The time-of-propagation (TOP) counter for Belle II

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on behalf of the Belle II PID Upgrade Group

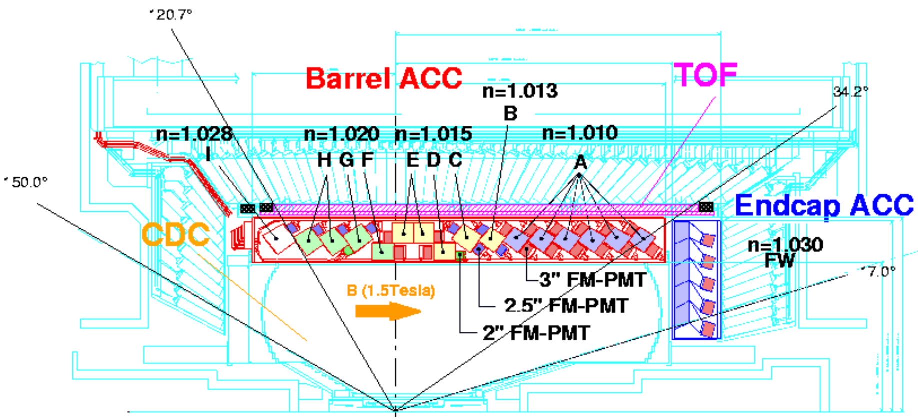
7th International Workshop on Ring Imaging Cherenkov Detectors

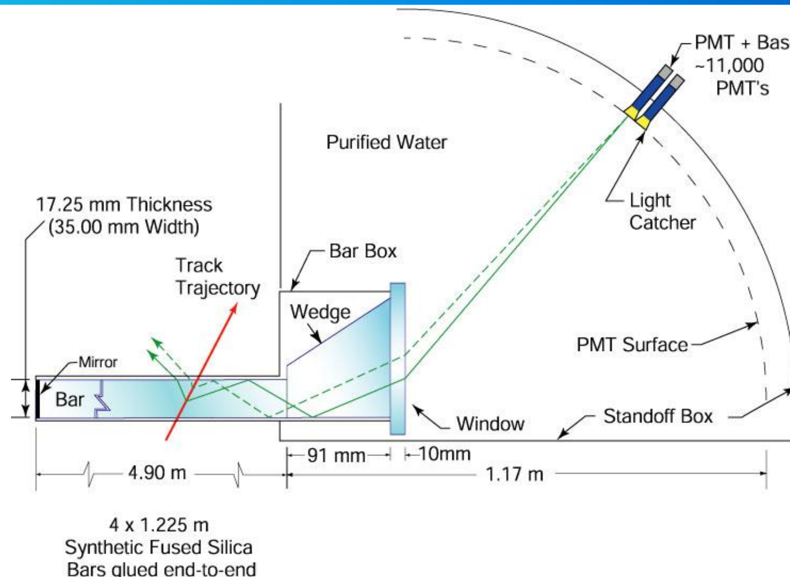
May 6, 2010

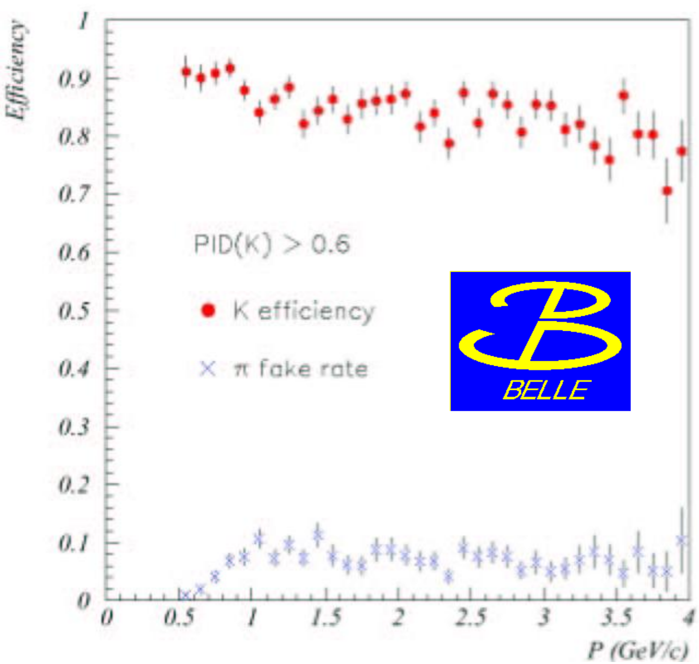
Barrel PID at Belle II

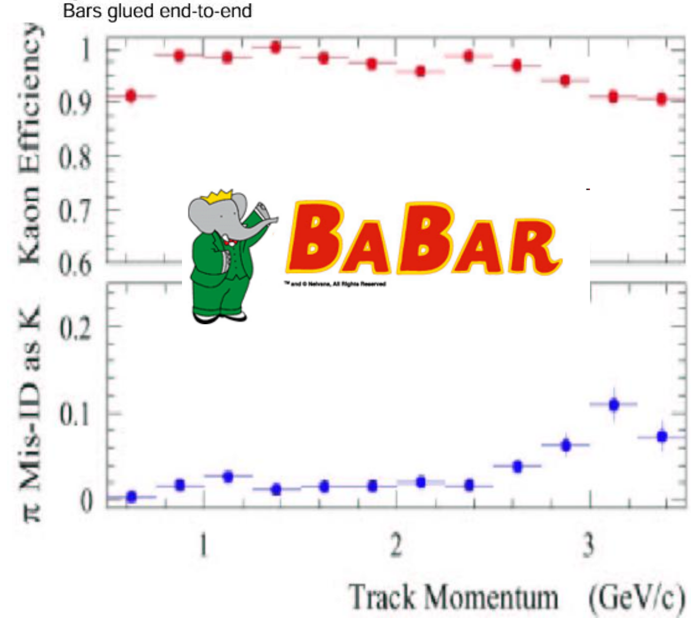
- Belle II at Super KEKB will perform high precision tests of the Standard Model and searches for new physics:
  - Requires high efficiency, low fake rates in separation of $K^{\pm}/\pi^{\pm}$ for momenta up to ~4 GeV/c.
    - For example, to distinguish between
      - $\mathbf{B} \rightarrow \rho\,(\pi\pi)\,\gamma$ / $\mathbf{B} \rightarrow \mathbf{K}^*\,(\mathbf{K}\pi)\,\gamma$
      - $\mathbf{B} \rightarrow \pi\pi$ / $\mathbf{B} \rightarrow \mathbf{K}\pi$
- Primary requirements:
  - Increased performance relative to Belle PID.
  - Barrel region is extremely space constrained → must be compact.

Particle ID at the B Factories





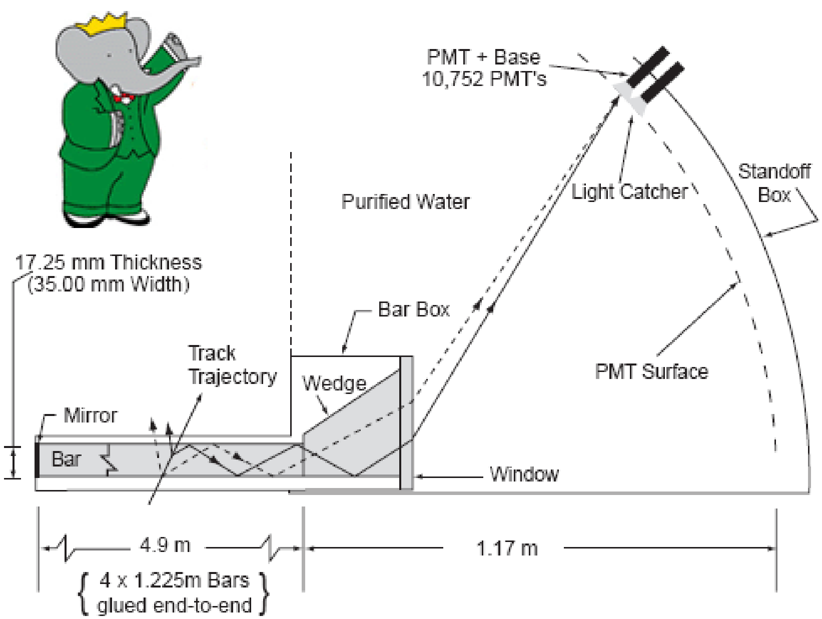


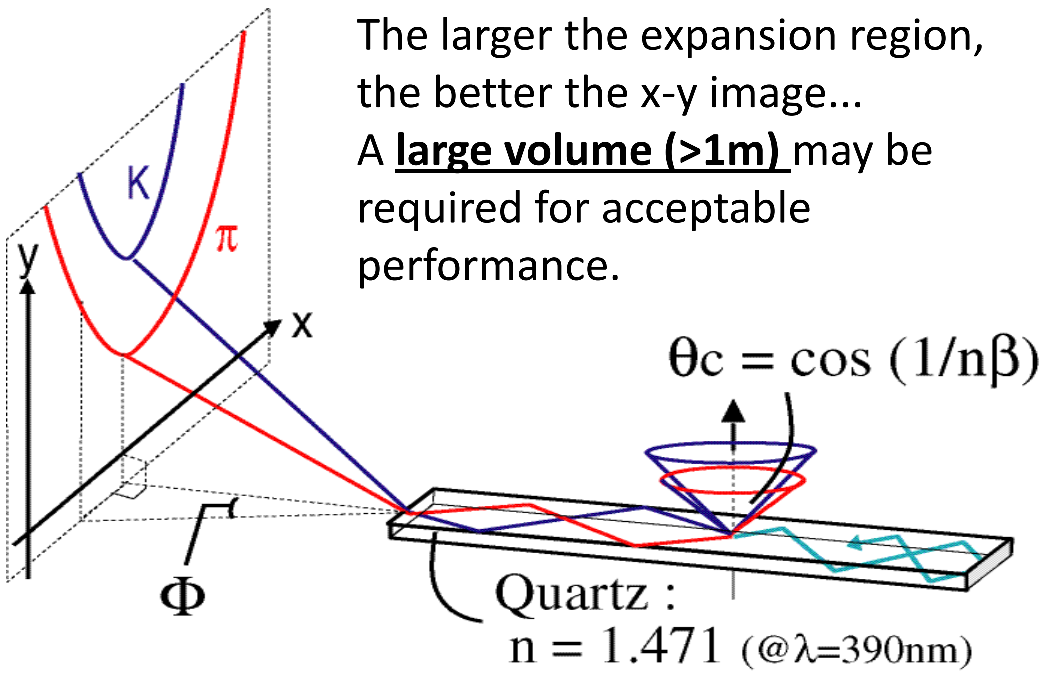


➔ Would like to improve performance over existing threshold aerogel + TOF system.

Detection of Internally Reflected Cherenkov Light

- Charged particles of same momentum but different mass (e.g., $K^{\pm}$ and $\pi^{\pm}$) emit Cherenkov light at different angles.
- Detect the emitted photons in 2+ dimensions (x,y,t)
- BaBar DIRC as a model:





The larger the expansion region, the better the x-y image...
A **large volume (>1m)** may be required for acceptable performance.

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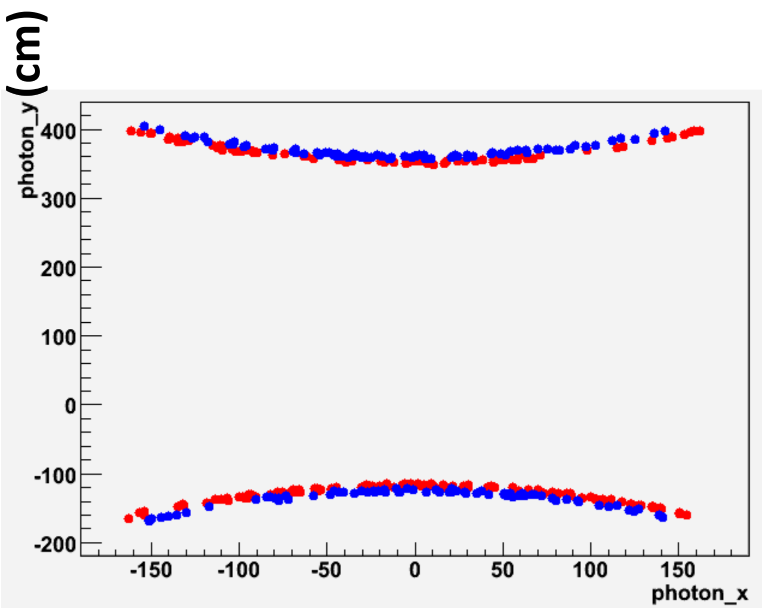

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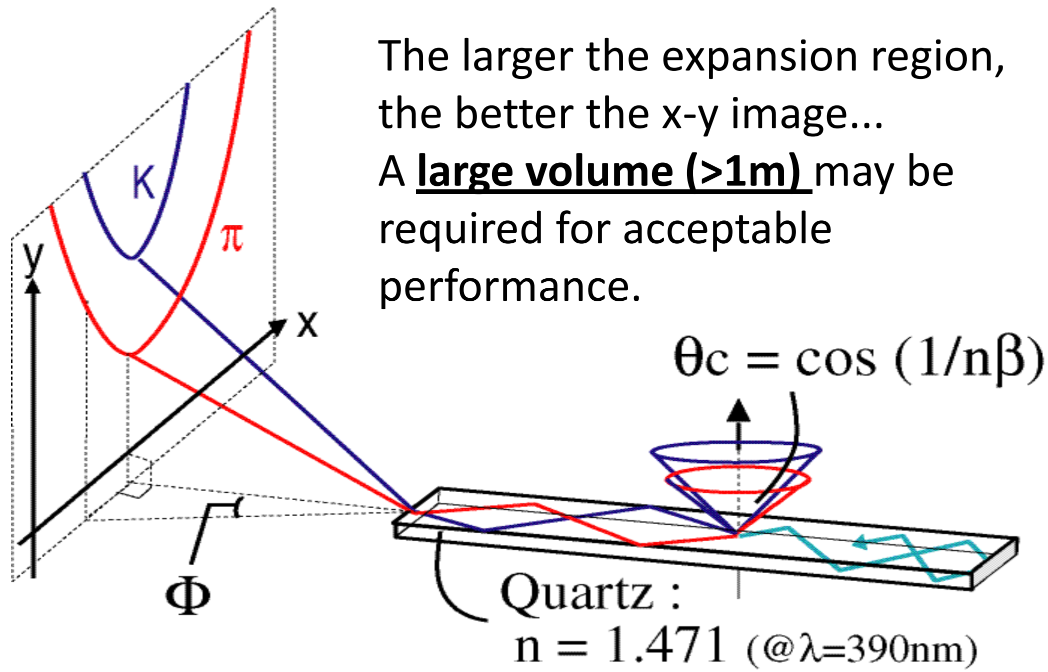

