TOP detector
for particle identification at Belle II

International Workshop on Future Tau Charm Facilities

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on behalf of the TOP group

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- TOP activity during LS1
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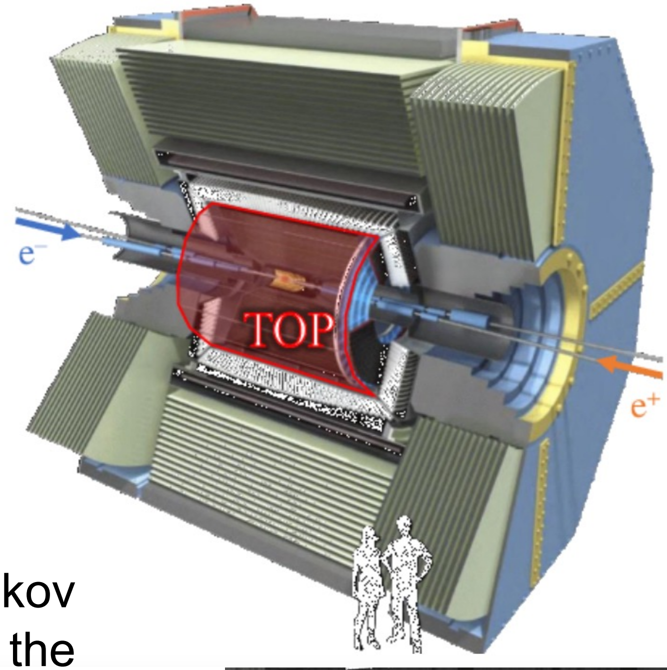
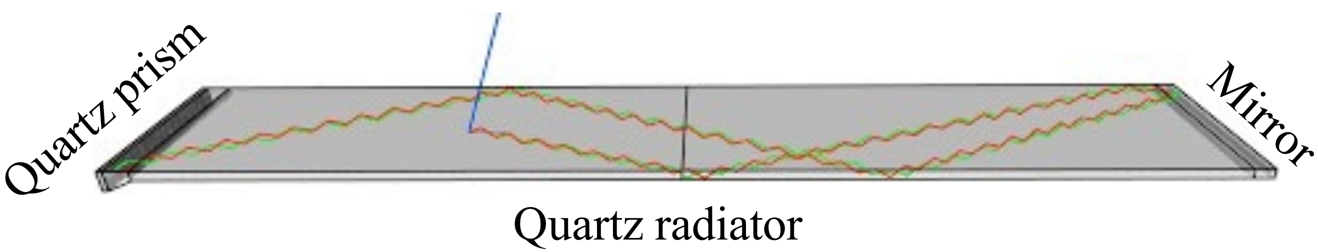
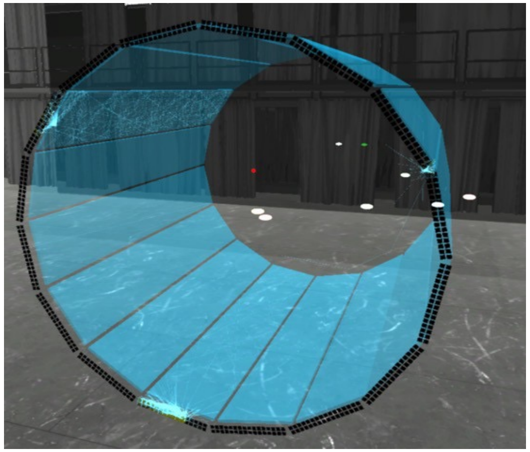
TOP detector

TOP stands for time-of-propagation, is the particle identification detector located in the barrel region of the Belle II experiment between the central drift chamber and the electromagnetic calorimeter.

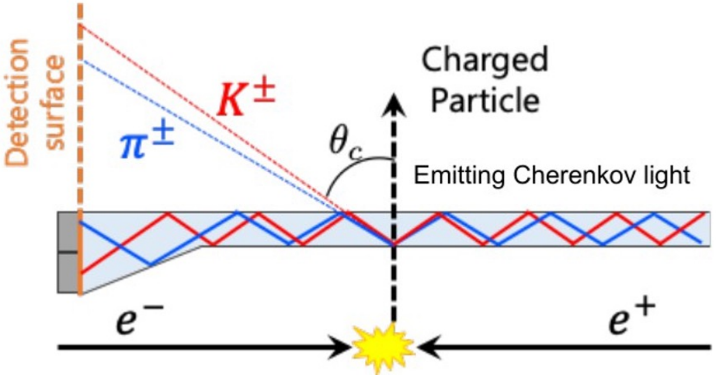


The detector uses 16 quartz bars acting as Cherenkov radiators. Each bar is glued to a spherical mirror in the forward region and to a quartz prism for photons expansion in the backward region.





