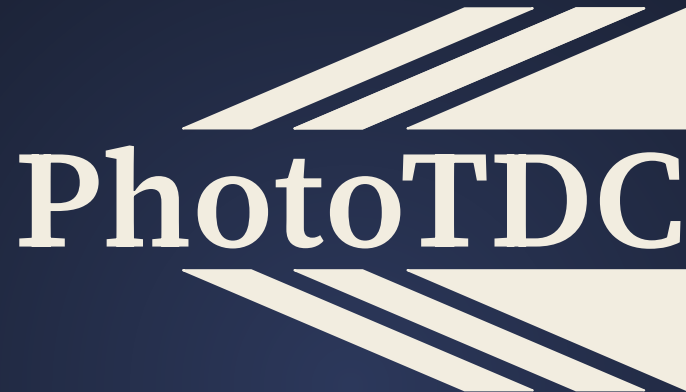




Time-to-Digital Conversion of Cherenkov Radiation using Photonic Techniques

Noah Paladino¹

Gillian Kopp¹

Neil Sinclair²

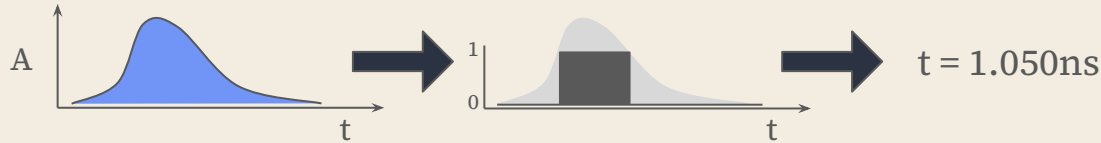
Philip Harris¹

(¹ MIT | ² Harvard)

Background

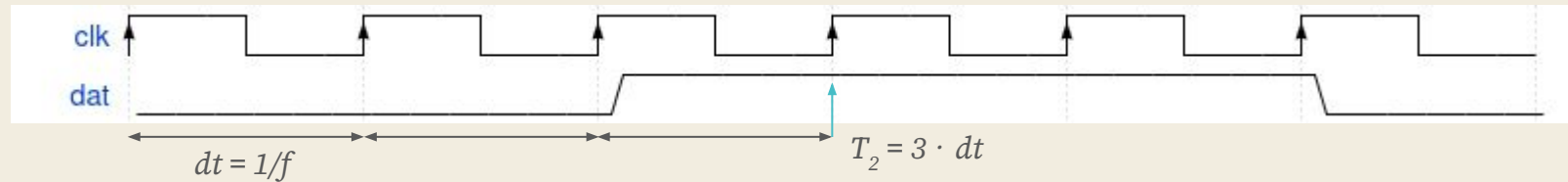
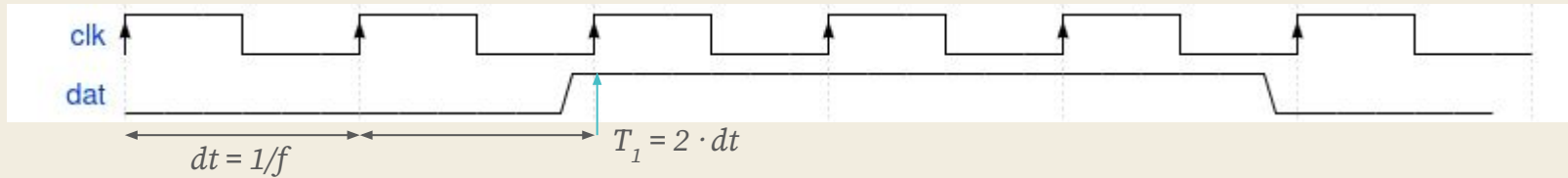
What is Time-to-Digital Conversion (TDC)?

- Representing the time of an “event” digitally
 - E.g. when a particle hits a detector and produces an output signal
- Described by **time resolution** (dt)
 - The smallest unit of time we can represent
- How does improving time resolution help do better physics?
 - Time-of-flight-based particle identification
 - Improved displaced particle reconstruction



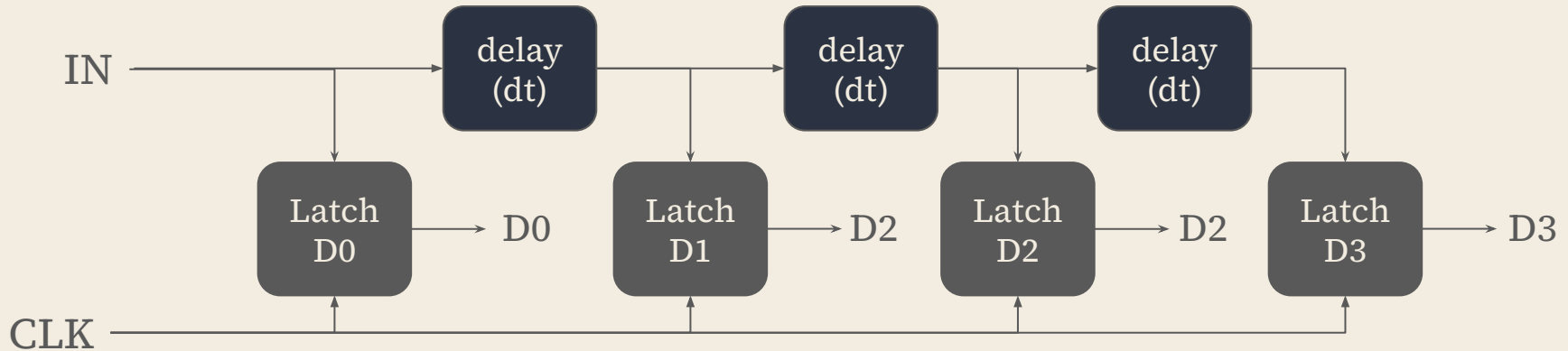
Time-to-Digital Conversion Techniques

- Counter/clock cycle sampling
 - Establish time from a sampling clock
 - Limited by max clock speed



