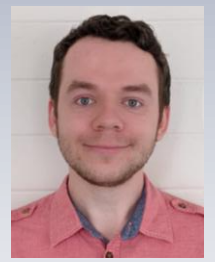
R&D towards a Water-Based Liquid Scintillator detector for ND280++



Daniel Ferlewicz
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LPNHE PARIS

IRN Neutrino

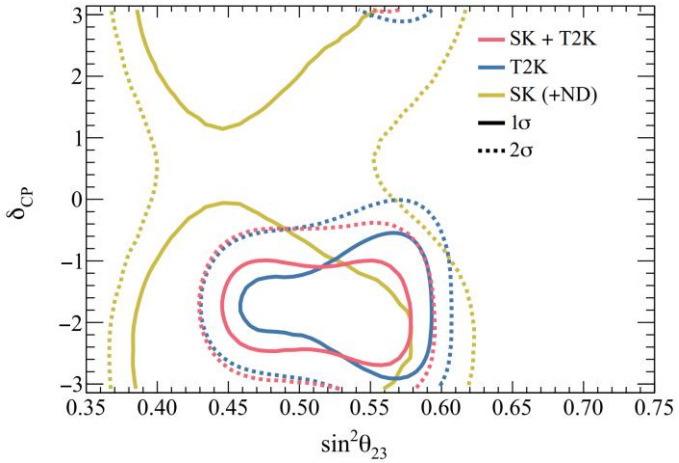
anr

Hyper-K

Physics motivations

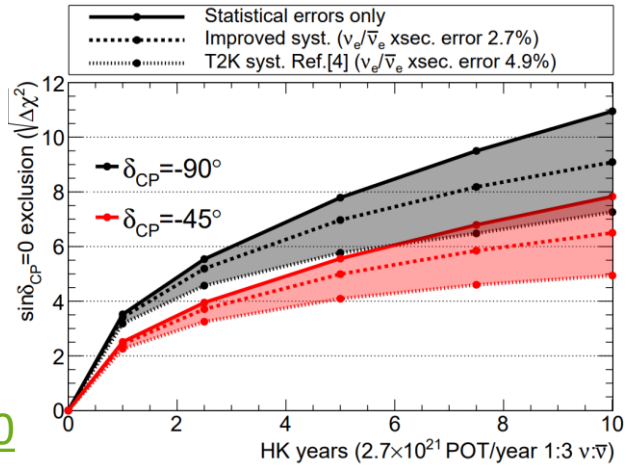
- Long baseline neutrino experiments measure CP violation by comparing $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

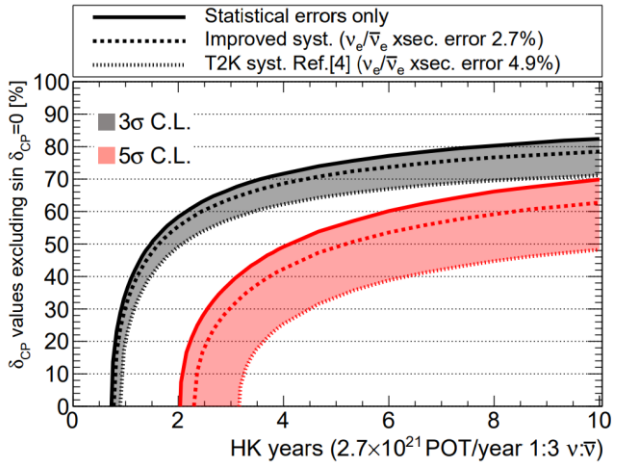
PRL 134, 011801 (2025)



- Searches of CP violation in neutrinos in T2K, SK, Nova
  - T2K+SK exclude CP conservation at 1.9σ, hinting at maximal CPV
  - T2K+Nova also shows hints of $\delta_{\mathrm{CP}} \neq 0$ depending on mass ordering

- Maximal CPV discovery at 5σ during the high-statistics HyperK era impacted by a **4% systematic uncertainty in $\sigma_{\nu_e}/\sigma_{\bar{\nu}_e}$**





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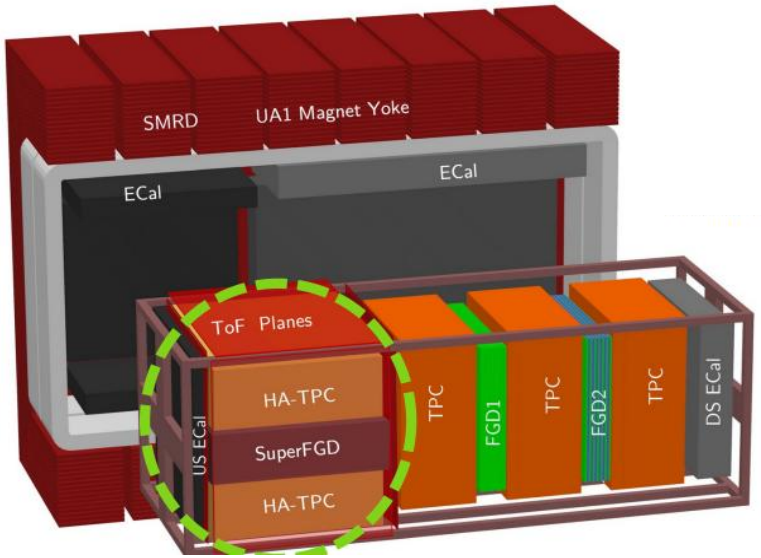
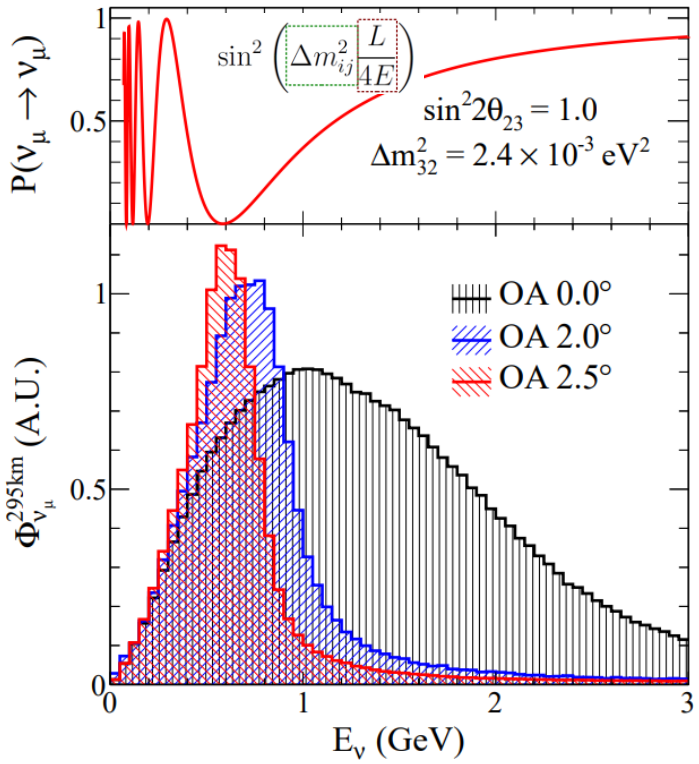
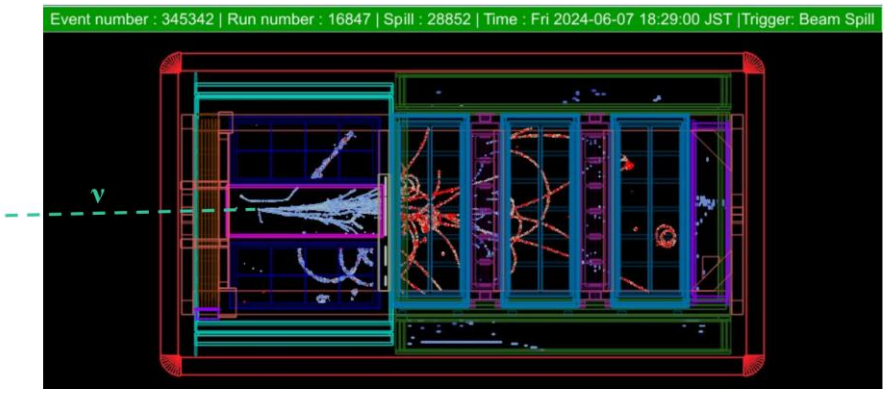
ND280

