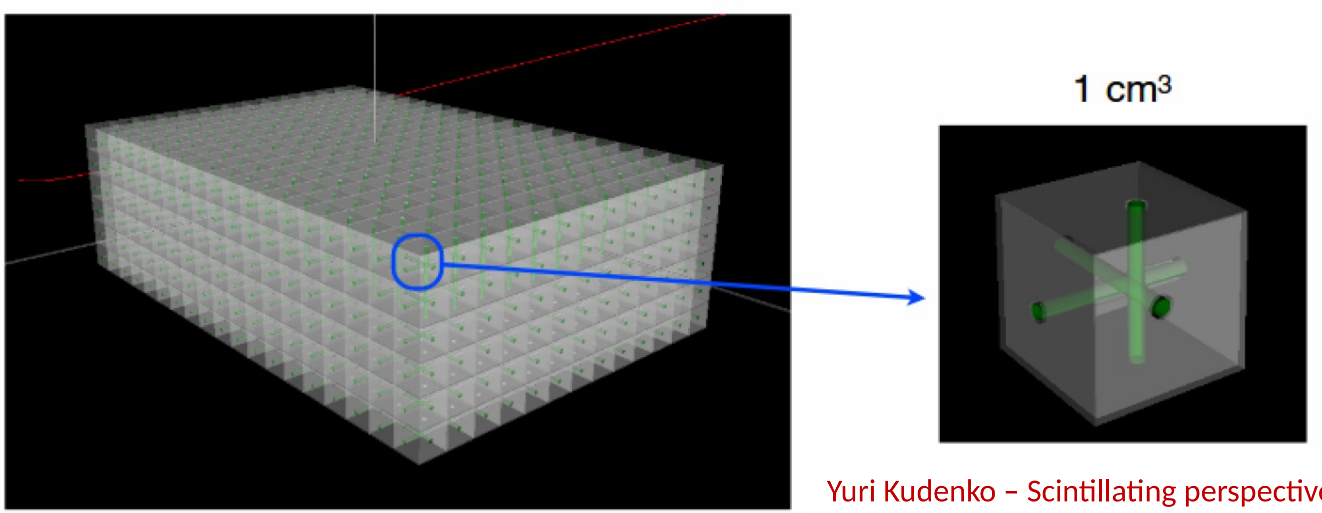
Physics Opportunities at the Near Detector$_2$

The 3DST
(3D projection Scintillator Tracker)

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



Yuri Kudenko – Scintillating perspective, 2017

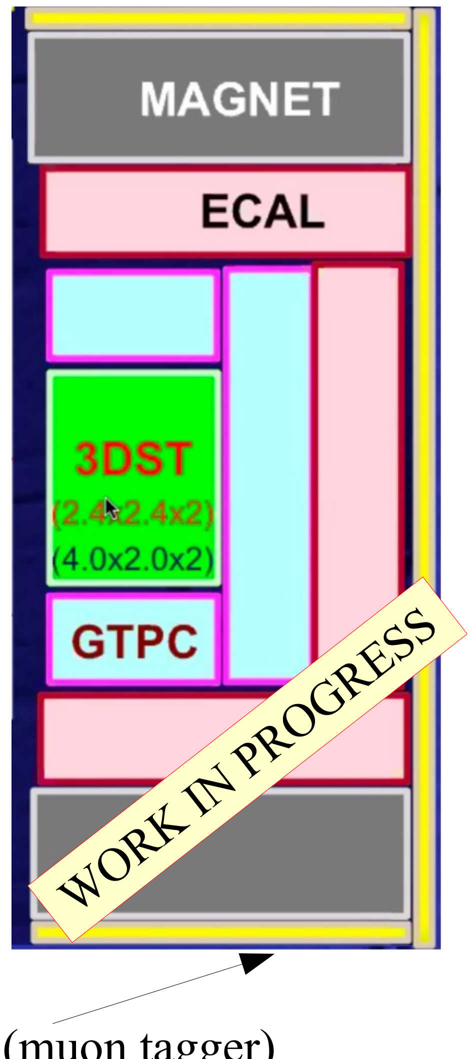
Some 3DST Goals

- 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
      - ν_μ / anti-ν_μ
    - 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

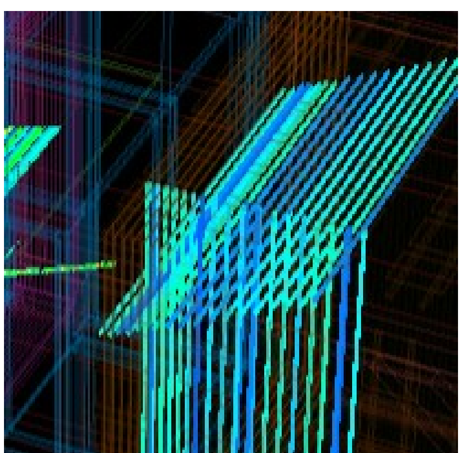
- Large Target Mass
  - Event rate for rare processes (e.g. ν-e scattering)
  - This talk mentions targets between 2.4m×2.4m×2m and 4m×2m×2m
    - Fiducial mass between 5.7t and 8.3t
- Identification of Interaction Morphologies
  - Fine-grained spatial resolution
  - Fully active target
  - Neutron tagging
- 4π 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

An example 3DST configuration (just to be specific)

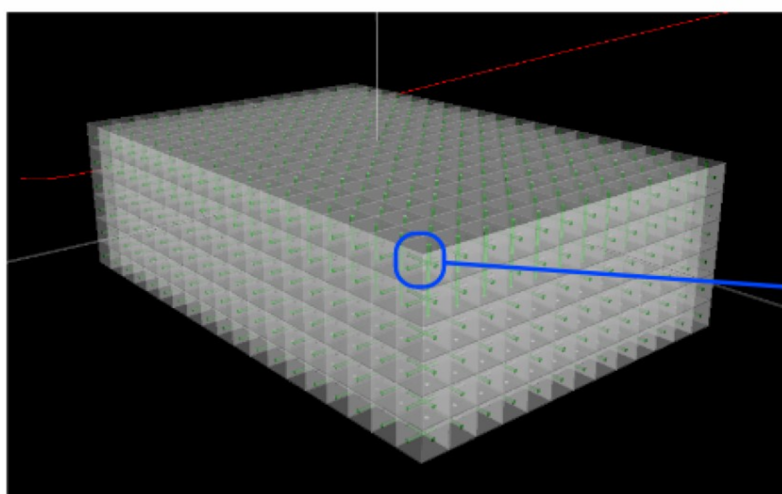


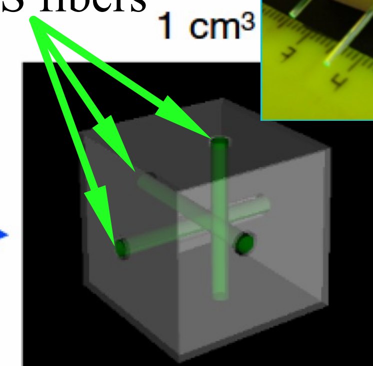
The 3DST Active Target Concept

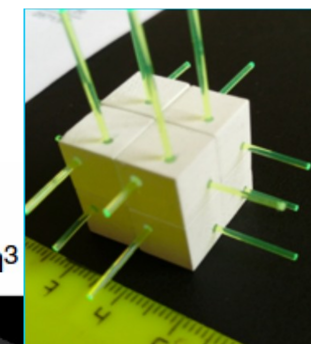
- Neutrino interactions have particles going in all directions
- A plastic scintillator active target is usually constructed with bars and has a preferred axis (poor high-angle acceptance)
- Need a 4π scintillator detector
  - Use cubes not bars
    - Spatially contain light in cubes
  - Read-out in 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)



A T2K ND280 CR Muon
Need 2 layers for 3D





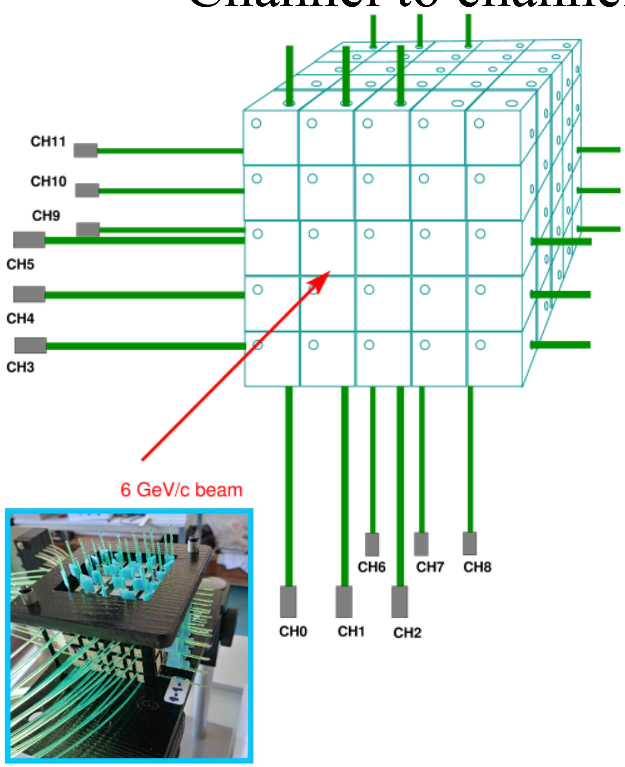


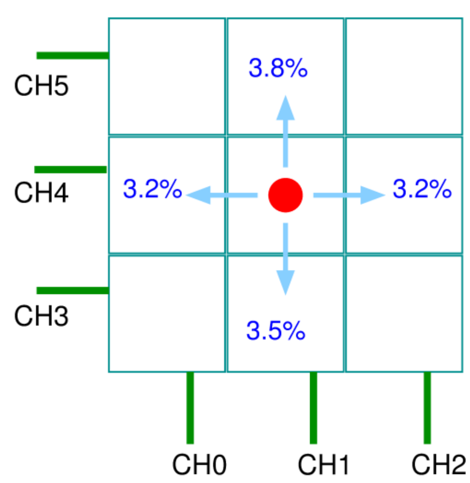
Yuri Kudenko – Scintillating perspective, 2017

