

Sub-mm tracking in tonne-scale detectors using SPAD arrays

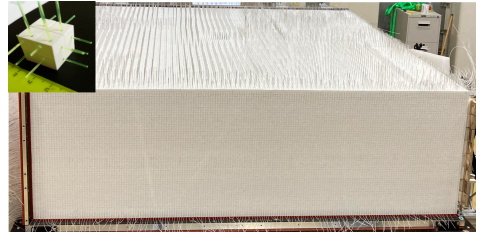
International Conference on Position Sensitive Detectors 2026

Till Dieminger

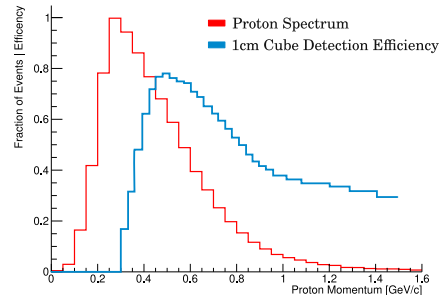
ETH Zürich
tilld@phys.ethz.ch

Long Baseline Neutrino Oscillation Experiments (LBL)

- LBL experiments determine neutrino oscillation parameters
 - High-resolution tracking required around the neutrino vertex at the Near Detector (ND)
- Current: SFGD at the T2K ND
 - $\sim 2\,000\,000$ 1 cm^3 plastic scintillator cubes (~ 2 tonnes)
 - 3 wavelength-shifting fibres/cube read by SiPMs $\rightarrow \sim 56\,000$ channels
- Segmentation sets the 3D tracking resolution
 - Proton momentum threshold $\sim 350\text{ MeV}/c$ ($\rightarrow 3\text{ cm track}$)
 - Goal: track protons down to $< 200\text{ MeV}/c$ ($T_{\text{kin}} \sim 20\text{ MeV} \rightarrow \sim 4\text{ mm}$) for ND280++

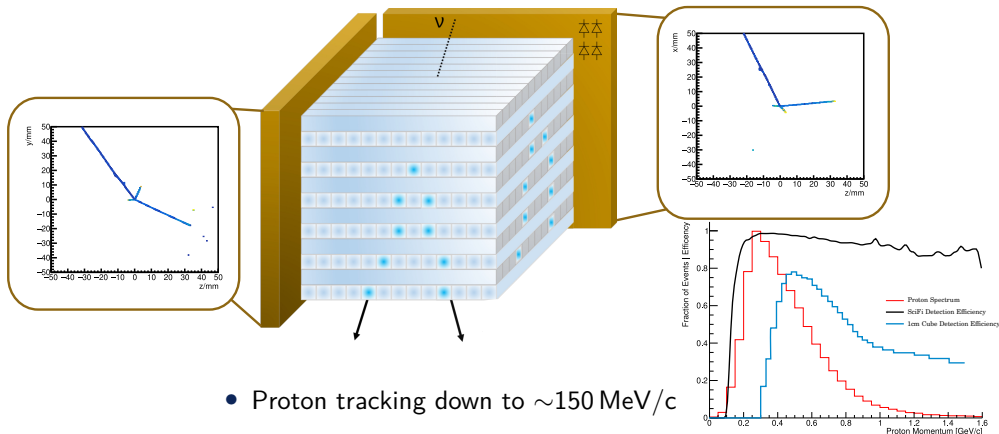


SFGD of the T2K ND, Sgalaberna, CERN Det. Seminar



Solution #1: Imaging of Scintillating Fibres

- 3D tracking with XY SciFi layers
 - # fibres $\sim$ # SiPMs
 - 1-tonne detector: $\sim 10\text{M}$ SiPMs
 - Instrumentation with SiPMs infeasible
- ⇒
- Replace SiPM readout with SPAD array
 - All electronics on chip
 - Binary signal per $\text{O}(\mu\text{m})$ pixel
 - Single array covers a few hundred fibres



