Physics performance of the DUNE "Day 1" Near Detector

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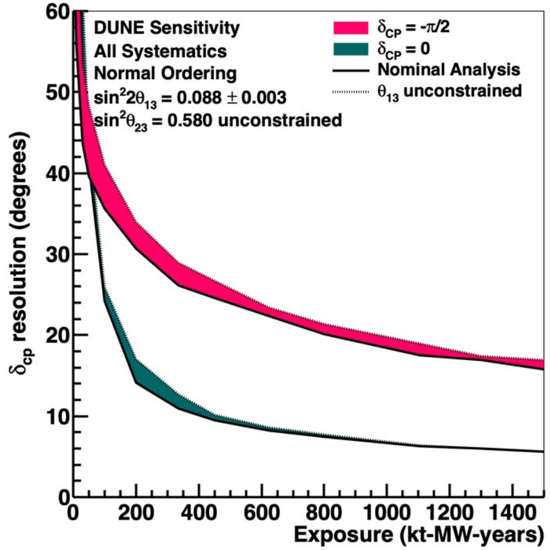
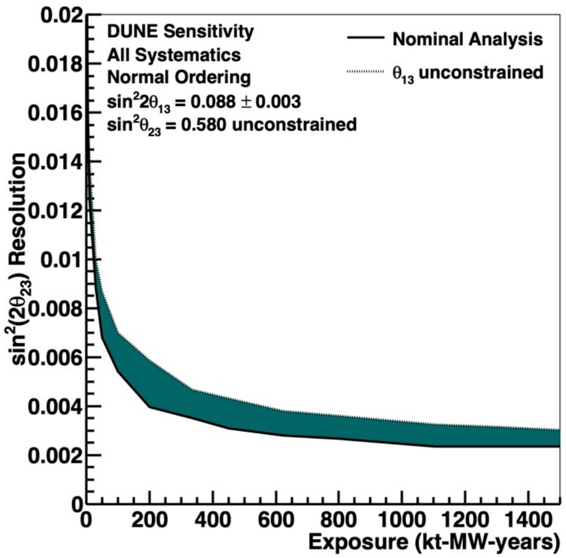
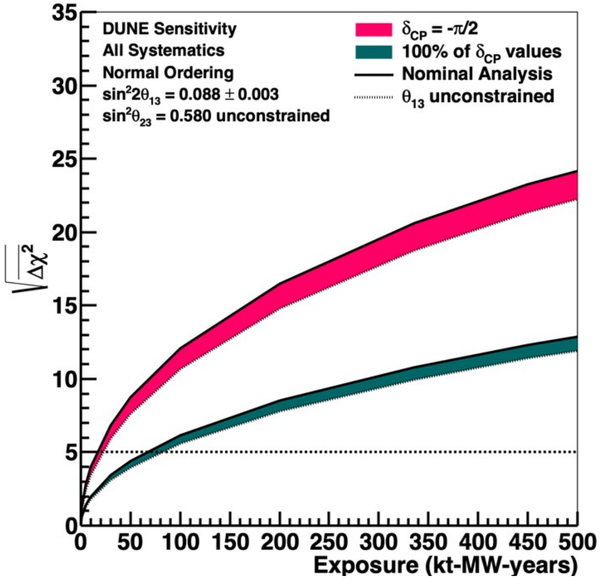
DUNE Oscillation Physics: long term

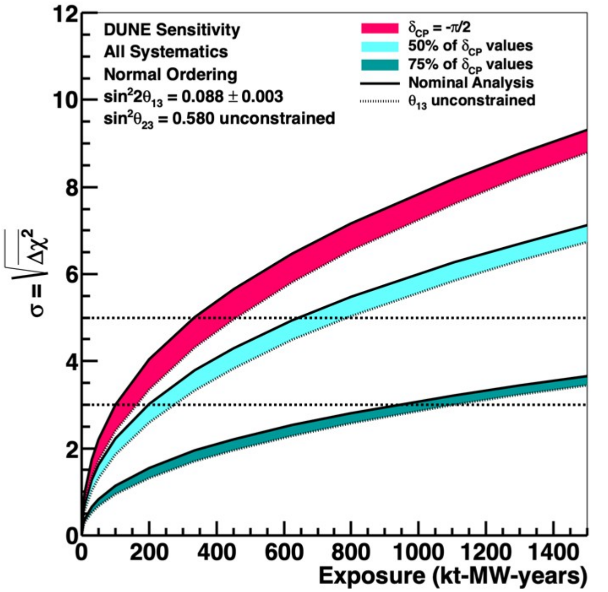




- In the long term, DUNE will make precision measurements of oscillation paramters, including δ_{CP}
- Required exposure for beginning to think about precision measurements is few 100s kton-MW-years
- This requires few-percent constraints on flux and cross section uncertainties, achievable with a robust near detector program

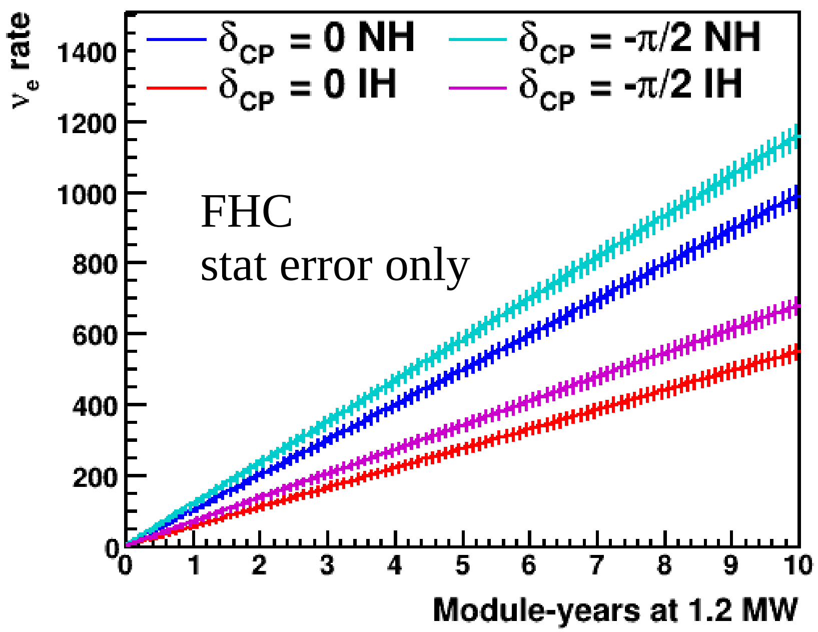
DUNE Oscillation Physics: short term & "Day 1"

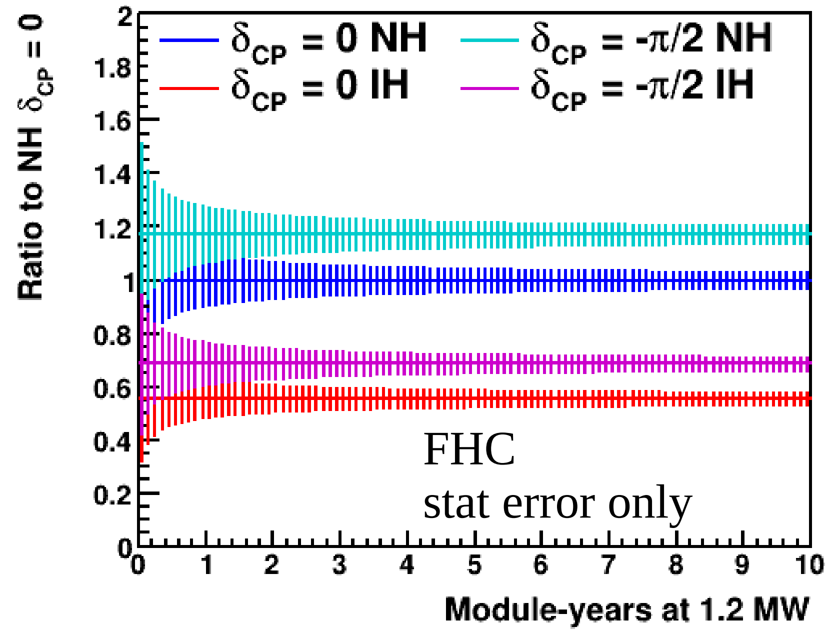




- Due to its baseline and beam intensity, DUNE can make high-impact measurements in the first 1-3 years of operation
- In particular, with ~70 kton-MW-yrs exposure, DUNE can
  - Resolve the neutrino mass ordering at >5σ significance, regardless of true values of other parameters
  - Observe CP violation at 3σ if δ_{CP} is nearly maximal

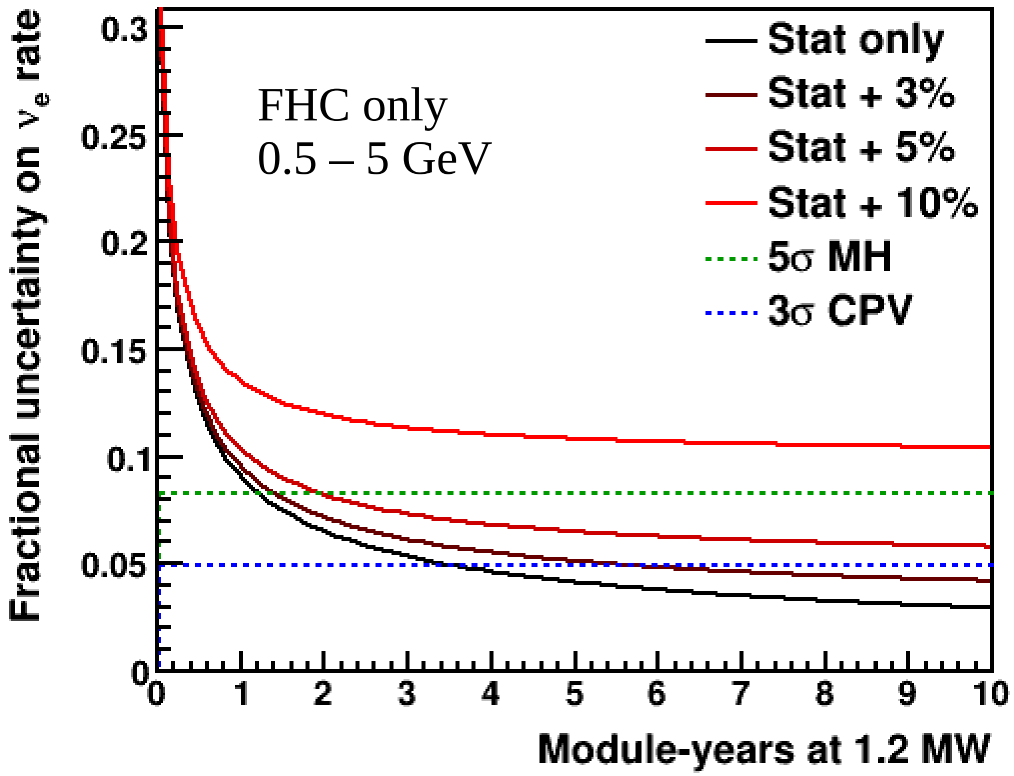
Early sensitivity to MH, CPV is dominated by FD ν_e rate





