名古屋大学
NAGOYA UNIVERSITY

Belle II

The operation and performance of the TOP detector at the Belle II experiment

Kazuki Kojima (Nagoya University)
on behalf of the Belle II TOP group

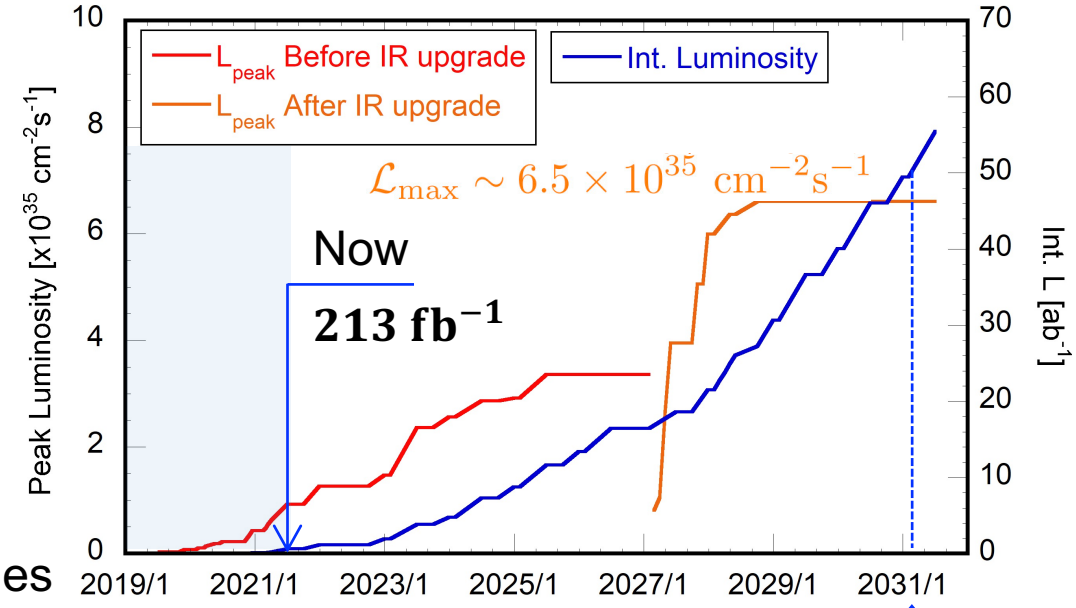
EPS-HEP Conference 2021
July 26th, 2021

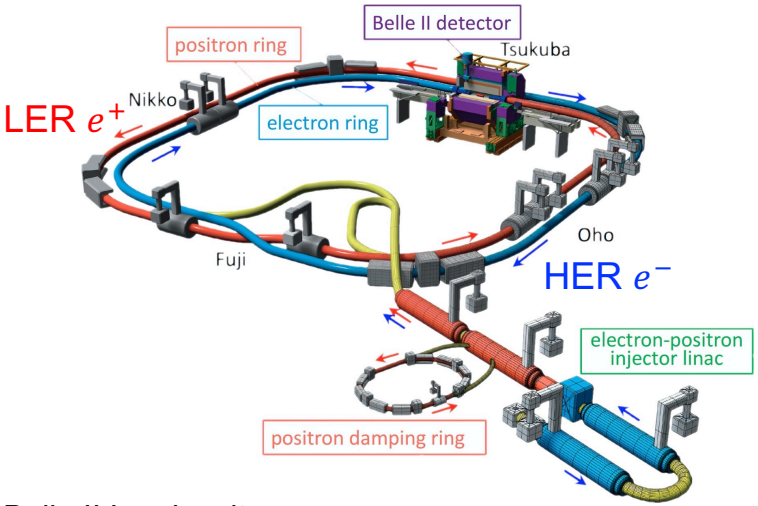
The SuperKEKB/Belle II Experiment

Electrons and positrons are collided at a center of mass energy of 10.58 GeV

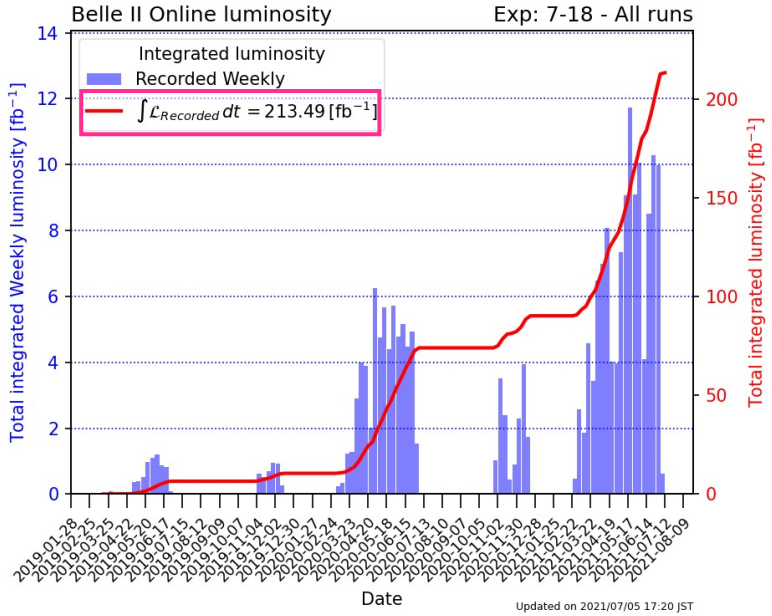
We have achieved the world highest instantaneous luminosity of $3.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

To search for physics beyond SM through precise measurements of decays of B mesons, τ particles, etc., using the world's largest dataset at B-factories





