Performance of the MCP-PMTs of the TOP counter in the first beam operation of the Belle II experiment

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on behalf of the Belle II TOP group

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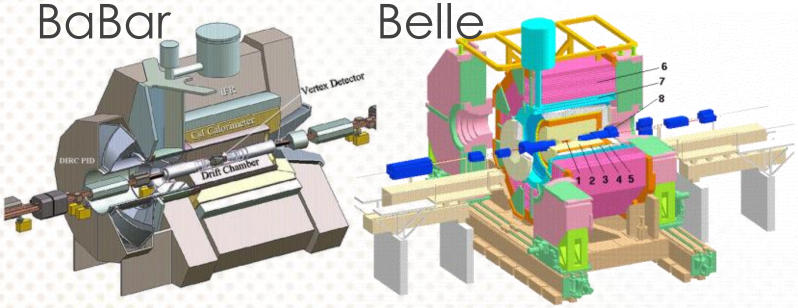
The Belle II experiment

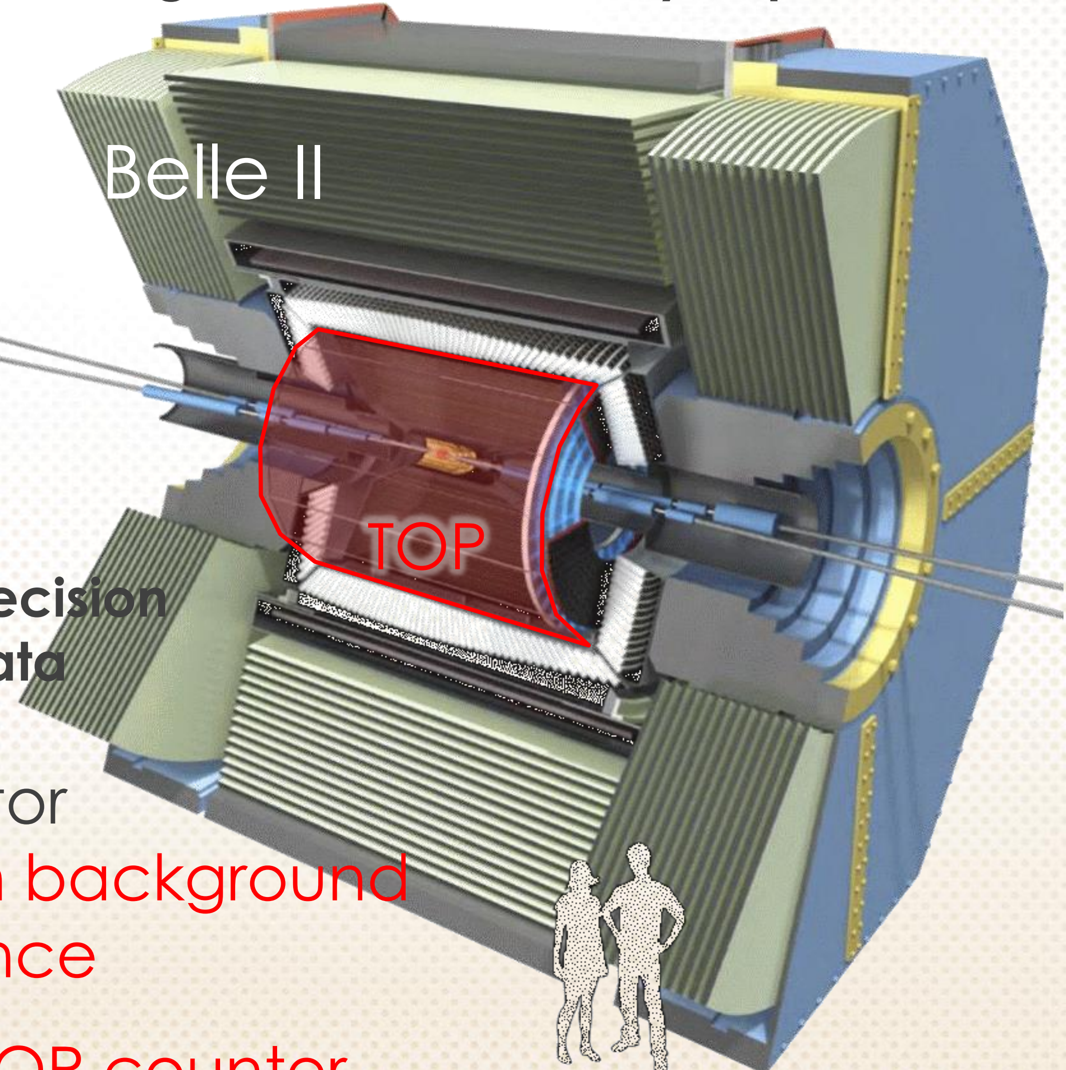
B-factory experiments



Confirmed Kobayashi-Maskawa theory with > 1 ab^{-1} data

Search for new physics via precision measurements with 50 ab^{-1} data

Next generation B-factory experiment



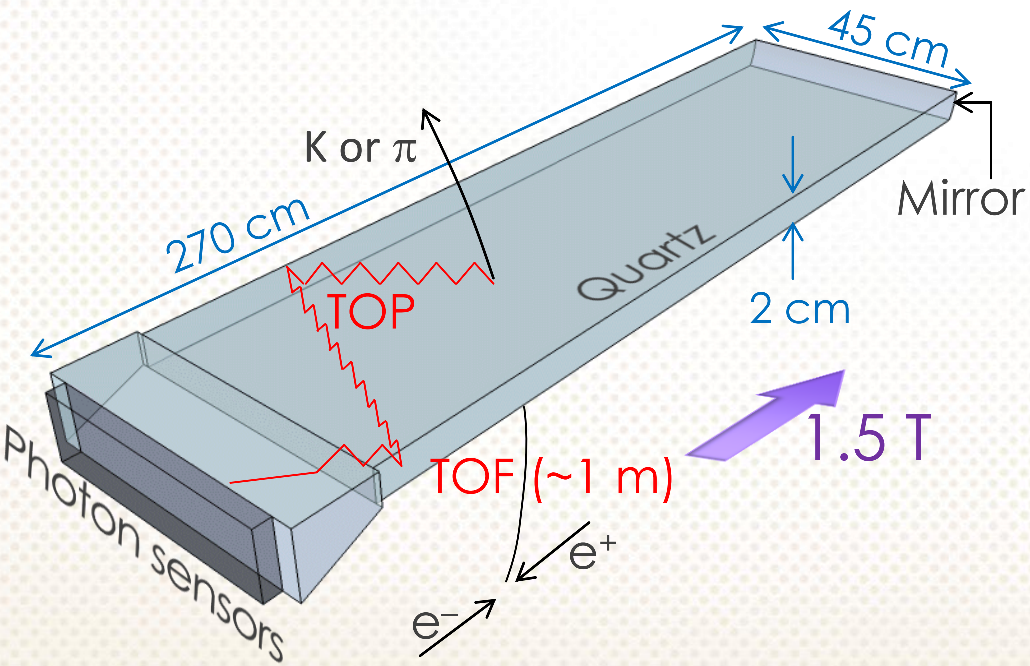
Challenge on the detector

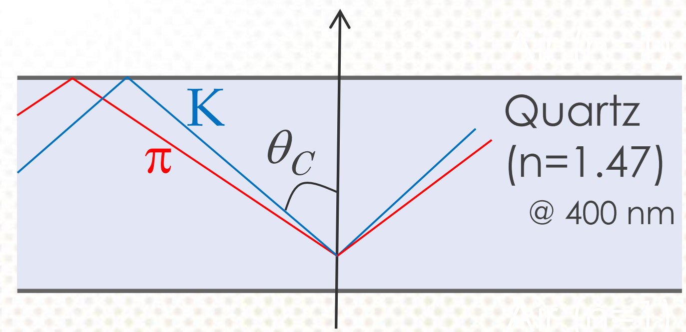
- Cope with harsh beam background
- Improve the performance

Barrel PID → TOP counter

TOP counter

- State-of-the-art Cherenkov ring imaging detector
- K/π identification by means of β reconstruction using precise timing measurement of internally reflected Cherenkov photons





