Neutrino Interaction Physics at nuSTORM

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Outline

Benefits of Muon Storage Rings for Neutrino Interactions

Produce multiple high quality beams of different flavours

- μ^+ decay produces ν_e and $\bar{\nu}_\mu$ in equal quantities
- ν_μ beam from π^+ decay (specific to nuSTORM and MOMENT)

Excellent energy range for interaction studies

- All neutrino beam energies between 0 and 4 GeV.
- Equal shares of QES and DIS interactions in this region.

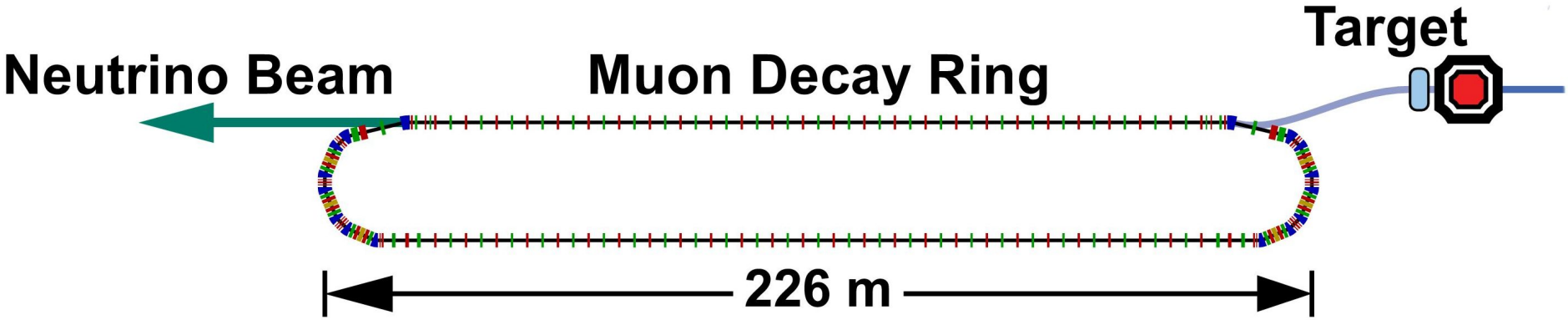
Strong control over systematic effects

- Muon-decay beam energy and content precisely known.
- Pion beam flux with low contamination.

The nuSTORM Facility

- 120 GeV proton beam incident on a graphite target produce pions.
- Pions are horn captured, transported, and injected into ring.

  52% of pions decay to muons before first turn
- Muons within momentum acceptance circulate in ring.



- Schematic representation of nuSTORM

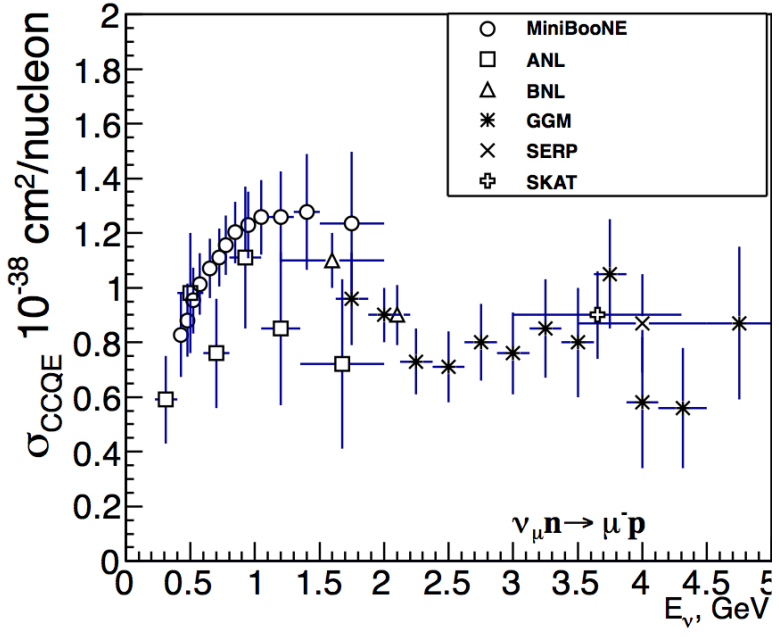
Interaction Specific Studies at nuSTORM

- Interaction rates must be understood by type.
  - Dictates significance of systematic effects in oscillations.
- Many interaction types only accessible with nuSTORM beams
- Data deficient in ν_e interactions.
  - Muon storage ring the best known method to fill this gap.

