Constraining the Accelerator Flux With Muon Monitors

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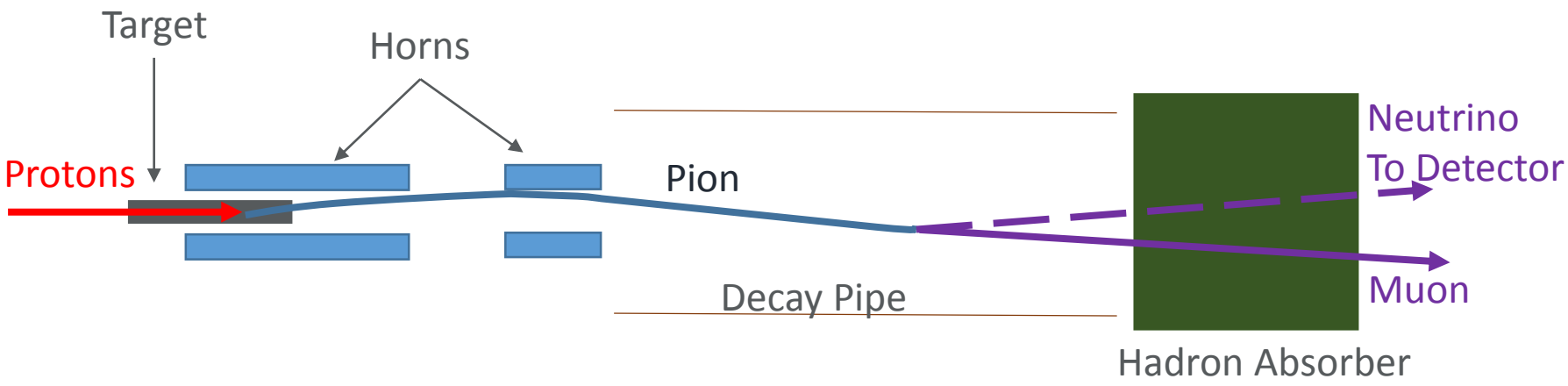
Outline

1) Neutrino Beamline Muon Monitoring: Basics
2) Muon Monitors in Existing Beamlines
   - CNGS
   - NuMI
   - J-PARC/T2K
3) Future Beamlines
   1) LBNF/DUNE Plans
   2) Prototype Testing at NuMI

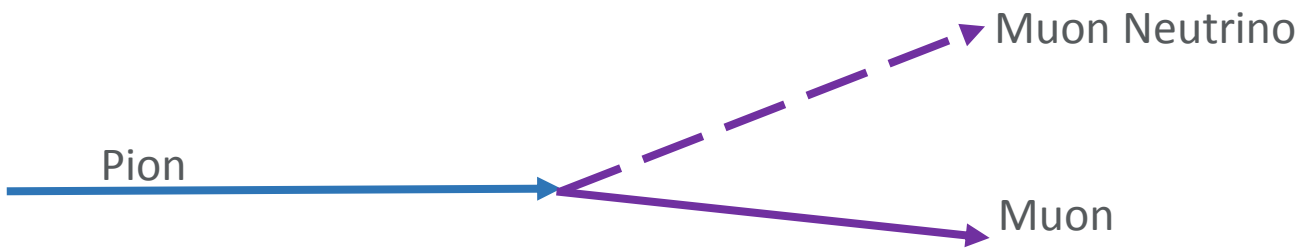
For more info on muon monitoring for all the beamlines, the NBI series of workshops is a good resource

Muons in Neutrino Beamlines



- Muons produced in great quantities by decays of hadrons in the decay pipe
- Muons with enough energy to pass through the hadron absorber can be measured

Why Muon Measurements?

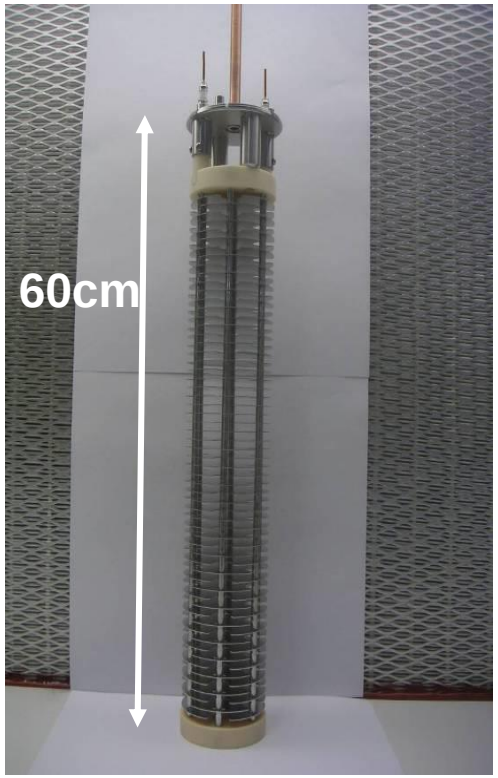


- Created in conjunction with neutrinos
- Muon decays create additional neutrinos
- Most direct way to measure neutrino beam properties without actually measuring neutrinos
- Can quickly extract information about the beam

