Response to Spokes' questions and descope options

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on behalf of the 3DST working group

DUNE ND Design Group meeting

17th of April 2019

The request of the Spokespersons

To help us respond to the LBNC, we are asking all ND sub-groups to address these recommendations, and in particular, to assess the impact of descoping their detector component. As we understand it, the current 3DST concept envisages a 2 x 2 x 4 m^3 scintillator volume surrounded by calorimetry, and a magnetic spectrometer to perform muon momentum measurements.

Specifically, could you please address the following points?

1. Articulate (concisely) the goals of the 3DST system with regard to measurements that will be performed to impact the neutrino oscillation measurements at DUNE.

2. Investigate a descoped 3DST system, with an approximately 1 m^3 scintillator fiducial volume and a forward tracking spectrometer focused on on-axis beam monitoring, as suggested by the LBNC. Describe the tradeoffs/compromises between this descoped system and the current concept with regards to the impact on DUNE oscillation measurements.

The goals of DUNE ND

- Over-arching goal of the 3DST-S, in combination with Ar-based detectors is to form a robust measurement system that can meet the stringent requirement of the 2% systematic error

- We don't know what issues we may found in the models in 10 years from now. In the case where "unknown unknown" systematic errors emerge it becomes even more important to make our ND system as much robust as possible

- The DUNE oscillation analysis will have to rely on neutrino interaction models at some levels

- The 3DST-S, in combination with Ar-based detectors, can provide the robust system required for such a complex and high-precision measurement

The goals of 3DST-S

- Providing complementary measurements to Ar target detectors and forming a robust ND system as a whole against uncertain and unknown systematic error sources

- Detect and measure neutron energy

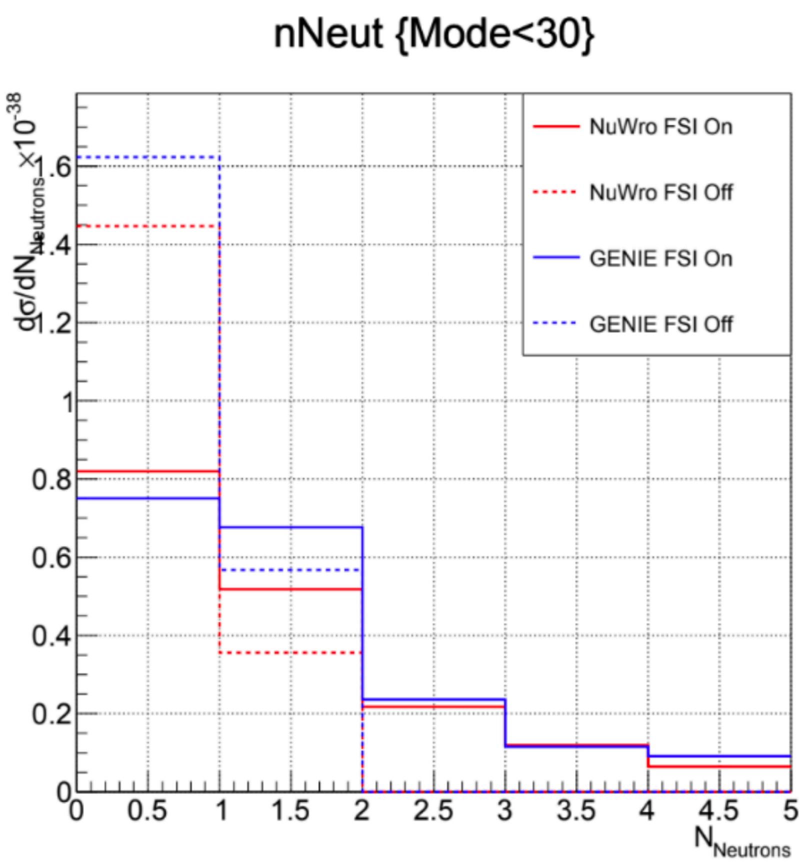
  ✦ Lack of our knowledge on neutron content is a known source of uncertainty in calorimetric energy reconstruction and is known to be different for neutrino and antineutrino interactions

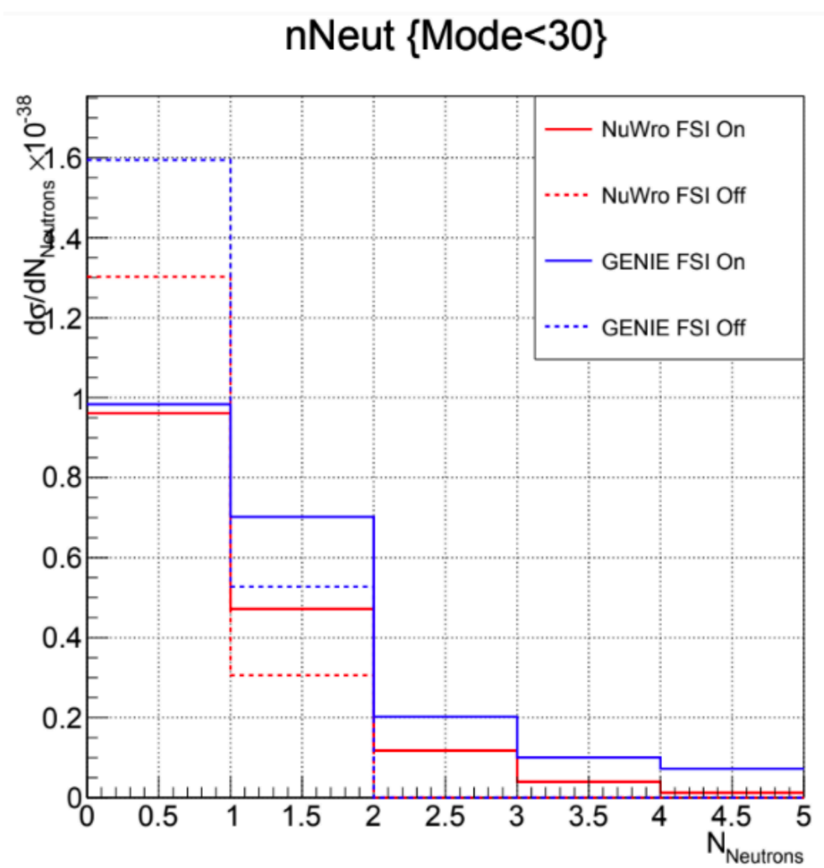
  ✦ Capability to include neutrons in reconstruction event-by-event provides powerful avenue to explore and improve interaction models and measure the NuBar flux with minimal nuclear effects

The goals of 3DST-S

- Current models (checked GENIE and NuWro event generators) 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 E_{KIN} than would otherwise be possible





Made by Luke Pickering

- Recent papers (https://arxiv.org/pdf/1902.06338.pdf) show that A-scaling for 1p1h and 2p2h is quite well understood and has been validated with JLab data

The goals of 3DST-S

- Measure flux with multiple techniques with a detector that has different systematic uncertainties from the LAr detector

- Measure neutrino and antineutrino interactions on nucleus other than Ar

    - ✦ This allows for exploration of A dependence and thereby reduce systematic errors associated with interaction models

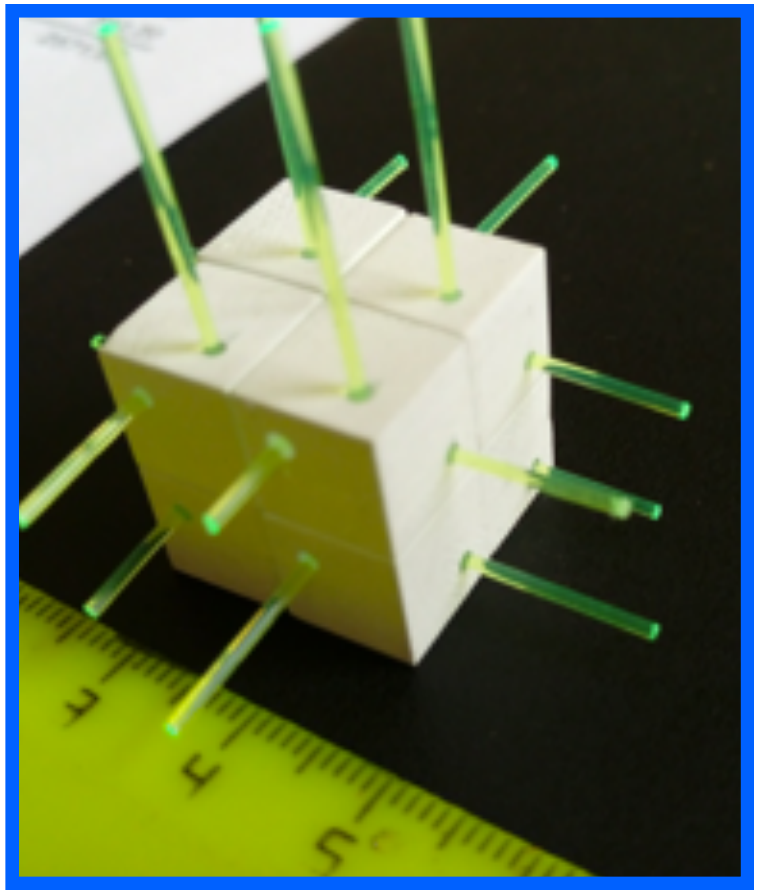
- Beam monitor as only detector always on-axis:

    - ✦ Measure the neutrino energy spectrum, beam position/width on daily basis

    - ✦ High statistics detector that separates neutrino from antineutrino events

The 3DST Spectrometer (3DST-S)

