FERMILAB-SLIDES-24-0110-AD

Neutrino Beam Instrumentation

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Overview

Beam instrumentations – used to control & measure particle beams

Instruments of interest

- **Measure a spatial distribution of charged particles**
  - e.g., beam centroid position, angle and beam profile
  - Beam Position Monitor (BPM), Target Position Thermometer (TPT), Hadron Monitor (HM)
- **Measure an integrated charge of particles passing through a monitor**
  - e.g., a total beam intensity per spill
  - Toroidal Current Transformer (CT), Muon Monitor (MM)
- **Measure time structure of charged particles**
  - Differentiated beam intensity or a bunch structure
  - Pico-sec particle detectors
- **Detect anomaly**
  - Monitoring condition of secondary/tertiary particle production target &/ anomaly event detection
  - Thermocouple sensors (TC), Muon Monitor(MM), application of Machine Learning

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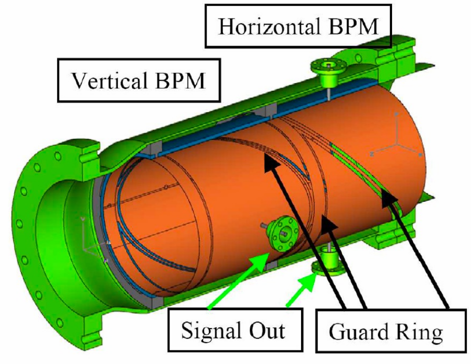
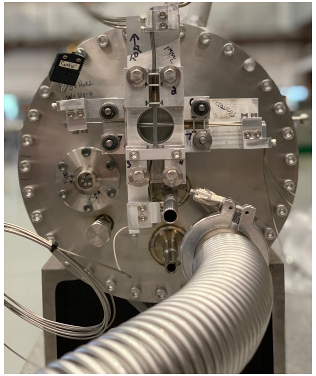


BPM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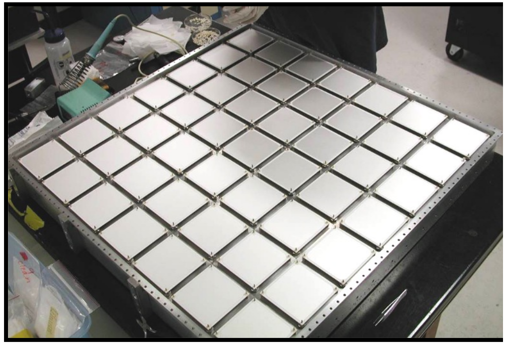
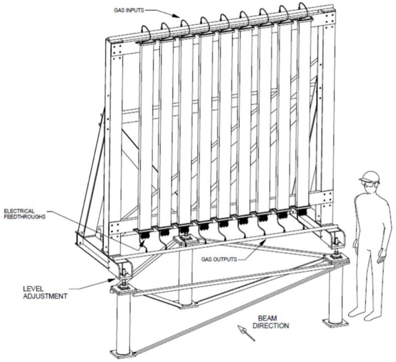

HM



MM

Overview

Instruments of interest

Beam Position	Beam Angle	Beam Profile	Beam Intensity
BPM MM TPT	BPM MM	Profile Monitor (centroid, RMS)	CT MM

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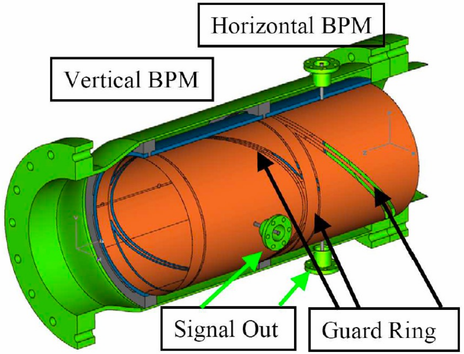
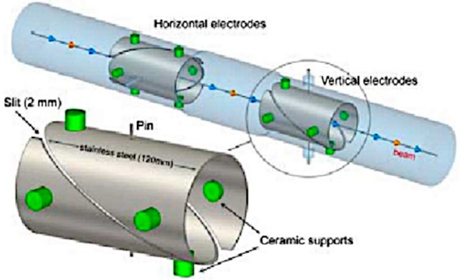
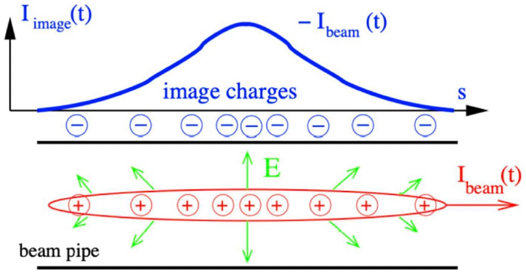
BPM

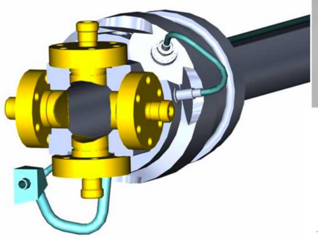
- Beam Position Monitor (BPM)
  - Observe ratio of mirror beam charge on paired electrodes
  - **Linear-cut BPM** is the default BPM for NuMI
  - **Linear-cut BPM** is applied for **autotune***
  - **Button BPM** has curvilinear conductive region instead of a planar
  - Expect to have a good performance at high power beam operation

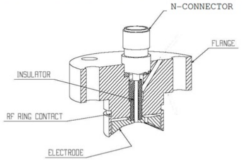




Linear-cut BPM



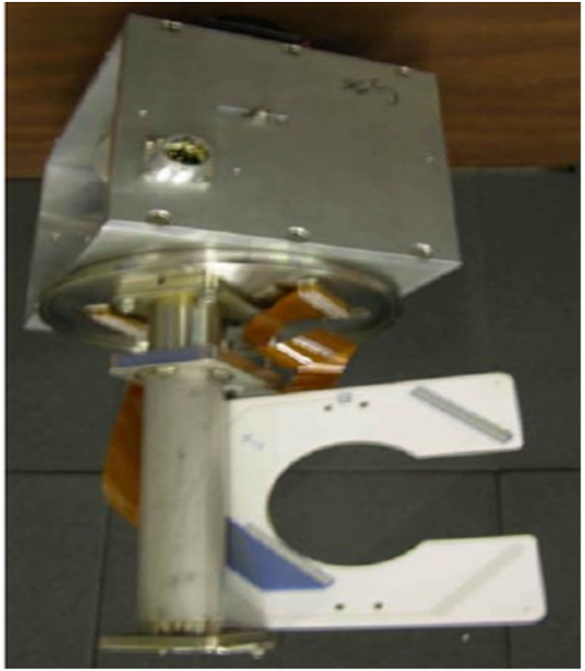




Button BPM

Charge distribution generated by proton beam traveling through BPM

PM

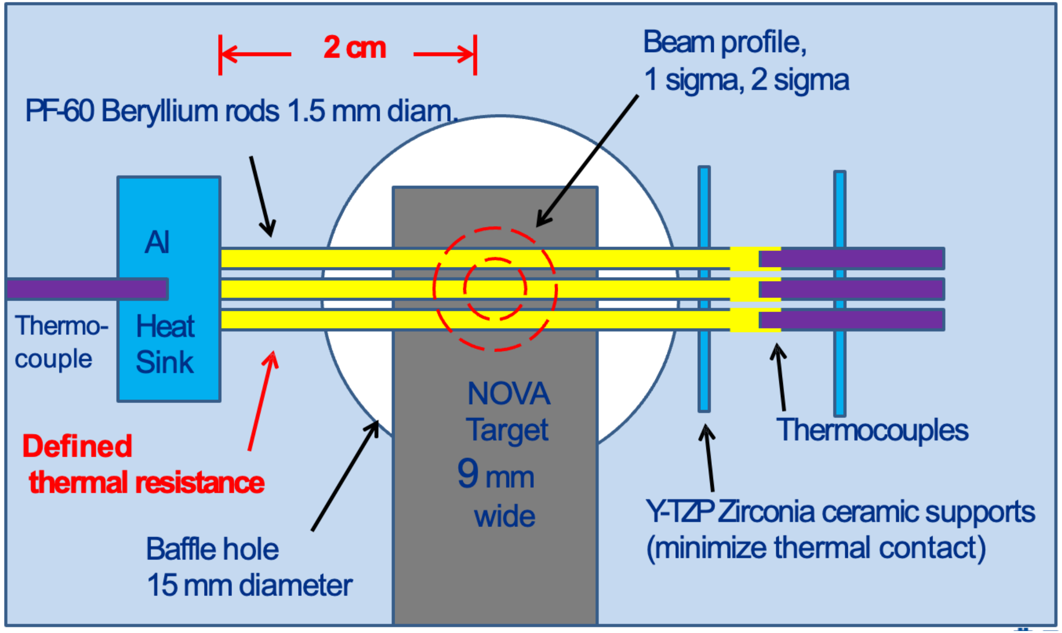


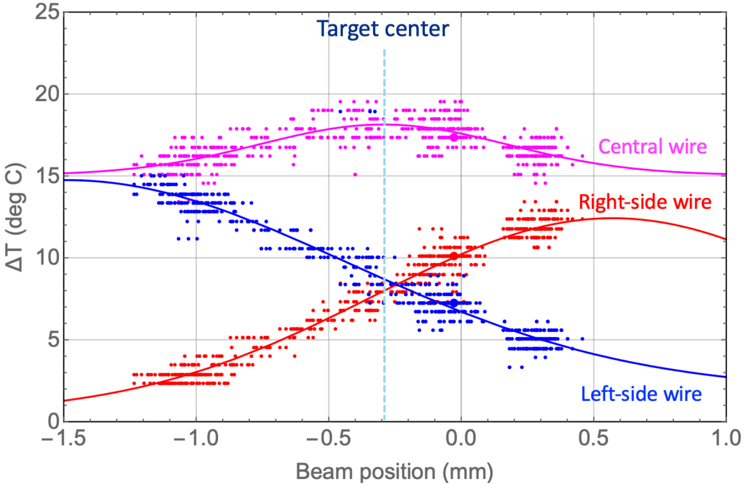
Beam profile monitor

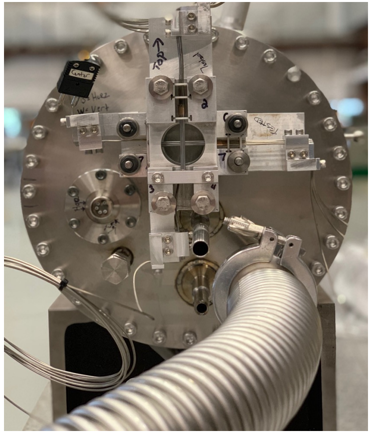
- Profile Monitor (PM)
  - Multiwire SEM chamber
  - 47 + 47 wires to measure projection of beam profile in horizontal & vertical planes
  - It can extract **beam centroid** and **RMS beam width**
  - PM is usually removed from beam line to mitigate beam loss & beam spot size growth at PM except for PMTGT
  - PMTGT is always in

