KMI Topics

Development of the TOP counter for the Belle II experiment

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The Belle II experiment

- Elucidate a physics beyond the Standard Model through precise measurement of B and τ decays at Super-KEKB.

- Luminosity: x40 of KEKB

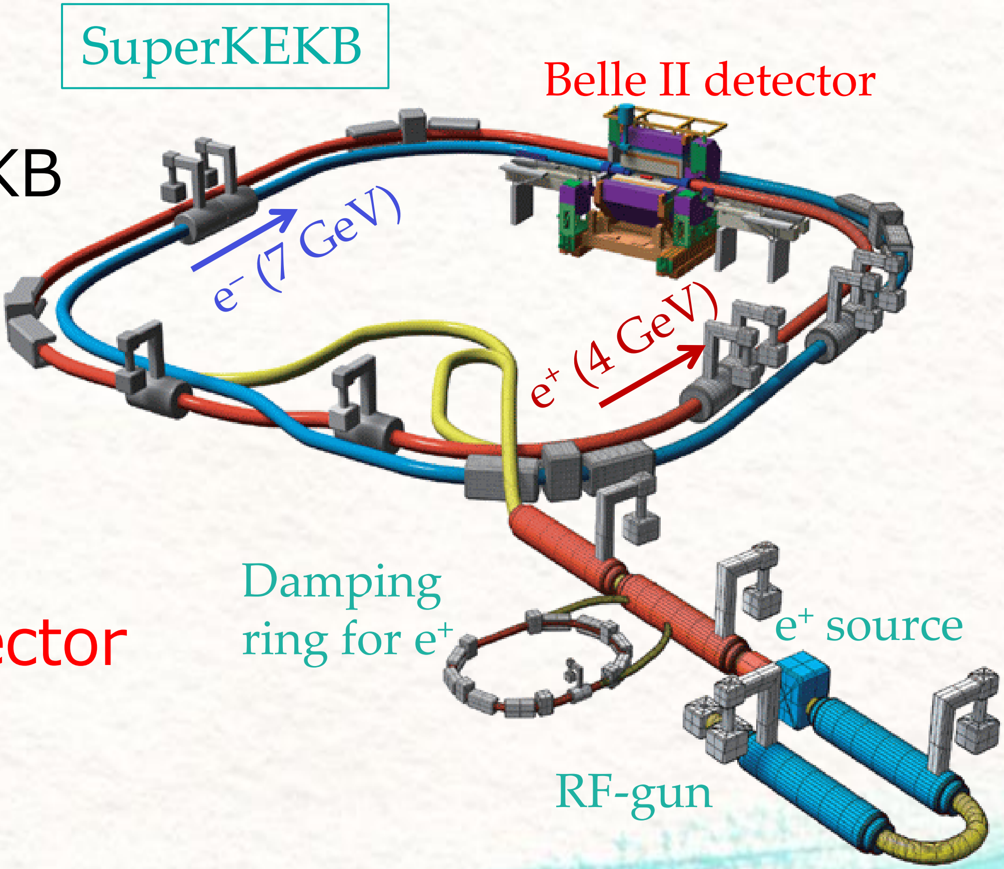
  → 8×10^{35} $cm^{-2}s^{-1}$

- Statistics: x50 of Belle

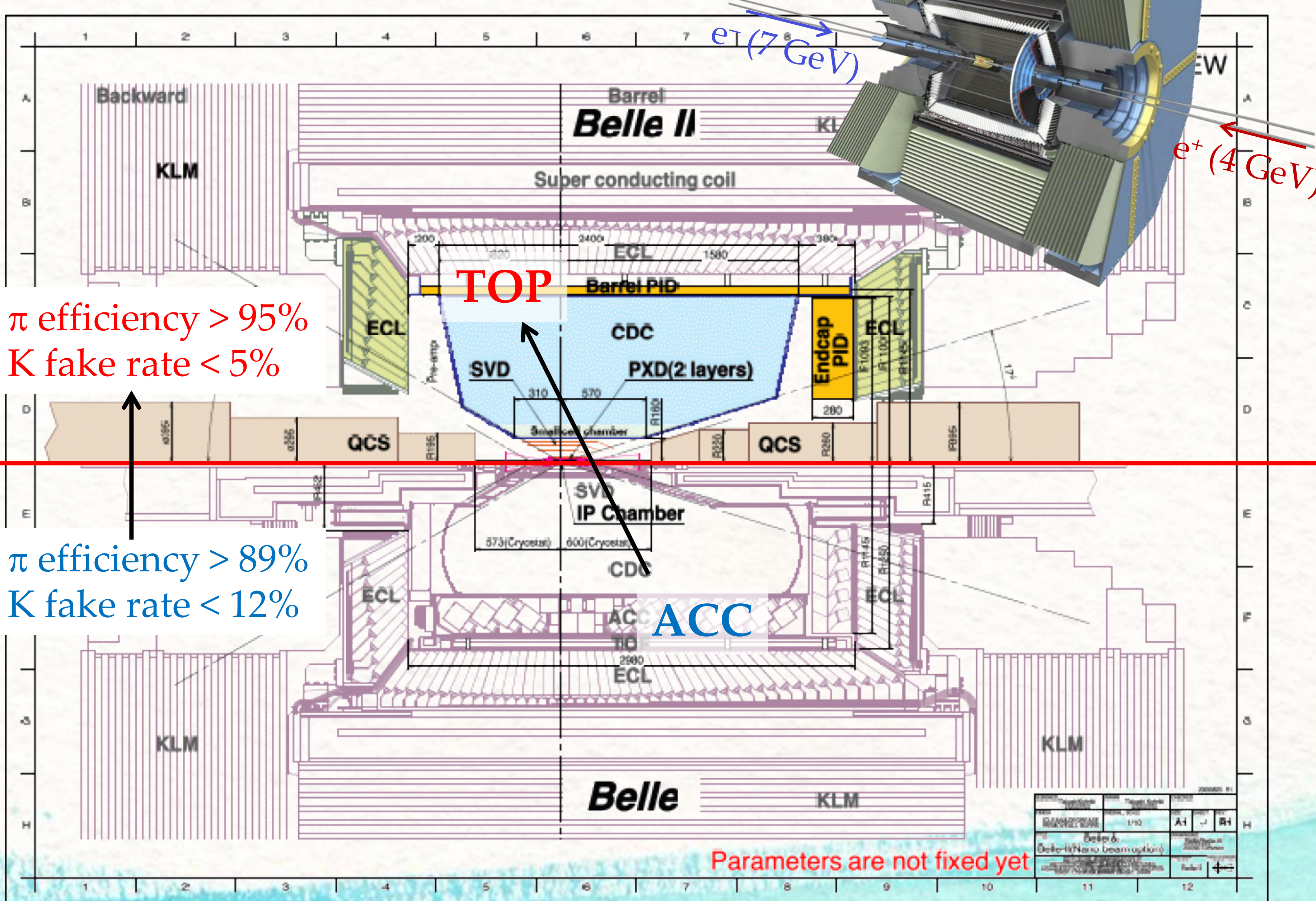
  → 50 ab^{-1}

- Upgrade the Belle detector

  → Belle II



The Belle II detector



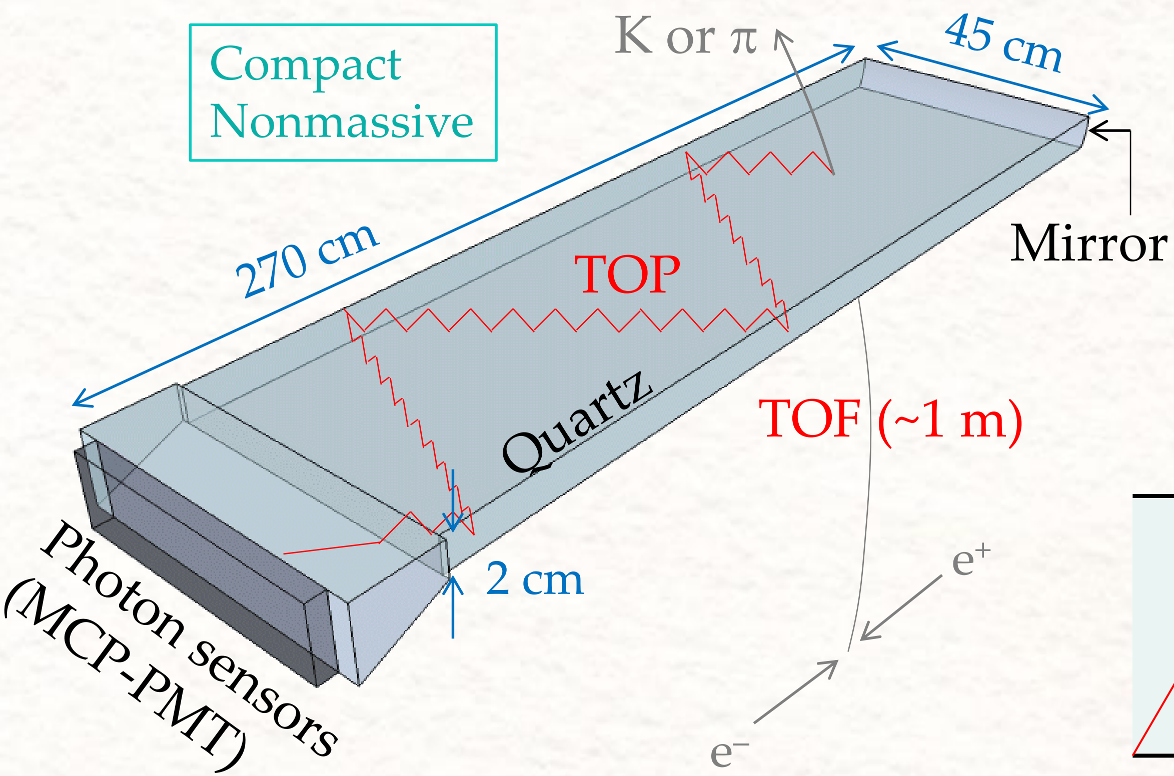
Contents

- Focus on the detector R&D
  - Design and concept of the TOP counter
  - Components of the TOP counter
  - Assembly of a prototype TOP counter
  - Test of the prototype with the positron beam at LEPS

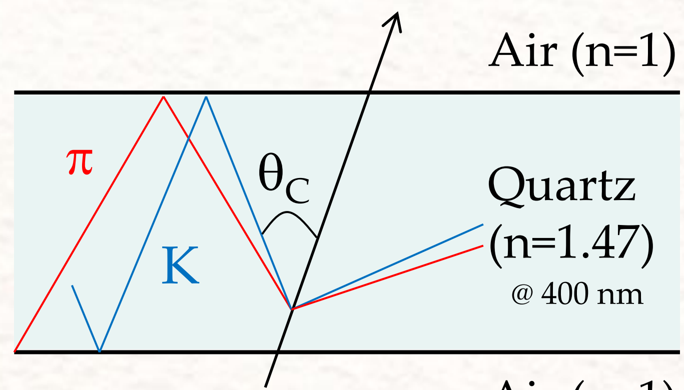
Design and concept of the TOP counter

TOP (Time Of Propagation) counter

- A novel RICH (Ring Imaging Cherenkov) detector



Cherenkov photons generated in the quartz bar travel in the bar as they are totally reflected on the quartz/air boundaries.



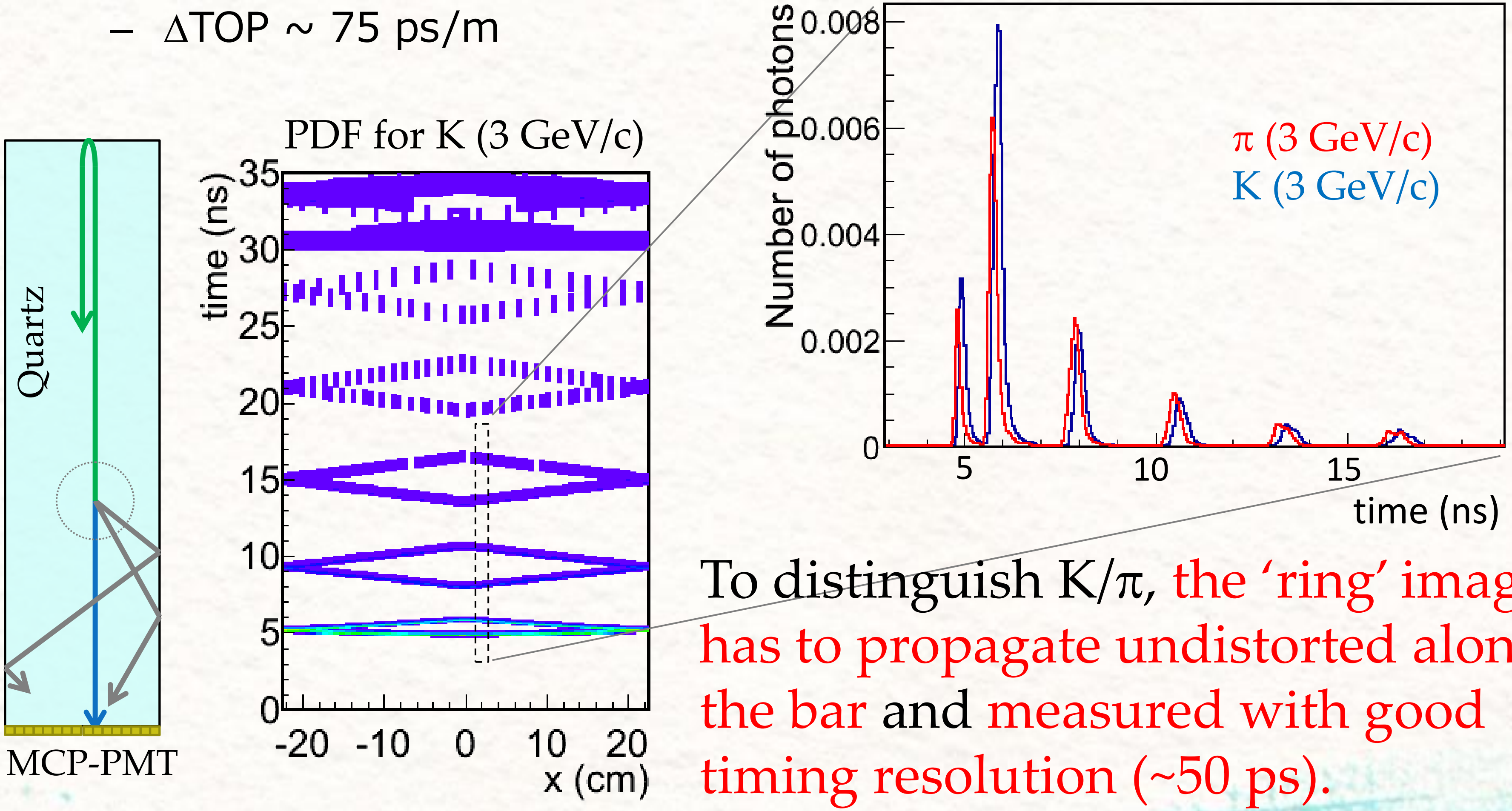
$$\mathrm{TOP} \propto \cos\theta_C = \frac{1}{n\beta}$$

TOP depends on θ_C or β.

