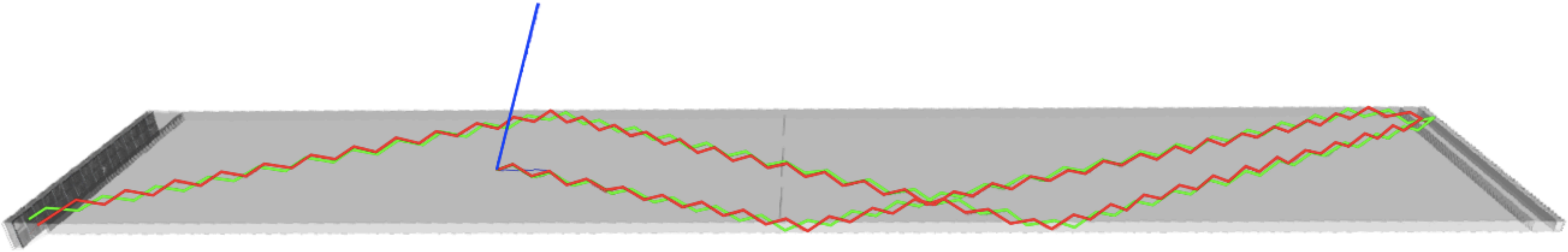
The iTOP Particle Identification Detector at Belle II



K. Nishimura[1]*, on behalf of the Belle II Barrel Particle Identification Group

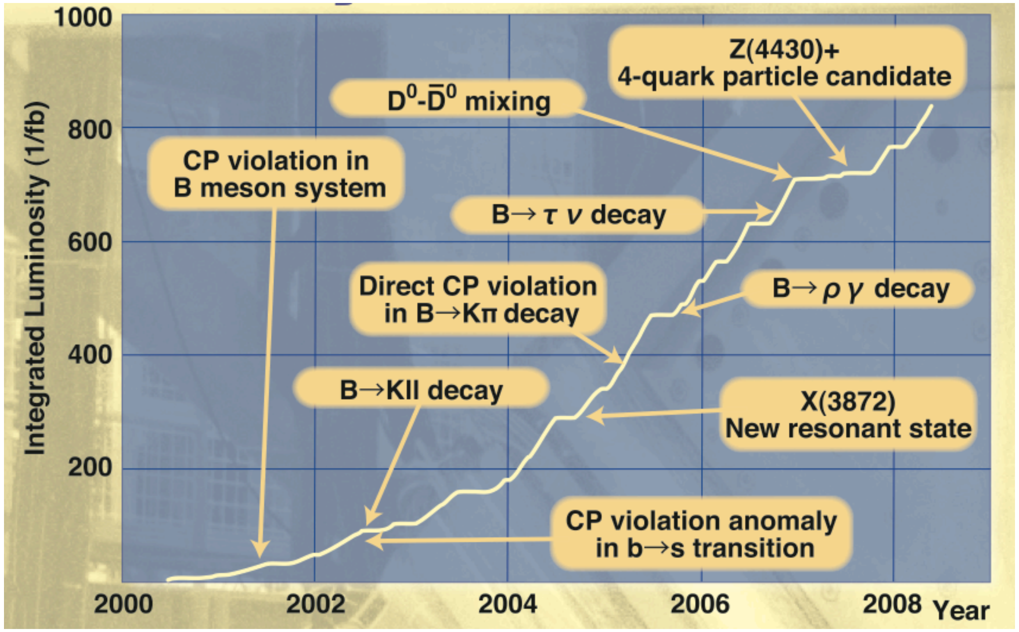
[1]University of Hawaii at Manoa

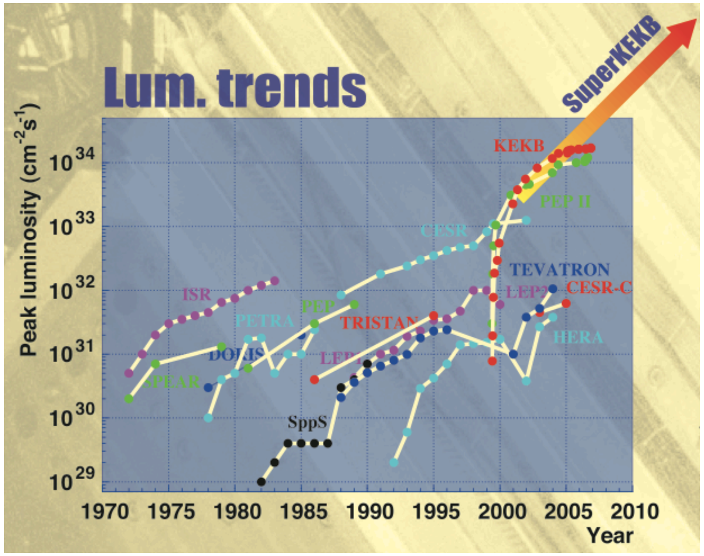
Wednesday, August 5, 2015
DPF 2015, Ann Arbor MI
Accelerators, Detectors, Computing Session

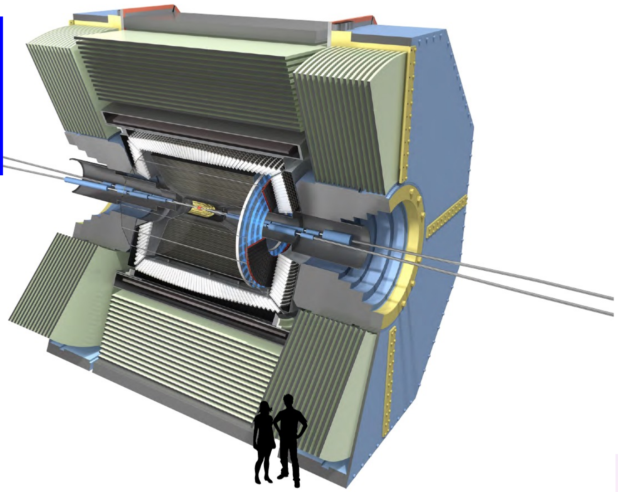
*Currently at Ultralytics

Belle-II Upgrade at Super KEKB

- B factory experiments (Belle & BaBar) have rich history of discoveries.
  - Belle II at Super KEKB will push luminosity by ~40x for precision New Physics searches.

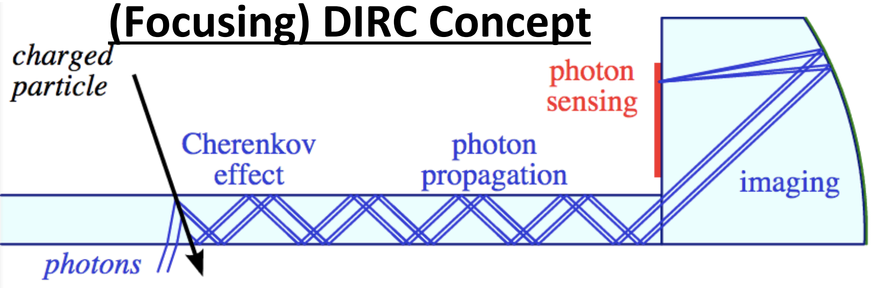




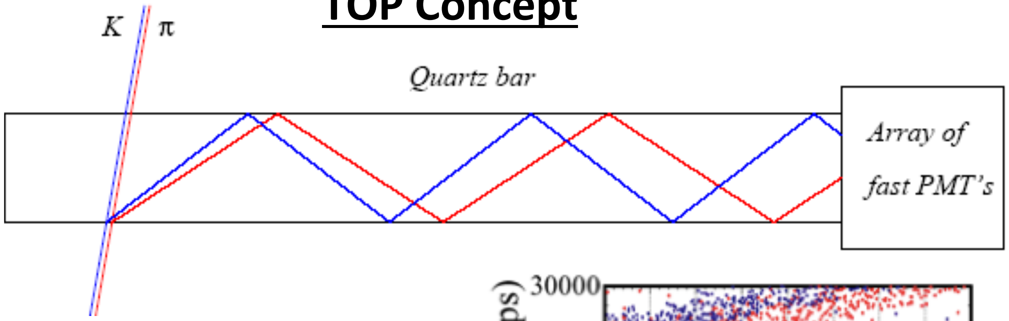


- K/π identification devices at Belle II:
  - Endcap: proximity focusing aerogel RICH.
  - Barrel: time of propagation detector.

Time of Propagation (TOP) Concept

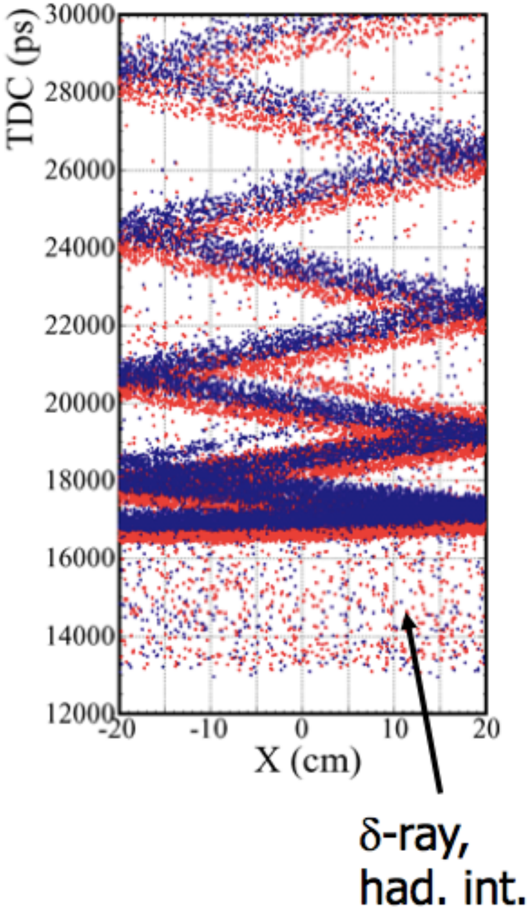


(Focusing) DIRC Concept



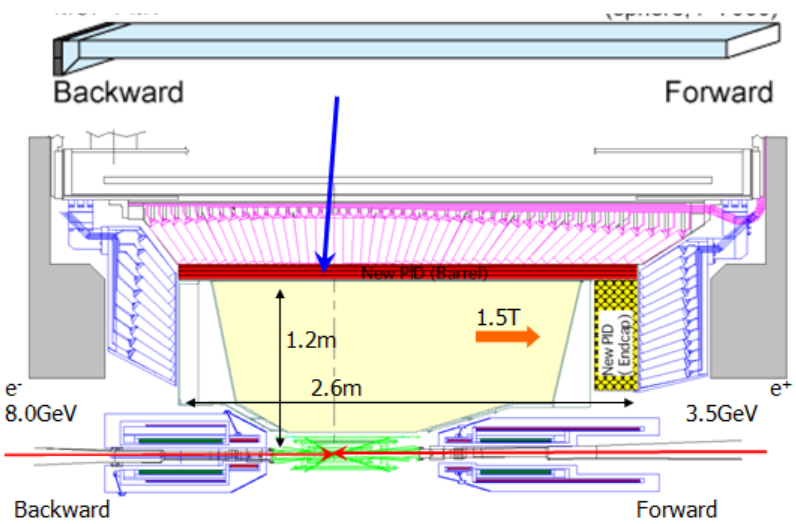
TOP Concept

- TOP is a variant of detection of internally reflected Cherenkov (DIRC) device.
  - Light generated with angle $cos\theta_c = \frac{1}{n(\lambda)\beta}$
  - Propagates to end of bar via TIR.
  - DIRC: primarily measures *x*,*y* of each photon.
    - Can use *t* to suppress background, and/or correct chromatic effects.
  - TOP: uses timing in place of y coordinate.
    - Typical timing separation between K/π of order 100 ps.
    - Requires precision timing.

