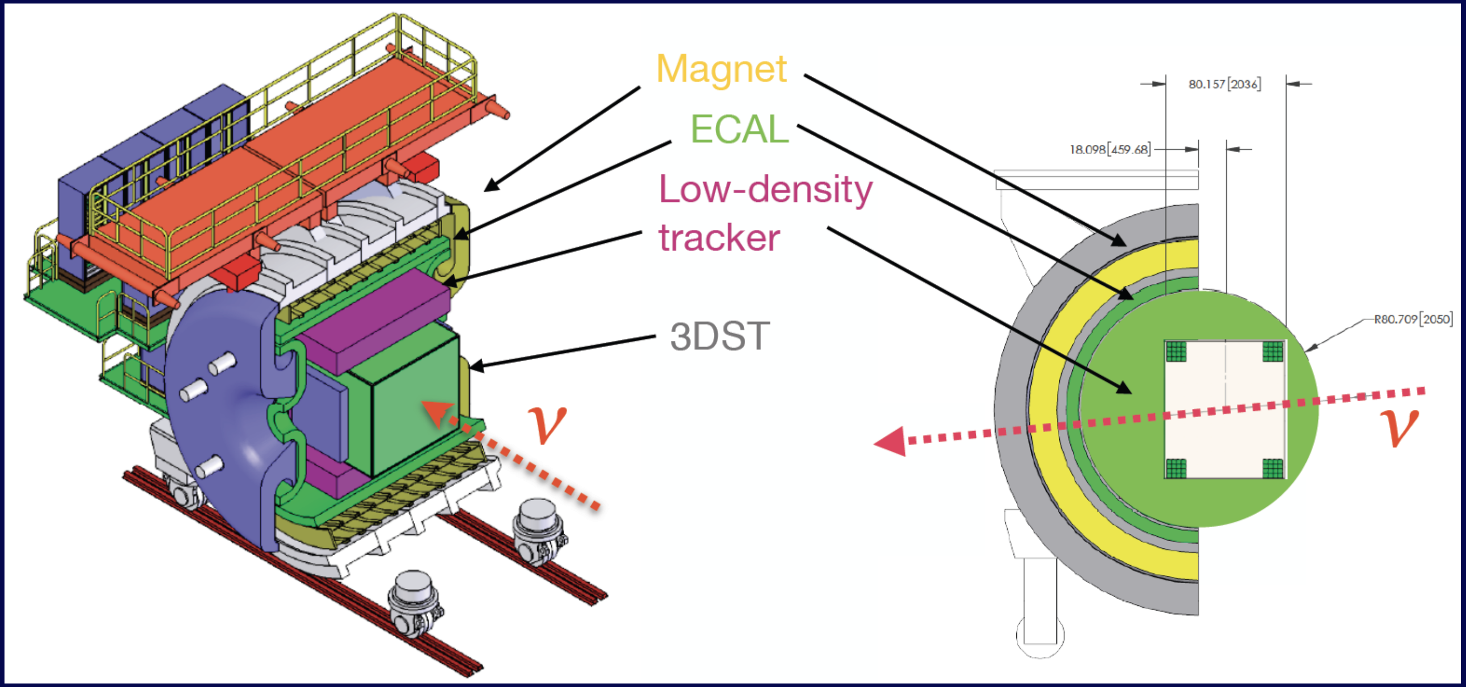
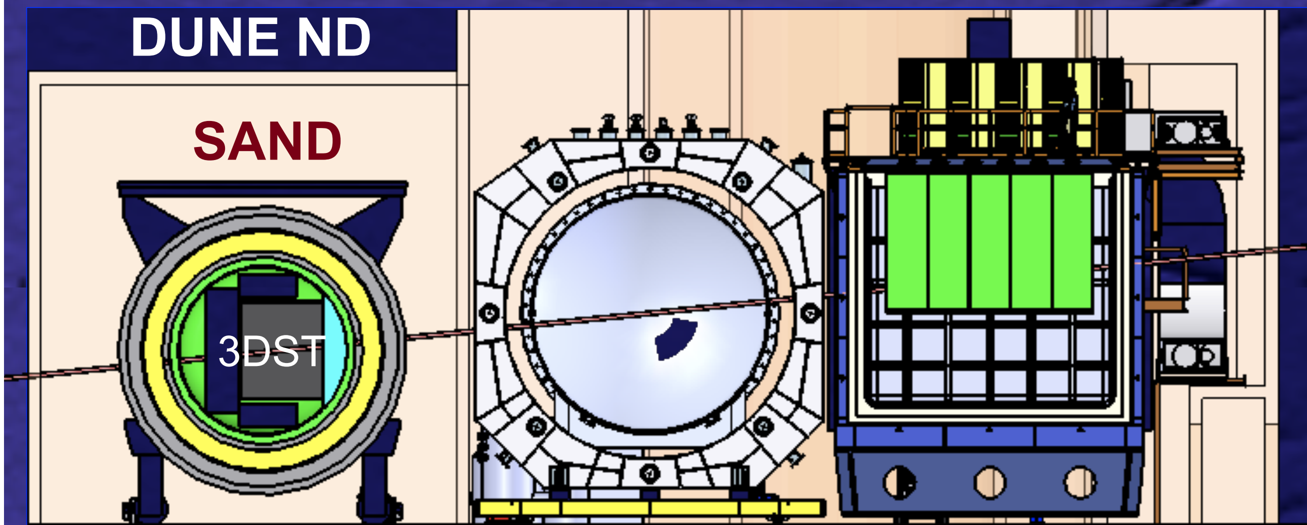
SAND 3D-projection Scintillator Tracker (3DST)

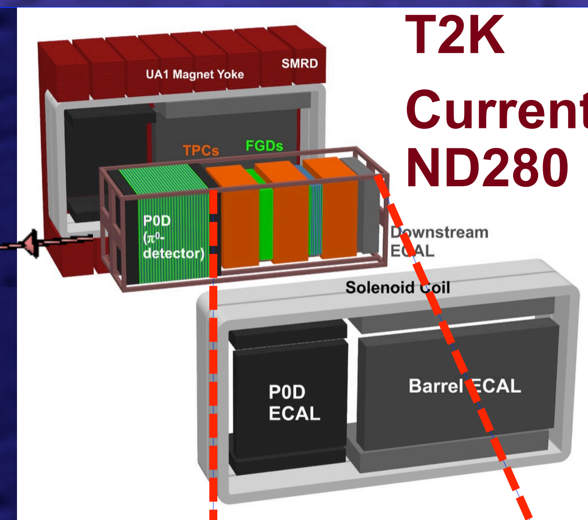


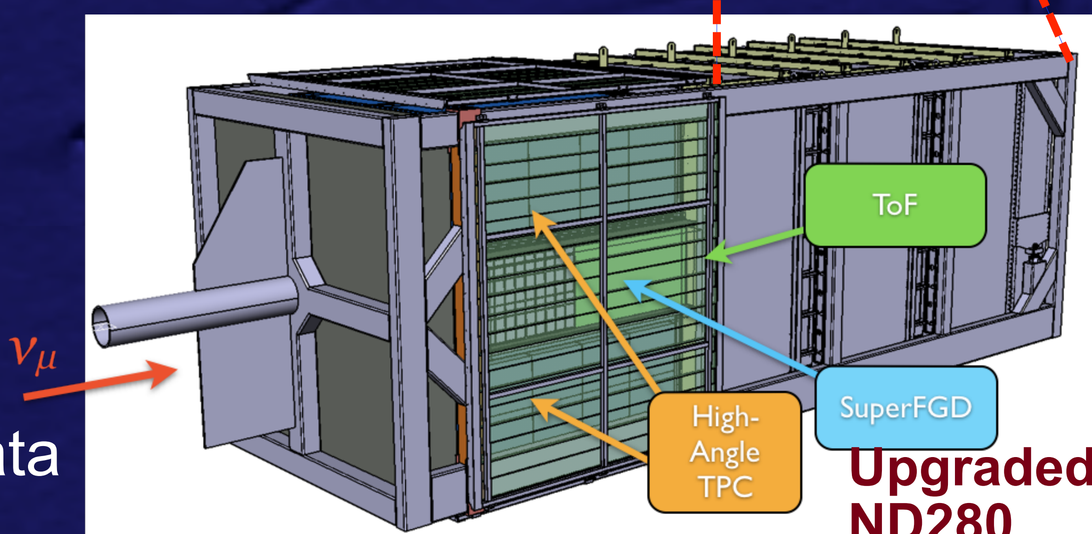
Chang Kee Jung, Stony Brook University
for the DUNE SAND group

