Budker Institute of Nuclear Physics

Online Luminosity Monitor at Belle II

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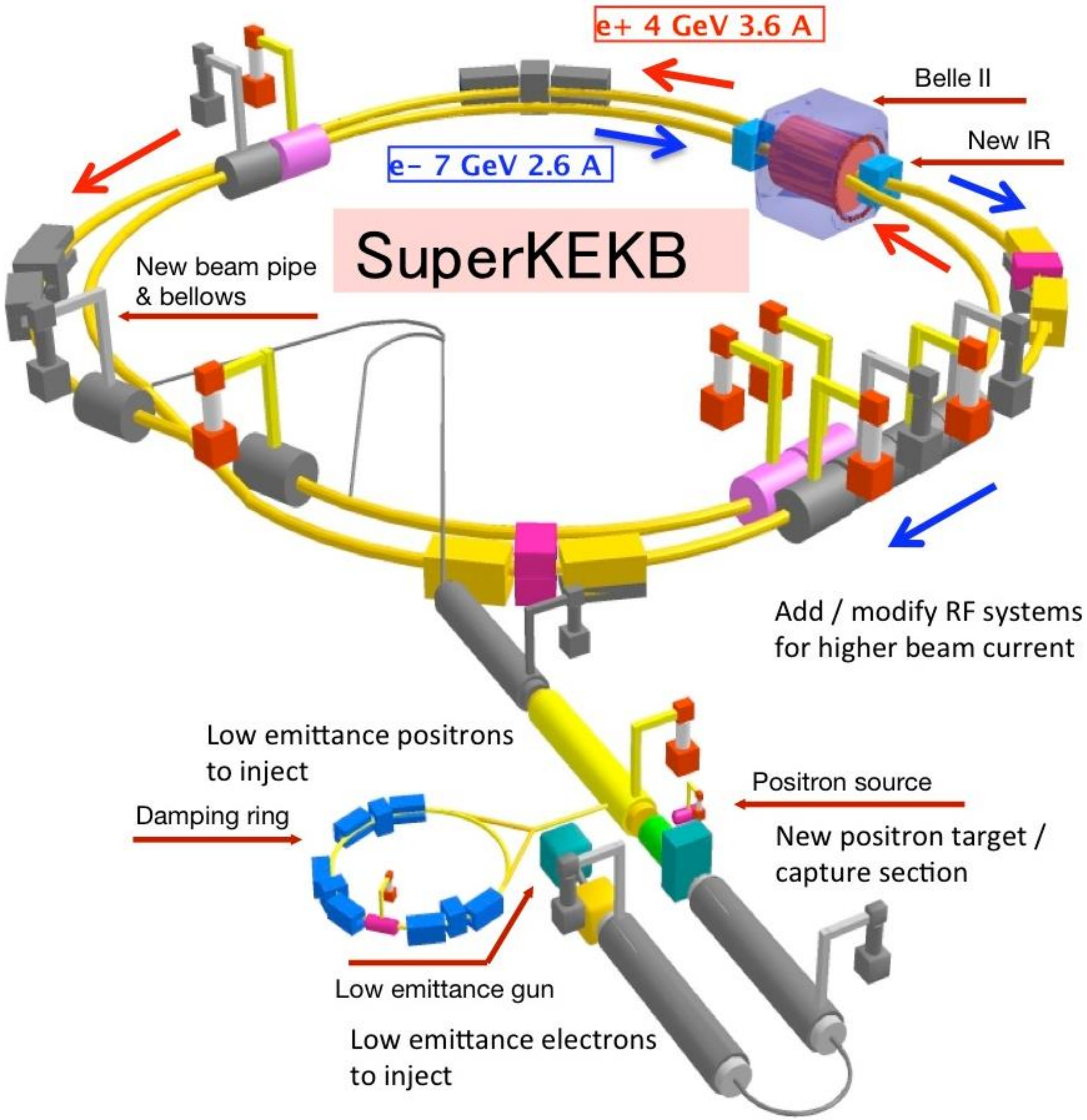
Belle II

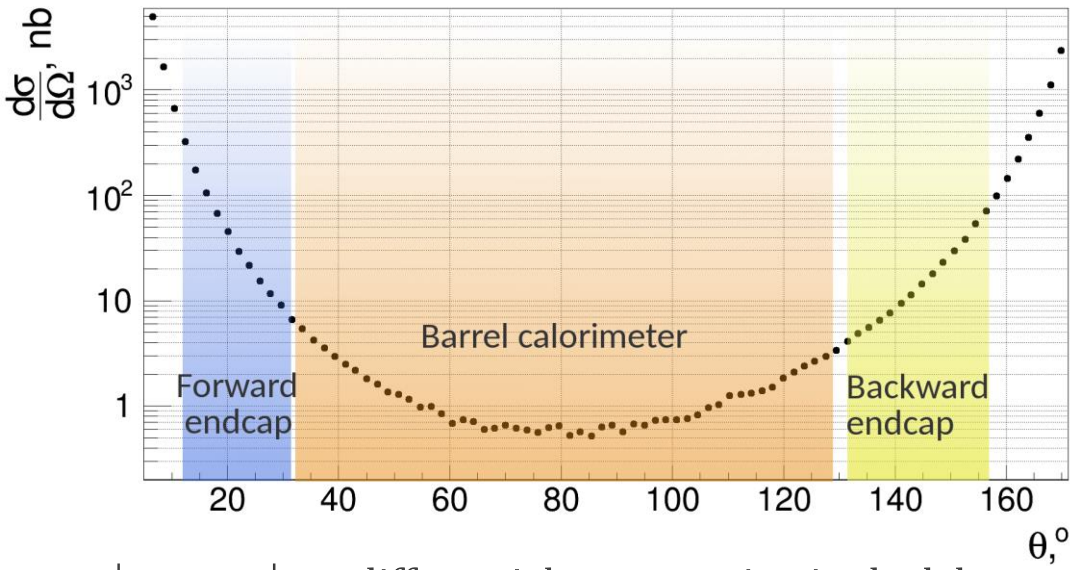
Belle II experiment is ongoing at the SuperKEKB asymmetric collider since 2018

