The Time of Propagation Barrel PID Detector in the Belle II Experiment

Oskar Hartbrich
University of Hawaii at Manoa
for the Belle II TOP Group

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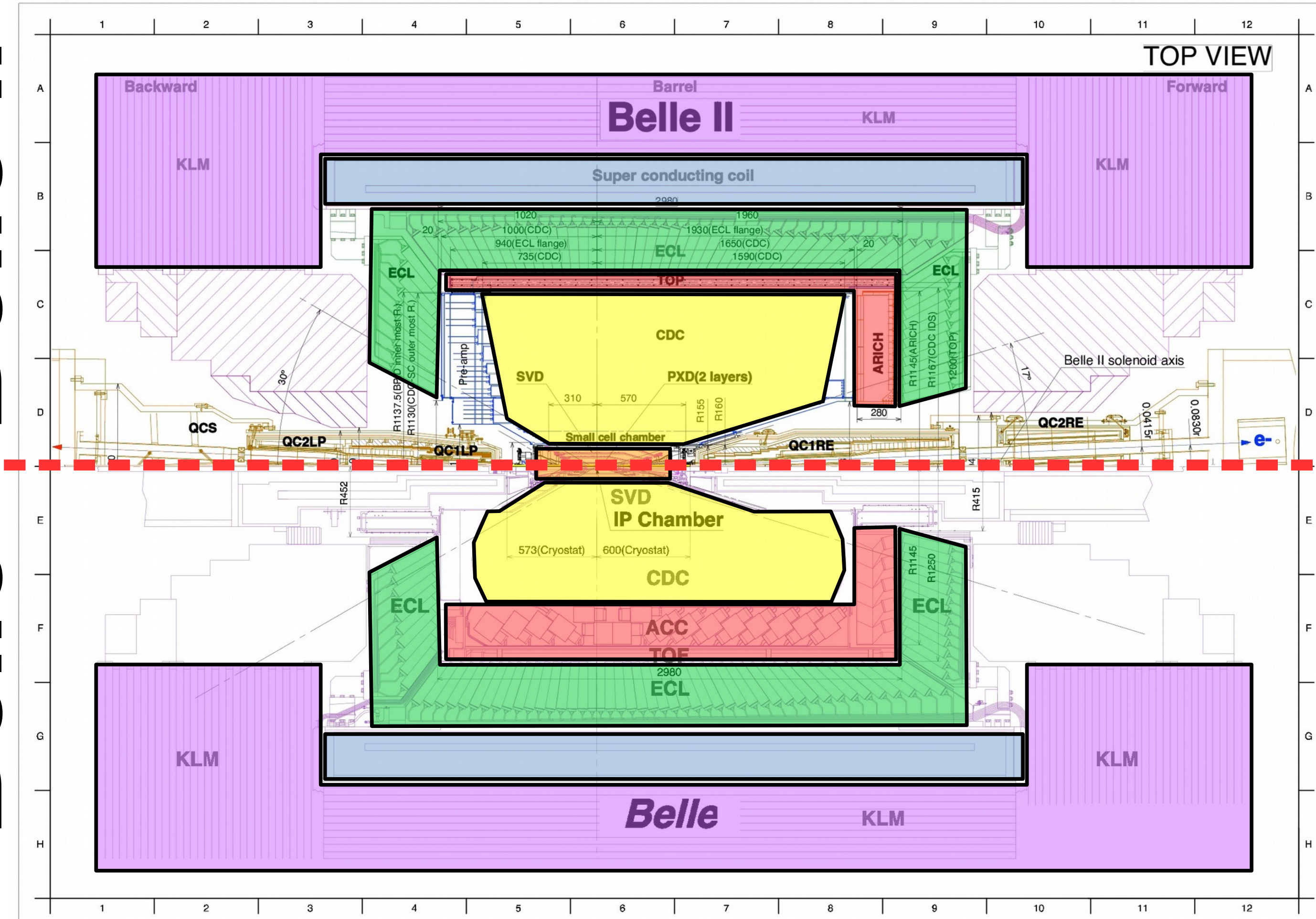
Belle II Detector Upgrade