→ Measure (TOF + TOP) to identify K/π.

Key of the TOP counter

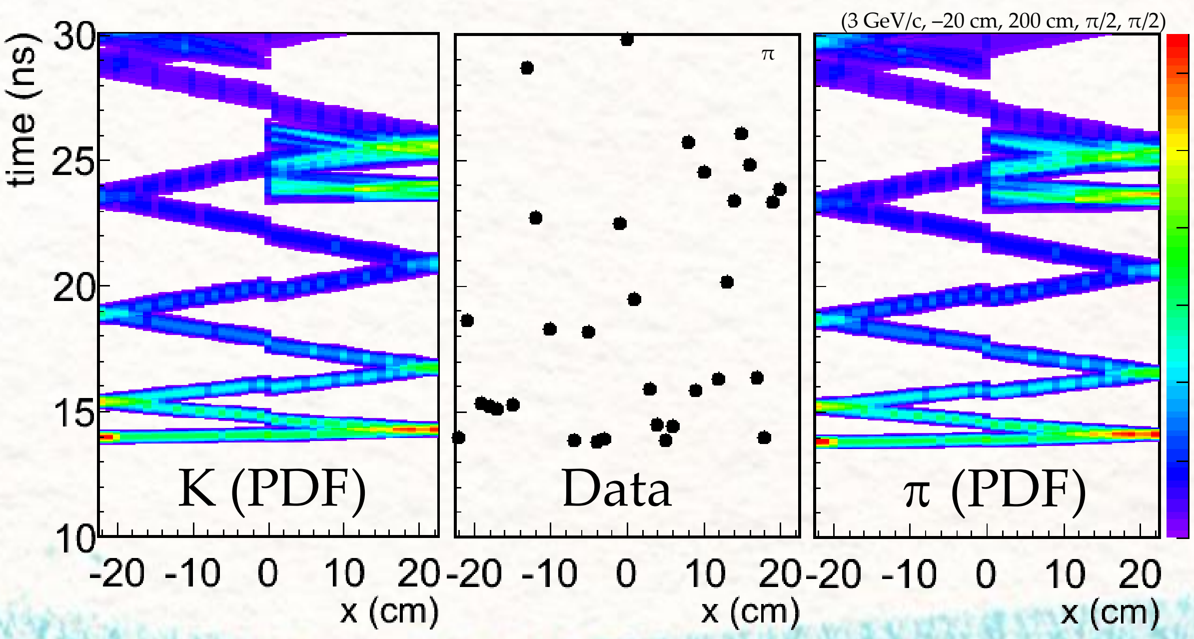
- Hit timing difference between 3 GeV/c K and π
  - ΔTOF ~ 50 ps/m
  - ΔTOP ~ 75 ps/m



To distinguish K/π, the 'ring' image has to propagate undistorted along the bar and measured with good timing resolution (~50 ps).

PID with the TOP counter

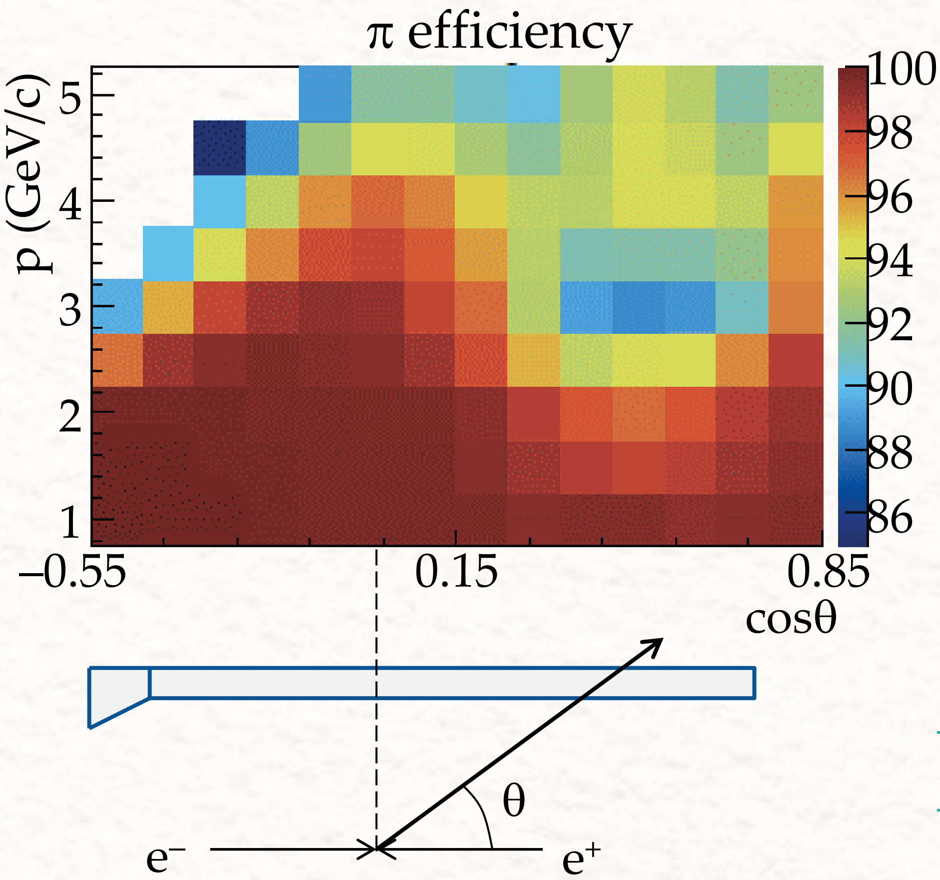
- Measure the hit timing of ~20 Cherenkov photons.
  - In addition, background ~3 hits/50 ns
- Calculate likelihood for K and π using the PDFs.
  - Inputs for the PDF:
    - Momentum and incident position of the track measured by the inner detectors.

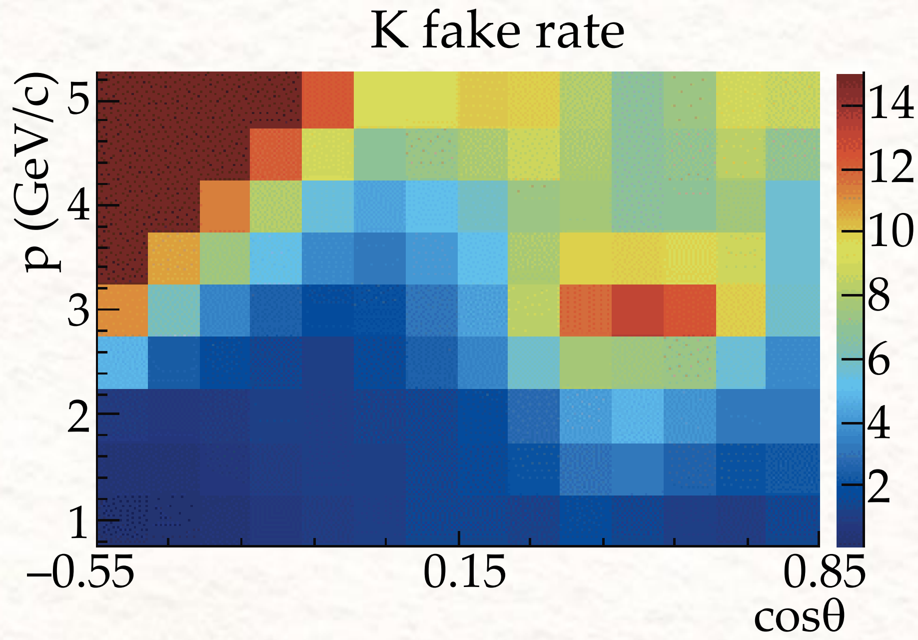


TOP counter is a challenging detector.

Expected performance

- From a MC simulation





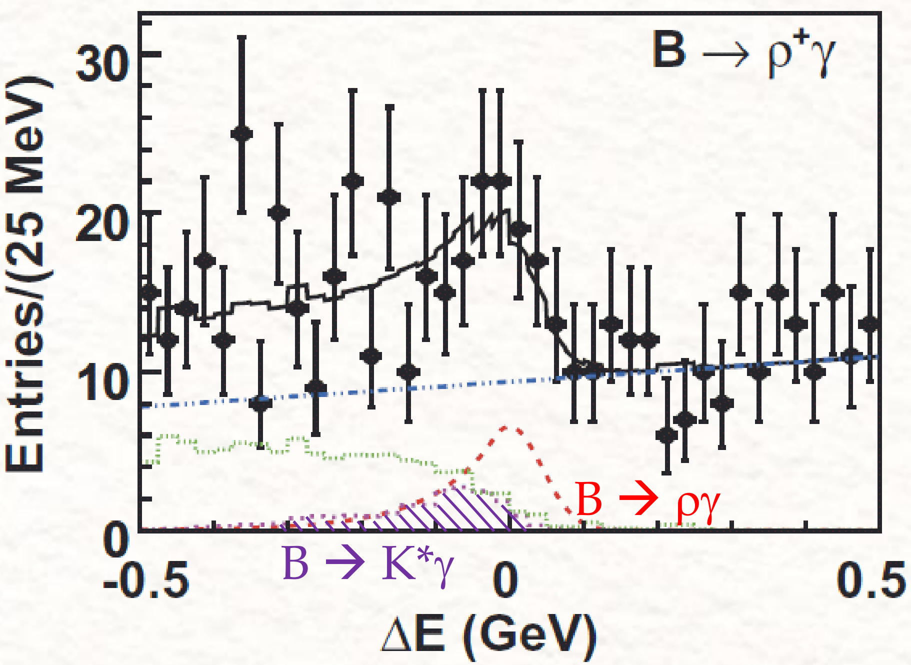
Benchmark channels

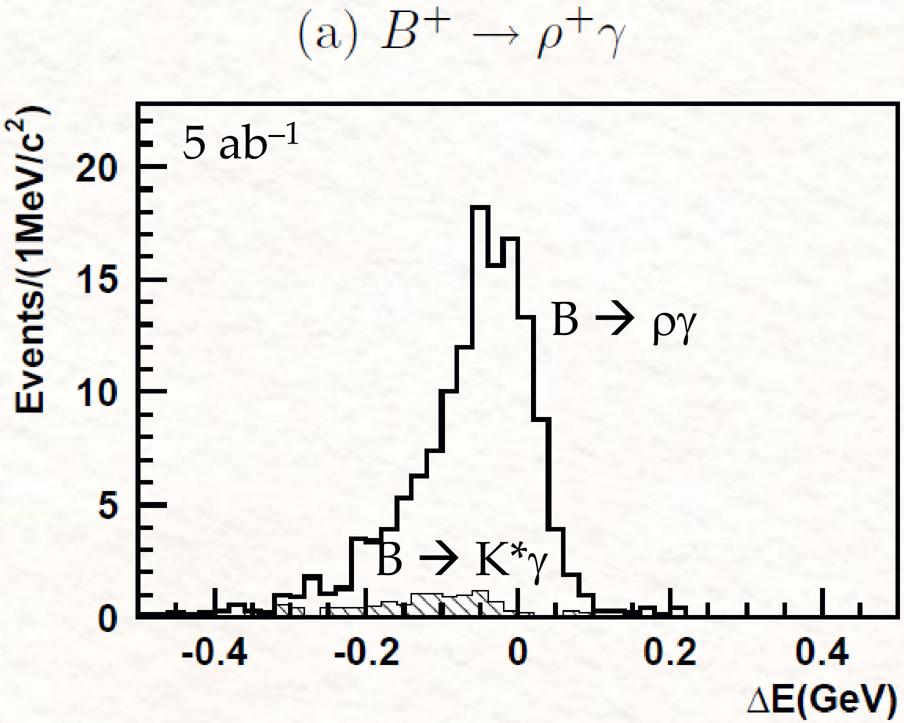
	Efficiency	Fake rate
B → ππ	~95%	~6%
B → ργ	~98%	~3%

Need to verify this expected performance with a beam data.

Example of the impact of the PID improvement

- Separation of K and π is a critical issue for the study of B → ρ γ.





Belle (Phys. Rev. Lett. 101 (2008) 111801)
- 86% π efficiency
- 8.3% K fake rate

Belle II LOI
- 90% π efficiency
- 3% K fake rate

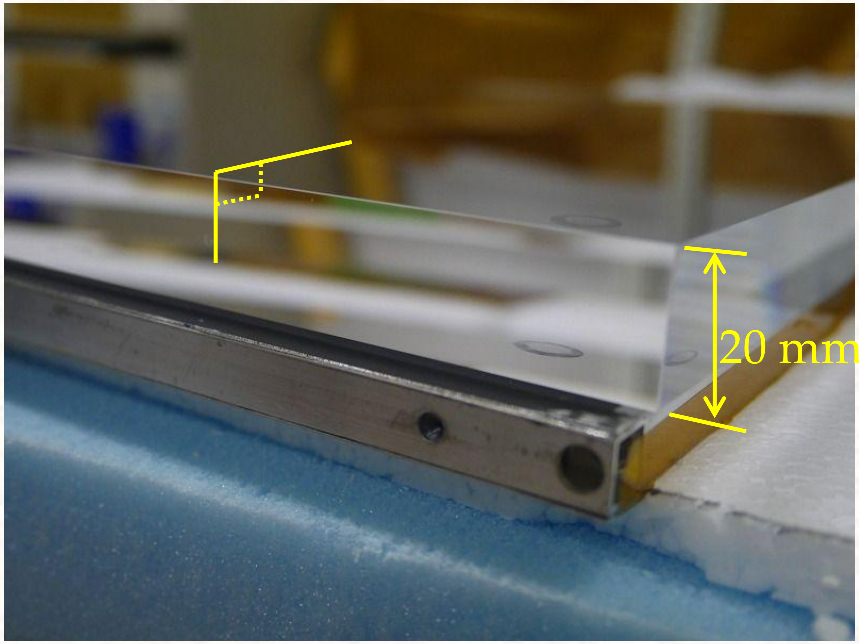
Components of the TOP counter

Quartz bar

- The quality of Cherenkov ring image has to be maintained after O(100) reflections on the quartz surface.

