An Imaging Time-of-Propagation (iTOP) System for Charged Particle Identification at a Super B Factory

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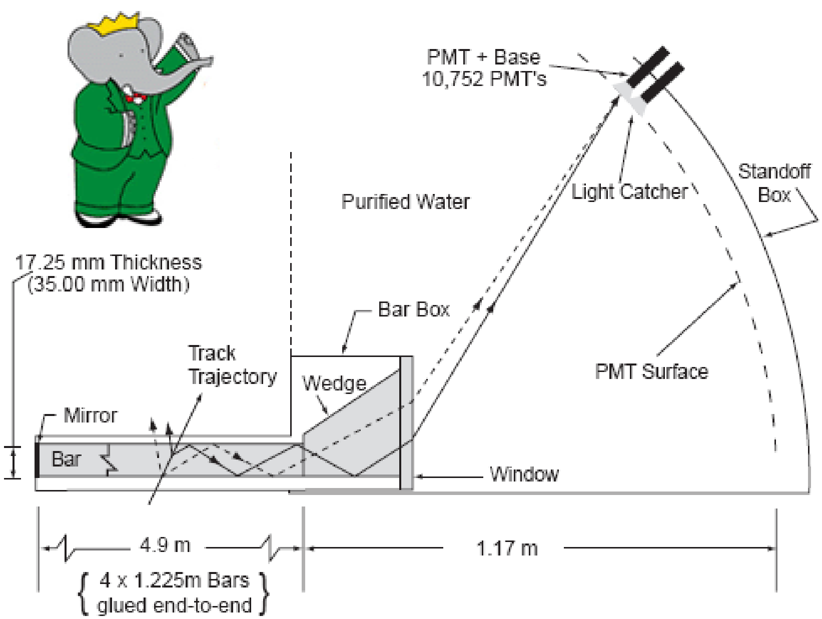
Particle ID at a Super-B Factory

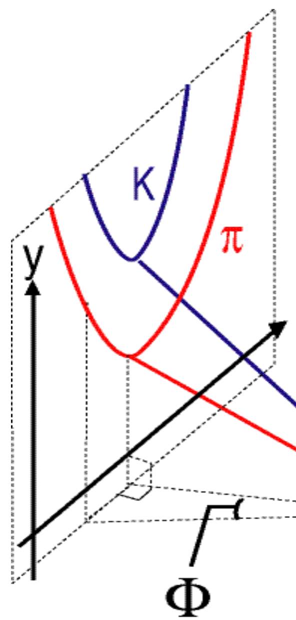
- High precision test of the Standard Model & searches for new physics.
  - Requires high efficiency, low fake rates in separation of $K^{\pm}/\pi^{\pm}$ in the momentum region ~2-4 GeV/c.
    - For example, to distinguish between
      - $\mathbf{B \rightarrow \rho\ (\pi\pi)\ \gamma}$
      - $\mathbf{B \rightarrow K^*\ (K\pi)\ \gamma}$
    - Or…
      - $\mathbf{B \rightarrow \pi\pi}$
      - $\mathbf{B \rightarrow K\pi}$
- Work presented here is tailored to KEKB detector upgrade (Belle II), but generally applicable in this momentum range.

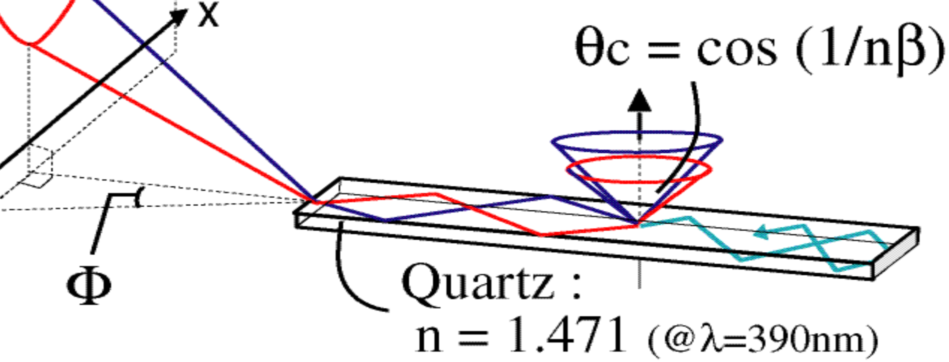
Detection of Internally Reflected Cerenkov Light (DIRC)

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



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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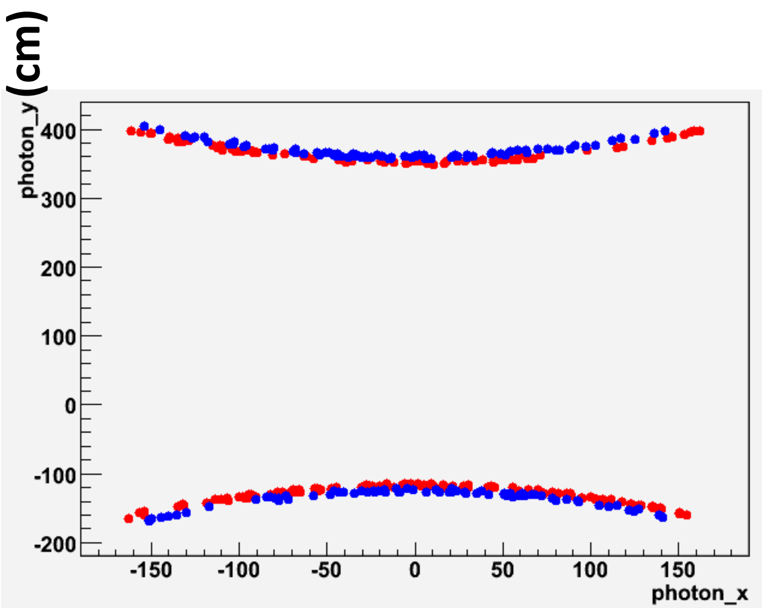

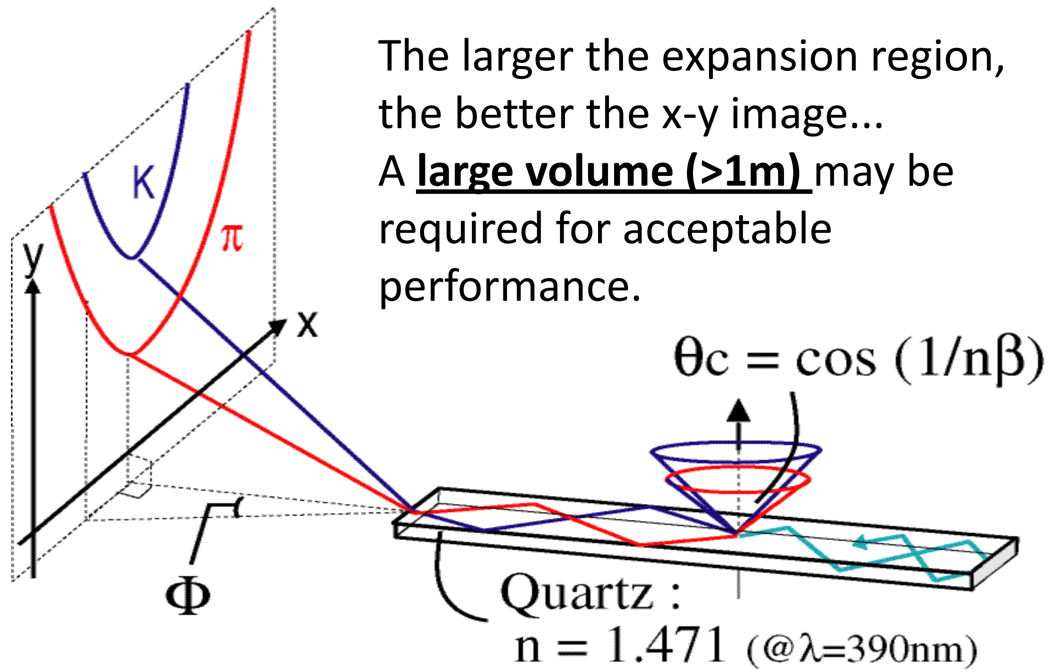

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Left: Simulations w/ large (2 m) expansion volume, 2 GeV K/π

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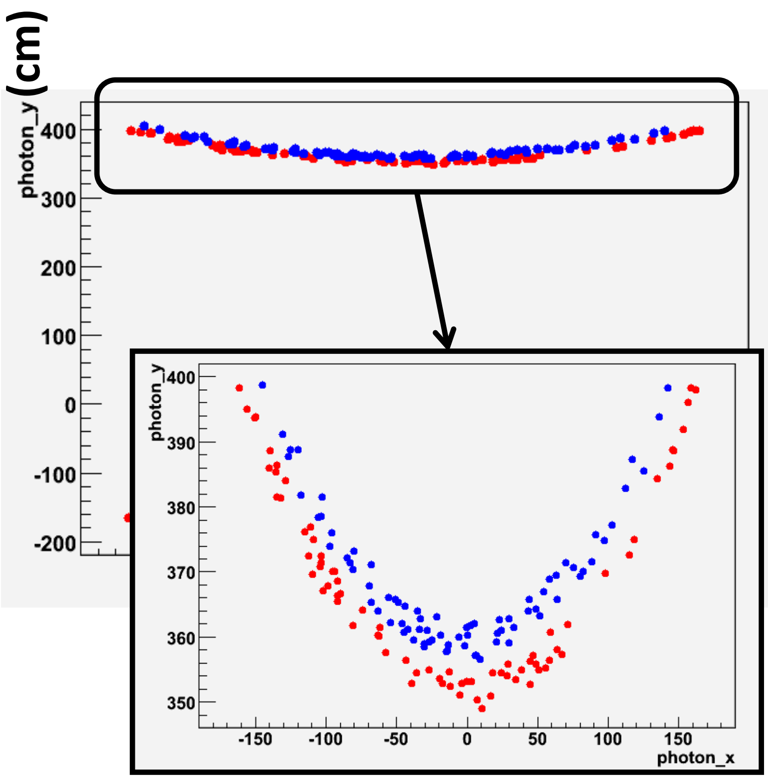

