The Belle II upgrade program

HQL2023 Mumbai

Peter Mandeville Lewis | University of Hawaii
on behalf of the Belle II collaboration

High-*precision* measurements at very high *luminosities*

[Quarkonium, Renu, Tuesday]

[R(X) H. Junkerkalefeld Tuesday]

[TDCPV, S. Bahinipati, Friday]

[CPV in charmless, L. Santelj, Saturday]

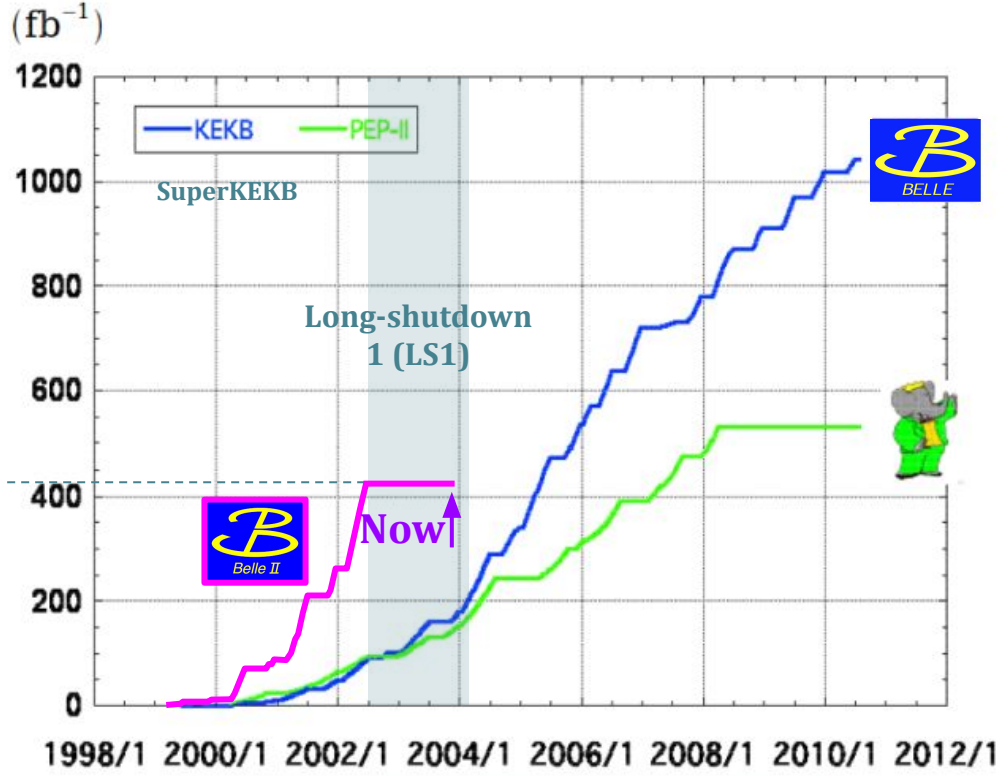
[Kνν, R. Volpe, Saturday]

[LFV, D. Kumar, Wednesday]

[Taus, J. Libby, Tuesday]

[Rare decays, S. Choudhury, Friday]

World-record luminosity…



Recorded: **~420** fb^{-1}

+ 20 years

> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

…but there's still a long way to go…

World-record luminosity…

We need:

- **120-fold** increase in integrated luminosity ($0.4 \rightarrow 50\ \mathrm{ab}^{-1}$) *via*…
- **16-fold** increase in instantaneous luminosity ($0.4 \rightarrow 6\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)

This is an enormous challenge for the **accelerator** and **detector**…

…and **backgrounds** are higher than anticipated

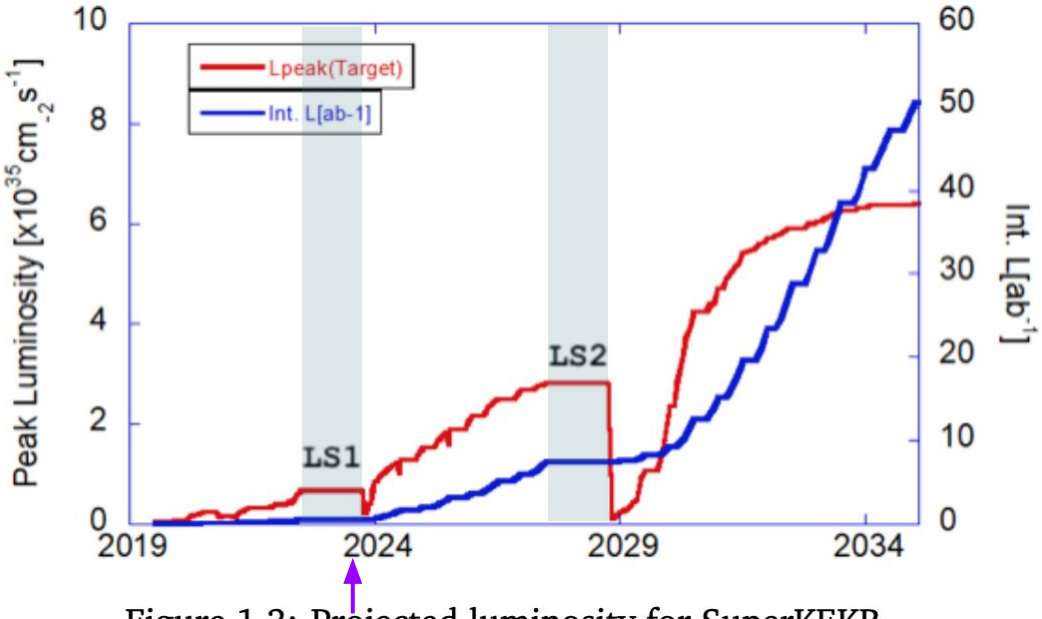


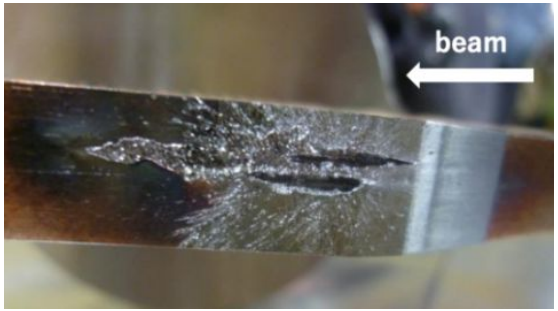
Figure 1.3: Projected luminosity for SuperKEKB.