Left: Simulations w/ large (2 m) expansion volume, 2 GeV K/π

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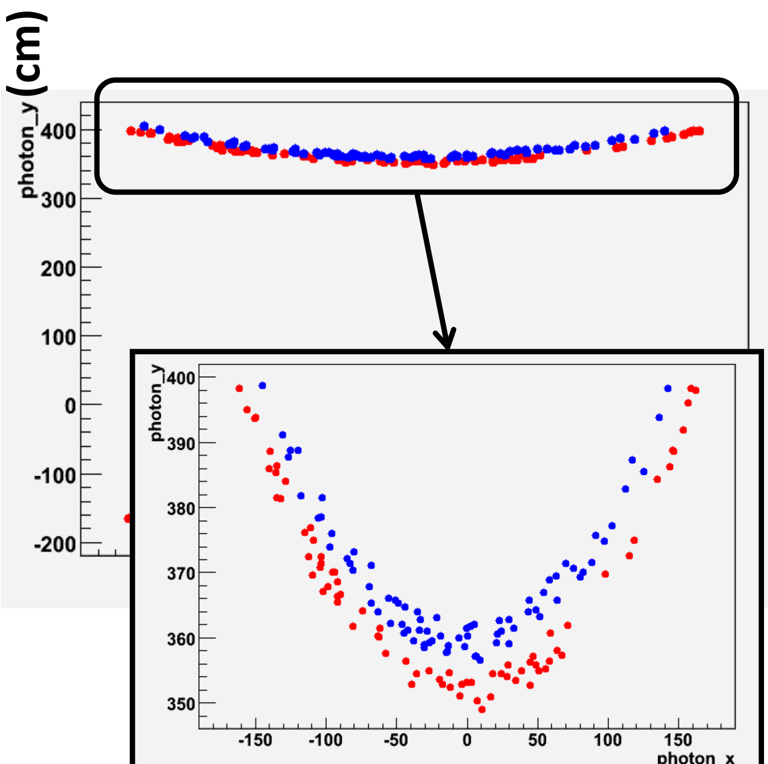

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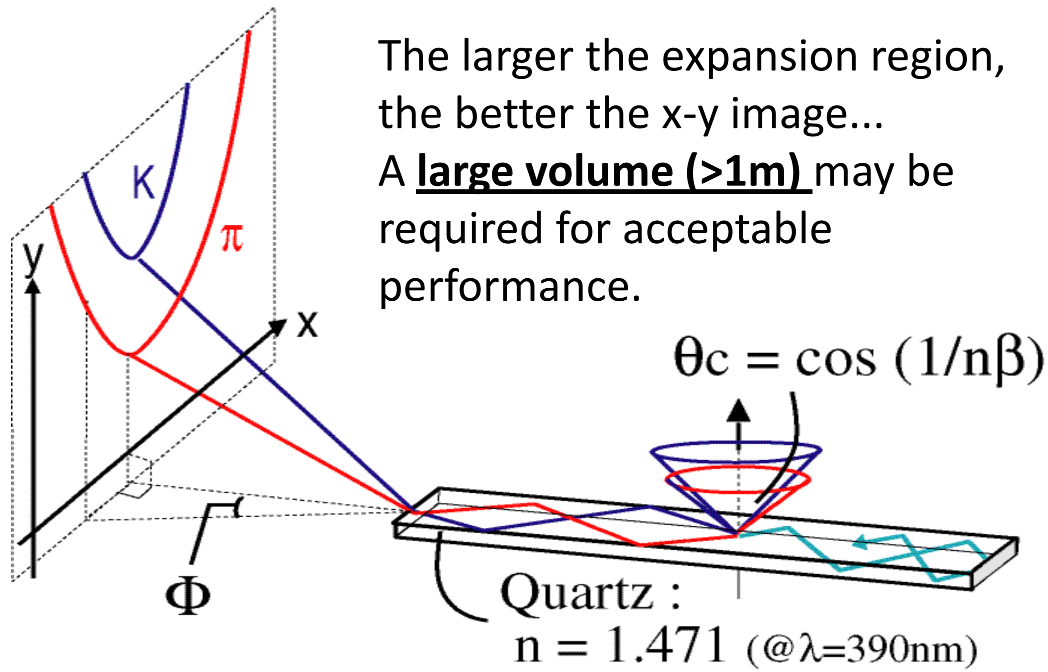

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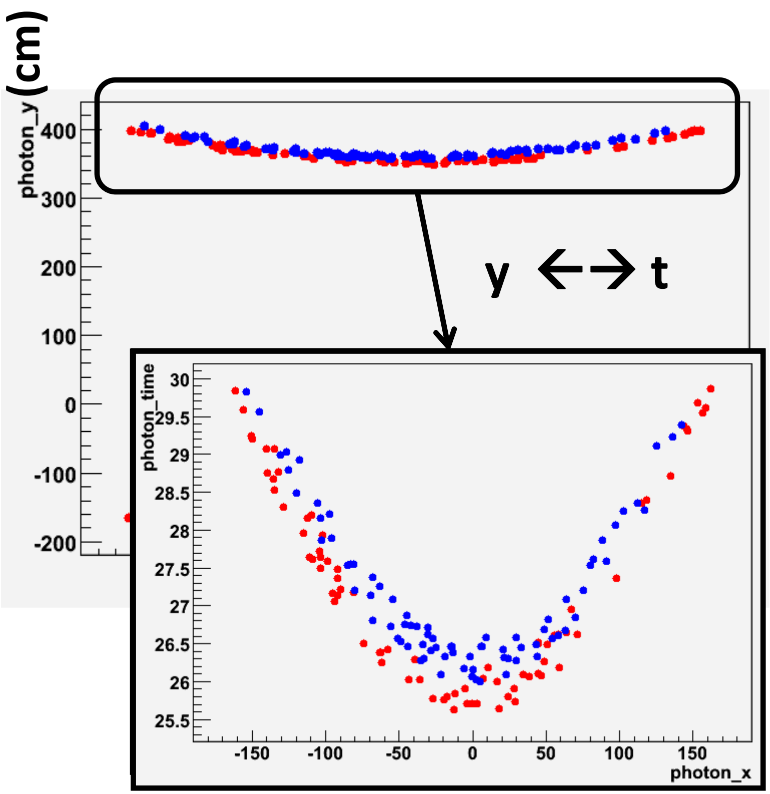

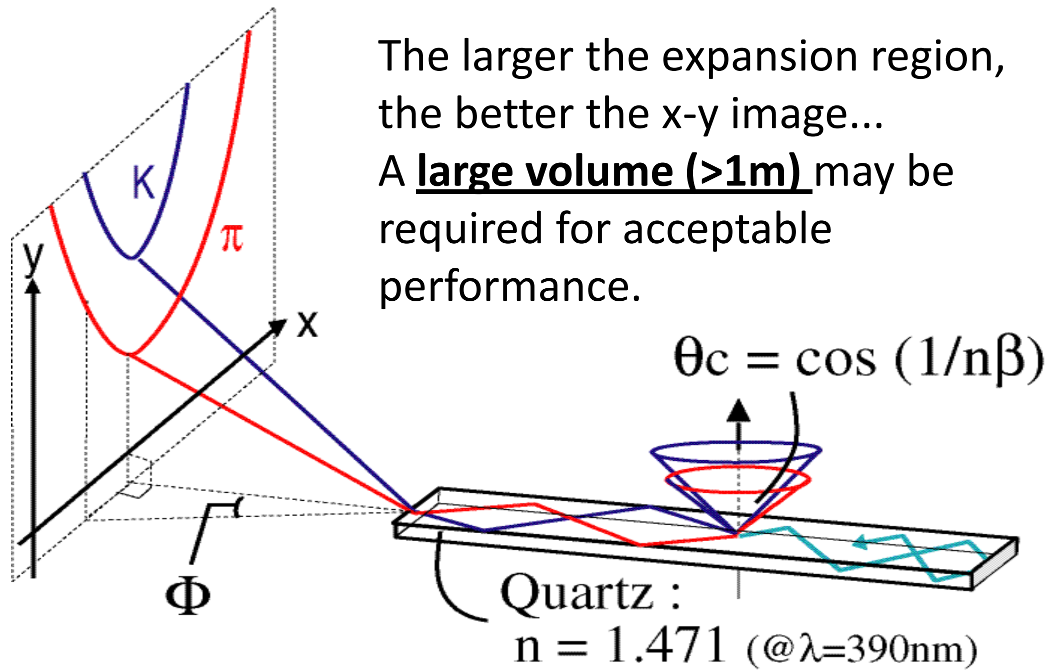

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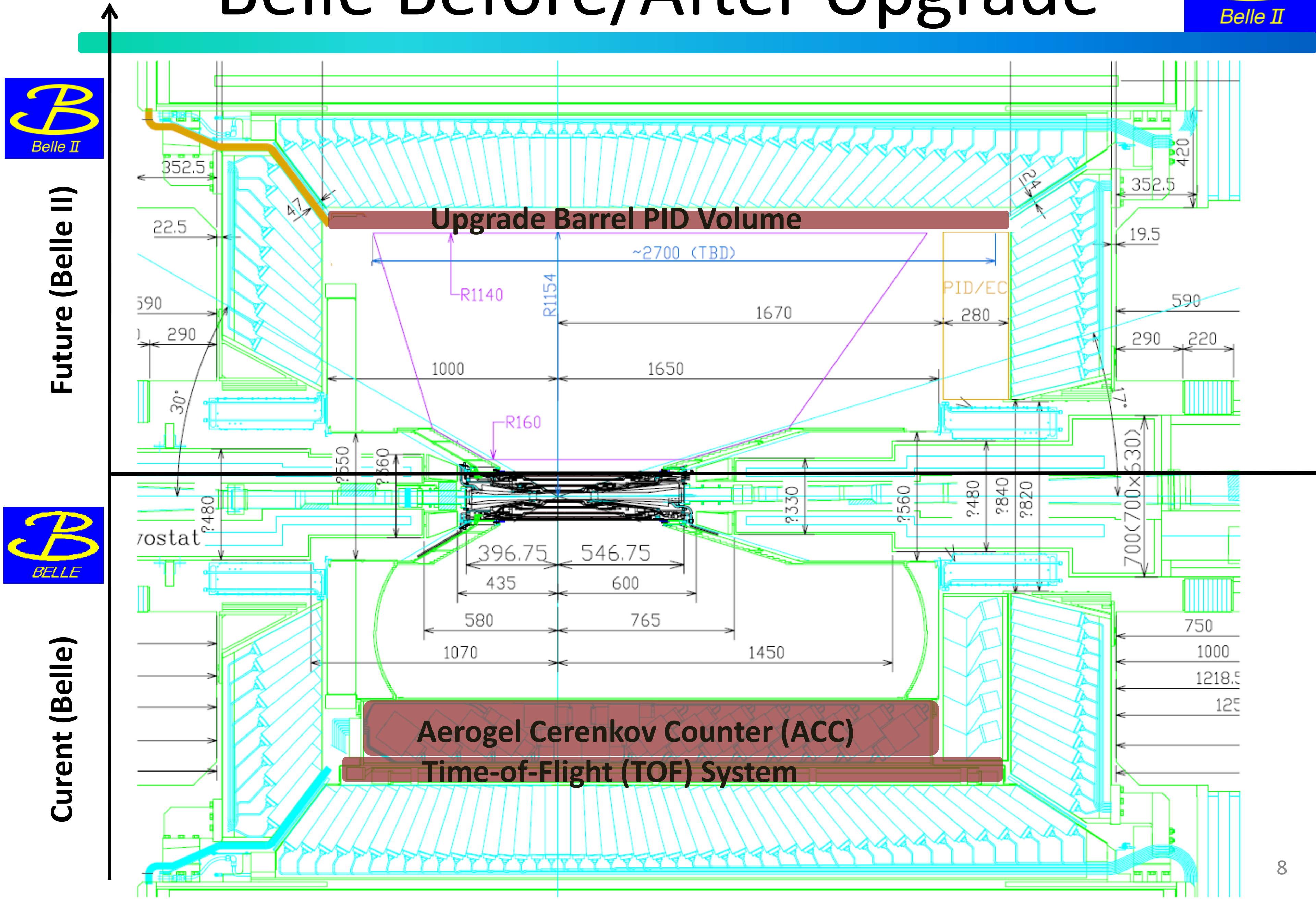
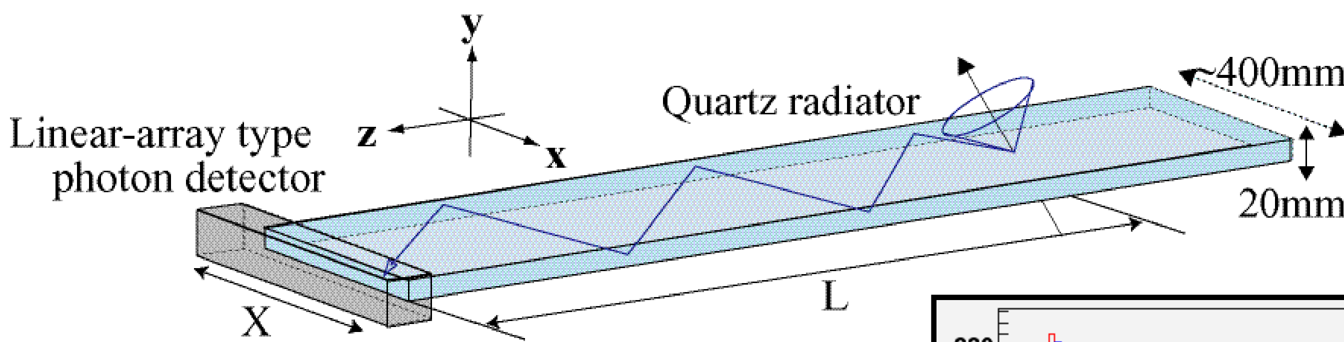
Belle Before/After Upgrade

