Neutrino beams and sources

Žarko Pavlović

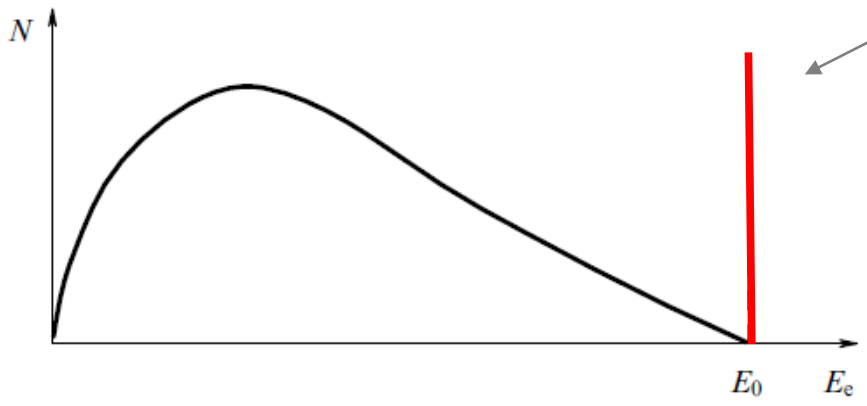
Intensity Frontier summer student lecture, Fermilab 06/05/2014

Outline

- Brief history of neutrinos
- Neutrino sources
- Accelerator neutrino beams and neutrino beams at Fermilab
- Precisely predicting accelerator neutrino fluxes

Brief history

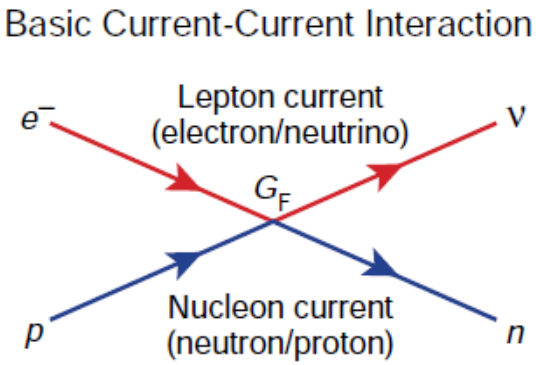
- 1930 Pauli introduces neutrino
- Explains continuous beta spectrum



- Expected discreet spectrum for two body decay
- Observed continuous beta spectrum

Weak interactions

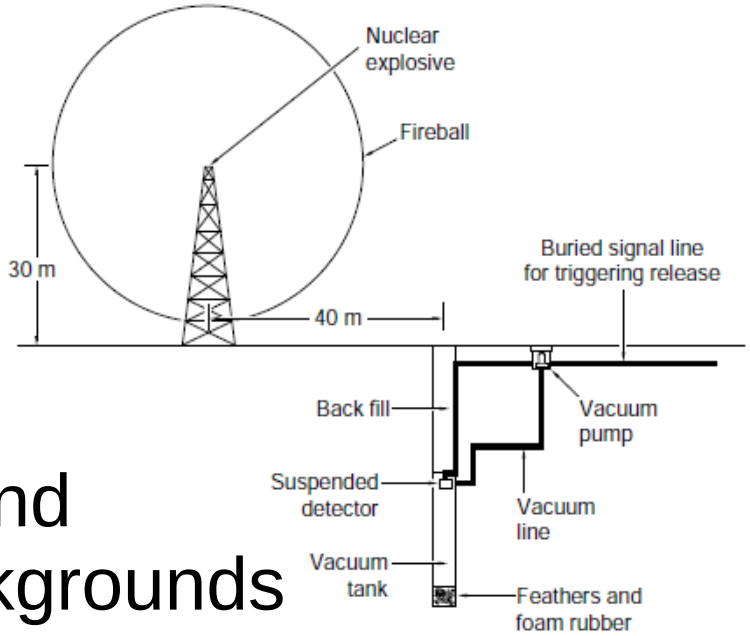
- 1934 Fermi develops Theory of Beta Decay



- Bethe-Peierls calculate the cross section for neutrino interaction $\sigma_{\nu p} \sim 5 \times 10^{-44} cm^2$
- Need light years of steel to stop neutrino

First neutrino detection

- Need intense source of neutrinos
- Nuclear bomb
  - Almost went with it, but found a better way to handle backgrounds



- Nuclear reactor
  - Source of electron anti neutrinos
  - 1956 Cowan & Reines detect first neutrinos

$$\bar{\nu} + p \rightarrow n + e^{+}$$

Neutrino sources

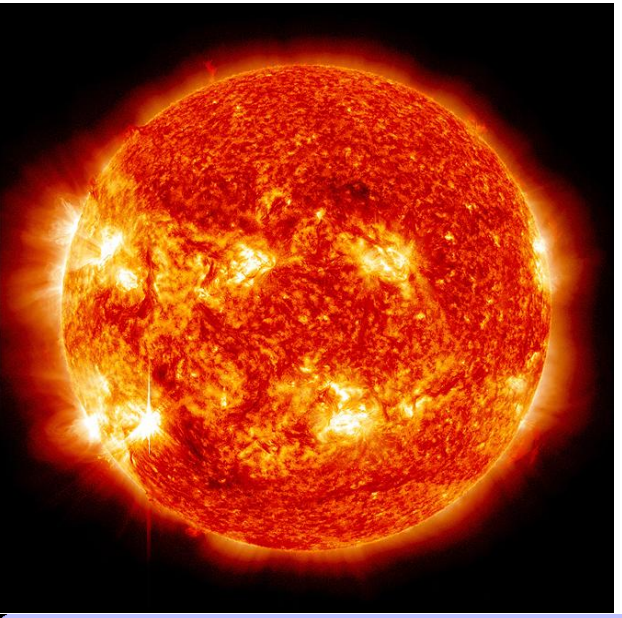
- Solar
- Atmospheric
- SN

No control over source

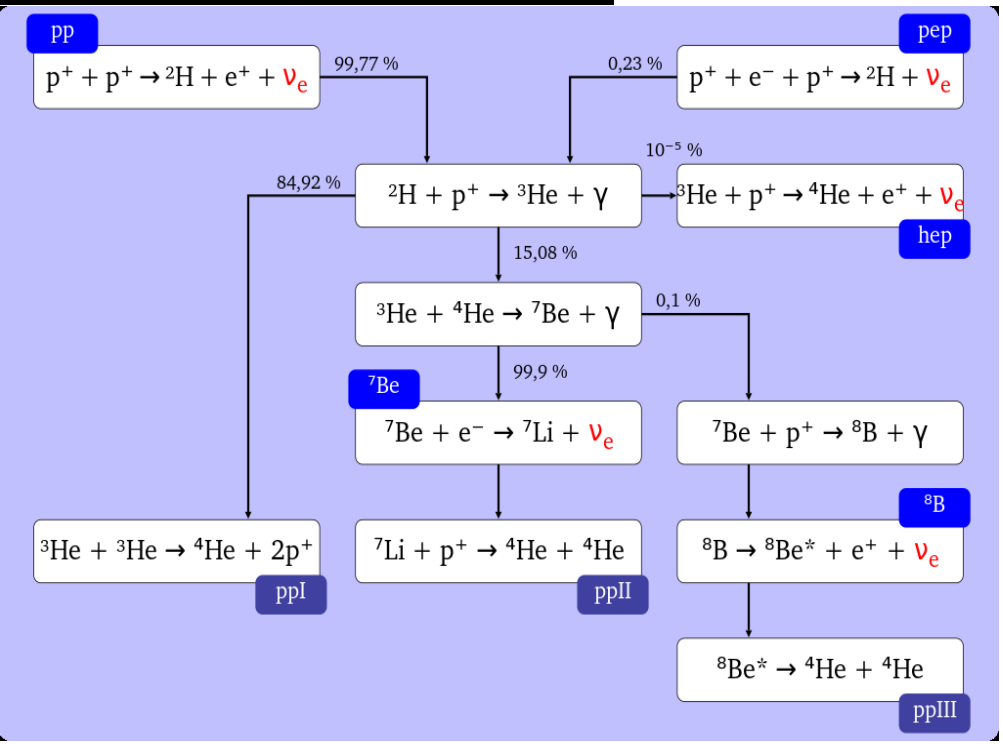
- Radioactive sources
- Reactor
- Accelerator

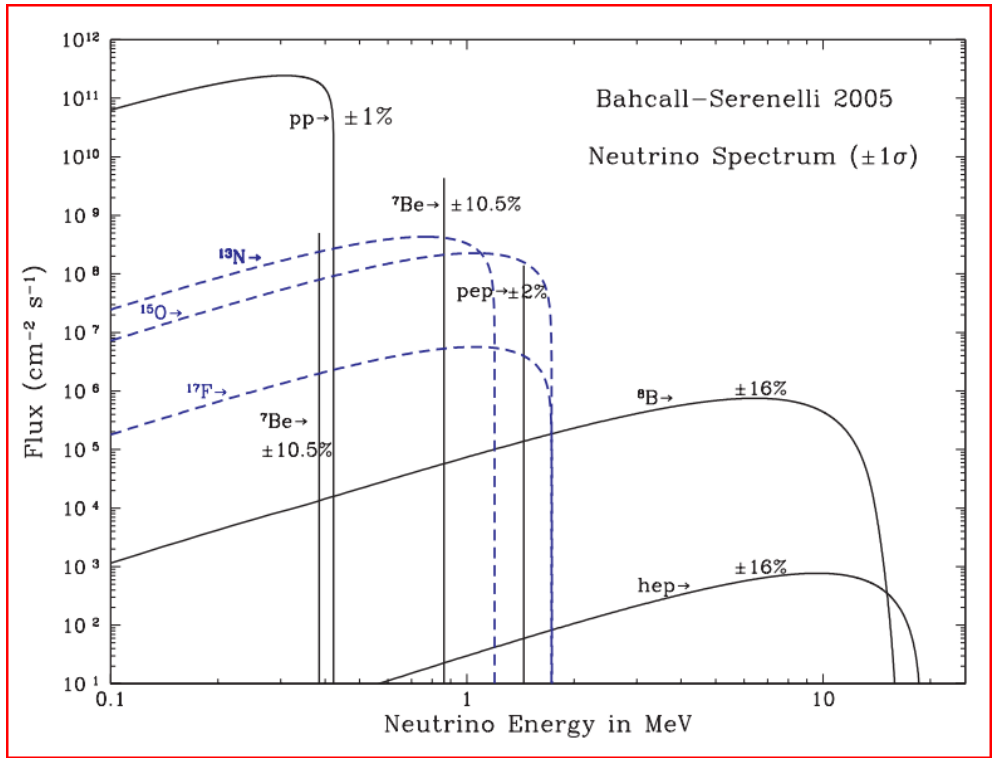
Controlled sources

Solar neutrinos

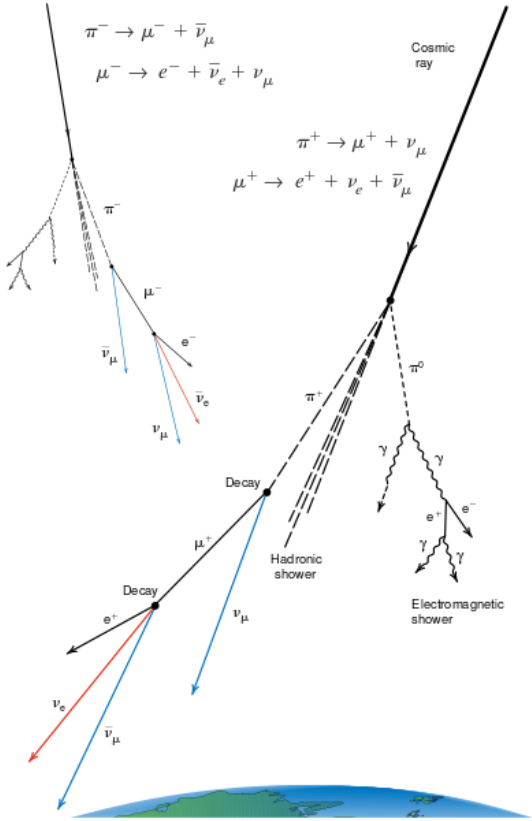


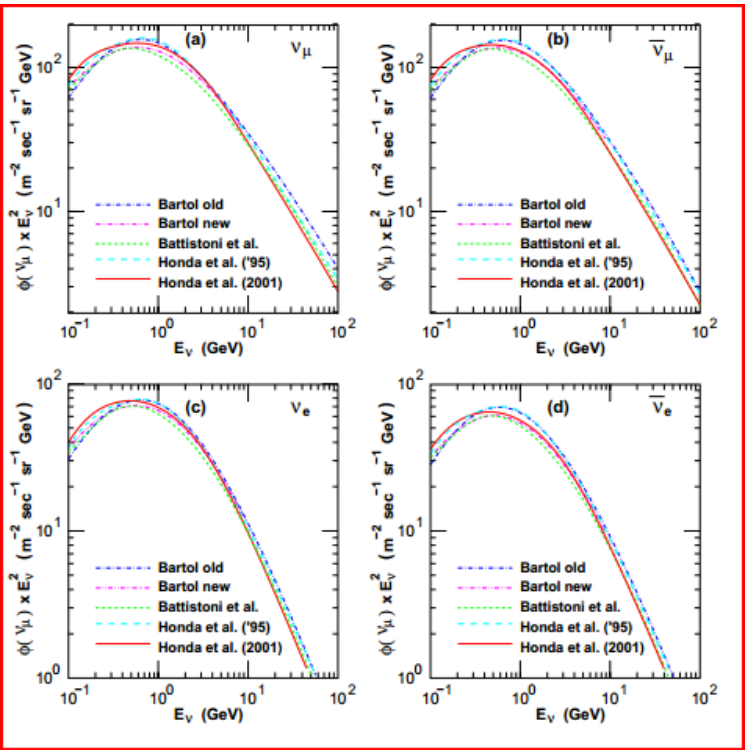
- Standard solar model
- Flux at Earth ~10^{11}/cm^2/s