Here's what we're doing to meet this challenge…

LS1 upgrades (now)

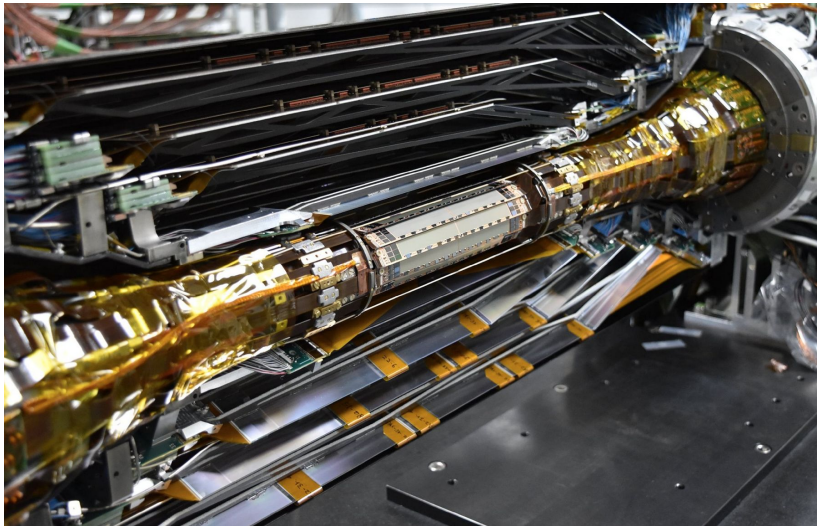
Machine

- New beam-loss monitors
- **More-resilient collimators**
- Improved neutron shielding
- RF cavity replacement, faster kicker magnets at injector
- Operations restart in **January 2024**