- Near detector 280m from the ν-beam origin at J-PARC
  - Installed in 2010 for the T2K experiment
  - To be inherited by HyperK experiment as its ND in ~ 2028
- Off-axis at 2.5° for narrow energy band at FD



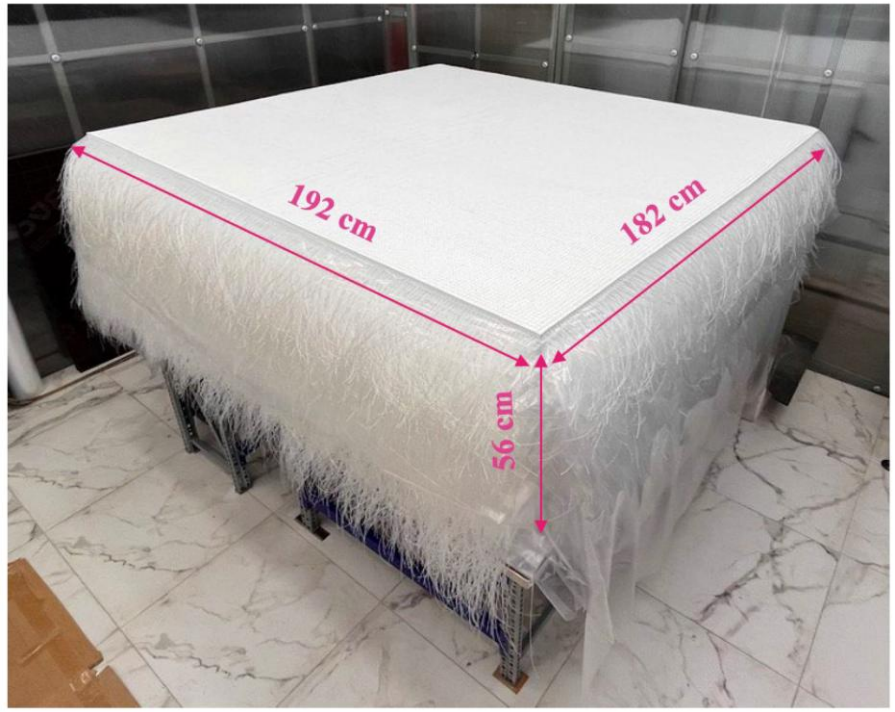


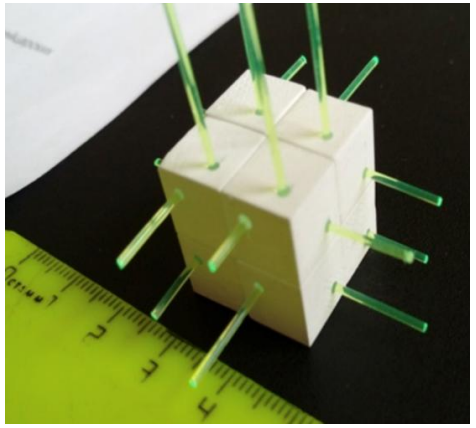
- Current configuration installed in April 2024 (“ND280+”)
- Downstream detectors: Time Projection Chambers (TPCs) for tracking and Fine Grain Detectors (FGDs) as targets
  - FGD2 has the only (small) water target in ND280
- Newer upstream detectors:
  - SuperFGD
  - Two High-angle TPCs
  - Six Time of Flight panels

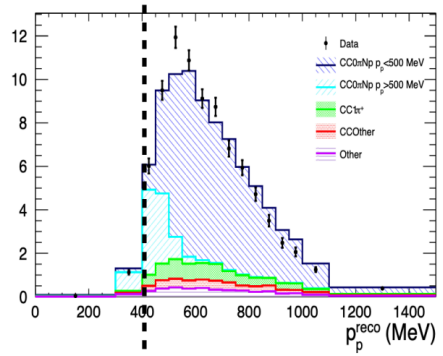


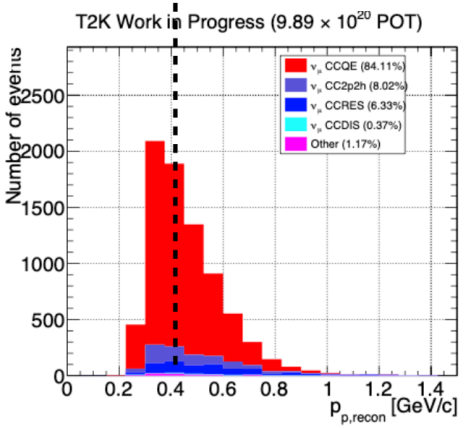
SuperFGD

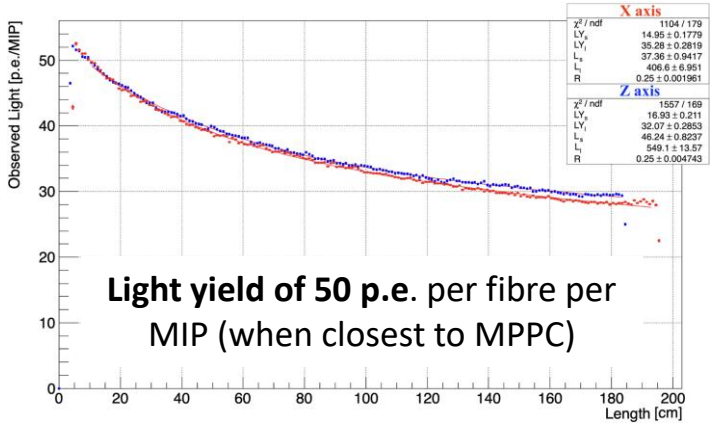
- 2 tonne target of optically separated **plastic** scintillator cubes
  - Improved low momentum proton efficiency
  - 4π angular acceptance











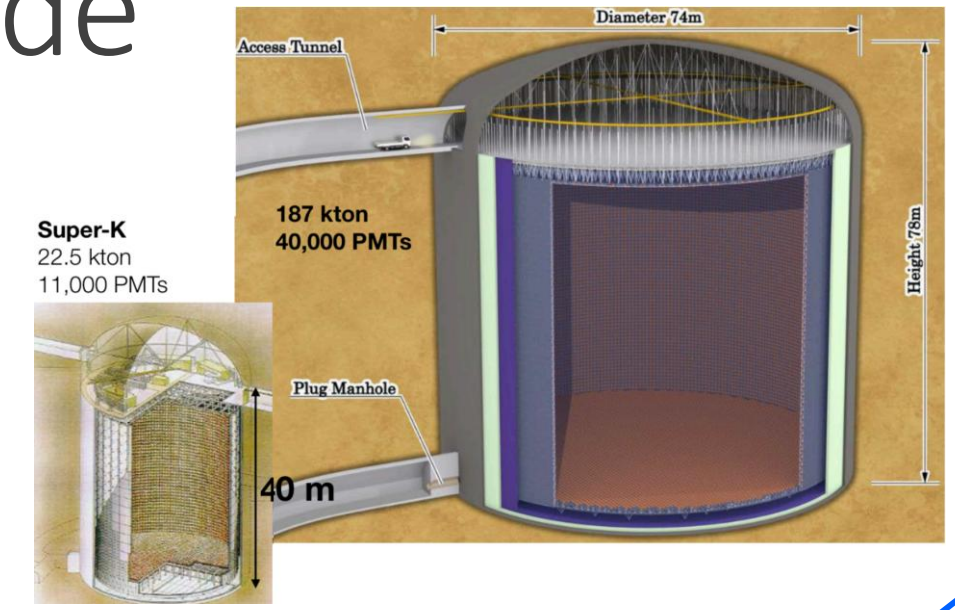
Light yield of 50 p.e. per fibre per MIP (when closest to MPPC)

