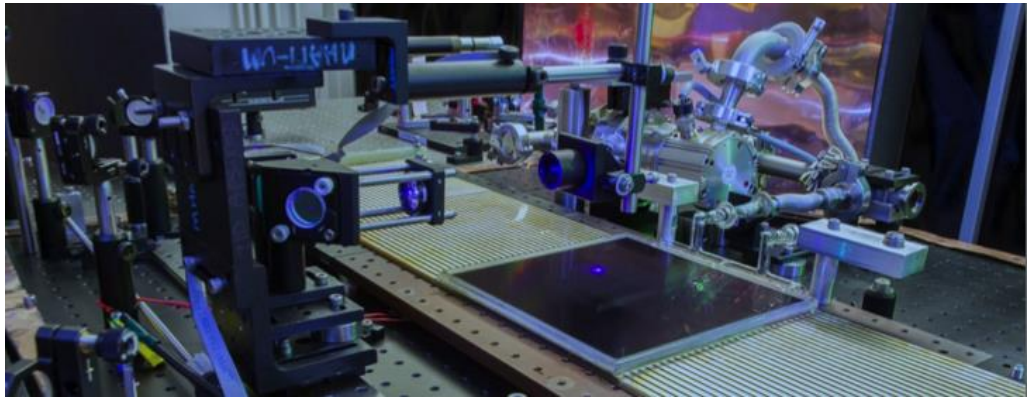
Developing a water Cherenkov optical time-projection chamber



25-Jan-2016
UChicago
Eric Oberla

HIGH ENERGY PHYSICS
THE UNIVERSITY OF CHICAGO

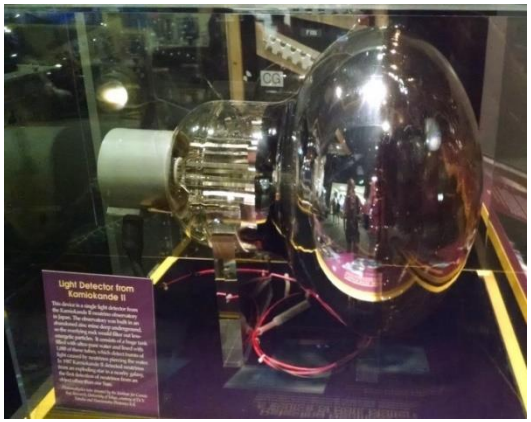
Outline

- The LAPPD project
  - Large-area microchannel plate PMTs
  - Custom waveform-digitizing integrated circuits
- A prototype optical time-projection chamber (OTPC)
- Experiment (T1059) and results
- …scaling up

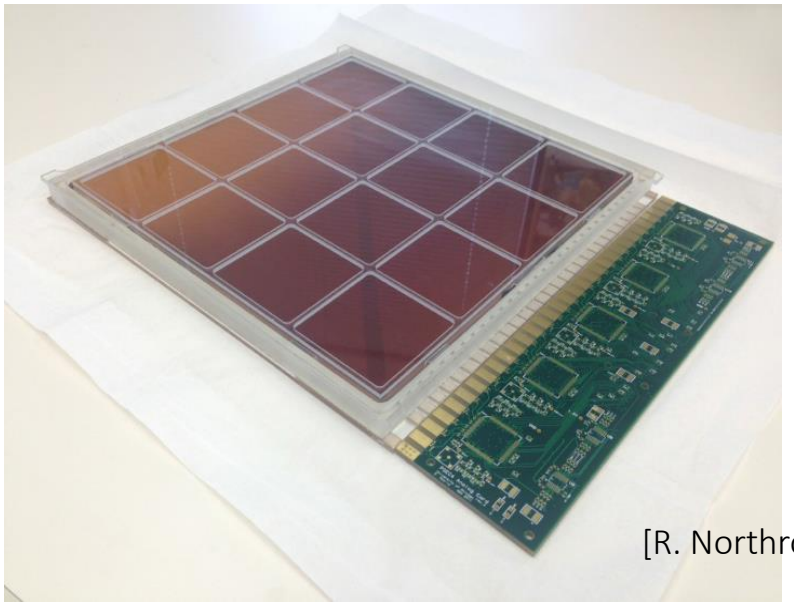
LAPPD™

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



Conventional Photo-multiplier tube (PMT), single pixel.
(Kamiokande PMT from the Smithsonian Air & Space Museum)



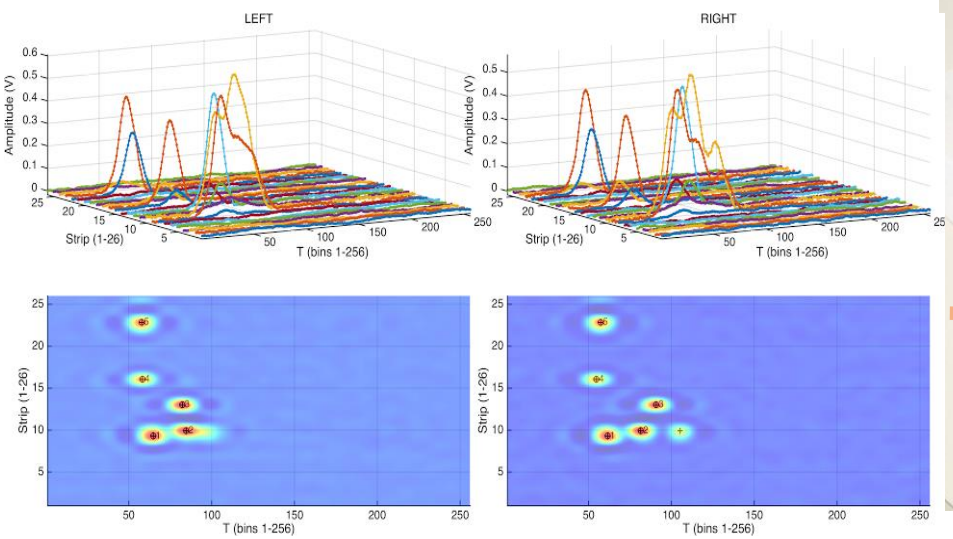
[R. Northrop photo]

400 sq. cm LAPPD mock-up. (Actual components, not hermetically sealed, no photocathode)

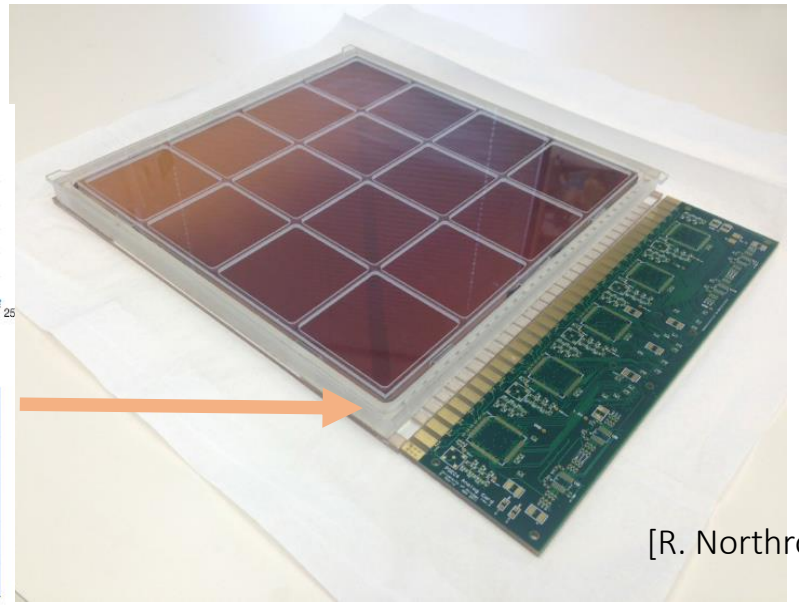
LAPPD™

LAPPD = Large Area Picosecond Photo-Detector

The 20 x 20 cm^2 glass package:



Data-driven simulation of detector response + photon disambiguation + reconstruction [G. Jocher et. al]

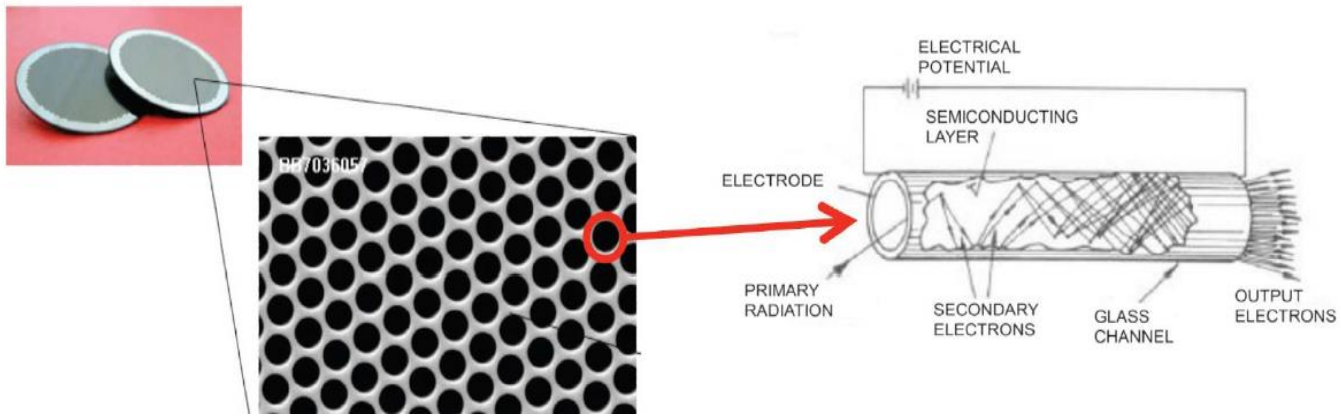


[R. Northrop photo]

400 sq. cm LAPPD mock-up. (Actual components, not hermetically sealed, no photocathode)

Micro-channel plate

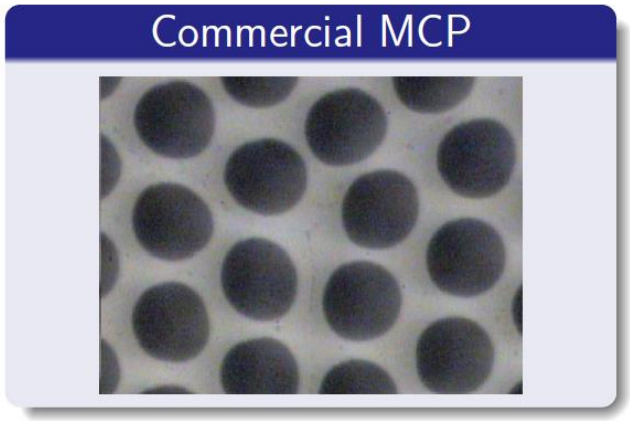
Each pore is a continuous-dynode electron multiplier



Standard manufacturing process is expensive / complex:

Chemically produced and treated Pb-glass does 3-functions:

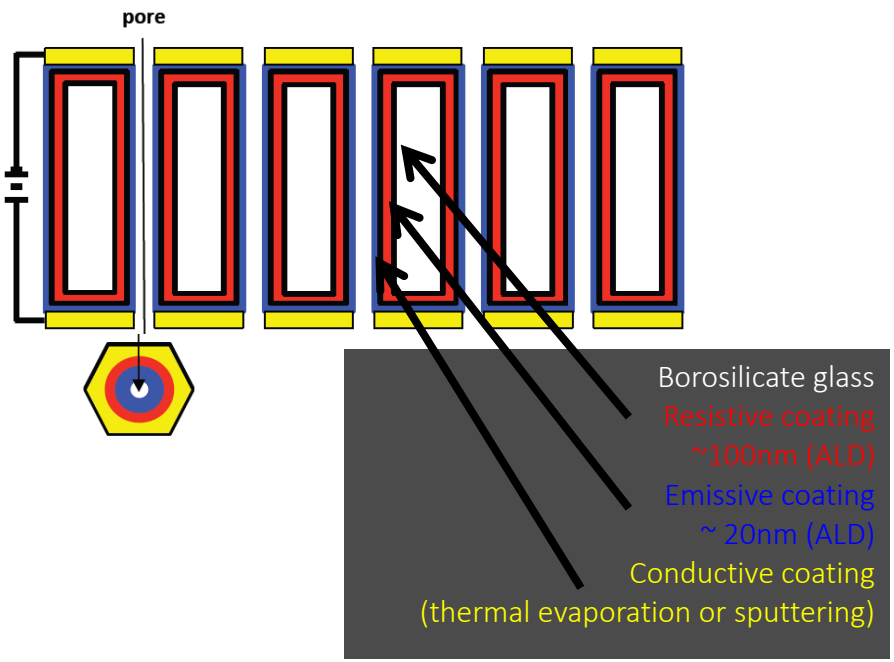
- Provide pores
- Resistive layer supplies electric field in the pore
- Pb-oxide layer provides secondary electron emission



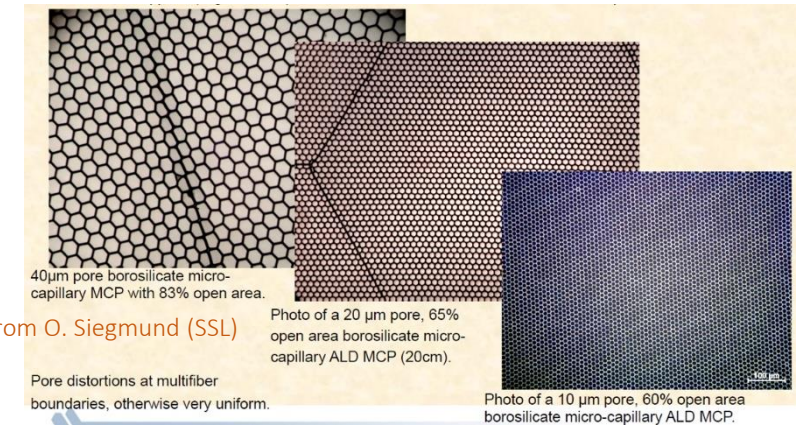
MCPs from glass micro-capillary array

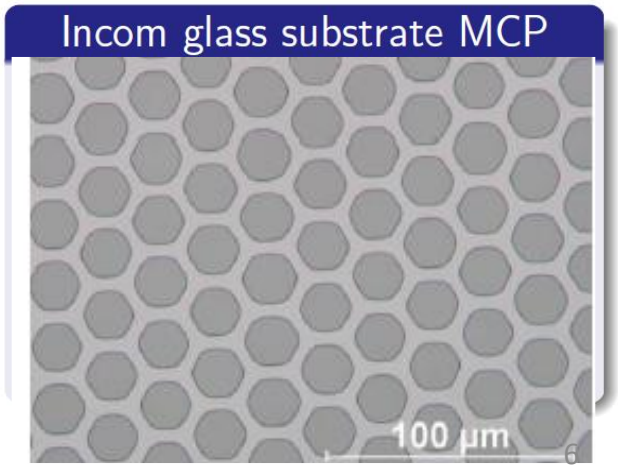
The LAPPD fabrication process separates the substrate and functionalization steps

- Hard glass substrate provides pores – array of fused glass pores (Incom, Inc.)
- Tuned resistive Layer (via Atomic Layer Deposition [ALD]) provides electric field bias across the pore
- Secondary-emitting layer layer via ALD



slide from O. Siegmund (SSL)





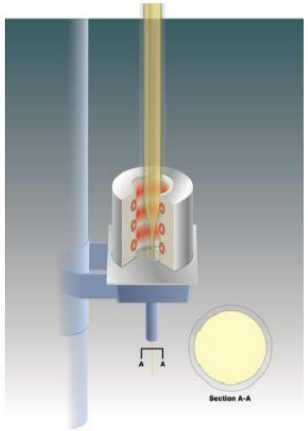
LAPPD MCP

~80 million Ø20 µm pores in 400 cm^2 square glass substrate…

LAPPD MCP

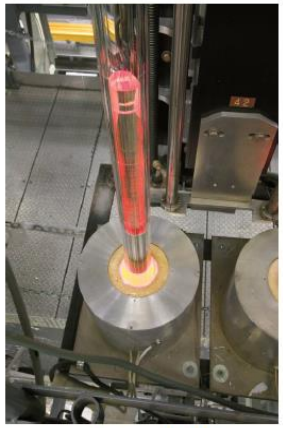
Commercialization underway at Incom, Inc. (Charlton, MA)

Step 1: draw glass



Incom's proprietary "etchless" approach. A wide range of glasses can be used.

Incom draw towers



Conventional MCPs are drawn as fiber optics, with core and clad glass

We are developing capability to fabricate large area sealed detector tiles, not just MCPs

In-house equipment being brought in for:

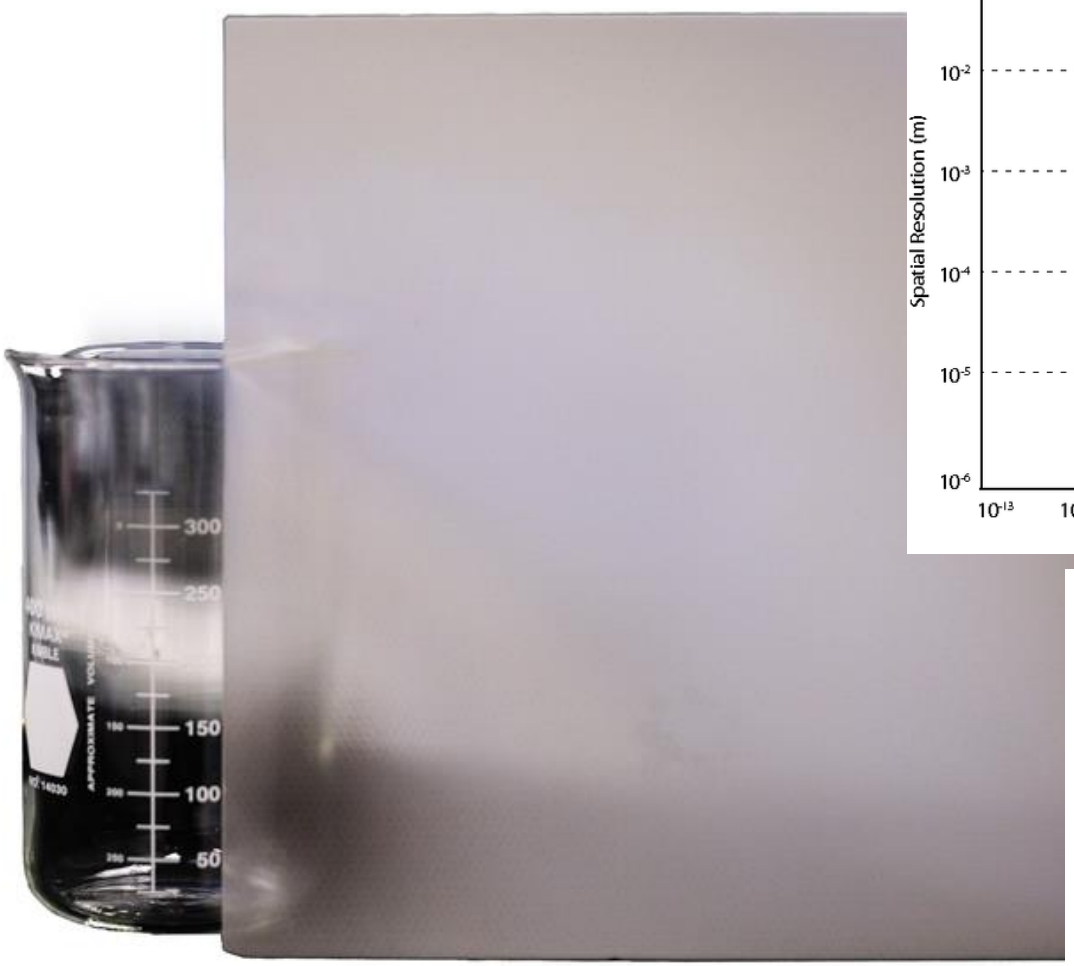
- Electrode deposition
- ALD coating
- Detector tile assembly
- Additional testing electronics

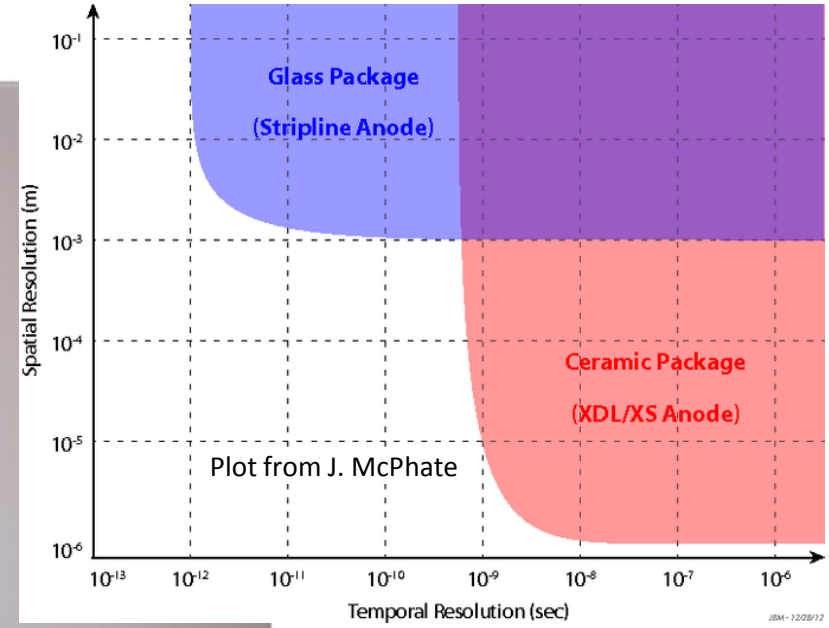
courtesy of Chris Craven, Incom

- Incom is the company commercializing the LAPPD™
- 2-year contract with the US DoE, April 2014 – April 2016

LAPPD MCP

~80 million Ø20 µm pores in 400 cm^2 square glass substrate…



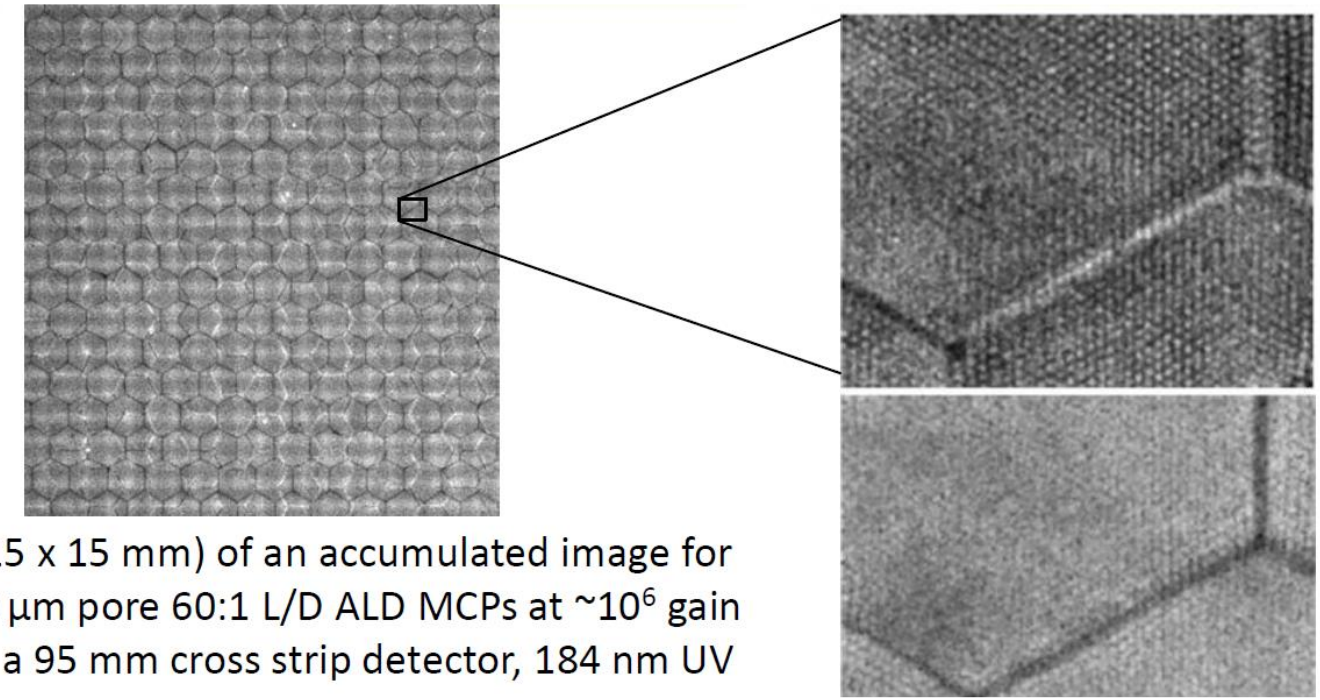


…. How to readout?