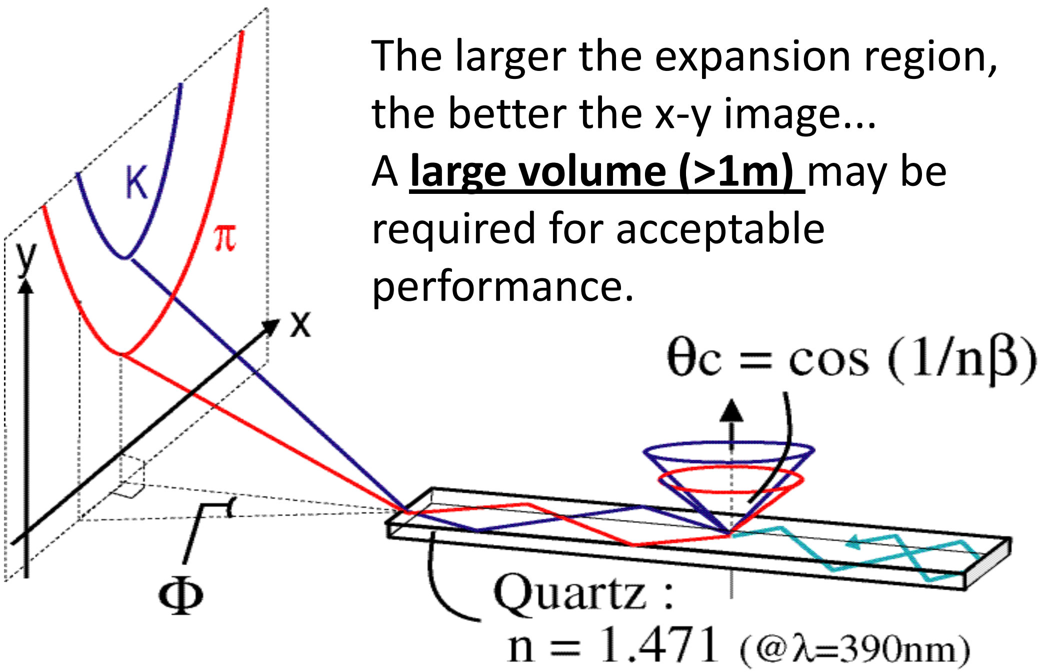

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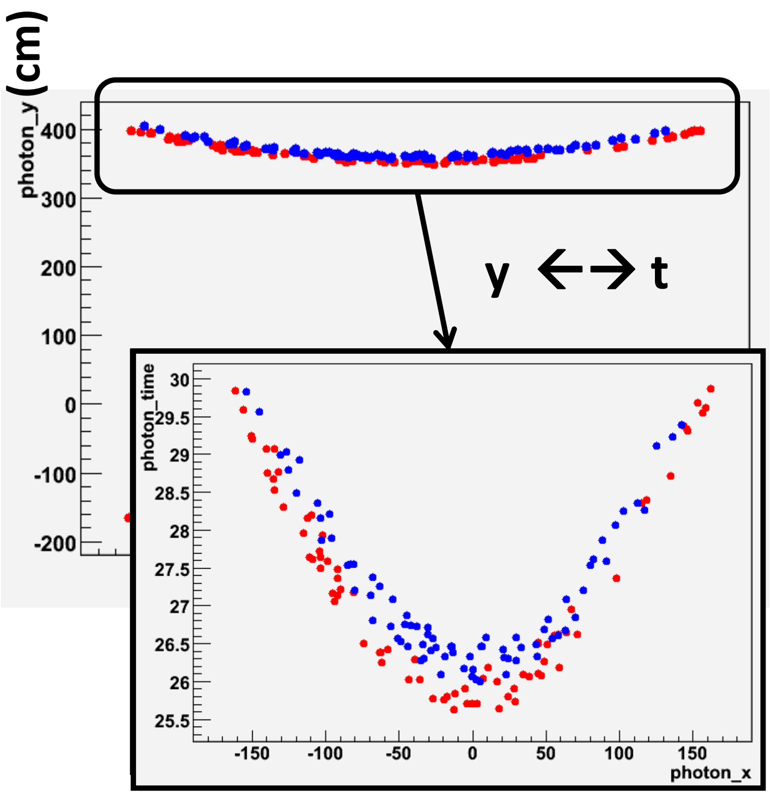

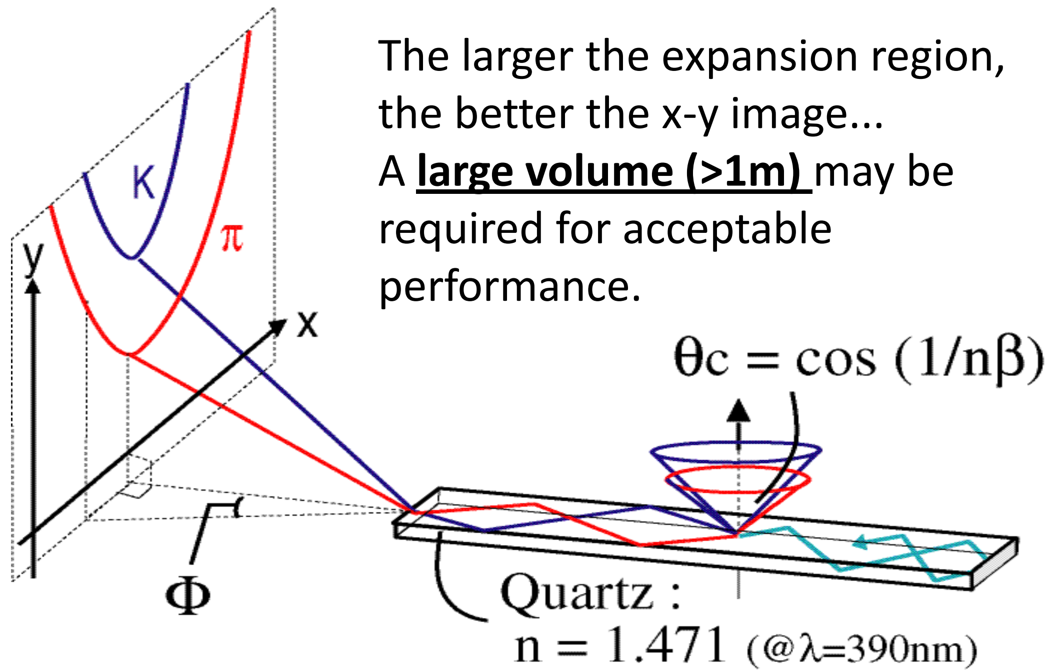

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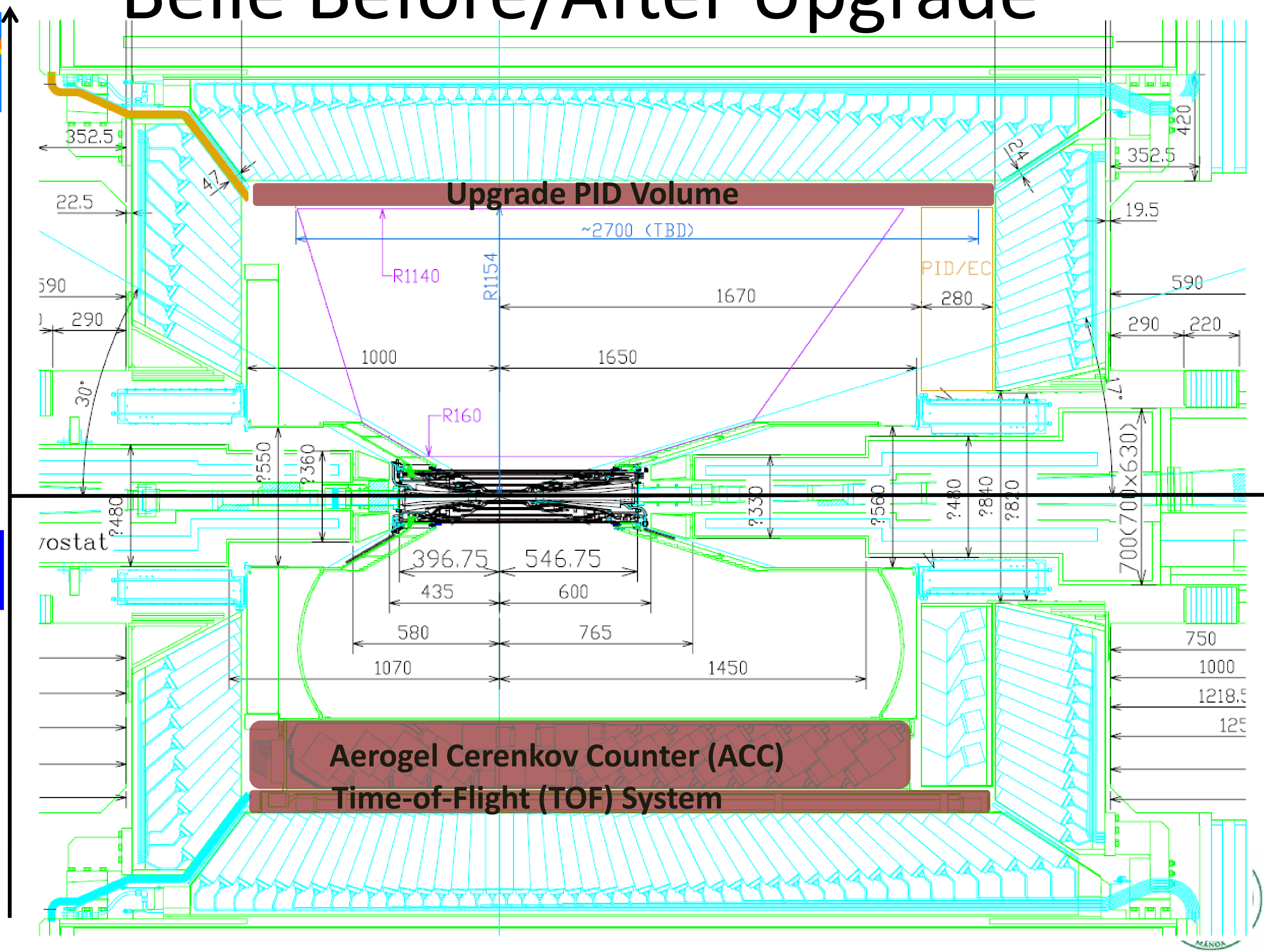
Belle Before/After Upgrade

Future (Belle II)

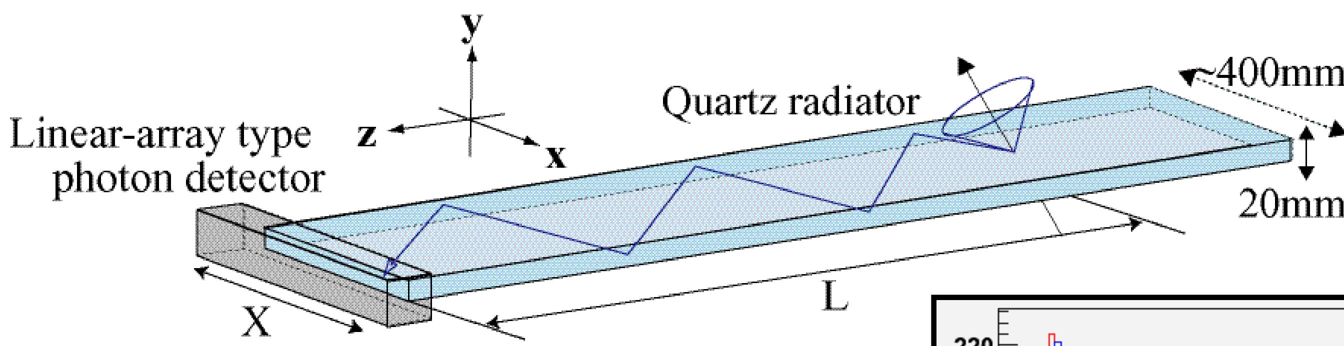
Curent (Belle)

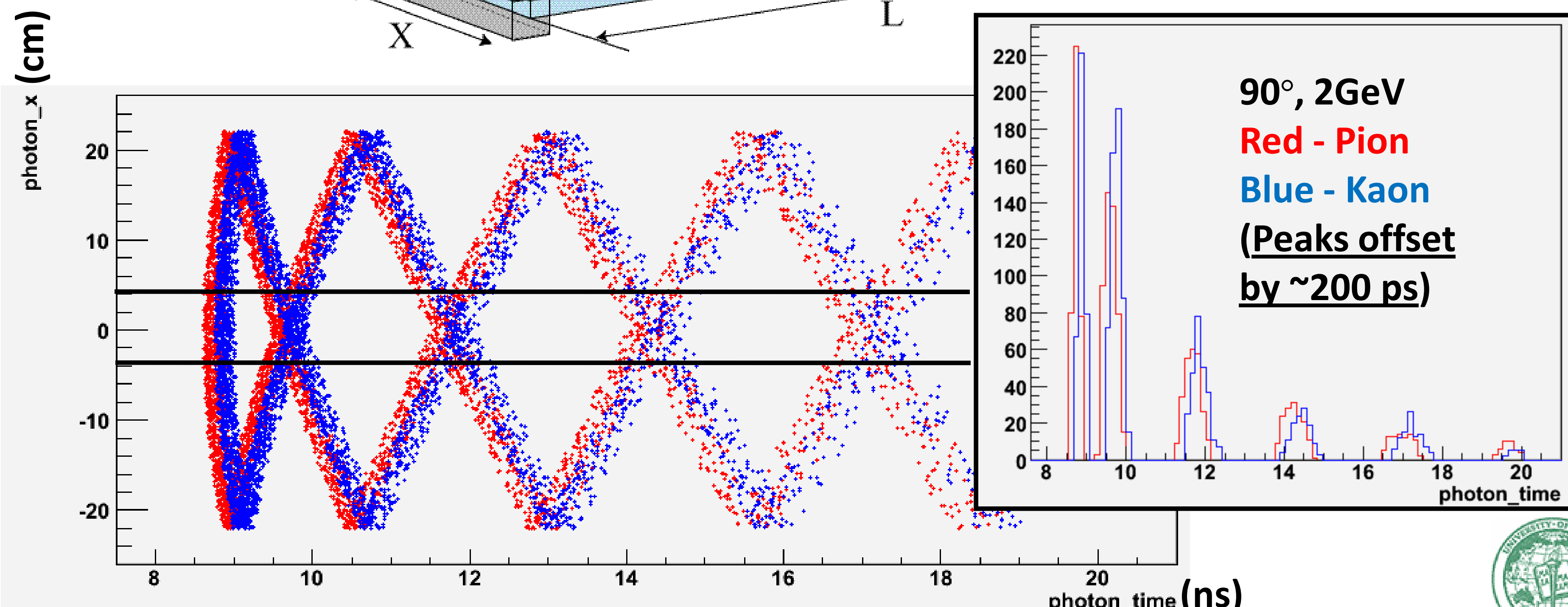


Time-of-Propagation (TOP) Counter

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

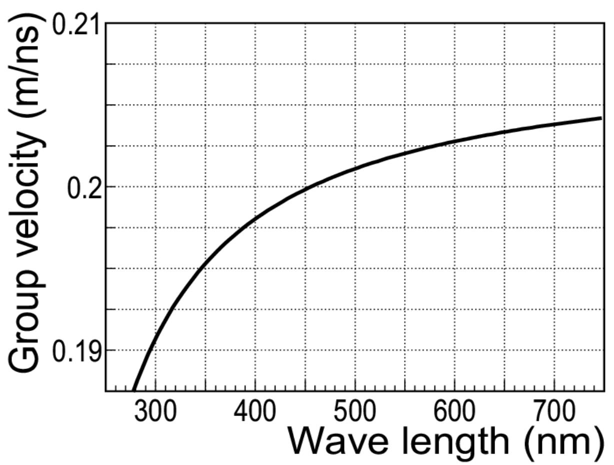
- Work at bar end, measure x,t, not y ➔ compact!





