TOP counter for particle identification at the Belle II experiment

K. Inami (Nagoya univ.)
Belle II PID group

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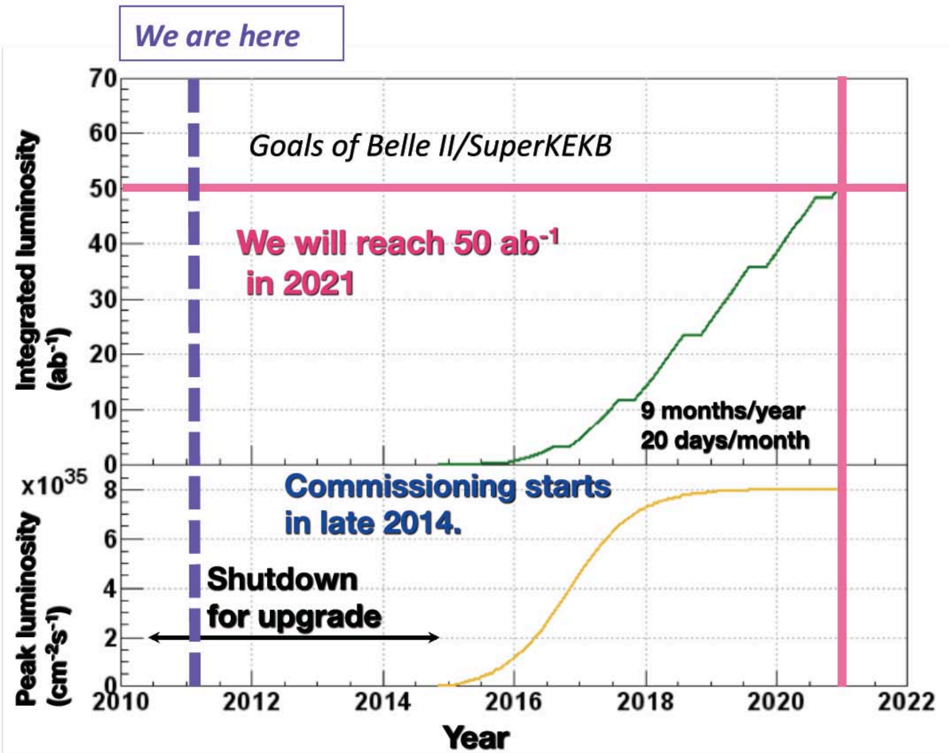
Upgrade to SuperKEKB/Belle II

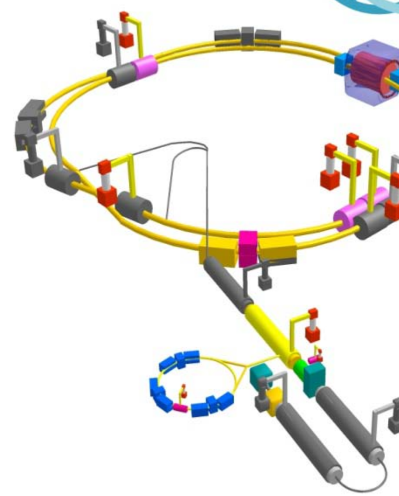
- Higher luminosity B-factory

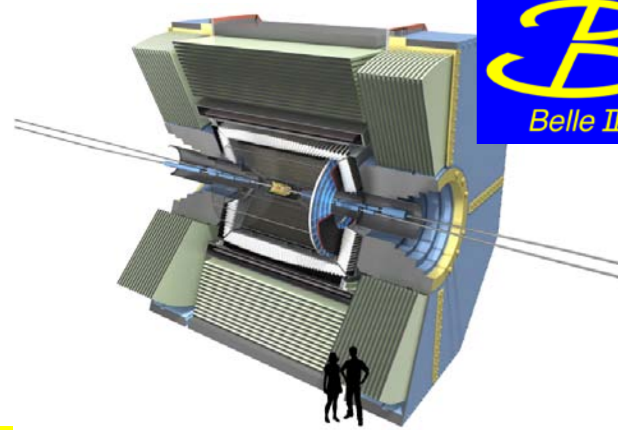
Target Lum. = $8 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Higher beam currents
- Smaller beam size

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$



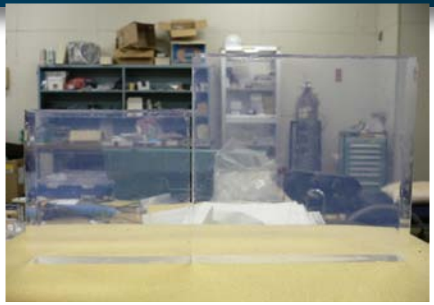


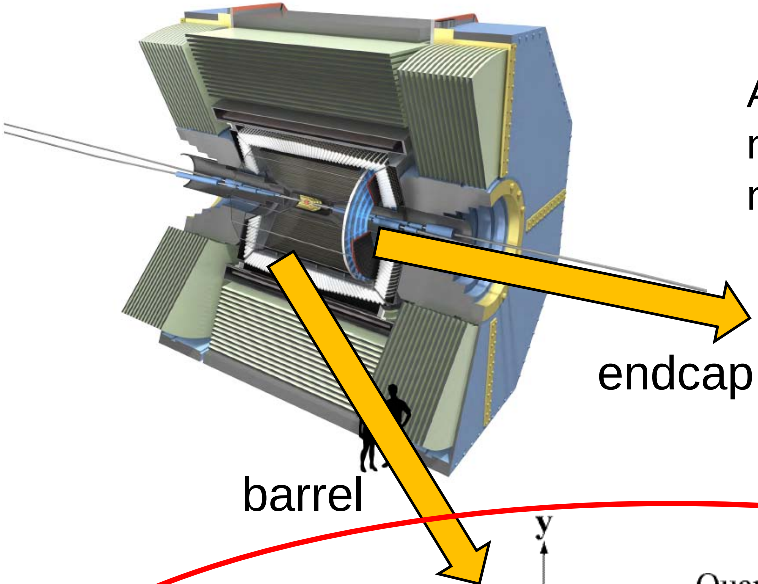


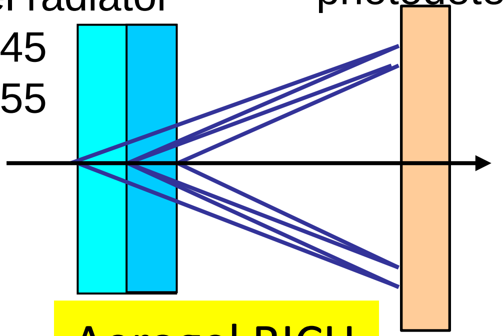
Physics with $O(10^{10})$ B, τ, charm

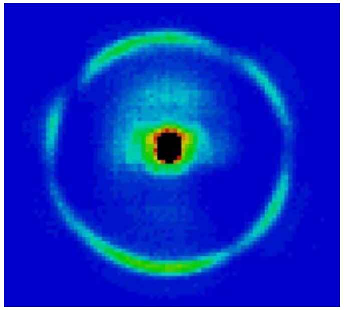
Particle ID (K/π) for Belle II

- Ring Imaging Cherenkov detectors
  - A fake rate for K/π separation 2-5 times smaller than Belle