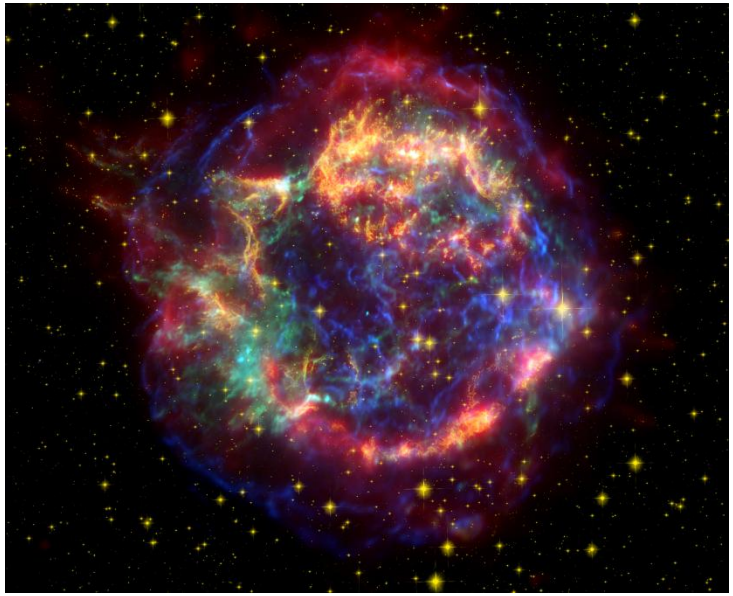
Atmospheric neutrinos

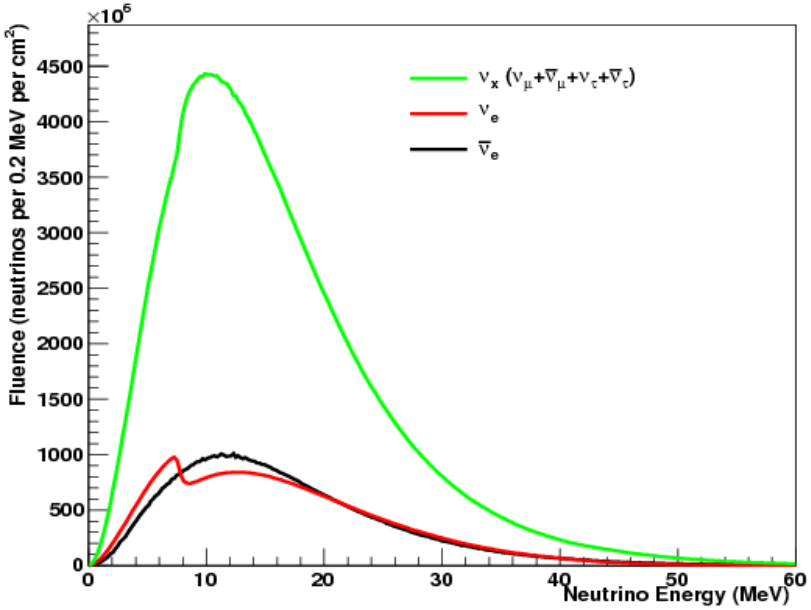




- Cosmic rays (mostly protons) interact in upper atmosphere creating hadronic showers (mostly pions)
- Roughly 2:1 muon neutrinos to electron neutrinos
- Total fluxes known to ~20%, however ratios at few % level

Supernova neutrinos





Integrated flux over 10s

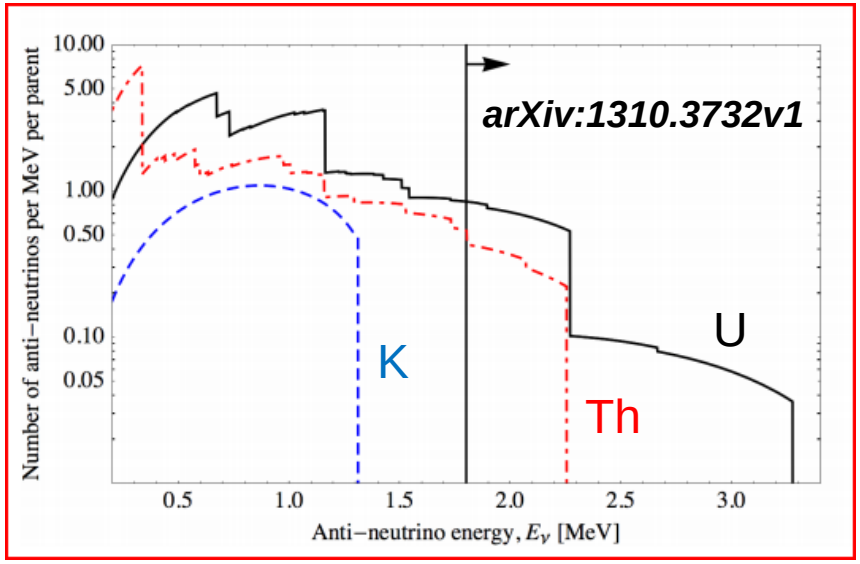
- Core collapse supernova produces a large burst of neutrinos (~10^{58})
- Carry information about supernova mechanism
- Help us understand physics of neutrinos

Scholberg, Kate Ann.Rev.Nucl.Part.Sci. 62 (2012) 81-103 arXiv:1205.6003 [astro-ph]

Radioactive sources

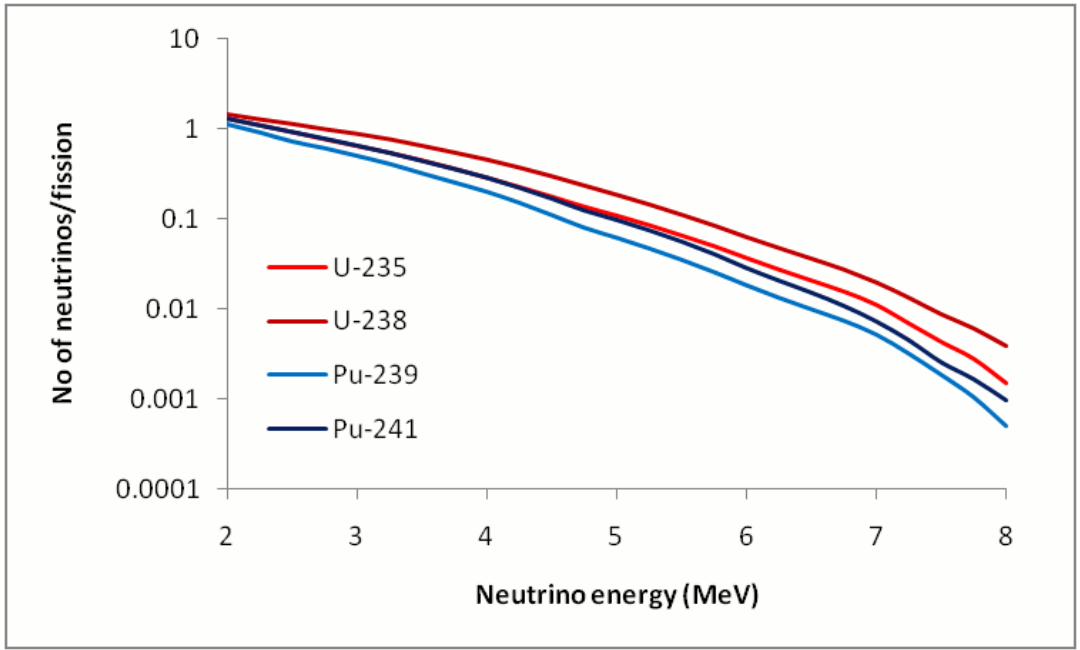
- Radioactive source
  - ~MCi sources
  - Pointlike
  - 10^{12}-10^{16} ν/kg/s

- Geoneutrinos
  - Decays of Uranium, Thorium, Potassium within Earth
  - ~10^6 ν /cm^2/s



Reactor neutrinos

- Powerful source of $\bar{\nu}_e$
- Neutrinos from beta decays of fission products
- Average reactor core produces ~10^{20} $\bar{\nu}_e$/s



Accelerator neutrinos

- Intense source
- Well controlled
  - Energy
  - Timing

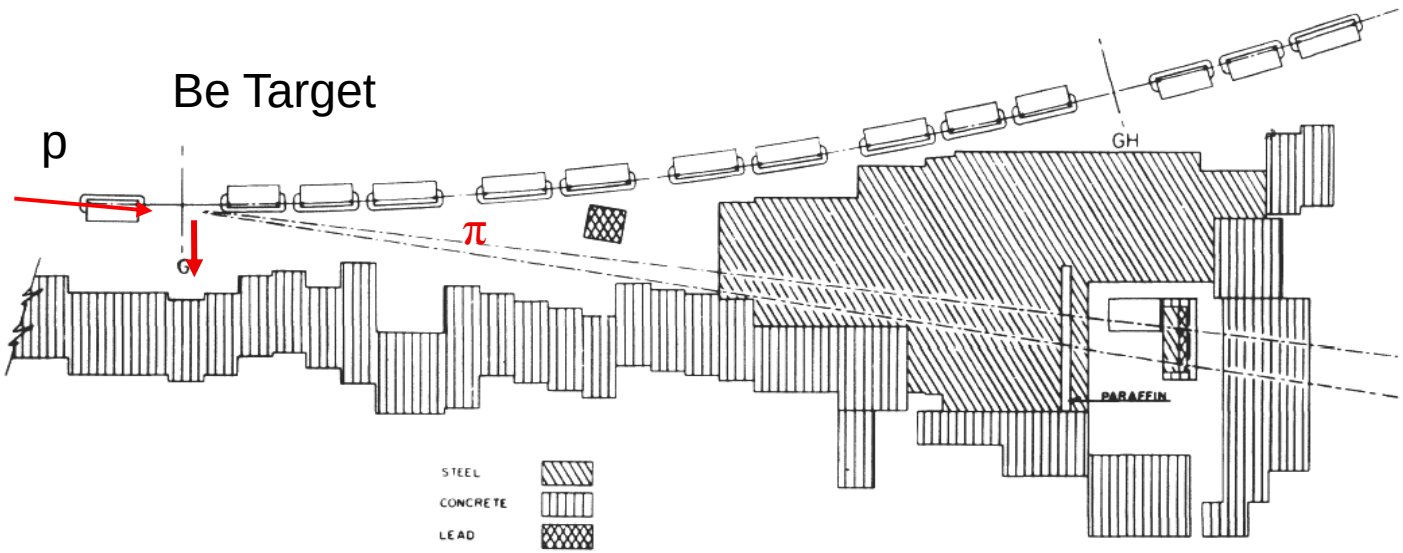
- I'll focus on conventional neutrino beams (not going to talk about stopped pion sources, beta beams, neutrino factory)
- Neutrinos produced in π/K/μ decays

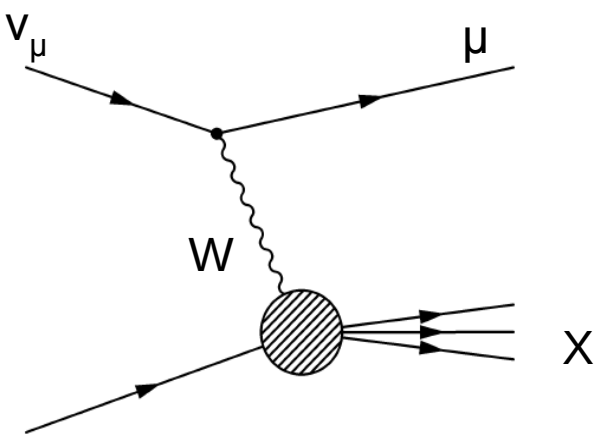
First accelerator experiment

- Idea independently proposed by Pontecorvo and Schwartz
- 1962 Lederman, Schwartz & Steinberger using AGS at BNL

$$p + Be \rightarrow \pi^+ + X$$
$$\hookrightarrow \mu^+ + \nu_\mu$$

- Detected muon neutrino → existence of two kinds of neutrinos





Phys.Rev.Lett. 9, 36 (1962)