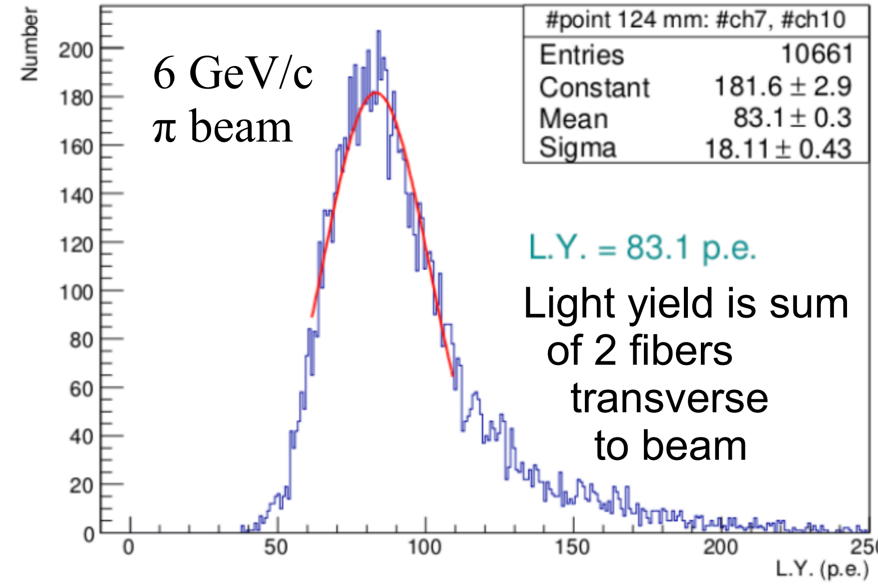
Basic Active Target Performance

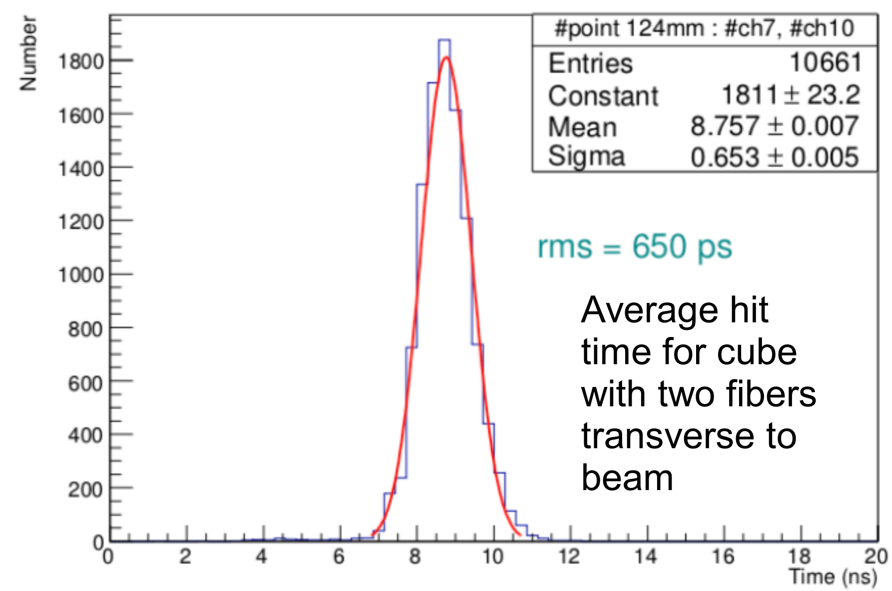
(CERN 2017 Beam Test – arXiv:1808.08829)

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







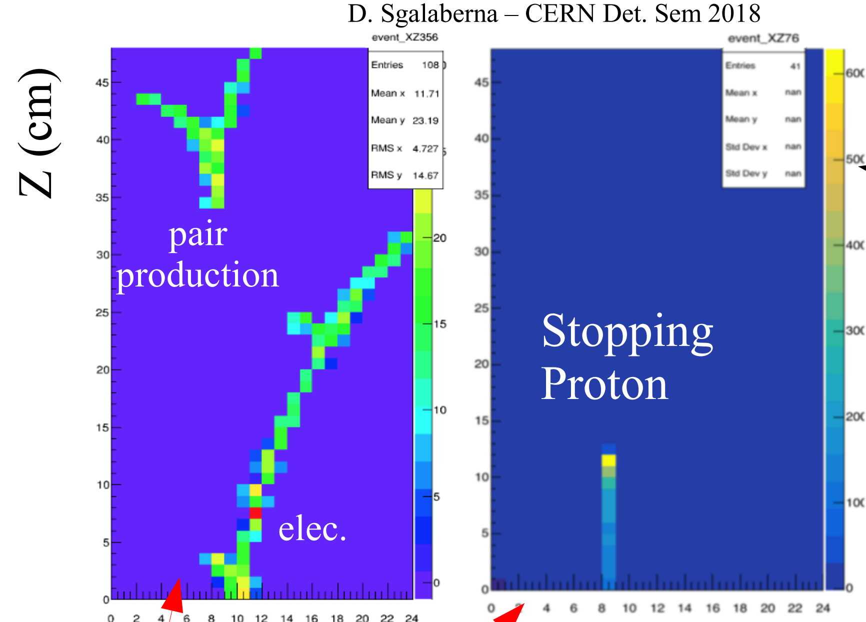


Complementarity between DUNE 3DST and T2K SuperFGD

- 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 2nd oscillation

Events from SuperFGD Beam Test

D. Sgalaberna – CERN Det. Sem 2018

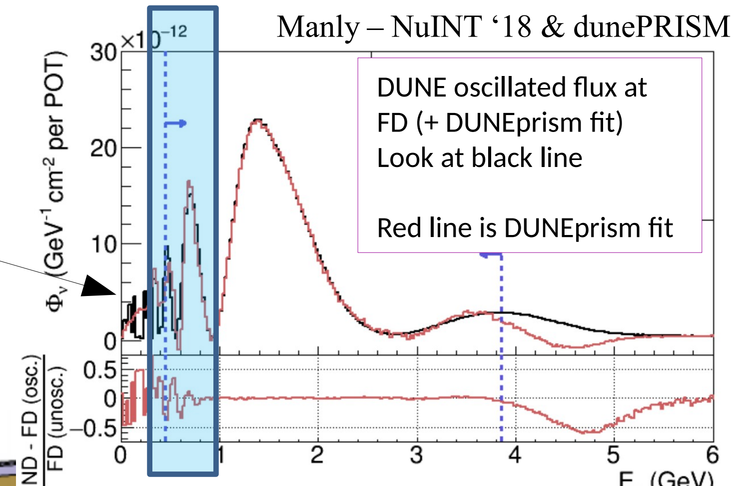


Different color scales

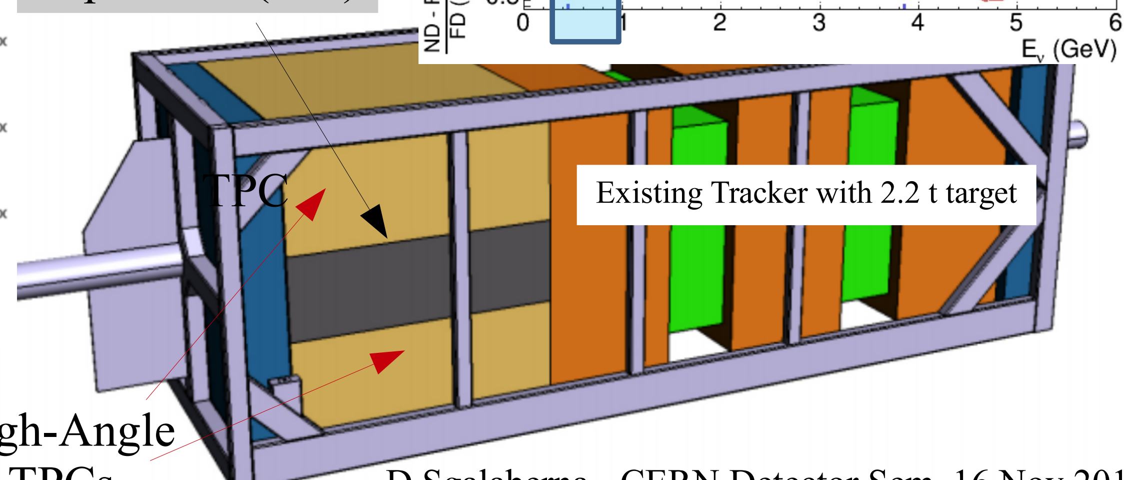
Peak Energies for T2K ND280 Flux

500 pe!

Manly – NuINT '18 & dunePRISM



SuperFGD (4.3t)