Interaction Channels

data exists

ID	Stored μ^+	Stored μ^-
1	$\bar{\nu}_\mu p \to \mu^+ n$	$\nu_\mu n \to \mu^- p$
2	$\nu_e n \to e^- p$	$\bar{\nu}_e p \to e^+ n$
3	$\bar{\nu}_\mu n \to \mu^+ \pi^- n$	$\nu_\mu n \to \mu^- \pi^+ n$
4	$\bar{\nu}_\mu p \to \mu^+ \pi^0 p$	$\nu_\mu n \to \mu^- \pi^0 p$
5	$\bar{\nu}_\mu p \to \mu^+ \pi^- p$	$\nu_\mu p \to \mu^- \pi^+ p$
6	$\nu_e n \to e^- \pi^+ n$	$\bar{\nu}_e n \to e^+ \pi^- n$
7	$\nu_e p \to e^- \pi^0 p$	$\bar{\nu}_e p \to e^+ \pi^0 n$
8	$\nu_e p \to e^- \pi^+ p$	$\bar{\nu}_e p \to e^+ \pi^- p$
9	$\bar{\nu}_\mu, \nu_e \to X$	$\nu_\mu, \bar{\nu}_e \to X$



Potential for Cross-Section Measurement

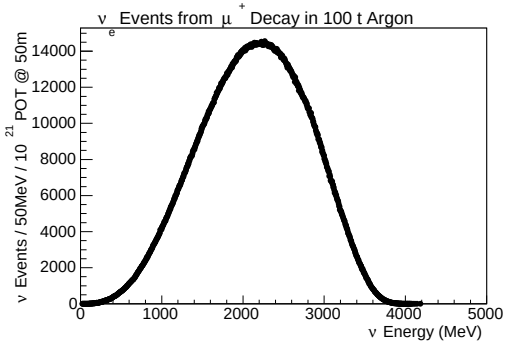
- Flux uncertainties a significant contribution to cross-sections

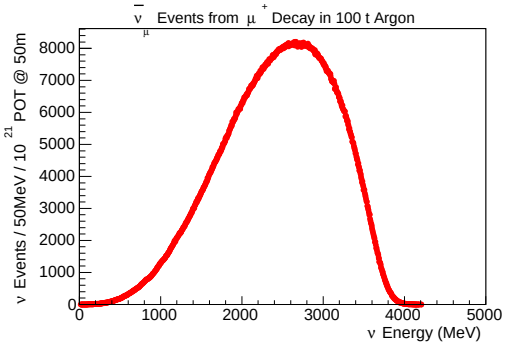
Experiment	Flux Error
MiniBooNE	6.7—10.5%
T2K	10.9%
Minerva	12%
nuSTORM	**<1%**

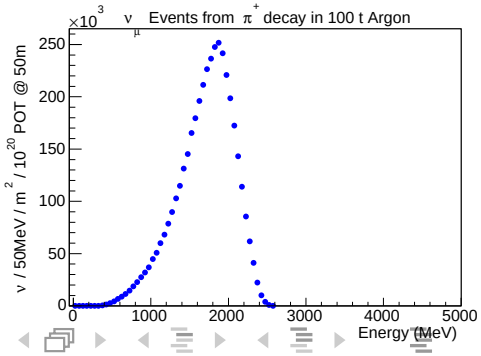
Event Rate per 10^{21} POT, 100 tonnes at 50 m

μ^+		μ^-	
Channel	N_{evts}	Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

- nuSTORM measurements limited by detector systematics.