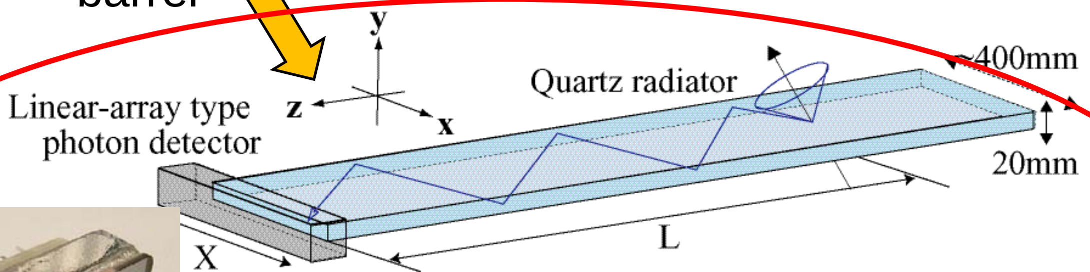


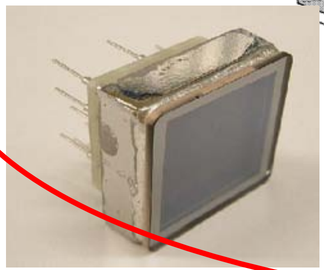


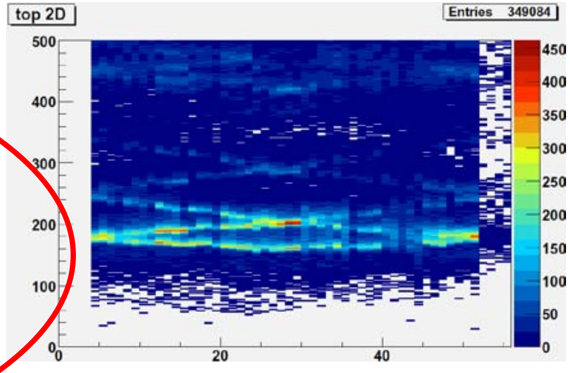




Aerogel RICH





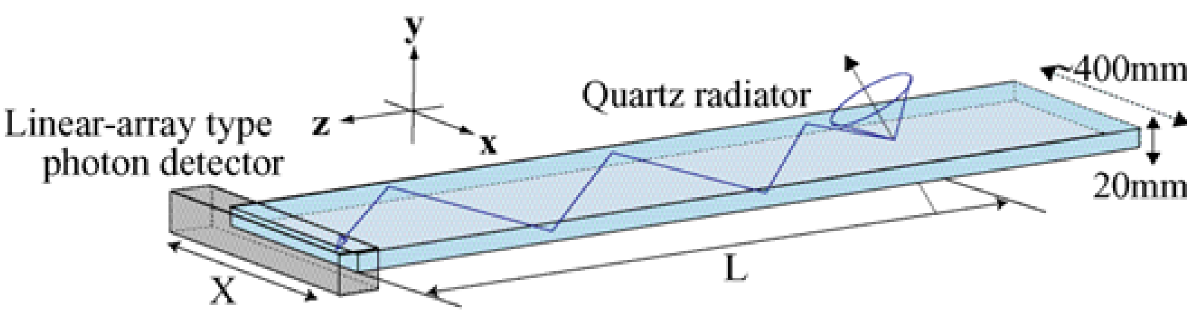


TOP（Time-Of-Propagation）Counter

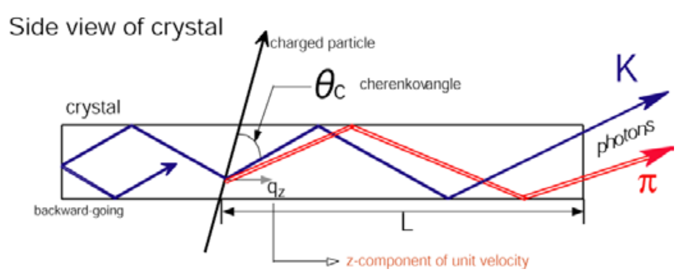
Basic concept

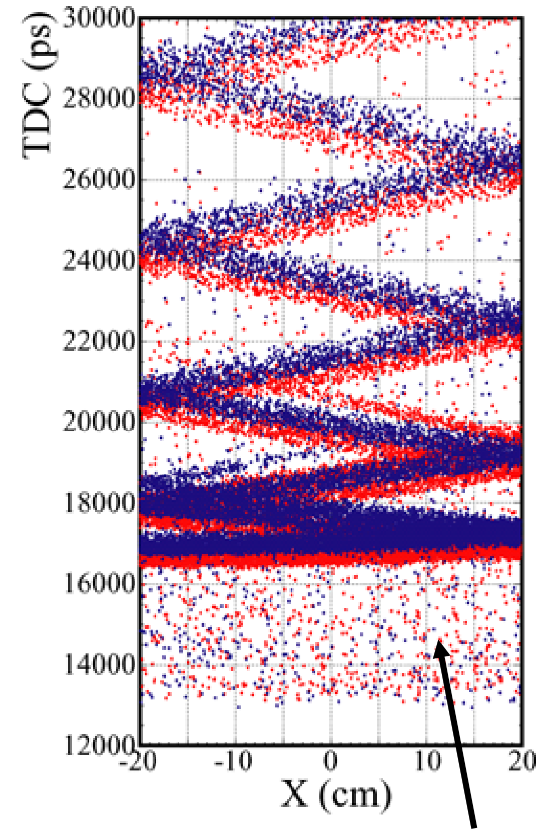
Simulation
2GeV/c, θ=90 deg.

- Cherenkov ring imaging using timing information
- Very compact, suitable for collider geometry.
- Key technologies:
  - Single photo detection with precise timing
  - Accurately polished quartz bar



$$\cos\theta_c = \frac{1}{n(\lambda)\beta}$$





δ-ray,
had. int.

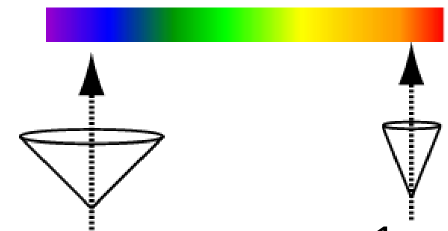
Difference of path length → Difference of time of propagation (TOP)
~150-200ps from TOP + TOF from IP
with precise time resolution (σ~40ps) for each photon

Focusing mirror + 3D imaging

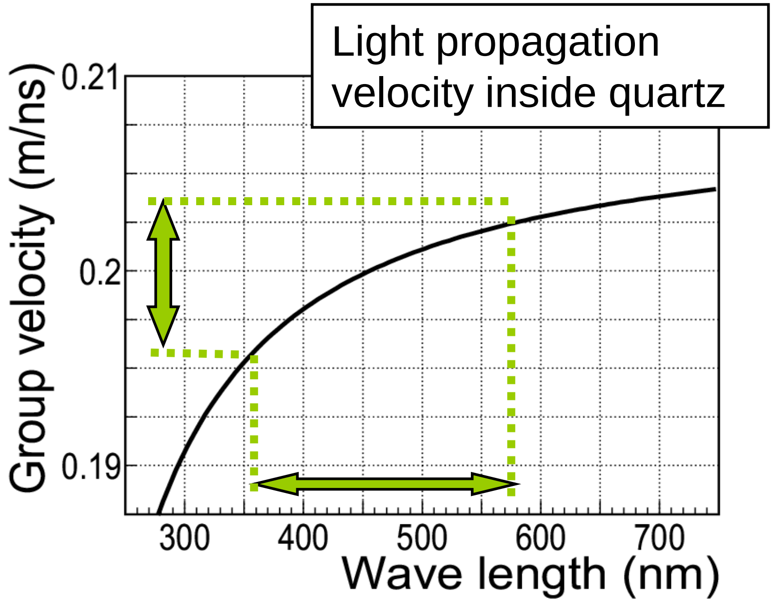
- Chromatic dispersion smears the TOP by ~100ps.
- Use λ dependence of Cherenkov angle to correct chromaticity

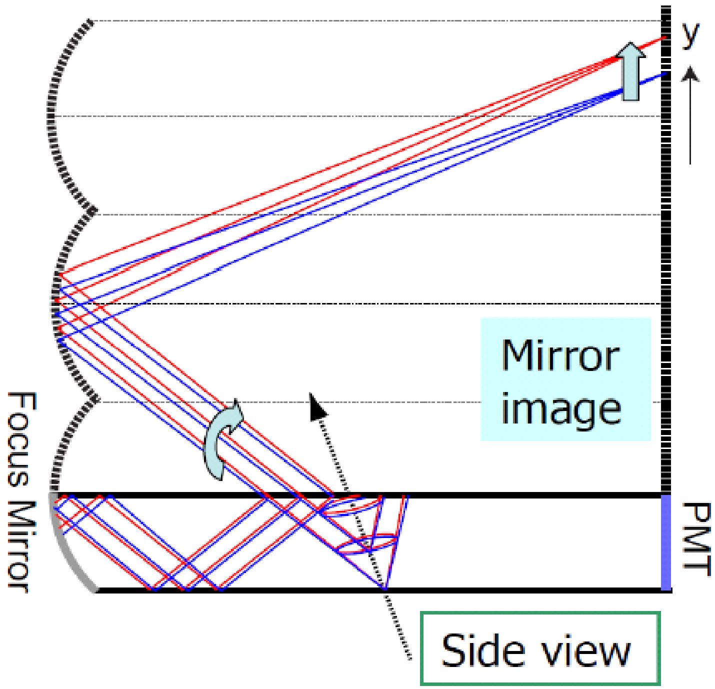
➔ Focusing system to measure θ_c

  - $\lambda \leftarrow \theta_c \leftarrow$ y position
  - Reconstruct ring image from 3D information (time, x and y).
  - Long focusing length enlarges y difference.
    - $\Delta\theta_c$~5mrad → Δy~14mm for 2.5m length



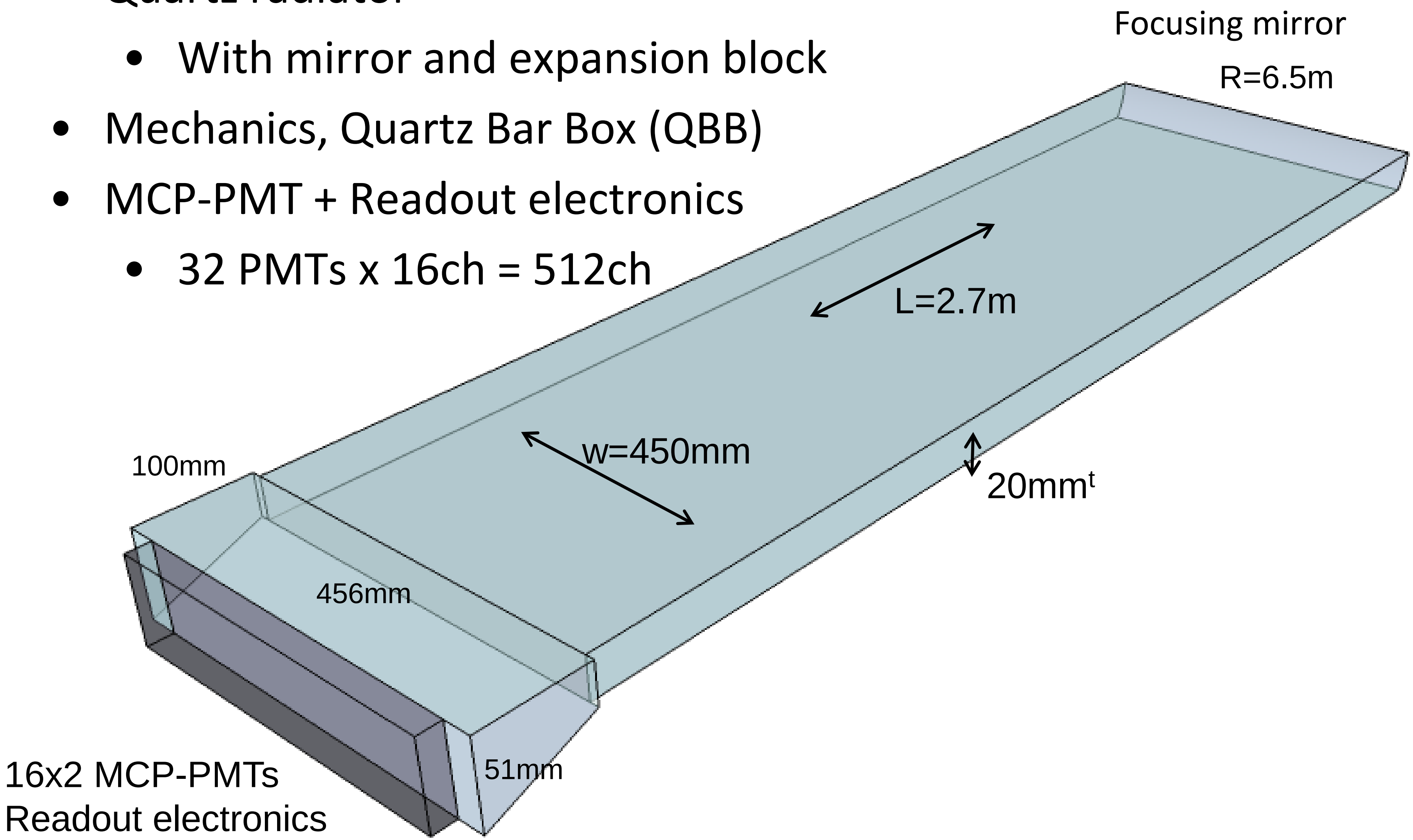
$$\theta_c(\lambda) = \cos^{-1}\left(\frac{1}{n(\lambda)\beta}\right)$$