3DST



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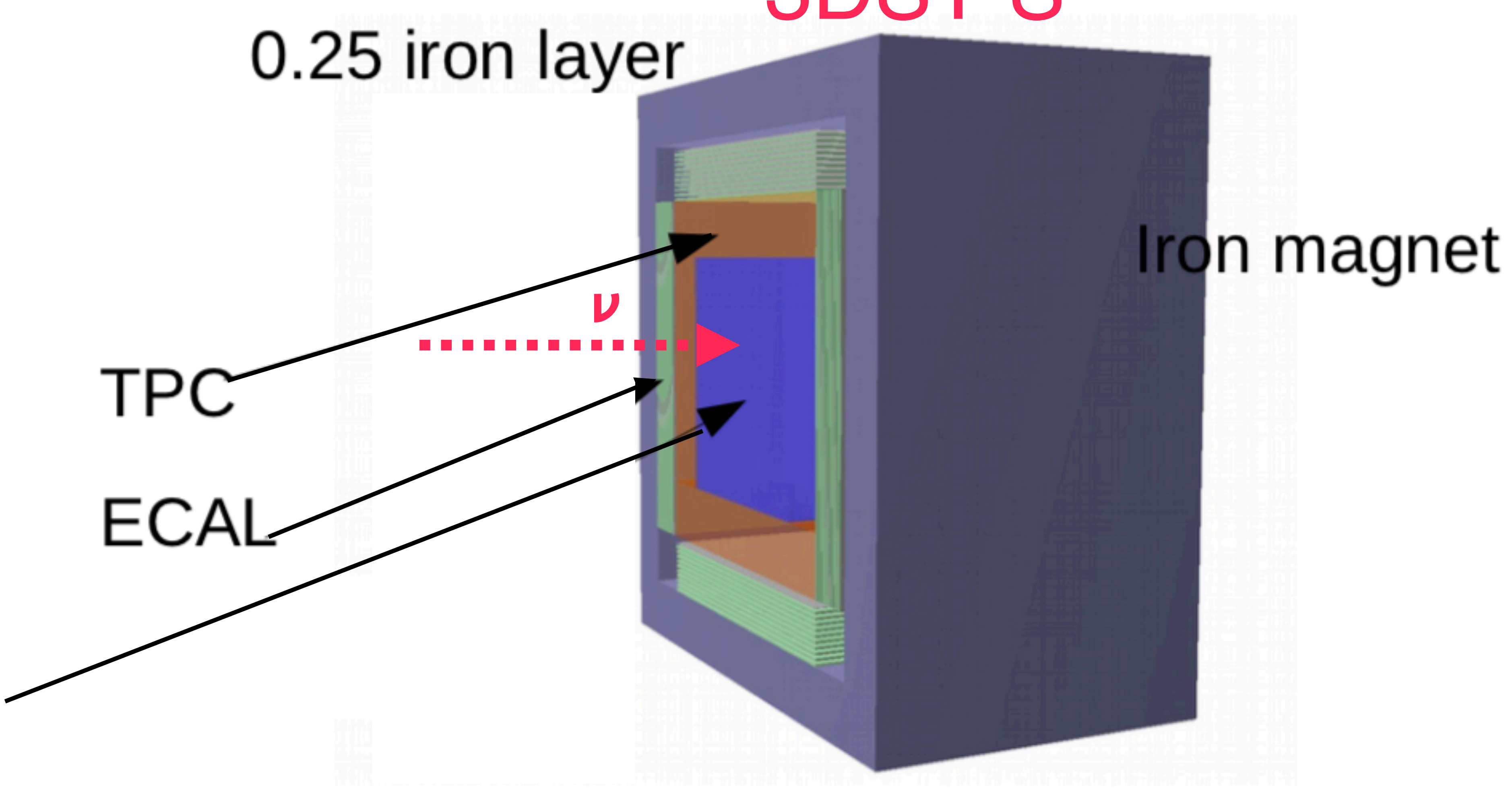
3DST-S



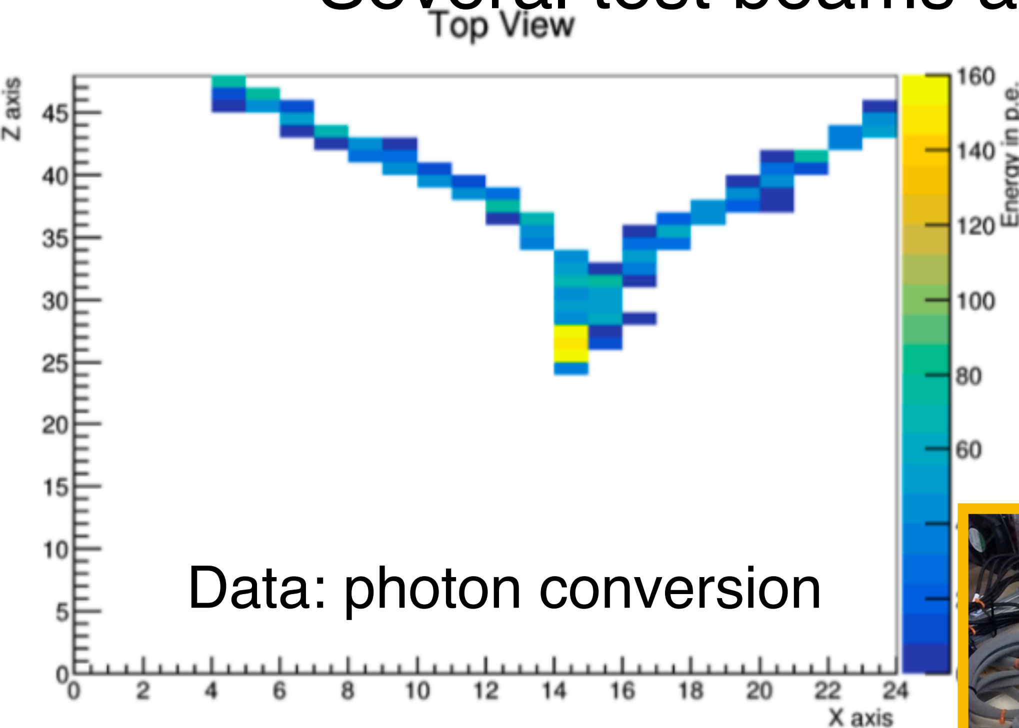
- Muon detection efficiency >90% at 4π
- Detect protons above ~300 MeV/c
- Very good neutron detection capability

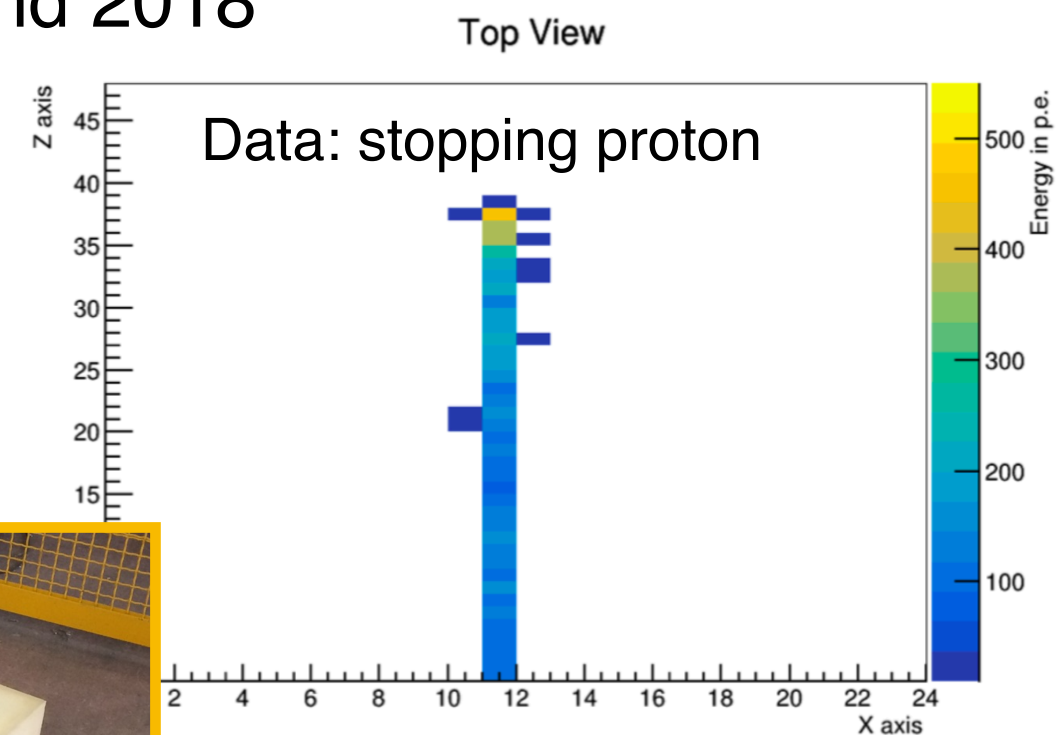
- 3DST baseline size is 2.4x2.4x2 m^3
- Fully active, ~12 tons total mass
- Whole size of the 3DST spectrometer is ~ 3x5x5 m^3
- 0.5 m depth for both TPC and ECAL

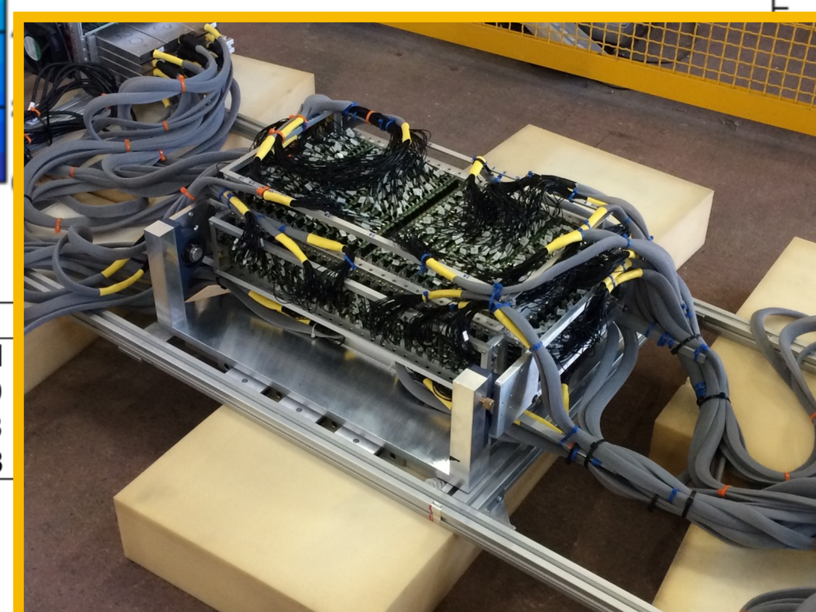
T2K Near Detector will be upgraded with 2 tons of cubes —> 3DST-S prototype

