3DST-S report to spokespersons for LBNC

March 31, 2019

1 Introduction

The 3DST-Spectrometer (3DST-S) is a complex of three detector systems in a 0.4 T magnetic field: a 3D Scintillator Tracker (3DST), Time-Projection Chambers (TPCs) and an Electromagnetic CALorimeter (ECAL).

The 3DST is the plastic-scintillator, active target core of the detector. Thanks to its novel geometry, made of many cubes, each optically isolated and read out by three wavelength shifting (WLS) fibers, it improves the timing and tracking resolution as compared to the current, x-y layered plastic scintillator bar detectors. Moreover, MC simulation studies show very good neutron detection capabilities with low background and the ability to measure the neutron energy by Time-of-Flight (ToF).

The over-arching goal of the 3DST-S, in combination with the Ar-based detectors, is to form a complementary and robust measurement system that can meet the stringent requirement of the 2% systematic error even in the case where unknown unknown systematic errors emerge. Based on the current understanding of neutrino oscillation analyses, it will be DUNE will have to rely on neutrino interaction models. Therefore, constraining the systematic uncertainty from the neutrino interaction model is important. Current experiments such as NOvA and T2K have demonstrated substantial need and use of the neutrino interaction model. For instance, the uncertainty raised by simple systematic uncertainty such as binding energy can be a few percent, so that having different A-dependent measurements with different nucleons is important to ensure our measurement is robust and confident.

The 3DST-S component of the near detector complex is proposed for a number of reasons:

- It is imperative to have a consistent, high rate measure of the neutrino direction and spectrum on axis as a function of time. This will require a high mass target and a muon spectrometer. The 3DST-S accomplishes this and has additional capabilities.
- The flux determined with the 3DST-S via CC interactions, neutrino-electron scattering, and low-ν all have un-correlated systematics and backgrounds from ArgonCube, and constitute good crosschecks. This does not seem important when the observed data agrees with the simulation, but it will provide critical input when there is a discrepancy between the modeling and the observed flux. (MINERvA worked for two years diagnosing a disagreement between the NuMI ME flux model and observations. The collaboration sought every handle possible to understand the issue.)

- Neutron production plays a critical role in the interaction model since the near and far liquid argon detectors are largely blind to neutrons. Because the neutron content of neutrino and anti-neutrino interactions differ, the model for neutrons is particularly important for a CP violation measurement. The 3DST is likely to be able to measure neutron spectrum to lower neutron KE than other detectors and pursue event-by-event analysis with fully reconstructed final state particles including neutrons. GENIE and NuWro event generators both indicate neutron spectra for Ar and C are qualitatively similar. Observations of neutrons produced by (anti)neutrino interactions on C can provide a higher level of confidence in the extrapolation of the Ar neutron model to lower KE_n than would otherwise be possible.
- When DUNE ND sees the inevitable disagreement of the near detector data with the simulation, the question will arise as to whether the difference is due to the fact that DUNE has a different energy spectrum from the SBN experiments (and the corresponding difference in processes), or if the difference comes from argon-carbon differences. Either way, the modeling problem must be mitigated and/or propagated to the far detector systematic error budget. Comparisons with low energy neutrinos in the same DUNE flux and the study of samples with different A should be to be useful for this.
- The ND goal of achieving a total systematic uncertainty down to 2% is very demanding even if all sources of the systematic uncertainties are limited to sources that are already known. However, the current cross-section models may be affected by so-called "unknown unknowns", i.e. we do not currently know what interaction effects we may observe with the more precise data in the future, as was the case of 2p2h for the current experiments. Thus it is important to design a ND complex that can extract complementary information from data with as many handles as practically possible to check and tune the flux and neutrino interaction models.

Note that the 3DST is a detector technology recently developed also for the T2K Near Detector upgrade [2], which is scheduled to install a ~ 2 tons detector by 2021. This will be a crucial step for the future updates in the design of 3DST, as we will profit from the neutrino data that will be collected at the T2K Near Detector.

2 Nominal detector configuration

The 3DST detector consists of 12M $1 \times 1 \times 1\ cm^3$ plastic scintillator cubes, optically isolated and read out by three orthogonal wavelength shifting fibers (WLS). The scintillator composition is polystyrene doped with 1.5% of paraterphenyl (PTP) and 0.01% of POPOP. After fabrication the cubes are covered by a reflecting layer by etching the scintillator surface with a chemical agent, resulting in the formation of a white polystyrene micropore deposit over the scintillator. Three orthogonal through holes of 1.5 mm diameter are drilled in the cubes to accommodate WLS fibers. This novel geometry can provide a full angular coverage to any particle produced by neutrino interactions and reduce the momentum threshold for protons down to about 300 MeV/c (if at least three hits are requested).

The 3DST-S configuration consists of the 3DST detector surrounded by Time Projection Chambers (TPCs), to measure the kinematics of charged particles produced but not stopping

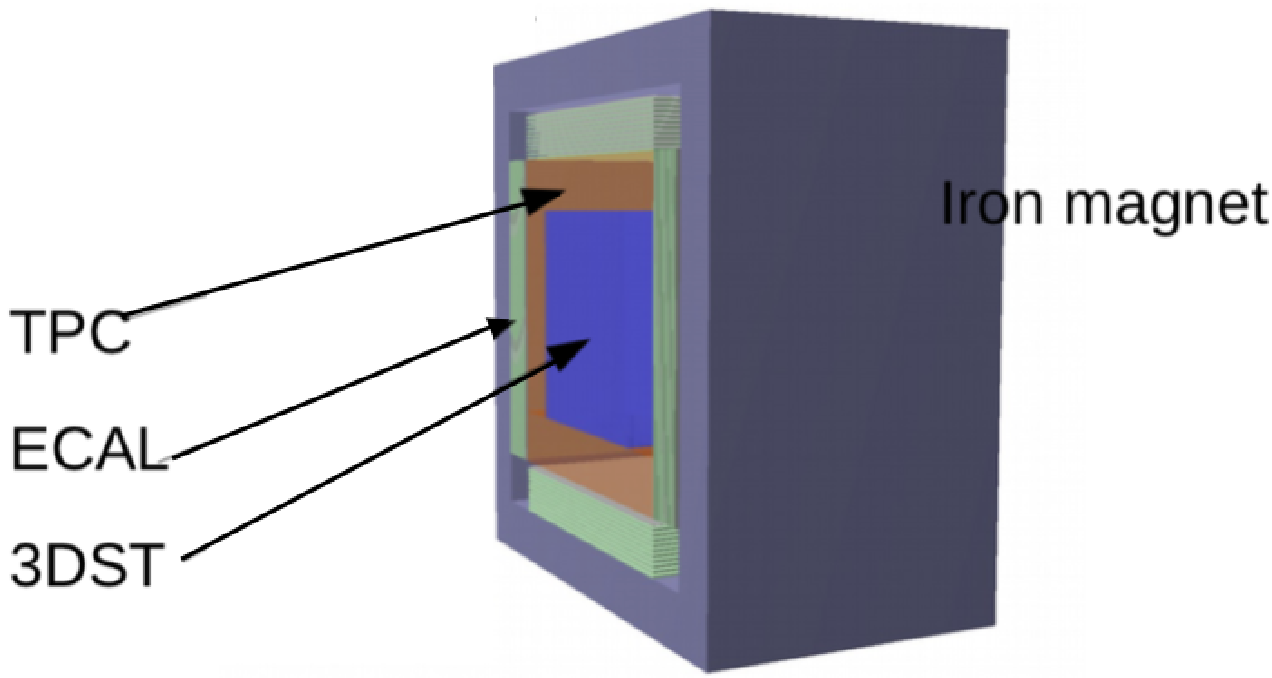

Figure 1: The detector configuration, that includes the 3DST (blue), the TPCs (orange), the ECAL (green) and the magnet (purple) is shown.