The **anode and front-end electronics** design choice is a trade-off in time resolution, spatial resolution, occupancy, cost, analog bandwidth, and event rate

Anode trade-off: precision spatial resolution

credit: O. Siegmund (SSL)



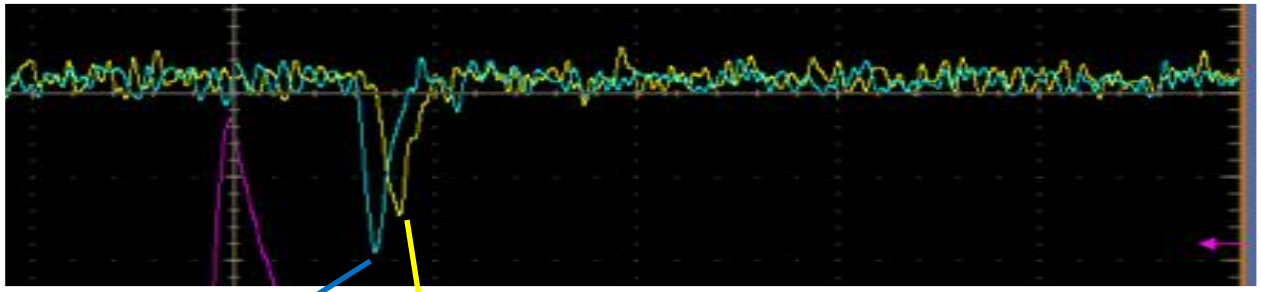
Section (~15 x 15 mm) of an accumulated image for a pair of 20 µm pore 60:1 L/D ALD MCPs at ~10^6 gain taken with a 95 mm cross strip detector, 184 nm UV

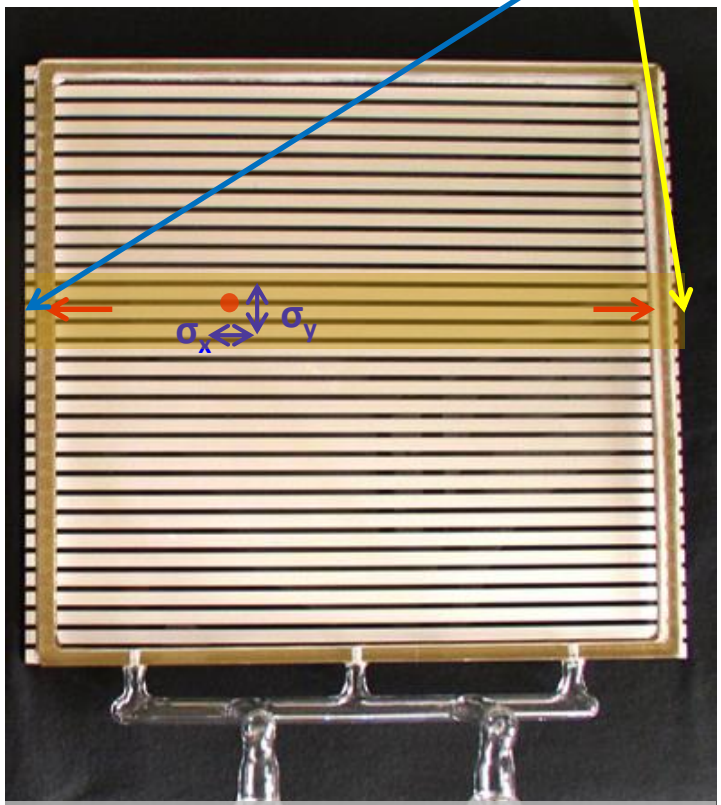
Spatial resolution is largely determined by the anode design, which sets effective pixel size

Cross-delay line/strip anode:

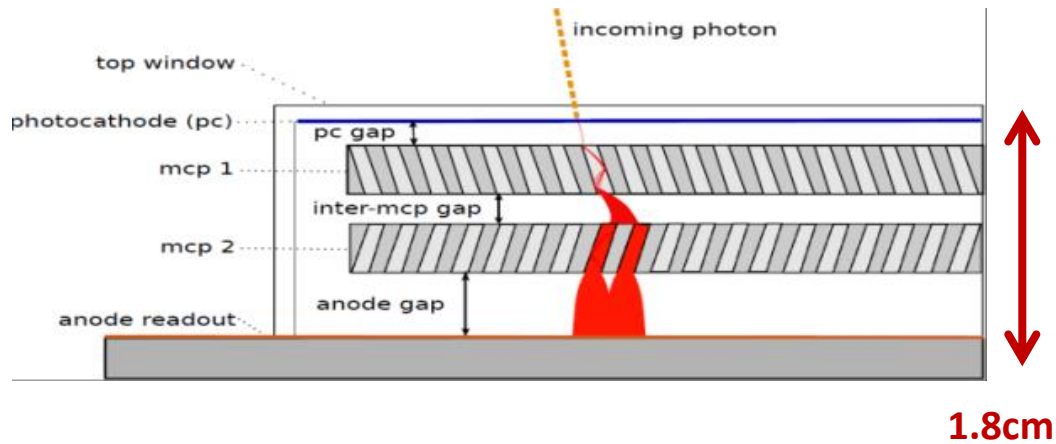
- ~micron-level imaging
- ~ns timing resolution
- $$$

Anode trade-off: optimized for timing / economy





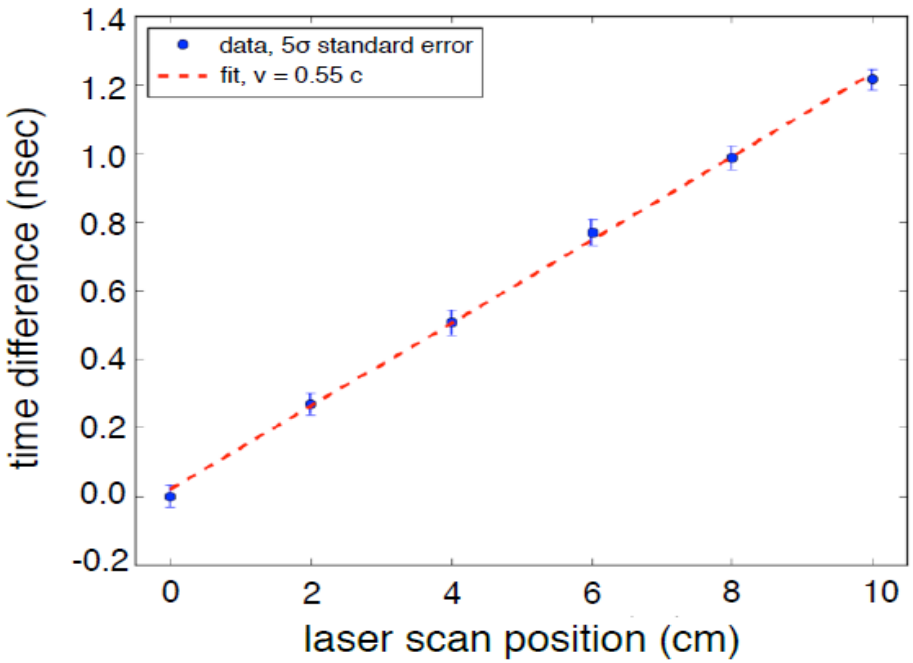
Anode 'tile-base'. Thirty 50Ω microstrips

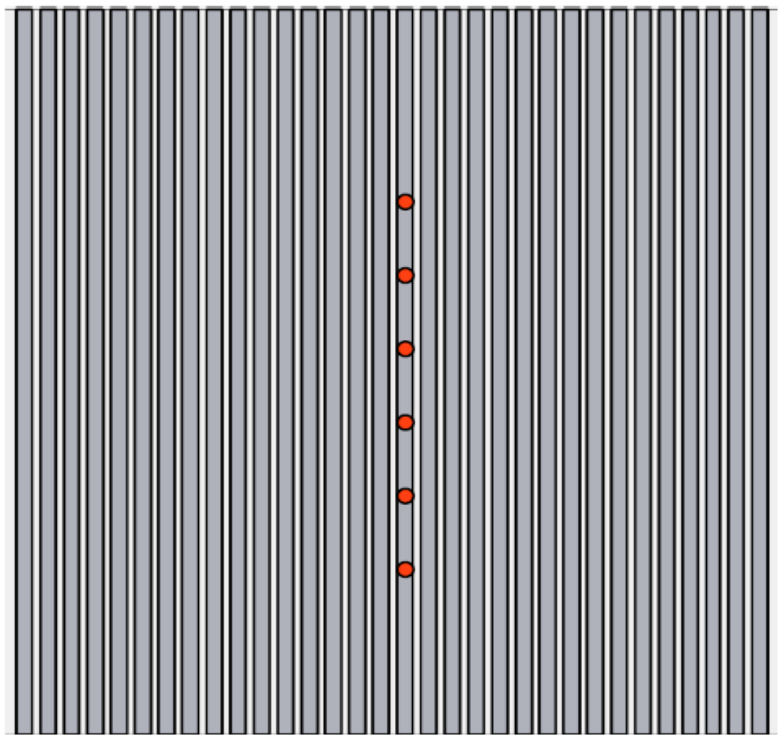


Array of 1-D striplines

- Glass or ceramic packaging
- 50 ohm strips (geometry determines impedance)
- Preserve MCP timing resolution (<100 ps single p.e.)
- Economical
  - -hermetic package sealed over strip-lines

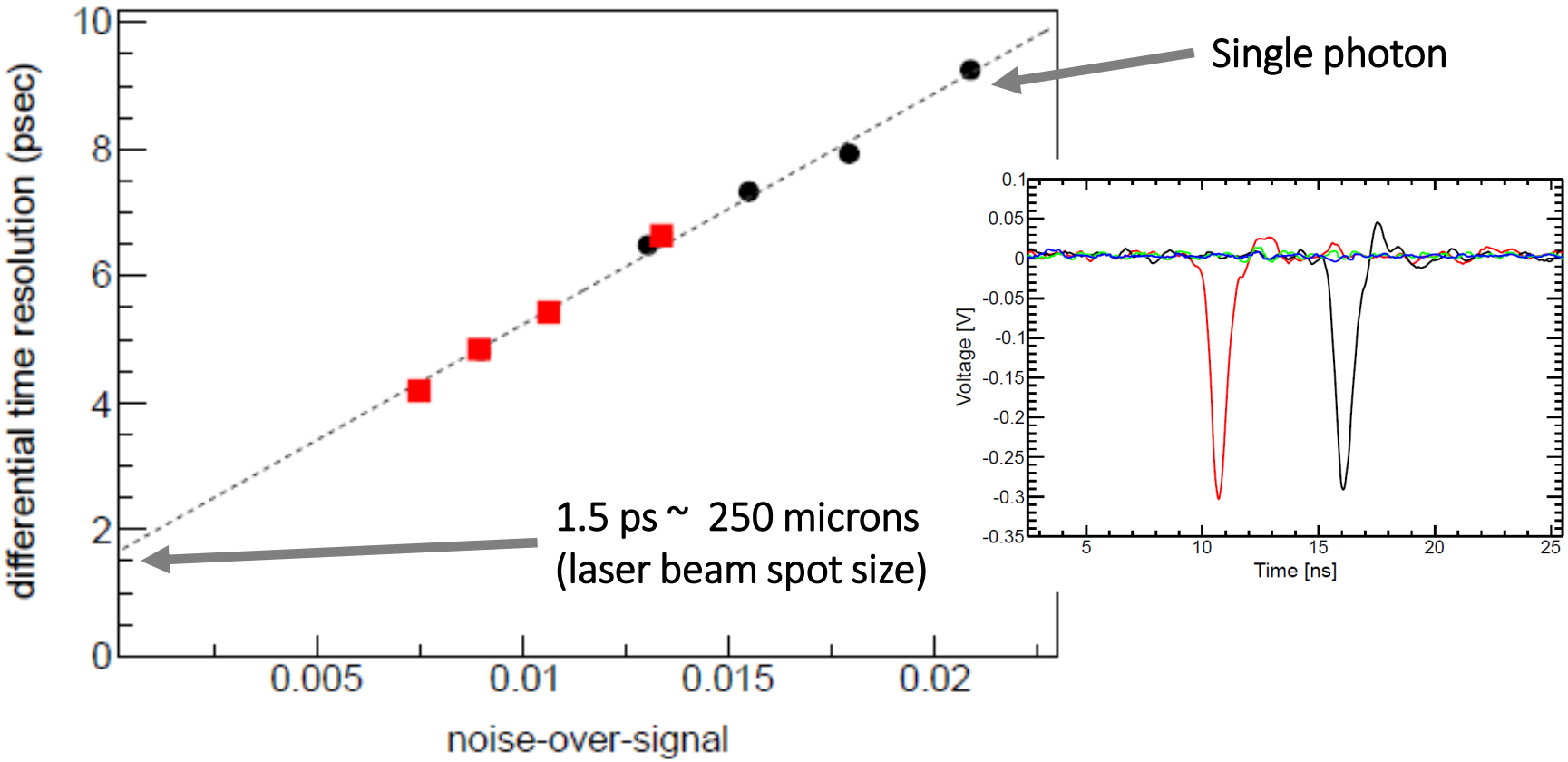
Differential timing along strip-line





Relative timing between the 2 anode terminals, waveform fitting. Few mm spatial resolution at single-photon level.

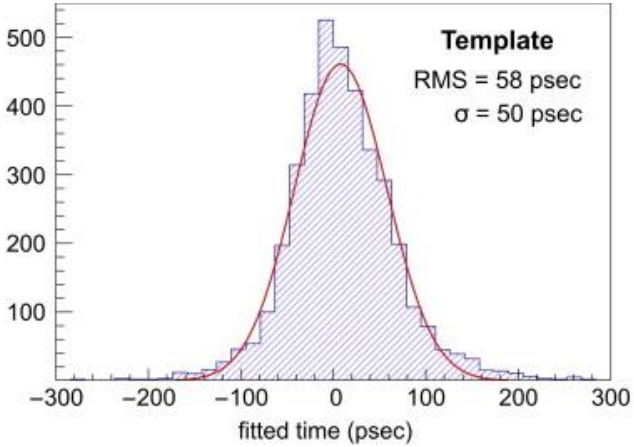
Differential timing along strip-line



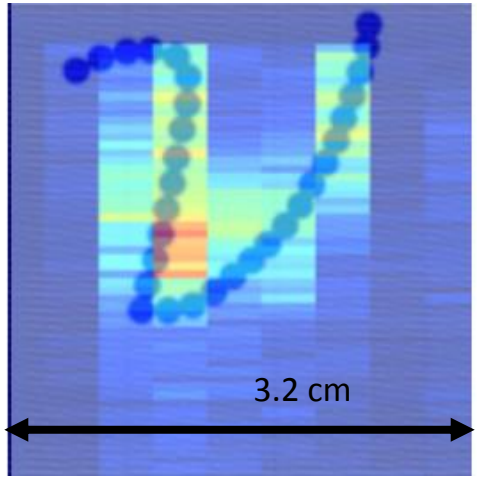
Resolution vs. 1/SNR, measured at a single laser spot

Timing characteristics of Large Area Picosecond Photodetectors [NIM A 795, 2015, 1-11]

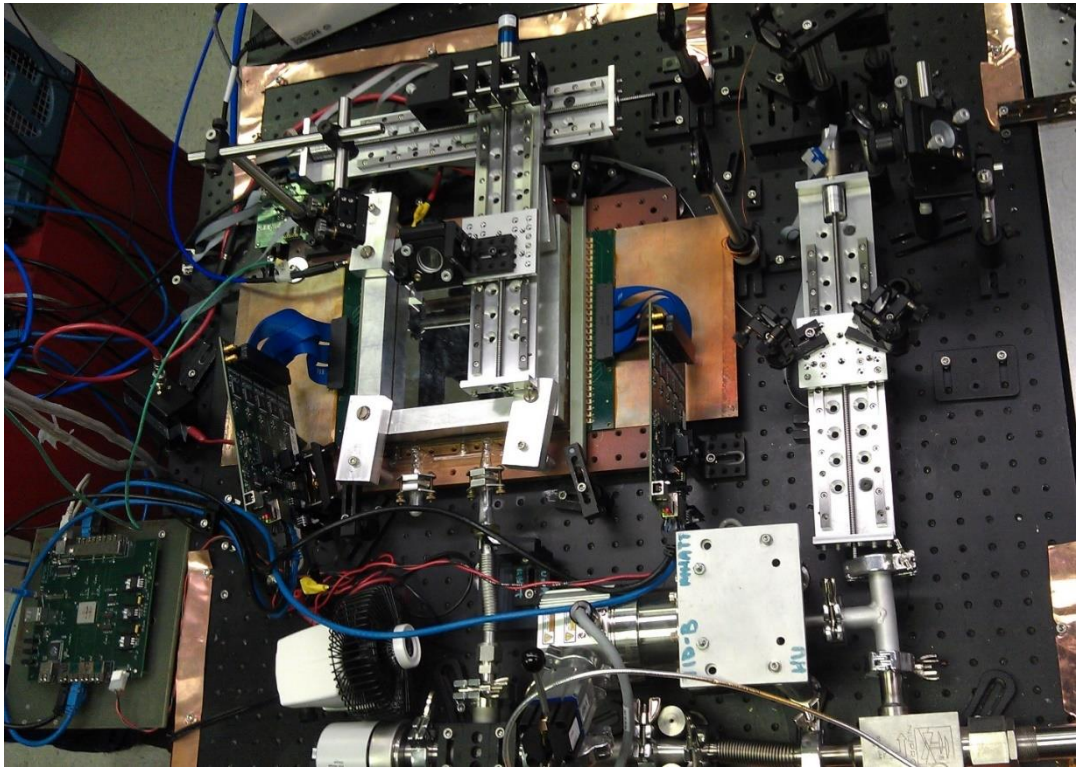
LAPPD Performance



single photoelectron absolute time resolution (psec)

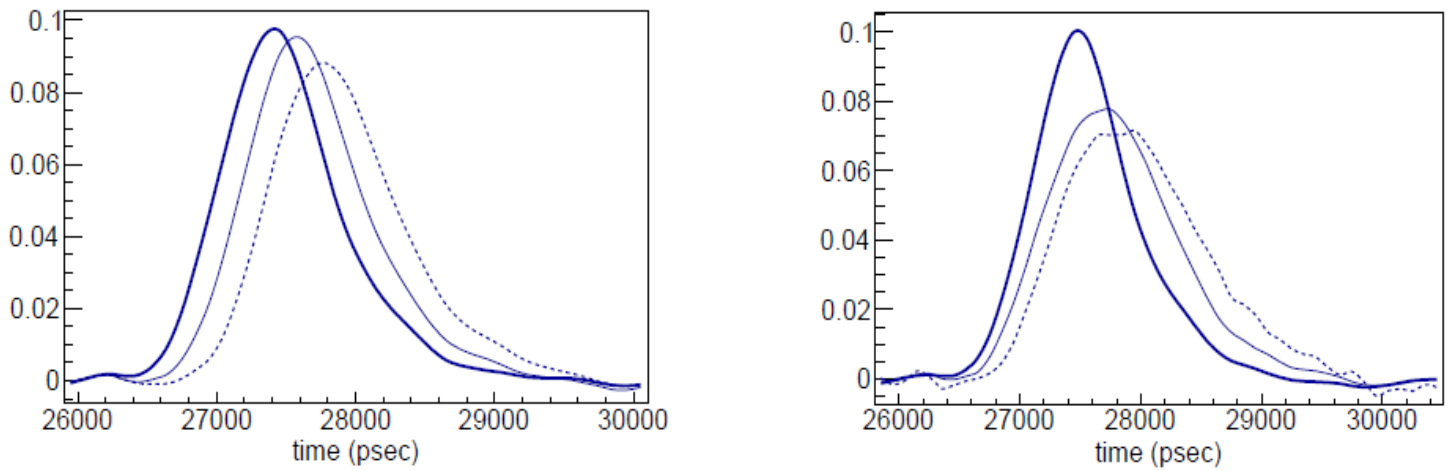


former test-stand at the Advanced Photon Source, Argonne



The LAPPD 'Demountable'
[NIM A 795, 2015, 1-11]

LAPPD analog output



Average LAPPD pulse shape into the 50 ohm strip-line anode shown for three different photocathode-gap voltages (500, 200, 100 V) and 1 kV across each MCP

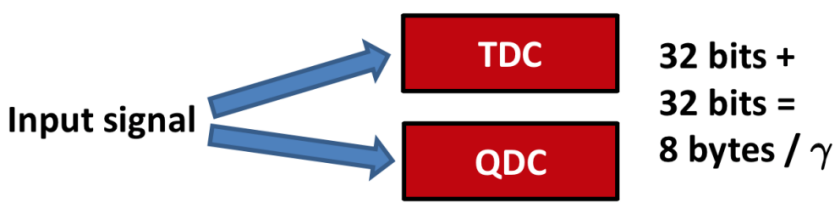
Typical single photo-electron pulse: ~1 ns FWHM
3dB bandwidth ~ $0.35/(\tau_R)$
~ 700 Mhz
[analog signal bandwidth limited by anode and interconnects: MCP impulse response> 1 GHz]

<u>Electronics requirements:</u>
+ 30/60 channels per LAPPD + ability to handle overlapping photons (pile-up) + charge centroiding

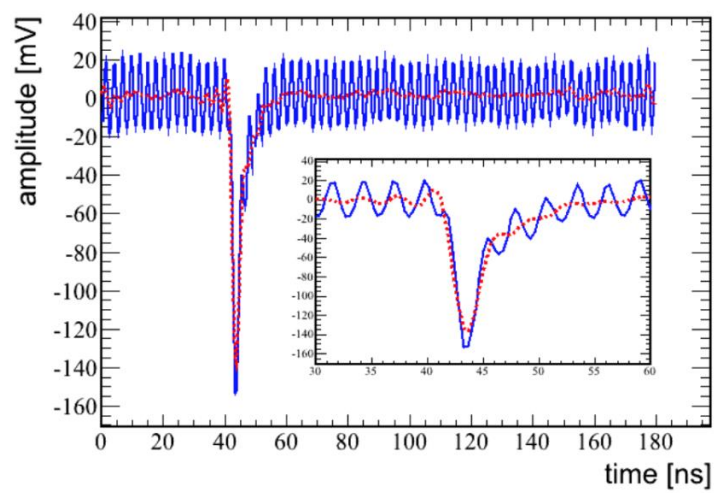
LAPPD front-end electronics – full waveform digitization

- Access to waveform is a terrific diagnostic tool: analyzing noise, pileup, etc.
- In general, less hardware overhead (ADC + FPGA)
- Flexibility in signal feature extraction algorithms (online firmware-based or offline software-based – can be modified without changing hardware)

- Caveats: required to log much more data to disk or reduce on-the-fly in a companion field-programmable gate array (FPGA)



256 samples * 12 bits/sample = 384 bytes / γ



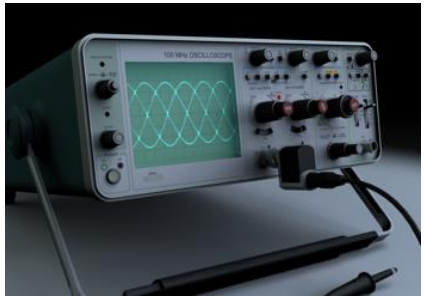
Switched Capacitor Array integrated circuits

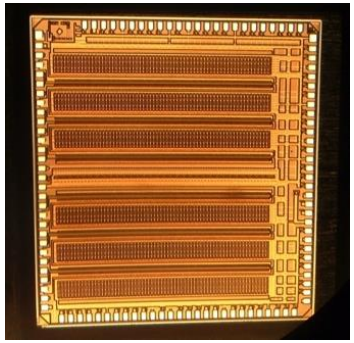
- LAPPD Electronics requirements: multi-GSPS sampling rate and GHz bandwidth
- Ideally low-power, and scalability to 1000's of channels
- Off-the-shelf electronics?
  - [No. >0.5k$ and >1W per channel for commercial ADCs, mostly prohibitive for >3 GSPS options]

Alternative :: CUSTOM Application Specific Integrated Circuits (ASIC)

- Relatively inexpensive access to high performance CMOS via multi-project wafers
- Scalable, each detector channel an independent oscilloscope
- Take advantage of a 'triggered-event' readout architecture that is typical feature of HEP/astro-particle experiments

  Sample the detector output at >1 GHz, and read data off chip at 10-100 MHz (`analog down-conversion') ----> an application-specific *switched capacitor array* (SCA) chip





SCA waveform-sampling chips

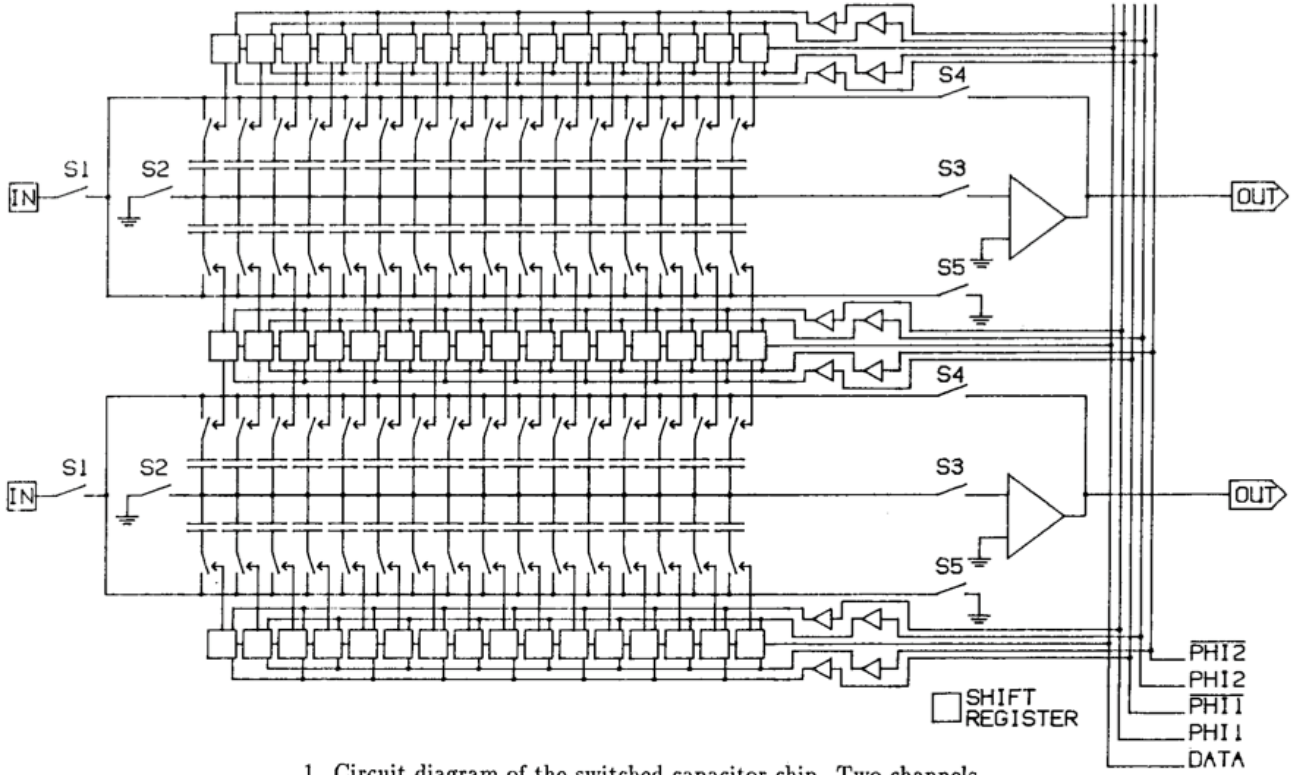
IEEE Transactions on Nuclear Science,
Vol. 35, No. 1, Feb. 1988