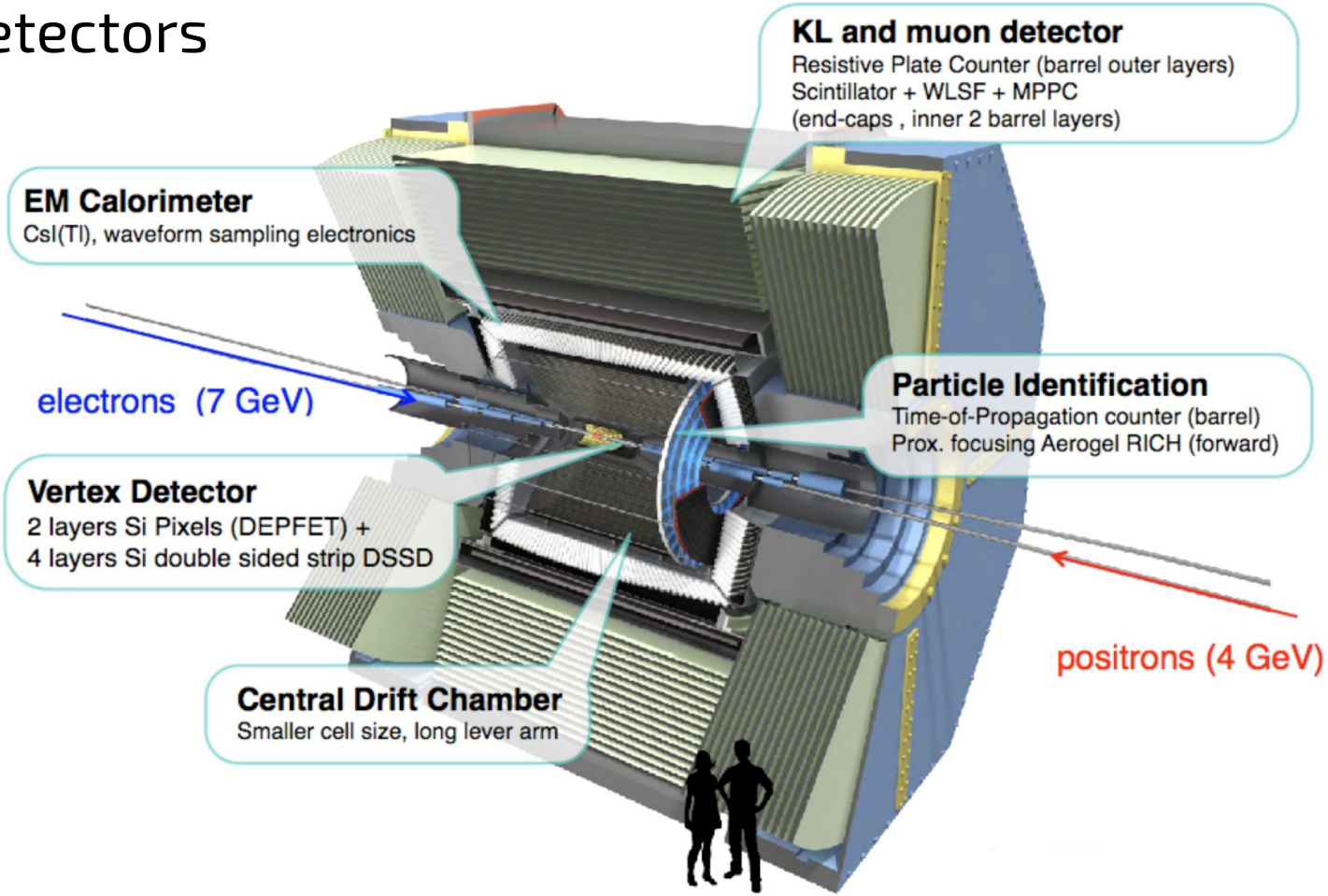


Detector

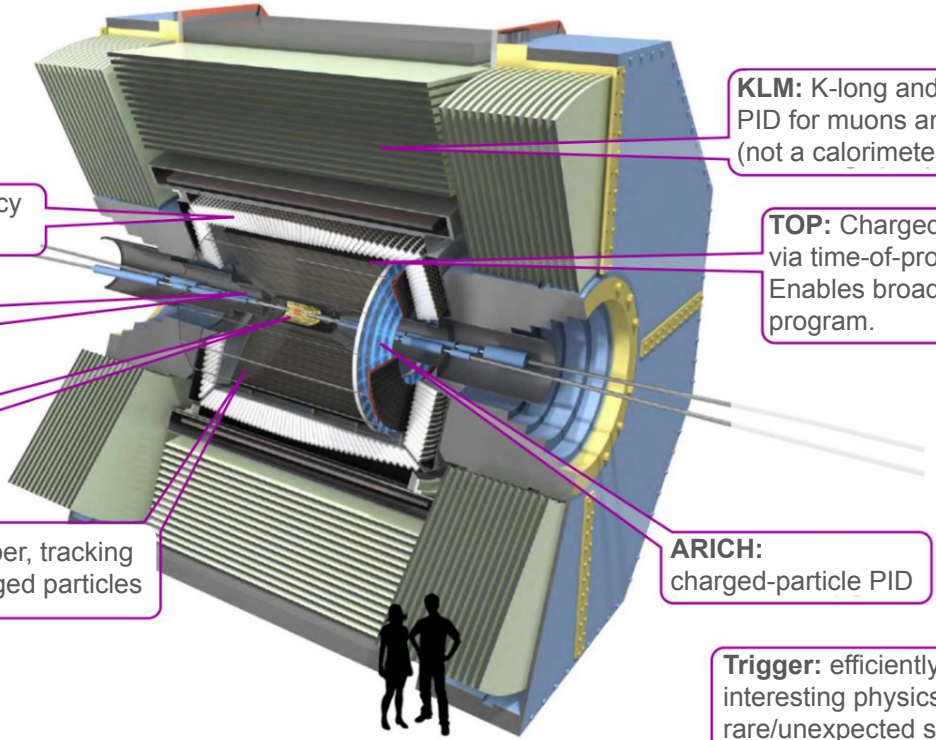
- Installation of **complete pixel detector**
- Replacement of ~50% of TOP MCP-PMs
- Improved CDC gas distribution and monitoring
- DAQ system upgrade to PCIe40



Subdetectors



Subdetectors and their physics impact



KLM: K-long and muon detector. PID for muons and tagging of K-long (not a calorimeter)

ECL: EM calorimetry, high-efficiency e/γ detection

TOP: Charged-particle PID via time-of-propagation. Enables broad flavor program.

IR: interaction region; enables high lumi./low bkg.

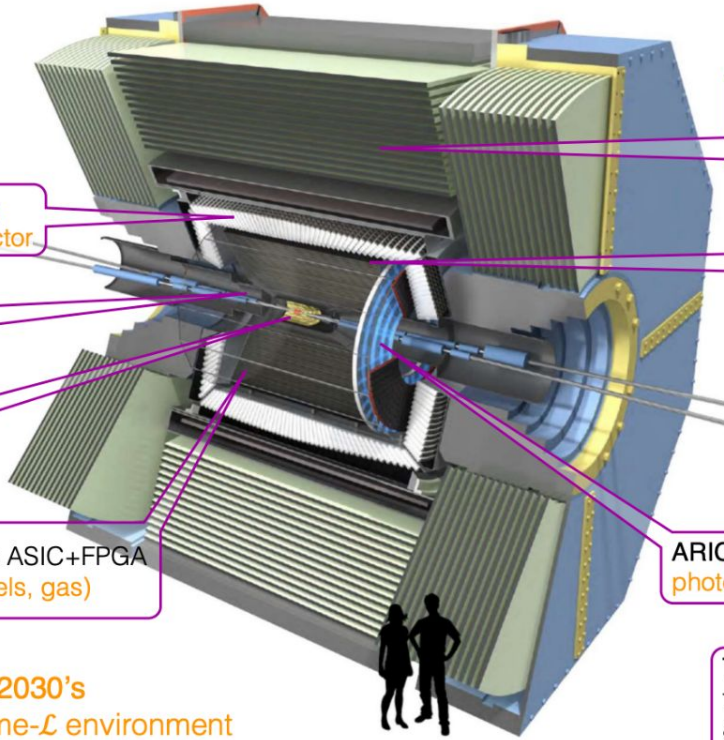
VXD: vertexer, displaced vertices

CDC: drift chamber, tracking and PID for charged particles

ARICH: charged-particle PID

Trigger: efficiently identify interesting physics, including rare/unexpected signatures

LS2 and longer-term upgrades



KLM: replace RPCs with scintillators in barrel (some with fast timing for K_L time-of-flight); replace readout

ECL: replace crystals with pure CsI; APD readout; add pre-shower detector

TOP: replace readout to reduce size & power; replace ~50% MCP-PMTs with life-extended ALDs **(or SiPMs?)**

IR: accommodate QCS replacement and repositioning

VXD: all pixels DMAPS

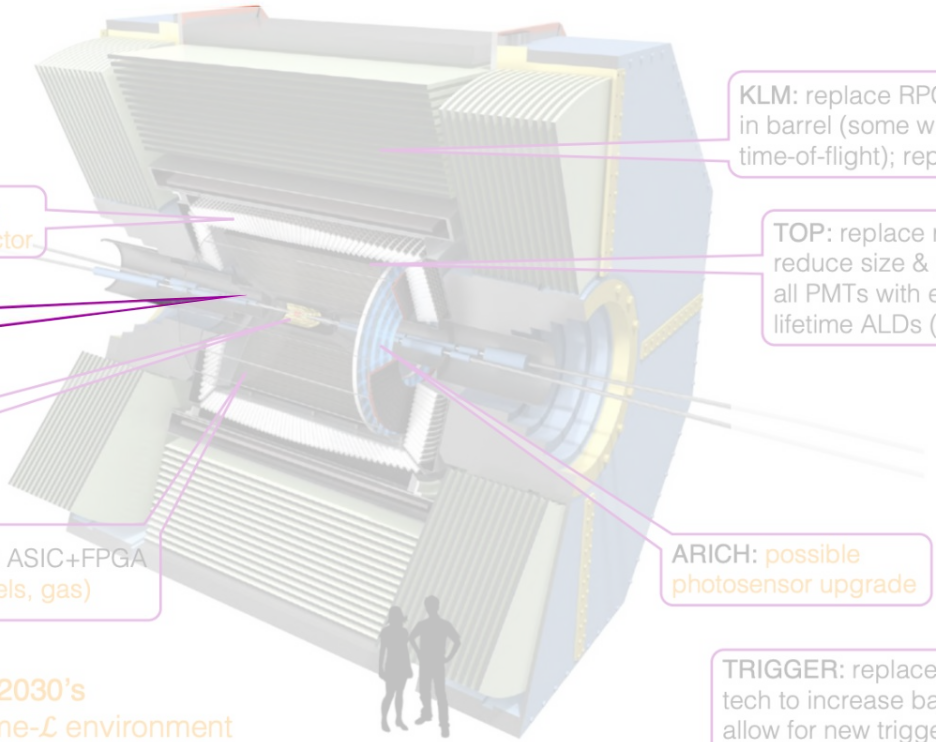
CDC: replace r/o ASIC+FPGA
New tracker (pixels, gas)