TOP detector concept



The arrival **time** and **position** of Cherenkov photons is used for particle identification.

Cherenkov photons emitted from kaons arrive later and in a different position than photons emitted from pions.

Time of arrival is measured relative to the e^+e^- collision time, it includes time-of-propagation (Top) and time-of-flight (Tof) of the particle.

K/π Tof difference ~ 50 *ps / m*

K/π Top difference ~ 75 *ps / m*

PID sensitivity $\propto \frac{\Delta Tof + \Delta Top}{\sigma_{Time}} \sqrt{N_\gamma}$

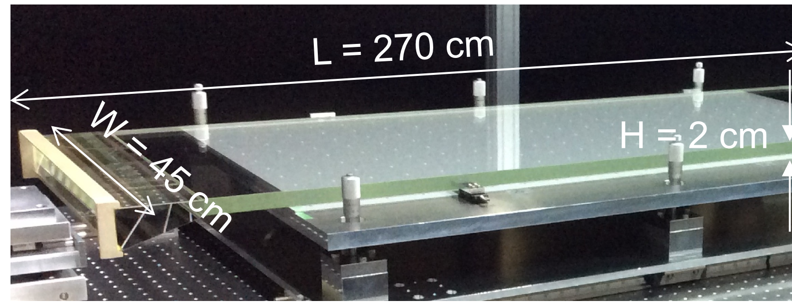
$\sigma_{TIme} \lesssim 100\ ps$

TOP detector elements

Key elements in each TOP module:

1) Cherenkov radiator

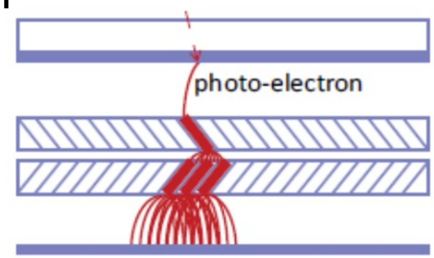
Quartz properties	Requirements
Flatness	< 6.3 μm
Perpendicularity	< 20 arcsec
Parallelism	< 4 arcsec
Roughness	< 0.5 nm (RMS)
Bulk transmittance	> 98% / m
Surface reflectance	> 99.9% / reflection

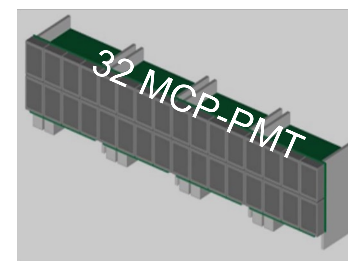


NIM A 876 (2017) 252-256

2) MCP-PMT micro channel plate photodetectors

- 2 planes of microchannels with 10 μm diameter
- gain 3 x10^5
- time resolution 37 ps
- works in 1.5 T magnetic field



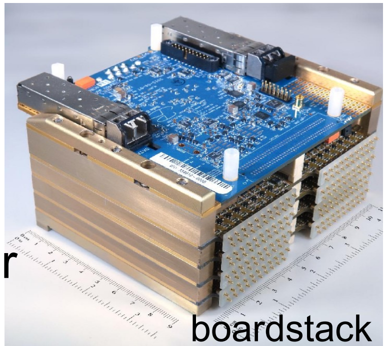


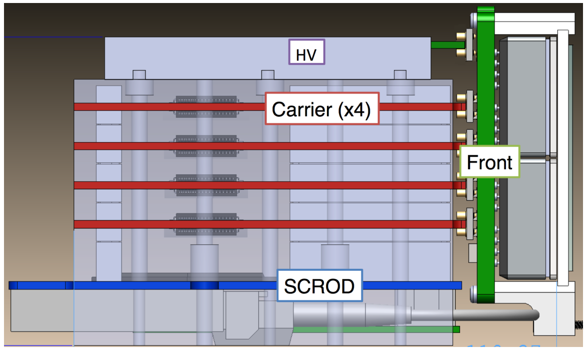
NIM A 936 (2019) 556-557

TOP detector elements

3) front-end readout electronic

- 4 boardstacks per module
- 16 ASIC's / boardstack
- 8 channels/ASIC with 10 μs long buffer
- waveform sampling with 2.7 Gs/sec
- digitization and feature extraction (50% CFD)
- data sent-out by optical link
- time resolution 30 ps measured with calibration pulses





