Particle ID in the Belle II Experiment

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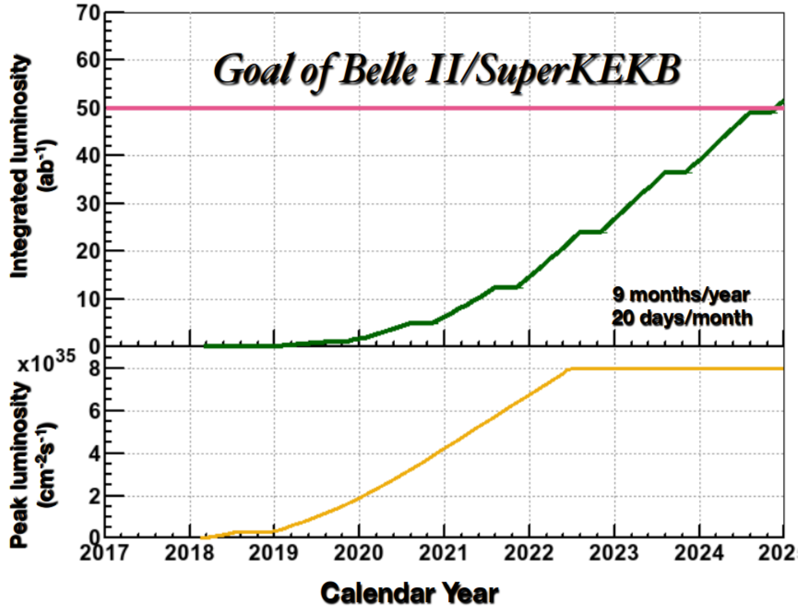
for the Belle2 TOP Group

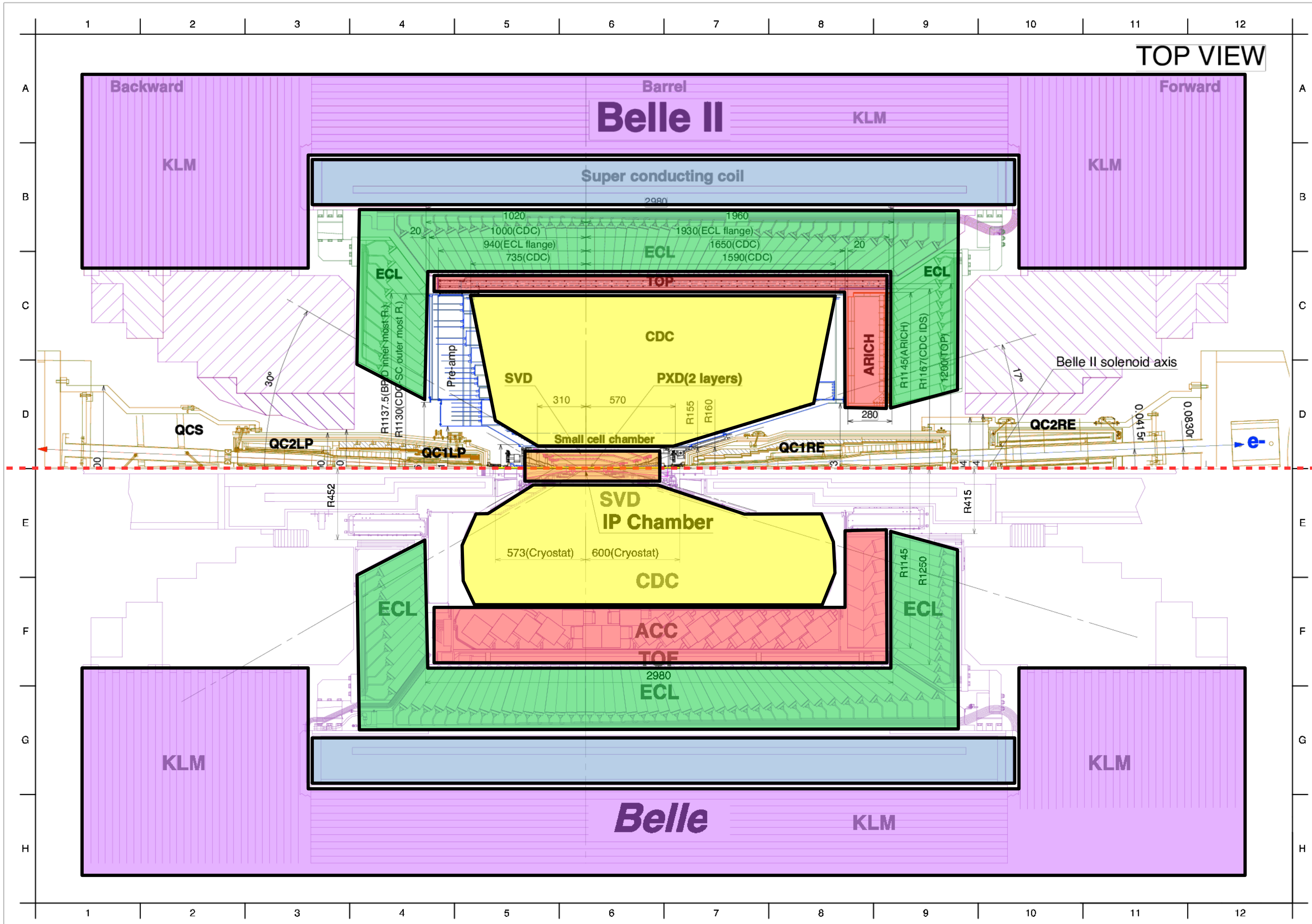
IAS HEP 2017, HKUST

SuperKEKB & Belle II

- Next generation B factory at the intensity frontier
  - Asymmetric $e^+ e^-$ collider
  - Center of mass energy tuned to Y(4[5/6]s)
  - Located at KEK (Tsukuba, Japan)
- Accelerator upgrade
  KEKB → SuperKEKB
  - 40 fold increase in instantaneous lumi.
  - 50 times integrated lumi. over KEKB/Belle



Belle II Detector Upgrade



K$_L$/Muon System

Magnet Coil

EM Calorimeter

π/K Identification

Drift Chamber

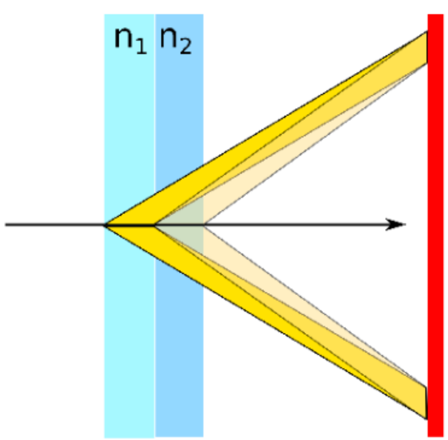
Silicon Tracking

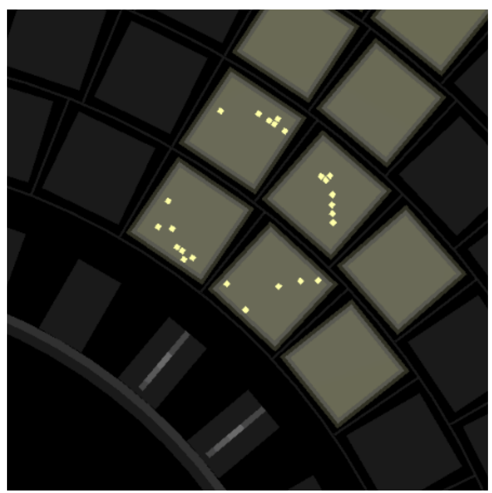
Belle II Particle Identification

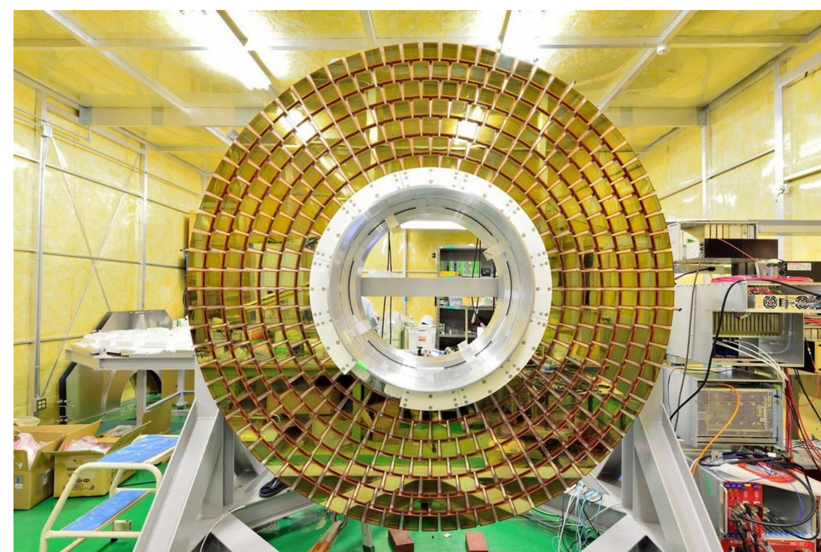
- B physics requires reconstruction of final state particles
- $e^{\pm}$, γ: ECL + tracking
- $\mu^{\pm}$, K_L^0: KLM + tracking
  - Bad energy resolution for K_L^0, using propagation direction
- $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$: TOP/ARICH + tracking (dE/dx)
  - Mass differences: Cherenkov opening angle, time of flight

Endcap Particle ID: ARICH

- Aerogel Ring Imaging Cherenkov Detector
- Two aerogel layers with different refractive indices
- Hamamatsu Hybrid Avalanche Photo Detector sensors
  - Avalanche photo diode in vacuum tube