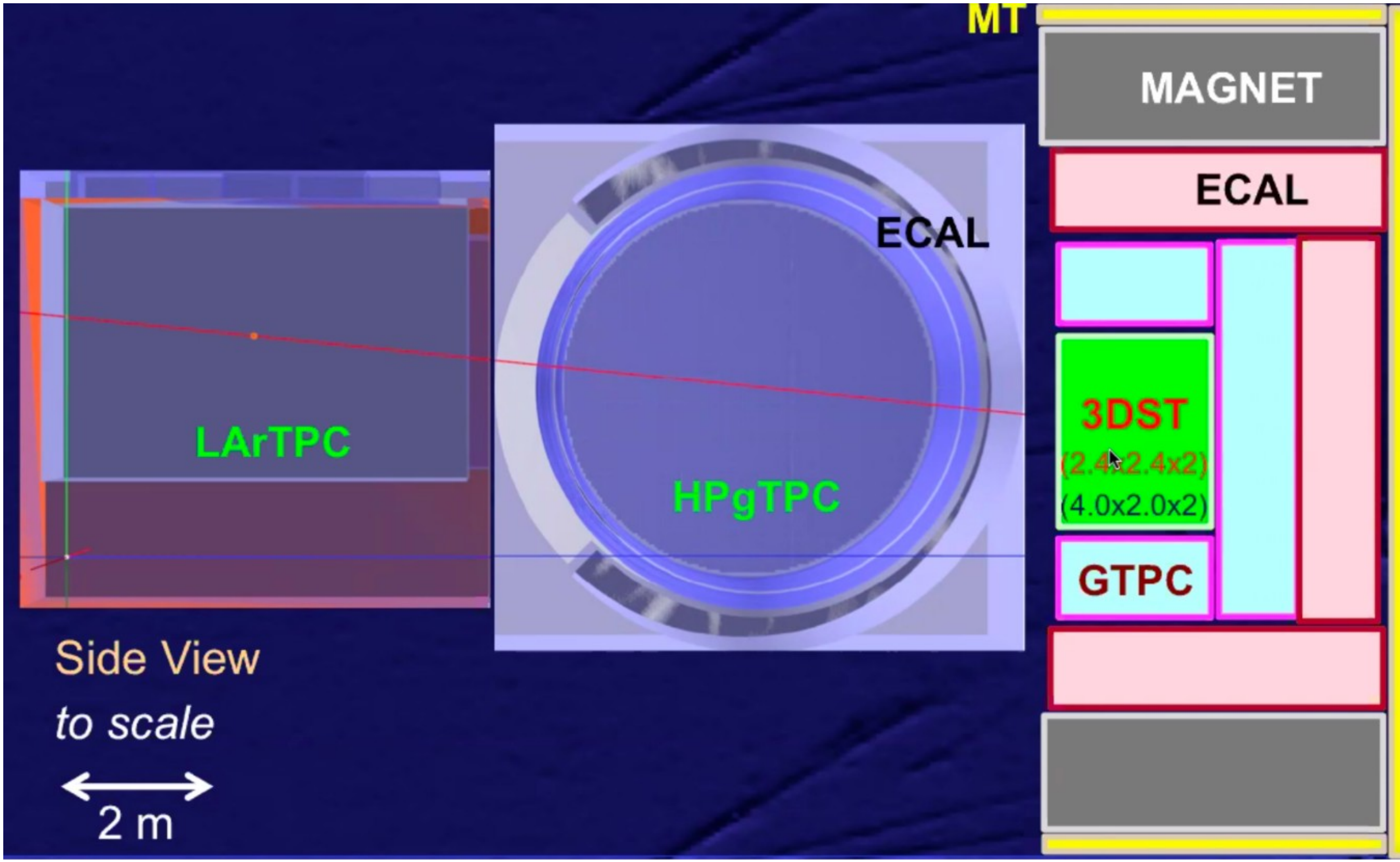


High-Angle TPCs

McGrew - PONDD

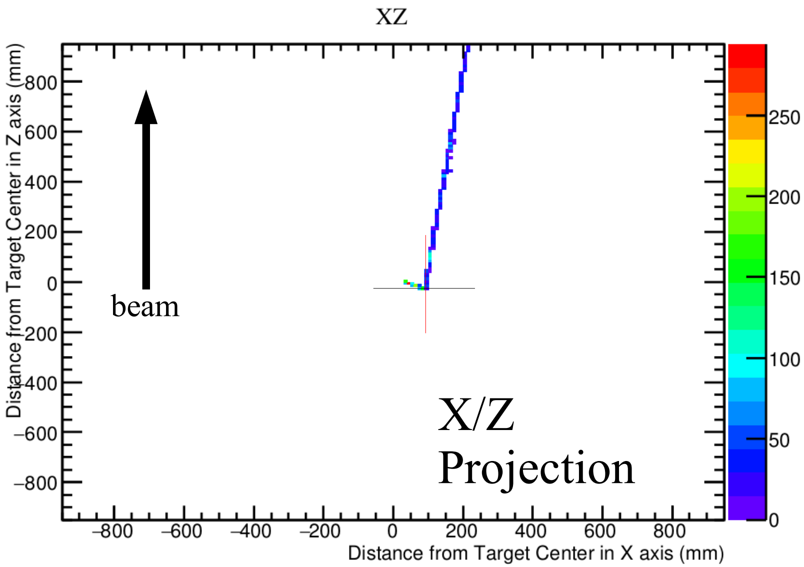
D Sgalaberna - CERN Detector Sem. 16 Nov 2018

Possible DUNE ND Configuration

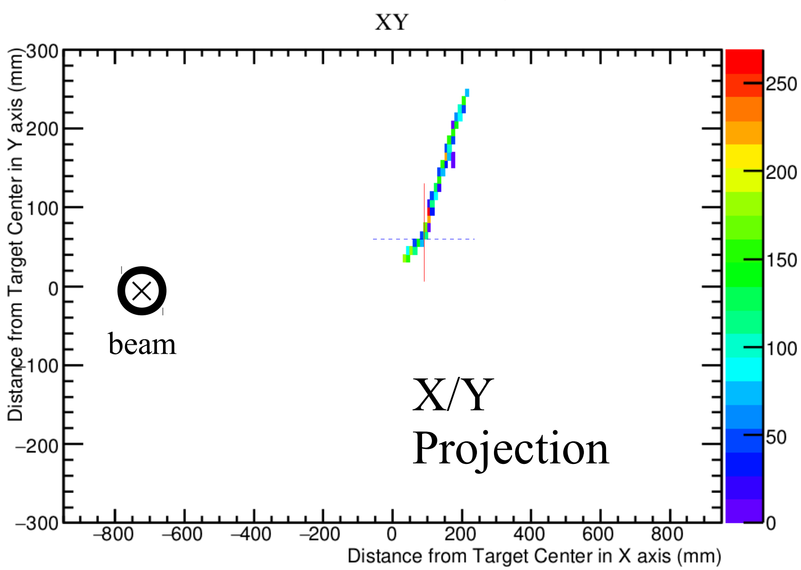


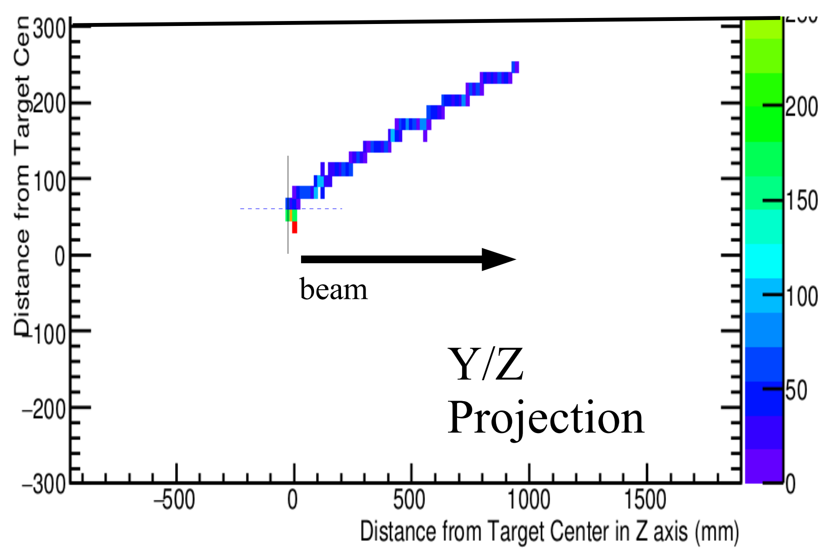
A standalone DUNE ND hybrid detector similar to T2K ND280.
This configuration is "pre-preliminary."
Configuration studies are on-going.

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





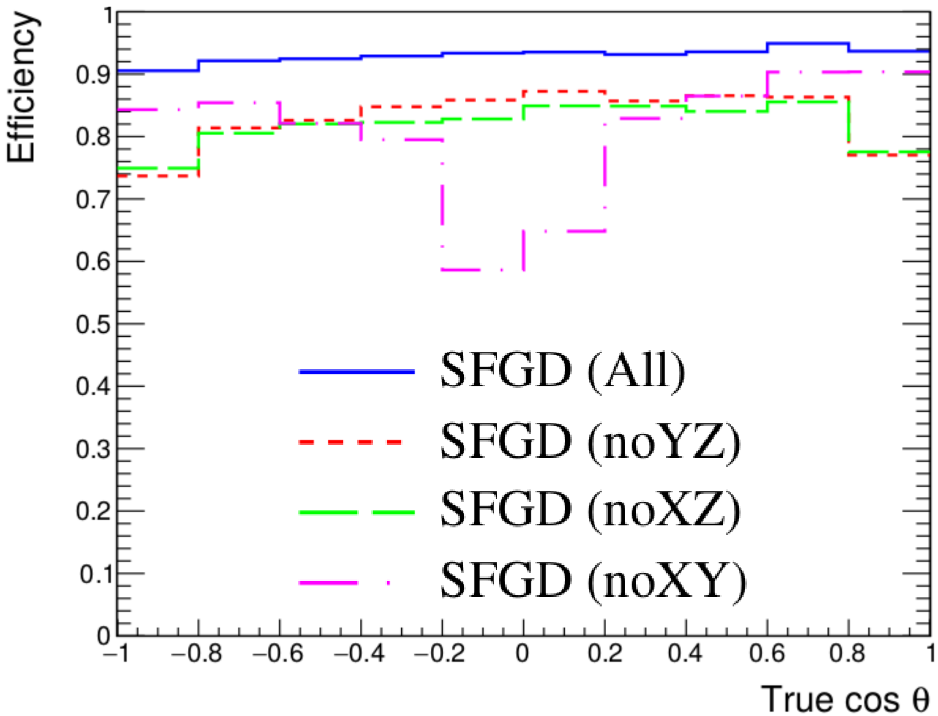
Color shows number of measured photoelectrons