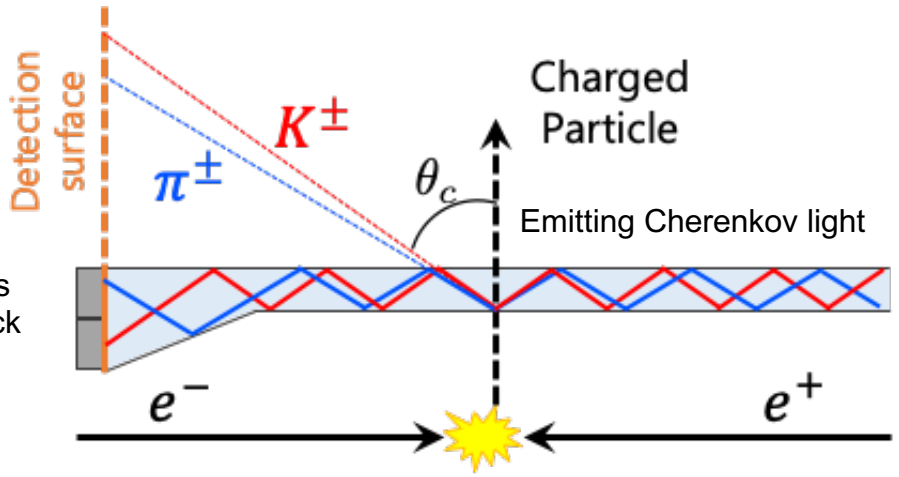
Belle II Luminosity
https://confluence.desy.de/display/BI/Belle+II+Luminosity



Target data amount
$50\ \mathrm{ab}^{-1}$ by 2031

The Time-Of-Propagation (TOP) Detector

Belle II barrel particle identification system
with Cherenkov ring imaging, which consists of 16 TOP modules.