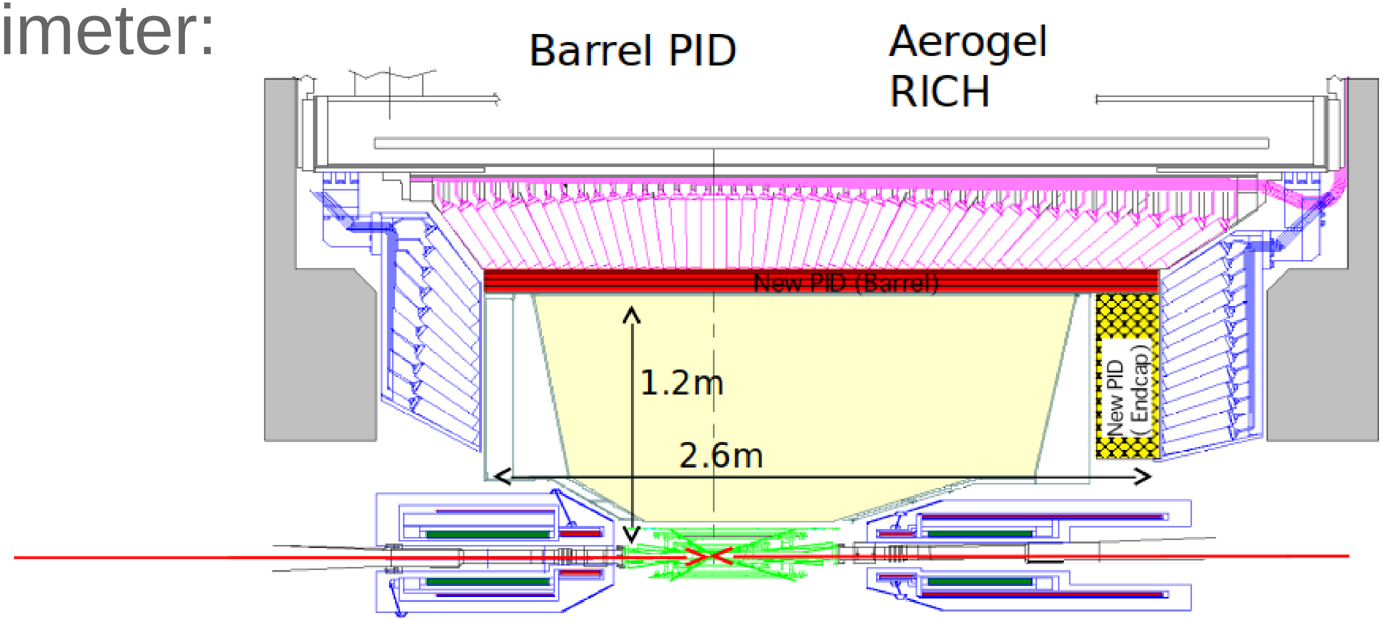






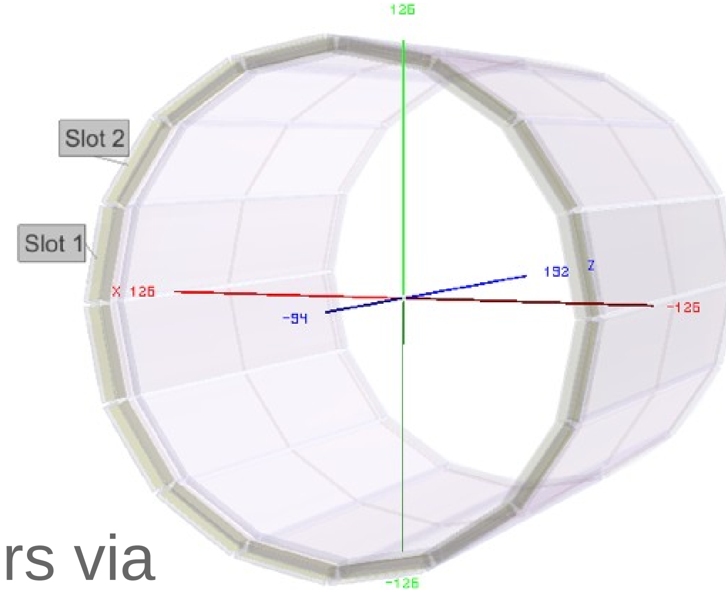
Barrel Particle ID Requirements

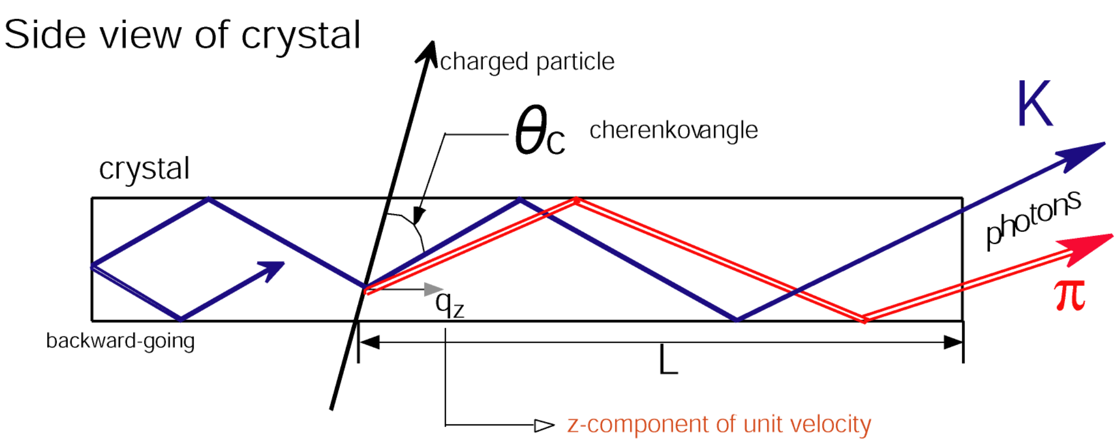
- $\pi^{\pm}$-$K^{\pm}$ separation in Belle2 barrel region
  - Momentum range up to 5GeV
  - ~95% efficiency at 5% fake rate
- Geometry defined by available space between tracker and calorimeter:

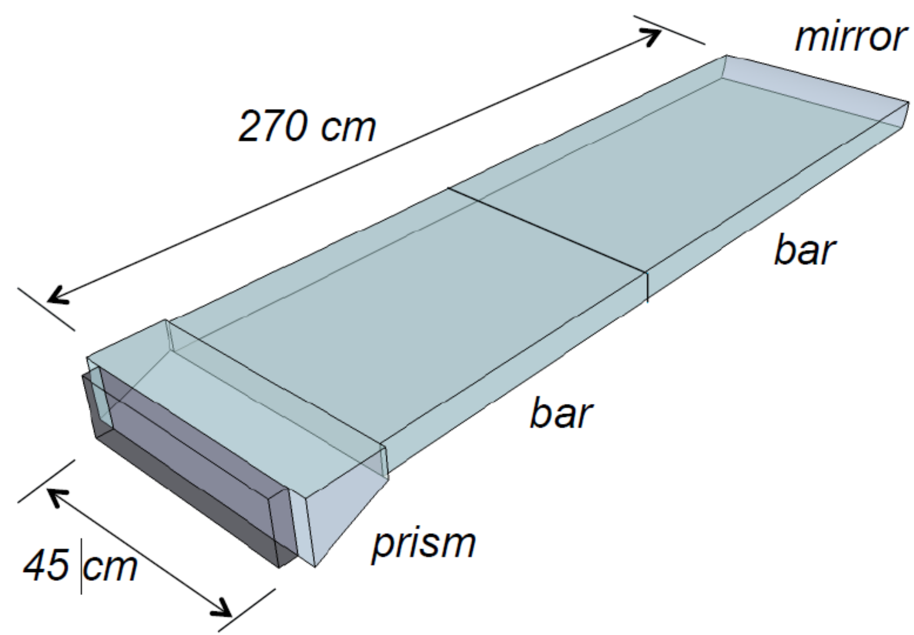


TOP: Concept

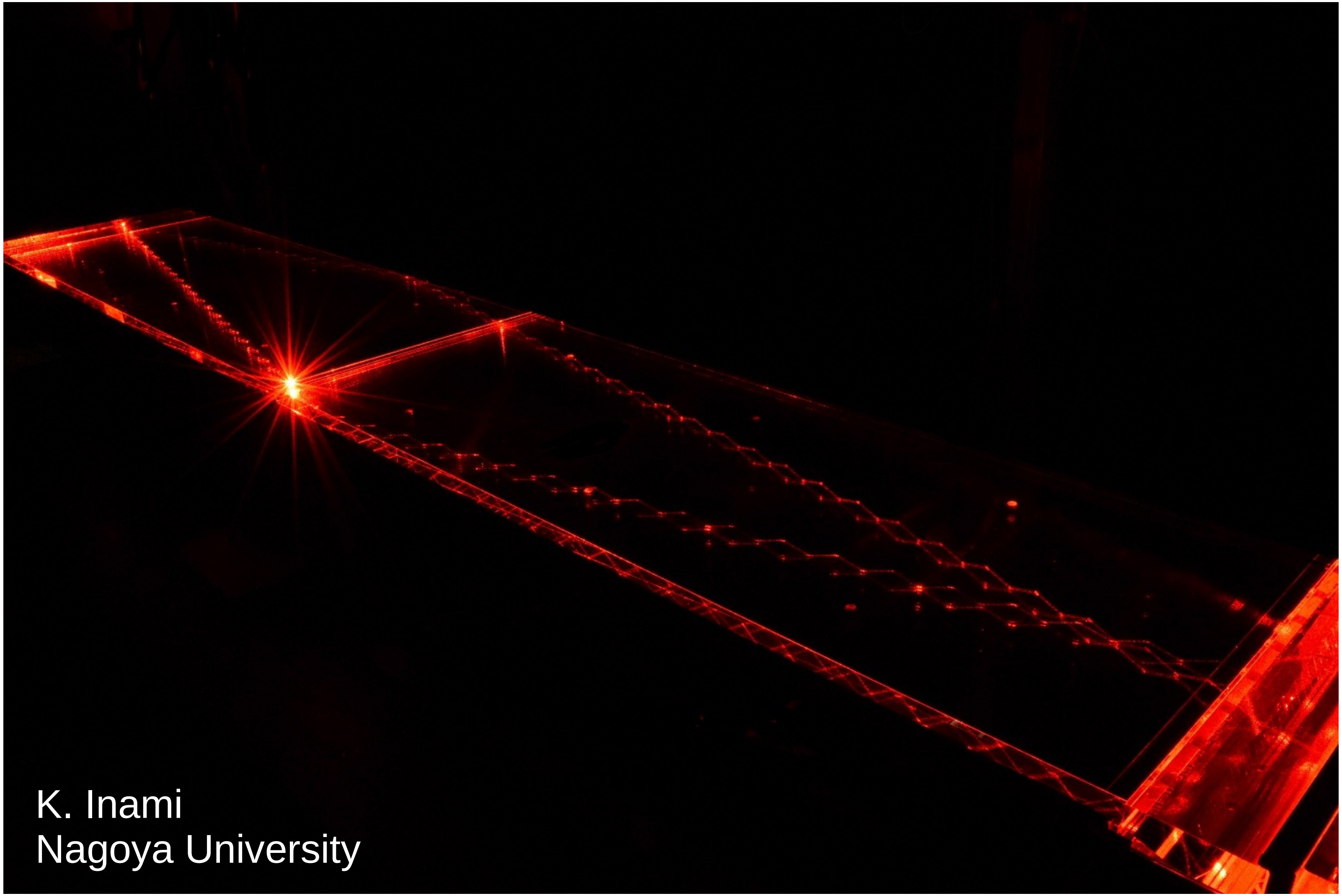
- 16 Quartz Cherenkov radiator bars
  - 270cm * 45cm * 2cm each
  - Small expansion volume
- Cherenkov photons propagate to sensors via total internal reflection



