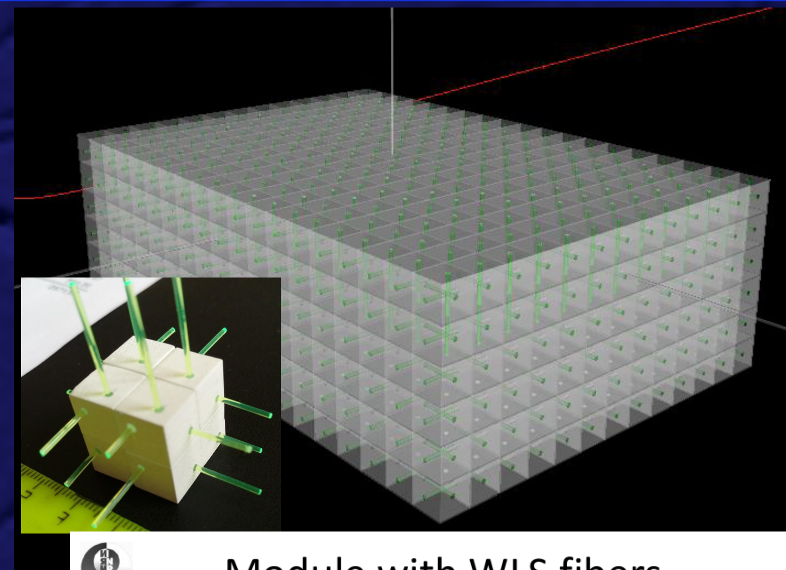
Brief Overview of the 3DST Spectrometer (3DST-S) in DUNE ND

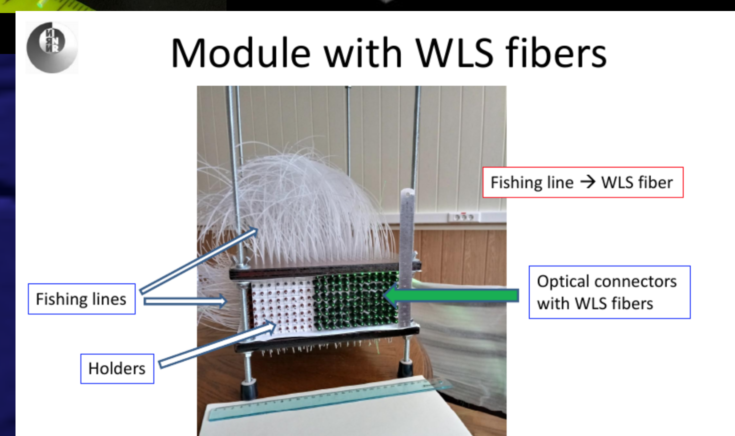
Chang Kee Jung, Stony Brook University
for
the 3DST-S Group

DUNE ND Workshop: Magnet Systems
Fermilab
September 5, 2019

The 3DST Detector

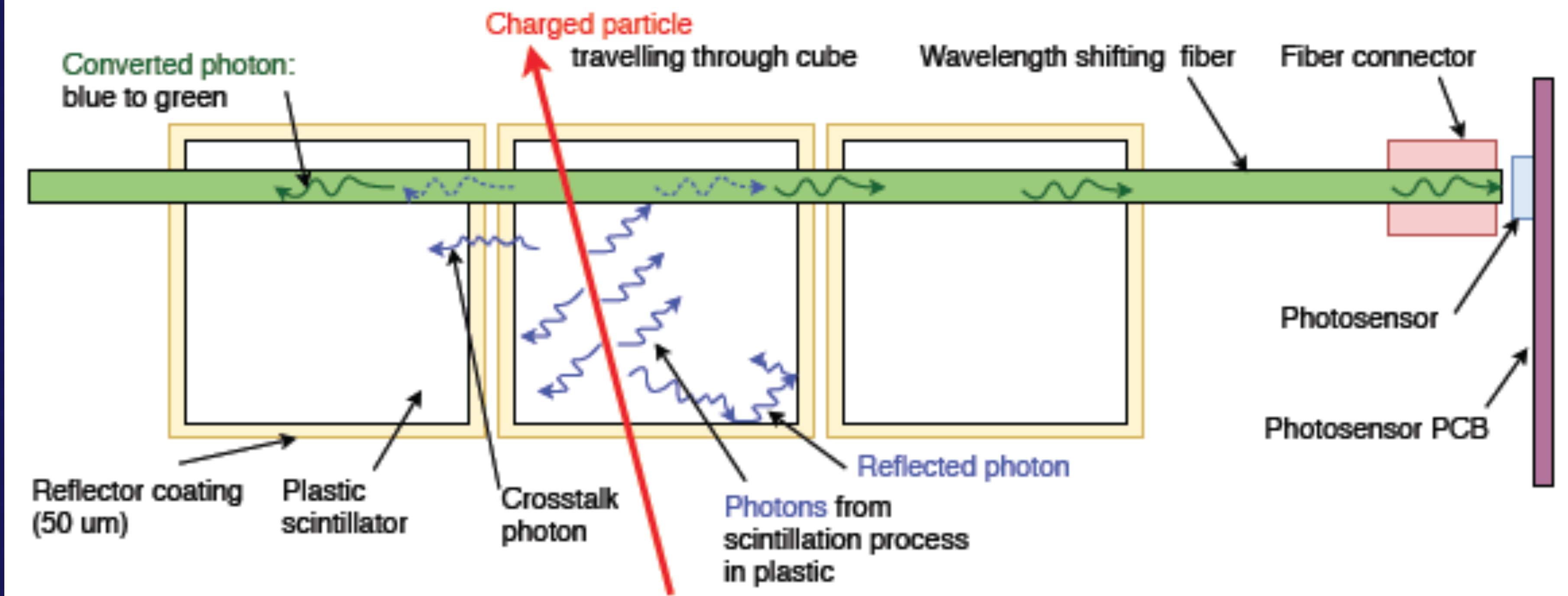
- Fully active target (~12 tons)
  - ¬ Plastic scintillator (2.4x2.4x2 m^3) + WLS fiber + MPPC
  - ¬ 1x1x1 cm^3 scintillator cubes assembled in rows and columns
  - ¬ Provide 3D projected views w/ fine segmentation
  - ¬ 4π acceptance w/ low momentum threshold for protons (~300 MeV)
  - ¬ The exact dimensions of 3DST and the detector "system" configuration still being optimized