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.

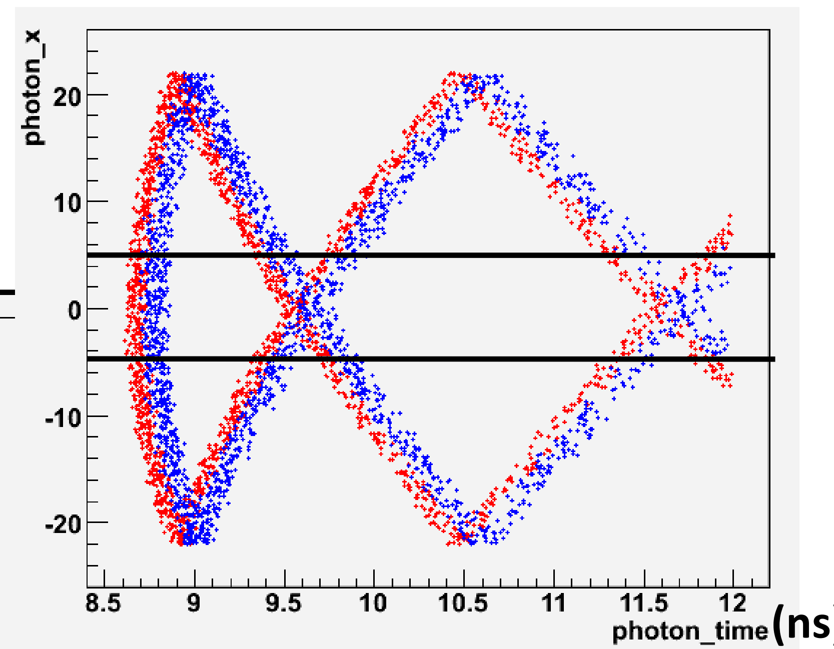


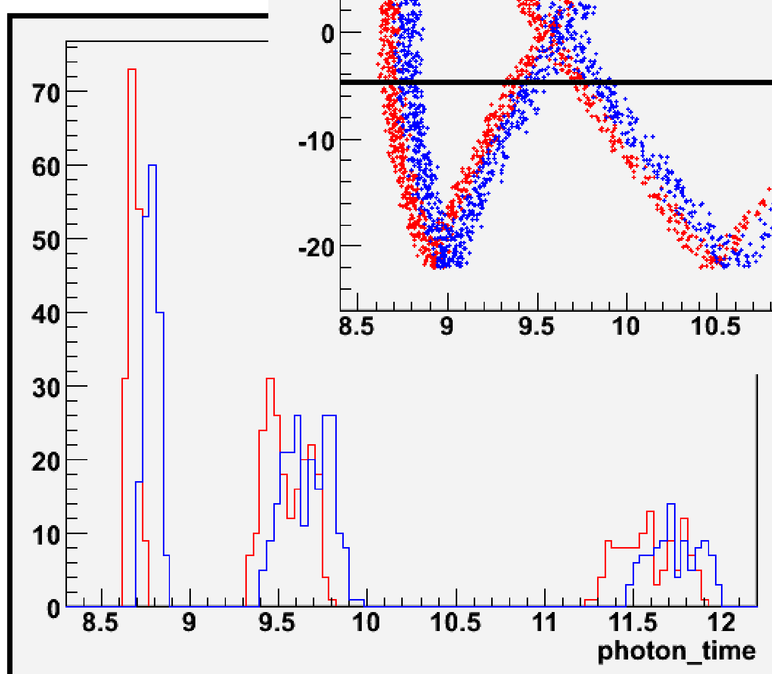
Simulated TOP – 2 GeV π^+ at 90°

Red – $\lambda \approx$ 525 nm

Blue – $\lambda \approx$ 375 nm

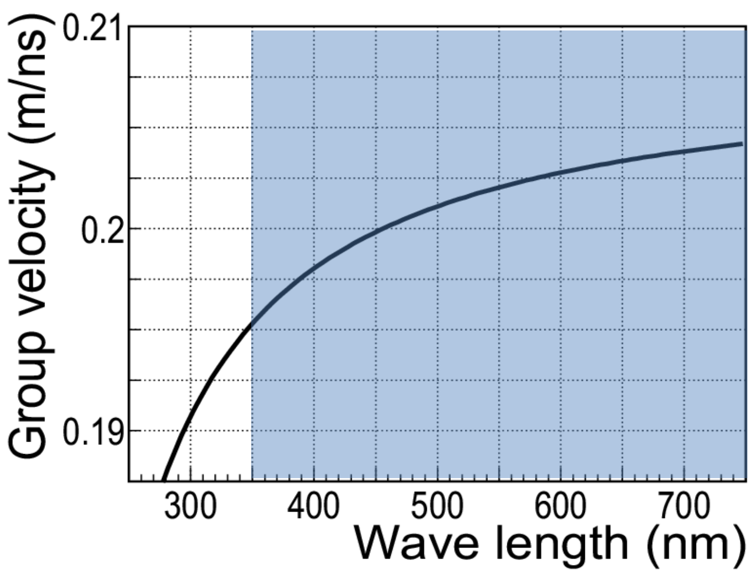
Red and blue offset by ~100 ps

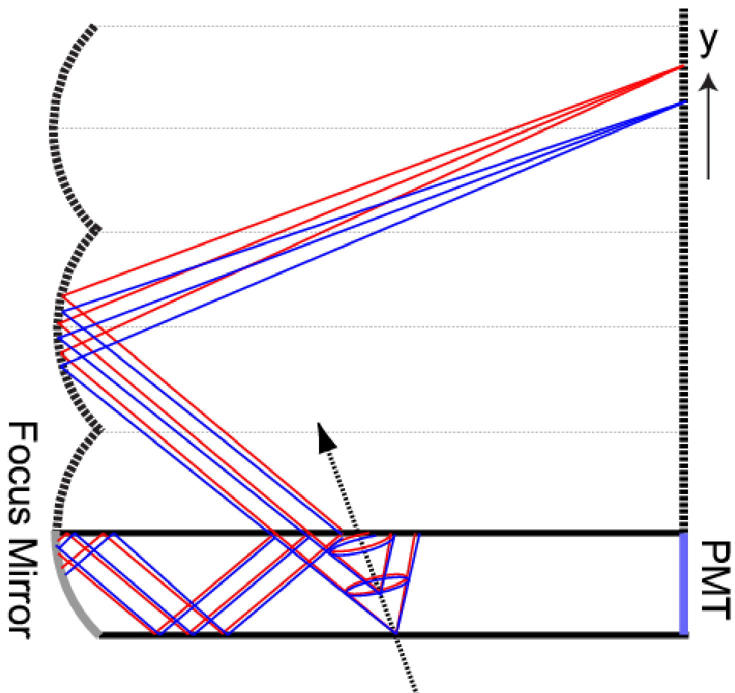




Focusing TOP (fTOP)

- Chromatic dispersion:
  - Add some pixelization in vertical direction ➔ different colors end up at different pixels.
  - 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 remove this for fraction of tracks in proper direction.