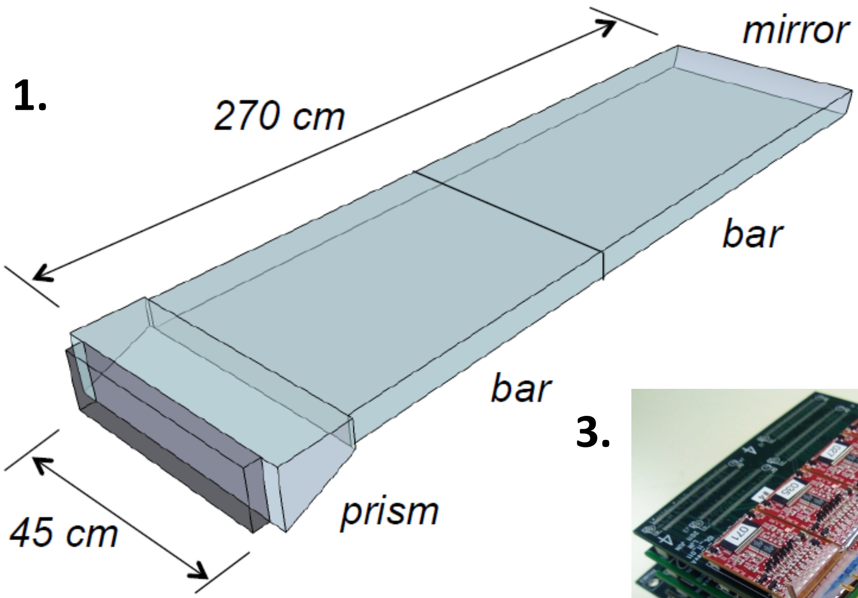


Belle II Imaging TOP (iTOP) Detector

- Key elements:
  1. Quartz bars, mirror, prism.
     - Limited imaging relative to *x*,*t* TOP.
  2. MCP-PMTs for fast timing.
  3. Integrated readout electronics.



1.



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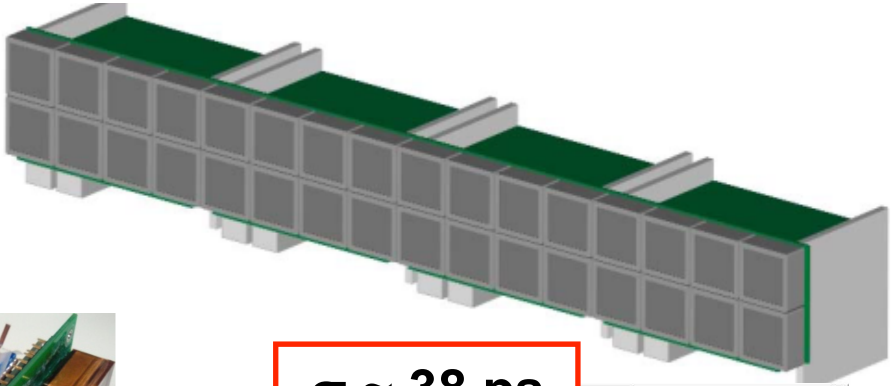

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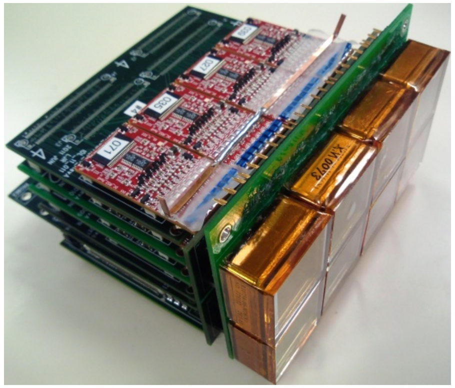
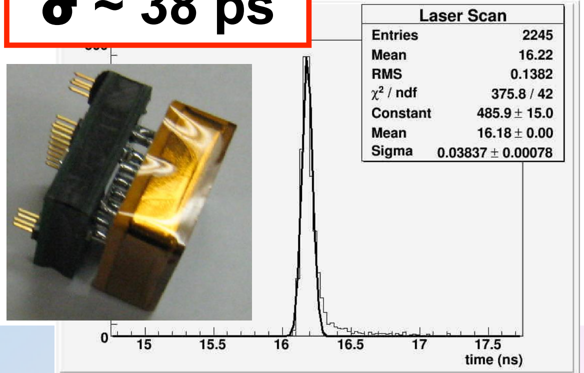
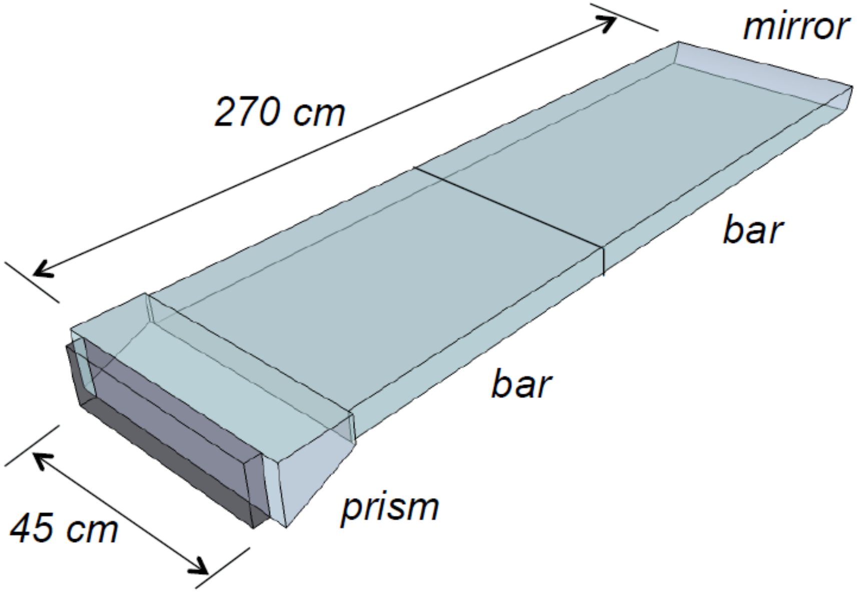


σ ~ 38 ps

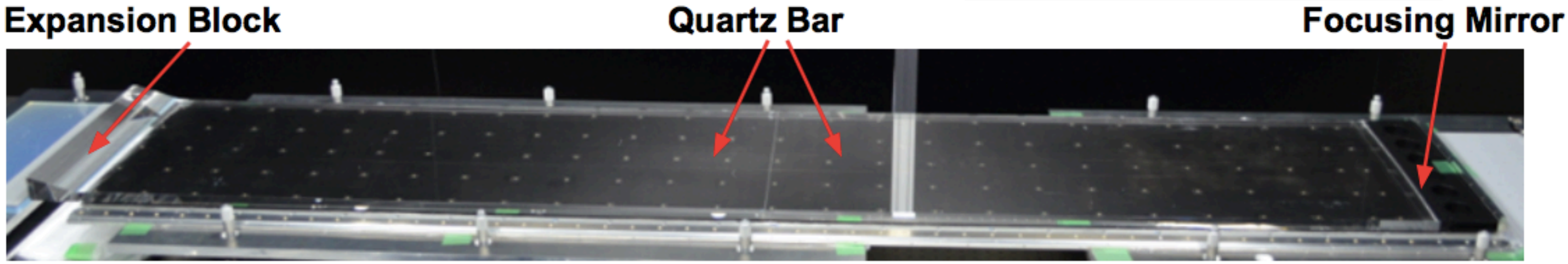


Quartz Optics

- Optics consists of three main elements:
  - Quartz bar, made of two pieces.
  - Focusing mirror in forward direction.
  - Expansion block / prism in backward direction.
- Strict requirements on optics in order to:
  - Preserve photon angles as they undergo TIR.
  - Retain high efficiency for photons as they propagate.

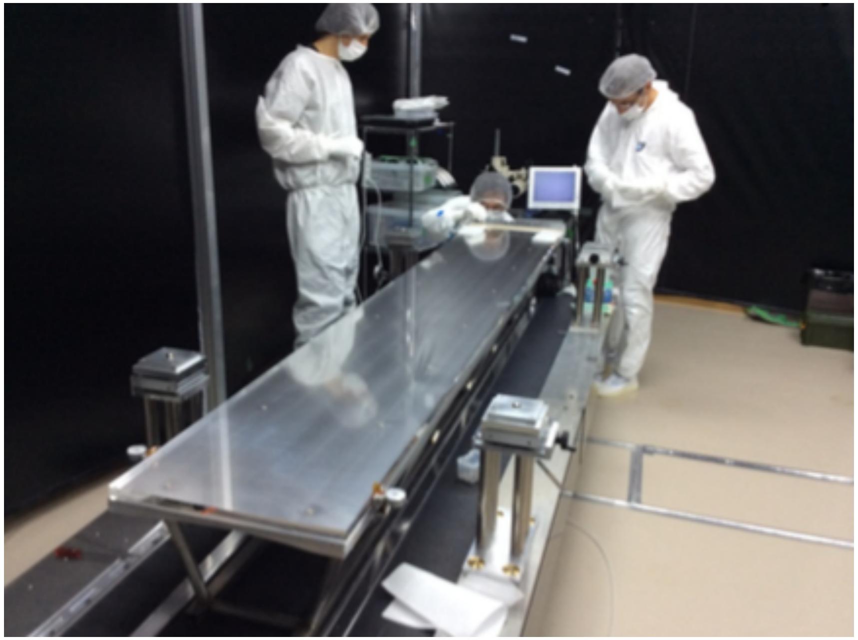


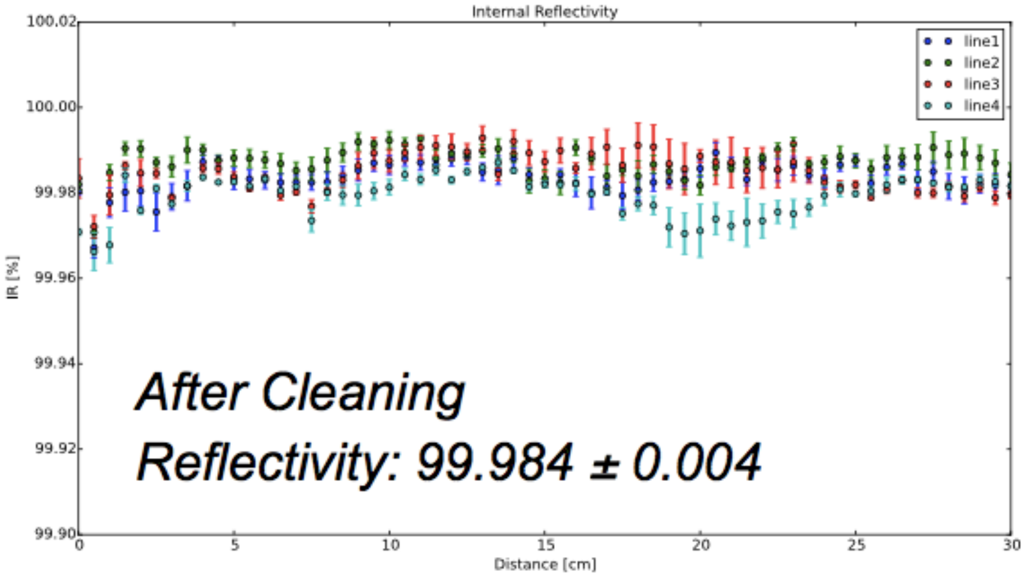
Flatness	< 6.3 μm
Perpendicularity	< 20 arcsec
Parallelism	< 4 arcsec
Roughness	< 5 Å (RMS)



Quartz Optics – Status & Schedule

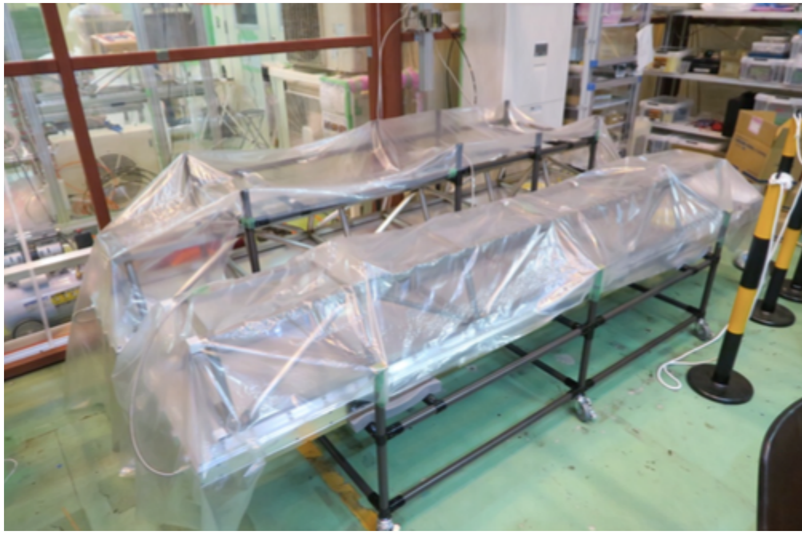
- QA of prisms and mirrors is being conducted at Cincinnati.
- Clean rooms have been set up at KEK to perform acceptance testing, gluing/assembly, and storage of assembled optics.
- Assembly procedures are well defined.
- Many test, assembly jigs available to streamline processing.
- Scheduled to complete 17 modules by Spring 2016.