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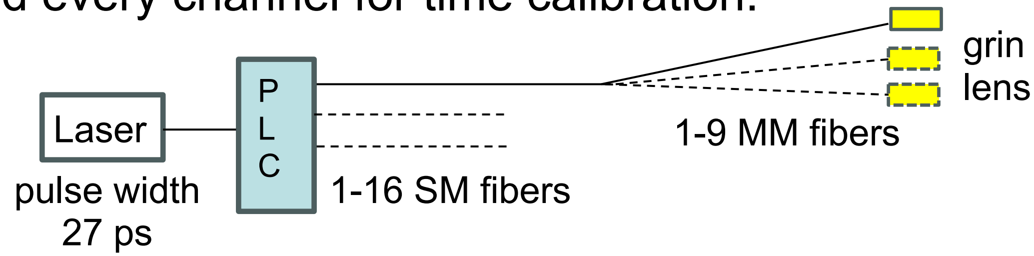
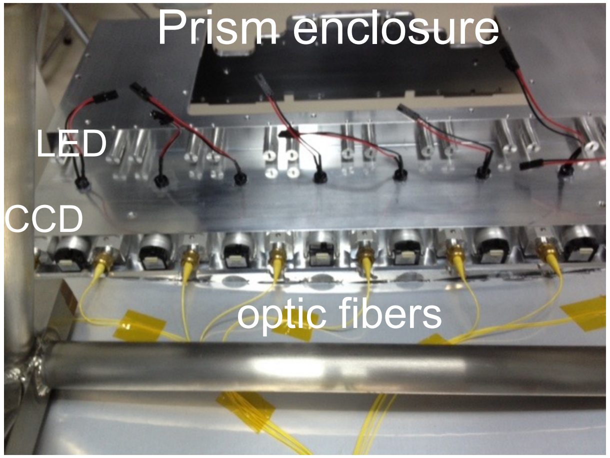
4) laser calibration system and optical check

- LED and CCD to control the quality of the optical coupling between quartz and PMT
- 9 optic fibers / module to reach every MCP-PMT and every channel for time calibration.





NIM A 876 (2017) 59-61

Time calibration

1) Time base calibration (TBC)

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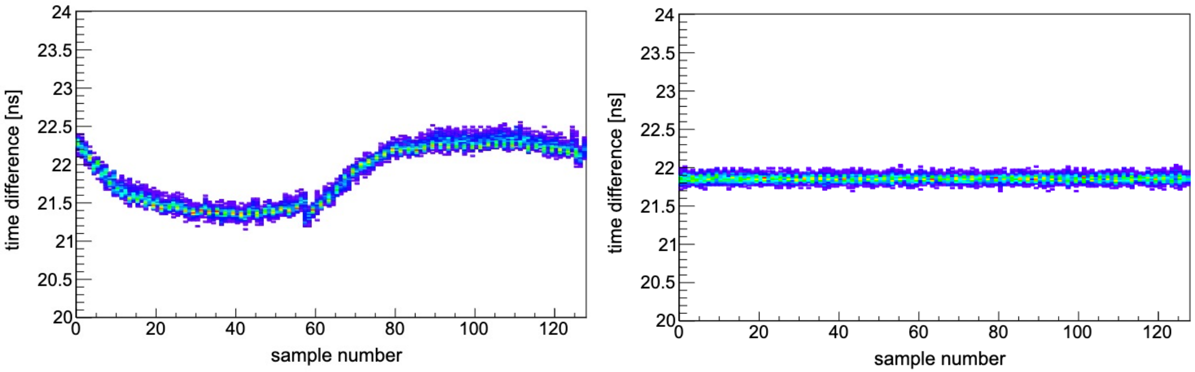
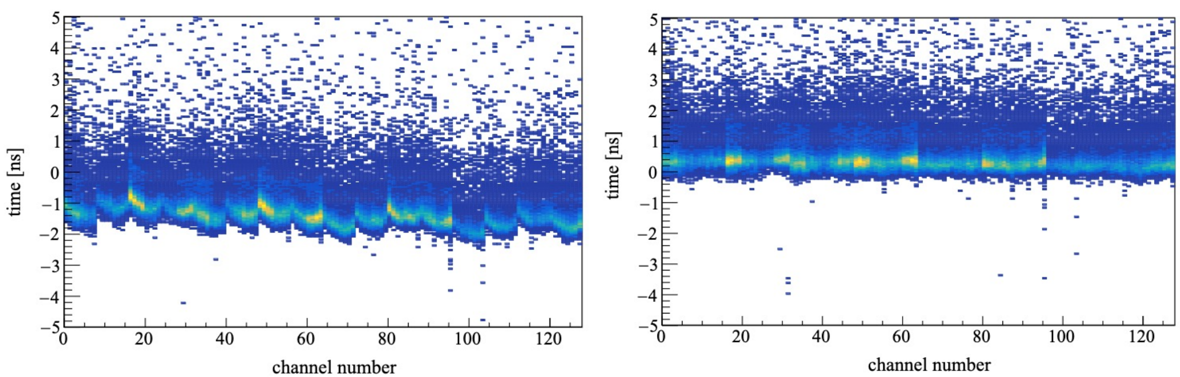