Successful large scale test assembly at INR, Russia

From Deposited Energy to a Photosensor Electrical Signal Output

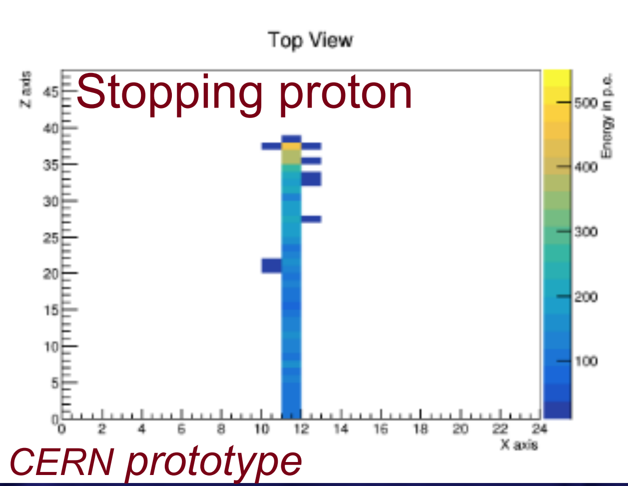


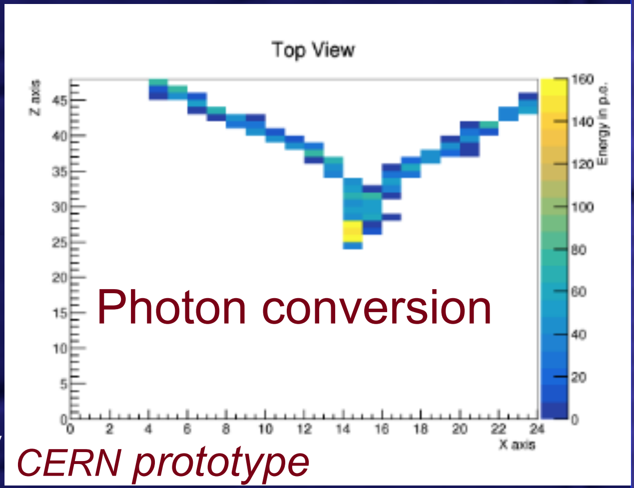
See sample cube handout

- 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

The 3DST Detector

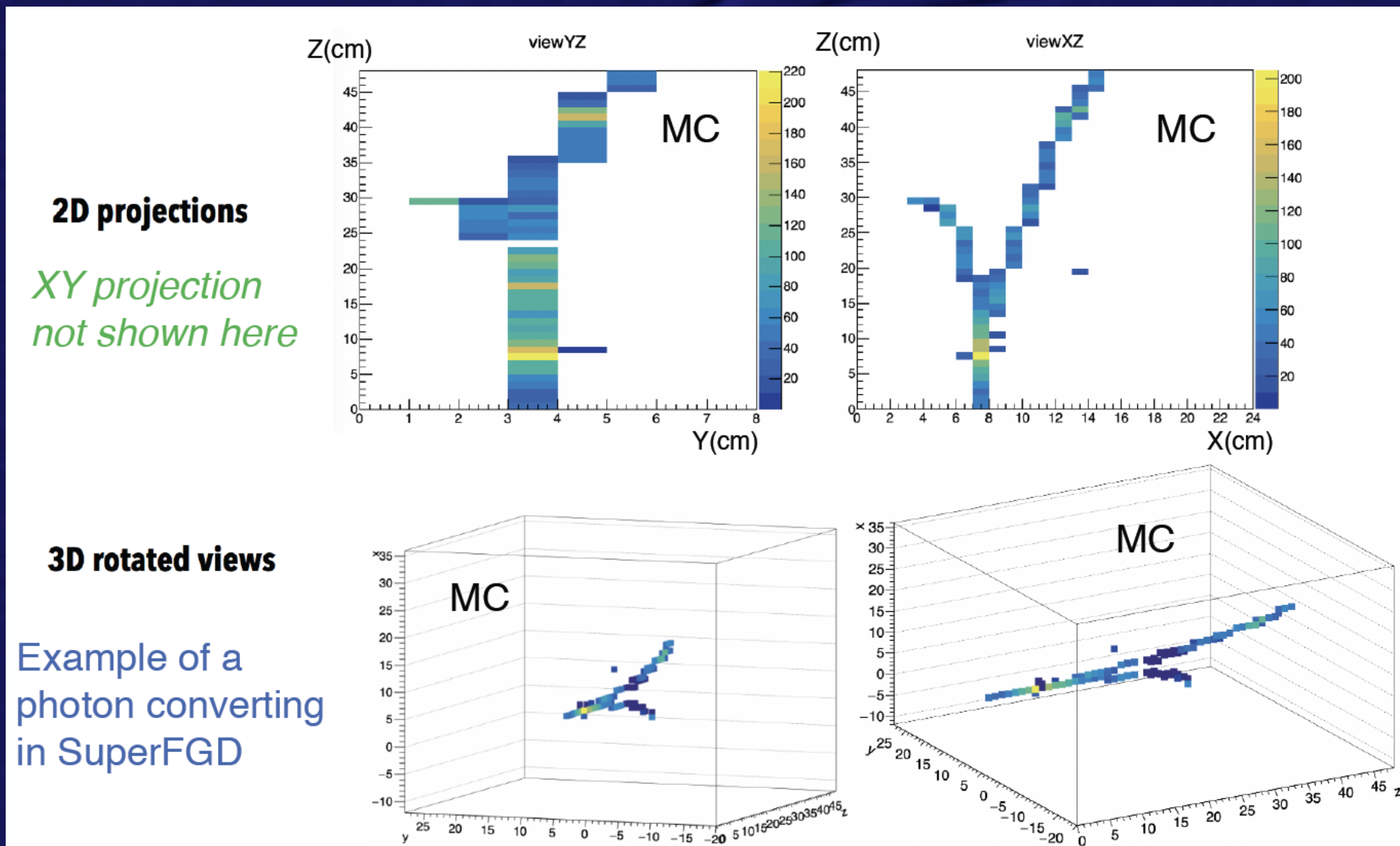
- R&D well in progress
  - Beam test at CERN in 2017
    - $5x5x5\ cm^3$ array
      - Excellent timing resolution: < 1ns
      - Plenty of light: ~40 p.e. per fiber (for 1.3 m)
  - More beam test done at CERN in 2018
    - $8x24x48\ cm^3$ array (CERN prototype)
  - Neutron beam test to be done at LANL in 2019
    - CERN prototype + $8x8x32\ cm^3$ array (US-Japan prototype)
    - Beam time allocated in December 2019 (~20 days)
- Synergy w/ T2K SuperFGD
  - Share essentially the same detector characteristics
  - Large overlap in the participating institutions
  - T2K SuperFGD will be a working prototype for DUNE 3DST taking data near the 2nd oscillation maximum (critical for the CPV measurement) of the DUNE/LBNF beam





3DST: Fully Active FGD with Three Views

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



Why 3DST in DUNE ND?

- Beam monitoring
  - Beam stability (position, width, rate, spectrum)
    - Requires high statistics → fully active target (as largest mass as possible)
  - Particularly critical under DUNE-PRISM scheme
- 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.
- Advancing our understanding on neutrino interaction and model tuning
  - Comprehensive CC and NC, inclusive and exclusive channel measurements
  - Measurements with different A in the same beam flux
  - Utilization of STV w/ neutron detection
  - Comparison with the global data
  - Application to the Ar target data

→ 3DST aims to provide key independent (possibly unique) measurements to reduce overall sys. errors and provide confidence in the measurements made by the Ar target detectors

→ see following talks by Sgalaberna, Yang and Dolan for more details

→ Also, prepare for unknown unknown systematic error sources

A bit of history …

- September 2016, DUNE CM
  - It was suggested (by ckj) that we consider a “Hybrid” ND anchored with a LAr TPC rather than choosing one of the three detector options we had at that time
- January 2017, 1st DUNE ND Workshop
  - “Initial Consideration of Hybrid DUNE ND” presented by ckj
- June 2017, 3rd DUNE ND Workshop
  - 3DST was proposed as a part of Hybrid DUNE ND
- May 2018, DUNE CM
  - Adoption of the LArTPC+HPgTPC+3DST as the DUNE ND Concept by the ND working group
- September 2018
  - Approval of the DUNE ND (including 3DST) Concept by the DUNE EB
  - → Further development of 3DST-S as on-axis detector under DUNE-PRISM scheme
- June 2019
  - Approval of KLOE magnet+ECAL to be used for DUNE ND On-Axis detector
  - → Ensuing Initial discussions to merge KLOE and 3DST into a comprehensive on-axis 3D-tracking, active target spectrometer

January 2017, 1st DUNE ND Workshop

Why a hybrid detector can be attractive for DUNE ND?

- Hybrid Detector: Active Ar target detector + FGD
- More versatile to adopt the advance in the neutrino physics
  - ¬ Projecting to the status of our knowledge in 10 years
    - Utilize both the knowledge to be gained from the LAr TPC experiments (ProtoDUNE and SBN detectors) and Scintillator detectors (MINERvA, T2K and NOvA)
    - Prepare for unexpected sources of systematic errors

      e.g.) 2p2h
- More diverse and rich cross-section measurements and ND physics program
- A broader participation of collaborating institutions and countries leading to Broader funding sources
- Can start with all ideas on the table with participation open to all collaborators
- Achieve the final design through a collaboration-wide consensus

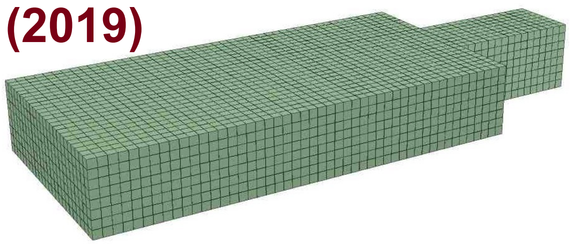
CERN, Jan. 2017 Chang Kee Jung Stony Brook University

Global Strategy: Synergy with T2K SuperFGD

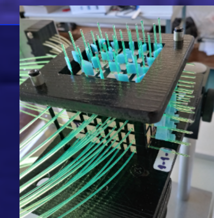
- May 2018
  - Approval of US-Japan proposal for SuperFGD/3DST development
  - US-Japan Prototype for Neutron Beam Test
- 2018 US DOE HEP Portfolio Review
  - T2K Upgrade including SuperFGD
    - Received highest priority classification
- July 2019
  - DOE Approval of US participation in the T2K Upgrade SuperFGD

Worldwide Progression in SuperFGD/3DST Programs

LANL Neutron Beam Test (2019)



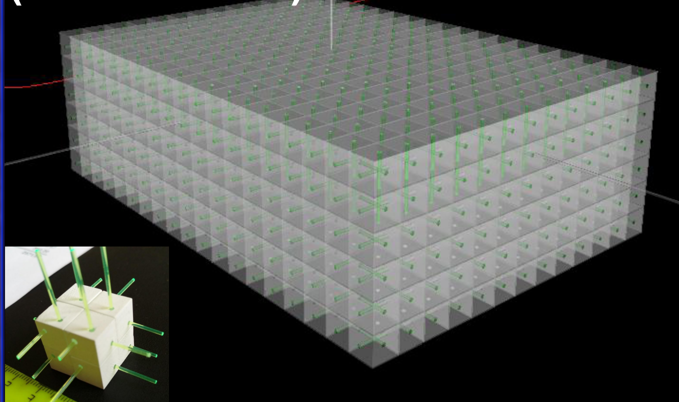
CERN Beam Test (2018)
Prototype (8x24x48)



5x5x5 Prototype (2017)

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

T2K SuperFGD (2021)
(200x60x180)



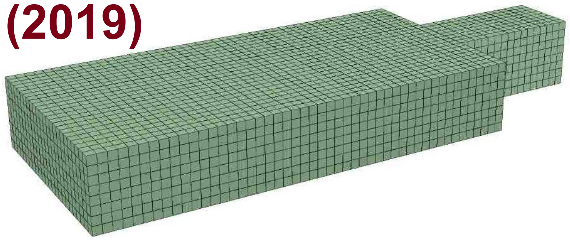
Fermilab
DUNE ND Prototype?