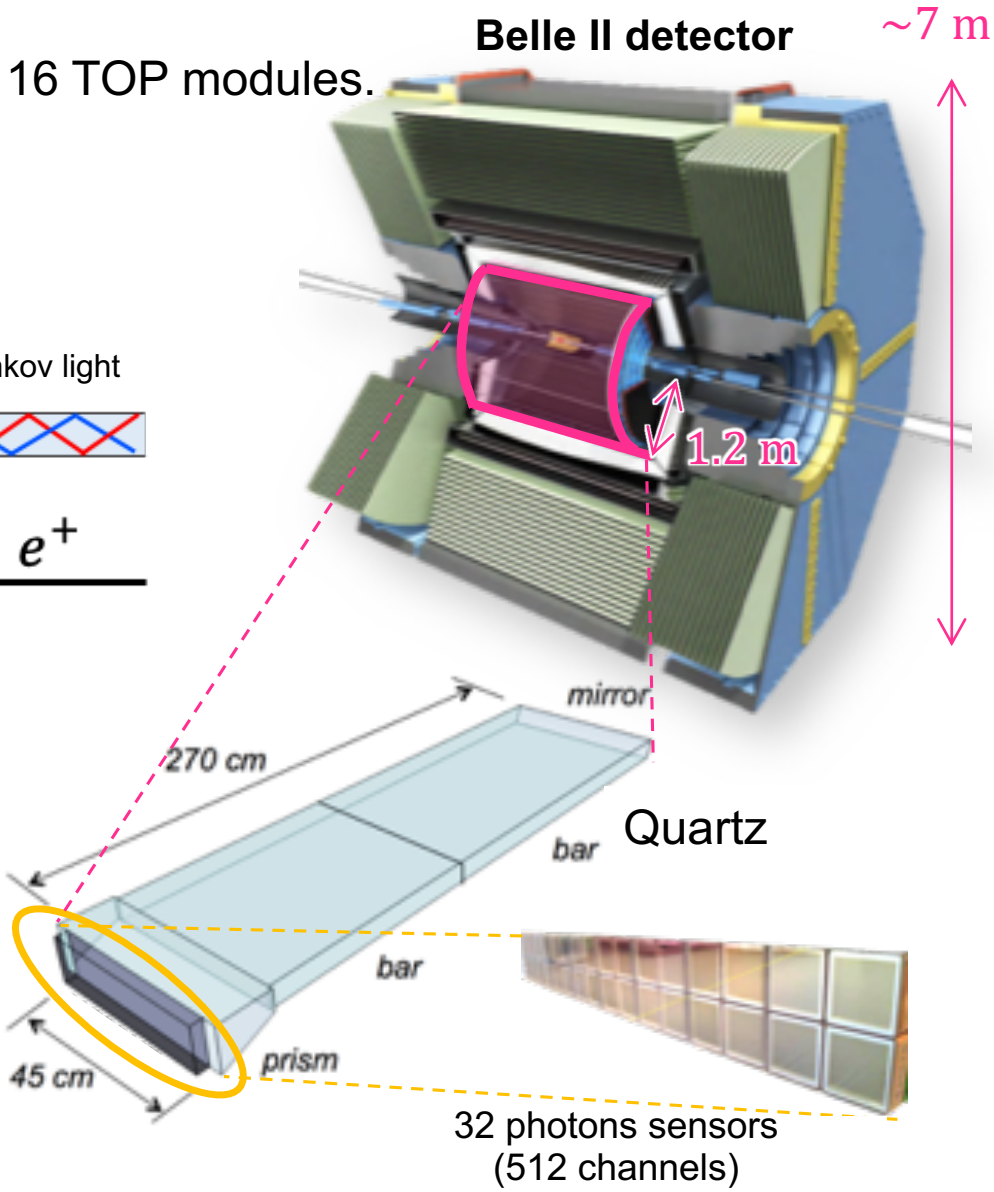


20 to 40 photons per charged track are detected

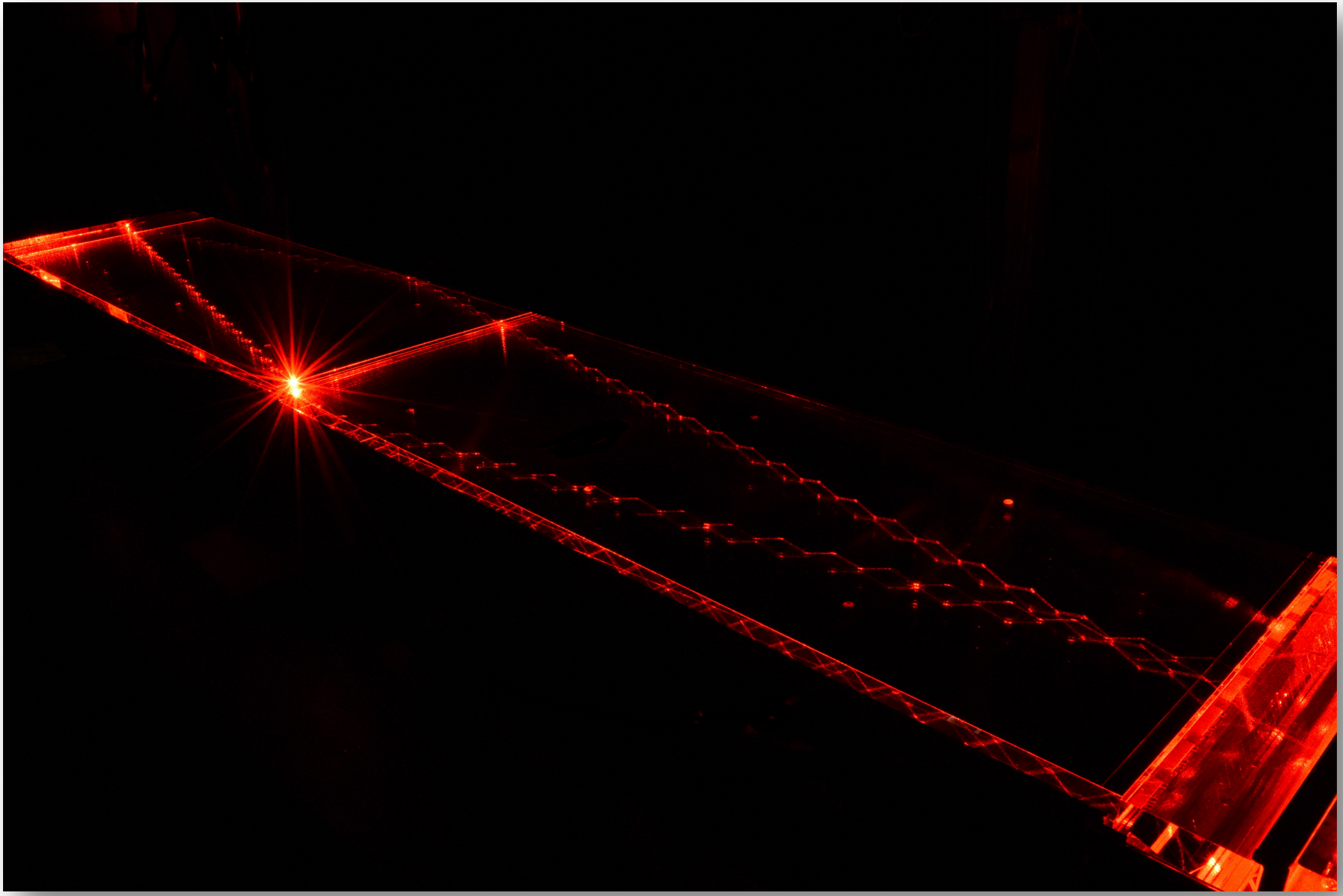
$$\cos\theta_c = \frac{1}{n\beta} = \frac{\sqrt{m^2+p^2}}{np}$$

$p = 3$ GeV π/K
$\Delta\theta_c \simeq 0.6^\circ \Longrightarrow \Delta t = \mathcal{O}(100)$ ps

$$\text{Performance} \propto \frac{\sqrt{\#\text{ of photons}}}{\text{Time resolution}}$$

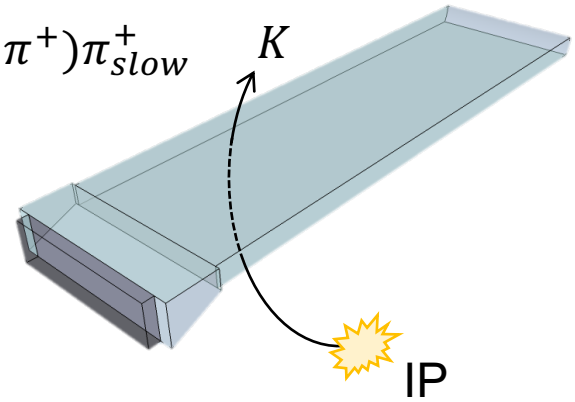


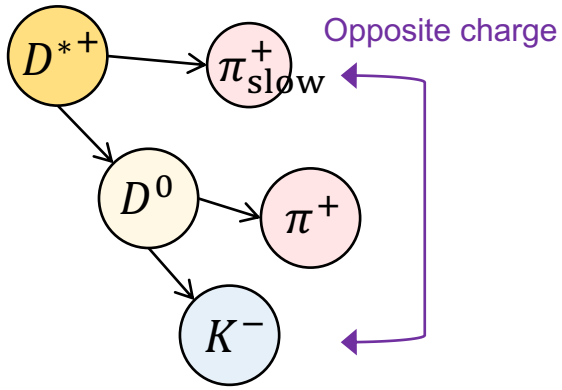
Internal Reflection of Light in the Quartz Bar