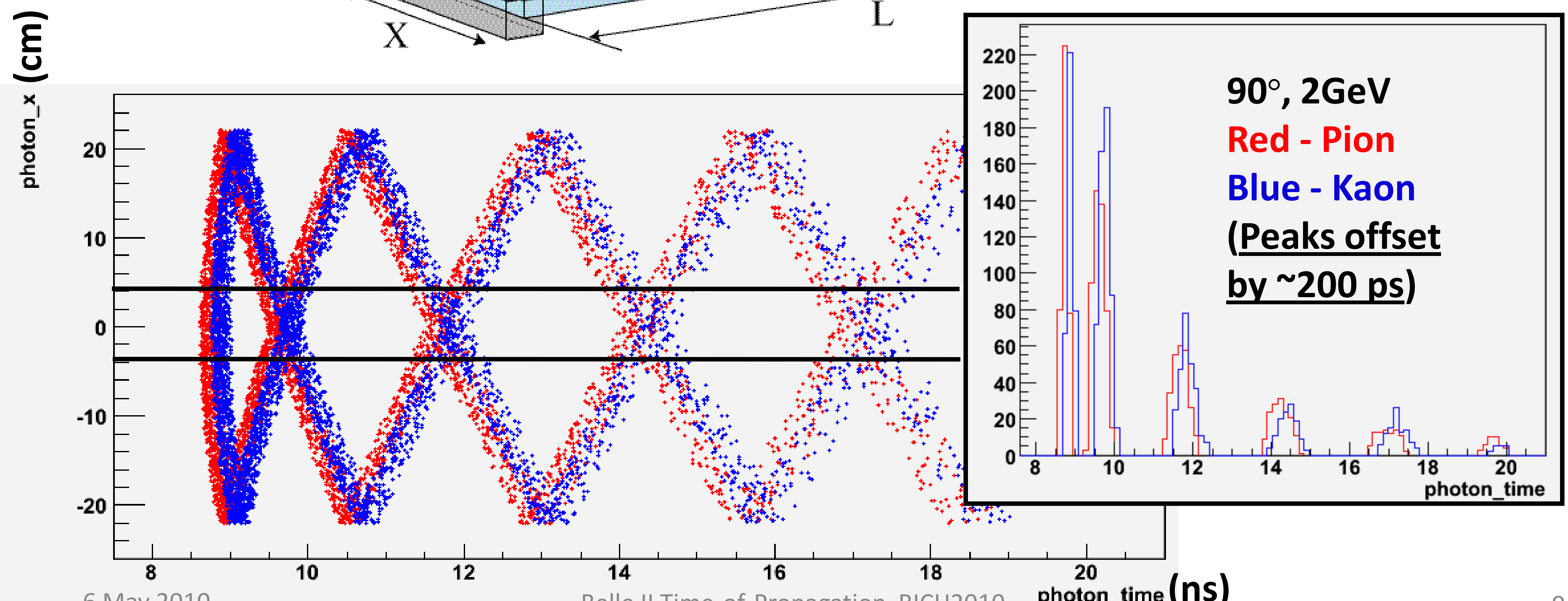


Time-of-Propagation (TOP) Counter

e.g., NIM A, 494, 430-435 (2002)

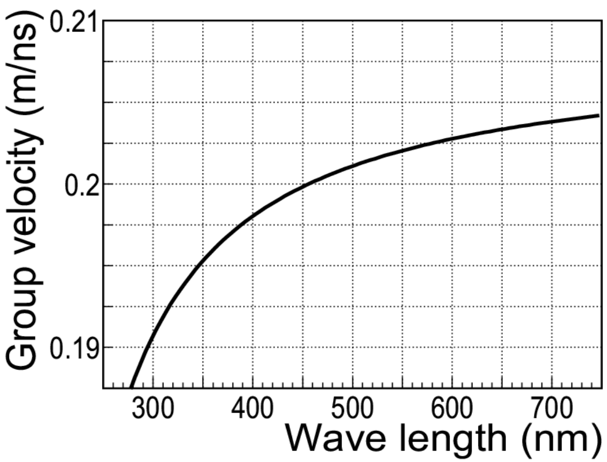
- Work at bar end, measure x,t, not y ➔ compact!



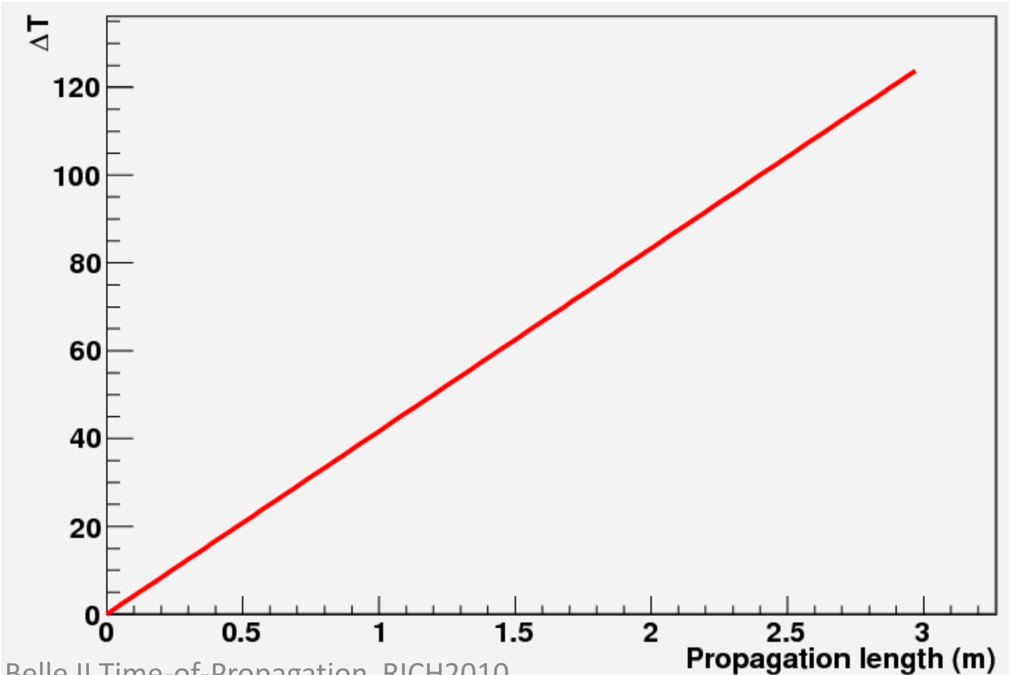


Chromatic Dispersion

- A range of photon energies is produced in radiator.
  - Each wavelength is emitted at different Cerenkov angle: $\cos\theta = \frac{1}{\beta n(\lambda)}$
- Changing index of refraction changes group velocity for different wavelengths of light.



ΔTOP (375 nm, 525 nm) (ns) vs. L_{prop}



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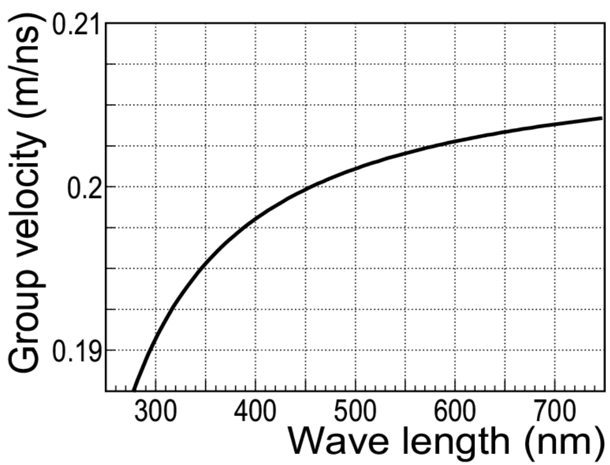
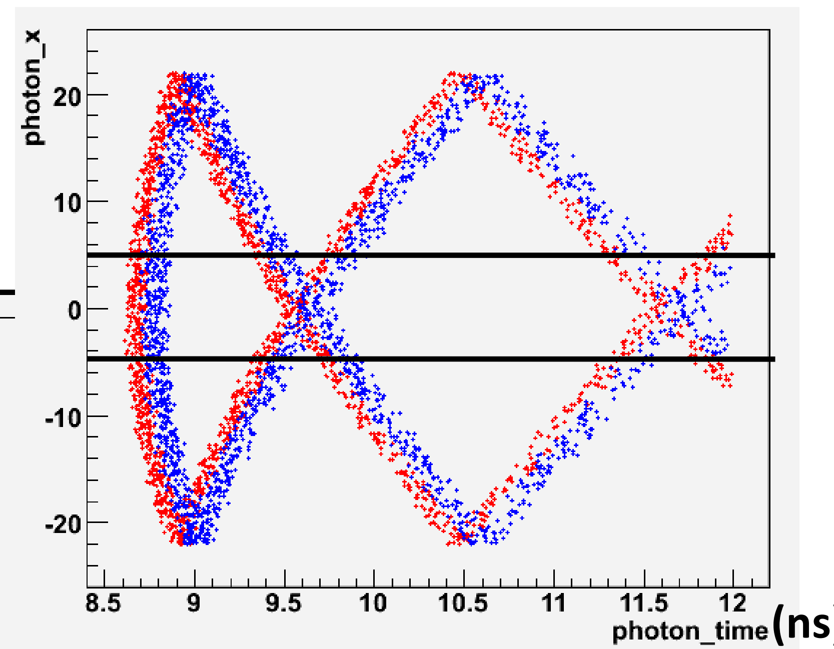


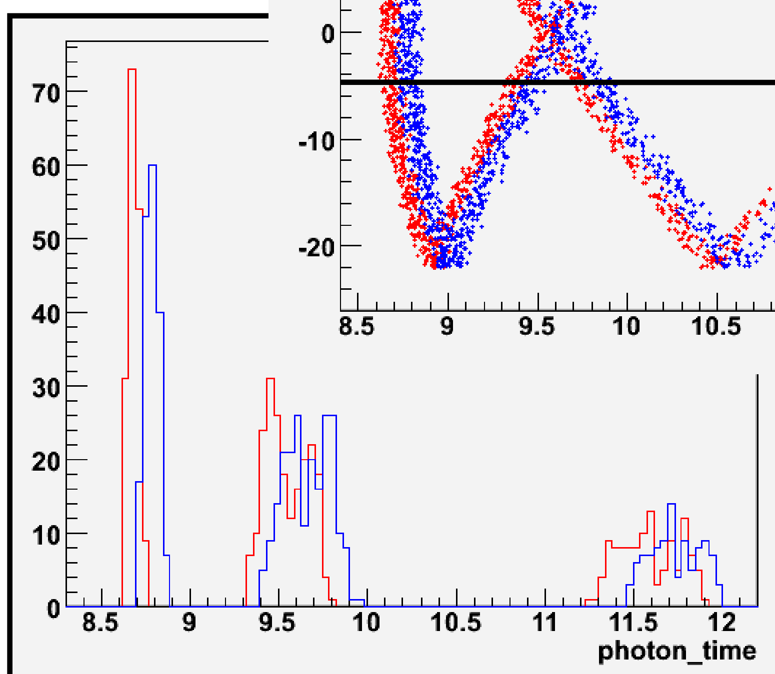
Simulated TOP – 2 GeV π^+ at 90°

Red – $\lambda \approx$ 525 nm

Blue – $\lambda \approx$ 375 nm

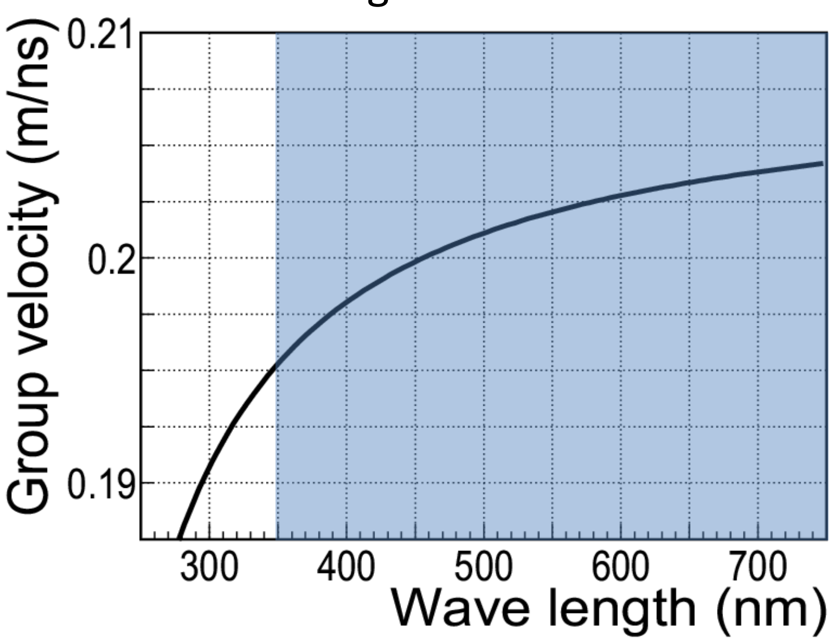
Red and blue offset by ~100 ps

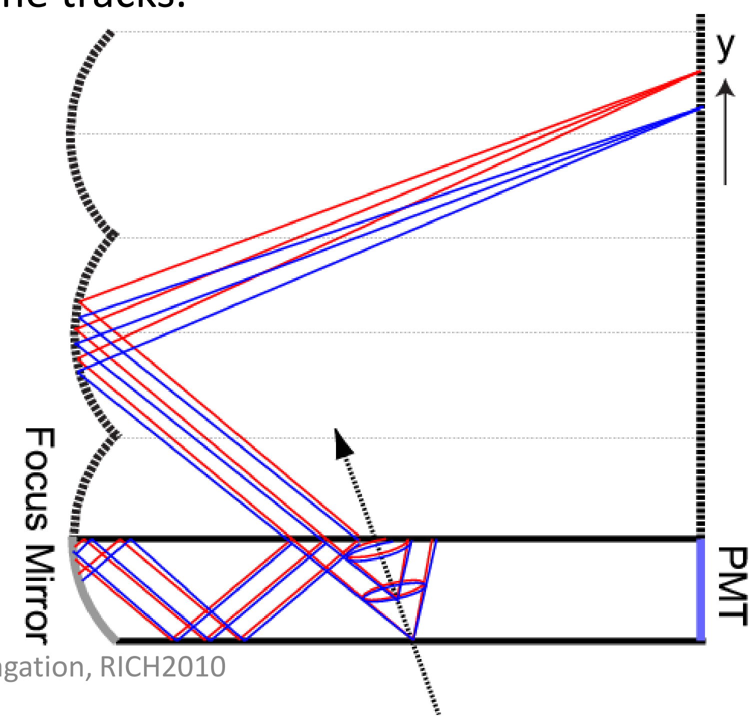




Focusing TOP (fTOP)

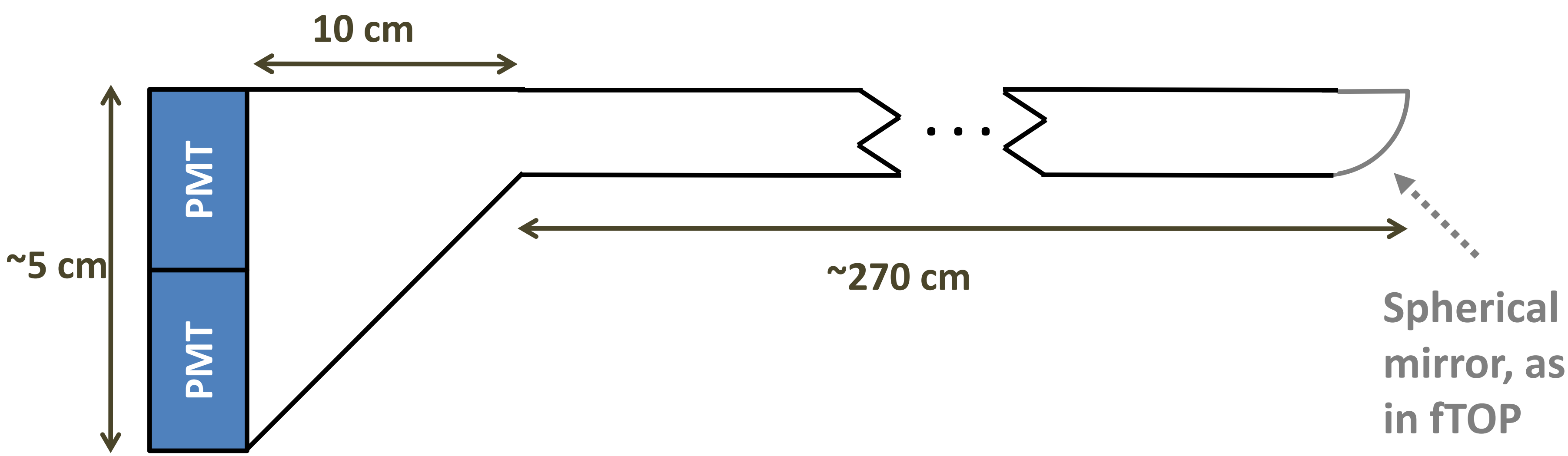
- Add focusing mirror and vertical pixelization.
  - Spreads wavelengths over more pixels.
- Chromatic dispersion:
  - Add a wavelength filter ➔ use part of spectrum where dispersion is not as severe, at cost of some photons. (Valid for any TOP concept, not just fTOP)
- Finite bar thickness:
  - Focusing mirror can reduce this for some tracks.