Belle II

Belle



K_L/Muon System

Magnet Coil

EM Calorimeter

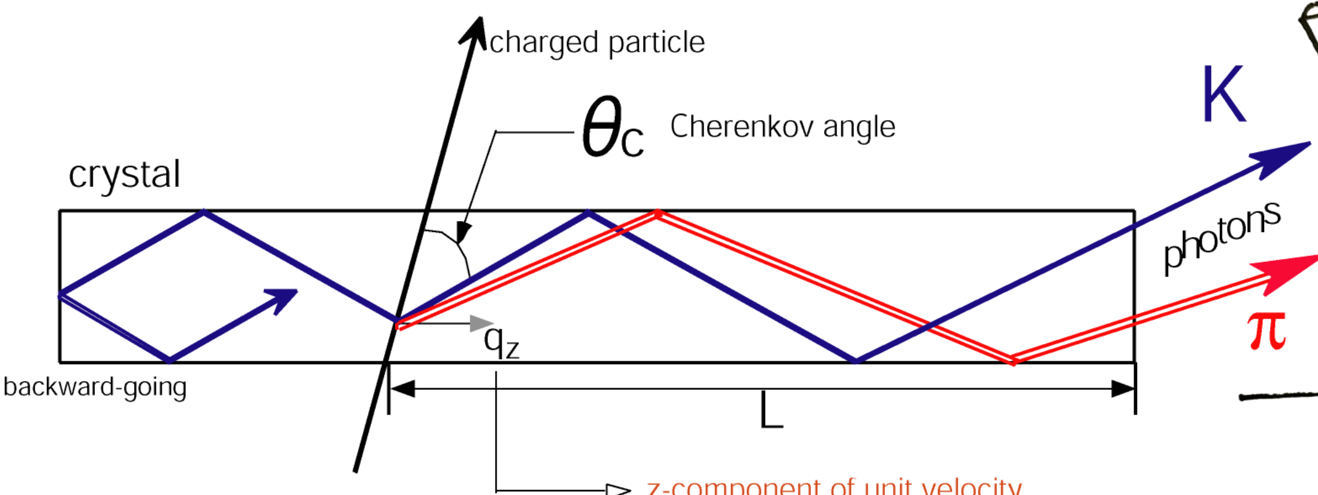
π/K Identification

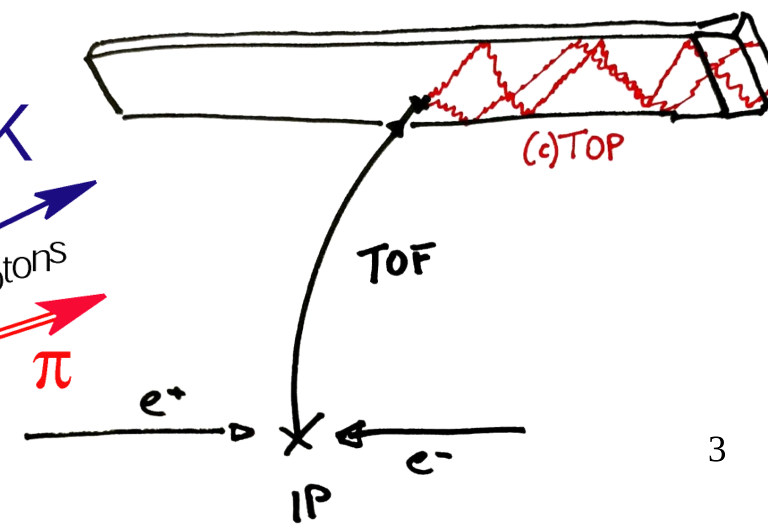
Drift Chamber

Silicon Tracking

The “Time of Propagation” (TOP) Detector I

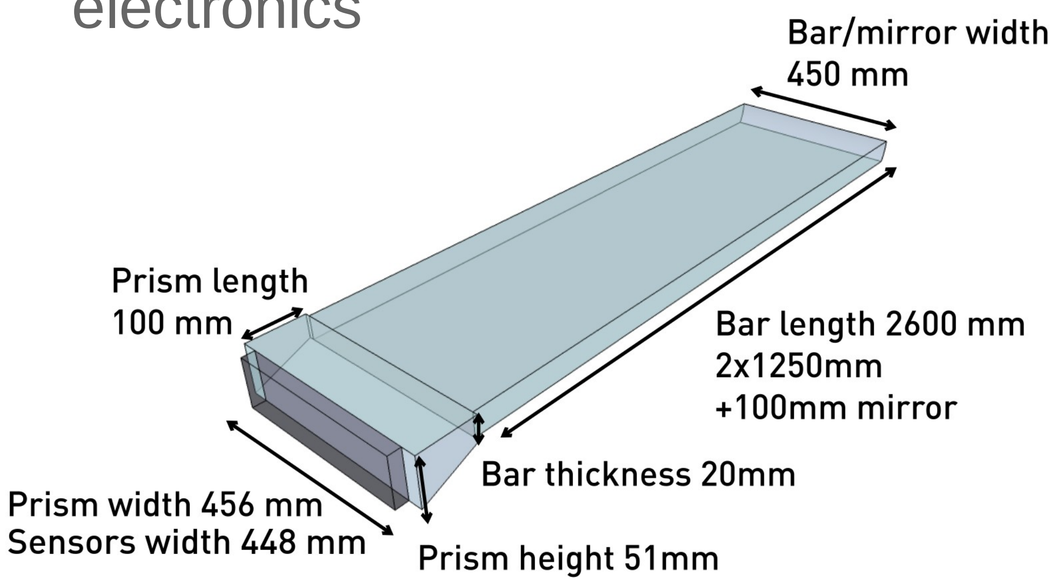
- Cherenkov photons can be captured inside radiator medium if highly refractive
  - Total internal reflection then preserves angular information if all surfaces smooth and square
- Instead of reconstructing the full ring image, measure time of propagation (path length) of individual Cherenkov photons at one end of the radiator
  - Cherenkov photons from lighter particles arrive earlier on average
  - Since collision timing is well known (in principle), measure ToF at the same time
- Chromatic dispersion limits the reach of pure time-of-propagation reconstruction
- Similar approaches by LHCb TORCH project, PANDA DIRC

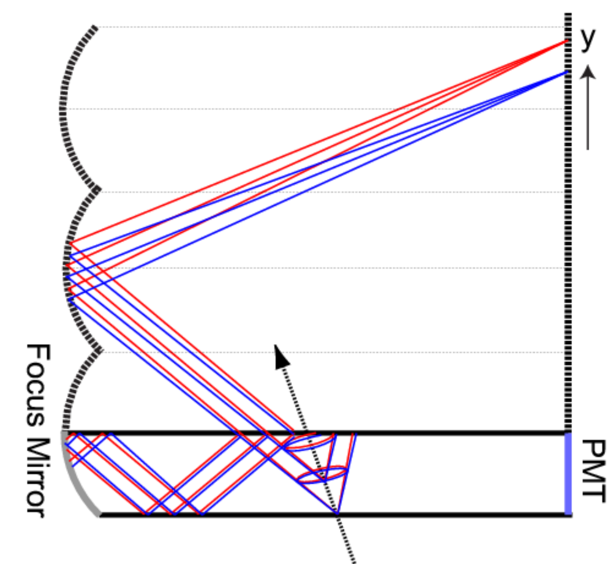




The “Time of Propagation” (TOP) Detector II

- 16 quartz Cherenkov radiator bars arranged around IP
- Forward side: spherical mirror
  - Effectively removes bar thickness for reflected photons
  - Wavelengths are focused on slightly different space points
- Backward side: small expansion prism, sensors, readout electronics