Time of propagation (TOP)

$$\propto \cos\theta_C = \frac{1}{n\beta}$$

Key techniques:

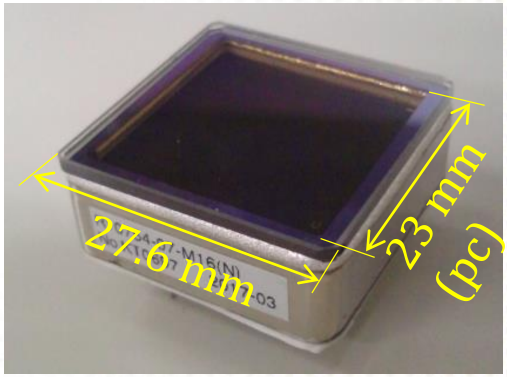
✓ Propagate the “ring” image undistorted

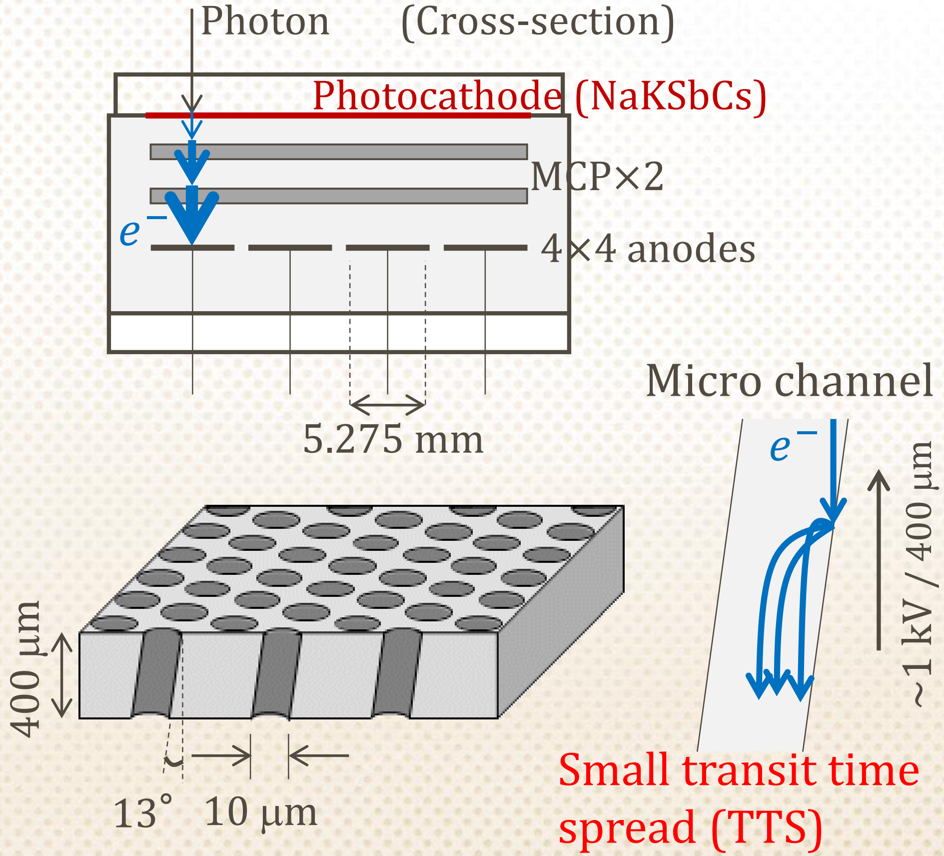
✓ Detect the photons with a high efficiency (~20 hits/track) and with an excellent time resolution (<50 ps)

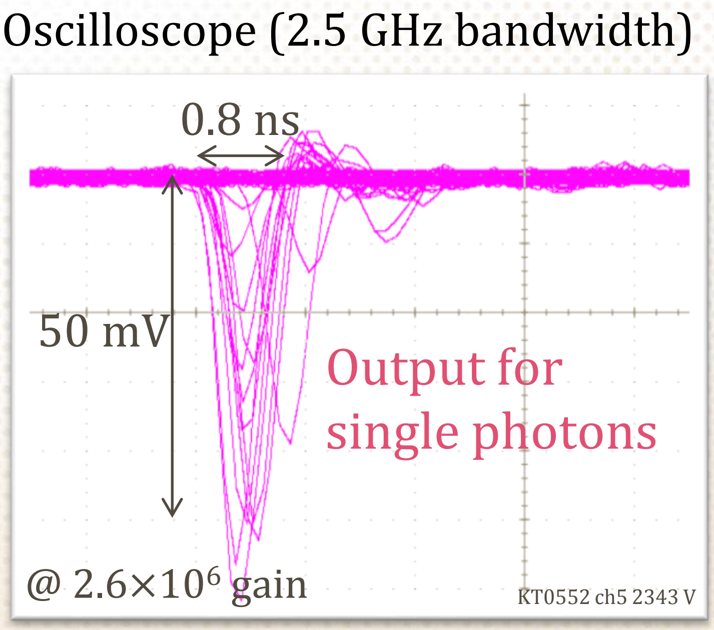
→ Only MCP-PMTs can meet the requirements.

MCP-PMT for the TOP counter

- Square shape multi-anode MCP-PMT with a large photocoverage
  - Developed for the Belle II TOP counter at Nagoya in collaboration with Hamamatsu



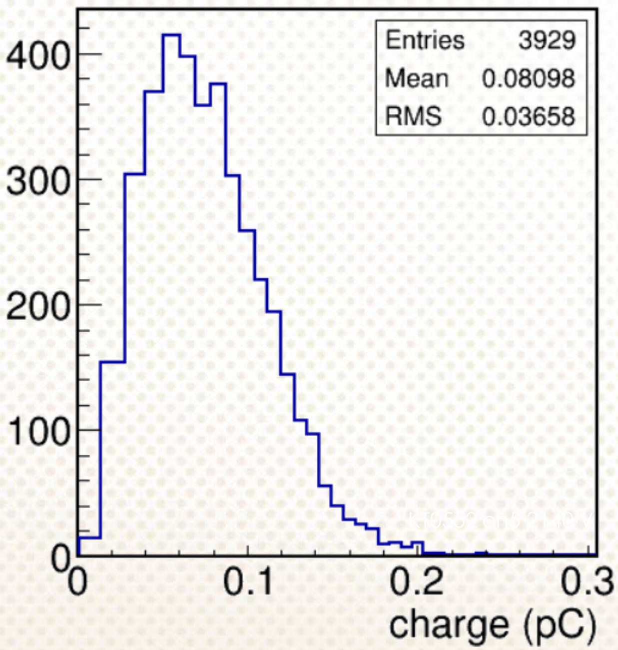




The best time resolution ($\sigma \sim 30$ ps) of photon sensors

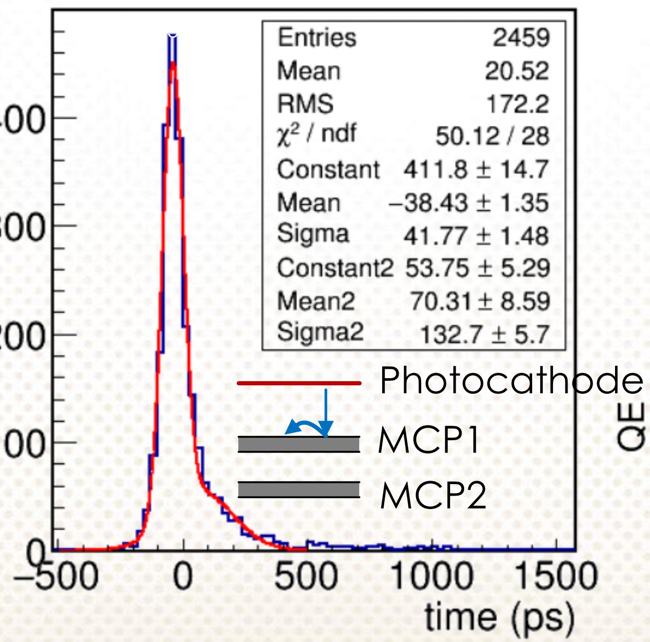
Performance of the MCP-PMT

ADC distribution for single photons



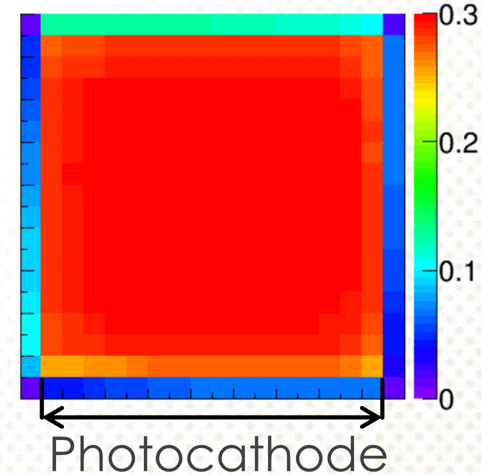
Gain
≡ mean of the distribution
= 5.1×10^5