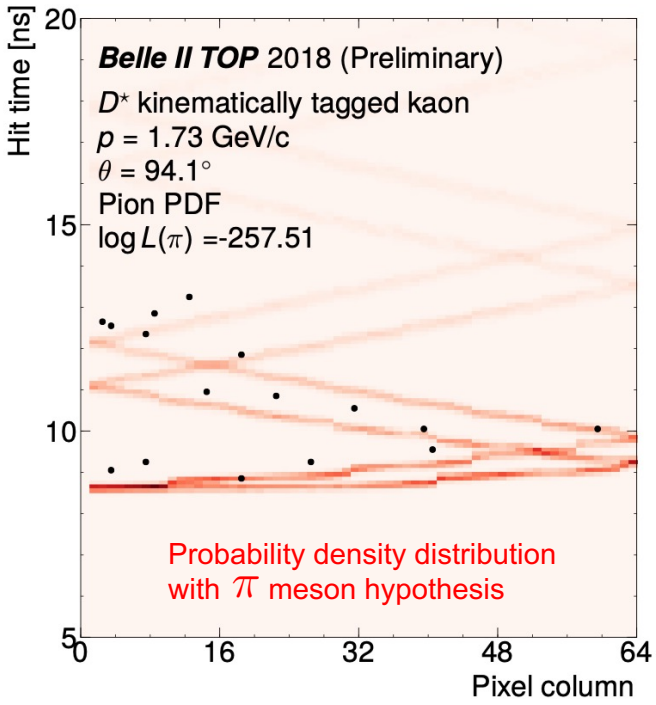


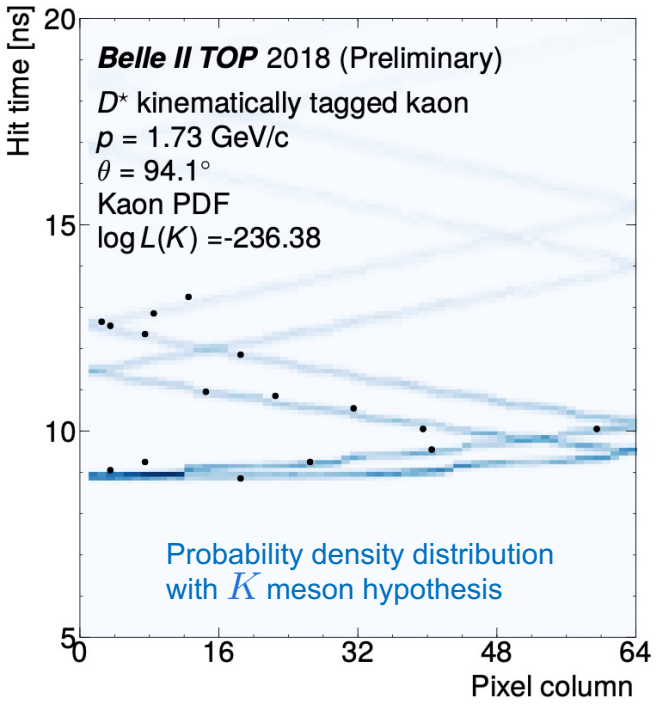
Photon Hit Patterns in the Real Data

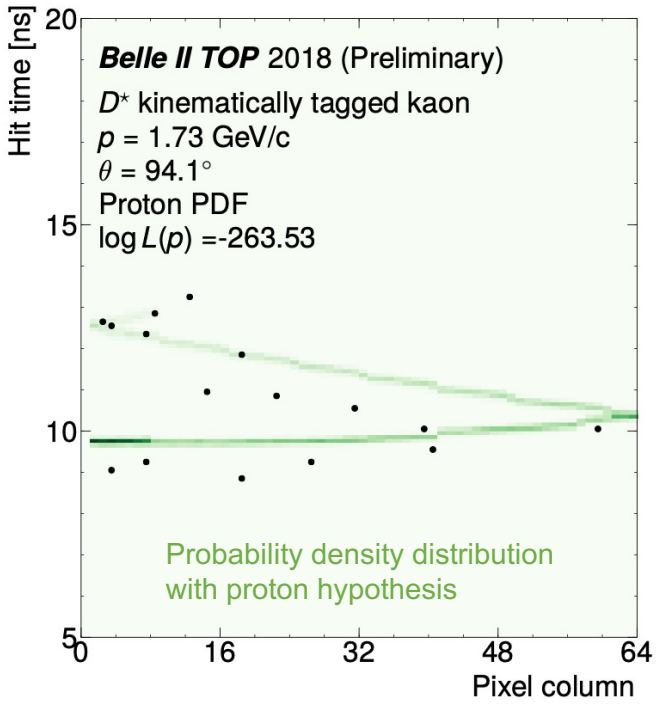
Kinematically tagged K with π_{slow}
in the reconstruction of $D^{*+} \to D^0(\to K^-\pi^+)\pi^+_{slow}$











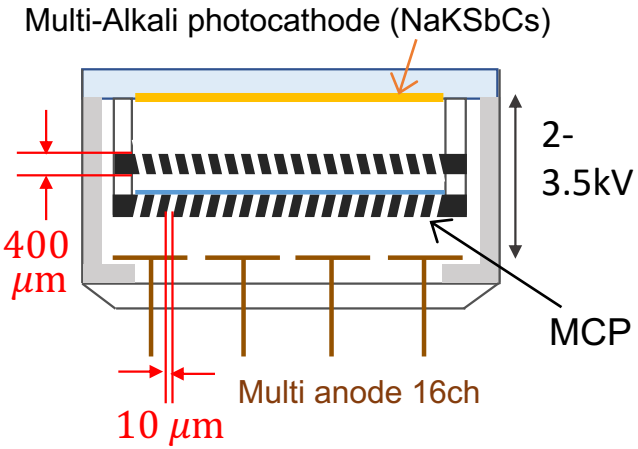
MCP-PMT & Readout System for the TOP Detector