- ~2 million 1x1x1 cm^3 cubes
- 3D readout using WLS fibres, ~56k channels

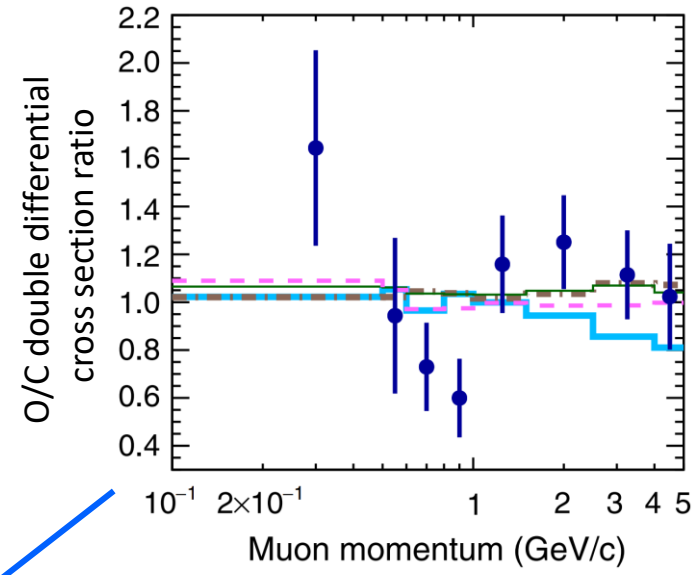
Paper under review with NIM
arXiv: 2603.14921

HyperKamiokande

- FD completion in 2028
  - Fiducial volume 8x larger than SK
  - Beam power: 750kW (T2K) → 1.3MW
  - 1 year HK data ≈ 20 years of T2K
- Intermediate water Cherenkov detector under construction
  - See backup slides
- HK will inherit ND280:



PRD 101, 113004 (2020)



Neutron kinematics important for $\bar{\nu}$ interactions but many escape SFGD

⬇

Need larger target

Scaling carbon interactions in ND to oxygen in FD will be a larger uncertainty

⬇

More water target in ND280

δ_{CP} will be dominated by $\nu_e/\bar{\nu}_e$ in H_2O cross section uncertainties

