Picosecond Timing with Cherenkov Light in a "Head-on" Geometry

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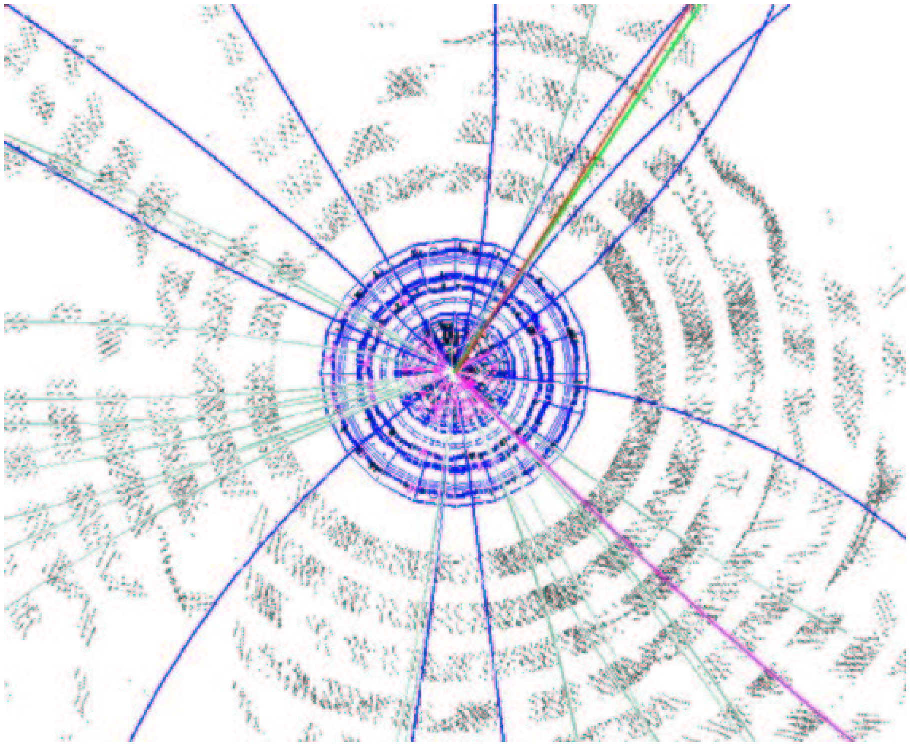
Overview

- Time of flight measurements in particle physics
- Cherenkov radiation production and detection
- Estimating the number of photons detected
- Estimating the time resolution