Neutrinos in the beam

- Dominant source is pion decay $\pi \rightarrow \mu + \nu_\mu$ (BR≈100%)
  - Simple 2 body decay in CM system
  - Neutrino energy:

$$E_\nu \approx \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

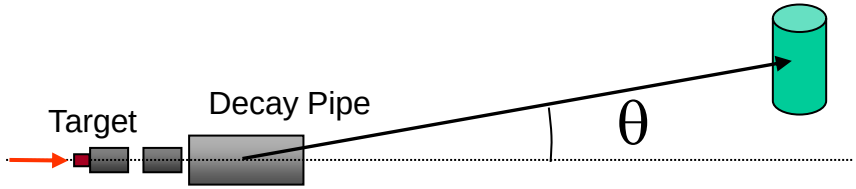
- Neutrinos boosted in the direction of the proton beam

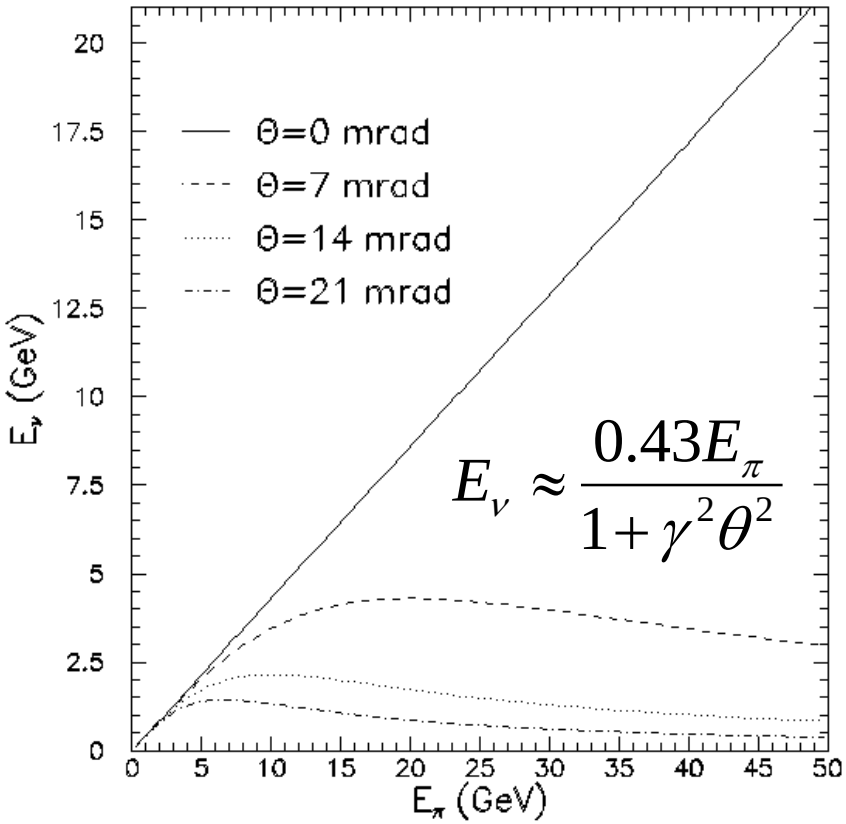
$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

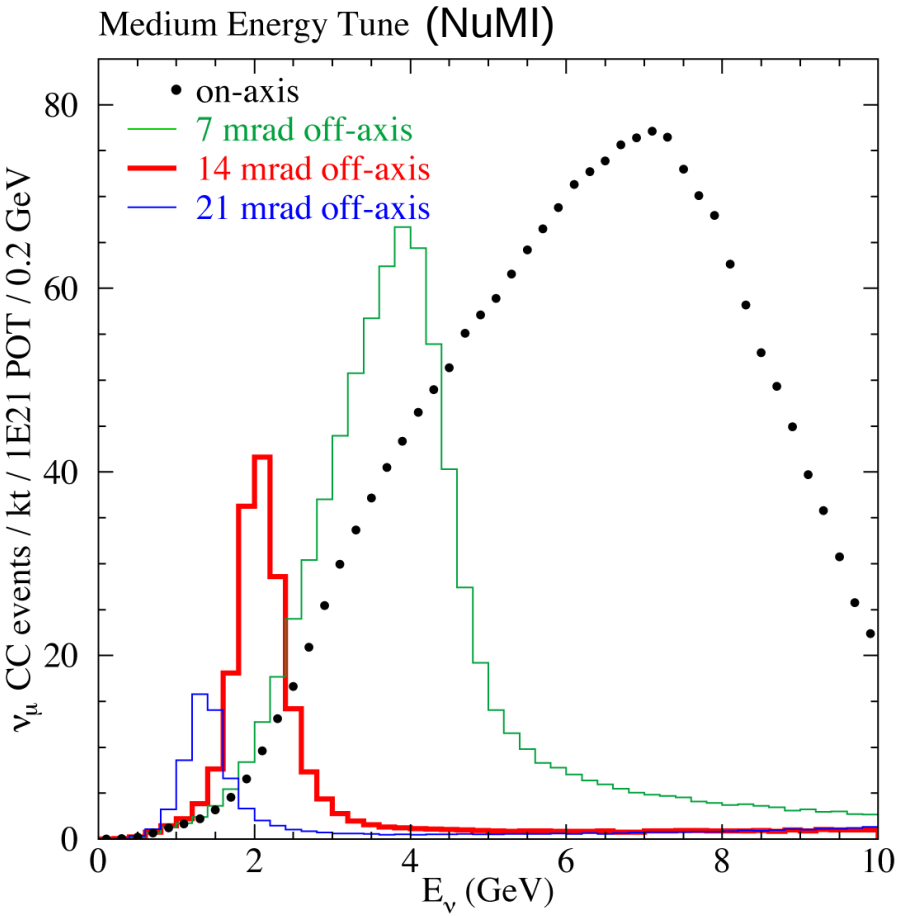
- Fraction of events from kaon and muon decays – add electron neutrino component

Off-axis flux

- On-axis neutrino energy tightly related to hadron energy
- Off-axis, neutrino spectrum is narrow-band and softened
- Concept used by NOvA and T2K







Focusing the beam

- Angle of neutrinos from pion decays with respect to pion momentum ~1/ γ
- Pions emerge from target with angle ~2/γ
- Removing pion divergence would increase flux by ~25x
- Simon van der Meer developed magnetic device to focus secondaries emerging from the target

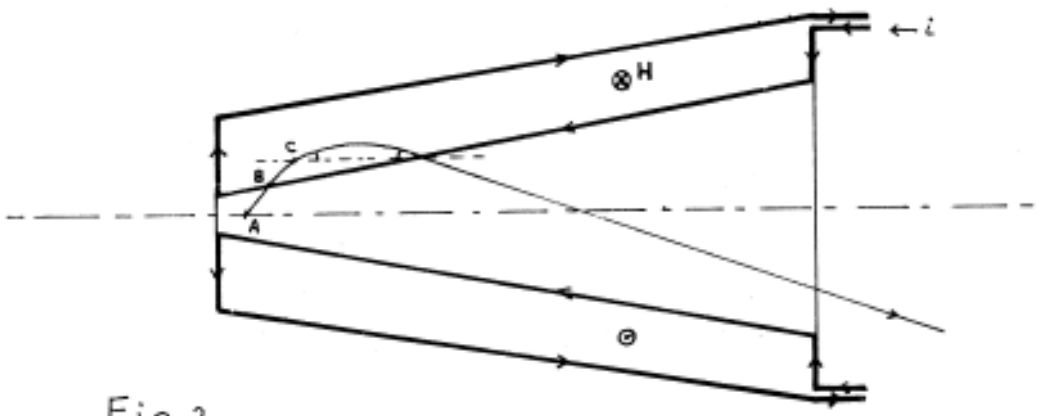
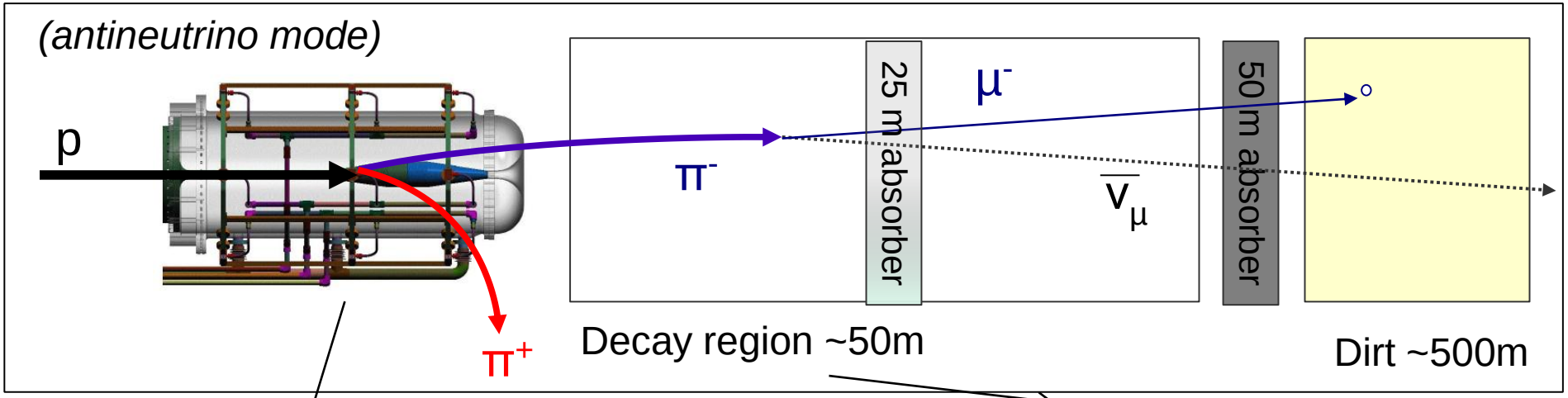
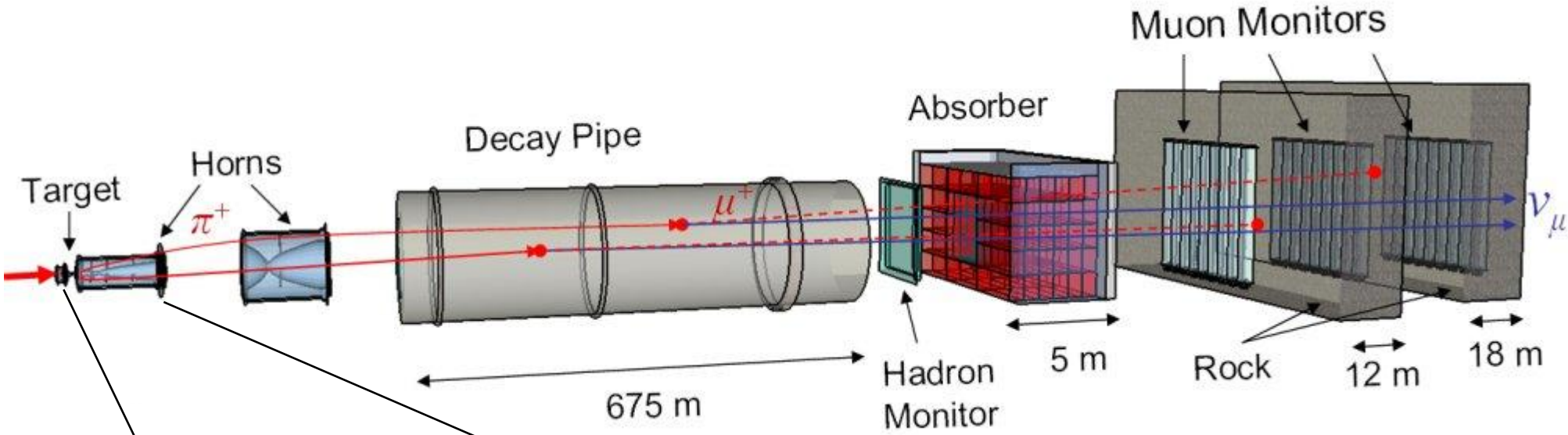