The sampling clock is not uniform in time. TBC performed with signal injection in each electronic channel

σ_t ~300 ps → ~40 ps

2) Time assignment of channels within module



Laser pulses injected into every module. For every channel mean light path studied with simulation.

$\sigma_t < 50$ ps

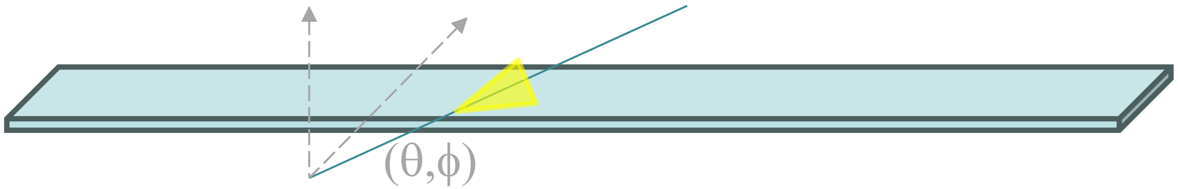
3) Time alignment of modules

4) Alignment relative to collision time

} collision data (dimuon events) $\sigma_t < 10$ ps

Particle Identification

We need a precise extrapolation of the entrance point and of the entrance angles of the charged track with respect to the quartz bar.



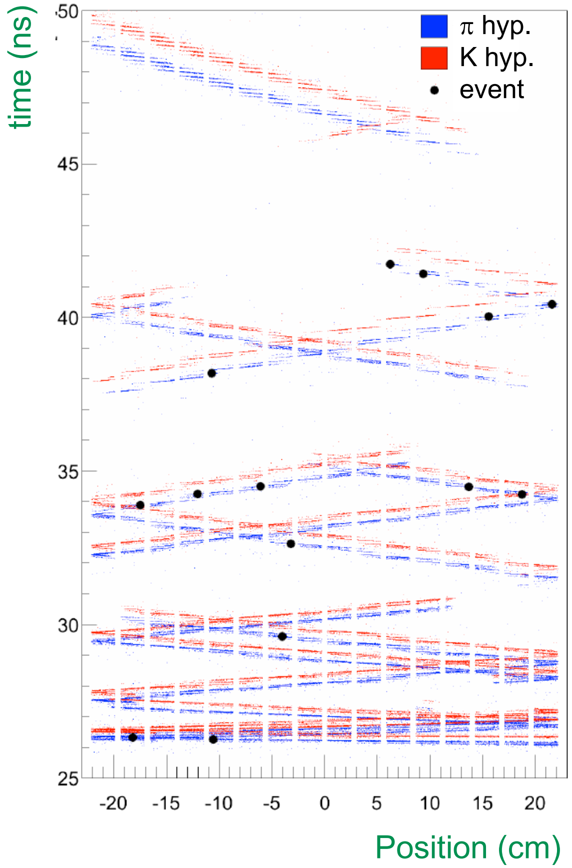
Considering N photons distributed at different positions $\{ x_i , y_i \}$ and times t_i there are different probability density functions for the six long life particle hypotheses $h = \{e, \mu, \pi, K, p, d\}$

$$\mathcal{L}_h = \prod_{i=1}^{N} \mathcal{L}_h^i = \prod_{i=1}^{N} \frac{S_h(x_i + y_i + t_i) + S_B(x_i + y_i + t_i)}{N_\gamma} P_N(N_\gamma)$$

- N detected photons
- N_γ expected photons N_h (signal) + N_B (background)
- $P_N(N_\gamma)$ Poisson probability to observe N photons with expected N_γ
- S_h signal distribution for the particle hypothesis h
- S_B background distribution