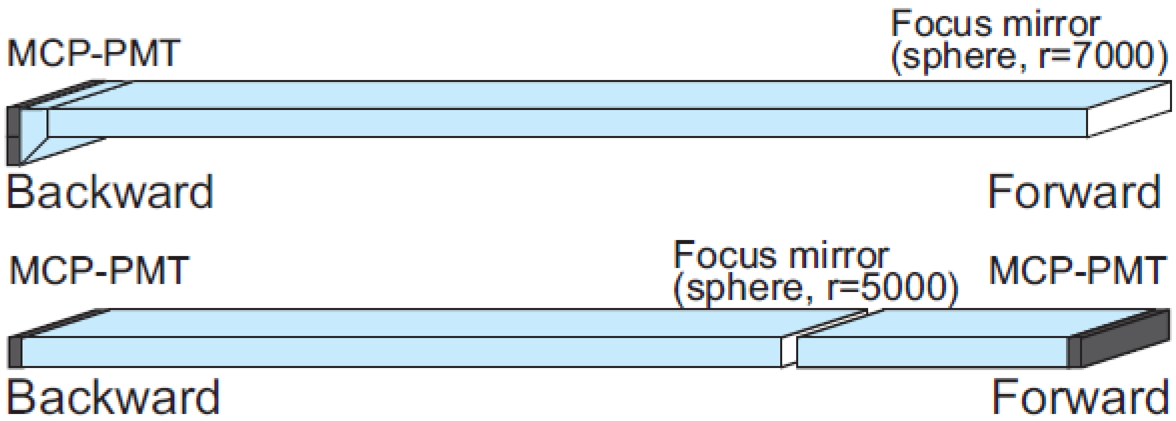
Adding imaging → iTOP

- Starts with a single bar, single readout design of focusing TOP (including focusing mirror).
  - Adds a small quartz expansion volume.



  - Asymmetric shape was chosen over a symmetric one to allow smaller gap to ECL.

Two Baseline Configurations



Single bar option

L_{bar} ~ 2600mm

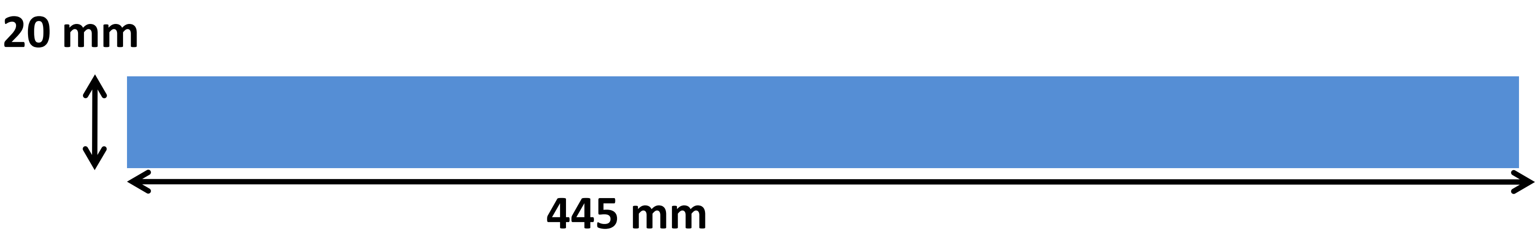
$L_{expansion}$ ~ 100 mm

Two bar option

$L_{backward}$ ~ 1850mm

$L_{forward}$ ~ 750 mm

TOP Quartz Cross Section:



x16 modules

BaBar DIRC Quartz Cross Section:

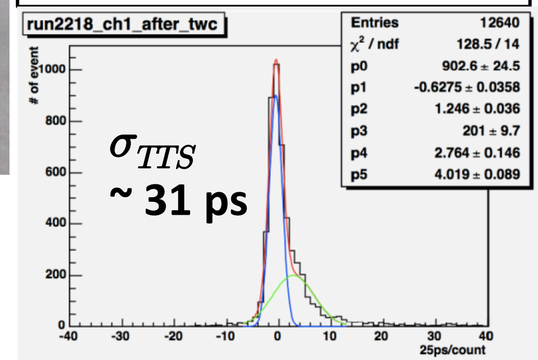
x12 modules

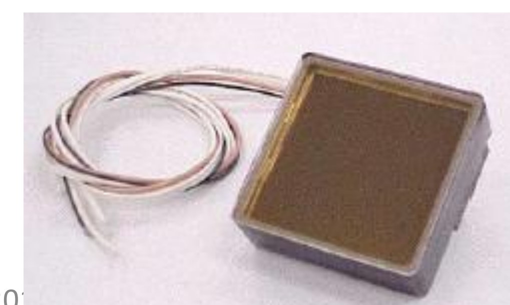
L ~ 5 m each

PMT Requirements & Options

- TOP counters require excellent single photon timing resolution: $\sigma_{TTS} \lesssim$ **50 ps**
- Must work in 1.5T magnetic field ➔ MCP-PMTs
- Devices considered:
  - Baseline photodetector:
    - Hamamatsu SL10
    - 10 μm pore MCP
    - 4x4 pixels, each: (5.5 x 5.5) mm^2
    - R&D ongoing to check/improve:
      - Timing: **single photon σ_{TTS} ~30-40 ps**
      - Lifetime: < 10% QE drop in ~3 Belle II years
      - Efficiency: **multi-alkali ➔super bi-alkali**, $\gtrsim$ 28% @ 400 nm
    - (***More by K. Inami Friday!***)
  - Backup option:
    - Photonis Planacon (10 μm pore)

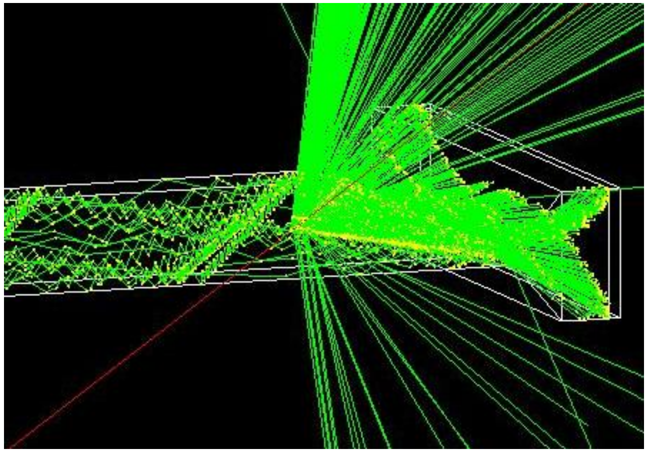
*K. Inami, et al.,
NIM A 592 (2008) 247-253

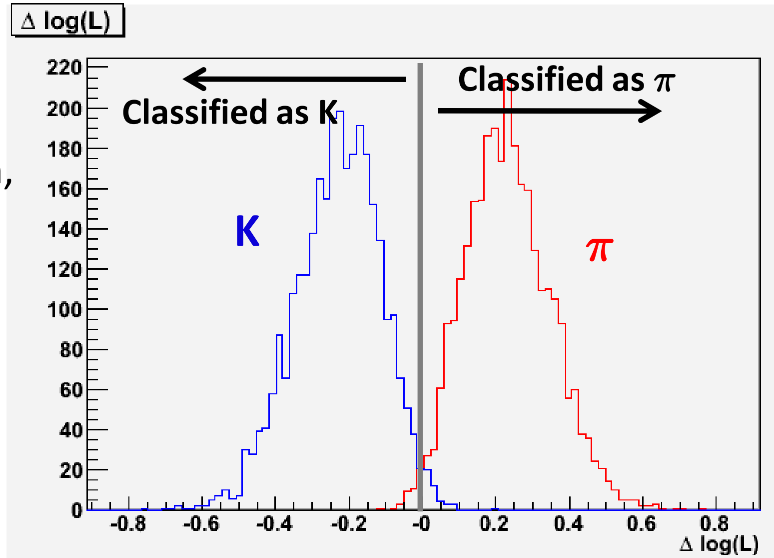




Simulation Studies

- Independent simulations:
  - Belle Geant3 + standalone code (Nagoya)
  - Geant4 (Hawaii)
  - Standalone code (Ljubljana)
- All utilize a Δlog(Likelihood) approach to determine particle classification.
  - PDFs are defined in x,y, and t
  - Geant-based versions take probability distribution functions (PDFs) from simulated events.
    - ➔Extremely time consuming to generate the PDFs, but can include all the effects (scattering, ionization, delta-rays, etc.) that Geant can provide.
  - Δlog(Likelihood) in Ljubljana code utilizes analytical expressions for the likelihood functions.
    - ➔Much faster! *(**<u>More by M. Staric later today!</u>**)*
    - ➔Working to integrate with full simulated data and improve performance.

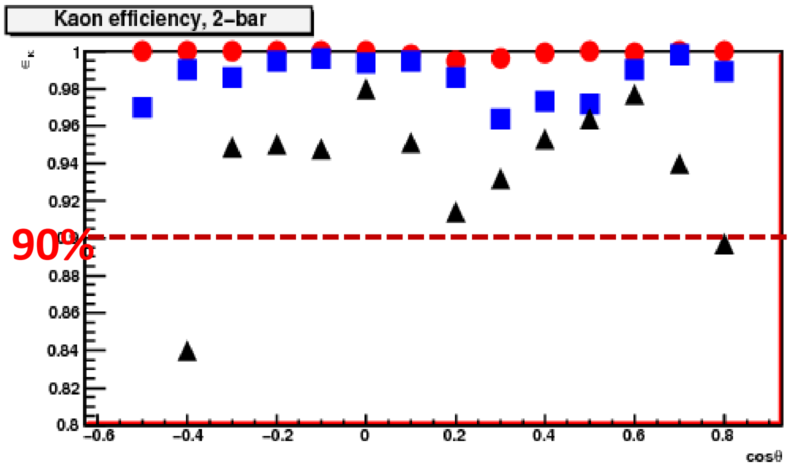


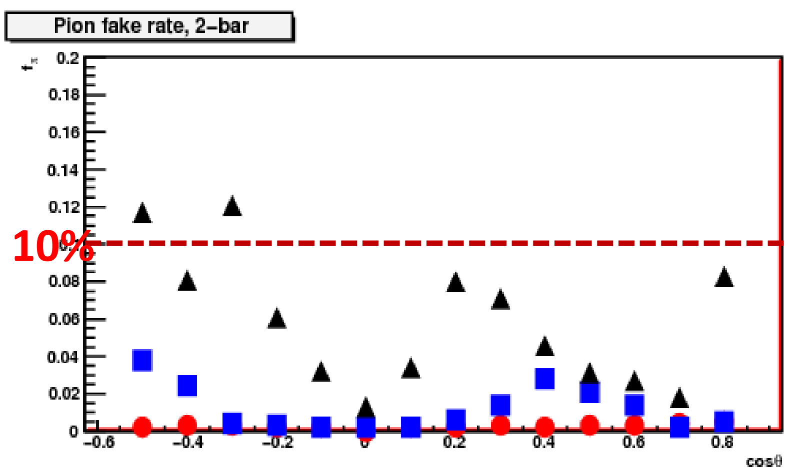


Simulated Performance (Multi Alkali)

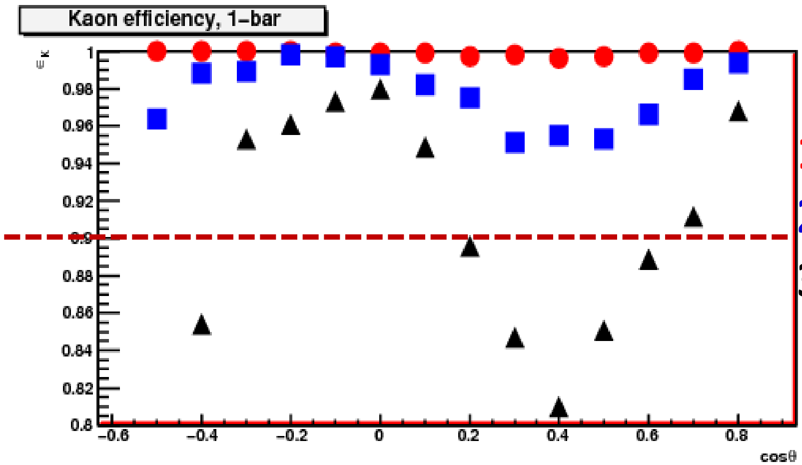
Belle II

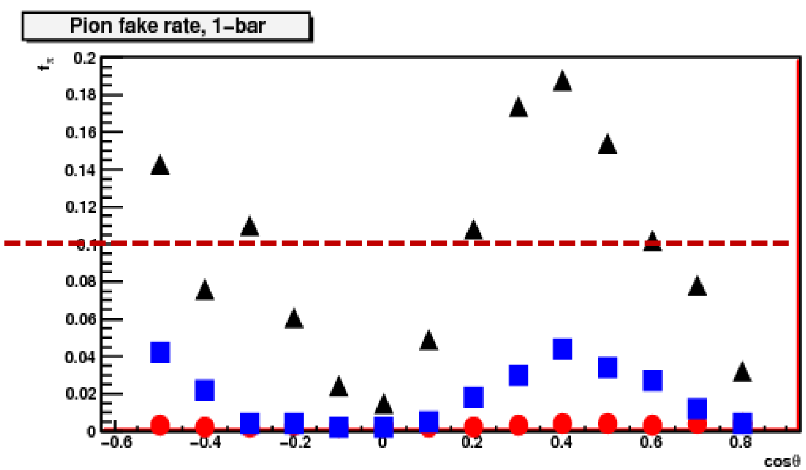
2 bar type





1 bar type





1.5 GeV/c
2.5 GeV/c
3.5 GeV/c

Sensitivity to Event Uncertainties

- Different geometries are sensitive to different event uncertainties.
- Examples:
  - Tracking uncertainty
    - One bar type is more affected by increases in angular uncertainties.
  - Event start time uncertainty
    - Two bar type is more affected by increases in start time uncertainty.
    - Example…