50 MSa/s in
3.5 µm CMOS

DEVELOPMENT OF A SWITCHED CAPACITOR BASED MULTI-CHANNEL TRANSIENT WAVEFORM RECORDING INTEGRATED CIRCUIT

Stuart A. Kleinfelder

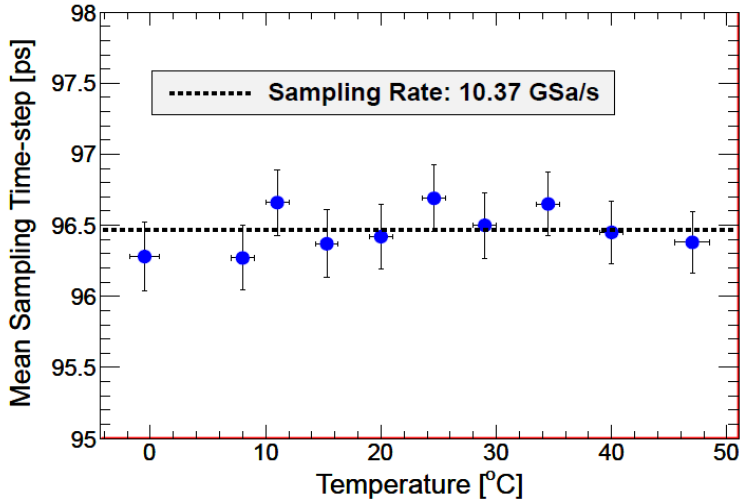
Lawrence Berkeley Laboratory
Berkeley, California 94720

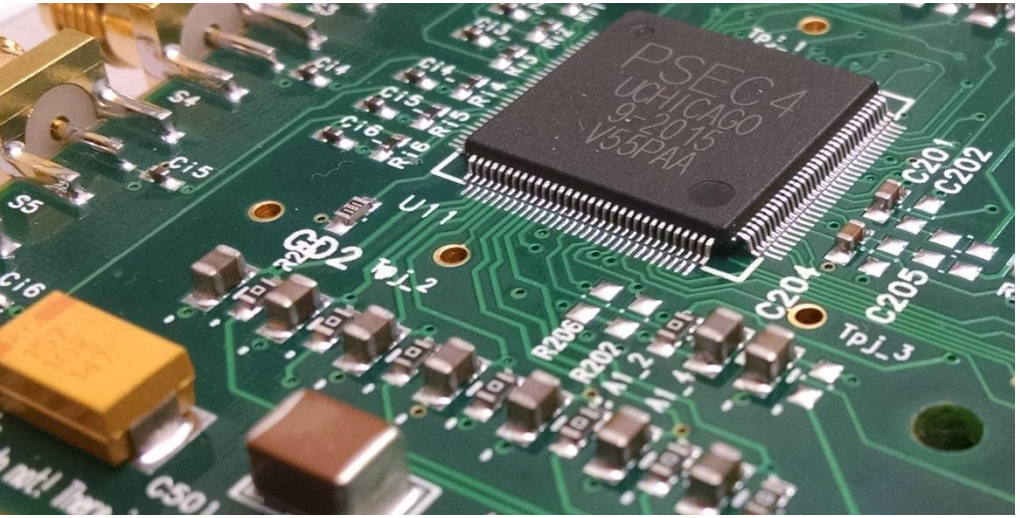


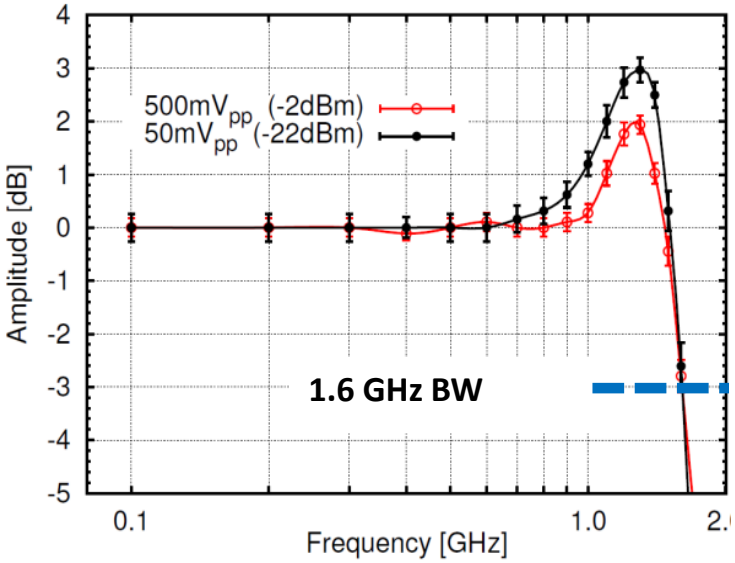
1. Circuit diagram of the switched capacitor chip. Two channels of 32 sample and hold cells per channel are shown. The I.C. contains 16 channels of 128 cells per channel.

PSEC4: 10 GSa/s front-end digitization

- Push for higher sampling speeds and lower power 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. Readout rate ~50 Mhz.



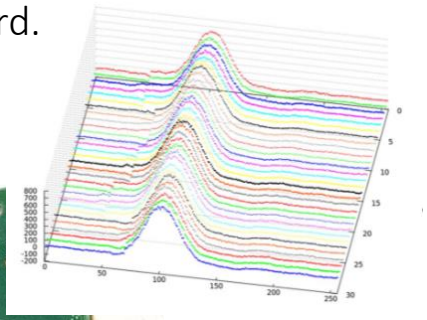


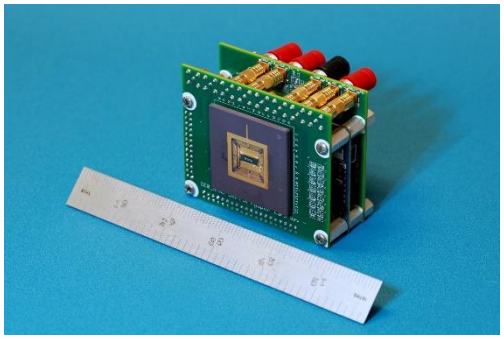


PSEC4: A 15 GSa/s, 1.5 GHz bandwidth waveform digitizing ASIC [NIM A 735, 2014,]

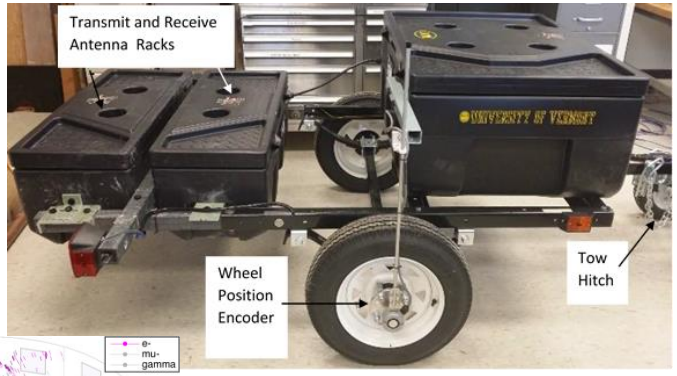
PSEC4 data-acquisition systems

30-channel, 10 GSPS, PSEC4 board. Modular, can build systems with many 100's of channels with an additional 'central' board

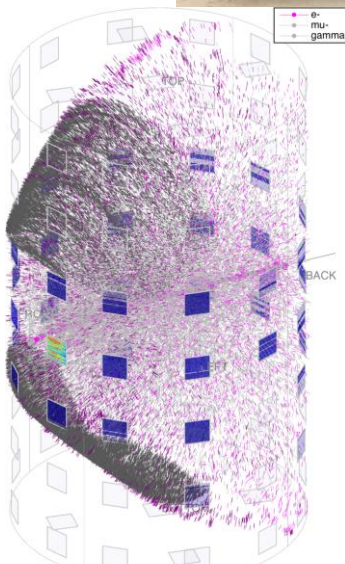




x-rays, Sandia National Lab



Ground penetrating radar, UVermont



ANNIE, Fermilab
[G. Jocher simulation]

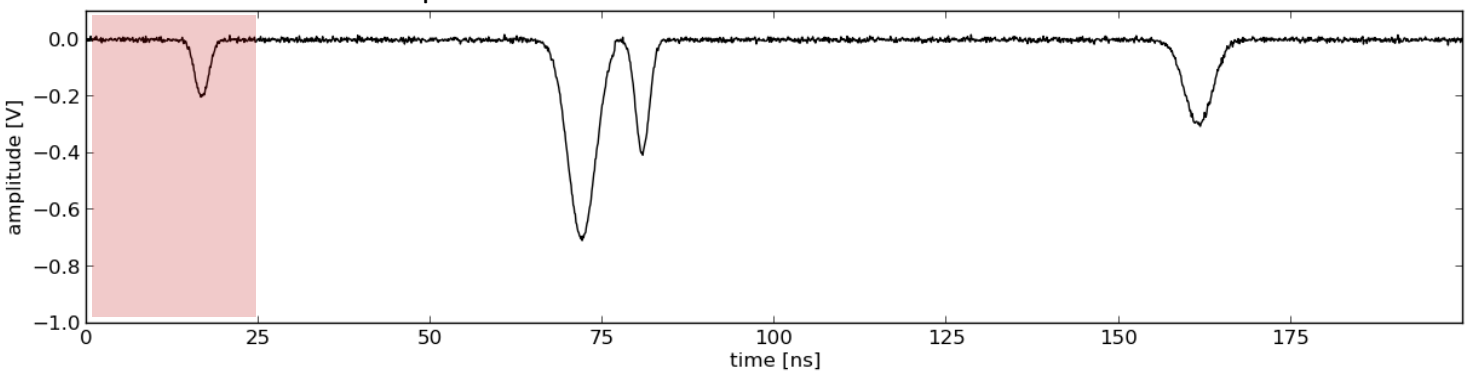
PSEC4 front-end digitization -> upgrade to PSEC4a

Main improvement is the moderate increase in sample length = the ability to *multi-hit buffer events that are close in time*. PSEC4a will be able to sample/digitize/readout simultaneously.

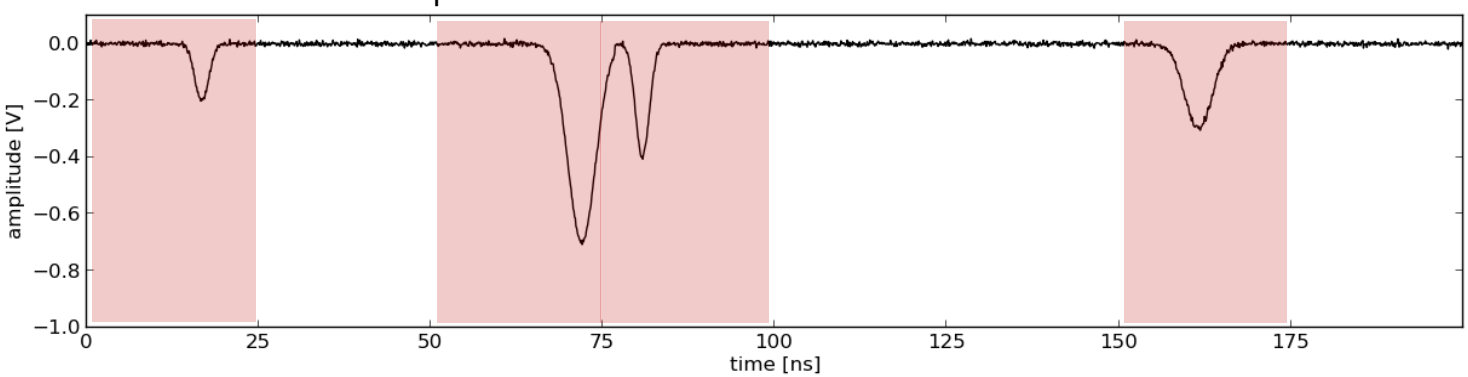
→ **Enables dead-time less operation for a certain experimental event rate (CW+burst)**

- Fix the primary PSEC4 limitation: sample depth at 10 GSa/s

PSEC4: red = acquired

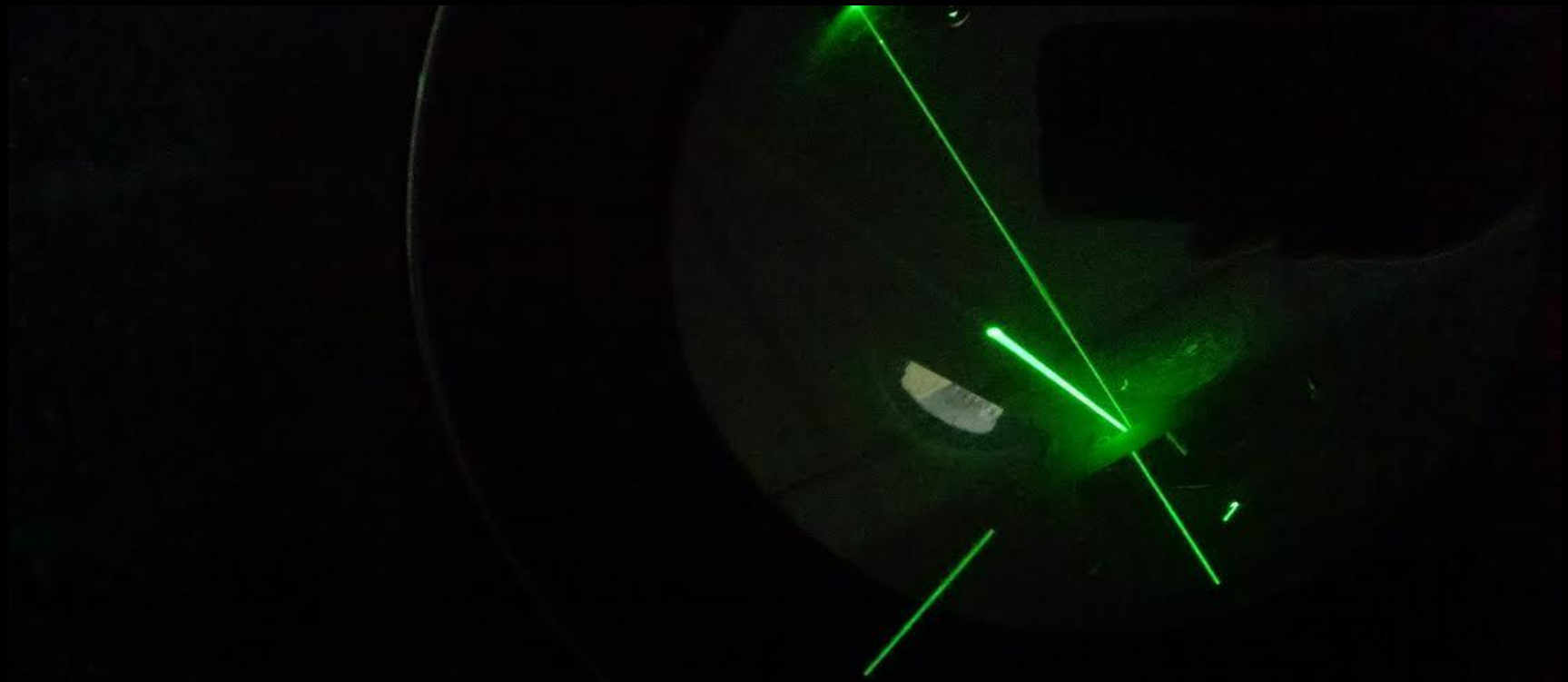


PSEC4a: red= acquired



From December workshop: http://psec.uchicago.edu/workshops/PSEC4A/

optical time-projection chamber



- New technologies:
  - LAPPD photodetectors with spatial and timing resolution
  - Scalable, fast sampling electronics for measuring time and amplitude

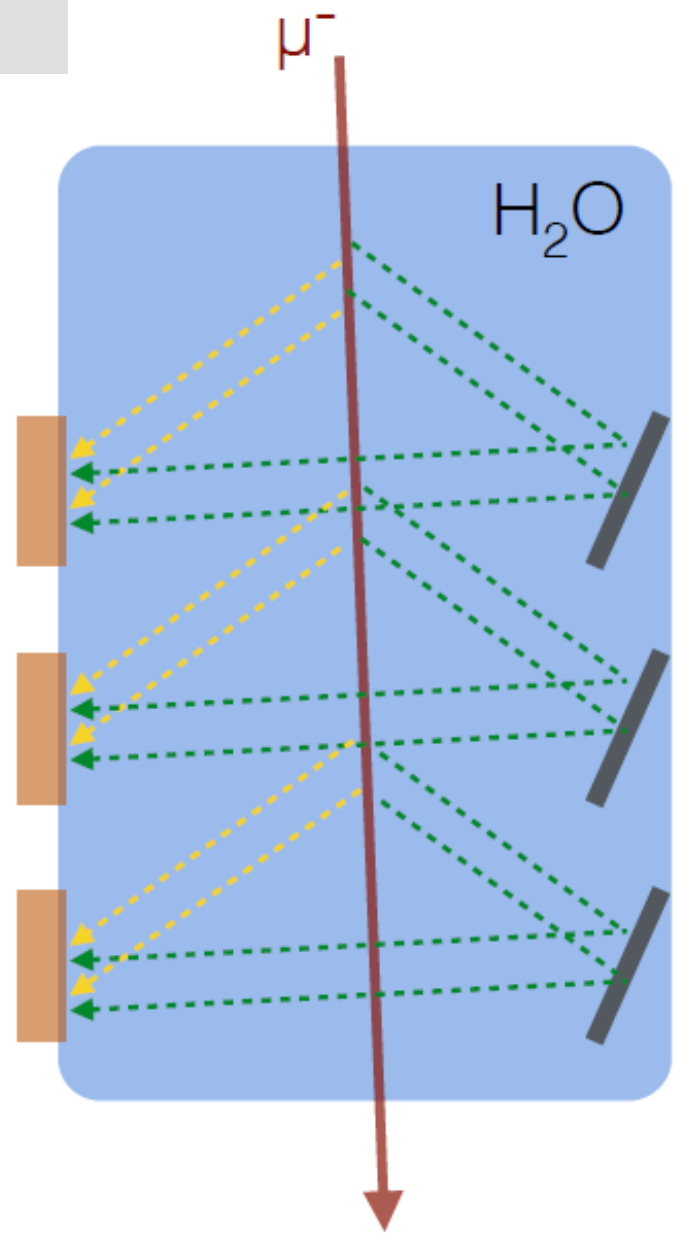
→ Enable new particle detection techniques?

the (prototype) OTPC concept

With 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).

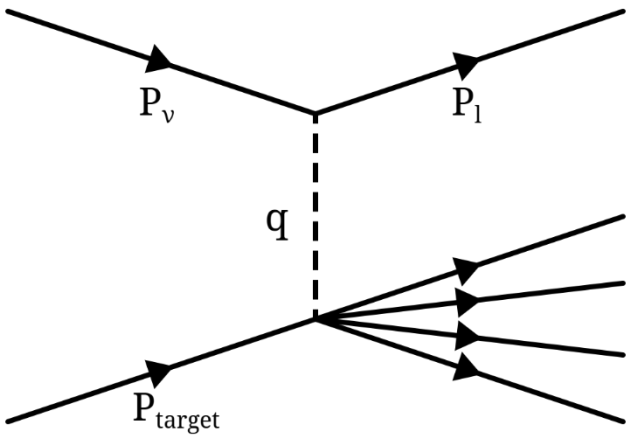
Towards the tracking relativistic charged particles by resolving the relative time and position of the `drifted' Cherenkov photons

Prototype OTPC (using mirrors!)

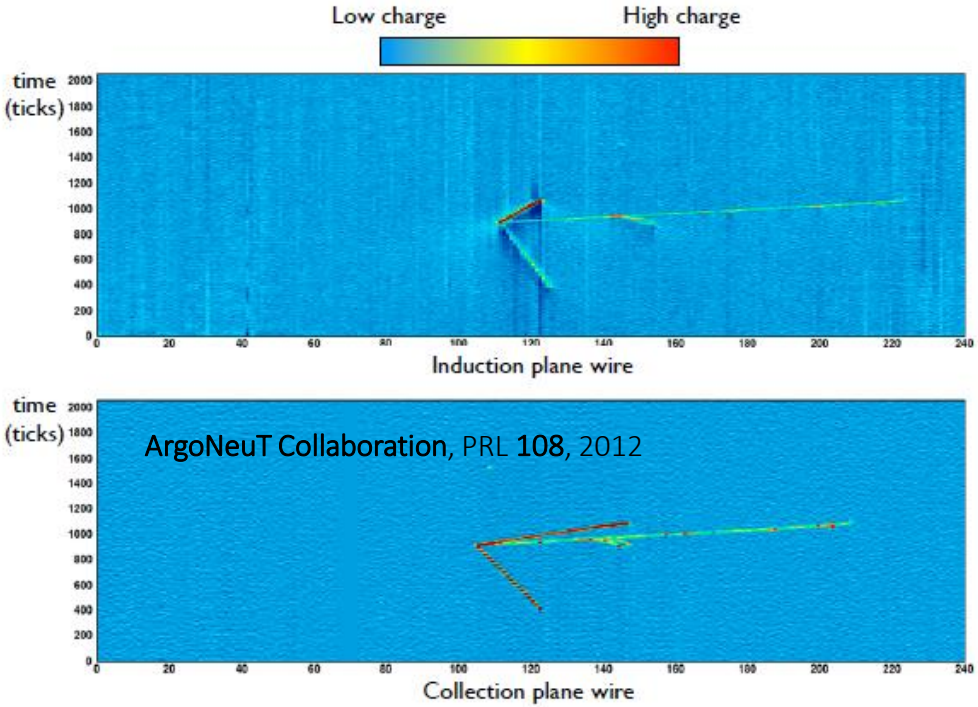


Adding a tracking dimension to a water-based neutrino detector

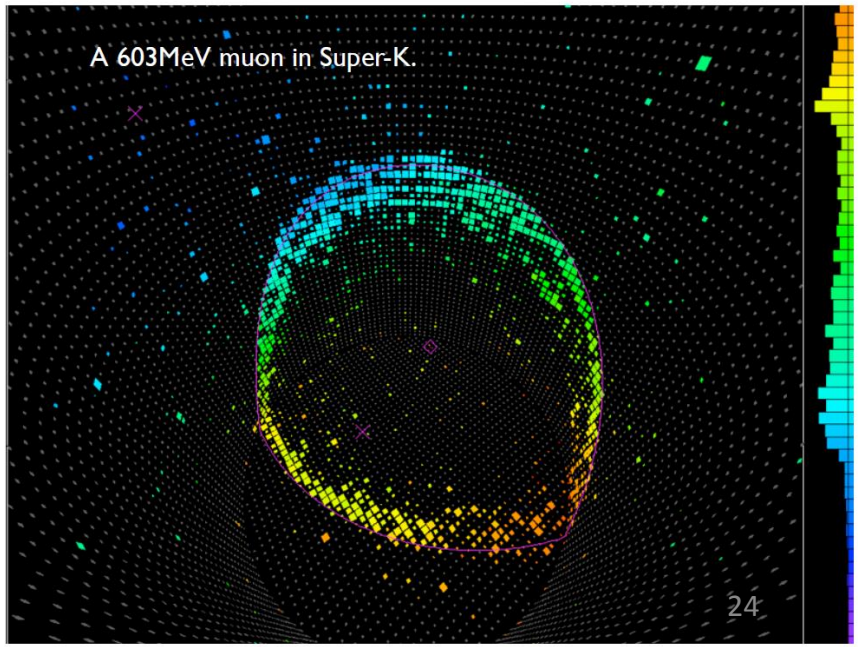
Generic neutrino interaction with a target, which leaves a final-state lepton (either charged or neutral) and an unspecified number of final-state recoil particles



State-of-the-art liquid Ar TPCs offer extremely high granularity tracking and calorimetry



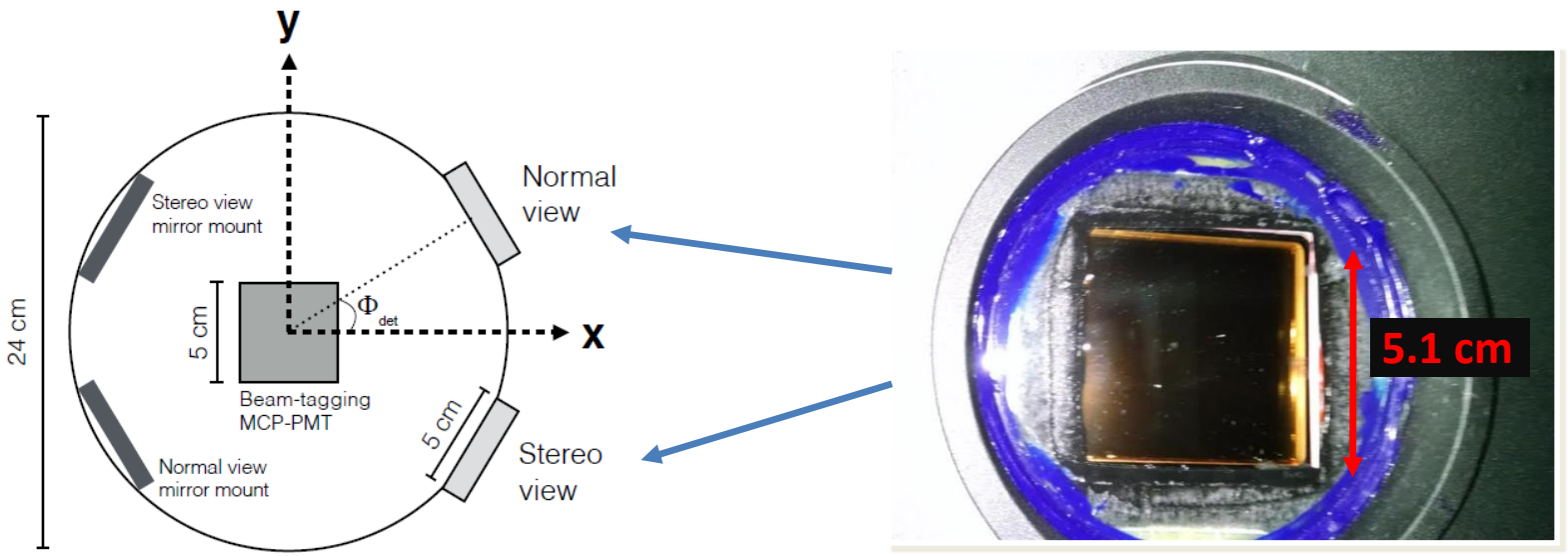
ArgoNeuT Collaboration, PRL **108**, 2012



A prototype OTPC concept on the Fermilab test-beam

The detector is constructed from a 24 cm inner-diameter PVC cylindrical pipe cut to a length of 77 cm

