ETH zürich

Swiss National
Science Foundation

New developments in scintillator-based near detectors for the Hyper-K program

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LPNHE CNRS - Paris

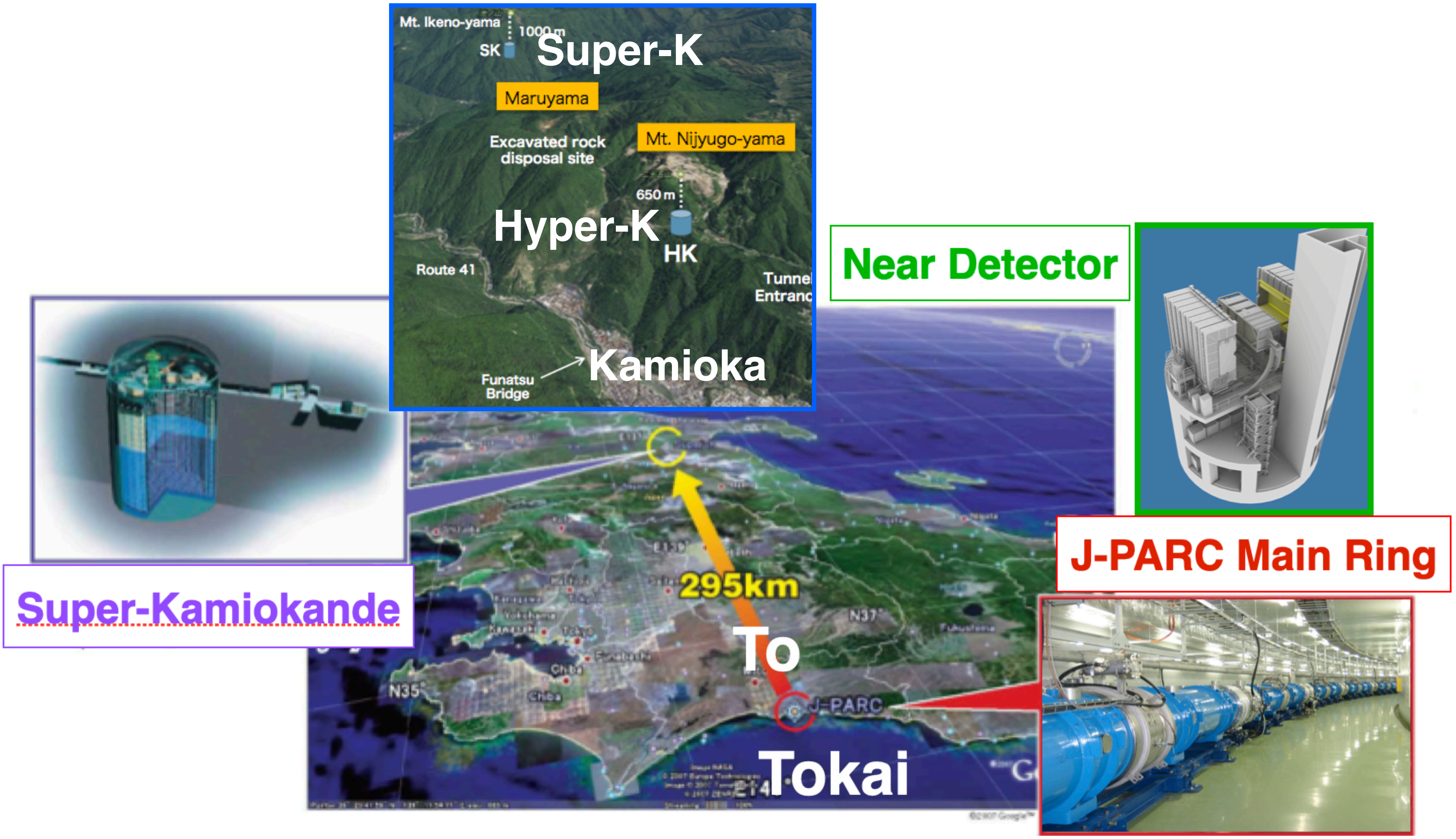
3rd April 2023

Long-Baseline Neutrino Oscillation experiments in Japan: T2K and Hyper-K

Intense ν_μ / $\bar{\nu}_\mu$ beam from J-PARC to a Near and a Far Detector

- ν_μ and $\bar{\nu}_\mu$ disappearance ⇒ P($\nu_\mu \rightarrow \nu_x$) and P($\bar{\nu}_\mu \rightarrow \bar{\nu}_x$)
- ν_e and $\bar{\nu}_e$ appearance ⇒ P($\nu_\mu \rightarrow \nu_e$) and P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

$\nu_x = \nu_e, \nu_\tau$

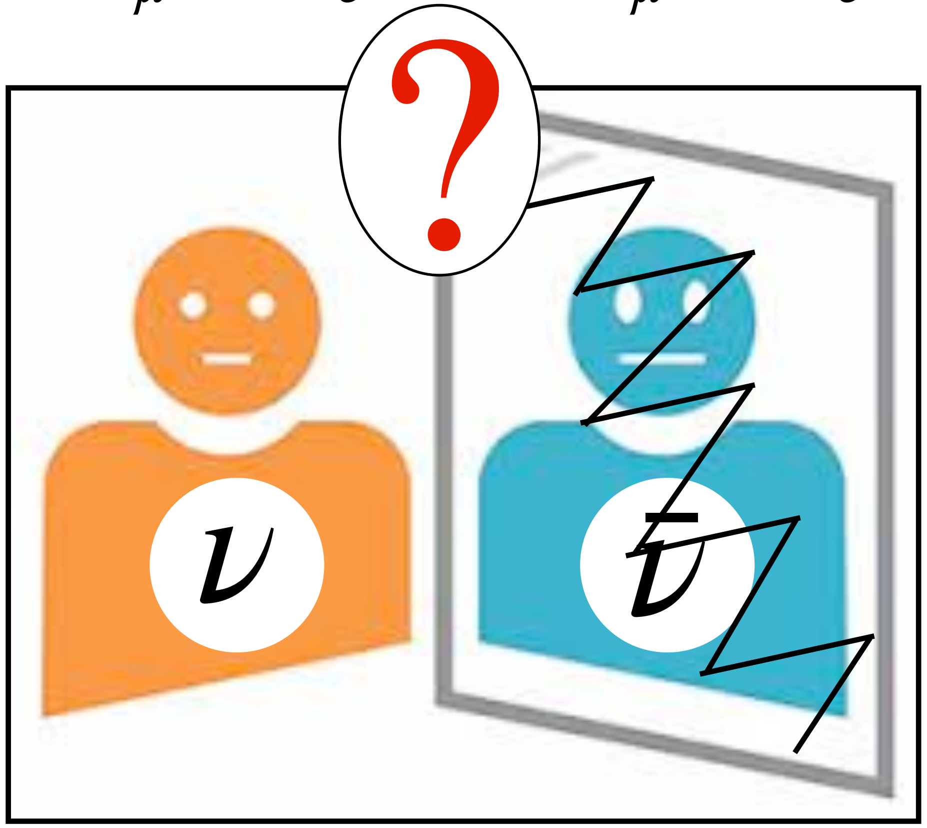


Super-Kamiokande

Near Detector

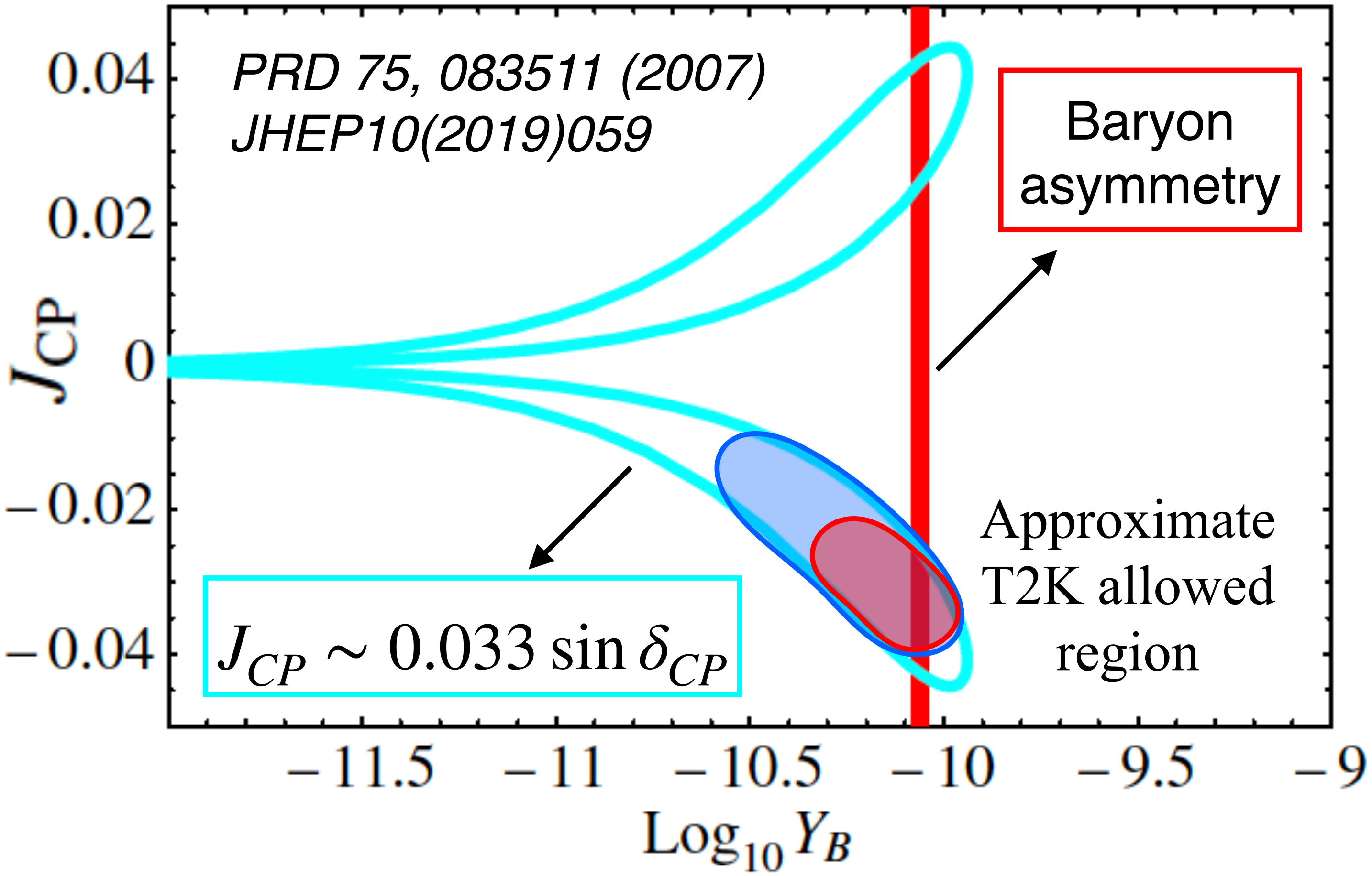
J-PARC Main Ring

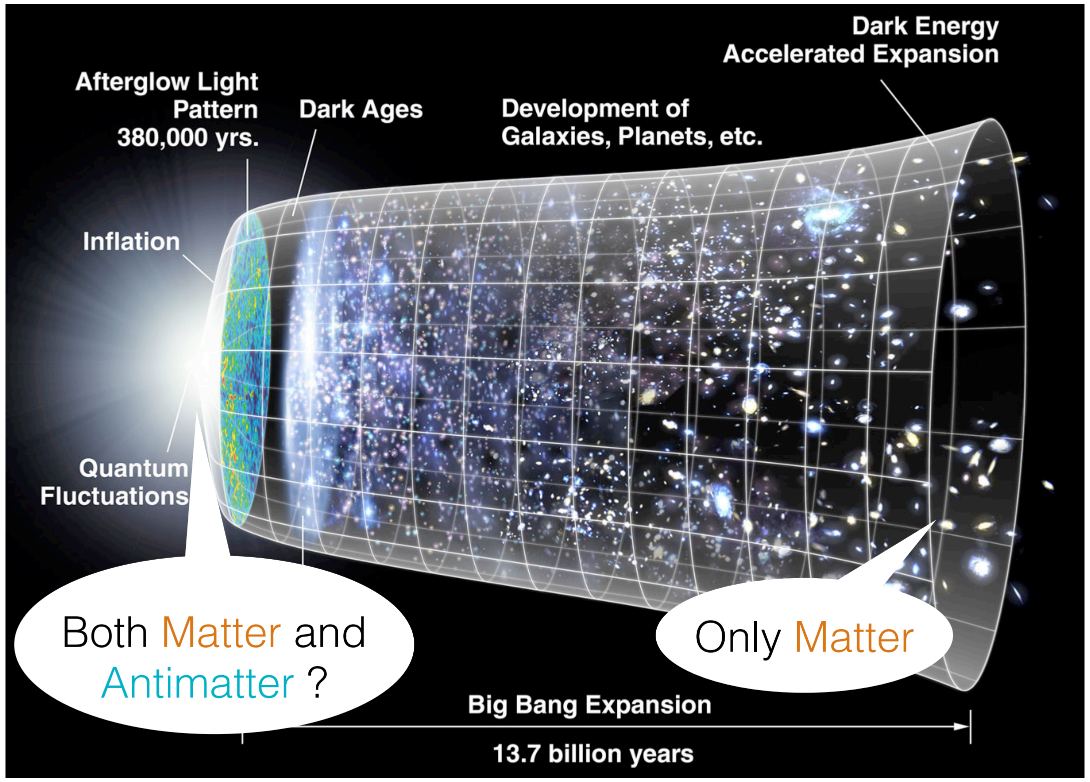
P($\nu_\mu \rightarrow \nu_e$) ≠ P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)



CP Violation and the Matter-Antimatter imbalance in the Universe

- Large matter-antimatter imbalance
- Need a mechanism to change the physics of matter and antimatter ⇒ CP violation





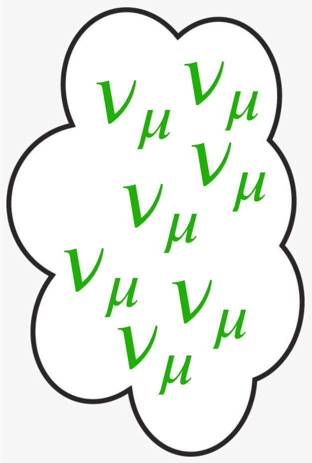
Too small CP asymmetry in Quarks

Possible that a not-small fraction of the matter-antimatter imbalance was generated starting from leptons (Leptogenesis)

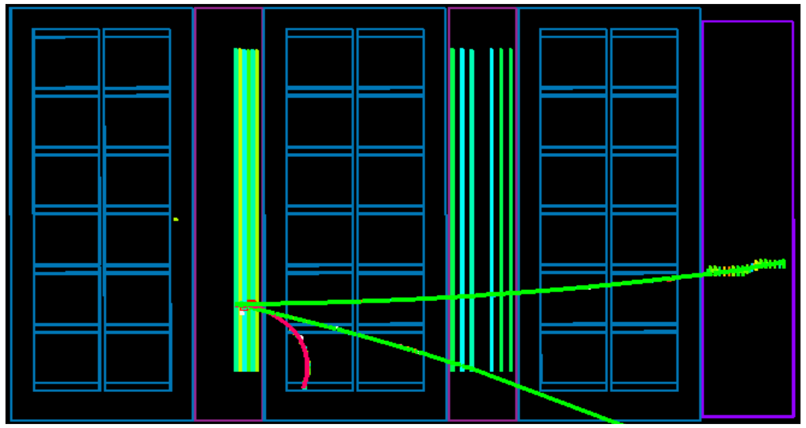
It is important to precisely measure δ_{CP} in neutrino oscillations

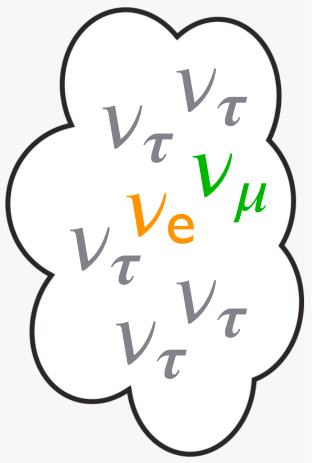
The T2K/HK neutrino oscillation experiment

Proton Accelerator

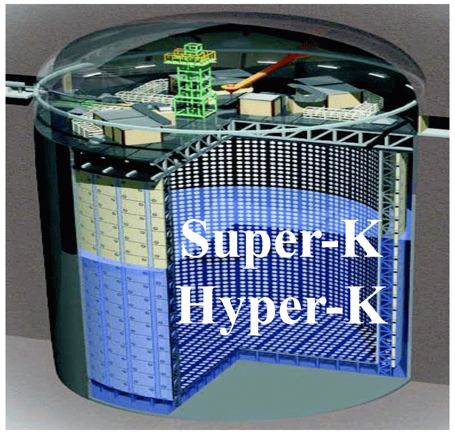


Near Detector

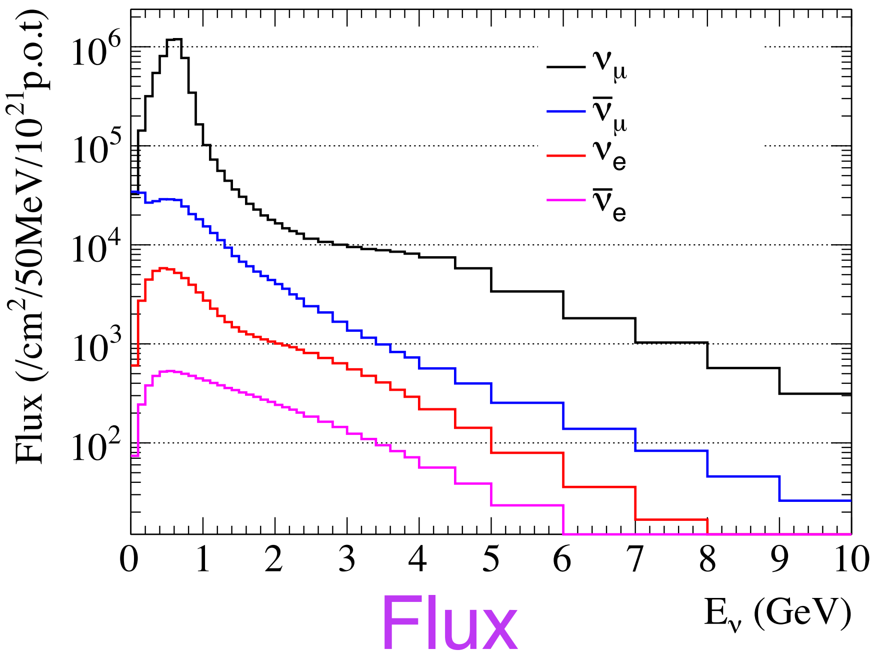




Far Detector

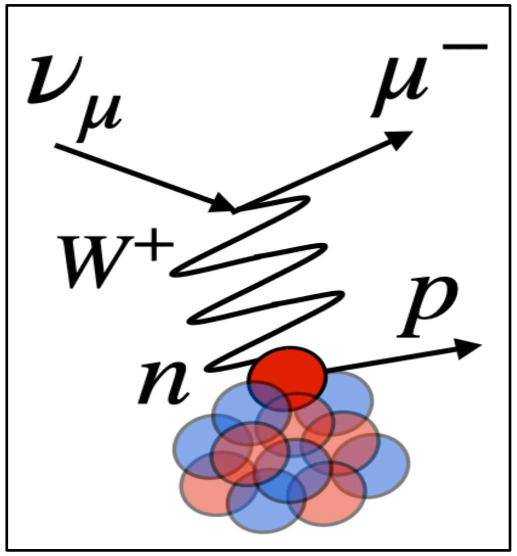


0 km — 0.28 km - - - - 295 km →



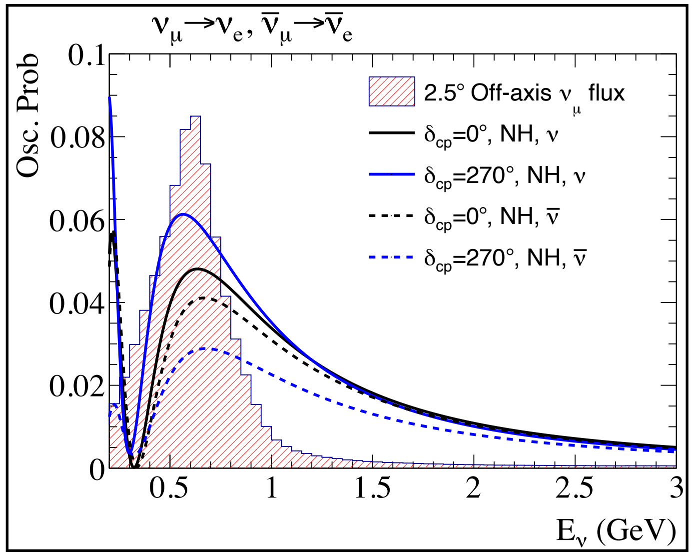
Flux

⊗



Interaction with Matter

⊗



Oscillations

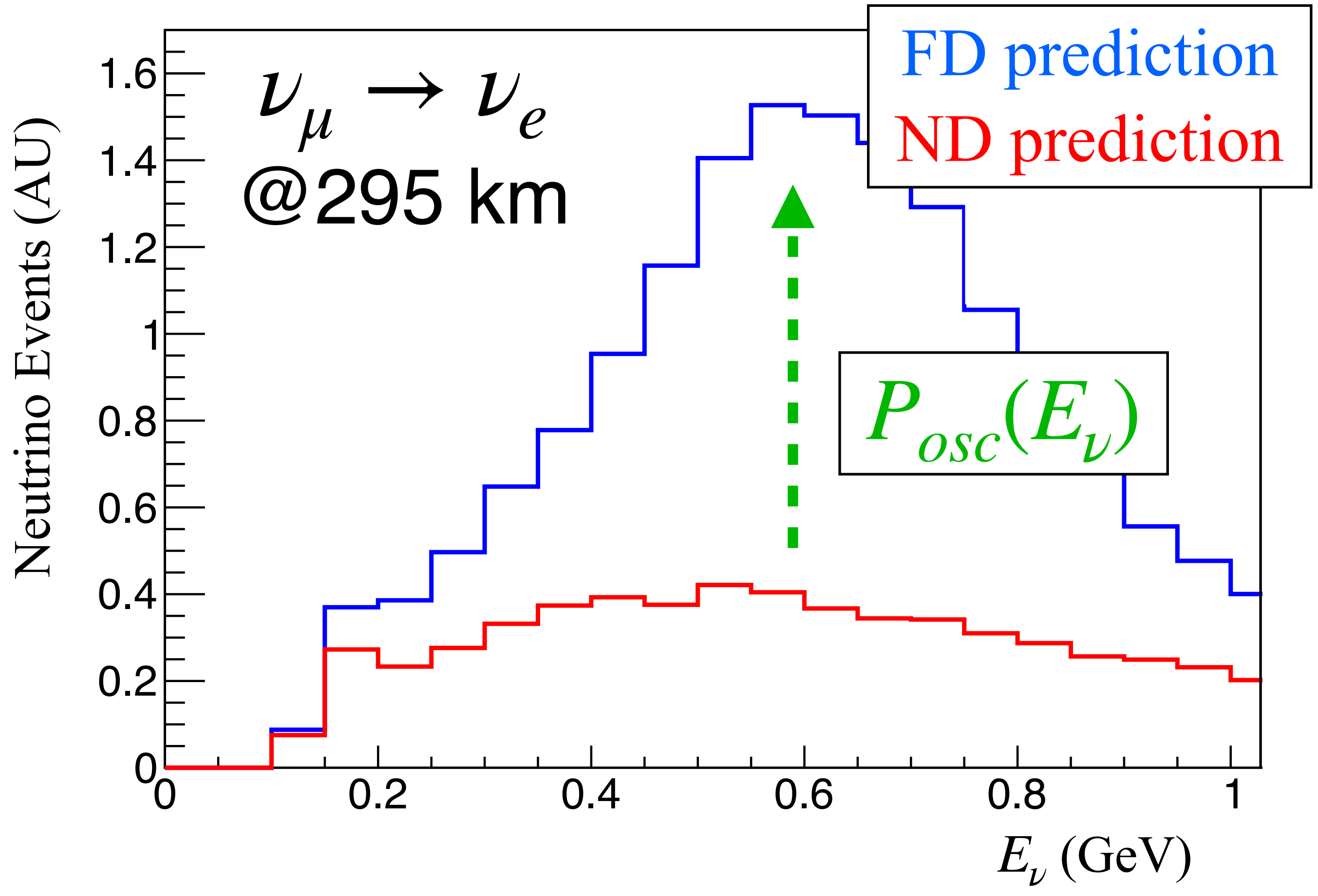
$$N(E_\nu) = \int \Phi(E_\nu) \times \sigma(E_\nu) \times R_{det}(E_\nu, \sigma(E_\nu), \vec{r}) \times P_{osc}(E_\nu)$$

The role of the Near Detector

$$N(E_\nu)^{ND} = \int \boxed{\Phi(E_\nu) \times \sigma(E_\nu)} \times R_{det}(E_\nu, \sigma)$$

Extrapolate prediction from ND to FD
and apply the oscillation probability

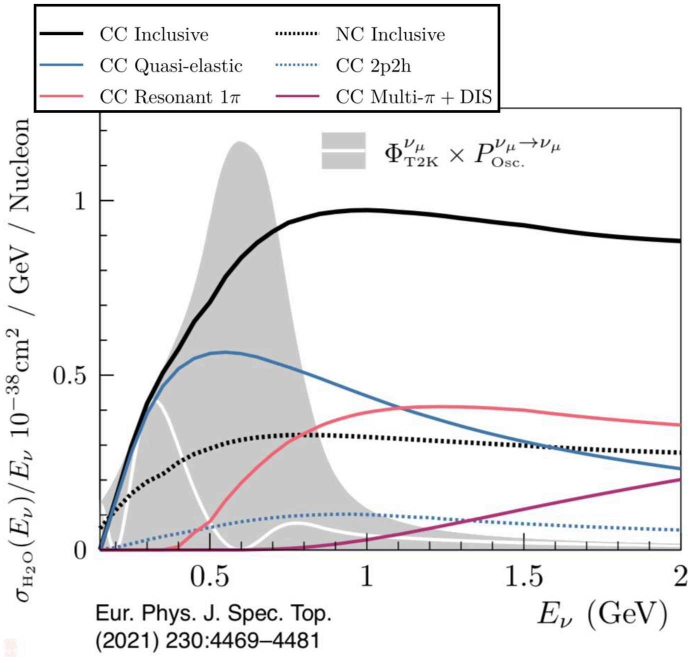
$$N(E_\nu)^{FD} = \int \Phi(E_\nu) \times \sigma(E_\nu) \times R_{det}(E_\nu, \sigma) \times P_{osc}(E_\nu)$$



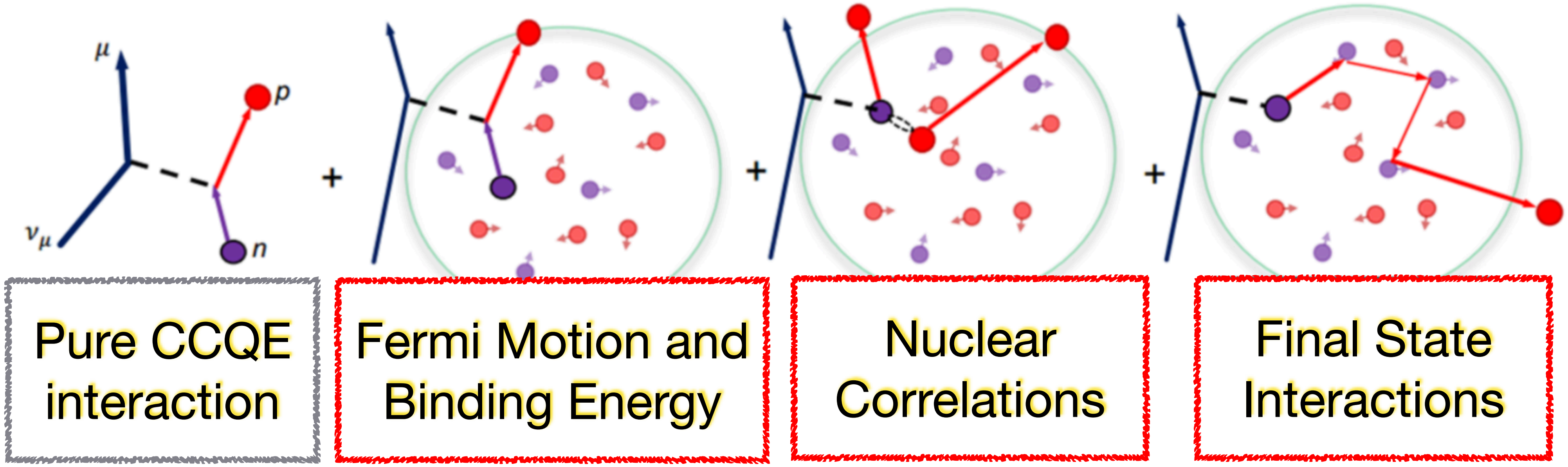
The Near Detector builds the prediction of the ν energy distribution at the Far Detector

⇒ Measure the Oscillation Probability

The Neutrino-Nucleus interaction



Eur. Phys. J. Spec. Top. (2021) 230:4469–4481

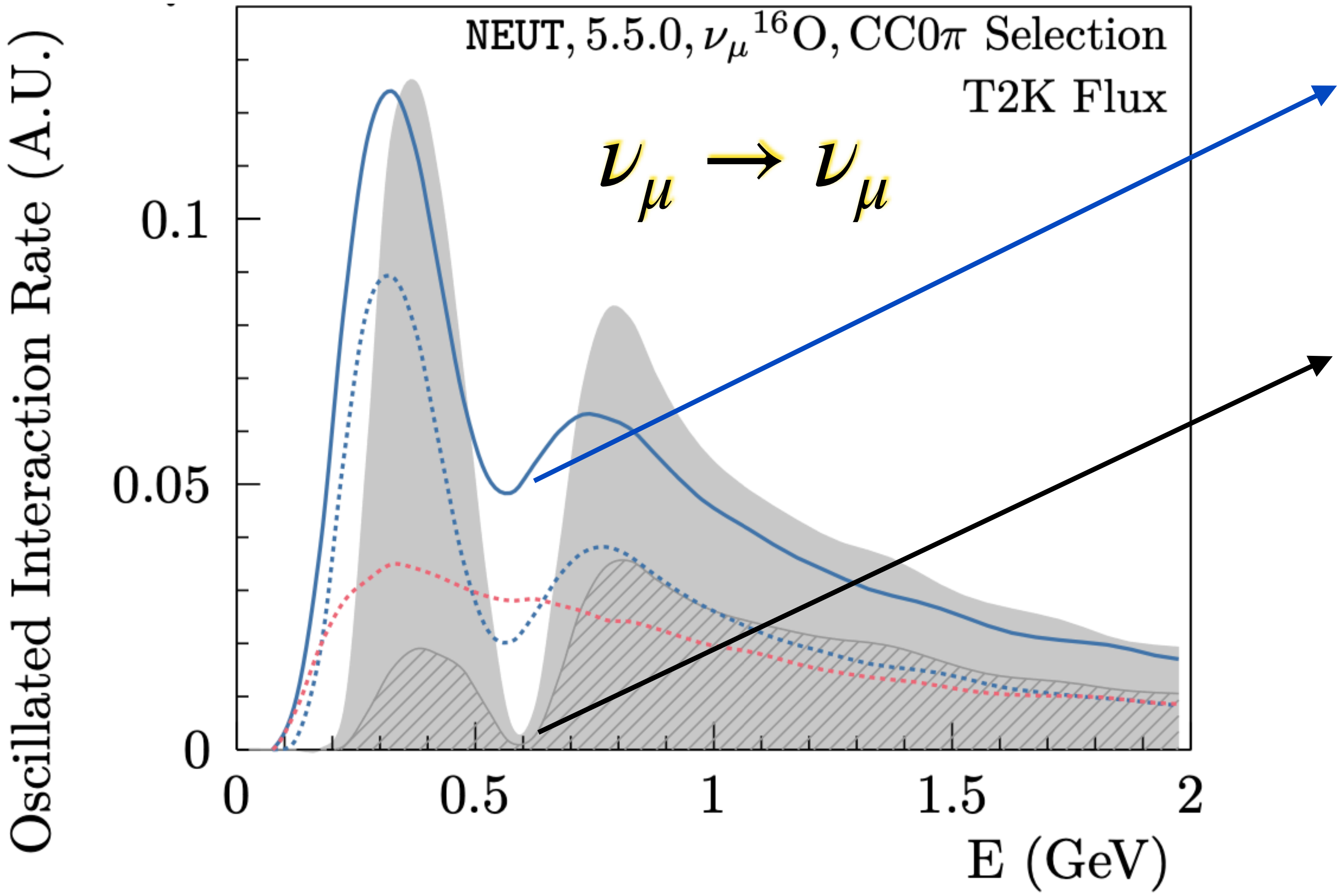


Pure CCQE interaction

Fermi Motion and Binding Energy

Nuclear Correlations

Final State Interactions

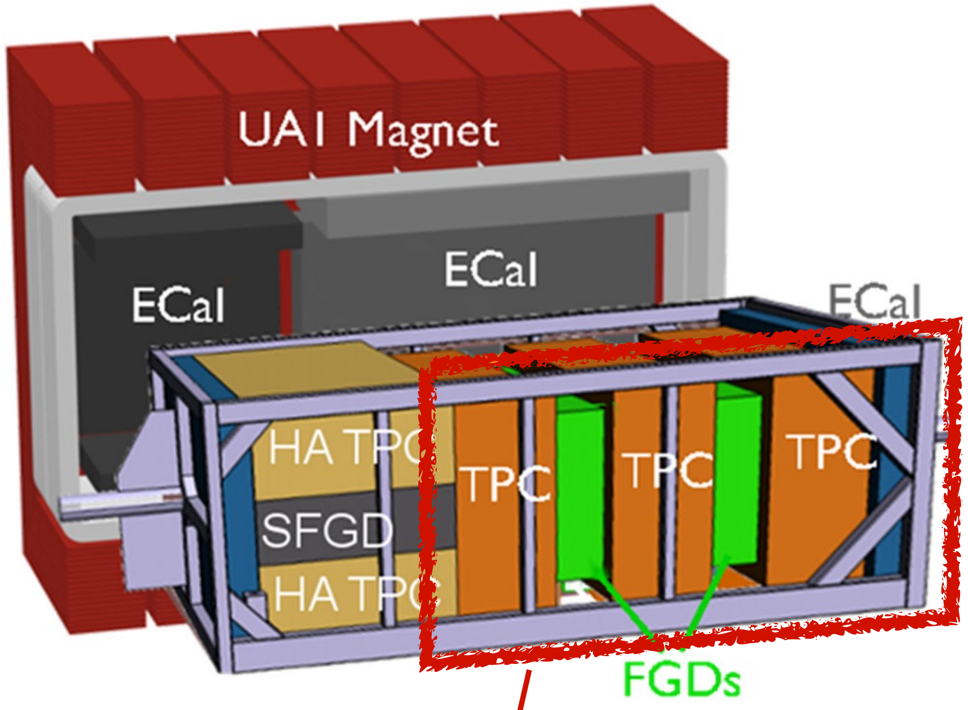


Dip observed in data

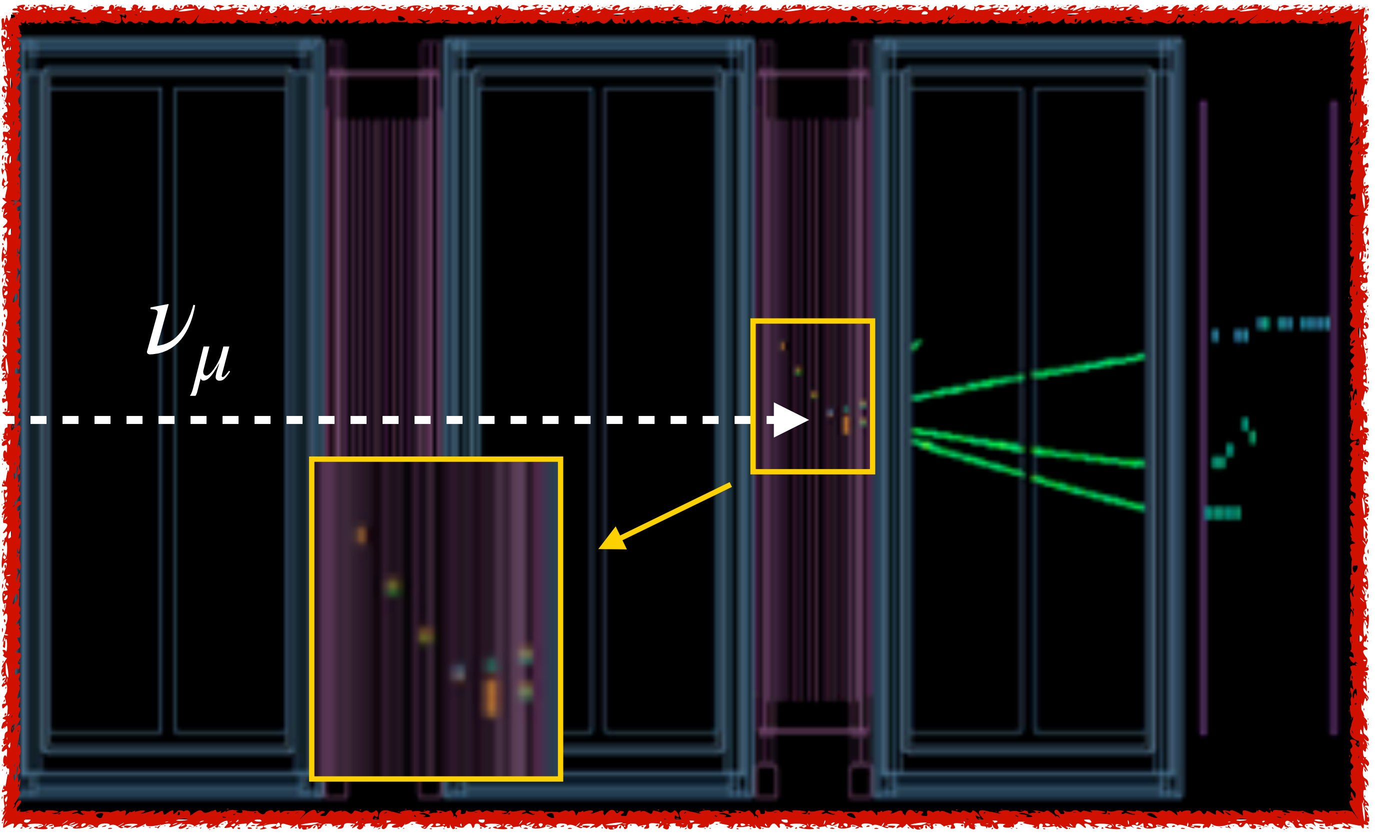
Very narrow dip from disappeared ν_μ if the energy is perfectly reconstructed

