MINOS Flux Determination

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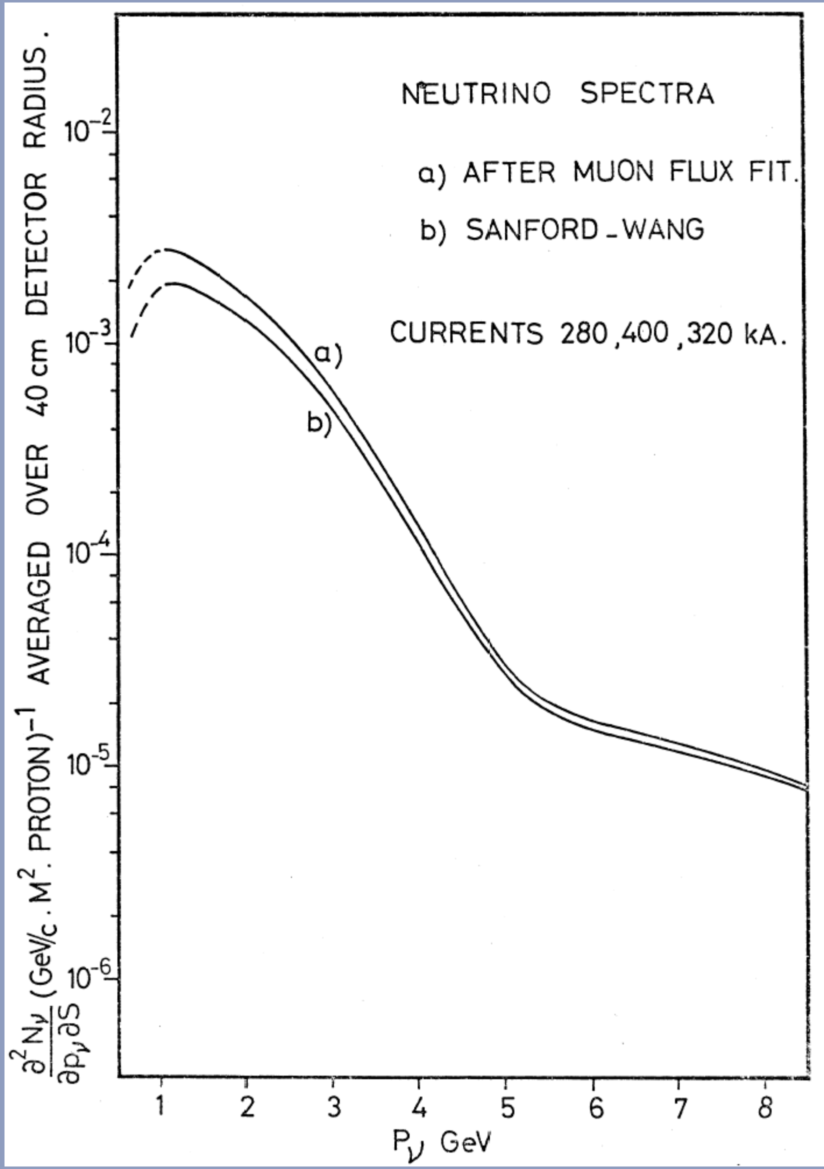
Outline

- Introduction
- MINOS experiment and NuMI beam
- Calculating flux and systematic errors
- Fitting the ND data (Beam tuning)
- Conclusion

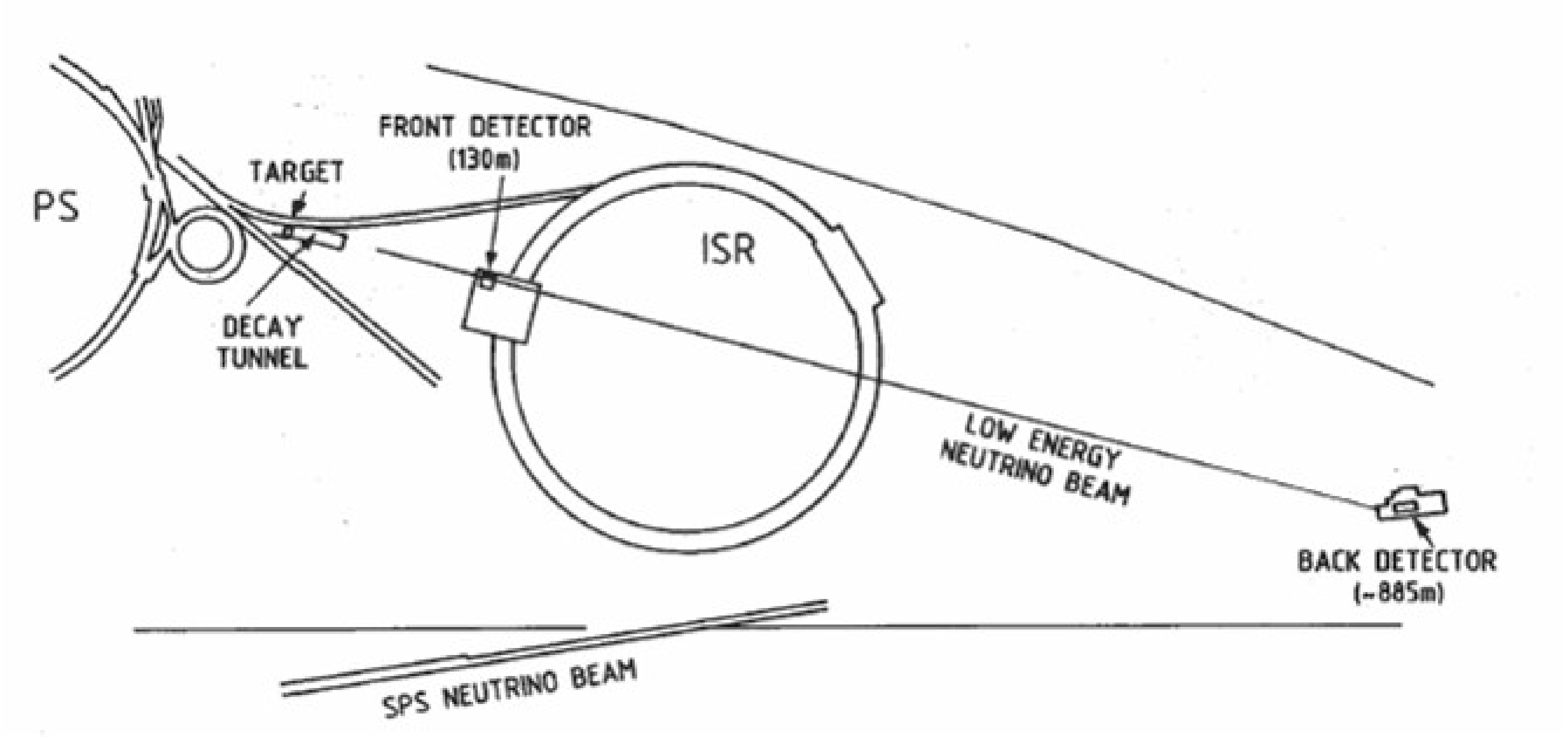
Past neutrino experiments

- Determining flux not easy
  - Use MC simulation
  - Measure in the detector using process with known x-section
- In past, experiments often applied corrections
- Large 10-30% uncertainty