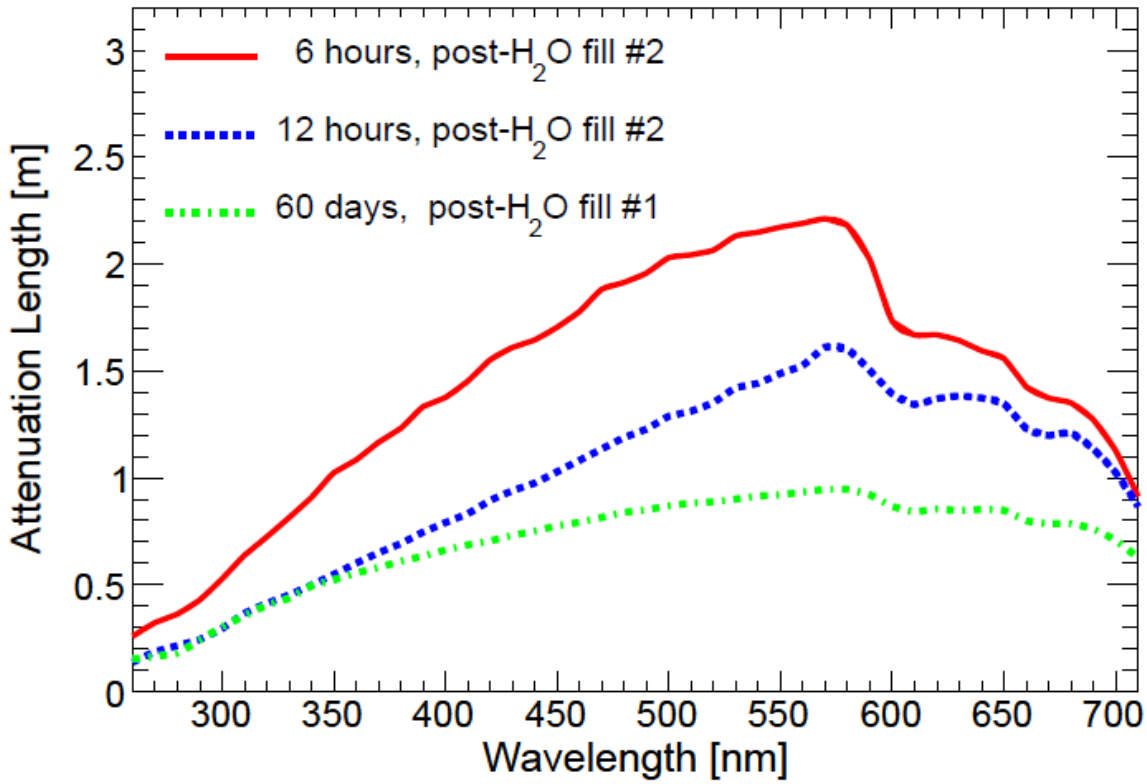
- Photodetector modules (PM) are mounted on 2 columns along the longitudinal axis with an azimuthal separation of 65 degrees ('normal' and 'stereo' view)
- For each PM, an optical mirror is mounted on the opposing wall, facing the PM port
- Remaining exposed PVC surfaces painted black
- Detector volume is 40 L of DI water. No filtration system



No LAPPDs yet- relegated to the use of small, commercially available devices ---> less than 7% of the OTPC surface area is instrumented with photocathode (mirrors enhance)

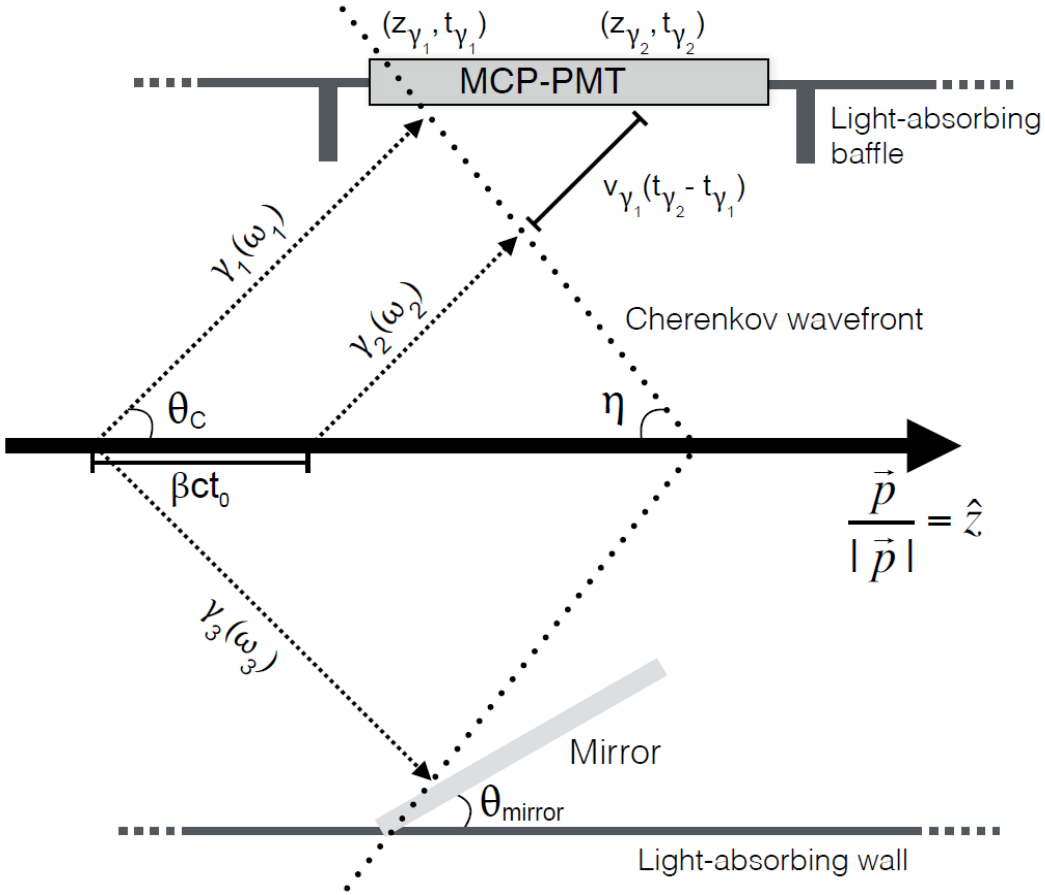
Water quality

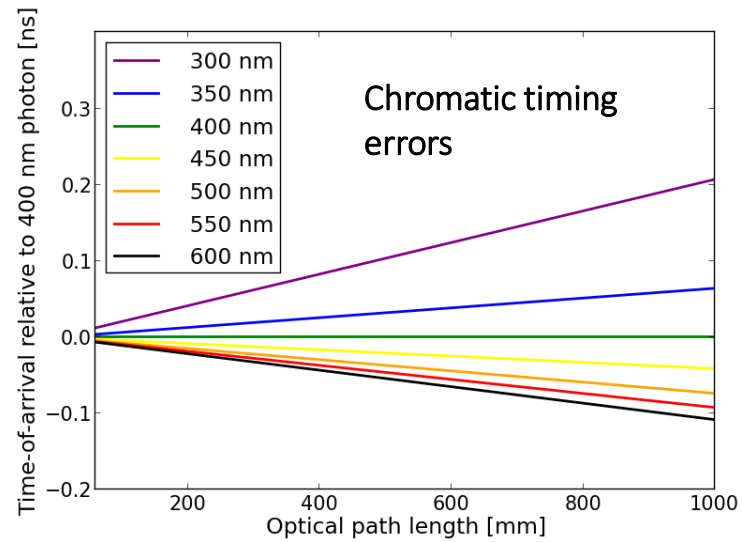
(or lack thereof)

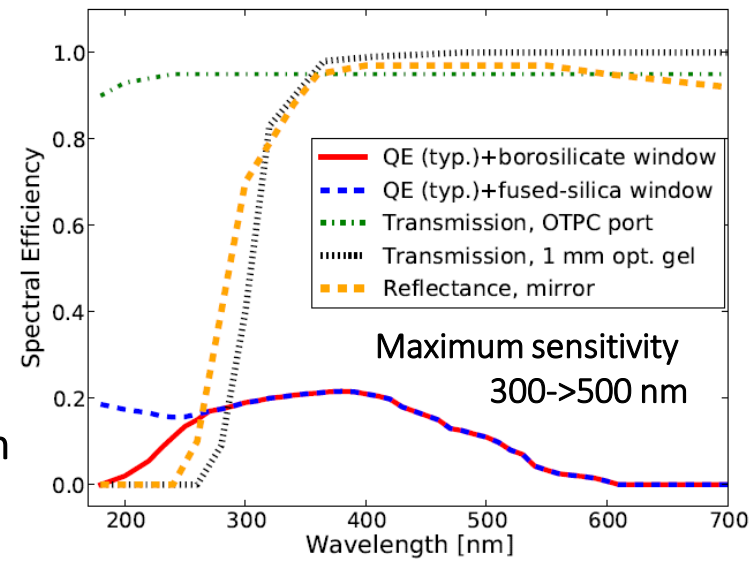


50-100 times worse than pure water in the 300-500 nm range
Path lengths are short, not a huge factor

Optics

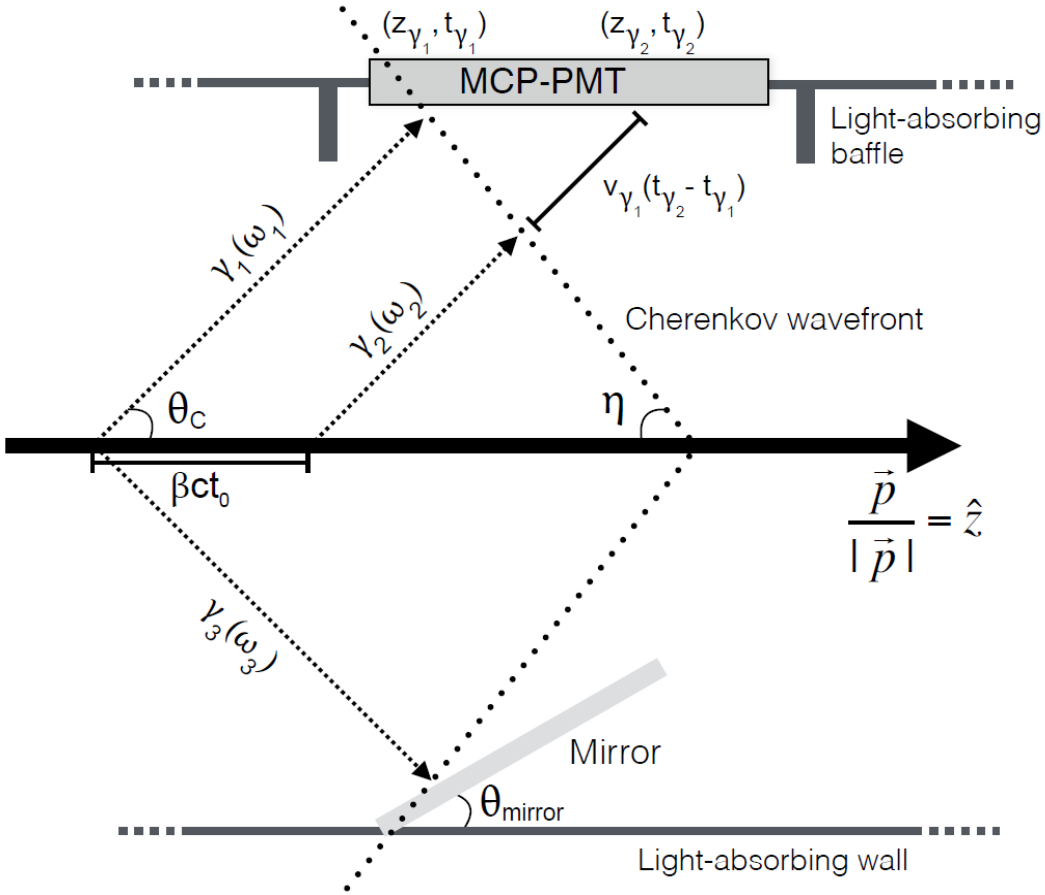






OTPC diameter 0.24 m, longest optical path lengths ~35 cm

Optics



Averaging over dispersion effects, the coherent Cherenkov radiation is emitted at a polar angle:

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

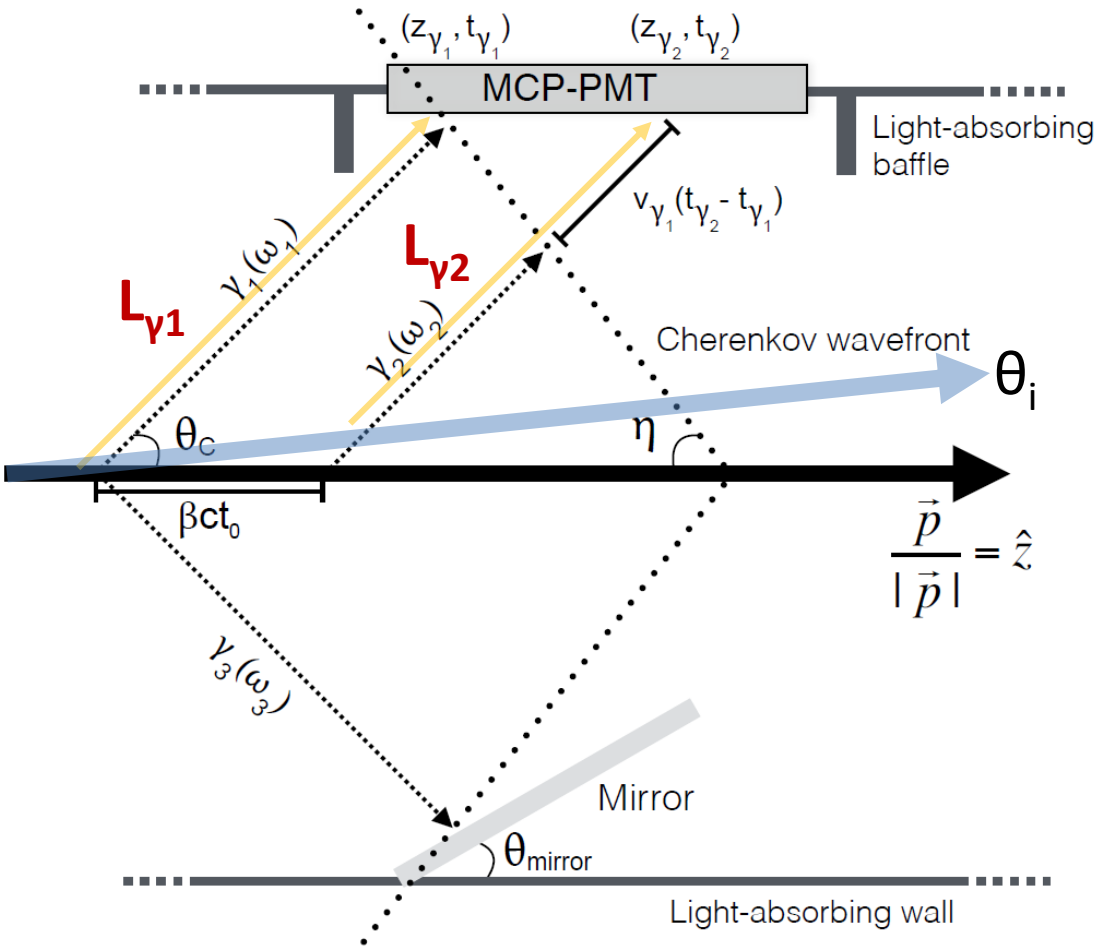
The Cherenkov photons propagate at the group velocity of water:

$$v_g(\omega) = \frac{c}{n_g(\omega)} = \frac{c}{n(\omega) + \omega\,(dn/d\omega)}$$

Taking into account the spectral efficiencies of the OTPC, we find the weighted average of the group velocity **$\langle v_{group} \rangle$ = 218 mm/ns** (i.e. the OTPC 'drift speed')

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

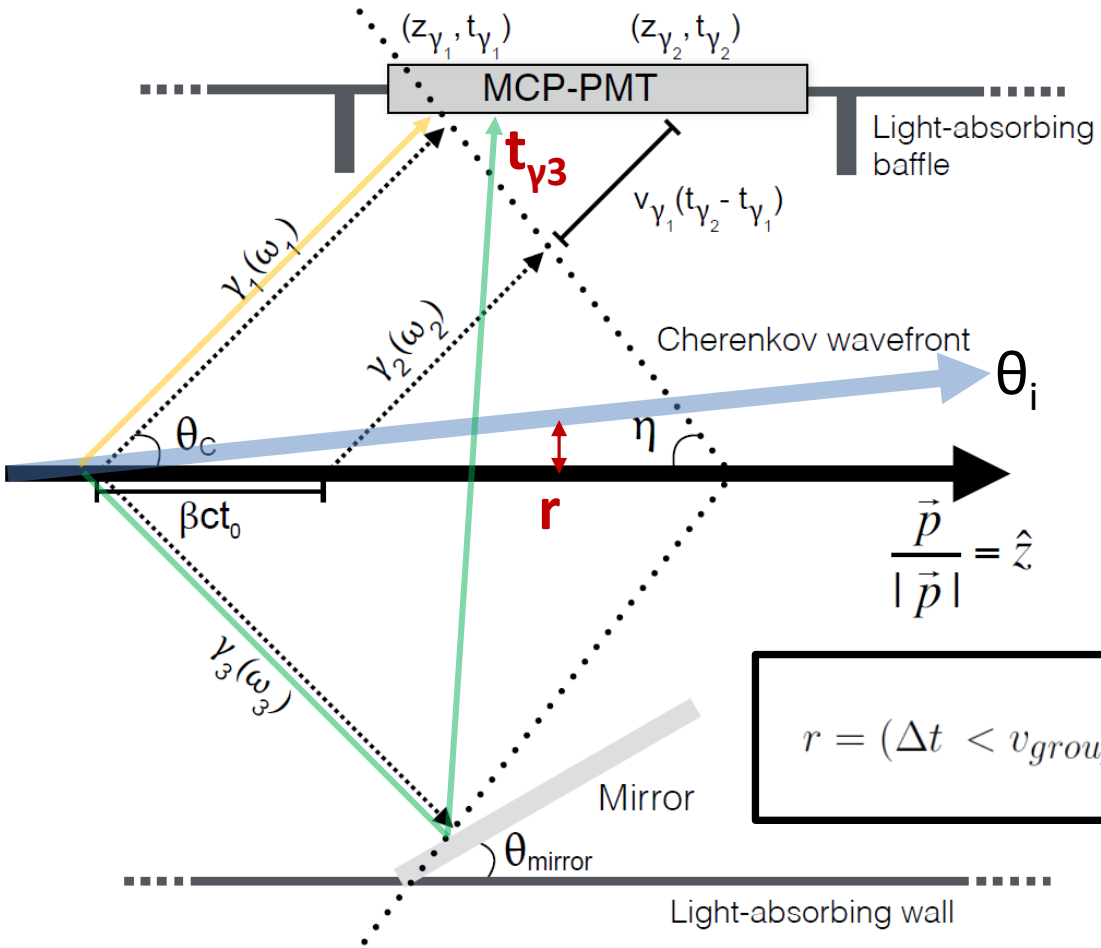
$$\Delta t_{\gamma_{21}} = t_o \left(1 - \frac{\beta\, c}{< v_{group} >} \tan\theta_i\right)$$

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

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

Optics – track reconstruction

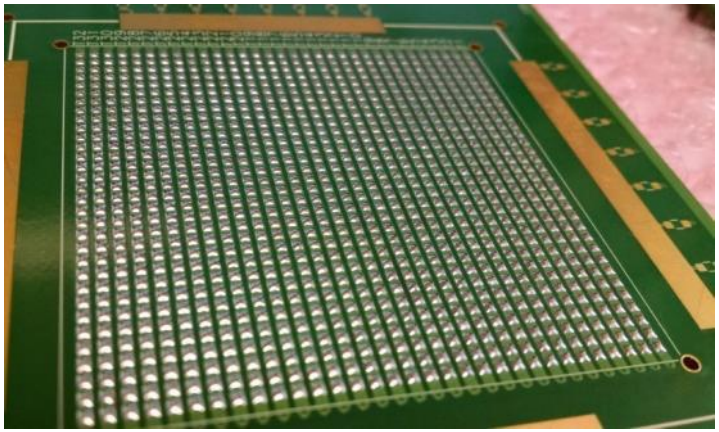
In simplest case, track parameters can be solved analytically through ray tracing (ignoring dispersion and scattering)



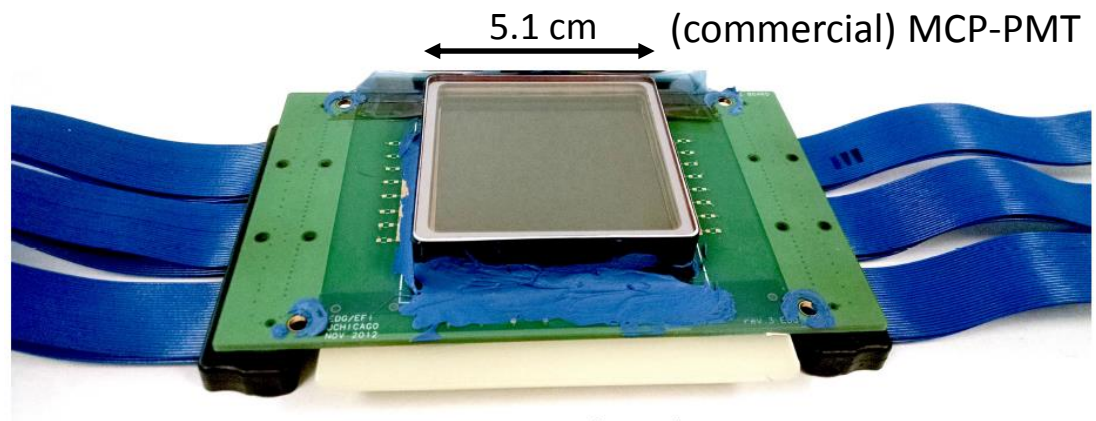
Time-resolving the direct and reflected photons provides the lateral particle displacement from the OTPC center-line as a function of z- and ϕ-position

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

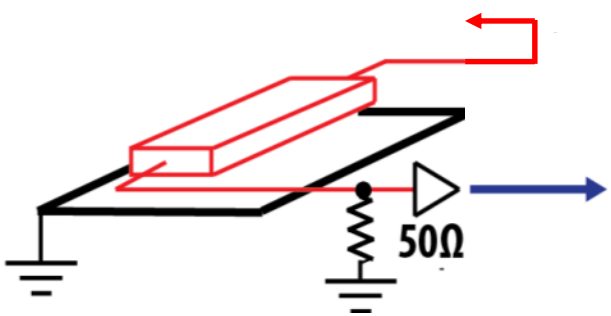
OTPC Photodetector Module

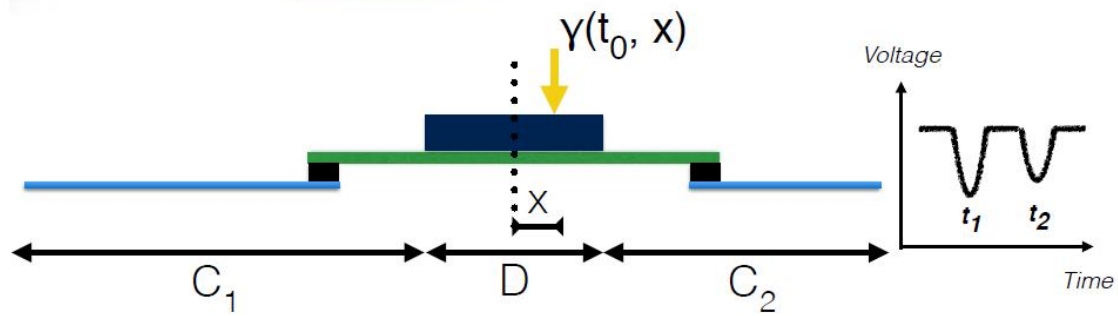


PHOTONIS XP85022 (commercial) MCP-PMT



- 1024 anode pad mapped to thirty-two 50Ω micro-strips with custom anode card
- MCP-PMT mounted to anode card with low-temperature Ag epoxy
- Terminate one end of micro-strip, other end open (high-impedance):



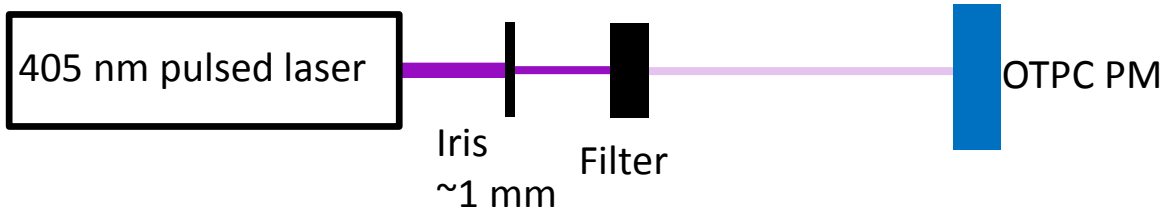


Expressions for the position and time-of-arrival of the detected photon

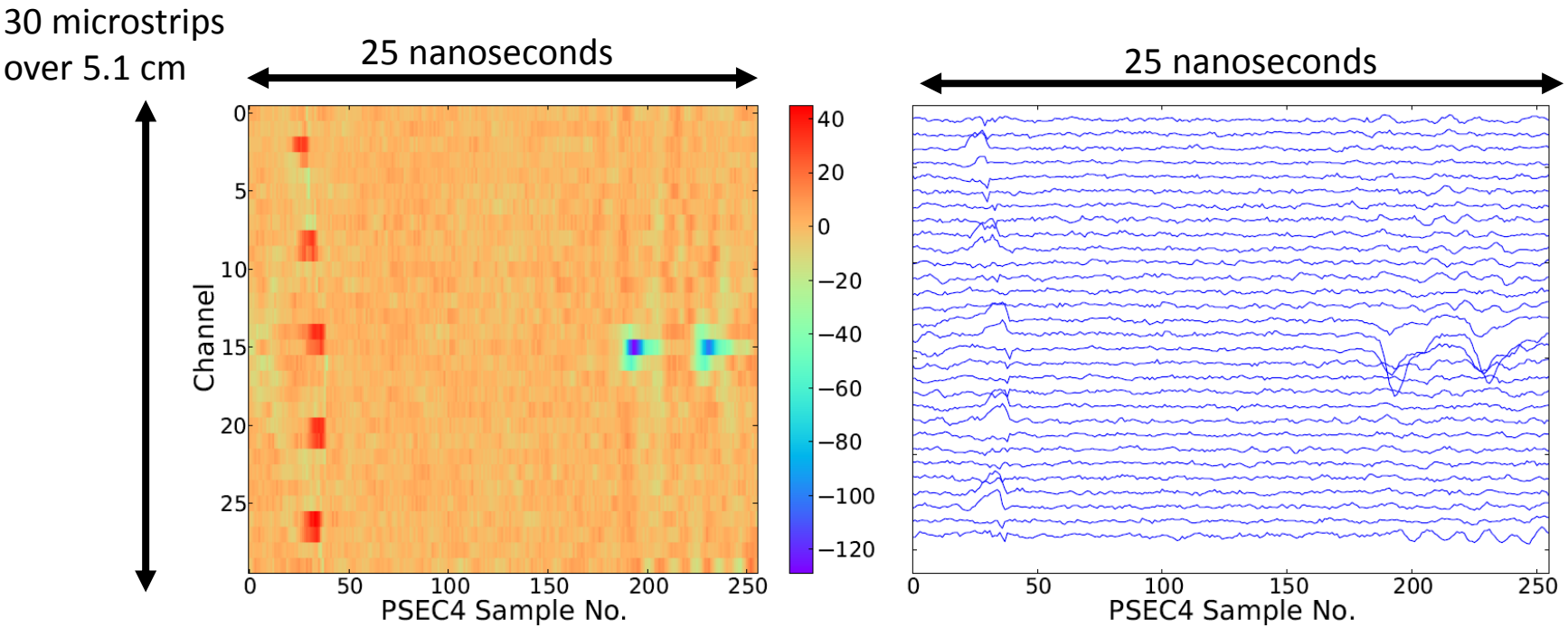
$$x = v_{prop}\,\frac{t_2 - t_1}{2} - \frac{D + 2\,C_1}{2}$$

$$t_0 = \frac{t_2 + t_1}{2} - \frac{1}{v_{prop}}(D + C_2 + C_1)$$

OTPC Photodetector Module (PM) single p.e.