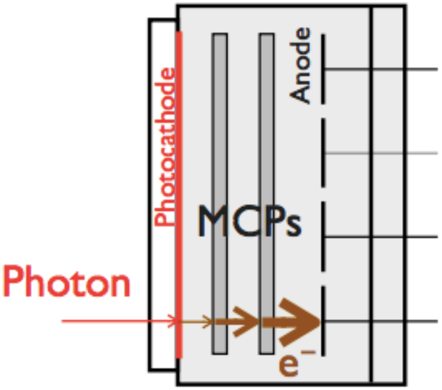


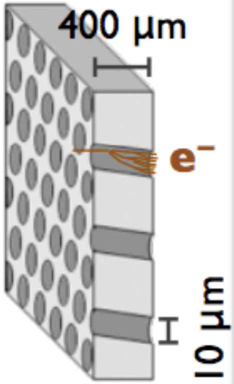
After Cleaning

Reflectivity: 99.984 ± 0.004



Photodetectors

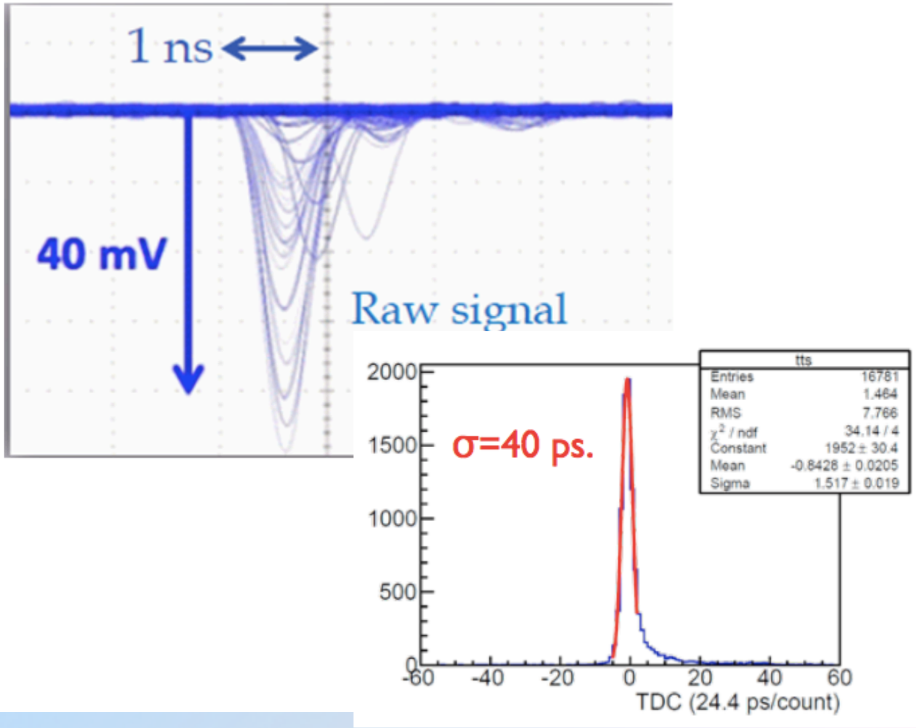




Requirements:

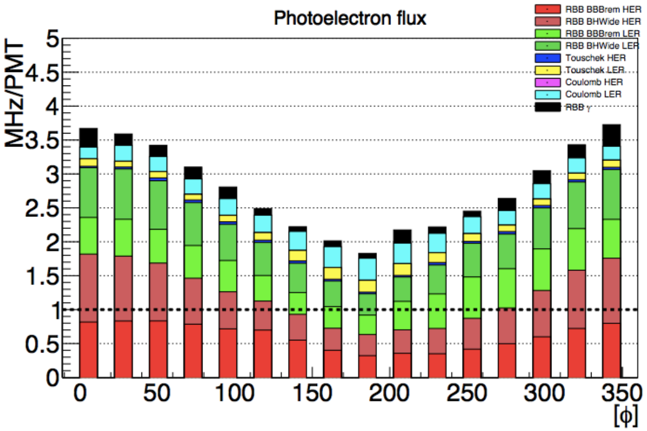
- Excellent timing, O(100 ps).
- Operation in 1.5 T magnetic field.
- Lifetime suitable for Belle II operation.

- Hamamatsu “SL10” MCP-PMT.
  - Developed as collaboration between Nagoya University and Hamamatsu.
  - Transit-time-spread (TTS) of ~40 ps.
  - 4x4 anode structure.
  - QE > 24% at 380 nm.
    - QE ~28% ave.
  - Nominal gain ~3-5x10^5.
    - Tradeoff between efficiency and lifetime.



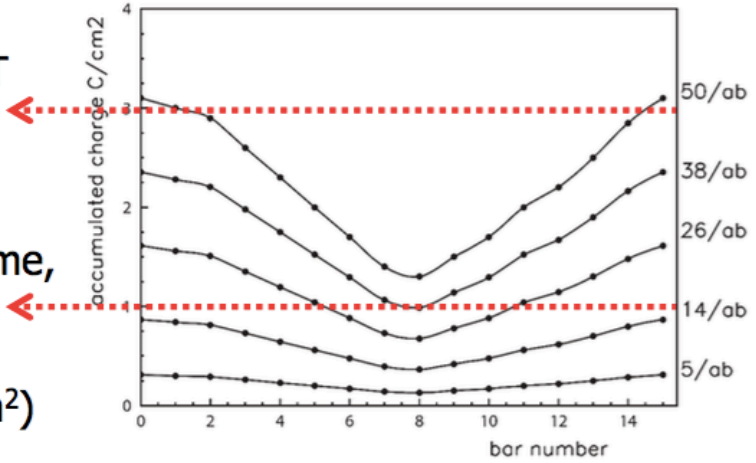
MCP-PMT Lifetime, Production Status

12th campaign



Min. lifetime,
ALD MCP PMT
(>3 C/cm²)

Average lifetime,
Conventional
MCP PMT
(0.3-1.8 C/cm²)



2023: 50/ab

2022: 38/ab

2021: 26/ab

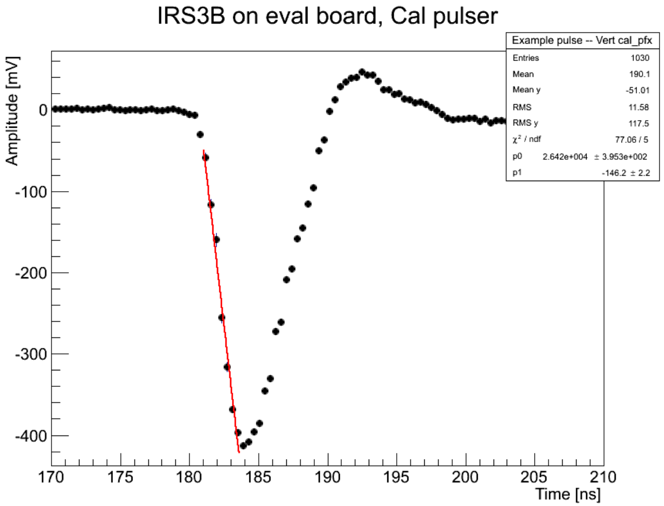
2020: 14/ab

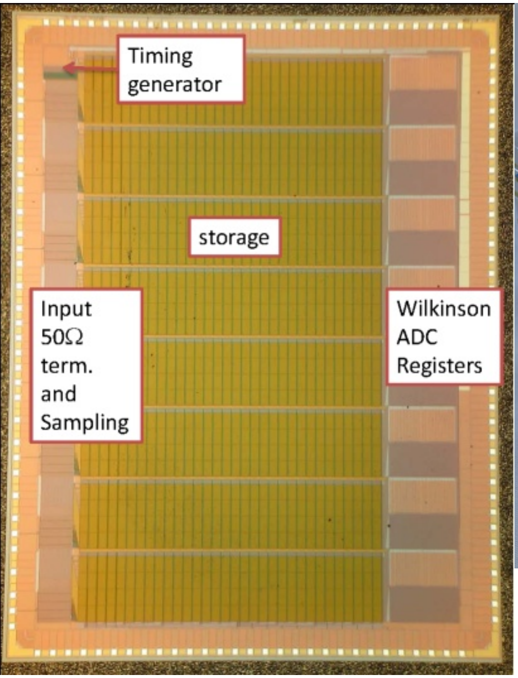
2019: 5/ab

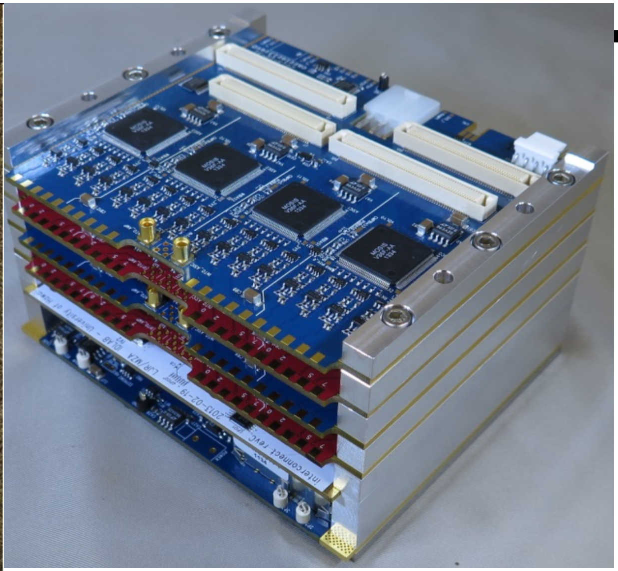
- Lifetime of MCP-PMTs is a significant concern.
  - ALD shows significant improvement in lifetime over conventional.
  - R&D into lifetime improvement has been conducted, will provide further improvements for a subset of MCP-PMTs.
- Total of 569 MCP-PMTs will be produced for Belle II.
  - 514 already in-hand.
  - 283 are conventional MCP-PMTs, may need to be replaced at high integrated luminosity.
    - Conventional MCP-PMTs optimally placed for ease of access.

Readout Electronics

- Requirements:
  - Deadtimeless at L1 trigger rate: 30 kHz.
  - Trigger latency of ~5 μs sets buffer depth.
  - Typical occupancy dominated by background:
    - >3 MHz / PMT for worst case modules.
    - Corresponds to ~1-2% occupancy.
  - Preserve MCP-PMT's excellent timing.