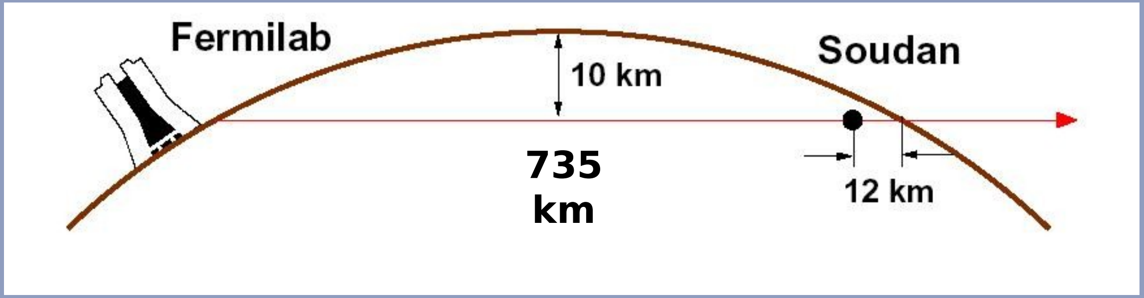
Two detector experiments

- Measure flux at Near Detector to infer flux at Far
- Need to calculate corrections (on top of R^{-2})
  - For MINOS 20-30%

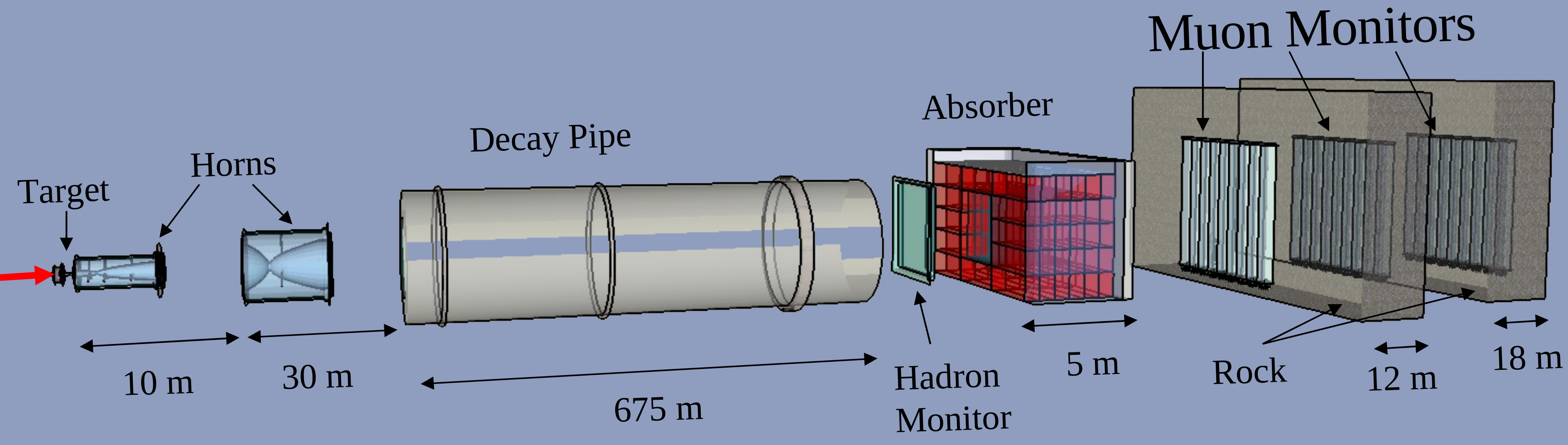


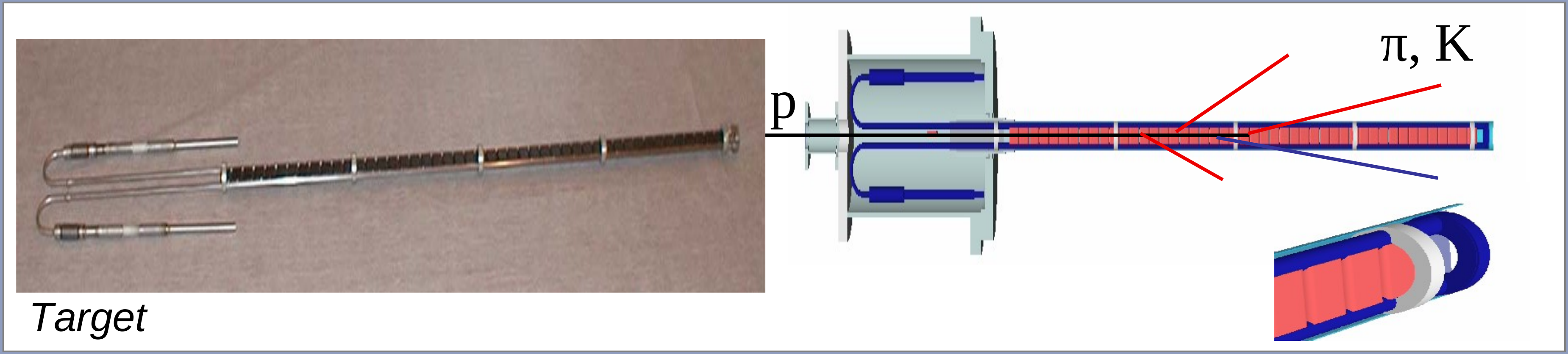
MINOS Experiment

- Two neutrino detectors
- Fermilab’s NuMI beamline
- Verify $\upsilon_\mu \rightarrow \upsilon_\tau$ mixing hypothesis
- Measure precisely Δm^2_{23}
- Test if $\sin^2 2\theta_{23}$ maximal