(sFGD) Reconstruction Efficiency

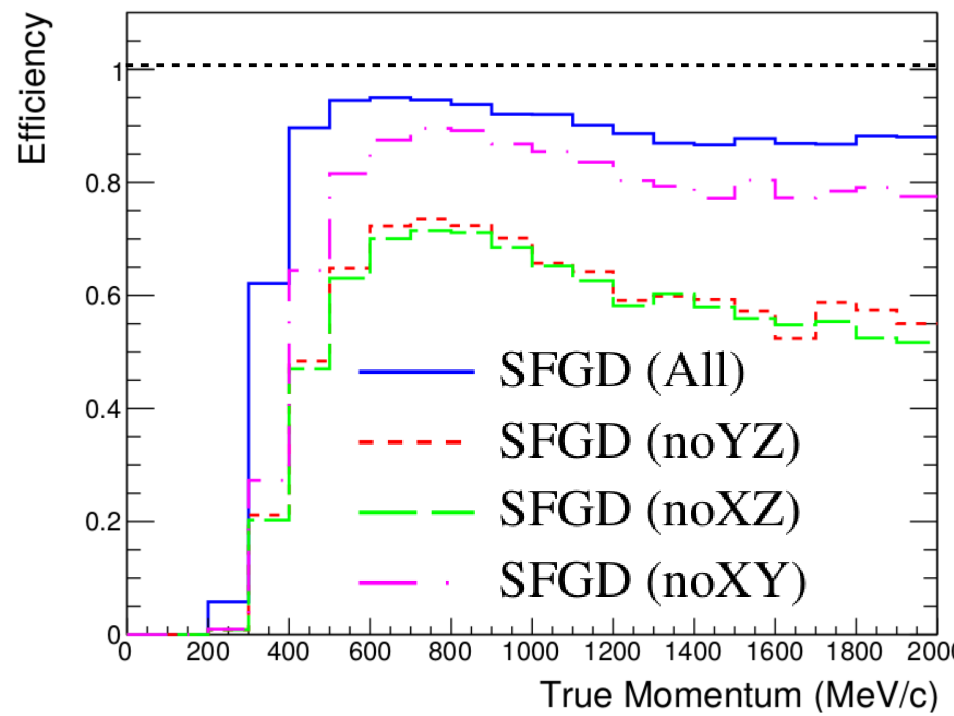
(near DUNE second oscillation maximum)

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

sFGD-only Muon Eff. vs Beam Angle



sFGD-only Proton Eff. vs Momentum



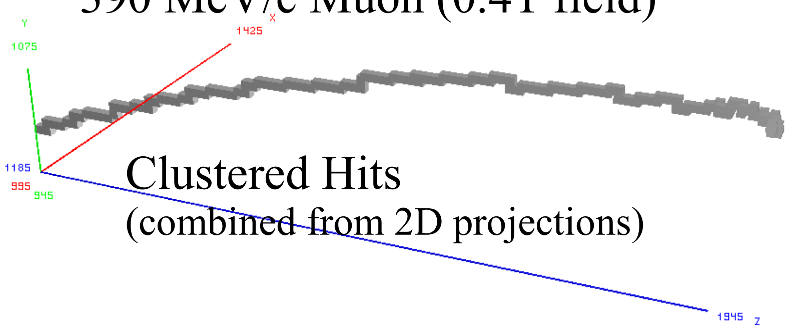
T2K ν Beam Interactions

Sgalaberna – CERN detector seminar 2018

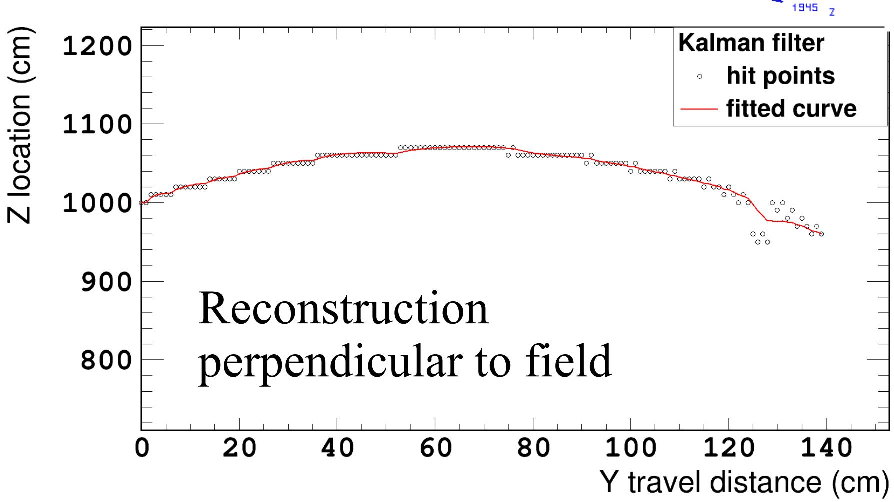
Contained Event Reconstruction

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

390 MeV/c Muon (0.4T field)



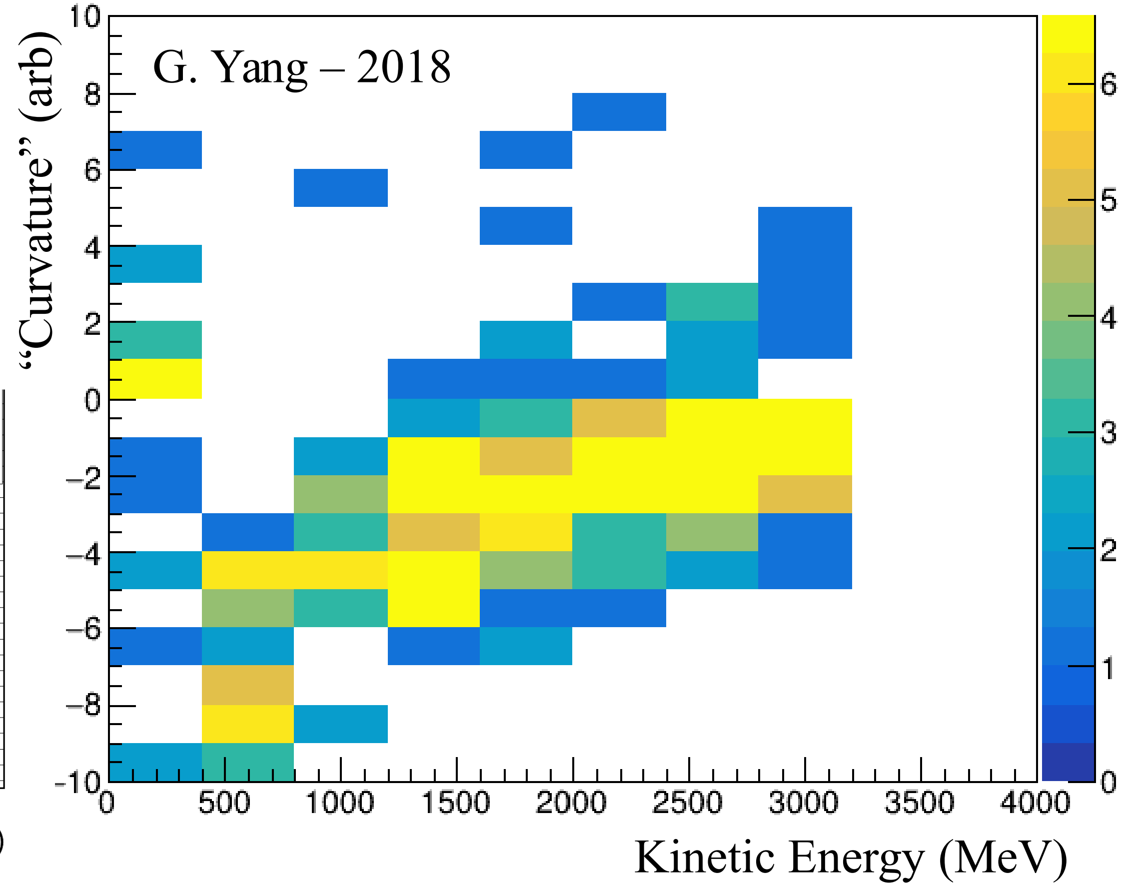
Clustered Hits
(combined from 2D projections)



Reconstruction
perpendicular to field

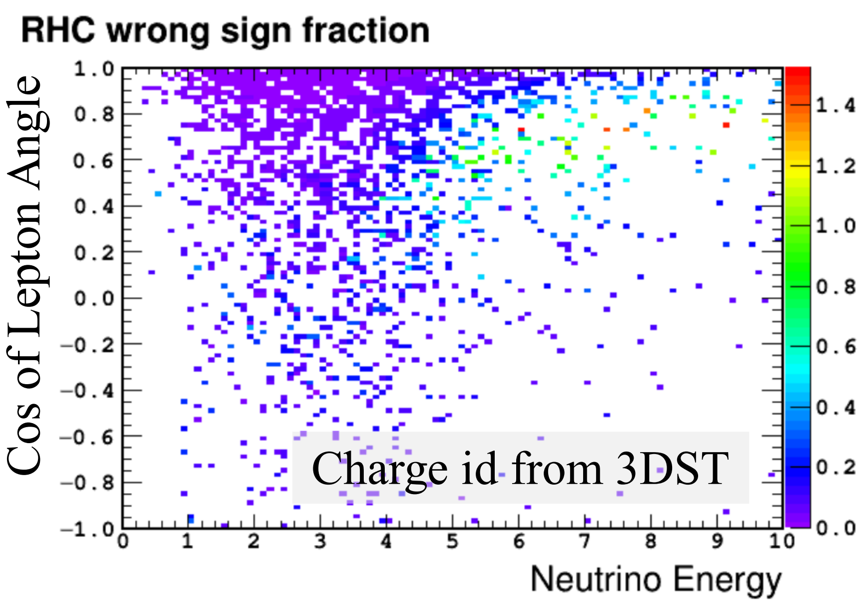
Work in Progress

Muons between 300 MeV and 3 GeV (Kinetic)



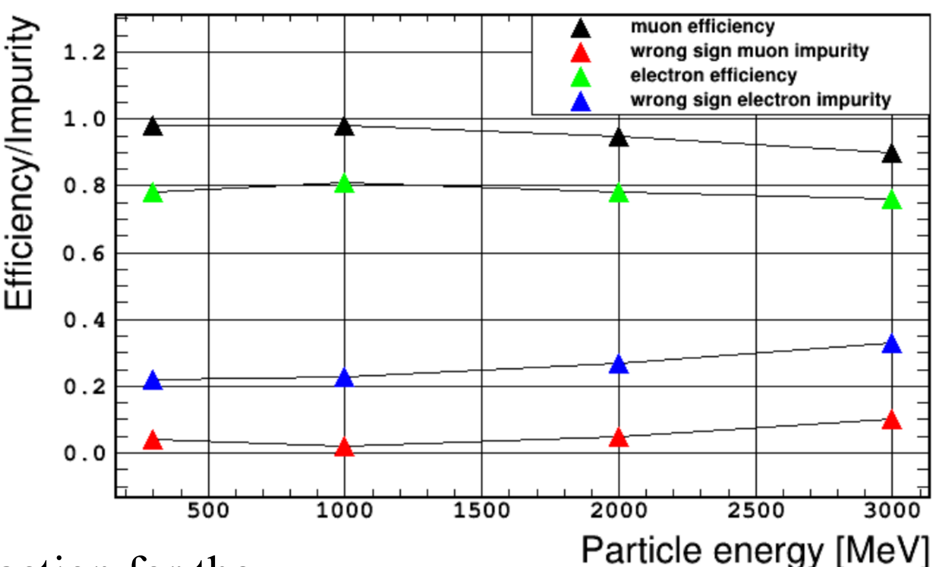
Charge Identification for Contained Particles

