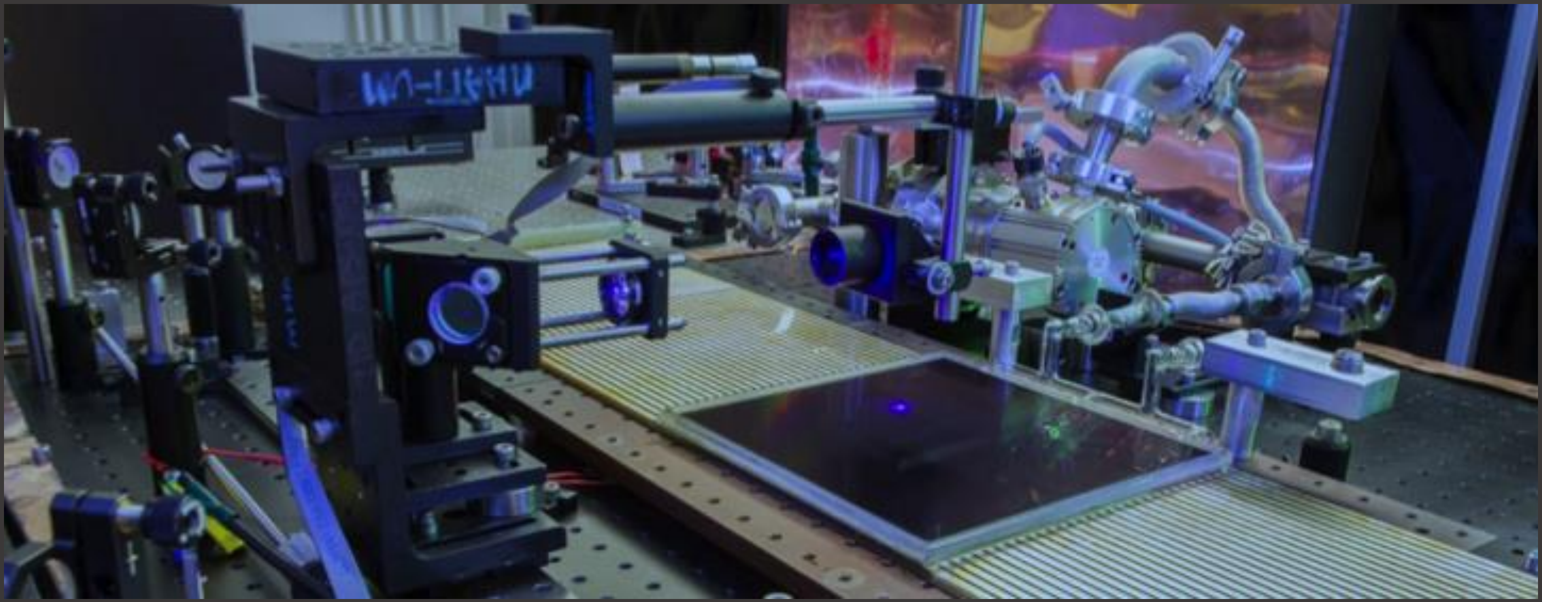
Developing a water Cherenkov optical time-projection chamber



Eric Oberla

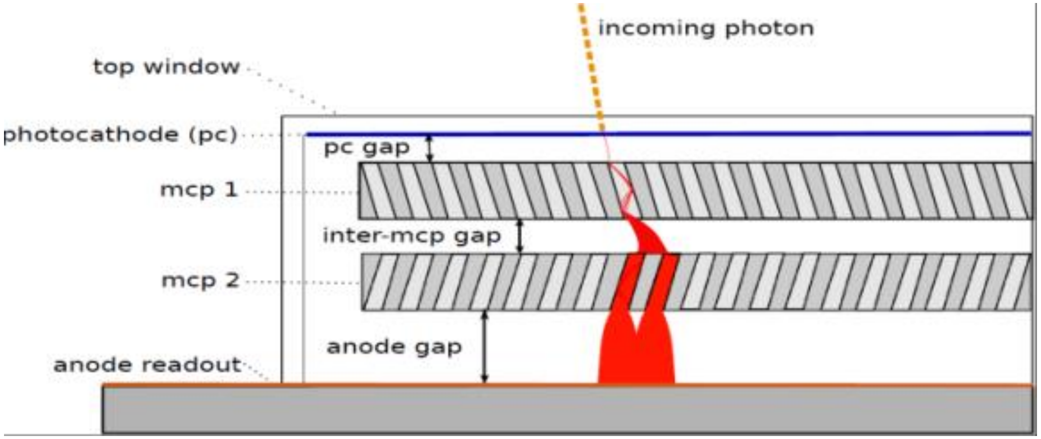
University of Chicago

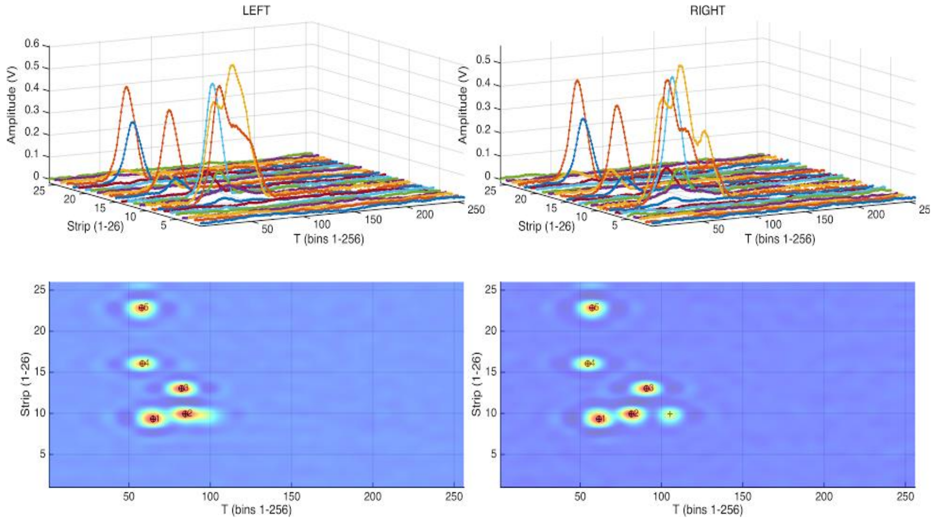
6 August 2016

ICHEP2016CHICAGO

Microchannel Plate PMTs (MCP-PMT)

MCPs are made from micro-capillary array substrates. Each pore is functionalized as a continuous-dynode electron multiplier:



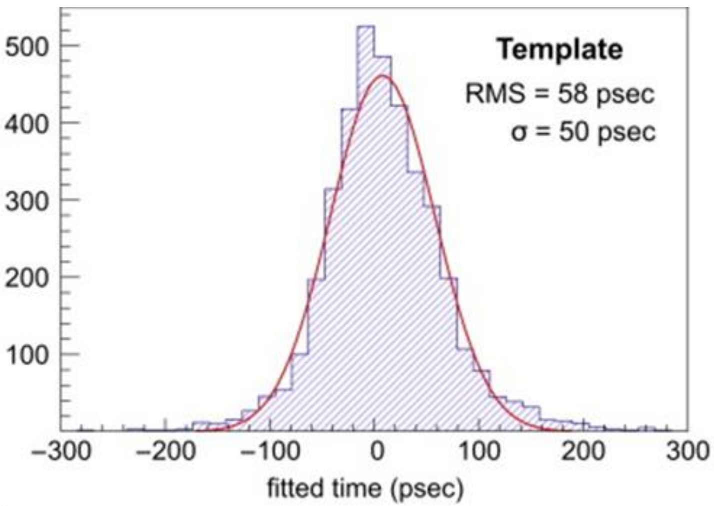


Ability to resolve concurrent single-photons in space and time, with spatial resolution largely determined by the anode design (figure is from simulation, microstrip-line anode [G. Jocher])

Microchannel Plate PMTs (MCP-PMT) & LAPPD™

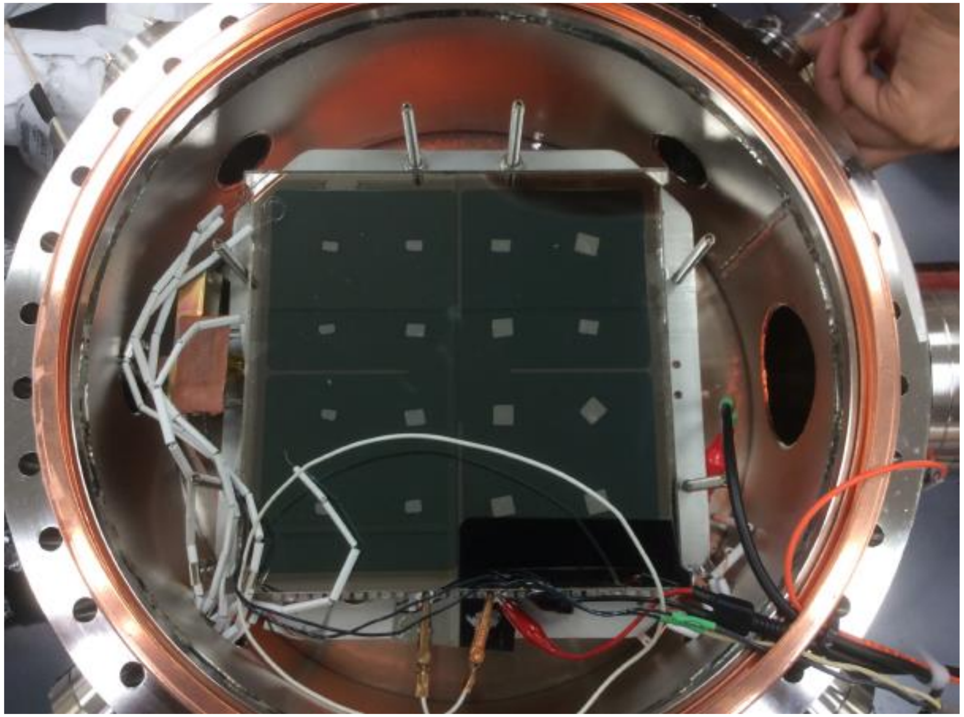
LAPPD = Large Area Picosecond Photo-Detector

The LAPPD MCP-PMT was primarily developed as an economical, large-area photodetector for precise time-of-flight measurements in large-scale detectors for High Energy Physics



single photoelectron absolute time resolution (psec)

Gains of > 10^7 have been demonstrated with LAPPD MCPs, along with single-photon **timing resolutions of ~50 ps**.



Sealed 20x20 cm^2 glass tile, pictured after Cesiation process, in the UChicago lab. [From A. Elagin's ICHEP 2016 talk (yesterday)]

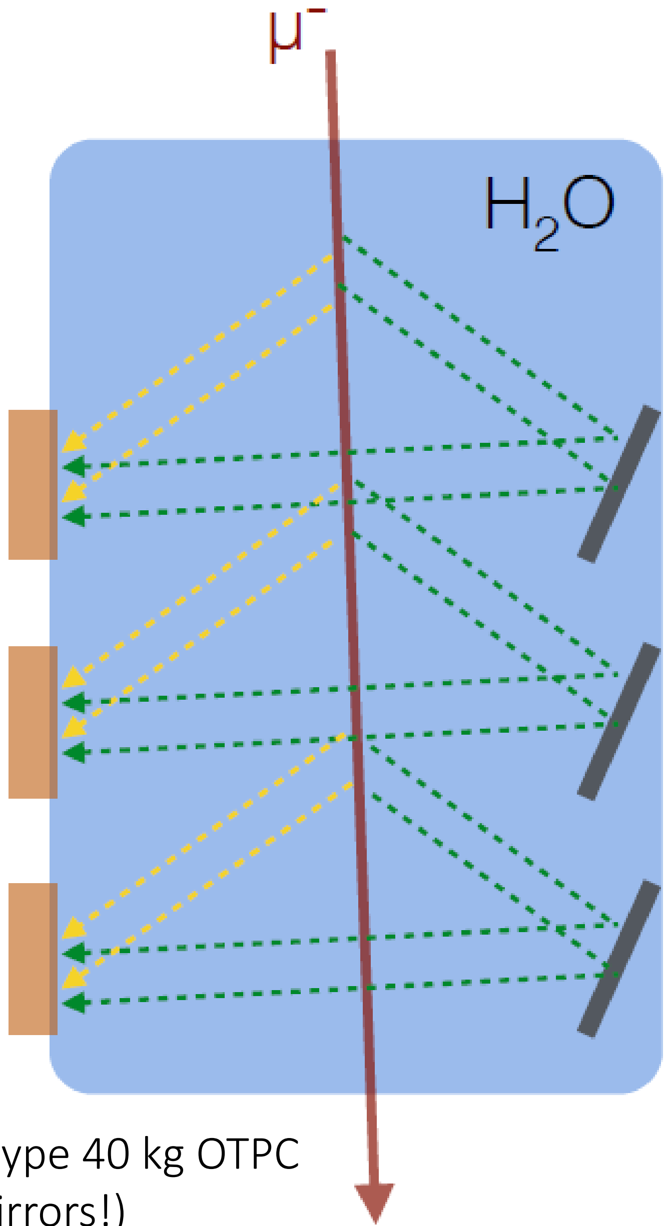
references:
1) Timing characteristics of Large Area Picosecond… [NIM A 795, 2015]
2) psec.uchicago.edu
3) Swing by the INCOM booth here at ICHEP 2016

the (prototype) OTPC concept

With position and time-sensing MCP-PMTs and matching readout electronics, each photon can be resolved in 3-dimensions (2 space + 1 time) permitting the concept of a ‘photon-’ or ‘optical-’ TPC (OTPC).