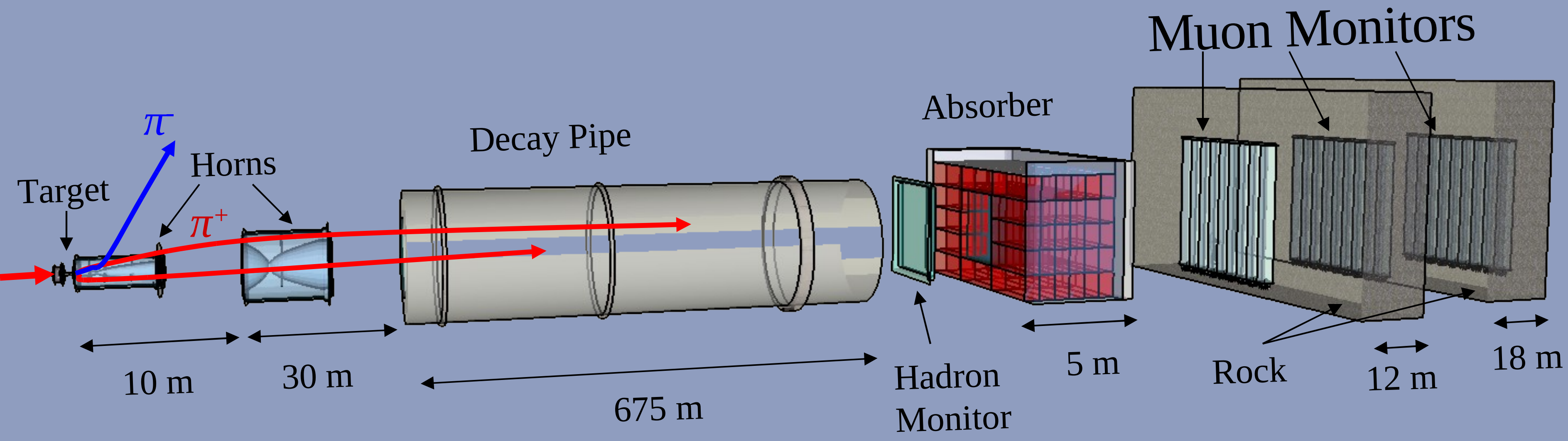
NuMI Neutrino Beamline

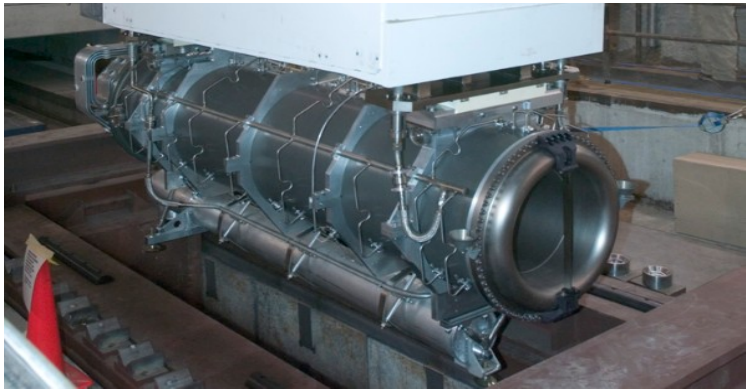


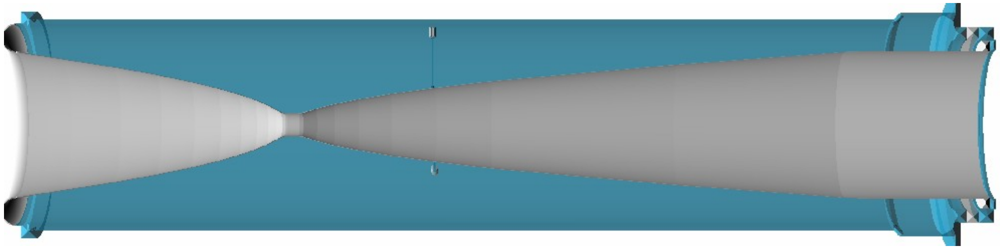


- 120 GeV protons hit graphite target

NuMI Neutrino Beamline



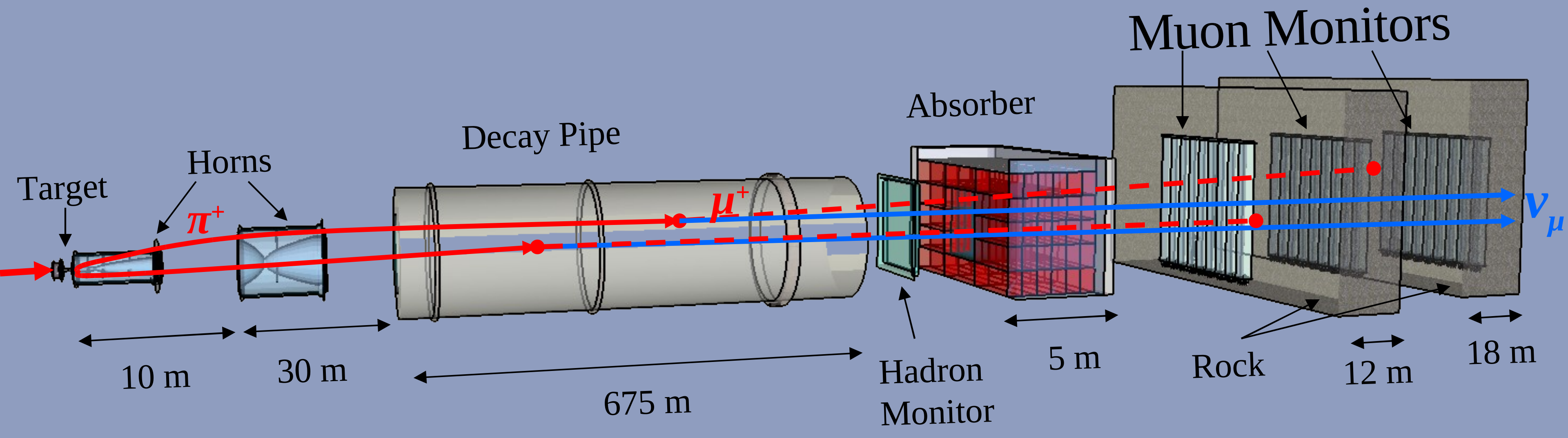




2^{nd} *horn*

- Two magnetic horns focus positive π & K
- Parabolic Horn focal length: $f \approx \frac{2\pi}{\mu_0 I a} p$

Neutrino Beamline



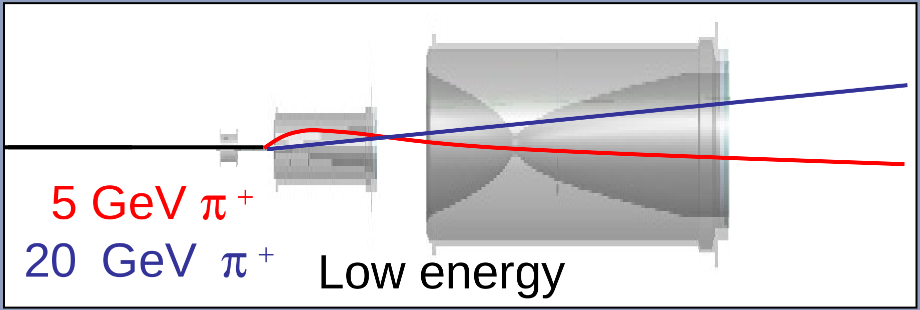
- Mesons decay in flight in decay pipe
- Beam composition (LE10/185kA):
  - 92.9% υ_μ
  - 5.8% $\bar{\upsilon}_\mu$
  - 1.3% υ_e / $\bar{\upsilon}_e$

MINOS Detectors

- Near Detector:
  - 1 km from target
  - 1 kton
  - 282 steel and 153 scintillator planes
  - Magnetized B~1.3T

