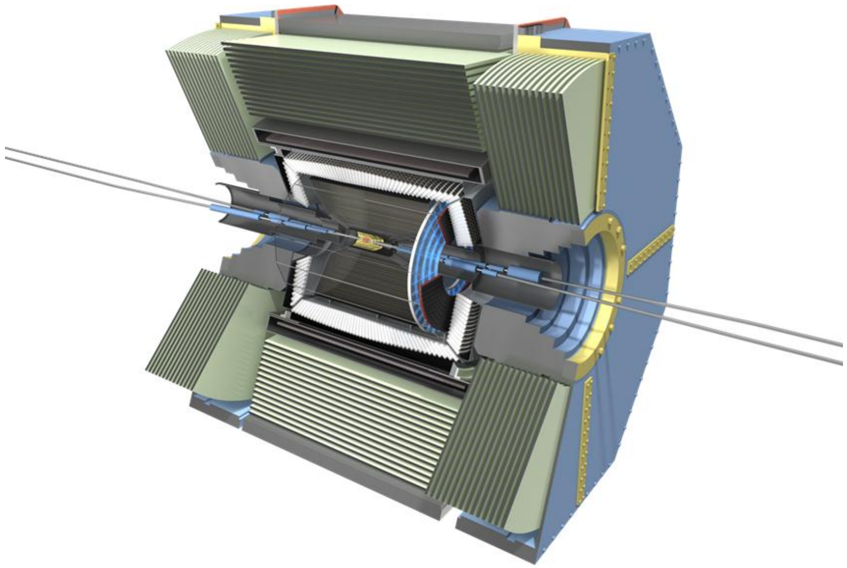
The time-of-propagation (TOP) counter for Belle II

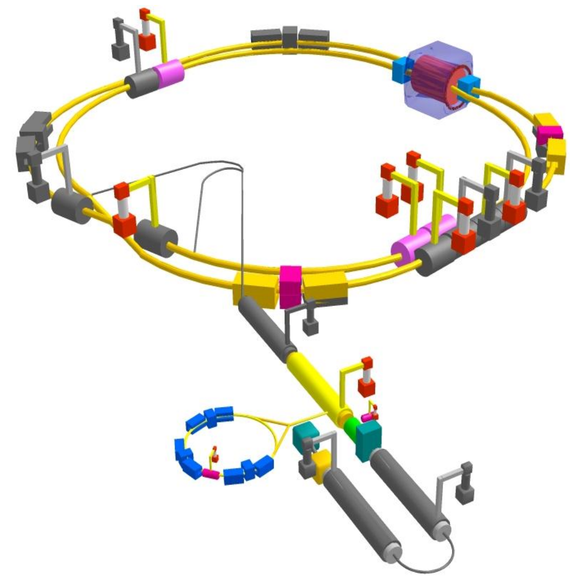
Kurtis Nishimura, University of Hawaii
on behalf of the Belle II PID Group

Technology and Instrumentation in Particle Physics, Chicago

June 11, 2011

Belle-II @ Super KEKB

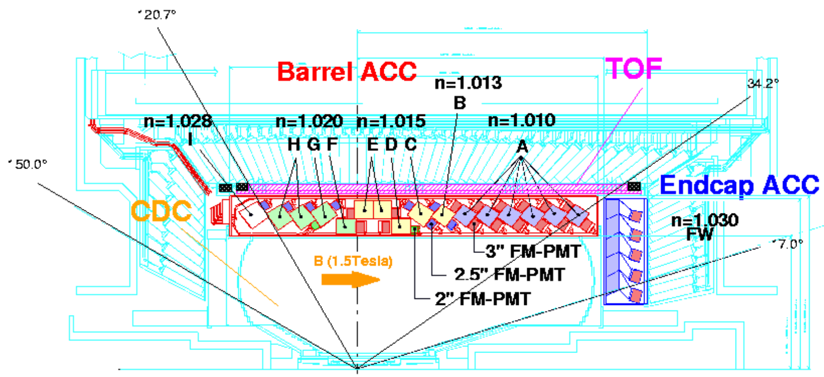


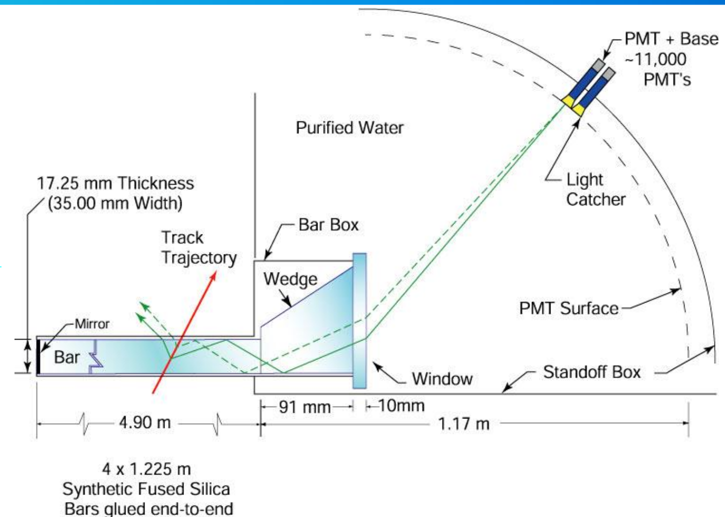


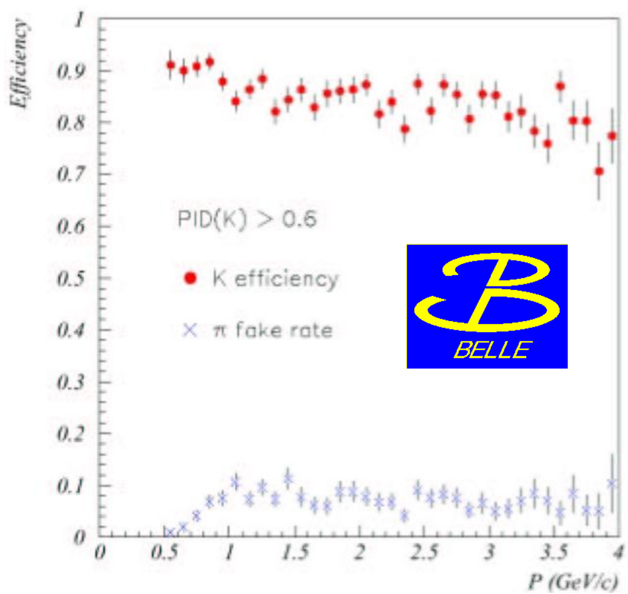
- Belle II at Super KEKB* will perform high precision tests of the Standard Model and searches for new physics:
  - Requires high efficiency, low fake rates in separation of $K^{\pm}/\pi^{\pm}$ for momenta up to ~4 GeV/c.
    - For example, to distinguish between
      - $\mathbf{B} \to \rho\,(\pi\pi)\,\gamma$ and $\mathbf{B} \to \mathbf{K}^*\,(\mathbf{K}\pi)\,\gamma$
      - $\mathbf{B} \to \pi\pi$ and $\mathbf{B} \to \mathbf{K}\pi$

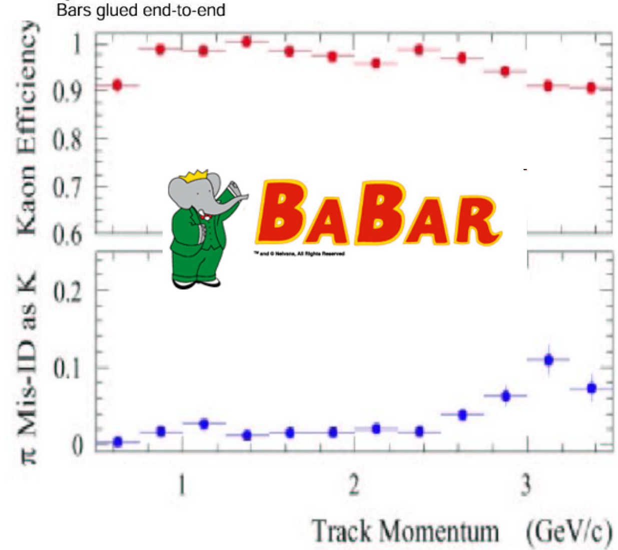
***See G. Varner's slides (Thurs.), "The Belle-II Detector" (Experimental Detector Systems)**

Particle ID at the B Factories









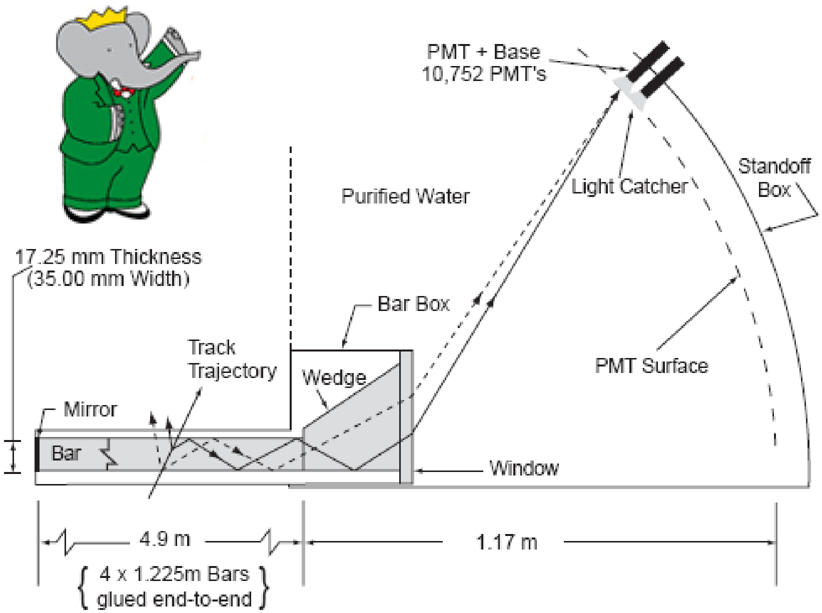
For Belle II barrel PID:

➔ Improve performance over existing threshold aerogel + time-of-flight…

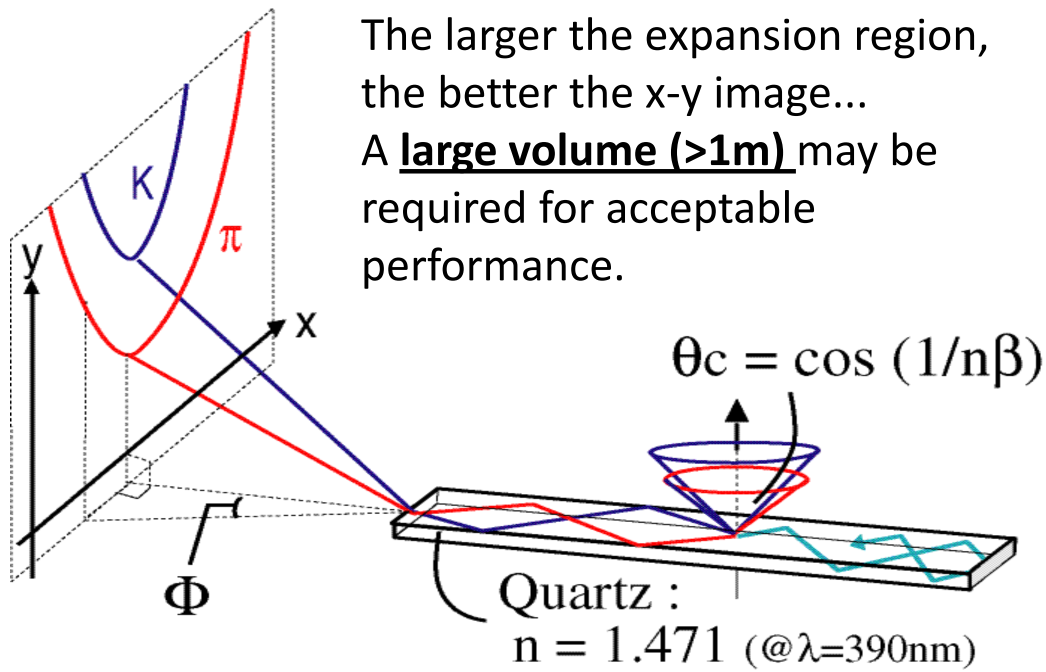
➔ …while accommodating space constraints of barrel region.

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 **<u>large volume (>1m)</u>** may be required for acceptable performance.



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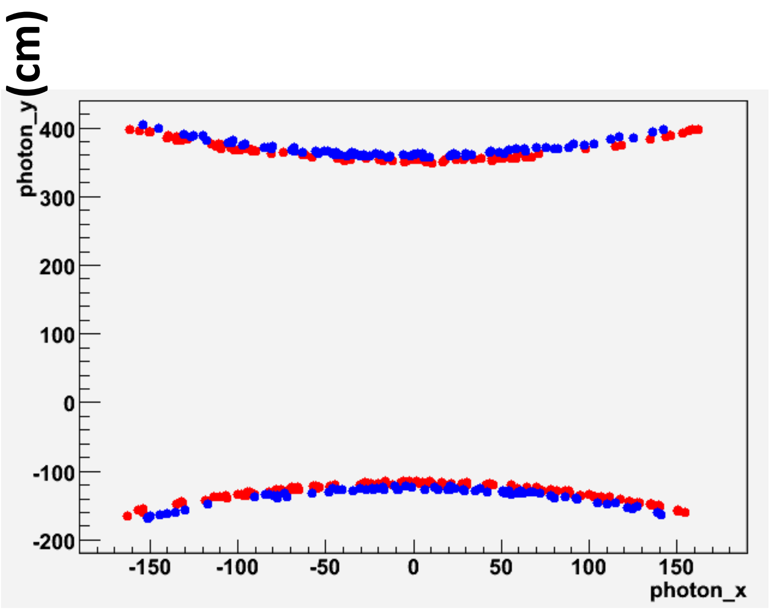

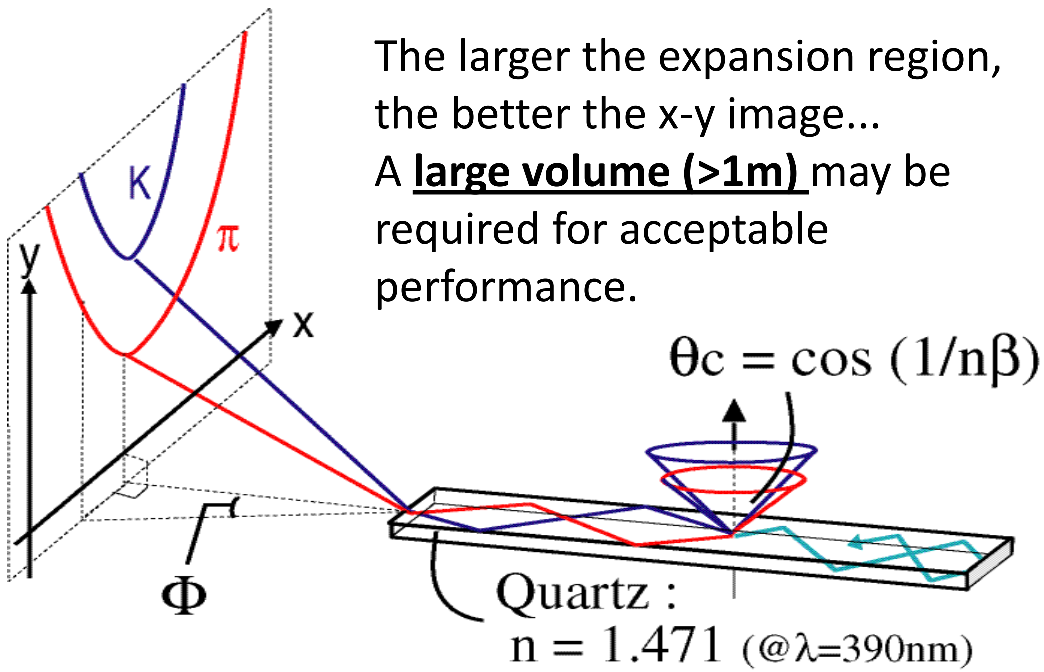

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Left: Simulations w/ large (2 m) expansion volume, 2 GeV K/π