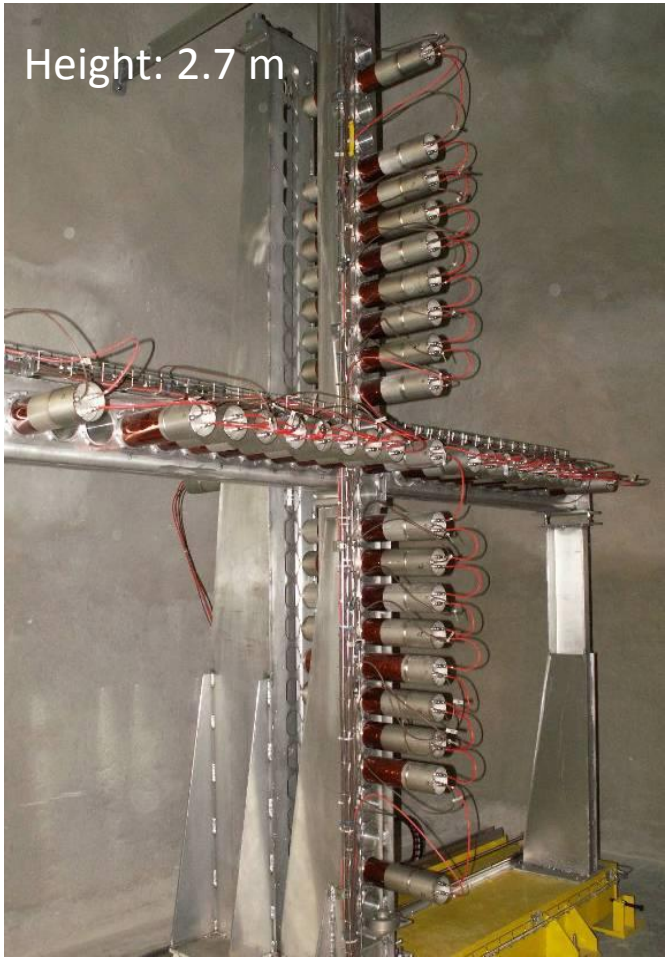
Muon Monitoring Basics

1) Place an array of detectors at one or more points downstream of the absorber
2) Make measurements on a spill by spill timescale as well as over a long period of time
   - Monitor beam direction using muon spatial distribution
   - Keep track of beam intensity over time
3) Do this with robust, cost-effective detectors that need little direct intervention for repairs

CNGS Muon Monitors

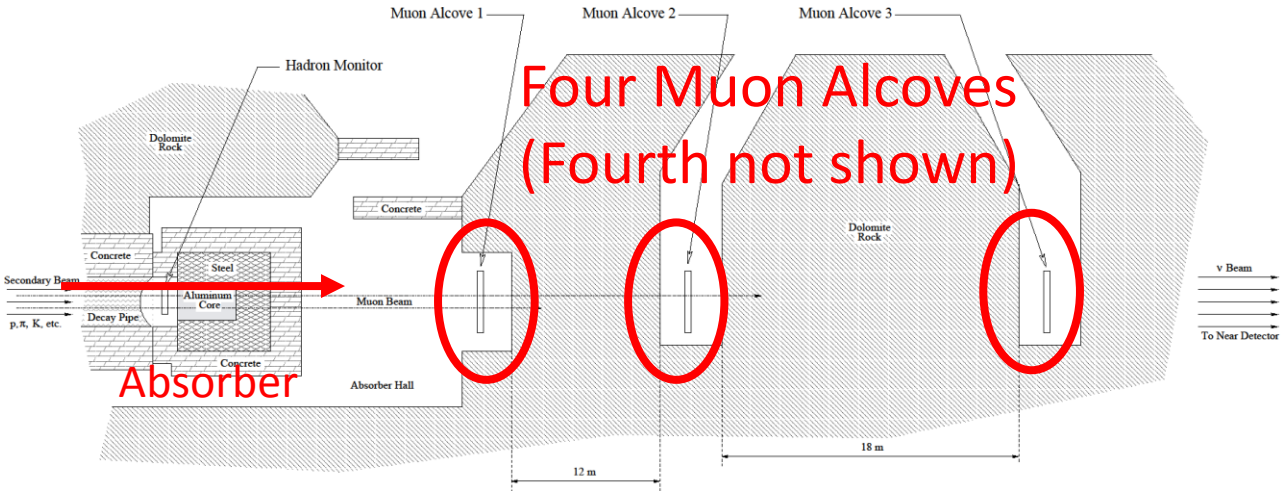


- Cylindrical Ionization Chambers arranged in a cross geometry
- Two sets of monitors, separated by 67 m of material
- Based on LHC beam loss monitor design