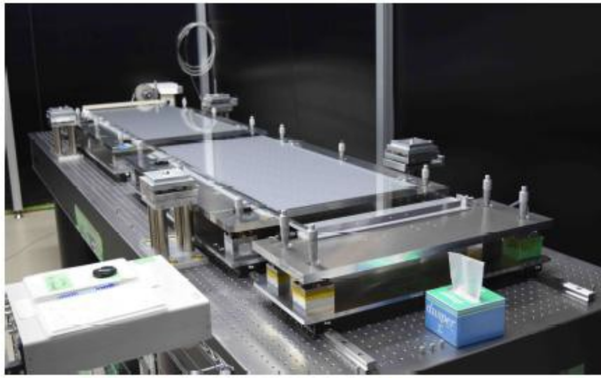




TOP: Total Internal Reflection



Module Production Process



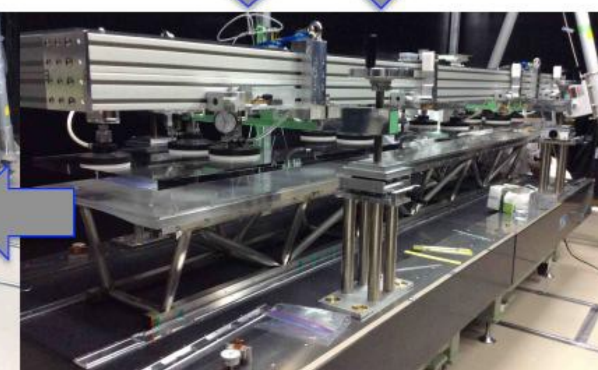
Optics: alignment, gluing, curing and aging (~2 weeks).

Enclosure: gluing CCDs and LEDs, integrating fiber mounts.

QBB: strong back flattening, button & enclosure gluing.

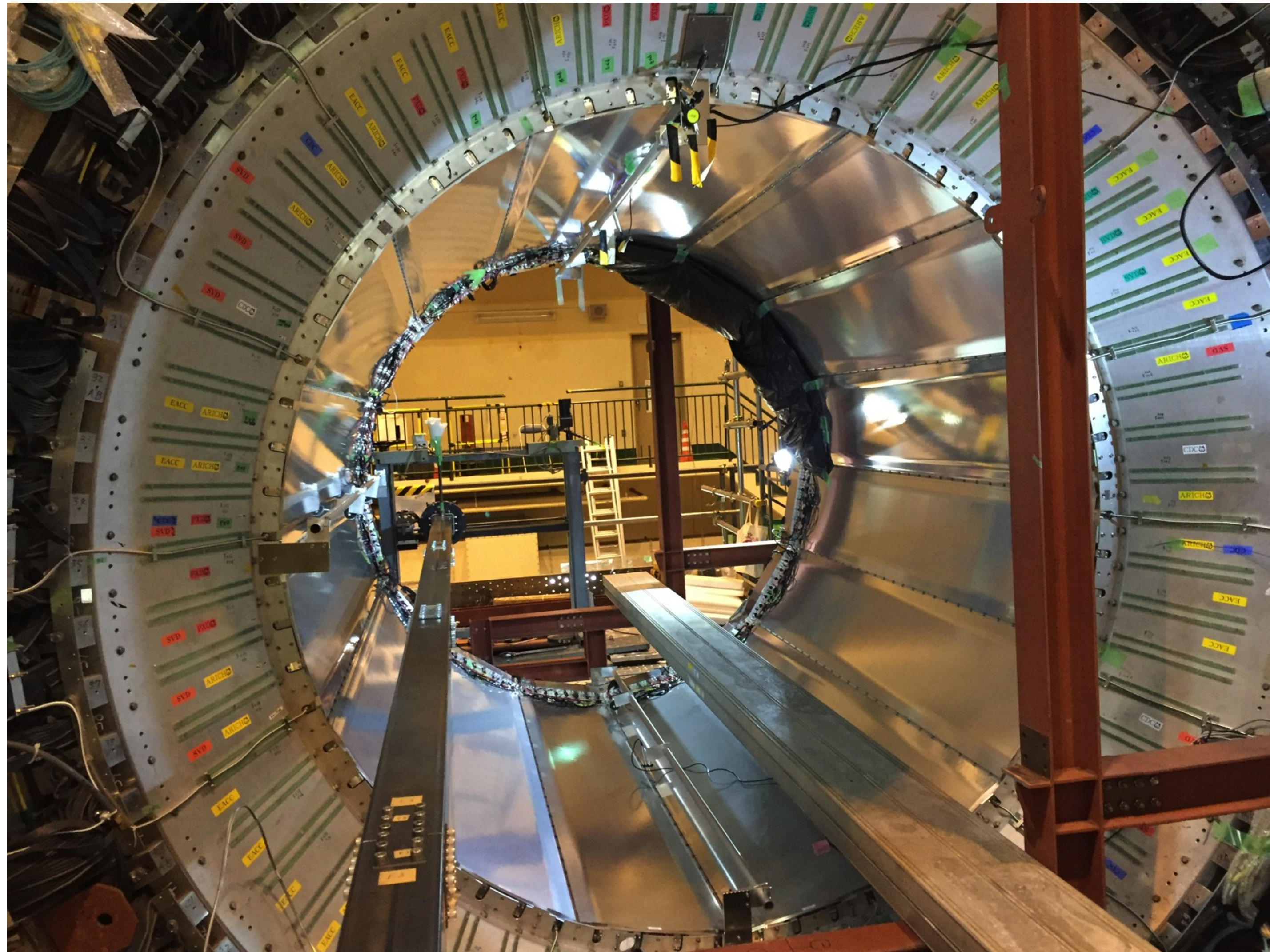
Put on a cart. PMT and front-end integration, performance check.

QBB assembly and gas sealing.



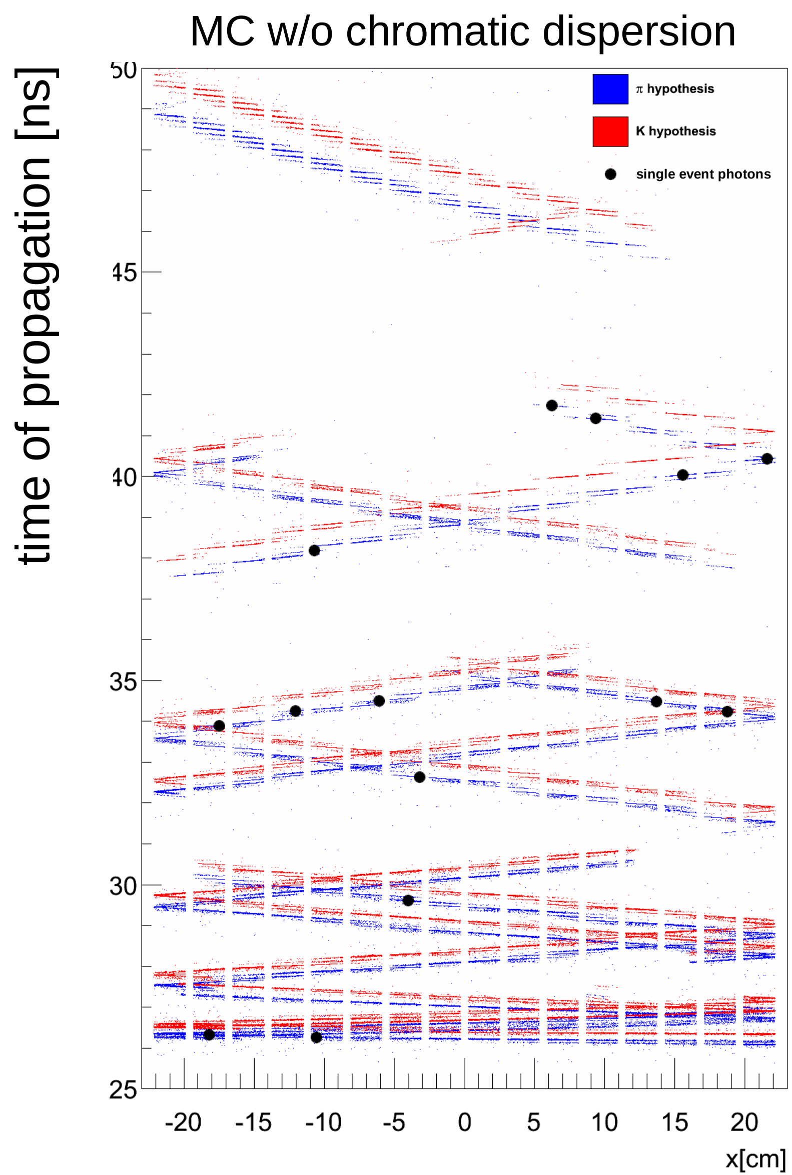
Move optics to QBB using the “lifting jig”.