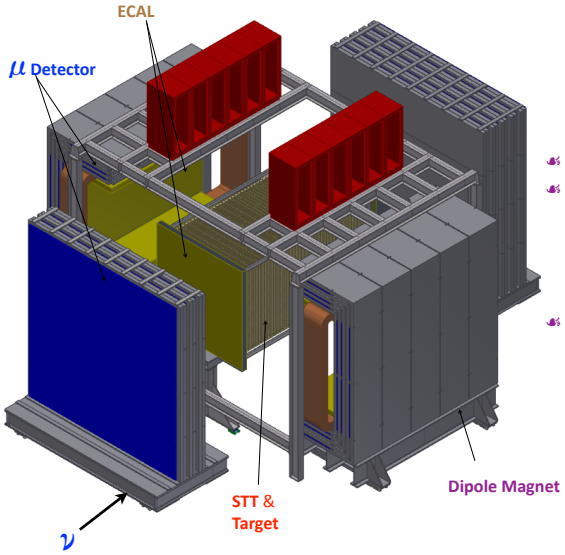


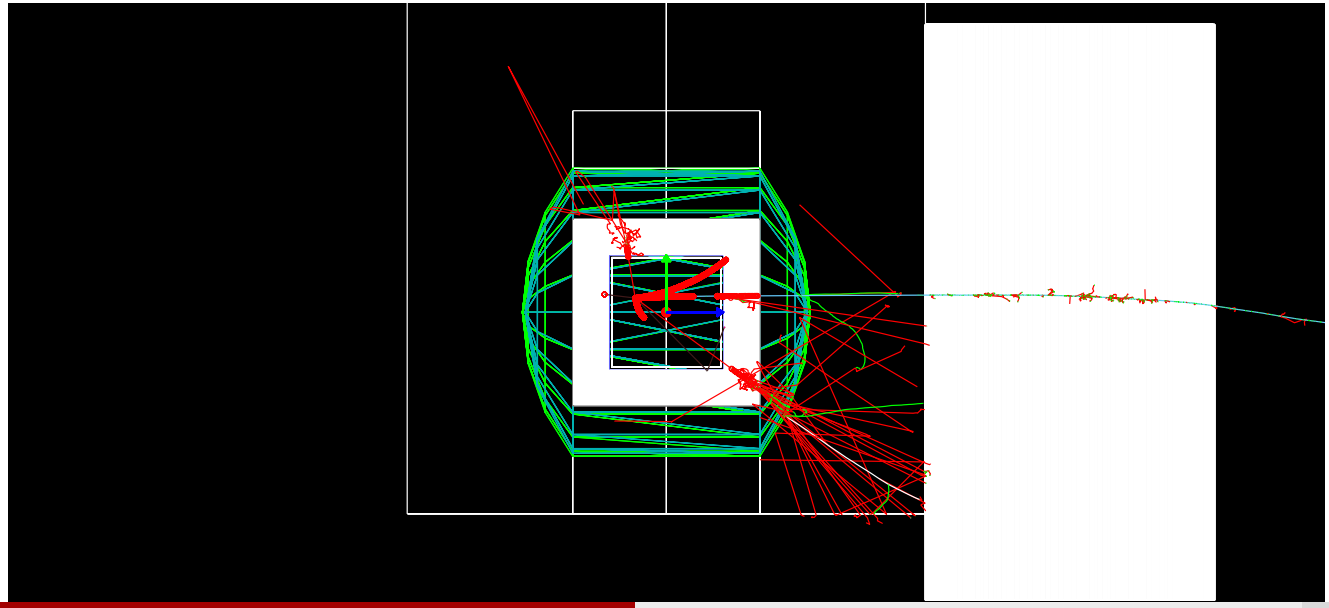
Near Detector Requirements at nuSTORM

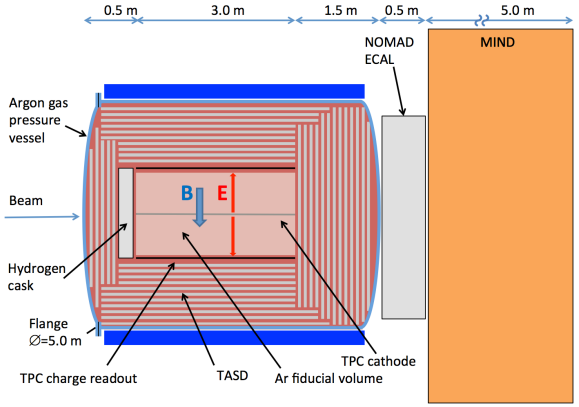
- Charge and flavour separation needs a magnetic field.
- Cross-section studies require good vertex resolution.
- Strong hadron calorimetry.
- Muon catcher (read as MIND) a universal requirement.
- Candidate technologies include
  - totally active scintillating detector.
  - liquid argon TPC.
  - high pressure gas argon TPC.
  - scintillating fibre tracker.
  - bubble chamber
- One detector will not be enough.
  - What makes a good vertex detector confounds PID
  - A system of detectors should be considered i.e. MINERνA

Proposed Near Detector Systems

- LBNE Near Detector, HIRESMUNU
  - Straw tube tracker, (S. Mishra & R. Petti).
  - Builds on NOMAD experience