ARICH: possible photosensor upgrade

TRIGGER: replace with latest tech to increase bandwidth, allow for new trigger primitives

More distant future: ~mid-2030's
✓ Detector R&D for extreme-$\mathcal{L}$ environment

LS2 and longer-term upgrades



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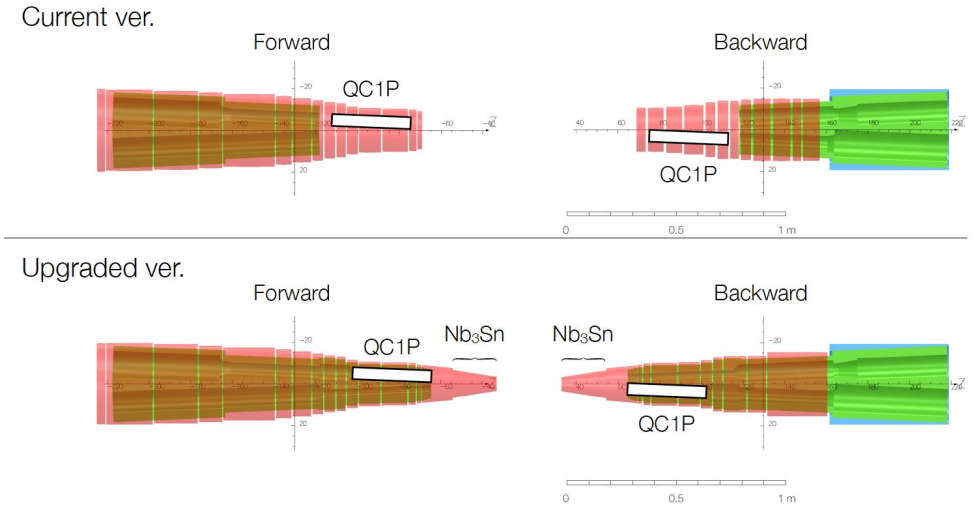
Interaction region

Potential upgrade

- Limit beam-beam effects, preserve beam lifetime
- Redesign final focus:
  - Extend final magnet closer to IP
  - New anti-solenoid Niobium-tin coil placed between final magnet and IP; complex R&D ongoing
  - Overall: nearly **double the Touschek lifetime** in simulations

→ *if adopted*, the envelope for inner detector services will change



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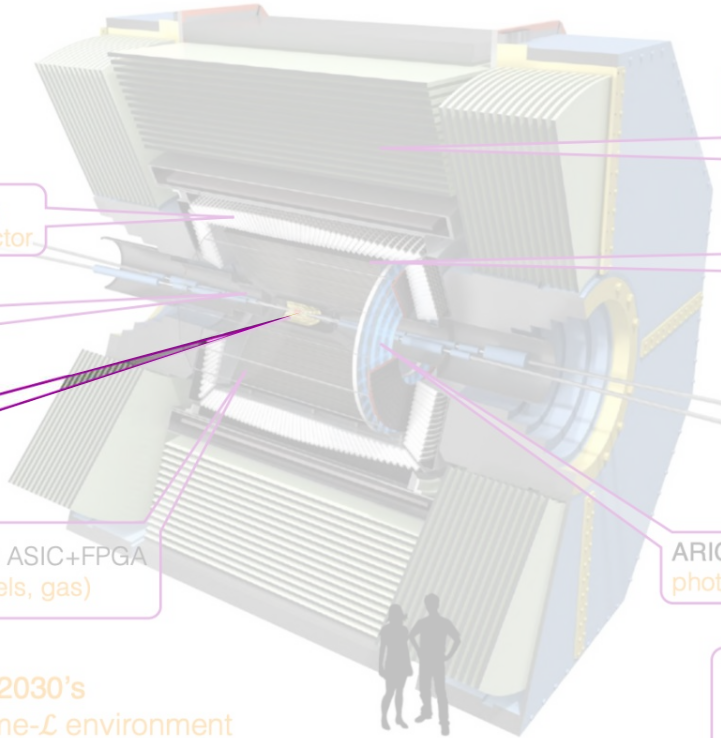

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VXD upgrade

Motivation

- Handle high background rates
- *Improved* tracking and vertex resolution
- Simplify vertex system (pixels + strips → pixels)
- Contribute to L1 trigger
- Operation without data reduction

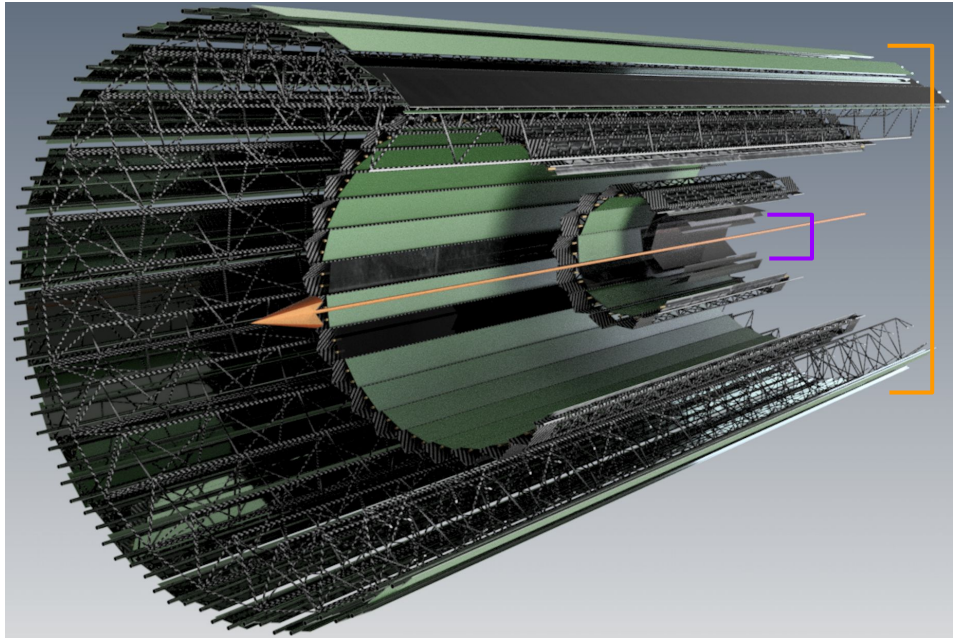
Specifications

Chip	
Pixel pitch	30-40 μm
Integration time	≲ 100 ns
Performance	
Single-point resolution	< 15 μm
Material budget	0.1%−0.8% X_0 (inner-outer layers)
Environment	
Hit rate	120 MHz/cm^2
Total ionizing dose	100 Mrad
NIEL fluence	5x10^{14} n_{eq}/cm^2