Fig.2

Fermilab neutrino beams - BNB



Fermilab neutrino beams - NuMI



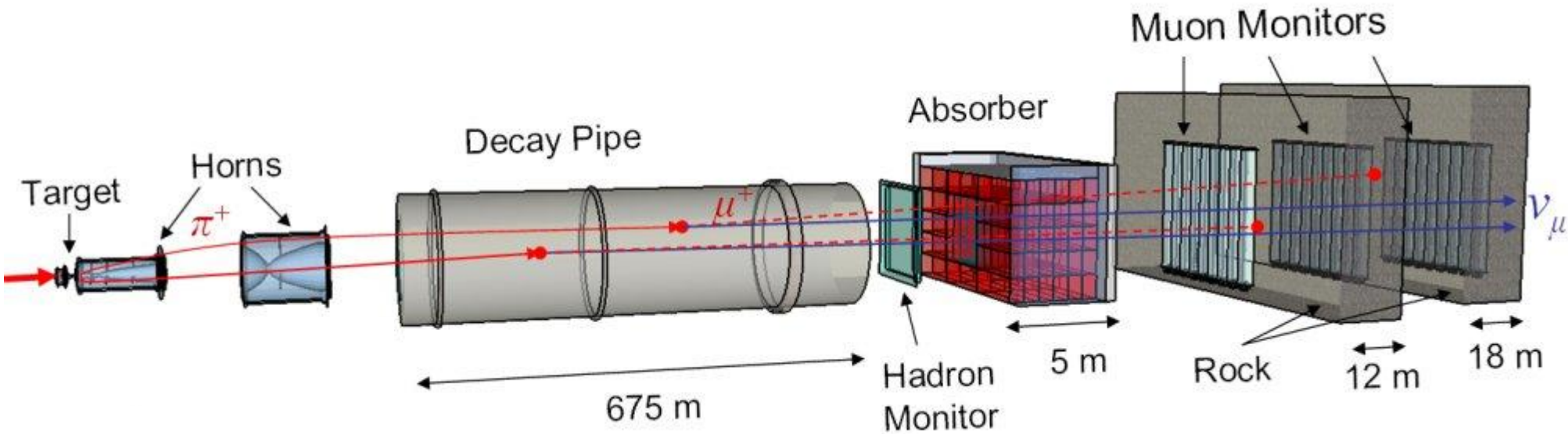
Fermilab neutrino beams

	BNB	NuMI
Primary proton beam	8 GeV from Booster	120 GeV from Main Injector
Spill length	1.6us	10us
Protons/spill	5e12	5e13
Rate	5Hz	0.75Hz
Target	Beryllium	Carbon
Focusing	1 horn	2 horns
Decay pipe length	50m (deployable 25m absorber)	730m

The experiments

- BNB
  - MiniBooNE
  - SciBooNE
  - MicroBooNE
- NuMI
  - MINOS, MINOS+
  - ArgoNeut
  - Minerva
  - NOvA

Flux predictions



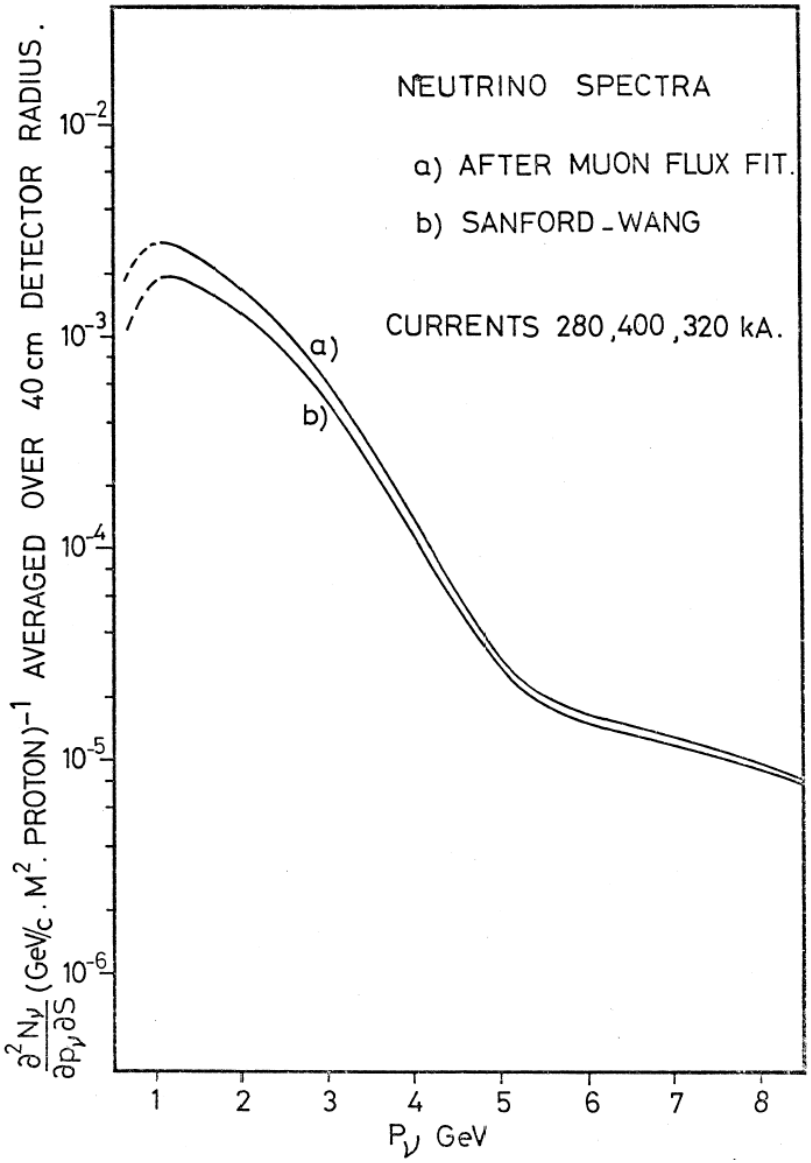
- Use MC to:
  - Predict hadron production in p+Target interactions
  - Simulate particle reinteractions in target and downstream material
  - Track charged particles through magnetic field and down to their decay point

Systematic errors

- Hadron production
  - Dominant source
- Non-hadron production
  - Proton beam
  - Focusing of secondaries
  - MC geometry

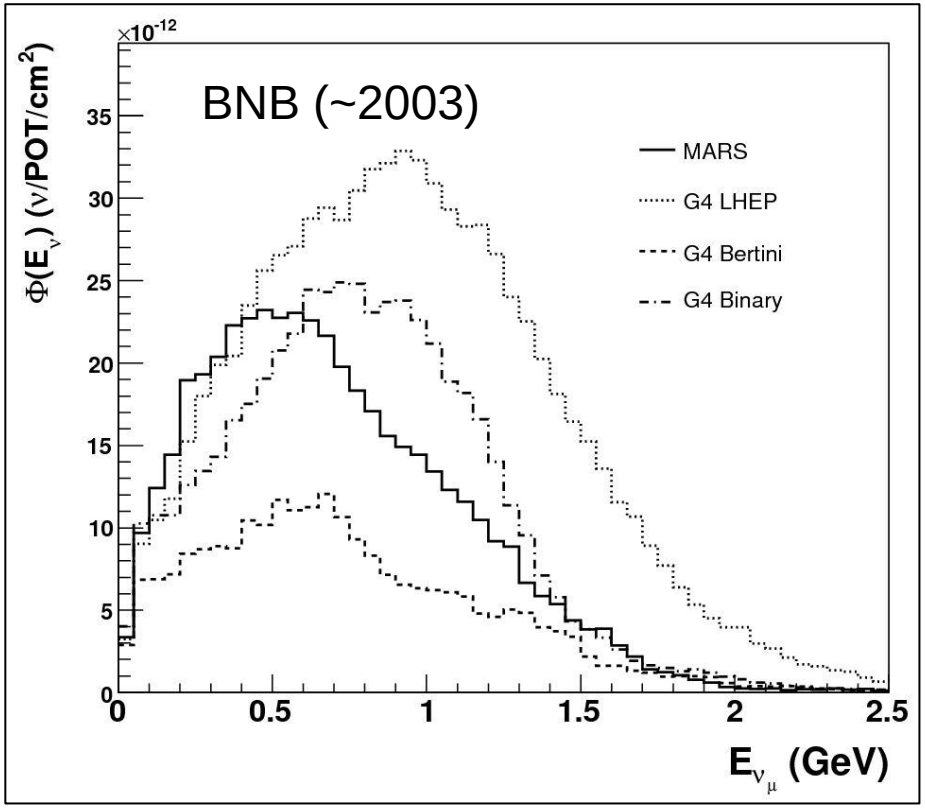
Calculating flux is hard

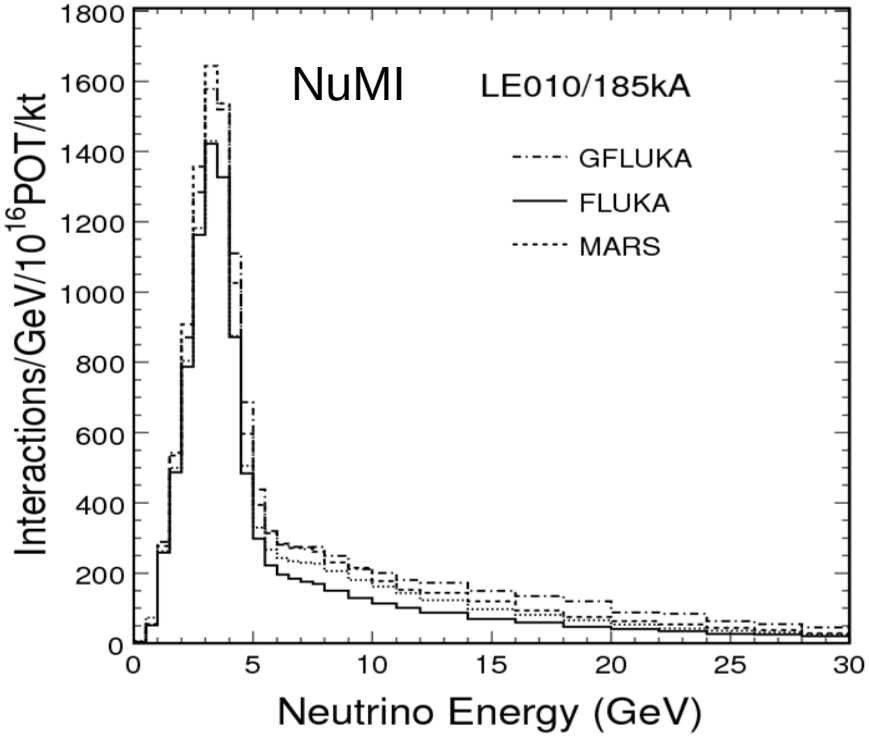
- Past neutrino experiments had to apply corrections
- More often than not flux prediction didn't match data
  - Using some process with known cross section
- Flux uncertainty large 10-30%