- 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

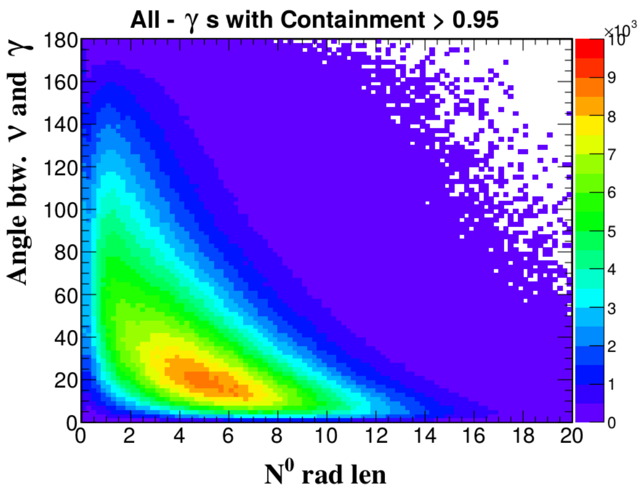
GENIE NuMI Low Energy Beam Neutrino Interactions



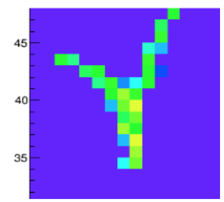
Work in Progress

Photons and π^0's

- Fully active target is well suited to measure photons (and π^0's)
  - Need to reconstruct both π^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

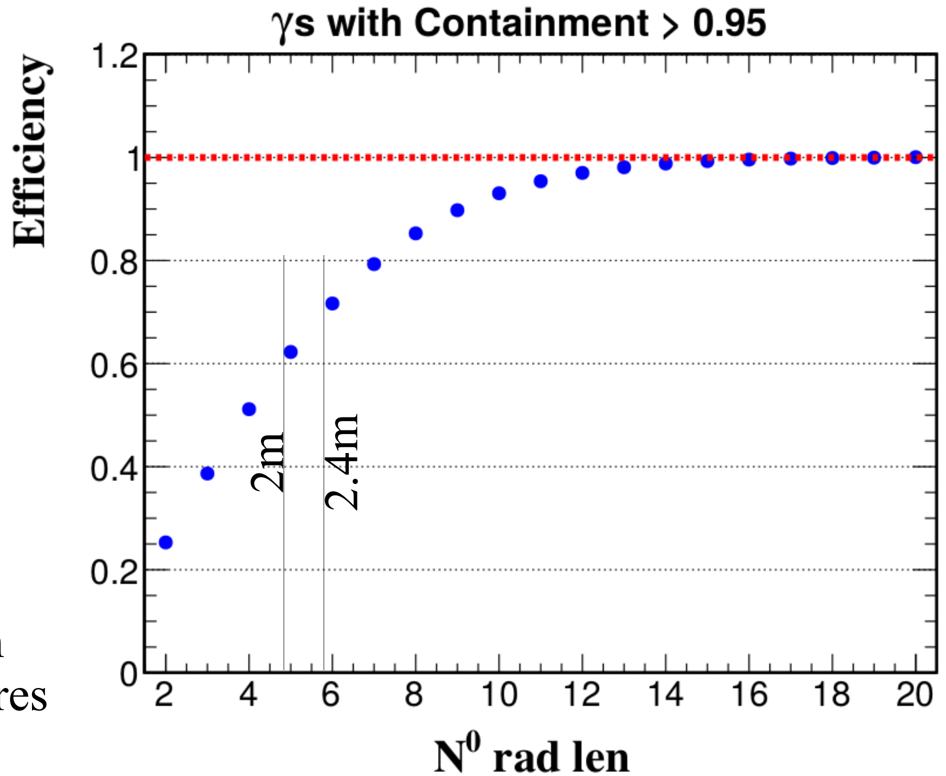


Radiation length in 3DST is ~41cm.



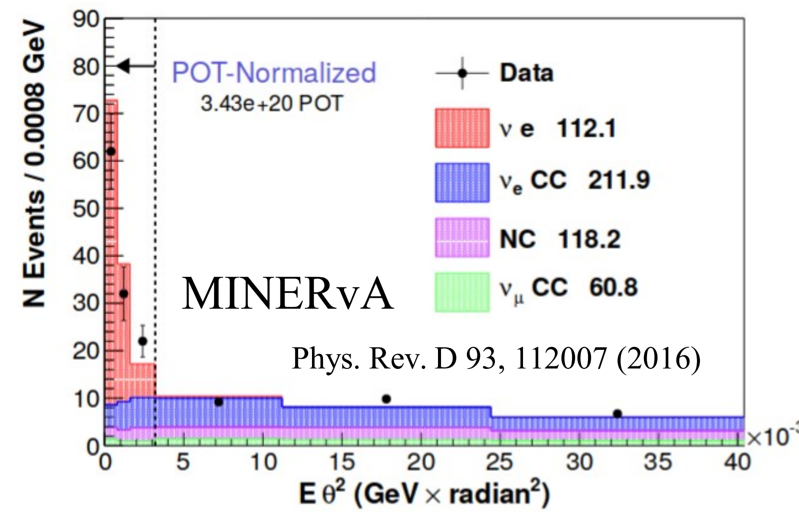
Pair Production in SuperFGD Test

A π^0 can be tagged with one γ, but π^0 reco.requires two (95% → 90%)



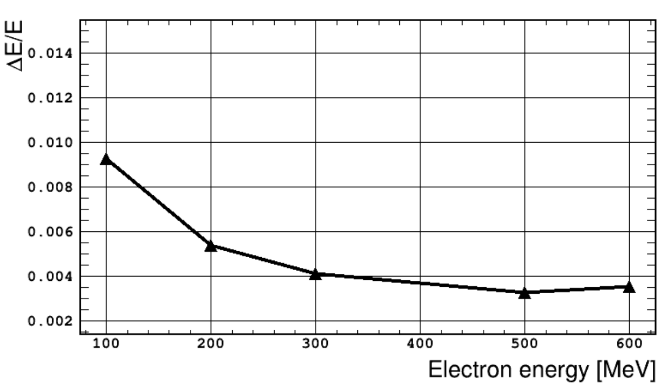
Neutrino Electron Scattering

- 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

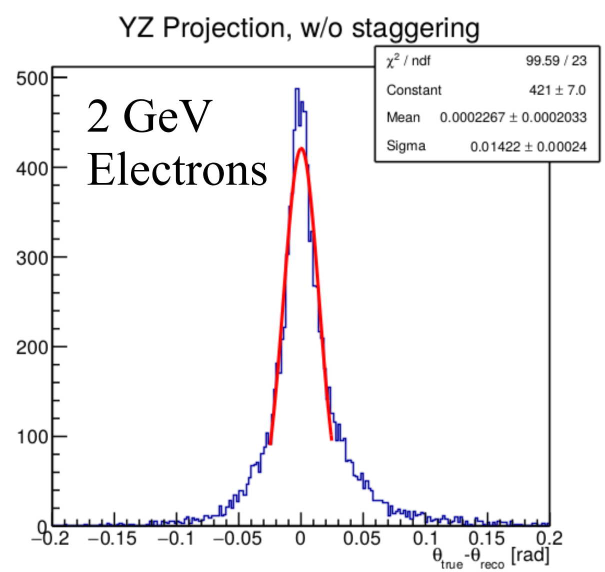


Channel	FHC	RHC
ν_μ CC inclusive	8.4×10^6	3.1×10^6
CCQE	1.8×10^6	1.0×10^6
CC π° inclusive	2.4×10^6	0.6×10^6
NC total	3.0×10^6	1.3×10^6
ν_μ-e$^-$ scattering	960	660
ν_e CC inclusive	1.6×10^5	0.35×10^5

For a 2.4m×2.4m×2m target



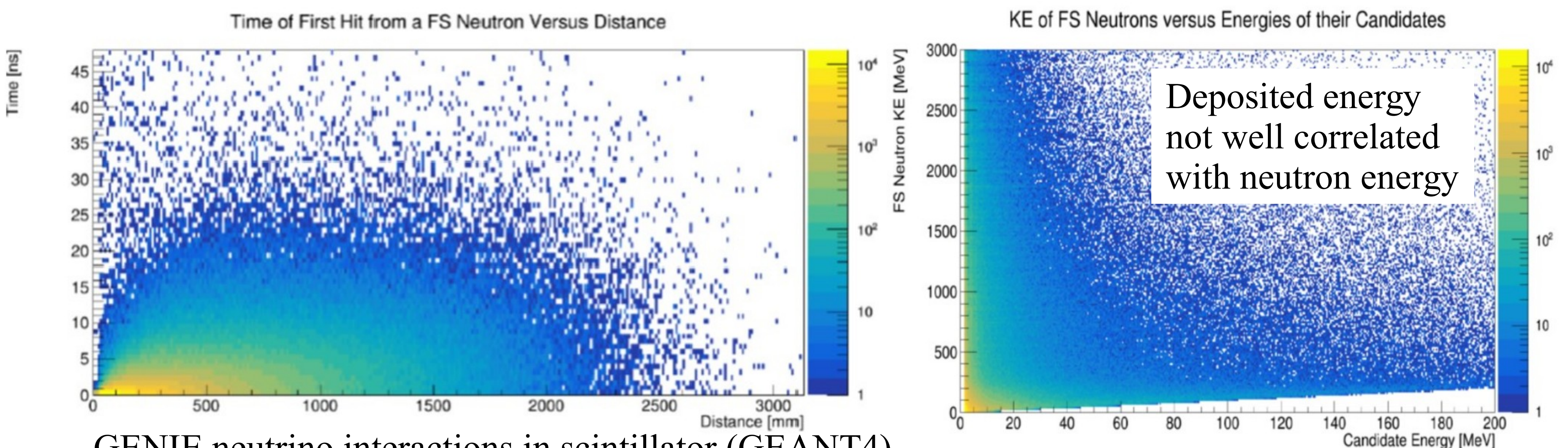
Deposited vs true energy for electrons (Does not include full optical and digitization simulation)