Towards the 3D tracking of relativistic charged particles in a water volume by resolving the relative time and position of the `drifted' Cherenkov photons.
Application: Add a real-time tracking dimension to a water-based neutrino detector

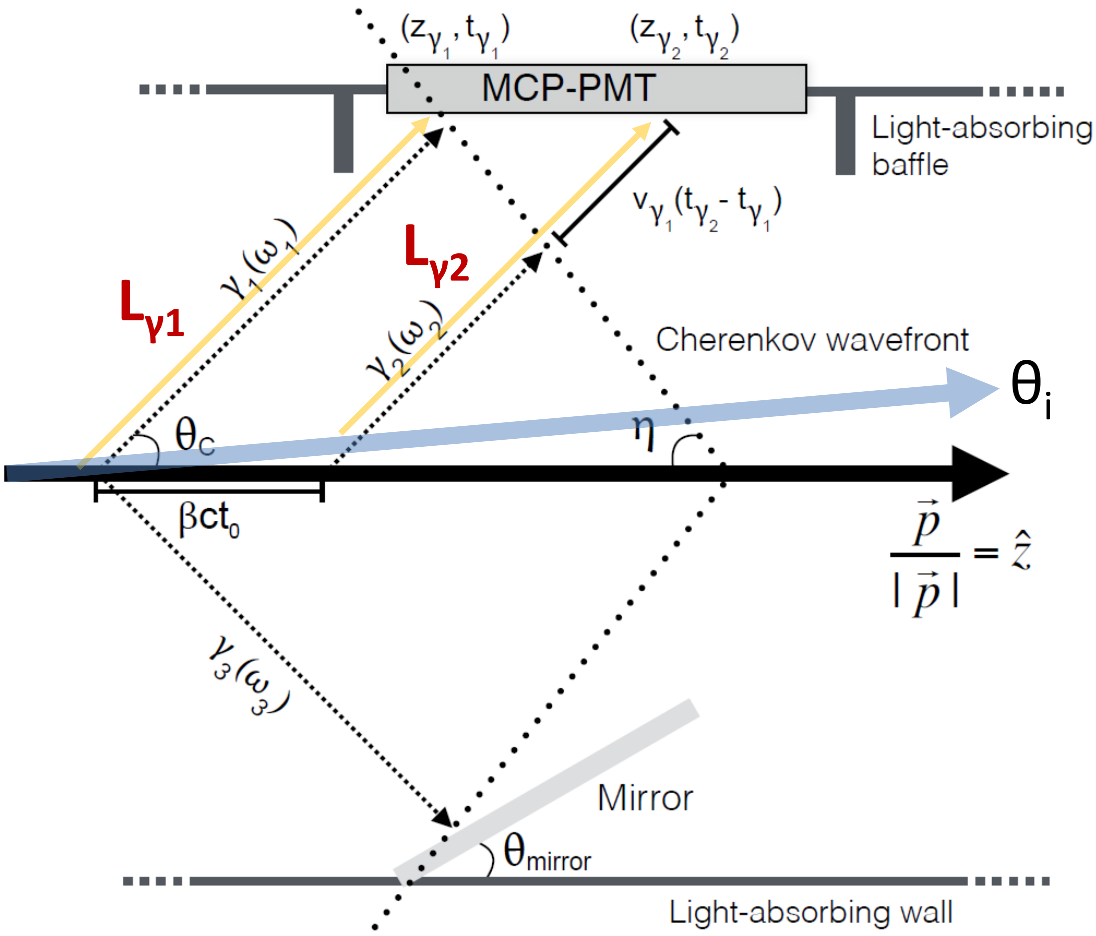
No LAPPDs during beam tests in 2014/2015- relegated to the use of small, commercially available devices (1/16th the LAPPD area)



Prototype 40 kg OTPC (w/ mirrors!)

Optics – track reconstruction

In simplest case, track parameters can be solved analytically through ray tracing (ignoring dispersion and scattering)



The time projection of the direct Cherenkov photons on the OTPC z-axis is a measure of the Cherenkov angle (β) and the particle angle with respect to the OTPC longitudinal axis

$$\Delta t_{\gamma 21} = t_o\,(1 - \frac{\beta\, c}{< v_{group} >}\tan\theta_i)$$

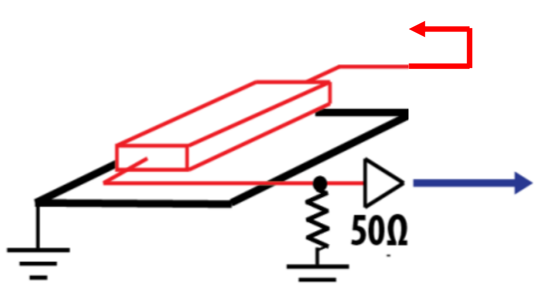
$$\Delta z_{\gamma 21} = \beta\, c\, t_o\, \cos\theta_i$$

$$\frac{dt}{dz} \approx \frac{1}{\beta\, c} - \frac{\tan\theta_i}{< v_{group} >}$$

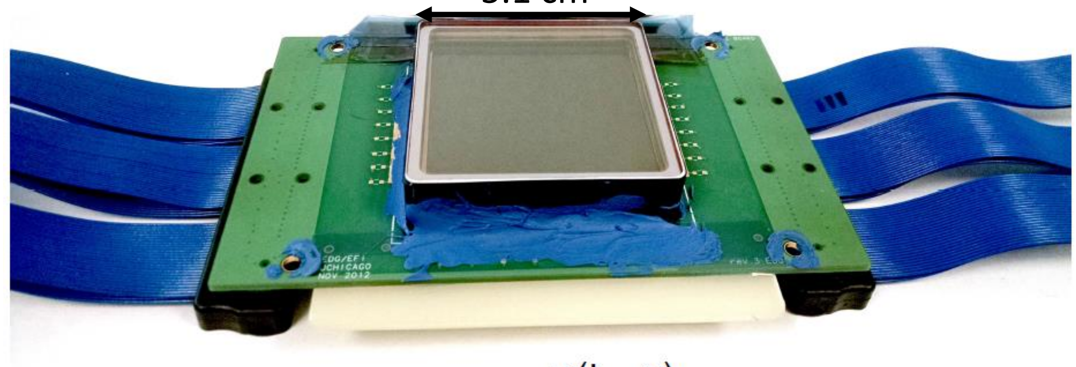
The Cherenkov photons propagate at the group velocity of water. The mean OTPC group velocity **$<v_{group}>$ = 218 mm/ns** (i.e. the OTPC 'drift speed')

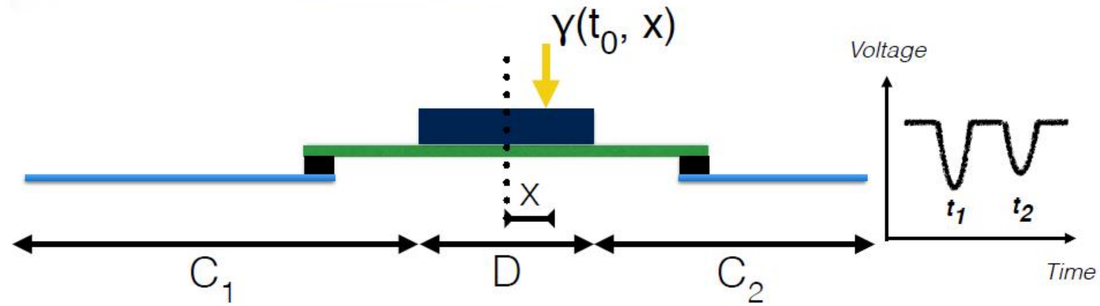
OTPC Photodetector Module

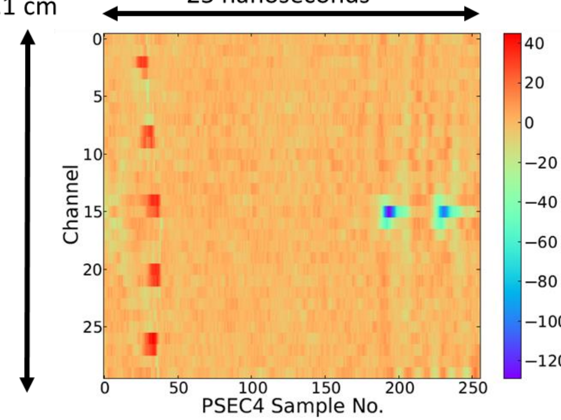
- 1024 anode pad mapped to thirty-two 50Ω micro-strips with custom anode card, pictured above
- MCP-PMT mounted to anode card with low-temperature Ag epoxy
- To efficiency use electronics channels, use a single-ended microstrip readout: Terminate one end of micro-strip, leave other end open (high-impedance):

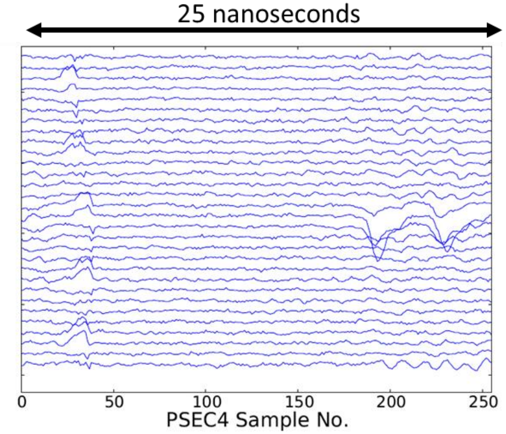


PHOTONIS XP85022 (commercial) MCP-PMT









Single photon event

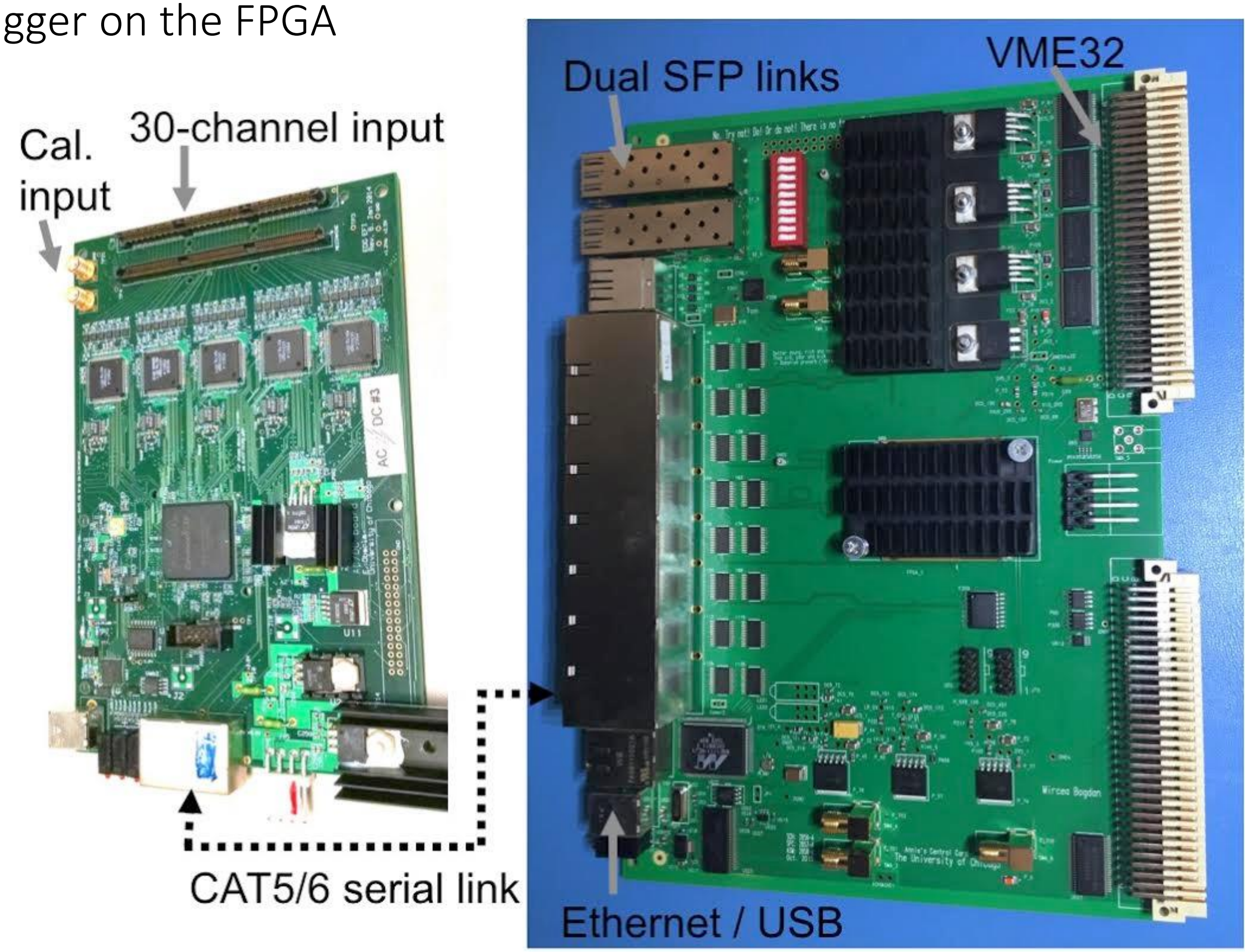
Readout electronics

Based on the PSEC4 ASIC, a waveform sampling chip operating at 10.24 Gigasamples/second.

- The OTPC uses 180 channels of PSEC4 readout.
- Each PSEC4 channel has a built-in threshold discriminator
- Multi-level, configurable trigger on the FPGA

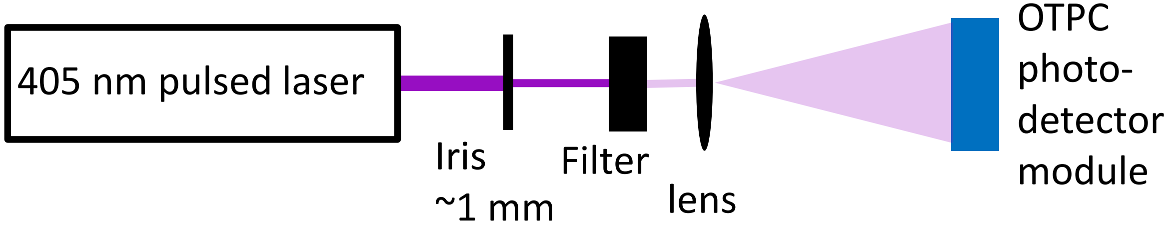
Left: **ACquisition and Digitization with pseC4 (ACDC) card**
30-channel, 10.24 GSPS, PSEC4 board. The front-end analog bandwidth is above 1 GHz. Standalone readout or system interface.

Right: **ANNIE Central Card (ACC)**
Each back-end ACC manages up to 8 front-end ACDC boards using two network cables per board. Data are at a rate of up to 1.6 Gbps.