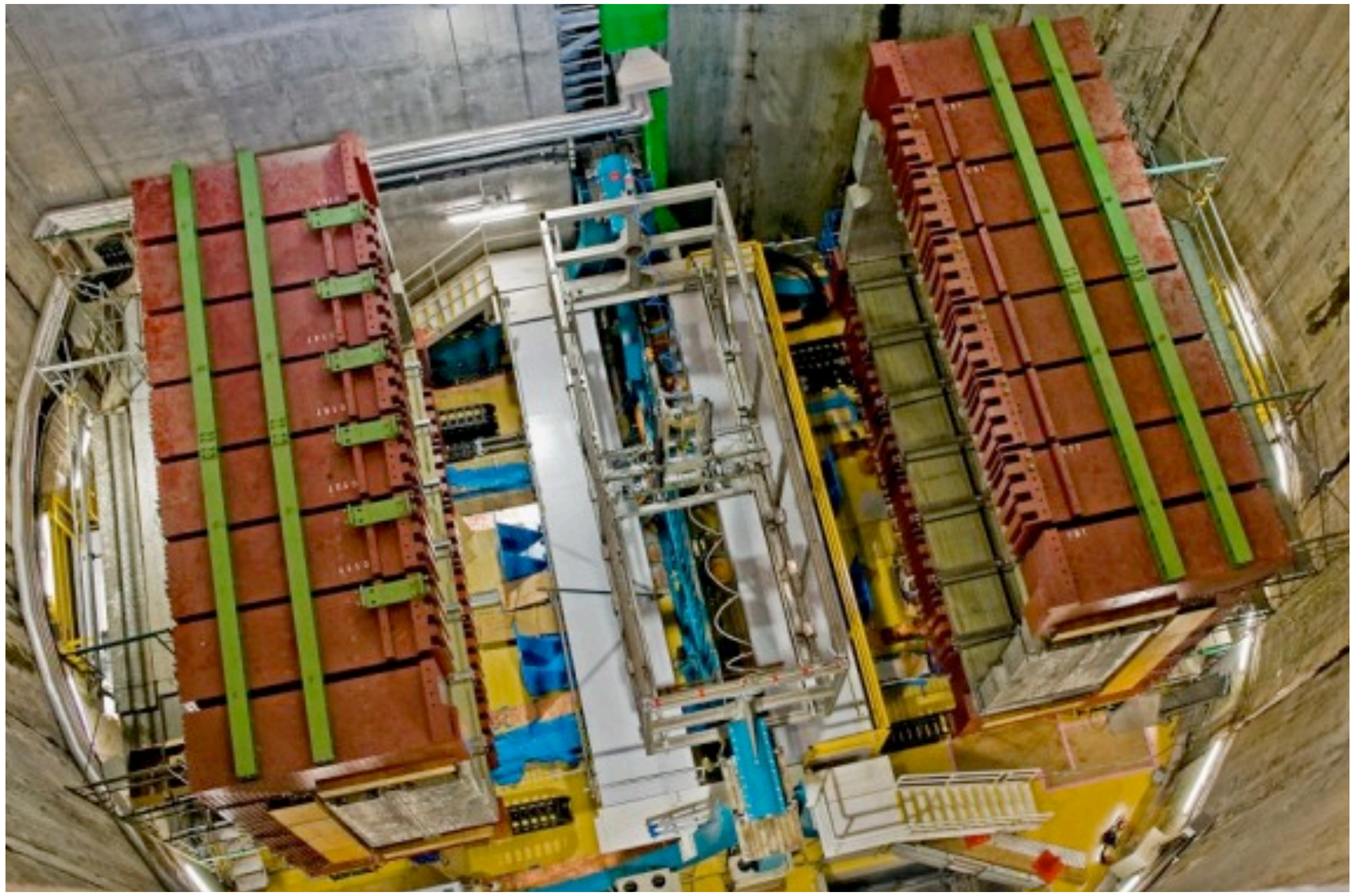
The precise knowledge of the neutrino energy requires an accurate modelling of neutrino interactions

The T2K Magnetised Near Detector: ND280



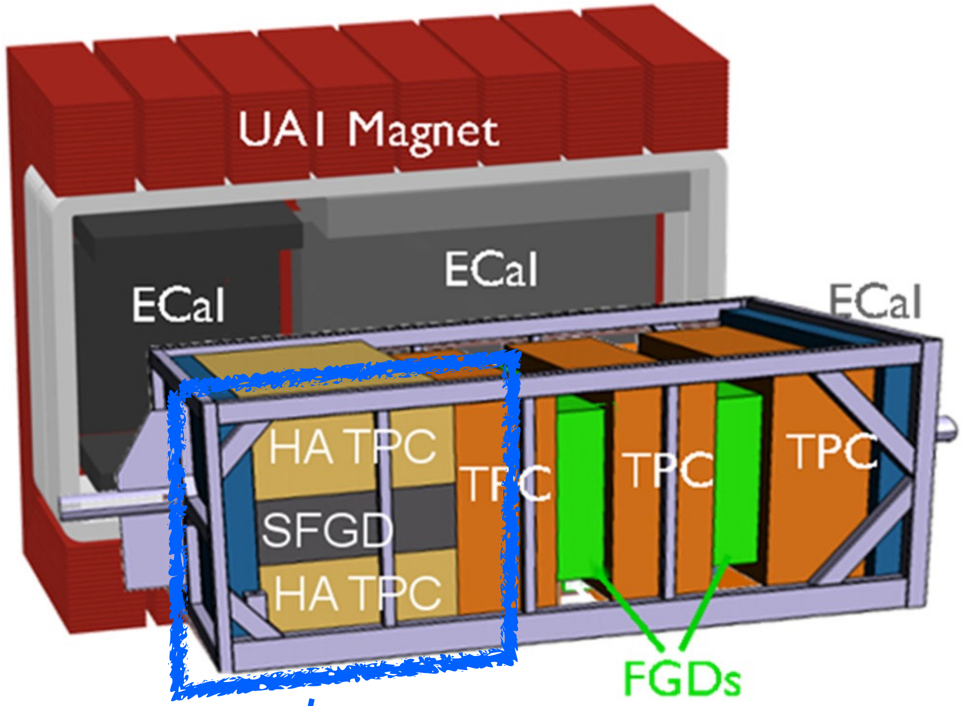
Since 2010

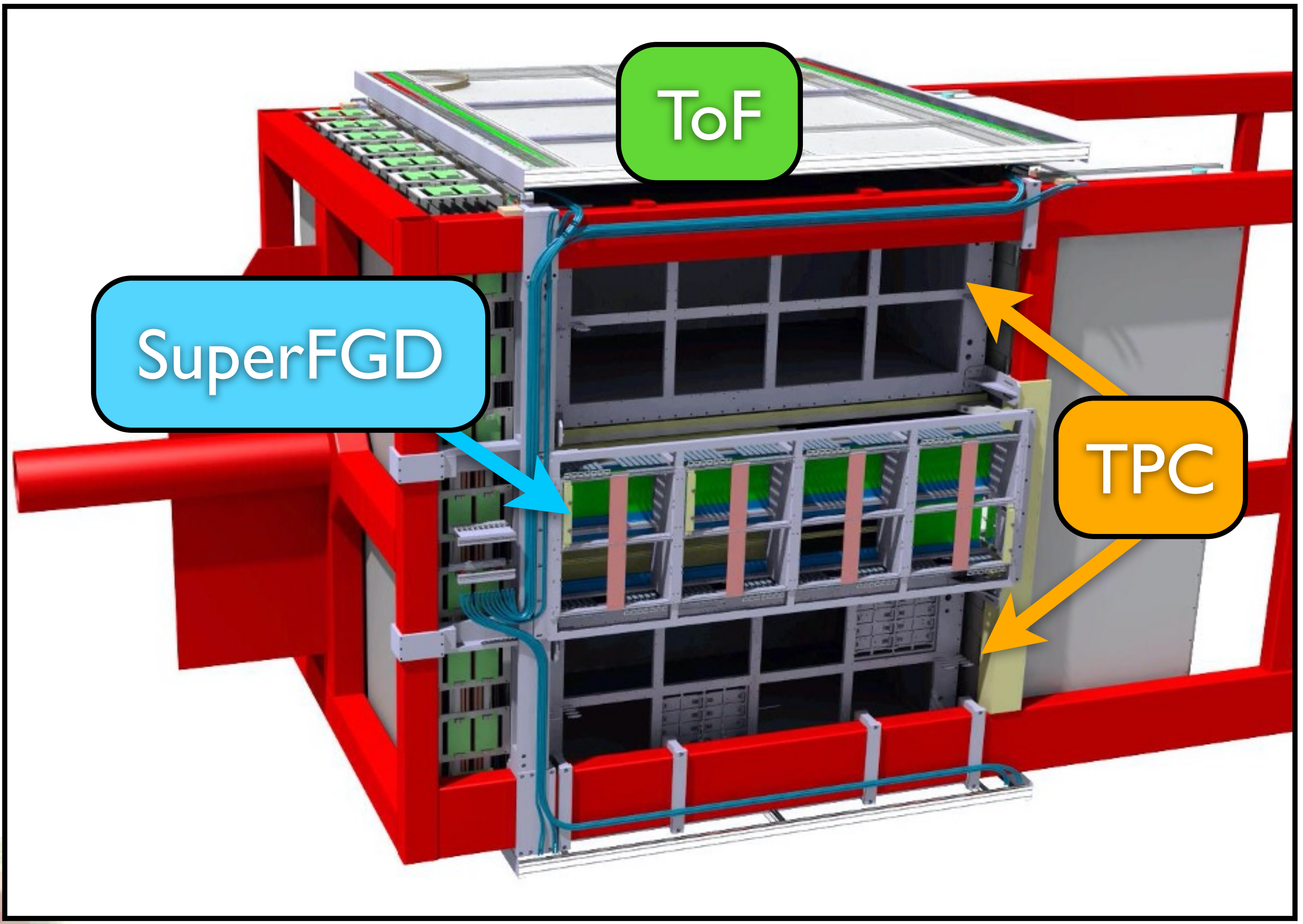




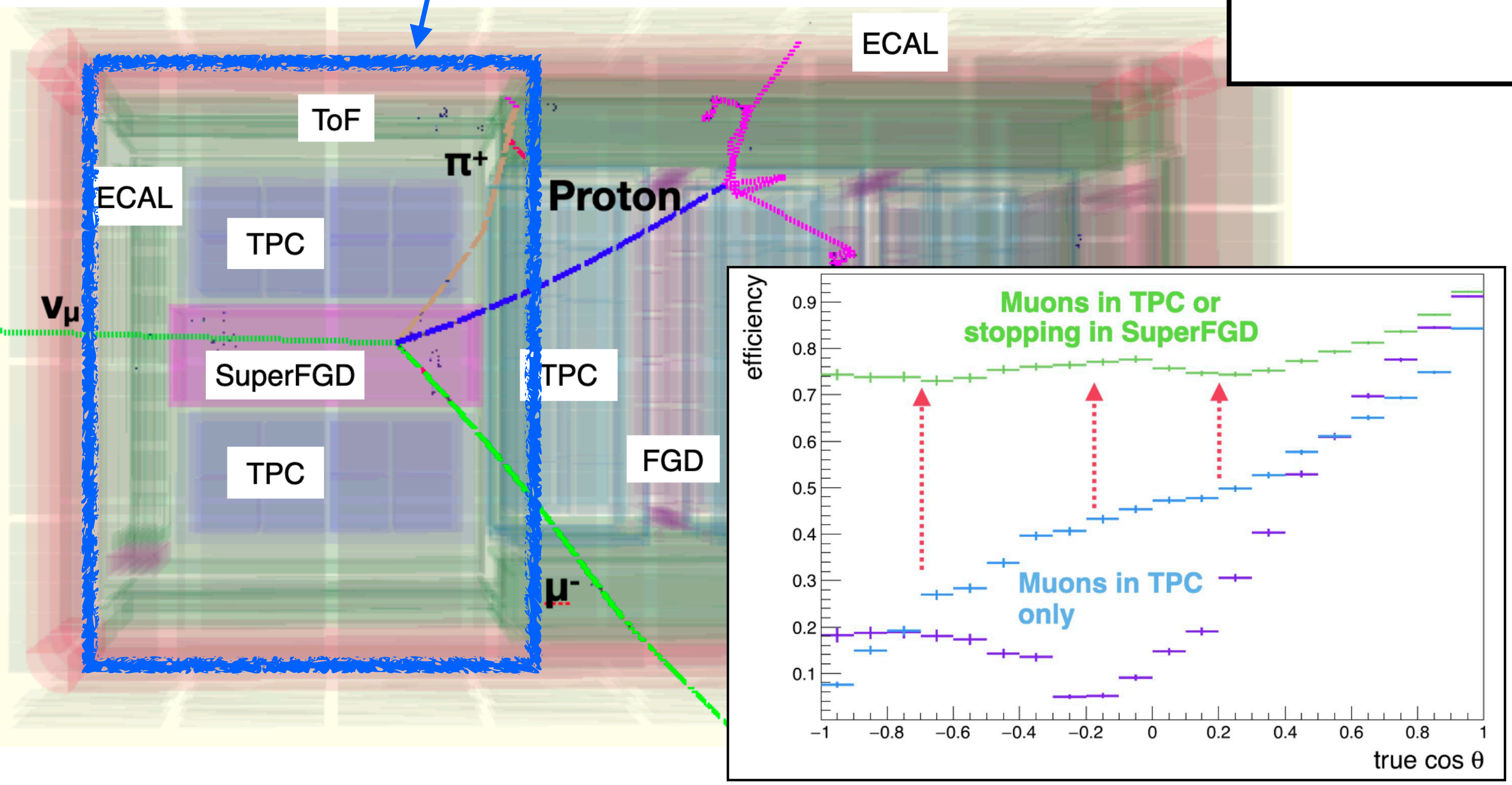
- ✓ Scintillator target (FGD - CH and H_2O)
  - ✦ ~2 ton for ν interactions
  - ✦ (Rough) tracking, range, PID
- ✓ Magnetised volume to identify ν vs $\bar{\nu}$
- ✓ Time Projection Chambers (TPC)
  - ✦ Momentum, charge, PID
- ✓ E.M. CALorimeter (ECAL)

The T2K Magnetised Near Detector: ND280



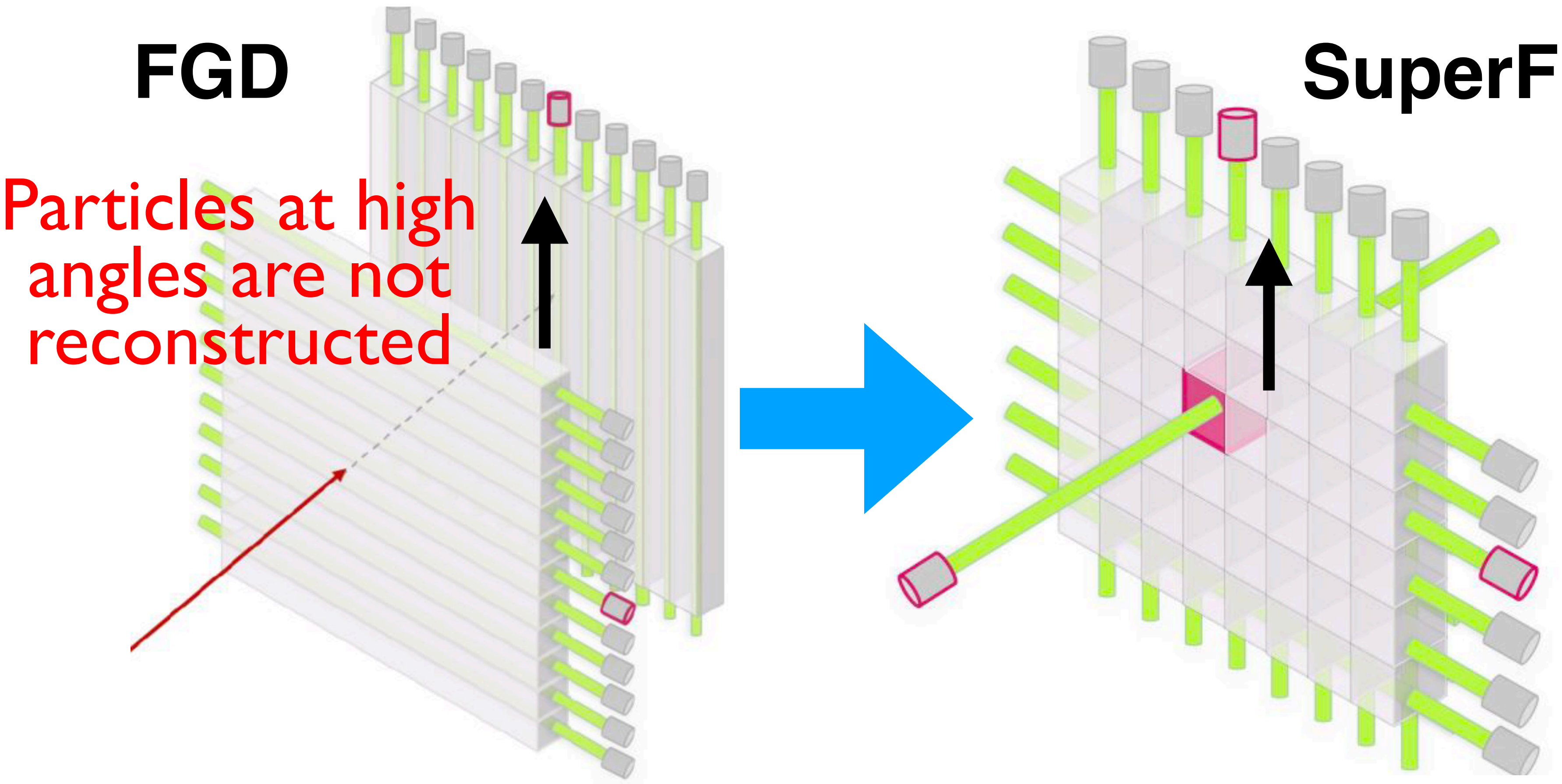


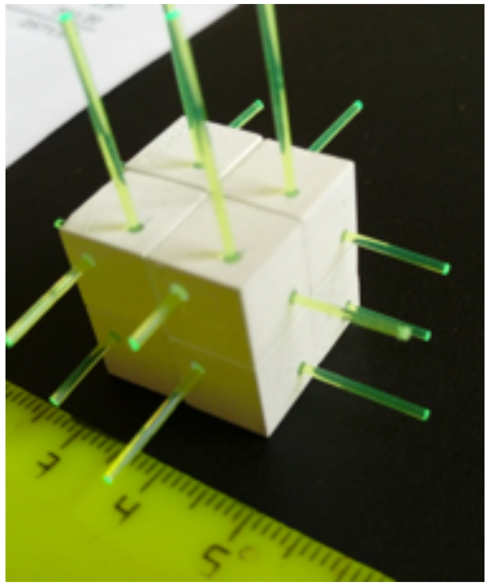
Ongoing upgrade



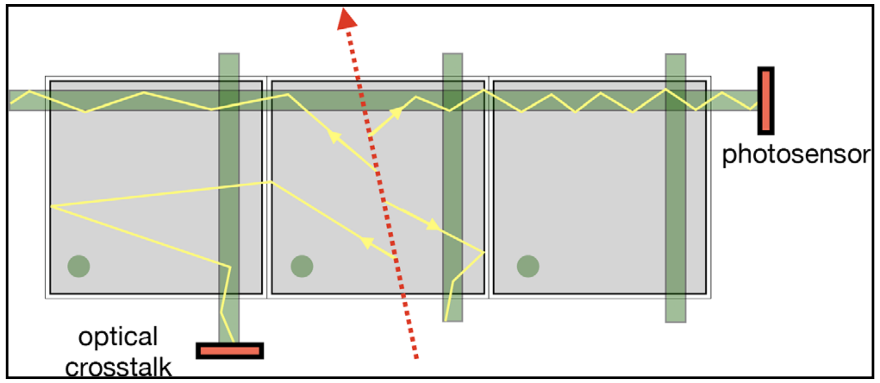
- ✓New scintillator (Super-FGD)
  - ✦~2 ton for ν interactions
  - ✦4π tracking and range
  - ✦Improved PID by dE/dx
- ✓New TPC's
  - ✦Improved momentum and charge resolution

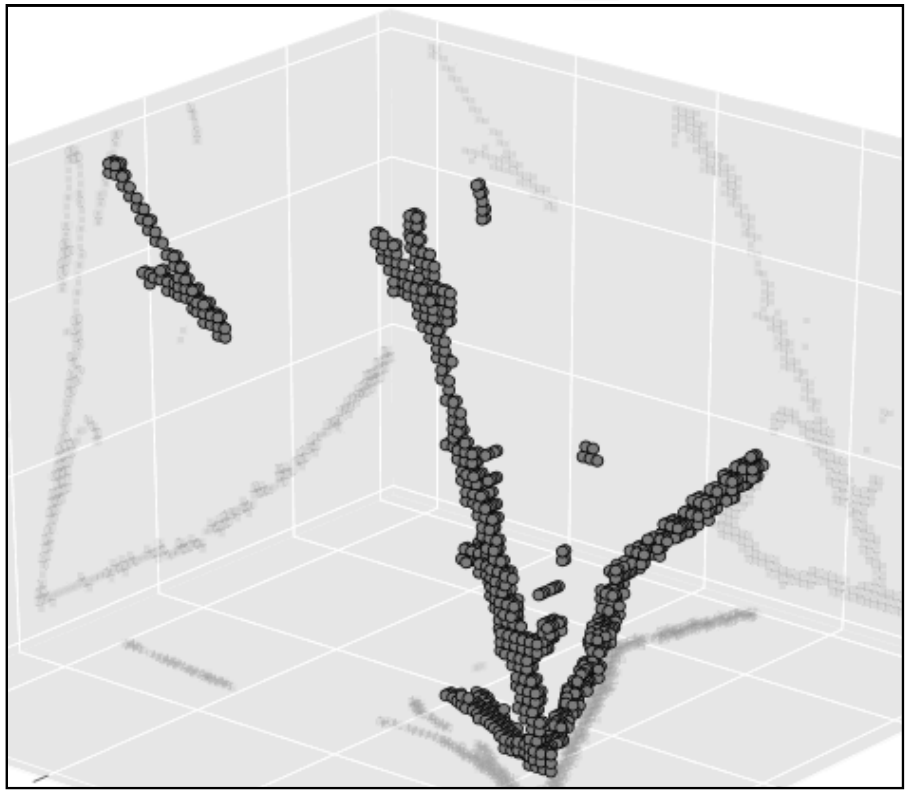
The SuperFGD detector





2018 *JINST* **13** P02006





Plastic scintillator cubes
read out with WLS fibers + SiPM:

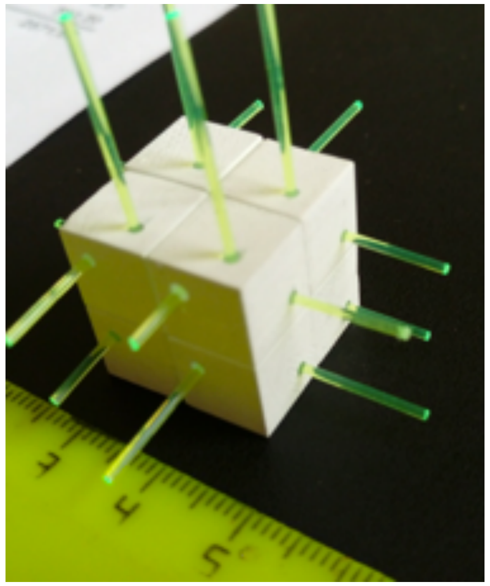
- ✓Three projections ⇒isotropic
- ✓3D granularity ⇒ reconstruct shorter tracks
- ✓$\sigma_t \sim$ 0.6 ns per cube ⇒neutron energy

The SuperFGD detector

✓2’000’000 scintillating cubes

✓Contained in a Carbon/Glass-fiber box with 120’000 holes for WLS fibers

✓60’000 SiPM + electronics channels



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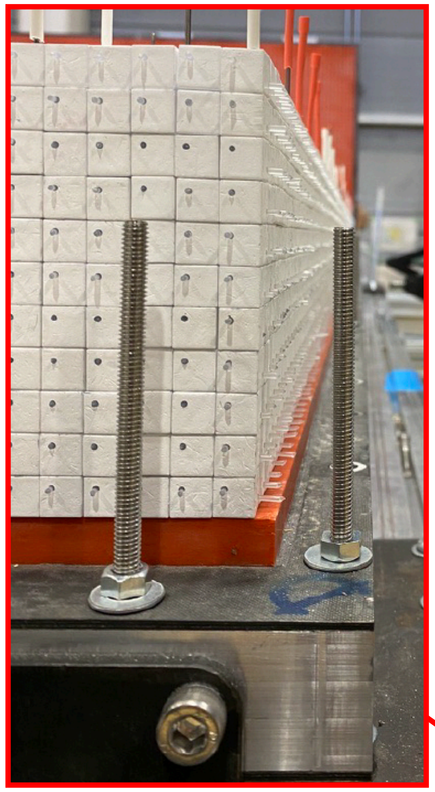
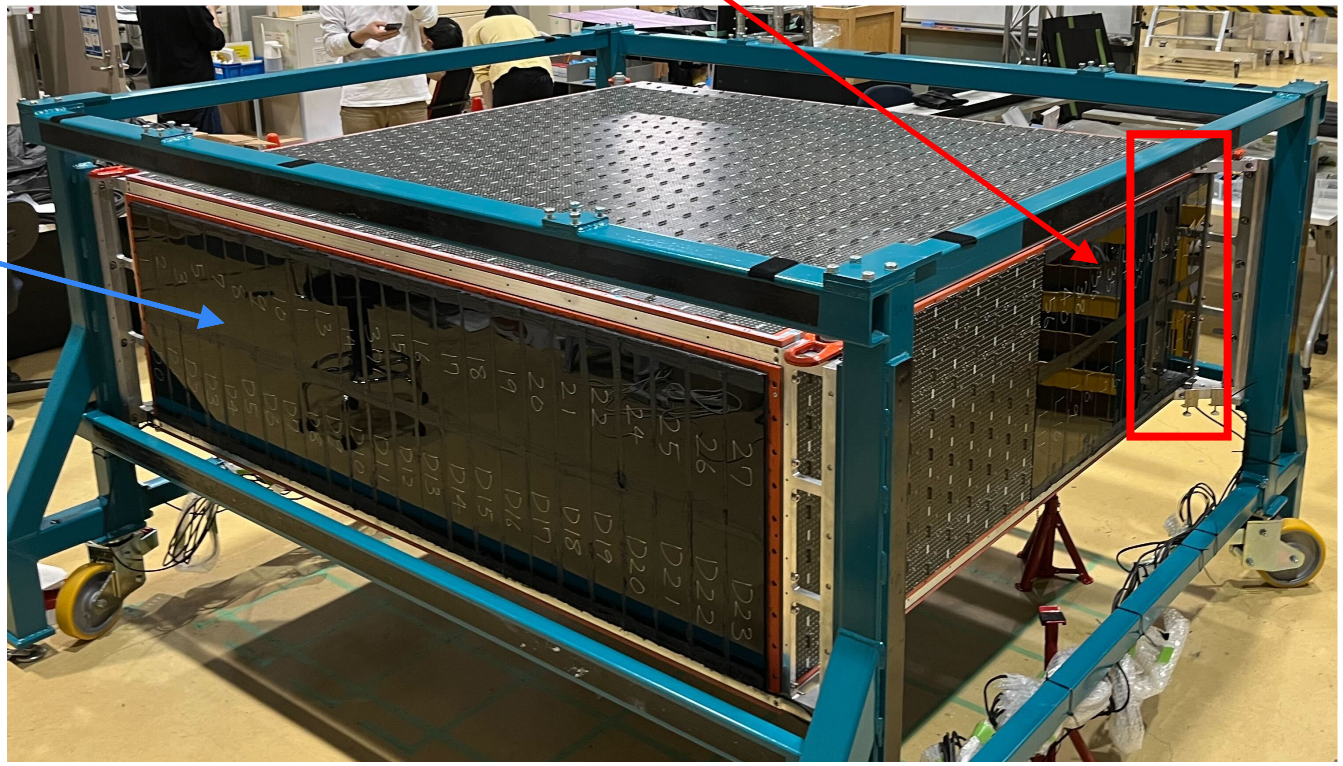
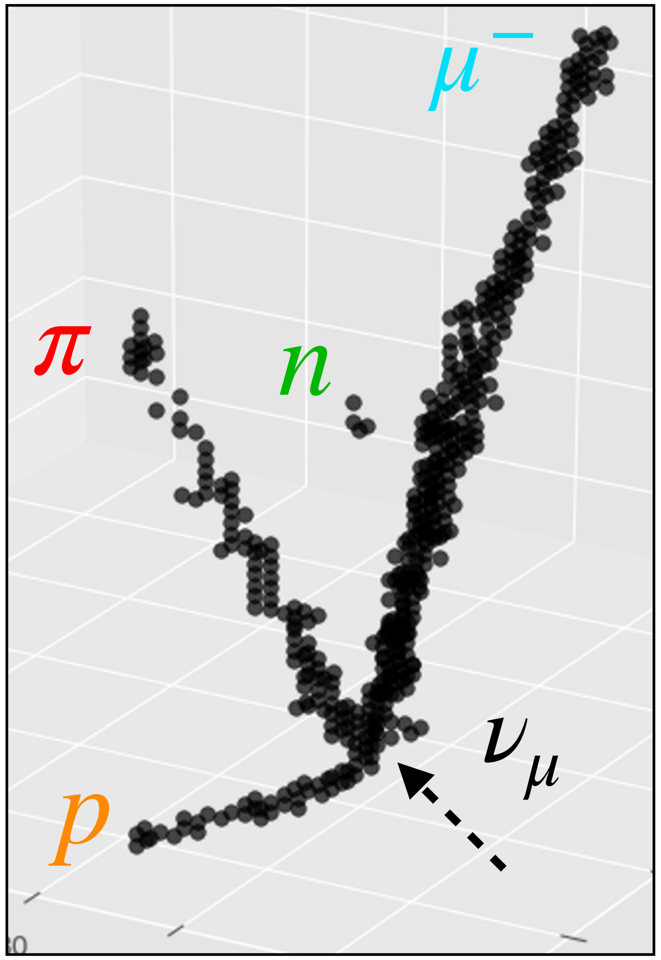
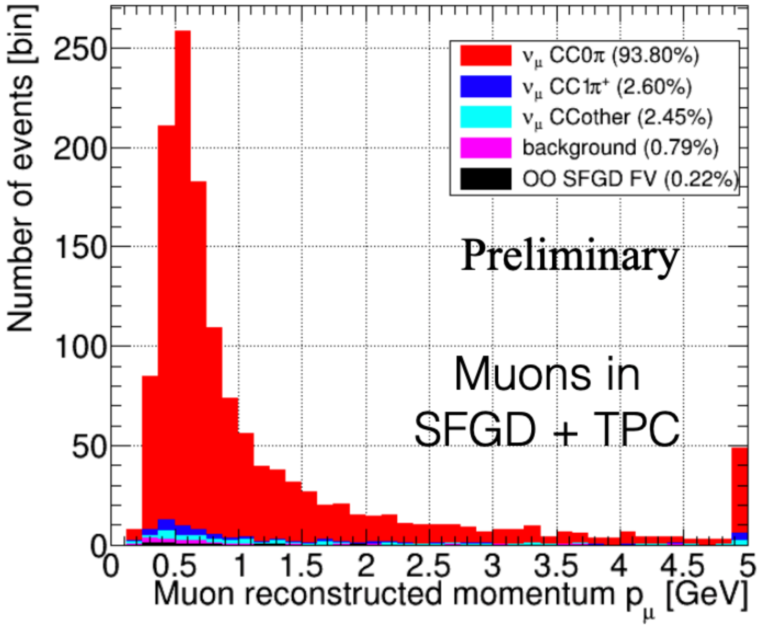


