Measuring the NuMI Beam Flux for MINERvA

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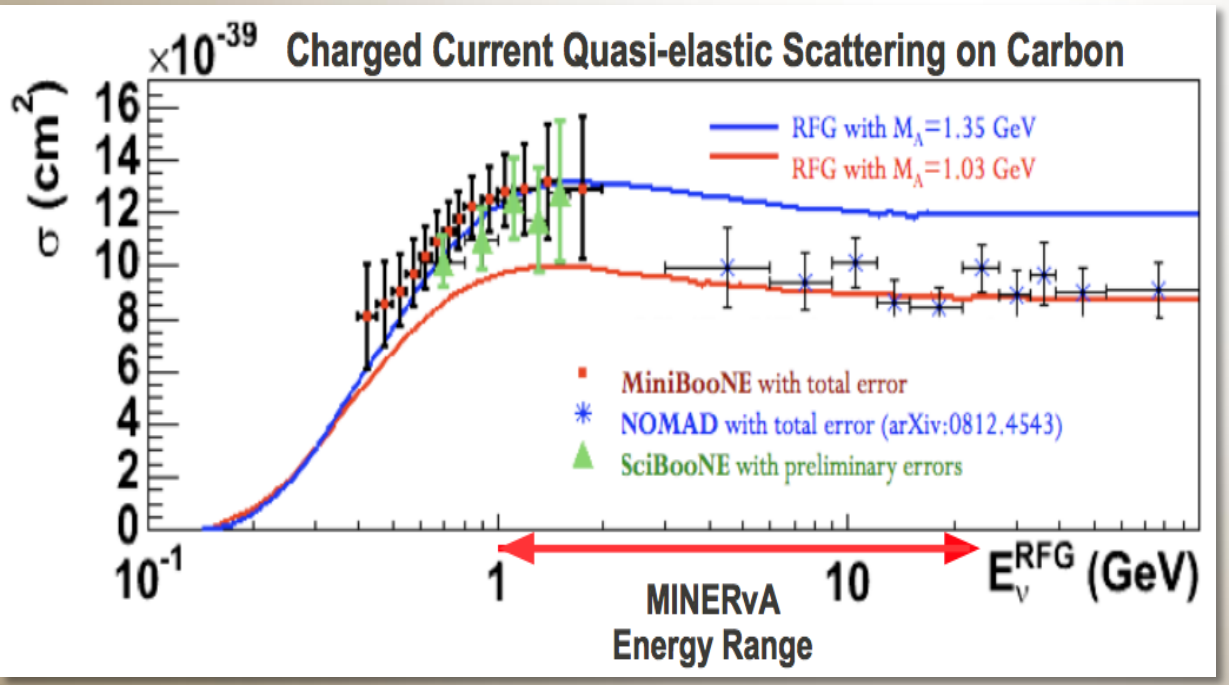
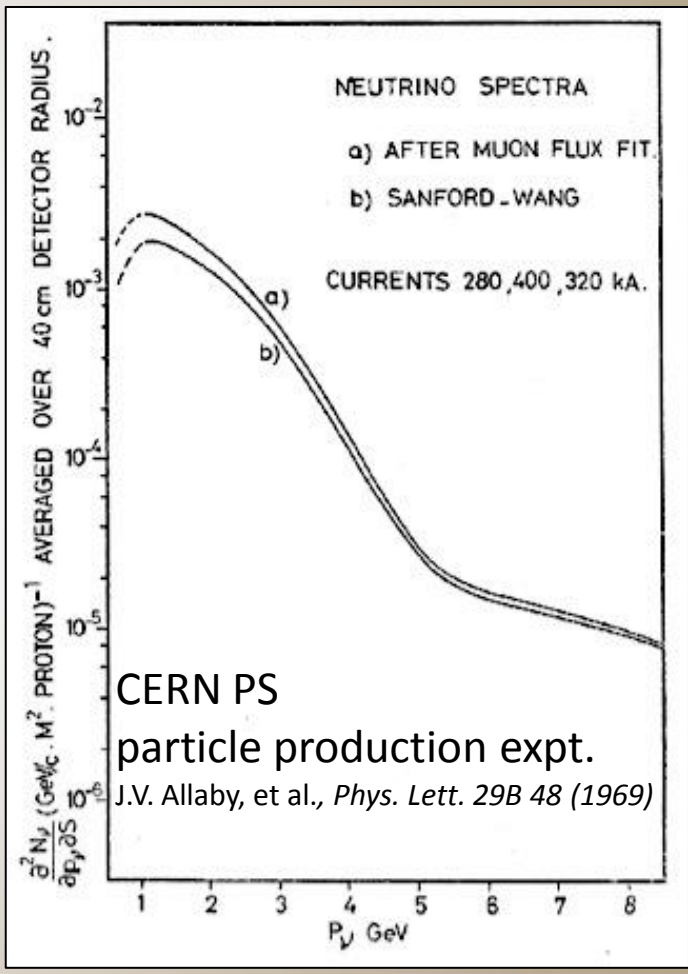
NUINT 2011: Dehradun, Uttarakhand

Measuring Flux: Introduction

Knowing your flux is difficult, and crosschecks are helpful

- CERN PS: *In situ* measurement using μMons increased predicted flux by 50%
- MiniBooNE and SciBooNE data appear to conflict with NOMAD results at higher energy





Measuring Flux: Introduction

MINERvA will utilize three methods to understand its flux:

1. **External data** (*ab initio)*
2. **Flexible beam design** for *in situ* measurements
3. **Muon monitors** (*in situ)*

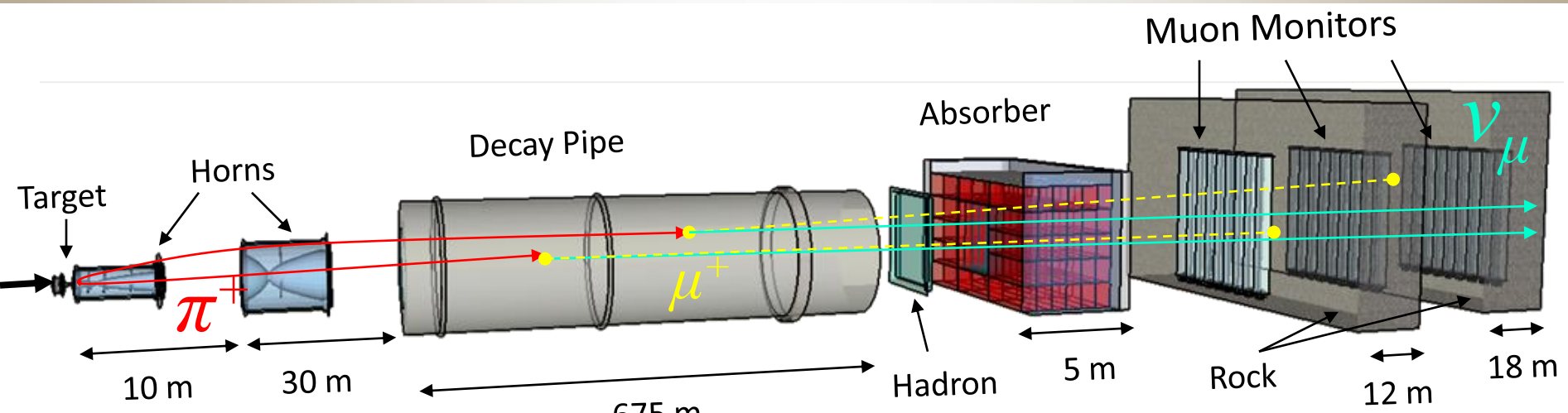


figure courtesy Ž. Pavlović

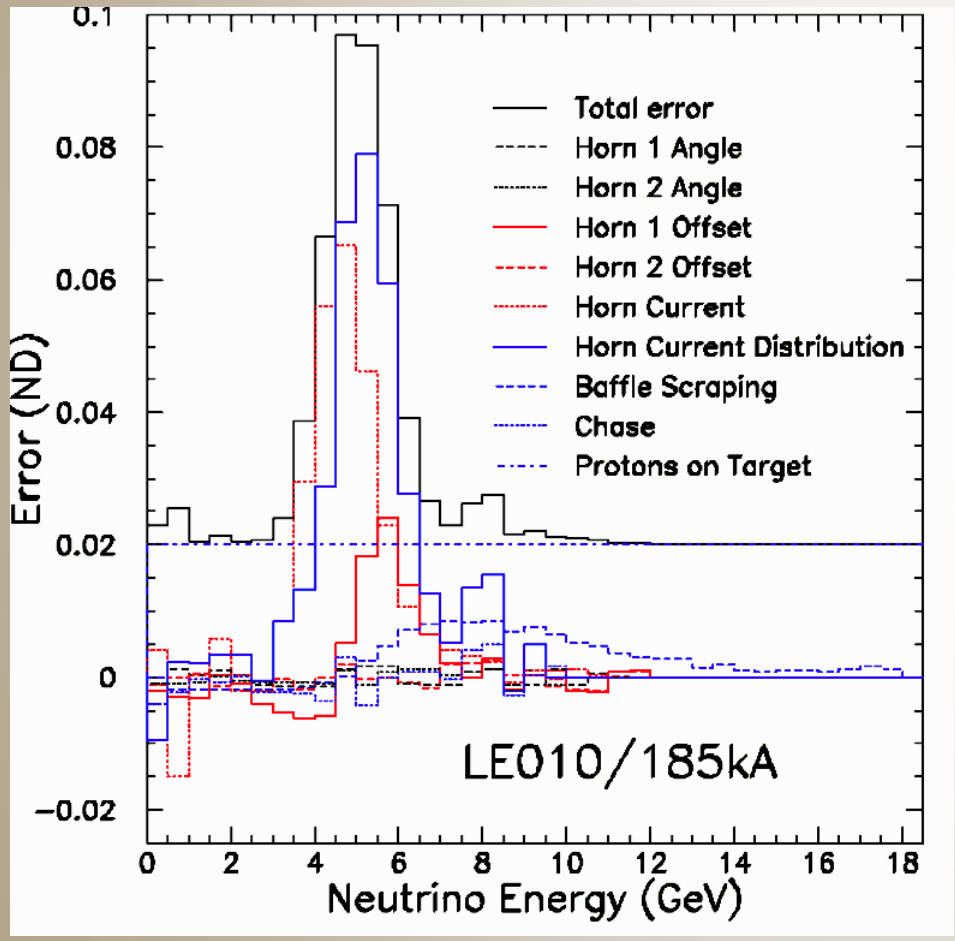
- Neutrino-nucleus interaction experiment in the NuMI beamline at Fermilab