  - Foil layers for some nuclear targets
- LBNO / LAGUNA Near Detector
  - High pressure gas Ar TPC
  - Totally active scintillating calorimeter.
  - Magnetized iron muon catcher.
  - Potential for hydrogen target.





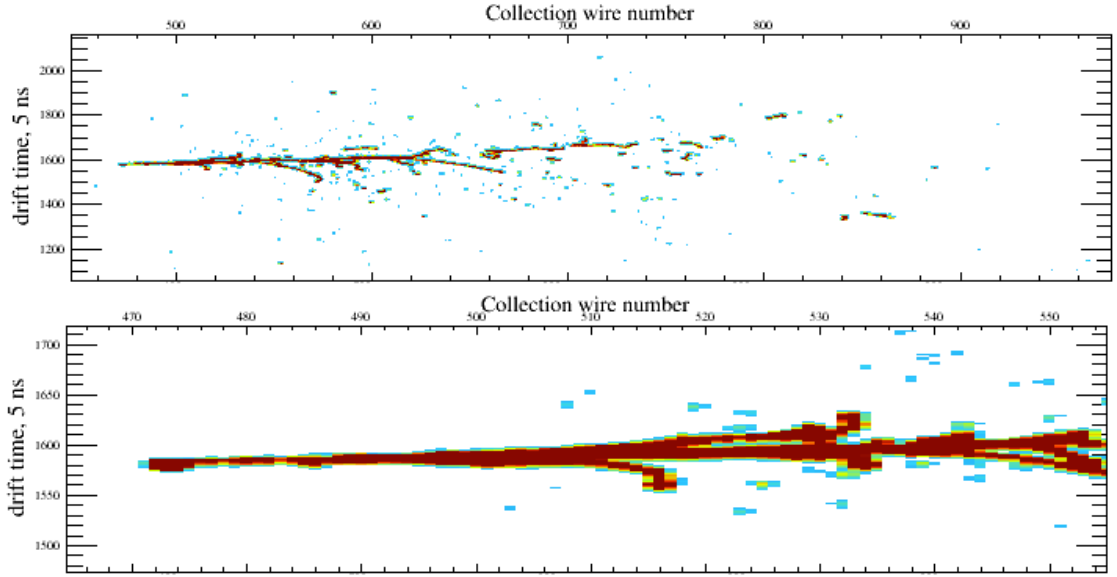


Inclusive Cross-Section Measurement in Liquid Argon[1]

- Considered a 100 t LAr detector in the CCQE channels.
- Clean event reconstruction wi/ good fiducial cuts.
- Assuming 10 million events/year and 10 ms window
  - Event rate: 1 mHz
  - Pile up of a few events per hour.
- Clustering and PID is still in development.

Assumed LAr simulation parameters

Effect	Value
Momentum resolution of contained tracks	3%
Angular resolution	3%
Minimum range for track finding	2 cm



- Determined that a potential 6 fold increase in precision possible.