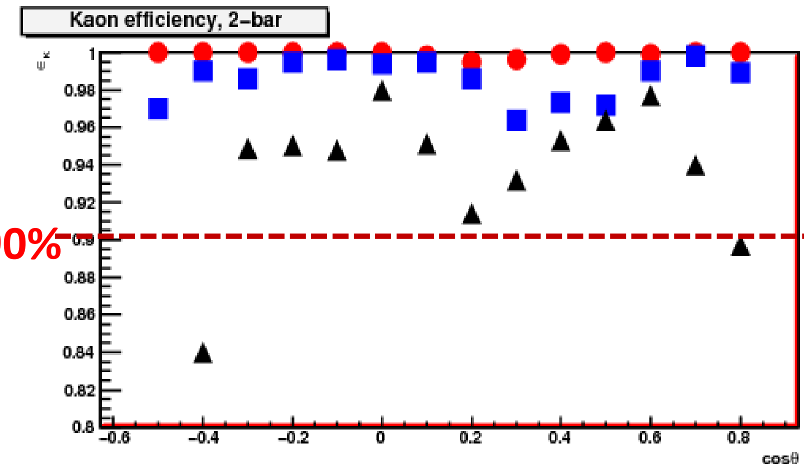
Sensitivity to σ_{T_0}

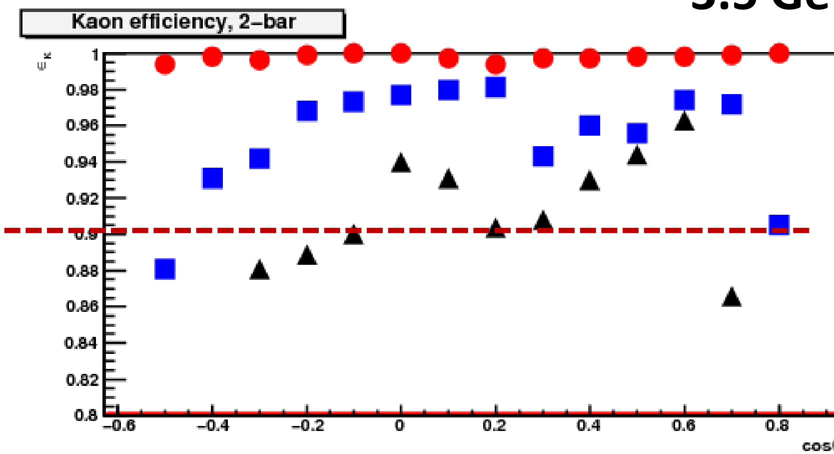
σ_{T_0} = 25 ps ➔ σ_{T_0} = 50 ps

1.5 GeV/c
2.5 GeV/c
3.5 GeV/c

2 bar option

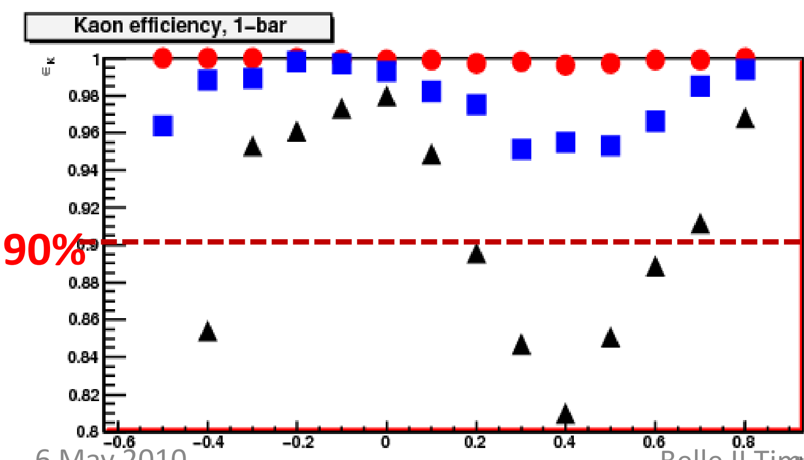
90%

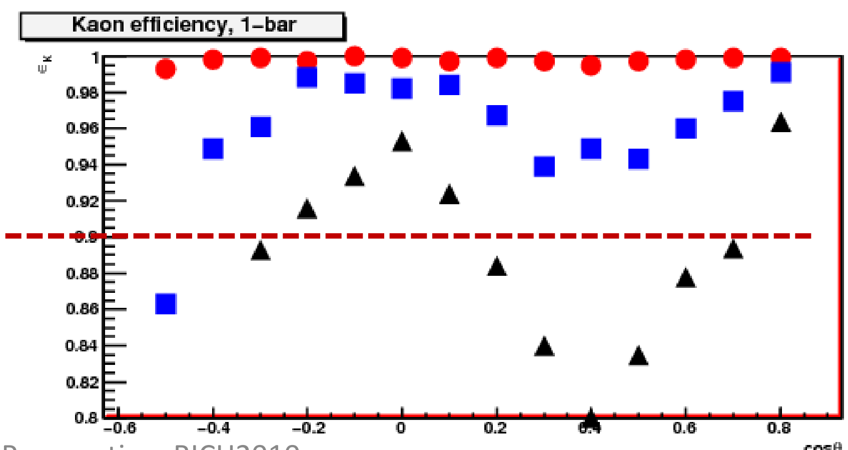




1 bar option

90%



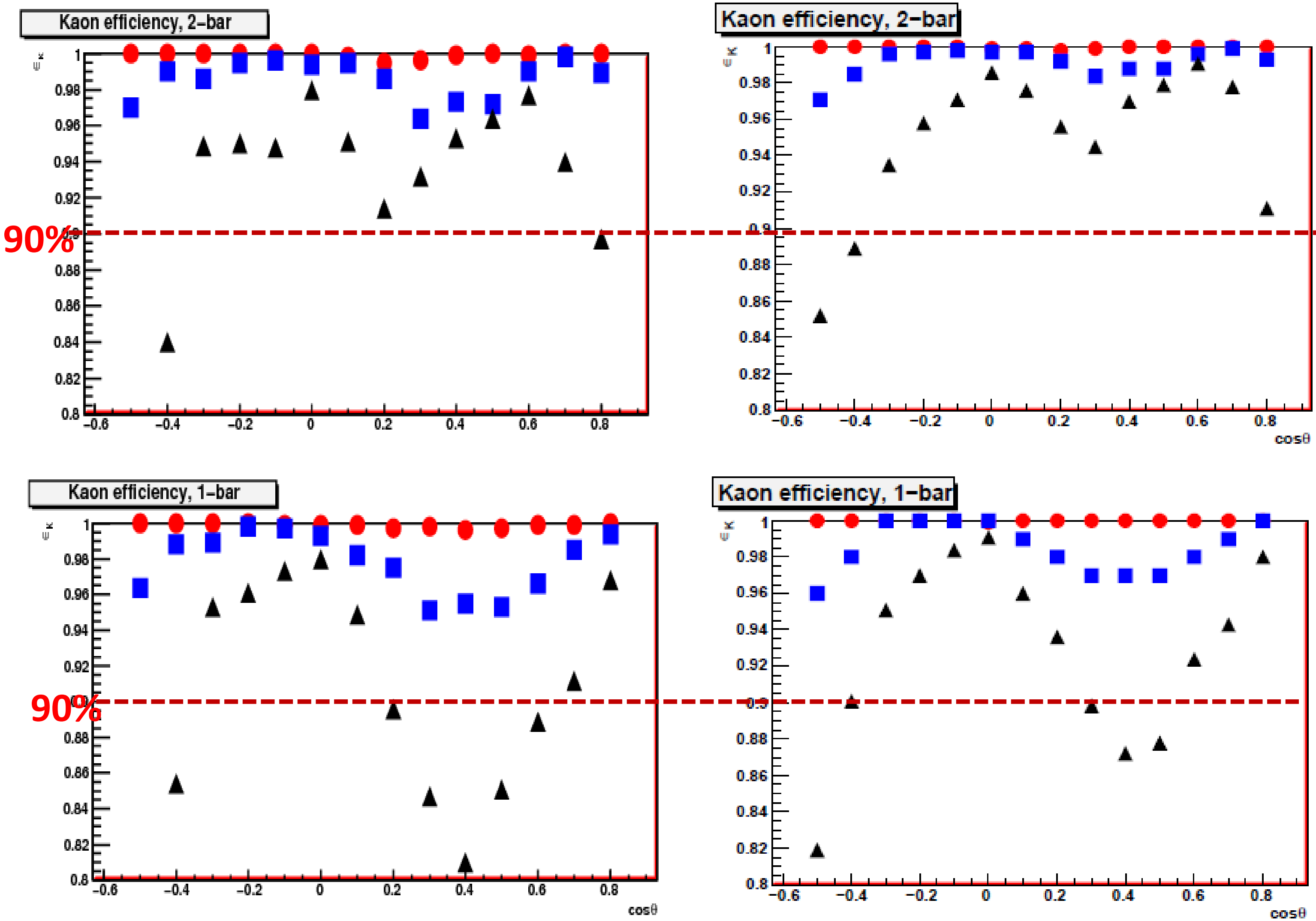


Simulated Performance (MA → SBA)