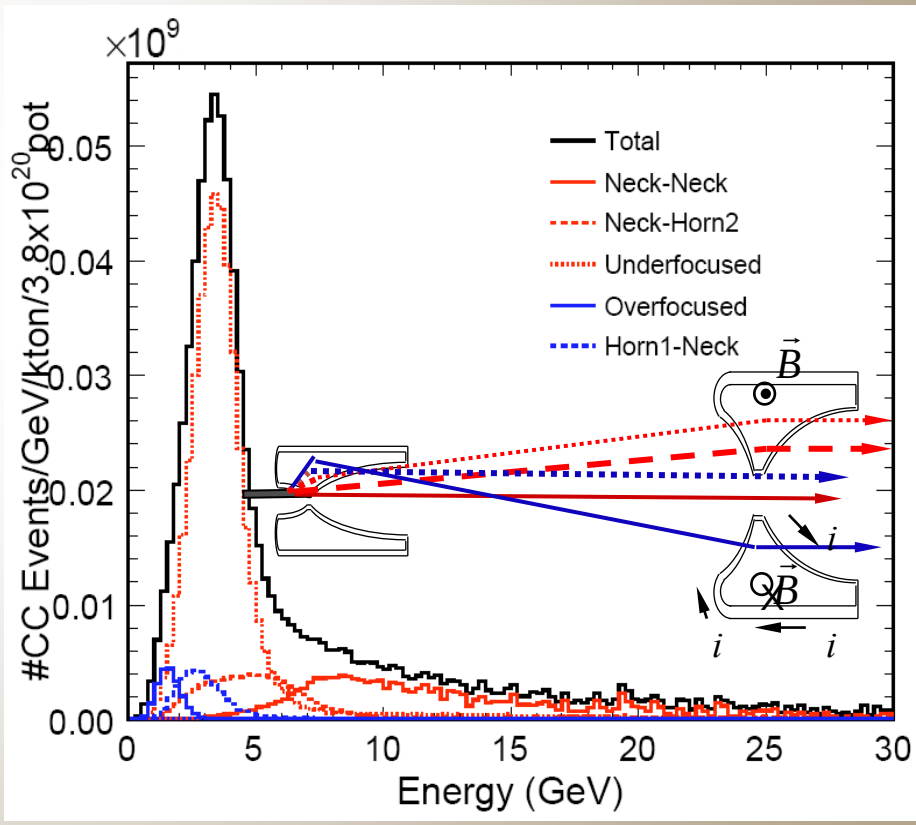
$$\sigma = \frac{N(observed)}{Flux}$$

- Low energy (<10 GeV) precision cross section measurements

Measuring Flux: Focusing Uncertainties

Focusing uncertainties are smaller and easier to model than hadron production uncertainties



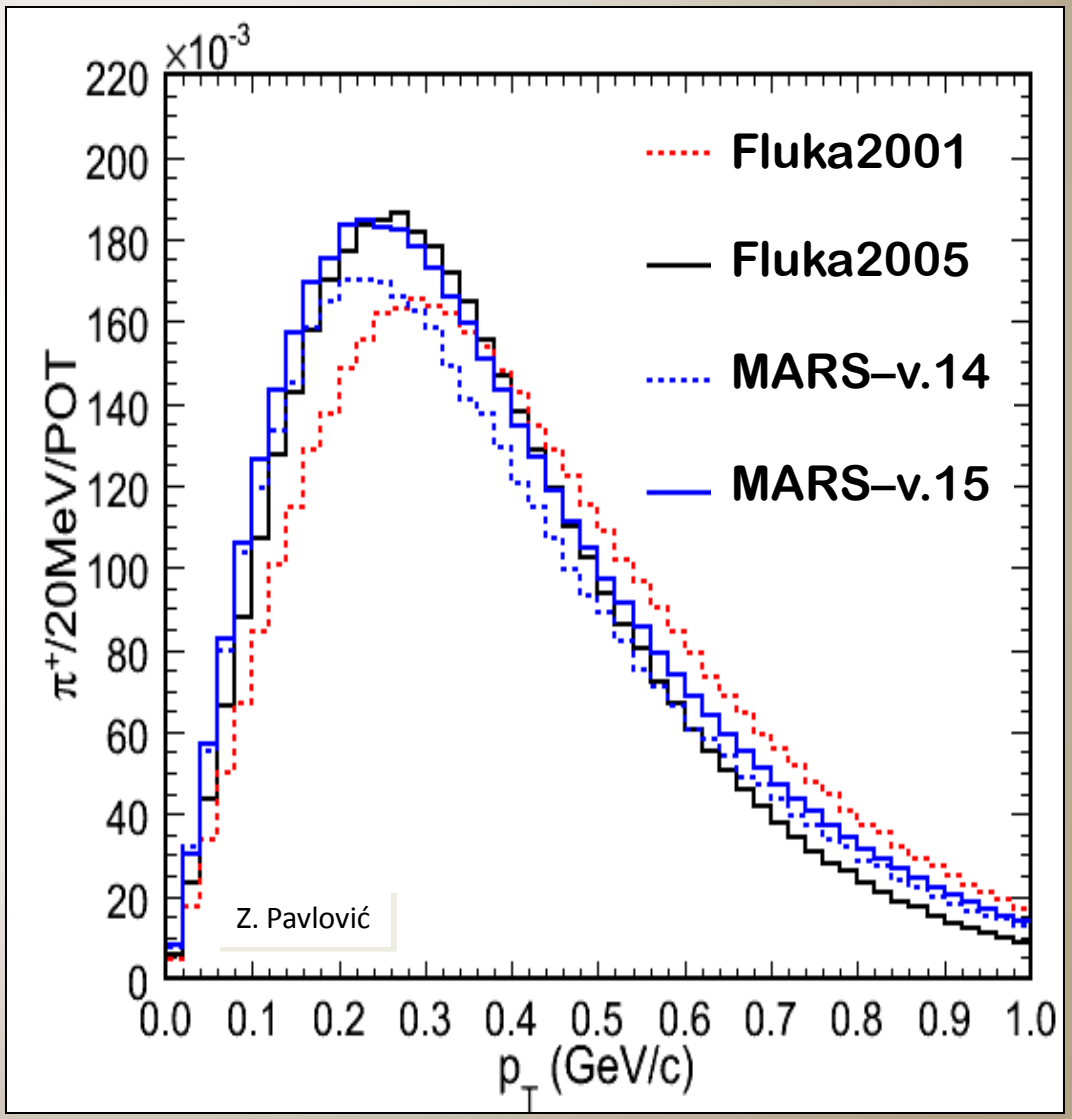


Z. Pavlovic, "A Measurement of Muon Neutrino Disappearance in the NuMI Beam," PhD Thesis, UT Austin 2008

Measuring Flux: Hadron Production

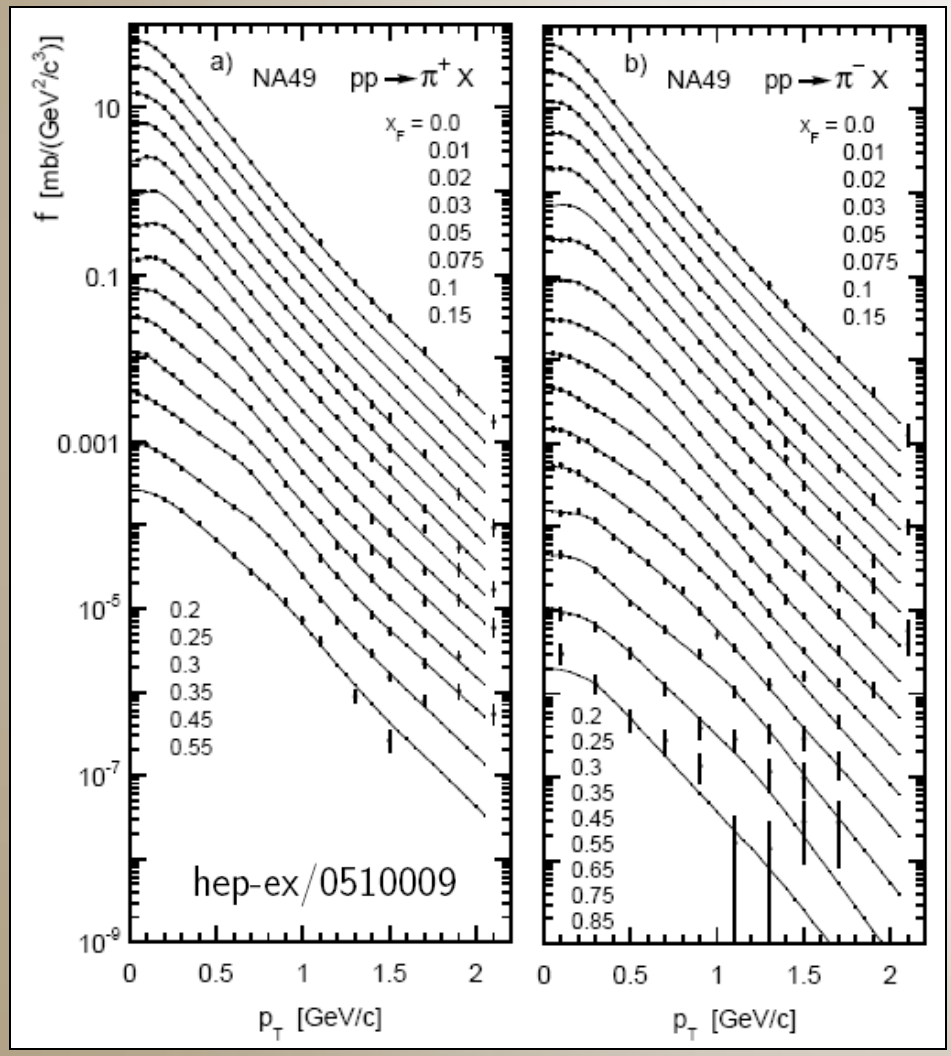
Relying on Monte Carlo models alone isn't a good option

Model	$\langle p_T \rangle$ (GeV/c)
GFLUKA	0.37
Sanf.-Wang	0.42
CKP	0.44
Malensek	0.50
MARS – v.14	0.38
MARS – v.15	0.39
Fluka 2001	0.43
Fluka 2005	0.36



Measuring Flux: Hadron Production

Can't modern data sets solve our problems?



Sadly … no. **Production data ≠ Flux**

Thick target effects:

- Experiments are mostly on thin targets
- NuMI target is is ~$2\lambda_{int}$ lengths
- Reinteractions are 20-30% effect

***In situ* temporal variations of flux:**

- Target changes
- Focusing changes

Downstream interactions:

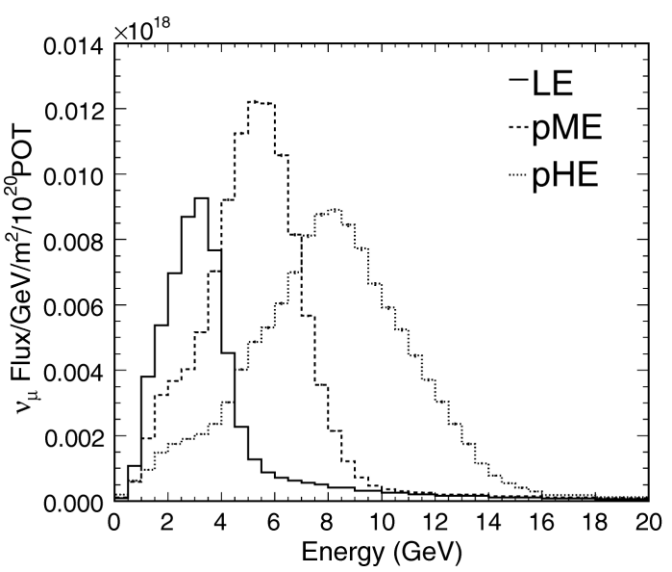
- Interactions in horns, windows, shielding, ect.