TDC distribution for single photons from picosecond pulse laser

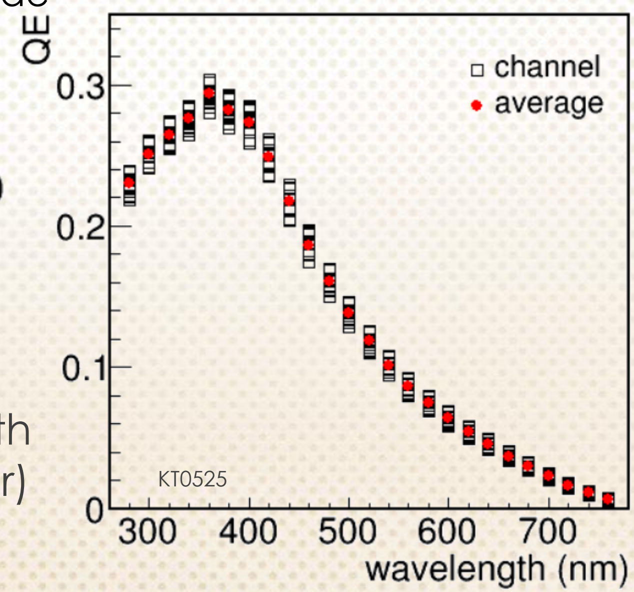


TTS ≡ σ of 1st Gaussian
= 41.8 ps
(incl. ~17 ps laser pulse width and ~24 ps electronics jitter)

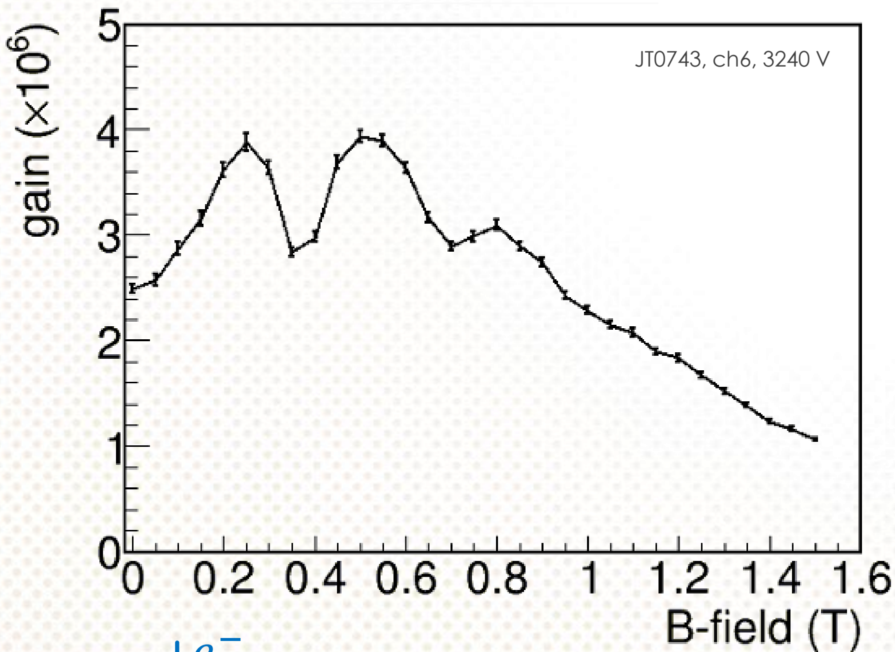
QE distr. at 360 nm

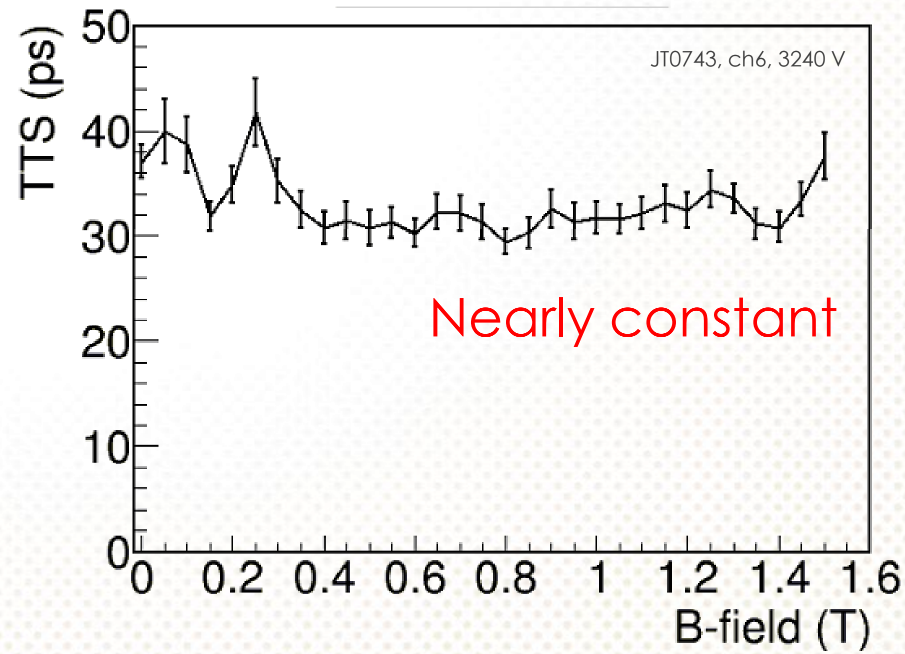


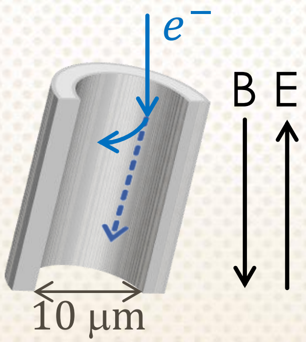
Typical QE spectrum



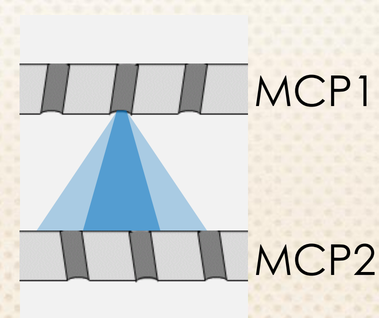
Performance in B-field







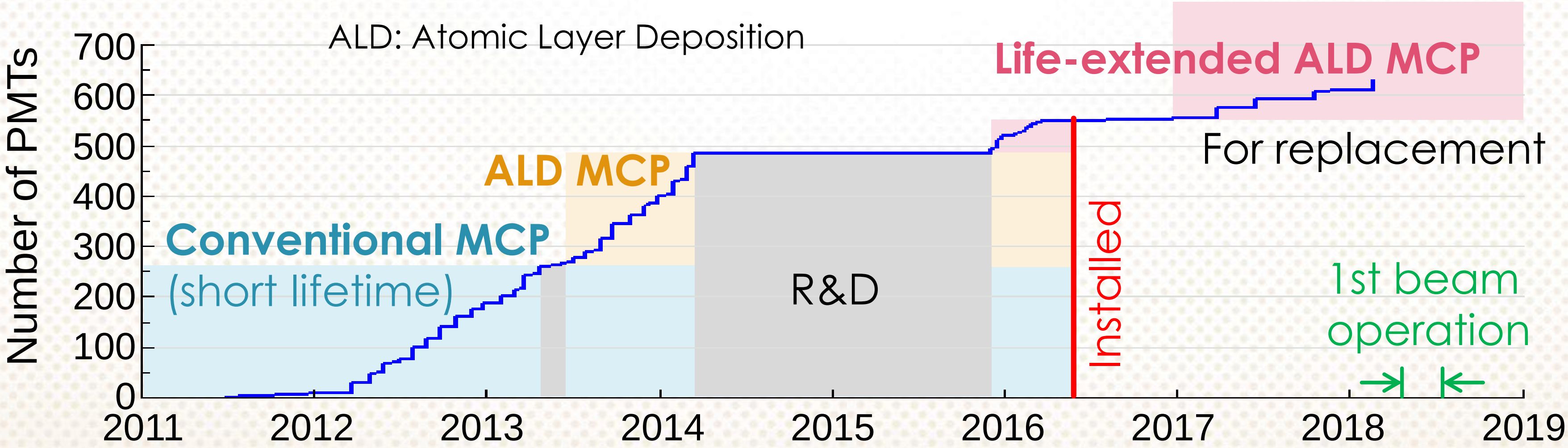
Shorter path in a higher B-field
→ More bounces / Lower energy
→ Higher gain
/ Lower secondary electron yield



