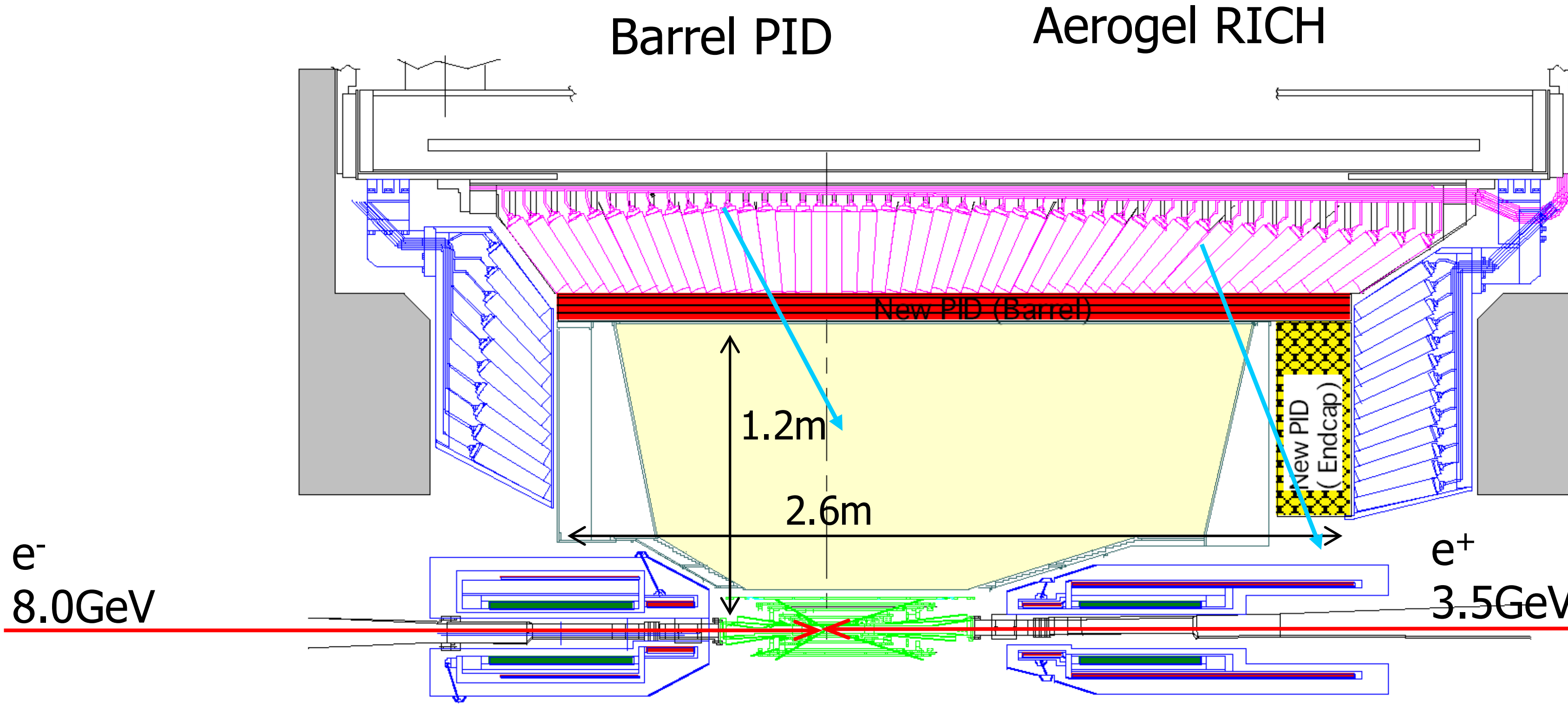
Lessons learned from Commissioning and first colliding beam data of the Belle II imaging Time-Of-Propagation Detector

Gary Varner on behalf of the Belle II TOP Group

University of Hawaii

Upgrading Belle II PID Performance

- PID (π/K) detectors
  - Inside current calorimeter
  - Use less material and allow more tracking volume
  - → Available geometry defines form factor
    -

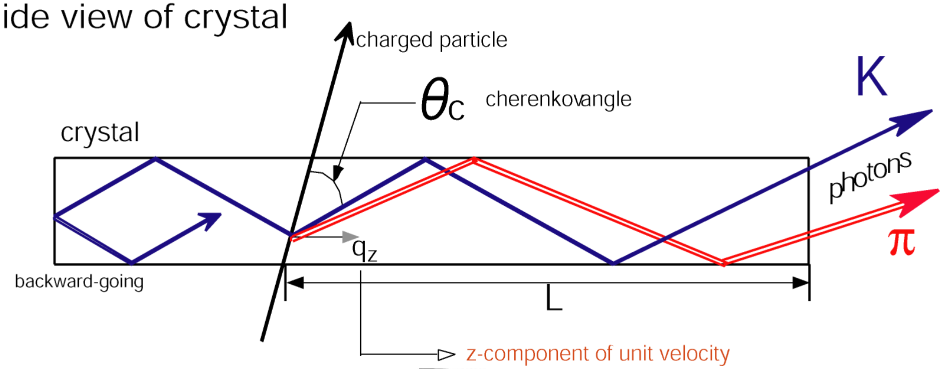


imaging TOP (iTOP)

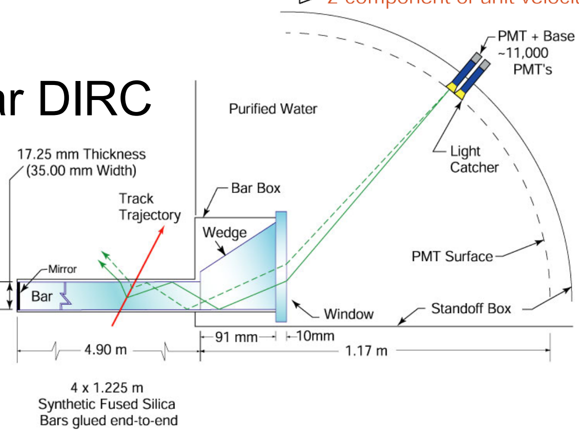
Concept: Use best of both TOP (timing) and DIRC while fit in Belle PID envelope

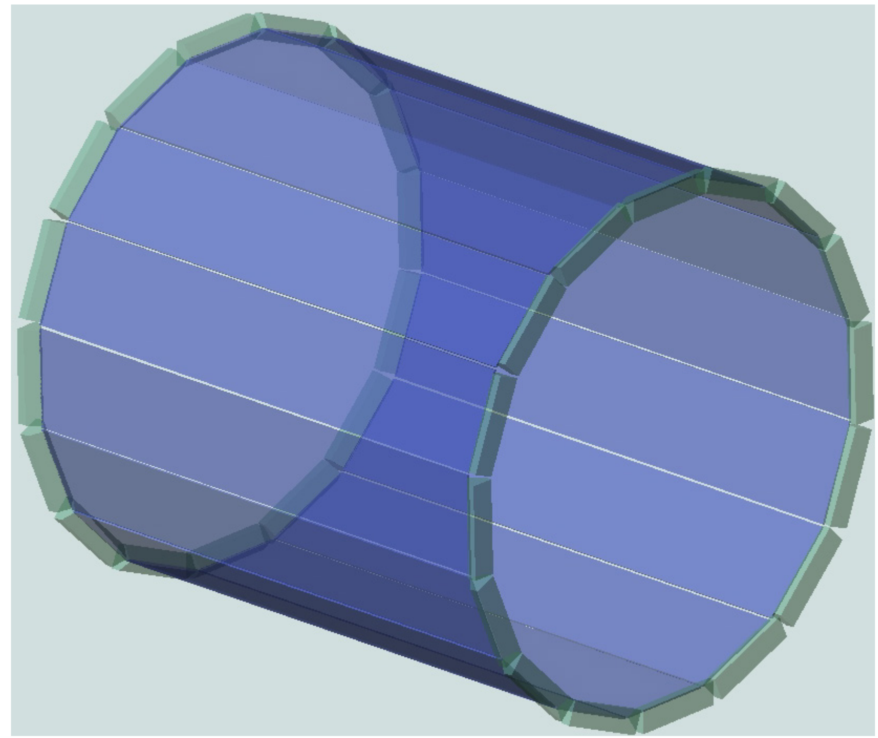
NIM A623 (2010) 297-299.

Side view of crystal



BaBar DIRC



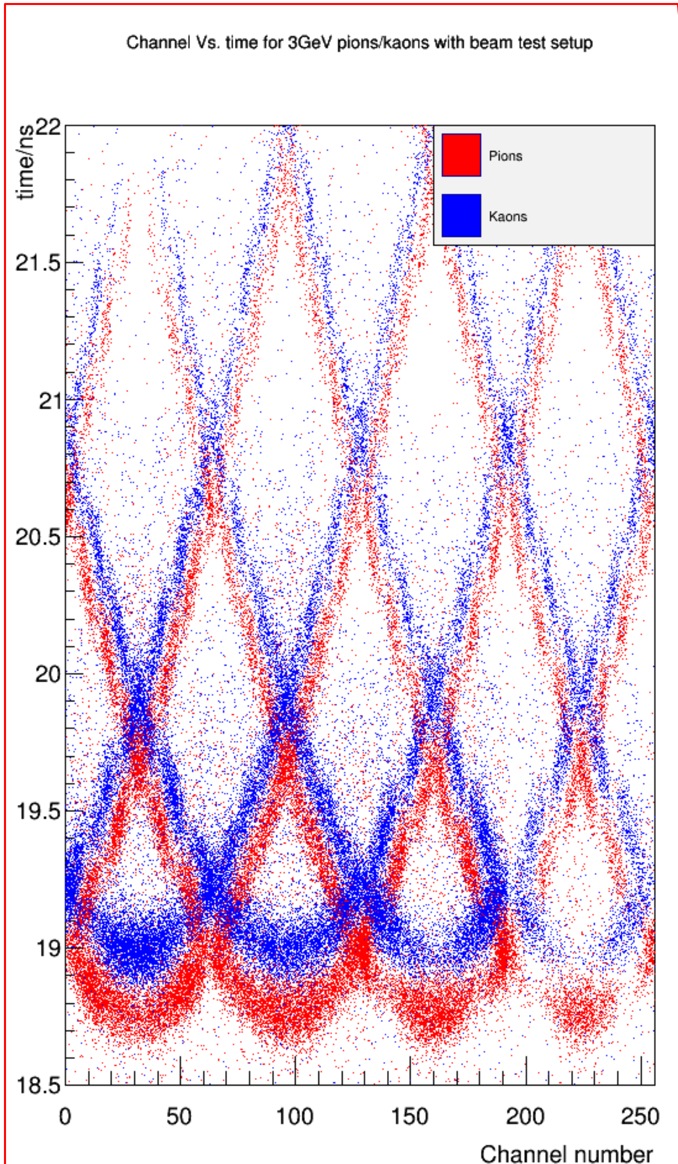


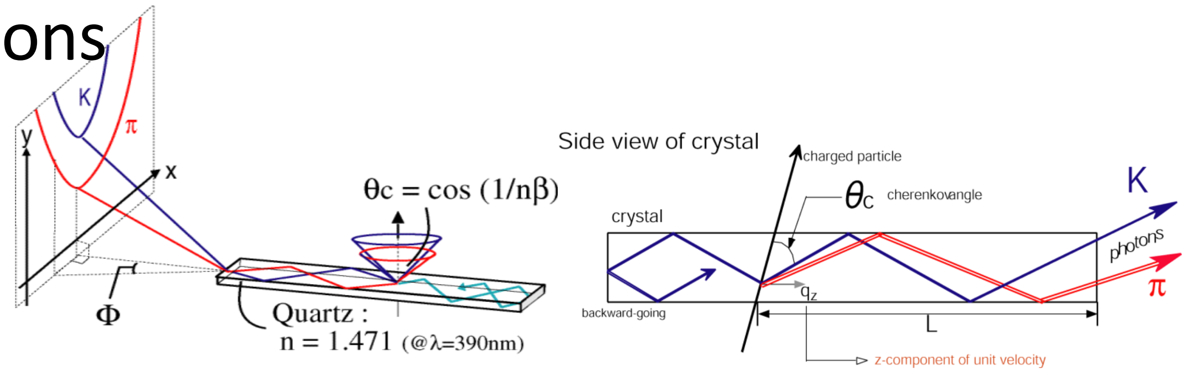
Use wide bars like proposed TOP counter

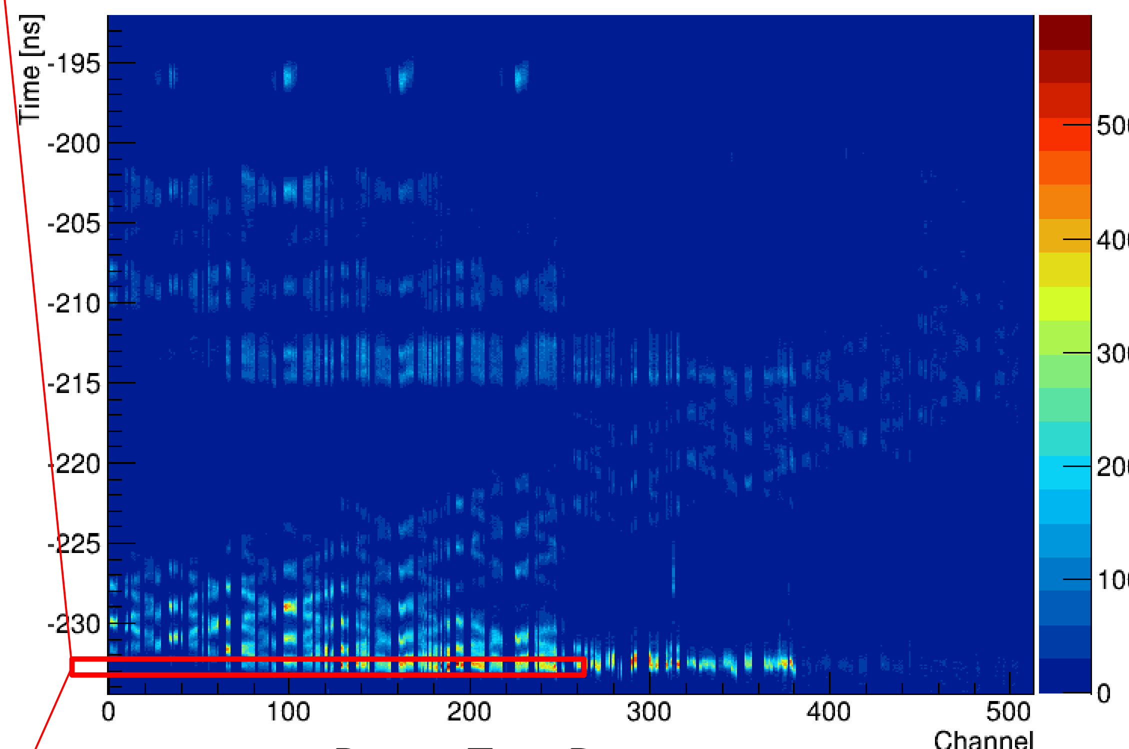
- Use new, high-performance MCP-PMTs for sub-50ps single p.e. TTS
- Use simultaneous T, θc [measured-predicted] for maximum K/π separation
- Optimize pixel size

iTOP relativistic velocity

- Space-time correlations







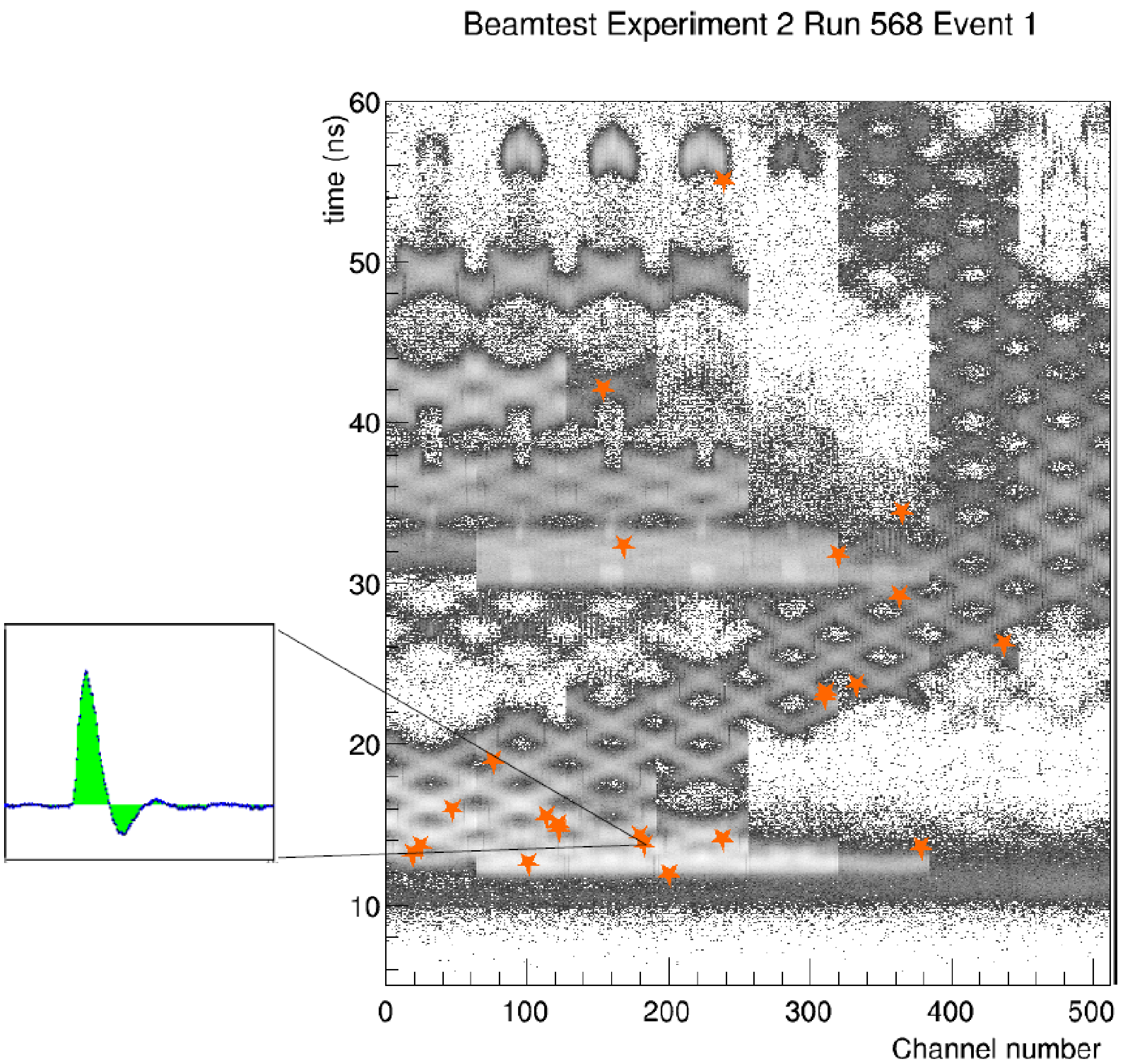
Beam Test Data

adout Le

These are cumulative distributions

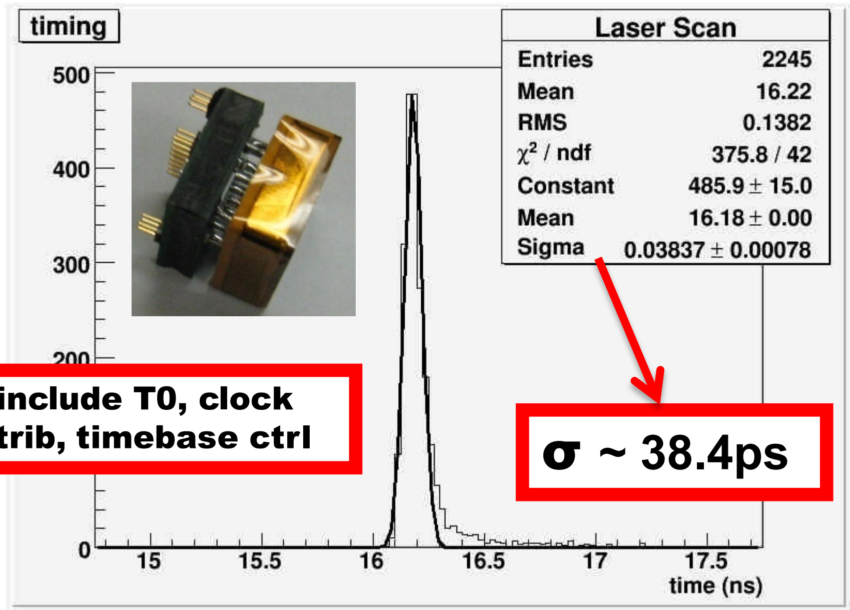
Actual PID is event-by-event

- Test most probable distribution



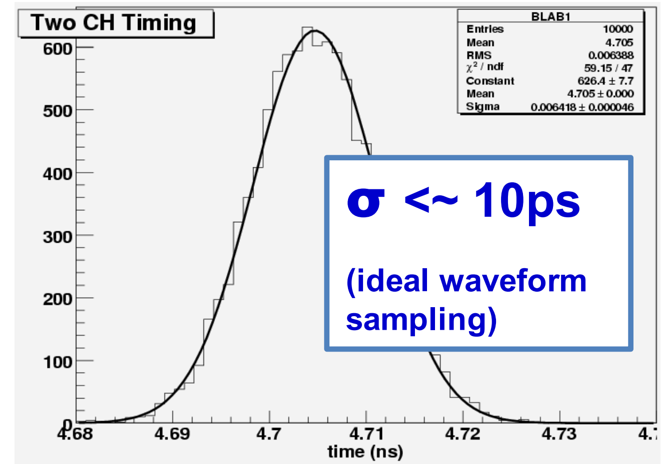
Performance Requirements (TOP)