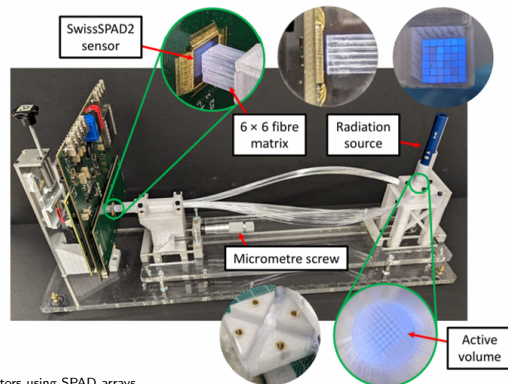
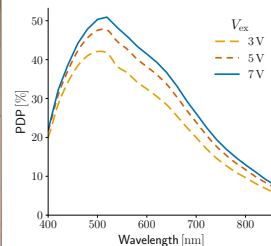
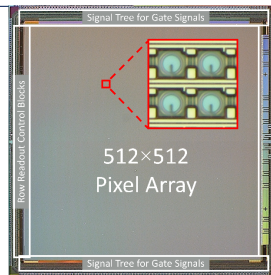
- Proton tracking down to $\sim 150 \text{ MeV}/c$

- SwissSPAD2 imager (AQUA, EPFL)
 - 512×512 independently read-out Single Photon Avalanche Diode (SPAD) pixels
 - Binary single-photon frames, ns-gated

SwissSPAD2 specifications

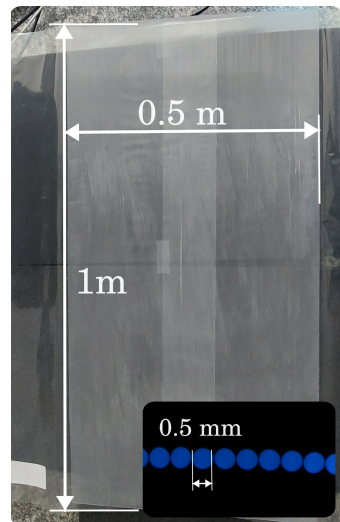
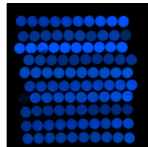
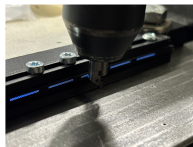
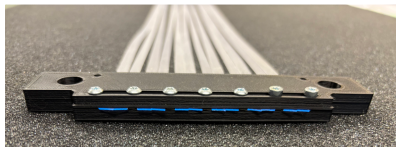
Sensor size	512×512 pixel
Pixel pitch	16.38 μm
Photon Detection Efficiency (PDE)	$\sim 5\%$
Dark Count Rate (DCR)	0.26 cps/ μm^2
Timing	10 ns – 10 μs gated

- Proof of principle: 3D-SciFi tracker built from individual fibres
 - 6×6 matrix of 1 mm square fibres
 - Demonstrated 3D tracking of ^{90}Sr electrons



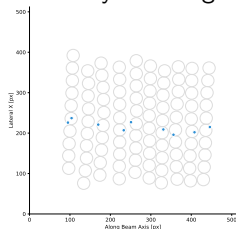
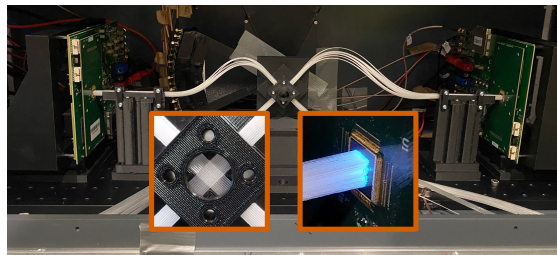
Scintillating Fibre Mats

- Aim for $2 \times 2 \text{ m}^2$ XY layers
 - Luxium offers pre-assembled fibre mats (up to $3 \text{ m} \times 0.5 \text{ m}$, $\varnothing 500 \mu\text{m}$)
- Received 6 mats of $1 \times 0.5 \text{ m}^2$
 - Stable and easy to handle
 - Promising for assembly into XY layers
 - Measured attenuation length ($\lambda_1 \sim 10 \text{ cm}$, $\lambda_2 \sim 3 \text{ m}$)
 - Measured light yield $\sim 8000 \gamma/\text{MeV}$
- Fibre mats cleanly polished with a diamond cutter