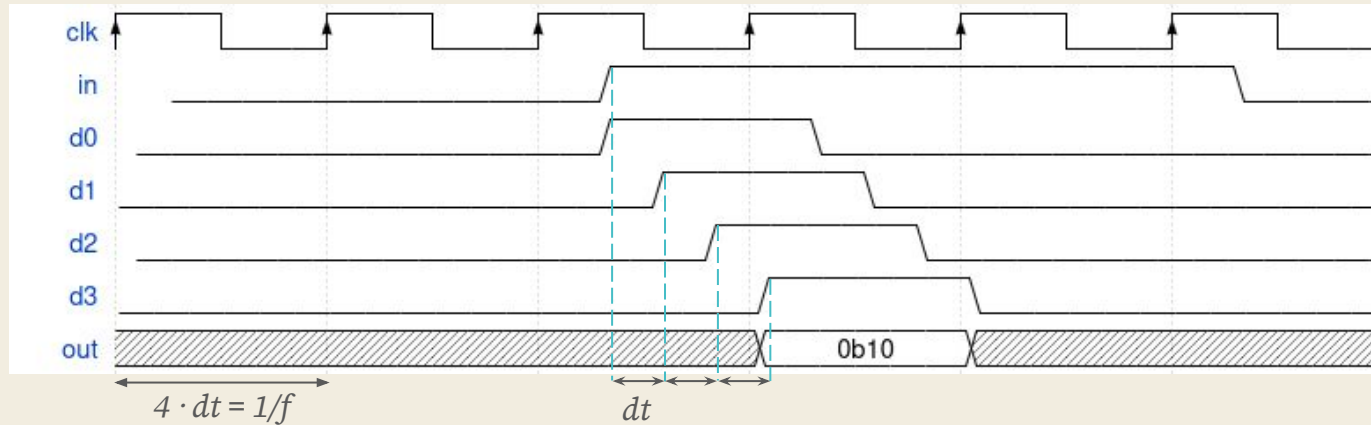
Time-to-Digital Conversion Techniques

- Tapped delay line
 - Add delay blocks to signal path and see how far along it gets in a sampling clock cycle
 - Implementable on FPGA



Time-to-Digital Conversion Techniques

- Tapped delay line
 - Requires care with signal routing
 - Effectively improves timing resolution for a given clock speed

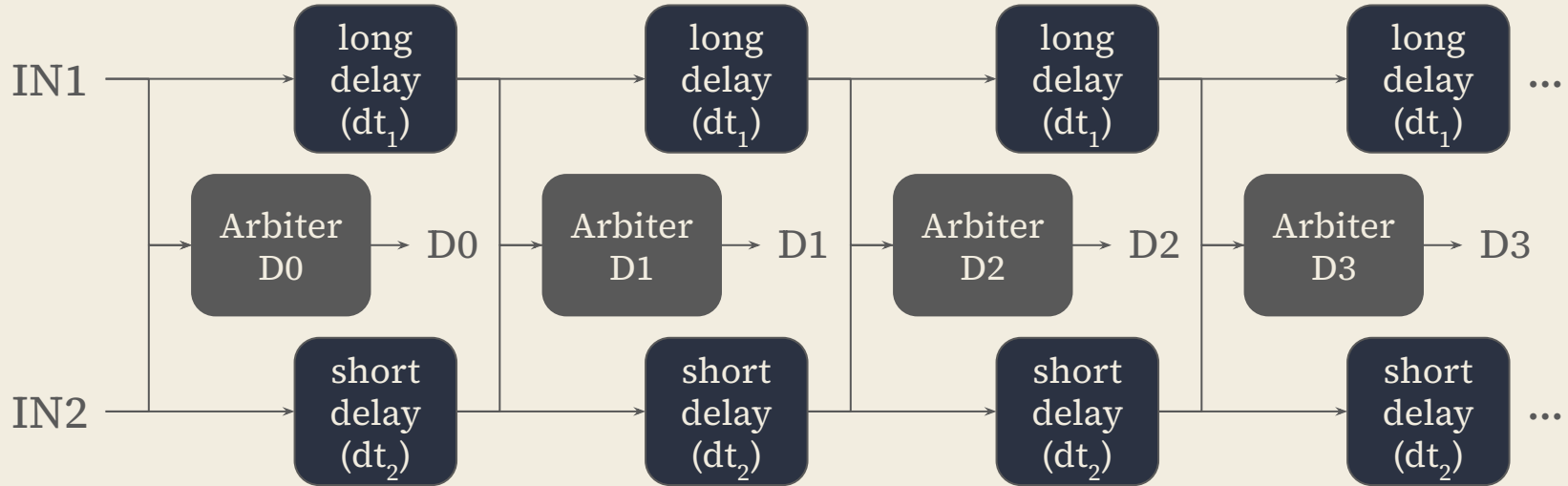


4 tap delay line (d0-d3), $dt = 1/(4 \cdot f)$ (where f is sampling frequency)

Time-to-Digital Conversion Techniques

- Vernier delay line

- Uses two separate delay lines and arbiters to measure time difference
- See when in the chain IN2 catches up with IN1



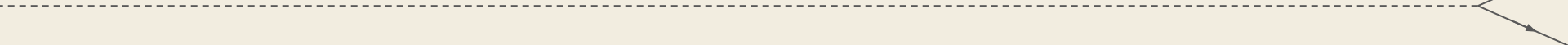
Current Best Timing Resolution

- Low-Gain Avalanche Detector (LGAD): ~20ps
- Large Area Picosecond Photodetectors (LAPPD): ~50ps
- Silicon: ~30ps
- Superconducting Nanowire Single-Photon Detectors (SNSPD): <10ps

→ Digitization is not necessarily the bottleneck!