Installation Complete



TOP: Reconstruction

- Detect 20-30 photons/particle/event
  - +5-10 photons from beam background
- Pion/kaon likelihood analysis of spatial/temporal distribution of photons
  - PDFs depend on exact particle trajectory
  - Generated event-by-event in reconstruction



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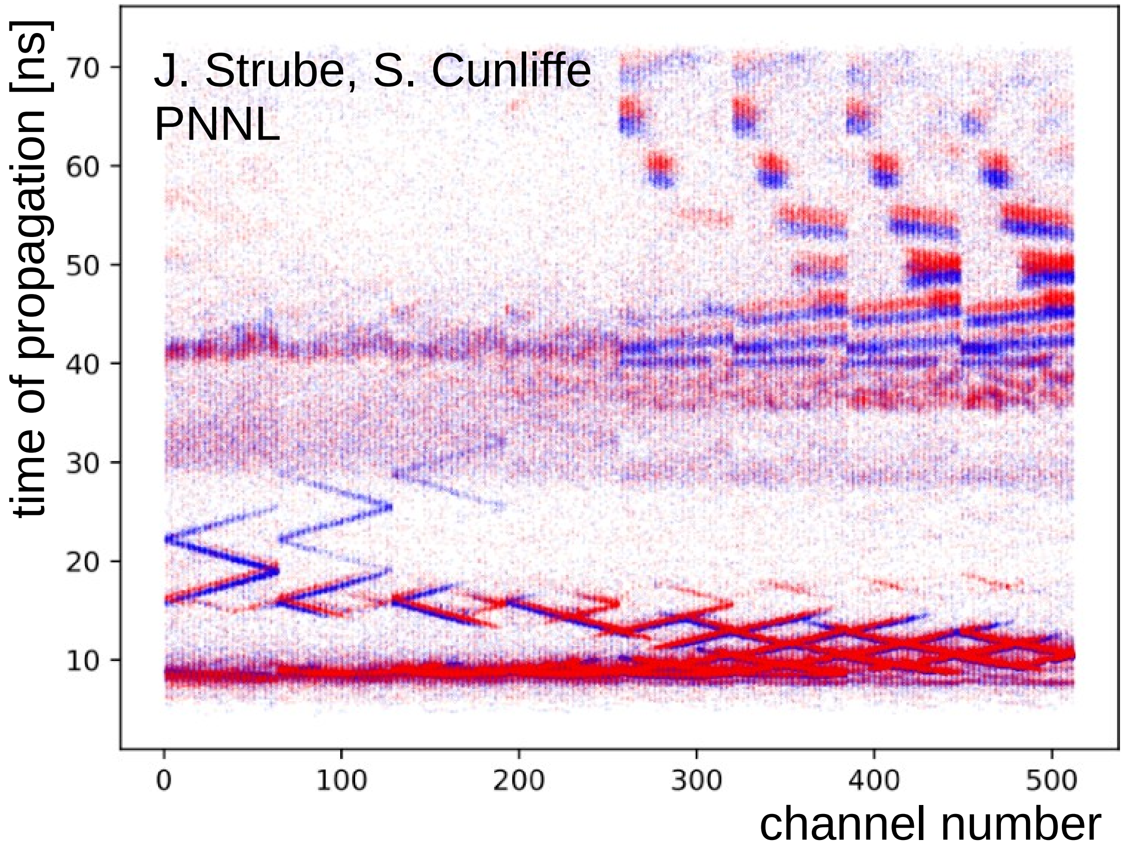
“Full” MC

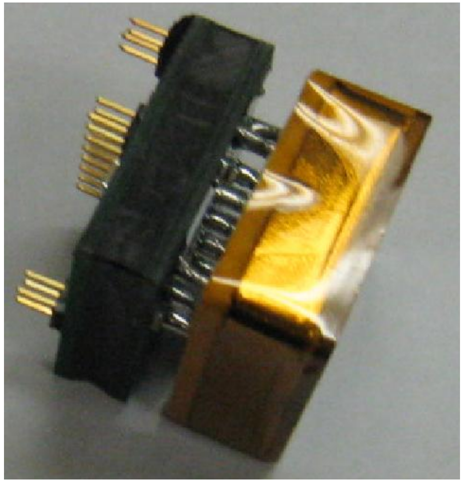


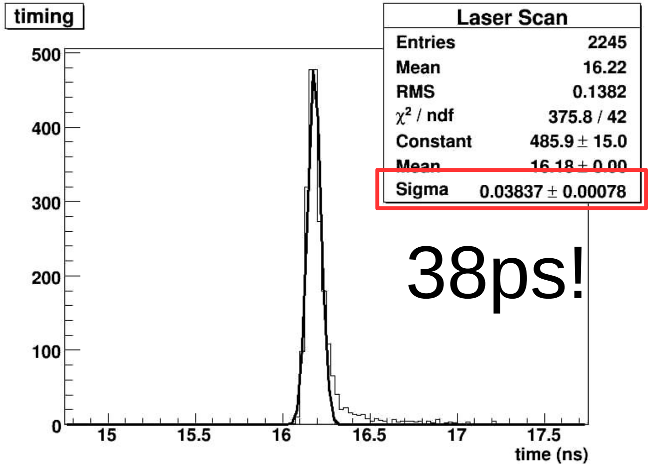
TOP: Electronics Requirements

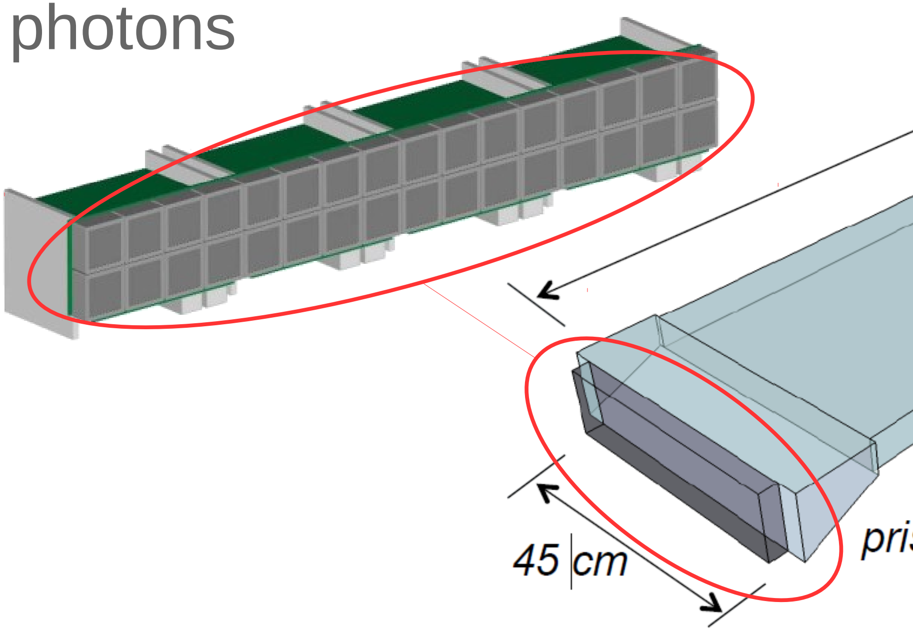
- Goal: <100ps single photon time resolution
- Sensor requirements:
  - single photon efficiency
  - <50ps single photon time resolution
  - ~few mm spatial resolution
  - Operation in 1.5T B-field
- Readout requirements:
  - 30kHz trigger rate
  - <50ps electronics time resolution
  - <50ps clock distribution jitter

Micro-Channel-Plate Photomultipliers

- Similar gain, photon efficiency as PMTs, but smaller
- (Mostly) resistant to B-fields
- Pixelated anodes for spatial resolution
- Very good time resolution for single photons







Readout Electronics: Requirements

- Reads MCP-PMT signals
- Time resolution ~30ps
  - ~Gsa/s sampling
  - ~500MHz bandwidth
- 8192 channels
- Affordable
- Low power
- Small form factor
- Online data processing
- etc. etc.

?

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IRSX ASIC

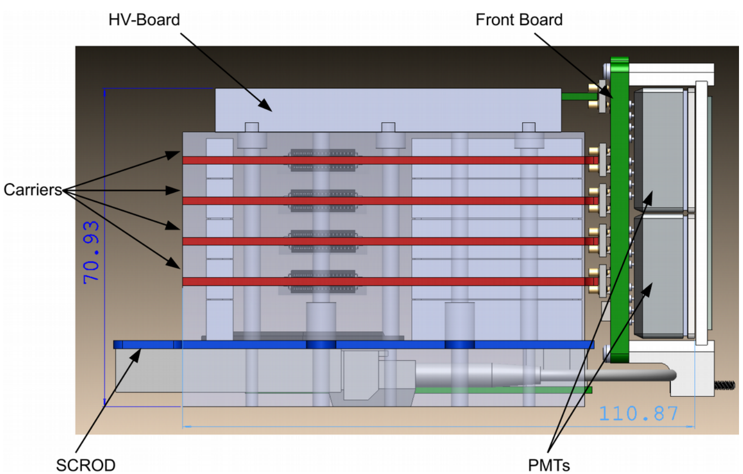
- Waveform sampling ASIC
  - Designed by IDLAB, UH (Prof. Gary Varner)
- 2-4GSa/s sampling speed
  - Operated at 2.7GSa/s in TOP
  - 12bit resolution
  - ~600MHz analog bandwidth
  - 32k analog storage cells (~10us)
  - Sampling/digitisation w/o deadtime
- 8 channels
  - ~100mW/channel

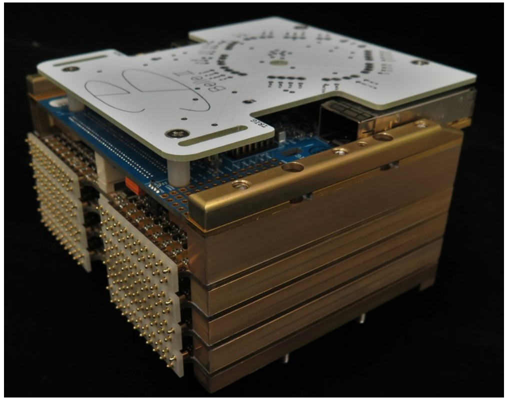
Online Data Reduction

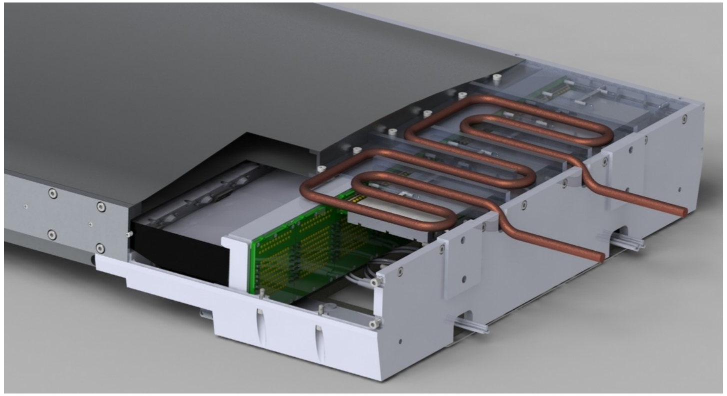
- Raw IRSX output bandwidth of TOP would be 265 Tbit/s!
- Only digitise relevant IRAX samples
  - Based on global trigger, IRSX channel triggers
- Apply all raw data conditioning in frontend
  - Pedestal subtraction
  - Time base calibrations
- Extract waveform features in frontend
  - Photon timing
  - Pulse amplitude, shape parameters etc. for debugging
- Write out only feature parameters
  - Waveforms transferred only for debugging and quality check