IRS3B on eval board, Cal pulser

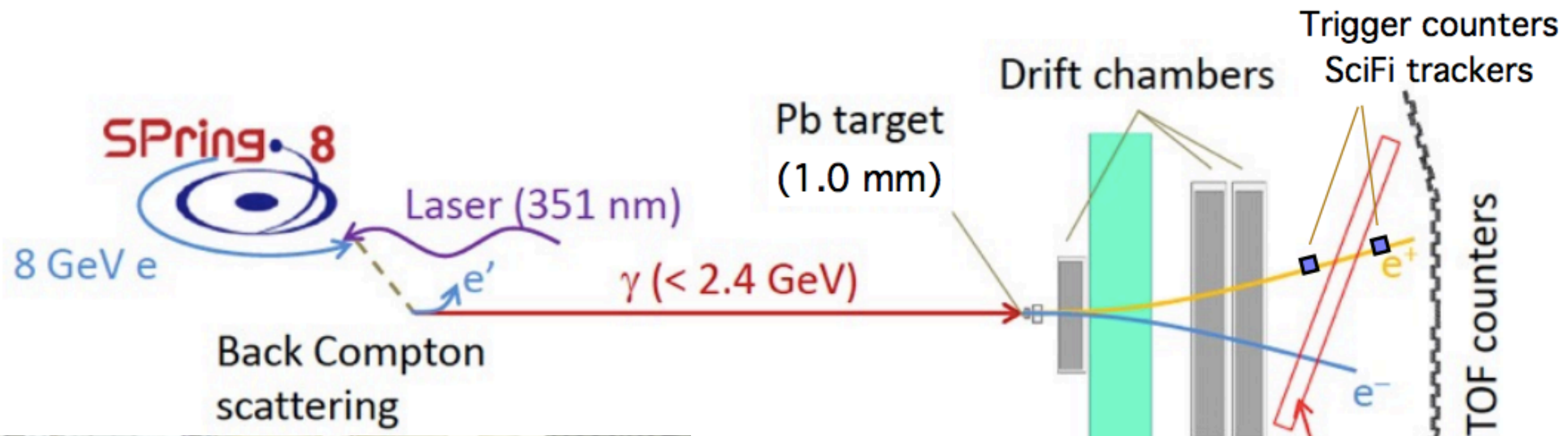


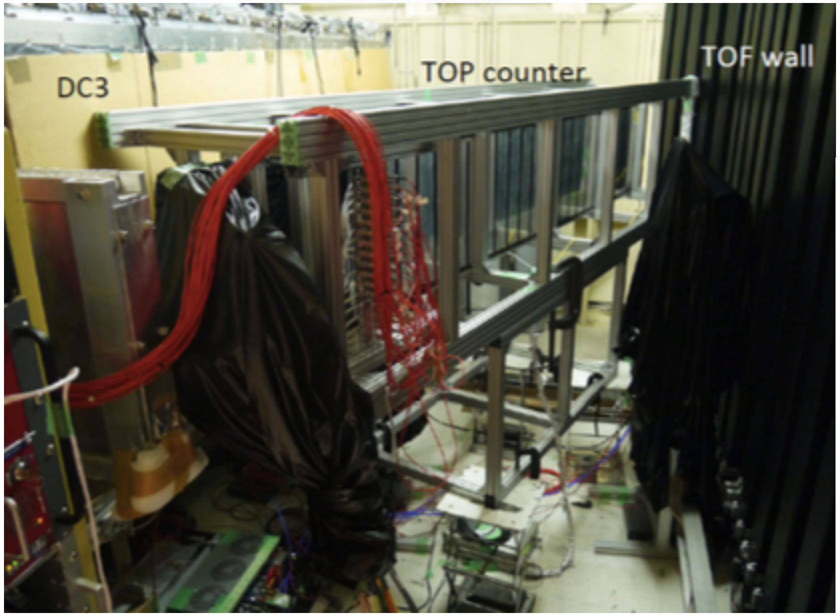


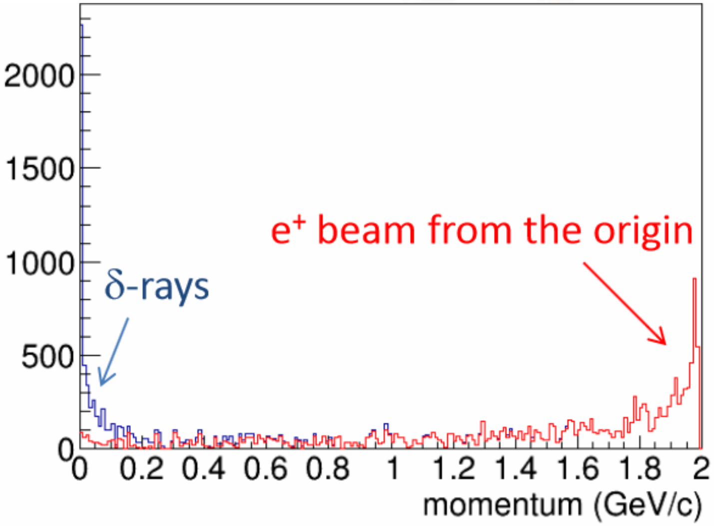
➔ Utilizes "IRS"series ASICs from U. of Hawaii.

- Samples at 2.7 GSa/s.
- Deep analog storage (~12 μs).
- Four front-end electronics modules (FEM) per iTOP:
  - 16 ASICs, 128 channels.
  - Supports 8 MCP-PMTs.

Prototype Test, LEPS @ SPring-8

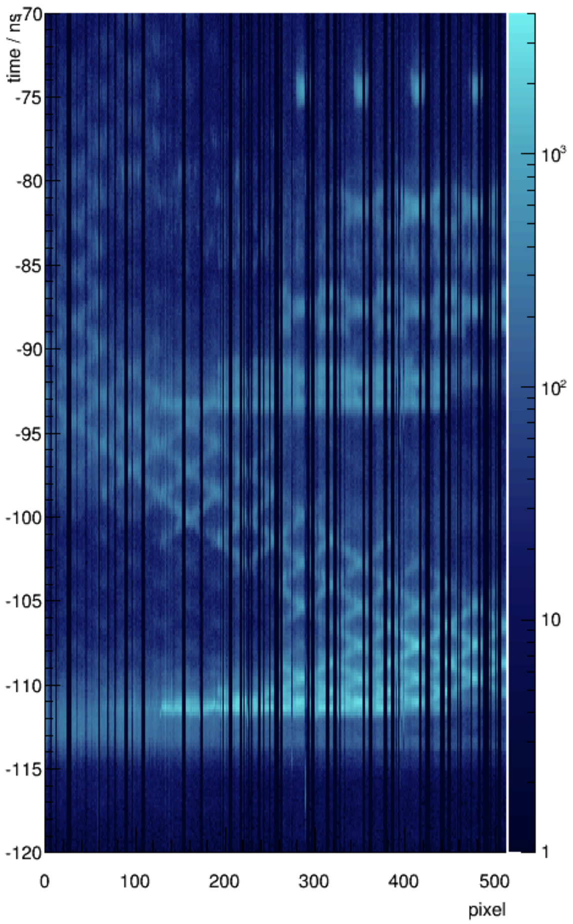




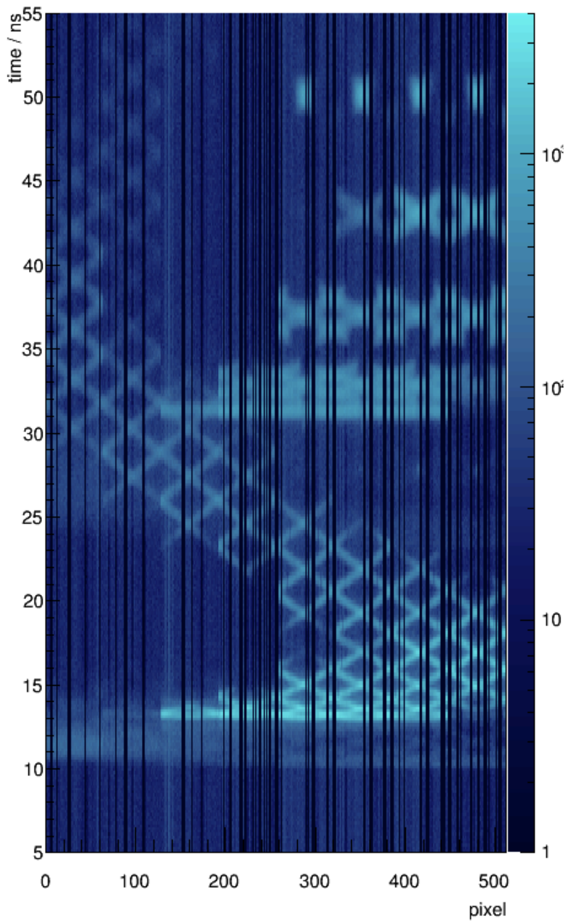


Prototype Data/MC Comparisons

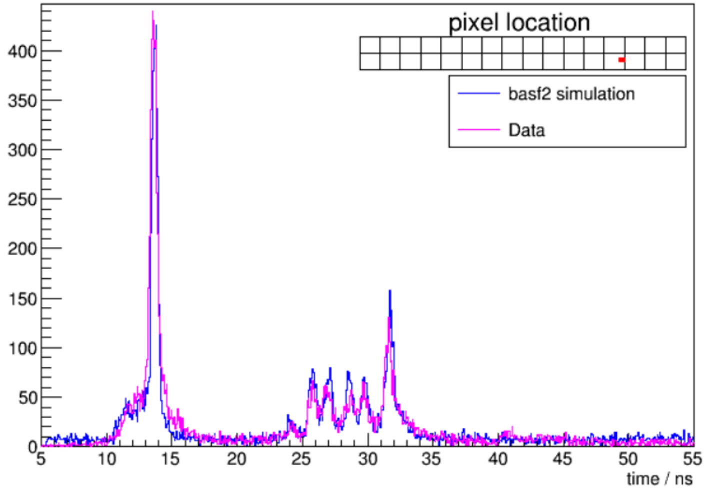
Data ring image for cosθ = 0.00



Simulated ring image for cosθ = 0.00



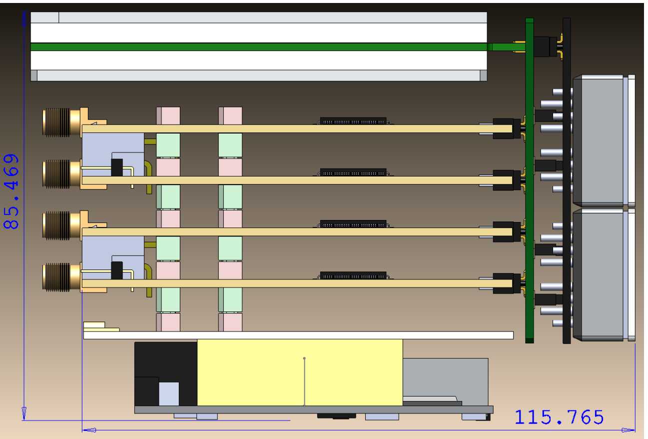
Time distribution for pixel 179 for cos θ = 0.00

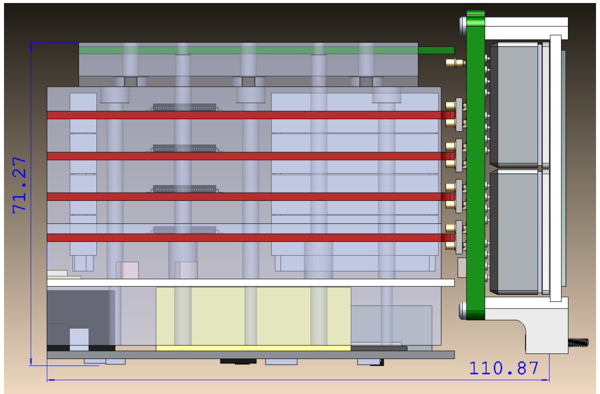


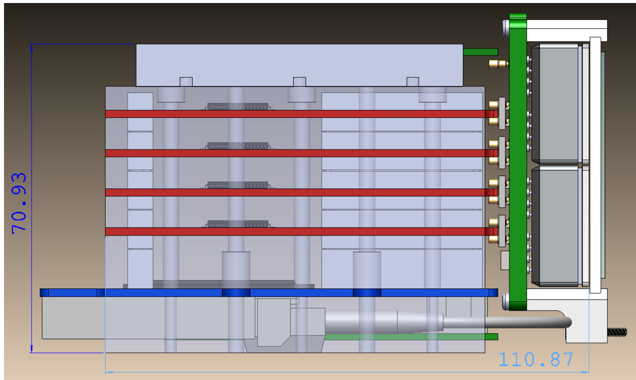
- Some limitations observed:
  - Electronics σ_t limited to ~90 ps.
  - Low channel trigger efficiency (~82%).
  - Dead channels.
- However, narrowest peaks in MC are O(100 ps) due to chromatic broadening.
- **MC/data show excellent agreement.**

➔ **Experience at LEPS led to significant improvements in electronics and mechanical designs to improve timing, raise efficiency, and reduce dead channel counts.**