in 3DST, an Electromagnetic CALorimeter (ECAL) to identify π^0, photons, electrons and reconstruct their energy. All the detectors are immersed in a 0.6 T magnetic field provided by the magnet. While the size of the 3DST detector is 2.4 *(width)* $\times$ 2.4 *(height)* $\times$ 2 *(length)* m^3, the outer dimension of the whole system is approximately 5 *(width)* $\times$ 5 *(height)* $\times$ 3 *(length)* m^3. The geometry in the concept design is shown in Fig. 1.

3 Neutron detection performance

As mentioned above, detecting neutrons with high efficiency and measuring their kinetic energy by ToF would be an important addition to the DUNE ND capability in terms of understanding/improving both neutrino and antineutrino interaction models, and also to handle any "unknown unknown" sources of systematic uncertainties. The MINERvA experiment demonstrated the ability of measuring neutrons produced in neutrino interactions with a plastic scintillator detector [3]. The 3DST should be able to do this far better than MINERvA because of its high granularity and exquisite timing resolution (both much better than MINERvA).

Simulated neutron scattering can be clearly seen in the 3DST. Fig. 2 shows an example of CC single charged pion interaction. The neutrino-induced blur due to proton recoil can be seen apart from the vertex region. Inspired by MINERvA, our recent studies have shown that 3DST can tag the presence of neutrons as well as determine the neutron energy via time-of-flight.

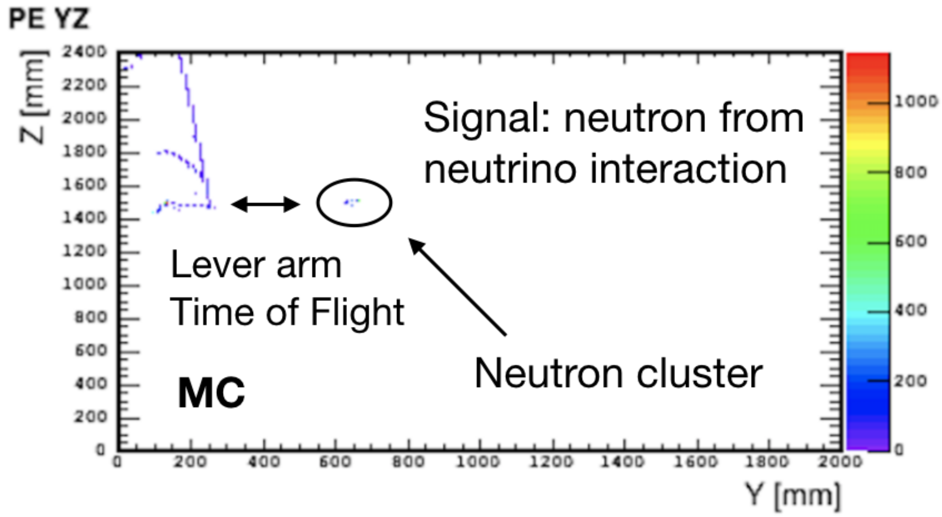

Figure 2: An example of the antineutrino interaction in a 2.4 x 2.4 x 2 m^3 3DST. The three panels correspond to 2D views in XY, XZ and YZ, respectively. The number of photo-electrons (PE) is plotted. An isolated cluster of hits corresponds to a neutron indirect signature produced by the antineutrino interaction.

With a 2.4 x 2.4 x 2 m^2 3DST detector, Fig. 3 shows the reconstructed neutron energy residual for 100 MeV kinetic energy neutron using time-of-flight with a lever arm (distance between neutron hit and neutrino vertex) larger than 0.5 m and smaller than 1 m. This study was conducted with a neutron particle gun simulation. The tail is due to both the timing resolution as well as the mis-reconstructed neutron flight distance due to non-visible interactions like elastic scattering with Carbon. The neutron energy resolution is about 18%.

A potential limitation to this measurement can be due to the neutrons produced by neutrino interactions happening outside the 3DST fiducial volume (out-FV), such as in the ECAL, Magnet, front detector and rock. As neutrons undergo many interactions before loosing all the energy and stopping, they loose the correlation with their original neutrino interaction and it may become hard to reject them. A simulation study has been performed to understand this source of background. A detector system, as described in Figs. 1, has been placed inside an alcove. In order to fake dead materials front to the detector, for example the HpGasTPC magnet, a 0.25 m thick iron layer has been placed 2 m upstream the 3DST.

For the background-related studies in the remaining of this section, the default nominal total size of the 3DST used for this study is 2 x 2 x 2 m^3. The FV corresponds to a inner core of 1 x 1 x 1 m^3. An out-of-FV cut of 0.1 m on the outer shell is applied. We will see how this cut is necessary to reduce the out-FV background, i.e. those neutrons produced by neutrino interactions outside of 3DST.

About 10,000 spills have been simulated. Each spill has a time separation of 1.3 s and the neutrino time distribution within a single spill is simulated as uniform. We search for