3D-Printing R&D

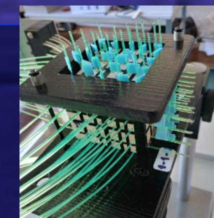
DUNE ND 3DST (2026)
(240x240x200)

Worldwide Progression in SuperFGD/3DST Programs

LANL Neutron Beam Test (2019)



CERN Beam Test (2018)
Prototype (8x24x48)



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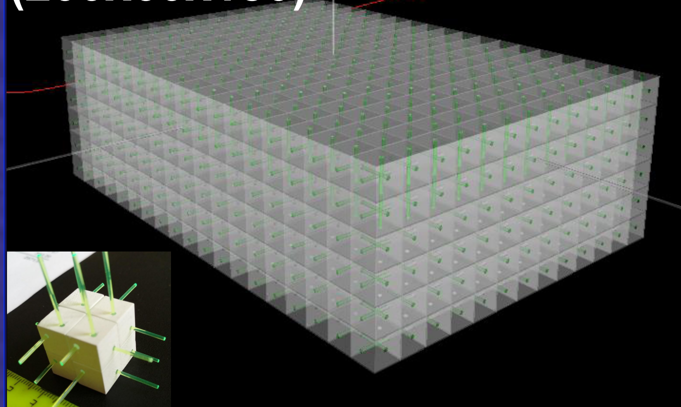
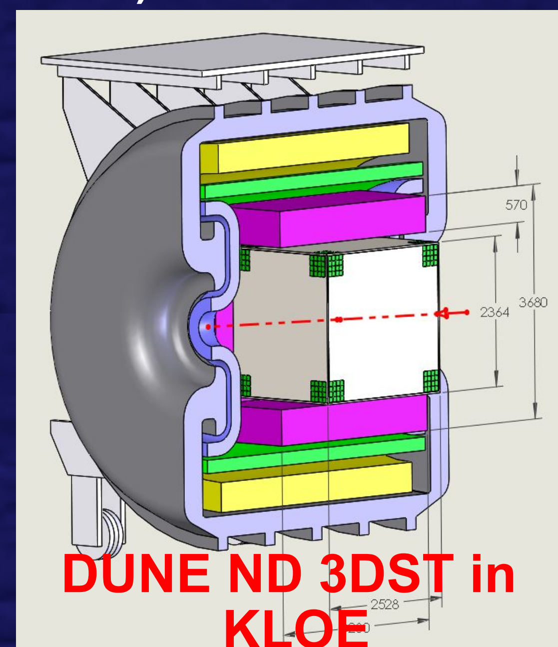


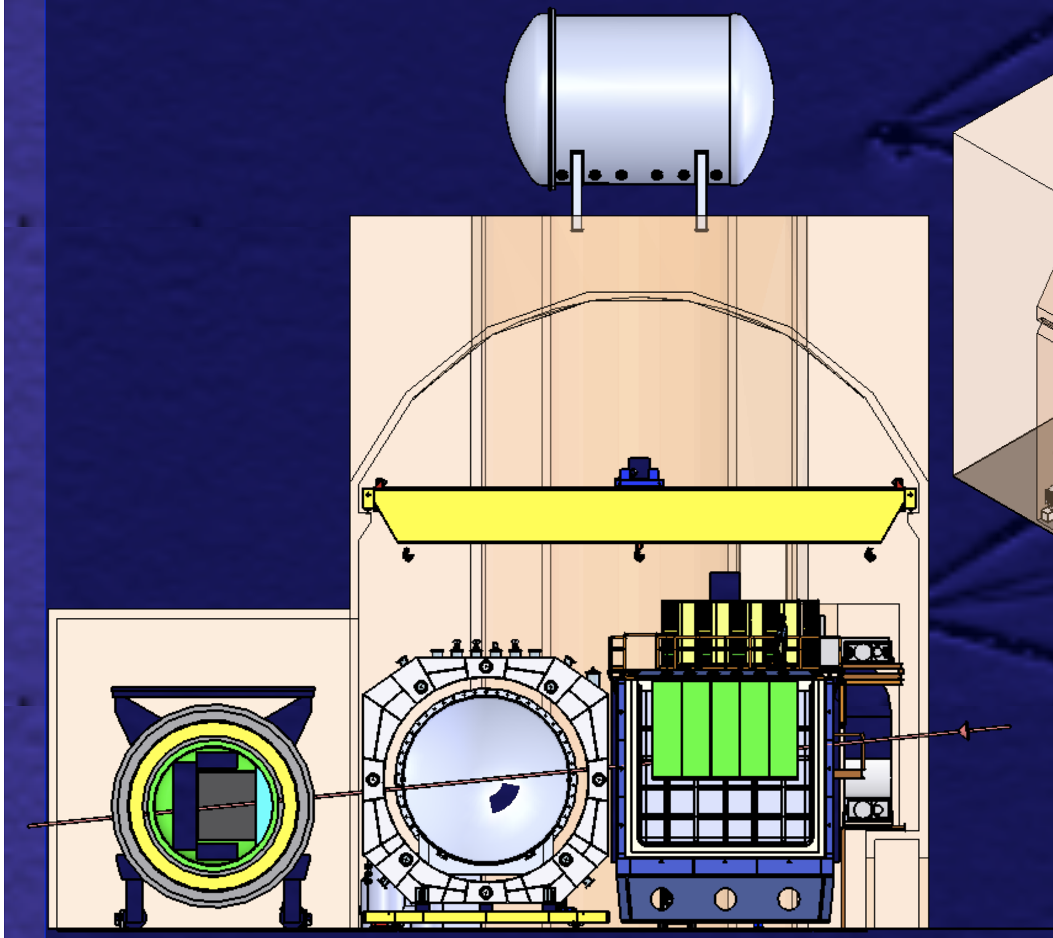
Fermilab
DUNE ND Prototype?