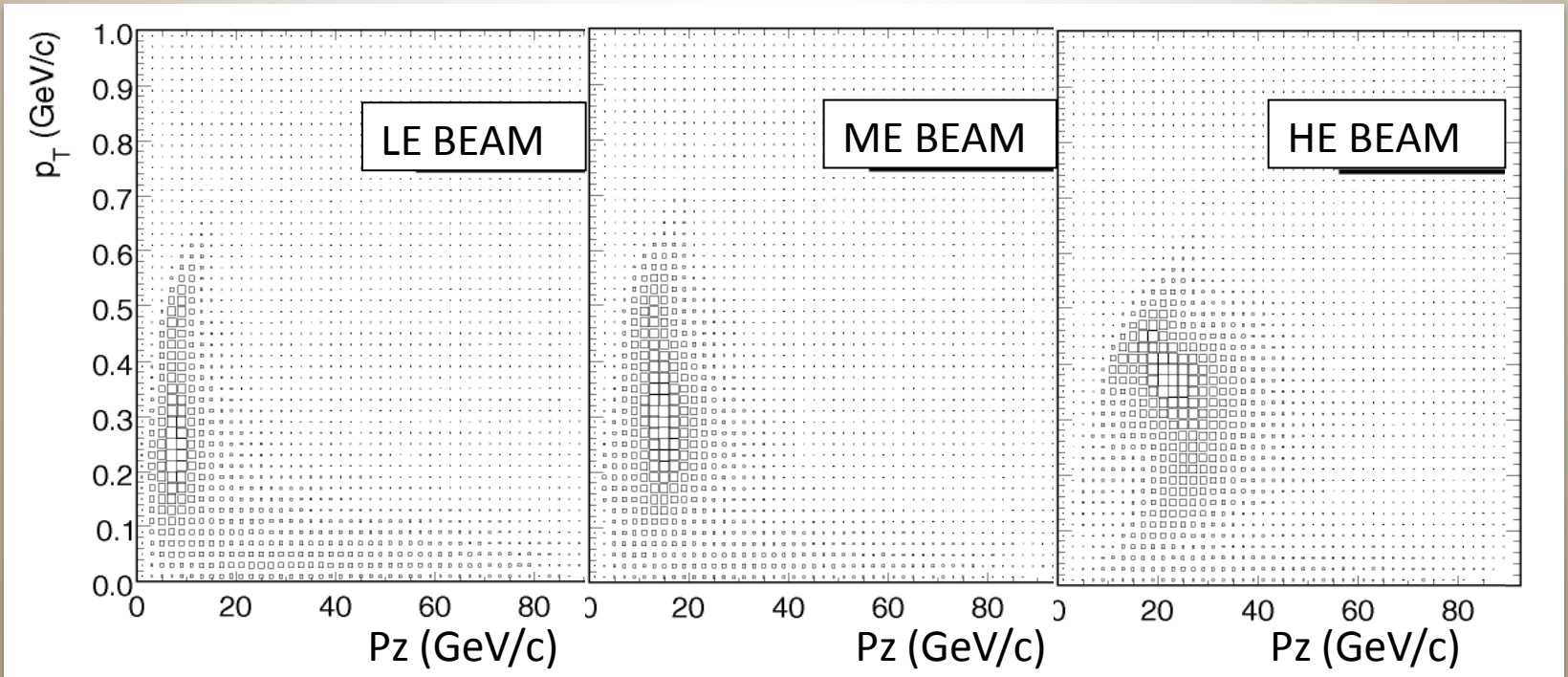
Measuring Flux: Hadron Production

We want an *in situ* measurement of $\phi_\nu(x_F,p_T)$

Allows us to correct the MC model for parent hadron x_F and p_T off the target

- Focusing and decay kinematics imply: flux ←→ hadron production
- Shape in p_T and x_F impact flux via focusing channel acceptance





Measuring Flux: Variable Beam

"Low" Energy

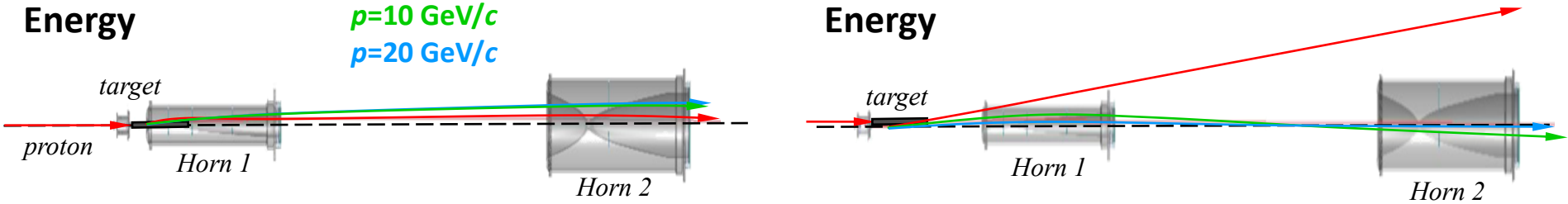
π^+ p_T=300 MeV/c and:

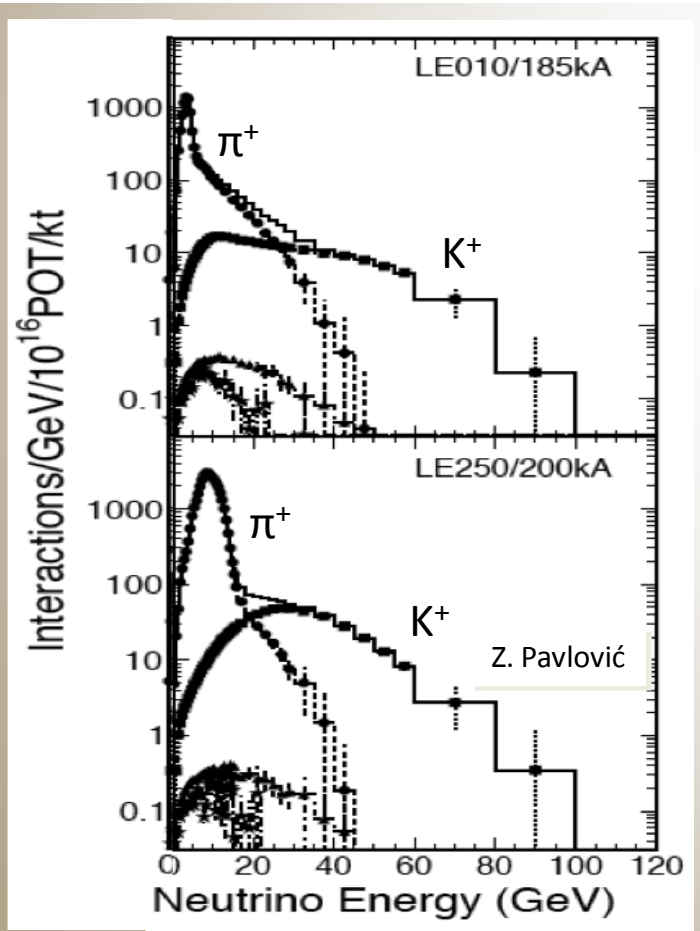
p*=5 GeV/*c

p*=10 GeV/*c

p*=20 GeV/*c

"High" Energy





Moving target in/out of 1st horn varies which pions are focused

Deconvolve systematics:

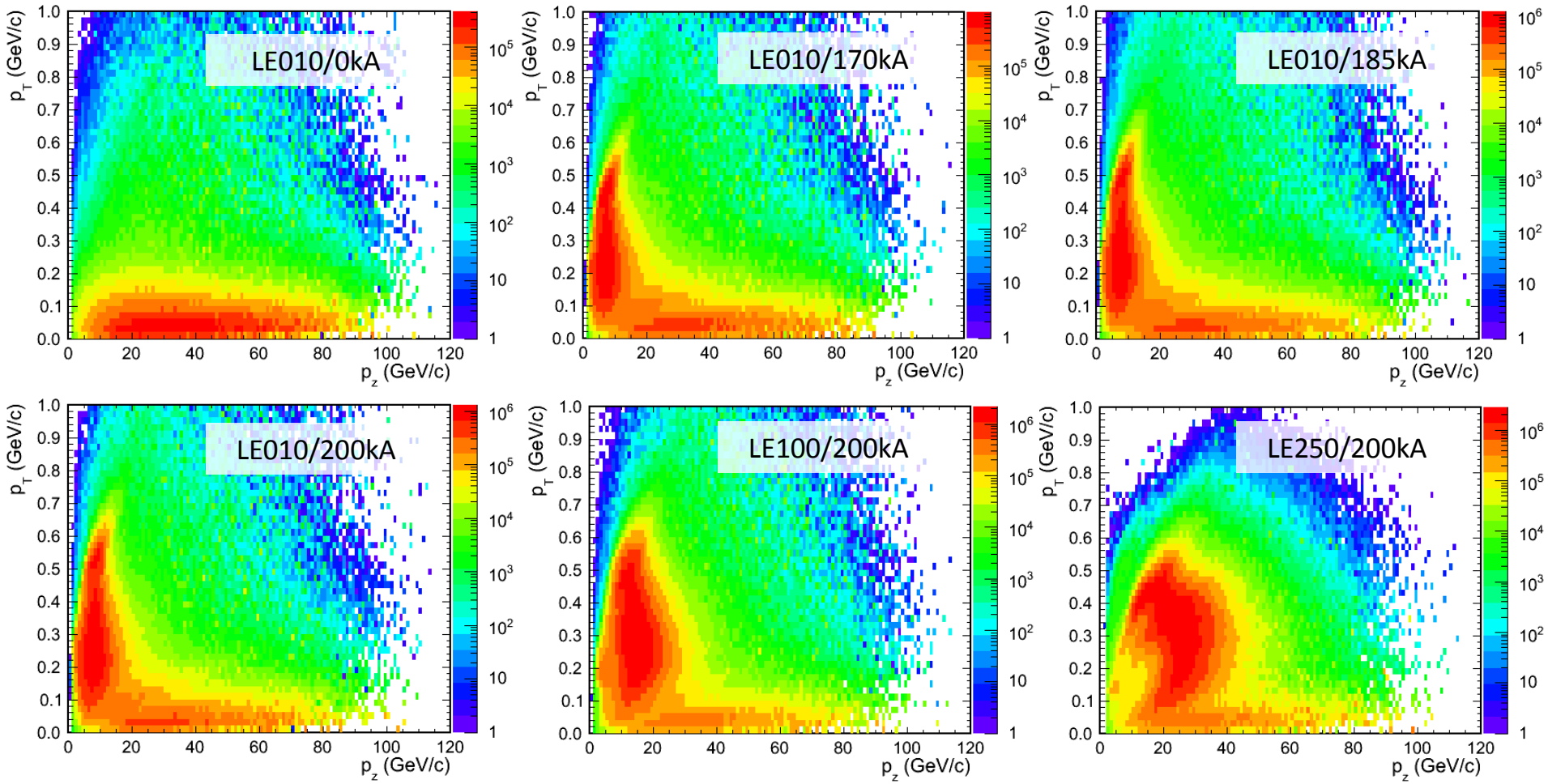
- Neutrino beam focusing
- π/K production off target
- Neutrino cross sections

Measuring Flux: Variable Beam

We can vary:

- Horn current (p_T kick supplied to pions)
- Target position (x_F of focused particles, where $x_F = p_z/p_o$)