- Including background, maximal CPV is ~18% effect on ν_e rate in FHC, MH is ~30% effect
- ~100 events per module-year at 1.2 MW for NH

Impact of systematics on rate measurements



- Short-term physics goals require 5-10% uncertainties on oscillated ν_e rate
- This is significantly smaller than *a priori* uncertainties, and comparable to the constraints achieved by current experiments
- Sufficient to measure $\Phi\times\sigma$ as a function of E_ν between 0.5 and 5 GeV and extrapolate to FD

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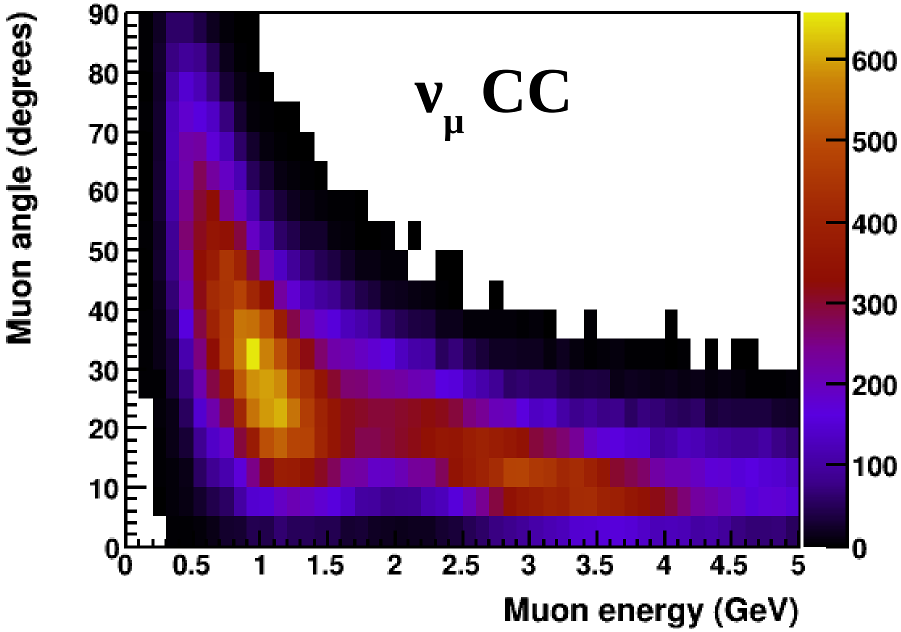
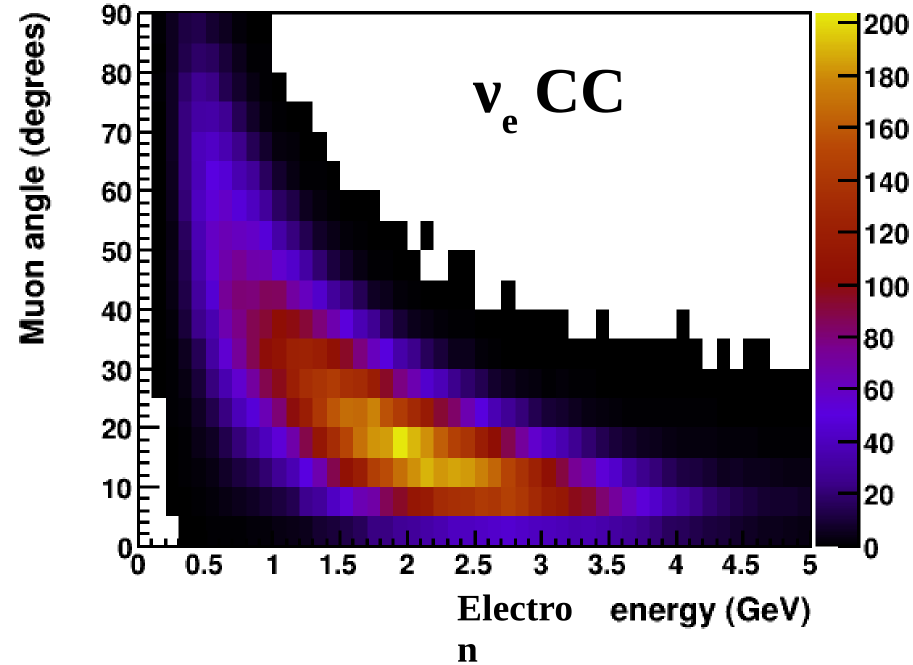
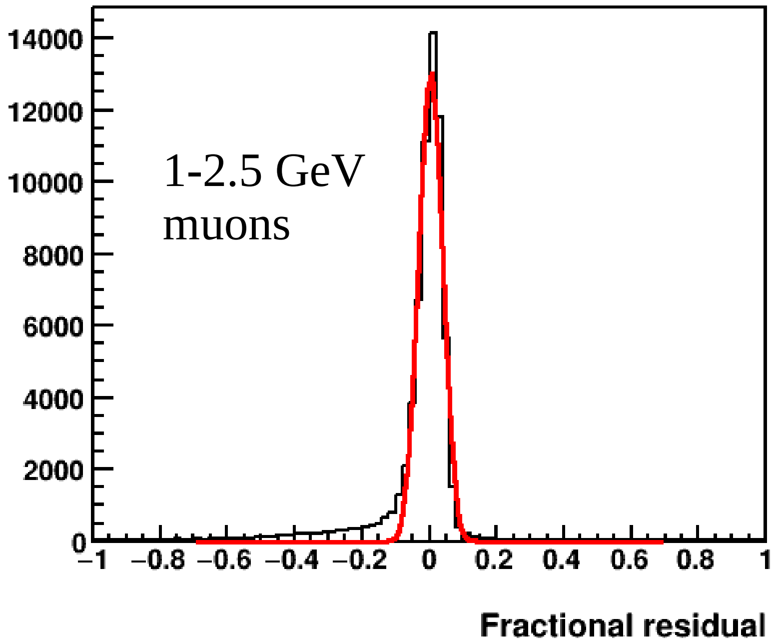
Kinematics of FD oscillated samples: 1-3 GeV, 5-40°

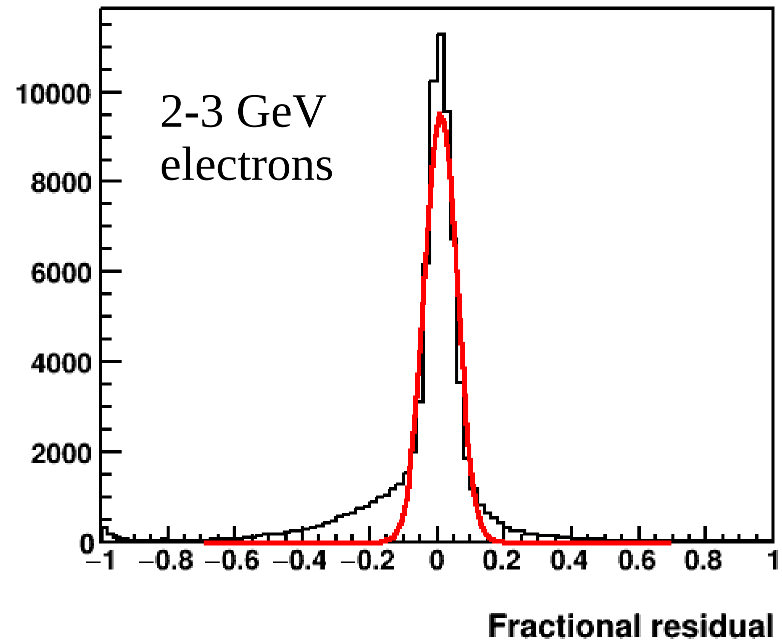




- Most important kinematic region is lepton energy between 1-3 GeV, and most events are relatively forward
- Almost no appearance signal above 5 GeV; there is a tail on the ν_μ distribution, but there is no oscillation

FD lepton resolution with current reconstruction algorithms: 4-6%

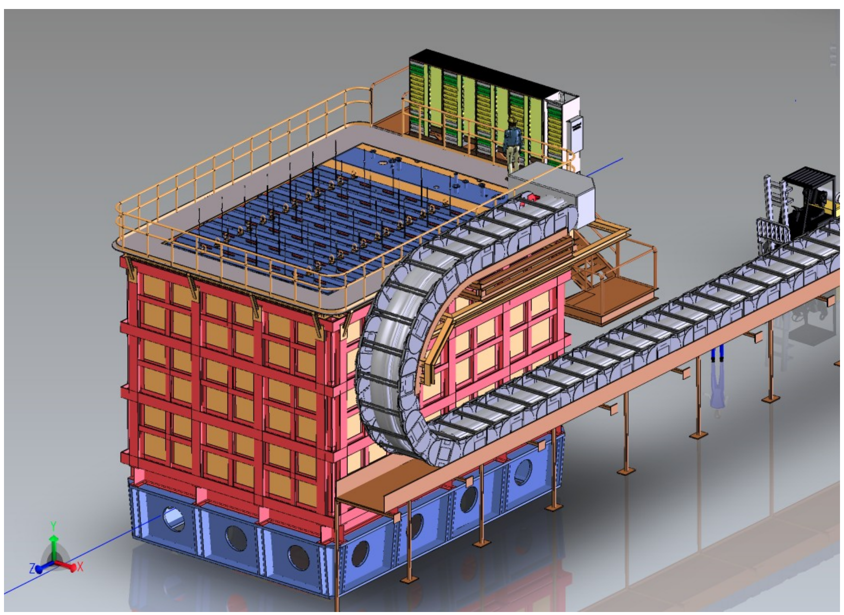


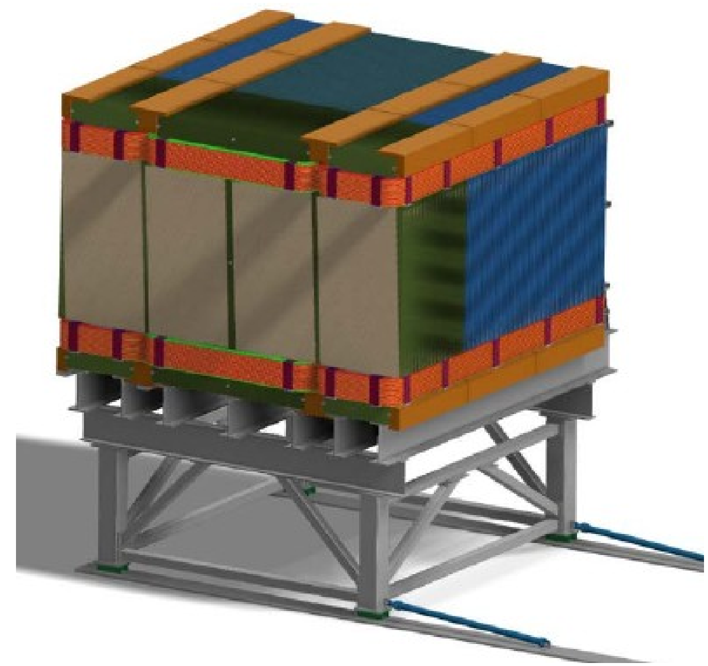


- Muon and electron energy resolution is ~4-6%
- Tail due mainly to reconstruction failures can likely be reduced with more effort
- Largely flat as a function of energy until muons stop being contained in a module (10-15 GeV)

