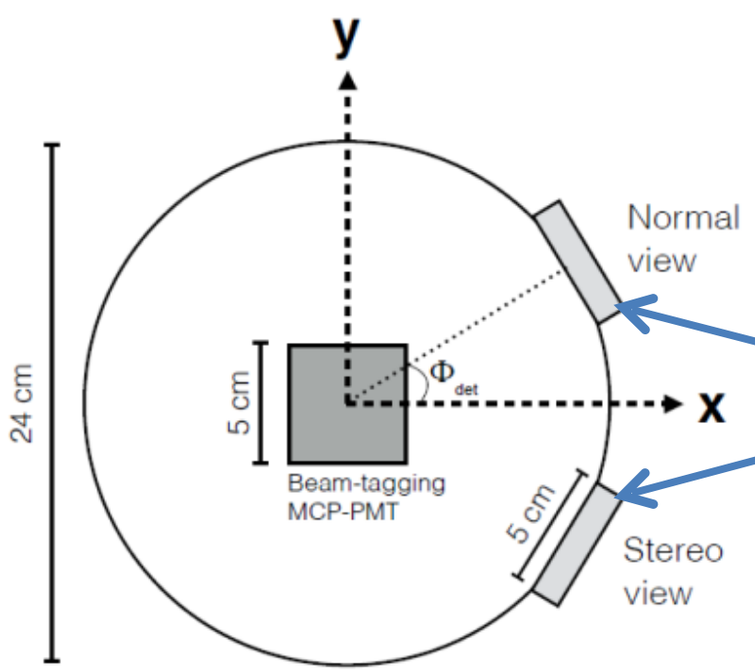
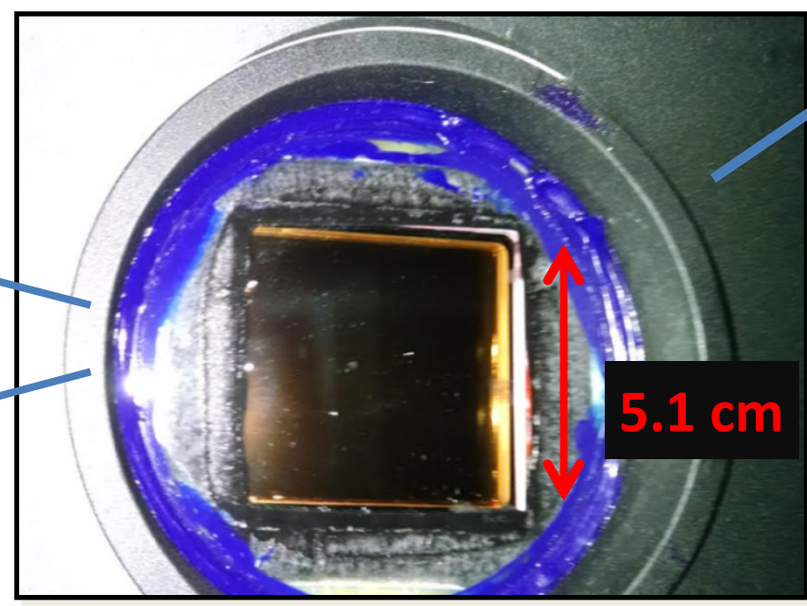
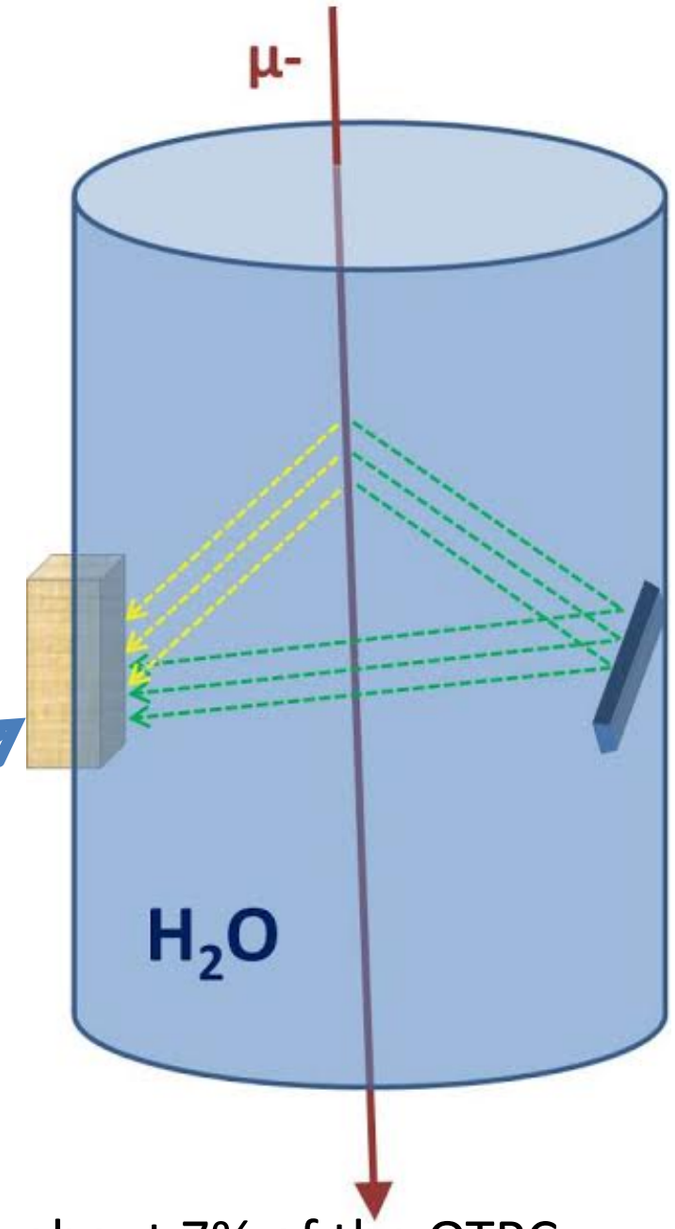
Prototype water Cherenkov OTPC

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 water

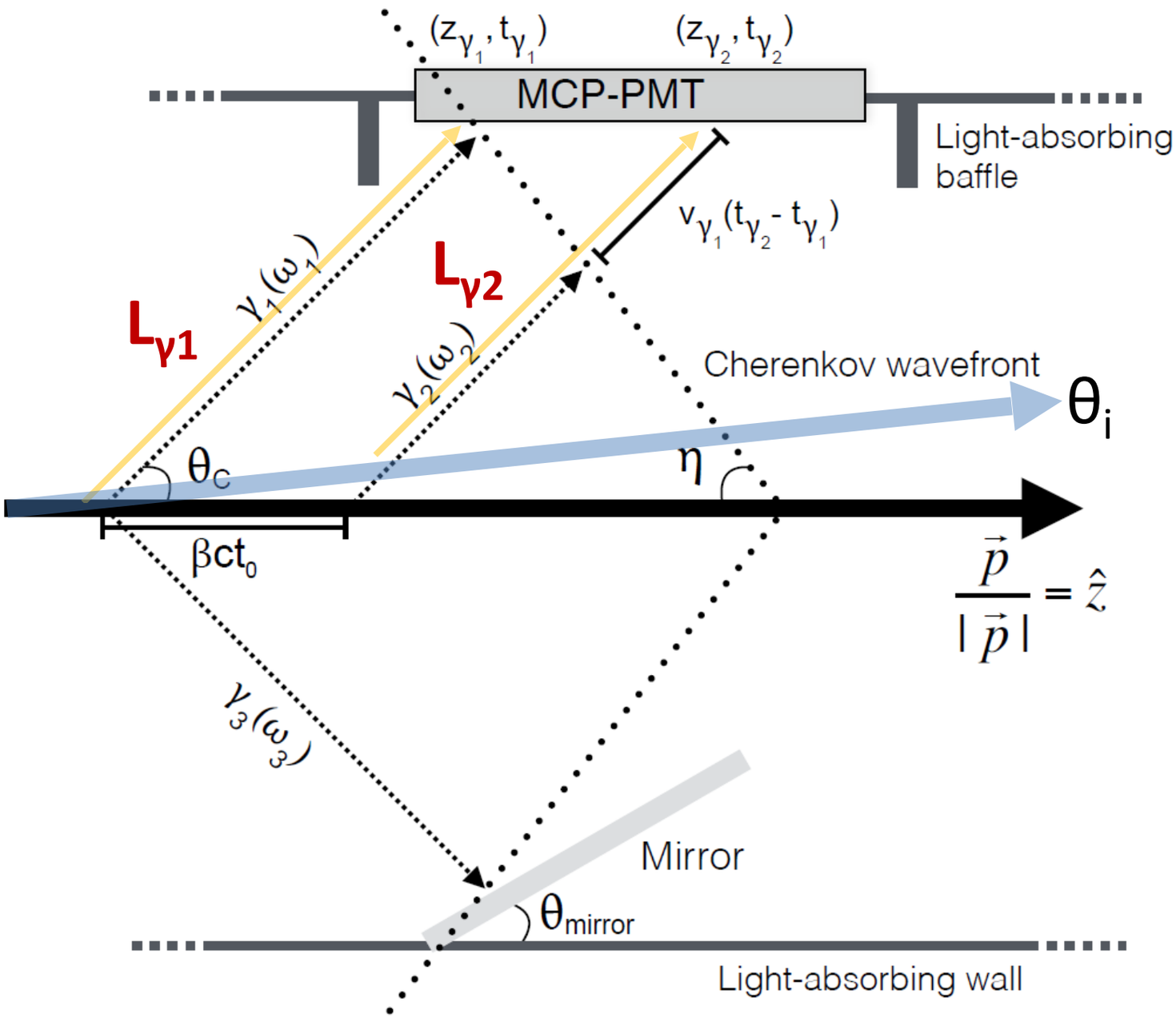






Only about 7% of the OTPC surface area is instrumented with photodetectors (mirrors enhance!)