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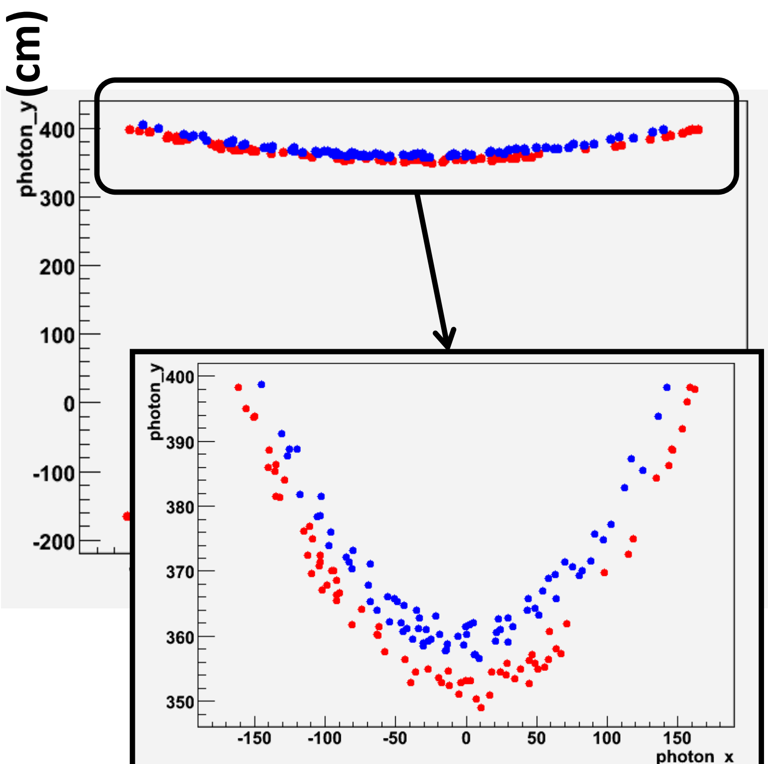

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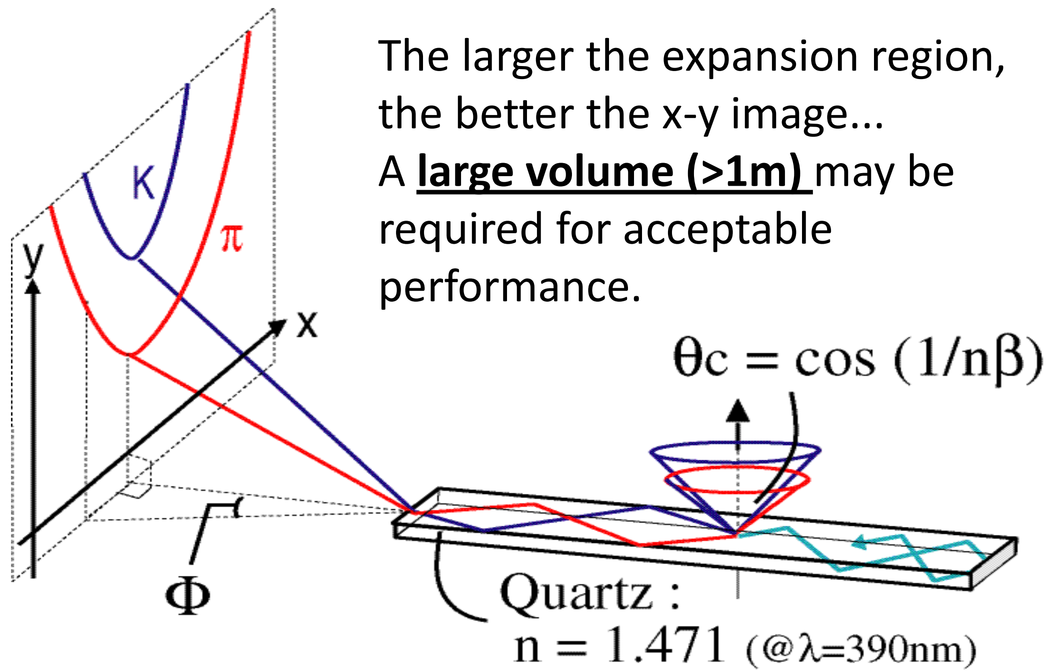

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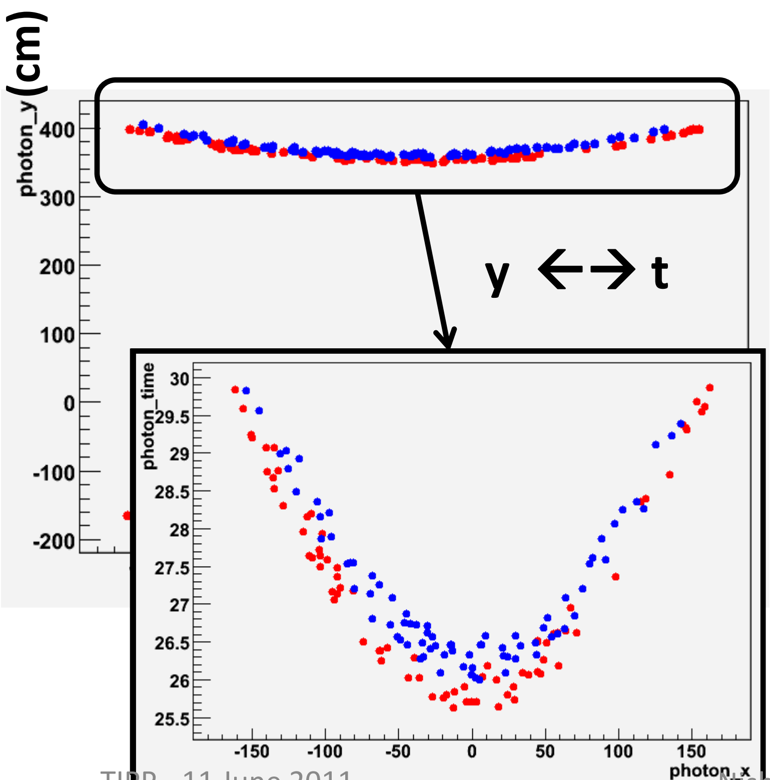

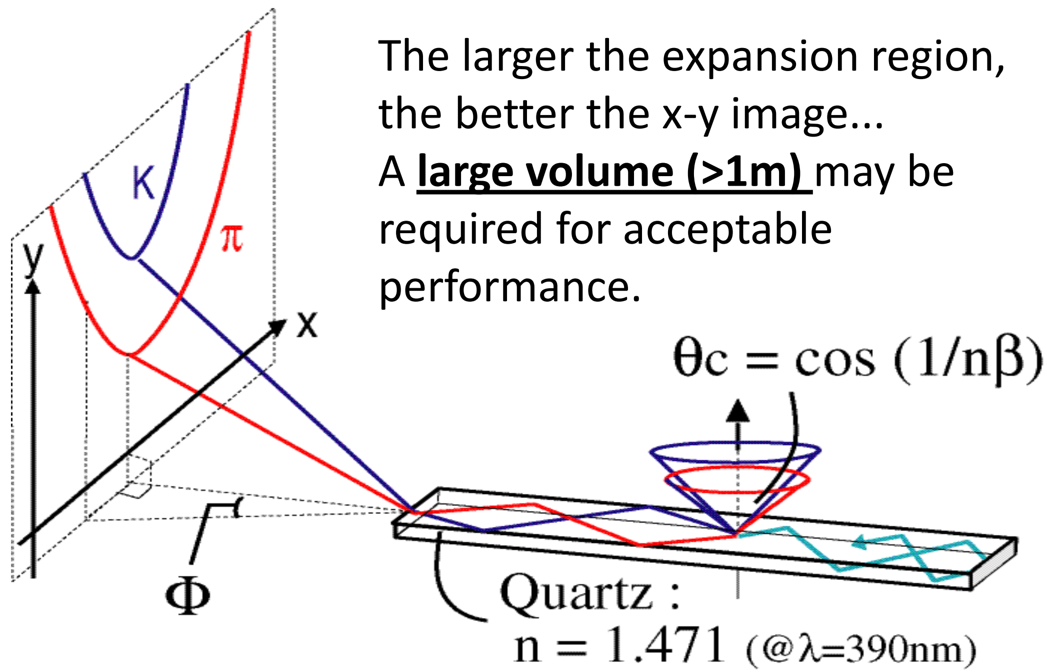

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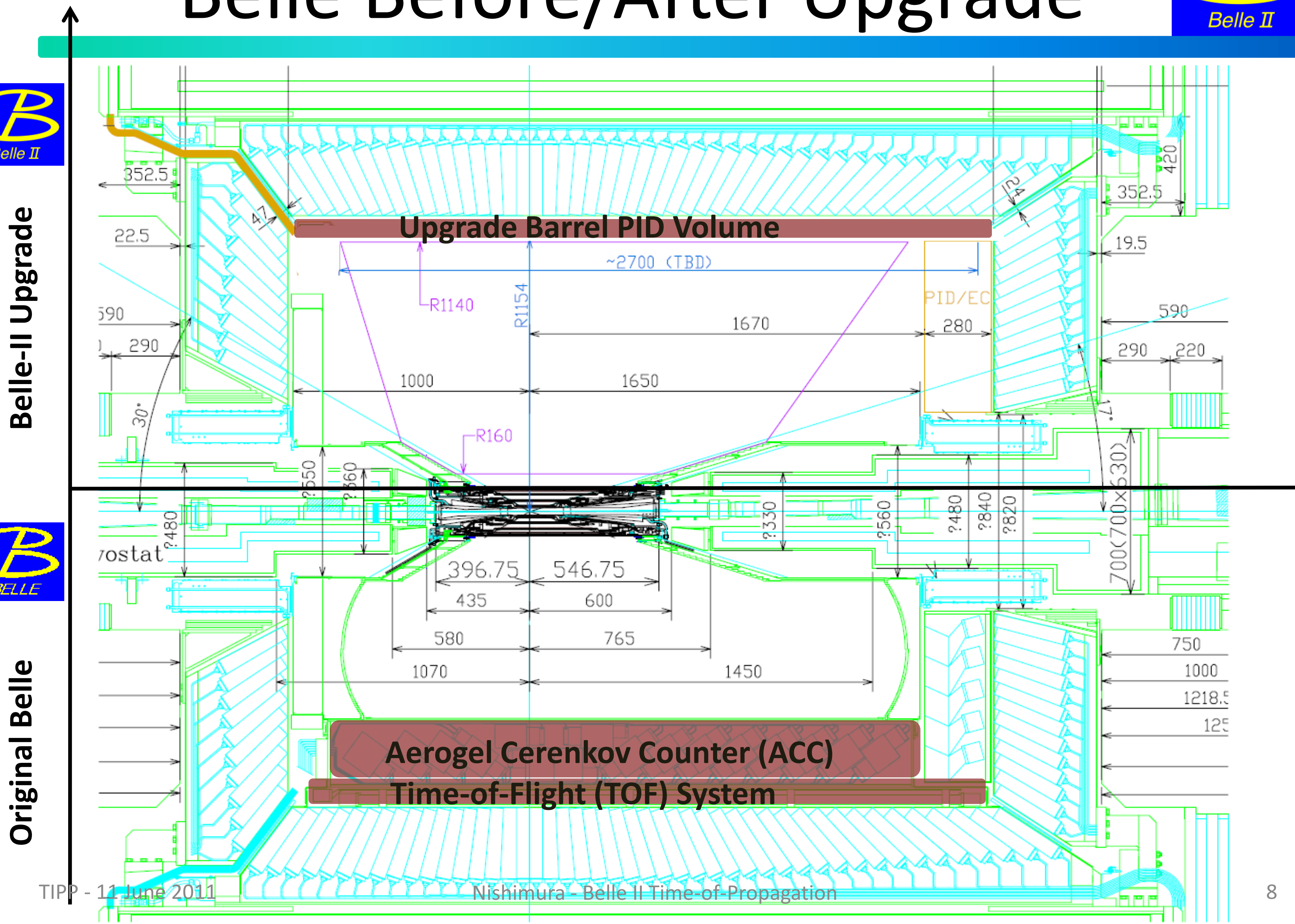
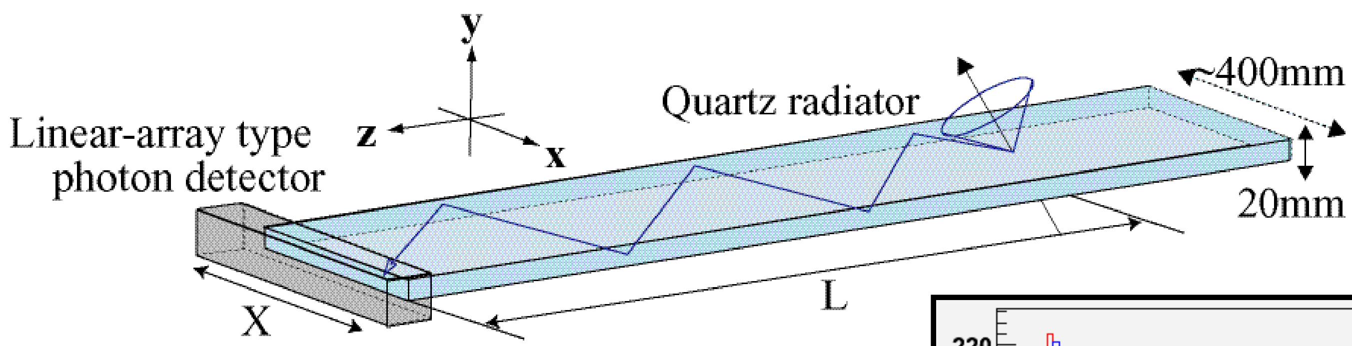
Belle Before/After Upgrade

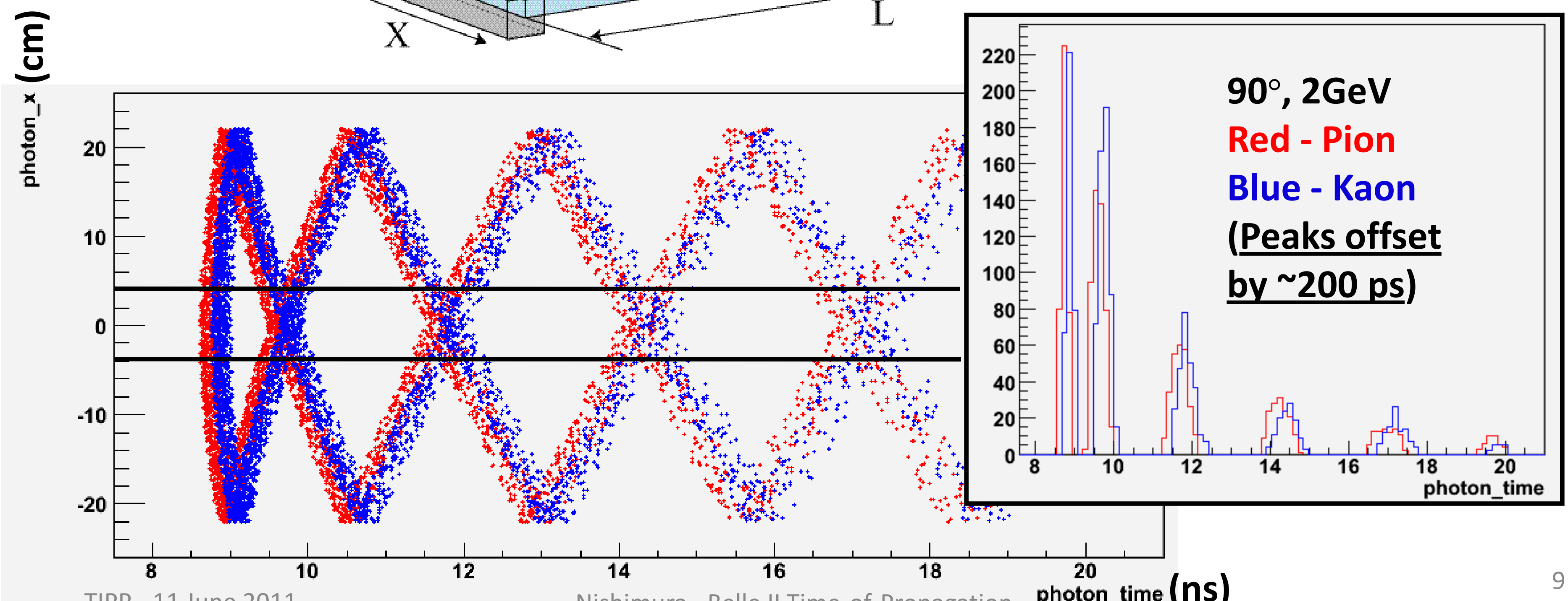


Time-of-Propagation (TOP) Counter

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

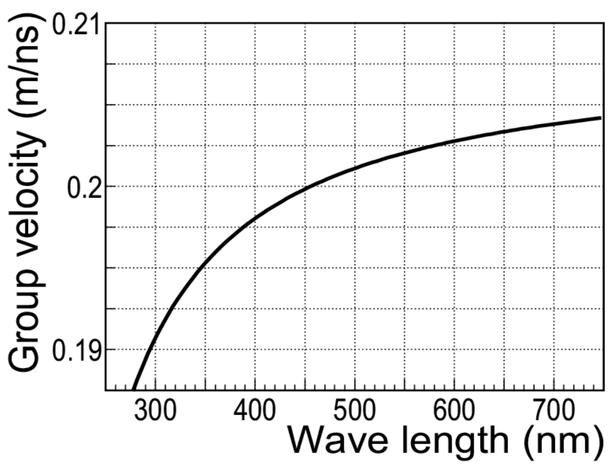
- Work at bar end, measure x,t, not y ➔ compact!





