Physics Requirements and Detector Parameters

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Joint Project Office TMS PDR
2/10/2025

This Talk:

1. Are the technical requirements and performance specifications suitably defined? Is there sufficient confidence that the design will meet these requirements/specifications?
2. Are lessons from past plastic scintillator detectors and recommendations from past reviews suitably applied?
3. Are interfaces adequately identified and documented at a level suitable for preliminary design, particularly with regard to:
   a. Maintaining adequate reconstruction capabilities for muons exiting the ND-LAr active volume?
   b. Installation and integration with the rest of TMS (steel, magnet, infrastructure) in the ND Hall?
      i. (planning for defining I&I process)
   c. Integration into the central data acquisition?
4. Are production and assembly plans suitably defined?
5. Are the following sufficiently well-developed to proceed to the final design phase
   a. Risk mitigation and prototyping plan?
   b. Codes and standards relating to engineering, ES&H?
   c. QA/QC plans?
   d. Servicing/maintenance during operations?
6. Is there adequate confidence in cost and schedule estimates to proceed to final design?
7. Is the design maturity at a satisfactory level for this stage to recommend the TMS Consortium to proceed to final design?

Outline

- Introduction
  - History of TMS (dates of previous reviews, etc.)
  - Introduce the Consortium (org chart?)
  - TMS as the muon catcher for ND-LAr
- Requirements
  - What are the high-level physics requirements?
  - What are the L2 system requirements?
- TMS Design
  - Briefly describe the current design
  - What are the main changes from the CDR
  - Feedback / responses to previous reviews
  - Emergent requirements
- Performance Studies
  - Describe simulation – what's in it, what's not
  - Describe current state of the reconstruction
    - Matching with ND-LAr events
    - Energy resolution
    - Sign selection (NO)
    - Acceptance
    - Horizontal Modules

History of TMS

2019: Review recommendation to explore a low-cost, low-risk spectrometer for DUNE ND. Design developed primarily by Tom LeCompte/ANL.

2020: Passed CD-1

2022: Passed CD-1RR

April 2022: TMS Consortium Formed

2023/2024: MOUs with SLAC / U. MN

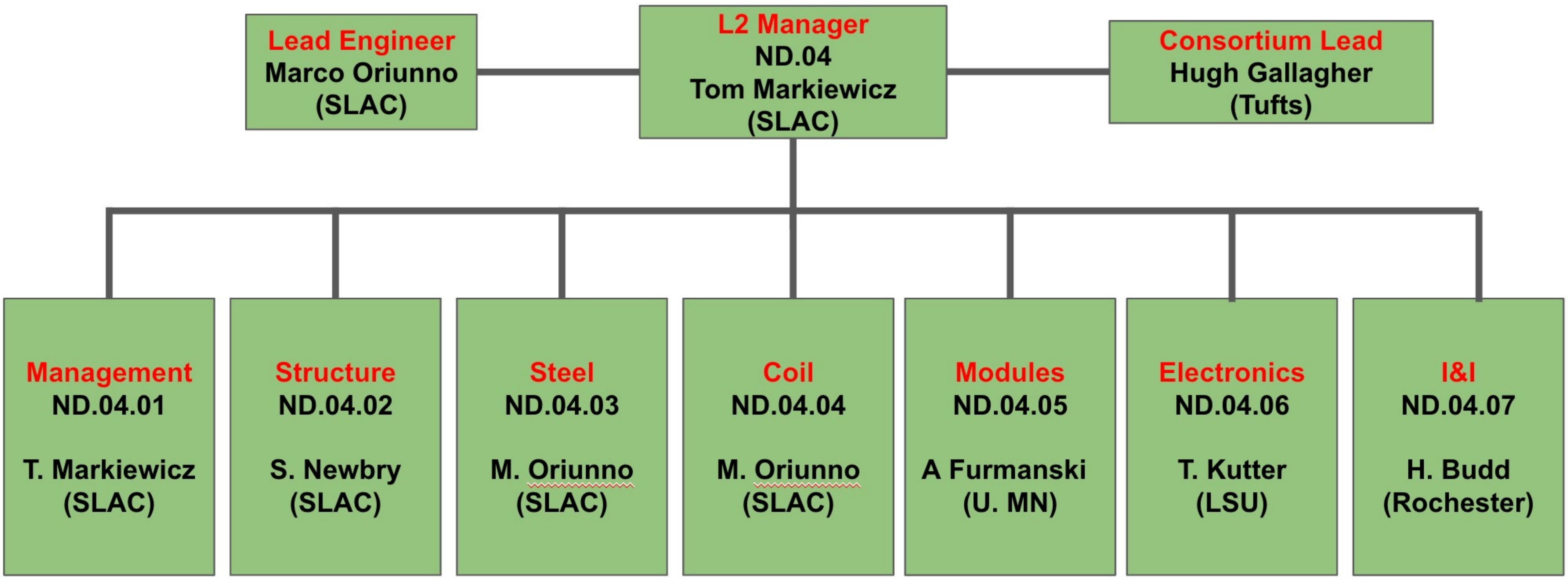
April 2023: Magnet internal review

Sept 2024: Electronics internal review

Oct 2024: Detectors internal review

Consortium institutions have considerable experience with similar detectors including MINOS, MINERvA, T2K, and NOvA.

Org Chart

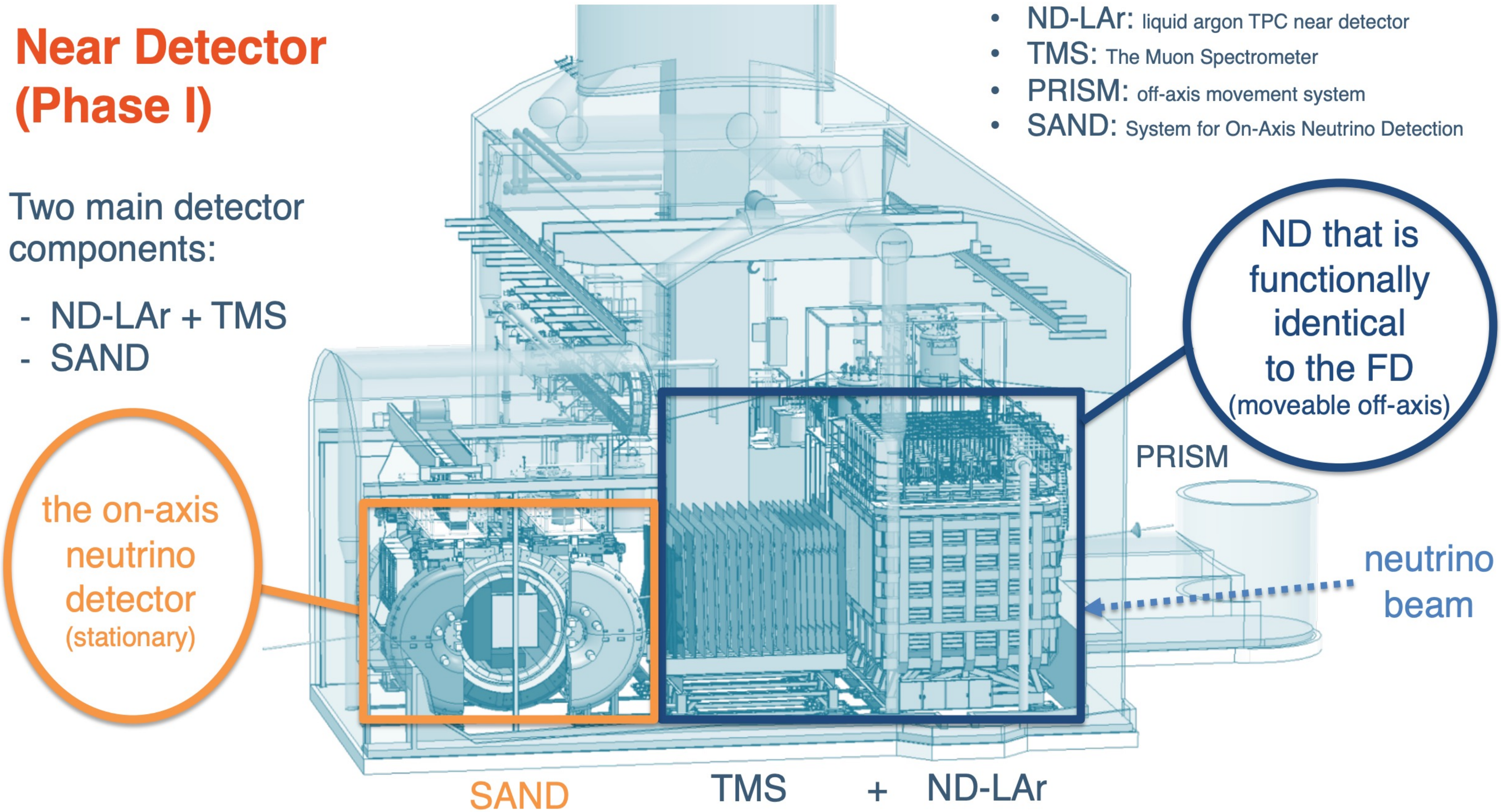


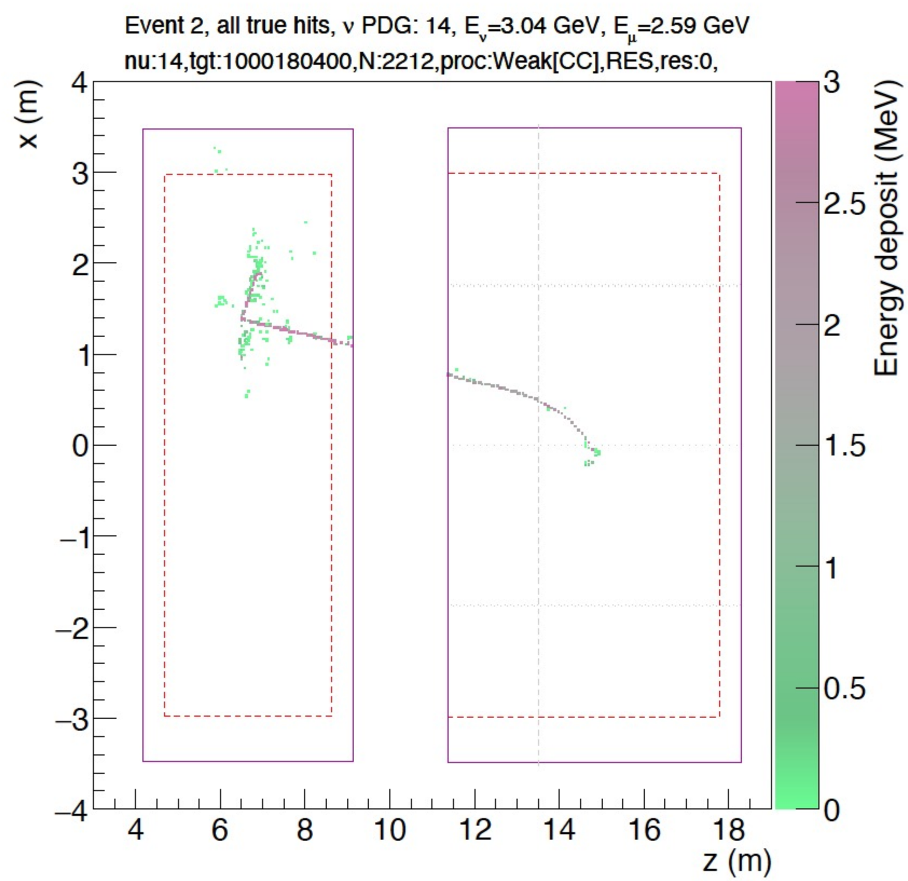
Lead Engineer
Marco Oriunno
(SLAC)
L2 Manager
ND.04
Tom Markiewicz
(SLAC)
Consortium Lead
Hugh Gallagher
(Tufts)
Management
ND.04.01
T. Markiewicz
(SLAC)
Structure
ND.04.02
S. Newbry
(SLAC)
Steel
ND.04.03
M. Oriunno
(SLAC)
Coil
ND.04.04
M. Oriunno
(SLAC)
Modules
ND.04.05
A Furmanski
(U. MN)
Electronics
ND.04.06
T. Kutter
(LSU)
I&I
ND.04.07
H. Budd
(Rochester)

Near Detector (Phase I)