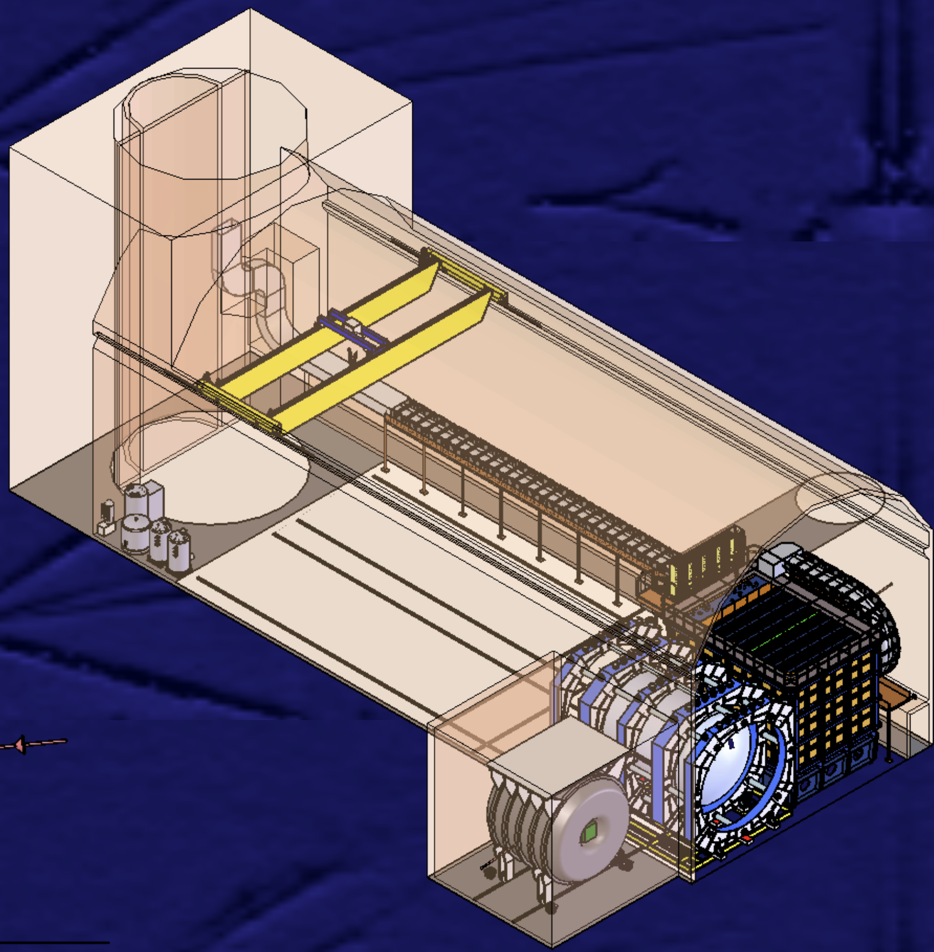
3D-Printing R&D



DUNE ND 3DST in KLOE

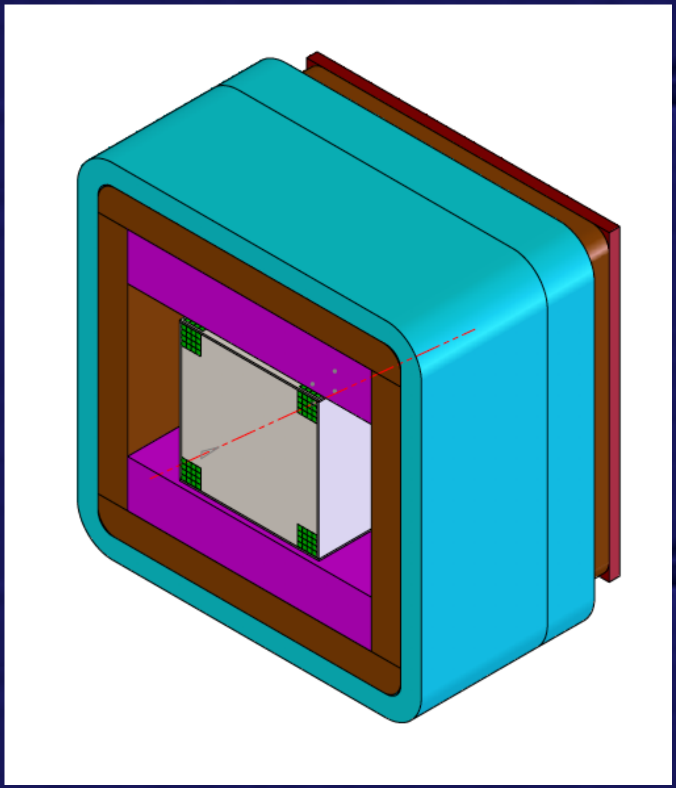
DUNE ND Current Configuration

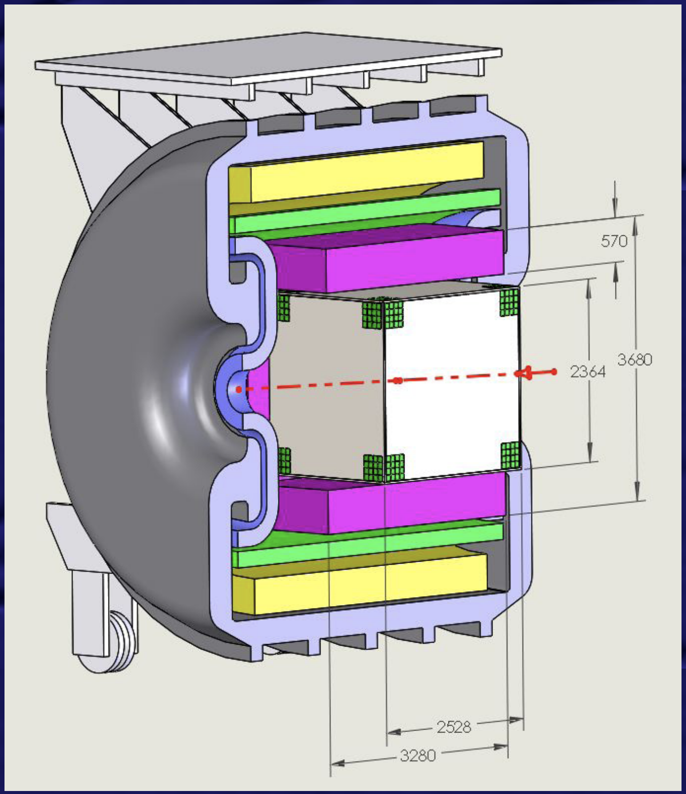




Bob Flight

Comparison of 3DST-S and 3DST in KLOE





Similar size, no reduction in the 3DST active volume is needed in the KLOE configuration → Surprisingly a good fit! → See Sgalaberna's talk for more detailed comparisons

Prototype Beam Tests Results

Prototypes

- 5 × 5 × 5 cubes
  - Tested at CERN in October 2017
  - Light yield
  - Optical crosstalk
  - Time resolution

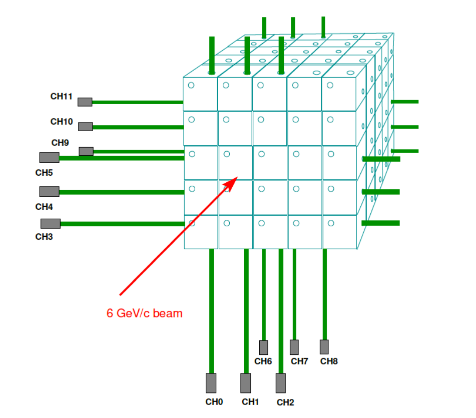
https://arxiv.org/abs/1808.08829

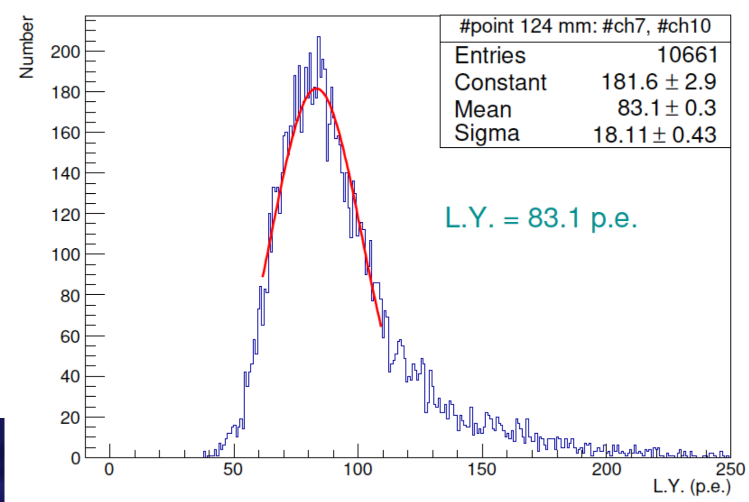
- 24 × 8 × 48 cubes
  - Tested at CERN summer 2018
  - Tested in 0.2 T magnet field
  - Cube response
  - Detailed crosstalk
  - Stopping protons
  - Photon conversion
  - Track and pattern recognition

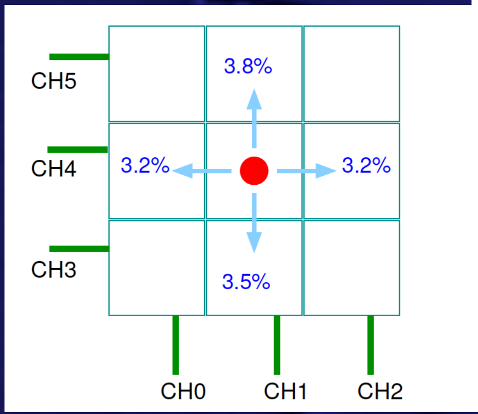
https://doi.org/10.1016/j.nima.2019.05.006