Requirements (for the largest surfaces)

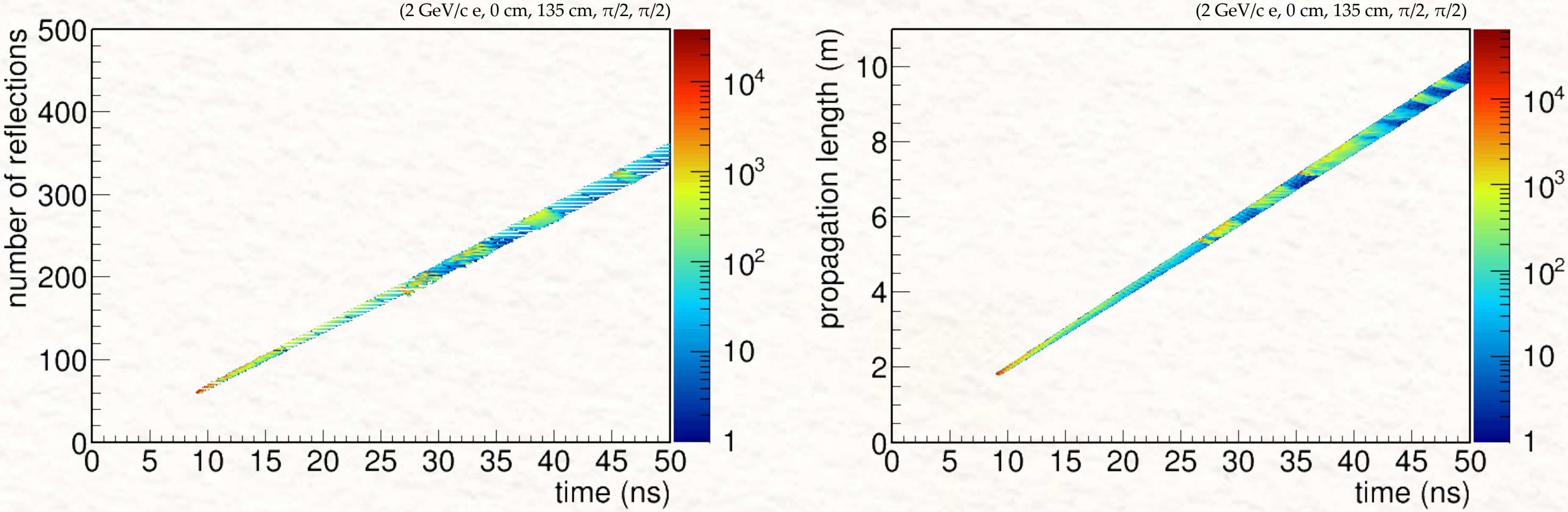
Length	1250 ± 0.50 mm
Width	450 ± 0.15 mm
Thickness	20 ± 0.10 mm
Flatness	< 6.3 μm
Perpendicularity	< 20 arcsec
Parallelism	< 4 arcsec
Roughness	< 5 Å (RMS)



Polished by companies to meet the stringent requirements.

Quartz reflectance and transmittance

- Requirement
  - Internal surface reflectance > 99.90%
  - Bulk transmittance > 98.5%/m

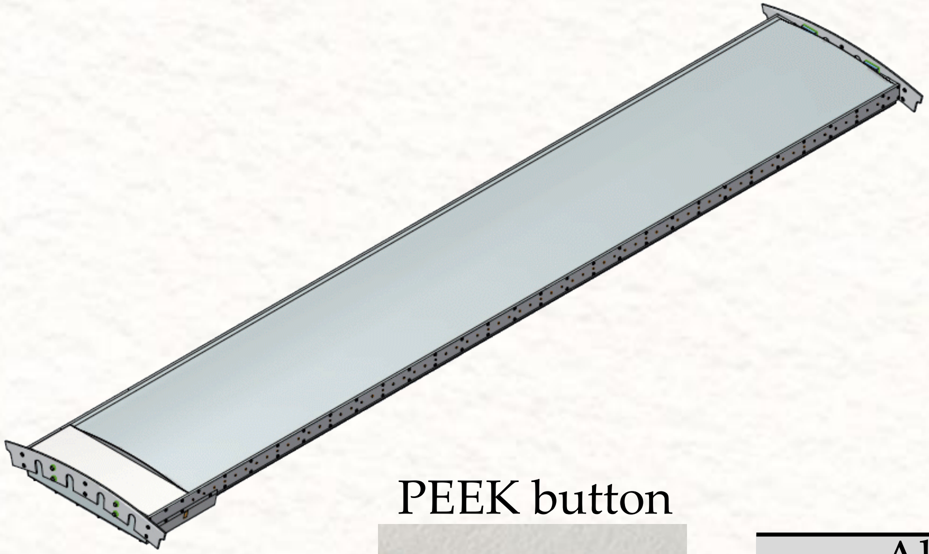


When roughness = 20 Å (RMS), reflectance ~ 99.82%
→ 16% (30%) loss after 100 (200) reflections
cf. 10% (18%) loss for 99.90% reflectance

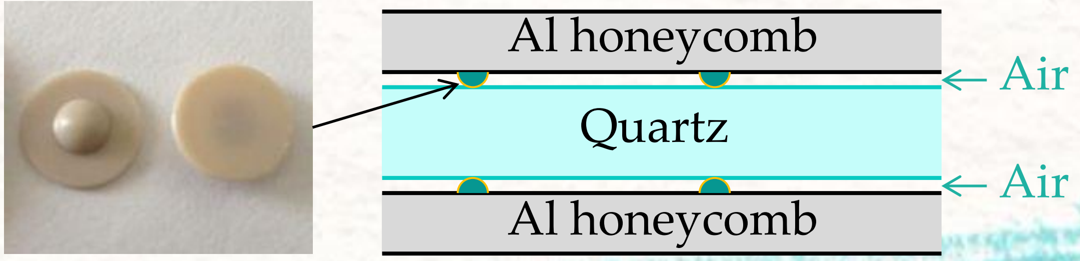
Transmittance = 98.5%/m
→ 10% loss after 7 m travel

Quartz bar box

- Made of aluminum honeycomb panels.
  → Low mass
- Support the quartz with PEEK buttons.
  → Enable the total reflection on the quartz surfaces.

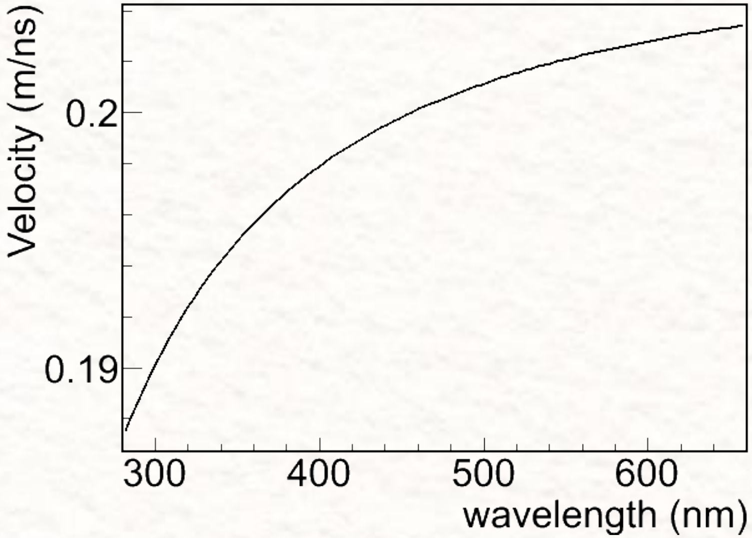


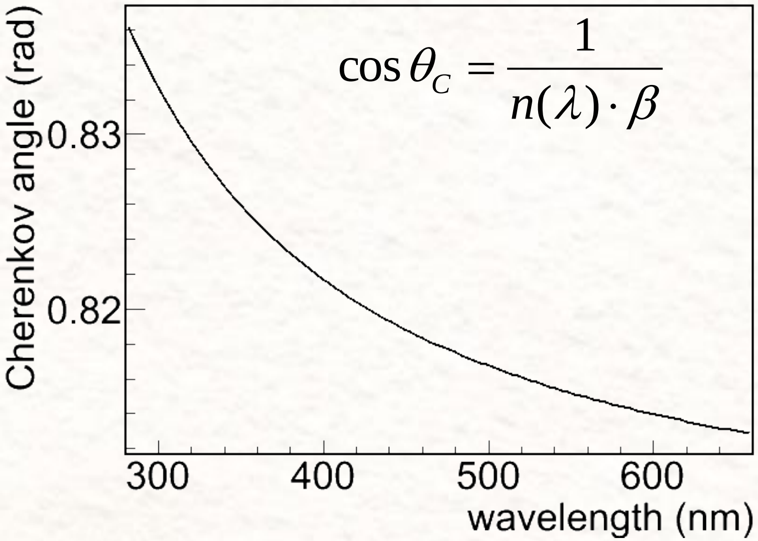
PEEK button



Focusing mirror

- The photon velocity in the quartz varies with the wavelength (chromatic dispersion) → worsen the time resolution.

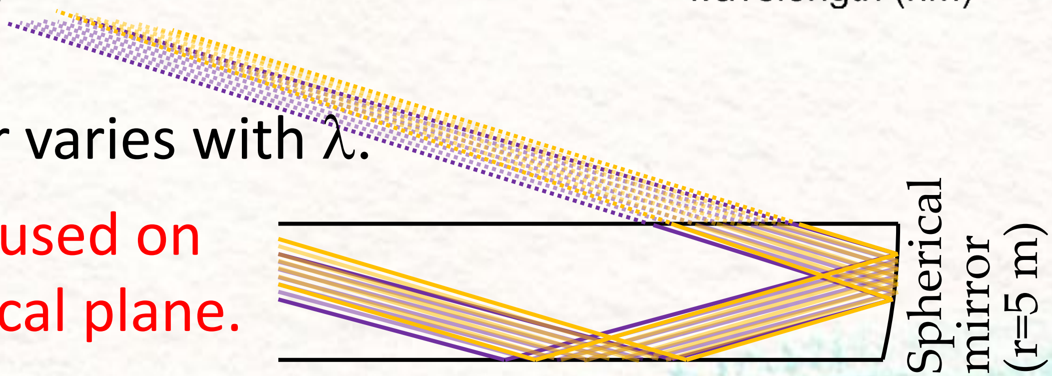




Incident angle to the mirror varies with λ.

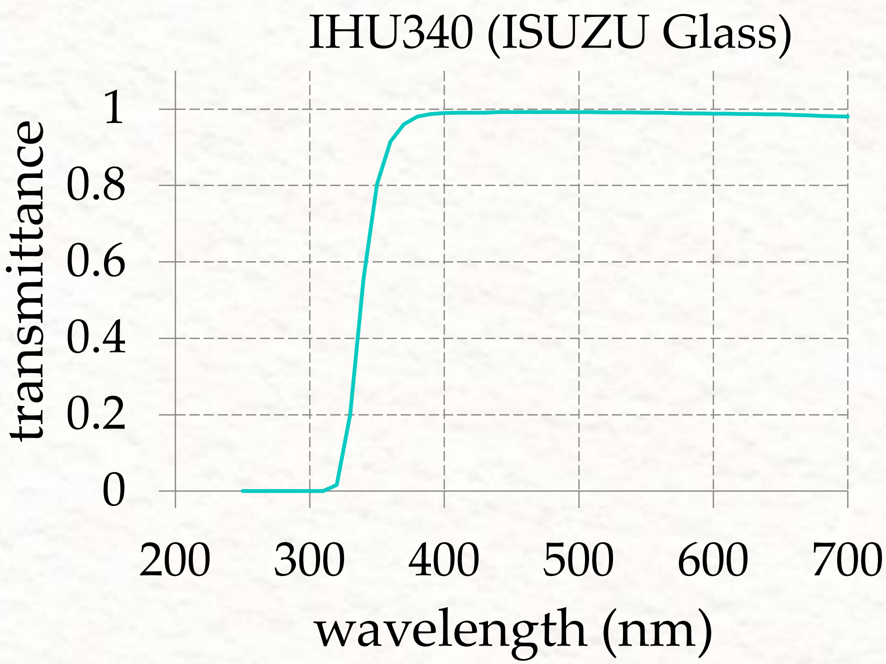
→ Light of different λ is focused on different points on the focal plane.

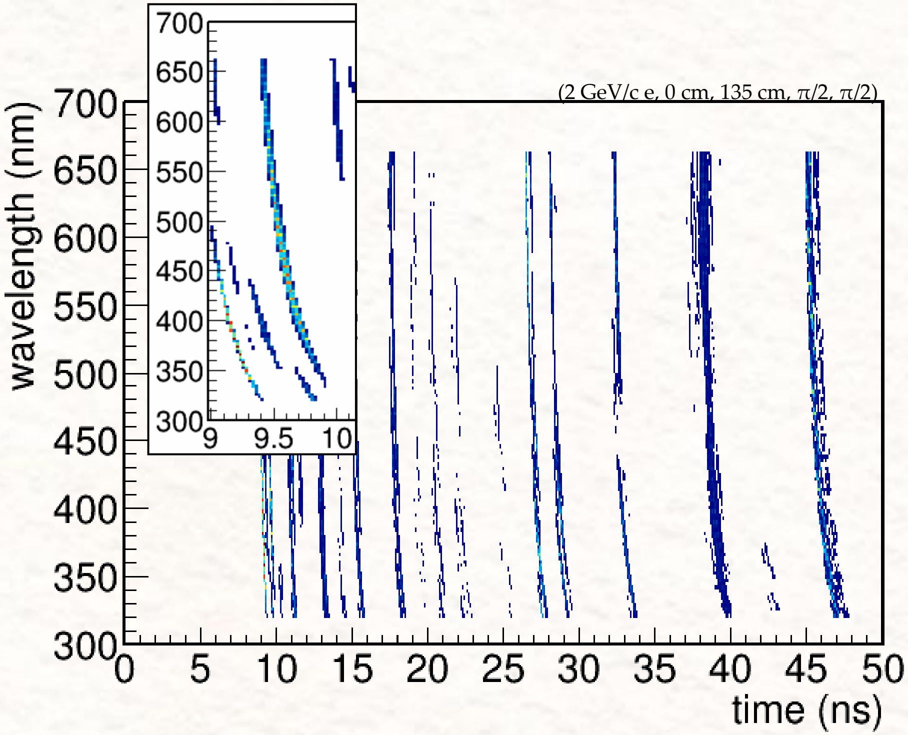
→ Correction of the chromatic error.



Wavelength cut filter

- To reduce the chromatic dispersion further, cut light below 340 nm with a filter in front of the PMT.



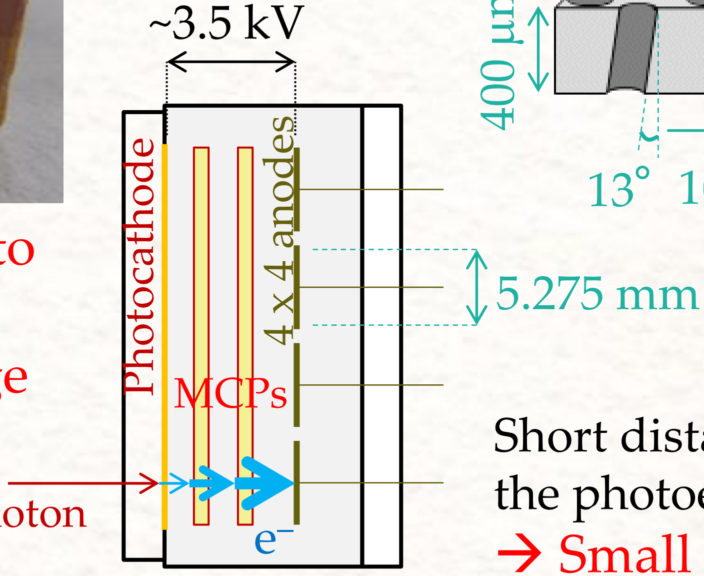


MCP-PMT (Micro Channel Plate PMT)

- Developed at Nagoya in collaboration with HAMAMATSU Photonics K.K. for the TOP counter.