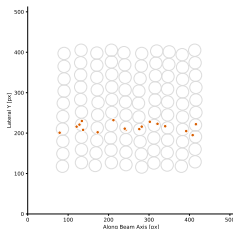


XYFi Prototype Using Fibre Mats¹

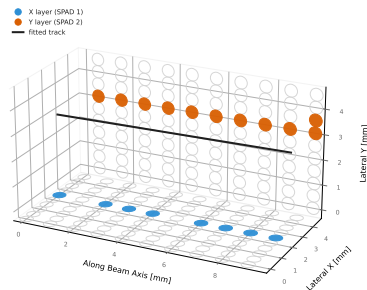
- Joined the DRD4 beam test at CERN
 - Dual-sided readout using two time-synchronised SwissSPAD2 imagers
 - 5 mm fibre bundles (10 $\varnothing$ 500 μ m fibres each, 200 fibres in total)
 - $5 \times 5 \times 10 \text{ mm}^3$ active tracker volume
 - 120 GeV/c π beam at the H6 beamline of the SPS
- Data analysis is ongoing



X-Projection



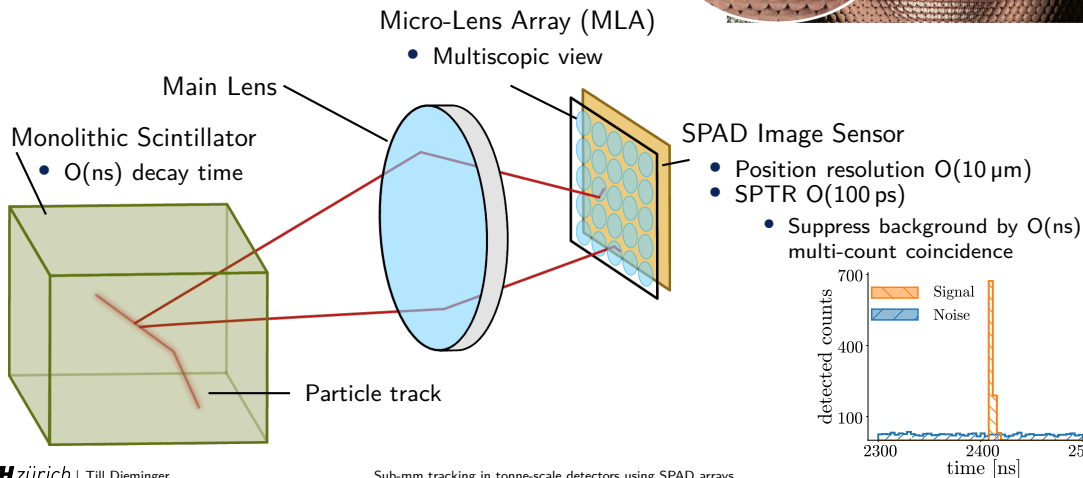
Y-Projection



¹Work with Lukas Lazek (ETHZ) and Dr. Paul Moş (AQUA, EPFL)

Solution #2: The PLATON Concept

- Take nanosecond-resolved 3D images of particles for sub-mm resolution in an unsegmented $O(1\text{ t})$ scintillator

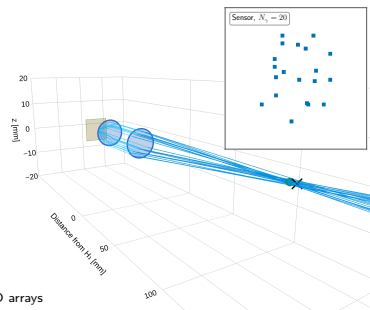
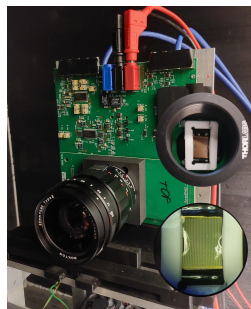