DUNE CDR: Near Detector Review, via video
July 9, 2020

Global Strategy: Synergy with T2K SuperFGD





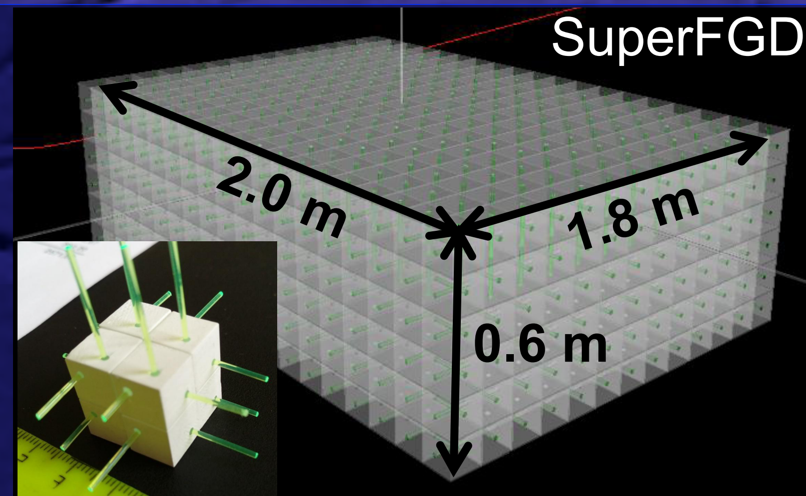


Effective Usage of
Resources and Expertise
and
Optimal Use of Physics Data

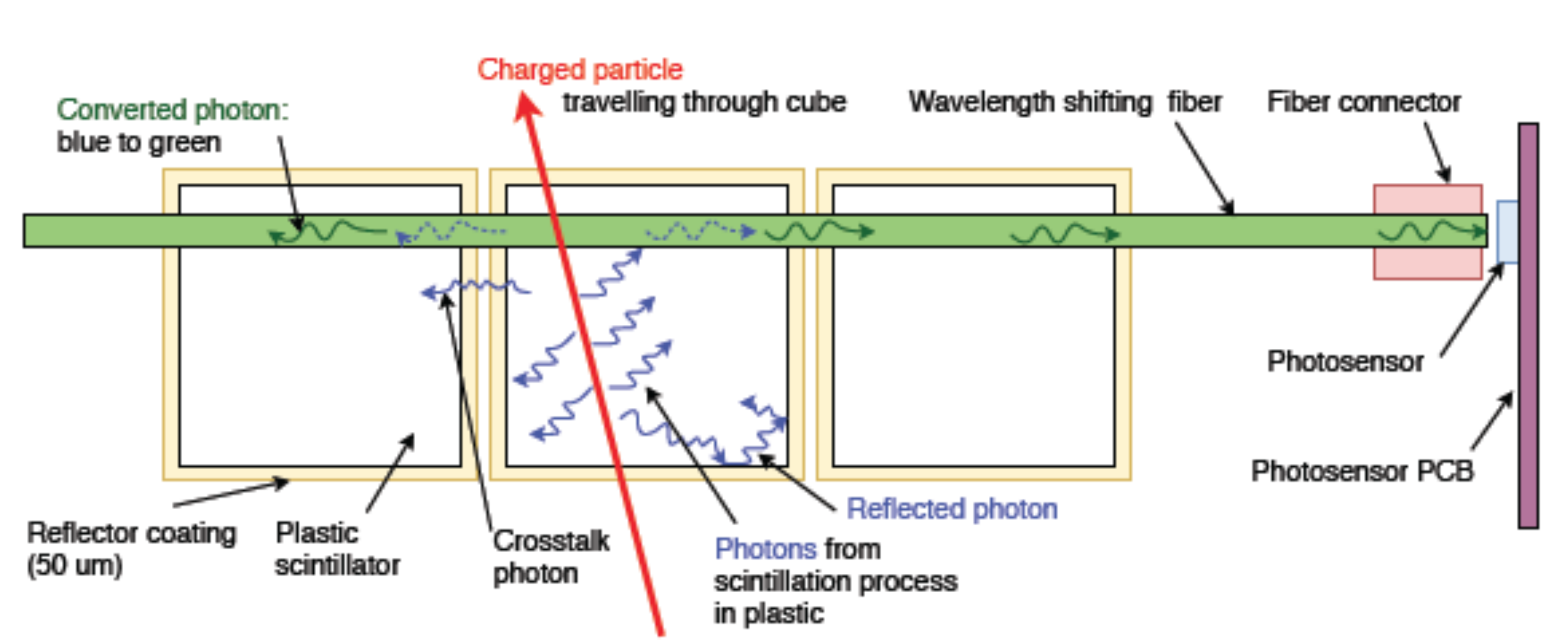
Fundamentals of DUNE 3DST & T2K SuperFGD

- Plastic scintillator + WLS fiber + MPPC
  - Fully active target
    - 3DST (2.36 x 2.36 x 2.12 m^3)

      12.5 ton total (11 ton FV w/ 10 cm cut)
  - 1x1x1 cm^3 scintillator cubes assembled in rows and columns
  - Provide 3D projected views w/ fine segmentation
  - 4π acceptance w/ low momentum threshold for protons (~300 MeV)
- Good timing resolution
  - Event-by-event neutron KE measurement using TOF
- The exact dimensions of 3DST and the detector "system" configuration still being optimized in the context of SAND 3DST



From Deposited Energy to a Photosensor Electrical Signal Output



Polystyrene-based Plastic scintillator
1.5% paraterphenyl and 0.01% POPOP
1x1x1 cm^3 cubes
Chemical etching as reflector
WLS fibers (Kuraray Y11, 2-clad, 1mm)
Multi Pixel Photon Counter detector

2018 *JINST* **13** P02006
NIM A936 (2019) 136-138

Envisioned Roles of the SAND 3DST in DUNE ND

- Beam monitoring (requirement)
  - Beam stability (position, width, rate, spectrum)
    - Requires high statistics → fully active target (as largest mass as possible)
  - Particularly critical under DUNE-PRISM scheme

→ *See Luca Stanco's talk*

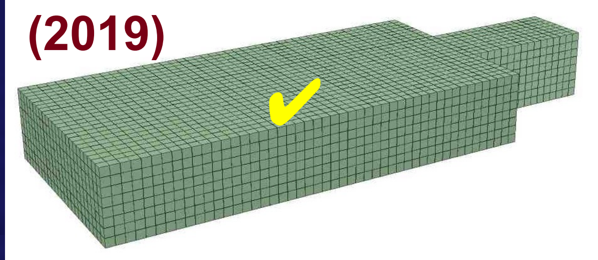
- Neutron detection capability
  - High purity and possibility of energy measurement by ToF
    - Requires sub-ns fast timing resolution
    - Neutrino interaction model tuning
- Semi-Independent flux measurements, in particular anti-nu flux
  - nu-e scattering, STV w/ neutron detection, possibly low-nu, etc.

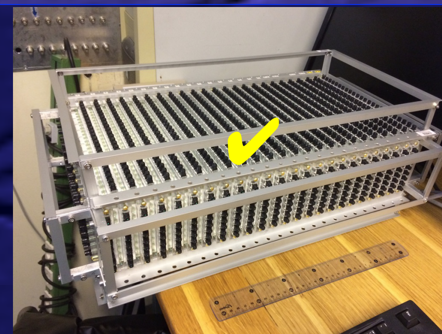
SAND 3DST Per-Year Event Rate

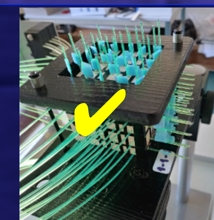
FHC Beam Process	Rate	RHC Beam Process	Rate
All ν_μ-CC	1.5×10^7	All $\bar{\nu}_\mu$-CC	5.4×10^6
CC 0π	4.4×10^6	CC 0π	2.4×10^6
CC $1\pi^\pm$	4.3×10^6	CC $1\pi^\pm$	1.5×10^6
CC $1\pi^0$	1.3×10^6	CC $1\pi^0$	5.3×10^5
CC 2π	1.9×10^6	CC 2π	5.0×10^5
CC 3π	8.7×10^5	CC 3π	1.7×10^5
CC other	1.8×10^6	CC other	2.8×10^5
ν_μ-CC COH π^+	1.3×10^5	$\bar{\nu}_\mu$-CC COH π^-	1.0×10^5
$\bar{\nu}_\mu$-CC COH π^-	1.2×10^{4}*	ν_μ-CC COH π^+	1.7×10^{4}*
ν_μ-CC ($E_{\text{had}} < 250$ MeV)	2.4×10^6	$\bar{\nu}_\mu$-CC ($E_{\text{had}} < 250$ MeV)	1.9×10^6
All $\bar{\nu}_\mu$-CC	7.0×10^5	All ν_μ-CC	2.3×10^6
All NC	5.3×10^6	All NC	2.9×10^6
All $\nu_e + \bar{\nu}_e$-CC	2.6×10^5	All $\bar{\nu}_e + \nu_e$-CC	1.7×10^5
$\nu e \to \nu e$	1.8×10^{3}*	$\nu e \to \nu e$	1.5×10^{3}*

Worldwide Progression in SuperFGD/3DST Programs

LANL Neutron Beam Test (2019)



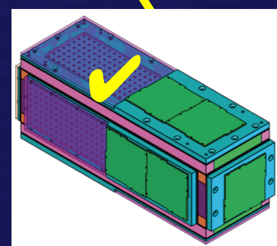




5x5x5 Prototype (2017)

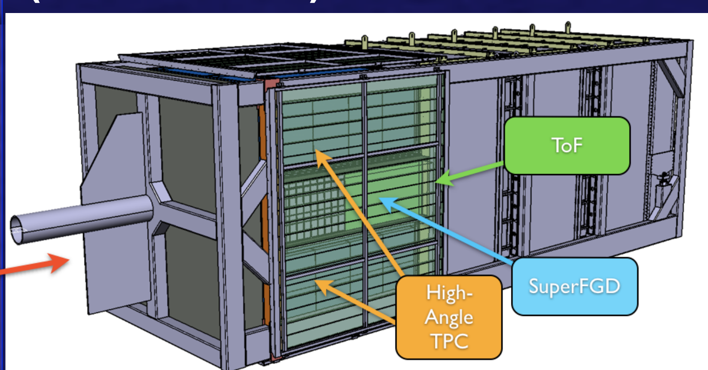
CERN Beam Test (2018)
SuperFGD Prototype (8x24x48)

Additional Neutron Beam Test Proposed (2020)

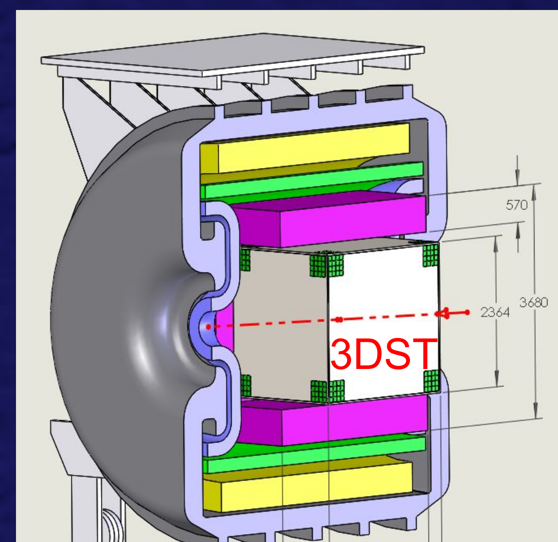


US-Japan Program (2019)
Prototype (8x8x32)

T2K SuperFGD (2022) (200x60x180)



3D-Printing R&D (on-going and planned)