Multialkali → SuperBialkali

2 bar option

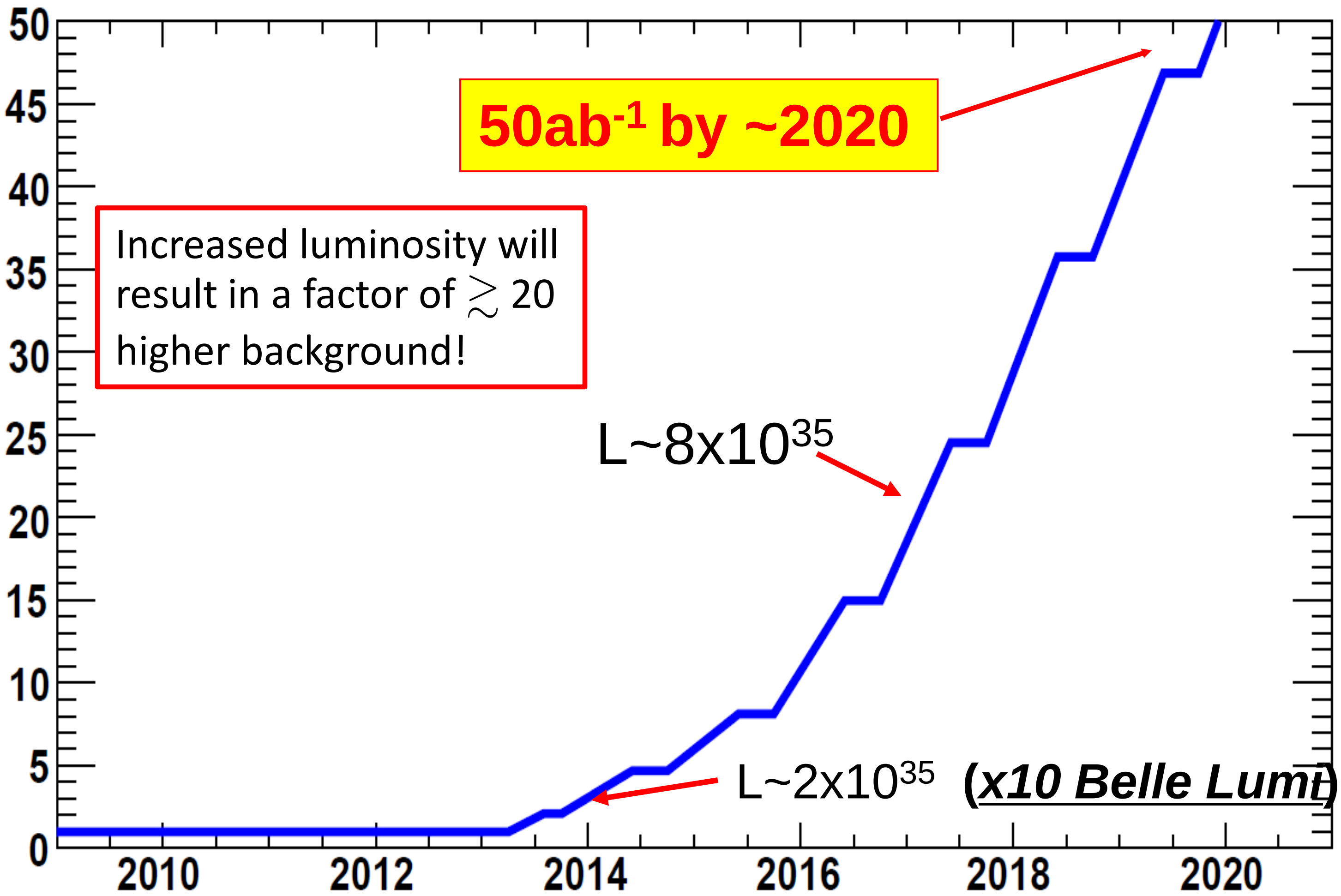
1 bar option



1.5 GeV/c
2.5 GeV/c
3.5 GeV/c

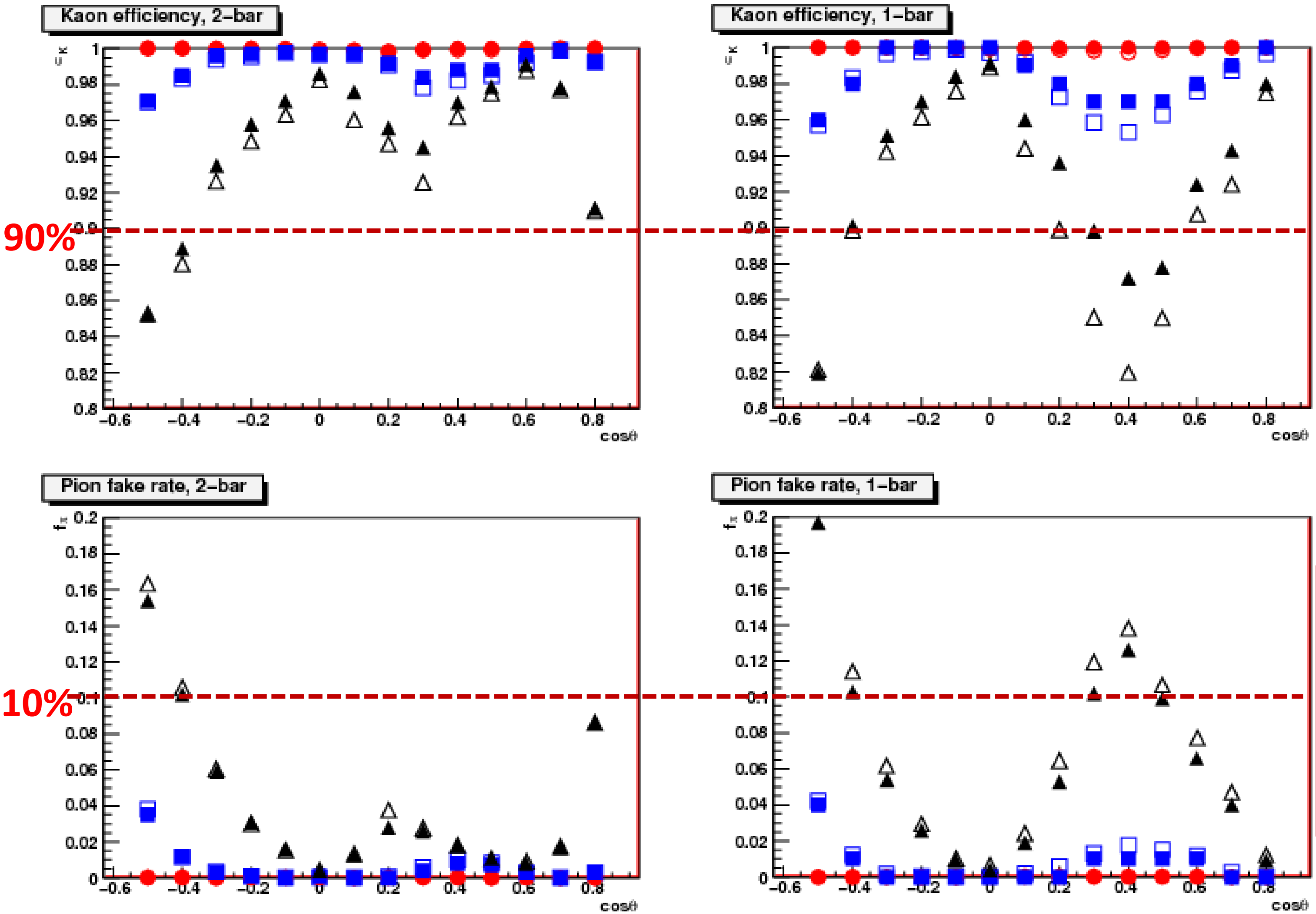
σ_{T_0} = 25 ps

Belle II Beam Background



3year shutdown for upgrade

Performance w/ Beam Backgrounds



1.5 GeV/c
2.5 GeV/c
3.5 GeV/c

σ_{To} **= 25 ps**

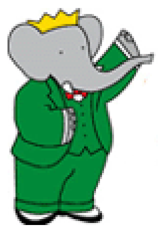
Filled: 1 γ bg
Hollow: 10 γ bg

➔ **Both geometries are relatively insensitive to background.**

Quartz Cherenkov Device Landscape

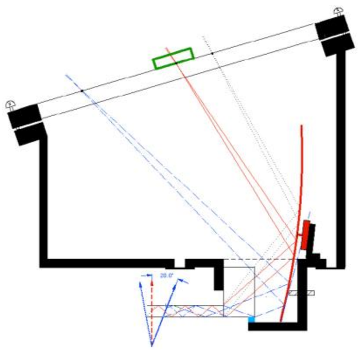
Performance

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 ~100 ps σ_t make chromatic corrections
(More tomorrow from Jerry V'avra)

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

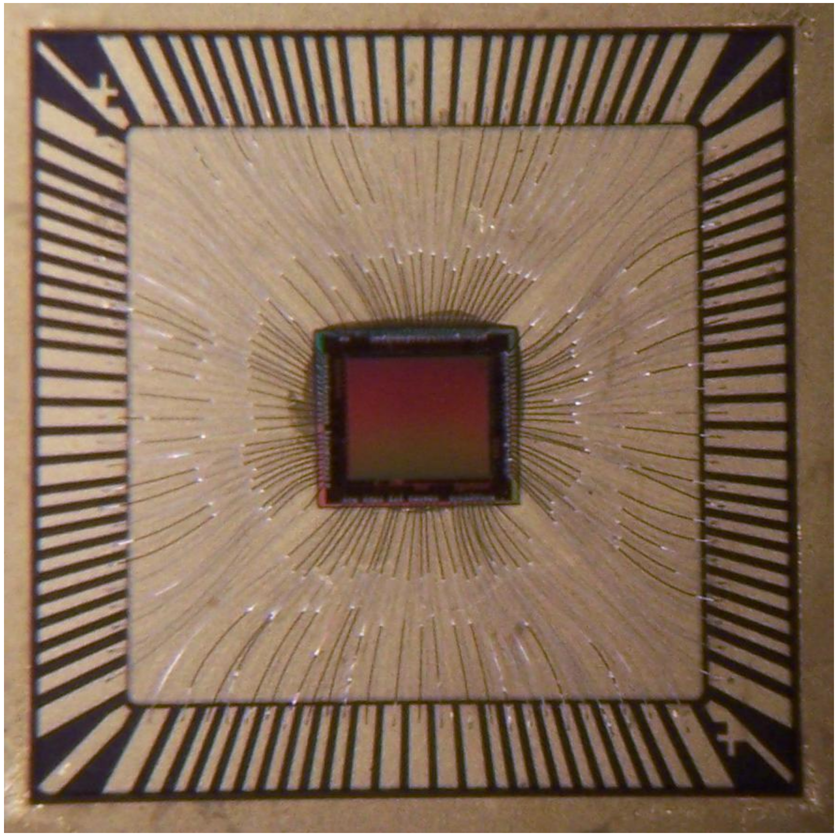
Mostly imaging ←

Mostly timing →

Compactness

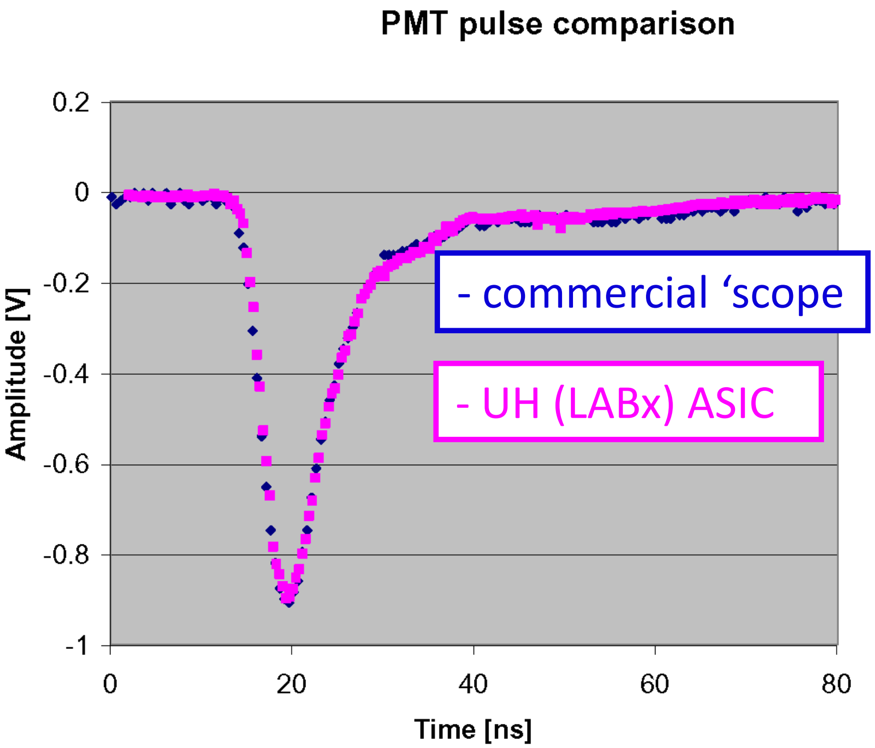
Waveform Sampling Electronics

Buffered Large Analog Bandwidth Recorder And Digitizer with Ordered Readout (LABRADOR)



BLAB1 Die floorplan: 128 x 512 samples
Single channel

3mm x 2.8mm, TSMC 0.25um

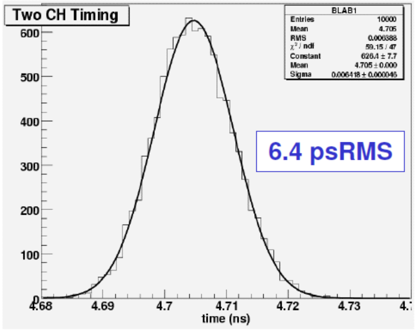


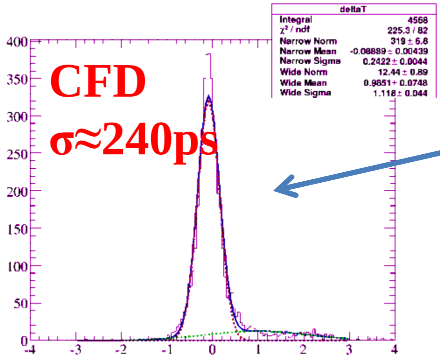
→Use large bandwidth capability developed at University of Hawaii for improved timing.

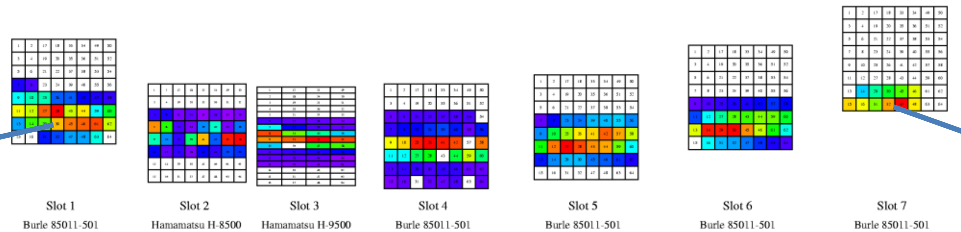
→Varner et al., NIM **A583**, 447 (2007)

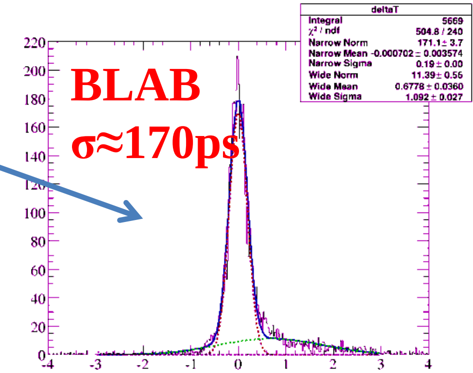
Electronics Performance

- First generation (BLAB1):
  - Single channel (no on-chip amplification)
  - Bench tested with pulser ➔ excellent $\sigma_{\Delta t}$:
  - 16 channels instrumented in fDIRC beam test:









➔**Improved timing** over high precision CFD, and **much lower power**.

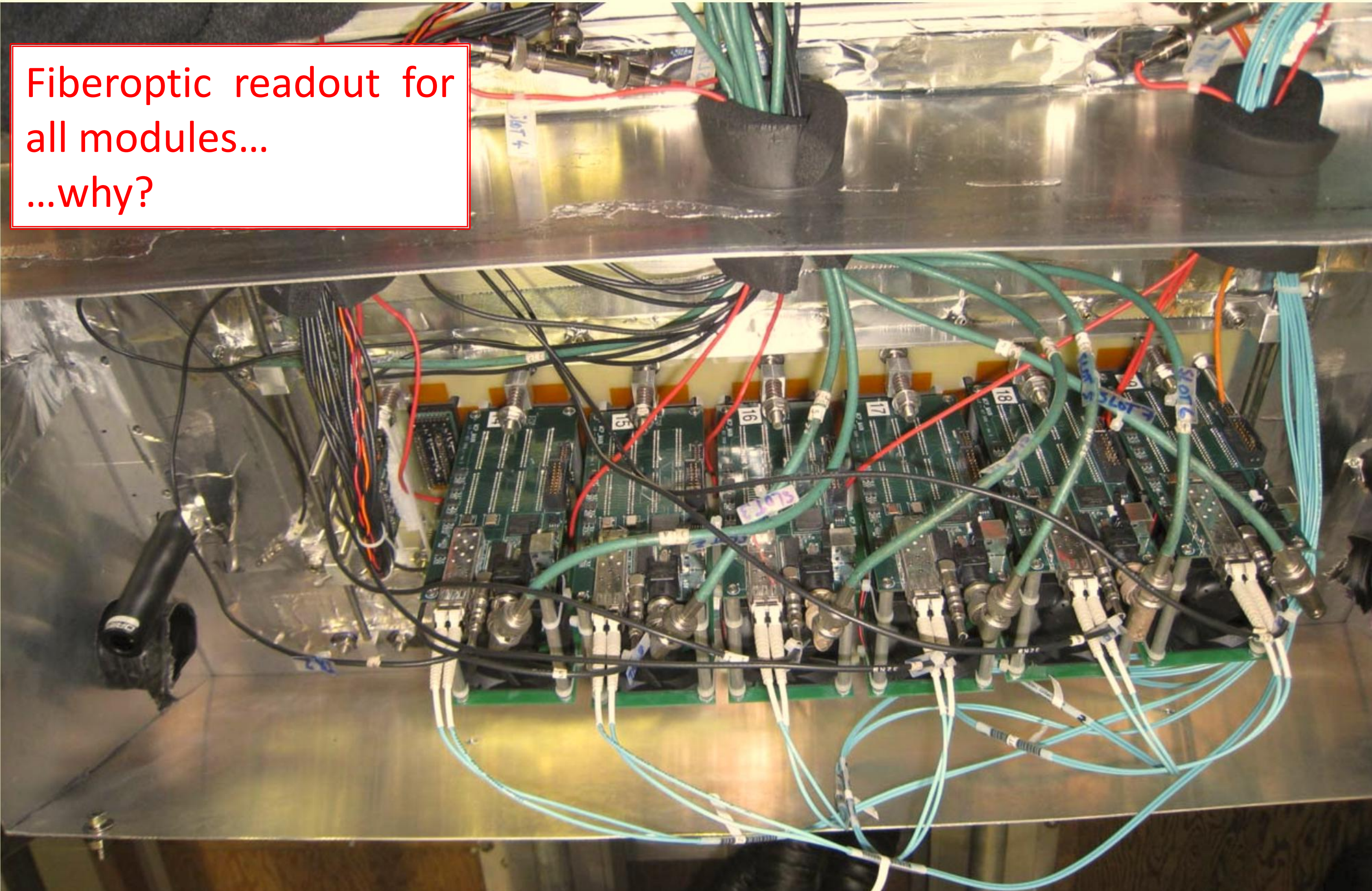
➔Timing limited by σ_t of MA-PMT.

- Second generation (BLAB2):
  - Compact ➔ ~450 chan. @ fDIRC cosmic test
- BLAB3 utilizes lessons learned… testing now.