OTPC Optics – direct light



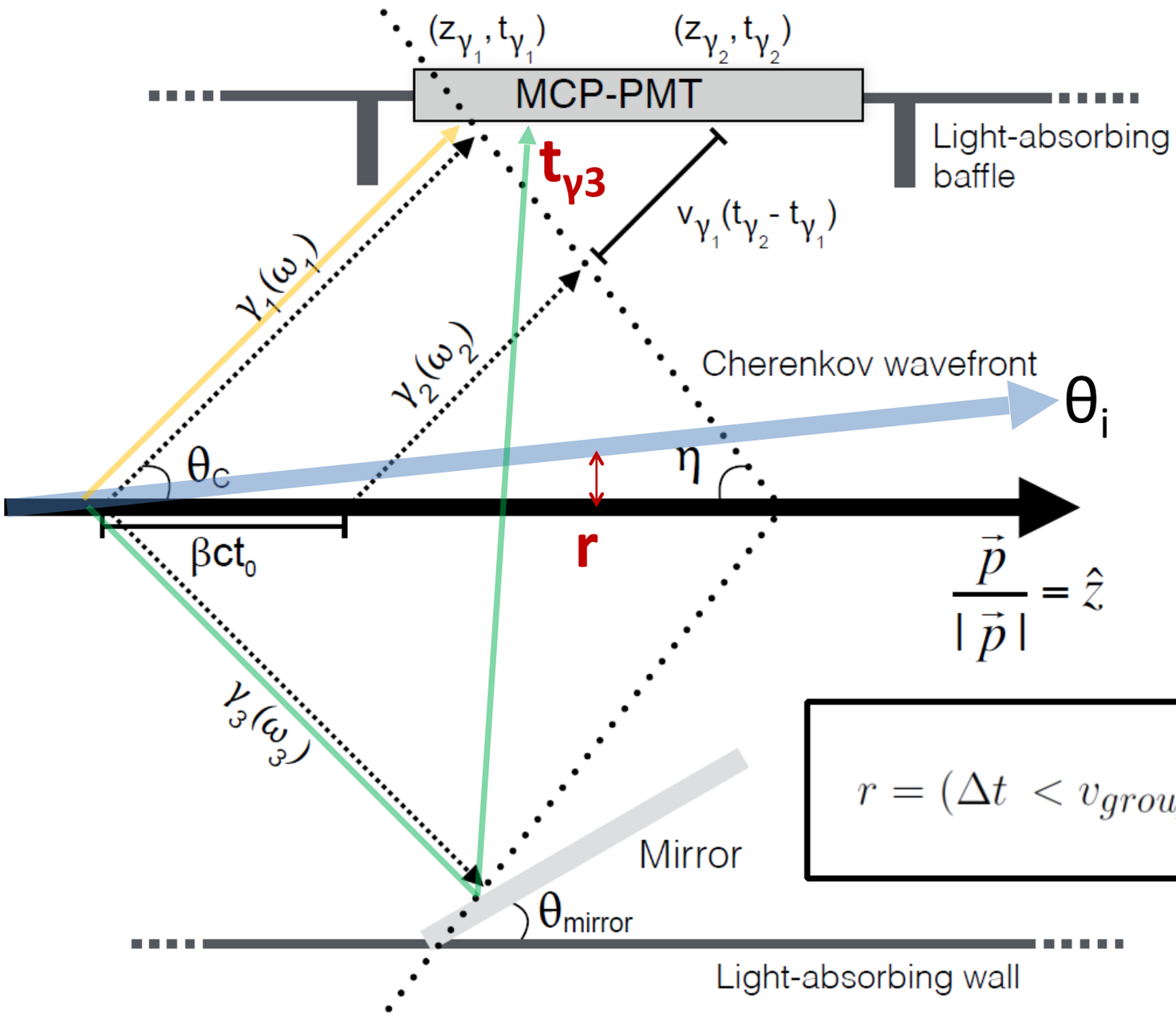
The time projection of the direct Cherenkov photons on the OTPC z-axis is a measure of the Cherenkov angle (β) and the particle angle with respect to the OTPC longitudinal axis

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

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

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

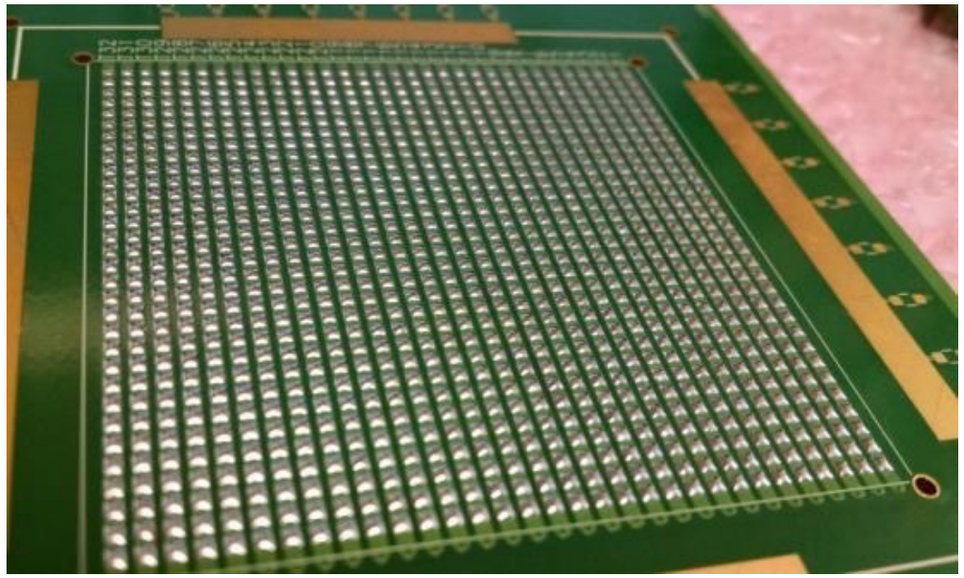
OTPC Optics – direct + reflected light



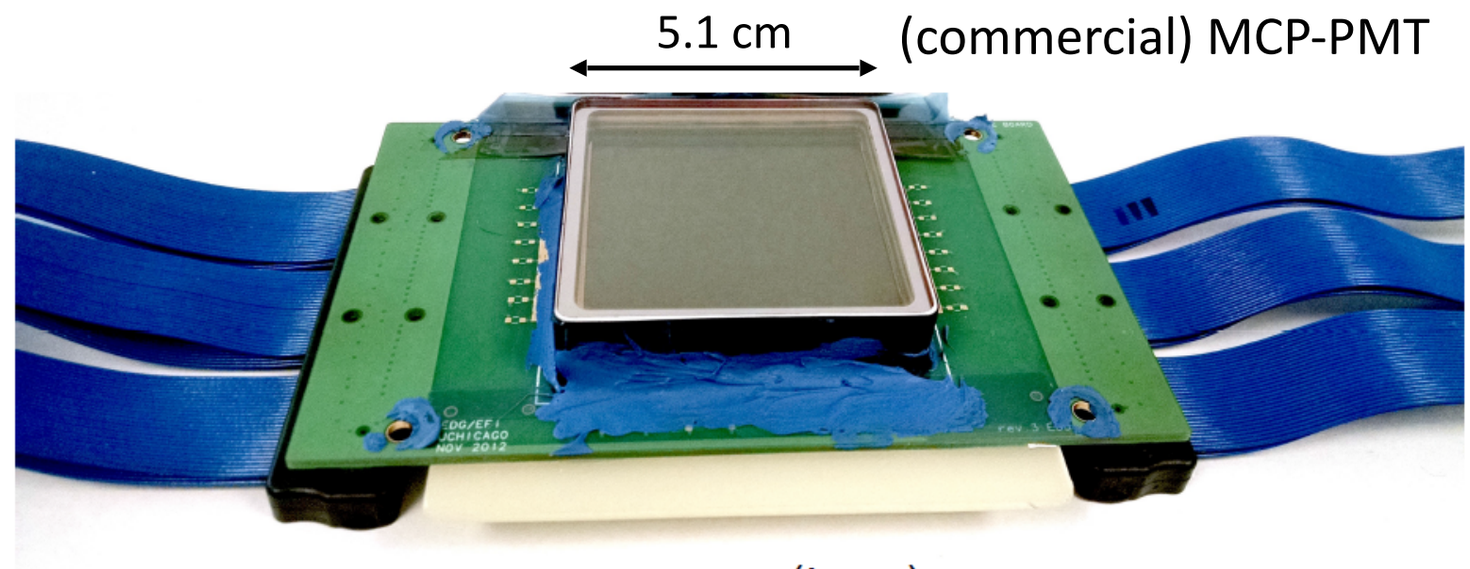
Time-resolving the direct and reflected photons provides the lateral particle displacement from the OTPC center-line as a function of z- and ϕ-position