- Single photon timing for MCP-PMTs

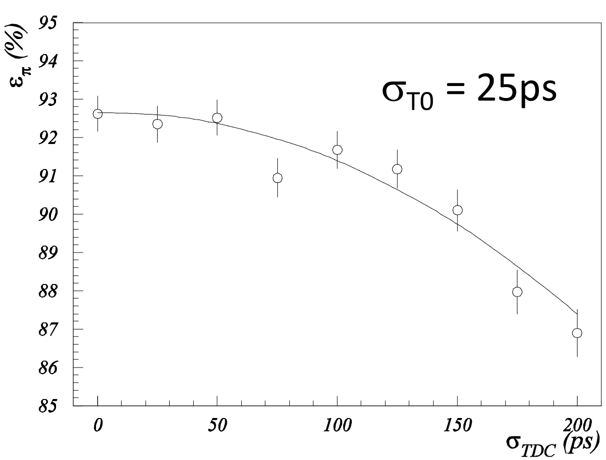


To include T0, clock distrib, timebase ctrl

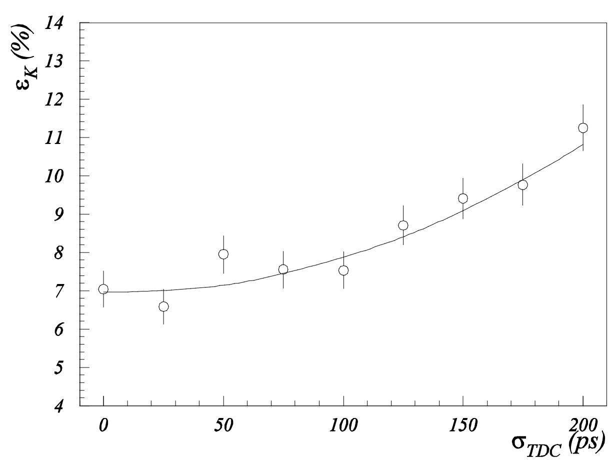
σ ~ 38.4ps



NIM **A602** (2009) 438



σ_{T0} = 25ps

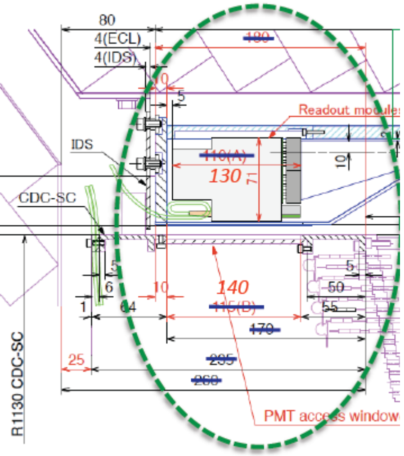


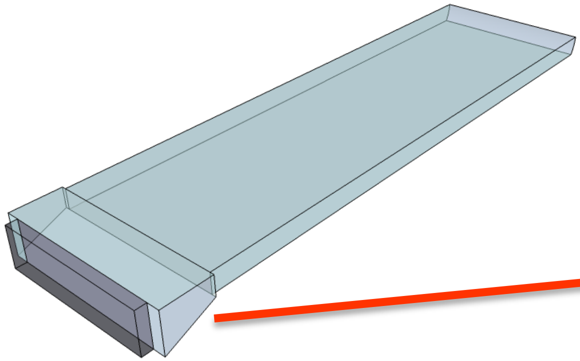
σ <~ 50ps target

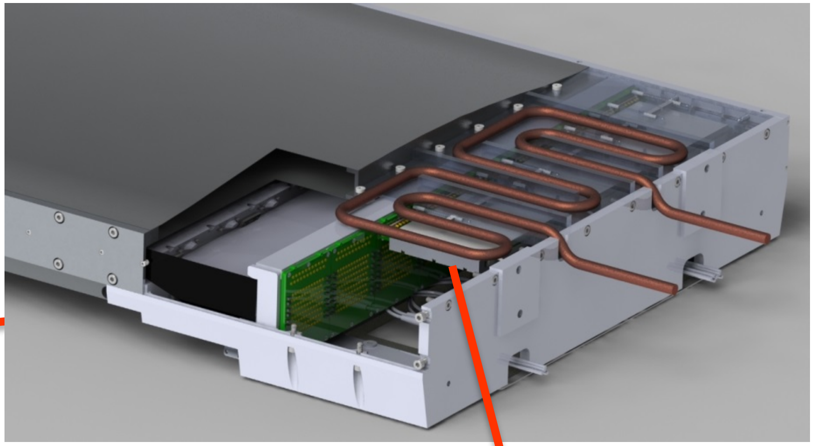
NOTE: this is single-photon timing, **not** event start-time "T_0"

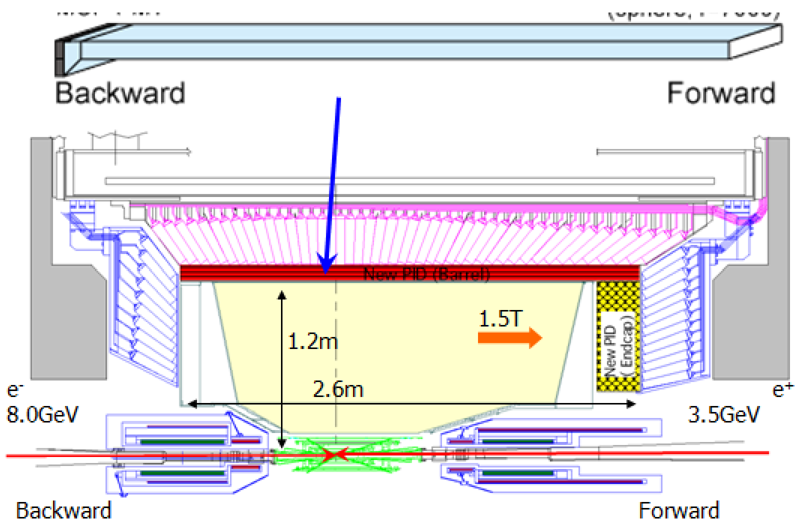
Mechanical complexity

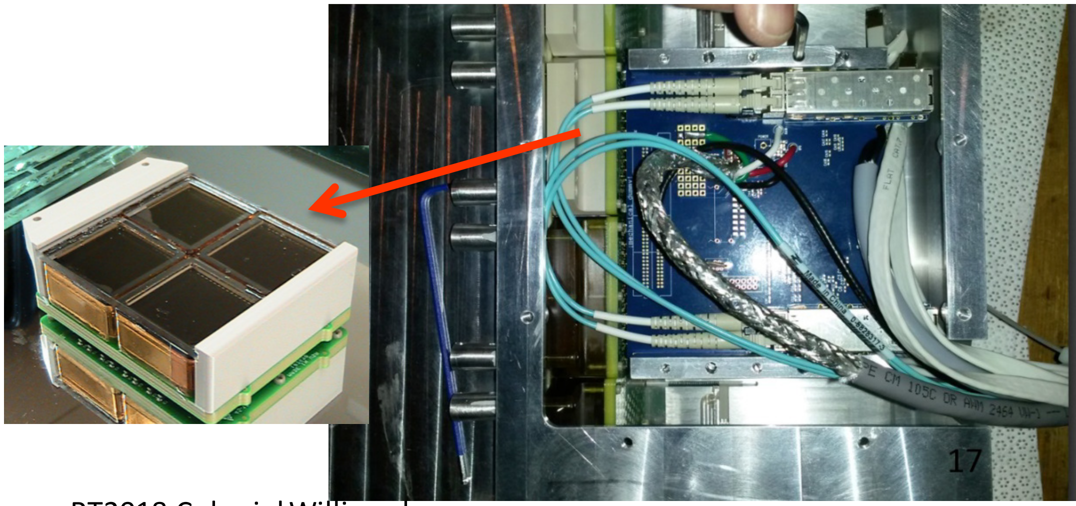
- A highly constrained space









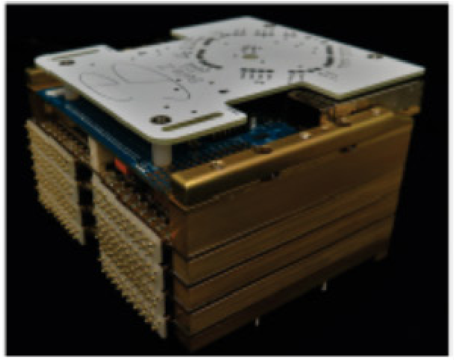


Readout Requirements

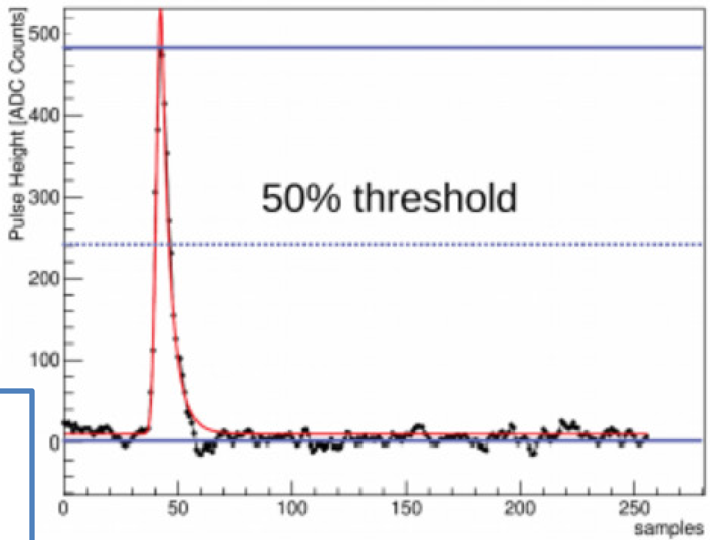
- Very stringent requirements:
  - 30 kHz trigger rate;
  - no deadtime;
  - low power consumption;
  - ~500 MHz bandwidth;
  - excellent time resolution;

- The output of each electronics channel is sampled at 2.7GHz, with 12 bit resolution;
- No way we can transfer 265 Tbit/s, Feature Extraction (and pedestal subtraction) must be performed online.

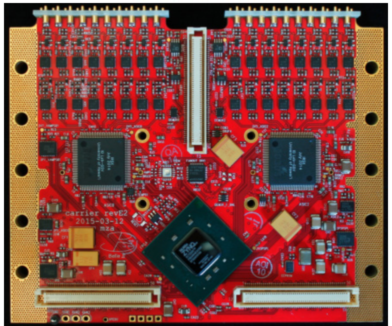
Fundamental FEE unit: the "boardstack"



Each boardstack reads out 1/4 of a TOP module (128 channels)



8

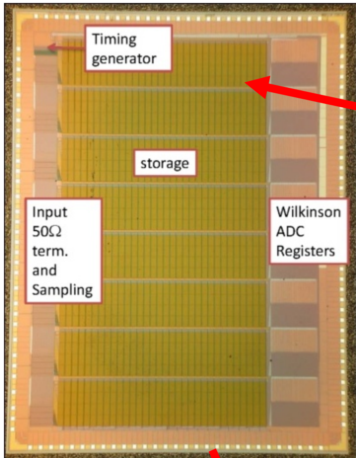


128 channels in ~ 7 x 10 x 10 cm!

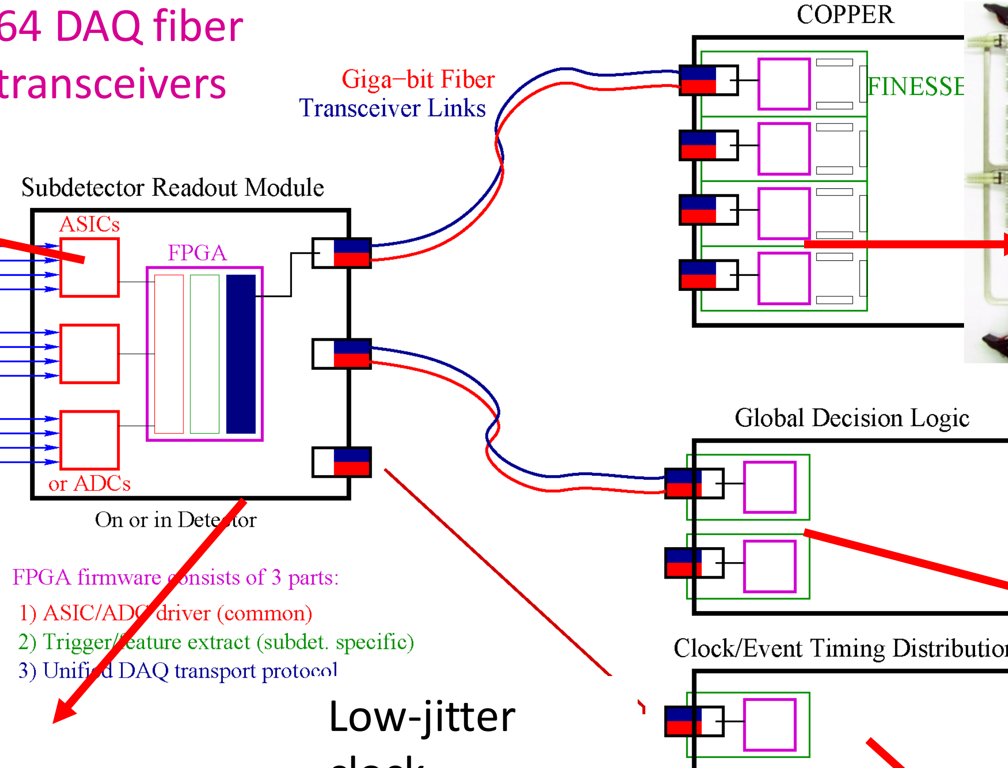
TOP Readout overview

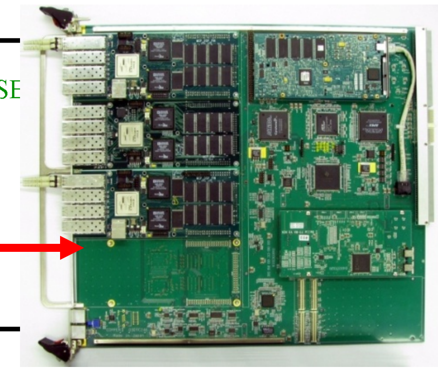
#534 Itoh-san (Poster session 1)

Waveform sampling ASIC



64 DAQ fiber transceivers



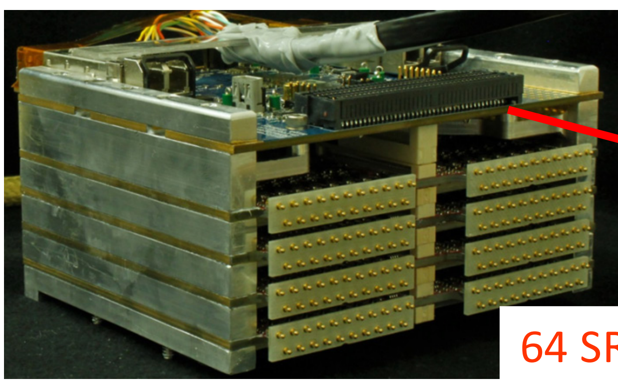


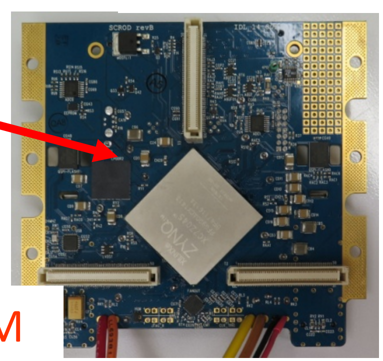
64 FINESSE
16 COPPER

8k channels
1k 8-ch. ASICs
64 "board stacks"

2x UT3 Trigger modules

Low-jitter clock



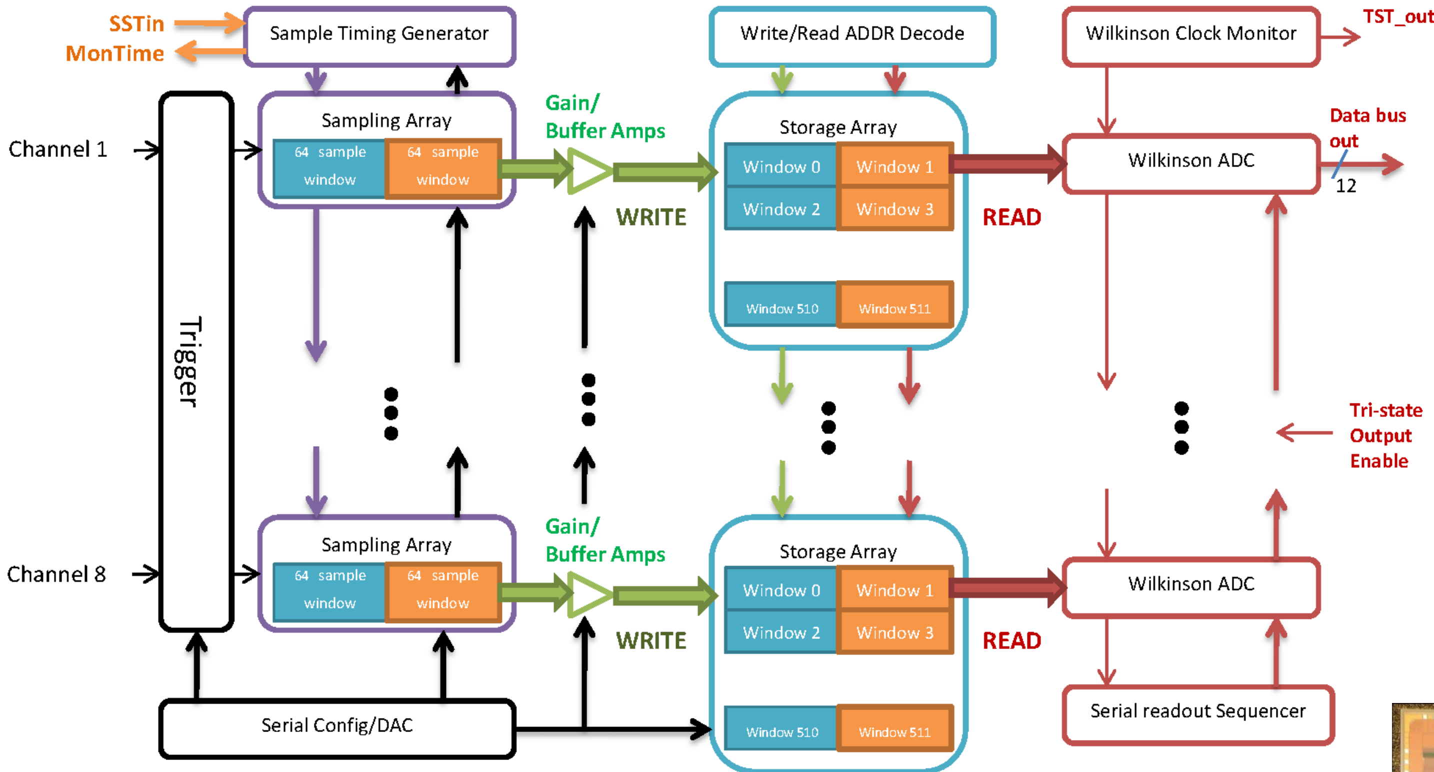


64 SRM

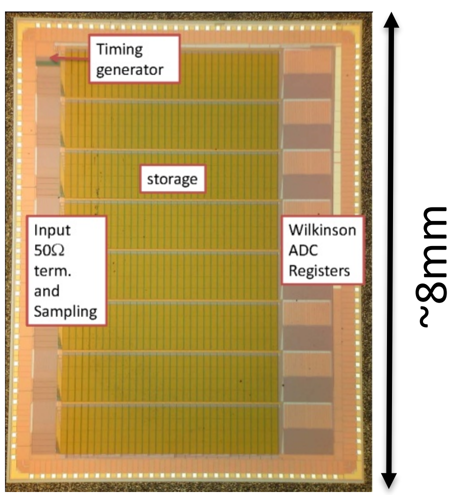
Clock, trigger, programming module (FTSW)

