Muon Monitoring for LBNF & DUNE

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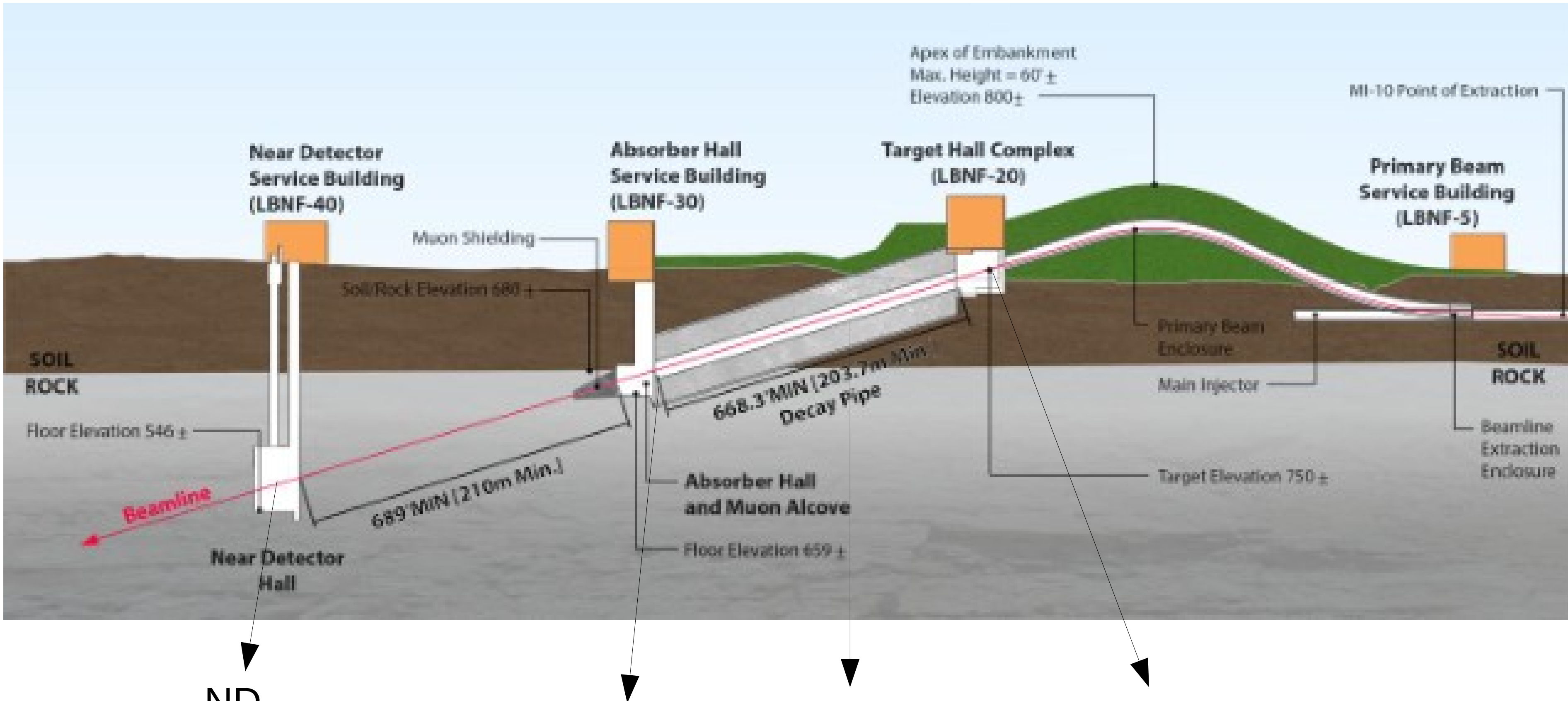
Beamline Overview

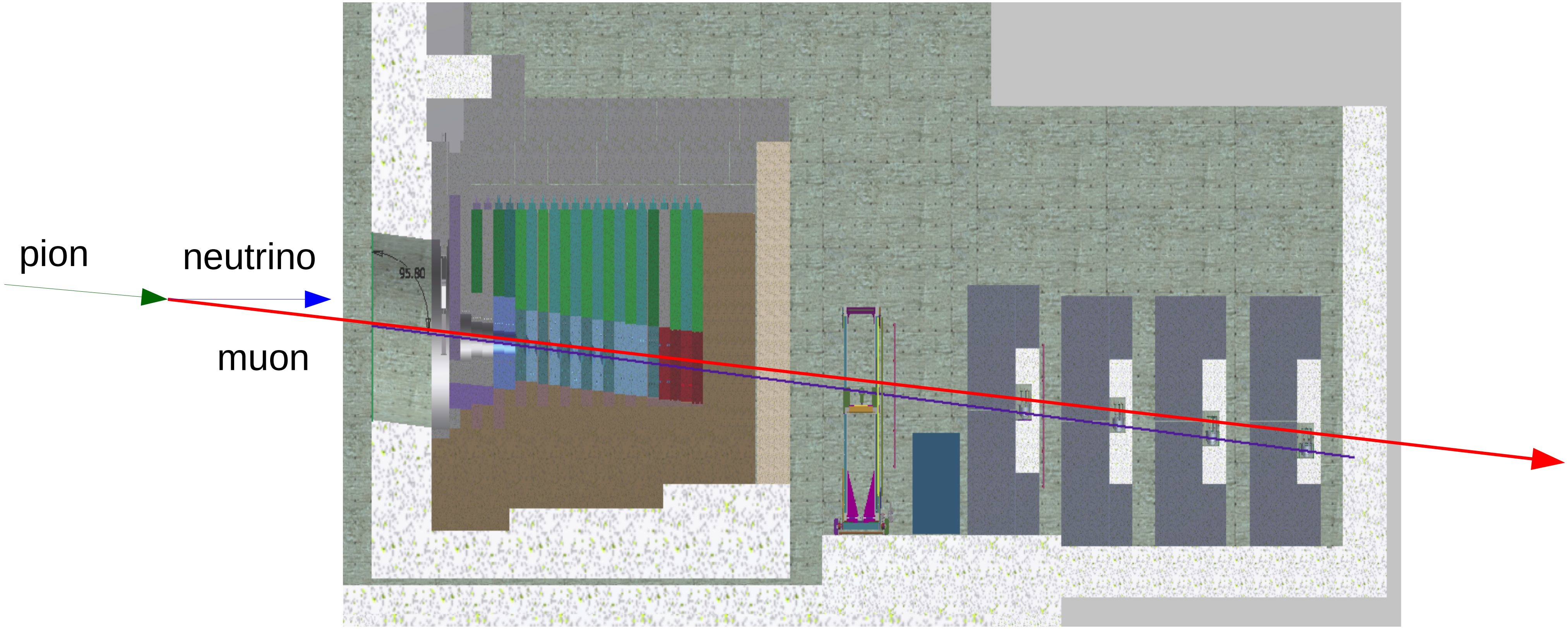


Monitors downstream of absorber, upstream of ND
Basically unlimited statistics. Measurements limited by:
1) Detector performance
2) Absorber geometry (energy threshold, profile shaping, etc)