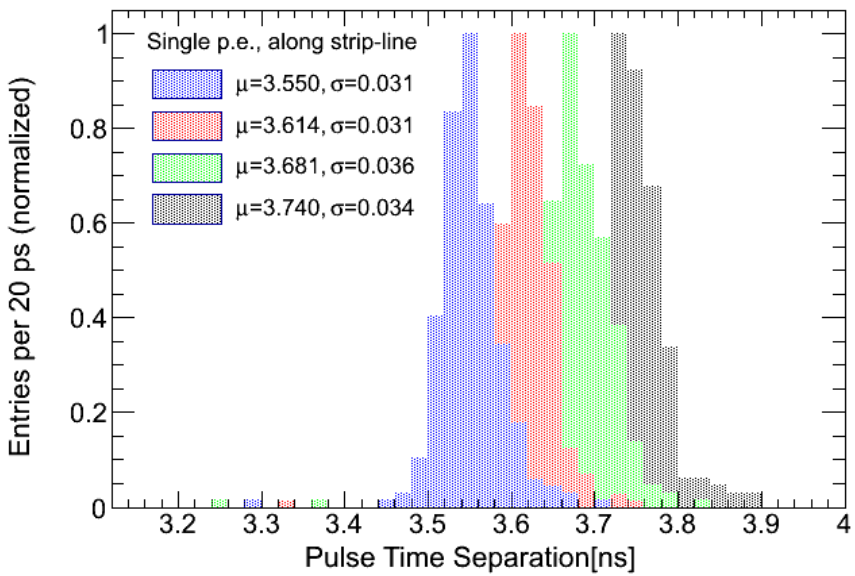
Pulsed laser (33 ps FWHM) attenuated to single photon level



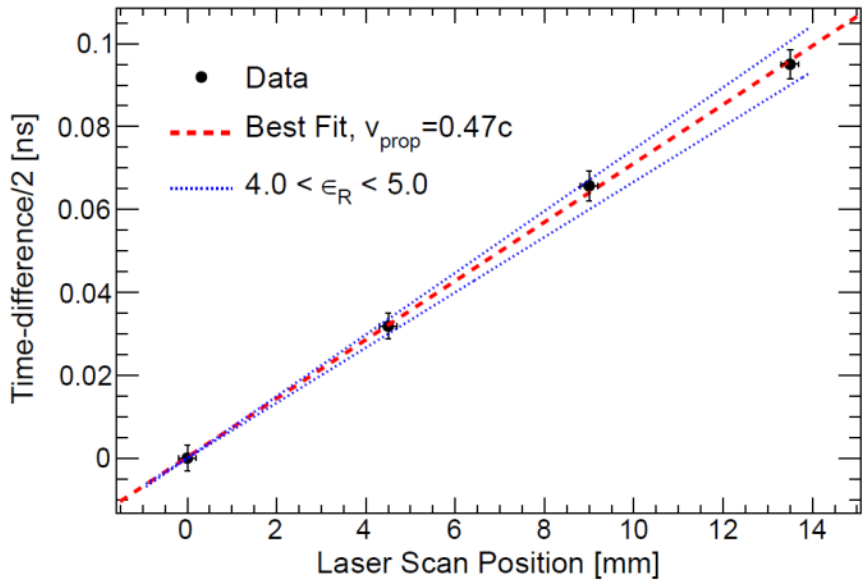
- Single photo-electron signal recorded by the PM
- 30 channels of 10.24 GSa/s waveform sampling per PM
- Pulses are ~1 ns wide; two pulses on the microstrip anode per photo-electron signal

OTPC Photodetector Module (PM) single p.e.

Scan the laser spot to measure the propagation velocity on the anode microstrip
(n.b. similar to prior LAPPD glass anode response, this module has an FR4 substrate)



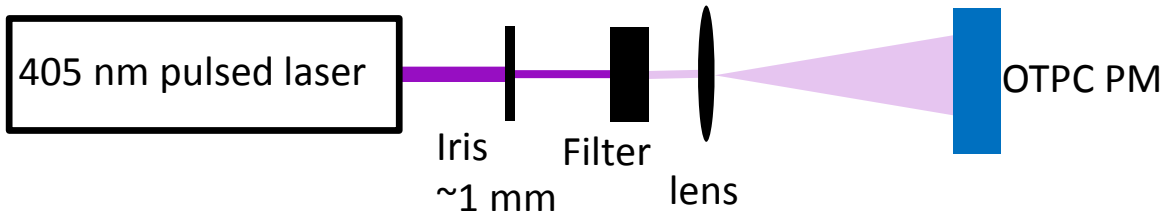
Measured timing at each beam spot



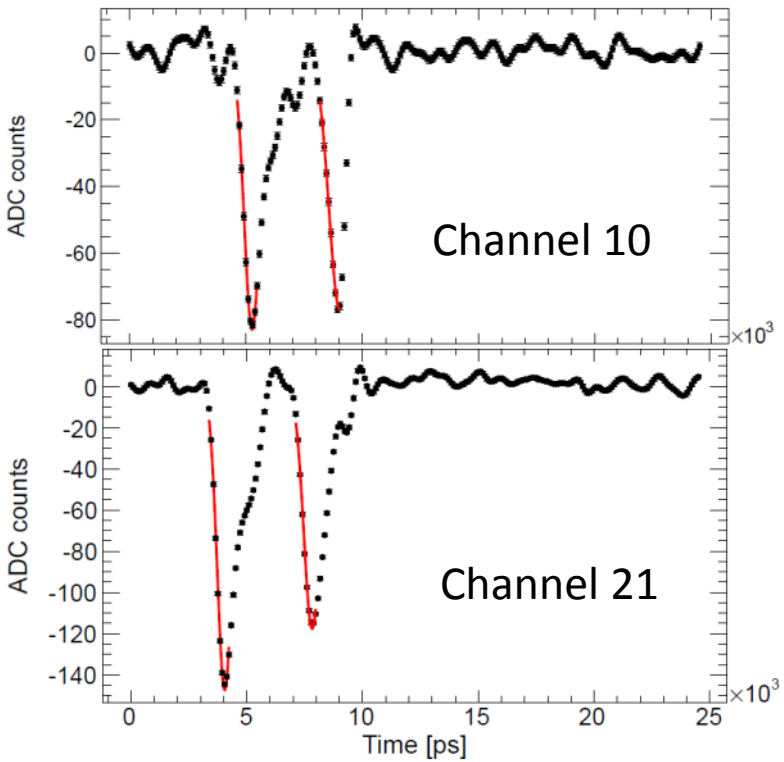
Timing vs. beam position

- Measure a single-channel timing resolution of 35 ps. (The PSEC4 digitized data are not fully calibrated in voltage and timing)
- The microstrip signal propagation velocity is found to be 0.47 c. Corresponds to a substrate dielectric constant of 4.5, which agrees with the expected value
- Position resolution along microstrip is 3 mm

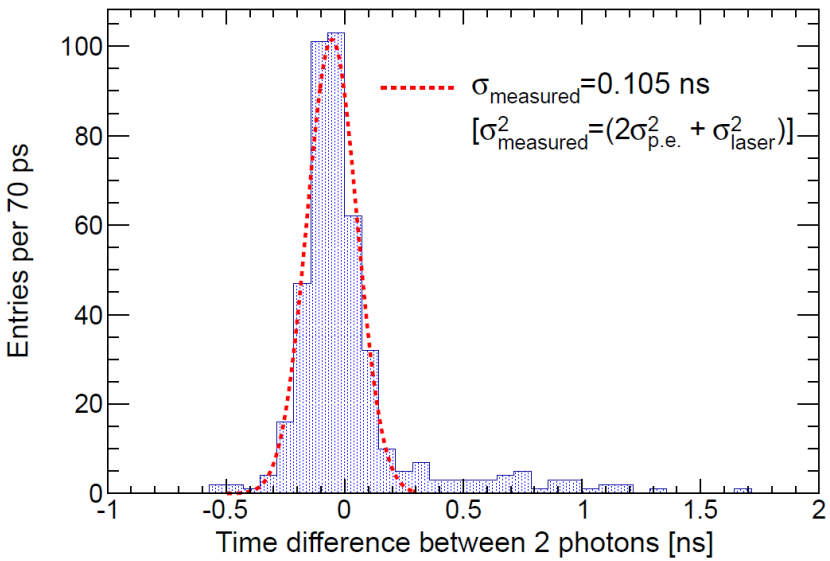
OTPC Photodetector Module (PM) multi-p.e.



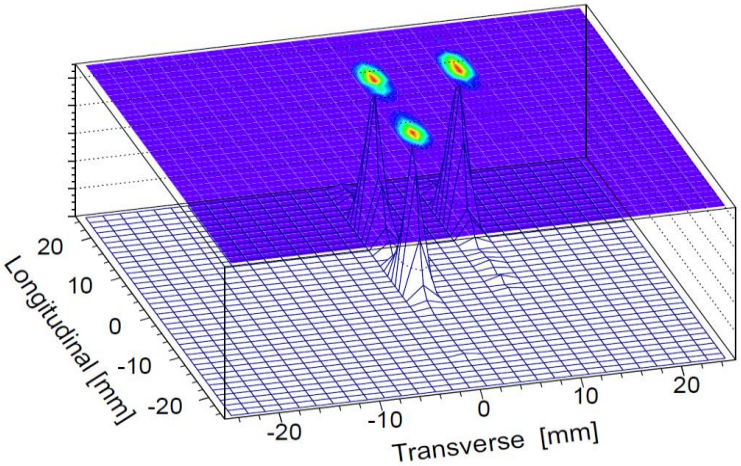
Pulsed laser (33 ps FWHM) attenuated to multi-photon level + lens



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



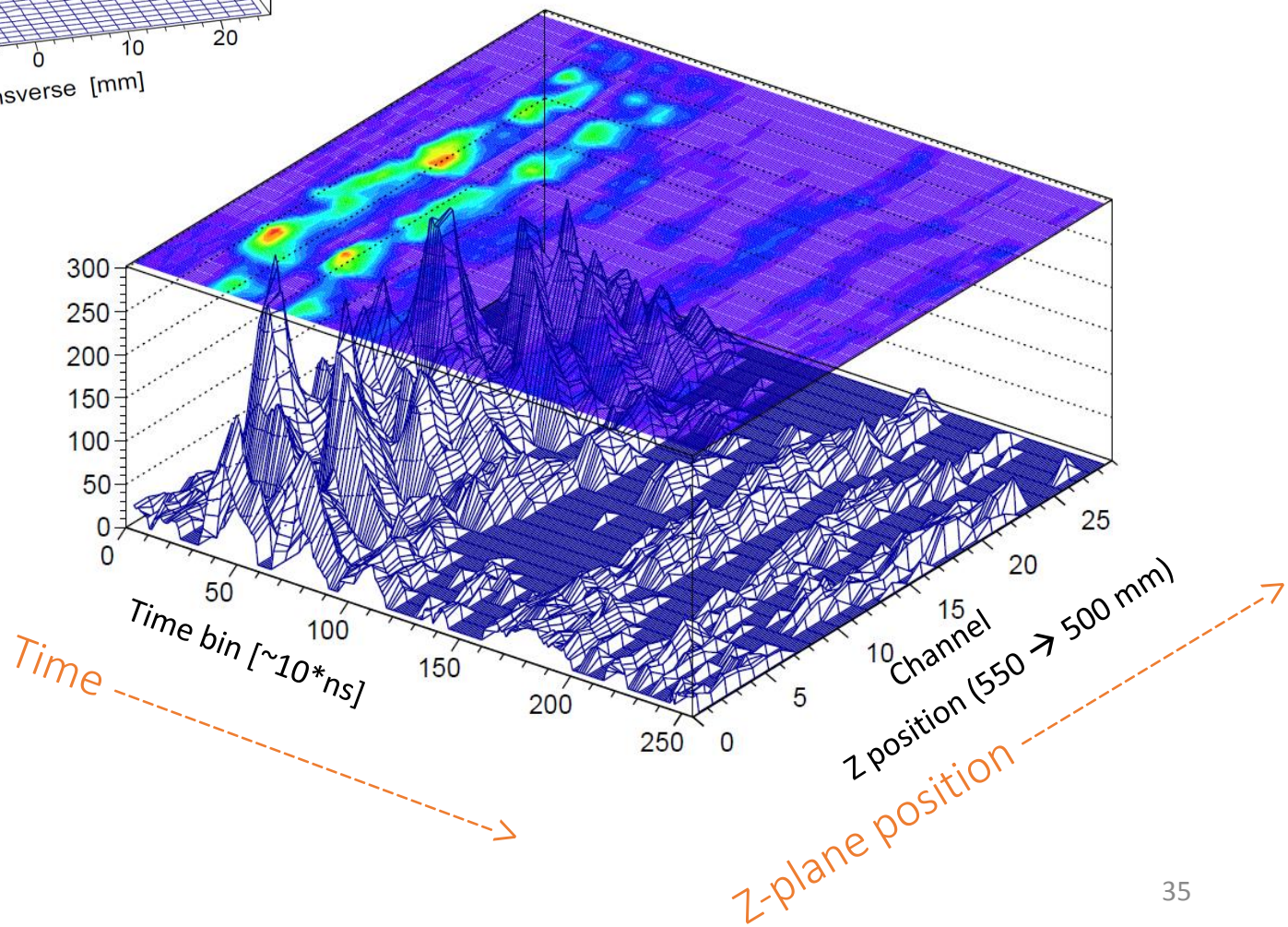
- Measure relative timing between 2 photo-electrons within same laser pulse, which are spatially separated on the MCP-PMT.
- Single photon time resolution is 75 ps.



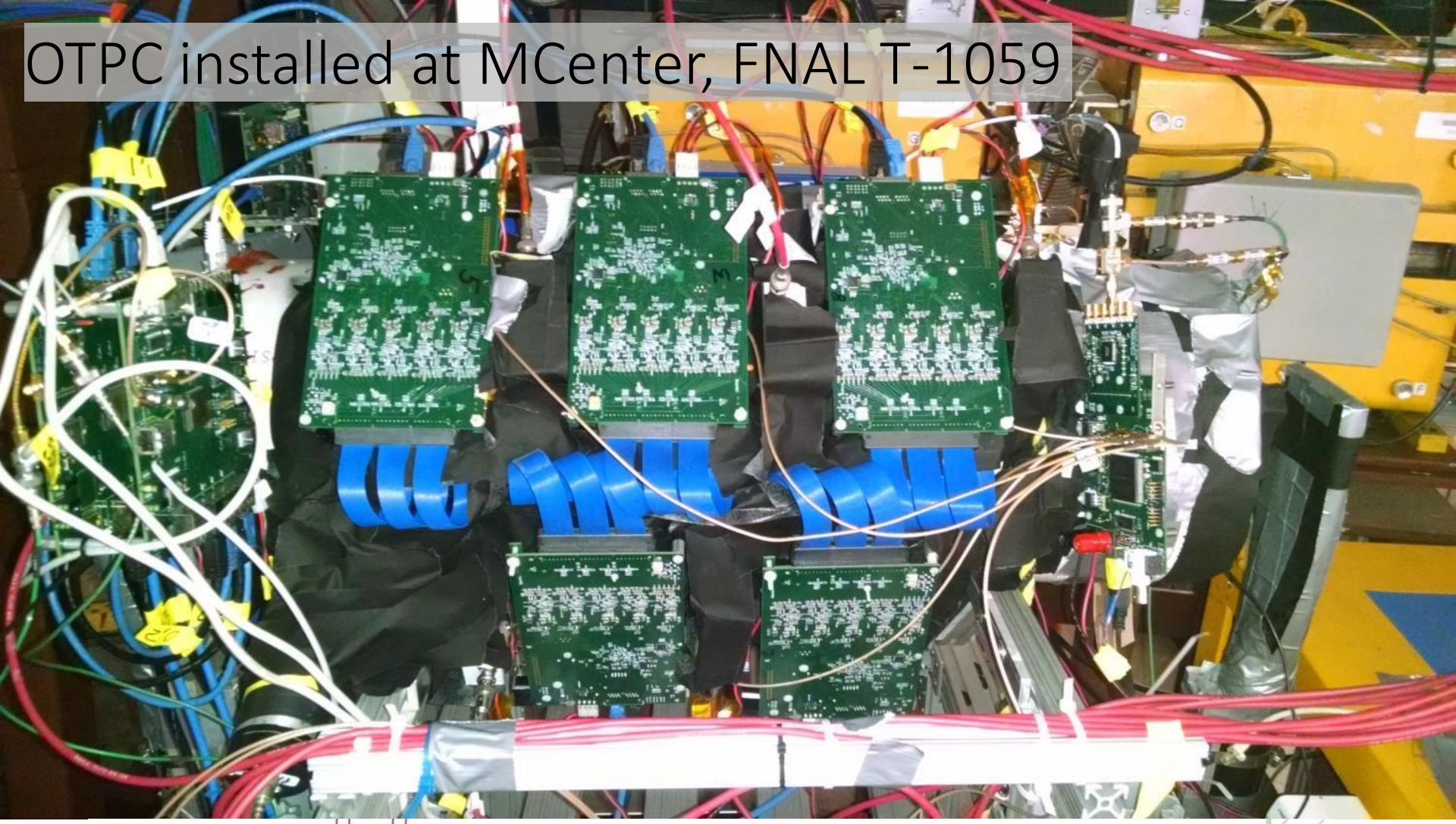
Reconstructed 2D coordinates over MCP-PMT active area

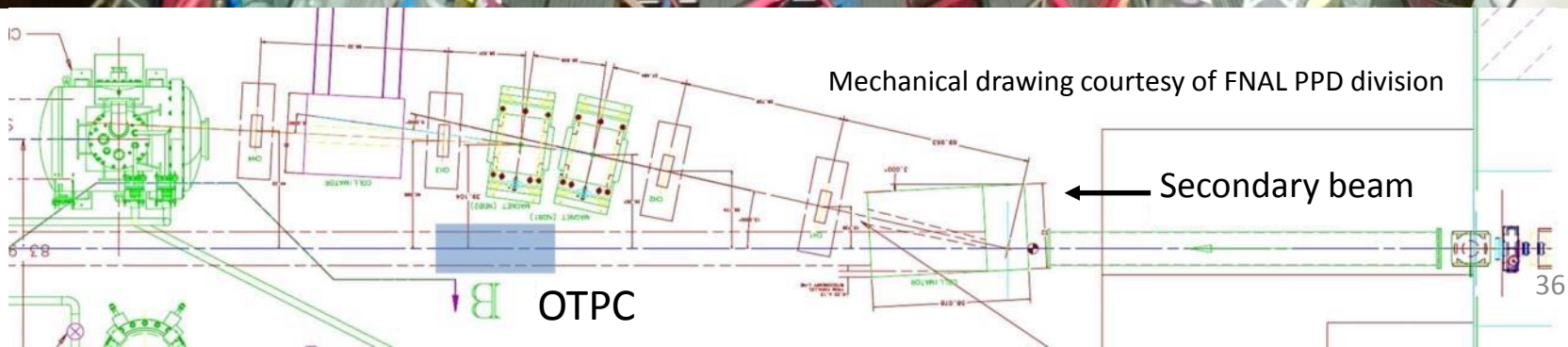
One-sigma statistical errors on the photon transverse position, longitudinal position, and time-of-arrival (x,y,t) =(2 mm, 3, mm 75 ps)

First cosmic ray muon, seen by a single OTPC photodetector module

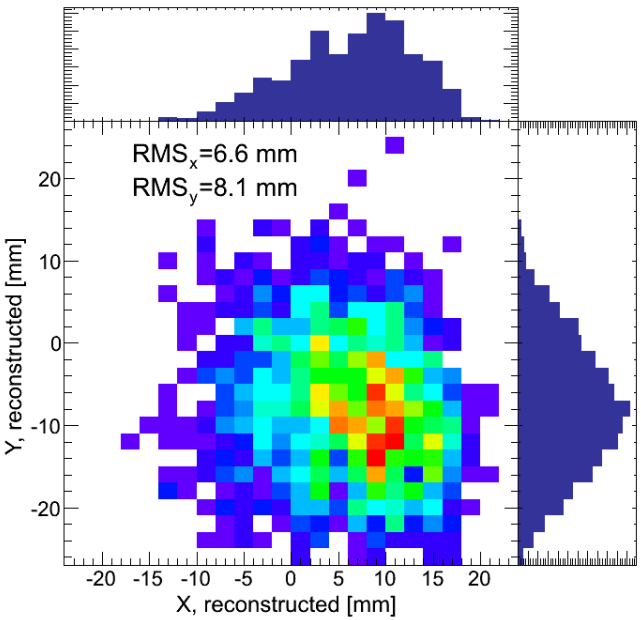


OTPC installed at MCenter, FNAL T-1059



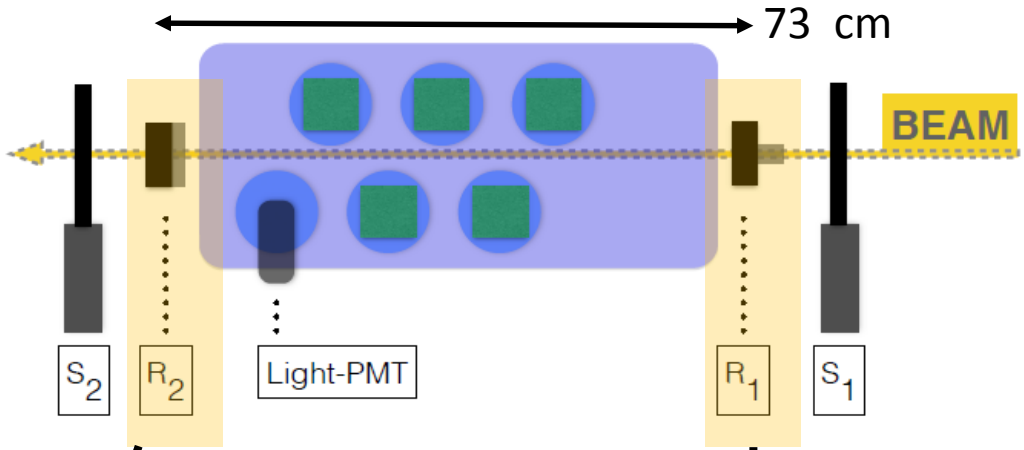


Beam trigger + particle tagging

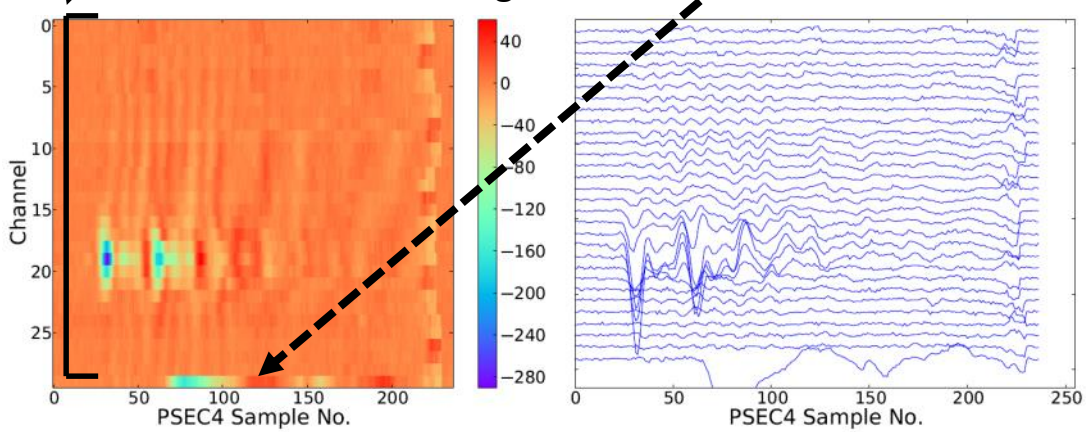


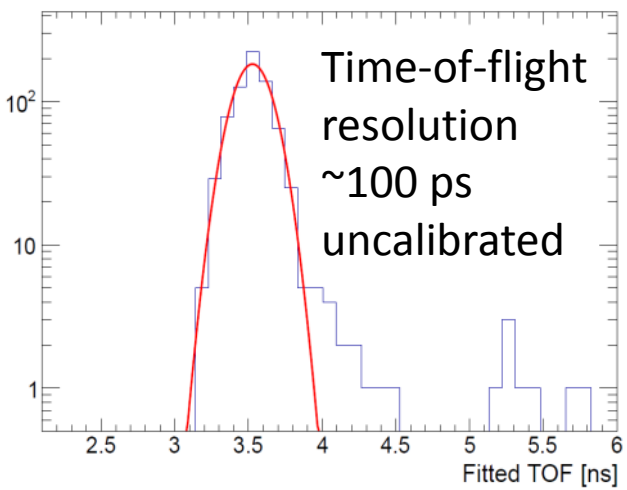
Particle output position at R_2

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



Waveforms from a single event

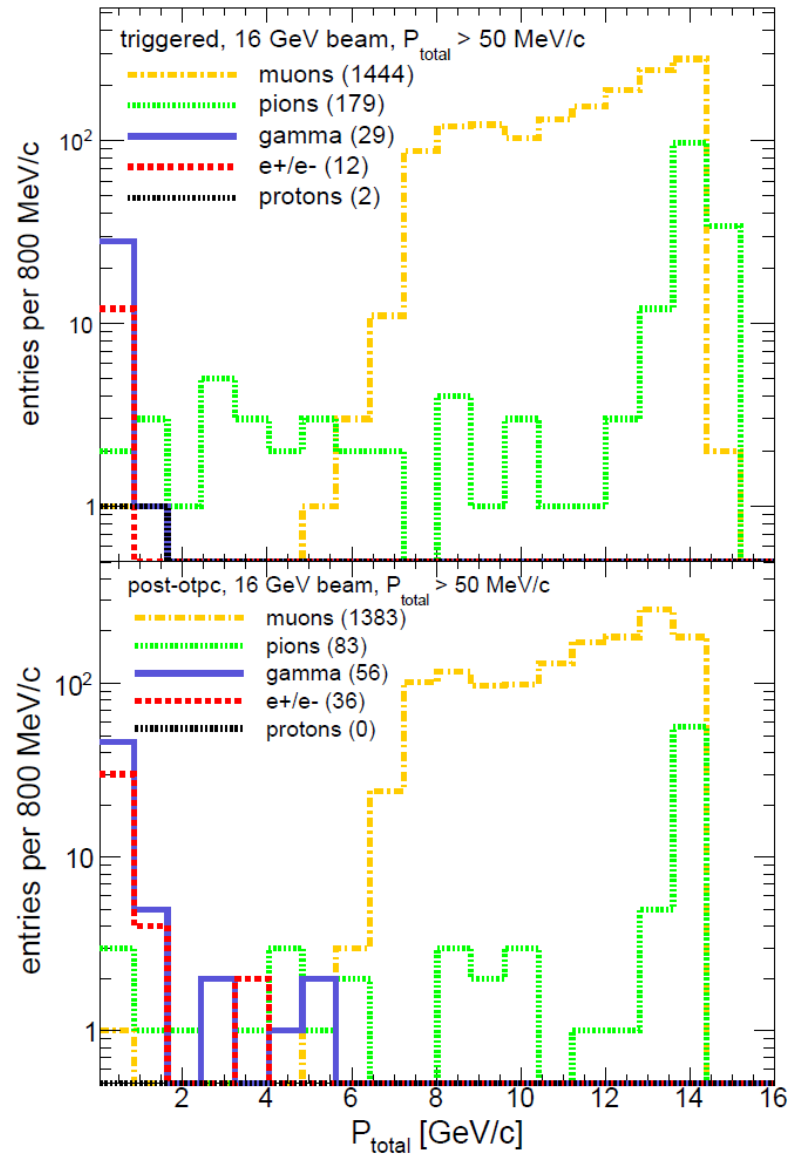




Future use LAPPDs as TOF + 2D position tagging for test-beam?