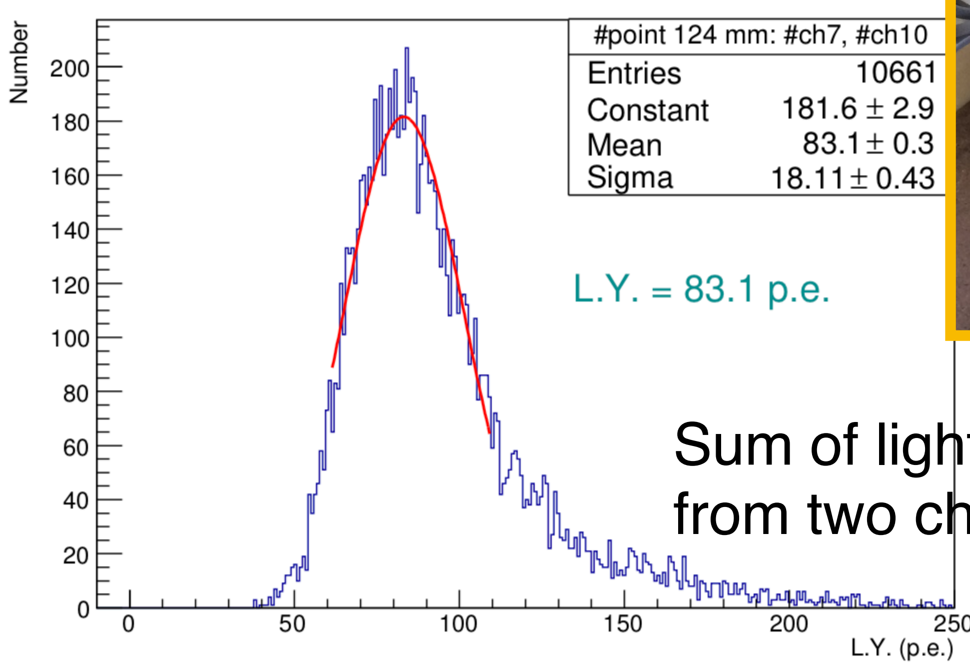
The 3DST performances

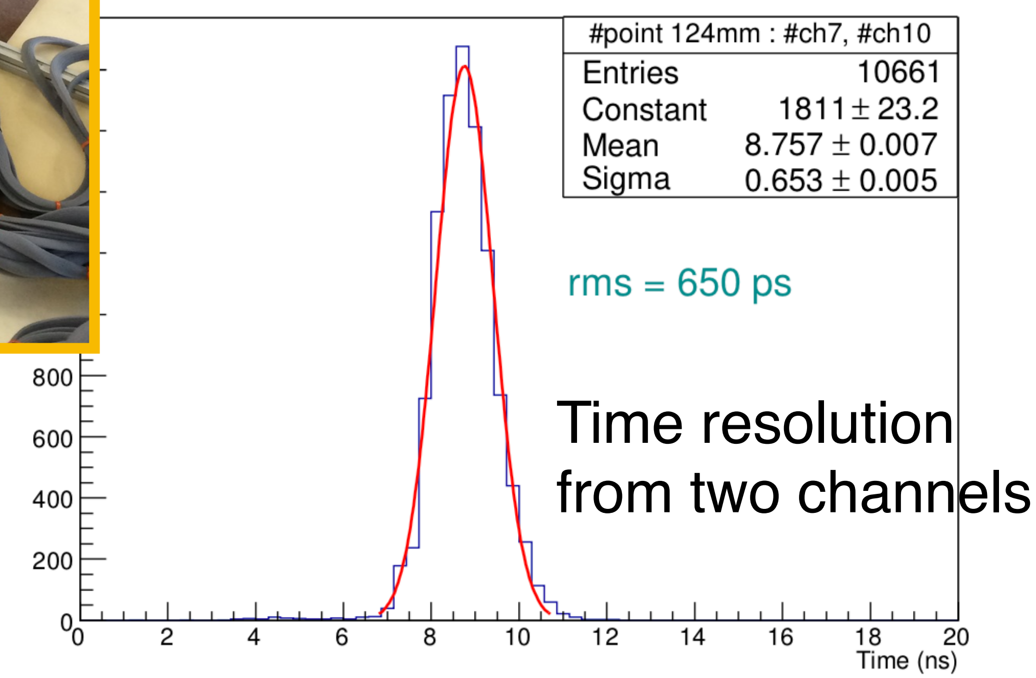
- Several test beams at CERN in 2017 and 2018











- Single cube light Yield for MIP ~ 41 p.e. / fiber (1.3m fiber length)
- Single cube time resolution ~ 0.92 ns / fiber
- Detector simulations based on data collected and analyzed

The 3DST event rate

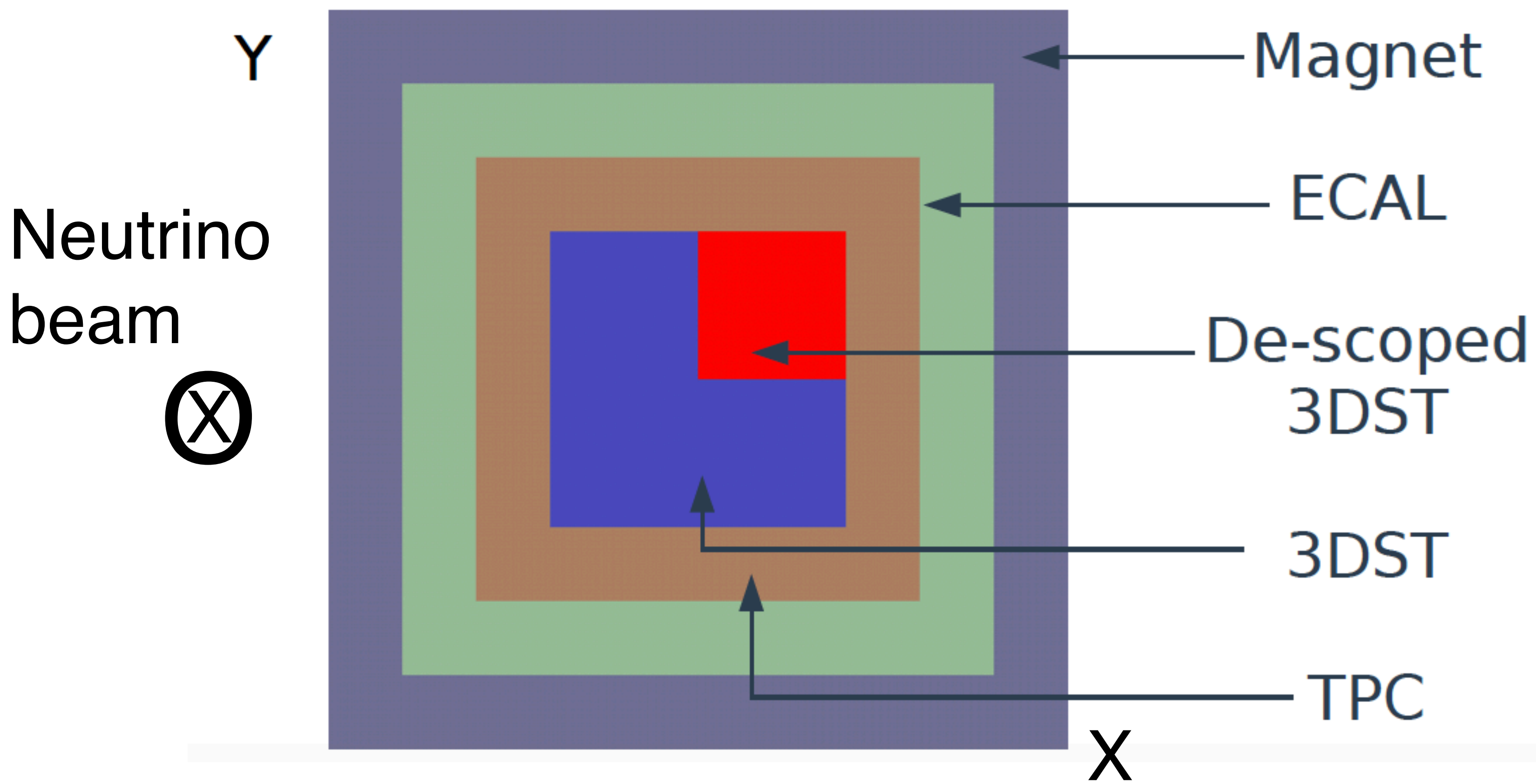
- Event rate for 1.46×10^{21} POT / year (80 GeV beam, three horns, optimized)
- Applied a 10 cm out-of-FV cut:
  - ✦ Fiducial Volume = 2.2 x 2.2 x 1.8 m^3
  - ✦ Fiducial Mass = 8.7 tons (only 3DST)

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_μ CC coherent	$1.26\ \times10^5$	$8.6\ \times10^4$
ν_μ CC low-ν (ν <250 MeV)	1.48×10^6	$8.8\ \times10^5$
ν_e CC coherent	2.1×10^3	719
ν_e CC low-ν (ν <250 MeV)	2.1×10^4	$4.7\ \times10^3$
ν_e CC inclusive	2.5×10^5	0.56×10^5

- The FV will have different definitions depending on the physics measurement
- Depending on the ECAL design, additional mass could be achieved for some physics channels

The de-scoped 3DST-S

- The fixed parameter is the Fiducial Volume: 1 x 1 x 1 m^3
- Applied the same out-FV cuts, i.e. 10 cm outer-shell:
  - ✦ Total Volume = 1.2 x 1.2 x 1.2 m^3
  - ✦ Fiducial Mass = 1 ton

