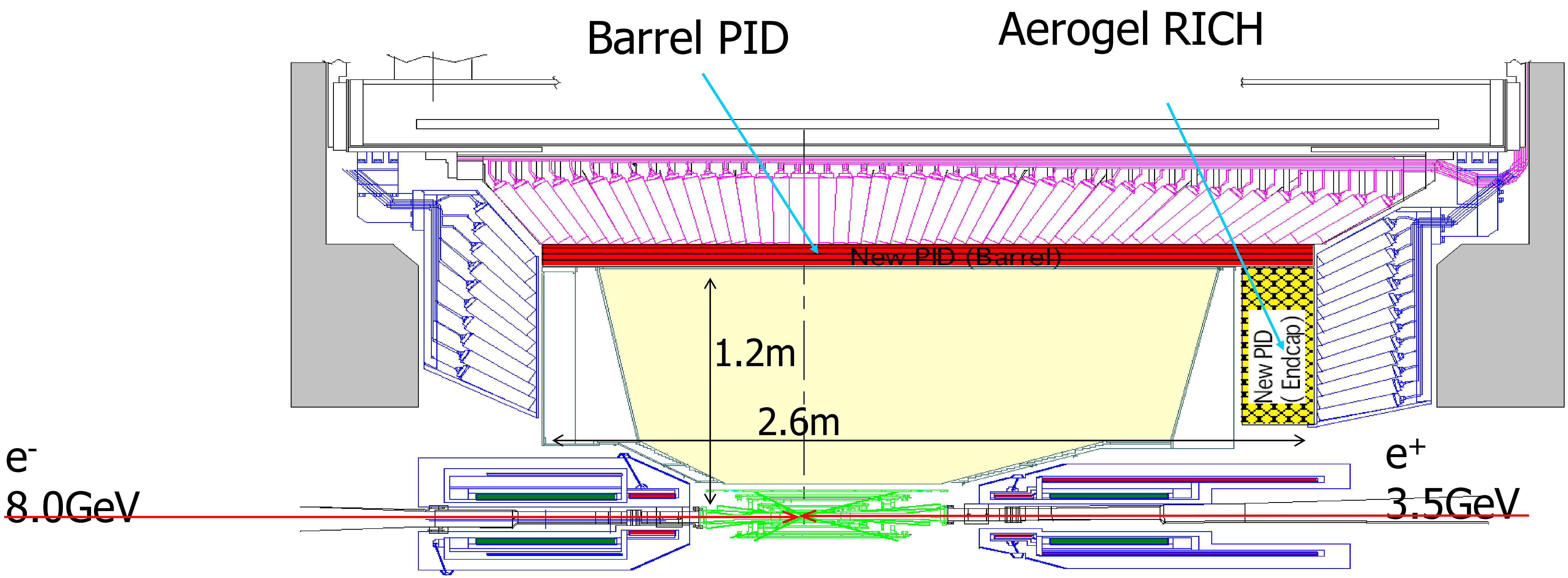
Performance of the imaging Time Of Propagation detector during the first Belle II Physics run

Gary Varner
University of Hawaii

Upgraded Belle II detector

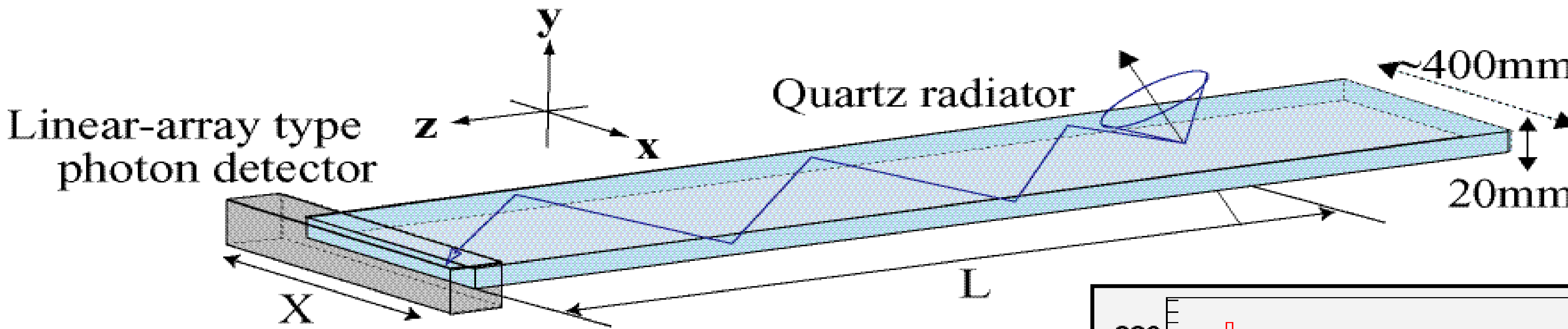
- PID (π/K) detectors
  - Inside current calorimeter
  - Use less material and allow more tracking volume
  - → Available geometry defines form factor
    -

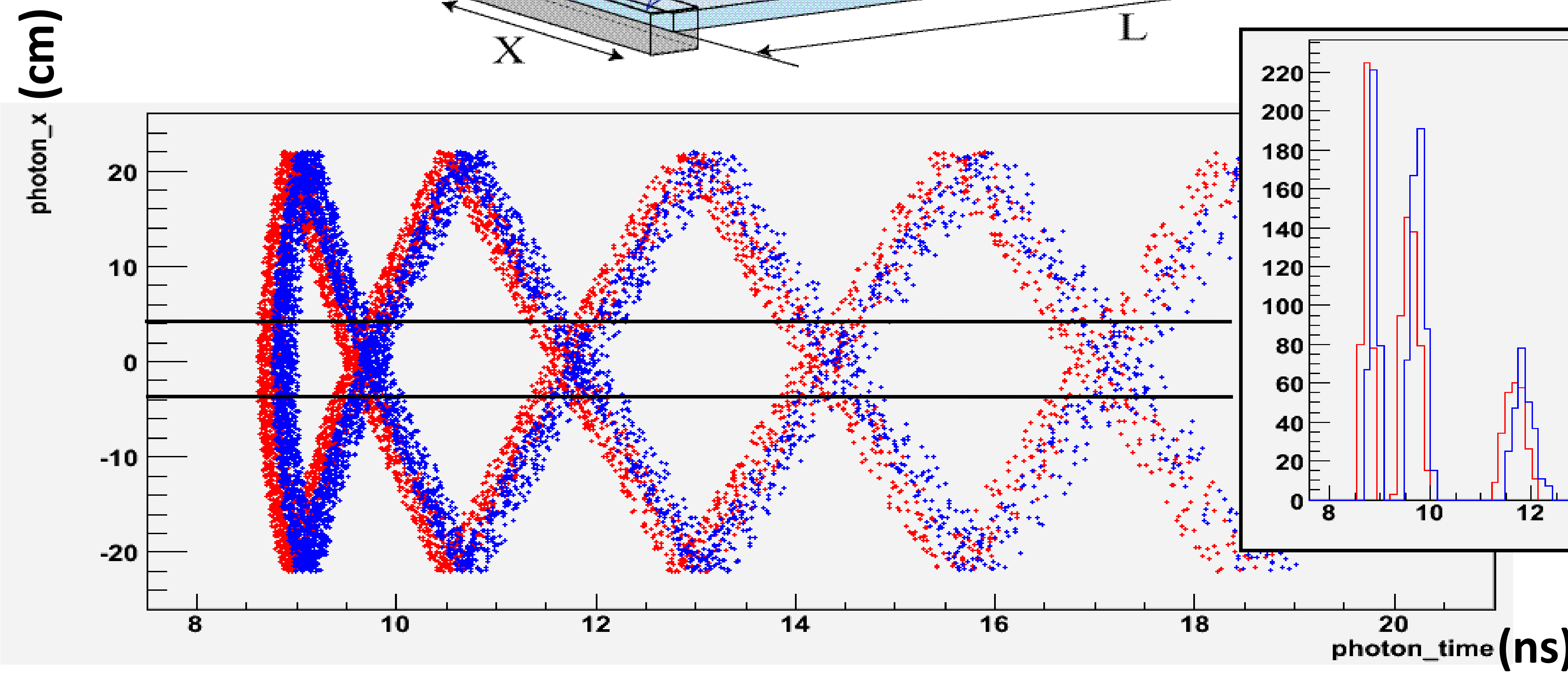


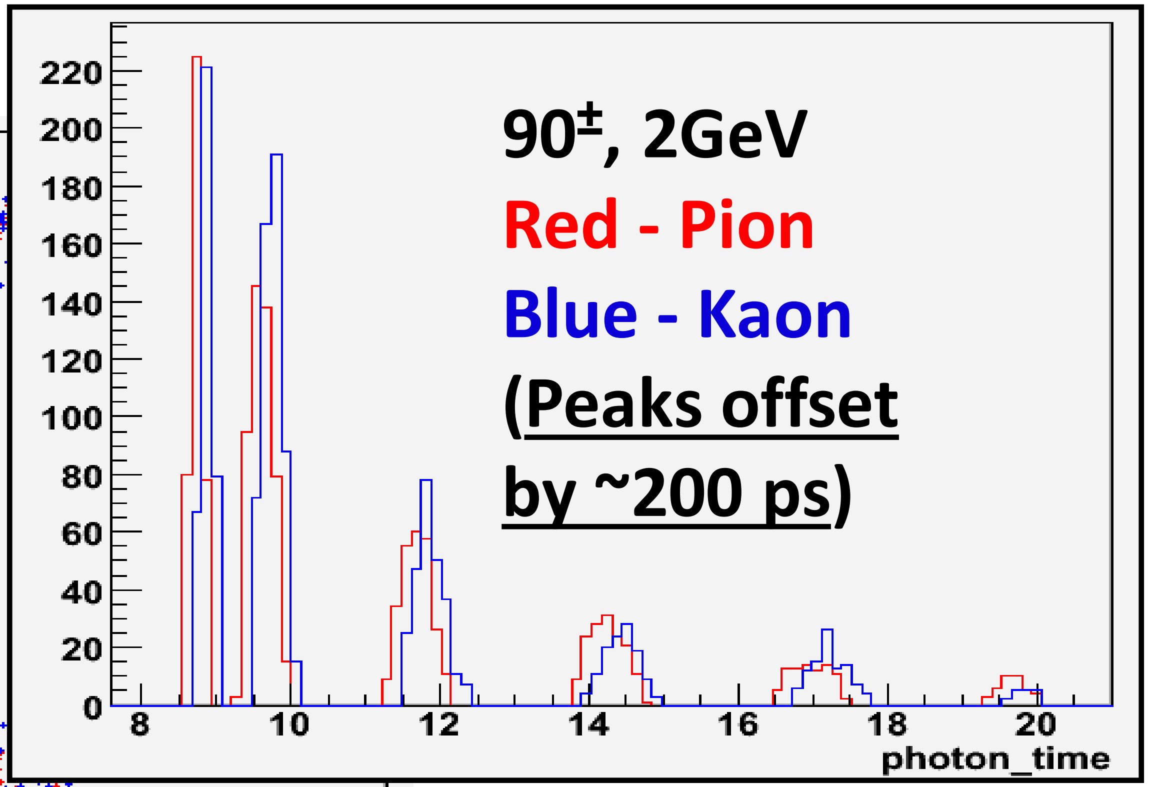
Time-of-Propagation (TOP) Counter

NIM A494 (2002) 430-435. **NIM A595 (2008) 96-99.**

- Work at bar end, measure x,t, not y ➔ compact!







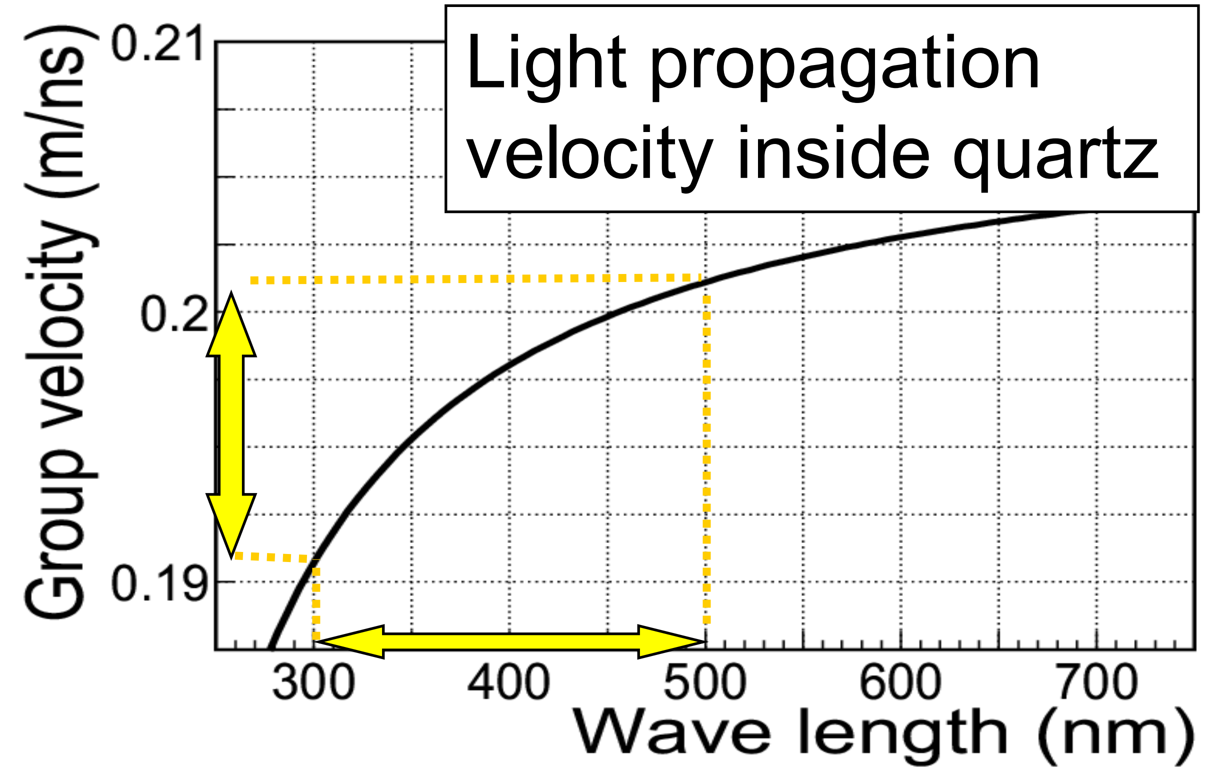
Chromatic dispersion

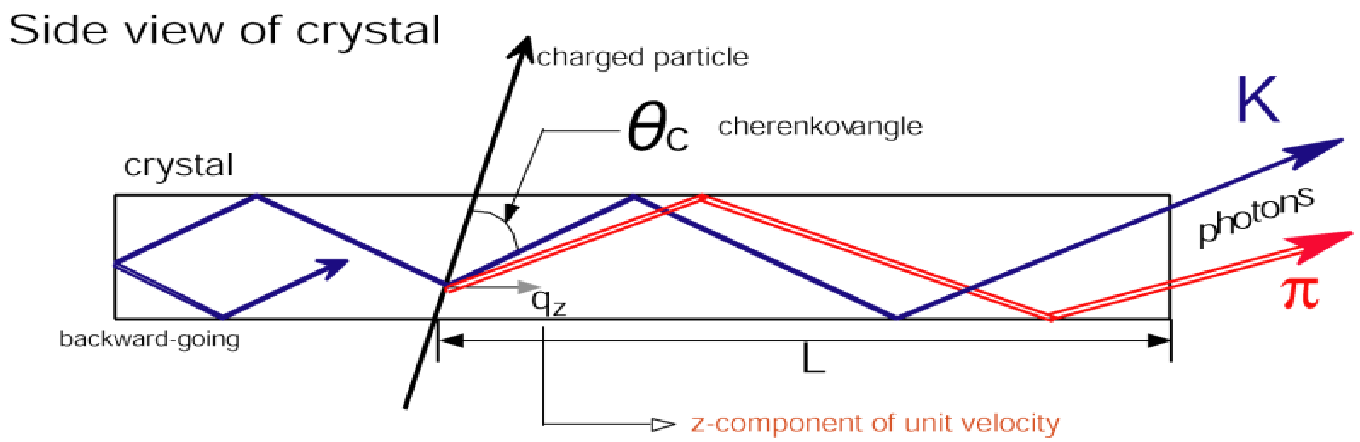
Variation of propagation velocity depending on the wavelength of Cherenkov photons

- Due to wavelength spread of detected photons
- → propagation time dispersion

- Longer propagation length

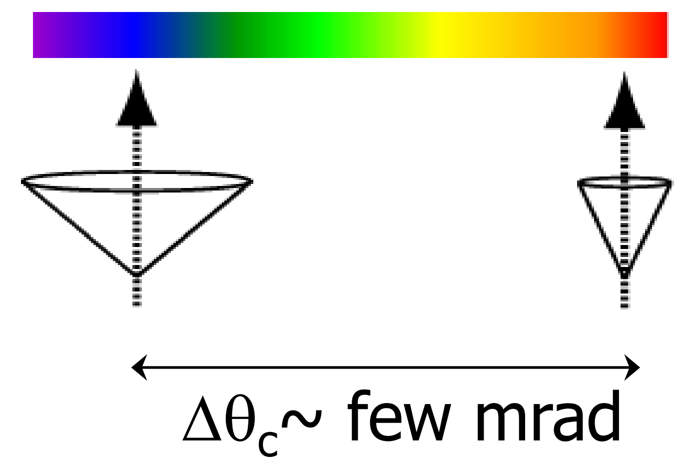
→ Improves ring image difference
But, decreases time resolution.

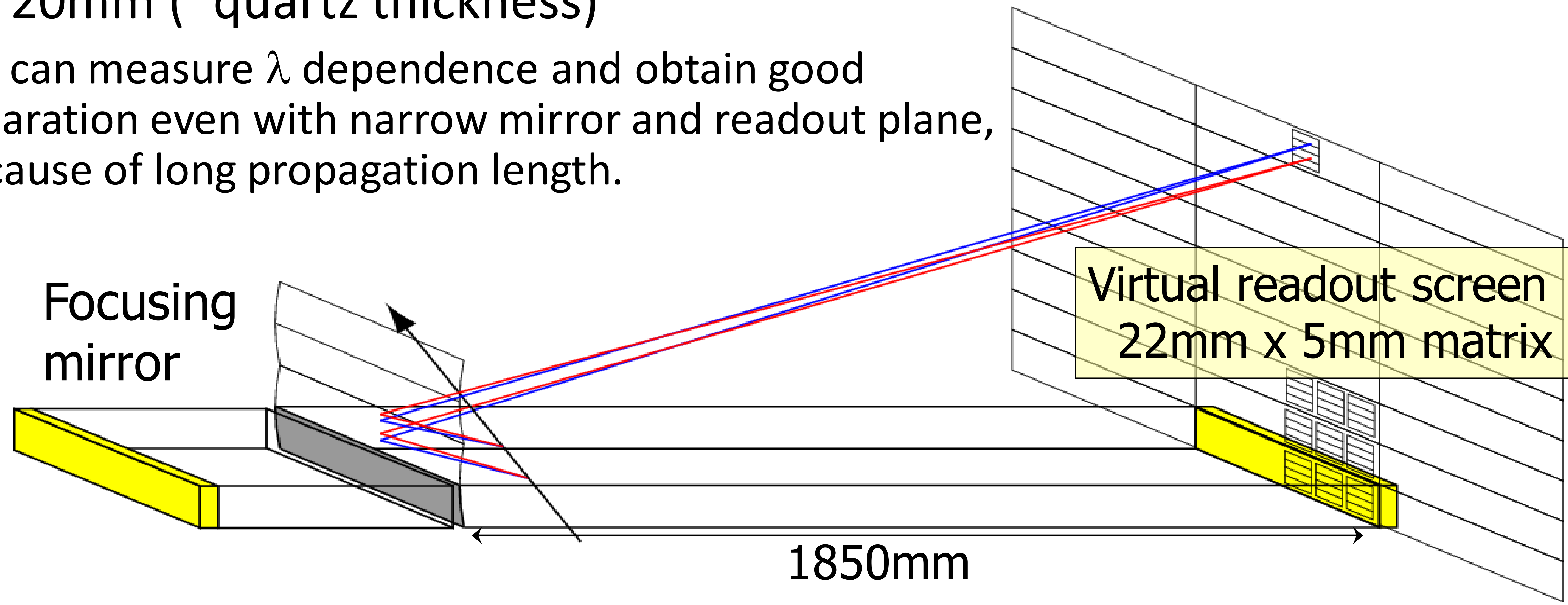




Focusing TOP

- Use λ dependence of Cherenkov angle to correct chromaticity
  - Angle information → y position
  - Reconstruct Ring image from 3D information (time, x and y).
- $\Delta\theta_c$~ few mrad over sensitive λ range
- → Δy~20mm (~quartz thickness)
  - We can measure λ dependence and obtain good separation even with narrow mirror and readout plane, because of long propagation length.



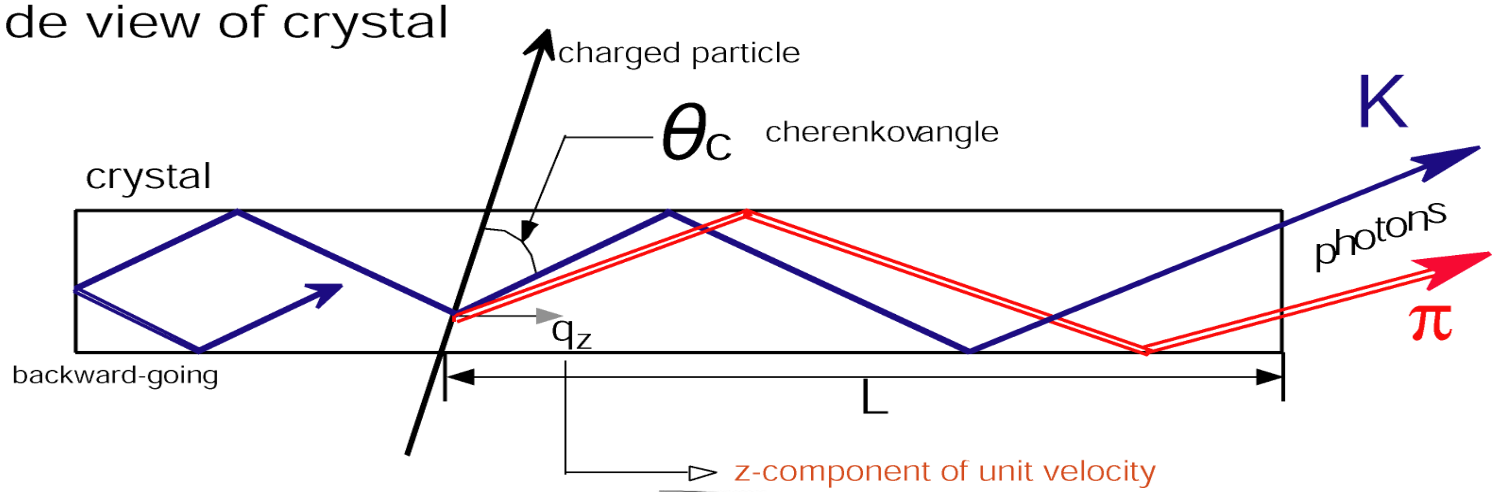


imaging TOP (iTOP)

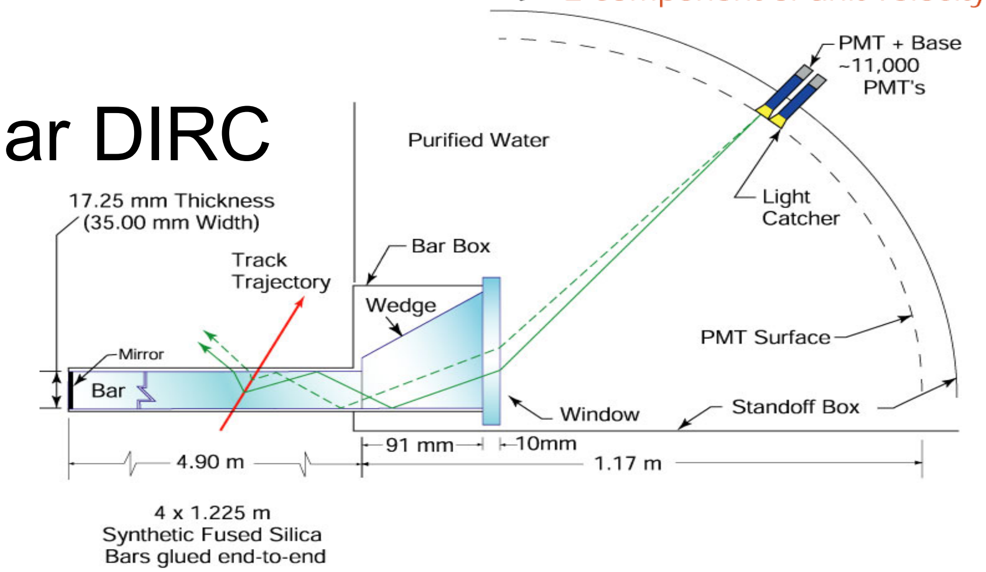
Concept: Use best of both TOP (timing) and DIRC while fit in Belle PID envelope

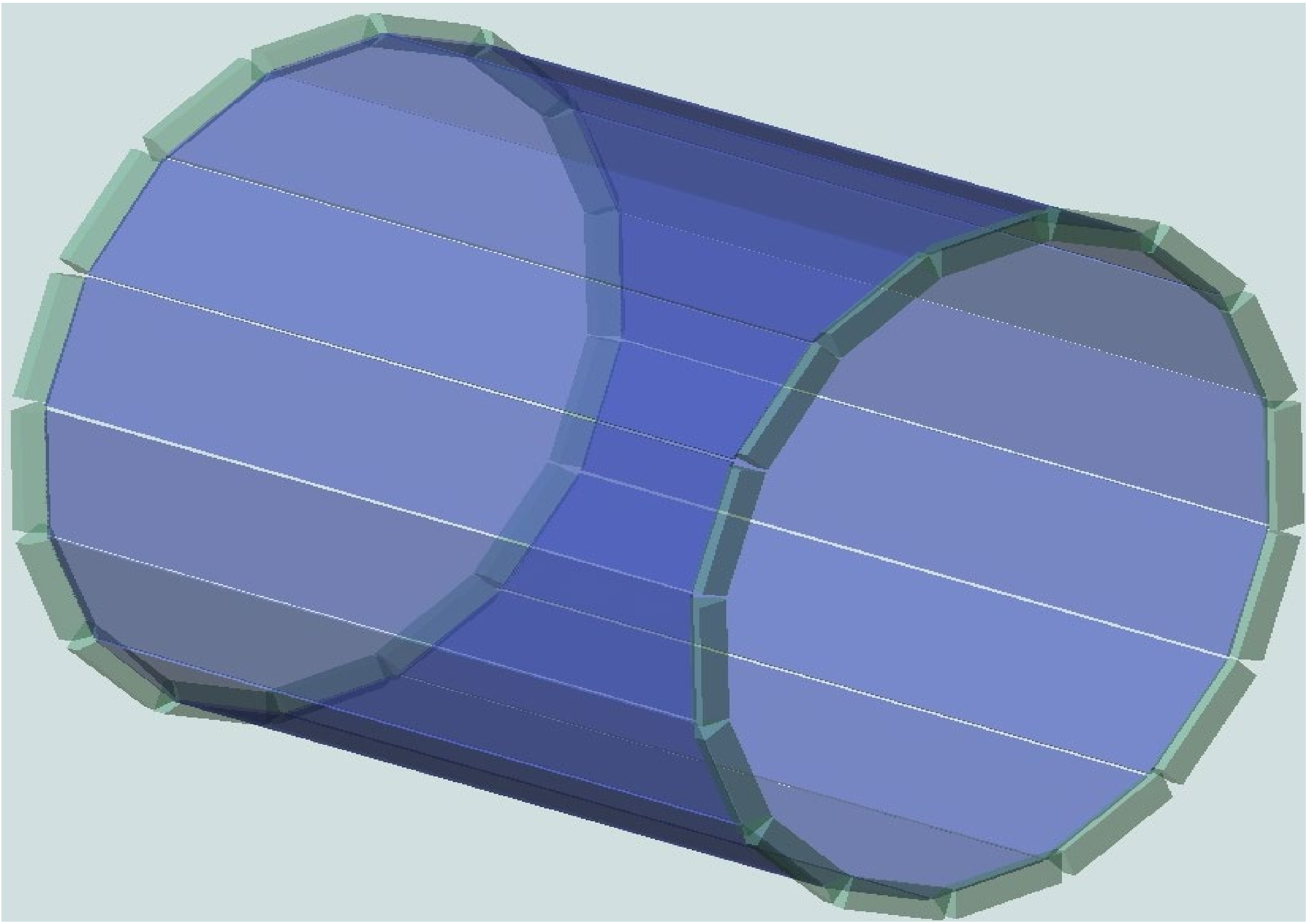
NIM A623 (2010) 297-299.