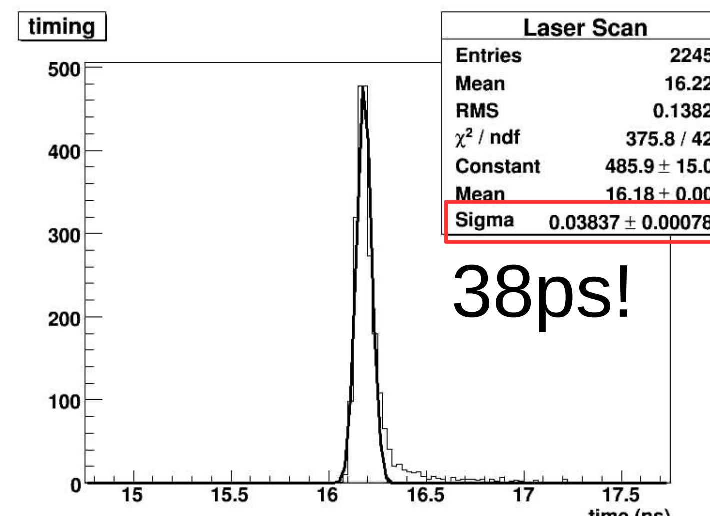


Readout Requirements

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

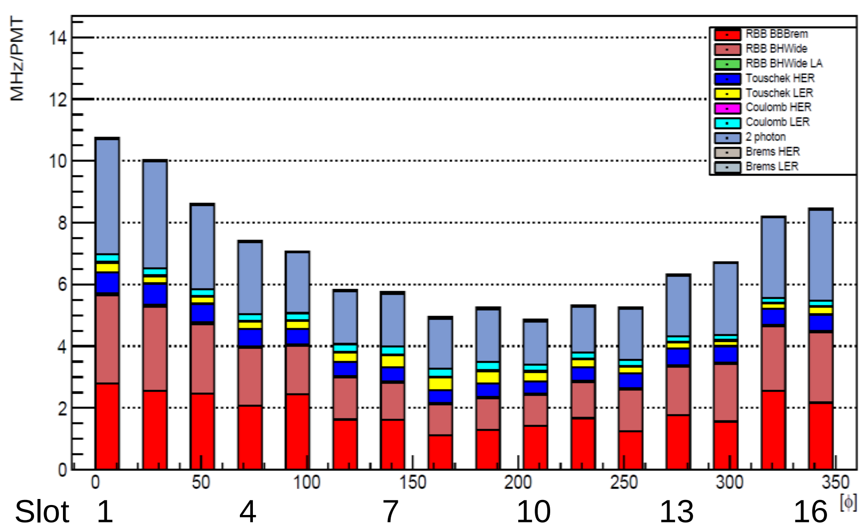
Sensors: Micro-Channel-Plate PMTs

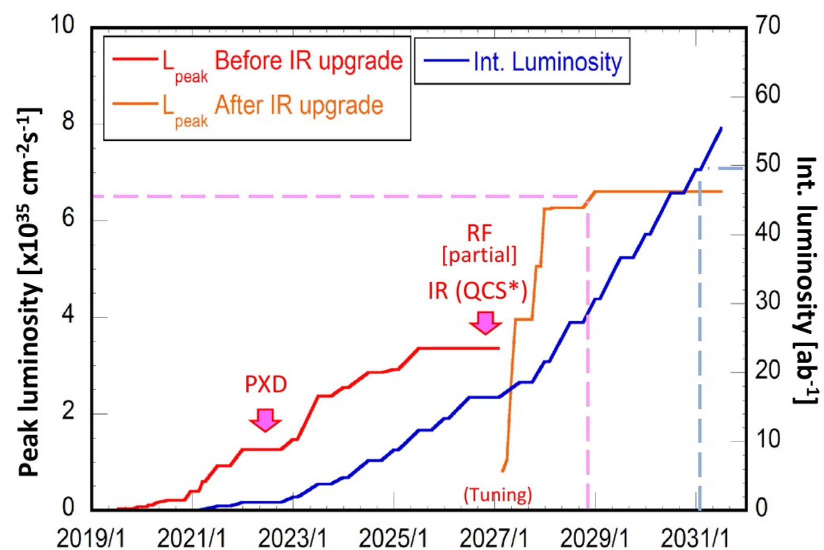
- Developed by Hamamatsu and Nagoya University
- Measured single photon time resolution <40ps
- (Mostly) resistant to B-fields
- ~5x5mm pixelated anodes
- Lifetime (integrated charge) is limited
  - Conventional type: ~1C/cm^2 (~50% of current TOP)
  - Life-extended type: >10C/cm^2 using atomic layer deposition (ALD) (other ~50% of current TOP)



PMT Degradation

- Integrated PMT charge dominated by beam induced backgrounds
  - Irreducible component averages ~7MHz/PMT at full luminosity
  - Other beam backgrounds depend on accelerator conditions, currently dominant
- Need to keep a close eye on the beam conditions so even life-extended PMTs will survive until the end of the experiment