Hadron production

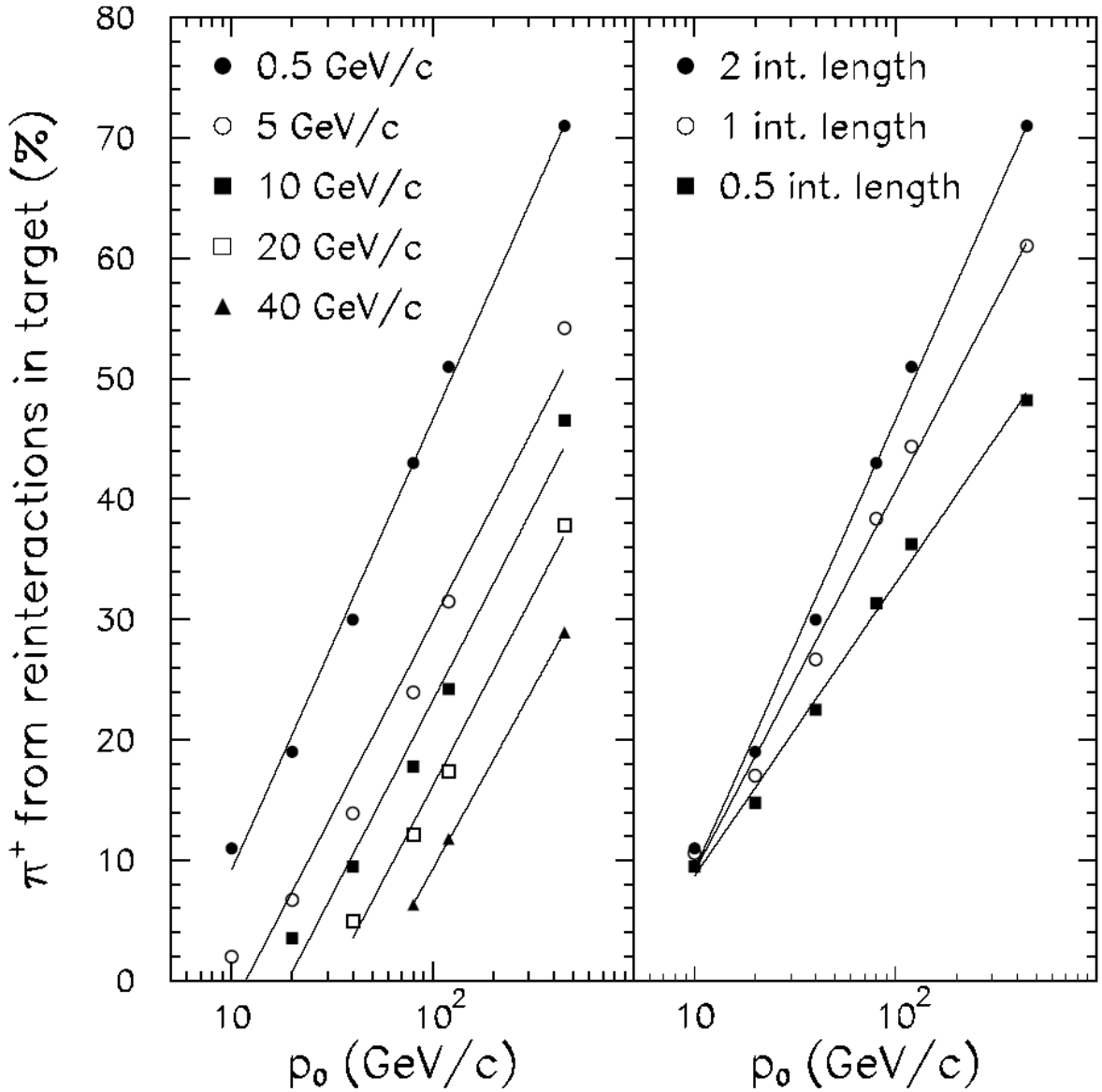
- Models give range of predictions
  - Scaling to primary proton momentum, target material
- Large initial flux uncertainty





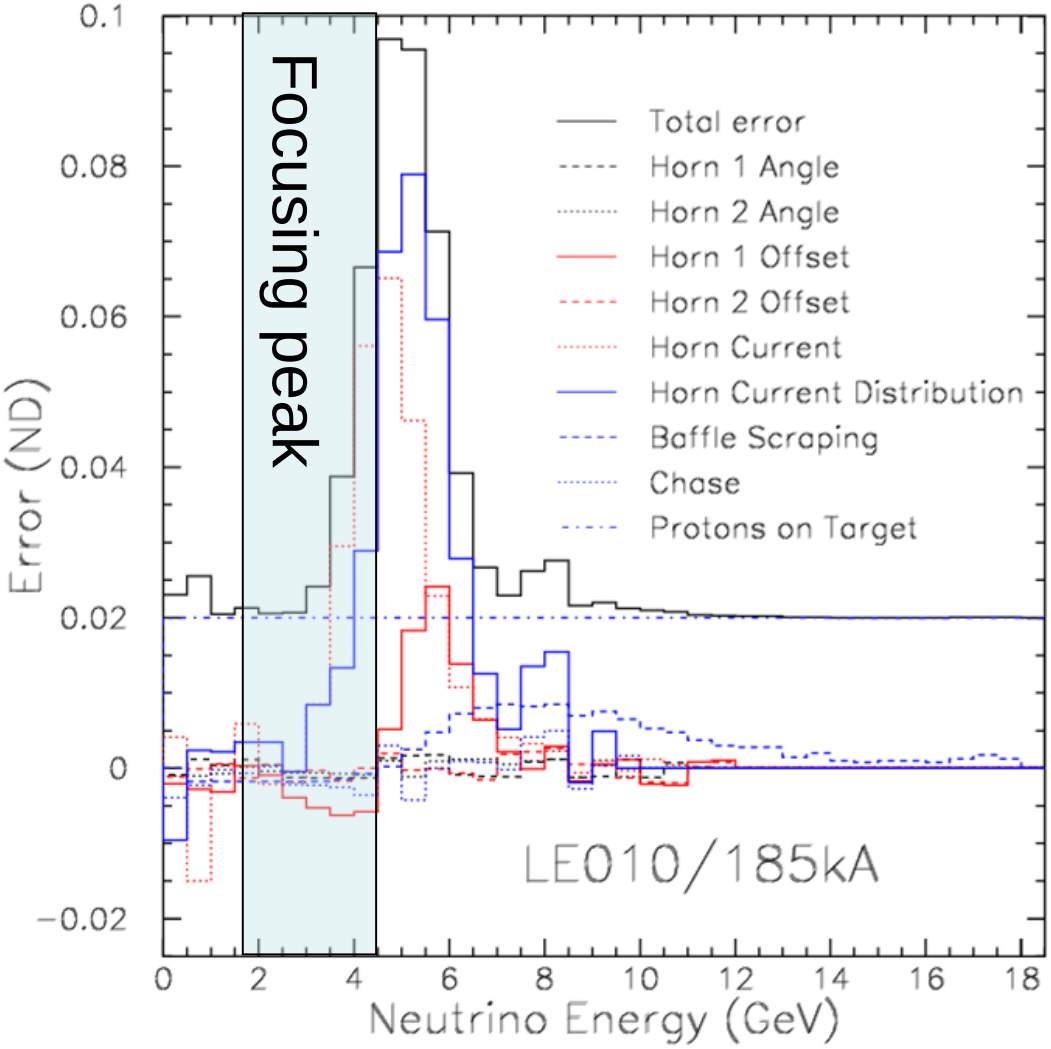
Thick-target effects

- Hadron production data largely from thin target experiments
- Neutrino production targets ~2 interaction lengths
- Large fraction of particles created by reinteractions in the target
- Hadron production experiments with replica targets (HARP thick target, MIPP)



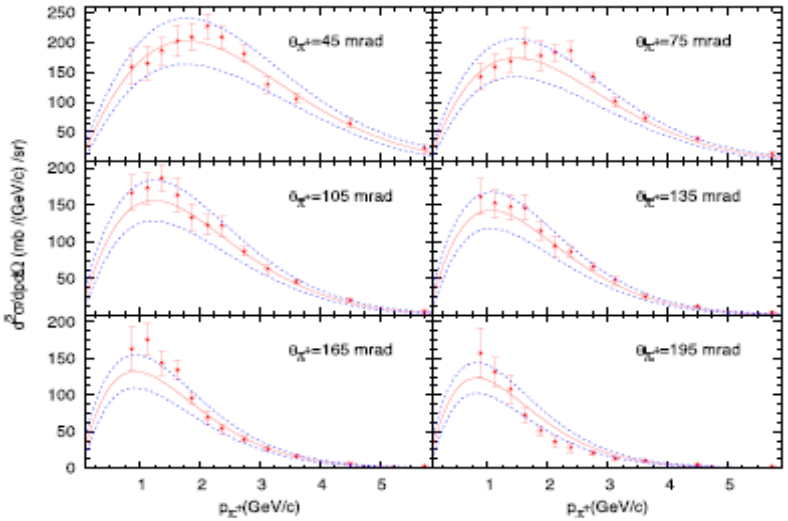
Non-hadron production errors

- NuMI example
- Errors biggest at the falling edge of the peak
- Use data to constrain errors
  - Calibration
  - Optical survey
  - Beamline instrumentation

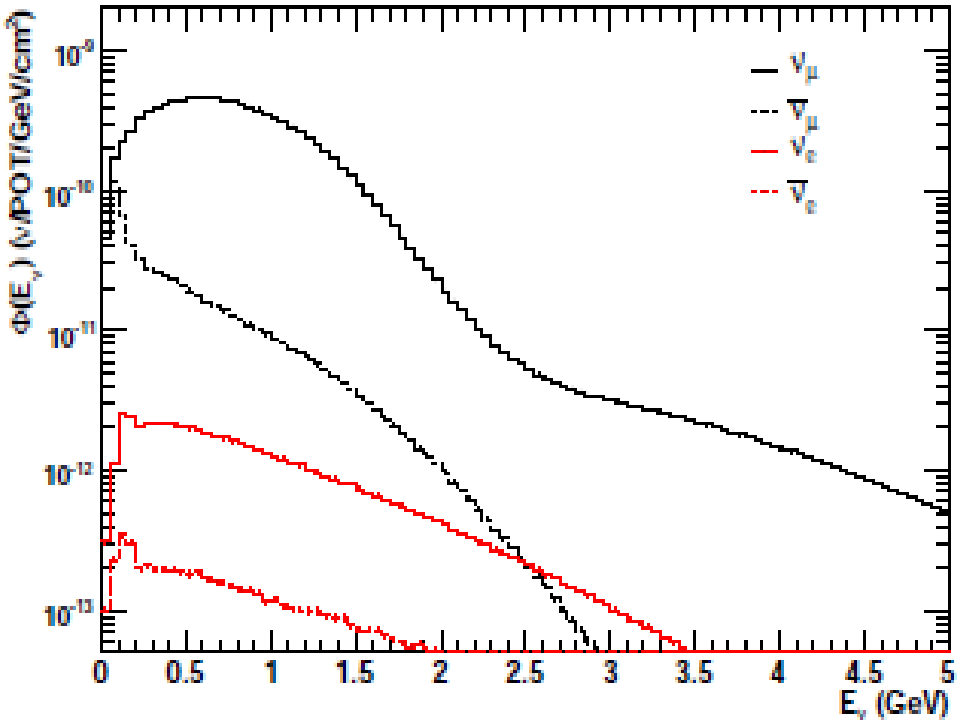


Single detector experiments (for example MiniBooNE)

- Use pi+/pi- production from HARP (p+Be at 8GeV)



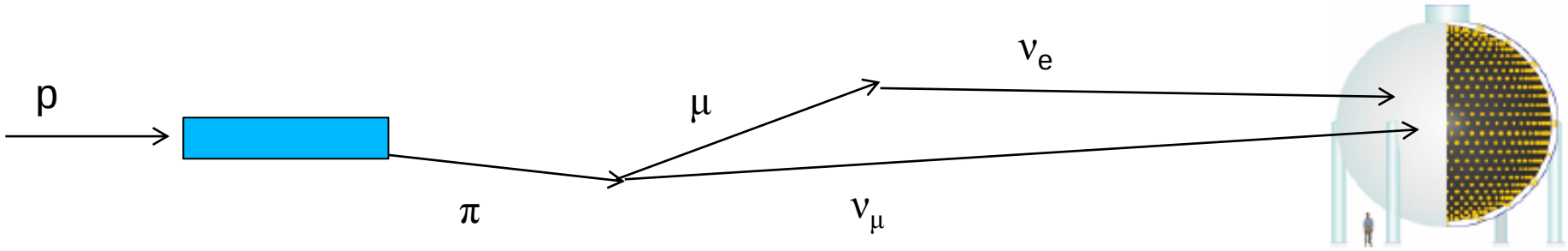
Phys. Rev. D79, 072002 (2009)



- Global fits to K production data
- With propagated uncertainties BNB flux known at the ~10% level

Single detector experiment (cont'd)

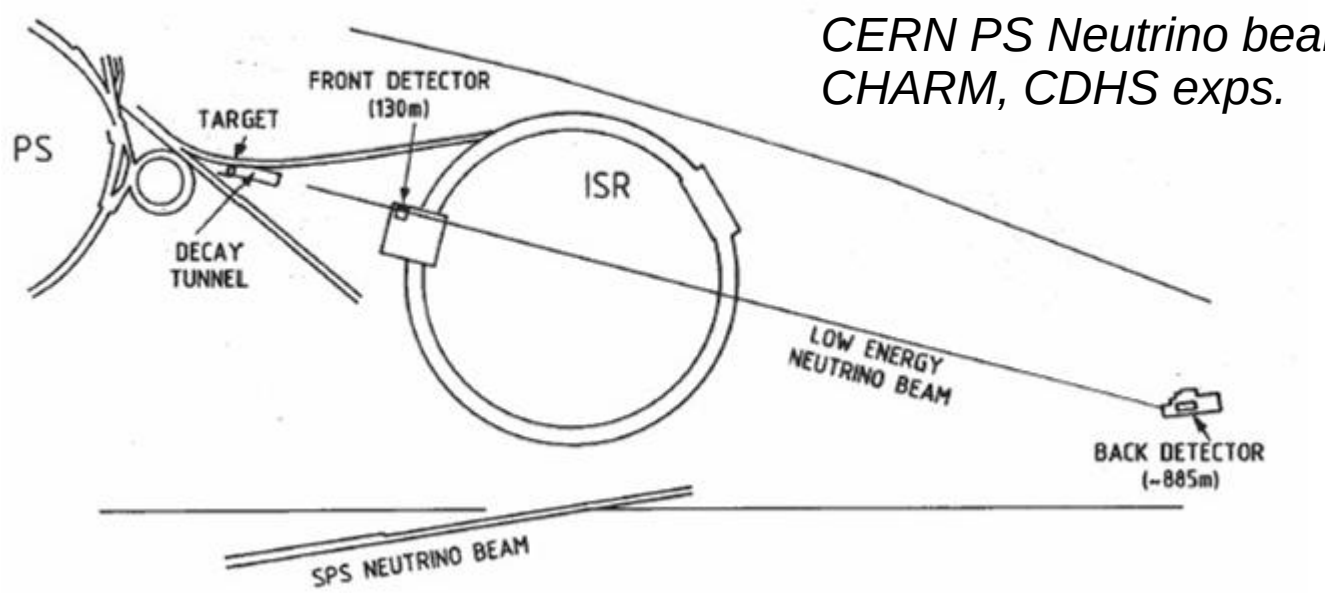
- MiniBooNE appearance analysis uses correlation between ν_μ and ν_e events (similar to ν_e/ν_μ ratio) to constrain ν_e backrounds further
- Use high statistics ν_μ event sample to constrain ν_e that share same π/K parentage



Two detector experiments

- Reducing neutrino flux uncertainties
- Measure neutrino flux in near detector to infer flux at far
- Same detector technology near and far to cancel other systematics
- Need to calculate corrections on top of R^{-2}
  - For MINOS 20-30%

CERN PS Neutrino beam – CHARM, CDHS exps.