Beam Monitoring Basics

- Monitoring systems (primary & secondary beamline) will need to:
  - Ensure safe (for people & property) operating conditions
  - Identify bad or near-bad spills (spill-to-spill monitoring for sudden changes in beam properties)
  - Identify emerging problems (monitor drifts in beam properties over time – near neutrino detector might help here too)

Muon Measurements



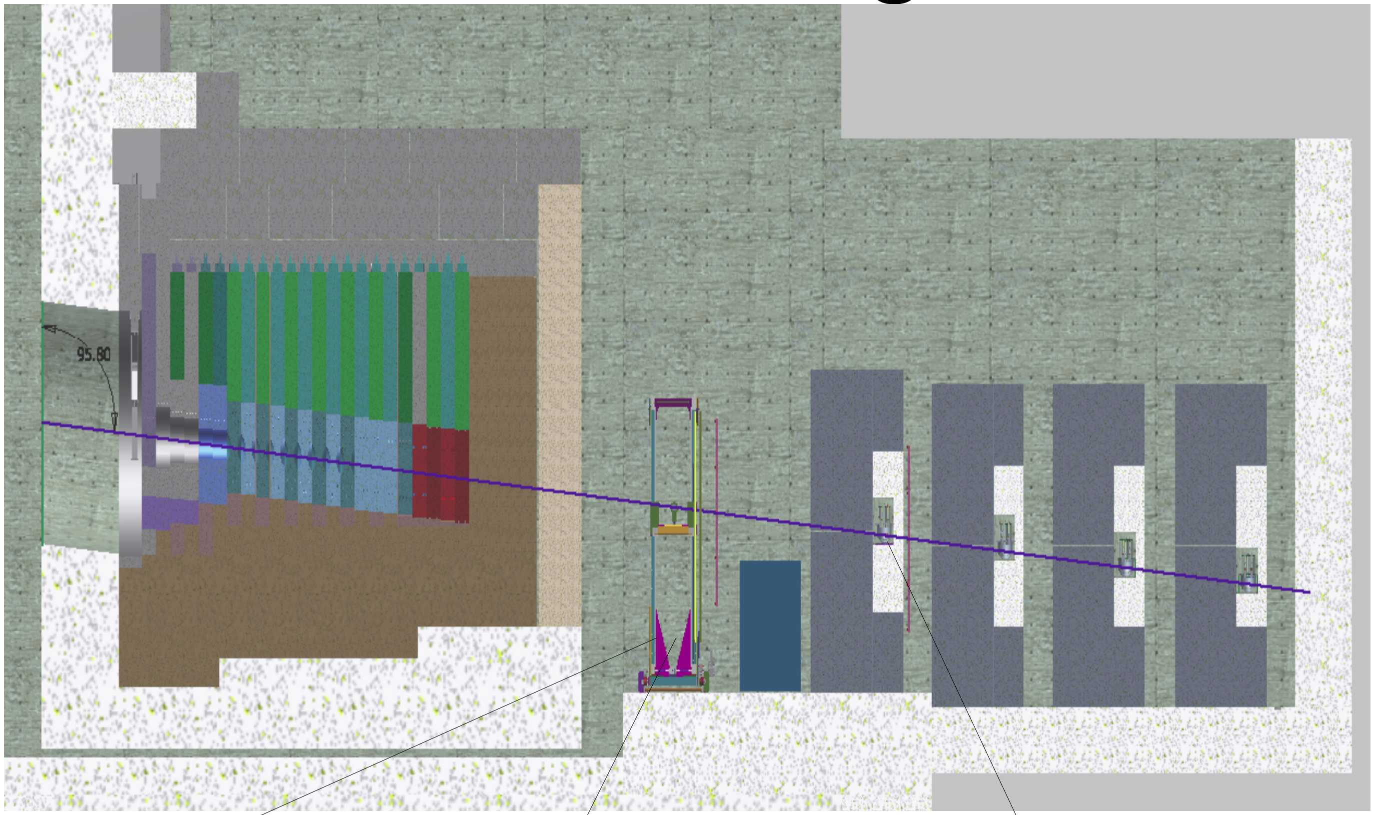
Muons tell us about properties of the beam:

- Direction
- Intensity
- Width
- Timing

But:

- Very harsh environment
- Absorber blocks low energy (<~6 GeV) muons, which may contain interesting physics info

Proposed Muon Monitor Technologies



1. 2D array of ionization counters:
Profile, intensity
If solid-state: timing

2. Threshold Cherenkov counter(s)
Intensity, flux shape, timing

3. Stopped muon counters
Flux shape, absolute flux normalization

Ionization Detector Technologies

- Gas detectors
  - Don't age much – change out gas
  - Less stable – gas detectors can be tricky to use
  - Easy to calibrate
  - Need down-time for refilling
  - Slow response – not great for timing, non-linear effects may be worse

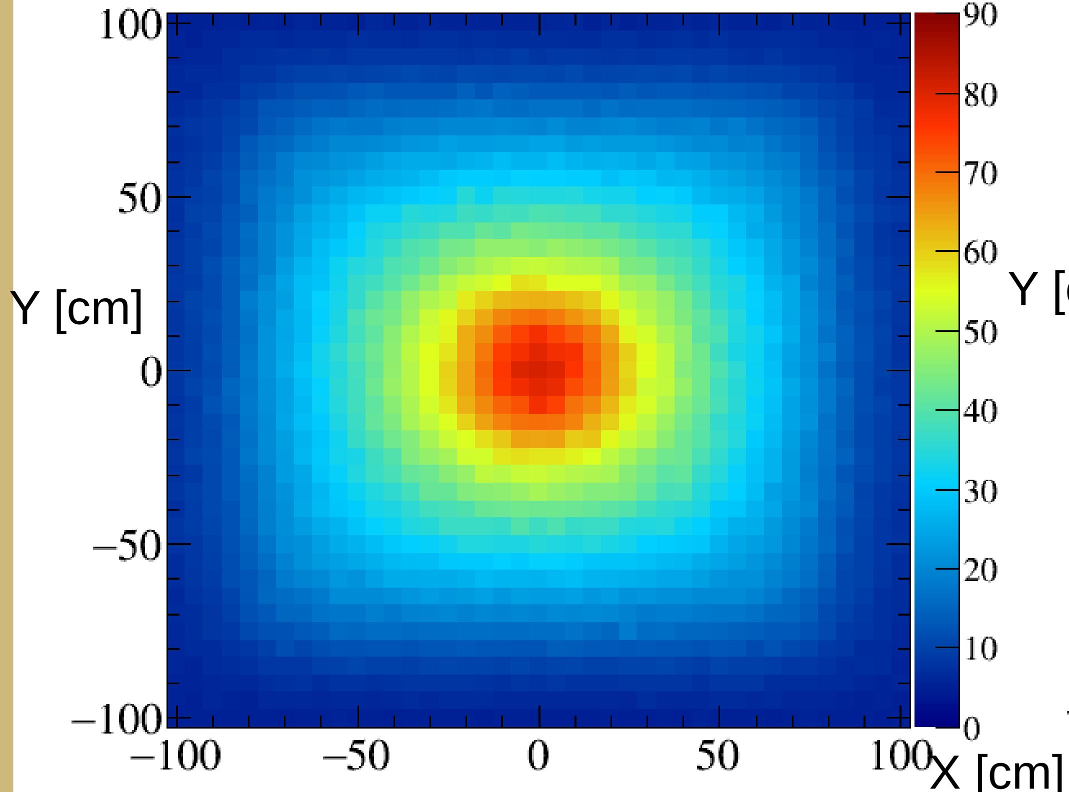
- Diamond detectors
  - Very fast (sub ns timing precision possible)
  - No compressed gases
  - Expensive, not as widely used
  - Will age, but should age slower than Si

