trigger improvements possible.
- Detailed technical documents in preparation



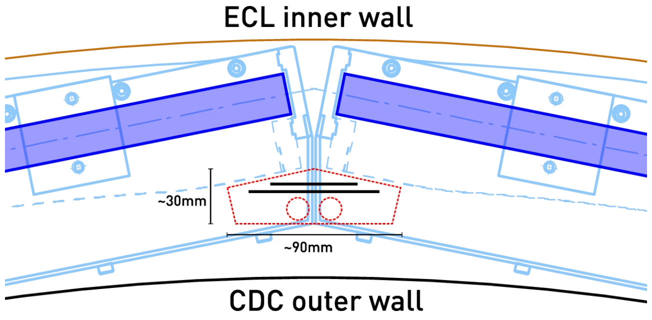
Component	Feature	Improvement	Time	#UT
CDC cluster finder	transmit TDC and ADC from all wires with the new CDC front end	beamBG rejection	2026	10
CDC 2Dtrack finder	use full wire hit patterns inside clustered hit	increase occupancy limit	2022	4
CDC 3Dtrack finder	add stereo wires to track finding	enlarge θ angle acceptance	2022	4
CDC 3Dtrack fitter (1)	increase the number of wires for neural net training	beamBG rejection	2025	4
CDC 3Dtrack fitter (2)	improve fitting algorithm with quantum annealing method	beamBG rejection	2025	4
Displaced vertex finder	find track outside IP originated from long loved particle	LLP search	2025	1
ECL waveform fitter	improve crystal waveform fitter to get energy and timing	resolution	2026	–
ECL cluster finder	improve clustering algorithm with higher BG condition	beamBG rejection	2026	1
KLM track finder	improve track finder with 2D information of hitting layers	beamBG rejection	2024	–
VXD trigger	add VXD to TRG system with new detector and front end	BG rejection	2032	–
GRL event identification	implement neural net based event identification algorithm	signal efficiency	2025	1
GDL injection veto	improve algorithm to veto beam injection BG	DAQ efficiency	2024	–

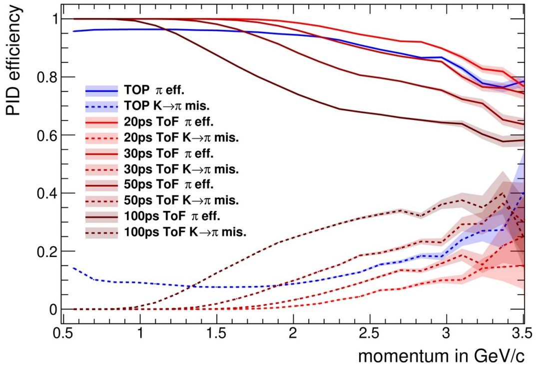
Table 14: TRG firmware upgrade plan.

STOPGAP

- Take advantage of development of fast CMOS sensors

- TOP Quartz bars do not overlap, geometric acceptance only ~94%
- Fill in the quartz gaps with timing sensors: 1-2m^2 active area to fill gaps
  - Pure timing could potentially/eventually replace Belle II barrel PID: ~20m^2 active area
- Feasible with ~50ps single MIP sensors (based on full MC study)





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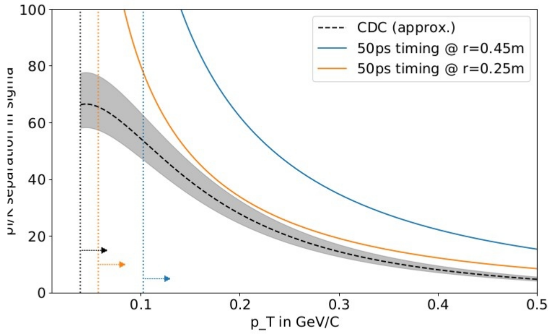
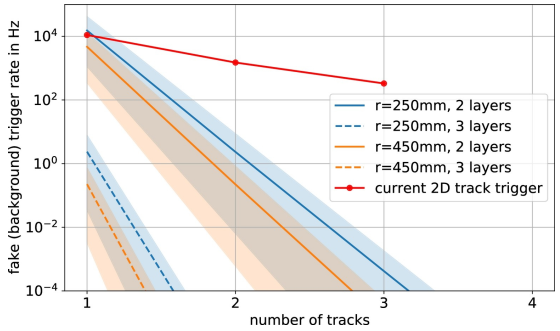
Timing Layers in Belle II Vertex Upgrade