Now in J-PARC

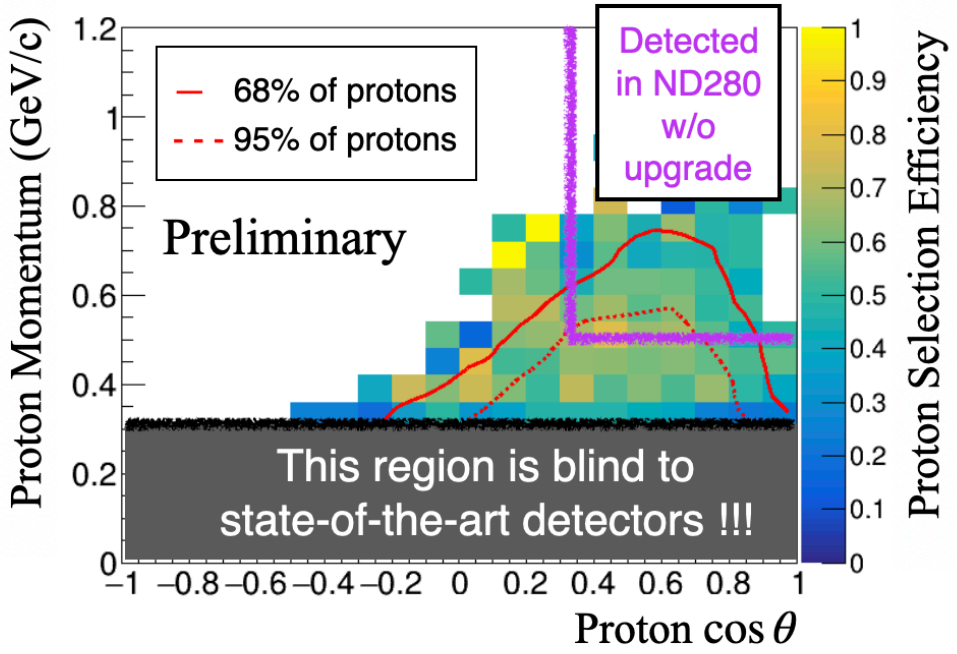


Physics with the SuperFGD detector

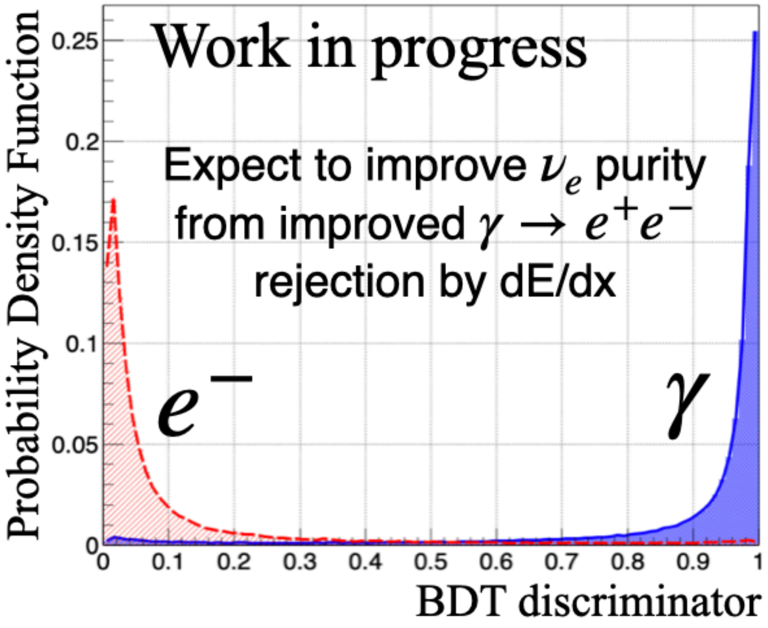




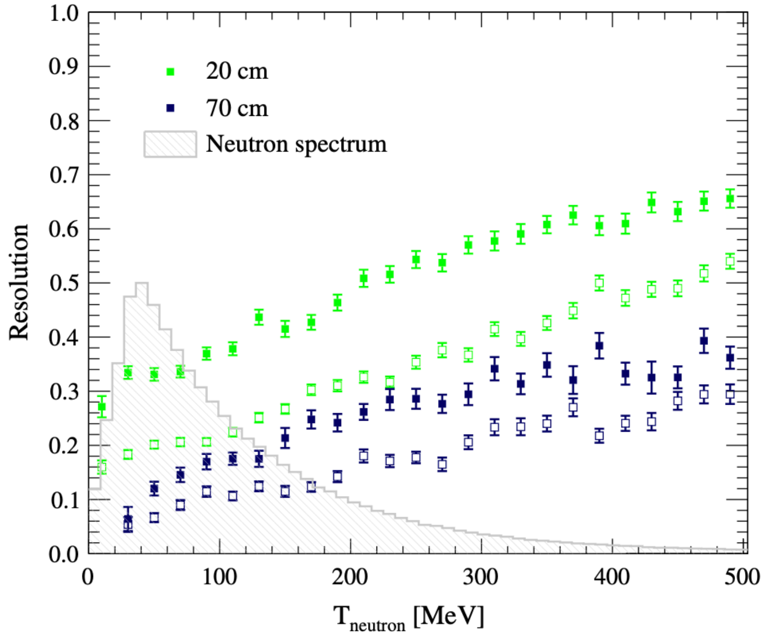
Very good purity for ν_μ CCQE-like but blind to low-energy protons



Protons down to 300-350 MeV/c



Excellent separation between e^- and $\gamma \rightarrow e^+e^-$



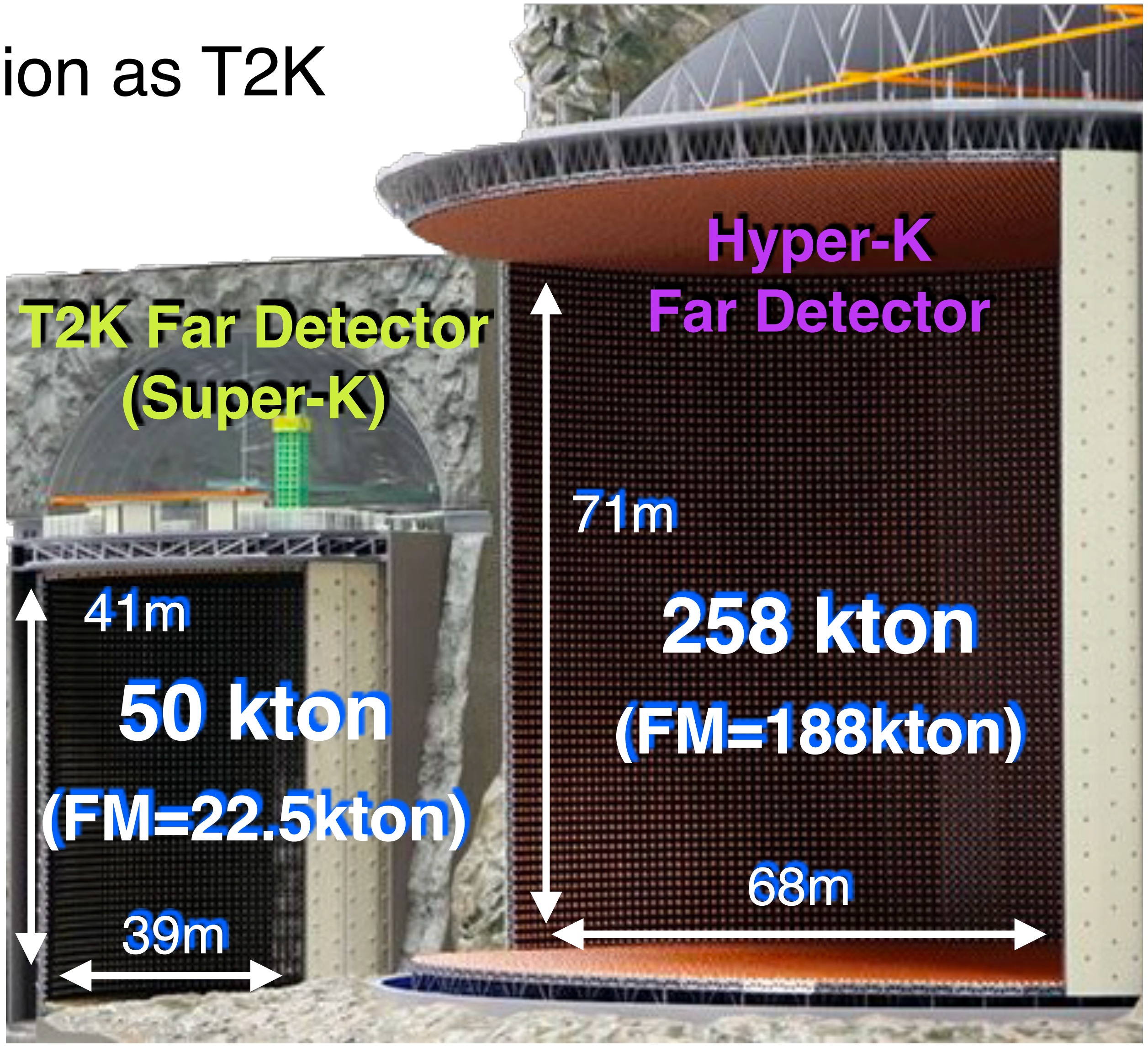
Neutron energy in ν_μ interactions from time-of-flight !

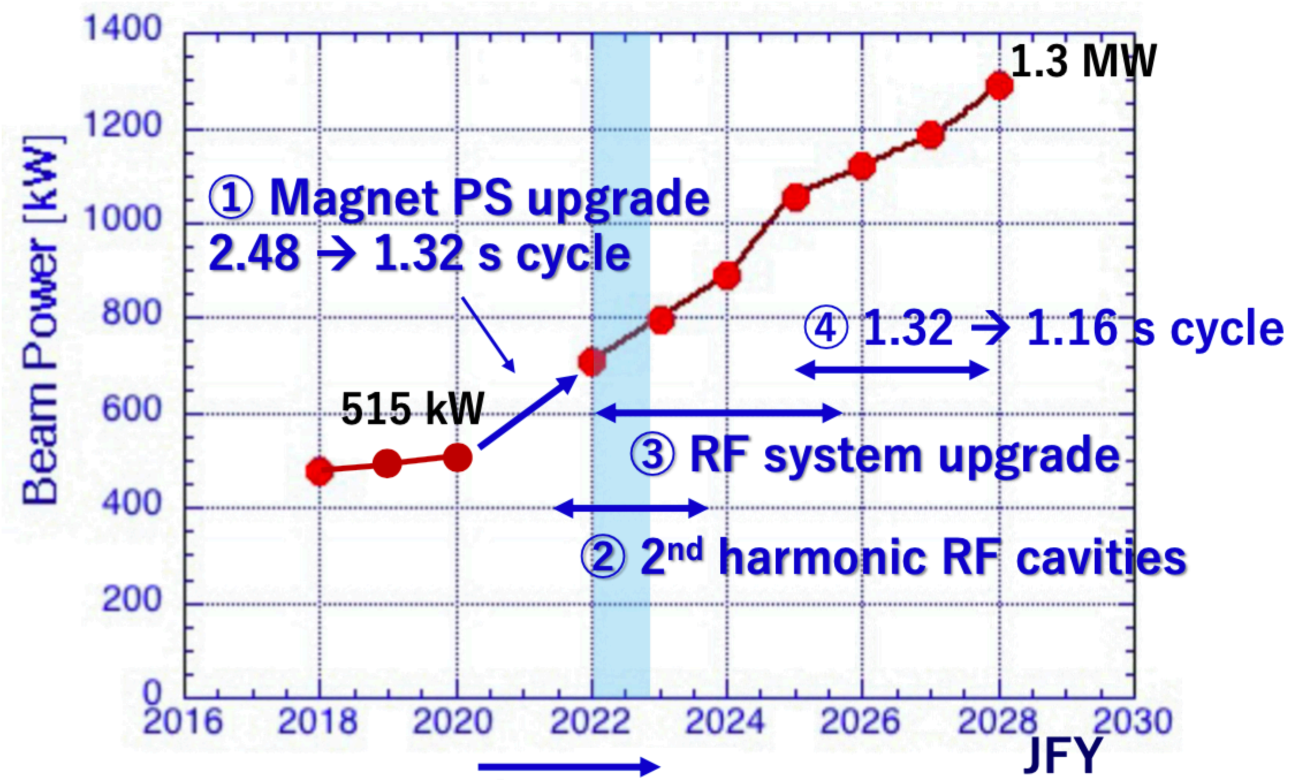
The Hyper-Kamiokande experiment

Exactly the same experimental configuration as T2K

✓Inherit the neutrino beam and ND280

✓Additional water Cherenkov detector at the near site (~800m)



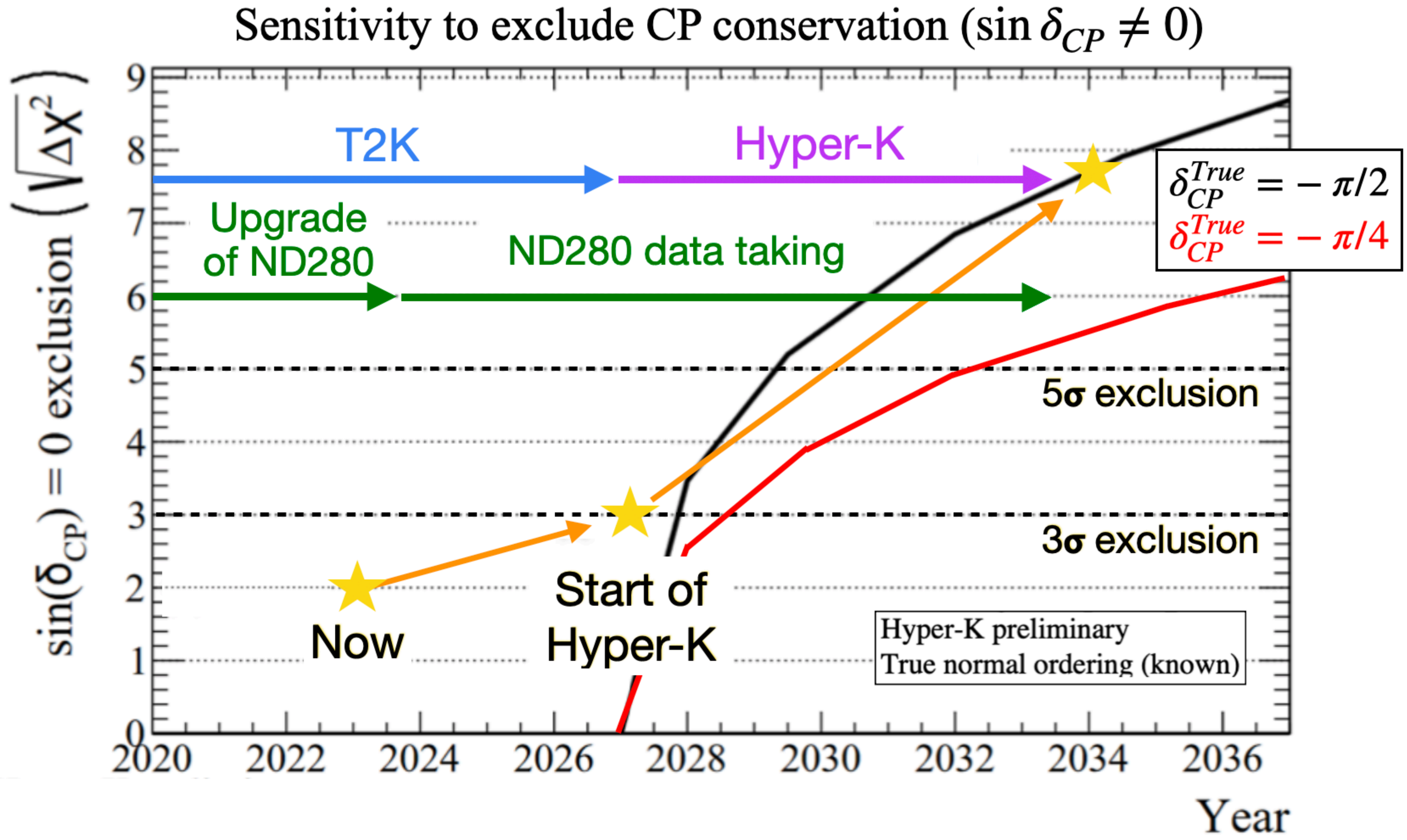


Comparison with T2K before shut down:

2020 beam power x2 & Target mass x8

⇒ *x16 more data*

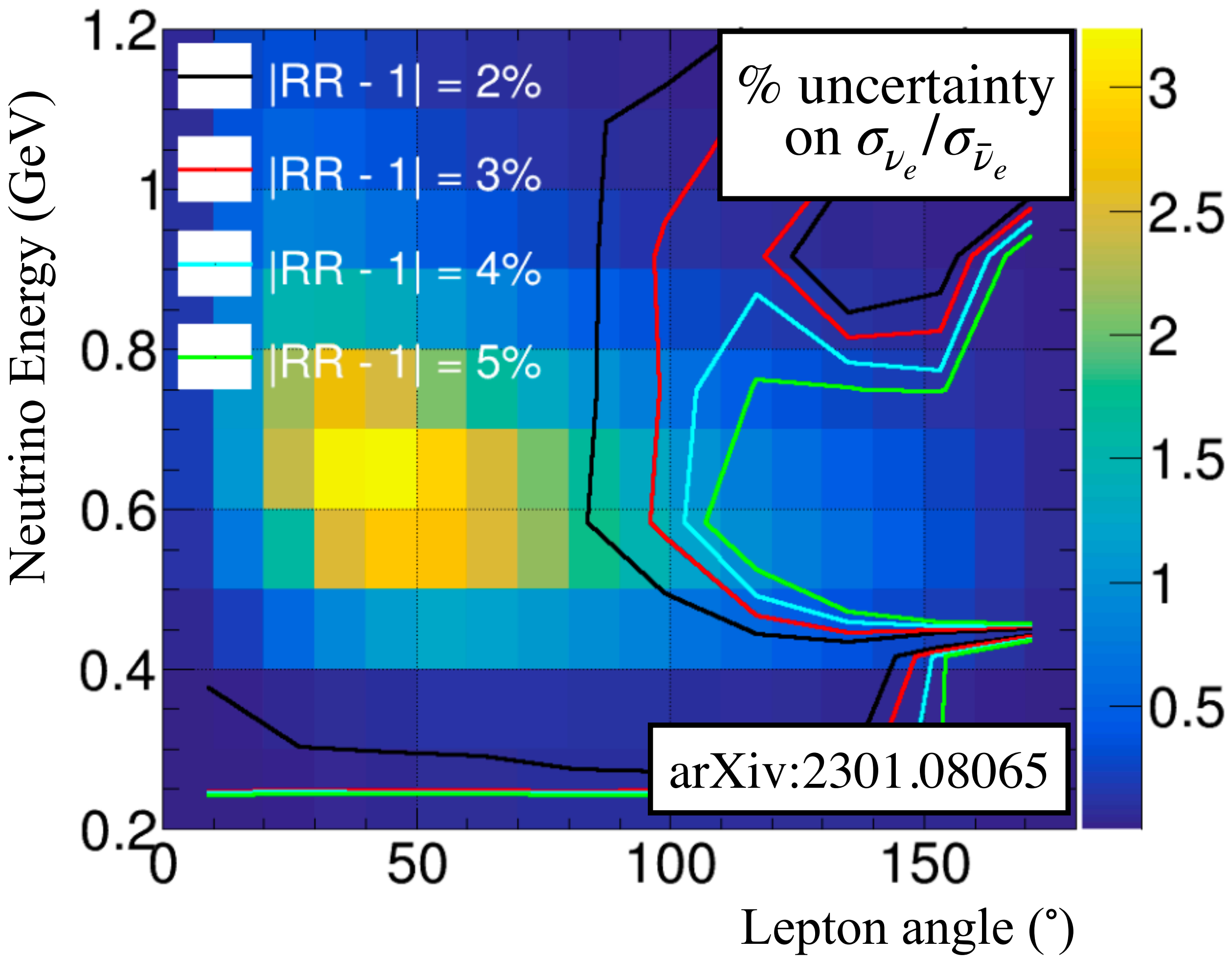
The Hyper-Kamiokande experiment

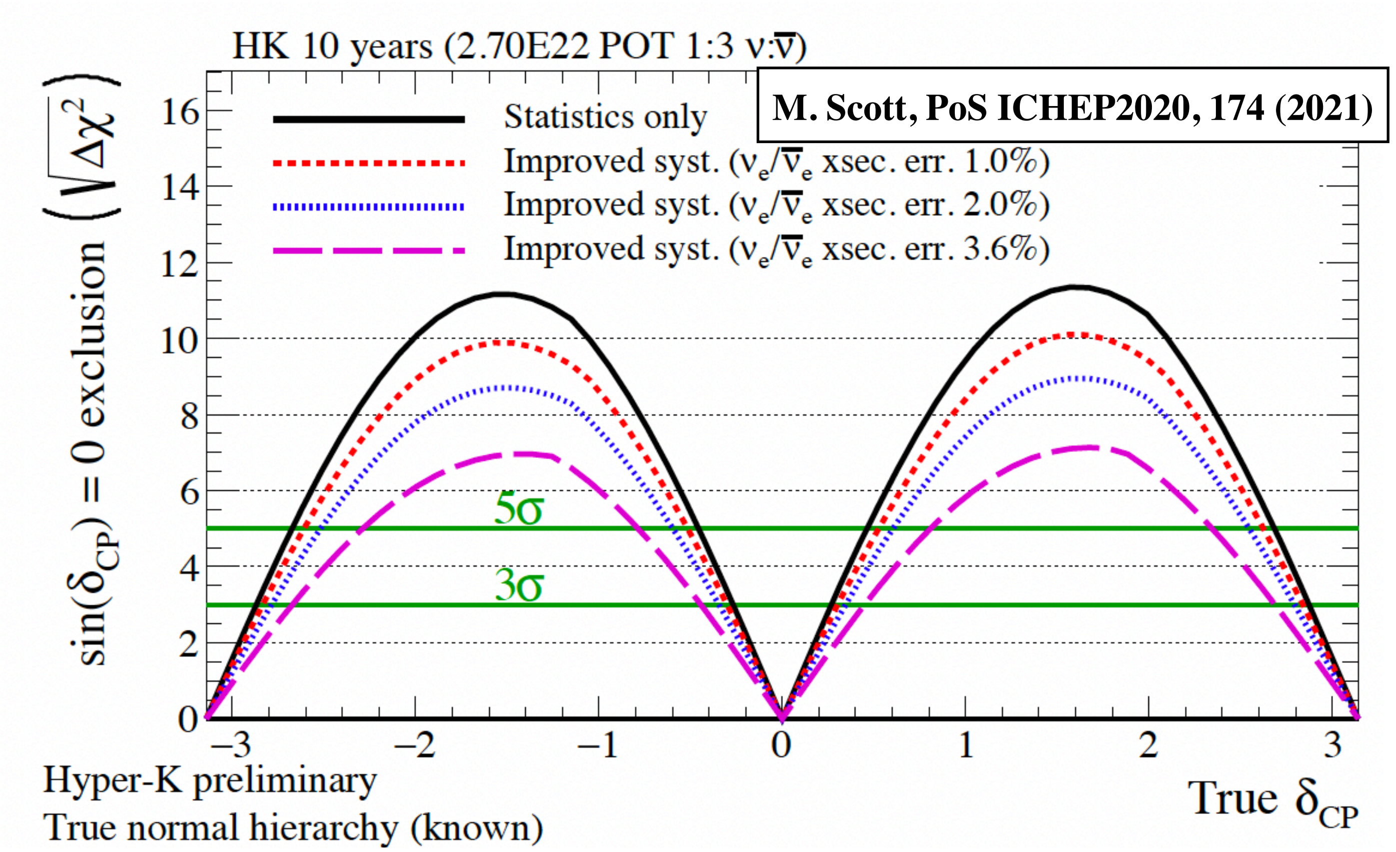


Hyper-K will start in 2027 and will measure δ_{CP} with a resolution better than 20° and determine the neutrino mass hierarchy with significance $> 4\sigma$

Systematics goal at Hyper-K: ν_e vs $\bar{\nu}_e$

- $\sigma_{\nu_\mu}/\sigma_{\nu_e}$ vs $\sigma_{\bar{\nu}_\mu}/\sigma_{\bar{\nu}_e}$ at 3% level
- Radiative corrections ~2%
- Nuclear Effects change the ratio between σ_{ν_μ} / σ_{ν_e} in a non-trivial way



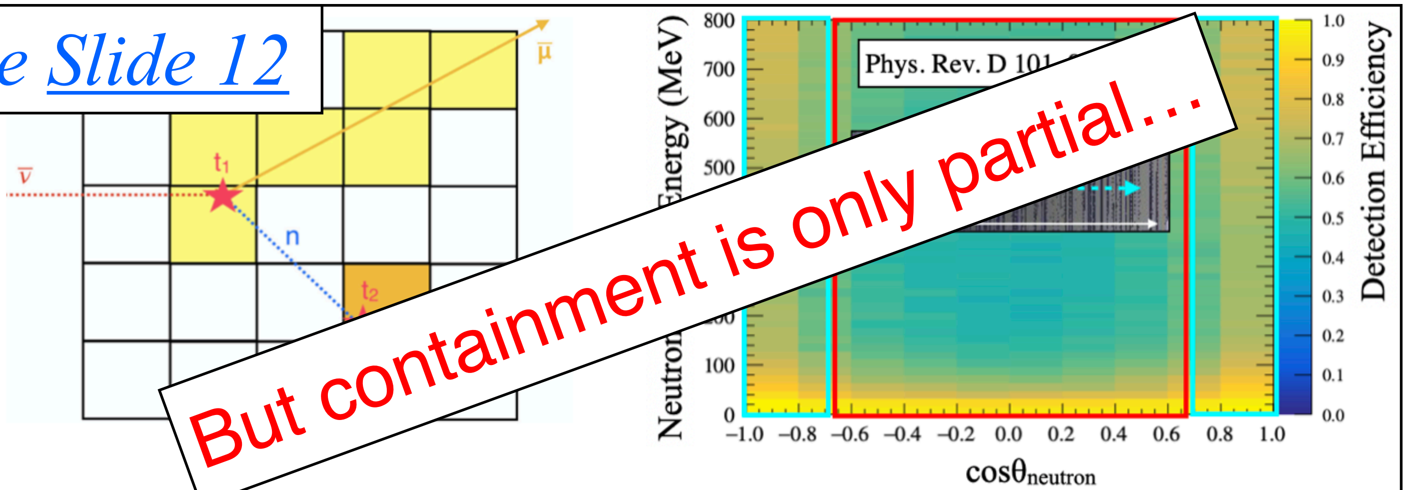


How can we improve ν_e and $\bar{\nu}_e$ cross section systematics ?
⇒ reduce systematics on ν_μ and $\bar{\nu}_\mu$ and extrapolation to ν_e and $\bar{\nu}_e$

Detect a large sample of ν_e and $\bar{\nu}_e$ and improve improve the ν_μ and $\bar{\nu}_\mu$ final state kinematics reconstruction

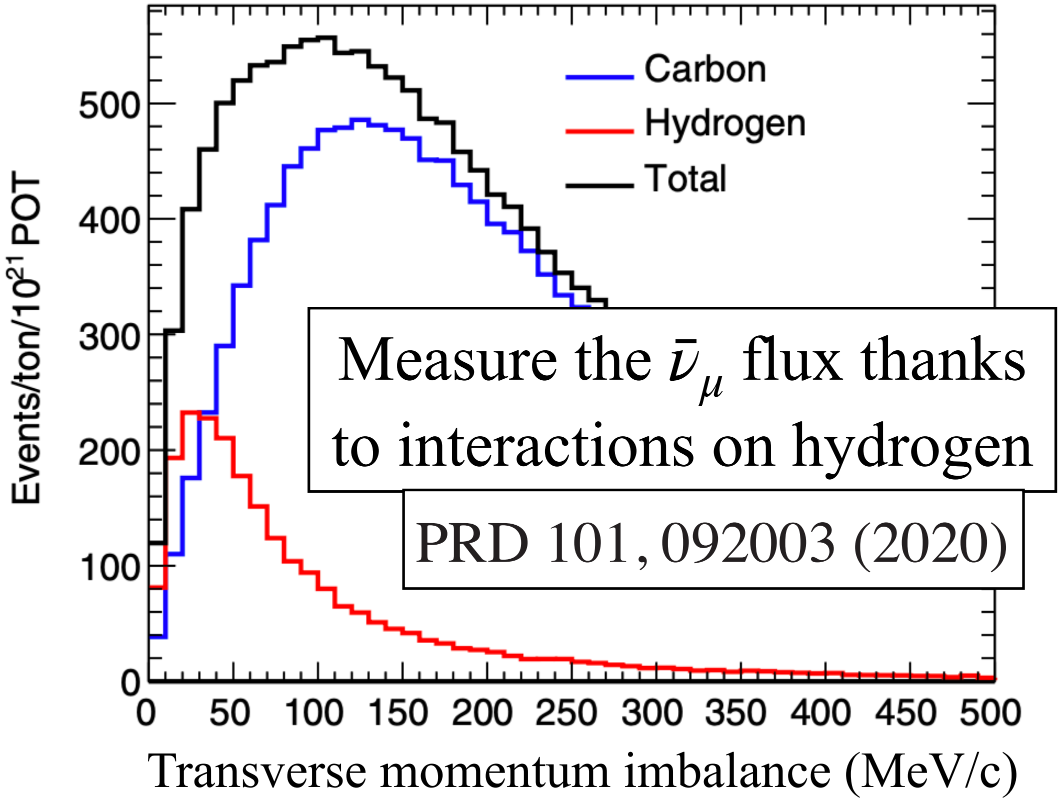
Systematics goal at Hyper-K: $\nu_\mu/\bar{\nu}_\mu$ & neutrons

See Slide 12



But containment is only partial…

Reconstruct energy of neutrons produced in ν_μ interactions !



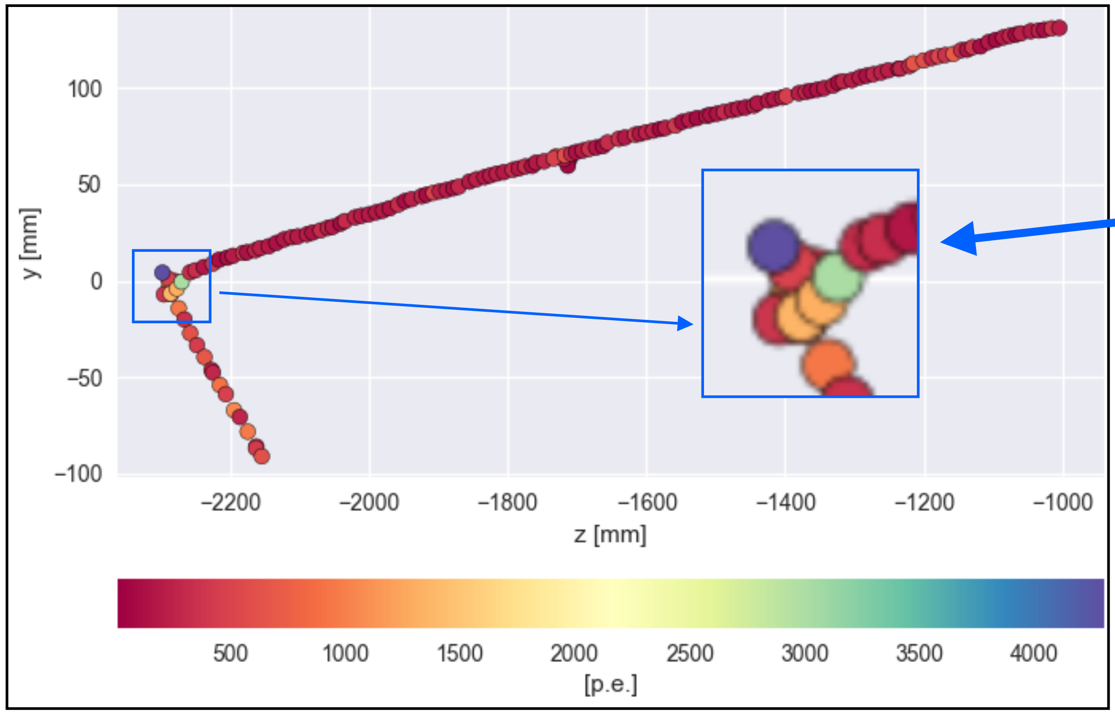
Measure the $\bar{\nu}_\mu$ flux thanks to interactions on hydrogen

PRD 101, 092003 (2020)

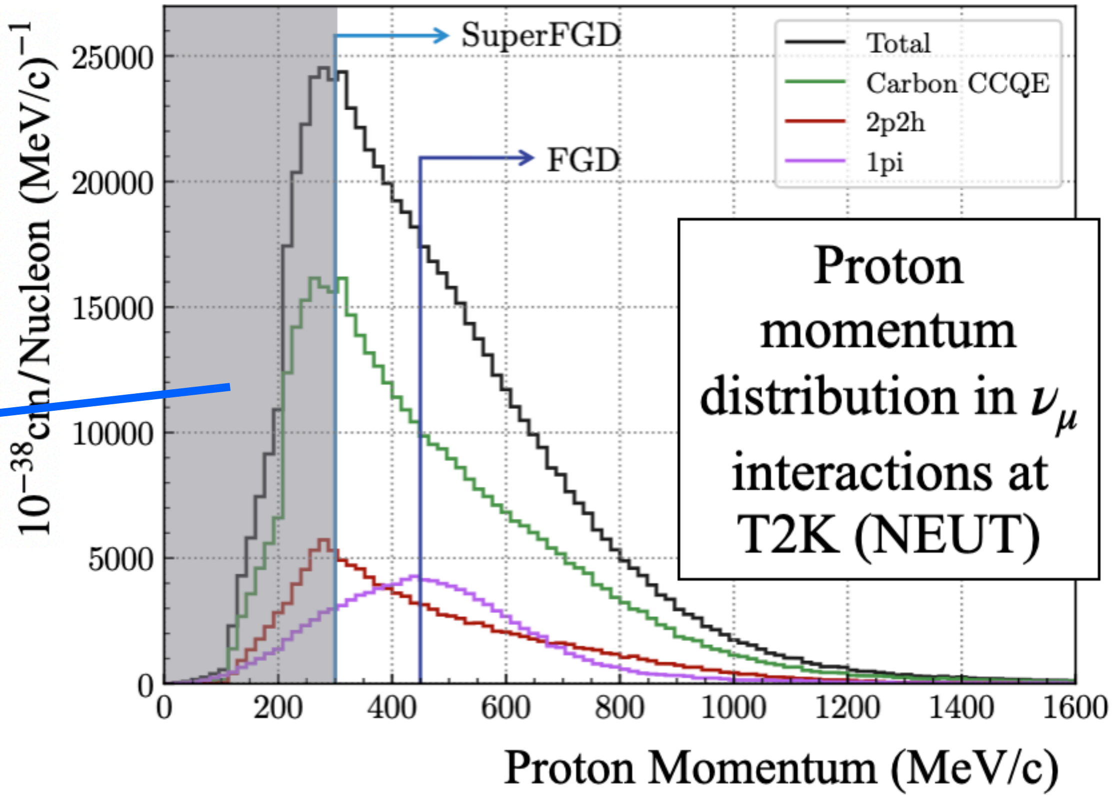
- A more efficient and precise detection of neutrons requires:
  - ✓ A larger volume of active plastic scintillator (~80% for 2x2x2 m^3)
  - ✓ Improved time resolution for neutron ToF measurement
    - ✦ Move from Kuraray Y11 (decay time ~8ns) to Kuraray Y2 or Y3 (~2-3ns)
    - ✦ Faster electronics (σ_t ~200 ps) - *Dominating the SFGD time resolution*

Systematics goal at Hyper-K: ν_μ & protons

- Improve reconstruction of ν_μ interaction final state on the transverse plane to enhance the separation between different types of ν_μ final states
- Detect low-energy hadrons, like protons, or nuclear clusters (PRD 106, 032009 (2022))



Only a few mm range in plastic !