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.

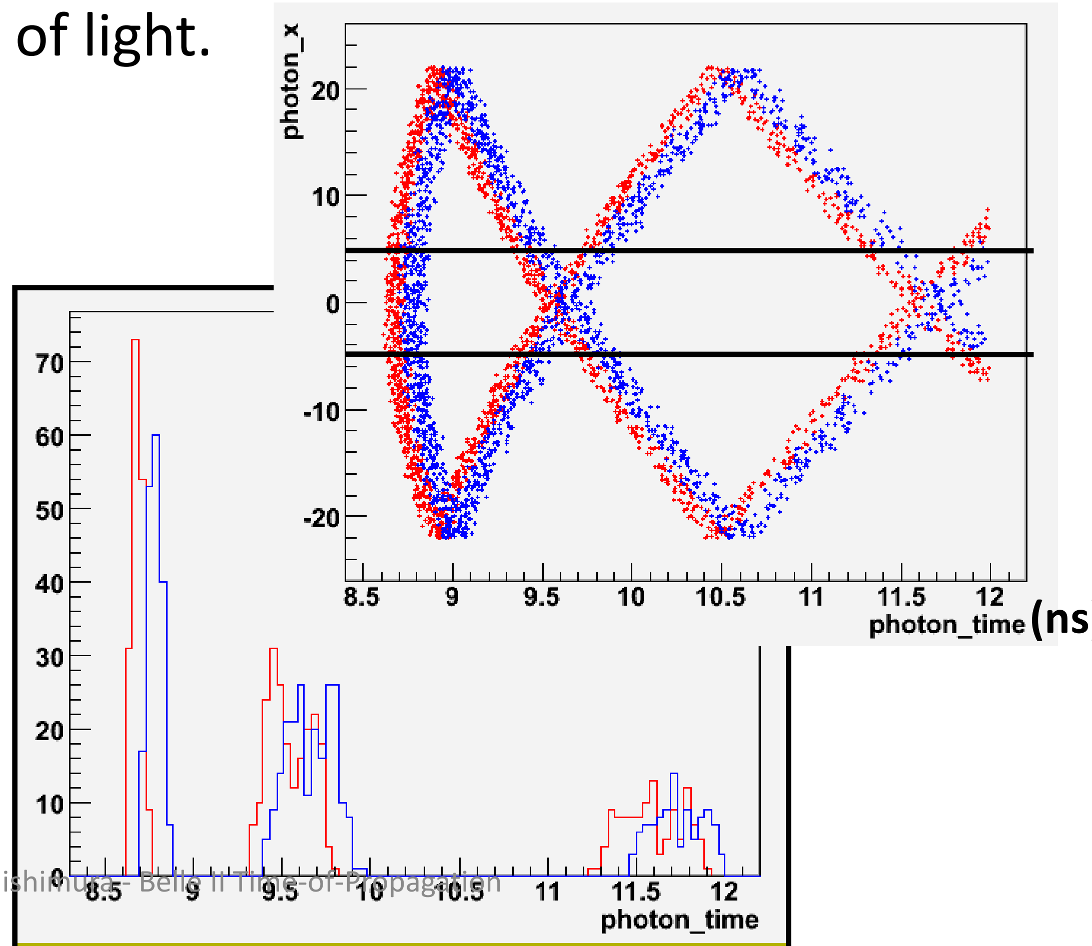


Simulated TOP – 2 GeV π^+ at 90°

Red – $\lambda \approx$ 525 nm

Blue – $\lambda \approx$ 375 nm

Red and blue offset by ~100 ps



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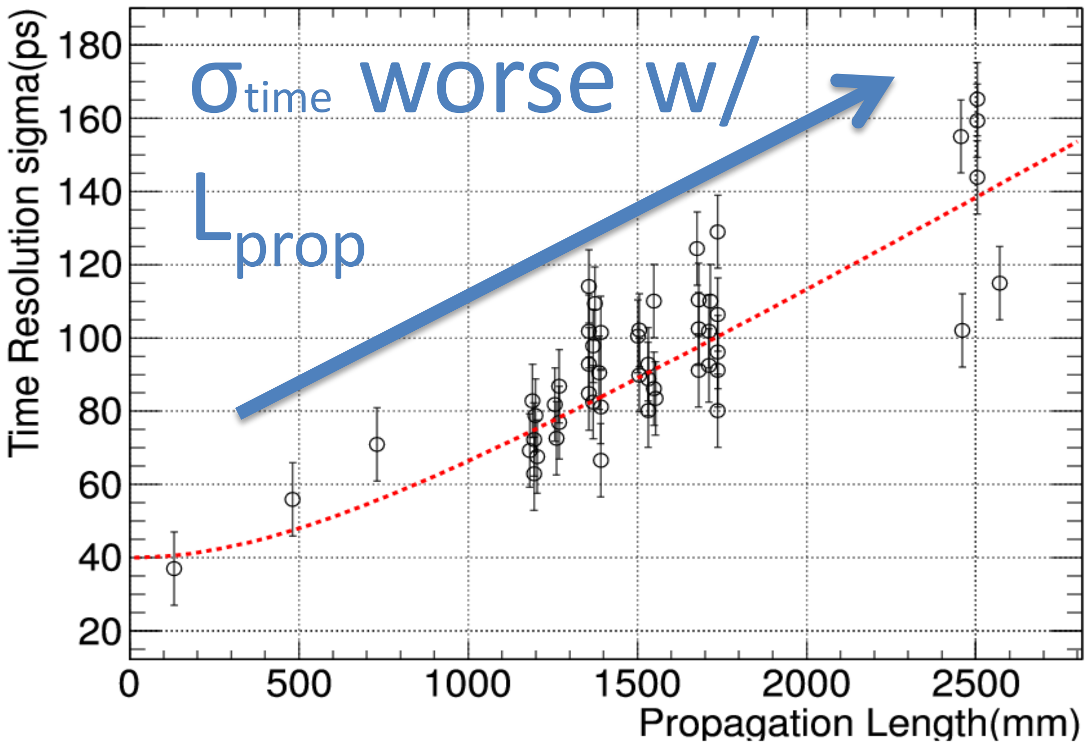
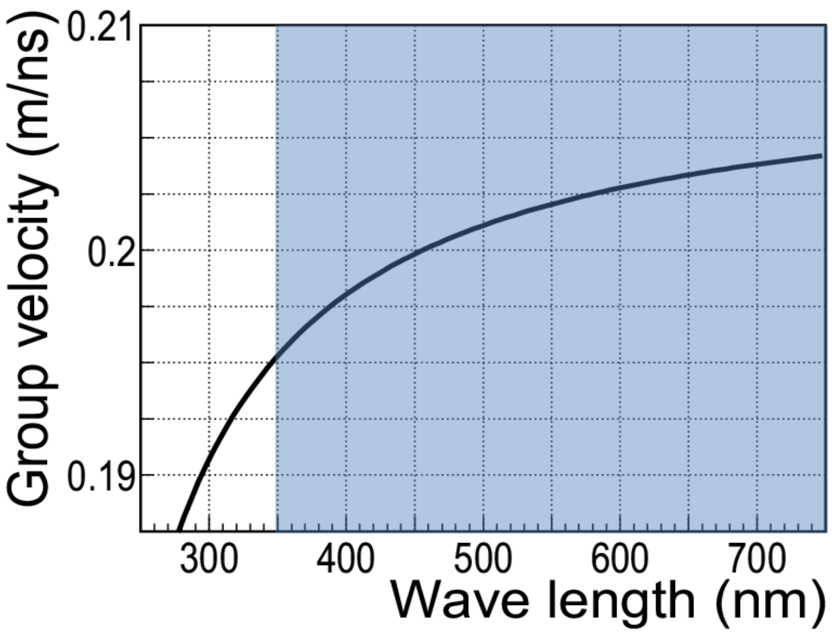
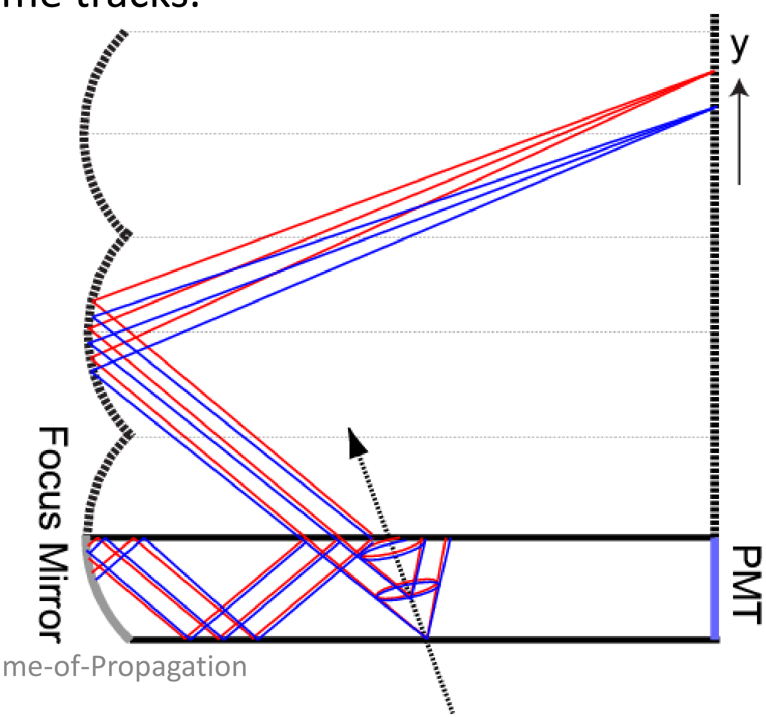


Focusing TOP (fTOP)

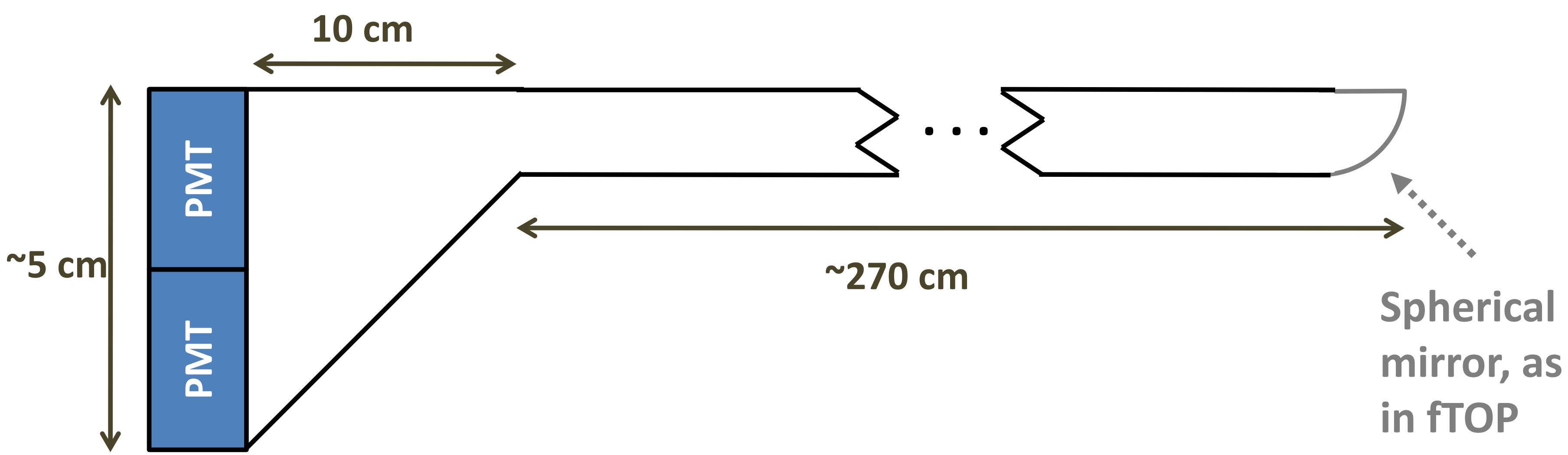
- Add focusing mirror and vertical pixelization.
  - Spreads wavelengths over more pixels.
- Chromatic dispersion:
  - Add a wavelength filter ➔ use part of spectrum where dispersion is not as severe, at cost of some photons. (Valid for any TOP concept, not just fTOP)
- Finite bar thickness:
  - Focusing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

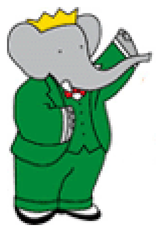


  - Asymmetric expansion was chosen to accommodate physical constraints.

Quartz Cherenkov Devices*

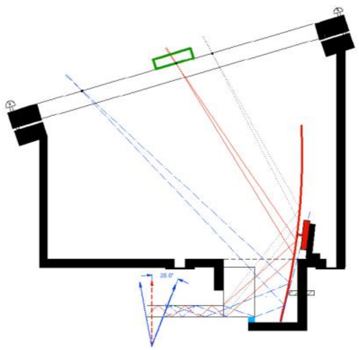
Performance

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 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

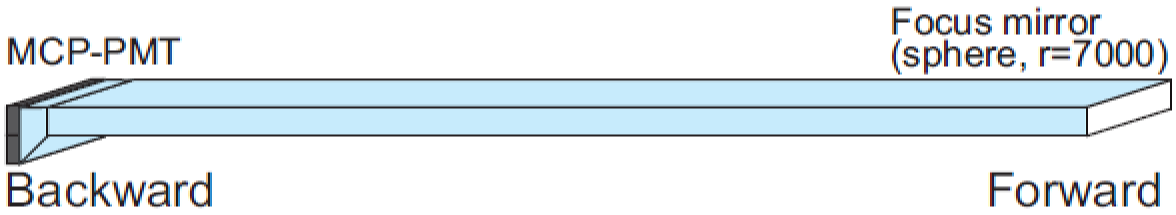
Mostly imaging ←

Mostly timing →

Compactness

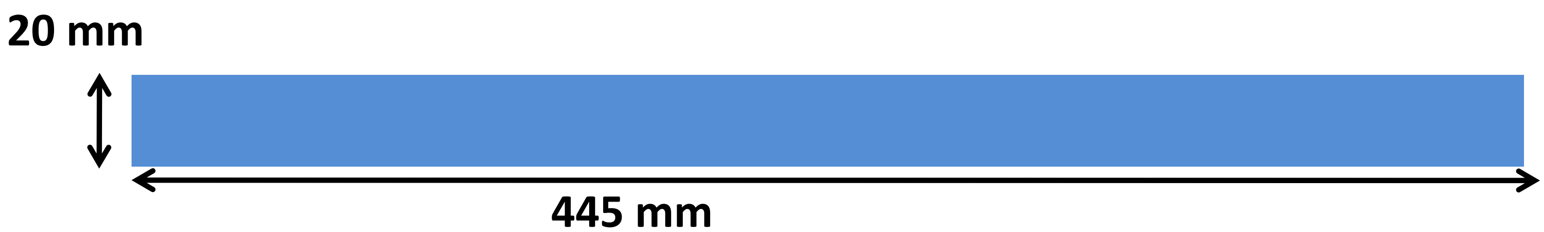
*by no means a complete list! See, e.g., previous talk.

Belle-II TOP Geometry



L_{bar} ~ 2600mm
$L_{expansion}$ ~ 100 mm

TOP Quartz Cross Section:



x16 modules

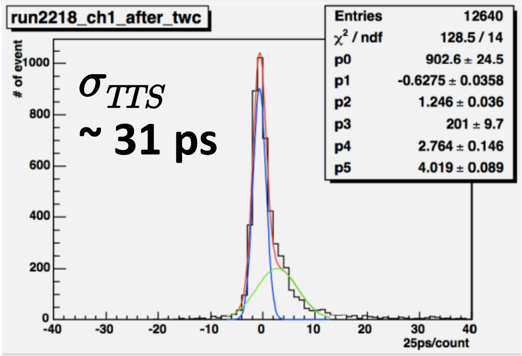
BaBar DIRC Quartz Cross Section:

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
- 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.