- LE = target @10cm
- pME = target @100cm
- pHE = target @250cm



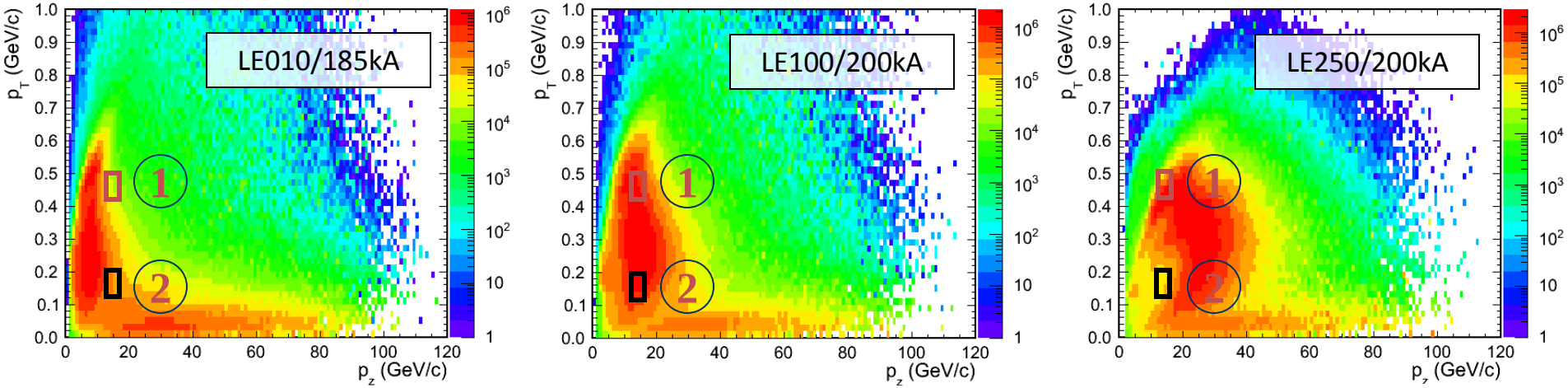
Measuring Flux: Hadron Production

1st *in situ* flux measurement tool:

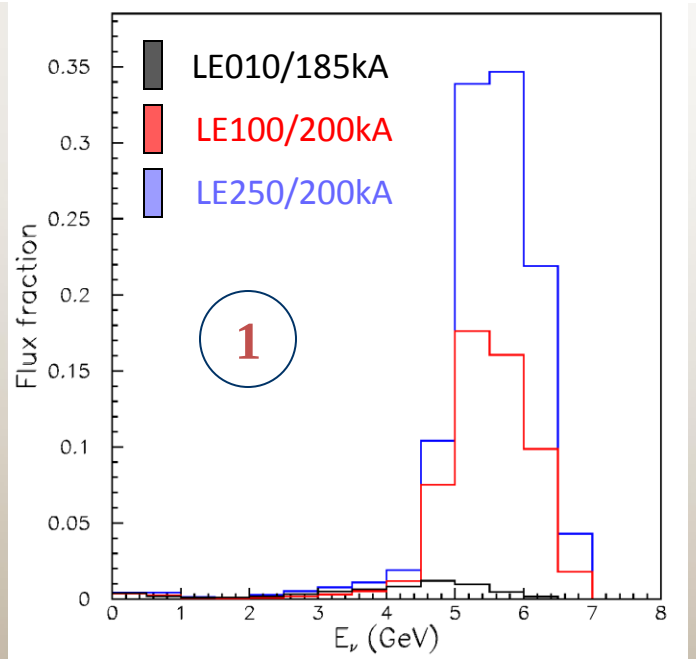
Tune MC parameterization of hadron production off the target so that it matches **MINERvA Detector Data** across several beam configurations

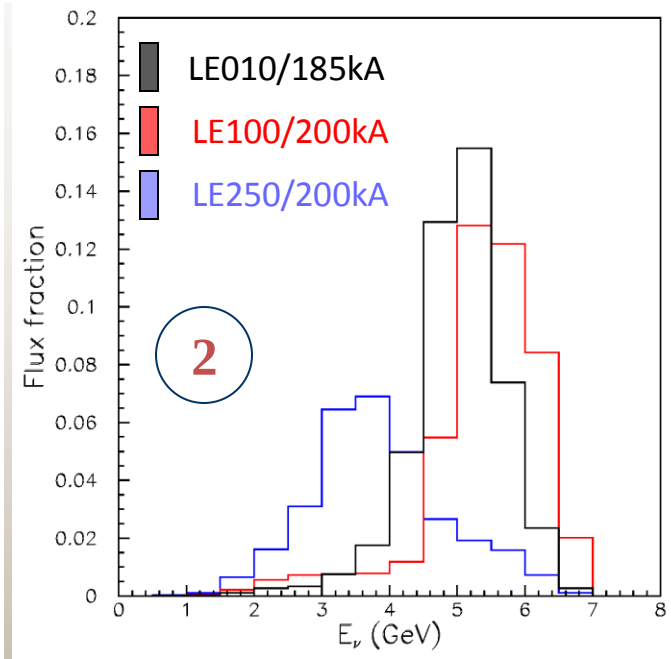
Measuring Flux: Fitting to Data

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



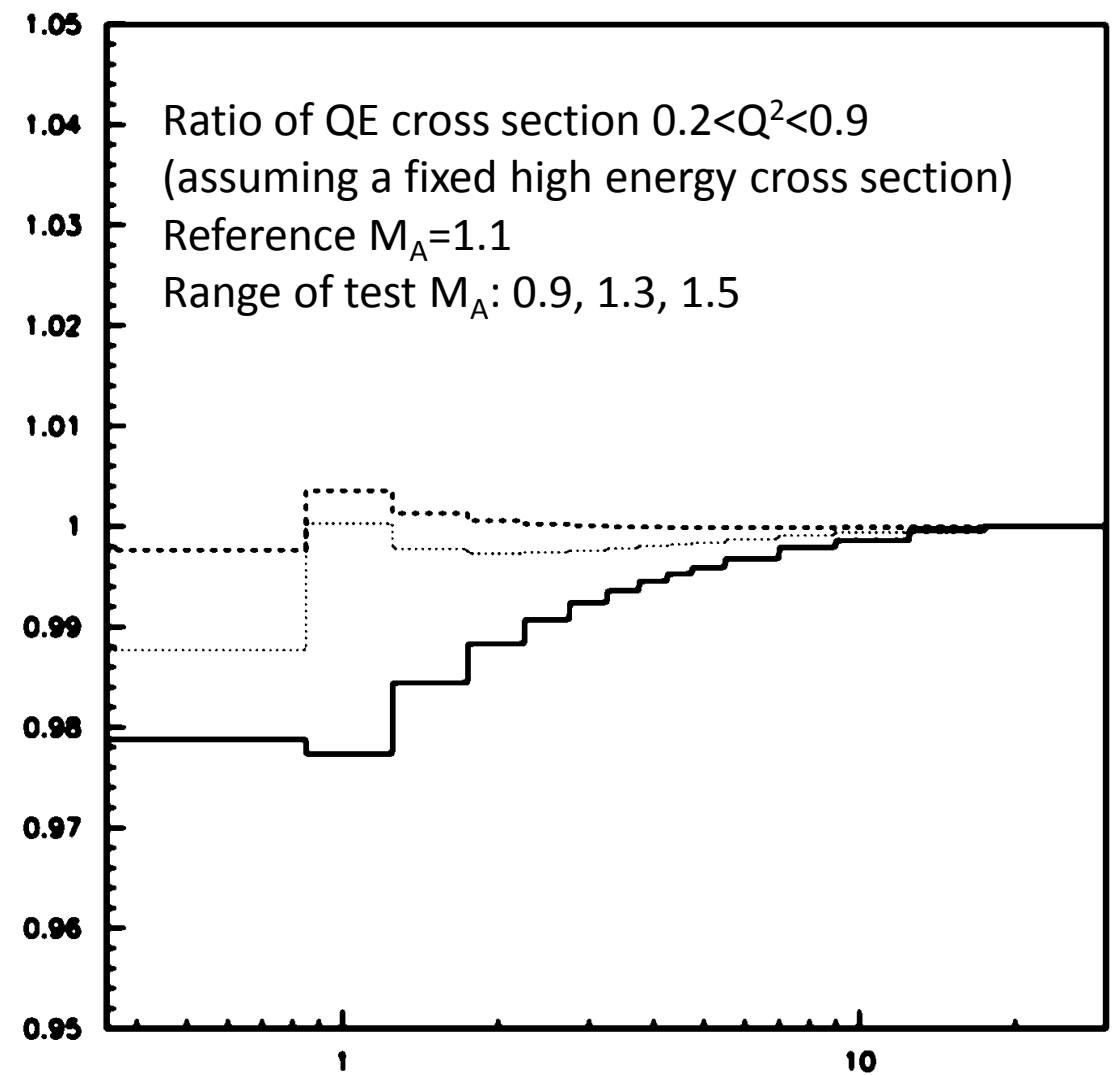
Each (x_F,p_T) bin contributes with different weight in each beam configuration





Measuring Flux: Fitting to Data

MINERvA's "standard candle" data set will be QEL events of moderate Q^2



Ratio of cross section of test M_A to reference M_A vs. E_ν

- QEL cross section on nucleons is a function of Q^2, independent of neutrino energy (even for extreme values of M_A)
- Low Q^2 events are excluded because of uncertainties due to nuclear effects
- High Q^2 events are excluded because of reconstruction difficulties
- Use inclusive CC sample above ~20GeV and compare to CCFR, CCFRR, and CDHSW data sets to fix the absolute normalization

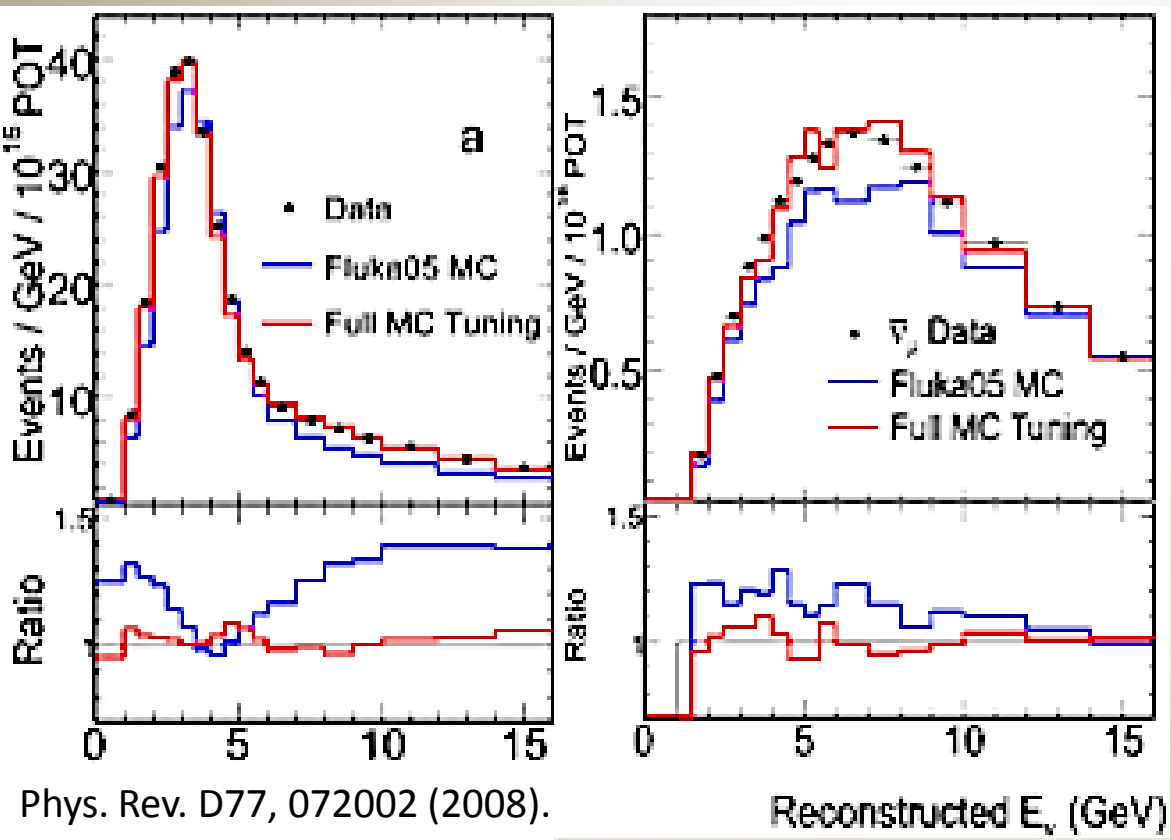
Measuring Flux: Fitting to Data

Result of fit = set of weights in (x_F,p_T) plane that should be applied to π/K yields