- ◆ CERN claims ~3ps for PicoTDC custom ASIC ([DOI:10.1088/1748-0221/18/07/P07012](https://doi.org/10.1088/1748-0221/18/07/P07012))
- ◆ Unfortunately, SNSPDs are expensive!

Discriminating Pions and Kaons



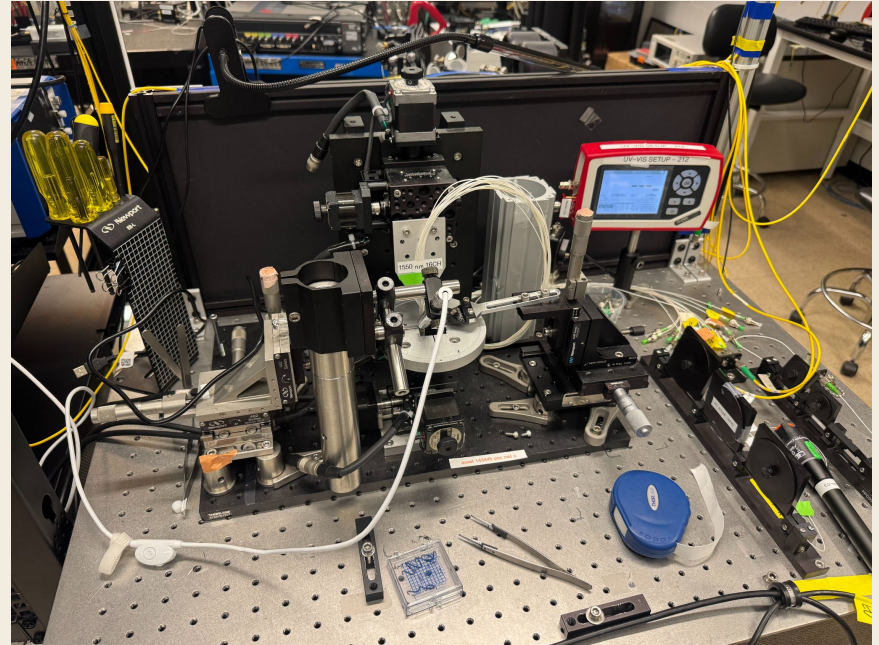
dt	$L = 1\text{m}$	$L = 2\text{m}$
50 ps ($\approx$ LAPPD)	1.6 GeV	2.2 GeV
20 ps ($\approx$ LGAD)	2.5 GeV	3.5 GeV
10 ps ($\approx$ SNSPD)	3.5 GeV	5.0 GeV
5 ps	5.0 GeV	7.1 GeV
1 ps	11 GeV	16 GeV

Max momentum for 3σ confidence time-of-flight Kaon-Pion discrimination at a given timing resolution dt and flight length L

Using **photonics**, we can
process data BEFORE the
frontend electronics

What is Photonics?

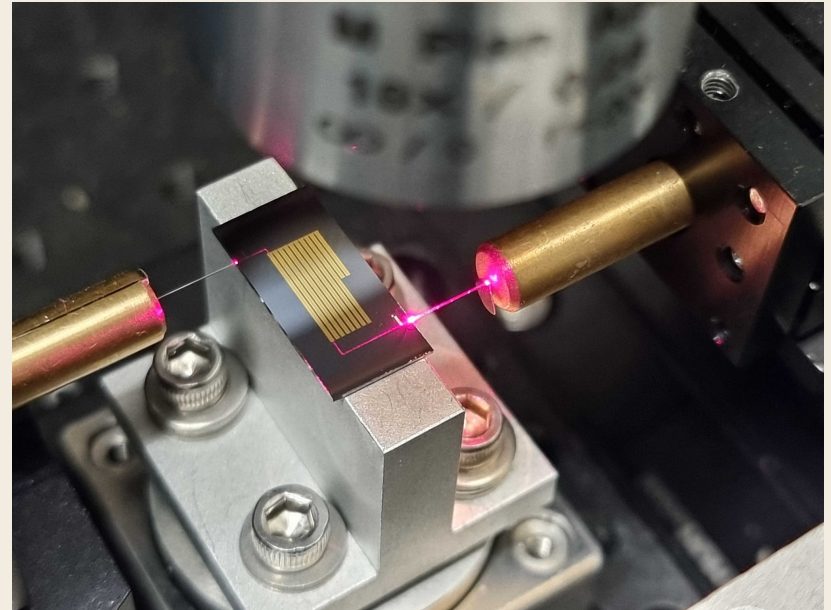
- The careful manipulation of light to carry information or perform a useful task or computation
 - “Electronics” with photons instead of electrons
- Light is confined to a high-index of refraction (n) waveguide core by total internal reflection (TIR)
- No electromagnetic interference or coupling
- Decades of development motivated by telecom applications



Typical photonics lab bench setup (G. Kopp)

