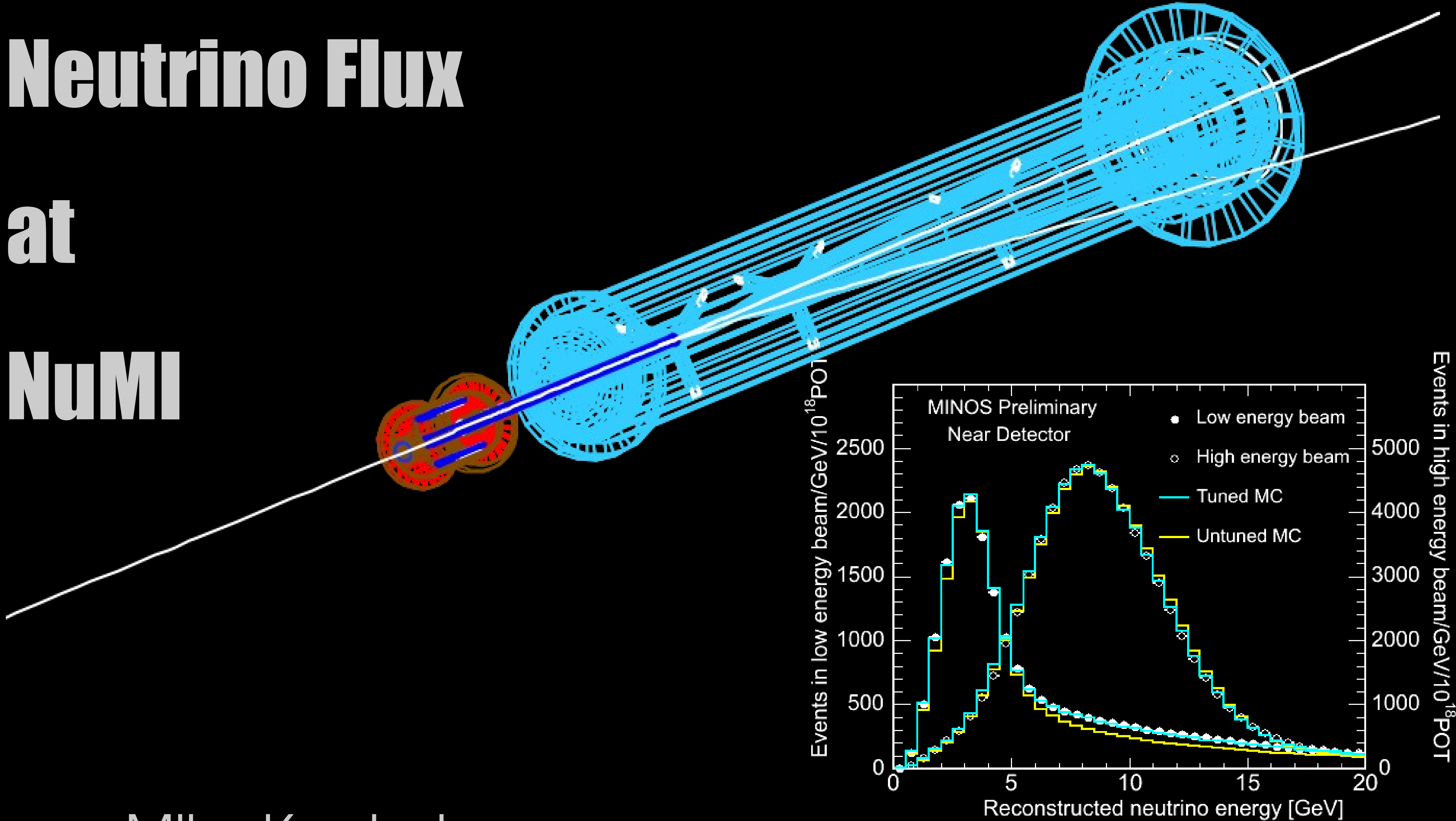
Neutrino Flux at NuMI



Mike Kordosky

William & Mary

August 3, 2011

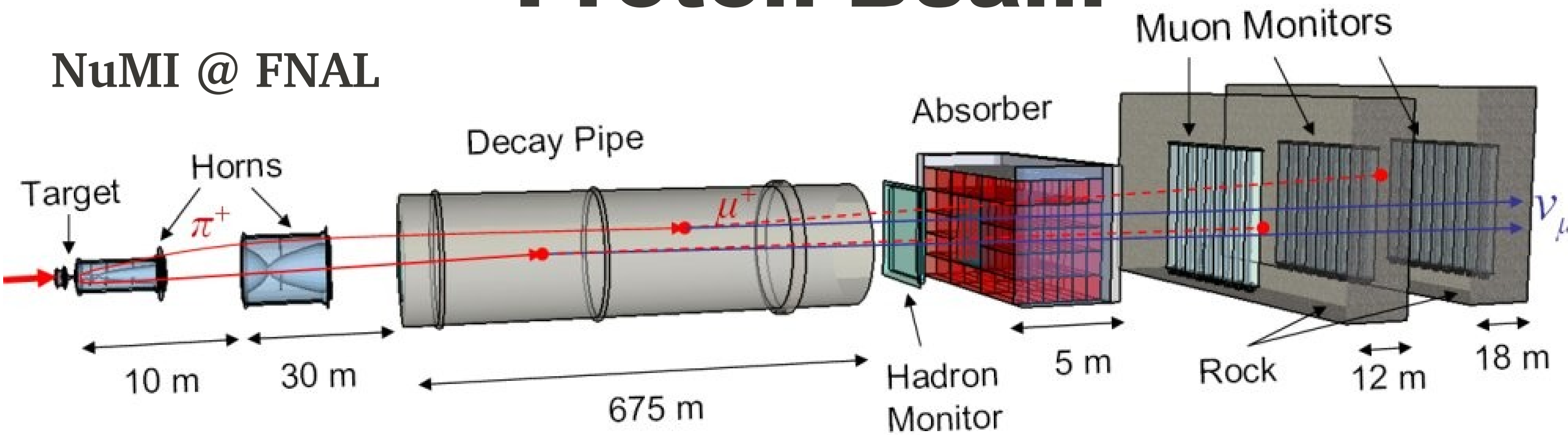
13th International Workshop on Neutrino Factories, Super Beams and Beta Beams
CERN/UNIGE Aug 1-6, 2011

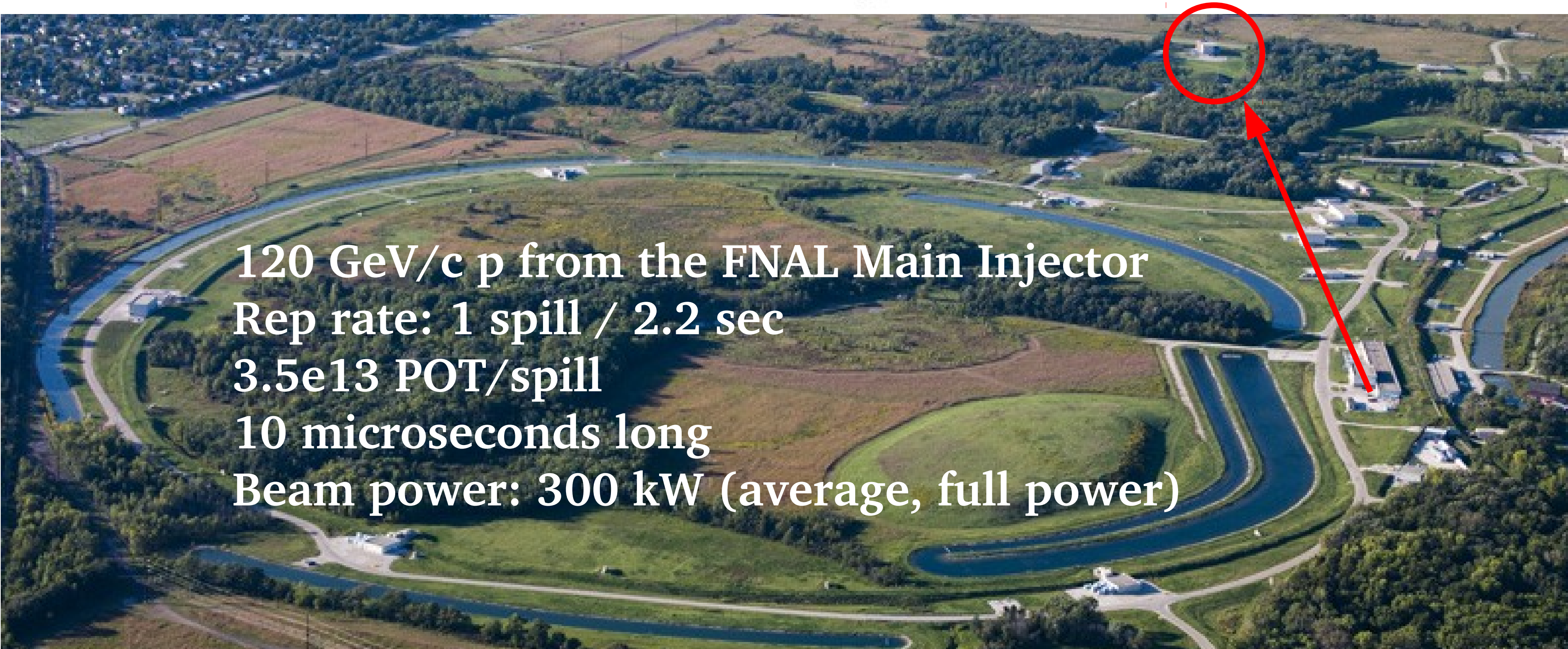
Plan For This Talk

- Description of NuMI
- What things are important for us to understand the flux?
- How well is the flux known *ab initio*?
- How can we improve knowledge and shrink uncertainties?

Proton Beam

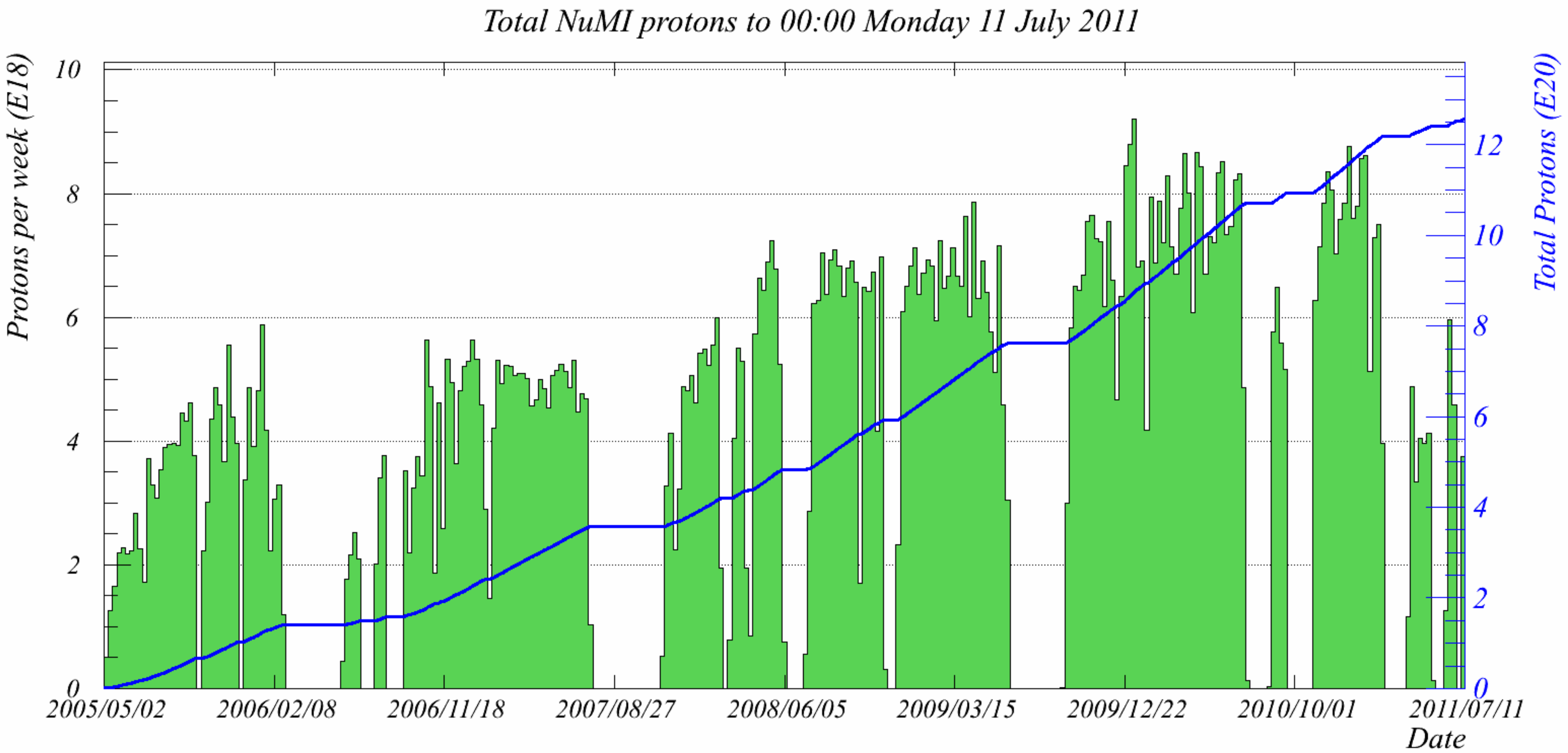
NuMI @ FNAL





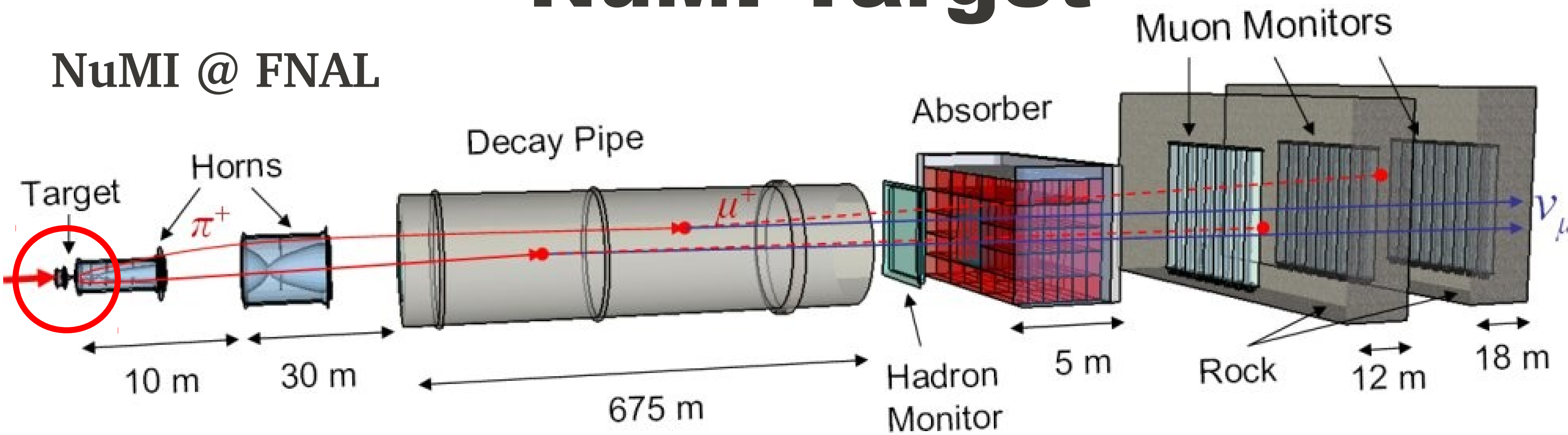
120 GeV/c p from the FNAL Main Injector
Rep rate: 1 spill / 2.2 sec
3.5e13 POT/spill
10 microseconds long
Beam power: 300 kW (average, full power)

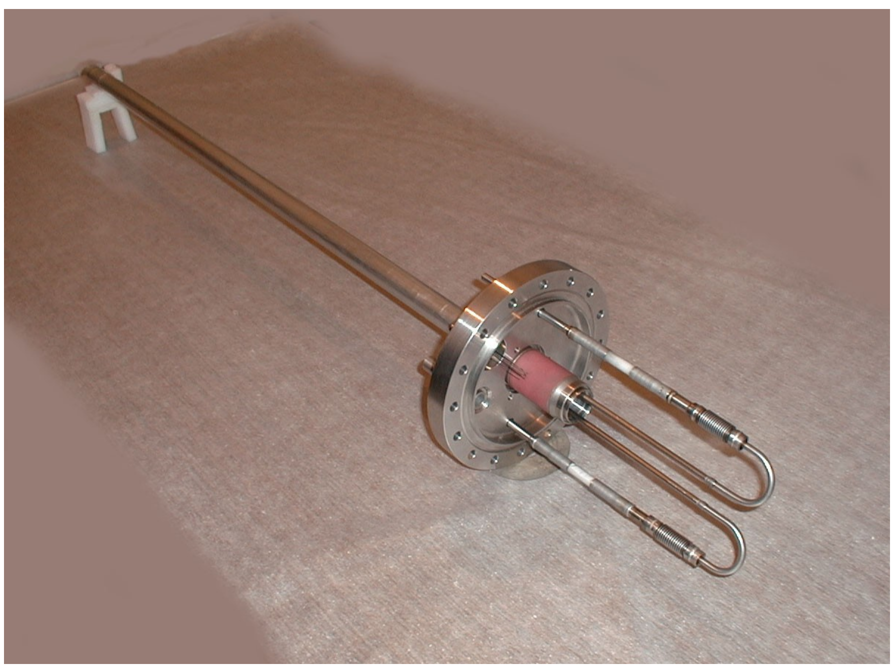
Proton Beam



Total NuMI protons to 00:00 Monday 11 July 2011
Protons per week (E18)
Total Protons (E20)
10
8
6
4
2
0
12
10
8
6
4
2
0
2005/05/02
2006/02/08
2006/11/18
2007/08/27
2008/06/05
2009/03/15
2009/12/22
2010/10/01
2011/07/11
Date