Proton momentum distribution in ν_μ interactions at T2K (NEUT)

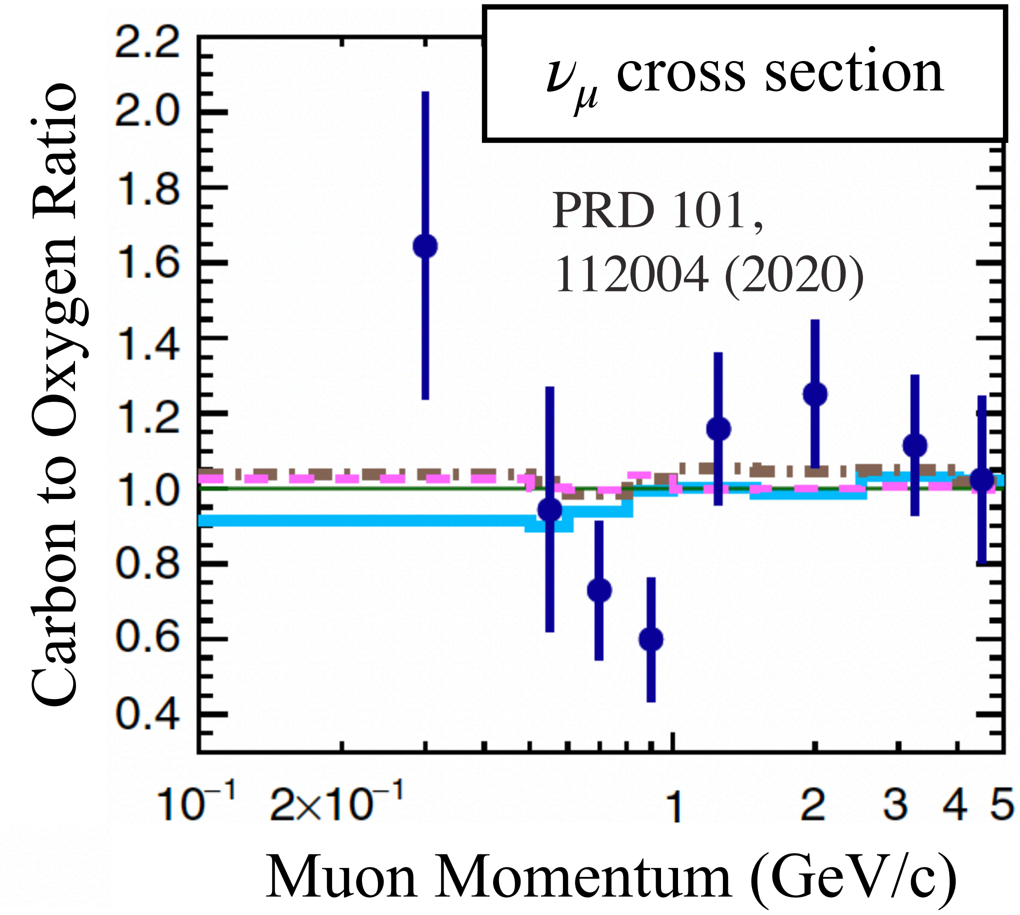
Improve the granularity of the scintillator detector

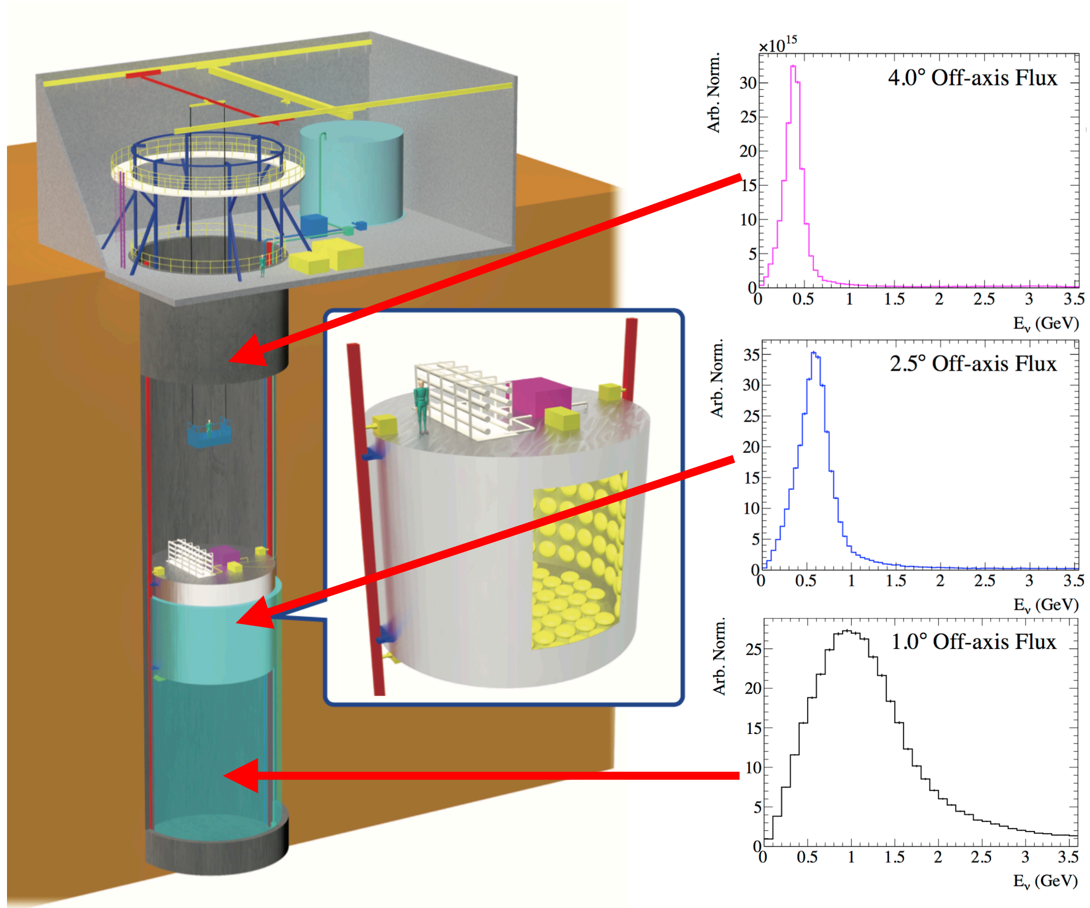
Systematics goal at Hyper-K: ν_μ in H_2O

- ν_μ in water (H_2O) vs plastic (CH):
  Theoretically small but we have to make sure it's under control with 2%

✓Measurements performed with water detectors in ND280 at multiple sub-detectors

✓Additional water Cherenkov detector at the near site (~800m)





Why do we need ND280++ ?

1. $\sigma(\nu_e)/\sigma(\nu_\mu)$ and $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ at theoretical uncertainties (~3%)

   ⇒ Large mass (10 tons) SuperFGD-like detector (good dE/dx)

2. Resolve nuclear effects with efficient “fast” neutrons reconstruction

   ⇒ Large mass (10 tons) SuperFGD-like detector (C_nH_n)

3. Flux w/ $\bar{\nu}_\mu$-Hydrogen interaction with efficient “fast” neutron reconstruction

   ⇒ Large mass (10 tons) SuperFGD-like detector (C_nH_n)

4. Resolve nuclear effects with low-energy proton reconstruction

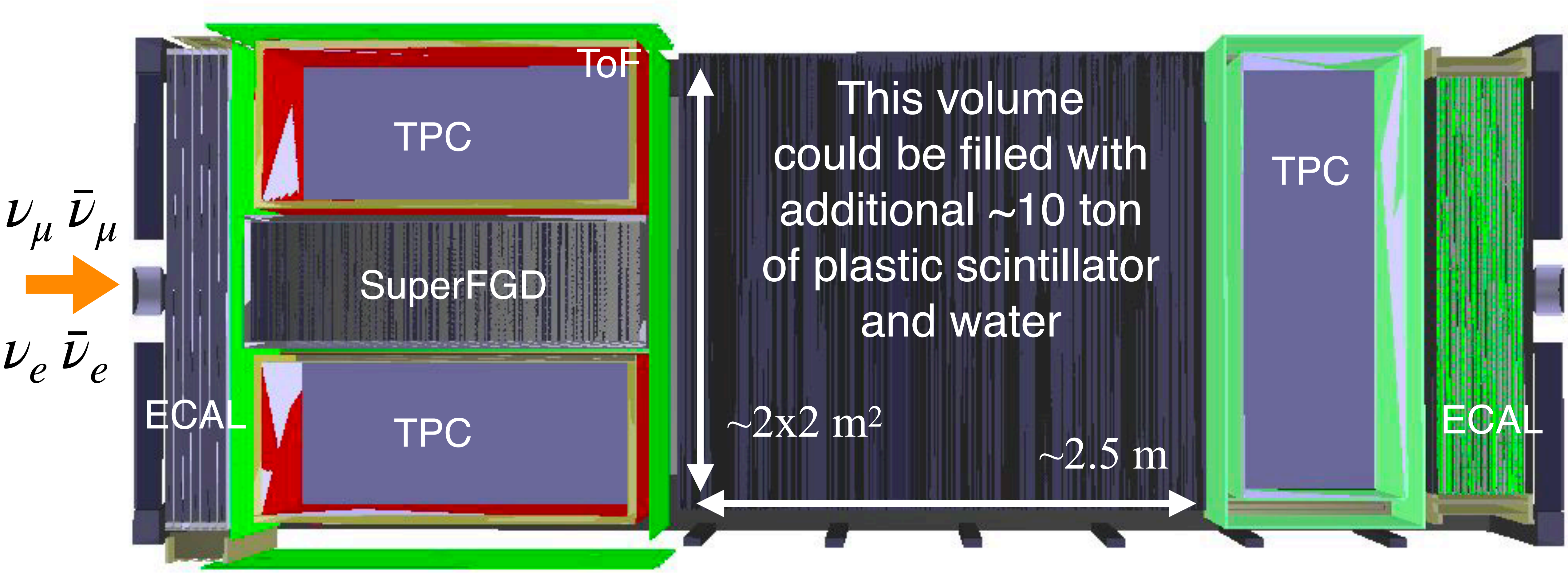
   ⇒ Very fine tracking resolution plastic scintillator (new configuration)

5. Measure interactions in water (ν_μ and $\bar{\nu}_\mu$)

   ⇒ High H_2O/CH content ratio in SuperFGD-like detector

Where could we further upgrade ND280 ?

- About 10t additional active mass (12t if we include SuperFGD)
- Trade off between amount of water and detection performance



Developing the technologies to allow for scalability of SuperFGD to O(10 ton) as well as for high tracking resolution detector

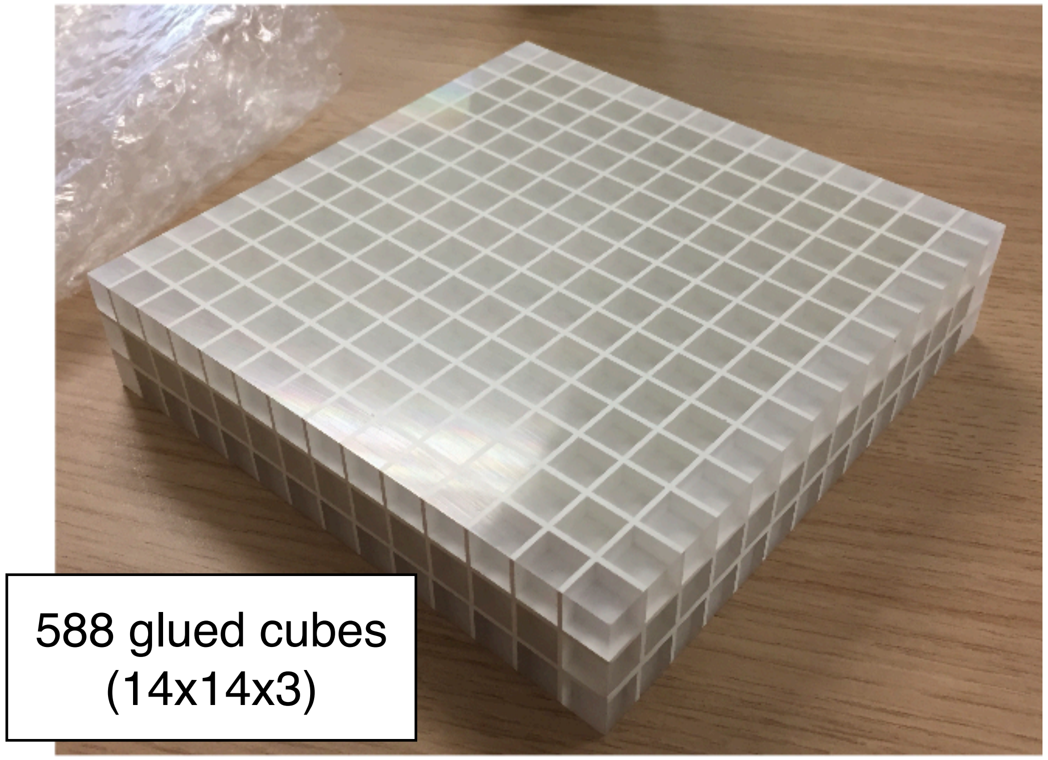
Single-Block

3D-segmented

Plastic-Scintillator

Single-Block 3D-segmented Plastic-Scintillator

- Plastic scintillator UPS 923A, produced with cast polymerization
  - polystyrene, 2% of PTP and 0.05% of POPOP by weight
  - Used in different HEP experiments (e.g. ICARUS veto)
- Then it's processed with CNC machine, using *array production technology*
  - 1 mm gap between the elements, filled with white-reflective epoxy resin
- The result is a matrix of optically-independent cubes glued together

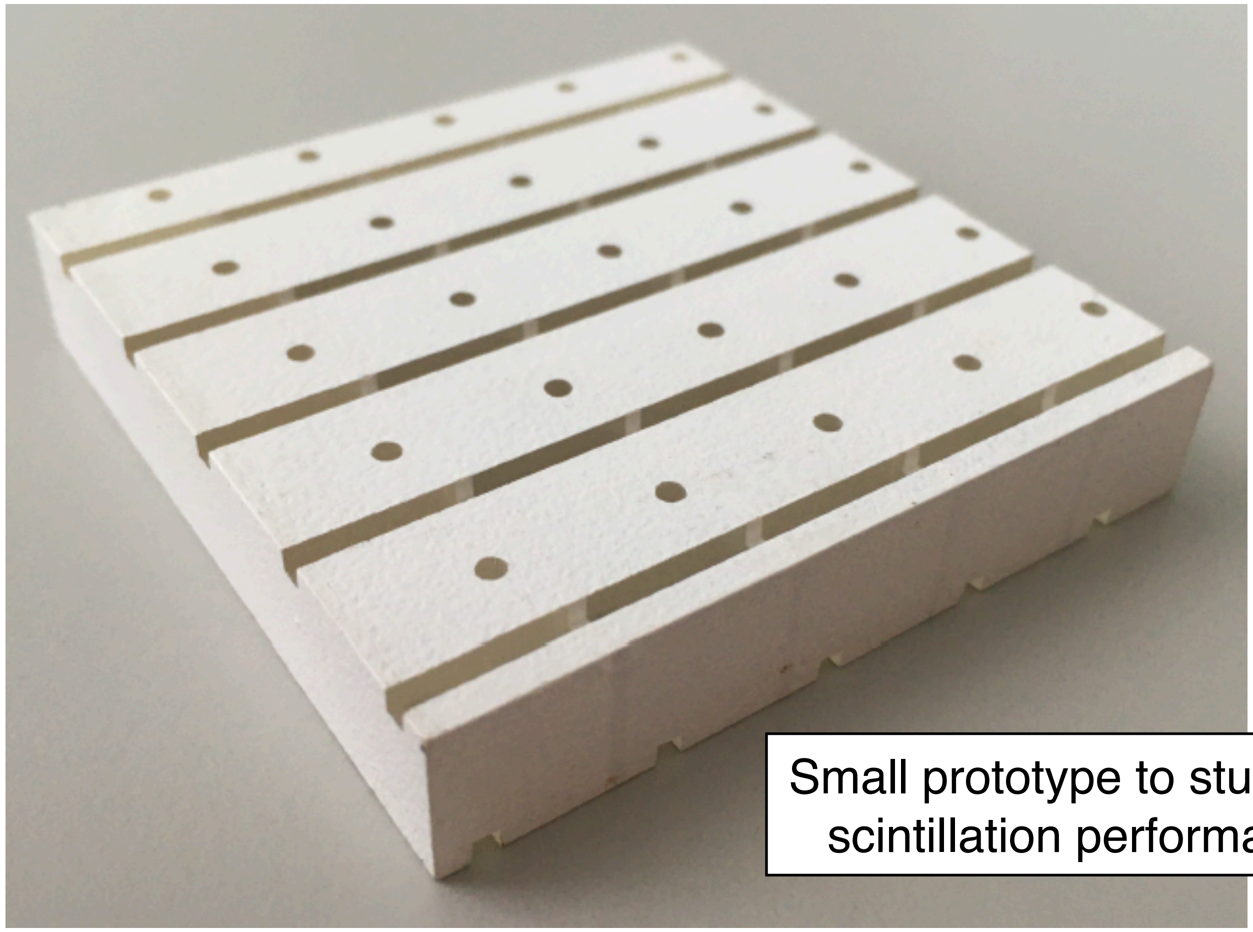


588 glued cubes
(14x14x3)

- The SuperLayer can reach sizes up to 50x100 cm^2 (potentially 50x200 cm^2)

Production at ISMA
(Institute for Scintillation
Materials in Ukraine)

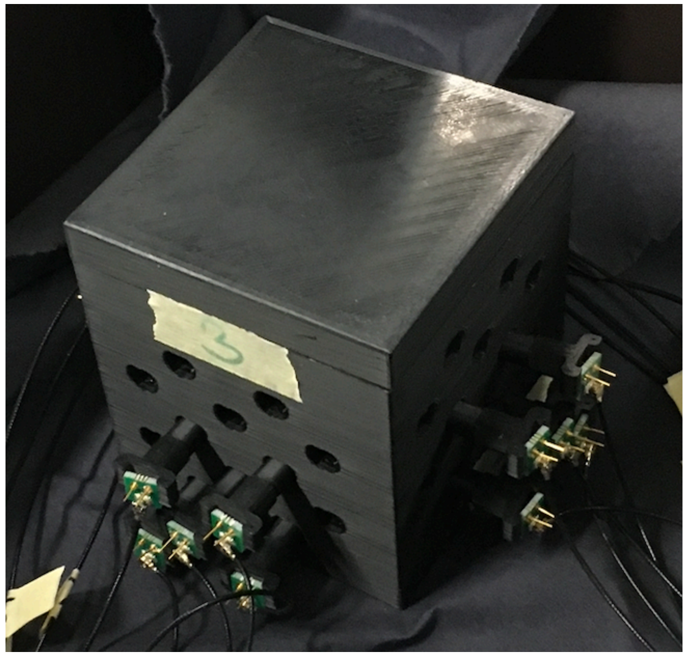
Single-Block 3D-segmented Plastic-Scintillator



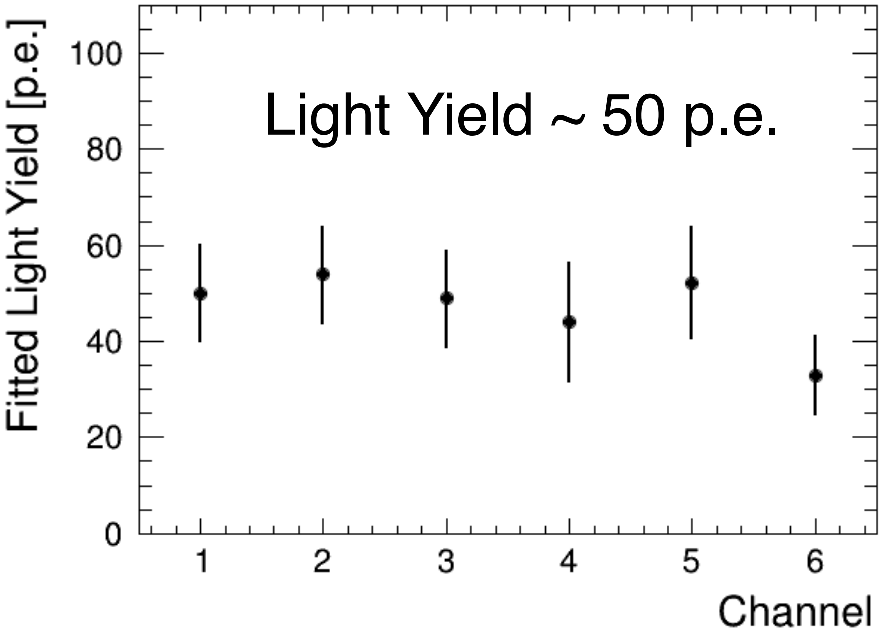
Small prototype to study the scintillation performance

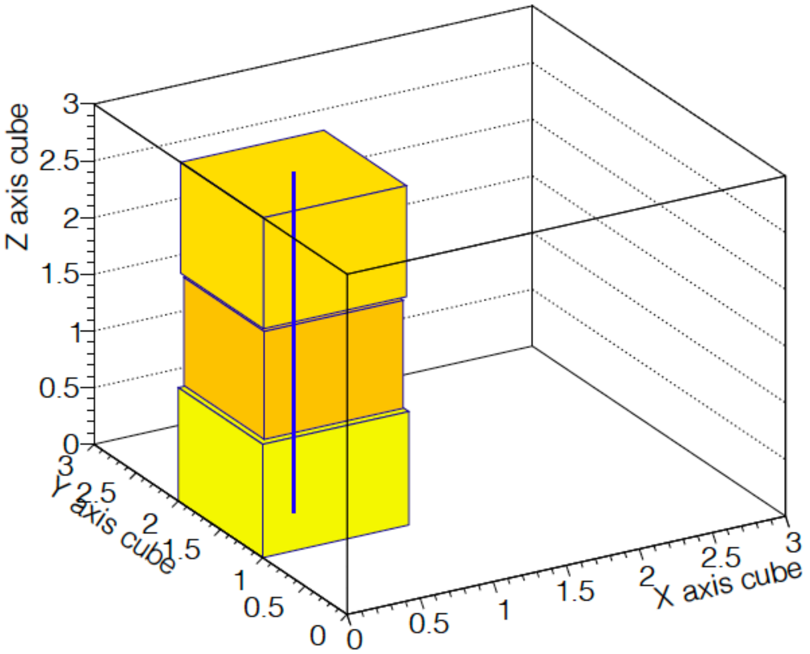
- Once it’s produced, the glued-cube matrix is painted with TiO_2 reflector
  - ✦ Overall tolerances up to 0.2mm (machining precision)
- Not possible to drill 1.5mm holes through several cm. We opted for:
  - ✦ Independent glued-cube layers (SuperLayer)
  - ✦ Two horizontal grooves and a vertical hole for three-view readout
  - ✦ Tyvek sheet provide addition optical isolation between SuperLayers

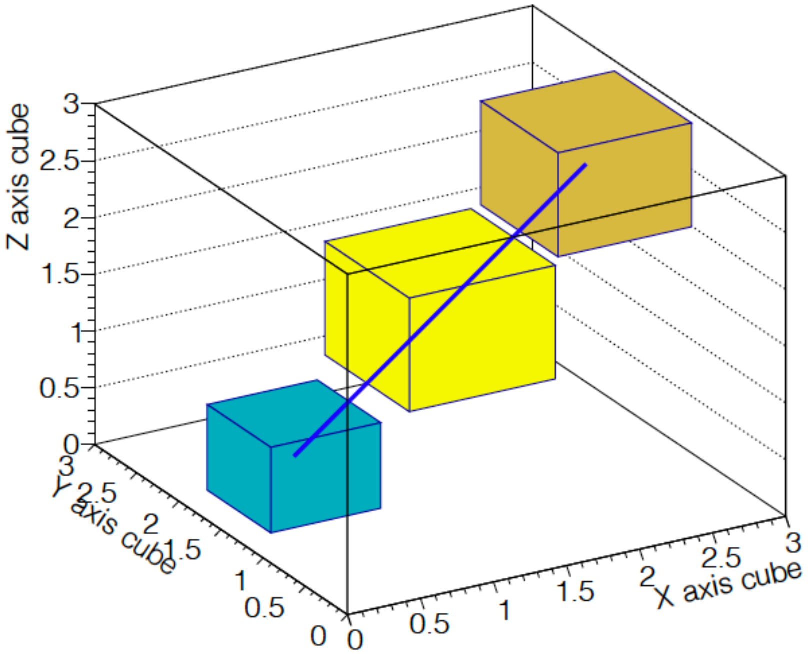
Single-Block 3D-segmented Plastic-Scintillator

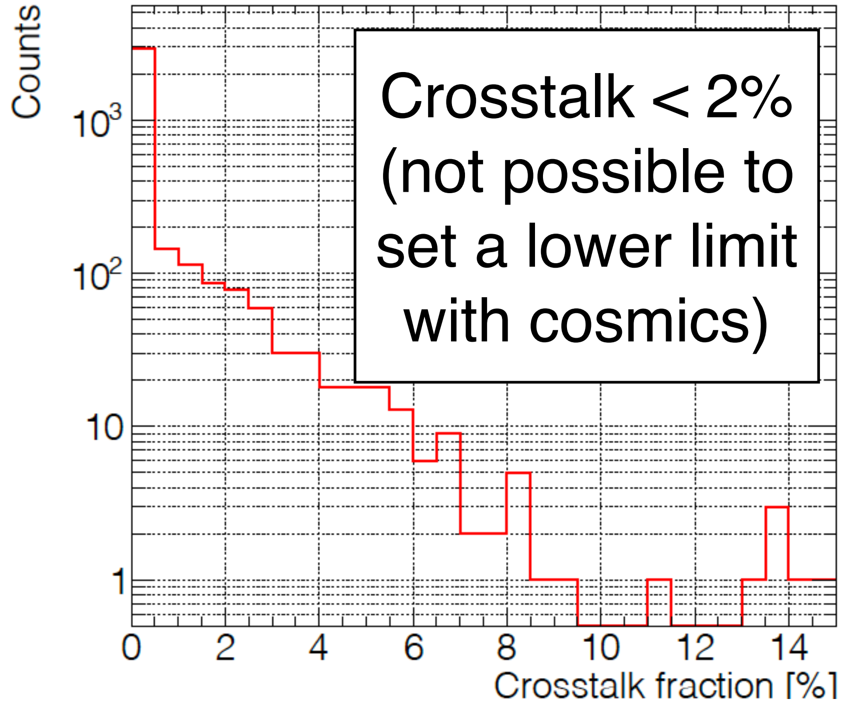


- MPPC S13360-1350CS (PDE~40%) and CAEN DT5702 board


Light Yield ~ 50 p.e.



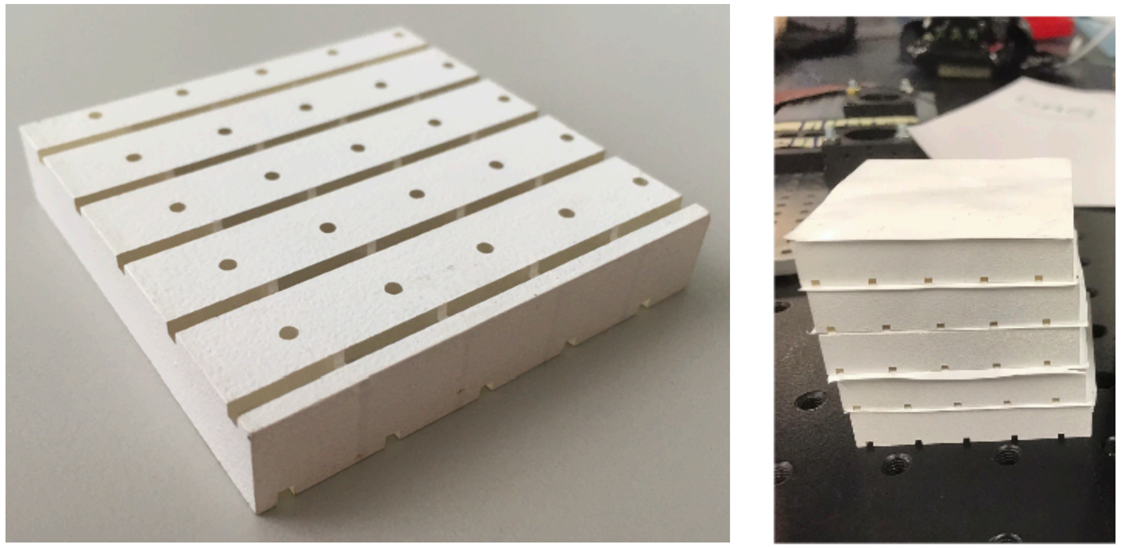


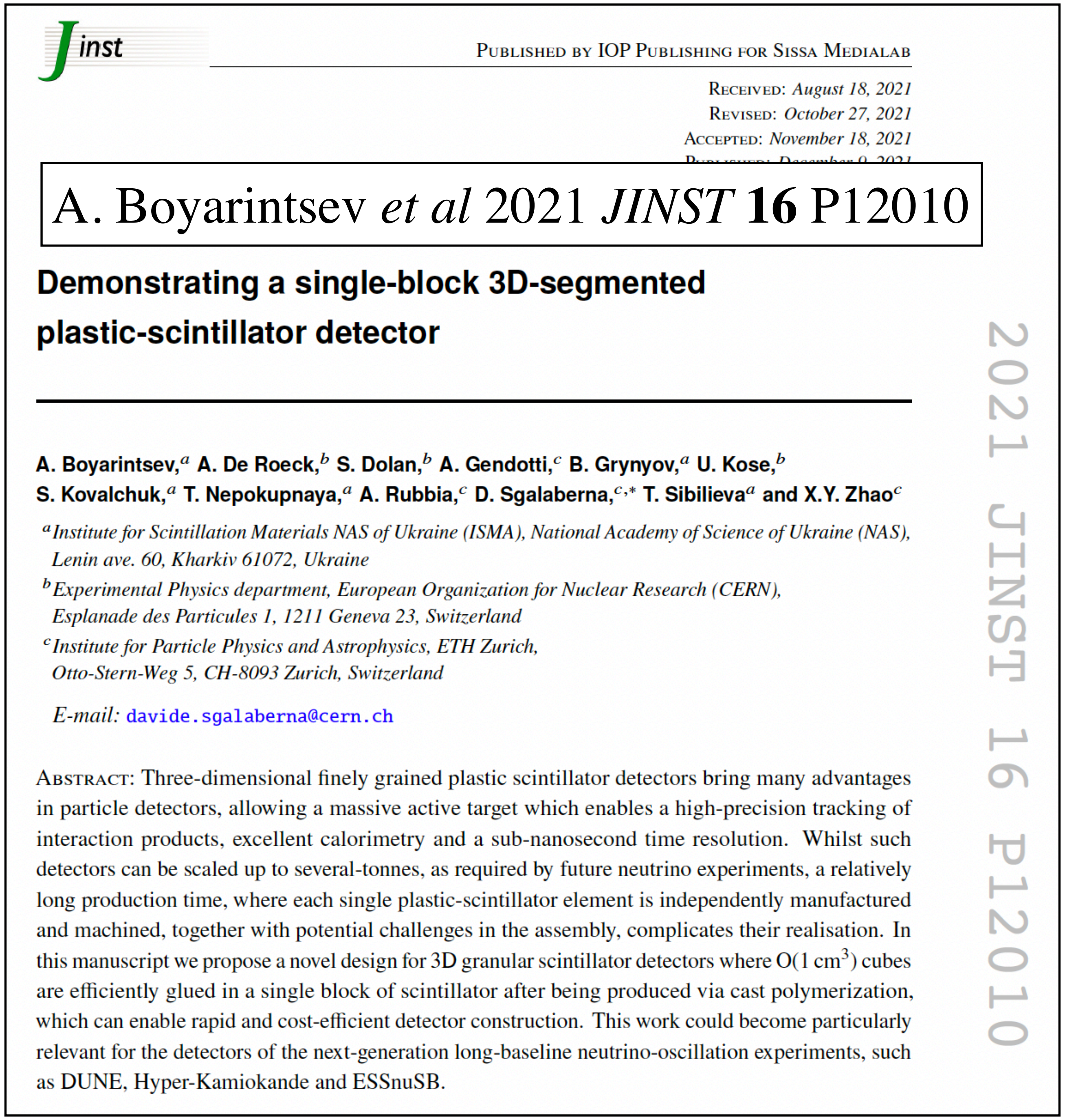

Crosstalk < 2% (not possible to set a lower limit with cosmics)

- LY ~20% lower than SuperFGD cubes but also crosstalk (<2% vs 3-4%)
- To increase the scintillator light yield, other plastic scintillator options can be used

Single-Block 3D-segmented Plastic-Scintillator

- Developed a production process to scale SuperFGD to several tonnes
  - *Successfully tested a SuperLayer*: glued optically-isolated 1cm^3 cubes made of polystyrene scintillator
  - We can reach sizes up to 50x100 cm^2 (potentially 50x200 cm^2)





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Demonstrating a single-block 3D-segmented plastic-scintillator detector

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Abstract: Three-dimensional finely grained plastic scintillator detectors bring many advantages in particle detectors, allowing a massive active target which enables a high-precision tracking of interaction products, excellent calorimetry and a sub-nanosecond time resolution. Whilst such detectors can be scaled up to several-tonnes, as required by future neutrino experiments, a relatively long production time, where each single plastic-scintillator element is independently manufactured and machined, together with potential challenges in the assembly, complicates their realisation. In this manuscript we propose a novel design for 3D granular scintillator detectors where O(1 cm^3) cubes are efficiently glued in a single block of scintillator after being produced via cast polymerization, which can enable rapid and cost-efficient detector construction. This work could become particularly relevant for the detectors of the next-generation long-baseline neutrino-oscillation experiments, such as DUNE, Hyper-Kamiokande and ESSnuSB.