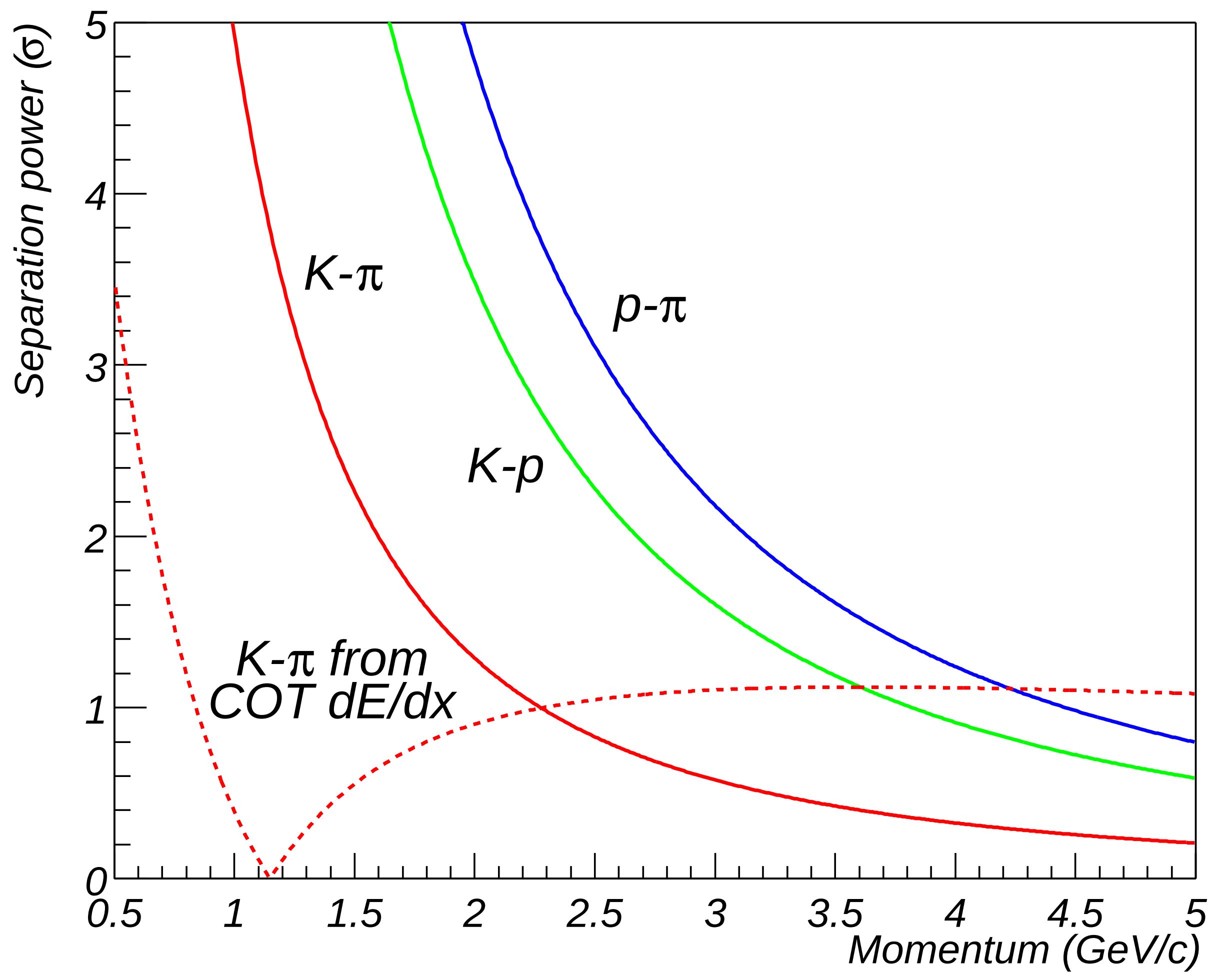
Time of Flight for Particle ID



- A collision will produce many secondary particles
- Identifying end particles helps us identify intermediate particles
- Identifying these particles helps us understand physics, e.g., flavor

- Momentum and penetration depth are not enough to tell charged hadrons (π/K/p) apart
- Time of flight and momentum can give us mass, which can distinguish these particles