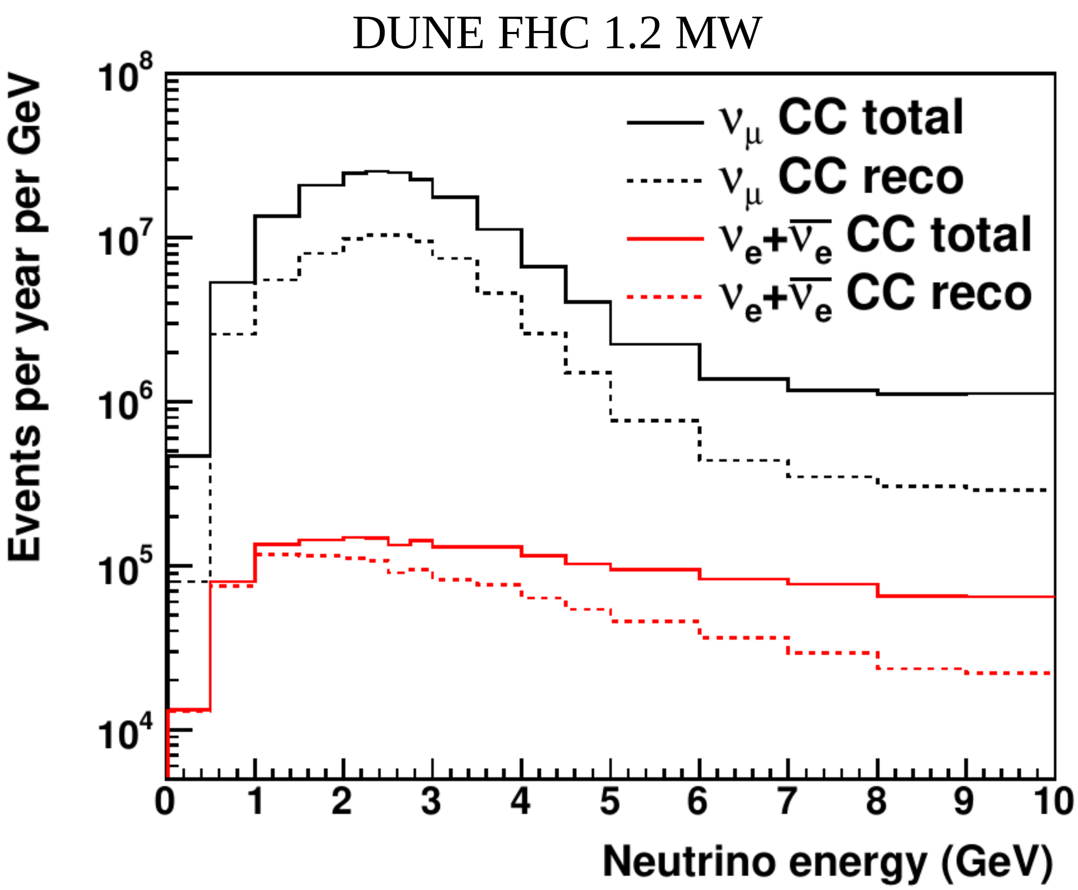
“Day 1” ND performance requirements

- Acceptance: Broad acceptance covering full neutrino interaction phase space up to ~5 GeV neutrino energy
- Resolution: Muon momentum resolution comparable to far detector ~4-6% up to momenta of ~4 GeV/c



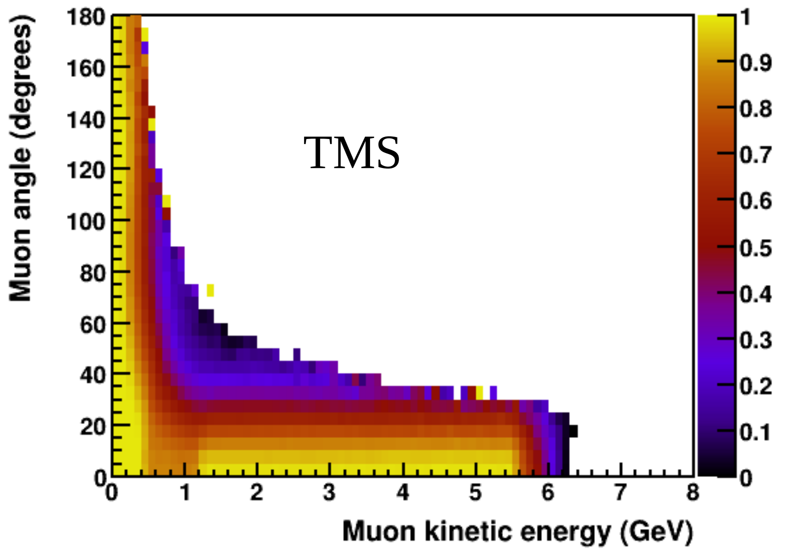


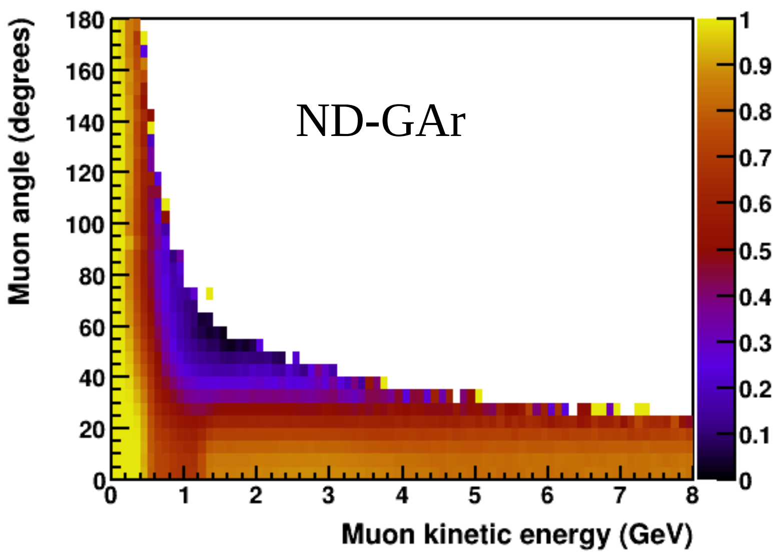
ND-LAr event rates: >10M fully-reconstructed events per year



- ND will accumulate huge samples very quickly, and ~15M CC ν_μ events per year with fully-contained hadronic showers + TMS muon
- ~1M CC ν_e events per year
- Sufficient rate to do highly exclusive multi-sample analysis even in first 1 year of running
- ND-LAr physics program is basically unchanged from what is described in CDR

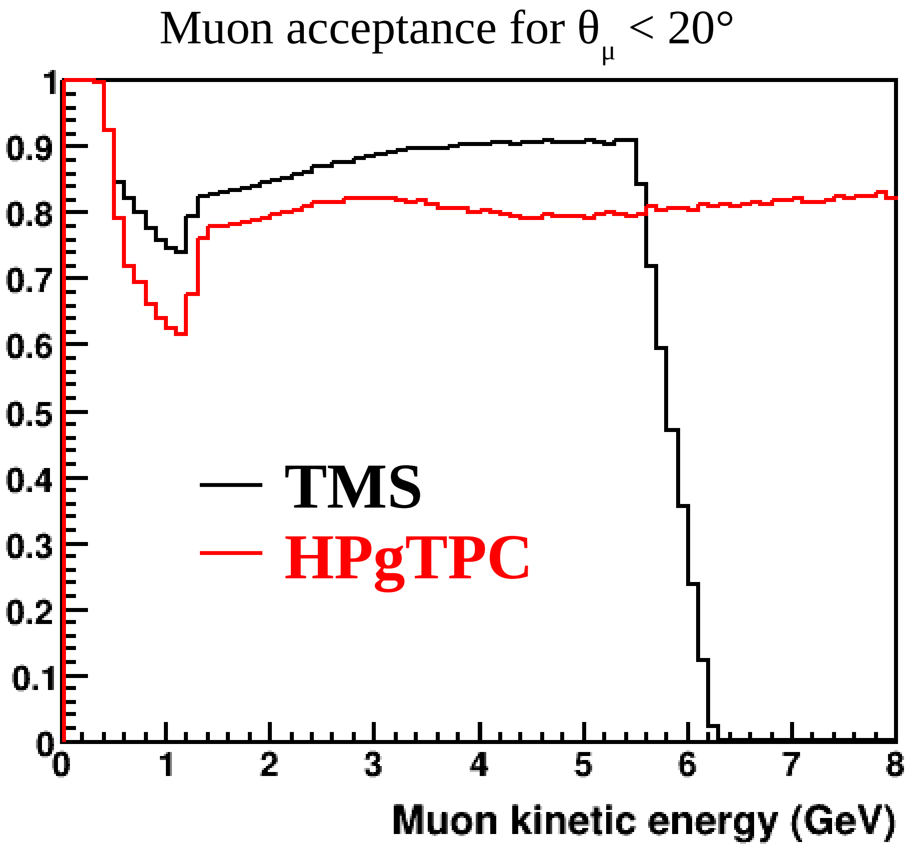
Muon acceptance in ND-LAr + TMS





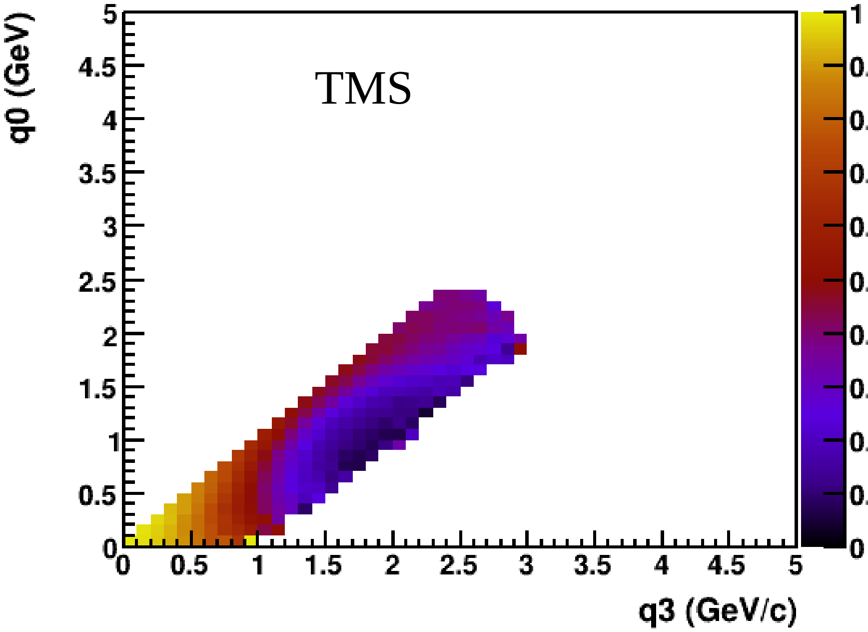
- TMS acceptance is better than ND-GAr because
  - Transverse dimensions are better matched to ND-LAr
  - Passive material between detectors is ~50% less (magnet cryostat)
- Dip around 1 GeV forward region is due to muons stopping in LAr cryostat
- Low acceptance region is wide angles and moderate energy – but translational and φ symmetry mitigate this somewhat

