Prospects for Improvements in Neutrino Flux Understanding

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Accelerator-Generated Beams

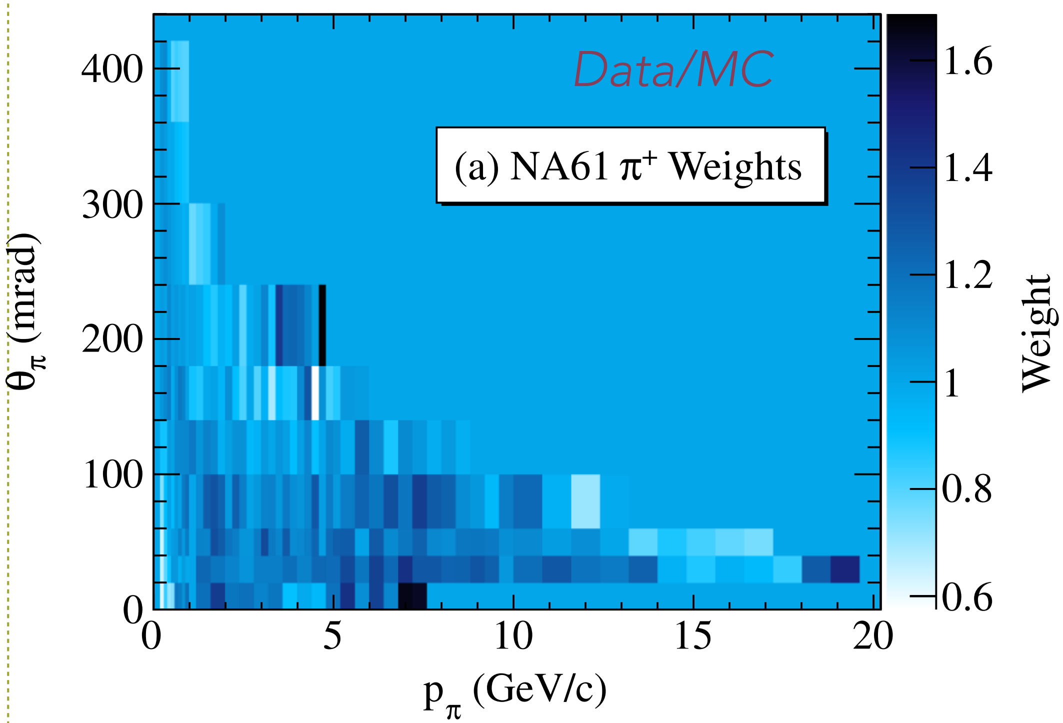
- This talk will primarily focus on improvements for future long-baseline beams, especially LBNE and T2K/HyperK

Outline

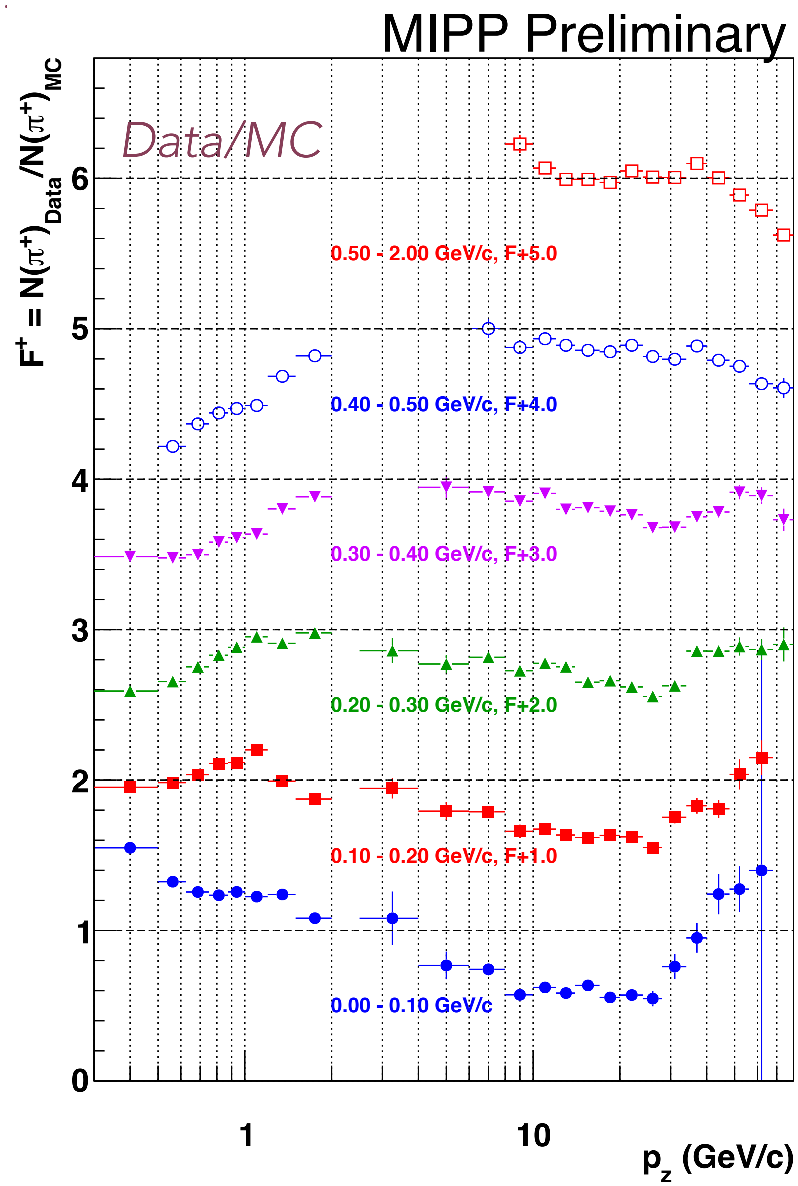
- Current Status of Flux Predictions
- In Situ Measurements
  - Muon Monitors
- External Hadron Production Measurements
  - MIPP
  - Future NA61/SHINE Measurements

MC Hadron Prod Predictions

*Phys Rev D **87** 012001 (2013)*

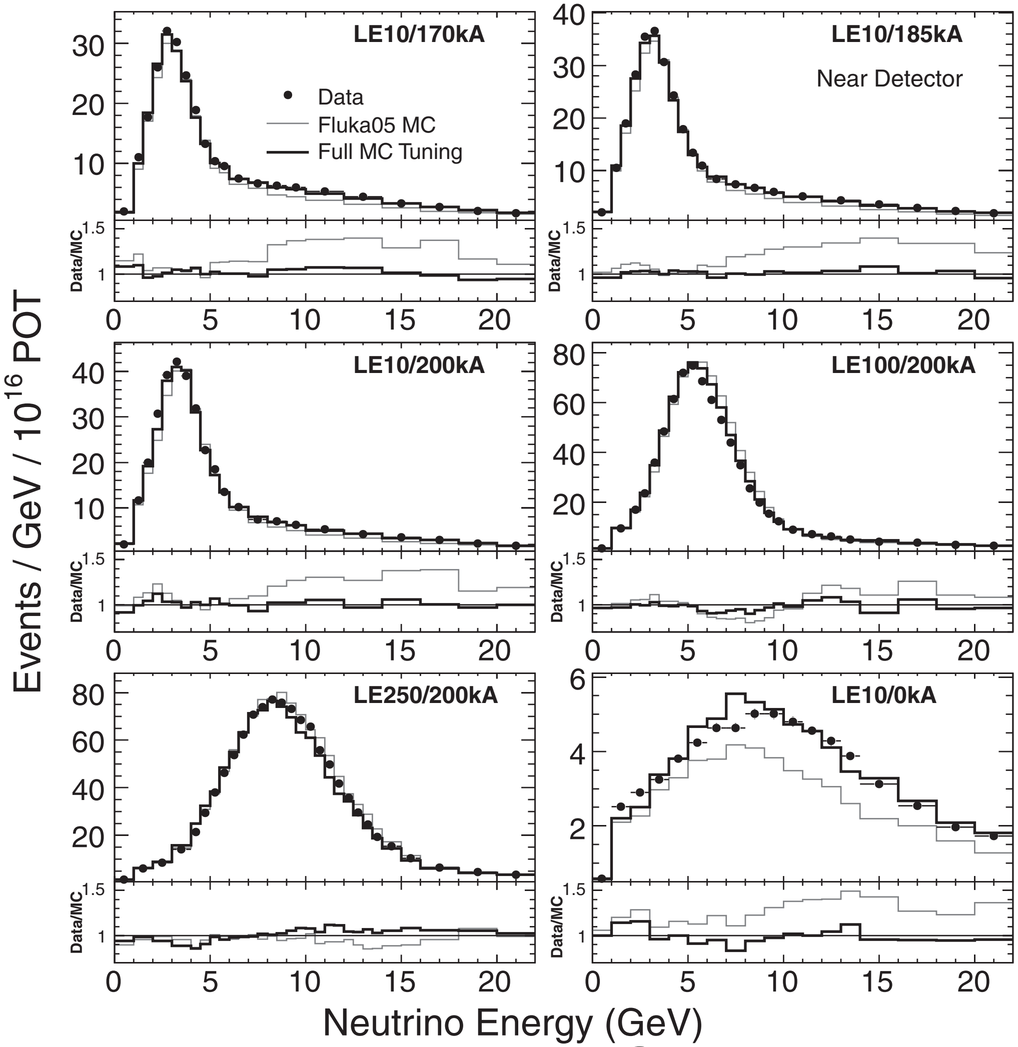


J. Paley, Fermilab Seminar April 8, 2014



- Disagree with MC predictions by 50% or more in some areas

MC ν Flux Predictions



Phys Rev D ***77*** *072002*

- Well known that out of the box MC flux predictions do not agree well with data

Flux Tuning

- MINOS used ND and many beam configs
- This strategy will continue to be useful for NOvA oscillation measurements
- But much harder to implement for T2K/HK and LBNE
- Would also like to constrain/tune the hadron production simulation with ν cross-section independent data
- Independent flux measurement also useful for short baseline sterile ν and heavy ν decay searches