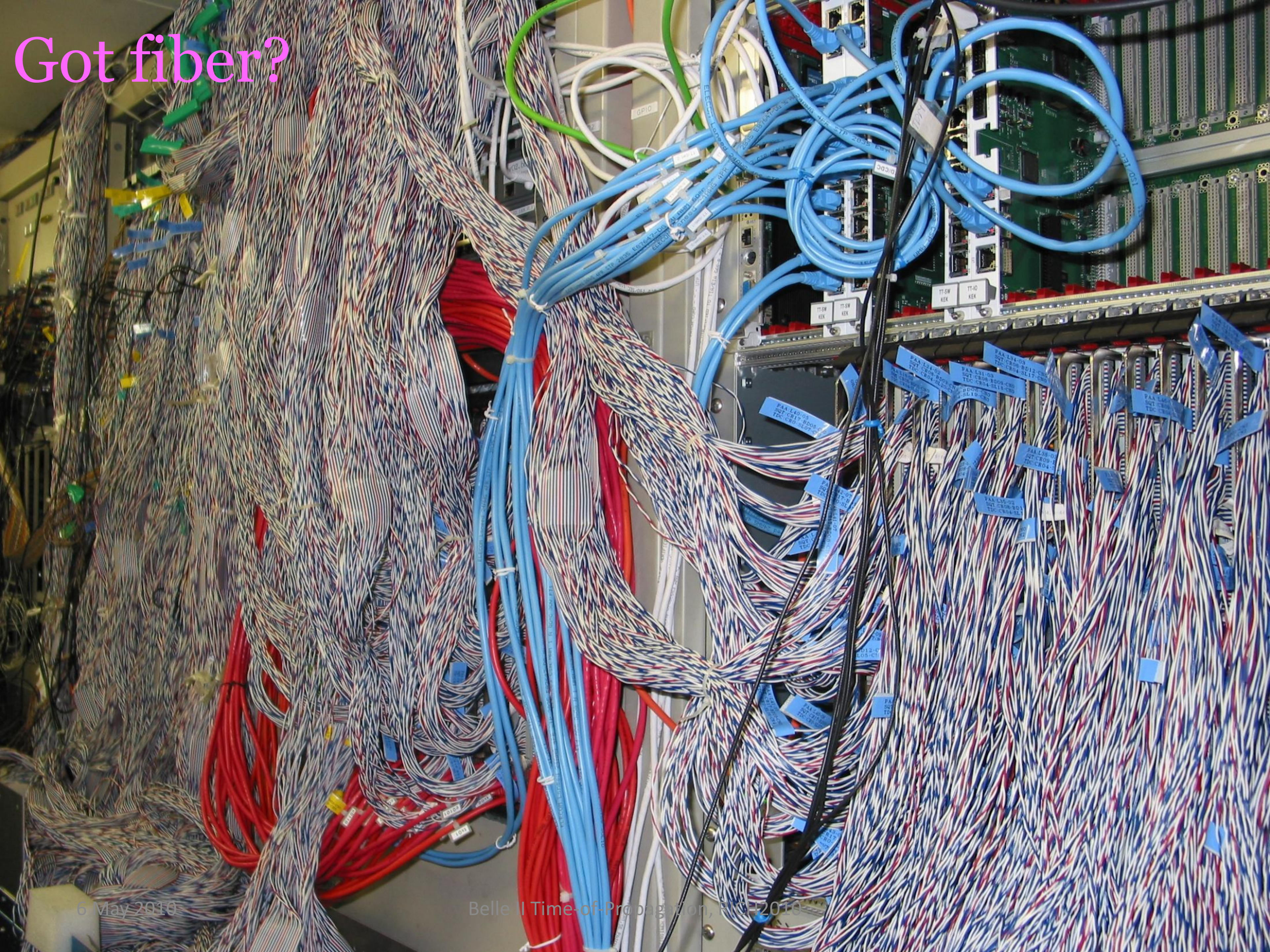
  ➔ We expect to be PMT limited for timing.

Integrated Readout (BLAB2 Example)

Fiberoptic readout for all modules…
…why?

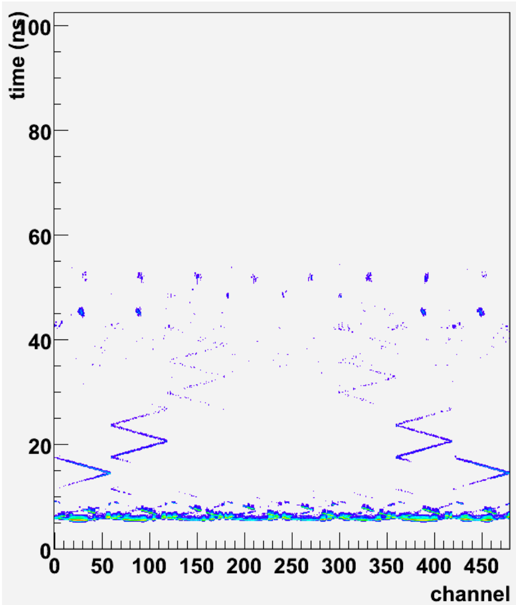


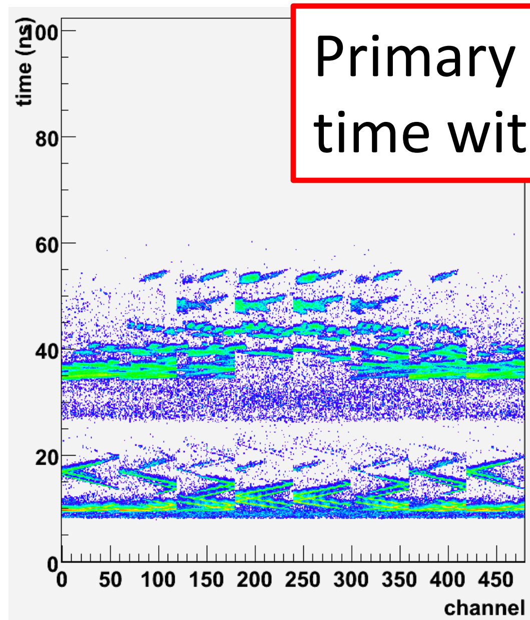
Got fiber?

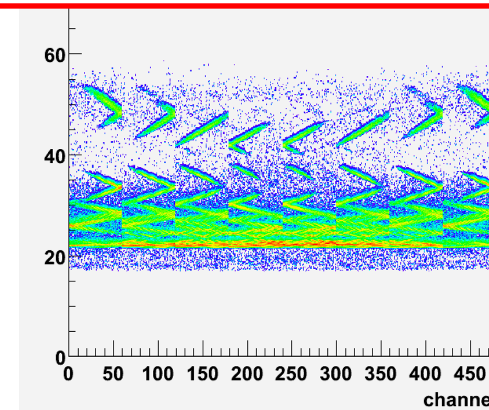


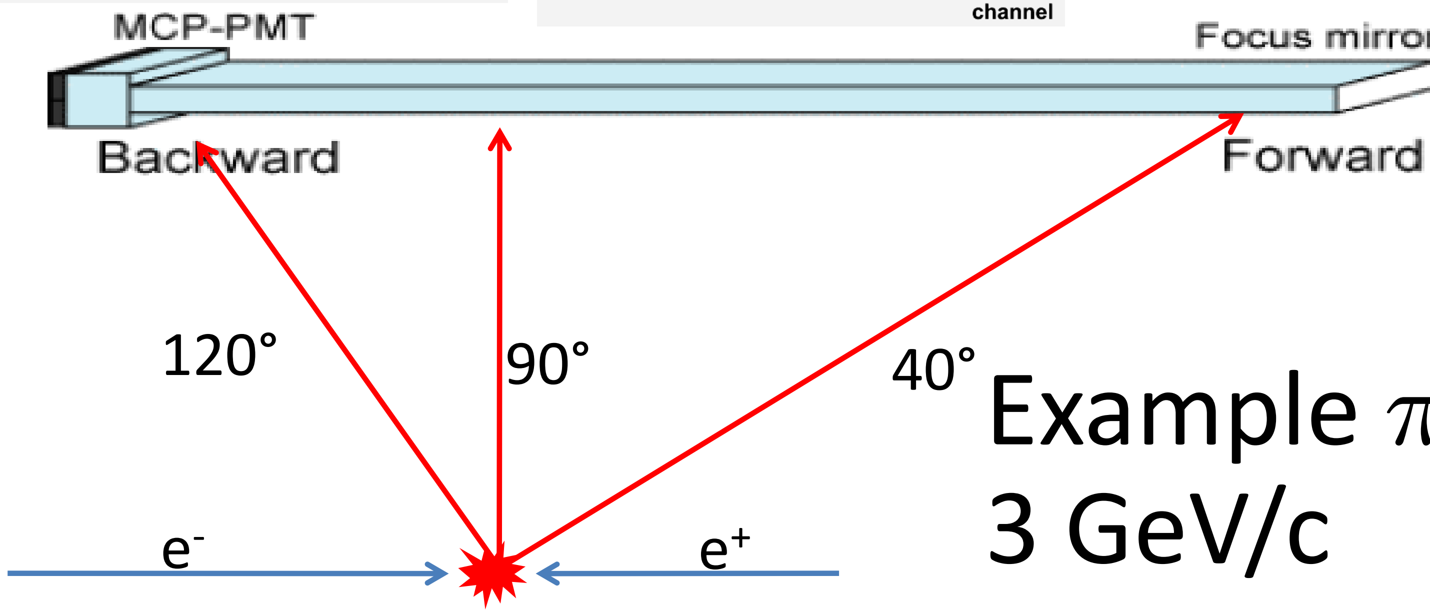
Trigger Issues

Primary goal → provide event time with resolution of 1-2 ns





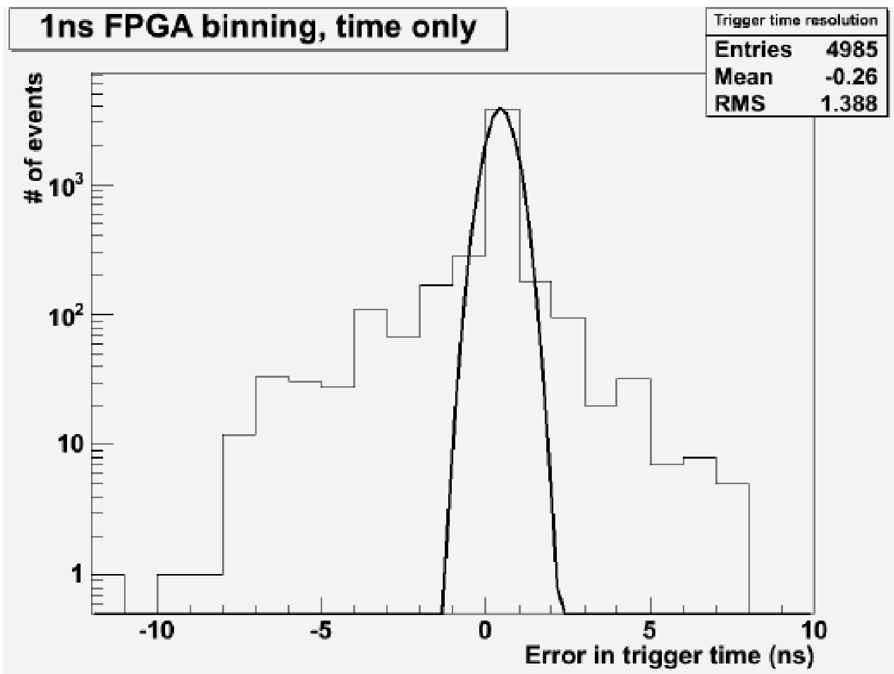


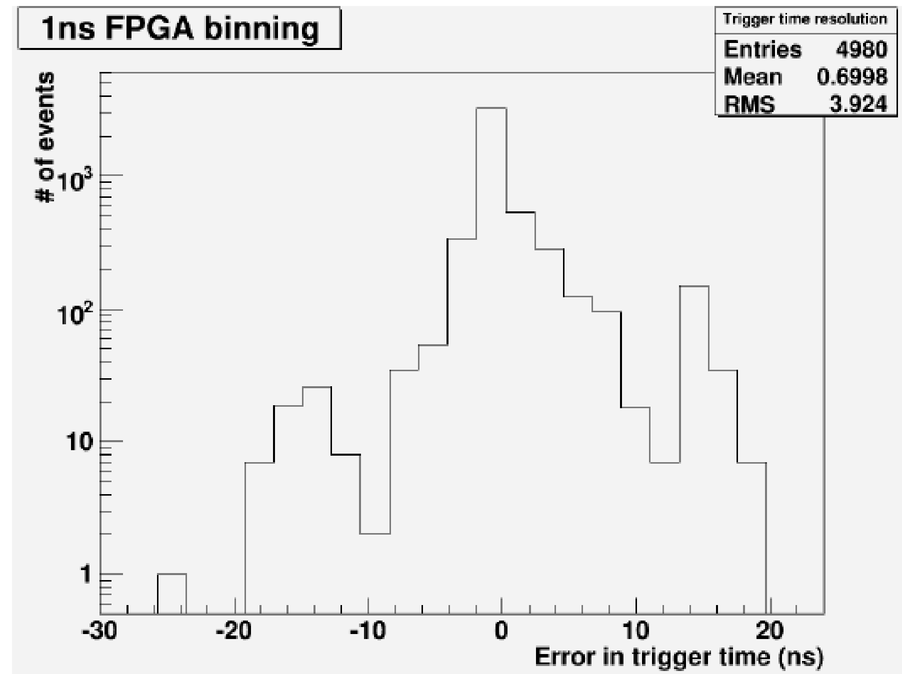


Example π PDFs
3 GeV/c

Trigger – Simulated Performance

Using photon time information only, no spatial information:





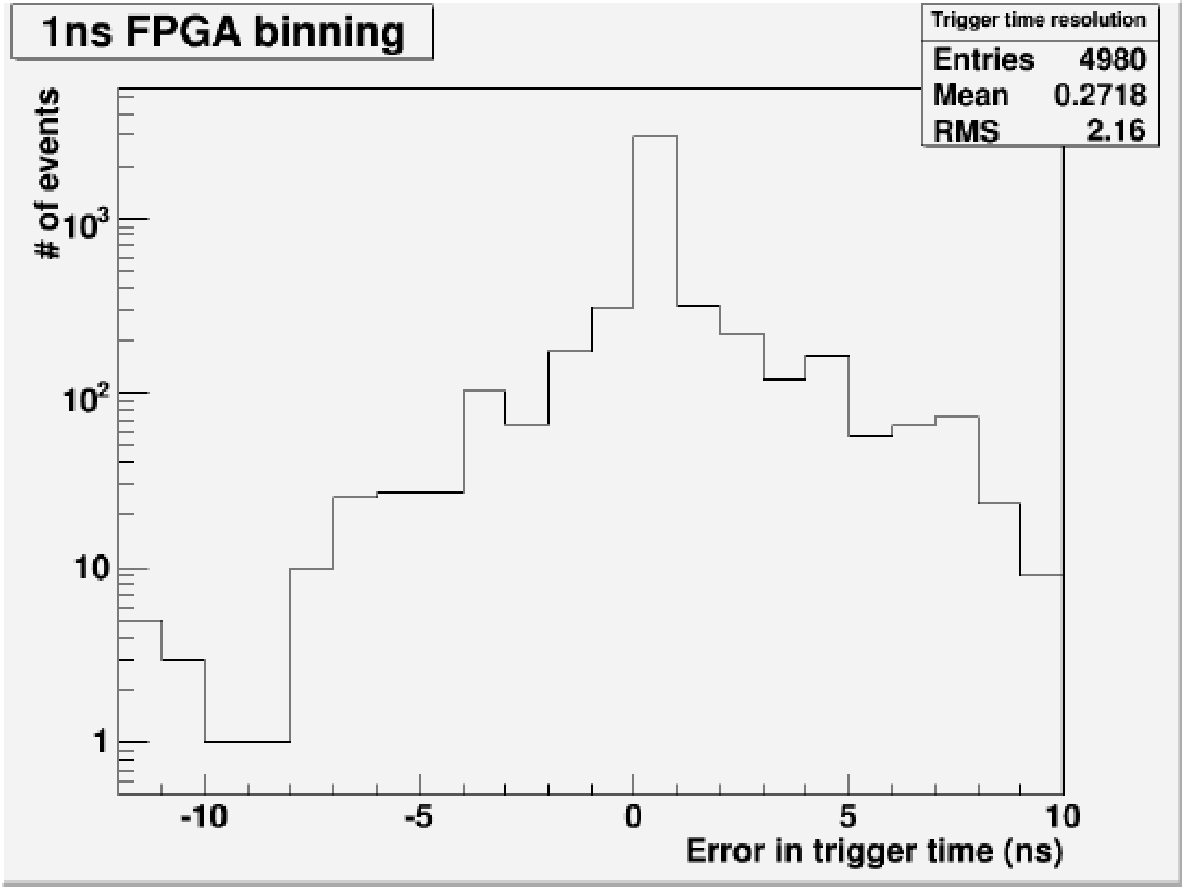
w/ 0 background photons… RMS ~1.4 ns

w/ 4 background photons… RMS ~3.9 ns

➔ Optimization is ongoing. Adding spatial information could help (but costs more FPGA resources). This may already be enough…