MINOS utilized such fits:

Flux uncertainty at far detector reduced (2-10)% → (1-4)%

$$weight = \frac{\left(d^2N/dx_F dp_T\right)_{tuned}}{\left(d^2N/dx_F dp_T\right)_{MonteCarlo}}$$



Phys. Rev. D77, 072002 (2008).

MINOS used inclusive event sample for its fits:

- Fine for Far/Near ratio … but not for xsec measurements
- QEL events provide a well-known process for MINERvA

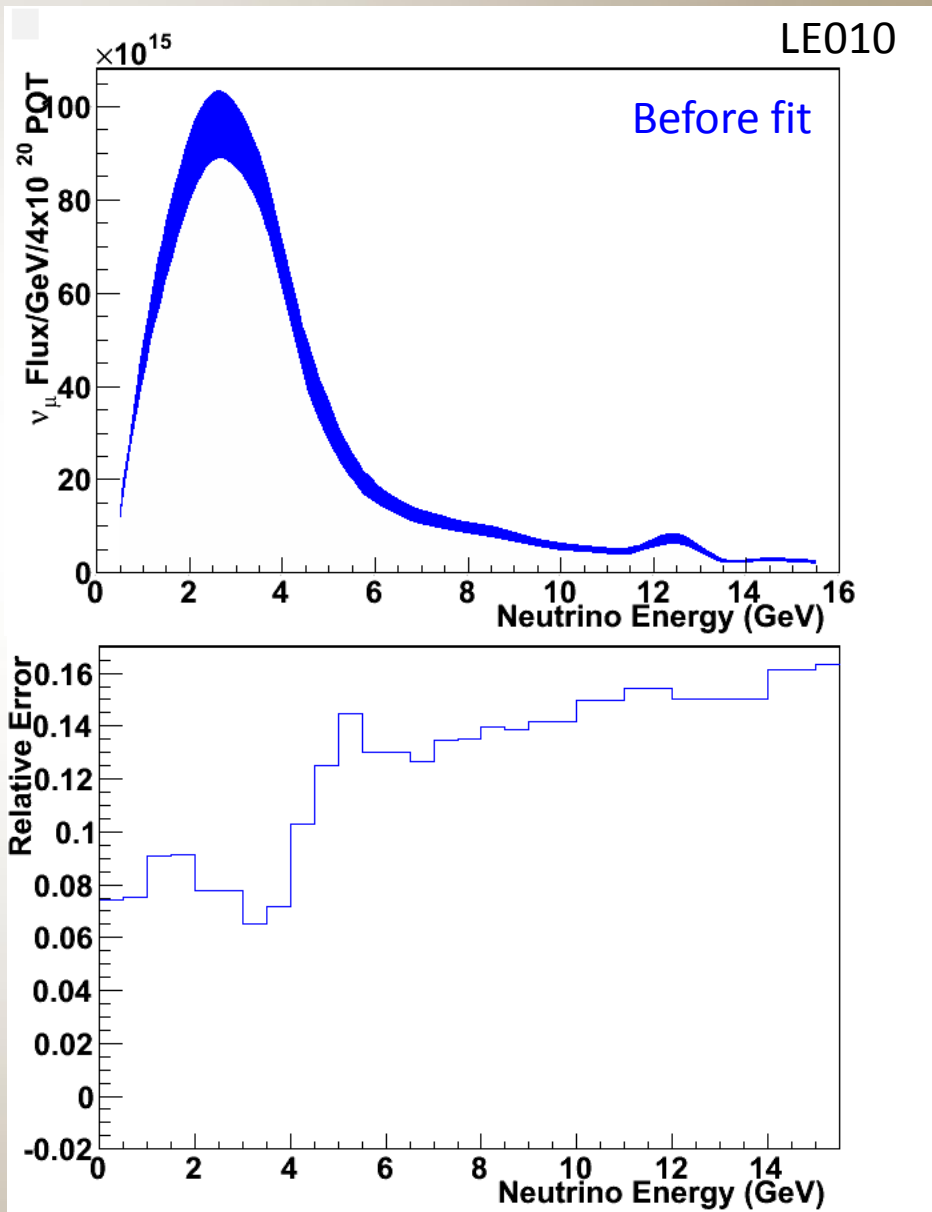
Measuring Flux: Fitting to Data

What kind of flux errors can MINERvA expect?

Blue error band = estimation of flux uncertainty based on "current knowledge"*

*Includes:
- Beam focusing uncertainties
- MC differences in π^+ production off target
- 5% yield uncertainty for π^+ production off target

Effort is underway to estimate our post-fit errors by warping the hadron production of Geant4 Monte Carlo to bring simulated Geant4 "data" (across many beam configurations) into agreement with simulated Fluka "data."

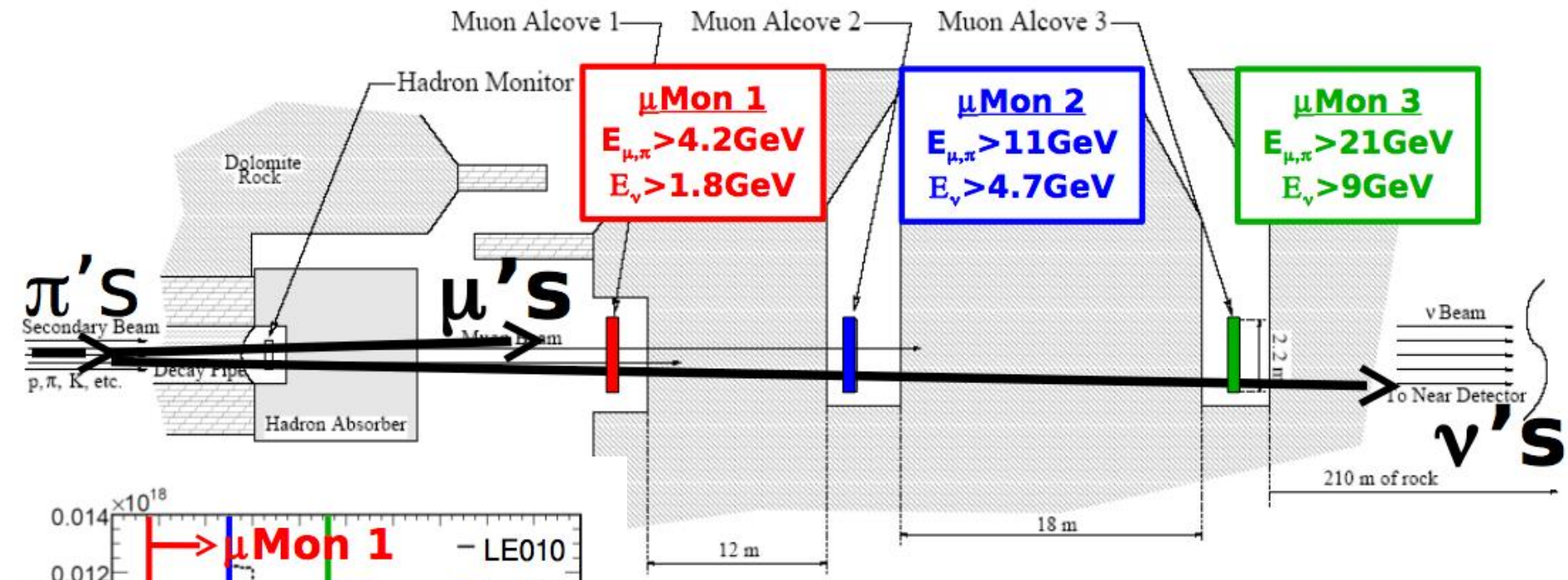


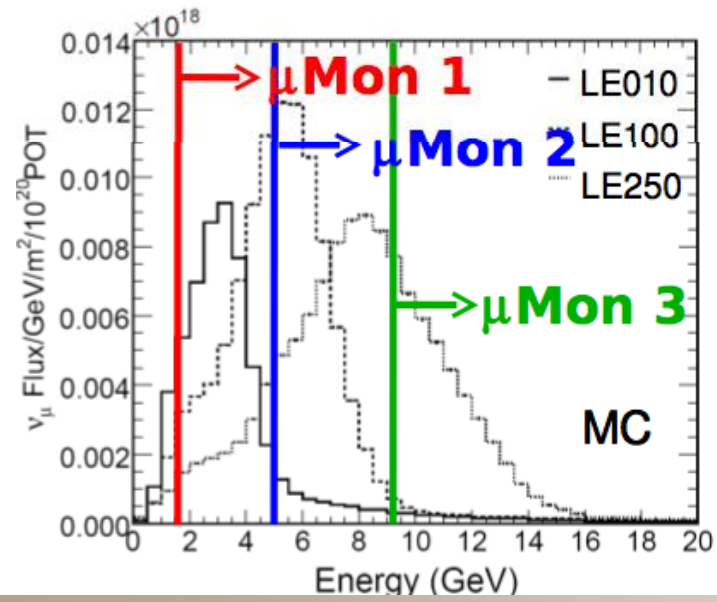
Measuring Flux: Muon Monitors

2nd *in situ* flux measurement tool:

Tune MC parameterization of hadron production off the target so that it matches **Muon Monitor Data** across several beam configurations