Current Hadron Production Data

- protons at 8.9 GeV on Be
- protons at 31 GeV/c on C
- protons at 120 GeV/c on C
- protons at 400-450 GeV/c on Be

Production Data Relevant for 8.9 GeV/c p + Be

Data	Experiment	Hadron	Published
8.9 GeV/c p + thin Be	HARP	$\pi^{\pm}$	Eur. Phys J C52 (2007)
6.4, 12.3, and 17.5 GeV/c p + thin Be	BNL E910	$\pi^{\pm}$	Phys. Rev. C77, 015209 (2008)

- MiniBooNE flux predictions, 7-10% PhysRevD.79.072002
- MicroBooNE will build on 10 years of experience with Booster beam
- Analysis of HARP thick target data currently in progress

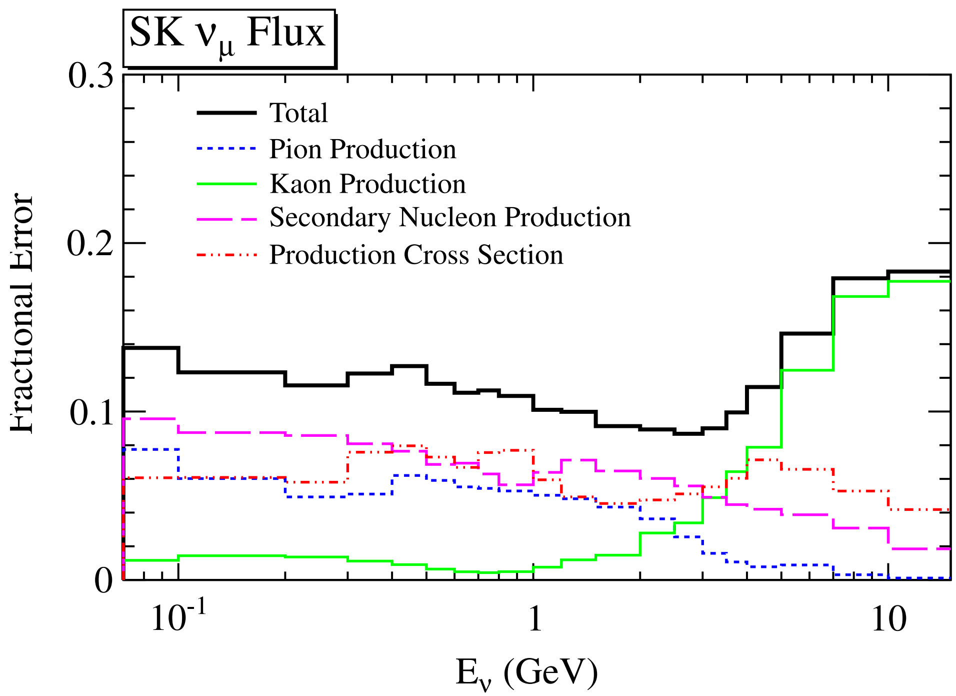
Production Data Relevant for 31 GeV/c p + C

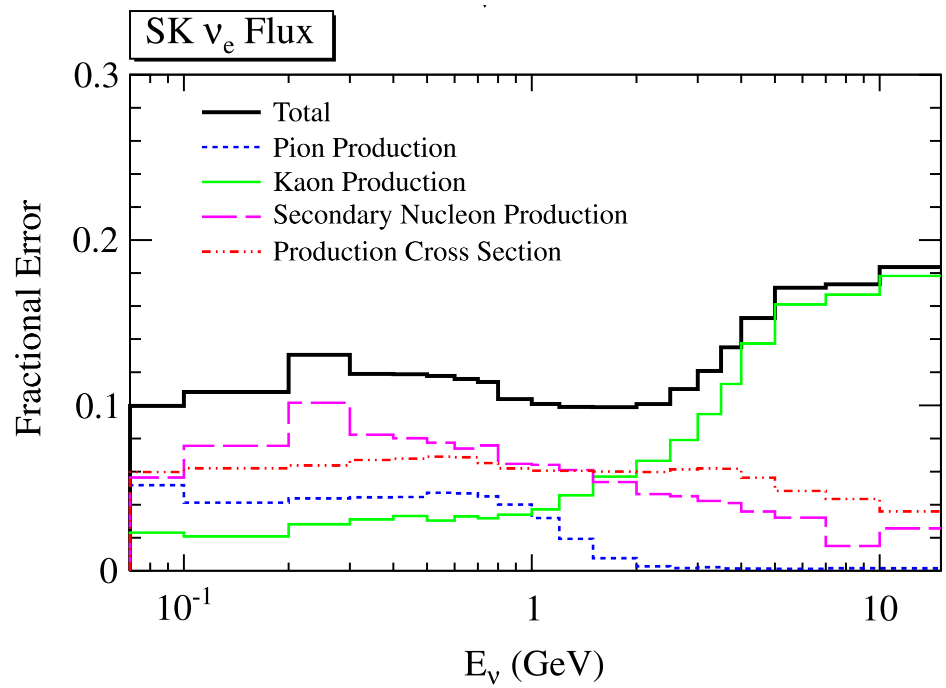
Data	Experiment	Hadron	Published
19.2 GeV/c p on p,Be, Al, Cu, and Pb	Allaby et al	p,pbar, $\pi^{\pm}$, $K^{\pm}$	Tech. Rep. 70-12 (CERN, 1970).
24 GeV/c p on Be, Al, Cu, and Pb targets	Eichten et al	p,pbar, $\pi^{\pm}$, $K^{\pm}$	Nucl. Phys. B 44, 333 (1972).
31 GeV/c p + thin C target	NA61/SHINE	$\pi^{\pm}$	Phys. Rev. C84 (2011) 034604
31 GeV/c p + thin C target	NA61/SHINE	K^{+}	Phys. Rev. C85 (2012) 035210

- Current published T2K flux predictions rely heavily on these datasets

Current Uncertainties - T2K

*Phys Rev D **87** 012001 (2013)*





- Hadron uncertainties (above) dominate T2K flux errors
  - Lower energies dominated by secondary p,n production
  - Higher energies dominated by kaon production

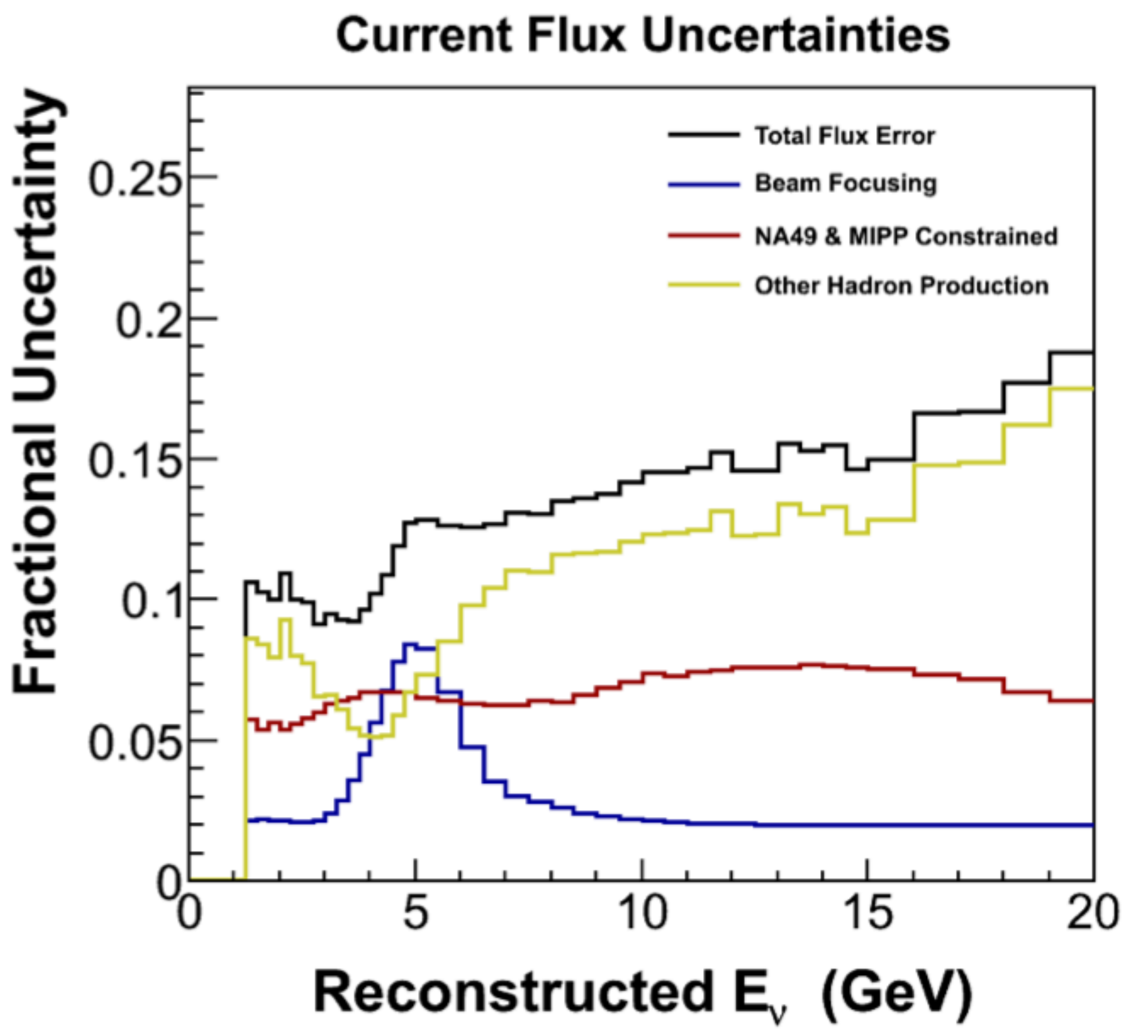
Production Data Relevant for 120 GeV p + C

Data	Experiment	Hadron	Published
158 GeV/c p + thin C target	NA49	$\pi^{\pm}$	Eur.Phys.J. C49 (2007) 897
158 GeV/c p + thin C target	NA49	K^{+}	G.Tinti Ph.D. thesis
158 GeV/c p + thin C target	NA49	p	Eur.Phys.J. C73 (2013) 2364
120 GeV/c p + thin C	MIPP	K/π ratio	A. Lebedev Ph D thesis
120 GeV/c p + NuMI C target	MIPP	$\pi^{\pm}$	arXiv: 1404:5882