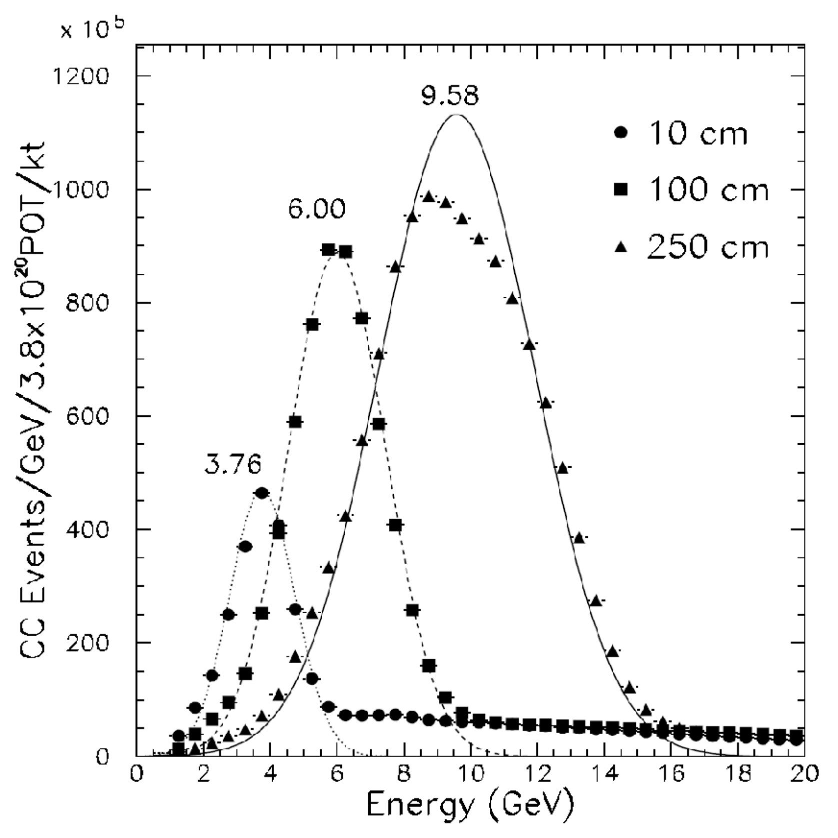
- Far Detector:
  - 735 km from target
  - 5.4 kton
  - 484 steel/scintillator planes
  - Magnetized B~1.3T

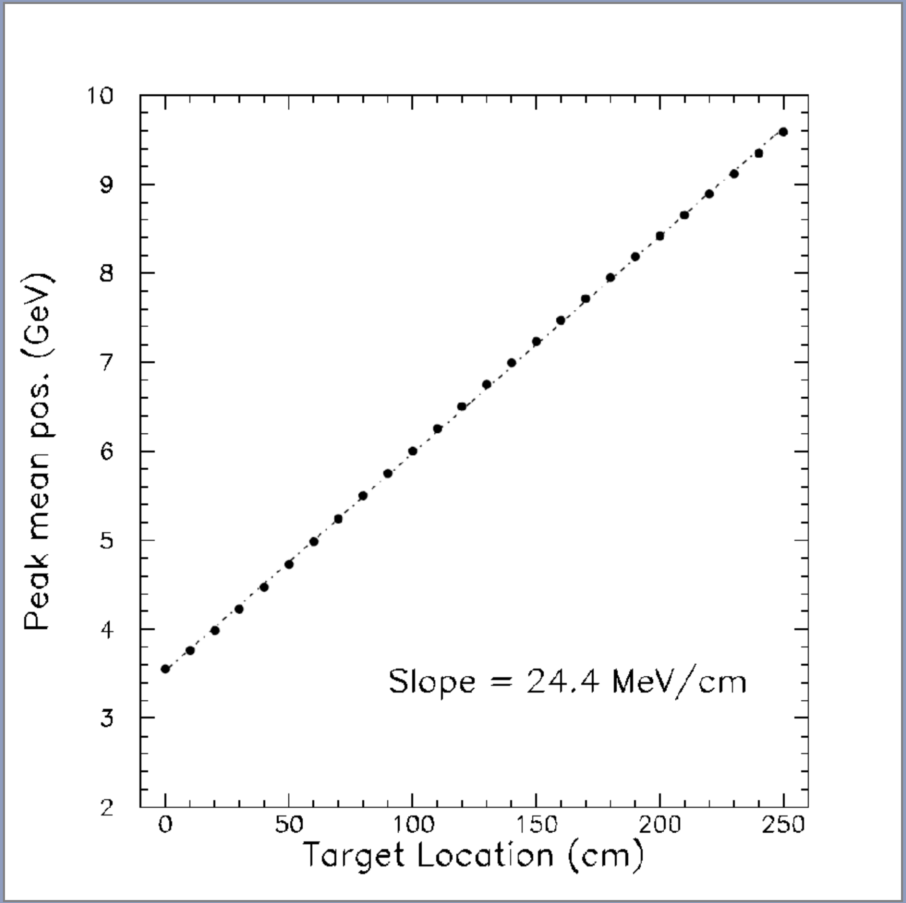
Variable energy beam



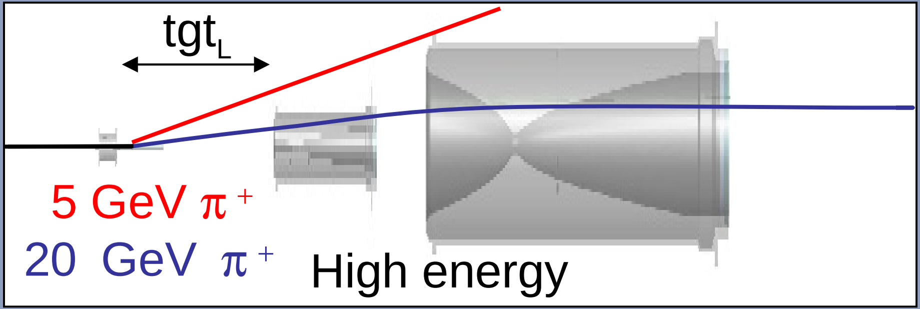
$\tan(\theta) \approx \langle p_T \rangle / p_z = r_{Horn} / tgt_L$