- Si detectors
  - Cheap
  - No compressed gases
  - Fast response
  - Age due to displacement of nuclei

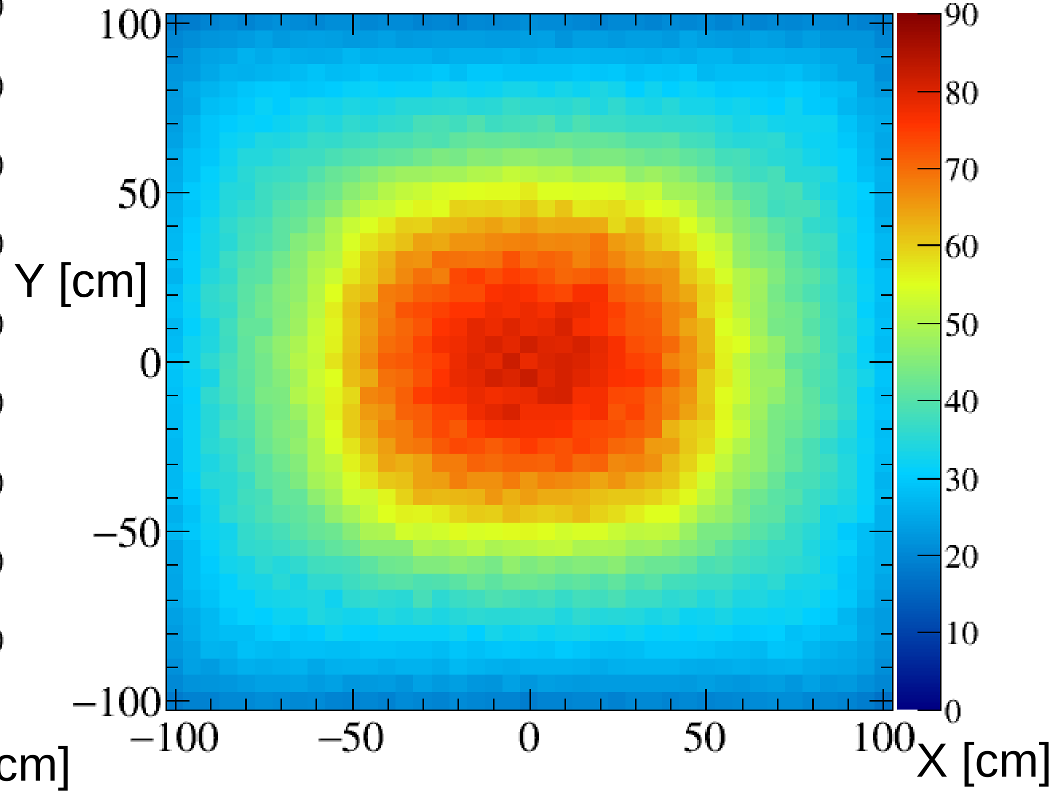
- For all
  - How often must detectors be replaced?
  - Can we keep them properly calibrated during running?
  - How stable are they during running?
  - How linear will the response be at full luminosity?

J-PARC: Gas, Si; NuMI: Gas; CNGS: Gas

Example Beam Profiles in Alcove



Standard G4LBNF optimized beamline

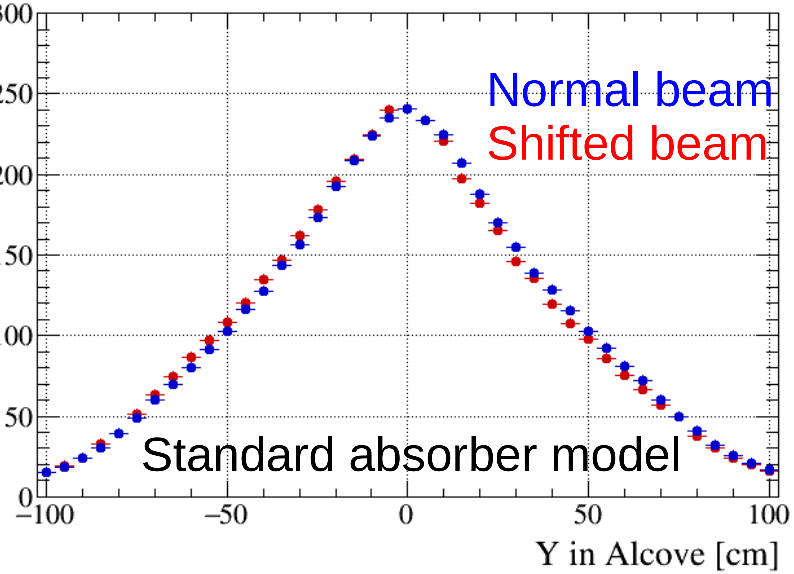


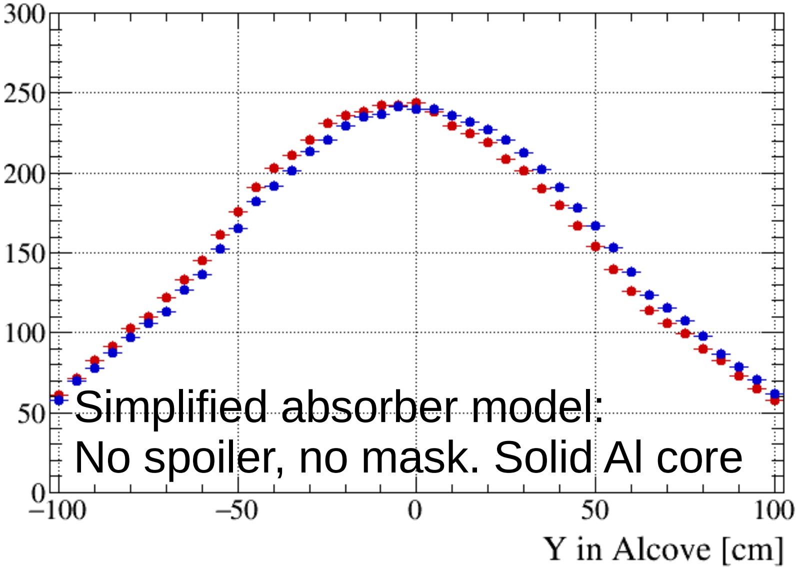
Highly simplified absorber: Solid Al core with no spoiler or mask – details in backup