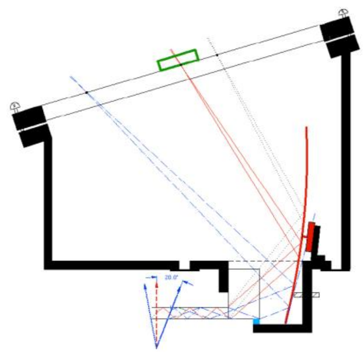


Quartz Cerenkov Device Landscape

- Competing concerns: performance vs. compactness

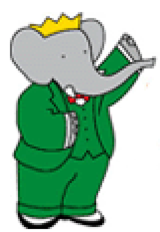
Performance

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

BaBar DIRC



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

Focusing TOP

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

TOP

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

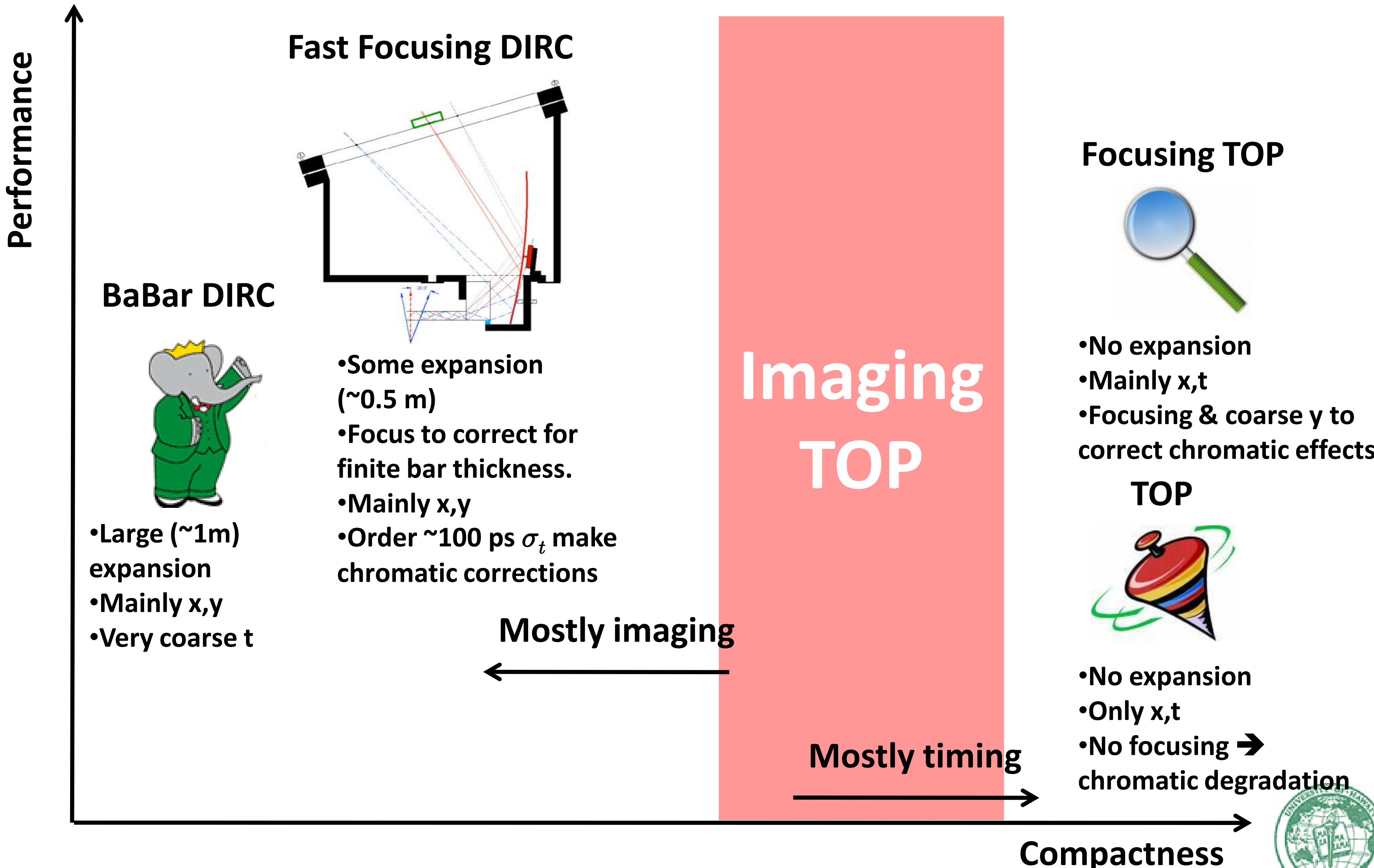
Mostly imaging ←

Mostly timing →

Compactness

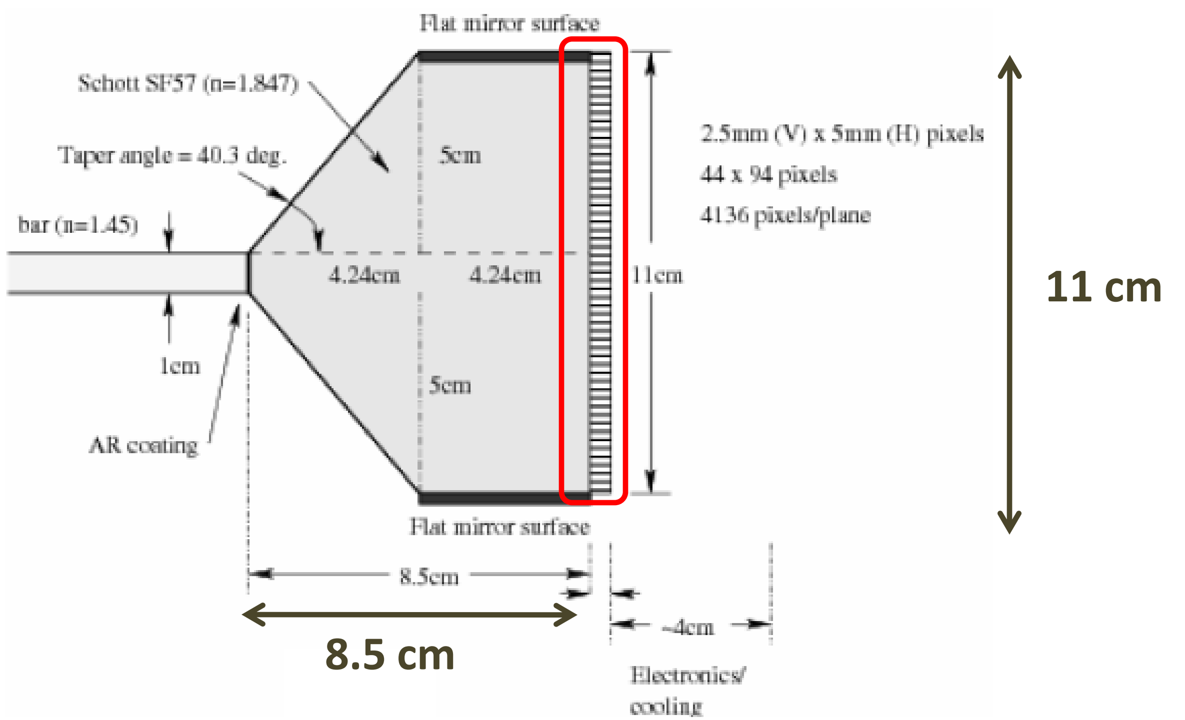
Quartz Cerenkov Device Landscape

- Competing concerns: performance vs. compactness



Imaging TOP (iTOP) – First Concept

- Limited expansion (~10 cm) – high optical index wedge (one on each end of bar) refraction keeps image compact.



Finely segmented solid state readout (2.5 mm x 5 mm)

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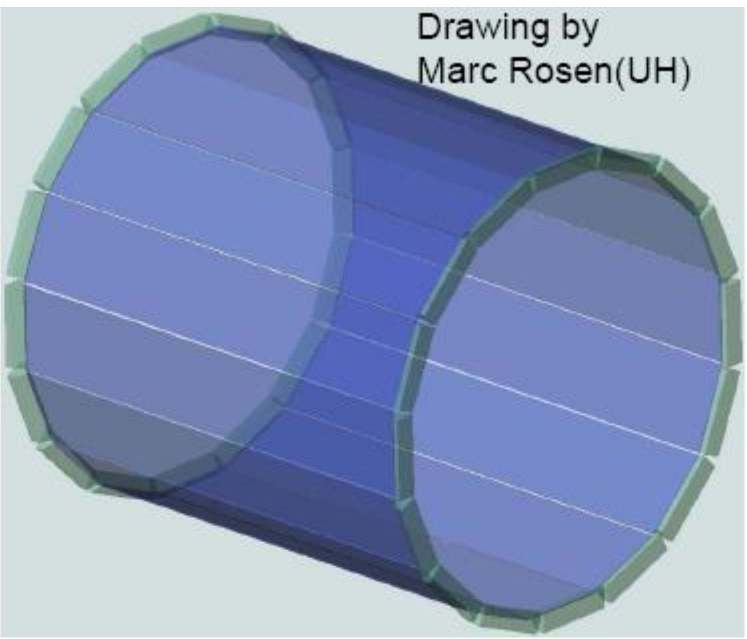
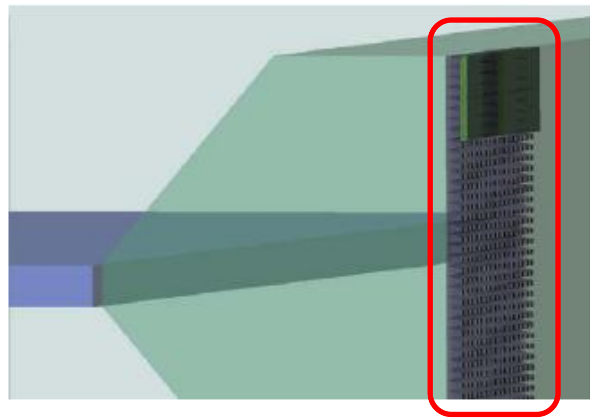
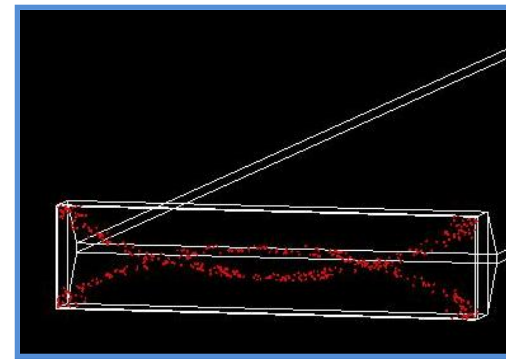
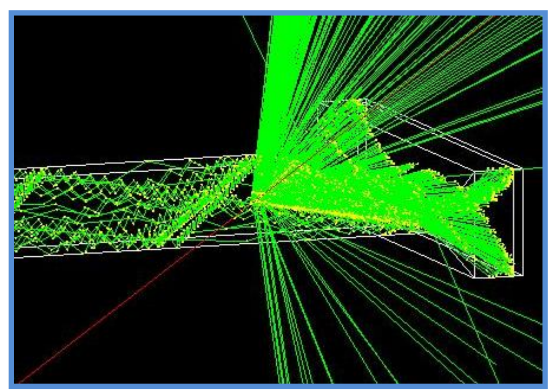






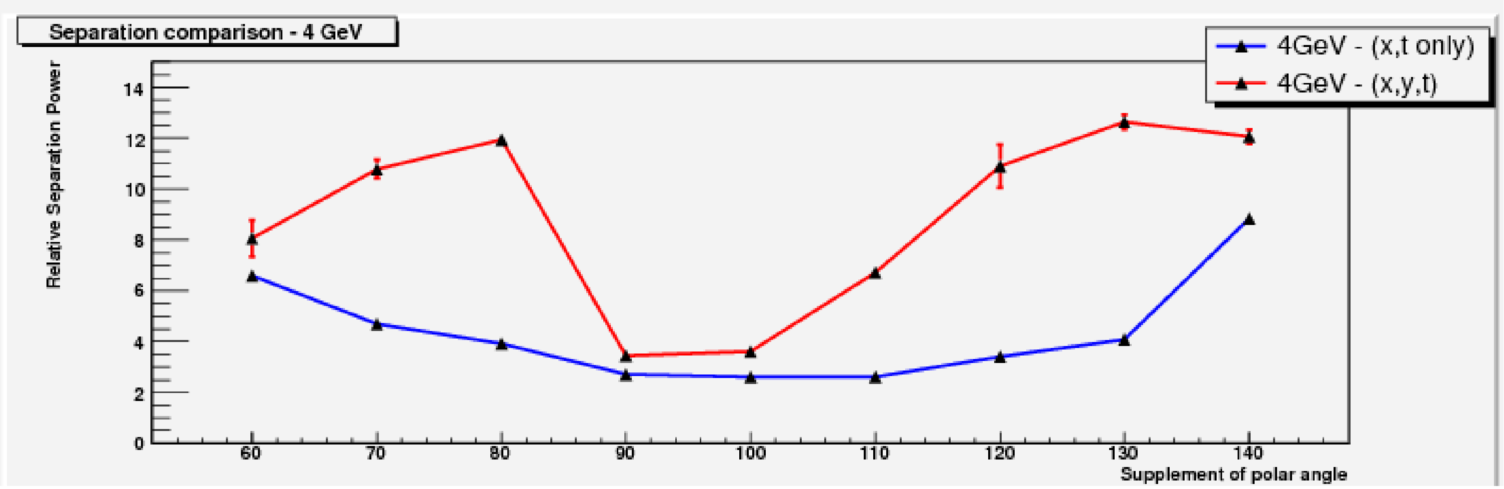


Geant4 visualization of a 40° π^+ event at 2GeV

Finely segmented solid state readout (2.5 mm x 5 mm)

Initial Concept Simulations

- Geant4 based results, w/ assumptions:
  - Relatively high photon detection efficiency for pixels: 50%
  - Single photon timing resolution of 30-50 ps
  - Perfect coupling out of expansion block into pixels.

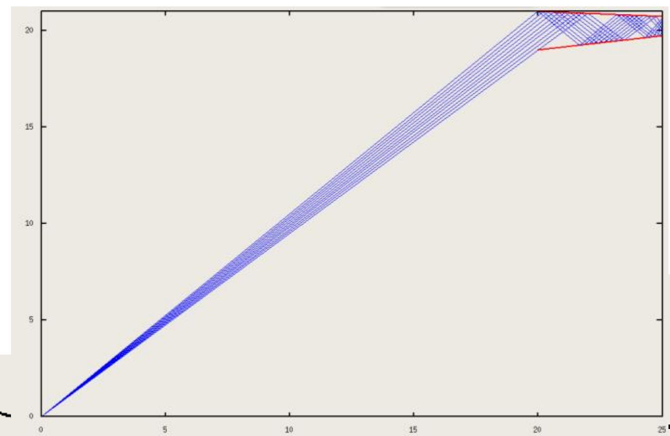


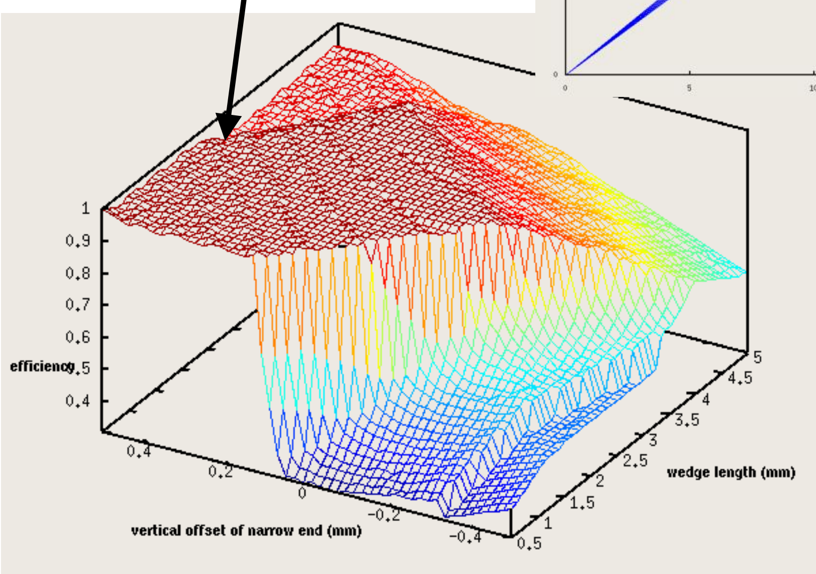
- Finely pixelated readout in 2 spatial dimensions helps, but perhaps unreasonably optimistic?
  - Also over-optimistic w/ other simulation parameters.