Time of Flight for Particle ID

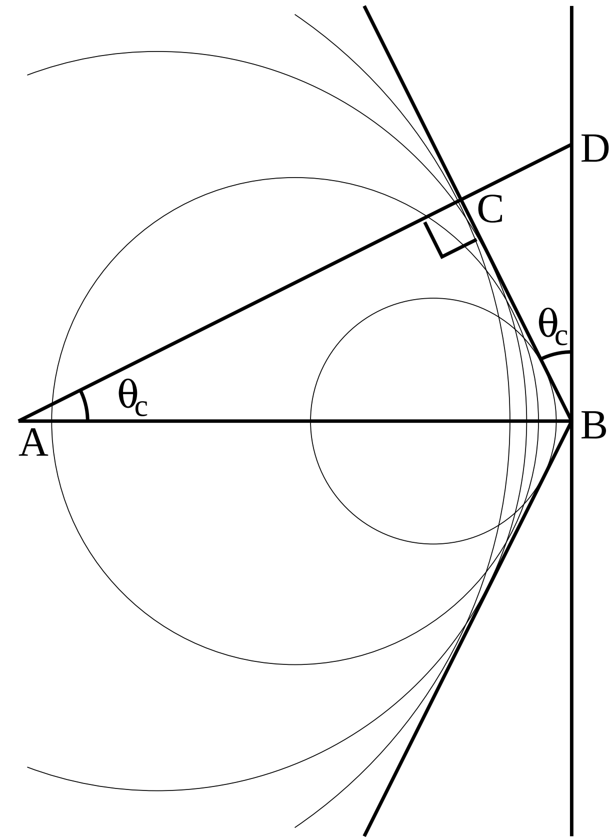


Separation power based on 100 ps resolution

Cherenkov Radiation

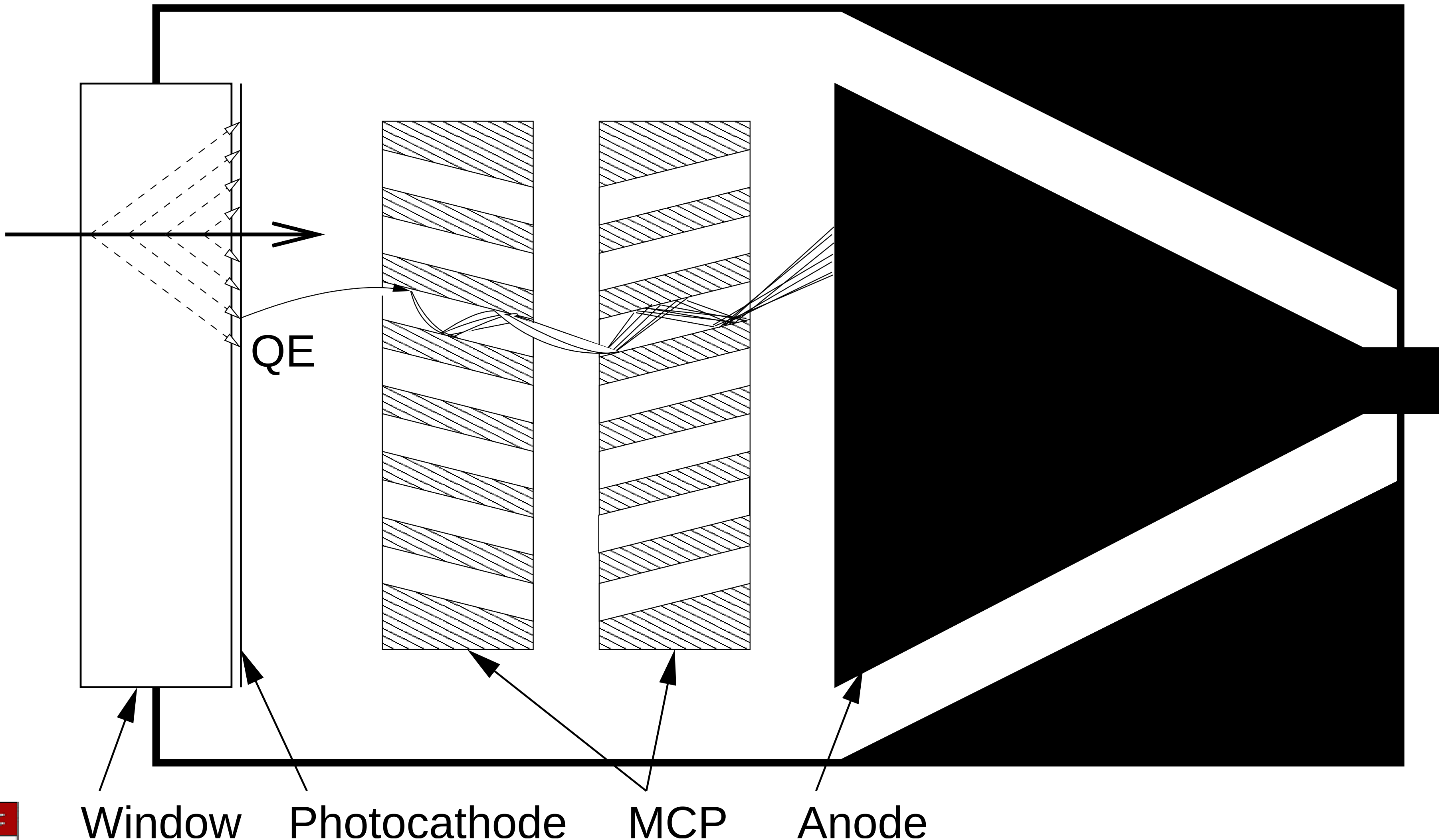
- Emitted from a charged particle when it exceeds c/n
- Emitted instantaneously — not a scintillator effect
- Forms a cone
- Number of photons given by

$$\frac{\partial^2 N}{\partial x \partial \lambda} = \frac{2\pi Z^2 \alpha}{\lambda^2} \left(1 - \frac{1}{\beta^2 n(\lambda)^2} \right)$$



Detection

- Micro-channel Plate Photomultiplier Tubes (MCP PMTs)



Sample Detectors

- We chose to use 5 Hamamatsu detectors as examples

Model R3809U-	Spectral Range (nm) Min.	Peak	Max.	Photo-cathode Material	Window Material	Peak QE (%)
50	175	430	850	Multi-alkali	Quartz	20
51	175	600	900	EMA [a]	Quartz	8.3
52	175	400	650	Bi-alkali	Quartz	20
57	110	230	310	Cs-Te	MgF_2	11
58	110	430	850	Multi-alkali	MgF_2	20

http://usa.hamamatsu.com/assets/pdf/catsandguides/PMTCAT_special_mcp-pmt.pdf

[a] Extended Red Multi-alkali

- All have window thickness of 3.2 mm
- Graph of QE vs. wavelength includes window losses

