Physics Opportunities at the Near Detector

The 3DST
(3D projection Scintillator Tracker)

Clark McGrew
Stony Brook Univ.
for the DUNE 3DST Group

Yuri Kudenko – Scintillating perspective, 2017
Some 3DST Goals

➢ Design Considerations
   ➢ High statistics measurement of the beam electron neutrino component
   ➢ High statistics tests of neutrino models
      ➢ Multi nucleon interactions (e.g. 2p2h)
      ➢ Neutrons from Neutrino Interactions
      ➢ Full angular coverage
      ➢ Charge identification
         - $\nu_\mu$ / anti-$\nu_\mu$
      ➢ Comparison to argon
   ➢ Sensitivity to final state neutrons
   ➢ Neutrino-Electron Scattering
      ➢ Accurate determination of the flux and energy spectrum stability

➢ Connection existing catalog of scintillator cross section measurements
   ➢ K2K, MiniBooNE, SciBooNene, MINERvA, T2K, NOVA
      ➢ Two decades of data and experience
   ➢ Proposed 3DST is functionally equivalent to the (upgraded) T2K ND280 SuperFGD
      ➢ Synergy between the two detectors
      ➢ A lot of what I will show comes from SuperFGD studies
What Drives the Hybrid Design

➢ Large Target Mass
  ➔ Event rate for rare processes (e.g. $\nu$-e scattering)
  ➔ This talk mentions targets between $2.4m \times 2.4m \times 2m$ and $4m \times 2m \times 2m$
    ➔ Fiducial mass between 5.7t and 8.3t

➢ Identification of Interaction Morphologies
  ➔ Fine-grained spatial resolution
  ➔ Fully active target
  ➔ Neutron tagging

➢ 4$\pi$ Acceptance
  ➔ No preferred axis

➢ Magnetic Field and TPC
  ➔ Charge Identification
  ➔ Momentum Measurement

➢ EM Calorimetry
  ➔ Target contains large fraction of electrons and photons
  ➔ Non contained energy also measured

➢ Muon / Pion Tagging
  ➔ Tagger and time-of-flight detector outside magnet
The 3DST Active Target Concept

- Neutrino interactions have particles going in all directions
- A plastic scintillator active target is usually constructed with bars and has a preferred axis (poor high-angle acceptance)
- Need a 4π scintillator detector
  - Use cubes not bars
    - Spatially contain light in cubes
  - Read-out in 3 projections using wavelength shifting fiber
    - A single hit gives the “XYZ” coordinate (usually just “XZ”, or “YZ”)
- Segmentation scales like volume → Readout scales like area
  - e.g. for 16M cubes → ~200K channels (for a 4m×2m×2m target)
- Uniform material (just plastic)
Basic Active Target Performance
(CERN 2017 Beam Test – arXiv:1808.08829)

- Measurements of
  - Light yield ~ 40 pe/fiber
    - MPPC readout
    - 1.3m fibers (1mm) with reflective paint
  - Timing resolution
    - $\sigma_t \sim 0.9$ ns/fiber and 0.7 ns for two fibers
  - Channel to channel cross talk (<4%)

Light yield is sum of 2 fibers transverse to beam

6 GeV/c $\pi$ beam

L.Y. = 83.1 p.e.

Average hit time for cube with two fibers transverse to beam
Complementarity between DUNE 3DST and T2K SuperFGD

➢ Further beam test in support of the T2K superFGD done last summer
  ➢ Used a 0.2 T to 0.7 T field
  ➢ Data analysis is on going (work in progress)

➢ T2K ND280 flux ↔ DUNE second oscillation maximum
  ➢ T2K is “monoenergetic” at 2\textsuperscript{nd} oscillation

Events from SuperFGD Beam Test
D. Sgalaberna – CERN Det. Sem 2018

Peak Energies for T2K ND280 Flux

500 pe!

SuperFGD (4.3t)

Different color scales

Stopping Proton

Pair production

Electron pair production

Events from SuperFGD Beam Test
D. Sgalaberna – CERN Det. Sem 2018

High-Angle TPCs

D Sgalaberna - CERN Detector Sem. 16 Nov 2018

DUNE oscillated flux at FD (+ DUNEprism fit)
Look at black line
Red line is DUNEprism fit

Manly – NuINT ‘18 & dunePRISM

Peak Energies for T2K ND280 Flux

Different color scales

TPCs

Existing Tracker with 2.2 t target

12/03/18
Possible DUNE ND Configuration

A standalone DUNE ND hybrid detector similar to T2K ND280. This configuration is “pre-preliminary.” Configuration studies are on-going.
Neutrinos in the 3DST

- Shown: a CCQE interaction
  - Beam is along the Z axis
- Particles are viewed from 3 axes
  - Tracks are contiguous.
    - Each energy deposit seen in XZ, YZ, and XY projection
  - Proton easily visible in two projections
  - Superb time resolution improves hit disambiguation between projections