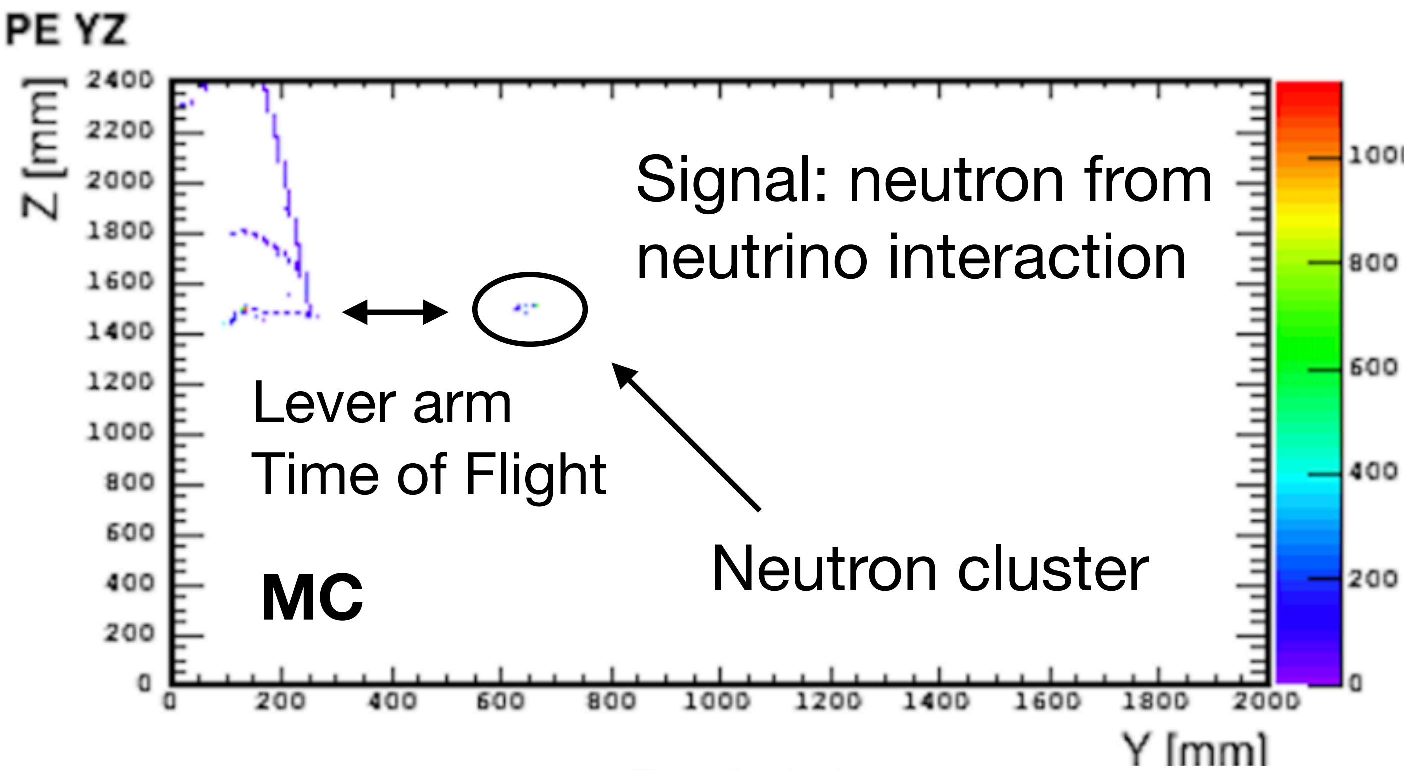


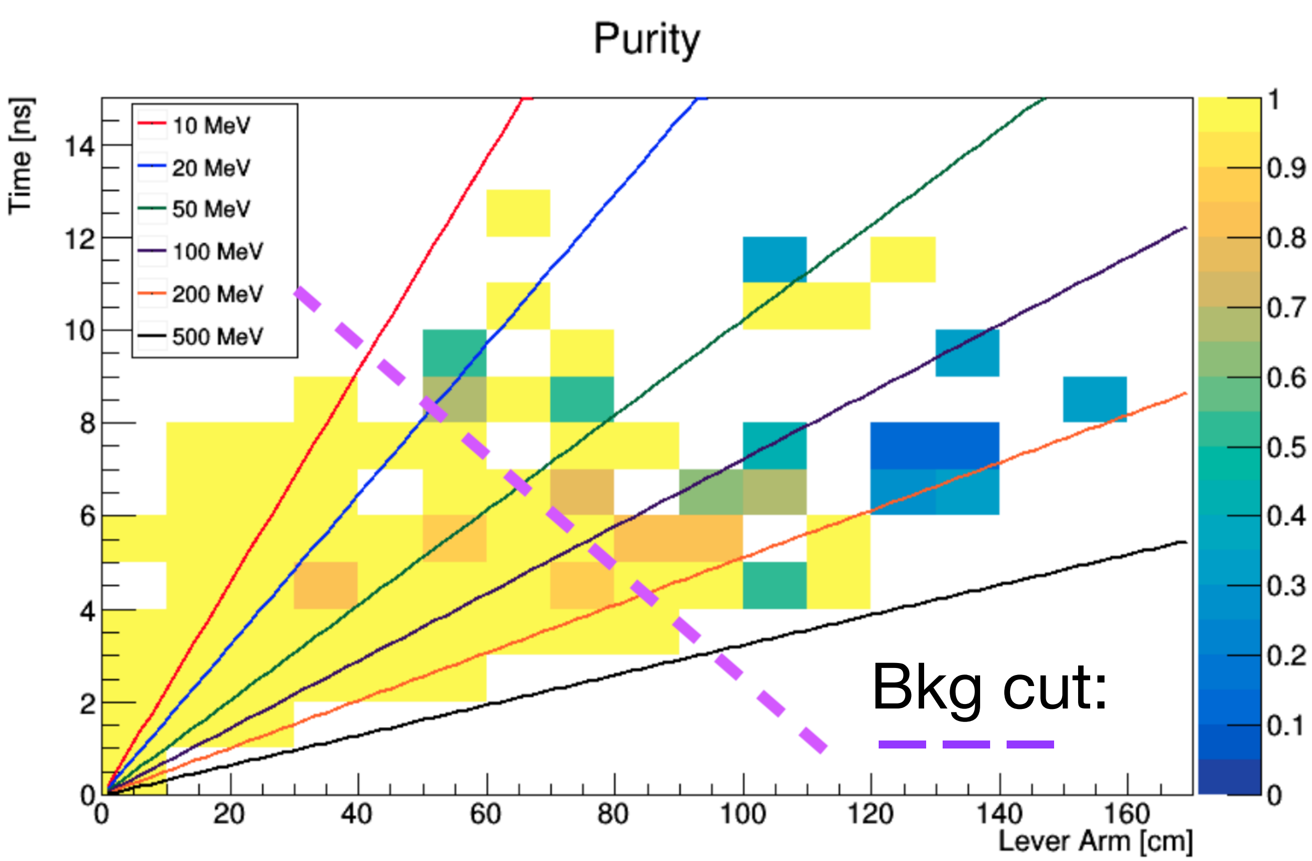
✦ The de-scoped configuration has 8.7 times less events than baseline configuration

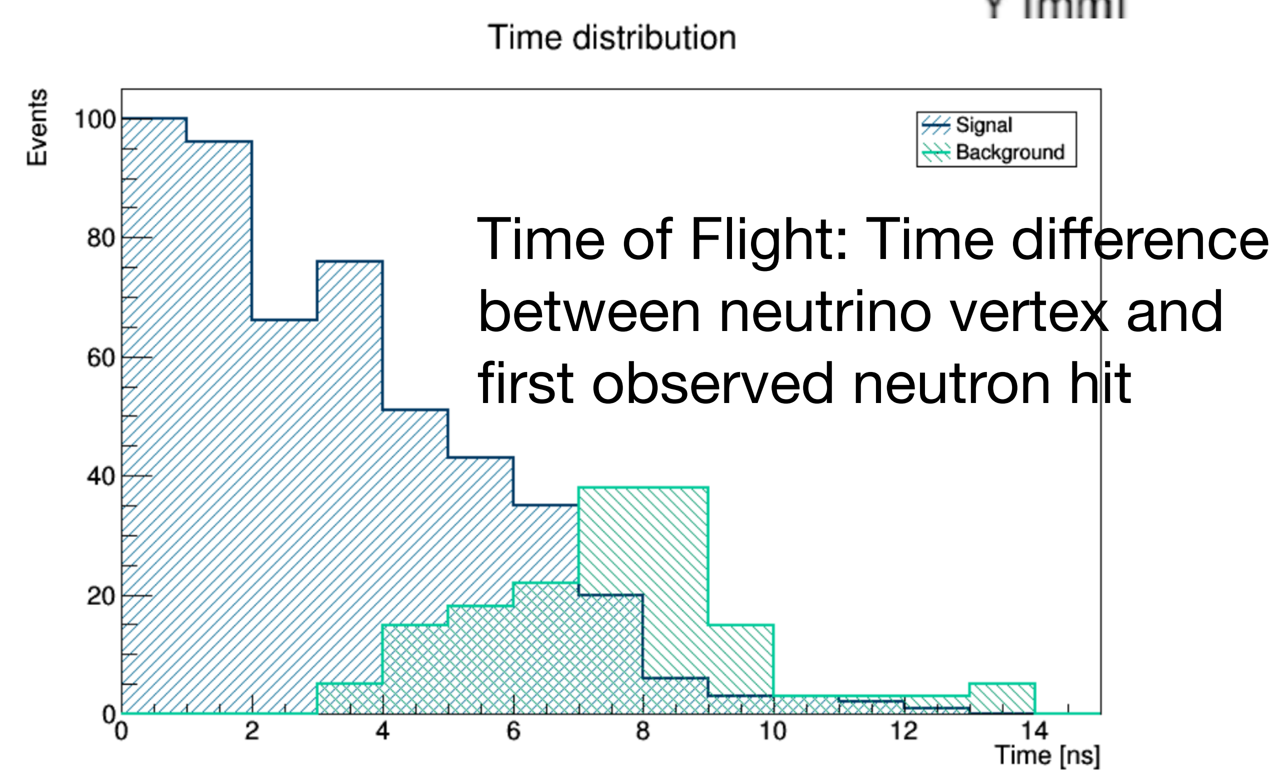
- The Fermilab queue was very busy with other jobs for more than a week
- Implemented the de-scoped configuration “by symmetry”, i.e. consider only bkg produced on the X, Y, Z side as 3DST de-scoped volume and multiply it by a factor x2. Now Running the full simulation

Neutron detection performance

- Simulated 10k spills (time structure recommended by Beam WG)
- Simulated neutrons produced by neutrino interactions in rock, magnet, ECAL, 0.25m thick iron upstream of 3DST
- FV cut —> inner core of 1x1x1 m^3
- Conservatively require deposited energy > 0.5 MeV per cube





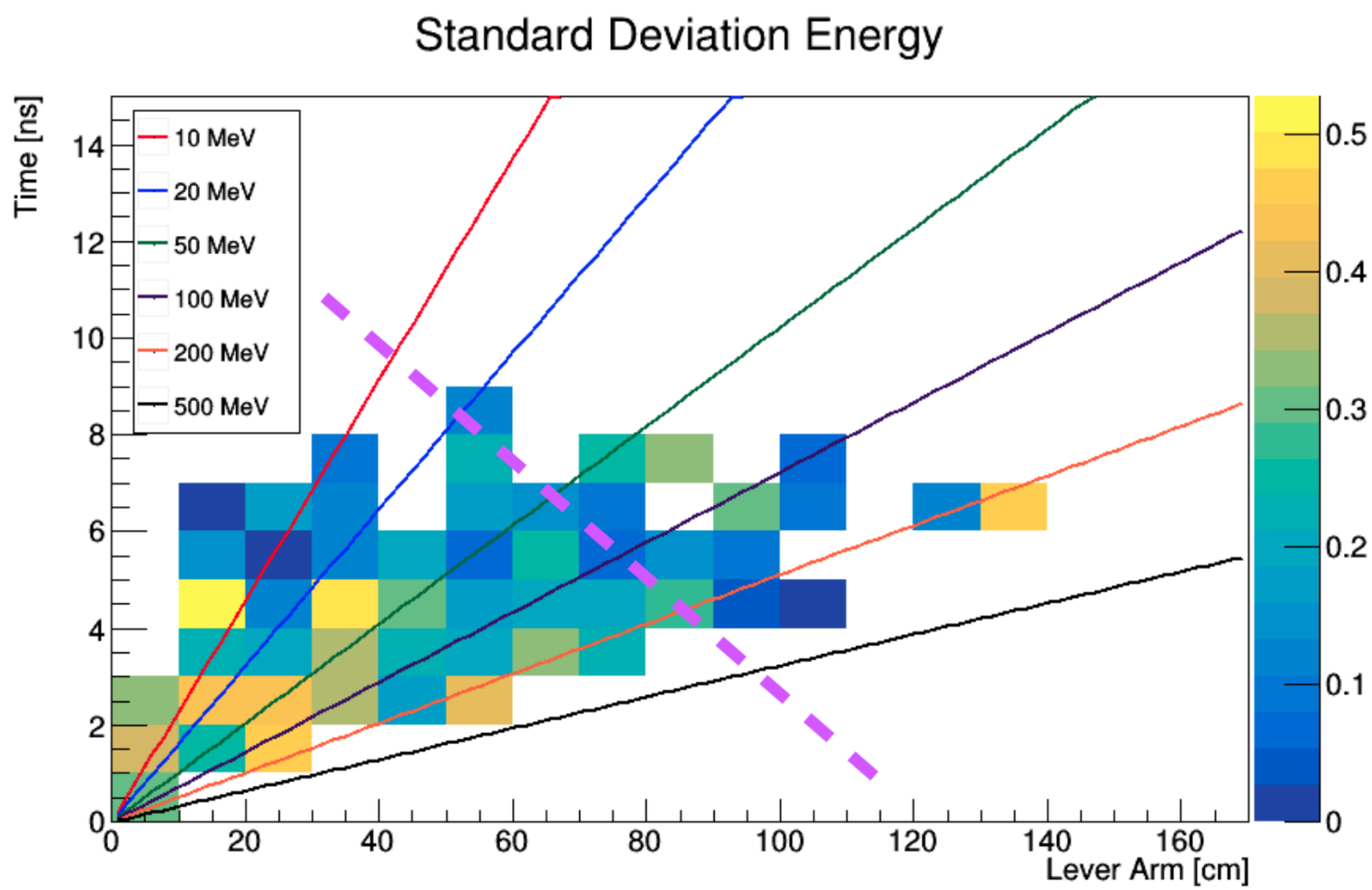


Selection of events by lever arm and the time difference allows to obtain a very pure neutron signal sample

Neutron detection performance

- The neutron kinetic energy obtained by ToF measurement
- Study performed with signal only
- The selection cut ensures an almost 100% pure sample, fundamental to obtain an unbiased and precise measurement of the neutron energy by ToF