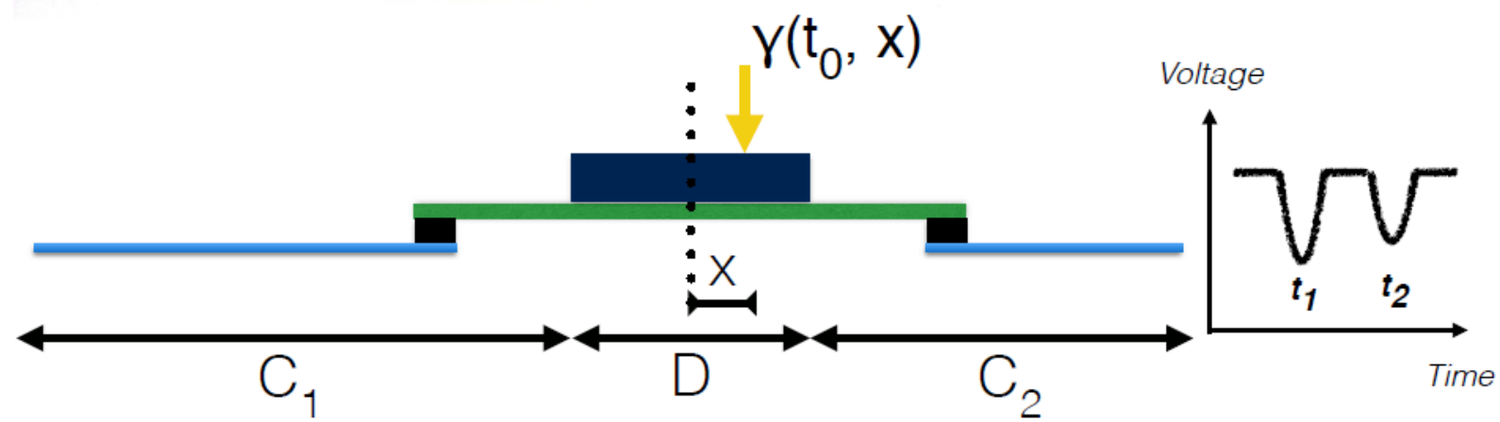
$$r = (\Delta t \ < v_{group} > -D)\,\frac{1}{2}\left(\frac{1}{\sin\theta_c} - \frac{< v_{group} >}{\beta c \tan(\theta_c)}\right)^{-1}$$

OTPC Photodetector Module (PM)

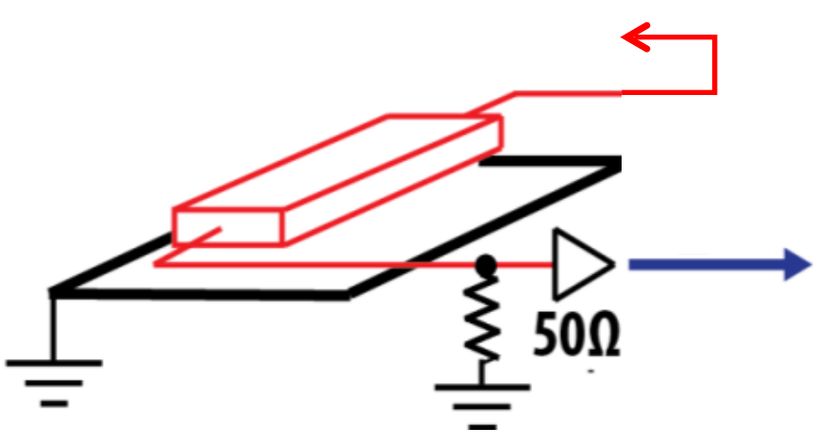


PHOTONIS XP85022 (commercial) MCP-PMT





- 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):

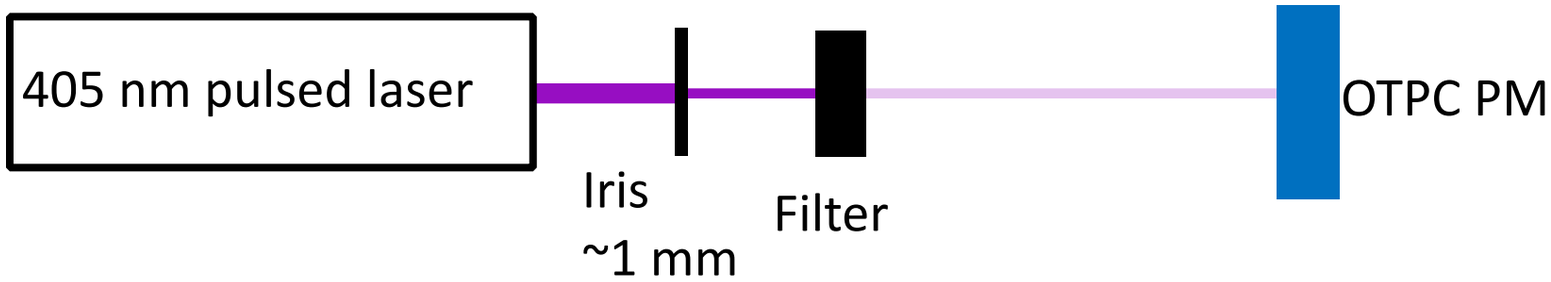


Expressions for the position and time-of-arrival of the detected photon

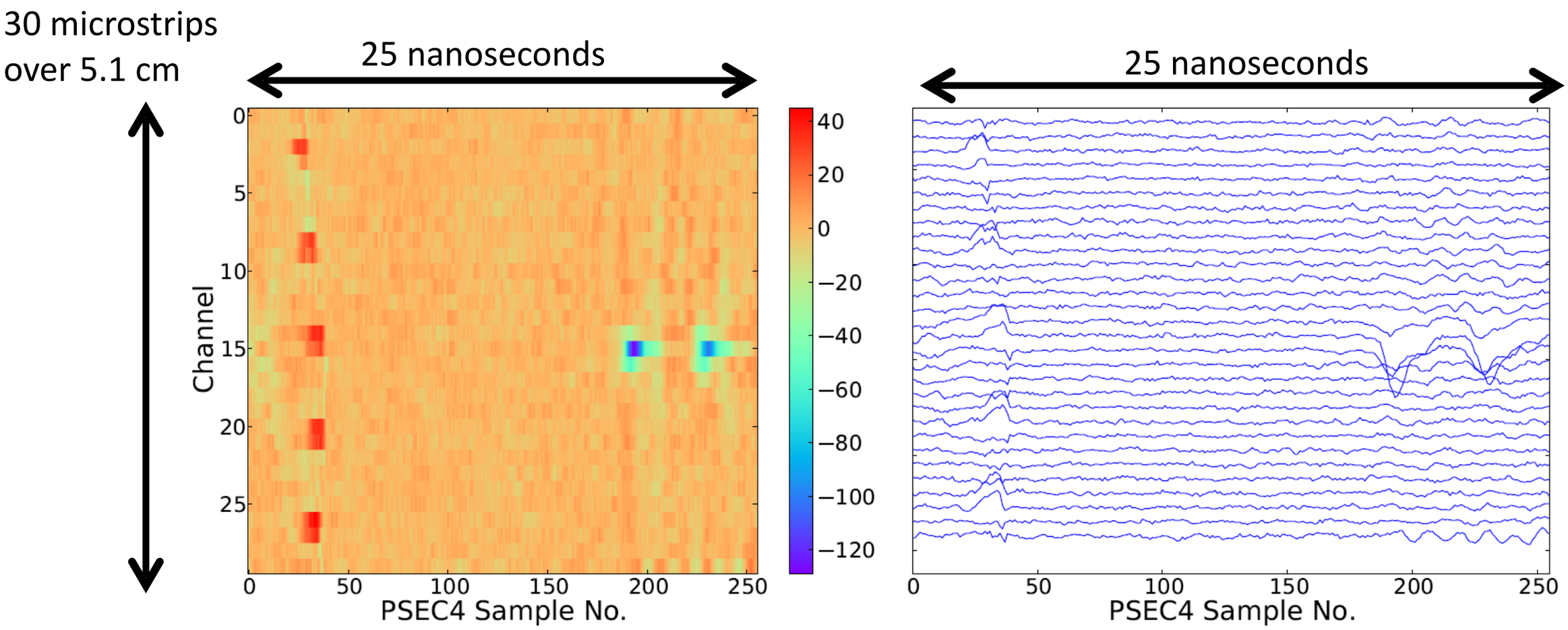
$$x = v_{prop}\,\frac{t_2 - t_1}{2} - \frac{D + 2\,C_1}{2}$$