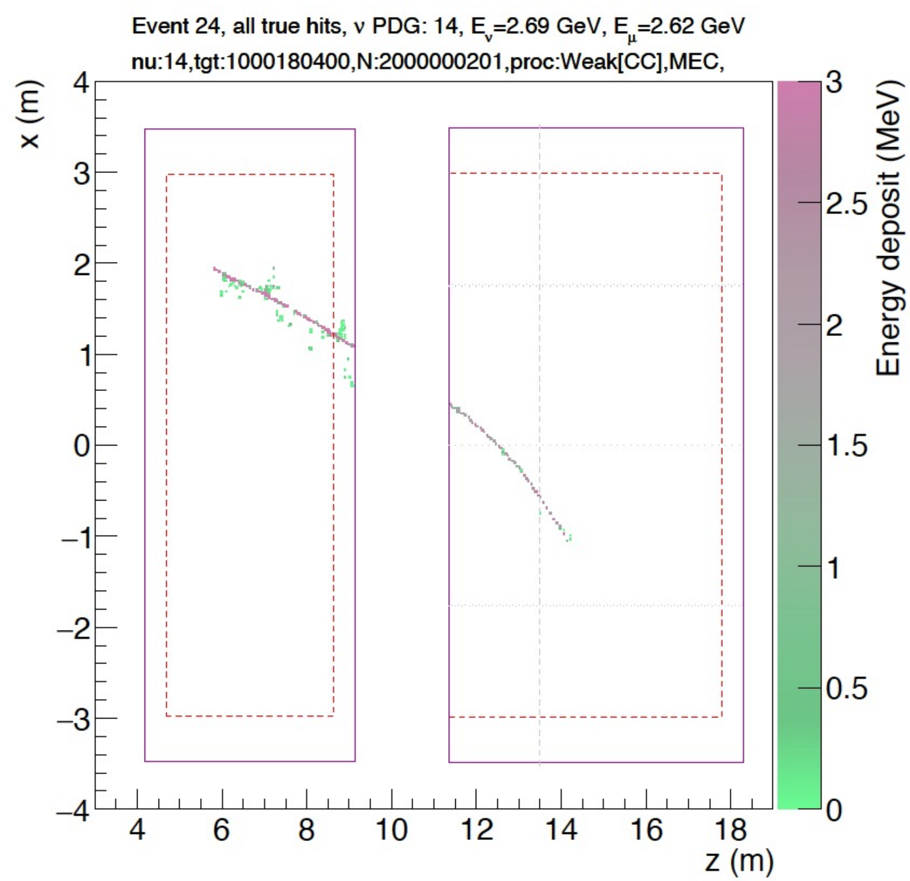
- Two main detector components:
  - ND-LAr + TMS
  - SAND

- ND-LAr: liquid argon TPC near detector
- TMS: The Muon Spectrometer
- PRISM: off-axis movement system
- SAND: System for On-Axis Neutrino Detection





Event 2, all true hits, ν PDG: 14, E_ν=3.04 GeV, E_μ=2.59 GeV
nu:14,tgt:1000180400,N:2212,proc:Weak[CC],RES,res:0,
x (m)
z (m)
Energy deposit (MeV)



Event 24, all true hits, ν PDG: 14, E_ν=2.69 GeV, E_μ=2.62 GeV
nu:14,tgt:1000180400,N:2000000201,proc:Weak[CC],MEC,
x (m)
z (m)
Energy deposit (MeV)

TMS CDR

Physics Requirements

1. Enables ND-LAr measurement of muon neutrino interactions with a comparable phase space and resolution (5%) to the FD.
2. Sign selection (>95%).
3. Moves with ND-LAr - PRISM.

In Addition:

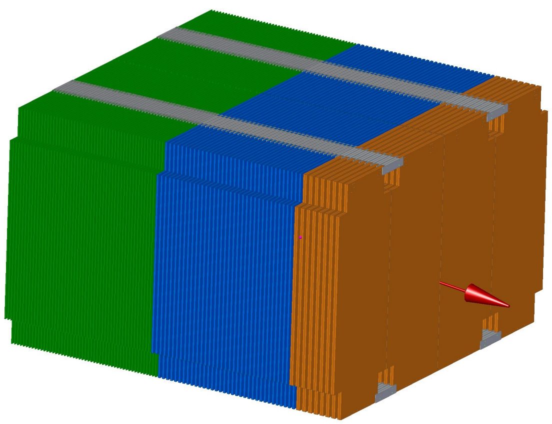
- Together with ND-LAr serves a beam monitoring function.
- Important for ND “Goals”: Cross Section Measurements!

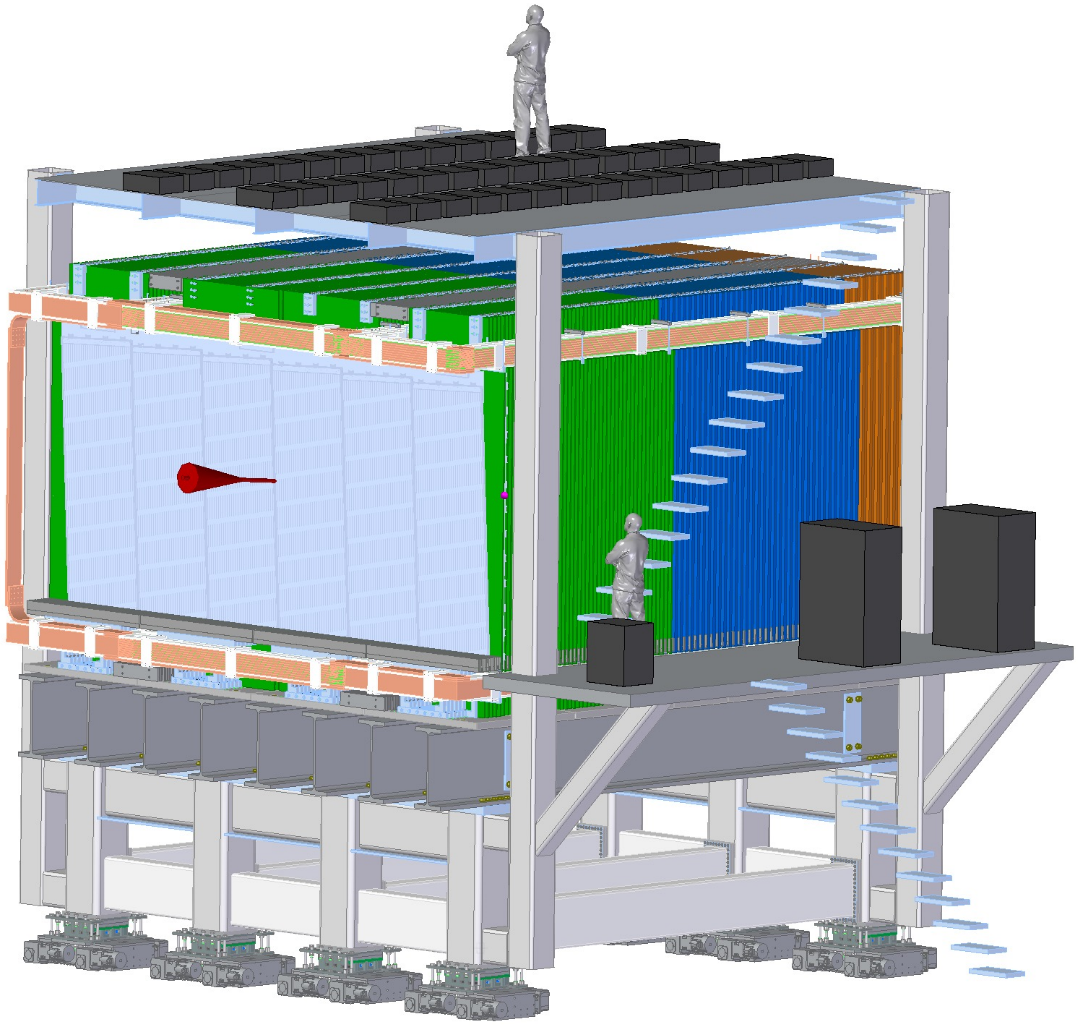
TMS System Requirements

Tag	Description	Specification or requirement
ND-T3.01	Areal coverage	TMS shall be >6.5 m wide and >2.6 m tall.
ND-T3.02	Stopping power	TMS shall have >2100 g/cm^2 areal density
ND-T3.03	Fiducial mass	TMS shall have >500 tons of fiducial mass for neutrino interactions.
ND-T3.04	Longitudinal sampling	TMS shall have sufficient longitudinal sampling to determine the muon track length to TBD cm.
ND-T3.05	Magnetic field strength	TMS shall have a nominal magnetic field of >0.9 T
ND-T3.06	Magnetic field uniformity	TMS shall have a magnetic field strength within 15% of nominal across the volume of the detector (Volume here means instrumented region in the UV view).
ND-T3.07	Horizontal sampling	TMS shall sample in the horizontal or bend plane with 3.5 cm granularity
ND-T3.08	Vertical track resolution	TMS shall have vertical position resolution <50 cm for neutrino interactions within TMS.
ND-T3.09	Longevity	TMS shall be capable of operating for 10 years.
ND-T3.10	Length	TMS shall fit into the 801.7 cm allocated to it in the near hall.
ND-T3.11	TMS Muon containment	TMS shall be capable of identifying where ND-LAr matched tracks stop in TMS.
ND-T3.12	Plane crossing efficiency	The efficiency for detection of a muon crossing the instrumented region of a TMS plane shall be >90% .

PDR Design

Parameter	Value
Steel dimensions	7.4 × 3.6 × 7.0 m
Steel plate thickness	50 planes of 15 mm, 34 planes of 40 mm, 8 planes of 80 mm
Steel mass	850 tons
Magnetic Field	Typically 1.0-1.1 Tesla
Active Area	22.1 m^2 (192 × 36 mm × 3.2 m)
Number of detector planes	93
Channels per plane	192, in 6 panels of 32 each
Total channels	17856
Timing resolution	$\leq$ 19 ns (single RF bucket)





PDR Design

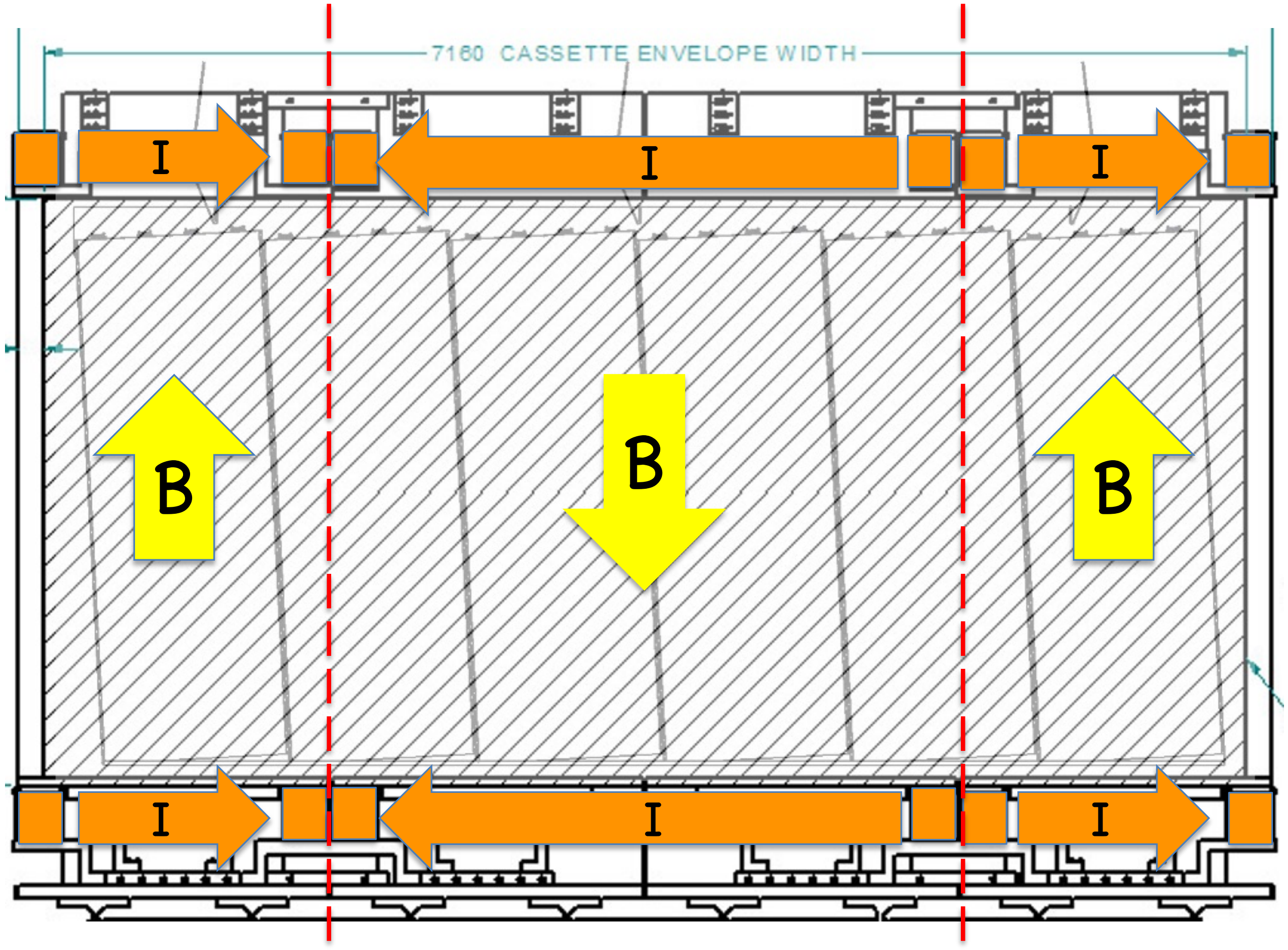
Magnet is assembled and tested first.