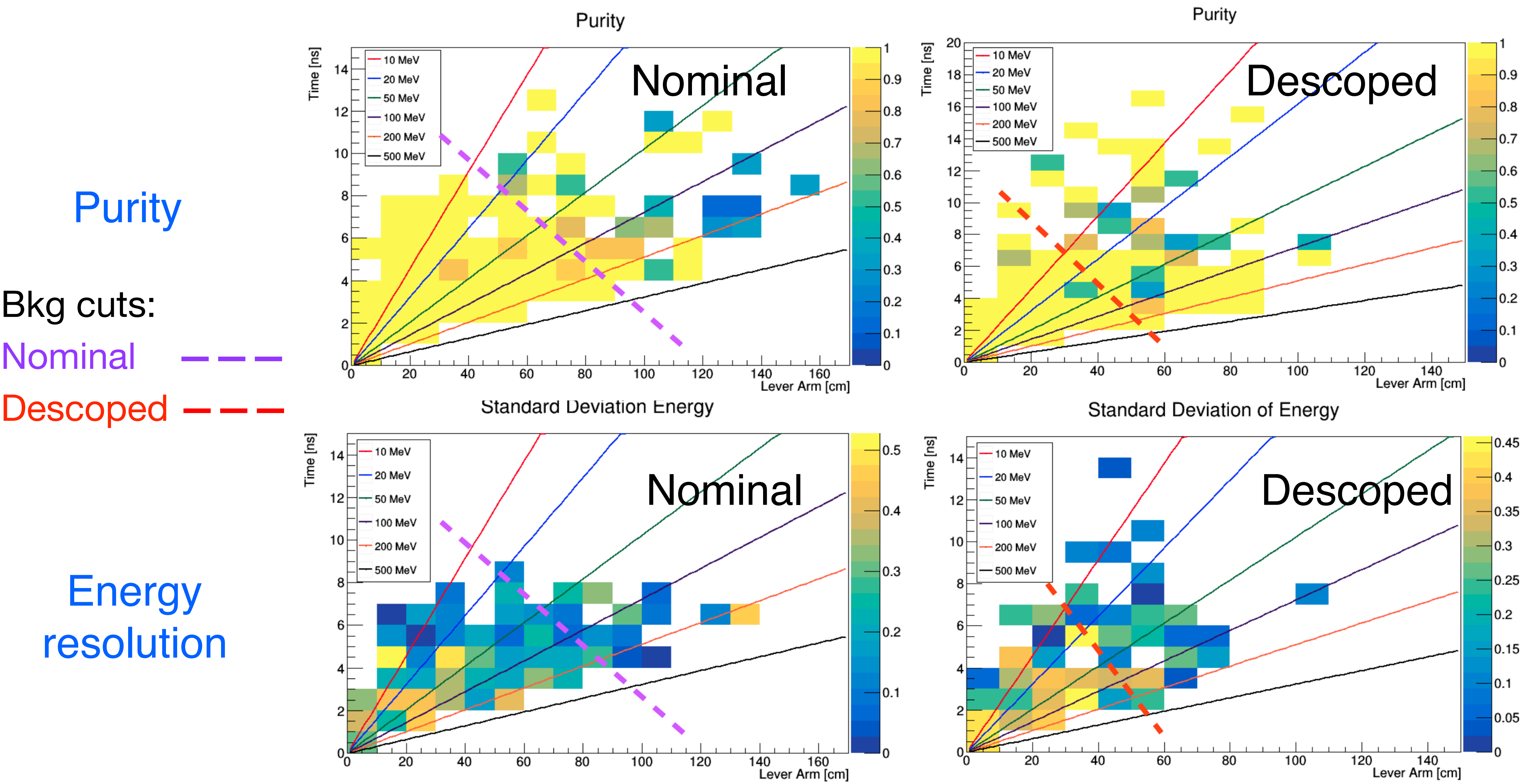
Bkg cut: – – –



- A neutron energy resolution between 10-20% is provided for a large region of the lever arm - time space

Comparison with descoped option

- Compare neutron study with descoped configuration:
  - ✦ 1x1x1 m^3 FV, 1.2x1.2x1.2 m^3 Total Volume, Out-of-FV cuts same as nominal

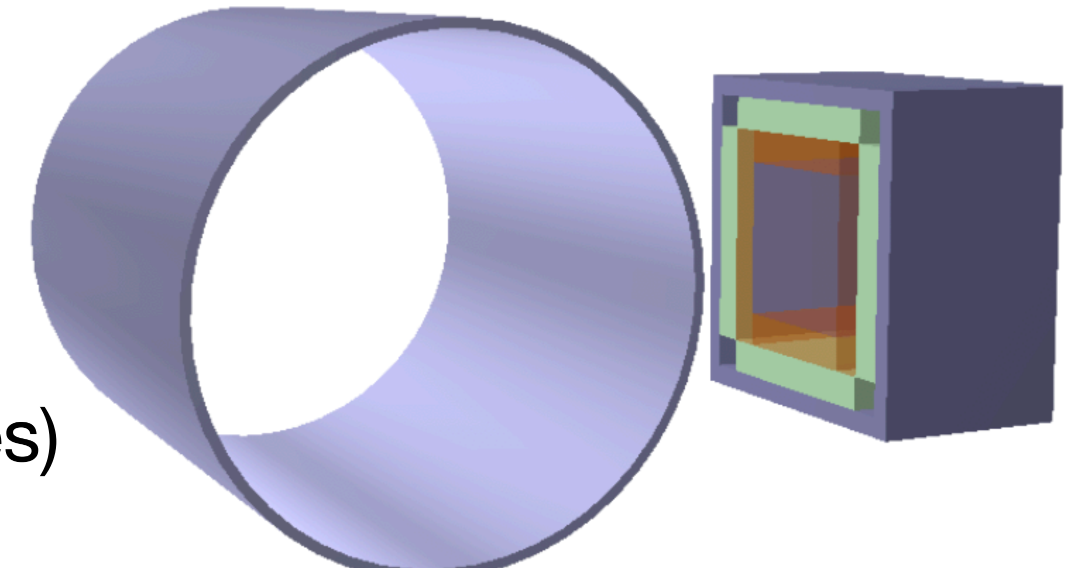


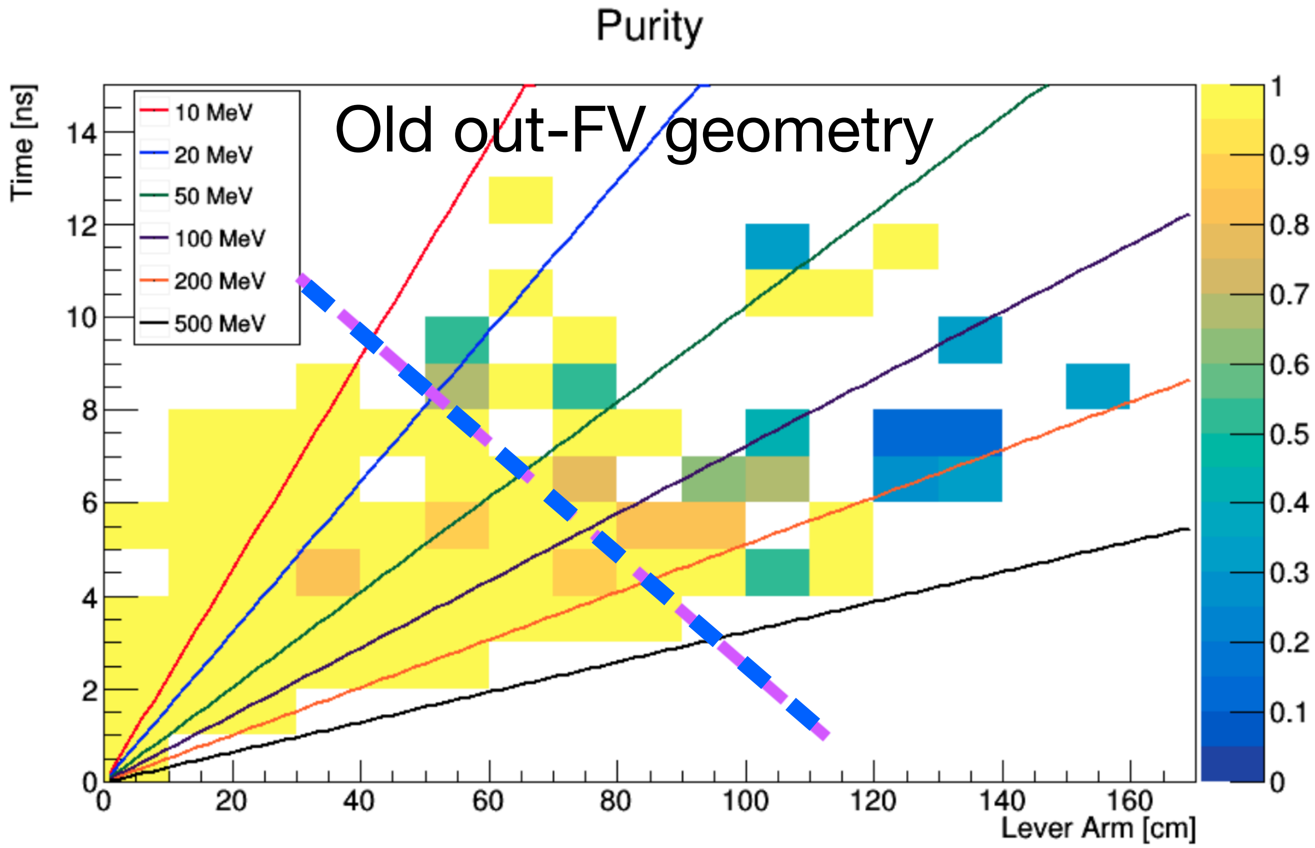
- Nominal configuration shows ~20% or better energy resolution for a large fraction of the lever arm - time. Above 30% for de-scoped configuration