TOP counter for Belle II

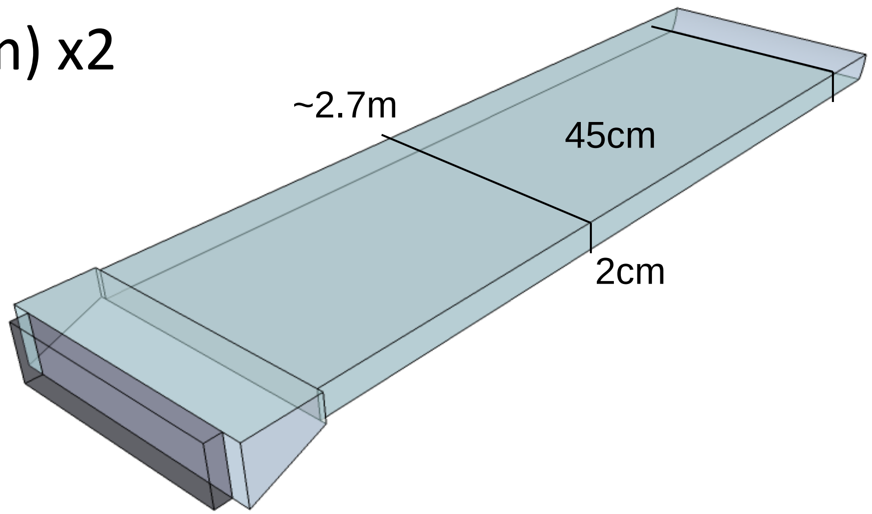
- Quartz radiator
  - With mirror and expansion block
- Mechanics, Quartz Bar Box (QBB)
- MCP-PMT + Readout electronics
  - 32 PMTs x 16ch = 512ch



Quartz radiator

- Quartz bar (1.25m x 45cm x 2cm) x2
- Focusing mirror (R=6.5m)
- Expansion block

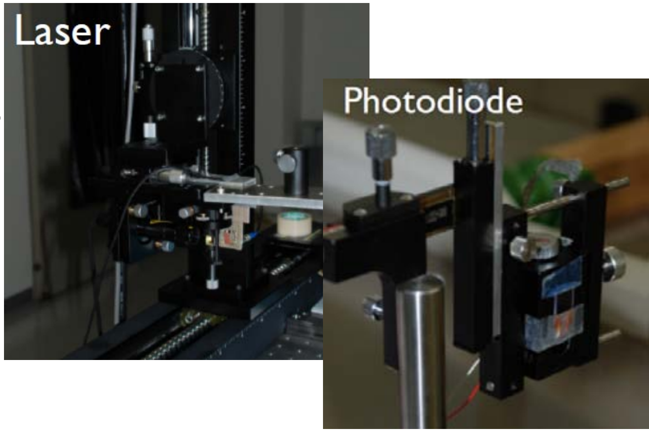
  → Glue each other

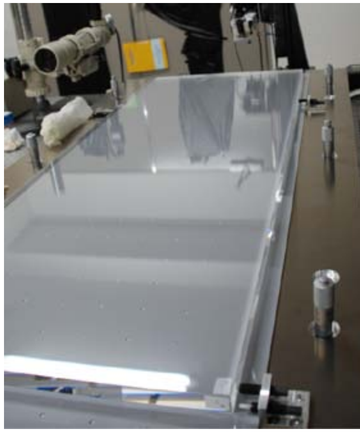


- Need high quality surface
  - Roughness: 0.5nm (to keep total reflectance)
  - Flatness: <10λ(6.3μm) over full aperture (to keep ring image)
  - Edge: <0.2mm
- Prototype production
  - Quartz bars made by Zygo and Okamoto optics
  - Mirror by Okamoto optics (R=5m)

Quartz radiator production

- Polished surface meets our requirements.
  - Roughness: 0.44nm
  - Flatness: 4.9, 5.1μm for 1.2m
- Quality confirmed by our laser system
  - Internal surface reflectance: 99.92~99.97%
  - No evidence of striae
- Gluing quartz bars and mirror
  - Built optical stage to align precisely
  - <u>Successfully finished</u>
  - Relative angle < 0.1mrad, Displacement < 100μm

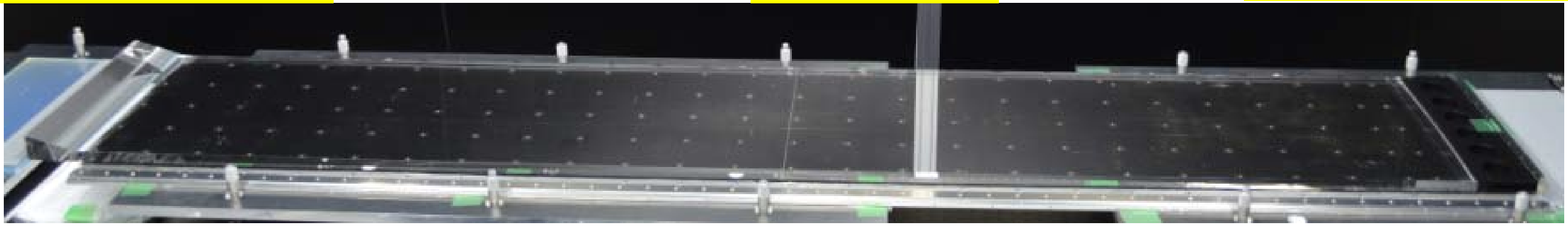




Expansion block

Quartz bar

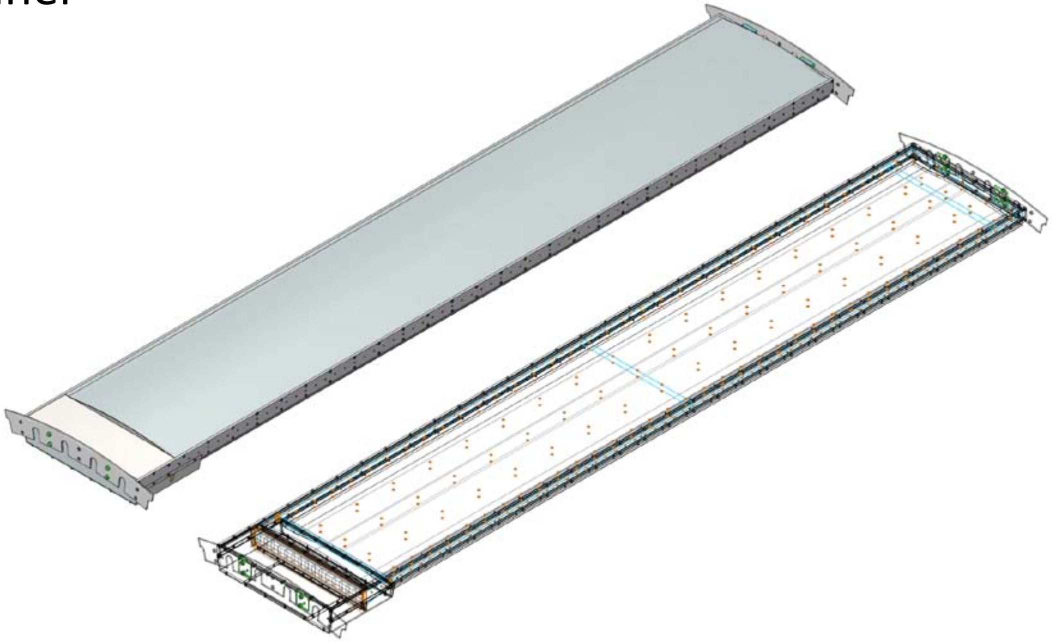
Focusing mirror



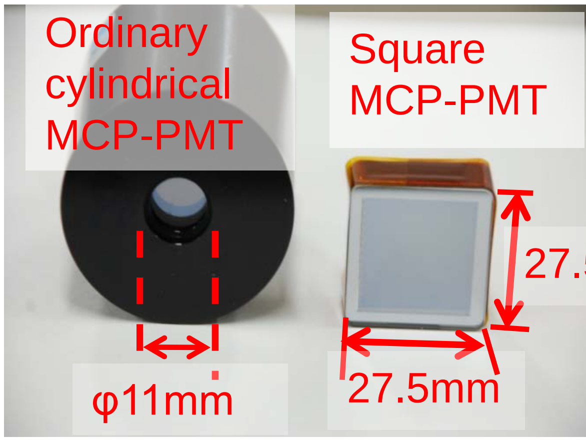
Mechanics development

- Quartz bar box and readout support
  - Honeycomb panels (low mass)
    - + side rails, + readout cover
  - Quartz radiator is supported with PEEK buttons, to allow the total reflection
- Rigid support required for the final system
  - Connect to adjacent modules
  - Round shaped honeycomb panel

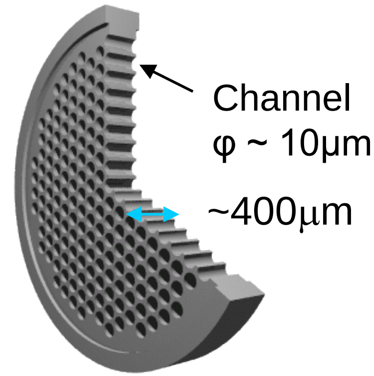
QBB prototype with
Round shaped panel and normal panel

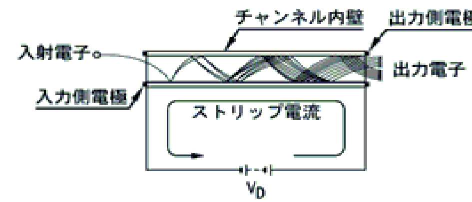


Square-shaped MCP-PMT

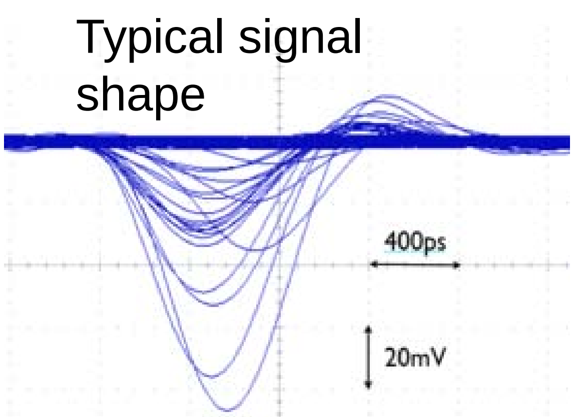


Co-development with Hamamatsu Photonics K.K.