Less divergence in a higher B-field
→ Rise and fall of the hole coverage or gain

Mass-production of the MCP-PMTs

- Unprecedented production of 512 (and spare) MCP-PMTs.
- In parallel, R&D for life extension.
  - Eventually three types of MCP-PMTs (Next talk by Muroyama-san)



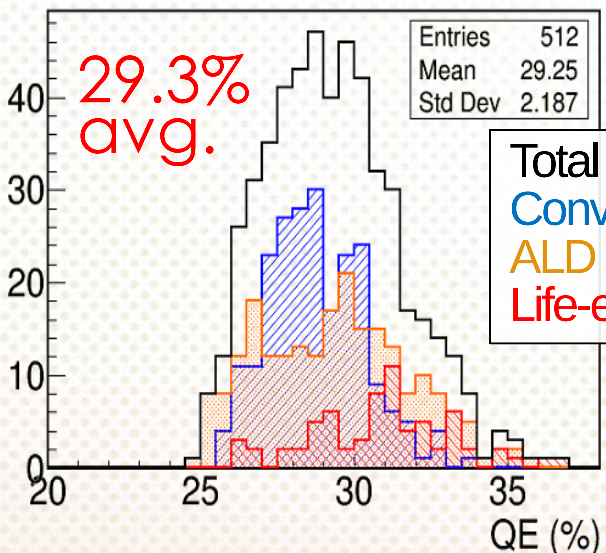
Succeeded in time for the TOP installation in May 2016.

- Mass-production is continued for the replacement of the 224 conventional MCP-PMTs in 2020 summer.

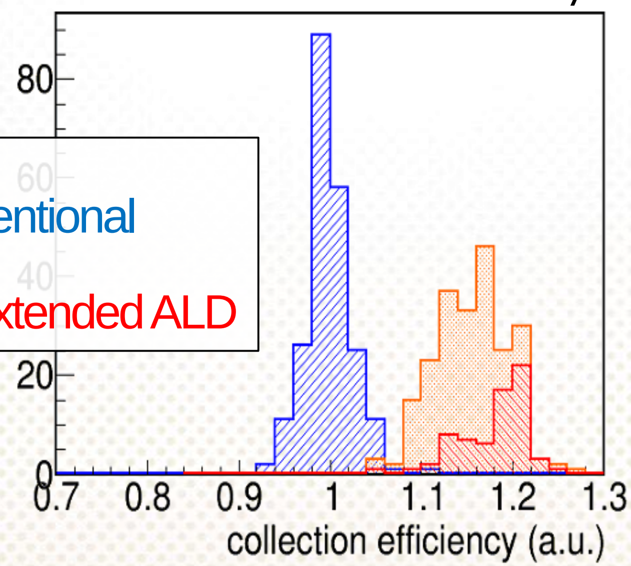
Performance check at Nagoya

- The performance of every MCP-PMT was checked in automated test benches in a systematic way.

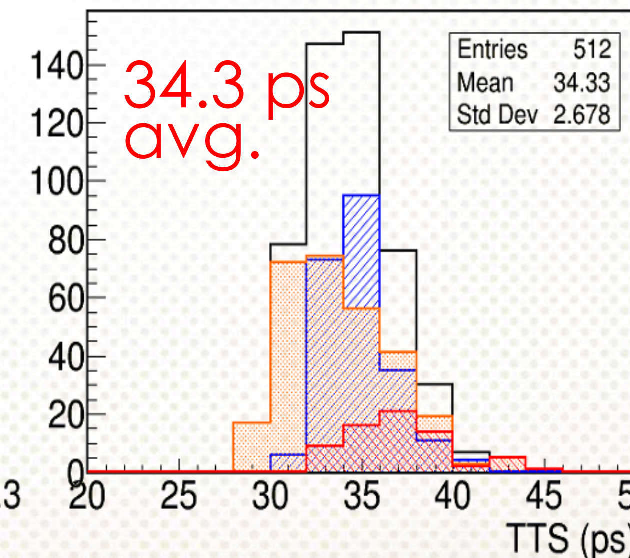
QE at peak (~360 nm)



Collection efficiency



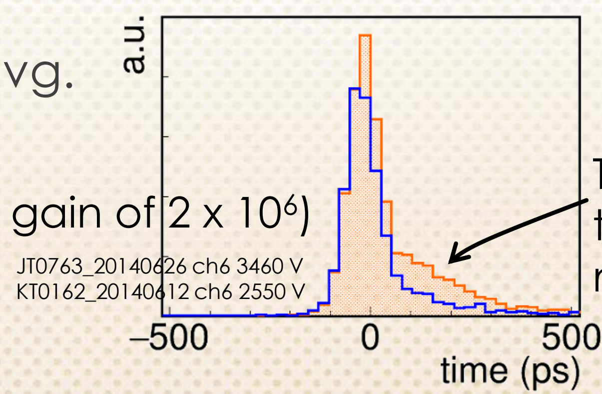
TTS



Requirement:
24% min and 28% avg.

Requirement:
less than 50 ps

(same gain of 2 x 10^6)

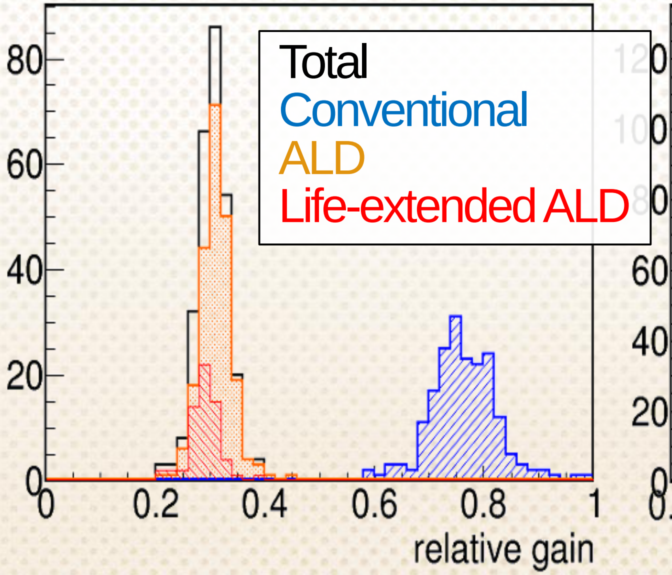


The difference only at the tail, where the recoil photo electrons contribute, makes the difference of CE.

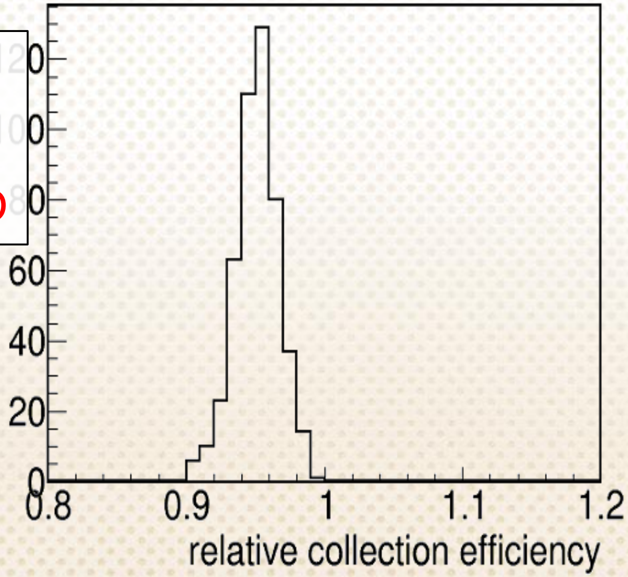
Performance check in 1.5 T

- The performance of every MCP-PMT was checked in a large dipole magnet at KEK.
    - Checked the difference between 0 and 1.5 T.