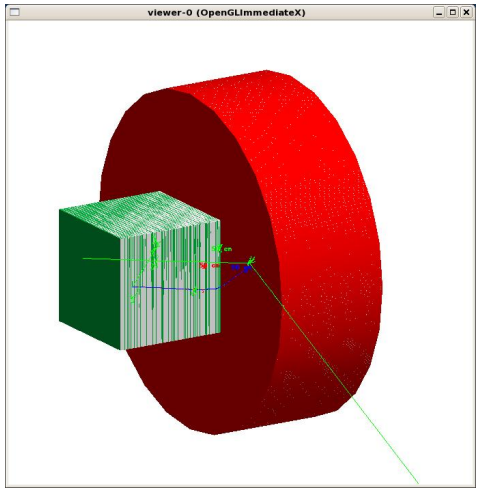
[1] arXiv:1308.6822v1

Attempt at a Detector System with Reconstruction.

- Consider a TASD paired with a MIND.
  - $2 \times 2 \times 2$ m^3 TASD in 2 Tesla dipole field next to 2 m SuperBIND

A proof of concept for a detector system

- Can we reconstruct continuous tracks from a vertex detector to a muon catcher?
- Can PID and track selection be conducted with sufficient purity for cross-section studies?
- What rates and efficiency can we expect with a detector at nuSTORM?



Pros

- We have the software to evaluate this detector.
- Direct comparison to existing detectors possible.
- Similar to LBNO model.

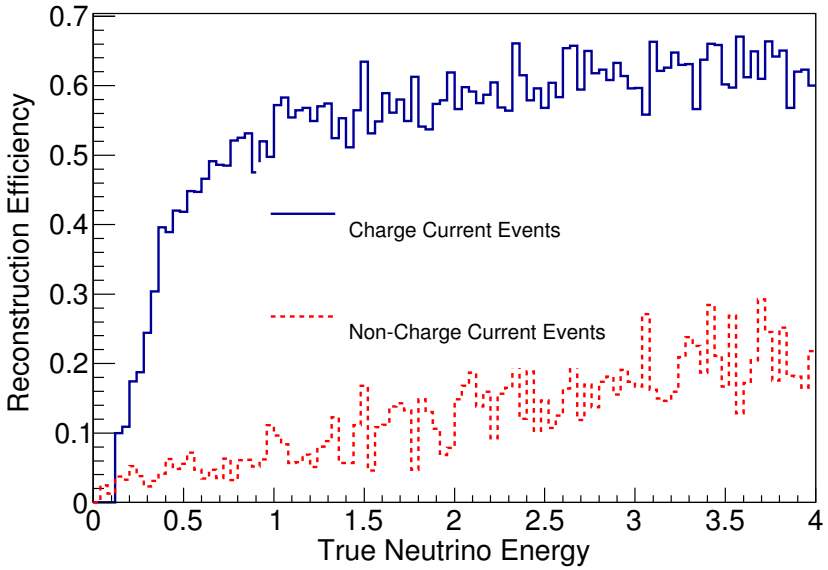
Cons

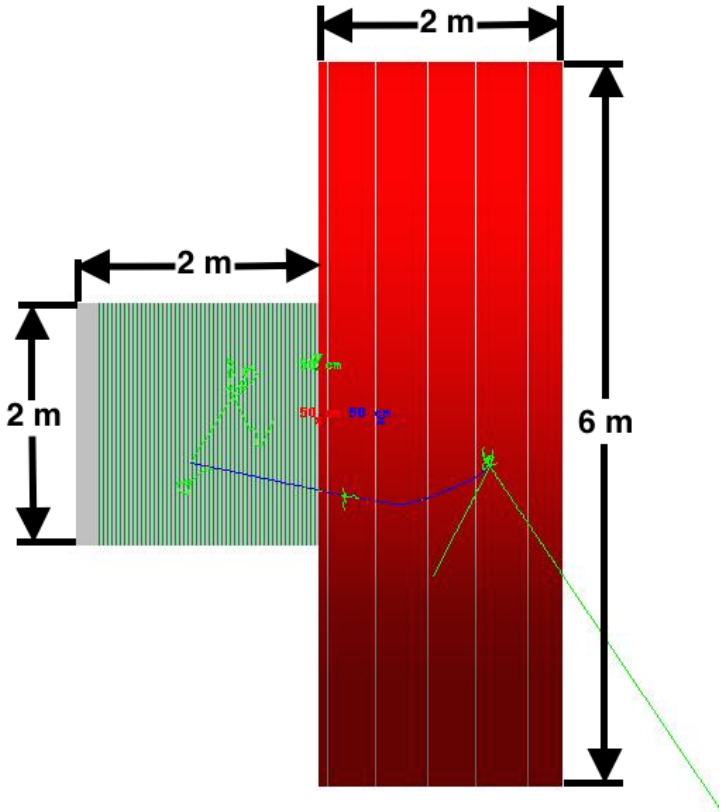
- "Wrong" nuclear target.
- Argon preferred for comparison to LAr detectors.