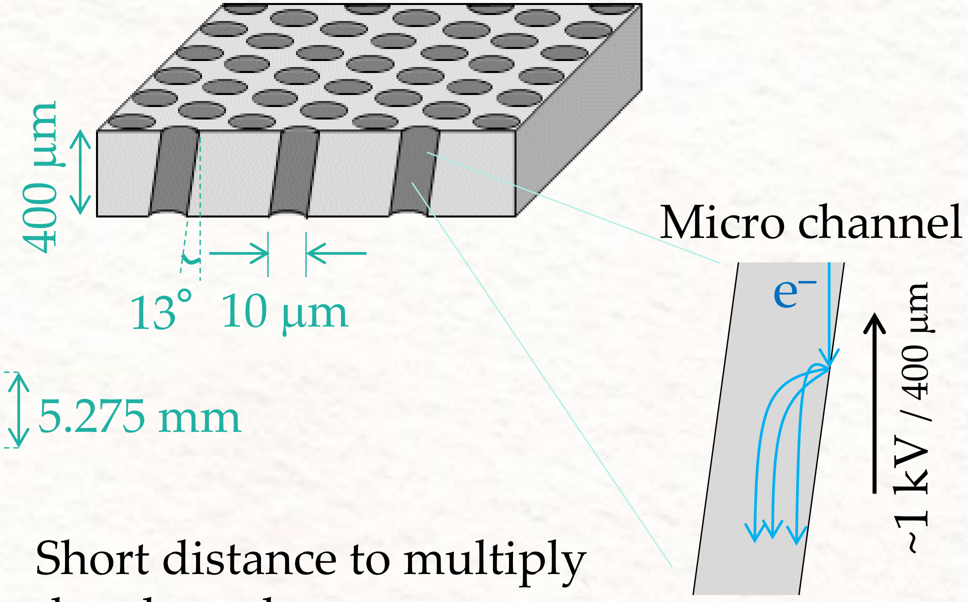
MCP-PMT

Square shape to maximize the photo-coverage



(Cross-section)

Micro Channel Plate (MCP)



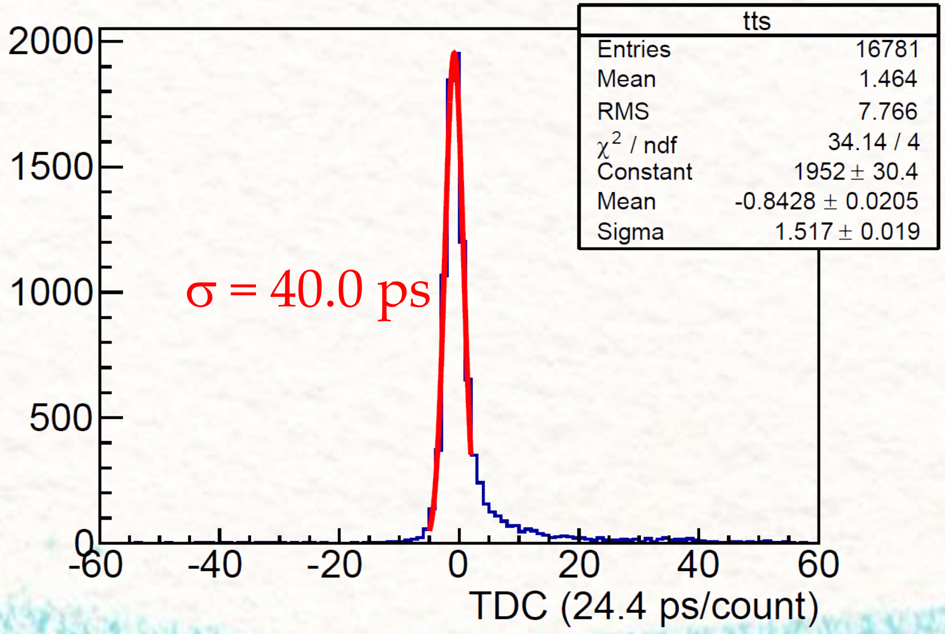
Short distance to multiply the photoelectron

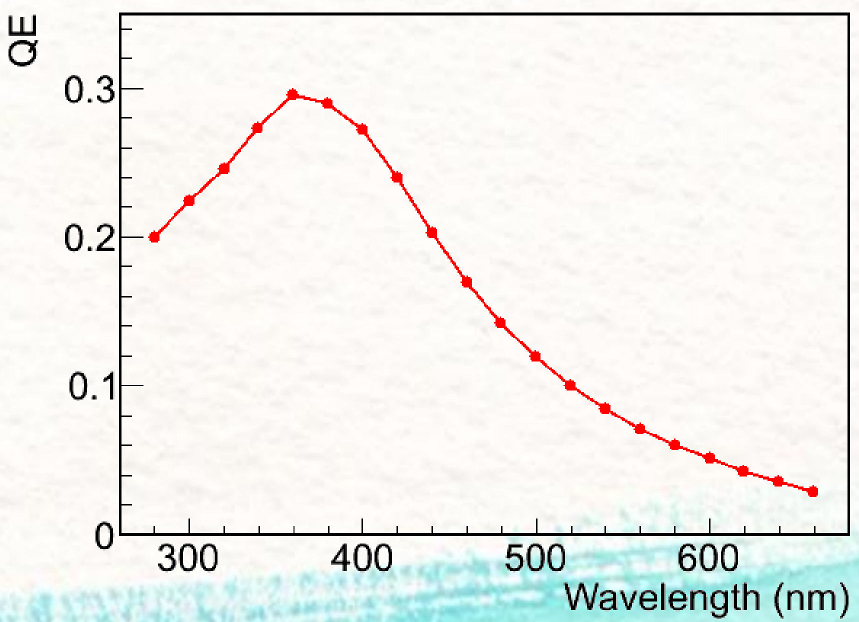
→ Small transit time spread

Use 32 PMTs per TOP module, 512 PMTs in total.

Specification of the MCP-PMT

- Square shape, small dead region (active area: 69.4%)
- NaKSbCs photocathode; QE ≥ 24% (28% on average) at 380 nm
- Collection efficiency: 50~55% (≈ MCP aperture ratio)
- 2 x 10^6 gain at ~3.4 kV → Capable of detecting single photon.
- Transit Time Spread (TTS): ~40 psec
- Dark noise rate < 100 kHz
- Work in 1.5 T

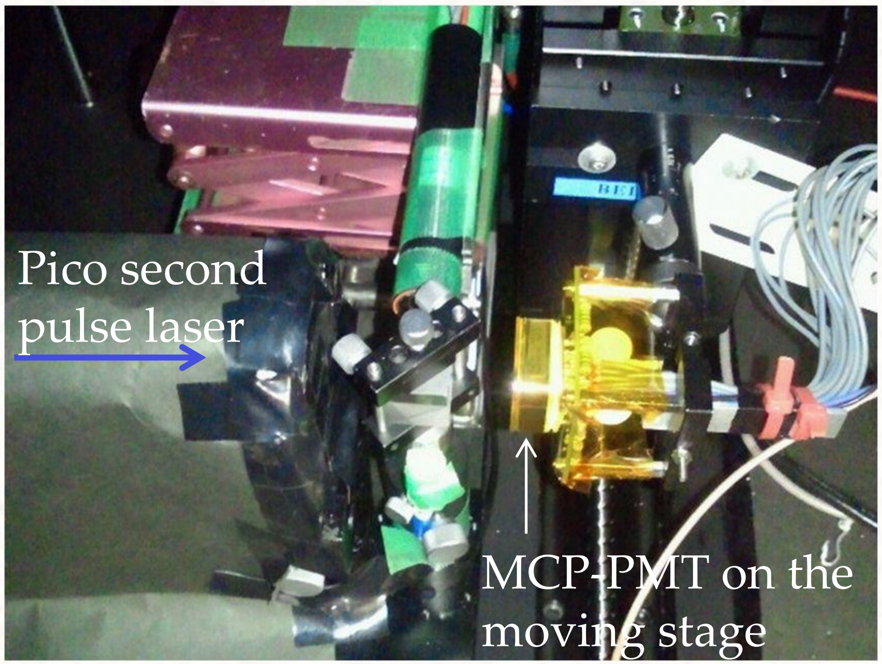




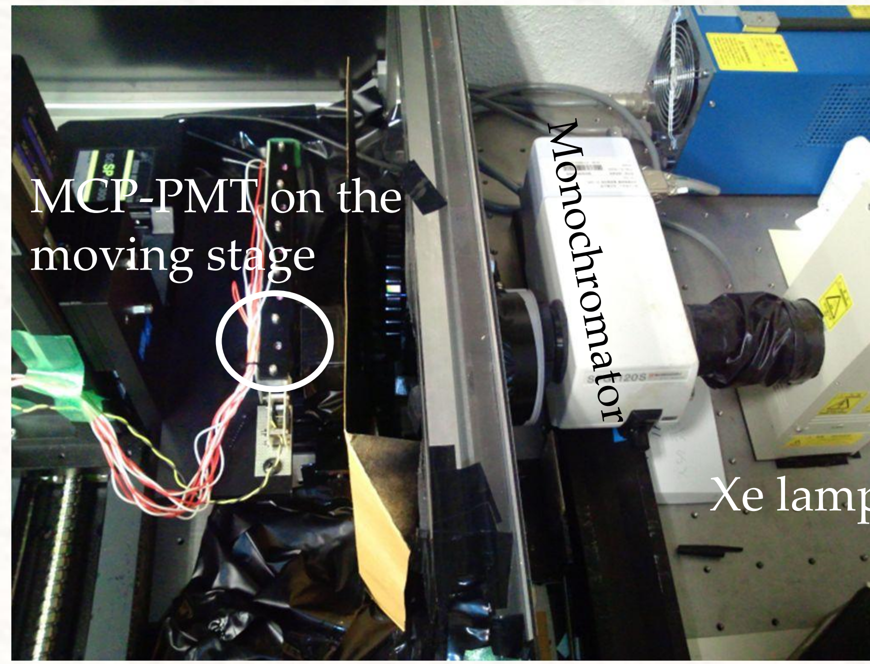
Mass production of the MCP-PMTs

- The mass production started in 2011.
  - The performance of every PMT is checked at Nagoya.

Setup to check the gain and TTS



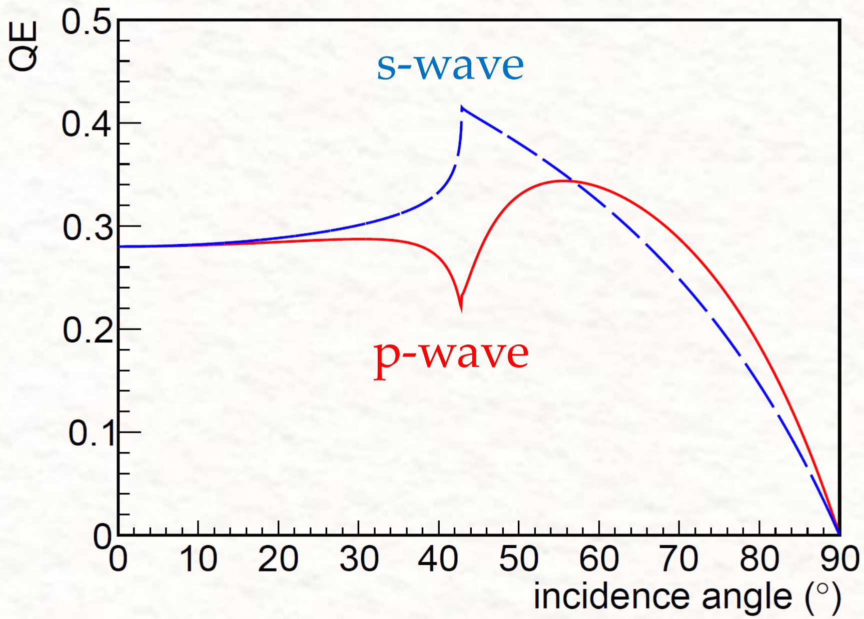
Setup to measure the QE

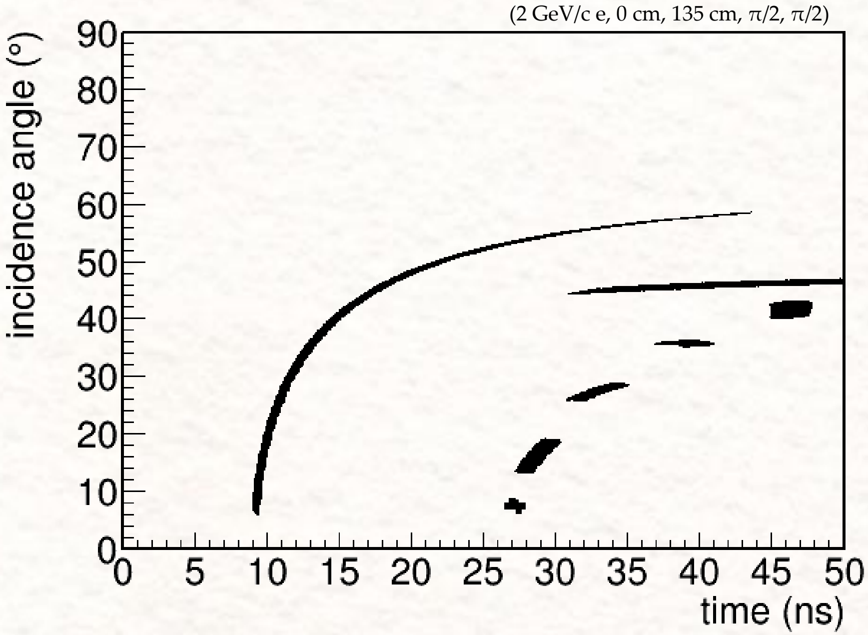


- More than 300 PMTs in hand.
- All the 550 PMTs will be delivered by March 2014.

Angle/polarization dependence of QE

- QE depends on the photon incident angle and polarization.
  - TOP counter detects photons at various angles.
  - Cherenkov light is linearly polarized.