Side view of crystal



BaBar DIRC

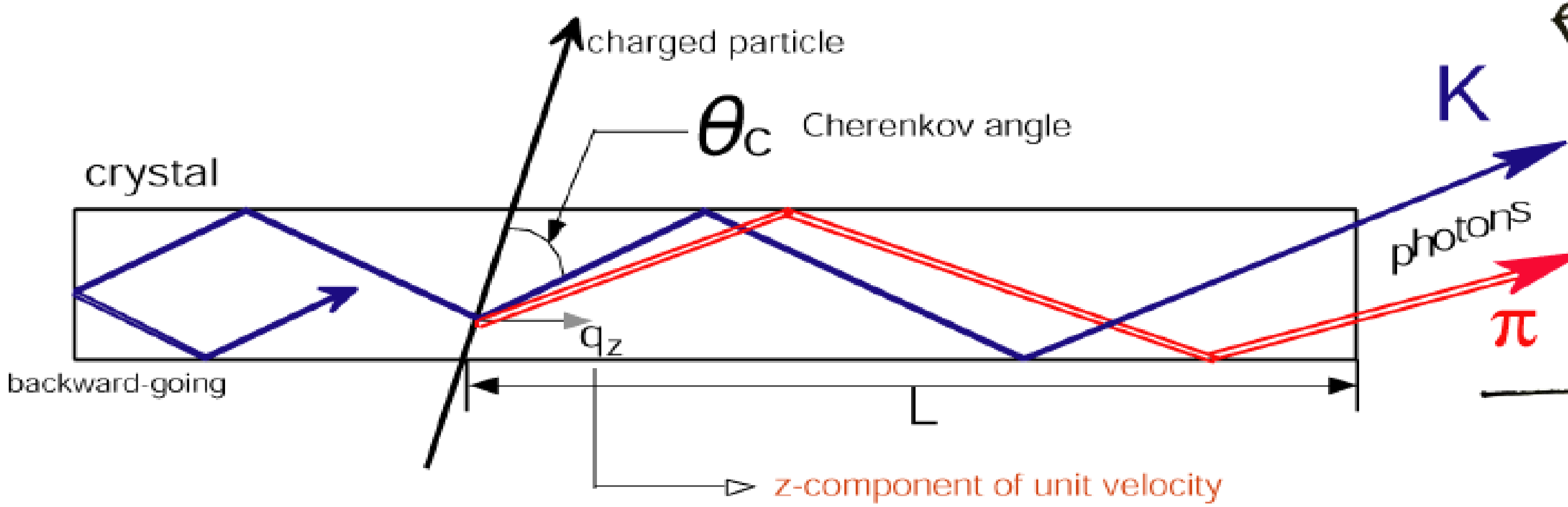


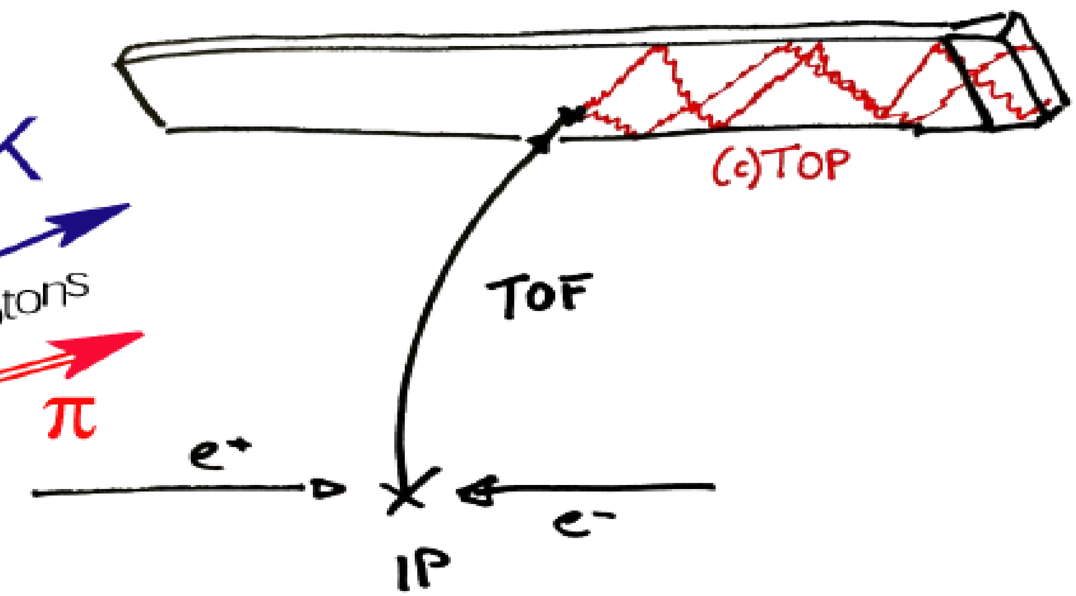


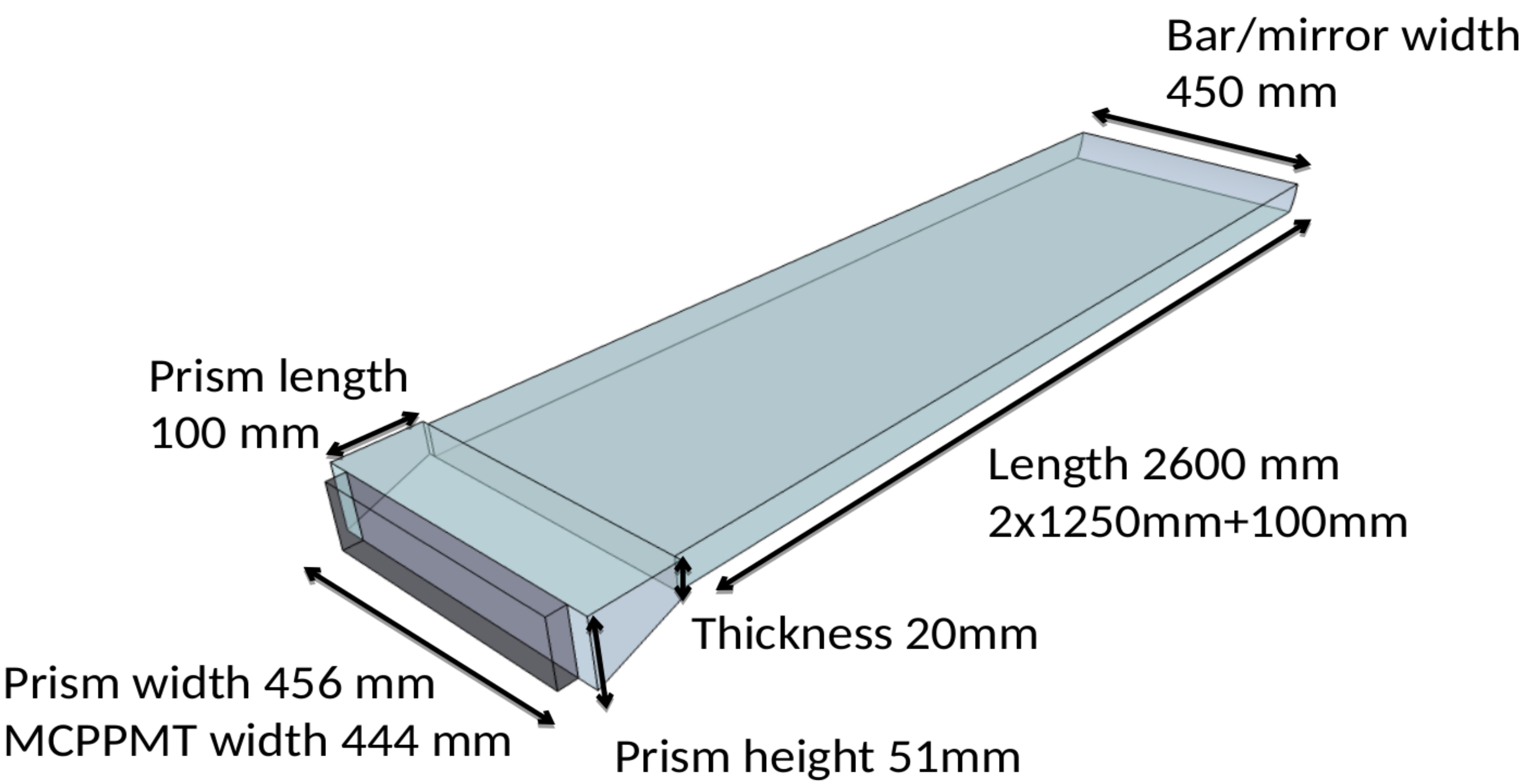
Use wide bars like proposed TOP counter

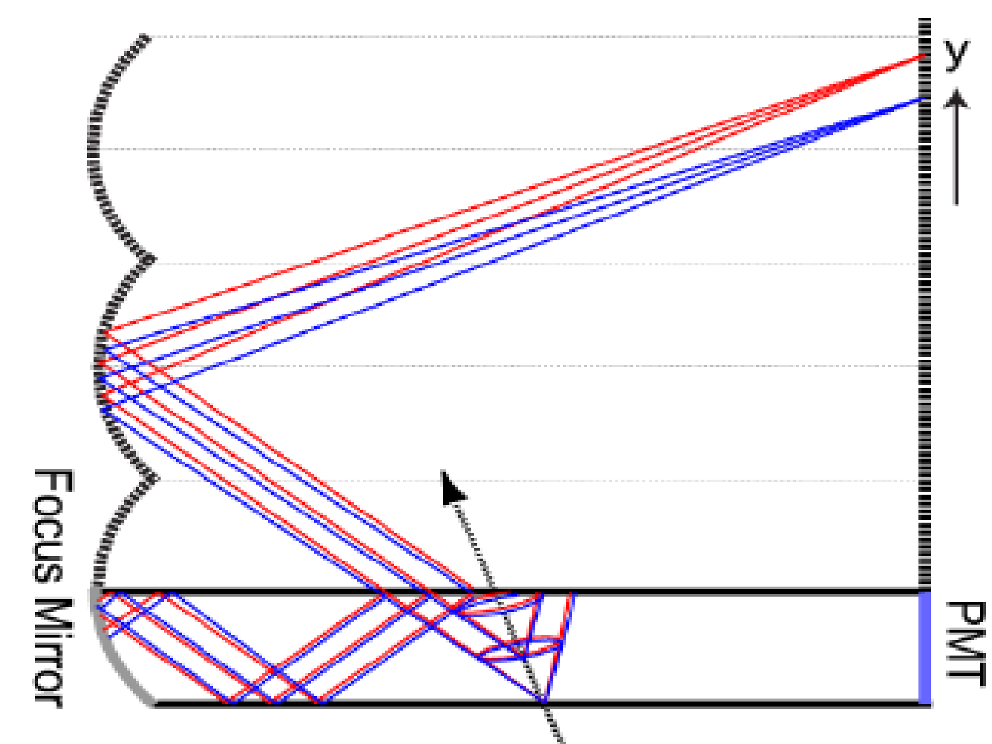
- Use new, high-performance MCP-PMTs for sub-50ps single p.e. TTS
- Use simultaneous T, θc [measured-predicted] for maximum K/π separation
- Optimize pixel size

imaging TOP (iTOP) realization





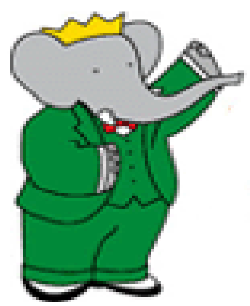




Quartz Cherenkov Device Landscape

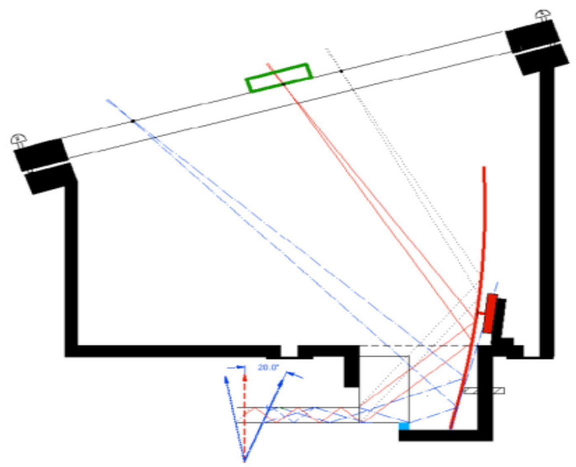
Performance

BaBar DIRC



- Large (~1m) expansion
- Mainly x,y
- Very coarse t

Fast Focusing DIRC



- Some expansion (~0.5 m)
- Focus to correct for finite bar thickness.
- Mainly x,y
- Order ~200 ps σ_t make chromatic corrections

↕ More sensitive to tracking uncertainties

Imaging TOP

- Small expansion (~.1 m)
- Mainly x,t
- Focusing, coarse y to correct chromatic effects

↕ More sensitive to t_0 uncertainties

Focusing TOP

- No expansion
- Mainly x,t
- Focusing & coarse y to correct chromatic effects

TOP

- No expansion
- Only x,t
- No focusing ➔ chromatic degradation

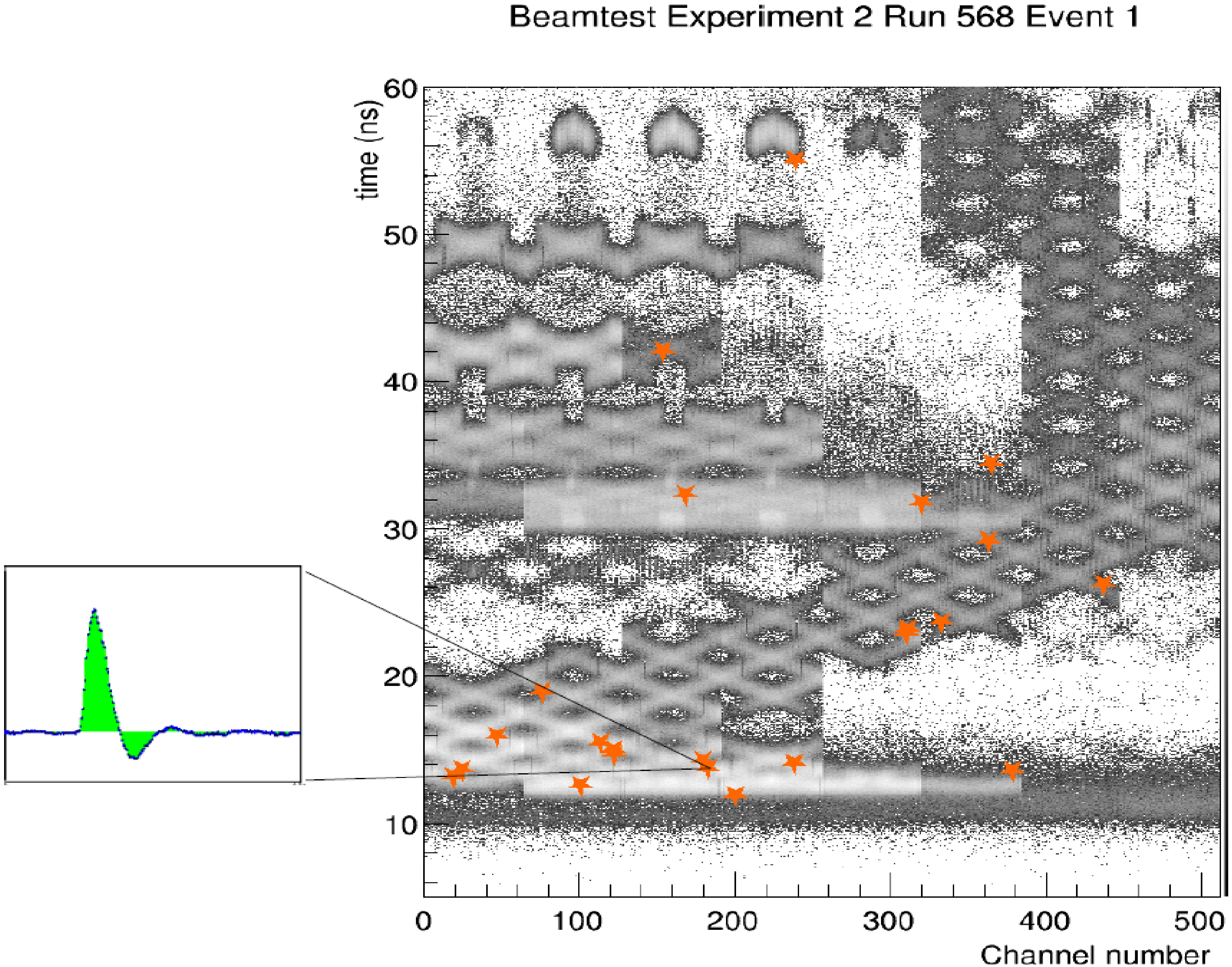
← **Mostly imaging**

Mostly timing →

Compactness

Actual PID is event-by-event

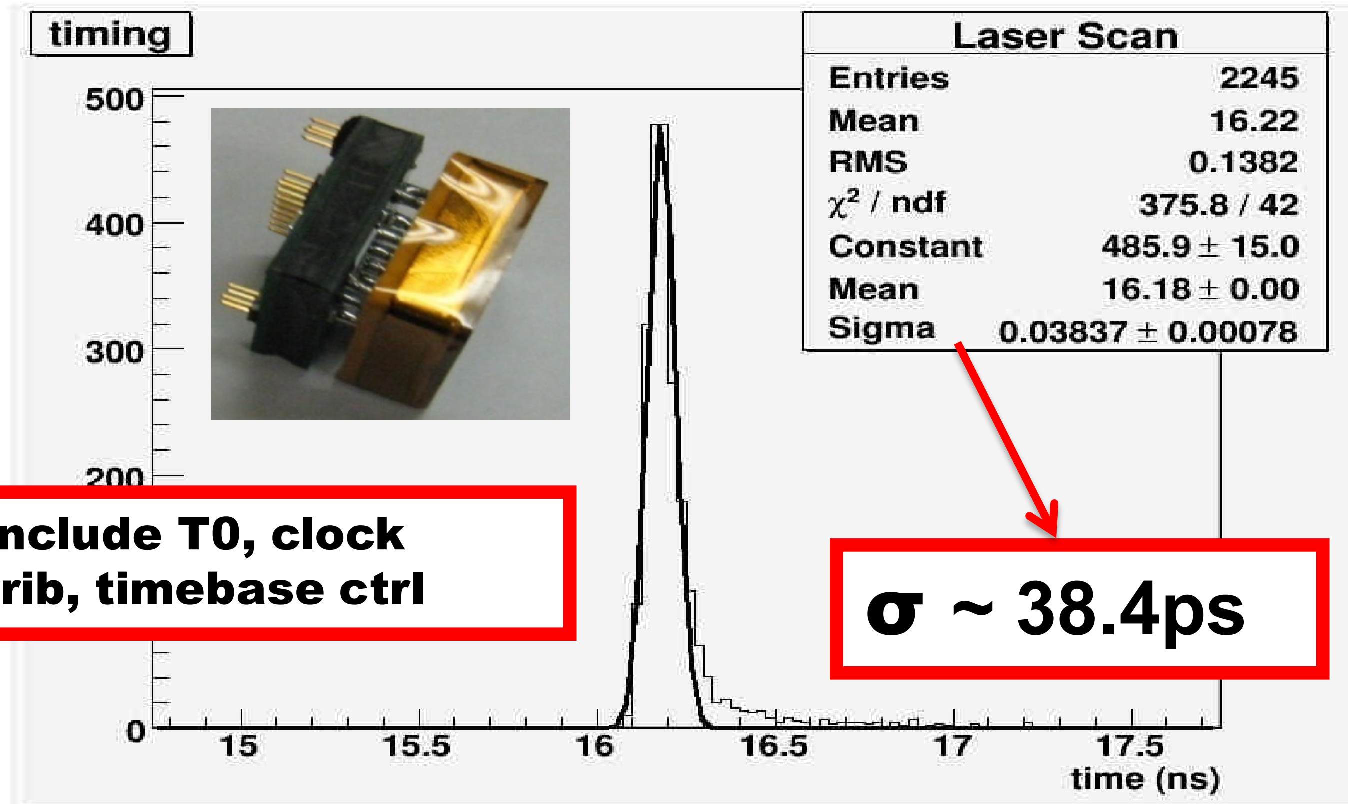
- Test most probable distribution



Performance Requirements (TOP)

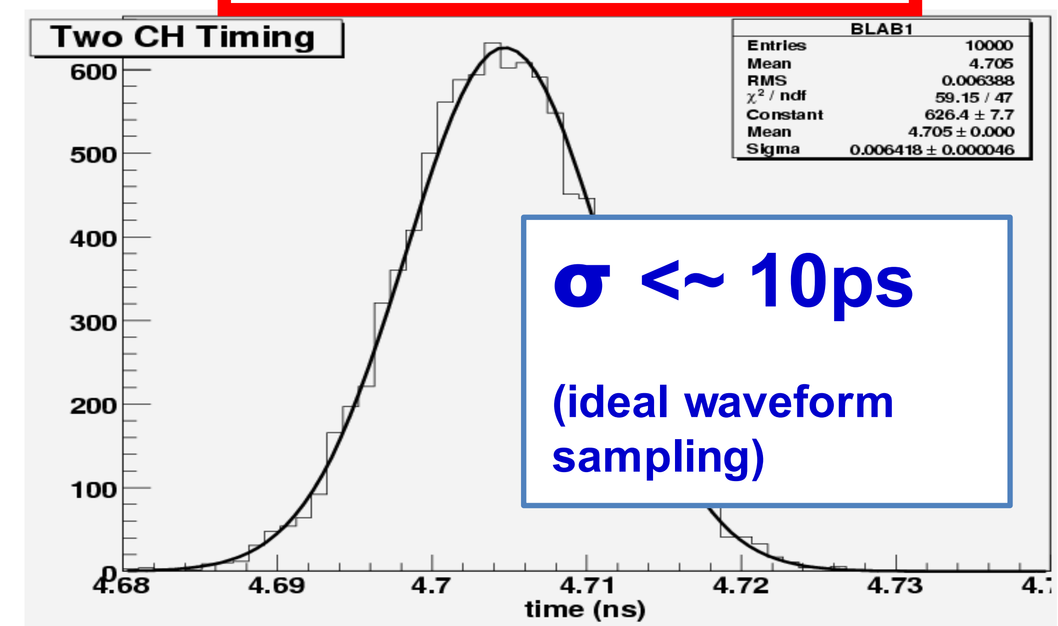
- Single photon timing for MCP-PMTs

Matsuoka-san's talk yesterday for details



To include T0, clock distrib, timebase ctrl

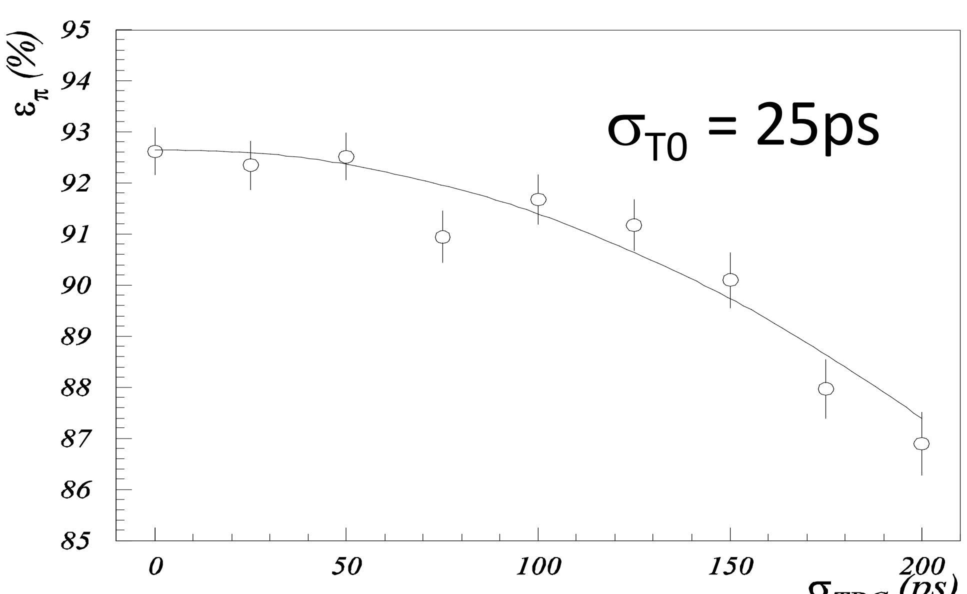
σ ~ 38.4ps

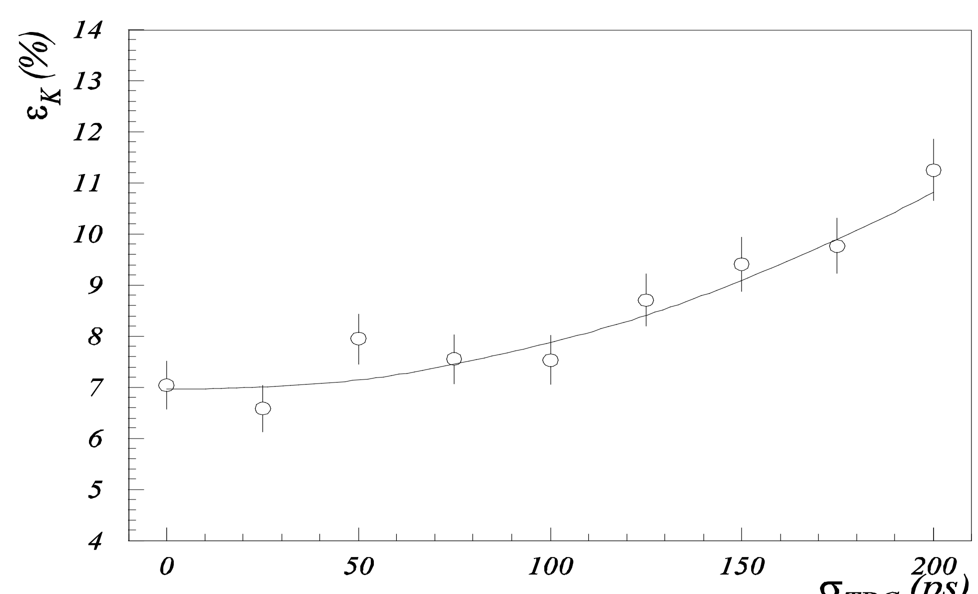


σ <~ 10ps

(ideal waveform sampling)

NIM **A602** (2009) 438



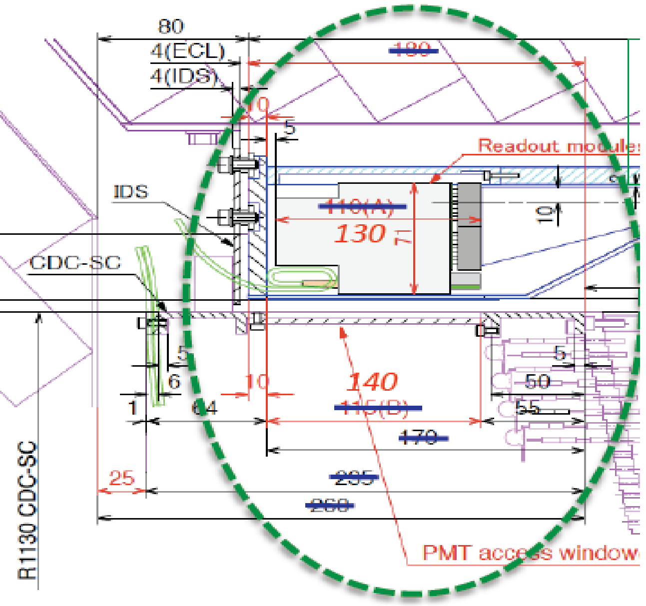


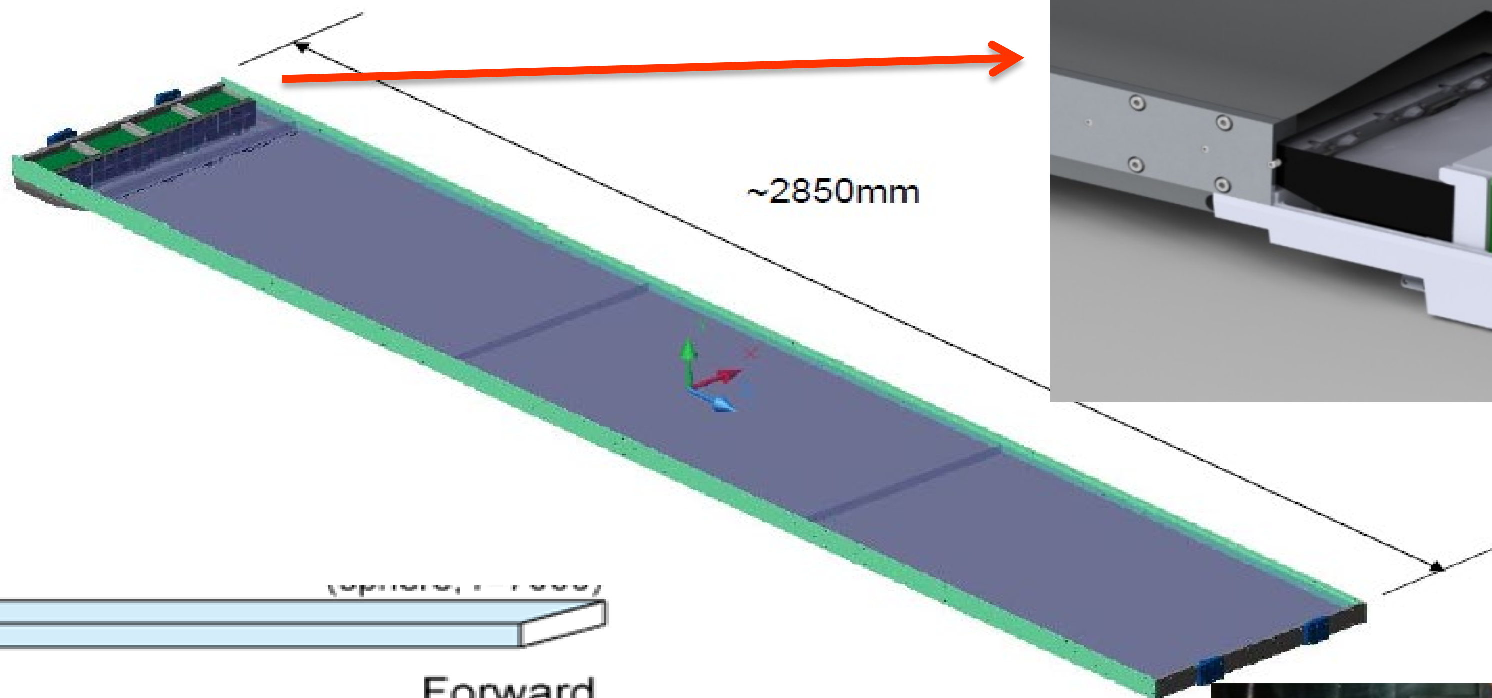
σ <~ 50ps target

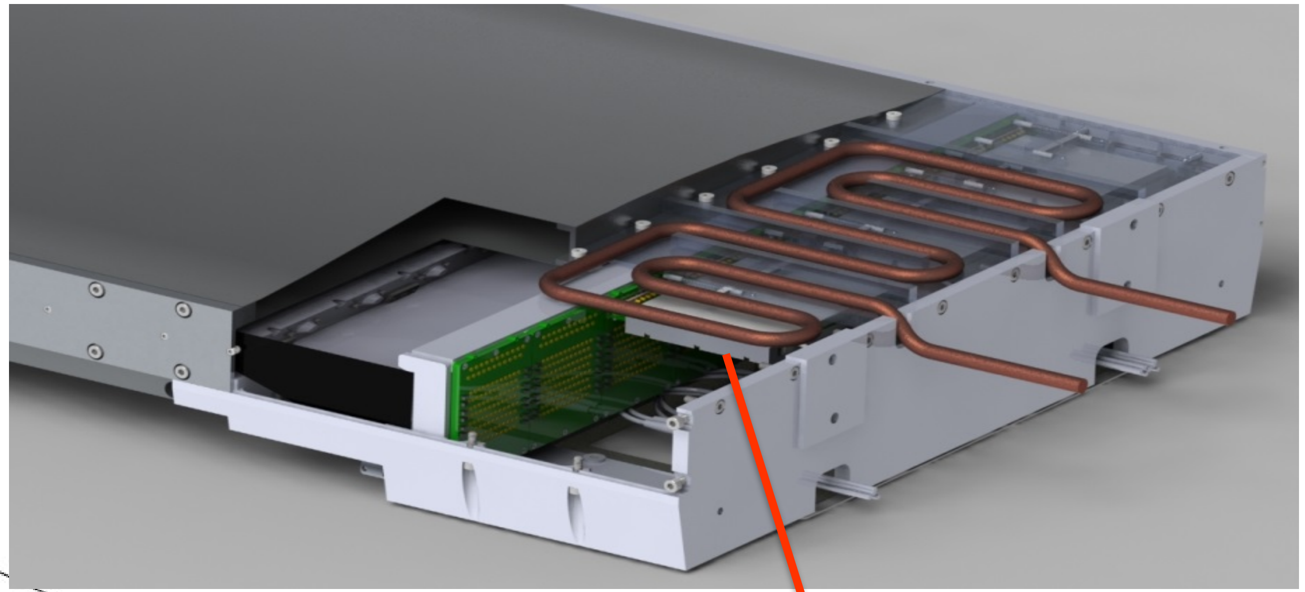
NOTE: this is single-photon timing, **not** event start-time "T_0"