NuMI Target

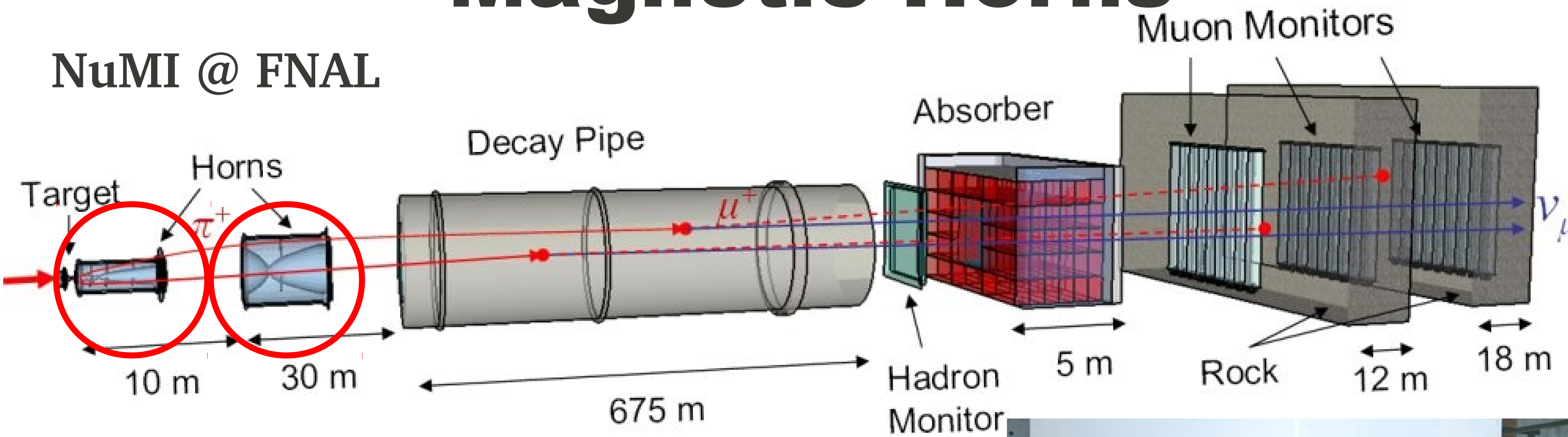


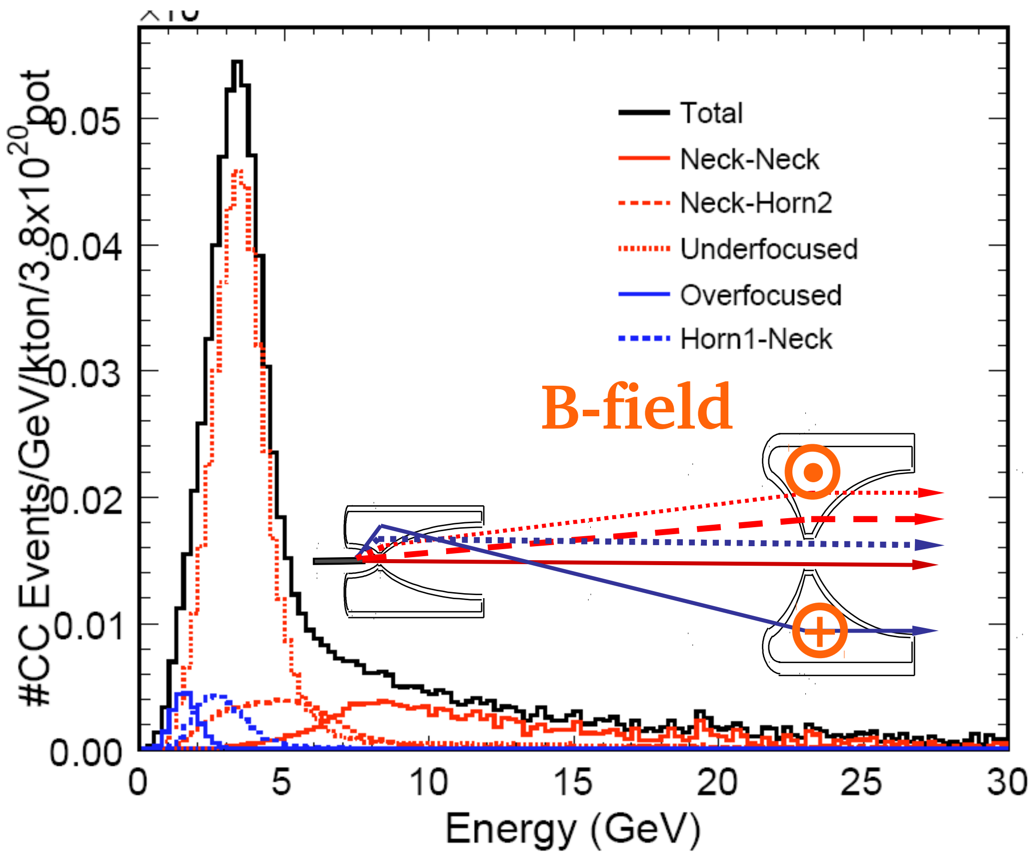


Rectangular graphite rod
6.4mm wide x 15mm high
Segmented in 47 "fins"
Total length 940mm (~2λ)
Water cooled
Enclosed in He filled steel can

Magnetic Horns

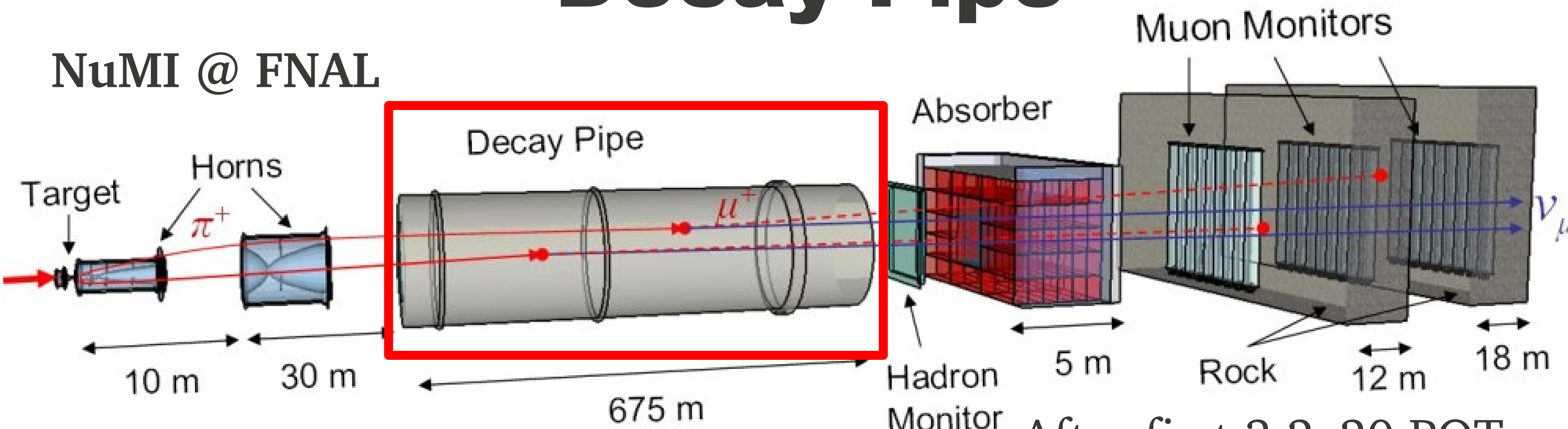
NuMI @ FNAL

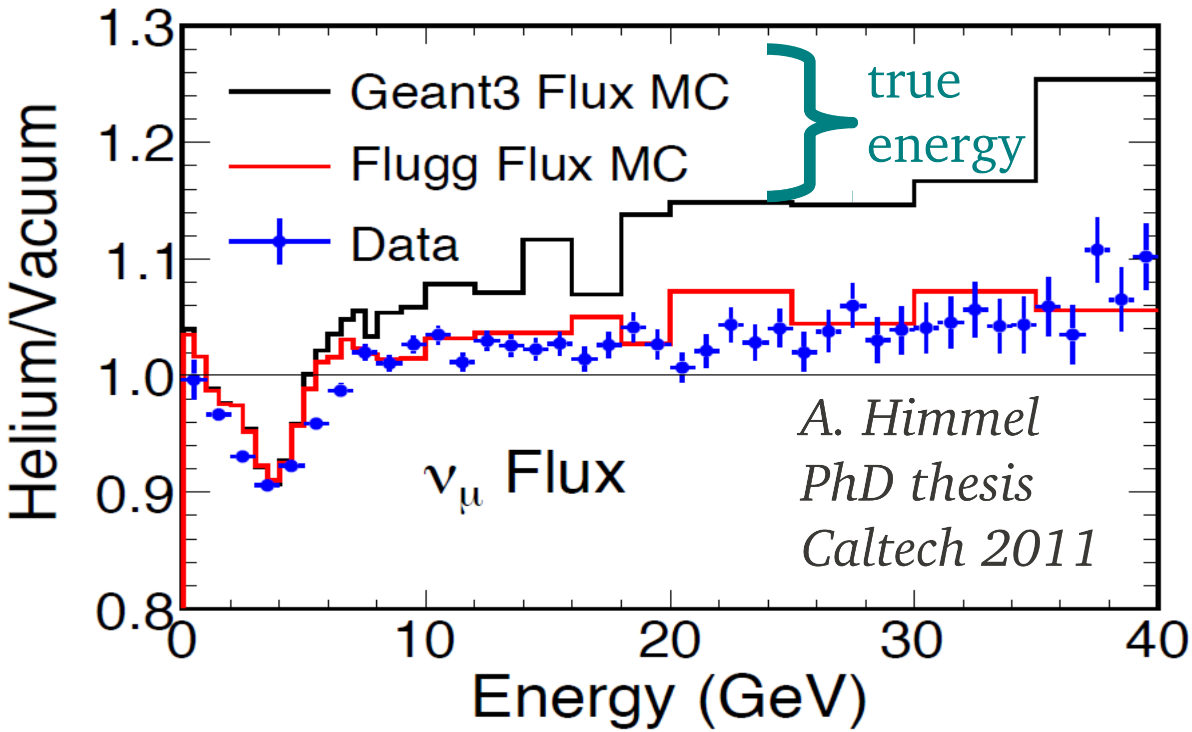




Decay Pipe

NuMI @ FNAL





After first 3.2e20 POT Decay pipe filled with He gas @ 0.9atm, 20^{o}C

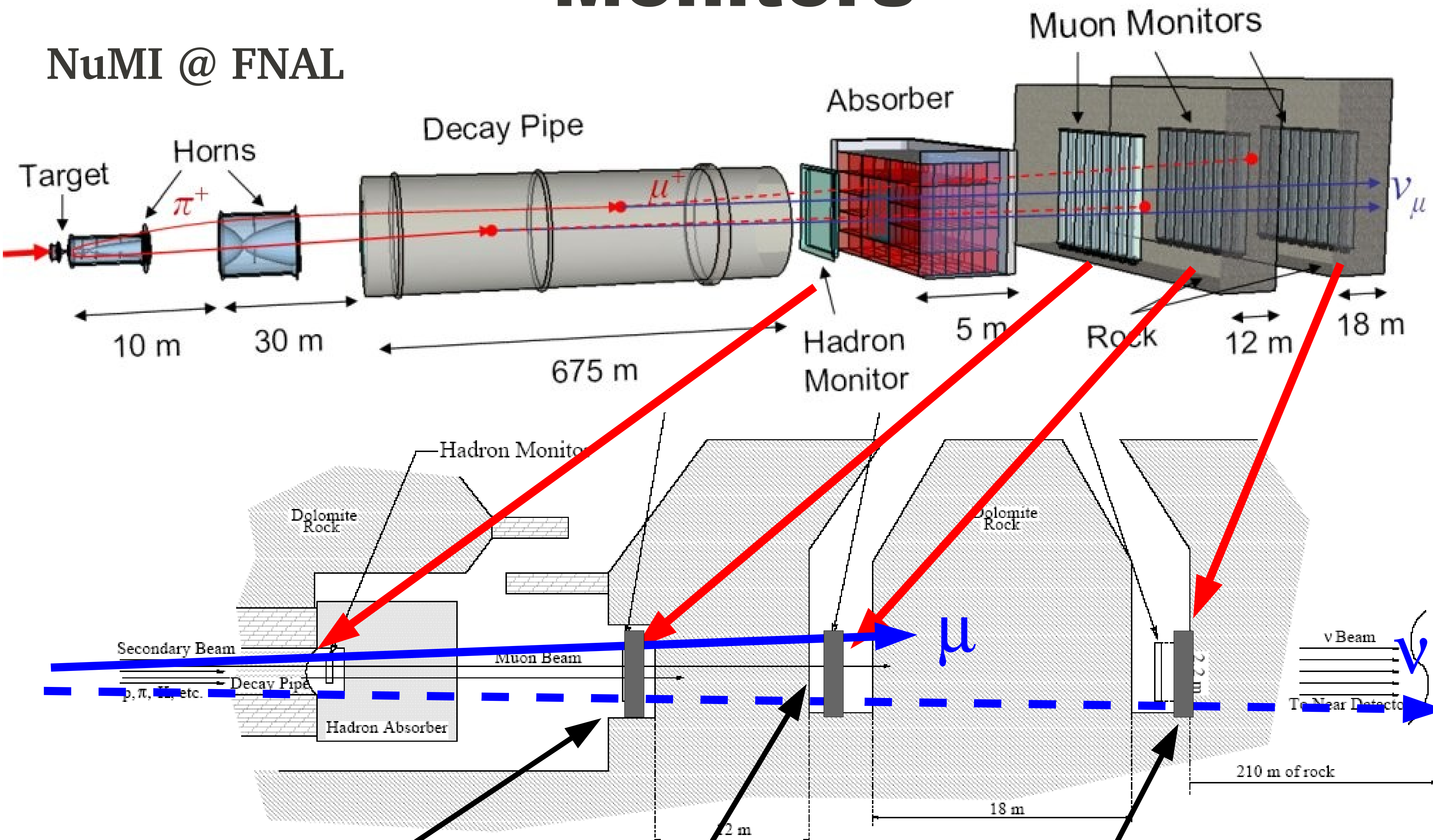
~10% reduction in LE focusing peak

- 1/2 from He
- 1/2 from target decay

~5% increase in HE tail

Monitors

NuMI @ FNAL



E_μ > 4.2 GeV

E_ν > 1.8 GeV

> 11 GeV

> 4.7 GeV

>21 GeV

> 9.0 GeV

Rough Sport

Horns, targets, monitors & windows are consumables of a neutrino experiment

Especially at NuMI

12.3e20 POT @ 120GeV/c

Components encounter:
High radiation, thermal stress, mechanical stress, water leaks