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

OTPC PM – single photon response

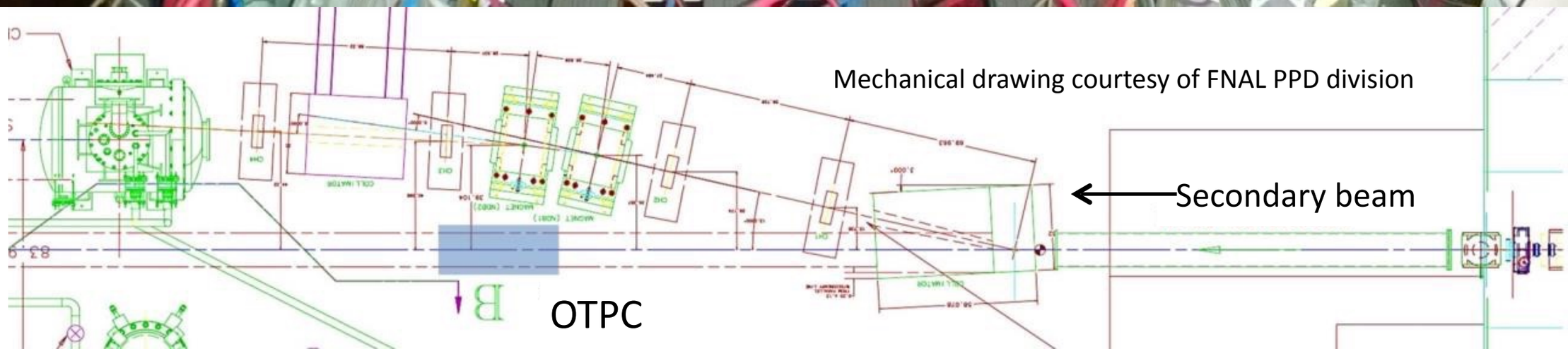


Pulsed laser (33 ps FWHM) attenuated to single photon level

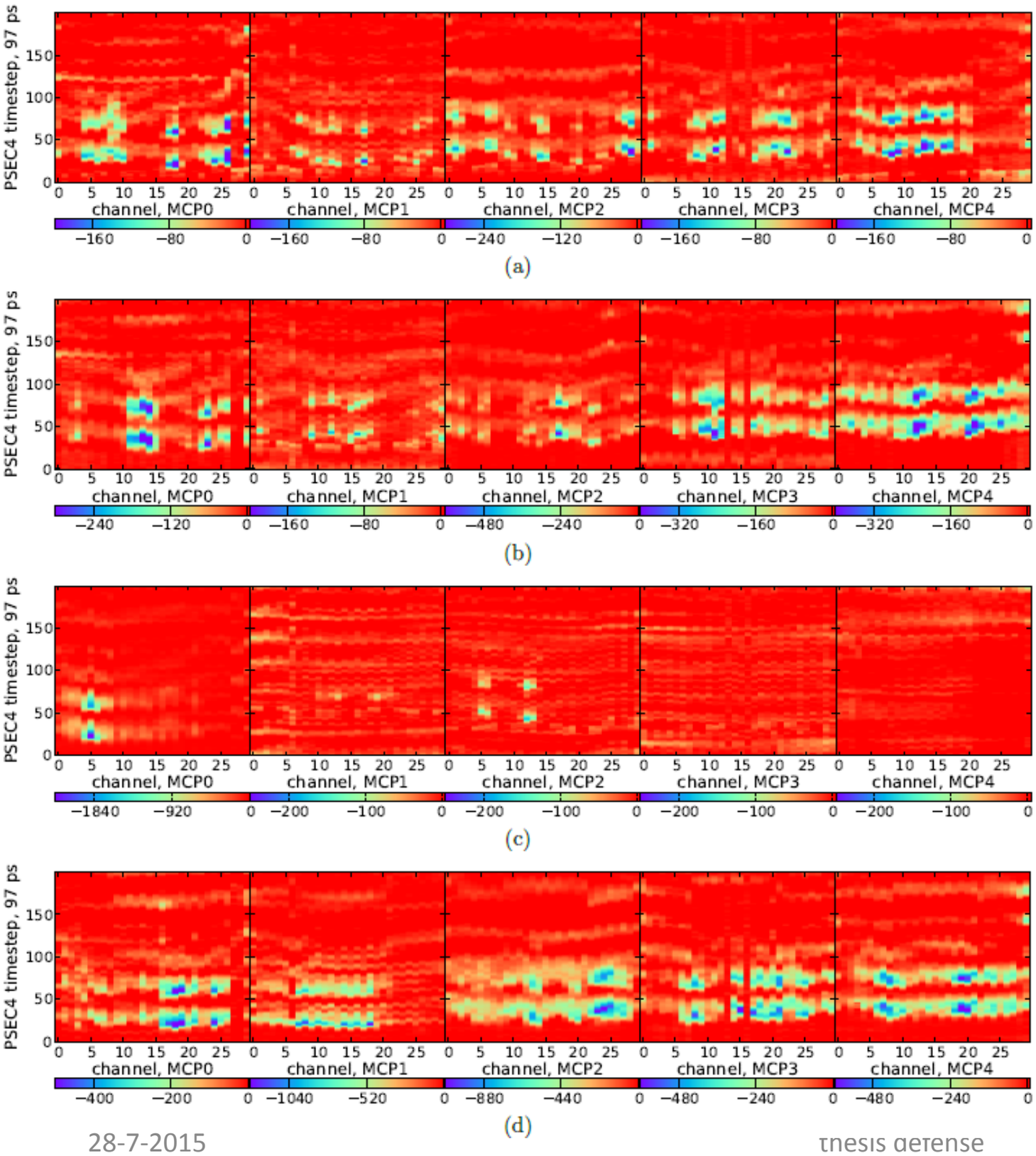


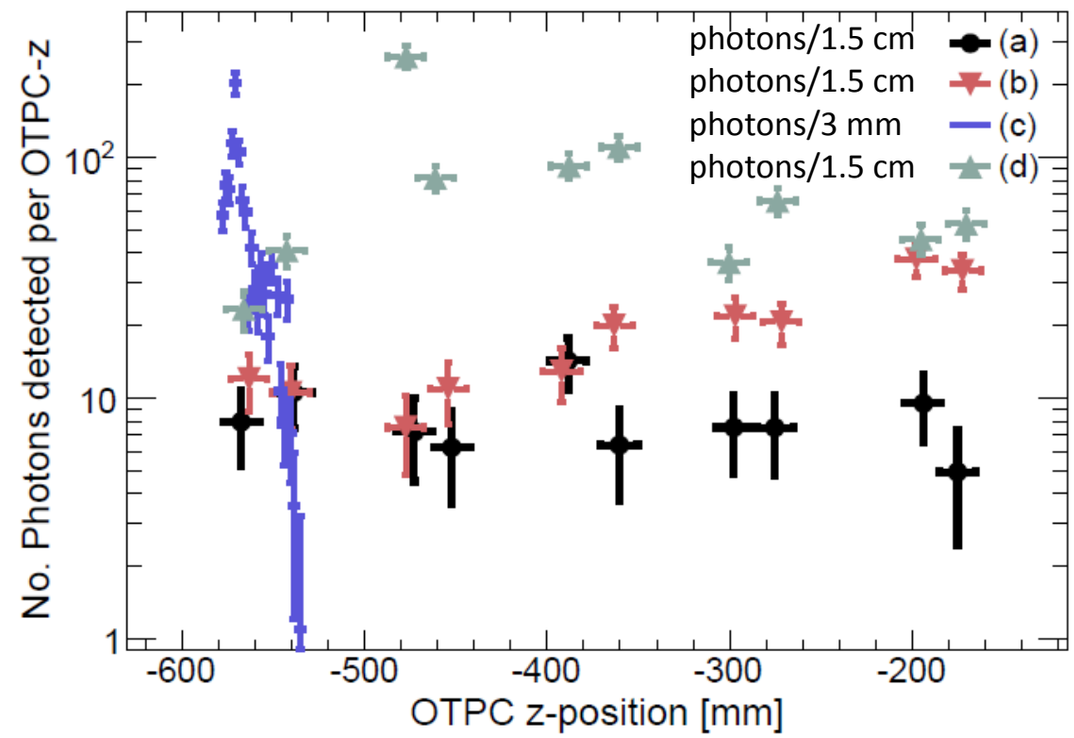
- Single photo-electron signal recorded by the PM
- 30 channels of 10.24 GSa/s waveform sampling per PM
- Pulses are ~1 ns wide; two pulses on the microstrip anode per photo-electron signal