Drawbacks & Problems

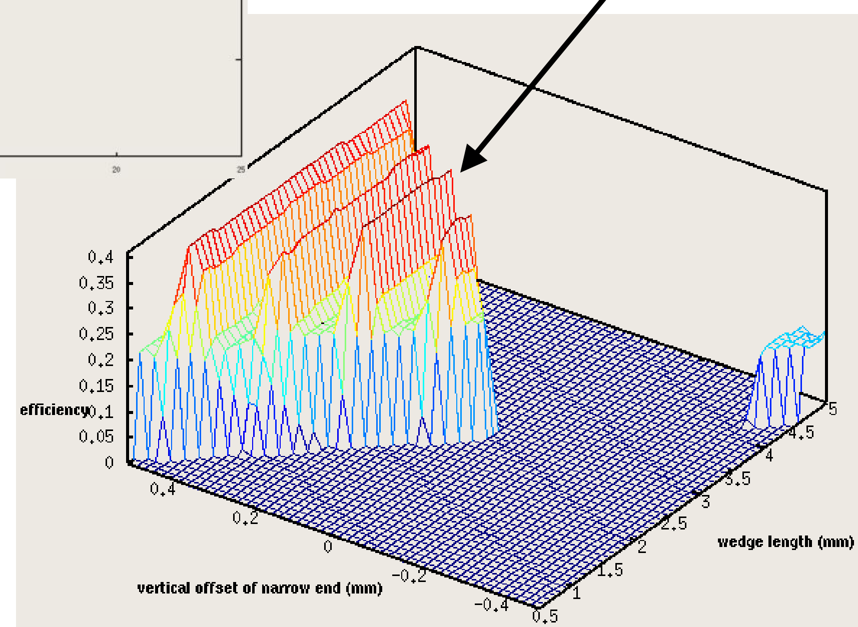
- Coupling out of expansion block into solid state devices proved to be difficult / highly inefficient.
- Performance and availability of solid state devices likely overestimated.
- Expansion areas create undesired mass in front of calorimeter in two θ regions.

With small offsets from bar axis, coupling can be done very efficiently (~100%).



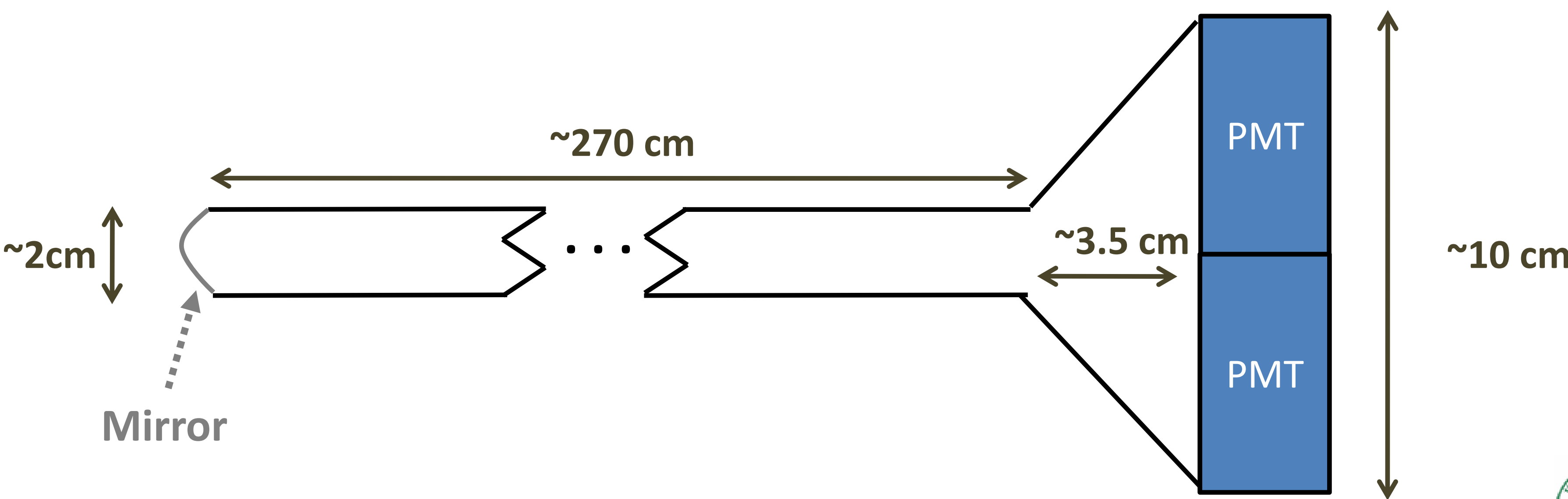


Off axis, maximum efficiency is limited (~40%)→light trapped.



Current iTOP Concept

- Starts with a single bar, single readout design of focusing TOP (including focusing mirror).
  - Adds a small expansion volume, also made of quartz. Precise dimensions vary with photodetector choice.



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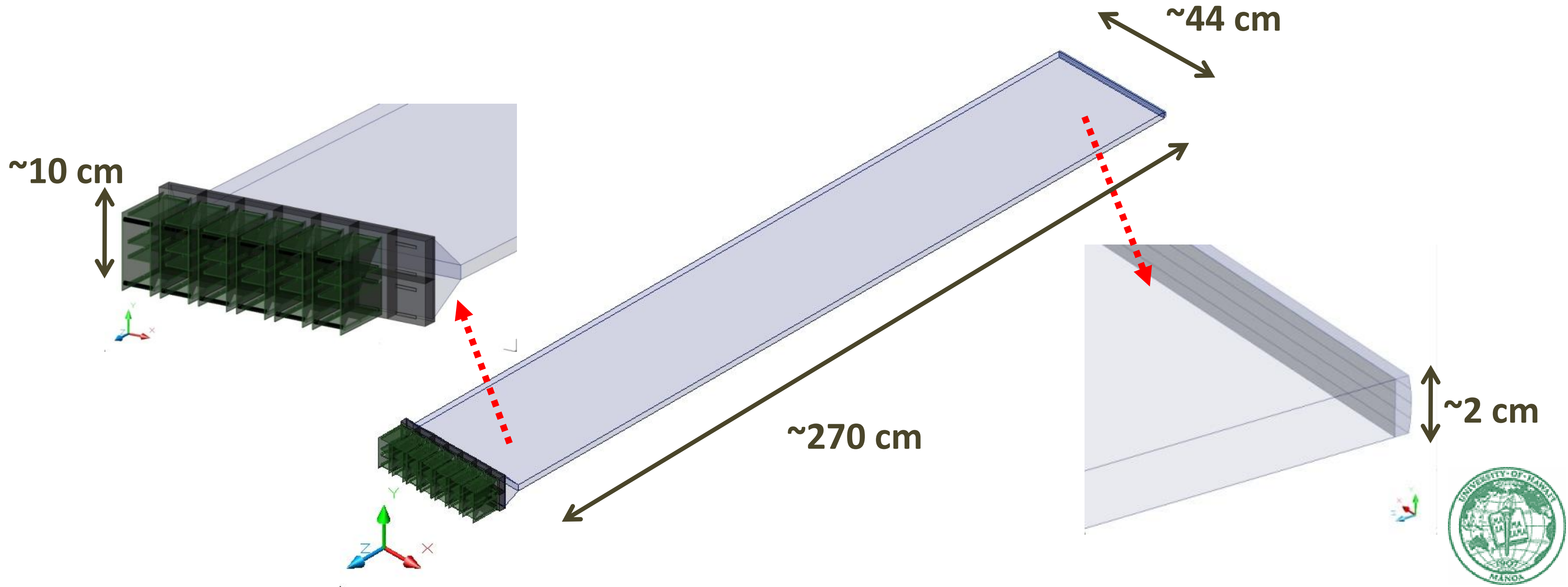


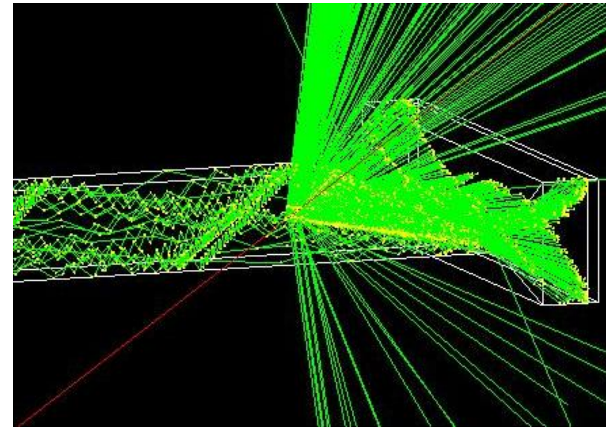
PMT Requirements / Options

- PMT needs σ_{TTS} < ~50 ps for any xTOP to function.
  - Performance further degraded by event start-time jitter (σ_{T_0})
- Working in 1.5T magnetic field ➔ MCP-PMTs
- Devices considered so far:
  - Hamamatsu SL10 MCP-PMT
    - Pixel size: 22 mm x 5.5 mm
    - Demonstrated σ_{TTS} ~ 40-60 ps
  - Photonis Planacon (10 μm pore)
    - Pixel size: ~ 6.4 mm x 6.4 mm
    - Comparable σ_{TTS} ~ 40-70 ps

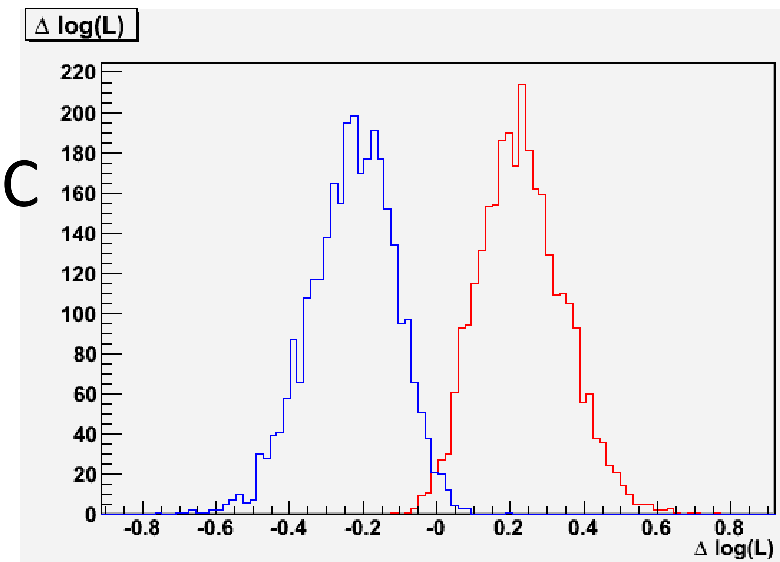
*K. Inami, et al.,
NIM A 592 (2008) 247-253