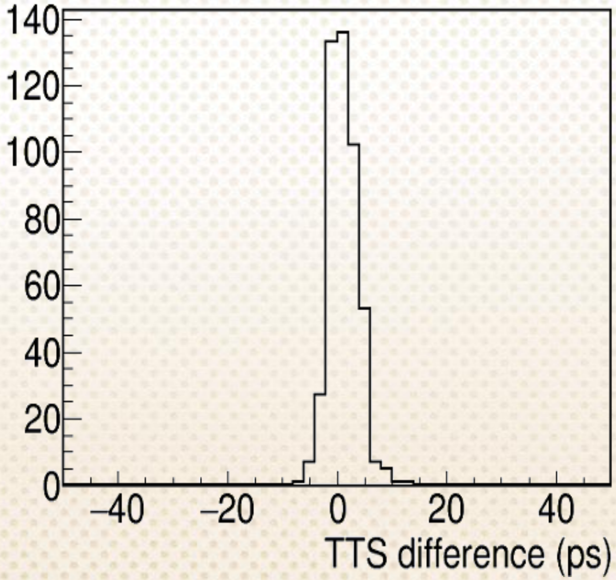
gain(1.5 T) / gain(0 T)



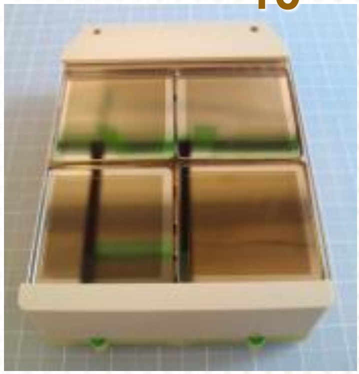
CE(1.5 T) / CE(0 T)



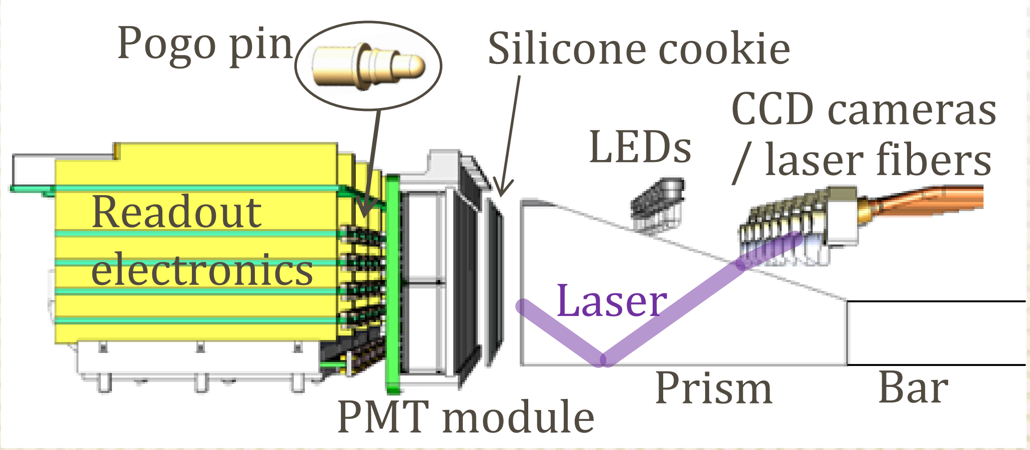
TTS(1.5 T) – TTS(0 T)

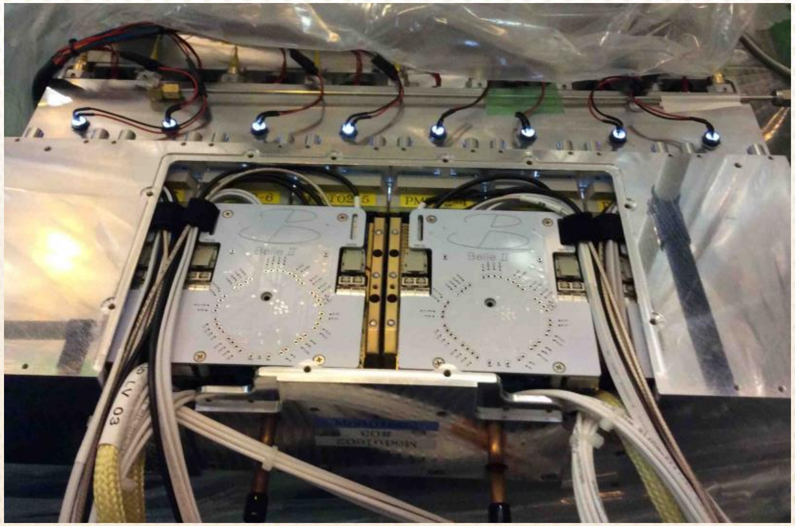


PMT module assembly / installation



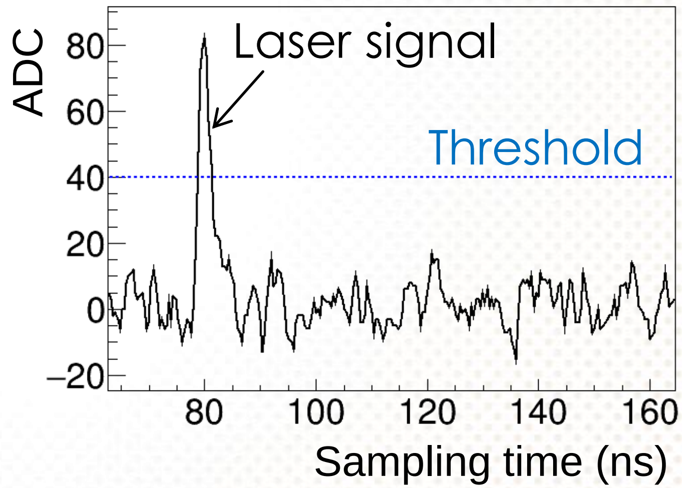
- 4 MCP-PMTs are assembled in a module.
  - PMT window is glued on a wavelength filter, which cuts $\lambda \leq 340$ nm to suppress chromatic dispersion.
- Bubble free optical contact between the PMT module and the prism by a soft cast silicone cookie.
- 2.7 GSampling/s of PMT signal by switched-capacitor array ASIC (IRSX). [arXiv:1804.10782]
- Laser single photons for the in-situ calibration.