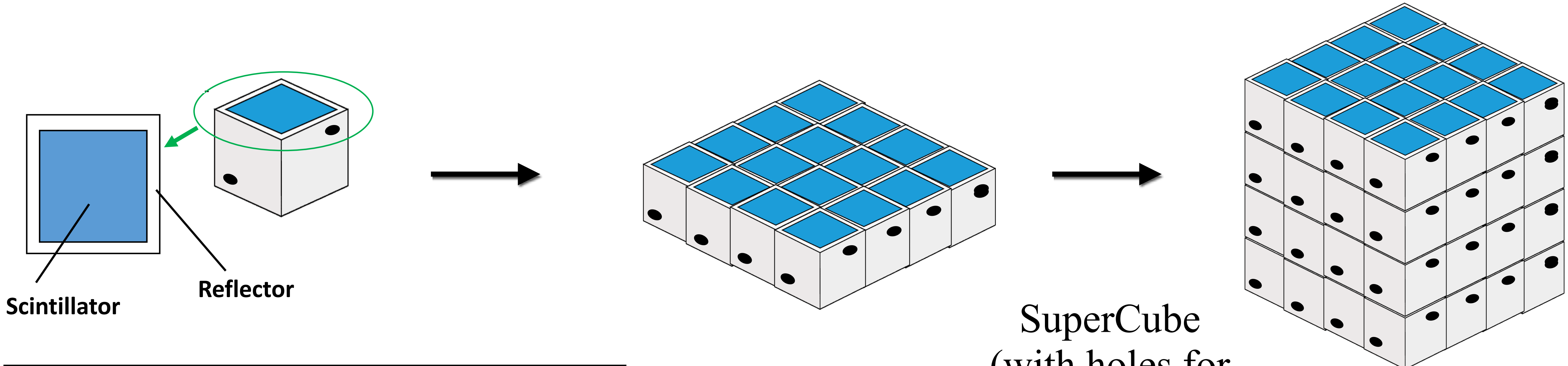
2021 JINST 16 P12010

Production time can be 1-1.5 years for 4-5 tons of scintillators
Assembly time is much shorter than one need for SuperFGD

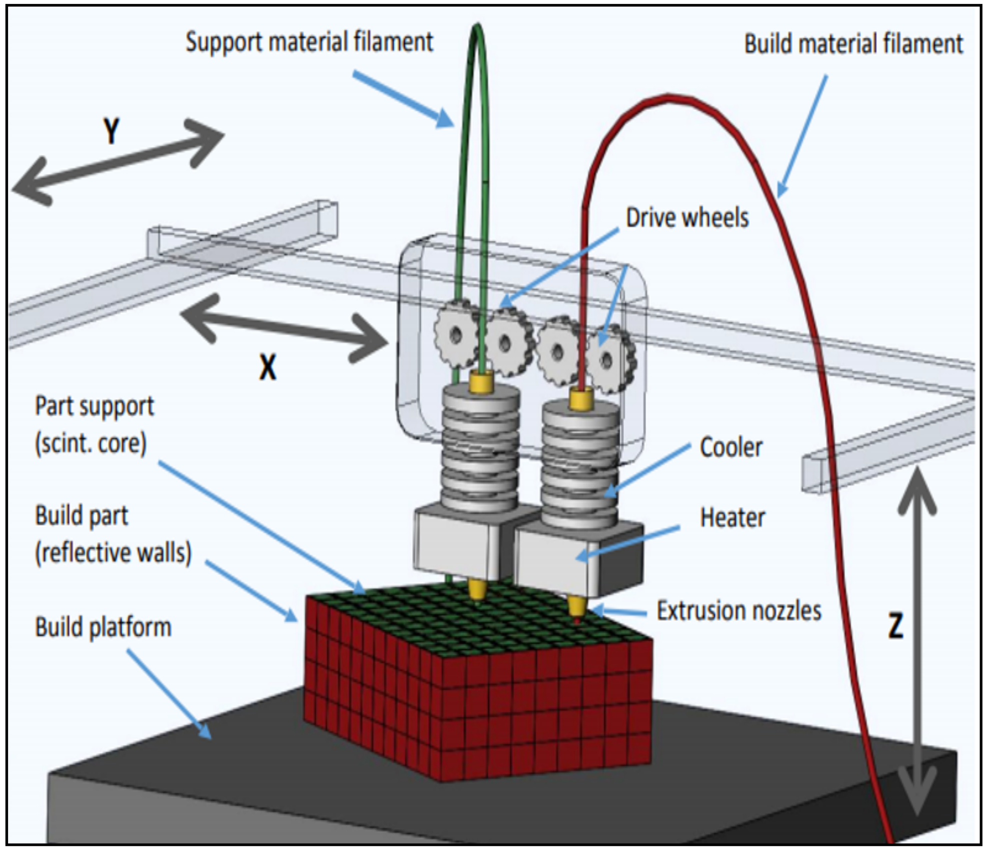
3D printing of

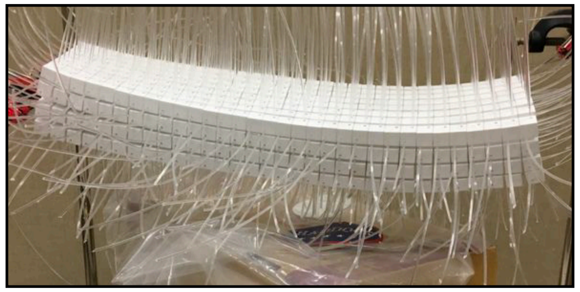
Plastic Scintillator

3D printing a scintillating "SuperCube"



SuperCube
(with holes for
WLS fibers)





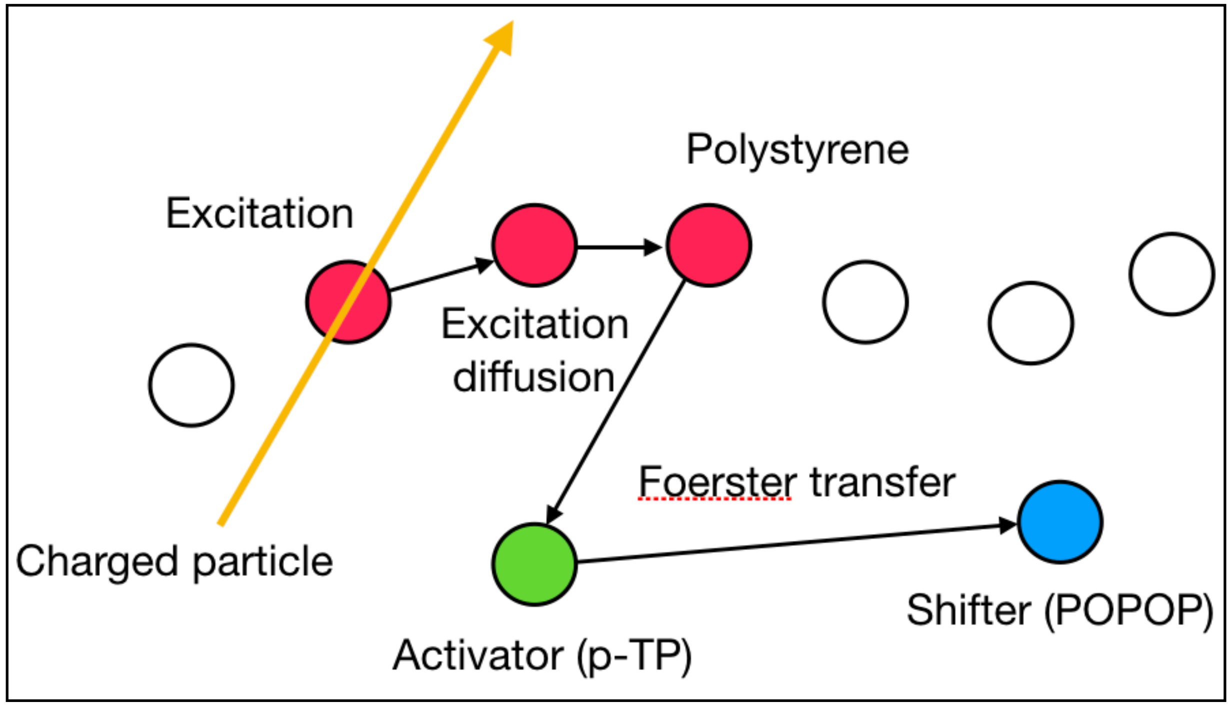
Need a technology that can:

- Achieve good scintillation performance and high transparency in the scintillator core
- 3D print big volumes in relatively short time
- Robust (and relatively cheap)
- 3D print simultaneously more materials

Fused Deposition Modeling (FDM) is a promising solution

Cheaper and faster than standard method with subtractive processes

The proof of the concept



Excitation

Polystyrene

Excitation diffusion

Foerster transfer

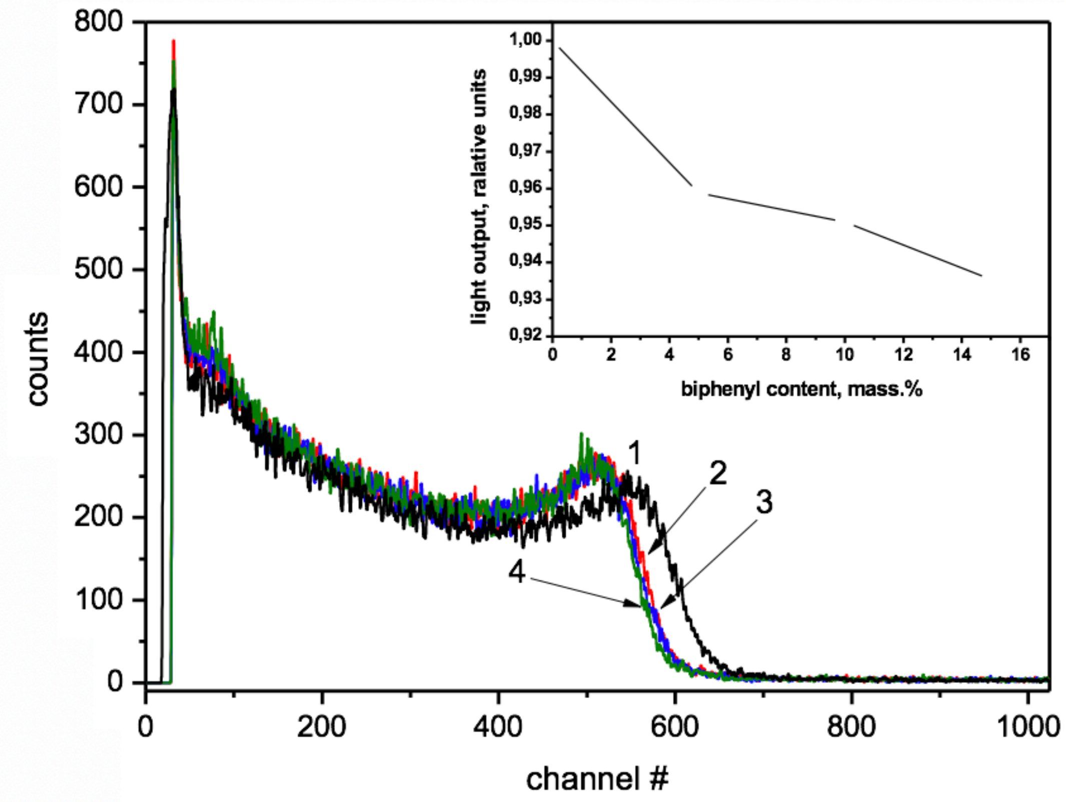
Charged particle

Shifter (POPOP)

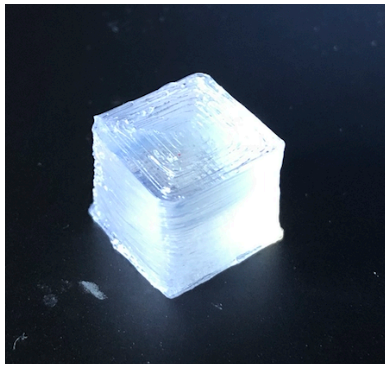
Activator (p-TP)

Optimal composition is polystyrene + pTP + POPOP: tested both w/ and w/o 5% biphenyl as plasticiser

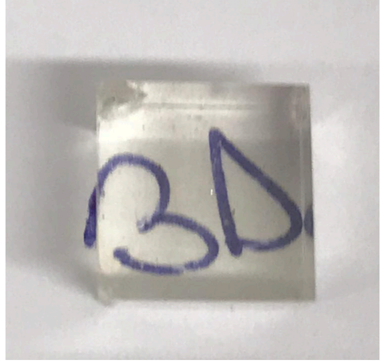
Polystyrene is well known
⇒No need to "invent" a new chemical composition !



The proof of the concept



The outermost surface is always opaque. Characteristic of FDM



MPPC coupled directly with scintillator cube in black connector (no white reflector envelope)

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Additive manufacturing of fine-granularity optically-isolated plastic scintillator elements

The 3DET collaboration

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Abstract: Plastic scintillator detectors are used in high energy physics as well as for diagnostic imaging in medicine, beam monitoring on hadron therapy, muon tomography, dosimetry and many security applications. To combine particle tracking and calorimetry it is necessary to build detectors with three-dimensional granularity, i.e. small voxels of scintillator optically isolated from each other. Recently, the 3DET collaboration demonstrated the possibility to 3D print polystyrene-based scintillators with a light output performance close to that obtained with standard production methods. In this article, after providing a further characterization of the developed scintillators, we show the first matrix of plastic scintillator cubes optically separated by a white reflector material entirely 3D printed with fused deposition modeling. This is a major milestone towards the 3D printing of the first real particle detector. A discussion of the results as well as the next steps in the R&D is also provided.

Keywords: Calorimeters; dE/dx detectors; Particle tracking detectors; Scintillators and scintillating fibres and light guides

ArXiv ePrint: 2202.10961

2022 JINST 17 P10045

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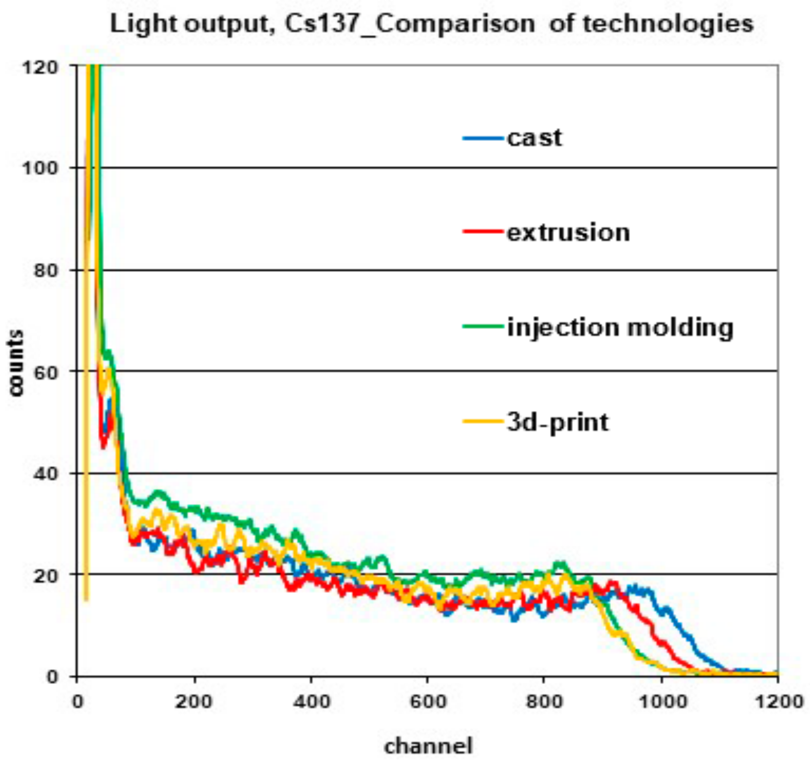
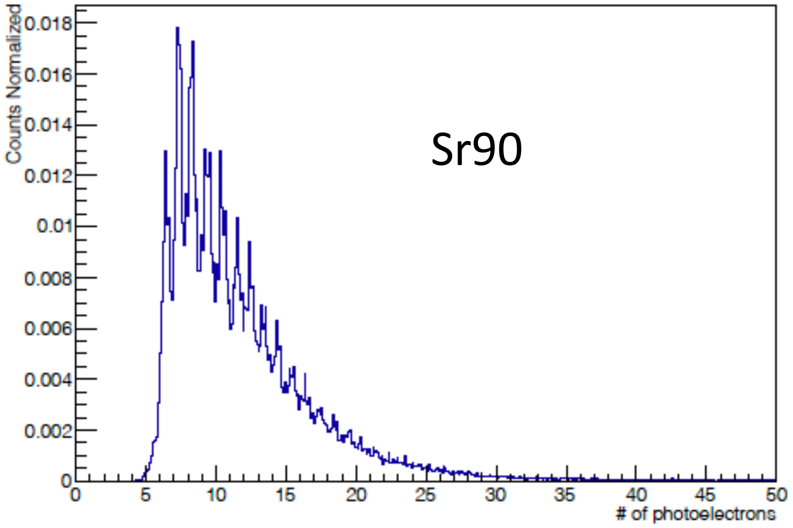
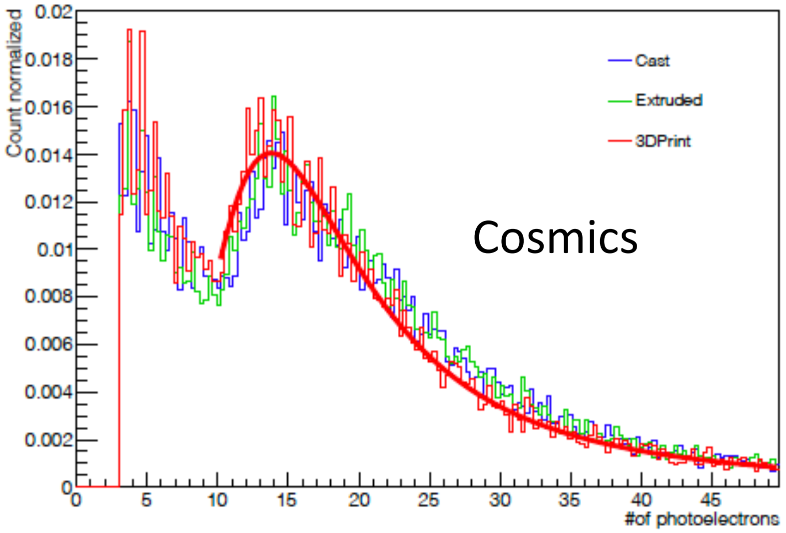
[*] Corresponding author.

Results confirmed with PMT on Cs^{137} source (with reflector envelope)



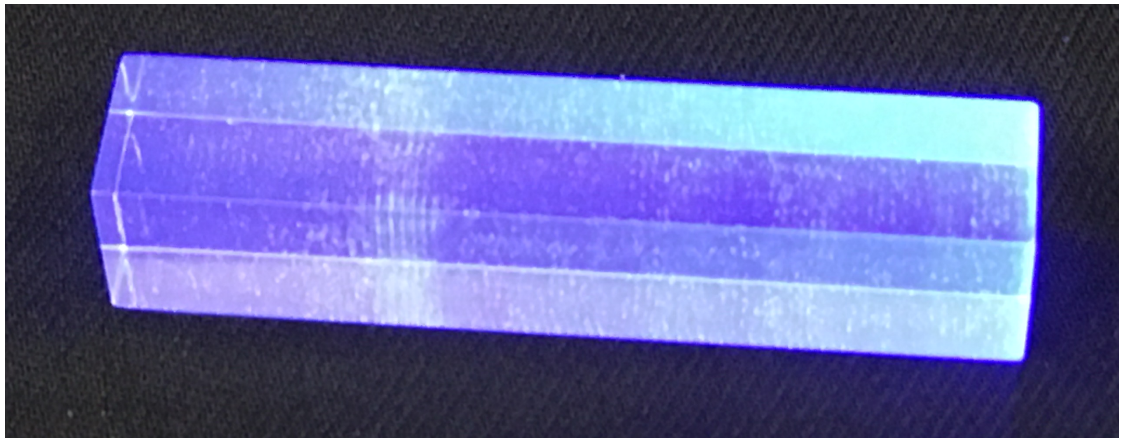


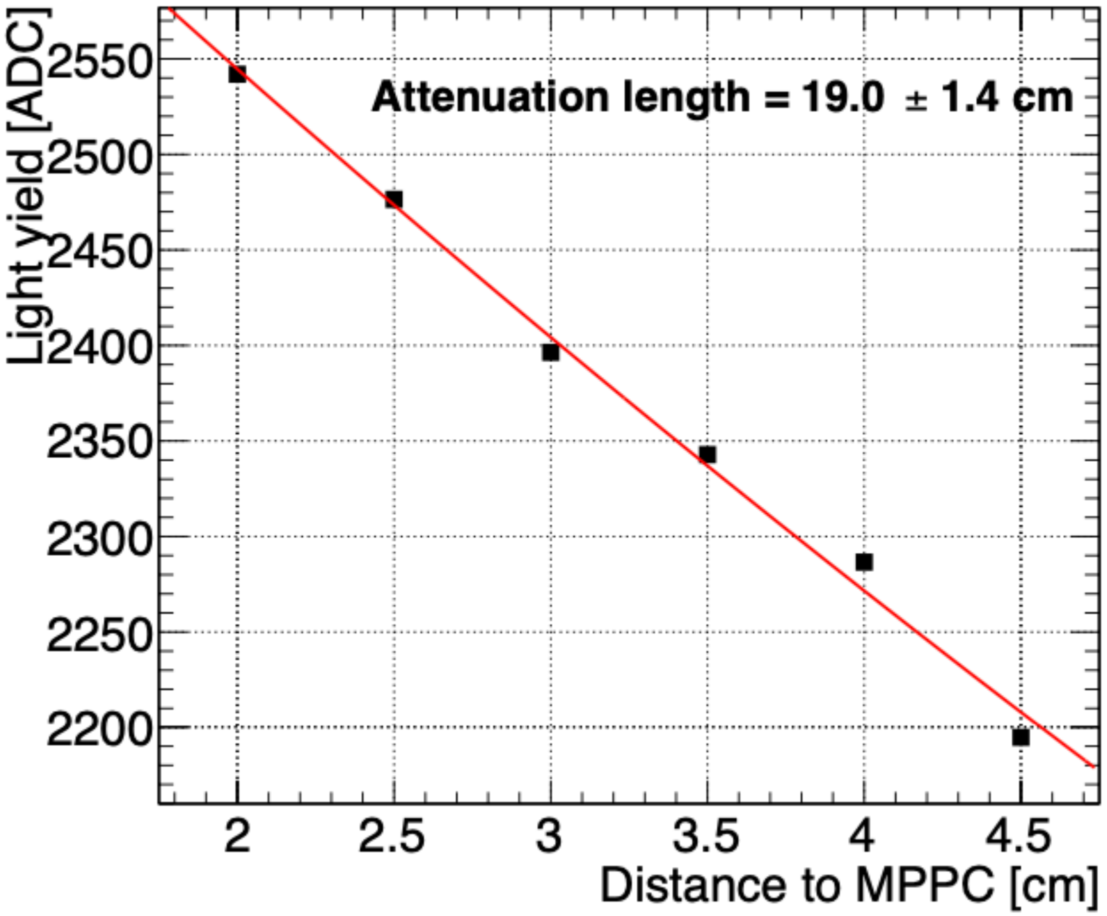


Light Yield comparable with the one of standard production techniques

Attenuation length (technical) with 3D printing

Transparency measured from 5 cm-long bar





- Polished on the outermost surface and covered with white teflon. Tests performed also with black cover.
- SiPM on one end + Sr^{90}/Y^{90} source moving at different positions
- Sparse presence of small air bubbles

The scintillator transparency was found to be sufficiently good for few-cm granularity detectors

Latest developments suggest an even better transparency (see next slides)

Opaque Scintillator

We managed to 3D print plastic scintillator with different opacity

- ✦ We can tune the transparency of the scintillator inside each voxel
- ✦ Possible application for beam monitoring or single particles events
- ✦ Ambiguities in dE/dx vs particle position
  ⇒ not optimal for accelerator neutrino interactions

From milky to transparent →

Optimal strategy for good surface not used here

Plan to perform tests and characterise it in the future

3D printed optical reflector

Polymer pellets

+

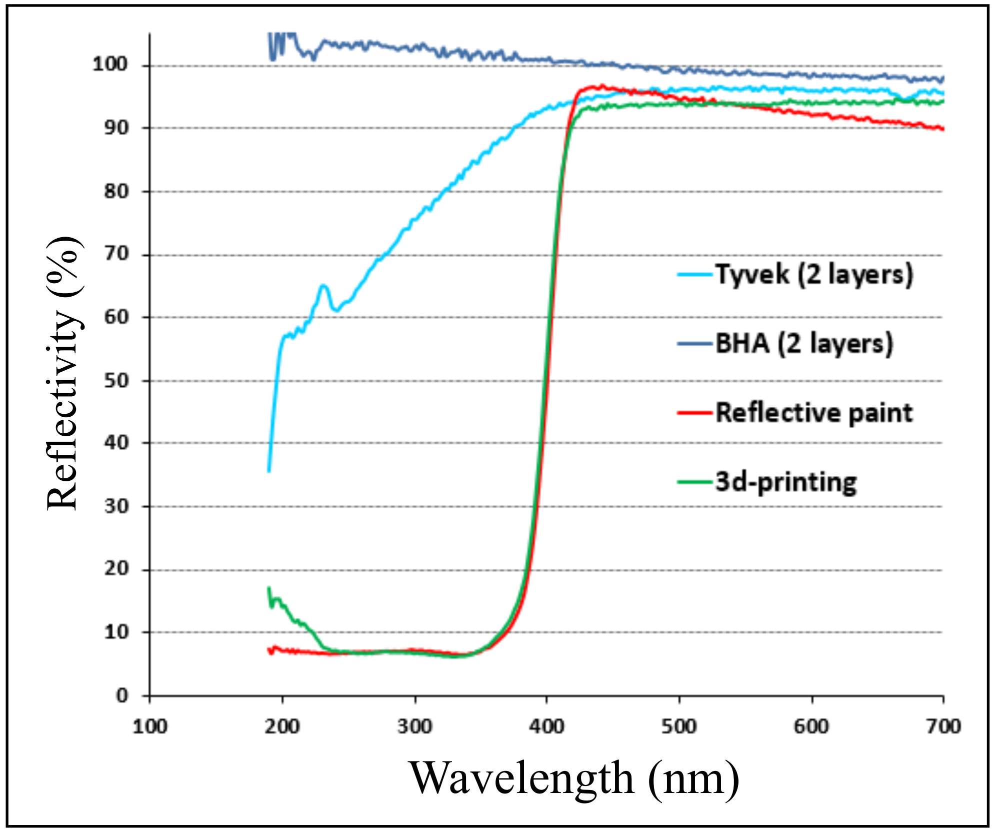
Reflective pigment TiO2
(or BaSO4, MgO…)

=

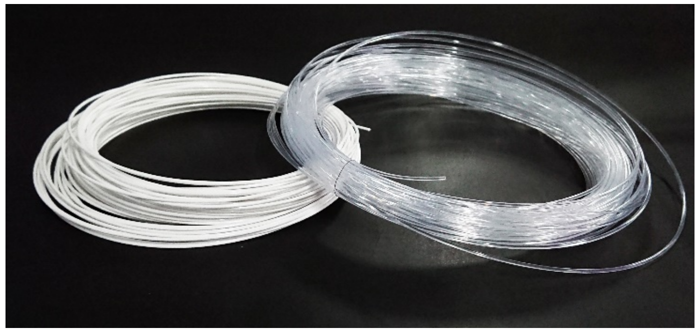
Reflective filament

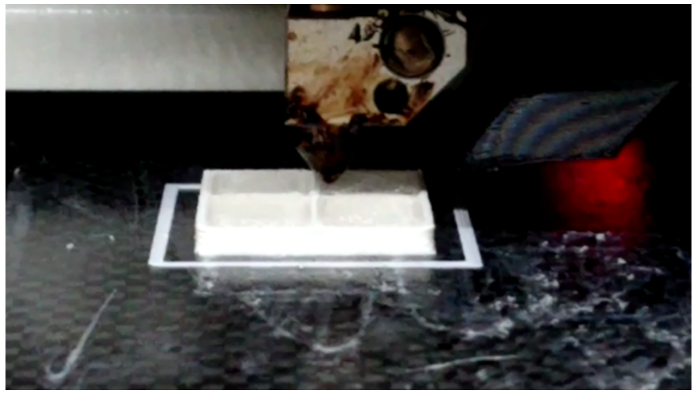
Polymer mixed with TiO_2	Reflectivity at $\lambda = 420$ nm (%)
ABS	87.5
HIPS	87.1
PC	76.1
PMMA	90.6
PS	91.1

Similar reflectivity to TiO_2 paint but less than Tyvek and PTFE (no air gap, lower reflection, surface roughness)



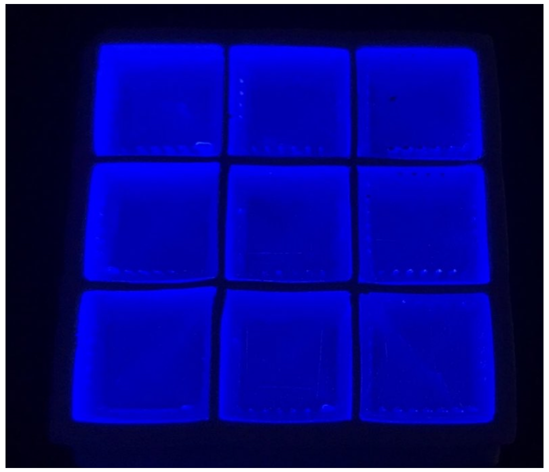
Multi material printing:

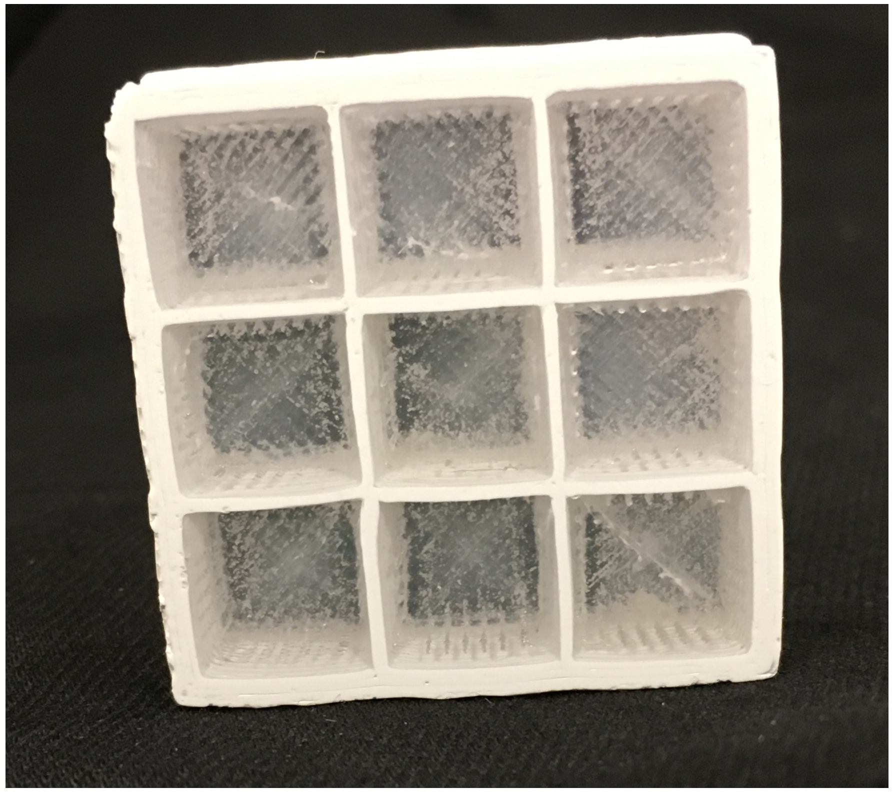




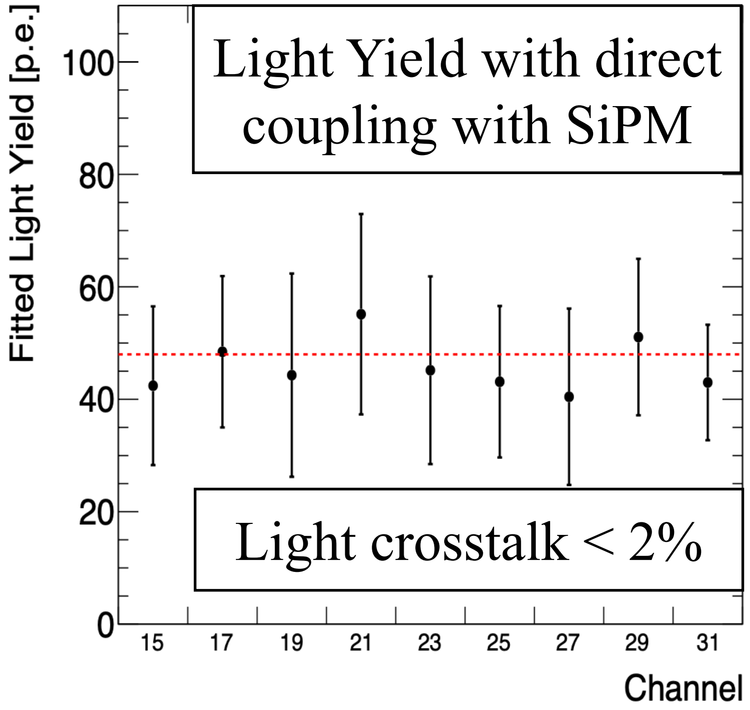
Optically-isolated scintillator cubes

Succeeded to 3D print a matrix of optically-isolated scintillator cubes



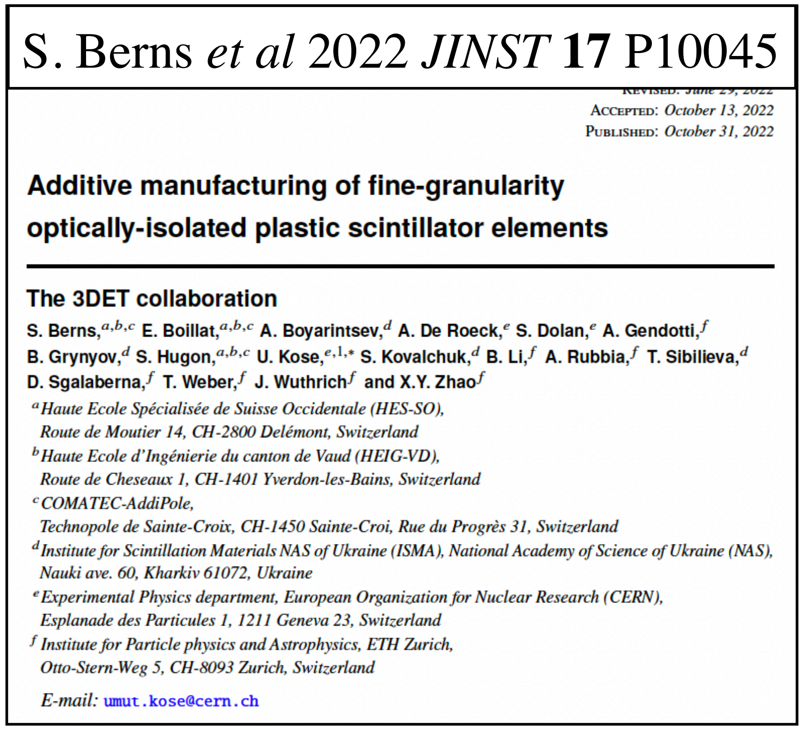


- Good scintillation performances
- Outermost surface not precise due to the melting of the material at high temperatures
- Tolerance on reflector thickness ~0.5 mm
- White remnants in the scintillator (extruder could not move up/down before changing material)