Targets Replaced

1 – → – *Resurrected, died again*

2 – → – *Took 6e20 POT, back again*

3 –

4 –

5 –

6 –

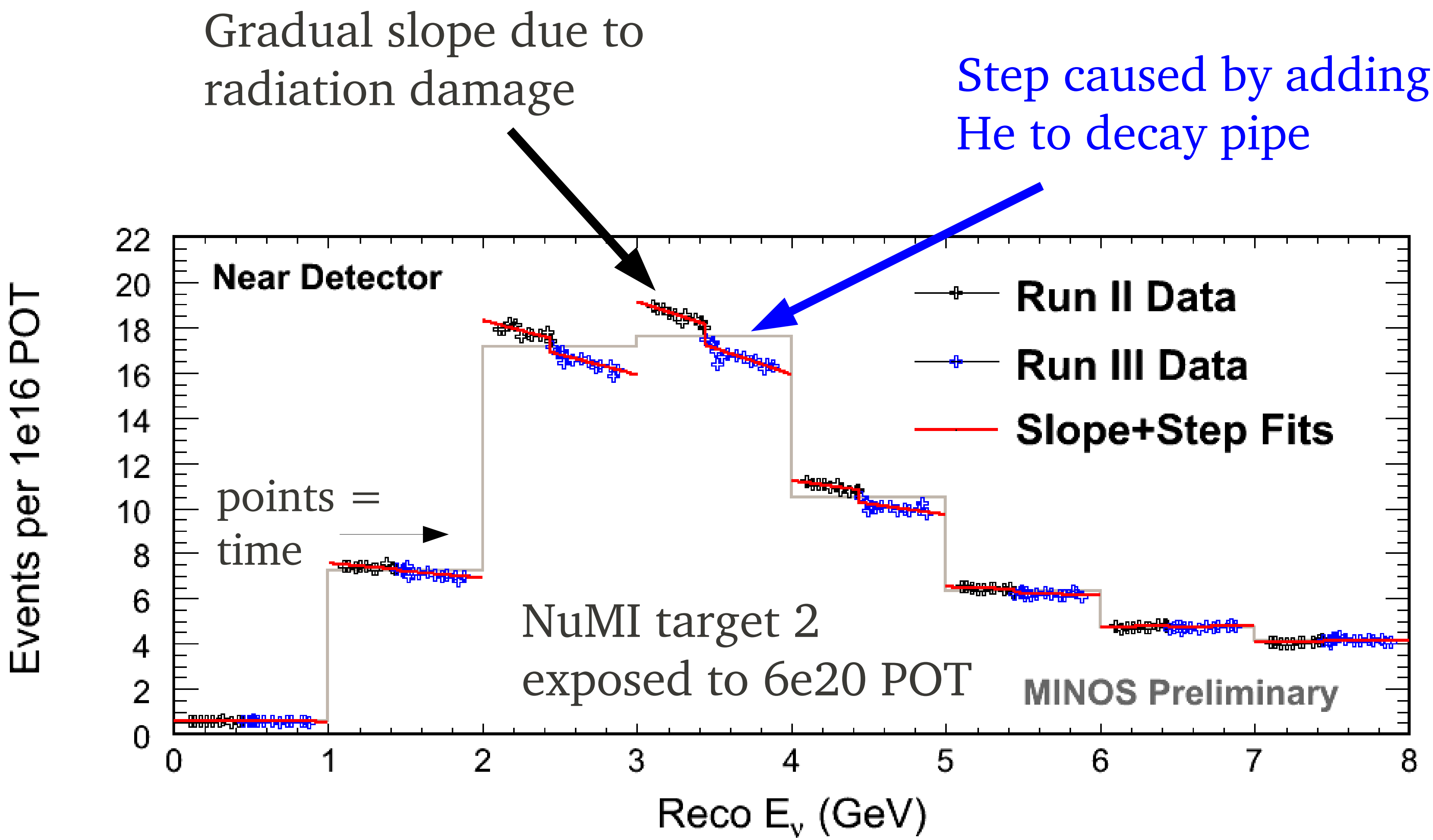
Horns Replaced

Hadron Monitors Replaced

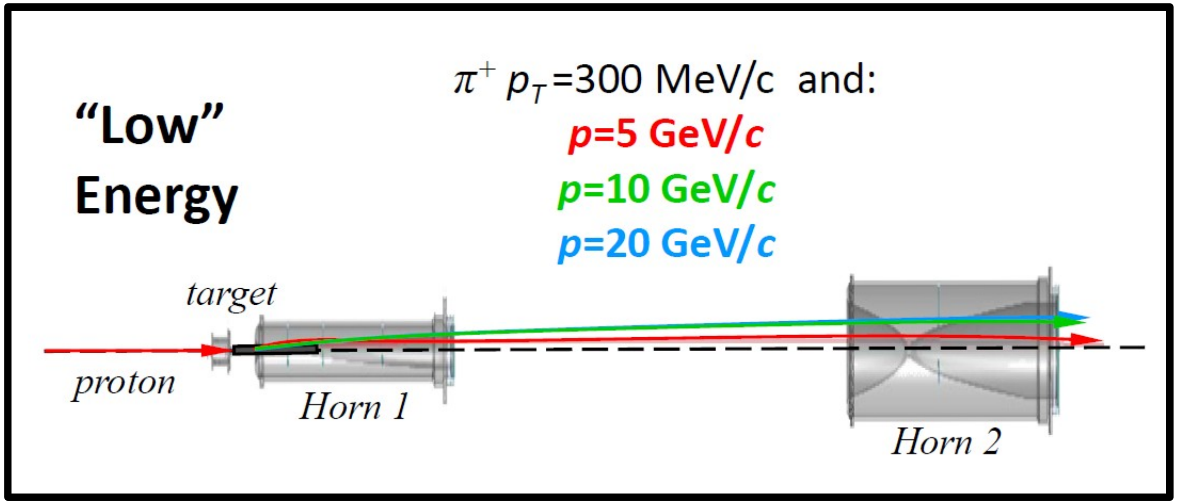
The Ultimate Monitor...

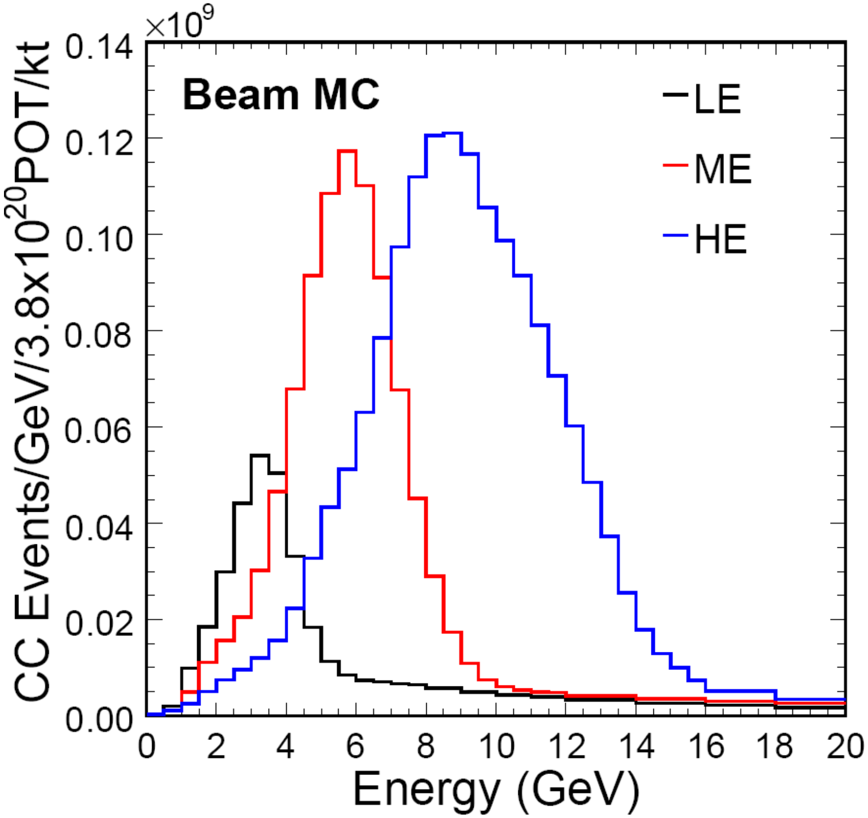
...is a neutrino detector.

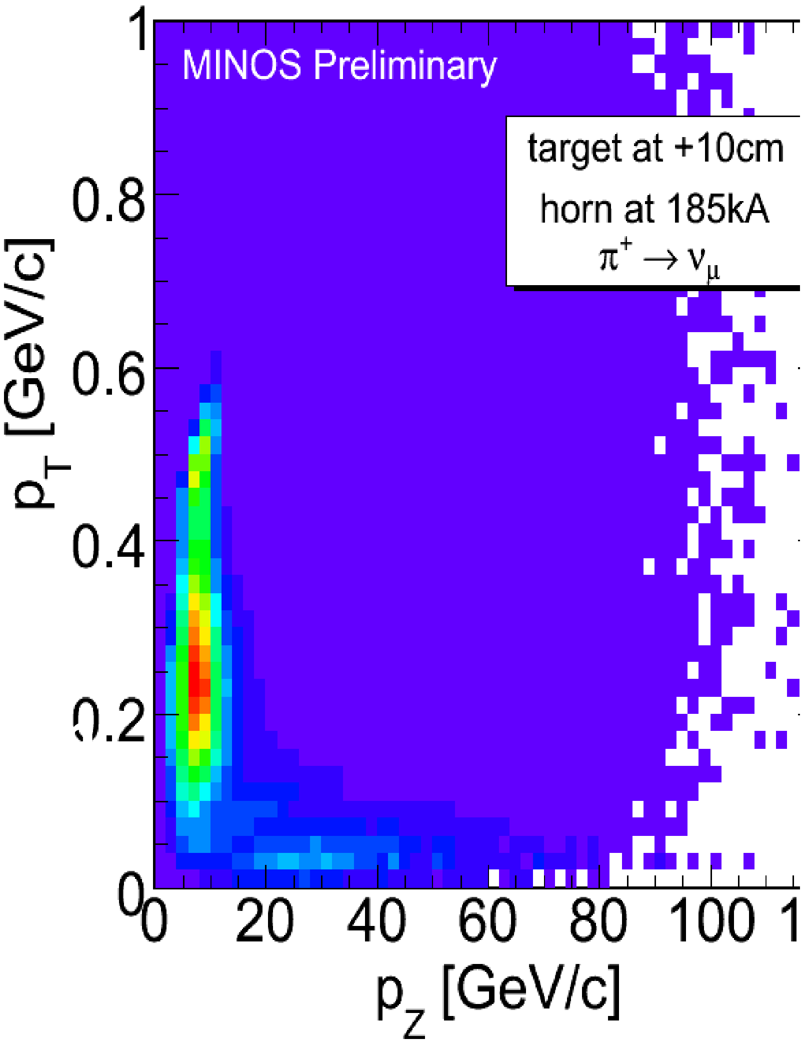
Wear and Tear



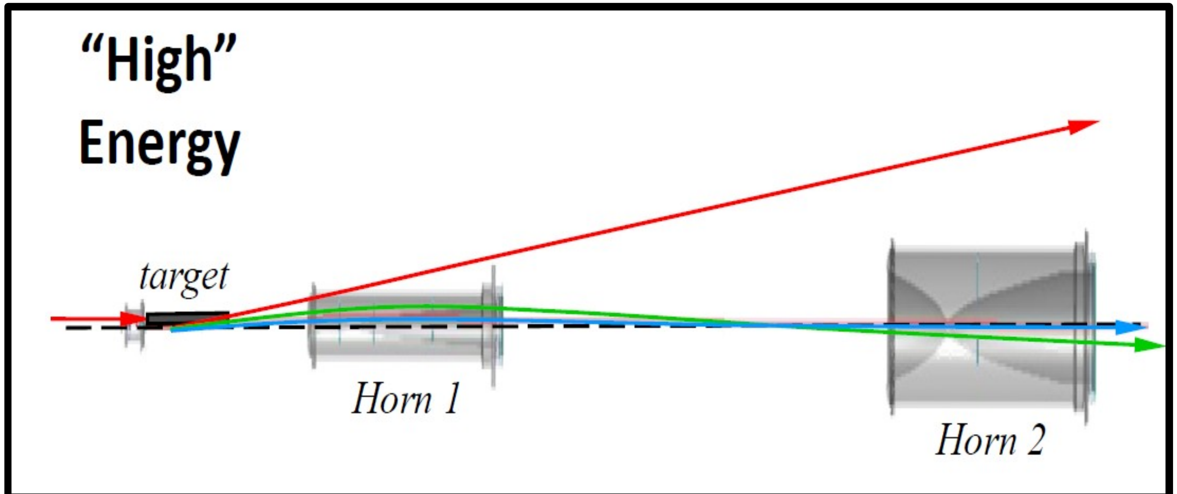
Focusing & (p_T,p_z)