- Center-of-Mass energy around 10.58 GeV
- $E_{e^-} = 7\ GeV,\ E_{e^+} = 4\ GeV$
- Physics program:
  - CPV in decays of B mesons
  - Study of B, D, τ physics
  - Search for New Physics
- Designed luminosity: $6.3 \times 10^{35}\ cm^{-2}s^{-1}$
- Achieved luminosity: $4.7 \times 10^{34}\ cm^{-2}s^{-1}$

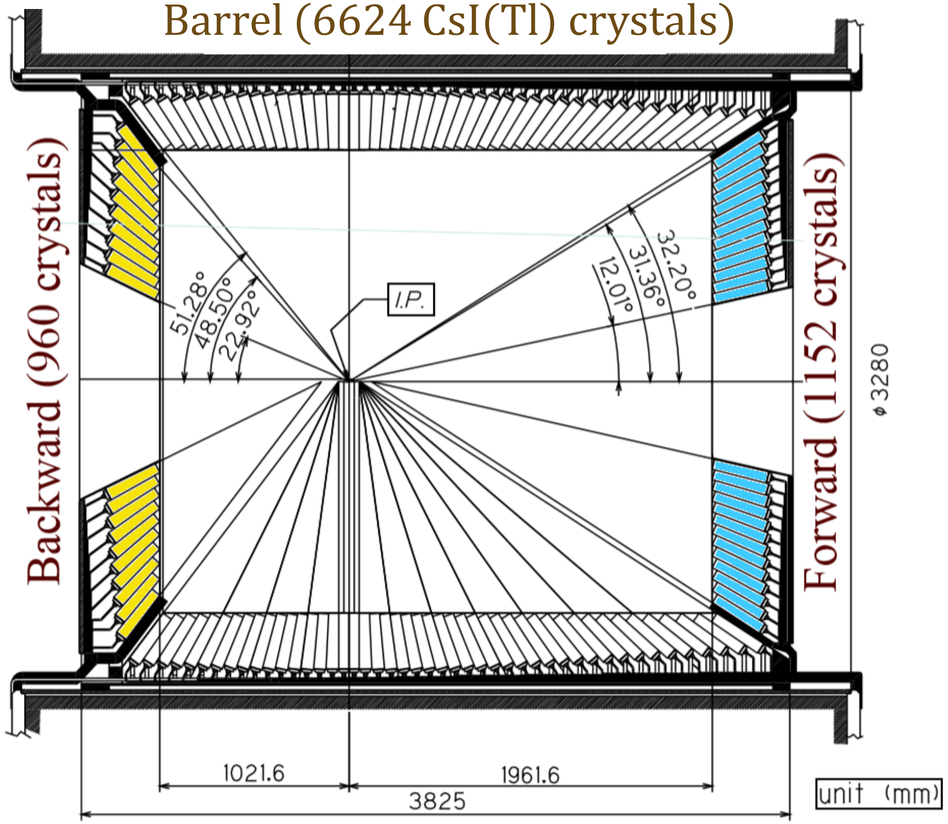


Luminosity online measurement

- Feedback to tune collider performance and preliminary results on the integrated luminosity
- Possible approach – measurement of $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ rates
  - Large cross section and accurate generation
  - Simple back-to-back signature
  - Electromagnetic Calorimeter is sufficient for reconstruction
- Instantaneous luminosity $L = \frac{dN/dt}{\sigma}$



$e^+e^- \to e^+e^-$ differential cross section in the laboratory frame



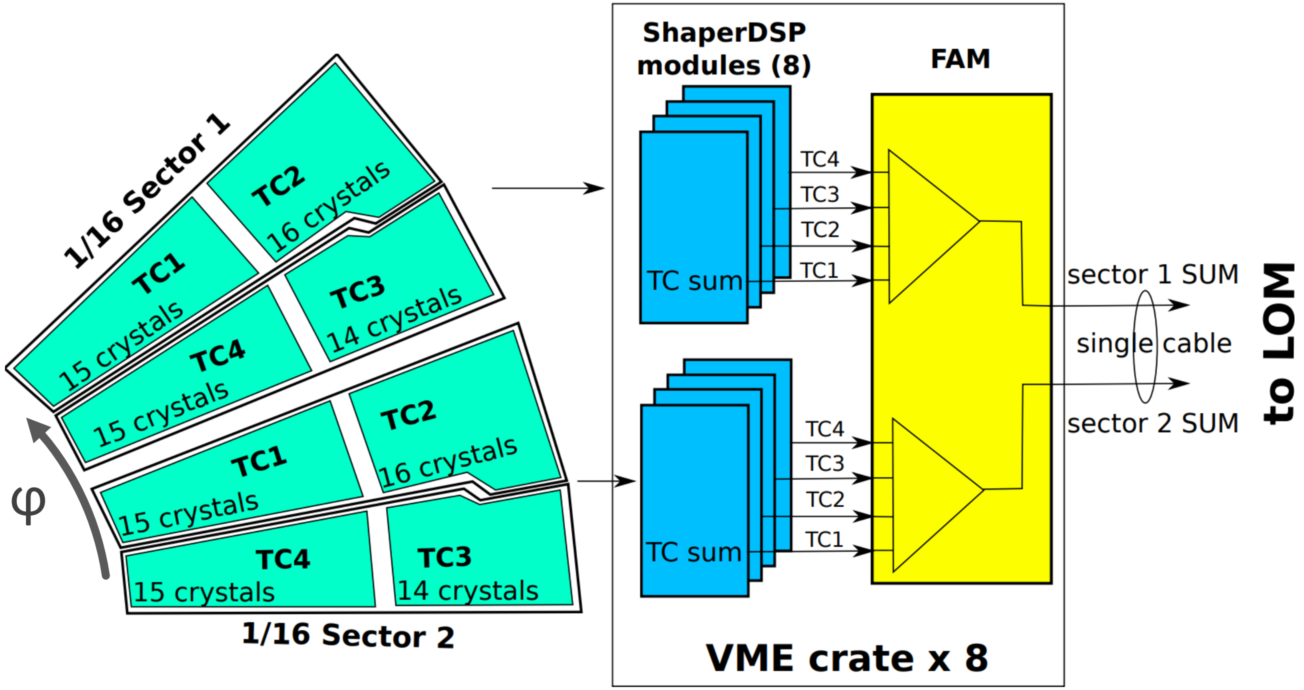
Belle II Electromagnetic Calorimeter (ECL)
Crystal size: 5.5 cm x 5.5 cm and 30 cm long (16 X0)

Luminosity Monitor (LOM)

- To measure independently from the main data acquisition system (DAQ), standalone module was developed
- Measures event rate based only on signals from the ECL endcap parts
- Operating since 2018.