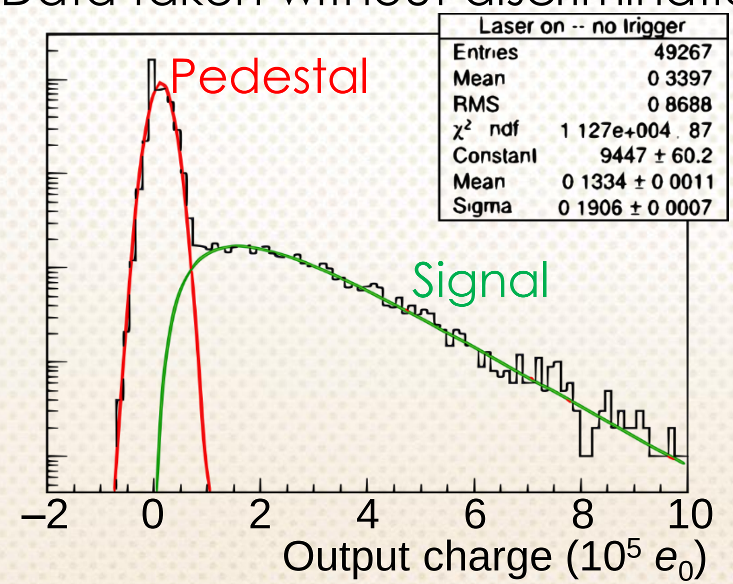


Threshold efficiency

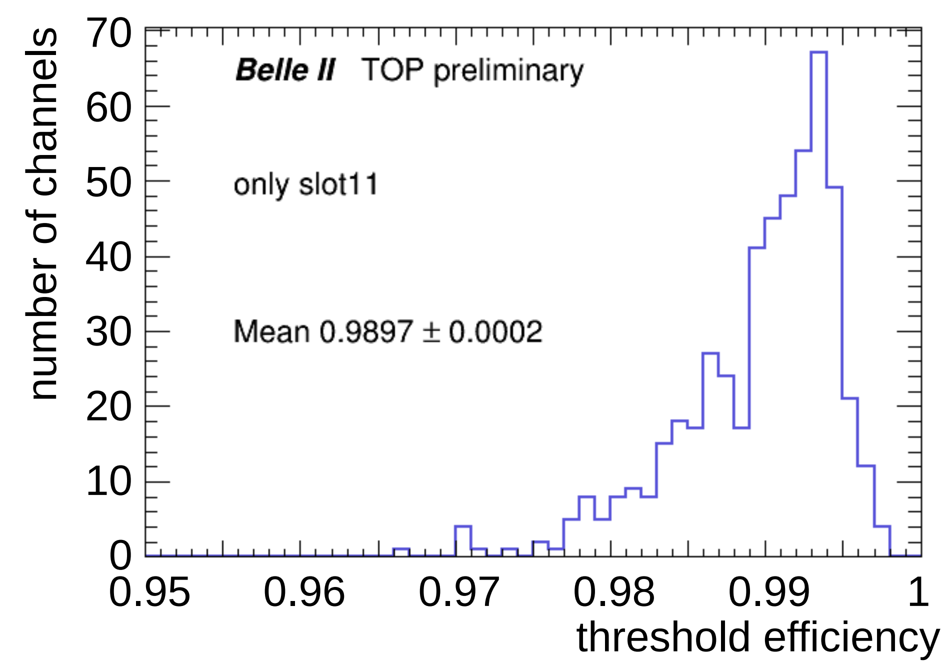
- The gain of every MCP-PMT was adjusted to 5 x 10^5.
  - Lower gain → longer lifetime but lower threshold efficiency
- Evaluated the efficiency with single photons from the laser.



Data taken without discrimination



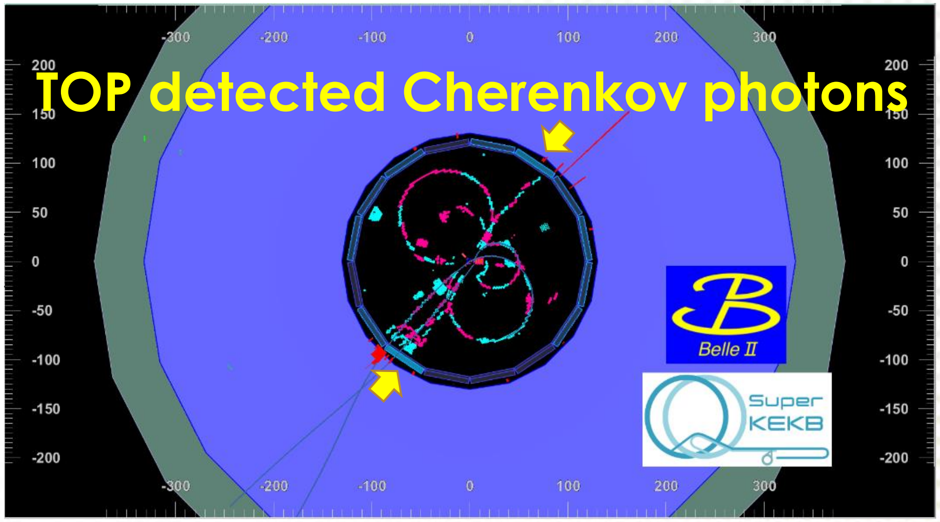
$$f(x) = p_0(x/x_0)^{p_1} \exp[-(x/x_0)^{p_2}]$$



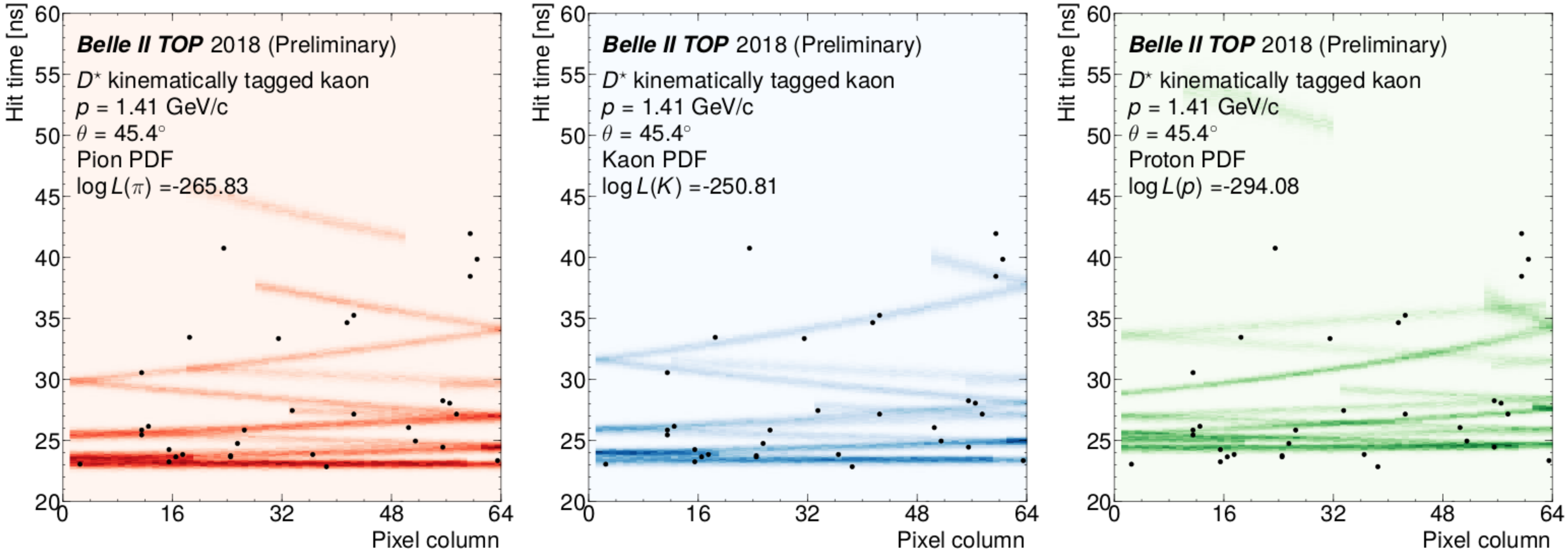
Beam operation

- MCP-PMT HVs were turned on during luminosity runs in Apr-Jul 2018.
- TOP counter worked for particle identification.