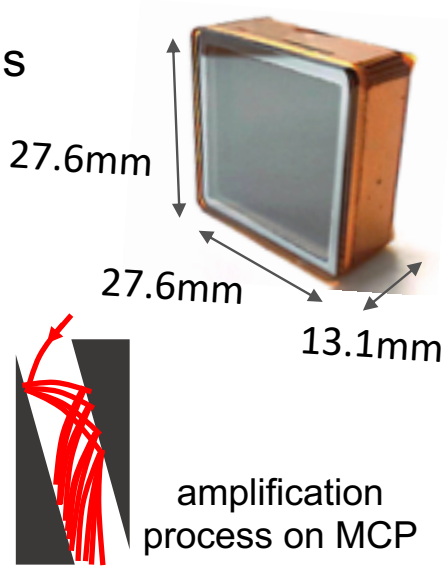
Photomultiplier tube with micro channel plates (MCPs) amplifying electrons

Performance for Single Photon

Average time resolution		34.3 ps
Gain	(Nominal)	3×10^5
Average quantum efficiency (QE) at the peak wavelength		29.3 %

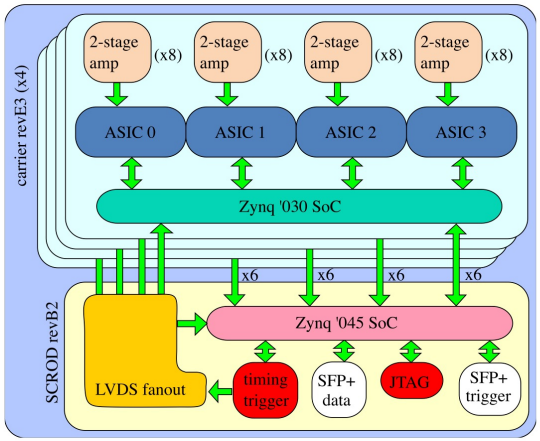
JPS Conf. Proc. **27**, 011020 (2019)





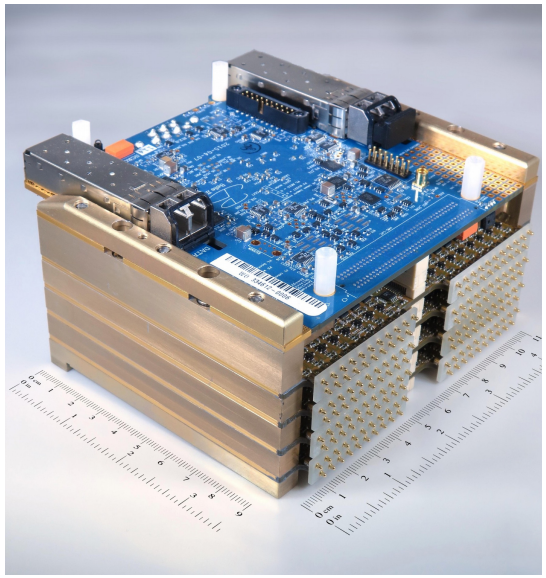
Waveform readout modules with 2.7 GSample/s on 8192 channels
Average time resolution: 27.6 ps

NIM A **941**, 162342 (2019)



Carrier board:
Custom-designed waveform sampling ASICs for 8 channels, "Ice Ray Sampler version X" (IRSX)
Storing waveform in a 11 μs-long analog ring buffer with switching capacitor arrays.

SCROD board:
Performing Feature extraction of waveform data.
Transferring data to downstream components of the Belle II data acquisition system



Operation & Performance

MCP-PMT Lifetime and Accumulated Output Charge

The decrease of QE follows the following function of accumulated charge Σ_Q in MCP-PMT.

$$R_{QE} = \frac{QE(\Sigma_Q)}{QE(0)} = 1 - 0.2\left(\frac{\Sigma_Q}{\tau}\right)^2$$

Type	Lifetime τ ($R_{QE} = 0.8$)
Conventional	$1.1\ \mathrm{C/cm^2}$ (average)
ALD	$10.4\ \mathrm{C/cm^2}$ (average)
Life-extended ALD	$> 13.6\ \mathrm{C/cm^2}$