Estimating the Number of Photons

- Integrate

$$\frac{\partial^2 N}{\partial x \partial \lambda} = \frac{2\pi Z^2 \alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n(\lambda)^2}\right)$$

- $Z^2 = 1$; $\beta = 1$
- Estimate $n(\lambda)$ with Sellmeier coefficients, taken from *Handbook of Thermo-Optic Coefficients of Optical Materials with Applications* (Ghosh, 1998)
  - Good to fifth decimal place
  - Use n_o for birefringent materials
- QE sampled from Hamamatsu graph; linear interpolation between samples

Estimating the Number of Photons

- For each wavelength:
  - Integrated over thickness of the radiator (dx = 10 μm)
  - Multiplied by QE to simulate detection
- Integrated over wavelengths ($d\lambda$ = 1 nm)

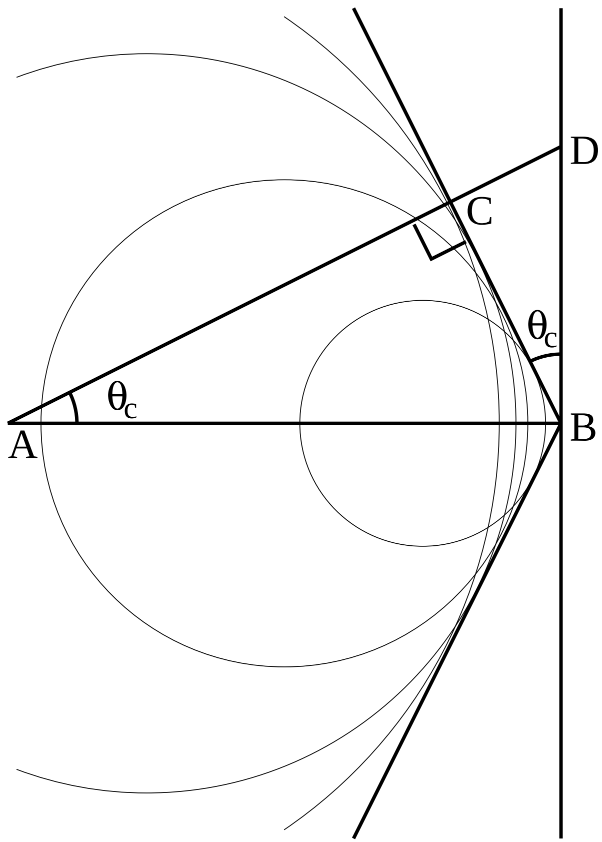
Model R3809U-	50	51	52	57	58
Window Material	Quartz	Quartz	Quartz	MgF_2	MgF_2
Photons Detected	49	13	47	38	74