$E_\nu \sim p_Z \sim tgt_L$





Variable energy beam



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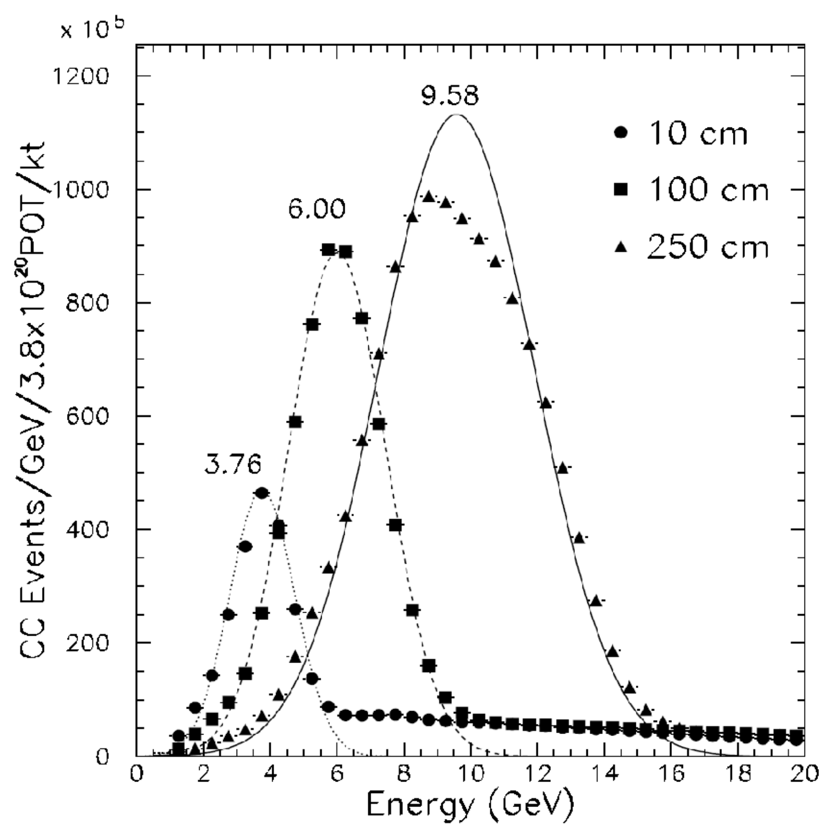
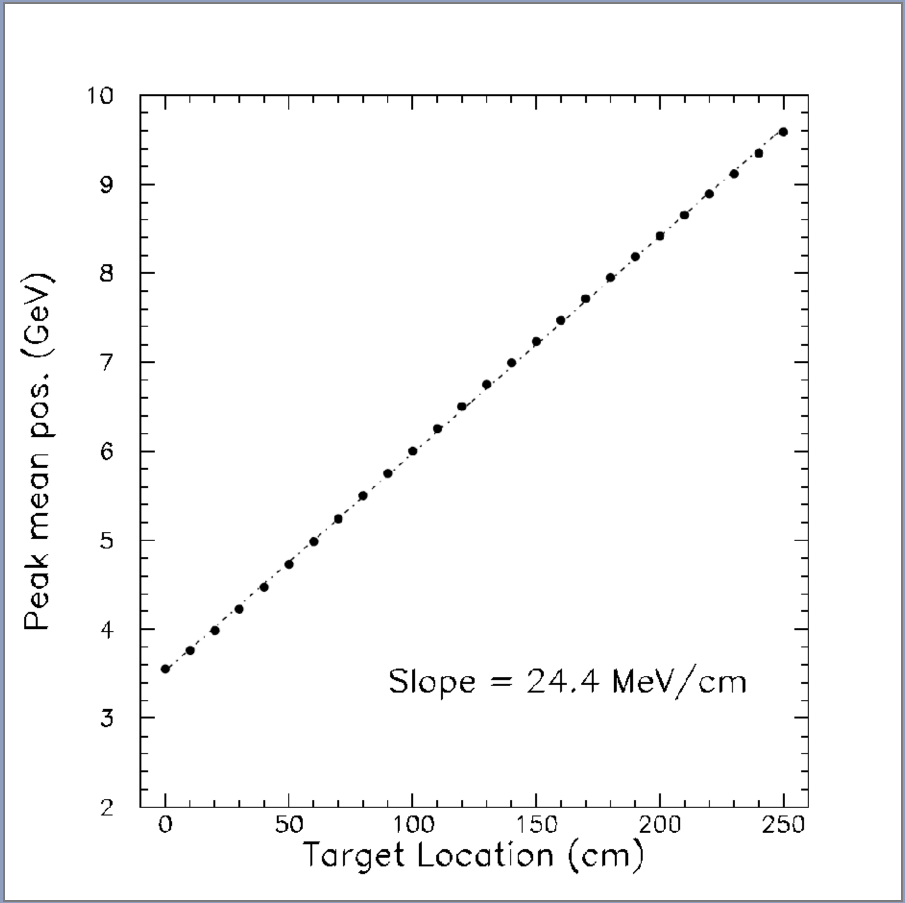
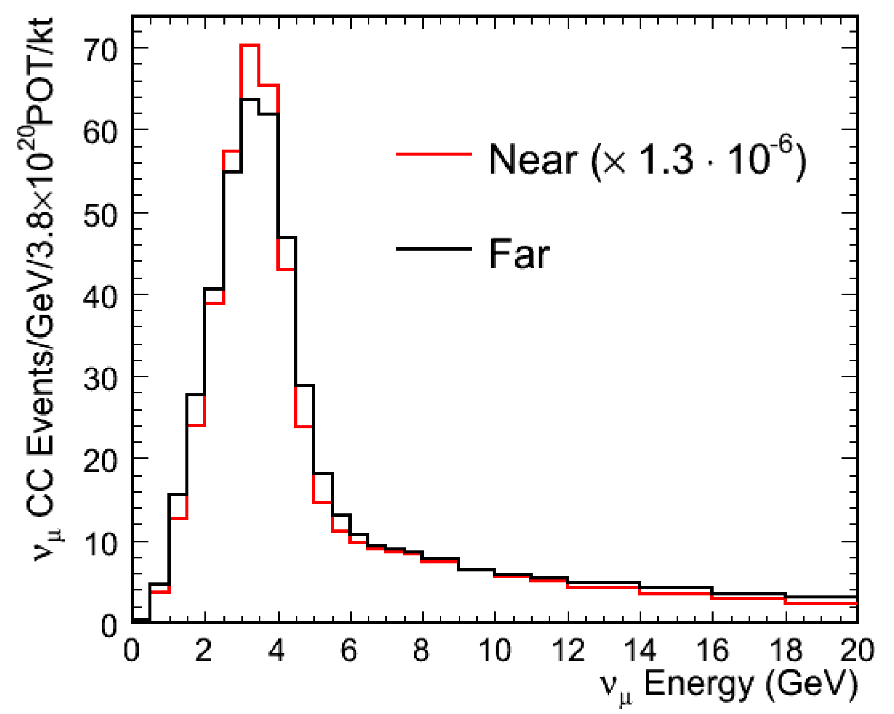