MCP(Micro channel plate)

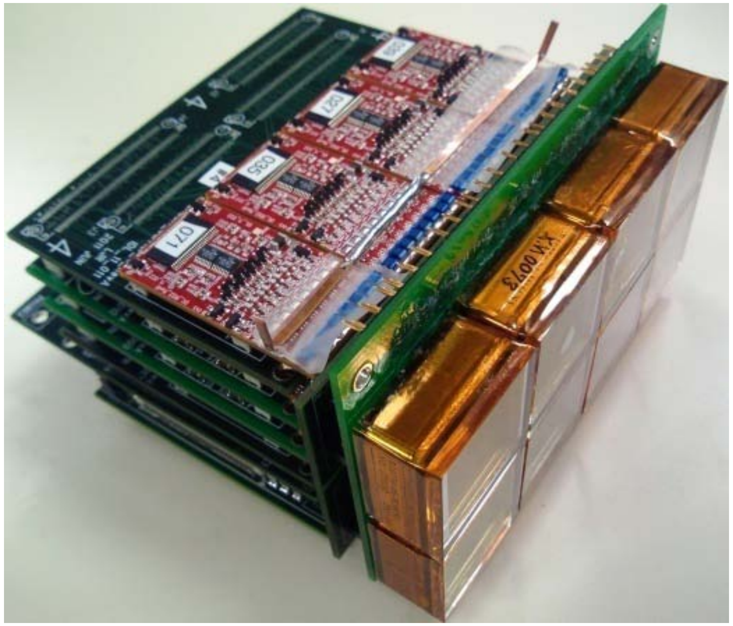


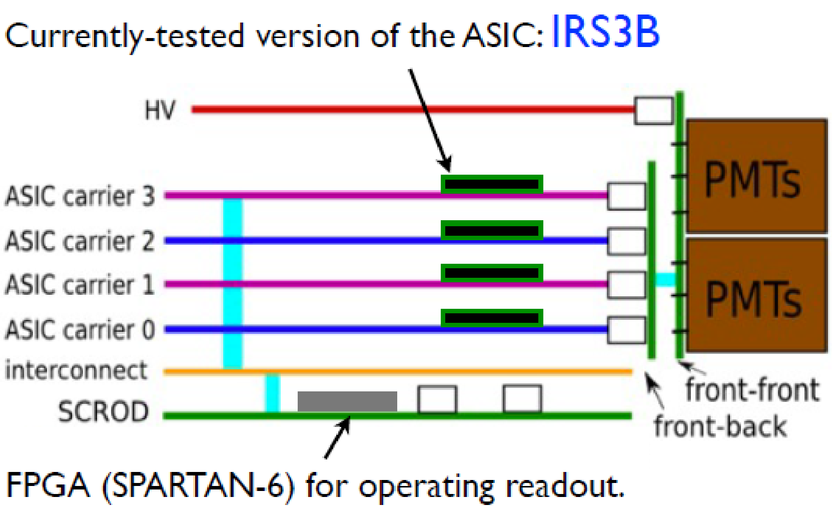
Single photon irradiation

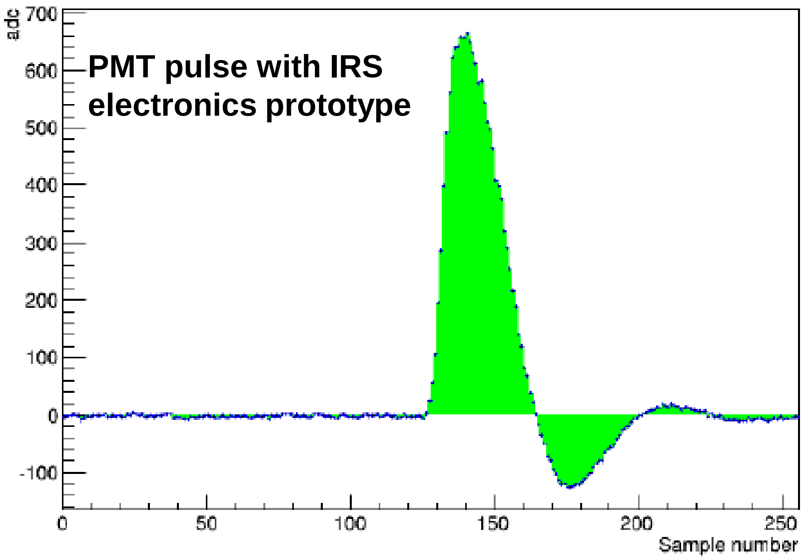
Catalog spec	
Photo-cathode	Enhanced multi-alkali (>28% QE at peak)
MCP Channel ϕ	10µm
MCP bias angle	13°
MCP thickness	400µm
MCP layers	2
Al protection layer	On 2nd MCP
Anode channels	4 × 4
Sensitive region	64%
HV	~ 2500 – 3500 V

Readout electronics

- MCP-PMT signal is readout by newly developed "IRS" series of ASICs.
  - Waveform sampling
    - Clear signal read out by ASIC.
  - High density, multi-hit buffering
    - 512ch / module, 30kHz trigger rate
  - Clock jitter measured with test pulse is about 20ps.



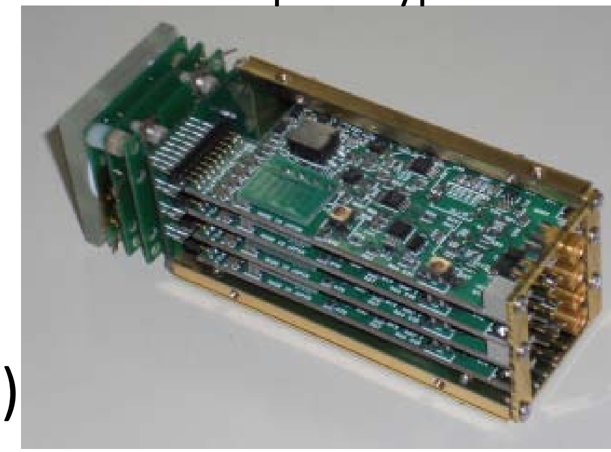


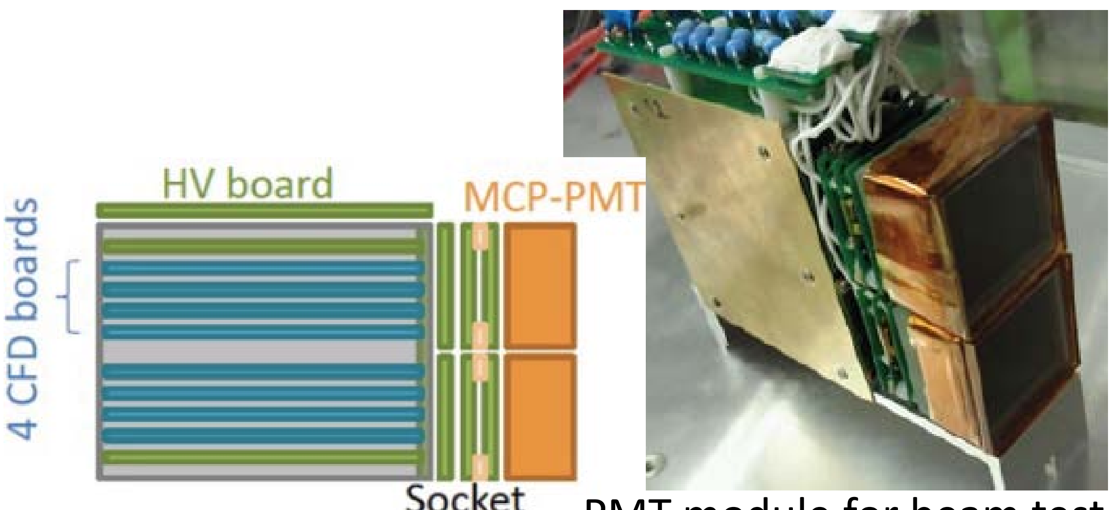


CFD readout for beam test

- CFD readout
  - Used already at previous beam tests
  - 1x4 readout.
    - 4-channels are combined (128ch/module).
  - Suitable back-up for beam tests.
- Good resolution (~40ps for single photon)
  - With MCP-PMT and CAEN VME TDC (V1290A)
  - Confirmed by laser