However: methods are transferrable.

Reconstruction in Compound Detector

Efficiency $\bar{\nu}_\mu$ rec. starting in TASD





- Multiple tracks reconstructed.
- Analysis entails
  - Conducting particle ID for reconstructed tracks.
  - Generating partial cross-sections for various final states.

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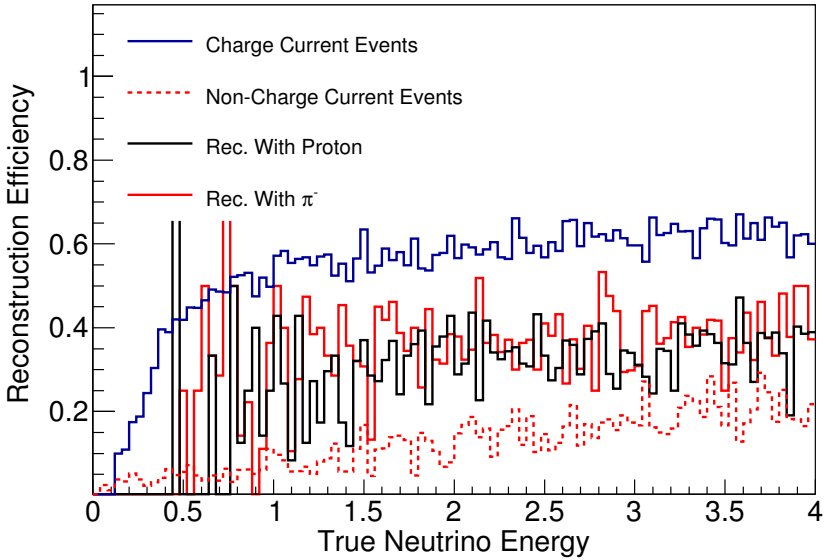

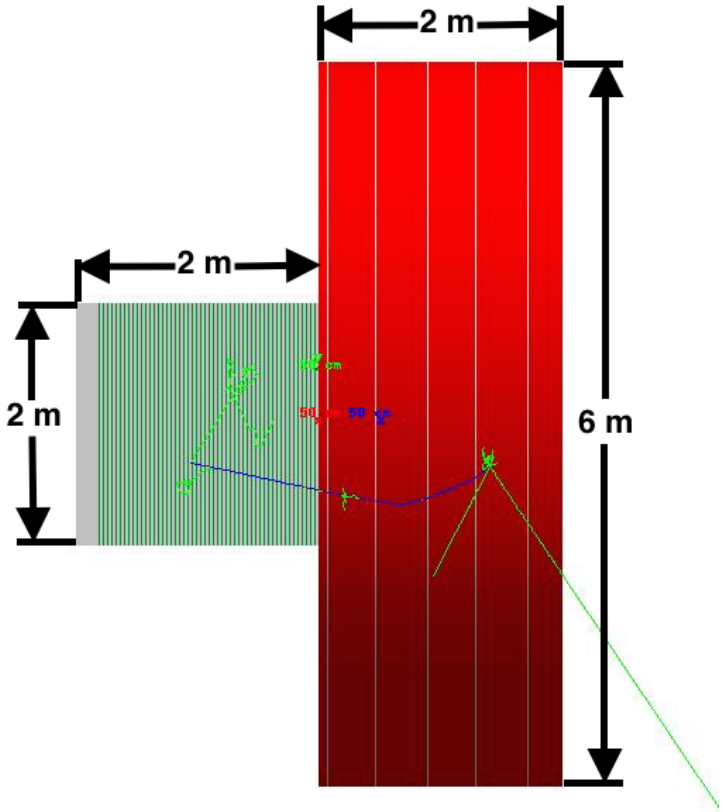

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Plans for Relative Cross-Section Analysis