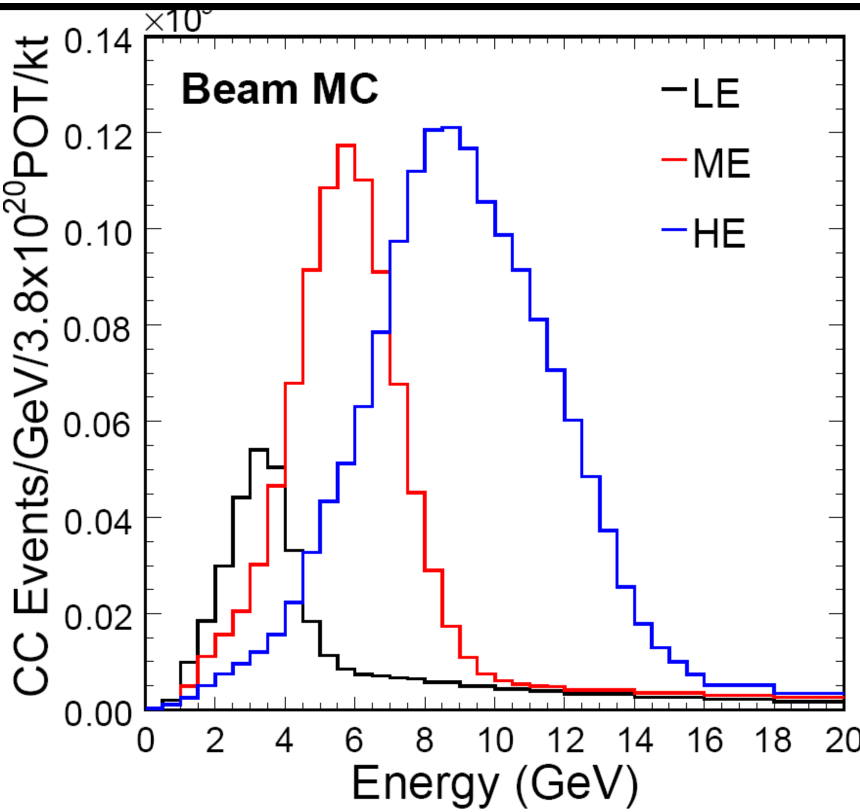


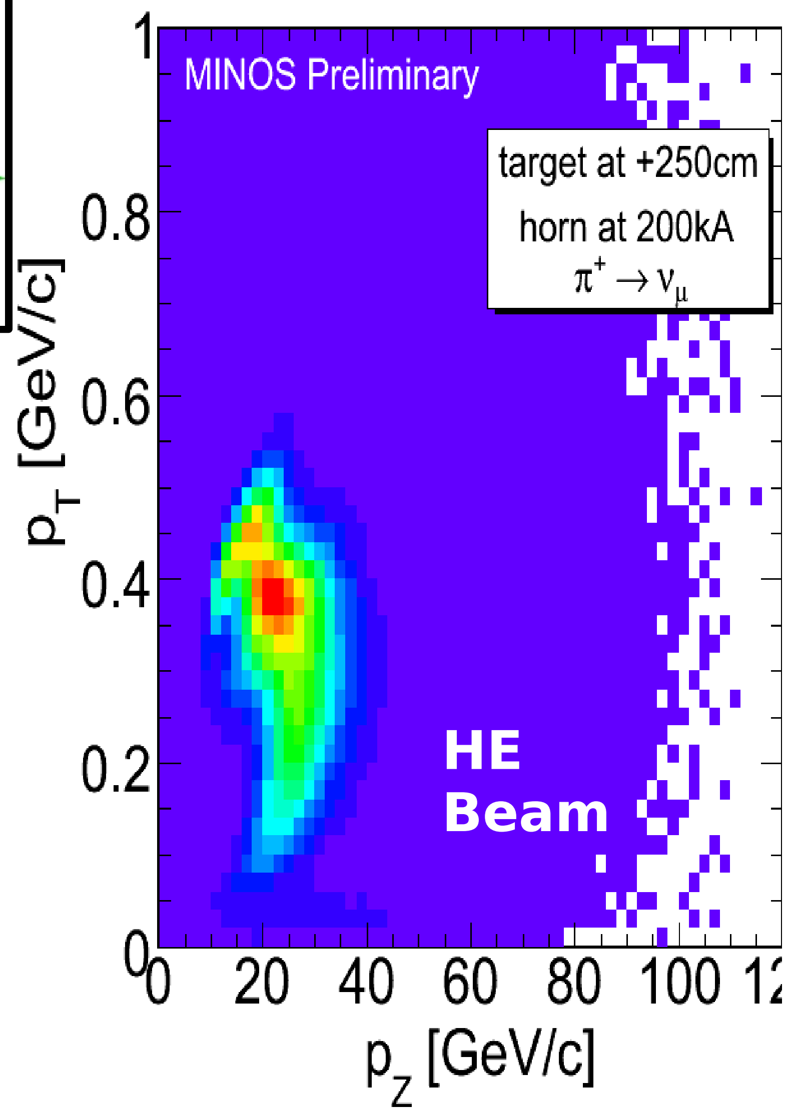




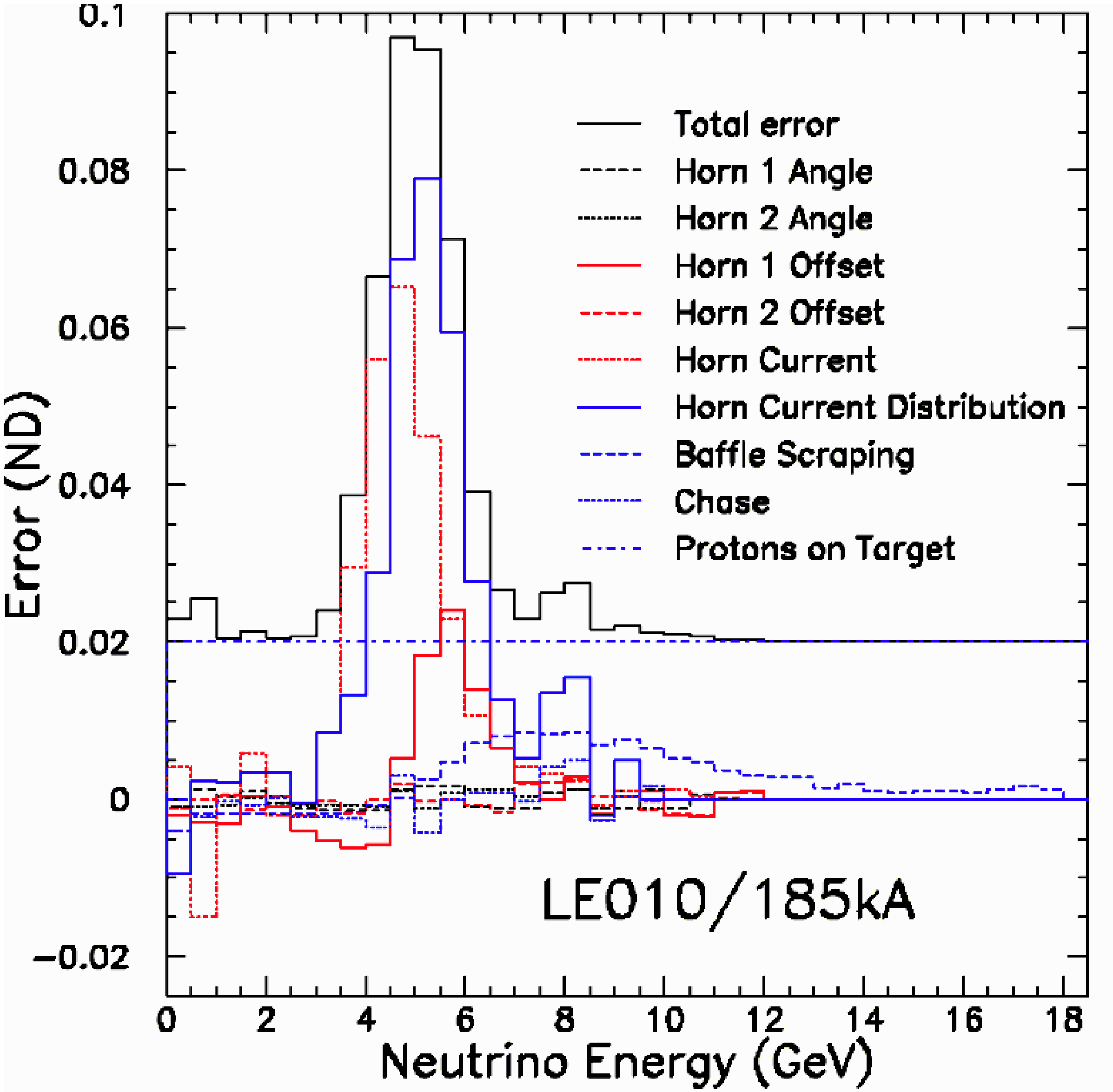
Focusing & (p_T,p_z)







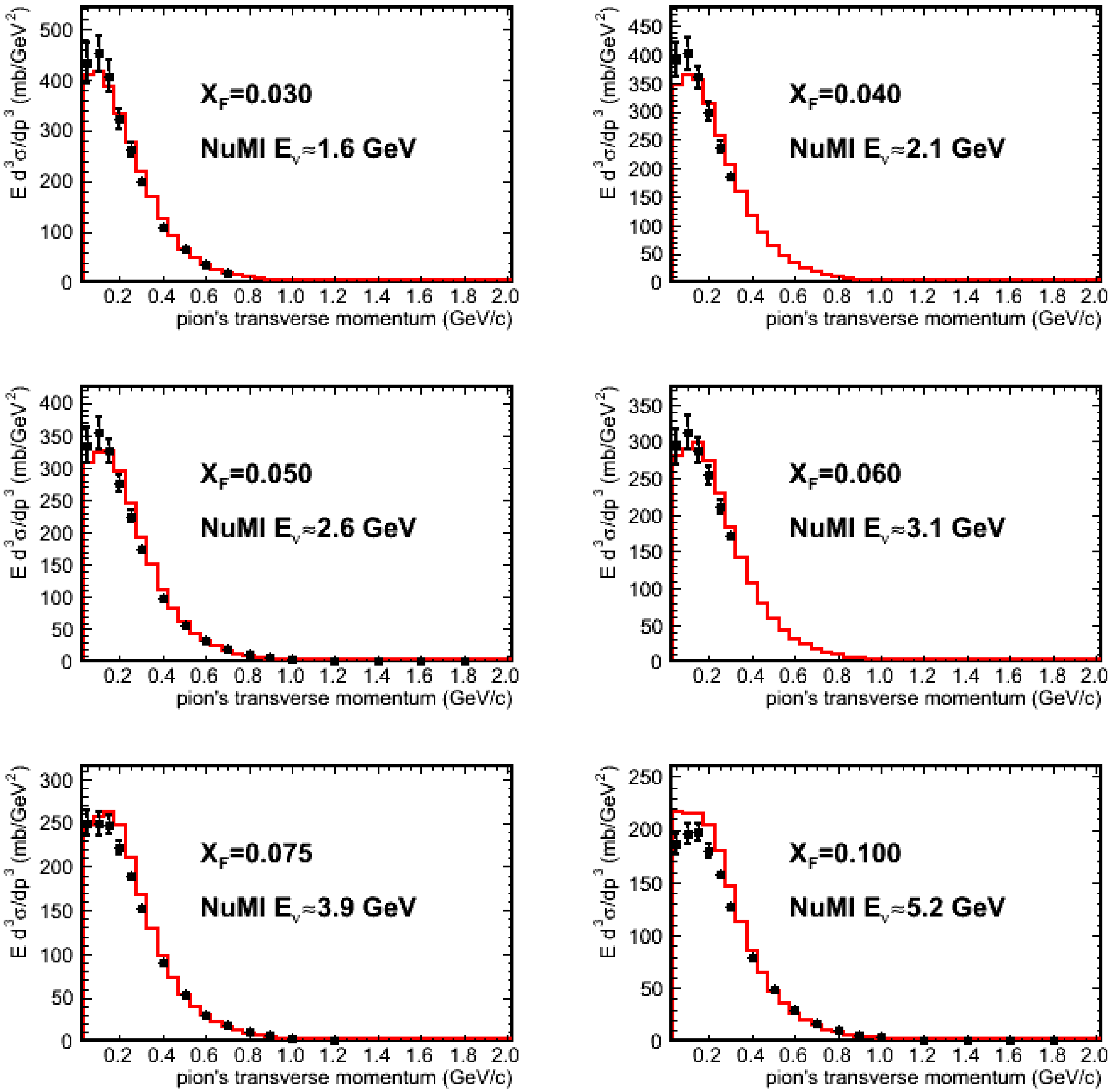
Focusing uncertainties



[Beam Optics]

Z. Pavlovich, "Observation of disappearance of muon neutrinos in the NuMI beam",
PhD thesis, UT Austin 2008

Hadron production uncertainties



Agreement between MC models and data

Fluka2005 vs NA49

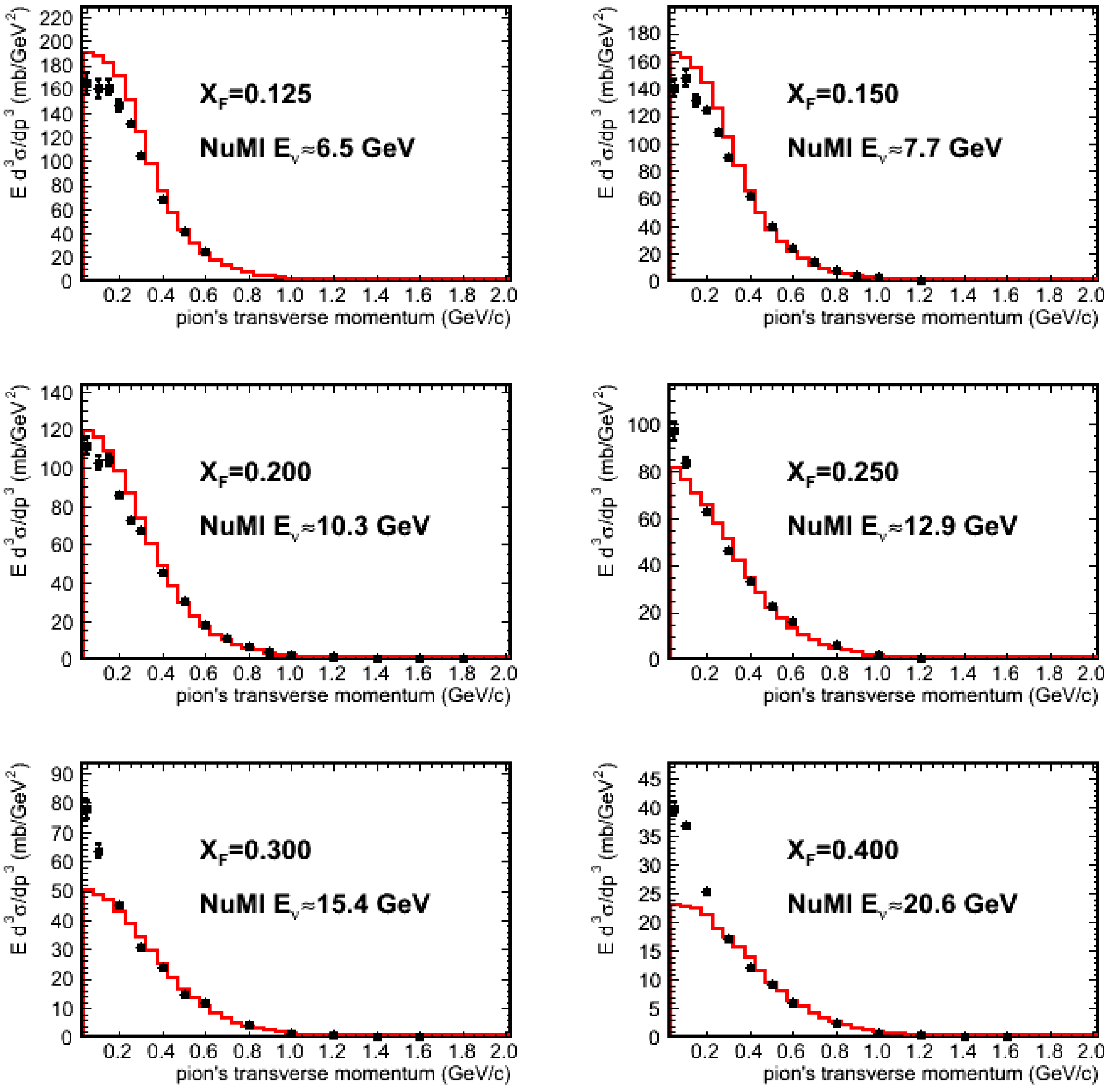
$pC \rightarrow \pi^+X$ @158 GeV/c

Eur.Phys.J. C49 (2007) 897-917

"The FLUKA code: Description and benchmarking"
G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso`, J. Ranft,
AIP Conference Proceeding 896, 31-49, (2007)

"FLUKA: a multi-particle transport code"
A. Fasso`, A. Ferrari, J. Ranft, and P.R. Sala,
CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773

Hadron production uncertainties



Agreement between MC models and data

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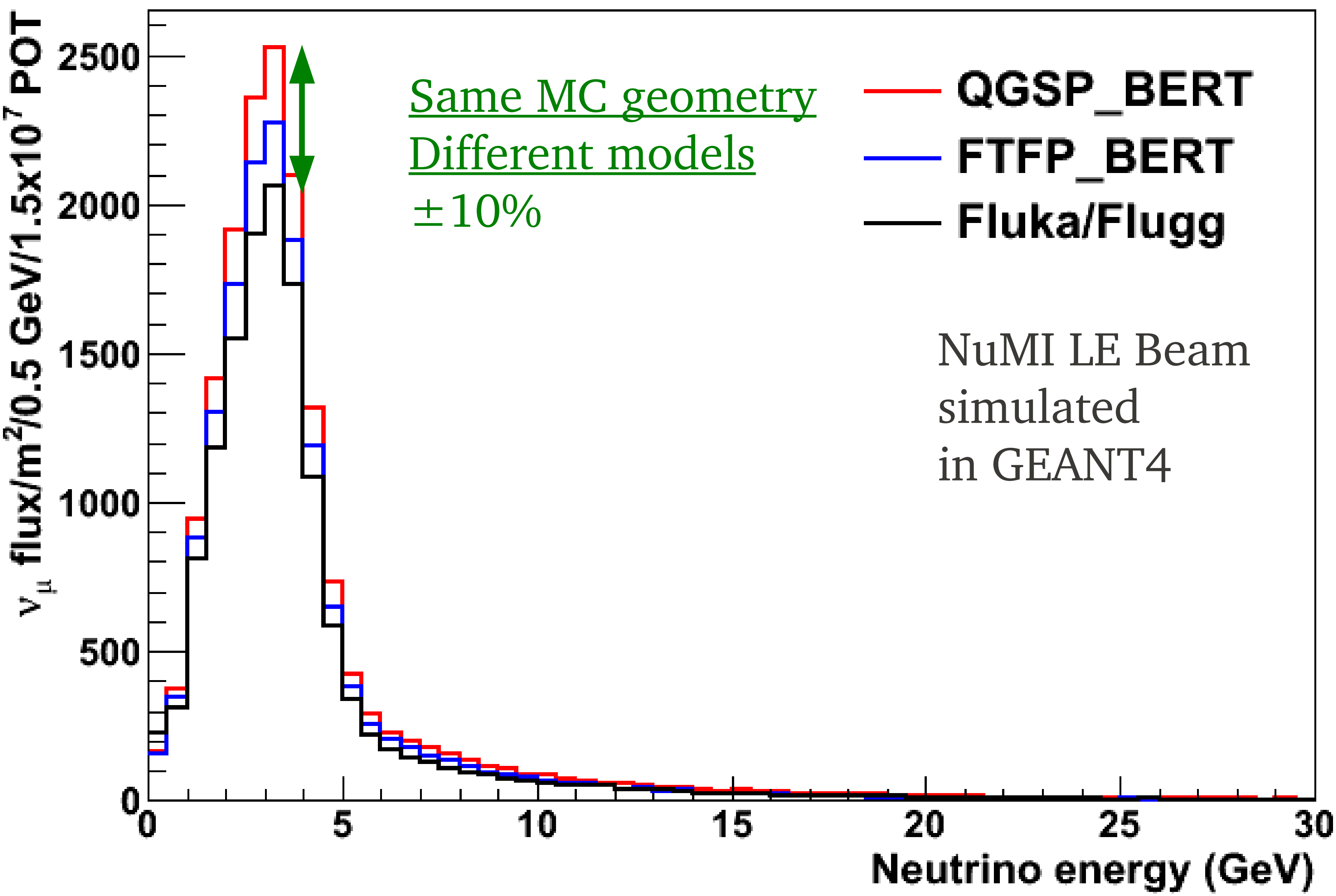
Hadron production uncertainties



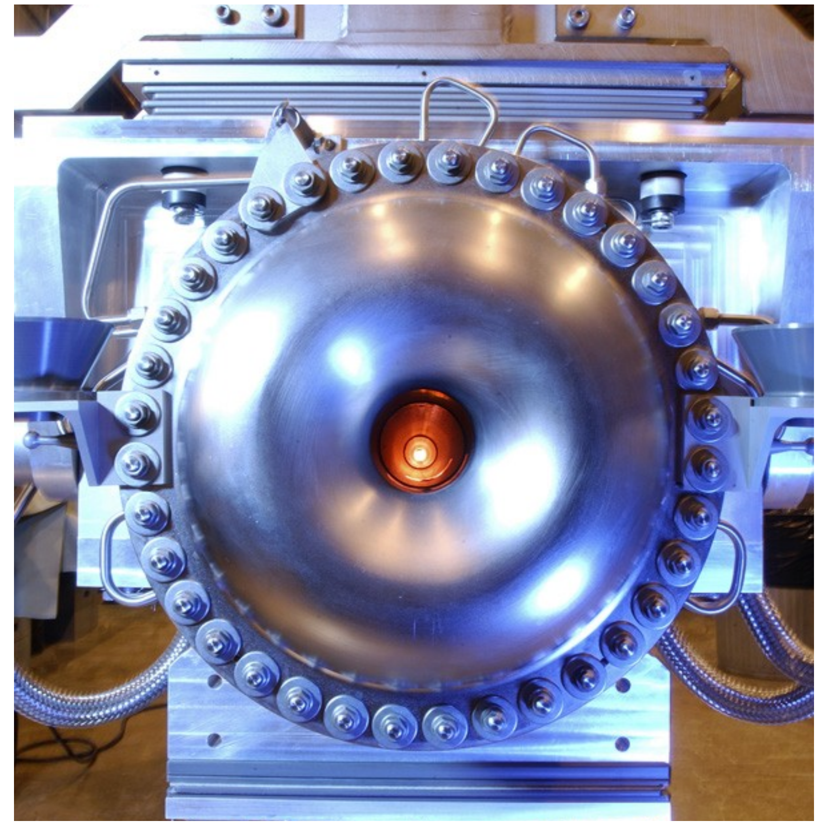
Where are mesons created?