Boardstacks

- Tower of 1 SCROD + 4 carriers + HV board
  - Mechanically and thermally coupled
- Directly connects to 8 MCP-PMTs each
  - Four boardstacks per TOP module

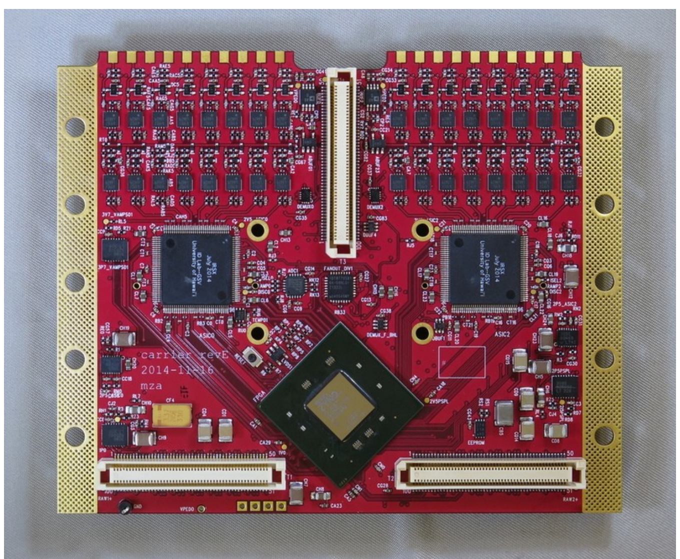


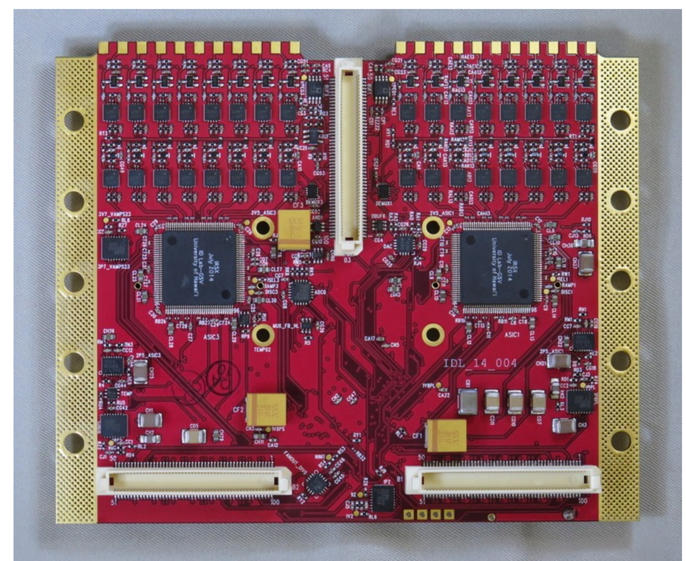




Carrier Board

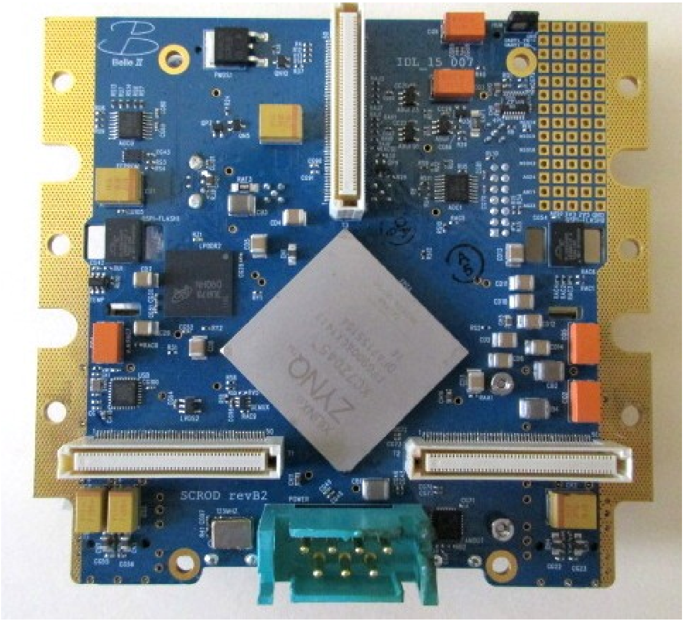
- PMT preamplifiers, 4 IRSX ASICs + Zynq 7030 SoC
- Zynq: FPGA + ARM processor core
  - FPGA interfaces four ASICs, pushes data to SCROD
  - ARM on carrier mostly idle, but could do data processing

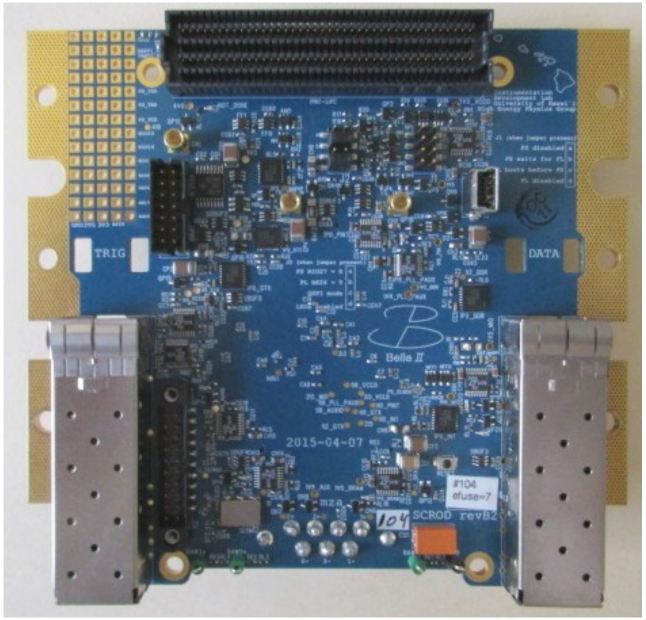




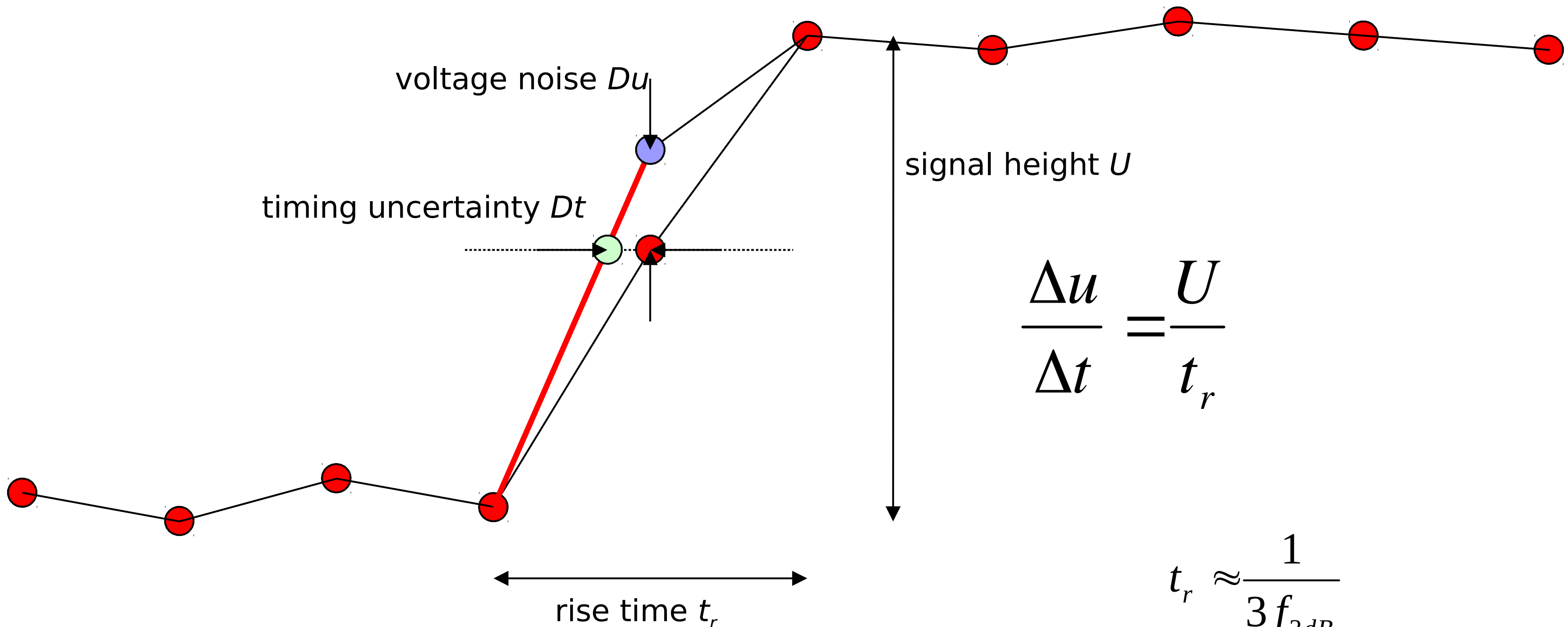
SCROD Board

- Single (large) Zynq 7045 SoC
  - FPGA receives data from carriers, manages transceivers
  - Processor performs online data processing
- Two fiber transceivers: datalink + trigger timestamps