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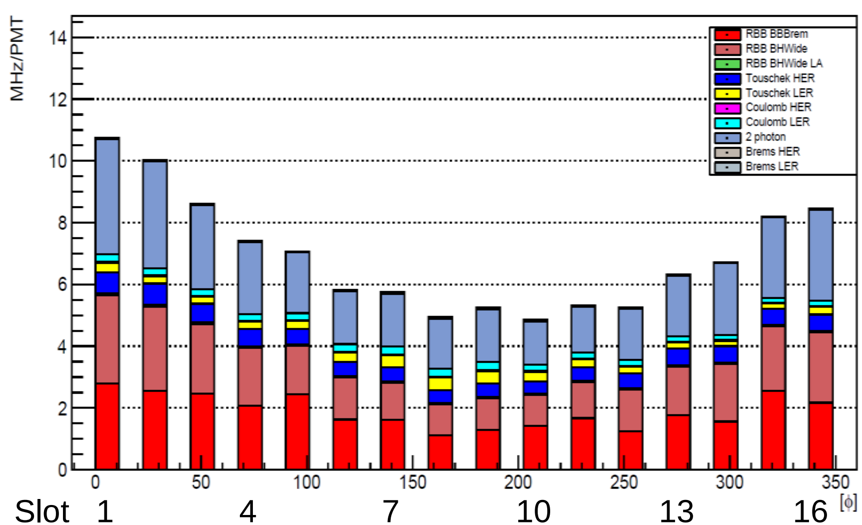
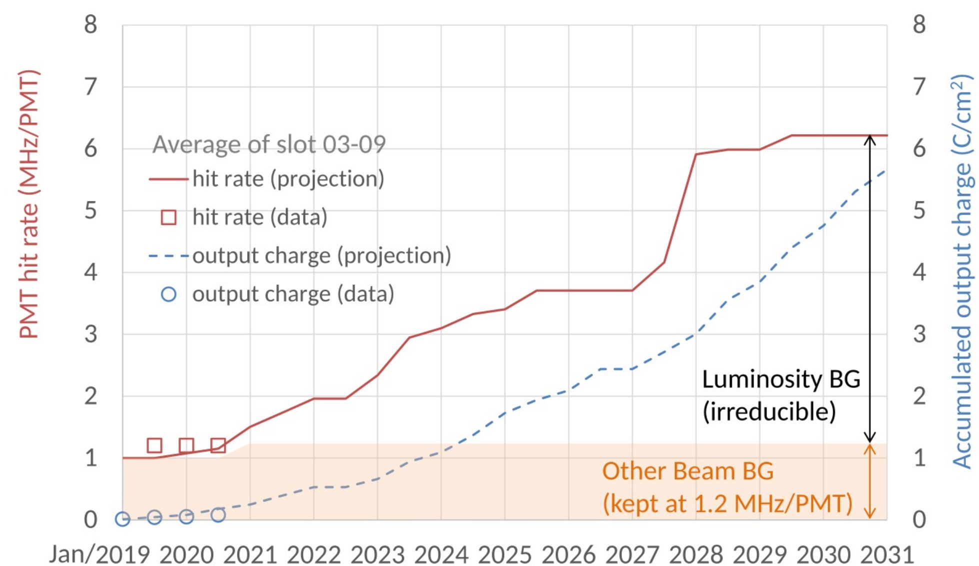
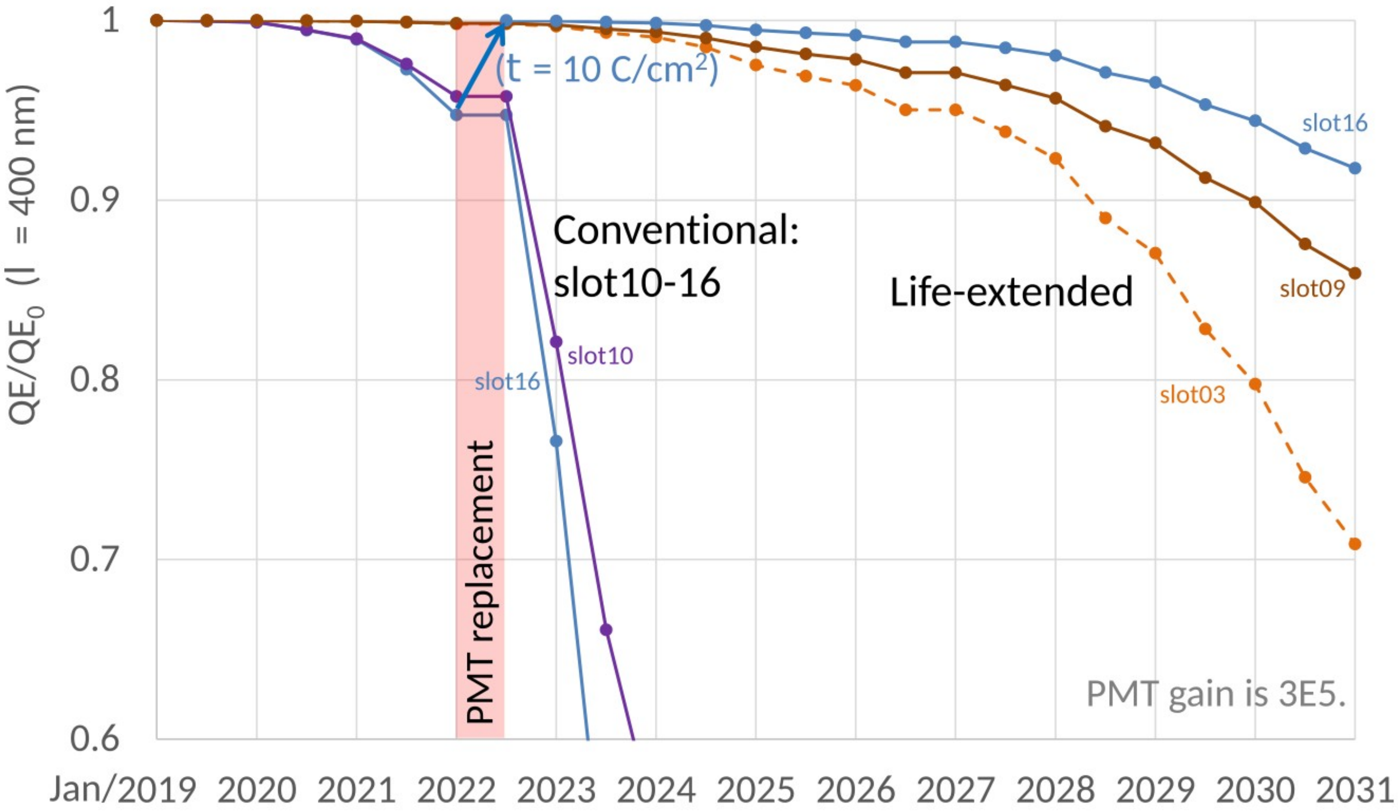




PMT Replacement

- Conventional PMTs will start to show QE reduction soon and fail eventually
- Full replacement of conventional PMTs in extended shutdown 2022
- PMT production and testing well underway