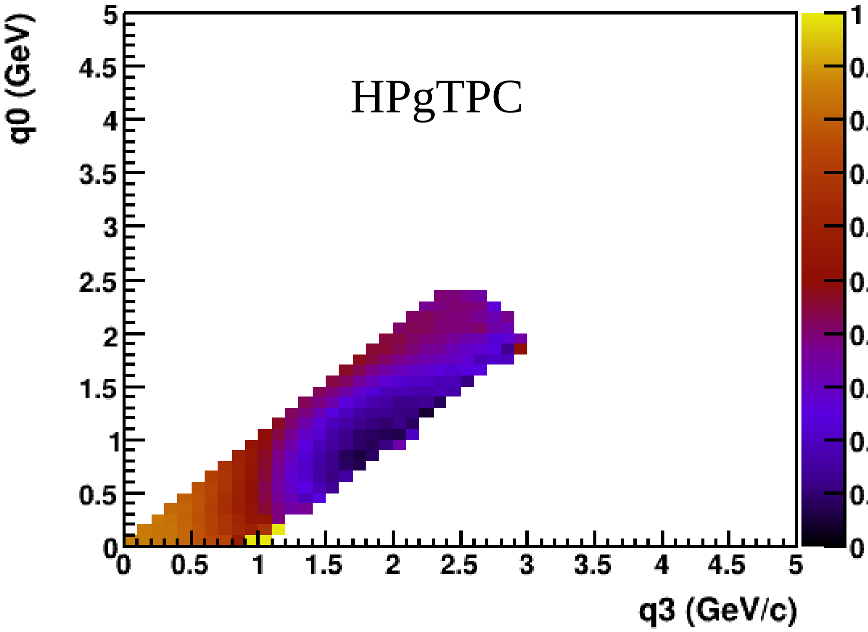
Muon acceptance in ND-LAr + TMS



- Dip region difference is due to the passive material, in particular the lack of a magnet cryostat in TMS
- Plateau is higher in TMS due to transverse dimensions
- Fall-off at 5-6 GeV assuming only reconstruction by range in TMS, curvature extends up to 10s GeV in HPgTPC

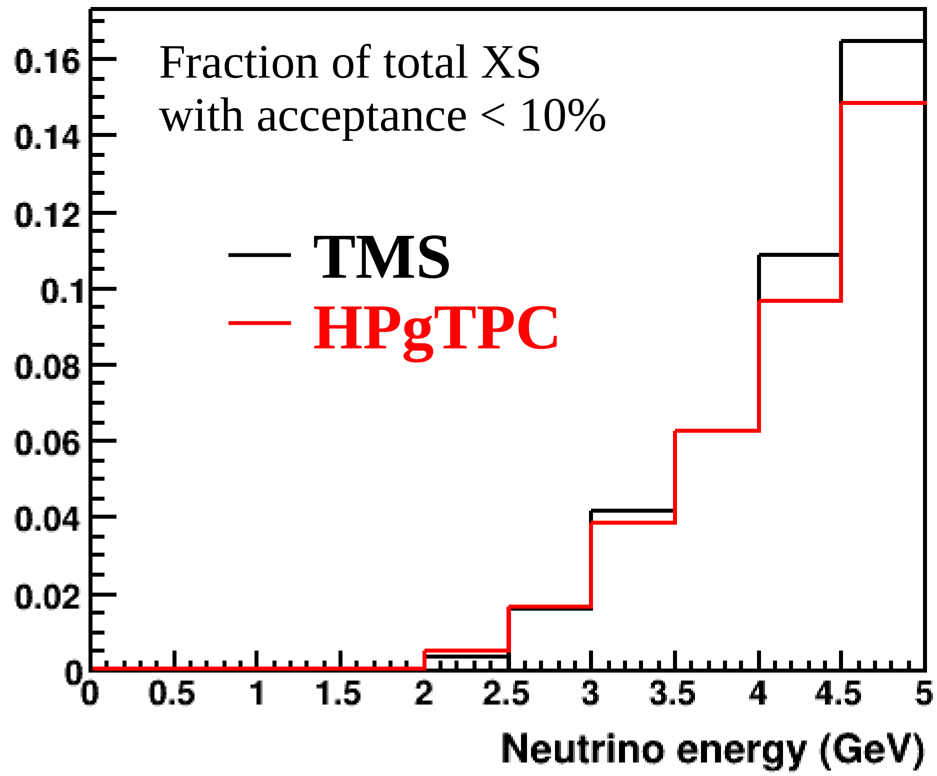
Acceptance in cross section phase space: 2.0 < E_ν < 2.5 GeV





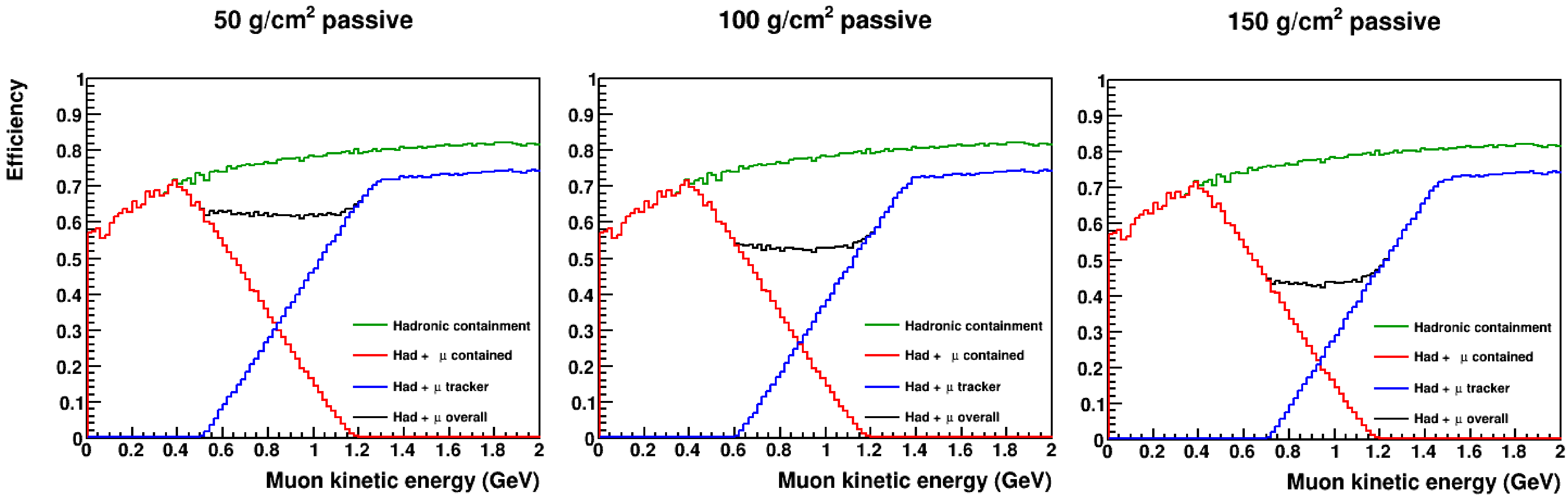
- We can look at the acceptance in slices of neutrino energy in the interaction kinematic space of energy transfer (q0) and 3-momentum transfer (q3)
- It is important to avoid regions in this space where the acceptance is very nearly zero

Fraction of total cross section in regions with very low acceptance



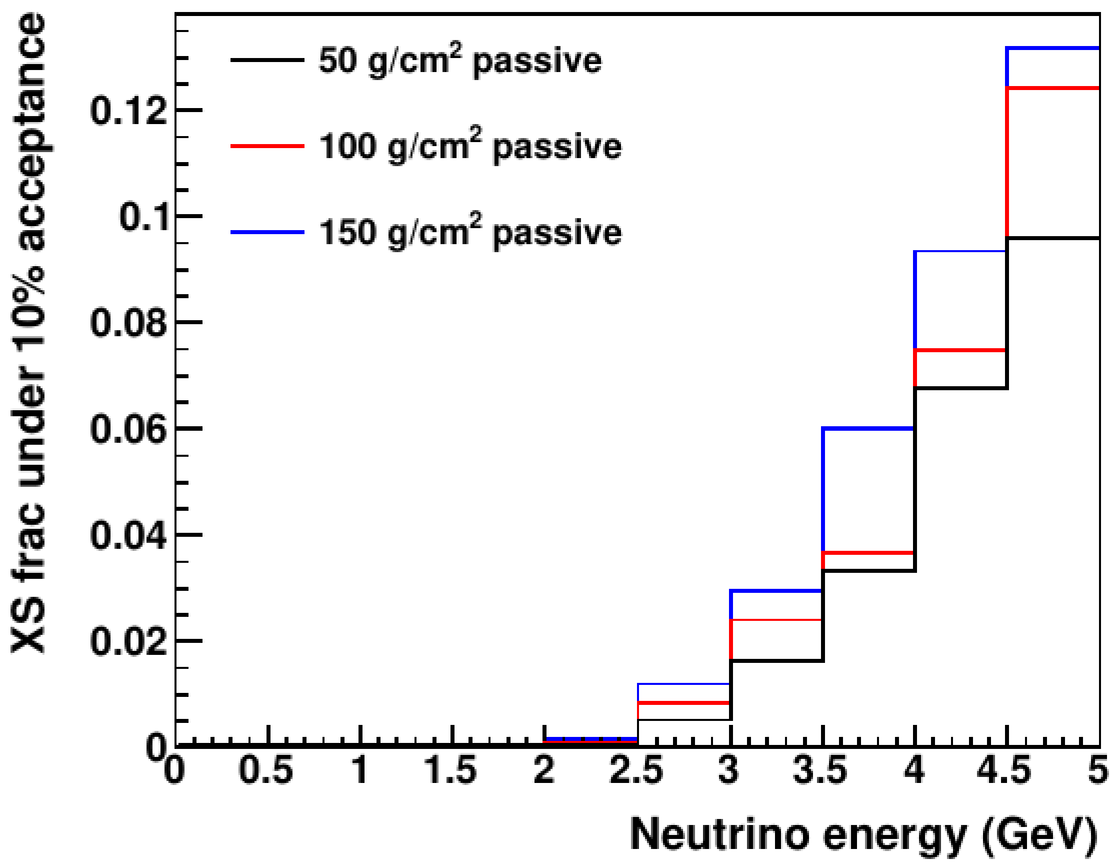
- This includes both the lepton reconstruction and hadronic shower containment
- In the flux peak, <2% of the cross section is in a very low acceptance region
- This increases as you get into the tail largely because of hadronic shower leakage
- TMS and HPgTPC are virtually identical

