Magnet Requirements:

H. Gallagher - Jan. 23, 2025

Sign Selection:

(Requirements on field – strength, uniformity, and how well we know it)

Matching FD Phase space:

Size: Transverse area for acceptance

Longitudinally: Stopping power and constrained by available space

ND-T3.01	Areal coverage	shall be > 6.5 m wide and > 2.6 m tall.	The TMS must have sufficient areal coverage to intercept muons exiting the downstream of ND-LAr fiducial volume. (ND-C1.4.1)
ND-T3.02	Stopping power	shall have > 2100 g/cm2 areal density	The TMS measures muon momentum primarily by range, which requires it to stop muons. (ND-C1.4.5)
ND-T3.03	Fiducial Mass mass	shall have > 500 tons of fiducial mass for neutrino interactions	The TMS must have sufficient mass to induce enough neutrino interactions to perform beam monitoring.

TMS μ sign selection	TMS shall separate μ− and μ+ . (Need a statement here about how well we need to do this)

Wrong sign fraction f

Using this criteria to solve for δf (keeping leading order terms only):

$$\delta f \leq \frac{\alpha}{(\Delta P + \Delta X)}$$

If ΔX=0, ΔP=0.13 gives δf=0.39. (Independent of f)

α is a target set by expected Phase-I FD statistics

ΔX is the difference in the neutrino and anti-neutrino extrapolation to the FD

ΔP is the neutrino-antineutrino oscillation probability difference.

Takeaways for Phase 1 physics:

- What matters is not how well we do the sign selection, but how well we understand it.
- Our requirements on this are not very strict.

What does this mean for mis-id (m)

In the ND we will measure the wrong-sign fraction with some amount of mis-identification (m), which we will know with some uncertainty (dm).

$$f_{rec} = (1 - f)m + f(1 - m)$$

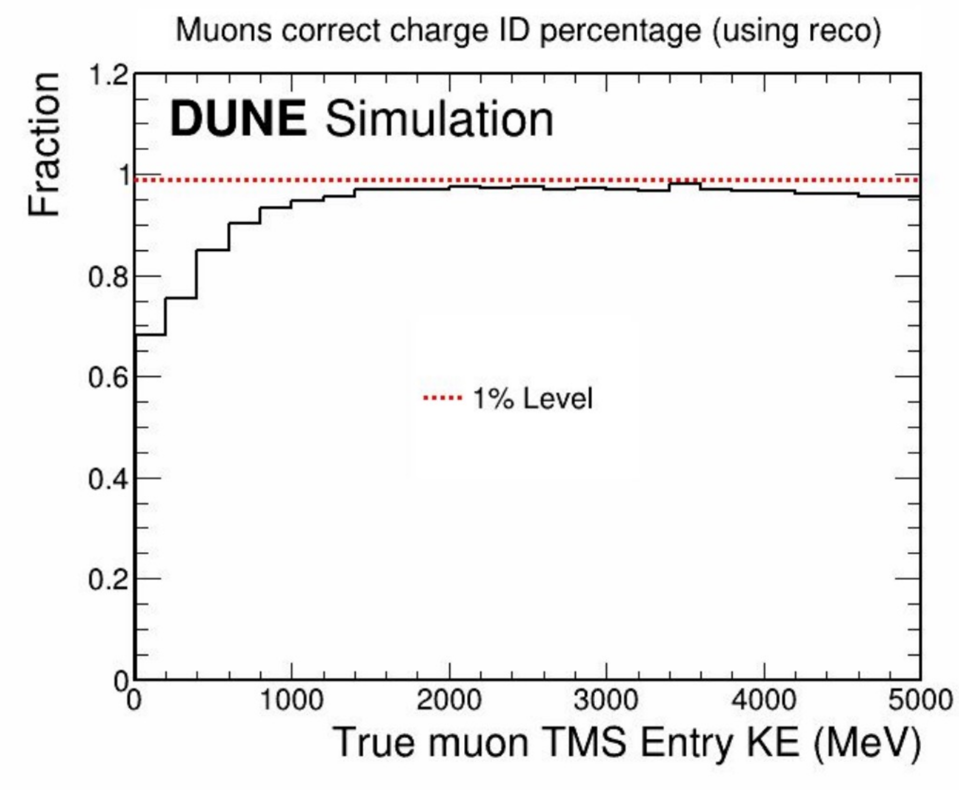
$$f = \frac{f_{rec} - m}{1 - 2m}.$$

To see the impact of δm, we can consider the inferred wrong-sign fraction f' when $m \to m + \delta m$:

$$f' = \frac{(1 - f)m + f(1 - m) - (m + \delta m)}{1 - 2(m + \delta m)} = \frac{f(1 - 2m) - \delta m}{1 - 2m - 2\delta m}.$$

TMS μ sign selection	TMS shall separate μ− and μ+ . (Need a statement here about how well we need to do this)

- The sign selection and uncertainty on the sign selection requirements both play a role.
- Suggest 95% correct charge ID for all stopping muons with > 500 MeV in TMS.
- Would require an uncertainty on the wrong sign fraction of around 75% of itself.