OTPC installed at MCenter, FNAL



Raw Events + gain calibration





(a) Typical through-going event
(b) Through-going event with increasing number of detected photons
(c) Track with a large number of photons over a short extent (not through-going)
(d) Large signal amplitude along entire track, peaking in 2nd panel (not through-going)

Number of photo-electrons per track

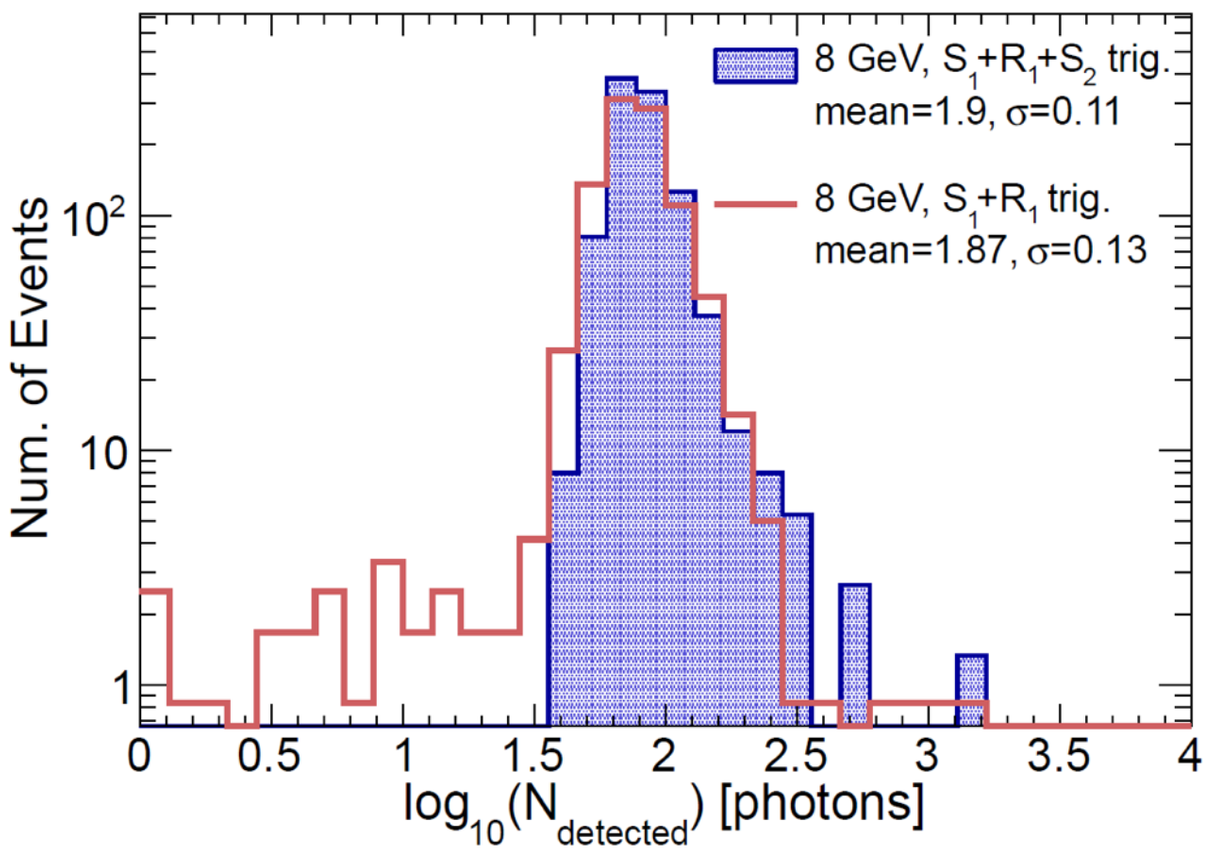
Using gain calibration we measure the number of photons per track, comparing different datasets (trigger configuration, water quality)

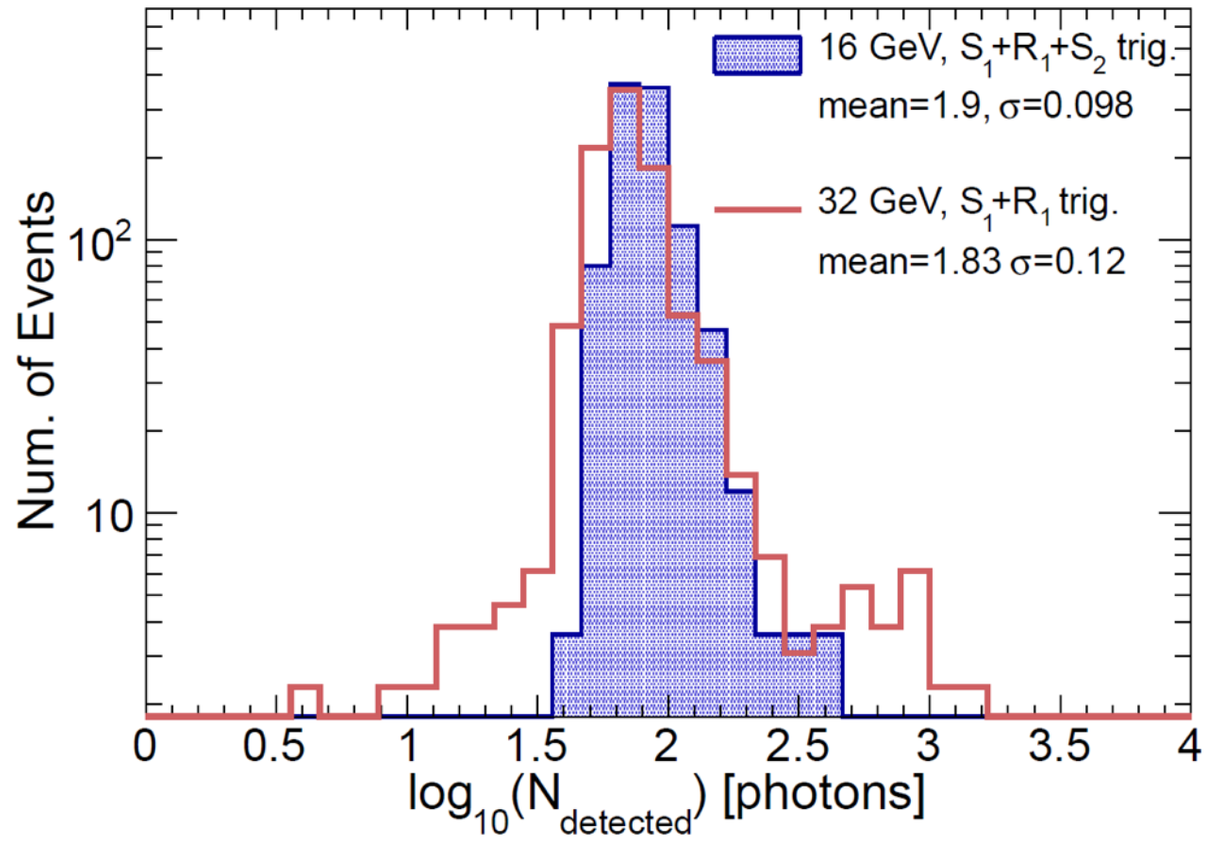
Comparison of 8 GeV/c secondary beam datasets

- Through-going trigger: 79 ± 20 photo-electrons per track
- Front-only trigger: 74 ± 25

Comparison of 16 and 32 GeV/c secondary beam datasets

- Through-going trigger: 79 ± 18 photo-electrons per track
- Front-only trigger: 67 ± 22