Scintillator near detector

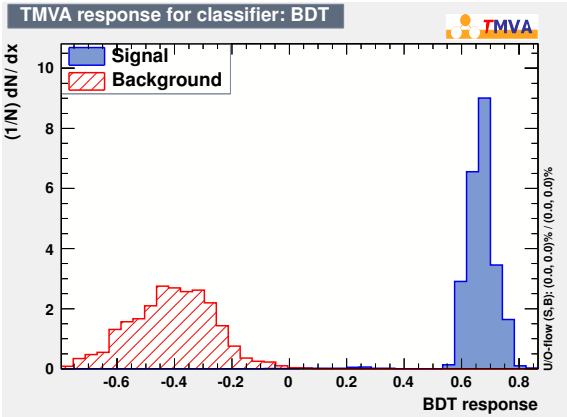
- Conduct analysis of interaction final states.

  Use a multi-variate analysis to ID μ versus π and p.
  MVA already exists from nuSTORM oscillation studies.

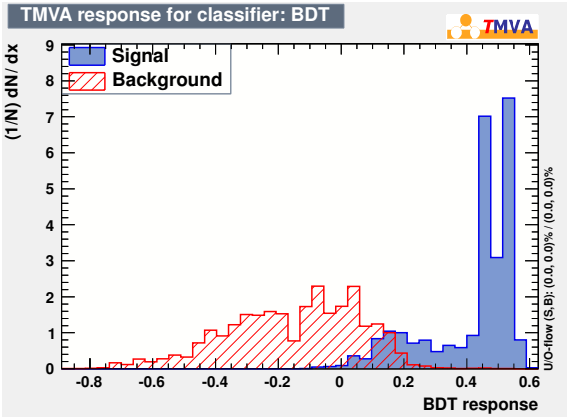
- Relative cross-section uncertainties can be assessed by final state.

MVA classifiers from simulations in 2 m long MIND

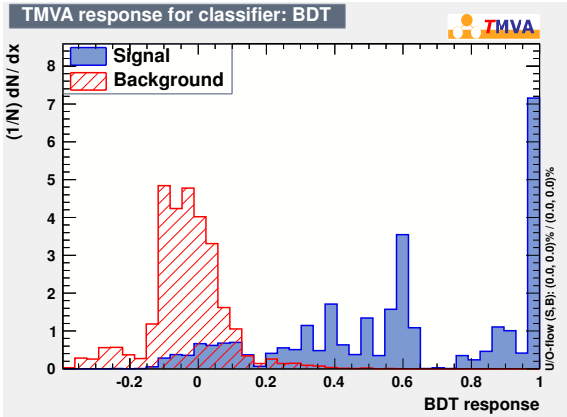
μ^+ Sig. vs. π^+ Bkgd.



μ^+ Sig. vs. p^+ Bkgd.



π^+ Sig. vs. e^+ Bkgd.



Summary

- nuSTORM could provide an excellent source for interaction studies
  - Potential for beams not available otherwise.
  - Three different neutrino beams are accessible simultaneously.
  - Uniquely provide ν_e interaction information.
- A number of near detectors have been proposed for the facility.
  - Very few comprehensive studies have been conducted.
- Toy studies have been conducted with liquid Argon.
  - Determined a 6 fold increase of precision in $\bar{\nu}_\mu$ studies.
- Initiating more comprehensive studies with TASD/MIND near detector.
  - Reconstruction of tracks between the two detectors have been completed.
  - Existing analysis tools can be used for final state cross-section studies.