FHC sample

Charge ID selections	Number of events	% of total
Correct muons	62220	90.4
Incorrect muons	3882	5.6
Correct antimuons	2573	3.7
Incorrect antimuons	124	0.2

RHC sample

Charge ID selections	Number of events	% of total
Correct muons	52237	18
Incorrect muons	3179	1.1
Correct antimuons	223471	77
Incorrect antimuons	11244	3.9

Magnetic field	shall have a nominal magnetic field of > 0.9 Tesla.	
Magnetic field uniformity	shall have magnetic field within 15% of nominal across volume of detector	

“Analysis volume"

Question: How well will we be able to determine the magnetic field, on average and locally, *in situ*?

- We’ll have BH curves
- We’ll have many stopping muons

Spatial distortions?
Field uniformity at top and bottom – leaving the detector.

Getting Technical Requirements:

We need to be able to reverse the field and run with no-field.

Needs to move with PRISM
Need to allow installation of the cassettes
Need to allow removal of the cassettes
Need to limit heating of the modules / detector
Power requirements
Slow controls
Needs to run for 10 years

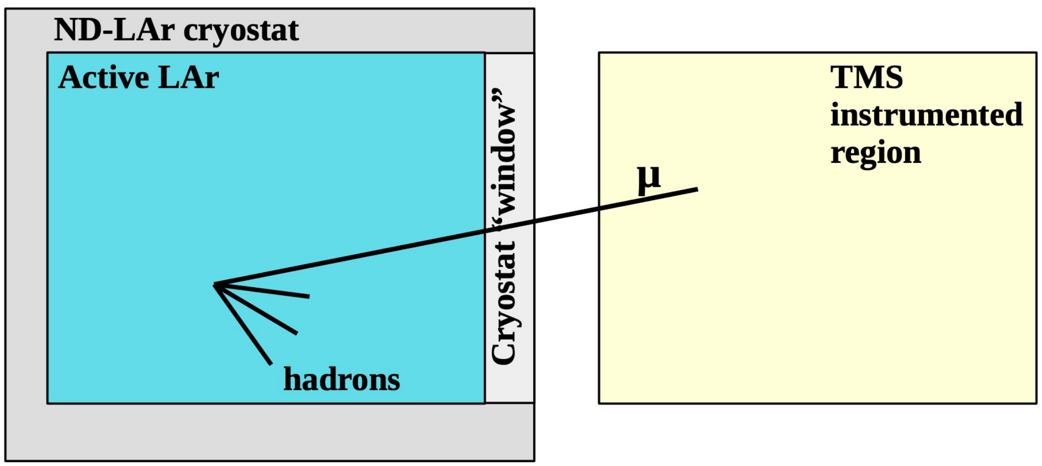
L3 System Requirements	Detector Steel	
	Steel dimensions shall be 7.4 x 5.0 x 7.0 m +/-4 mm	driven, transverse is ndlar, logitudinal driven by stopping power
	Steel plate thickness shall be 40 planes of 15 mm	
	Steel plate thickness shall be 60 planes of 40 mm	
	Steel mass shall be 850 tons +/- xx tons	
	90% (TBR) of the Magnetic Field shall be 1.0-1.1 Tesla	
	The active area shall be 20.22 m^2	
	Number of detector planes shall be 100	
	Channels per plane shall be 192, in 4 panels of 48 each	
	Total Channels shall be 19200	
	Timing resolution shall be for single RF bucket ≤ 19 ns	
L3 System Requirements	**Magnet Coils**	
Cu Material Quality		
Power		
Heat Dissipation		

BACKUP

Magnetic Field Requirements

C. Marshall, H. Gallagher
Dec. 18, 2024

Reminder: what is "accepted"



- Hadrons contained in ND-LAr
- Muon stops in ND-LAr active volume or TMS instrumented region

I'll call these events the **ND Physics Sample**.

C. Marshall / KiYoung Jung
September 2024 Collab Meeting
"TMS Physics Requirements: Width"
(talk here)

Defined a metric based on the ND acceptance in relevant phase space, required this to be greater than 10%.

Will require a large acceptance correction, which is largely geometric.

Key points:

1. ND-LAr + TMS measurements will be systematics limited.
2. We will not measure anything perfectly.
3. How large are the corrections we need to make?
4. How well do we know them?

Magnetic Field Requirements

Follow the same systematics approach used for previous ND-LAr physics / systematics studies. (ND measurements are systematics limited)

N: Total number of events in our ND Physics sample.

f: Fraction that are selected as wrong-sign by TMS.

$$N_{RS} = (1-f)*N$$
$$N_{WS} = f*N$$

Important to note that these two samples are completely anti-correlated.