Co-extruded scintillator strips with single WLS fiber are assembled into modules.

Modules are assembled into cassettes.

Cassettes are inserted into gaps between steel plates.

- 32 strips/module
- 6 modules/cassette
- 1 cassette/plane



PDR Design

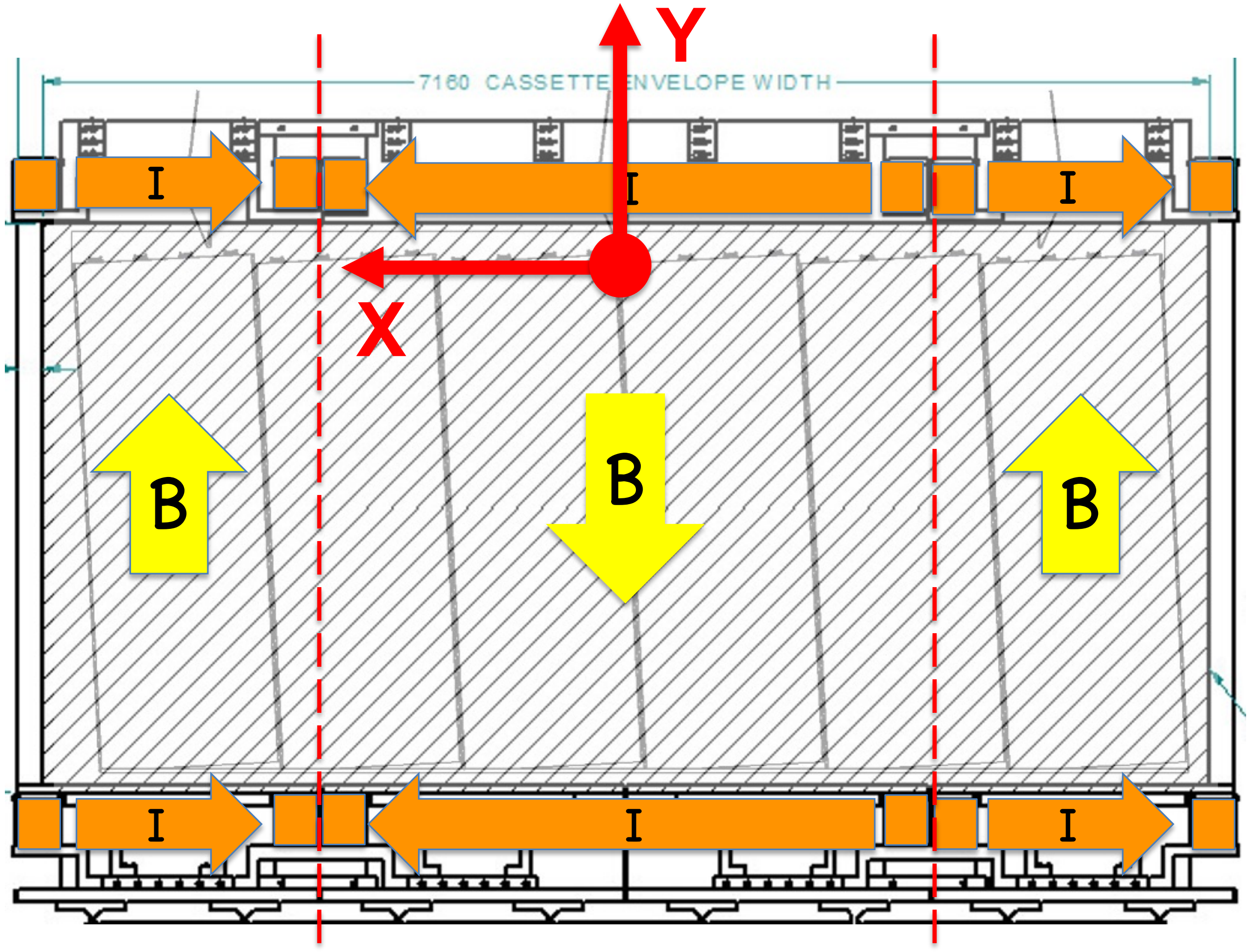
Magnet is assembled and tested first.

Co-extruded scintillator strips with WLS fiber are assembled into modules.

Modules are assembled into cassettes.

Cassettes are inserted into gaps between steel plates.

- 192 strips/module
- 6 modules/cassette
- 1 cassette/plane



Internal Reviews

Add EDMS Links here

- Magnet
  - Wes Craddock (SLAC), Alex Bainbridge (Daresbury), David Harding (FNAL)
  - Concerns about air cooling
  - Pre-fabricating coils rather than "threading the needle"
- Electronics
  - Francesco Poppi (U. Bologne), James Sinclair (SLAC)
  - Strongly advised making connectors accessible.
- Detectors
  - Craig Group (U. Virginia), Brian Rebel (U. Wisconsin), Charlie Young (SLAC)
  - Importance of prototyping: what you will build, how you will build it, transport, etc.
  - Valuable feedback on light-tightening, assembly, transportation. Streamline processes?

Changes from the CDR – LOTS

- High-Level Requirements have changed since 2022
  - Beam monitoring: Now no TMS-only role for beam monitoring (essentially a digital detector)
  - Temporary? End of Phase I → 200 kt-MW-years → 10 years

- Electronics
  - CDR deferred detailed electronics design
  - Availability of a COTS solution
- Magnet
  - Water vs. air cooling
  - Fabrication and installation
  - Flux return

- Detectors

+ More Prototyping!

  - Module Orientation
  - Cassette
  - Strip thickness (mechanical reasons)
- Assembly
  - **Make detectors accessible**
  - Build and test magnet first, then install detectors

From the PDR to the FDR

Two aspects of the detector design will require detailed optimization studies.

- **Steel Stacking Plan**
  - Our space in z is constrained, how best to use it?
  - Total stopping power just depends on total mass
  - 5% resolution for all muons would suggest linearly increasing steel thickness
  - To insert cassette – needs to be enough space in z accounting for steel tolerances.
- **Module Orientation Plan**
  - UV (stereo) orientation gives best resolution in bending plane (x-direction)
  - Having horizontal counters helps with… everything else.

The PDR design is very flexible with regards to changes in these two areas.

Performance

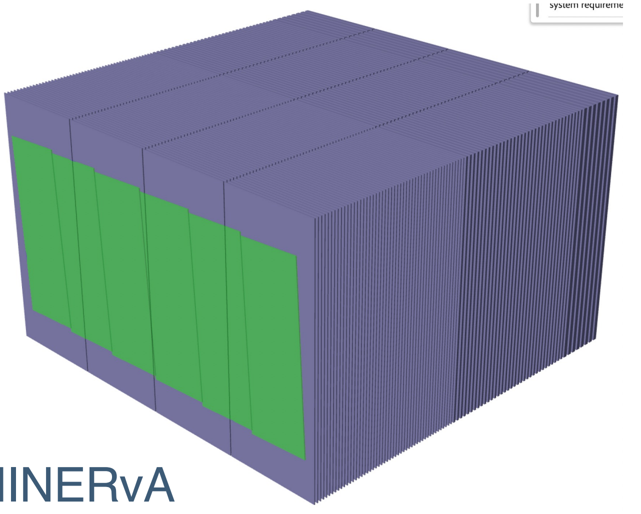
There are a variety of ways to demonstrate a design meets the requirements:

- Performance of previous detectors that used the same technology
- Results from prototypes
- Simulation, running the gamut from:
  - Truth-based
  - Full simulation and reconstruction

What we will be presenting is a mix of these.

Validating performance with realistic simulation and full reconstruction is a goal for the FDR.

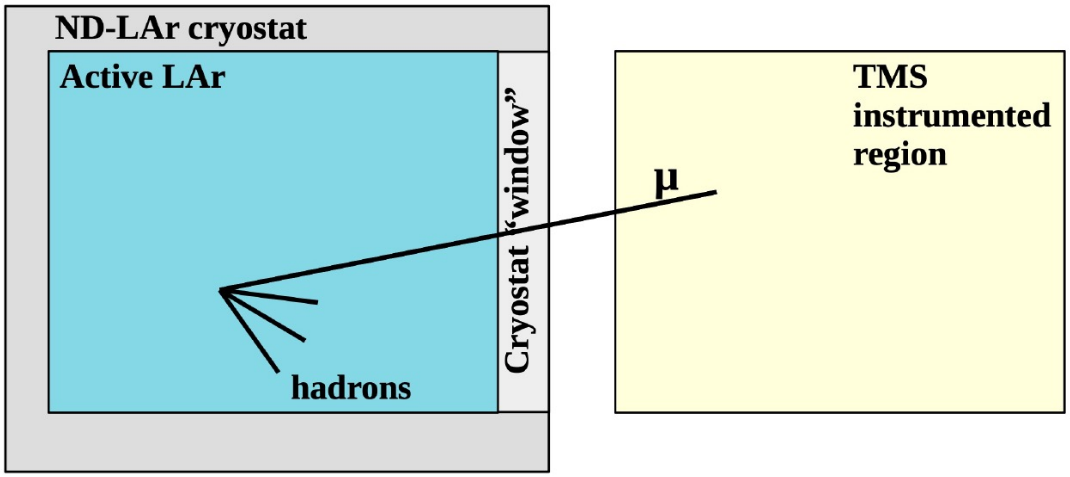
Detector Simulation

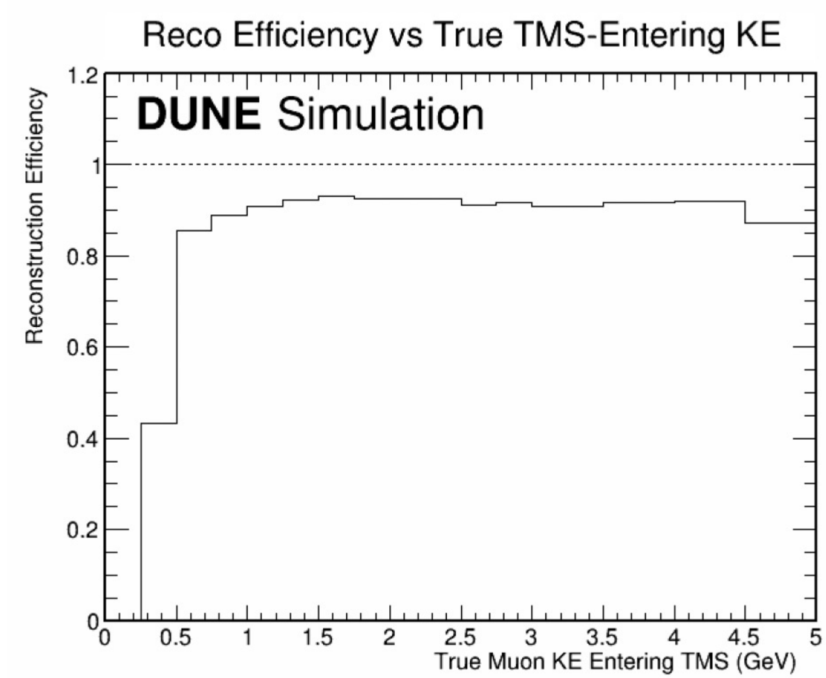


GENIE 3.4 (AR23_20i_00_000 tune) + GEANT4 (edep-sim)

1. Light yield (50 pe/MeV)
2. Birk's suppression
   - PE' = PE / (1 + B*de/dx) with B = 0.0905 mm / MeV from MINERvA
3. Poisson throws for #PE
4. Fiber path adjustments (mirror with R=0.95, attenuation=4.16m)
5. Hit merging, pedestal subtraction, and readout simulation
   - Photon timing simulation
   - Deadtimeless 120 ns readout
   - Readout noise gaussian with 0.4 pe sigma, threshold of 3 pe