- Toy study: a double timing layer with (very) moderate requirements can reliably provide track trigger information from temporal coincidence alone
  - Also provides excellent pion/kaon separation for $p_T < 1$GeV
  - Separating layers yields momentum estimate and z-cut





- Interesting concept for longer term upgrades. R&D needed

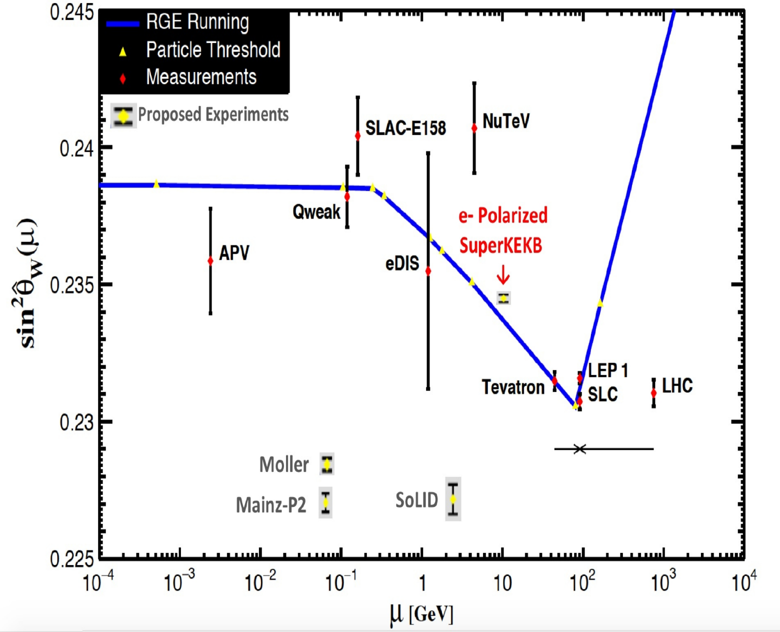
Polarized electron beam

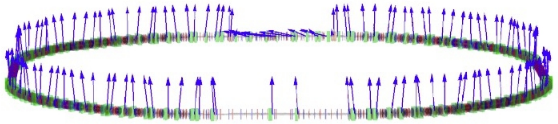
Physics case: precision $\sin^2 \theta_W$ measurements from b, c, e, μ & τ, probing its running and universality.

Planning 70% polarization with 80% polarized source.

NEW HARDWARE FOR POLARIZATION UPGRADE:

- Low emittance polarized Source: electron helicity can be flipped bunch-to-bunch by controlling circular polarization of source laser illuminating a GaAs photocathode (à la SLC). Inject vertically polarized electrons into the 7 GeV e- Ring, needs low enough emittance source to be able to inject.
- Spin rotators: Rotate spin to longitudinal before Interaction Point (IP) in Belle II, and then back to vertical after IP using solenoidal and dipole fields
- Compton polarimeter: monitors longitudinal polarization with <1% absolute precision, provides real time polarimetry. Use tau decays from $e^+e^- \rightarrow \tau^+\tau^-$ measured in Belle II to provide high precision absolute average polarization at IP.





e- spin vector around ring

Project under active development

Physics and performance challenges

- Identify crucial performance challenges impacting physics reach
  - Tracking at low momentum
  - Vertex and IP resolution
  - Calorimetry energy resolution and lepton ID
  - Trigger efficiency
  - K/pi separation
  - KL detection

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	✓	✓			

TABLE II. Key performance requirements vs subdetector upgrades.

Topic	VXD	CDC (i	PID	PID Ω	ECL	KLM
$\mathcal{B}(B \to \tau\nu, B \to K^{(*)}\nu\bar{\nu})$	✓			✓	✓	✓
$\mathcal{B}(B \to X_u \ell\nu)$	✓			✓		✓
$R, P(B \to D^{(*)}\tau\nu)$	✓				✓	
FEI	✓	✓				
$S, C(B \to \pi^0\pi^0, K_S^0\pi^0)$	✓	✓			✓	
$S, C(B \to \rho\gamma)$		✓			✓	
$S, C(B \to J/\psi K_S^0, \eta' K_S^0)$	✓	✓				
Flavour tagger	✓		✓			
τ LFV		✓			✓	
Dark sector searches					✓	✓

TABLE III. Selected key physics channels and the subdetector upgrades that would make substantial impacts to measurement reach.