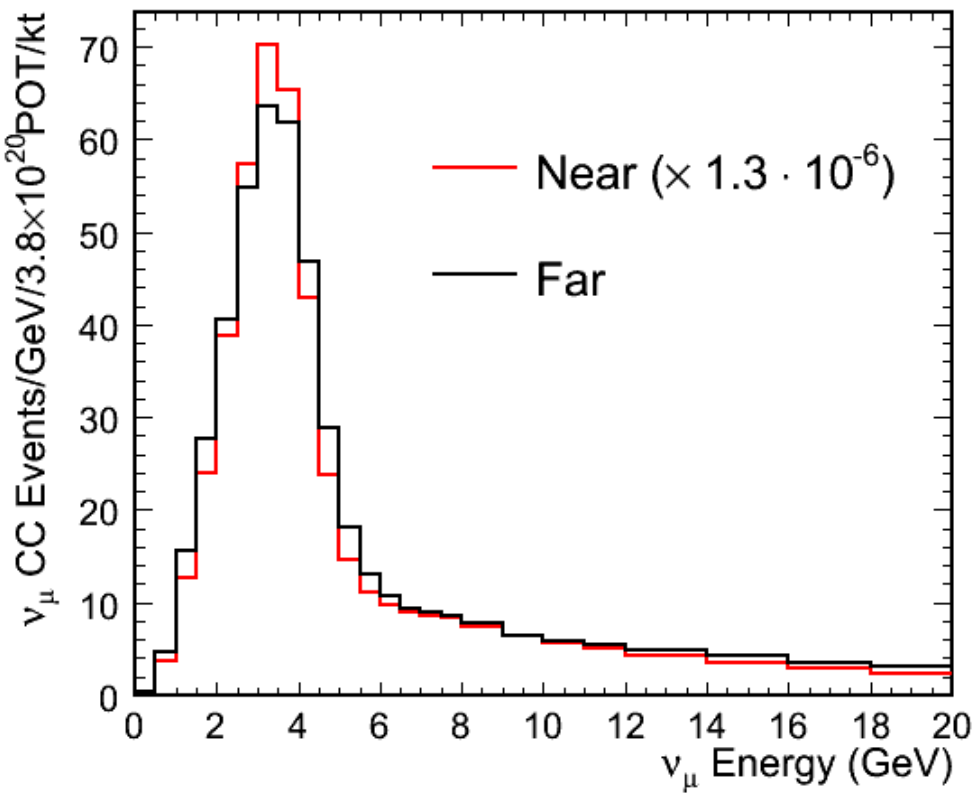


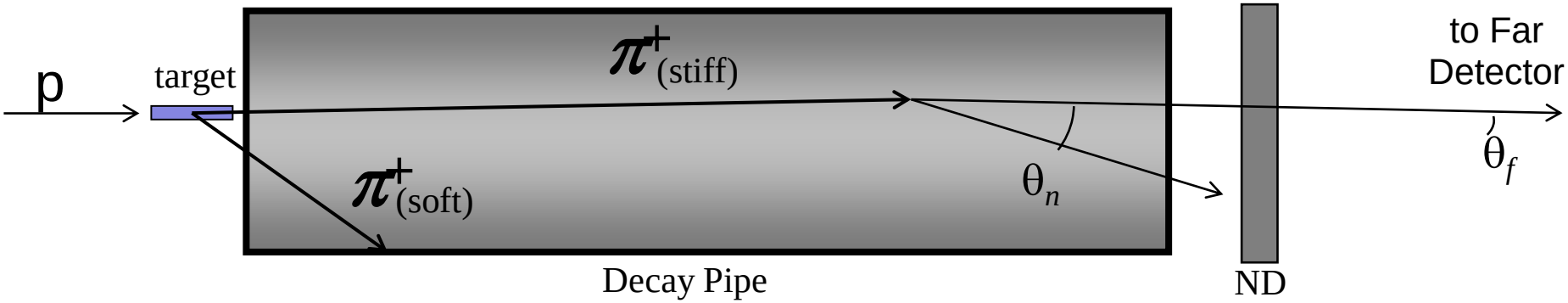
Near and Far spectra

- Flux not the same
- Recall E_ν dependence on parent momentum

$$E_\nu \approx \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

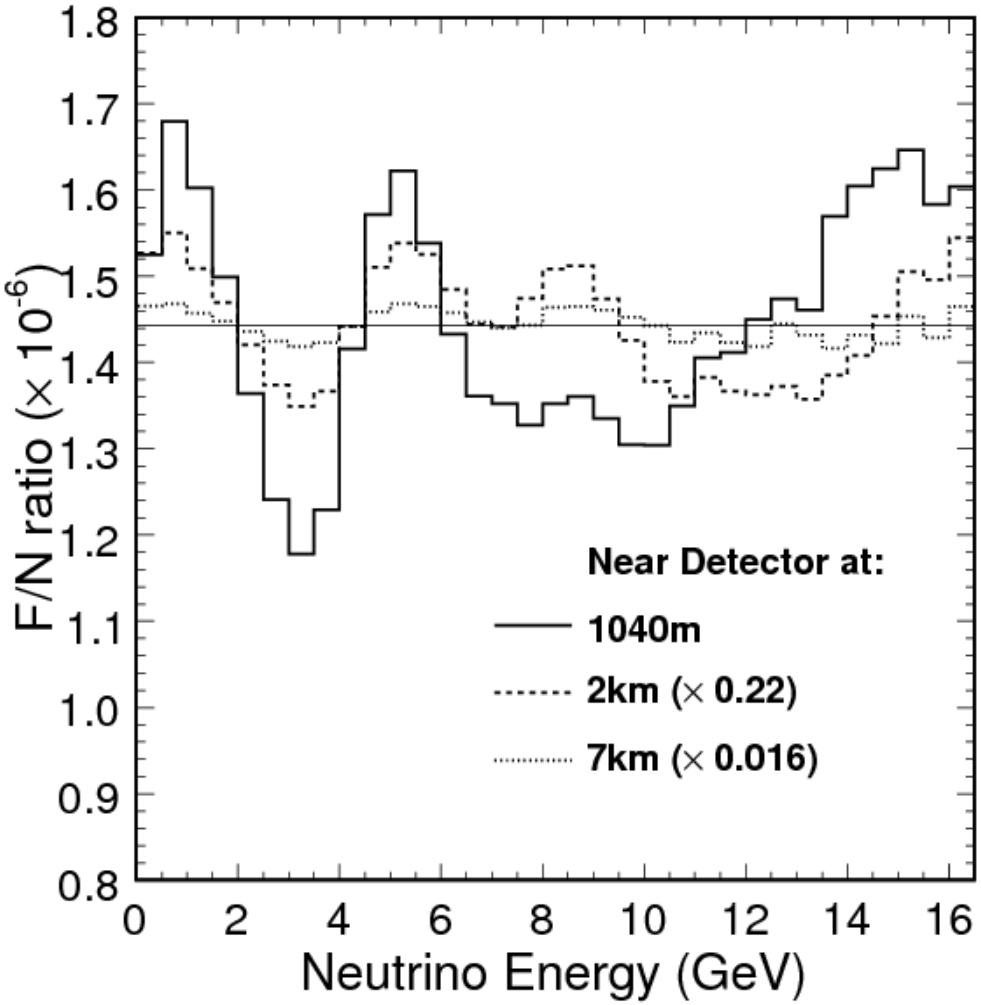
- Flux ~$1/L^2$





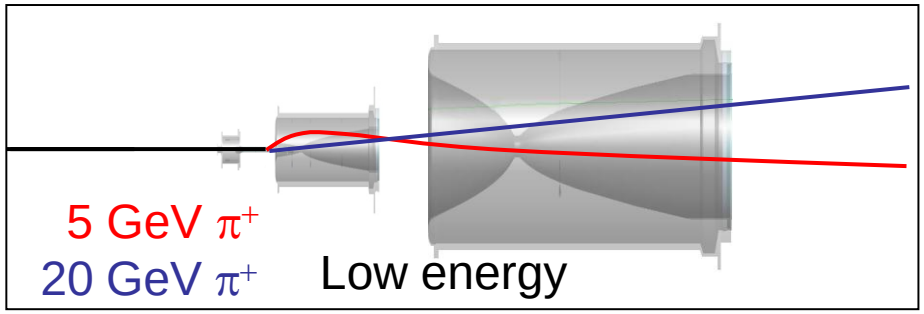
Far over Near ratio

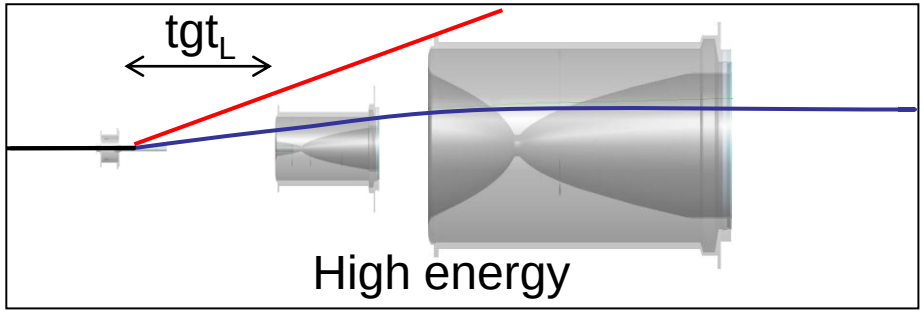
- 20-30% correction on top of R^{-2} with Near Detector at 1km
- To reduce these corrections to 2% level would have to put ND at 7km

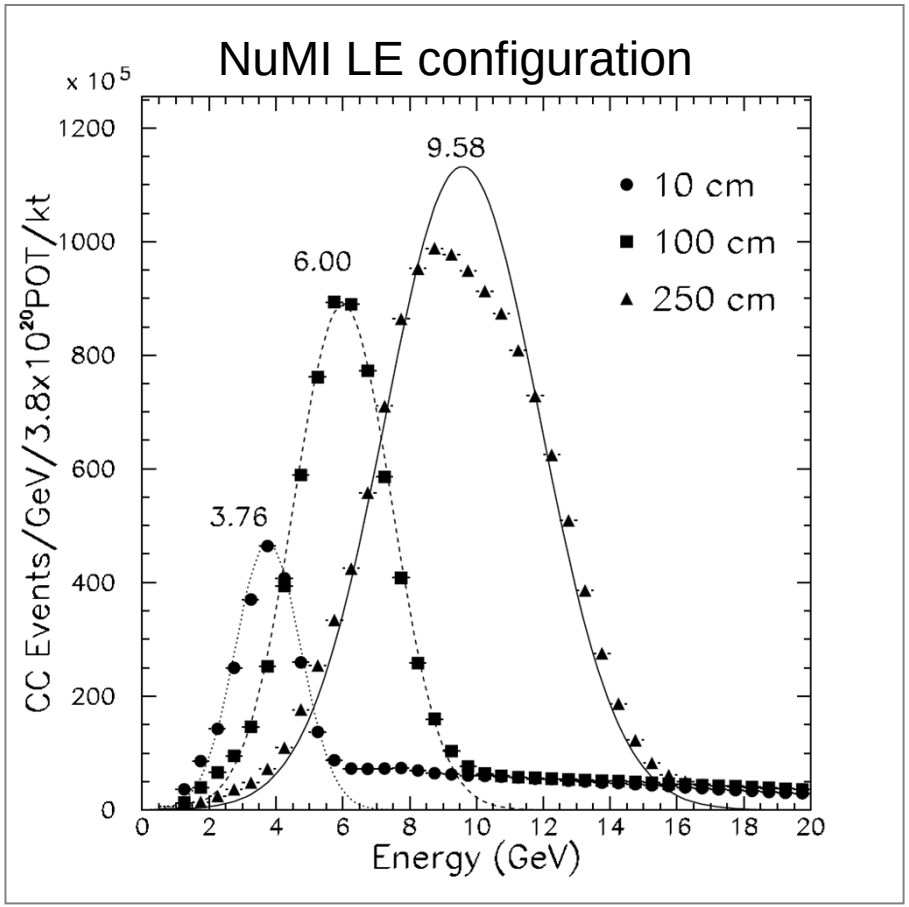


Tune neutrino energy

- Neutrino spectrum depends on target position with respect to horn
- NuMI had capability to tune the neutrino energy