Geant4 based simulation of the NuMI beamline

Z. Pavlovic, L. Loiacono, J. Ratchford, J. Koskinen, M. Jerkins, T. Le, et al.

Origin of π^+ which produce ν_μ hitting MINOS/MINERvA

Target Fins (84.4%) + "Budal" Monitor (4.6%) [C]	89.0%
Decay Pipe Walls [Fe]	2.6%
Target Hall Chase [air]	2.2%
Decay Pipe [He]	1.8%
Horn 1 Inner Conductor [Al]	1.5%
All other summed	2.9%



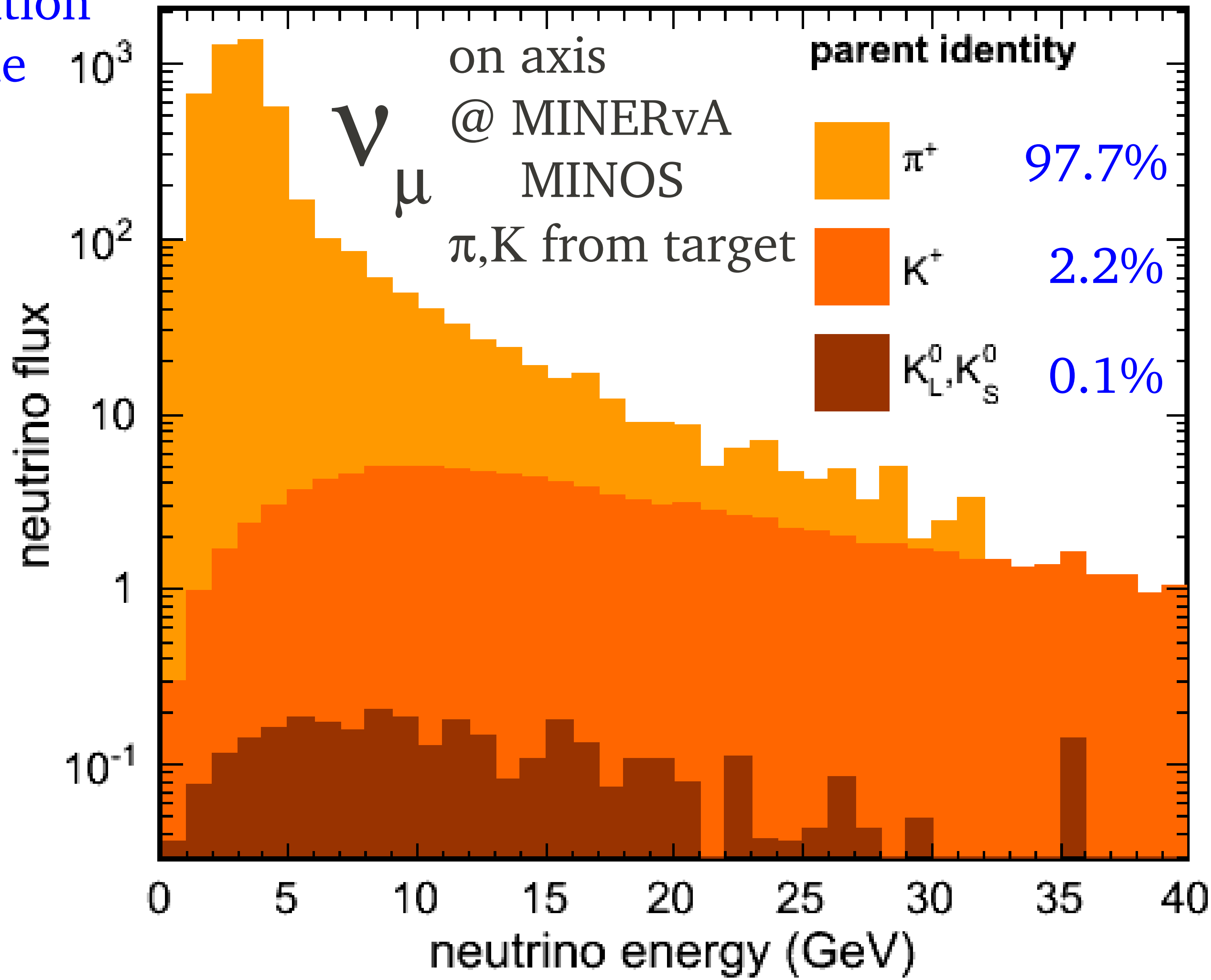
Predicted Neutrino Flux

Geant4 based simulation of the NuMI beamline

Z. Pavlovic, L. Loiacono, J. Ratchford, J. Koskinen, M. Jerkins, T. Le, et al.

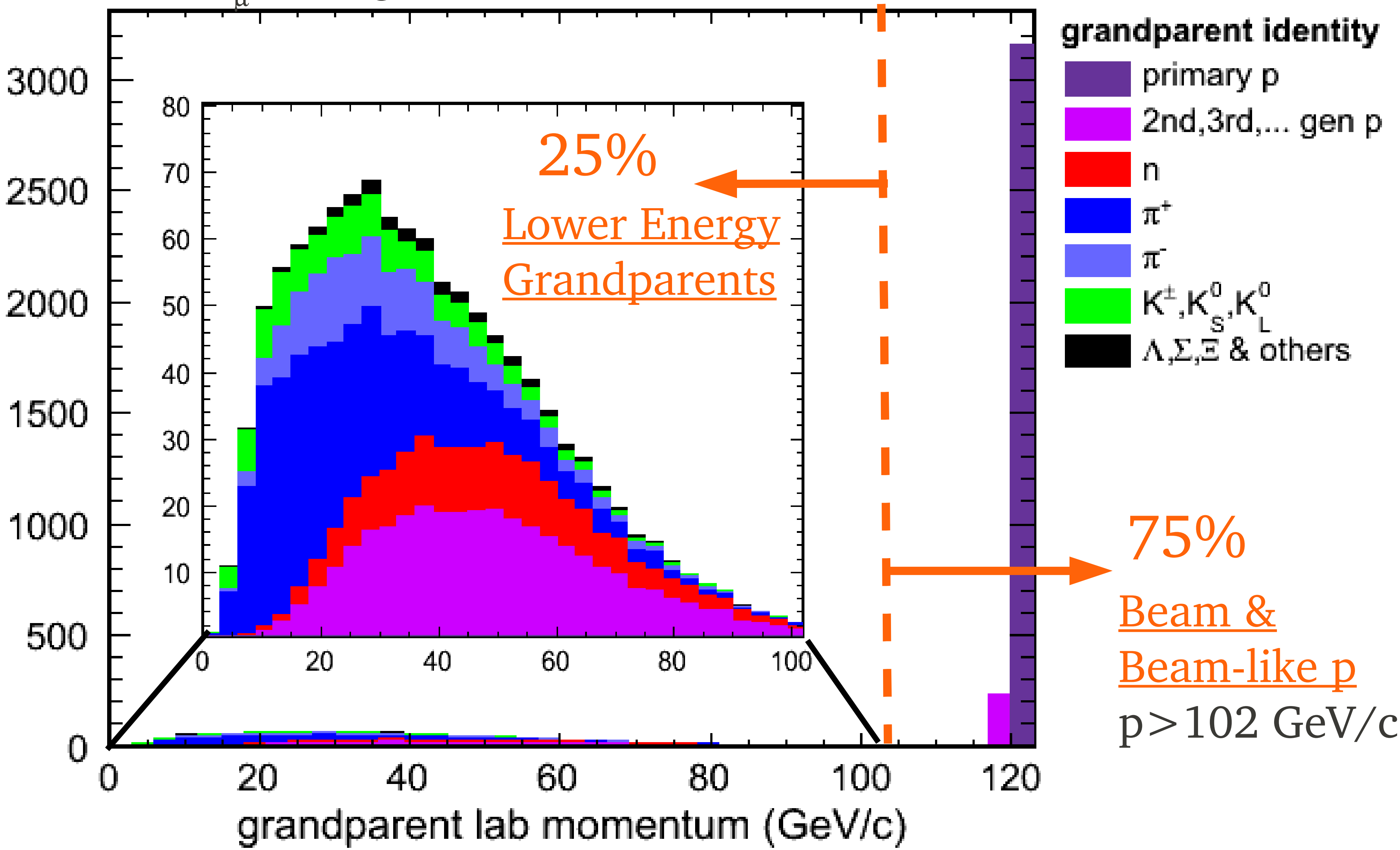
Event Rate

$\sim$50k ν_μ-CC for 1t plastic and 1×10^{20} POT

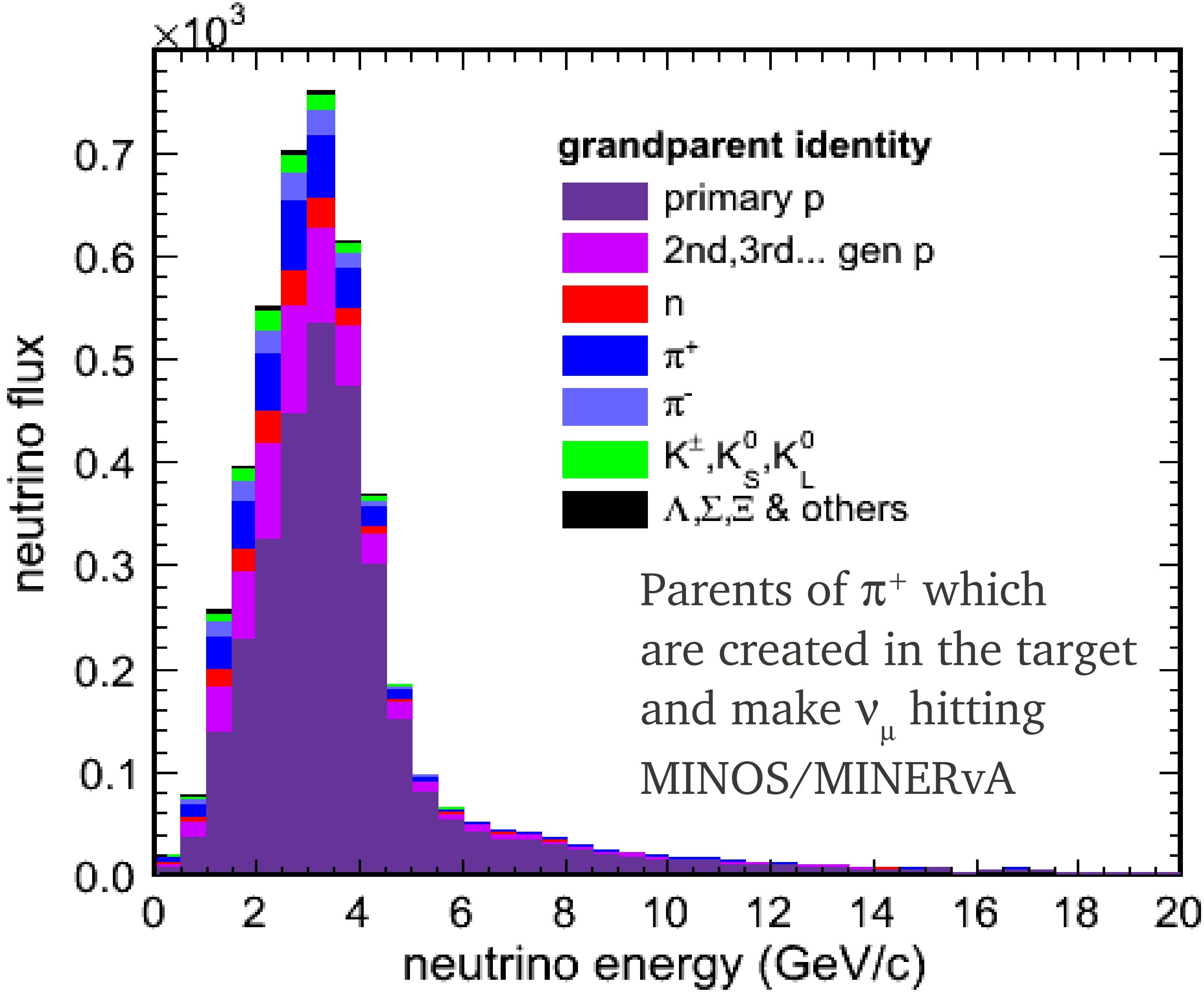


Neutrino grandparents?

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

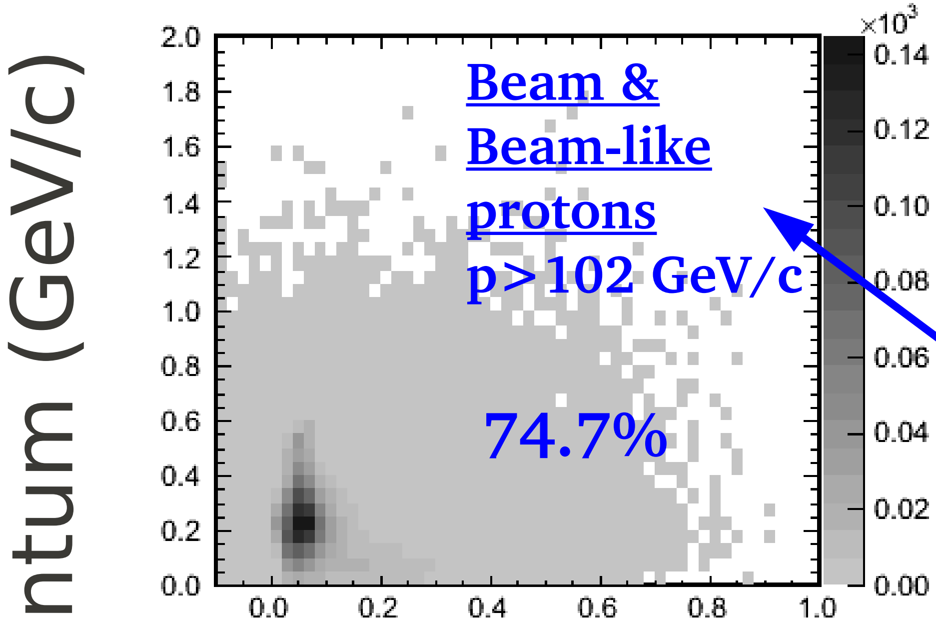


Neutrino grandparents?