Beam behind the collimator

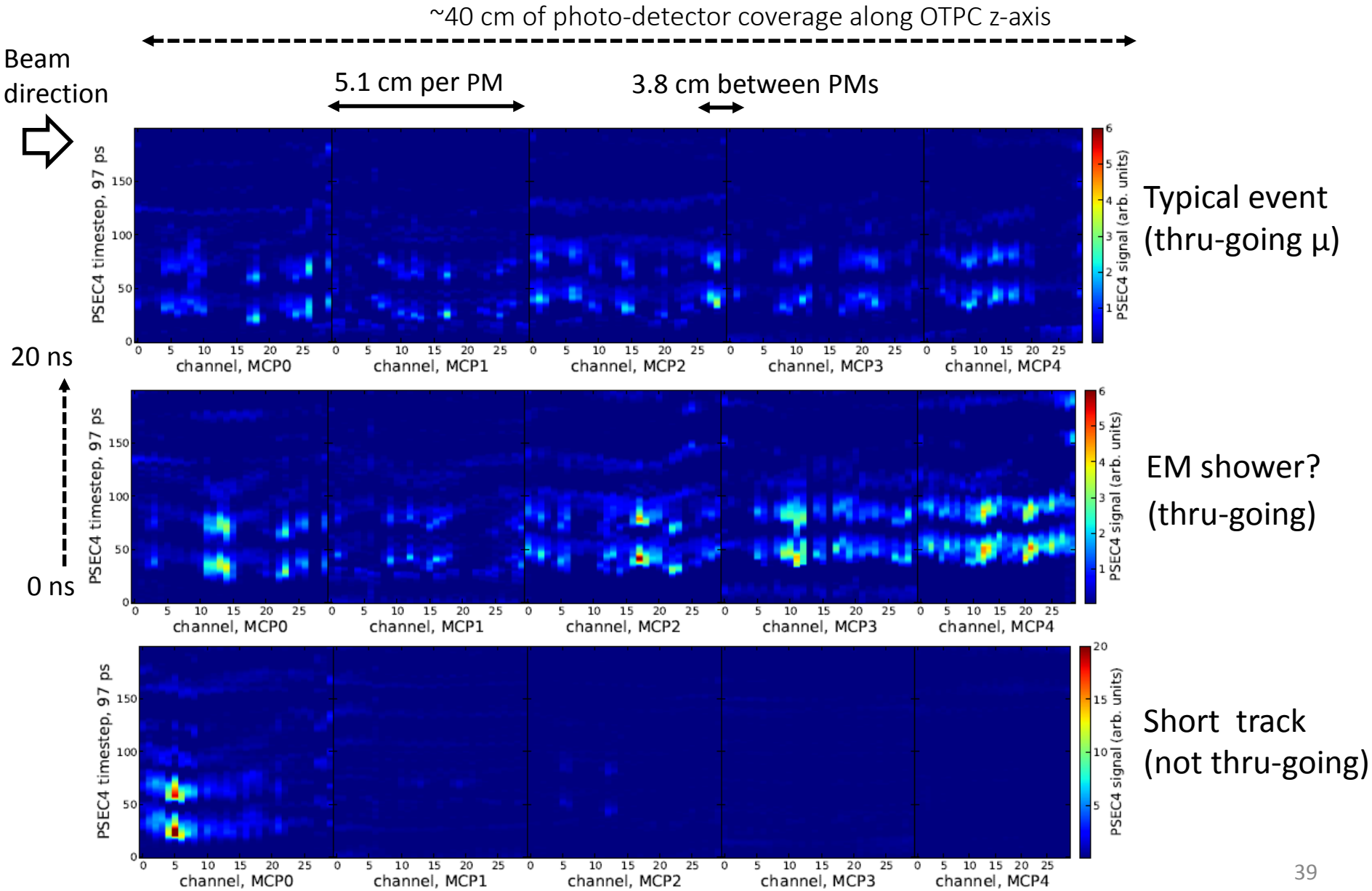
top: incident flux
bottom: through-going, satisfying trigger condition



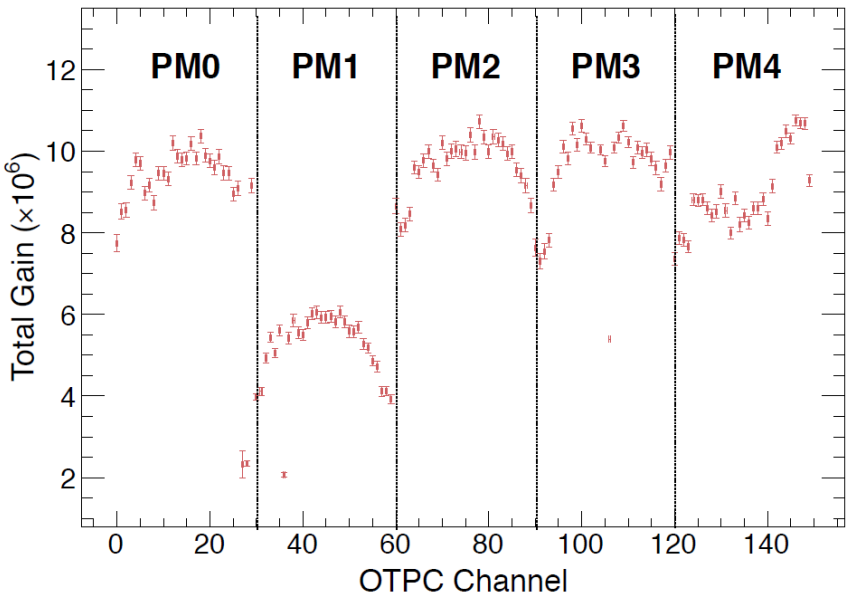
- G4beamline [1] simulation includes a 60 m long π^+ beam incident on a fixed copper target, through ~1m steel absorber, and OTPC water volume
- **Expected flux is > 90% muons at a secondary beam momentum of 16 GeV/c**
- Some particles from showering in the absorber (~1% electrons). Larger percentage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

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

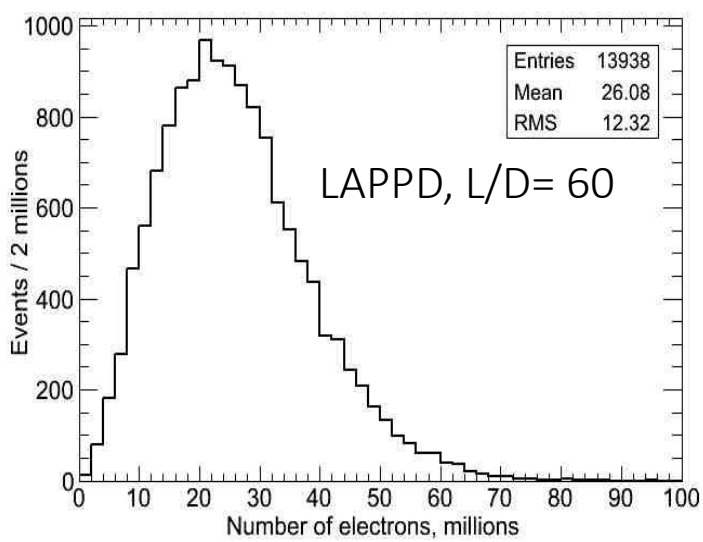
OTPC data


~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)

Gain calibration



- Calibrate the per-channel gain of the MCP-PMT and 20 dB pre-amp board
- Gain calibration using the average integrated charge from single photon signals
- **PMs 0,2,3,4 have MCP-PMT gains of ~10^6, PM 1 has an MCP-PMT gain of $5x10^5$**



n.b.: Measured gain of LAPPD: >10^7

→No pre-amp stage required (…for low-rate implementation)

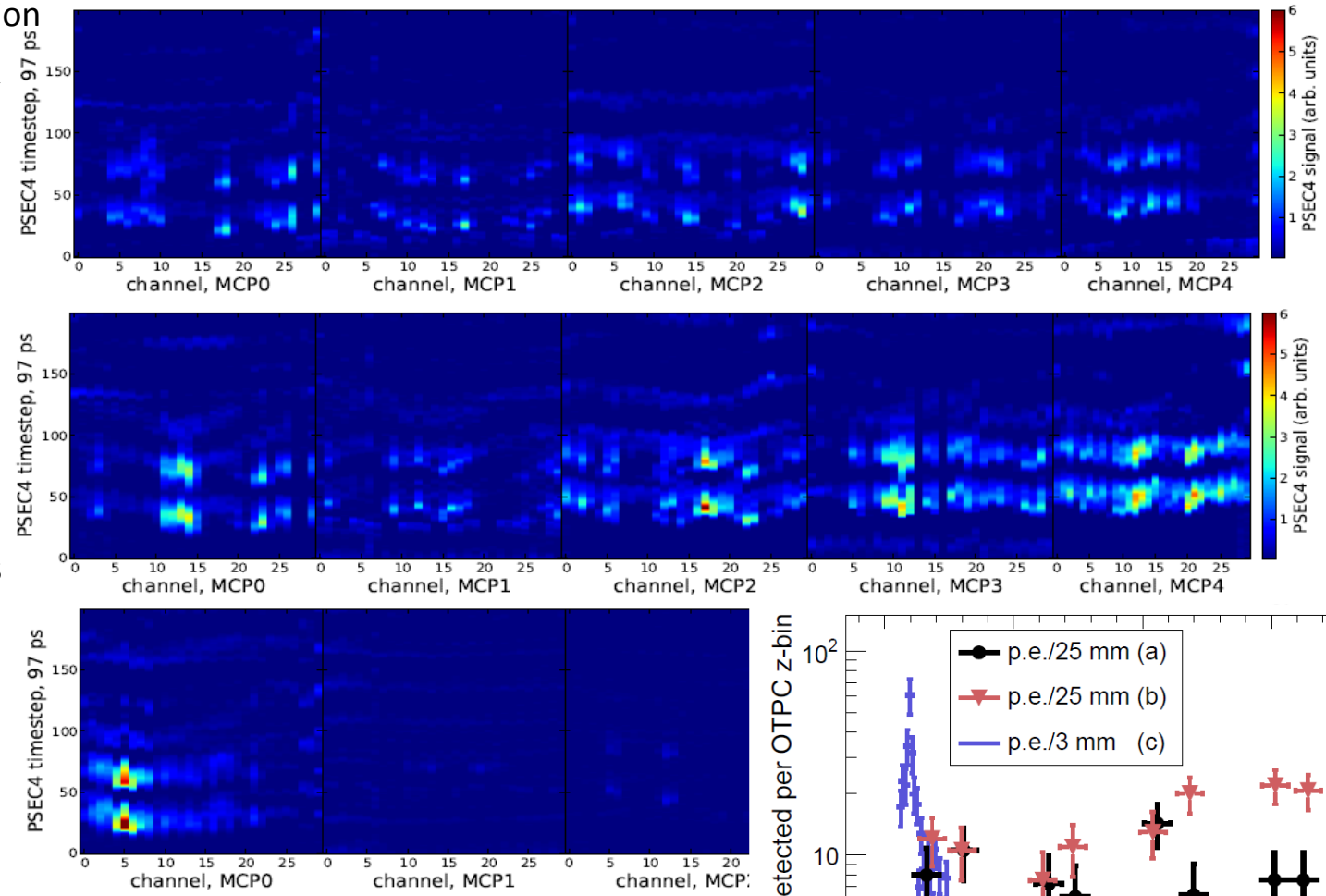
OTPC data + gain calibration

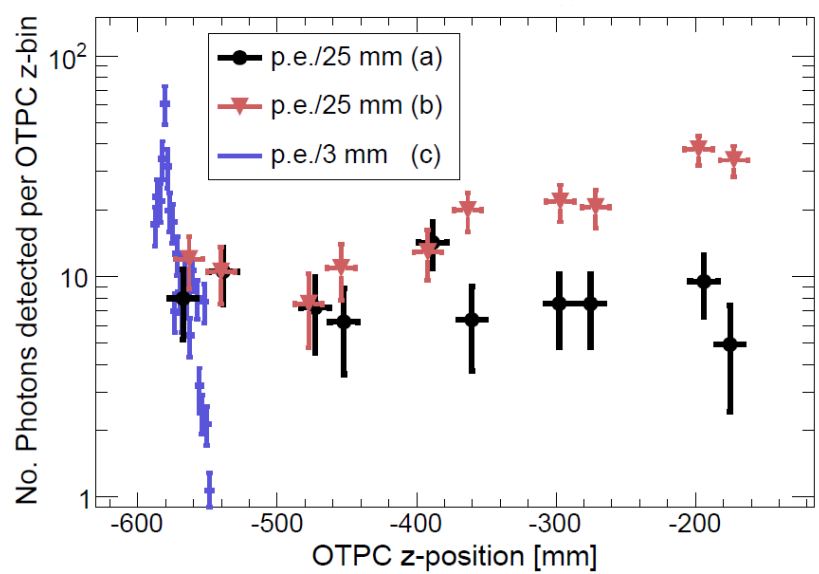
~40 cm of photo-detector coverage along OTPC z-axis

Beam direction

20 ns

0 ns



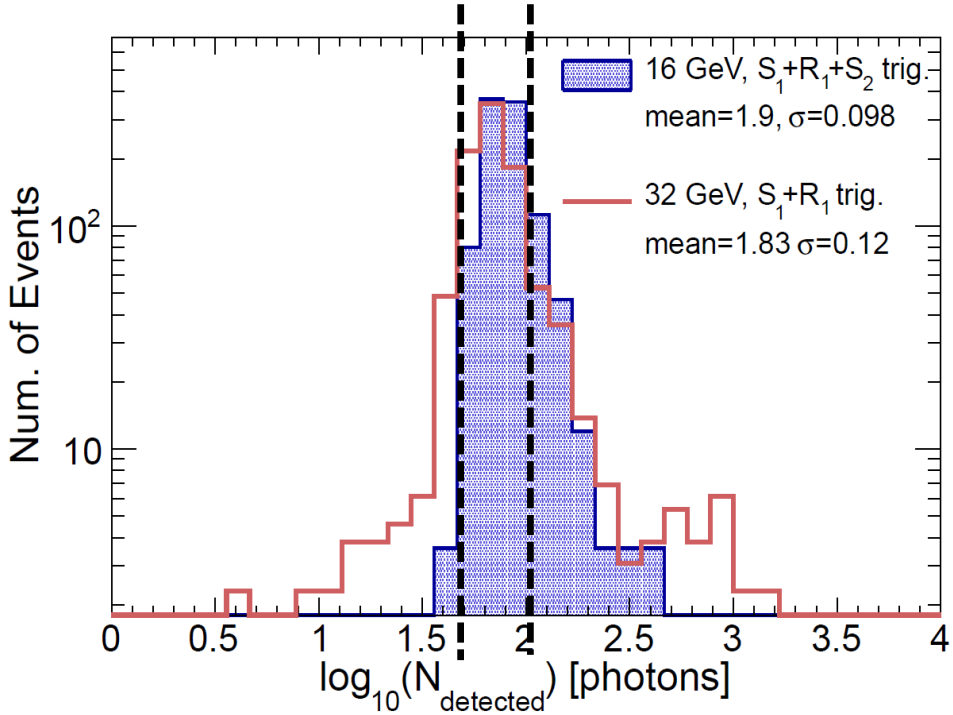


OTPC data: selecting muons for track reconstruction

-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)

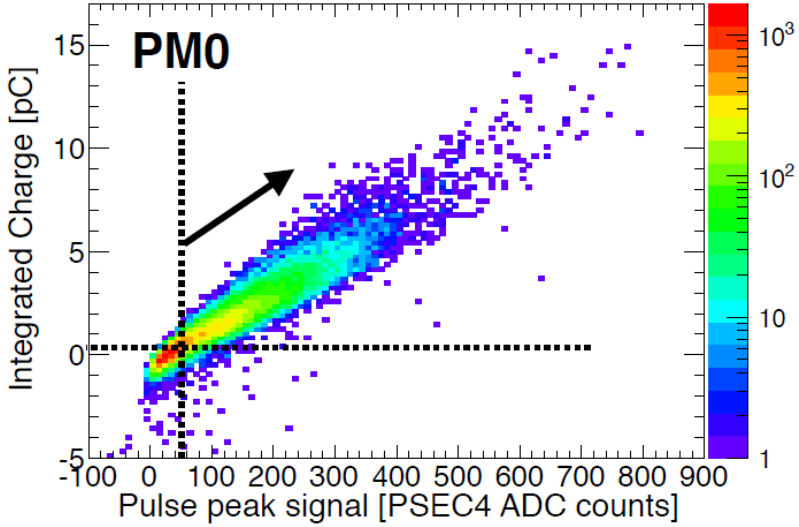
Comparison of 16 and 32 GeV/c secondary-beam datasets

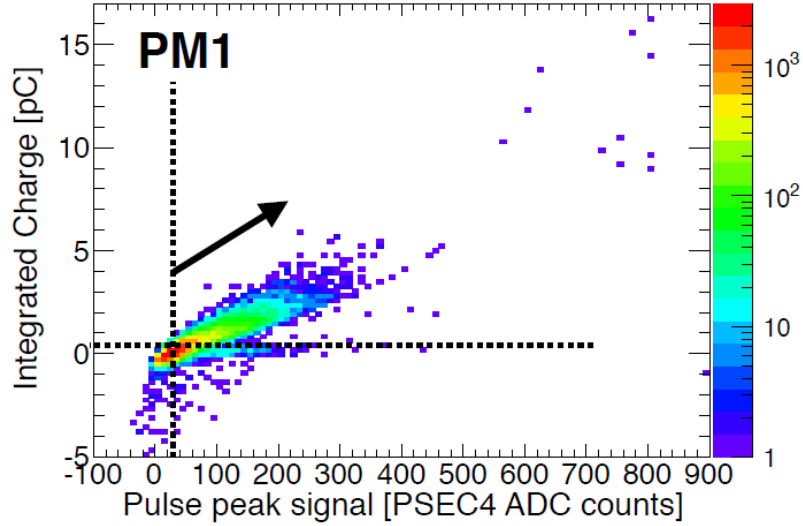
- Through-going trigger: 79 ± 18 photo-electrons per track
- Front-only trigger: 67 ± 25



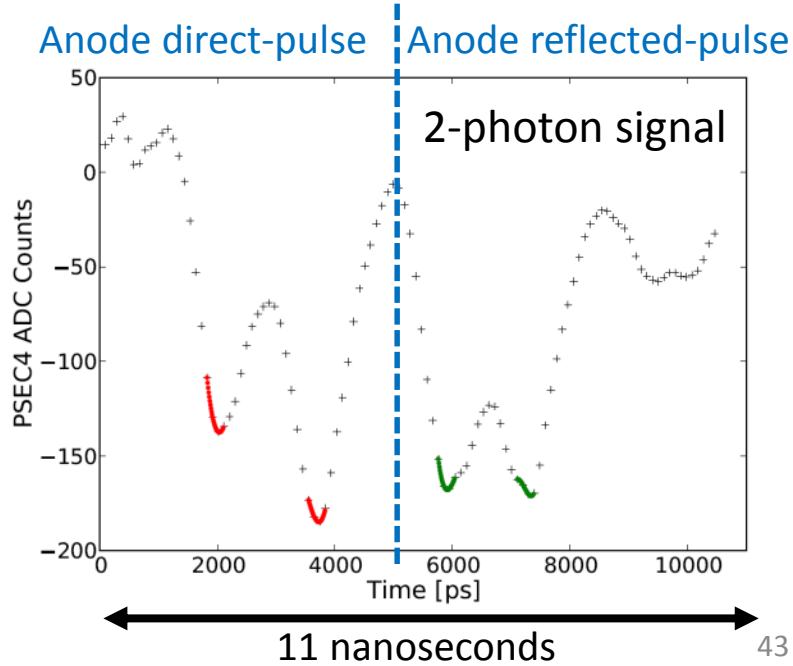
Water quality: blue > red

Signal selection / measuring photon time-of arrival



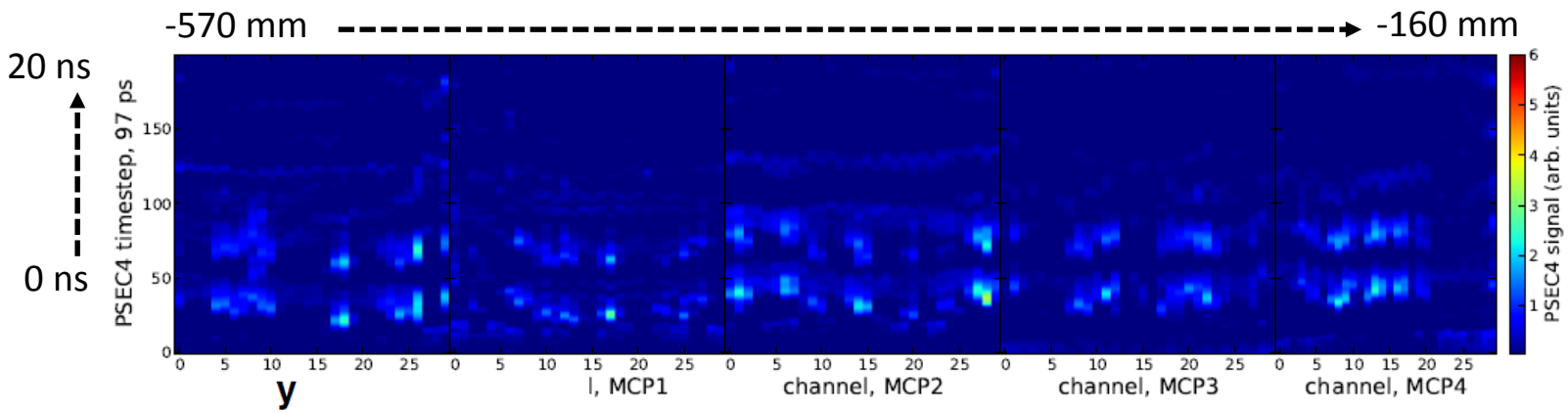


- OTPC channels above a threshold-level defined by the total integrated charge and the peak signal amplitude are fit for time-of-arrival
- The photon time-of-arrival is extracted by locating and interpolating the pulse peaks in the waveform
- Can resolve both single and double photon hits per channel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