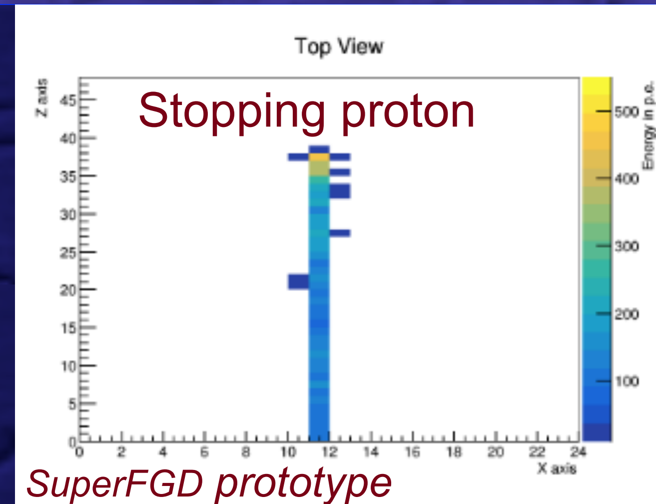


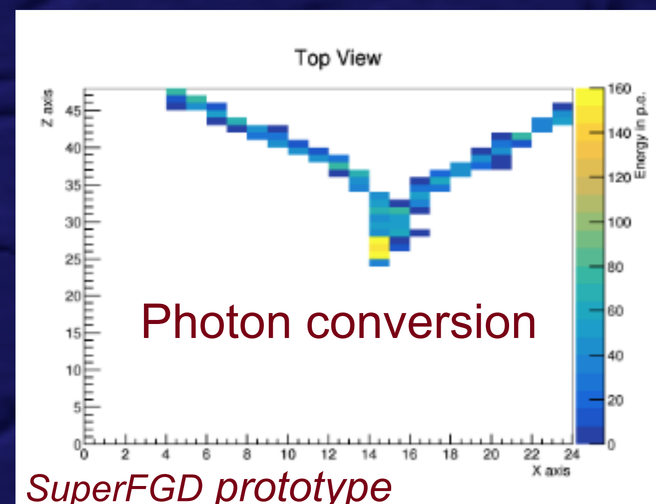
3DST in DUNE ND SAND (Ref. Design)

Prototype Beam Tests (Key) Results

SuperFGD Prototype and CERN Beam Test

- SuperFGD prototype (8x24x48 cm^3 array) was built by the contributions from the T2K institutions in 2018
  - Detector components are mostly same as the final SuperFGD design but not identical
- Beam tests at CERN was successfully carried out in 2018
  - Participation of US groups (LSU, Stony Brook) and also non-T2K members
  - High quality data for good detector characterization
  - Paper in preparation for publication

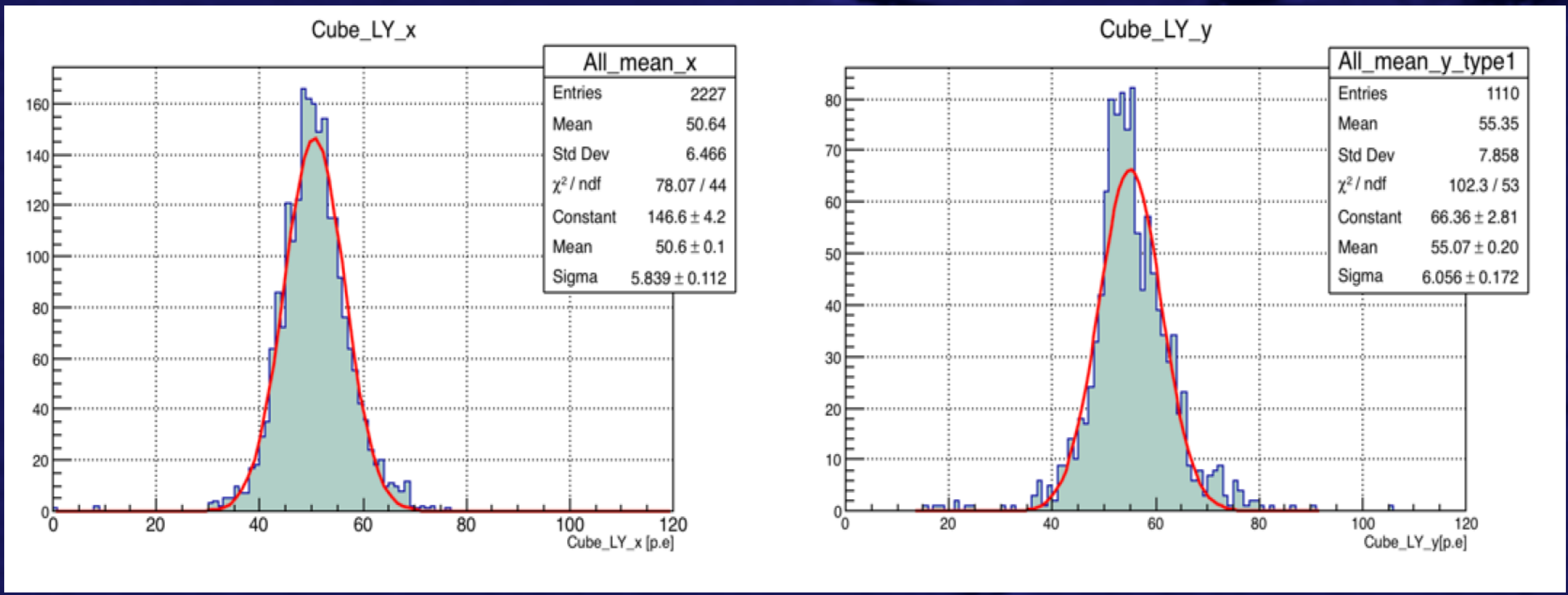




SuperFGD Prototype (24 x 8 x 48): Light Yield (Cube Response) Summary

2227 cubes read out with horizontal X (24 cm) fibers

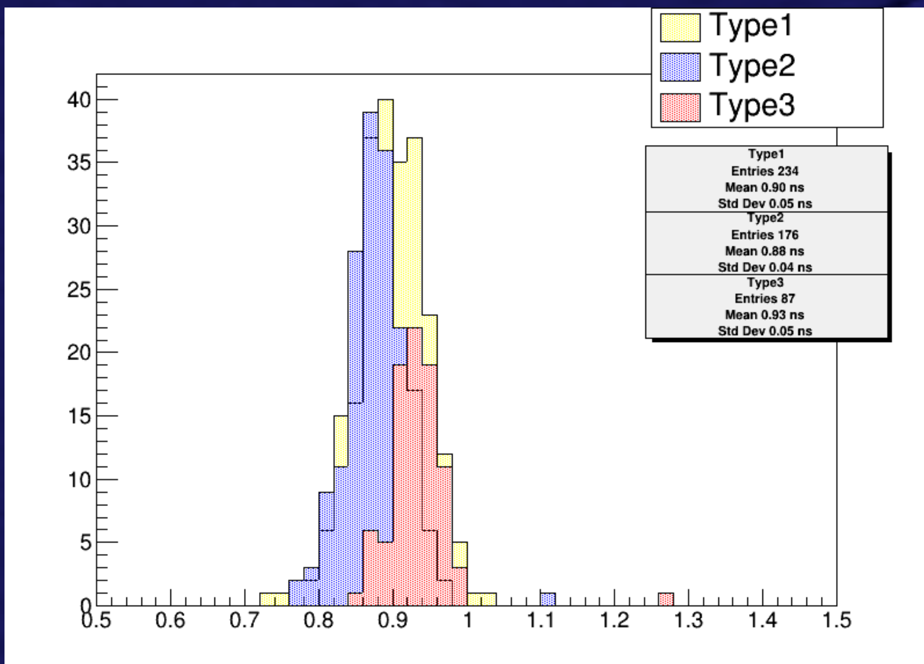
1110 cubes read out with vertical Y (8 cm) fibers



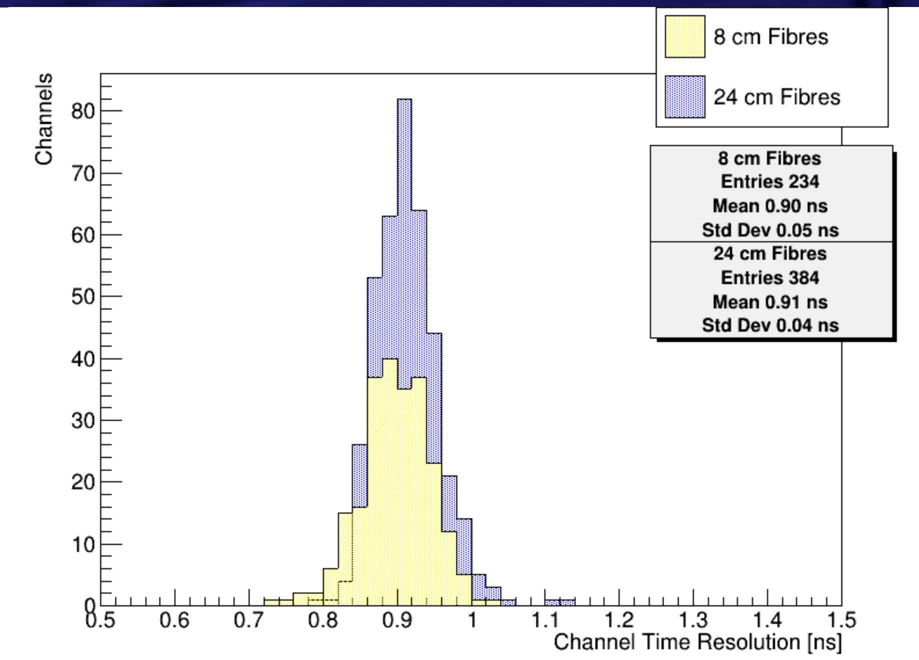
No corrections made for fiber attenuation

SuperFGD Prototype: Time Resolution Final Results for Single Fiber

Different Photosensor Types



Different WLS Fiber Lengths



Time resolution for a single fiber σ_t = 0.9 ns

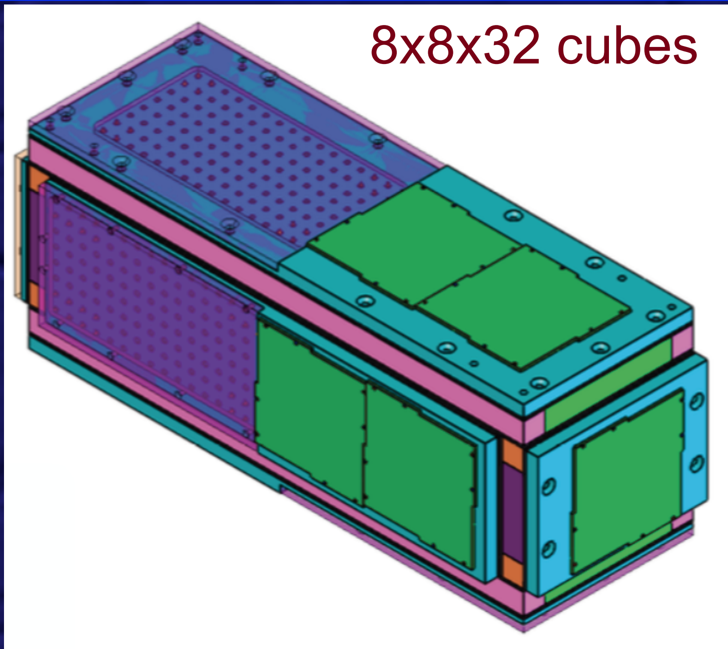
→ consistent with measurements from the 5×5×5 prototype which was done w/ completely different electronics (sampling rate at 5 GHz)