TPT

Thermocouple sensor







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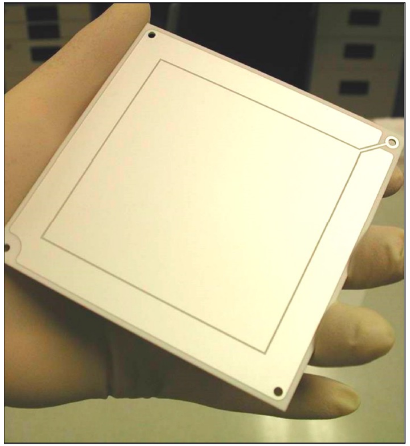
Hadron/Muon Monitor (Ion Chambers)

- Pixeled ion chamber (99.997 % Helium gas for ionization)
  - 5 x 5 Hadron Monitor since FY22 (NuMI)
  - 9 x 9 Muon Monitor (NuMI)



Sense wafer, chamber side

Parallel-Plate Geometry:
•Ensures a simple and uniform signal volume
•Ionization medium: Helium gas at atmospheric pressure
    •Low charge per cm
•10.2 x 10.2 cm^2 Al2O3 ceramic wafers
•Electrodes: Ag-plated Pt
•Corner holes for mounting
•Design includes electrical & mechanical contacts in corner holes; chamber gap varies by station

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Highlights of Talk

- Why do we need beam instrumentation
  - Constrain beam systematics

- Beam-based alignment
  - e.g., LBNF

- Near Detectors
  - e.g., LBNF

- Pico-second Detectors

- Anomaly detection
  - Application of ML

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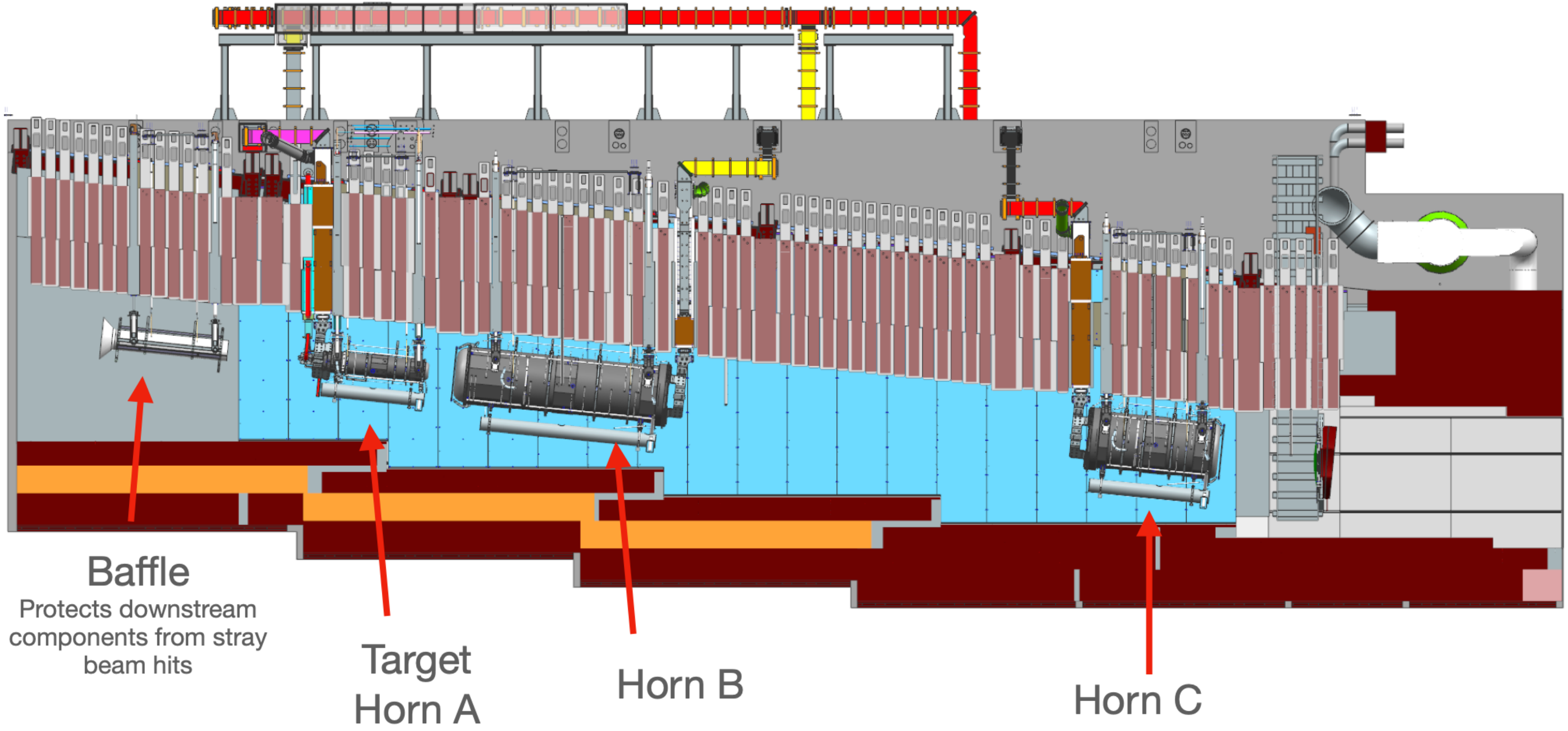
LBNF

- Neutrino beam for DUNE



LBNF Beamline & Locations of Neutrino Beam Instrumentation

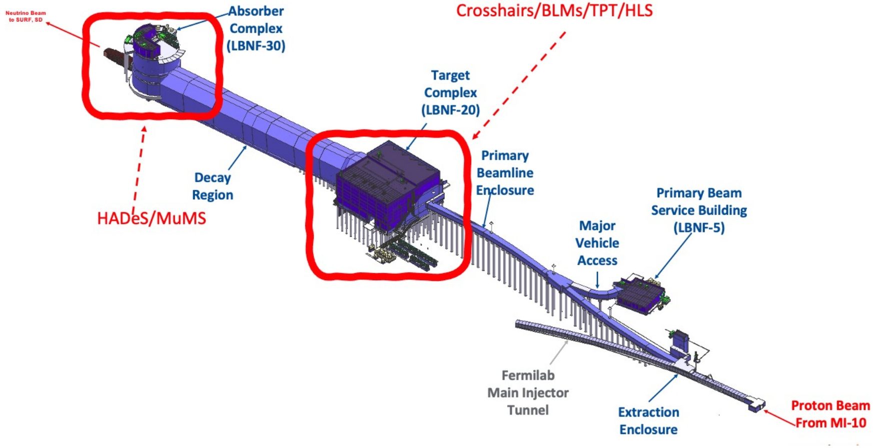
Consists of following systems

- Target complex: Crosshairs/BLMs/TPT, HLS
- Absorber complex: HADeS/MuMS

Used for beam-based alignment & monitoring neutrino beam

Upstream of target, not under purview of NBI

- Beam Position Monitors (BPMs)
- Secondary Emission Monitors (SEMs)



Requirements of Neutrino Beam instrumentation for LBNF

- Need to keep beam systematics constrained to achieve DUNE physics goals
- Ensure a well-controlled & stable beam
- Align beamline elements within specified tolerances
- Precisely steer the beam onto target

•Cross hairs and Beam Loss Monitors (BLMs)
  •Necessary components for Beam-based alignment (BBA)

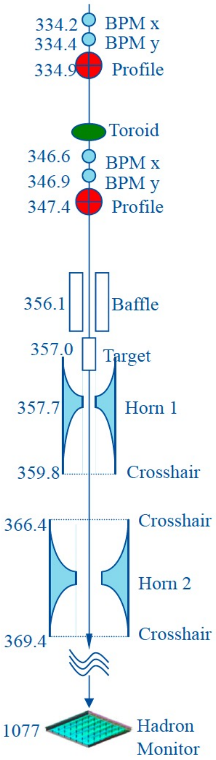
•Target Position Thermometer (TPT)
  •Used both during BBA & normal operations to secure beam on target

Quantity	1-sigma Shift	Notes	In TDR
Horn A Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	Y
Horn A Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Horn B Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	Y
Horn B Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Horn C Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	N
Horn C Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Target Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	N
Target Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Horn A Longitudinal Displacement	2 mm		N
Horn B Longitudinal Displacement	3 mm		N
Horn C Longitudinal Displacement	3 mm		N
Proton Beam Transverse Position	0.5 mm	X and Y shifted separately; added in quadrature	Y
Proton Beam Radius	10%	Updated from 0.1 mm for NuMI	Y
Proton angle on target	70μ rad	X and Y shifted separately; added in quadrature	Y
Decay Pipe Radius	0.1 m		Y
Horn Currents	1%	Changed in all three horns simultaneously	Y
Baffle Scraping	1%	To Be Updated	N
Bafflet Scraping		To Be Updated	N
Target Density	2%		Y
Horn Water Layer Thickness	0.5 mm	Changed in all three horns simultaneously	Y
Upstream Target Degradation			N
# Protons on Target	2%		Y
Near Detector Position			N
Far Detector Position			N
Field in Horn Necks			N
Decay Pipe Position	20 mm		N

Table 1: Sources of alignment and focusing uncertainties in the neutrino fluxes at DUNE. Sources that were considered in physics studies in the TDR are marked with a 'Y' in the 'In TDR' column.

DUNE-DocDB-19942 DUNE-DocDB-29233

Beam-Based Alignment Strategy



What would we like to align?