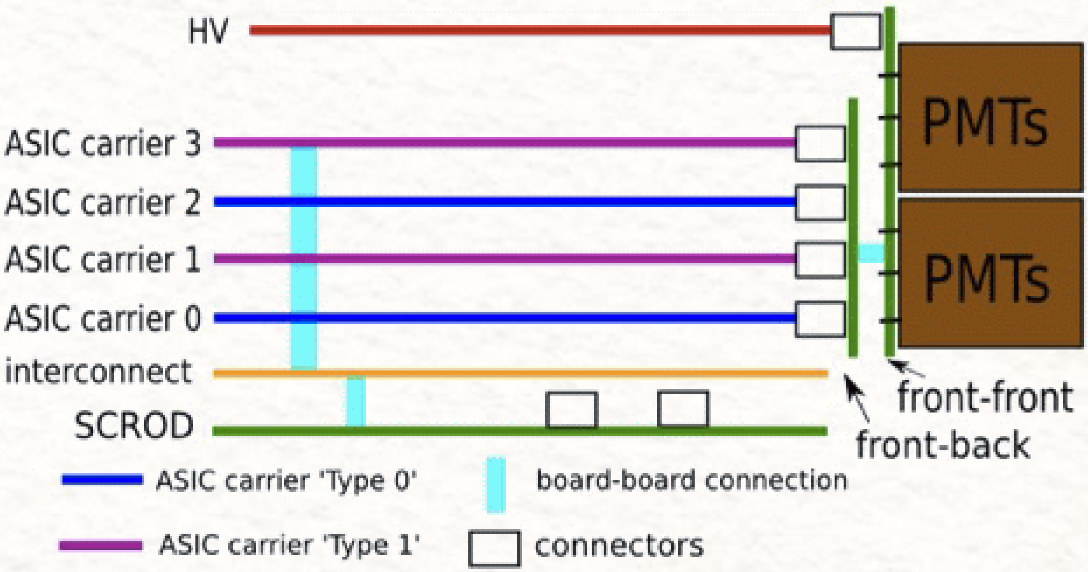


QE for p/s-wave at any angle can be calculated from Fresnel equations with n, k and d of the photocathode measured by ellipsometry.

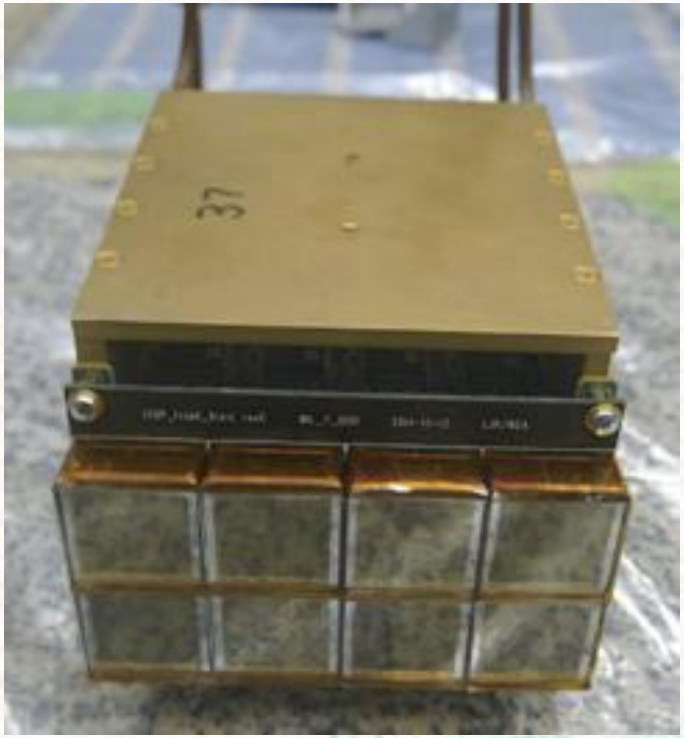
Readout electronics

- Based on a waveform-sampling ASIC (IRS**) being developed at Hawaii Univ.
  - Chip intrinsic time resolution is <25 ps.

(Cross-section)



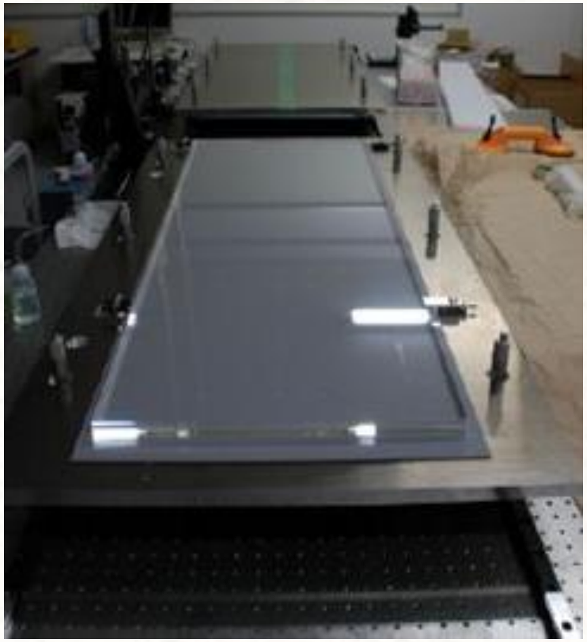
Front-end readout with 8 PMTs

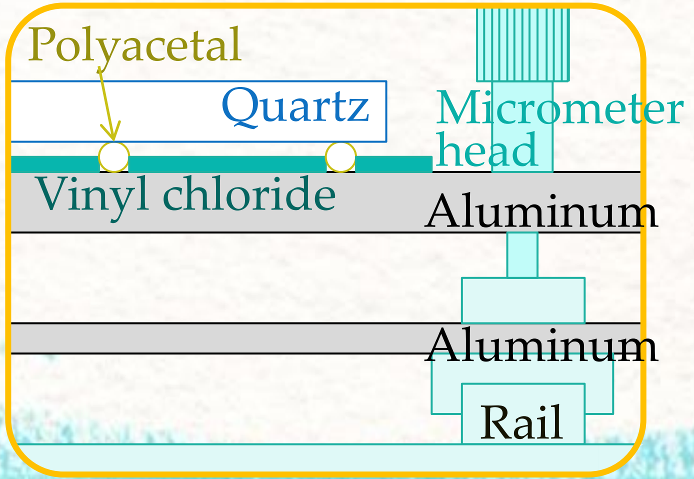


Assembly of the prototype TOP counter

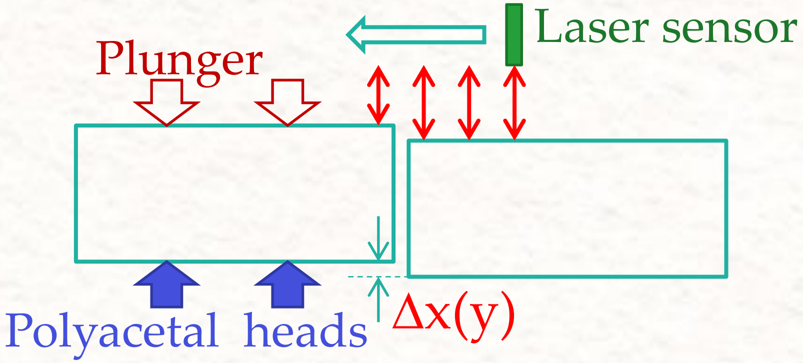
Alignment of the quartz bars

- Need to glue the two quartz bars w/ $\Delta\theta$ < 0.2 mrad and $\Delta x,y$ < 100 μm.





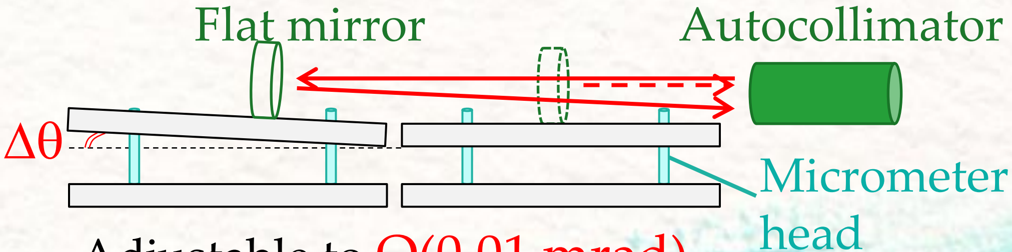
Adjustment of the relative position



Adjustable to O(10 μm)

Measurement precision: $\pm$5 μm

Adjustment of the relative angle

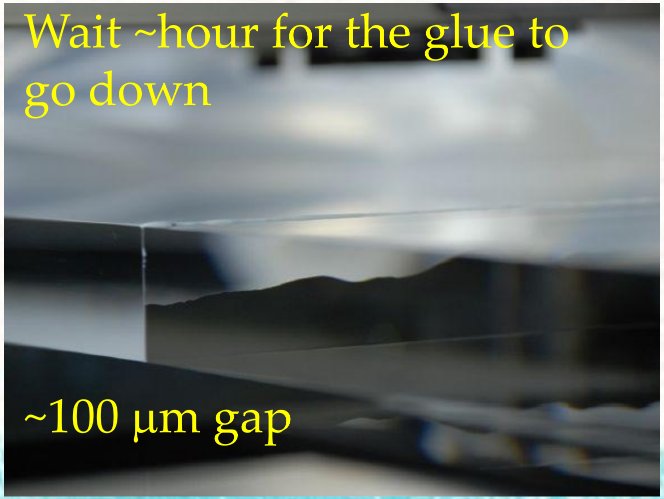


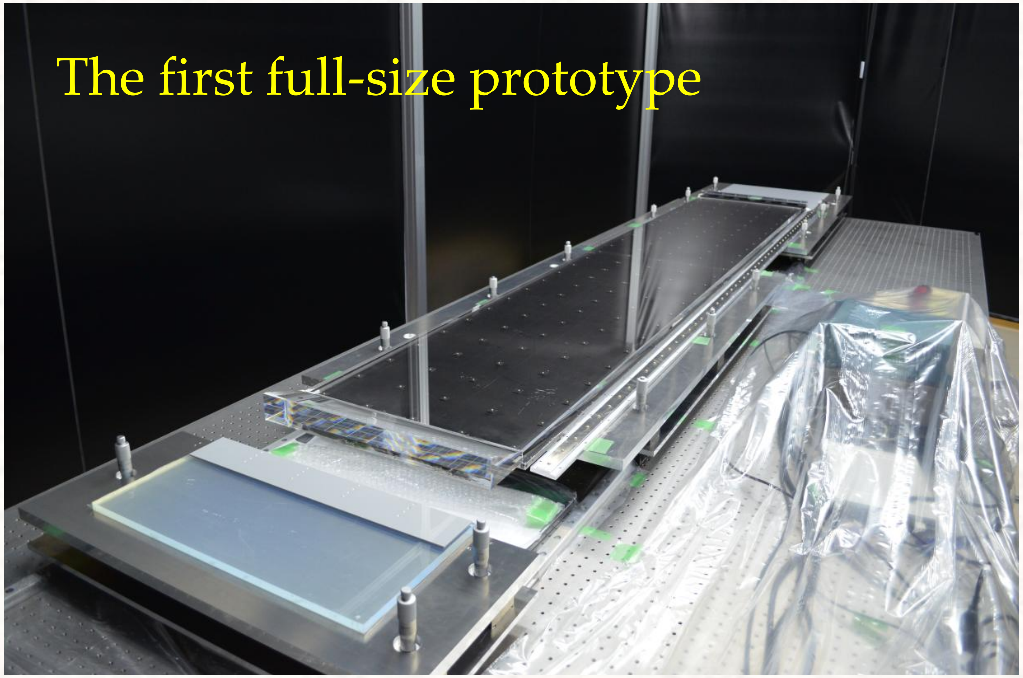
Adjustable to O(0.01 mrad)

Measurement precision: $\pm$0.01 mrad

Gluing of the quartz bars

- Two quartz bars, a short bar with the mirror and a prism were glued together with an optical adhesive, which was then cured by ultraviolet light.



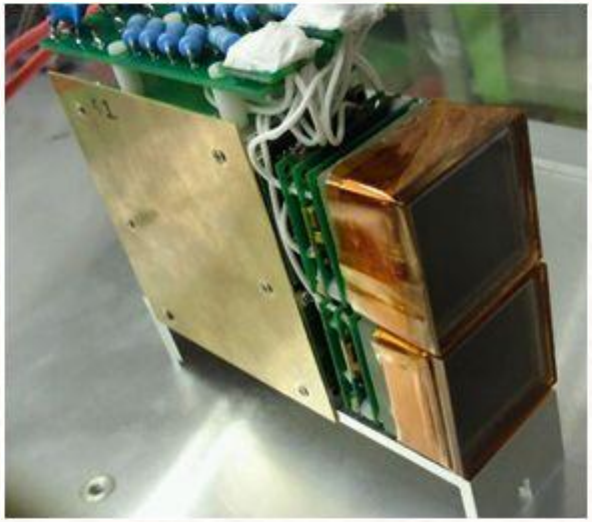


Succeeded gluing all the quartz components

Mounting the MCP-PMTs and electronics

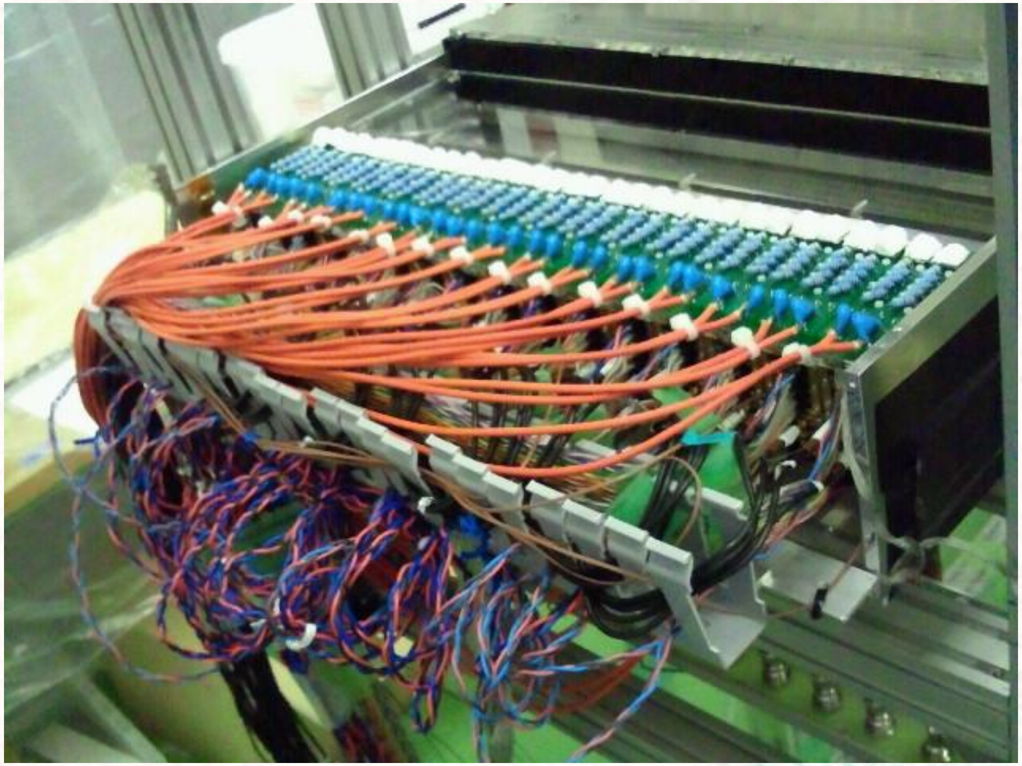
- Because the IRS readout was premature, we prepared a backup readout based on the CFD (constant fraction discriminator) as well as the IRS.