Current Uncertainties - Minerva

D. Harris, previous session

- No ND tuning here



Production at ~400 GeV/c

Data	Experiment	Hadron	Published
400 GeV/c p + 10-50 cm Be target	NA20	$\pi^\pm$, $K^\pm$,p,pbar	CERN 80-70 (1980)
450 GeV/c p + 10 cm Be target	NA56/SPY	K/π ratio	Phys. Lett. B420 (1998) 225
450 GeV/c p + 10 cm Be target	NA56/SPY	$\pi^\pm$	Phys. Lett. B425 (1998) 208
450 GeV/c p + Be target	NA56/SPY	$\pi^\pm$, $K^\pm$,p,pbar	Eur. Jour. Phys. C10 (1999) 605

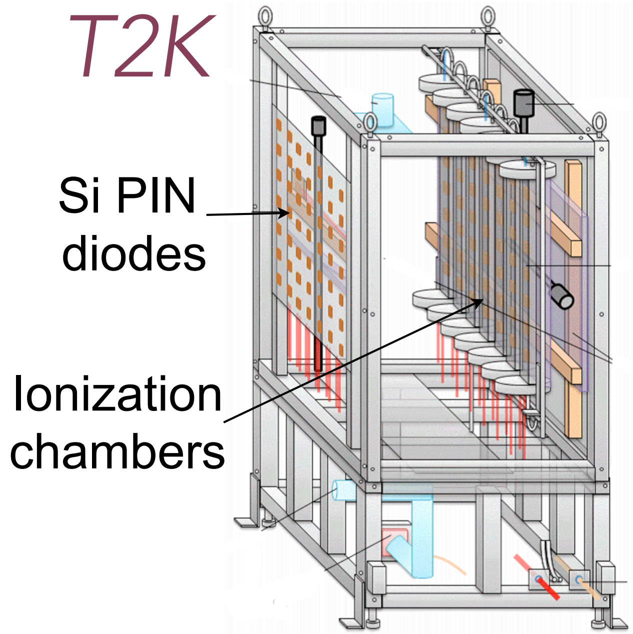
- Accuracies in the 5-10% range
- Parameterized in Eur. Jour. Phys. C20 (2001) 13

Impact on Future beams

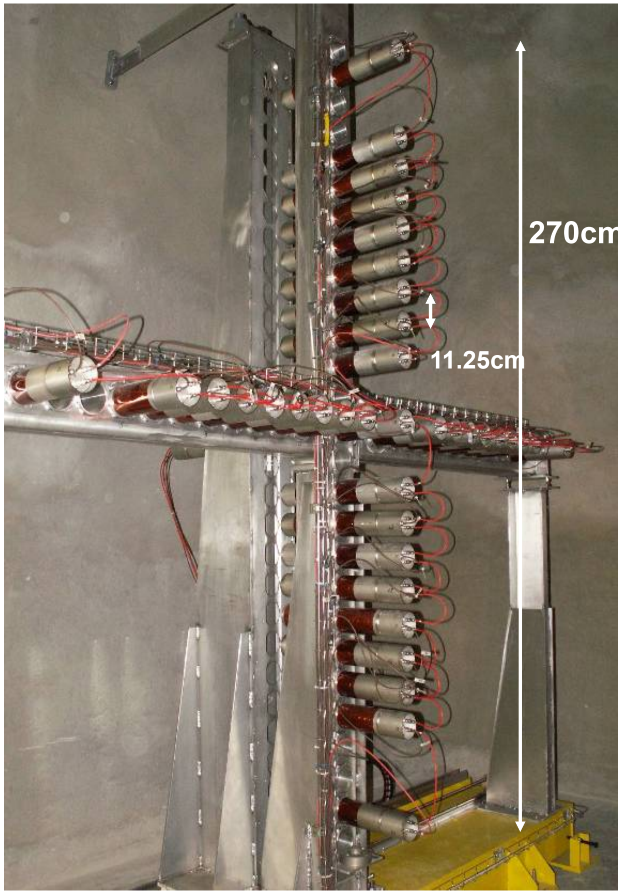
- For LBNE and T2HK
  - Near and far detectors likely will have very different detector technologies
  - Target is (likely) fixed in place
  - MINOS strategy will be difficult to implement here
- Need improvements in in-situ constraints (μ Monitors) and external measurements

Muon Monitors

T2K



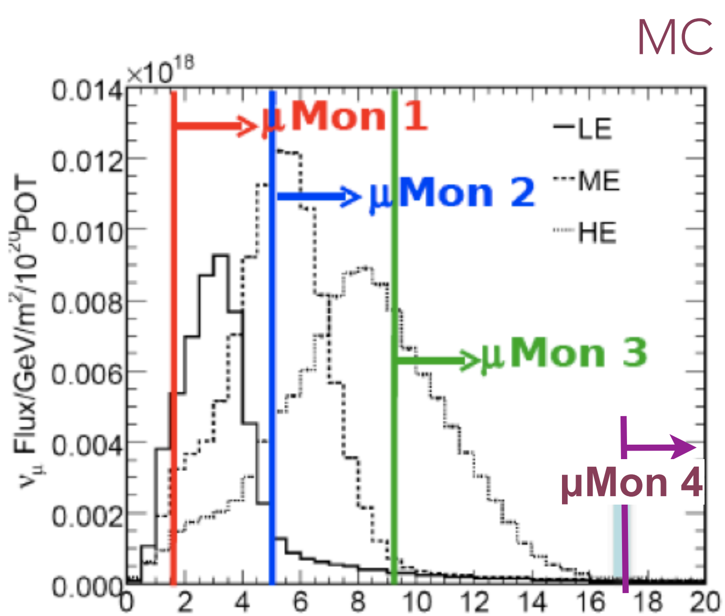
CNGS

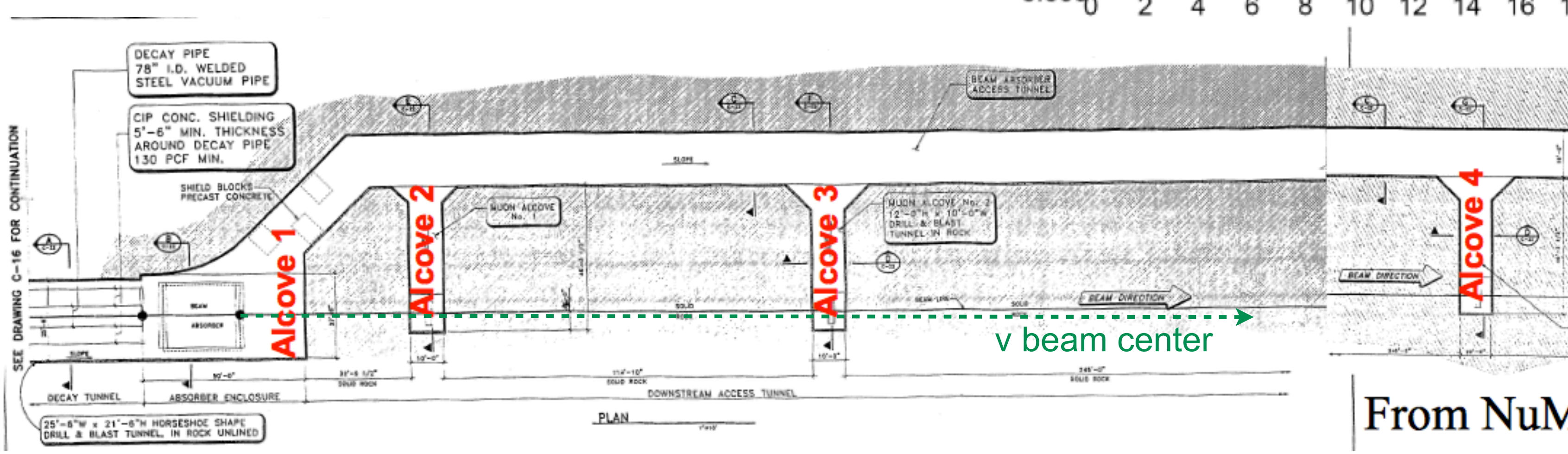


- Typically gas or solid state ionization counters
- Challenge to interpret since sensitive to e’s

NuMI Muon Monitors

- 4 sets of ionization chambers
- Each alcove sees a different threshold
- Vary horn current and target position to map out hadron p_t and p_z space