8 FTSW

IRSX ASIC Overview

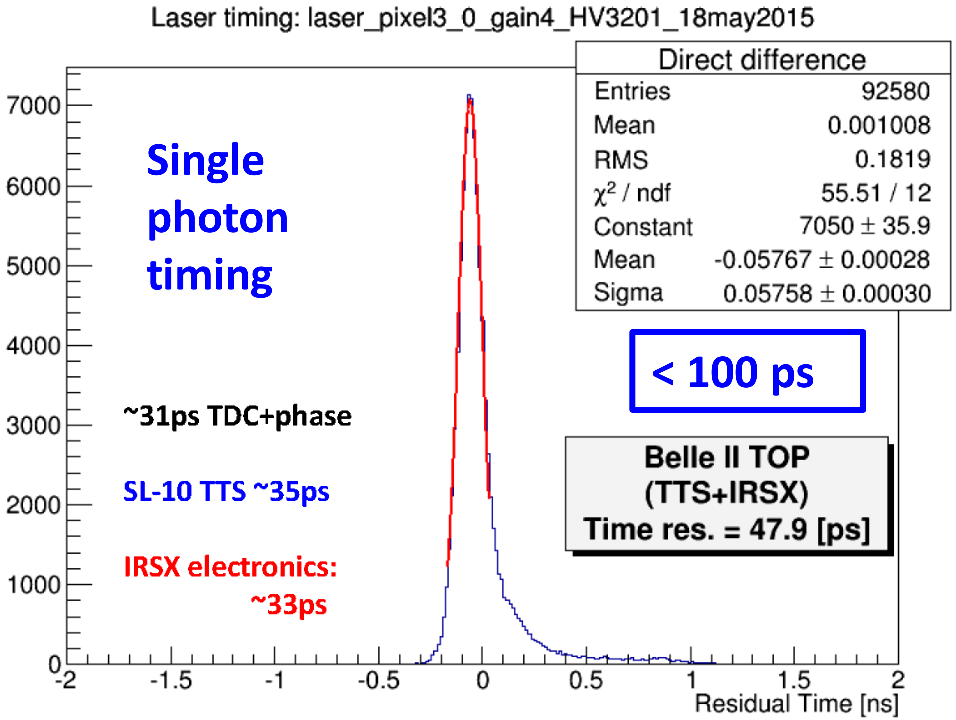


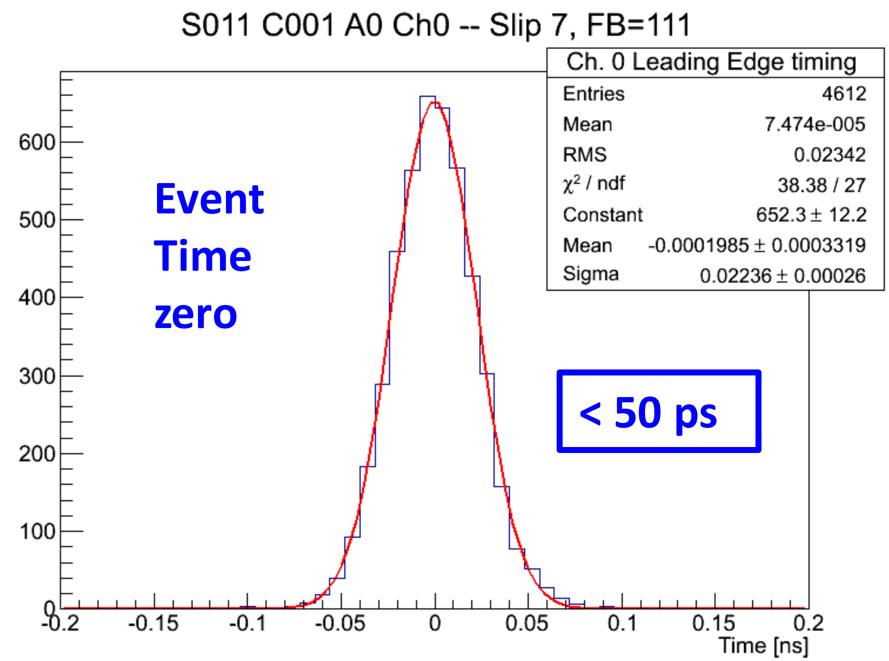
Die Photograph

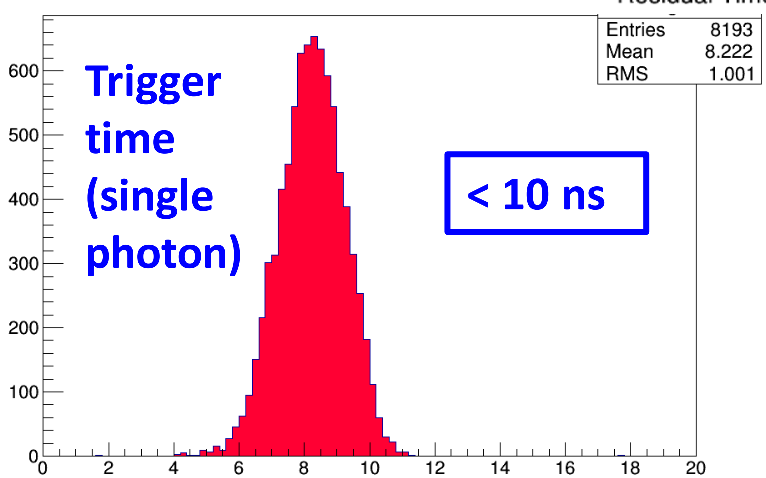


- **8 channels per chip @ 2.8 GSa/s**
- **Samples stored, 12-bit digitized in groups of 64**
- **32k samples per channel (11.6us at 2.8GSa/s)**
- **Compact ASICs implementation:**
  - **Trigger comparator and thresholding on chip**
  - **On chip ADC**
  - **Multi-hit buffering**

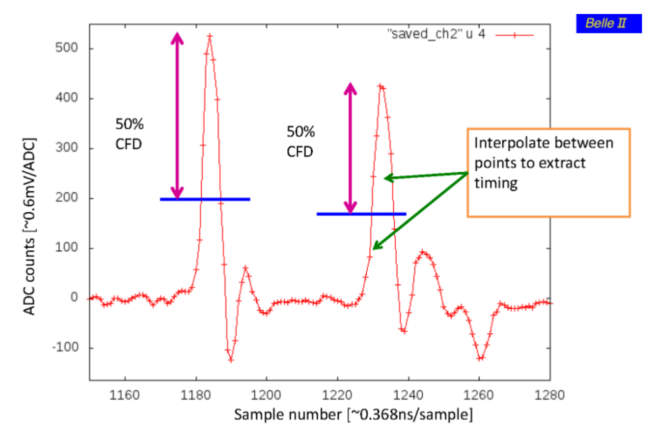
Readout Verification (pre-install, in-situ)







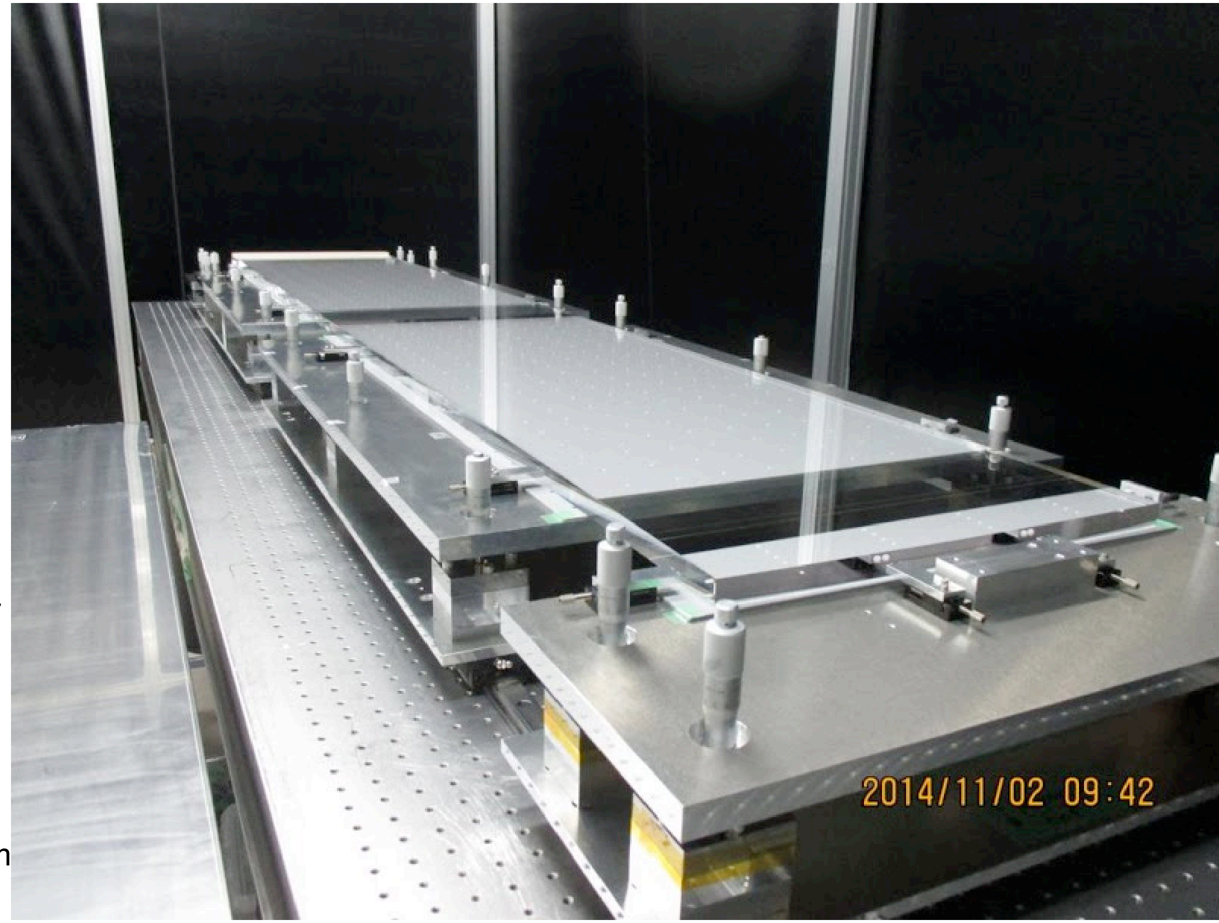
Pulser testing



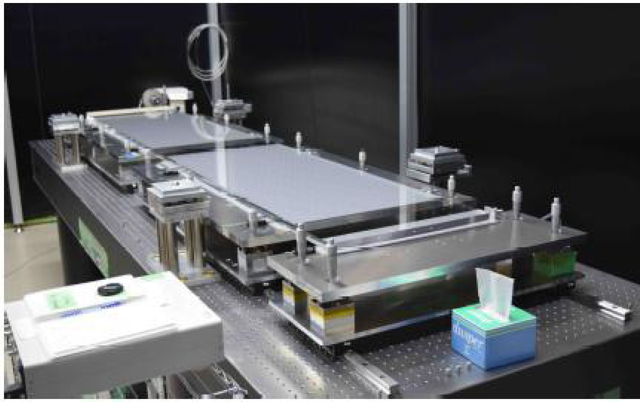
Quartz: procurement, verification

3 very challenging items: Quartz Radiator/optics #1

- Bars:
  1250 x 450 x 20 mm^3
  two bars per module
- Mirrors:
  100 x 450 x 20 mm^3
- Prisms:
  100 mm long, 456 x 20 mm^2
  at bar face expanding to
  456 x 50 cm^2 at MCPPMTs
- Material: Corning 7980
- DIN58927 class 0 material has no inclusions (inclusions ≤0.1 mm diameter are disregarded)
- Grade F (or superior) material having index homogeneity of ≤5 ppm over the clear aperture of the blank; verified at 632.8 nm
- Birefringence / Residual strain ≤1 nm/cm

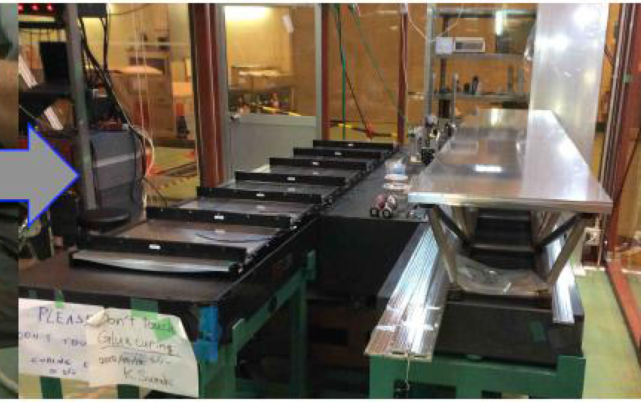


Quartz gluing, Module Assembly



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

Enclosure: gluing CCDs and LEDs, integrating fiber mounts.



QBB: strong back flattening, button & enclosure gluing.

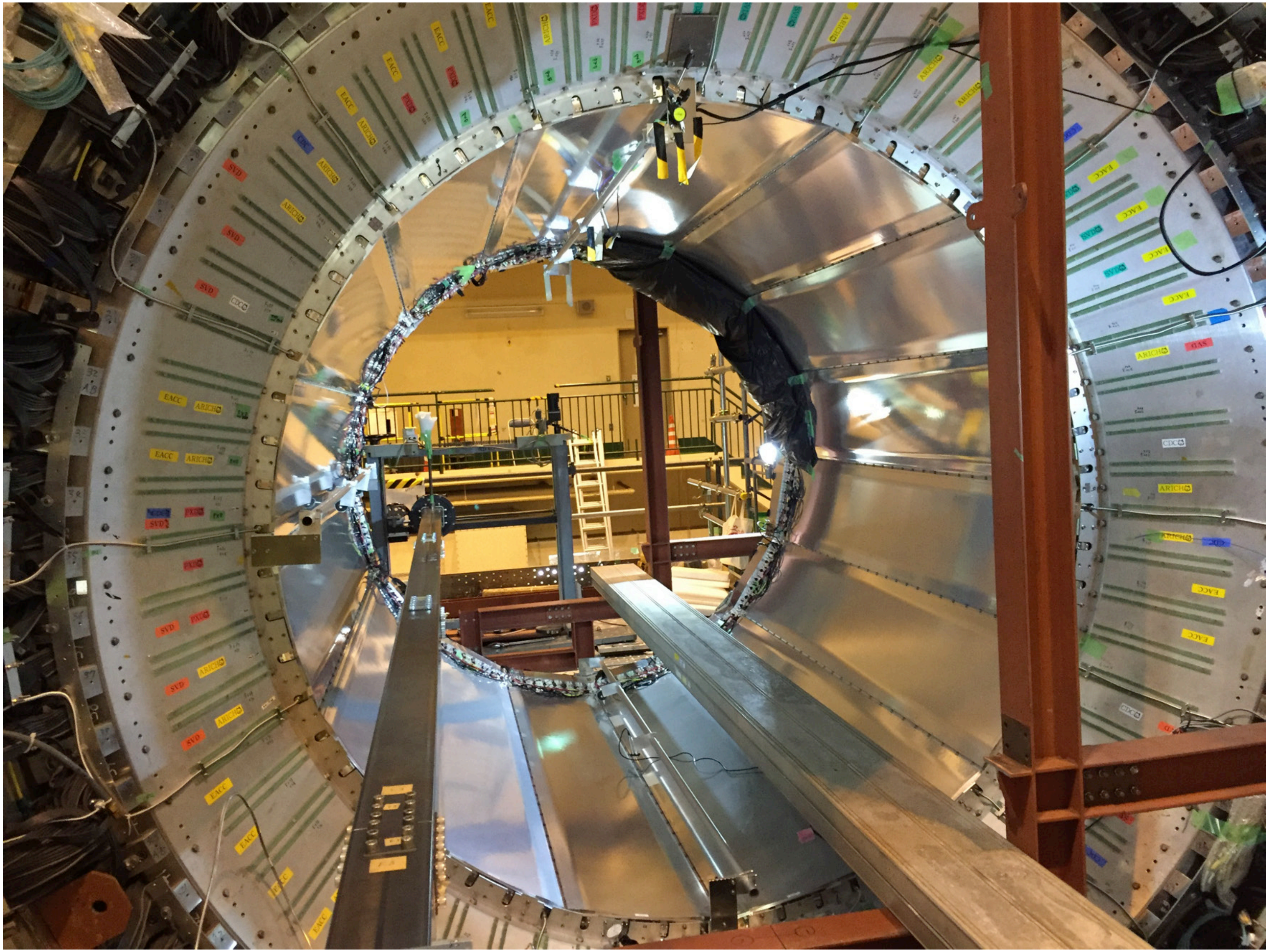
Put on a cart. PMT and front-end integration, performance check.

QBB assembly and gas sealing.

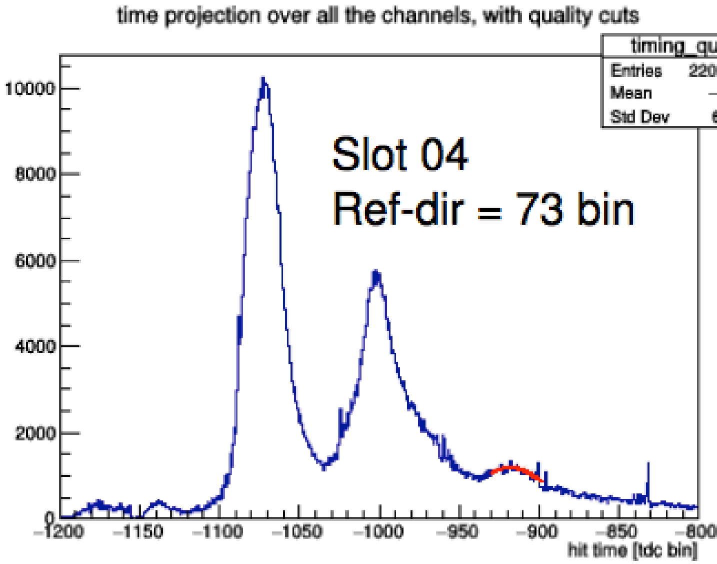
Move optics to QBB using the “lifting jig”.