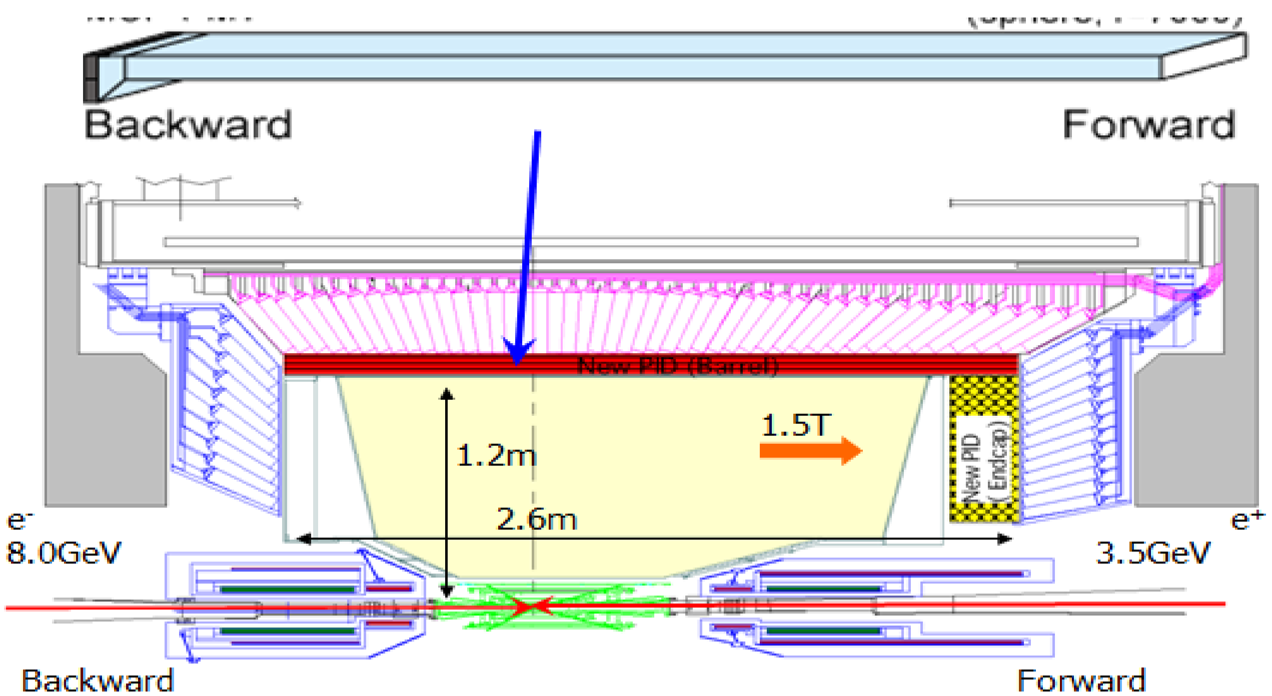
Mechanical constraints

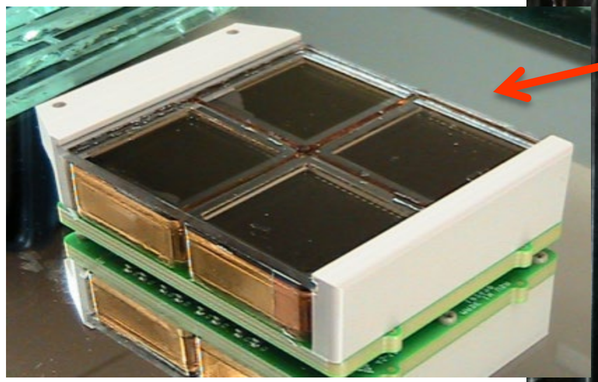
- A highly constrained space

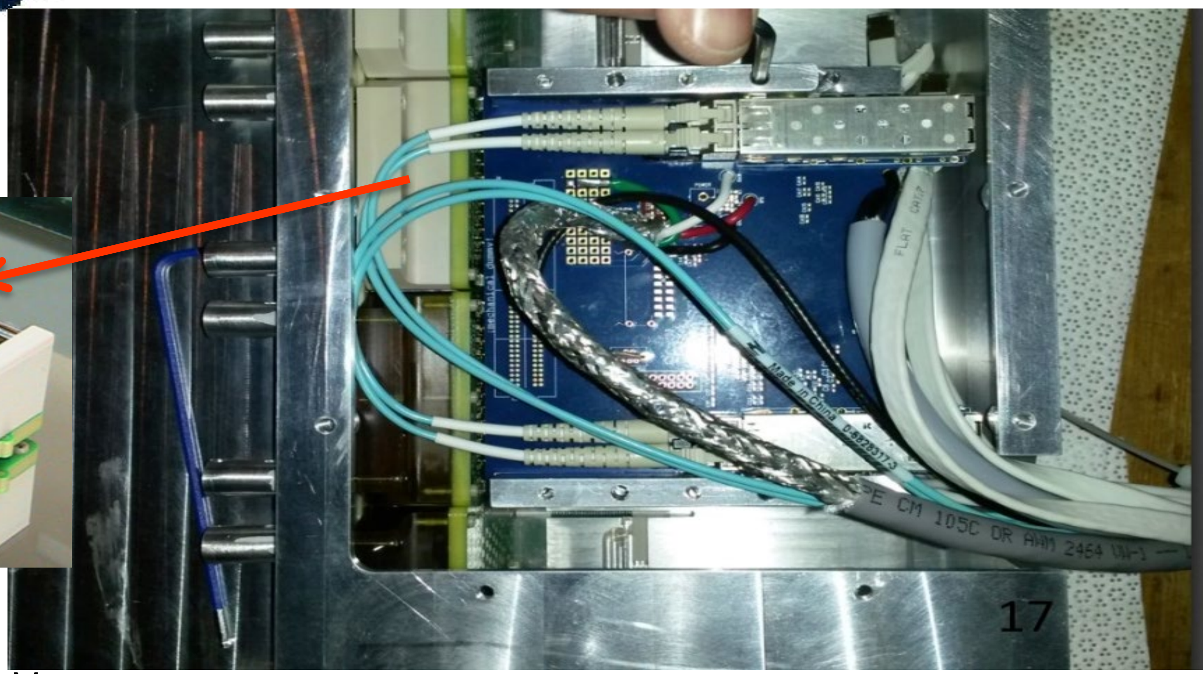






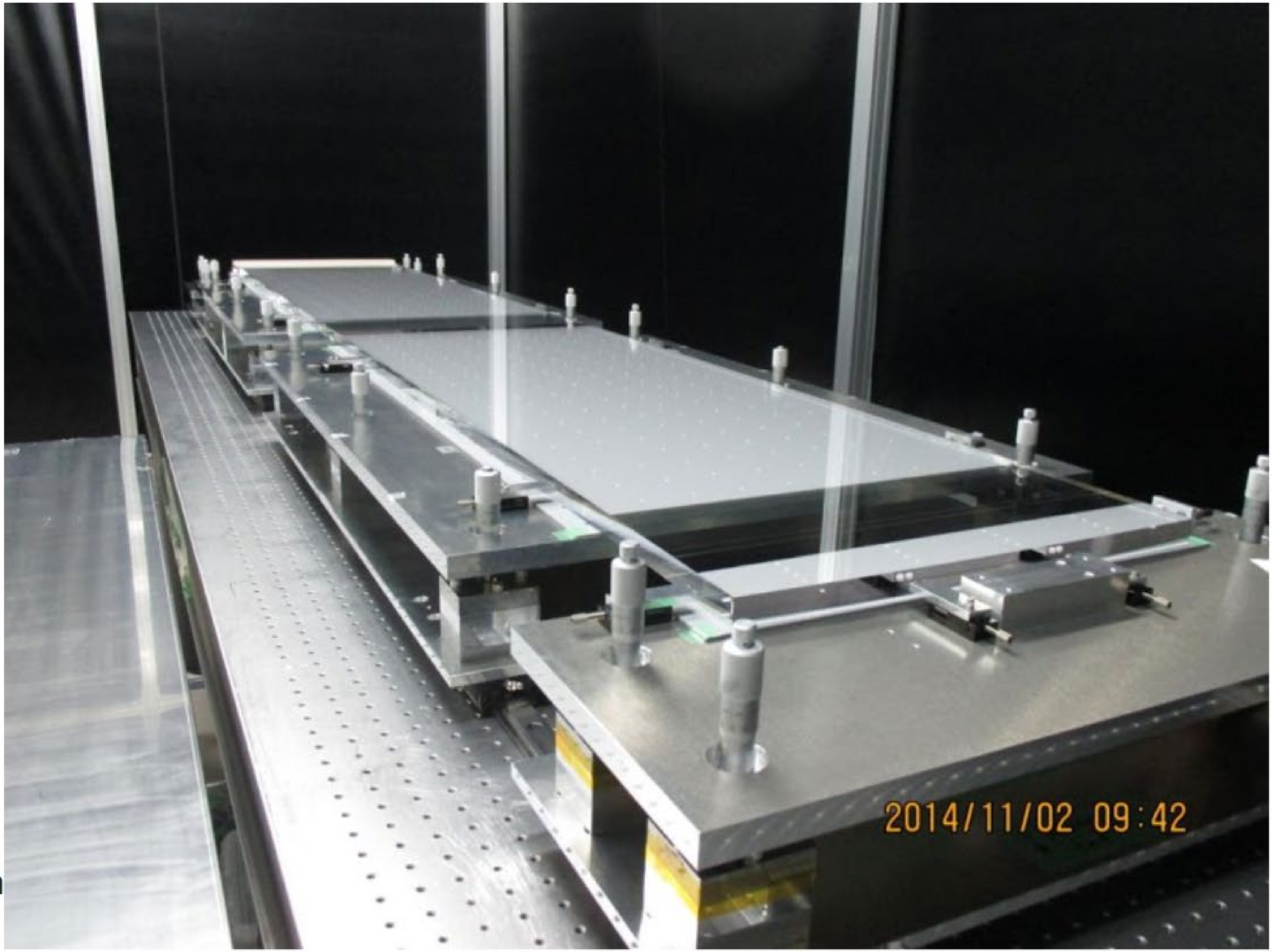






Quartz & Optics I

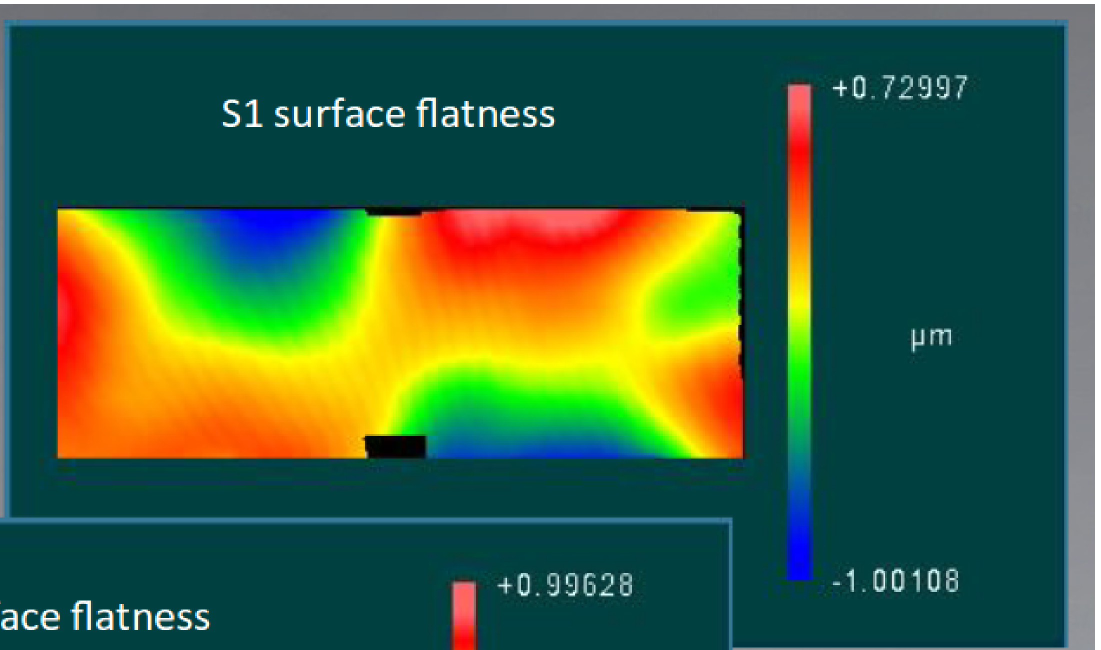
- Bars:
  1250 x 450 x 20 mm^3
  two bars per module
- Mirrors:
  100 x 450 x 20 mm^3
- Prisms:
  100 mm long, 456 x 20 mm^2
  at bar face expanding to
  456 x 50 cm^2 at MCP-PMTs
- Material: Corning 7980
- DIN58927 class 0 material has no inclusions (inclusions ≤0.1 mm diameter are disregarded)
- Grade 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

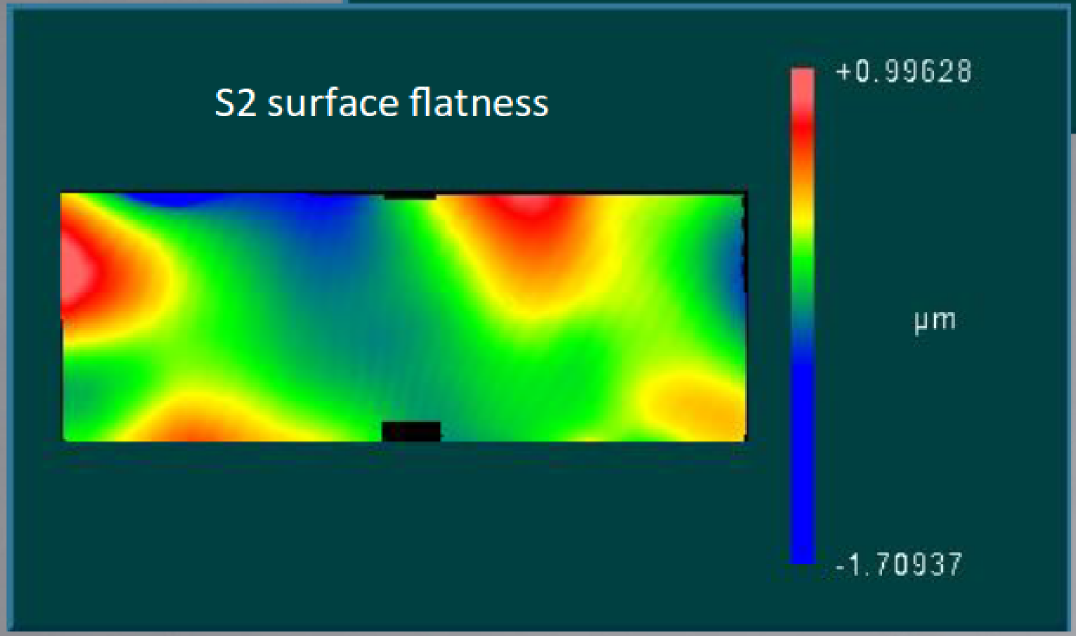


Quartz & Optics II

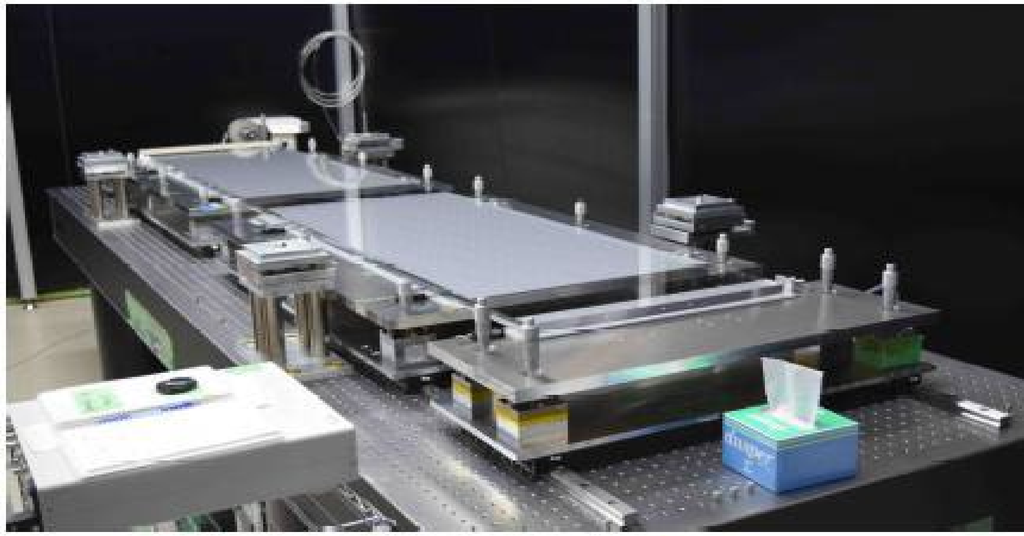
- Quartz most expensive part of the system (~10M$)
- Extreme surface quality requirements

Tolerance	Specification	Measurement	Pass	Fail
S1 Datum A Flatness	≤ 6.3µm	1.731	x	
S1 Local Flatness over 200mm Area	≤ 1.8µm	0.678 Max	x	
S2 Flatness	≤ 6.3µm	2.706	x	
S2 Local Flatness over 200mm Area	≤ 1.8µm	1.462 Max	x	
S3 Datum B Flatness	≤ 6.3µm	2.952	x	
S4 Flatness	≤ 6.3µm	1.472	x	
S5 Datum C Flatness	≤ 25µm	1.425	x	
S6 Flatness	≤ 25µm	2.633	x	
S1 Parallel S2	≤ 4 arcsec	≤ 1.4	x	
S1 Perpendicular S3	≤ 20 arcsec	≤ 5	x	
S1 Perpendicular S4	≤ 20 arcsec	≤ 3	x	
S1 Perpendicular S5	≤ 1 arcmin	≤ 0.083	x	
S1 Perpendicular S6	≤ 1 arcmin	≤ 0.05	x	
S3 Parallel S4	≤ 60µm (10 arcsec)	≤ 7 arc sec	x	
S3 Perpendicular S5	≤ 20 arcsec	≤ 5	x	
S3 Perpendicular S6	≤ 20 arcsec	≤ 5	x	
S5 Parallel S6	≤ 20 arcsec	≤ 10	x	
Surface Roughness S1	≤ 5 Å rms	3.064	x	
Surface Roughness S2	≤ 5 Å rms	3.045	x	
Surface Roughness S3	≤ 5 Å rms	4.035	x	
Surface Roughness S4	≤ 5 Å rms	3.127	x	
Surface Roughness S5	≤ 25 Å rms	13.887	x	
Surface Roughness S6	≤ 25 Å rms	16.991	x	
Length	1250 ±0.50mm	1250.37	x	
Width	450 ±0.15	450.08	x	
Thickness	20 ±0.10	20.09	x	





Quartz gluing, Module Assembly

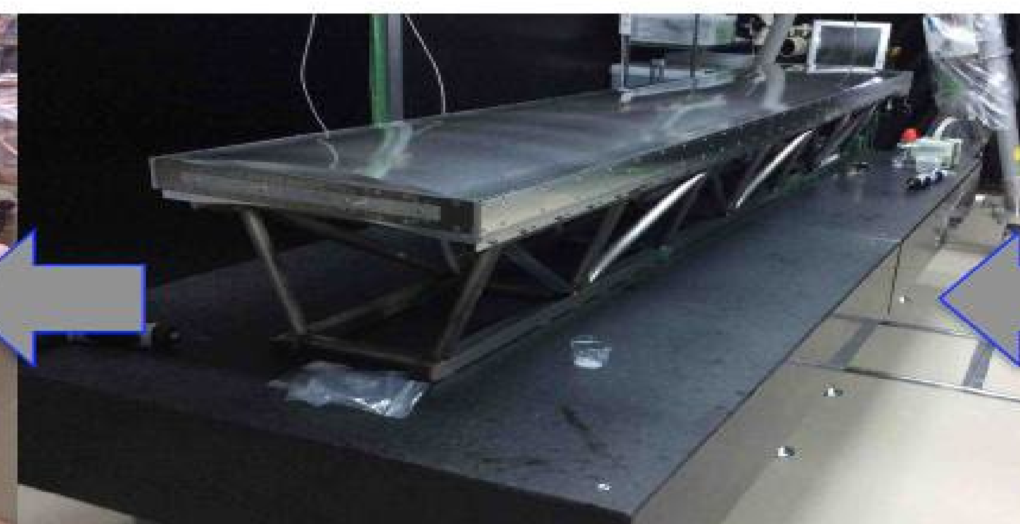


Optics: alignment, gluing, curing and aging (~2 weeks).

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.



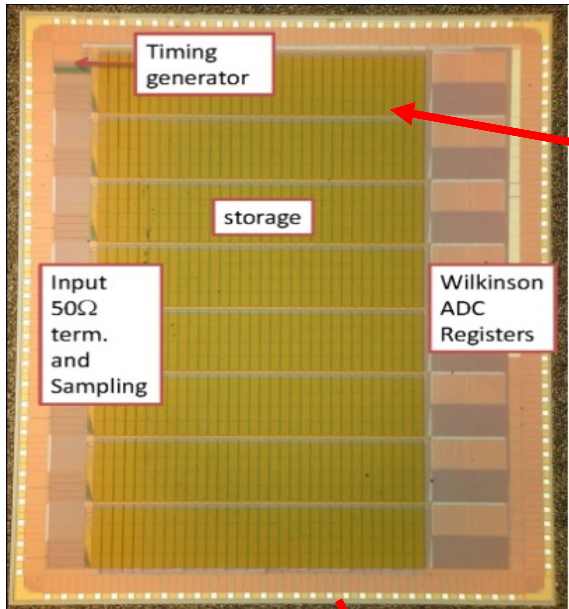
QBB assembly and gas sealing.

Move optics to QBB using the "lifting jig".

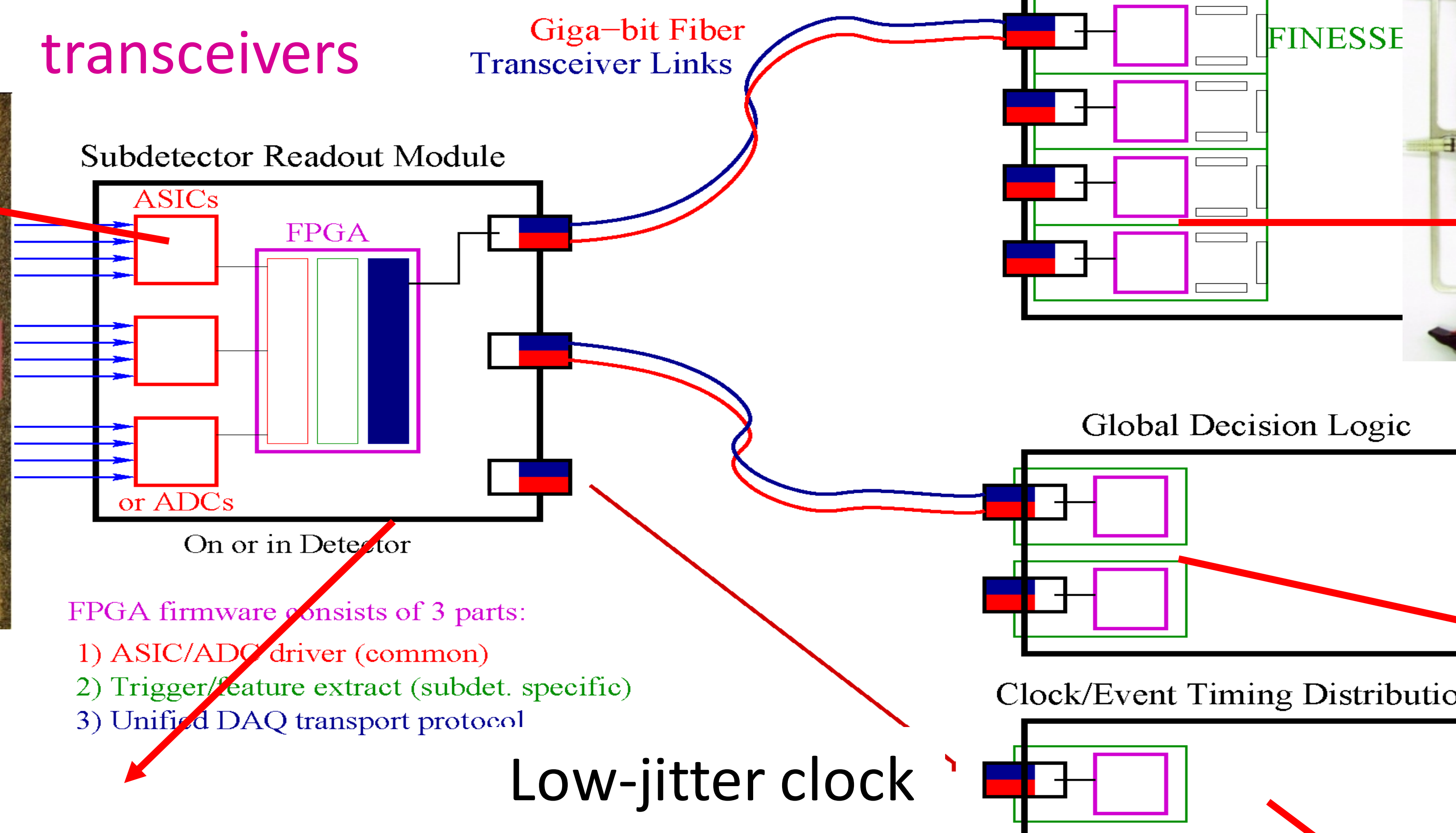
iTOP Readout

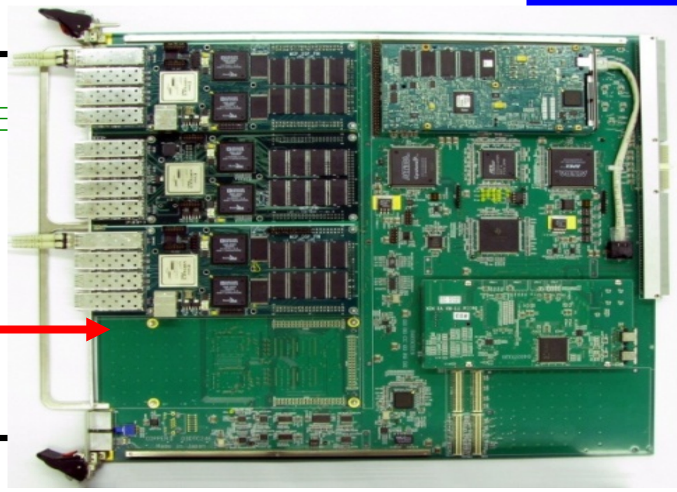
DAQ Upgrade 2020-2021

Waveform sampling ASIC



64 DAQ fiber transceivers





64 FINESSE

16 COPPER

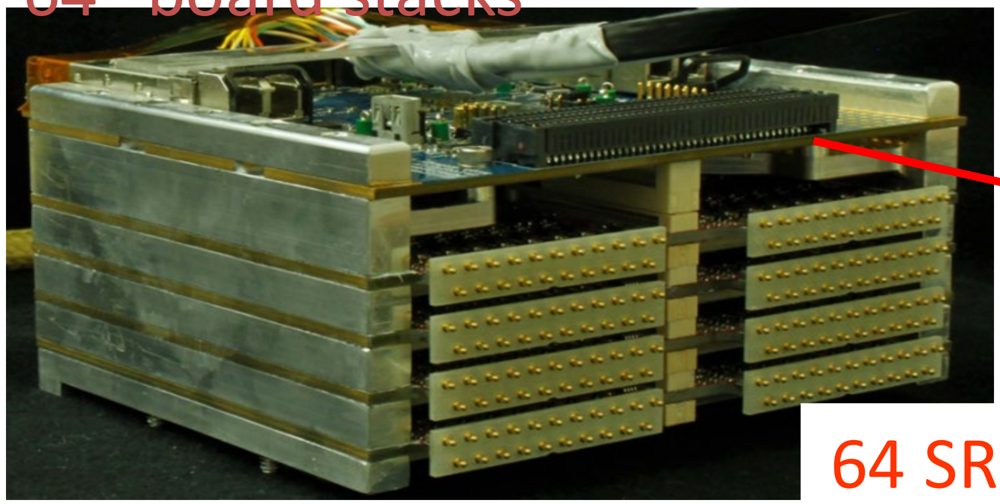
2x UT3 Trigger modules

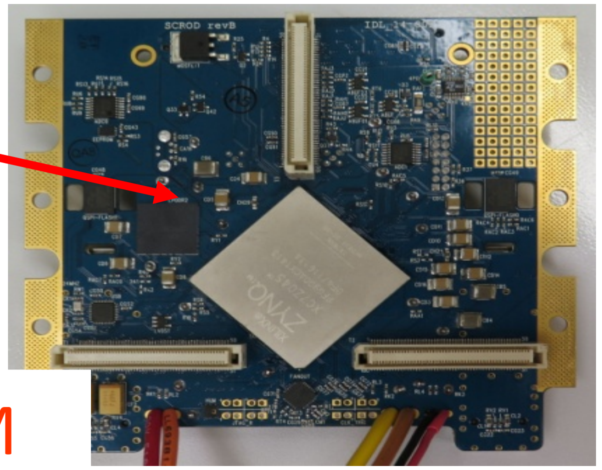
Low-jitter clock

8k channels

1k 8-ch. ASICs

64 "board stacks"