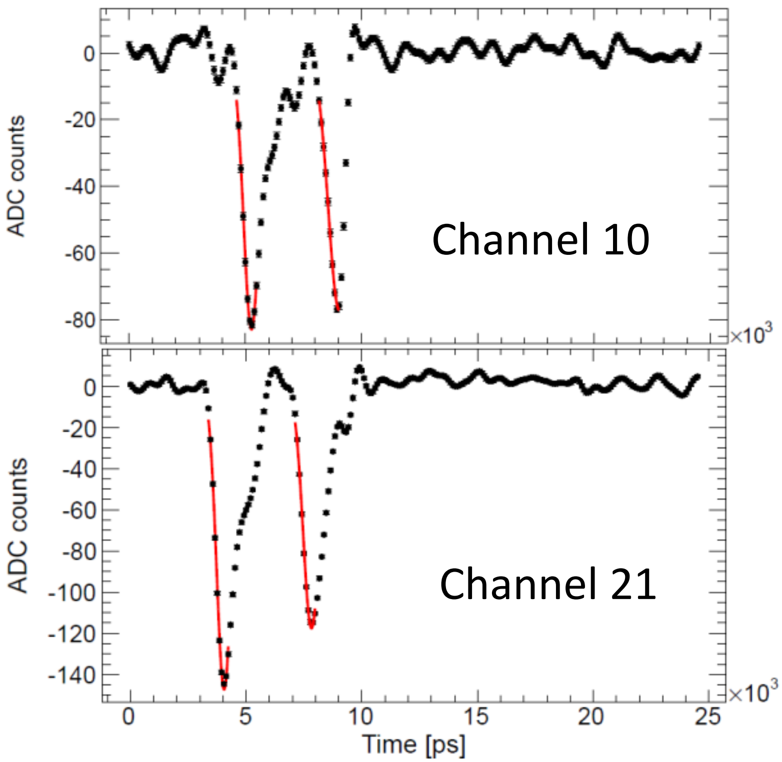
PSEC4: NIM A 735, 2014; arXiv:1309:4397
DAQ System: arXiv:1607.02395
ANNIE: arXiv:1504.01480

OTPC multi-photoelectron measurements

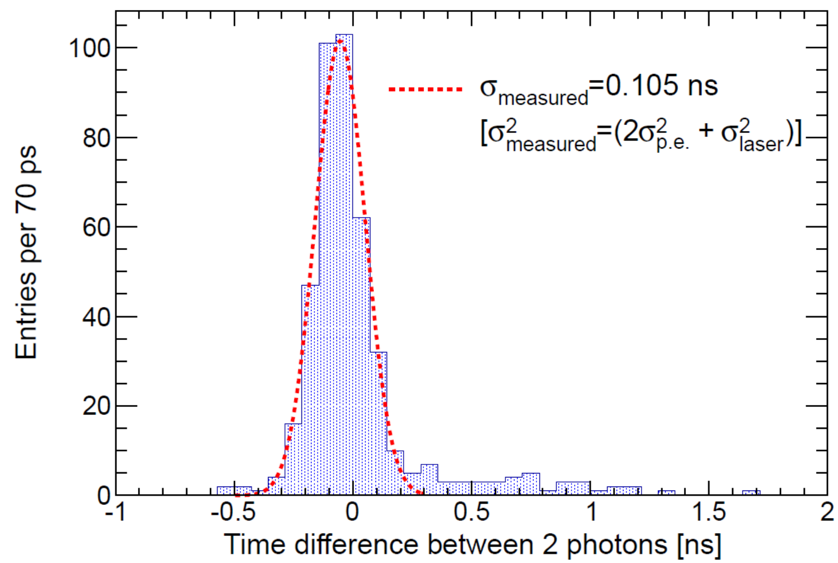


1 kHz Pulsed laser, 33 ps FWHM pulse width

Typical waveforms

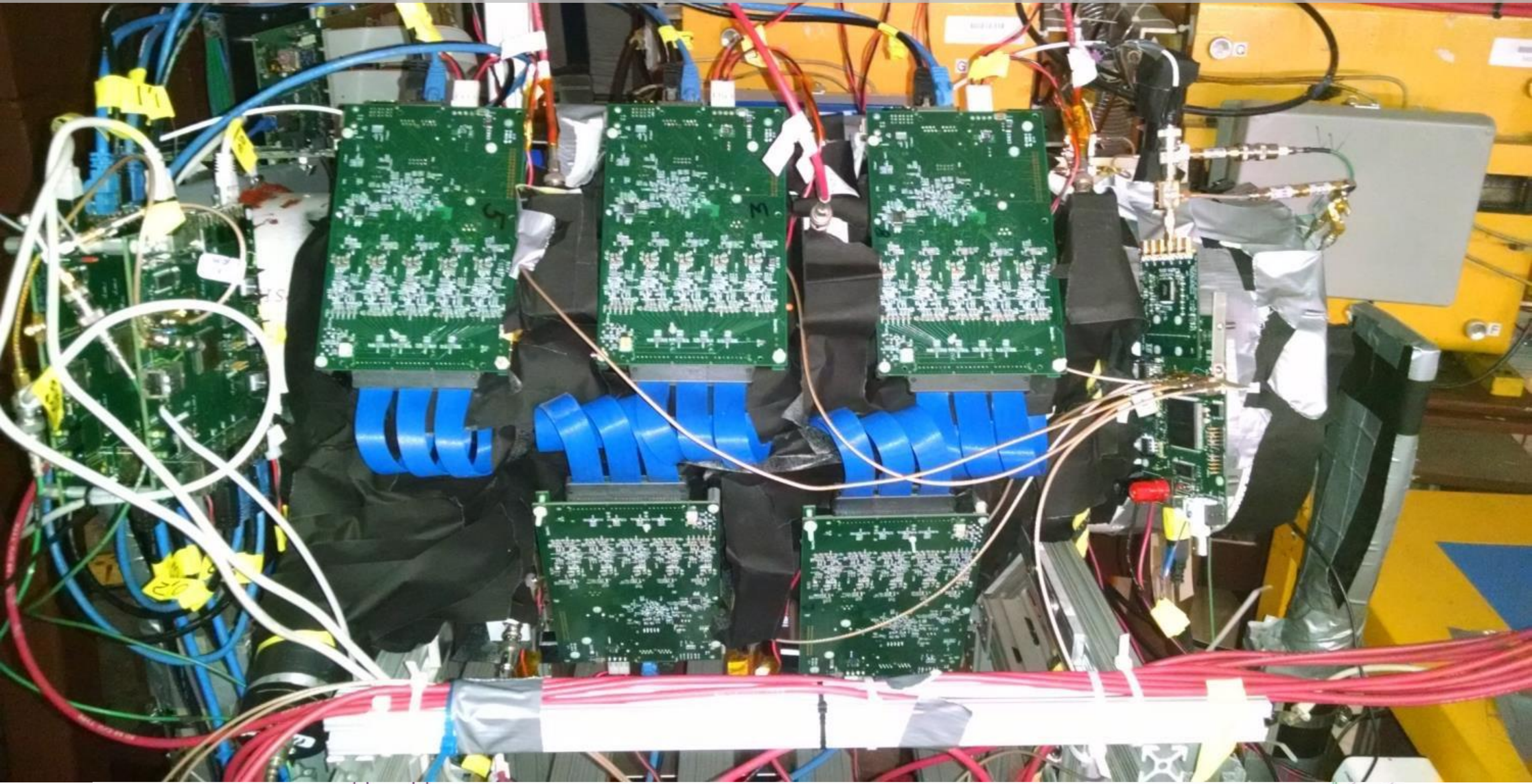


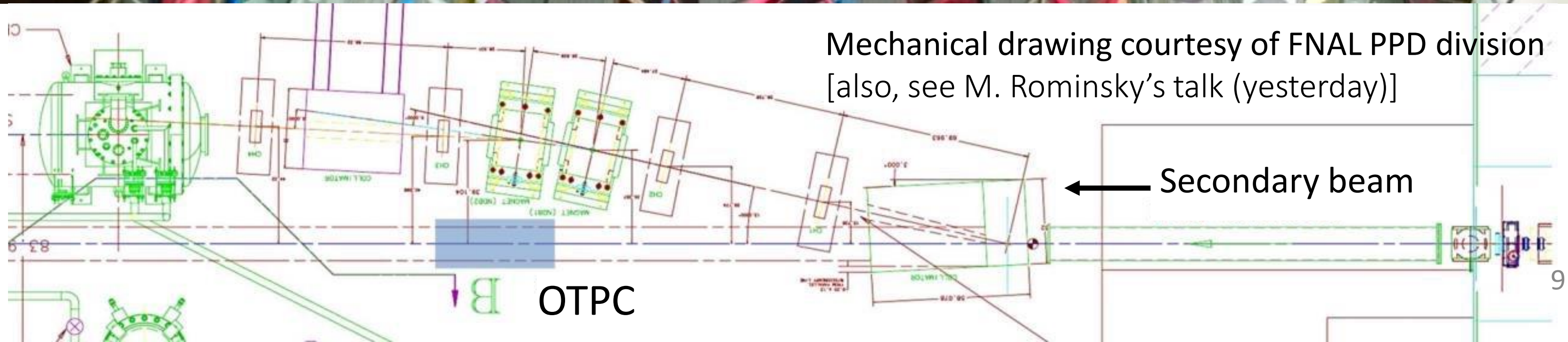
PSEC4 digitized waveforms + rising edge fits to extract the photon time-of-arrival



- Measure relative timing between 2 photo-electrons within same laser pulse, which are spatially separated on the MCP-PMT.
- Uncalibrated PSEC4 ASIC – data only pedestal subtracted
- Single photon time resolution is ~75 ps using this single-ended readout technique.

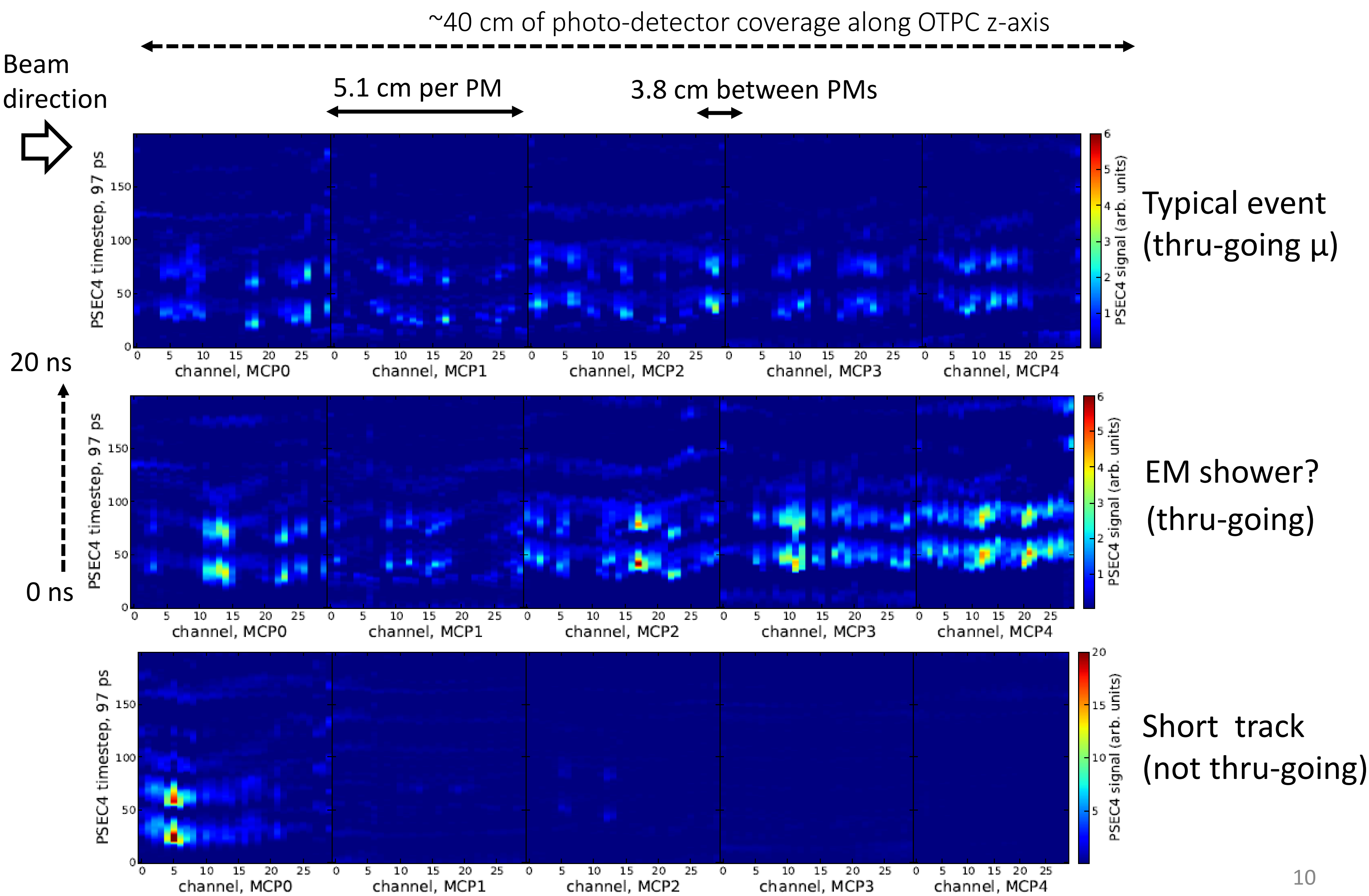
OTPC installed at MCenter, Fermilab T-1059





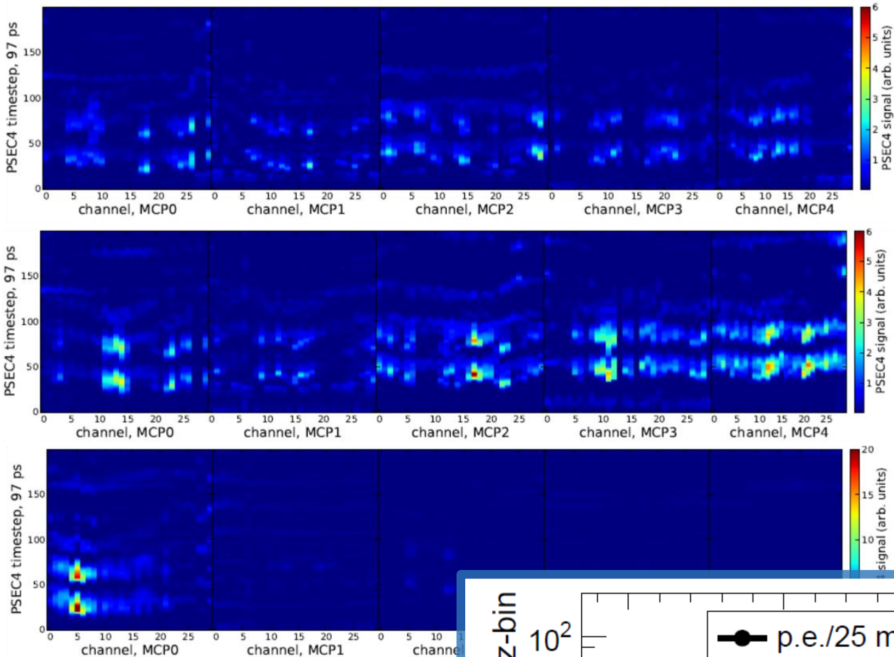
Mechanical drawing courtesy of FNAL PPD division
[also, see M. Rominsky's talk (yesterday)]

OTPC data


~40 cm of photo-detector coverage along OTPC z-axis
Beam direction
5.1 cm per PM
3.8 cm between PMs
20 ns
0 ns
PSEC4 timestep, 97 ps
channel, MCP0
channel, MCP1
channel, MCP2
channel, MCP3
channel, MCP4
PSEC4 signal (arb. units)
Typical event (thru-going μ)
EM shower? (thru-going)
Short track (not thru-going)

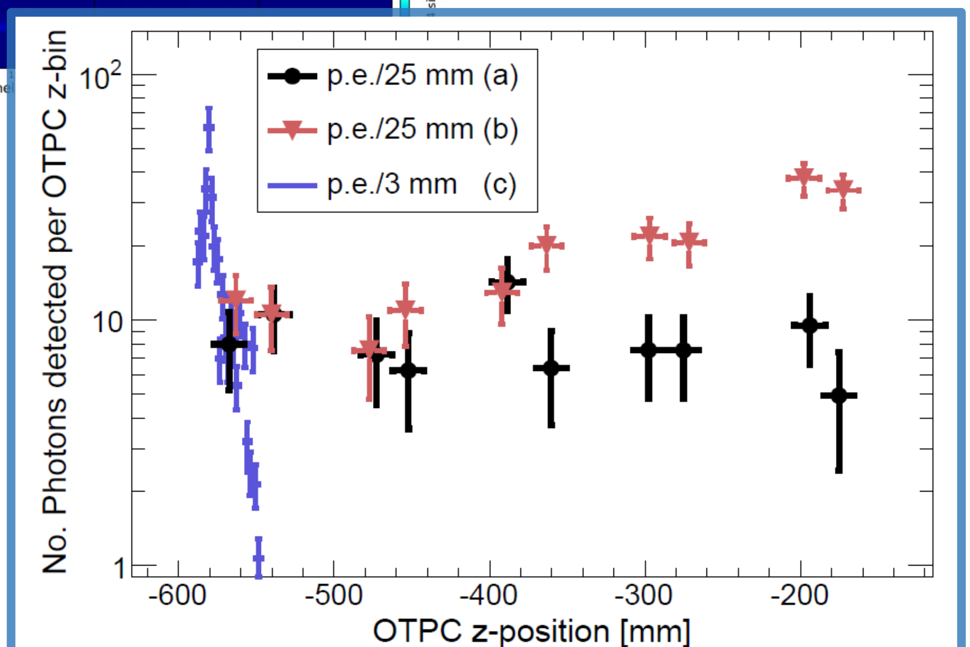
OTPC data + gain calibration

Same three events from previous slide:

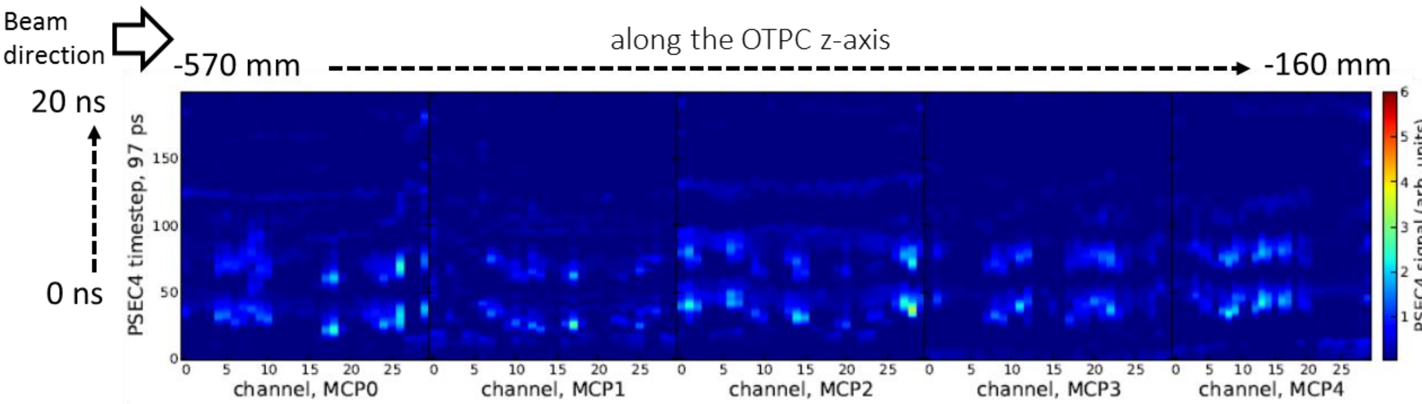


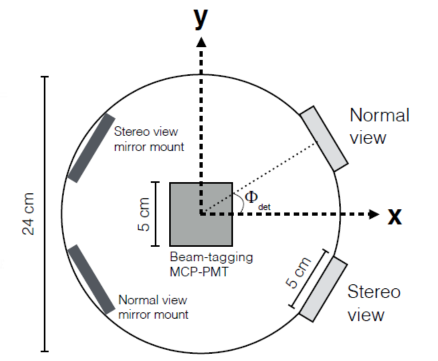
- Calibrate the per-channel gain of the OTPC
- Gain calibration using the average integrated charge from single photon signals

Find the number of photons detected along the track:



the time-projection





OTPC geometry, viewed from rear, showing the 'normal' and 'stereo' views

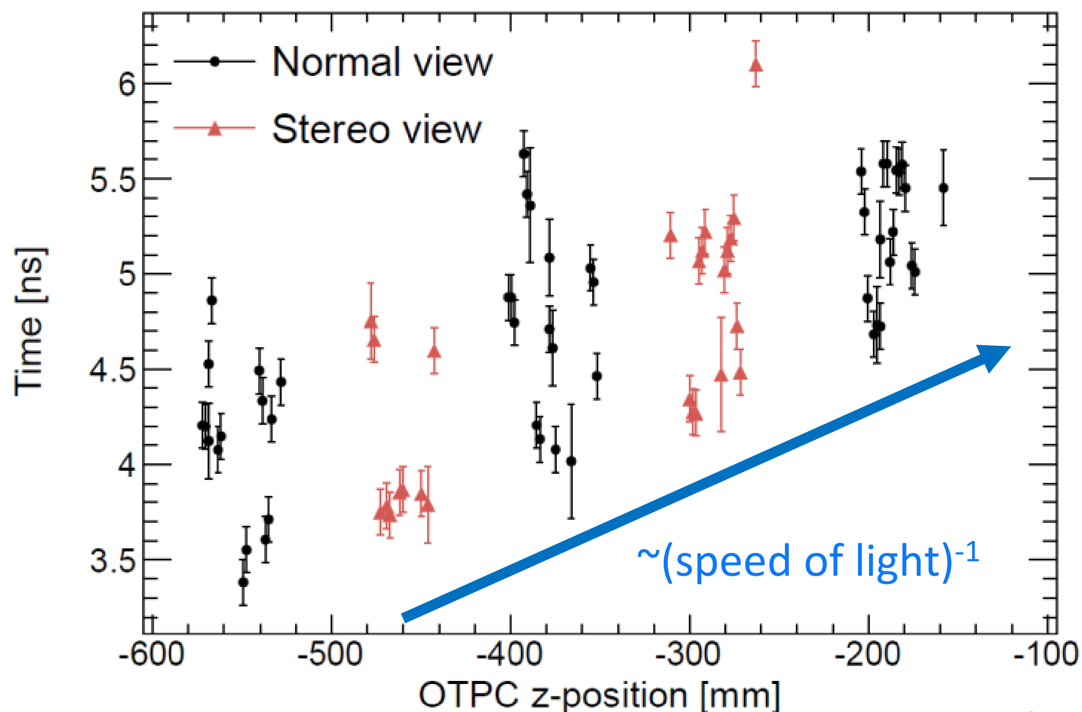
(1) This is the time-projection of the muon, pictured in the raw event data above, along the OTPC z-axis, from both the direct and mirror-reflected Cherenkov photons

(2) Each data point is an individually resolved photo-electron

(3) Error bars in z are smaller than data point (given by microstrip pitch)

(4) Cherenkov photons are recorded in a typical event duration of ~2 ns

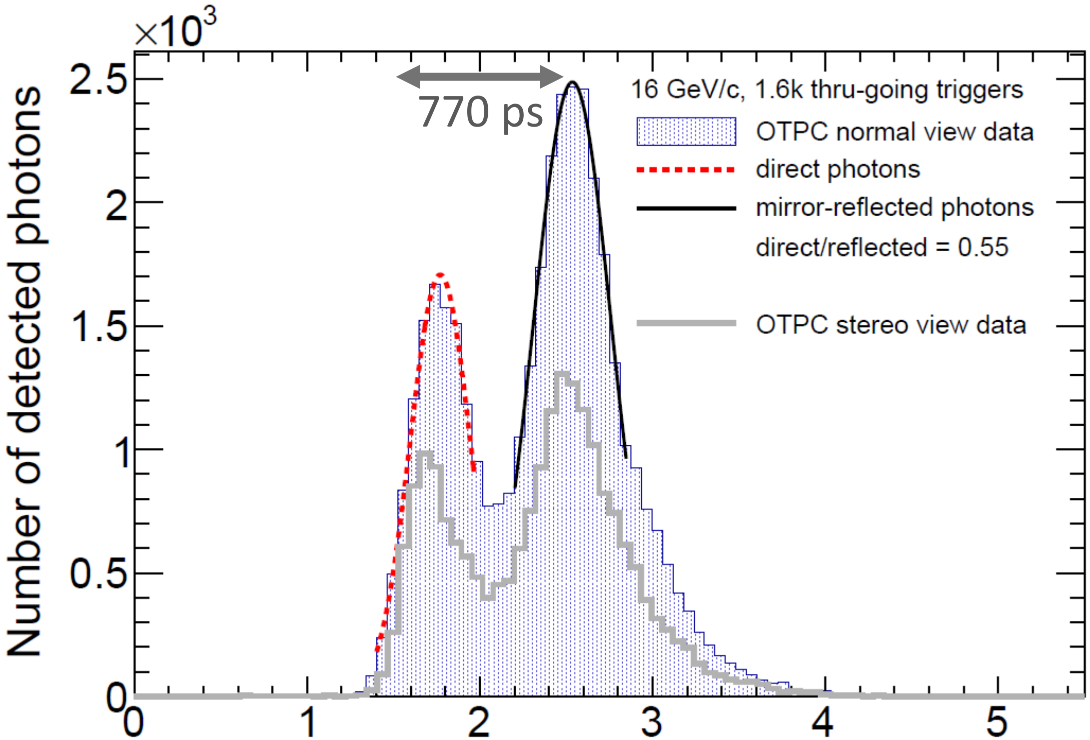
(5) The track can be fully reconstructed using these data (next slides)



Time-resolving the direct and mirror-reflected photons

Using a position-corrected time, remove contributions to the time-projection from the particle velocity (assume β=1)

$$t_i' = t_i - \frac{z_i}{c} \longrightarrow \frac{dt'}{dz} = \frac{dt}{dz} - \frac{1}{c} = \frac{\tan\theta}{< v_{group} >}$$

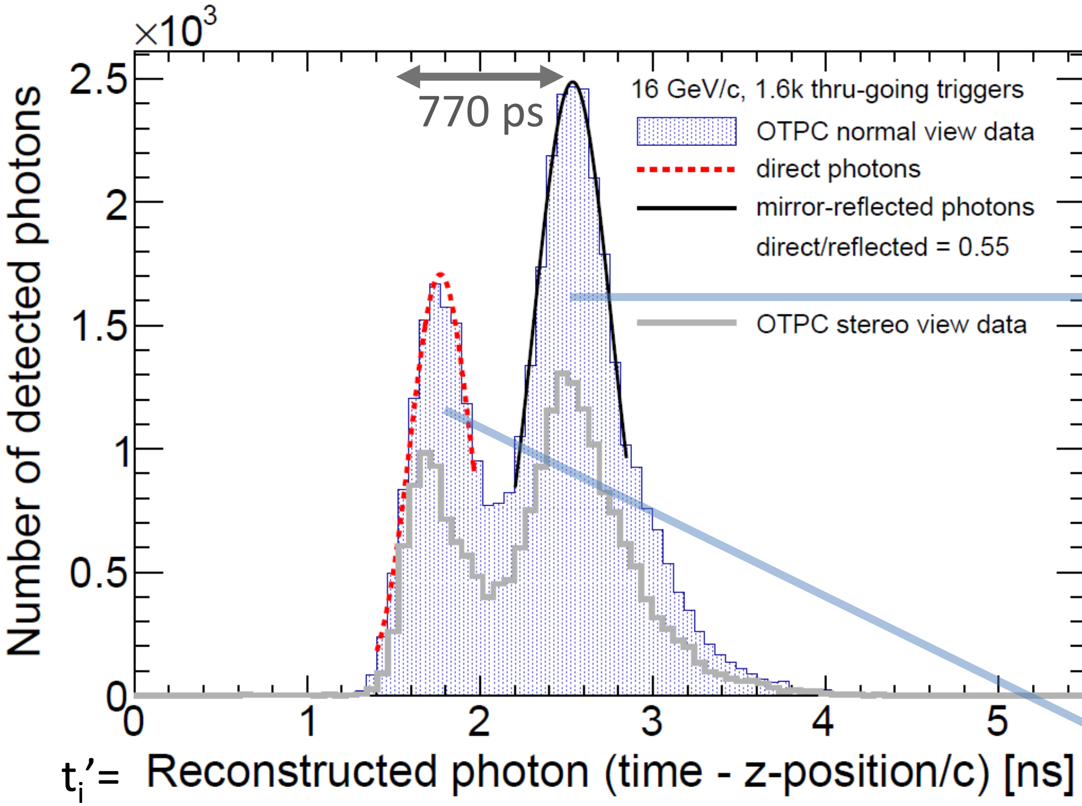


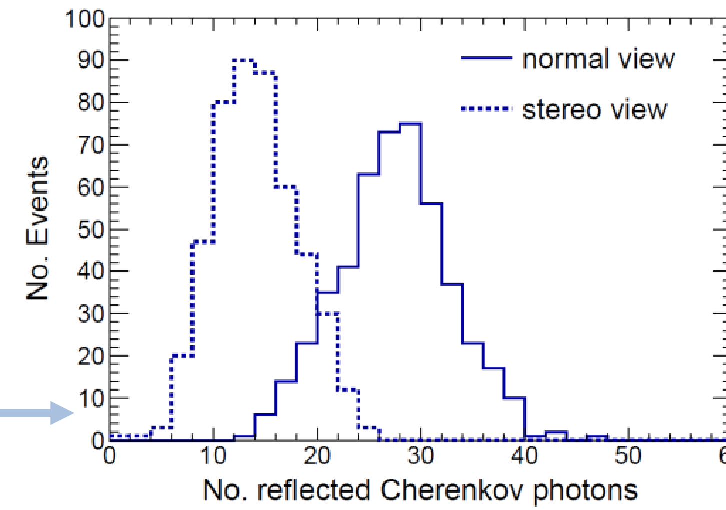
t_i'= Reconstructed photon (time - z-position/c) [ns]

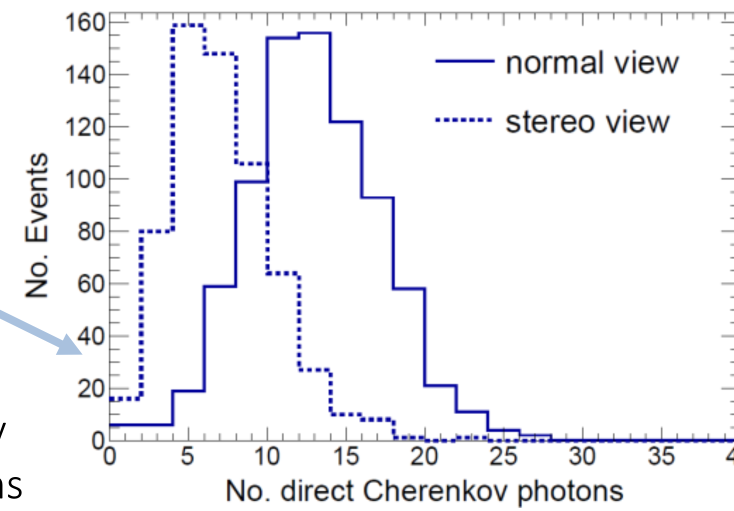
Time-resolving the direct and mirror-reflected photons

Using a position-corrected time, remove contributions to the time-projection from the particle velocity (assume β=1)

$$t_i' = t_i - \frac{z_i}{c} \longrightarrow \frac{dt'}{dz} = \frac{dt}{dz} - \frac{1}{c} = \frac{\tan\theta}{< v_{group} >}$$