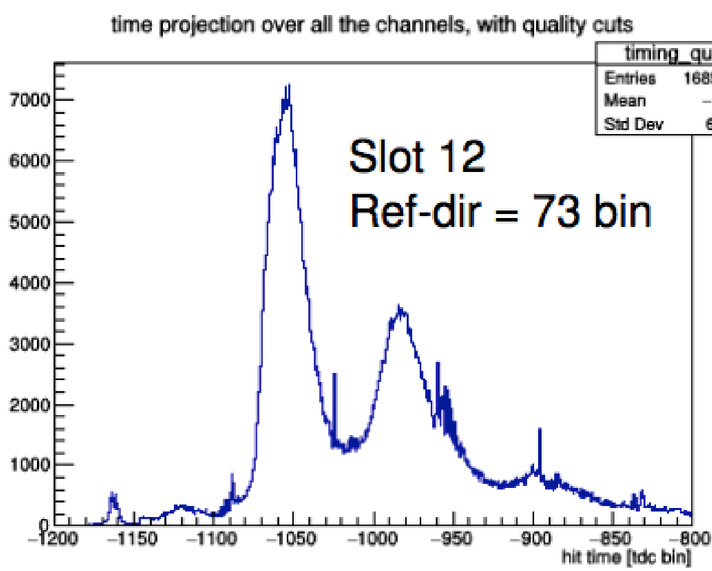
Installation (very tight fit)

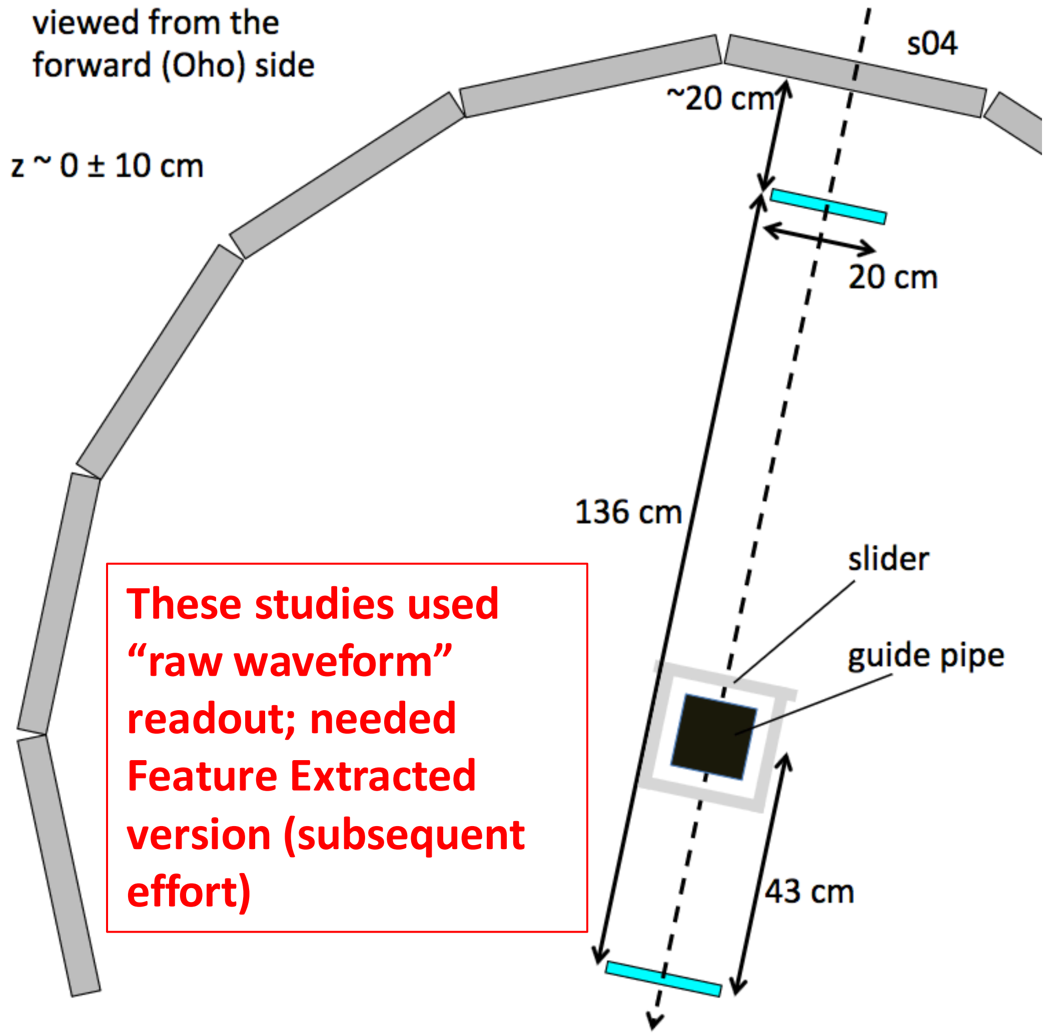
Installation Complete (May 2016)



After installation – continued development



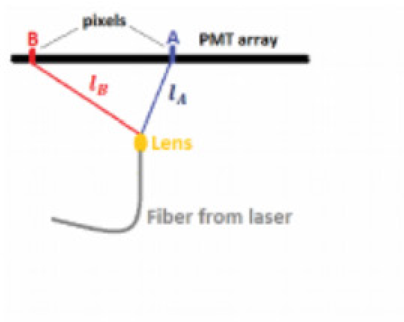


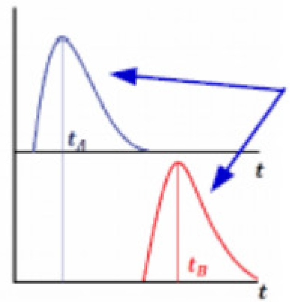


These studies used "raw waveform" readout; needed Feature Extracted version (subsequent effort)

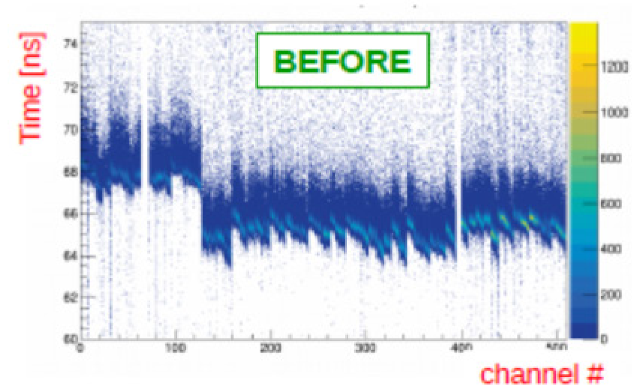
Timing alignment

- Effectively need fine tuning for all 8192 channels of TOP;

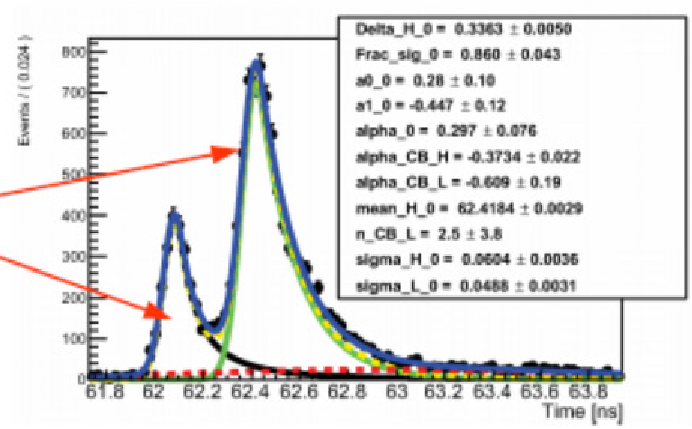


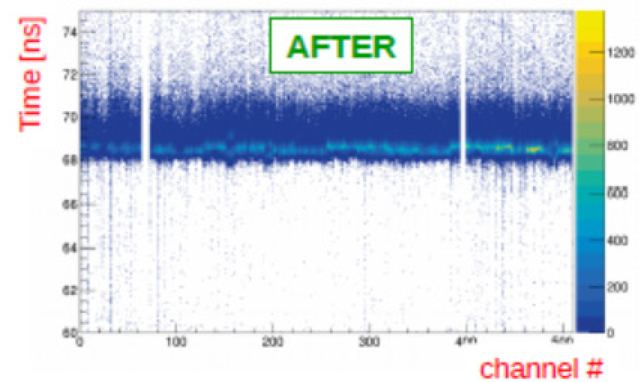


Different propagation times from one source to different channels

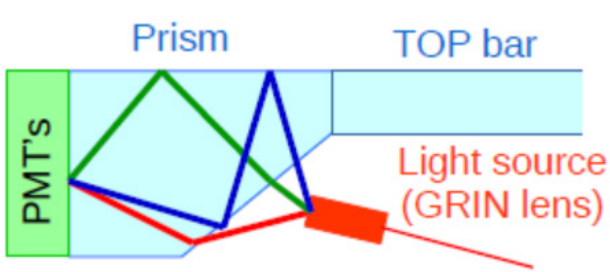


Contributions from two different sources to the same channel



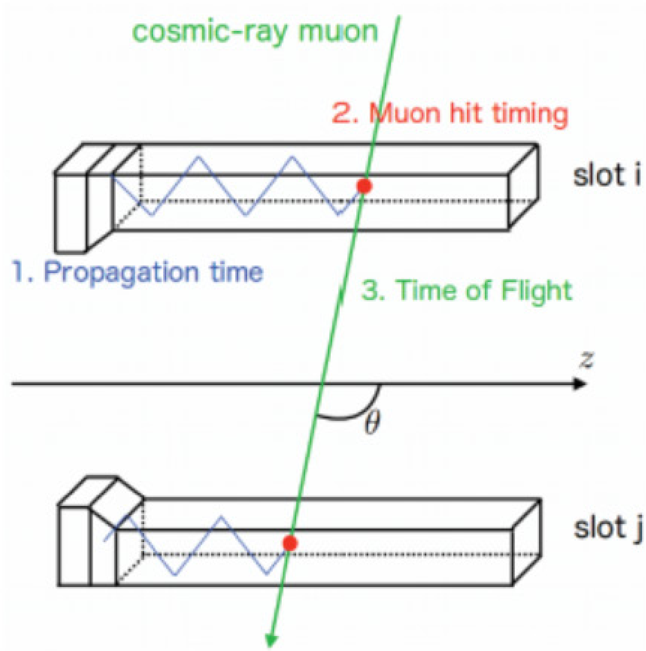


- Current status: precision ~100 ps (but still margin for improvement!).

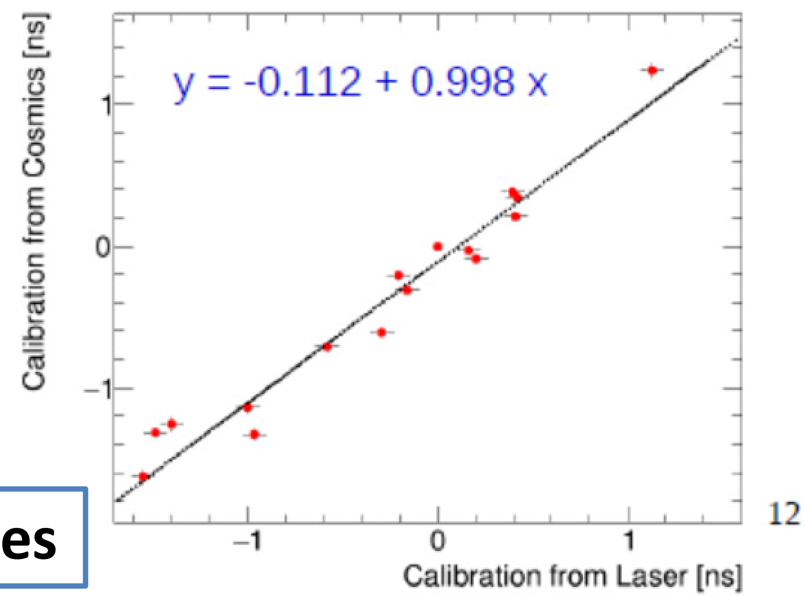


Module Timing alignment

- Idea: use cosmic events to align in time all TOP modules:



- Compare photon detection times for cosmic rays that hit two different modules, taking into account time of flight and different propagation times;
- Minimize a χ^2 to find the best calibration constants (one module taken as reference);

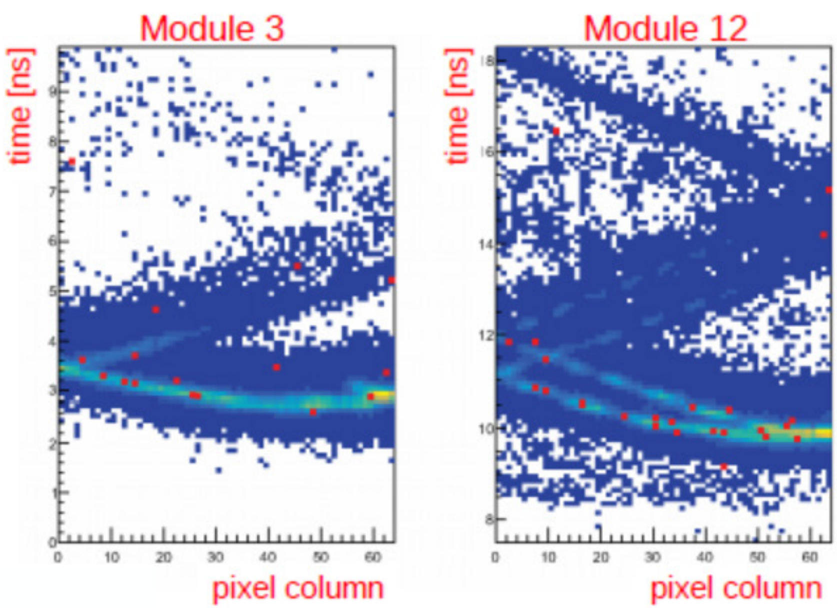


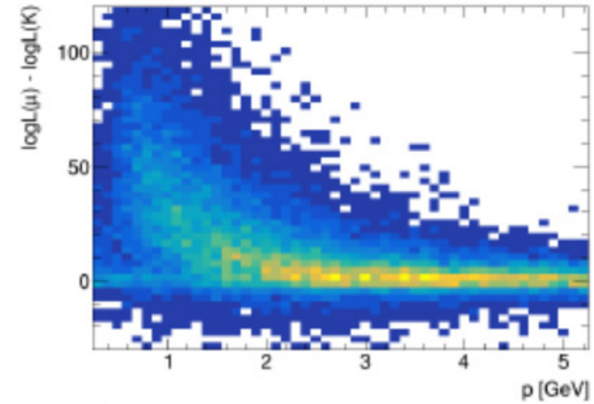
- Crosscheck with laser system (uncertainty from uniformity of fiber lengths) shows excellent consistency!

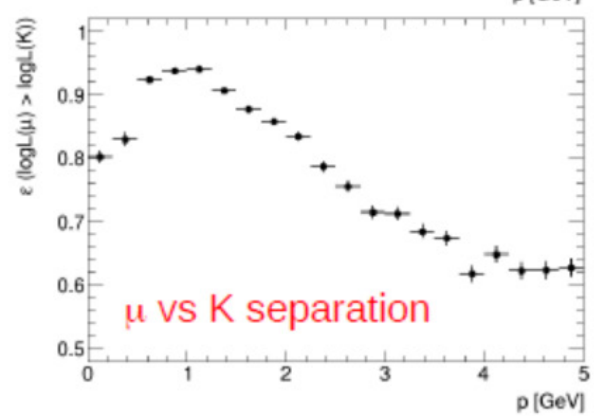
Length mismatch due to timing cables

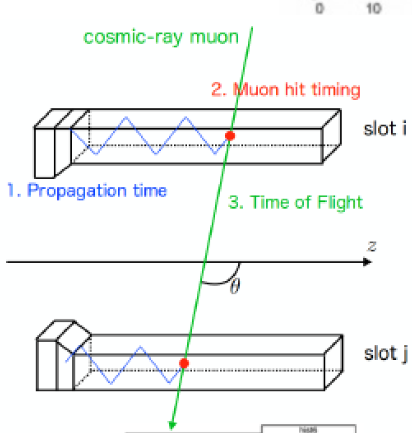
Cosmic Ray calibration data

- TOP joined the Global Cosmic Runs with other Belle II subdetectors since last Summer (>50M events recorded);
- Debugging opportunity + first performance assessment:









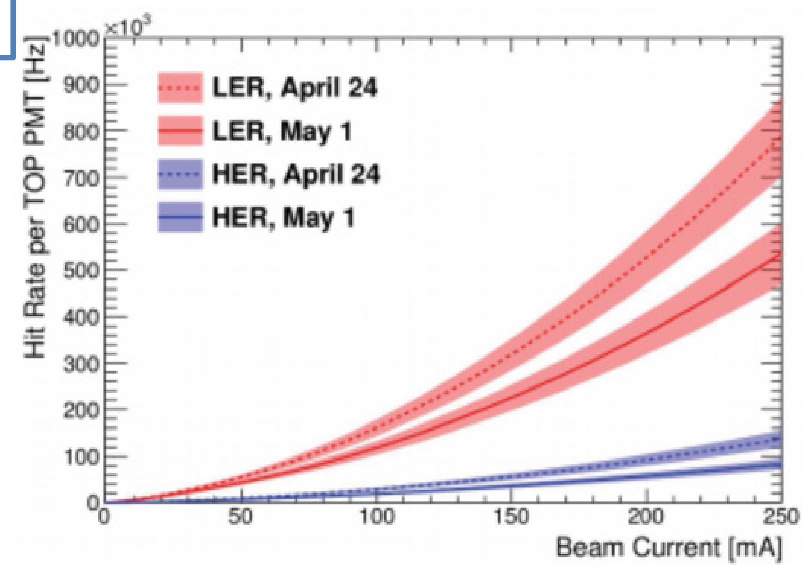
Points: detected photons
Colored bands: pdf

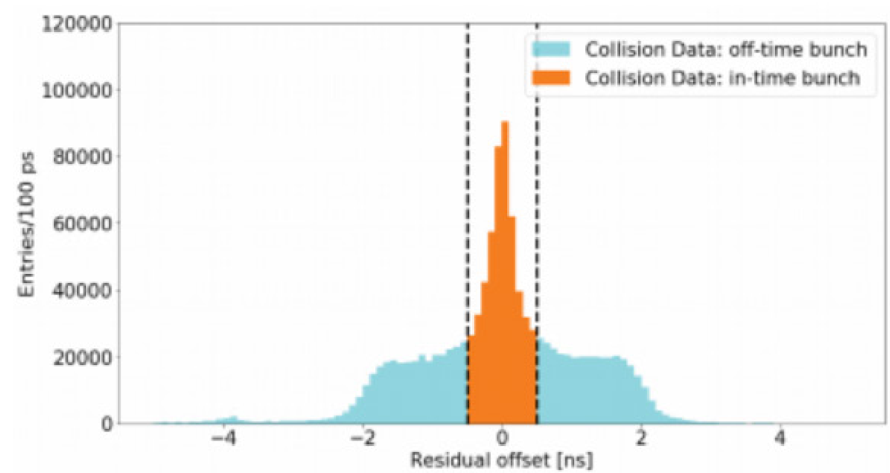
Very reasonable performance, despite calibration being still far from perfect!

First Collision Data

"Phase 2" (collisions) started in in April

- TOP stably included in DAQ, should have no problem coping with the expected rates this year;
- Hit rates give a robust measurement of (gradually improving) beam background conditions;
- We can use two-track events to determine the event T_0 and align with the other subdetectors;
- Cannot show PID performance on collision data yet: we need to reprocess the data with final calibrations... and collect large samples of K_S, D^*, Λ, ...