- First SPAD-based plenoptic camera
 - Using SwissSPAD2 from AQUA (EPFL)
 - MLA designed and mounted by Raytrix GmbH

Optics specifications

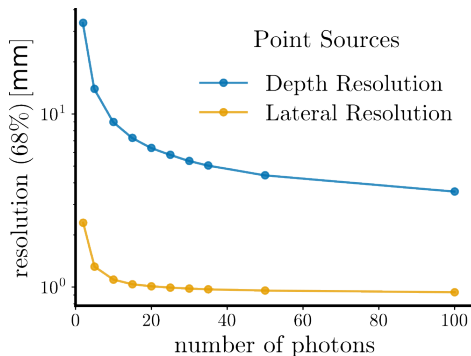
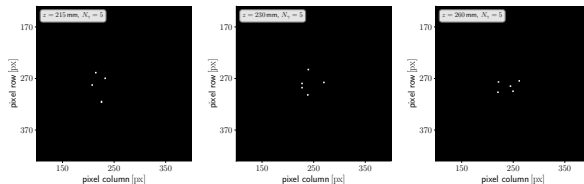
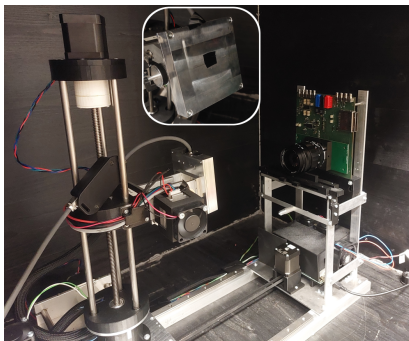
Lens	Nokton II 25 mm
$f/\#$	~ 2.4
Lateral Resolution	~ 1 mm
Depth Resolution	~ 5 mm
Depth of Field	~ 15 cm

- Developed a novel reconstruction method based on single-photon ray tracing
 - Reconstruct the path of each individual photon
 - Purely geometric, no dense image needed
 - Works with very few photons



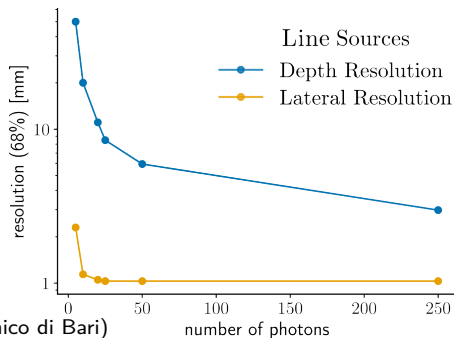
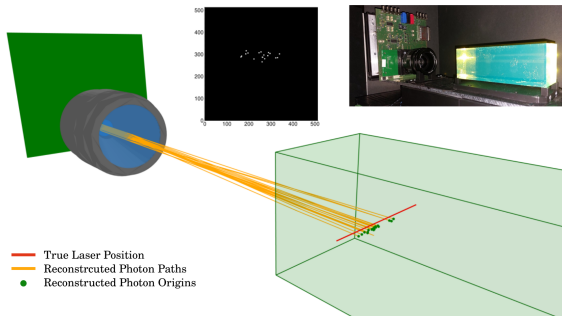
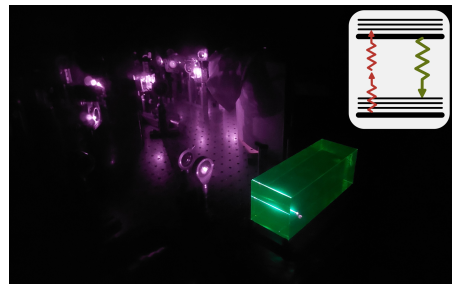
Swiss-PLATON Prototype: Point-Source Reconstruction

- 50 μm pinhole scanned on a 3-axis stage
- Point sources reconstructed with few-photon images
- Measured resolution reproduced with a custom optical simulation
 - Lateral resolution $\sim 1\text{ mm}$
 - Depth resolution $\sim 5\text{ mm}$