US-Japan Prototype

- US-Japan prototype was built with the funds from the U.S.-Japan Science and Technology Cooperation Program in High Energy Physics
  - Proposal: Development of a Novel 3D-projection Scintillator Tracker Technology for Near Detectors in Neutrino Experiments
    - Participating institutions

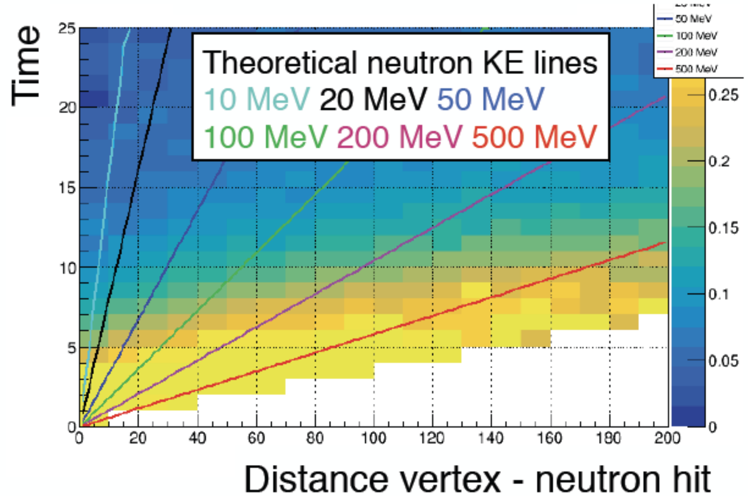
      US: BNL, LSU, Pennsylvania, Pittsburgh, Rochester, SBU

      Japan: Tokyo, Yokohama National, KEK, Kyoto
    - Approved in May 2018
    - $200k (in US) and 7.65M JPY (in Japan)



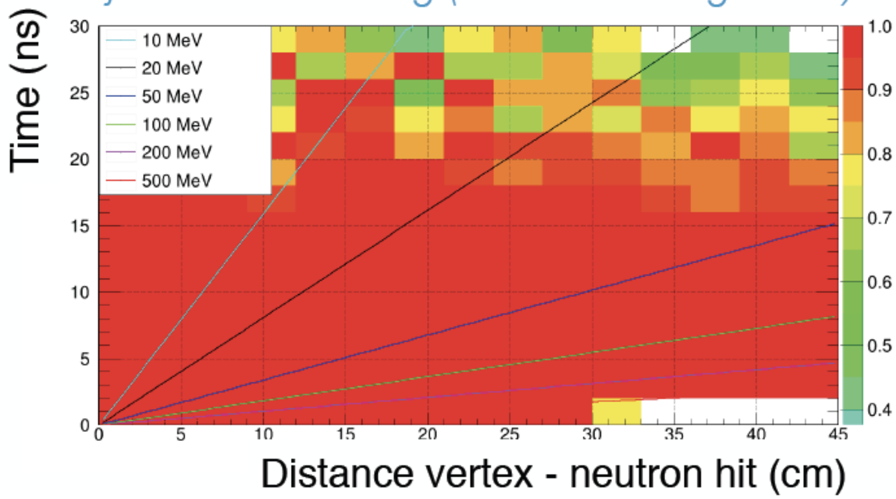
Event-by-event Neutron KE Measurement in 3DST utilizing TOF

Neutron KE resolution via ToF in 3DST

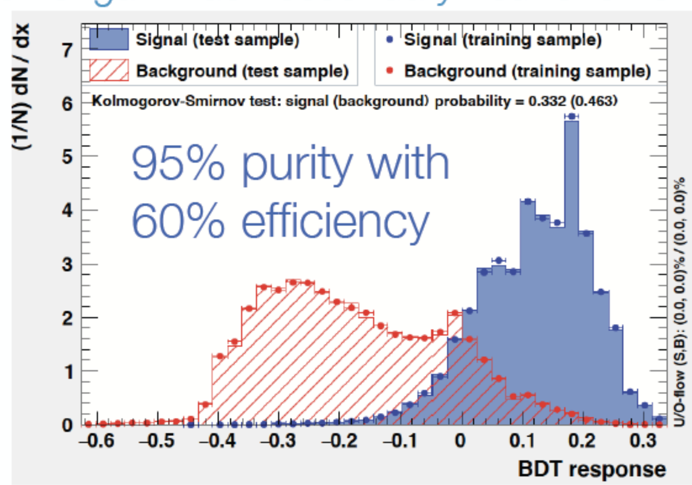


- 3DST best suited for neutron KE measurement
  - ¬ Fine granularity and sub-nano sec timing resolution (~.5 ns for 3 fibers)
  - ¬ Large fully active mass for neutron interactions (low-A nuclei & scintillating)
  - ¬ Low energy threshold (1 p.e. ~60 keV)

Rejection out-FV bkg (neutrons and gamma)

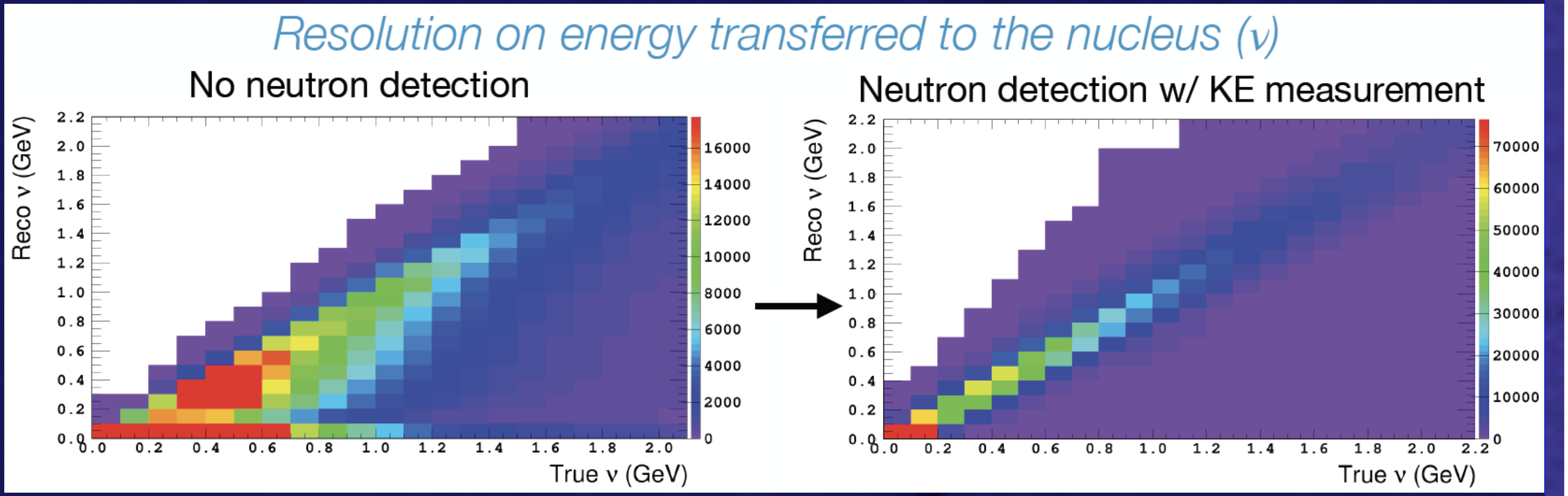


Rejection of gammas / secondary neutrons from 3DST



Importance of Event-by-event Neutron KE Measurement

- Event-by-event neutron energy measurement is one of the final, if not the final, frontiers in particle physics experiment
  - Allows full event reconstruction
    - Detailed studies of neutrino interaction models
    - Measurement of antinu flux, especially using antinu–hydrogen interactions which has limited model dependence (PRD 101, 092003 (2020))



- 3DST
  - Very good neutron detection efficiency and very low out-FV background
- Recent paper from Minerva (PRD 100, 052002 (2019))

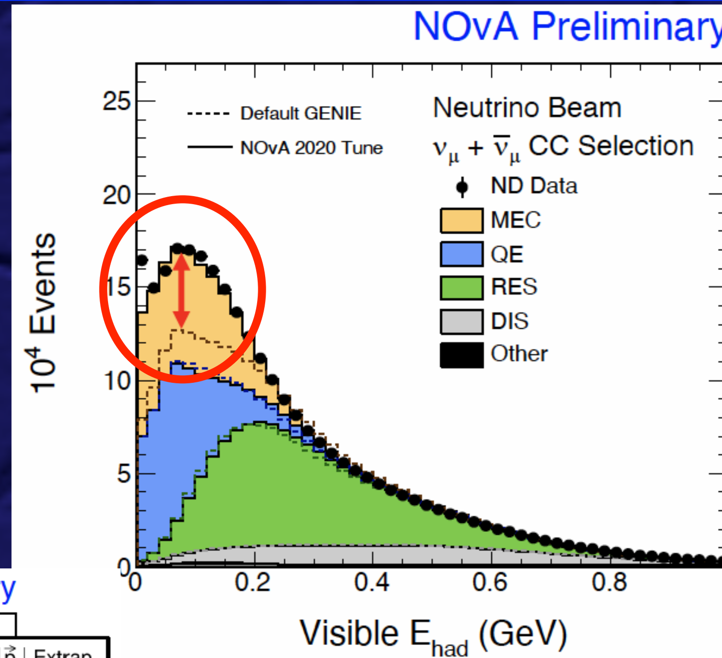
Importance of Measuring Neutron Energy in the Oscillation Analysis