Signal formation:

- Up to 16 crystals form trigger cell (TC) within the same board (ShaperDSP)
- We combine 4 TC into a sector by the shaping circuit (FAM) and send analogues signal to the monitor module
- Each sector is 1/16 of each endcap



Signal formation in example of two sectors in backward endcap

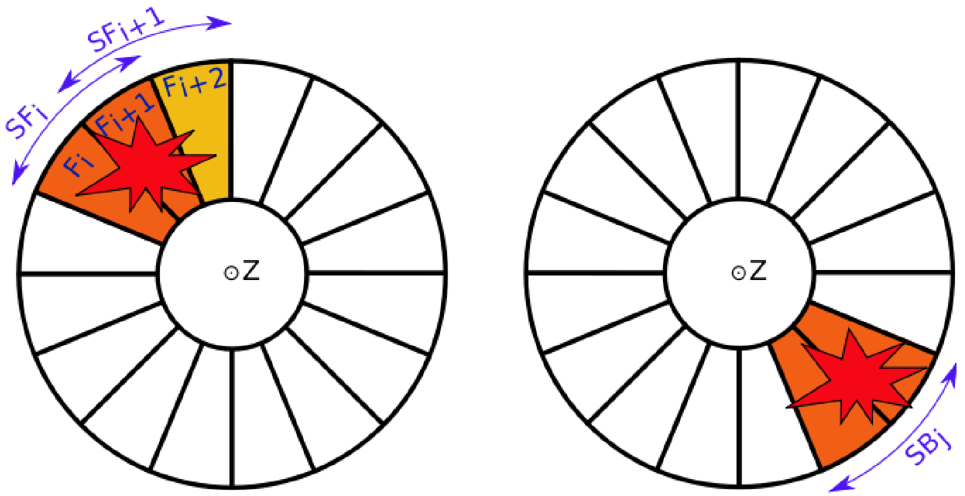
Event selection logic

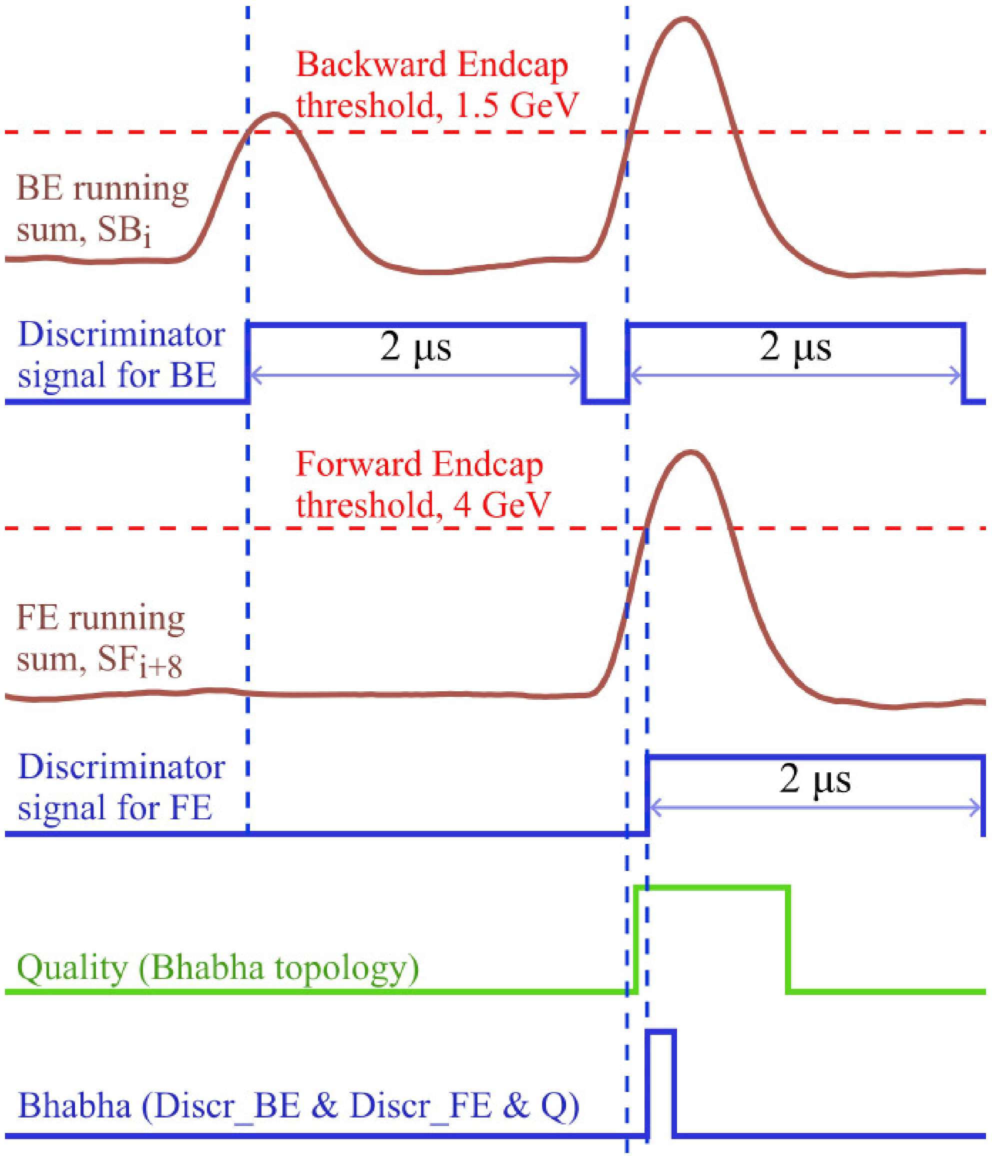
Event signature:

- High energy depositions in opposite sectors* of two endcaps
- Only one or two adjacent sectors exceed 1 GeV threshold (quality) in each endcap
- Coincidence within 2 μs

* Instead of one sector, i, we use running sum: $S_i = E_i + E_{i+1}$

Forward Endcap (FE) Backward Endcap (BE)