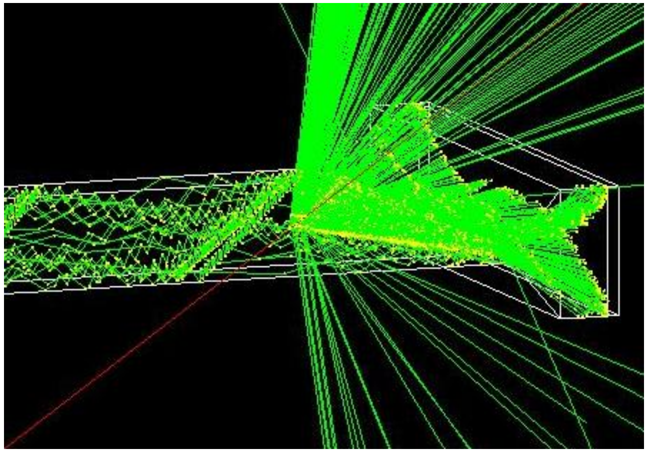
*K. Inami, et al.,
NIM A 592 (2008) 247-253

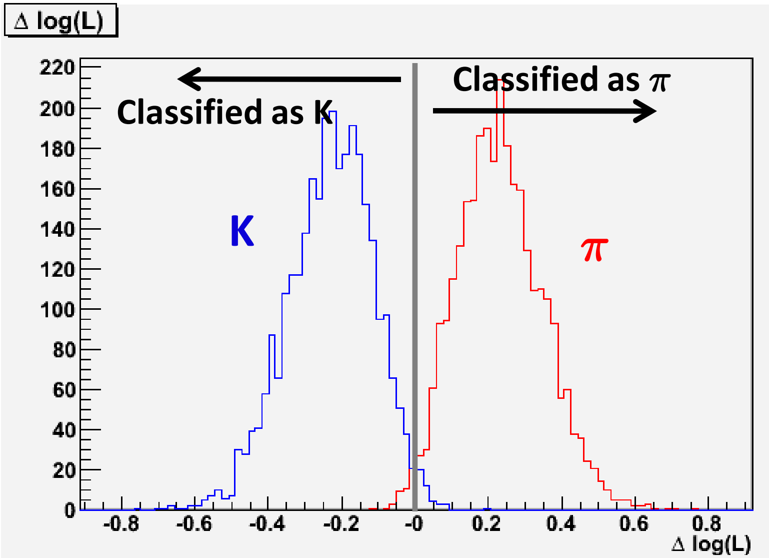


***See K. Inami's slides (Sat.), "MCP-PMT development for Belle-II TOP counter" (Photon Detectors)**

Standalone Simulation Studies

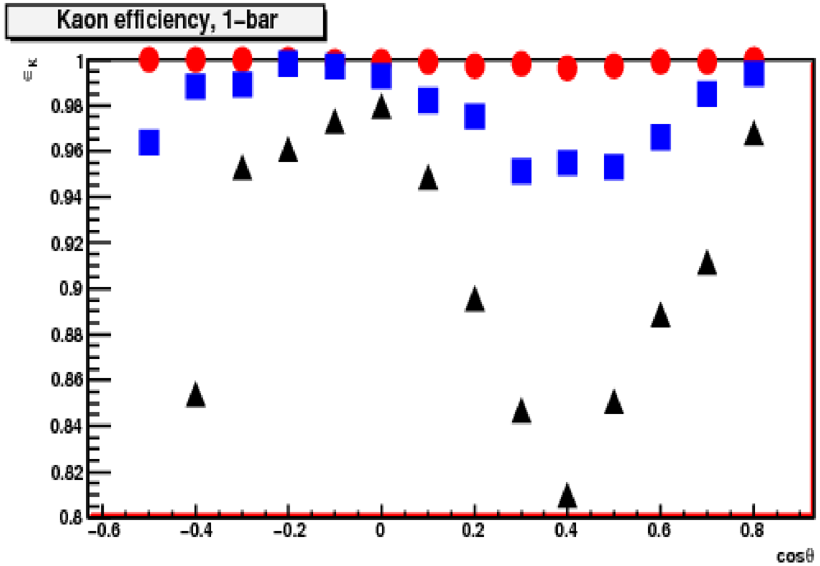
- Independent simulations:
  - Belle Geant3 + standalone code (Nagoya)
  - Geant4 (Hawaii)
  - Standalone code (Ljubljana)
- All utilize a Δlog(Likelihood) approach to determine particle classification.
  - PDFs are defined in x,y, and t
  - Geant-based versions take probability distribution functions 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.

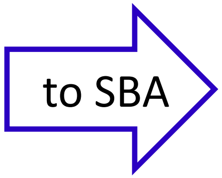


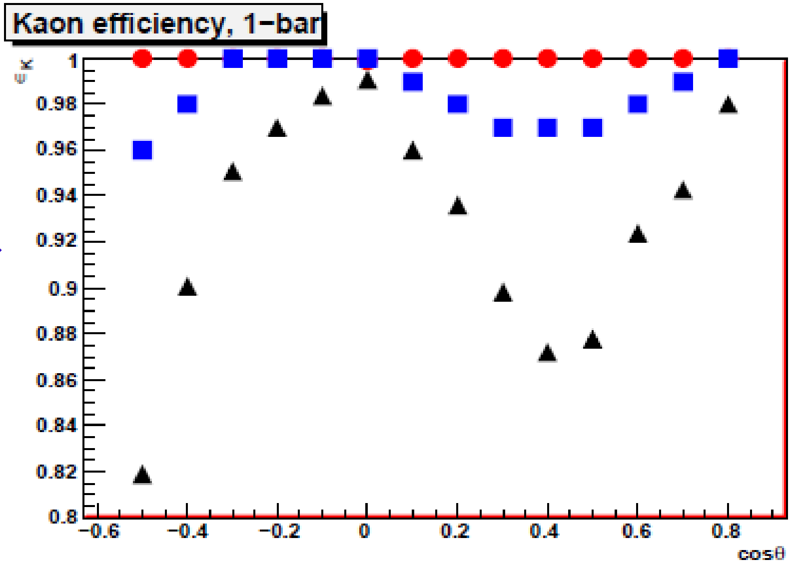


Examples of Performance Studies (1)

- Simulations have been used to evaluate many parameters, for example, the photocathode type…







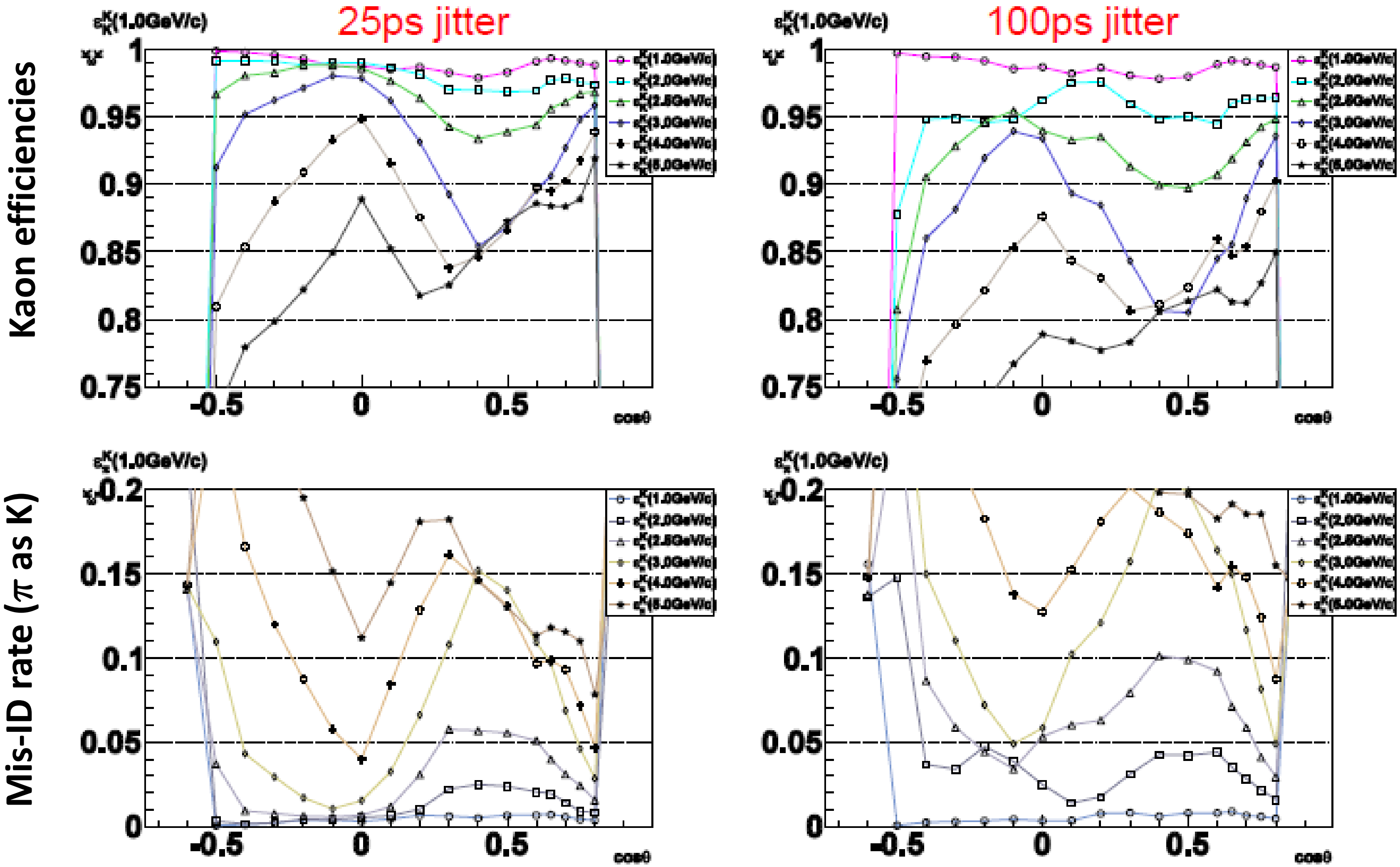
➔ **With similar trends in rate for the pion mis-ID rate to kaons, motivated the transition from multi-alkali to super bi-alkali.**

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

σ_{T_0} = 25 ps

Examples of Performance Studies (2)

- Potential degradation due to event start time jitter:



Examples of Performance Studies (3)

- Performance can be weighted to determine effects on physics modes:

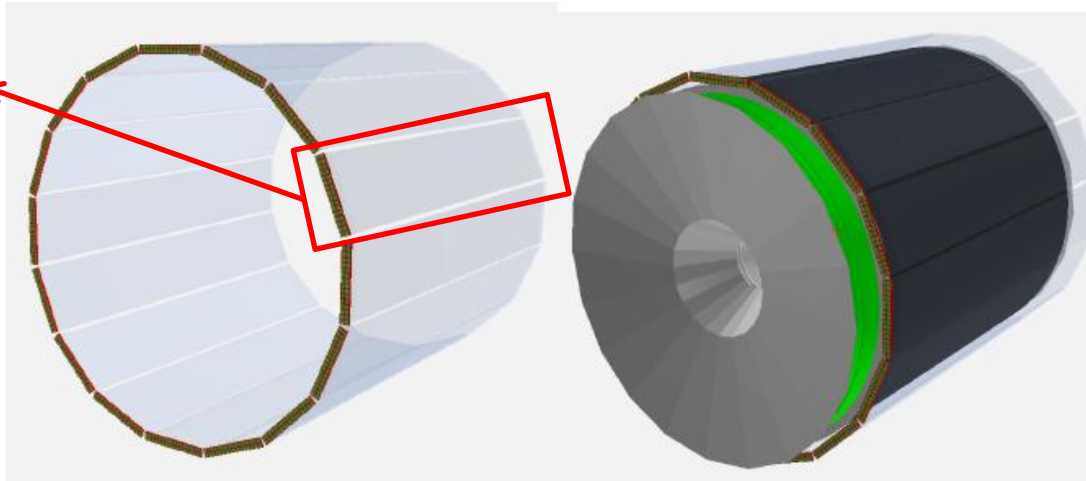
T0 jitter	$B \to \pi\pi$ Efficiency(%)	Fake rate(%)	$B \to \rho\gamma$ Efficiency(%)	Fake rate(%)
25ps	94.5	5.9	98.4	2.3
50ps	93.1	7.3	98.1	2.8
75ps	91.2	9.0	97.4	3.5
100ps	89.4	10.7	96.7	4.3
200ps	84.0	15.9	93.7	7.6

- Larger T_0 is not a show stopper… but does noticeably degrade performance.

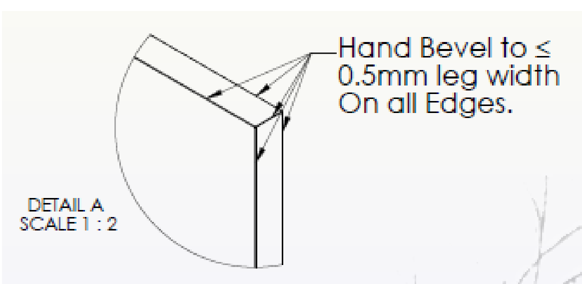
  → Reduce as much as possible! In Belle, contribution was $\sim$ 40 ps.

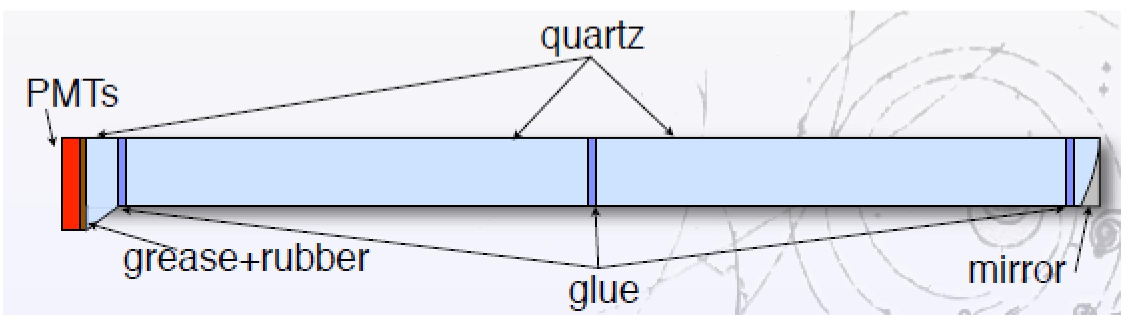
Belle-II Geant4 Simulations

- Basic geometry is now included w/ full detector:



- Adding realism…
  (e.g., bevels, glue
  joints, etc.)

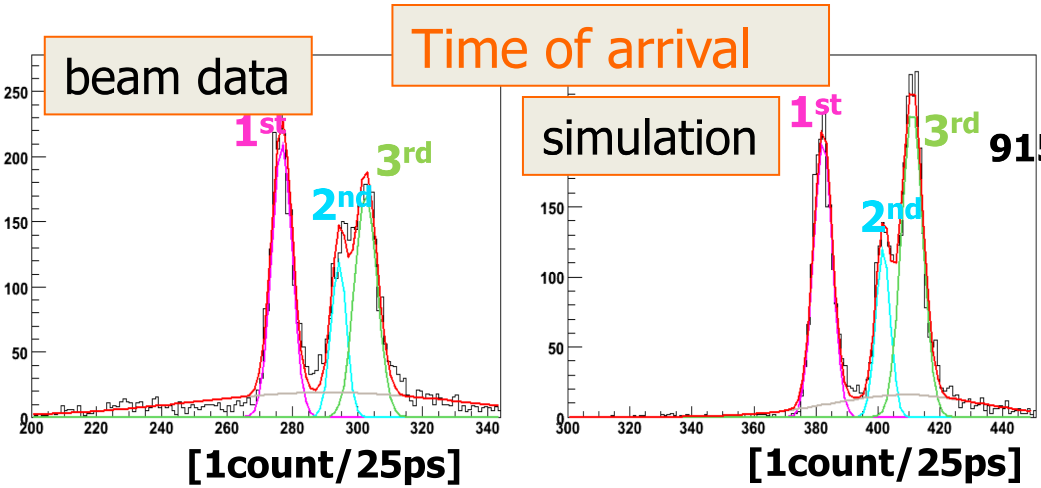


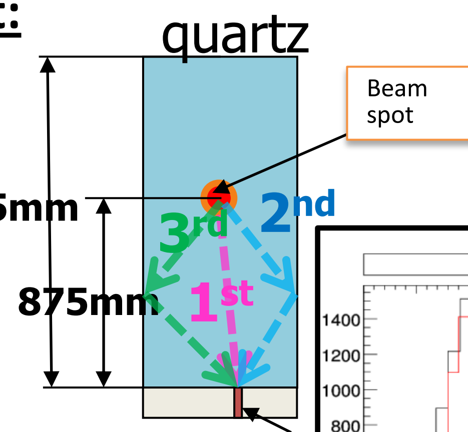


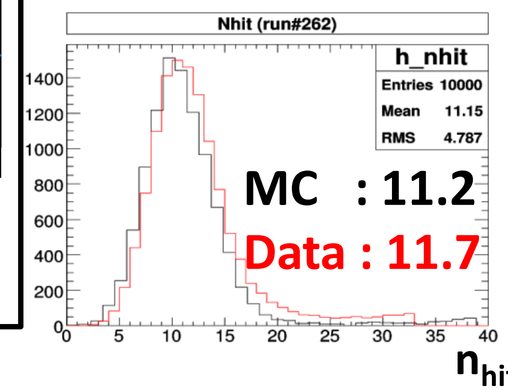
- Working to integrate tracking & fast reconstruction, increase sim speed.