Light Yield with direct coupling with SiPM

Light crosstalk < 2%



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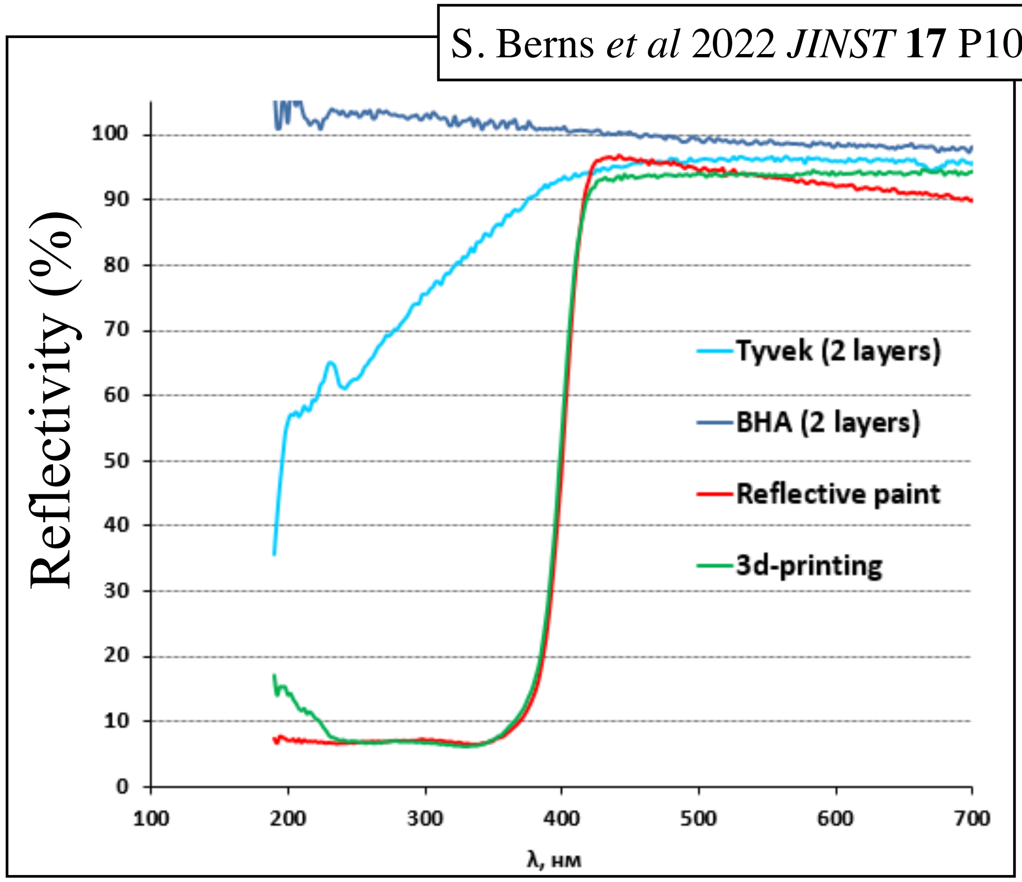
Not yet ultimate quality: it required polishing and no holes for WLS fibers

Heat resistant reflector



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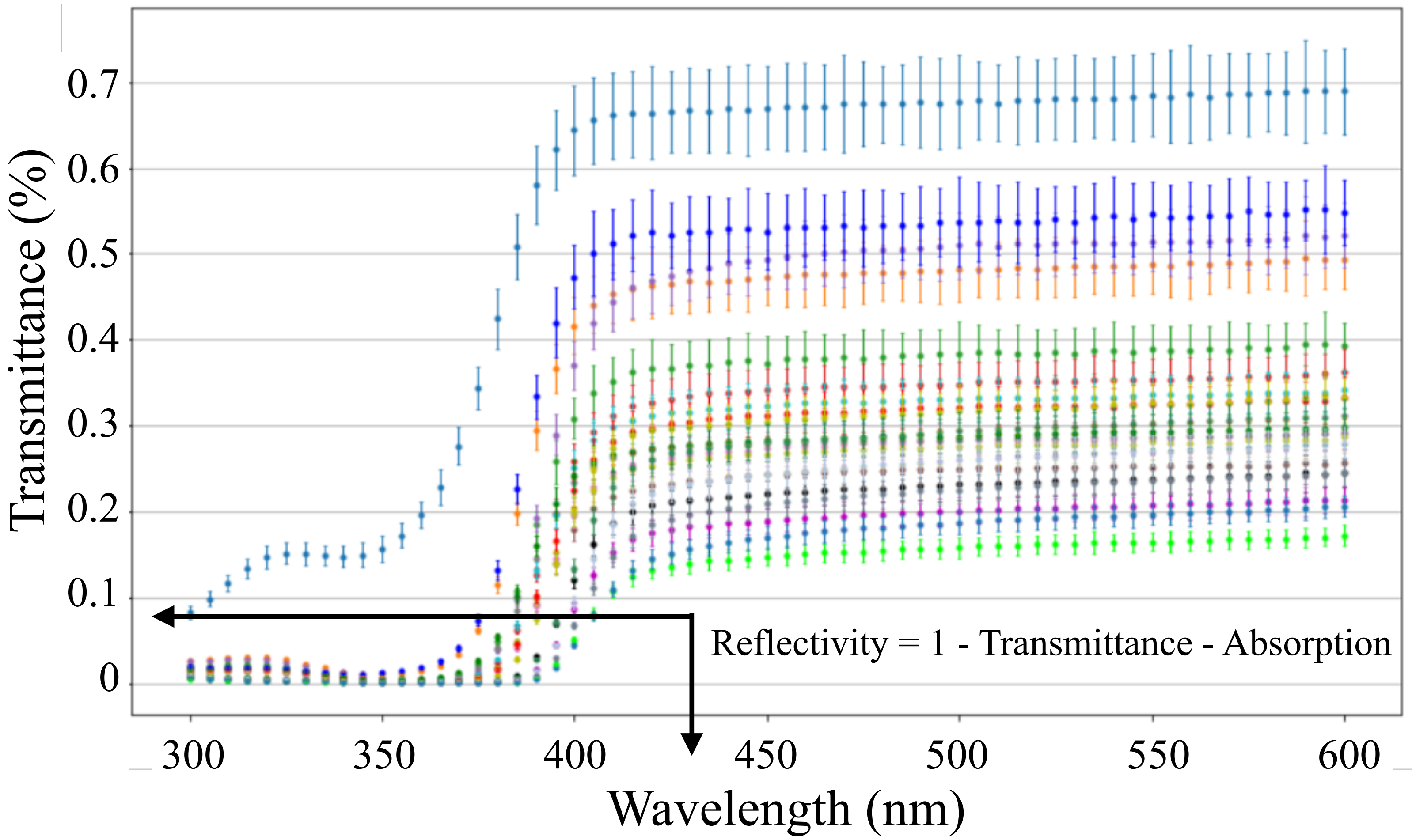
Tested several white filaments on the market resistant to heat up to 270°C (FDM reaches up to ~220°C)

⇒ Polycarbonate (PC) + polytetrafluoroethylene (PTFE)

Light transmittance is worse than our custom filament (~15% vs ~8% @420 nm)

Expect a bit higher cube-to-cube light crosstalk

But heat resistant…



Reflectivity = 1 - Transmittance - Absorption

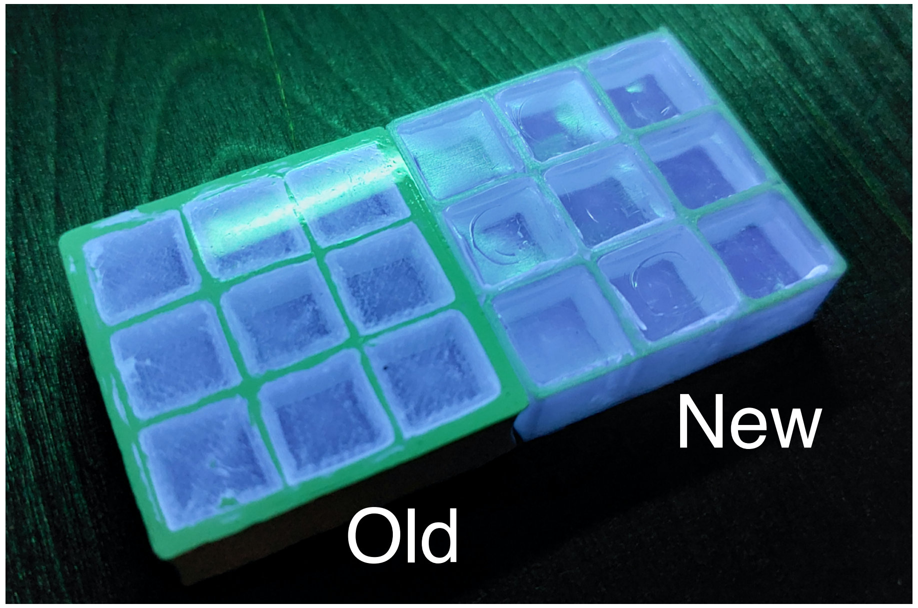
Towards a 3D printed SuperCube

Then, we improved the 3D printing technique to improve geometrical tolerance, transparency (quality) and make the holes for WLS fibers

It had to be polished...

After improving the technique →

Not Polished !!!



- *No polishing needed ! Ready to collect data !*
- Sr^{90} and Cosmic data
  - ✦ *Directly coupled to SiPM ~40 p.e. / cosmic*

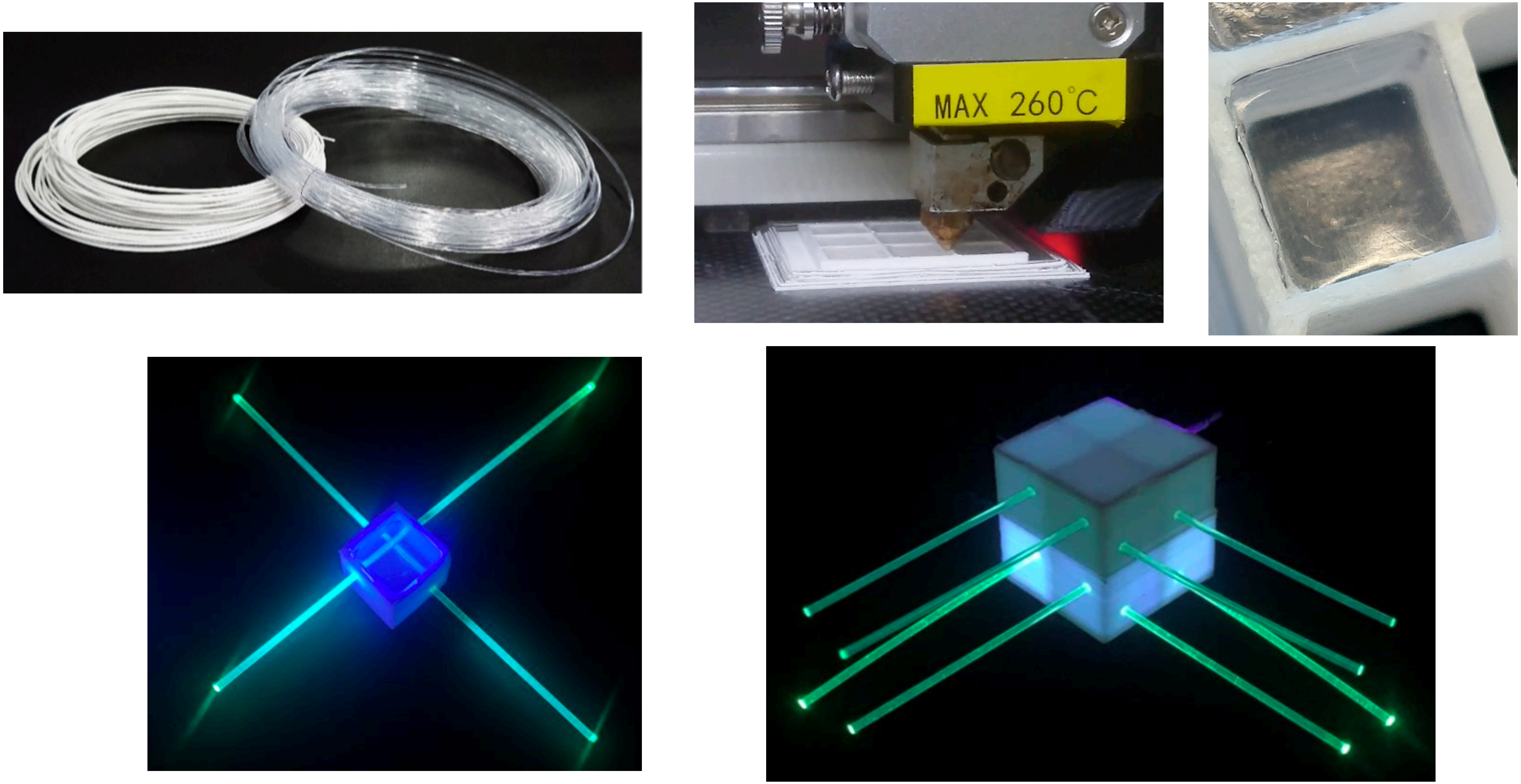
Towards a 3D printed SuperCube

9 optically isolated cubes ready to be directly coupled to SiPM
(no post-processing)

Ready to be instrumented with photosensors and electronics
→ particle detector

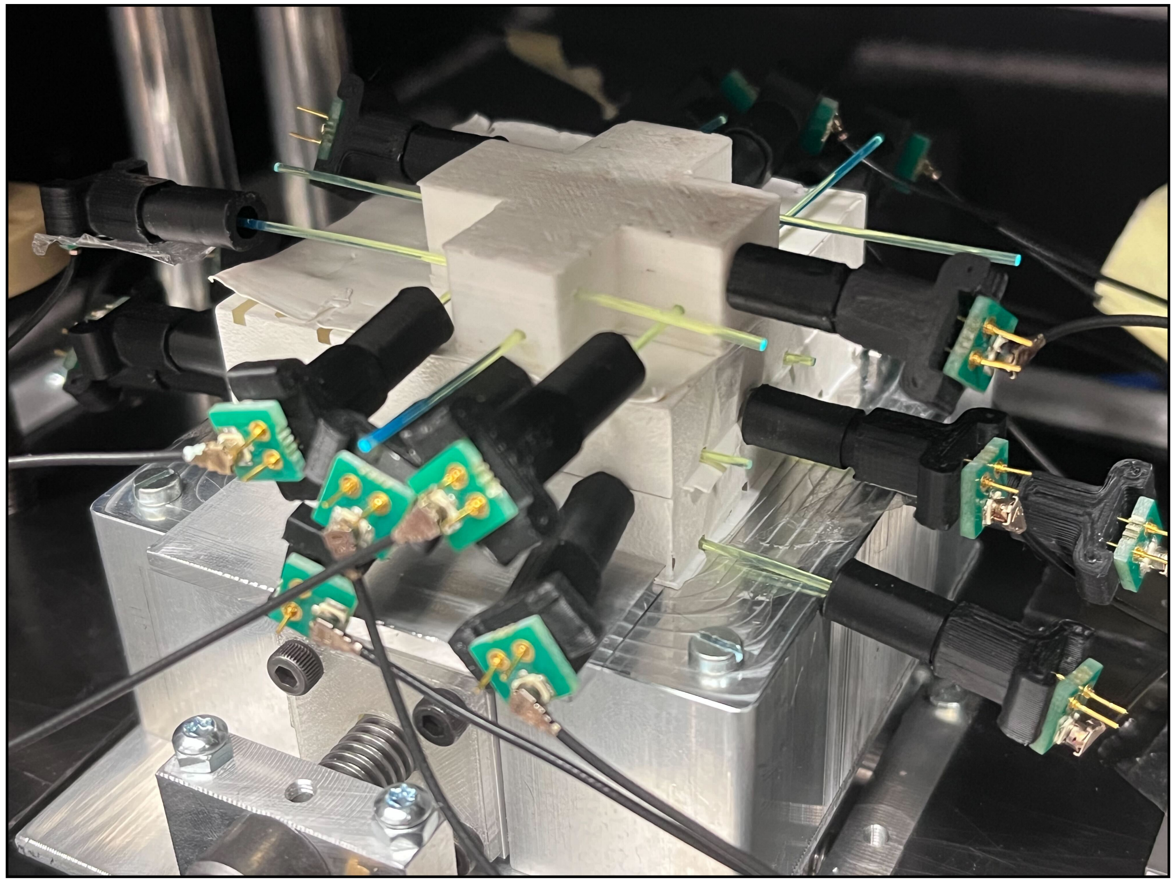
The 3D printed SuperCube

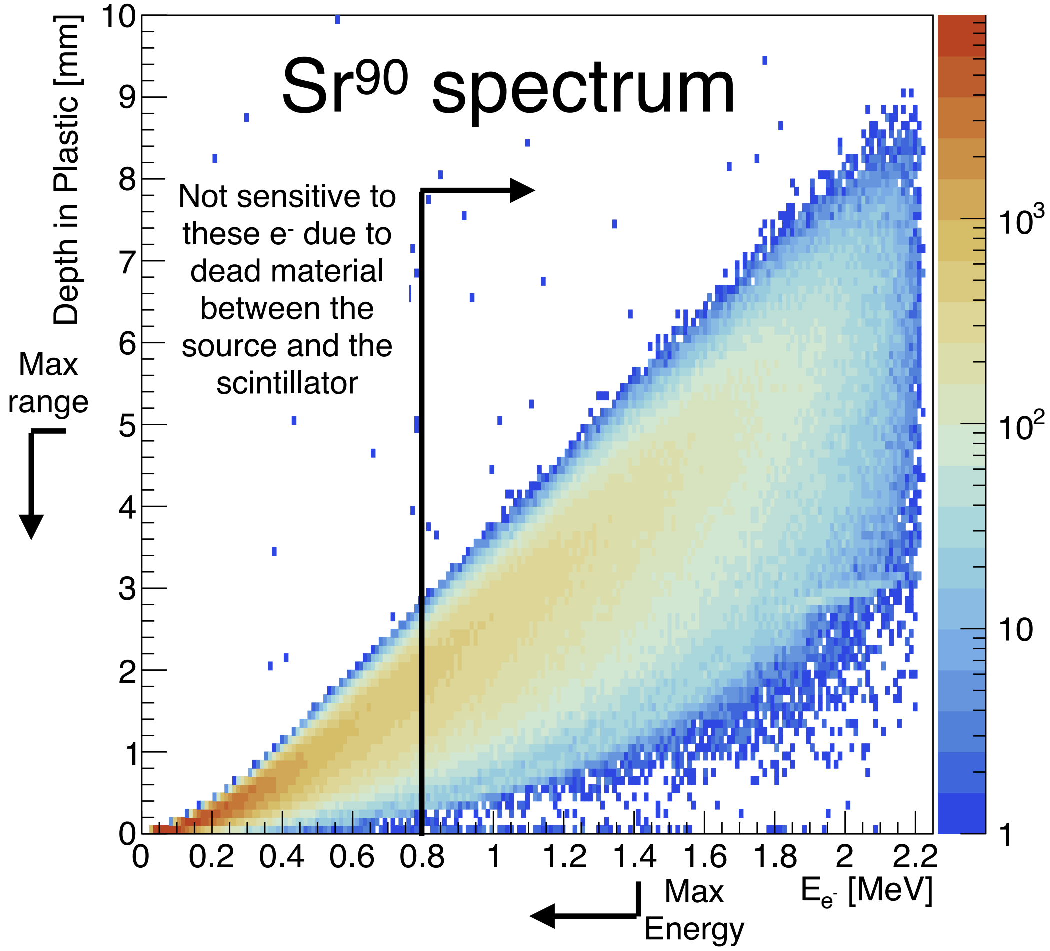
- We managed to make the holes (1.1 mm) to host the WLS fibers



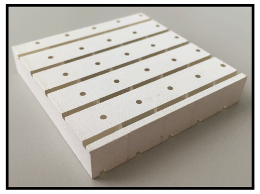
Very good quality right after the printing. No need for post-processing !

The 3D printed SuperCube



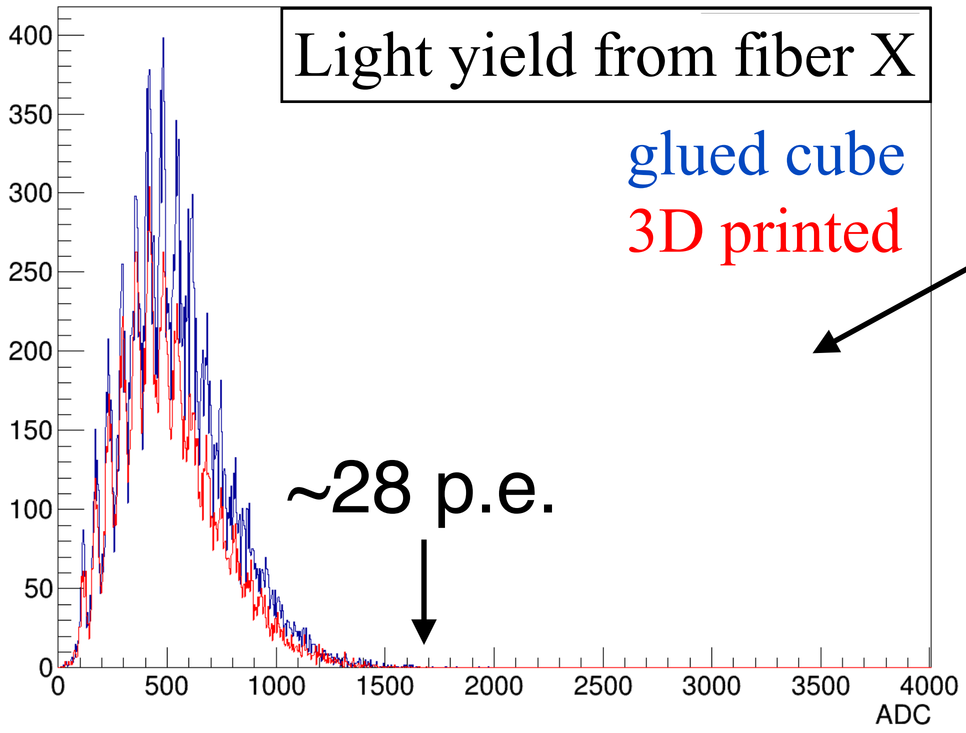


- Read out with Hamamatsu SiPM S13360-1325CS (PDE~25%)
- Electronics readout with CAEN FEB 5702 (CITIROC ASIC)
- Direct comparison with “glued cubes” (see slide 24)
    - ✦ 3D printed SuperCube less sensitive to low-energy electrons because of thicker (1.2 mm) reflector



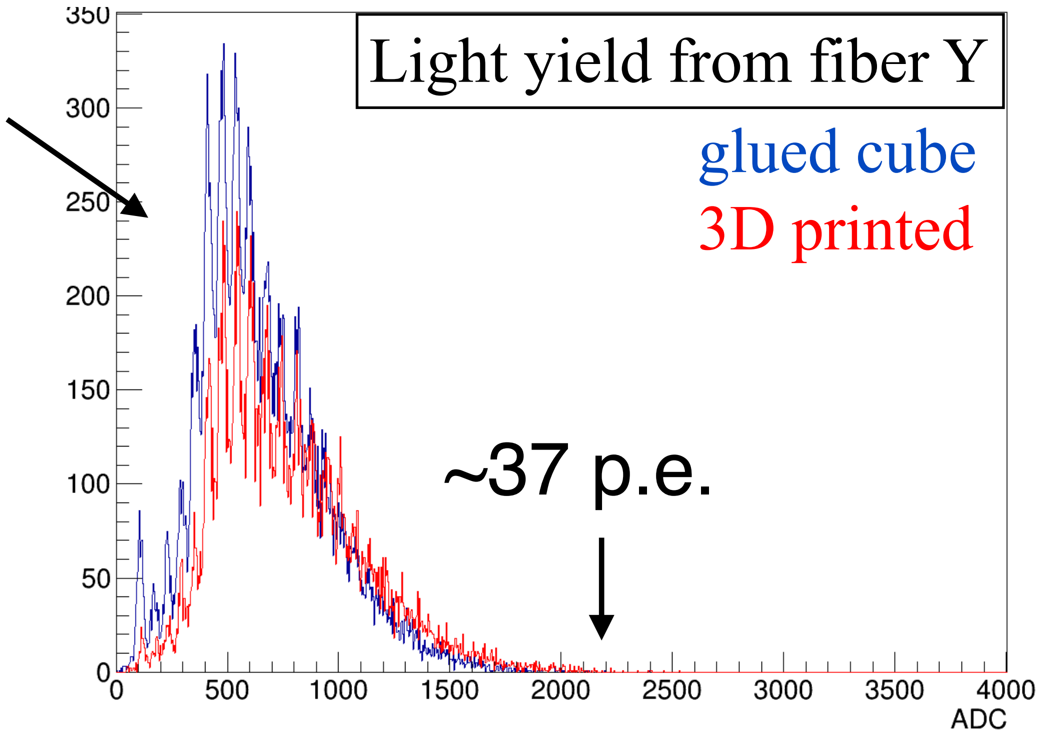
- Compare the measured Sr^{90} end points

The 3D printed SuperCube

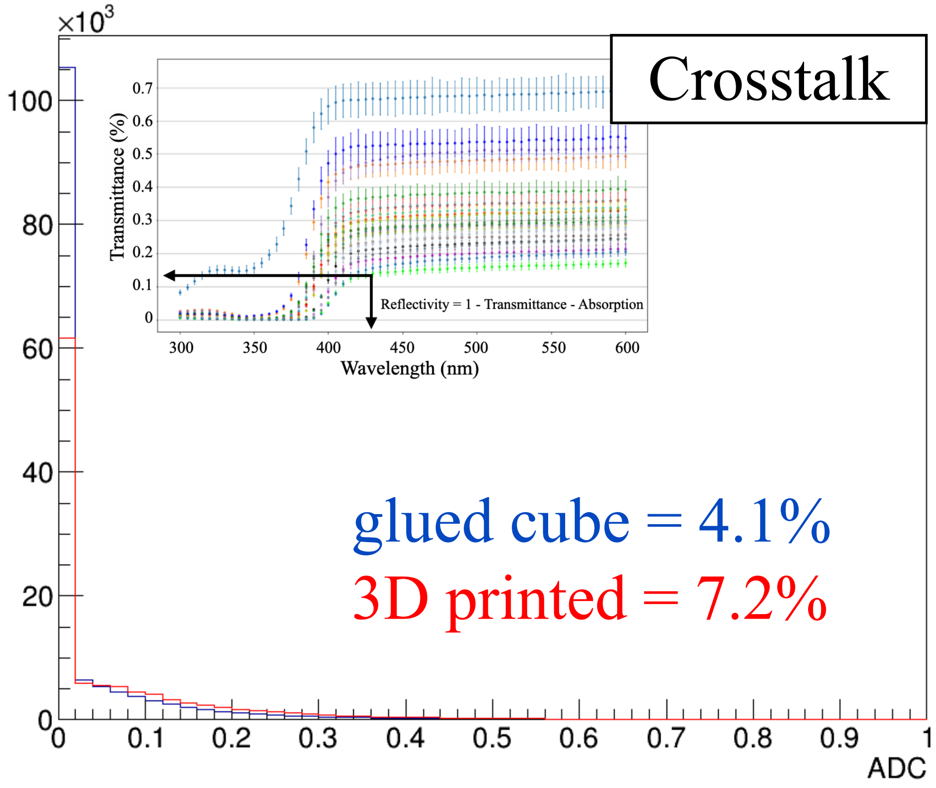

Light yield from fiber X

~28 p.e.

Farthest from
closest to
the electron
stopping point


Light yield from fiber Y

~37 p.e.


Crosstalk

glued cube = 4.1%

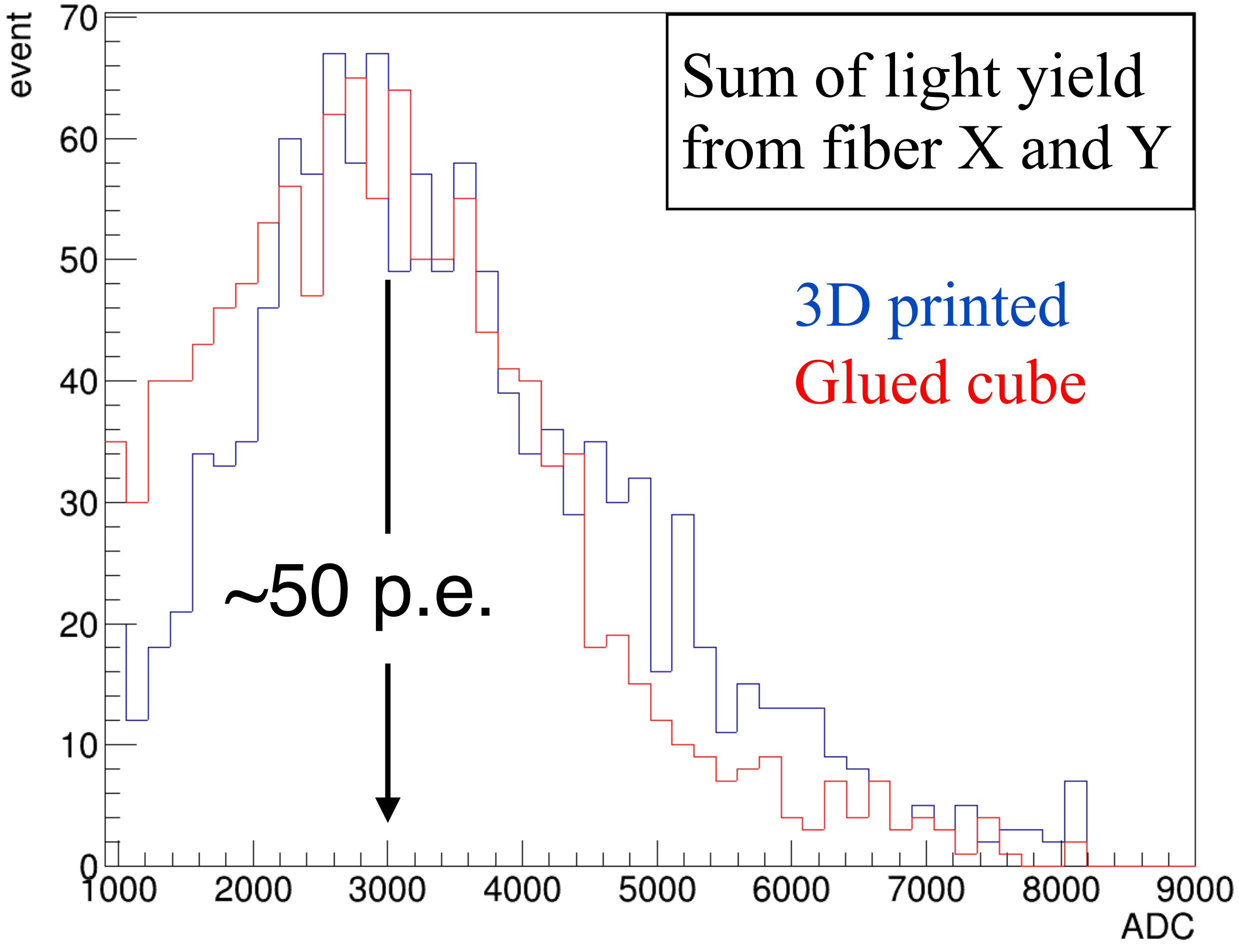
3D printed = 7.2%

Note:
measurements taken with
SiPM pitch = 25 µm (PDE~25%) instead of
SiPM pitch = 50 µm (PDE~40%)
from the previous measurements in this talk

- Light yield comparable to the one of “glued cubes”, depending on the distance between the WLS fiber and the e$^-$ entering point
- As expected, the crosstalk is higher (~7%)

The 3D printed SuperCube

- Collected data also from cosmics and compared again with glued cubes



Successfully tested for the first time a totally 3D printed "final" plastic scintillator detector (no post-processing) with performance acceptable for a particle physics experiment

Note:
measurements taken with
SiPM pitch = 25 µm (PDE~25%) instead of
SiPM pitch = 50 µm (PDE~40%)
from the previous measurements in this talk

Still plan to improve the reflector:

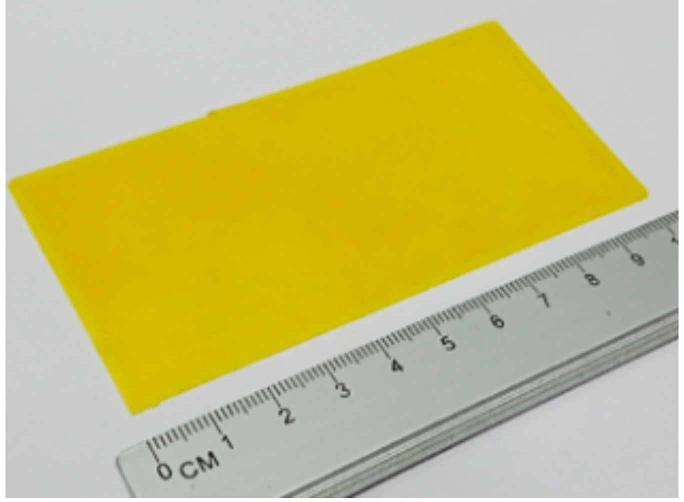
⇒ Heat resistant

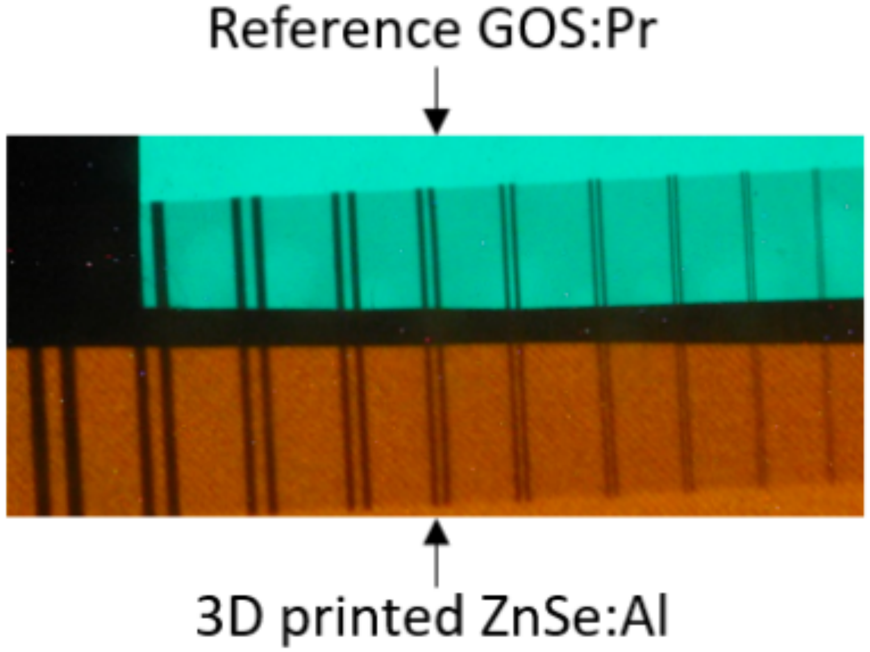
⇒ High reflectivity

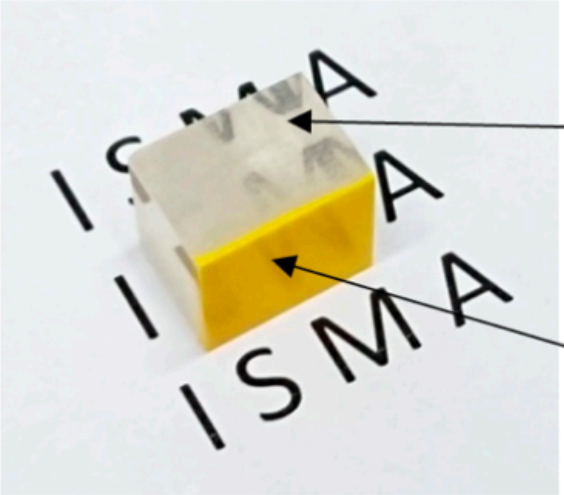
(goal is like 2022 JINST 17 P10045)

