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

LFV, D. Kumar, Wednesday

Taus, J. Libby, Tuesday

R(X) H. Junkerkalefeld, Tuesday

TDCPV, S. Bahinipati, Friday

CPV in charmless, L. Santelj, Saturday

K_{VV}, R. Volpe, Saturday

Rare decays, S. Choudhury, Friday
World-record luminosity...

+ 20 years

...but there’s still a long way to go...
We need:

- **120-fold** increase in **integrated luminosity** ($0.4 \rightarrow 50 \text{ ab}^{-1}$) via...
- **16-fold** increase in **instantaneous luminosity** ($0.4 \rightarrow 6 \times 10^{35} \text{ cm}^{-2} \text{s}^{-1}$)

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

...and **backgrounds** are higher than anticipated

*Here’s what we’re doing to meet this challenge...*

**Figure 1.3:** Projected luminosity for SuperKEKB.
**Upgrades**

**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

**EM Calorimeter**
CsI(Tl), waveform sampling electronics

**Vertex Detector**
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

**Central Drift Chamber**
Smaller cell size, long lever arm

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

**Particle Identification**
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

**electrons (7 GeV)**

**positrons (4 GeV)**
**Belle II**

**Subdetectors and their physics impact**

**ECL**: EM calorimetry, high-efficiency $e/\gamma$ detection

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

**VXD**: vertexer, displaced vertices

**CDC**: drift chamber, tracking and PID for charged particles

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

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

**ARICH**: charged-particle PID

**Trigger**: efficiently identify interesting physics, including rare/unexpected signatures
Belle II upgrades

**LS2 and longer-term upgrades**

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

**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

**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
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✓ Detector R&D for extreme-$\mathcal{L}$ environment
L2 upgrades (2027-2028)

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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**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/cm²      |
| Total ionizing dose | 100 Mrad         |
| NIEL fluence    | $5 \times 10^{14}$ n$_{eq}$/cm² |
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
L2 upgrades (2027-2028)

VTX

Physics impact, illustrated

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

…while also being far more robust against backgrounds
LS2 and longer-term upgrades

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More distant future: ~mid-2030’s
- Detector R&D for extreme-μ environment
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
L2 upgrades (2027-2028)

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✓ Detector R&D for extreme-$L$ environment
L2 upgrades (2027-2028)

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
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**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
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More distant future: ~mid-2030’s
✓ Detector R&D for extreme-L environment
LS1, LS2, and beyond

- At Belle II, \((\text{physics output}) \propto (\text{luminosity}) \times (\text{detector performance at high lumi.})\)
- 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