CFD module prototype

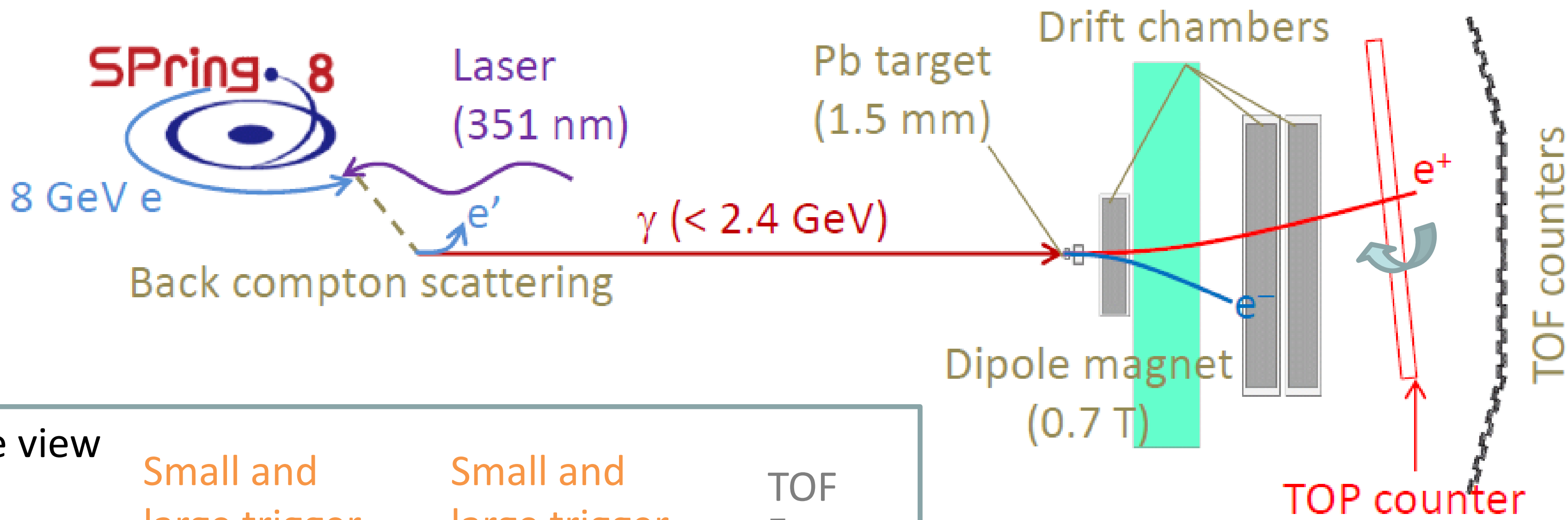


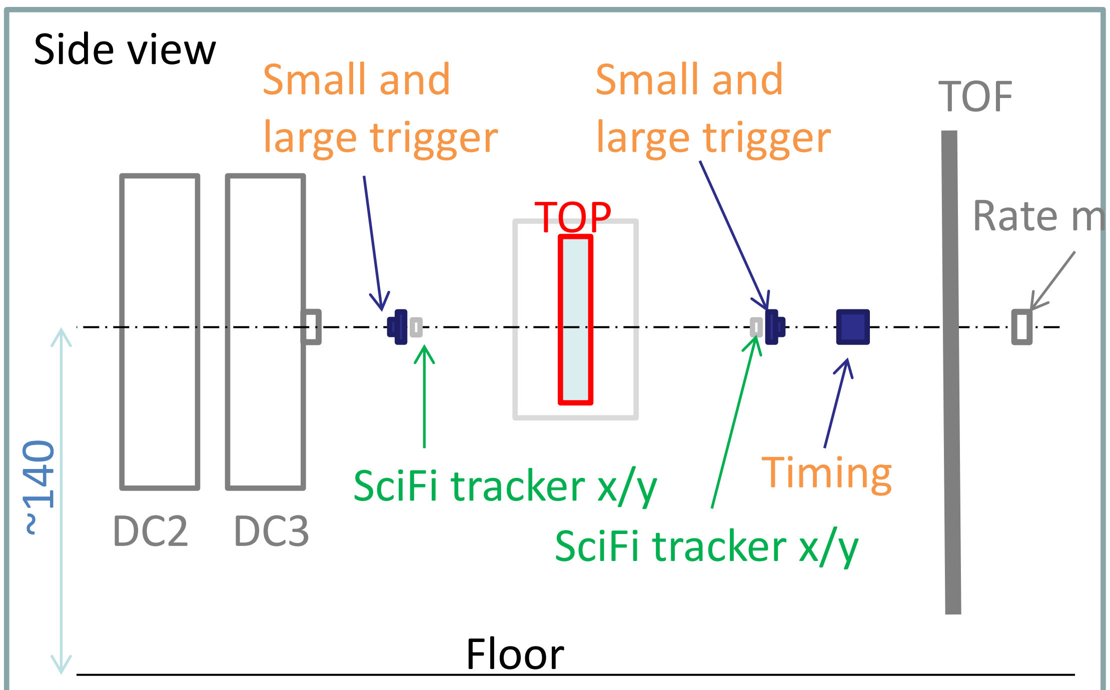


PMT module for beam test


PMT modules mounted

Beam test at Spring-8 LEPS





Triggered the 2 GeV/c e^+ beam with the four trigger counters (two 40 x 40 mm^2 and two 5 x 5 mm^2)

- γ rate: ~300 kHz
- Trigger rate: ~10 Hz
- DAQ rate: ~5 Hz (IRS run)
  ~10 Hz (CFD run)

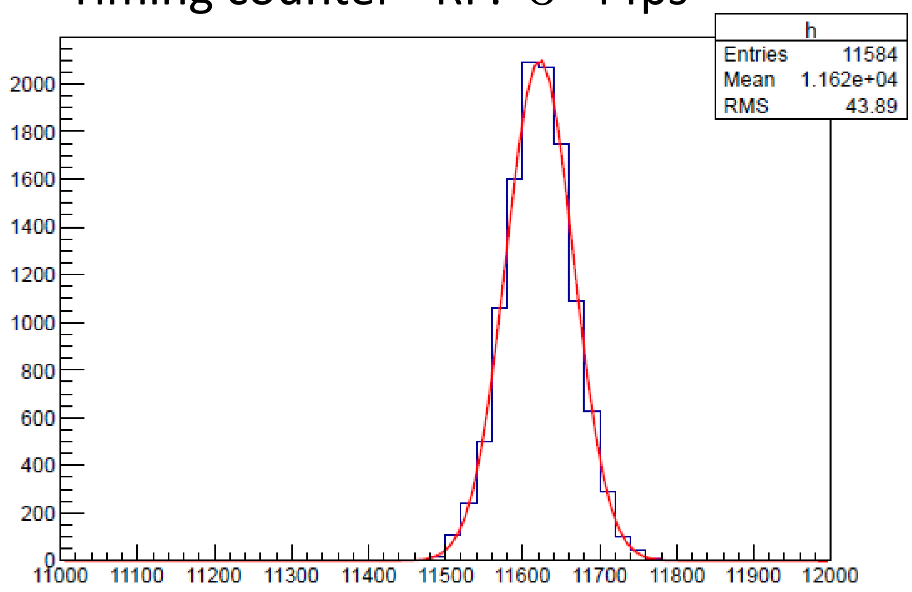
TOP counter in LEPS beam line

Beam timing

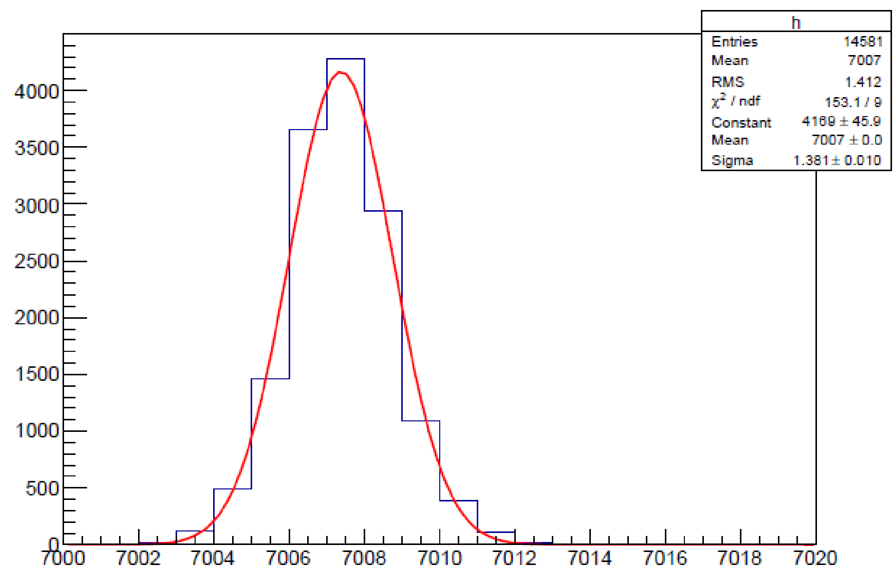
- RF clock from accelerator
- Timing resolution was confirmed with timing counter.
  - T_0 resolution : ~40ps
  - RF digitization resolution: ~24ps

10mm$^{\phi}$ quartz + MCP-PMT

Timing counter - RF: σ=44ps

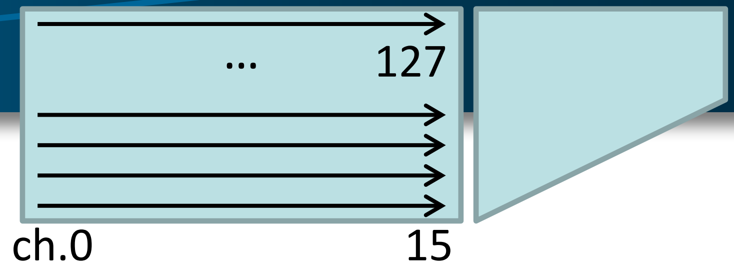


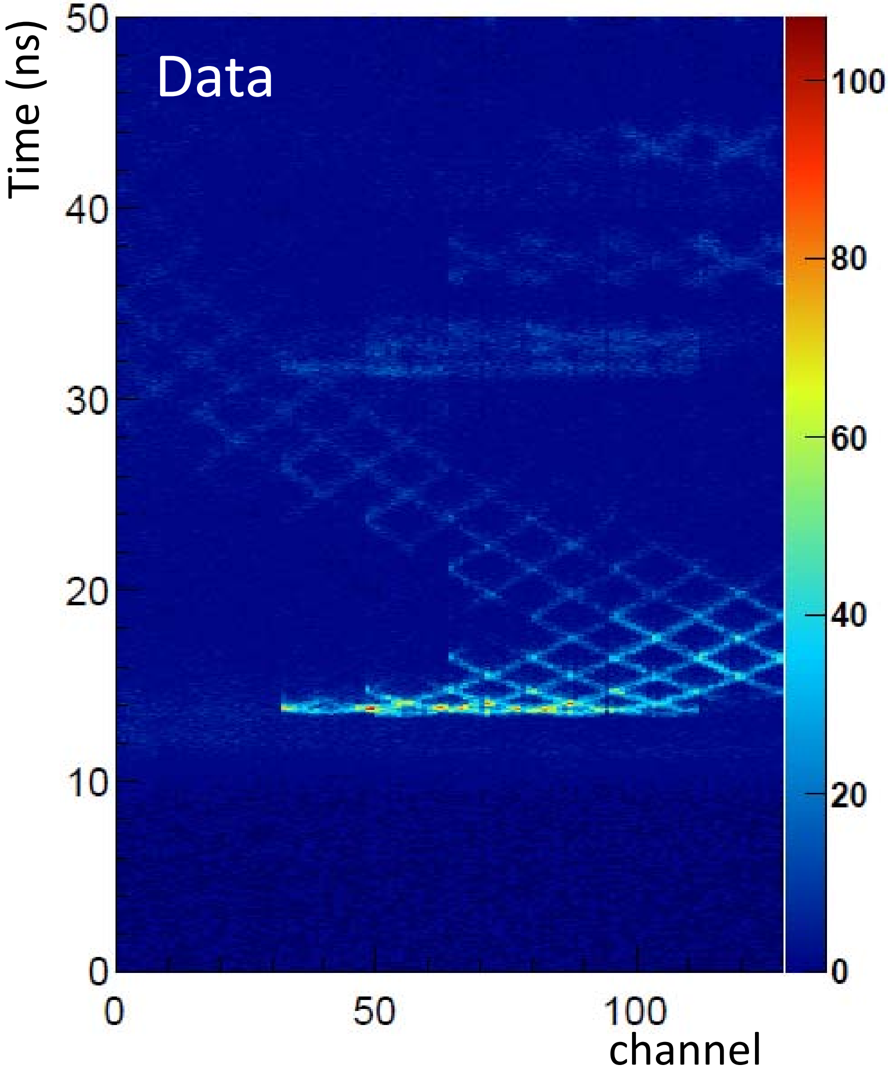
Two RF clock difference: σ=34ps/sqrt(2)