*C. Field, et al.,
NIM A 553 (2005) 96-106

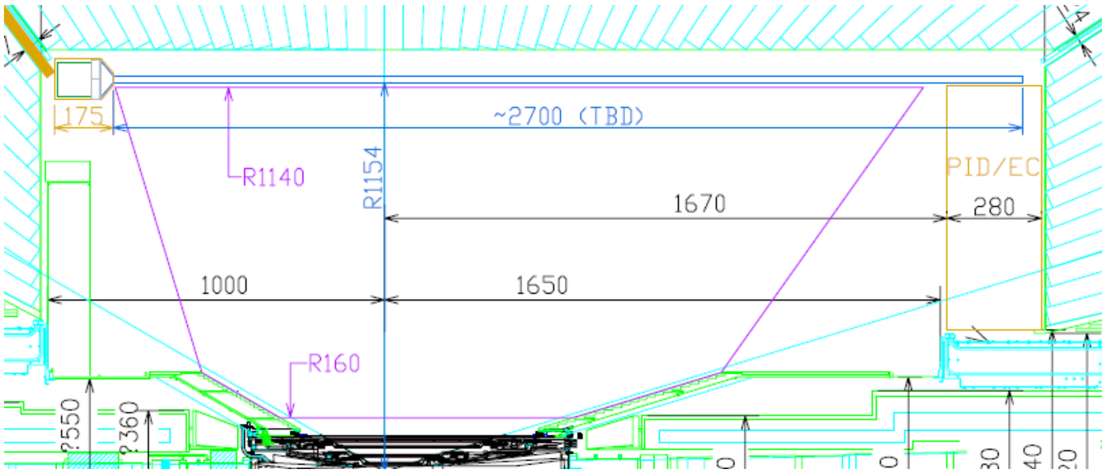
Simulation Studies

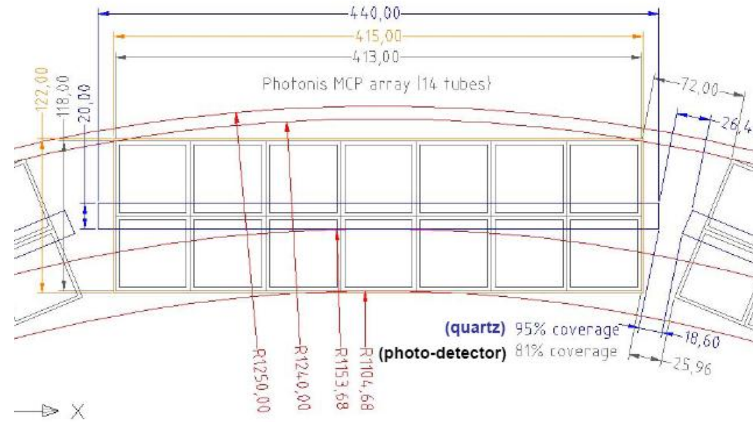


- Geant4
  - Generation of Cerenkov photons
  - Propagation to detector plane
  - PMT geometry (pads, dead space)
  - PMT spectral response (QE)
  - PMT collection efficiency
  - Transit time spread (TTS) of phototube
  - Event start time (T_0) jitter
  - Readout resolution
- Generate PDFs for K/π in MC
- Δlog(Likelihood) using K/π hypothesis
  - Efficiencies, fake rates:
    - $\pi^{\pm}$, $K^{\pm}$
  - Separability

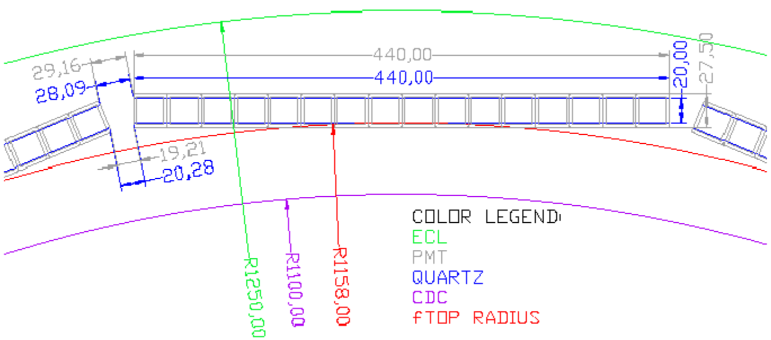


iTOP vs. fTOP Comparison

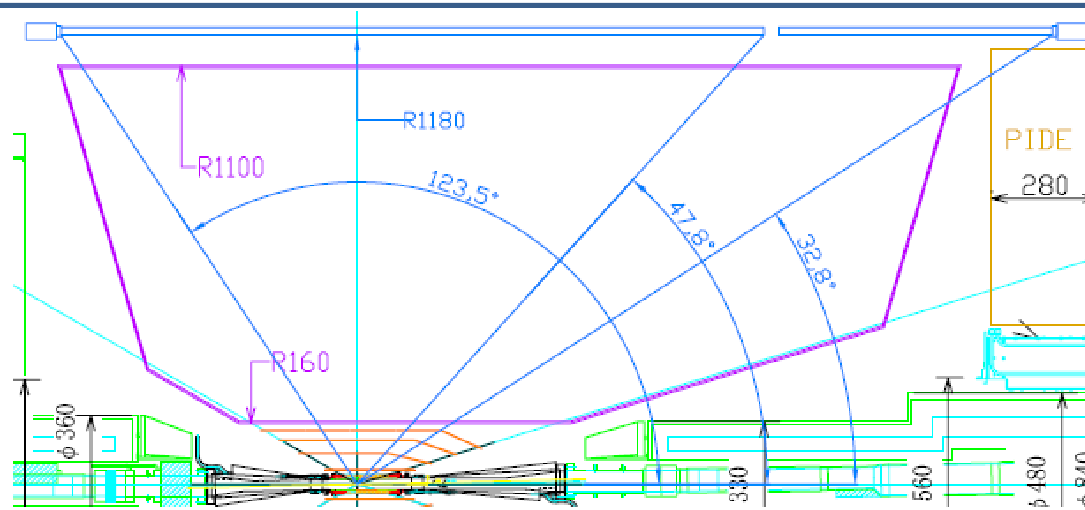




iTOP w/ backward readout of 7x2 10 μm pore Photonis MCP-PMTs

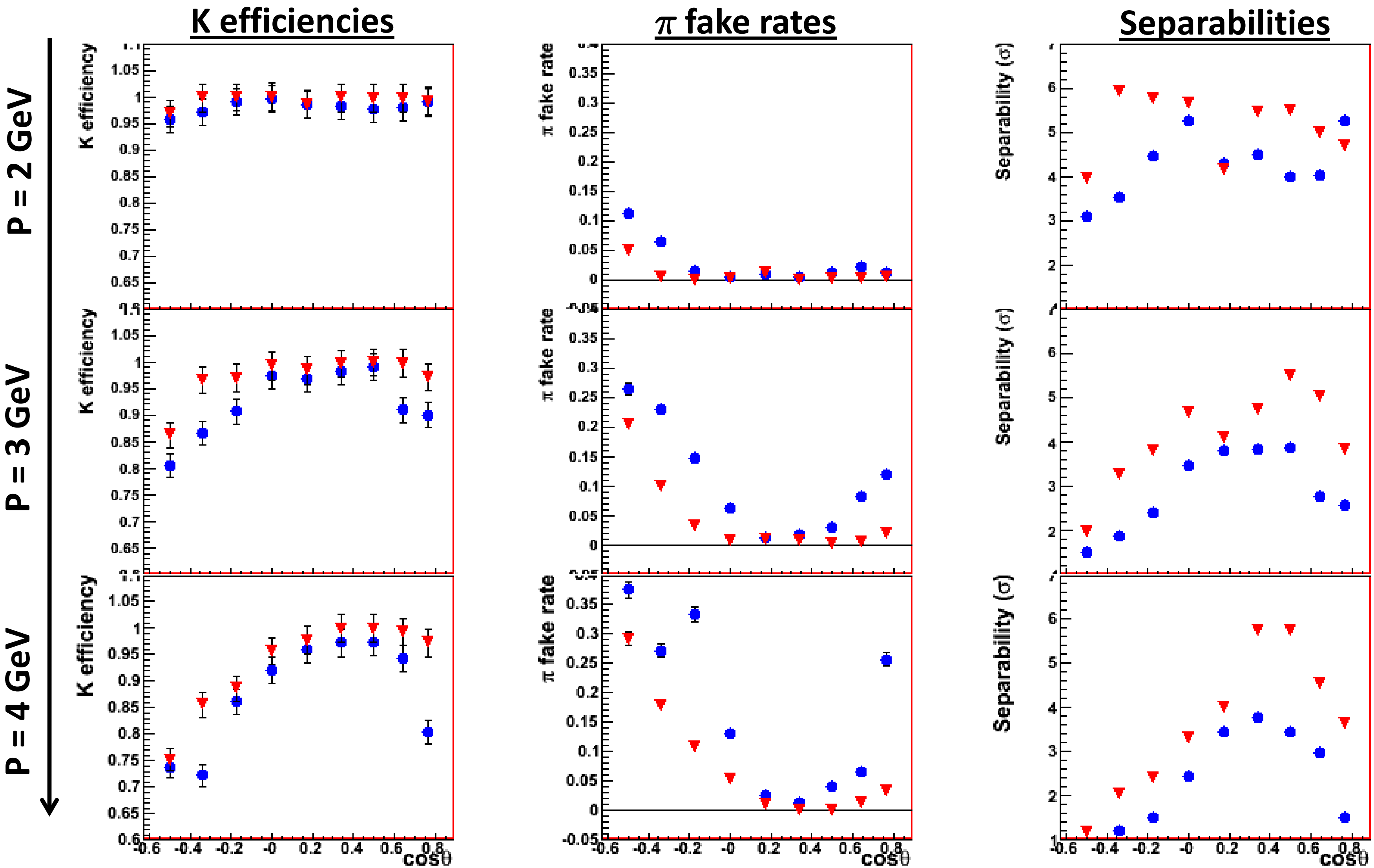


fTOP w/ forward+backward readout of 16 Hamamatsu SL10 MCP-PMTs each Belle II baseline [arXiv:0810.4084]



*Many configurations for both types possible; these are a Belle II biased sample…

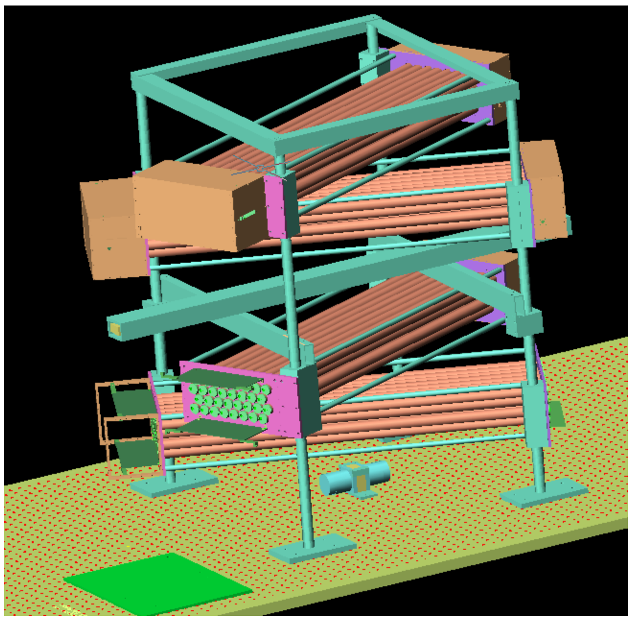
iTOP vs. fTOP Simulated Performance

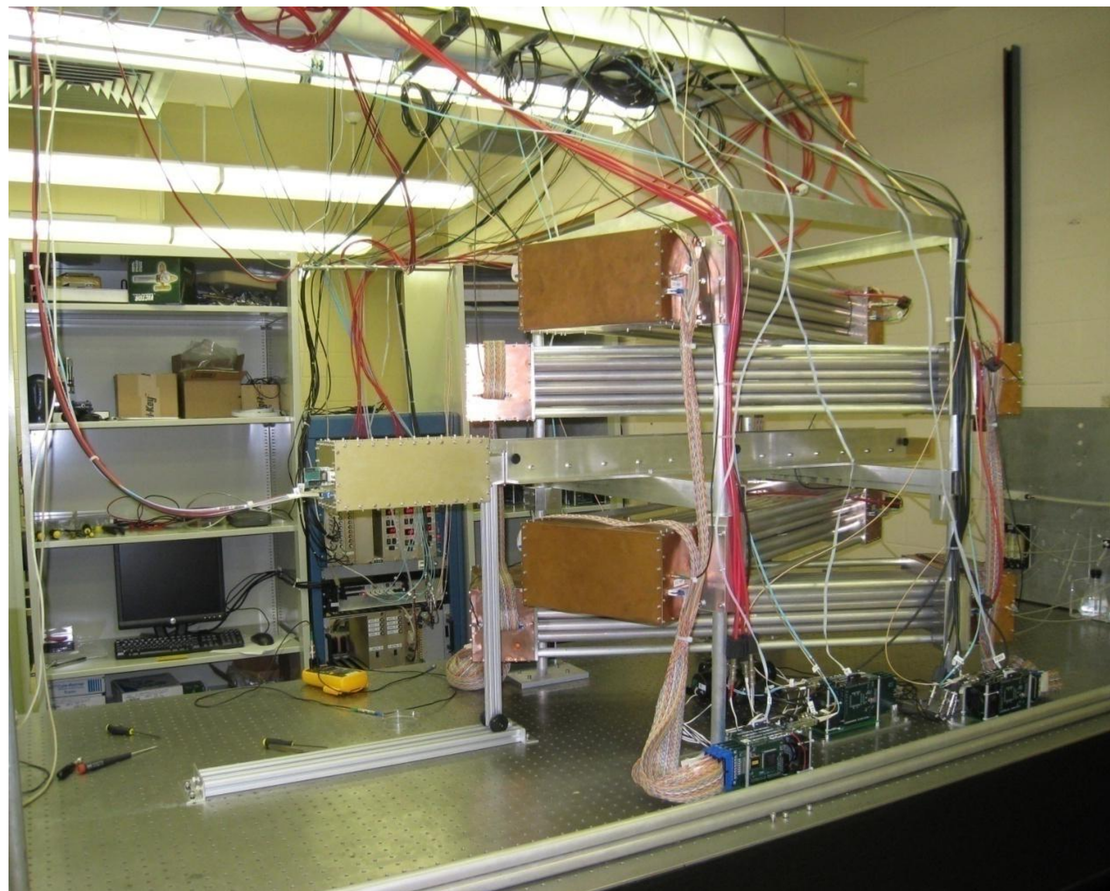


→Distinct improvements with iTOP!