CFD front-end with 2 PMTs



16 outputs of each PMT were merged into 4 at the PMT socket to reduce the number of channels (little impact on the PID performance)

Full 32 PMTs and the CFD mounted on the quartz

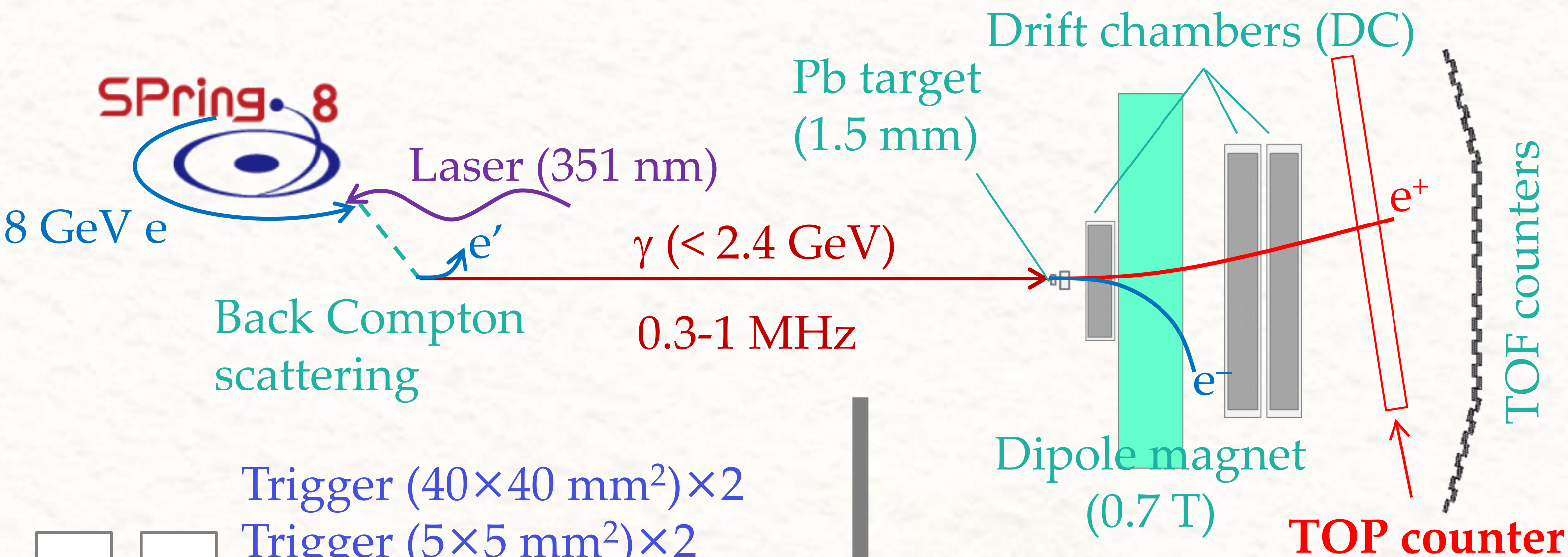


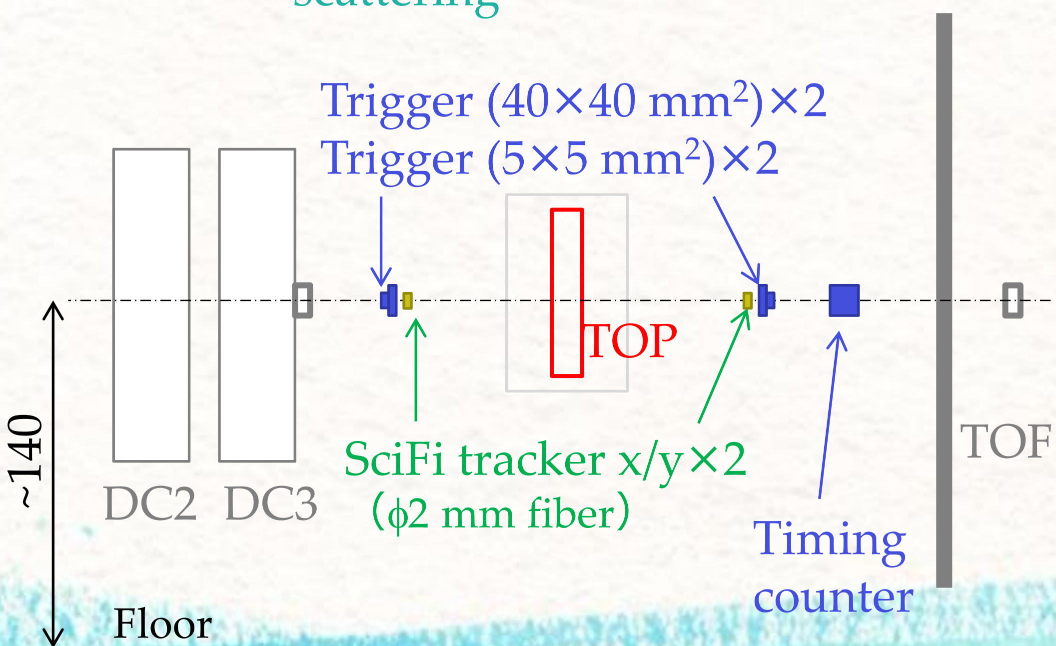
June 2013

Test of the prototype with the positron beam at LEPS

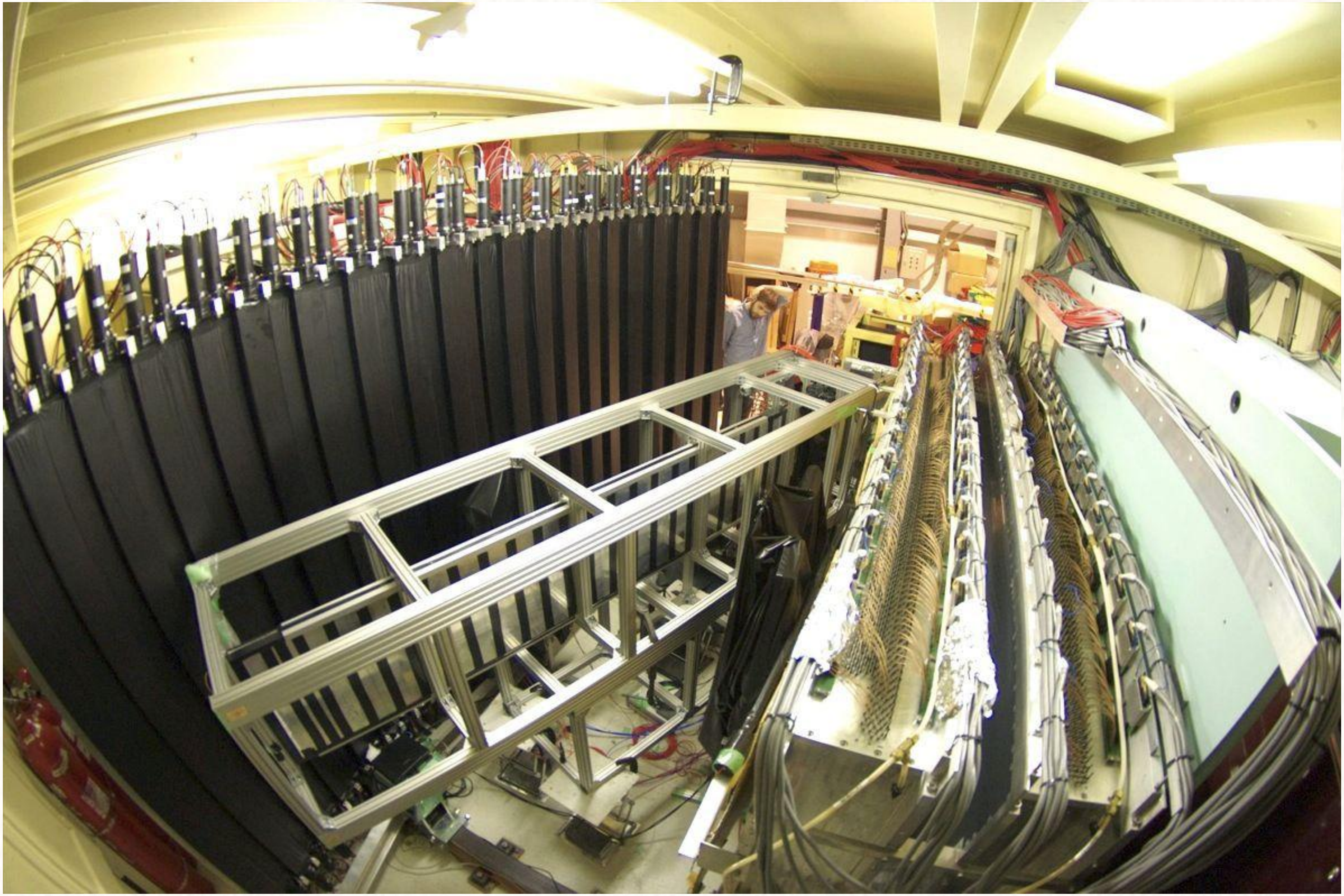
LEPS (Laser Electron Photon beamline at SPring-8)

- Evaluate the performance of the TOP counter with the 2 GeV/c positron beam at LEPS





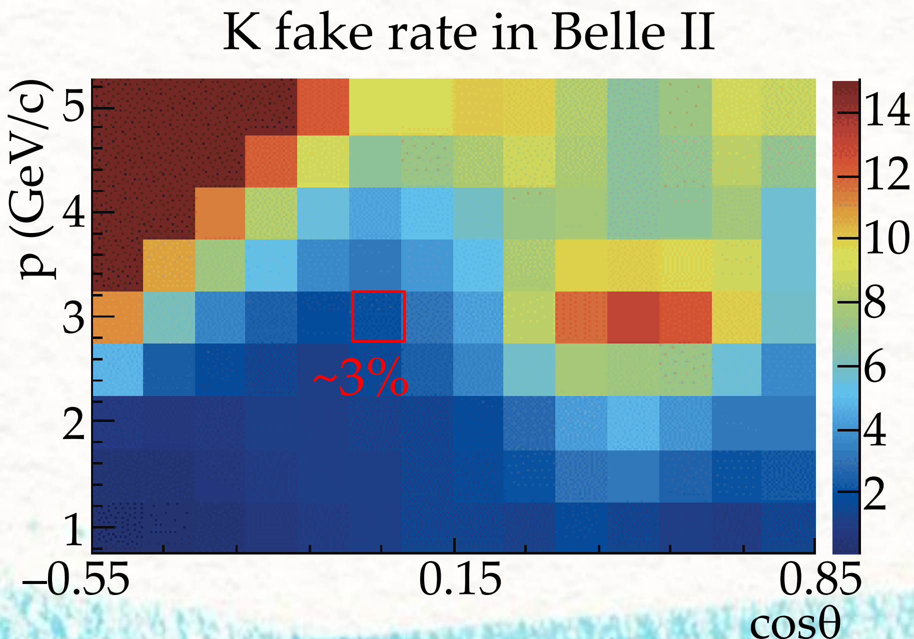
- Coincidence of the 4 triggers → Beam fluctuation ~1.5 mrad
- Trigger rate ~10 Hz
- e^+ momentum measured by the LEPS spectrometer
- EM shower cut by requiring $N_{TOF} = 1$

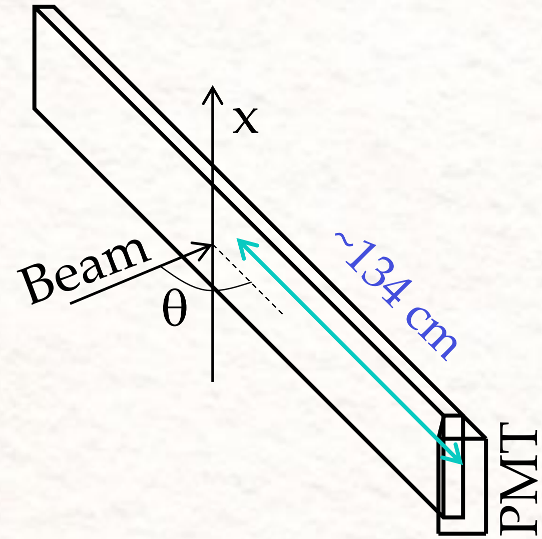


Data set

- Got the same data set both with the IRS and CFD readouts

1. cosθ ~ 0, x = 0 cm ← Only this data taken with the CFD is shown today
2. cosθ ~ 0.4, x = 0 cm
3. cosθ ~ 0.4, x = 20 cm

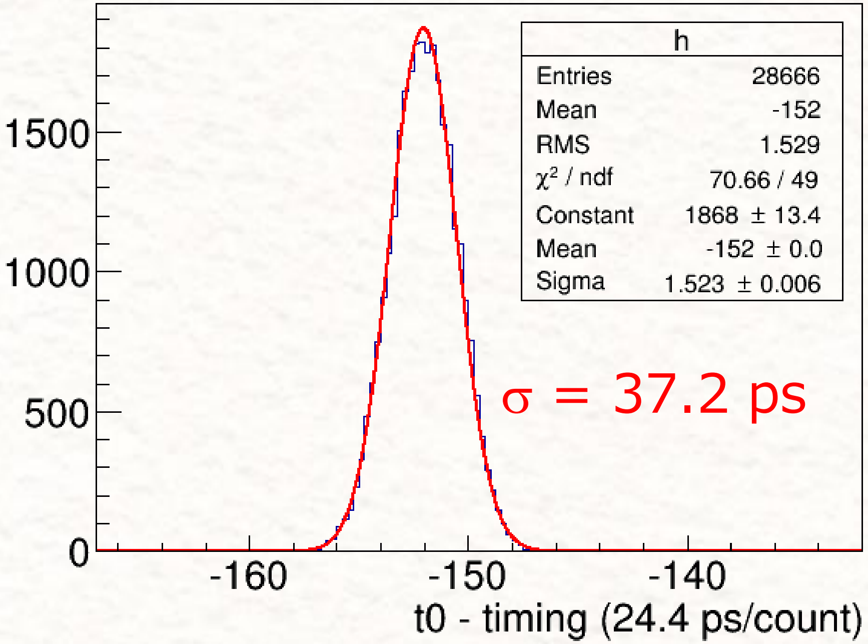


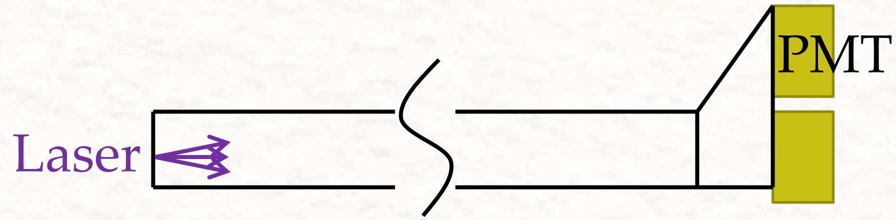


Because the distance between the beam incident position and PMTs is longer for cosθ ~ 0 in this beam test than in Belle II, the K fake rate should be worse a little.