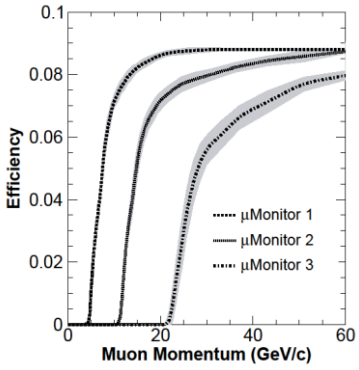


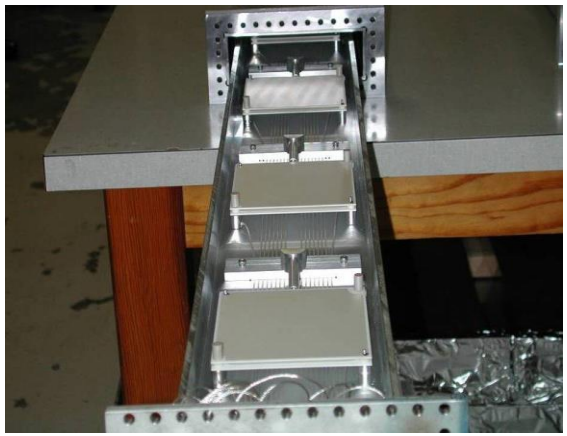
E. Gschwendtner, Talk at NBI 2010

NuMI Muon Monitors



- Grid geometry,
- 9x9 arrangement
- Parallel plate ceramic ionization chambers



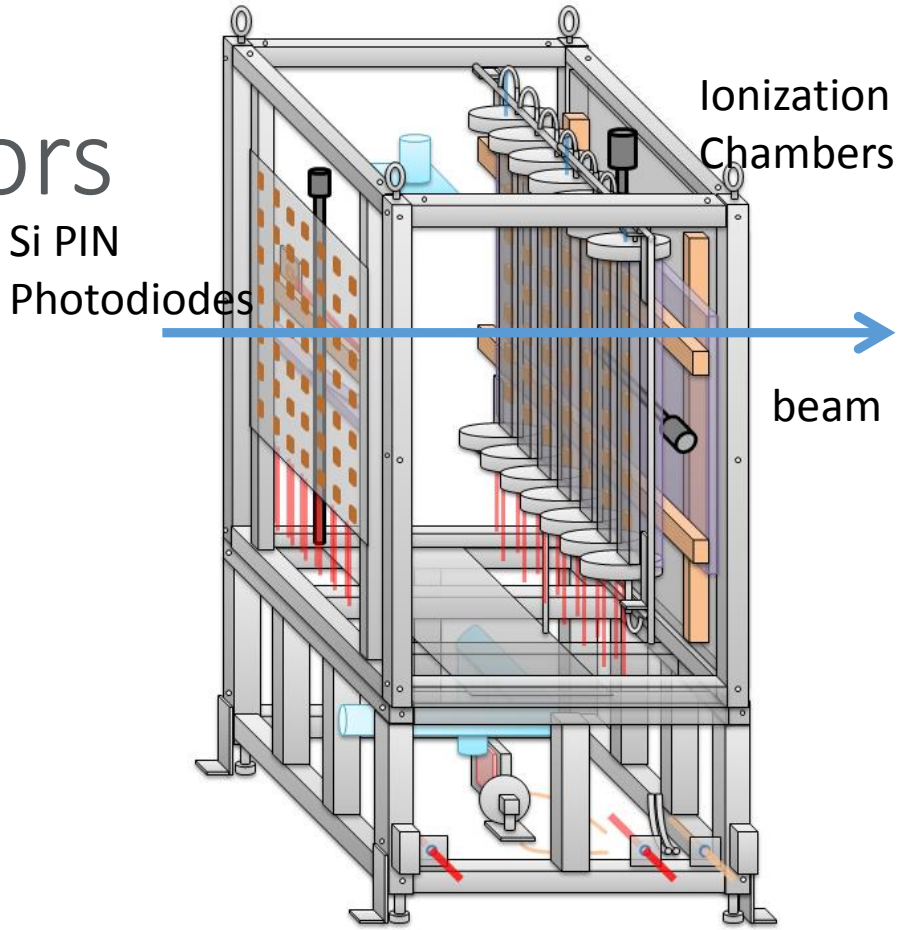


Have also attempted to constrain neutrino flux

Above Images: S. Kopp, Talk at NBI 2006
Plots: arXiv:1507.06690

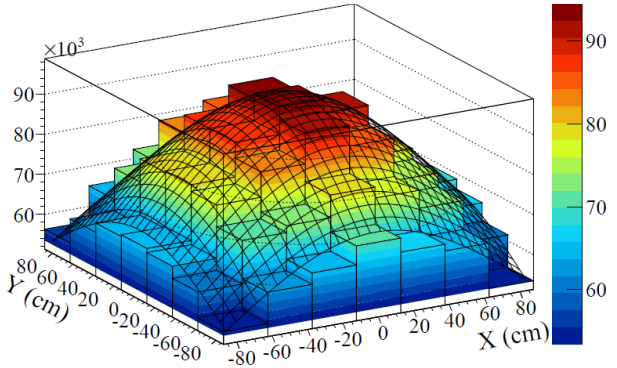
T2K Muon Monitors

- Measure beam direction, absolute muon flux
- Redundancy with two arrays (7x7 grids) of ionization detectors (Si, NuMI-like ion chamber)
- Si not very rad hard
- Have also used emulsions, tested diamond detectors