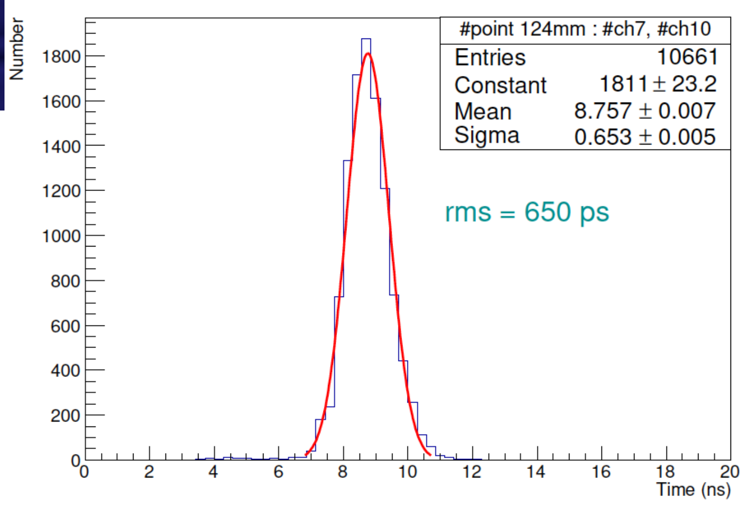
Summary of 5 x 5 x 5 Prototype Beam Test Results

- 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 %



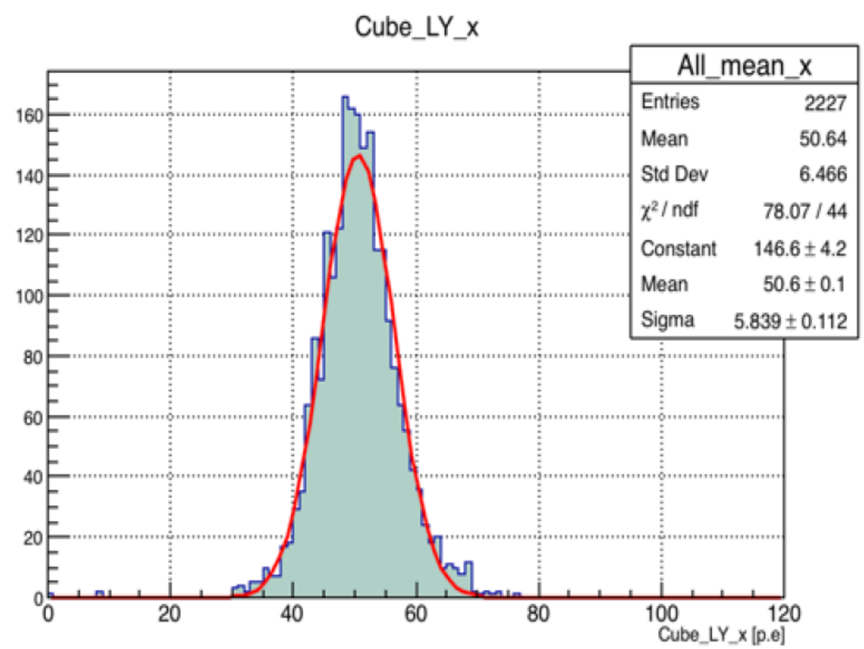




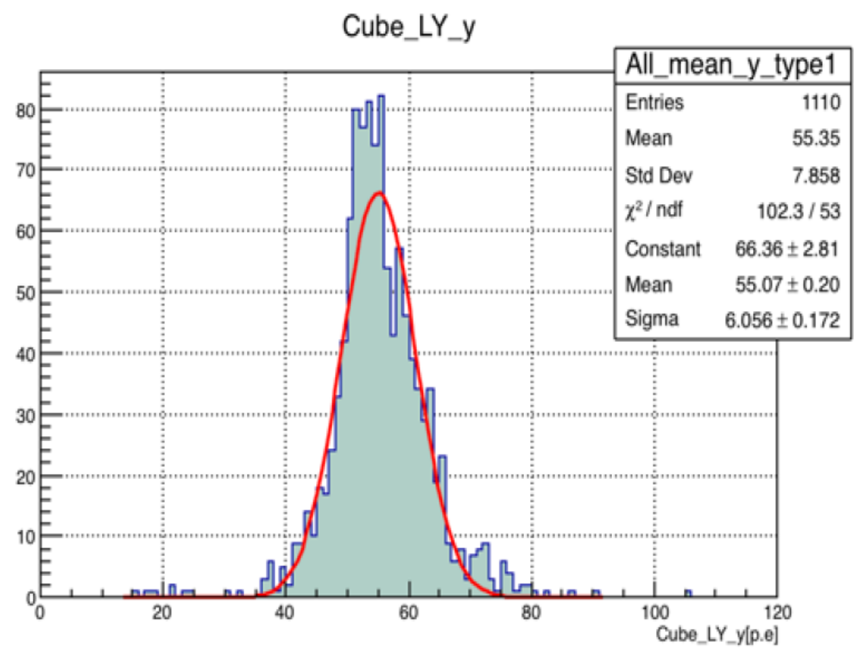


CERN Prototype: Light Yield (Cube Response) Summary

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



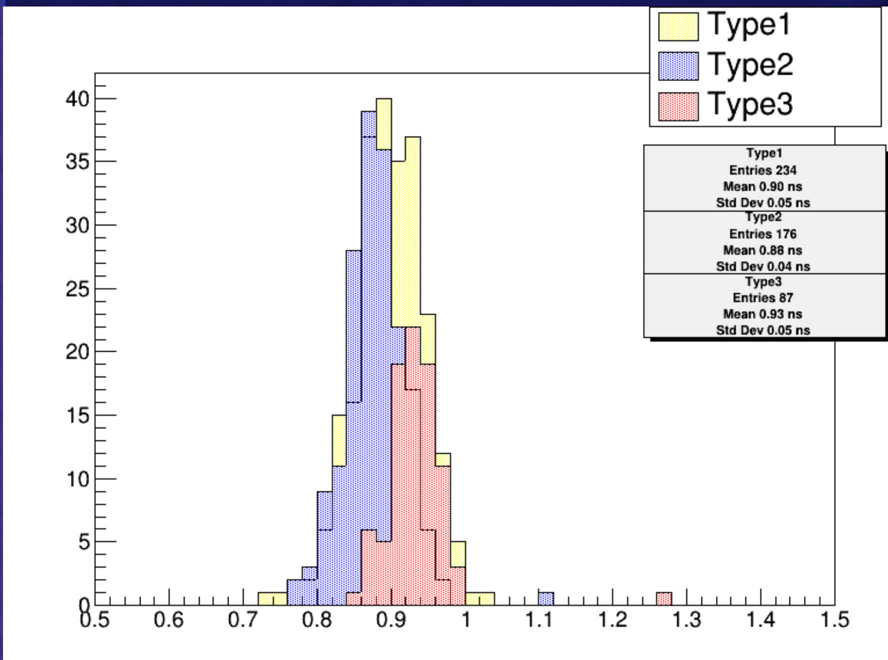
1110 cubes read out with
vertical Y (8 cm) fibers



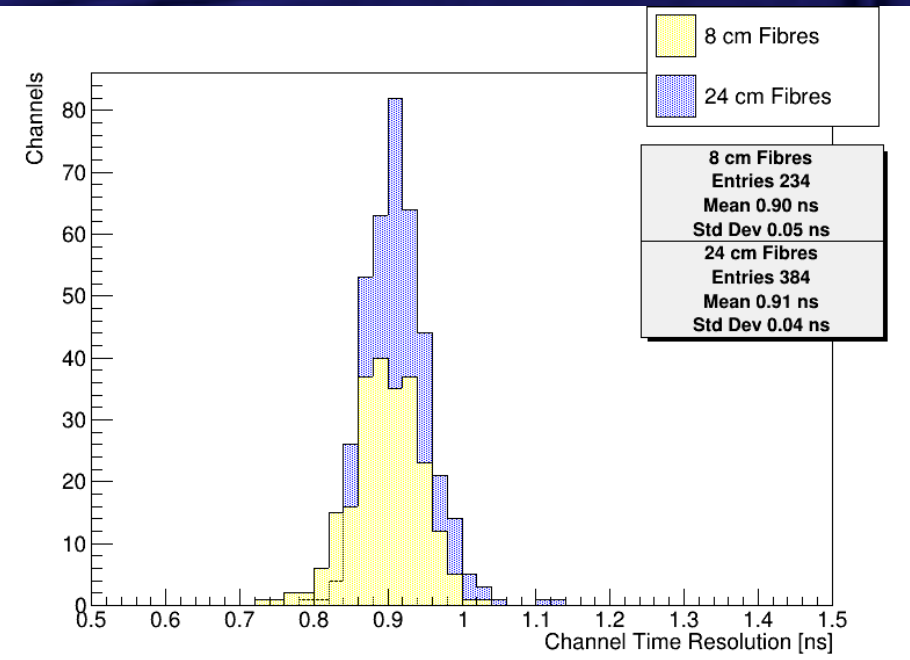
No corrections made for fiber attenuation