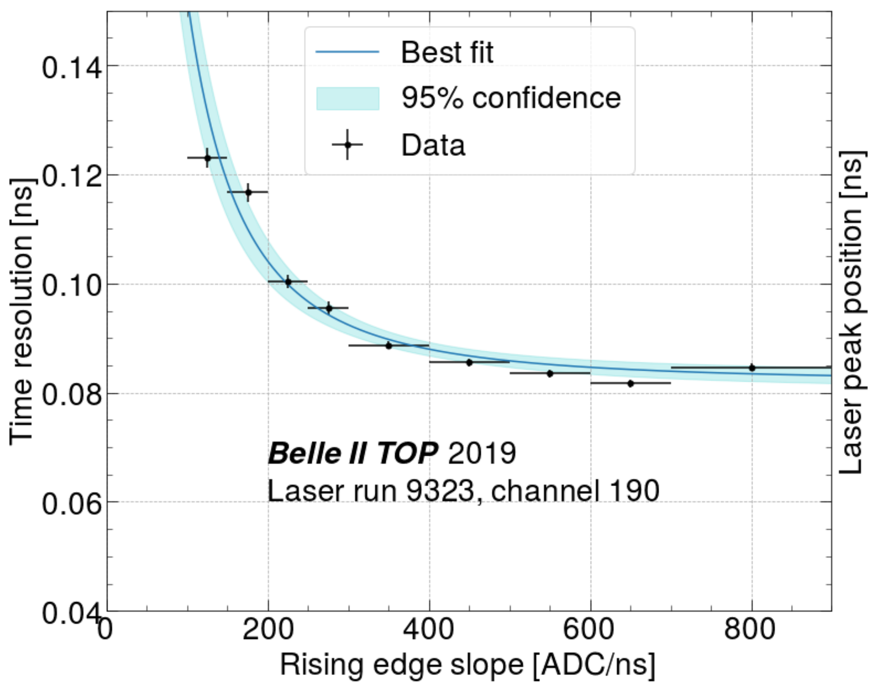


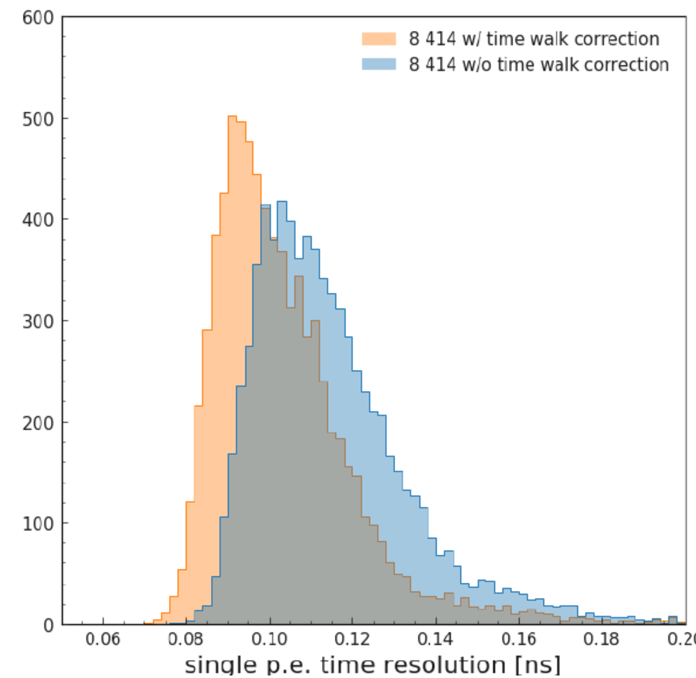
TOP Front End Electronics

- 8192 channels of 2.7GSa/s waveform sampling readout
  - IRSX switched-capacitor-array ASIC (Prof. Gary Varner, UH)
- <50ps electronics time resolution
- Full waveform feature extraction in frontend
  - Whole TOP stores $22x10^{12}$ samples every second
  - Extract and transfer photon timing, pulse shape parameters
- Powerful frontend processing: 320 FPGAs, 640 ARM cores (Zilinx Zynq 7030 and 7045)
  - Plenty of resources available to refine online processing
  - Power dissipation budget might become limiting
- https://dx.doi.org/10.1016/j.nima.2019.162342

Single Photon Time Resolution

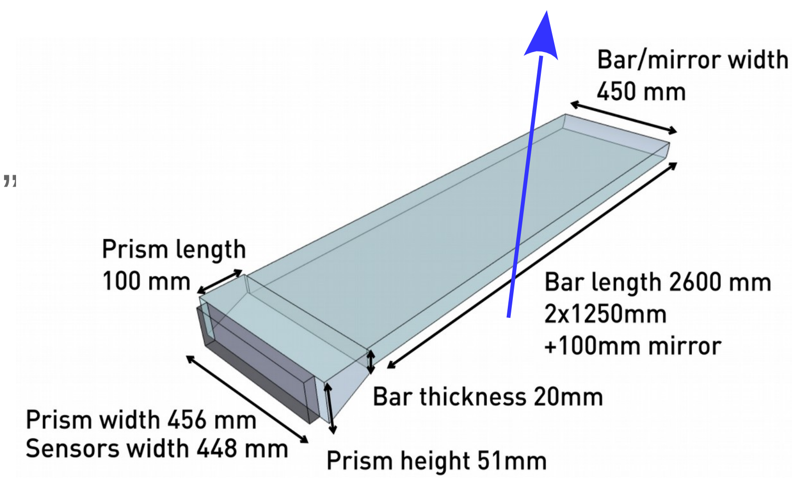
- Intrinsic resolution <100ps on most channels
  - Dominated by electronic noise in signal chain due to PMT operation at low gain
- Recent advances in time walk correction further improve single photon timing resolution
  - Only small effect on PID performance due to chromatic dispersion limit