VTX

All-layer DMAPS pixel detector

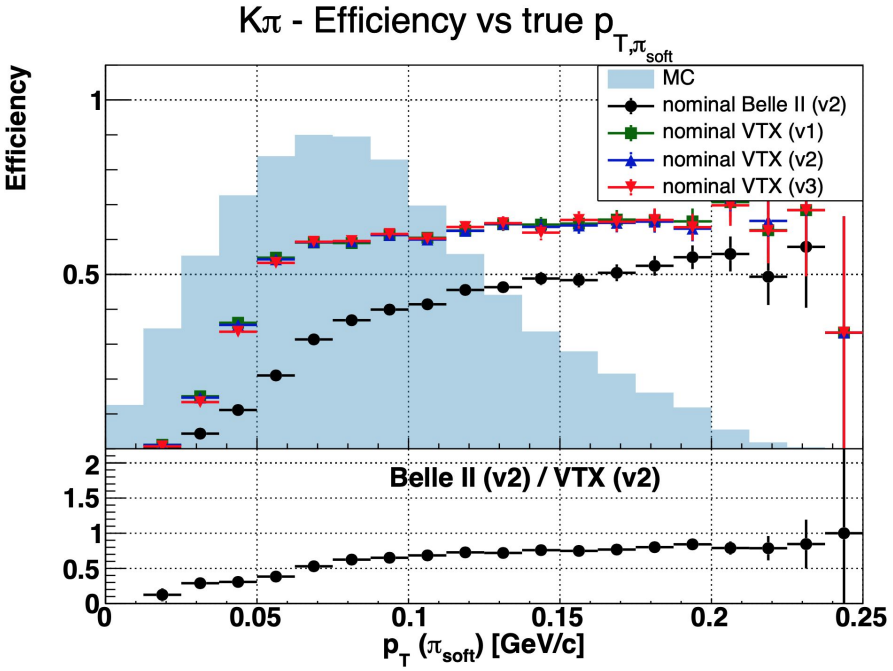
- Monolithic active CMOS pixels in 5 layers
- Sensitive layer thickness < 50 μm (~4000e from MIPs vs. 200-250e threshold)
- Sensor thickness < 100 μm
- **iVTX**: innermost 2 layers, self-supported, air-cooled
- **oVTX**: outer 3 layers, CF structure, single-phase coolant
- Prototype (TJMonopix2) has largely met these specifications, including irradiation tests



VTX

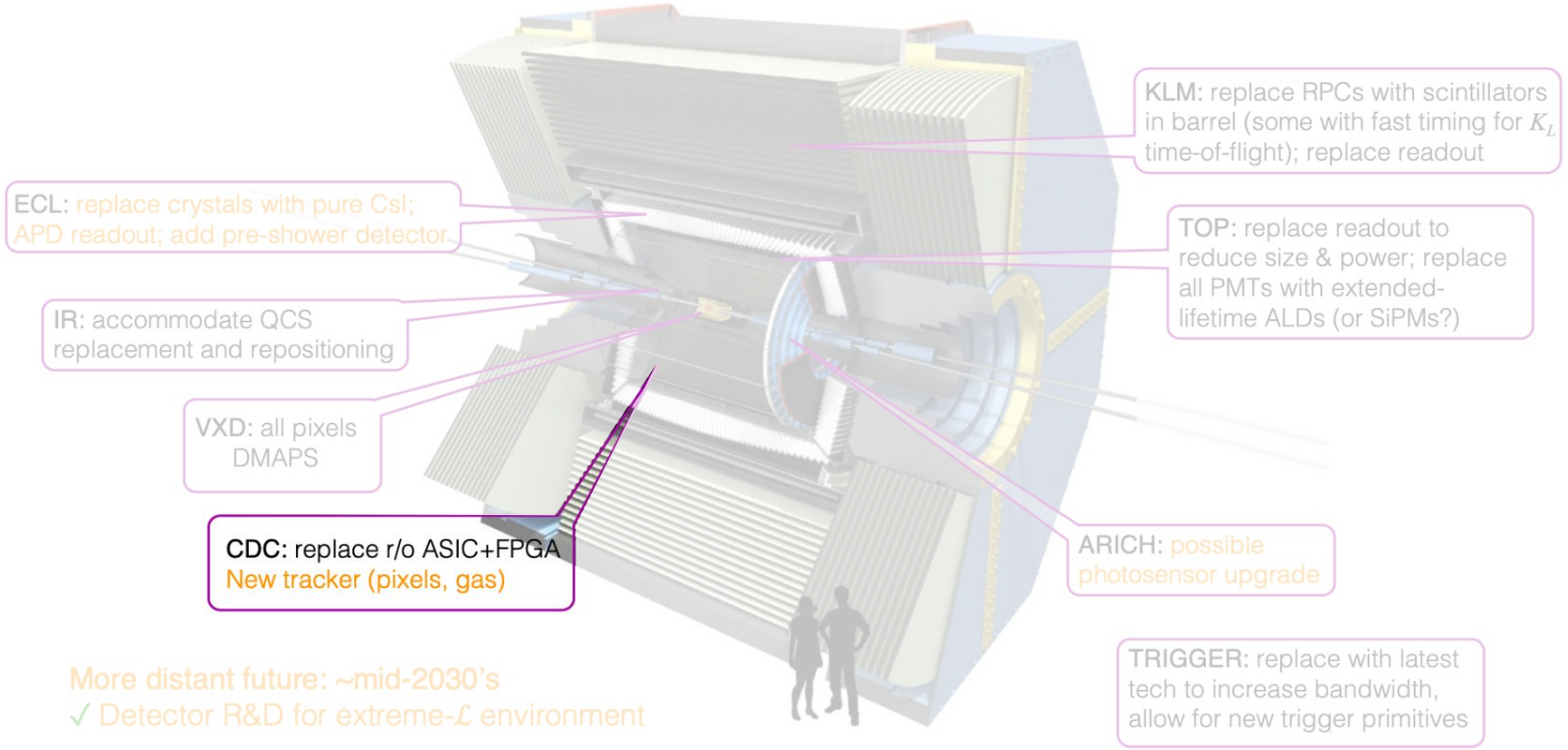
Physics impact, illustrated

- $B^0 \to D^{*-}\ell^+\nu$: "bread-and-butter" physics for Belle II (R(D*), angular analysis, $|V_{cb}|$, *B*-tagging, …)
- Slow pion from D* decay: low-p → low-efficiency
- **~70%** improvement in efficiency; like a massive lumi. boost
- Also: **~35%** better B-decay vertex resolution