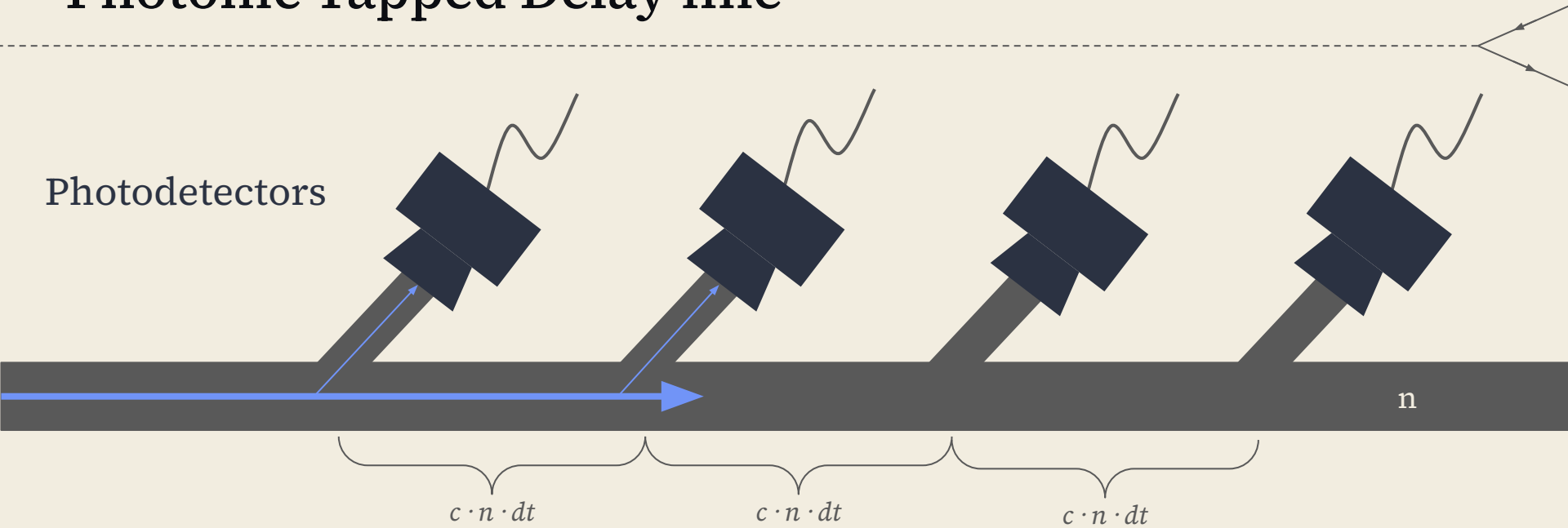
Photonic Integrated Circuits

- Waveguides are etched on a carrier chip using lithography
 - Much like custom integrated circuits
- Allow for precise, repeatable manufacturing of resonators, interferometers, and other photonic elements



A PIC being tested (courtesy K. Powell)

Photonic Tapped Delay line



Where Photonics Wins



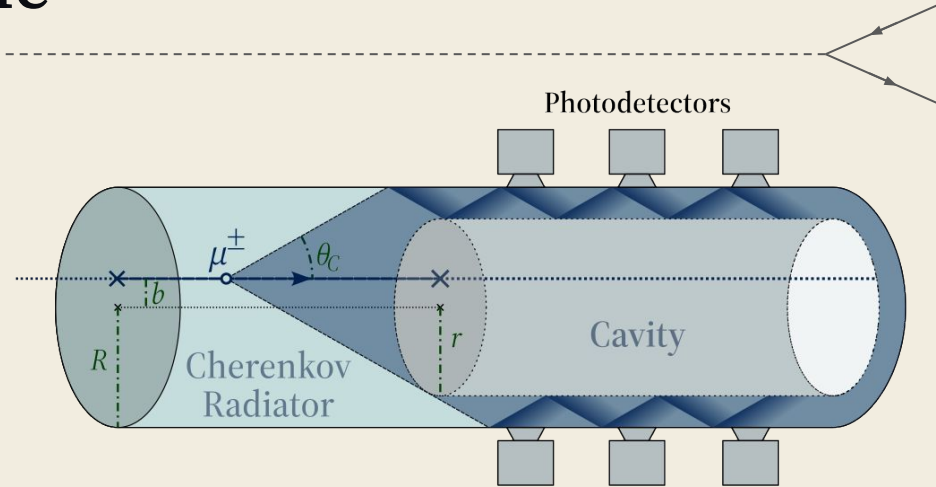
- Precision delays are free, since distance $\leftrightarrow$ time
- Reduced susceptibility to external noise
- Reduced frontend electronic heat load

But most importantly...

- Photodetector jitter no longer is the limiting constraint!
 - Time digitization is done *before* photon detection

Proposed Operation Principle

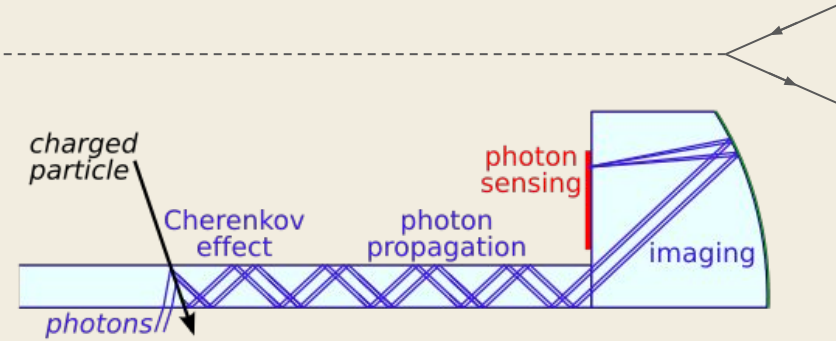
- Incoming charged particle radiates in a volume of Lithium Niobate ($n \sim 2.2$)
- The particle exits the radiator into a hollow cavity inside the outer shell of thickness $(R-r)$
 - Periodic photodetectors are the “taps” in a tapped delay line



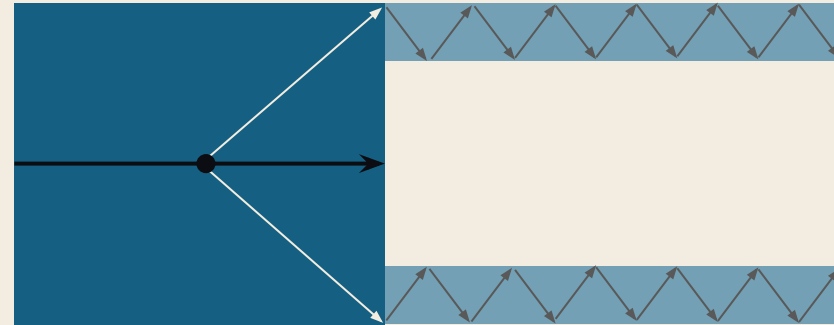
Impact parameter b
Cherenkov angle θ_c
Radiator diameter R
Shell thickness $R-r$