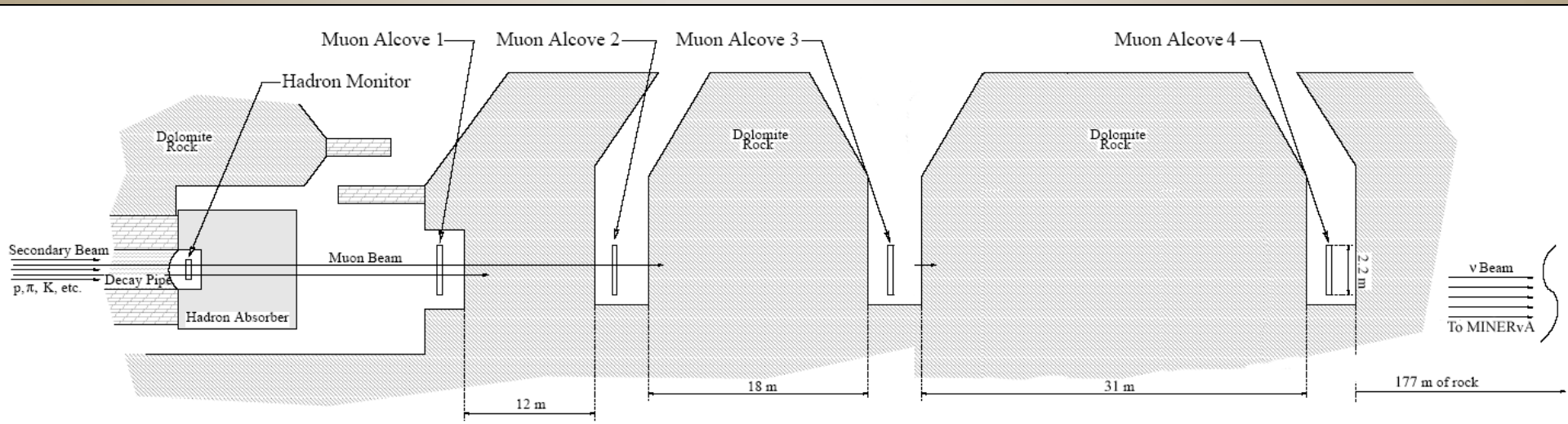
Measuring Flux: Muon Monitors



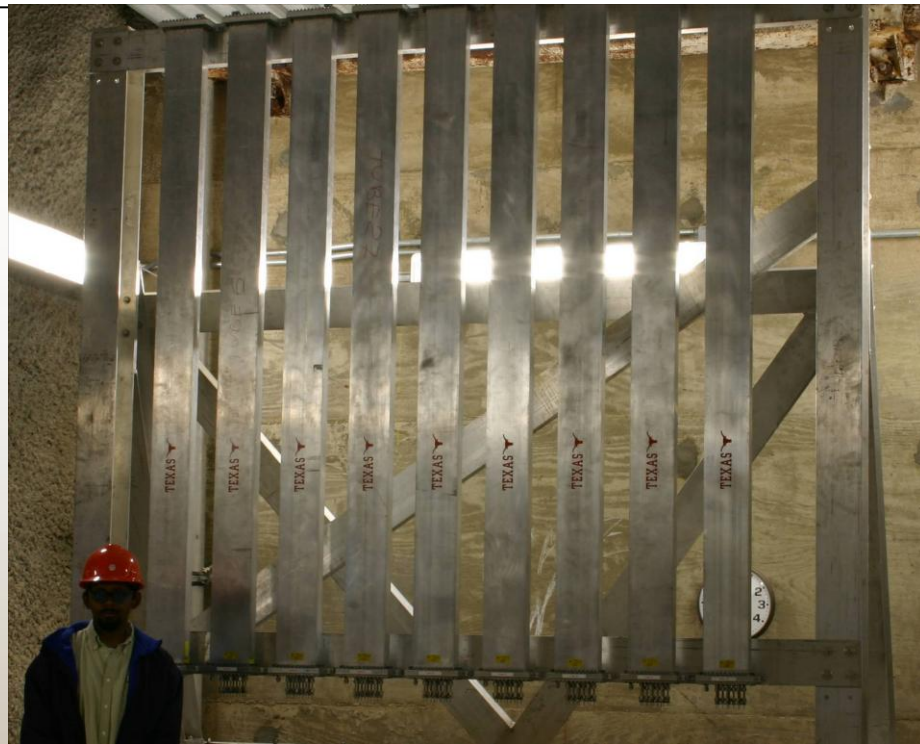


- Muon thresholds translate into ν thresholds
- Allows sampling of different energy regions of the flux
- 3 alcoves = poor granularity per measurement … but NuMI's flexible beam offers data from many (I_{horn},Z_{target}) combinations

Measuring Flux: Muon Monitors

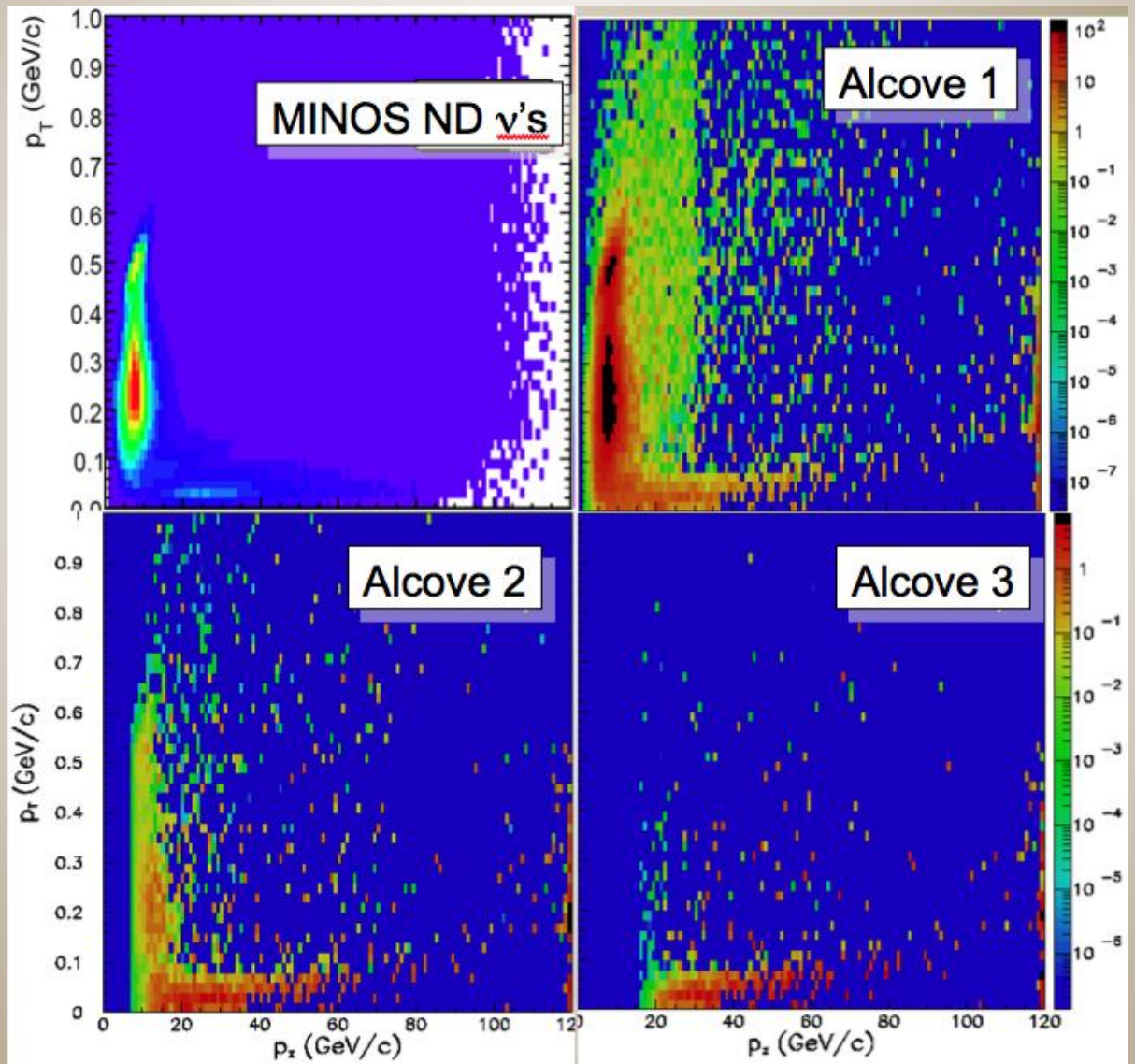


- 3 arrays of ionization chambers (2m x 2m)
- Plans to install a 4th chamber
- Beam μ's ionize He gas
- Signal = ionized electrons
- Sampling μ flux = hadrons off target = sampling ν flux
- Technique proven at CCFR, CERN-PS, CERN-SPS

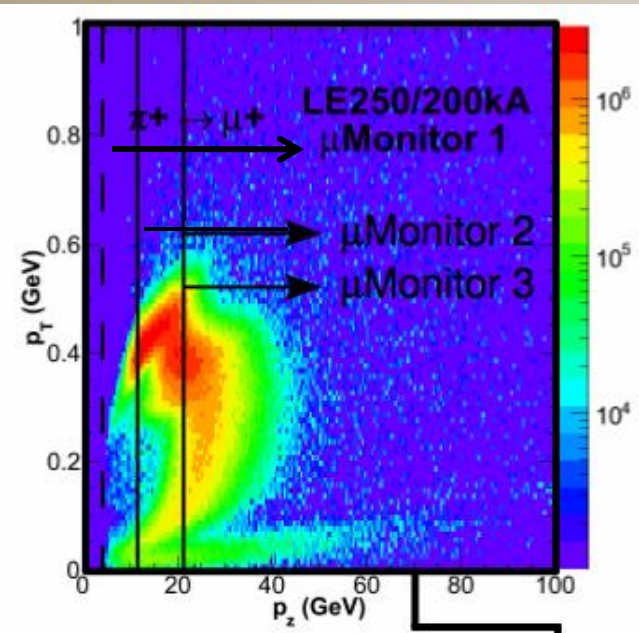


Measuring Flux: Fitting to μMon

We can fit muon monitor data to obtain (x_F,p_T) in the same way we fit MINERvA data