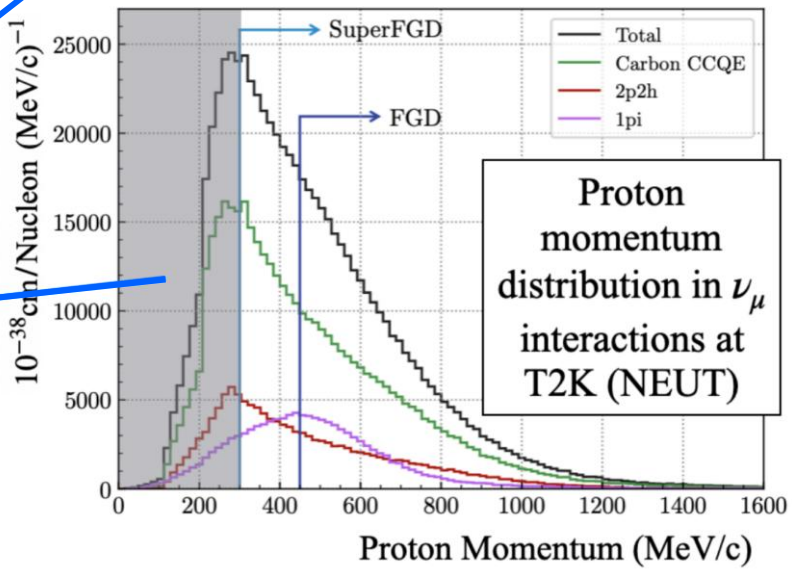
⬇

Need higher ND statistics

Proton threshold in the SFGD still misses half of tracks

⬇

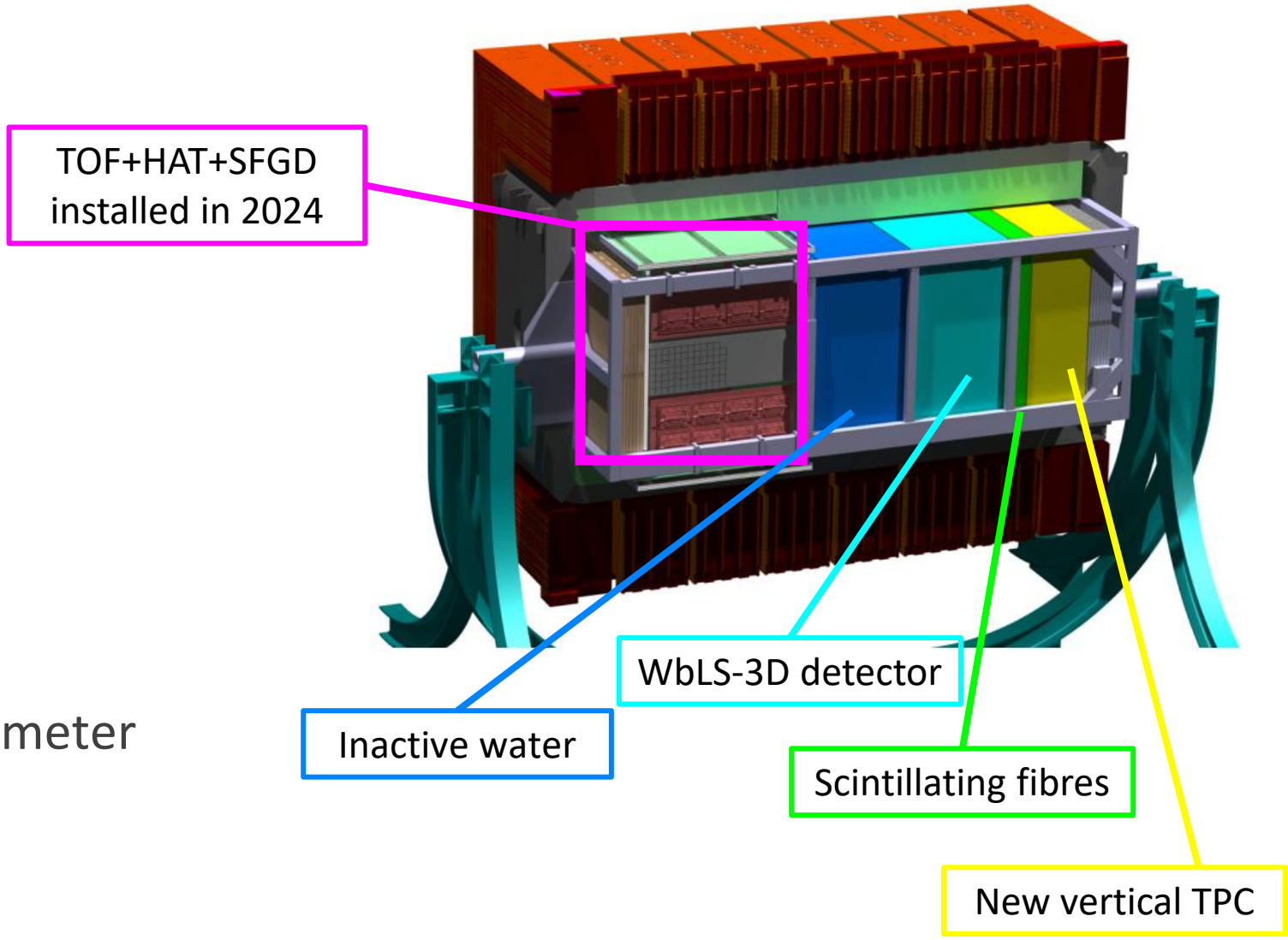
Need a target with better granularity



HK-ND280++

Reference for possible ND280++ design – not final

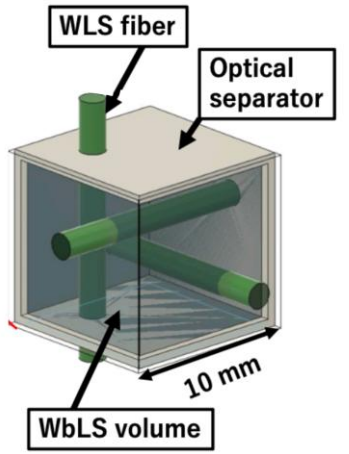
- R&D for ND upgrades underway:
  - Replace tracker region after 2030
  - New ND280+ detectors will remain
- **10 tonnes** available for new ideas
  - Large fraction for water
  - New vertical TPC
    - R&D for TPC optical readout at CEA Saclay
- Refurbished Electromagnetic Calorimeter
  - Replace MPPCs with latest available



- Expect $\sim 4000\ \nu_e/10^{21}$POT at 20% efficiency, comparable to IWCD

Water-based Liquid Scintillator

- SFGD-like highly segmented WbLS detector with 3D readout
  - Maximize H_2O content
  - Light Yield > 10 p.e.
- Developing prototypes at LPNHE, ETH Zurich and Kyoto U
  - In collaboration with WbLS inventor M. Yeh (BNL) NIM A 660, 51–56 (2011), JINST 19 P01003 (2024)



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↓

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↓

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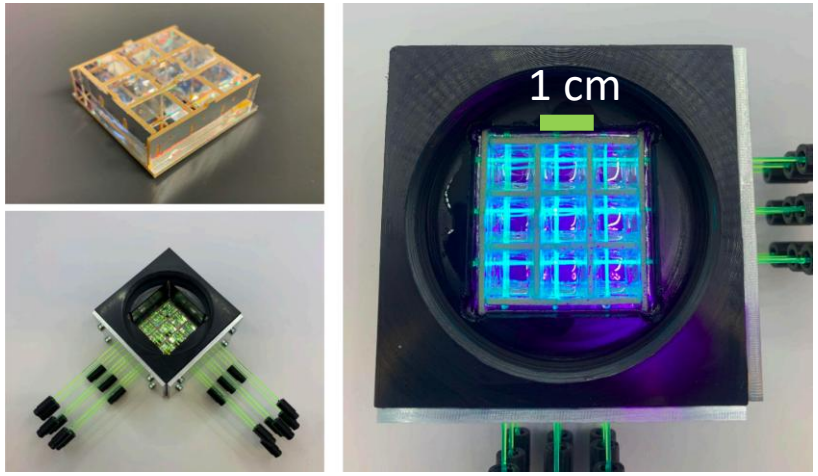
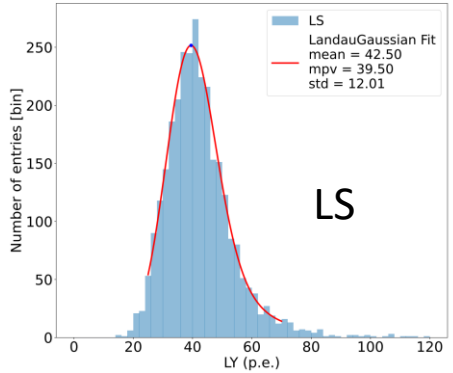


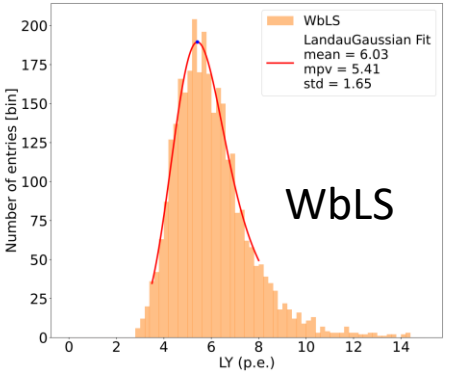
ETH prototype, submitted to JINST

JINST 21 (2026) 01, P01012

- ETH prototype:
  - Composition of **90% H_2O**, 10% LS (LAB+PPO+MSB)
  - 3M and Divinycell for optical separation, >80% water by weight
- Average light yield over 6 channels for cosmic rays:

	<LY> per fiber	xtalk
LS	42.5 p.e.	2.3%
WbLS	6.0 p.e.	1.9%





- PID in organic scintillator can be done at lower light yield than the SFGD

WbLS studies at LPNHE

- Exploring detector design: WLS fibres, SiPMs, reflective materials

- Experimental setups include:
  - 5x5x5 microSFGD
  - Precision fibre and SiPM characterisation
  - 8cm^3 SuperCube

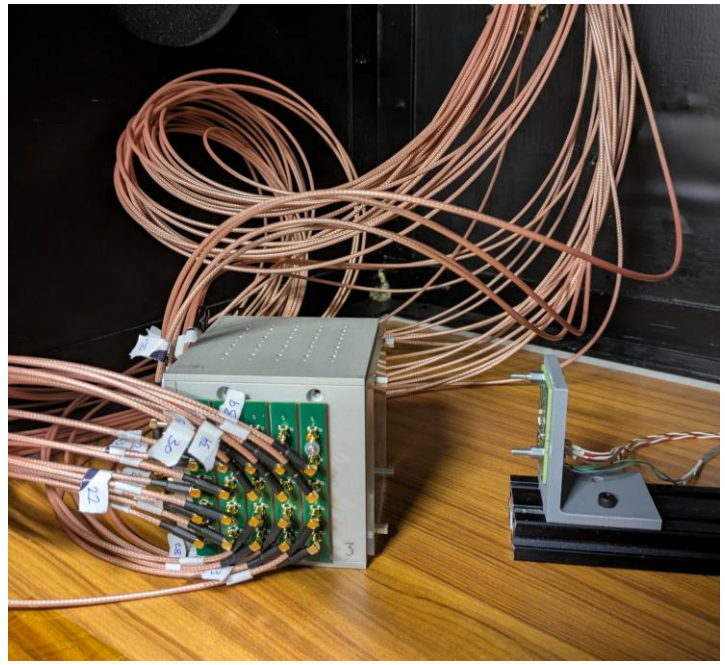
- Designing a small liquid-tight vessel for WbLS tests