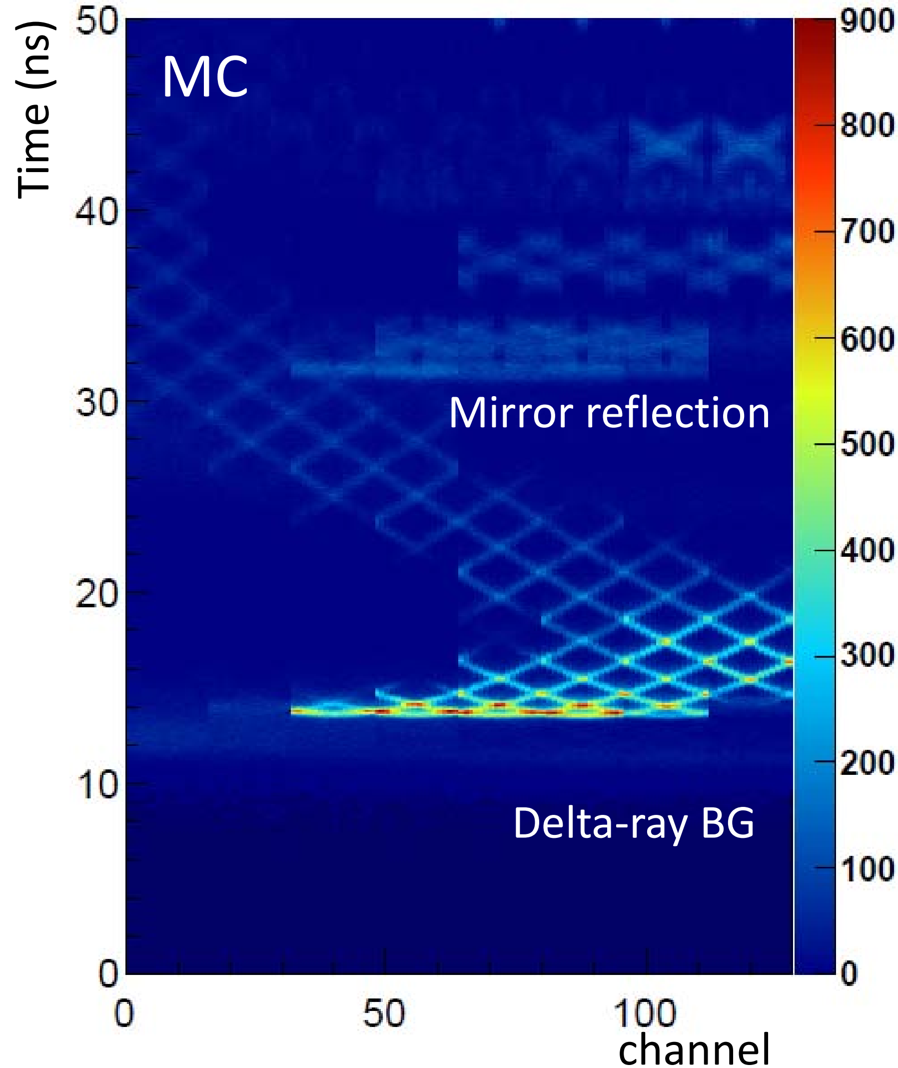


Ring image

- Normal incidence, CFD readout

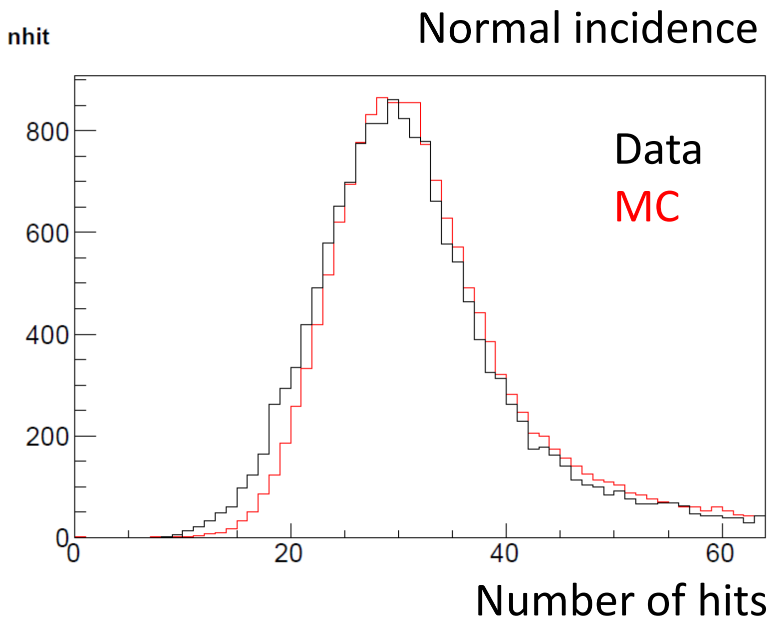


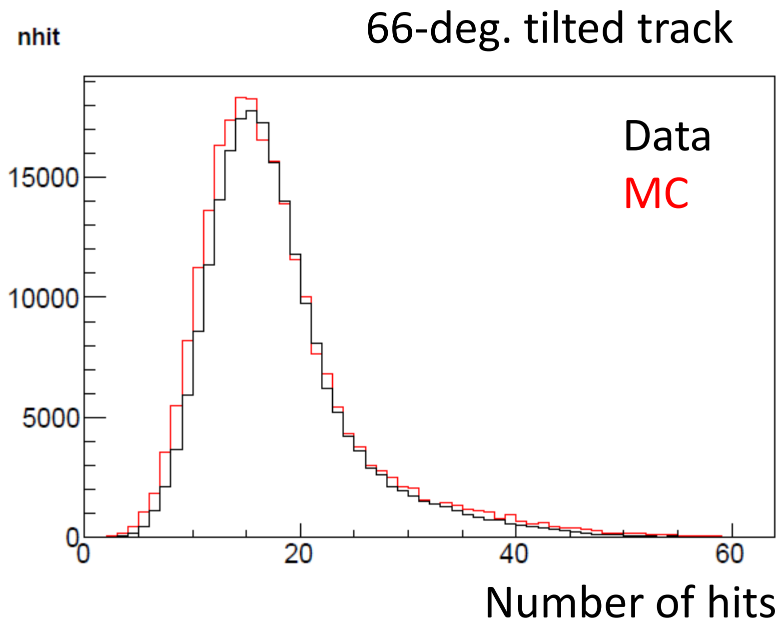




Number of detected photons per event

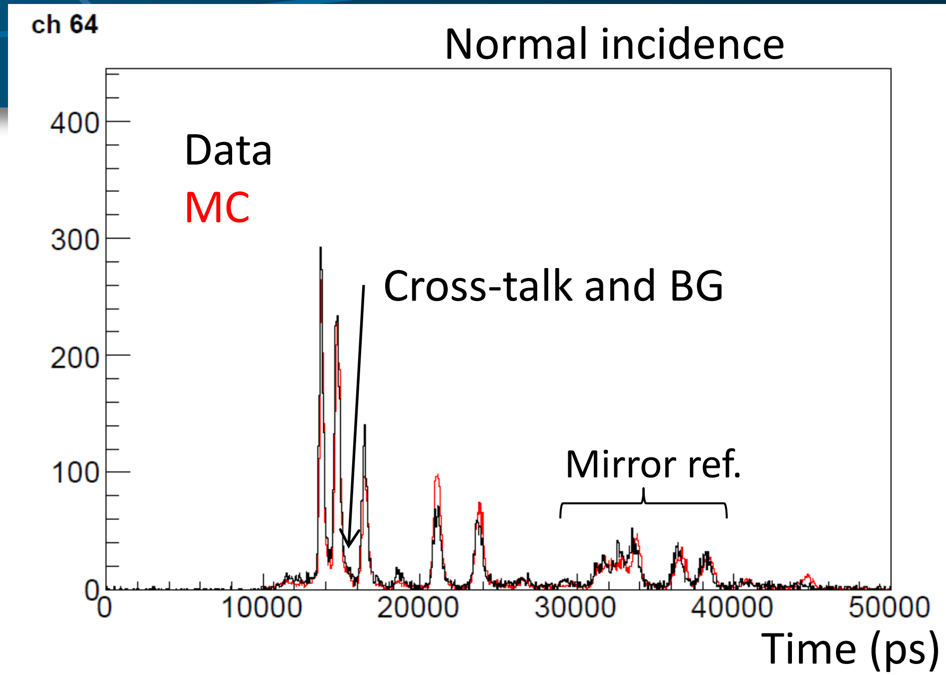
- Number of hits was obtained as expected.
  - Peak: 25 hits for normal incidence, 15 hits for tilted track
  - Considering path length, photon acceptance, QE (av. 29% at peak), cross-talk/charge sharing (~13%), etc.
  - Tail component is due to the delta-ray and shower tracks in the front of TOP counter (trigger and Scifi tracker) and TOP radiator itself.