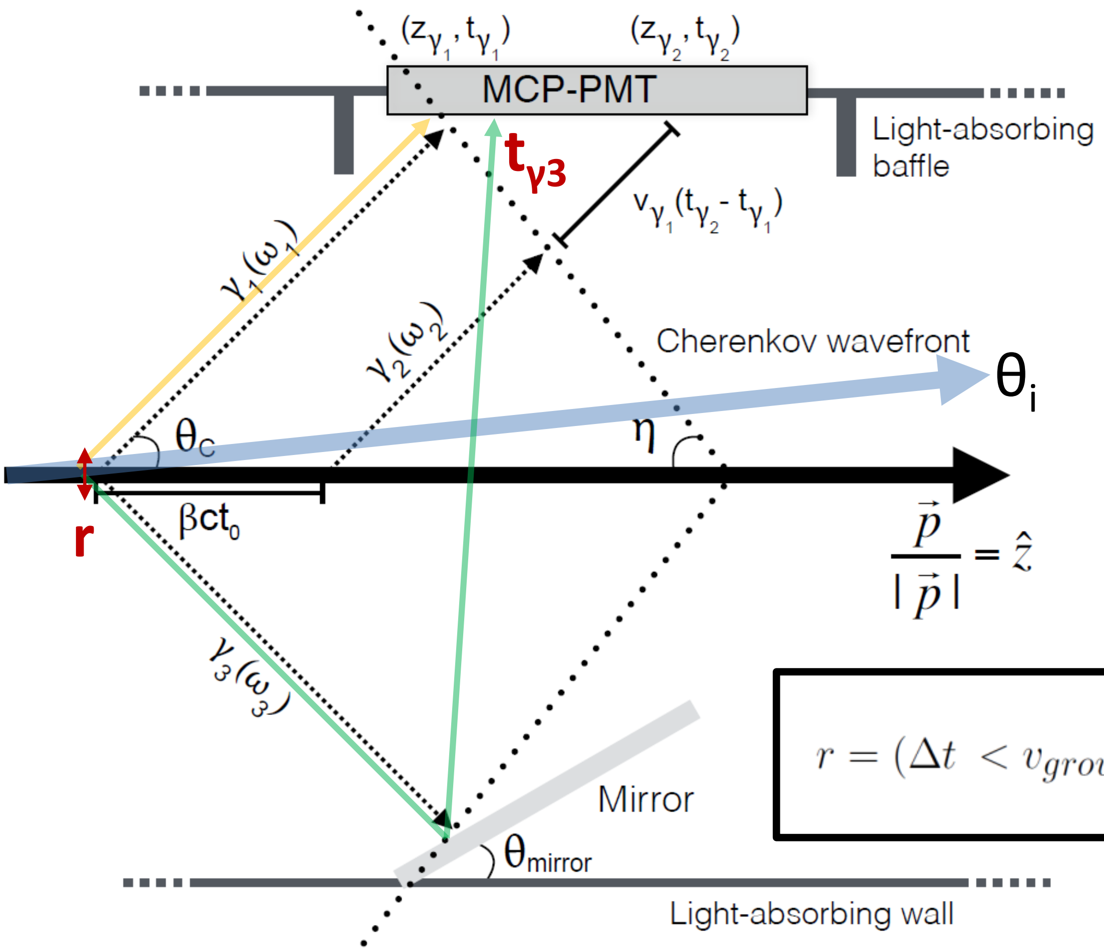




Direct and mirror-reflected Cherenkov photons are clearly separated. On average, there were more reflected photons detected than direct photons.

Optics – track reconstruction (using the mirror)

In simplest case, track parameters can be solved analytically through ray tracing (ignoring dispersion and scattering)



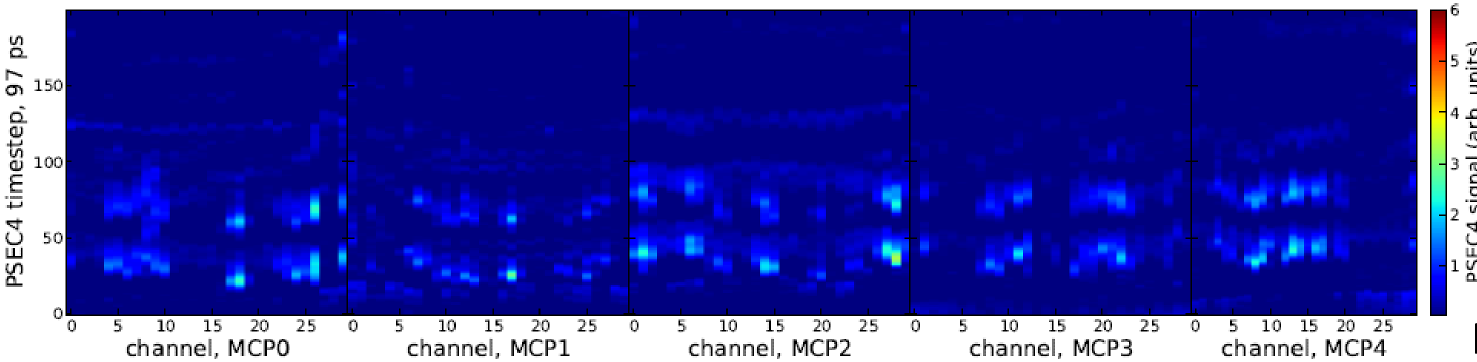
Time-resolving the direct and reflected photons provides the lateral particle displacement from the OTPC center-line as a function of z- and ϕ-position

$$r = (\Delta t \ < v_{group} > -D)\,\frac{1}{2}\left(\frac{1}{\sin\theta_c} - \frac{< v_{group} >}{\beta c \tan(\theta_c)}\right)^{-1}$$

The particle track position, with respect to the OTPC/beam axis, is determined at each OTPC photodetector using the relative timing (Δt) between the direct and mirror-reflected photons

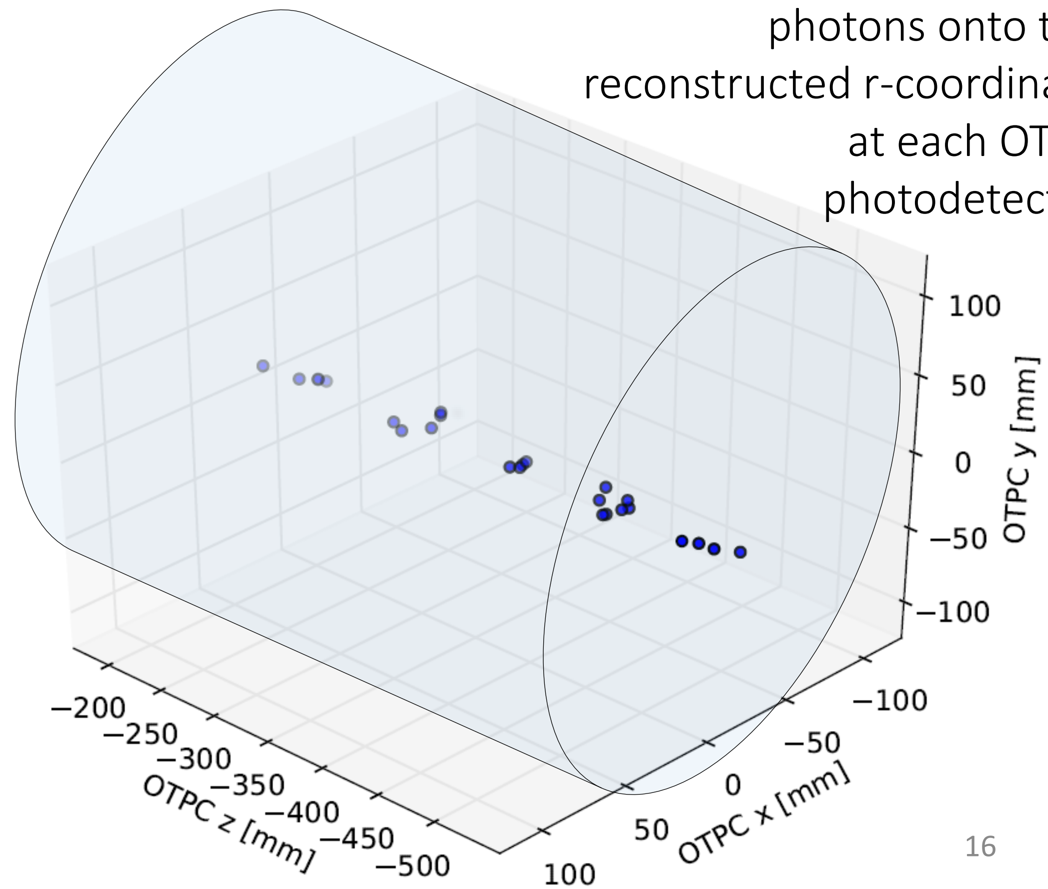
OTPC 3D reconstruction

(previously shown event)



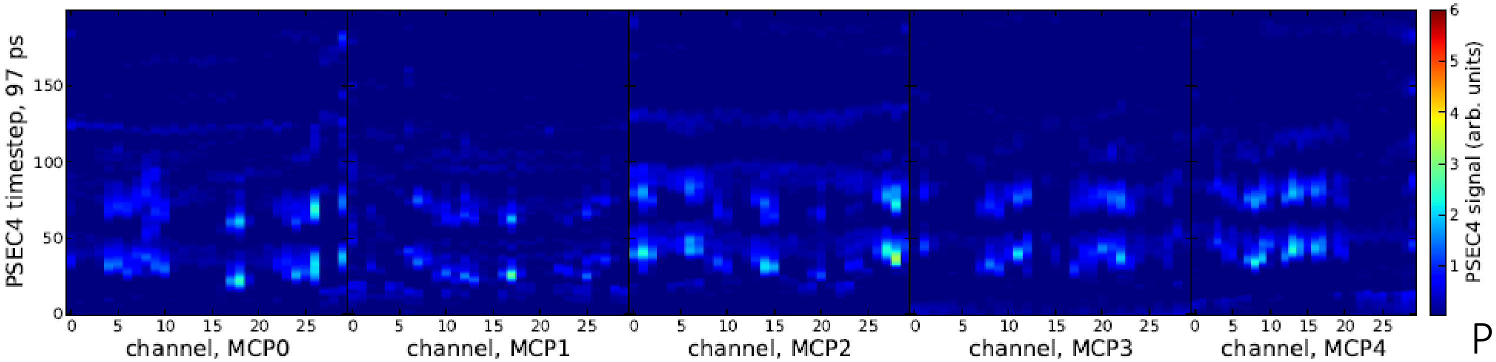
Typical event (thru-going μ)

Projecting the direct photons onto the reconstructed r-coordinate at each OTPC photodetector



OTPC 3D reconstruction

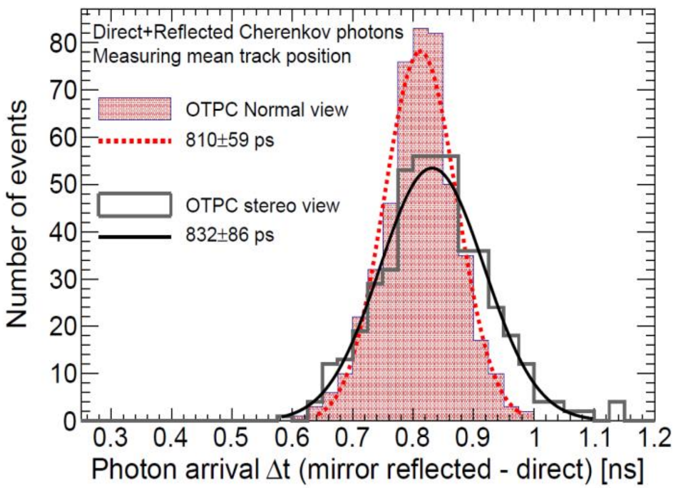
(previously shown event)



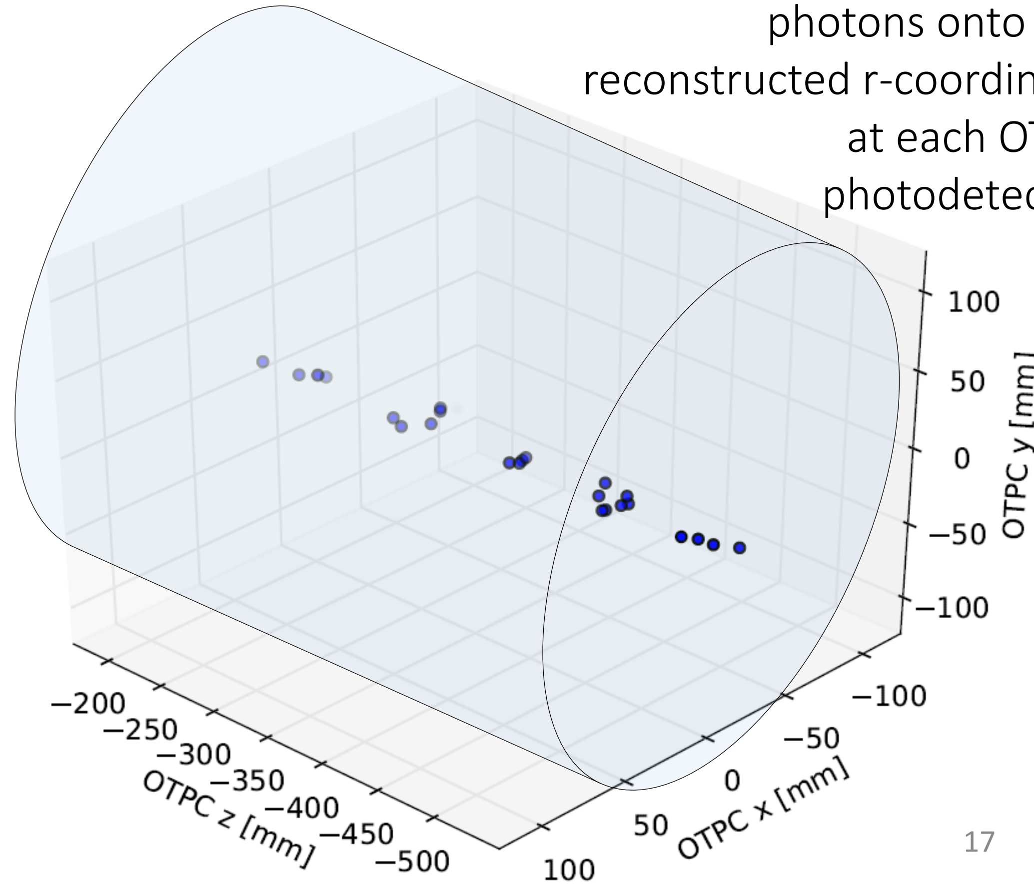
Typical event (thru-going μ)

Projecting the direct photons onto the reconstructed r-coordinate at each OTPC photodetector

The resolution of several hundred muon-like (non-showering) tracks:

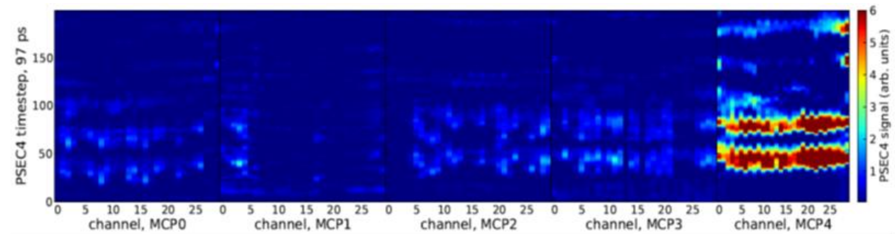


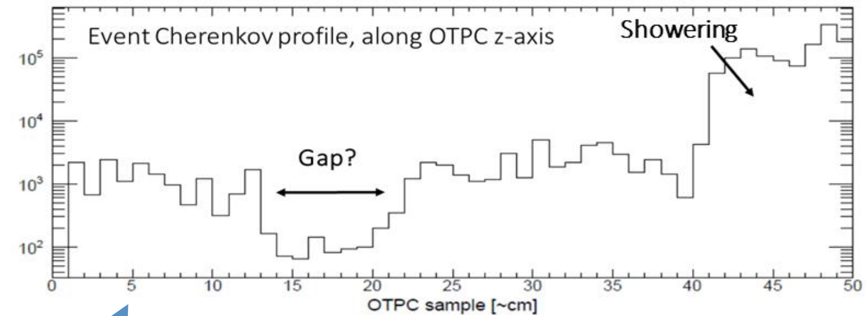
59 ps timing resolution =
10 mm *spatial resolution*
86 ps timing resolution =
14 mm *spatial resolution*



Conclusions

- An implementation of single-photon time and space resolving MCP-PMT photodetectors in a proof-of-principle water Cherenkov OTPC was described
- Demonstrated <100 ps timing resolution and 3x3 mm^2 2D spatial resolution on single photons with a PSEC4-based readout system and single-ended microstrip-anode readout
- At FNAL's MCenter test-beam facility, we tested the detection and tracking performance using primarily multi-GeV muons
- For a through-going muon/MIP, we detect 79 ± 20 Cherenkov photons
- By time and space resolving these photons, we measure an angular resolution of a few degrees (<50 mrad) and a spatial resolution on particle tracks of <15 mm





What's next?