LPNHE team

C. Giganti
R. Gaior
E. Hily
X. Aubert
G. Daubard
D. Laporte
M. Antonelli
D.F.

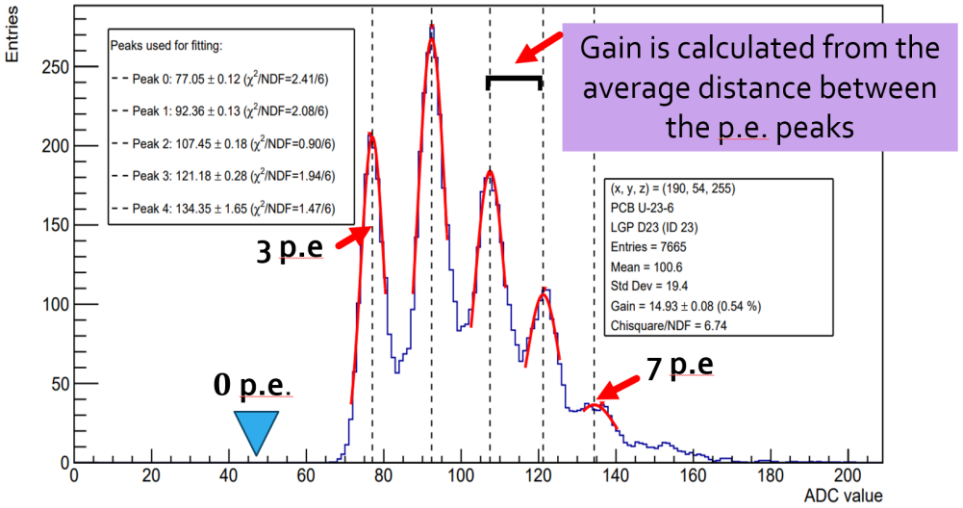
microSFGD

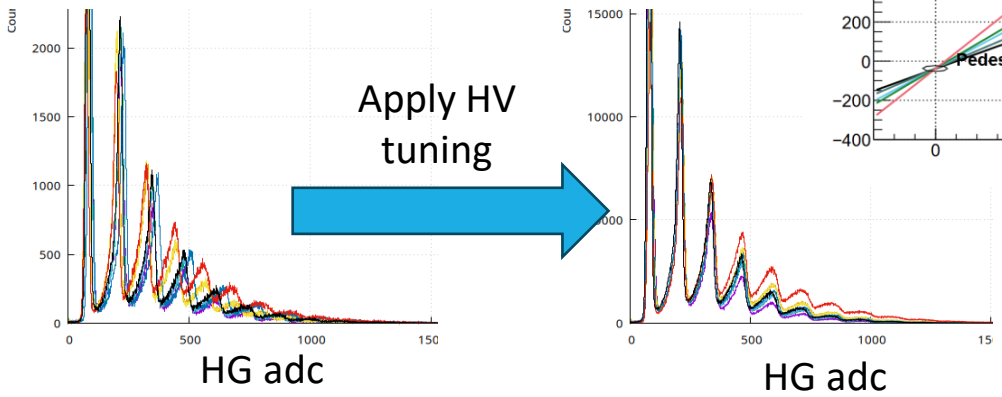
- 5x5x5 SFGD cubes, with additional gap in between
- Using CITIROC chips in a CAEN DT5202
- 3mm or 1mm SiPMs on a PCB with 3D printed guard
- Kuraray Y11 fibres polished on both ends
- Set up x- and y- sides with 20 channels each (40 total)

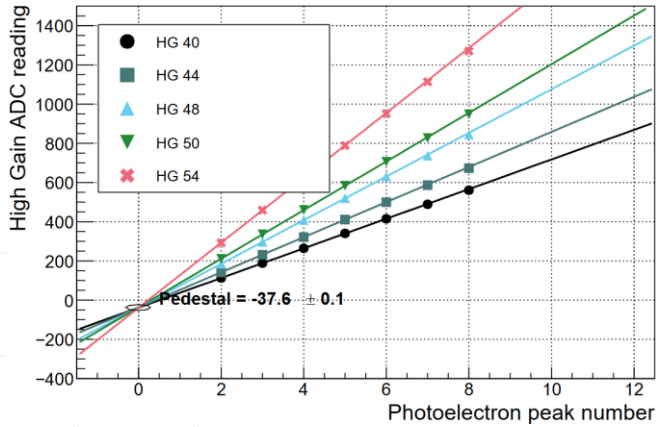


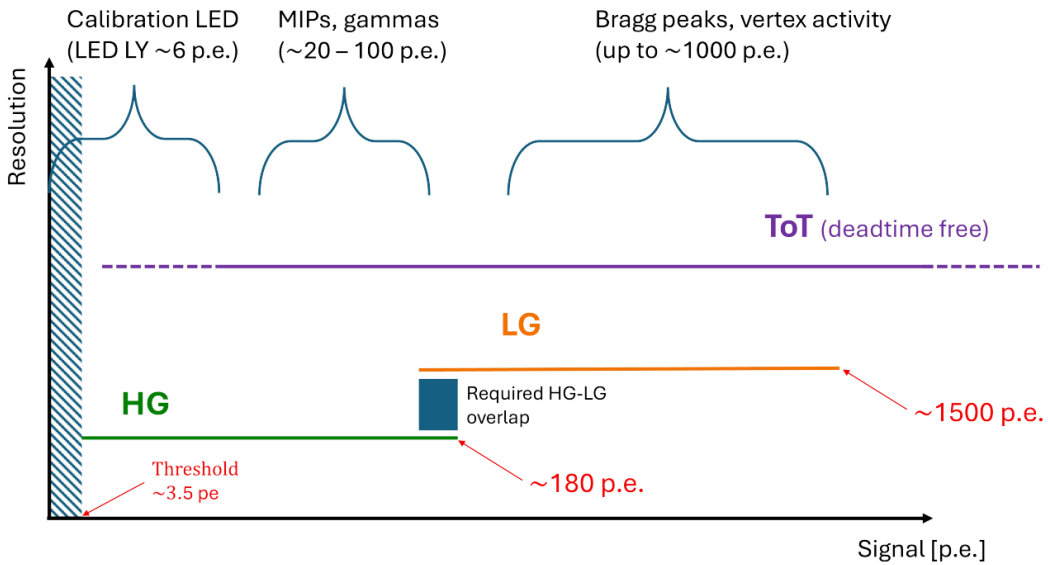
LED Calibration

- Low intensity LED pulses are used to characterise each MPPC, similar to the SFGD
- Tuned all bias voltages for similar channel responses
- For photoelectron charge deposit, need to measure high gain, pedestal and LG-HG conversion
  - Not considering ToT at this stage







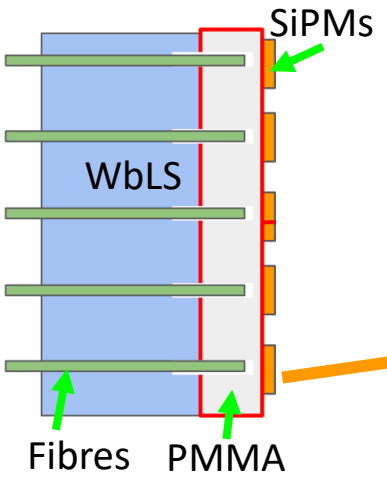


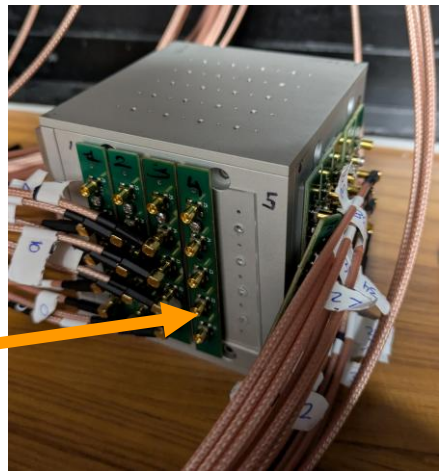
microSFGD studies

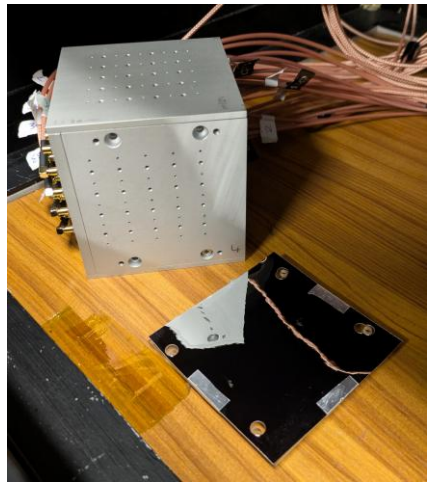
- Need a water-tight vessel in future – consider blind holes
  - Study effect of having PMMA between fibre end and SiPM