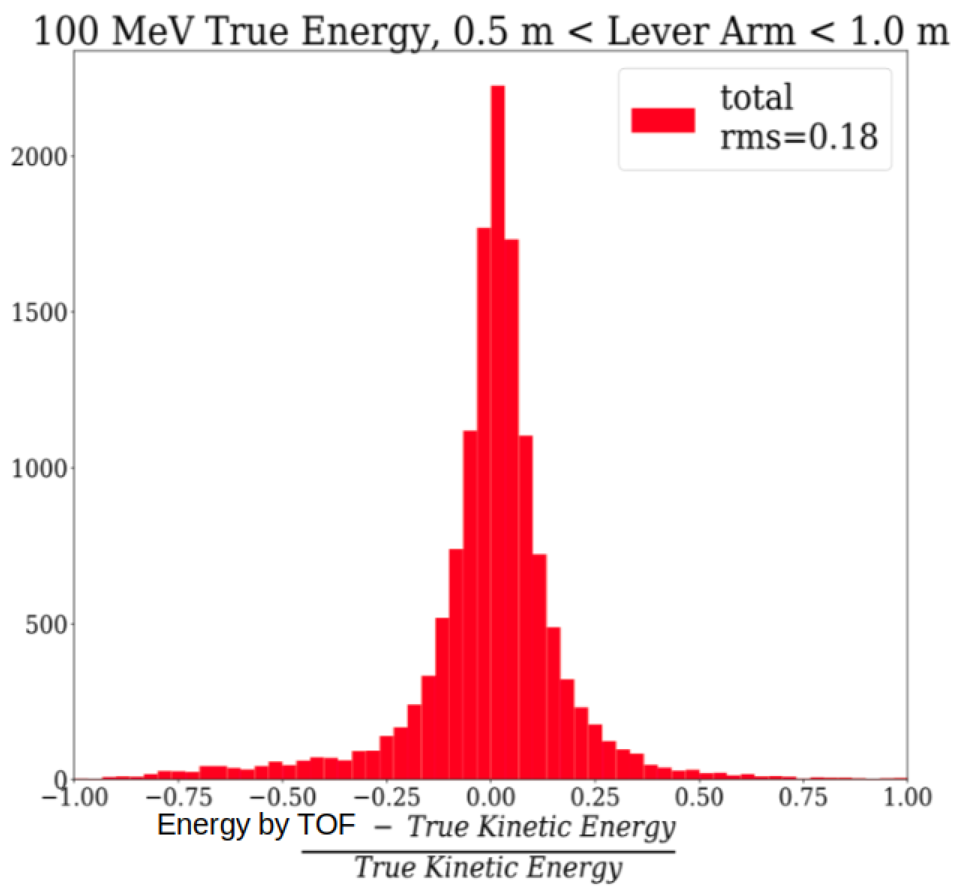

Figure 3: Reconstructed neutron energy residual with lever arm larger than 0.5 m and smaller than 1 m for 100 MeV for a 2.4 x 2.4 x 2 m^2 3DST detector.

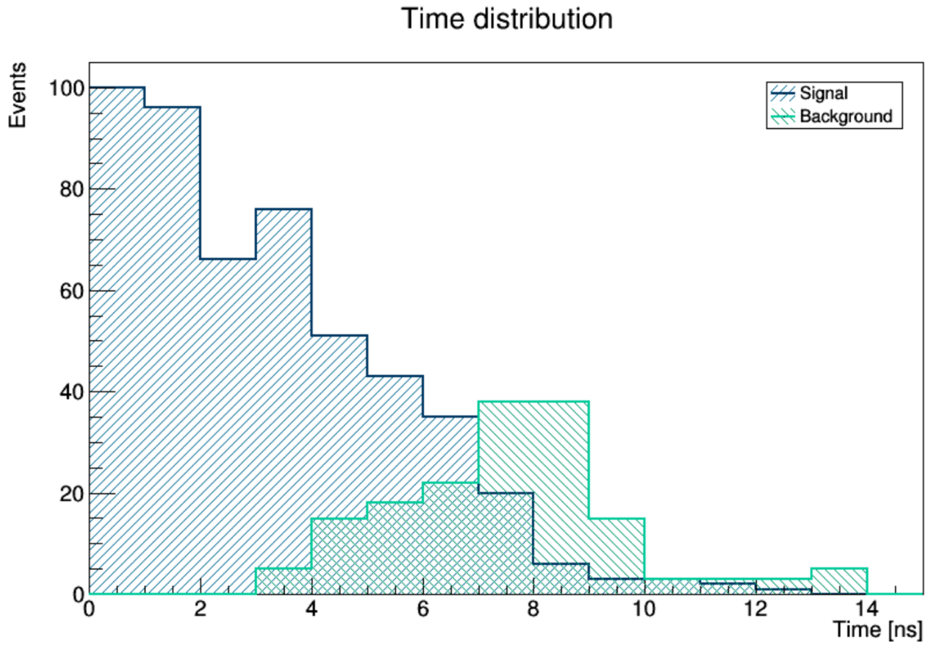

Figure 4: Time difference between the neutrino interaction vertex time inside FV (1 x 1 x 1 m^3core of 3DST) and the earliest neutron-induced hit time. The neutron-induced hit leaves at least 0.5 MeV in a single cube. Neutron-induced background hits are considered as all neutrino interactions happening outside FV.

neutrino signals inside the FV. Then the earliest neutron-induced hit that leaves an energy greater than 0.5 MeV in one cube is searched. If that hit is from the neutrino interaction vertex, it is a signal neutron-induced hit. On the other hand, if that hit is from out-FV, it is a background neutron-induced hit. Fig. 4 shows the time difference between the neutrino interaction vertex time (t_{vtx}) and the next earliest neutron-induced hit time ($t_{neutron}$).

As we search a sphere respect to the neutrino interaction vertex inside the FV, the searching volume increases as the time increases. In addition, the cut on the FV and the lever arm drives the acceptance to out-FV neutrons, which also need higher energy to penetrate through the outside region of the detector to reach the 3DST. We can see that a pure signal-neutron sample can be obtained by cutting on ($t_{neutron} - t_{vtx}$). The relatively short signal window would not allow many background neutrons coming in the FV. All kinds of neutrino interaction outside FV are considered as sources of background hits.

It is likely to be possible to veto neutrons from CC interaction and NC interaction with pions in the ECAL, magnet and even the detector in front of 3DST. This should reduce the background substantially. As shown in Tab. 1, most of the background hits are from the Upstream iron layer and the ECAL. In both cases there will be a high probability to detect a charged particle in 3DST, TPC or ECAL that is produced by the same out-FV (anti)neutrino interaction. We will investigate the possibility to improve the background rejection by vetoing on those observed out-FV interactions.

To quantify the background, the purity is defined as the ratio of events where the first

Origin of BG hits	ECAL	Magnet	Rock	Upstream iron layer	TPC
percentage	26%	9%	0%	65%	0%

Table 1: Origins of the neutron-induced hit background.