Particle identification

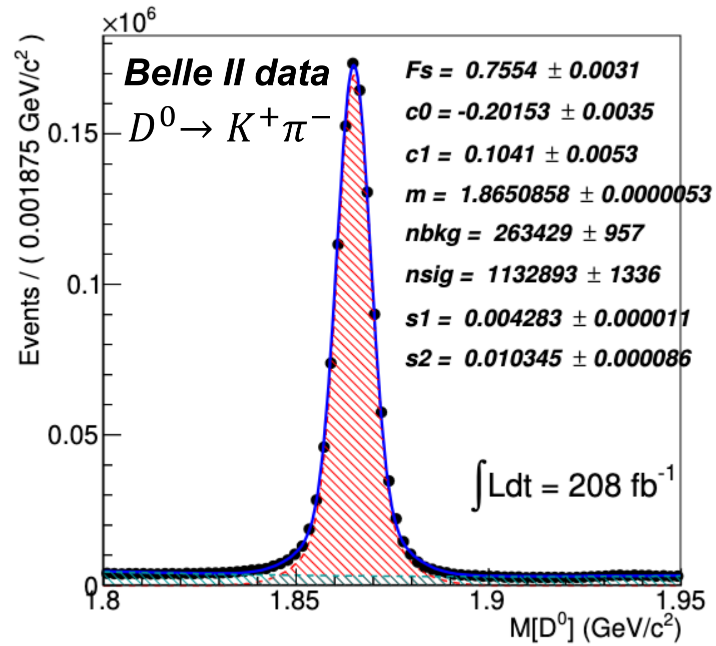
Distributions of the expected time of arrival of photons in each channel for π and K hypotheses compared with a real track tagged as pion.



To measure the particle identification performance for real data a D^{*+} reconstructed sample can provide relatively high purity π and K tracks.