– Target & Baffle

- Meson production varies with amount of material traversed
- Position of production important for other optics

– Horns

- Focusing depends on positioning and angle

•Procedure

– Scan proton beam across known features of beamline components

- Target & Baffle material
- Horn neck and cross-hairs

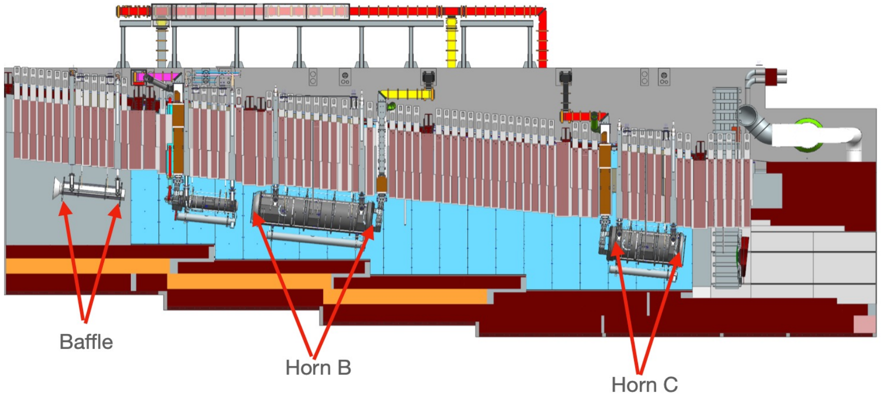
– Use instrumentation to correlate measured proton beam position with component features

- Target Position Thermometers (TPT)
- Beam Loss Monitors (BLM)
- Hadron Monitor (HM)

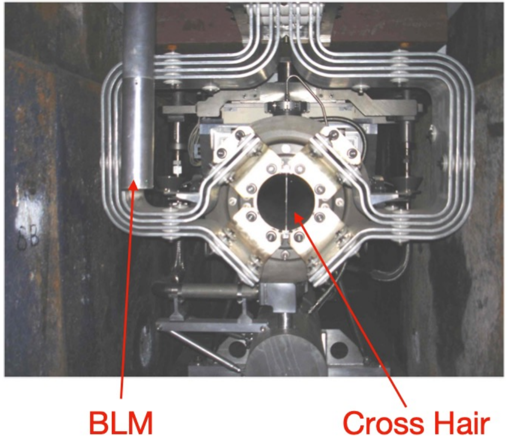
Example LBNF

Cross Hairs & BLMs

- Upstream and downstream of each component



NuMI Horn



Alignment of Baffle/Target/Horns in Beam-Based Alignment:

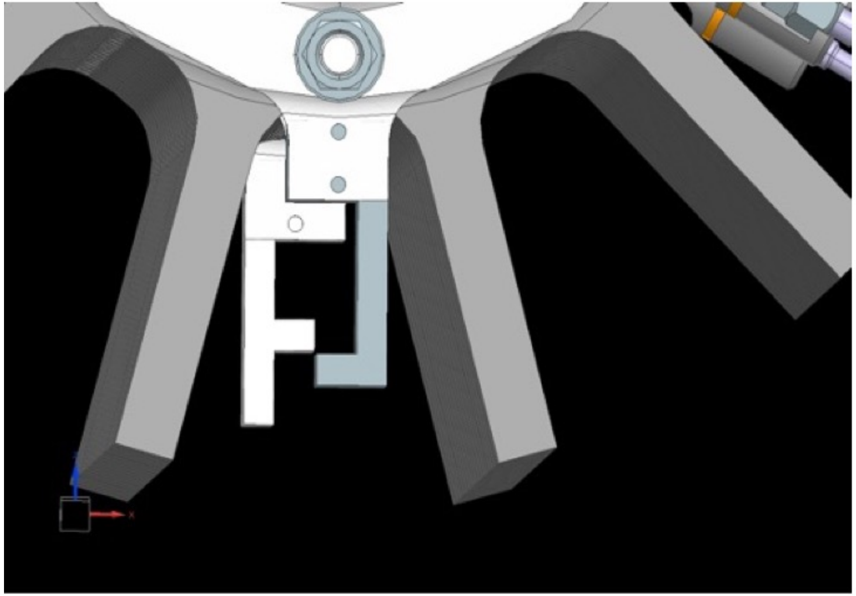
•Scan beam across known physical features to identify each element

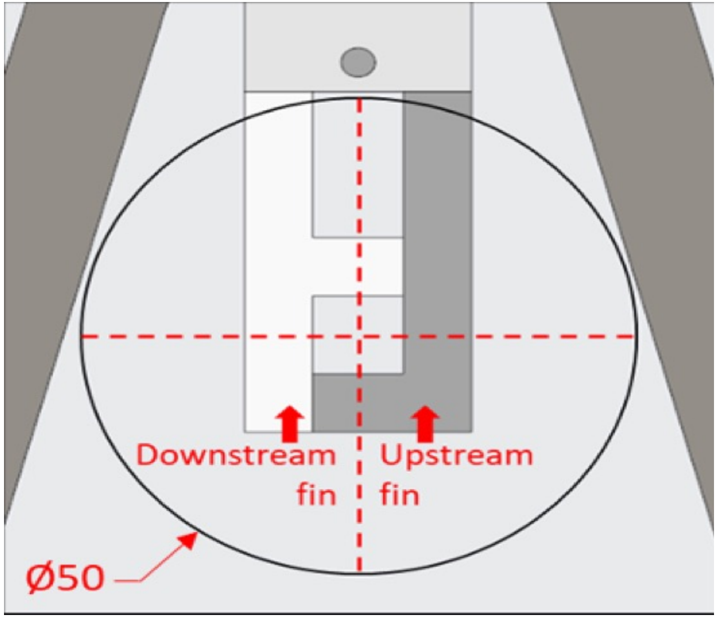
•Utilize crosshairs at upstream and downstream ends

•Independently measure transverse misalignment of each end (horizontal + vertical)

•Use beam loss monitor to detect beam scatter from crosshairs

LBNF Baffle Cross Hair





- Baffle crosshairs are positioned underneath baffle
- Cross hairs 141mm long along beam axis at upstream and downstream end
- Bars 6mm wide and at +-7mm from beam axis when baffle in BBA position

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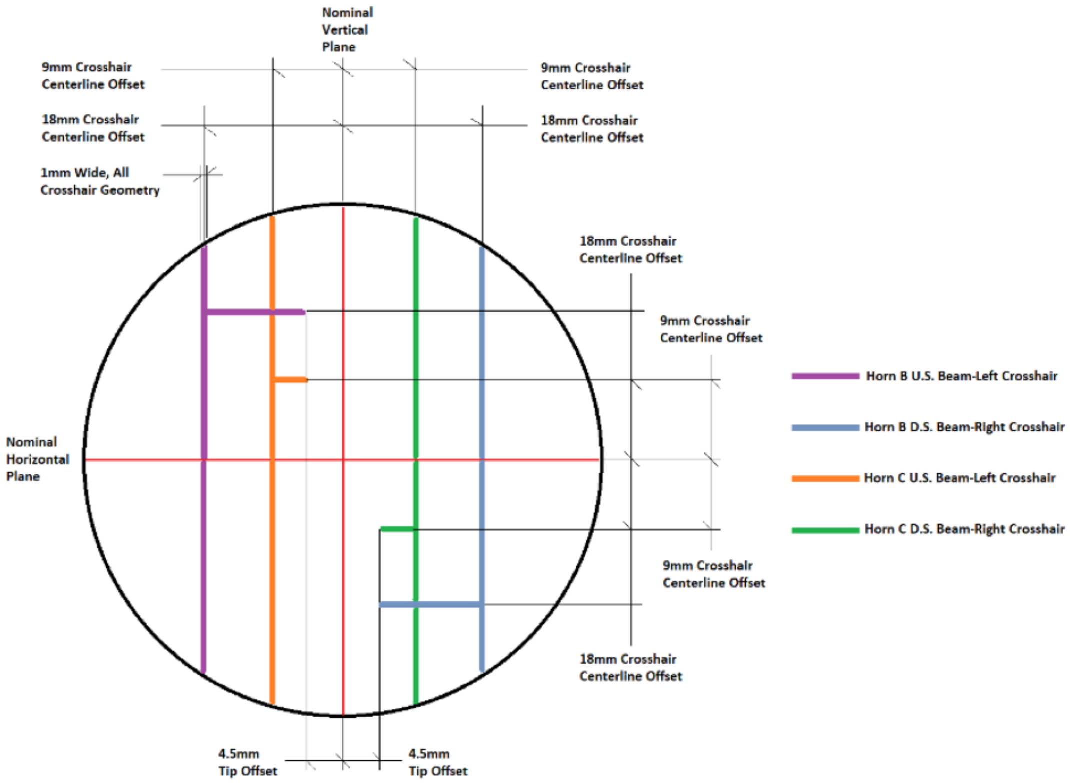
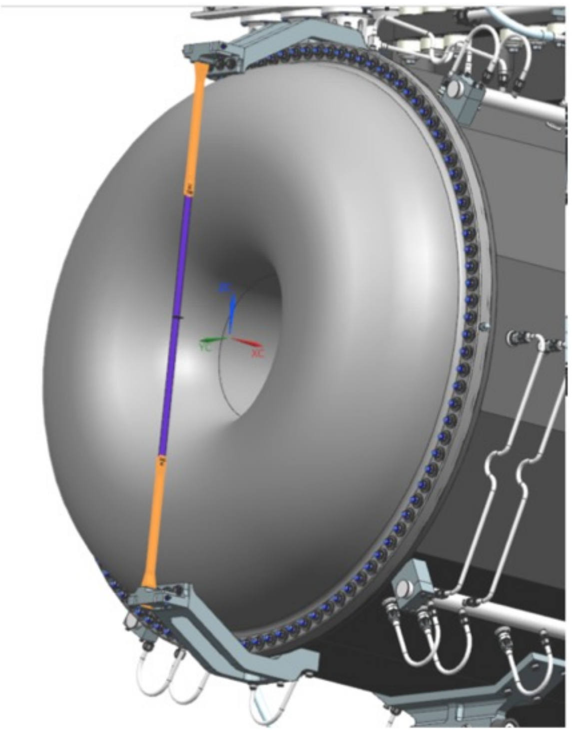
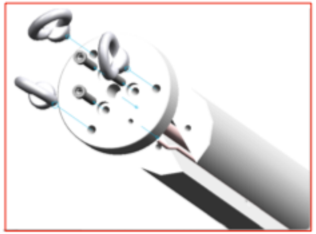
LBNF Horn Cross hair