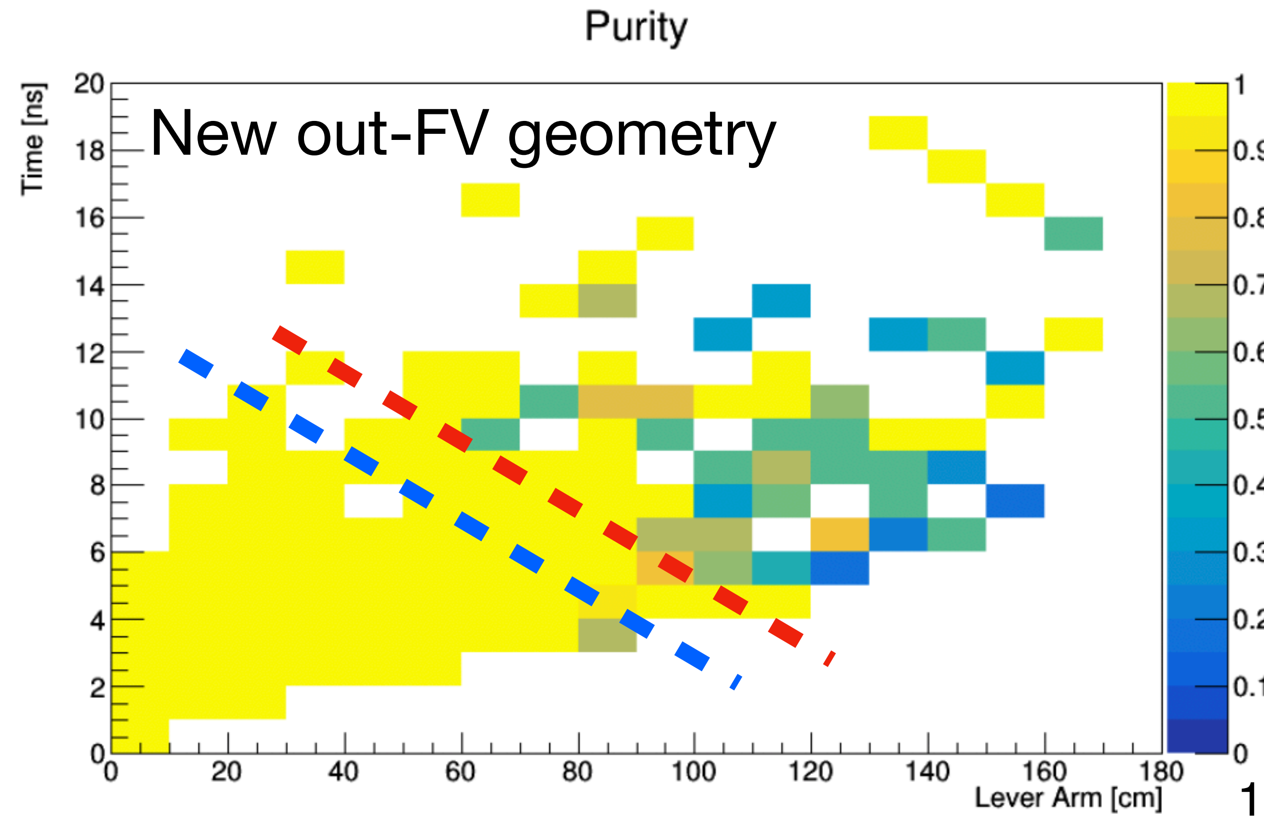
Updated out-FV geometry

NEW

- Previously the HpGasTPC magnet not implement in the simulation but faked
  - ✦ 0.25 m thick vertical layer upstream of 3DST
- Implemented a more realistic HpGasTPC magnet simulation geometry
  - ✦ 13 cm thick aluminum cylinder
  - ✦ Diameter equal to 6.5 m
  - ✦ Total mass of 75 tons
  - ✦ HPgTPC is 4 m away from 3DST (edges)

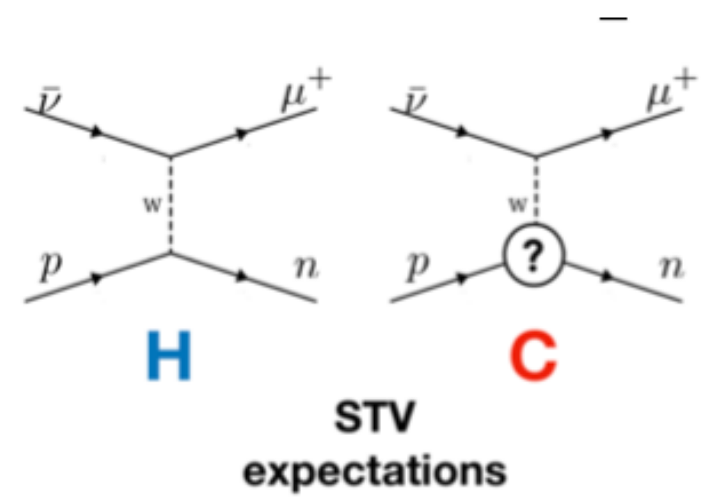


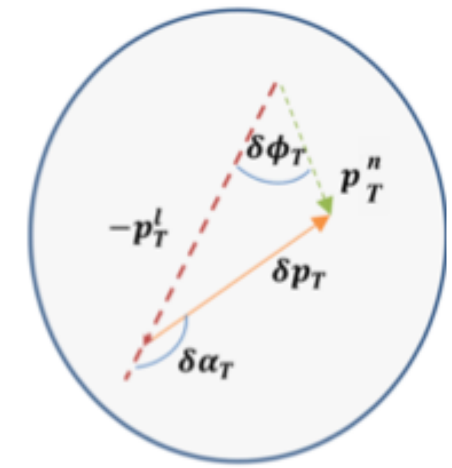




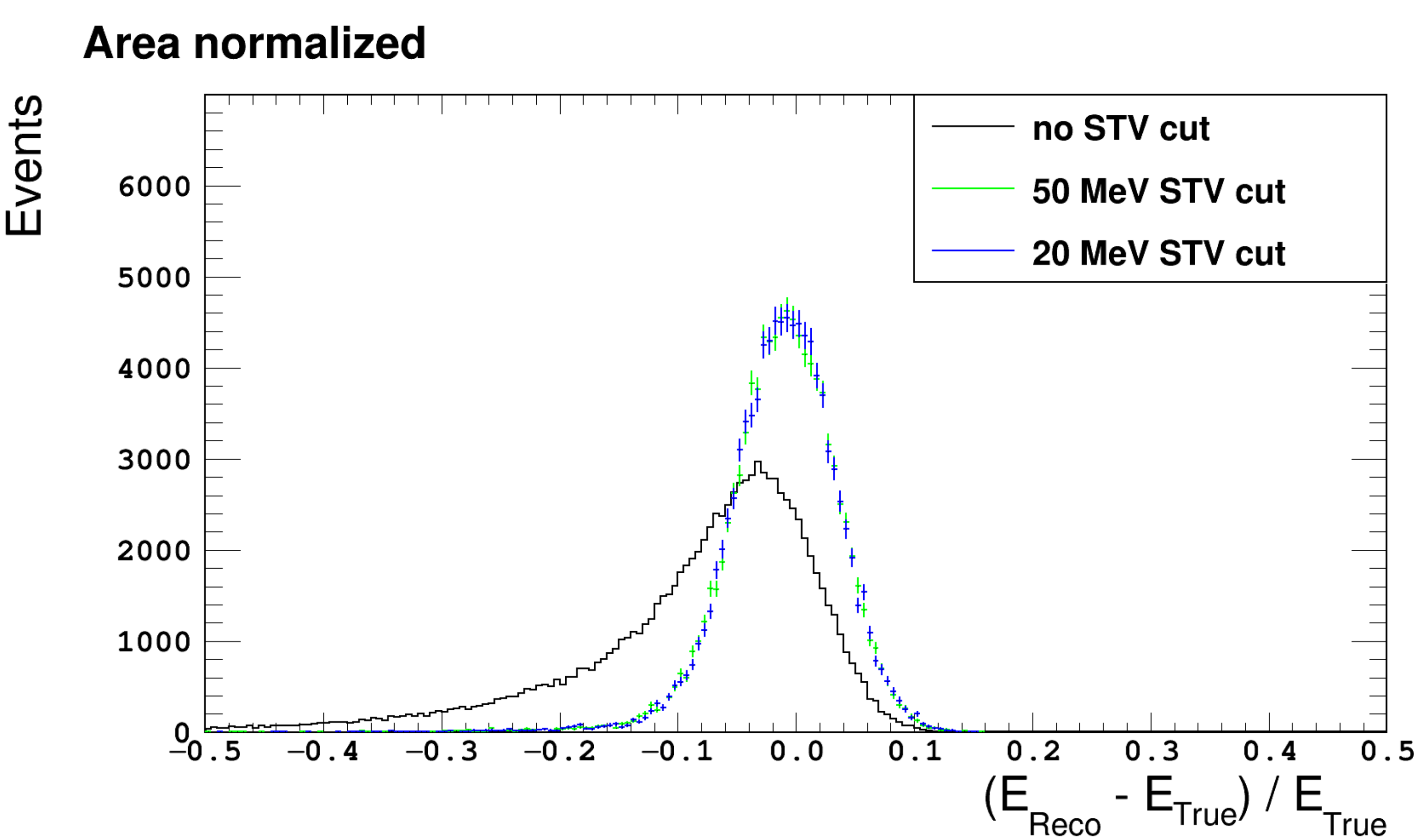
Impact of neutrons on neutrino energy resolution

- Selected signal NuBar CCQE events (~630k/year, about 30% of all events)
- Look at missing momentum in transverse plane and use the neutron momentum reconstructed by ToF (δp_T)





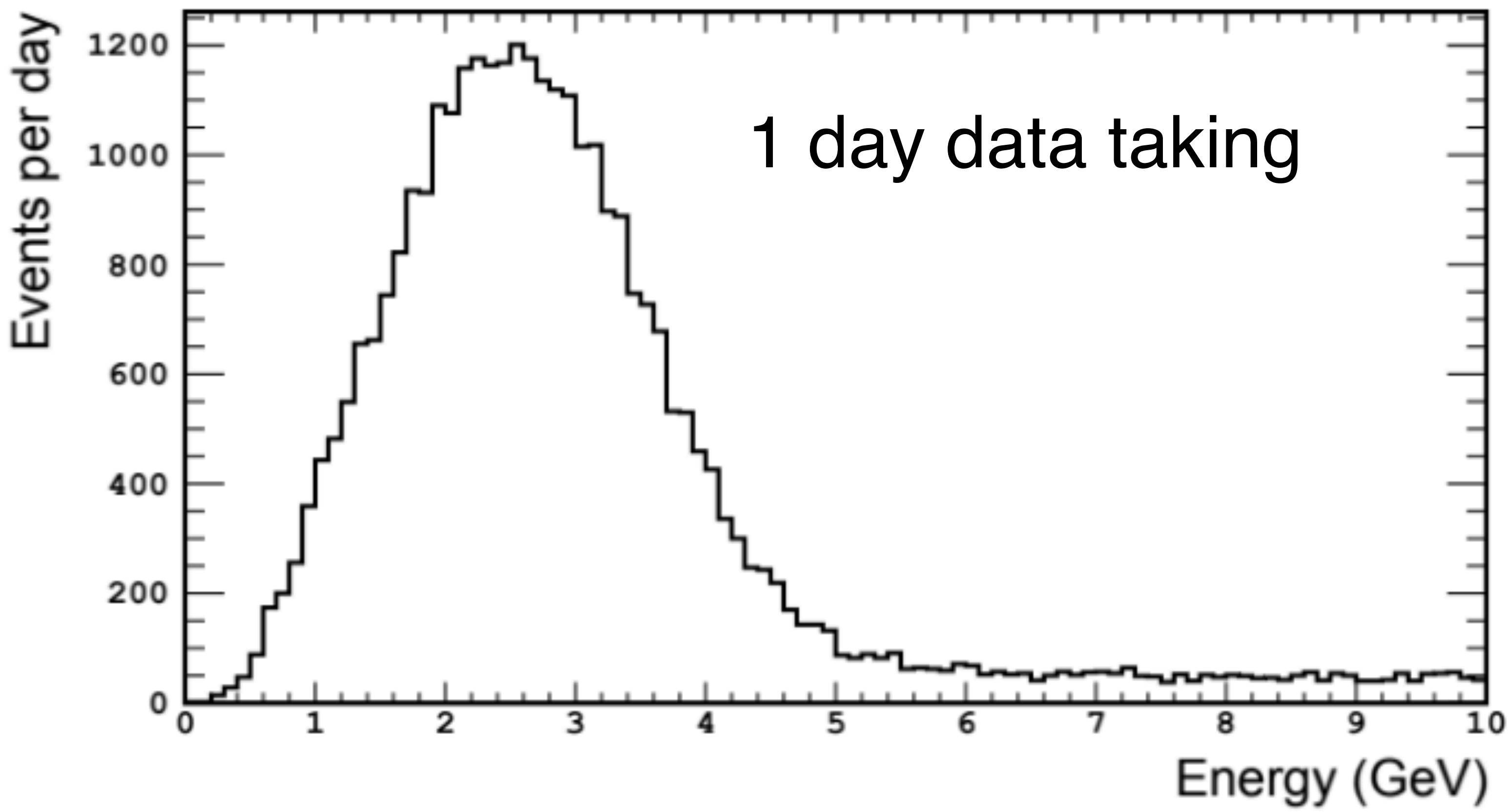
- If δp_T is small, neutrino interactions in Hydrogen or in Carbon but with low nuclear effects / FSI are selected —> cut at $\delta p_T < 20$ or 50 MeV/c