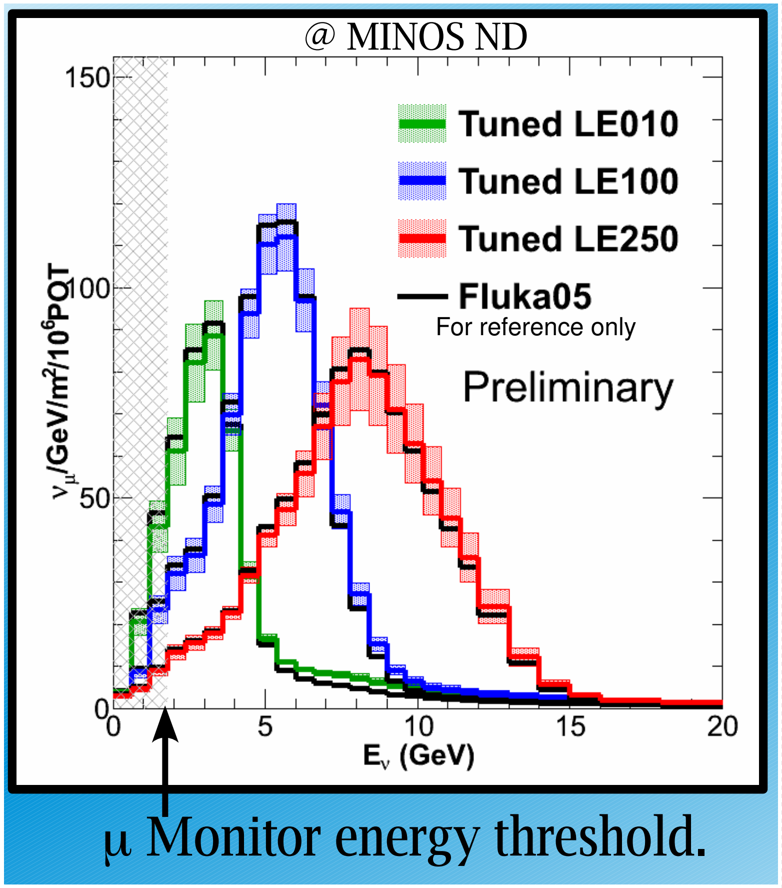


From NuMI TDR

Using Muon Monitors to Constrain ν Flux

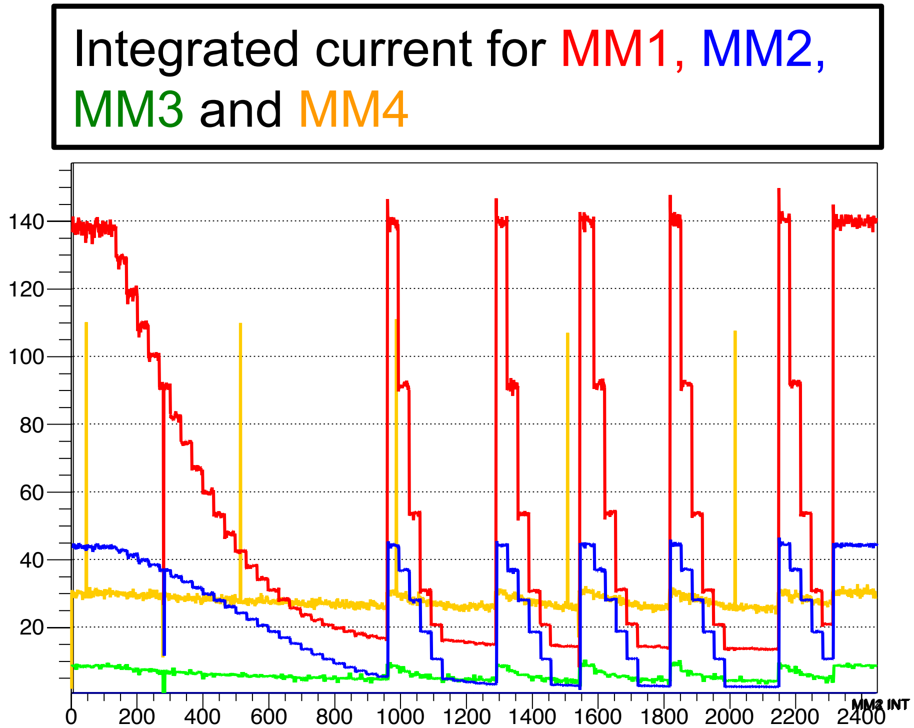
- NuMI muon monitors have been used to extract a ν_μ flux (L. Loiacono PhD dissertation, UT Austin 2010)
- Flux normalized to E_ν> 26 GeV ND data
- Errors dominated by non-muon backgrounds and mumon ionization scale

L. Loiacono, NBI, 2010



New μMon in Alcove 4

- Ionization counters recently placed in μ alcove
- Response for alcove 4 is largely insensitive to horn since it sees the highest energy muons from pions not in focussing peak



M-J. Bustamante-Rosell, 4/14/14 AEM talk

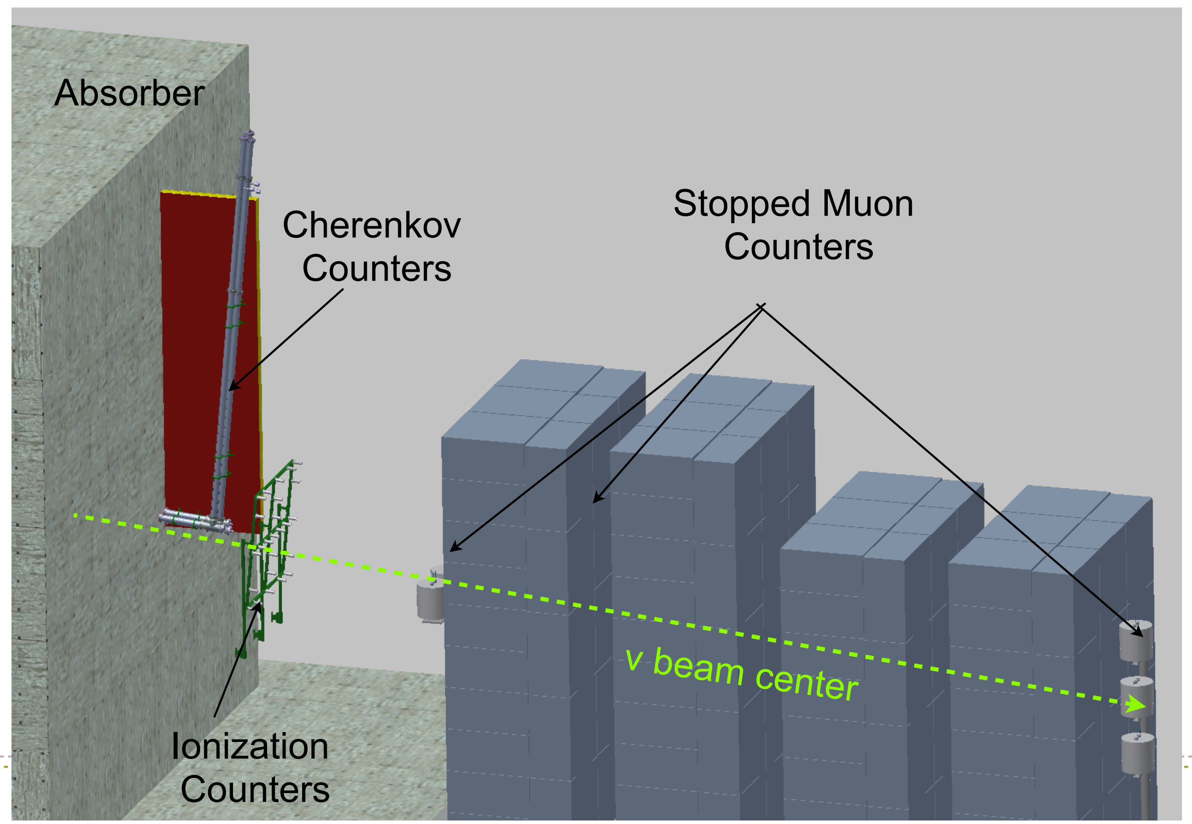
Data with variable horn current

Design Considerations

- Ideally the muon monitors should
  - Discriminate between muons and other sources of ionizing radiation
  - Provide an absolute normalization of the muon flux
  - Provide information about the energy spectrum of the muons

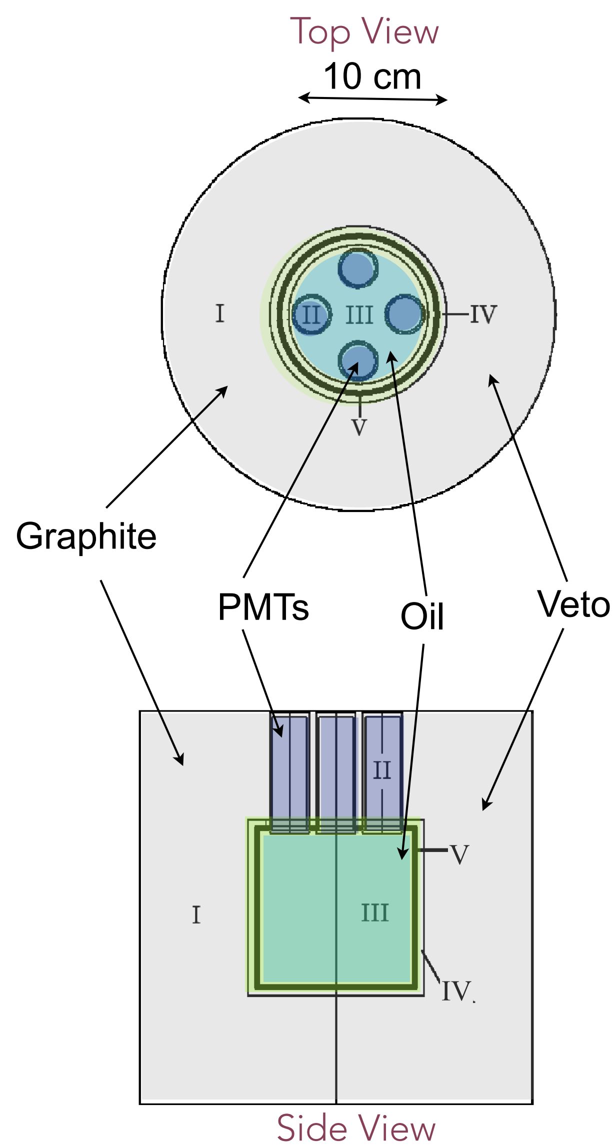
Alternative Designs

- In addition to ionization counters, LBNE also proposing
  - Stopped Muon Counters
  - Threshold Gas Cherenkov Detectors