Proposed Operation Principle

- Works similarly to ring imaging Cherenkov (RICH) detectors
- Effectively is an inverted Detection of Internally Reflected Cherenkov (DIRC) detector
 - Utilizes large radiating volume and guides light along small waveguides



DIRC Scheme - Klaus Foehl, CC BY-SA 3.0, [Wikimedia Commons](https://commons.wikimedia.org/wiki/File:DIRC_Scheme.png)

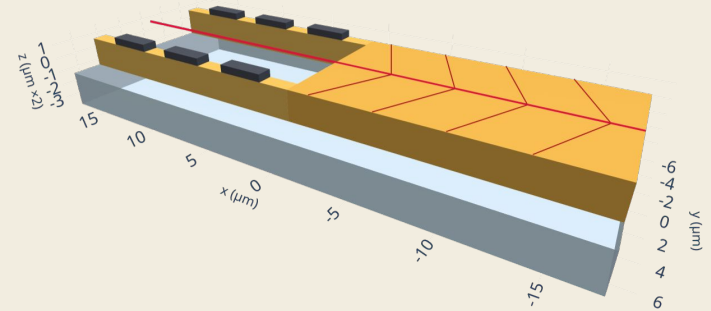


A cross section of the PhotoTDC design

Integrated Photonics Version

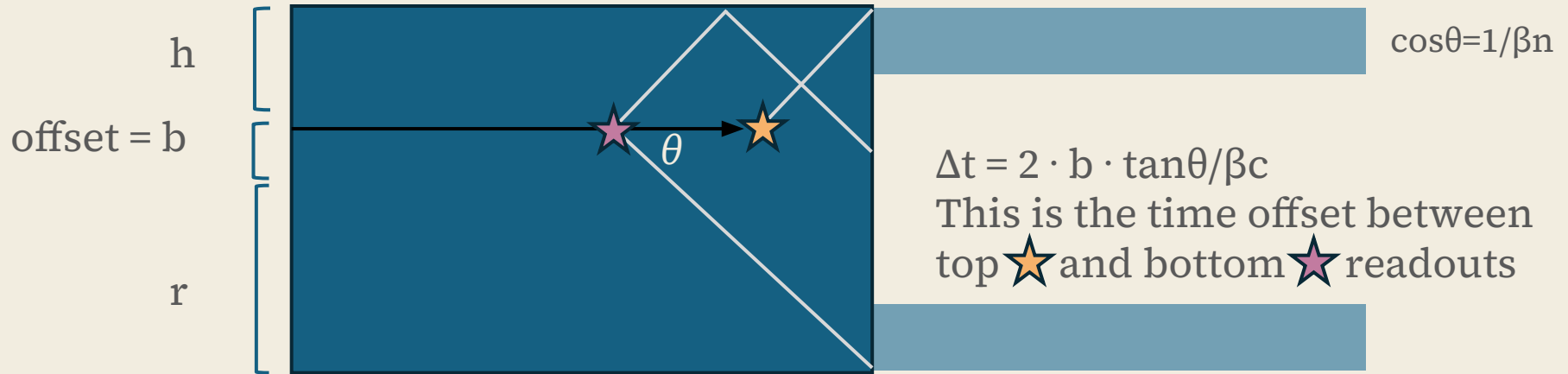
- Operates like a cross section of the cylindrical detector
- Incoming particles aligned along plane to maximize captured light
- Lower acceptance but better capture and easier to manufacture

- SiO₂ substrate
- edge waveguide = delay line
- radiating rectangle (LiNbO₃)
- detector tap
- muon track
- Cherenkov plane waves at 63°



Maximizing Geometry Information

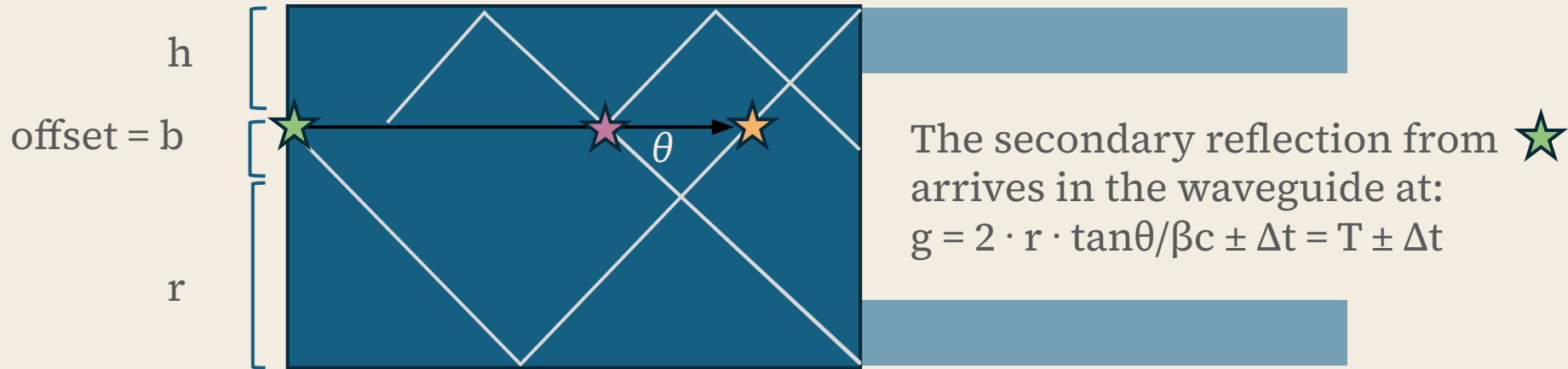
- The high time resolution can also be used to compute particle velocity and a precise position measurement