Beam Test Validations

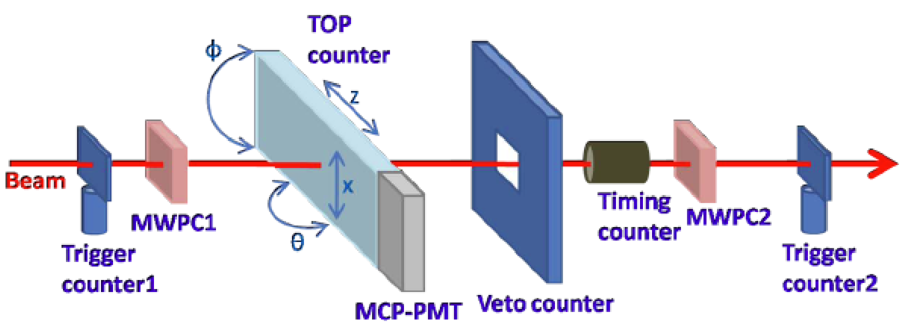
2008 beam tests show good MC/data agreement:

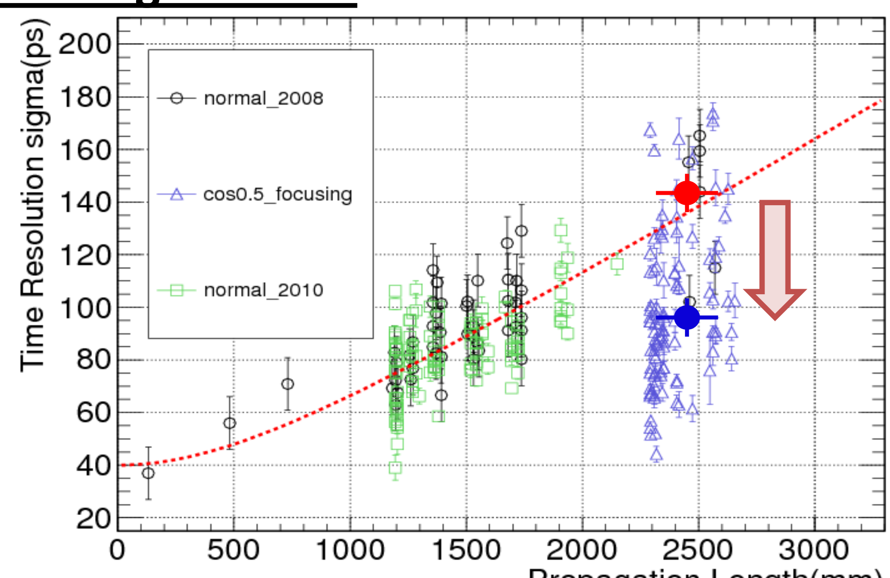






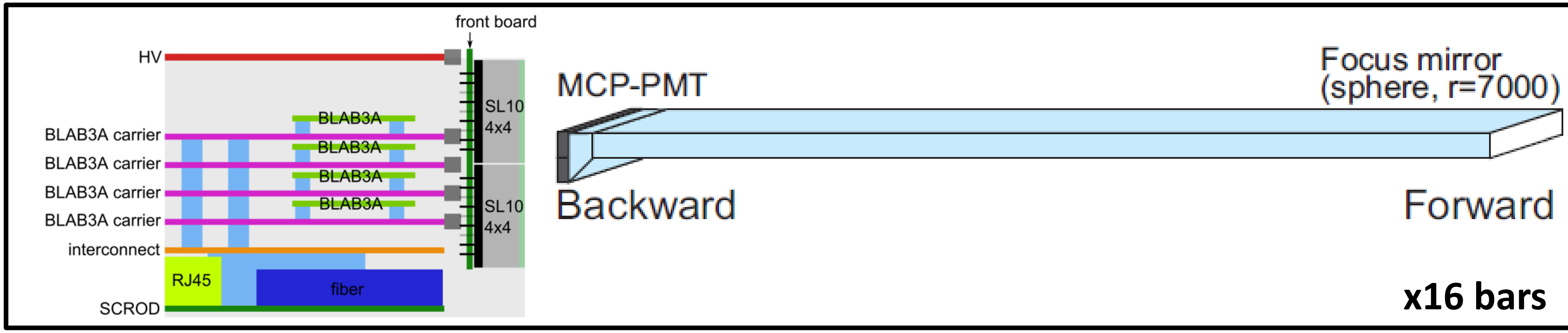
2010 beam test was conducted to verify focusing scheme:





***See Y. Arita's poster, "Verification of focusing system for Time of Propagation Counter"**

Belle-II TOP Electronics



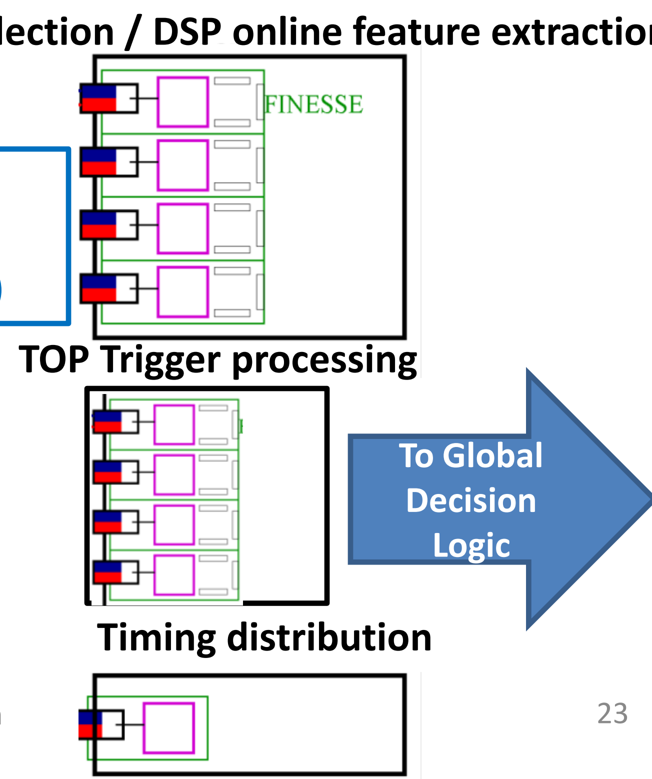
“Front-end board stack” (supports 8 SL10s, 128 channels; 4 total per bar)

Fiberoptic data link (2.6 GSa/s)

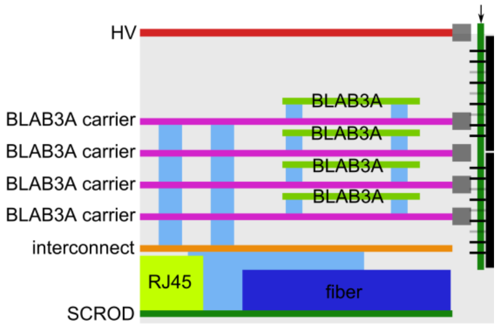
See D. Sun’s slides (Sat.), “Belle2Link” (Trigger and DAQ Systems)

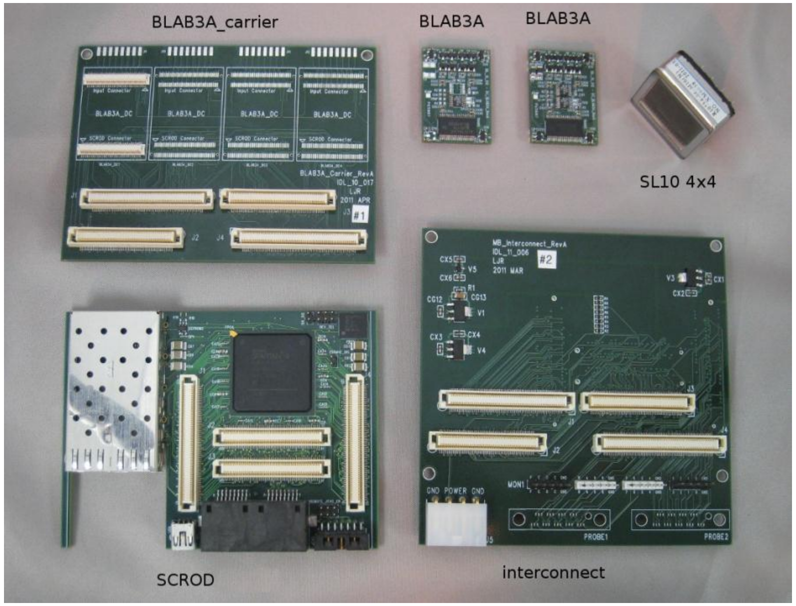
Fiberoptic trigger link (2.6 GSa/s)

CAT7 timing distribution link

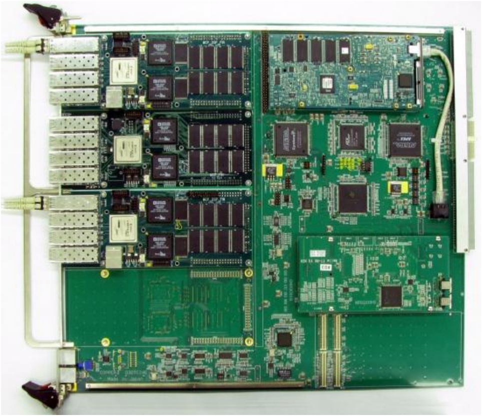


Electronics Hardware Status

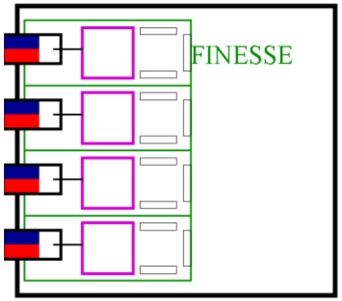




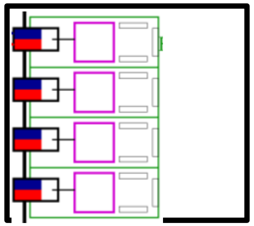
Preliminary versions of most front-end boards available. Continuing work to reduce size.



Data collection / DSP online feature extraction



TOP Trigger processin

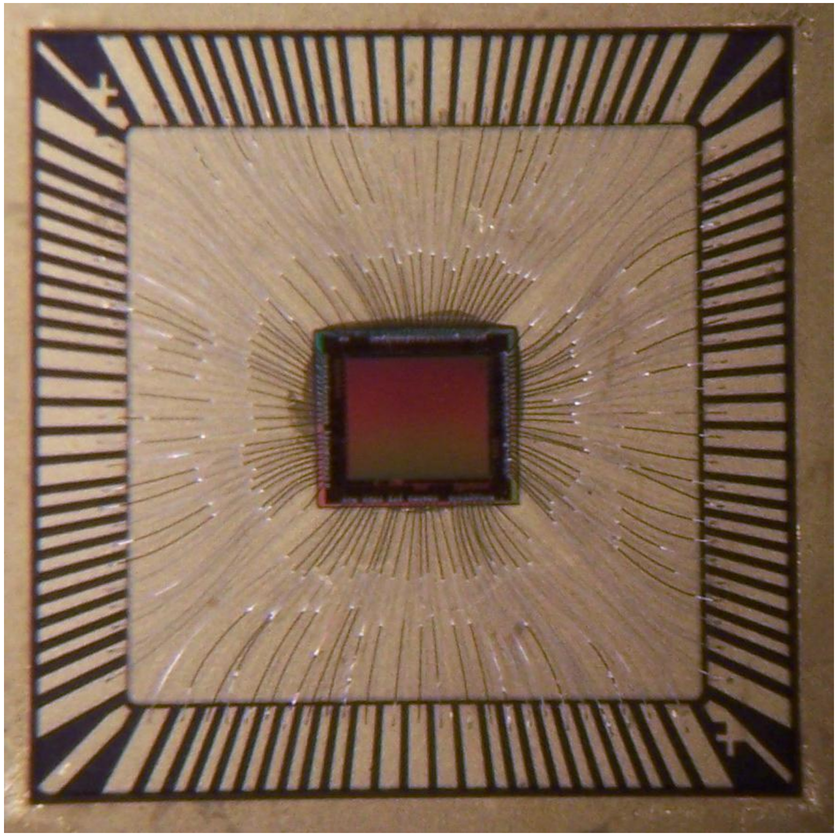


lock/Event Timing Distribution

Back-end boards all available!

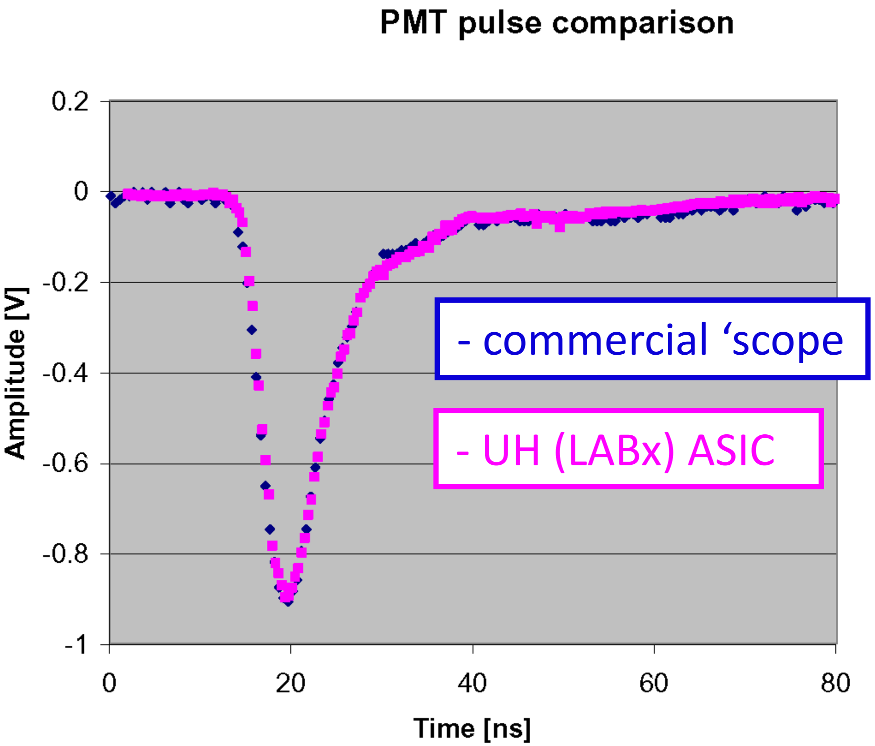
Front-end Waveform Sampling

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



BLAB1 Die

***See G. Varner's slides (Friday), "Deeper Sampling CMOS Transient Waveform Recording ASICs" (Front-end Electronics)**

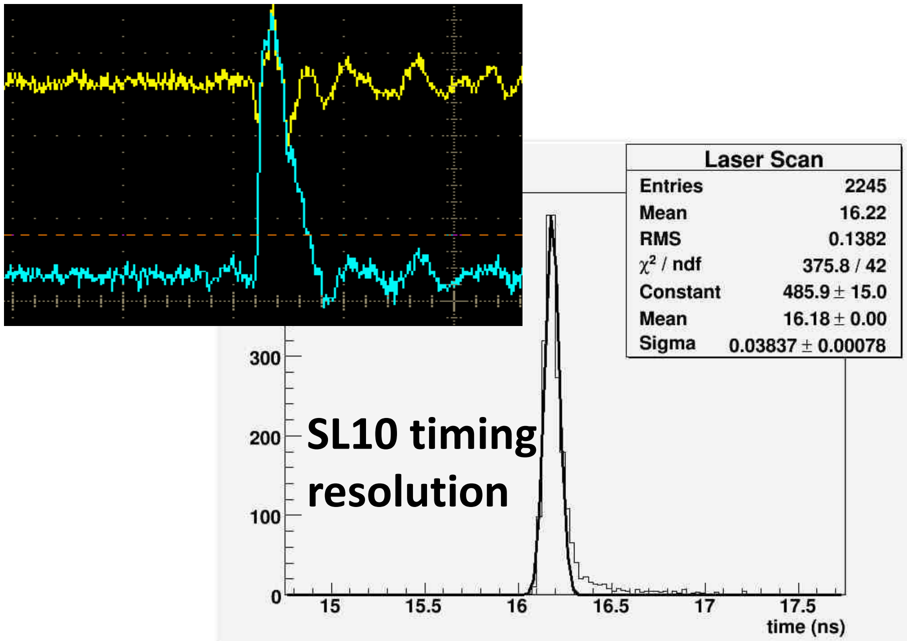


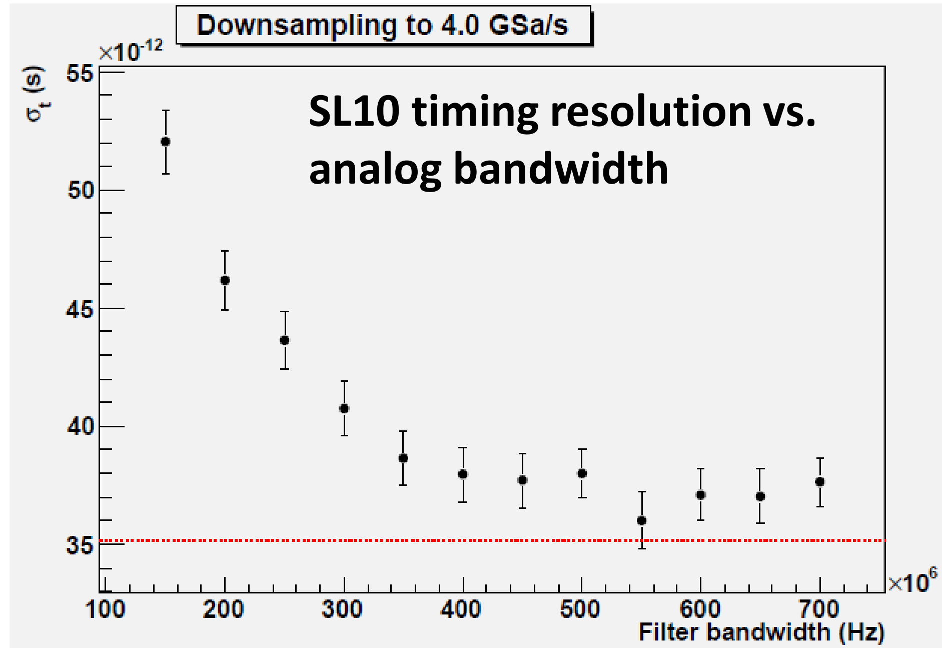
→Use large bandwidth capability developed at University of Hawaii for improved timing.