Timing Reconstruction



$$\frac{\Delta u}{\Delta t} = \frac{U}{t_r}$$

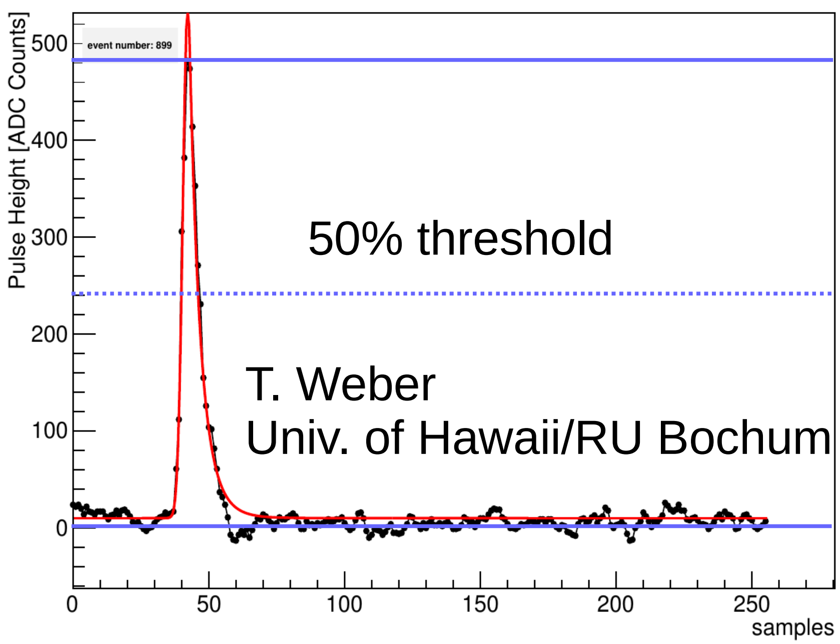
$$t_r \approx \frac{1}{3 f_{3dB}}$$

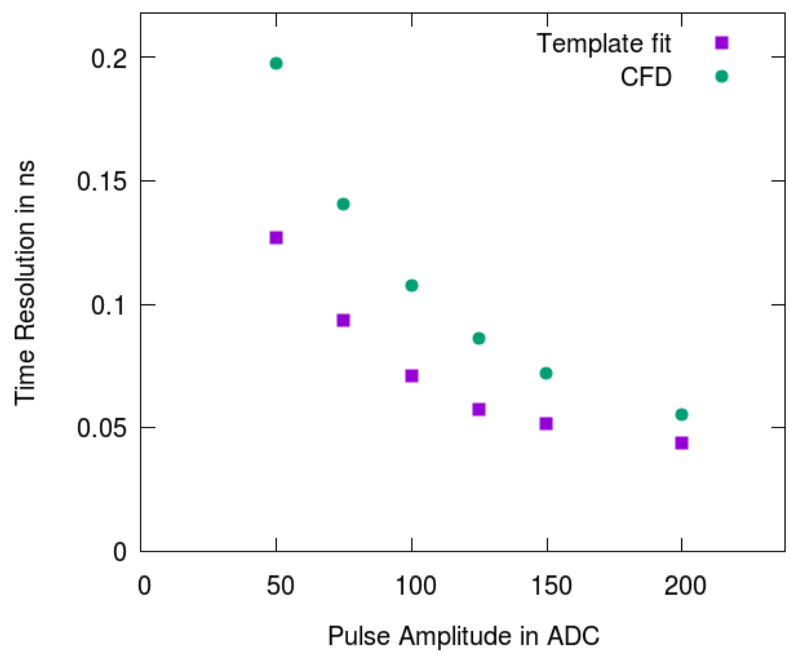
$$\Delta t = \frac{\Delta u}{U}\cdot t_r = \frac{\Delta u}{U\sqrt{n}}\cdot t_r = \frac{\Delta u}{U}\cdot\frac{t_r}{\sqrt{t_r \cdot f_s}} = \frac{\Delta u}{U}\cdot\frac{\sqrt{t_r}}{\sqrt{f_s}} = \overset{\textbf{SNR}}{\boxed{\frac{\Delta u}{U}}}\cdot\frac{1}{\sqrt{3 f_s \cdot f_{3dB}}}$$

*Diagram, formulas from Stefan Ritt

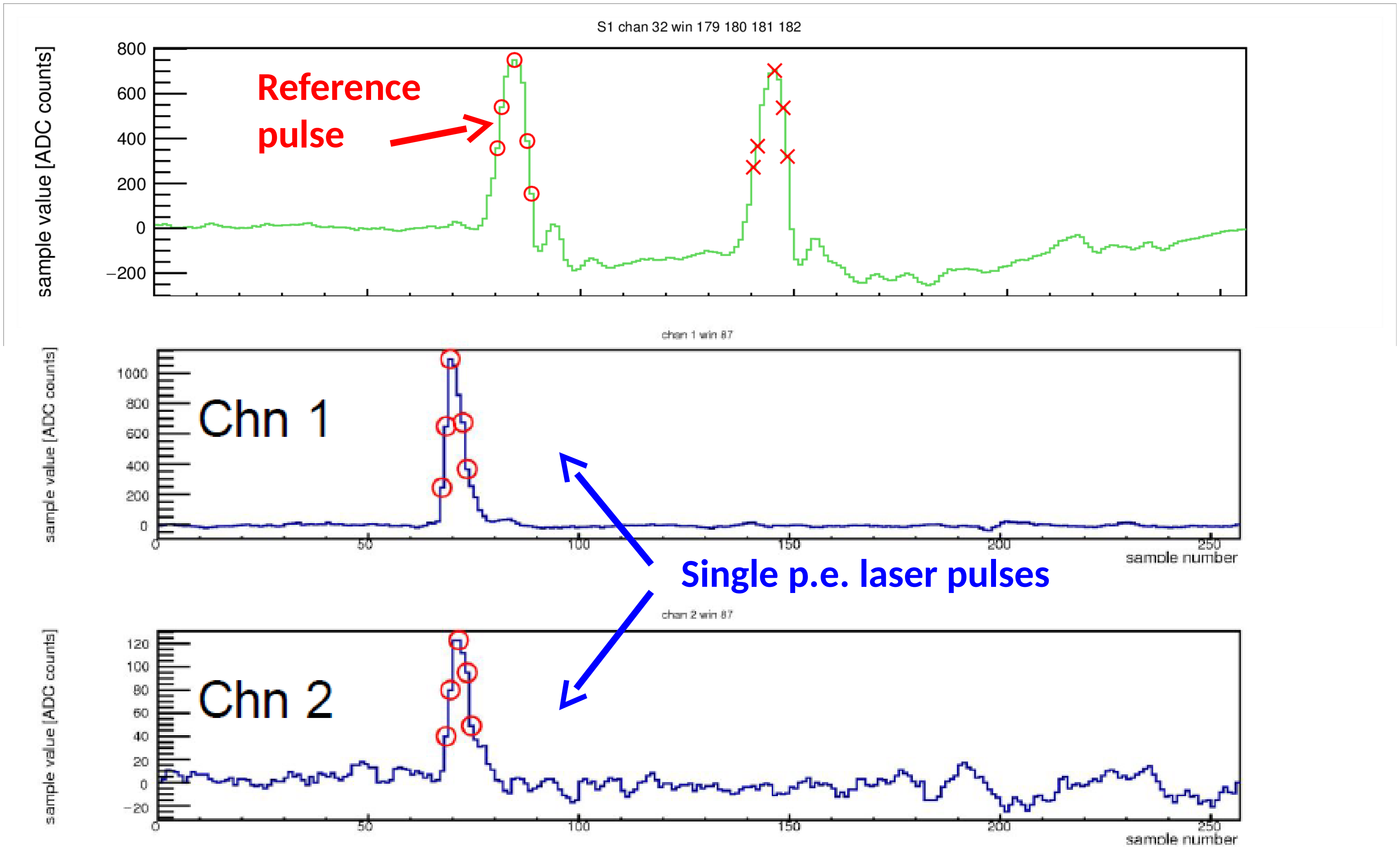
Feature Extraction

- Constant fraction discrimination
- Template fit to photon pulses
  - Computationally complex, possible on Zynq DSPs?
  - but only needed for low amplitude hits





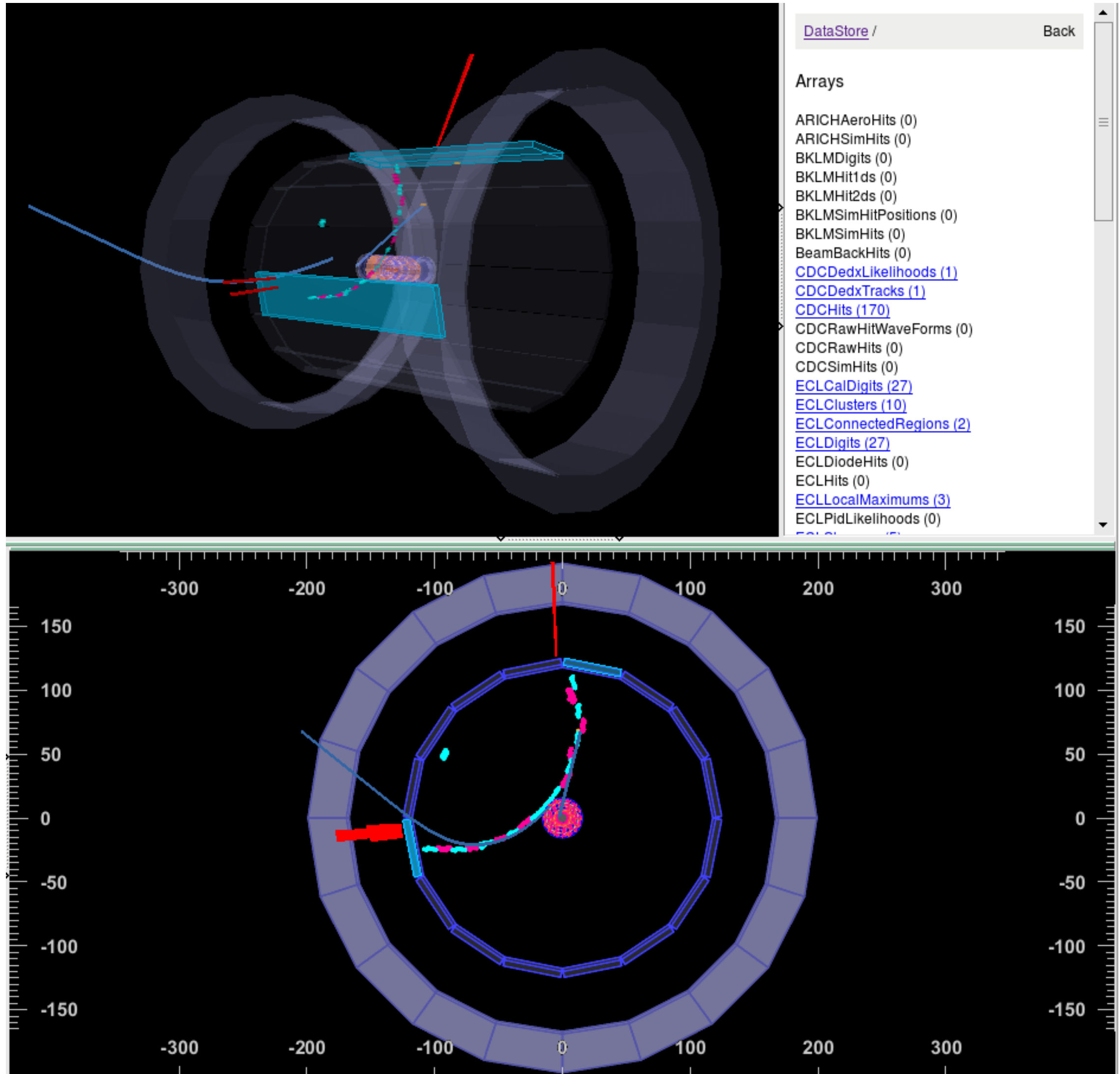
Feature Extraction Implementation Status