CERN Prototype: Time Resolution
Final Results for Single Fiber

Different Photosensor Types



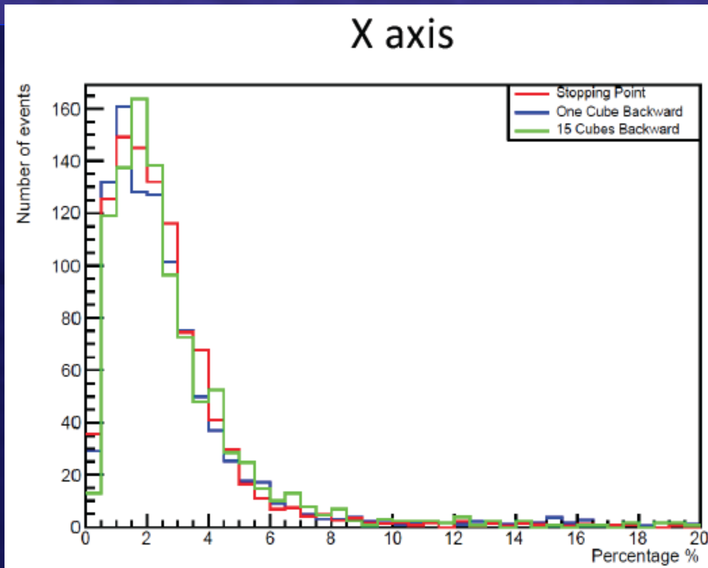
Different WLS Fiber Lengths

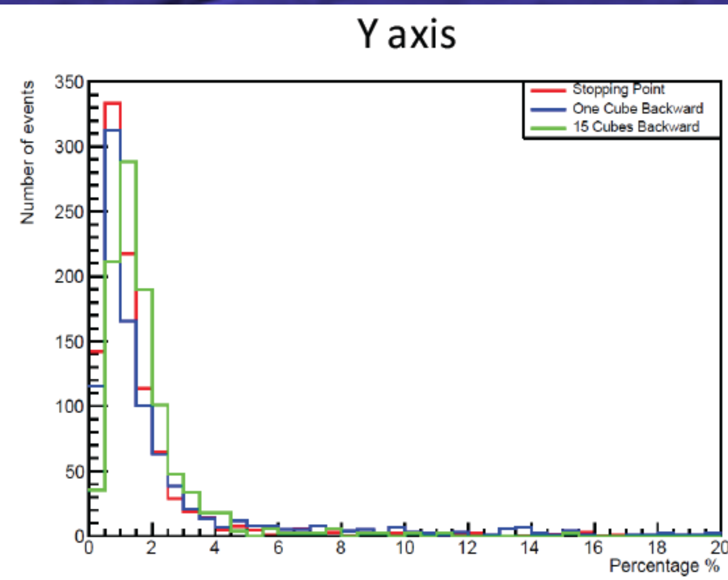


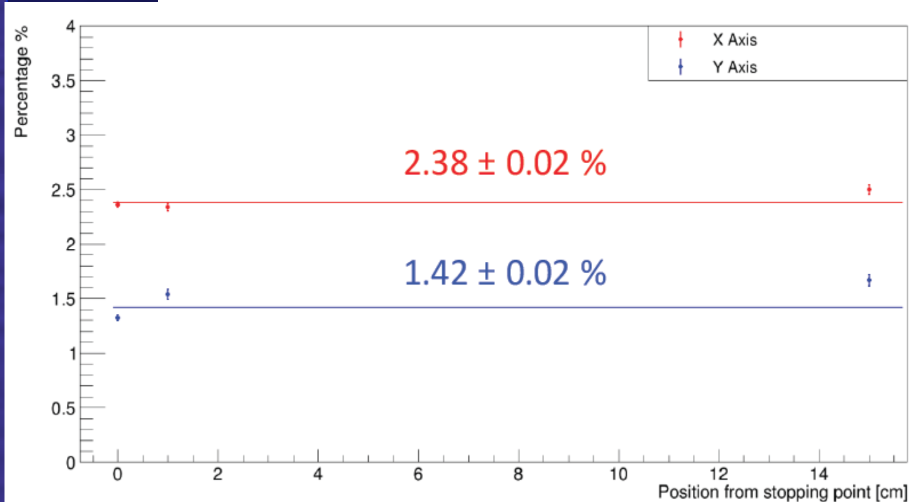
Time resolution for a single fiber σ_t = 0.9 ns

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

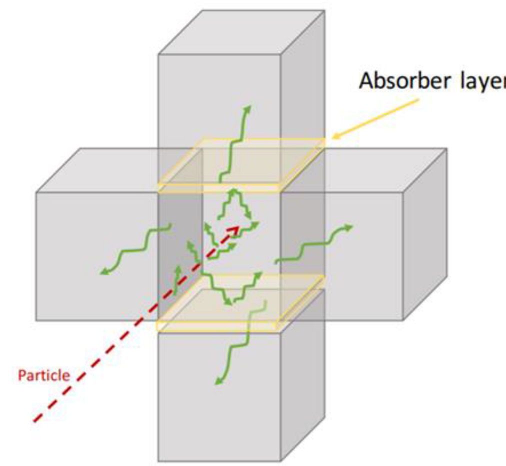
CERN Prototype: Optical Crosstalk Percentage



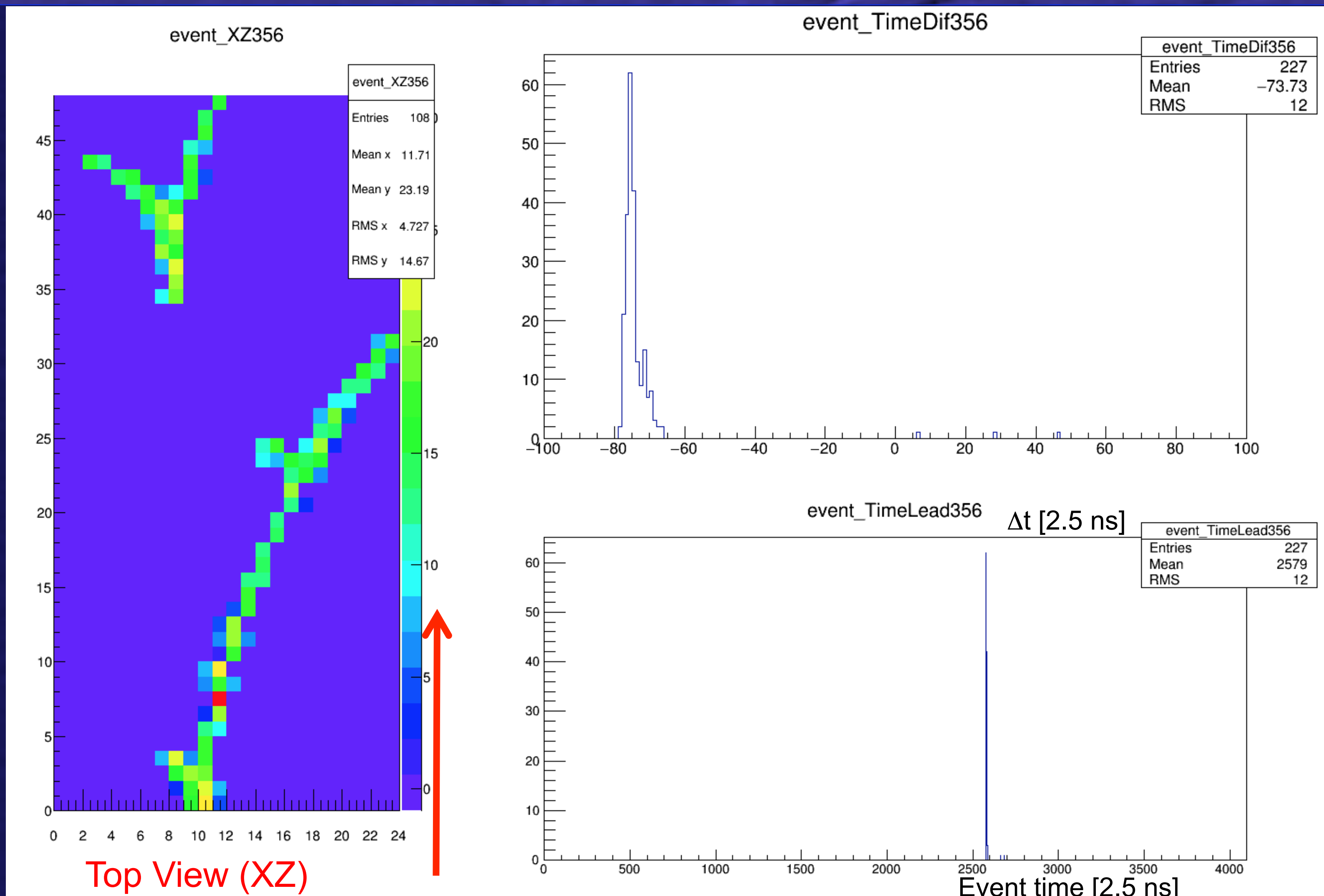




X axis different to Y axis
There are additional Tyvek reflector layers separating planes for Y axis