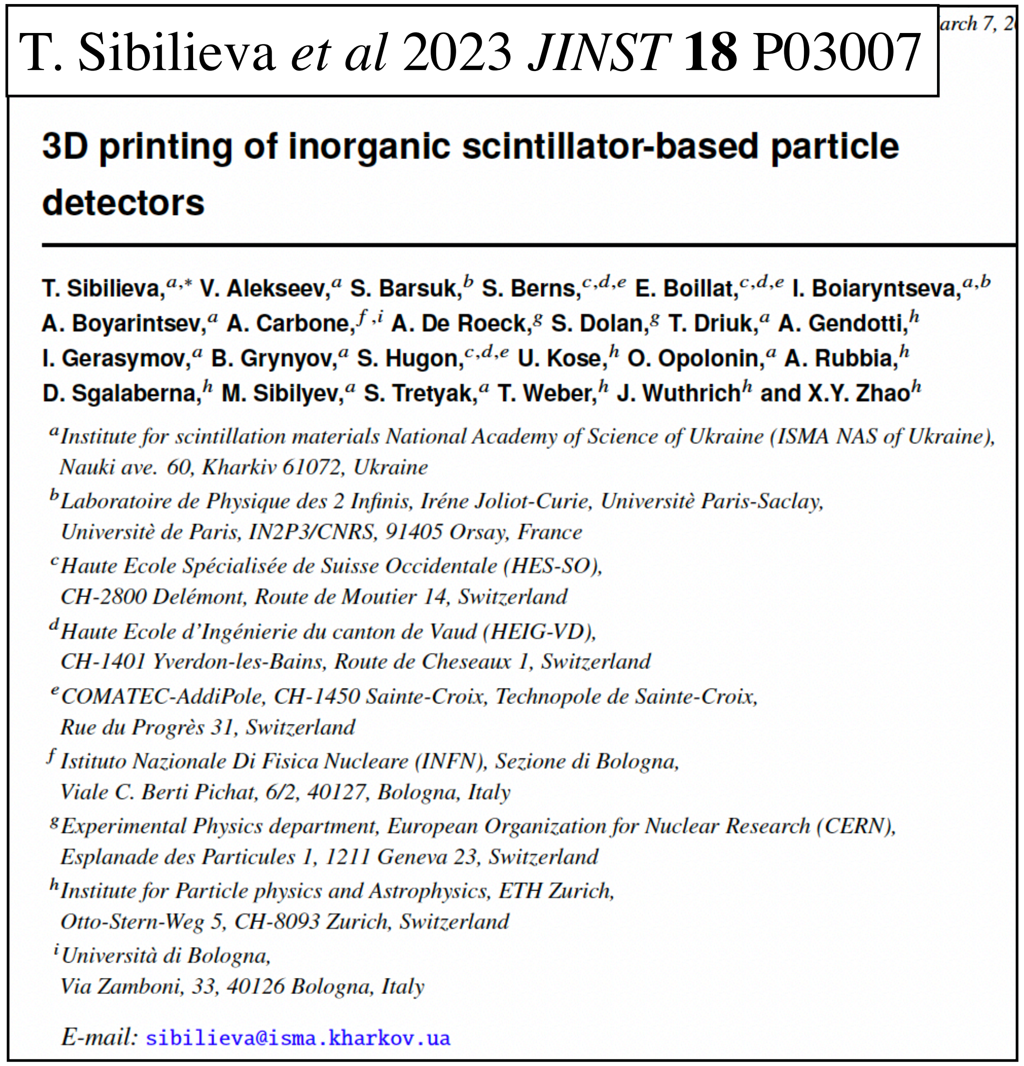
3D printed Inorganic Scintillator

We 3D printed inorganic scintillator for registration of Ionizing and X-ray radiation









T. Sibilieva *et al* 2023 *JINST* **18** P03007

arch 7, 2

3D printing of inorganic scintillator-based particle detectors

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Possibility to further develop the technology even for sampling calorimeters

The 3DET collaboration

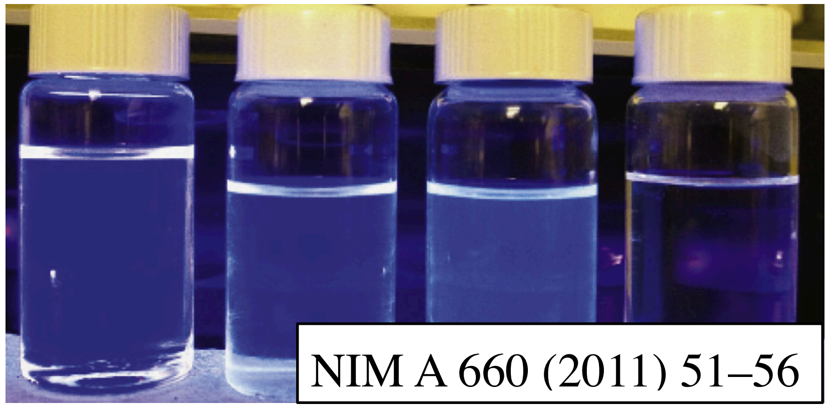
The **3**d printed **DET**ector (**3DET**)
R&D collaboration to develop additive manufacturing of future particle detectors
(CERN, ETH Zurich, HEIG-VD, ISMA)

✓Expertise in particle detectors, scintillator materials and 3D printing

✓Possibility to extend the collaboration to new institutes dedicated to particular developments (started a new collaboration with Ip2I Lyon on muon tomography)

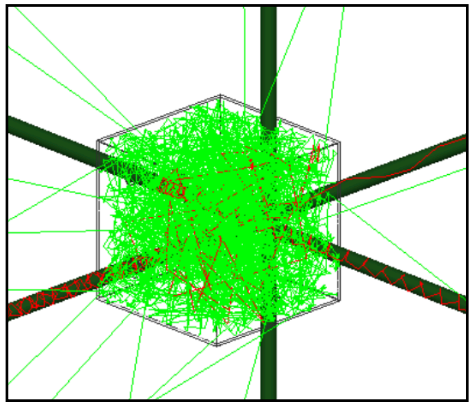
✓For more informations
https://threedet.web.cern.ch
or email: davide.sgalaberna@cern.ch

More R&D ongoing:
SuperFGD with Water-based Liquid Scintillator


NIM A 660 (2011) 51–56

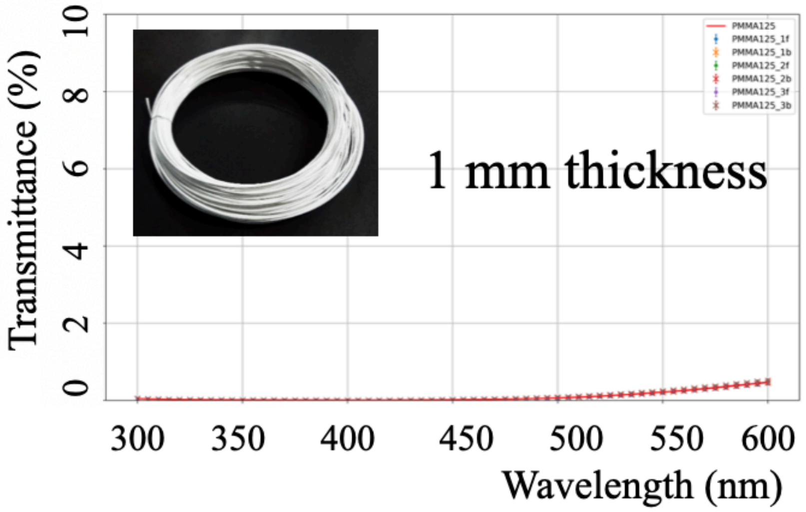
✓Light output proportional to % of LS in Water

✓Maximise H_2O : CH ratio



✓Optical simulations to identify key parameters relevant for the design

- ⇒ very long attenuation length
- ⇒ reflectivity
- ⇒ # of WLS fibers per voxel



1 mm thickness

✓*Prototypes in April / May to compare with developed optical simulations*

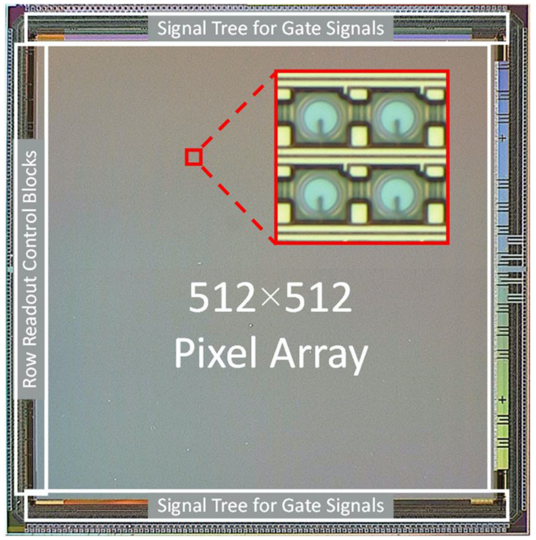
High-resolution

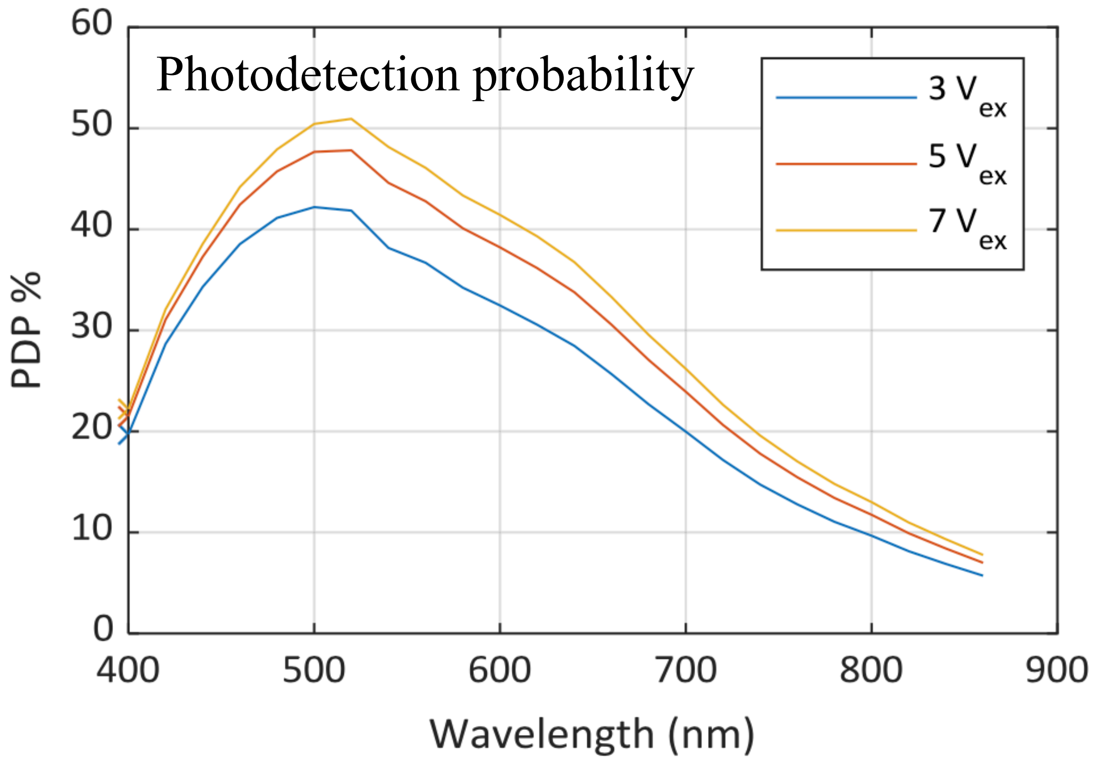
Particle Tracking

Single Photon Avalanche Diode (SPAD) array

High-resolution tracking of neutrino interaction final states (e.g. low-energy protons) requires an excellent spatial resolution in a massive detector

The key is the SPAD array





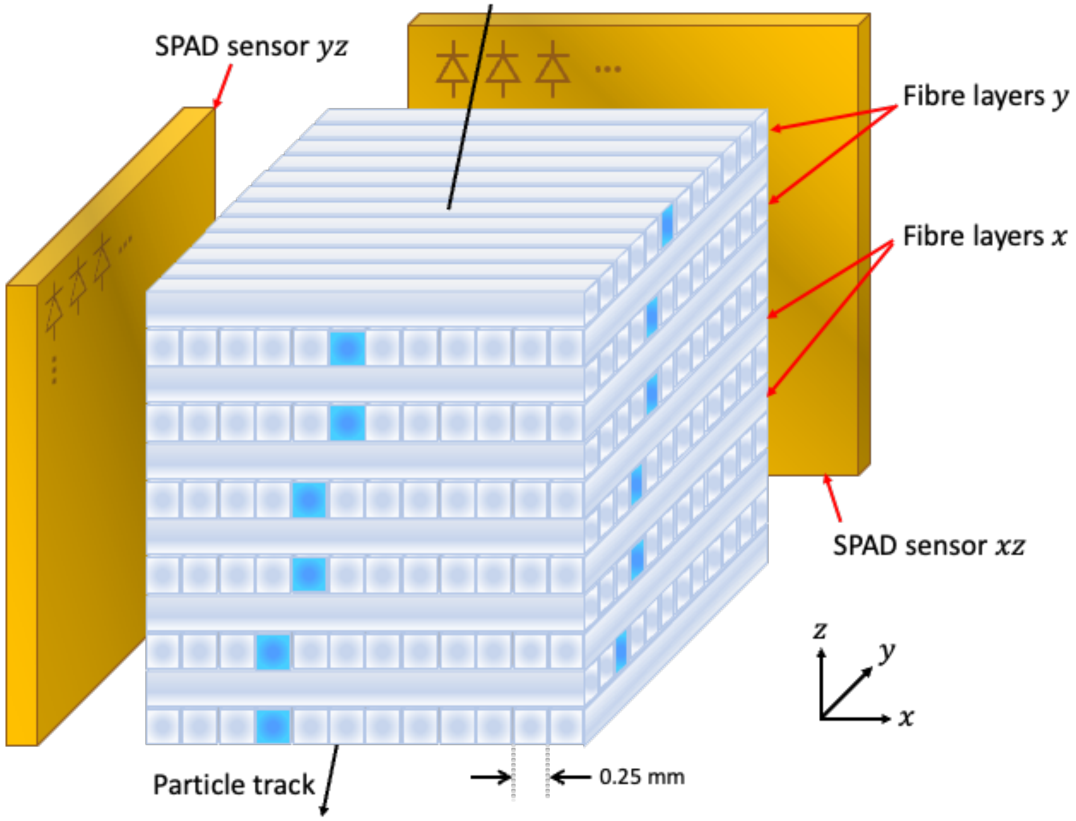
SwissSPAD2 (E.Charbon et al.)

IEEE Journal of Selected Topics in Quantum Electronics
(Volume: 25, Issue: 1, Jan.-Feb. 2019)

CMOS technology that, like SiPM, has single photon capability BUT…

- It measures the position of each single photon with O(10μm) pixel pitch
- The Front-End electronics is integrated in the chip, next to the SPAD pixels
    - ✦ Fill factor (10.5%) lower than SiPM
- Depending on the design it can also provide the Time of Arrival (~200 ps) - otherwise gate of 1-to-10 μs

SciFi read out with a SwissSPAD2



Advantages of SPAD vs SiPM:

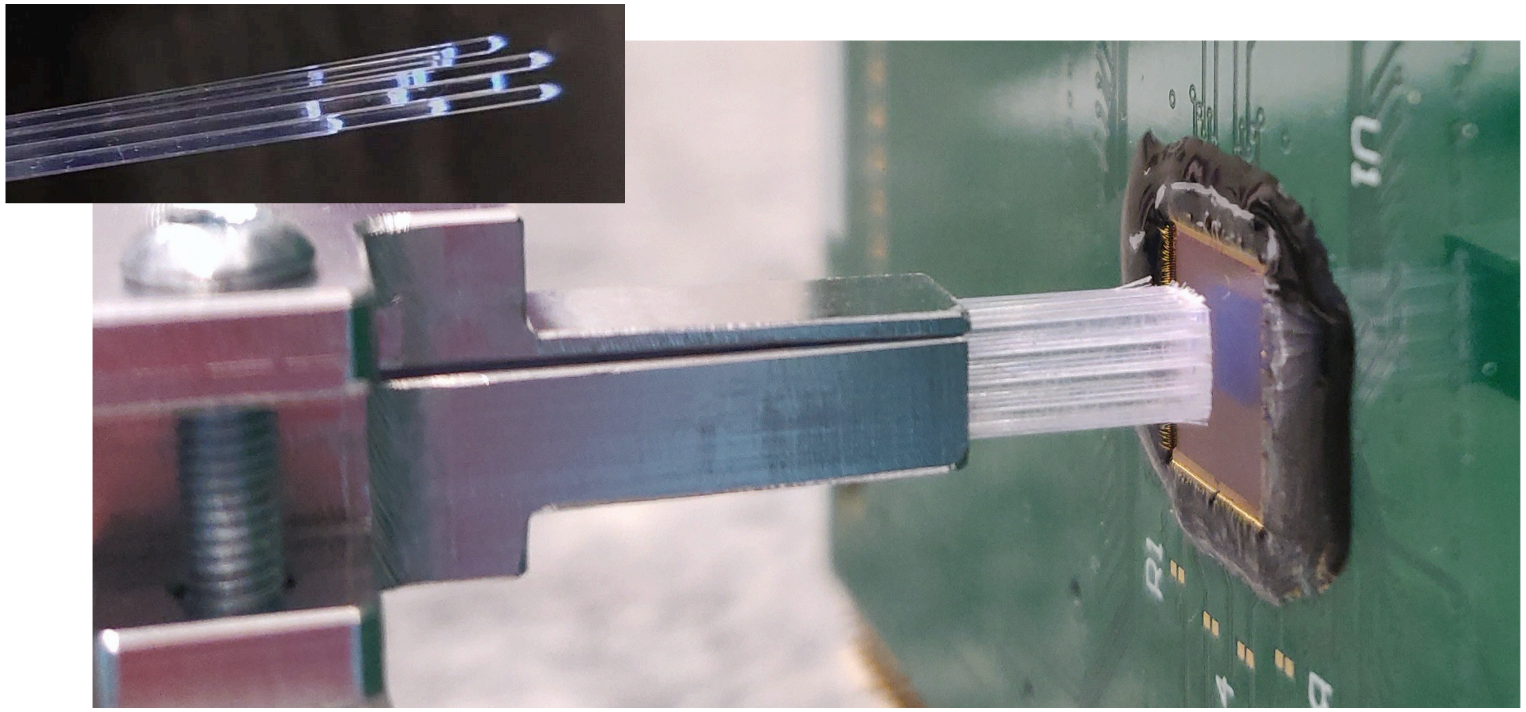
✓1 pixel = 1 electronics channel (at low yield)

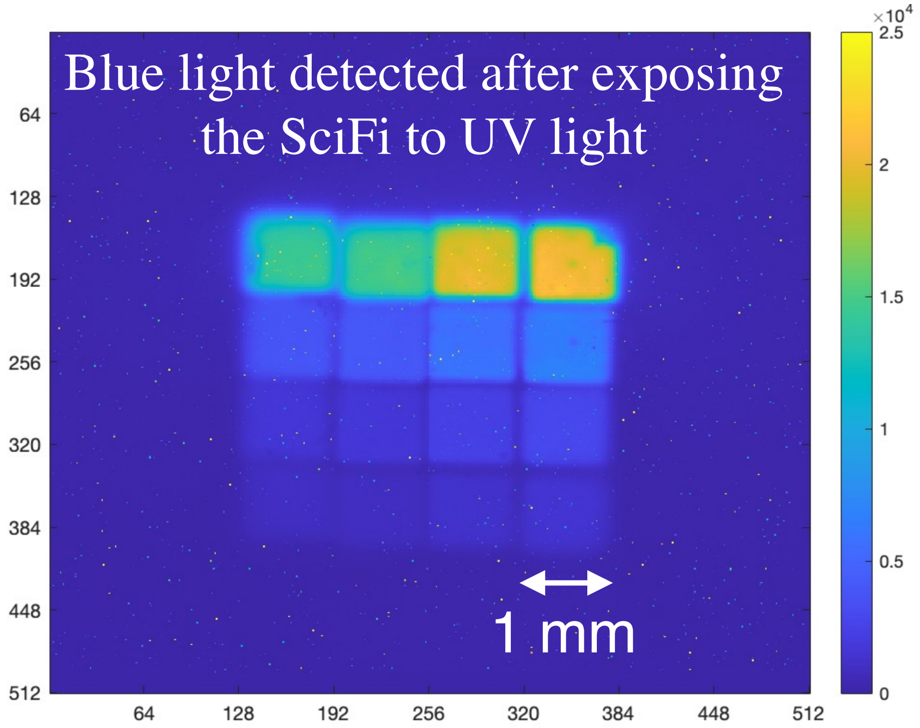
✓# of electronics channels scale with active area, NOT with # of scintillating fibers !

✓Don't need to group more fibers into a single readout channel (e.g. 1.25x0.25 mm^2 @LHCb)

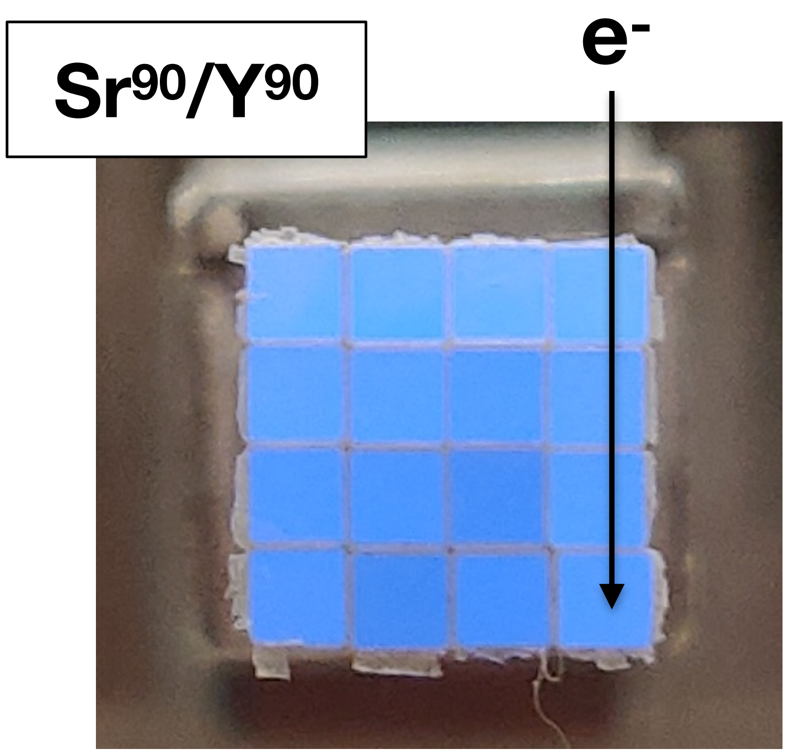
Disadvantages:

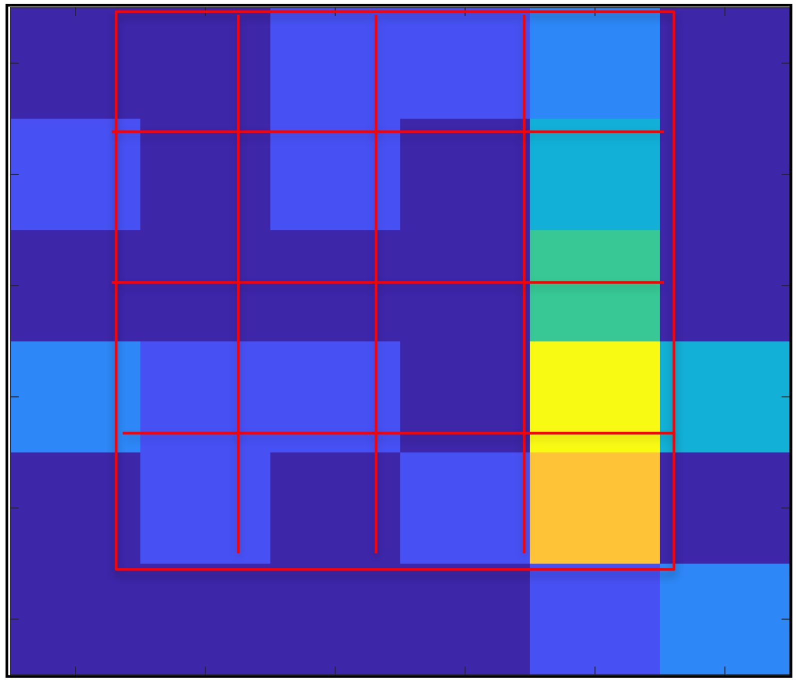
✓Lower Fill Factor, hence PDE (work in progress) ⇒However, around neutrino vertex we are interested to highly-ionising particles

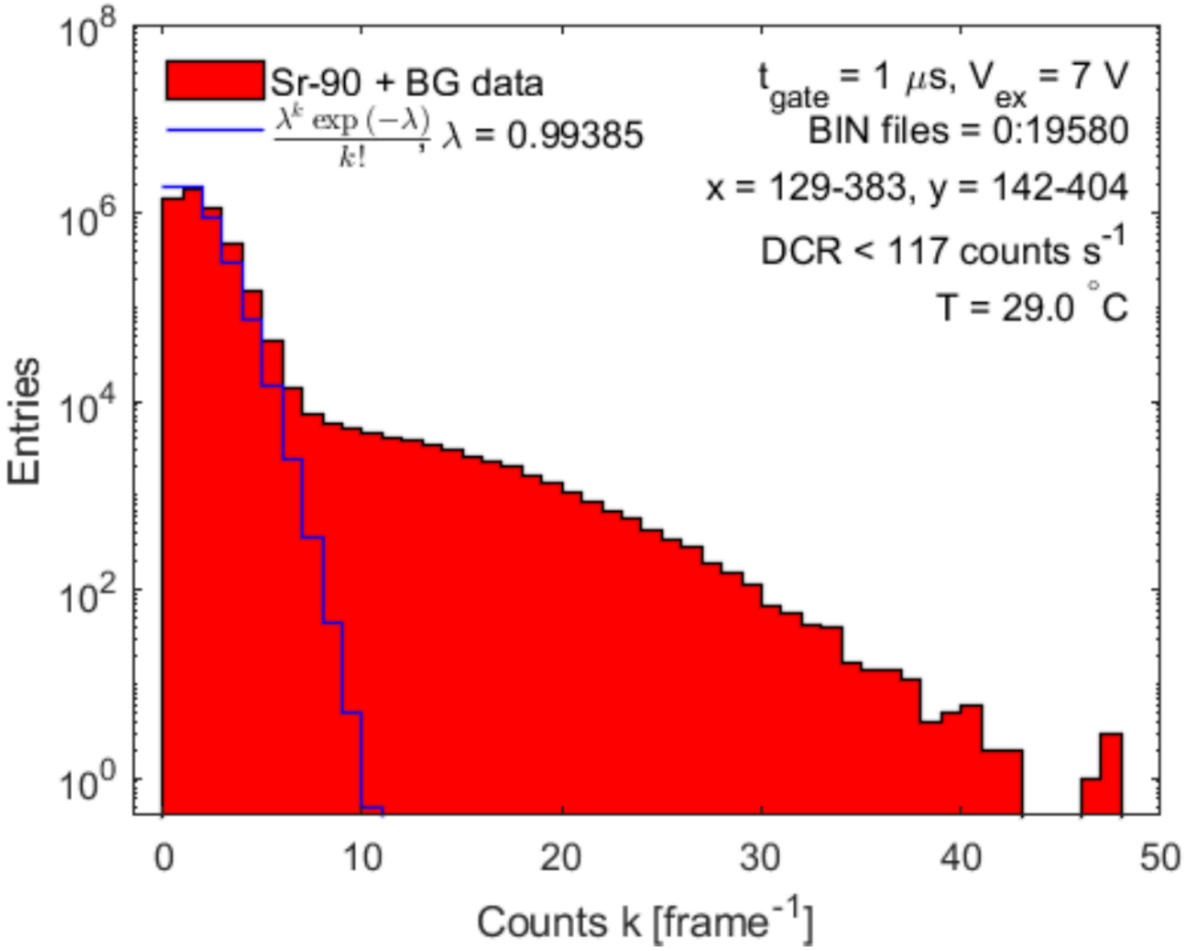



Blue light detected after exposing the SciFi to UV light

SciFi read out with a SwissSPAD2



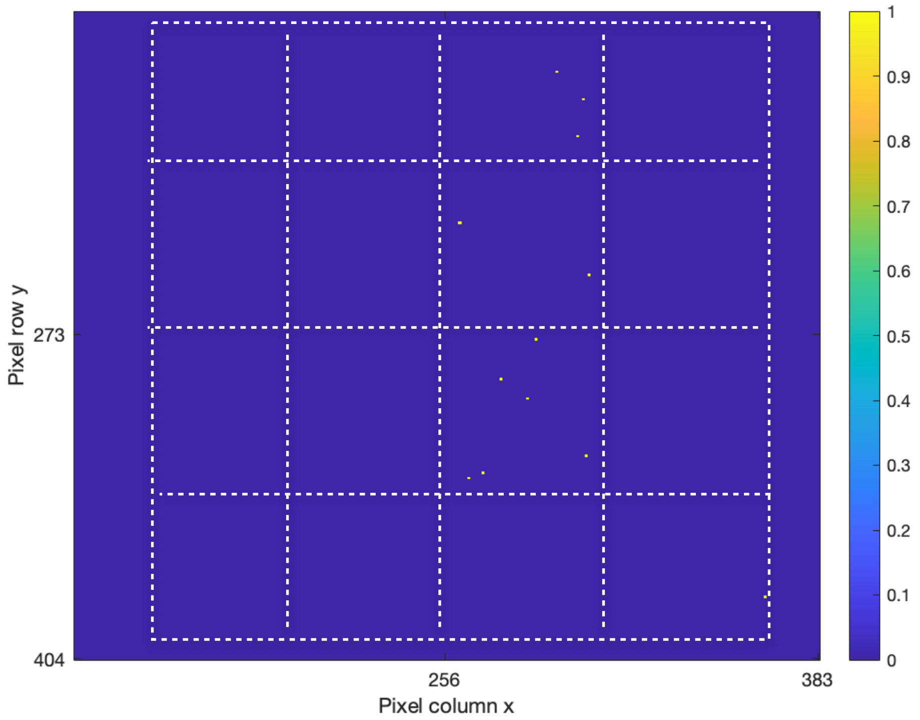




Successful first proof of concept of scintillating fibres read out with SPAD array photosensors

SciFi read out with a SwissSPAD2

11 counts in the Sr^{90} e^{-} track (1μs)



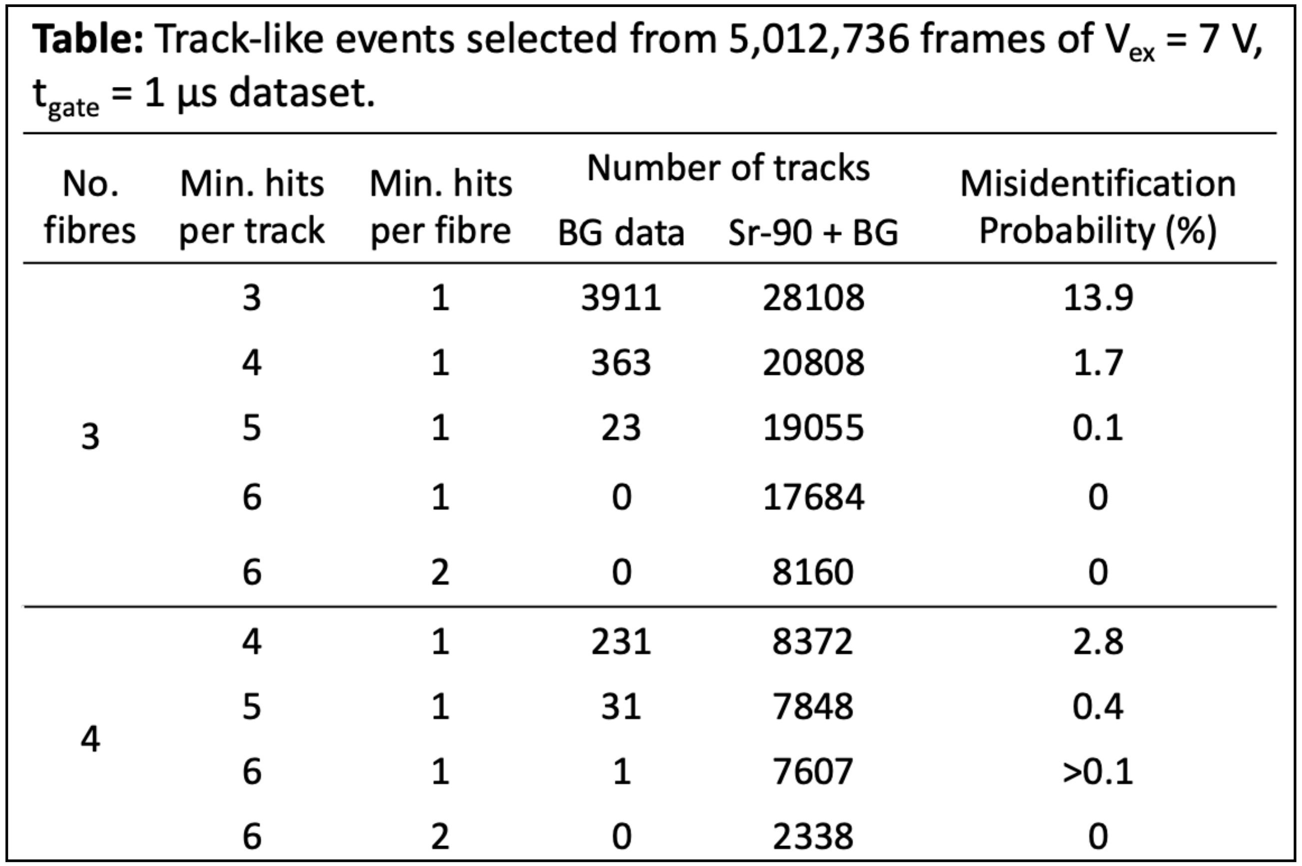
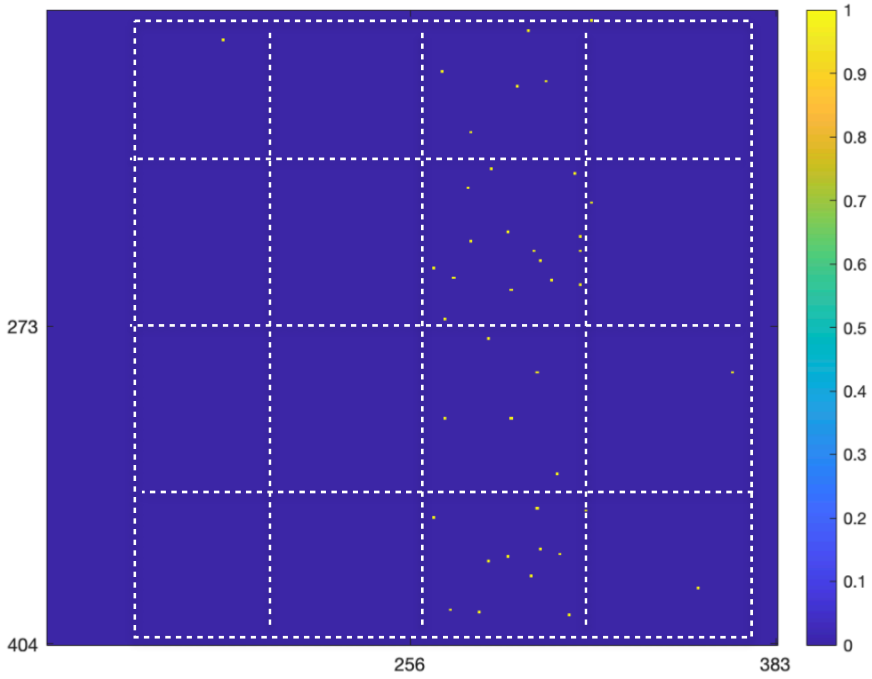


Table: Track-like events selected from 5,012,736 frames of $V_{ex} = 7$ V, $t_{gate} = 1$ μs dataset.