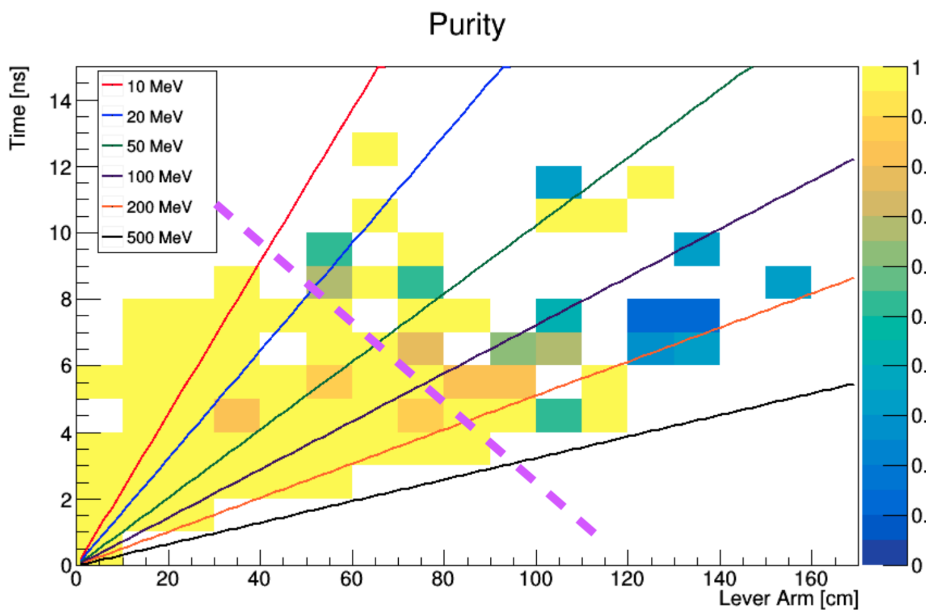

Figure 5: Purity of the neutron-induced hit in the (time, lever arm) space. The dashed line corresponds to the cut required to select an almost 100% pure sample of signal neutrons. The solid lines are theoretical curves for neutrons with different kinetic energies. Note that this study was performed with a total volume of 2x2x2 m^3. See text for details.

neutron-induced hit by time is from the signal vertex to all events which have a neutron-induced hit in the FV. Conservatively, we require the neutron-induced threshold to be 0.5 MeV in the first fired cube. This is a quite conservative requirement, as from test beam data we know that 0.5 MeV deposited energy corresponds to about 10 p.e. with a WLS fiber length of 1.3 m [4], which means that the 3DST energy threshold is well below 0.5 MeV. Fig. 5 shows the purity in the time - lever arm space. The overall purity is very close to perfect. A few background neutrons penetrate in the high lever arm region. In fact, the larger is the distance between the FV and the regions source of out-FV background, the lower is the probability that an out-FV neutron produces a hit selected as signal.

In addition, we studied the reconstructed energy resolution in the same (time, lever arm) 2D space. The time is smeared out with 1 ns in each fiber, so effectively with three fibers, the time smearing is ~ 0.58 ns. The higher light yield can help reducing the time resolution. This effect has been taken into account. Fig. 6 shows the reconstructed-by-ToF neutron energy resolution. In general, $\sim 20\%$ energy resolution can be reached with most of the lever arm and time windows, in the region select by the background cut.

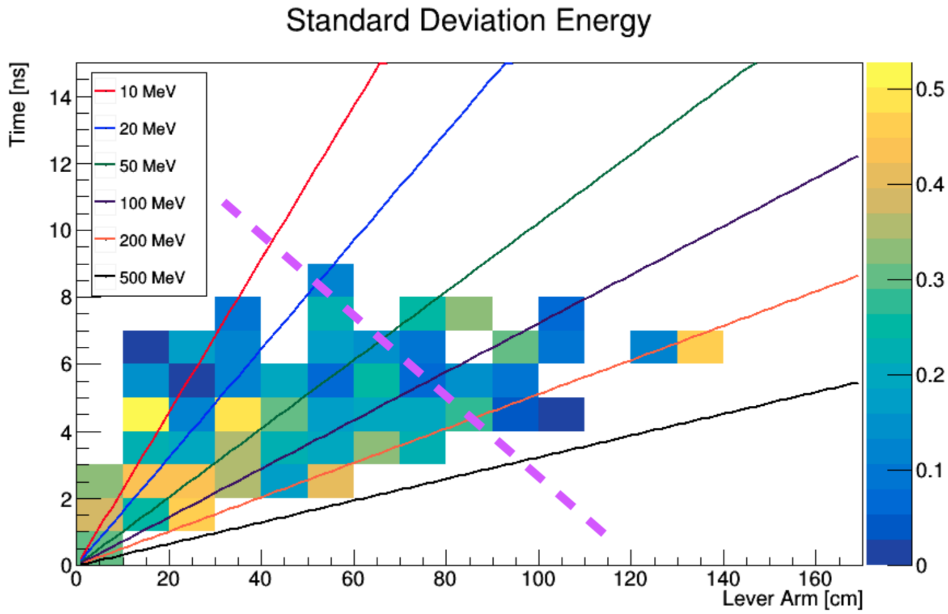

Figure 6: Energy resolution of the neutron-induced hit in the (time, lever arm) space. The dashed line corresponds to the cut required to select an almost 100% pure sample of signal neutrons. The solid lines are theoretical curves for neutrons with different kinetic energies. Note that this study was performed with a total volume of 2x2x2 m^3. See text for details.

A threshold of 0.5 MeV in the first neutron-induced hit cube is used. In addition, with a purity requirement, i.e. a 2D cut on (lever arm, time) space, the detection efficiency can be obtained. Tab. 2 shows the overall efficiency numbers requiring different purity values for the nominal geometry. In the efficiency, the numerator contains a cut on first cube in time has an energy deposit threshold 0.5 MeV and requirement on purity, which requires an effectively cut on the combination of time and lever arm space. The denominator contains all neutrons that leaving any amount of energy in the detector. The largest impact on the efficiency is given by the conservative cut of 0.5 MeV on the energy deposit threshold.

Purity	efficiency	efficiency w/o threshold cut
0.9	44%	90%
0.8	46%	95%
0.7	46%	95%

Table 2: With the nominal 3DST and 10,000 spills, the efficiency numbers of detecting neutrons with the requirements that first cube energy deposit threshold 0.5 MeV and different purity values. The denominator in the efficiency contains all neutrons that leaving any amount of energy in the detector. Note that this study was performed with a total volume of 2x2x2 m^3.

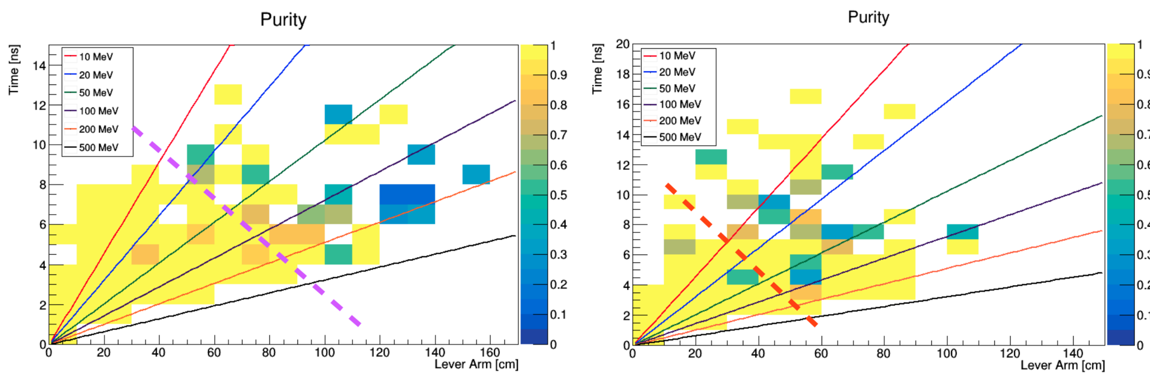

Figure 7: The descoped 3DST purity of the neutron-induced hit in the (time, lever arm) space. The nominal (left) and descoped (right) configurations are compared. The dashed line corresponds to the cut required to select an almost 100% pure sample of signal neutrons for nominal (purple) and descoped (red) configurations. The solid lines are theoretical curves for neutrons with different kinetic energies. Note that the nominal configuration study was performed with a total volume of 2x2x2 m^3. See text for details.