Front-End Electronics Development



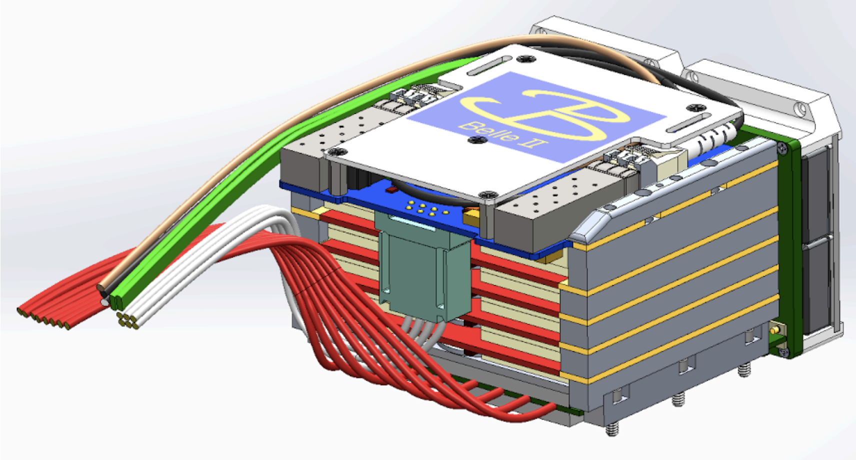


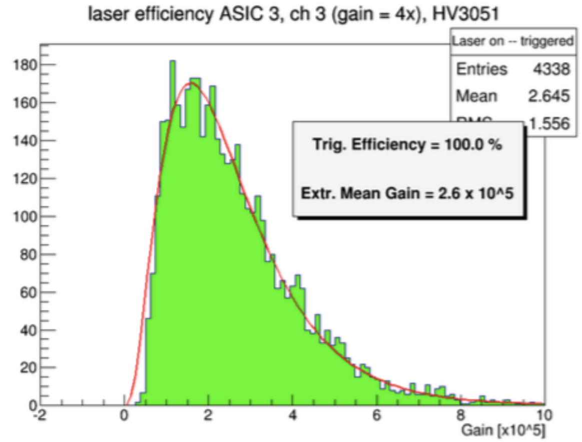


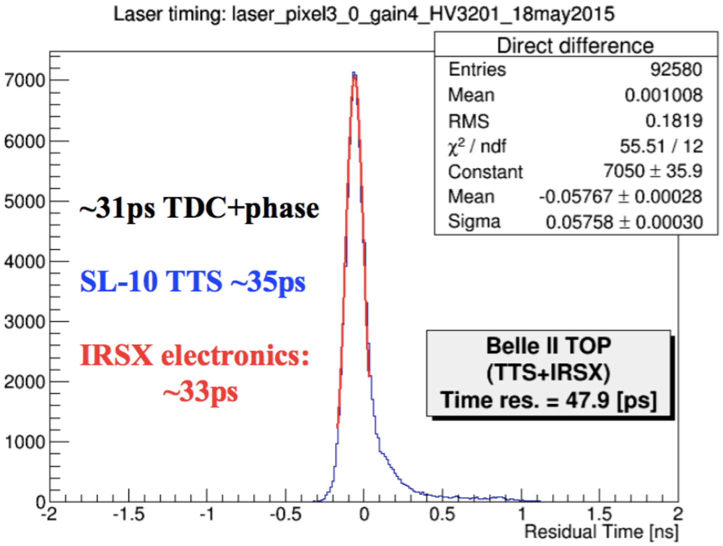
Prototype	Intermediate	Production
•IRS3B ASIC	•IRS3C ASIC –Improved dynamic range.	•IRSX ASIC –DLL improves time stablity. –Added gain for trigger path.
•1x Spartan6 FPGA. –Bussed ASIC control.	•1x Spartan6 FPGA. –Bussed ASIC control.	•4+1 Zynq SoCs. –Point-to-point ASIC control.
•Feature extraction in dedicated downstream module (or offline).	•Feature extraction in dedicated downstream module (or offline).	•Feature extraction in front-end (or offline).
	• Improved MCP-PMT coupling, alignment.	• Same HV/MCP-PMT coupling as intermediate.

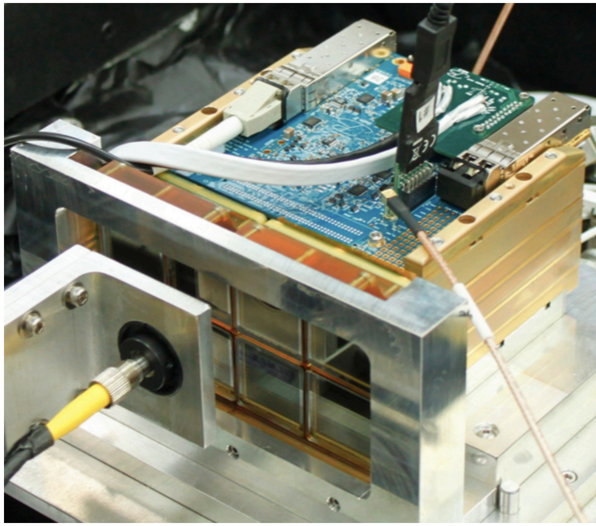
Production Electronics

- Electronics now in full production:
    - Efficiency ~100% at nominal gain.
    - Electronics timing resolution < 50 ps.
    - Dead channels significantly reduced (none on any accepted modules so far).
    - Well-defined pipeline between collaborating institutes for assembly, testing, QA, integration.

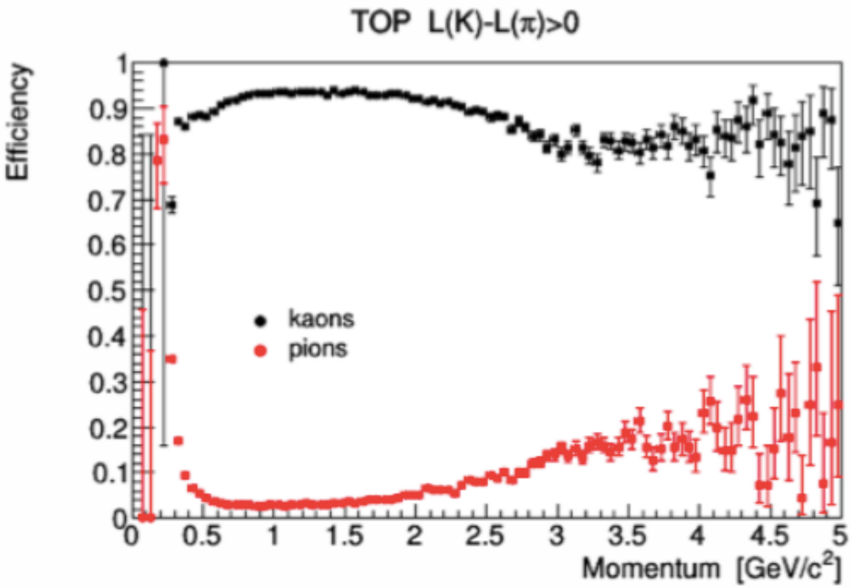


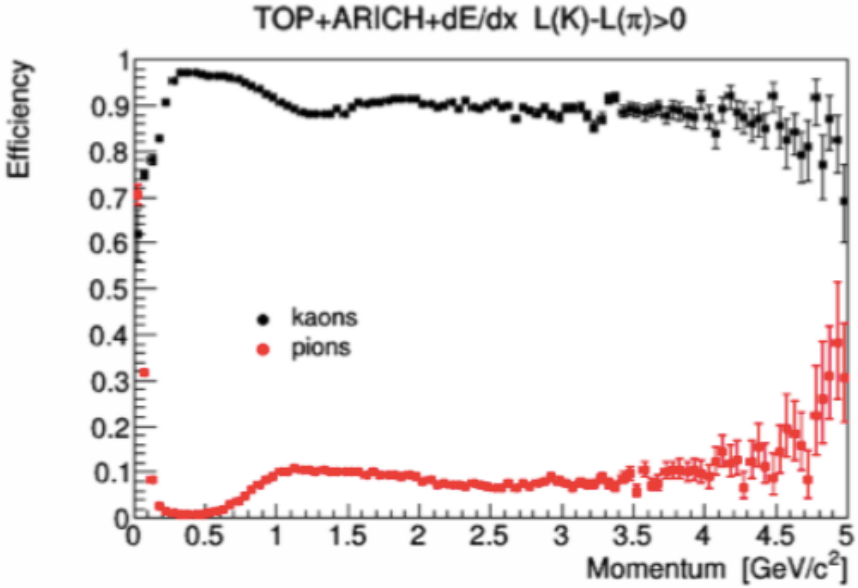




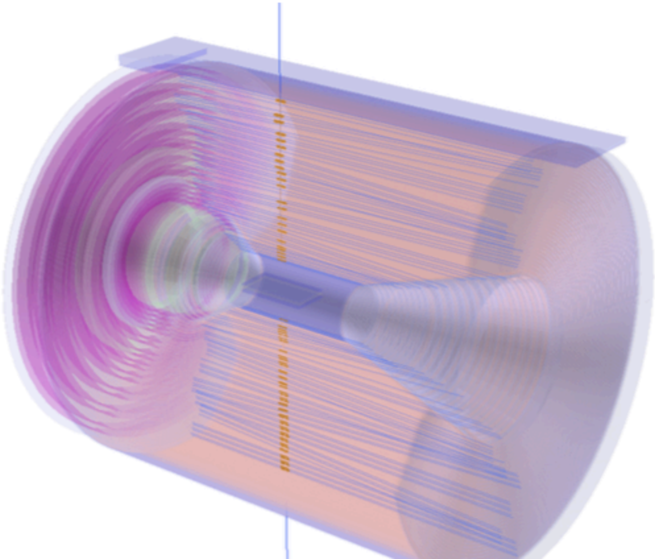


Reconstruction & Performance





- Software to perform K/π separation is now implemented into the Belle II Analysis Software Framework (basf2).
- Includes all required physical processes:
  - Optical: dispersion, surface roughness, reflectivity.
  - MCP-PMT: QE, CE, TTS.
  - Other: electronics σ_t, event t_0.
- Further verification (and system testing) this fall/winter with joint PID/CDC test.



Summary

- Barrel K/π PID at Belle II will be provided by imaging time of propagation detector.
- Performance relies on excellent performance of optics, MCP-PMTs, and readout electronics.
- This performance has been demonstrated with prototype modules, which showed excellent data/MC agreement.
- Production underway, incorporates further improvements from lessons learned during beam, bench tests.
- Fully assembled bars to be installed into Belle II next year.

BACKUP

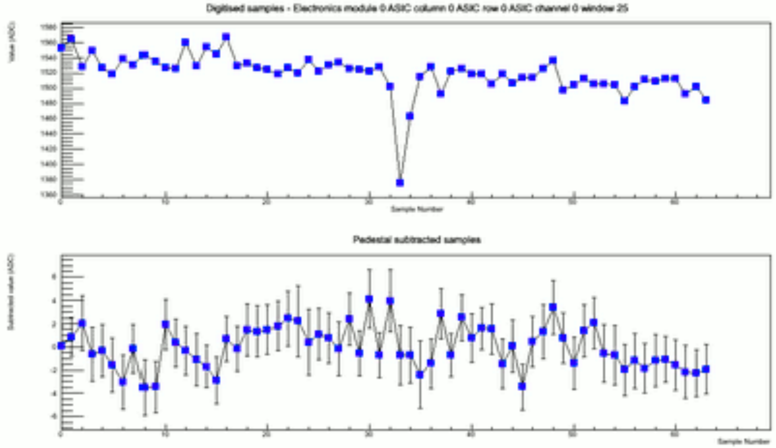
Feature Extraction Steps

1. Subtract storage cell pedestal (avg. ~2000 ADC +/- 100’s counts)
2. Linearity correction (optional)
3. Individual sample time offset correction

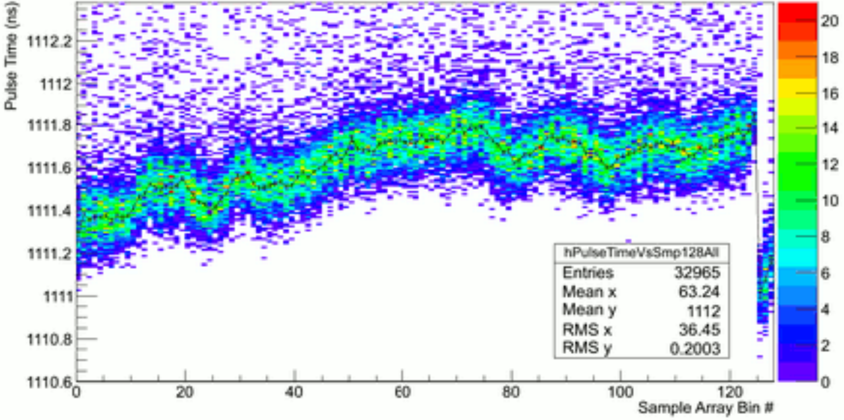
Three sets of calibration constants required:

- **Sample pedestal values**
  - (262144 samples/ASIC)
- **Sample time widths**
  - (128 values per ASIC)
- **Timewalk correction**
  - (~20 values per ASIC)