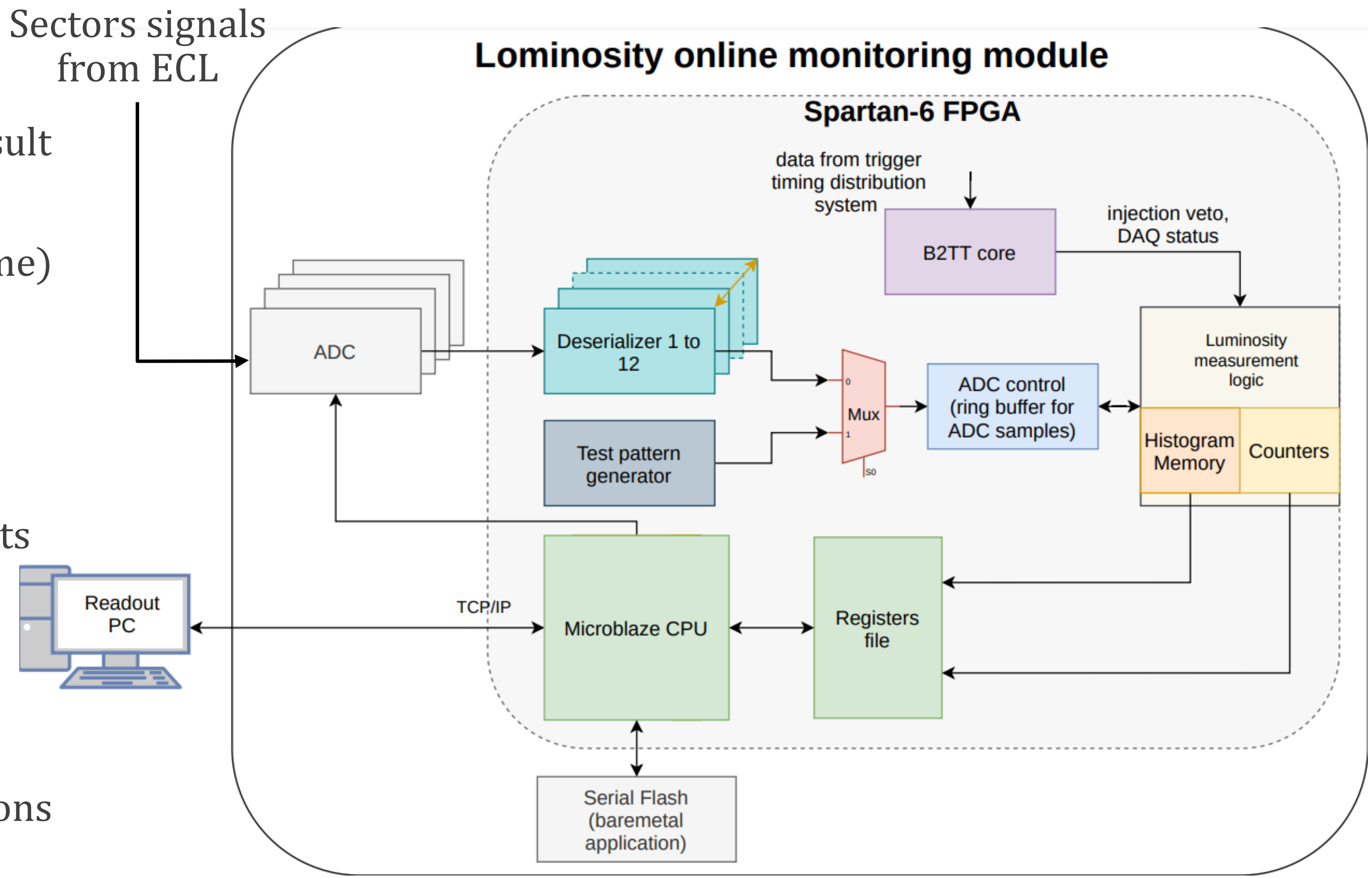
Timing diagram of the LOM logic

Block diagram of the FPGA firmware

- ADC digitizes signals from sectors
- Signals are processed by logic module
- Counters are incriminated according to result
- Separate counters consider external information (injection veto or DAQ deadtime)
- Microblaze CPU grants network access to results

Secondary components are provided for tests and quality monitoring:

- Test pattern generator
- ADC buffer to monitor waveforms
- Histogram memory with energy distributions



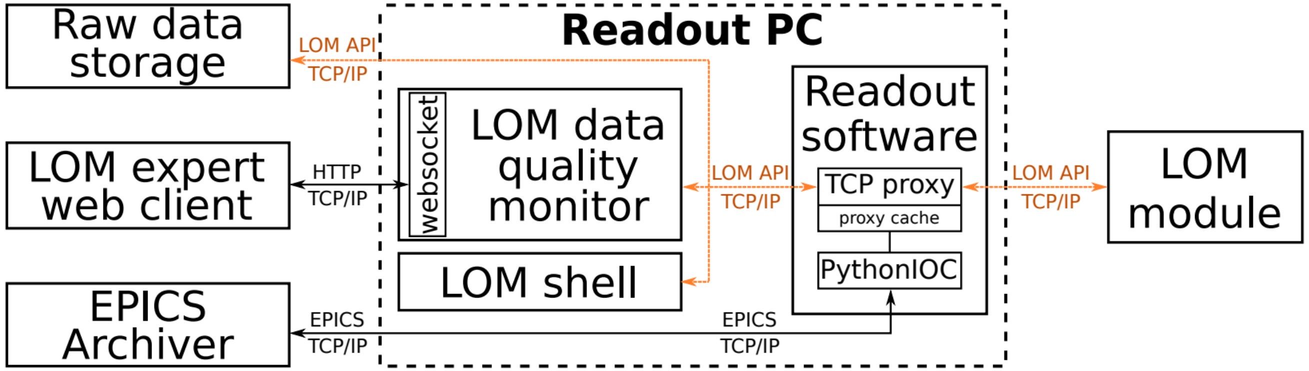
Readout software

- Reads information from the module
- Calculates luminosity
- Exports high-level information into EPICS network (accessible to all experts of Belle II)
- Forwards requests from TCP clients to the module
- Operates continuously, stably, independently from data acquisition system

TCP clients:

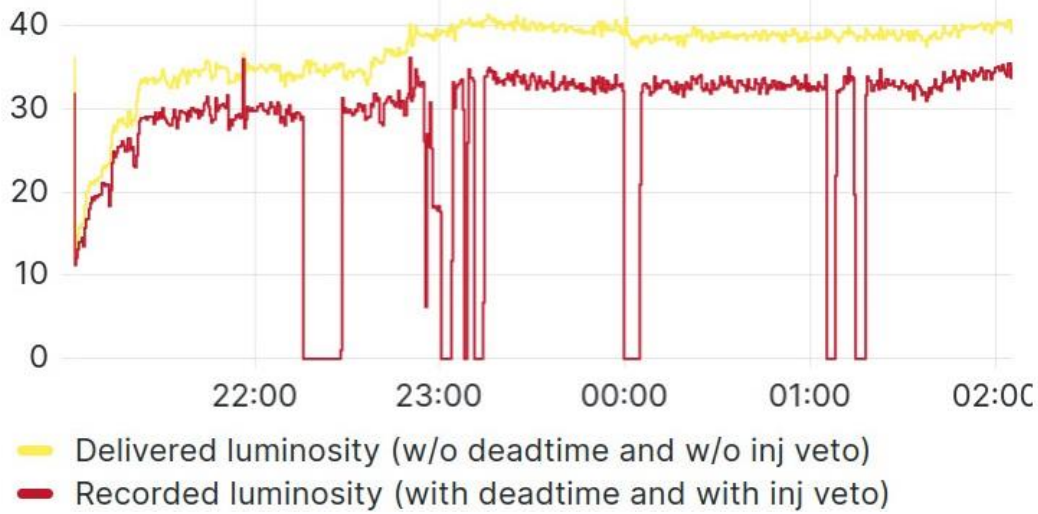
- LOM shell (tools to configure LOM)
- LOM data quality monitor (draws waveforms and energy deposition histograms)
- Raw data storage (saves low-level information)

Block diagram of the Luminosity online Monitor (LOM) software



EPICS archiver plot

Instantaneous luminosity, 10^{33} cm^{-2} s^{-1}



Expected hit rate and uncertainties

- Instantaneous luminosity $L = \frac{dN/dt}{\sigma_{vis}}$, σ_{vis} − effective cross section reconstructed by the module
- Determined based on the Monte-Carlo simulation of the Belle II detector:

  BabaYaga@NLO generator → GEANT4 based MC → Analysis script with LOM logic
  - $\sigma_{vis}^{e^+e^-\to e^+e^-} = 28.46 \pm 0.28^*$ nb
  - $\sigma_{vis}^{e^+e^-\to\gamma\gamma} = 0.92 \pm 0.01^*$ nb
  - $\sigma_{vis} = 29.38 \pm 0.29^*$ nb
- * Including systematic uncertainty of 1.0%
- Energy correction: $\sigma_{vis}(s) = \sigma_{vis}(s_0)\frac{s_0}{s}(1 + 0.02\frac{\sqrt{s}-\sqrt{s_0}}{1\ GeV})$
- Event rate is 18 kHz at the designed $6.3 \times 10^{35}\ cm^{-2}s^{-1}$
- Luminosity accumulated per second has statistical uncertainty of 2.7% at current value and up to 0.7% at the designed

Source	Uncertainty, %	Comment
ECL position	0.8	±5 mm
Simulation accuracy	0.4	BhabhaYaga@NLO uncertainty
Calibration	0.3	±5%
Total	**1.0**	