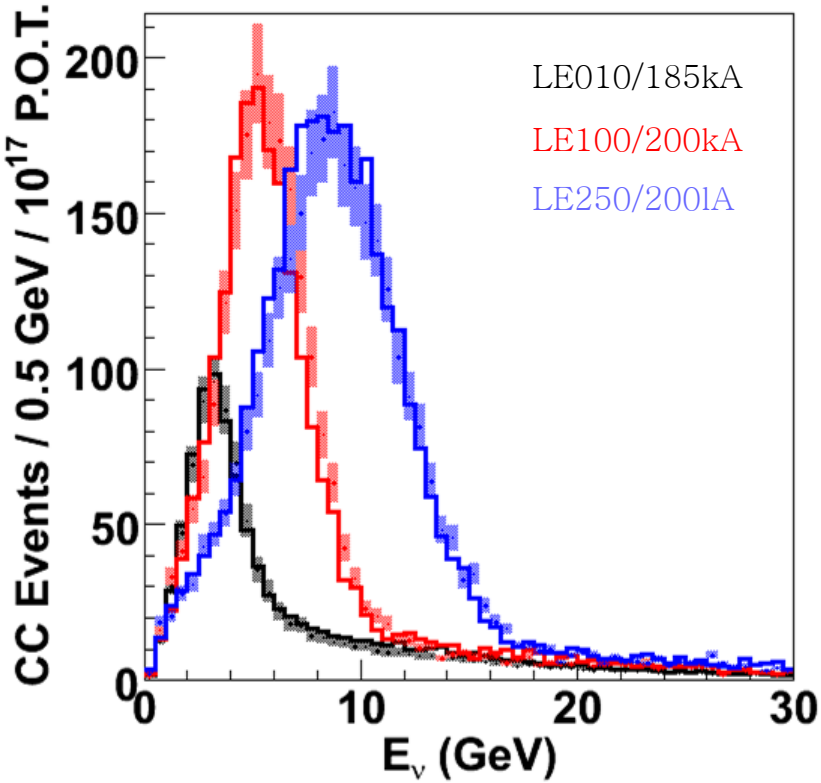


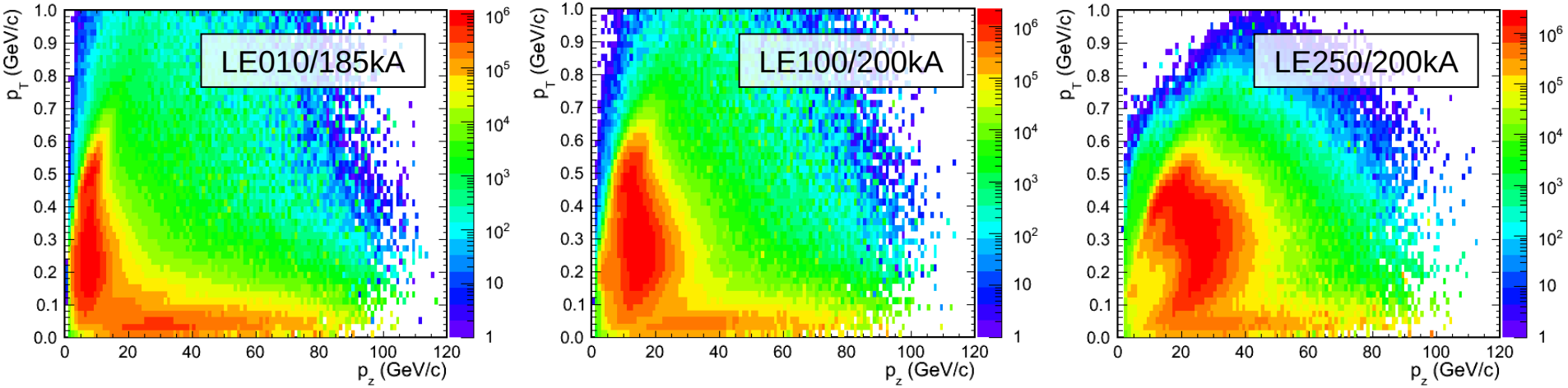




MINOS flux tuning

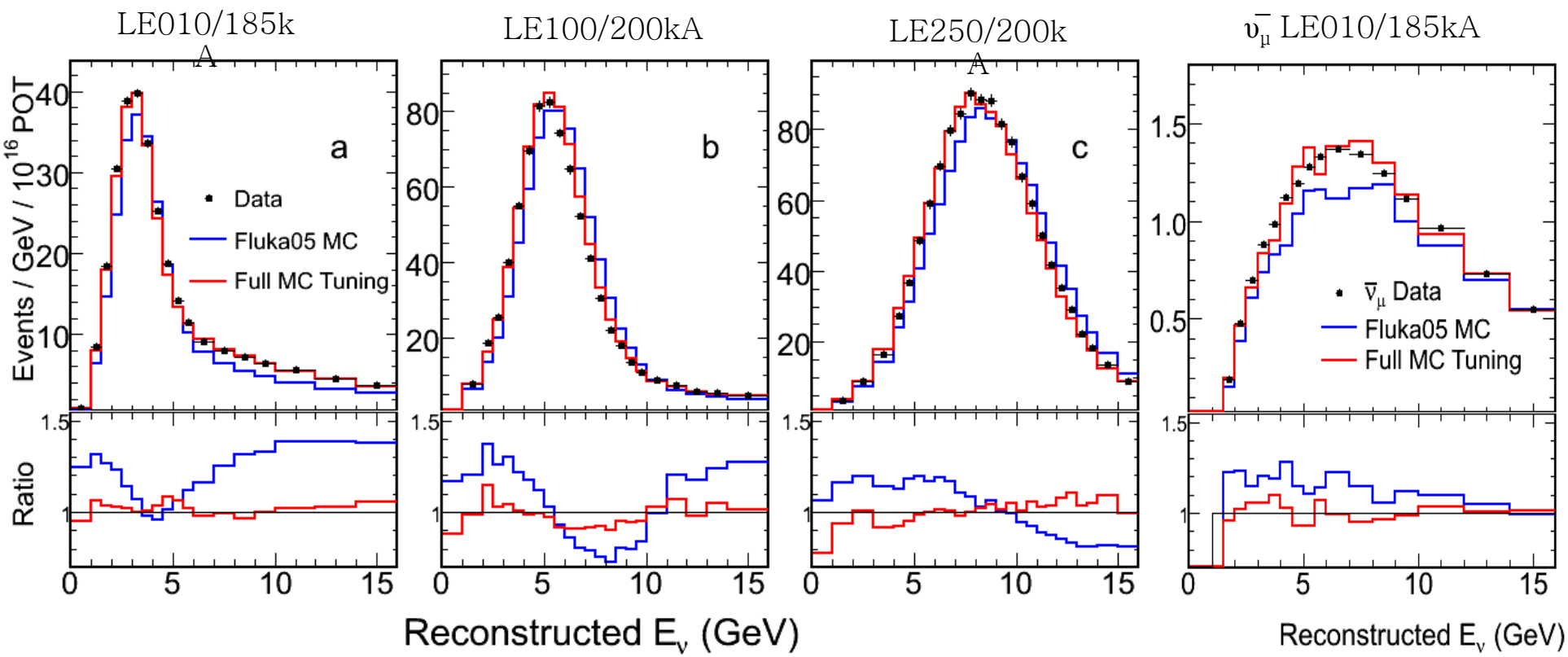
- Different beam tunes probe different regions of π (x_F,p_T)
- Use variable beam configuration to map this out
- Tune π, K yields to match the near detector data
- Break degeneracy between neutrino cross sections and hadron production





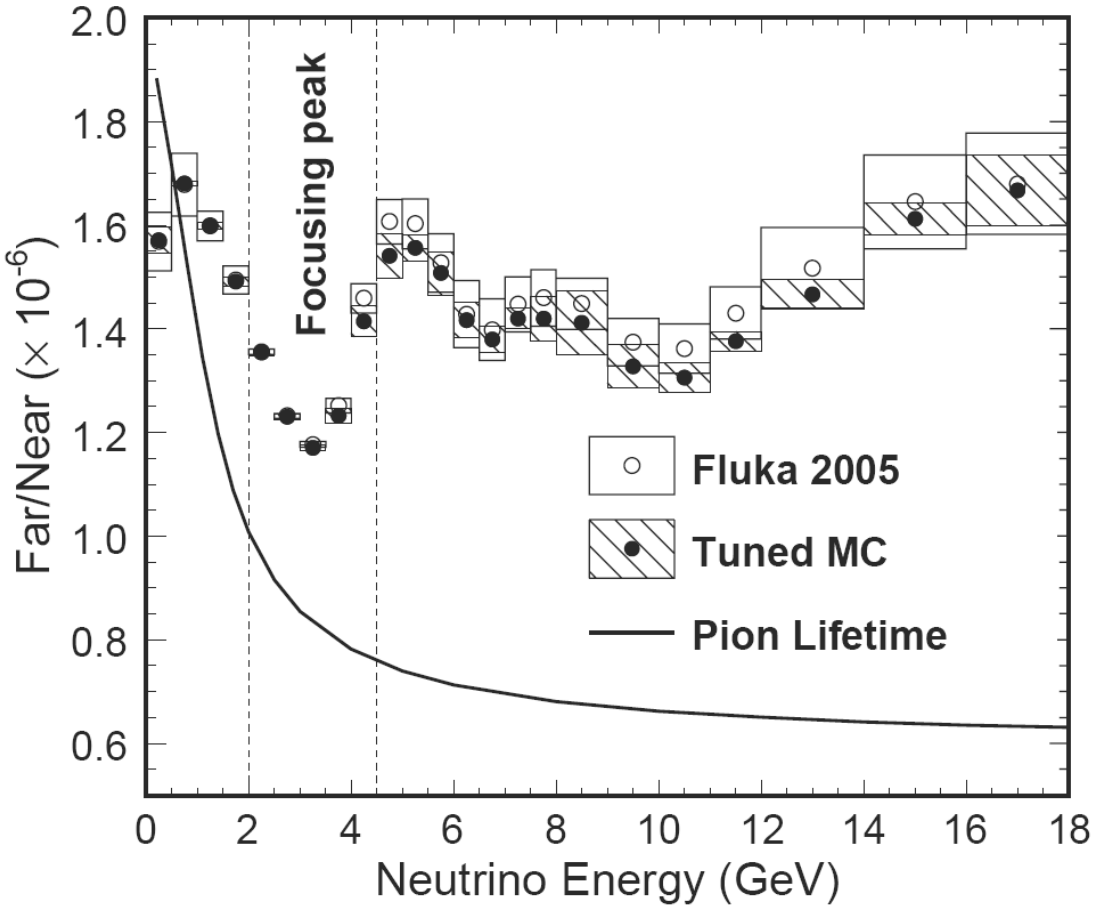
Tuned MC

- Simultaneous fit to multiple beam configurations
- Fit both ν_μ and $\bar{\nu}_\mu$ spectrum – sensitivity to both π^+ and π^- yields