…while also being far more robust against backgrounds

LS2 and longer-term upgrades



CDC front-end electronics

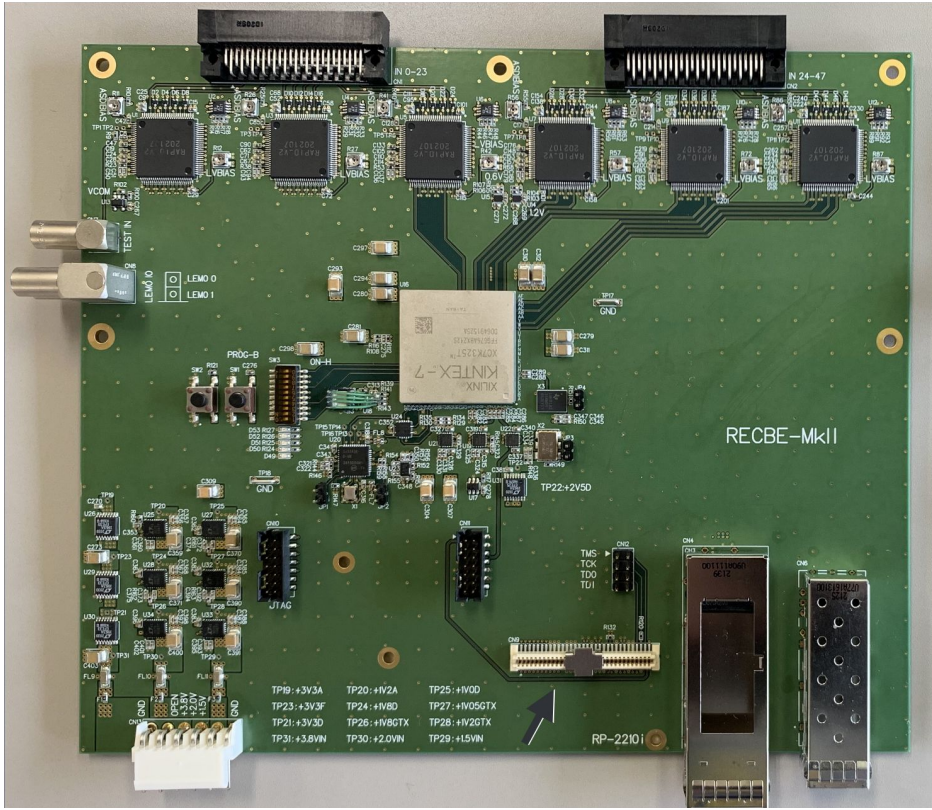
Toward better tracking performance

- Reduce cross-talk, power consumption, and increase output bandwidth
- Improve radiation tolerance

New ASICs, new FPGA, optical module

- ASIC: timing and waveform digitization
- FPGA: online data processing for trigger and DAQ
- Rad-hard fiber transceivers

Prototype front-end board upgrade



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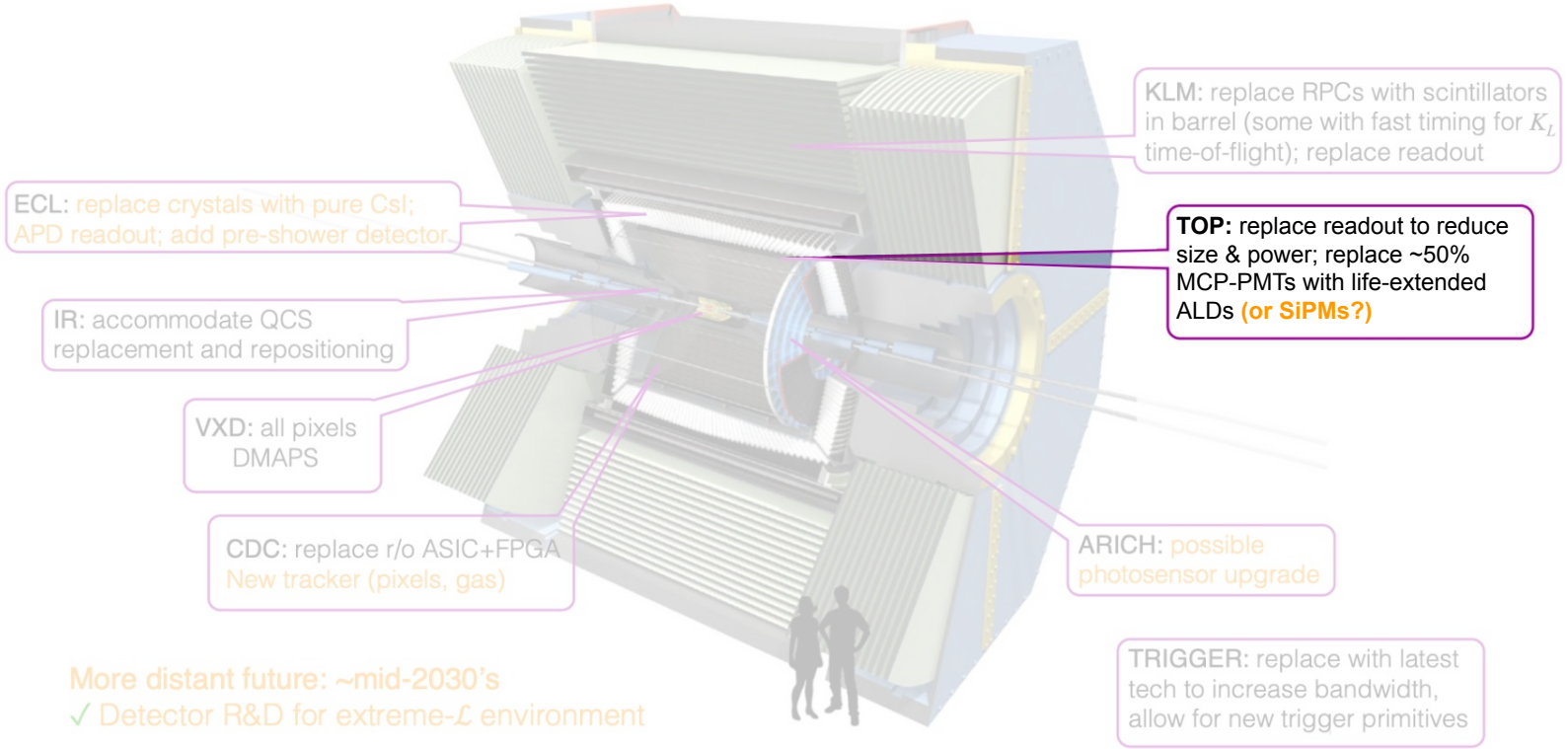