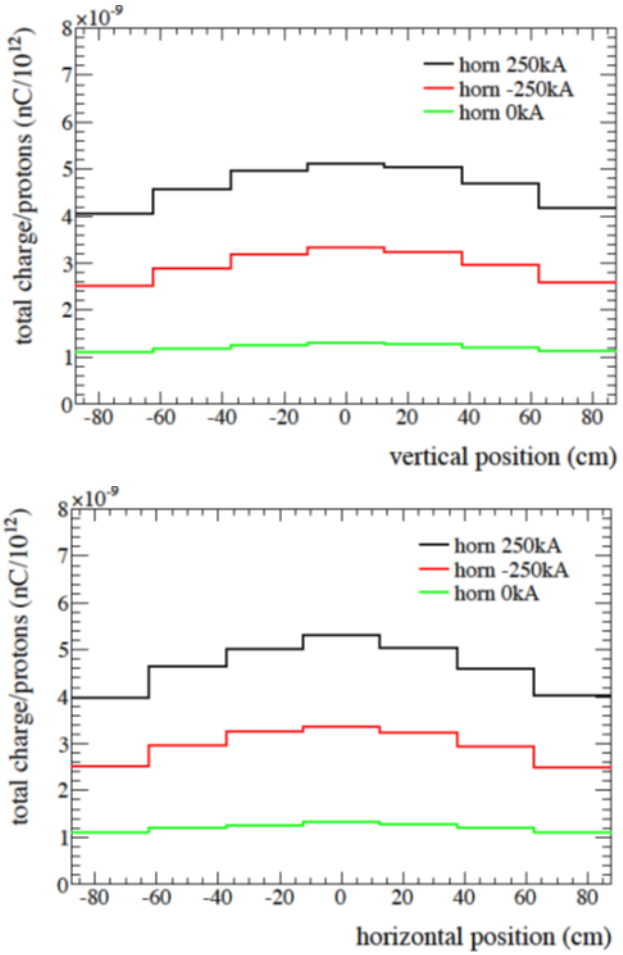
Silicon PIN Photodiodes

Ion Chambers

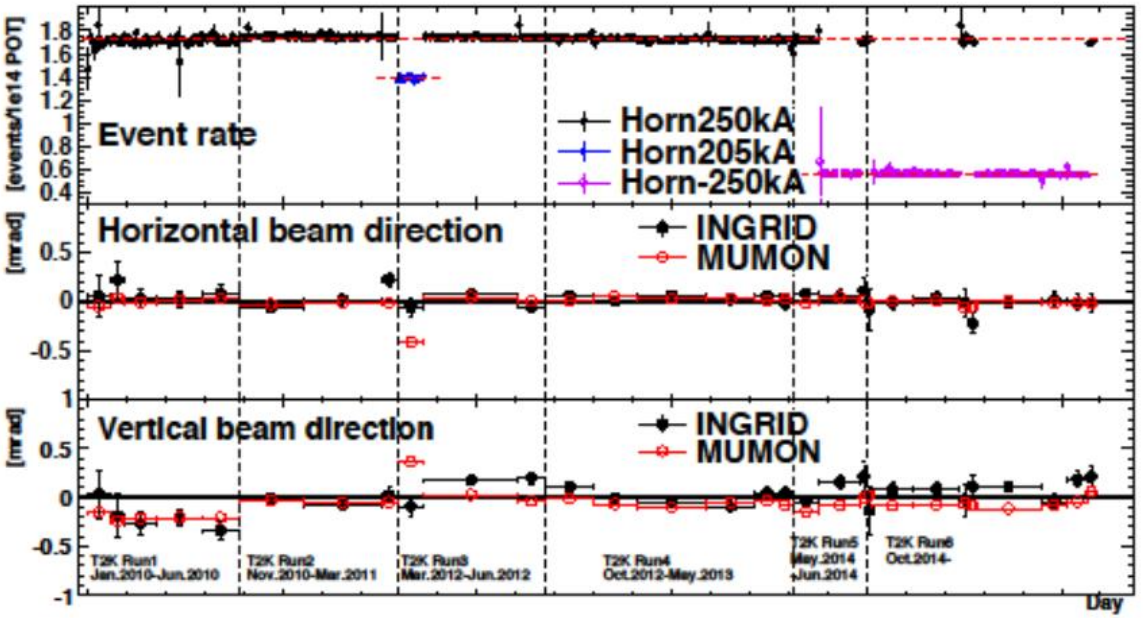


T2K Muon Monitors

1D Profiles

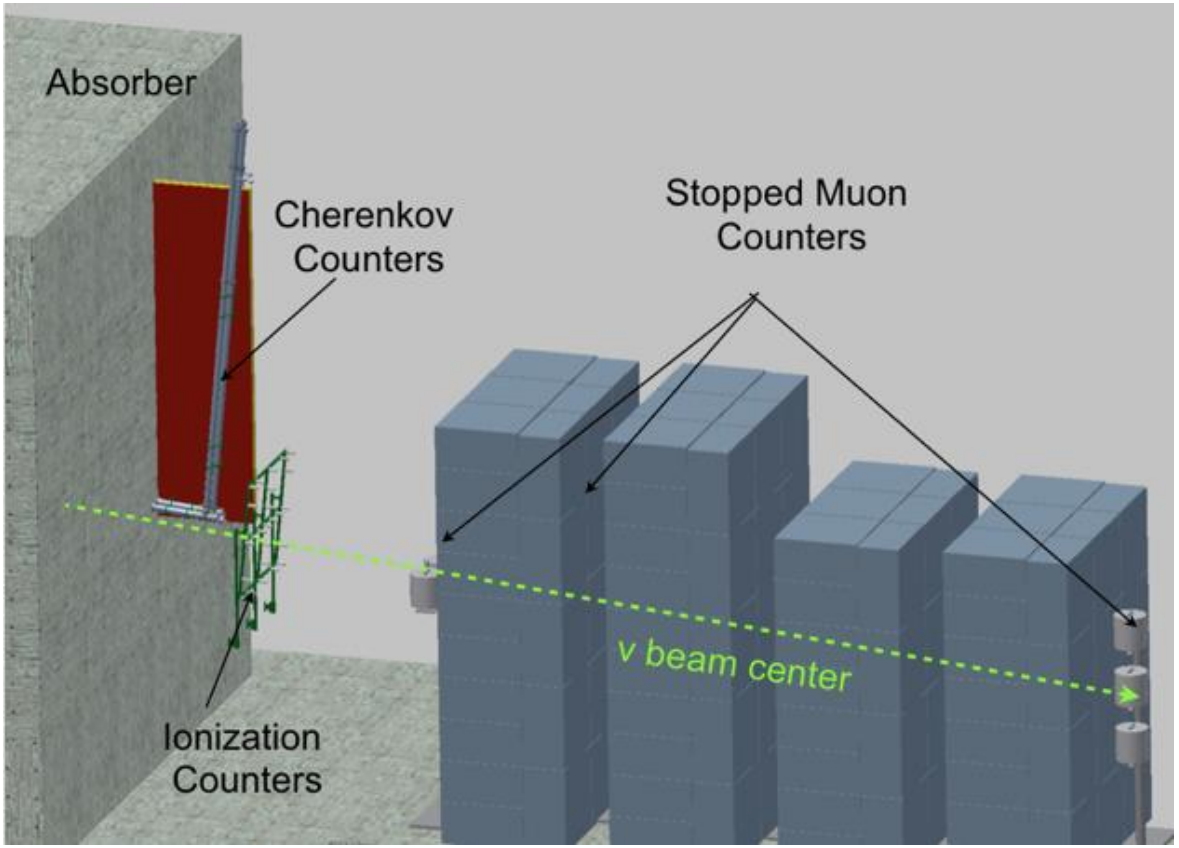


- Per-spill direction precision of 0.28 mrad
- Replace Si PIN detectors periodically to maintain performance



Refs: K. Matsuoka et al., Nucl. Instrum. Meth. A624: 591-600, 2010.
K. Suzuki et al., arXiv:1412.0194. Plots are more recent updates of those found here

Plans for LBNF/DUNE Muon Monitors



Constrain:

1) Beam Direction
2) Total Muon Flux
3) Muon Spectrum

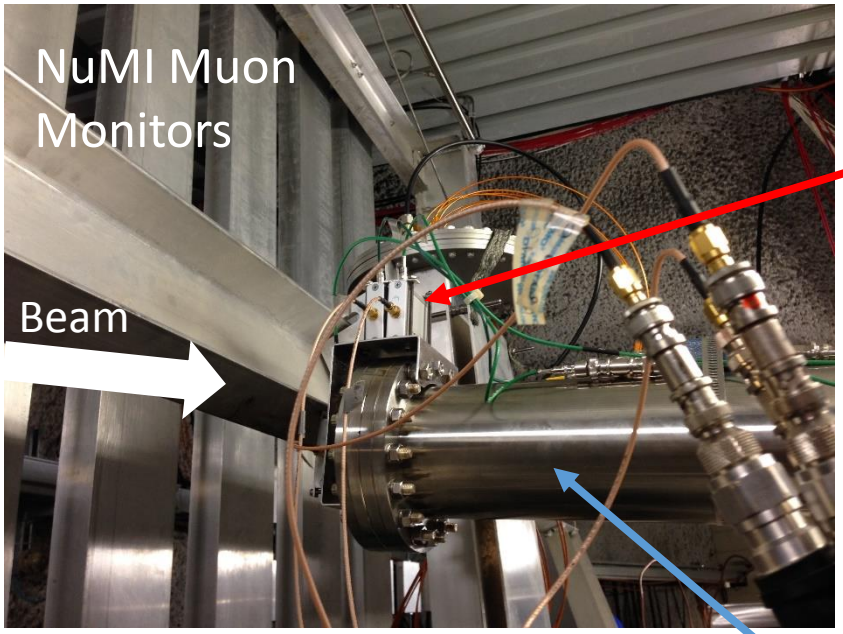
Monitor beam quality

Very different design:

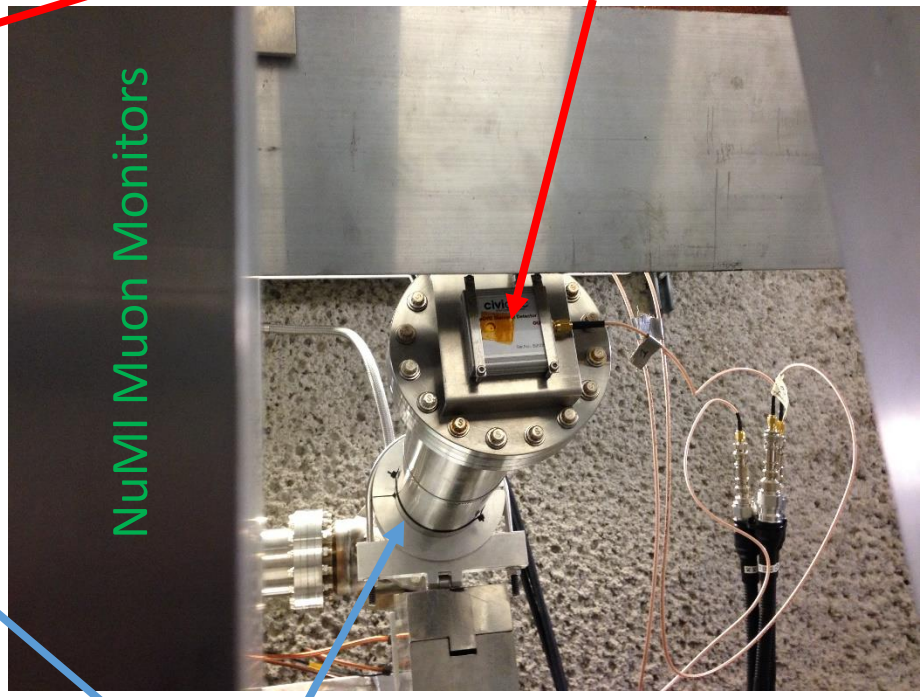
Combine:

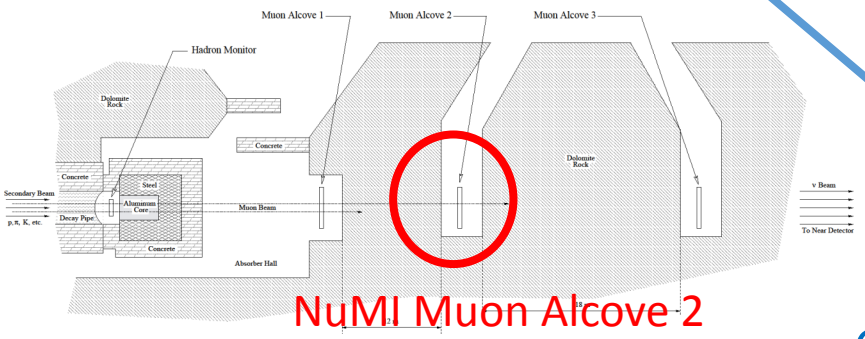
1) Ionization Counters
   - As in other beamlines
2) Cherenkov Counters: Muon flux above a tunable threshold
3) Stopped Muon Counters: Muon flux at specific energies

Testing LBNF Prototypes At NuMI



Three Diamond Detectors (Borrowed from CNGS)