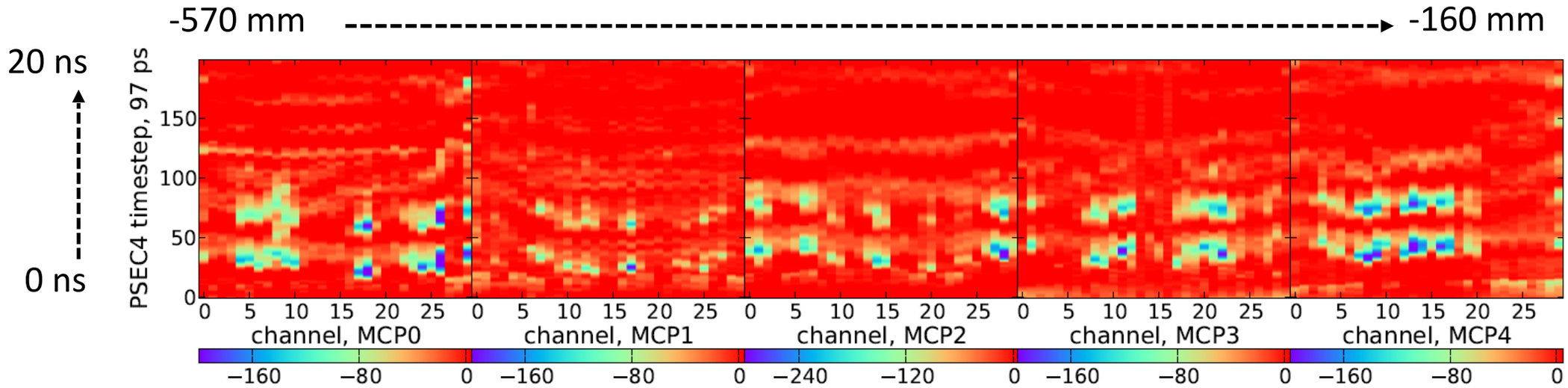




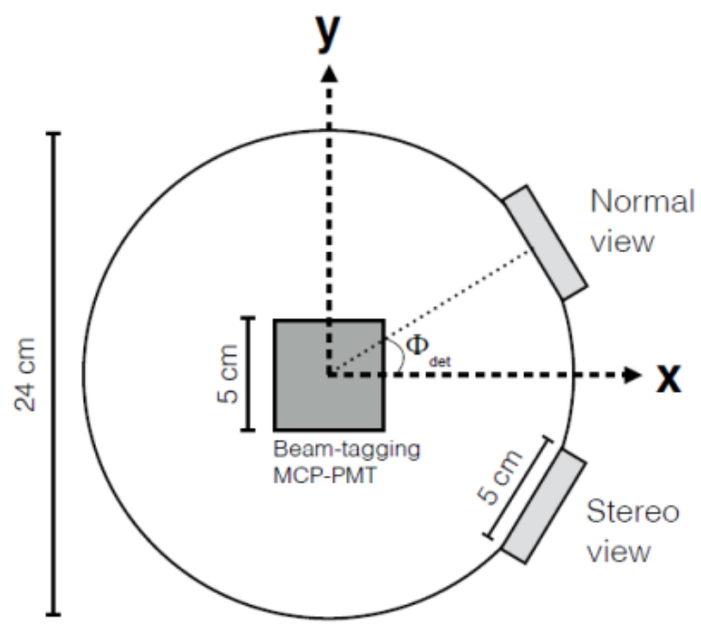
Water quality: blue > red

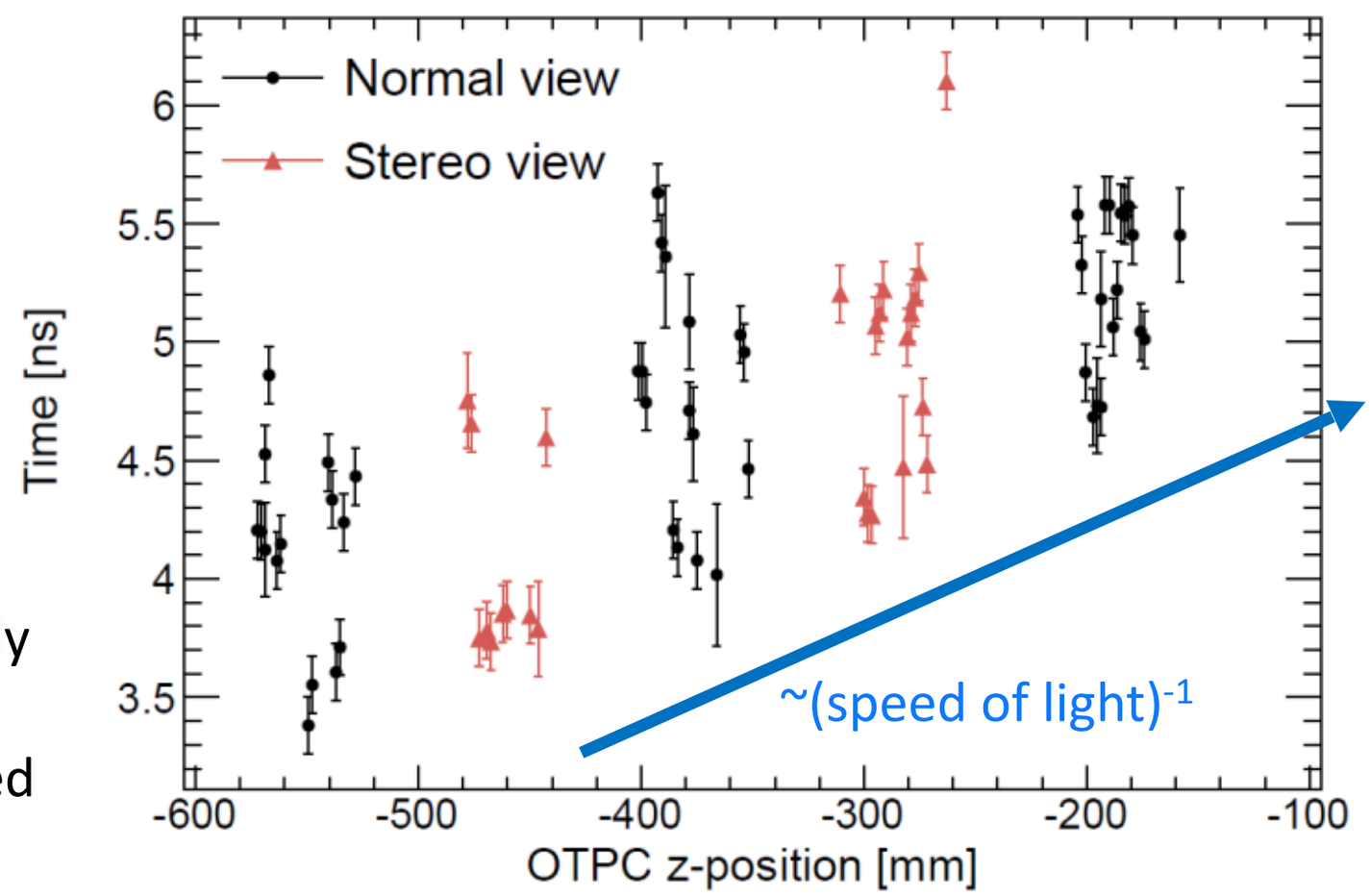
Time projection along the OTPC z-axis

Example event



Typical event (thru-going μ)





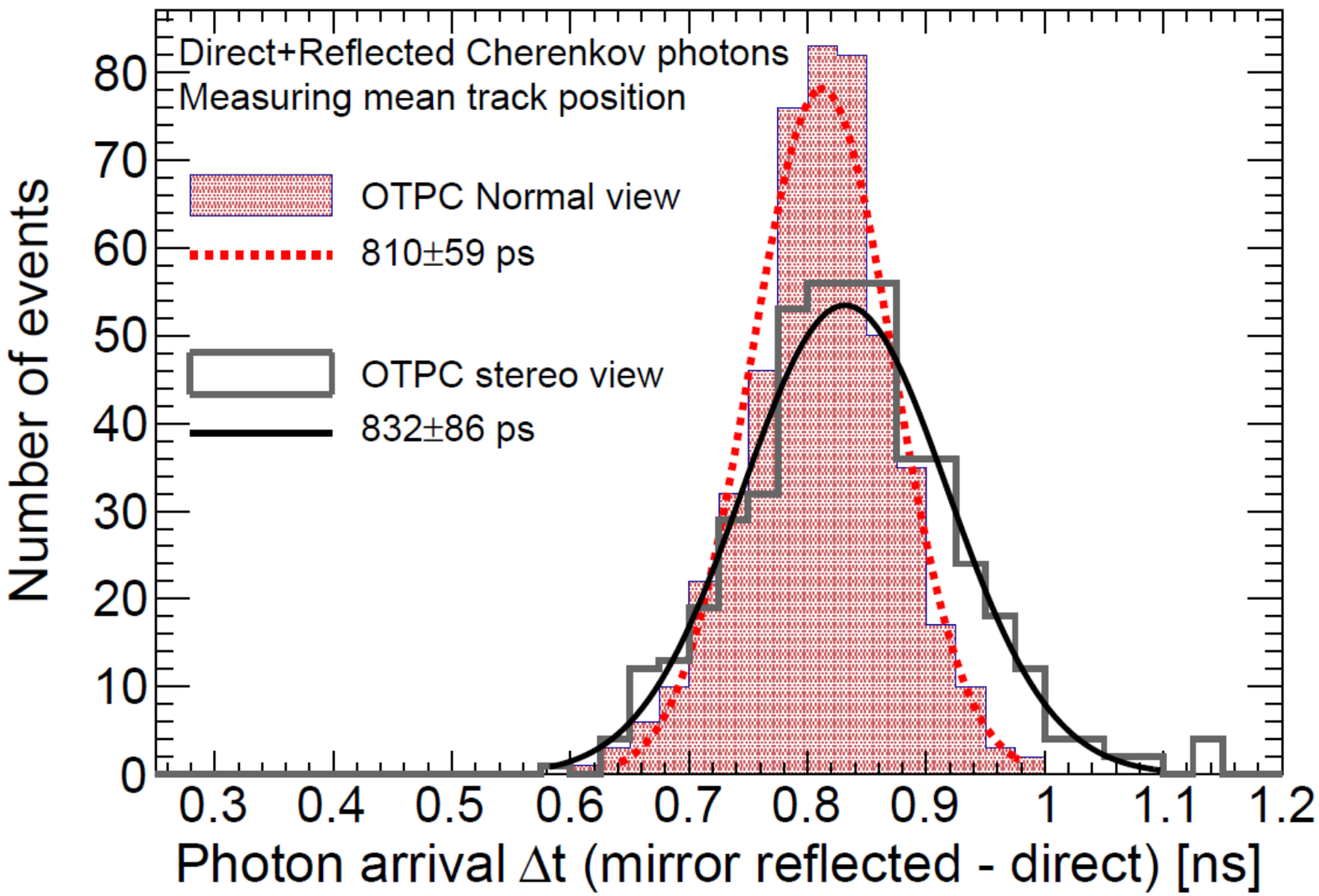
- Each data point is an individually resolved photo-electron
- Cherenkov photons are recorded over an event duration of ~2 ns