On-axis with 5.7t fiducial for 80 GeV, 3 horn, optimized LBNF beam, 1.46×10^{21} POT

Neutrons in the 3DST

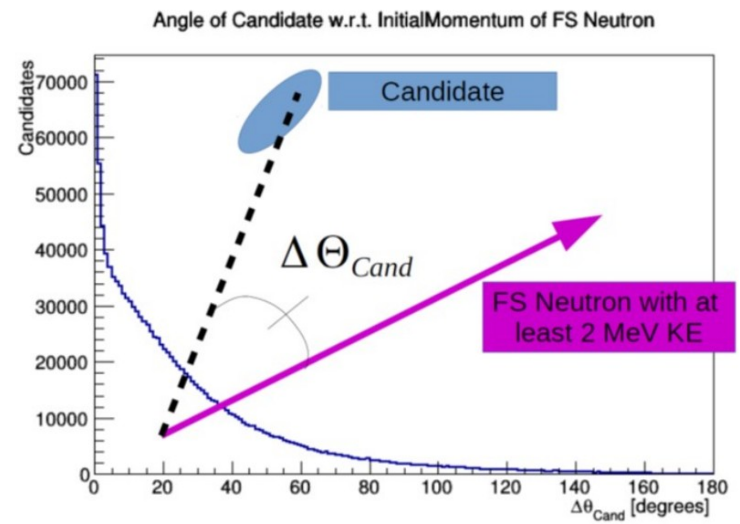
- MINERvA has demonstrated that neutrons from neutrino events can be reconstructed in a scintillation detector (Gran, FNAL, Nov '17)
  - Requires fast timing and a energy threshold
    - Tag the location of the first neutron interaction
  - Data matches GEANT "fairly well"
- The 3DST with a fully active 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.

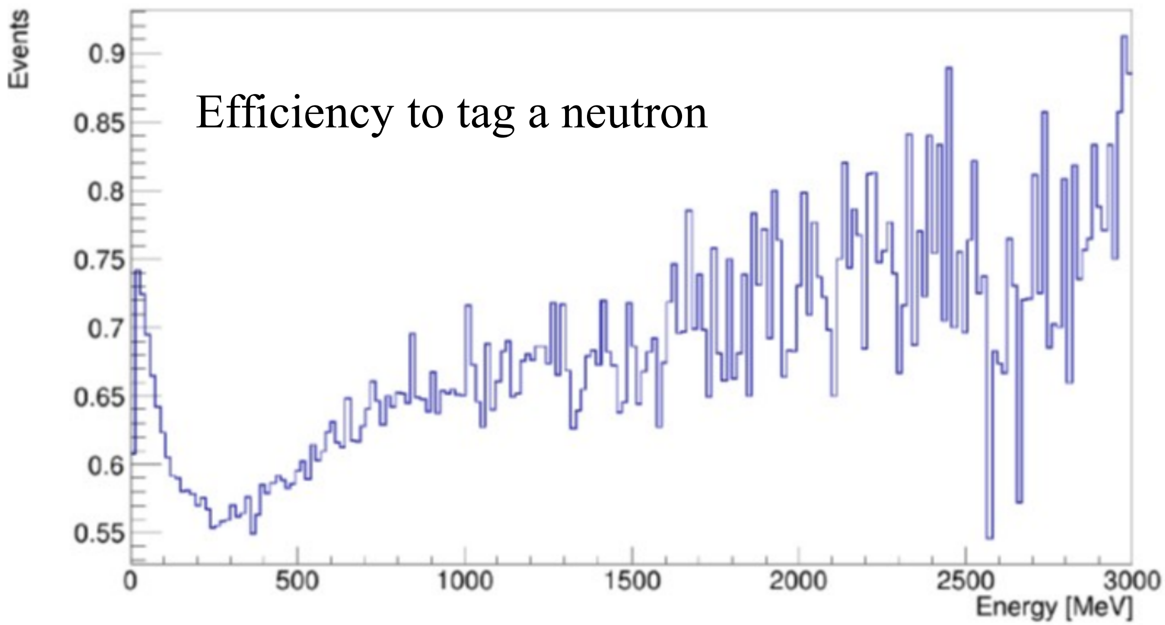


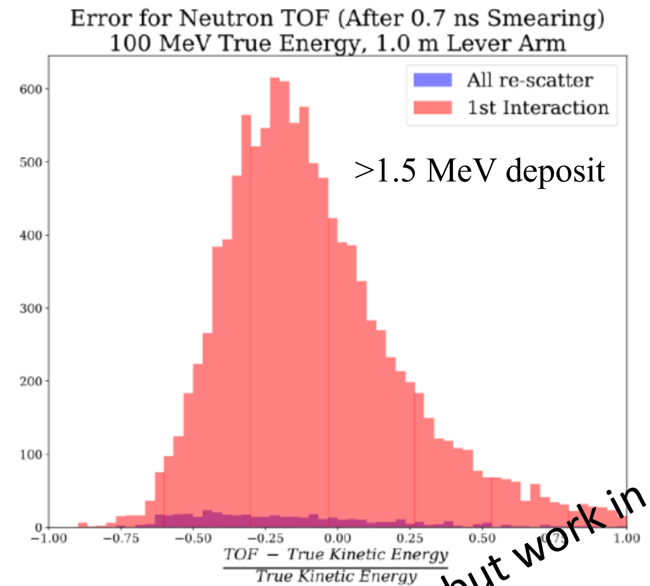
GENIE neutrino interactions in scintillator (GEANT4)

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







Exciting but work in progress

Summary and Comments

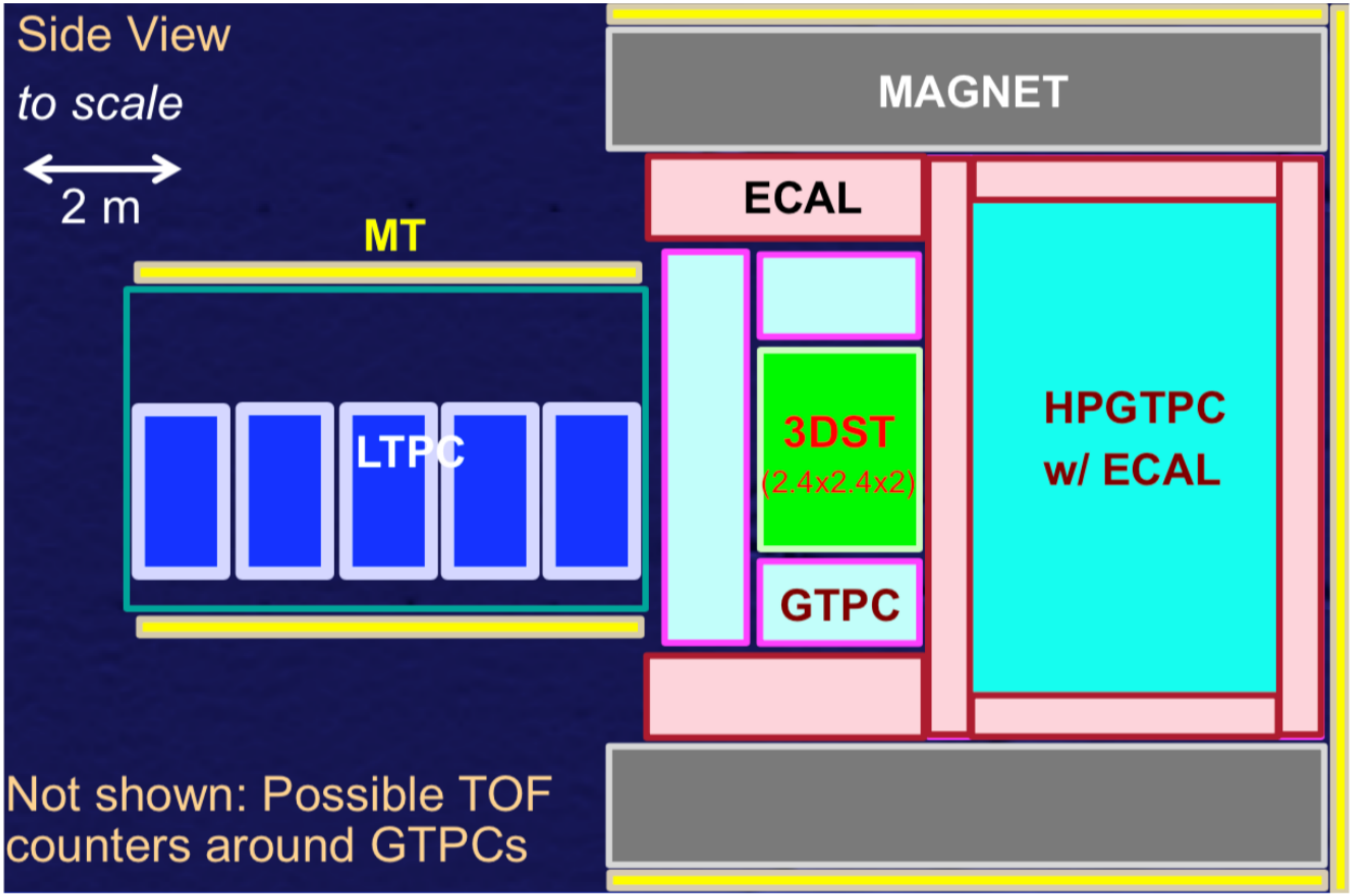
- Detector with
  - High Statistics
  - 4π coverage
  - fine grained (for scintillator)
  - fast timing for background
  - charge identification and pid
  - sensitivity to neutrons (and photons)
- Functionally equivalent to the T2K ND280 SuperFGD
  - Beam Tested now, and installing in T2K in a few years
- 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-ν" 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
      - ν_μ / anti-ν_μ 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