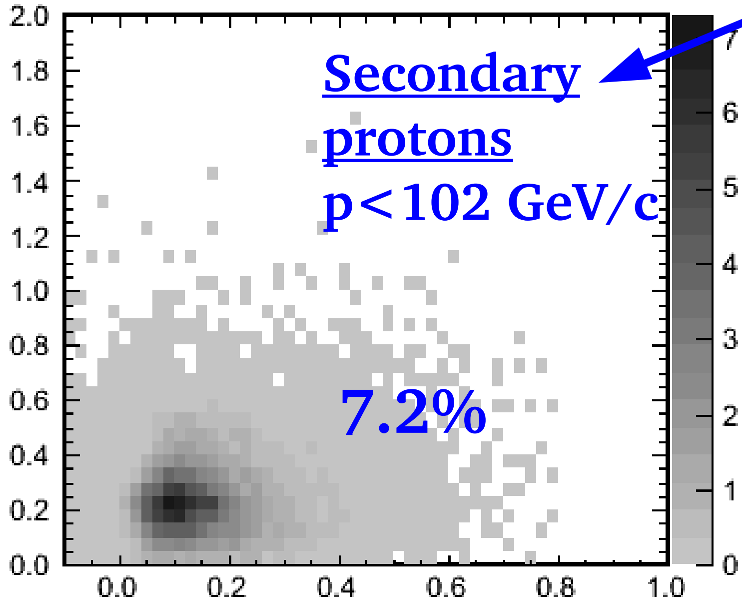
Parents of π^+ which are created in the target and make ν_μ hitting MINOS/MINERvA

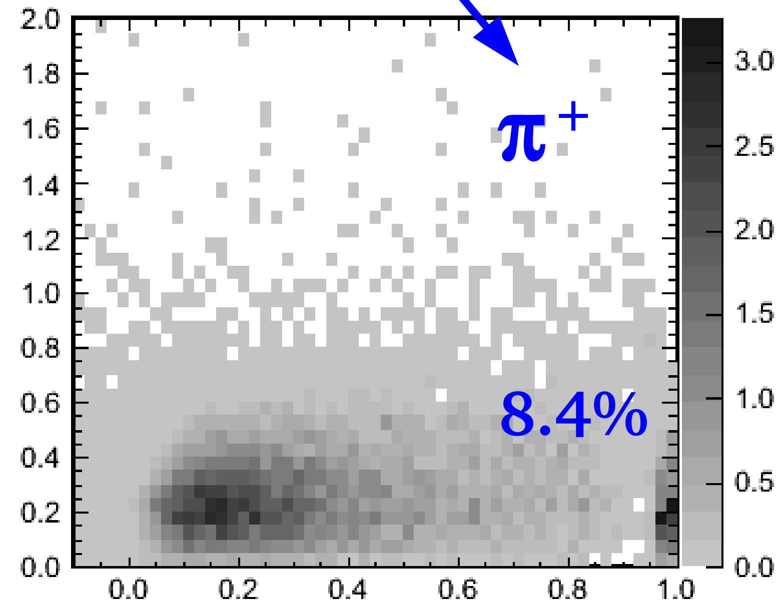
x_F p_T of π^+ neutrino parents



Three largest grandparent components

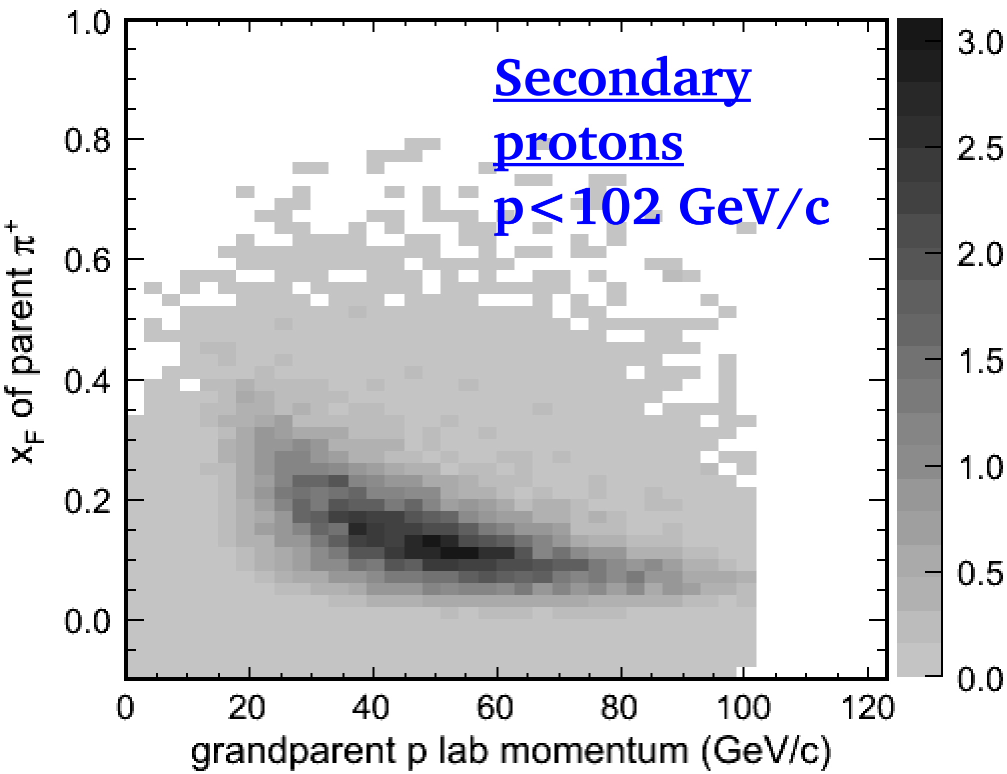
% of ν_μ

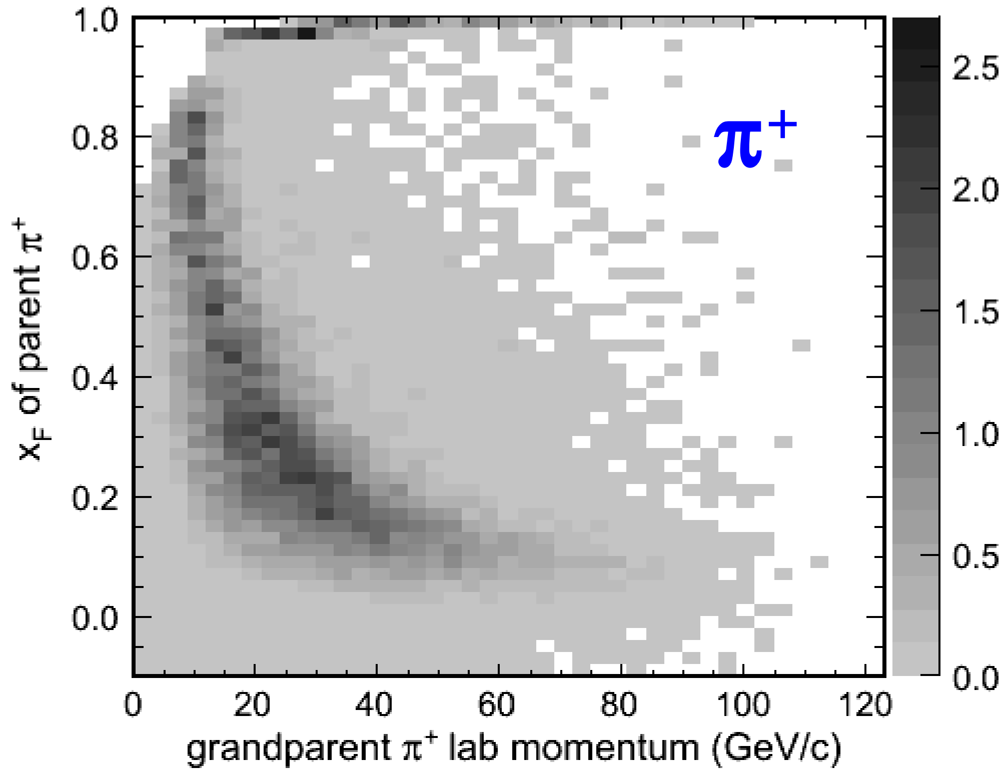




x_F

Relating x_F and grandparent p_{LAB}





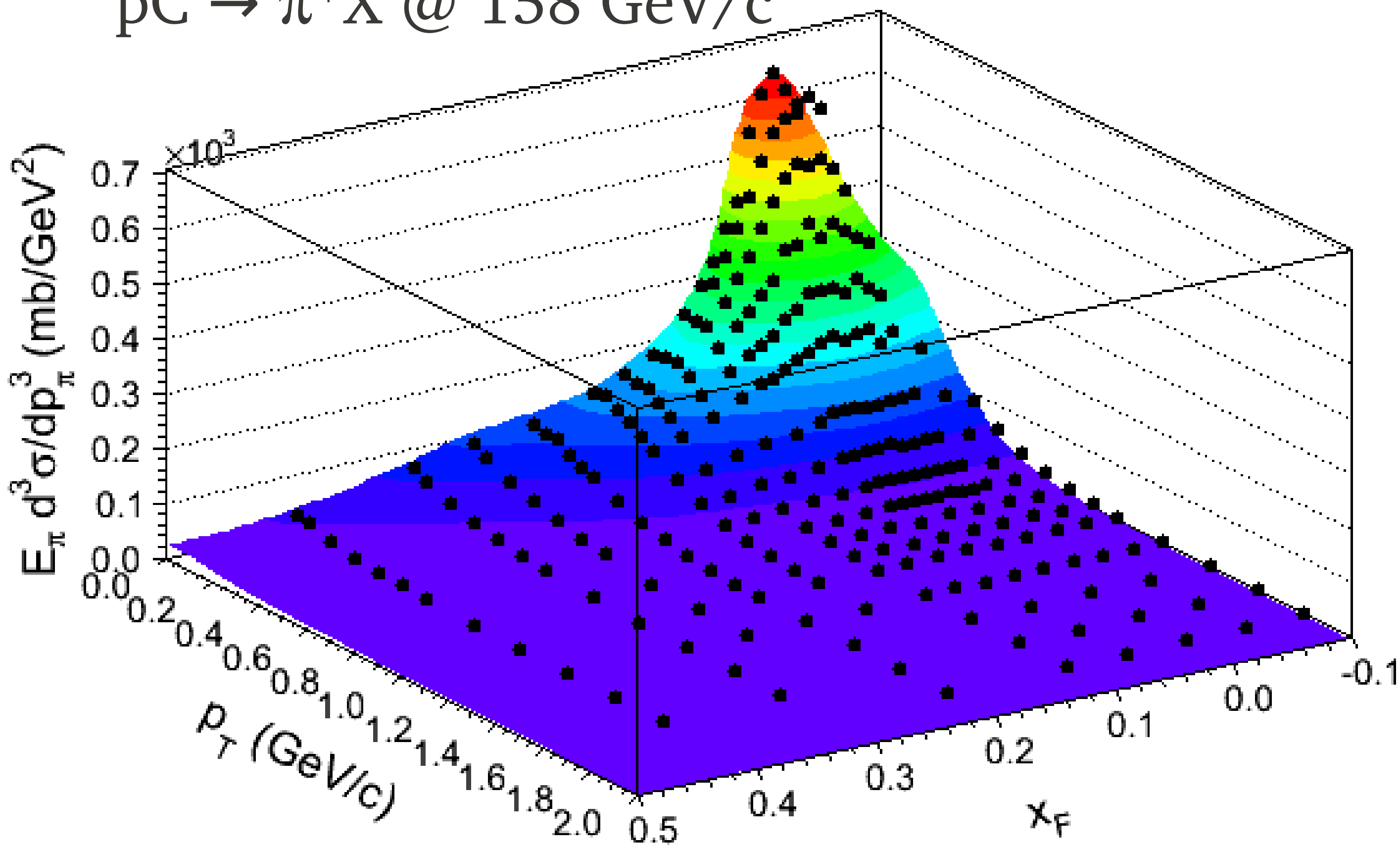
A few conclusions

- Mesons produced in the target decay to give you ~90% of ν_μ observed at MINOS/MINERvA
- For E_ν<20 GeV almost all those mesons are π^+
- 75% of target π^+ are produced directly by protons at ~ 120 GeV
- The remaining 25% are produced by lower energy pions and nucleons and are most important in the focusing peak
- What HP measurements are most helpful? → π off of replica target!
- Failing that:
  - pC → πX at **p**≈120 GeV/c → NA49 @ 158 GeV/c very useful
  - pC → pX at **p**≈120 GeV/c and $0.25<x_F<0.6$ → did NA49 collect this data?
  - pC → πX at 20<**p**<70 GeV/c and $x_F\approx0.1$ → T2K running @ NA61 may be useful
  - πC → πX at 10<**p**<40 GeV/c → did NA61 collect this data?

Using hadron production data

NA49 data
pC → π^+X @ 158 GeV/c

Eur.Phys.J. C49 (2007) 897-917



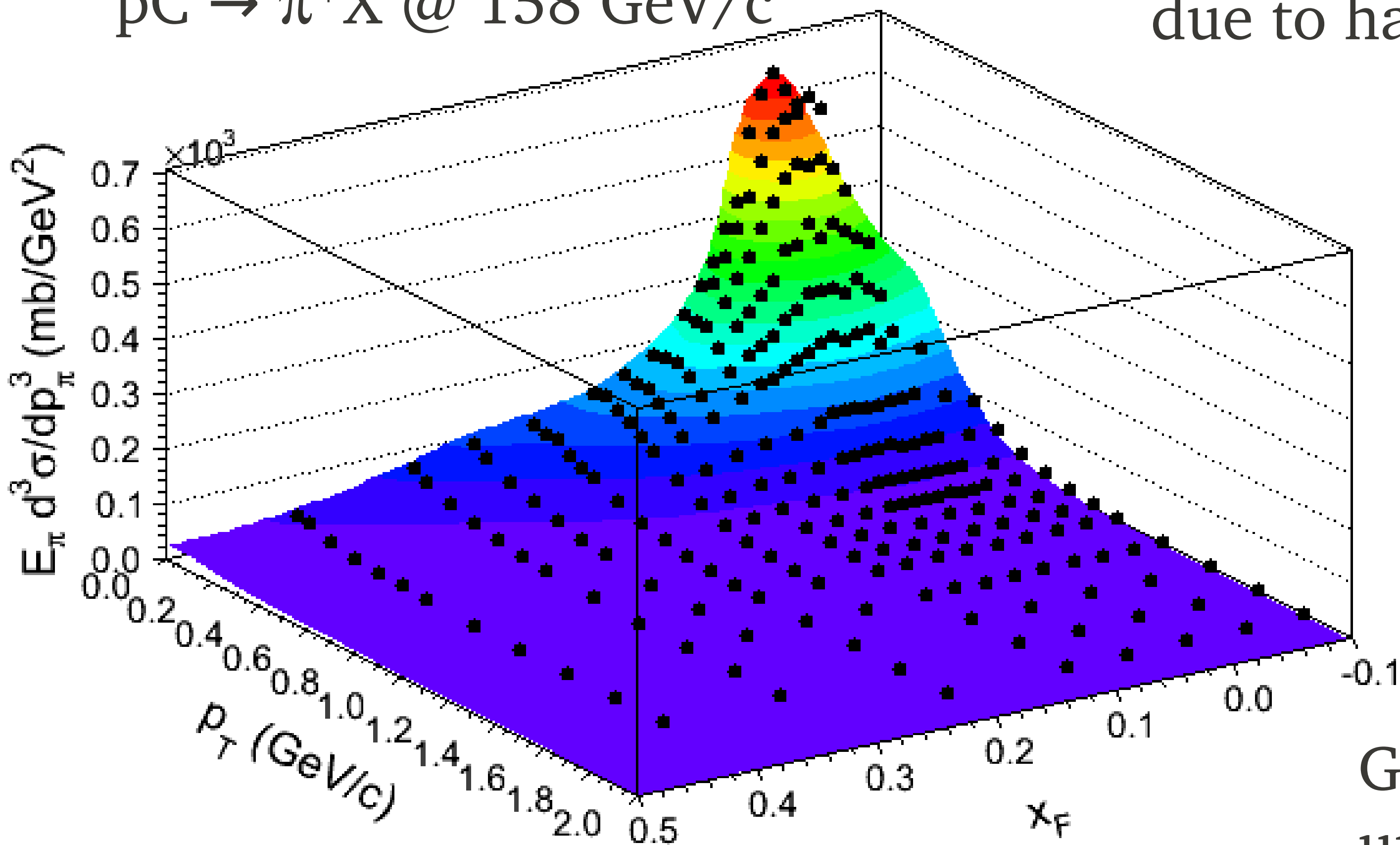
NA49 invariant σ interpolated in 2D

Build similar surface for default model (Fluka, G4, etc)

Weight events using ratio of the two

Using hadron production data

NA49 data
pC → π^+X @ 158 GeV/c



Possible to estimate, event by event, the uncertainty due to hadron production.

Record relevant NA49 bin, then vary bin scales according to NA49 uncertainties.

Correlated?
Uncorrelated?

Gets you some of the uncertainty.

Using hadron production data

typical tertiary π production chain

p(120GeV) C → p(60 GeV) X W_1, σ_1

↓

p(60 GeV) C → π(10 GeV) X' W_2, σ_2

↓

π(10 GeV) → μ ν(4 GeV)

Need to record the full history of each neutrino

HP weight for each stage.

Uncertainty at each stage, if possible.

Do our best with existing thin target data.

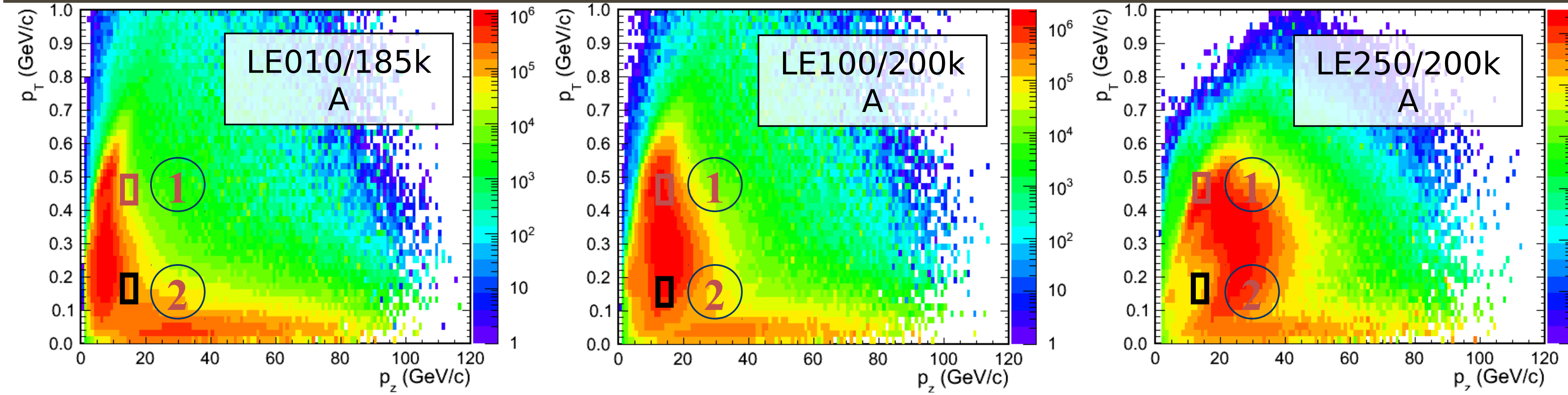
Evaluate the need for thick target and/or other measurements.