- Data presented here included only muon-like non-showering tracks which account for a small fraction of all the recorded events. Many other `interesting' events captured.
- Scaled-up version of the OTPC PSEC4-based electronics to be installed in ANNIE run-2 with LAPPDs

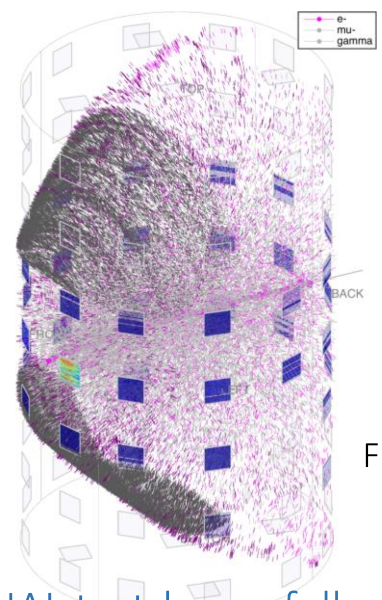
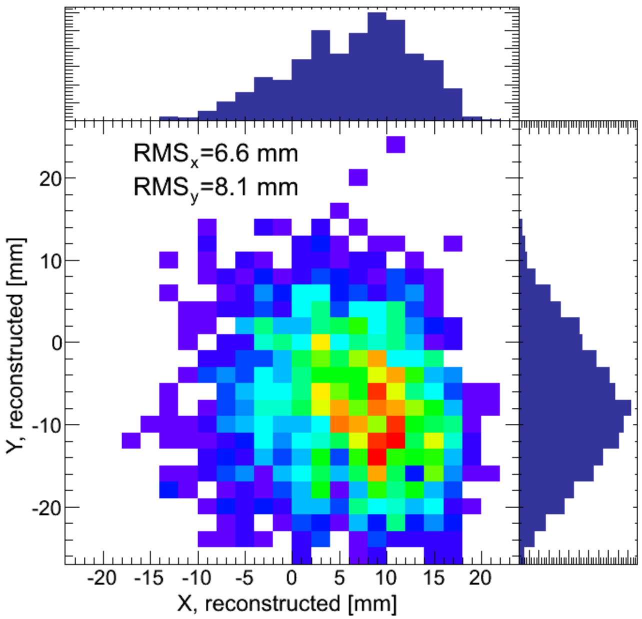


Fig: G. Jocher

Acknowledgements: Henry Frisch, UC PSEC group, & all the FNAL test-beam folks

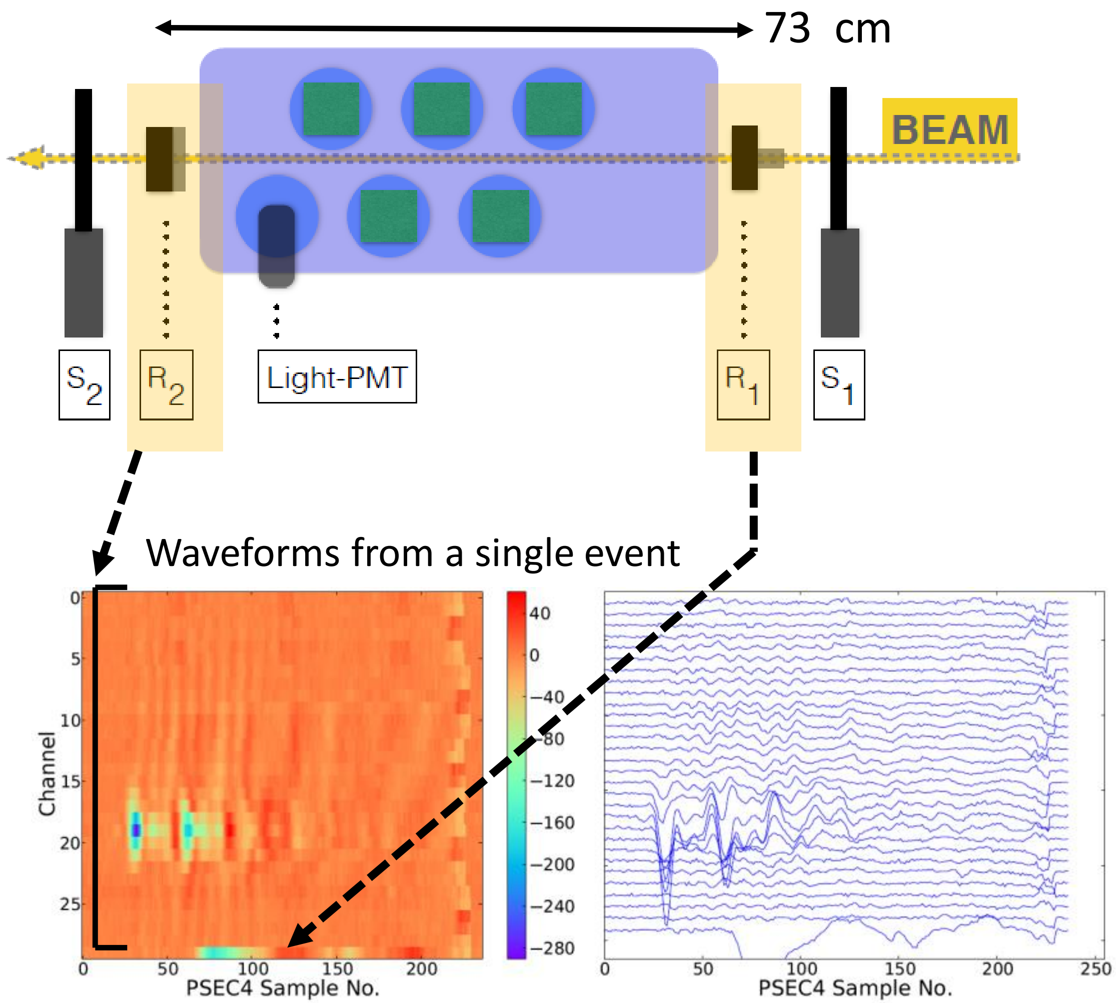
Back-up

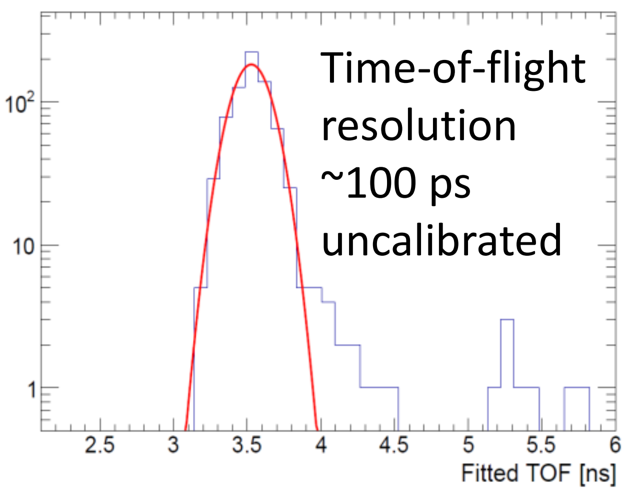
Beam trigger + particle tagging



Particle output position at R_2

Signals from MCP-PMT's R_1 and R_2 are digitized, providing information on the through-going particle

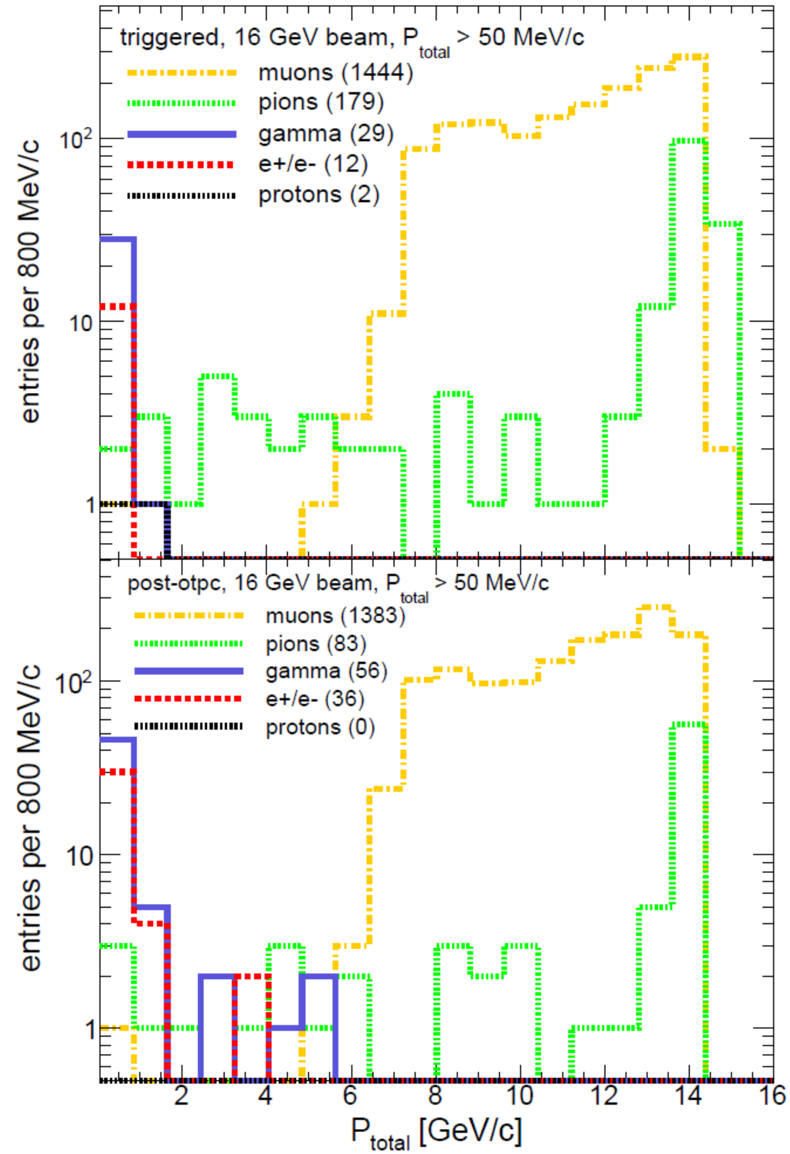




Future use LAPPDs as TOF + 2D position tagging for test-beam?

Beam behind the collimator

top: incident flux
bottom: through-going, satisfying trigger condition

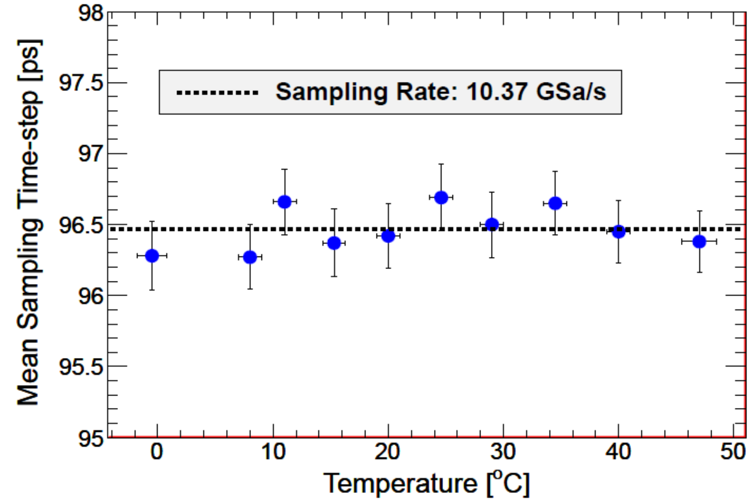


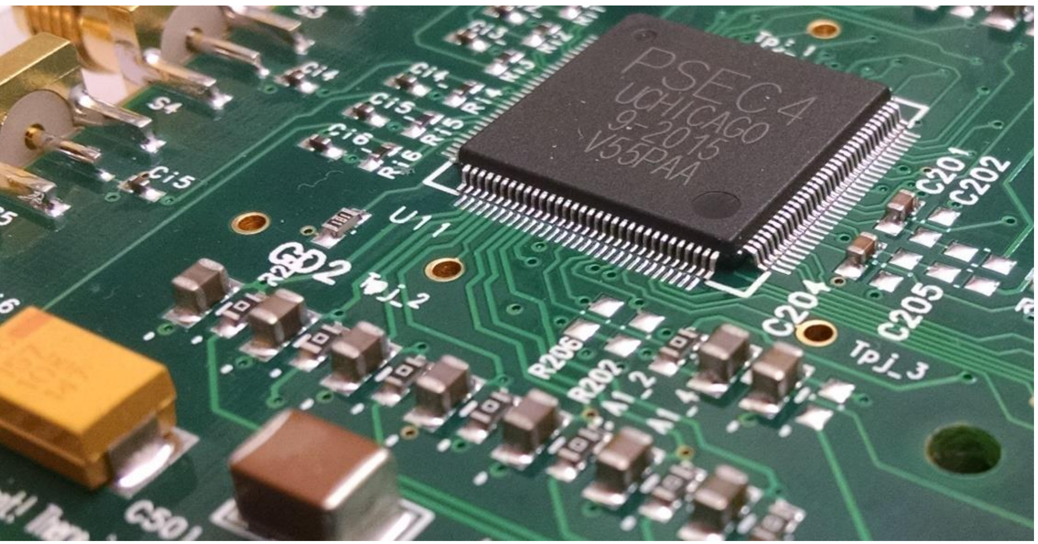
- G4beamline [1] simulation includes a 60 m long π^+ beam incident on a fixed copper target, through ~1m steel absorber, and OTPC water volume
- **Expected flux is > 90% muons at a secondary beam momentum of 16 GeV/c**
- Some particles from showering in the absorber (~1% electrons). Larger percentage at higher secondary beam energies