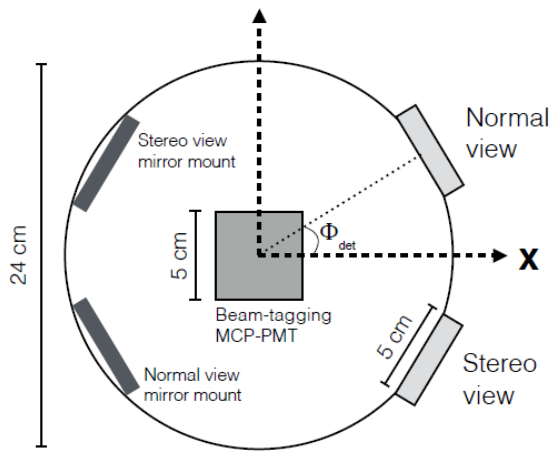


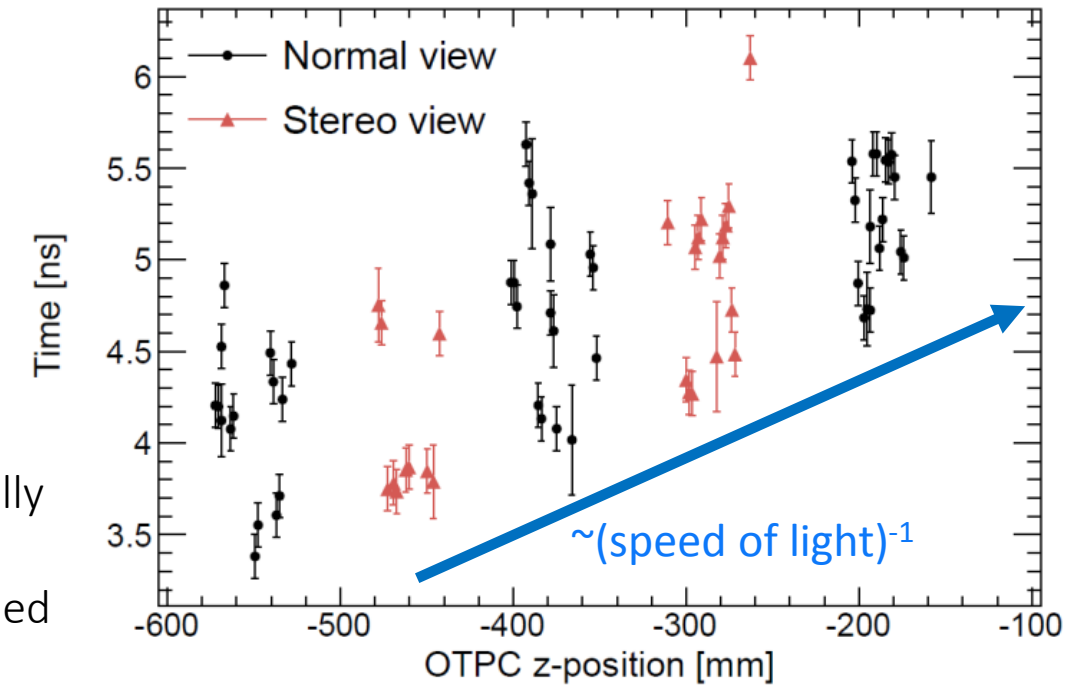
the time-projection

Example event along the OTPC z-axis



Typical event (thru-going μ)



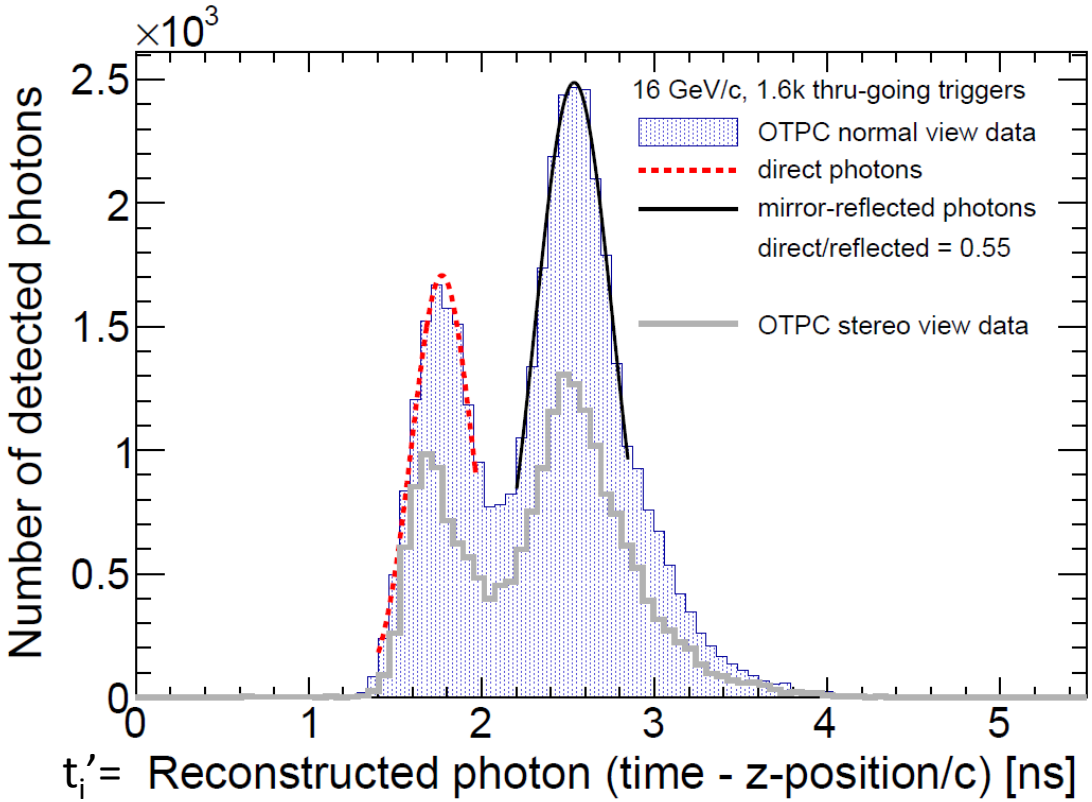


(1) Each data point is an individually resolved photo-electron
(2) Cherenkov photons are recorded over an event duration of ~2 ns

Time-resolving the direct and mirror-reflected photons

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

$$t'_i = t_i - \frac{z_i}{c} \longrightarrow \frac{dt'}{dz} = \frac{dt}{dz} - \frac{1}{c} = \frac{\tan\theta}{< v_{group} >}$$



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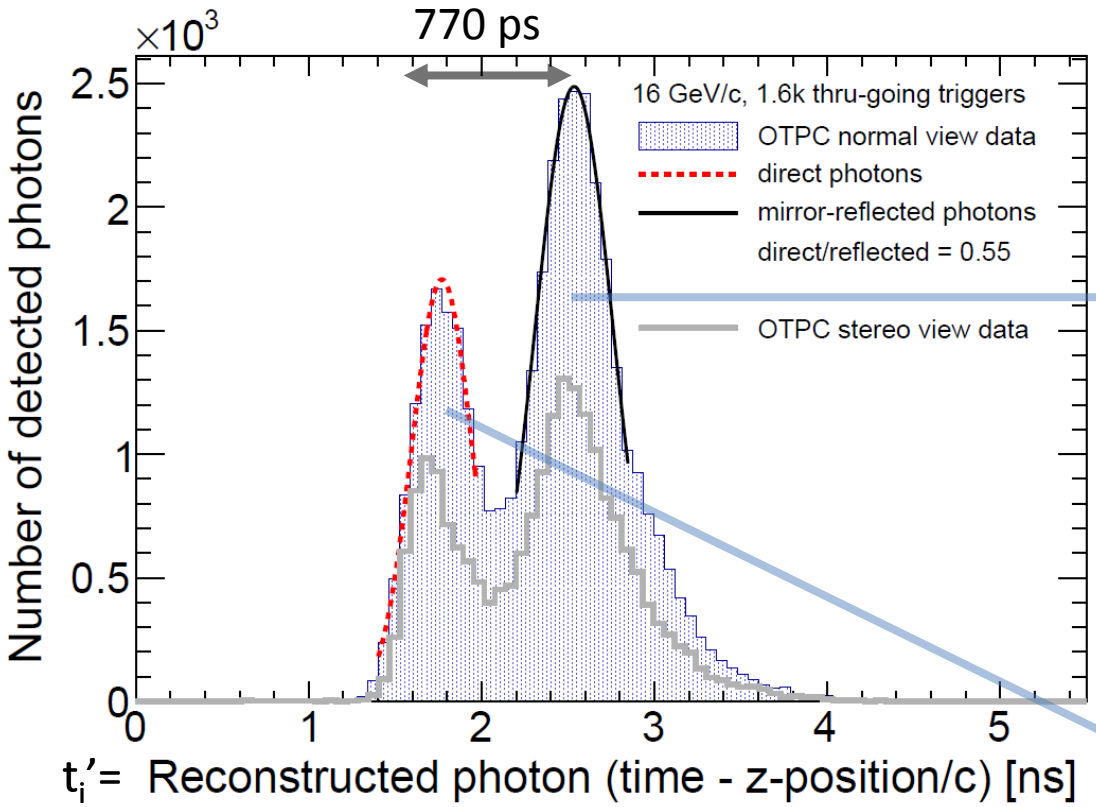
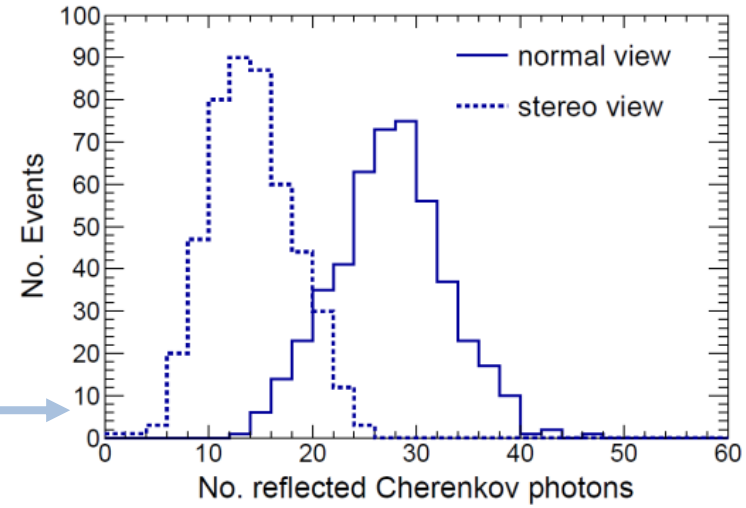
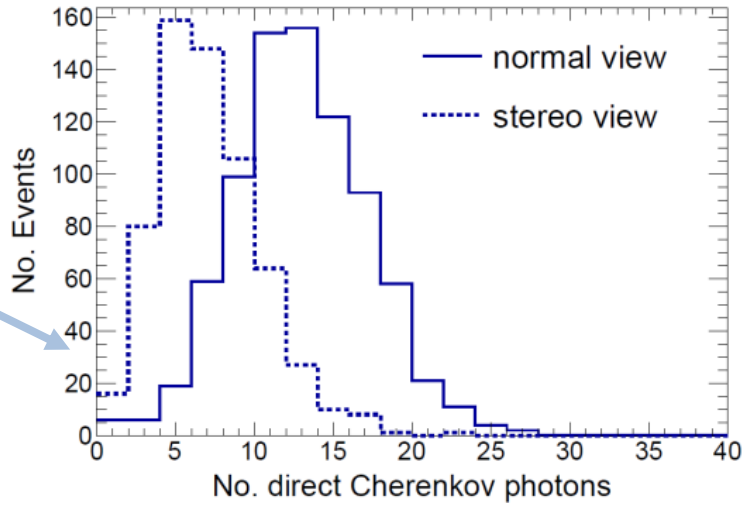




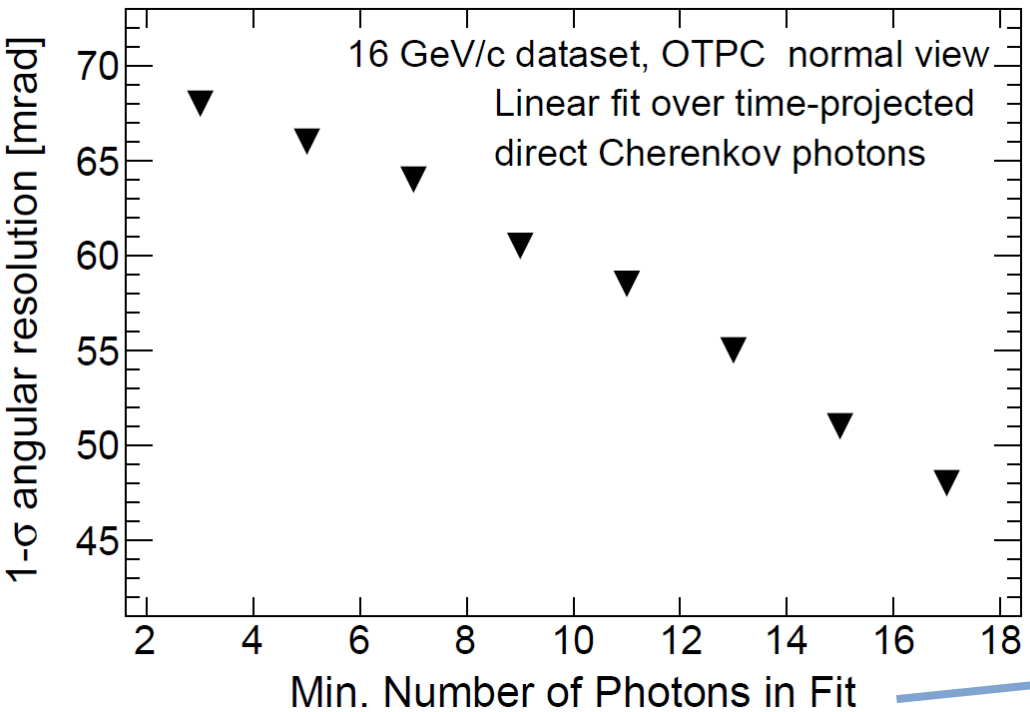


Direct and mirror-reflected Cherenkov photons are clearly separated. We collect more reflected than direct.

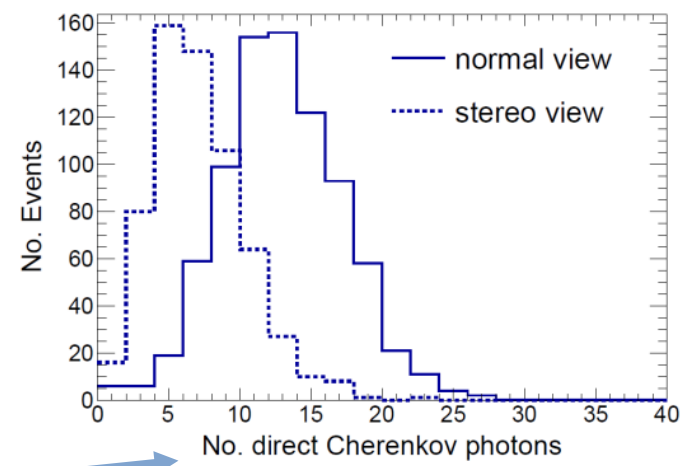
Angular reconstruction

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)



Spatial reconstruction in the prototype OTPC

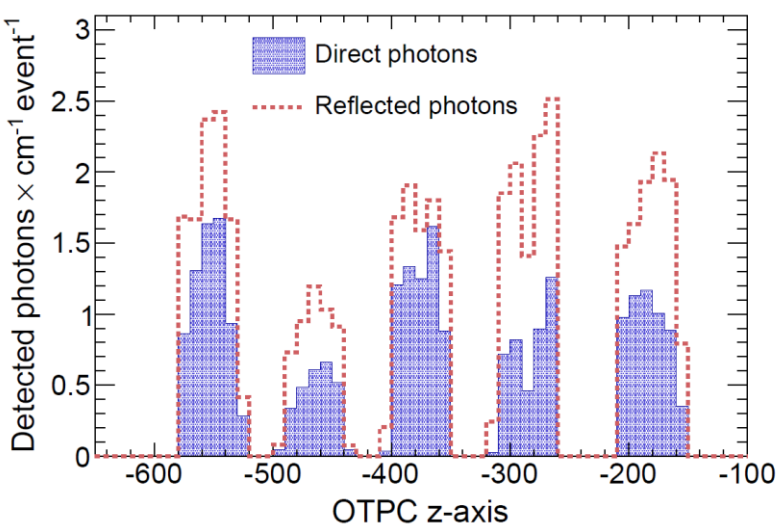
The particle track position, with respect to the OTPC/beam axis, is determined at each PM using the relative timing (Δt) between the direct and mirror-reflected photons:

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

A simple expression for Δt (at each PM) is the difference of the average photon times:

$$\Delta t_{PM} = \frac{1}{n}\sum_{i=1}^{n} t_i'^{mirror} - \frac{1}{m}\sum_{j=1}^{m} t_j'^{direct} - t_0$$

t_0 is the event reference time measured by the R_2 trigger



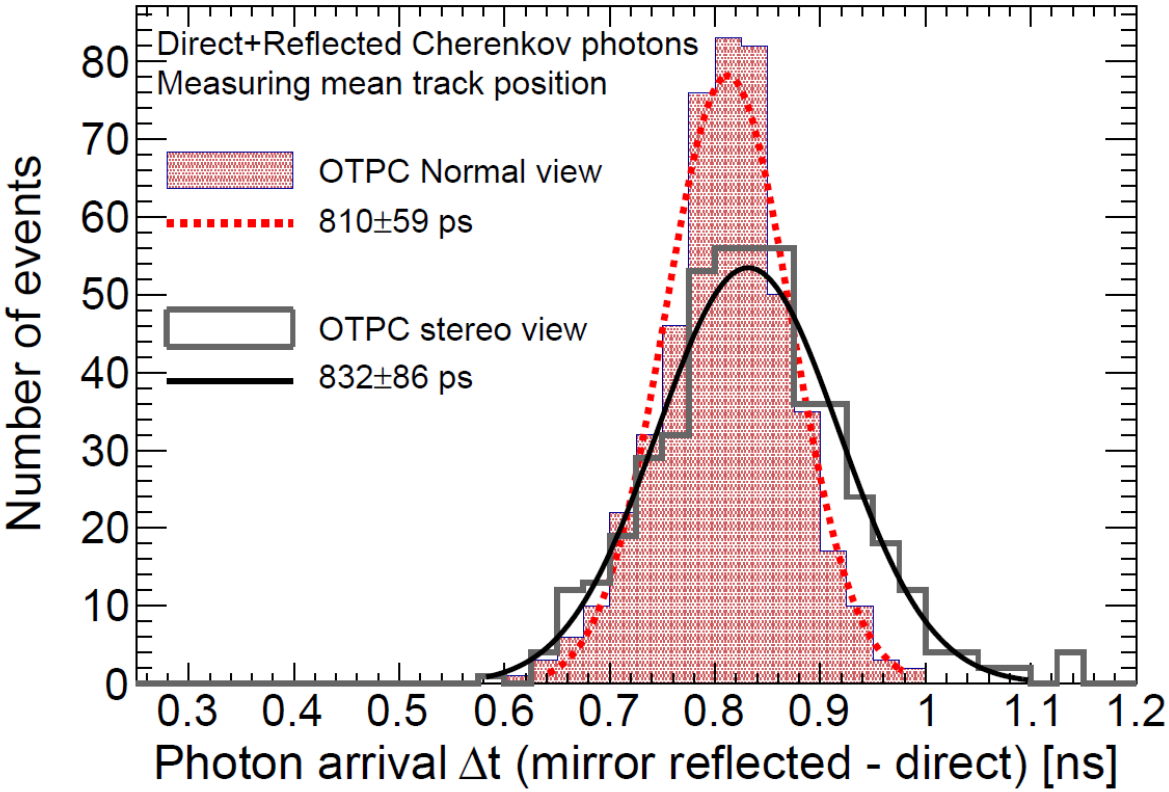
<u>The average event</u>:
number of direct and reflected photons per cm. The five discrete distributions along the OTPC z-axis are the 5 PM locations

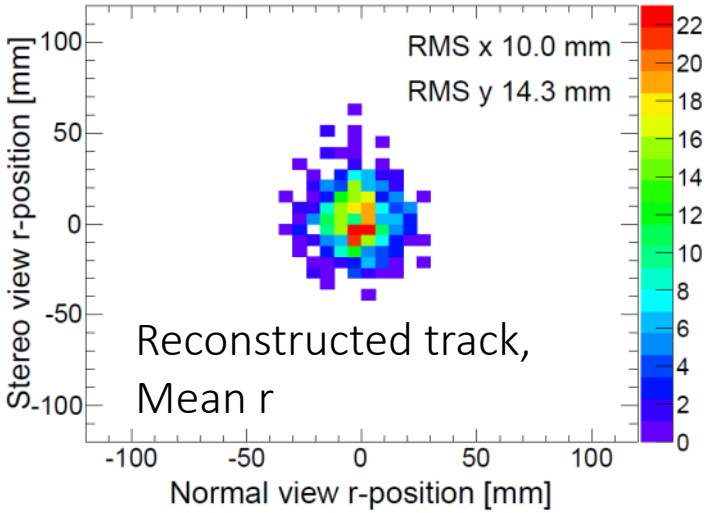
Spatial reconstruction in the prototype OTPC

Combining the data along the normal and stereo view PMs, we measure an average relative timing between the direct and mirror-reflected photons per event:

59 ps timing resolution →
10 mm spatial resolution

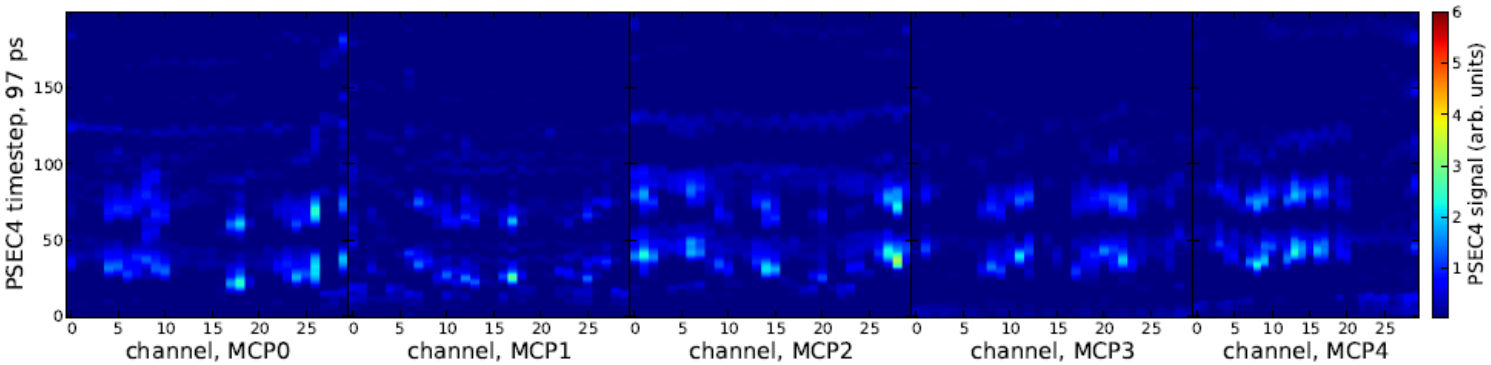
86 ps timing resolution →
14 mm spatial resolution



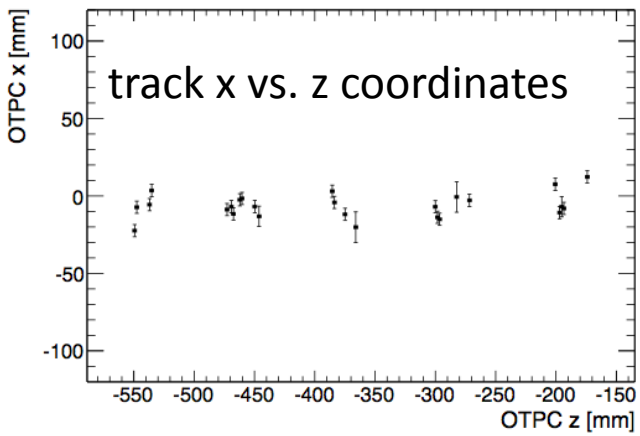


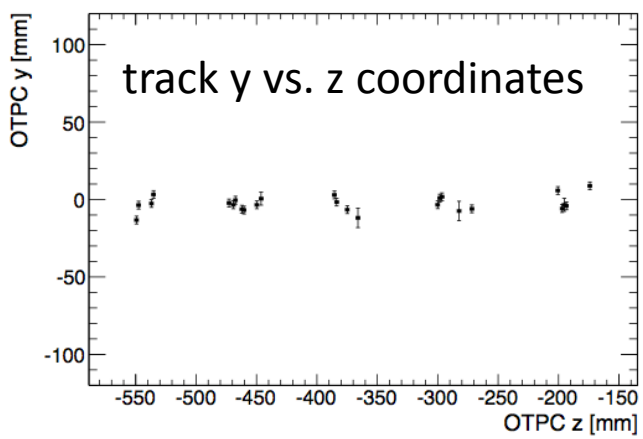
OTPC 3D Cherenkov reconstruction

(previously shown event)

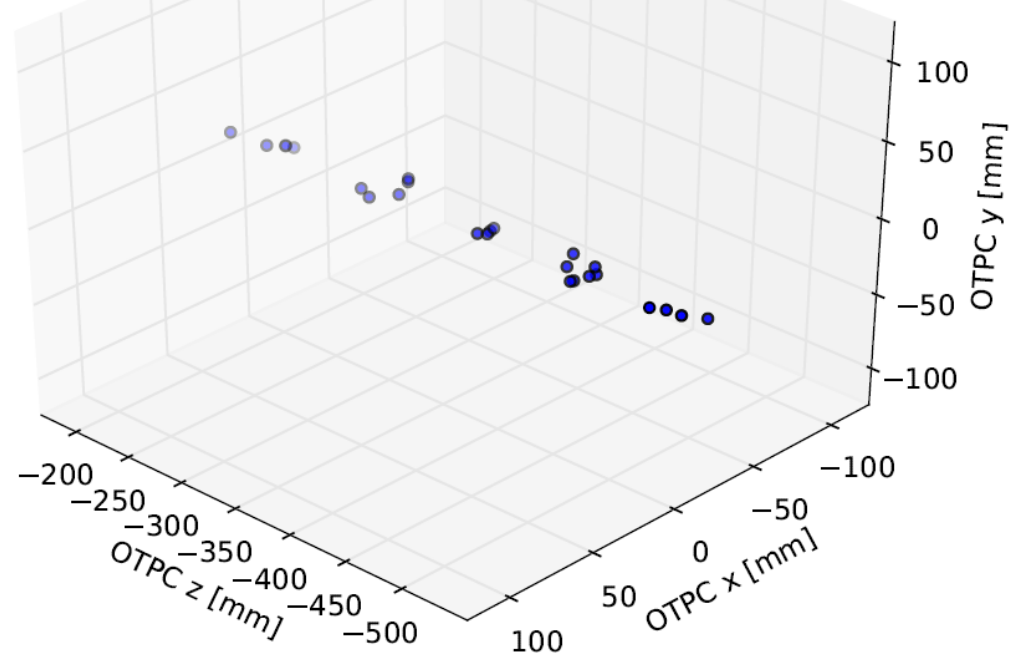


Typical event (thru-going μ)