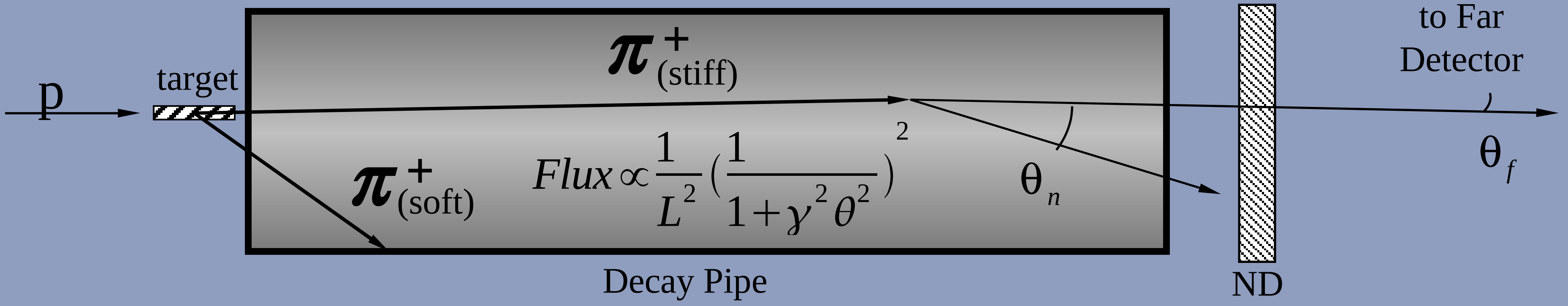


Near and Far Spectra

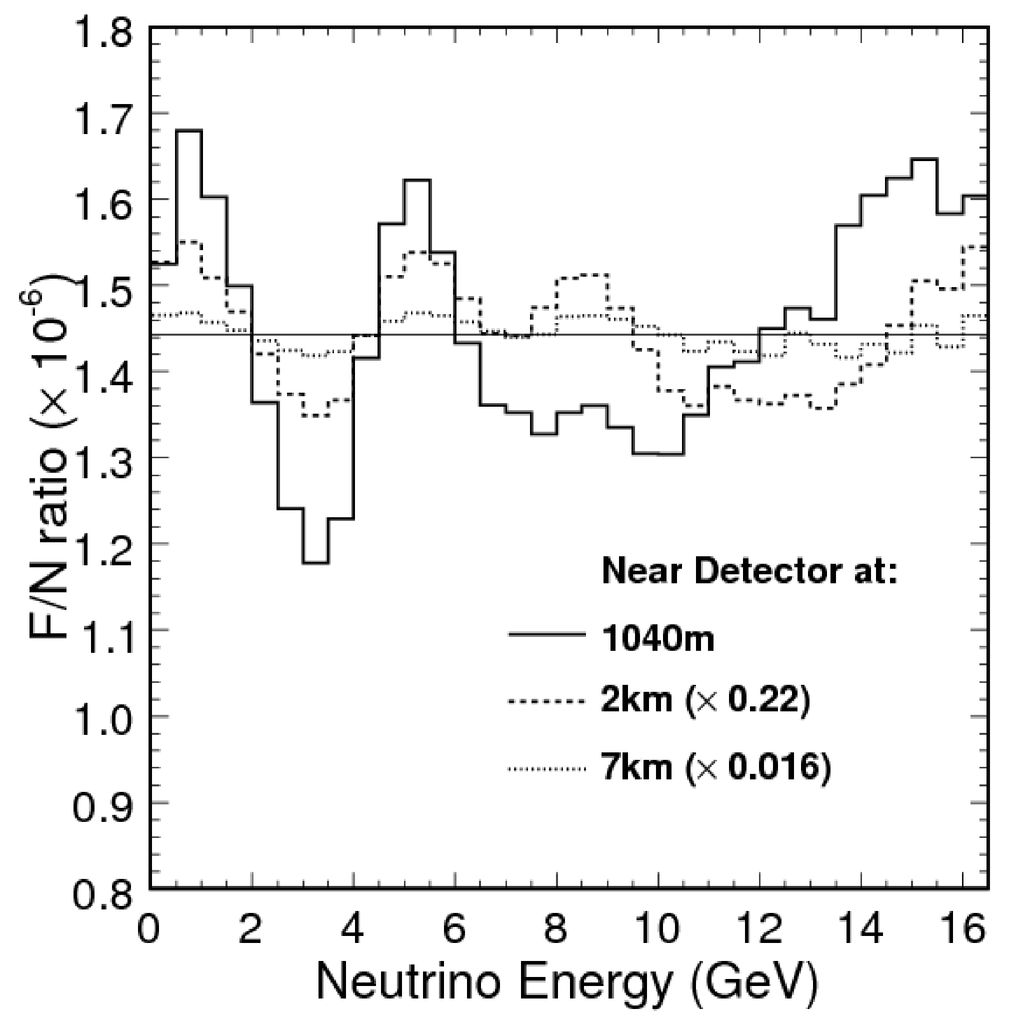
- Flux at Near and Far detector not the same
- Neutrino energy depends on angle w.r.t parent momentum

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





Far/Near ratio



- 20-30% correction on top of R^{-2} for ND at 1km

- For ND at 7km corrections at 2% level

Study of Beam systematics

- Non-hadron production
  1. Proton beam
  2. Secondary focusing modelling