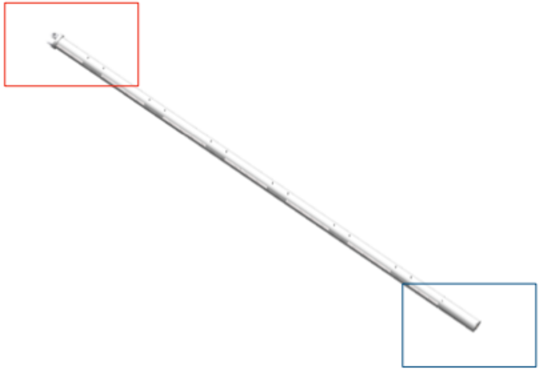


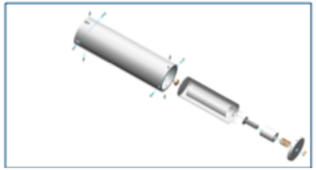


Beam Loss Monitor (BLM)

- Support structure
  - 2.7m long, 7cm diameter aluminum cylinder
  - Carries radiation-hard signal, HV, & ground wiring
  - Lower end has a cup to hold BLM
  - Upper end has support structure
- Can be inserted or pulled out of beam
- Electronics setup to give 1V per 10^7 particles (expectation from MC was few 10^7 per 10^{12} protons (90% of signal current shunted to ground))



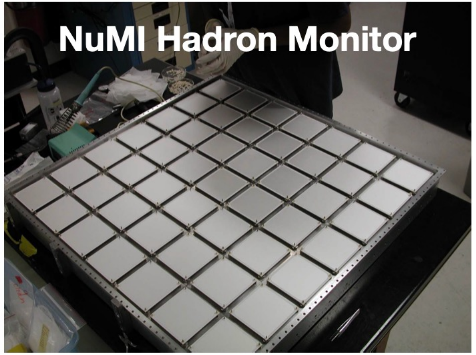


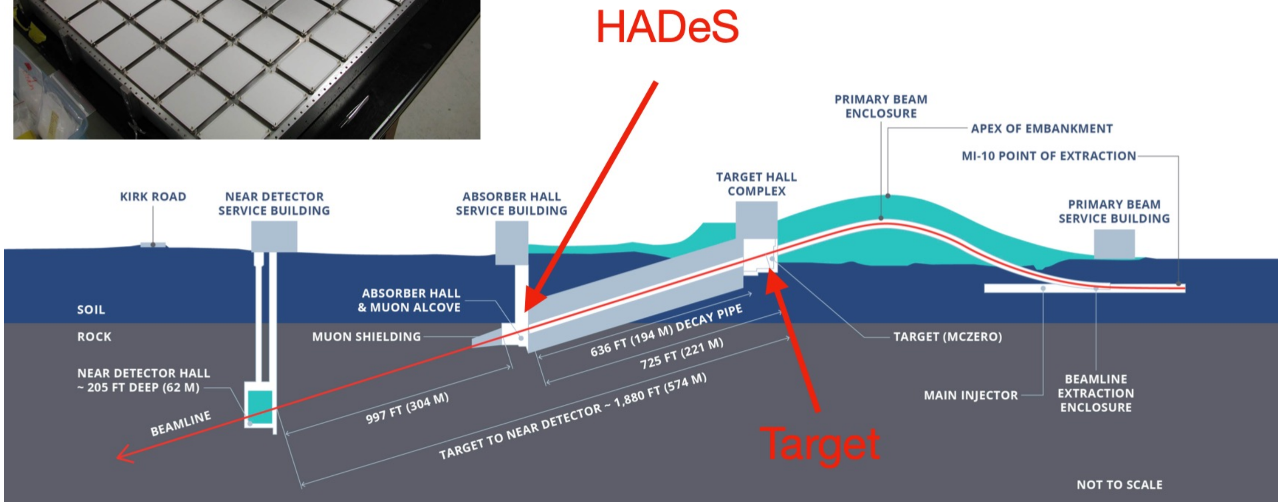


LBNF Hadron Monitor: HADeS

Hadron Monitor located 220m downstream of target at end of decay pipe:

- Designed based on NuMI
- Features an array of ionization chambers





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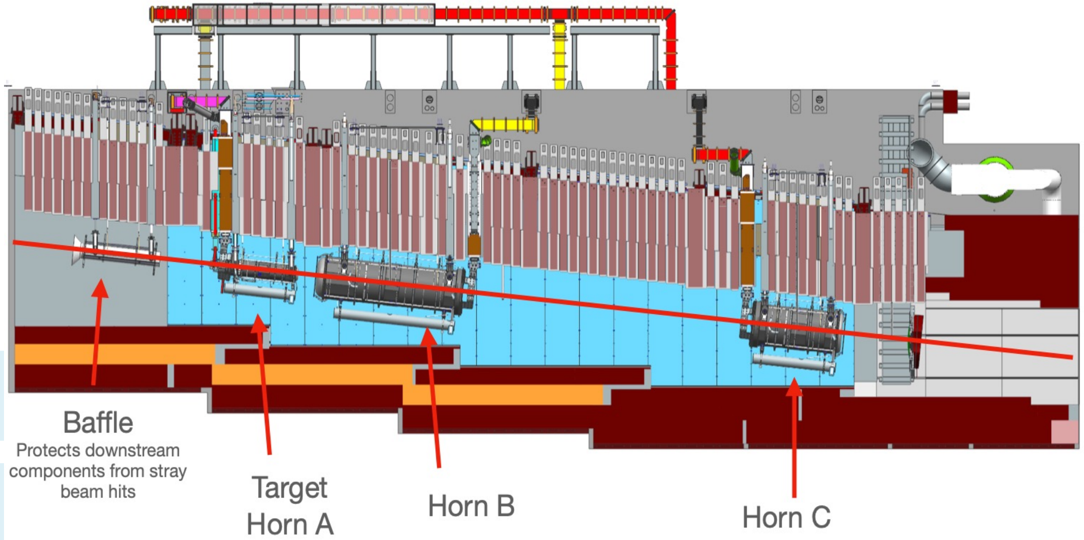
Beam-Based Alignment(BBA): LBNF

- Goal to align baffle, target/horn A, horn B, and horn C on beamline

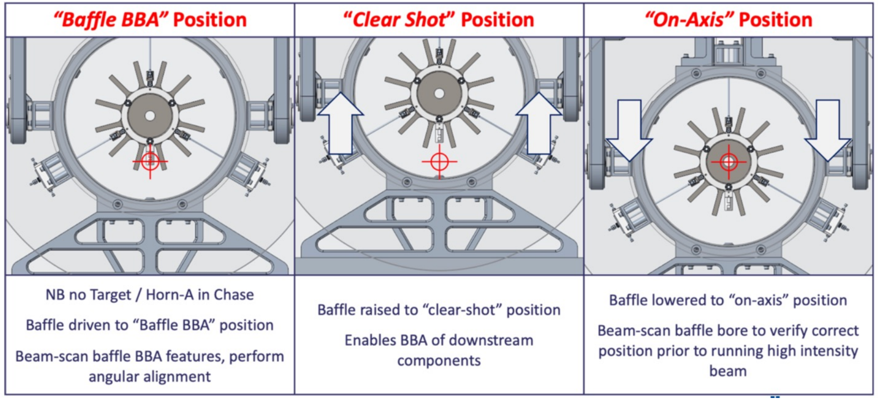


- Utilize 1 mm sigma beam spot size for scanning
- Operate at low intensity and low rate
- Scan beam parallel to nominal beam axis, both up/down and left/right, within +/- 25 mm
- Execute in multiple steps: Beam direction, Horn B&C, Baffle, Target, and Final alignment
- Employ TPT, Beam Loss Monitors, and HADeS for alignment and monitoring

Beam-Based Alignment(BBA): LBNF

- BBA done in 6 steps
- Each step changes beamline setup &/or uses different instrumentation

DUNE-DocDB-24865



Baffle transverse position can be modified for clear shot, BBA, & "On-Axis" alignments

Step	Baffle	Target/Horn A	Horn B	Horn C	Instrumentation
Beam Direction	Clear Shot	Out	In	In	HADeS
Horn B&C	Clear Shot	Out	In	In	BLMs, HADeS
Baffle	BBA	Out	In	In	BLMs, HADeS
Target	Clear Shot	In	In	In	HADeS
Final (low int)	On-axis	In	In	In	HADeS
Final (med int)	On-axis	In	In	In	TPT, HADeS

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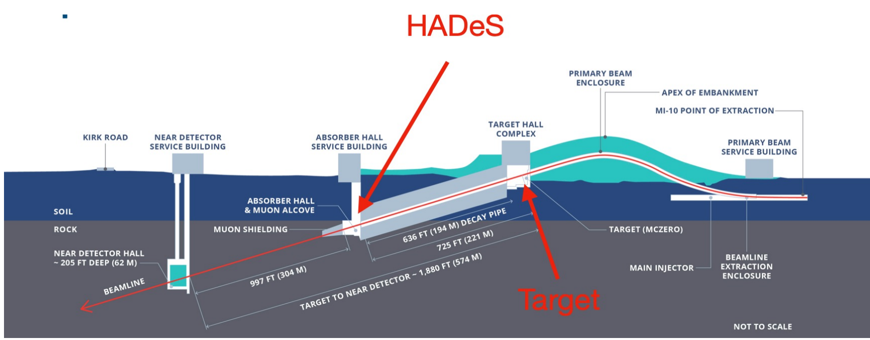
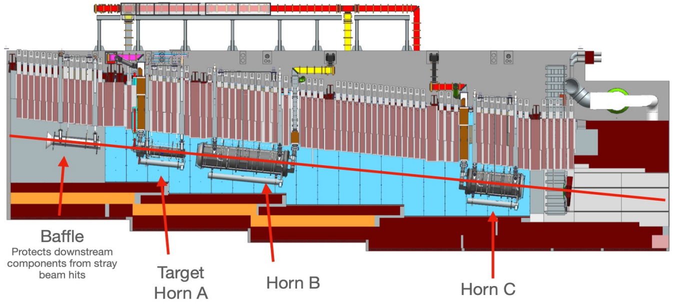
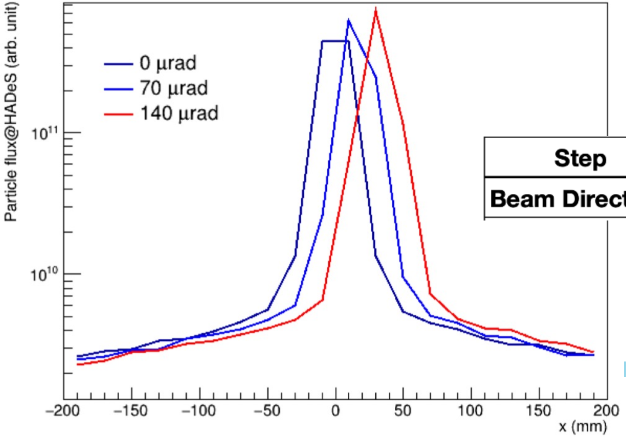
		Pulses							
	Device	**Hor**	**Ver**	**Passes**	**Total**	**POT/ Pulse**	**Sec/ pulse**	**Hours**	**Power/ kW**
Beam Direction	HADeS	200	200	2	800	1E+12	10	2.2	1.92
Horn B&C	BLM	500	500	4	4000	1E+12	10	11.1	1.92
Baffle	HADeS, BLM	500	500	3	3000	1E+12	10	8.3	1.92
Target	HADeS	250	250	3	1500	1E+12	10	4.2	1.92
All in (low int.)	HADeS	250	250	3	1500	1E+12	10	4.2	1.92
All in (med int.)	TPT	7500	7500	2	30000	1E+13	1.2	10.0	208