Additional Event Display (Data)
Positron w/ Radiated Photon Conversion



Status of Neutron Beam Test at Los Alamos Neutron Science Center (LANSCE)

Information provided by

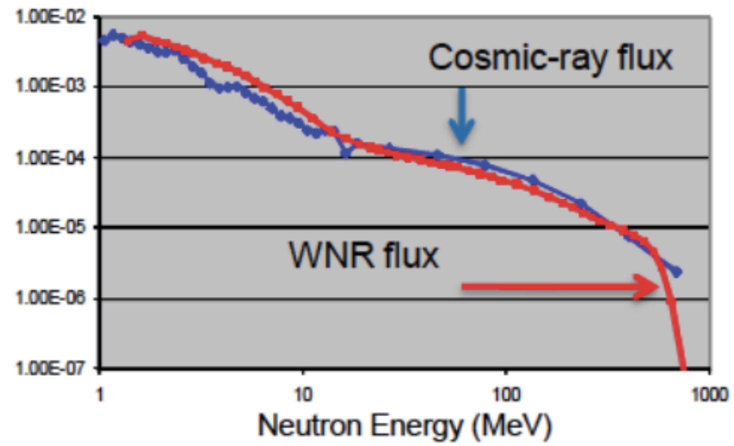
Christopher Mauger, U. of Pennsylvania

Neutrons and Neutrino Energy Reconstruction

- Neutrons often part of the hadronic system emerging from the nucleus in intermediate-energy neutrino interactions
- Typical kinetic energies - hundreds of MeV, so should account for them when reconstructing neutrino energies
- Measurement of neutrons contributes to understanding of transverse momentum
- Important to measure neutrons with SuperFGD/ 3DST – wish to understand the neutron response

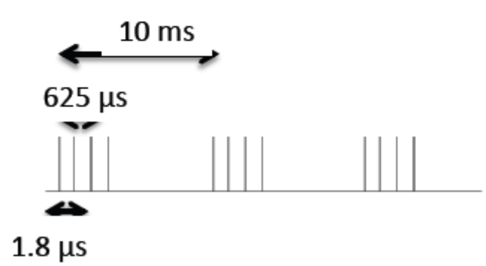
Neutron Beam at LANL

High flux neutron beam, broad energy spectrum similar to high altitude cosmic-ray spectrum



Neutrons up to energy of 800 MeV produced by protons impinging on a bare (un-moderated) tungsten target

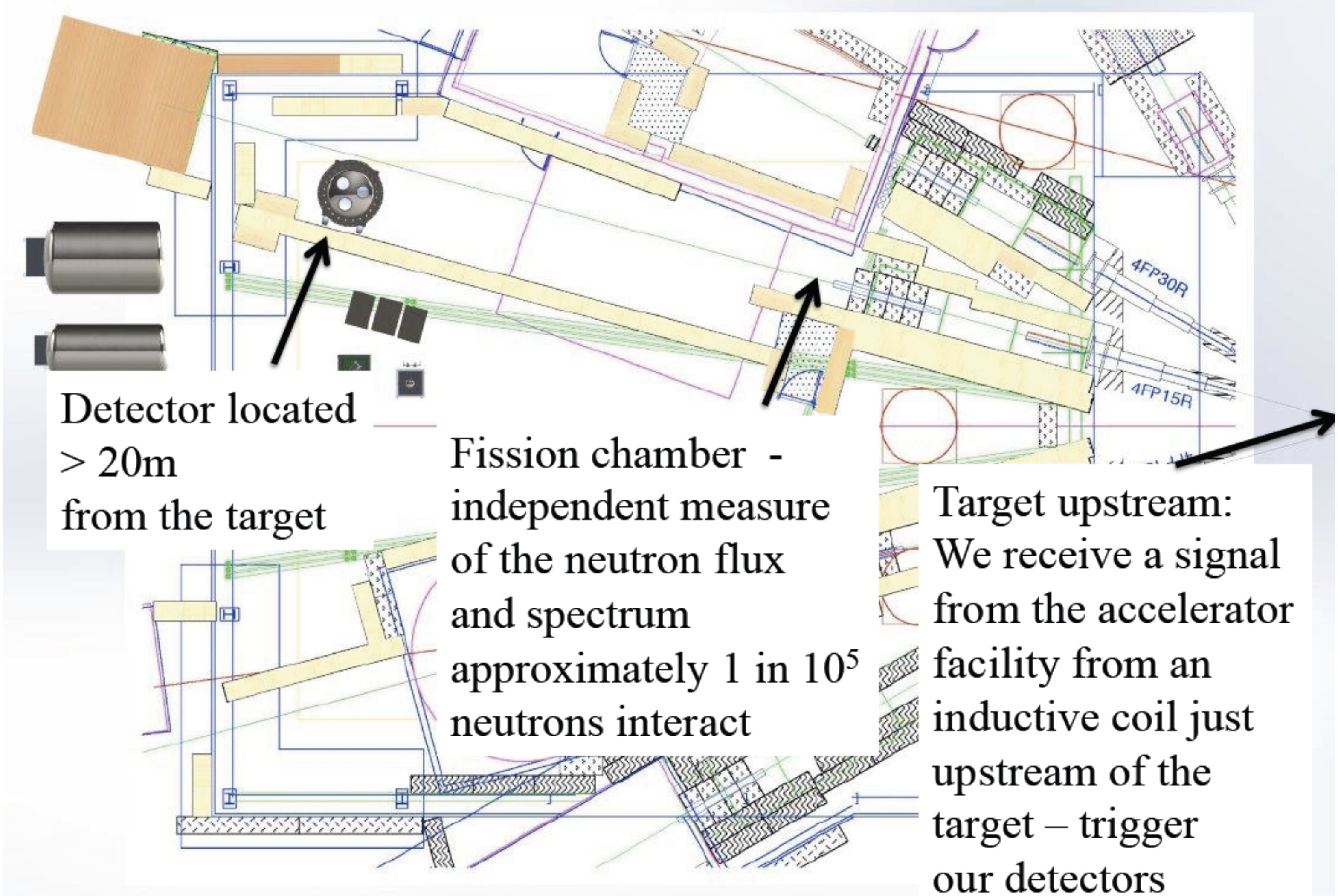
- Time structure of the beam
  - sub-nanosecond micro pulses 1.8 microseconds apart within a 625 μs long macro pulse
  - Repetition rate: 100 Hz



Several 3DST/SFGD members performed experiments at this facility have extensive experience with it. Phys. Rev. Lett. 123, 042502

Measurements as a function of neutron kinetic energy can be made via time-of-flight techniques.

LANSCE Neutron Beamline



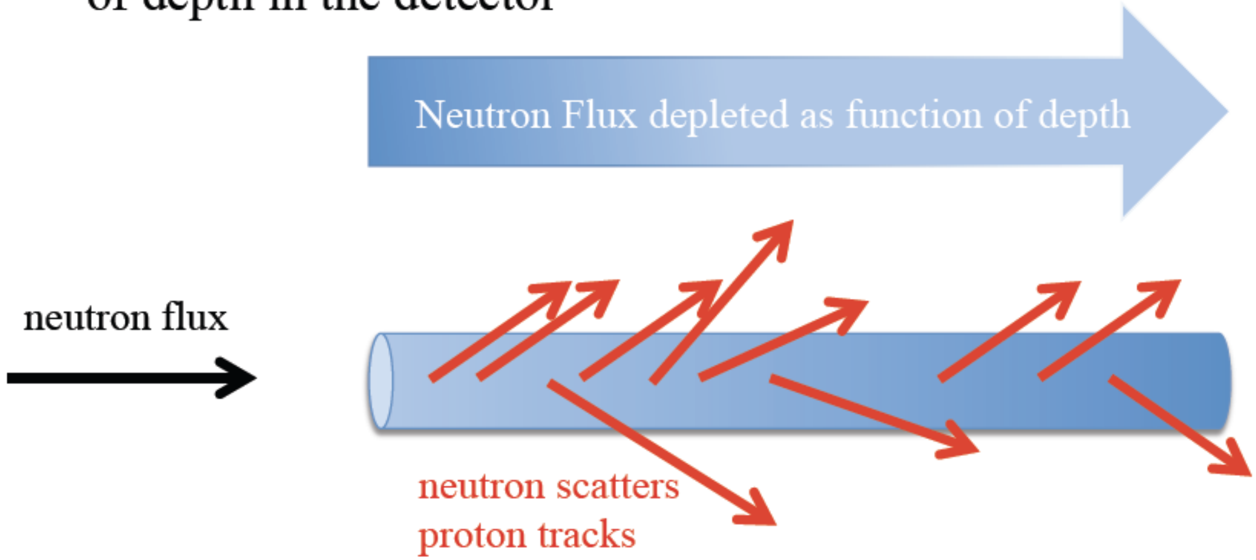
Detector located
> 20m
from the target

Fission chamber -
independent measure
of the neutron flux
and spectrum
approximately 1 in 10^5
neutrons interact