Magnetic Field Requirements

Let's now consider the systematic uncertainty on the expected event rate in the RHC FD ν_e sample due to the systematic uncertainty on f.

$$n = P(\bar{\nu}_\mu \to \bar{\nu}_e) * (1-f) * N * X^{RS}_{N\to F} + P(\nu_\mu \to \nu_e) * f * N * X^{WS}_{N\to F}$$

$$\delta n = \delta f * N * (-P(\bar{\nu}_\mu \to \bar{\nu}_e\ ) * X^{RS}_{N\to F} + P(\nu_\mu \to \nu_e) * X^{WS}_{N\to F})$$

"X" here extrapolate from ND to FD. Defining:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = P(\nu_\mu \to \nu_e) * (1+\Delta P)$$

$$X^{RS}_{N\to F} = X^{WS}_{N\to F} * (1+\Delta X)$$

Note that the Δ terms here are NOT uncertainties, but differences.

Magnetic Field Requirements

$$\delta n = -\delta f * N * P(\nu_\mu \rightarrow \nu_e) * X^{WS}_{N \rightarrow F} * (\Delta P + \Delta X - \Delta X * \Delta P)$$

Which behaves as we expect:

- Is zero when the wrong-sign fraction is measured perfectly
- Scales with exposure
- Since the wrong-sign and right-sign fractions are completely anti-correlated, the only way to introduce a difference in the FD rates is through an effect that is different for neutrinos and anti-neutrinos.

Criteria proposed by C. Marshall at the May 2024 collab mtg for Phase 1:

$\delta n \leq$ 0.05 n

Magnetic Field Requirements

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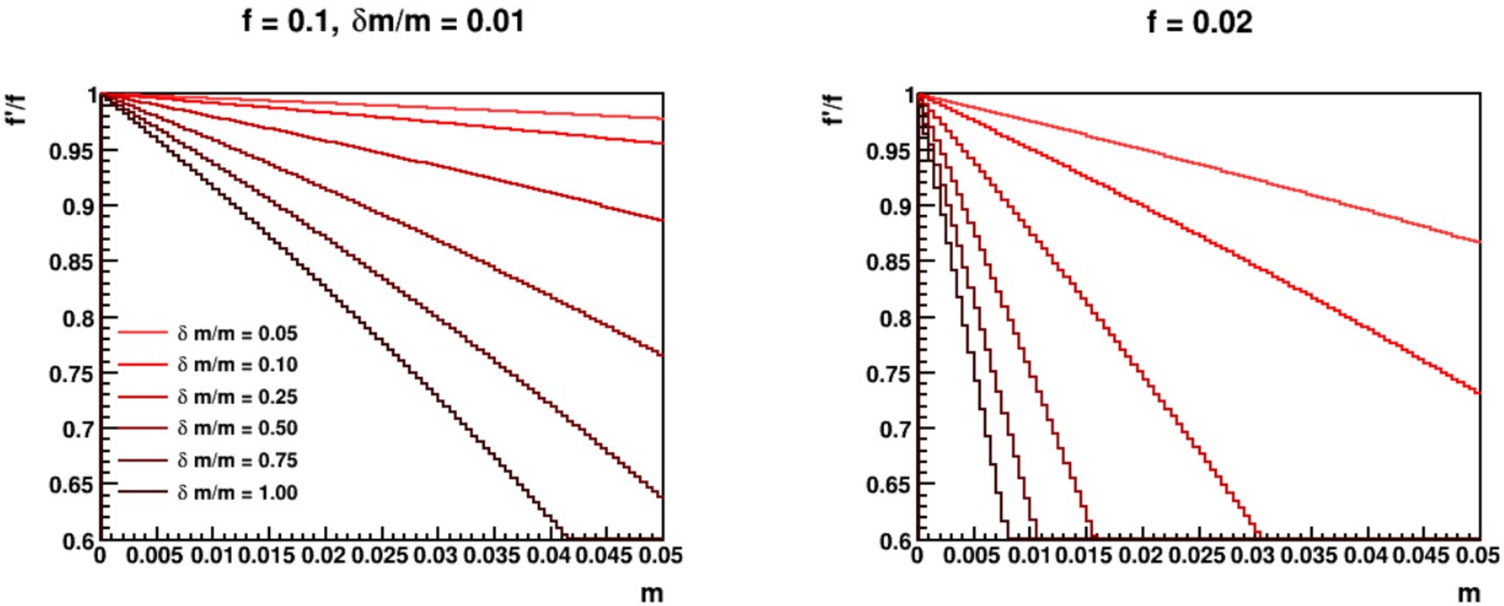

Figure 1: For a 10% wrong-sign fraction (left) and a 2% wrong-sign fraction (right), the impact on the inferred wrong-sign fraction due to a systematic uncertainty on the sign mis-ID rate, as a function of that rate.

For the 10% wrong sign fraction of RHC, this shows that a mis-ID rate of $< 4\%$ is able to tolerate a 100% systematic uncertainty ($\delta m/m = 1$), to obtain the required maximum allowed uncertainty from above.

The wrong sign fraction is a neutrino-energy dependent quantity (only).

Analysis strategies to take advantage of:

”Phase Space Symmetry”:

- Select events with the same energy / event kinematics in different regions of the ND-LAr volume.
- Could even extend this to events in TMS.

Running with different B-fields

- No field
- Field reversed

PRISM