BBA Example: Beam Direction

- Target/Horn A out of beam
- Baffle in “clear shot” position
- Aim beam at hadron absorber, establish beam center
- HADeS requirement to measure beam position with 1.5cm precision







Step	Baffle	Target/Horn A	Horn B	Horn C	Instrumentation
Beam Direction	Clear Shot	Out	In	In	HADeS

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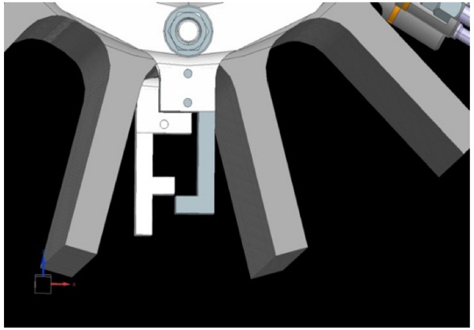
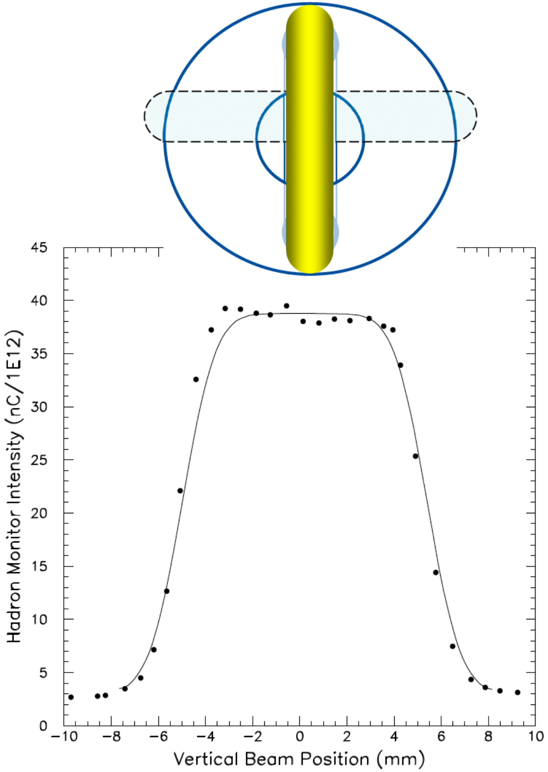
What do we get from HADeS & BLMs?

Example: Baffle moved to BBA position

- Scan beam across fins and determine position using HADeS (and BLMs)
- Using total signal and/or RMS in HADeS can find position of each fin





Hadron Monitor Intensity

Drops with Baffle absorption & scattering

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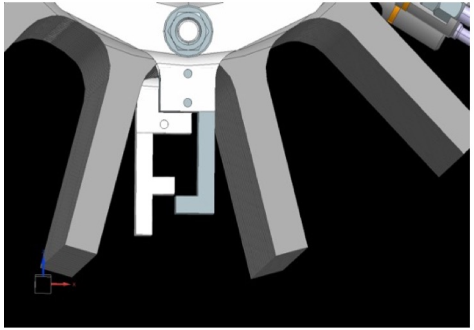
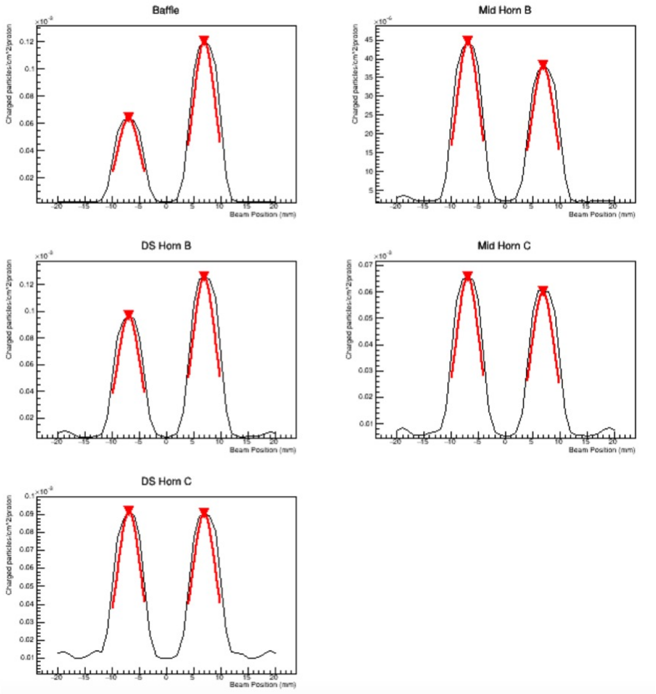


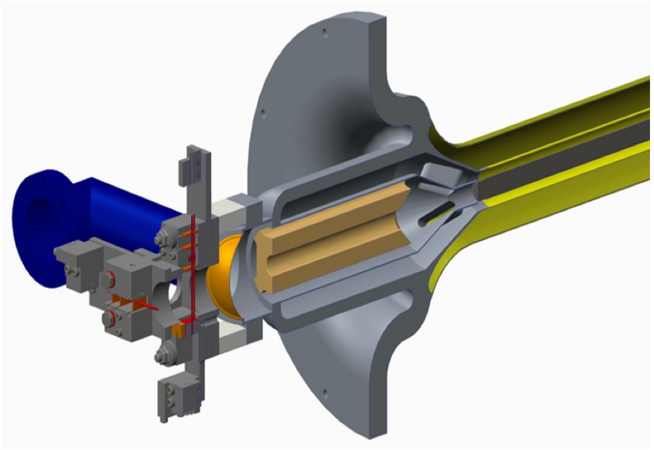


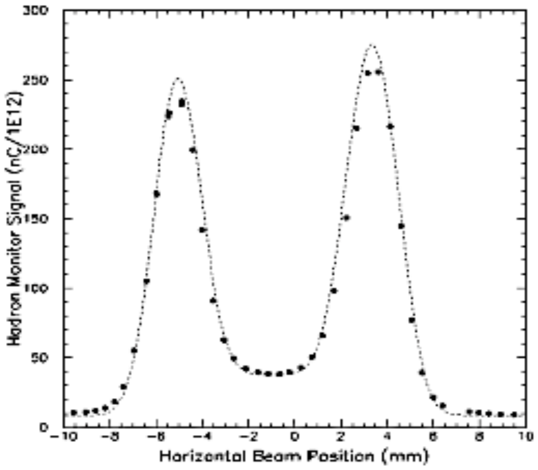
BLMs:

- Beam loss at specific points along beamline
- Signal is a measure of beam loss, which occurs when particles in beam interact with surrounding material and are lost (due to scattering, absorption etc.)
- Signal proportional to flux of charged particles at location of BLM

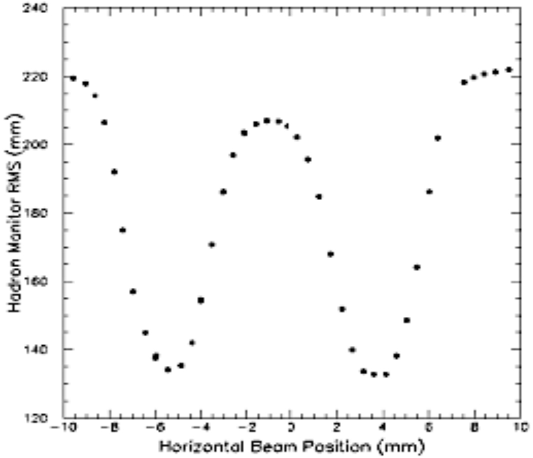
BBA Final Scan

- Baffle moved to in beam position
- Final scan, confirm baffle position
- Confirm beam centered on target using TPT as ramping intensity