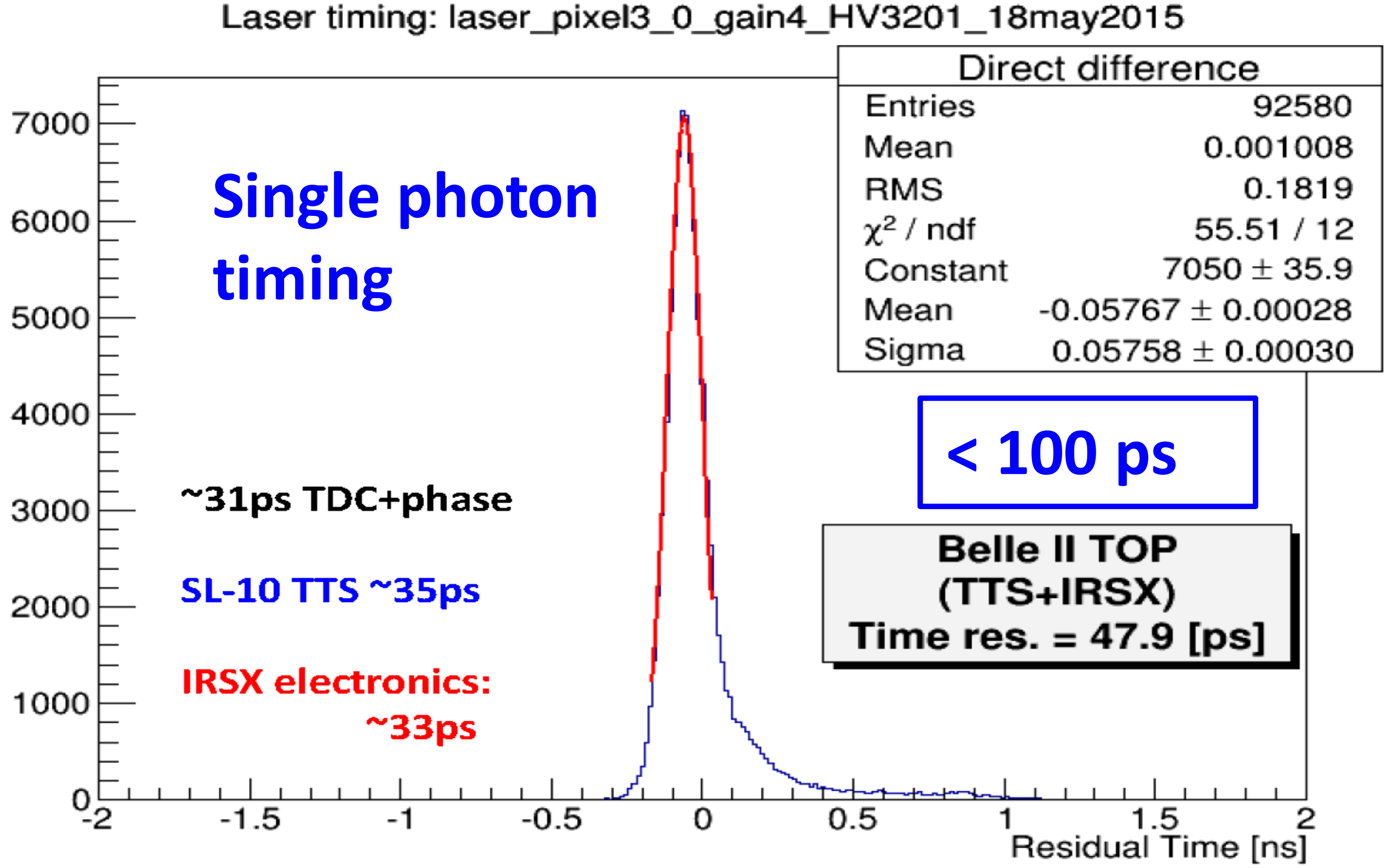
64 SRM

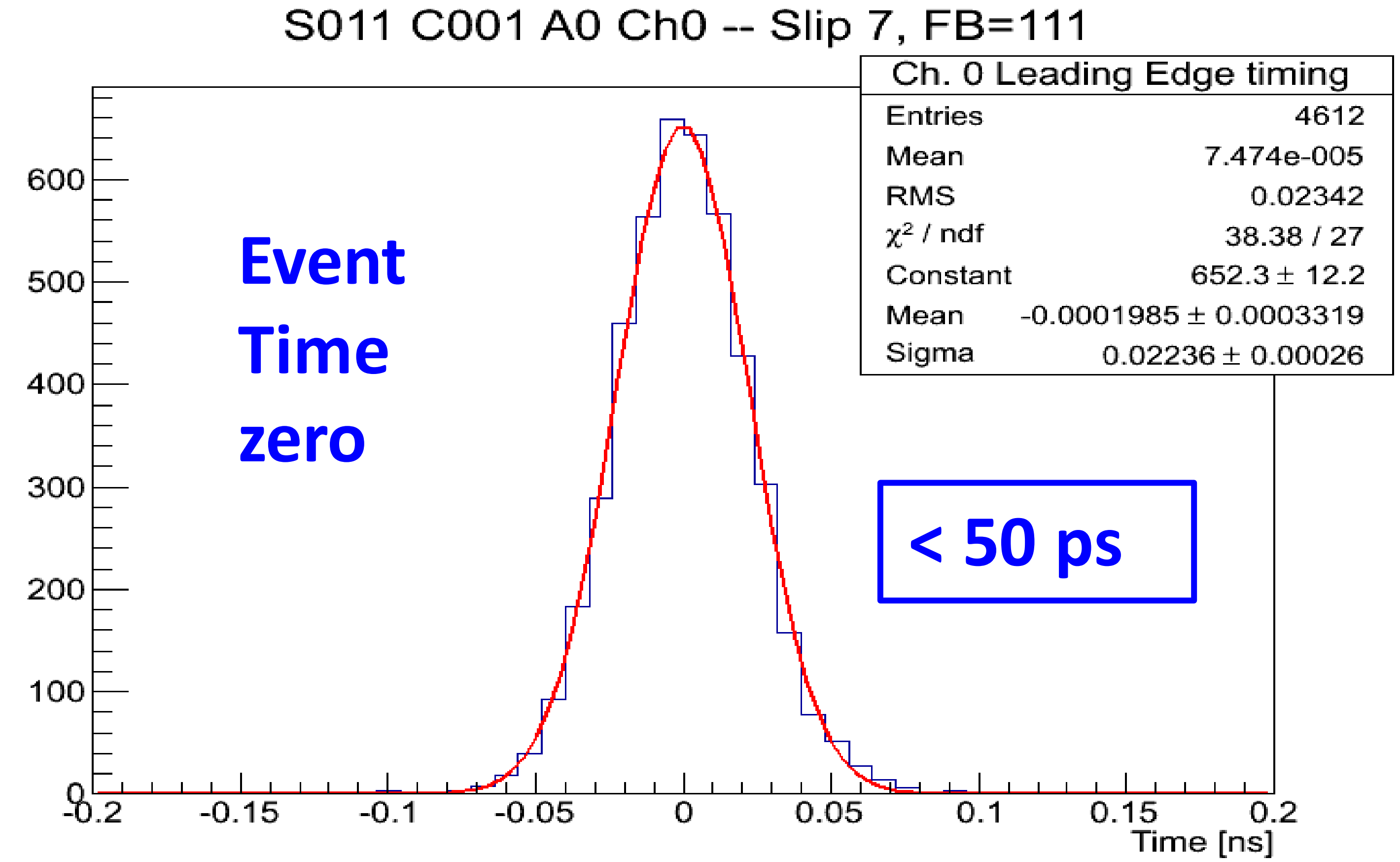
Clock, trigger, programming module (FTSW)

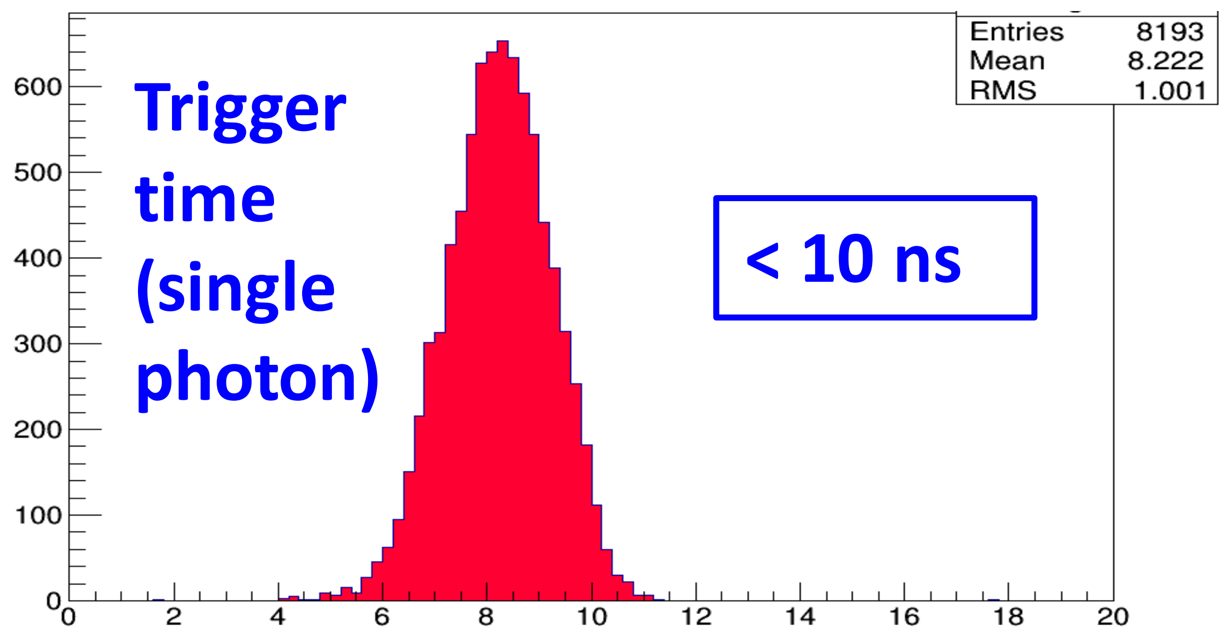
8 FTSW

NIM A941 (2019) 162342.

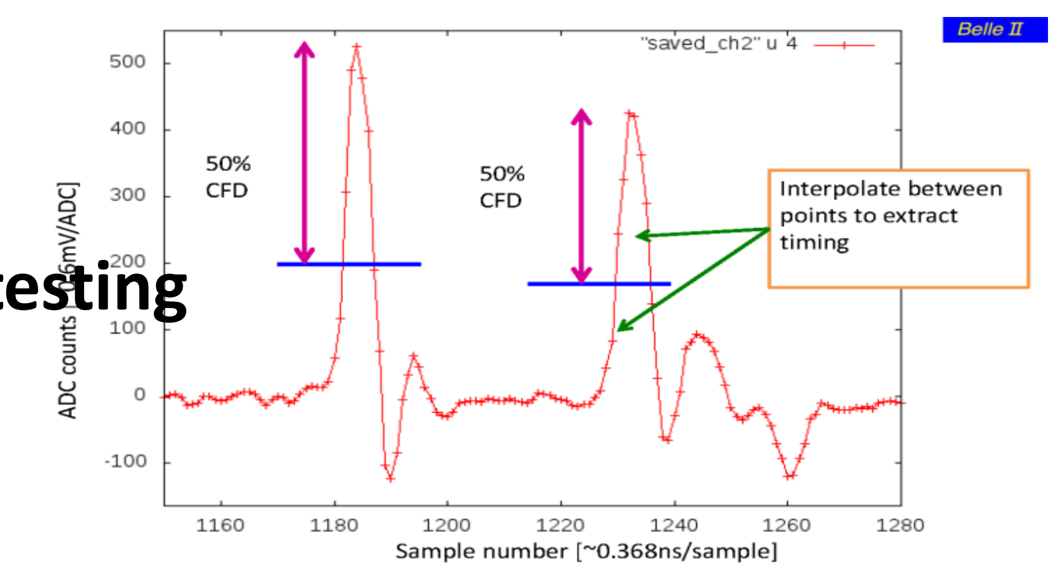
Readout Verification (pre-install, in-situ)





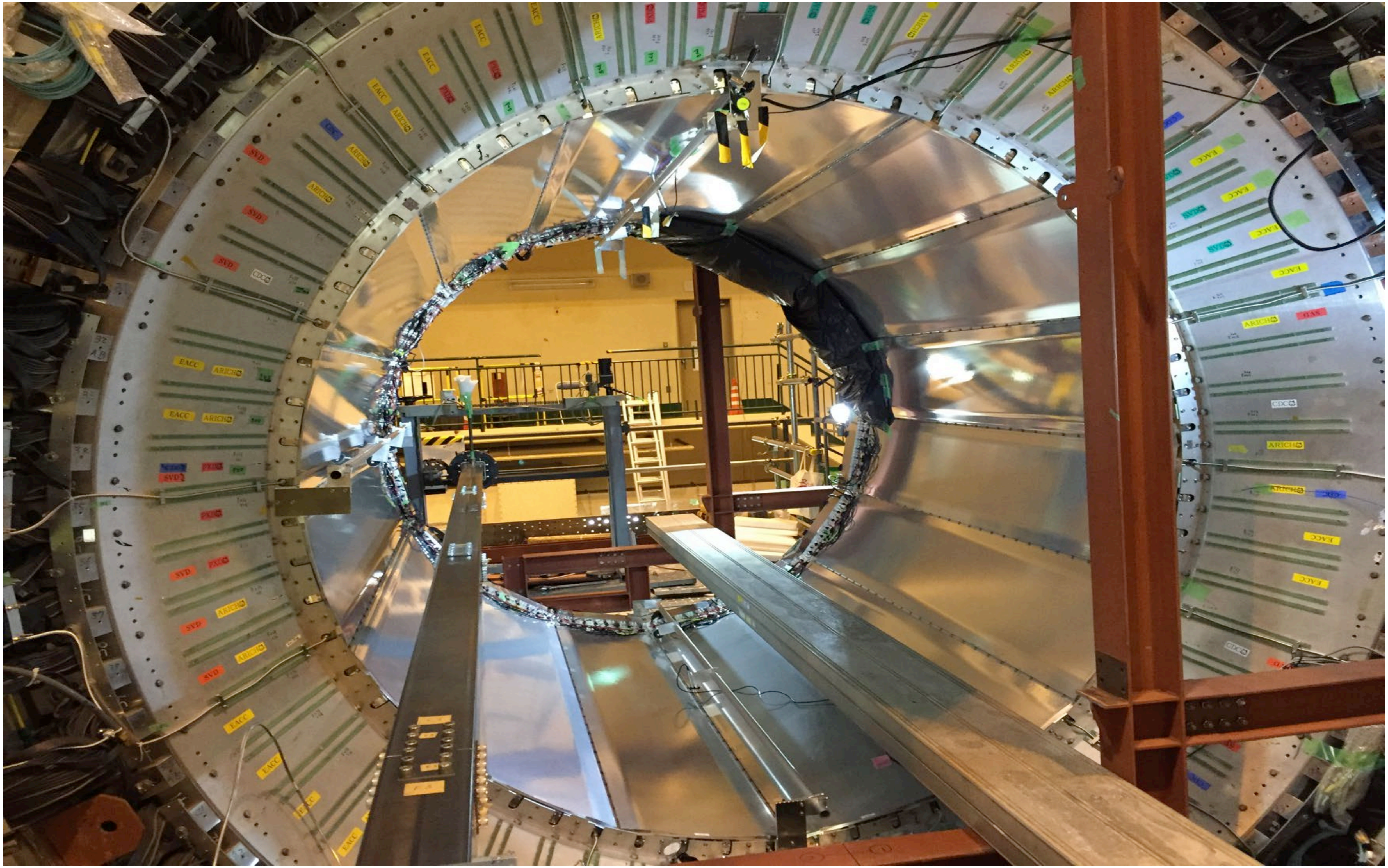


Pulser testing

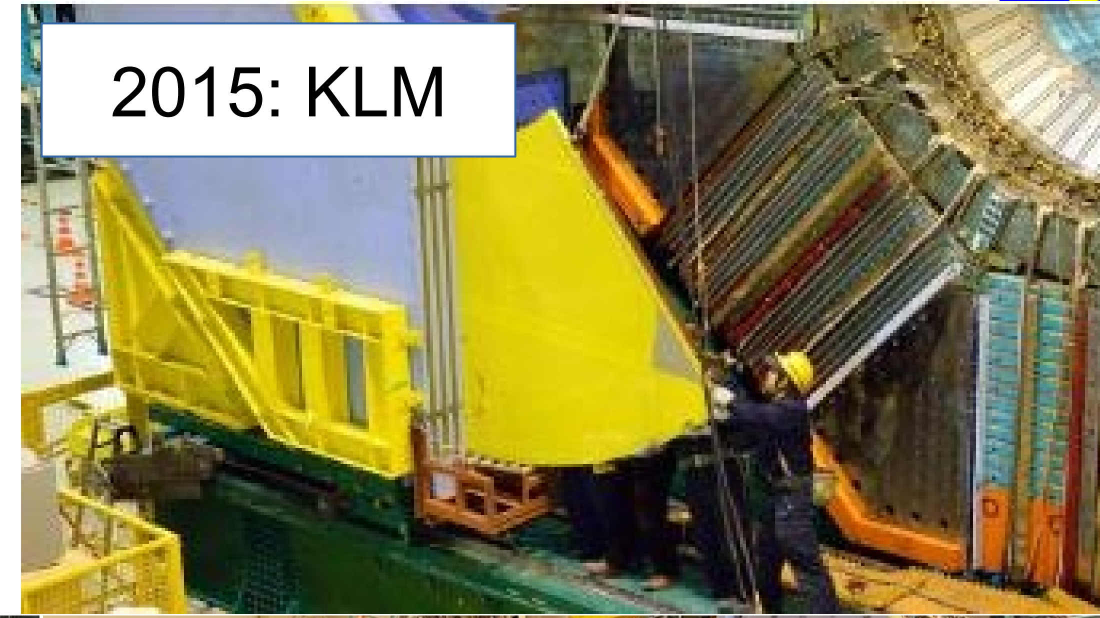


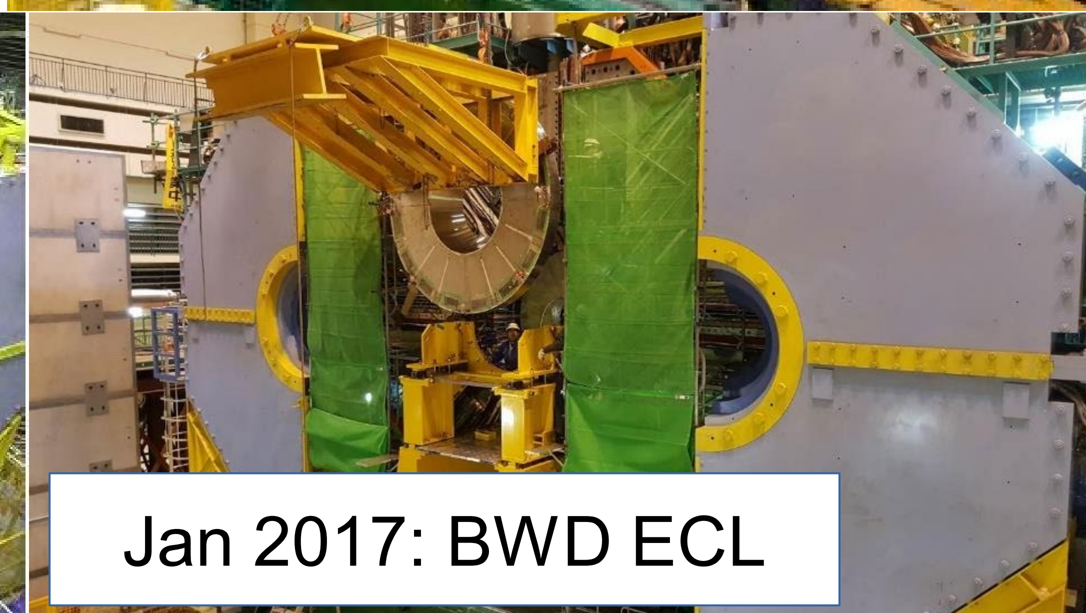
Installation (very tight fit)

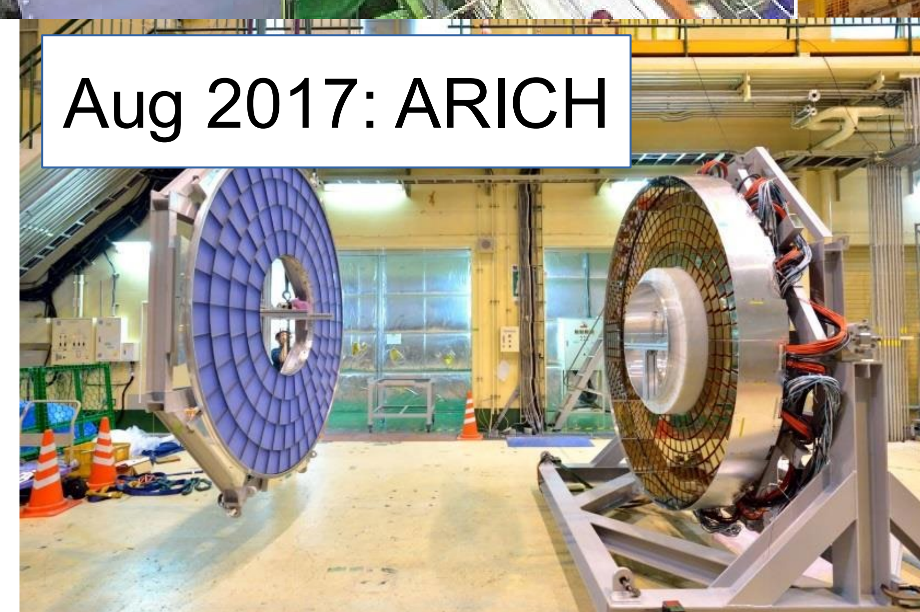
Installation Complete (May 2016)

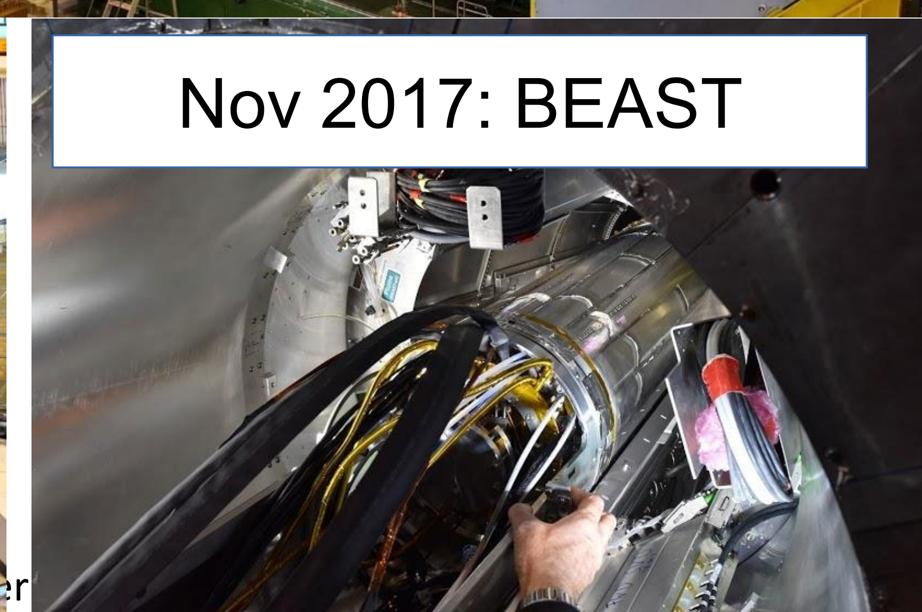


Belle II Installation
Phase 2 configuration









Timebase Calibration

- Took a while to get FW, SW working

/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/.

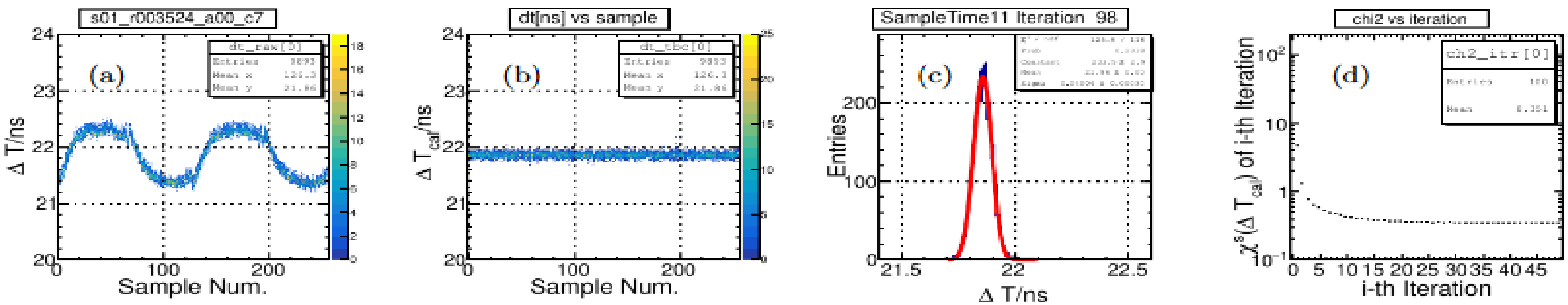


FIG. 1: Example of calculation on Slot_01 ASIC_00. (a) is the shape of time difference (ΔT) of the double pulses in channel_7 from the raw data, (b) is the dime difference after correction, (c) is the project of ΔT after correction and a fit performed to the distribution to show the mean and the resolution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

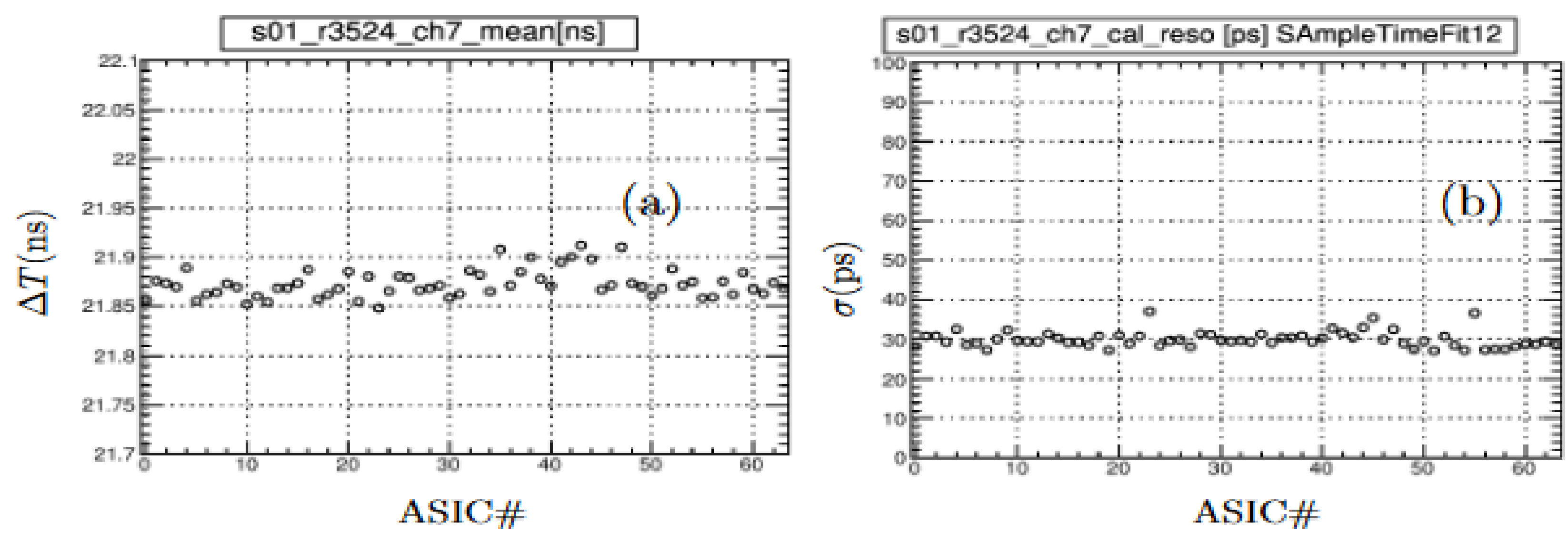
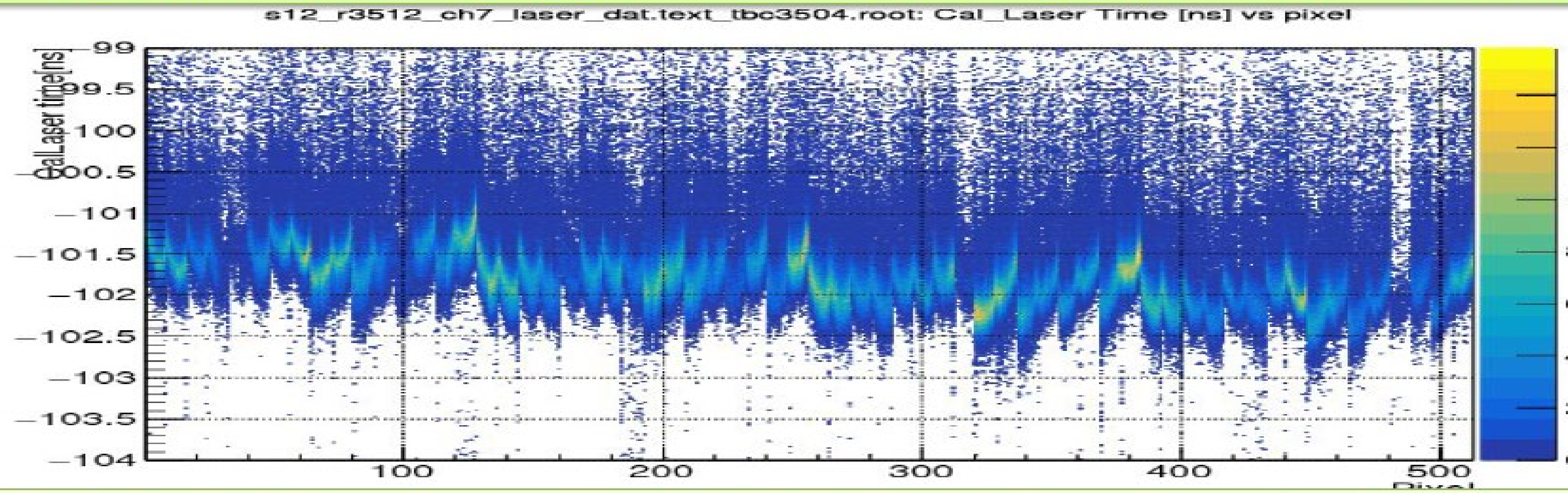


FIG. 2: Summary of calculation results of the 64 ASICs of Slot_01. Plot (a) is means of the time difference of double pulses, and (b) is the time resolution.