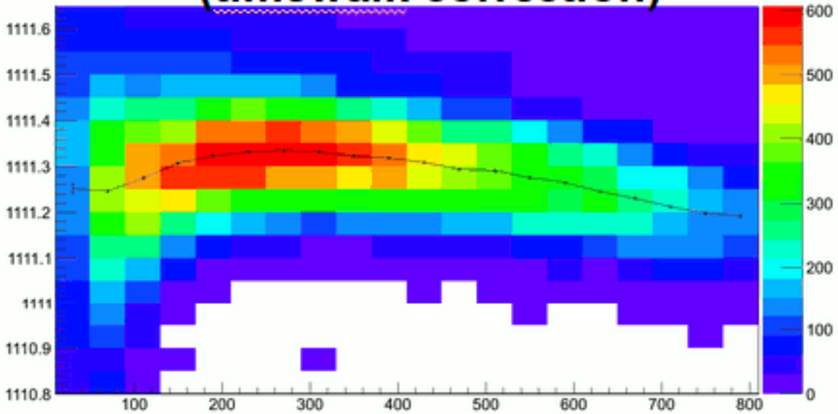
Waveform Pedestal Correction



Pulse Time Vs Sample Array Bin #
(used to measure Sample-DTs)

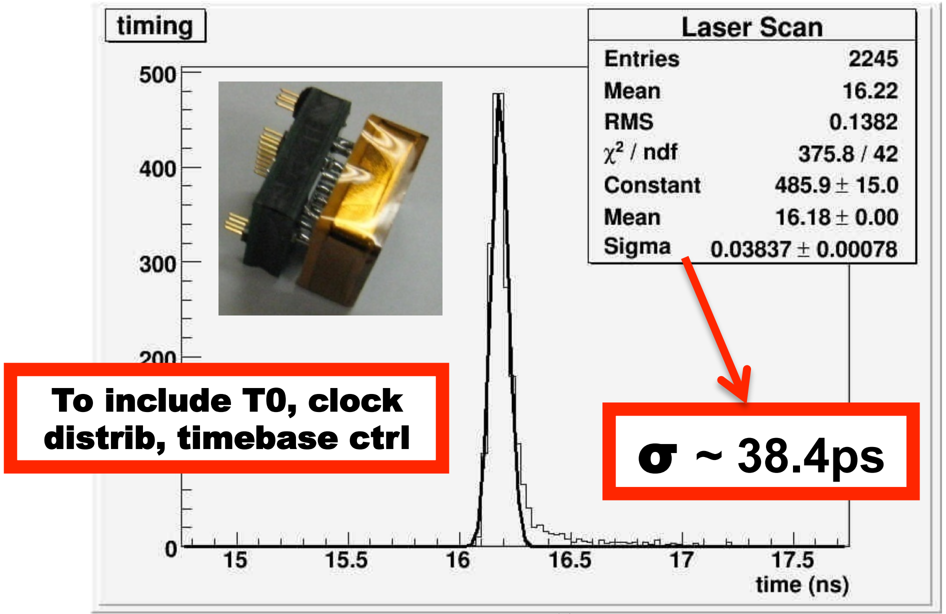


Pulse Time Vs Height
(timewalk correction)



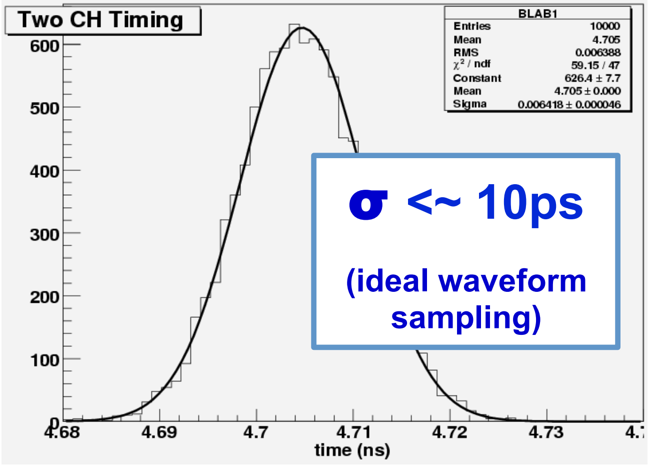
Performance Requirements

- Impact of electronics timing



To include T0, clock distrib, timebase ctrl

σ ~ 38.4ps



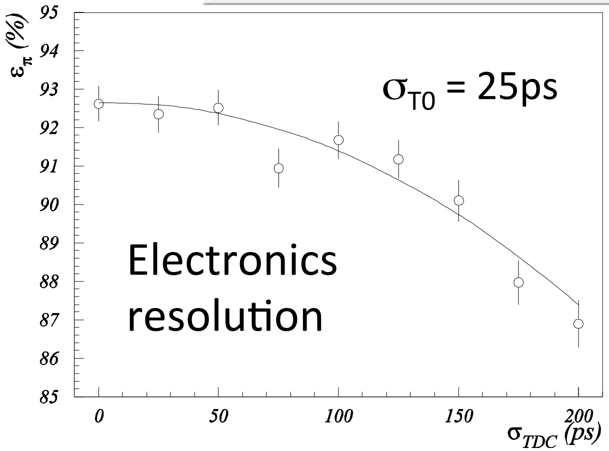
σ <~ 10ps

(ideal waveform sampling)

NIM **A602** (2009) 438

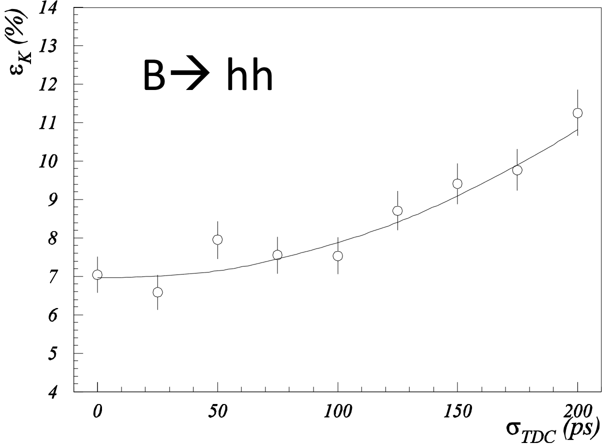
σ <= 100ps → 1% impact

σ <~ 50ps target



σ_{T0} = 25ps

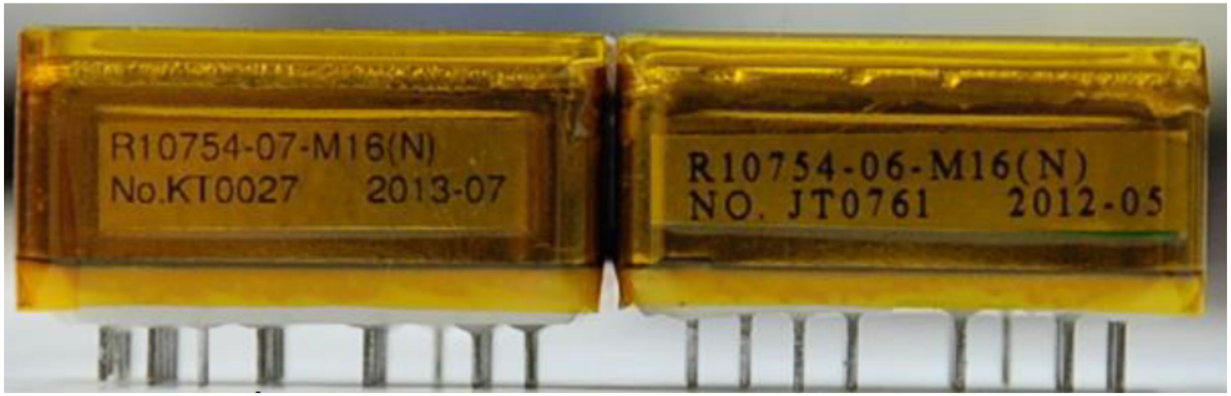
Electronics resolution

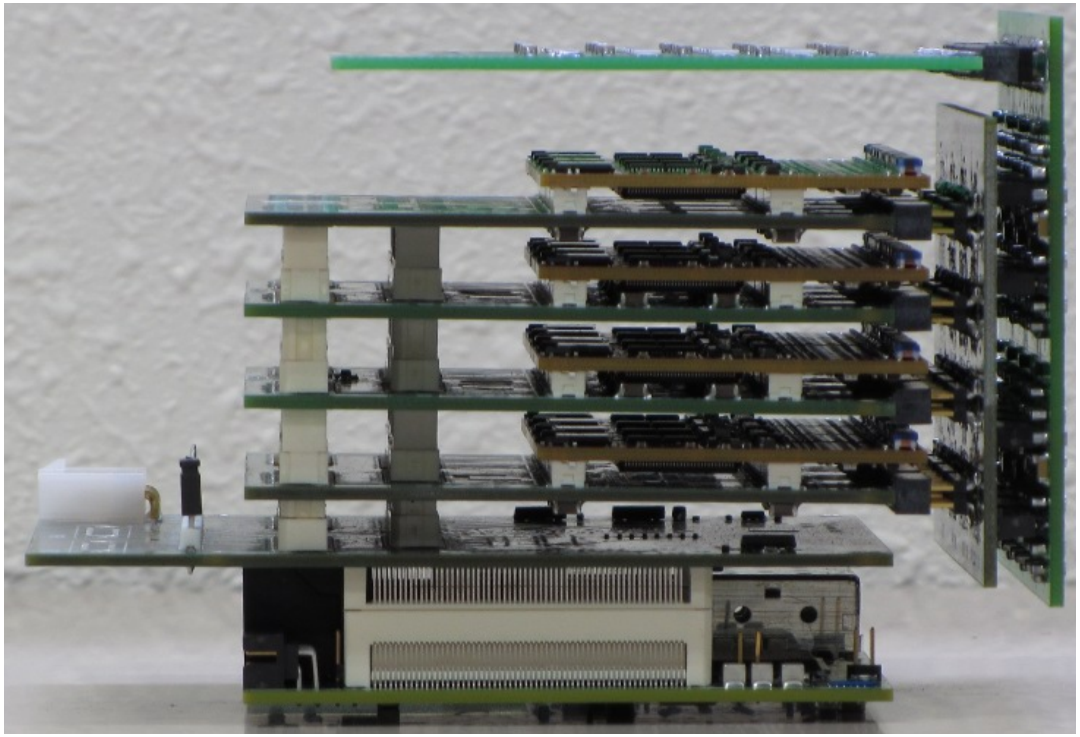


B→ hh

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

MCP-PMT Socket Seating



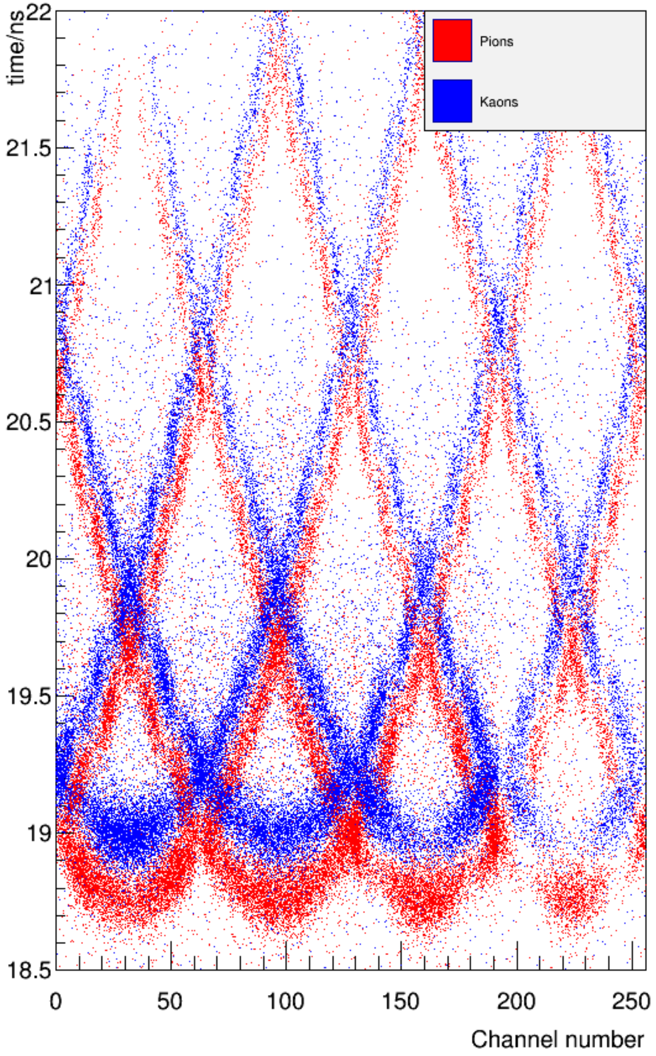


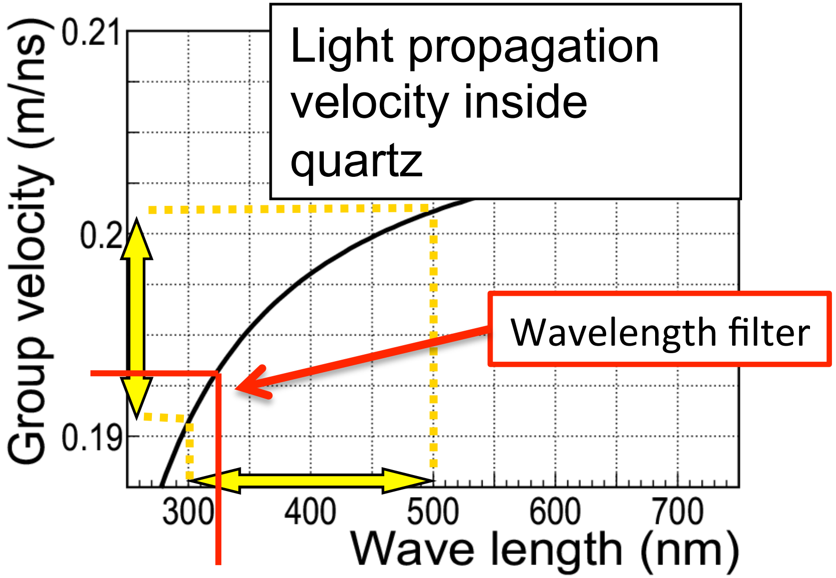
Unable to control depth of insertion:

- → Sockets not protected
- → Discharges
- → Had to lower some HV (wanted to run at +100V over nom.)