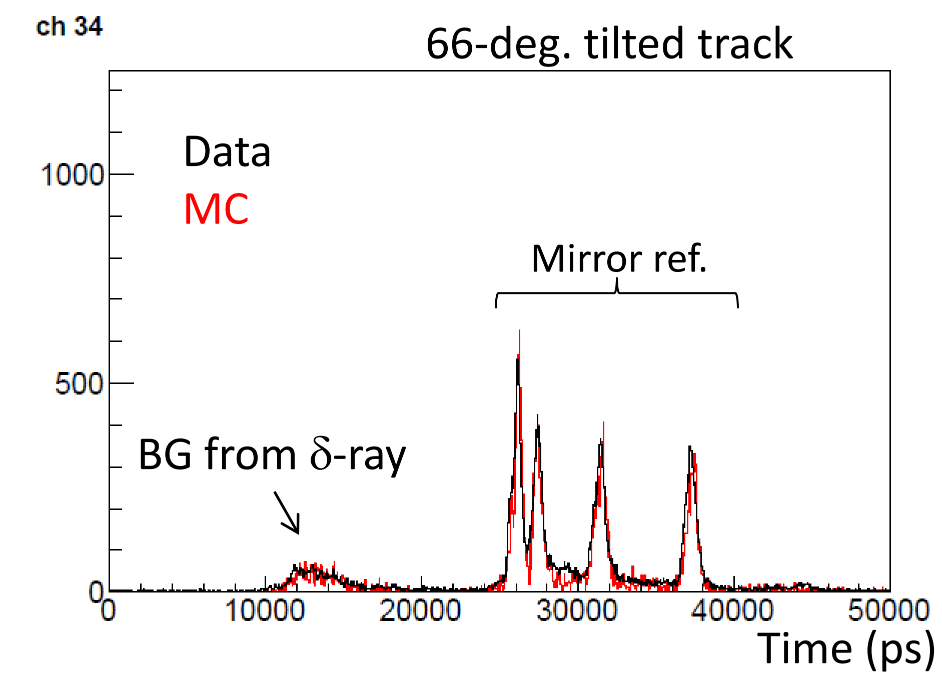




TDC distribution

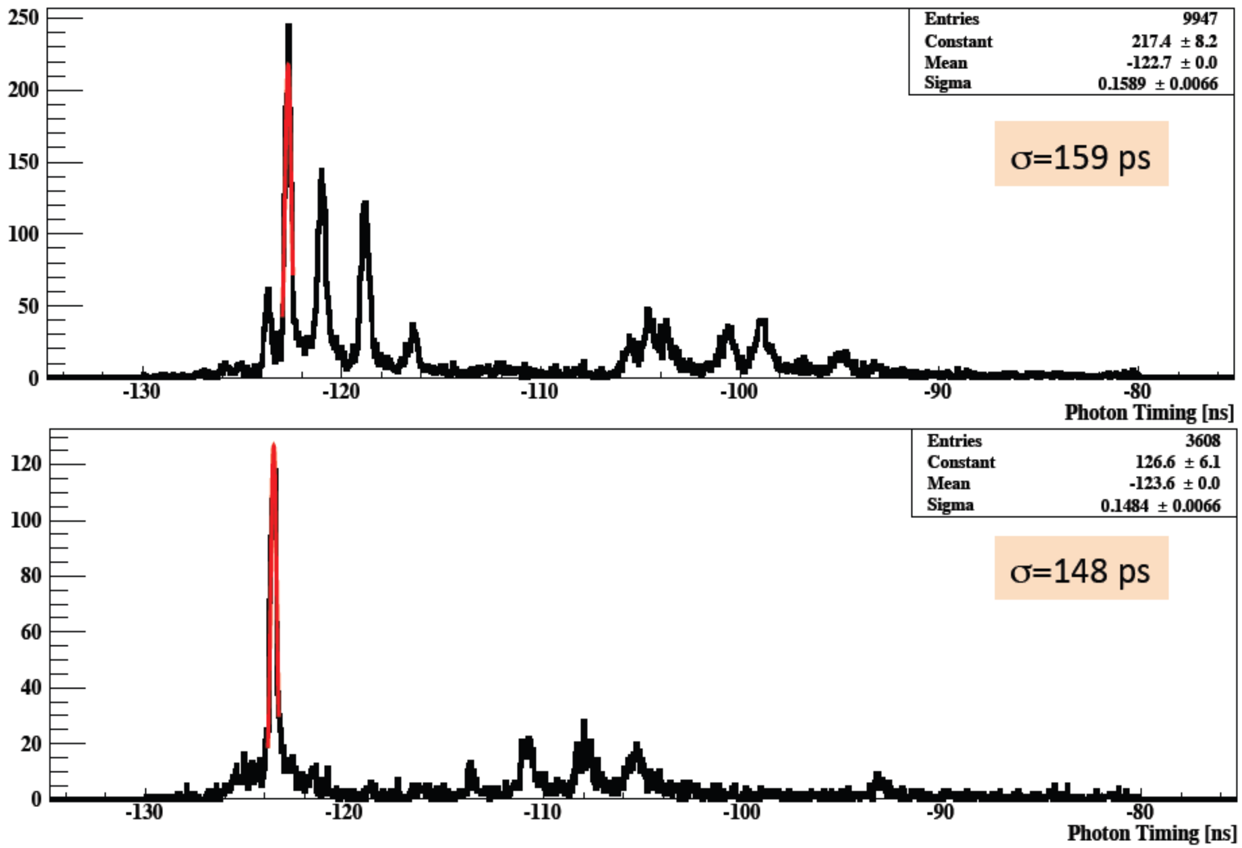
- Good agreement between data and MC expectation.
  - Background component (especially for the data before first peak)
    - Due to delta-ray/showering tracks by the electron beam interaction with the material in front of detector.
  - Tail component
    - Reproduced by cross-talk hits and background





Timing resolution by IRS

- Data with IRS ASIC prototype
- Good ring image obtained although several channels are dead due to trouble related on HV
- Readout resolution is ~100ps including IRS intrinsic resolution and PMT, distributed clock, trigger, etc.



$$\sqrt{(120\,ps)^2 + (100\,ps)^2} = 156\,ps$$

TOP Physics
(Chromatic dispersion)

IRS, PMTs, clock, trigger, …

Summary

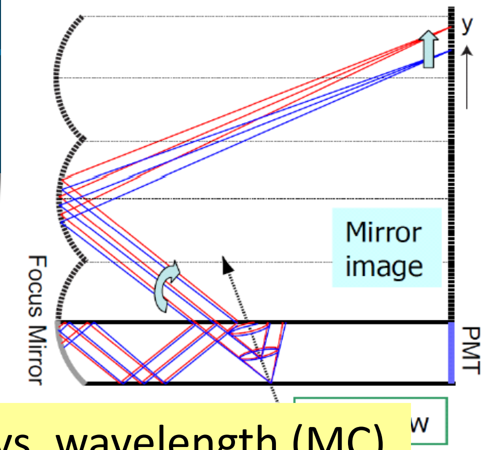
- Belle II Cherenkov detector development
  - Our novel PID device significantly improves physics reach of Belle II.
- TOP counter
  - Utilizes Cherenkov photon timing
  - High quality quartz + MCP-PMT + high timing-resolution electronics

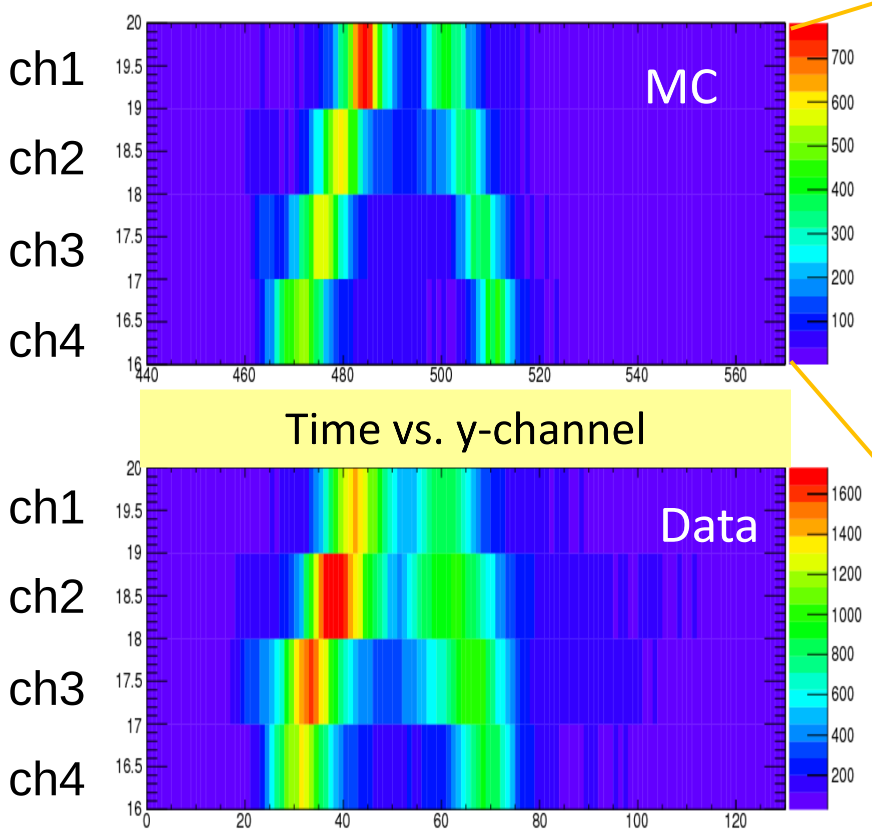
- Developed TOP counter prototype and test with beam
  - Quartz production and assembling procedure worked well.
  - Prototype readout module has adequate performance.
  - Beam test data shows good agreement with MC
    - After the calibration on data and correction on MC
    - Ring images, number of detected Cherenkov photons, timing information as well as background levels are in agreement with expectations.