HADeS/Hadron Monitor Signal



Baffle	Target/Horn A	Horn B	Horn C
In Beam	In Beam	In Beam	In Beam

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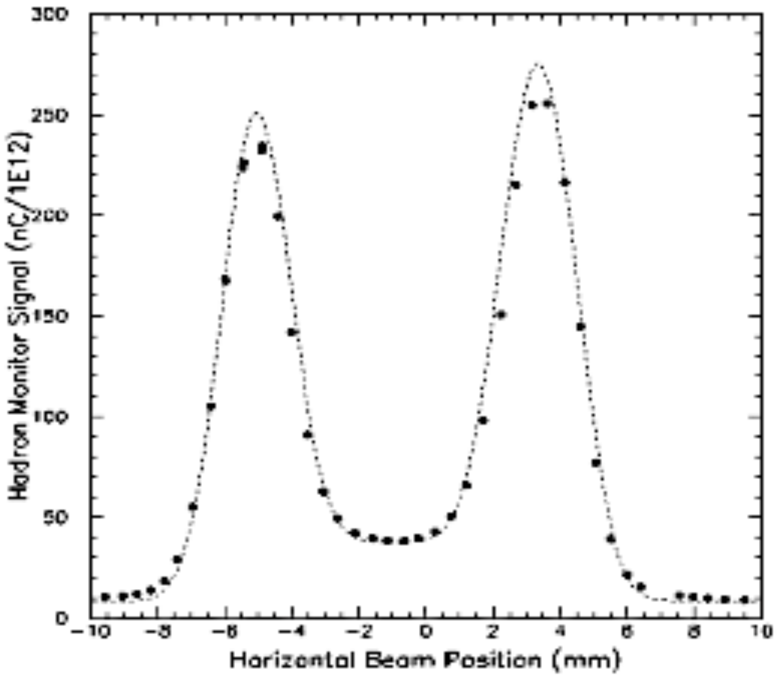
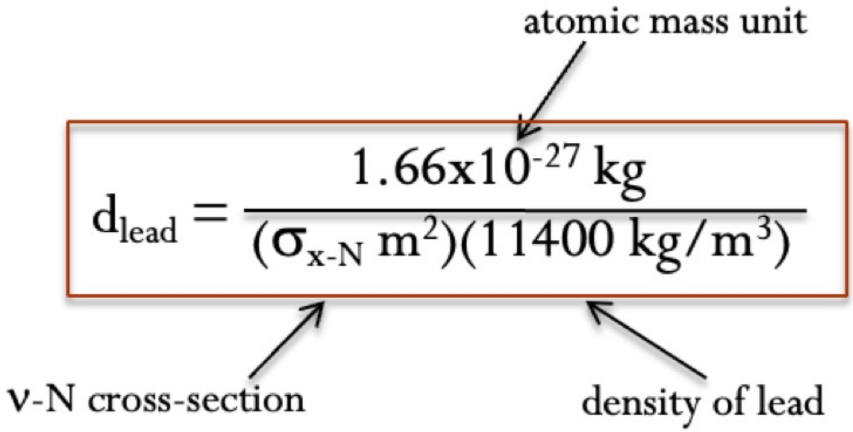
- Question
- Why do we see 2-peaks?
- Why different peak heights?



Think, Pair, Share your answer: https://docs.google.com/document/d/1jR2OlR-pMifQRYnWWYd9oEMcDOLuYBCqIA6VVTj8M0/edit?usp=drive_link

Detecting Neutrinos

- Challenging!
- They are invisible (no charge)
- They are extremely weakly interacting
- Mean free path of a neutrino in lead
- MeV-scale neutrino: $d_{lead} \sim 10^{16}$ m (over a light year of lead)
- GeV-scale neutrino: $d_{lead} \sim 10^{12}$ m (still almost a trillion miles of lead)
- What about a GeV-scale proton? $\sigma \sim 10^{-25}$ cm2
- GeV-scale proton: $d_{lead} \sim 10$ cm



•Generate Neutrinos in Abundance: Aim to produce a substantial number of neutrinos within a well-defined area

•Employ Dense, Large, and Sensitive Material: Utilize materials that are exceptionally dense, big, and highly sensitive to neutrino interactions

Typical Oscillation Experiment

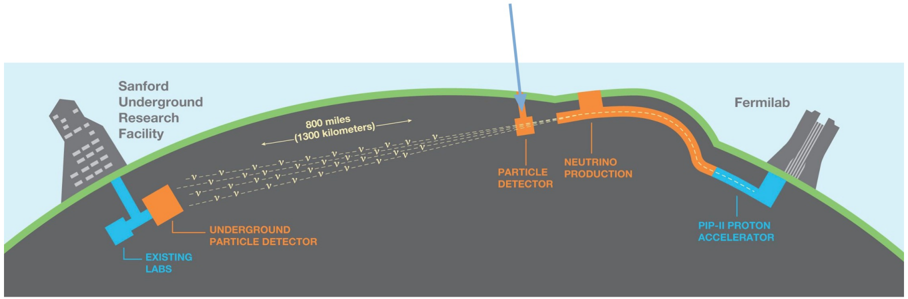
L. Pickering

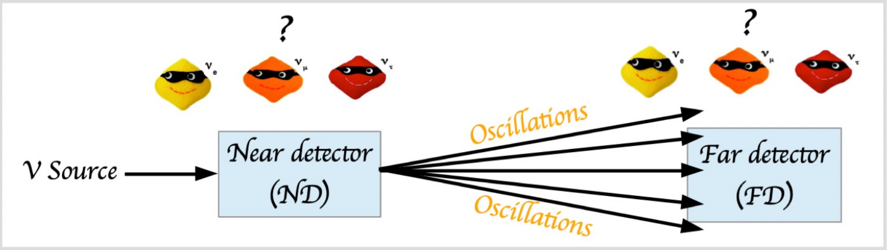
The Deep Underground Neutrino Experiment

- Sample osc. beam
- Infer osc. params

- Sample unosc. beam
- Constrain flux*xsec

- Produce beam



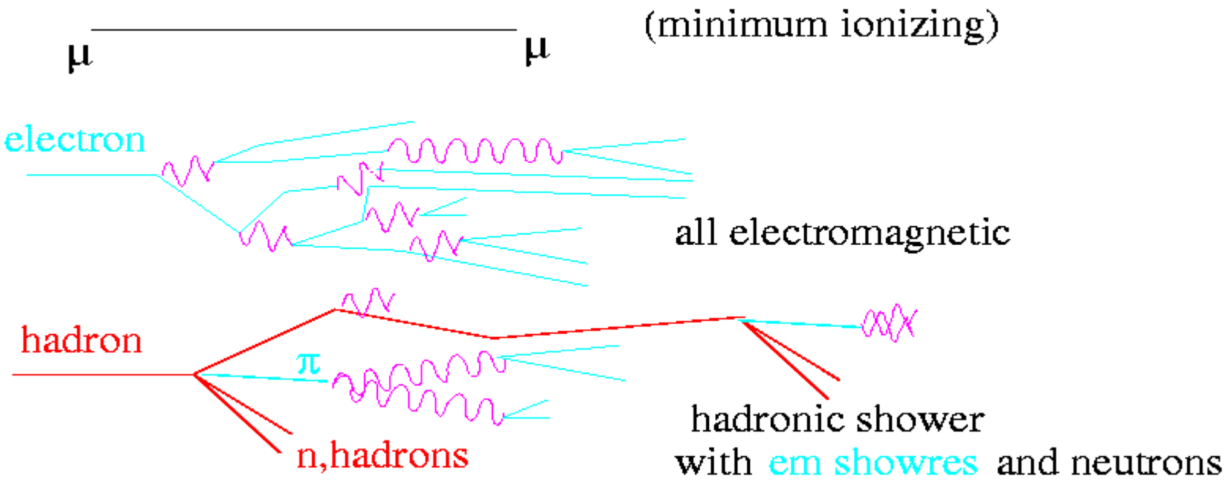


Number of Near Detector events = Flux · Cross section · Detector effects

Number of Far Detector events = Flux · Oscillation probability · Cross section · Detector effects

Three Kinds of Particle Signatures

- Particle interactions in matter
  - Energy loss by ionization
  - Electromagnetic shower
  - Hadronic shower



- Three fundamentally different signatures
- Question: how do you expect energy resolution to change with energy for these three?

Think, Pair, Share your answer:
https://docs.google.com/document/d/1jR2OlR-pMifQRYnWWYd9oEMcDOLuYBCqIA6VVTj8M0/edit?usp=drive_link

Particle Passing Through Detector Material

Particle	Characteristic Length	Dependence
Electrons	Radiation length (X_o)	Log(E)
Hadrons	Interaction length (λ_{INT})	Log(E)
Muons	dE/dx	E
Taus	Decays first	$\gamma c t = \gamma 87 \mu m$

Material	X_o (cm)	λ_{INT}(cm)	dE/dx (MeV/cm)	Density (g/cm^3)
Liquid Argon	14	83.5	2.1	1.4
Water	37	83.6	2.0	1
Steel	1.76	17	11.4	7.87
Scintillator (CH)	42	~80	1.9	1
Lead	0.56	17	12.7	11.4

https://indico.in2p3.fr/event/9418/contributions/49210/attachments/39658/49000/Invisibles_DH_lecture2_v2.pdf

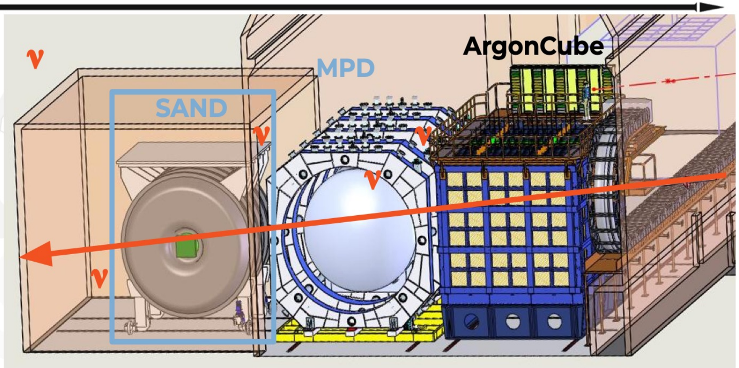
Different Neutrino Detectors

- Example detectors:
  - Cerenkov Detectors – Water Cerenkov
    - – Heavy Water Cerenkov
  - Scintillator Detectors
    - – Liquid Scintillator (Reactor Energies)
    - – Segmented scintillator
  - Liquid Argon TPC

L. Pickering

DUNE Near Detector Concept

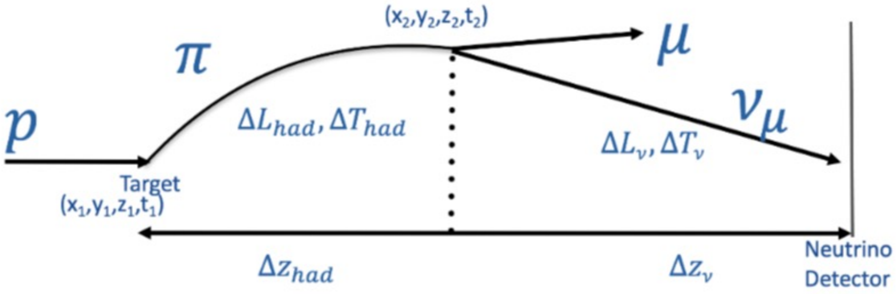
- **ArgonCube**: LAr TPC
  - Primary target, similar to FD
- **MPD**: GAr TPC + ECal + Low mass magnet
  - Charge/momentum/PID
  - Low threshold neutrino target
- **SAND**: 3D plastic scintillator detector inside a superconducting solenoid:
  - Beam monitor