$$D^{*+} \rightarrow D^0\pi^+ \;,\quad D^0 \rightarrow K^+\,\pi^-$$

Selection based on charge sign, impact parameters, invariant mass



BELLE2-CONF-PROC-2023-026

TOP performance

binary PID

$$R[\mathrm{K}/\pi] = \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi}$$

global PID

$$p(h) = \frac{\mathcal{L}_h}{\sum_{h'} \mathcal{L}_{h'}}$$

only TOP

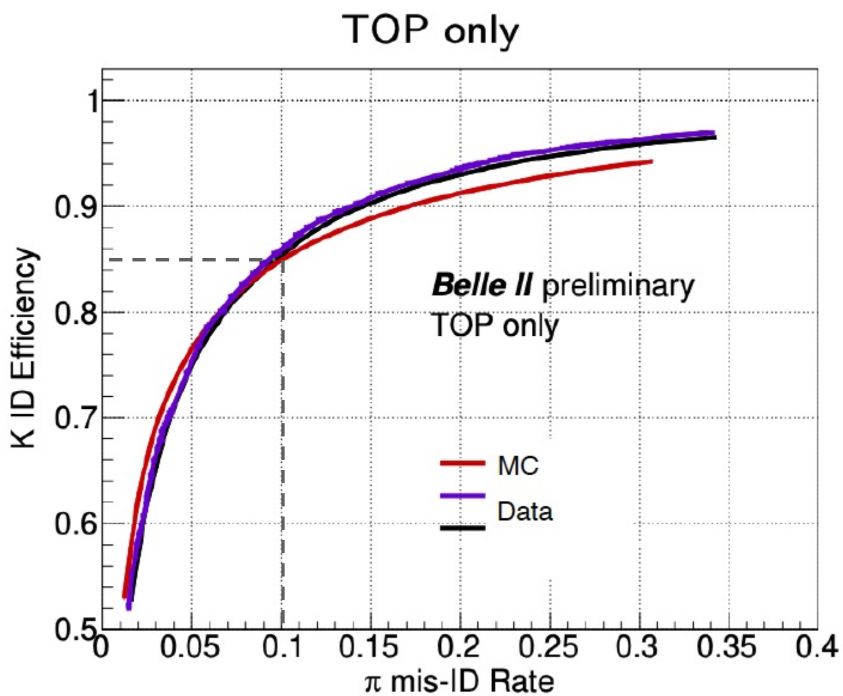
$$\mathcal{L}_h = \mathcal{L}_h^{TOP}$$

all detectors

$$\mathcal{L}_h = \prod_{det.} \mathcal{L}_h^{det.}$$

{SVD, CDC, TOP, ARICH, ECL, KLM}

K efficiency vs p mis-identification increasing $R[\mathrm{K}/\pi]$ selection



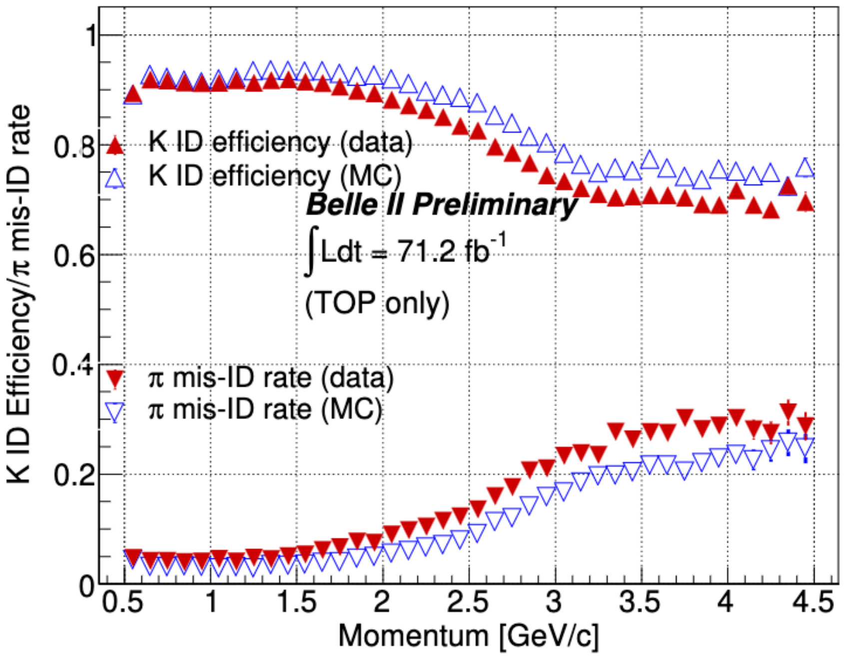
85% $\boldsymbol{K}$ ID efficiency
with 10% $\boldsymbol{\pi}$ mis-ID rate

Small discrepancy between the data and the Monte Carlo simulation

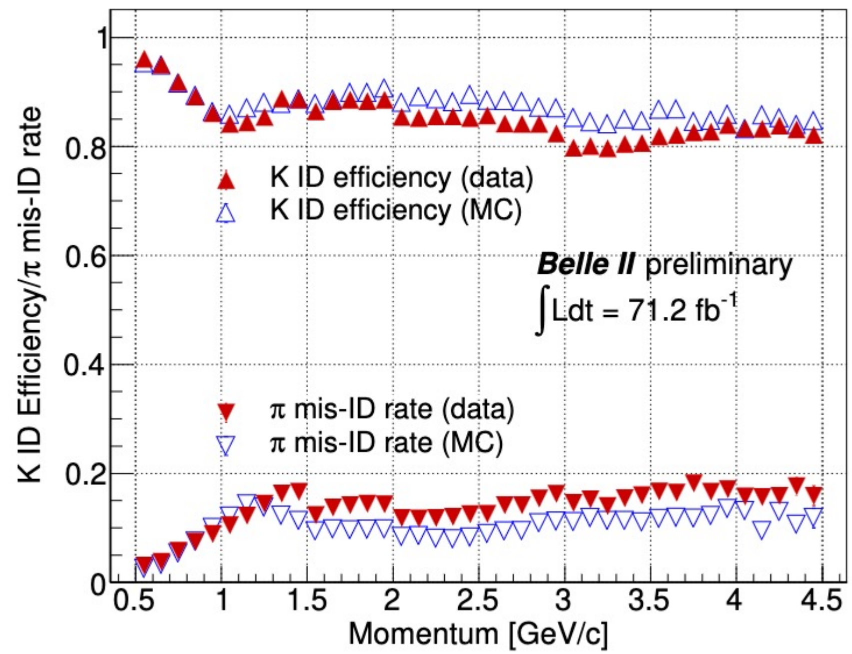
VCI2022 conf.