Stopped Muon Counters

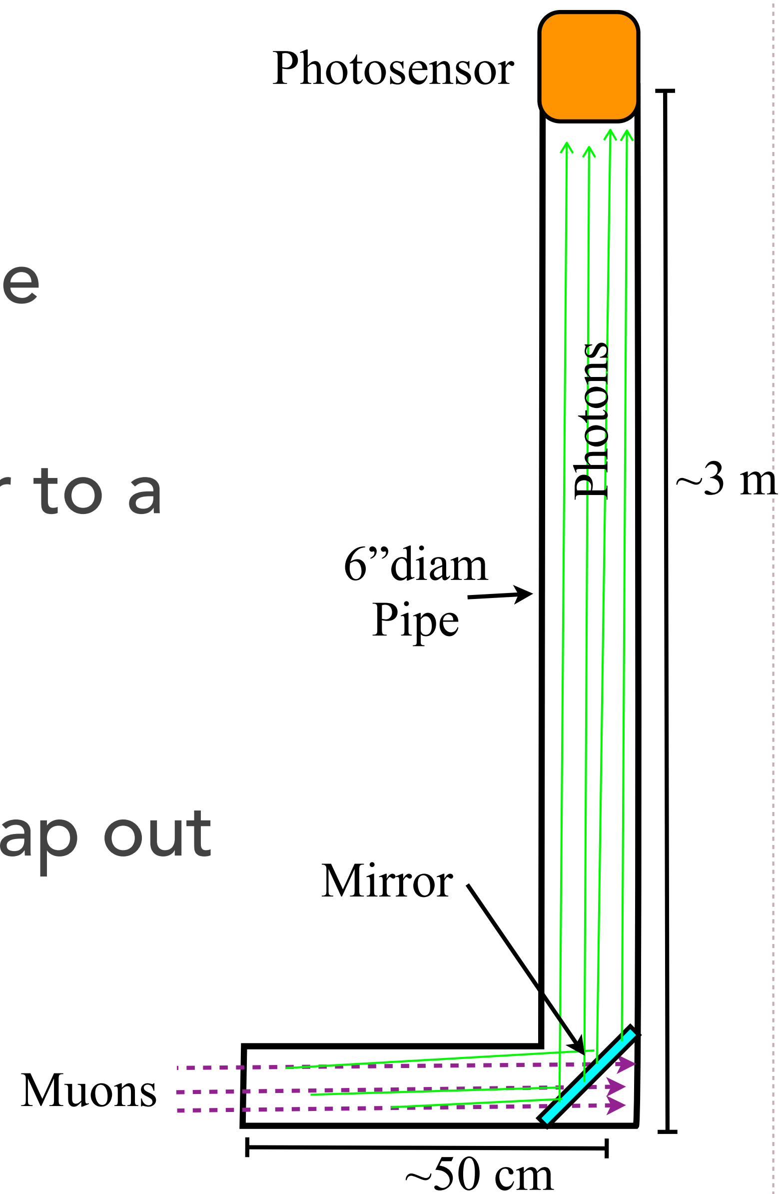
- Muons stop in non-scintillating oil
- Look for muon decay electrons after beam pulse
- Also look for ^{12}B decay following μ^- capture on ^{12}C
- Scintillating veto to reject external n's
- Place detectors at different depths of shielding to pick out flux at specific energies



E. Zimmerman & D. Poulson, Colorado

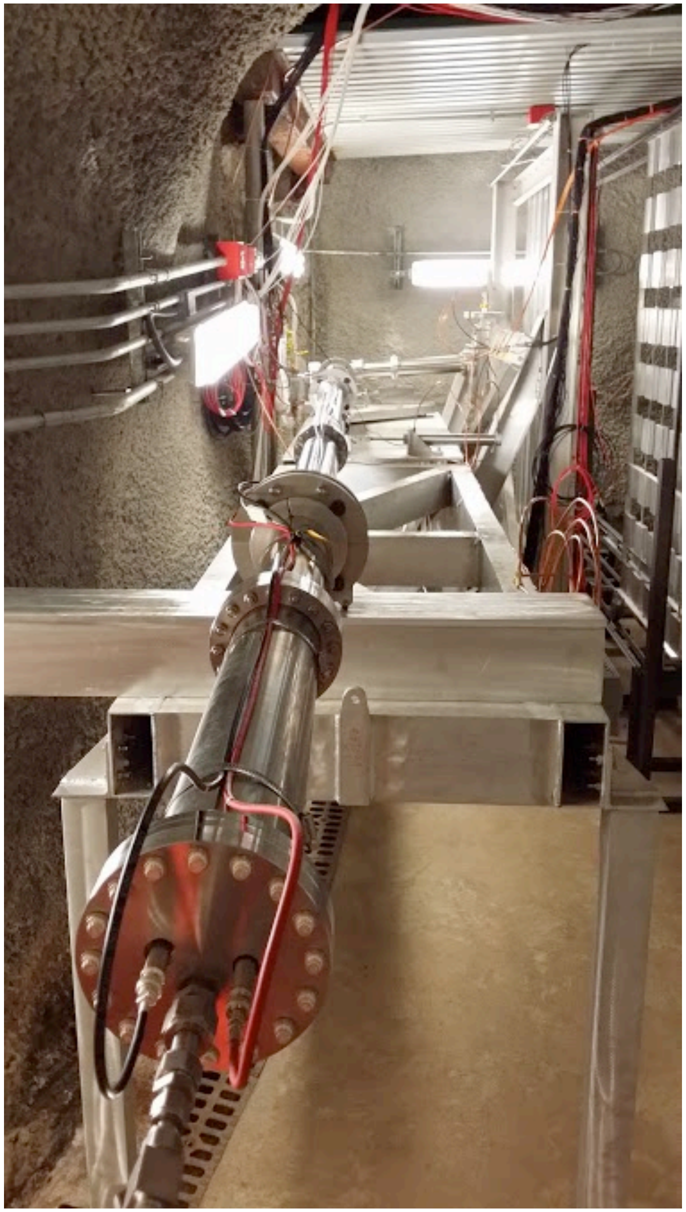
Threshold Gas Cherenkov

- Pipe filled with argon at variable pressure
- Light reflects off of a flat mirror to a PMT
- Not sensitive to neutrons
- Apparatus can be rotated to map out angular profile of muons



Prototype Detectors

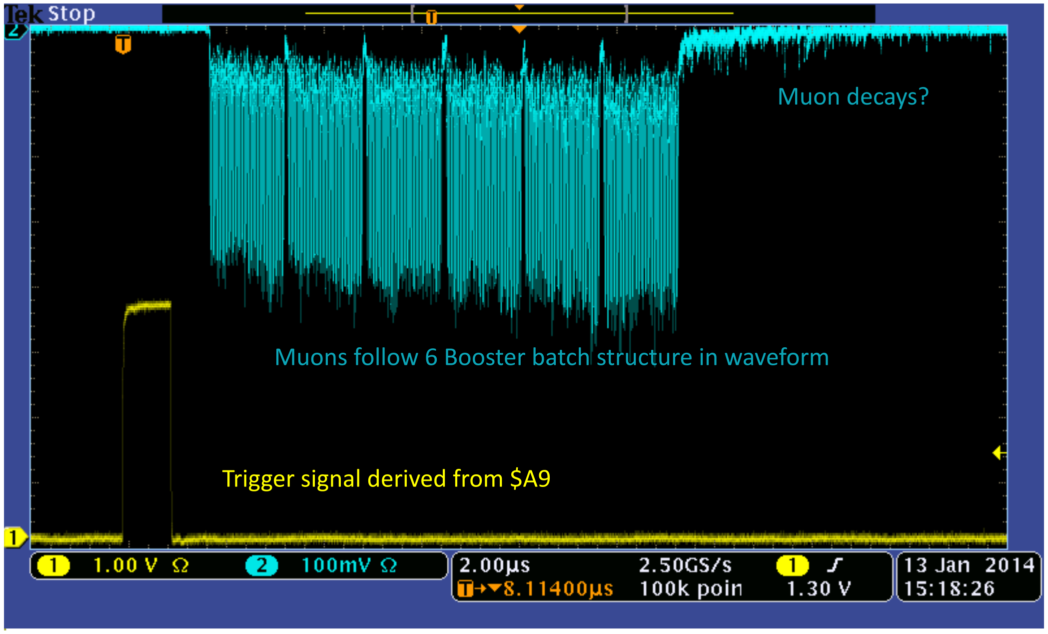
- Prototype stopped muon and gas Cherenkov detectors currently located in NuMI Alcove 2