Color shows number of measured photoelectrons
**{(sFGD)} Reconstruction Efficiency**

(near DUNE second oscillation maximum)

- With three (2D) projections, there is no favored axis
  - “4π” coverage means side-going tracks are reconstructed in sFGD
  - Proton threshold $\approx 300$ MeV/c
    - Energy from unresolved tracks at vertex is also measured

---

**T2K v Beam Interactions**

Sgalaberna – CERN detector seminar 2018
Contained Event Reconstruction

- Magnetic field gives charge identification for contained tracks
  - Exiting tracks analyzed in TPC
- Momentum from Range

390 MeV/c Muon (0.4T field)

Clustered Hits
(combined from 2D projections)

Reconstruction perpendicular to field

Muons between 300 MeV and 3 GeV (Kinetic)

Kinetic Energy (MeV)
Charge Identification for Contained Particles

- Good charge separation with a very simple algorithm (not a full fit)
  - Fit line to first 20 cm and count hits “above” and “below” line.
- Contained muons (e.g. muons below several hundred MeV)
  - Charge identification better than 95%
  - Exiting particles measured by surrounding TPC
- Electrons also have charge id
  - Roughly 80% are correctly identified

Wrong sign fraction for the lepton angle versus the neutrino energy

Charge id from 3DST

Work in Progress
Photons and $\pi^0$’s

- Fully active target is well suited to measure photons (and $\pi^0$’s)
  - Need to reconstruct both $\pi^0$ photons (high energy and low energy)
- Photons travel in all directions
  - Higher angle photons are lower energy (low threshold needed)
- Because of low 3DST hit threshold (e.g. 2 MeV) and fully active target, interaction vertex is also frequently tagged
  - Even for neutral current

Radiation length in 3DST is ~41cm.

Pair Production in SuperFGD Test

A $\pi^0$ can be tagged with one $\gamma$, but $\pi^0$ reco. requires two (95% $\rightarrow$ 90%)
Neutrino Electron Scattering

- The 3DST active target energy and angular resolution will be comparable to MINERvA
  - MINERvA efficiency is ~73%
- With DUNEprism, the LAr detector moves
  - 3DST provides long term on-axis flux monitoring

For a 2.4m×2.4m×2m target

For 2 GeV Electrons

Deposited vs true energy for electrons
(Does not include full optical and digitization simulation)

\[ \text{Electron energy [MeV]} \]

\[ 0.002 - 0.014 \]

\[ 0.012 - 0.014 \]

\[ 0.010 - 0.012 \]

\[ 0.008 - 0.010 \]

\[ 0.006 - 0.008 \]

\[ 0.004 - 0.006 \]

\[ 0.002 - 0.004 \]

\[ 0.000 - 0.002 \]

\[ 0.0000 - 0.0002 \]

\[ 0.00000 - 0.000002 \]

\[ 0.000000 - 0.0000002 \]

\[ 0.0000000 - 0.00000002 \]

\[ 0.00000000 - 0.000000002 \]

\[ 0.000000000 - 0.0000000002 \]

\[ 0.0000000000 - 0.00000000002 \]

\[ 0.00000000000 - 0.000000000002 \]

\[ 0.000000000000 - 0.0000000000002 \]

\[ 0.0000000000000 - 0.00000000000002 \]

\[ 0.00000000000000 - 0.000000000000002 \]

\[ 0.000000000000000 - 0.0000000000000002 \]

\[ 0.0000000000000000 - 0.00000000000000002 \]

\[ 0.00000000000000000 - 0.000000000000000002 \]

\[ 0.000000000000000000 - 0.0000000000000000002 \]

\[ 0.0000000000000000000 - 0.00000000000000000002 \]

\[ 0.00000000000000000000 - 0.000000000000000000002 \]

\[ 0.000000000000000000000 - 0.0000000000000000000002 \]

\[ 0.0000000000000000000000 - 0.00000000000000000000002 \]

\[ 0.00000000000000000000000 - 0.000000000000000000000002 \]

\[ 0.000000000000000000000000 - 0.0000000000000000000000002 \]

\[ 0.0000000000000000000000000 - 0.00000000000000000000000002 \]

\[ 0.00000000000000000000000000 - 0.000000000000000000000000002 \]

\[ 0.000000000000000000000000000 - 0.0000000000000000000000000002 \]

\[ 0.0000000000000000000000000000 - 0.00000000000000000000000000002 \]

\[ 0.00000000000000000000000000000 - 0.000000000000000000000000000002 \]

\[ 0.000000000000000000000000000000 - 0.0000000000000000000000000000002 \]

\[ 0.0000000000000000000000000000000 - 0.00000000000000000000000000000002 \]

\[ 0.00000000000000000000000000000000 - 0.000000000000000000000000000000002 \]

\[ 0.000000000000000000000000000000000 - 0.0000000000000000000000000000000002 \]

\[ 0.0000000000000000000000000000000000 - 0.00000000000000000000000000000000002 \]

\[ 0.00000000000000000000000000000000000 - 0.000000000000000000000000000000000002 \]

\[ 0.000000000000000000000000000000000000 - 0.0000000000000000000000000000000000002 \]

\[ 0.0000000000000000000000000000000000000 - 0.00000000000000000000000000000000000002 \]

\[ 0.00000000000000000000000000000000000000 - 0.000000000000000000000000000000000000002 \]

\[ 0.000000000000000000000000000000000000000 - 0.0000000000000000000000000000000000000002 \]

\[ 0.0000000000000000000000000000000000000000 - 0.00000000000000000000000000000000000000002 \]
Neutrons in the 3DST