Trigger – Simulated Performance

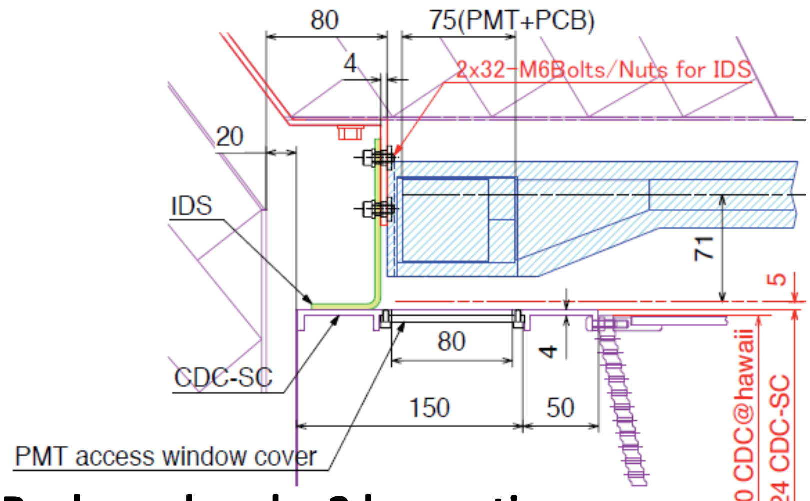
Using photon time information only, no spatial information:

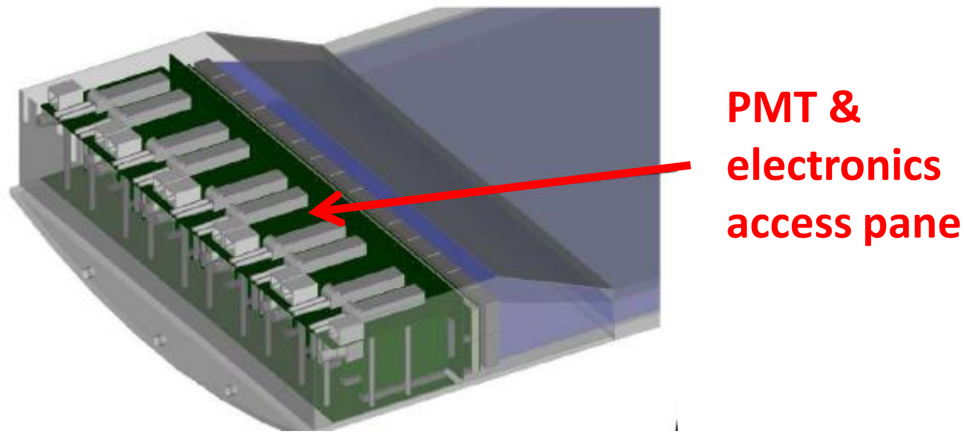


With 4 background photons & combining tracks... RMS ~2.2 ns

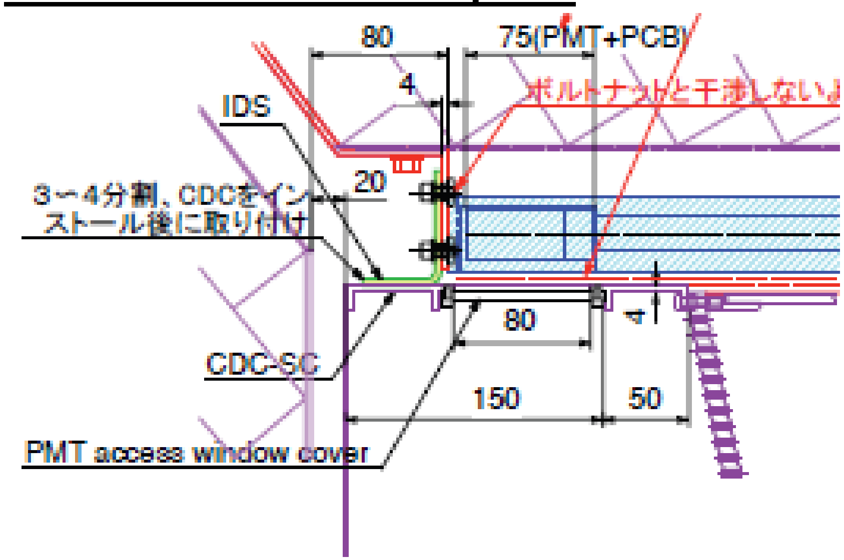
Structural Considerations

Backward end – 1 bar option





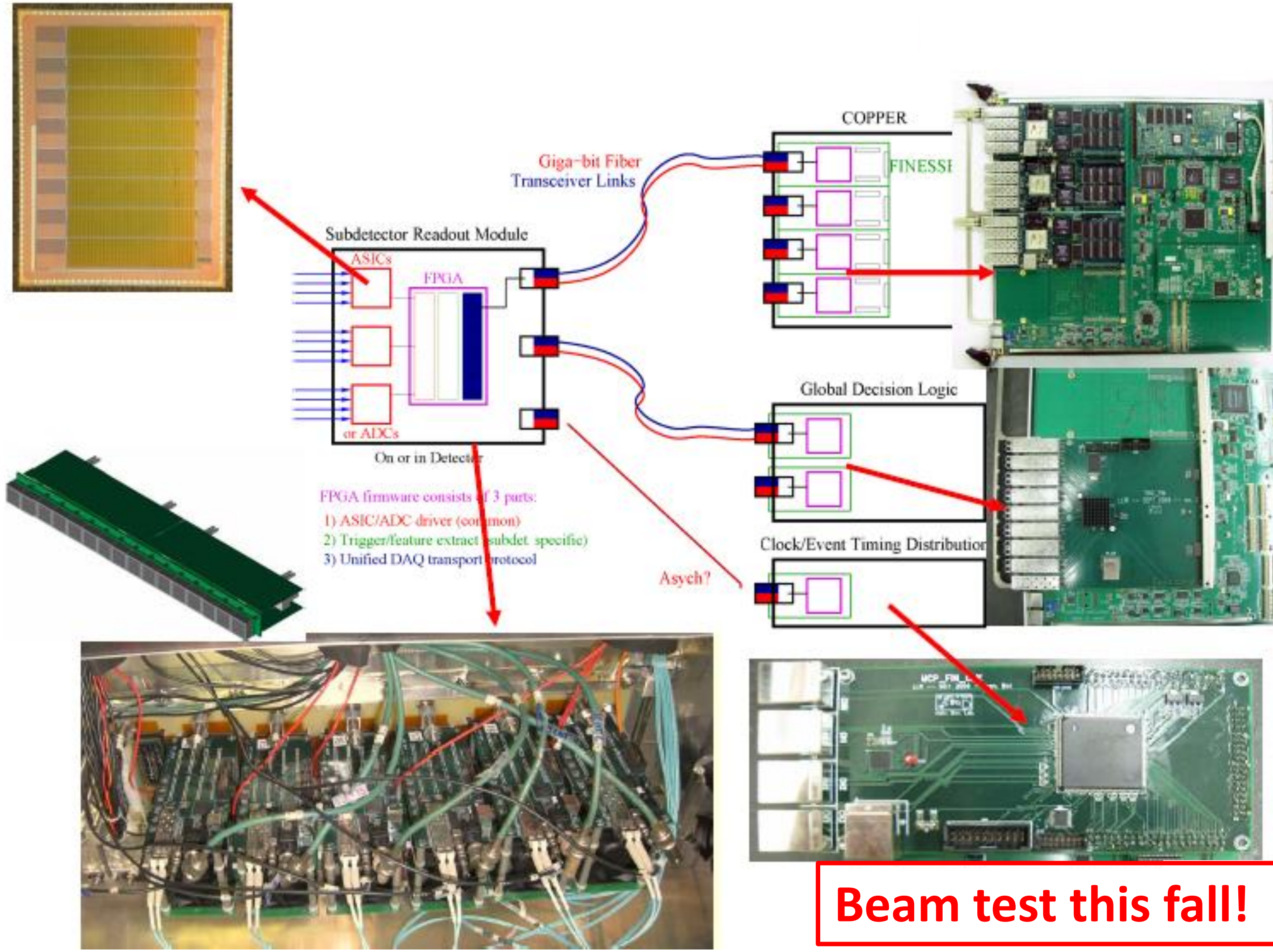
Backward end – 2 bar option



Important features:

- Both baseline designs are being studied structurally.
- Integrated with existing barrel ECL support structure.
- Provides support for the drift chamber.
- Panels to allow access to PMTs and electronics.

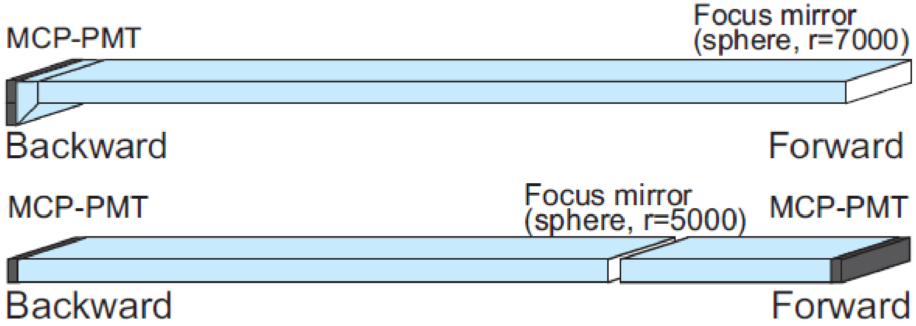
Toward Full Module Test



Beam test this fall!

Summary

- Belle II will utilize a time-of-propagation (TOP) counter for particle identification in the barrel region.
  - Compact device to accommodate strict space requirements.
  - Two baseline configurations (final decision expected soon):



  - Simulated performance indicates improved performance, robustness to backgrounds. Some tradeoffs relative to expected event uncertainties (event start time, tracking, etc.)
  - Beam test of full size bar with waveform-sampling readout electronics is planned for this fall.

BACKUP SLIDES

Electronics Specifications

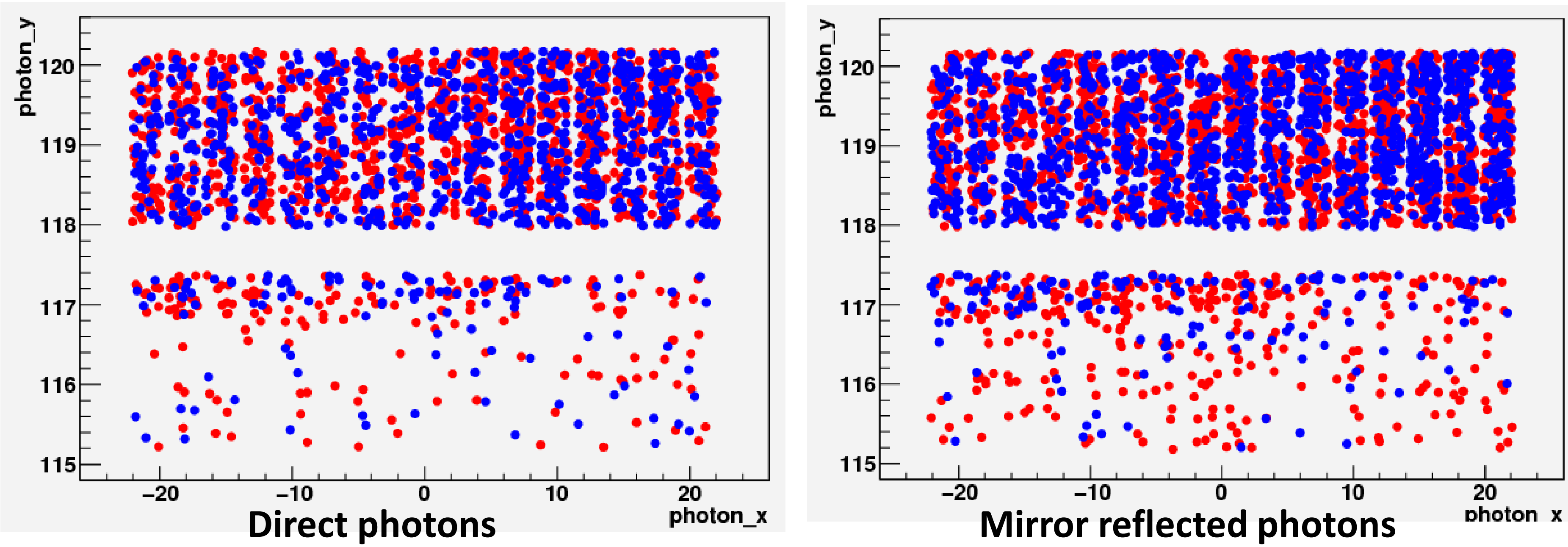
Parameter	Value	Comment
Total electronics channels	8k	either 1-bar or 2-bar
Number of BLAB3 ASICs	1k	8 channels/ASIC
Number of channels/SRM	64	8 BLAB3 ASICs
Number of SRM	128	Subdetector Readout Modules
Bi-directional fiber links/SRM	1+1	DAQ/Trigger (see relevant Chapters)
Total DAQ/Trigger links	128	10% bandwidth at full luminosity
Number FINESSE	64	2 fiber links (COPPER limited)
Number COPPER	16	COPPER bus limited
Average size/event	4	kByte (2.5% occupancy)

Parameter	Value	Comment
Channels/BLAB3	8	die size constraint
Sampling speed	4	Giga-samples/second (GSa/s)
Samples/channel	32768	allows $\geq$5 μs L1 trig latency
Amplifier gain	60	voltage (3$k\Omega$ TIA)
Trigger channels	8	for hit matching/zero suppression
Effective resolution	$\approx$9	bits (12/10 bit logging)
Sample convert window	64	samples ($\approx$16ns)
Readout granularity	1	sample, random access
Readout time	$1 + n * 0.02$	μs to read n samples (same window)
Sustained L1 rate	30	kHz (multi-buffer)

Imaging? TOP

- Are we really imaging?

Example 2.5 GeV/c K/π @ 90°, composites of 100 events.



- In actuality, we still rely mostly on timing, but expansion + larger image plane helps reduce ambiguities.