Temporal Broadening

- Cherenkov ring opening angle β dependent
- Propagation velocity is wavelength dependent





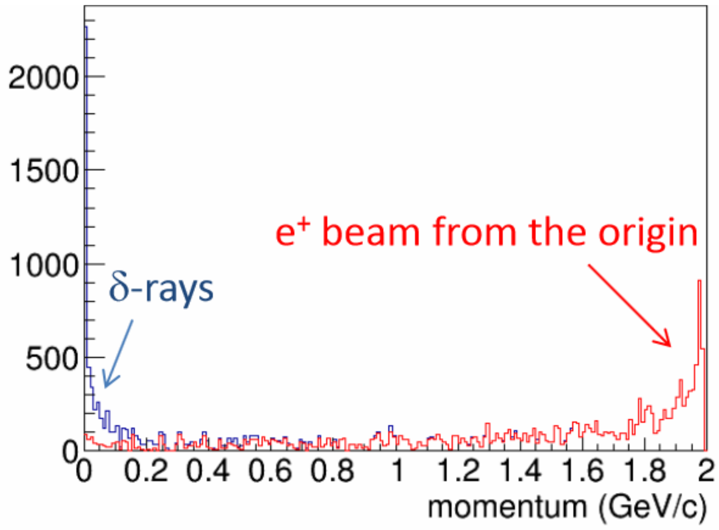
- Detected photons wavelength spread

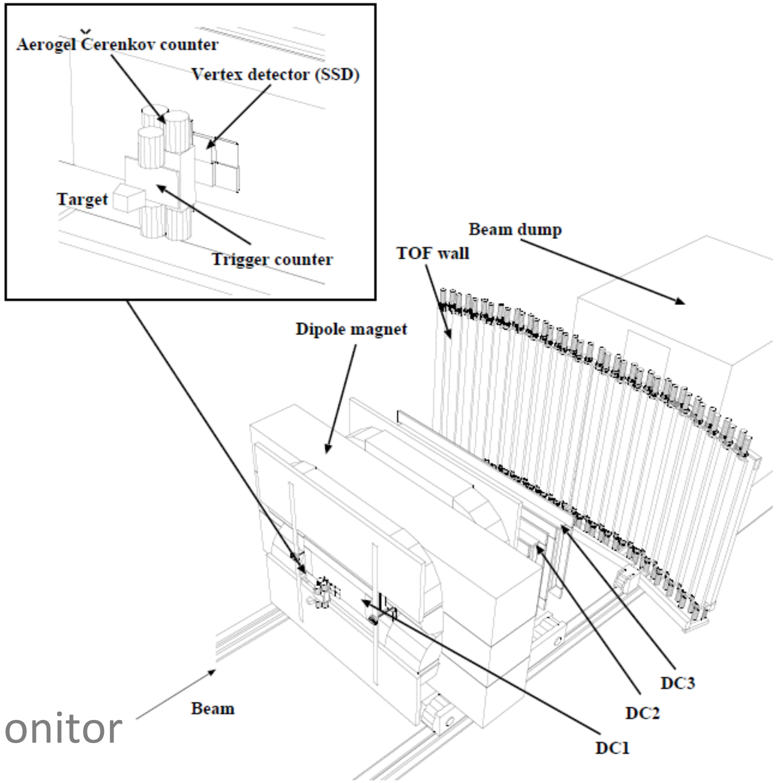
→ propagation time dispersion

- Longer photon propagation length

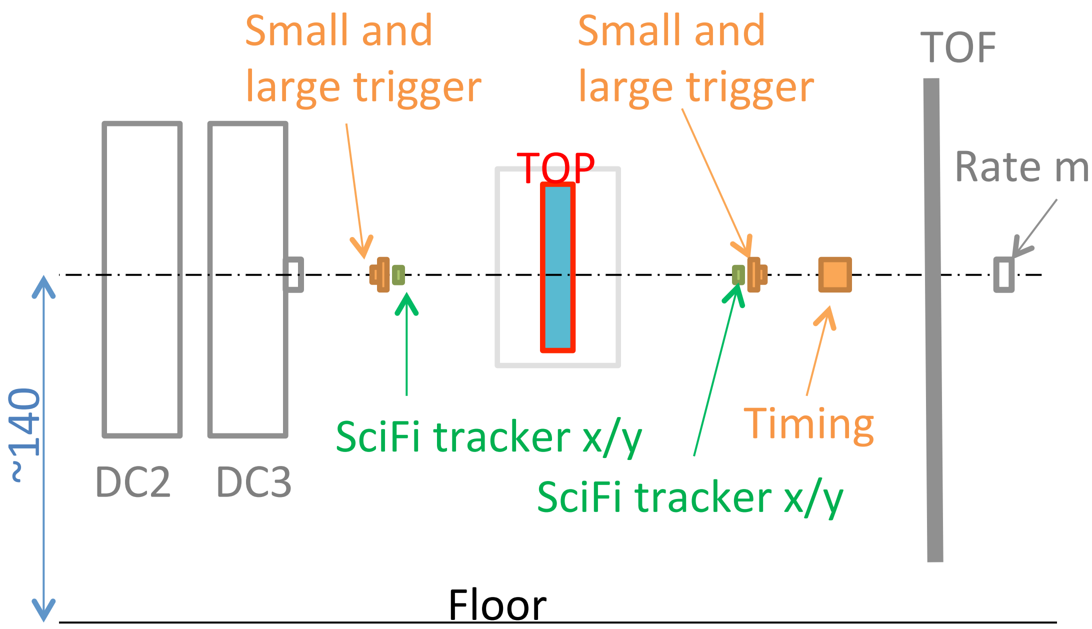
→ Improves projected ring image difference
But broadens time distribution

Prototype Modules @ LEPS, SPring-8





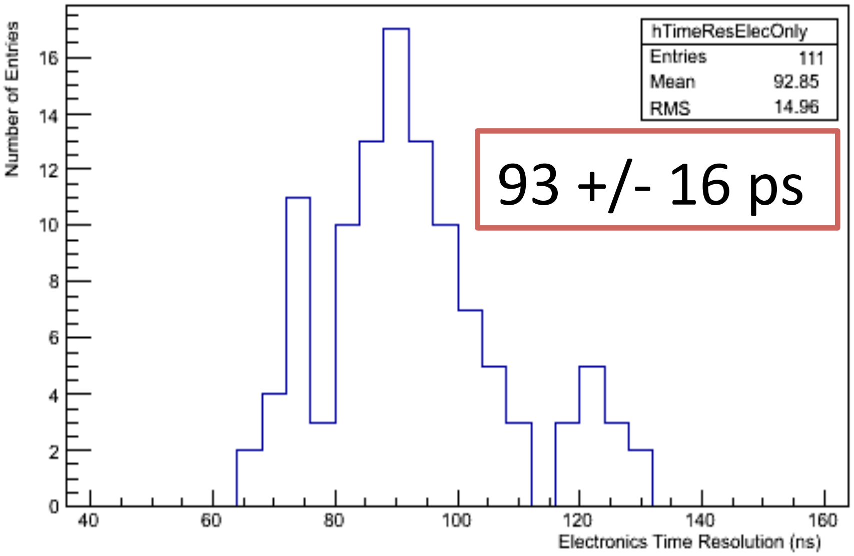
Side view



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: ~30 kHz
- Trigger rate: ~10 Hz
- DAQ rate: ~5 – 10 Hz

Prototype Modules – Timing Performance



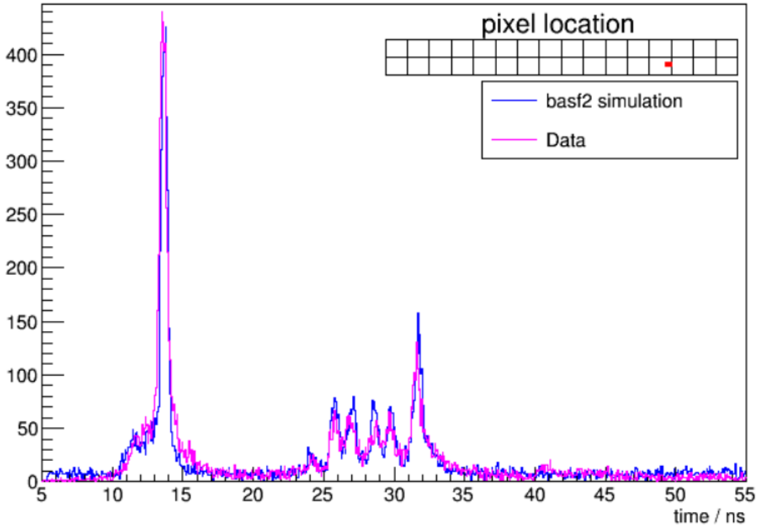
93 +/- 16 ps

MCP-PMTs run at lower gain than bench:

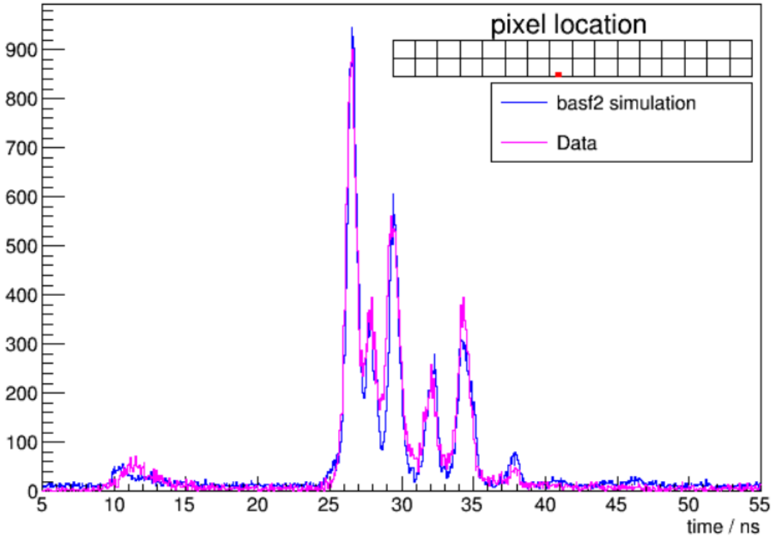
- Trigger efficiency lower (~82%).
- Timing resolution worse.

- Narrowest peaks in MC are O(100 ps) due to chromatic broadening.
- MC/data show excellent agreement.