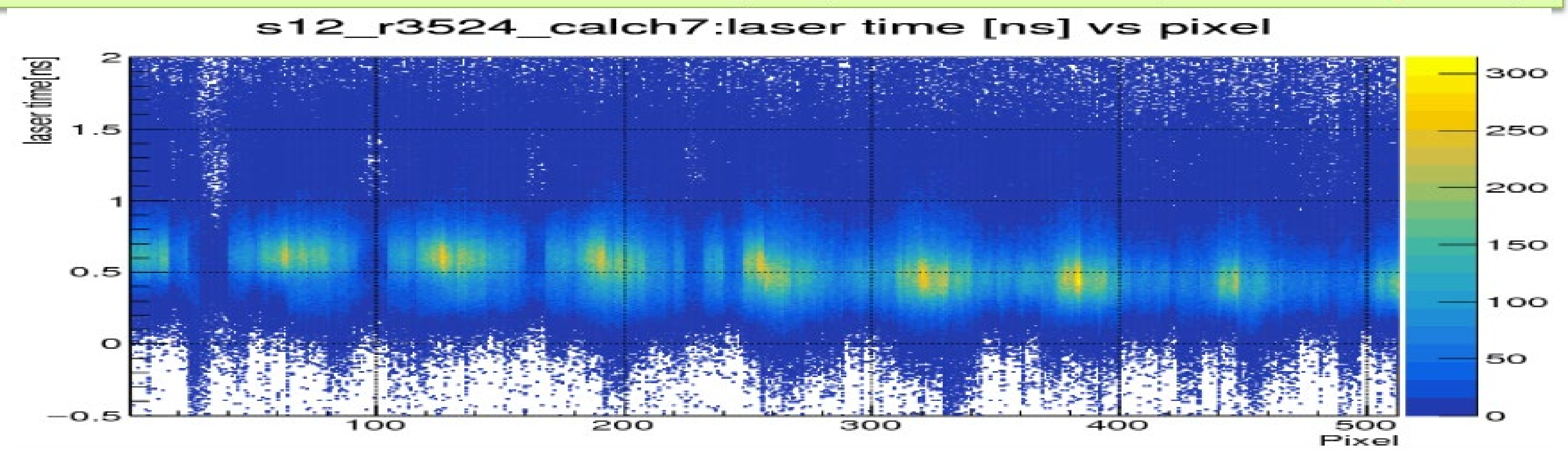
Channel-by-channel Timing alignment

- Global timing alignment – laser studies

DATA slot12-r3512: Laser time as a function of pixel (after TB correction, before time alignment)



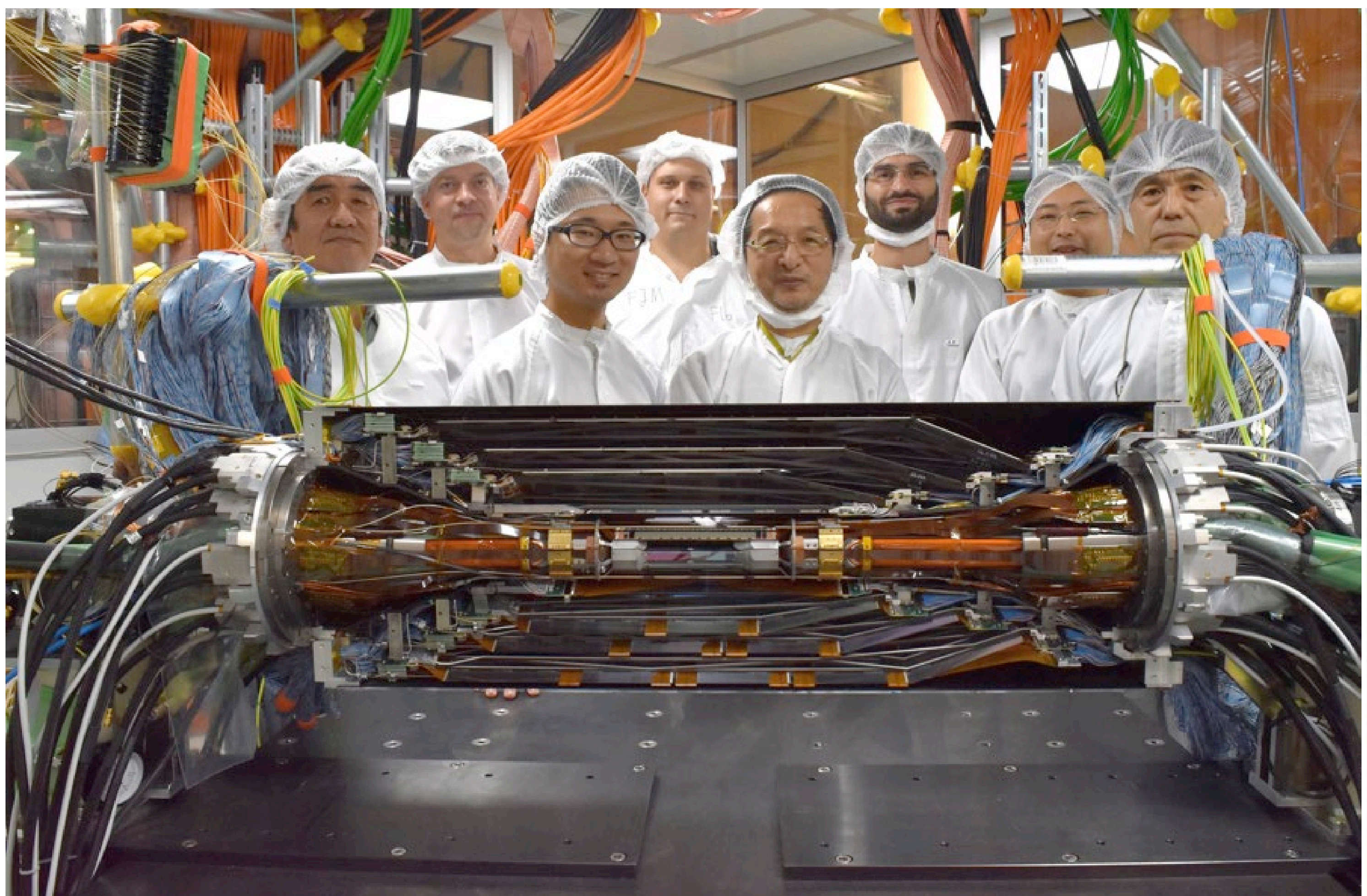
DATA slot12-r3512: Laser time as a function of pixel (after TB correction, after time alignment)

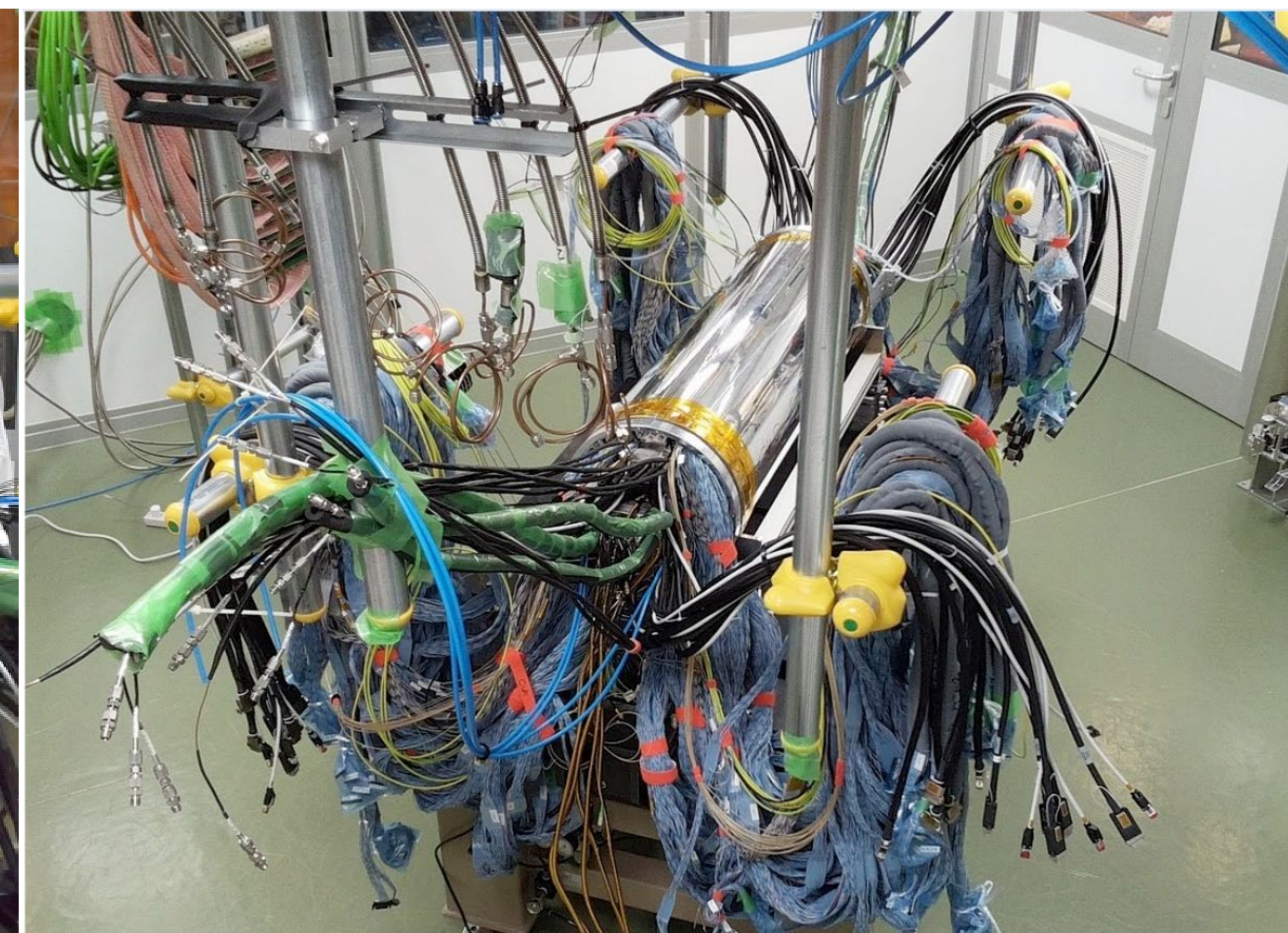


NOTE: Different Time Scales!

Silicon detectors coming together

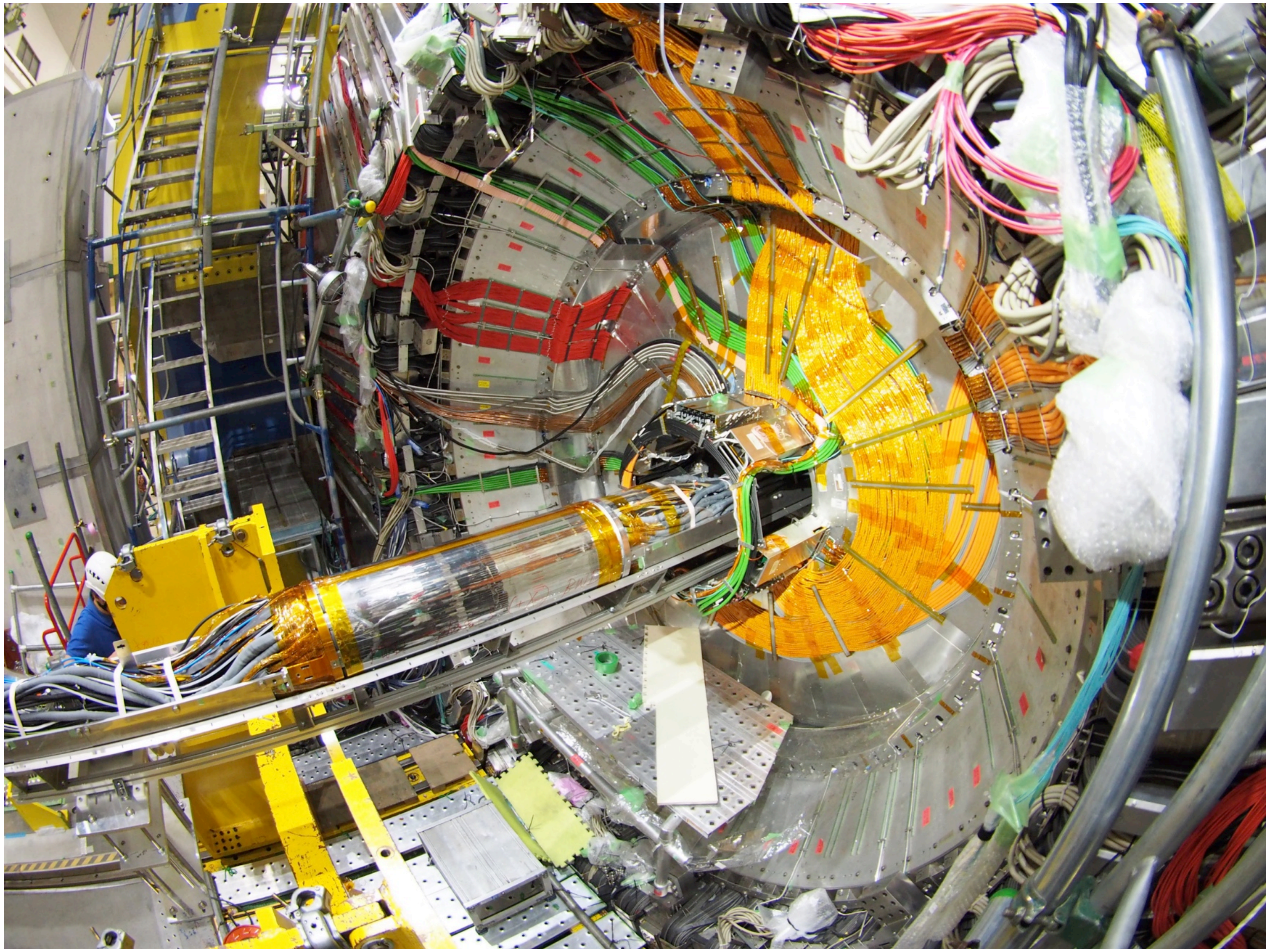
- PXD & SVD "married" since October 2018



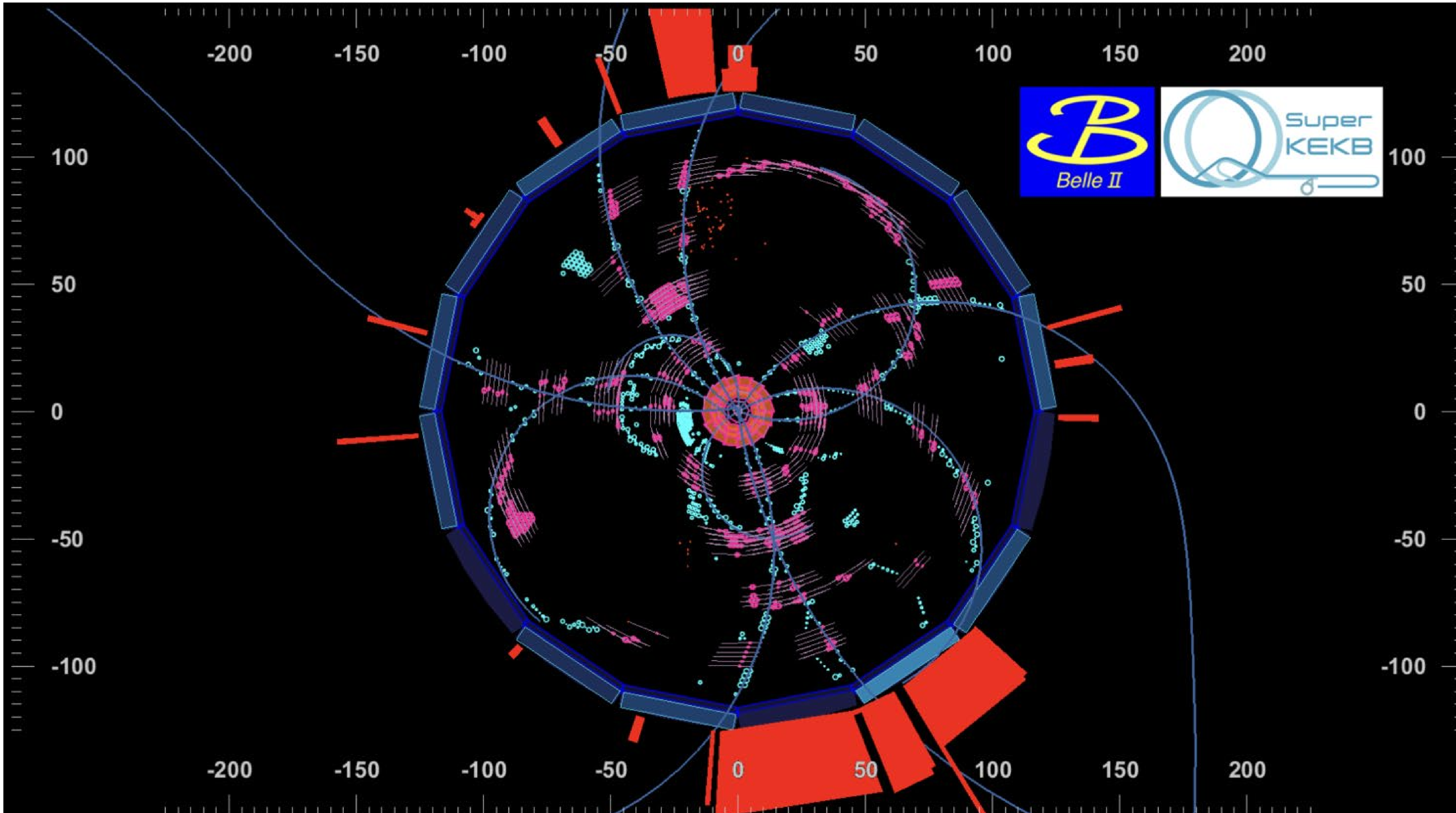


VXD Installation

- VXD installed November 21st 2018, Belle II detector complete!



First Collision in Physics Run - 03/25/2019



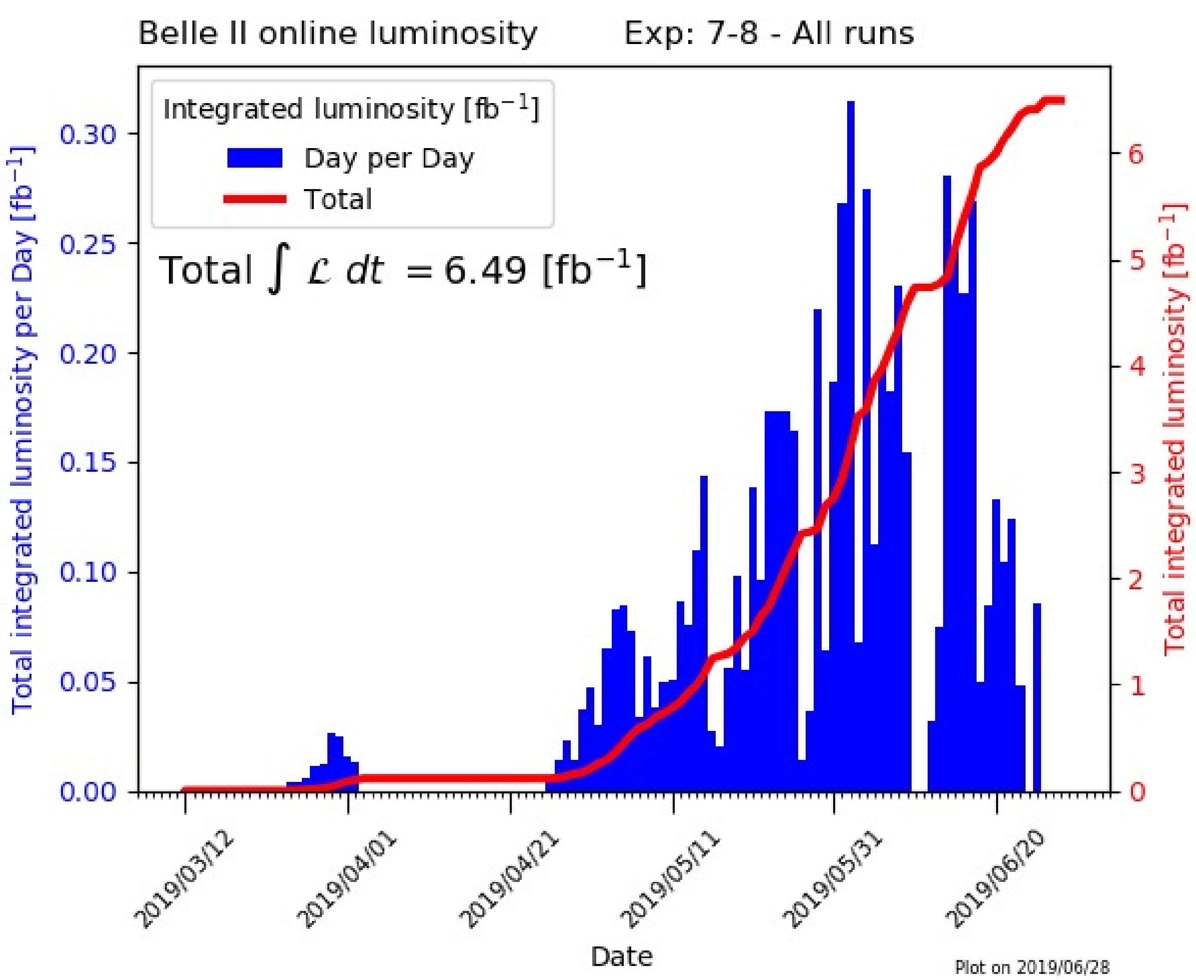
e+e→Y(4s)→BB

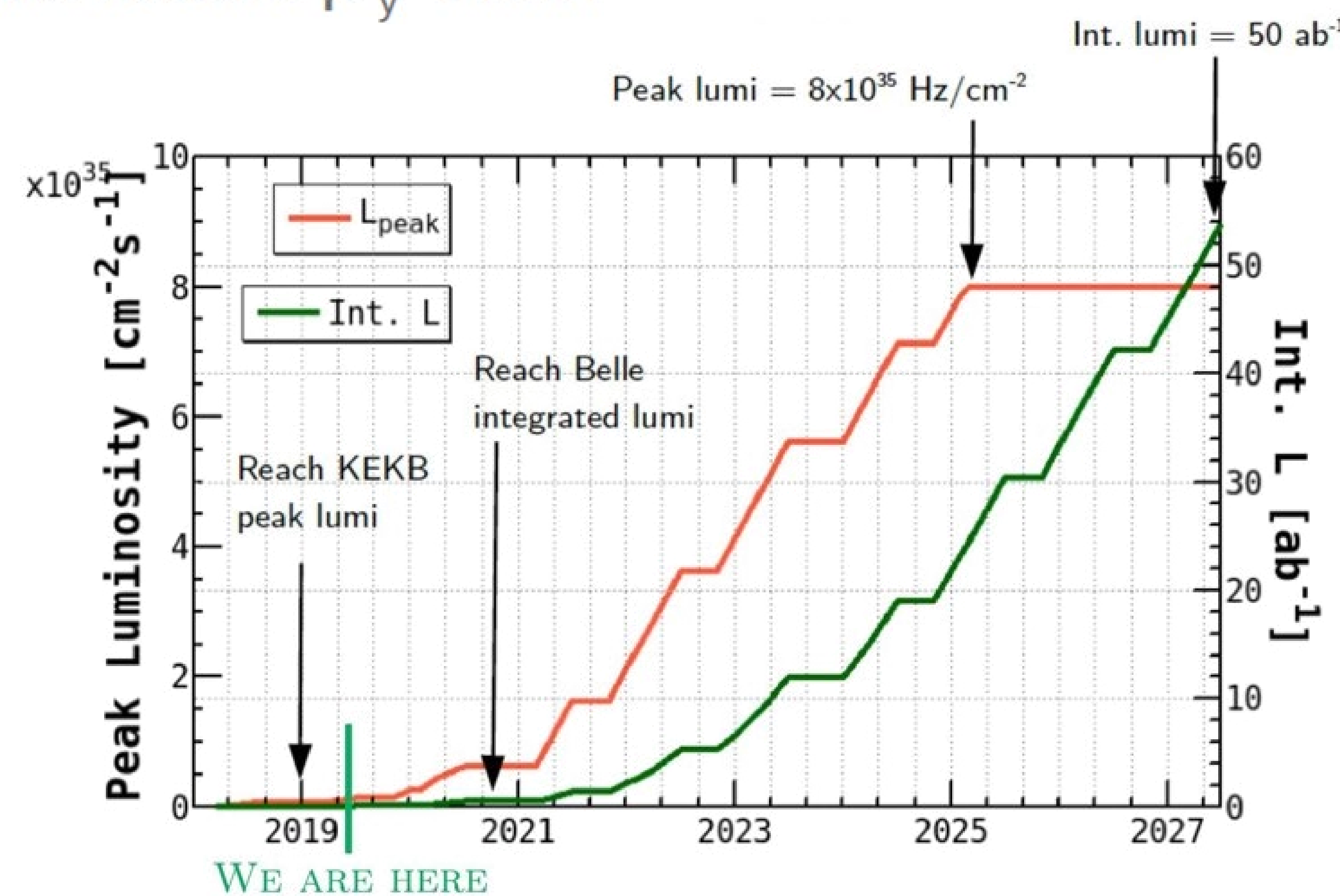
… and the Reaction

Luminosity in spring/summer 2019 run

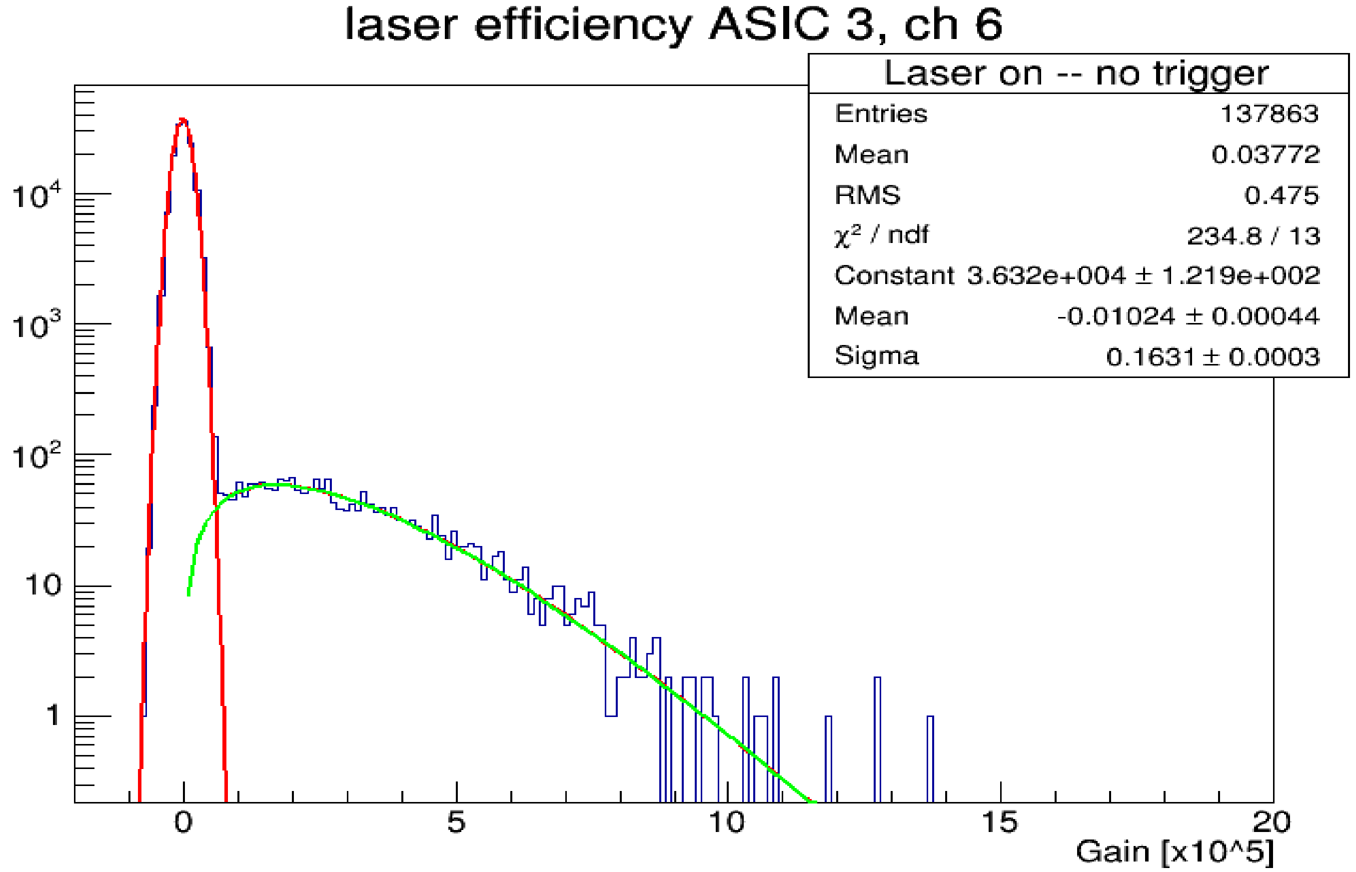
- 6.5fb^{-1} integrated from March 25th to July 1st 2019
  - L_{peak}: 6.1x10^{33} cm^{-2} s^{-1} (12x10^{33} with Belle II off)
  - Limited by backgrounds, beam-beam blowup
- New machine, entirely new concept, requires tuning
  - Already running at world record β^*_y=2mm

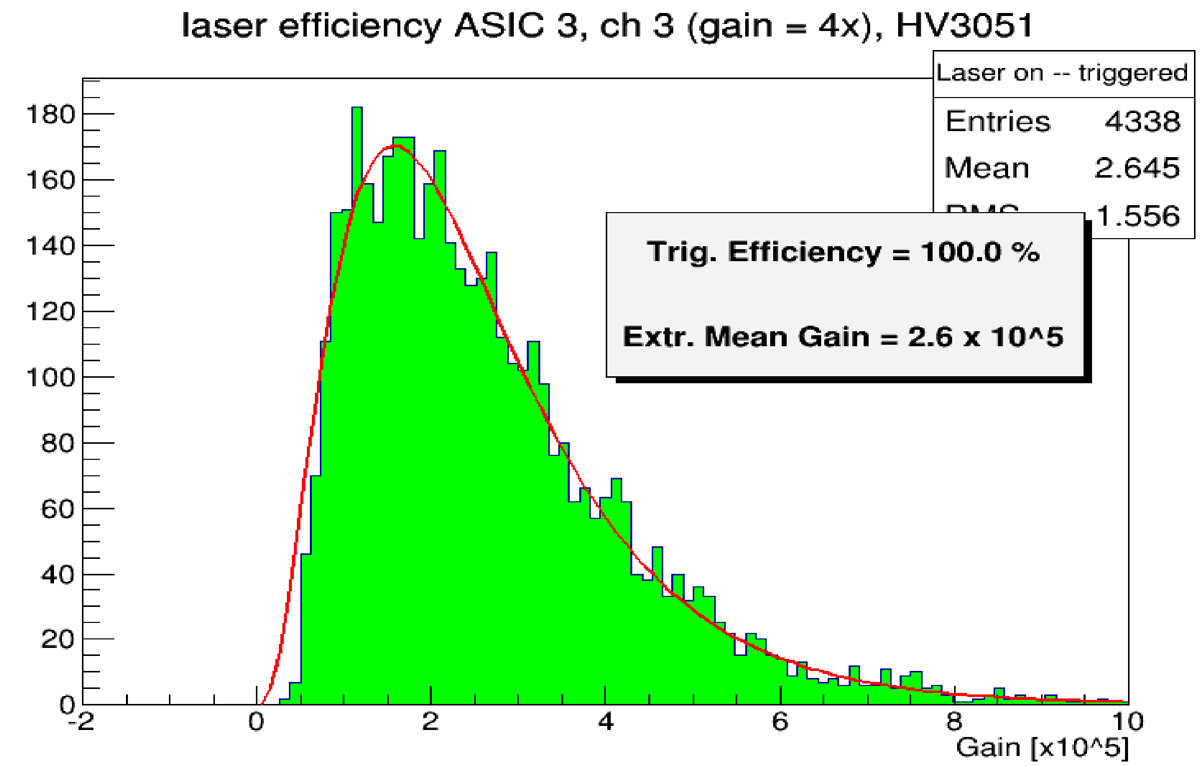
TOP hit rate < 2MHz

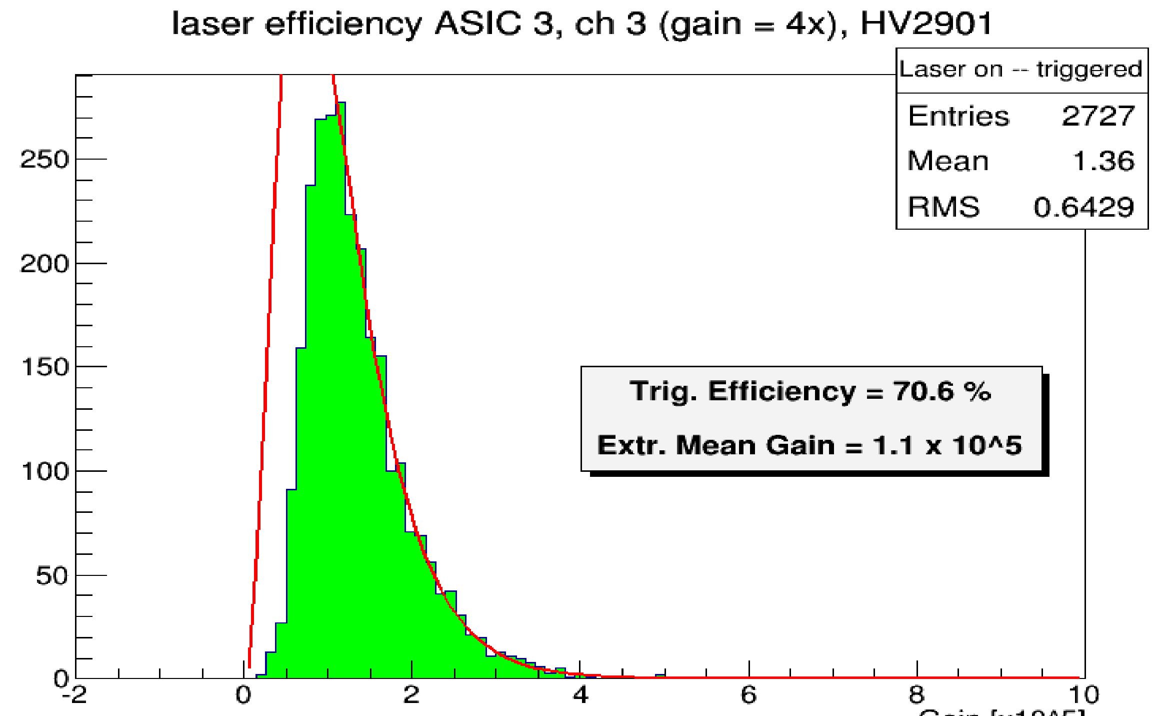


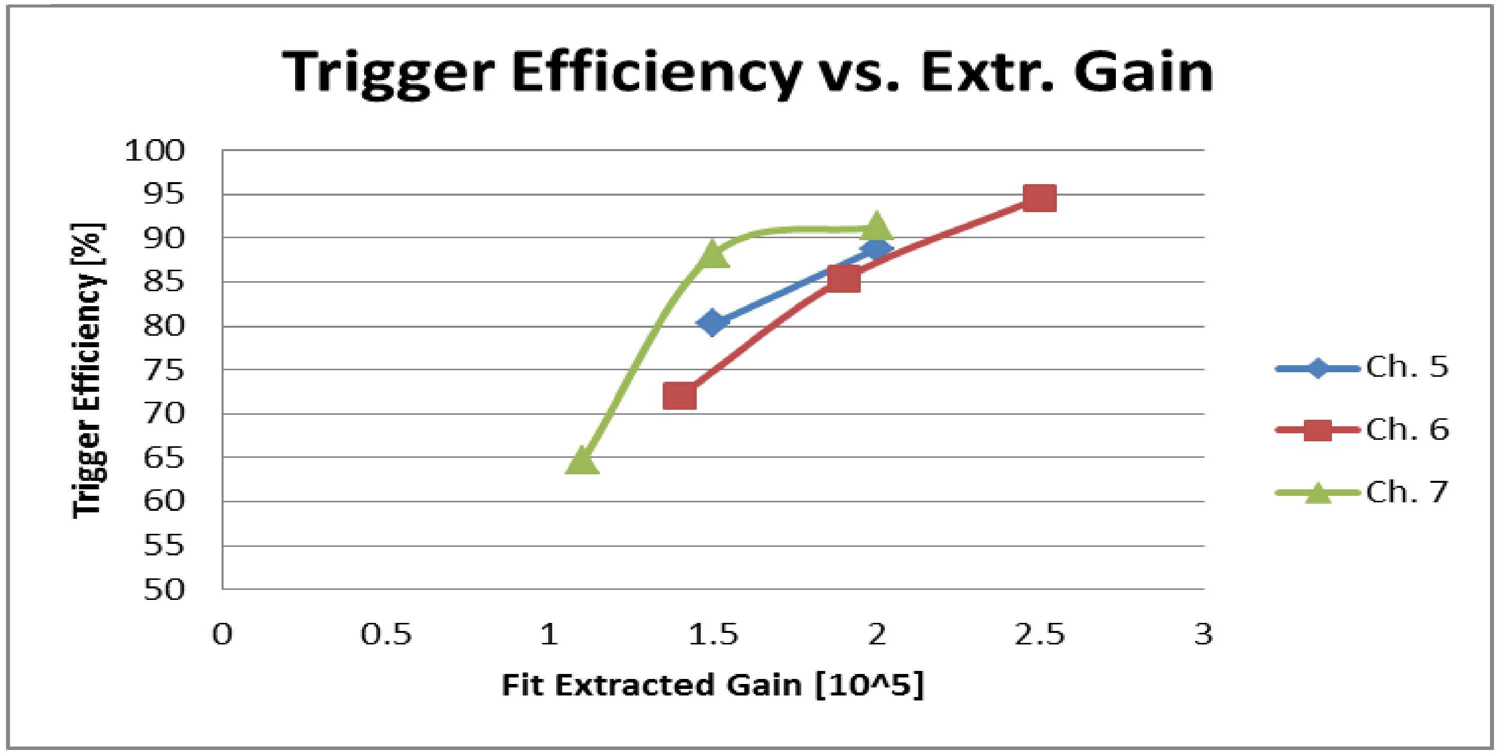


Why not run at lower gain?