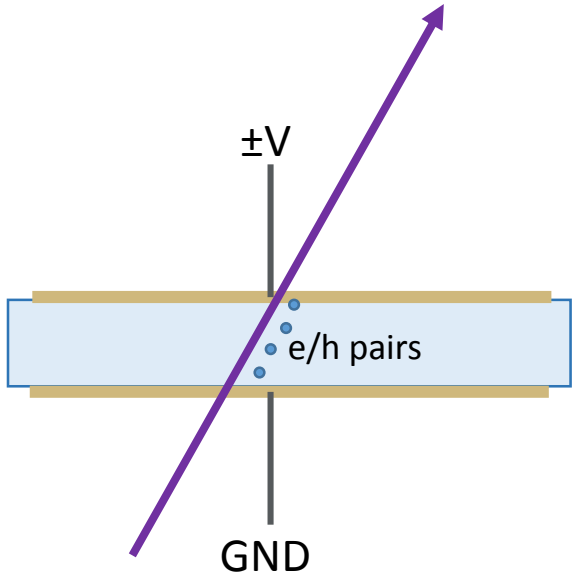


NuMI Muon Alcove 2

Gas Cherenkov Prototype

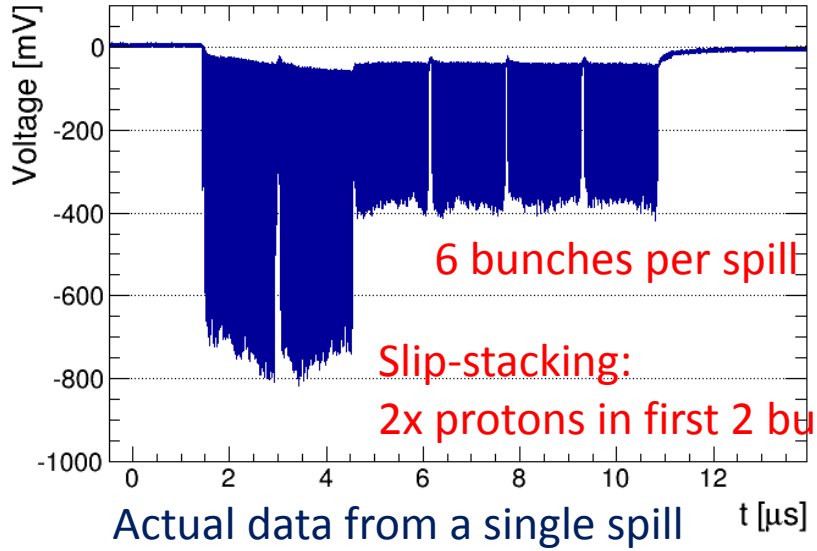
Diamond Detectors

- Solid state detector, MIP creates electron-hole pairs that drift apart in an electric field
- Using three pCVD diamond detectors previously used in CNGS beamline for intensity & timing measurements
- But: Diamonds are a less mature technology than Si or gas detectors, diamonds are expensive

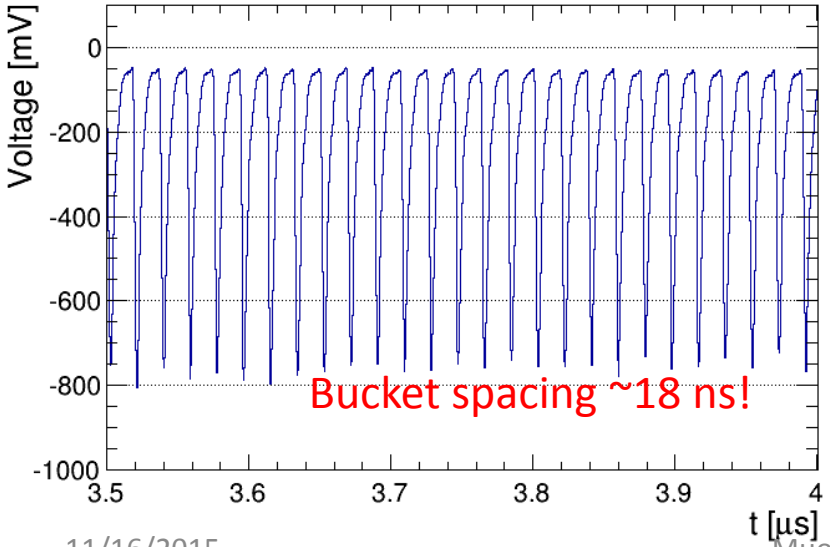


Earlier CNGS Diamond Tests:
H. Jansen et al., JINST 8, P01017, 2013.
H. Jansen talk at NBI 2012

Diamond Detectors in Alcove 2



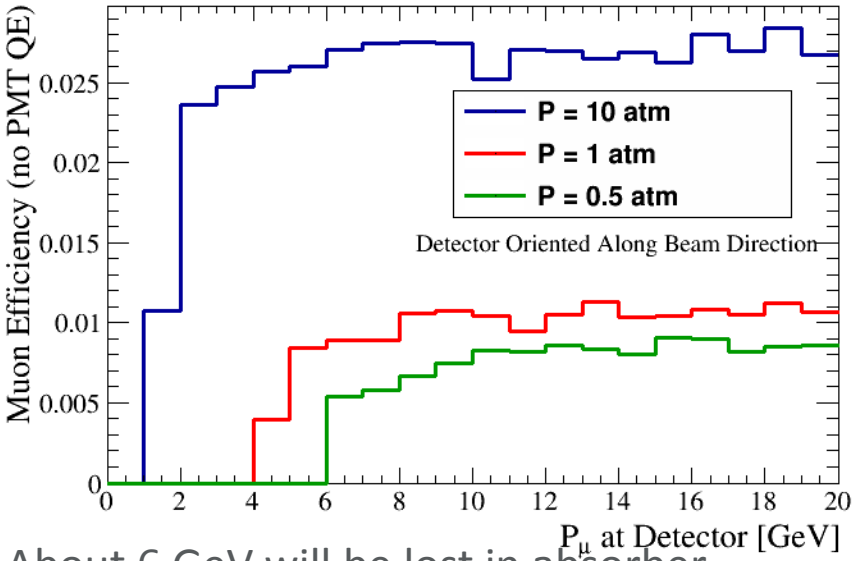
Actual data from a single spill



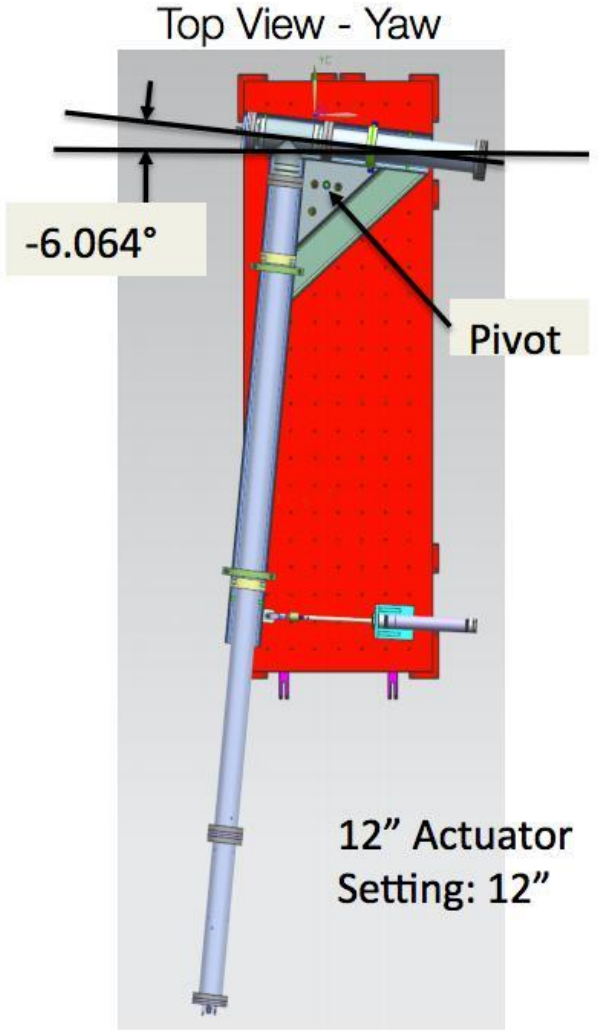
- Fast signals (faster than Si, much faster than gas)
- More rad hard than Si
- See much more detail than possible with more standard gas detectors
- Total signal size (single spill) measured with ~0.3-0.4% precision