Prototype and Validation

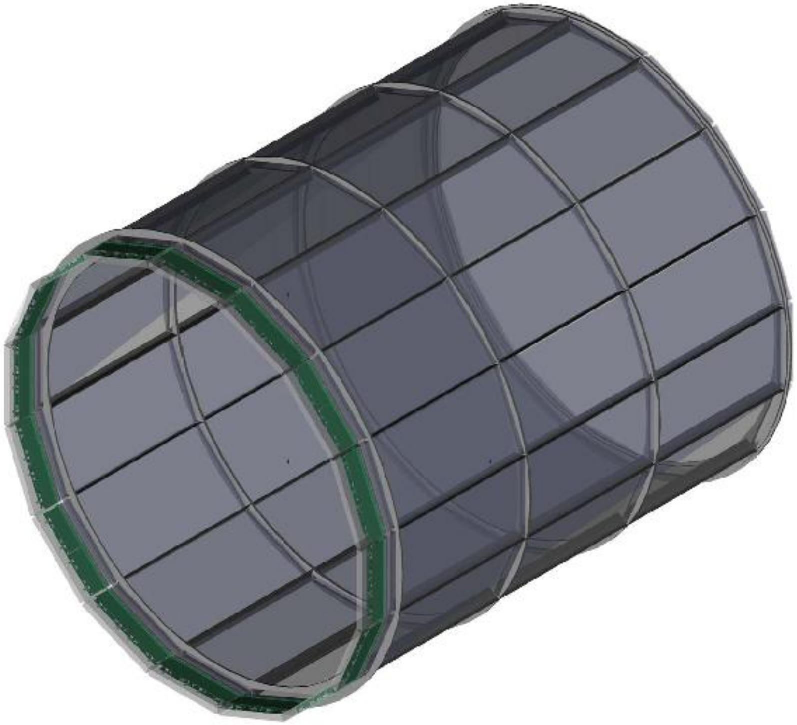
- A cosmic test stand has been constructed at University of Hawaii to test readout electronics and begin validating simulation…

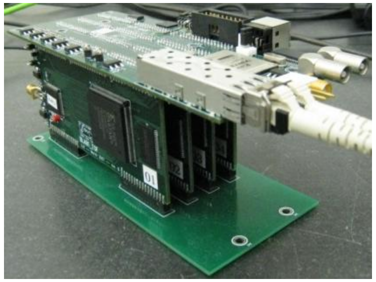


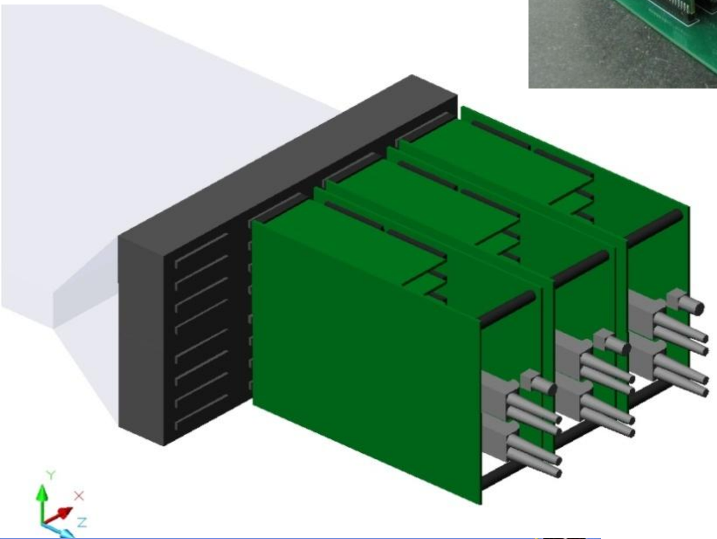


*Prototype uses a narrow bar: ~4 cm x 2 cm x 120 cm (approximately 1/10 length of full scale bar)

Full System Engineering



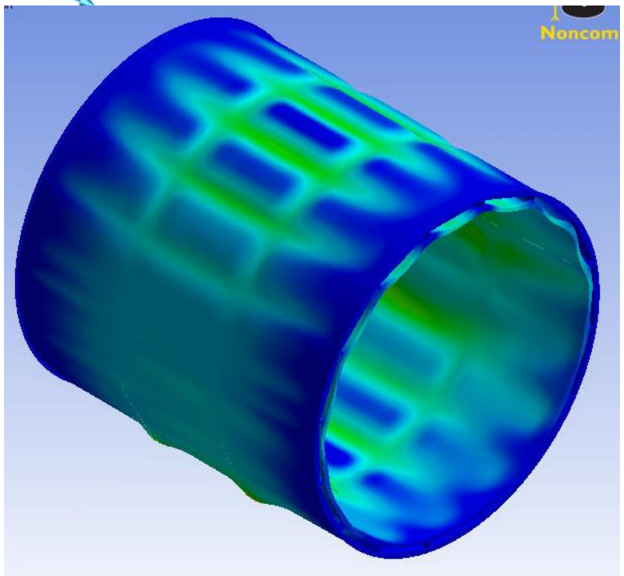


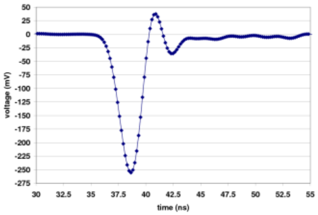


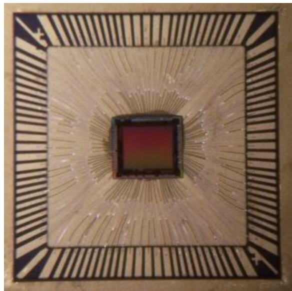
Engineering considerations are being studied for various configurations:

•Quartz bars: total number, coverage, structural support, cost, **available space**

•Electronics readouts: speed, data rates, radiation hardness, timing performance







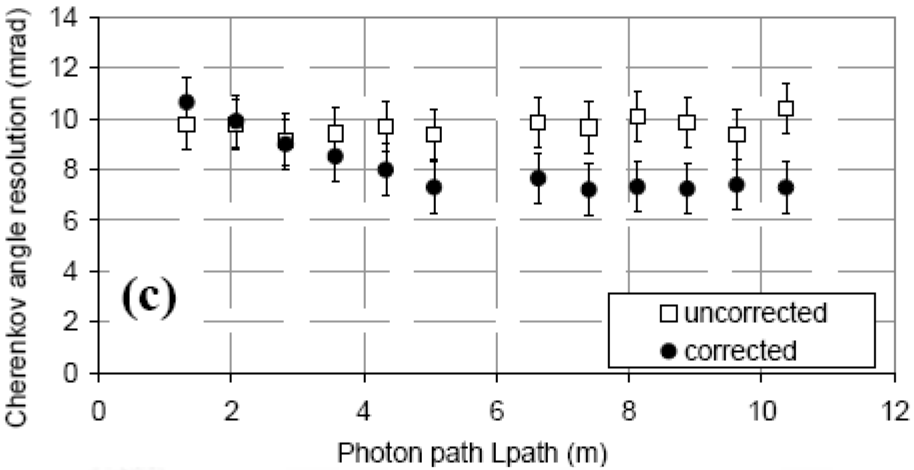
Outlook & Summary

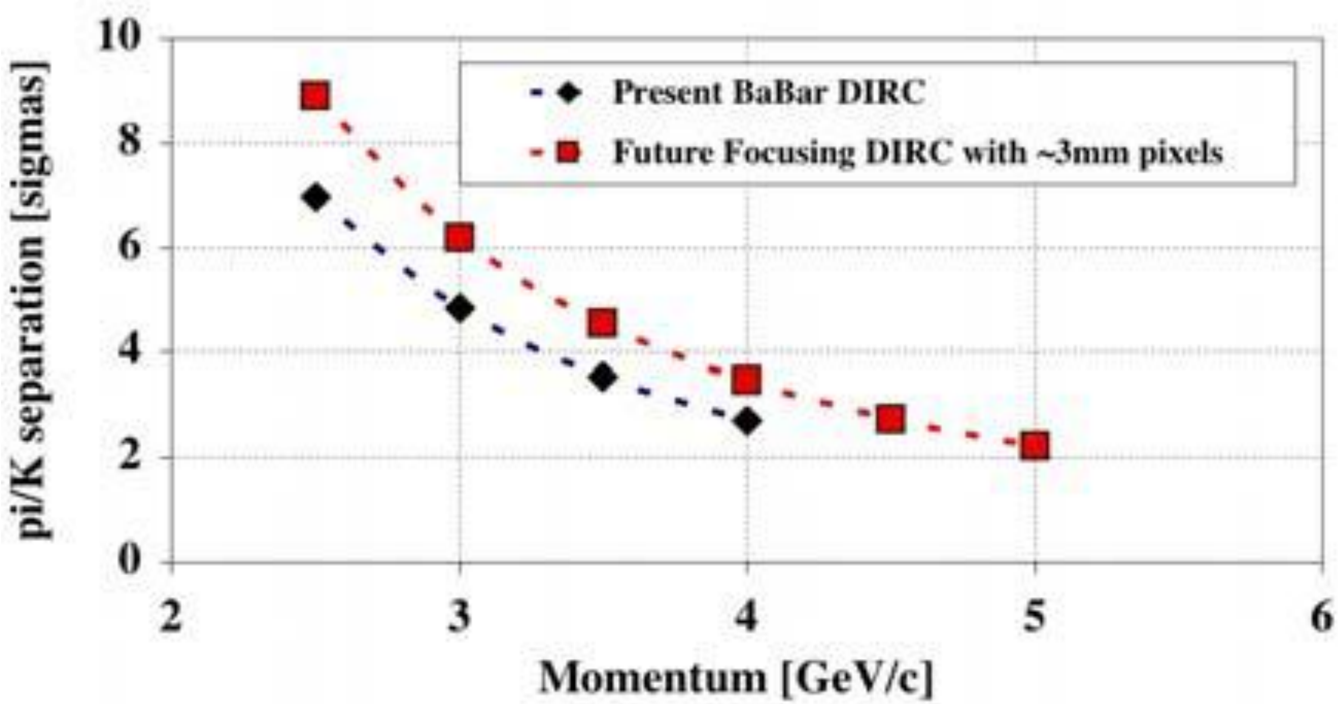
- Ongoing efforts:
  - Optimize geometry.
    - e.g., mirror & expansion volume shapes
    - For Belle II: Can we really make it fit?
  - Add more and more realism into simulations.
    - e.g., optical couplings, PMT cross-talk, etc.
  - Validate simulation results w/ prototype.
- Imaging Time-of-Propagation counter
  - Middle ground between "primarily imaging" and "primarily timing" classes of DIRCs.
  - Performance improved over TOP/fTOP, with only a small addition to detector envelope.