- Array will sample from this distribution (~25 cm spacing)
- Simulated with G4LBNF, 3-horn optimized beamline (see BOTF report), NuMI-style target, 10 mm wide & 2 m long, 90 GeV protons

If Beam Shifts in Y by 1 mm

Slices around x = 0

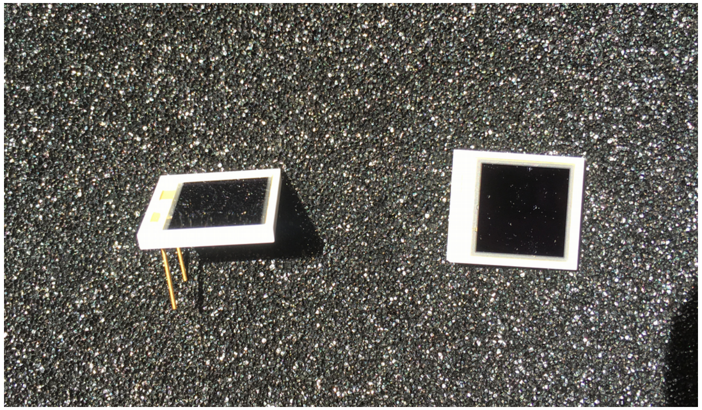




- Will hopefully notice in proton beam monitors (proton beam monitors will not be sensitive to target & horn problems)
- If not, see effects on muon signals
- Left/Right Asymmetry evident
- Muons reaching alcove shifted around 5 cm in -y direction
- Shaping from absorber geometry makes peak shift less noticeable

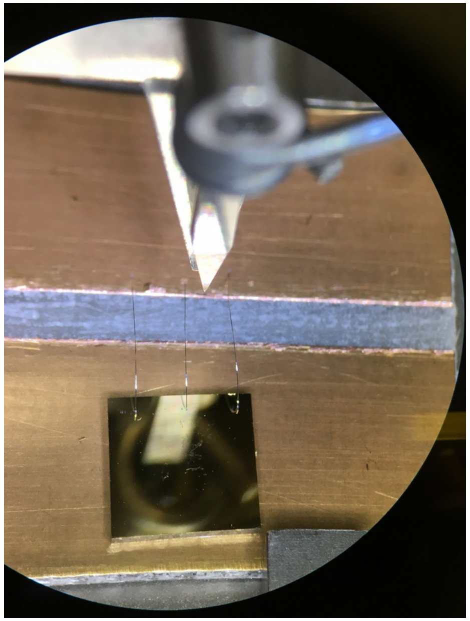
Detector Tests at NuMI

- 3 diamond detectors in NuMI Muon Alcove 2
  - Borrowed from CNGS beamline – were used for timing
- Plan to also install Si photodiodes (commercial device) and diamond detector produced at Colorado from a bare diamond
- No tests of gas detectors at this point



Silicon photodiodes

Diamond det. in progress at Colorado

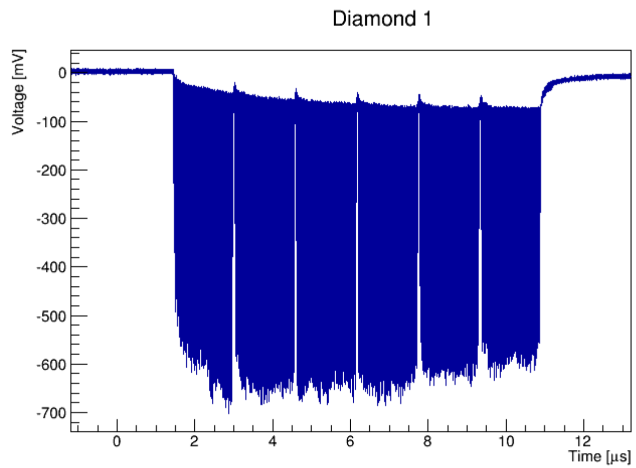


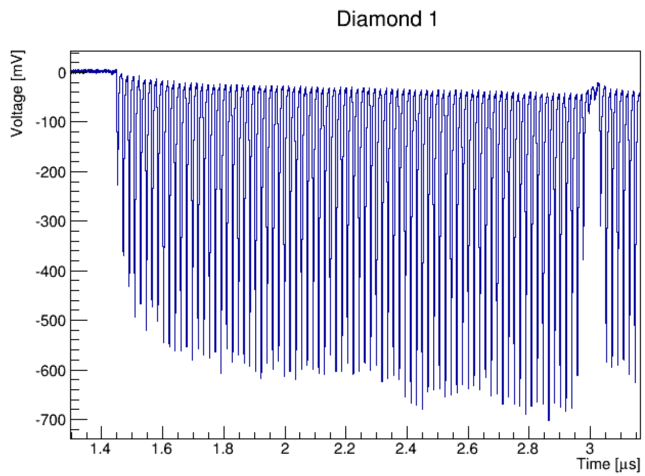
Diamond Detector Tests at NuMI

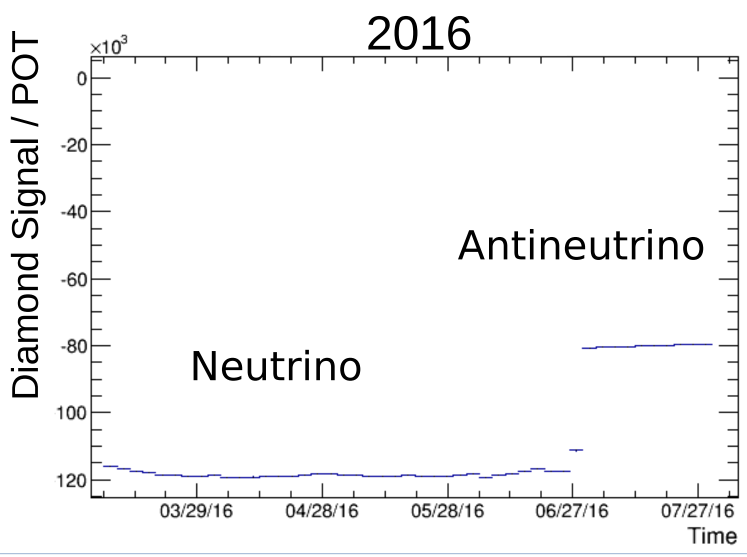
Raw scope traces:

-Very detailed view of beam structure
-Very fast timing

LBNF will have the same basic beam structure



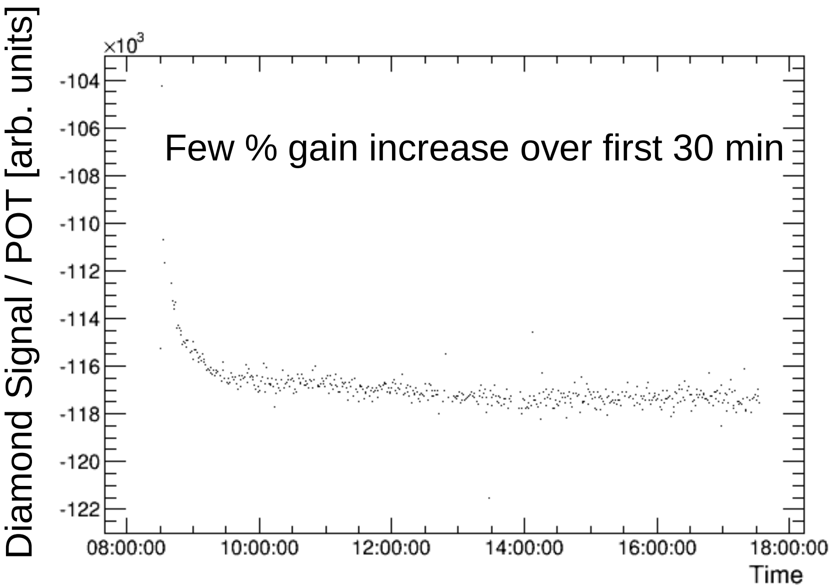


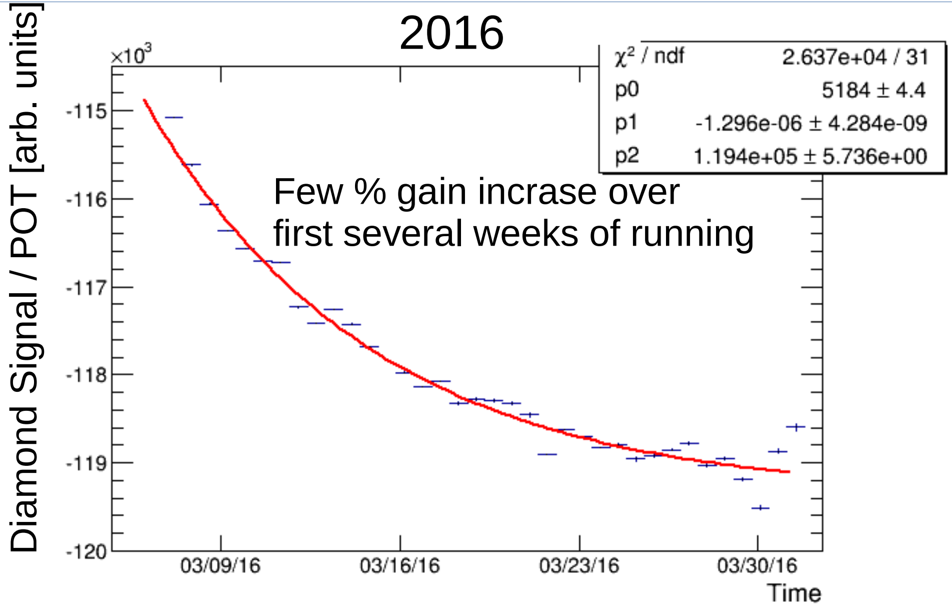


Antineutrino to Neutrino Beam Ratio:

Data: 0.67±0.02
G4NuMI: 0.68±0.03
(G4NuMI result does not yet include energy loss corrections)

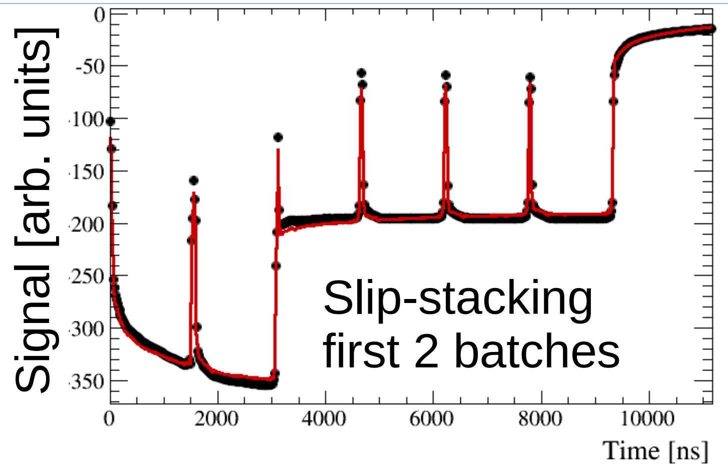
Still Some Things to Understand





Startup (detector HV turn-on and beam start) effects:

Can we understand and avoid or calibrate for these?