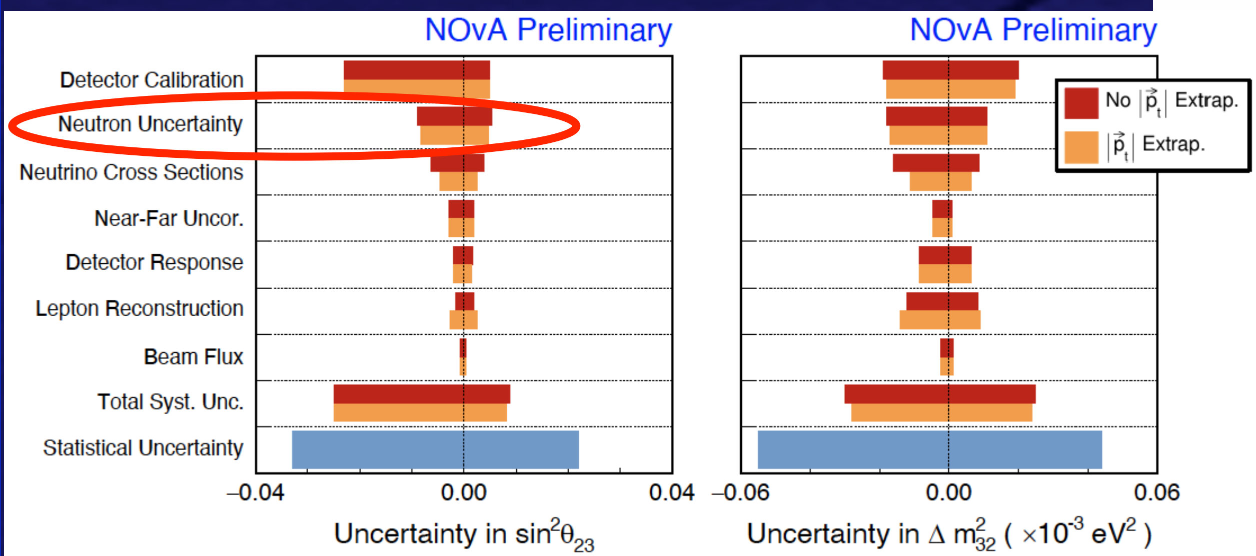
NOvA

Large disagreement between neutrino interaction model (Default GENIE) and data, especially in the hadronic energy

→ Model needed to be tuned to NOvA ND data

A. Himmel, Neutrino 2020





NOvA

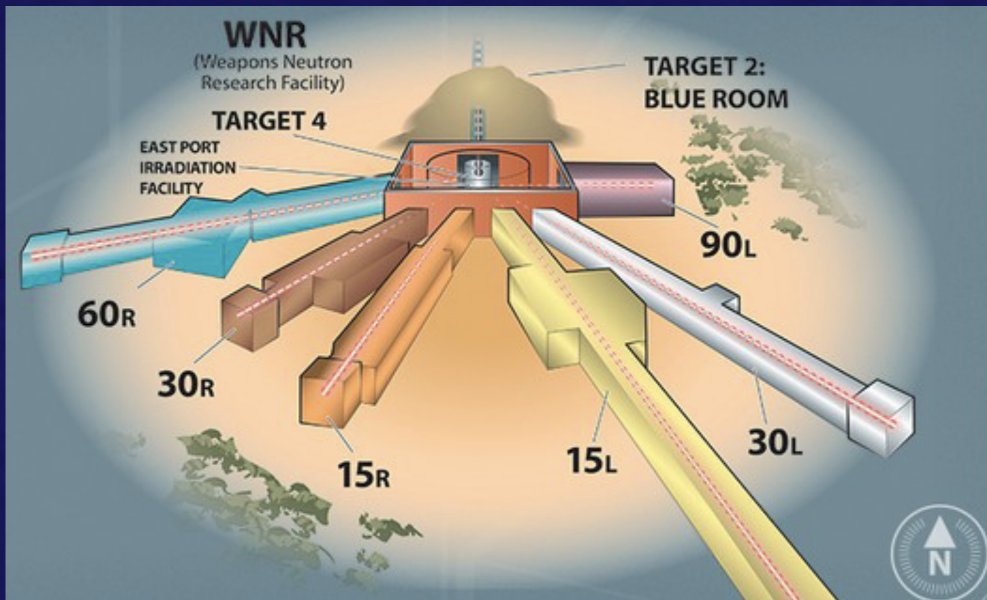
Oscillation Analysis Systematic uncertainties

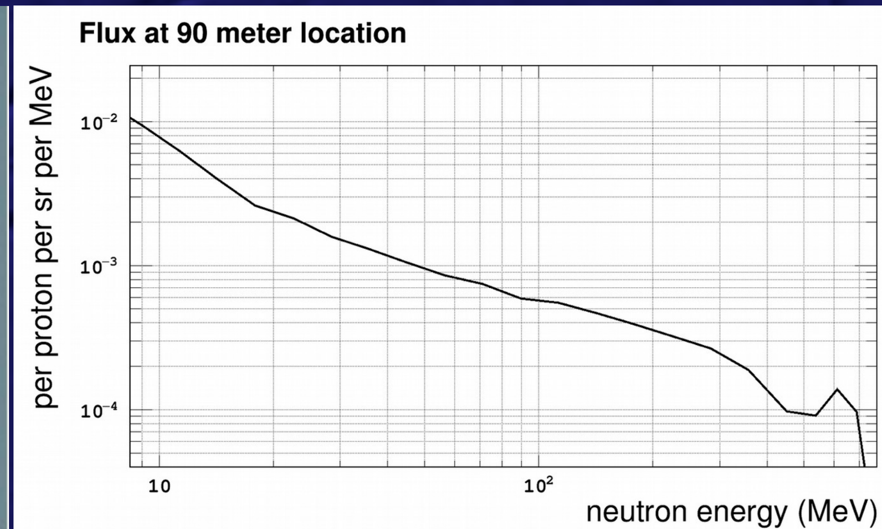
→ Neutron related uncertainty is the second largest

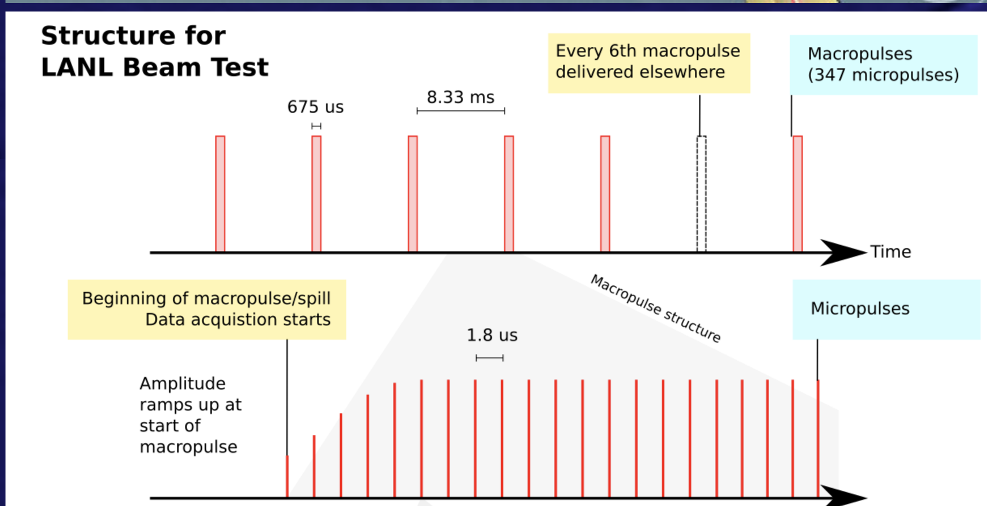
LANL (LANSCE) Neutron Beam Test
December 2019

- To characterize the detector neutron response
- Both **SuperFGD** and **US-Japan** prototypes were employed
- Large number of participating institutions
  - CERN, Chung-Ang U, ETH Zurich, U. of Geneva, Imperial College, INR, KEK, Kyoto U., LSU, U. of Pennsylvania, U. of Pittsburgh, U. of Rochester, South Dakota School of Mines and Technology, Stony Brook U., U. of Tokyo
- Supported by the US-Japan funds as well as the individual institution grants and funds
- High statistics, good quality data taken w/ the SuperFGD prototype; limited statistics data w/ the US-Japan prototype
- On-going data analysis toward total cross-section measurement
- Additional beam test proposed in fall 2020 (likely in December)