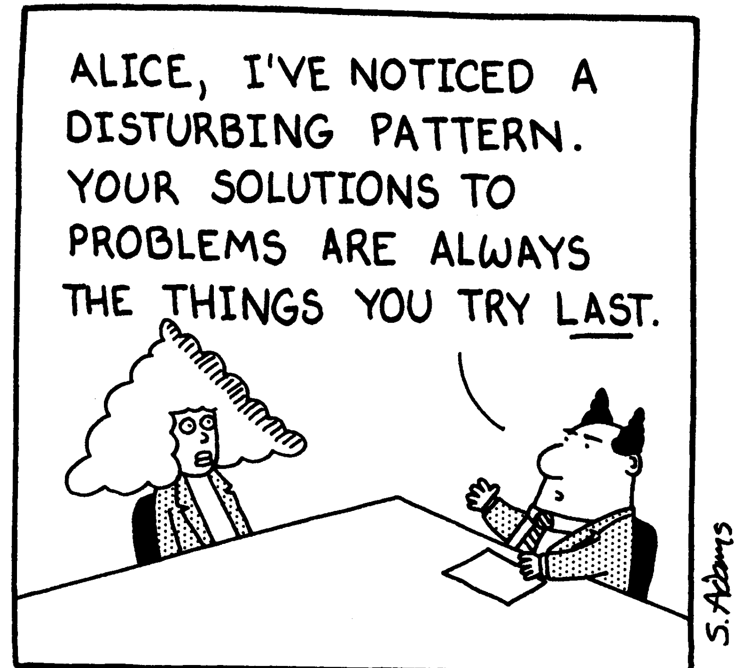




“Fake” Summary

Belle II TOP Detector Readout status

- **Present status:**
  - **Many small Production Firmware issues**
  - **Readout basically working**
- **Phase 2 (no vertexing):**
  - **Detector alignment**
  - **Di-muon, event T0 calibration**
  - **Verify PDFs**
- **Phase 3 readiness (early 2019):**
  - **Basically ready**
  - **Speeding up digitization, feature extraction**



illiamsburg

Student Question?

Point A **Point B**

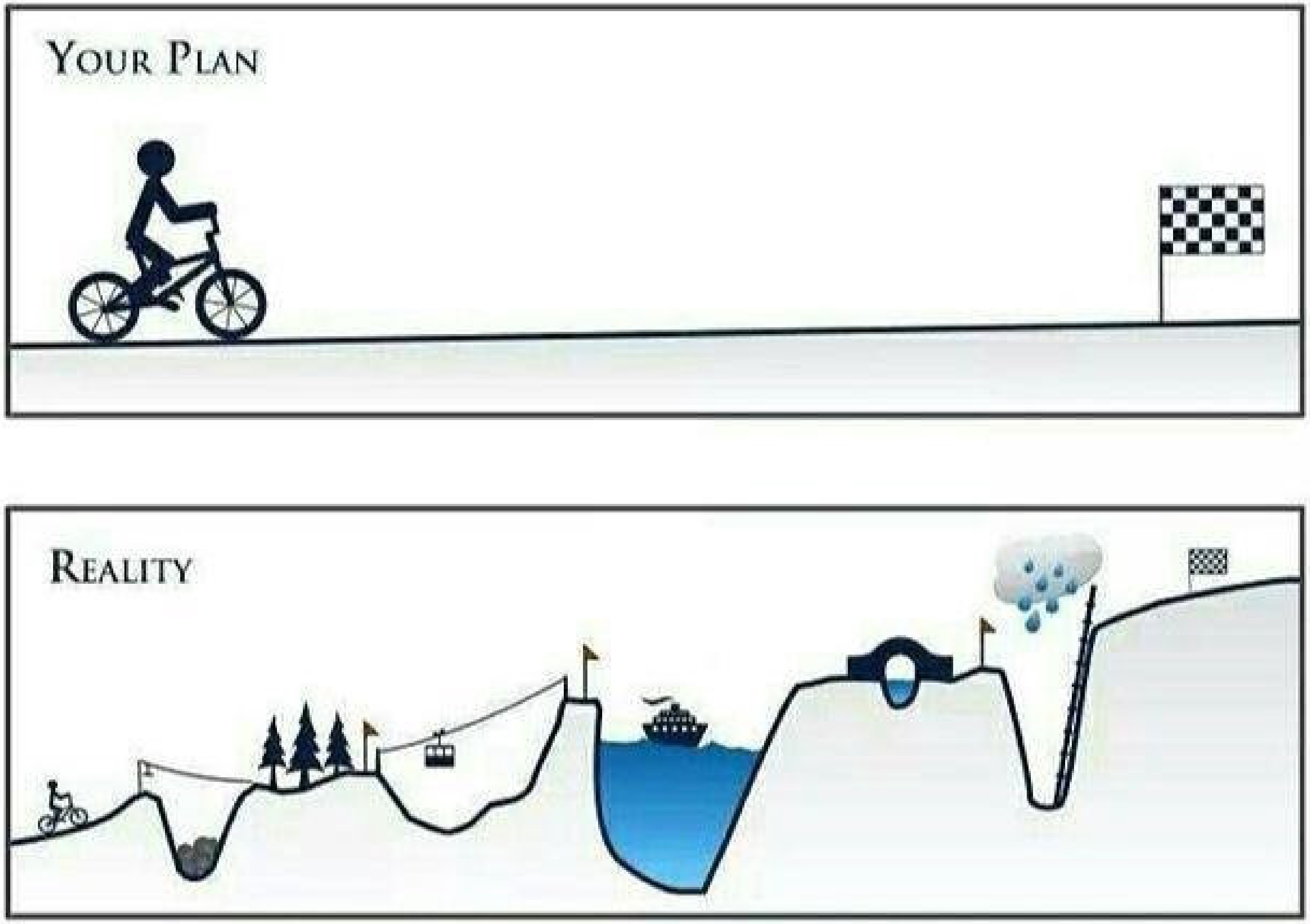
What is the Shortest Distance Between 2 points A & B ??

One answer

Point A **Point B**

The cynic might answer:

Another view



The answer is usually more subtle

The full calibration suite

Time Base Calibration

Ensure the linearity of time digitization: performed by measuring the interval of double charge pulses across the sampling range

Local T_0 Calibration

Align in time all channels within a module, using the laser calibration system

Module T_0 Calibration

Align in time all modules of the TOP counter, using cosmics and collision data

Geometrical Alignment

Determine the actual position of each TOP module in the common reference frame using collision (cosmic) data

Common T_0 Calibration

Align in time with the other Belle II subdetectors

GOAL: uncertainty < 100 ps on the single detected photons

Timebase Calibration

- Took a while to get new FW release, SW work continued

/group/belle2/users/wangxl/iTOP/TBC/DB201612b/xval/. The data of run3523 and run3524 are also processed and skimed, and finally saved at **/ghi/fs01/belle2/bdata/group/detector/TOP/Skim-wangxl/2016-12/**.

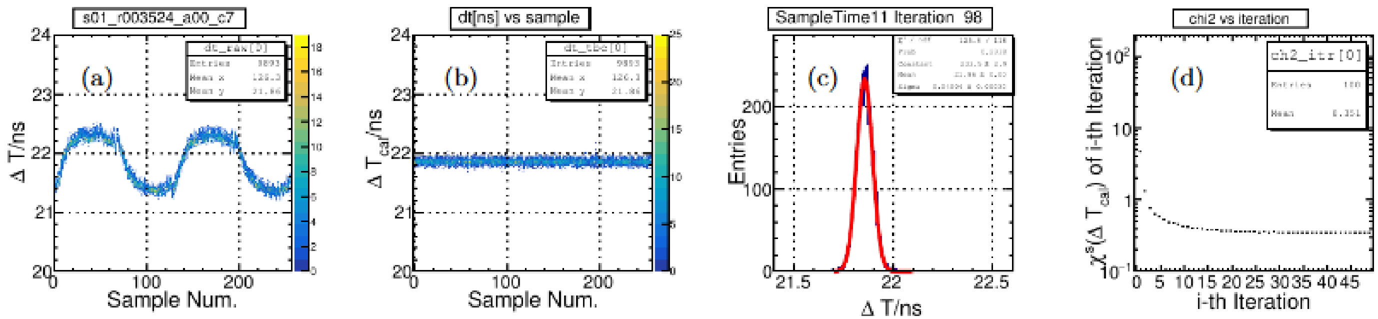


FIG. 1: Example of calculation on Slot_01 ASIC_00. (a) is the shape of time difference (ΔT) of the double pulses in channel_7 from the raw data, (b) is the dime difference after correction, (c) is the project of ΔT after correction and a fit performed to the distribution to show the mean and the resolution of ΔT, (d) shows how the χ^2 values change in the iterations of calculation.

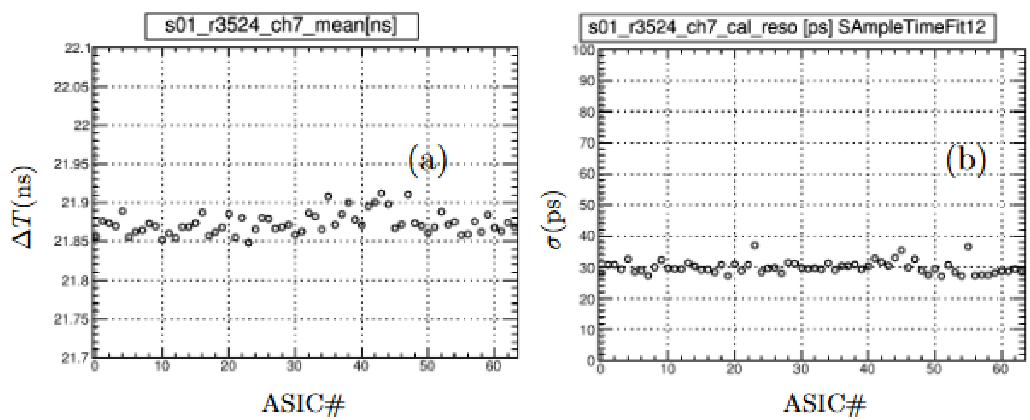
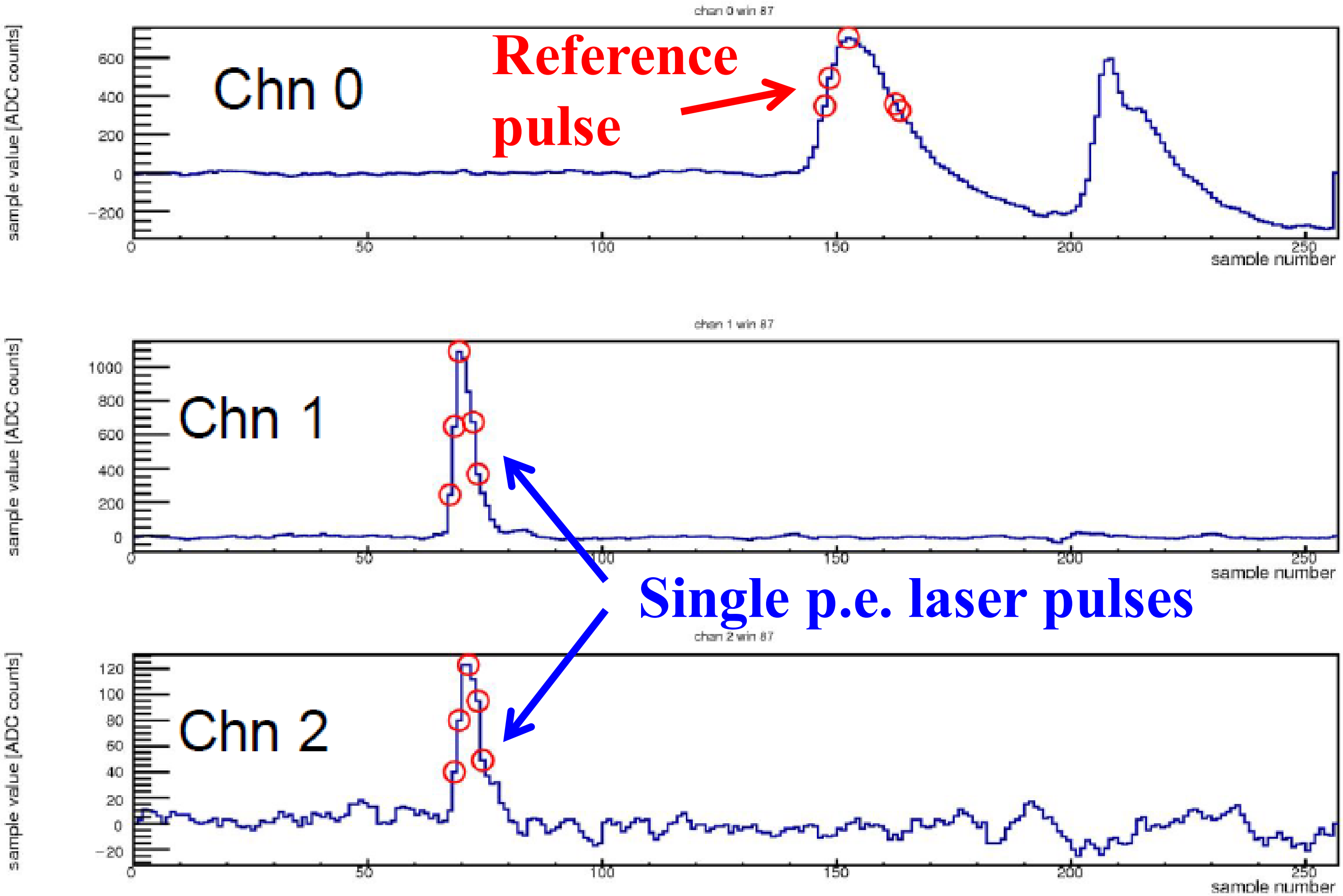


FIG. 2: Summary of calculation results of the 64 ASICs of Slot_01. Plot (a) is means of the time difference of double pulses, and (b) is the time resolution.

Region of Interest and Feature Extraction



Region of Interest and Feature Extraction Firmware running on Zynq "PS" side – too slow at highest rates

Single p.e., why bother?

- Postulate 1 (background level stays constant)
  - PMT gain: 5×10^5
  - Background hit rate: 500 kHz/PMT on average
  - Total exposure time in phase2: 10 hours/day x 60 days = 2.16×10^6 sec

→ 0.016 C/cm^2 (could be acceptable)

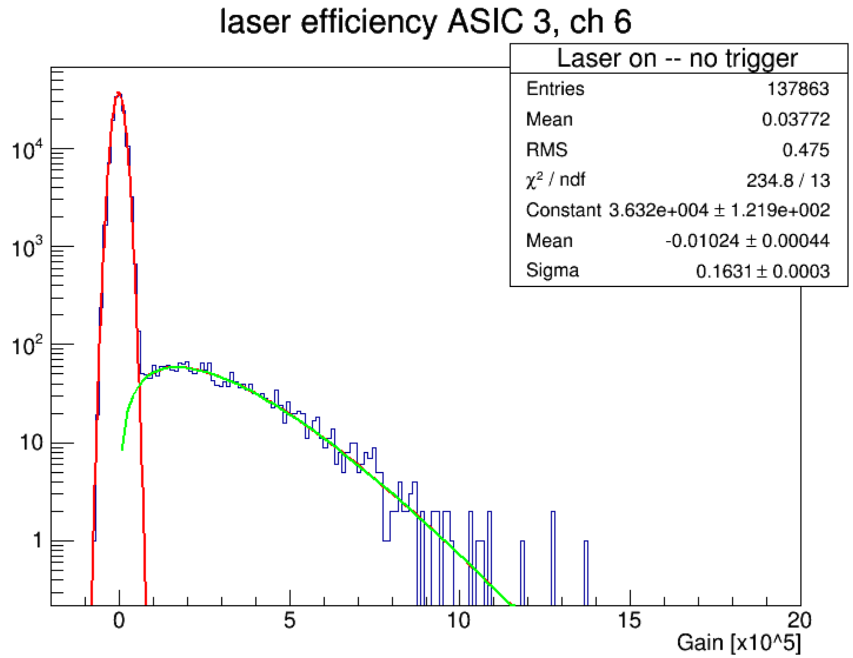
- Postulate 2 (background level normalized by the luminosity)
  - PMT gain: 5×10^5
  - Background hit rate and luminosity at this moment: 500 kHz/PMT and 8×10^{32} $/cm^2/s$ on average
  - Integrated luminosity in phase2: 20 fb^{-1}

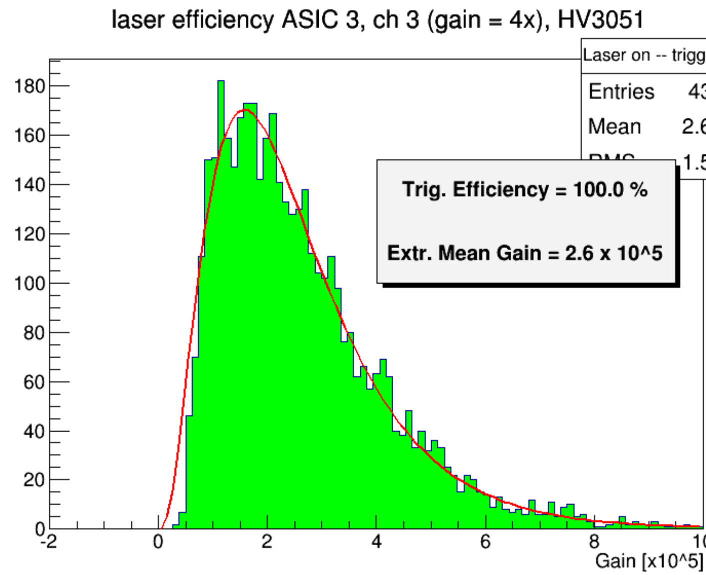
→ 0.189 C/cm^2 (not acceptable)

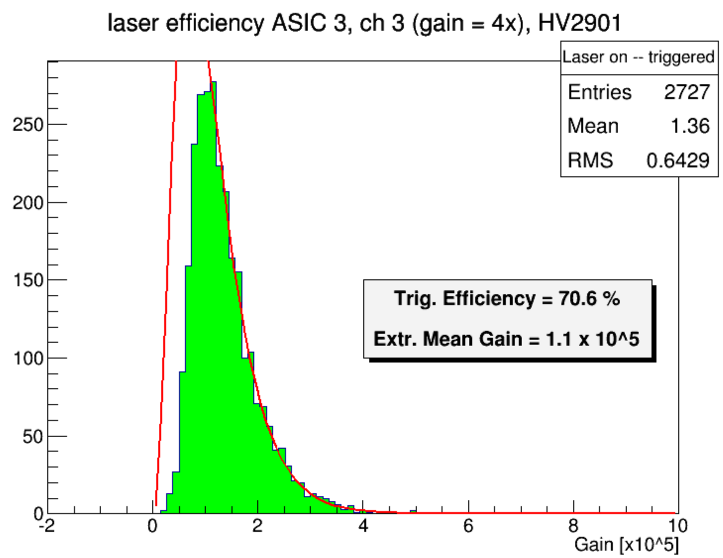
cf. life of conventional MCP-PMT = 0.3-1.8 C/cm^2

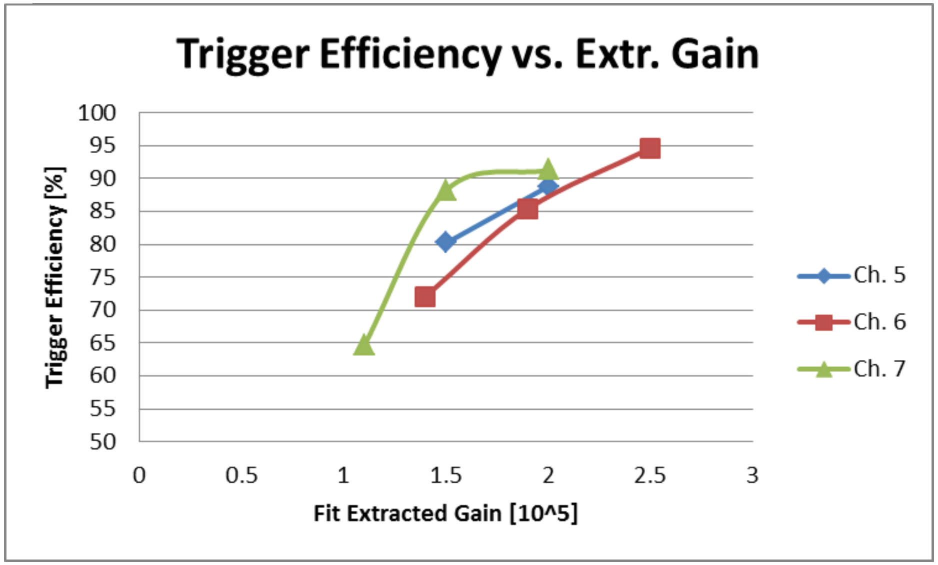
K. Matsuoka (Nagoya) – 50% of PMTs are conventional