3.1 De-scoped configuration

The same study was performed with an alternative configuration. Since the same FV as the nominal is required to obtain enough statistics, the difference with the nominal configuration is in the out-of-FV cut and, consequently, in the total volume. The descoped configuration consists of:

- Total Volume $= 1.2 \times 1.2 \times 1.2 m^3$
- Fiducial Volume $= 1 \times 1 \times 1 m^3$
- Out-of-FV cut: 0.1 m (off-shell)

The same studies as for the baseline design were performed. In Fig. 7 the purity comparisons of the the nominal (left) and the descoped (right) configurations are given. In order to precisely measure the neutron energy, it is very important to reject all the out-FV background, as it would produce a very large bias in the ToF measurement. The cut required to select an almost 100% pure sample of neutrons is clearly more stringent in the descoped configuration. This is due to the fact that the ECAL and magnet, source of out-FV background, are nearer to the FV core and the lever arm and time cuts are, consequently, weaker.

In Fig. 8 the neutron energy resolution is shown for both configurations. In both cases it was obtained only a signal sample as the out-FV background simulation requires a lot of CPU time. The overlapped cut shows the region where the sample purity is nearly 100% and the reconstruction of the neutron energy by ToF is reliable. While in the nominal configuration a large fraction of the selected lever arm - time space shows a neutron energy resolution of 20% or better, in the descoped configuration the energy resolution is mostly worse than 30%. Moreover, it is worth noting that the out-FV neutron background is hard to model, so a sample with a not near-to-100% purity would suffer of large systematic uncertainties.

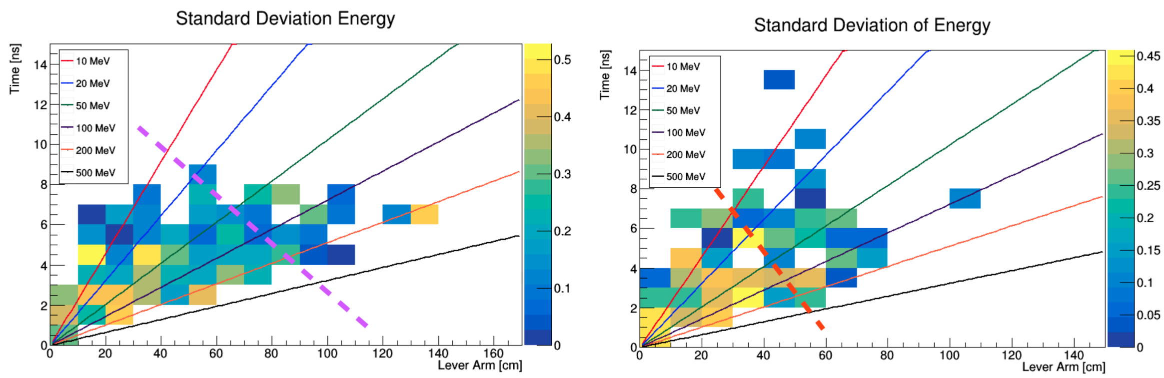

Figure 8: The energy resolution based on the first neutron-induced hit of the descoped 3DST in the (time, lever arm) space. The nominal (left) and descoped (right) configurations are compared. The dashed line corresponds to the cut required to select an almost 100% pure sample of signal neutrons for nominal (purple) and descoped (red) configurations. The solid lines are theoretical curves for neutrons with different kinetic energies. Note that the nominal configuration study was performed with a total volume of 2x2x2 m^3.

Purity	efficiency
0.9	32%
0.8	33%
0.7	34%

Table 3: With the descoped 3DST and 10,000 spills, the efficiency numbers of detecting neutrons with the requirements that first cube energy deposit threshold 0.5 MeV and different purity values. The denominator in the efficiency contains all neutrons that leaving any amount of energy in the detector.

Tab. 3 shows the overall efficiency numbers requiring different purity values for the descoped geometry. The efficiency definition is the same as for the nominal geometry. The largest impact on the efficiency is given by the conservative cut of 0.5 MeV on the energy deposit threshold. The nominal configuration will give us more statistics than the descoped one as the final state neutrons have larger volume to interact.

4 Expected statistics for (anti)neutrino interactions

Default size of the 3DST is defined to be 2.4 m x 2.4 m x 2 m. This gives a total target mass for the 3DST of 12 metric tons. Implementing a generic veto region around each side of the detector of 10 cm, gives a fiducial mass of 8.7 tons. Then, the fiducial volume and mass of the baseline configuration is:

- Total Volume = $2.4 \times 2.4 \times 2.0\ m^3$
- out-FV cut (outer shell): 0.1 m

Channel	ν mode	$\bar{\nu}$ mode
ν_μ CC inclusive	13.6×10^6	5.1×10^6
CCQE	2.9×10^6	1.6×10^6
CC π° inclusive	3.8×10^6	0.97×10^6
NC total	4.9×10^6	2.1×10^6
ν_μ-e$^-$ scattering	1067	1008
ν_e CC inclusive	2.5×10^5	0.56×10^5

Table 4: This table summarizes the projected event rates per year for a 2.4 x 2.4 x 2.0 m^3 3DST detector, assuming the 80 GeV, three horn, optimized LBNF beam. A 10 cm veto region at each side was required.

- FV = $2.2 \times 2.2 \times 1.8\ m^3$
- Fiducial Mass = 8.7 tons

The above FV is based on the detection of numu cc inclusive events. Table 4 gives the number of events expected per year in this fiducial volume of a 3DST of the size described above. The numbers given in the table are assuming the 80 GeV, 3 horn, optimized LBNF beam flux and 1.46×10^{21} POT/year.

The descoped 3DST configuration is:

- FV = $1.0 \times 1.0 \times 1.0\ m^3$
- out-FV cut (outer shell): 0.1 m
- Total Volume = $1.2 \times 1.2 \times 1.2\ m^3$
- Fiducial Mass = 1 ton

As the number of events scale simply by the mass, the total number of events for each neutrino beam and interaction mode is smaller by a factor 8.7.