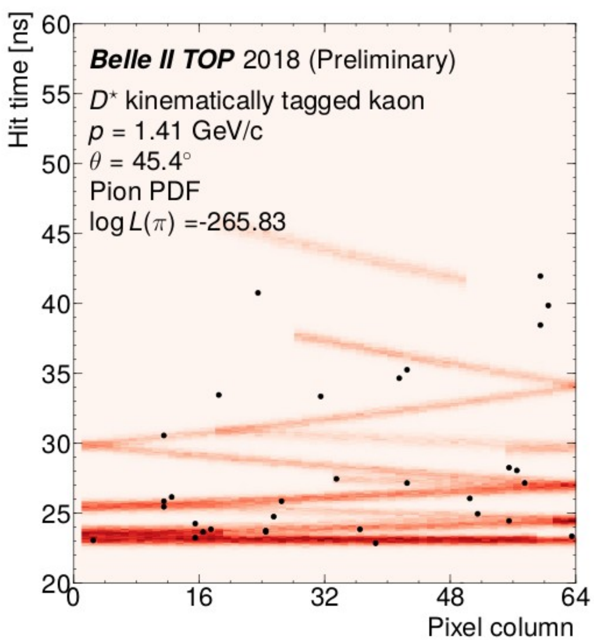


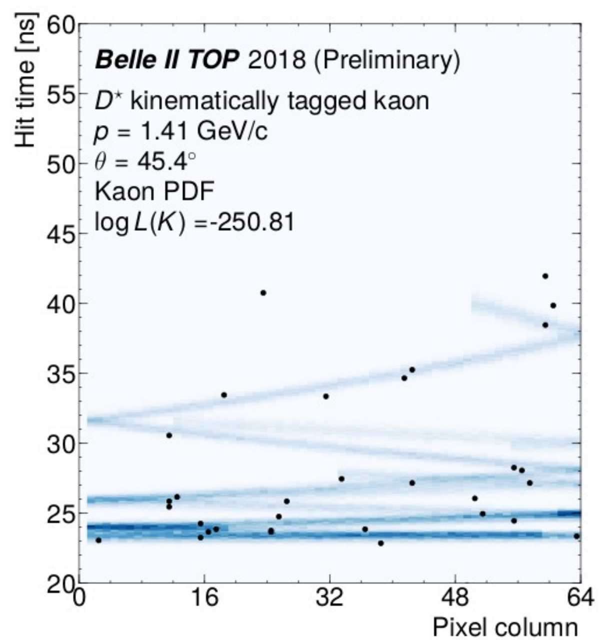


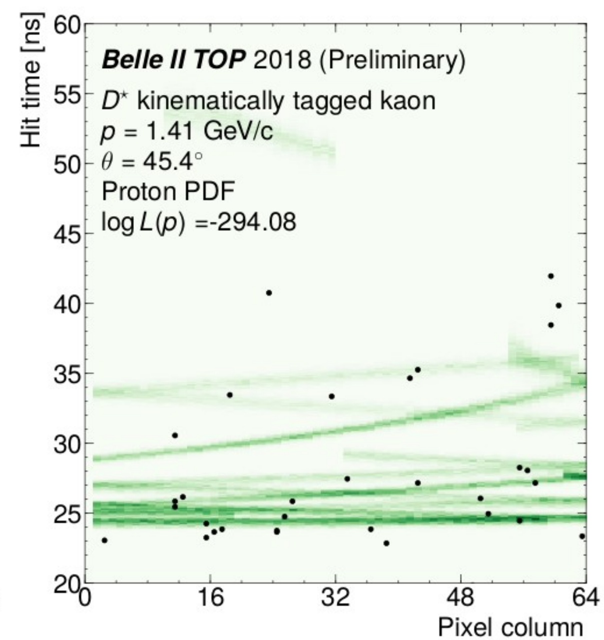
TOP "Cherenkov Rings"

- $D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$ "Nature's MC truth"
- Kaon facing mirror-side of TOP bar
  - PDF differences dominated by shape