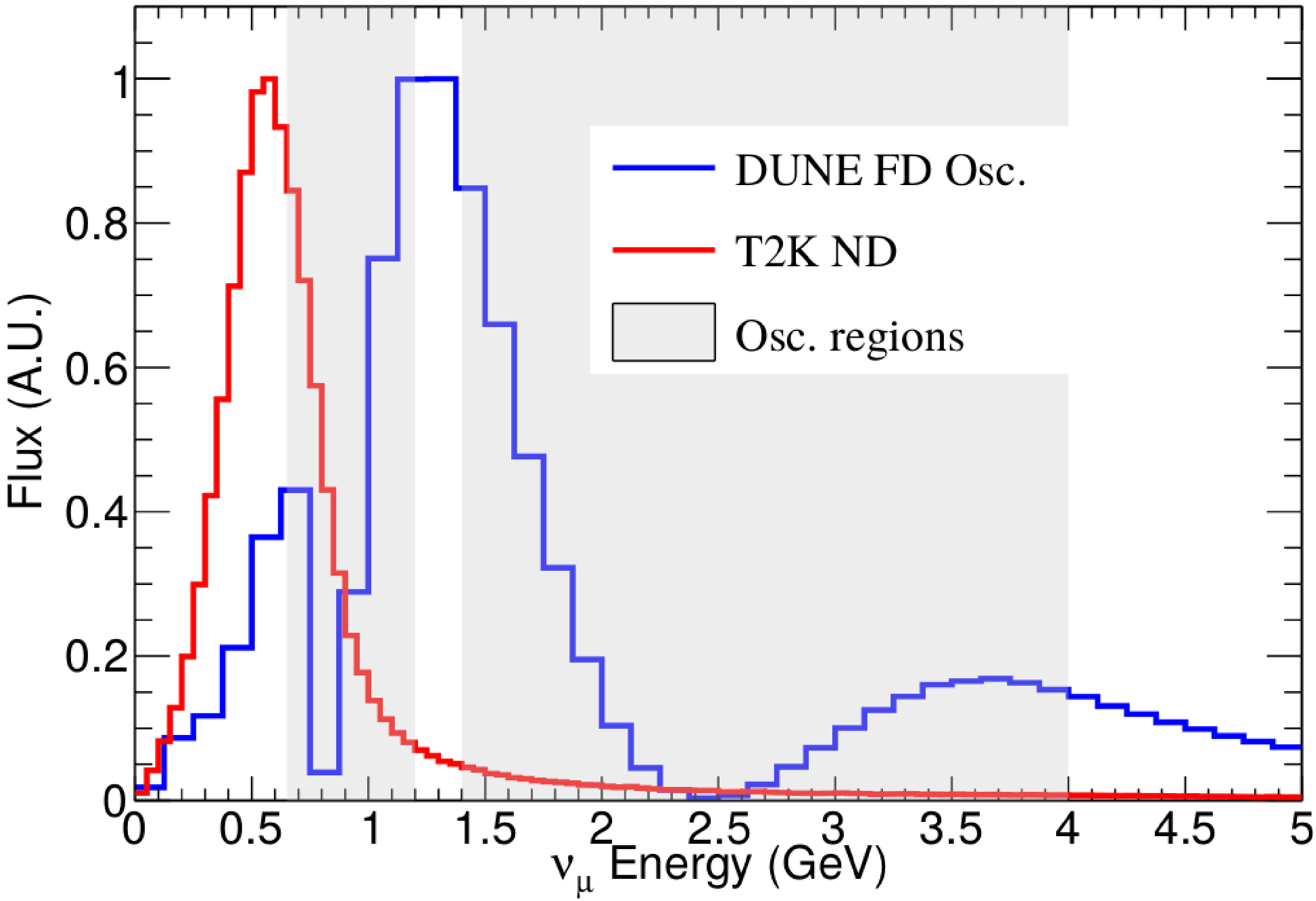
Backup Slides

Another Possible ND Configuration



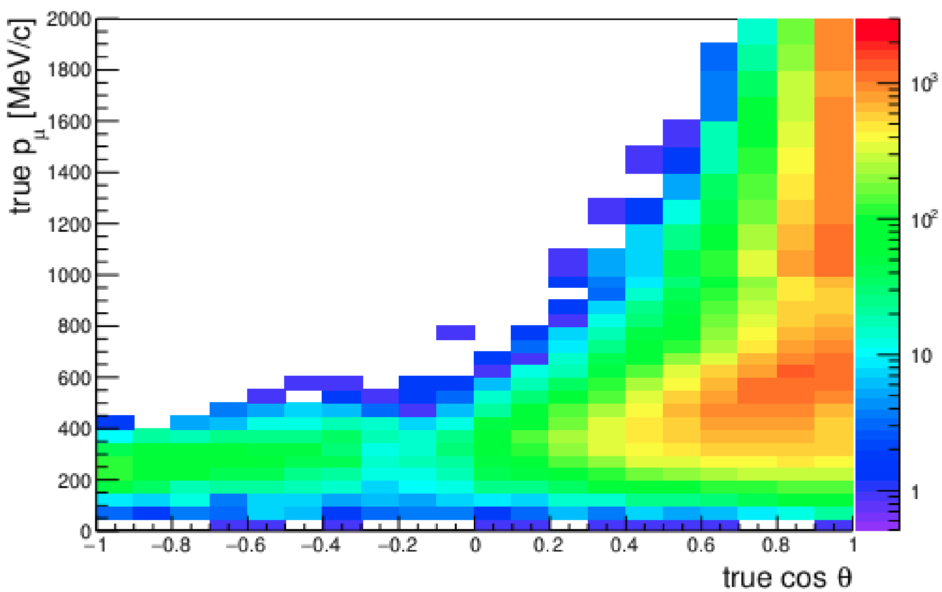
First Alternative: LArTPC, 3DST and HPGTPC tighly integrated minimizing overall size of ND, but requires larger (new) magnet.