- Enough photons to make this practical

Time Resolution

Two main factors affect time resolution

- Spread in arrival of Cherenkov radiation to photo-cathode



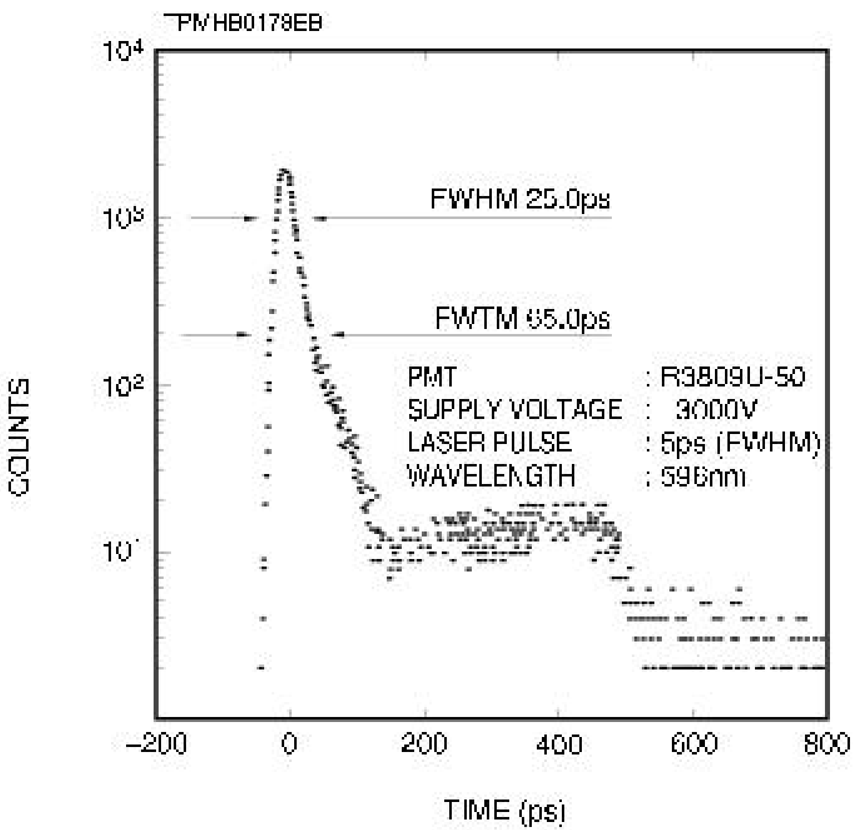
$$\cos\theta_c = \frac{1}{\beta n}$$

$$\Delta t = \frac{x}{\beta c}\left(\beta^2 n^2 - 1\right)$$

Time Resolution

Two main factors affect time resolution

- Spread in arrival of Cherenkov radiation to photo-cathode
- Transit time spread (jitter) of PMT



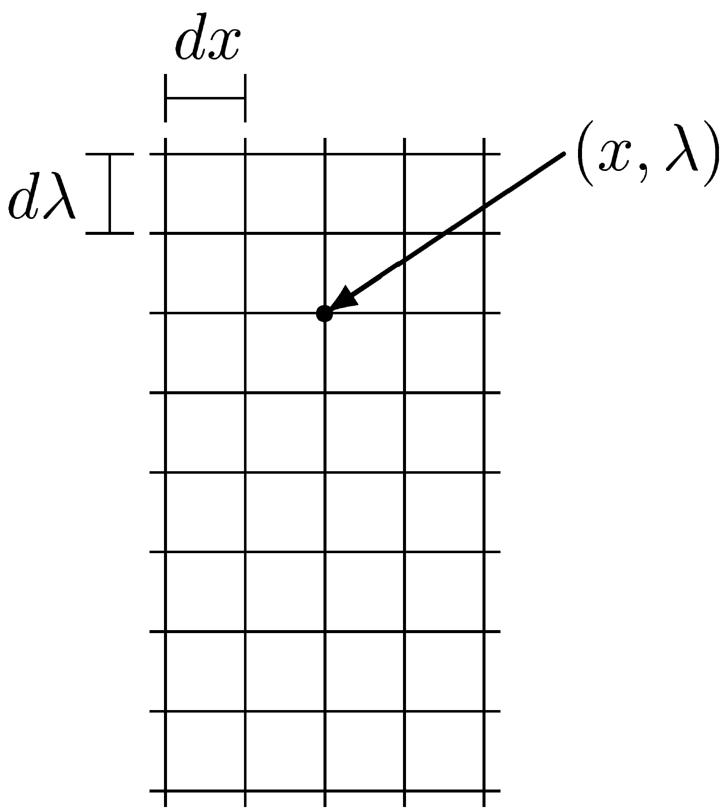
Data from Hamamatsu for the R3809U line.

We approximate this curve by a Gaussian with FWHM of 25 ps.