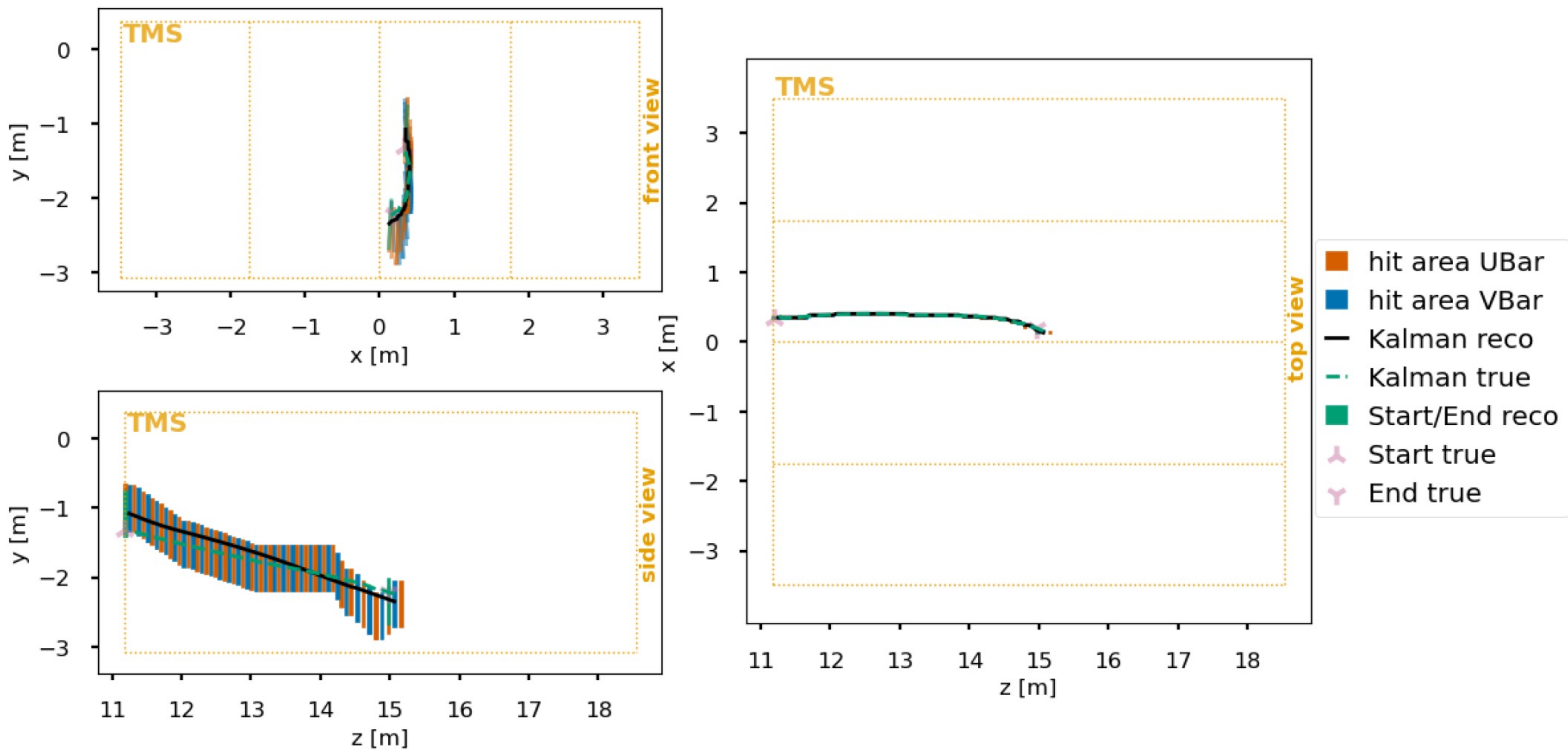
Reconstruction



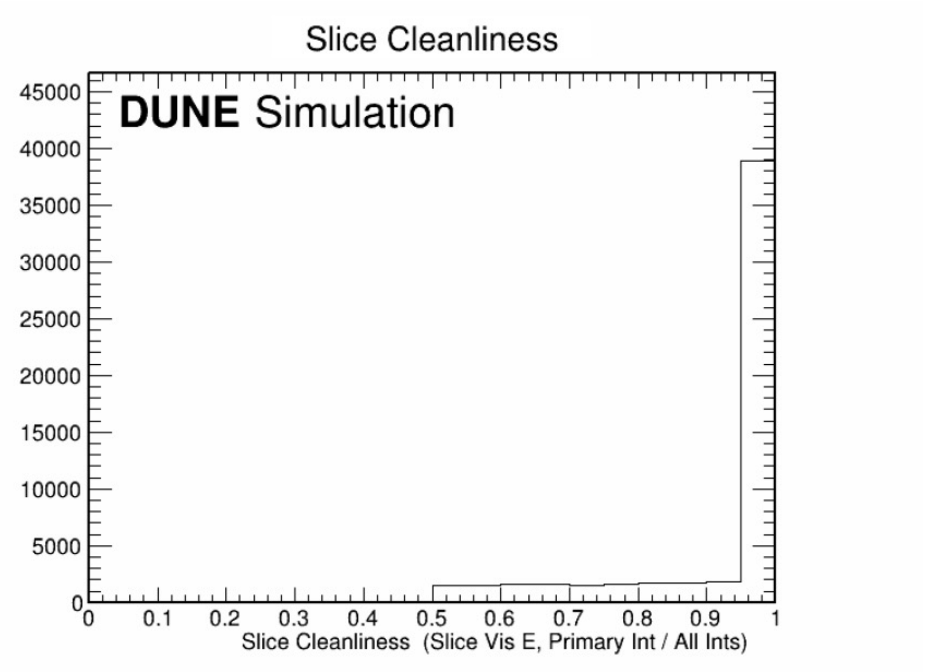


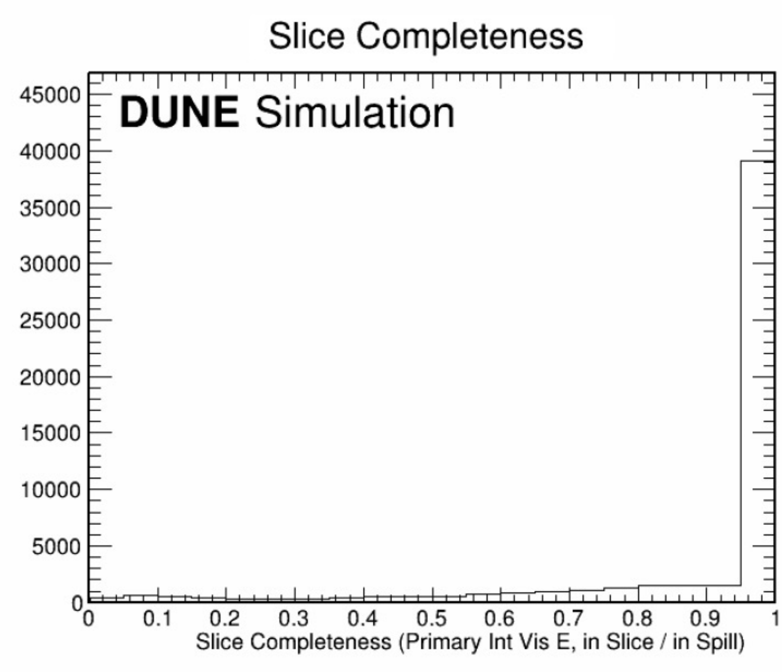
- Time Slicing utilizing MINERvA approach
- Identify 2-d tracks:
  - Hough transform, add hits at the end of the track using A* algorithm
- Match 2-d tracks to form 3-d tracks
- Run Kalman filter on 3-d tracks to determine energy

Simulations and Reconstruction



Single Event Identification



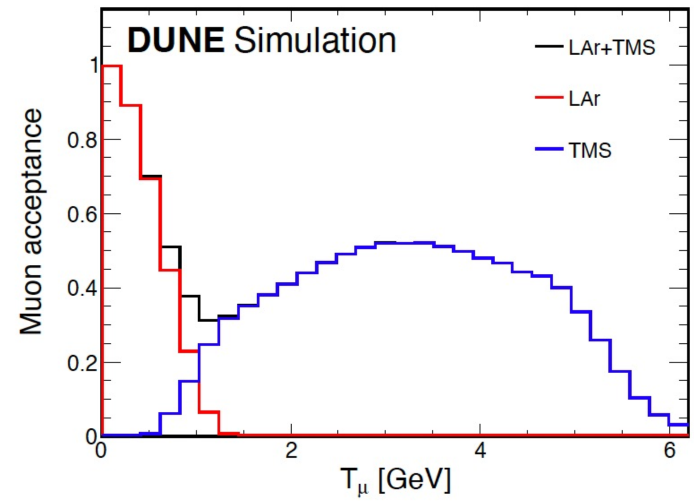


Using timing information only.
20% chance of an interaction in TMS in this same slice (not simulated)
Spatial information will also be used to separate interactions.

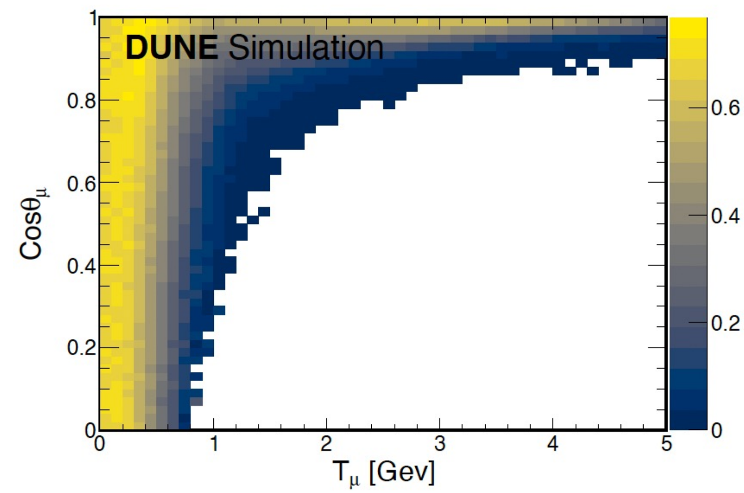
RHC full spill simulation in ND-LAr

Acceptance

- ND-LAr accepts low energy events
- TMS does well with forward going mu up to ~ 5 GeV.
- Low acceptance region is medium E, high angle.



Acceptance corrections are based largely on geometry, translational/rotational symmetry.



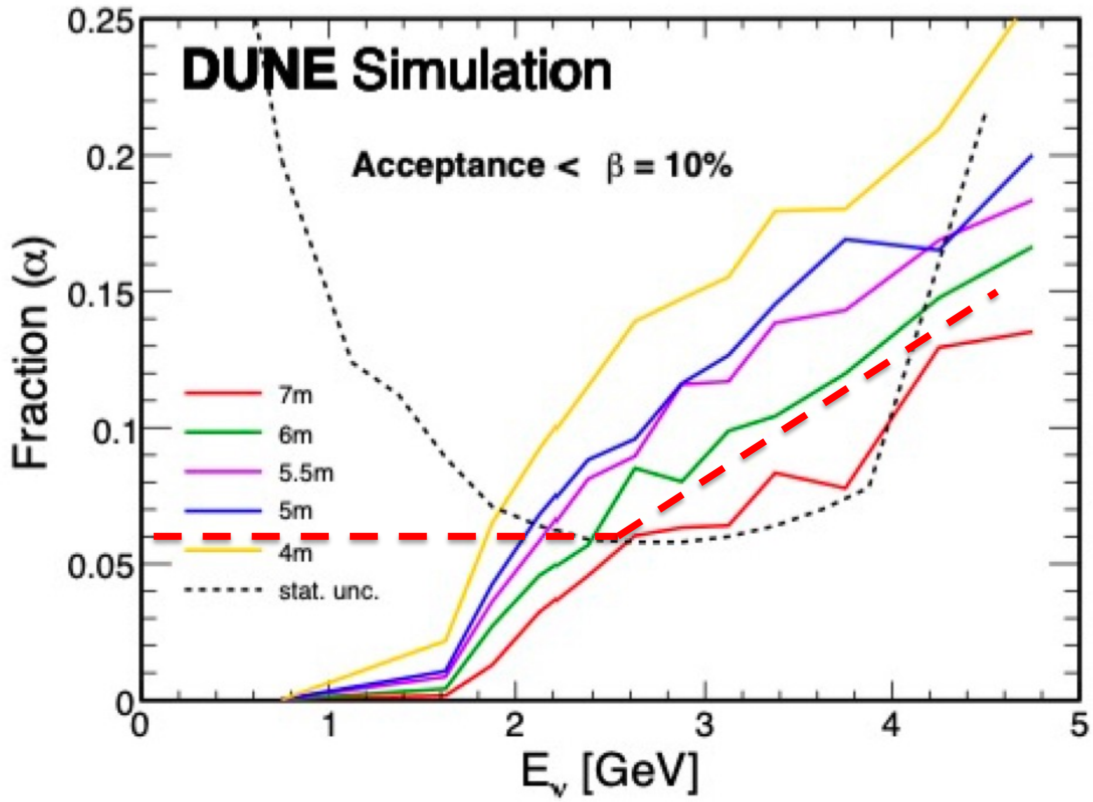
Regions with <10% acceptance will be difficult to reliably acceptance-correct.