LANSCE Neutron Beam Test Facility

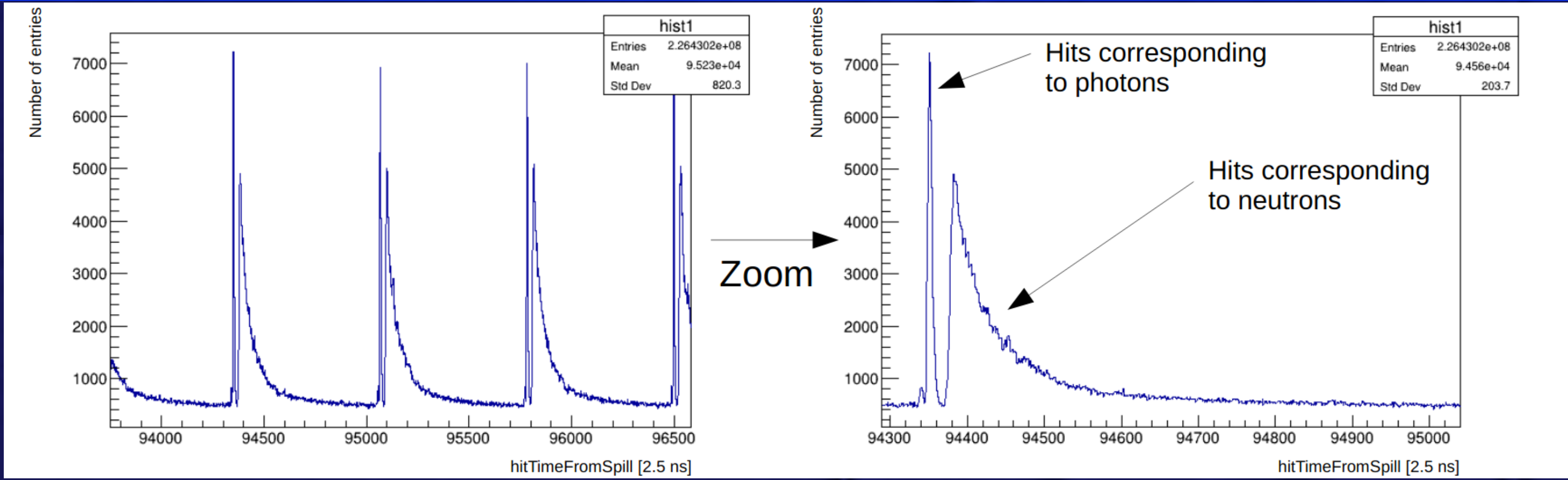




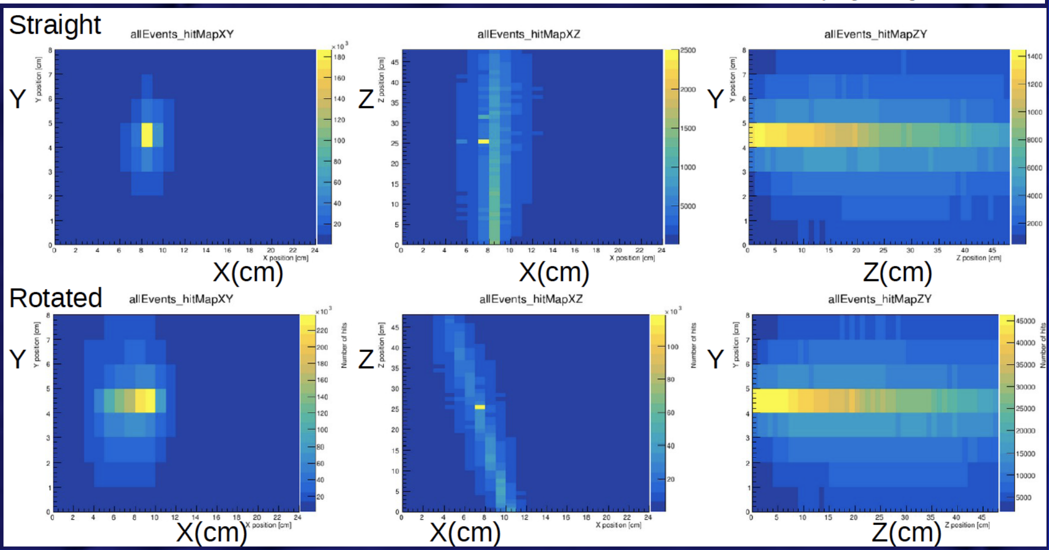


- Collimated neutron beam from 0-800 MeV
- Two runs:
  - ~ 3 weeks at 15L 90 m location
  - ~3 days at 15R 20 m location

Neutron Beam Test Data



Detector (SuperFGD prototype) was rotated at various angles to characterize the fiber/MPPC responses



T2K ND280 Upgrade: SuperFGD

- ND280 Upgrade: Improved performance to reduce sys. errors (<4%) for demanding CPV measurement
- SuperFGD:
  - Participating institutions/countries
    - INR Russia, Geneva Switzerland, CERN, IN2P3-LLR France, US, Japan
  - Total project cost: ~$3.6M (no unified accounting, assume ¥100 = $1 = €1 = 1 CHF)
  - On-going construction → installation in Spring 2022

SFGD Item	Sum contribution
Scintillator	1100
Assembly	50
WLS fiber	350
MPPC	450
Optical coupling	100
SFGD mechanical structu	250
Electronics (FEB)	690
Electronics (other)	550
Calibration system	50
Installation	50
Total	3640

(in k$)

US Contributions to SuperFGD

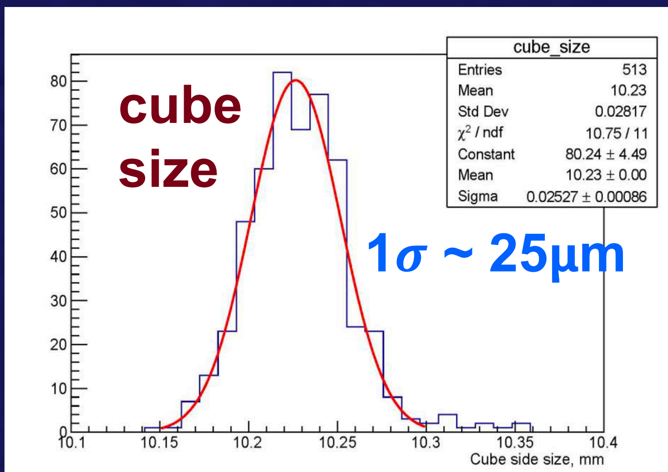
- 2018 US DOE HEP Portfolio Review
  - T2K received the highest priority classification along with NOvA despite the fact that T2K is a non-US based experiment and a competition to NOvA and in some extent to DUNE
    - Included plan for US participation in the T2K Upgrade/SuperFGD
- 2019 DOE approval of the US participation in the T2K ND280 Upgrade (SuperFGD)
  - $1.1M for 3 years (Nov. 1, 2019 – Oct. 31, 2022)
    - More than the proposed amount
    - No overhead included/charged
  - T2K SuperFGD, a working "prototype" for DUNE 3DST, taking data near the 2nd oscillation maximum (critical for the CPV measurement) of the DUNE/LBNF beam
    - Effective usage of resources and physics data

US Contributions to SuperFGD

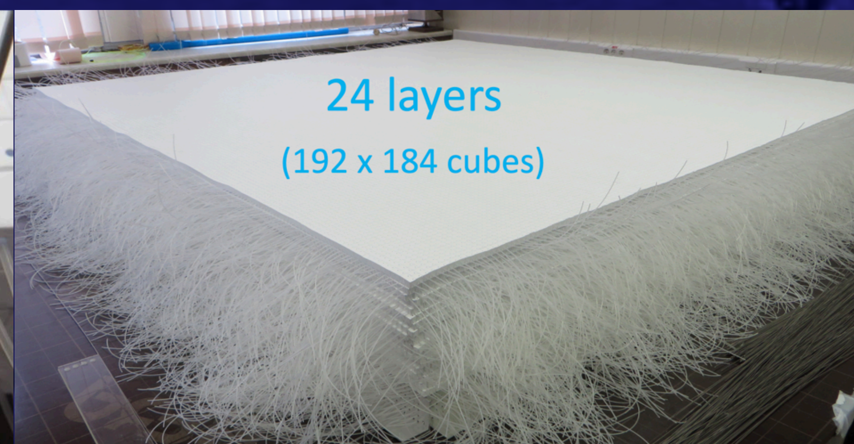
- Many 3DST institutions benefit from this approval
  - Scintillator Cubes (Stony Brook)
  - WLS fibers (Rochester)
  - MPPCs (LSU)
  - Mechanical Structure (Colorado)
  - Electronics (Penn, Pittsburgh, LSU)
  - Installation & Commissioning (all)
  - Project Management (Stony Brook)
- Possibly Increased probability of US contribution to 3DST

SuperFGD Cubes and Assembly

- About 1.5M cubes manufactured thus far (~75% of total # of cubes) at UNIPLAST → on track

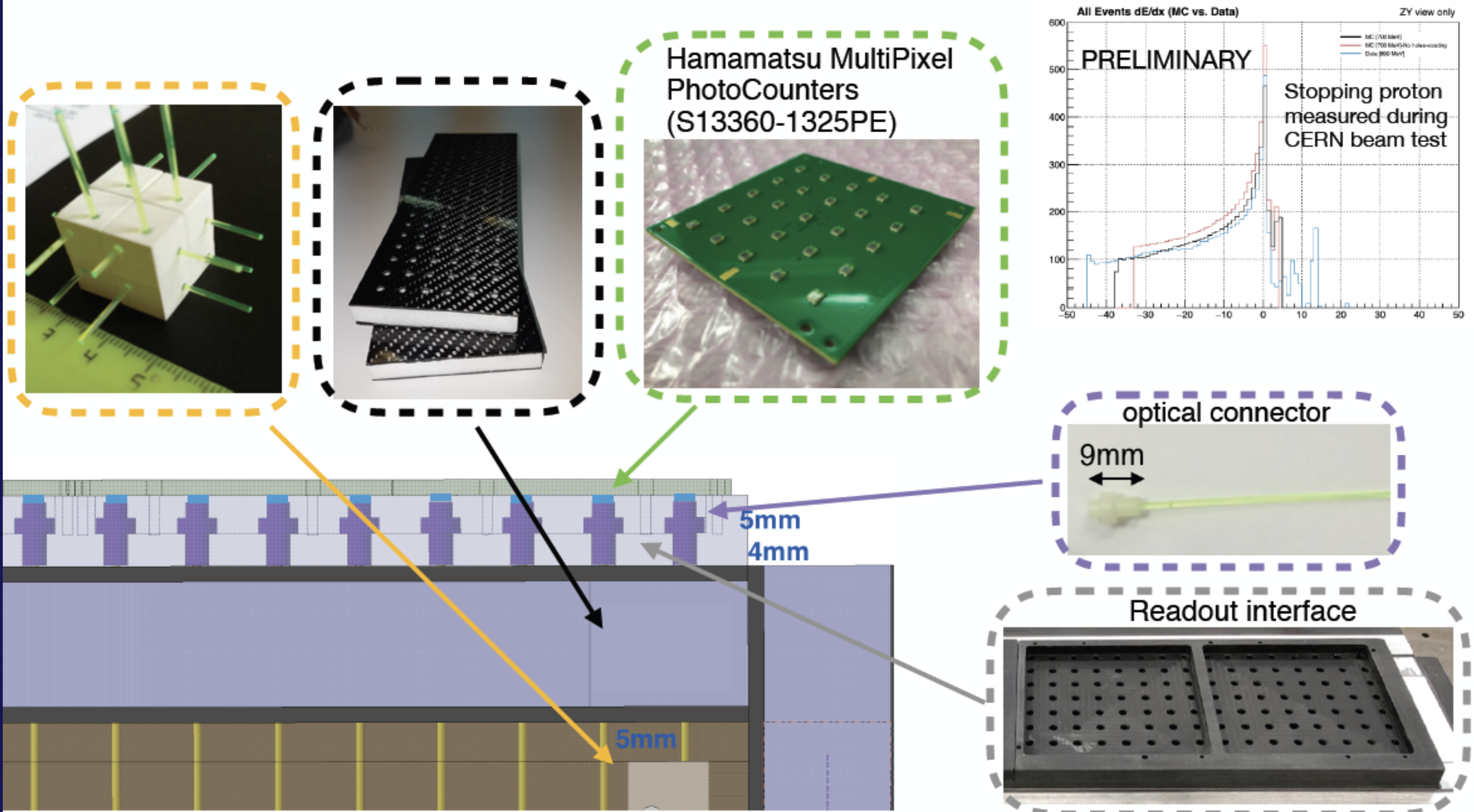


- Initial assembly uses ∅1.3 mm fishing lines to align cubes → fishing lines are eventually replaced by WLS fibers
- ~75% of the full layers has been assembled at INR in Moscow