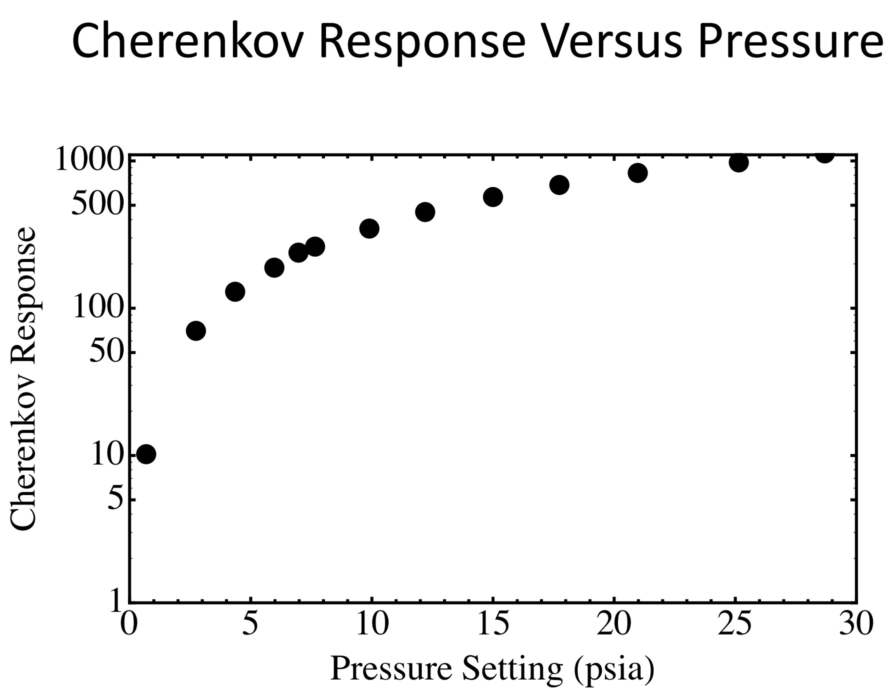


G. Mills, LANL

Gas Cherenkov Prototype Data

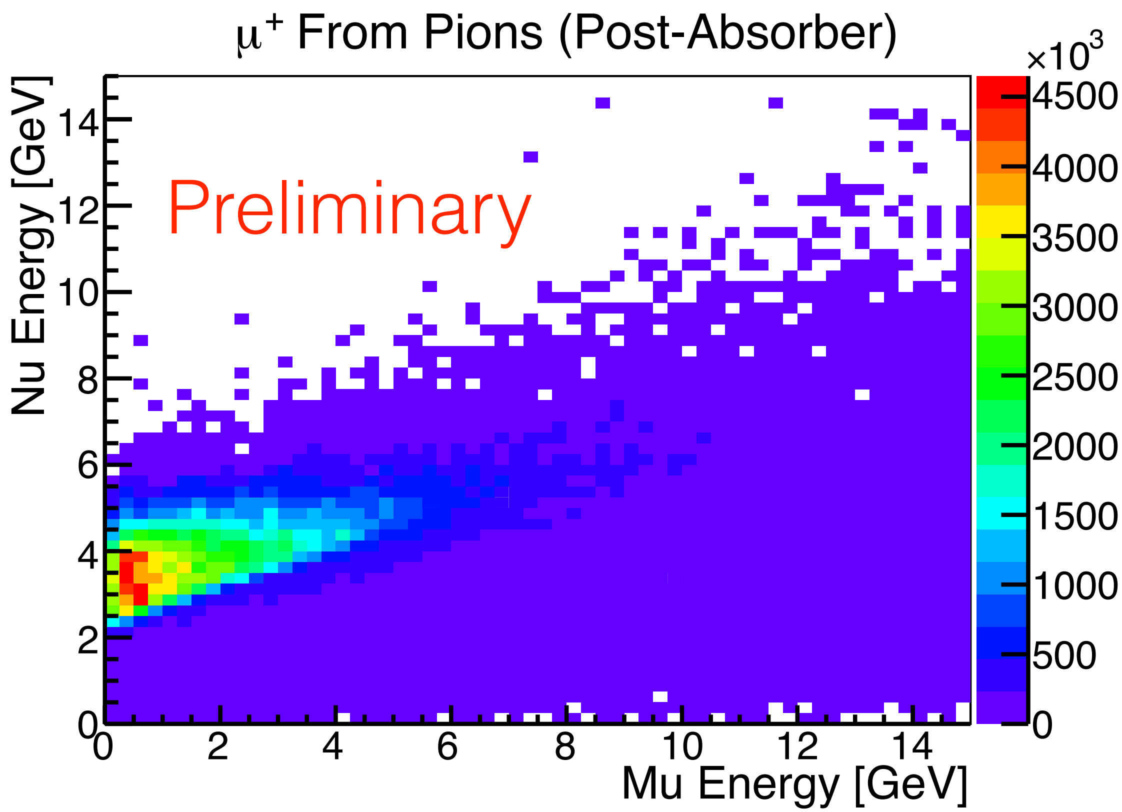
NuMI pulse in Gas Cherenkov G. Mills, LANL





- Also plan to place detectors in alcove 1 this year

Connection to ν Flux



R. Johnson, Colorado

Note: LBNE absorber not finalized

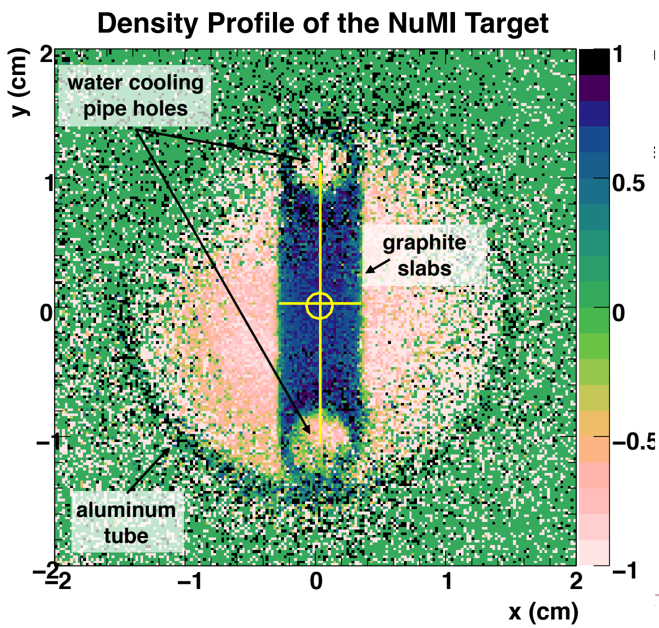
- Muons that exit absorber originate from pions that contribute to neutrino flux above 4 GeV

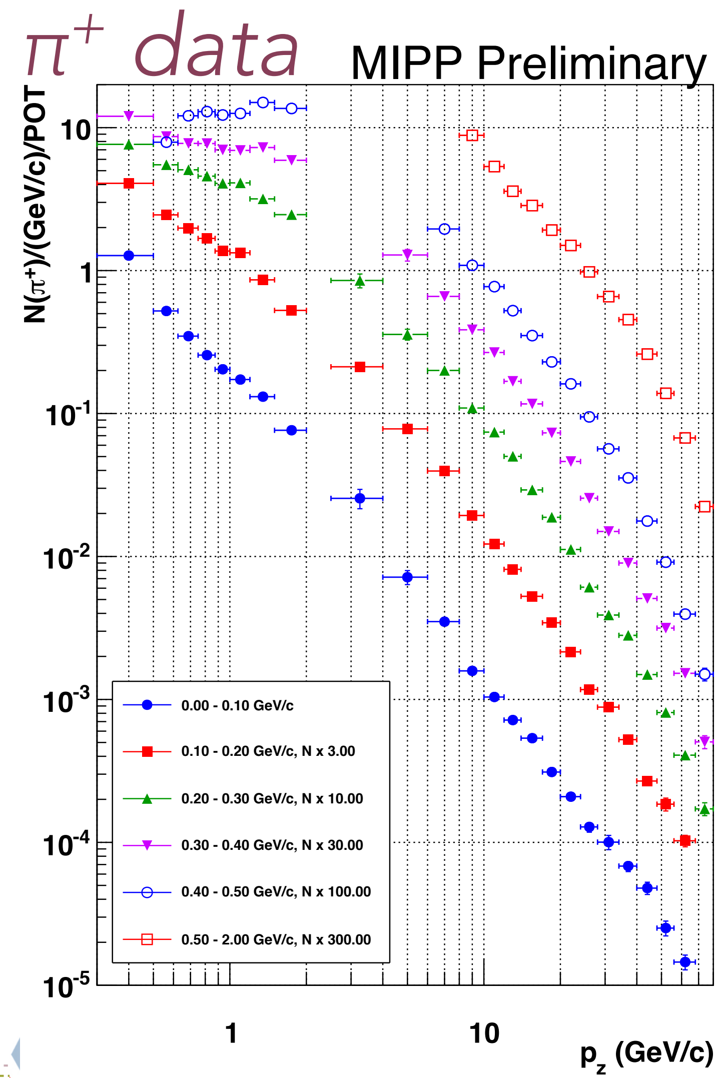
External Measurements

- Fermilab E907: Main Injector Particle Production (MIPP)
  - p, π,K beams 5 GeV/c-120 GeV/c on thin LH_2,C,Be, Bi, U targets and NuMI LE replica target
  - Collected data from 2004-2006
- CERN NA61: SPS Heavy Ion & Neutrino Experiment (SHINE)
  - p and heavy ion beams, from 31 GeV/c - 350 GeV/c
  - Collecting data since 2007

Improvements at 120 GeV/c from MIPP Data

- Just released p+replica target data @ 120 GeV/c arXiv: 1404:5882
- 5-10% uncertainties
- Forward n measurement too
  Phys.Rev.D83:012002,2011





Improvements at 31 GeV/c from NA61/SHINE

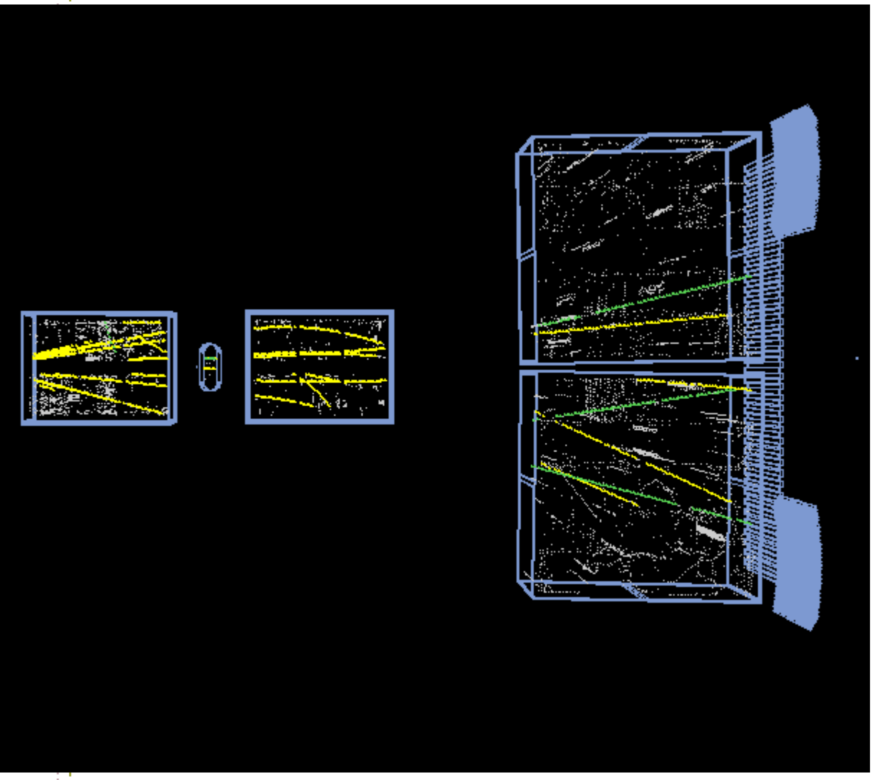
Data	Year	evts ($\times 10^6$)	Status
2 cm target	2007	0.7	$\pi^{\pm}$:Phys. Rev. C84 (2011) 034604 K^{+}:Phys. Rev. C85 (2012) 035210 Λ, K_0: Phys. Rev. C89 (2014) 025205
2 cm target	2009	5.4	Preliminary $\pi^{\pm}$, $K^{\pm}$, p, K^0_s, Λ To be published soon
full target	2007	0.2	$\pi^{\pm}$ method: Nucl. Inst. Meth. A701 (2013) 99
full target	2009	2.8	End of 2014?
full target	2010	10	