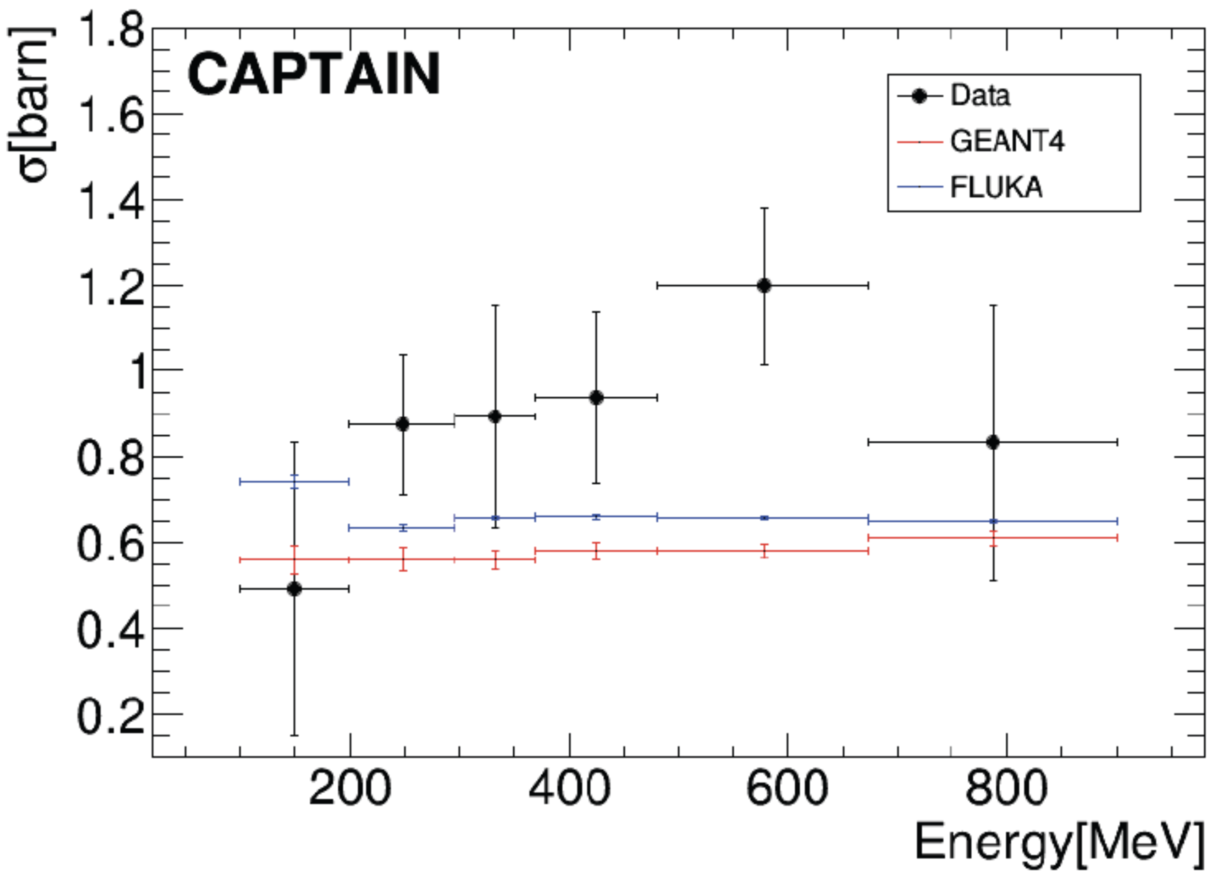
Target upstream:
We receive a signal
from the accelerator
facility from an
inductive coil just
upstream of the
target – trigger
our detectors

Basic Analysis Strategy

- For the CAPTAIN analysis, we did not use the flux detectors
- Find tracks in the time-projection chamber (TPC) in time with the beam and in the beam spot
- Match the tracks in the TPC to hits in the photon detection system (PDS)
- Use the timing from the PDS to determine the neutron energy – kinetic energy bin
- For tracks in each kinetic energy bin, fit an exponential as a function of depth in the detector



Total Neutron Cross Section on Argon



Energy averaged cross section: 0.91±0.10 (stat.)±0.09 (sys.) barns
Phys. Rev. Lett. 123, 042502

SuperFGD/3DST Prototype Neutron Beam Experiment

- Beamtime reduced this cycle due to major repair
- Our beam time has been fixed
  - 1 December in 15L at the 90m location
  - 18 December in 15R (20m location)
  - 21 December 8:00 beam stops for the year
- Neutron kinetic energies up to 800 MeV
- Neutron energy in the detector independently determined by time of flight

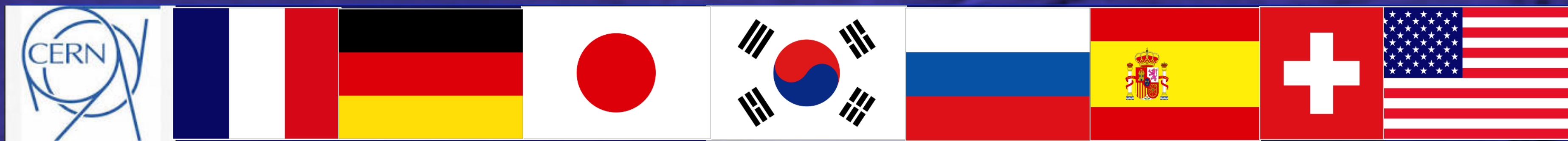
Detectors for the Neutron Beam Test

- "CERN" Prototype
  - ¬8x24x48 cm^3
  - ¬Ready
  - ¬U.S. members visit to CERN/Geneva to gain experience
- "US-Japan" Prototype
  - ¬8x8x32 cm^3
  - ¬Being constructed
- Simulations of configurations underway

What measurements can we make?

- We can study the detector response as a function of neutron kinetic energy up to 800 MeV – mostly via n-p scattering
- Can also look at charged pion production
- Measurement of the absolute cross section should be possible via attenuation of events as a function of depth in the detector – expect ~20 percent reduction in event rate from the front to the back for 400 MeV neutrons

The SuperFGD/3DST(-S) Group
(23 institutions, 8 countries + CERN)



CERN

France
CEA Saclay

Germany
MPI Munich

Japan
KEK
Tokyo Metropolitan U.
U. Kyoto
U. Tokyo
Yokohama National U.

Korea
Chung-Ang U.

Russia
INR

Spain
IFAE, Barcelona

Switzerland
U. Geneva

USA
BNL
Fermilab
Louisiana S. U.
S. Dakota School of Mining and Technology
Stony Brook U.
U. California, Irvine
U. Colorado
U. Minnesota, Duluth
U. Pennsylvania
U. Pittsburgh
U. Rochester

* Institutions in yellow have expressed specific interests in DUNE ND 3DST-S

* Monireh (Minoo) Kabirnezhad, Oxford, just joined the 3DST effort

Going Forward …

- Input to DUNE ND CDR (Dec. 2019?)
- Input to DUNE ND TDR (Dec. 2020?)
- Preparation for DUNE ND US proposal (Dec. 2019?)

→ Efficient and focused work is needed

→ Establishment of unified (KLOE+3DST-S) working group ASAP is highly desired

¬ With a new name, e.g.):

- 3DOK (3DST in On-axis KLOE, pronounced "three-dok")
- 3DK (3DST in KLOE)
- K3D (KLOE w/ 3DST)
- …

→ Suggest a naming contest (enthusiastic participation by young people are desired)

Concluding Comments

- KLOE + 3DST forms a cost effective comprehensive spectrometer that has many concrete ways to contribute to reducing the overall systematic errors. Together with LArTPC (ArgonCUBE) and MPD, it forms a versatile ND that is complementary and robust
  - ¬Detection of neutron and measuring its energy may turn out to be a key new tool in dealing with future unknowns in the interaction/xsec modeling
- It is not clear we can achieve our sys. error goals even with the full suite of the ND detectors and the DUNE-PRISM scheme
  - ¬We should defend vigorously what we have concluded after very long studies and discussions (1% sys. error ~ one FD module)

The End