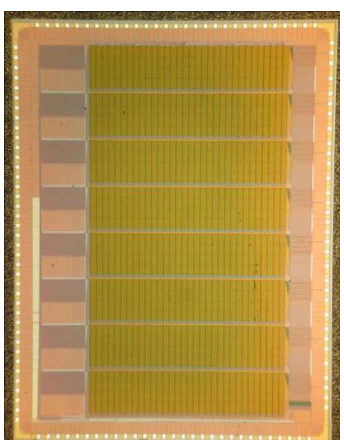
→Varner et al., NIM **A583**, 447 (2007)

Waveform Sampling Specifications

- Guided by signal processing studies:







Studies of single p.e. SL10 signals:

- 350-400 MHz bandwidth
- ~4 GHz sampling rate

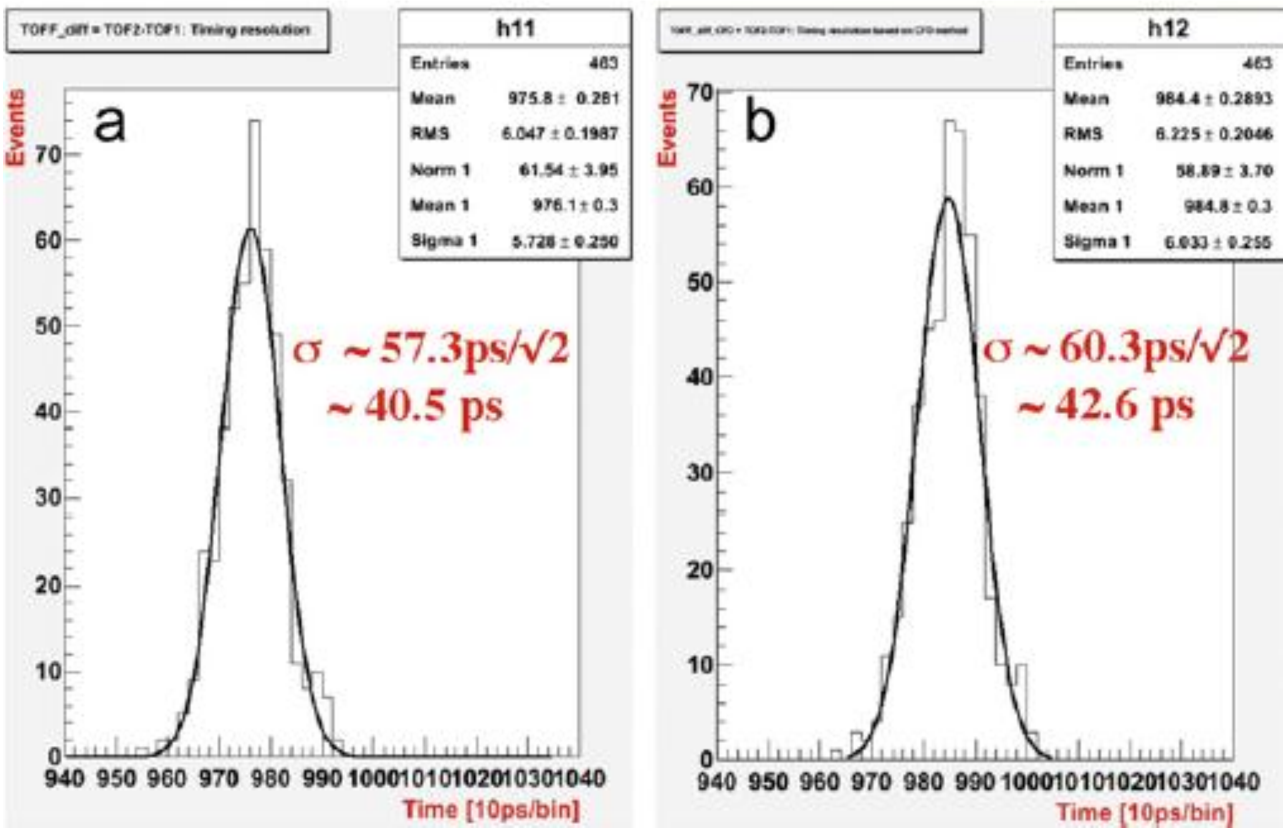
→ BLAB3A ASIC for short term.

→ BLAB3B ASIC for more compact final system.

Back-end Data Reduction

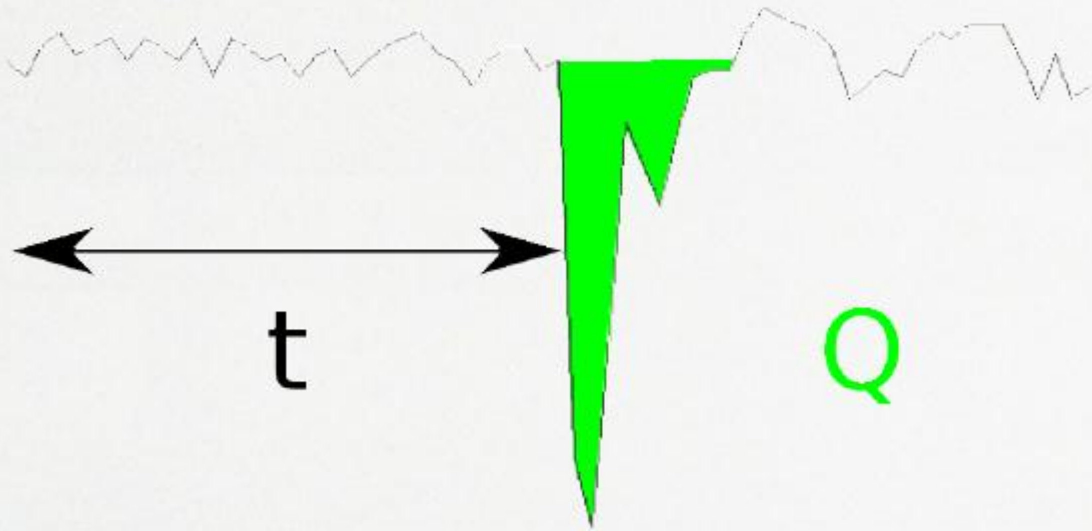
Studying algorithms for feature extraction:

- Example, comparison between software version of constant-fraction discrimination (right) and template fitting (left) **(NIM A 629, 123)**.
- Find the least complex algorithm that preserves timing information.



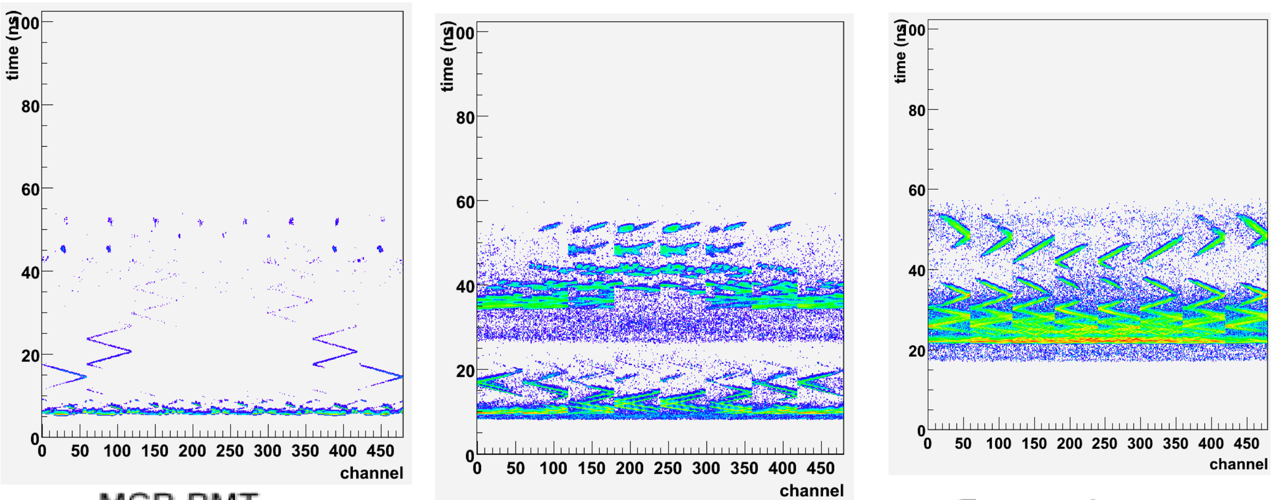
Back-end Data Reduction

- Current baseline algorithm based on CFD.



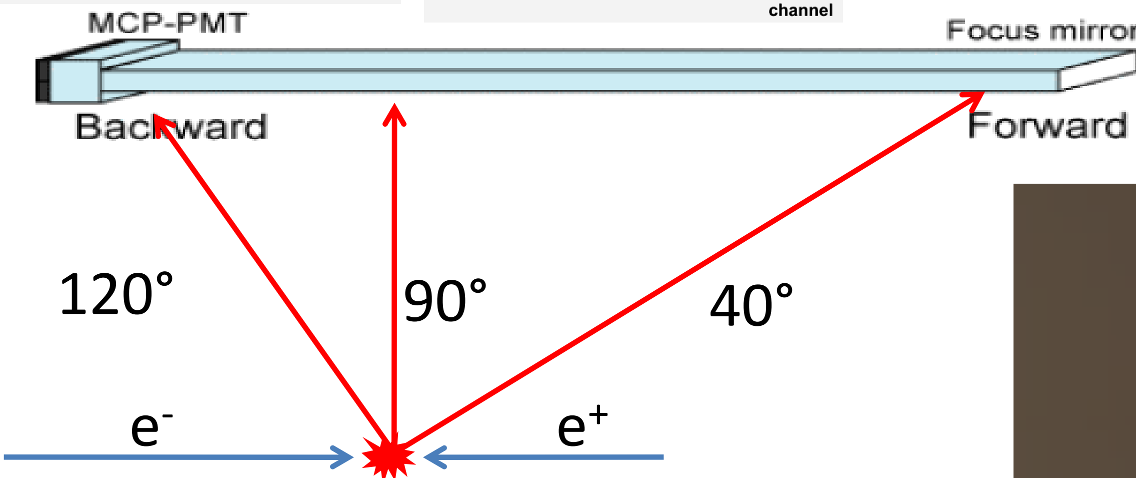
- finds time to a constant fraction of pulse height
- preliminary algorithm performs pedestal subtraction, delta-t correction, FFT/iFFT to filter unwanted frequency components and straight-line fit to leading edge of pulse
- each DSP core can handle 60k waveforms per second

TOP Trigger System

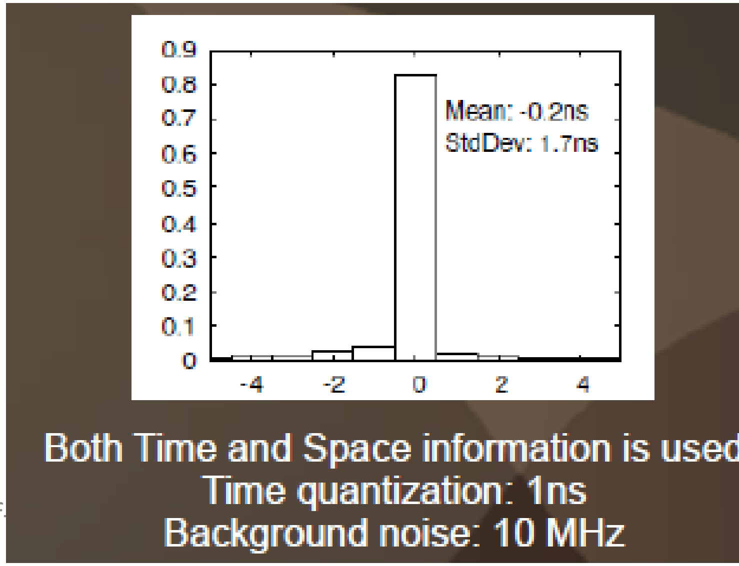


Primary goal: provide event time (t_0) with resolution of 1-2 ns

(Left) Example π PDFs, 3 GeV/c



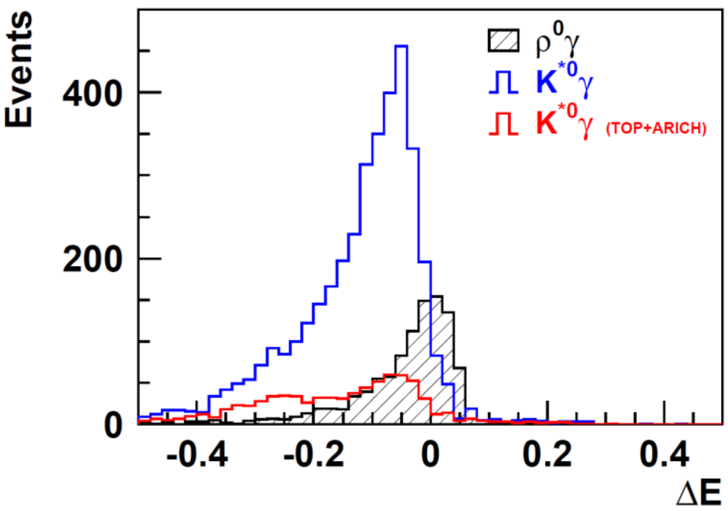
(Below) t_0 resolution, preliminary implementation



➔ **Tested and capable of processing trigger hits at 75 MHz. (Expect < 10 MHz)**

Summary

- Belle II will utilize a time-of-propagation (TOP) counter for particle identification in the barrel region.
  - Compact device (including front-end readout electronics) to accommodate strict space requirements.
  - Expect improved performance relative to original Belle PID systems.