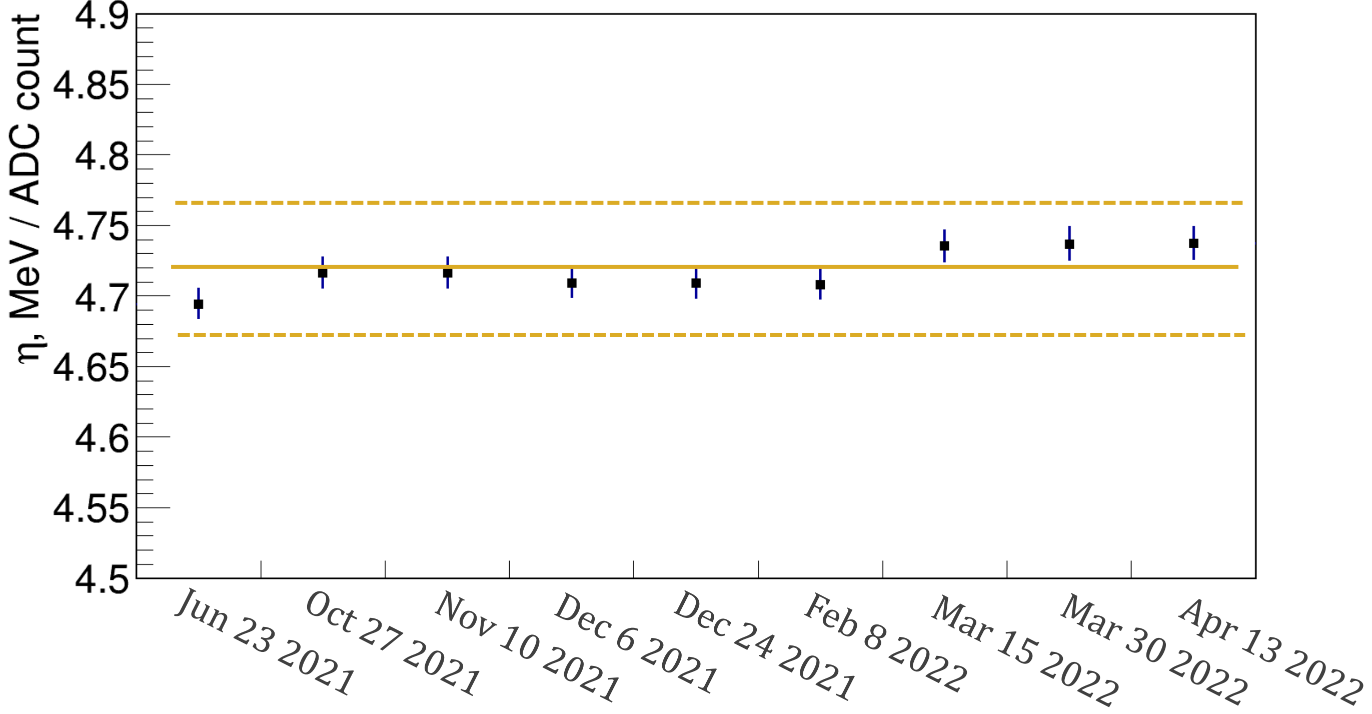
Systematic uncertainties

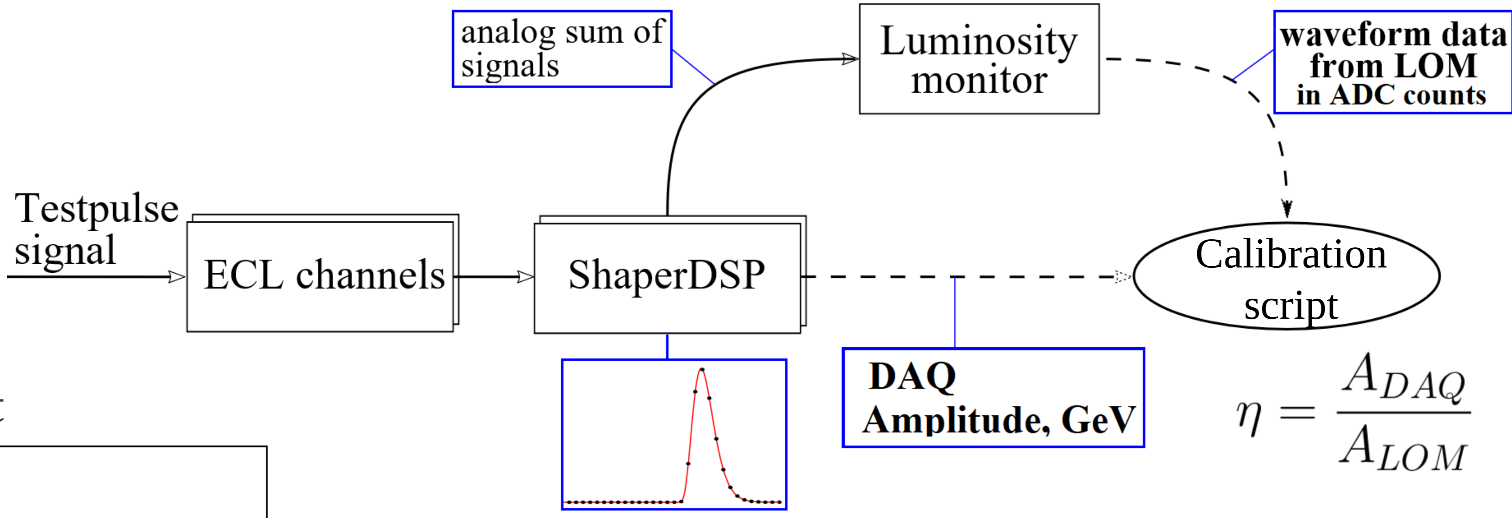
Calibration

To set thresholds correctly, we periodically perform calibration and calculate:

- Pedestals
- ADC count → MeV calibration coefficient

Average calibration coefficient





$$\eta = \frac{A_{DAQ}}{A_{LOM}}$$

Calibration scheme

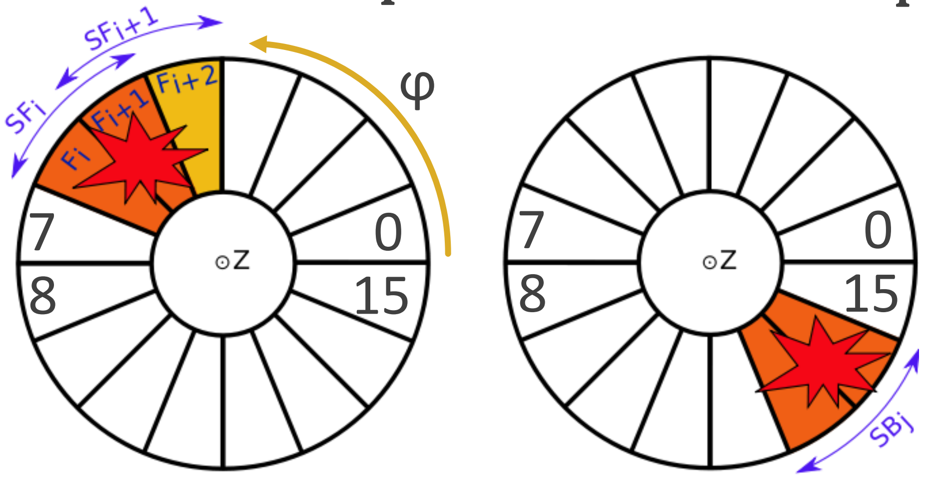
- Calibration coefficients are stable within 1% over time

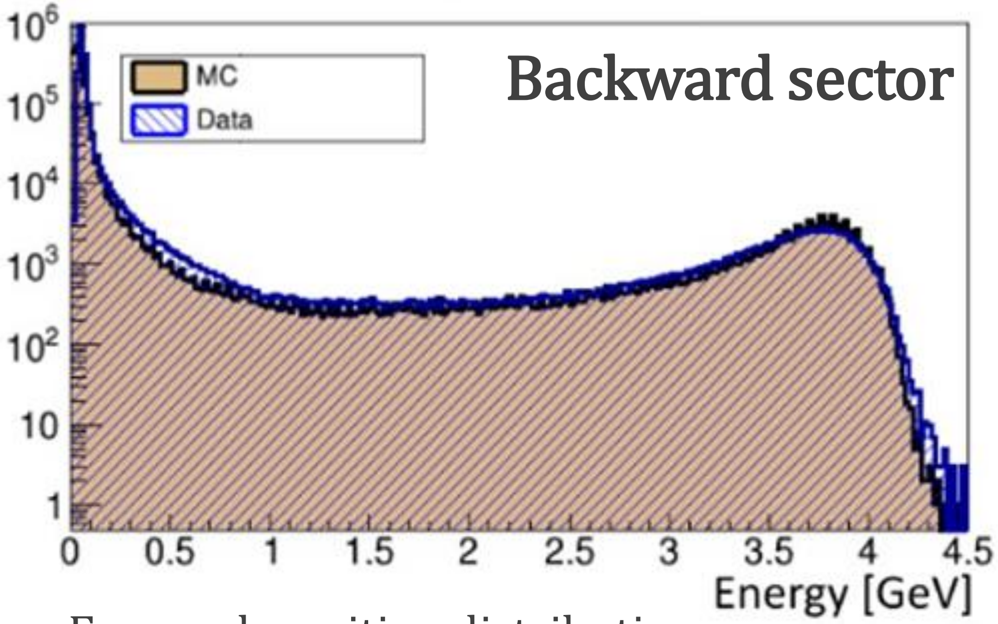
Data vs MC

To verify validity of implemented selection logic:

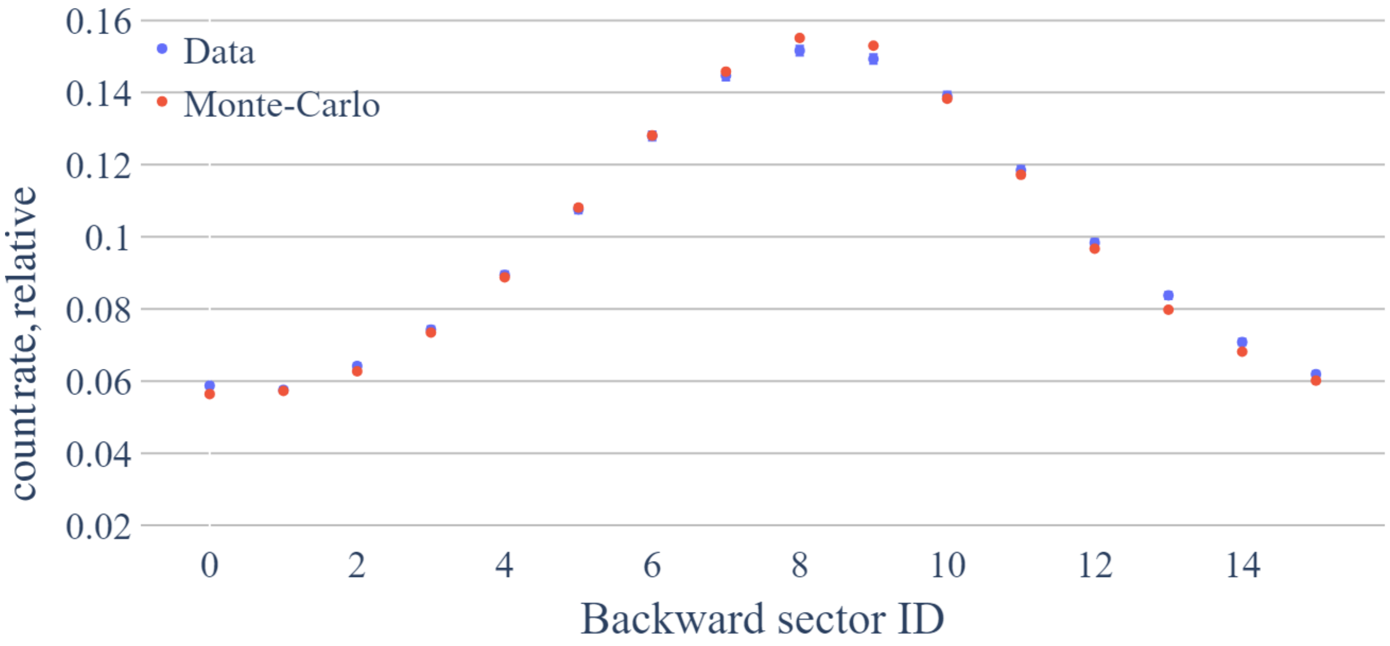
- Each second we save waveform of signal event
- These waveforms then analyzed as MC events
  - Results are in agreement
- Waveforms processing with full FPGA simulation produces the same result