http://usa.hamamatsu.com/assets/pdf/parts_R/R3809U-50.pdf

Estimating the Time Resolution

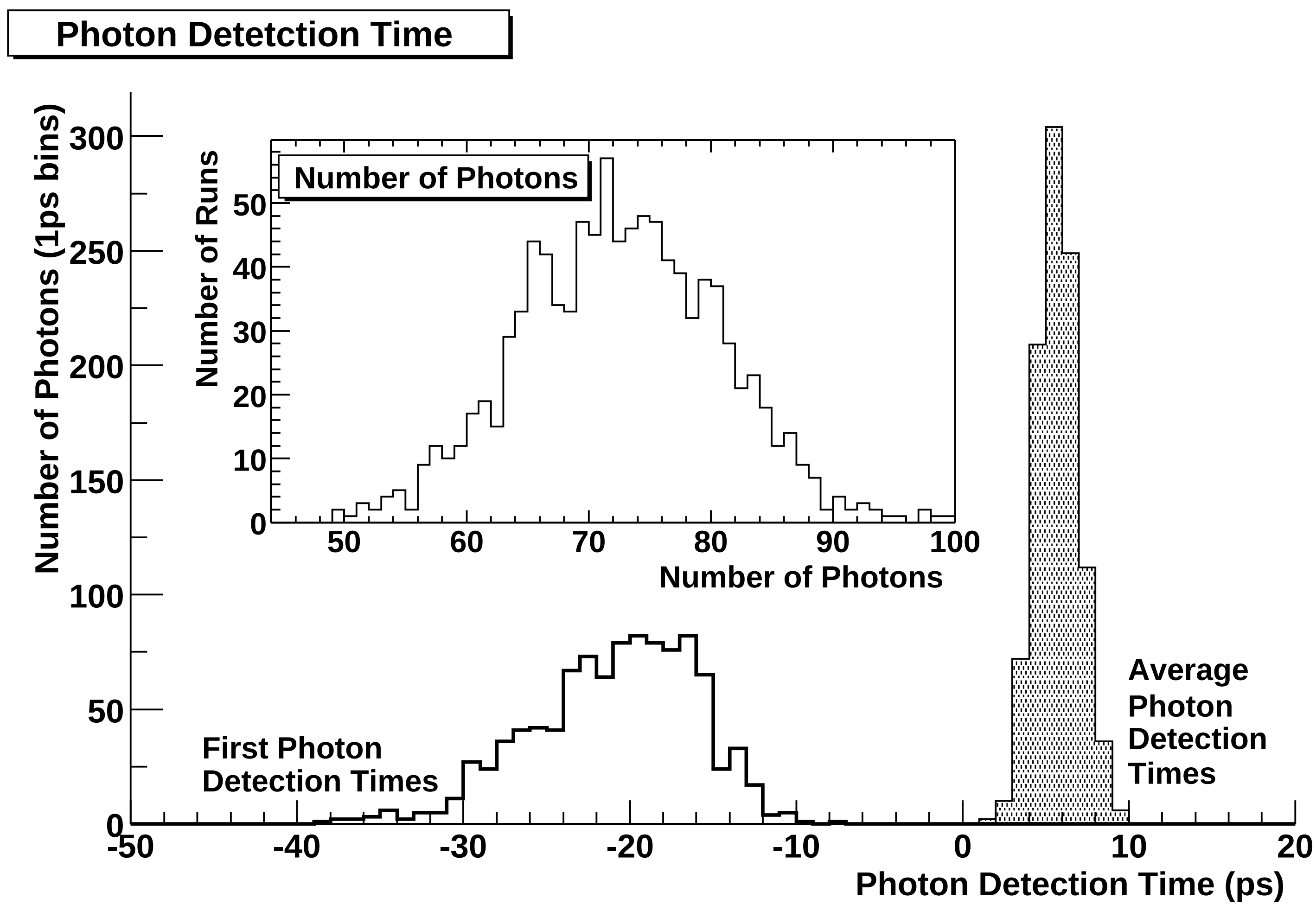
- We estimated the time resolution with a Monte Carlo algorithm



- Probability of a photon at (x, λ): $\frac{\partial^2 N}{\partial x \partial \lambda}\big|_{(x,\lambda)} \cdot dx\, d\lambda\, QE(\lambda)$
- Add delay of $\frac{x}{\beta c}\left(\beta^2 n(\lambda)^2 - 1\right)$
- Add a Gaussian variable with mean 0 and FWHM 25 ps to simulate jitter
- Keep track of:
  - First photon time
  - Average photon time
  - Number of photons

Estimating the Time Resolution

- Ran 1000 simulations with dx = 100 μm and $d\lambda$ = 10 nm
- For Model -58:



Estimating the Time Resolution

- For all of the PMTs:

Model R3809U-	50	51	52	57	58
First Photon Time					
Mean (ps)	-18.83	-11.91	-18.49	-17.85	-20.84
RMS (ps)	5.266	6.493	5.575	5.405	5.295
Average Photon Time					
Mean (ps)	6.496	6.412	6.604	6.188	5.637
RMS (ps)	1.682	3.129	1.691	1.922	1.347

- Time resolution in the 1 ps range is possible with present equipment

Conclusions

- A several mm thick MgF_2 radiator will produce enough Cherenkov radiation for detection
- With currently available detectors, time resolution of < 10 ps is possible
- Custom-built designs may do even better

Future Research

- Talk to Hamamatsu and Burle Industries
  - Pricing and delivery on available MCP MPTs
  - Manufacturing custom devices
- Investigate custom designs at Fermilab
  - Can we reach the levels we think we can?
- Research electronics and anode designs to improve time resolution