Swiss-PLATON Prototype: Two-Photon Absorption

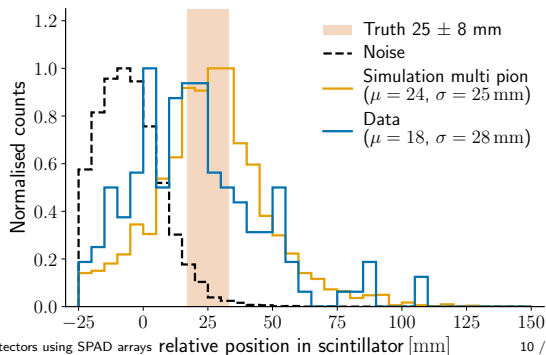
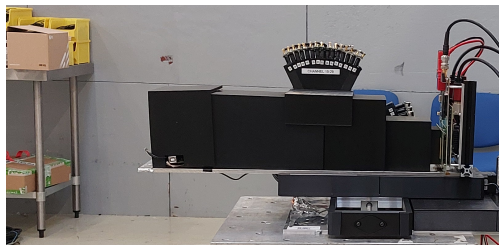
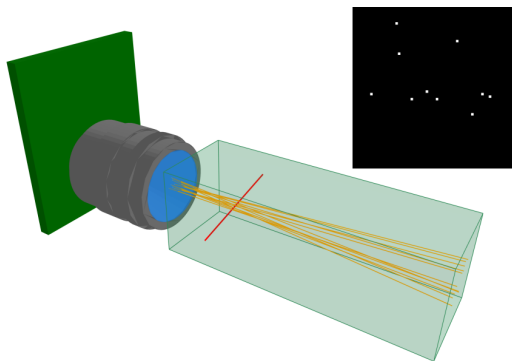
- Fake particle tracks using two-photon absorption¹
 - Scintillator absorbs two laser photons and emits a single scintillation photon
 - Measured laser tracks at different depths
- Resolution achieved over a 10 cm depth of field, in agreement with simulations
 - Shows the feasibility of the concept and of the reconstruction method

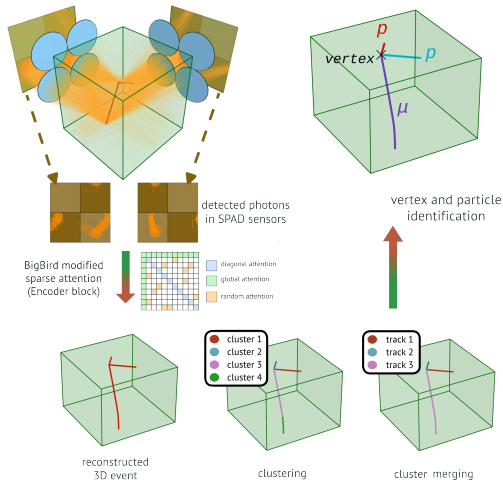


¹Work with Prof. Barbieri (U. Roma Tre) and Prof. Berardi (Politecnico di Bari)

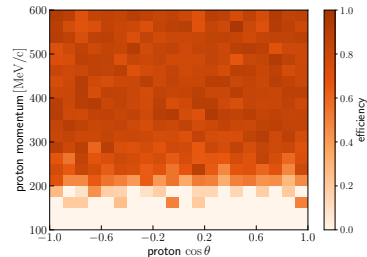
Swiss-PLATON Prototype: Pion Beam Test

- Pion beam test at CERN (PS, T9)
- Successful reconstruction of the beam depth inside the scintillator
- Reconstruction in good agreement with the simulation