TOP performance

$R[\mathrm{K}/\pi] > 0.5$ only TOP



all detectors

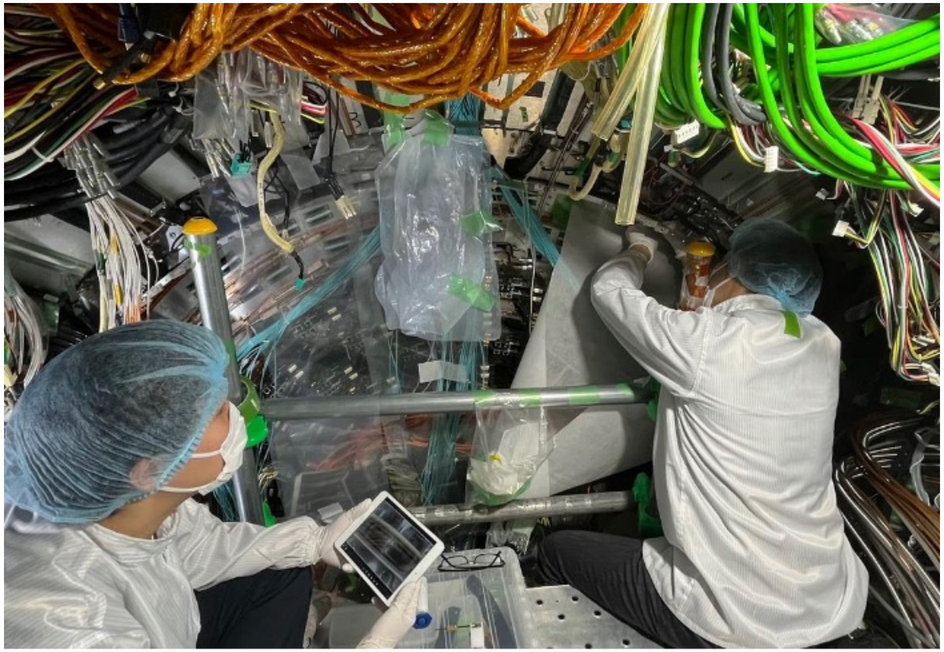


J. Phys.: Conf. Ser. 2374 012107 (2022)

Calibrated weights for each detector improved the PID performance.

Machine learning approach is under study where weights used to combine PID information are not static but function of charge of the track and its kinematics.

TOP activity during LS1



Replacement of MCP-PMTs belonging to the first production generation with short lifetime.

Replacement or repair of cables and readout electronics.

Update of Graphical User Interface panels to speed up restart.

Update of slow-control software and DQM plots.

Channel occupancy **before LS1**

4 boardstacks dead (512 channels)
10 boardstaks with problems
Tot. 600-700 dead channels / 8192

91-93% efficiency

Channel occupancy **after LS1**

2 dead ASICS (16 channels)
1 dead MCP-PMT, few bad pins
Tot. 40 dead channels / 8192

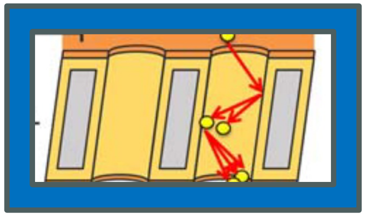
99.5% efficiency

TOP upgrade

Three generations of MCP-PMT have been used in the TOP detector:

Conventional

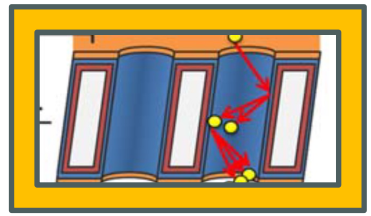
average lifetime
1.1 C/cm^2



Lead reduction layer
for electron multiplication

ALD

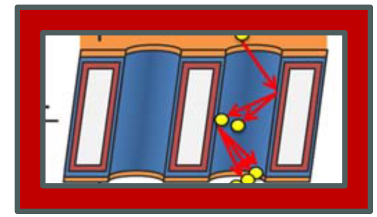
average lifetime
10.4 C/cm^2



Resistive film and secondary film
for electron multiplication

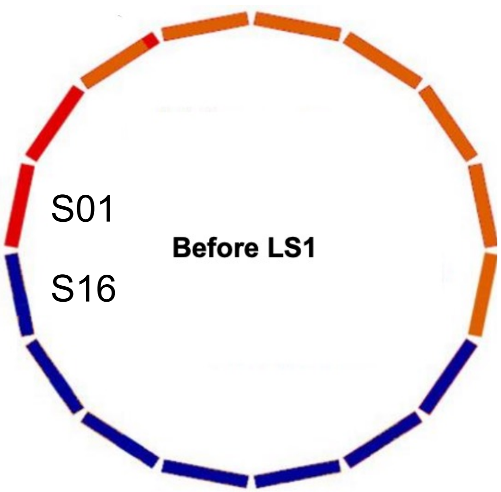
life-extended ALD

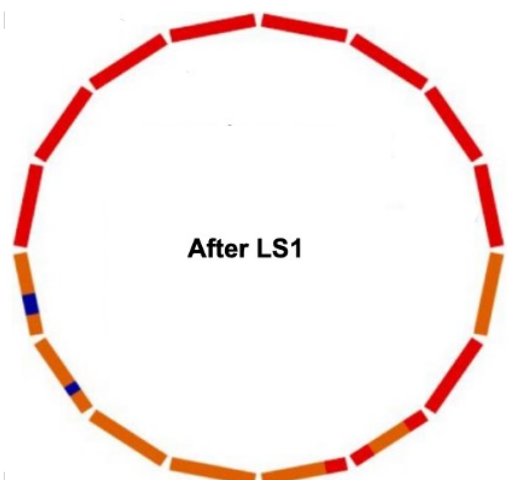
lifetimes
15-30 C/cm^2

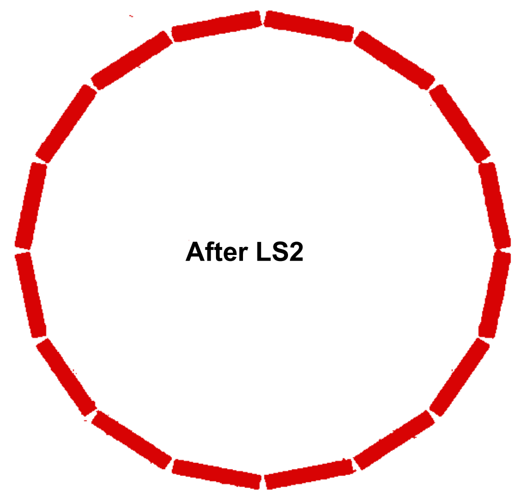


Residual gas reduction
with improved production process

During LS1 (2022-2023) conventional MCP-PMT have been replaced.
During LS2 (2027-2028) the residual 220 not live-extended ALD will be replaced,
150 new MCP-PMTs already delivered or ordered.

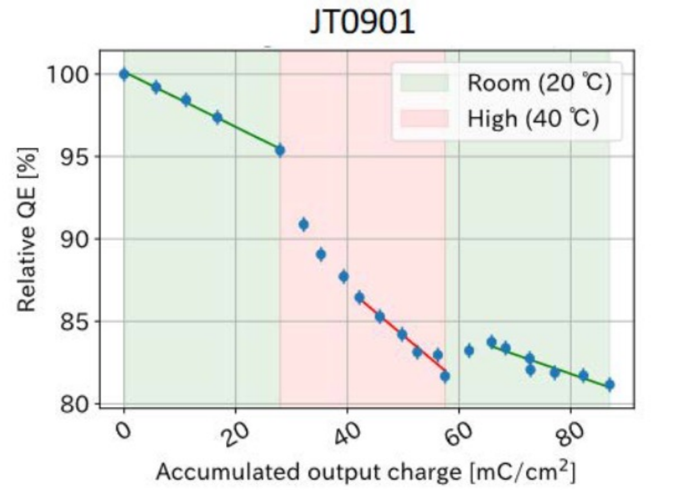




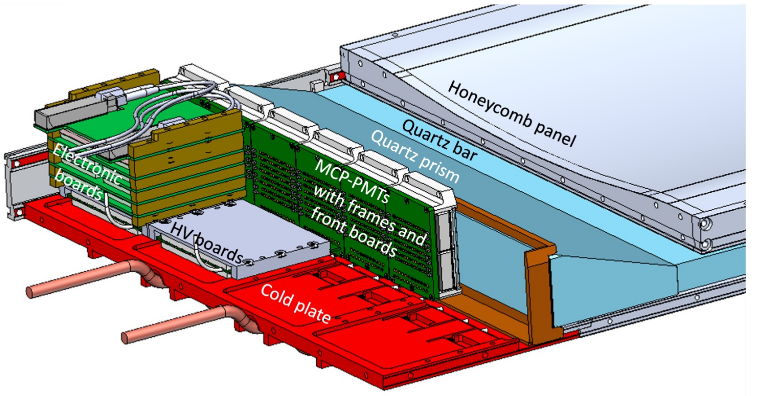


TOP upgrade

Quantum-efficiency measurements performed in the laboratory as a function of the accumulated charge show a faster degradation at higher temperatures



Planned to replace the readout electronic to improve readout robustness under high backgrounds. New analog to digital converter has been considered with about 50% lower power consumption than the current ASIC



R&D has started on a possible silicon photomultiplier (SiPM) replacement option. This option looks promising, although the required cooling will reduce the space available for the readout electronics and limit its acceptable heat load.

Summary

TOP is a new concept of compact Cherenkov detector for particle identification which relies on multichannel long-lifetime MCP-PMTs for the precise measurement of the arrival position and time of individual photons.

The installation of the TOP detector has been completed in May 2016, it is successfully operating since the start of physics collisions in April 2018.

TOP only binary PID gives 85% of K ID efficiency with 10% π mis-ID rate

After LS1 the fraction of active channels increased from 91-93% to 99.5%

The TOP upgrade program is well underway with 150 new MCP-PMTs already delivered or ordered over a total of 220 to be replaced in LS2.