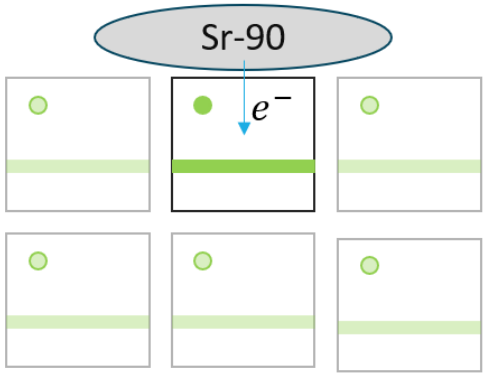
- Compare 1mm and 3mm SiPM performance
  - 1mm is Hamamatsu S13081-050CS
  - 3mm is Hamamatsu S13360-3075CS

- Study the effect of adding a reflective sheet on the opposite fibre end
- Took measurements with Sr-90 beta source and verify with cosmic data

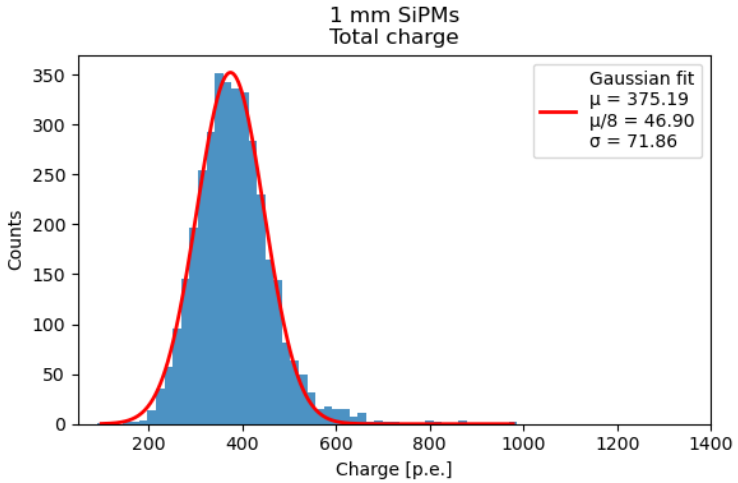


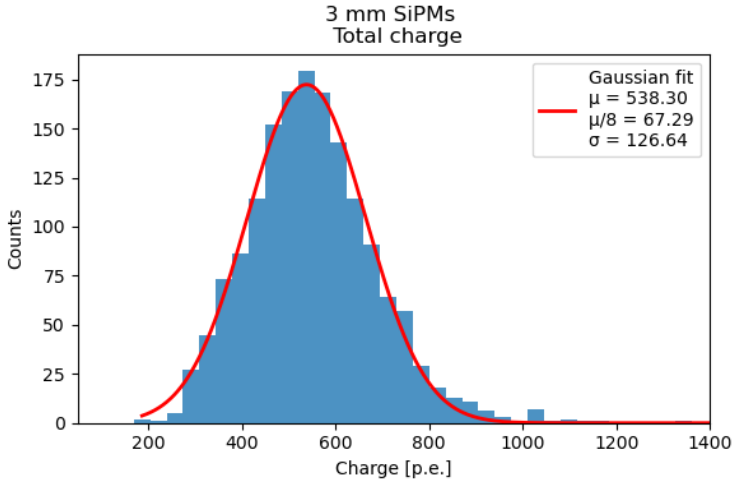






microSFGD results





- In cosmics, took events that had vertical tracks
- 3mm SiPM has higher LY than 1mm by factor 1.4
- Adding a reflective sheet improves LY by factor 1.15
- Adding PMMA between fibre end and SiPM reduces LY by only a factor of 0.91

SiPM size	Reflector	PMMA	Mean L.Y/fibre [p.e.]
1mm	No	No	47
1mm	Yes	No	53
3mm	No	No	67
3mm	Yes	No	77
3mm	No	Yes	61
3mm	Yes	Yes	72

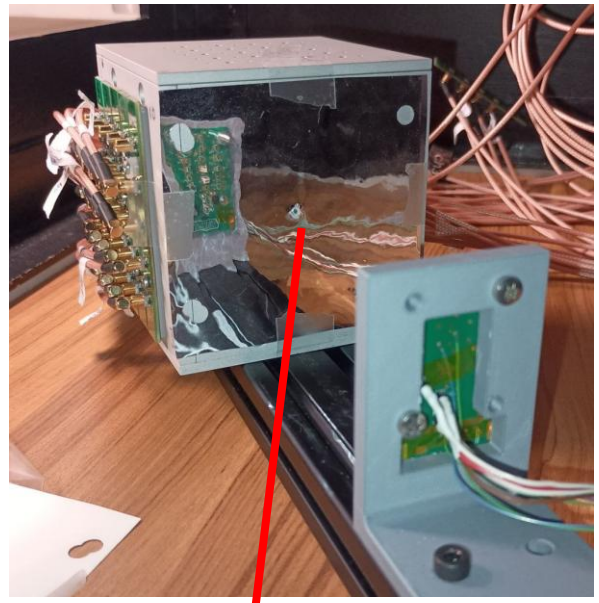
1.4x

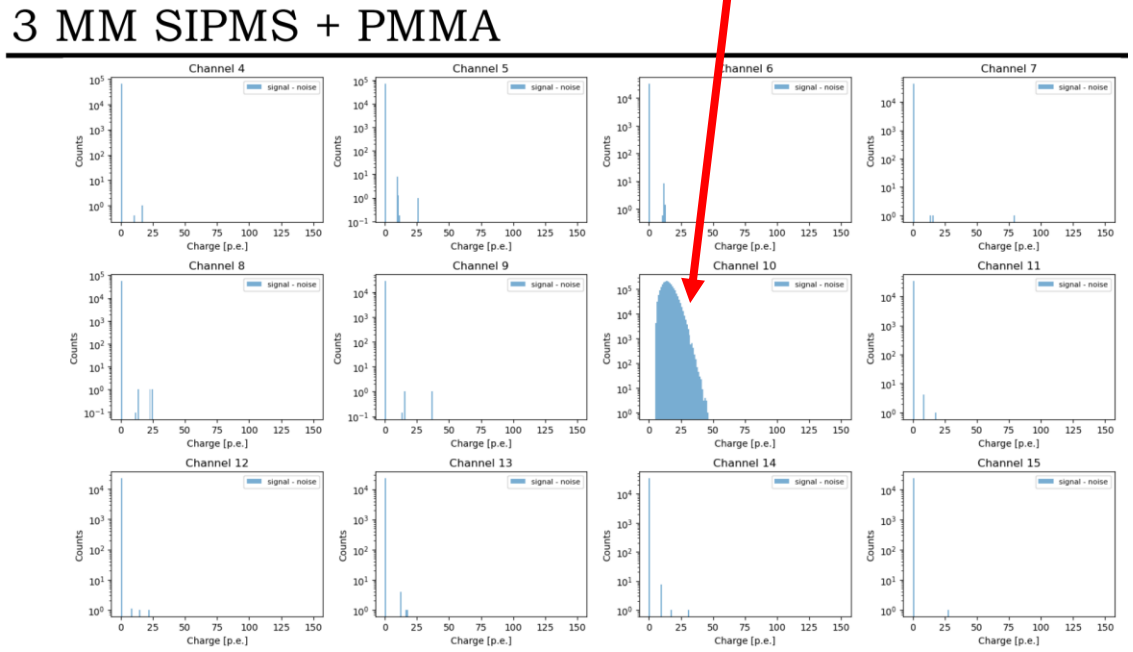
0.91x

1.15x

microSFGD optical isolation

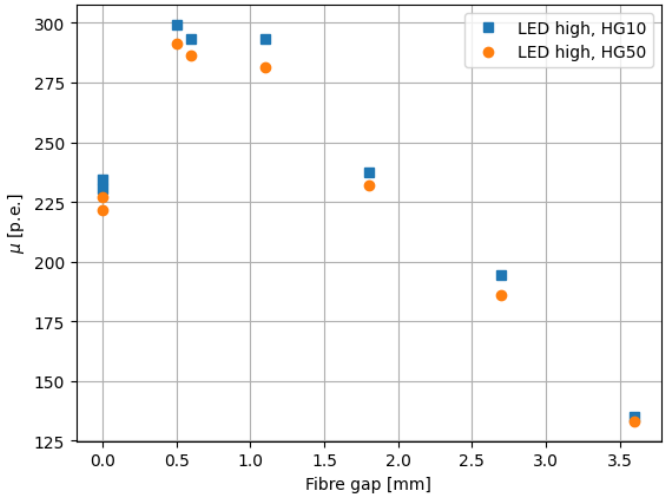
- PMMA between fibre and SiPM will spread light, and bigger SiPM surface may pick up signal from other channels
- Shine LED on only one fibre end and measure LY in surrounding channels
- Subtracted the noise and found no significant difference with and without PMMA