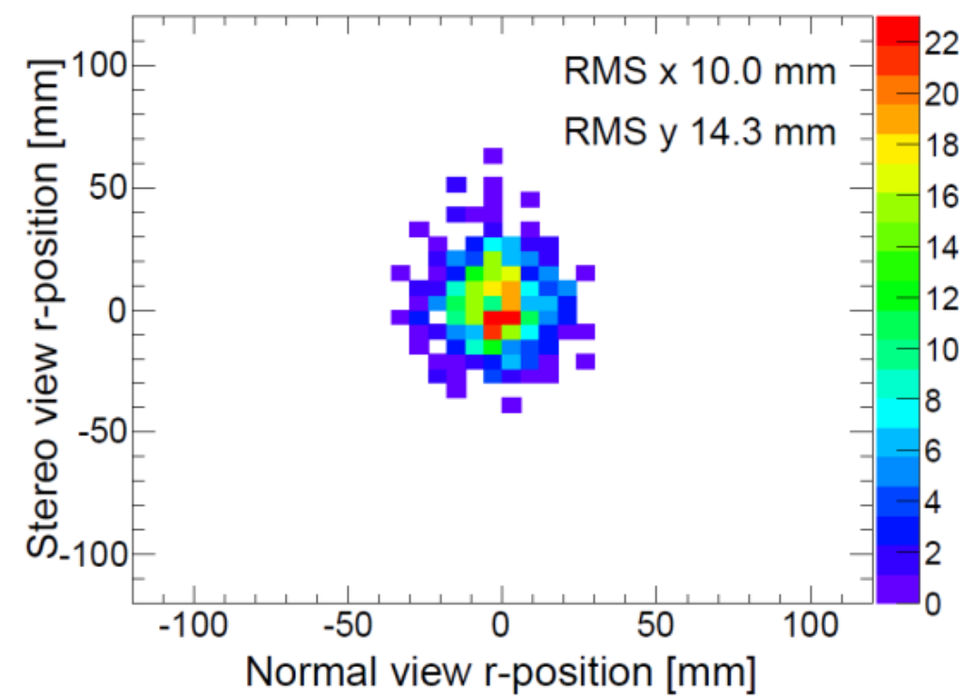
OTPC spatial reconstruction

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

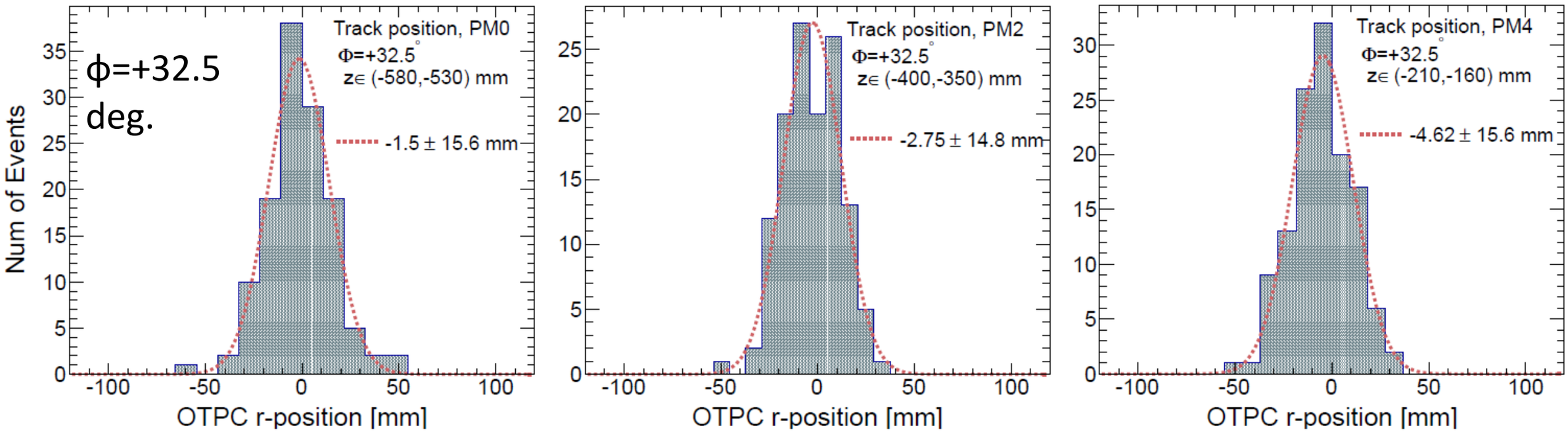
86 ps timing resolution →
14 mm spatial resolution





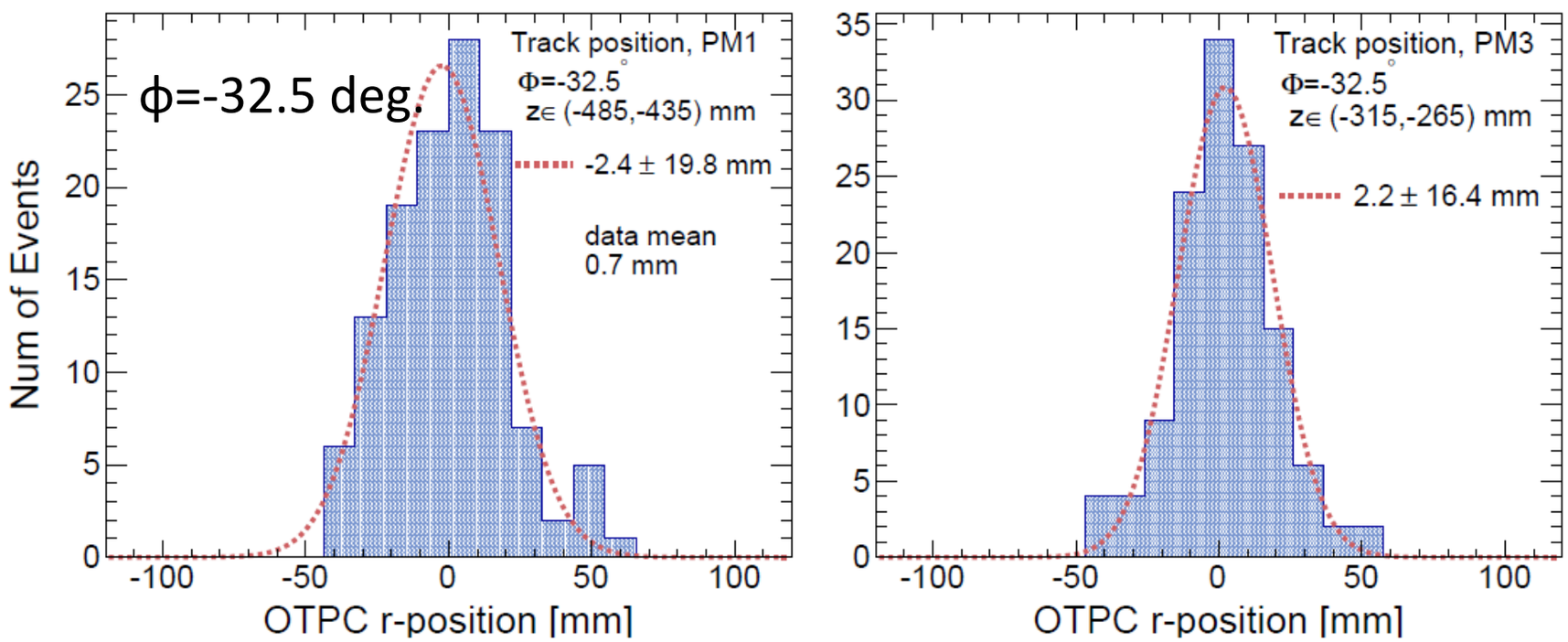
OTPC spatial reconstruction (2)

track position at
each PM, 127 events



(a) (b) (c)