If the Cherenkov angle is known, the offset can be computed

Maximizing Geometry Information

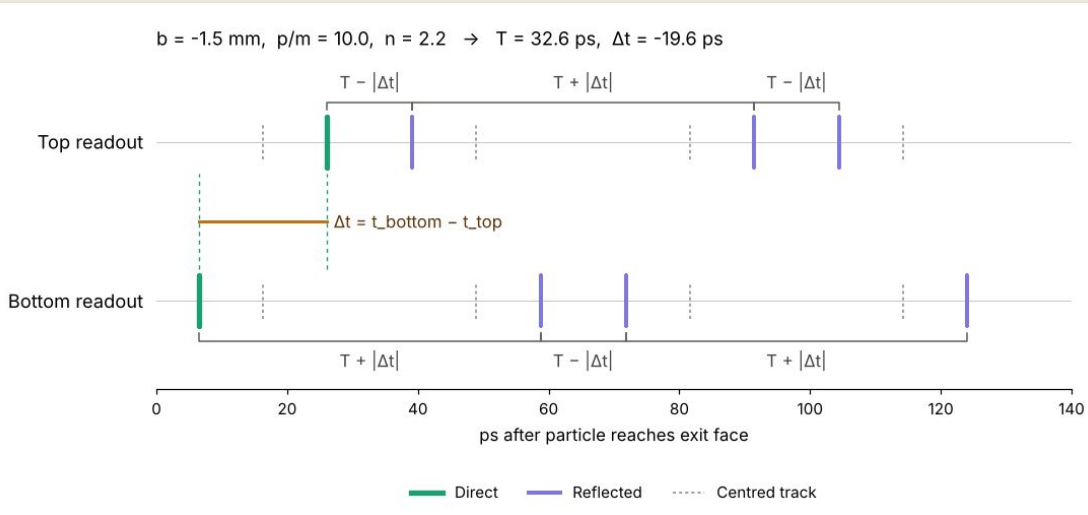
- The high time resolution can also be used to compute particle velocity and a precise position measurement



Both the angle and offset can be measured now!

Maximizing Geometry Information

- Pulses are expected at: $T \pm \Delta t$
- From T (average time between pulses in a waveguide), θ (and thus v) can be measured, while from the spacing Δt , the offset can be measured.



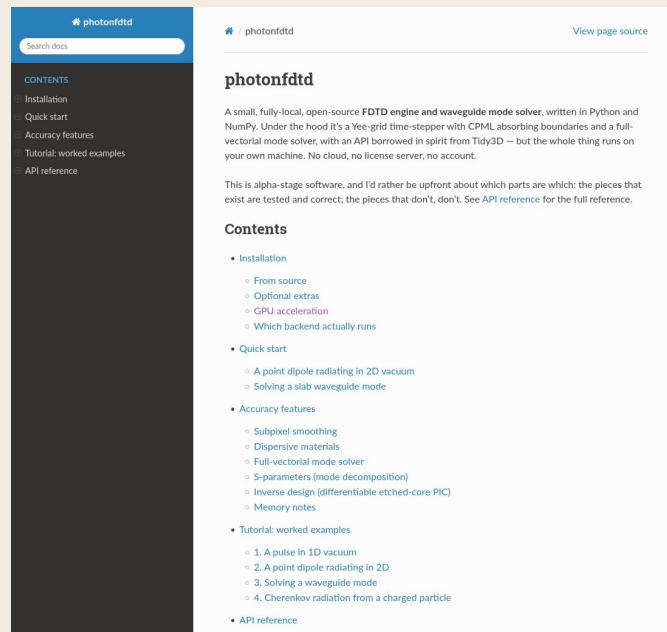
Material	n (index of refraction)	Cherenkov angle (θ)	Δt per mm of offset
SiO ₂ (glass)	1.5	48	7.5 ps / mm
LN	2.2	63	13.1 ps / mm

Position resolution of about 0.3-0.5 mm assuming a timing resolution of 3 ps

Simulations

PhotonFDTD

- PhotonFDTD is a JAX-accelerated finite difference time domain (FDTD) mode solver designed to better describe particle sources of electromagnetic radiation (like Cherenkov radiation)
 - Standard way of simulating propagation
- Faster than existing open source solutions, and accurate against them



photonfddd

A small, fully-local, open-source FDTD engine and waveguide mode solver, written in Python and NumPy. Under the hood it's a Yee-grid time-stepper with CPML absorbing boundaries and a full-vectorial mode solver, with an API borrowed in spirit from Tidy3D — but the whole thing runs on your own machine. No cloud, no license server, no account.

This is alpha-stage software, and I'd rather be upfront about which parts are which: the pieces that exist are tested and correct; the pieces that don't, don't. See [API reference](#) for the full reference.