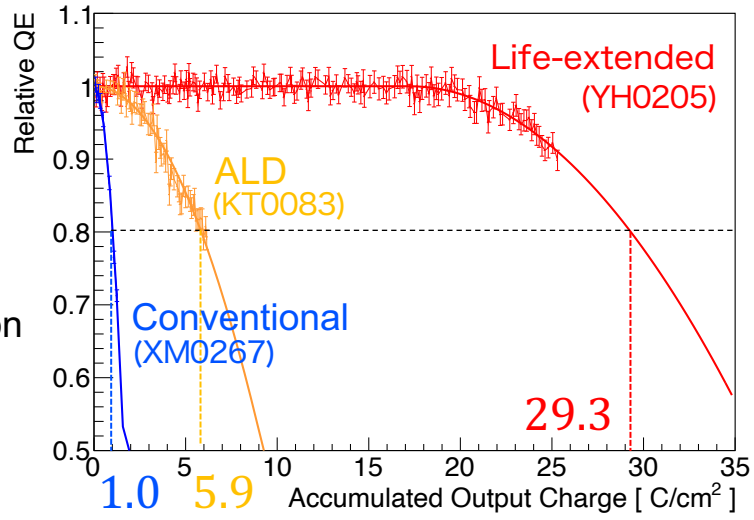
→ Replace in 2022

Atomic Layer Deposition (ALD) coating on MCP

Additional countermeasures

Reduced residual gas

NIM A **876** (2017) p.93-p.95



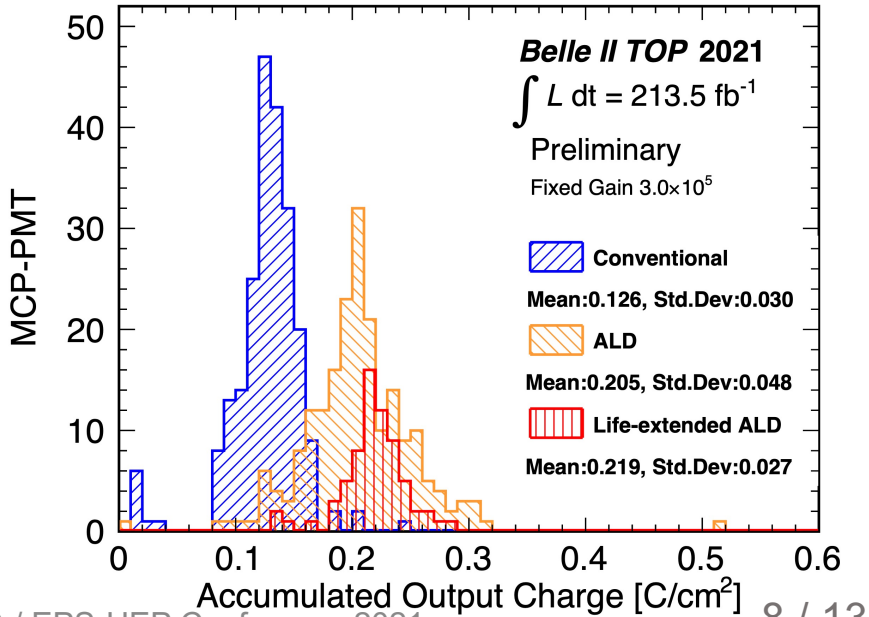
Monitoring accumulated output charge using scaler rates in physics run

Output charge $\Sigma_Q = \int_{t_0}^{t} G(t) \cdot F(t)\, dt$

$G(t)$: gain

$\Sigma_Q = 0.126\ \mathrm{C/cm^2}$ on $\tau = 1.1\ \mathrm{C/cm^2}$

$\Longrightarrow$ Expected QE decrease is 0.3%



The Relative Detection Efficiency of MCP-PMTs by 2021

Relative detection efficiency is evaluated from the hit rate of Cherenkov photons per μ track in di-muon events from Nov. 2nd, 2019, to Apr. 7th, 2021, with corrections by threshold efficiency.

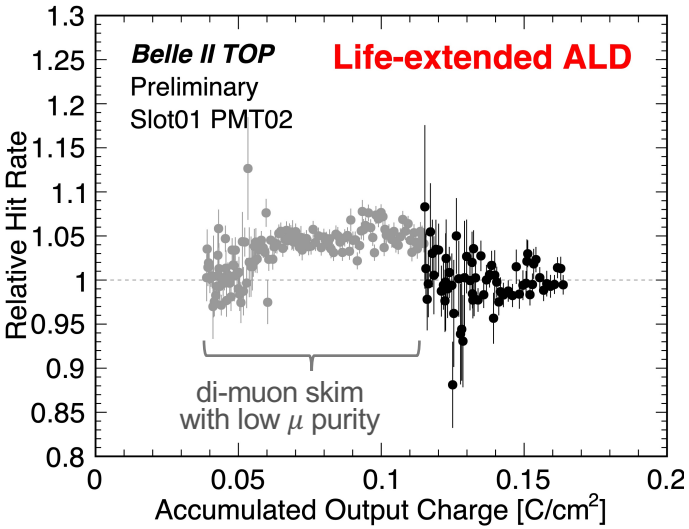
Two di-muon skims with low and high($> 98\%$) μ purity are used before and after Oct. 30th, 2020, respectively.

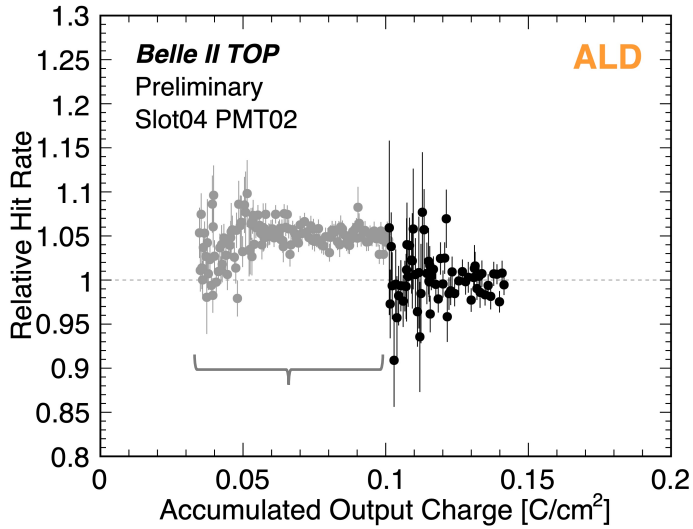
Preliminary results

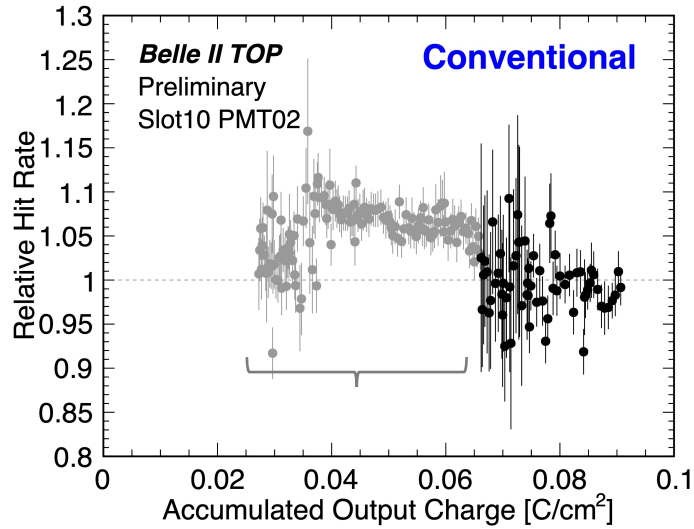
- Almost all of MCP-PMTs have equivalent hit rate in Apr of 2021 to that in 2019, and constant hit rate in skim data with high μ purity.
- Relative hit rate is decreasing in about 5% of total MCP-PMTs.