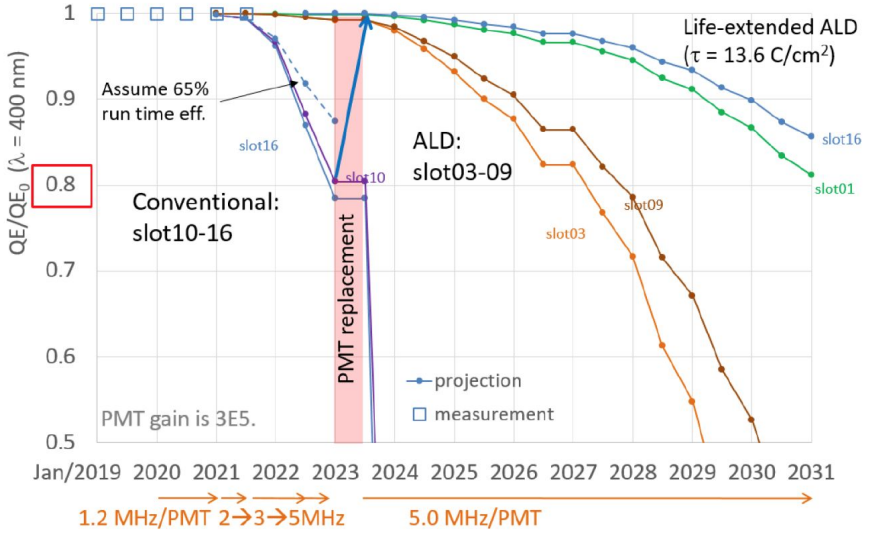
PID: Time of Propagation

Photosensor upgrade

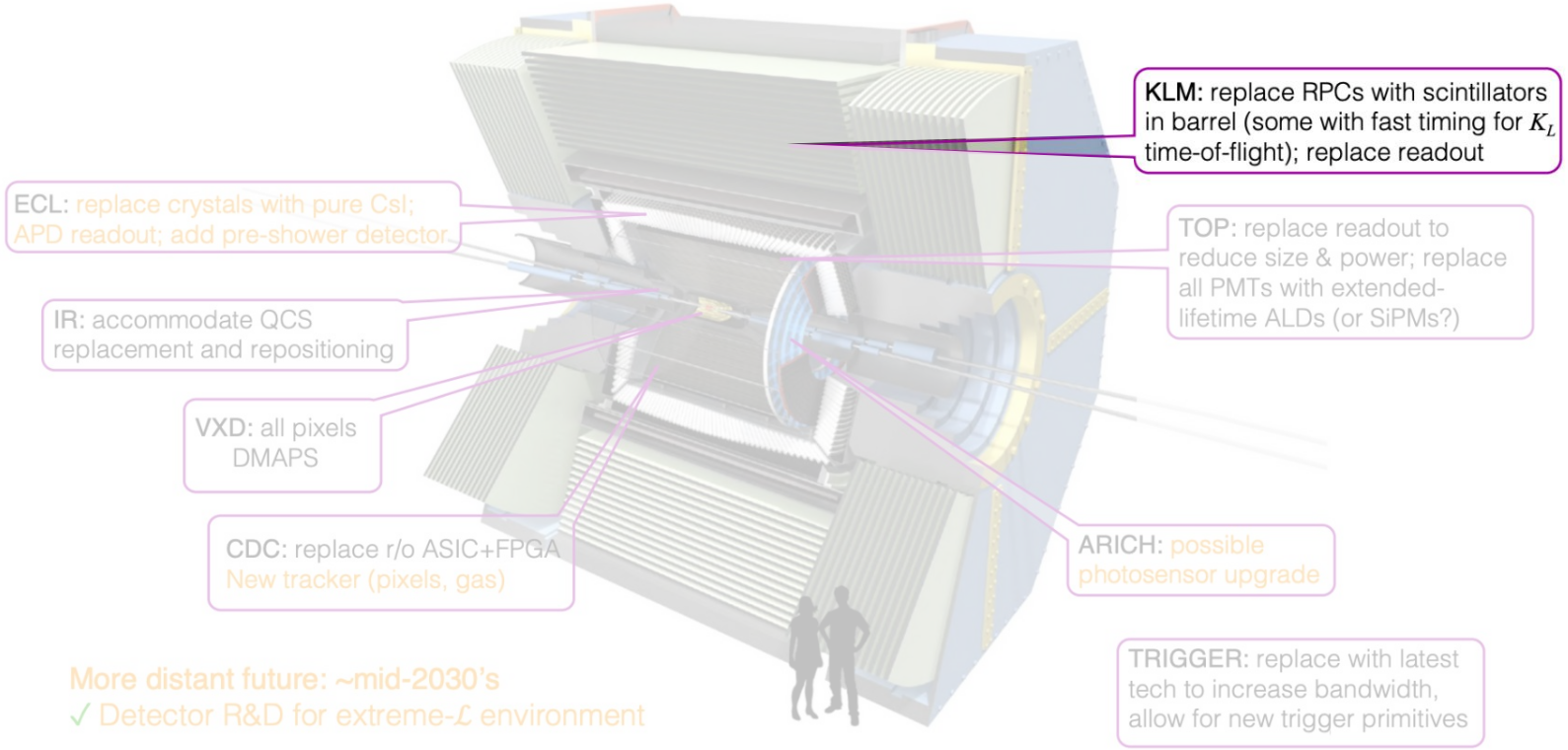
- MCP-PMTs degrading under **higher-than-expected backgrounds**
- Complete residual ~50% MCP-PMT upgrade with life-extended ALD type
- (Potential replacement of MCP-PMTs with SiPMs)

Readout upgrades

- Frontend board: reduce size and power (to accommodate potential SiPM's)
- ASoC on ASIC boards with Gpbs to FPGA