Cherenkov Detector Prototype

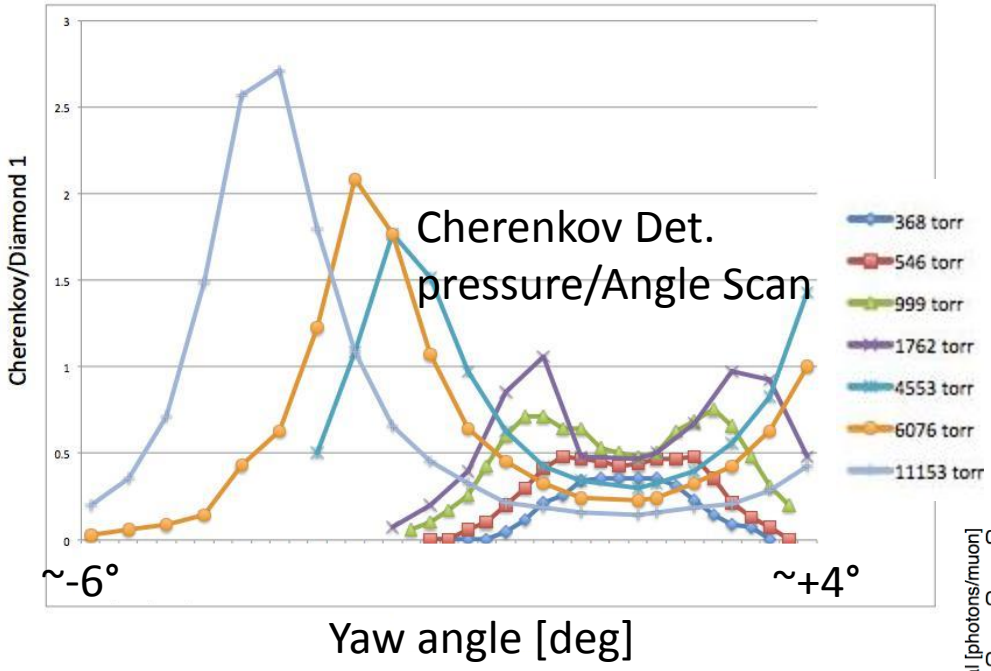
- Can change angle w.r.t. beam, Ar gas pressure
- Increase pressure → Lower threshold
- Use pressure/angle scan to extract differential muon flux info



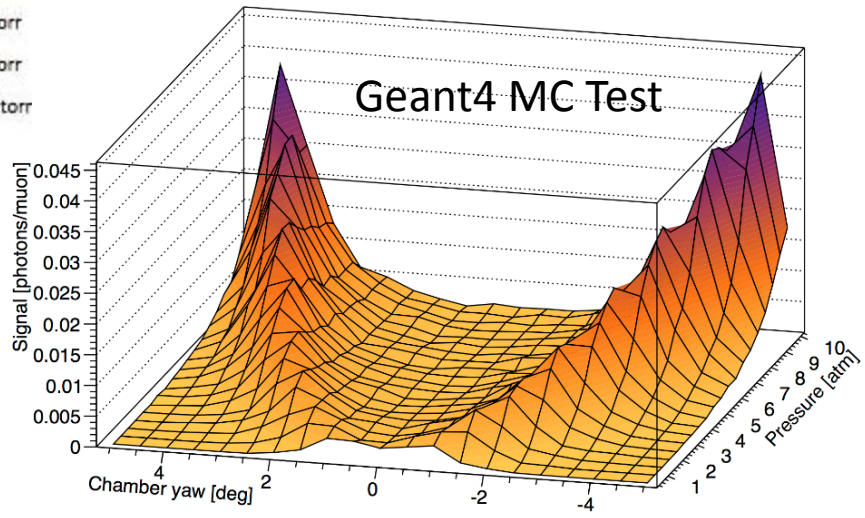
About 6 GeV will be lost in absorber



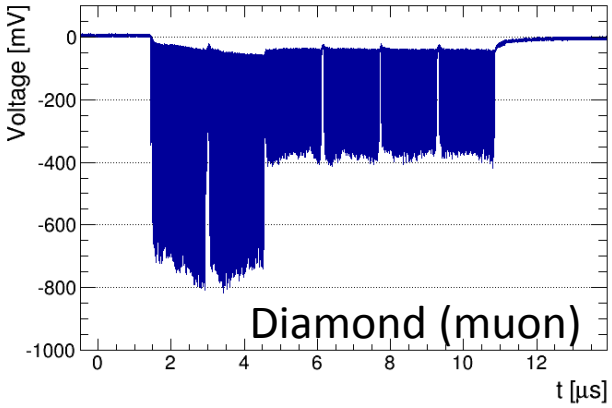
Understanding Detector Output

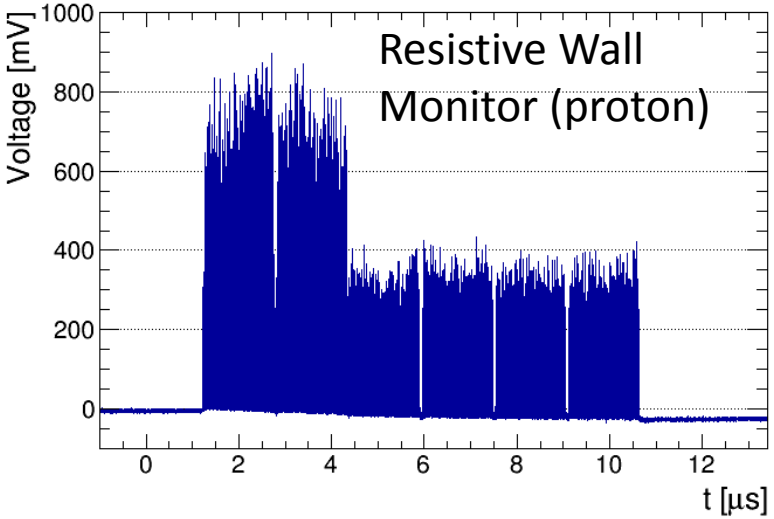


More advanced simulations in progress to better understand expected detector output