- Very good neutrino energy resolution is achieved
- Study will be extended to events with other interaction modes
- Can be used to select nuclear effect free events for flux measurement and nuclear effect enhanced events to study particular nuclear effect

Beam monitor with single 3DST module

- Study uses single 3DST module (2.4x2.4x2 m^3 volume, FM 8.7 tons)



Statistics reduced by a factor 8.7 for the de-scoped configuration (1m^3)

- Using single 3DST module, the 10 cm uncertainty on the beam center can be achieved with a weekly data taking
- Better than 3% statistical error in each 100 MeV energy bin around the peak per day
- If ECAL is designed to have capability to detect the event vertex, it can be used as part of the beam monitor system. In such case it would increase the statistics by nearly a factor of 3 (by mass)
- Current plan: optimize the # of off-axis modules required to achieve the goals

Comments on the de-scoped configuration

- Another de-scoped configuration was also considered:
  - ✦ Fiducial Volume: 1x1x1 m^3
  - ✦ Without TPCs, ECAL and magnet
  - ✦ Forward spectrometer only downstream of 3DST
- Neutron bkg would increase, depending on the distance between rock and 3DST FV and alcove size to be optimized
- Expected event rate will decrease because
  - ✦ FV is smaller by a factor 8.7 ($1m^3$)
  - ✦ Only mostly forward particles would be measured. Only a region of the phase space would be measured with an impact on the robustness of the neutrino interaction model

Comments on the de-scoped configuration

- Containment of particles (hadron and e.m. showers) would be compromised
- Hard to obtain a reconstruction on event-by-event basis. This will greatly diminish the usefulness of precisely measure the neutrons
- Also not possible to measure the momentum balance for each single event preventing from inferring the NuBar energy reconstruction
- Beam / spectrum monitor would be affected by all the reasons explained above
- In summary the de-scoped configurations would not allow to perform all the precise measurements foreseen with the nominal configuration

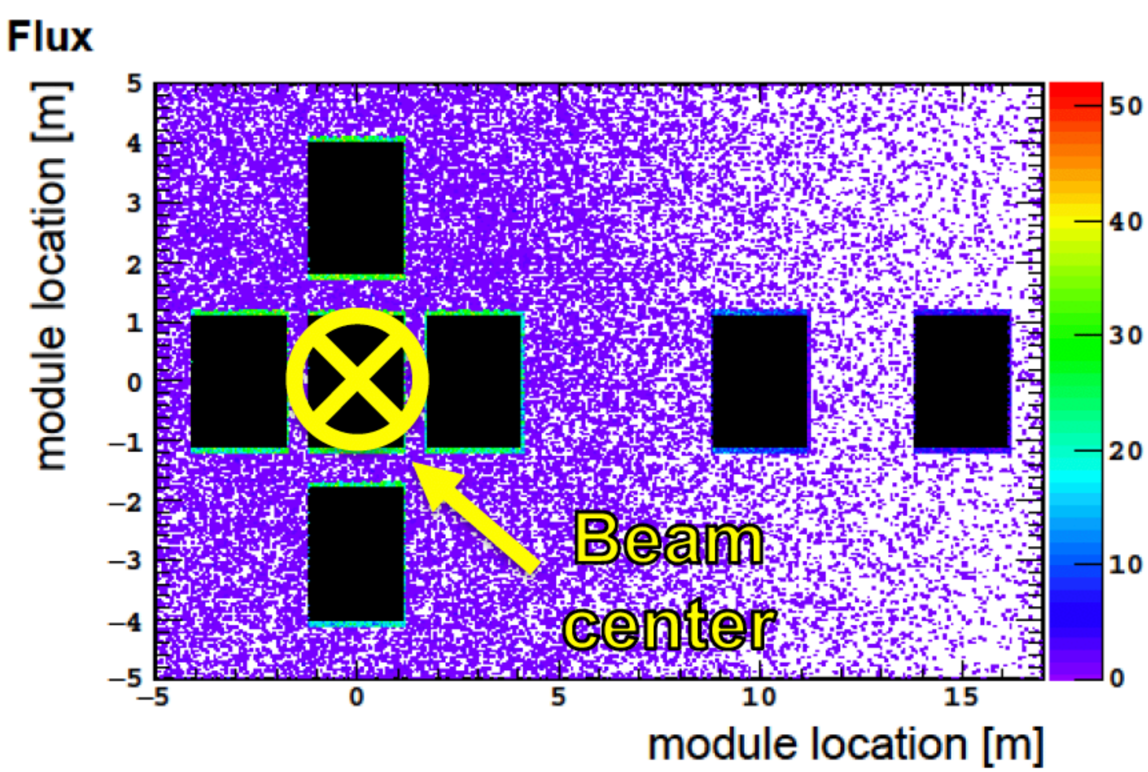
Plans toward the next LBNC meeting

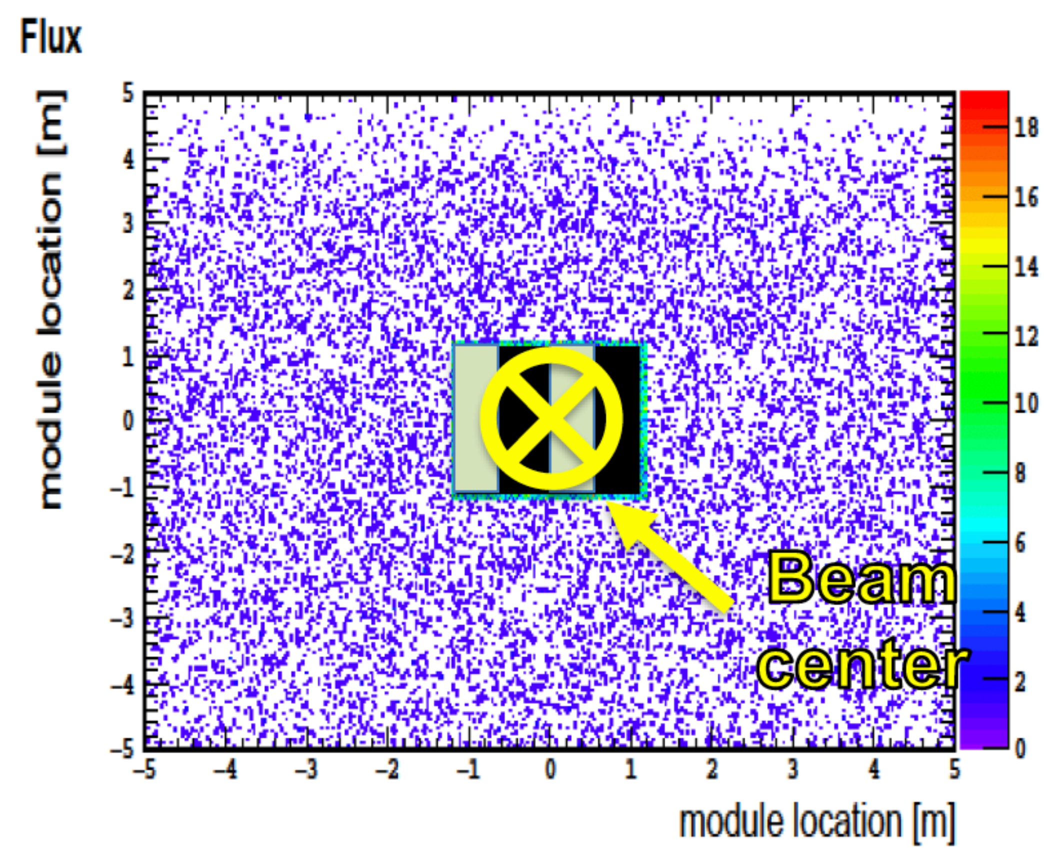
- Perform de-scoped neutron study with full simulation
- Keep improving the detector geometry, e.g. out-FV geometry of HpGasTPC, magnet, etc for neutron measurements
- Optimize the number of off-axis modules for beam monitoring
- Impact of 3DST to CP violation with sensitivity studies
- Mechanical design of the 3DST-S (Bob Flight, U.Rochester)
- Development of full event reconstruction in synergy with T2K-ND280 SuperFGD working group

BACKUP

Beam monitoring using 3DST detector

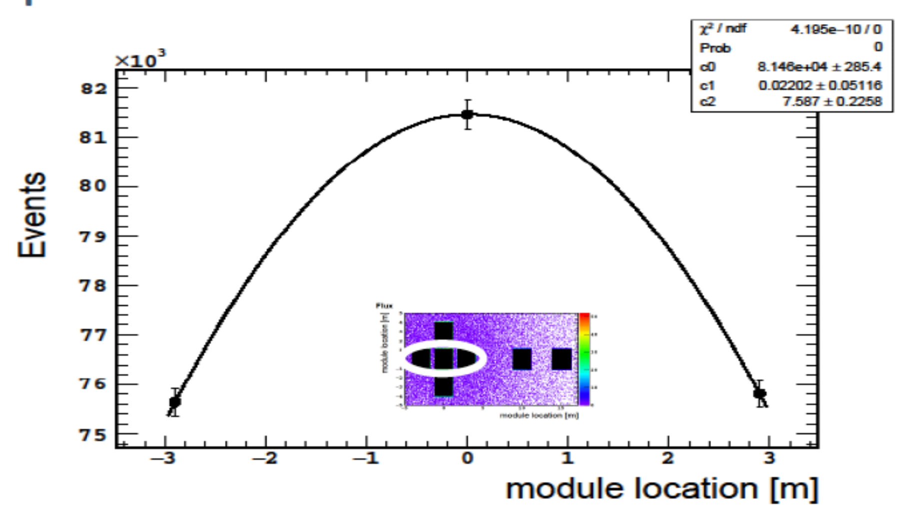
- Using the 3DST detector, we did preliminary studies in measurement of beam shape and beam center and its uncertainty.
- We tested two different geometries. One with 5 3DST modules in center plus 2 off beam axis, and other one single module on beam axis
- Both geometries were exposed ~2 days to the DUNE optimized beam.