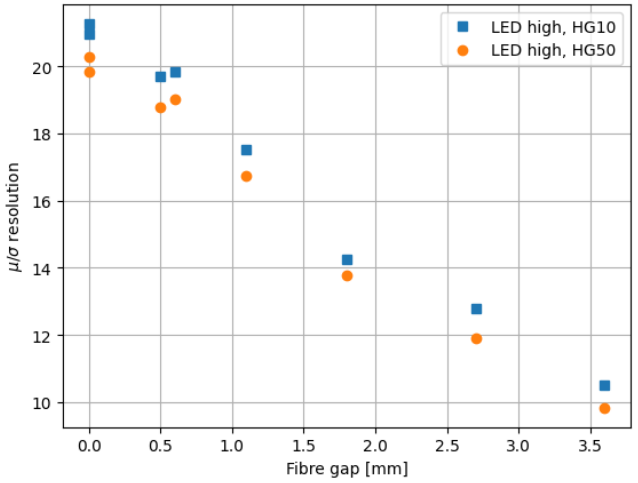


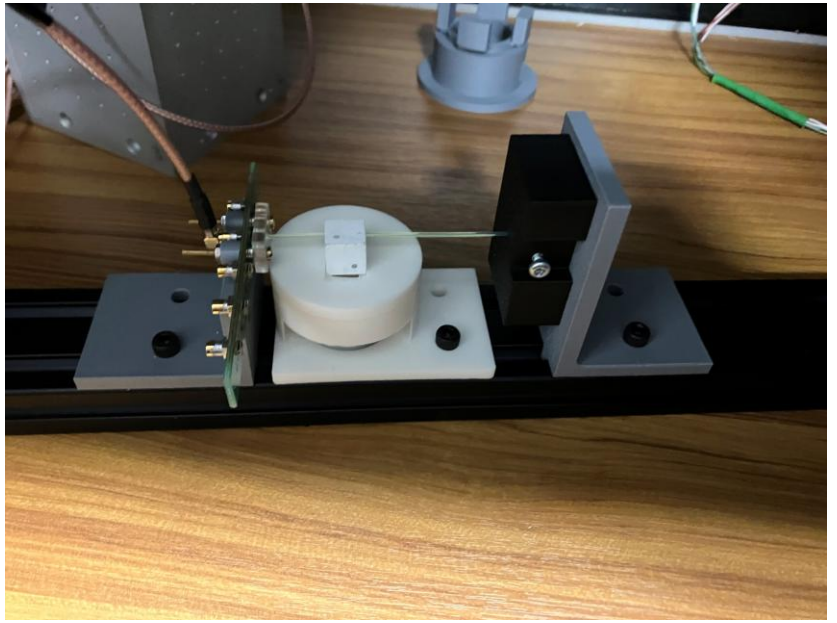


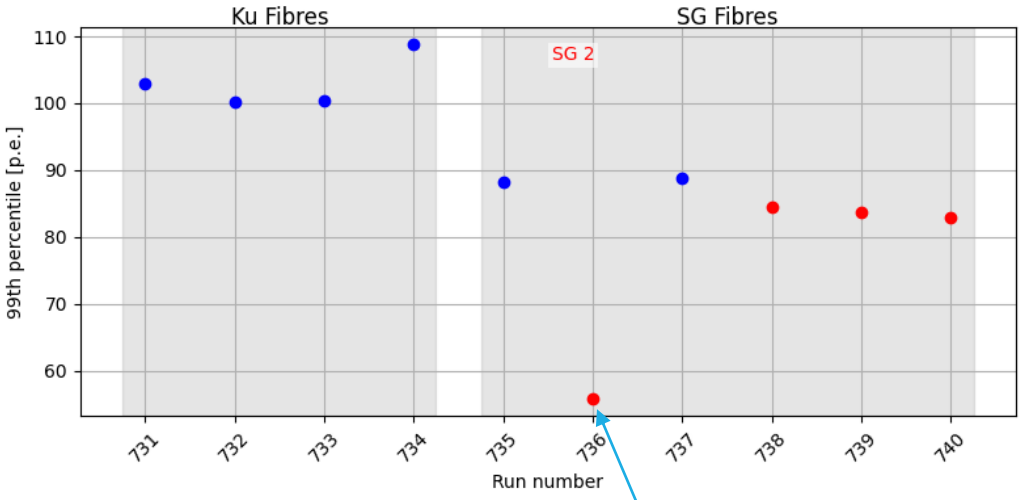
Fibre precision studies

- Fixed PCB and fibre+LED onto guided rails
- Measured mean light yield and resolution in 3mm SiPM as a function of fibre distance from SiPM









- Compared light yield from Kuraray Y11 and Saint Gobain BCF 92 fibres
  - Found Ku fibre had 15% higher light yield

Outlier result with one SG fibre. Repeated measurement and found consistent results

Conclusion

- Developing ND280++ to reduce ν_e cross section uncertainties
  - Planning construction in the 2030s
- Results at LPNHE are guiding the WbLS detector design
  - 3mm SiPMs: LY ↗ by 40%
  - Reflective sheets on fibre ends: LY ↗ by 15%
  - PMMA does not introduce significant LY loss or optical cross-talk between SiPMs
  - Larger prototype will be built in Japan to be exposed to particle beam
- Developing our own small prototype to use with WbLS

Back up

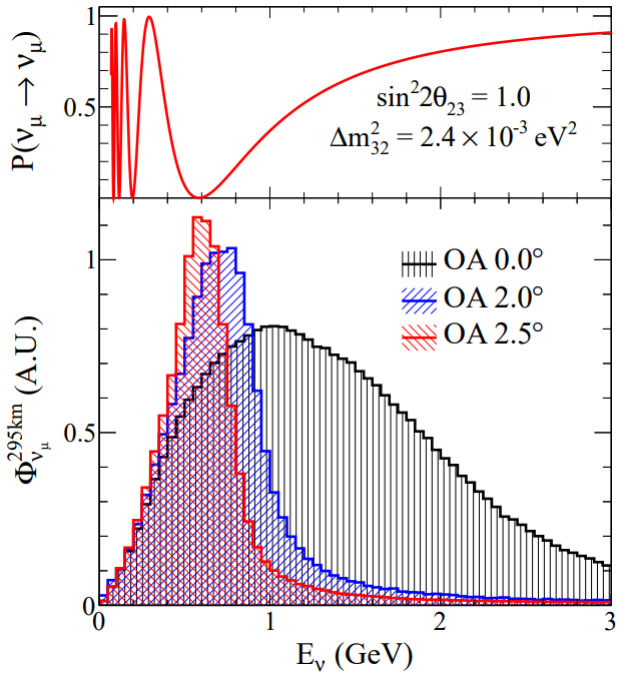
Acronyms

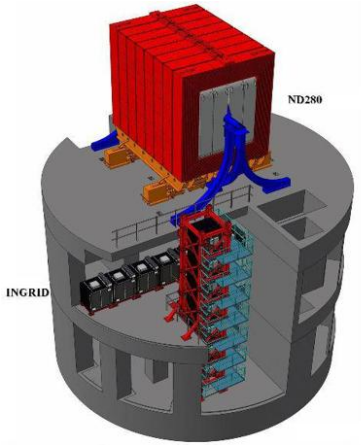
- LAB: Linear Alkyl Benzene
- PPO: Primary solute 2,5-diphenyloxazole
- bisMSB: p-bis-(o-methylstyryl)-benzene
- PC: pseudocumene
- BC: benzethonium chloride
- LAS: linear-alkylbenzene-sulfonate
- PTFE: polytetrafluoroethylene
- PMMA: Poly(methyl methacrylate)