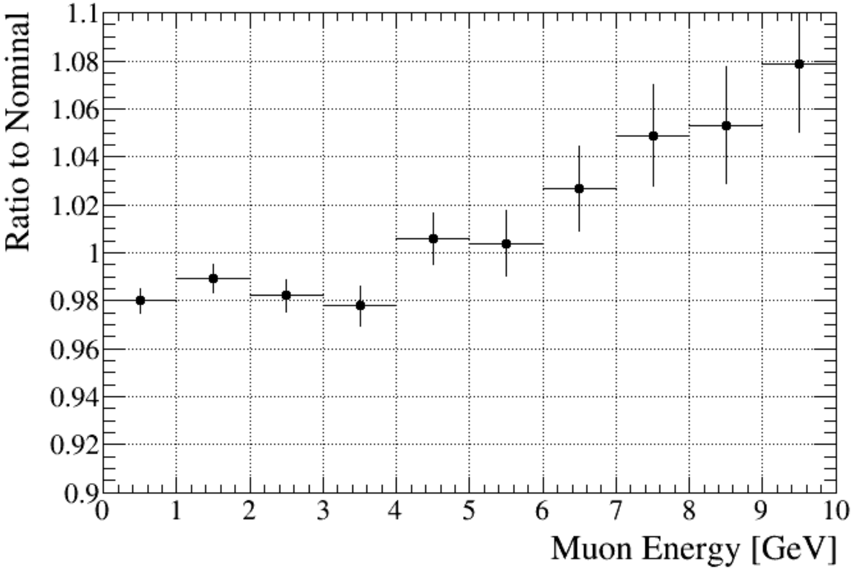


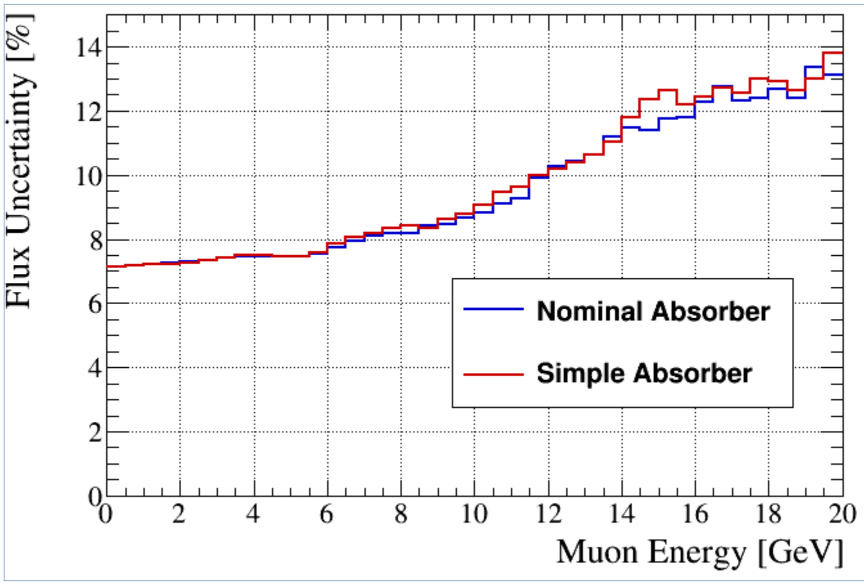
- ~2 ns decay at end and increase in signal at beginning
- Muon capture/decay? Materials activation? RC time constant in electronics?

Flux Measurements

Target damage/target aging

- May get reduction in effective density
- Causes decrease in low energy muon flux, increase in high energy flux
- Right: Ratio of the muon energy spectrum for a 5% reduction in target density and nominal target density

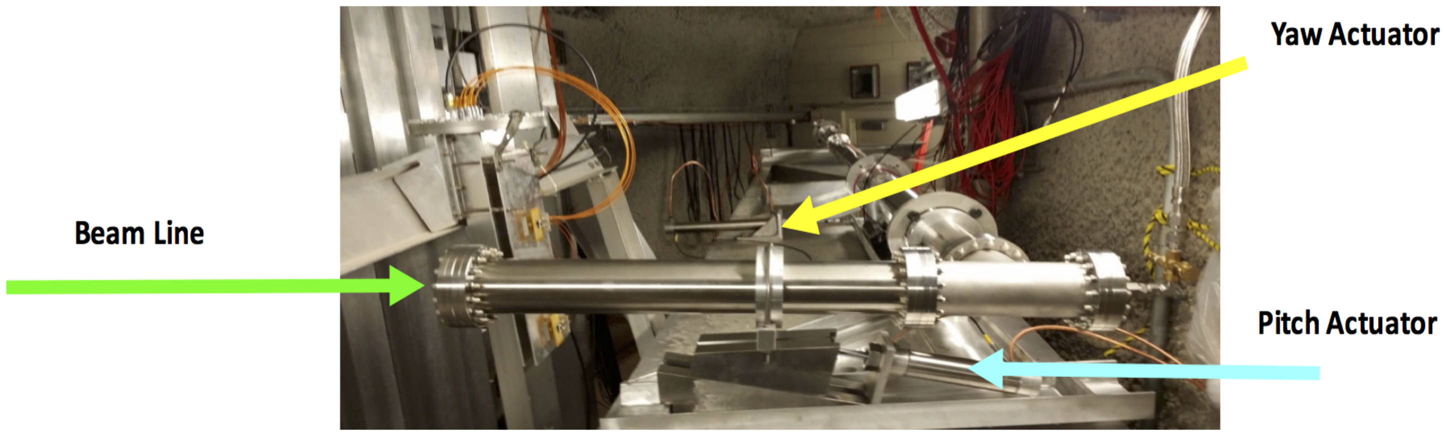




Flux uncertainties

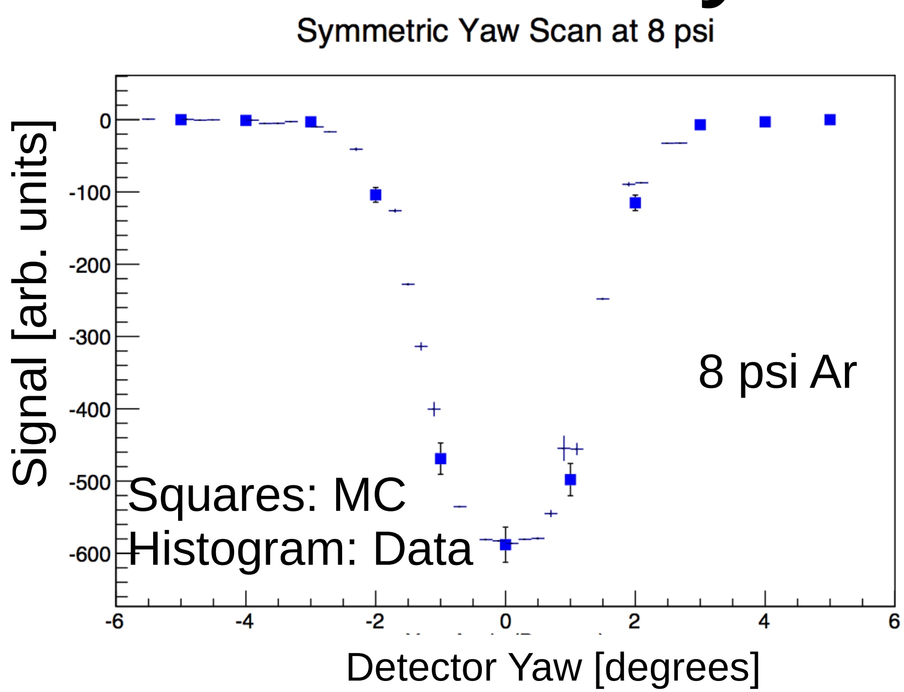
- Left: Work in progress approximation of muon flux uncertainties based on neutrino covariance matrix
- Includes hadron production and beam/beamline alignment uncertainties
- Muon spectrum measurements can (1) help out with monitoring beam conditions and (2) help constrain the neutrino flux