  3. MC geometry
- Hadron Production

NB: Much of the inputs backed up with beamline instrumentation

1. Proton Beam

- Beam position and width can change the neutrino flux:
  - protons missing the target
  - reinteractions in target
- Use profile monitor measurements to correct MC

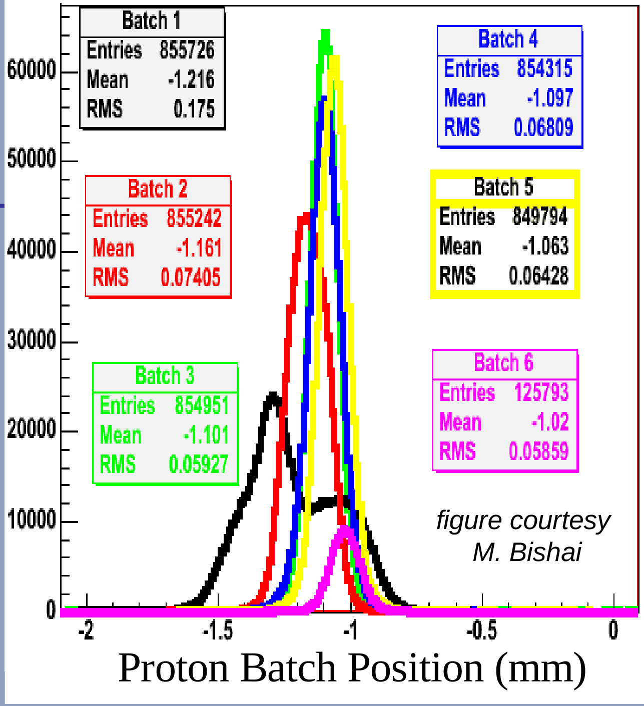
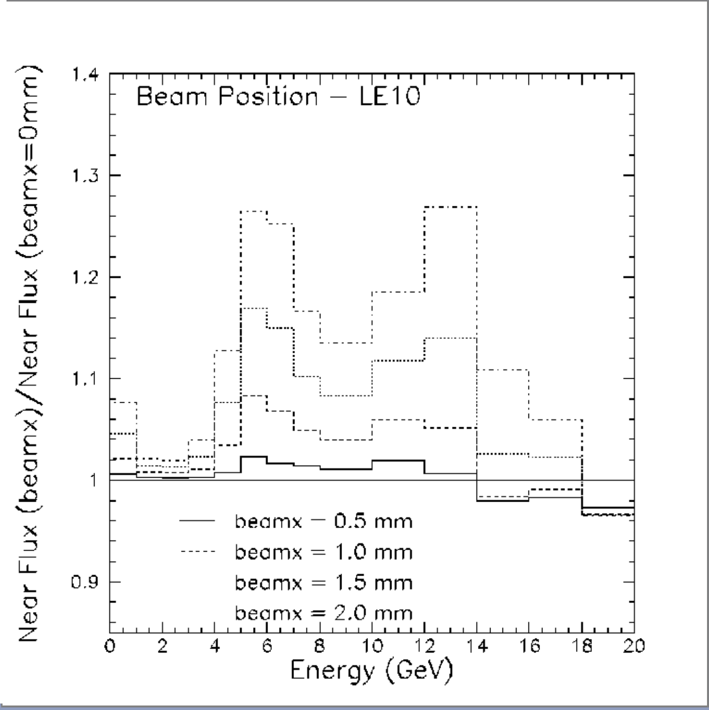
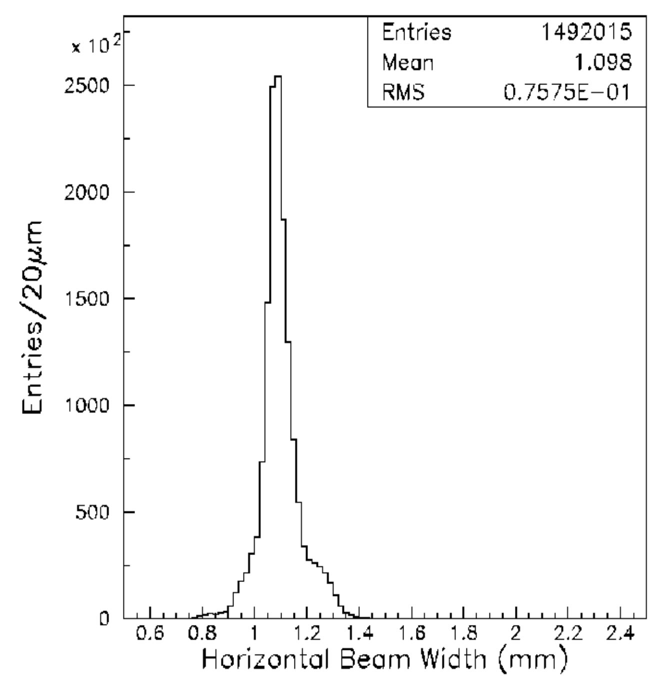
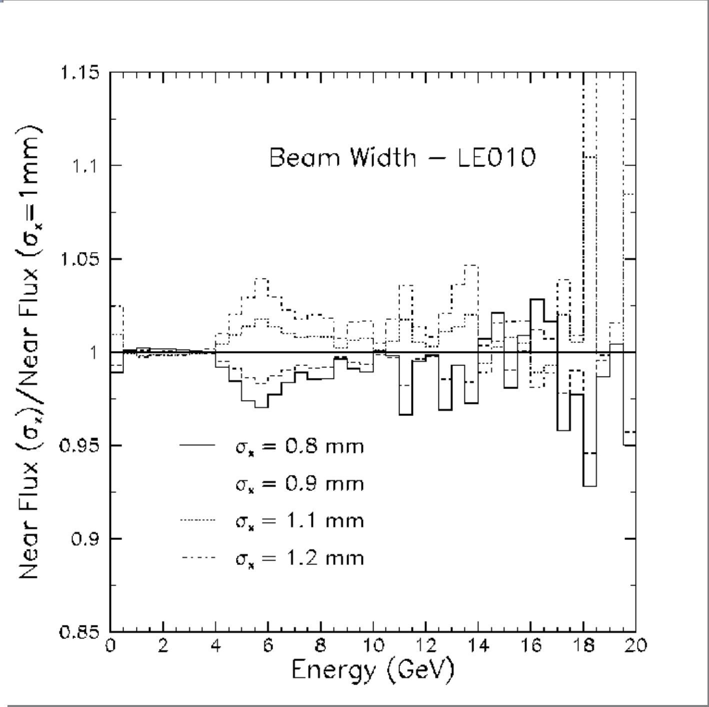