Acceptance

PSAC : "Phase Space and Acceptance Coverage"

The fraction of FD ν_μ CC events in phase space regions with < 10% acceptance shall be:

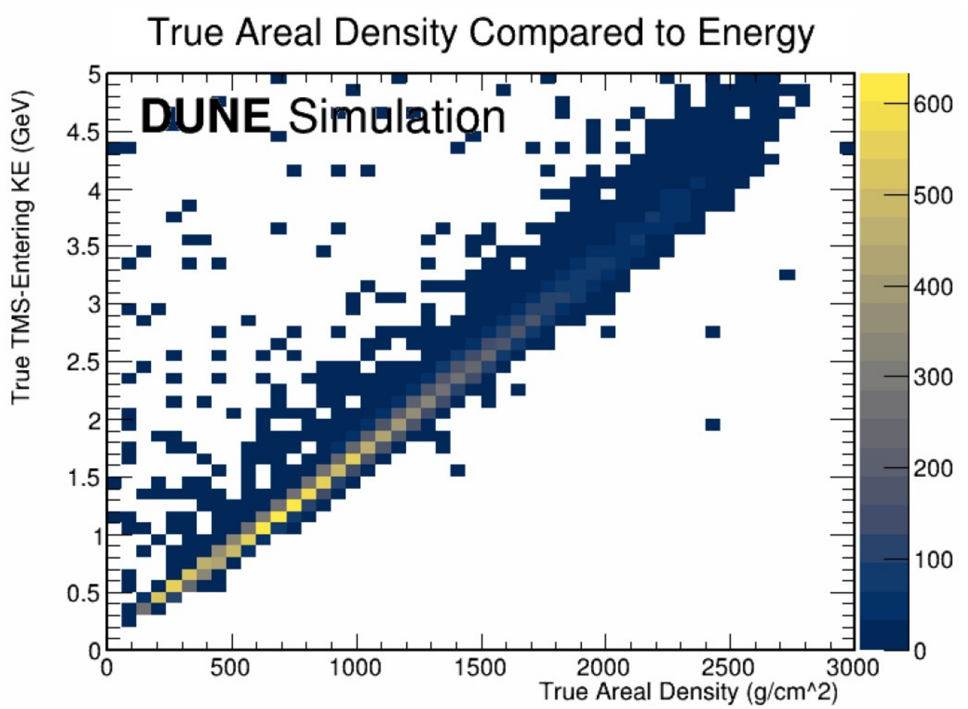
- < 0.06 for E_ν = [0.5 – 2.5] GeV
- < 0.15 for E_ν = [2.5, 4.5(5.0)] GeV

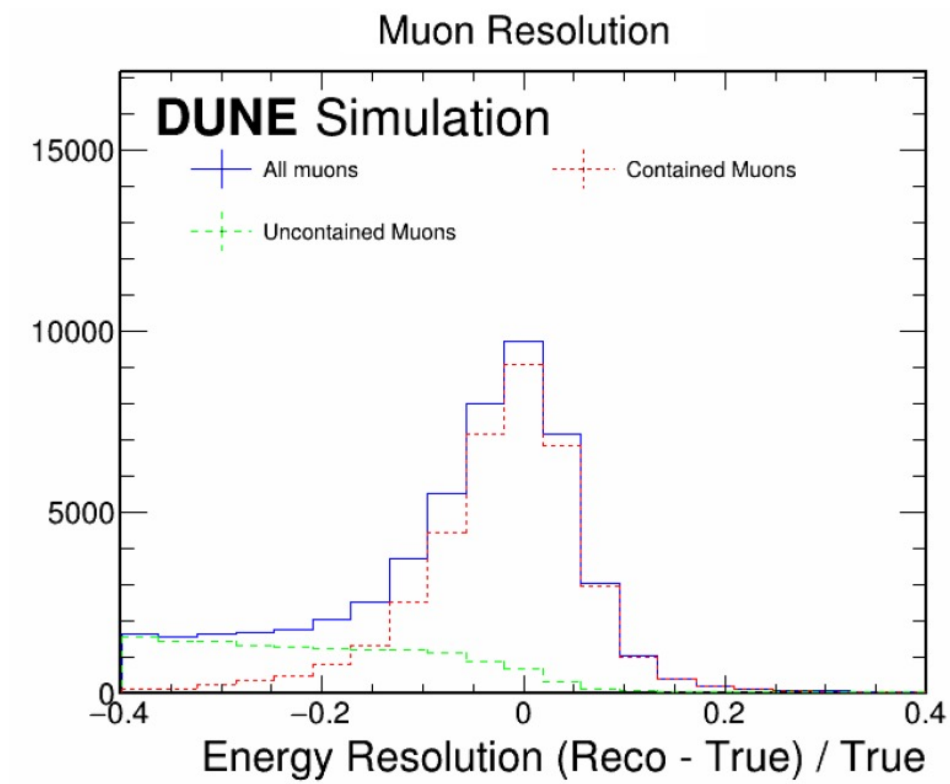


Study based on simulation, but truth energy deposits

Muon Resolution

CDR steel stacking (40/60)
Stereo module orientation

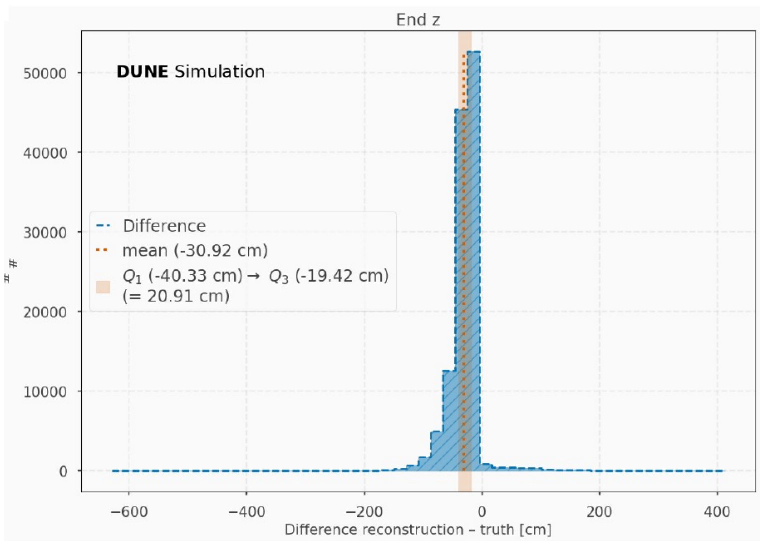




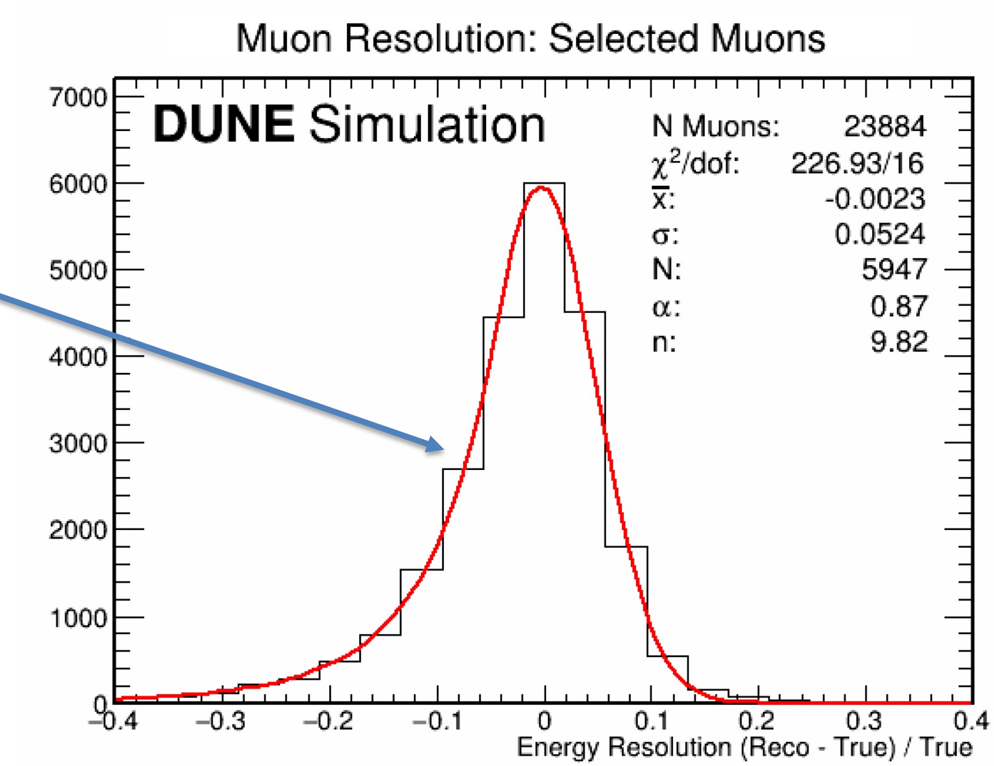
Full TMS reconstruction
Vertex in ND-Lar fiducial volume

Muon Resolution

Fit energy resolution to a "Crystal Ball" function – gaussian with power law tail.   Resolution is 5.2%

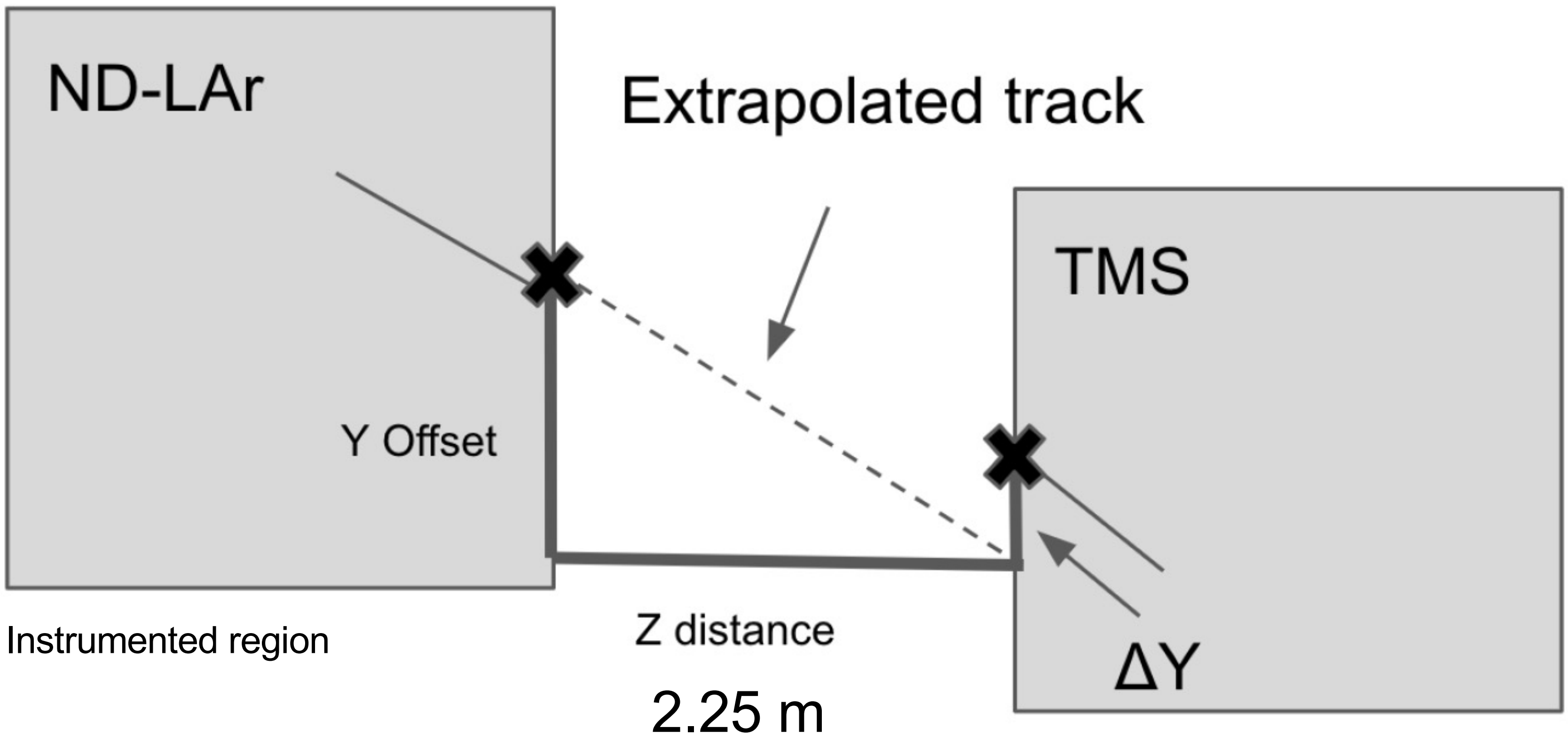


End of track is hard –
multiple scattering and bending.