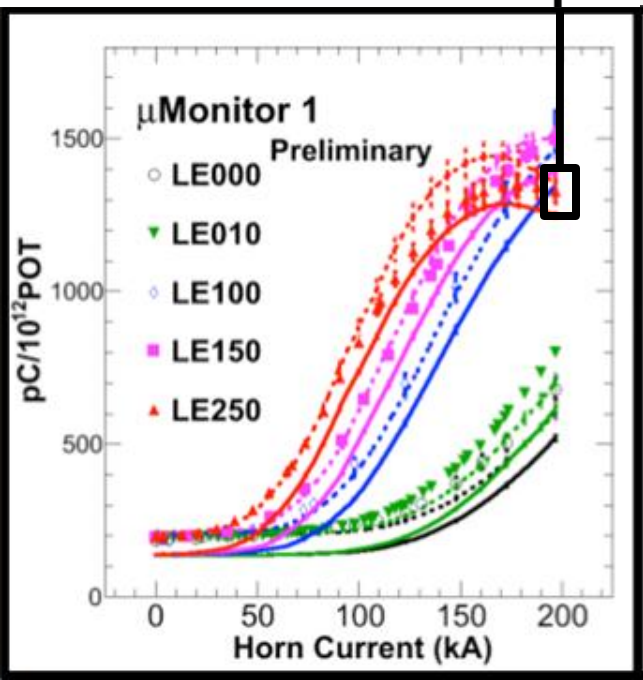
Measuring Flux: Fitting to μMon

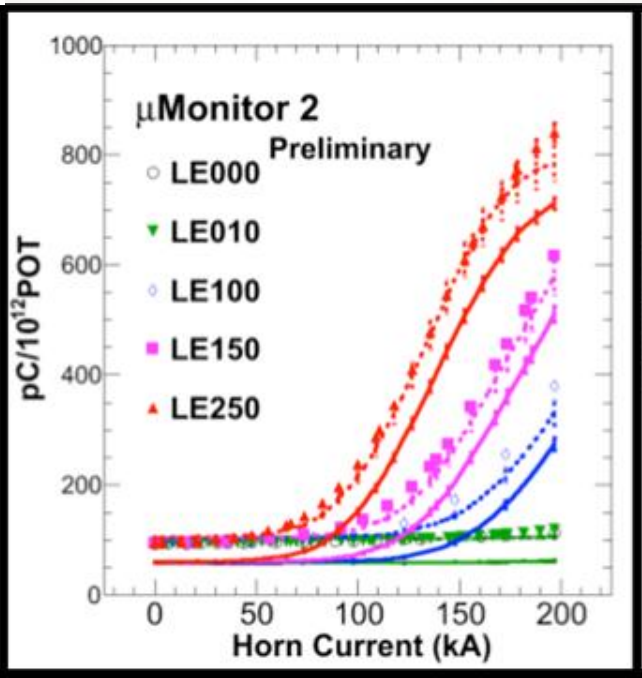


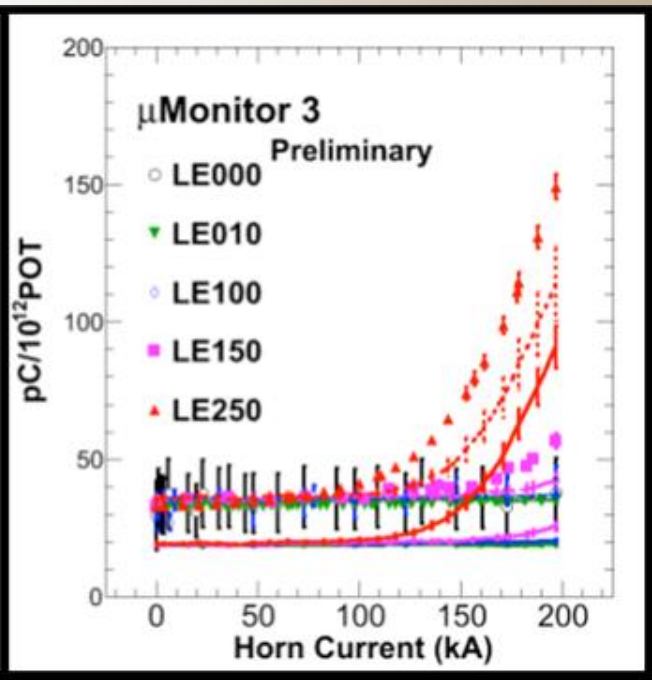
Successfully tuned MC to match μMon data

- Empirical parameterization for hadron production
- Warp p_T and p_z to tune MC to μMon data
- Allow π^+ parameters to float
- Fix π^+/π^- ratio to NA49 and fix K/π ratio to MC

- Data ——— Monte Carlo – – – Tuned Monte Carlo







Measuring Flux: Fitting to μMon

Obtained a flux shape measurement from its μMonitors

Largest sources of error:

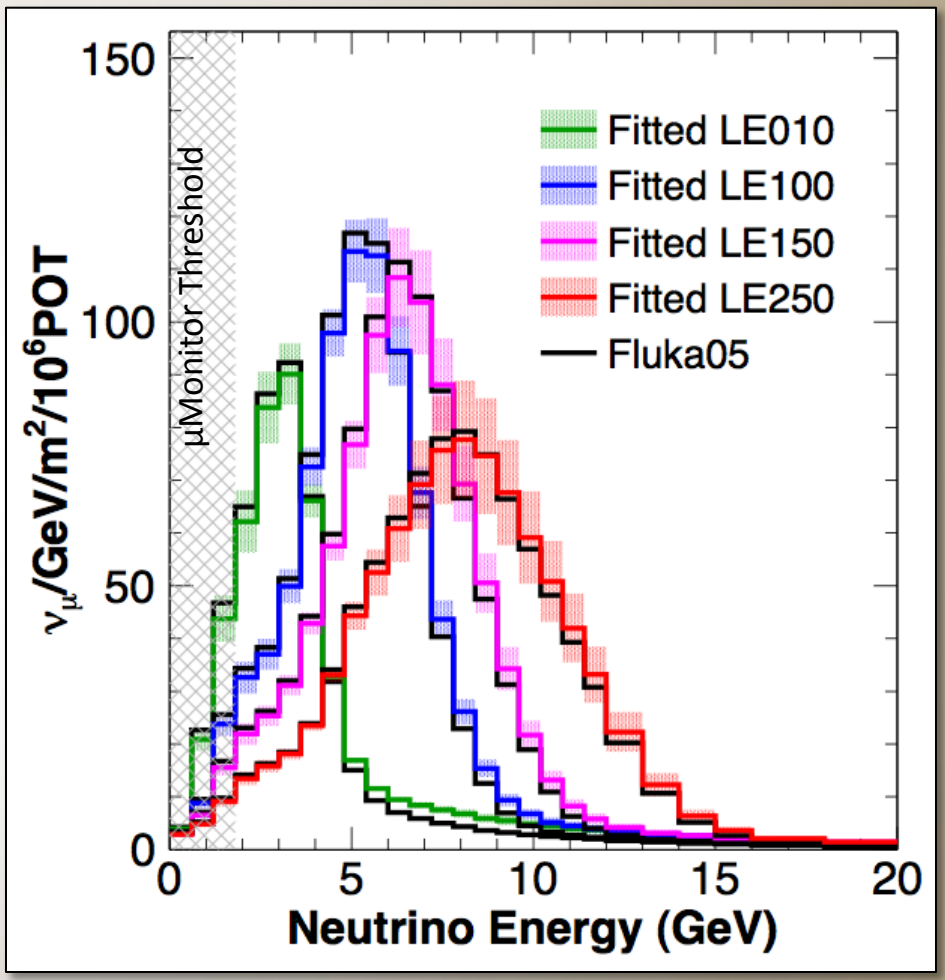
- Delta-rays
- Scaling pC/μ by ± 10%

Other sources of error:

- Bethe-Block energy deposition by μ in He
- Scaling K/π ratio by ± 10%
- Fixing π^+/π^- ratio to MC value
- Scale non-linearity correction in data ± 1σ
- Scale dump backgrounds ± 1σ

Due to large uncertainties, the flux was normalized to MINOS data for $E_\nu > 25$ GeV.

How can MINERvA reduce those uncertainties?



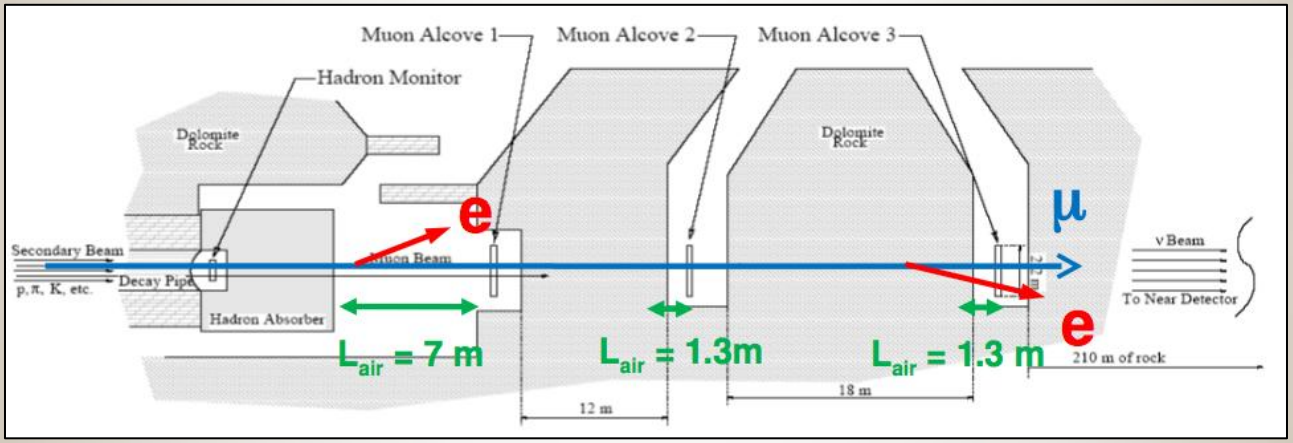
L. Loiacono, "Measurement of the Muon Neutrino Inclusive Charged Current Cross Section on Iron Using the MINOS Detector," PhD Thesis, UT Austin 2010

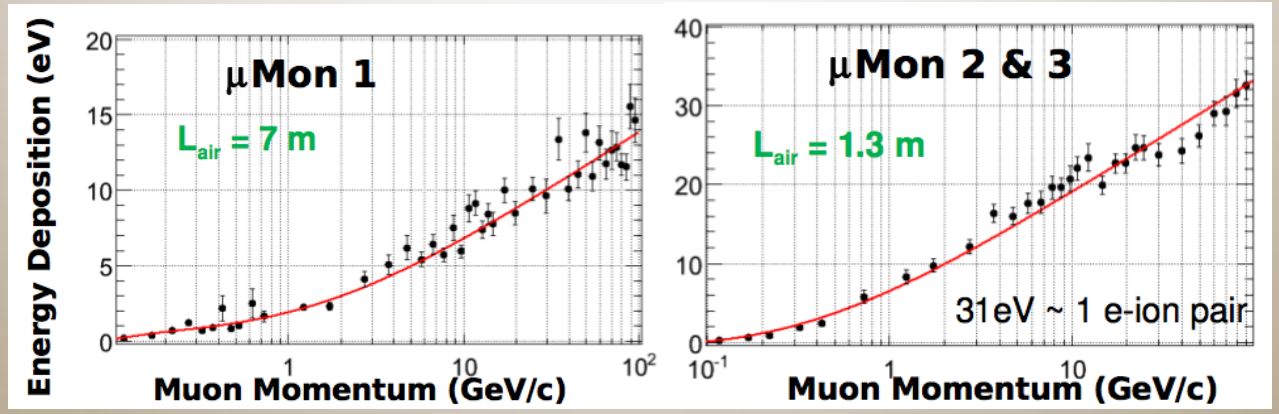
Measuring Flux: Fitting to μMon

Significant backgrounds must be included in the μMon MC

δ-Rays:

- Muons can create knock-on electrons while traveling through the rock, air, ect.
- MC indicates δ-rays can be as much as ~30% of the monitor signal