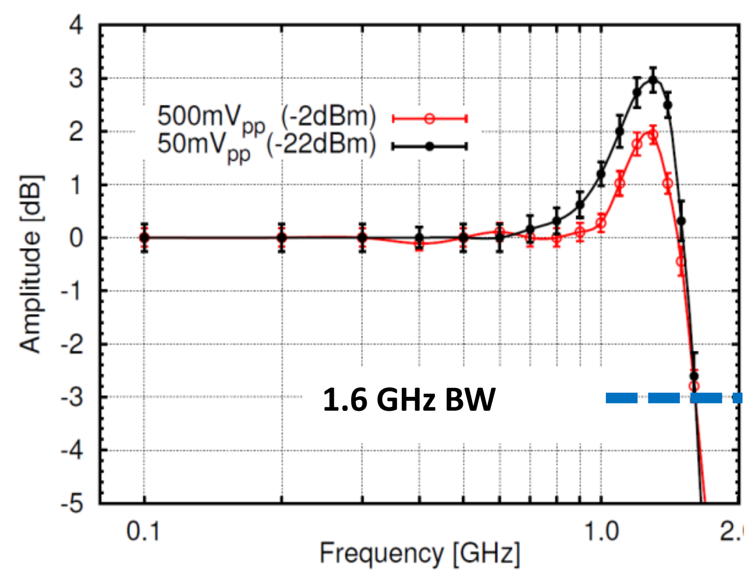
[1] Roberts et. al., 2007 PAC IEEE,
Beam simulation modified from D. Jensen

PSEC4: 10 GSa/s front-end digitization

- Push for higher sampling speeds and lower total power consumption by designing in deep-submicron CMOS processes
- PSEC4: **0.13 µm CMOS**
- On-chip analog-to-digital conversion
- Sampling rate up to 15 GSa/s on 256 sample cells/channe. Readout rate ~50 Mhz. (downsampling factor ~200)



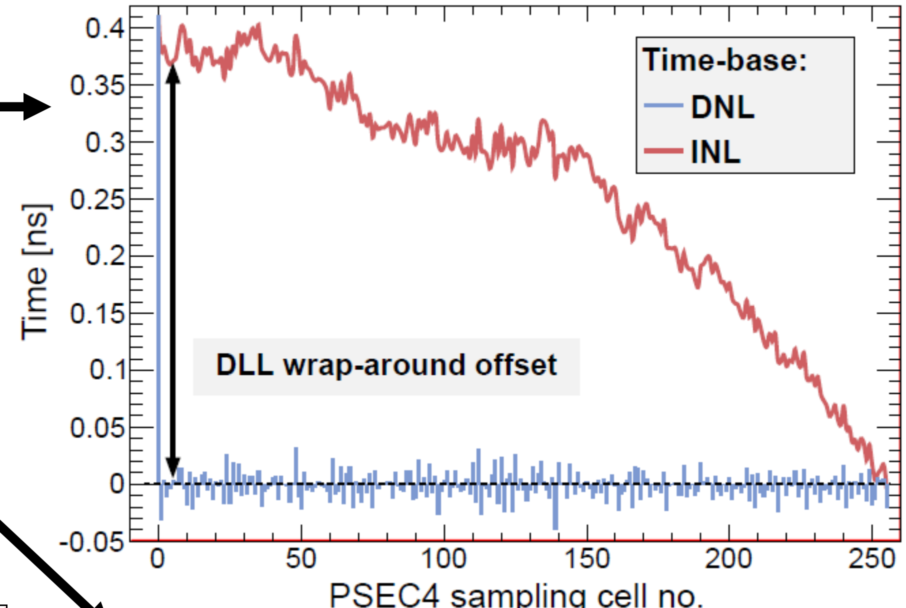


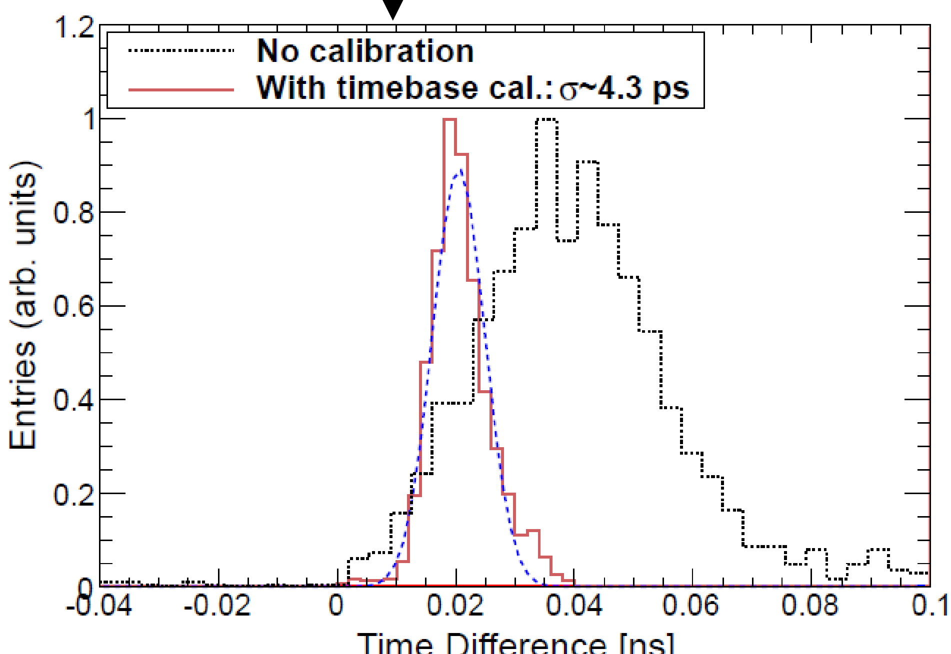


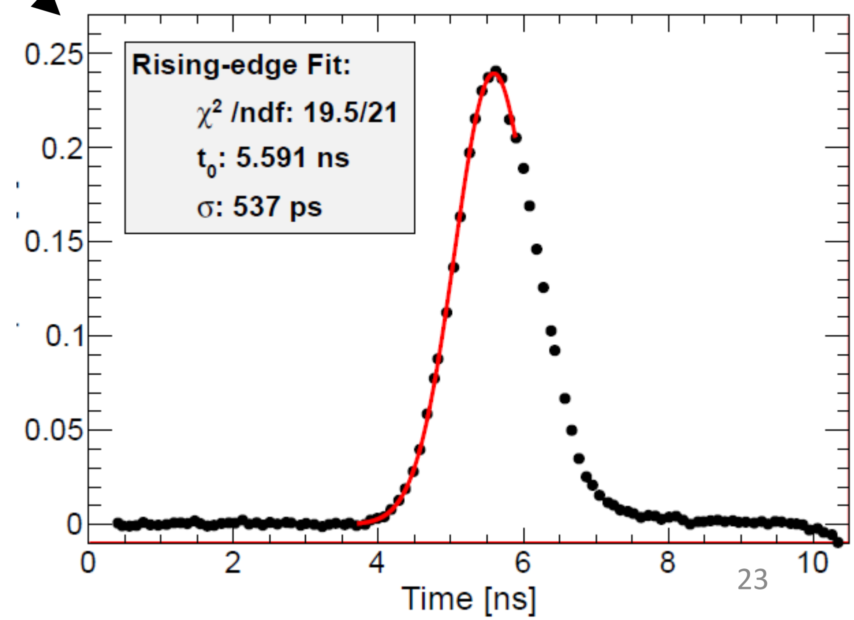
PSEC4: A 15 GSa/s, 1.5 GHz bandwidth waveform digitizing ASIC [NIM A 735, 2014,]

Measuring time with PSEC4

- (1) Calibrate time-base. Non uniformities in the timebase generator due to CMOS process variations. ~10% RMS/mean val.
- (2) Fit waveforms. Full waveform template fitting or cross-correlations=best results.
- (3) Measure time

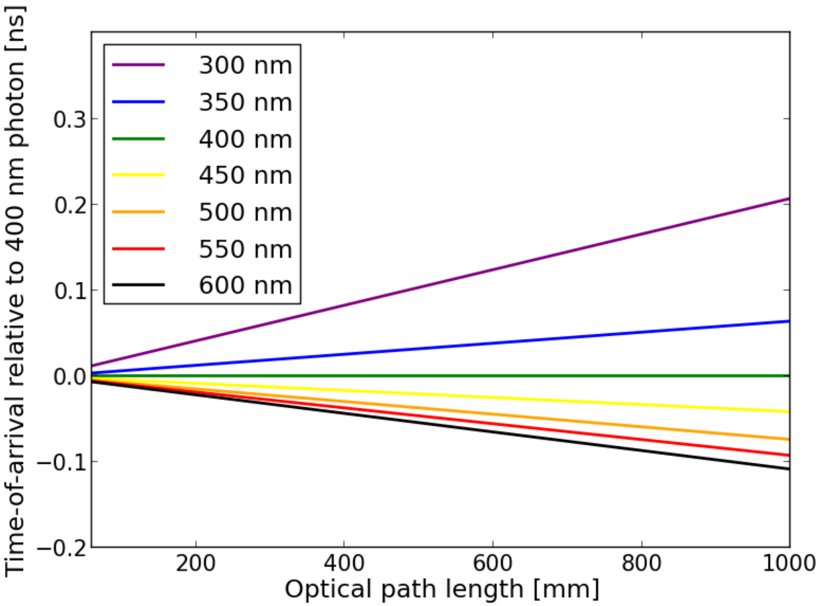




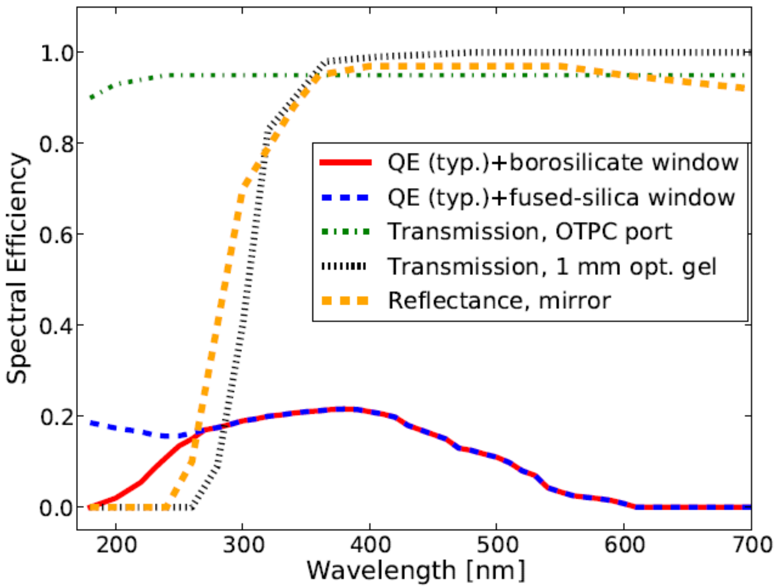


Optics

Chromatic timing errors



Maximum sensitivity
300<->500 nm



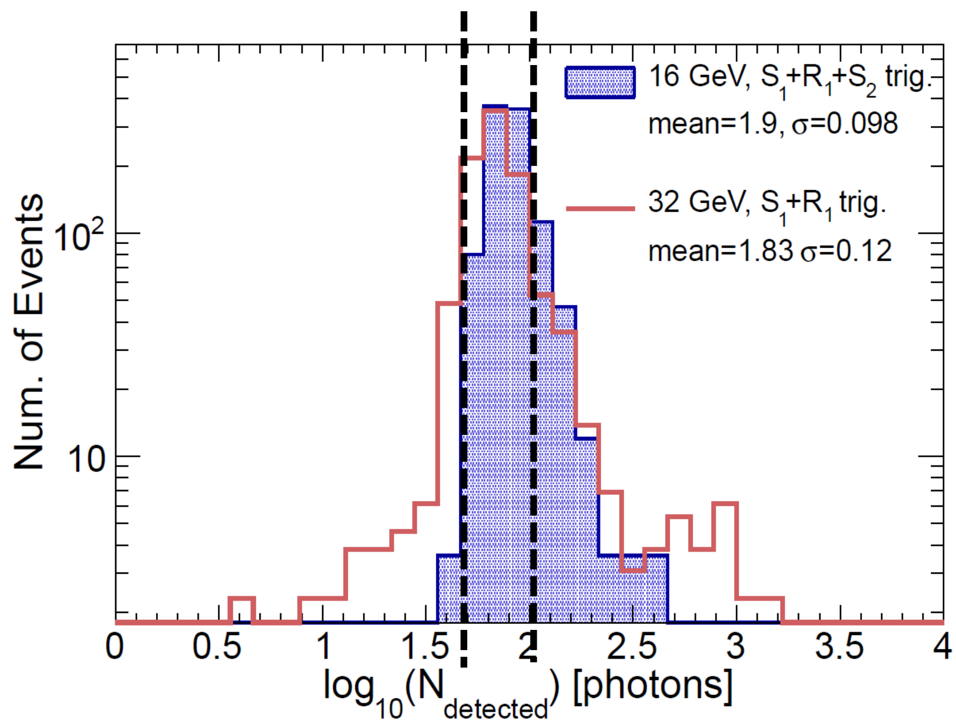
OTPC diameter ~0.25 m, longest optical path lengths ~35 cm

OTPC data: selecting muons for track reconstruction

-Using gain calibration we measure the number of photons per track, comparing different datasets (trigger configuration, water quality)
-For single-track reconstruction analysis, select muons based on number of photons in event (try to remove events with delta-rays, etc)

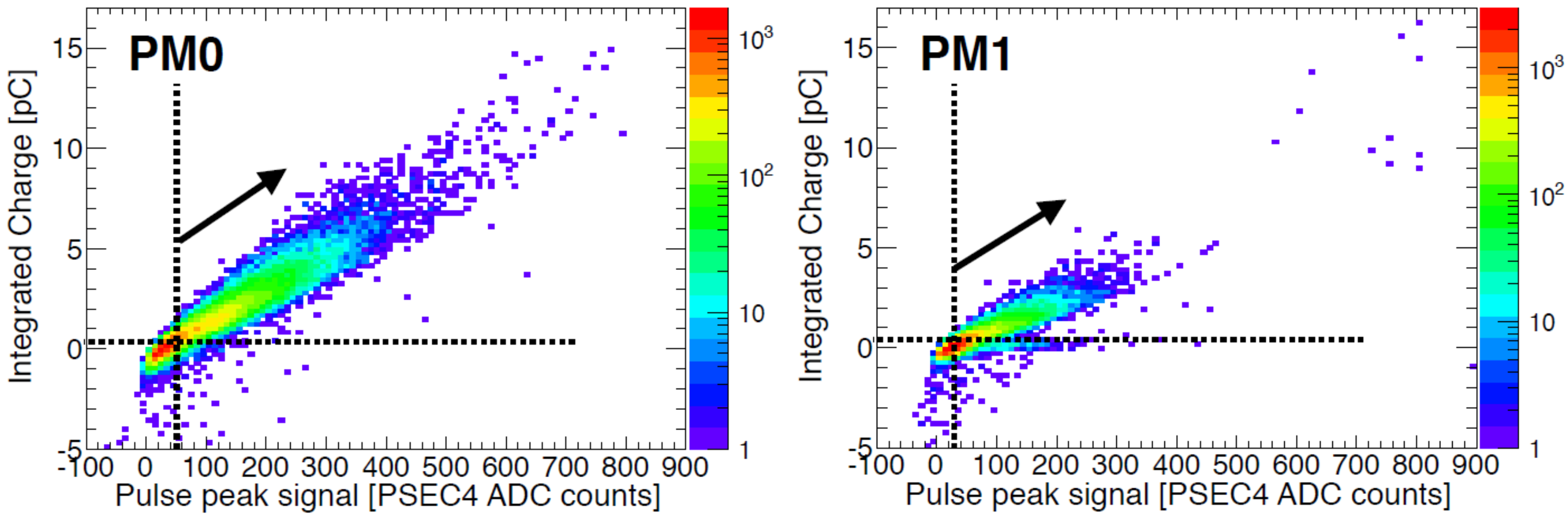
Comparison of 16 and 32 GeV/c secondary-beam datasets