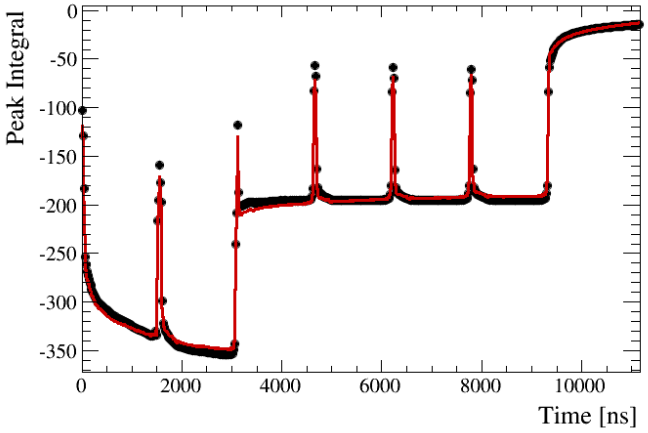


Understanding Detector Output





Fit diamond to RWM (proton) + Exponential decays



Average of Many Spills,
1 pt = Integral of 1 bucket

More advanced simulations in progress to better understand expected detector output

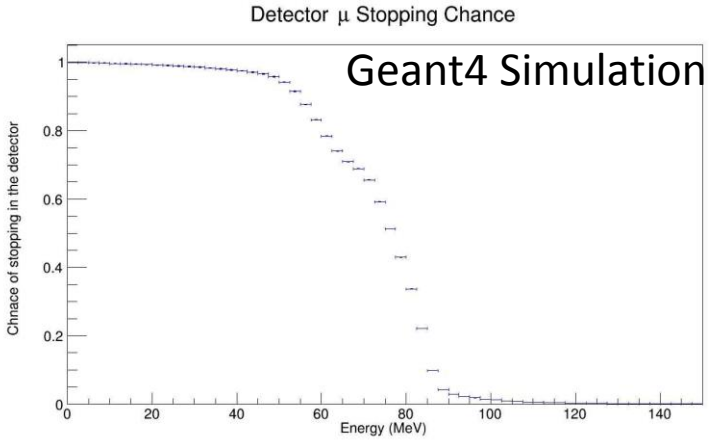
Goals of NuMI Tests

- Test performance of detectors in an actual beam
- Experimentally check long term performance (Do these last long enough to be useful & affordable?)
- How do these compare with regular NuMI monitoring systems?
  - Several months of data (but not every spill) collected so far

In other words:

Evaluate using experimental measurements if these detectors can work in proposed LBNF beamline designs

Stopped Muon Prototype

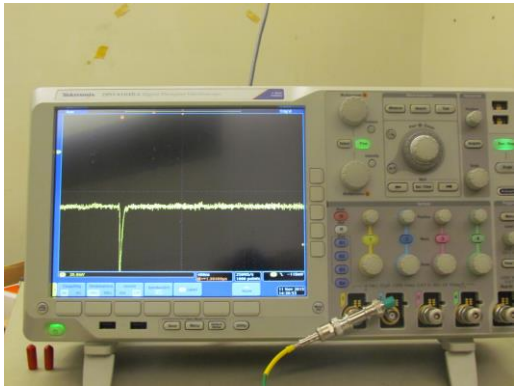


Stops muons below ~90 MeV

Will sample the flux at several specific energies:

-Advantage of using steel blocks instead of natural rock to separate detectors

May be able to separate μ^+ and μ^- by finding signal of μ^- capture on ^{12}C



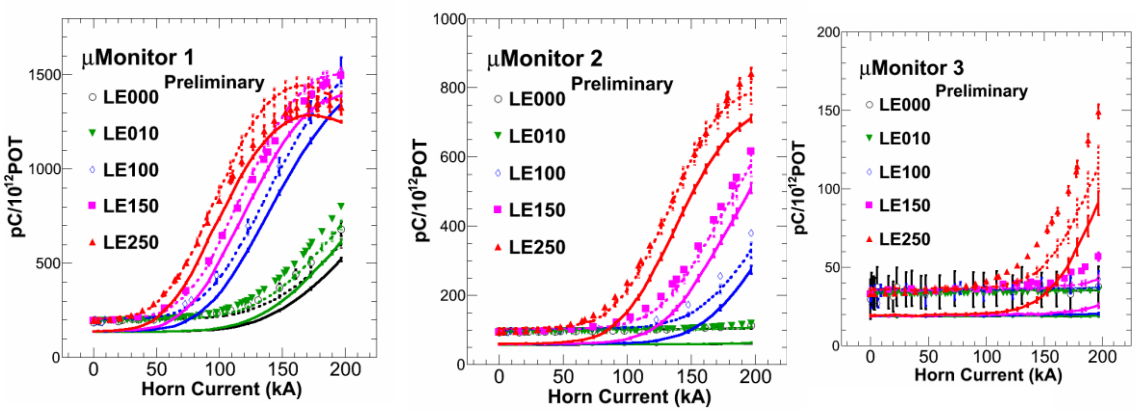
- Outer scintillator veto
- Inner non-scintillating oil volume
- Measure Cherenkov light from inner volume
- Construction recently finished, testing on cosmics at Colorado before moving to NuMI

Conclusions

- Muon detectors are an important way to monitor neutrino beam properties, such as intensity and direction
- Various types of monitors have been successfully deployed at a number of beamlines, such as CNGS, NuMI, and J-PARC
- LBNF will include a suite of muon monitors
- Prototype detectors of several possible technologies are already being built and tested in the NuMI muon alcoves

Thank You

Constraining the Differential Muon Flux



- Work has been done to do this with data from the NuMI muon monitors
- Talk by L. Loiacono at NBI 2012
- Much easier to do if the beam can be kept constant and the detectors changed