DUNE FD and T2K ND ν_μ flux

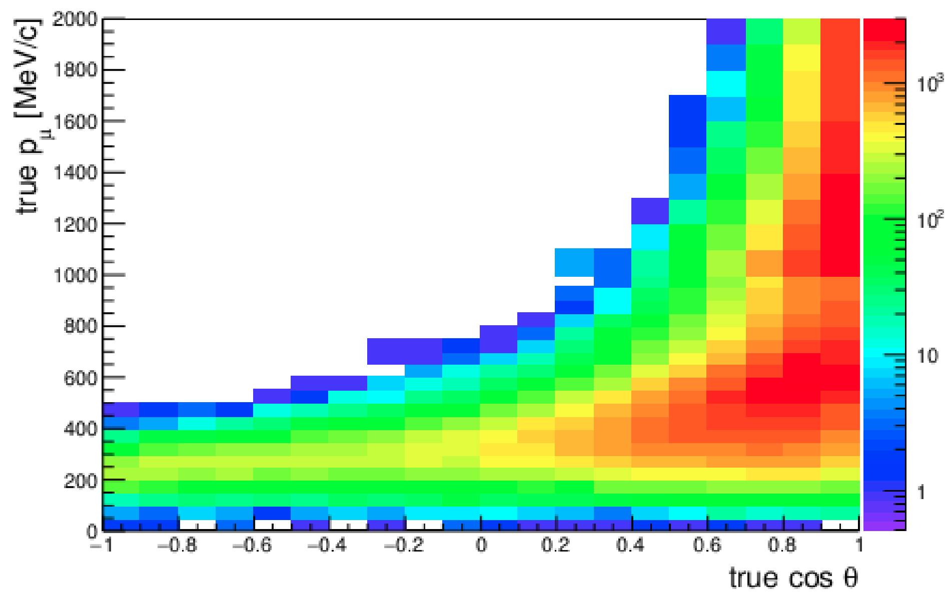


sFGD CC Inclusive Coverage

- 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



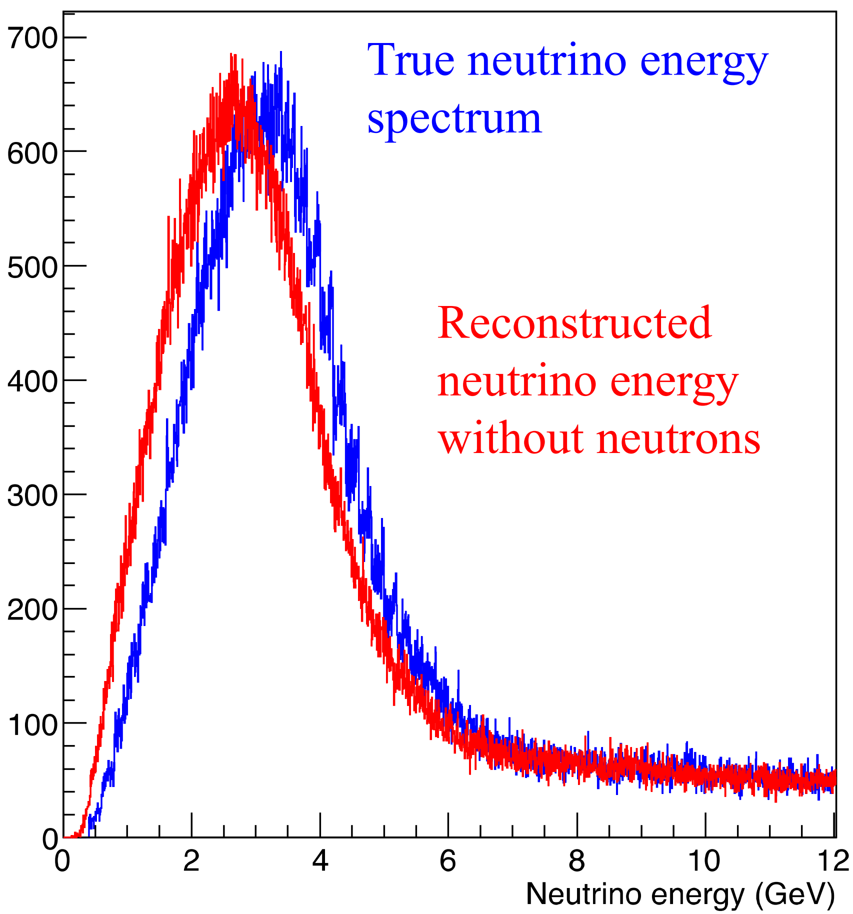
(a) Current ND280



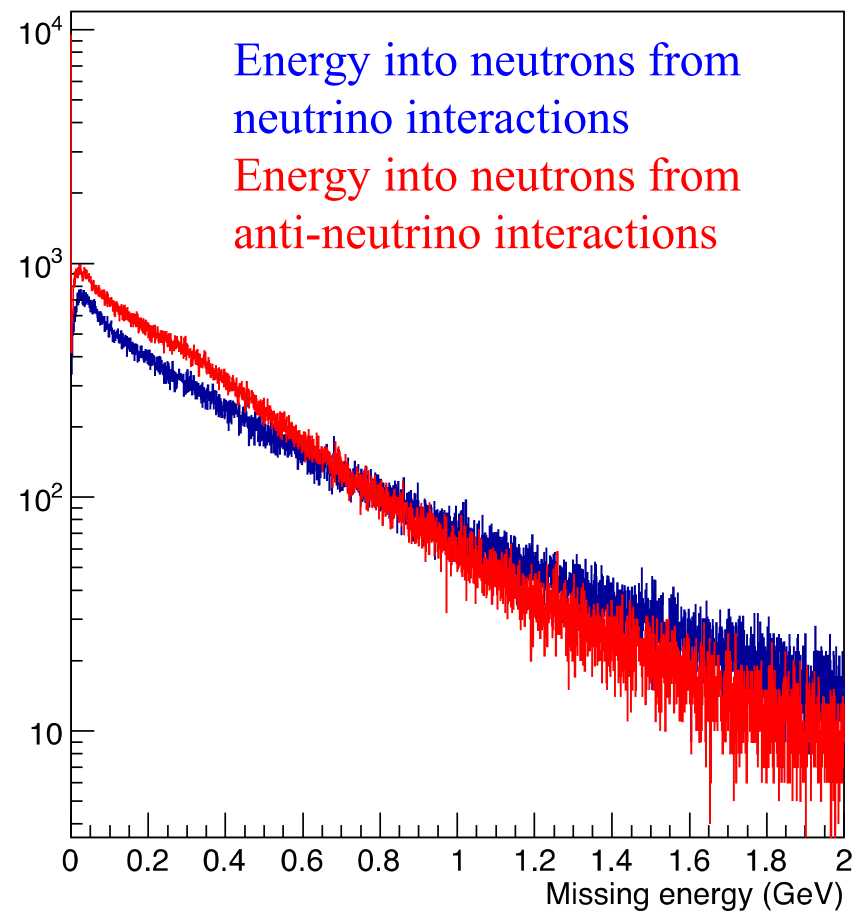
(b) Upgraded ND280

Reconstructed E_ν without Neutrons

LBNF Neutrino Energy Spectrum



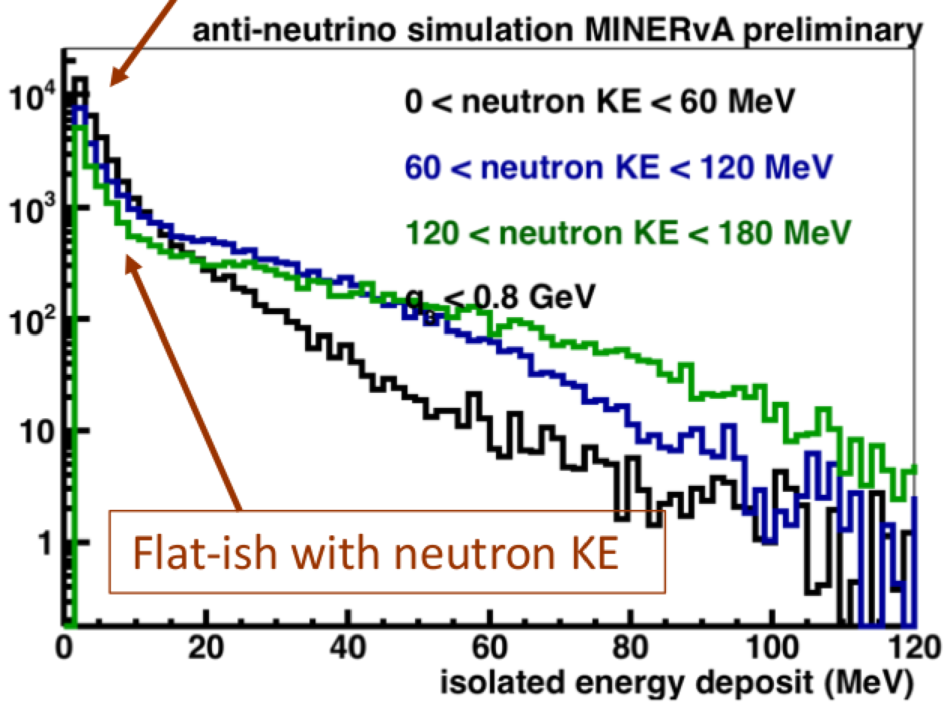
Outgoing energy in neutrons



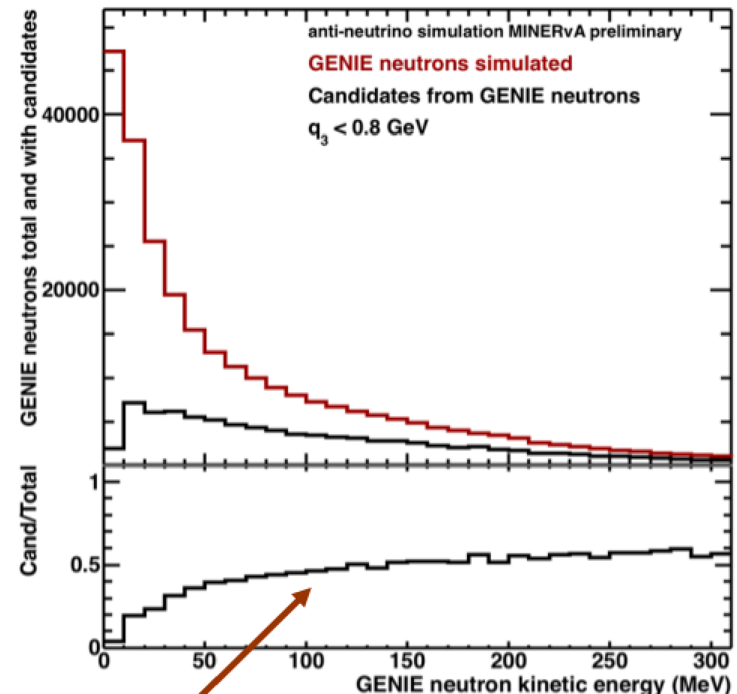
Elena Guardincerri

Expectation from MINERvA GENIE/GEANT simulation

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



Flat-ish with neutron KE



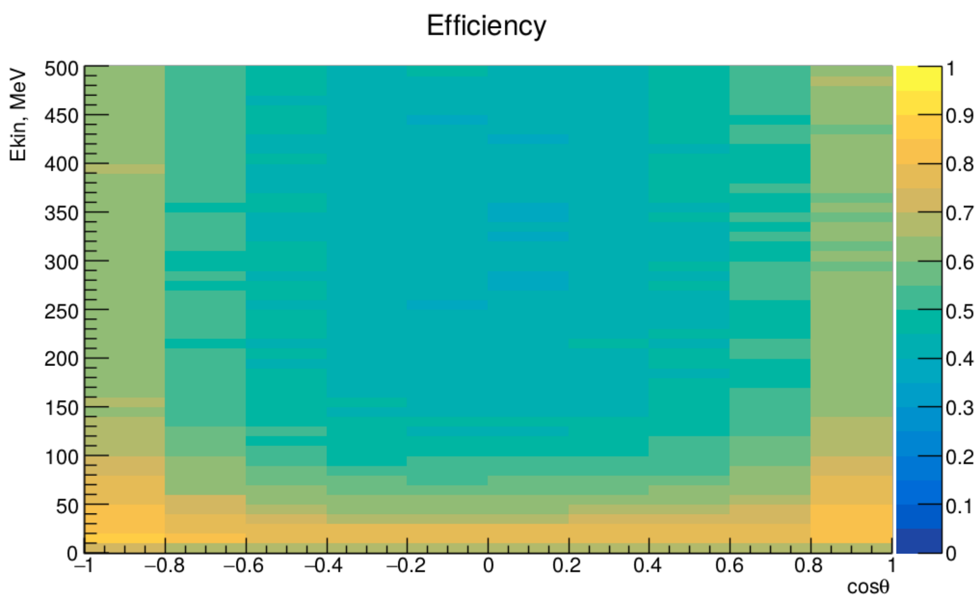
Neutron detection efficiency rises with neutron KE and reaches 50-60% for KE>50 MeV

Manly – NuINT 2018

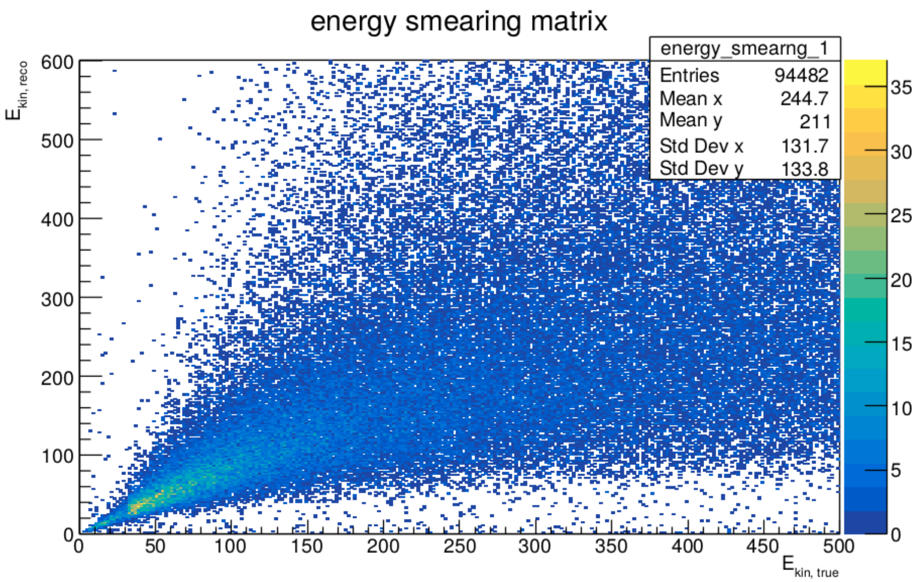
7

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