Far/Near ratio

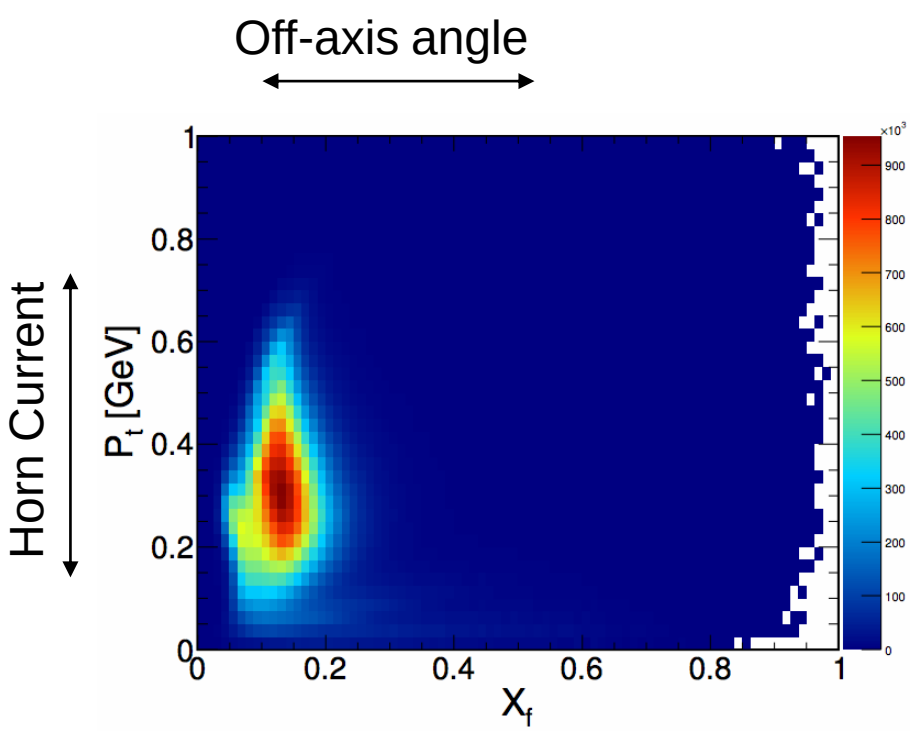
- Fits to Near Detector data constrain the errors on Far/Near ratio
- Errors at couple percent level



NuMI-X

- Consortium comprising Fermilab neutrino experiments collaborating on the modeling of NuMI beam
- Beam tune can't be easily changed in current NuMI configuration (NOvA target)
- Can modify the horn current – scan over p_T
- Multiple experiments, each probing different region of π (p_T,x_F)

Experiment	Angle
MINOS+	On-axis
Minerva	On-axis
NOvA ND	12 mrad
MicroBooNE	130 mrad

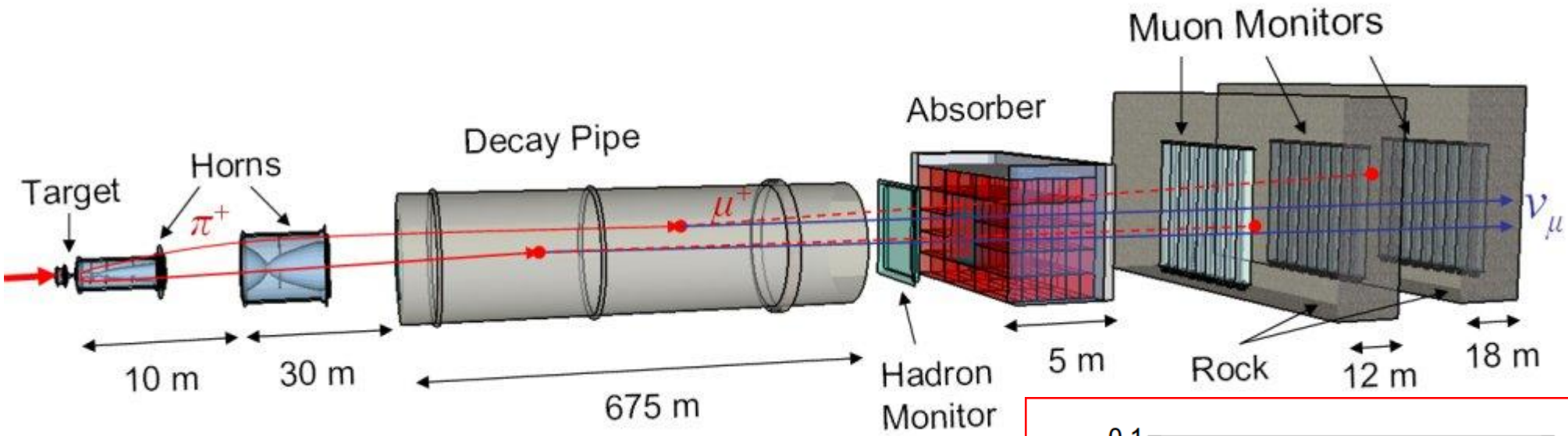


Conclusion

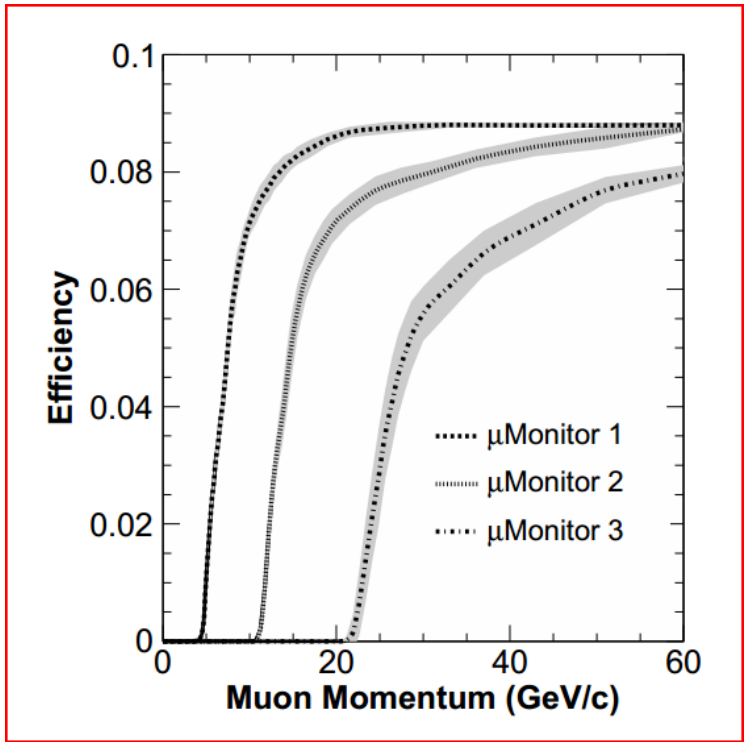
- Neutrino experiments getting more and more precise
- Need well understood flux
- Two neutrino beams at Fermilab
  - 8 GeV Booster Neutrino Beamline (BNB)
  - 120 GeV Neutrinos at Main Injector (NuMI)
- Flux predictions based on:
  - Dedicated hadron production experiments
  - Two detector setup reduces errors
  - Beam fits to constrain flux even further

Backup

Muon monitors (NuMI)

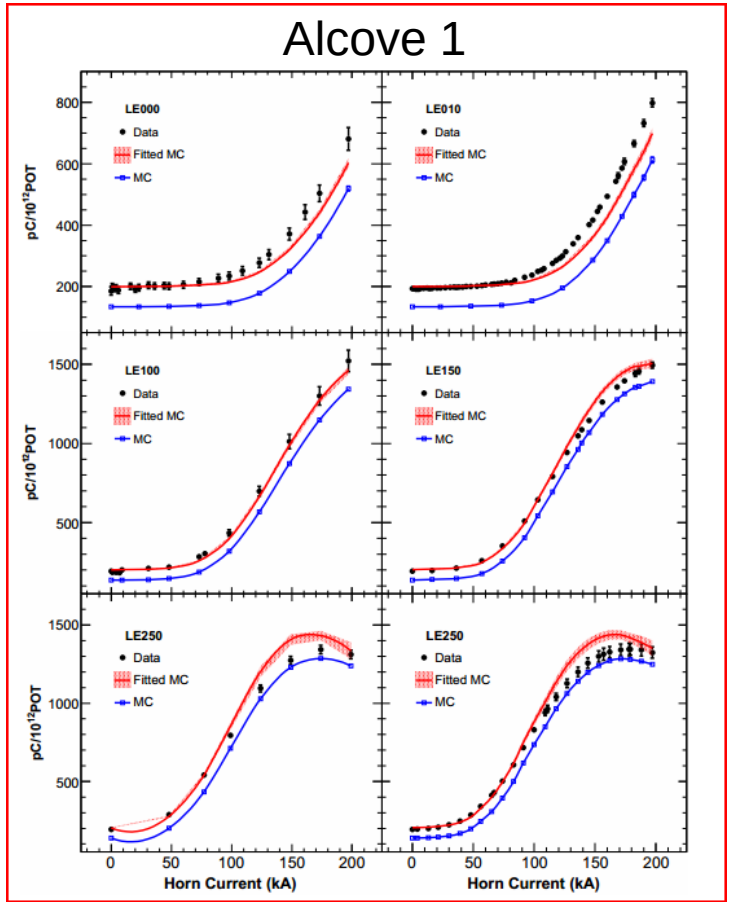
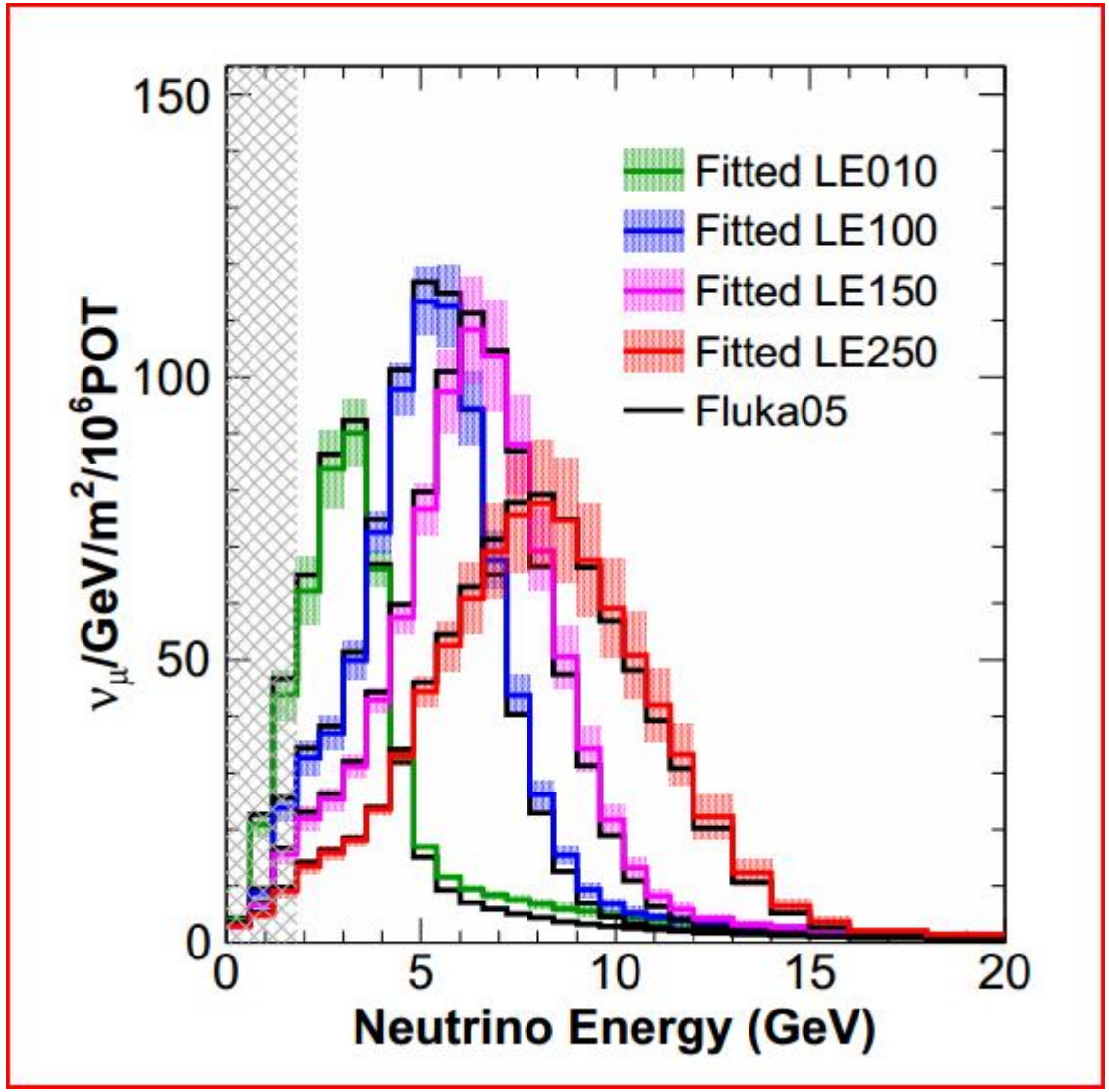


- Tune p+C hadron production to match the muon fluxes in muon monitors
- 3 monitors at various rock depth along the beam



L. Loiacono, FERMILAB-THESIS-2010-71

Muon monitors (NuMI)

- 3 muon monitor alcoves, each with a different threshold

L. Loiacono, FERMILAB-THESIS-2010-71