5 Electromagnetic and hadronic shower containment

A study was performed to evaluate the containment of the hadronic and electromagnetic showers in the 3DST detector. The default 12 ton 3DST is used in the center of 3DST-S, surrounded by the 0.5 m thick TPC and 0.5 m thick ECAL. The ECAL material budget was defined in order to achieve 10 radiation lengths. A magnet surrounds this system. The efficiency of gamma containment inside the 3DST detector with respect to the traversed distance was calculated for events with an angle of less than 40 degrees. This is shown in Figure 9. In comparison, in the descoped geometry 3DST is shrunk to 1.2x1.2x1.2 m^3 in total volume, surrounded by the TPC and ECAL with the same thickness. With DUNE flux and the FV event selection, the fraction of hadronic leakage can be calculated as the hadronic energy that leaking out of the ECAL volume over the total hadronic energy for each event. A comparison of the leaking fraction with the nominal geometry and the descoped geometry

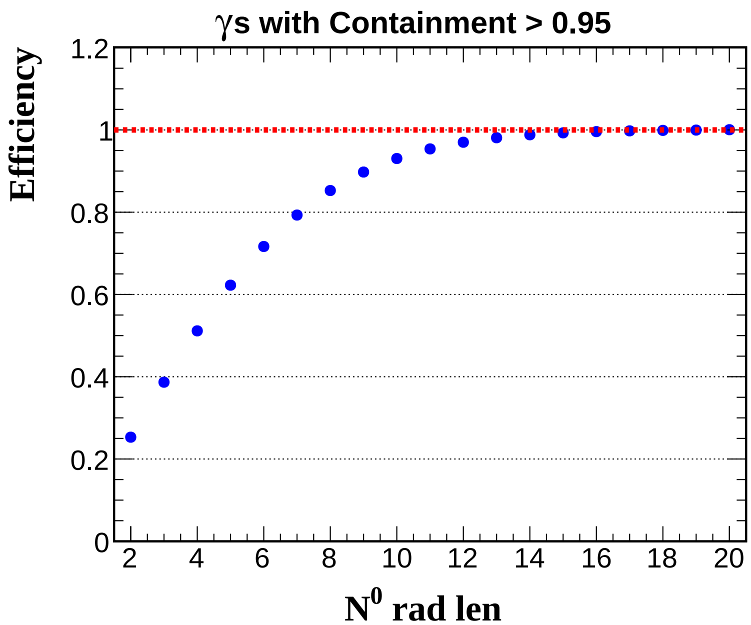

Figure 9: Efficiency to contain at least 95% of the gamma energy in the 3DST detector, as a function of the depth along the beam in terms of radiation lengths.

can be seen in Fig. 10. The solid red and blue curves are with same POT exposure, and in order to compare their shapes, the red dashed curve shows the red solid one normalized to the blue one.

6 Beam monitoring

In the context of DUNE-PRISM, liquid argon TPC or liquid argon TPC plus high pressure gas TPC will move off-axis. In such case, the only detector that could provide reliable statistics for neutrino beam monitoring on a daily basis in the ND hall is 3DST-S. Muon monitor in the beamline can potentially measure the rate of produced muons but the knowledge of the neutrino spectrum will be lacking. Therefore, one of the complementary usages of 3DST to the Ar target detectors is to monitor the beam profile as well as the neutrino spectrum stability. Using the default 2.4 x 2.4 x 2 m^3 3DST with 2.2 x 2.2 x 1.8 FV, we have divided the volume into four parts along the x direction, so that four measurements of the muon event rate can be obtained at four different X beam positions. In each module along X, CC inclusive events are used with the daily POT exposure. Fig. 11 shows the gaussian fit to the four module points along x for one day statistics. An uncertainty of 22 cm is obtained. We expect to have less than 10 cm uncertainty with per-3-day 3DST CC inclusive measurement. In this study the ECAL was not taken into account. However the ECAL could provide a considerable increase in the collected events per day for beam monitoring if it is designed to detect neutrino interaction vertex, helping to improve the beam width uncertainty. With the baseline ECAL design, the mass of ECAL can be over 20 tons, which can triple the beam

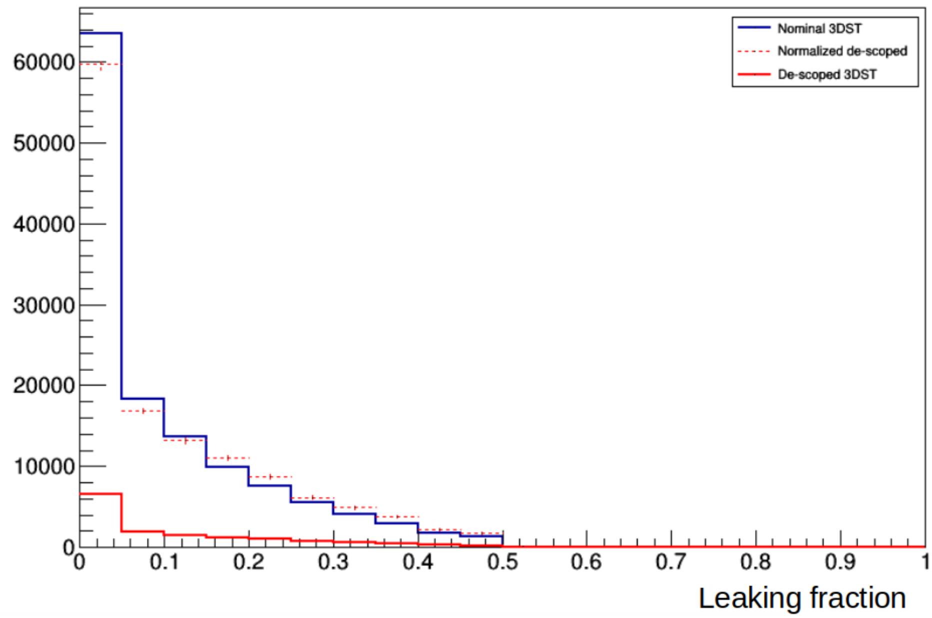

Figure 10: The distribution of the fraction of the hadronic shower not contained in the 3DST-S detector is shown.

monitoring statistics. If necessary, additional scintillator modules can be added. These do not need to have the fine granularity cube structure as 3DST and would allow to increment the number of readout channel by a small amount.

It would be highly valuable if 3DST-S could monitor the neutrino spectrum. A spectrum with daily exposure is shown in Fig. 12. For weekly measurement, we can reach 1% statistical error in each of the 100 MeV slices between 2 - 3 GeV region. It provides valuable information of the spectrum stability that could be important to the oscillation analysis. In order to reach comparable beam monitoring results as mentioned above, the de-scoped 3DST will need 8.7 times more run time, which will make it difficult to monitor the neutrino energy spectrum in weekly-basis.