- Next beam test this fall: full size module, fully instrumented w/ MCP-PMTs and waveform digitizing electronics.
- **Stay tuned for new results!**

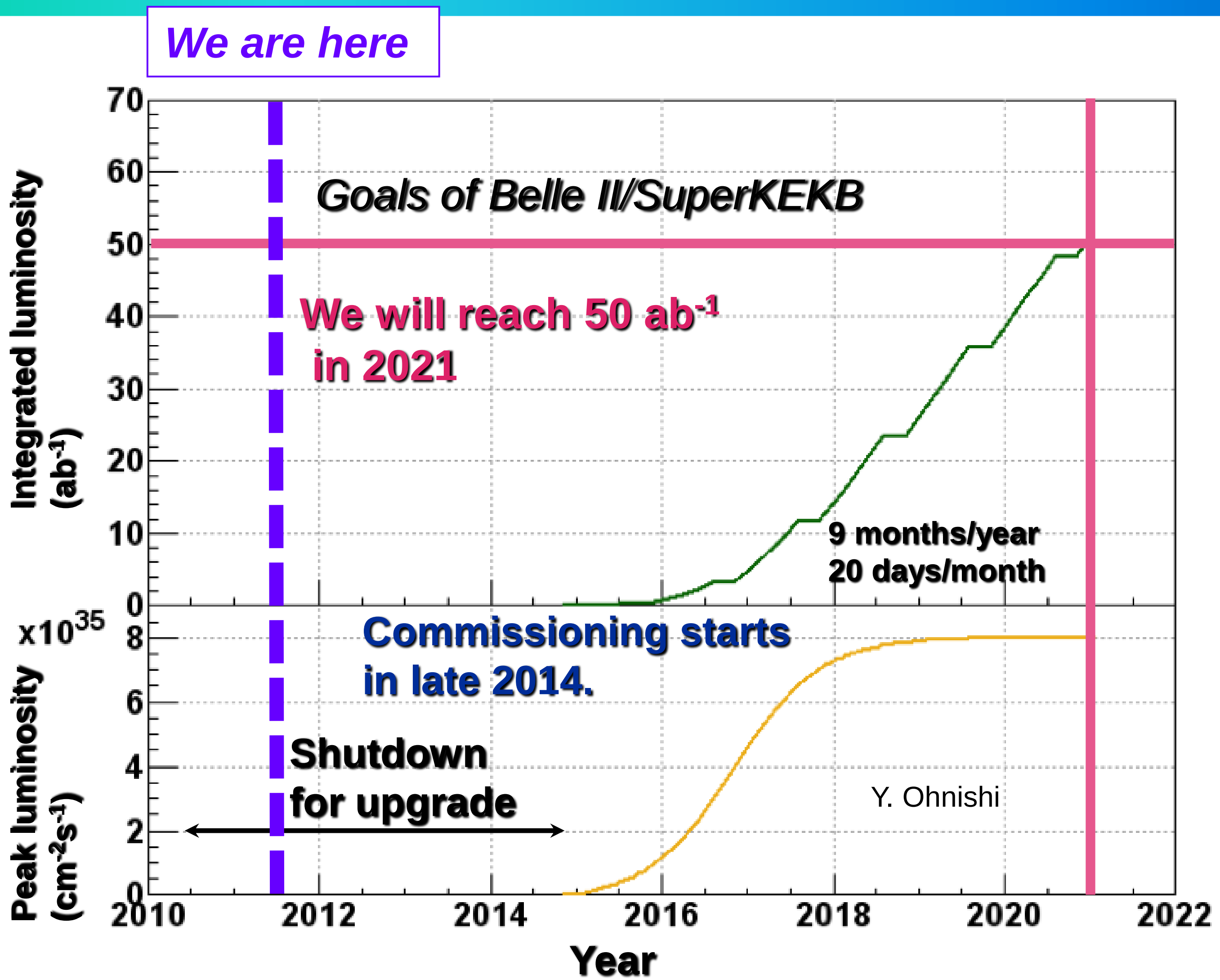
BACKUP SLIDES

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)

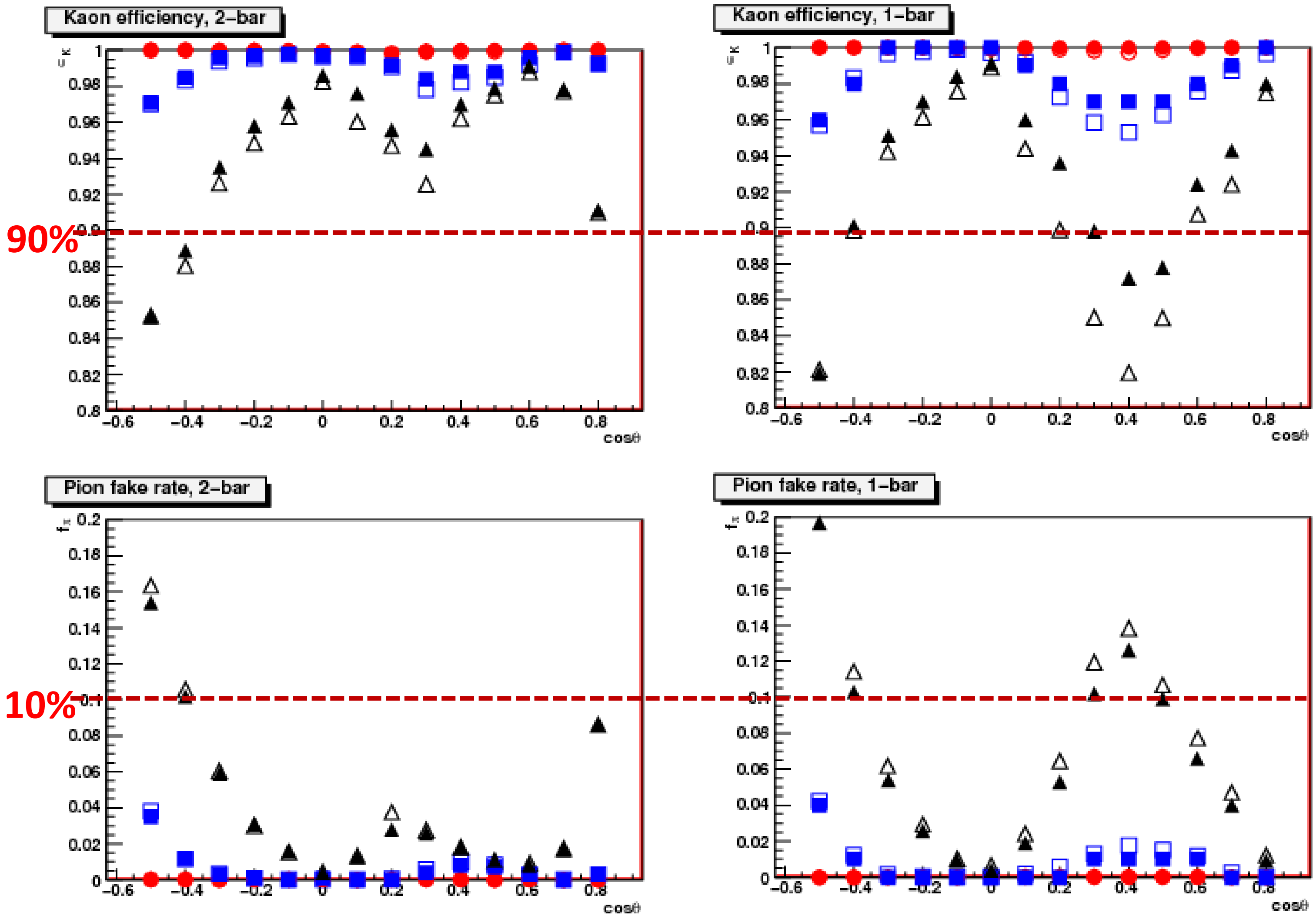
Parameter	Value	Comment
Channels/BLAB3	8	die size constraint
Sampling speed	4	Giga-samples/second (GSa/s)
Samples/channel	32768	allows $\geq$5 μs L1 trig latency
Amplifier gain	60	voltage (3$k\Omega$ TIA)
Trigger channels	8	for hit matching/zero suppression
Effective resolution	$\approx$9	bits (12/10 bit logging)
Sample convert window	64	samples ($\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)

Belle II Beam Background



Increased luminosity will result in a factor of $\gtrsim$ 20 higher background!

Performance w/ Beam Backgrounds



1.5 GeV/c

2.5 GeV/c

3.5 GeV/c

σ_{T_0} **= 25 ps**

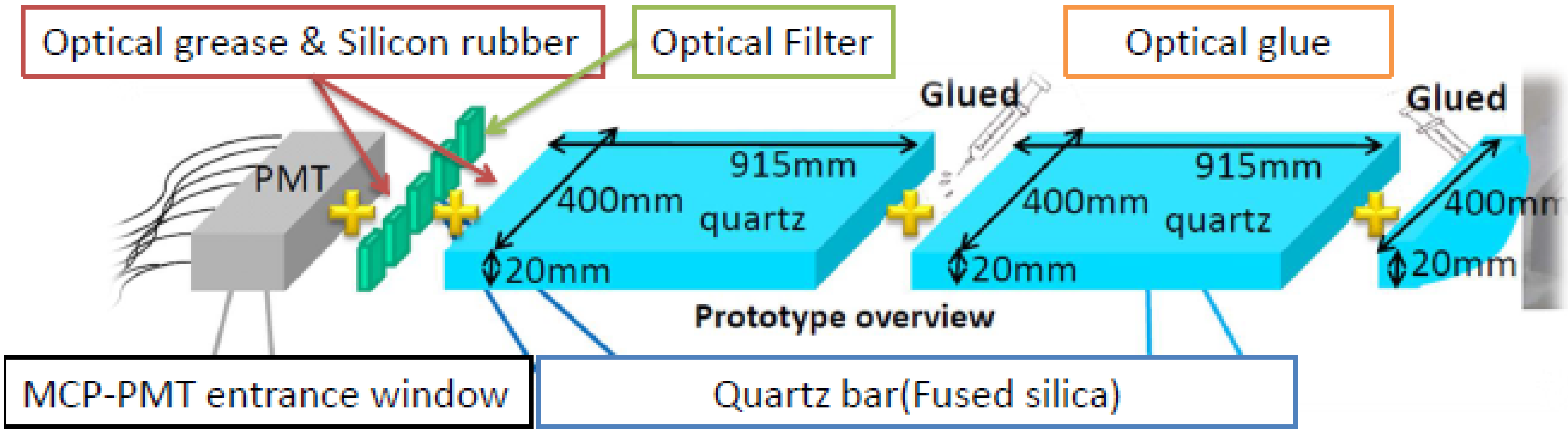
Filled: 1 γ bg

Hollow: 10 γ bg

➔ Both geometries are relatively insensitive to background.

Optical Radiation Testing (1)

Many optical components to qualify for radiation:



Candidate of each components

★Optical grease
- cargille06350(cargille)

★Silicon rubber
- EJ-560(Elgen technology)

★Optical Filter
- ZJB340(xiang-yang)
- L37(HOYA)
- IHU340(isuzu-glass)
- IHU350(isuzu-glass)

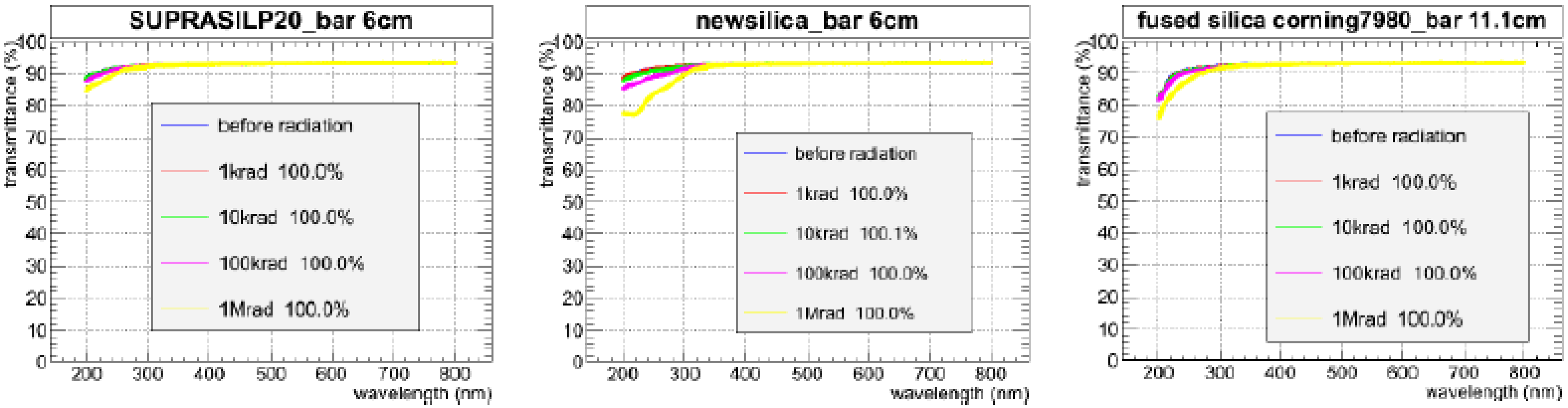
★Optical glue
- NOA61(Norland)
- NOA63(Norland)
- Epotek301-2(Epotek)

★MCP-PMT entrance window
- corning7056(borosilicate)
- SUPRASIL-P20(fused silica)
- T4040(fused silica)

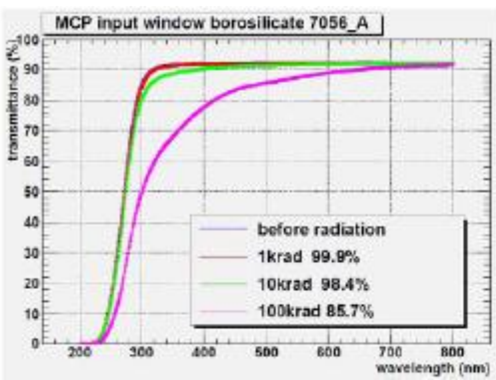
★Quartz bar(fused silica)
- SUPRASIL-P20(shinetsu)
- new silica(shinetsu)
- corning7980(corning)

Optical Radiation Testing (2)

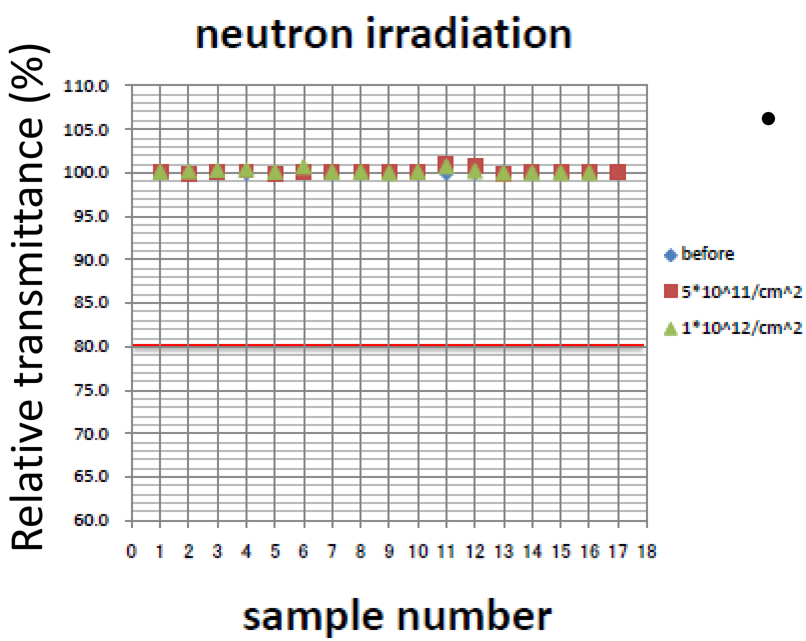
- Quartz (3 candidates)



- No significant γ damage to quartz up to 1 MRad (10 kRad $\approx$ 10 Belle years).

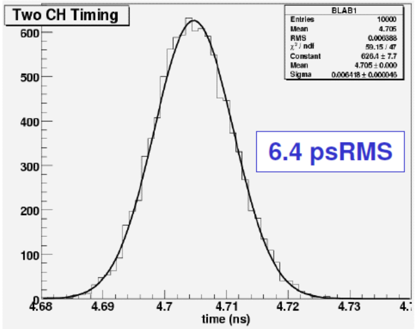


- Borosilicate window shows a few percent loss at 10 kRad of γ dose.