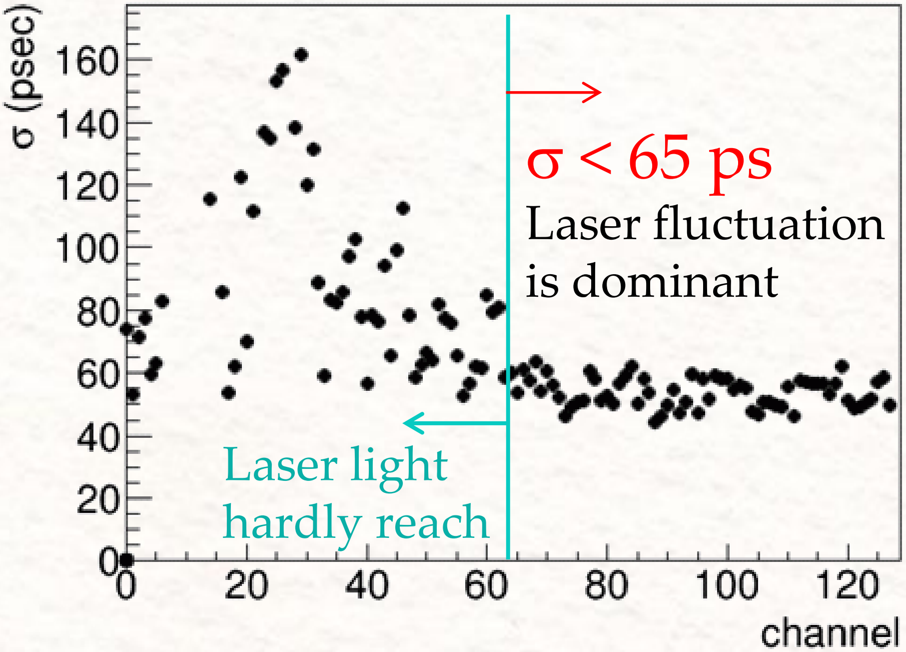
Timing resolution

Time difference between the beam timing estimated from the accelerator RF clock and the timing counter





Timing resolution measured by the laser



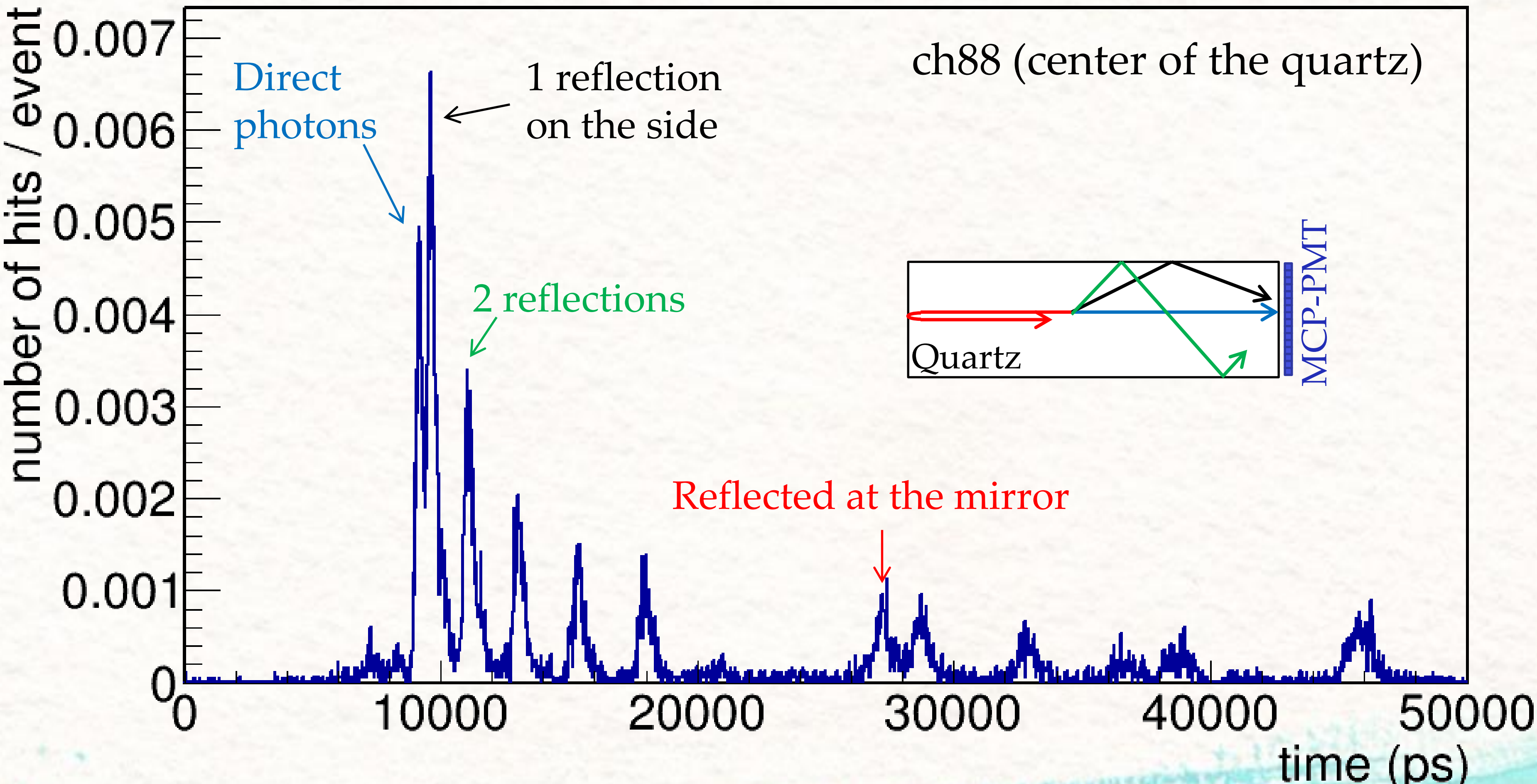
RF resolution = 37.2/√2 = 26.3 ps
(TDC resolution of 25 ps is dominant)

→ Use the RF clock as the beam timing

The timing resolution of the system was proved to be good.

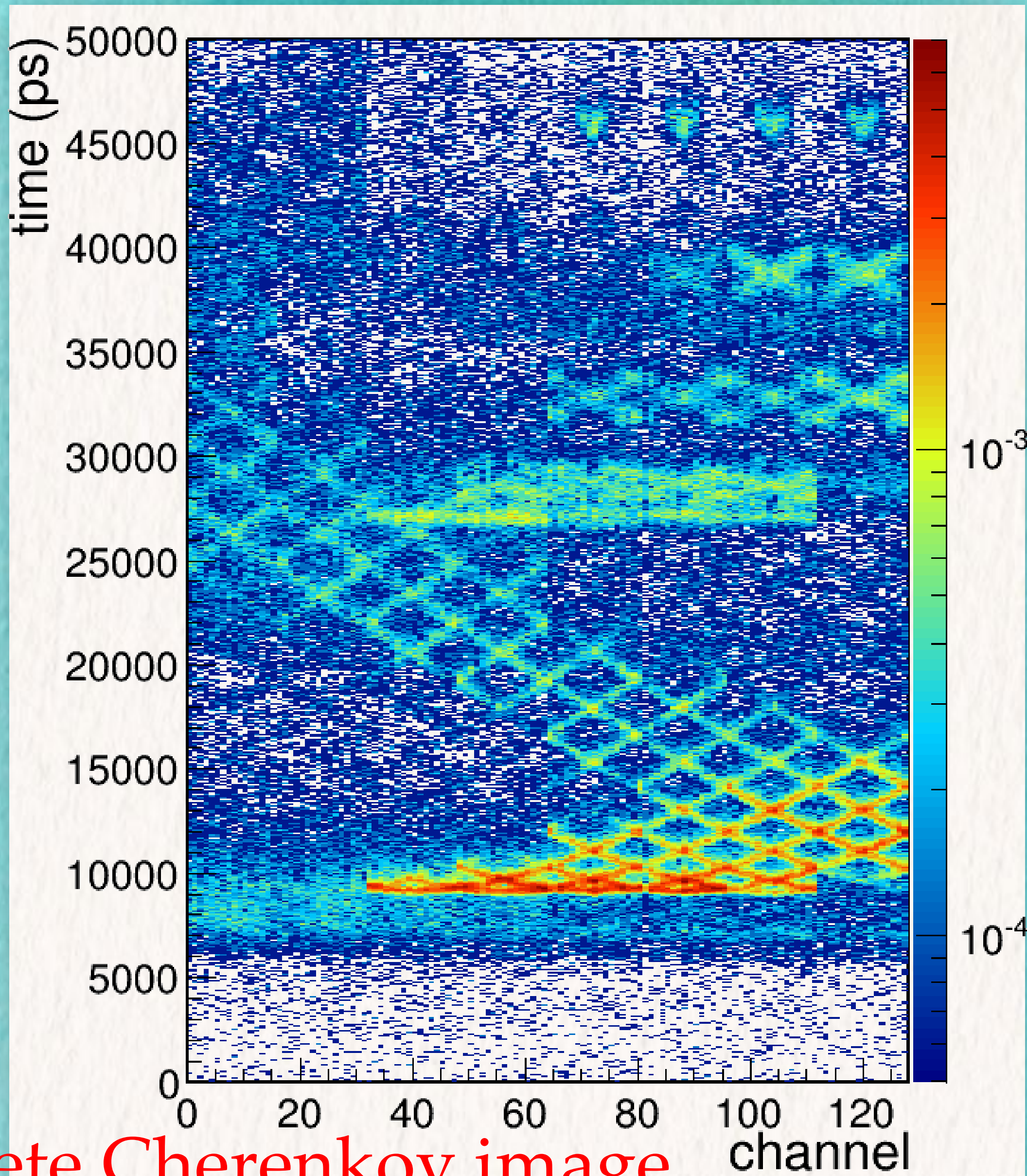
TOP distribution for the beam

Histogram of the photon detection timing relative to the beam timing (sum of 16,750 events)



Cherenkov “ring” image

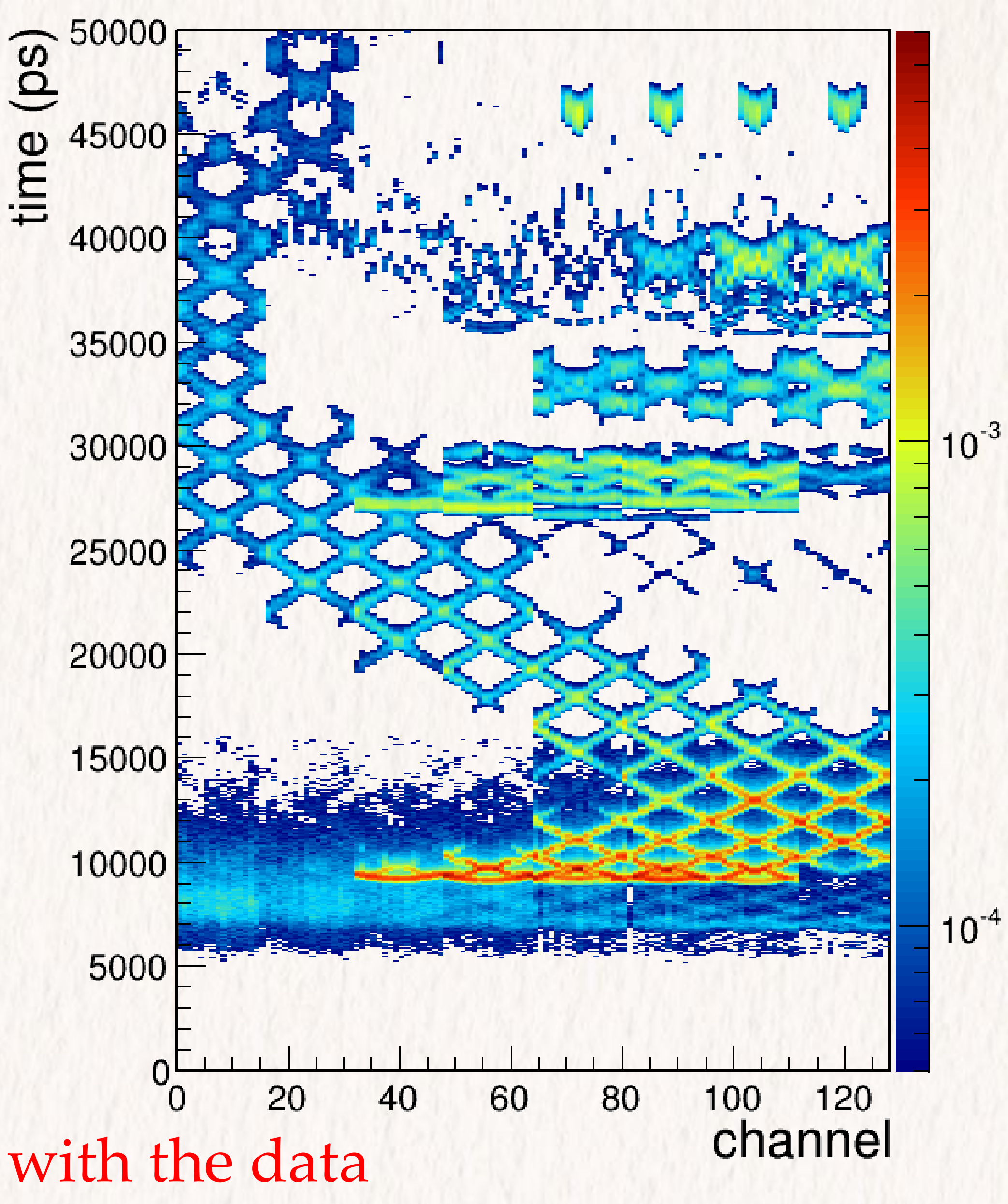
Beam data
(cosθ ~ 0)



World-first complete Cherenkov image measured by the TOP counter!