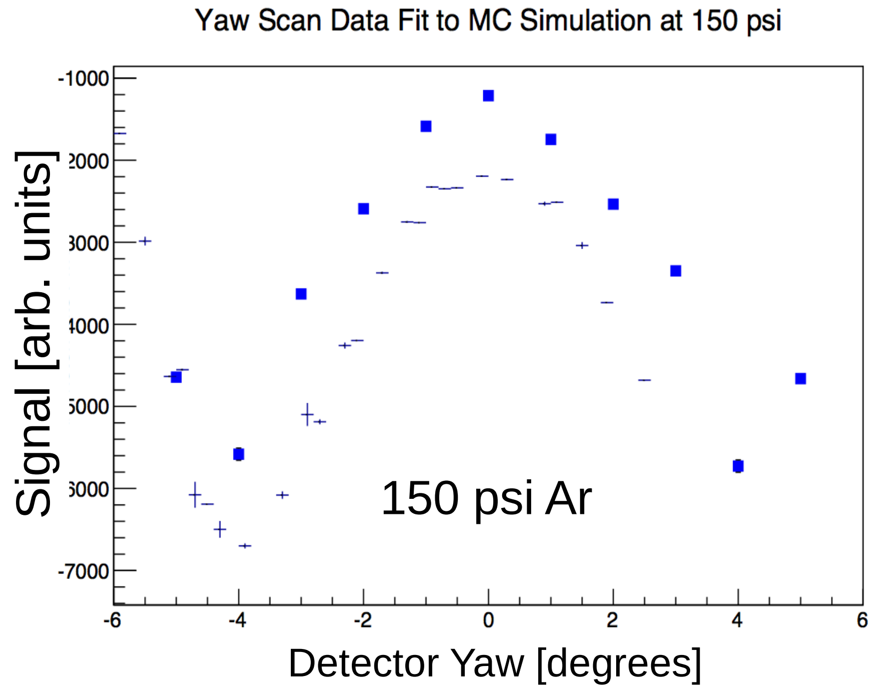
Cherenkov Detector



- Simple detector: Tubes filled with gas with a mirror, viewport, & PMT
- PMT moved far from beam center
- Gas pressure sets Cherenkov threshold
- Actuators change detector angle to change sensitivity to different angles of Cherenkov radiation
- Scan over pressure & detector angle to sample different muon kinematics

Basic Sketch of Cherenkov Detector Analysis Concept





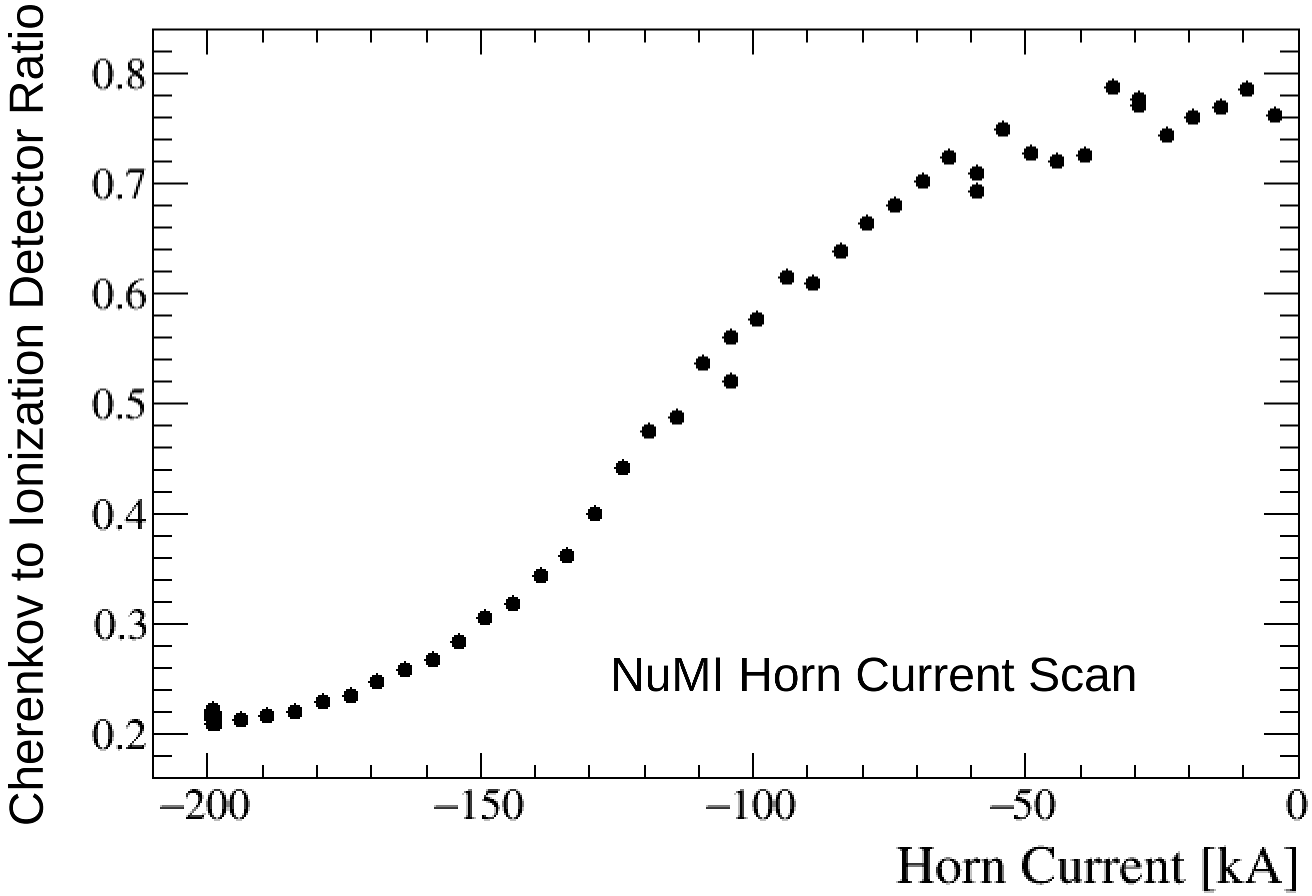
MC: G4 detector model with input from G4NuMI, normalized to 8 psi data

1) Take data at different pressures, angles

2) Do deconvolution or likelihood fit to estimate/constrain muon spectrum in alcove

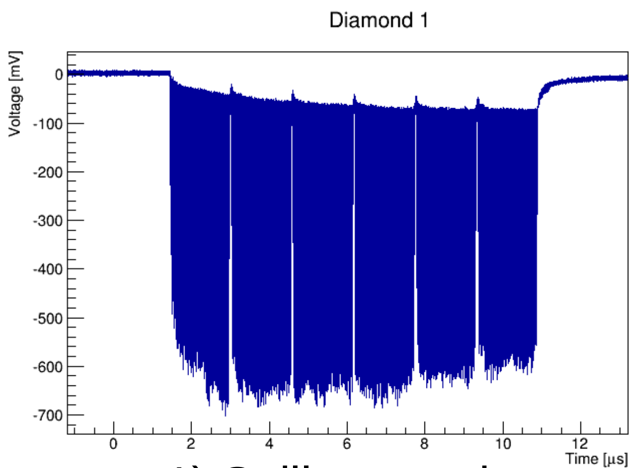
3) Use muon spectrum to constrain hadron or neutrino kinematics

Flux Monitoring



- Without changing detector operating parameters, can see changes in the muon spectrum in Alcove 2 as the horn current decreases