T2K using these so far, Syst errors 5-8%, but dominated by stat error

- Improved syst. and stat. errors in 2009 data

Future Measurements at Higher Energies with SHINE

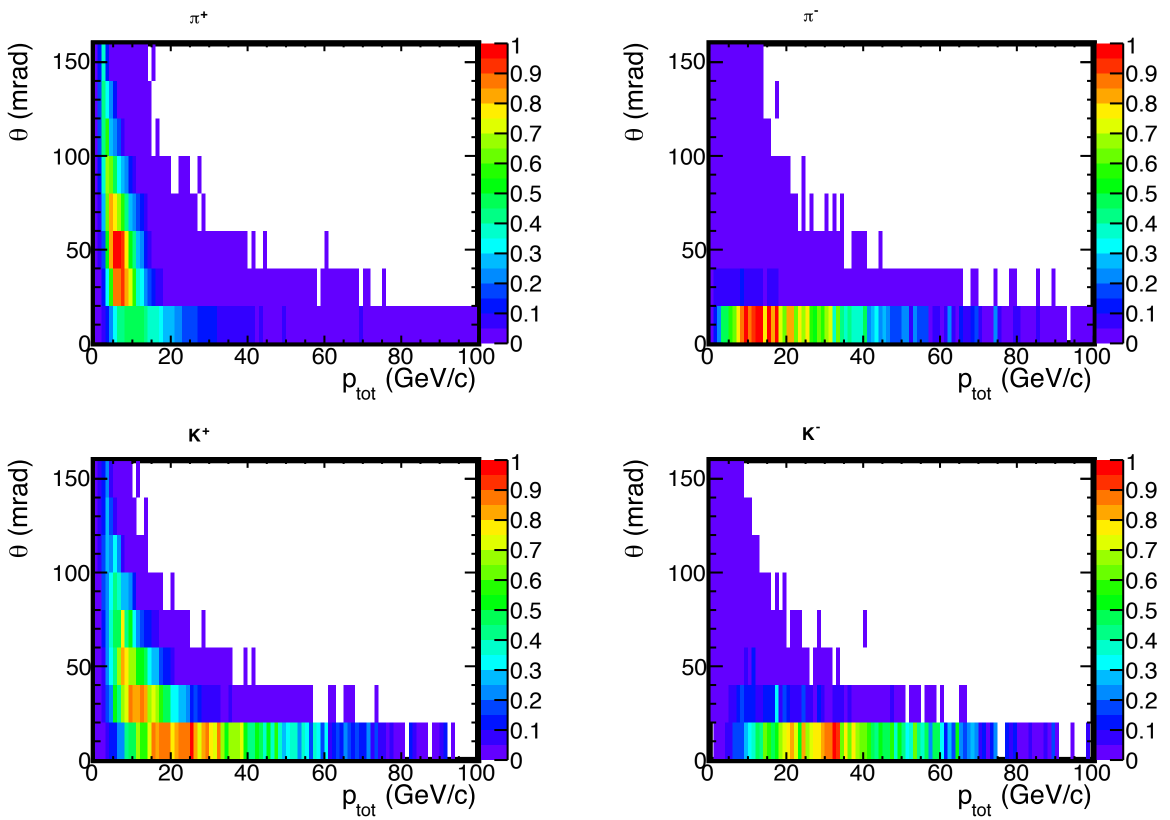
- Proposal to take p and π data at 60-120 GeV/c to benefit future Fermilab neutrino program
  - Thin Be, C, and Al targets
  - Potentially also NOvA or LBNE replica target data
  - Goal is <5% uncertainties
  - Tentatively plan start collecting data in fall 2015 (subject to SPSC approval)