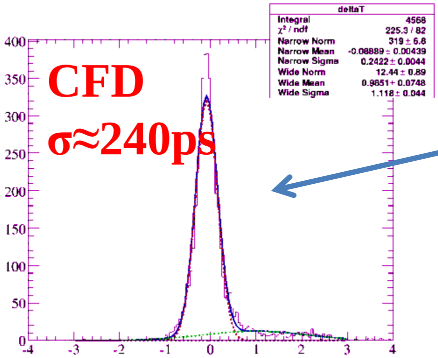


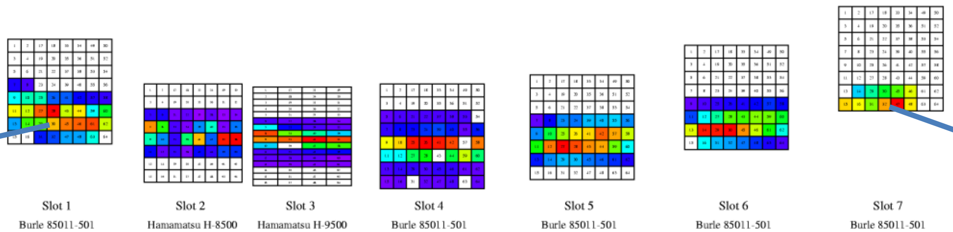
- No measurable degradation to optical components w/ 5 x 10^{11} neutrons/cm^2 ($\approx$ 10 Belle-II years)

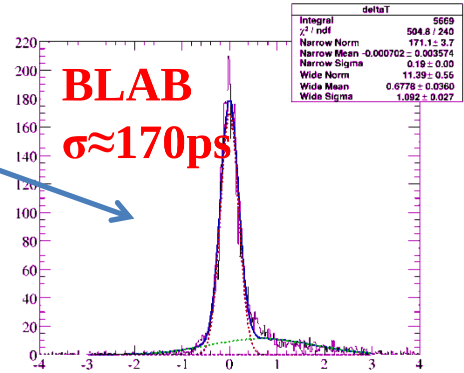
Electronics Performance



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







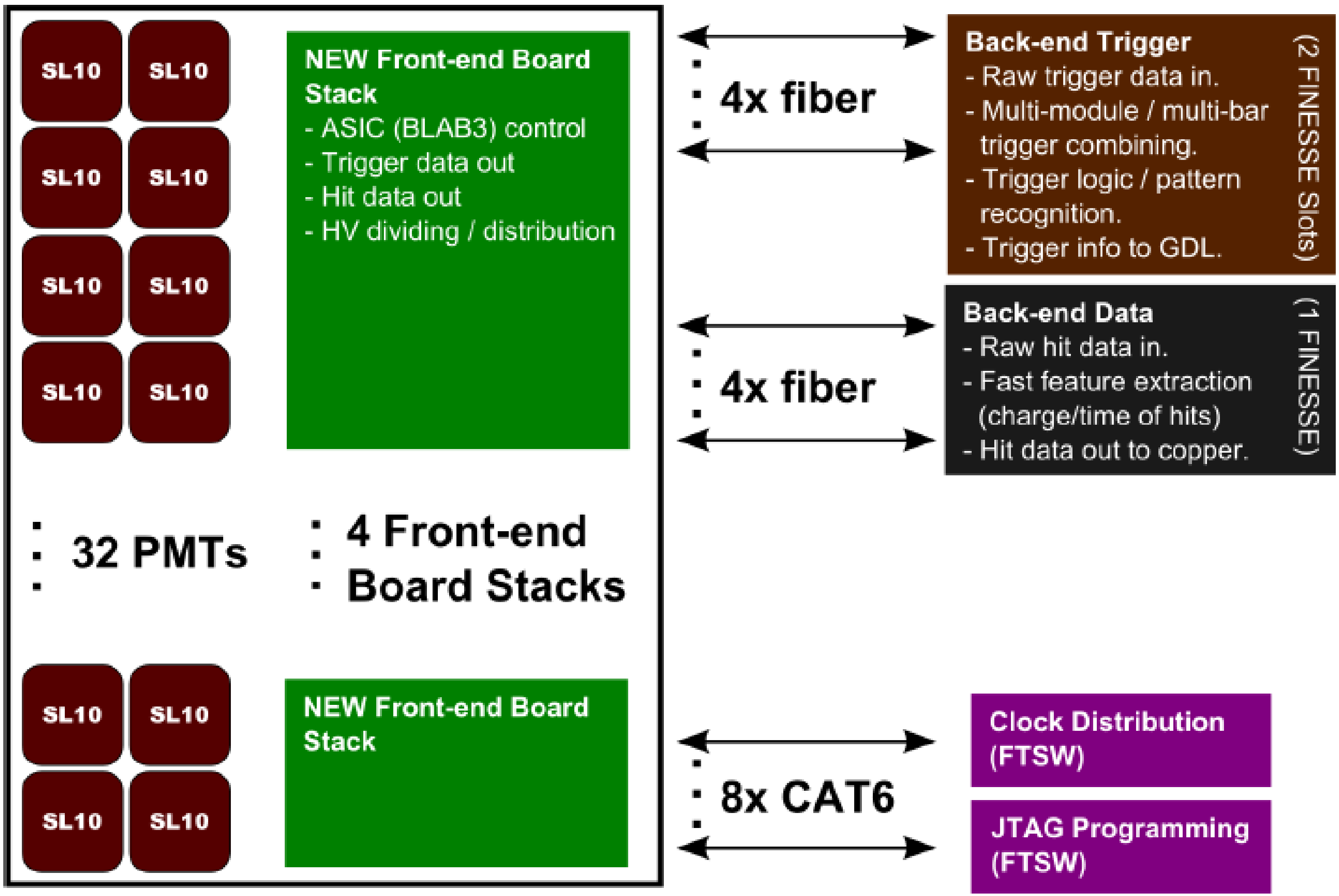
➔**Improved timing** over high precision CFD, and **much lower power**.

➔Timing limited by σ_t of MA-PMT.

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

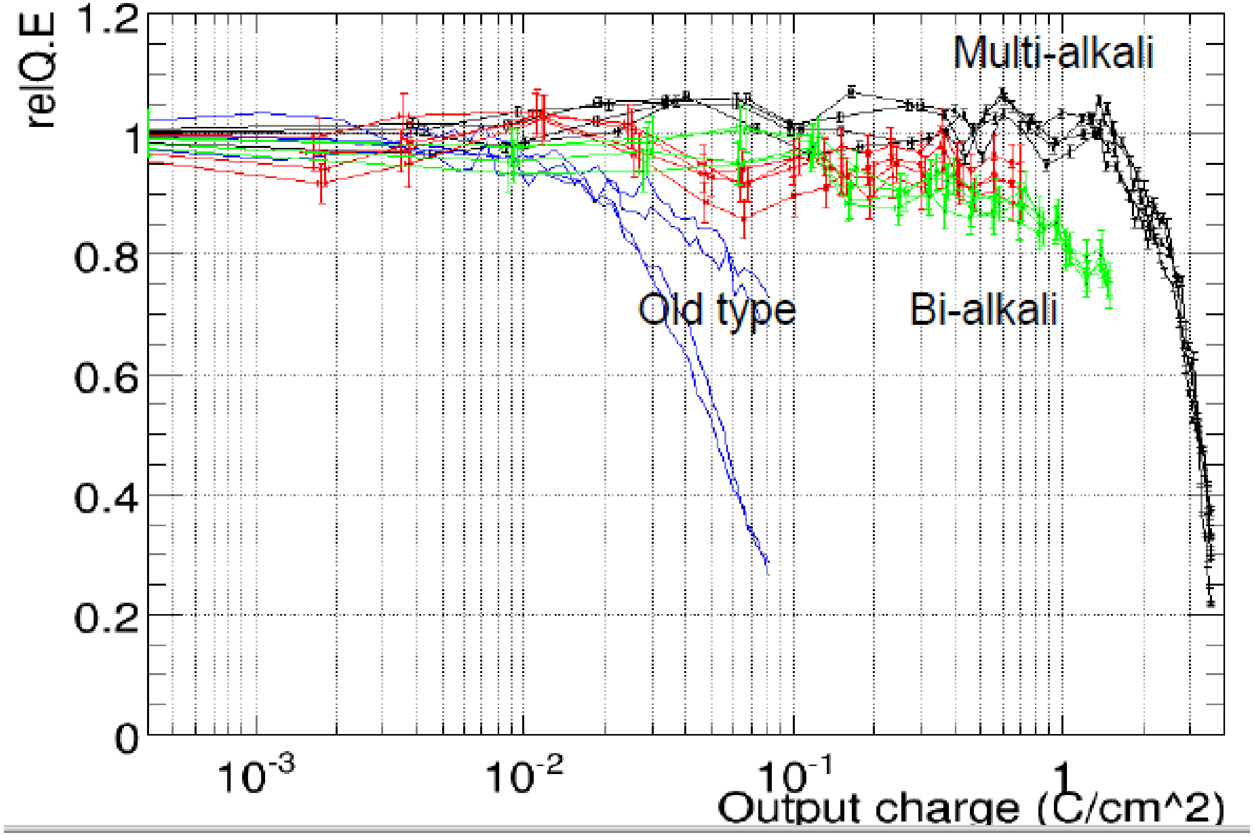
➔ We expect to be PMT limited for timing.

Electronics Block Diagram



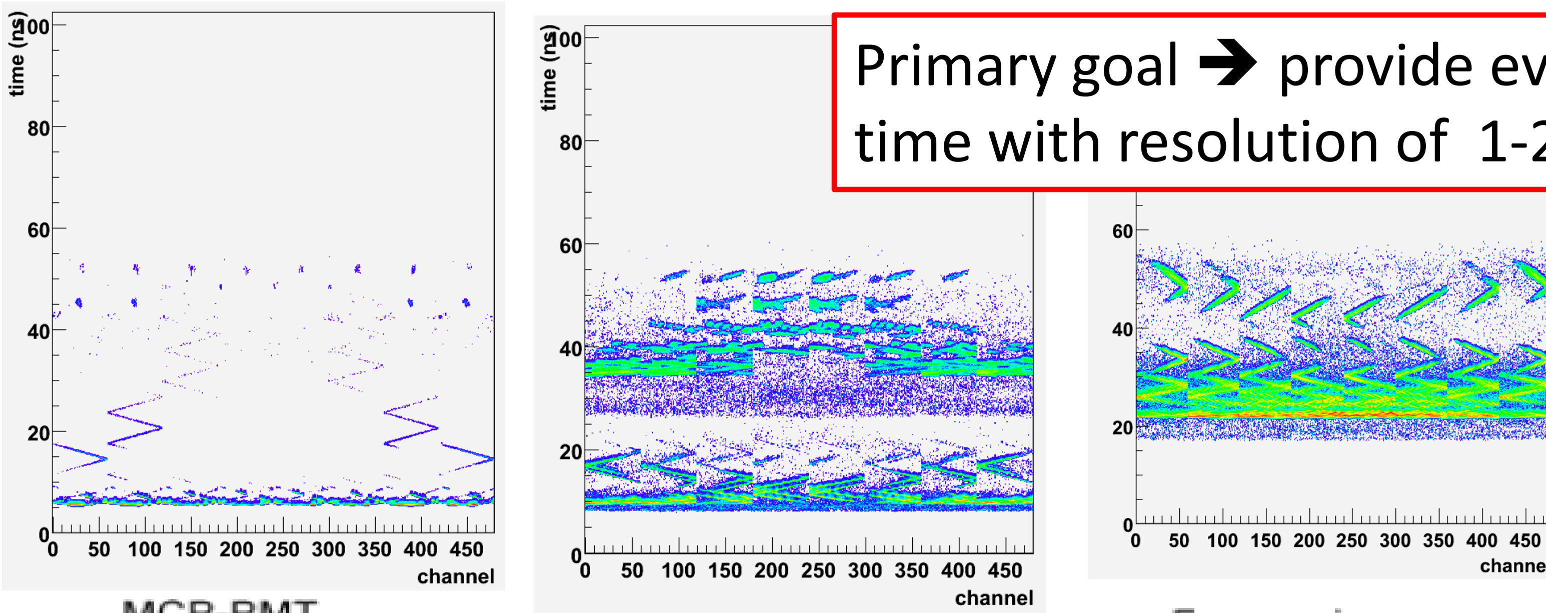
Lifetime

- Recent status
  - 1~2 C/cm^2 for 80% QE drop

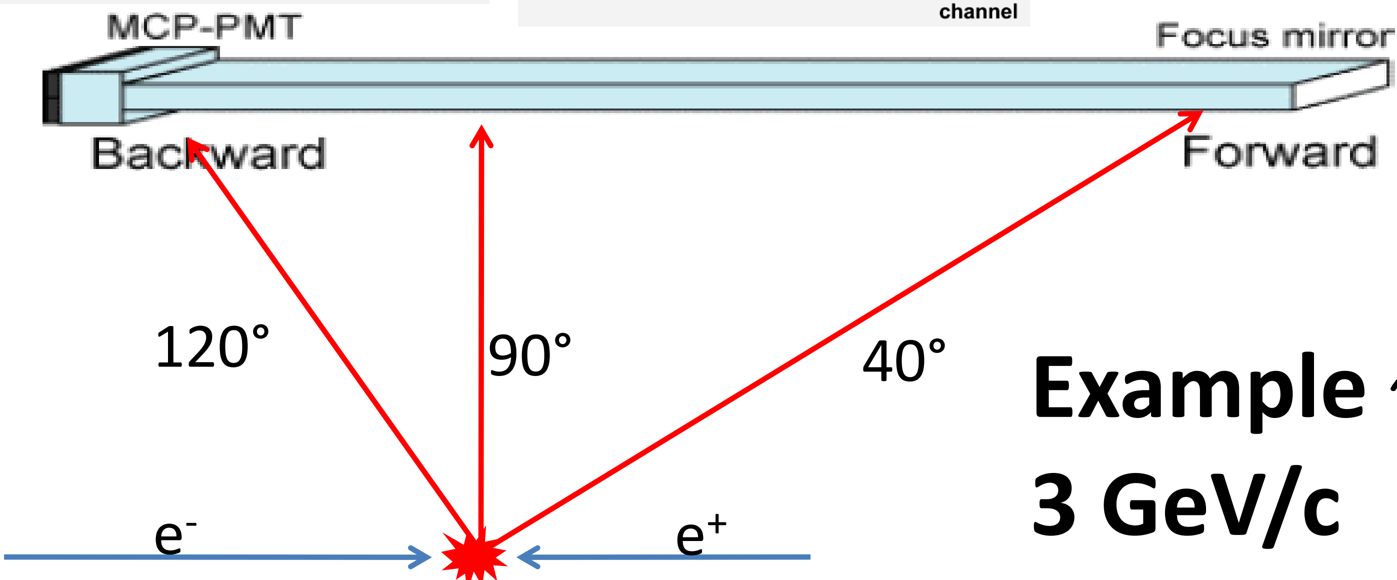


Belle-II est.: ~170 mC/cm2/year

Belle-II TOP Trigger

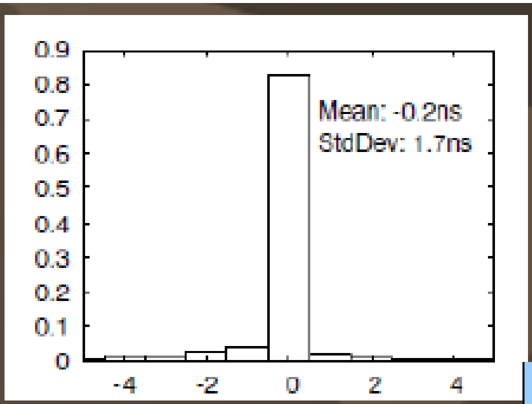


Primary goal ➔ provide event time with resolution of 1-2 ns

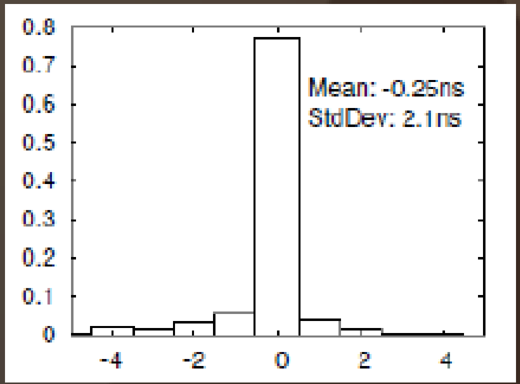


Example π PDFs
3 GeV/c

Trigger Implementation and Performance



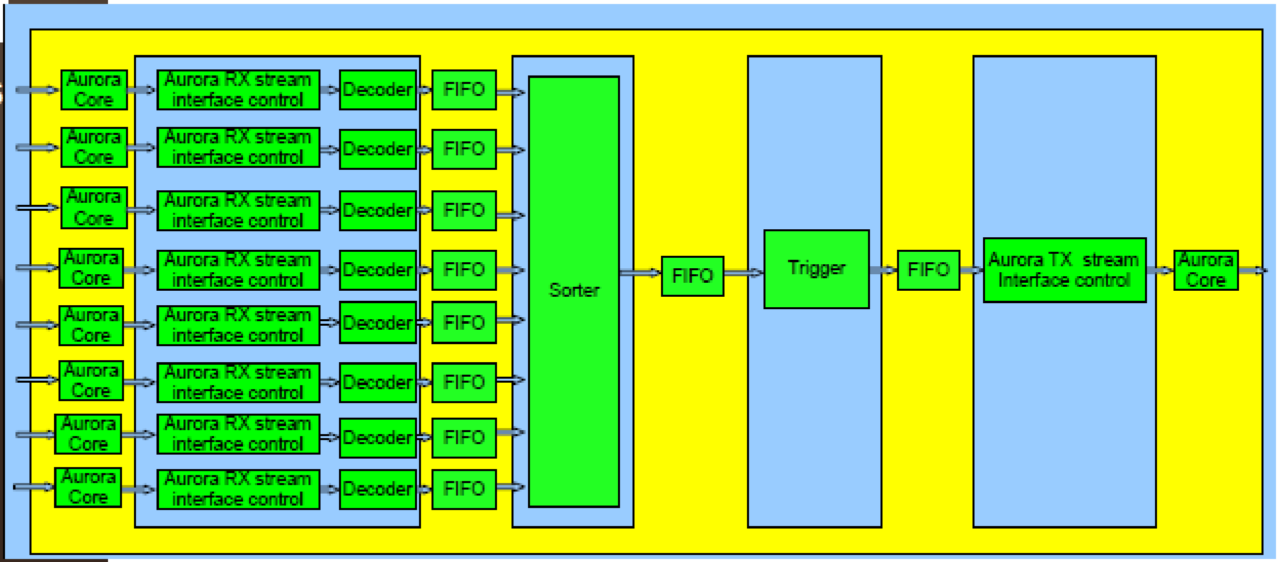
Both Time and Space information is
Time quantization: 1ns
Background noise: 10 MHz



Only Time information is used
Time quantization: 1ns
Background noise: 10 MHz

(Left) Trigger time resolutions based on Geant4 simulated events.

(Below) Block diagram of trigger logic as implemented and verified in firmware.



➔ Tested and capable of processing trigger hits at 75 MHz. (Expected hit rates < 10 MHz)