7 Ratio of Ar vs. CH cross section

Comparisons between DUNE-Ar and 3DST CH measurements can diagnose any potential problem in the understanding of the (anti)neutrino interactions. As an example, Fig. 13 shows the neutron numbers generated from GENIE and NUWRO generators with Final State Interactions (FSI) ON and OFF. The number of neutrons produced with neutrino interactions is shown for ν-Ar and ν-Carbon interactions. The similarity between the Ar and CH can help us to tune the model, as well as diagnose some of the detection problems in LAr. This comparison is useful to precisely measure the large cross-section systematics to neutrino oscillation measurements, such as subtle effects like nuclear effects or FSI. However, assuming that these interaction models represent the reality correctly, from these figures it

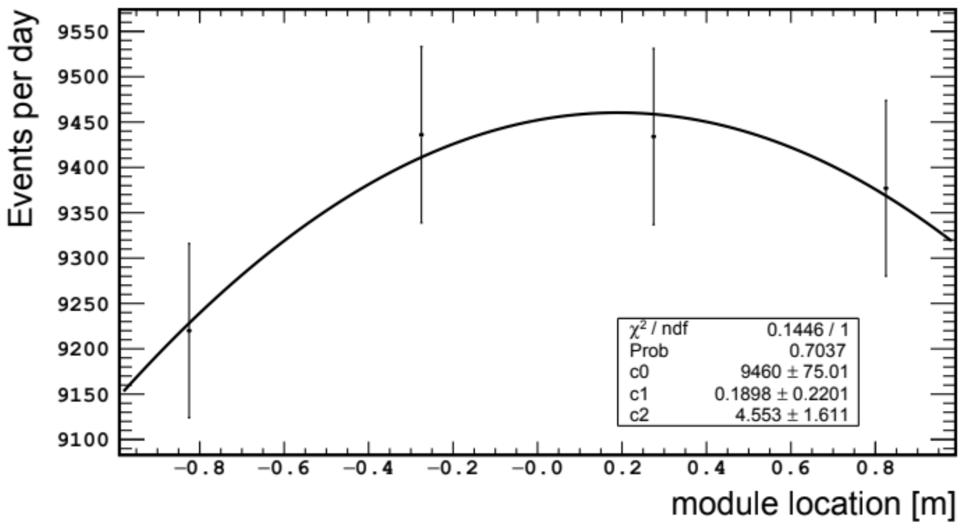

Figure 11: The Gaussian fit for the event rates with four selected volumes along x inside the default 3DST. This study is limited by MC statistics, in particular it may be affected by the re-usage of hadron-to-ν decay flux events, due to lack of CPU time.

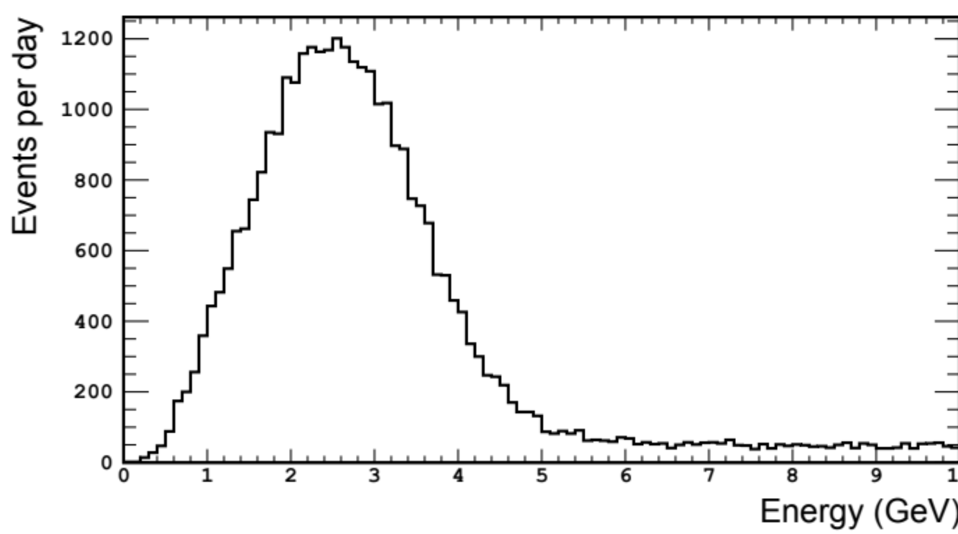

Figure 12: The distribution of the neutrino events, collected in one day of data taking, is shown as a function of the true neutrino energy.

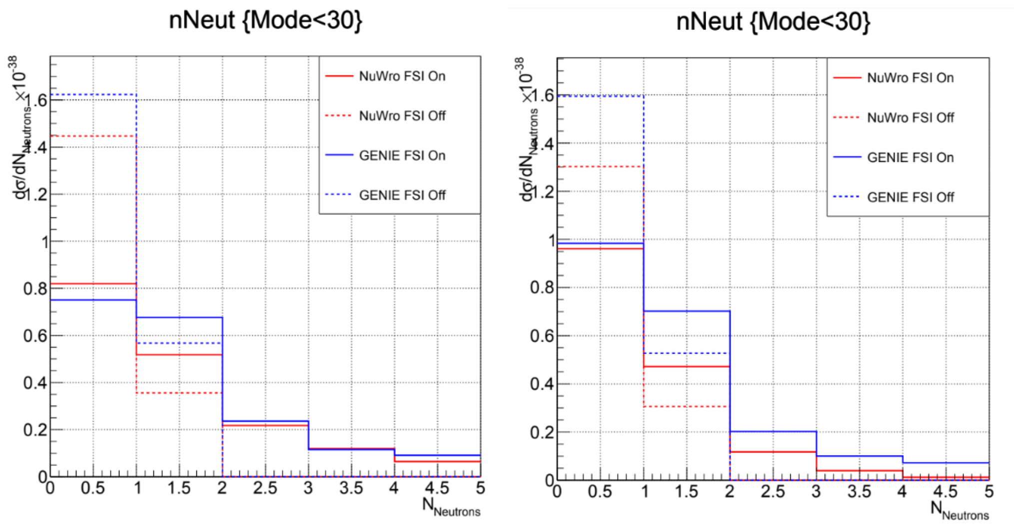

Figure 13: Left: neutron number from ν-Ar^{40} interaction with GENIE and NUWRO with FSI ON and OFF. Right: neutron number from ν-C^{12} interaction with GENIE and NUWRO with FSI ON and OFF.

becomes visible that the neutron production in Argon and Carbon does not sensibly differ. We think that very precise measurements in CH, i.e. by measuring the kinematics of all the particles produced including the neutrons, we can further reduce the total systematic uncertainty, in a complementary way to the Argon interaction measurements.

8 Flux measurement

There are various channels that can be used to do the flux measurement in 3DST. The first one would be the neutrino-electron scattering. The neutrino-electron scattering cross section is well measured and essentially free from theoretical uncertainties as the interaction is a pure weak interaction. Thus, this channel can provide a good flux constraint. The neutron-electron scattering tends to give a forward-going electron. Consequently, there is a premium on measuring the electron angle precisely and accurately. The 3DST detector provides an angular resolution below 15 mrad for GeV electrons. The neutrino-electron scattering channel can be perfectly utilized. Ref. [1] shows a direct flux constraint with the neutrino-electron scattering channel. The containment of electron would be crucial for this measurement, and the descoped geometry would definitely compromize the ability to measure the flux using this channel. Since 3DST will be the only detector always on axis, it will collect more ν - electron scattering per mass unit. Moreover it will be always sensitive to the DUNE flux peak region, where the ν - electron cross-section is high, while the other detectors will suffer from lower cross-section when moved off-axis, and will be sensitive only to lower energies.