First collision event on April 26

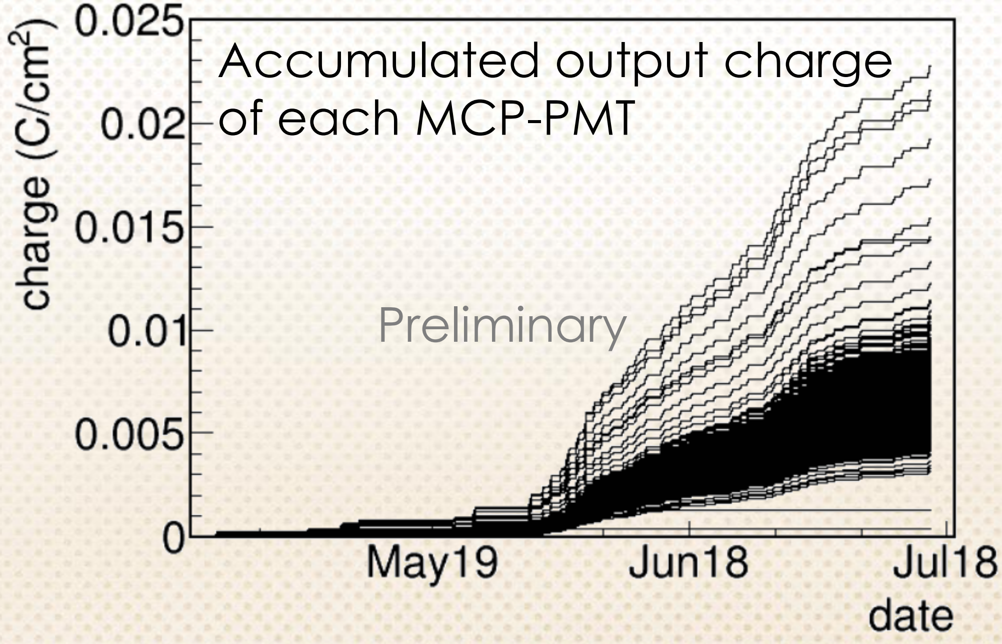


Example of Cherenkov "ring" image



Beam background

- PMT hits are dominated by γ rays from the accelerator
  - γ → Compton scattering / pair creation in the quartz bar → electrons → Cherenkov photons
  - MC estimation: 5-8 MHz/PMT at the design luminosity
- ~0.5 MHz/PMT in the start-up luminosity runs in 2018
  - Much higher than predicted, but still tolerable.



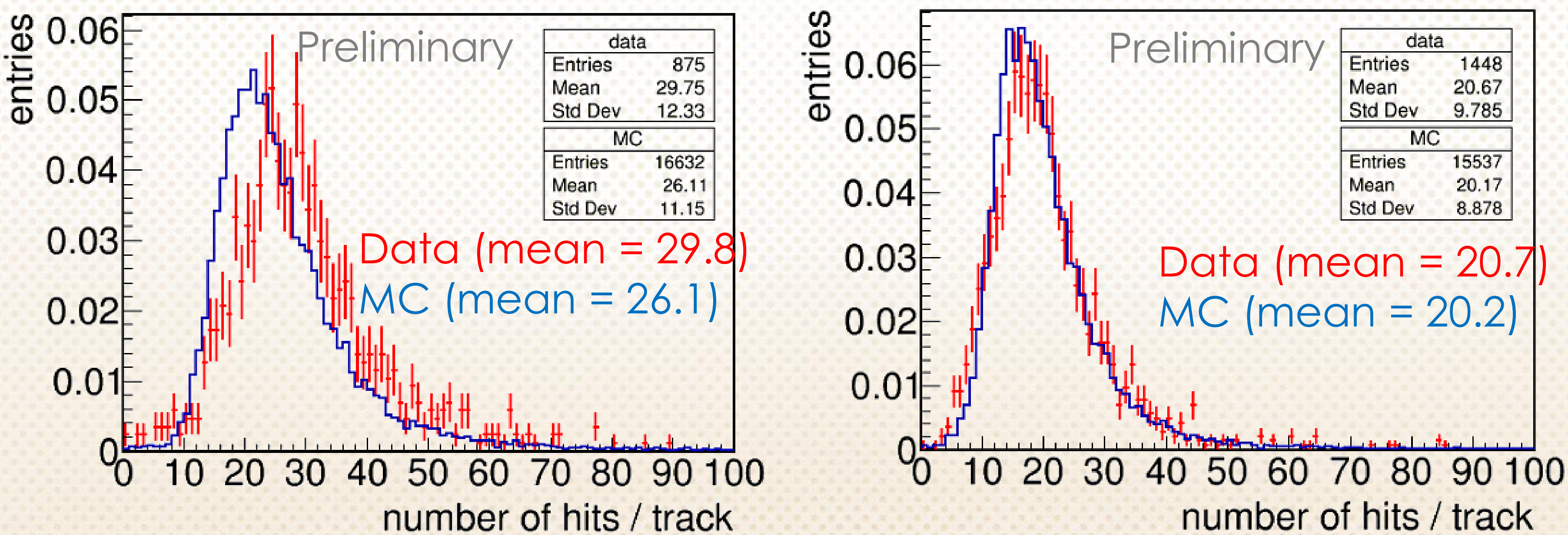
Kept below 0.023 C/cm^2

cf. QE drops by 20% at 0.3-1.7 C/cm^2 for the conventional MCP-PMTs

Evaluation of number of hits

- Number of hits of Cherenkov photons for di-muon events
- MC based on the measured parameters of each component
  - Quartz internal reflectance and transmittance
  - MCP-PMT QE and collection efficiency (dark noise negligible)
  - Readout efficiency (~77%, to be improved) and noise hits (a few %)
  - Beam background hits (~1 hits/slot)

Slot01 (life-extended ALD MCP-PMTs) Slot11 (conventional MCP-PMTs)



The difference is under investigation.

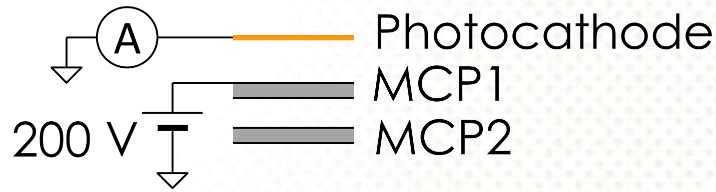
Summary

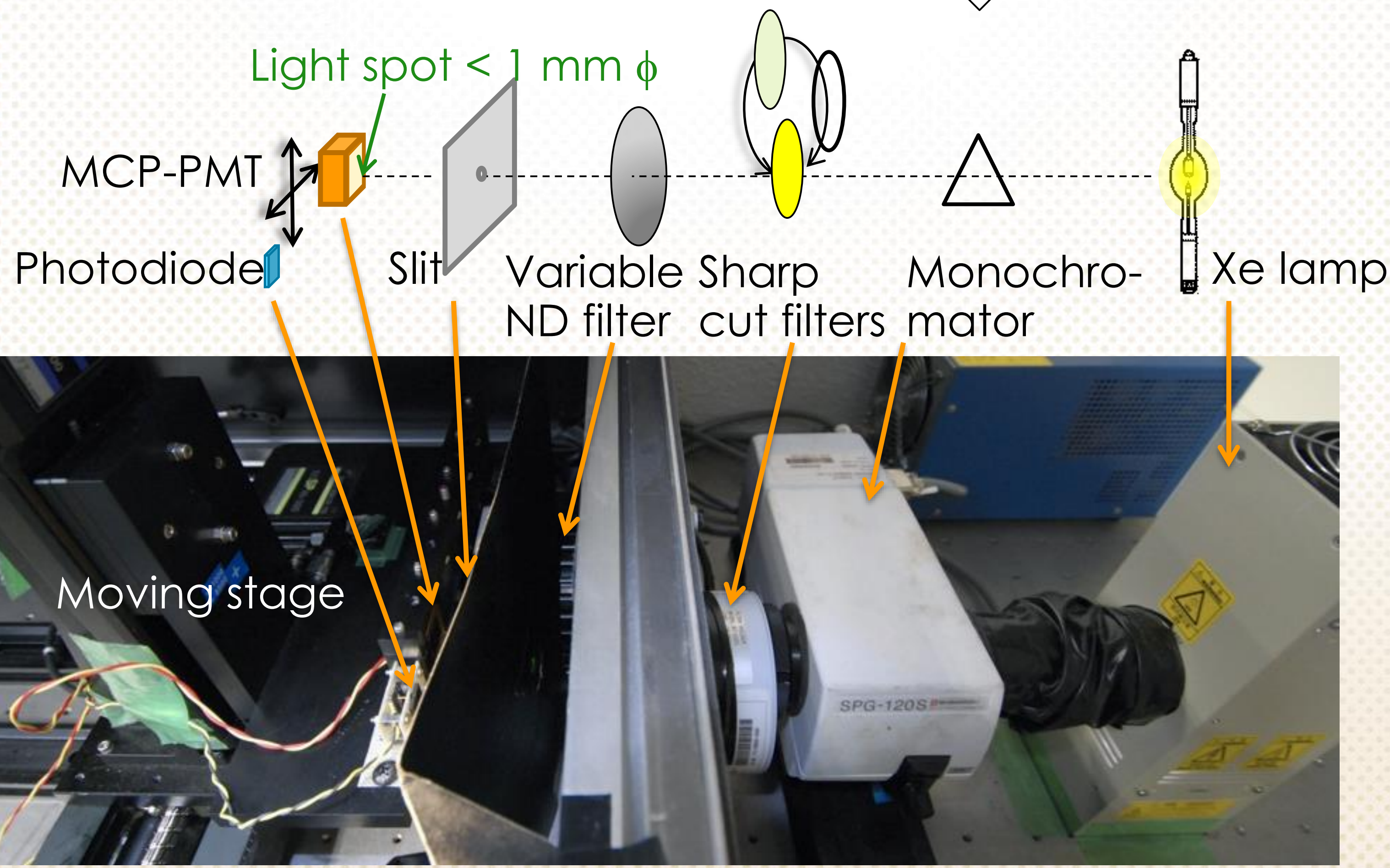
- The MCP-PMT is one of the key components which bring the Belle II TOP counter into life.
- Succeeded in developing and producing 512 (and spare) MCP-PMTs for the Belle II TOP counter.
  - ~34 ps TTS for every PMT
  - 29.3% avg. QE at ~360 nm
  - Work in 1.5 T
- Installation of the TOP counter finished in May 2016.
- The MCP-PMTs worked as expected in the first beam operation in Apr-Jul 2018.