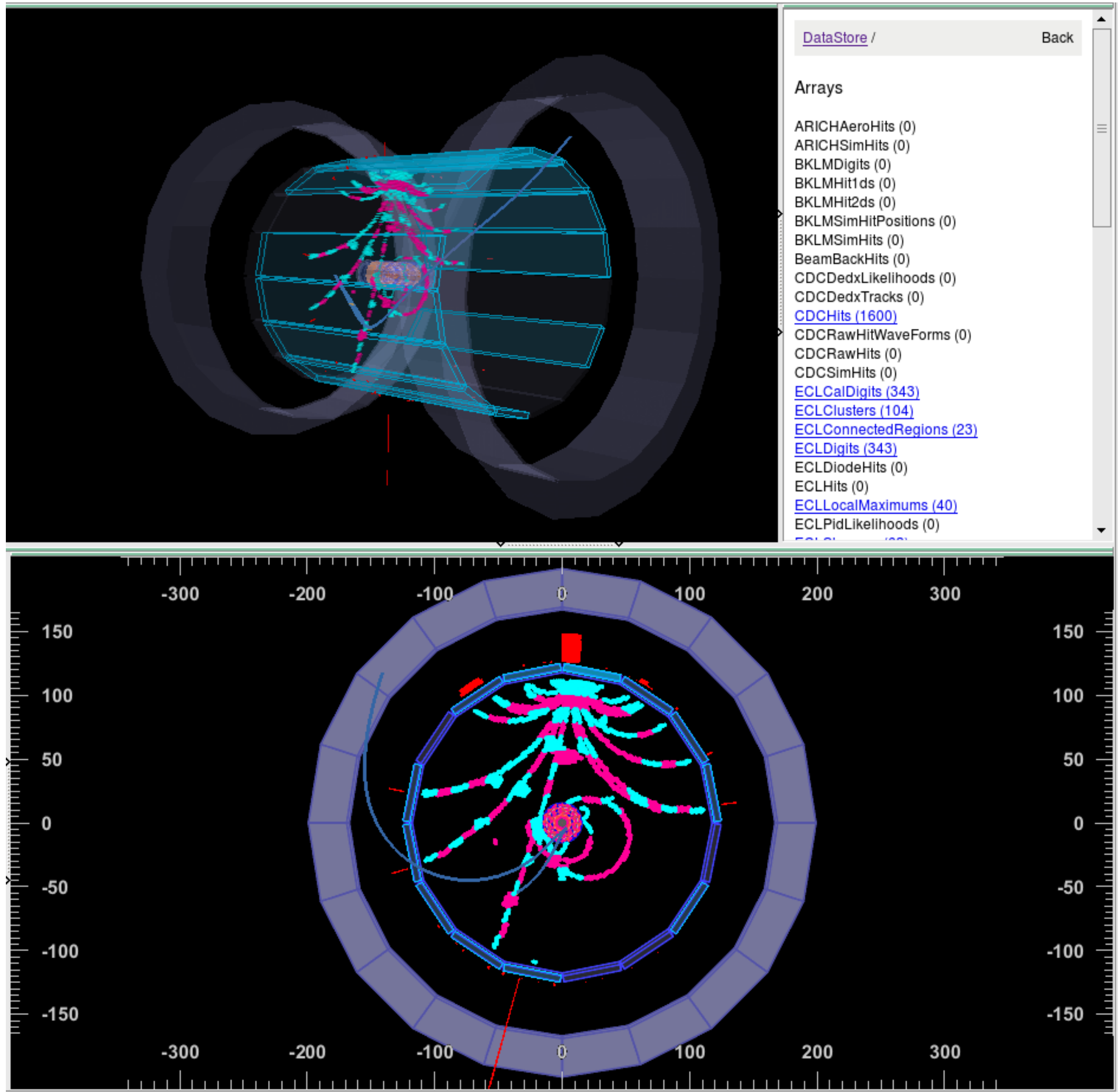
Global Cosmic Ray Campaign

- Full dress rehearsal of outer subdetectors
  - With full solenoid field
- Tracking chamber, calorimeters, TOP integrated into DAQ
  - Synchronous datataking, realistic data flow to HLT and storage
- True global triggers
- First cosmic ray tests with a new detector
  - This happens maybe every ~10 years
  - What a time to be part of this now!