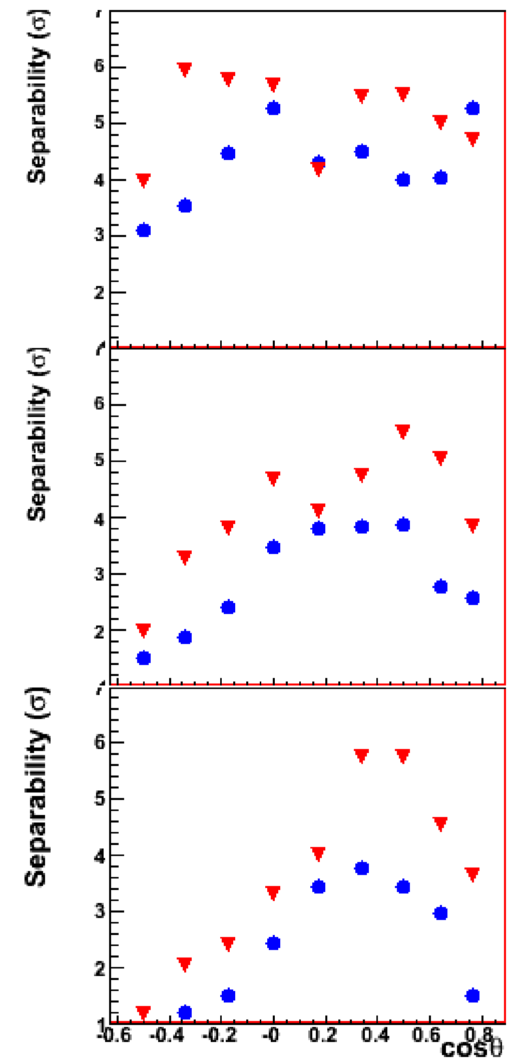
BACKUP SLIDES

Comparisons w/ (f)DIRC

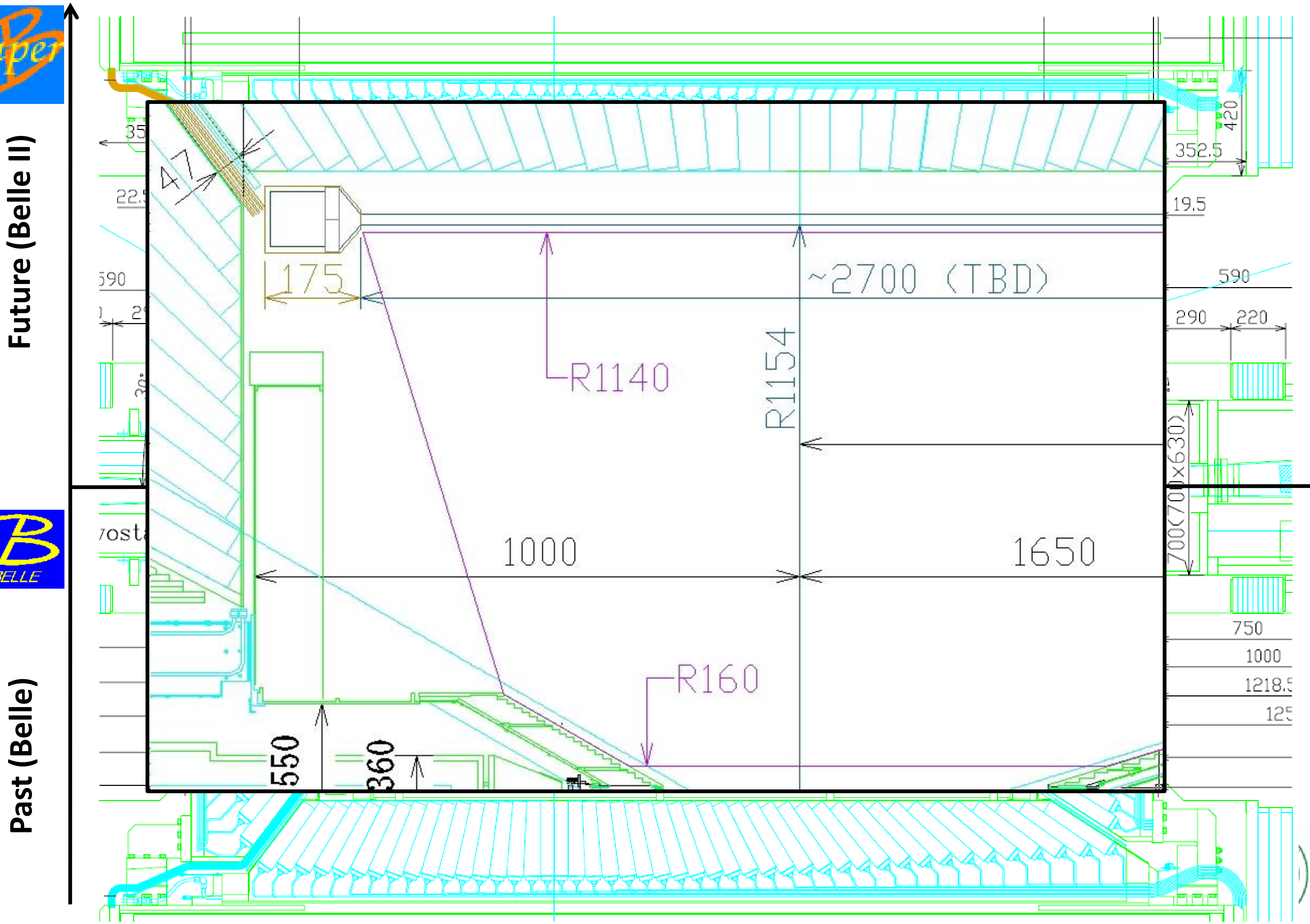
NIM A, 595, 104-107 (2008)





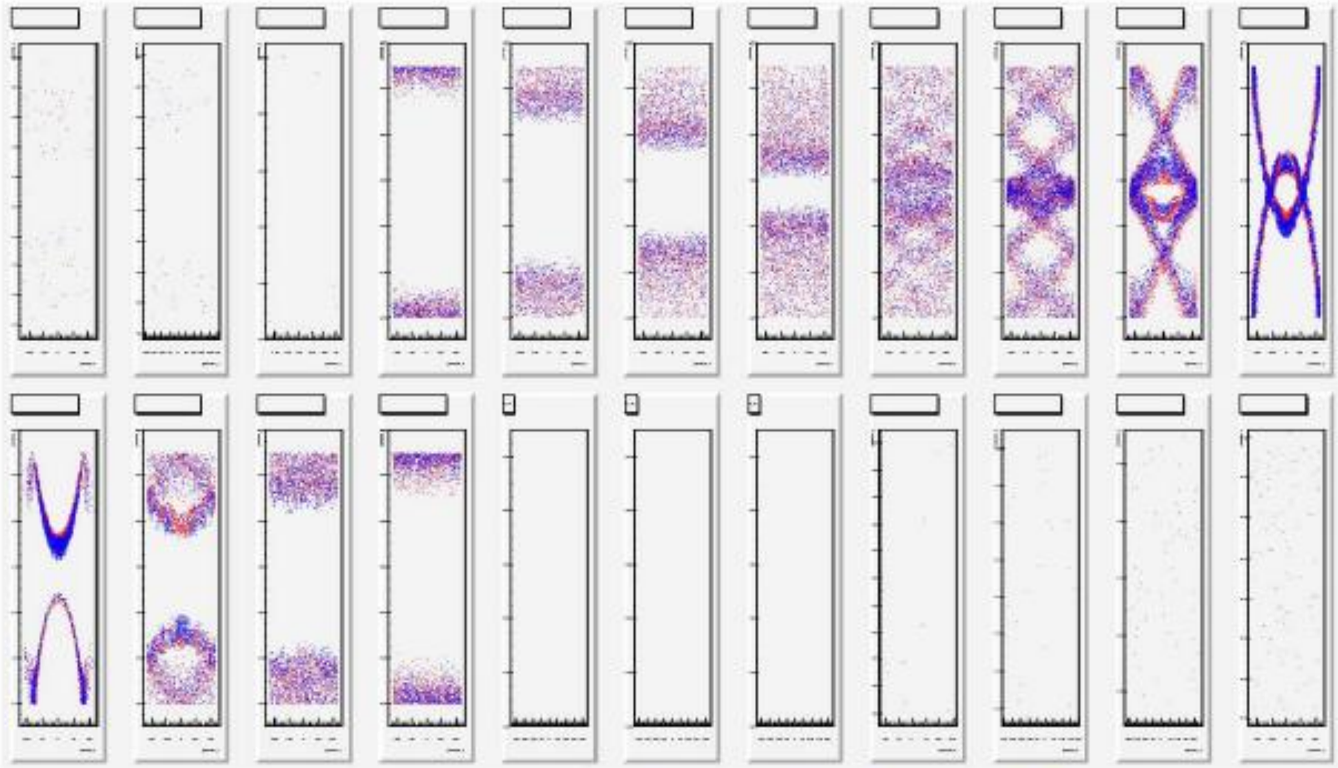


iTOP in Belle II



Trigger Timing?

- Use FPGA (simple) pattern recognition to improve



- 25cm segments ~ 2ns trigger timing, within 200ns

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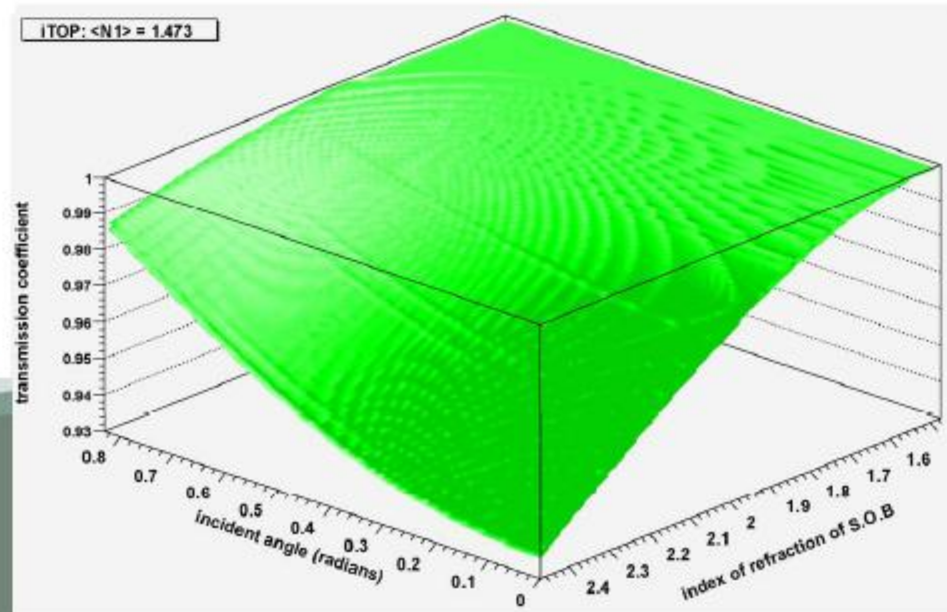
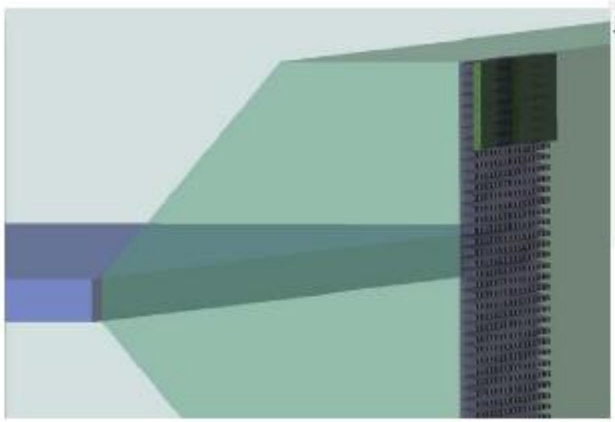
Stand-Off Block (SOB) Coupling





44 x 92 pix/plane = 4048 channels
16 bars x 2 ends x 4048 = ~130k channels

20

Comparison of PID Methods