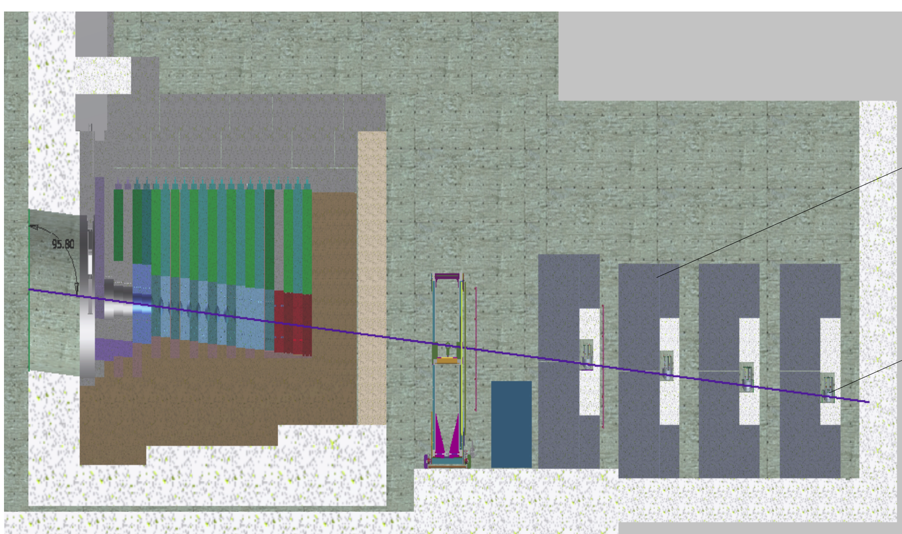
Stopped Muon Counters



1) Spill comes in

2) Wait

3) Measure muon decays once rate is low enough



Different amounts of shielding:
Stop muons with different energies
(need one large alcove or several smaller alcoves)

Different positions (not just at beam center):
Sample different events

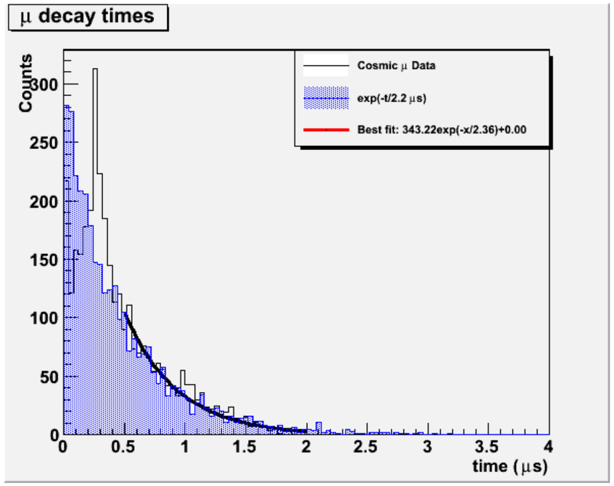
May get very pure muon signal: Absolute muon flux measurement

Stopped Muon Counter

- Want calorimeter type detectors that can distinguish Michel electrons from neutron interactions
- Measure individual Michel electrons from muon decays inside the detector volume
- Goal: Measure the muon flux in several narrow energy bands, use to constrain

Stopped Muon Detector Prototype

- Liquid scintillator outer veto volume (Readout: 4 PMTs)
- Read Cherenkov light in mineral oil inner volume (Readout: 4 PMTs)
- ~1 ft^3 total volume
- PMTs gated – turn on after beam spill ends, off before next spill
- Developed & being commissioned using cosmic muons at Colorado
- To be installed in NuMI beamline soon, take data in upcoming runs



“MARGARITA” Detector

- Water, glycerol, WLS, (KCl)
- Measure Cherenkov radiation associated with stopping & decaying muons
- KCl – reduce mu- lifetime, disentangle mu+ & mu- fluxes
- Installed in NuMI Alcove #2 on 10/27. Awaiting beam startup.

C. Lane, Drexel U.

Muon Monitors Physics Requirements

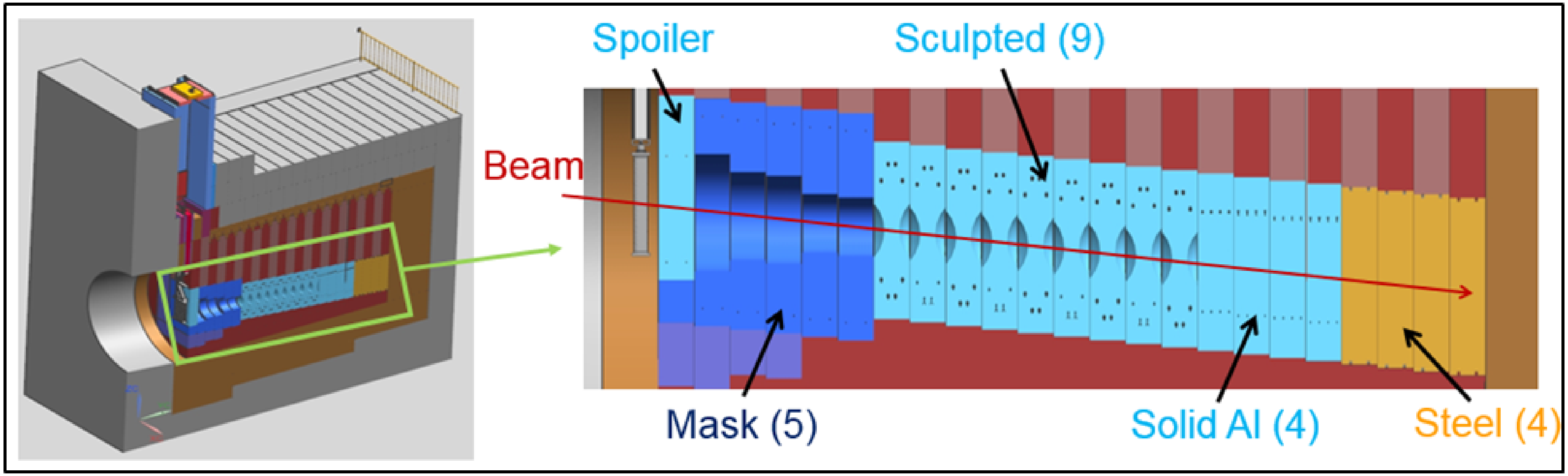
- Have done various simulations of anamolous beam conditions
- Starting to write a tech note (1st draft hopefully in a few weeks)
- Some preliminary conclusions (for monitoring well enough to ensure good physics beam – monitoring for safety will have looser requirements):
  - Need 1-2% precision on total muon signal
  - Need to measure muon peak position to within ~5 cm or so (direct measurement or an asymmetry)
  - Need to measure the muon signal in several energy ranges to a few % or so
- Physics requirements will inform detector performance requirements

Conclusions

- Muon monitoring provides important information to help quickly identify problems with the beamline
- Ionization detectors can measure the muon profile to monitor the intensity and beam direction/position
- Measurements sensitive to the muon spectrum can aid in identifying anomalous beam conditions
- Spectrum measurements may also enable us to quickly get systematics-limited constraints on the neutrino flux
- Detector work is ongoing at NuMI to see how different technologies perform in an actual neutrino beamline (though at much lower intensity than in the LBNF alcove)

Backup

Absorber



- Mask, sculpting, transition between core Al layers and outer Fe layers all shape the muon profiles
- To see how shaping affects the beam, simplified model removes the spoiler and mask layers (replace with air), removes the sculpting (solid Al blocks) and expands the size of the core to match a square inscribed in the decay pipe