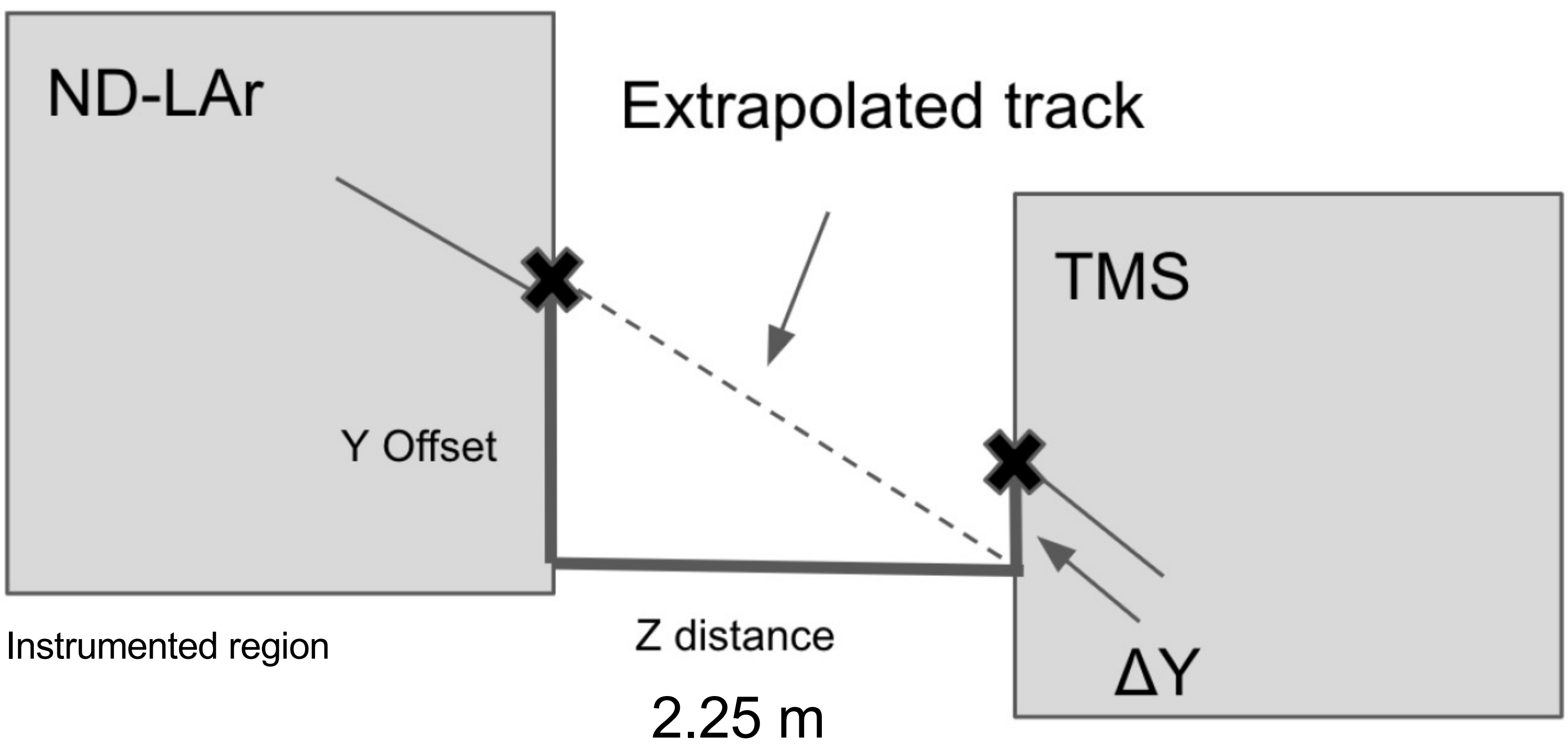


Full reconstruction, vertex in ND-LAr, contained in TMS.

ND-LAr / TMS Track Matching

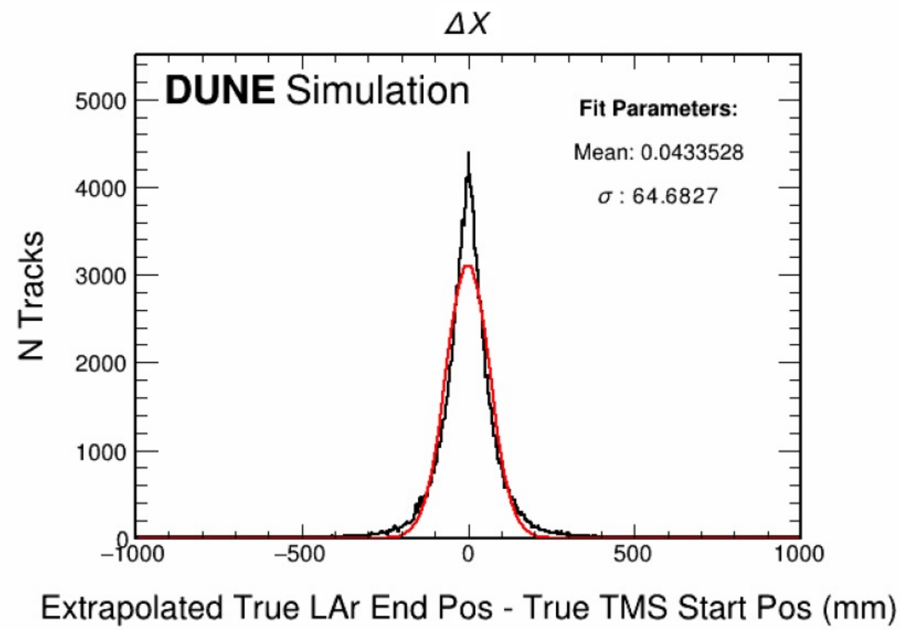


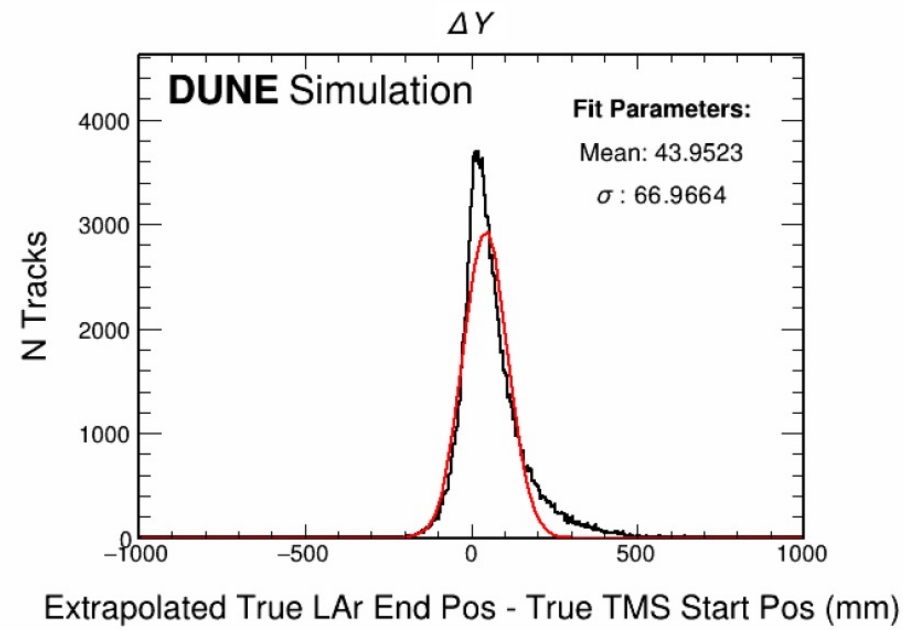
ND-LAr / TMS Track Matching



ND-LAr / TMS Track Matching - Truth

Require 33 cm in TMS

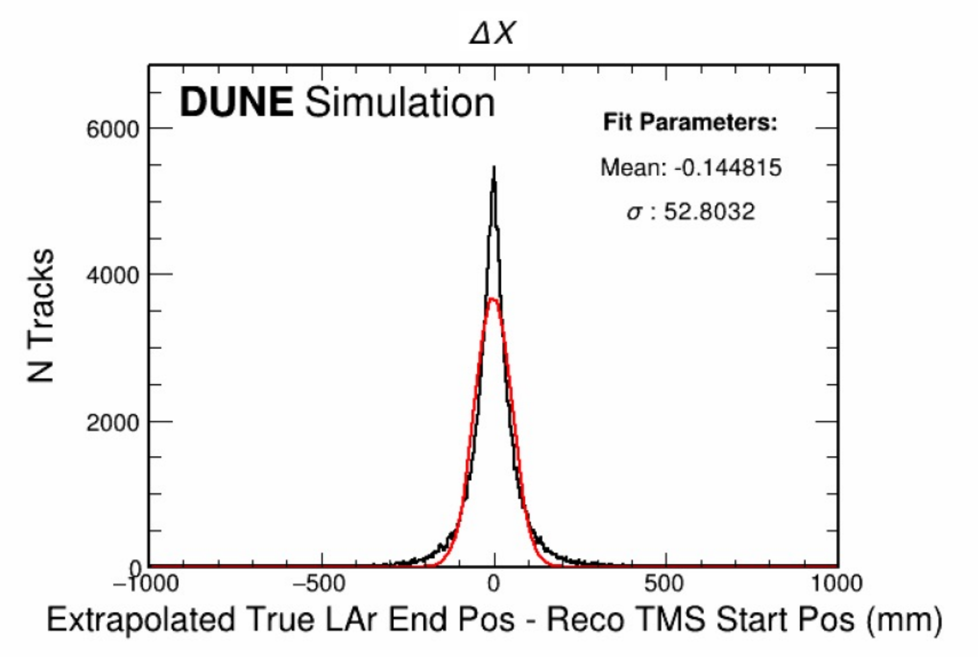


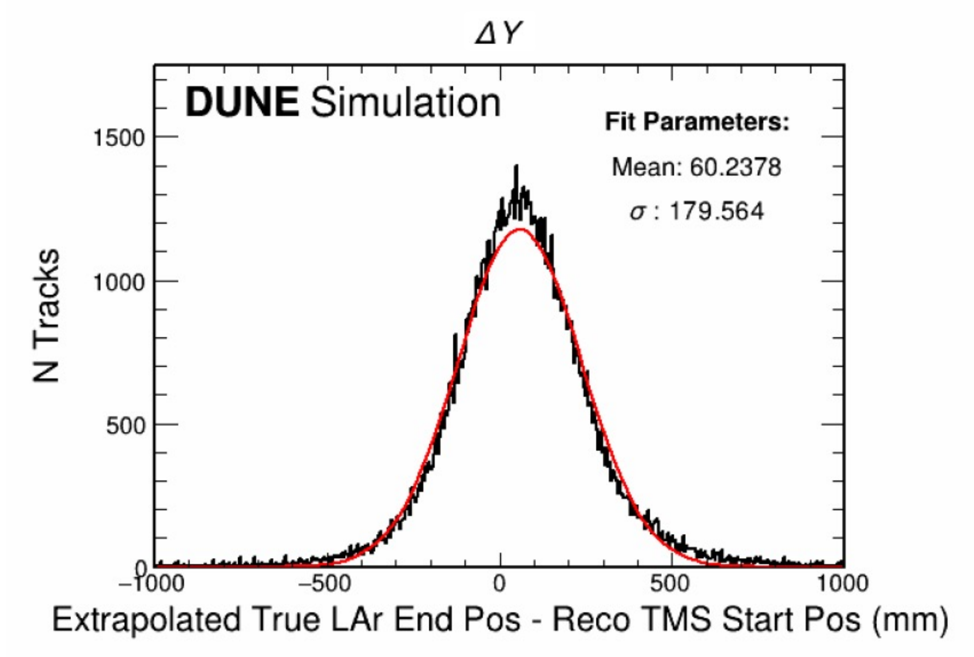


Most tracks have a less than 5^{o} difference in angle.

Quantifies effect of multiple scattering in uninstrumented LAr and cryostat window.