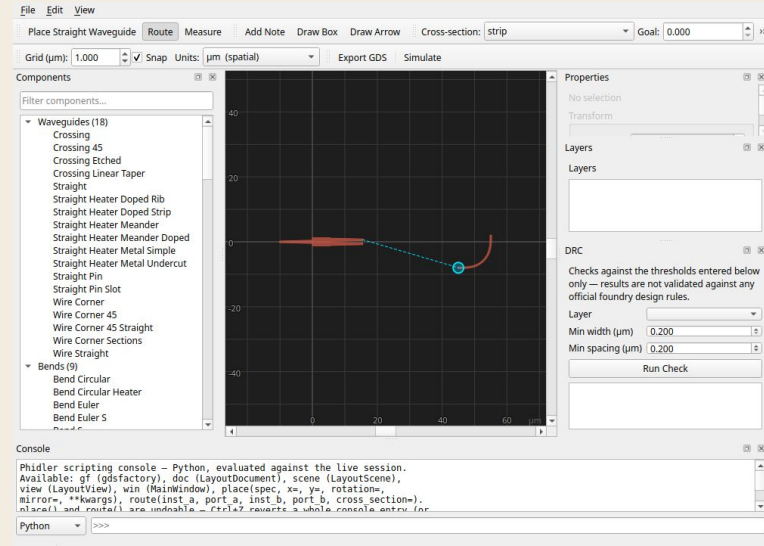
Contents

- Installation
 - From source
 - Optional extras
 - GPU acceleration
 - Which backend actually runs
- Quick start
 - A point dipole radiating in 2D vacuum
 - Solving a slab waveguide mode
- Accuracy features
 - Subpixel smoothing
 - Dispersive materials
 - Full-vectorial mode solver
 - S-parameters (mode decomposition)
 - Inverse design (differentiable etched-core PIC)
 - Memory notes
- Tutorial: worked examples
 - 1. A pulse in 1D vacuum
 - 2. A point dipole radiating in 2D
 - 3. Solving a waveguide mode
 - 4. Cherenkov radiation from a charged particle
- API reference

<https://www.noahpaladino.com/photonfddd/>

Phidler

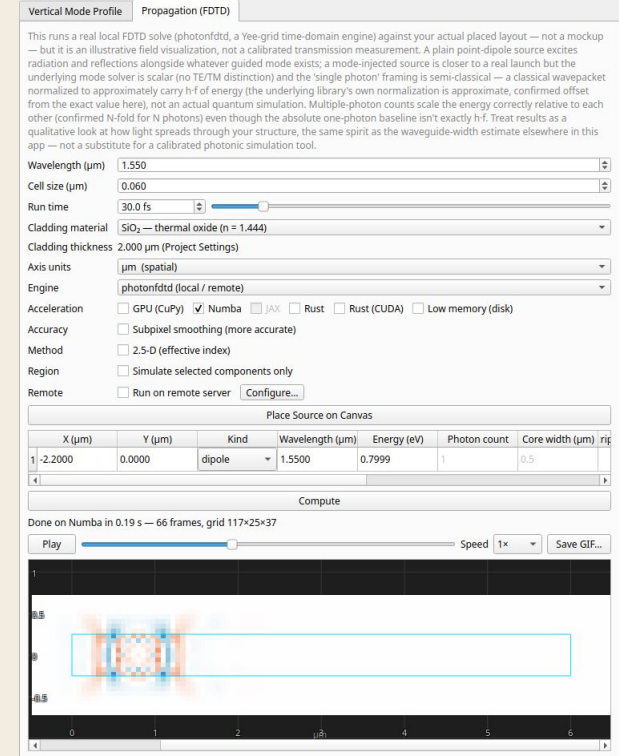
- Phidler is a CAD program for photonics chip design, taking inspiration from electronics and 3D CAD software
- Based on existing GDSFactory python library under the hood
 - Allows for python scripting and Claude code integrations
 - Ultimately generates a python script that builds the final layout file
- Integrated PhotonFDTD simulations
- Greatly accelerates time-to-design for non-photonics experts