Gain and Efficiency



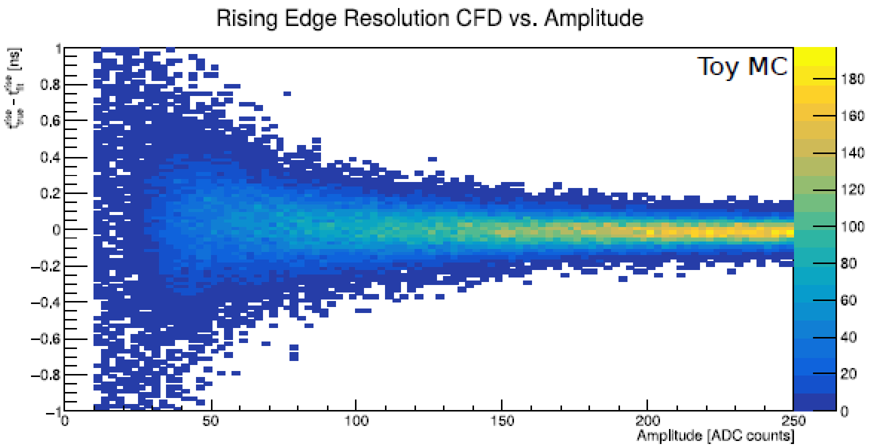






Low PMT Gain Operation

- current feature extraction uses constant fraction discrimination to extract signal timing
- resolution deteriorates at small signal amplitudes

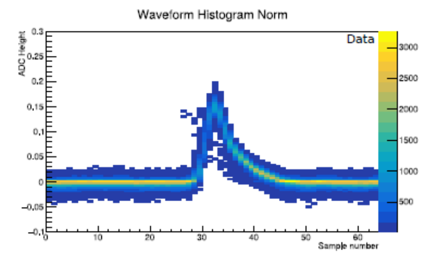


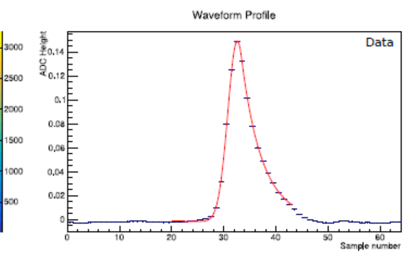
- use template fitter to improve resolution at small amplitudes/high noise

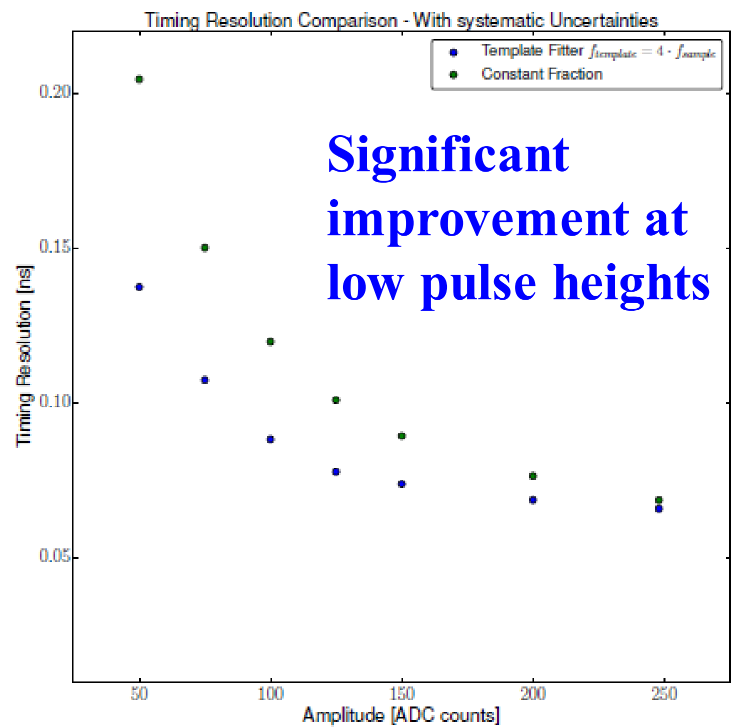
Necessary to maximize MCP lifetime

Studying how best to implement (PS is probably too slow)

- using laser data from Hawaii test setup
- TProfile to get waveform template
- fit with central Gaussian and exponential tail



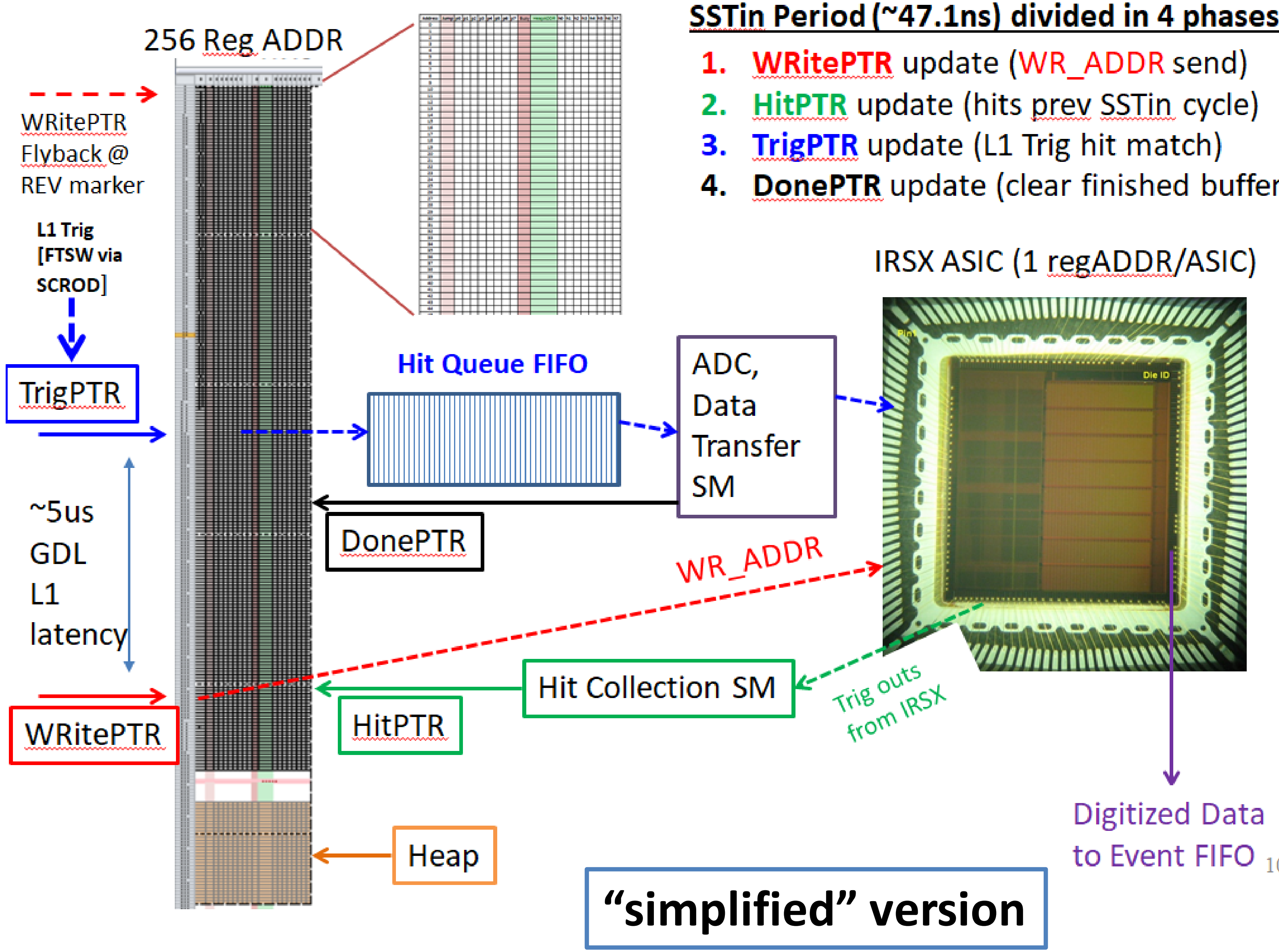




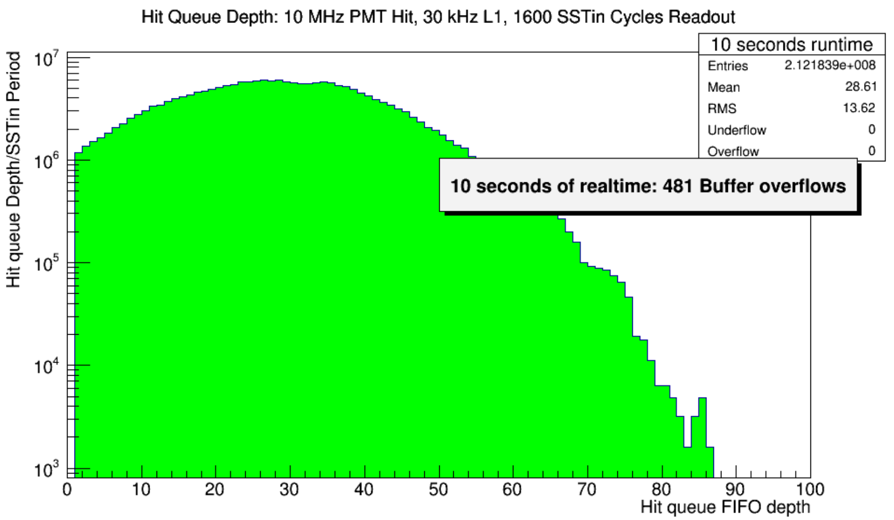
Multi-hit Analog Buffer Management

SSTin Period (~47.1ns) divided in 4 phases:

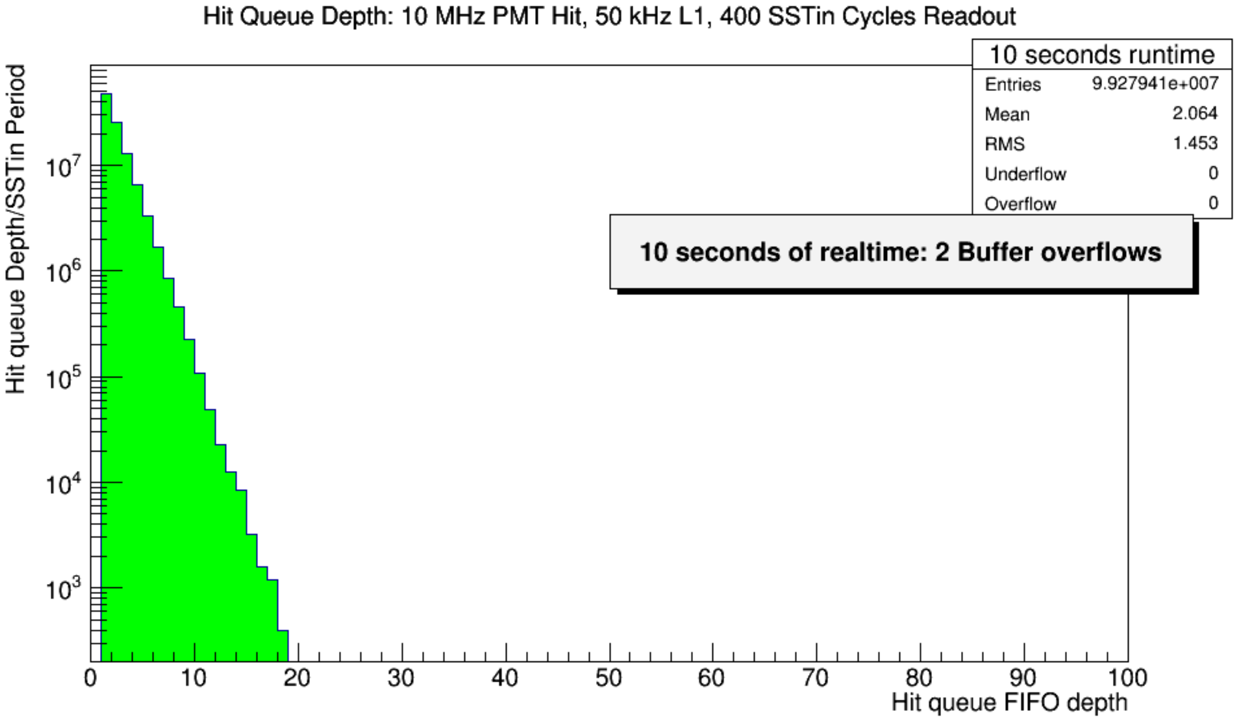
1. **WRitePTR** update (WR_ADDR send)
2. **HitPTR** update (hits prev SSTin cycle)
3. **TrigPTR** update (L1 Trig hit match)
4. **DonePTR** update (clear finished buffers)



30kHz L1, high occupancy emulation



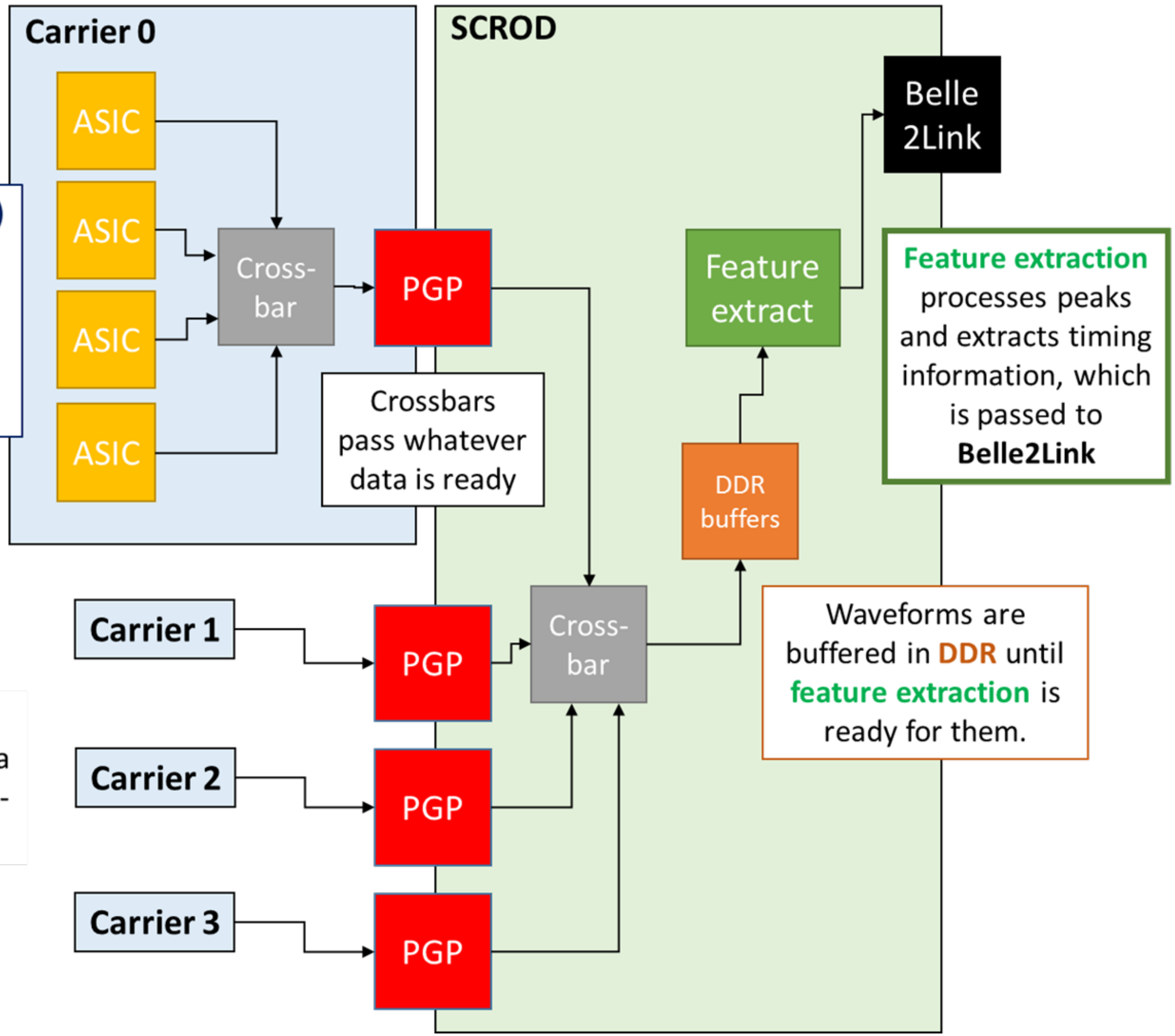
30kHz L1 trigger, 10 MHz background photons/PMT, multi-hit, multi-event buffering



At 400 SSTin Cycles (~19us per single photon hit), can run at 50kHz, so plenty of margin

Firmware Complexity (100k lines of code…)

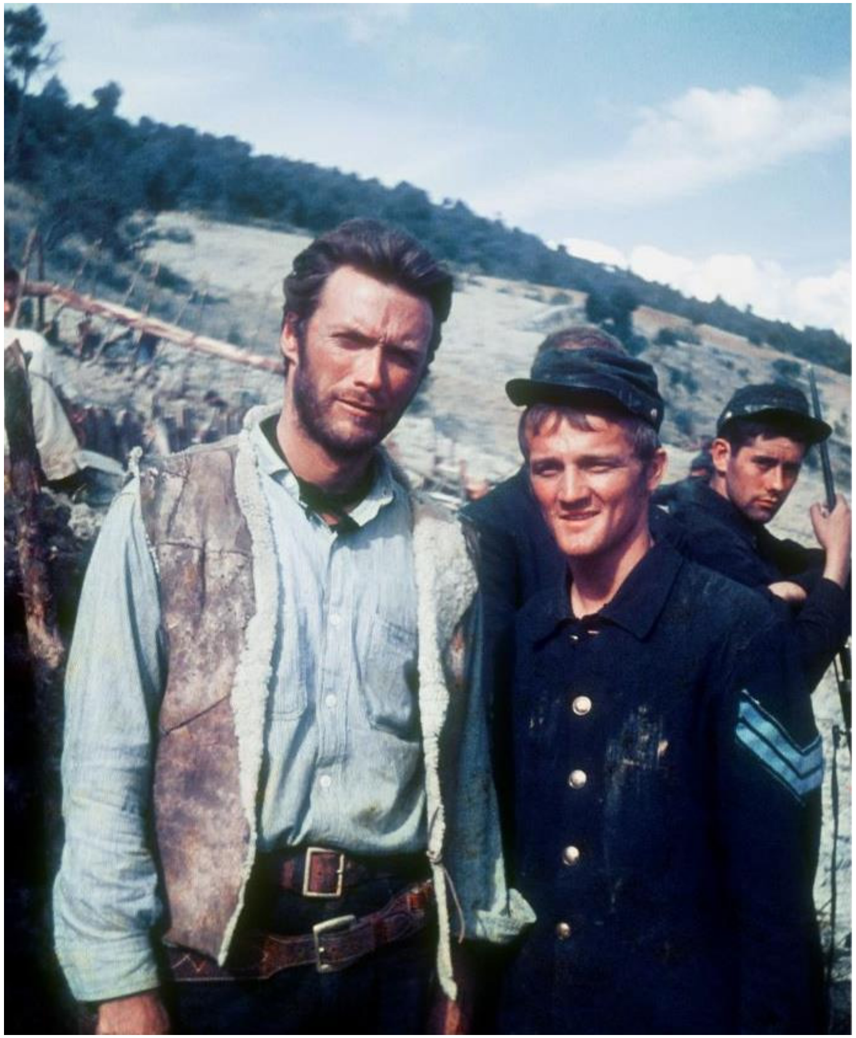
Region of interest (ROI) firmware on carrier selects only windows with threshold trigger matches and passes them to the crossbar.