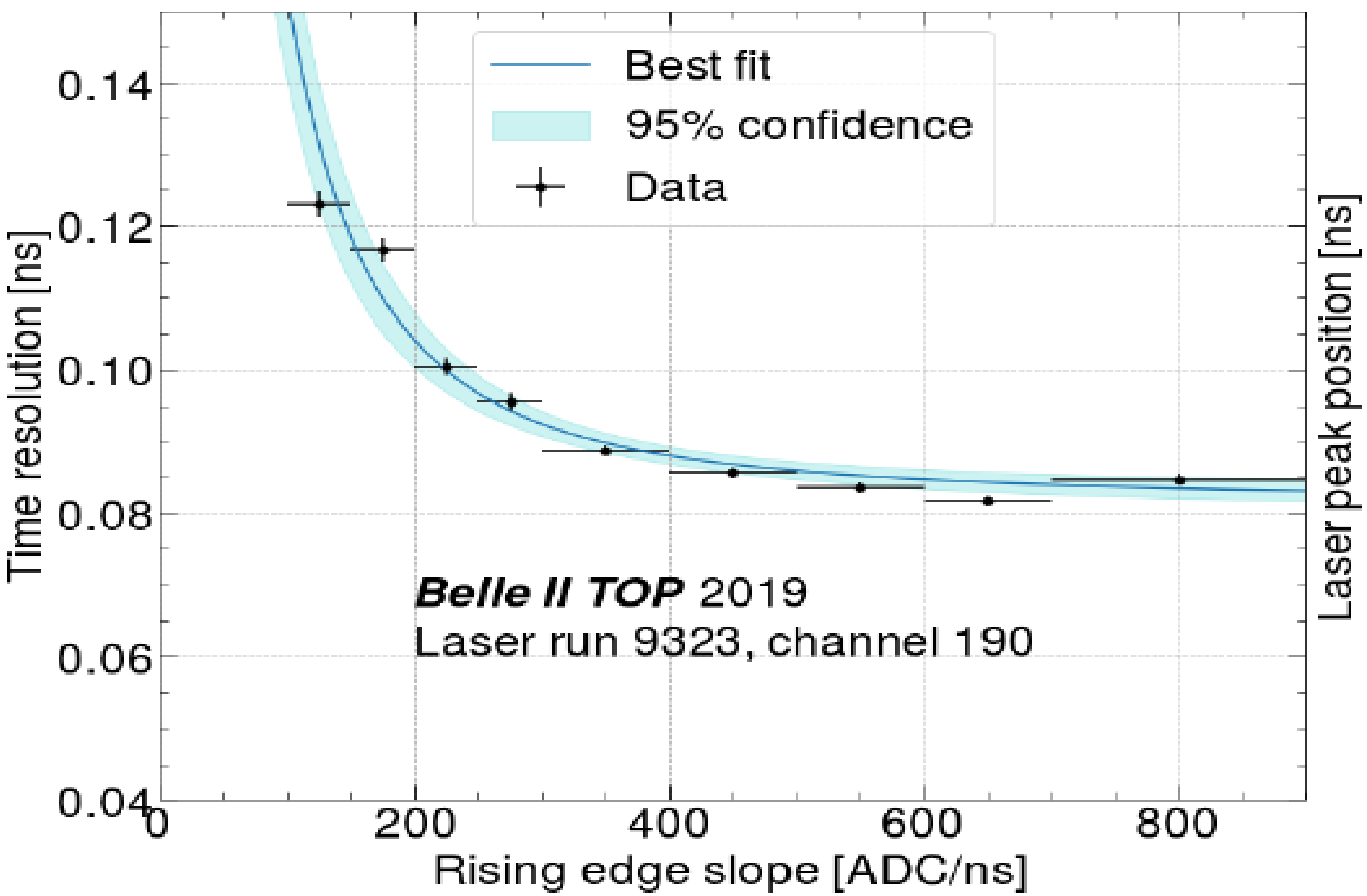


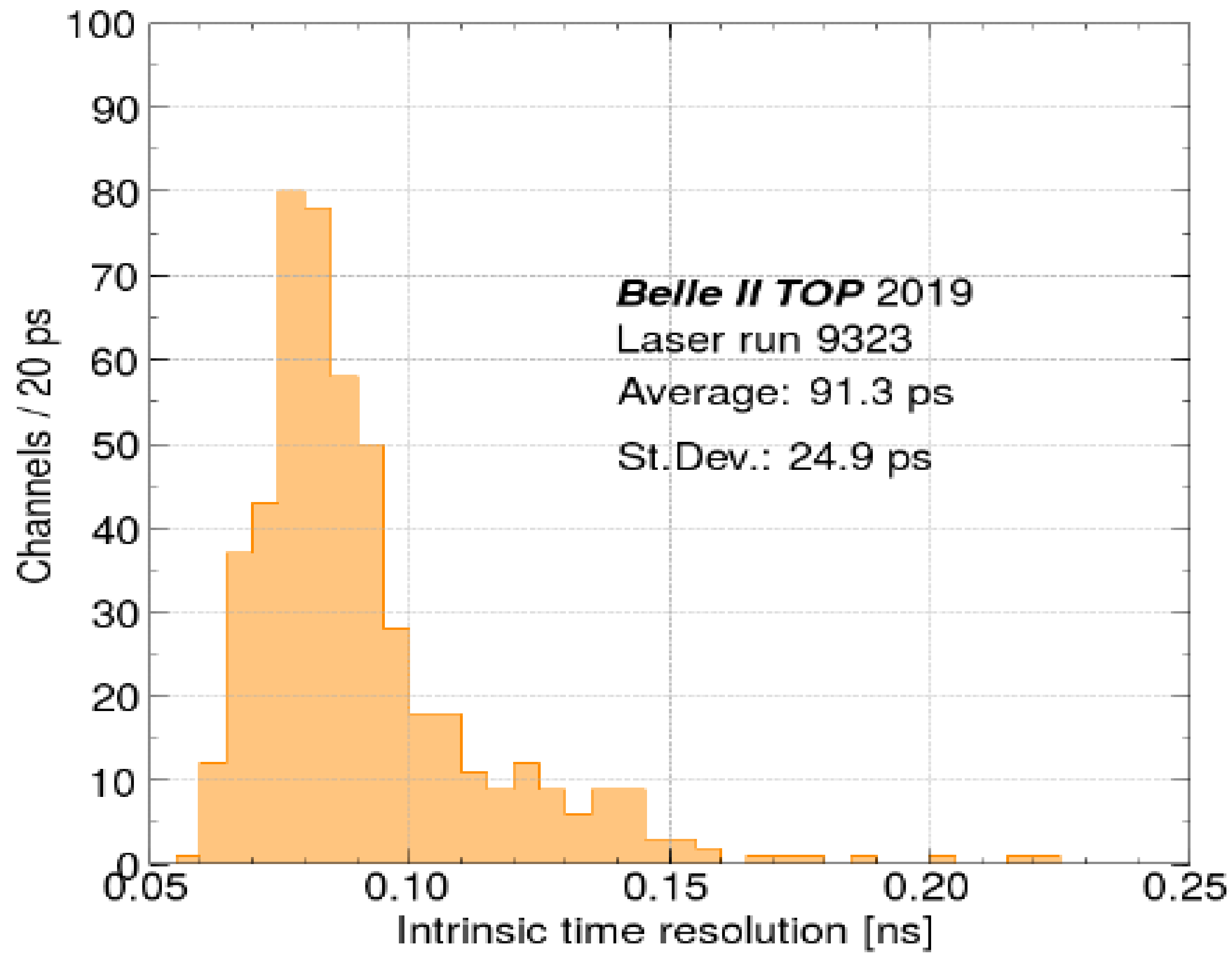




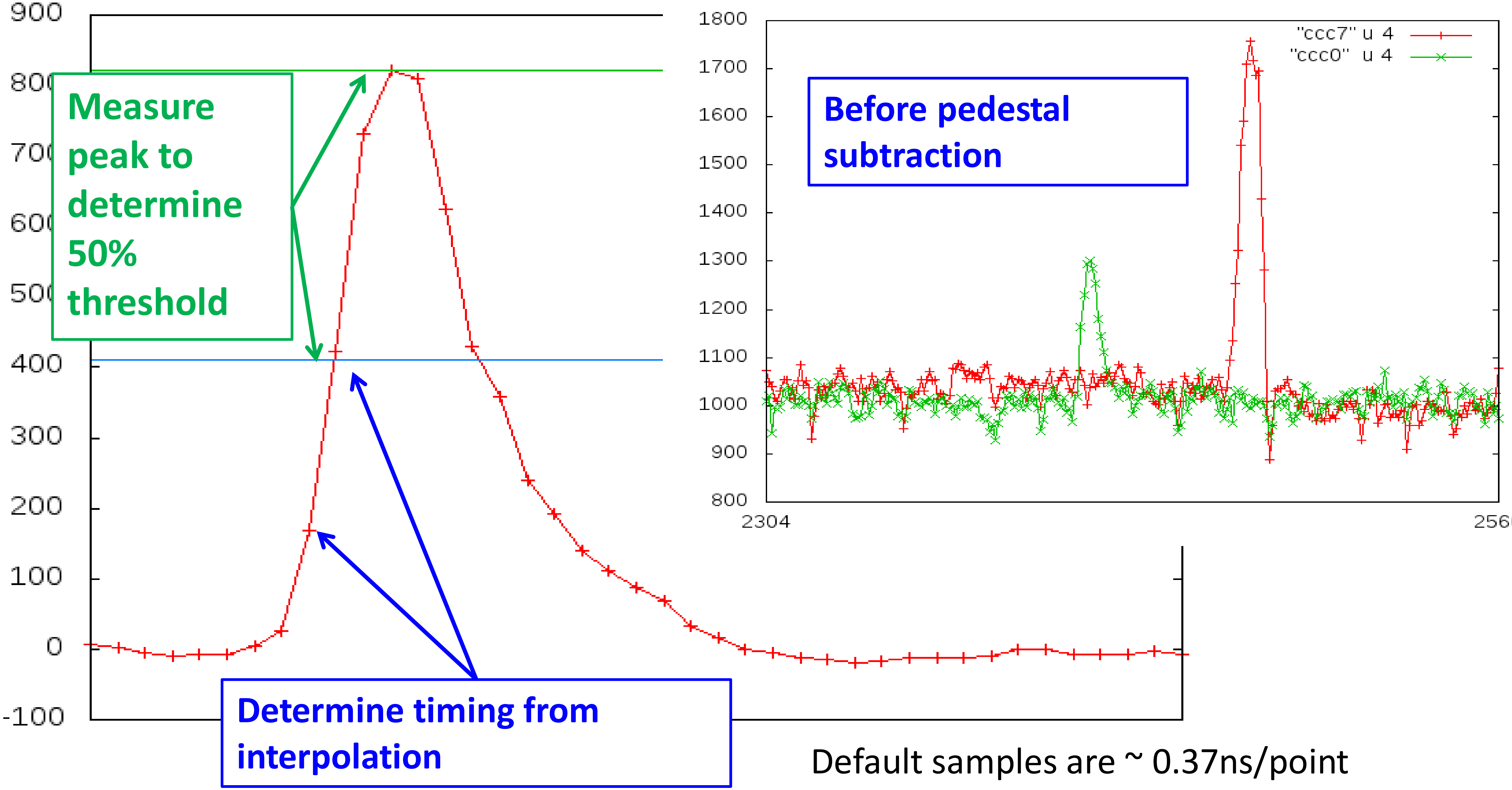
TOP Detector Single photon timing

- Intrinsic resolution <100ps on most channels
  - Laser jitter, pulser reference included (but small)
- Dominated by electronic noise in signal chain due to PMT operation at low gain





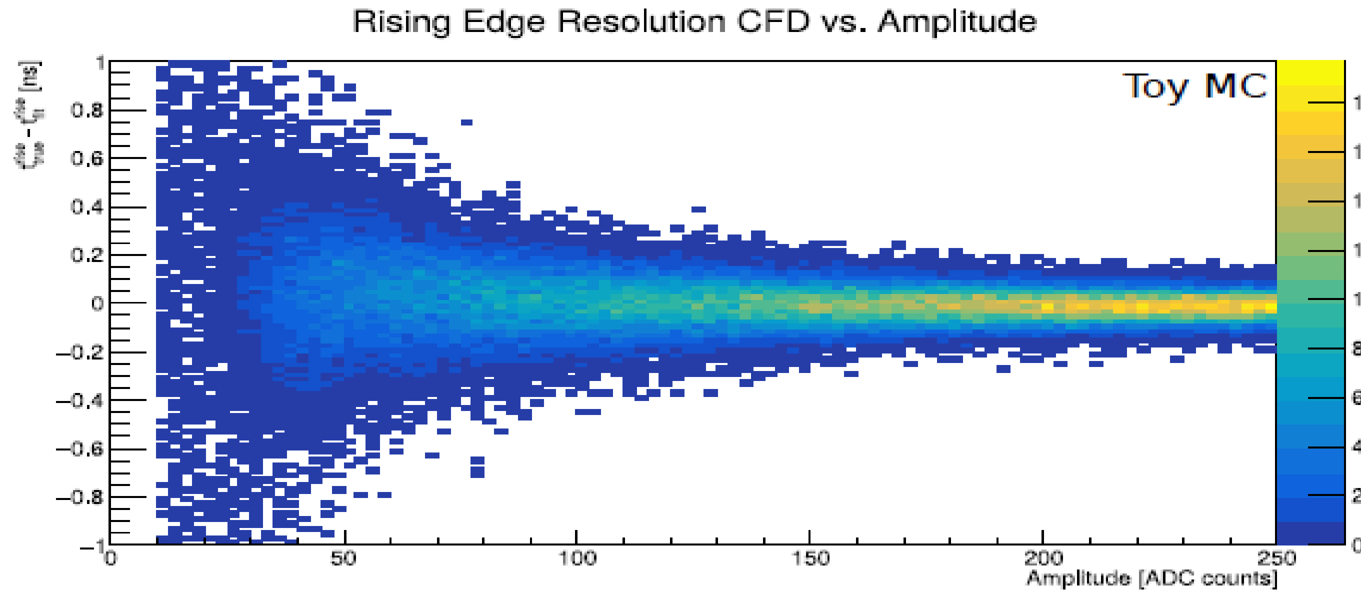
Pedestal subtract & 50% CFD



Default samples are ~ 0.37ns/point

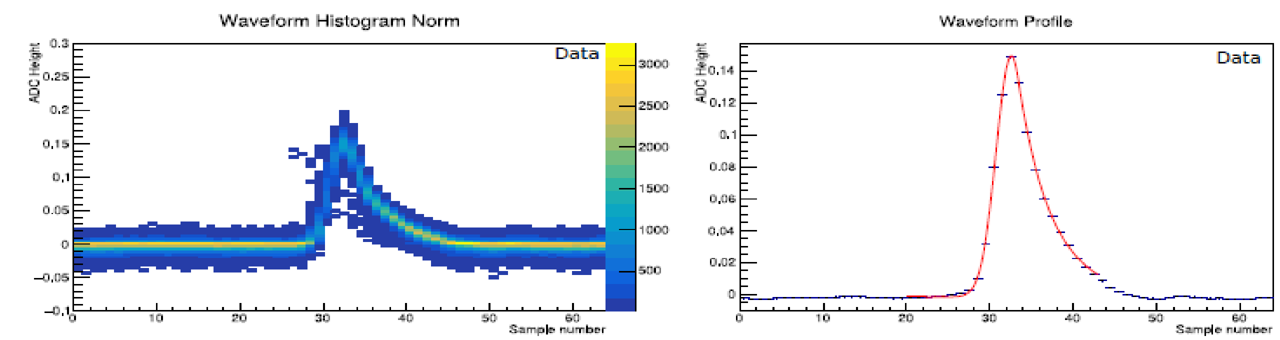
Low PMT Gain Operation

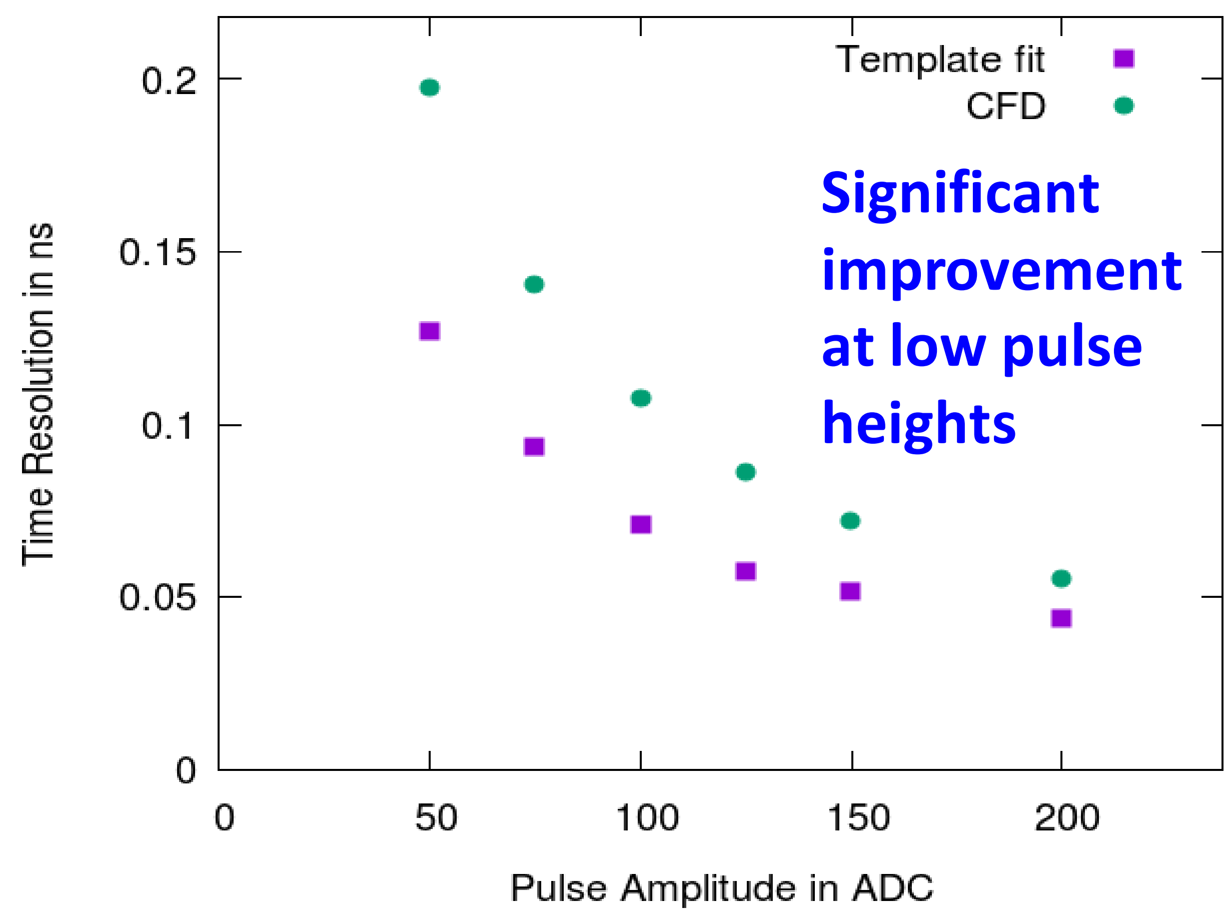
- current feature extraction uses constant fraction discrimination to extract signal timing
- resolution deteriorates at small signal amplitudes



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

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



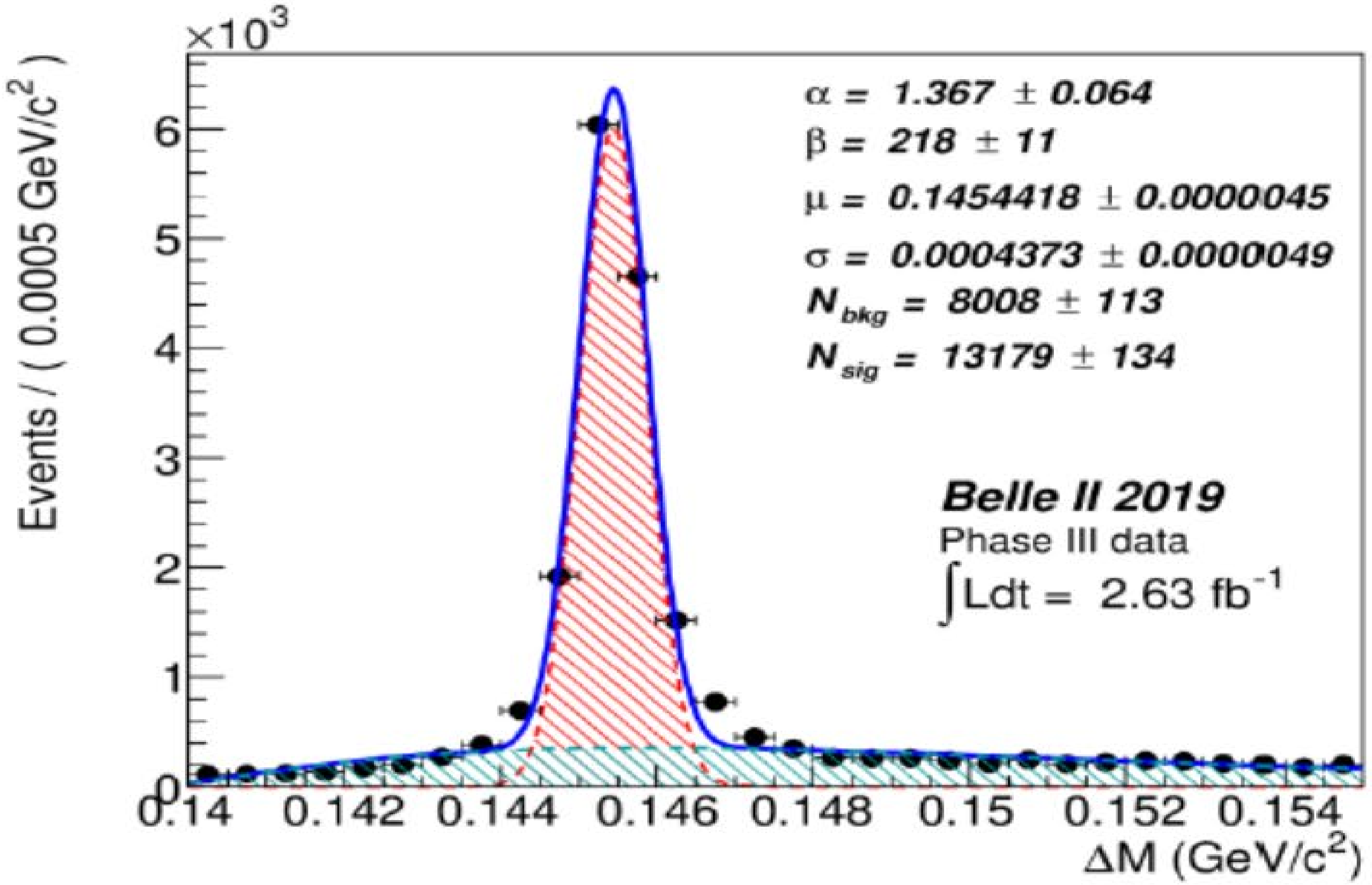


Necessary to maximize MCP lifetime

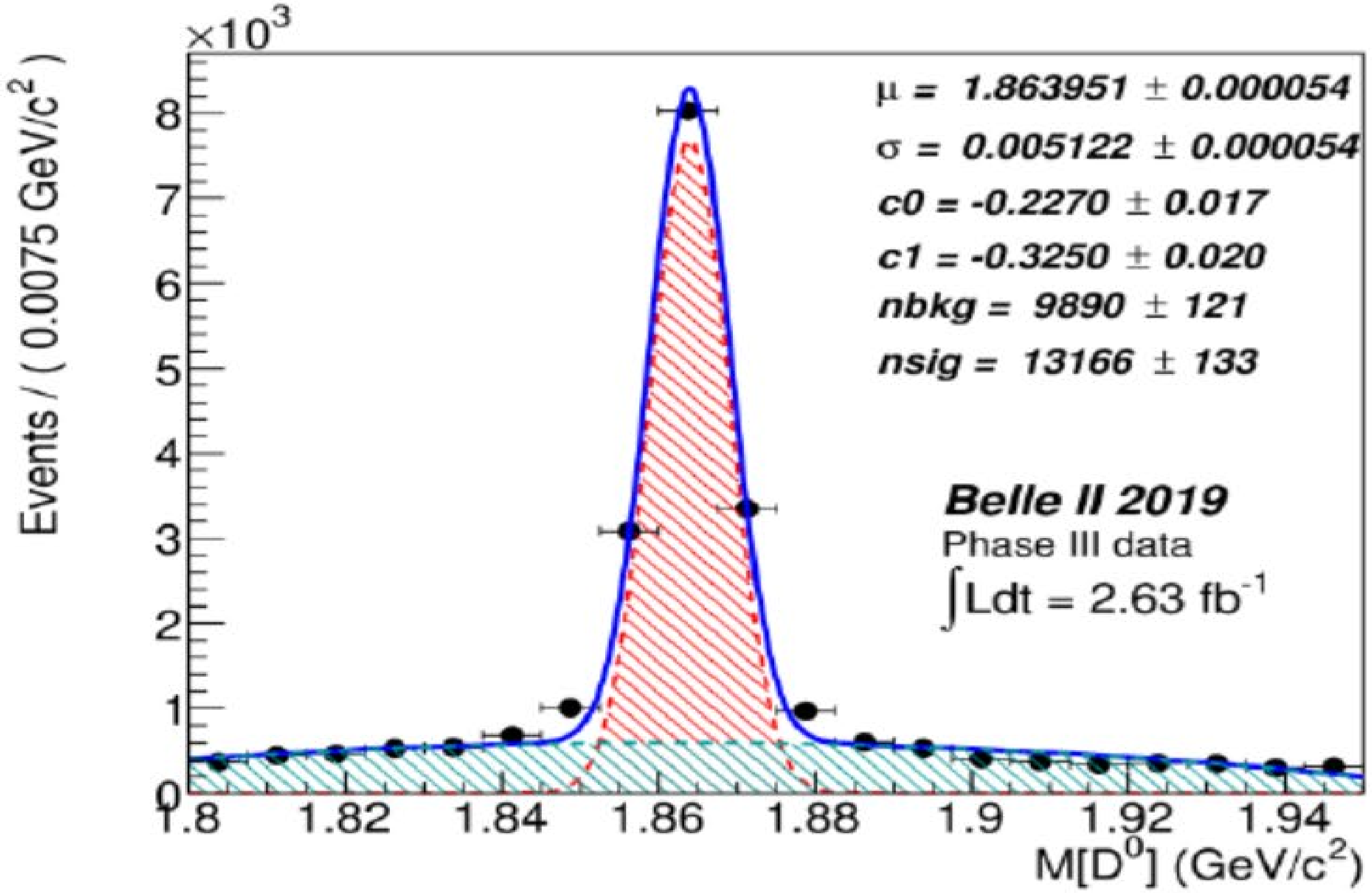
Studying how best to implement (probably PS is too slow?)