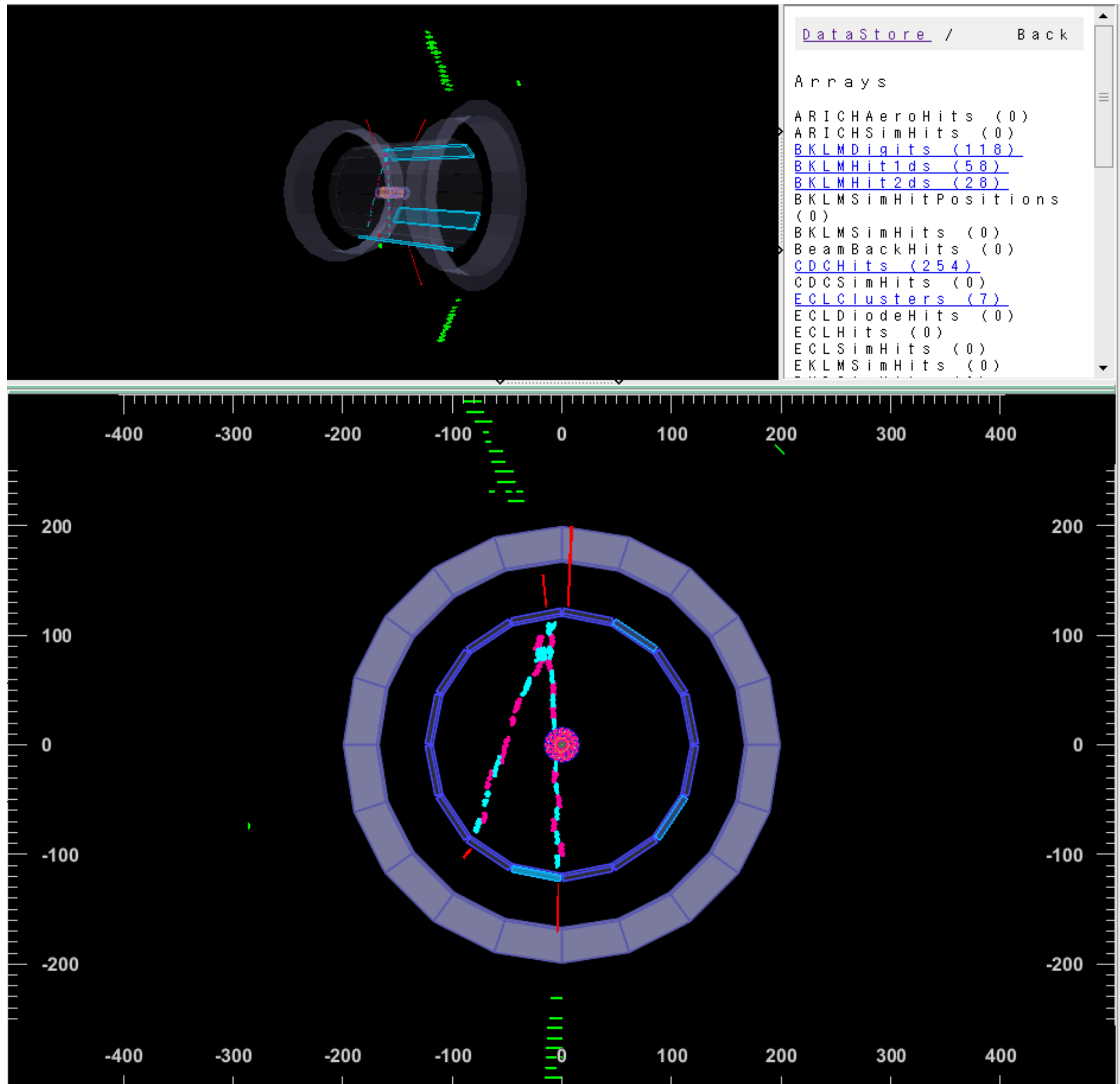
First Bent Track in CDC+ECL+TOP



First Shower in CDC+ECL+TOP

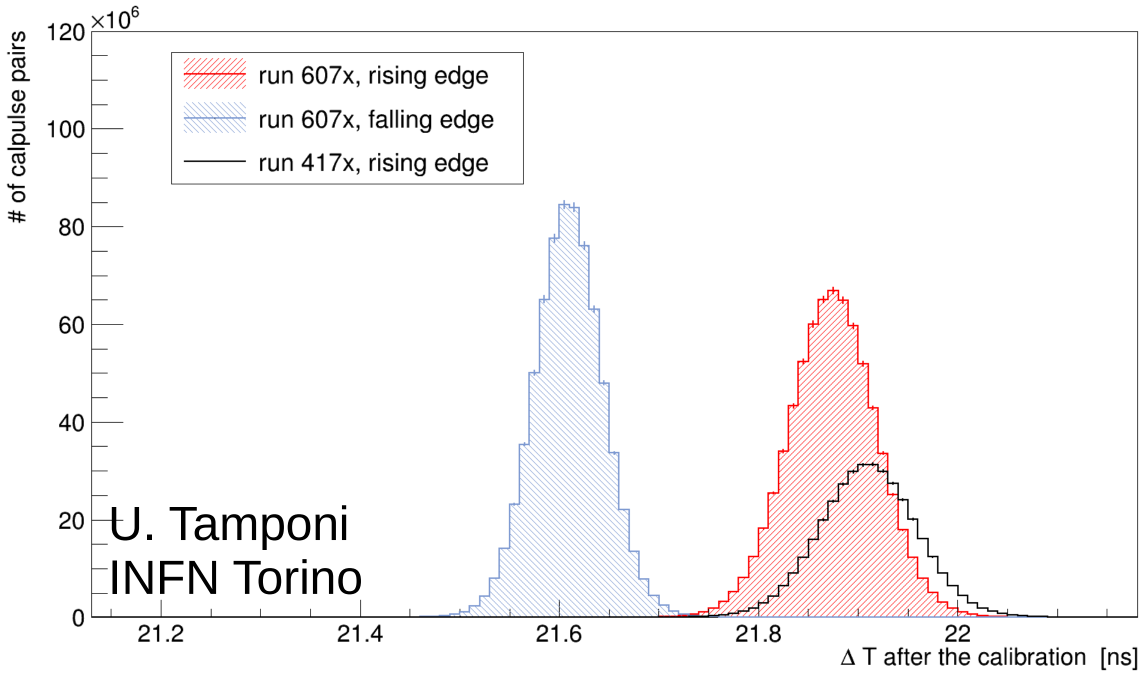


First Track in CDC+ECL+TOP+KLM



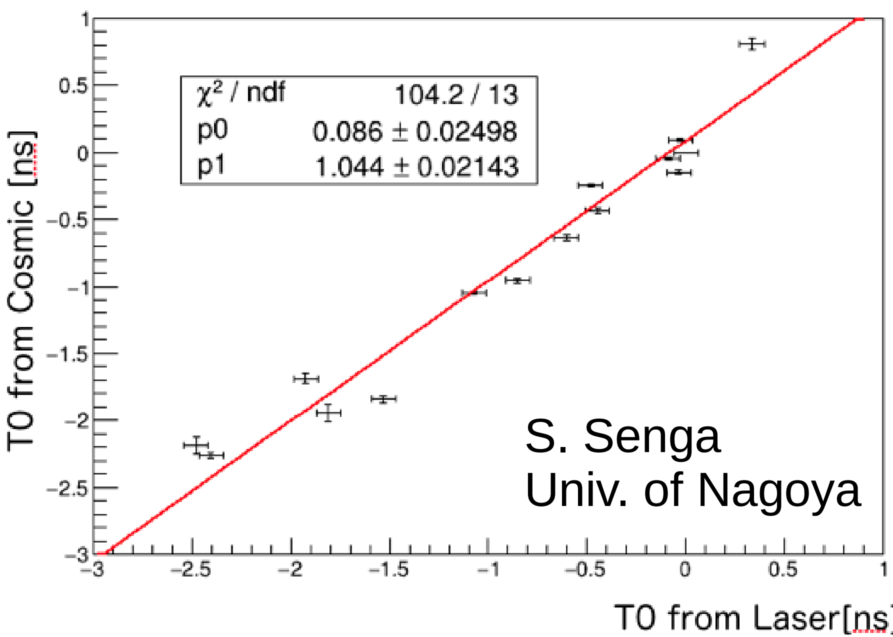
TOP Timing Calibration

- Calibrating IRSX time base with injected double pulses
- <30ps single edge timing resolution of electronics in installed A modules
  - Calibrated in-situ
  - Comparable to module qualification tests



TOP Module Timing Offsets

- Relative module timing offsets estimated from cosmics runs, laser pulses
  - Laser calibration does not resolve all contributions
  - Anyway good correlation between results
- Expect alignment to <1ps from cosmics
  - To be crosschecked with di-muons



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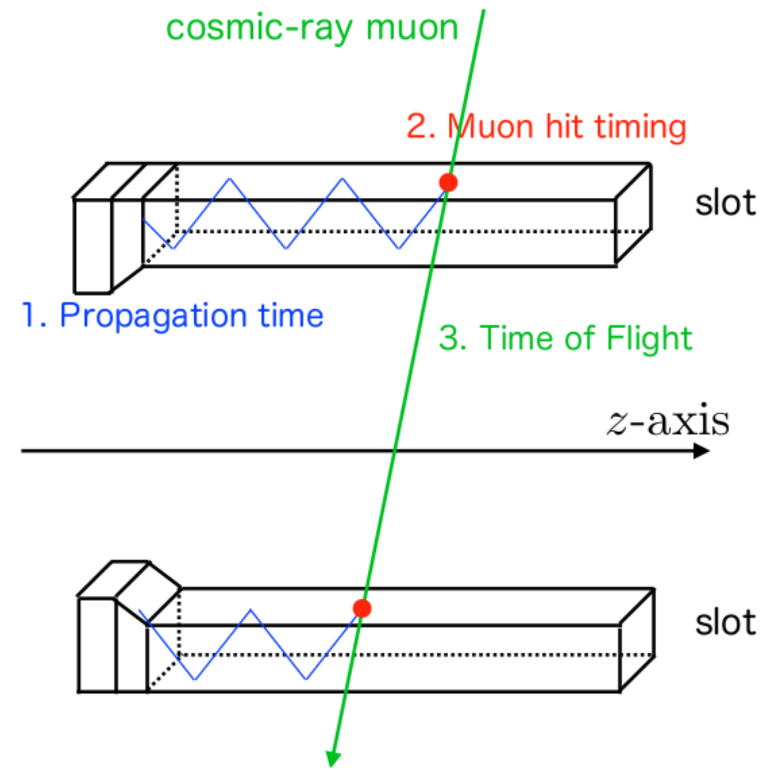
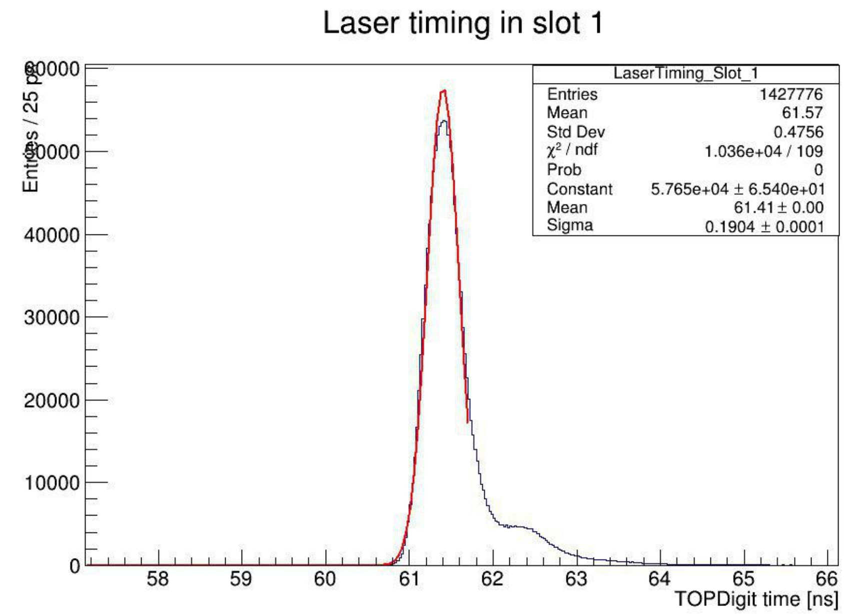
Univ. of Nagoya

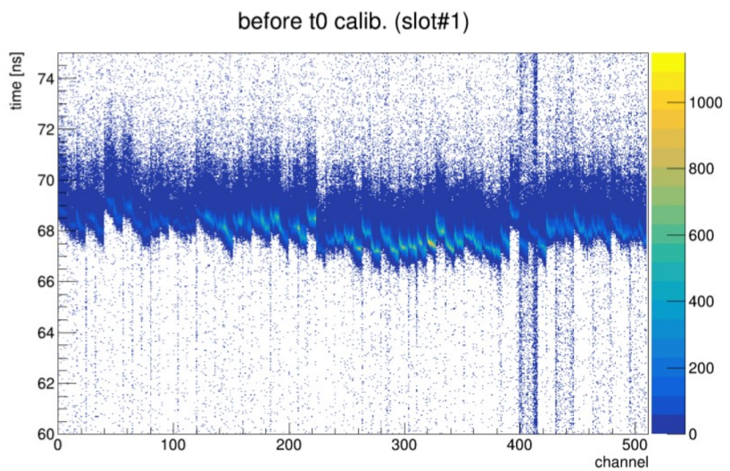


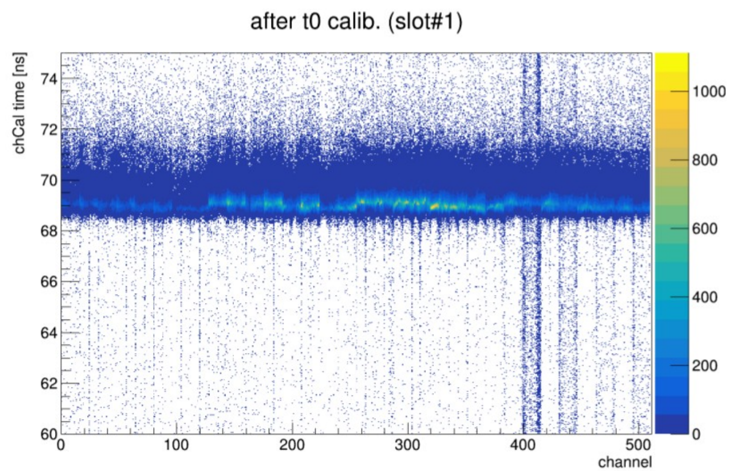
TOP Channel Timing Offsets

- Calibrate channel timings with laser pulses
- Total time resolution for laser pulses <200ps
  - 150ps contribution from laser pulse propagation smearing

→ ~120ps time resolution on optical photons with current calibrations







W. Yuang
INFN Padova

Summary and Outlook

- TOP is installed and alive
- Front end electronics are (almost) fully operational
  - Performance so far according to specifications
  - Firmware work continues
  - Paper submitted to NIM A, now in revision
- Successful global cosmic ray campaign
  - Integrating all outer sub-detectors
- Phase II: Outer sub-detectors only
  - First collisions March 2018
- Phase III: Physics operation
  - Starting early 2019