- MINERvA has demonstrated that neutrons from neutrino events can be reconstructed in a scintillation detector (Gran, FNAL, Nov ‘17)
  - Requires fast timing and an energy threshold
  - Tag the location of the first neutron interaction
  - Data matches GEANT “fairly well”

- The 3DST with a fully active target is well suited to tag neutrons from neutrino interactions
  - More completely characterize neutrino interaction morphologies
  - Current studies require > 2.0 MeV isolated energy deposit.

Genie neutrino interactions in scintillator (GEANT4)

Deposited energy not well correlated with neutron energy
Reconstructing Neutrons

➢ Selection of a neutron candidate
  ➢ Separated deposit of more than >2 MeV
  ➢ Hit closest to neutrino vertex taken as the first neutron interaction point
➢ Direction from “line” between neutrino and neutron first hit
➢ Energy from time-of-flight

Efficiency to tag a neutron

FS Neutron with at least 2 MeV KE

Error for Neutron TOF (After 0.7 ns Smearing)
100 MeV True Energy, 1.0 m Lever Arm

>1.5 MeV deposit

Exciting but work in progress
Summary and Comments

- Detector with
  - High Statistics
  - $4\pi$ coverage
  - fine grained (for scintillator)
  - fast timing for background
  - charge identification and pid
  - sensitivity to neutrons (and photons)

- Functionally equivalent to the T2K ND280 SuperFGD
  - Beam Tested now, and installing in T2K in a few years

- Combination of low threshold, exquisite timing, and large mass opens up the study of neutral particles in the interaction final state
  - Neutrons in addition to photons

- Things not discussed:
  - High statistics “low-$\nu$” measurement
    - Muons for sure, possibly electrons
Conclusion

➢ 3DST is an on axis magnetized detector
  ➢ Well matched to the MPD
    ➢ Large target mass/high statistics
    ➢ Fast timing (sub nanosecond)
  ➢ Well matched to the LArTPC
    ➢ Can remain on axis → measures flux and energy spectrum stability
      – Enough mass to measure “time dependent” flux with neutrino-electron scattering
    ➢ Charge identification
      – $\nu_\mu$ / anti-$\nu_\mu$ identification

➢ Different target nucleus confronts neutrino interaction models

➢ Connection to MiniBooNE, NOvA, MINERvA, SciBooNE, T2K ND280, K2K measurements
  ➢ More direct comparison with NOvA and T2K oscillation results
Backup Slides
Another Possible ND Configuration

First Alternative: LArTPC, 3DST and HPGTPC tightly integrated minimizing overall size of ND, but requires larger (new) magnet.
DUNE FD and T2K ND $\nu_\mu$ flux
sFGD CC Inclusive Coverage

➢ This selection only requires a muon entering a TPC
   ➢ Does not consider improved tracking near the vertex in the sFGD
➢ The acceptance for charged current inclusive interactions is expanded
   ➢ Good acceptance for muons that are perpendicular to the beam
   ➢ Timing resolution in scintillator improves forward/backward separation
➢ Will translate into improved systematic uncertainties

(a) Current ND280

(b) Upgraded ND280
Reconstructed $E_\nu$ without Neutrons

LBNF Neutrino Energy Spectrum

True neutrino energy spectrum
Reconstructed neutrino energy without neutrons

Outgoing energy in neutrons

Energy into neutrons from neutrino interactions
Energy into neutrons from anti-neutrino interactions

Elena Guardincerri
Expectation from MINERvA GENIE/GEANT simulation

Bulk of neutron energy depositions are small (2-6 MeV) – Note log scale

Flat-ish with neutron KE

Neutron detection efficiency rises with neutron KE and reaches 50-60% for KE>50 MeV

Manly – NuINT 2018
Neutrons in the sFGD

- Preliminary studies
  - High granularity gives significant efficiency for neutrons
  - Energy resolution for longer path lengths

- Neutron selection looks for hits separated from the vertex
  - Must also be outside of a 3cm x 3cm cube around the reconstructed vertex.
  - Time defined by the first neutron hit

- Neutron energy reconstructed from time-of-flight
  - Assumes a 0.9 ns time resolution

Neutrons start at center of the sFGD

Resolution for travel distance > 40 cm
3DST Wrong Sign Fractions
(NuMI Low Energy Flux w/ GENIE)

➢ Determine sign base on first 20 cm of track