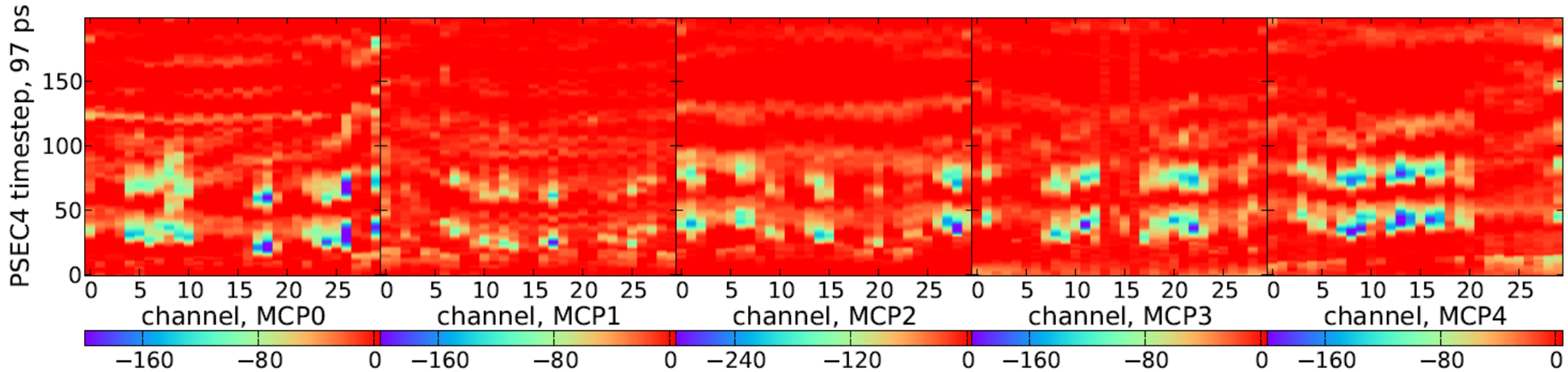
Beam direction
+z



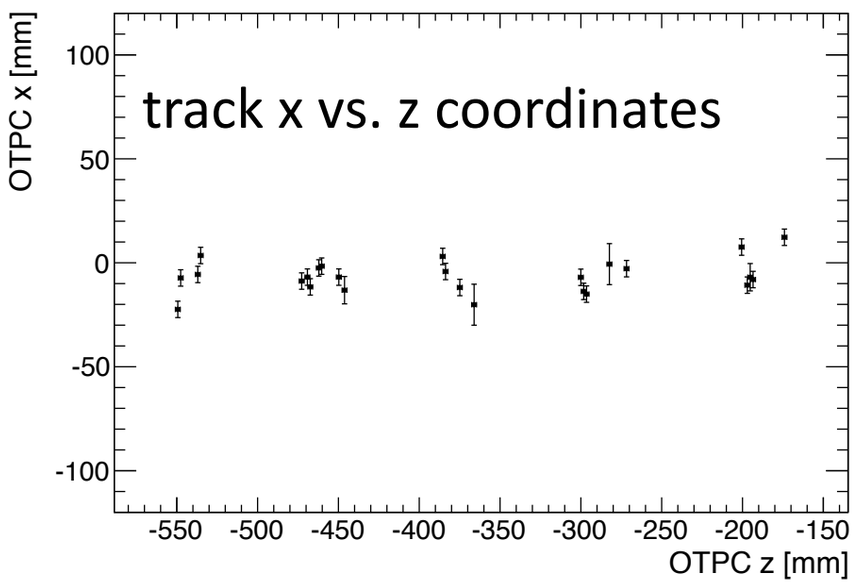
(d) (e)

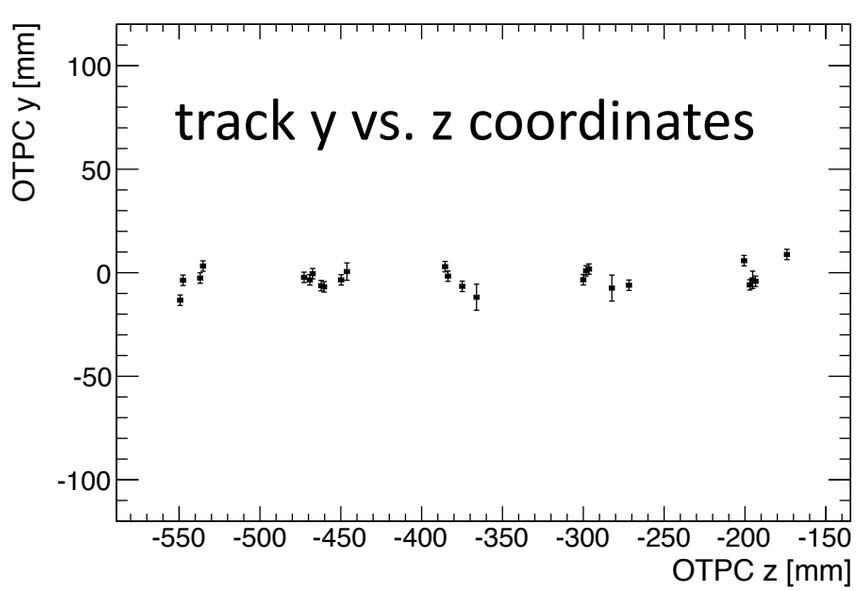
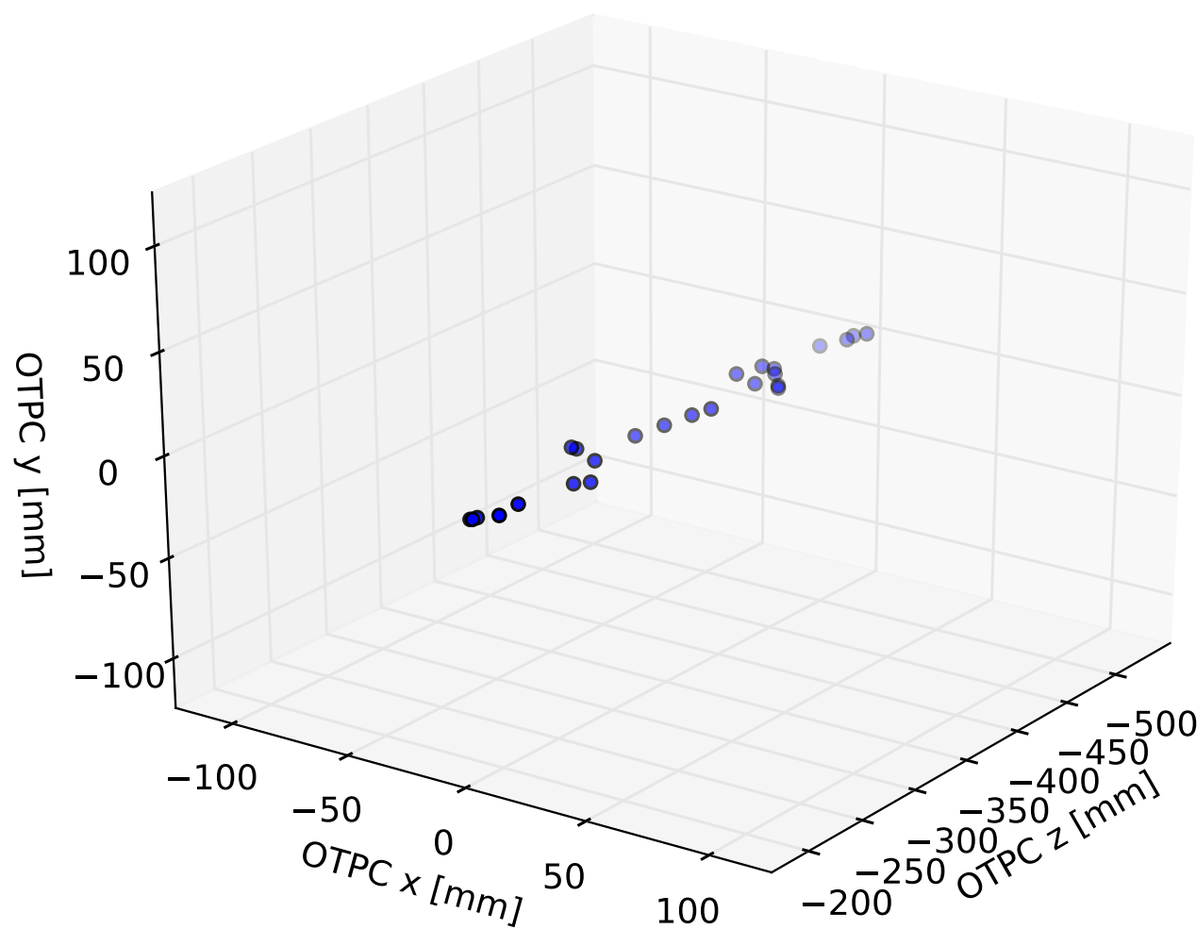
OTPC spatial reconstruction (3)

Example event



Typical event (thru-going μ)





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