ND-LAr / TMS Track Matching – Truth (stereo)

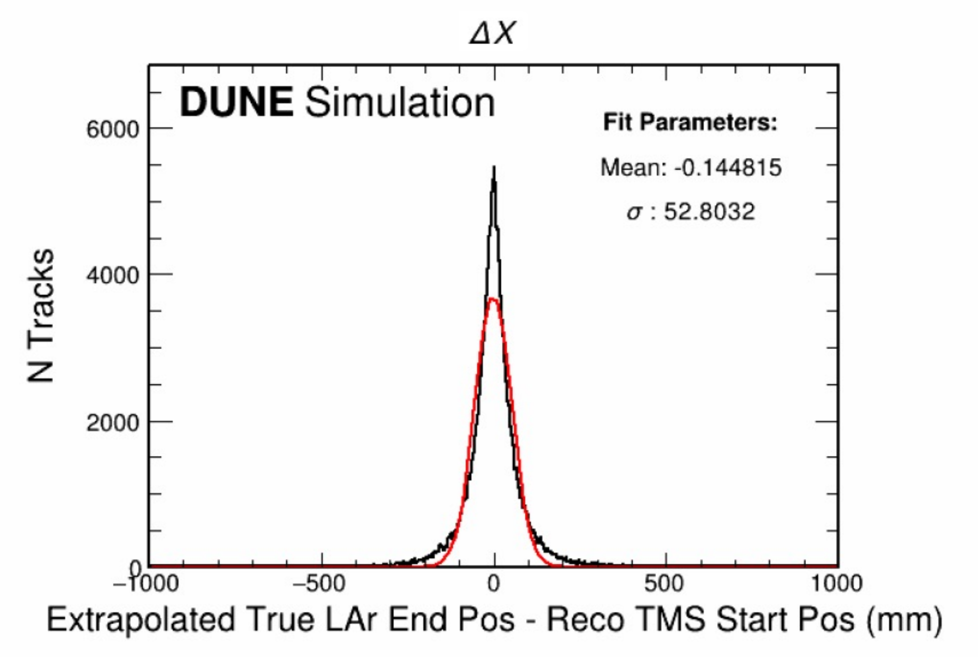


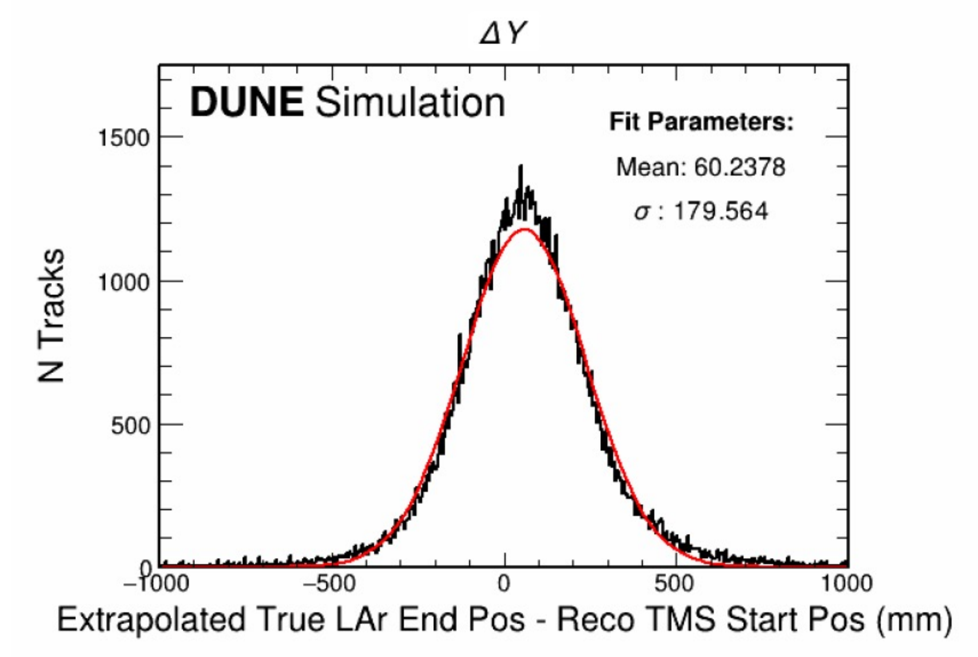


Basically no change in X – limited by multiple scattering.

Poor y-hit resolution in stereo degrades matching.   Will add horizontal strips at front.

ND-LAr / TMS Track Matching – Truth (stereo)





Basically no change in X – limited by multiple scattering.

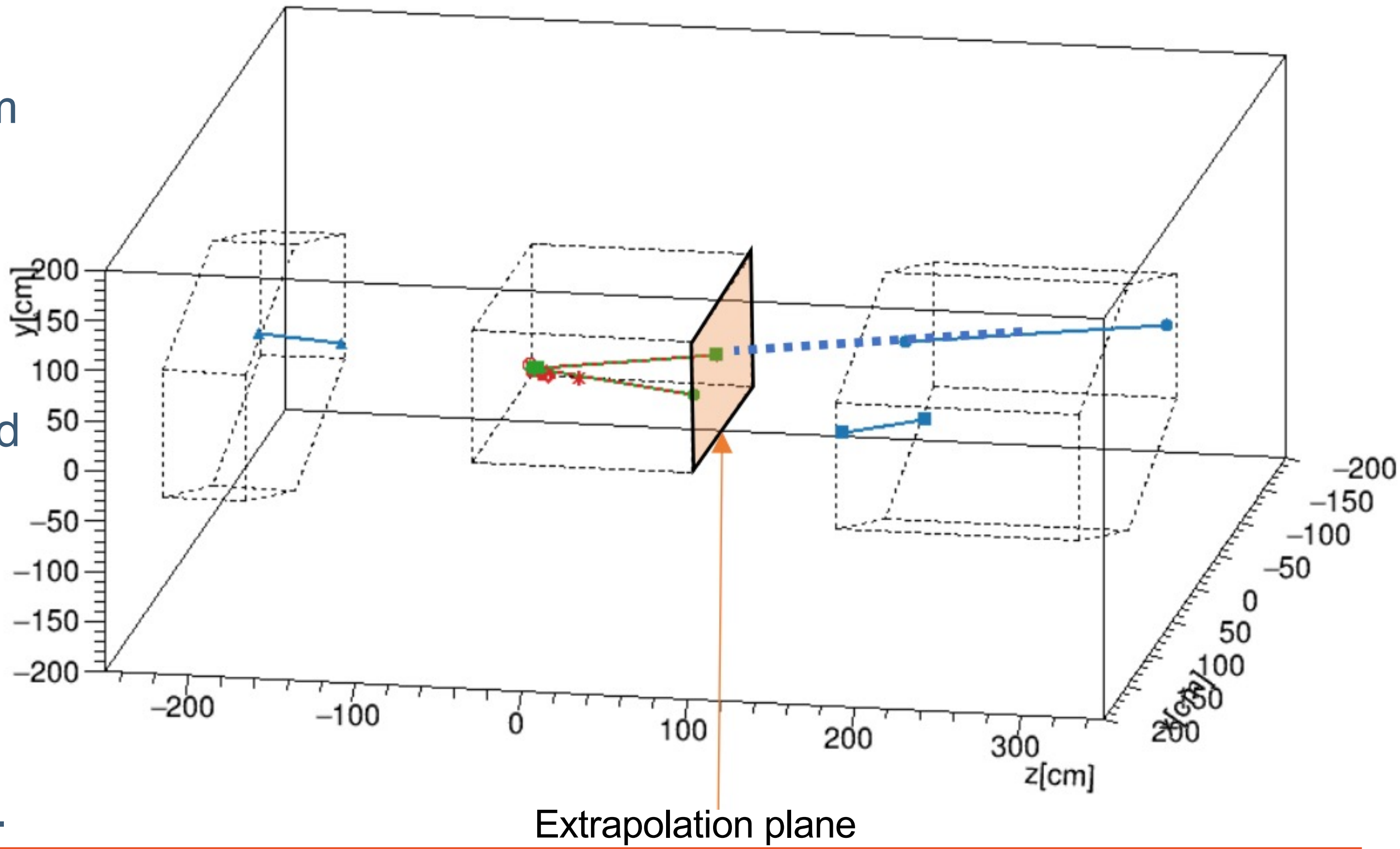
Poor y-hit resolution in stereo degrades matching. Will add horizontal strips at front.

ND Prototype Data - 2x2+MINERvA

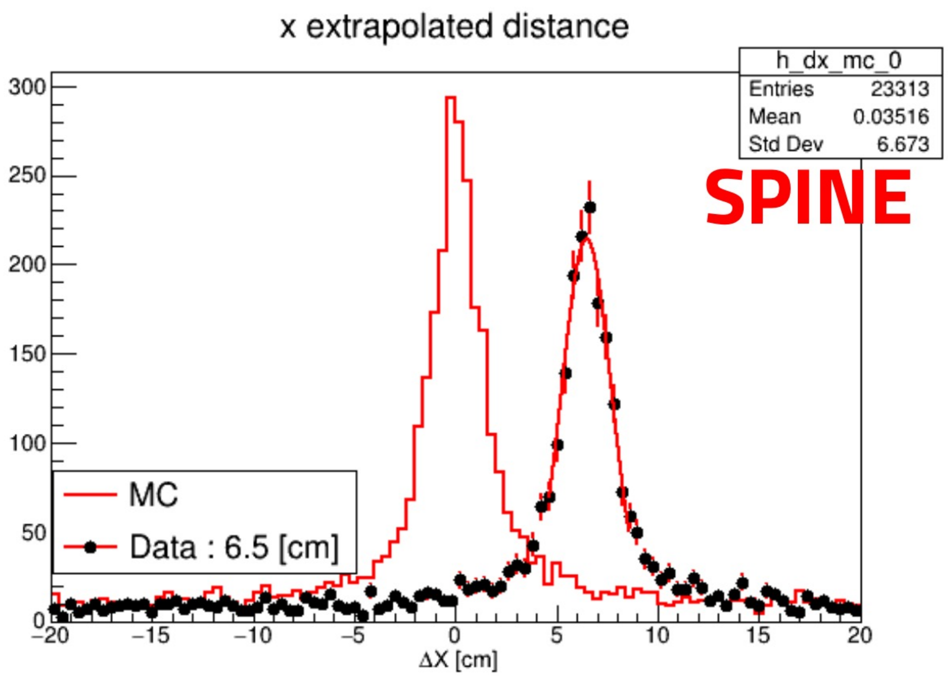
Most recent DUNE collaboration results from Noë Roy (York U).

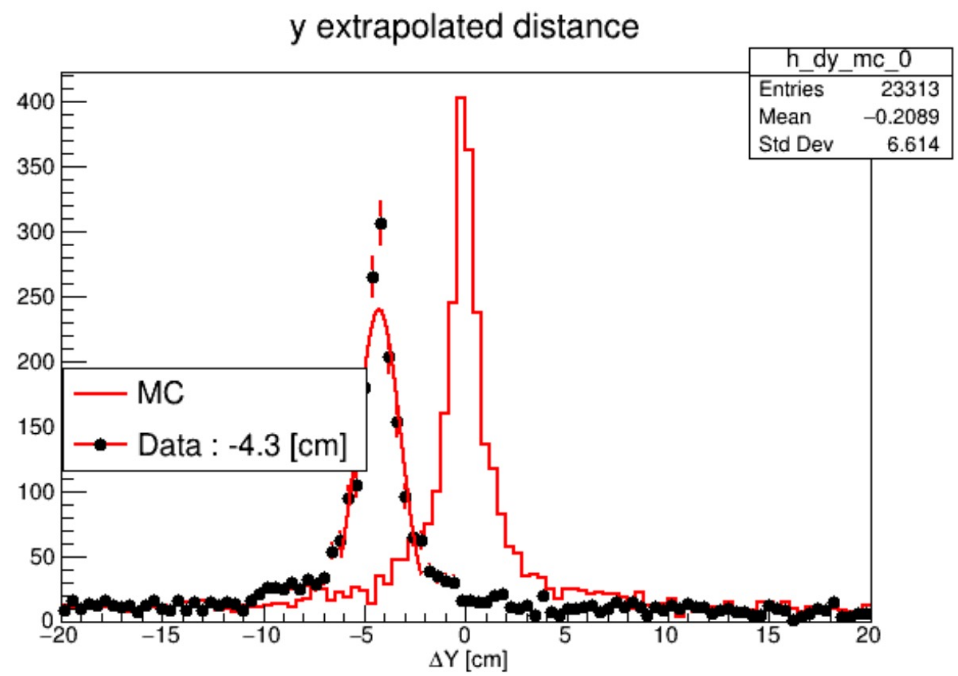
Solving the same problem, track matching between ND-LAr 2x2 and downstream MINERvA planes.

Rock muons – long tracks: Compare 2x2 and Minerva reco tracks.