- Through-going trigger: 79 ± 18 photo-electrons per track
- Front-only trigger: 67 ± 25

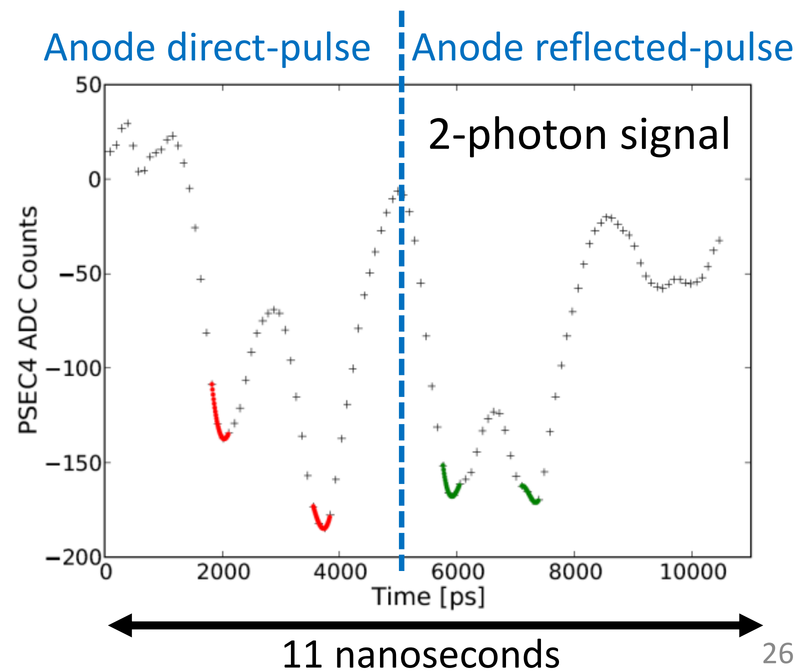


Water quality: blue > red

Signal selection / measuring photon time-of arrival



- OTPC channels above a threshold-level defined by the total integrated charge and the peak signal amplitude are fit for time-of-arrival
- The photon time-of-arrival is extracted by locating and interpolating the pulse peaks in the waveform
- Can resolve both single and double photon hits per channel (per microstrip)

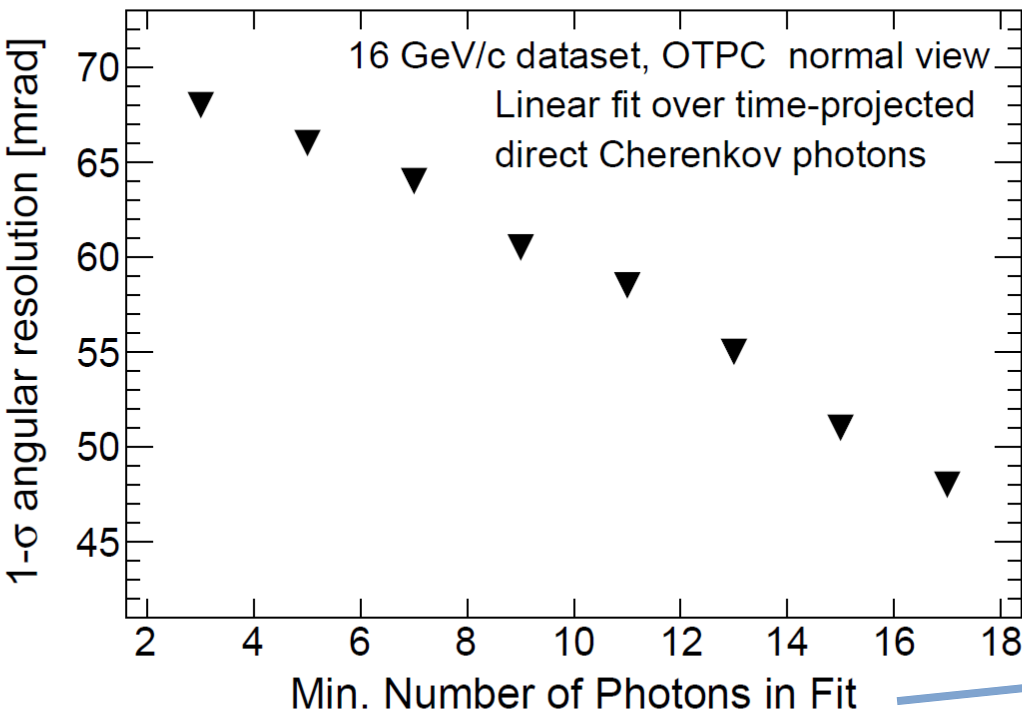


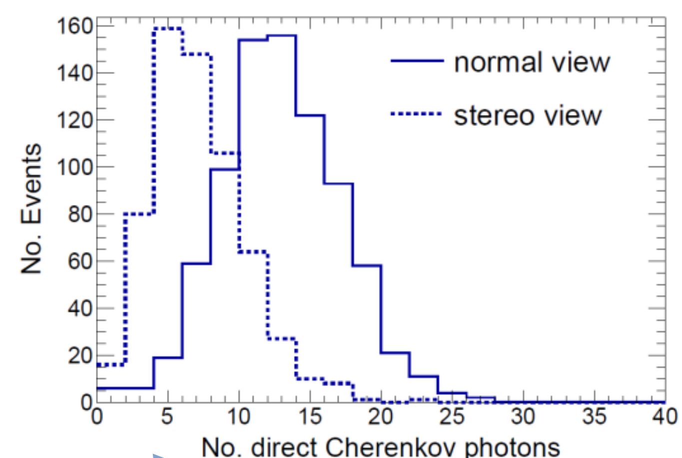
Angular reconstruction

Assuming a straight track over the ~40 cm length of the OTPC fiducial volume: a linear fit to the time-projected direct Cherenkov photons is a measure of the track angle with respect to the OTPC/beam axis.

$$\frac{dt'}{dz} = \frac{dt}{dz} - \frac{1}{c} = \frac{\tan\theta}{< v_{group} >}$$

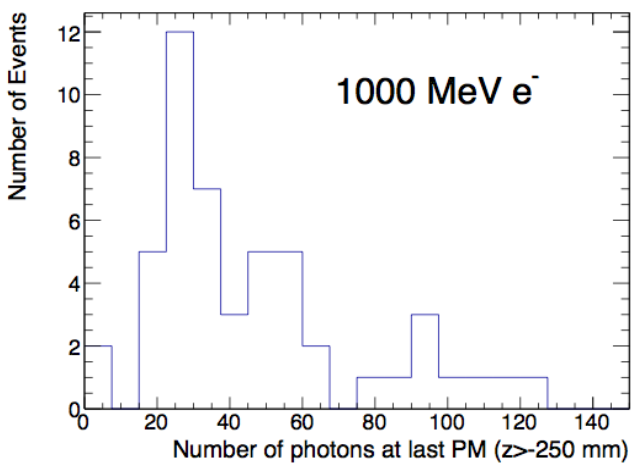
For events with >17 direct photons in normal view, we measure a 1-σ angular resolution of 48 mrad (~3 degrees over 0.4 m)

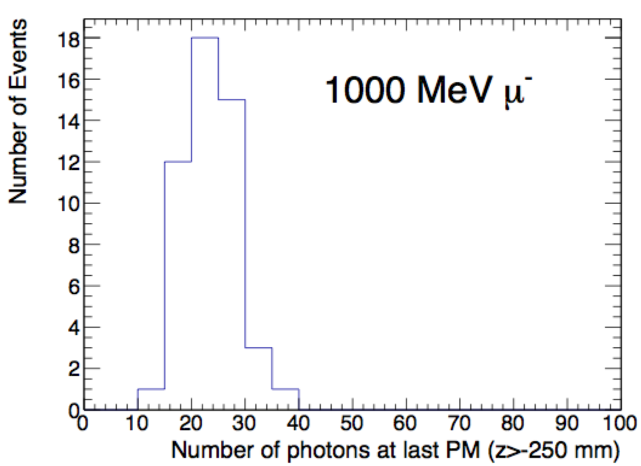




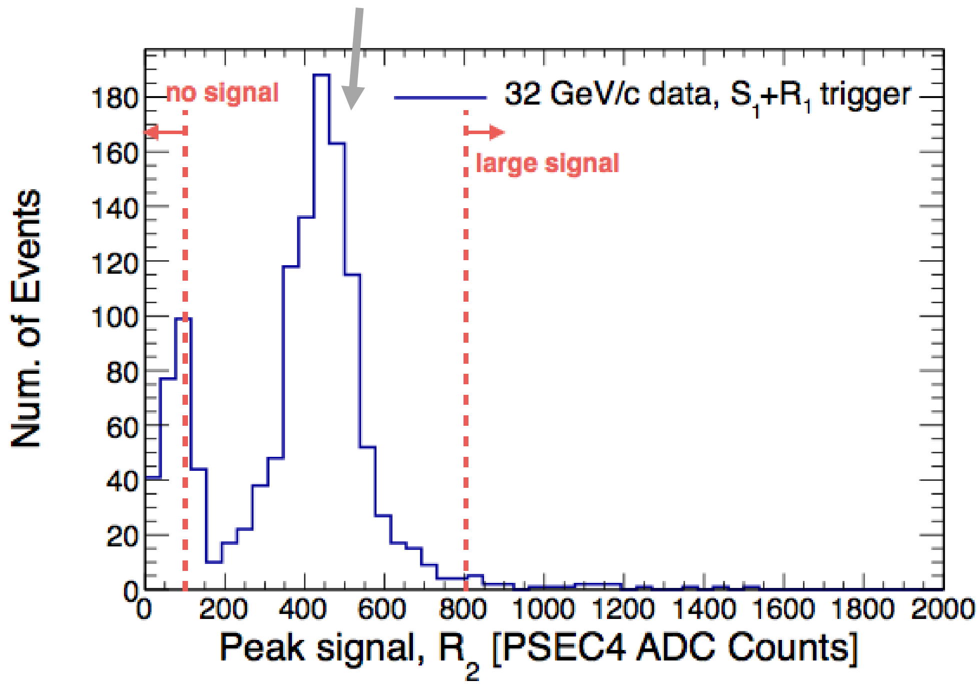
Particle ID

[Preliminary] Muon vs showering-electron ID. Cut events based on signal (charge) deposited in the OTPC rear MCP-PMT trigger





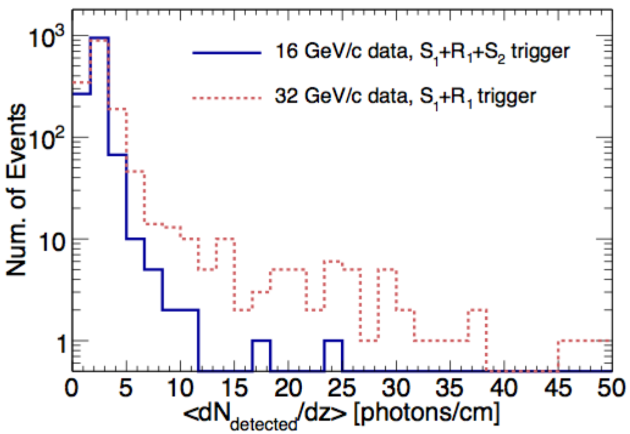
Peak distribution from typical thru-going MIPs (muons, pions, or non-showering electrons)

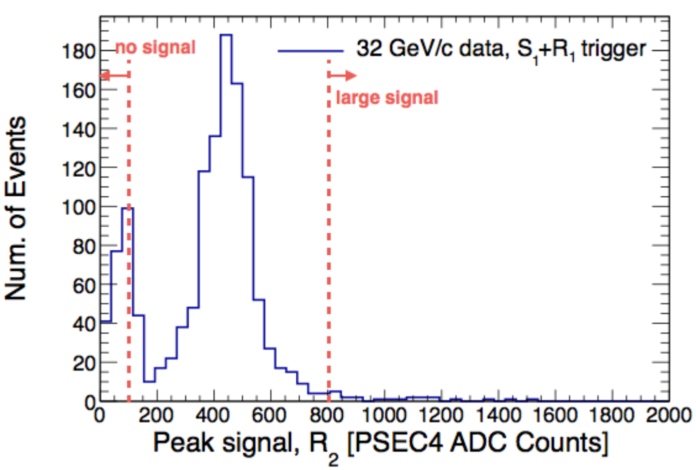


Remove central region events from sample; keep others (which may be events with an EM showering component)

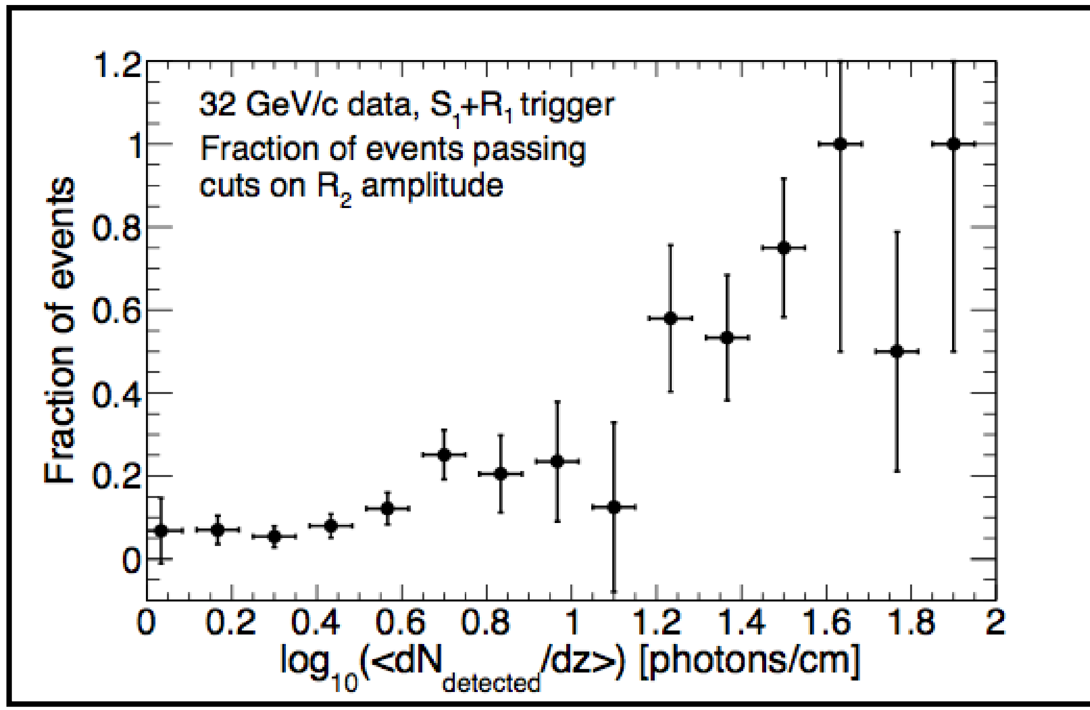
Particle ID

[Preliminary]





Strong correlation between the events cut from the OTPC trigger and the measured number of photo-electrons along the track in the water volume



[To do a better job, really need a larger detector (more containment), more photodetector coverage, more instrumentation on the beam, and a lower-energy beam ~GeV]