We are developing an evaluation method of quantum efficiency using calibration laser runs for the cross check.

Typical examples:



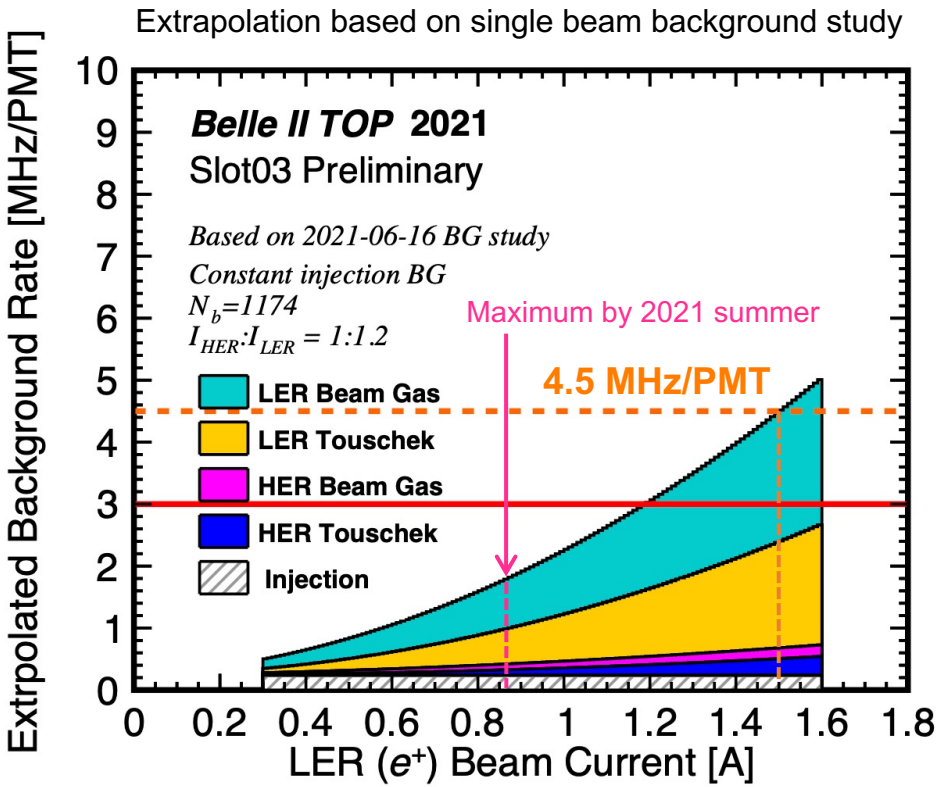




Operation from Autumn 2021

We set a limit on MCP-PMT hit rate by converting expected output charge at Belle II.
The hit rate limit was at **3.0 MHz/PMT** for beam background in the 2021 spring run.

We have revised acceptable PMT hit rate to **4.5 MHz/PMT** from 2021 autumn run based on the current accumulated charge and QE variation.
→ **~1.5 A** in LER (e^+) ring at the limit of 4.5 MHz/PMT