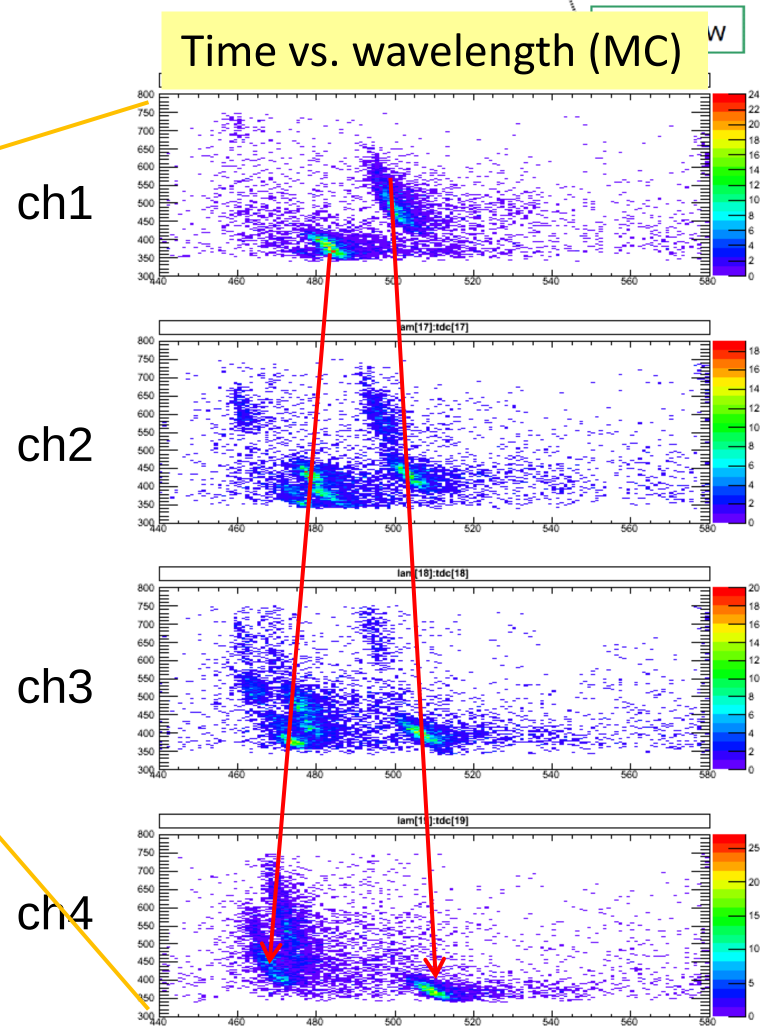
- Back up

Chromatic effect

- Beam data obtained at CERN
- Tilted incidence (cosθ=0.3)
- Expected time distribution along y-channel
  - Indicates the dependence on the wavelength

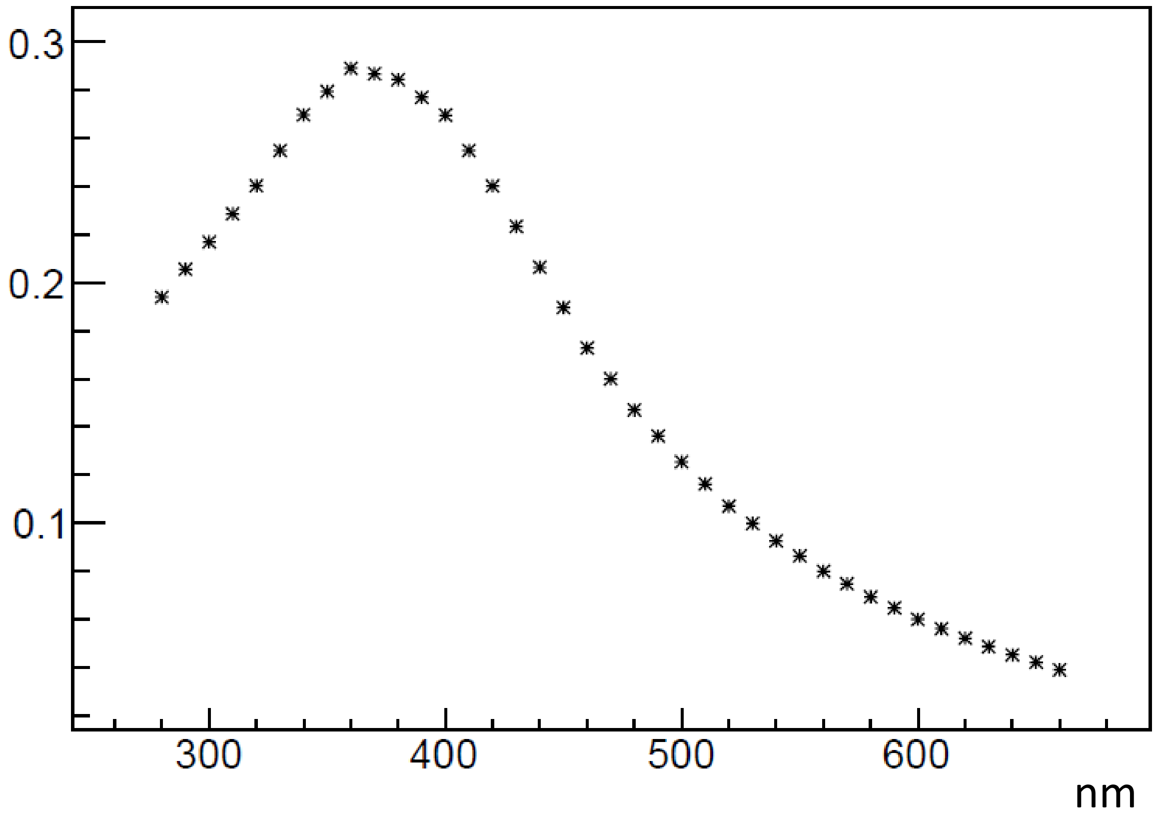






QE distribution

- Average of PMT used at beam test

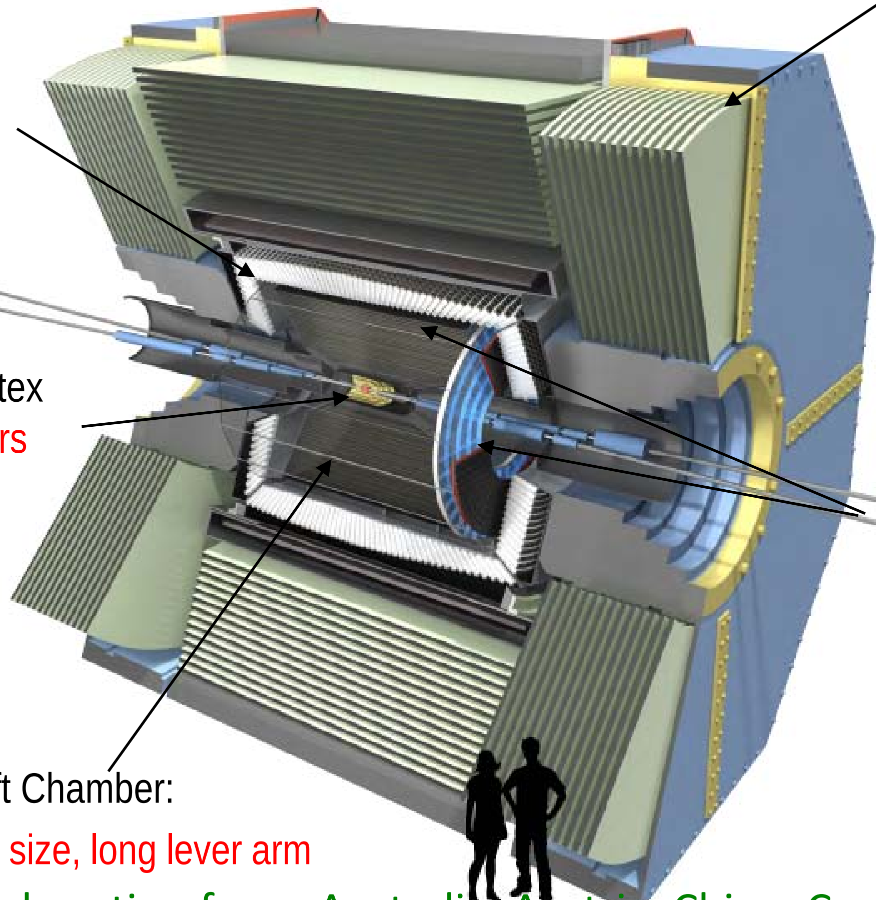


Belle II Detector

- Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity

CsI(Tl) EM calorimeter:
waveform sampling electronics, pure CsI for endcaps

RPC μ & K_L counter:
scintillator + Si-PM for end-caps



4 layers DS Si vertex detector → 2 layers PXD (DEPFET), 4 layers DSSD

Time-of-Flight, Aerogel Cherenkov Counter → Time-of-Propagation (barrel), prox. focusing Aerogel RICH (forward)

Belle II

Central Drift Chamber:
smaller cell size, long lever arm

International collaboration from: Australia, Austria, China, Czech, Germany, Inida, Korea, Poland, Russia, Saudi Arabia, Slovenia, Spain, Taiwan, USA, Japan

Impact of PID improvement

$B^0 \to \rho^0 \gamma$

No upgrade BAD ← → Upgrade GOOD

Luminosity loss / gain

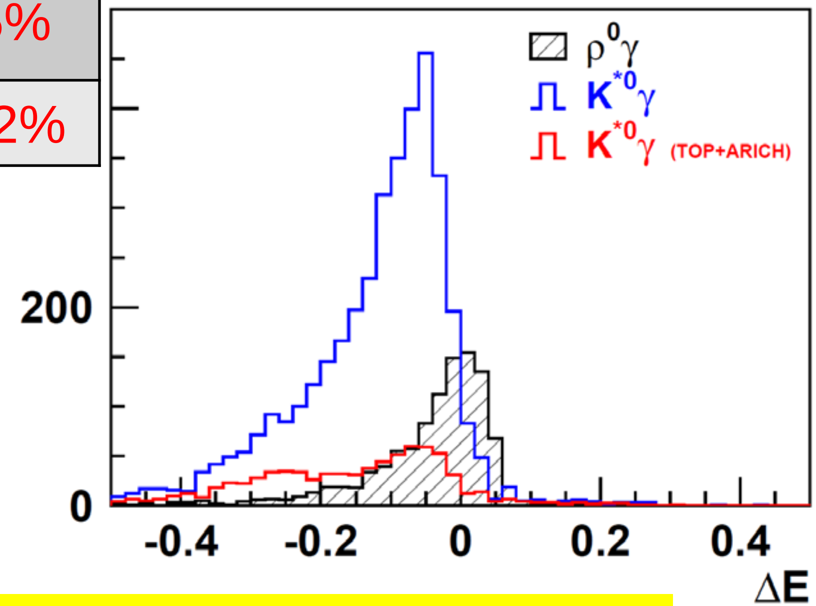
FWD / BRL	dE/dx NA	As good as Belle	A-RICH	A-RICH +TOF
TOF, dE/dx NA	–33%	–33%	–30%	–30%
TOF NA	–34%	–33%	–29%	-29%
As good as Belle	–1%	0% (definition)	+5%	+5%
TOP opt.2	+70%	+72%	+82%	+82%

No upgrade BAD ↑ ↓ Upgrade GOOD

Completely different world with excellent PID detectors!

$B^0 \to \pi^+ \pi^-$

FWD / BRL	As good as Belle	A-RICH
As good as Belle	0% (definition)	+6%
TOP opt.2	+16%	+23%



PID improvement brings x 2 equivalent luminosity

Readout Electronics