D* Truth Sample

- $P^*[D^*] > 2.5$ GeV/c
- $M[D^0] \in (1.85, 1.88)$ GeV/c².



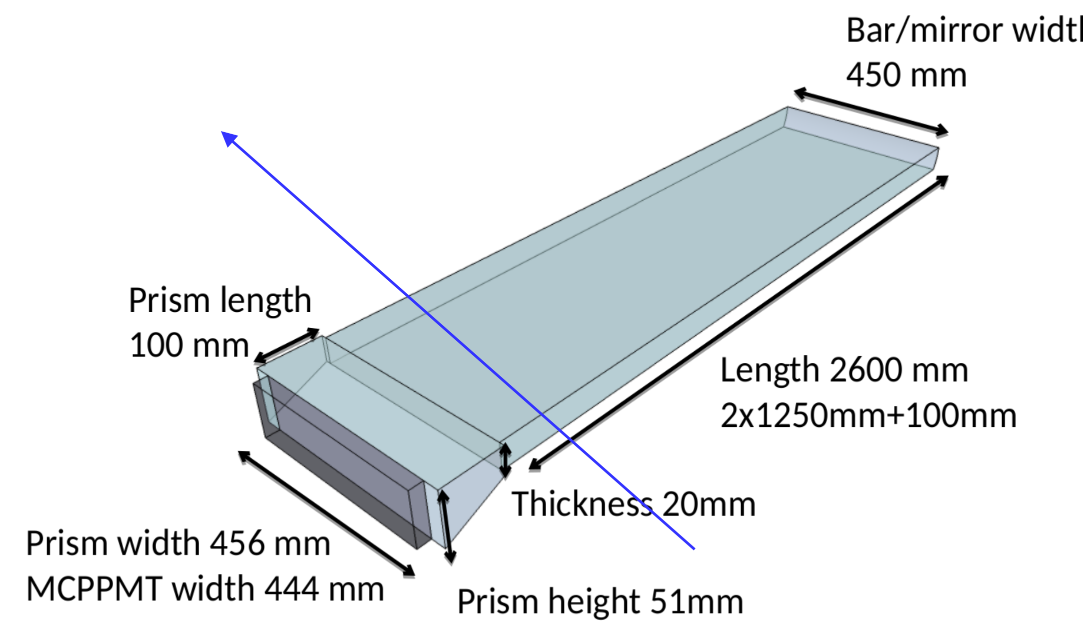
- $P^*[D^*] > 2.5$ GeV/c
- $|\Delta M - 0.14543| < 1.5$ MeV/c².

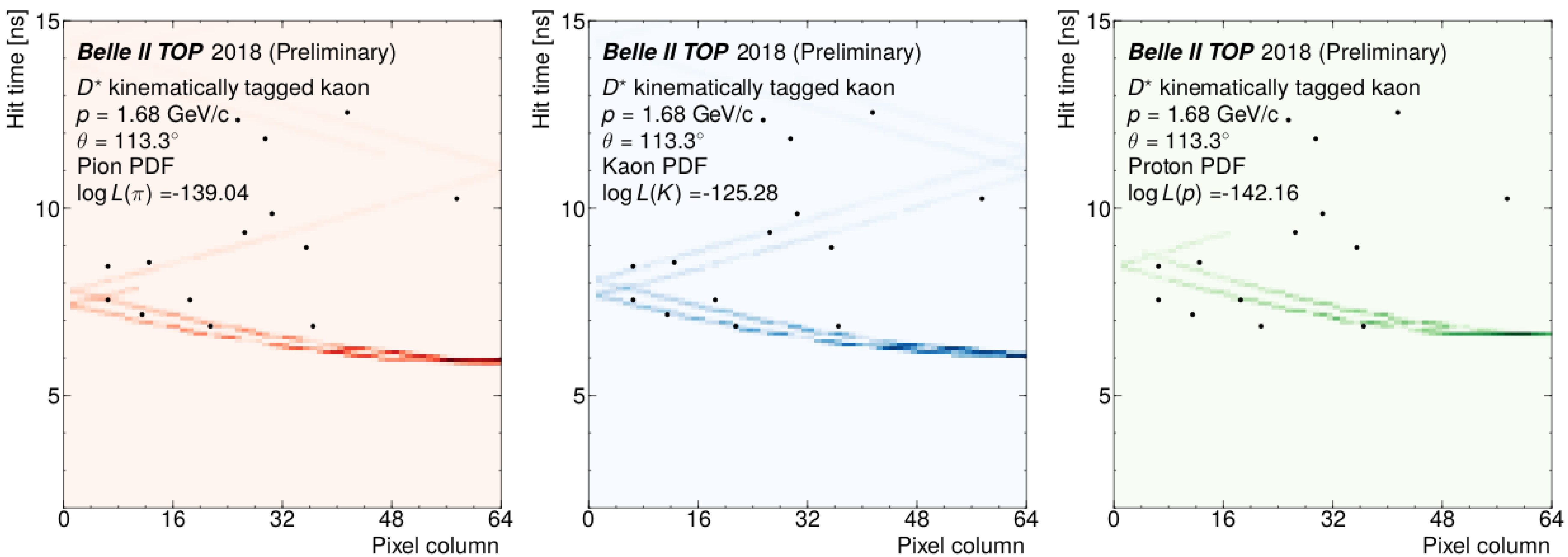


PID performance will be based on fitting $M[D^0]$ distribution

TOP "Cherenkov Rings" I

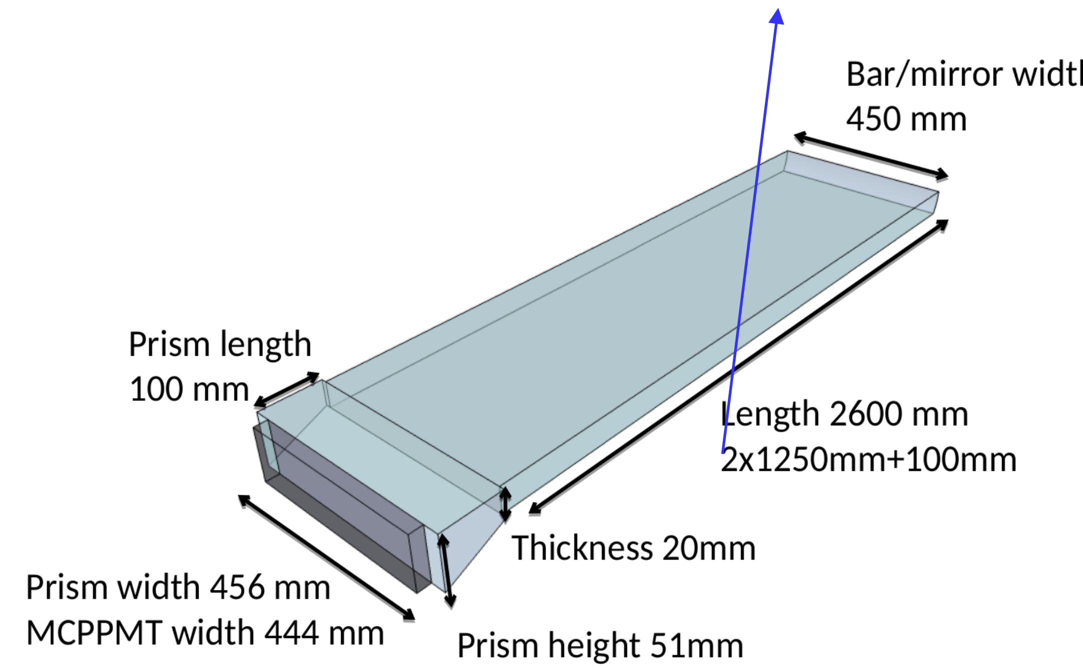
- $D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$
- Kaon facing prism-side of TOP bar
  - Little room for Cherenkov cone to open up
  - PDF differences dominated by ToF offset

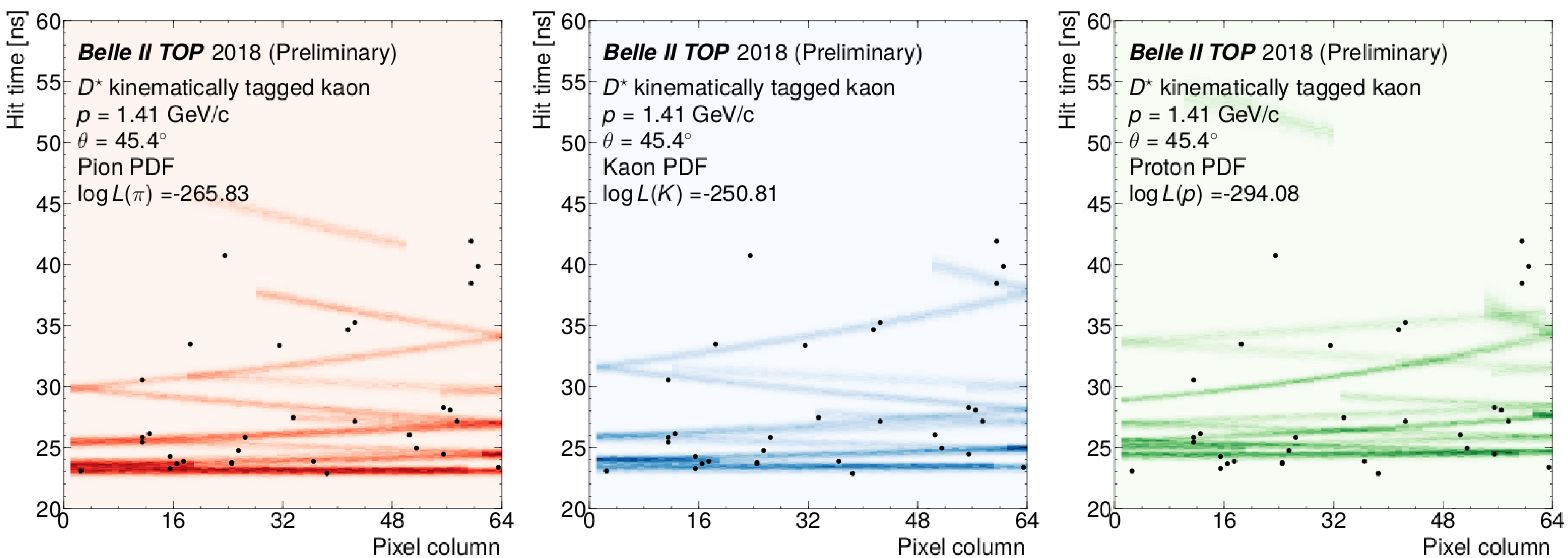




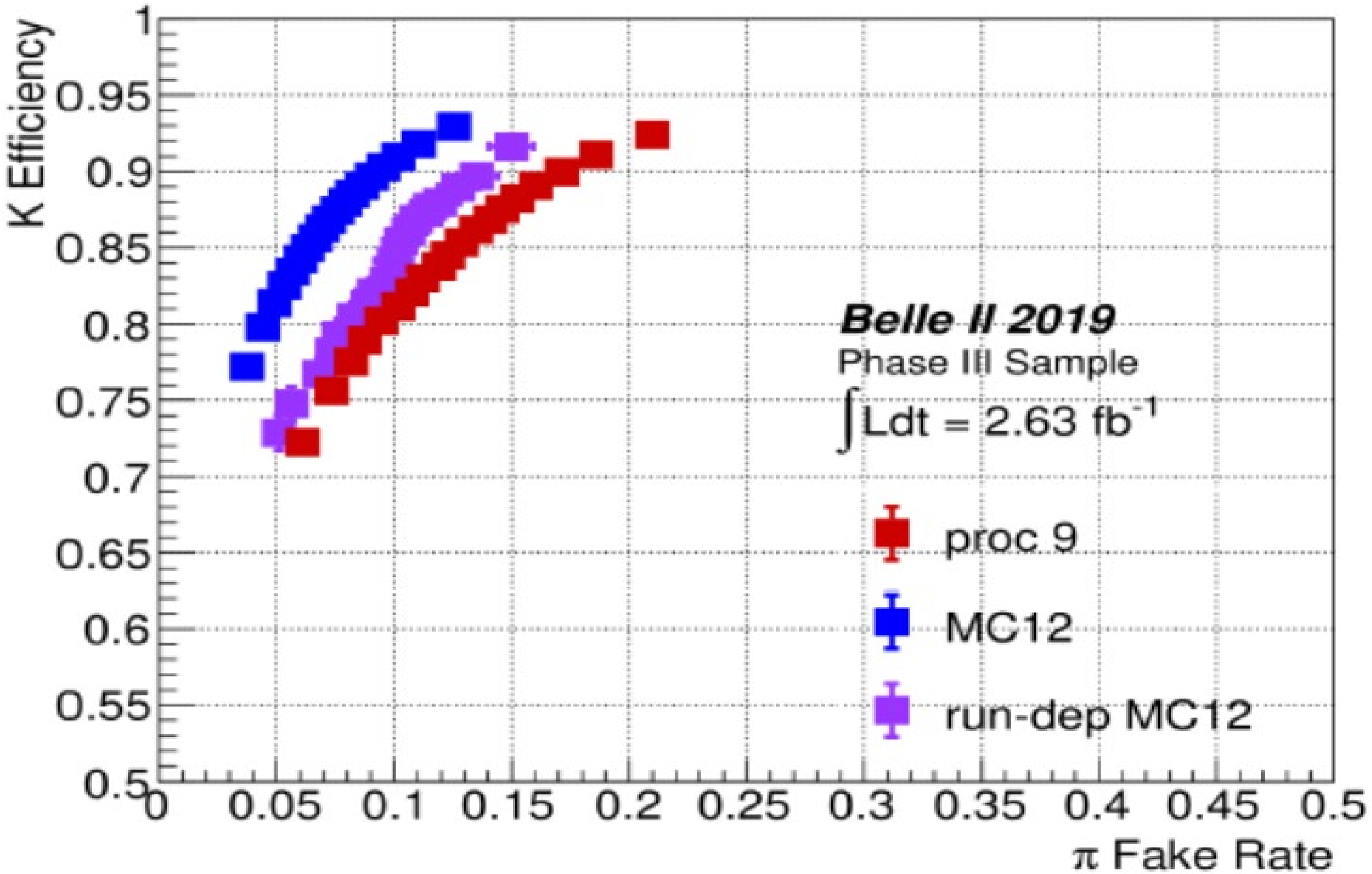
TOP "Cherenkov Rings" II

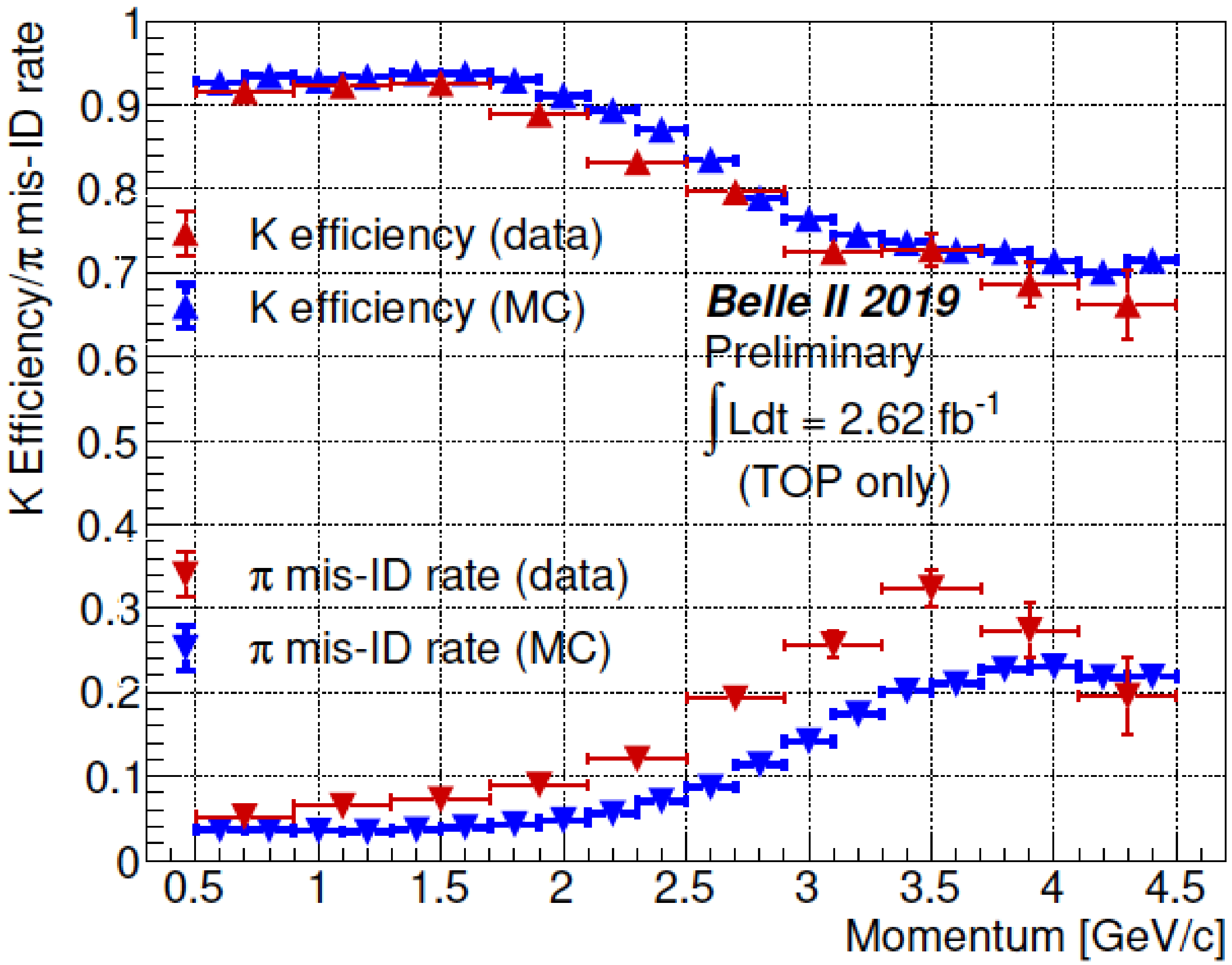
- $D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$
- Kaon facing mirror-side of TOP bar
  - PDF differences dominated by shape
  - Though for proton, also timing





TOP PID Performance (TOP only)

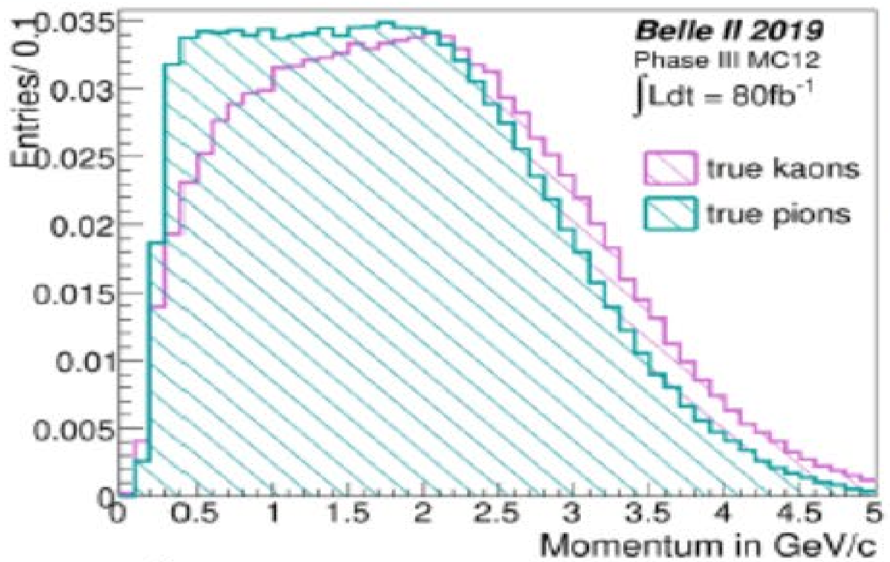




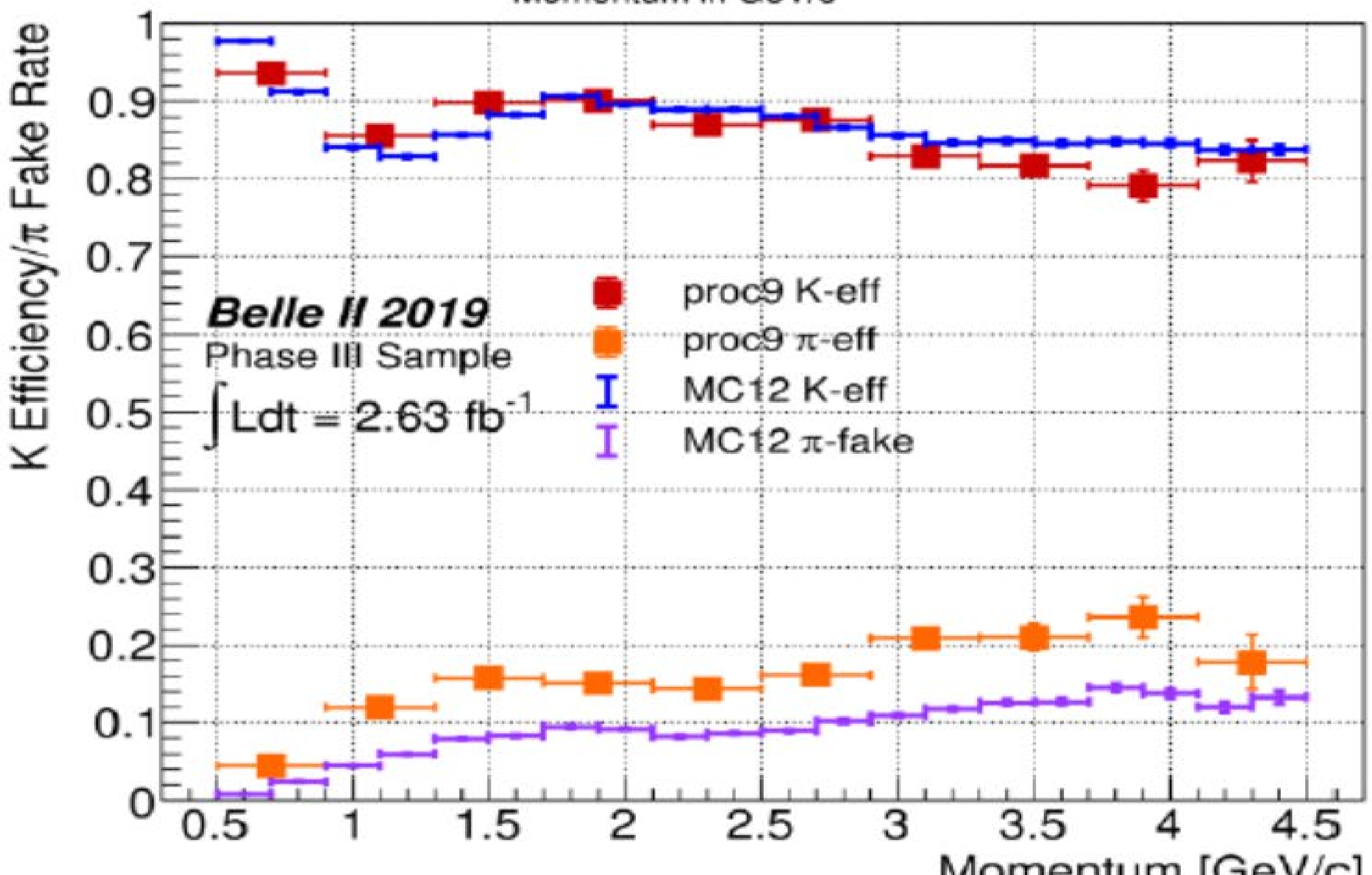
TOP performance is approaching MC expectations. The summer-conference MC release (MC12, July 2019) does not include embedded random triggers to correctly represent the effect of beam background.

Combined PID Performance

Momentum distributions for kaons and pions

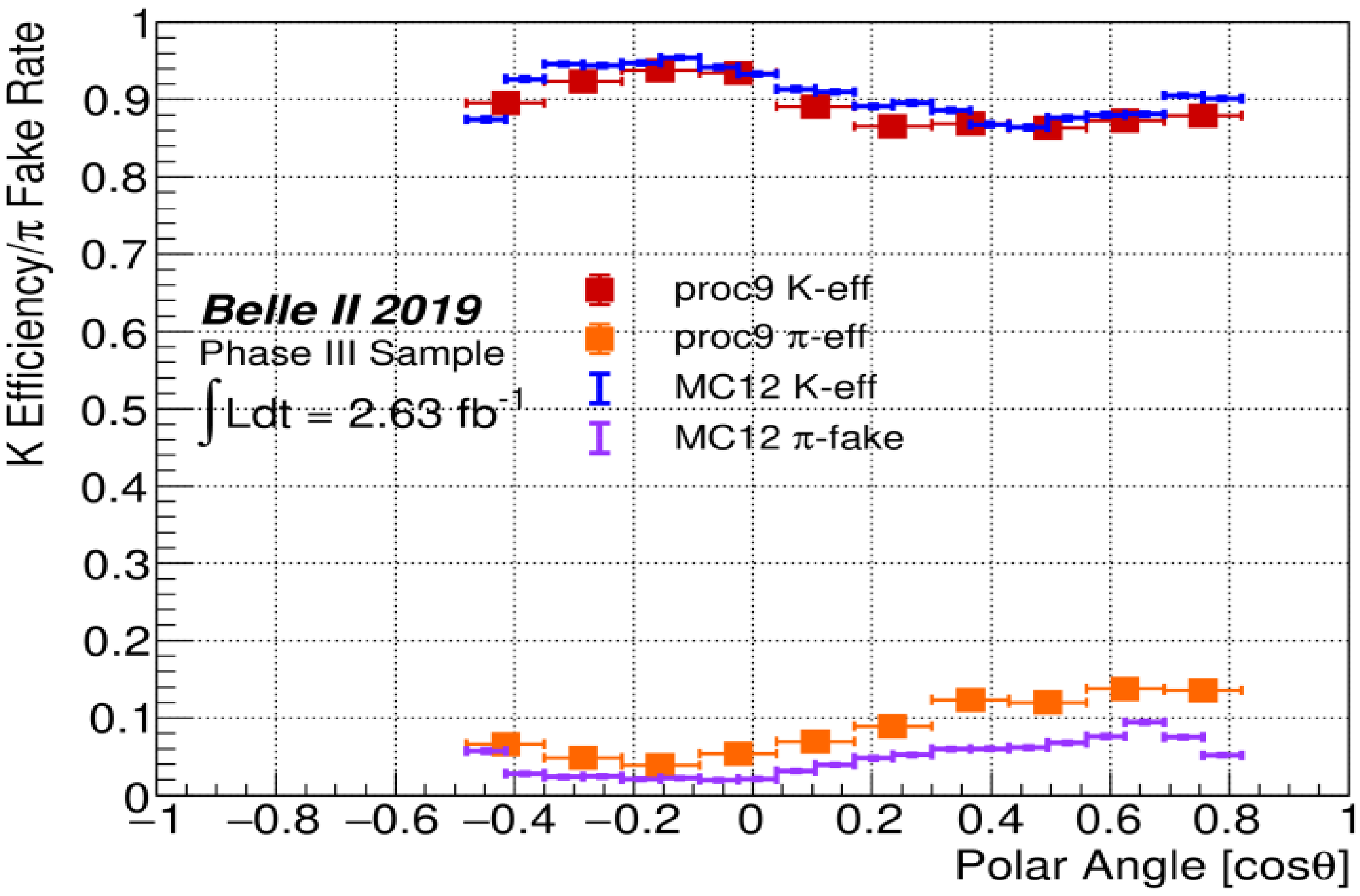


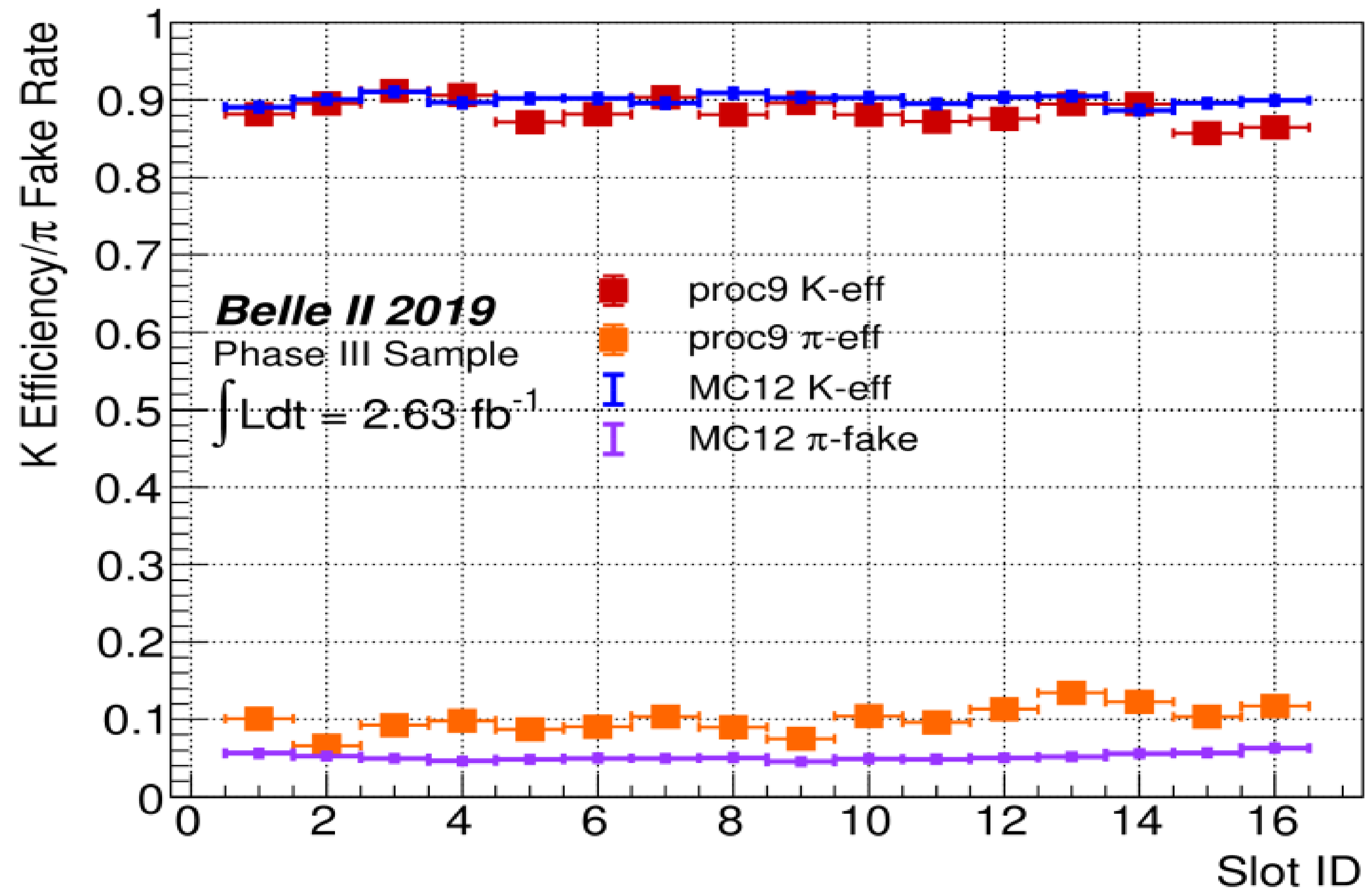
← MC 12 sample, truth matched distributions



- K -efficiency and π-fake rate vs. momentum for the PID criteria [ALL] > 0.5
- The shape of the distribution is consistent
- K-efficiency is mostly consistent in all momentum range.
- π-fake rate discrepancy for all momentum range.