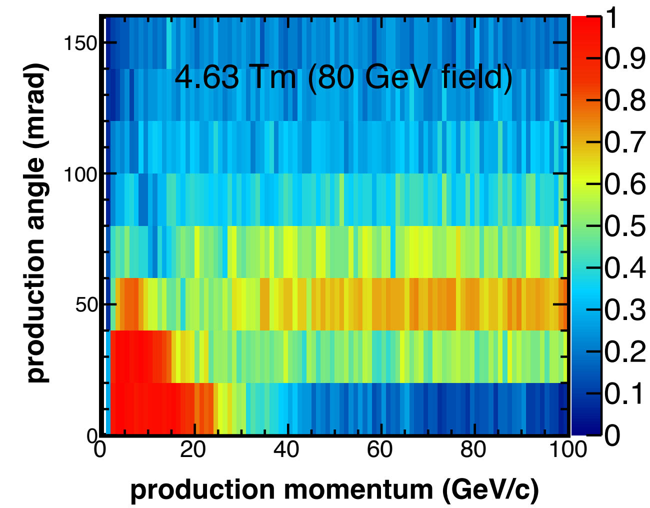
120 GeV p+C event in NA61

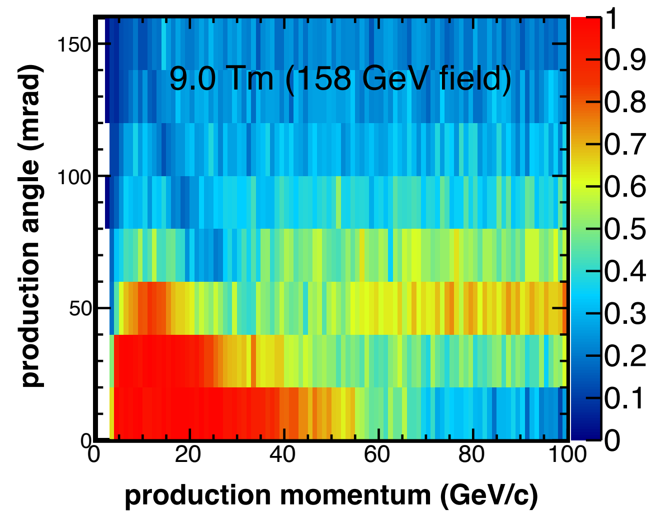
LBNE Phase Space

π and K contributions to flux at LBNE far site



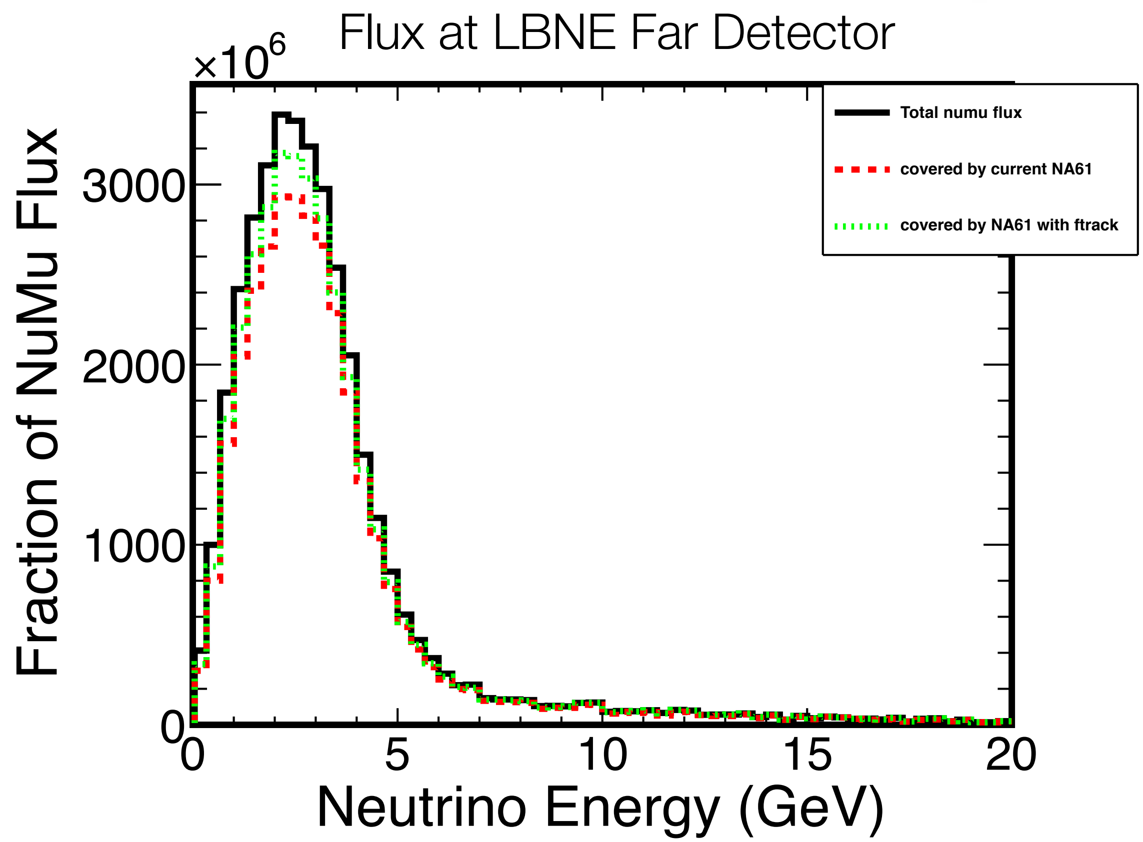
NA61 Acceptance





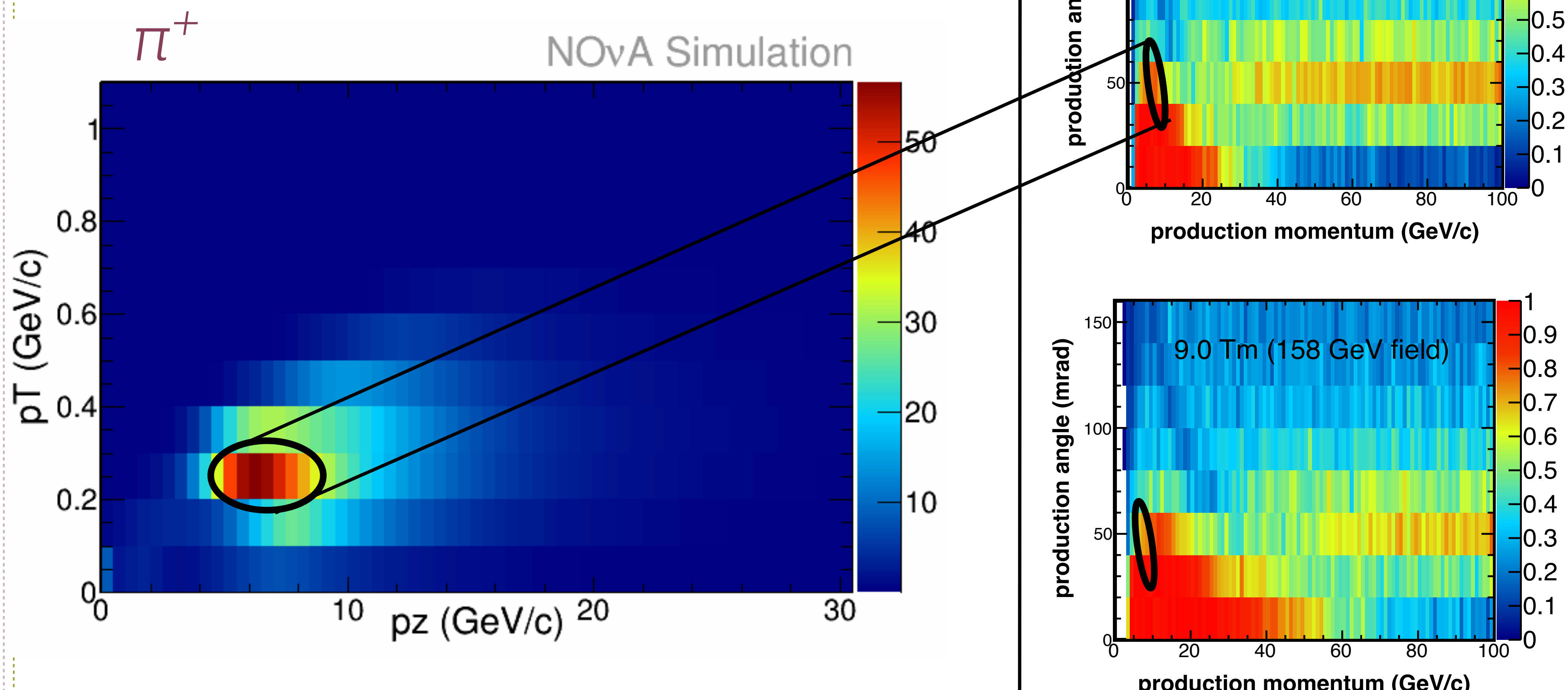
- Regions of phase space that contribute to LBNE flux are well matched to NA61 phase space

LBNE Coverage



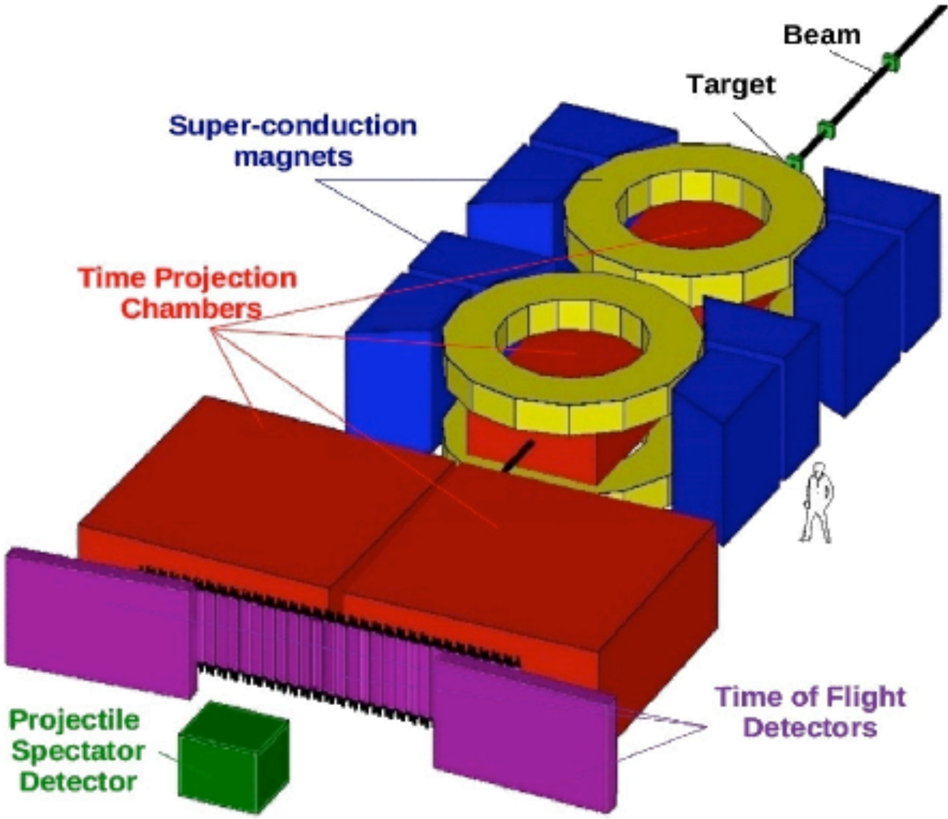
- Current NA61/SHINE has good coverage of π,K,K_{0s}, p, n, Λ_0 that contribute to LBNE flux (red line).
- With additional forward tracking could be improved (green line).

NOνA Coverage



Neutron Measurements?

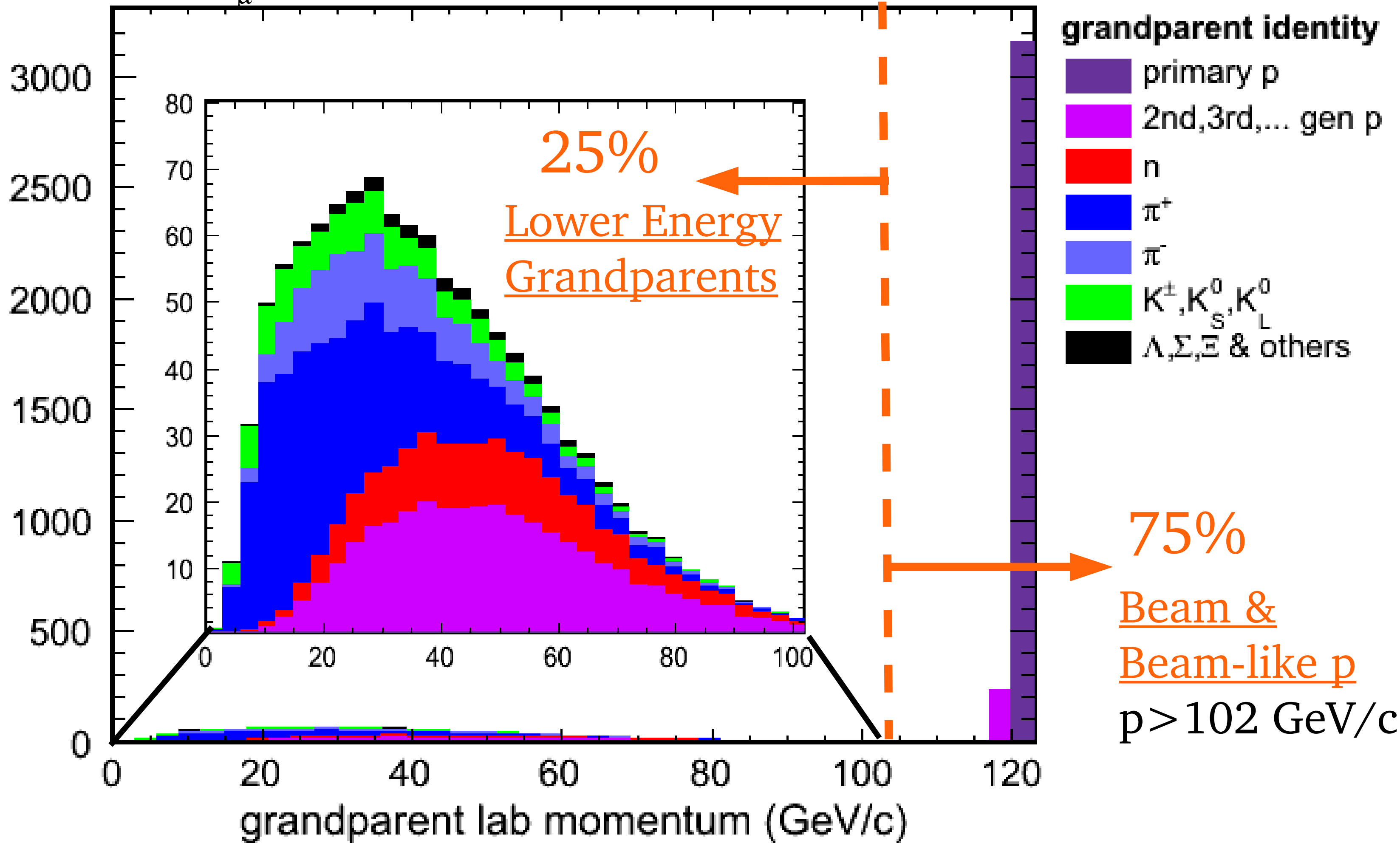
- A new projectile spectator detector (an ECAL) was commissioned for NA61 in 2013
- Could potentially use this to make direct measurements of forward n production



Need for π data

Parents of π^+ which are created in the target and make ν_μ hitting MINOS/MINERvA

M. Kordosky, William&Mary



- π^+ from π reinteractions are a sig part of ν_μ flux

Summary

- Better flux predictions are needed for future cross section measurements and oscillation measurements with accelerator beams
- Requires improved sensitivity with in situ measurements and additional hadron production data
  - Increased statistics and data analysis improvements from NA61 will improve flux predictions for T2K/T2HK over the next 2 years.
  - Possible opportunity to take data starting in 2015 at in SHINE at 60-120 GeV/c could similarly benefit NuMI and LBNE.