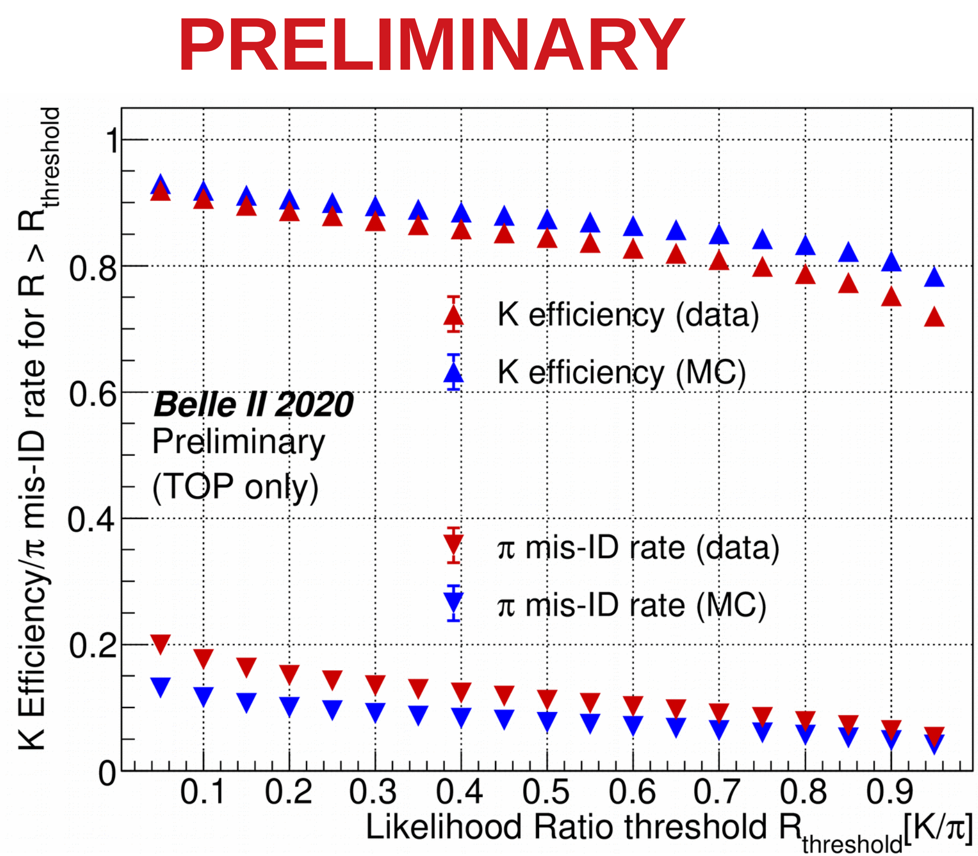


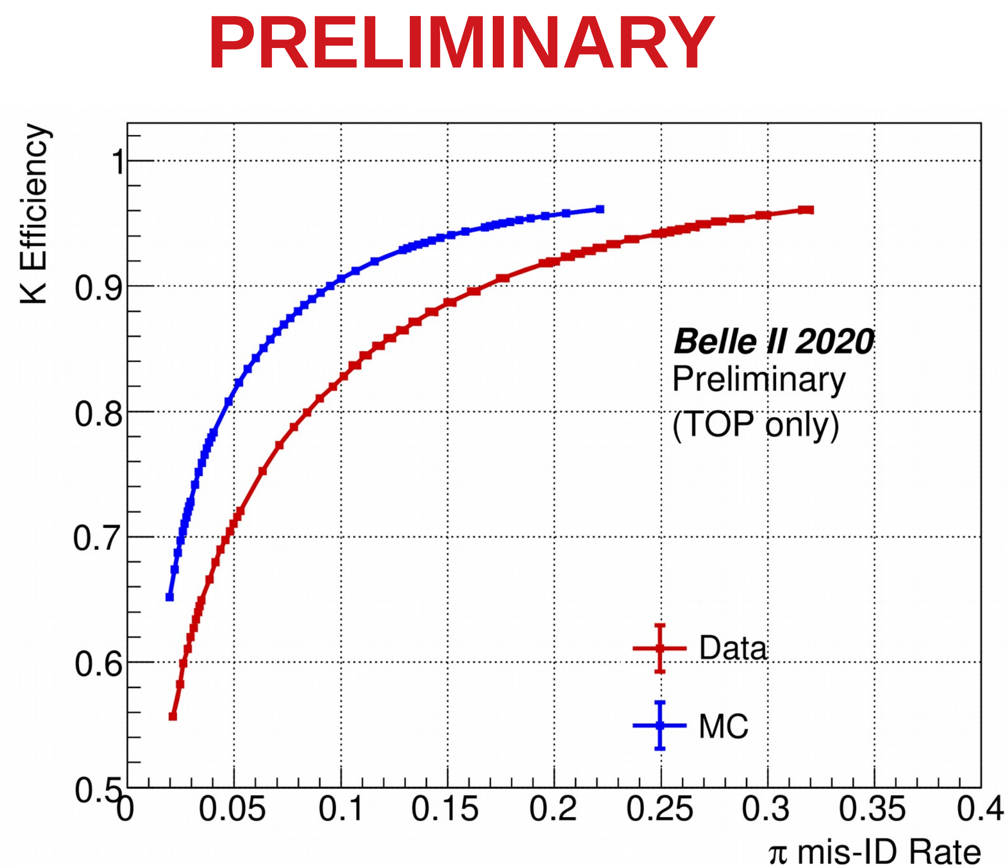






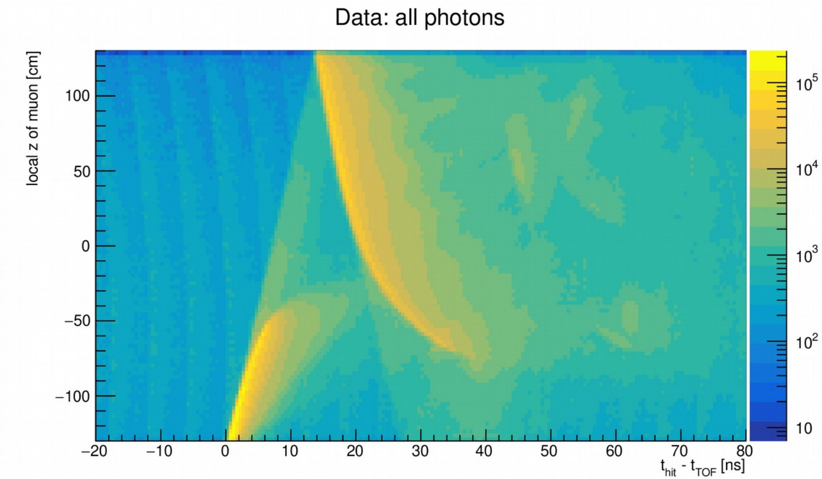
TOP PID Performance: K-π Separation

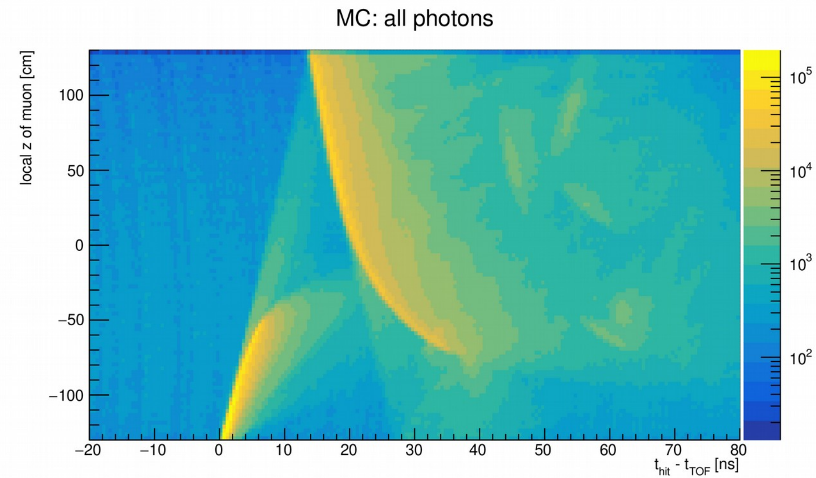




Ongoing Improvements

- TOP reconstruction entirely depends on generating PDF for a given track
  - Progress in analytical PDF: now includes delta ray modeling https://doi.org/10.1016/j.nima.2010.09.176
  - Detailed studies to extract quartz parameters from data
- ML techniques under study by joint task force of PNNL, Uni Hawaii, KIT, Nagoya University, INFN Torino
  - For both simulation and reconstruction
- All such studies have the potential to improve performance and data/MC matching
- Frontend processing: full waveform template fits