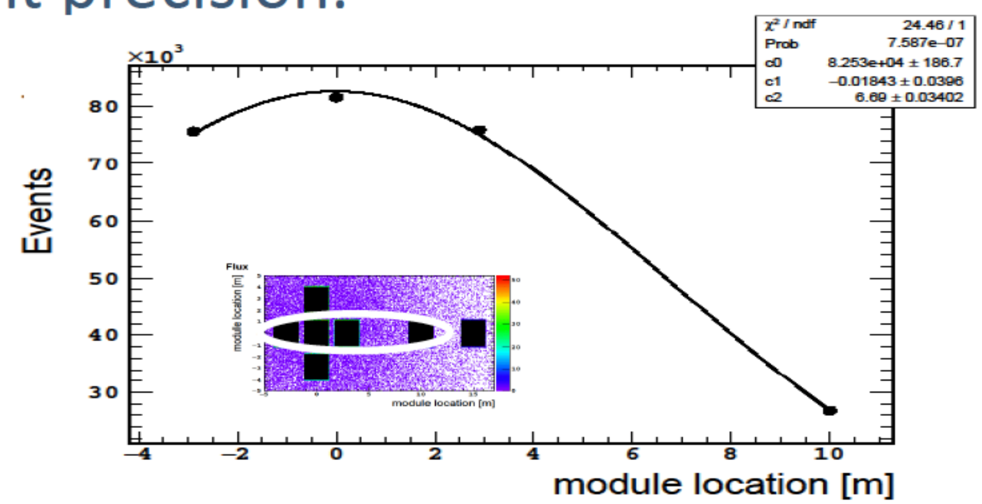


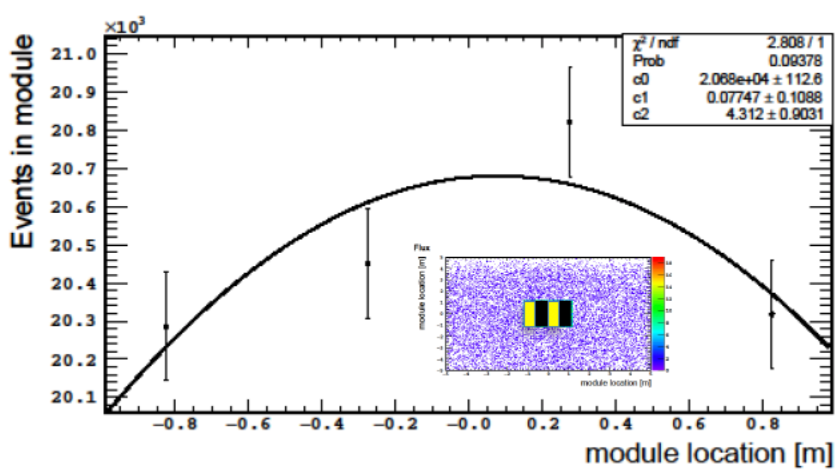


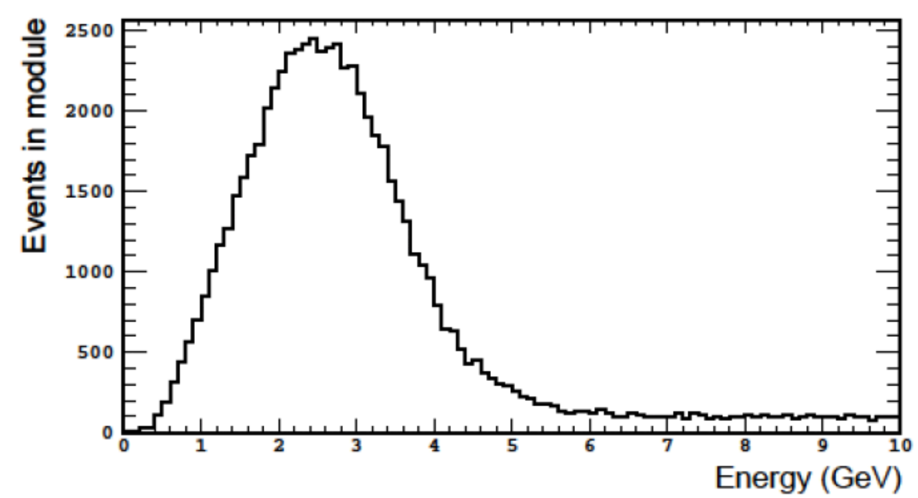
Beam monitoring using 3DST detector

- The goals of beam monitor could be done.
- Monitoring the neutrino energy spectrum could be done.
- Optimization of number of modules to achieve the DUNE goals is ongoing.
- 3DST detector exposed ~2 days to the DUNE optimized beam.
- Studies were done only consider detectors in X direction, Y direction expected to have similar measurement precision.



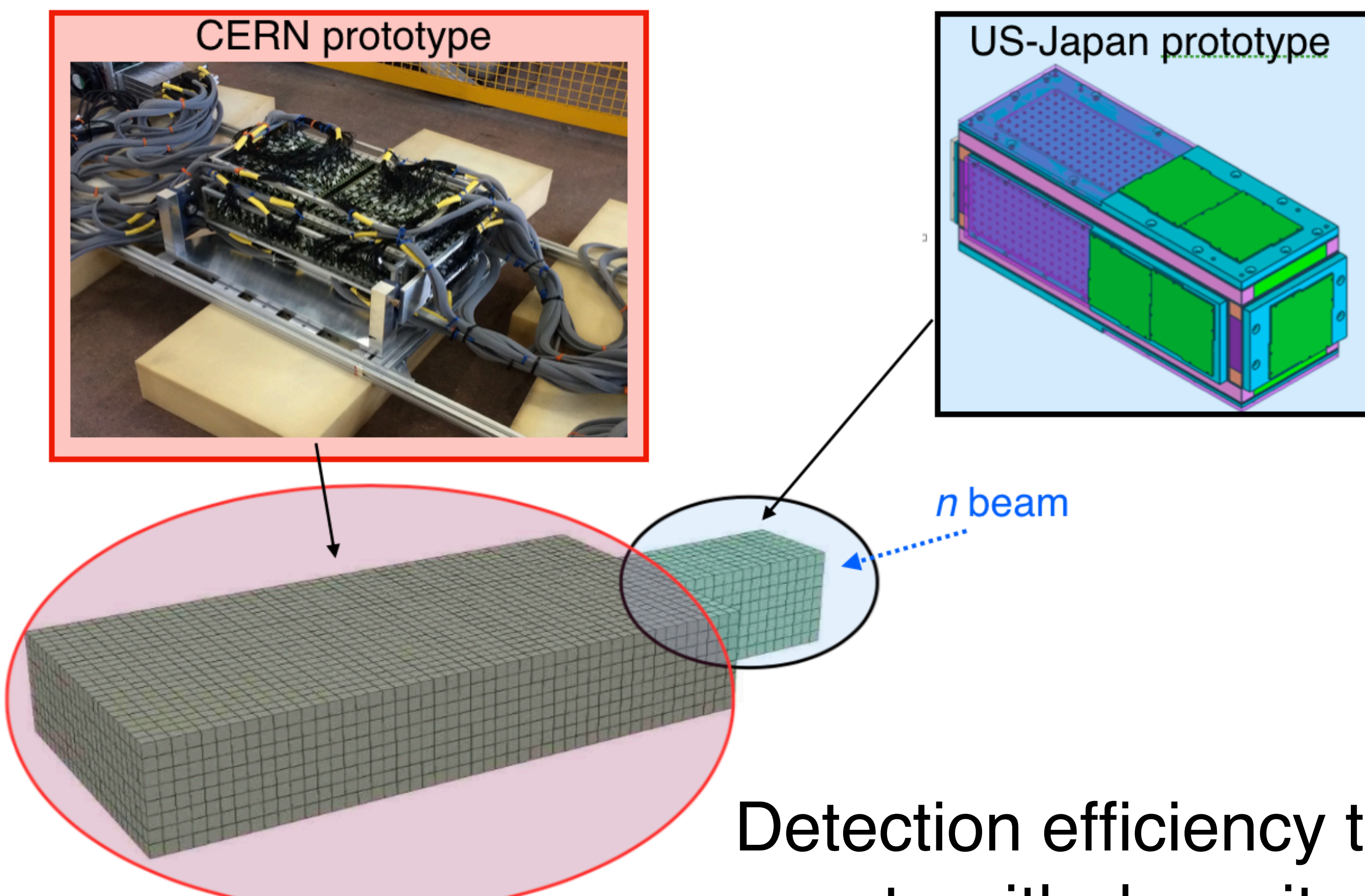




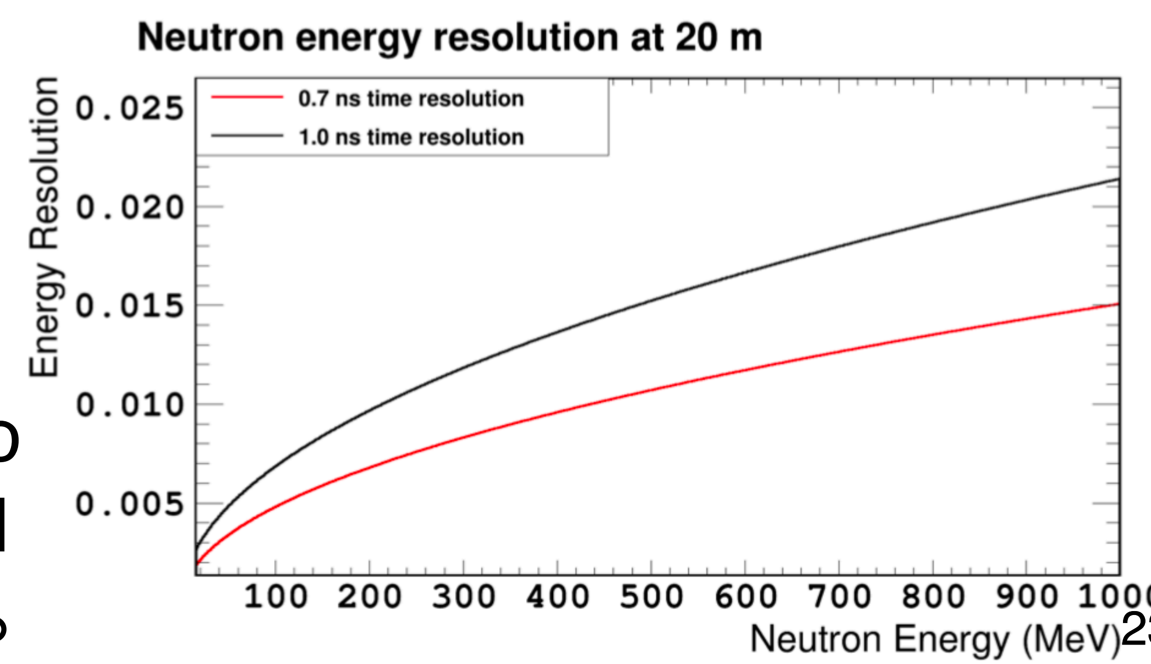


Future plans for test beams

- Submitted a proposal to LANCE for neutron beam test this year
- Collaboration of 11 institutes from Europe, Japan and US
- Two detectors will be installed in the beam line (~11 kg mass):
  - ✦ CERN protoype: already tested in test beams at CERN (24x8x48 cubes)
  - ✦ US-Japan: under construction. Joint US-Japan funds (8x8x32 cubes)



- Slow extraction beam line
- Neutron energy resolution better than 2% for all the range covered by DUNE
- ~350k neutrons / hour



Detection efficiency to events with deposited energy close to 100%