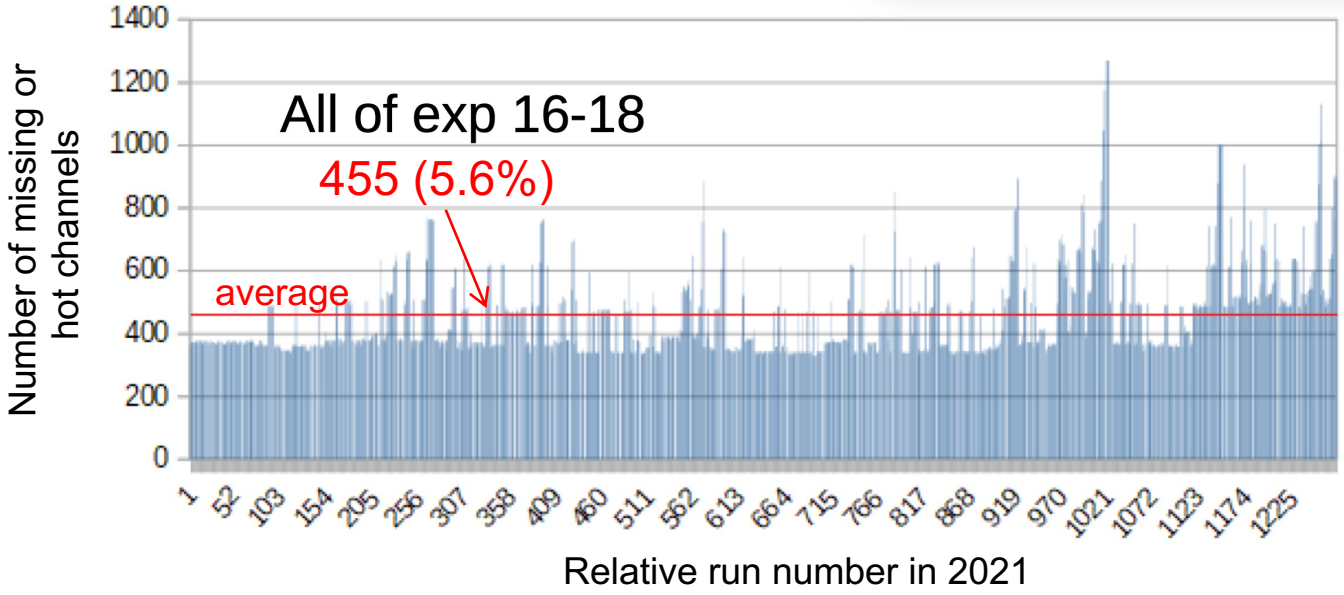
TOP Operational Efficiency in 2021

The active channels were 94.4% (7737 channels out of 8192 channels) on average.

- 94.8% is working while three board stacks, a quarter of a module, are disabled due to a hardware connection problem, or configuration failure.
  → The disabled board stacks will be replaced in 2022 long shutdown.

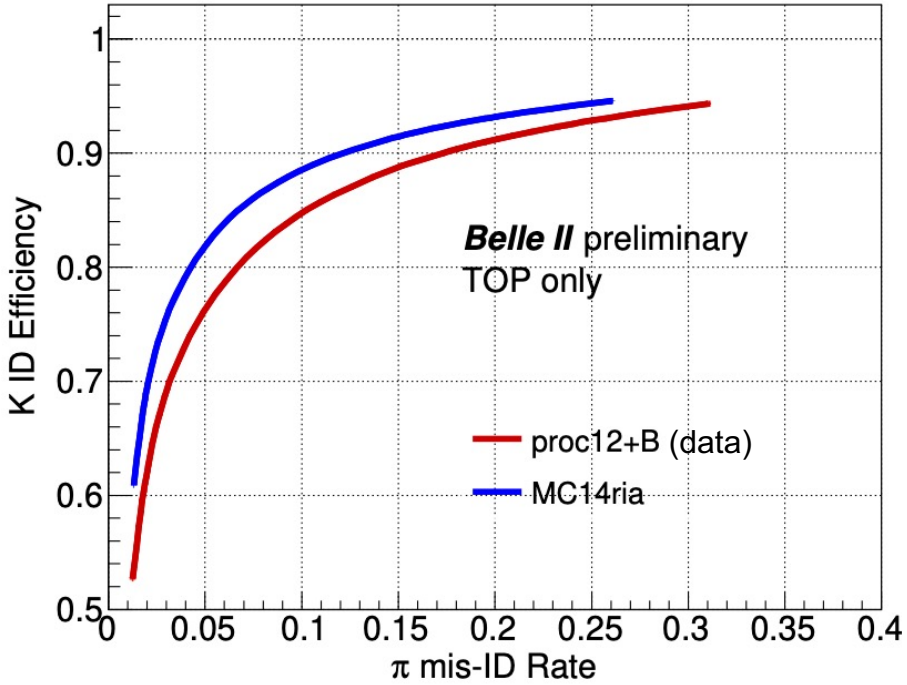
- Radiation-induced Single Event Upsets regularly cause stops of board stacks that require to be masked, at a few board stacks per day.
  → Auto detection and recovery via GUI.

An error message automatically posted to channels on our operation chat tool



Particle Identification Performance of the TOP Detector

The TOP detector provides 85% K ID efficiency at 10% π mis ID rate in data.
The difference between data and MC mainly comes from the forward region.



Future Improvement

- Waveform template fit
- Updates on software modules
  Improvement of beam bunch identification, etc.
- Development of neural networks for better PID performance than PDFs

Summary

The SuperKEKB/Belle II experiment has targeted $50\ \mathrm{ab}^{-1}$ by 2031
The highest peak luminosity is recorded this year: $3.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

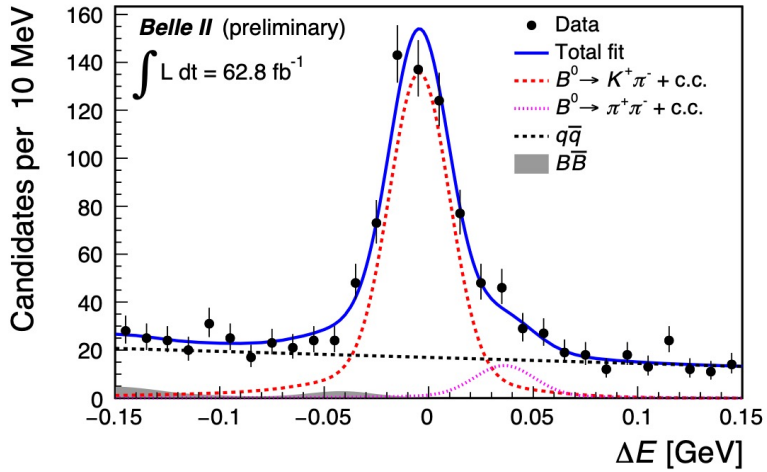
The TOP detector is an upgraded particle identification system in the barrel region.
Microchannel plate PMTs + waveform readout modules with 2.7 GSample/s.

Concern: lifetime of MCP-PMTs in harsh beam background

- The accumulated output charge is about 10% of Conventional type's lifetime by summer 2021.
- The degradation of detection efficiency is not observed in 95% MCP-PMTs.

The TOP detector was operated **with 94.4% active channels** in 2021.

The TOP detector provides **85% K ID efficiency at 10% π mis ID rate in data.**



$\Delta E \equiv E_B^* - \sqrt{s}/2$ distribution
in the analysis of $B^0 \to K^+\pi^-$
with K/π identification
arXiv:2106.03766