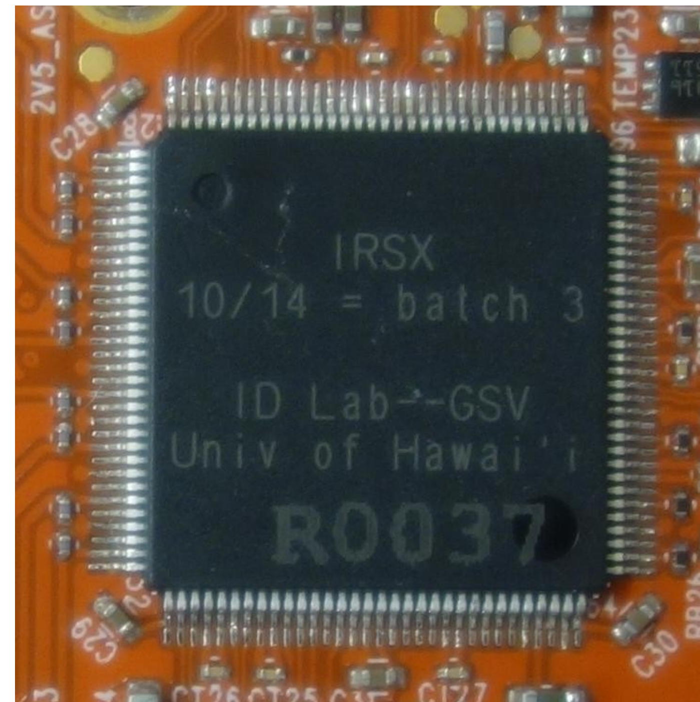


Summary

- The TOP detector is a novel particle identification system for the Belle II barrel region
  - Strong requirements on sensors, readout electronics, calibration to achieve single photon time resolutions <100ps
- TOP performance is getting close to MC expectations
  - PID performance will continue to improve in the future with refined frontend processing, reconstruction and ML techniques
  - TOP PID is actively used by many Belle II analyses
- 50% of PMTs will be replaced with life-extended models in extended shutdown 2022
  - Still need to keep a close eye on beam backgrounds so PMTs stay efficient for the next ~ten years

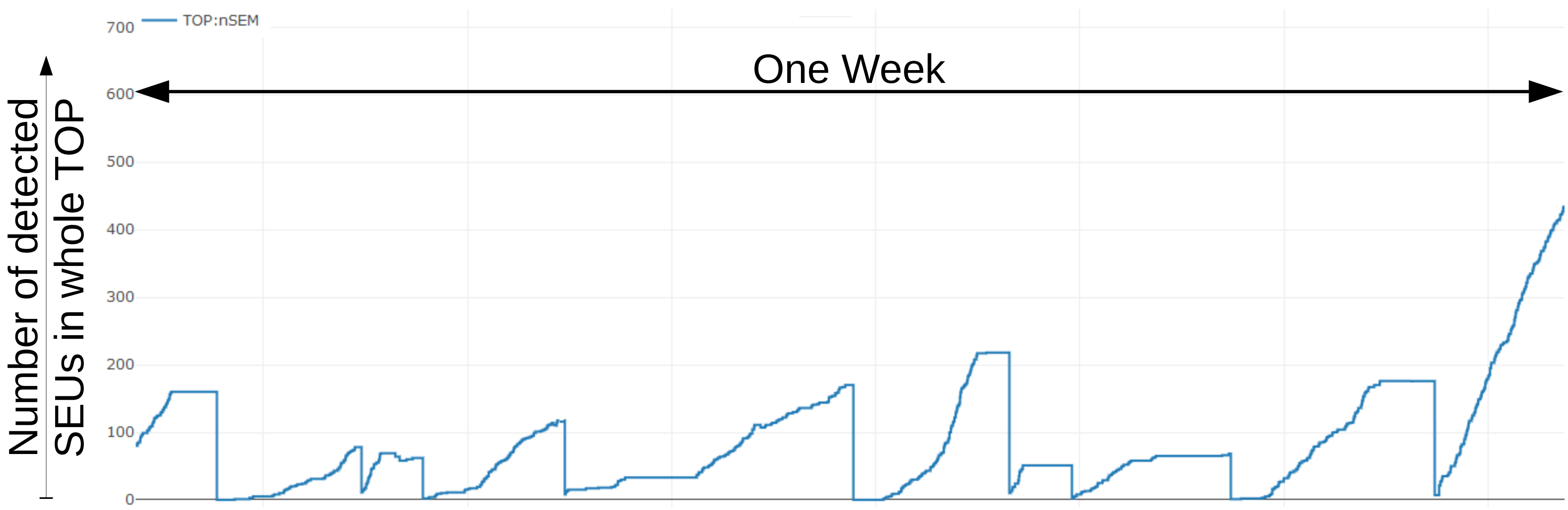
Readout: Electronics

- "Oscilloscope on a Chip": IRSX ASIC
  - Designed by IDLAB, UH (Prof. Gary Varner)
- Operated at 2.7GSa/s in TOP
  - ~600MHz analog bandwidth
  - 32k analog buffer cells (~10us)
  - 12 bit digitisation w/o deadtime
- Power budget ~600mW/ch
  - ASIC: ~125mW/ch
  - Preamp: ~120mW/ch
  - FPGAs: ~300mW/ch
  - PMT/HV: ~30mW/ch



Neutrons/Single Event Upsets

- Xilinx SEU core detects ~100-200 SEUs per day in whole TOP system (640 FPGAs)
  - few uncorrected per day, no negative specific effects seen
- Rare Zynq ARM crashes (<1/day) suspected due to SEU effects on interrupt handling
  - Modifying software/firmware to reduce reliance on interrupts



TOP "Cherenkov Rings" I

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