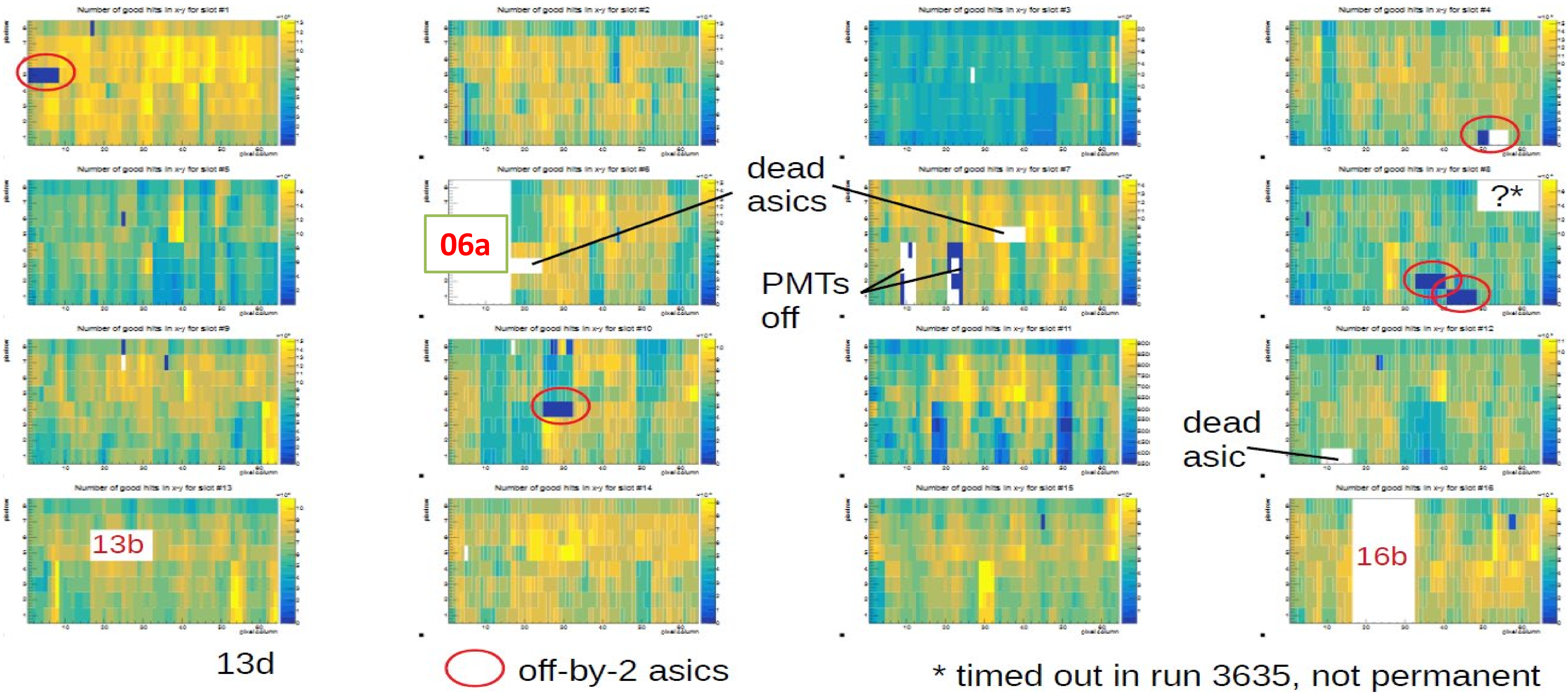
TOP Detector Performance





- **Detailed studies of MC versus data**
- **Run-dependent MC, with missing channels/boardstacks, and more realistic backgrounds account for some of the differences**
- **But not all, consider slots 6 and 16 in next slide**

TOP Operational Status



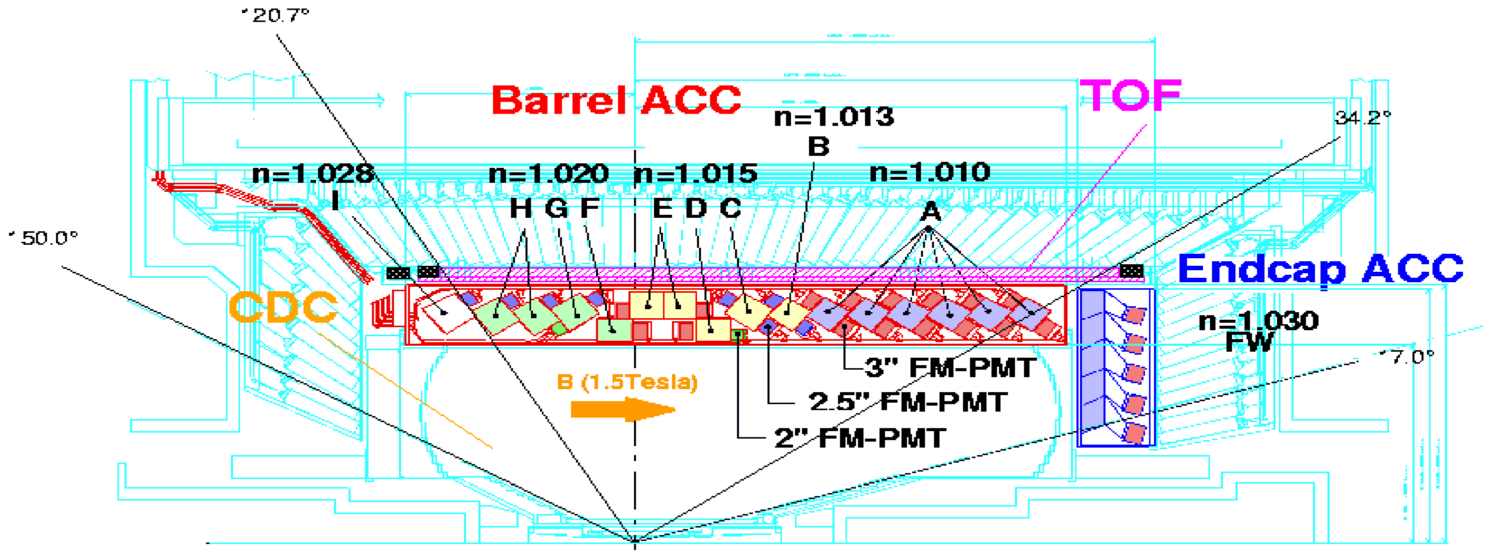
- **Operation generally stable (2 PMTs of 512 were off)**
- **During Phase 3 running about 1 boardstack/day dropped out (recover with power-cycle/reconfig (~30 min.))**

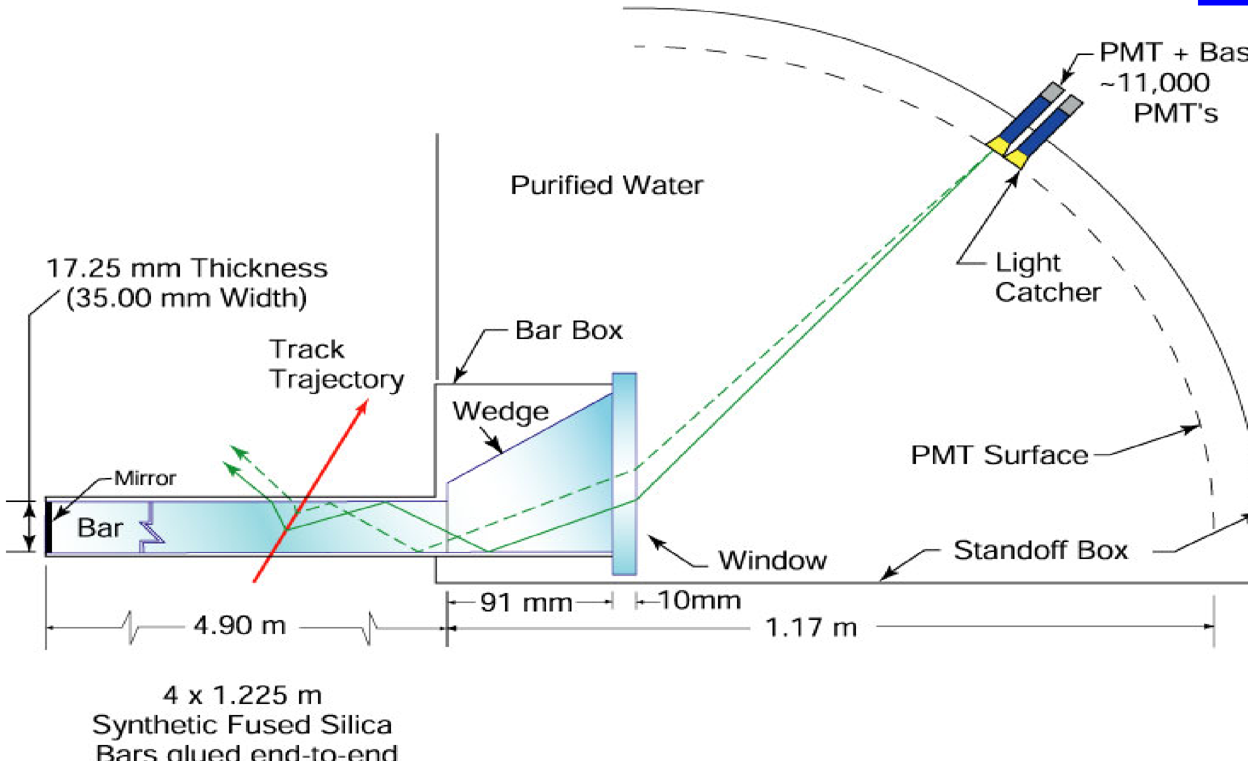
Summary and Outlook

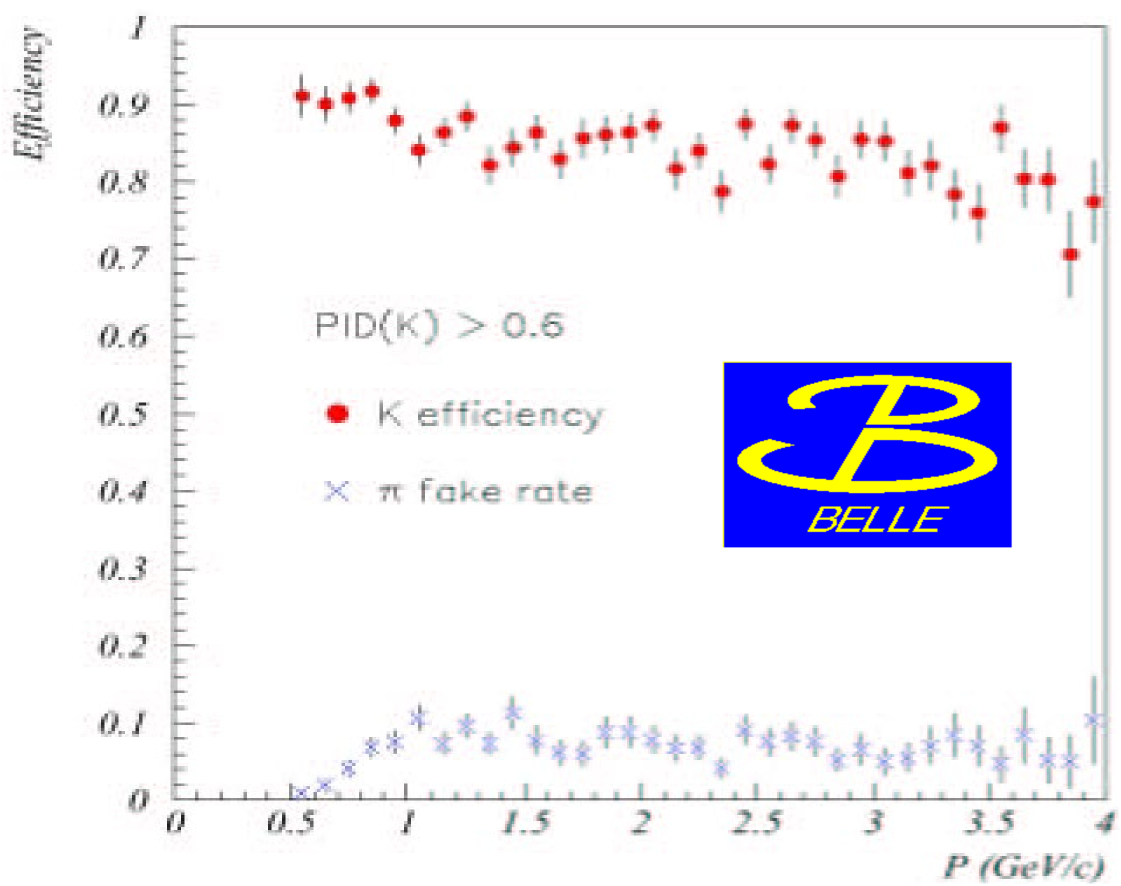
Basically running stable

- **Performance approaching MC expectation**
- **Still a couple of mysteries**
- **Originally planned to replace ~50% of PMTs (non-ALD) in summer 2020 (still keeping to that schedule just in case)**
- **Due to expected long shutdown in summer 2021, going to try and last until then, so gain and integrated charge monitoring important**
- **Can replace faulty components only during access (impossible otherwise), > 96% channels working**
- **Fall 2019 running, adding in SEU detection and mitigation to firmware**
- **Template fitting and other algorithms under study**

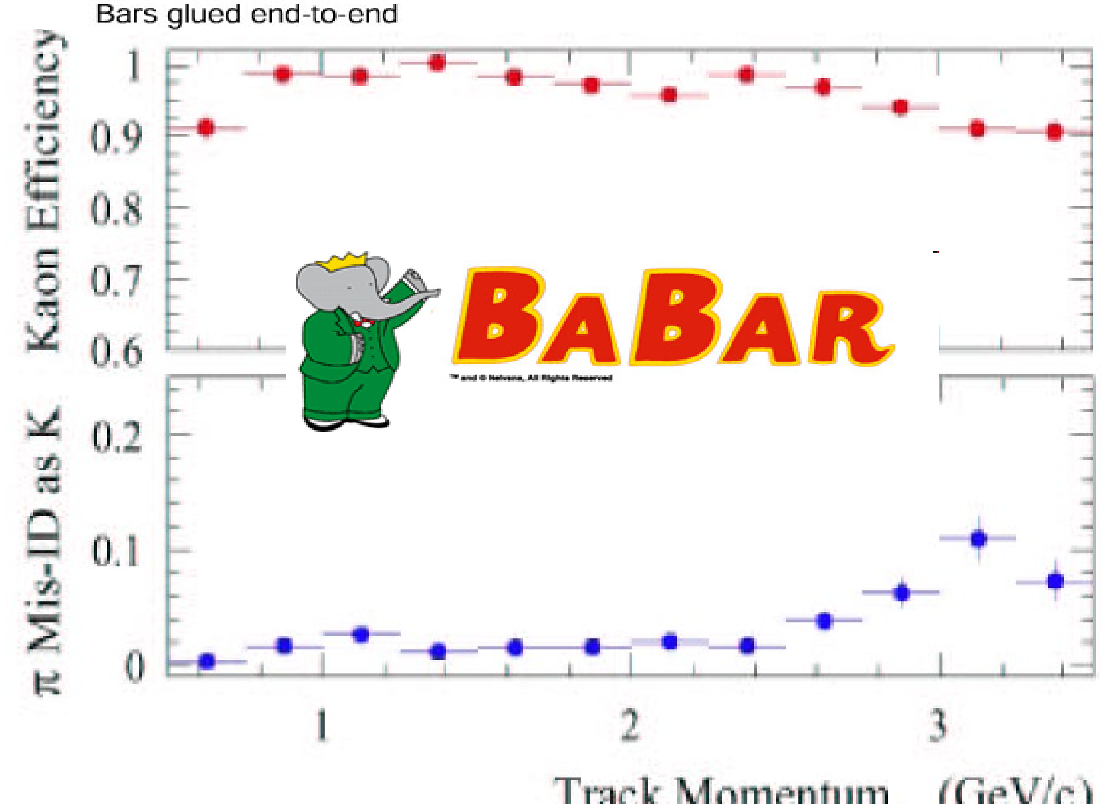
Particle ID at the B Factories





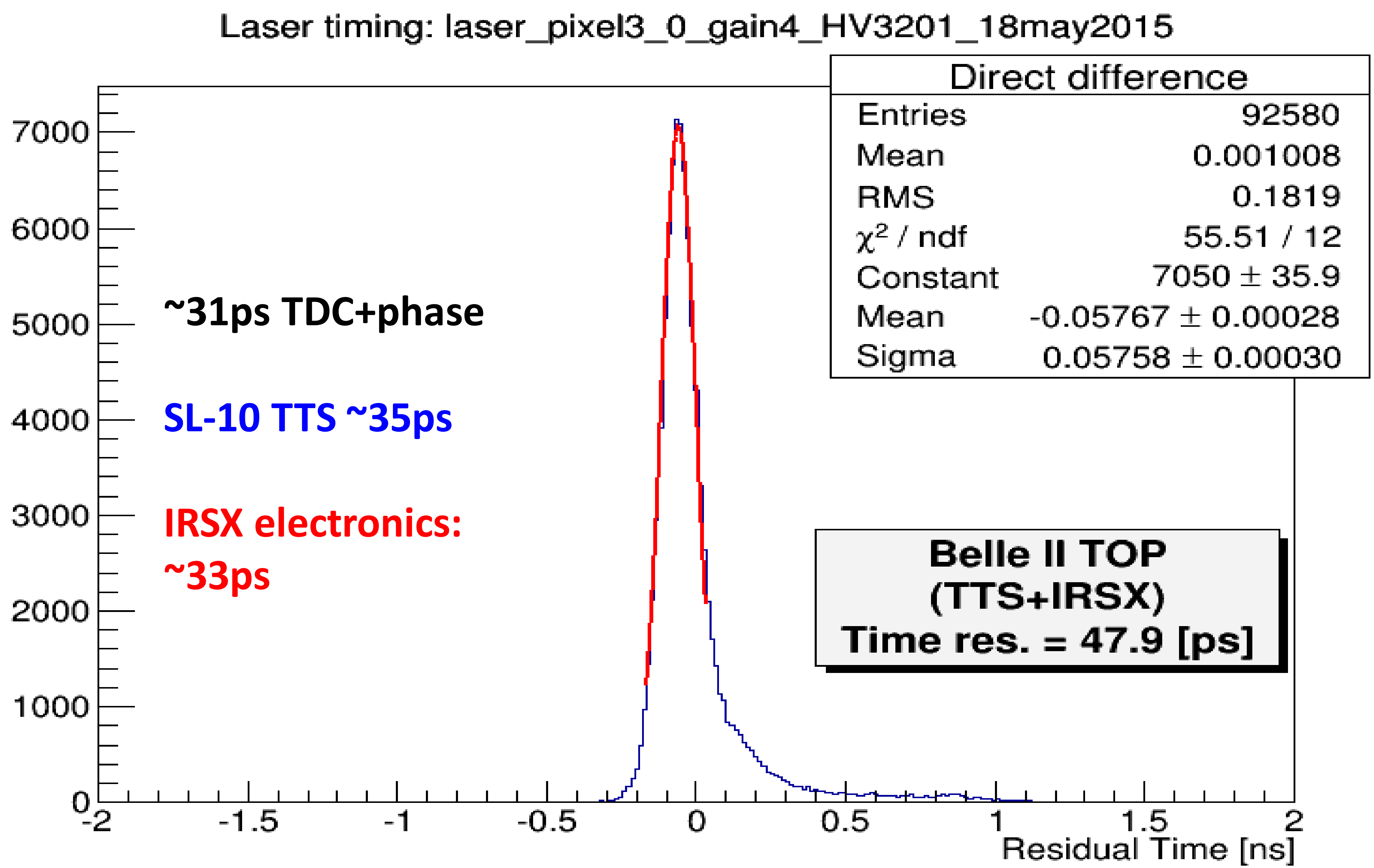


NIM A494 (2002) 402-408.

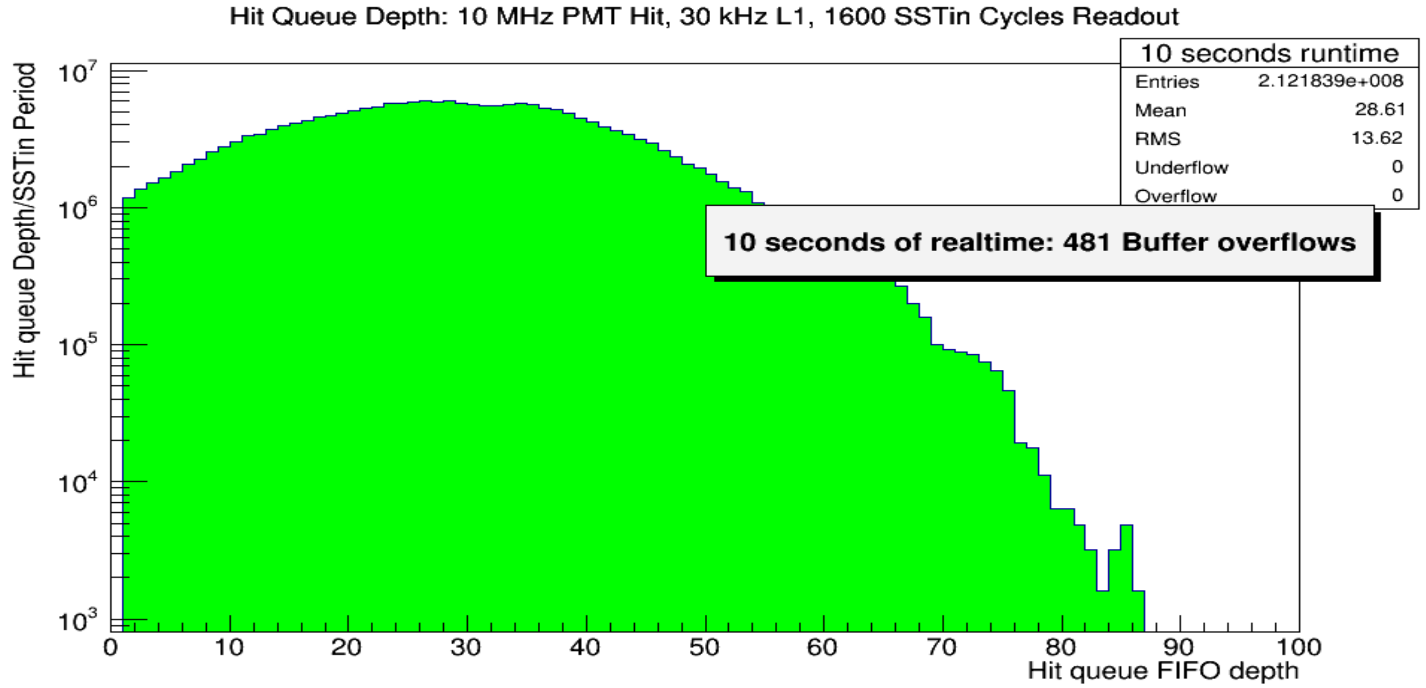


NIM A553 (2005) 317-322.

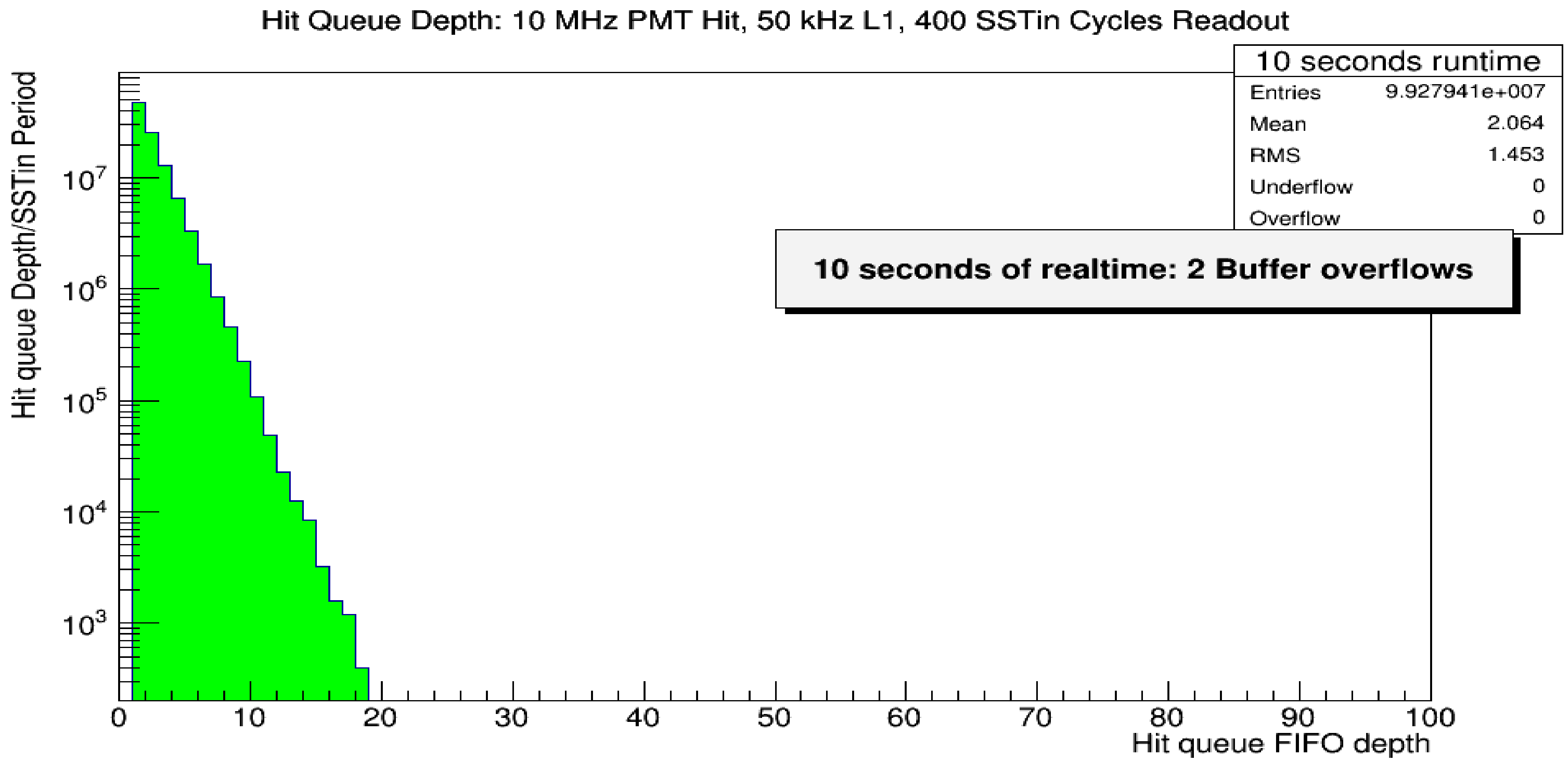
Production single photon testing



30kHz L1, high occupancy emulation

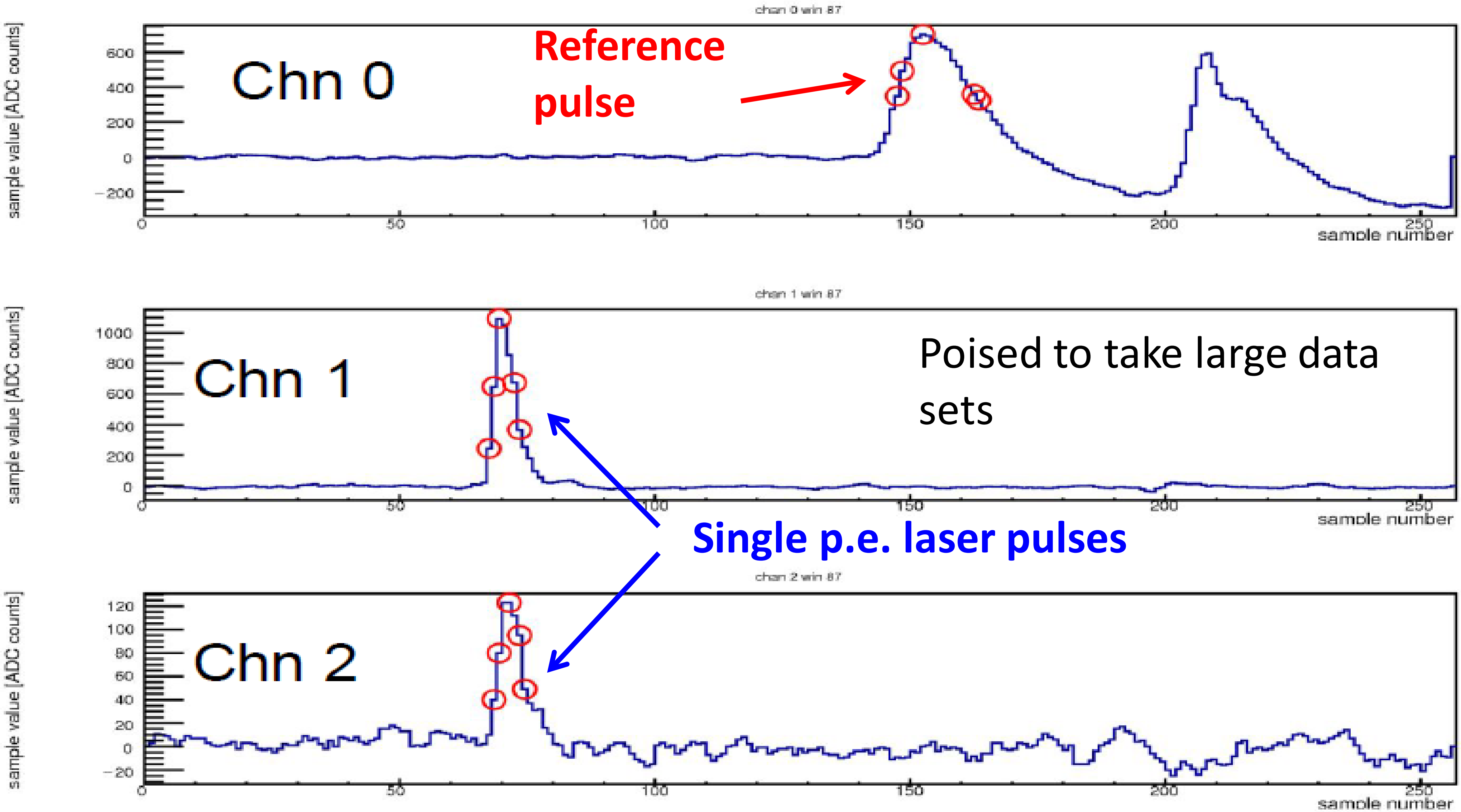


30kHz L1 trigger, 10 MHz background photons/PMT, multi-hit, multi-event buffering



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

ROI & FE (laser data)



Poised to take large data sets

Region of Interest and Feature Extraction Firmware running on installed modules

PERFORMANCE SUMMARIES