Using hadron production data

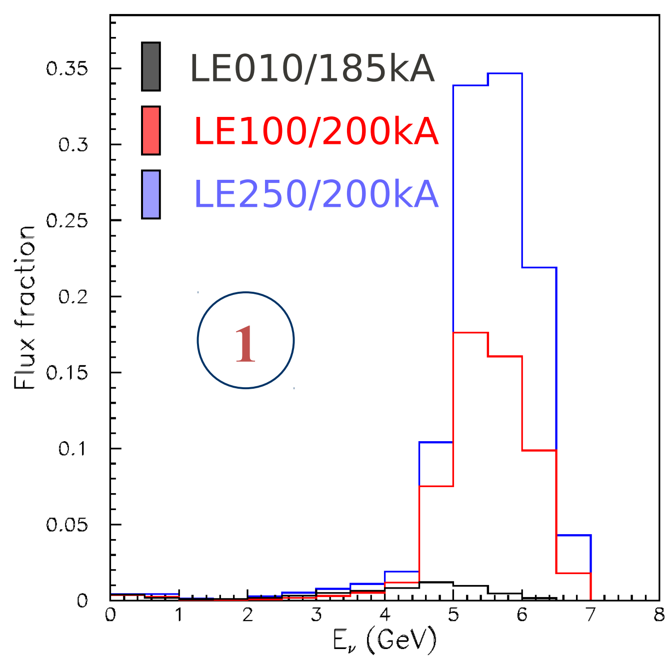
- NA49 data at 158 GeV/c available for π and K
  - But, coverage in x is not complete. What to do?
  - Secondary nucleons are important. Data?
- How to best leverage existing measurements?
  - If I have a measurement of $pA \rightarrow \pi X$ @ Z GeV does this help me with $pA' \rightarrow \pi X$ @ Z' GeV?
  - If so, how? What is the best way independent way of connecting $A \rightarrow A'$, $Z \rightarrow Z'$?
  - And, how do I get an error bar?

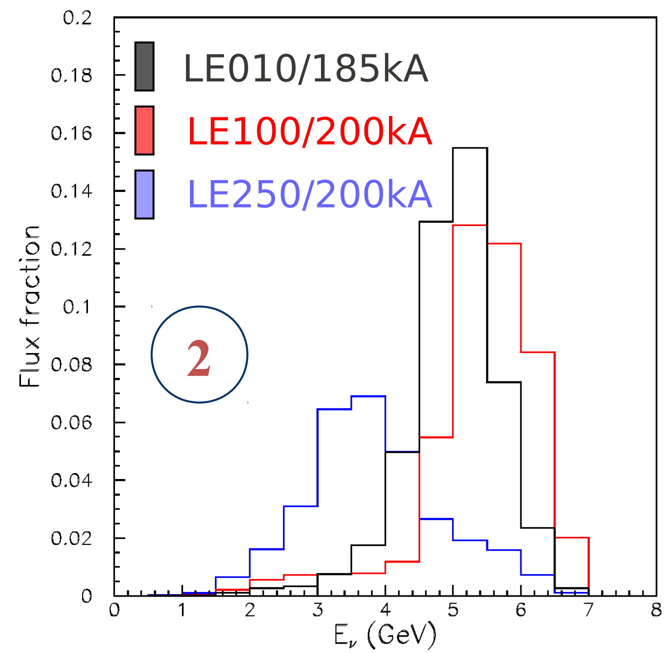
Using neutrino data

Flexible beam configurations permit *tuning* hadron production yields to match data.



Each (xF,pT) bin contributes with different weight in each beam configuration



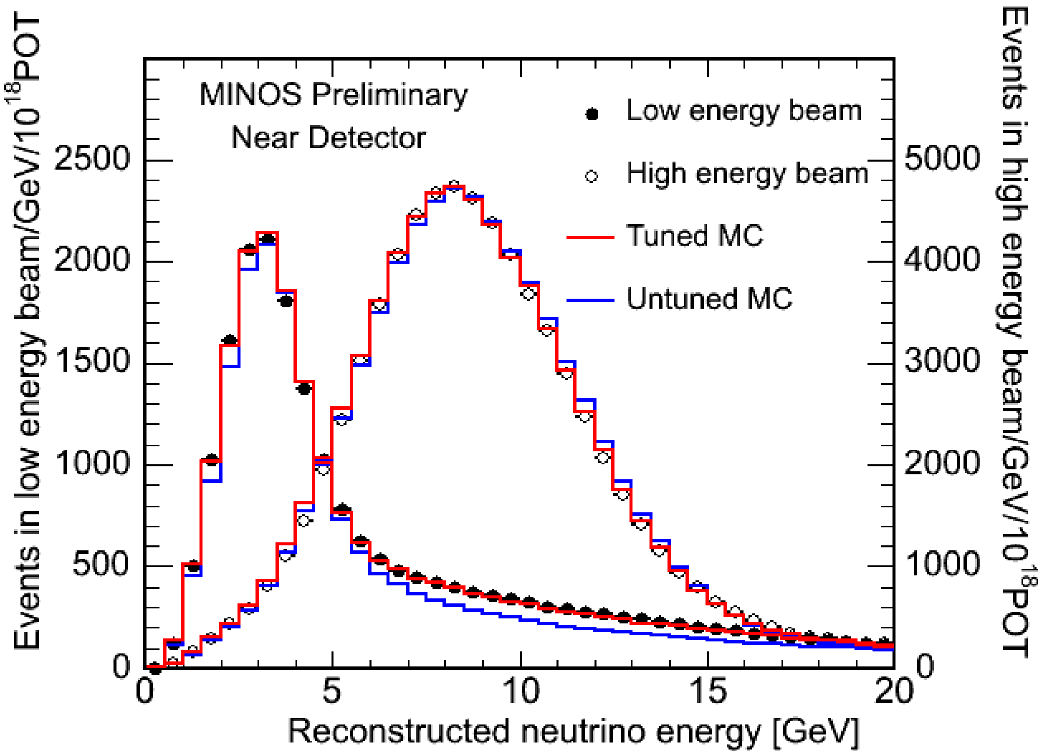


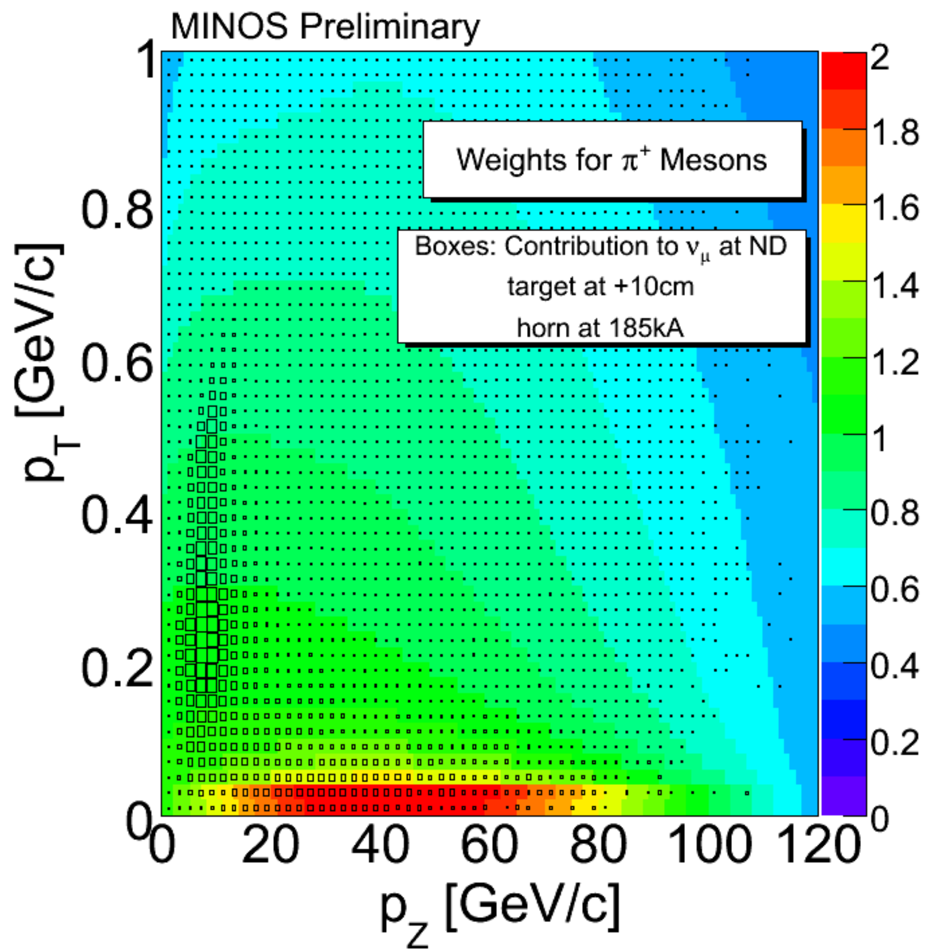
Using neutrino data

Fit MC to Data by tuning weights in π,K (*x*F,*p*T) plane
In MINOS, ν_μ-CC inclusive are used → OK to improve Far/Near

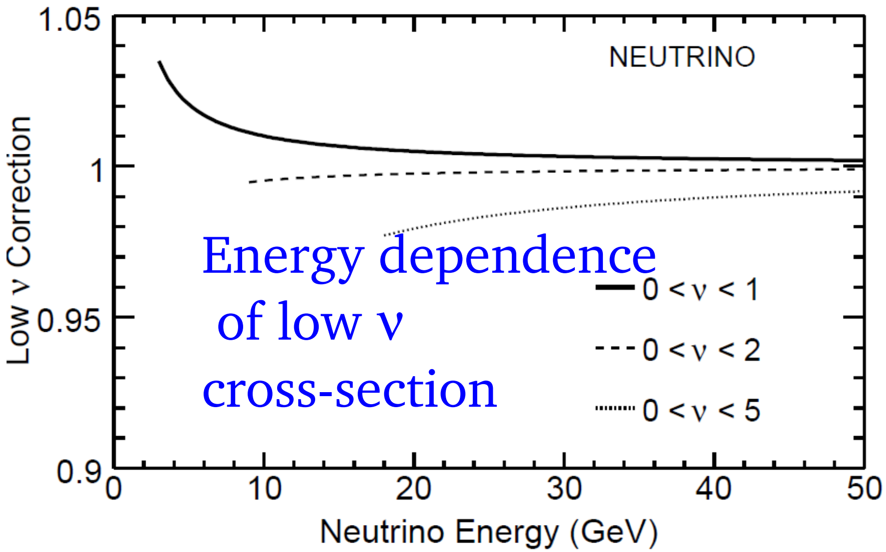
$$weight = \frac{(d^2 N / dx_F\, dp_T)_{tuned}}{(d^2 N / dx_F\, dp_T)_{MC}}$$

Phys. Rev. D77, 072002 (2008).

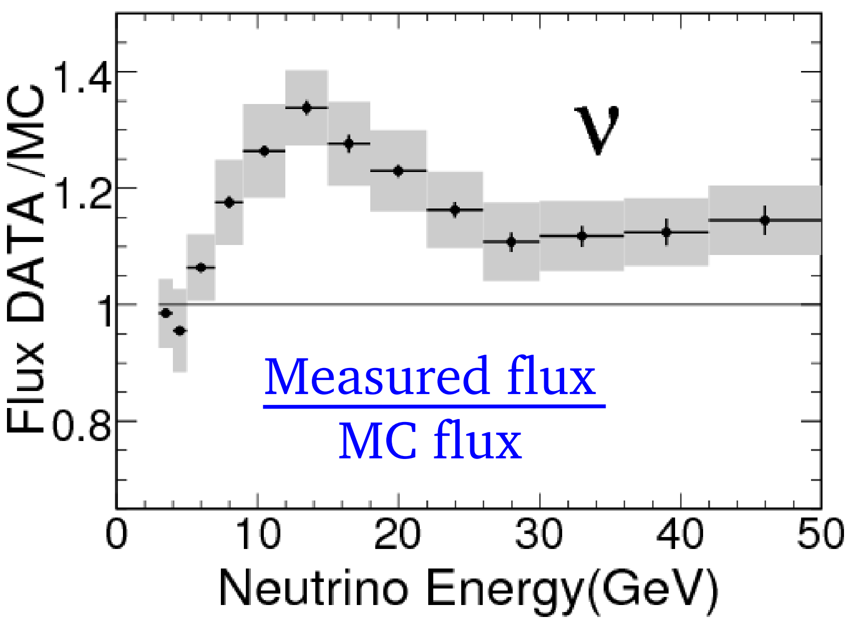




Using neutrino data



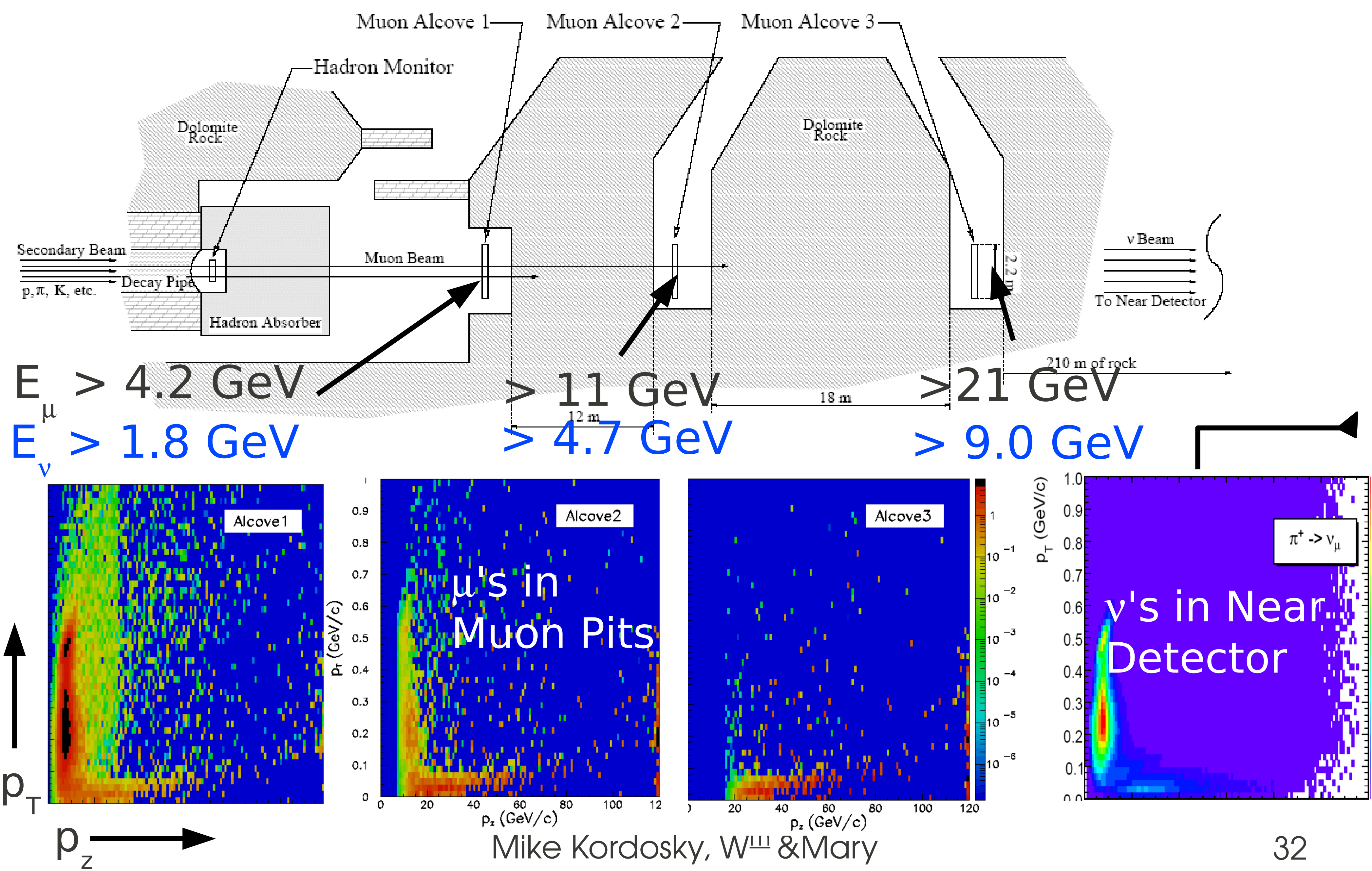
- MINOS tunes to inclusive $\nu_\mu/\bar{\nu}_\mu$-CC
  - Marginalizes over cross-section, background and energy scale uncertainties
- This is inadequate for MINERvA. What can be done?
  - Use world cross-section to normalize at high energy. Few % error.
  - Low $\nu = E_{HAD}$ cross-section has weak energy dependence → Flux shape
  - Similar argument can be made for QEL and samples defined via W & Q^2
  - Worry: model dependent… MEC,2p2h
  - νe → νe produces 45 events/1e20 POT
- Neutrino data is not the lone answer