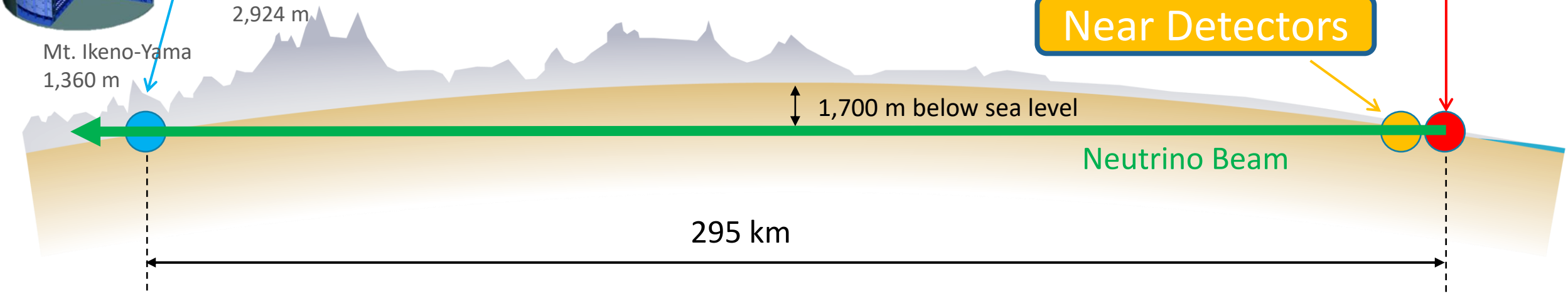
T2K

- **T**okai **2** **K**amioka taking neutrino data since 2010
- J-PARC's 30GeV proton beam → ν_μ ($\bar{\nu}_\mu$) beam at ~800kW
- ND280 and SK 2.5° off-axis → narrower E_ν

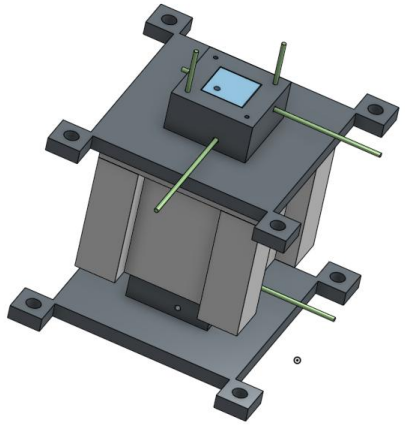
$$\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right)$$



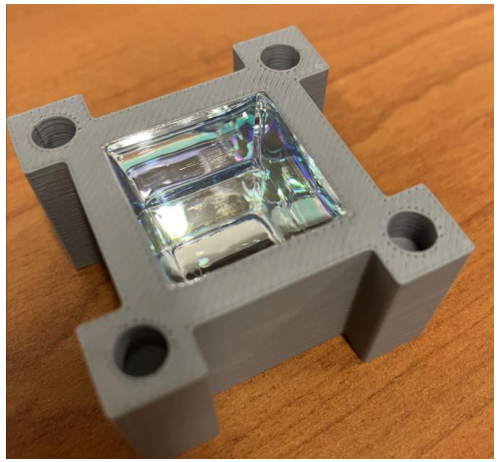


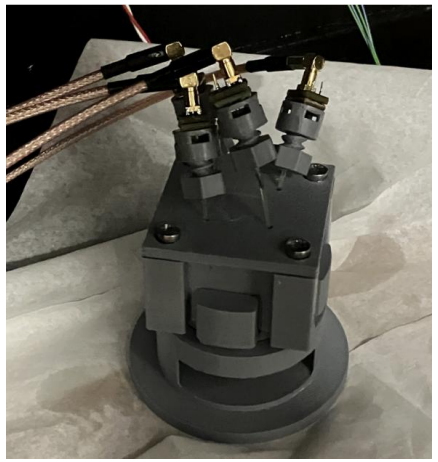


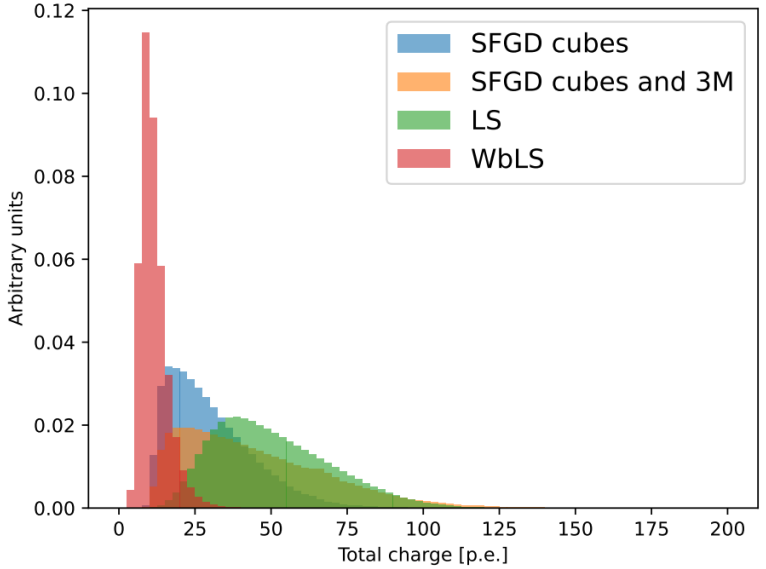
Previous study: 8cm^3 SuperCubes

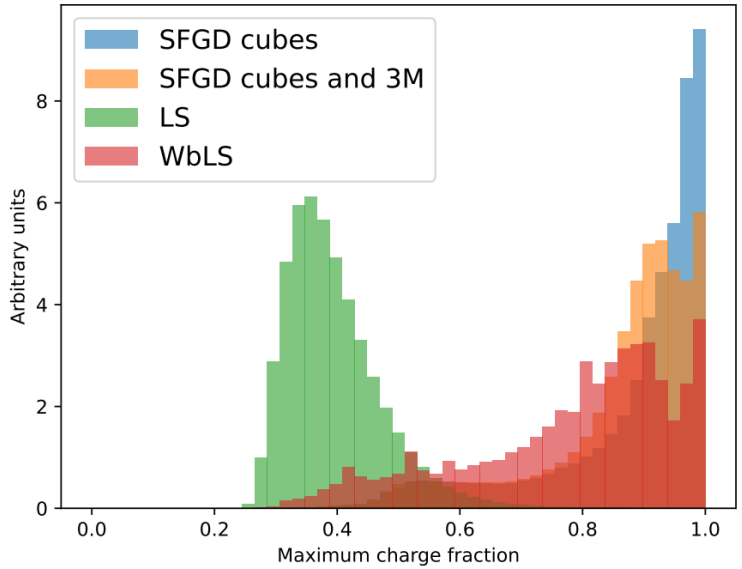


- Set up with 4 channels, and 3M reflector on the edges
- Compared light yield from SFGD cubes, LS and WbLS
- Found WbLS to have LY 5x smaller than LS
- Design flaws included non-watertight lid, unstable SiPM placement, incorrect pedestal calibration algorithm (now updated), no segmentation
- Considering re-design for better precision









microSFGD results