ND-LAr cryostat downstream wall



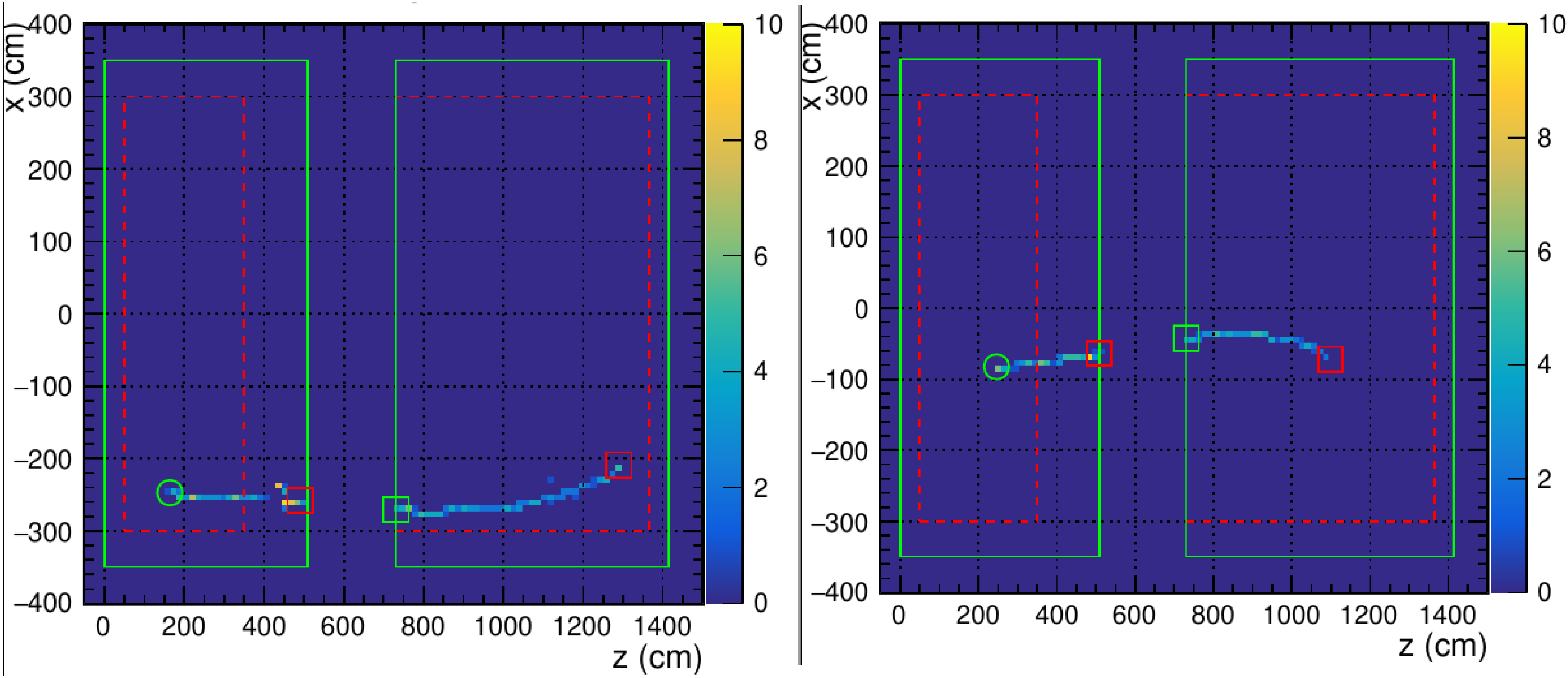
- Forward muons (θ < 20°) for different amounts of passive material (uninstrumented LAr + membrane + foam + steel structure)
- Tracker-matched (blue) is shifted to the right as tracker is effectively farther from LAr active volume
- Assumes TMS dimensions – separate effect of transverse size and passive material

Fraction of cross section with low acceptance



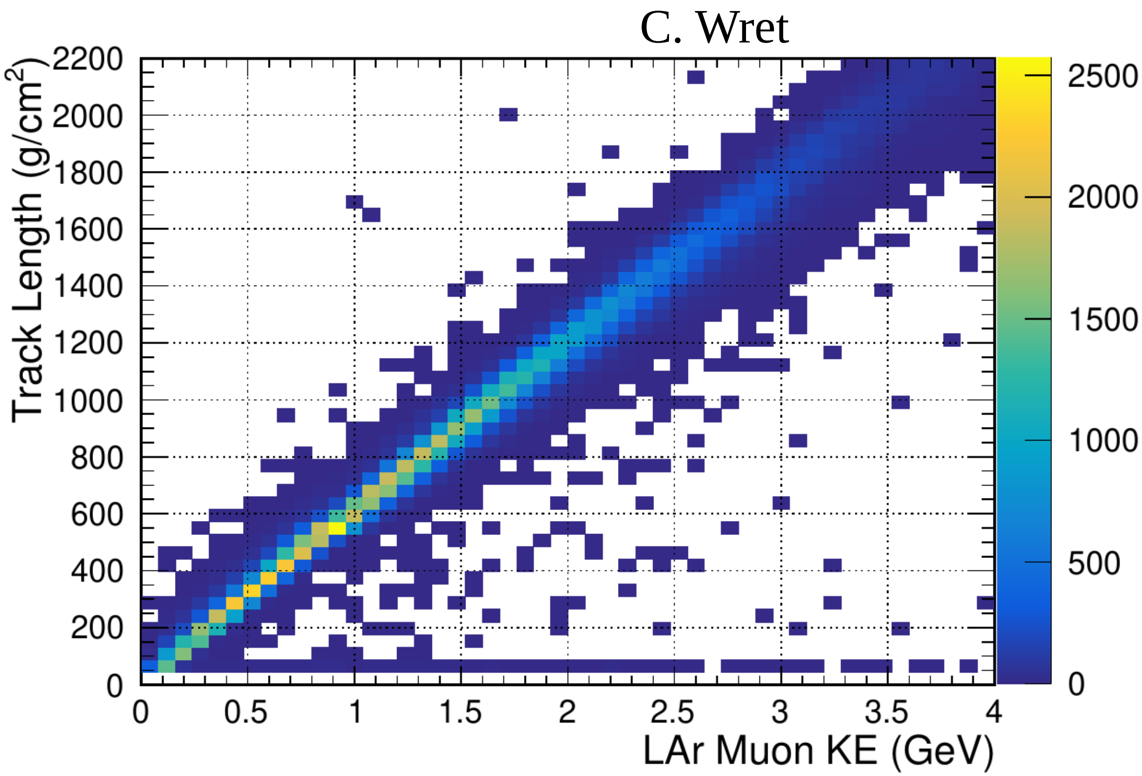
- Increasing cryostat thickness pushes more events into regions of very low acceptance, especially around falling edge of flux peak
- Target is 50g/cm^2 for LAr cryostat, with additional ~30g/cm^2 in current ND-GAr magnet design

Muons in ND-LAr + TMS (top view)



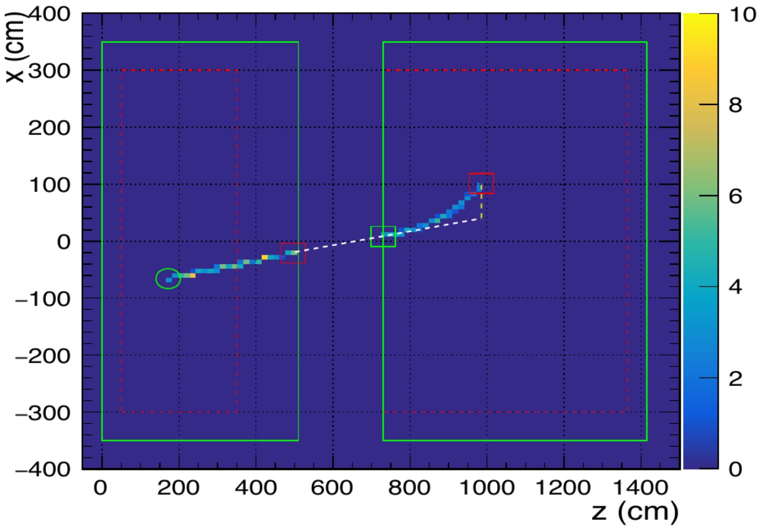
- Simulation of neutrino interactions in ND-LAr fiducial volume, with Geant4 simulation of particles in ND-LAr + TMS
- Can see bending of tracks in magnetic field
- Start point and end point of tracks in each detector is shown

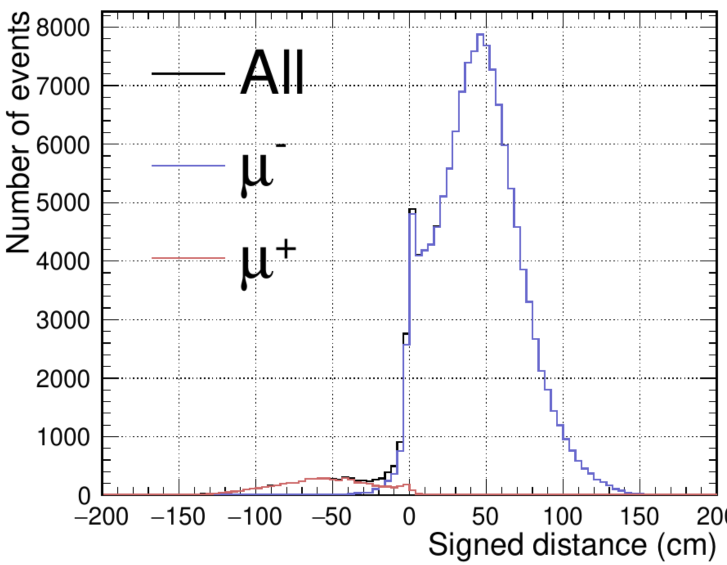
First look at momentum resolution



- Muon energy is measured by range – curvature is enough to get the sign but not enough to meaningfully inform the energy reconstruction
- Track the muon through the LAr, material between detectors, and TMS
- Track total areal density correlates with true muon kinetic energy with resolution of ~5%