Data transfer between boards is via **PGP (SLAC)**, a multi-virtual channel high-speed serial link.

True Summary

Belle II TOP Detector Readout status



True Summary

Belle II TOP Detector Readout status

- **The Good:**
  - **Mostly things are working as designed**
  - **Quite a bit of margin for increased performance**
- **The Bad:**
  - **Programing and configuration lengthy**
  - **At thermal limit**
- **The Ugly**
  - **Detector installed 2 years ago, Production FW still a work in progress**
  - **Very complicated (huge barrier to entry)**

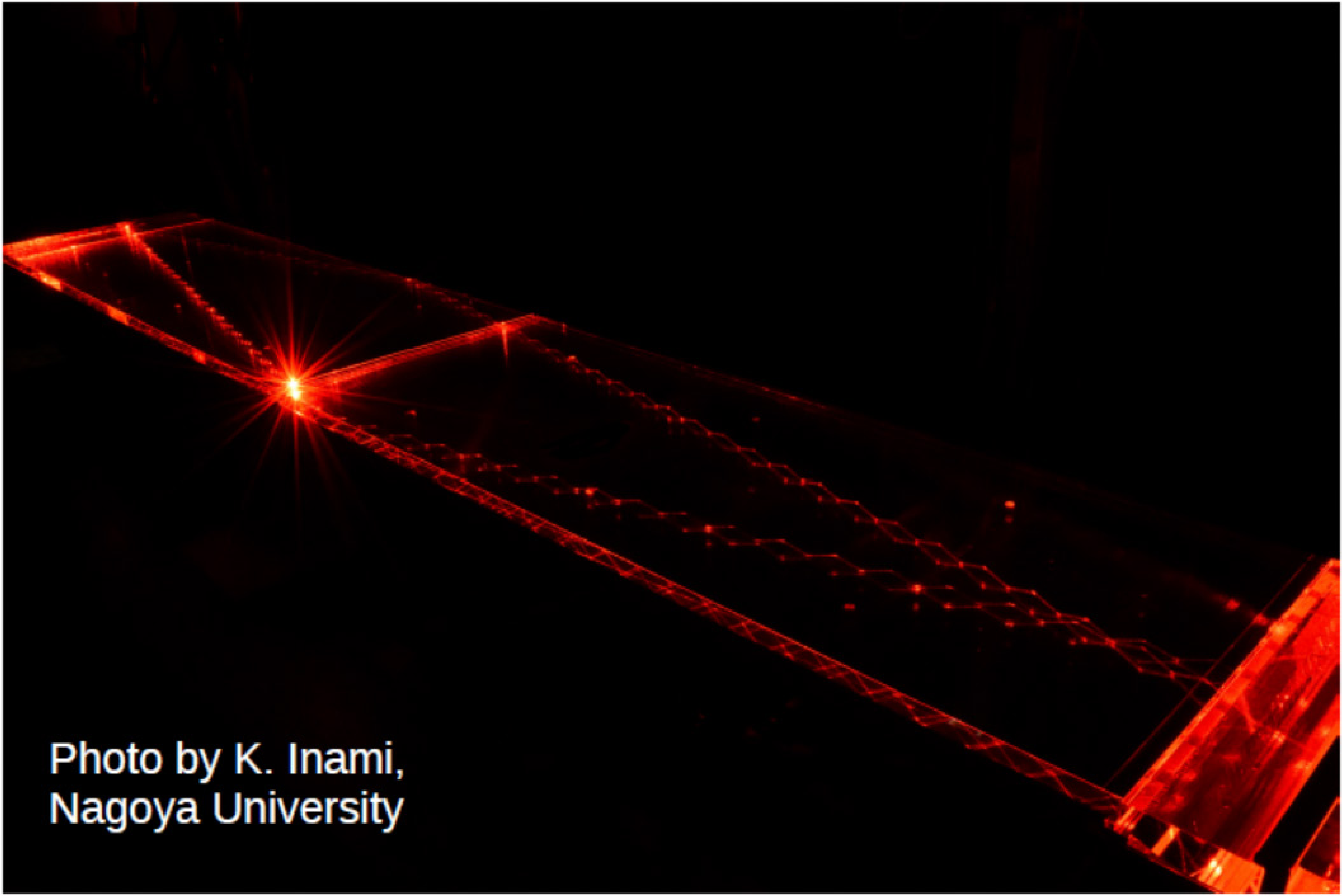
What might do differently?

1. **Programming and Configuration**
   - **Higher speed JTAG interface (or …)**
   - **Taking on both Vivado and Zynq (SDK) ?**

2. **Architecture**
   - **High speed serial communications – reduce to single FPGA?**
   - **Dedicated amplifier ASIC?**

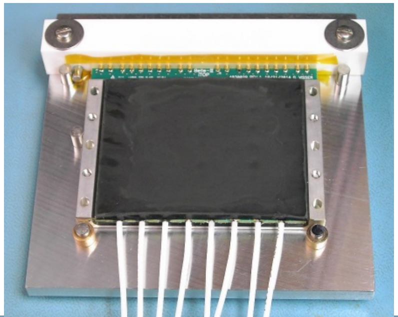
3. **ASIC**
   - **Simpler storage scheme**
   - **Incorporate simple buffer management, readout state machines on chip**

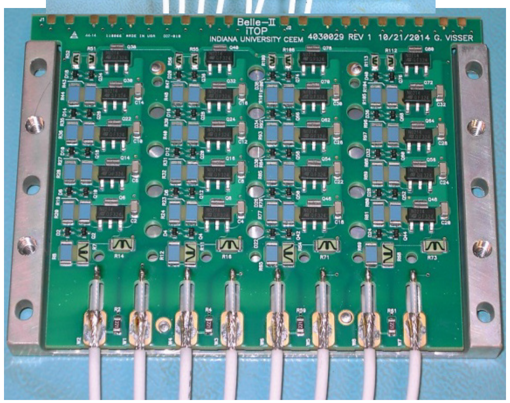
Back-up slides

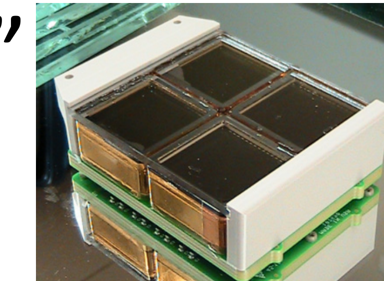


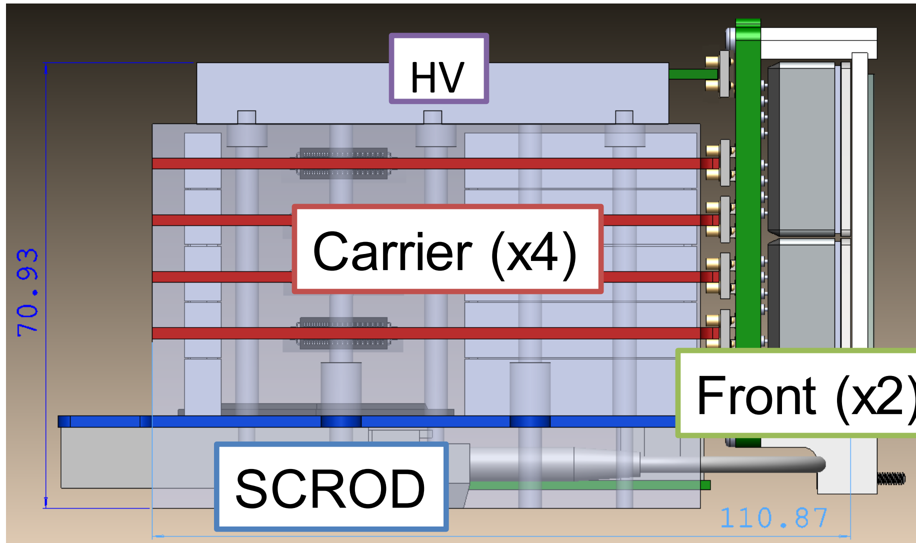
iTOP Readout "boardstack"

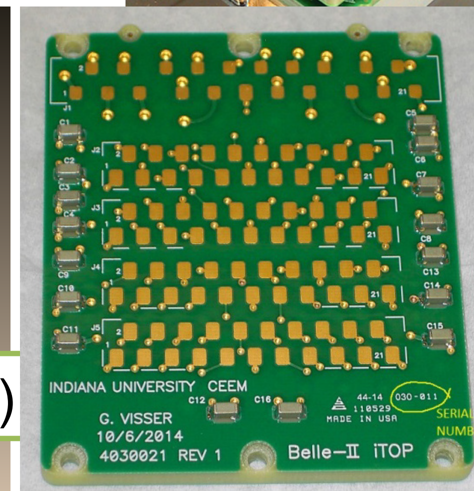
(1 of 4 per TOP Module)

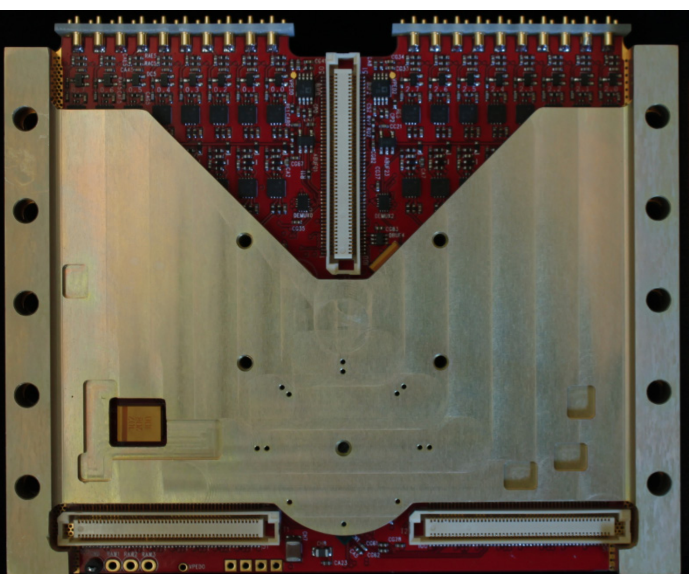


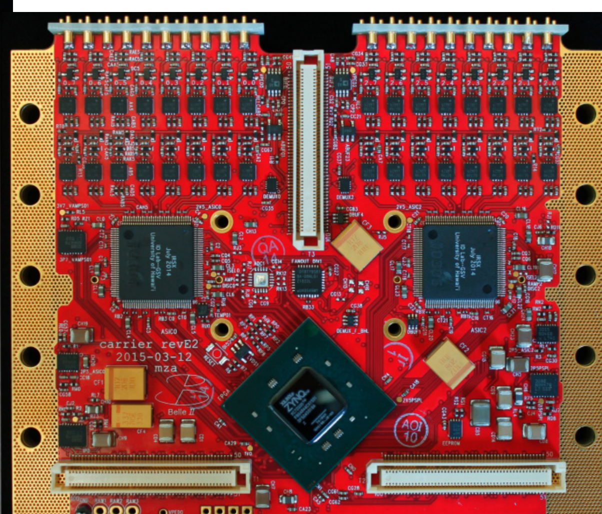




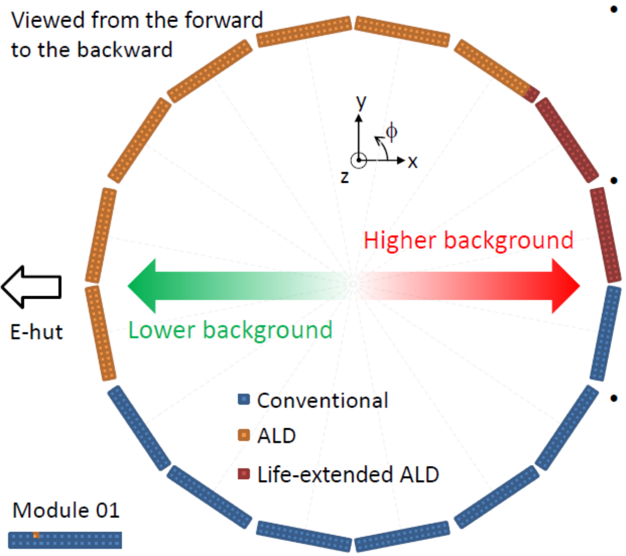








PMT Replacement

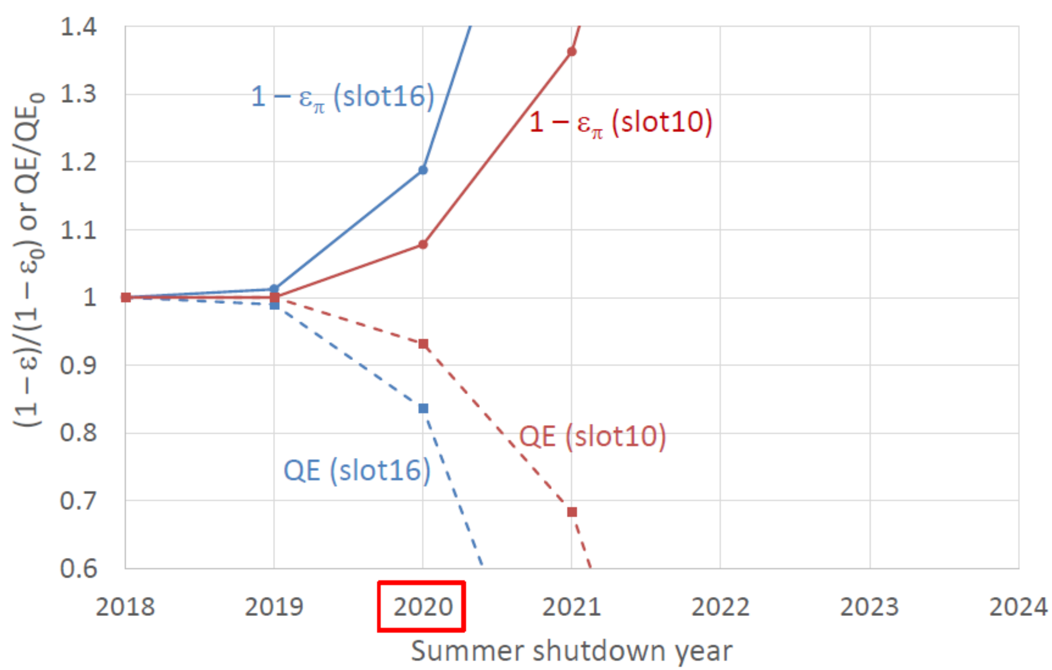


- The 224 conventional MCP-PMTs in the 7 slots have to be replaced due to the QE degradation by the beam background.
- In 2015 the time of the replacement was estimated as the 2020 summer shutdown.

→ Revisit the estimation.

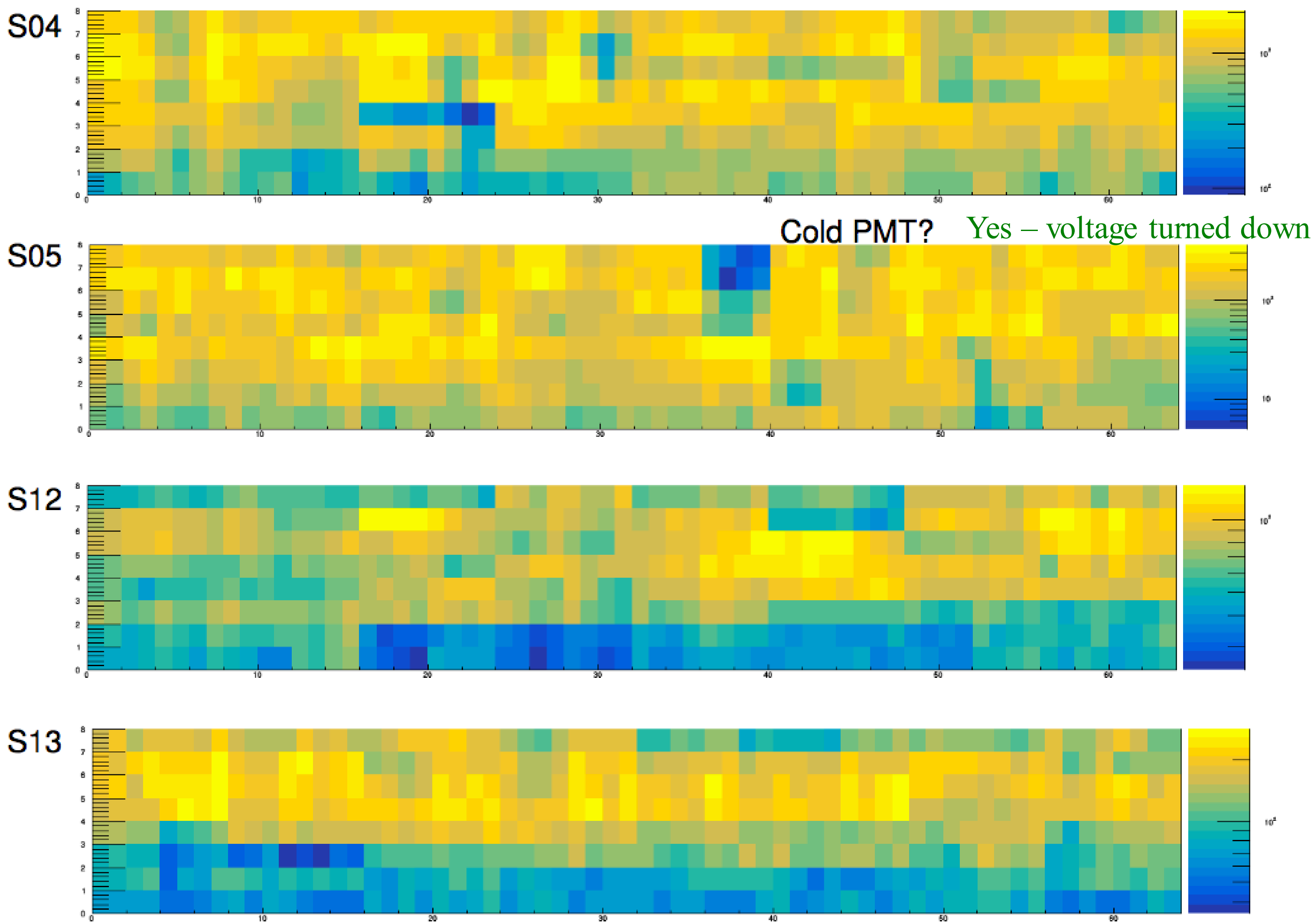
- Need additional mass production of the MCP-PMTs for the replacement.

→ Discuss the production plan.