QE measurement setup

- Measure the photocathode current with a picoammeter:

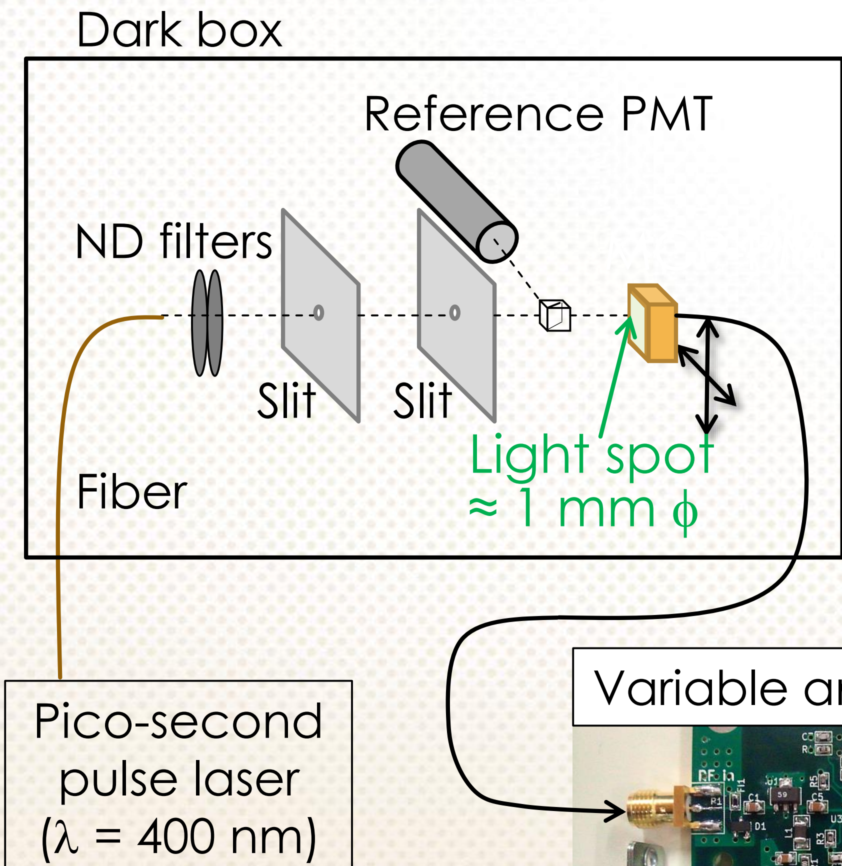
$$QE_{MCP} = {}^{I_{MCP}}/_{I_{PD}} \cdot QE_{PD}$$

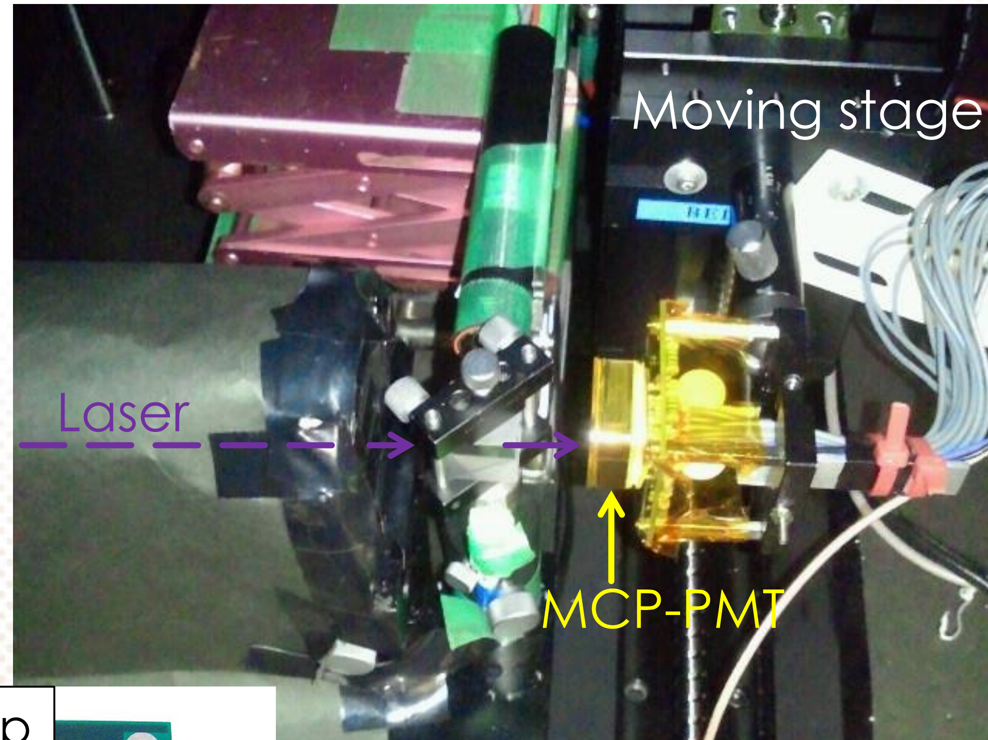


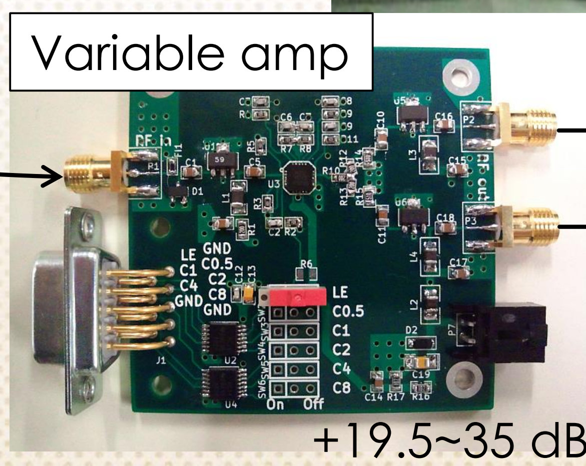


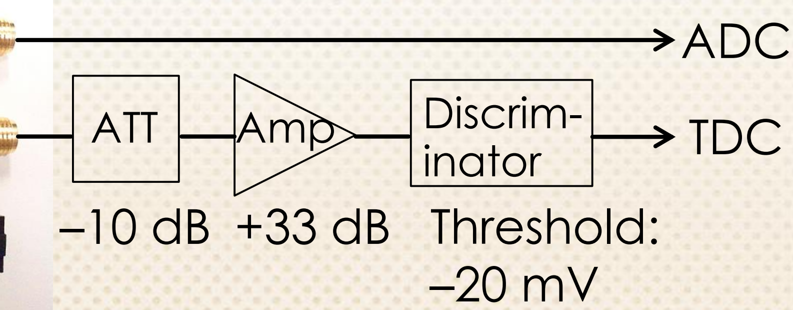
Laser measurement setup

- Single photon irradiation to each channel one by one.









Installation of the TOP counter