Forward endcap   Backward endcap





Energy deposition distribution



Angular (ϕ) distribution of events

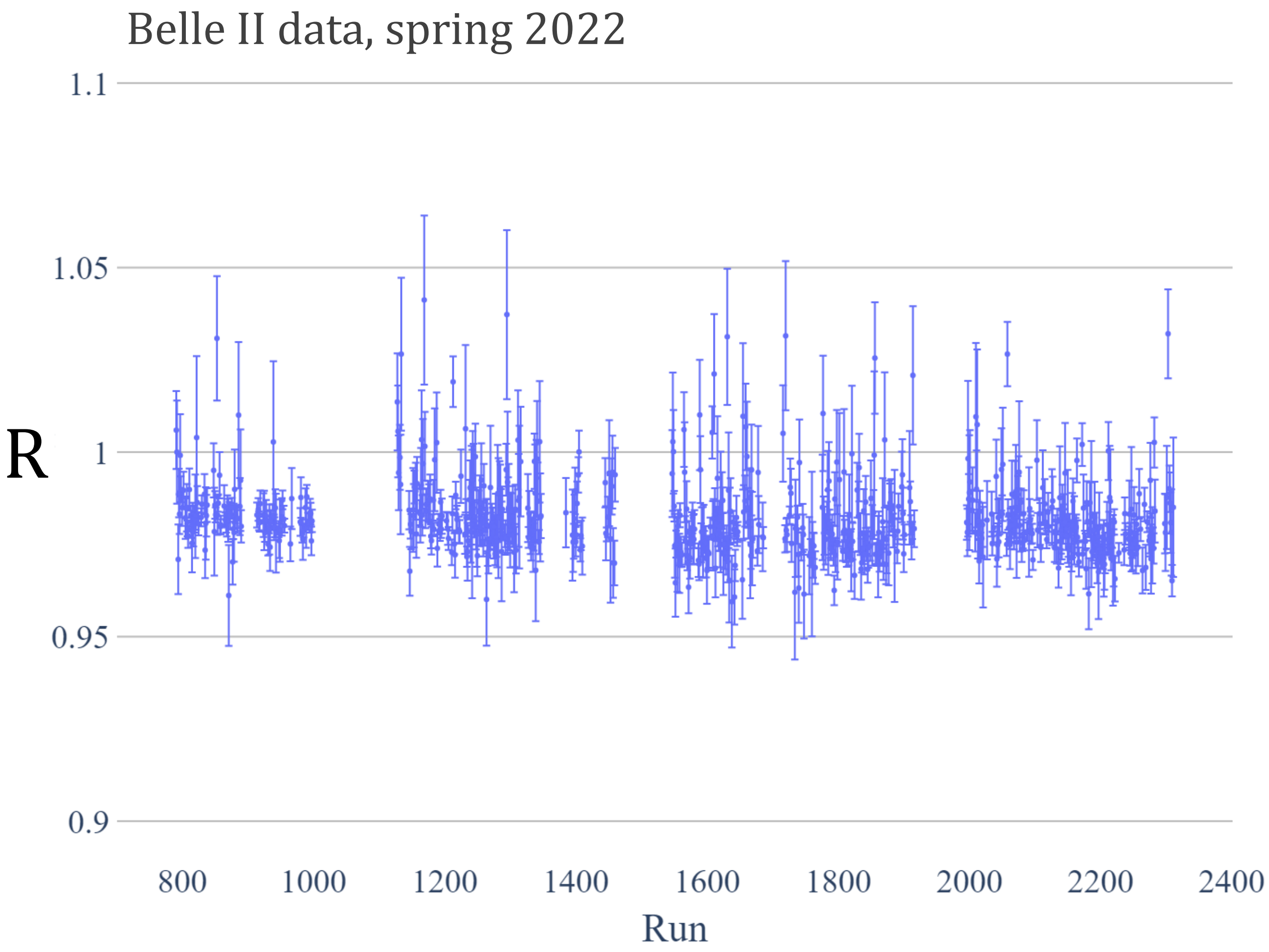
Comparison with offline measurements

The offline measurement of integrated luminosity:

- Based on full event reconstruction
- Uses Barrel ECL (independent from LOM)
- Measures L_{off} based on $e^+e^- \to e^+e^-$ (syst. uncert. 0.6%)

$$R = \frac{L_{online}}{L_{off}}$$

We observe 2% systematic discrepancy that is almost within expected systematic uncertainties.



The ratio of online to offline luminosities integrated per run

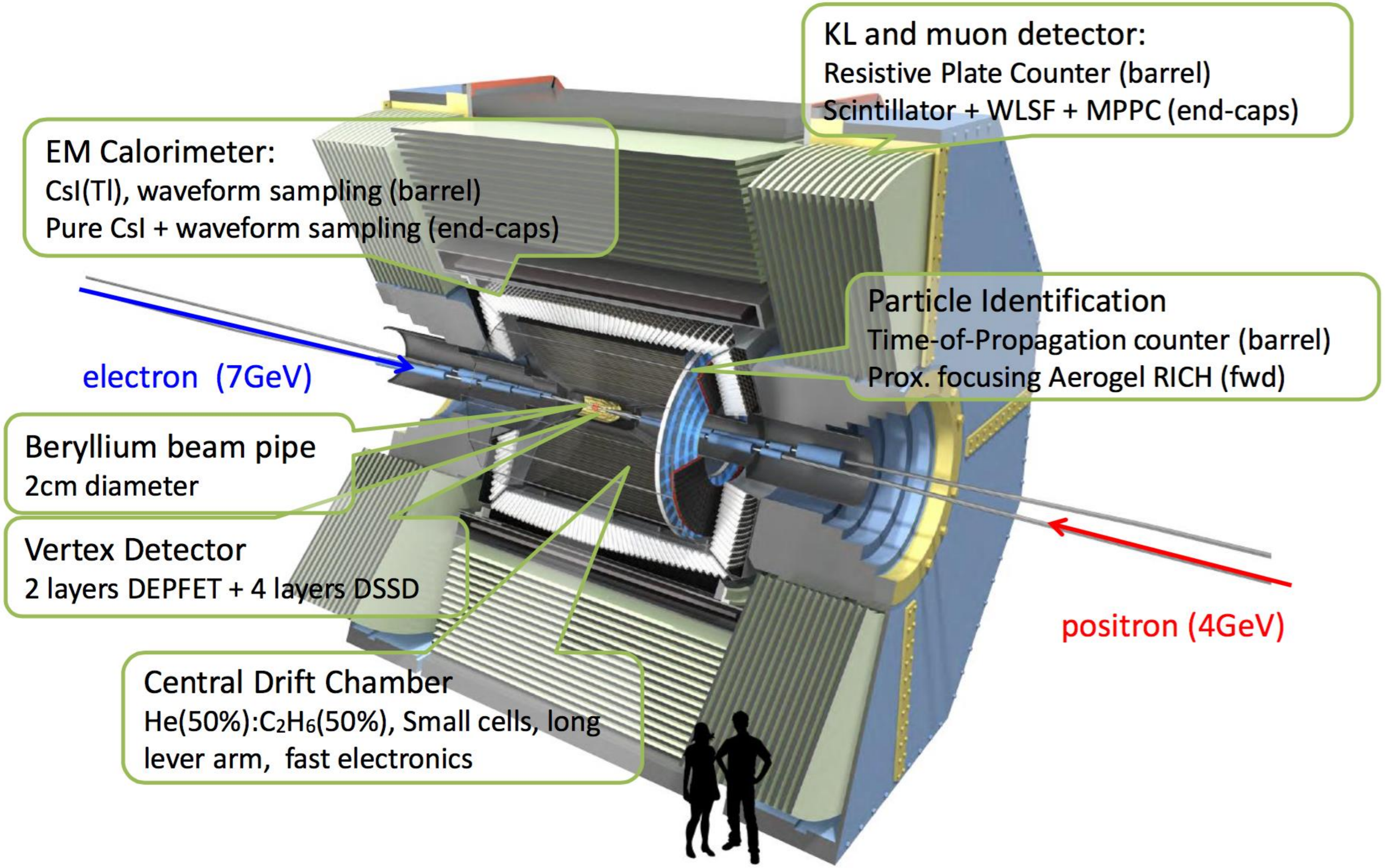
Conclusion

Luminosity Monitor

- Provides SuperKEKB/Belle-II luminosity in real-time
- Operates since 2018
- Demonstrates stable performance
- Instantaneous luminosity has statistical uncertainty of 2.7% at current value of $4.7 \times 10^{34}\ cm^{-2}s^{-1}$ and up to 0.7% at the designed $6.3 \times 10^{35}\ cm^{-2}s^{-1}$
- Results agree with independent offline measurement with accuracy of 2%

BACKUP

Belle II detector



Injection influence

- The R was influenced by the injection background (due to 1 μs veto mismatch, has been fixed)
- Recalculated luminosity (based on intervals w/o injection) shows almost no correlation with background
- Systematic shift $\approx 1-1.5\%$