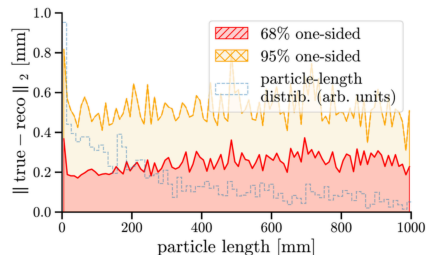
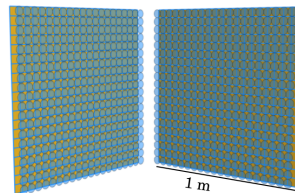
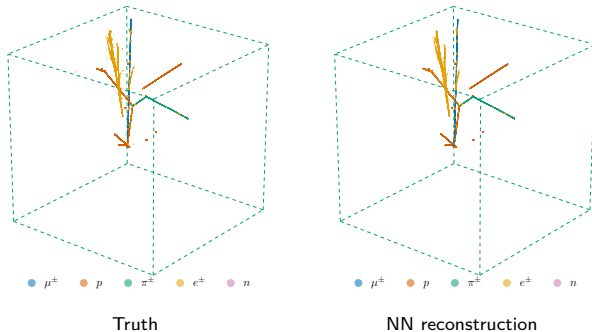
- Using optical simulations of GeV-neutrino interactions in a $(10, \text{cm})^3$ plastic scintillator
 - Using SPAD array with 24% PDE
- 3D reconstruction using a Transformer¹
 - Captures correlations between pixels in the same event $\rightarrow$ 200 μm 3D resolution
- Particle clustering using Gaussian Mixture Models
 - Proton tracking down to $\sim 200 \text{ MeV}/c$ in multi-particle events
 - 4π coverage: no proton angle dependence



¹Developed by Dr. Saul Alonso-Monsalve (ETHZ)

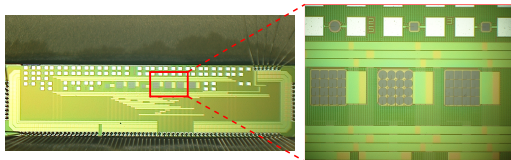
Design of a 1-Tonne PLATON Detector¹

- Optimised optical design for a 1 m depth-of-field plenoptic camera for particle detection
- Point-source 3D resolution of 0.36 mm at 10 000 emitted photons
- Neural network achieves $\approx 200 \mu\text{m}$ resolution



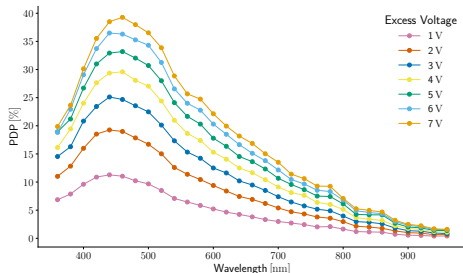
¹Work with Levin Martschke (ETHZ)

- Custom time-resolved SPAD array, with a 16-pixel cluster TDC sharing architecture
 - Single-pixel resolution, two 200 ps timestamps
 - Characterised in a previous tapeout
 - DCR ~ 0.5 cps/ μm^2 at 7 V
- Full 9×9 mm² sensor received from the foundry
 - Validation & characterisation ongoing
- Multi-chip readout: synchronous operation via a single FPGA



9×9 mm² sensor specifications

Sensor size	192 $\times$ 160 pixel
Pixel pitch / diameter	37 μm / 21 μm
PDE	~ 10 %
DCR	~ 0.5 cps/ μm^2
Timing	200 ps single-photon timestamp



¹Work by Kodai Kaneyasu (EPFL, Prof. Charbon's group)

Conclusion

- Goal: push the spatial-resolution limits of tonne-scale neutrino detectors for future experiments

Scintillating Fibres with SPADs EPJC (2024) 84:202

- Demonstrated the potential of SPAD arrays as a compact readout system
- Single fibre mats of $O(m^2)$ from Luxium allow efficient construction

PLATON Concept Nat. Com. 17, 4204 (2026)

- Demonstrated 3D imaging of scintillation with a good understanding of the optical system
- Achieved sub-mm resolution in simulation of a 1-tonne detector

PLATON SPAD arXiv:2511.16684

- Selected the pixel structure and the cluster layout
- $9 \times 9 \text{ mm}^2$ SPAD array in the validation and testing phase

Project in Sgalaberna's group (ETH Zürich) in collaboration with Prof. Charbon's group (EPFL). Funded by the Swiss National Science Foundation.