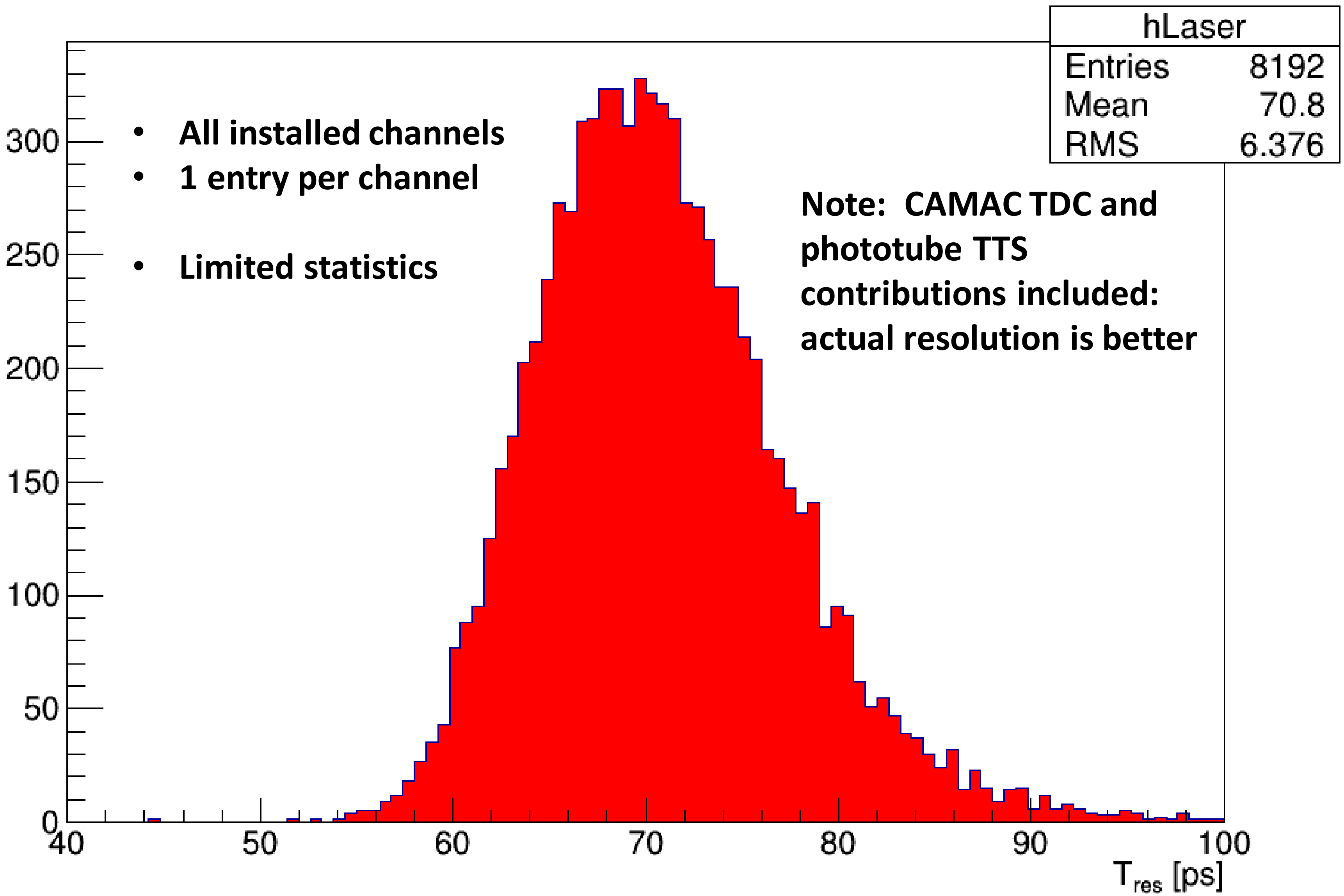


"1x BG"

Direct hitmap



Single photon timing

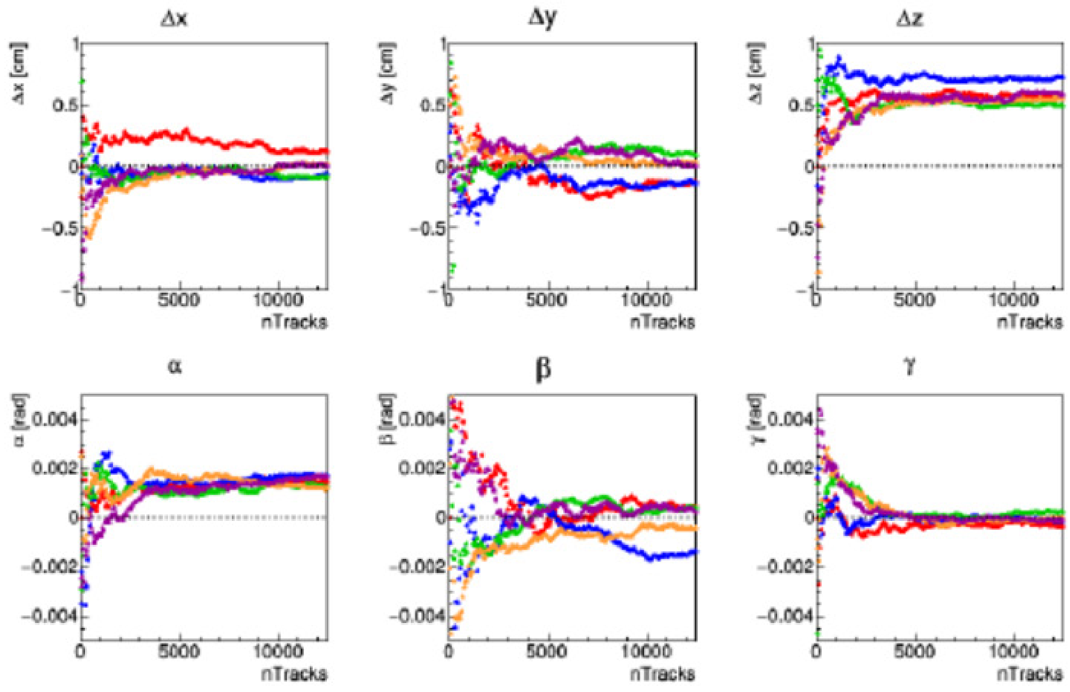


- **All installed channels**
- **1 entry per channel**
- **Limited statistics**

Note: CAMAC TDC and phototube TTS contributions included: actual resolution is better

Geometrical Alignment

- Still missing: precise determination of actual position of TOP modules;
- Strategy: select a sample of muons, and iteratively maximize the Likelihood L_{μ} varying the shifts Δx, Δy, Δz and rotation angles α, β, γ about the three coordinate axes;
- With $e^+e^- \to \mu^+\mu^-$ events, can get a precision of ~0.3 mm on the shifts and 0.3 mrad on the rotation angles;
- Tested the procedure on cosmic data (some biases are expected).



Alignment on 5 independent samples of cosmic data.
Very preliminary!

PMT Rotation Update (2 rotation issues)

- The PMT tube is made of Kovar and suffers ~1 kgf/PMT in 1.5 T (maximum ~1.4 kgf/PMT in ~1.1 T).

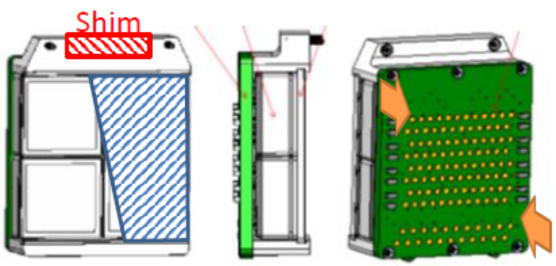
<u>Rotation of PMT module</u>

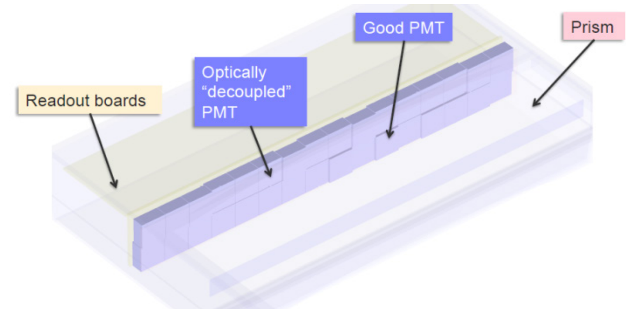
- Large effect on photon transmittance due to bubbles of the optical oil on the Si cookie
- Has been fixed in situ by shimming

<u>Rotation of PMT</u>

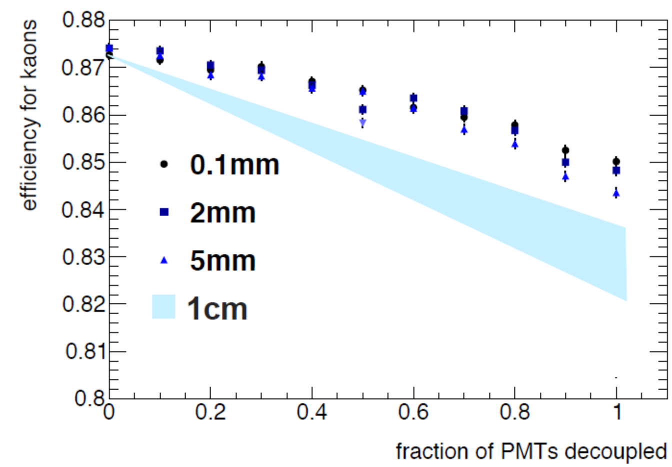
- Effect only for photons of larger incident angles than ~43° if the peel-off surface is clear.
- Wil be fixed if necessary after phase 2

Study of physics impact of decoupled PMTs (Modest effect)



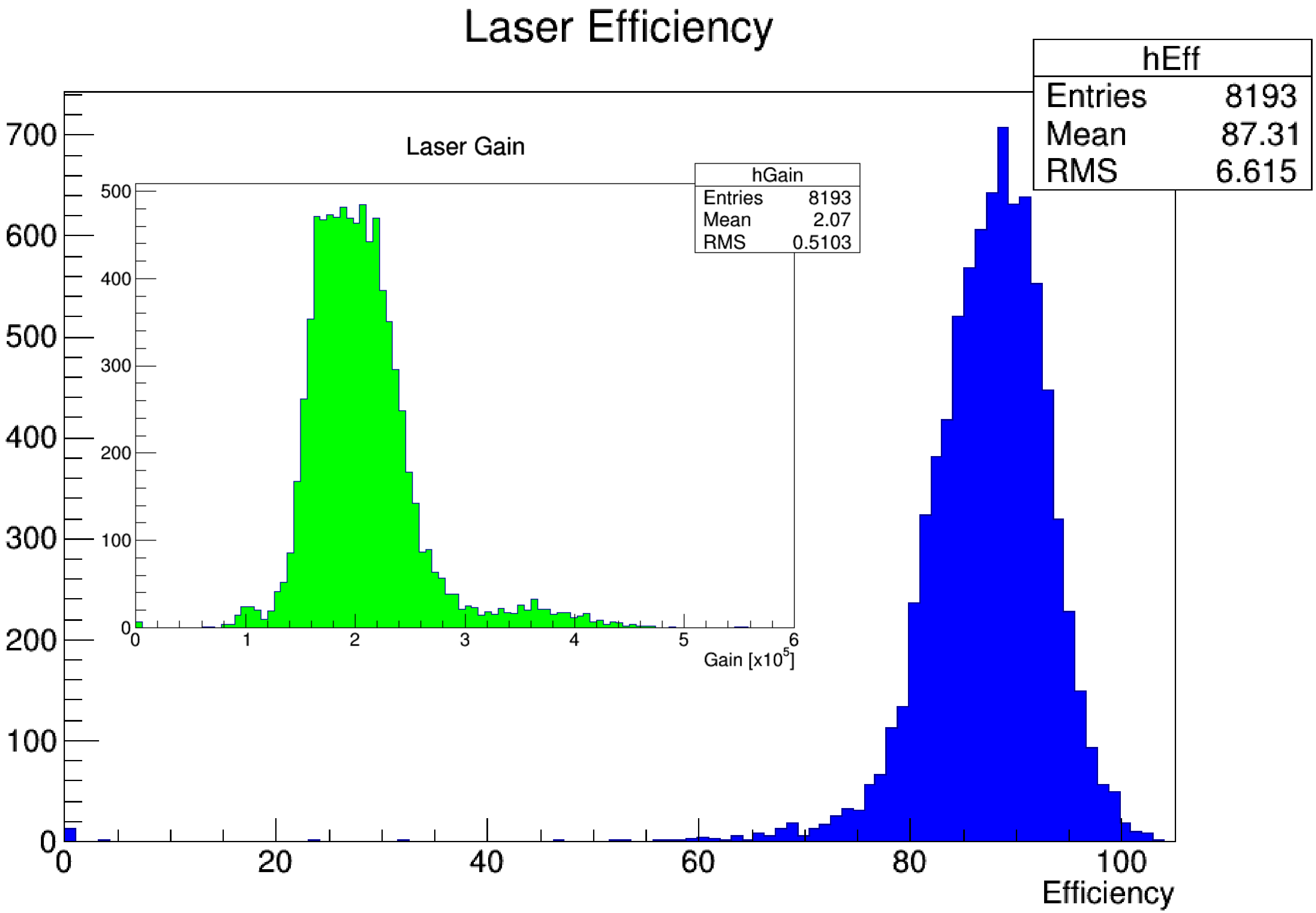


Year	2017				2018				2019				2020		
Month	1	4	7	10	1	4	7	10	1	4	7	10	1	4	7
Global schedule					Phase 2				Physics run			Physics run			
PMT production	Current production														
			Another small production												
							Mass production if necessary								
PMT test	■	■	■	■	■	■	■	■	■	■	■	■	■		
PMT installation													Assy		Install

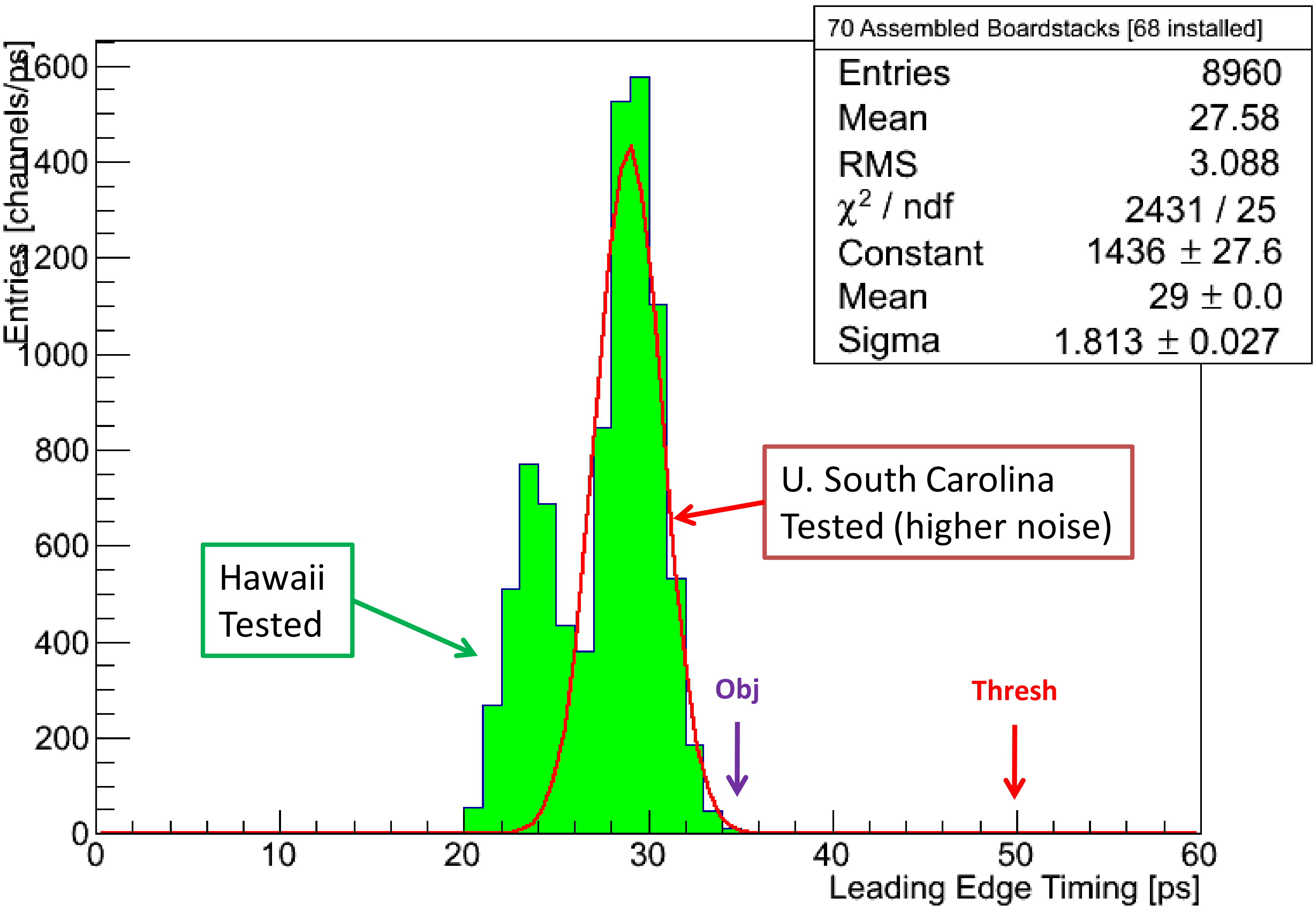


Plan in place to replace ~50% of PMTs

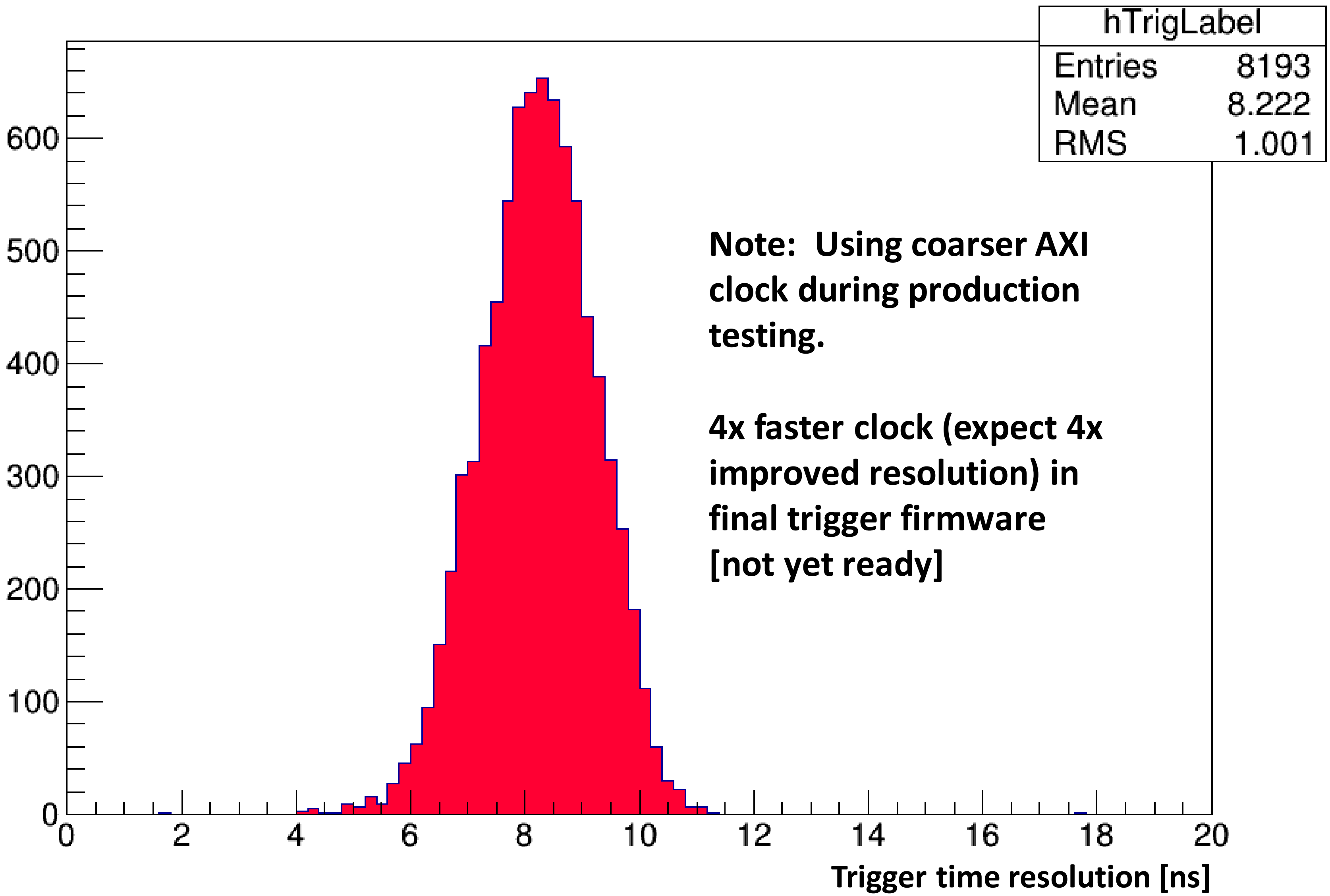
PERFORMANCE SUMMARIES



Verification: Event Time Zero



Verification: Event Trigger Time



Note: Using coarser AXI clock during production testing.

4x faster clock (expect 4x improved resolution) in final trigger firmware [not yet ready]

Production single photon testing