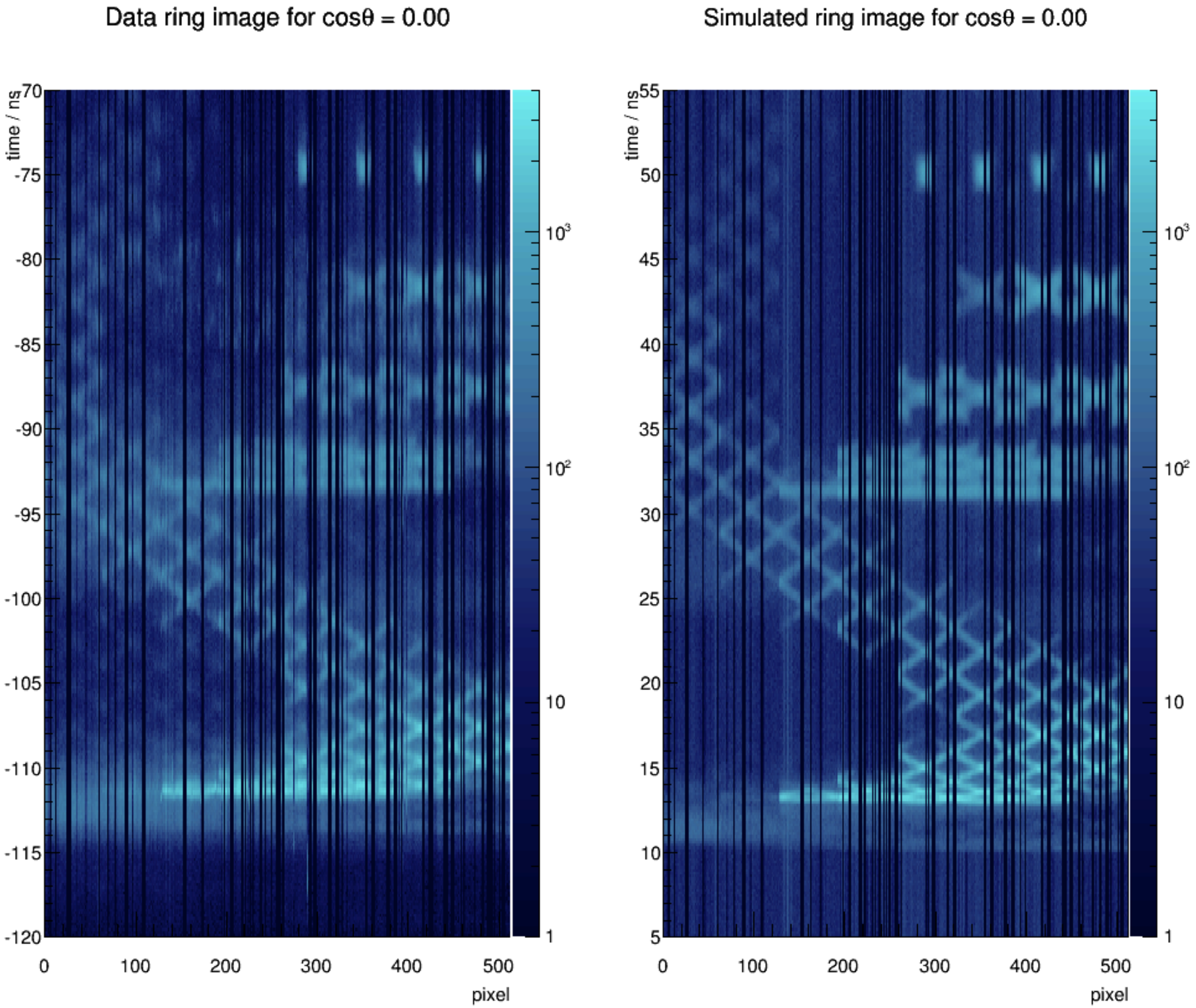
Time distribution for pixel 179 for cos θ = 0.00



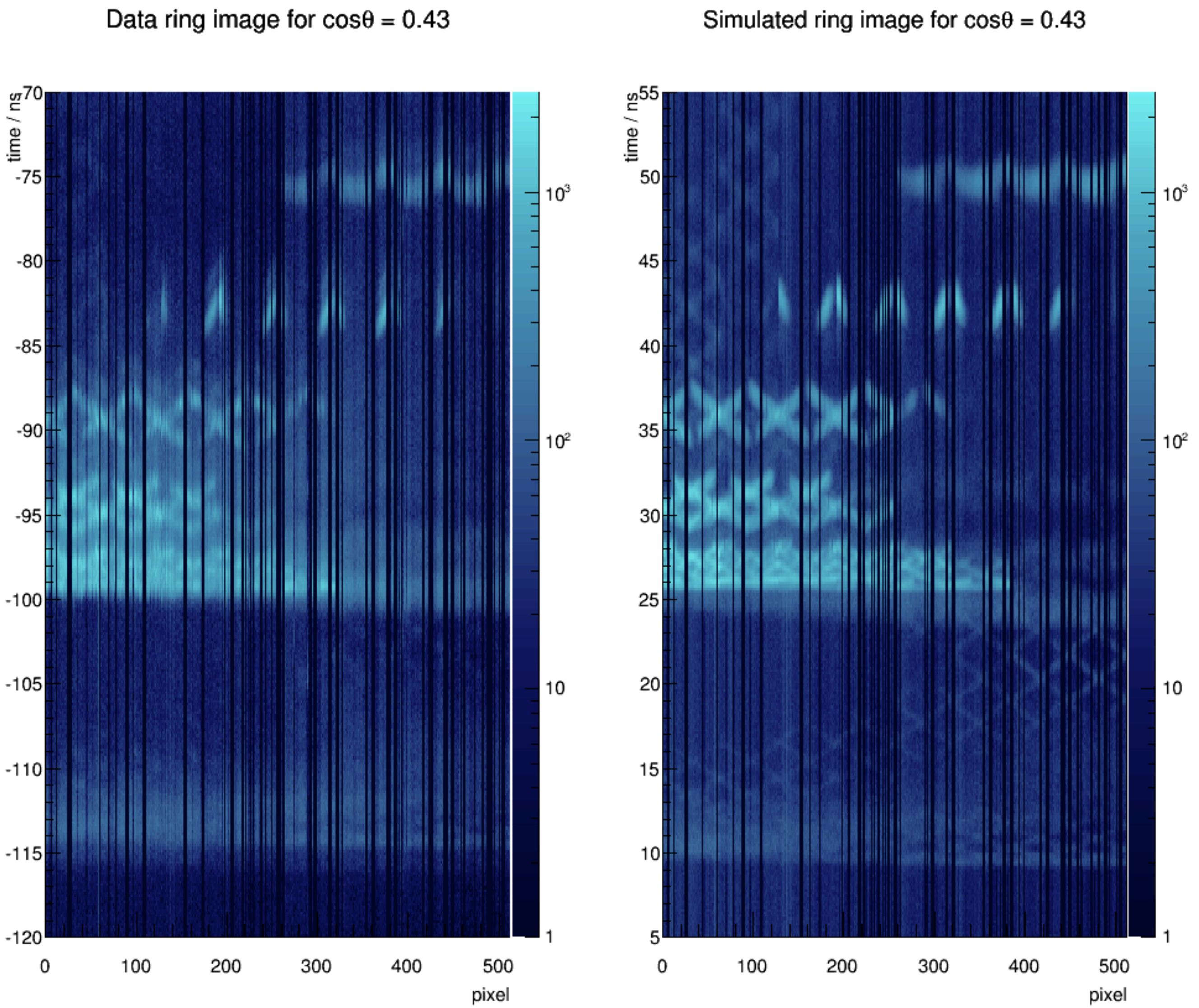
Time distribution for pixel 29 for cos θ= 0.36, x = -19cm



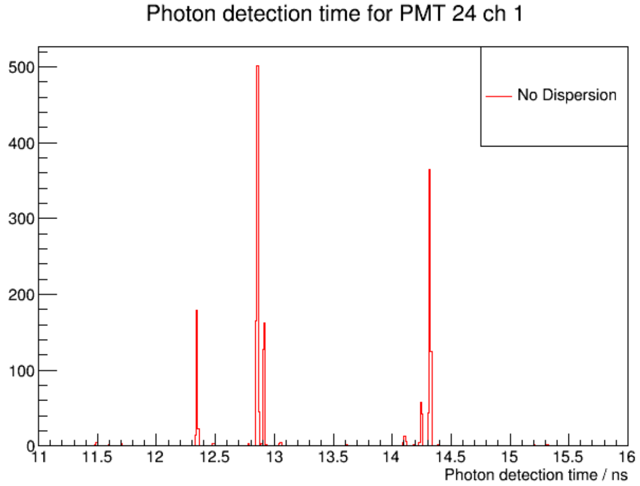
Prototype Modules – Normal Incidence

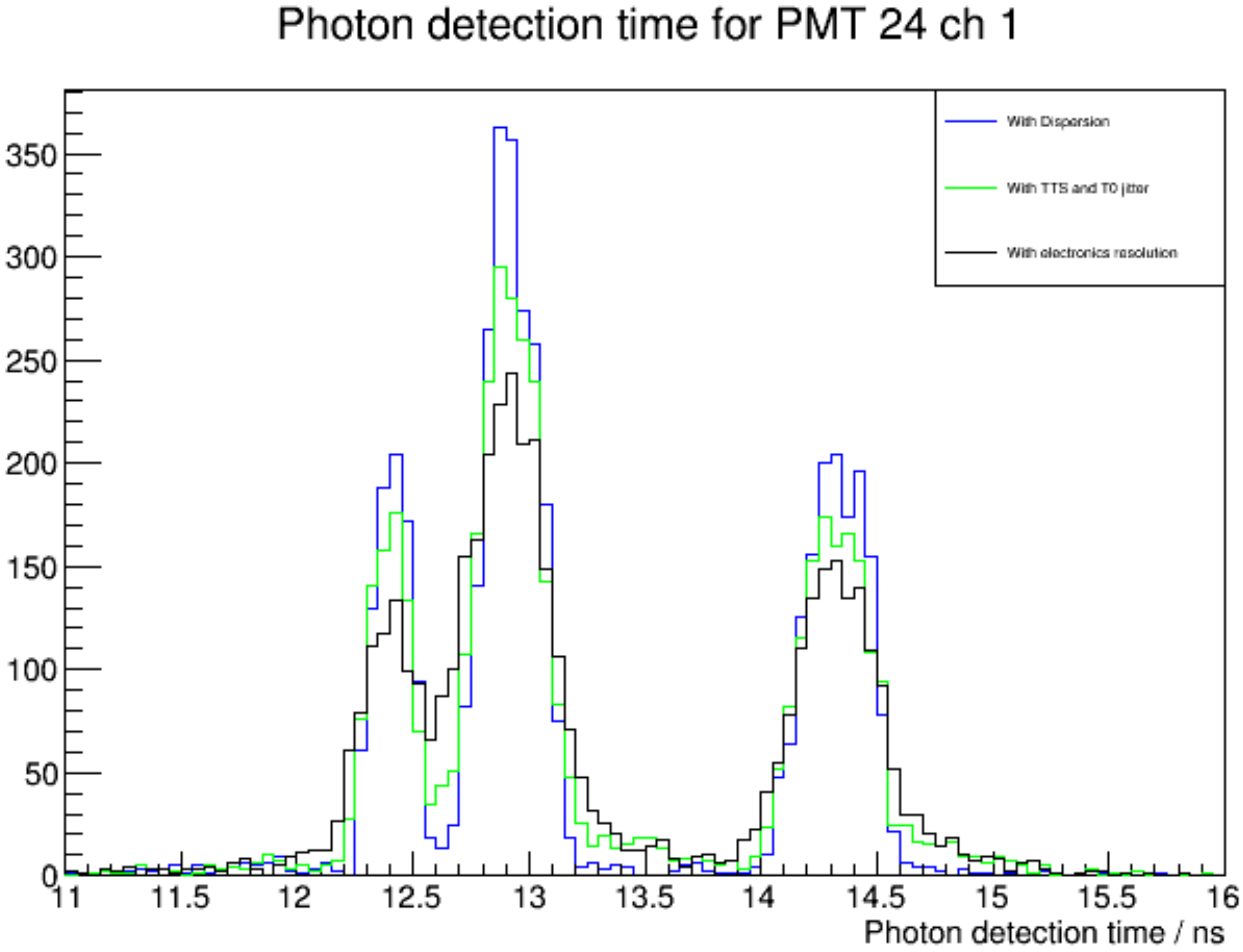


Prototype Modules – Inclined Angle



Narrowest Peaks in Spring-8 LEPs Beam Test MC





Normal Incidence
1st peak width:

No dispersion:	6-8ps
With dispersion:	90-100ps
+TTS/T0 jitter:	110-120ps
+ electronics:	120-150ps

Data/MC Photon Yield Comparison