SuperFGD Readout Interface

CERN-SPSC-2018-001 SPSC-P-357, arXiv:1901.03750



Scintillator Cube R&D at Fermilab: LDRD on Injection-molded plastic scintillator

- A proposal titled “Injection-molded plastic scintillator” has been funded by the Fermilab LDRD program (Anna Pla-Dalmau (PI), James Freeman, Alan Bross)
  - ¬ Develop injection-molded plastic scintillators for high-granularity detectors using small plastic scintillator elements
    - Scintillator tiles for calorimetry applications (CMS and DUNE)
    - Scintillator cubes for DUNE (3DST)
      Molded with holes – No machining
  - ¬ ~$270k in funding over FY20, 21, 22 (with adjustments for covid-19).
- Uses newly installed injection molder in Lab 5
- Tooling
  - ¬ Tiles: mold exists
  - ¬ Cubes: Out for bid

provided by A. Bross

3DST Activities in S. Korea

- Proposing to contribute to 3DST
  - Interested in 3DST scintillator cube production
  - Collaboration with Fermilab started
- Two proposals submitted (one to Samsung and one to NRF of Korea) recently
  - NRF proposal: "3D plastic scintillator cube array detector for neutrino interactions"
    - Requested funding: $750k for 4.5 years
- Two more proposals are planned to be submitted in 2021
  - "Focused Research Lab." proposal to NRF
    - $6.3M for 9 years (~2/3 for DUNE)
  - "Large Global facility usage" proposal to NRF
    - Fermilab as the target facility for usage
    - $450k for 3 years (mostly for travel)

provided by C.H. Ha

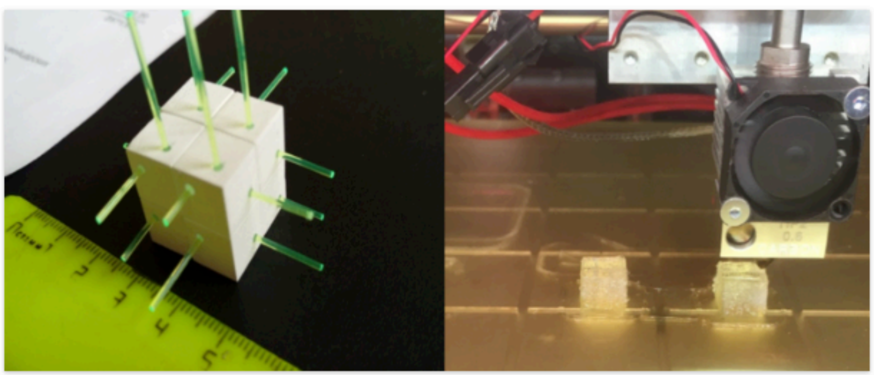
3D-Printing of Plastic Scintillator Detector R&D

- Recent CERN News

A CERN-led international collaboration develops 3D-printed neutrino detectors

A 3D-printed "super-cube" scintillator would be the first occurrence of additive manufacturing being used in particle detectors and would allow more precise data collection

22 JUNE, 2020 | By Thomas Hortala



Example of a plastic Scintillator detector (left) and a stage of its 3D-printing process (right) (Image: CERN)

R&D agreement among:
CERN EP-NU, ISMA and HEIG-VD

https://home.cern/news/news/experiments/cern-led-international-collaboration-develops-3d-printed-neutrino-detectors

Also, a few proposals are planned in US

→ an exciting and inspiring project w/ far reaching potential applications

Conclusion

- Global effort toward 3DST is progressing well
  - Multiple prototypes built/being built, including a real detector T2K SuperFGD
  - Ample test beam data, including neutron test beam

→ Detailed technical issues have been studies and being addressed

- Final design of 3DST can be completed by 2022 employing most of the design and experience gained from SuperFGD
  - No known major technical issues
- The full detector can be constructed in ~3 years (2023-2025) for installation in 2026
- R&D to increase production efficiencies and reduce cost is continuing
- One or two additional beam tests may be desirable to test and calibrate the final components of the detector
- Effort to secure funding and resources to build 3DST has started …

Supplement

Fully Active FGD with Three Views

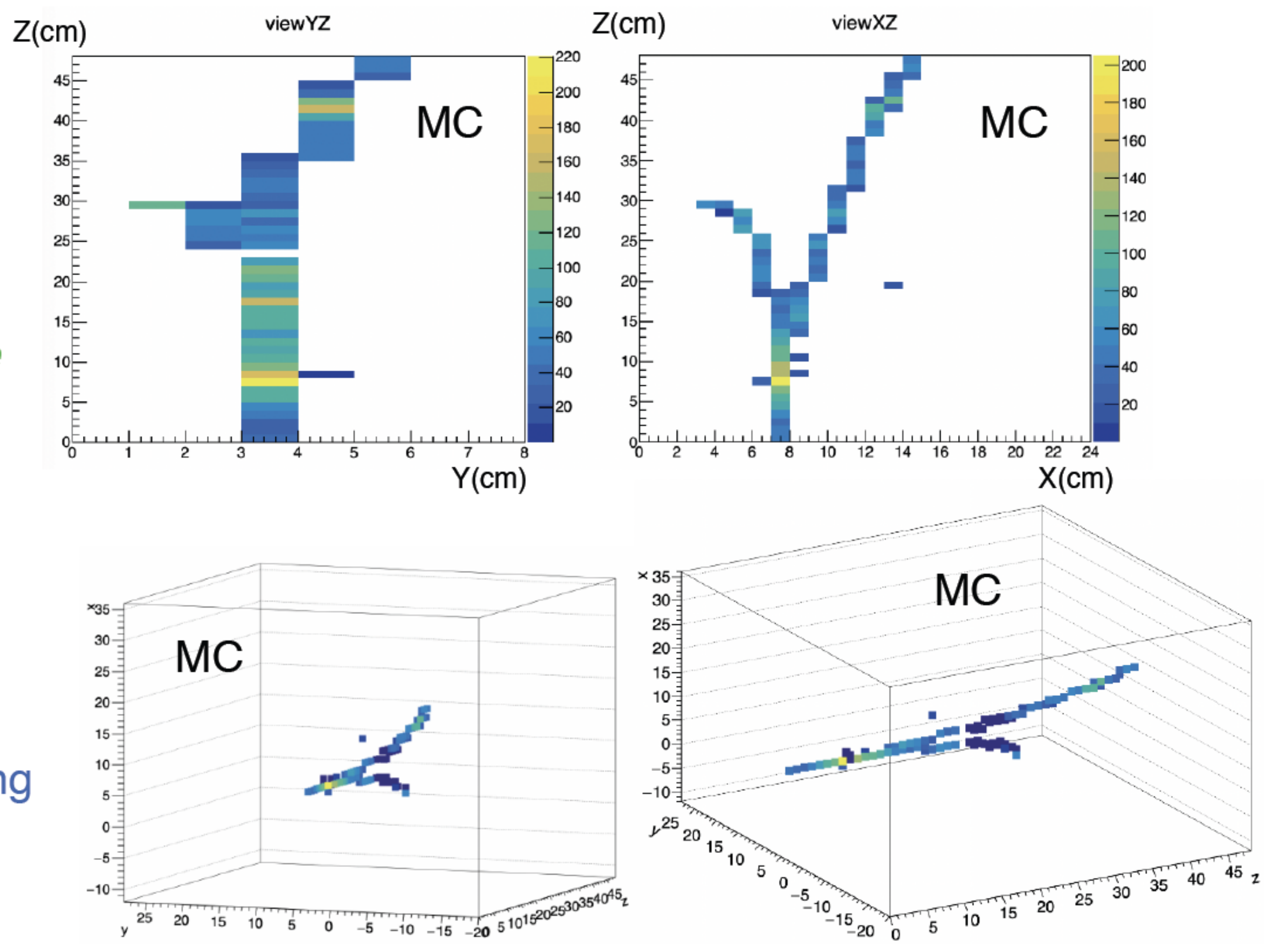
- Three views from XYZ fibers → 4π acceptance, 3D reconstruction

2D projections

XY projection not shown here

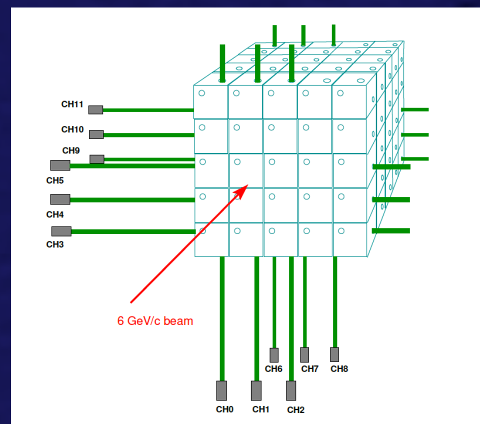
3D rotated views

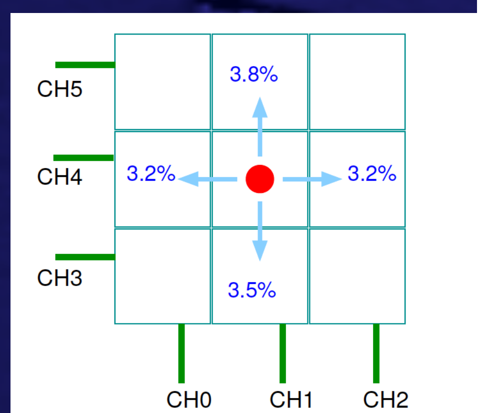
Example of a photon converting in SuperFGD