Preliminary sign selection

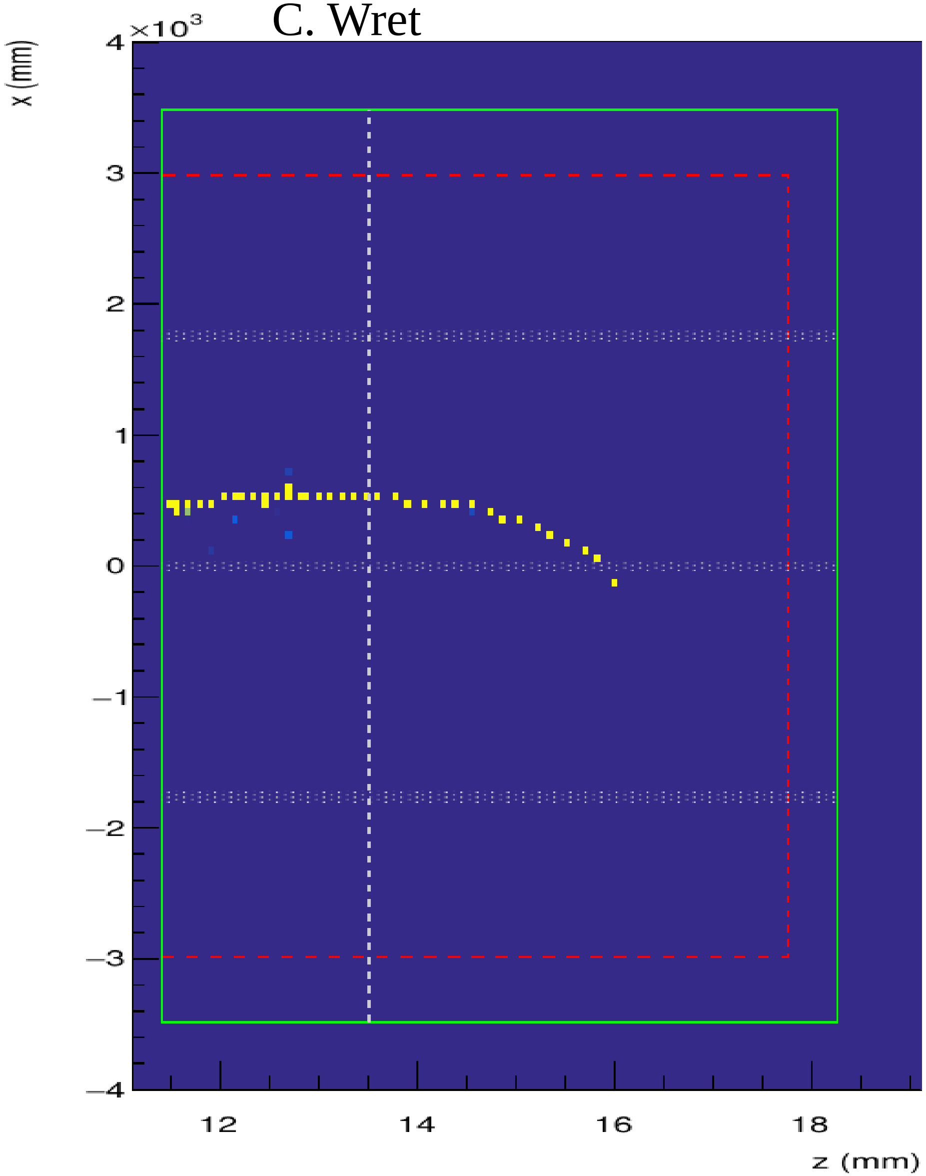




- Looks for distance between track endpoint in the bend plane transverse to the track direction as determined by propagating from LAr
- Higher momentum tracks have less bend, but greater track length, and sign ID actually improves with energy
- 99.7% efficient above 1 GeV with wrong-sign reduced by ~99%
- Poor rejection for very short tracks, but most wrong-sign is at higher neutrino energy

First attempt at pattern recognition

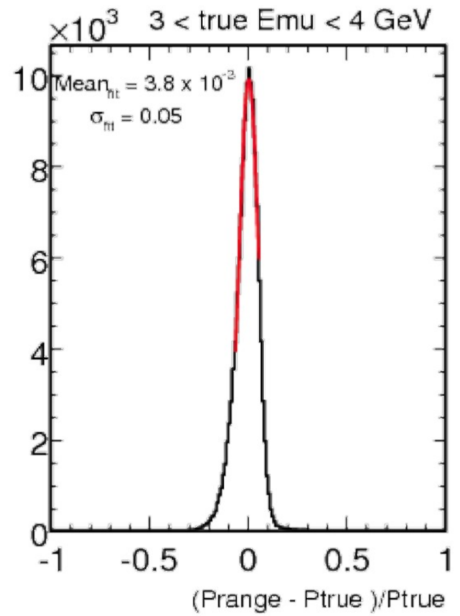
C. Wret

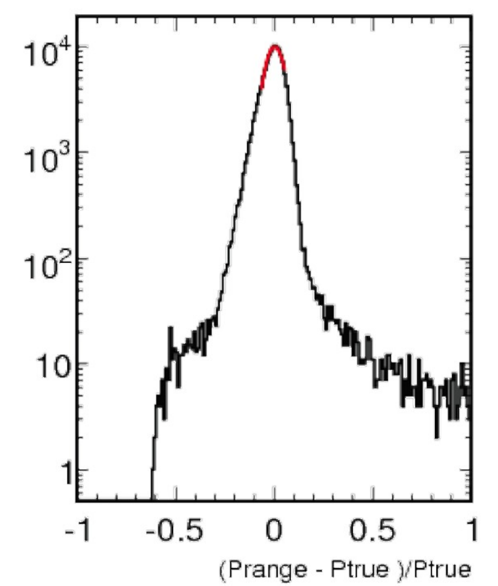


- Two algorithms have been written and work on TMS simulation, one based on A*, and one that is a Hough transform
- Yellow hits are correctly associated to track object using A*-based algorithm
- Work ongoing on implementing Kalman filter algorithm for momentum fitting

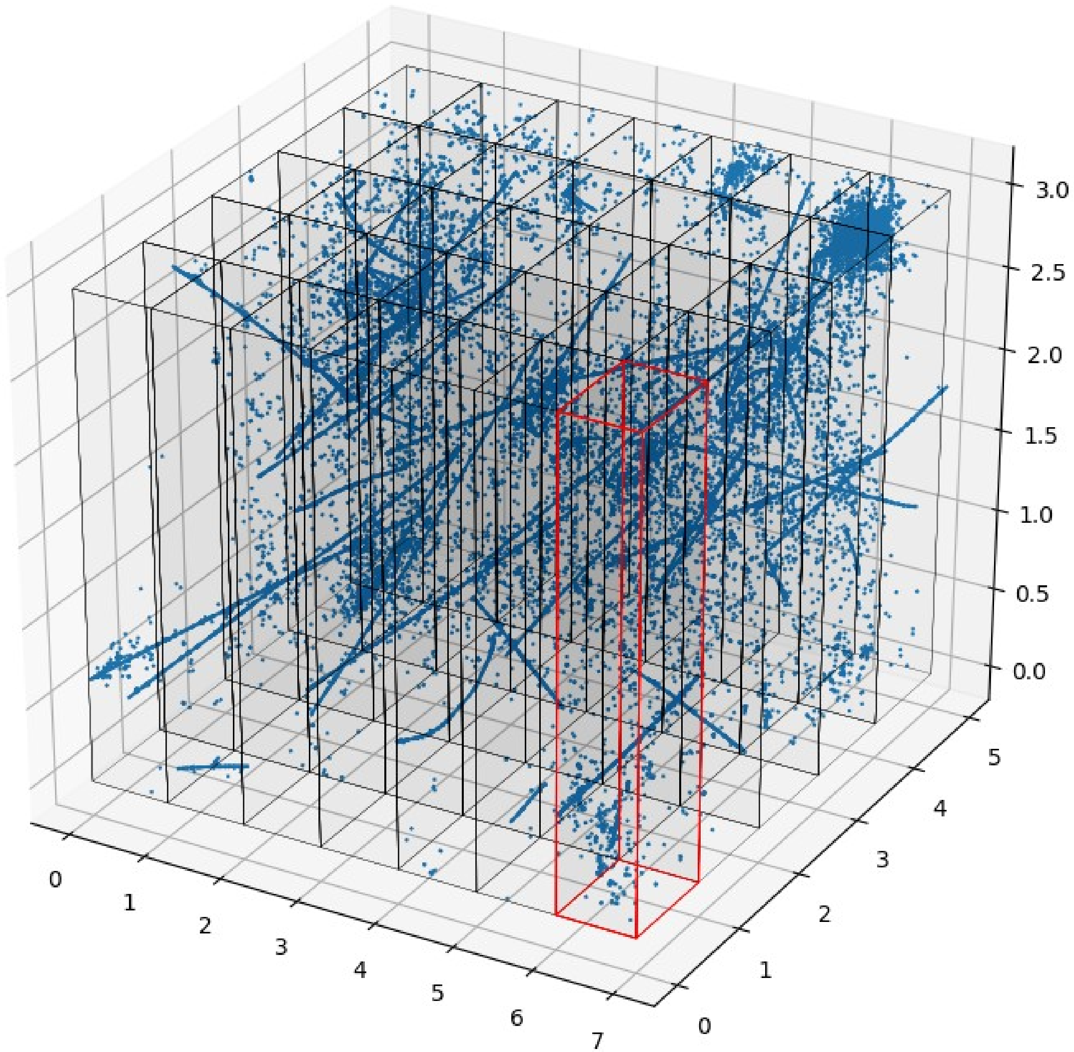
MINOS achieves ~5% resolution with similar detector

- MINOS near detector is similar design to TMS
- In relevant energy range of ~few GeV, MINOS achieved ~5% momentum resolution by range
- Expect very similar performance in TMS with full reconstruction