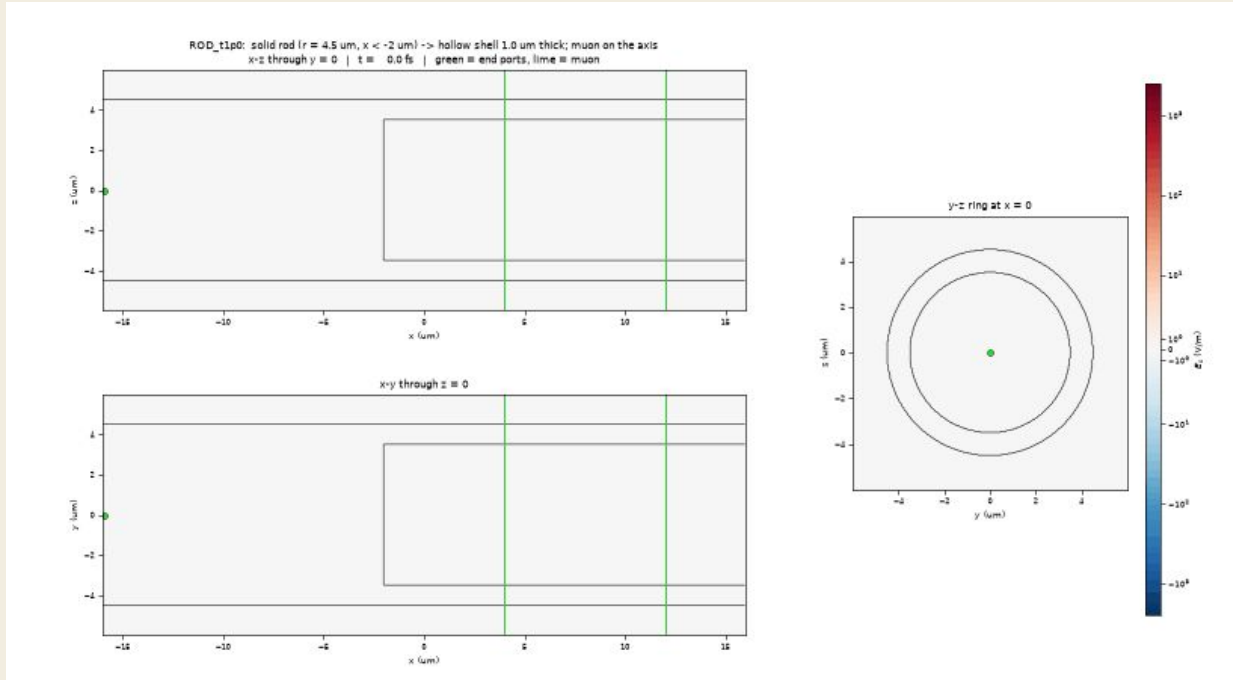
<https://www.noahpaladino.com/phidler/>

Limitations

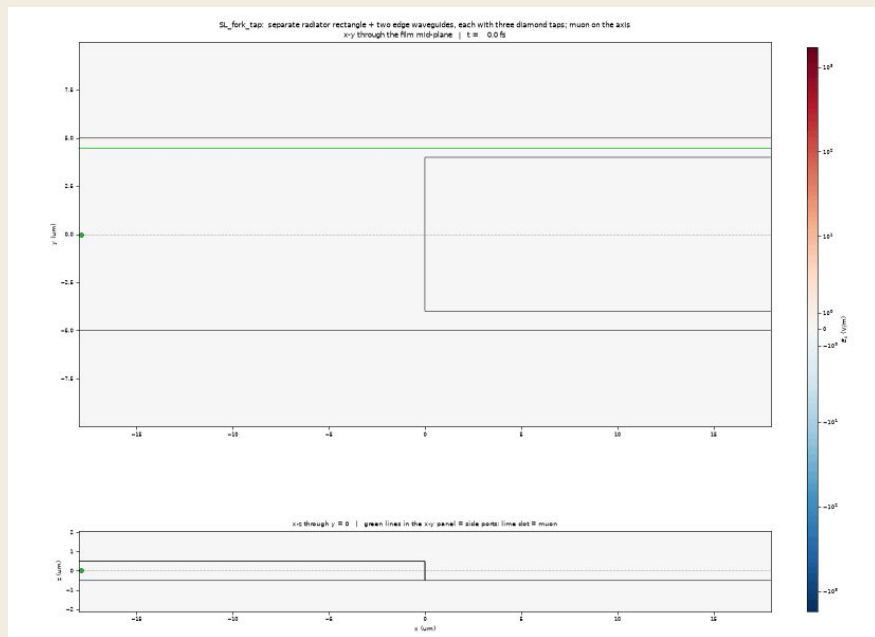
- For macro-scale simulations (as in the Cherenkov radiation capture) we need to resort to ray-tracing due to memory constraints and the massive simulation volume
 - Hopefully will be less constrained as high-memory GPUs and shared memory tools become more common due to LLMs
- No funding to check against commercially available solutions like Tidy3D



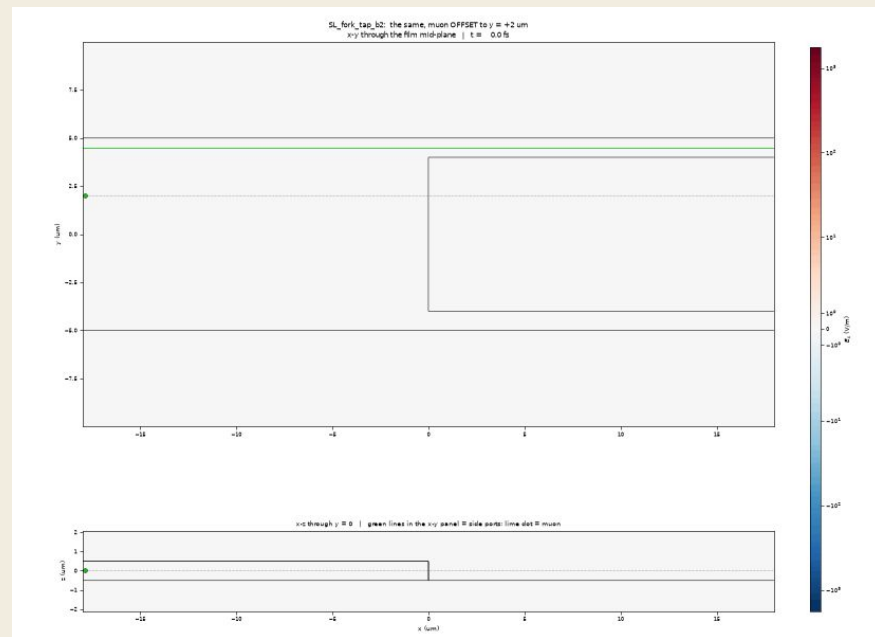
Simulation Results - Cylindrical Geometry



Simulation Results - Planar Geometry



The planar geometry with **on-axis** muon



The planar geometry with **off-axis** muon

Next Steps

Next Steps

- Fine tuning the geometry parameters
 - Radiator length, waveguide width, height
- Full integrated simulation chain with GEANT
- Constructing a prototype at Harvard's Center for Nanoscale Systems

Summary

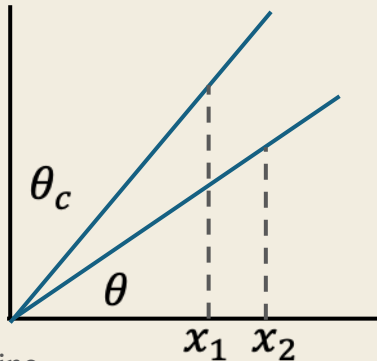
- Timing detectors stand to see significant benefit from applying photonic techniques
 - Cherenkov light can be generated and captured in PICs
 - New tools like PhotonFDTD and Phidler help make PIC design more accessible to particle physicists
- It's an excellent time to be exploring photonics for new detectors!

Backup

Total Internal Reflection from Cherenkov Light

If θ_i is greater than some θ_c , then there will be total internal reflection. For this to result from the Cherenkov radiation, this means that: $\theta + \theta_i = \pi/2$ and thus $\theta + \theta_c \leq \pi/2$.

This sets the condition that the Cherenkov light will have total internal reflection as long as it will not Cherenkov radiate in the external (n_2) material.



$$\sin \theta_c \leq \cos \theta$$

$$\frac{n_2}{n_1} \leq \frac{1}{n_1 \beta} \quad \rightarrow \quad \beta n_2 \leq 1$$