In addition, low-ν measurements can be performed to infer the flux shape. The low-ν

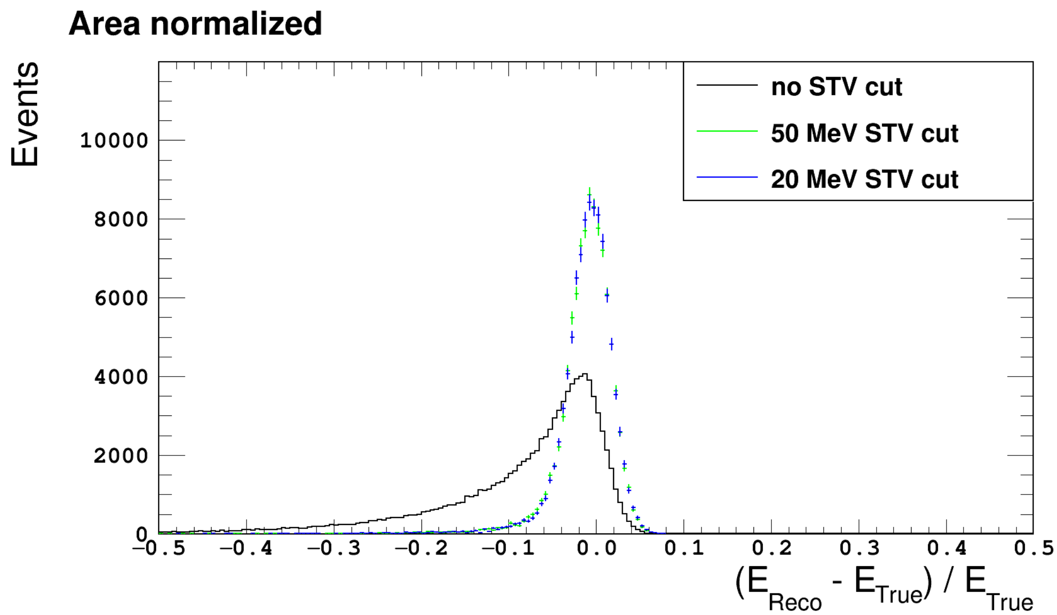

Figure 14: Residual of the true and reconstructed energy with different δP_t cut with the antineutrino CCQE channel only. See text for details.

channel cross section is relatively independent from the neutrino energy, so that if we can select some certain neutrino energy low-ν channel events, those events can be used to project to the whole neutrino spectrum. In here, the sample size would be important. And thus the nominal 3DST configuration is also preferred.

The capability of 3DST of measuring the neutron kinematics with an almost free background sample and an event-by-event neutron selection may have an impact on the reconstruction of the neutrino original energy. If the neutron momentum is measured, it is possible to precisely measure the momentum balance of the event on the transverse plane. In turn, if the momentum imbalance in the transcerse plane to the neutrino direction is small, it is a sign that the outgoing particle produced in the interaction are minimally affected by nuclear effects or FSI. This enables the measurement of the antineutrino flux with minimal interaction model dependence [5]. Fig. 14 shows the the residual between the true and reconstructed energy with different δP_t cut assuming we have the knowledge of the neutron energy. The muon momentum is smeared with a 4% resolution. Only the antineutrino CCQE channel with DUNE flux is shown.The bias is significant if we have no ability to track the transverse momentum due to the lack of neutron information. On the other hand this feature can be used to measure nuclear effects and FSI more precisely, as the correlations between flux and cross-section would be greatly reduced.

For simplicity, this study was performed with only true CCQE interactions (about 30% of the events at DUNE). However in the future the study will be extended to all the other interaction modes.

9 Descoped configuration # 2

An alternative configuration, named descoped # 2, would consist of the same descoped configuration considered in the sections above (# 1), i.e. same mass and volume, but without the TPCs, ECALs and the magnet. A forward spectrometer would be placed only downstream of the 3DST.
We expect that the neutron out-FV background could increase, depending on the distance between the rock and the 3DST FV. In order to achieve a purity similar to the nominal configuration, the alcove size must be optimized in order to have a distance between 3DST FV and the rock the same as the distance between 3DST FV and ECAL in the nominal configuration.
The expected event rate will decrease with respect to the descoped configuration # 1. In fact, such configuration would not be able to measure the momentum of those muons either not stopping inside 3DST or not reaching the forward spectrometer. Moreover, this will have an impact on the robustness of the neutrino interaction studies, as only a reduced part of the phase space can be measured. For instance, an analogous situation is the reason why the T2K experiment is now upgrading its near detector to improve the detection efficiency to particles produced at any angle [6].
The beam monitor performances would be affected for the same reasons explained above, such that monitoring the (anti)neutrino spectrum on a daily basis will become not possible. The precise measurement of neutrino interactions would be also obstacled by the fact that the kinematic of any particle, charged or neutral, exiting the 3DST volume cannot be measured.
The descoped configuration # 2 would suffer its inability in identifying the charge of all particles not reaching the forward spectrometer. This will make it impossible to identify the full neutrino event topology, particularly for the higher multiplicity events involving multiple charged particles. This will greatly diminish the usefulness of the neutron detection and its energy measurement.
The absence of the ECAL will also play an important role. Electromagnetic showers will not be precisely detected, as only a fraction of the shower can be contained. This will drastically reduce the potential of the detector to tag π^0's, with the possibility of biasing the energy balance of the event. Moreover, there would be a big deficit on the hadron shower reconstruction, as the only 3DST volume would not be sufficient.
One of the powerful tools of the 3DST-S system is the capability of precisely measure the momentum unbalance of the event, even when neutral particles are produced. The descoped configuration # 2 will be able to measure the momentum unbalance for a lower number of events, i.e. only if all the particles are stopping inside 3DST or re,caihg the f ronrd spectromeaetrwand the total statistics available to constrain the antineutrino flux would be lower than the other configurations.

In conclusion, the descoped configuration # 2 will not allow to perform all the precise measurements foreseen with the nominal configuration.

References

[1] C. Marshall and C. Wilkinson, presented at the DUNE Near Detector Workshop, November 2017.

[2] T2K collaboration, arXiv:1901.03750, CERN-SPSC-2019-001 (SPSC-TDR-006)

[3] Minerva collaboration, arXiv:1901.04892, FERMILAB-PUB-19-014-ND

[4] A. Blondel et al, JINST 13 (2018) no.02, P02006, arXiv:1707.01785

[5] S. Dolan, talk at ECT Modelling Workshop (Trento, 2018), "Exploring nuclear effects with transverse imbalances"

[6] K. Abe et al, "T2K ND280 Upgrade Technical Design Report", arXiv:1901.03750