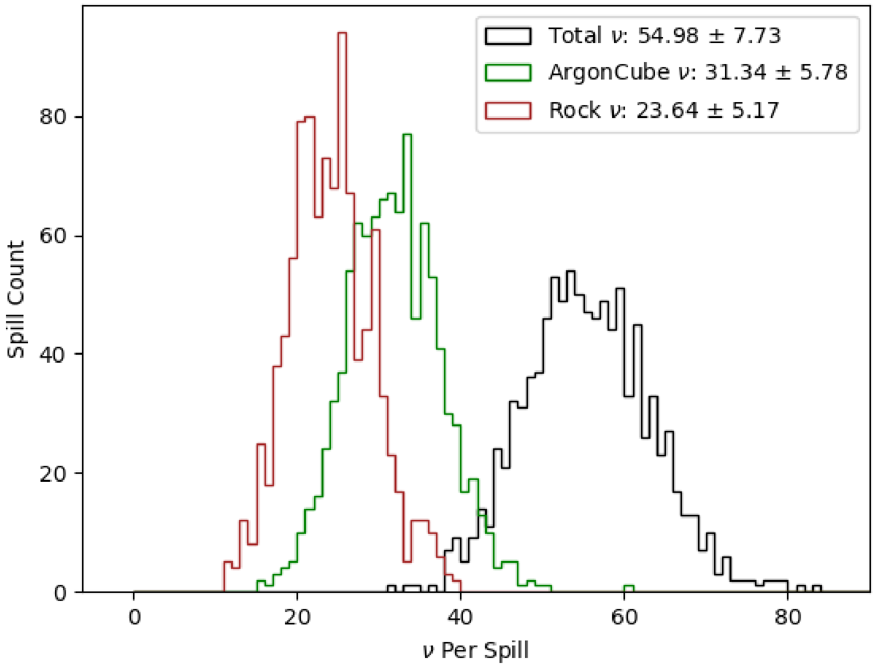


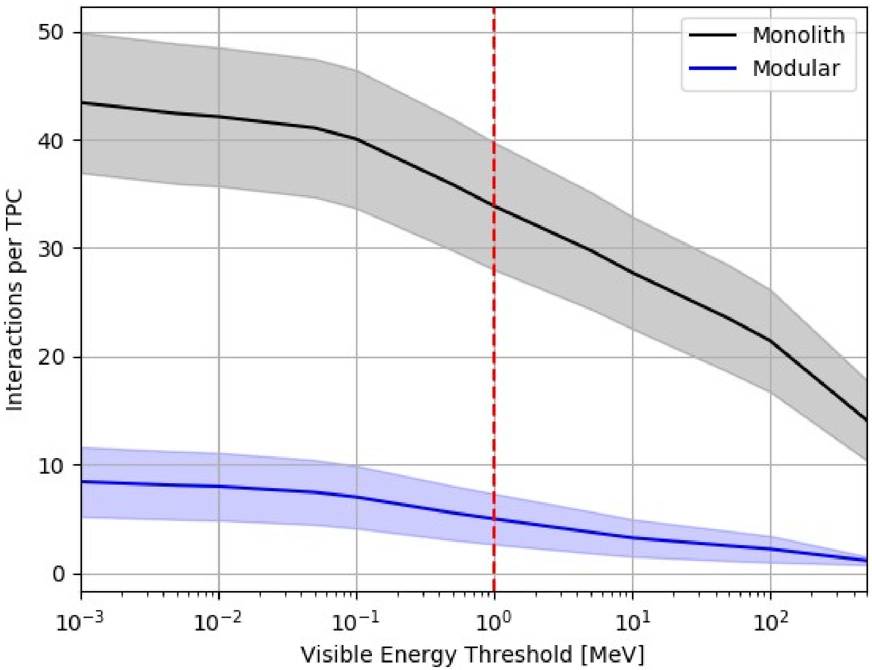
Timing and pileup in ND-LAr



- ND-LAr is very busy, and charge readout is slow
- Intrinsically 3D readout → signals don't actually overlap, even though 2D projected event displays look scary
- Challenge is associating charge signals to the correct neutrino interaction, especially when neutral particles create gaps in signals

Modularity of optical readout reduces interactions from ~35 to ~5





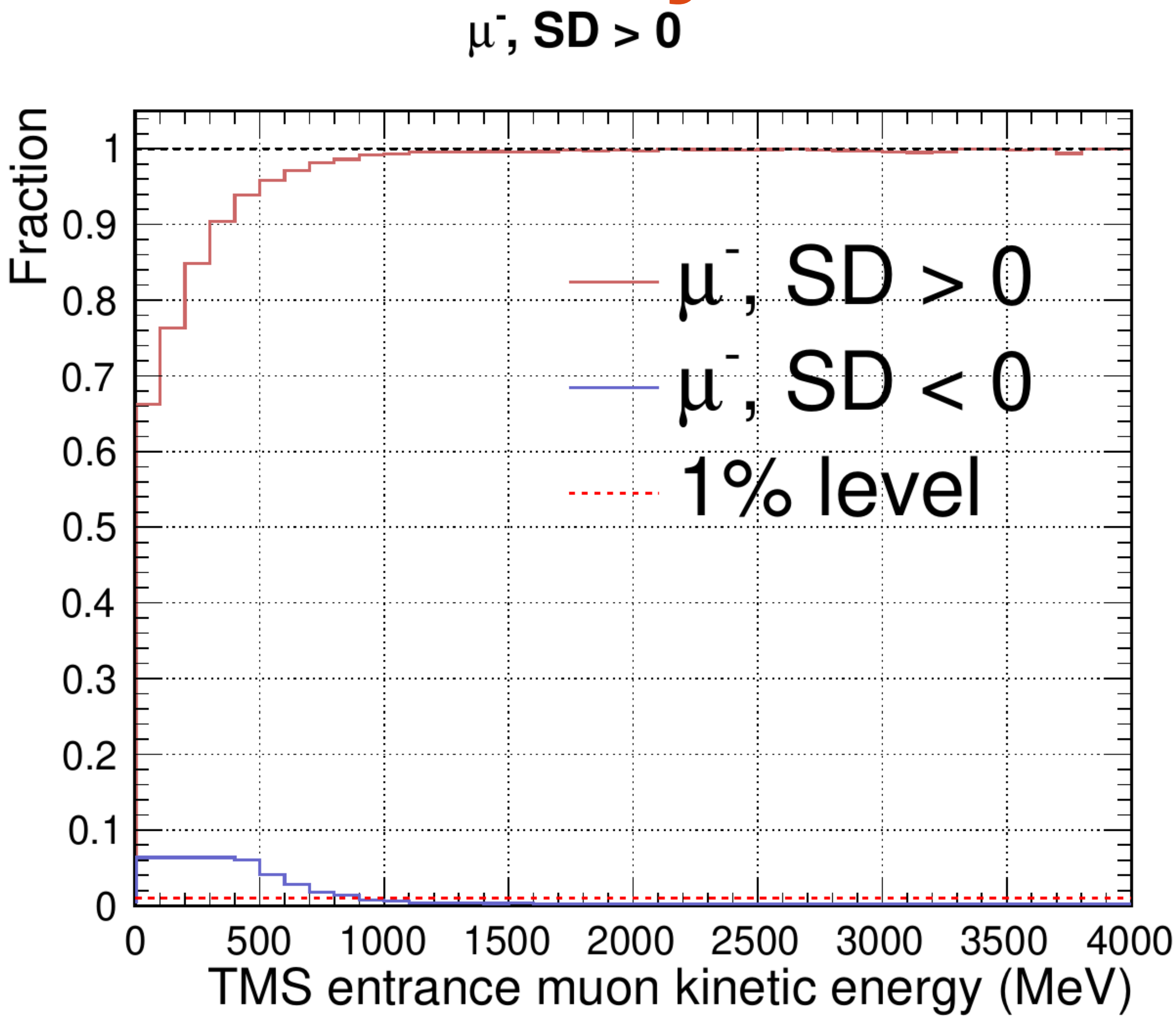
- Monolithic detector sees ~55 events per spill, with roughly ~35 different interactions hitting each TPC (separated by cathode)
- But 1x1m modules see only ~5 events per spill
- Charge-light matching is challenging but tractable problem with modular light readout

Summary

- Day 1 Near Detector preserves ND-LAr physics program with large acceptance and ~5% muon momentum resolution over energy range relevant for oscillations
- Enables high-impact oscillation measurements that do not require precision ND constraints: mass ordering, CPV if maximal
- Significant progress has been made toward full reconstruction in TMS + LAr

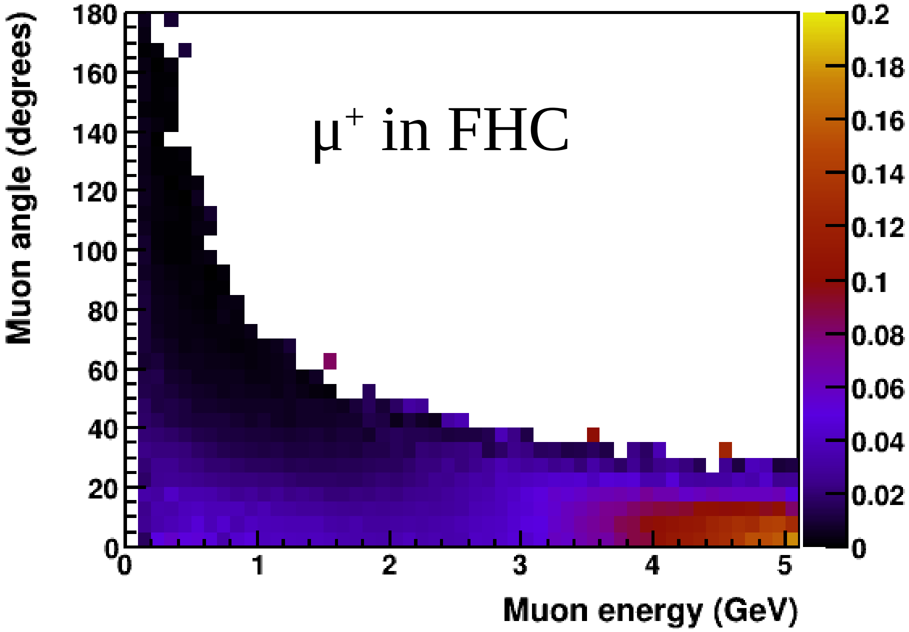
Backups

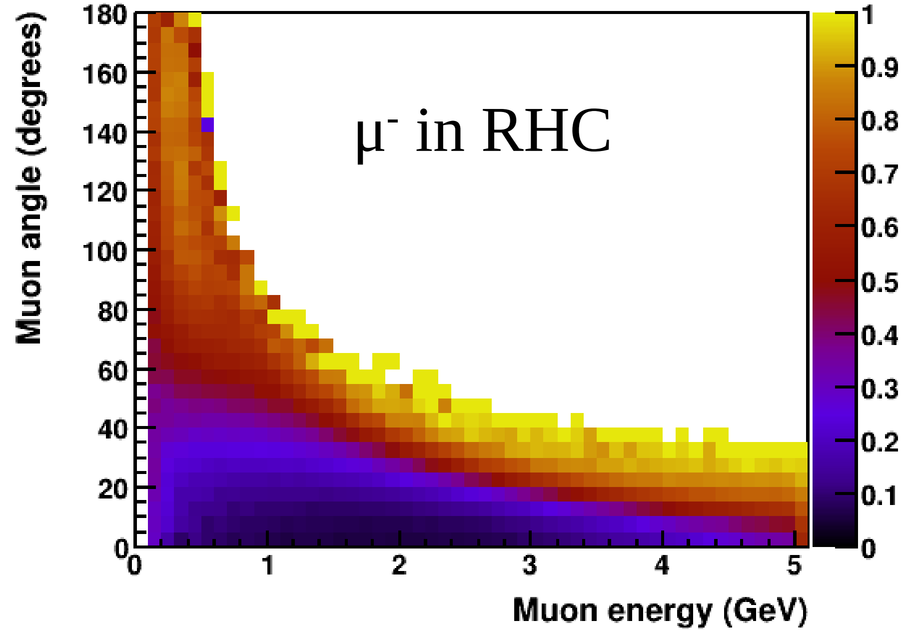
Preliminary sign selection efficiency vs. muon energy