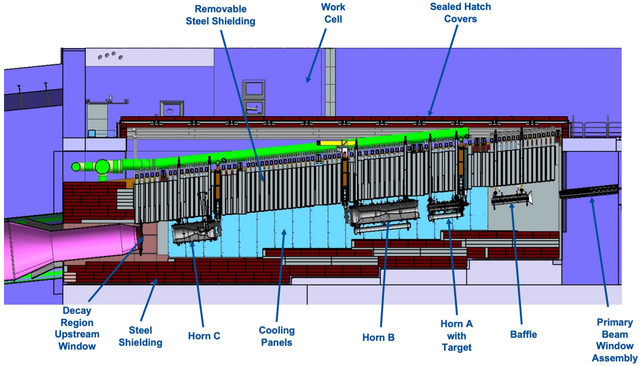


DUNE Preliminary	ArgonCube FV				MPD FV
	All int.	Selected			All int.
Run duration	$N\nu_\mu$CC	NSel	WSB	NC	$N\nu_\mu$CC
$1/2$ yr.	25.5M	11.3M	0.2%	1.4%	680,000

Fermilab

Neutrino Beam Timing





$$T_A = \Delta T_{had} + \Delta T_\nu = (t_2 - t_1) + \Delta L_\nu / c$$

$$T_A^{prompt} = \Delta z / c = (\Delta z_{had} + \Delta z_\nu)/c$$

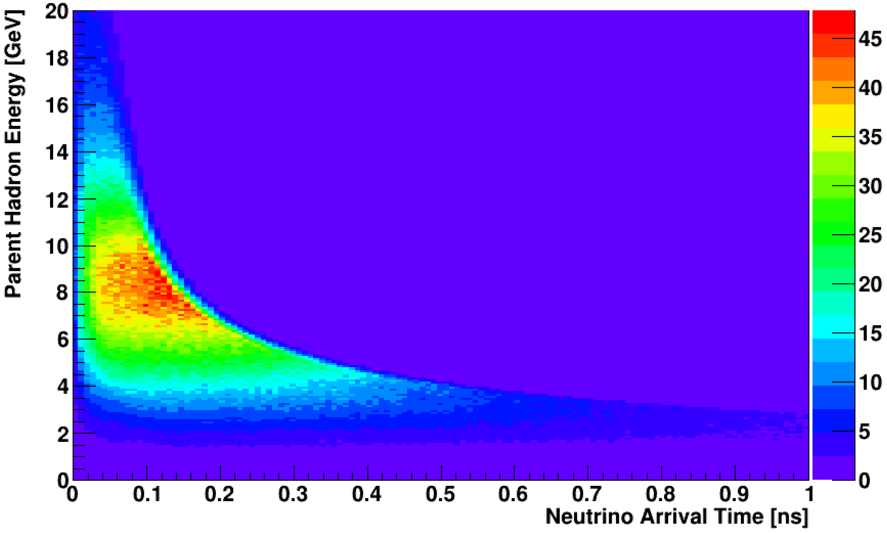
$$\Delta T_{had} = t_2 - t_1 \qquad \Delta T_\nu = \Delta L_\nu / c$$

$$\textbf{Eqn1}: \Delta T = T_A - T_A^{prompt}$$
$$= \Delta T_{had} + \Delta L_\nu / c - (\Delta z_{had} + \Delta z_\nu)/c$$

For $\Delta L_\nu \approx \Delta z_\nu$

$$\textbf{Eqn2}: \Delta T \approx \Delta T_{had} - \Delta z_{had}/c$$

Neutrino Beam Timing



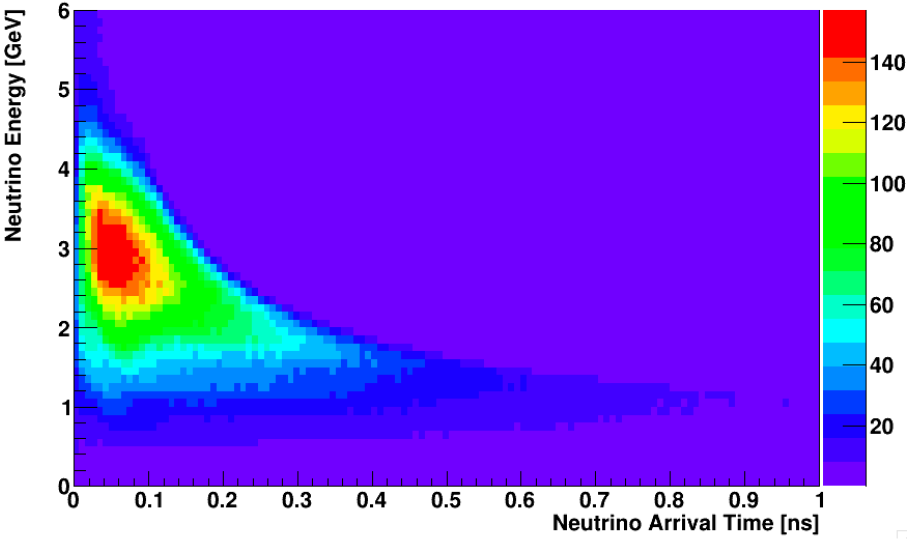
With simulated data of LBNF beam in Forward Horn Current Mode

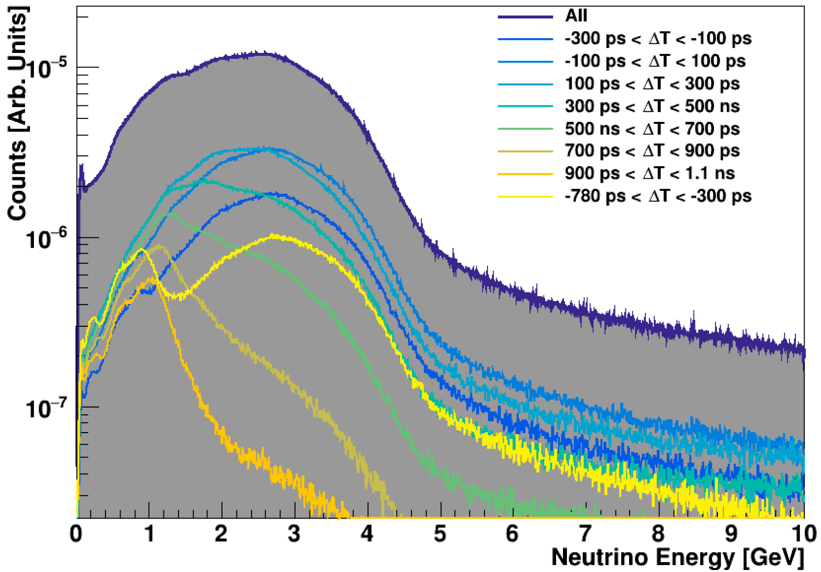
Arrival time difference b/w neutrinos from relativistic hadrons & neutrino from hadron of energy E

For more information: https://arxiv.org/pdf/1904.01611

Fermilab

Neutrinos at Near Detector

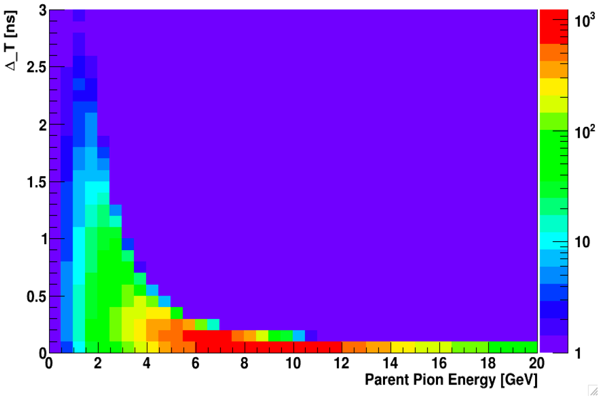


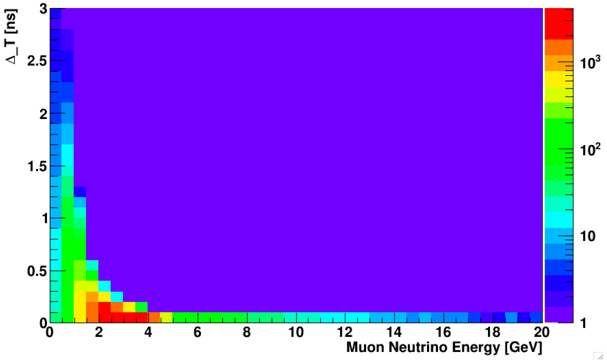


Relative neutrino arrival times versus neutrino energies for all neutrinos with simulated data of the LBNF beam

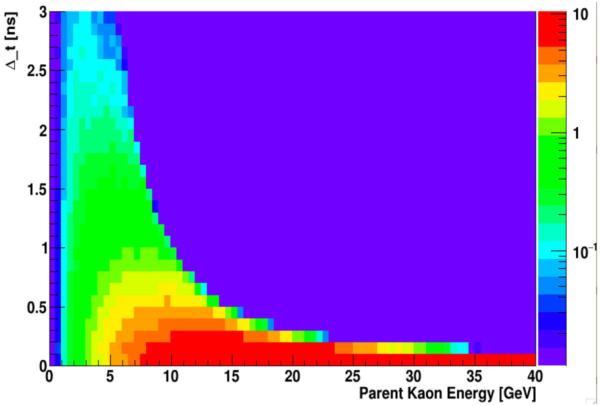
Neutrinos at Near Detector

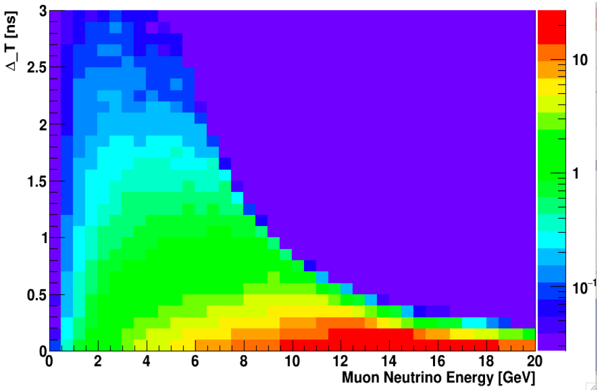
$P+C \rightarrow \pi^{+} \rightarrow \nu\mu$