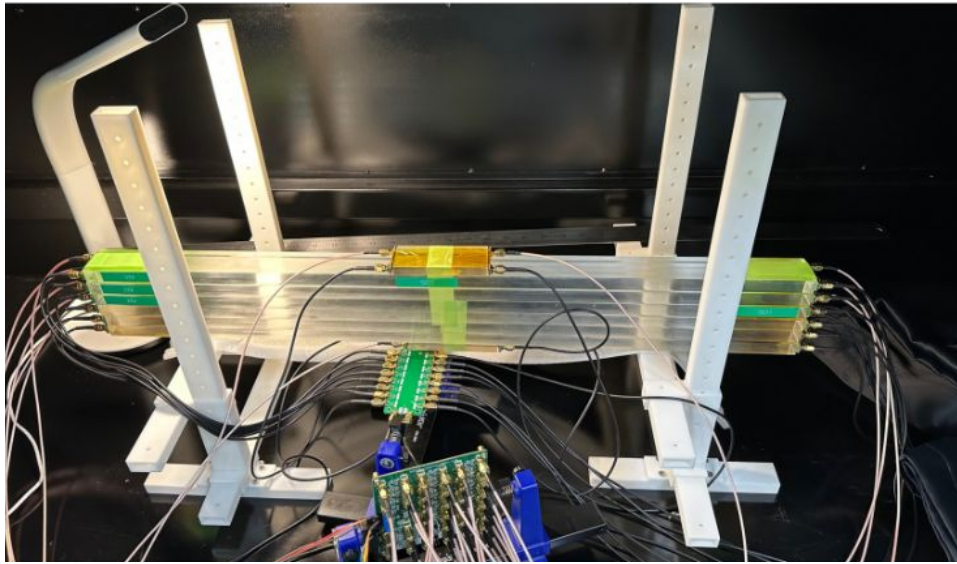
LS2 and longer-term upgrades



KLM: K_L^0 and muon detector

New capability: K_L^0 energy measurement

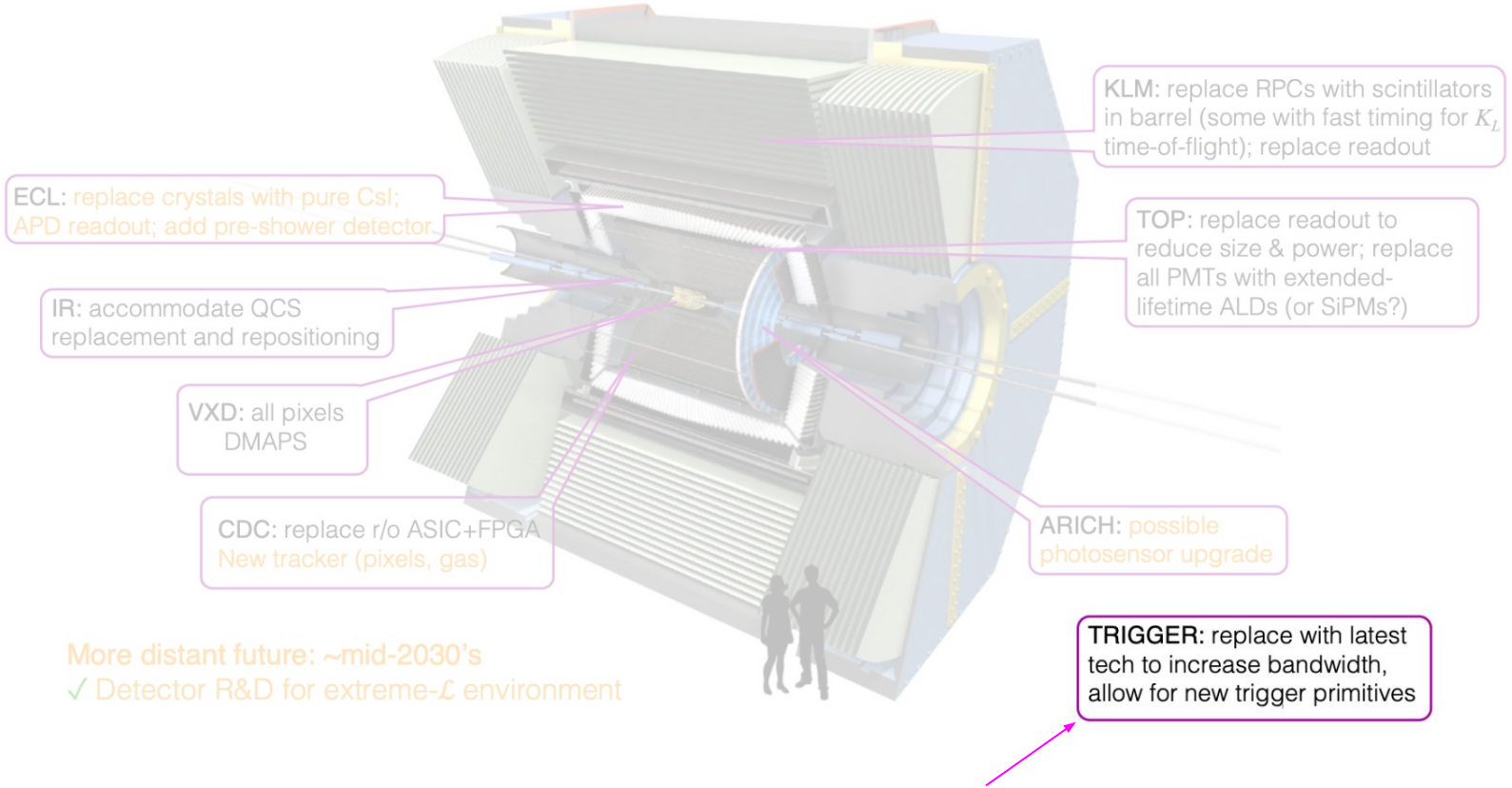
- Replace remaining RPC's with scintillators + SiPM's (very complex operation)
- **Fast timing** (~100ps) gives K_L^0 *E* via TOF
- Not settled: physics impact still under study



Readout upgrades

- Move feature extraction to frontend ASIC
- Replace many km of twisted-pair ribbon cables with a few fibers

LS2 and longer-term upgrades



LS1, LS2, and beyond

- At Belle II, **(physics output) ∝ (luminosity)×(detector performance at high lumi.)**
- Achieving **both** is an iterative process…
- … we have a rich set of short-, medium-, and long-term upgrades in the works

Look for the Belle II Upgrades CDR soon

Thank you!