- Correct sign is >99.2% by 0.5 GeV and >99.7% by 1 GeV
- Wrong sign is reduced by ~99% at 1 GeV

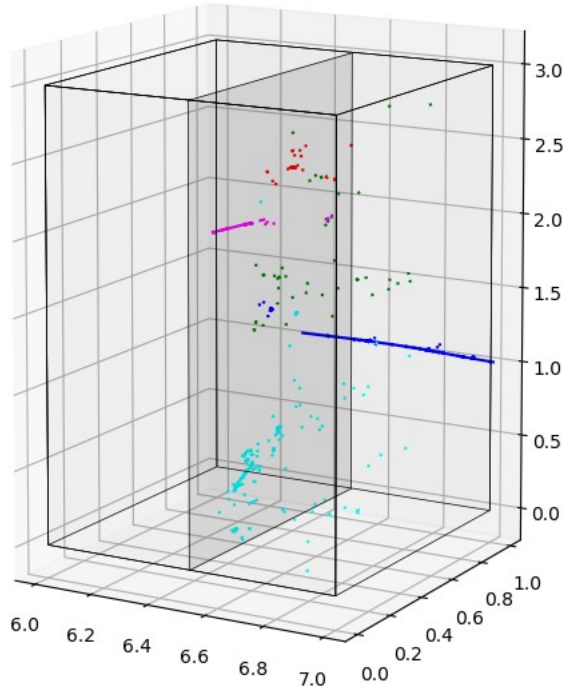
Wrong sign fraction (GENIE kinematics)

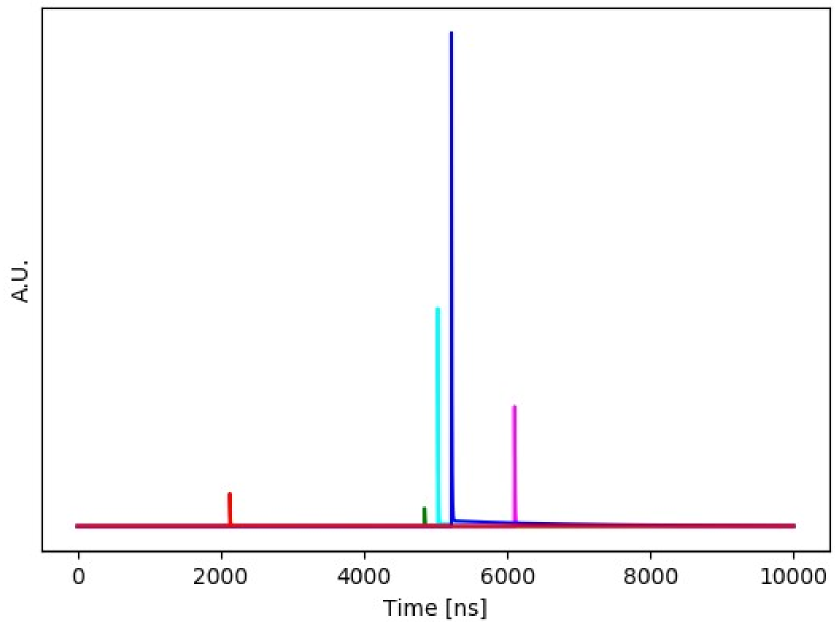




- FHC wrong sign fraction is <3% in region where TMS sign selection performs poorly, RHC is ~5%
- Tail region where wrong sign fraction is high is where TMS is >99.7% efficient

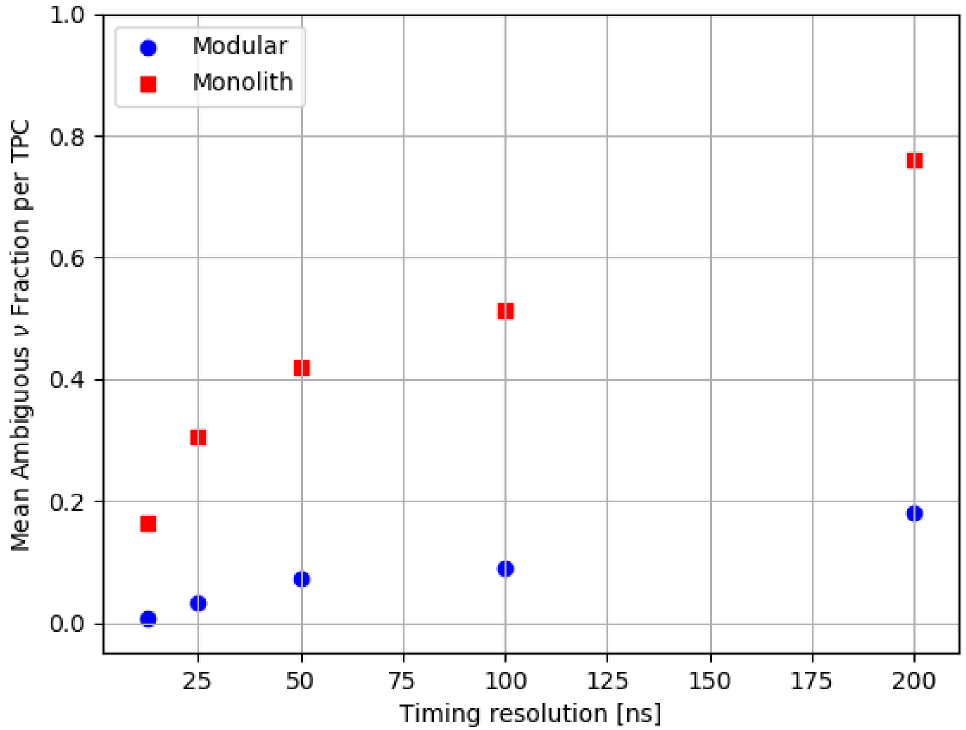
Example: light signal in one TPC





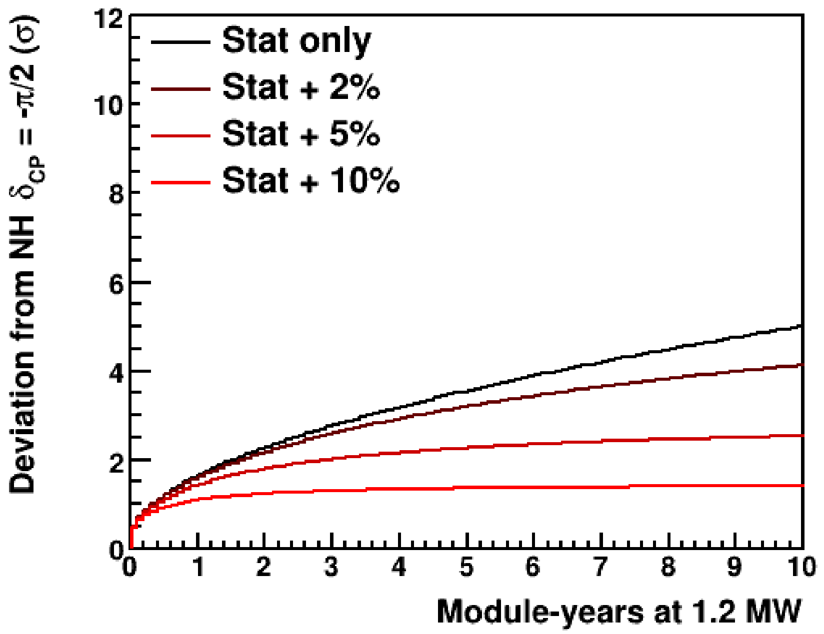
- Pulse height is proportional to energy deposit, which can be used to pair charge and light signals
- Will have additional spatial information from photon detector
- Another handle is correlations in signals between TPCs

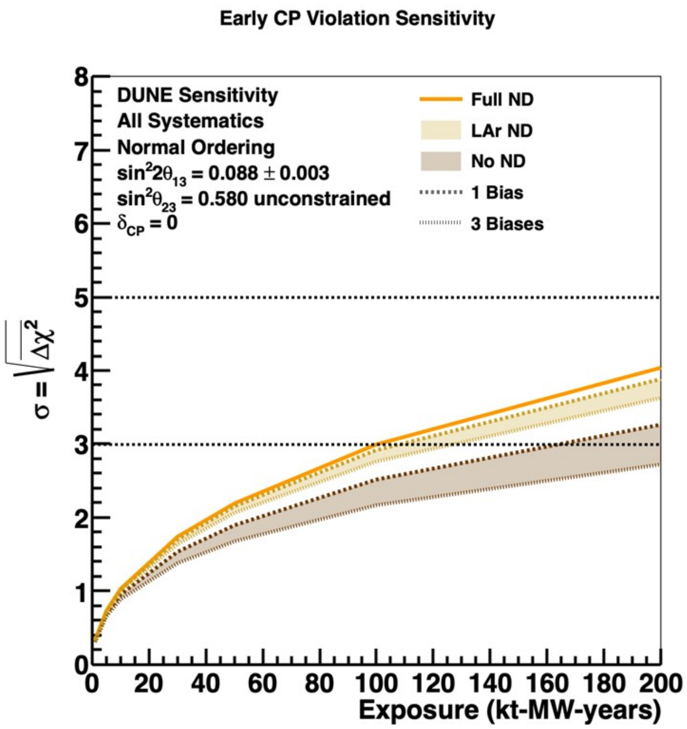
Rate of truly ambiguous signals vs. timing resolution



- Irreducible pile-up when signals in same TPC can't be resolved by photon detection
- With modular TPC and timing resolution < 20 ns, this rate is at the percent level, even without incorporating spatial resolution

FHC rate only vs. full shape fit





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