No. fibres	Min. hits per track	Min. hits per fibre	Number of tracks BG data	Number of tracks Sr-90 + BG	Misidentification Probability (%)
3	3	1	3911	28108	13.9
	4	1	363	20808	1.7
	5	1	23	19055	0.1
	6	1	0	17684	0
	6	2	0	8160	0
4	4	1	231	8372	2.8
	5	1	31	7848	0.4
	6	1	1	7607	>0.1
	6	2	0	2338	0

34 counts in the Sr^{90} e^{-} track (1μs)

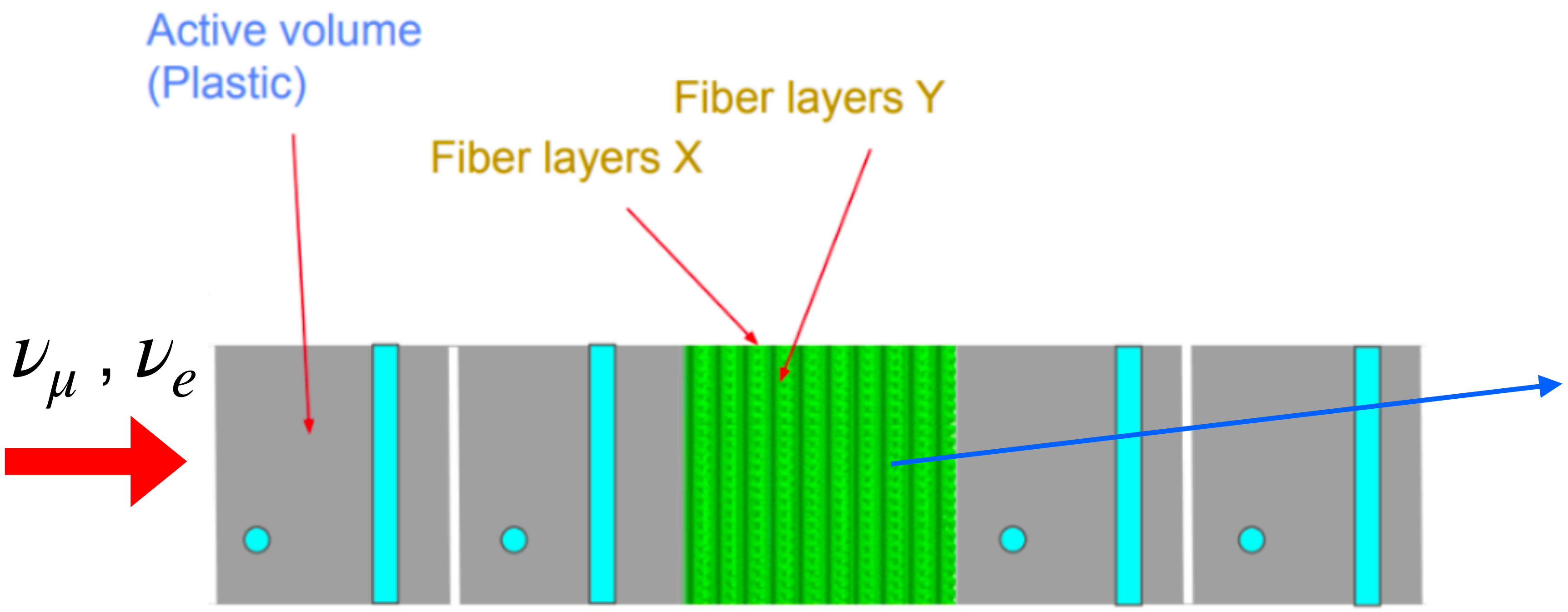


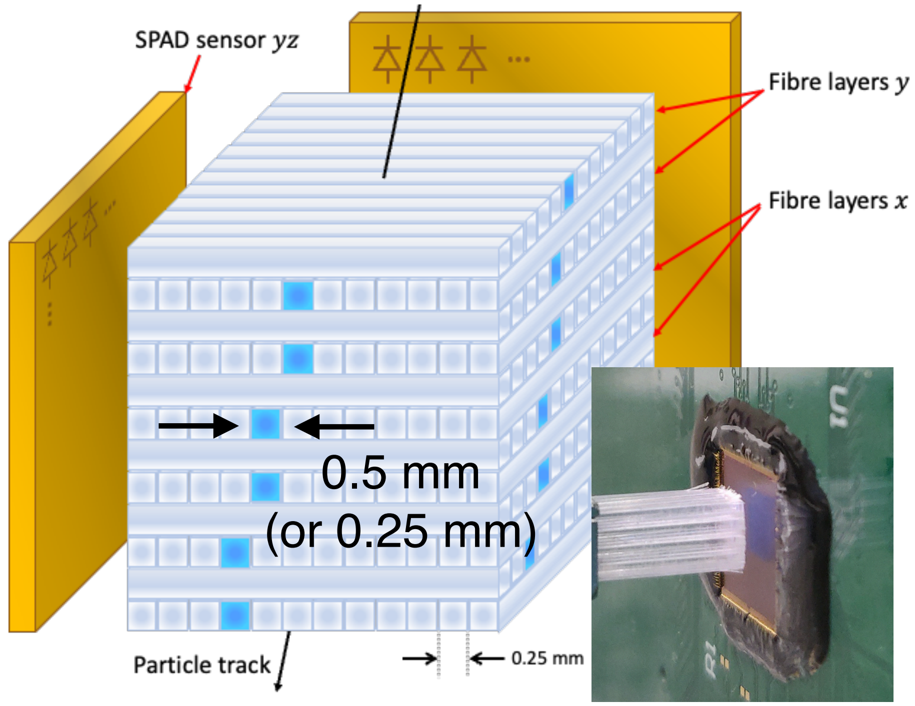
Get rid of most of fake tracks from dark counts with gate~1μs and only 4 counts in 3 fibres thanks to spatial distribution along a straight track

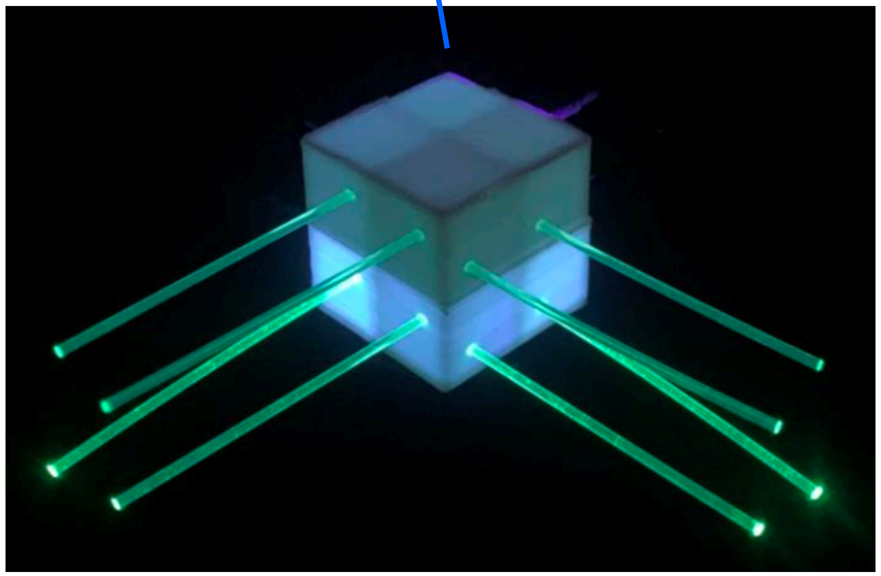
⇒ *smaller fibers will further reduce the # of fake tracks (~ proportional to 1/diameter)*

A combined SciFi + SuperFGD configuration

A 10mm-thick SciFi module is made of 20 (40) fibers of ϕ=0.5mm (ϕ=0.25mm) alternated along X and Y ⇒ 3D tracking of very short particles !







SciFi modules can be alternated with plastic (or water ?) SuperFGD-like modules

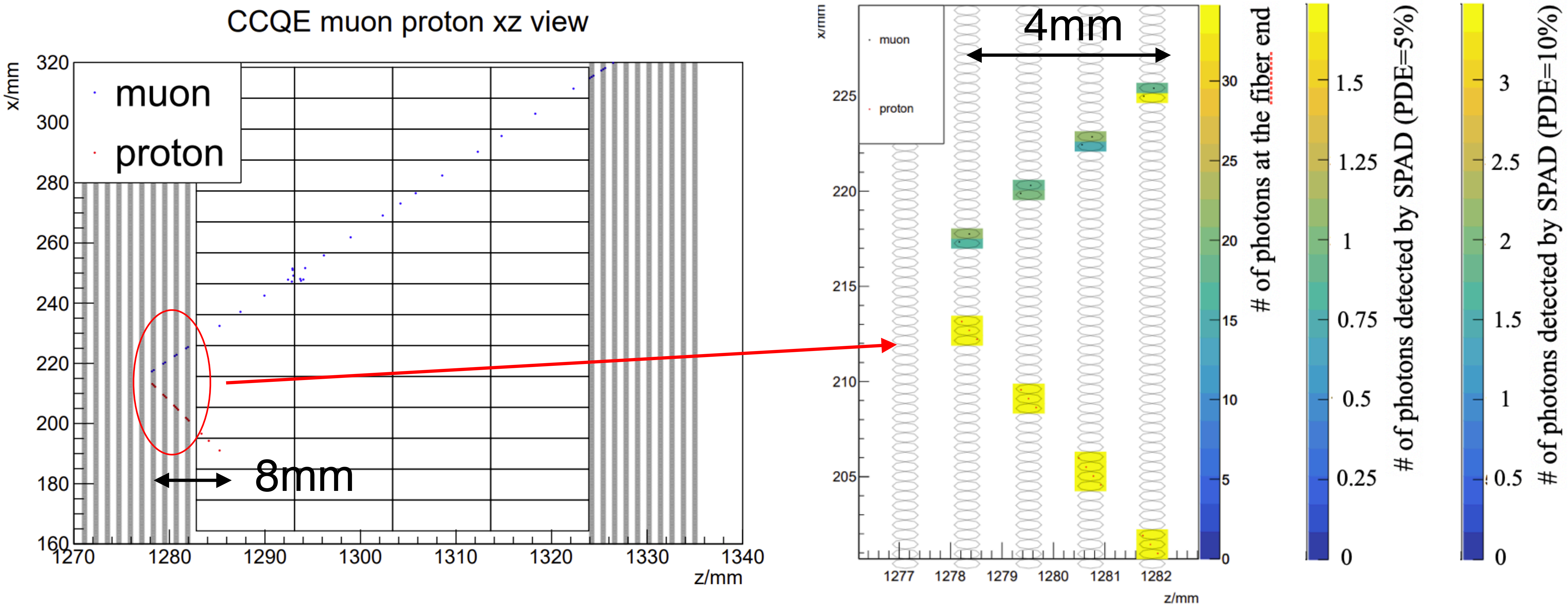
⇒ unprecedented tracking resolution (e.g. protons and $\gamma \rightarrow e^+e^-$)

⇒ efficient neutron energy reconstruction

⇒ EM shower calorimetry

A combined SciFi + SuperFGD configuration

SciFi modules can be alternated with SuperFGD-like modules



Protons are highly ionising particles and, depending on the PDE, can produce a few photoelectrons in most of the 0.5mm fiber along a thin track

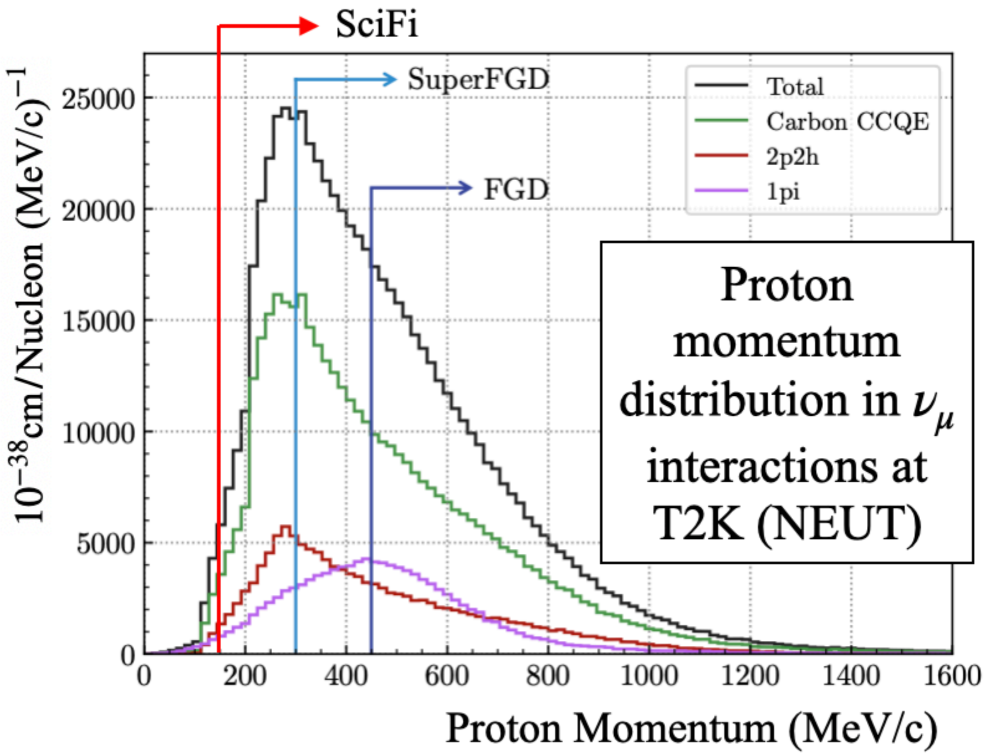
⇒ even a relatively low photodetection efficiency would be sufficient for tracking short protons (highly-ionizing)

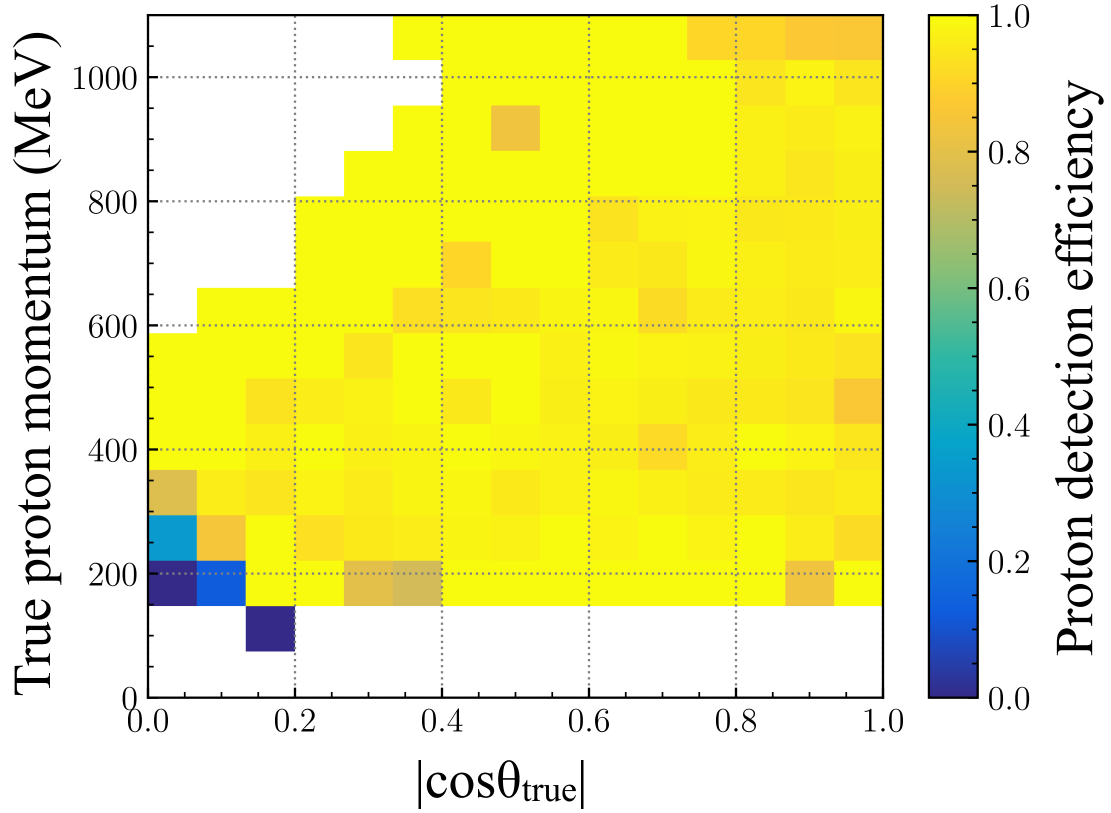
⇒ tracking of MIPs is complemented by SuperFGD modules

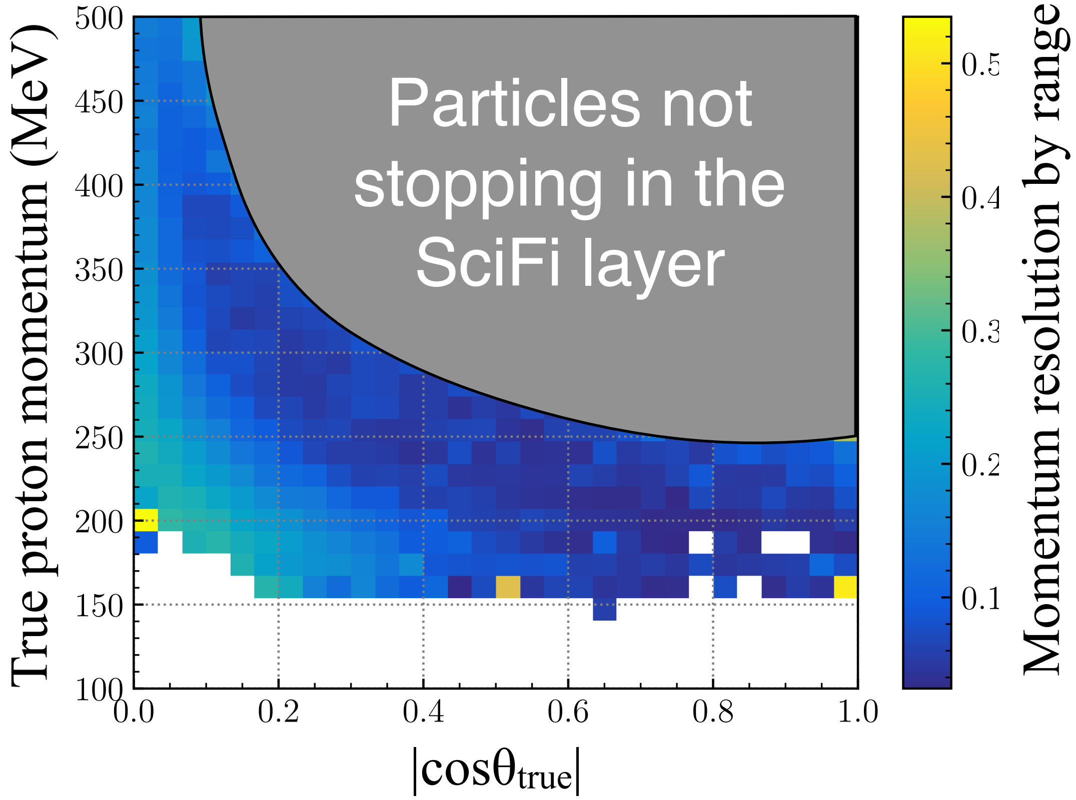
A combined SciFi + SuperFGD configuration

Possibility to track very short protons at any angle, like an emulsion detector or a High-Pressure TPC, BUT…

- ⇒ like an electronic emulsion
- ⇒ very precise timing information
- ⇒ sufficient mass in small volume
- ⇒ It may be mixed with thin water layers





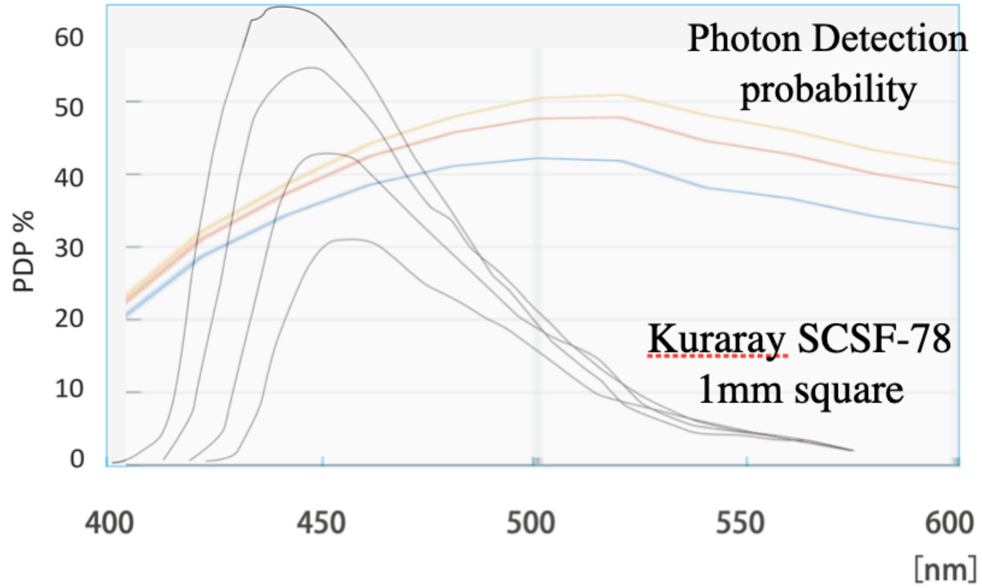


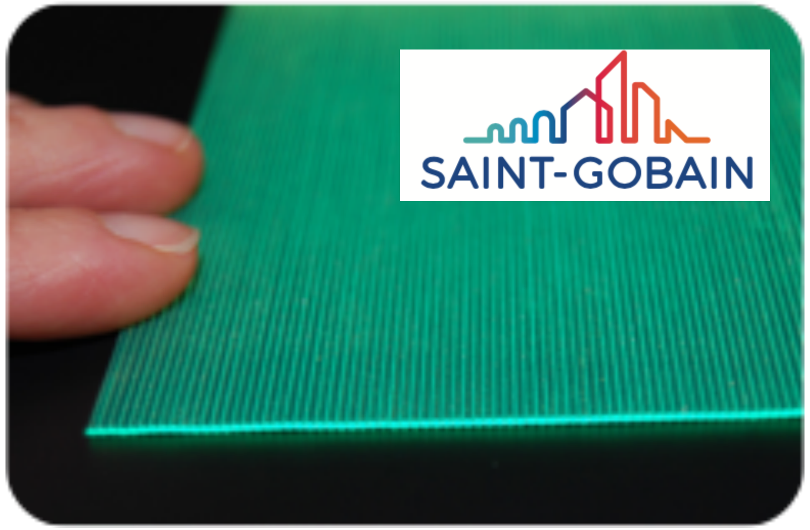
Work in progress towards studies on sensitivity to ν interaction modeling

SPAD and SciFi: further developments

So far, tests were conducted with blue SciFi, i.e. not perfectly matching the SwissSPAD2 PDP, and square single cladding (not best trapping efficiency)

Future tests with 0.5mm (0.25mm) green fibers already glued together





Developing a novel SPAD ("PLATON") array in collaboration with EPFL AQUA

- ✓ *Improve the fill factor, hence the PDE*
- ✓ *Provide single photon Time of Arrival with sub-ns time resolution*

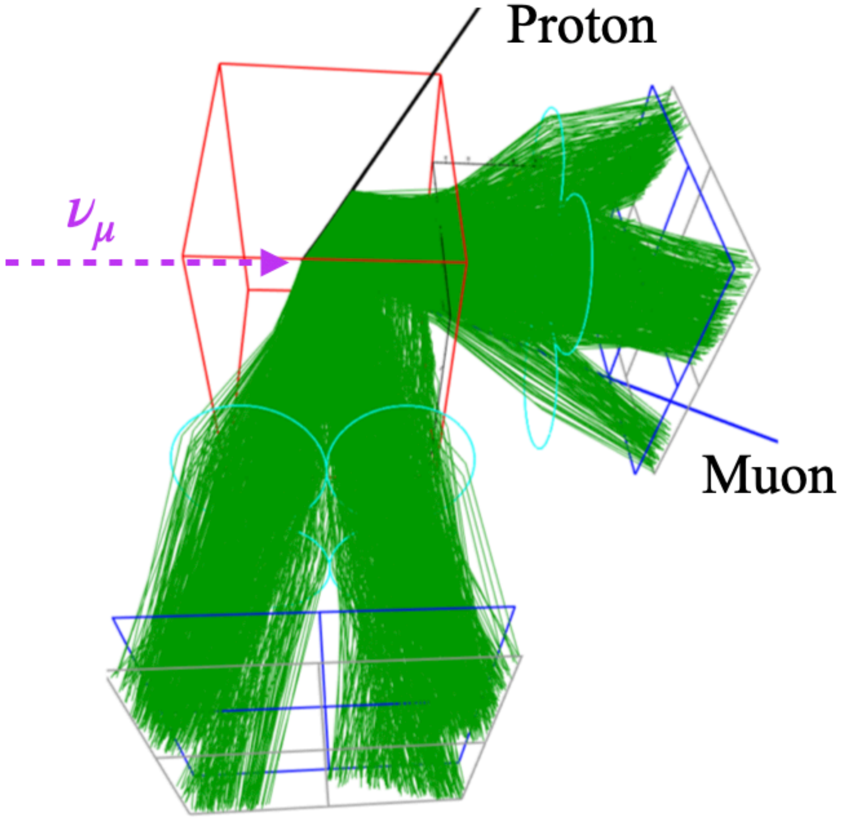
More R&D ongoing:
3D images of ν in unsegmented scintillator

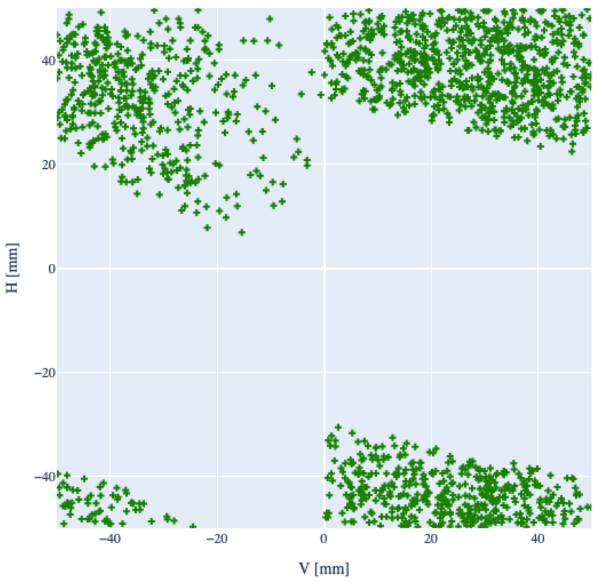
✓Super-fast photographs of neutrino interactions in large block of scintillator
$\Rightarrow$ SPAD

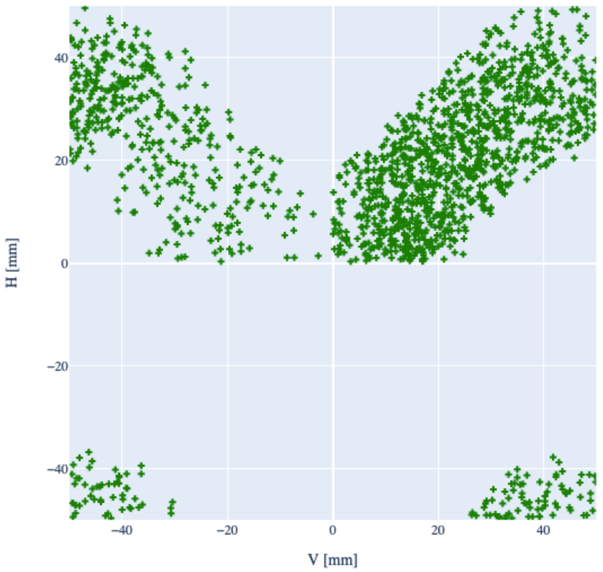
✓ Potential for sub-mm resolution

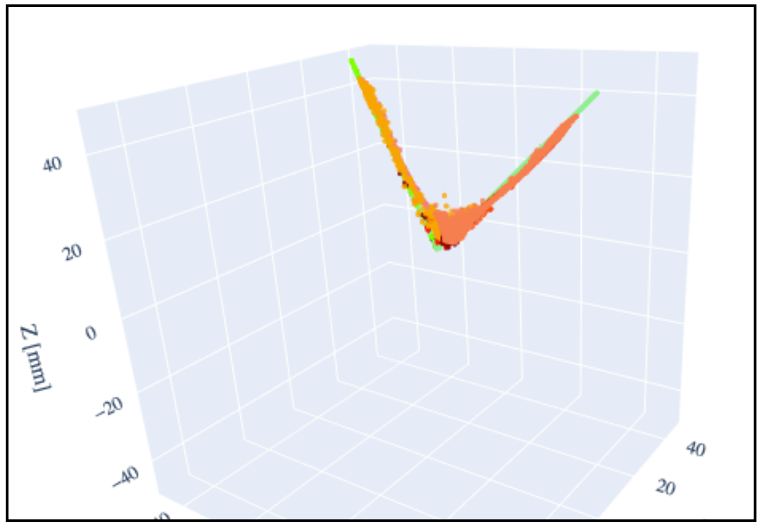
✓ Simulation and reconstruction ready

✓ *First prototype under construction*









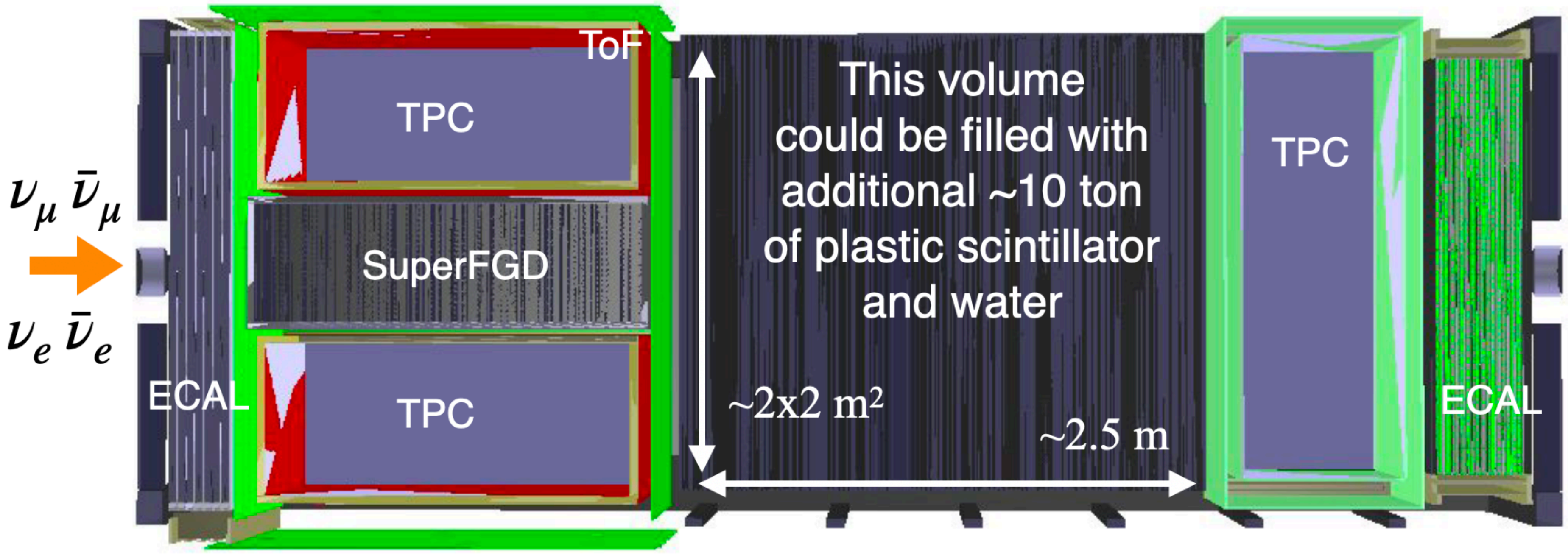
Summary

- Hyper-K systematic goal is beyond the need of the current LBL experiments
- Developing the scintillator technology for the 2x2x2.5 m^3 volume in ND280

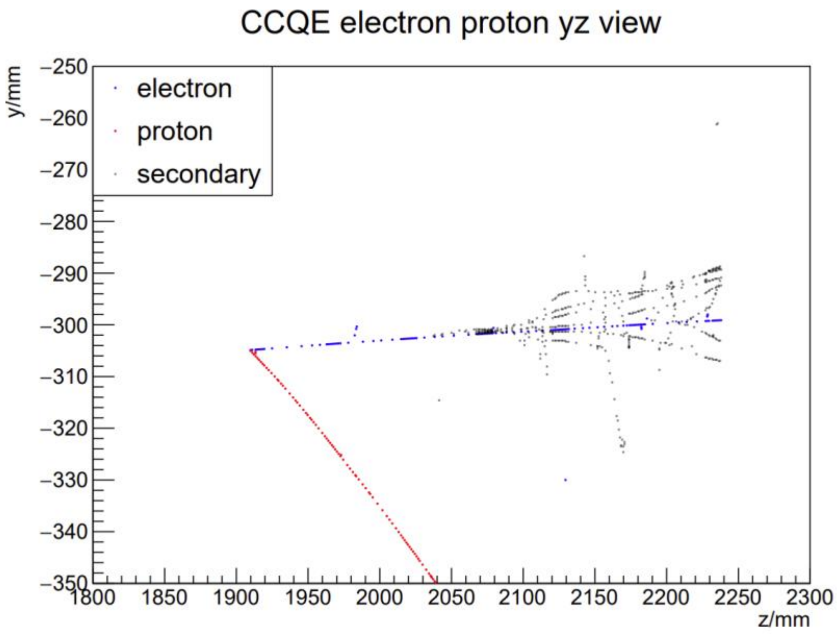
  ⇒ up to 10 ton of plastic + water-based scintillator

  ⇒ 3D segmented plastic scintillator scalable to many tons

  ⇒ Very high tracking resolution detector
- Simulation studies ongoing to be compared with R&D data as well as to optimise the ND280++ configuration



This volume could be filled with additional ~10 ton of plastic scintillator and water


CCQE electron proton yz view

BACKUP