ND Prototype Data - 2x2+MINERvA





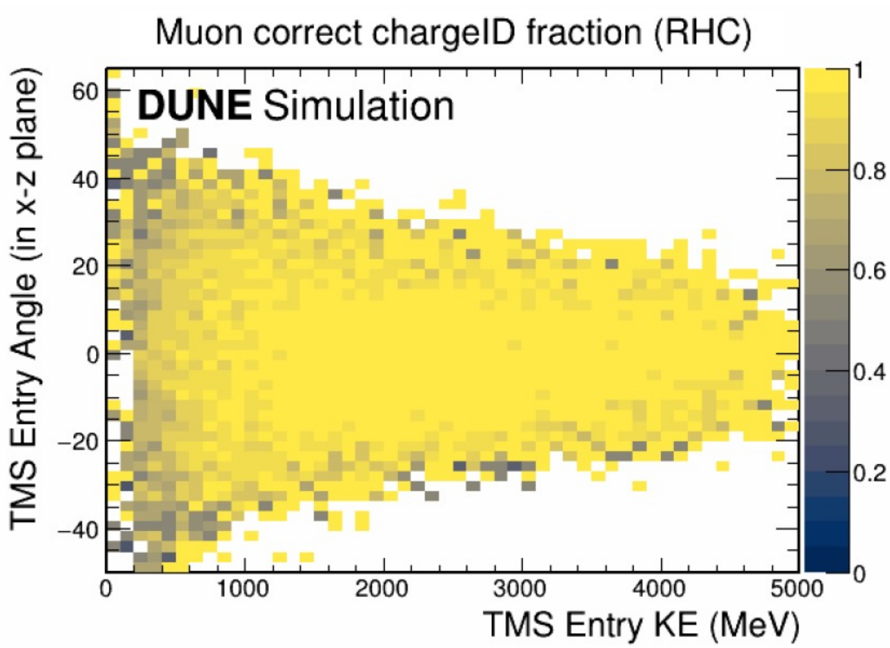
- Efficiency of 97%, purity of 99%
- Excellent extrapolated position resolution
- Identified small horizontal and vertical offsets between MINERvA and 2x2!

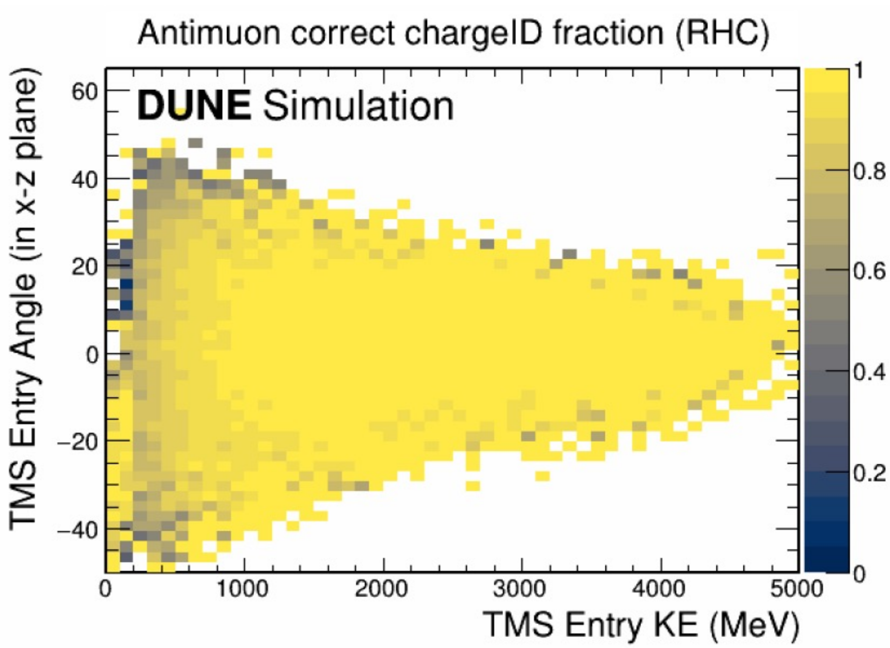
Sign Selection

Using signed distance between first and last hit

Sign selection is excellent for E > 500 MeV muons.

CDR steel stacking (40/60)
Stereo module orientation





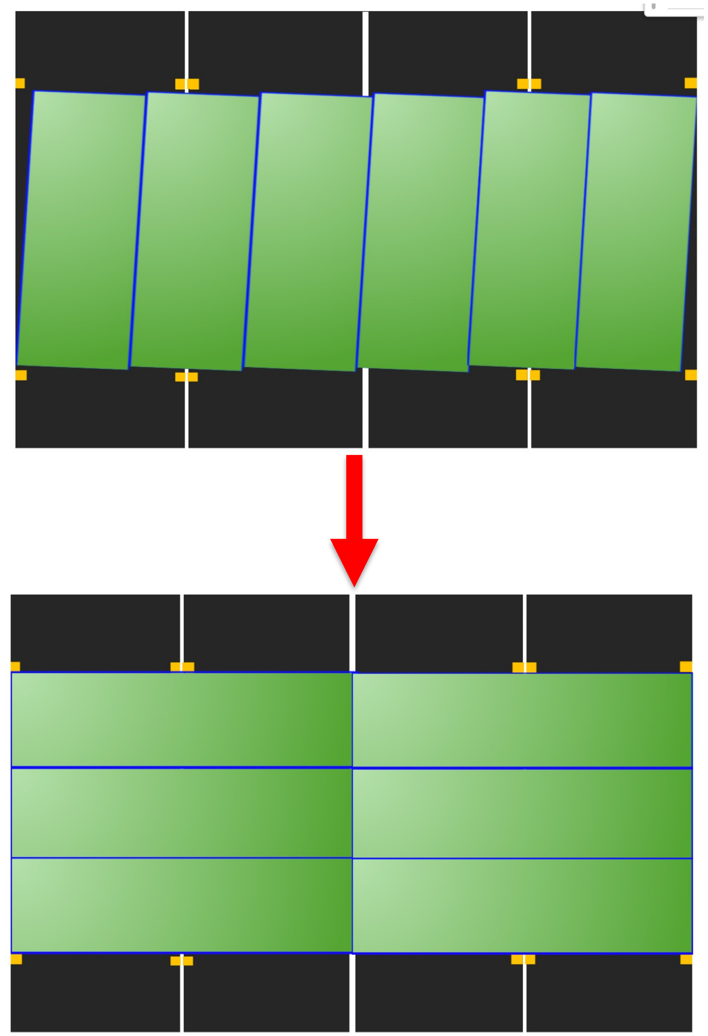
Module Orientation

Having strips oriented horizontally would benefit TMS in multiple ways:

- Track Matching
- Energy resolution
- Containment (acceptance)
- Isolating single interactions

We have evaluated a ”hybrid” geometry:

- UVUV… → YUVYUV…

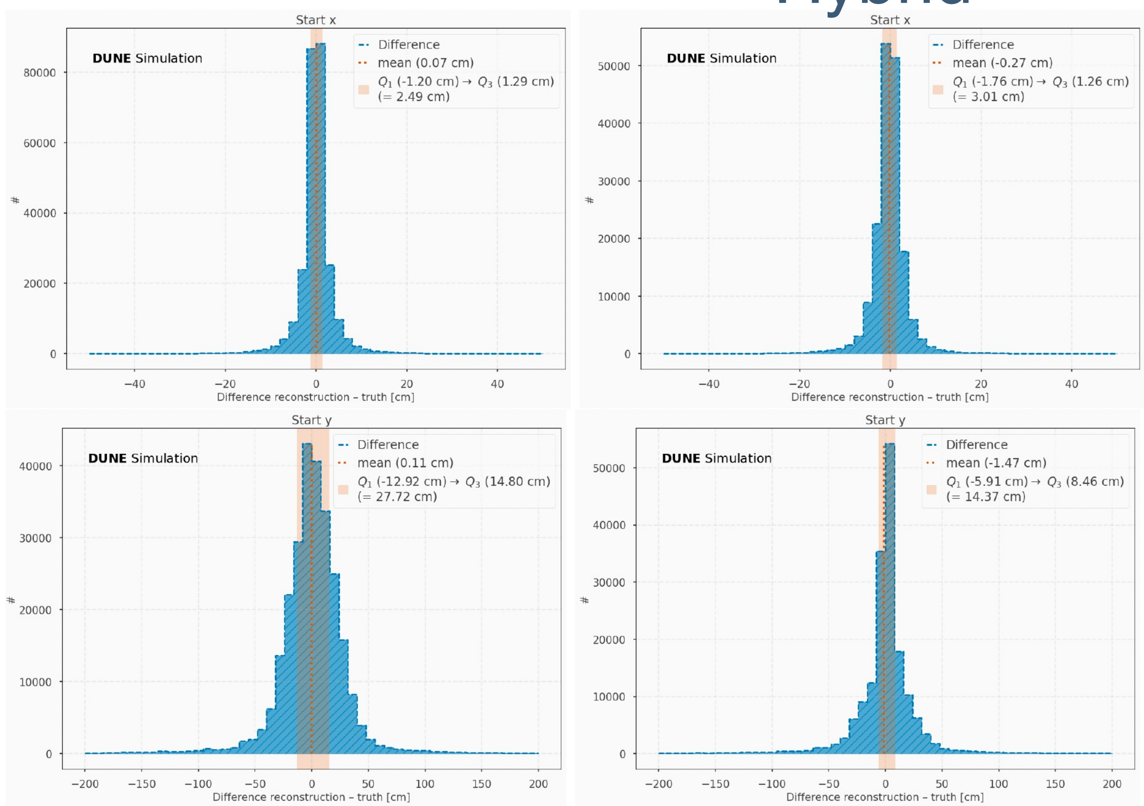


Module Orientation – Start point resolution

Stereo Hybrid

X

Y

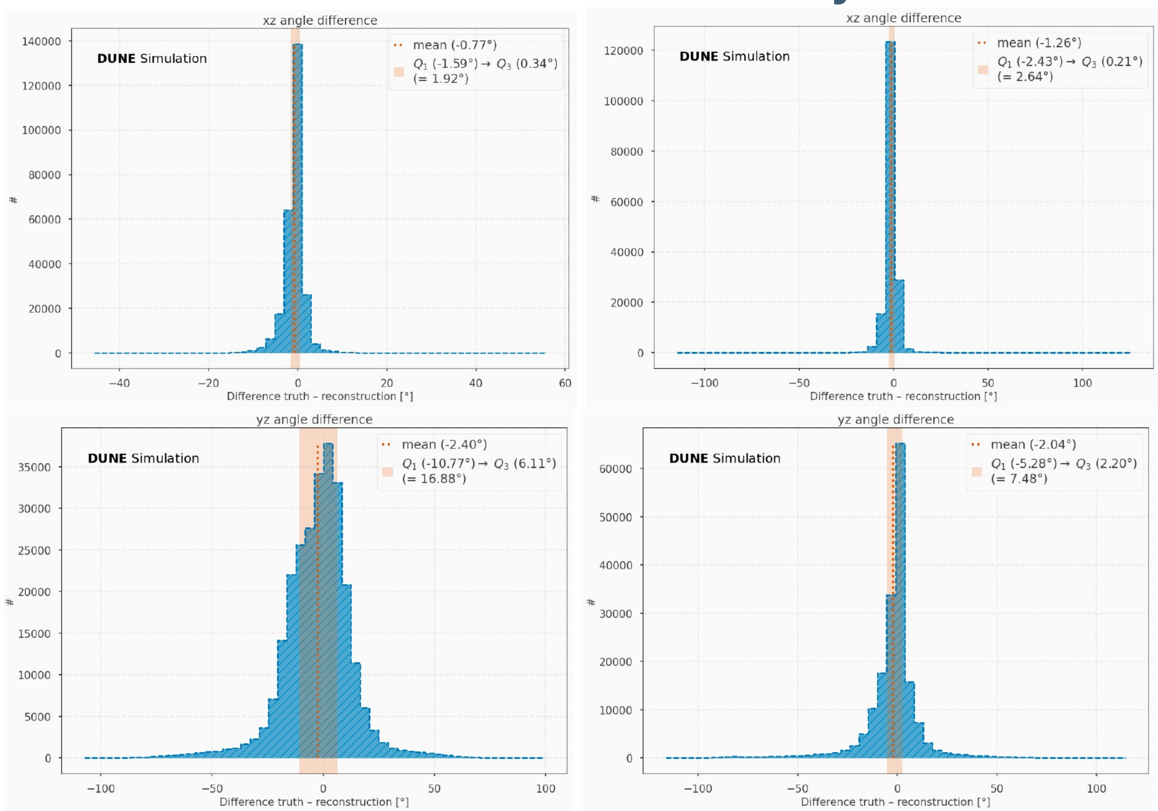


Module Orientation – Direction resolution

Stereo | Hybrid

XZ

YZ



Conclusion

1. Are the technical requirements and performance specifications suitably defined?

Many derive from the ND physics goals and the ones most relevant to the physics mission have been identified. However, some improvement here will be needed to sharpen the questions that will be pursued in further studies. (e.g. is acceptance instrumented region or containment region?)

Is there sufficient confidence that the design will meet these requirements/specifications?

The physics simulations, prototyping results, and performance of previous plastic scintillator detectors give confidence that the design will meet the requirements.

Conclusion

2. Are lessons from past plastic scintillator detectors and recommendations from past reviews suitably applied?

Numerous important modifications to the CDR design have been made based on feedback from the three internal reviews. The consortium brings considerable expertise from past plastic scintillator detectors like MINOS, MINERvA, and T2K.

3a. Are interfaces adequately identified and documented at a level suitable for preliminary design, particularly with regard to: Maintaining adequate reconstruction capabilities for muons exiting the ND-LAr active volume?

Simulation studies and prototyping results indicate that ND-LAr + TMS track matching will be sufficient to meet the physics goals.