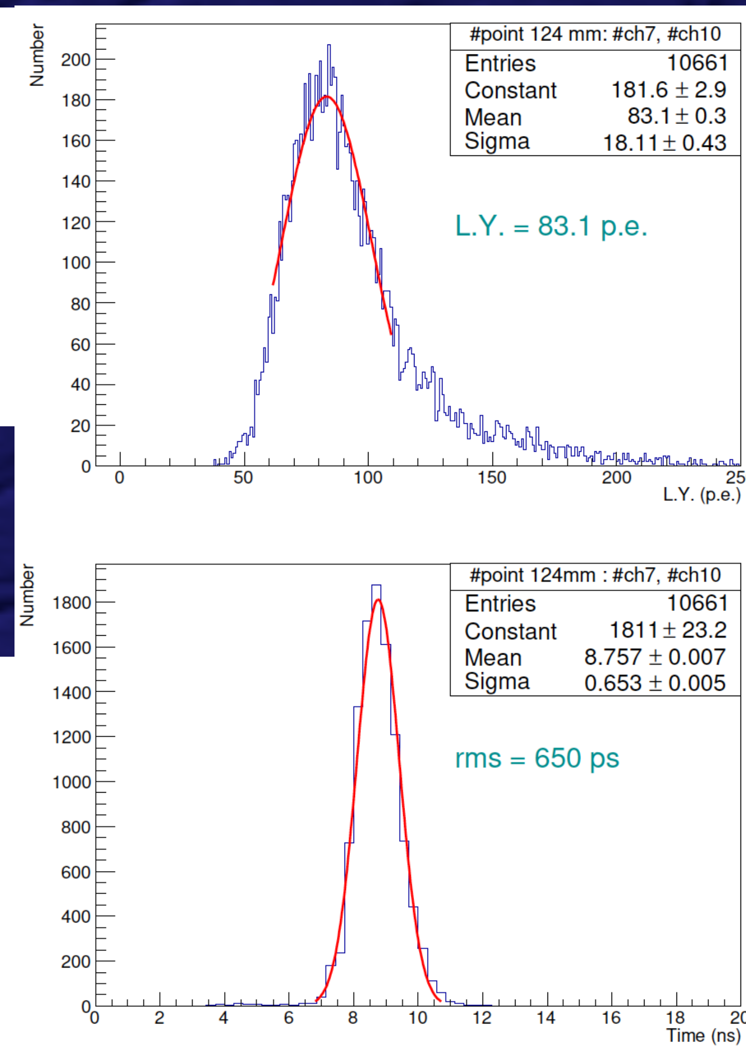


Summary of 5 x 5 x 5 Prototype CERN Beam Test Results

- Charge and time distribution for a single cube, two fibers
- Time resolution for a cube with two fibers is σ_t = 0.65 to 0.71 ns
  Fast sampling electronics: 5 GHz
- Optical crosstalk average value per cube side is 3.7 %

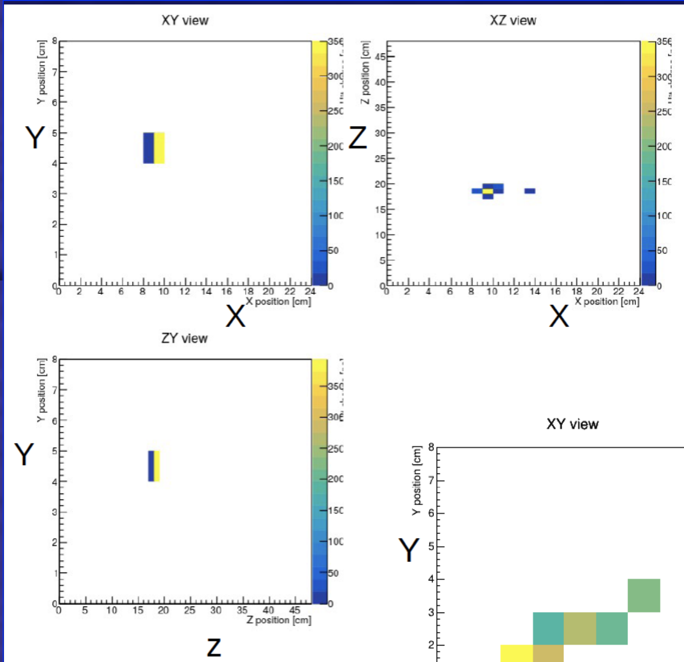




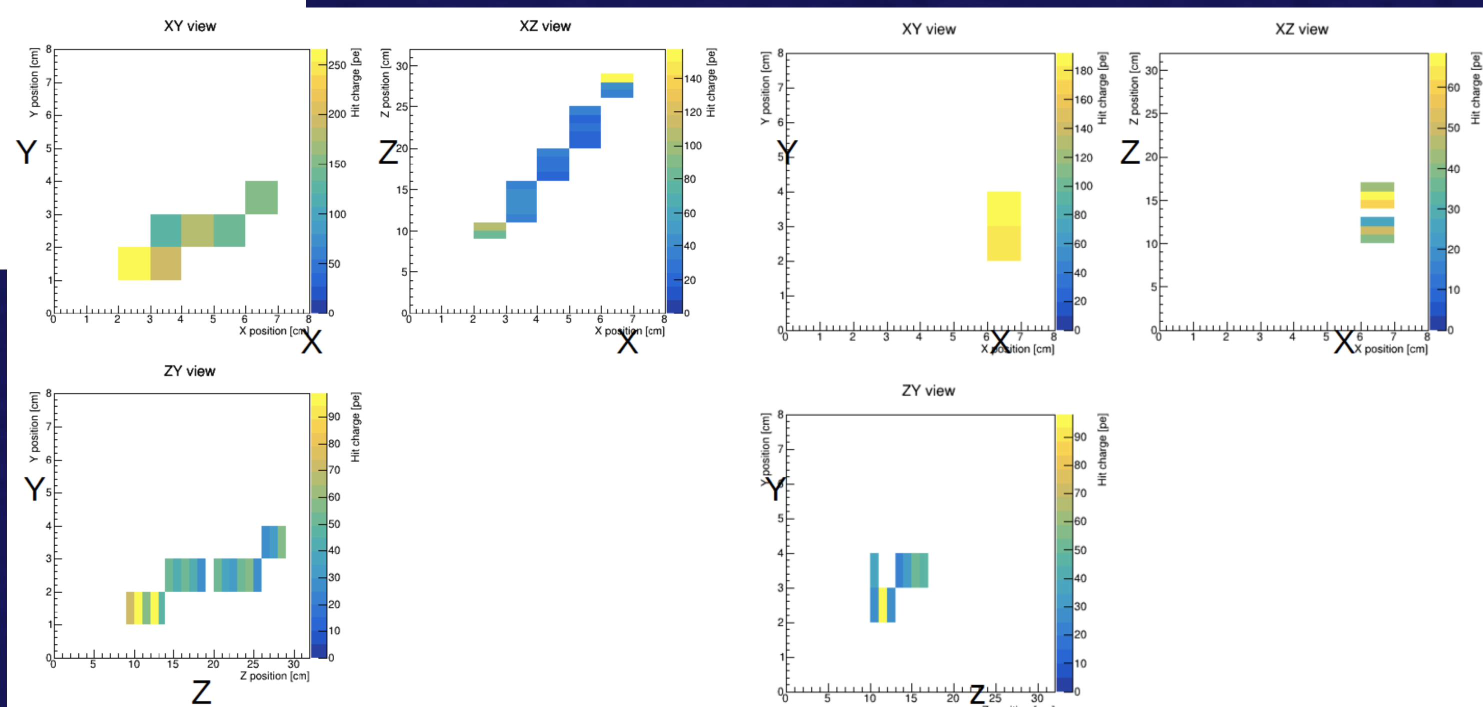


Neutron Interaction Candidate Events (LANL Beam Test)

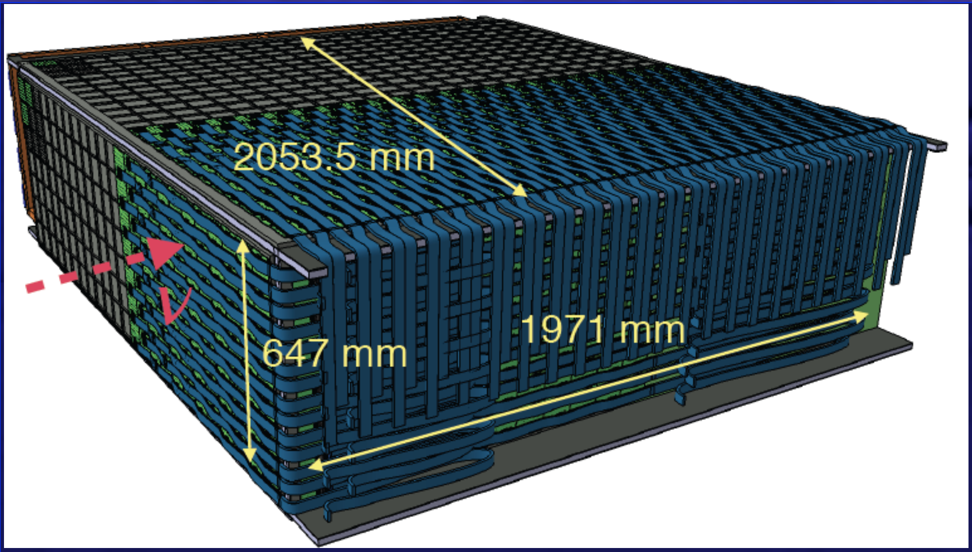
SuperFGD prototype @ 90 m location



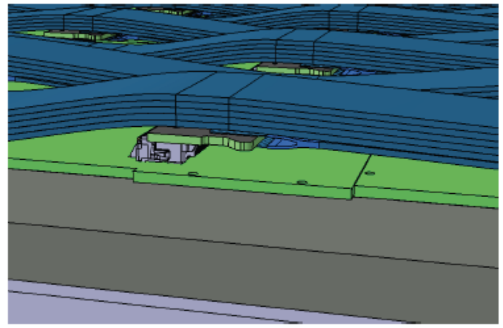
US-Japan prototype @ 20 m location

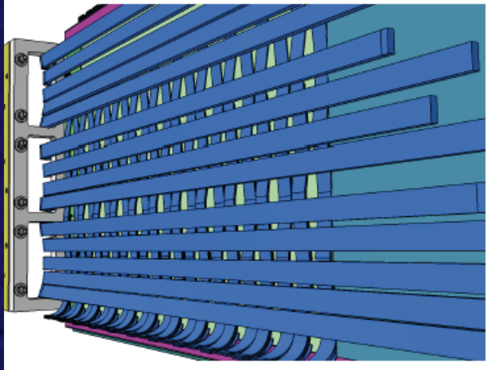


SuperFGD Readout Interface



- Flat cables bring the analog signal from MPPCs to FEBs placed at left / right sides of SuperFGD
- Brackets at four corners to fix the detector to the mechanical frame





- Electronics based on CITIROC chip, same as Baby MIND: Charge peak + ToT, high/low dynamic range. No strict requirements on time resolution at T2K
- For 3DST electronics conceptual design is ongoing for additional requirements:
  - ¬ Time resolution per channel as low as 200 ps

The End