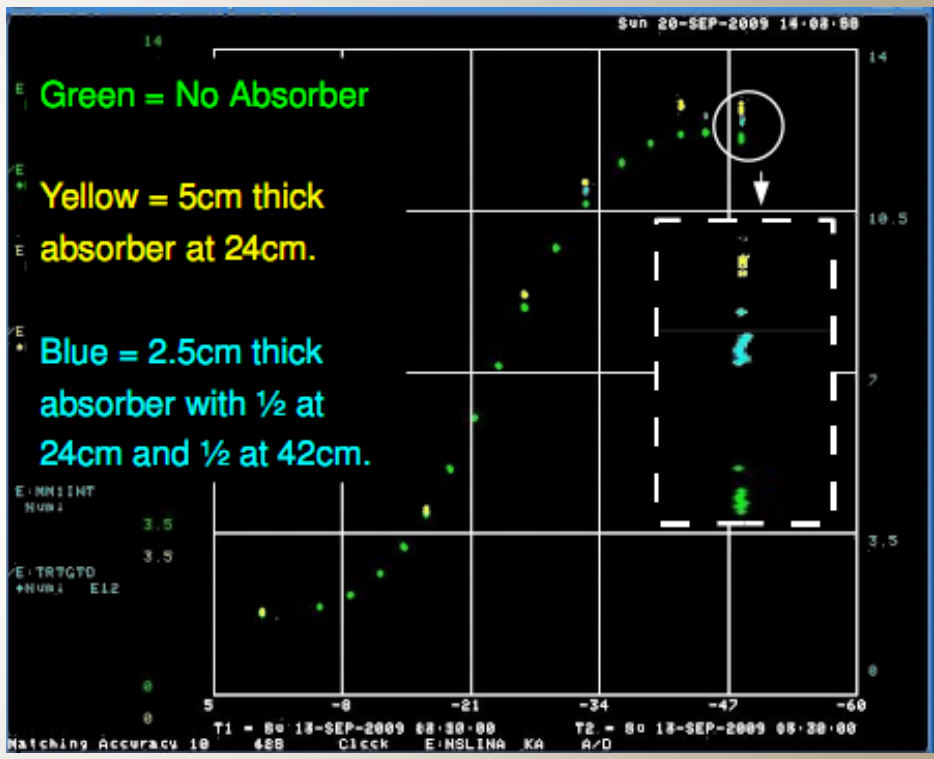


Measuring Flux: Fitting to μMon

Experiment to correct MC δ-ray production by comparing it to data in which we deliberately introduced more δ-rays

- Placed "absorbers" (plates of aluminum) in front of the μMonitors to increase δ-rays

- Al blocks 15 x 15 x 2.5 cm
- 2 absorbers/curtains (set of 45 blocks): located 24 cm and 42 cm in front of monitor



δ rays increase with absorber thickness and decrease with separation between absorber and monitor

Measuring Flux: Summary

MINERvA has multiple tools available to understand its flux:

- *In situ* measurements provide checks against external hadron production measurements
- NuMI's flexible beam design allows us to map out hadron production in (xF,pT), and we can measure our flux *in situ* using two techniques:
    1. Fits to QEL data in MINERvA
    2. Fits to muon monitor yields
- MINERvA will augment and upgrade our muon monitor system to provide more constraints
- MINERvA's initial estimated flux uncertainty is ~30%, and by performing these studies we can reduce it to 5-10%

The entire MINERvA collaboration thanks NuInt and its organizers for the opportunity to give these presentations.

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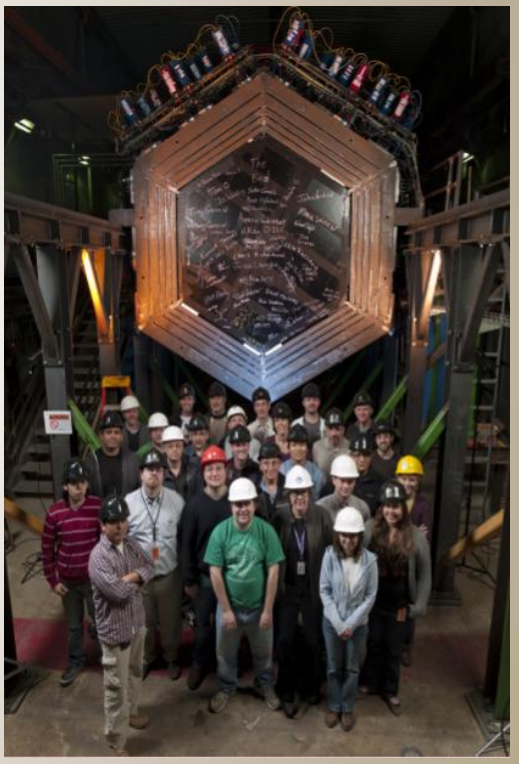


Refereces

S. Kopp, *"Accelerator Neutrino Beams,"* Phys. Rep. 439, 101 (2007)

M. Kostin *et al*, "Proposal for continuously-variable neutrino beam energy for the NuMI facility," Fermilab-TM-2353 (2001).

Proc. Informal Workshops on Neutrino Beams: CERN-63-37, CERN-65-32, CERN-69-28

S. Kopp *et al*, "The Secondary Beam Monitoring System for the NuMI Facility at FNAL," accepted in *Nucl. Instr. Meth.*

Z. Pavlovic, PhD Thesis, University of Texas, 2008

L. Loiacono, PhD Thesis, University of Texas, 2010

Backup slides

Measuring Flux: Fitting to μMon

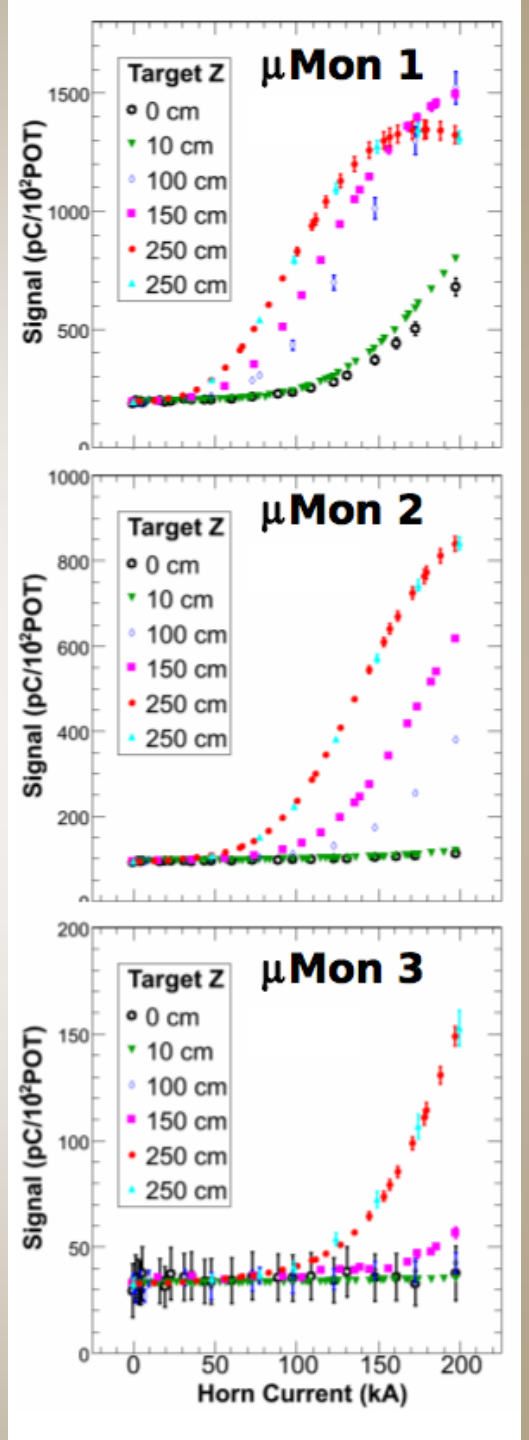
Each data point is the integral of a flux plot from a given beam configuration.

Data needs various corrections:

- Ambient pressure and temperature corrections
- Correction for chamber non-linearity with muon flux intensity
- Relative correction for helium gas quality

Geant4 Monte Carlo needs various corrections:

- Overall scale factor from pC/μ, which can vary 5-10% due to even 20 ppm O_2 contamination of He gas
- Backgrounds need to be estimated



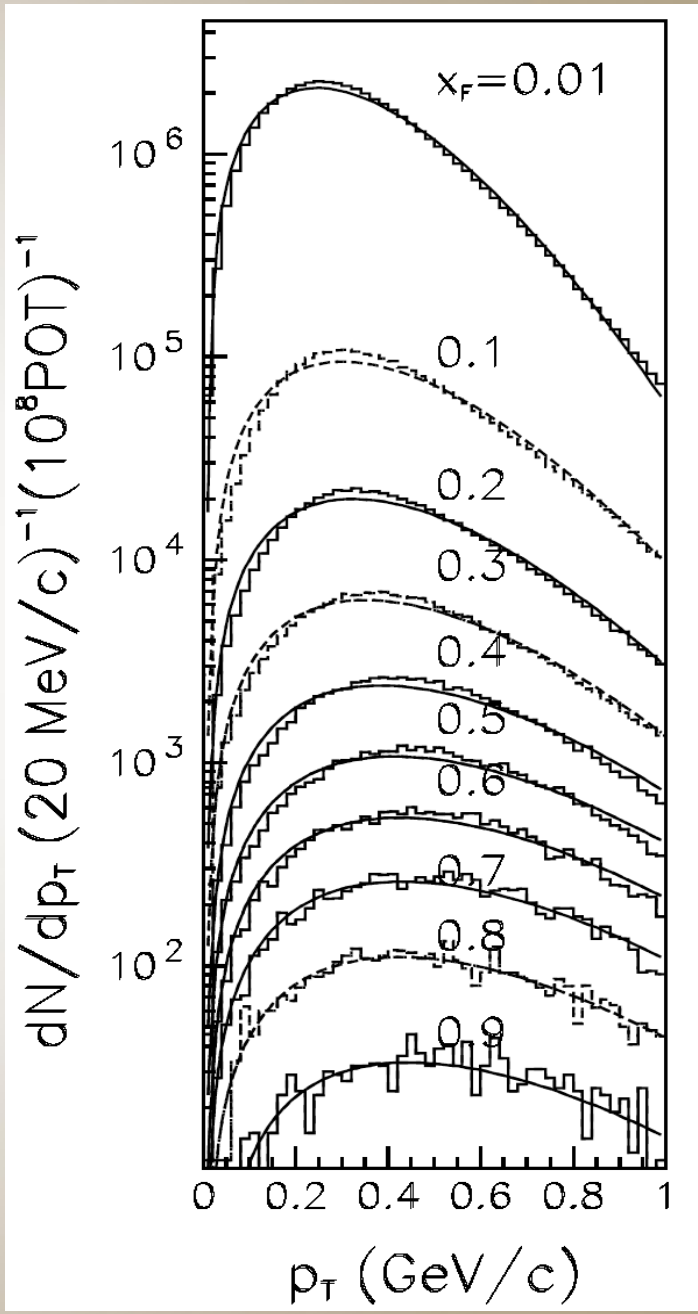
Measuring Flux: Hadron Production

Flexible beam configurations permit *tuning* hadron production yields

Use empirical form *similar* to BMPT to parameterize Geant4:

$$\frac{d^2N}{dx_F dp_T} = \left\{A(x_F) + \left[B(x_F)p_T\right]\right\}e^{-C(x_F)p_T^{3/2}}$$

$$\begin{aligned} A(x_F) &= a_1 * (1. - x_F)^{a_2} * (1. + a_3 * x_F) * x_F^{-a_4} \\ B(x_F) &= b_1 * (1. - x_F)^{b_2} * (1. + b_3 * x_F) * x_F^{-b_4} \\ C(x_F) &= c_1/x_F^{c_2} + c_3 \end{aligned}$$

Tune parameters of the fit to match data in multiple different beam configurations

$$\begin{aligned} A'(x_F) &= (p_1 + p_2 x_F)A(x_F) \\ B'(x_F) &= (p_3 + p_4 x_F)B(x_F) \\ C'(x_F) &= (p_5 + p_6 x_F)C(x_F) \end{aligned}$$