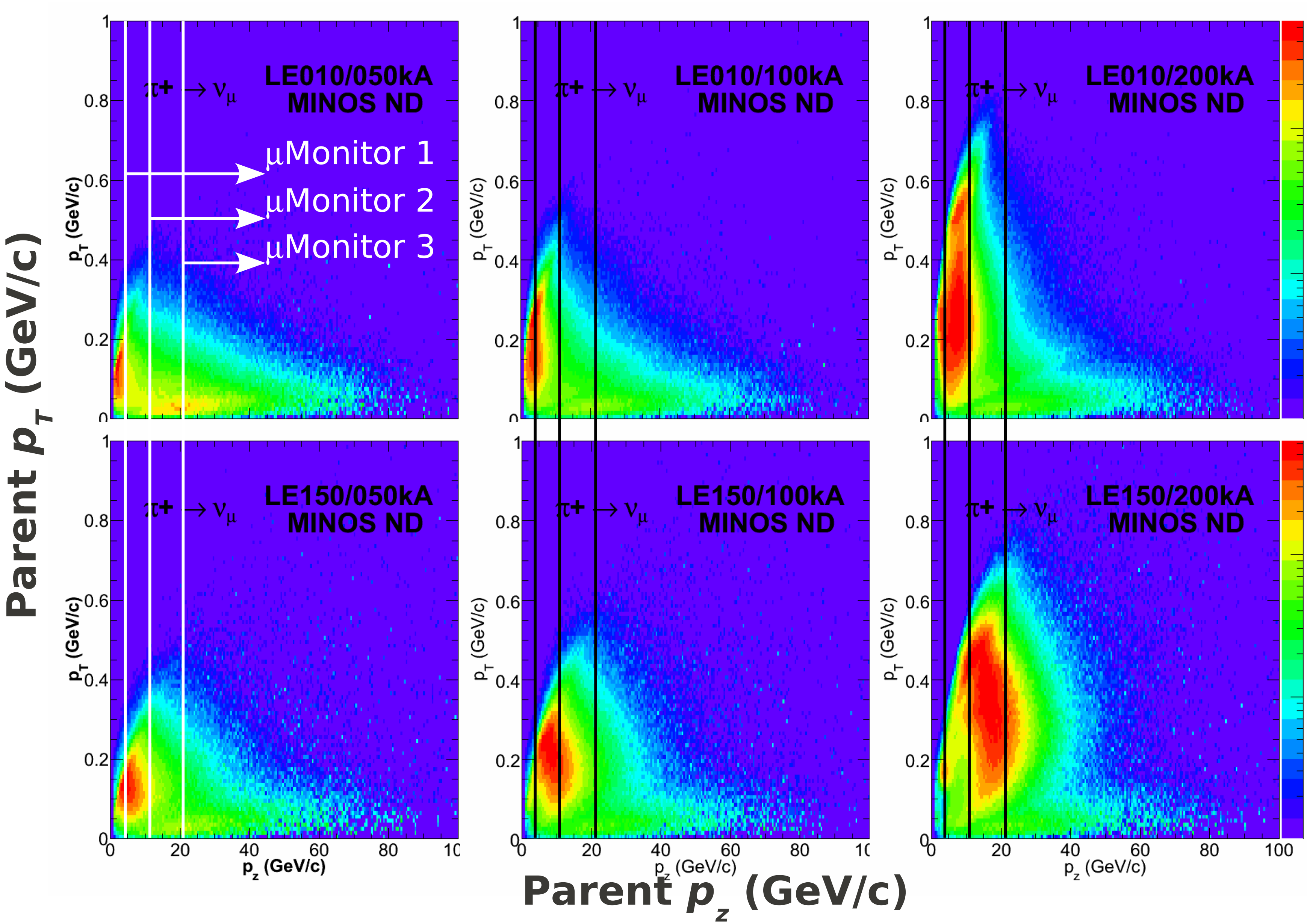
Phys.Rev. D **81** (2010) 072002

Using monitors

L. Loiacono, "Measurement of the Muon Neutrino Inclusive Charged Current Cross Section on Iron Using the MINOS Detector," PhD Thesis, UT Austin 2010

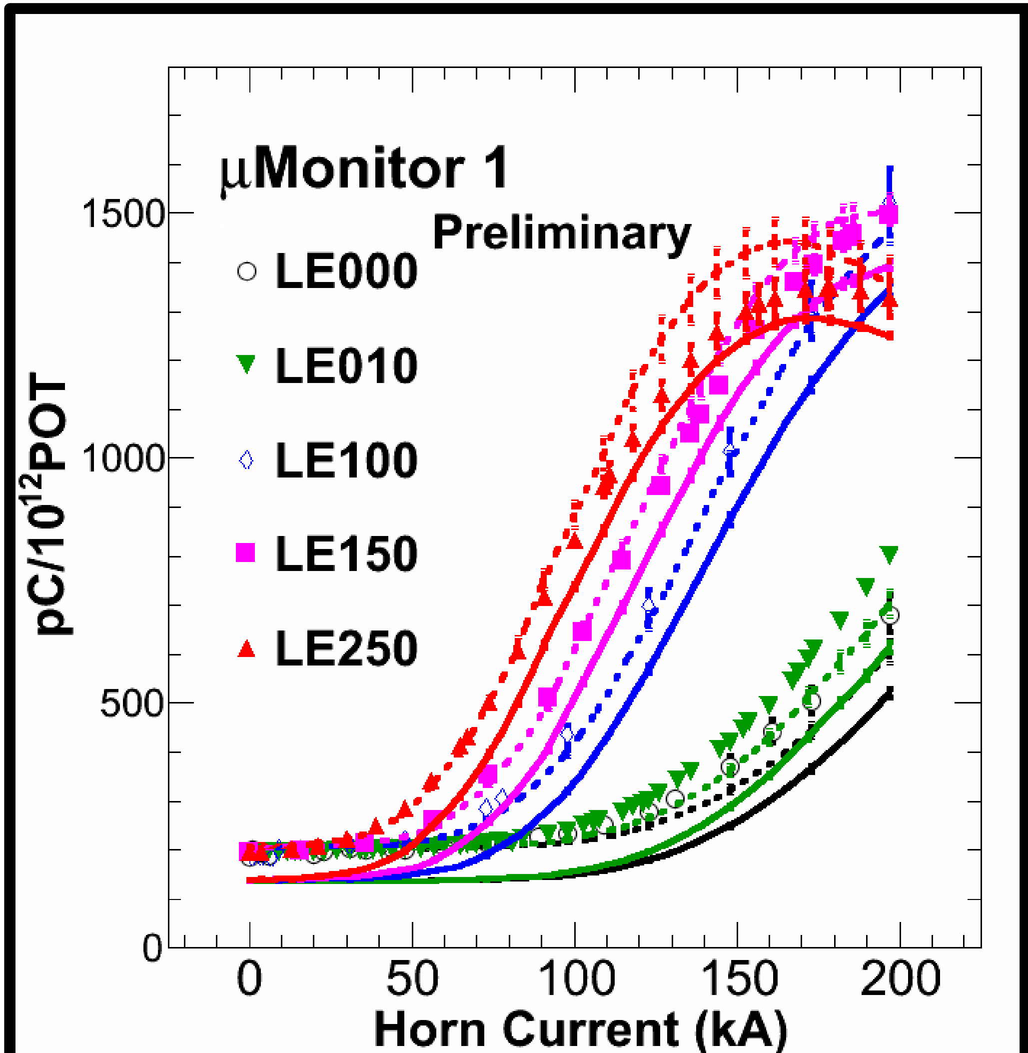


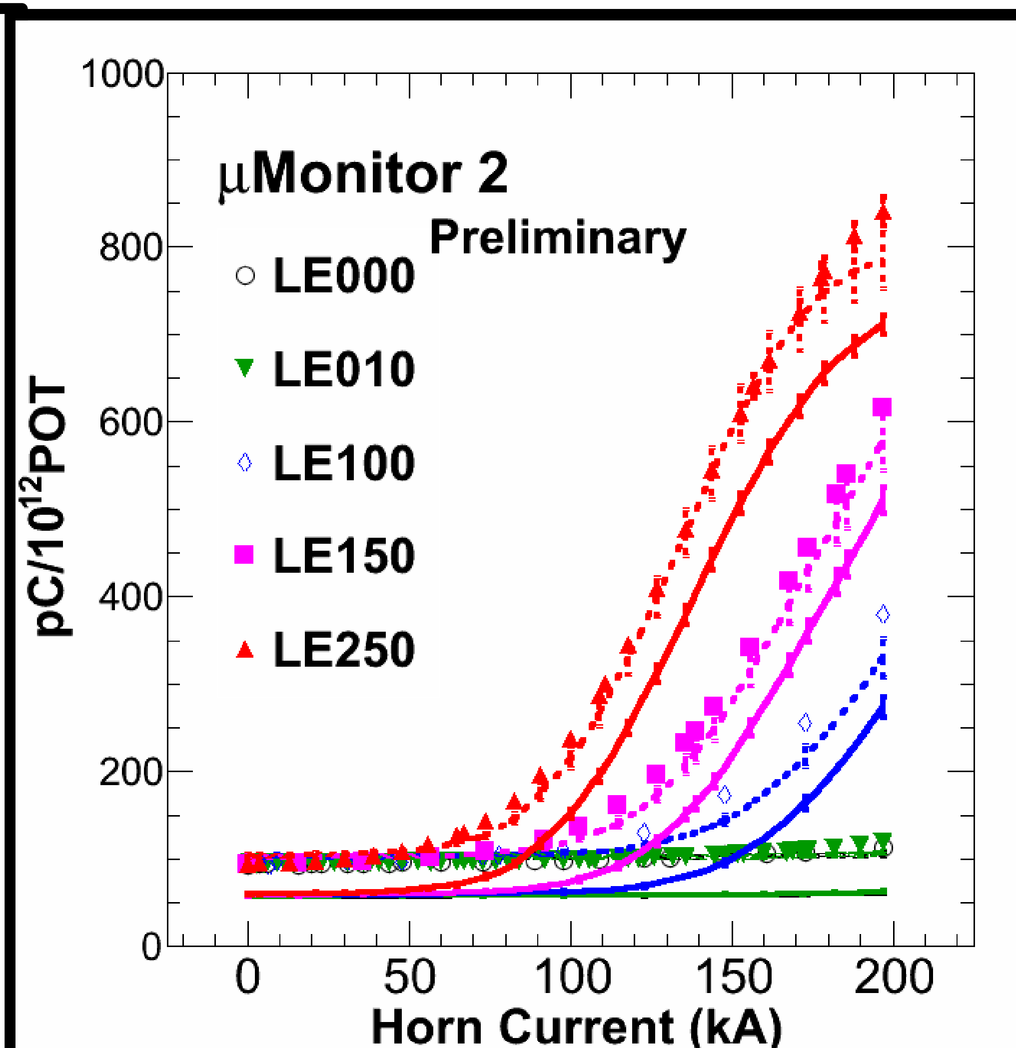
Using monitors



Using monitors

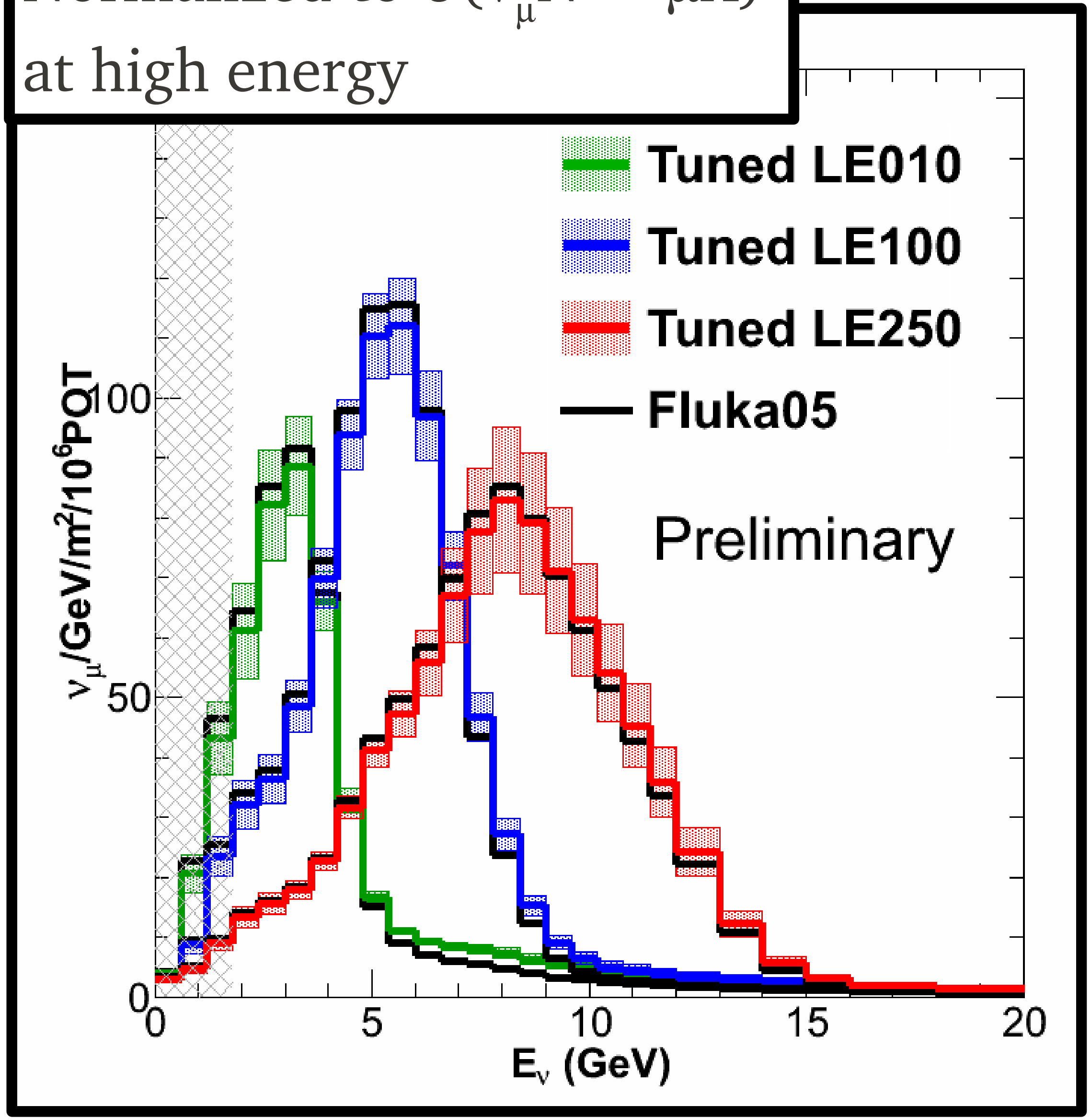
○ Data ▬▬ Monte-Carlo - - - - Tuned Mont-Carlo





Using monitors

Normalized to $\sigma(\nu_\mu N \rightarrow \mu X)$ at high energy



Uncertainties

- δ-rays
- μ energy loss in He
- K/π and π⁺/π⁻ ratios
- calibrations
- beam dump background

L. Loiacono, "Measurement of the Muon Neutrino Inclusive Charged Current Cross Section on Iron Using the MINOS Detector," PhD Thesis, UT Austin 2010

The likely strategy for MINERvA

- Tune simulation at least for pC → πX, and more if possible.
  - Improves "central value" of simulation.
- MINOS-style fit using a QEL-like sample in multiple beam configurations ← have some of this data now
  - use HP data in fit (already done by MINOS for π/K ratios)
  - Marginalize over cross-section uncertainties
- Improve monitor fitting technique.
  - More flexible fit.
  - Work on systematics. Studies + new hardware & 4^{th} alcove.
  - Include HP uncertainties.
- Easier said than done but much can go in parallel and we are working

Backups

Low ν correction

Differential cross-section

$$\frac{d\sigma}{d\nu} = A\left[1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{2A}\frac{\nu^2}{E^2}\right]$$

Event rate vs. ν

$$\frac{dN}{d\nu} = \frac{d\sigma}{d\nu} \times \Phi$$

As $\frac{\nu}{E} \to 0$ $\quad \frac{d\sigma}{d\nu} \to A = \text{constant}$

Correction for finite ν / E

$$\Phi(E) \propto \frac{\sigma(\nu < \nu_0, E \to \infty)}{\sigma(\nu < \nu_0, E)} N(\nu < \nu_0, E)$$

"Low ν correction"