Summary and outlook

- Belle II and SuperKEKB have started a successful physics run
- Machine improvements are being studied and implemented to reach target luminosity
- Detector upgrade ideas are being explored and R&D is in progress
  - more robustness against background and radiation damage
  - more physics performance
  - readiness for interaction region redesign
- The Belle II upgrade organization is in place
  - Upgrade Working Group and Upgrade Advisory Committee have been established to help establish priorities and direct the effort
  - Belle II Upgrades Whitepaper will be submitted to Snowmass process
- The transition to a construction project is needed soon
  - SKB International Task Force should reach conclusion by summer 2022
  - The preparation of an Upgrades Conceptual Design Report should start afterwards, ready in 2023
- Longer term perspectives
  - Important to start exploring a longer term plan for SKB and Belle II
- There's lots of physics at high luminosity

Thanks !

Additional material

Upgrades and physics performance

- VXD systems: The proposed upgrades all improve occupancy levels, with higher robustness against tracking efficiency and resolution losses from beam background. This implies improved tracking efficiencies with $p_{\mathrm{T}} < 200$ MeV/c.
- CDC: The proposed electronics upgrades improve the quality of tracking through cross-talk reduction, and faster more reliable triggering. This affects general tracking efficiencies, as well as dE/dx measurements.
- TOP: The TOP detector's sensitivity to single photons, i.e. the quantum efficiency, will degrade under irradiation without sensor replacement and upgrade. This directly impacts overall efficacy of the TOP system, as well as time resolution, which is critical for particle ID PDFs.
- ECL: Three upgrade options include new pure CsI crystals with APDs, a pre-shower detector in front of the ECL, and an option where the existing CsI(Tl) are read-out with APDs. The performance of the ECL will degrade with higher background rates. At nominal luminosity, the efficiency may decrease by around 50% for π^0 reconstruction, while extra energy (E_{ECL}) and pulse shape discrimination techniques will degrade in performance.
- KLM: The RPCs will be replaced with new scintillator layers to handle high rates, and an overall upgrade to read-out will be considered with better timing resolution. The inner layers of the KLM may suffer hit efficiency losses of order 10-30%. While this can have 2-5% efficiency losses for muons at momenta below 1 GeV/c, it may lead to 20-30% losses in K^0_{L} detection, due to the much lower penetration depth of hadrons through the iron yoke.
- Solid angle coverage (e.g. STOPGAP): The current particle identification systems still lack full coverage, such as regions between TOP bars, and the backward endcap. This may adversely affect analyses that require strong vetoes based on particle identification. STOPGAP-like upgrades could remedy this.

Physics competition

2026

Observable	2022 Belle(II), BaBar	2022 LHCb	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	LHCb 23 fb^{-1}	Belle-II 250 ab^{-1}	LHCb 300 fb^{-1}
$\sin 2\beta/\phi_1$	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/ϕ_3	13°	5.4°	4.7°	1.5°	1.5°	0.4°	0.4°
α/ϕ_2	4°	–	2°	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	4.5%	6%	2%	1%	3%	< 1%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	–	0.03	0.015	–	0.007	–
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	–	0.07	0.04	–	0.02	–
$S_{CP}(B \to \eta' K^0_S)$	0.32	–	0.11	0.035	–	0.015	–
$R(B \to K^* \ell^+ \ell^- : 1 < q^2 < 6\ \mathrm{GeV}/c^2)$	0.24	0.1	0.09	0.03	0.03	0.01	0.01
$R(B \to D^* \tau\nu)$	6%	10%	3%	1.5%	3%	< 1%	1%
$\mathcal{B}(B \to \tau\nu)$	24%	–	9%	4%	–	2%	–
$R(B \to K^* \nu\bar{\nu})$	–	–	25%	9%	–	4%	–
$\mathcal{B}(\tau \to e\gamma)$ UL	120×10^{-9}	–	40×10^{-9}	12×10^{-9}	–	5×10^{-9}	–
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	46×10^{-9}	3×10^{-9}	0.3×10^{-9}	16×10^{-9}	0.06×10^{-9}	5×10^{-9}

TABLE I. Projected precision of selected flavour physics measurements at Belle II and LHCb.