Cherenkov “ring” image

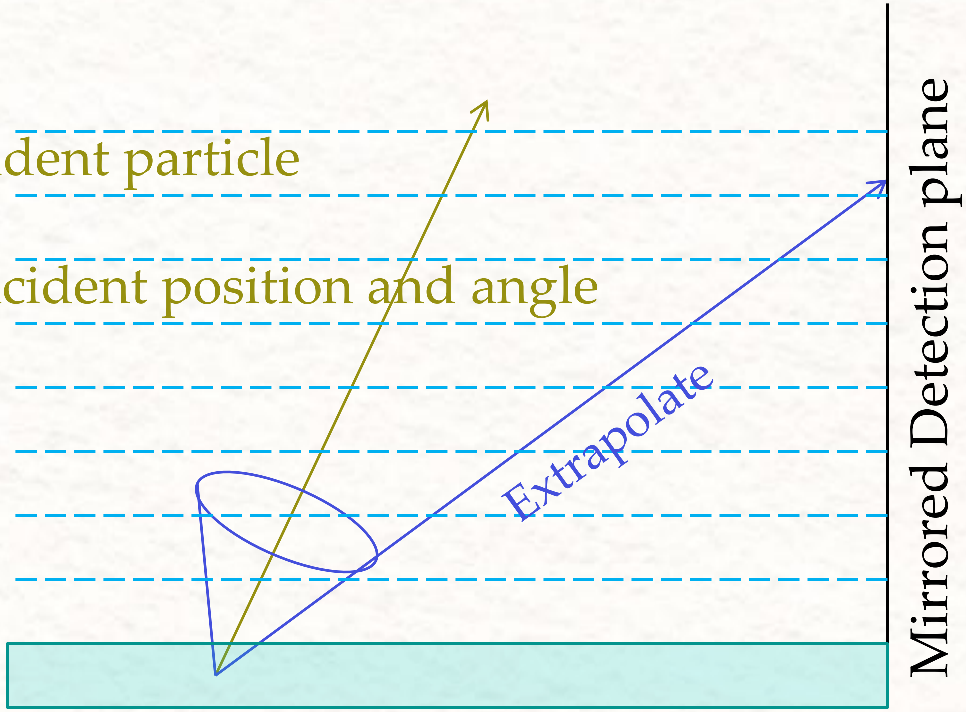
PDF
(expectation)



Good agreement with the data

PDF calculation

Incident particle
- β
- Incident position and angle



MCP-PMTs
- QE(ch, λ)
- Index and thickness of the photocathode
- CE(ch)
- TTS(ch)
- Charge sharing rate (~10%)
- Cross-talk rate (~3%)
- Light reflection on the photocathode and edge
- PMT alignment

Quartz bar
- Dimensions
- Index(λ)
- Reflectance
- Transmittance

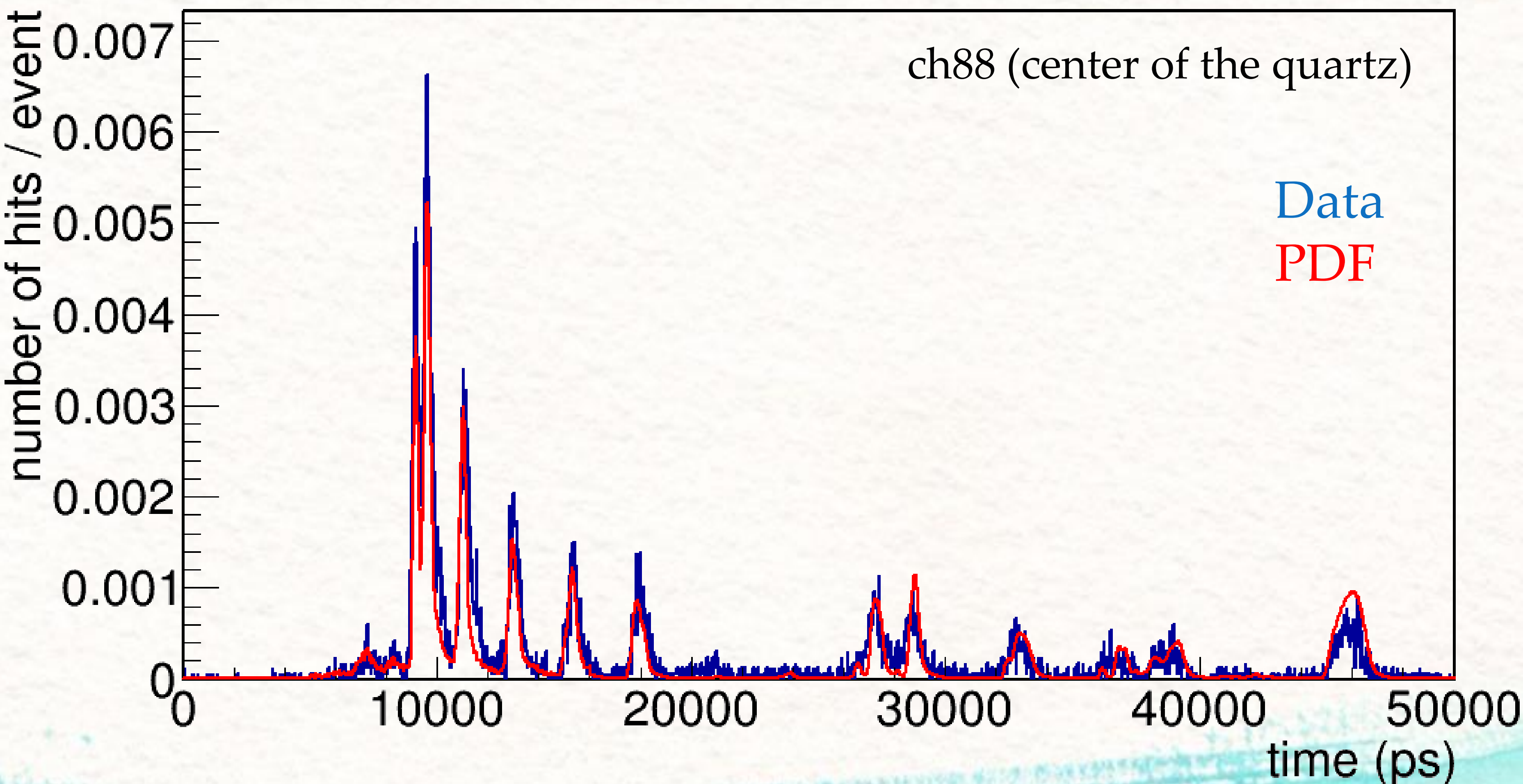
Cherenkov light
- $\theta_C(\lambda)$
- Number of photons produced
- Polarization
- Phase shift at reflections

Readout electronics
- Jitter
- Efficiency
- Cross-talk

There are many things which we have to understand.

Comparison between the data and PDF

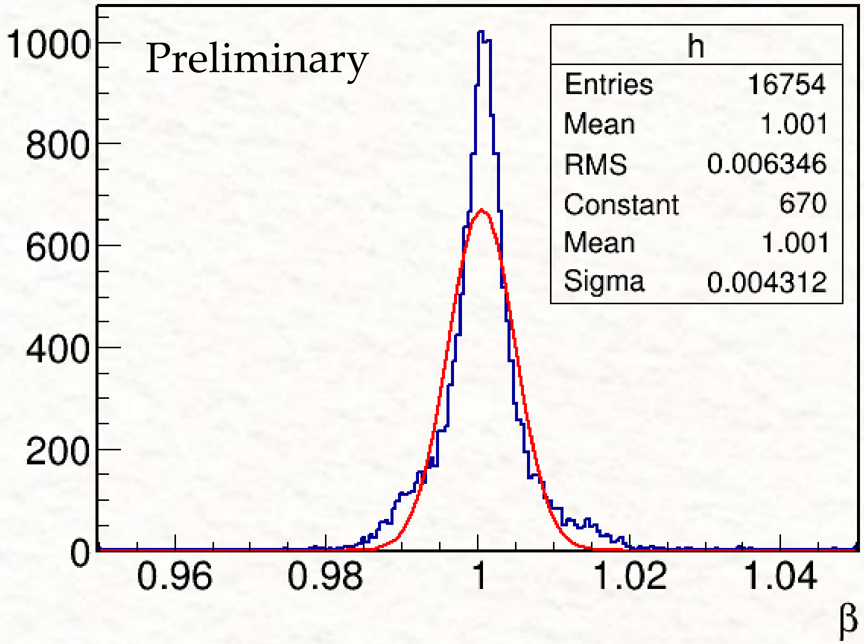
Achieved this level of our understanding



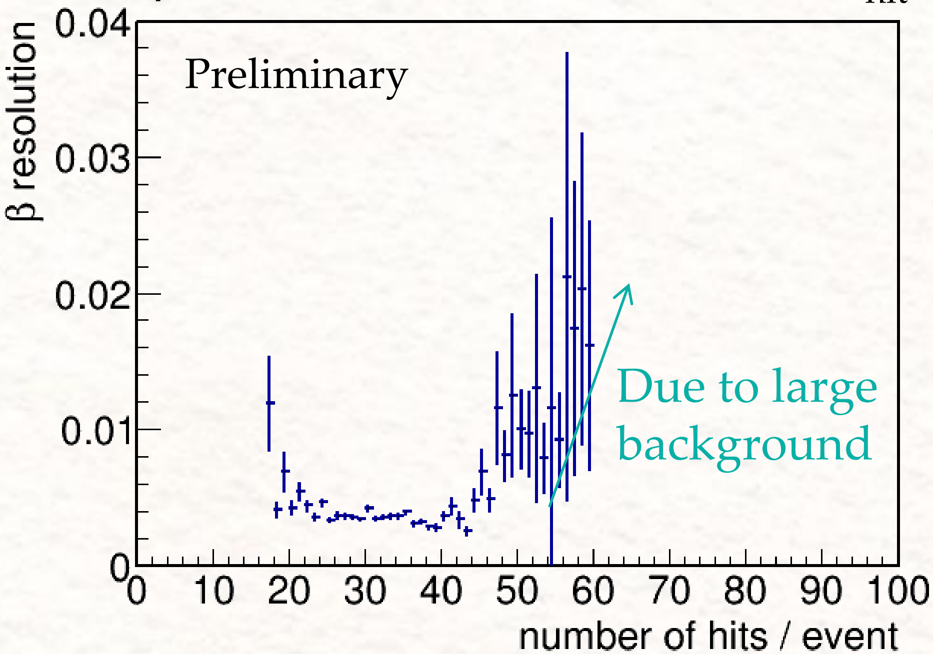
β reconstruction

- Calculate likelihood with PDF(β) event-by-event and get β at the maximum likelihood

β at the maximum likelihood



β resolution as a function of N_{hit}

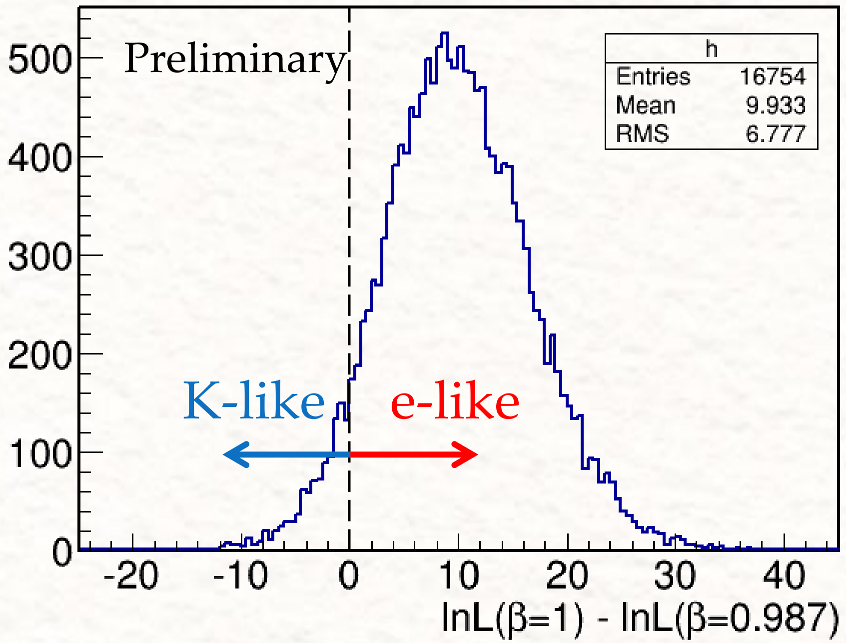


β_{mean} = 1.001
σ_{β} = 0.0043

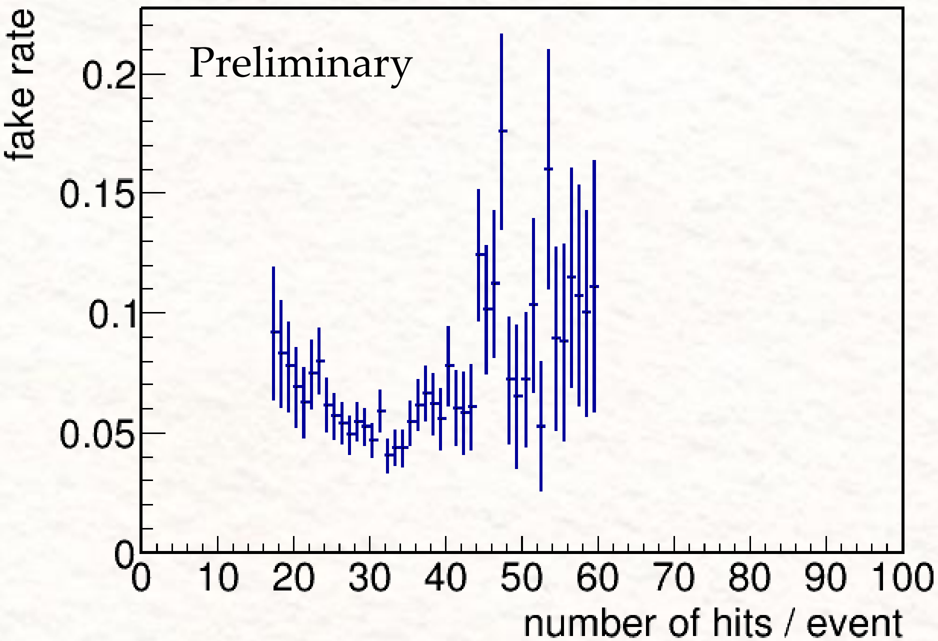
Pseudo PID test

- Calculate likelihood for 2 GeV/c e^+ (β=1) and for 3 GeV/c K (β=0.987) event-by-event

Likelihood ratio



Likelihood ratio as a function of N_{hit}



Fake rate = 6.4%

(comparable to a MC result)

Preliminary but promising result

Summary and plan

- The TOP counter is a novel RICH detector from Nagoya developed for the Belle II experiment.
- After tremendous studies for more than a decade, the prototype TOP counter with almost the same design as the final one was successfully fabricated.
- The prototype was tested with the 2 GeV/c e^+ beam at LEPS.
  - This is the first data for the full size TOP counter.
  - Deepened our understanding of the TOP counter.
  - Will prove the principle of TOP with this data.
- Fabricate 16 TOP counters next year and install them on March 2015.
- Belle II physics run starts in autumn of 2016.