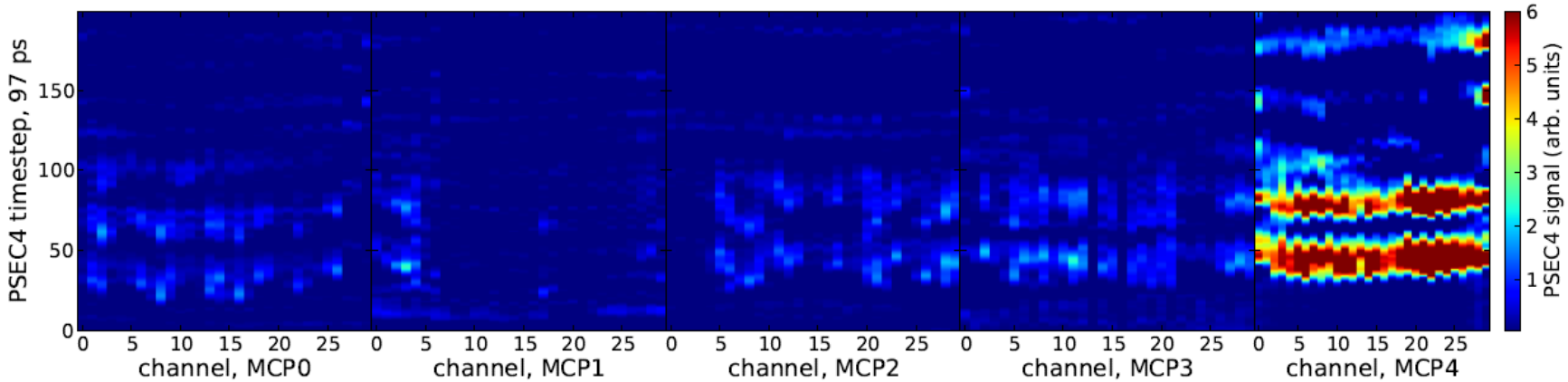


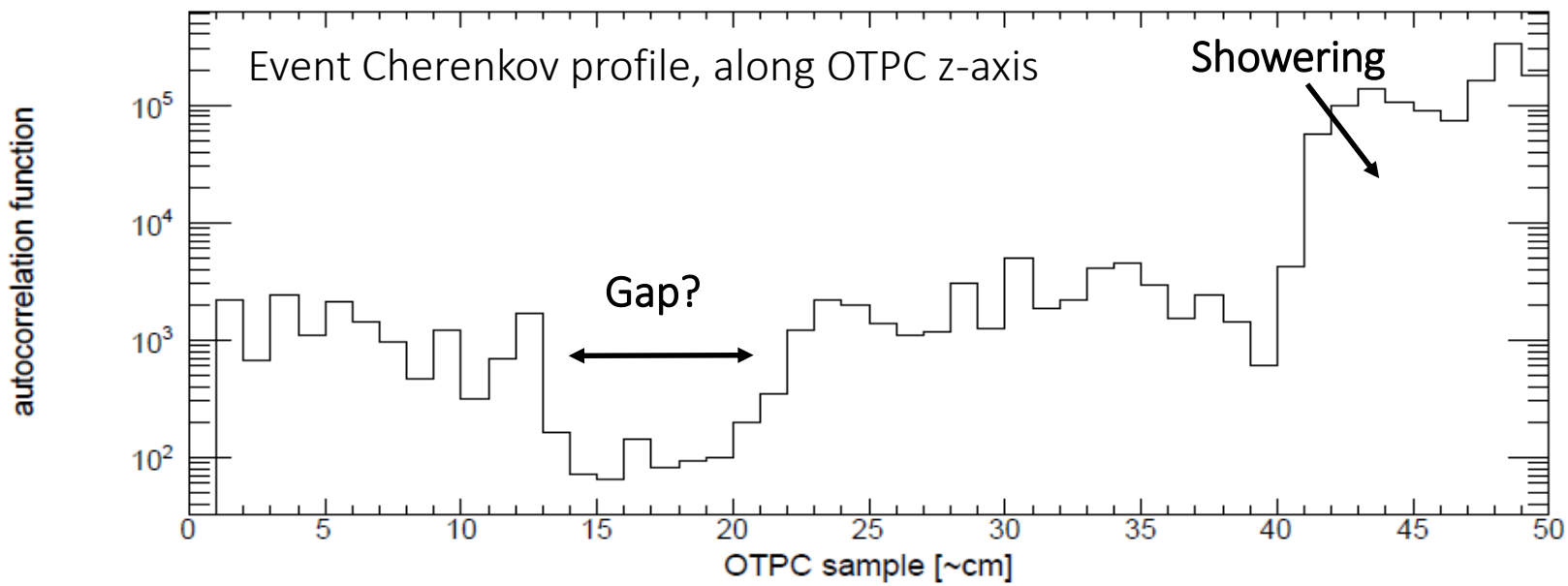
Projecting the direct photons onto the reconstructed r-coordinate at each PM



Particle ID

An `interesting' event:

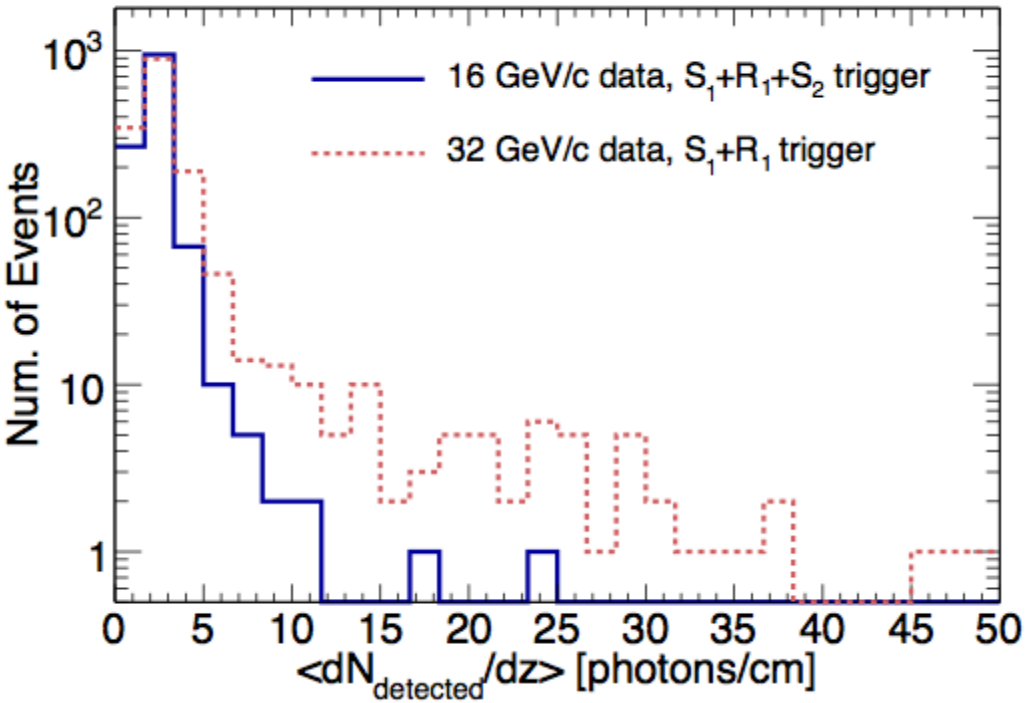




Particle ID

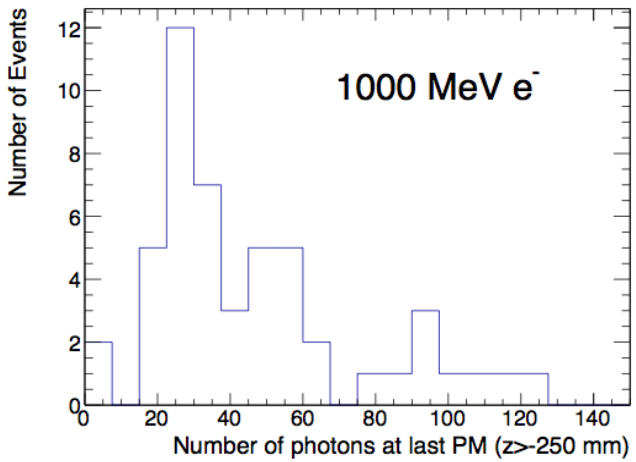
[Preliminary] Muon vs showering-electron ID. Compare different trigger configurations and secondary beam momenta. Higher momenta = more electrons (=showering events) in sample.

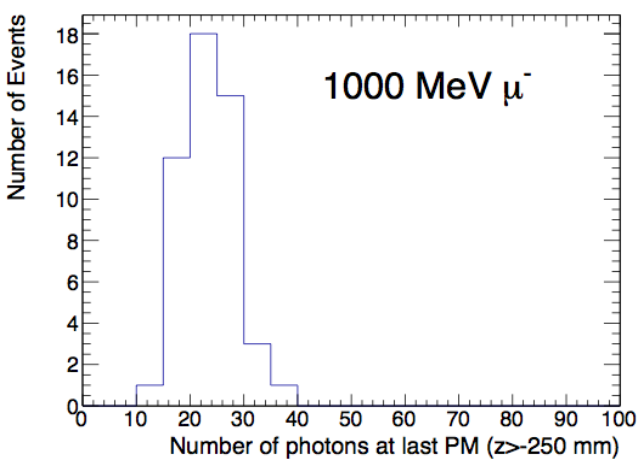
Measure the average number of photons along the track:



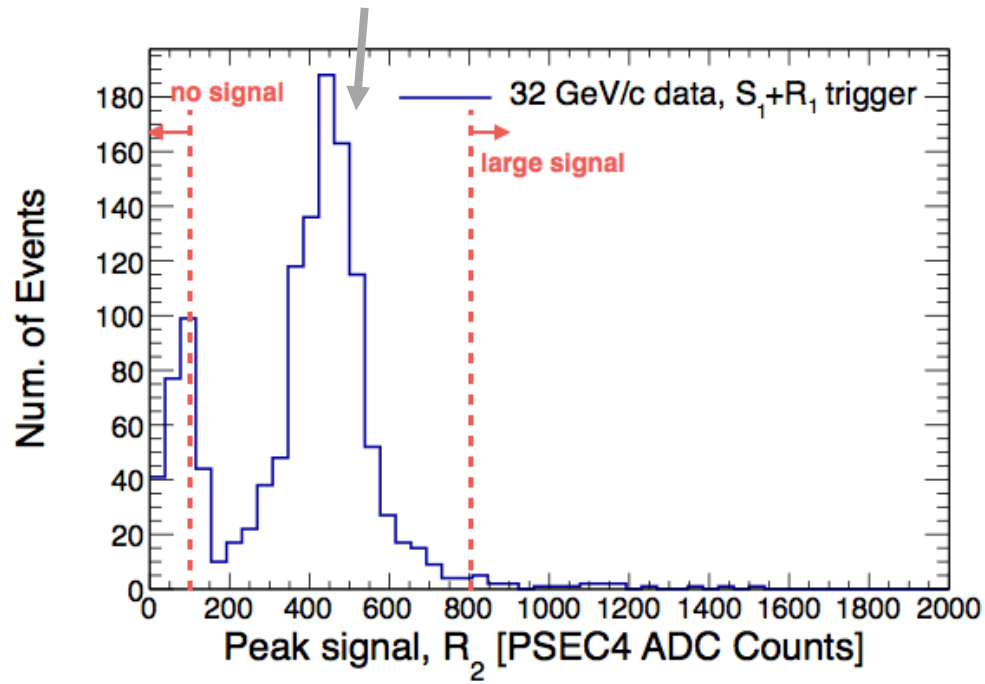
Particle ID

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





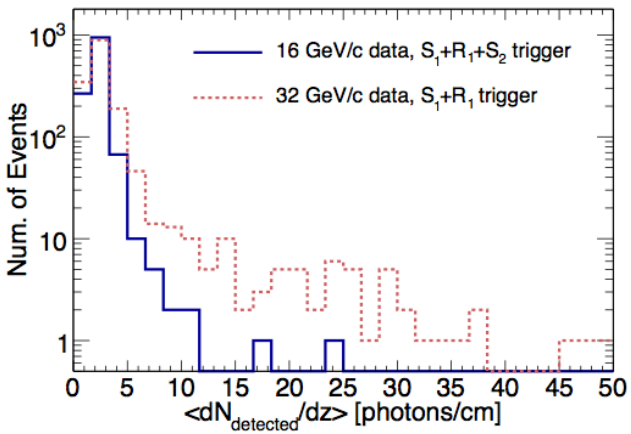
Peak distribution from typical thru-going MIPs (muons, pions, or non-showering electrons)

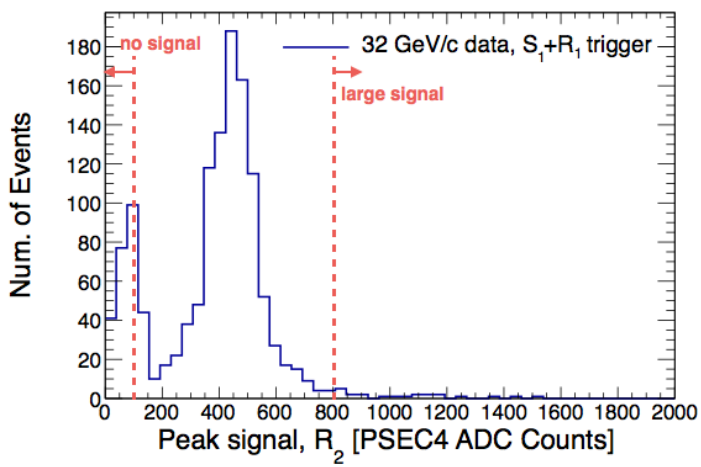


Remove central region events from sample; keep others (which may be events with an EM showering component)

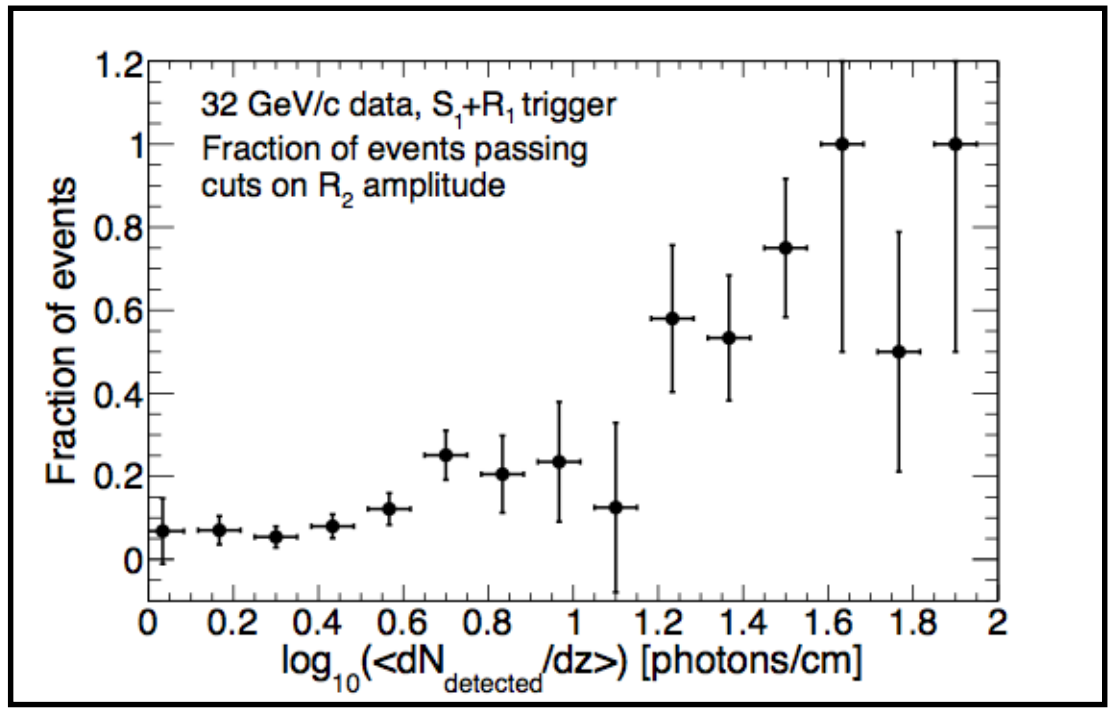
Particle ID

[Preliminary]





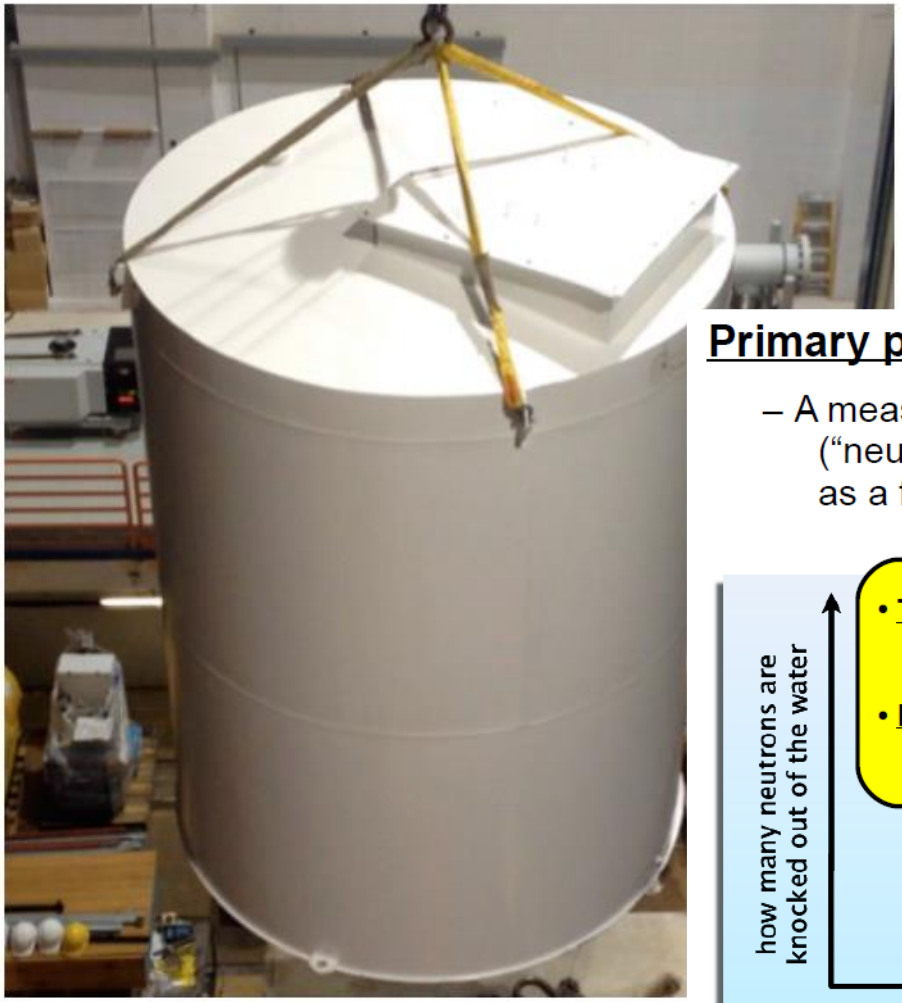
Strong correlation between the events cut from the OTPC trigger and the measured number of photo-electrons along the track in the water volume



[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]

scaling up…

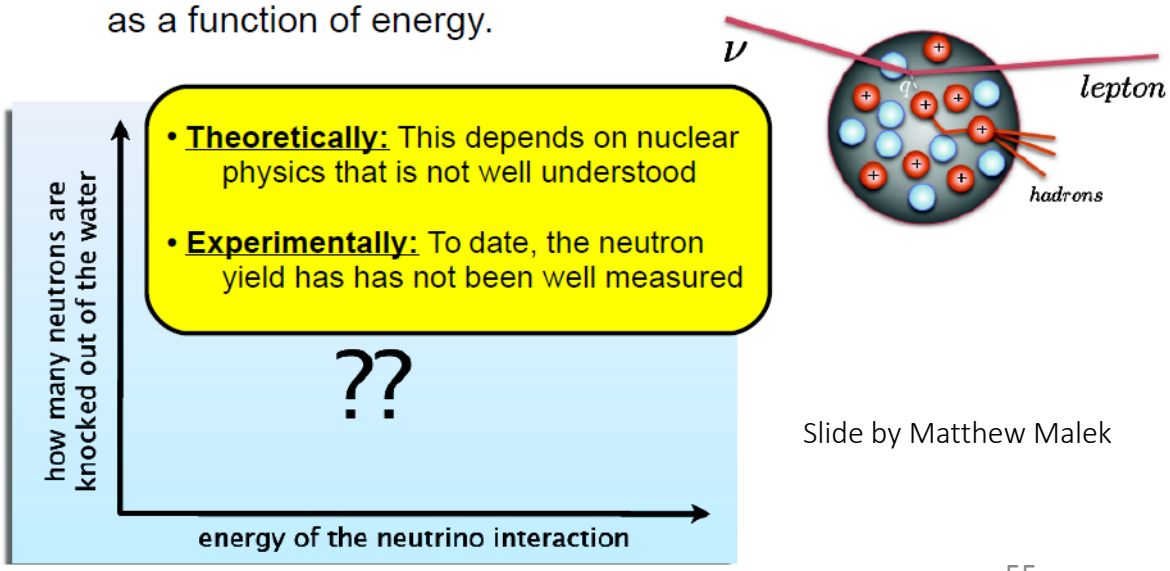
Accelerator Neutrino-Nucleus Interaction Experiment (ANNIE)



- 30 tons Gd-loaded water
- ScibooNe Hall Fermilab
- Phase II run-plan (planned from ~late 2016 onwards):
  - 60-200 conventional PMTs
  - 20+ submerged LAPPD PMTs (OTPC mode!) using OTPC electronics
  - CC-inclusive measurement of muon-neutrino on water

Primary physics objective:

– A measurement of the abundance of final state neutrons ("neutron yield") from neutrino interactions in water, as a function of energy.



Slide by Matthew Malek

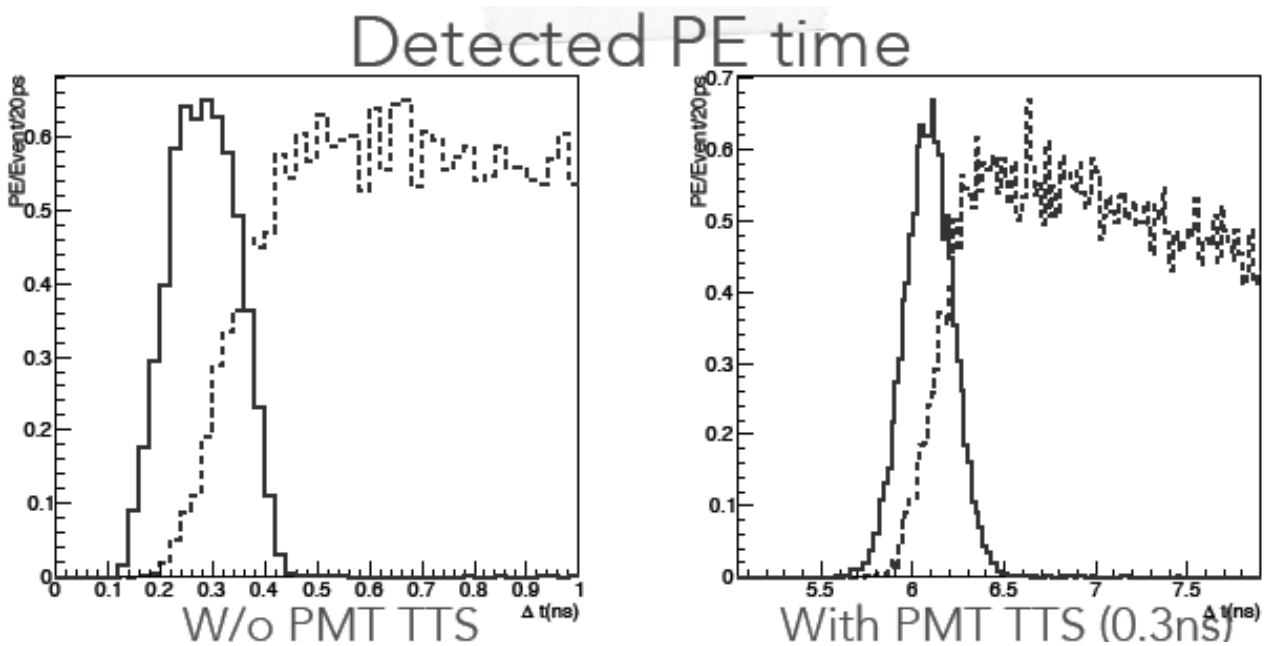
ANNIE LOI: arXiv 1504.01480

scaling up…

‘OTPC’ test-beam run-2?

- Proposal (Berkeley, LBNL, LLNL UC Davis, others) for proton test-beam water Cherenkov + water-based liquid scintillator (WbLS).
- Potential PSEC4a readout (revision on PSEC4 ASIC – deeper analog buffer)
- Lower energy threshold with WbLS
- Combination of conventional PMTs and MCP-PMTs, ton-scale detector

Separation of scintillation light and Cherenkov light, J. Caravaca simulation:



More info on Cherenkov/scintilla-tion separation, see: Elagin et. al arXiv 1307.5813

A summary:

- LAPPD = large area MCP-PMT, in commercialization process
- Full electronics systems designed and produced using 10 GSPS front-end ASIC
- 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.
- At Fermilab's MCenter test-beam facility, we tested the detection and tracking performance using primarily multi-GeV muons
- For a through going muon, we detect 79 ± 20 Cherenkov photons:
  ~64% are mirror-reflected, ~36% are direct (non-reflected)
- 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

UC engineering acknowledgements:
Bob Metz, Richard Northrop, Mary Heintz, Mircea Bogdan, Mark Zaskowski