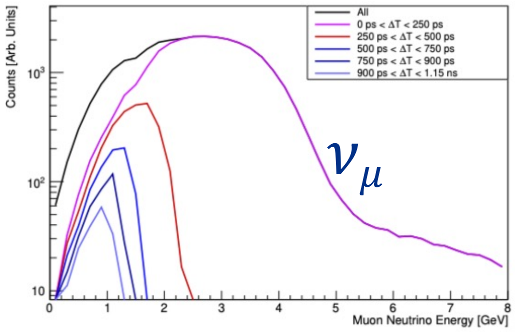


$P+C \rightarrow K^{+} \rightarrow \nu\mu$

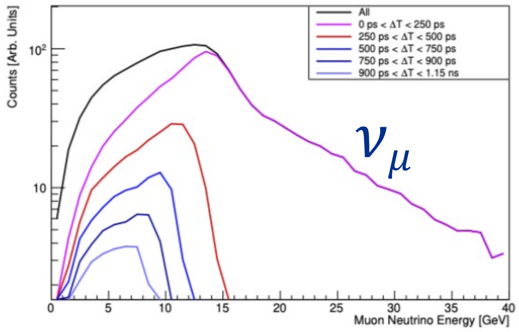




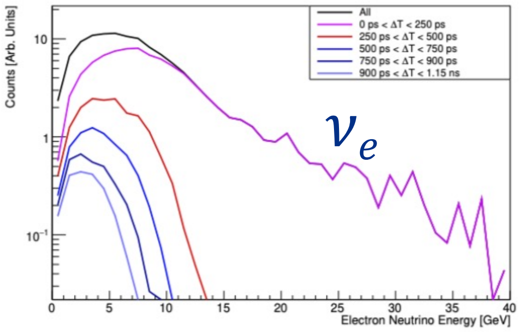
Timing to Separate Out Neutrino Family Types, Parent Hadron Components



Parent hadron: pion only

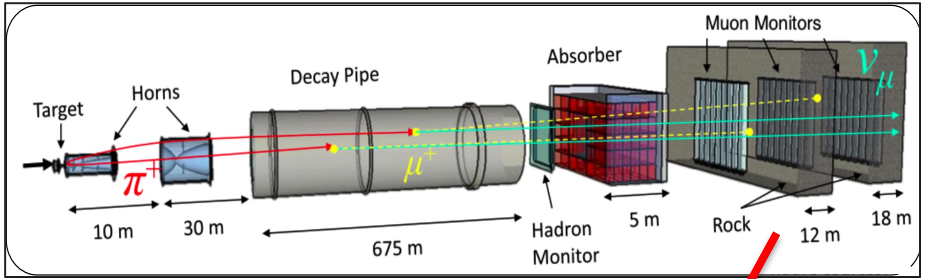


Parent hadron: kaon only



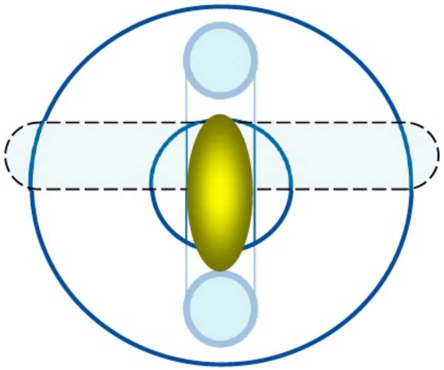
Parent hadron: kaon only

Muon Monitors

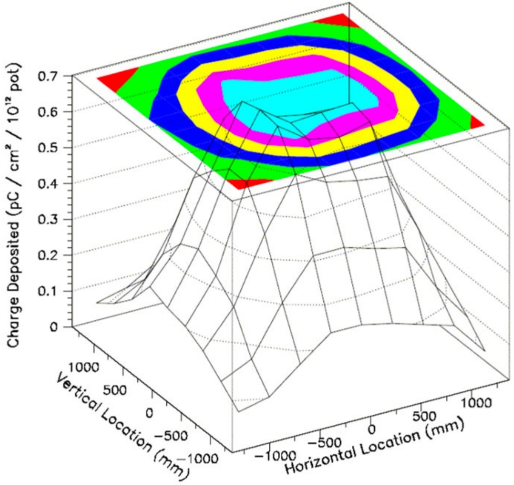


- Muon Monitor intensities show baffle and target positions
- Profiles change with horn focusing

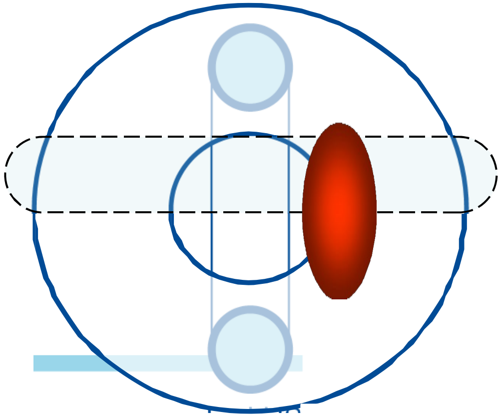
Muon Monitors



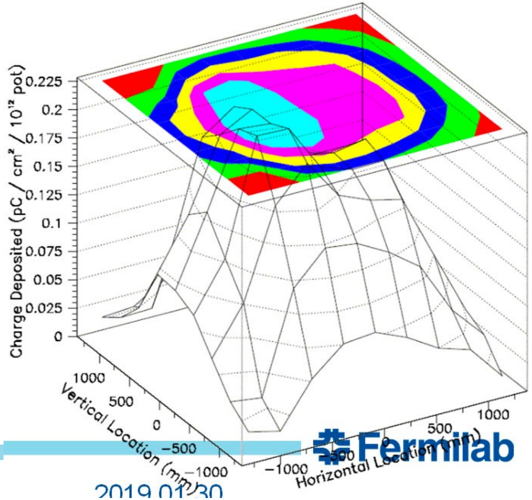
Beam centered on target



Muon
Alcove 1



Beam off 6 mm
horizontally



Muon
Alcove 1

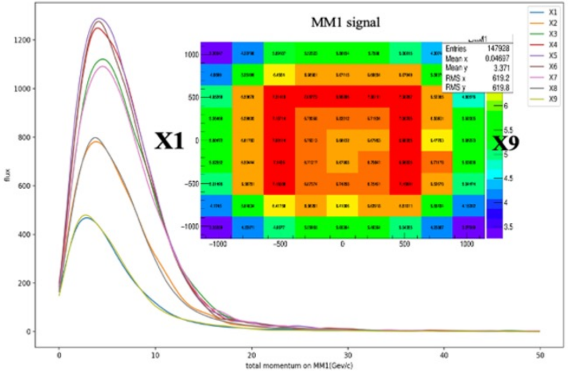
New Instrumentation Ideas

- Large Area Picosecond Photodetector (LAPPD)

- Use LAPPD as muon monitors, provides muon TOF measurement in alcoves across transverse plane
- Allows application of precision timing in neutrino experiments

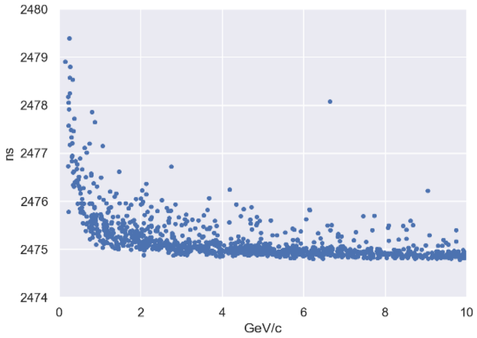
- LAPPDs already offer a space resolution of 1x1 mm and a time resolution of ~55 ps or better

Simulated momentum spectra on central row of MM1



- Individual pixel sees different muon spectrum
- X1 & X9, X2 & X8, X3 & X7, X4 & X6 shows similar shape

Simulated time-of-flight vs muon momentum at MM1



- Observed time distribution will be different at different pixel position

New Instrumentation Ideas

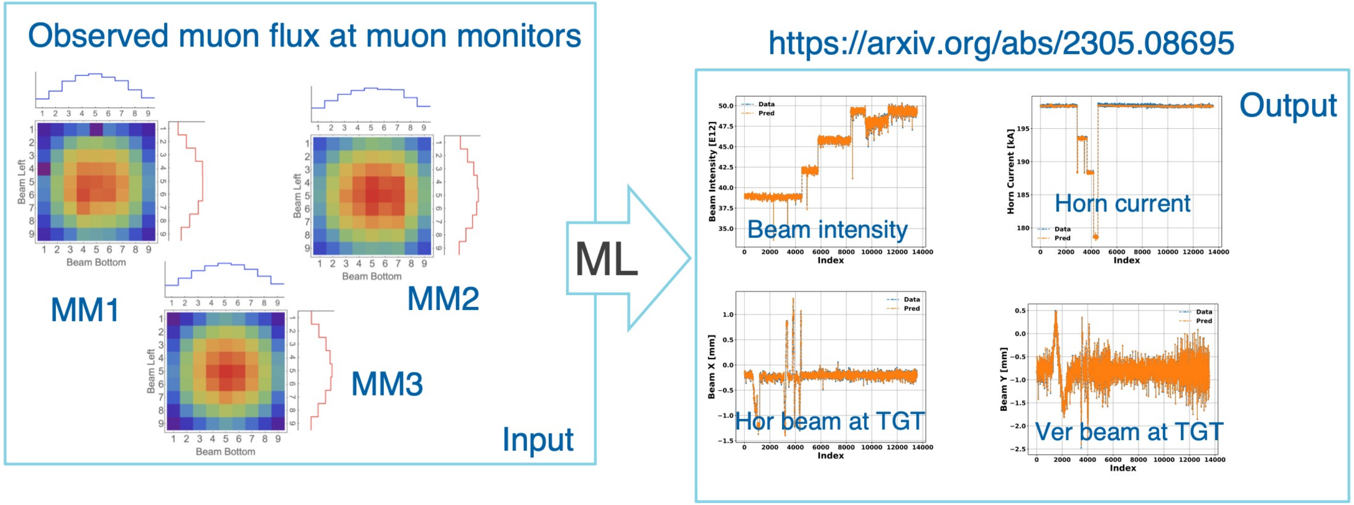
Machine Learning for Beam Quality Assessment in NuMI:

•NuMI horn's linear beam optics implies linear response to beam changes.

•ML algorithm with ANN predicts target beam positions.

•Based on 241 observed values, accuracy: ±0.018 mm horizontally, ±0.013 mm vertically observed

•ML matches traditional instrumentation accuracy



> 1,000 flux images are required for training ML