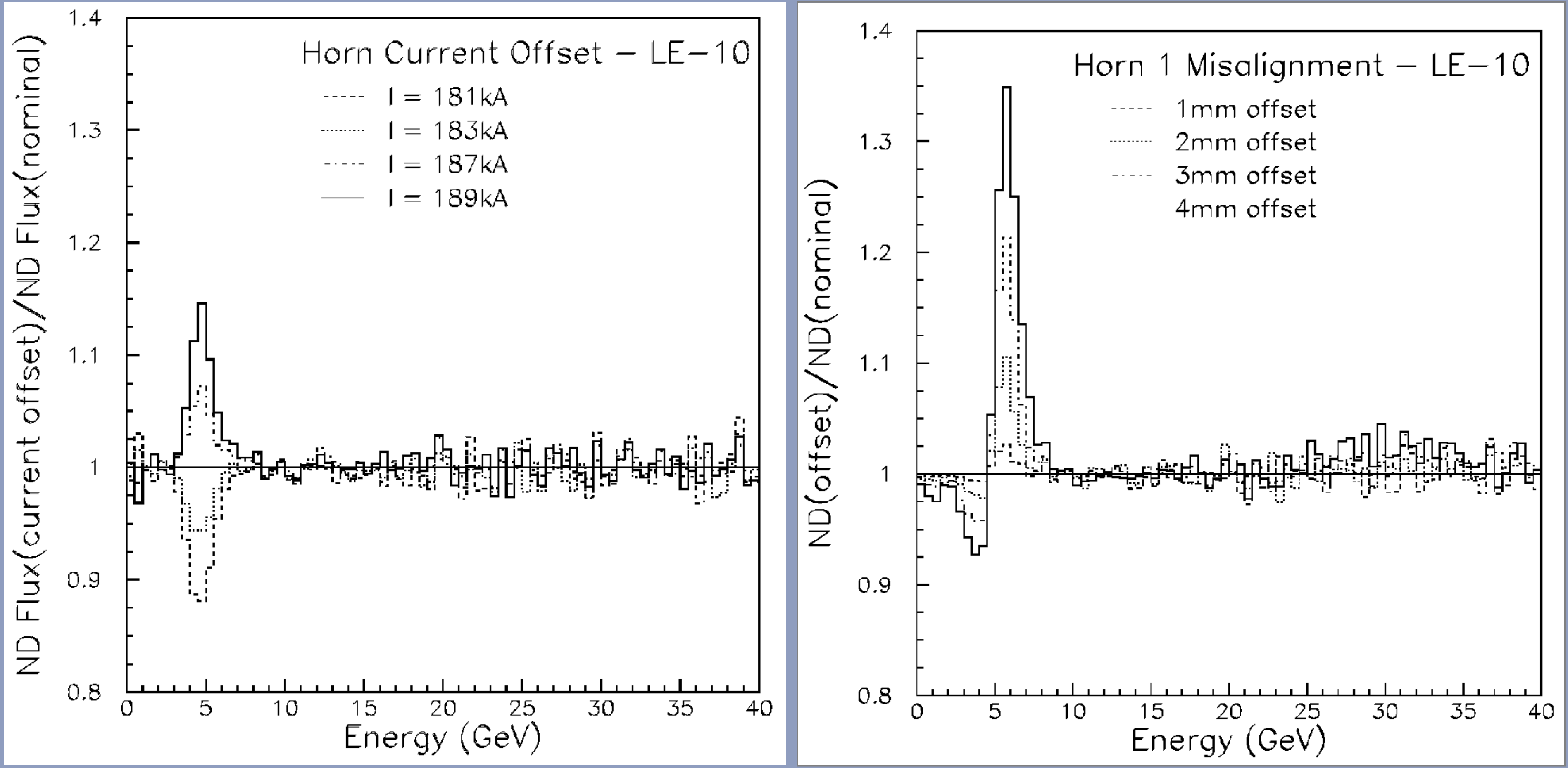
figure courtesy M. Bishai





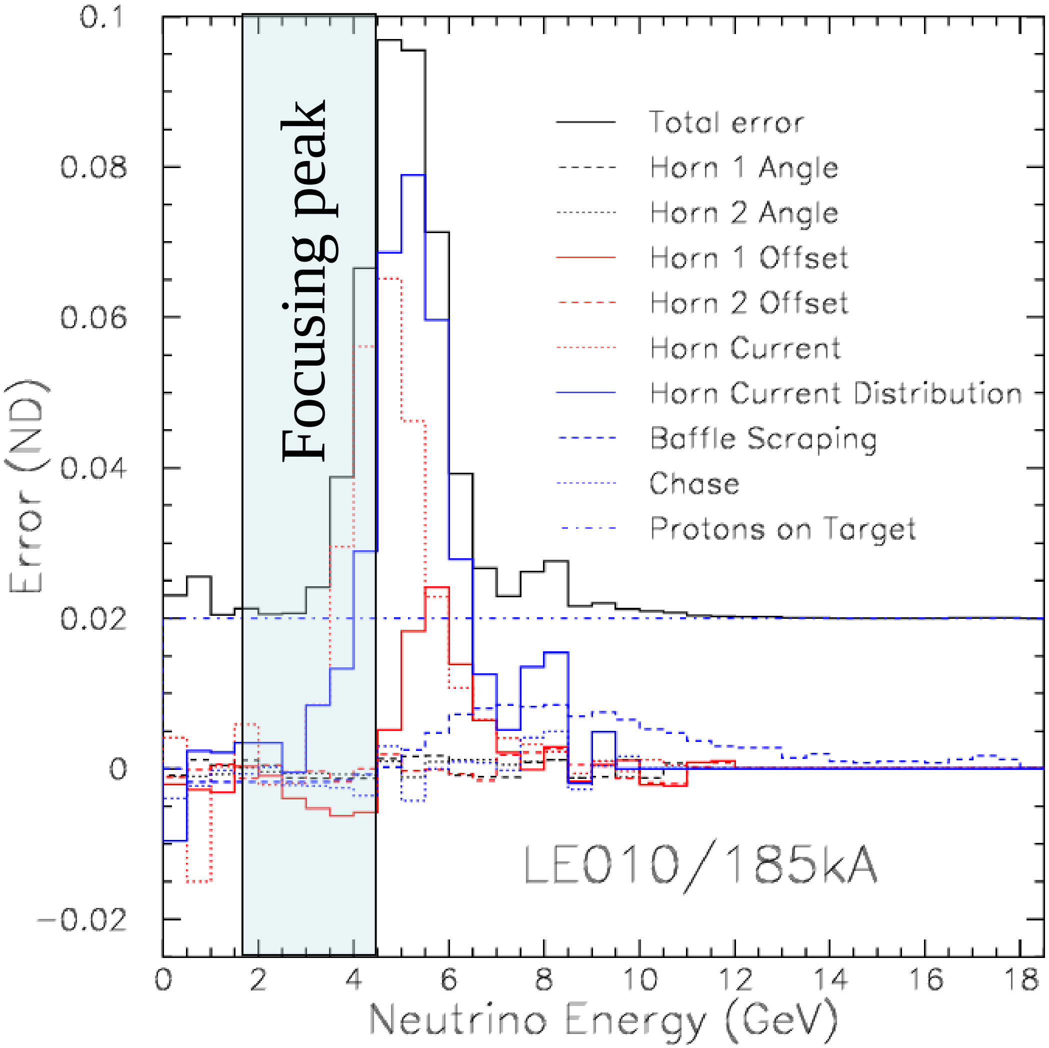


2. Modelling of Focusing



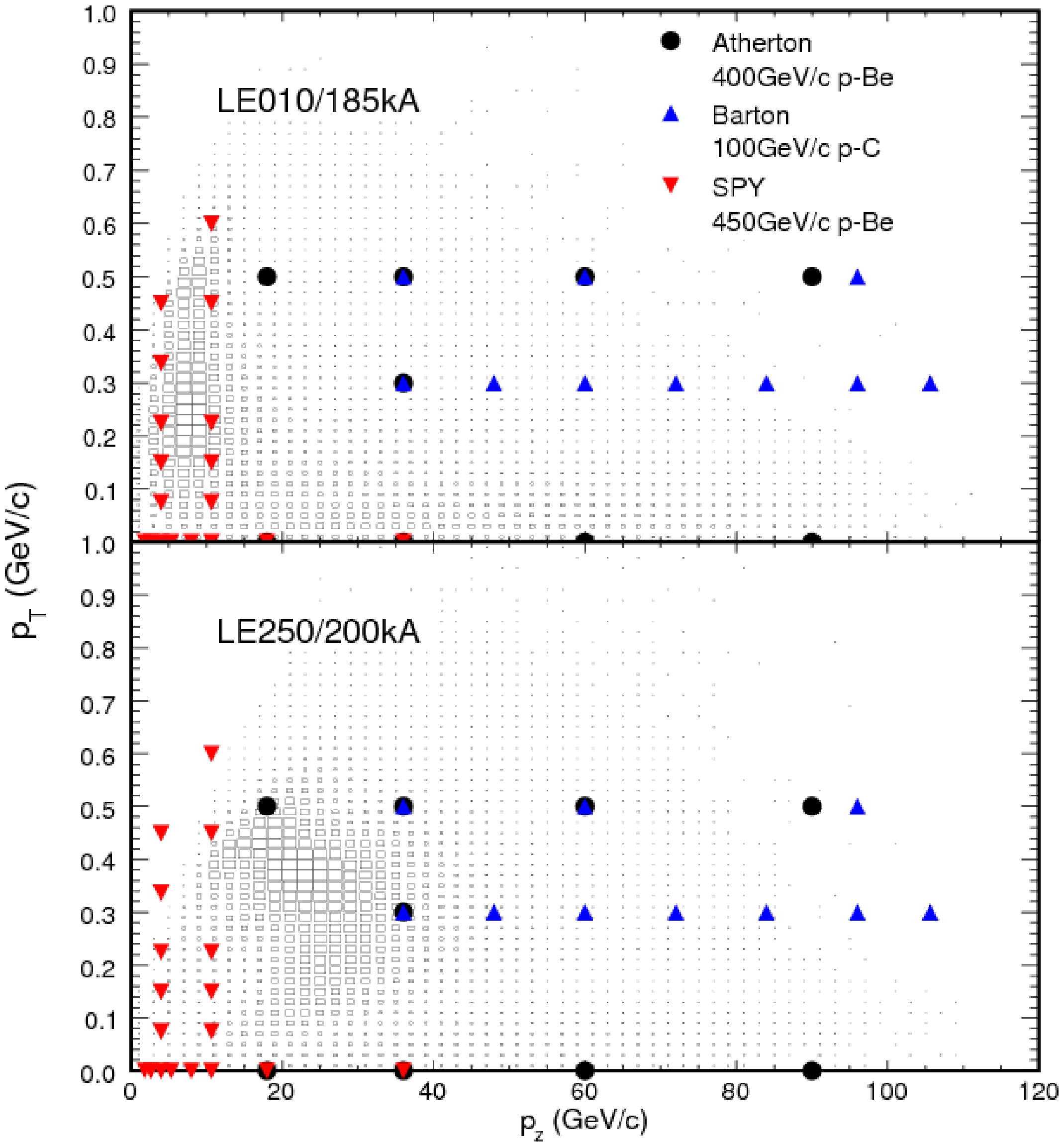
- Also studied: Horn current miscalibration, skin depth, horn transverse misalignment, horn angle

Focusing uncertainties



- Misalignments & miscalibrations
- Input from beamline instrumentation
- Affects falling edge of the peak

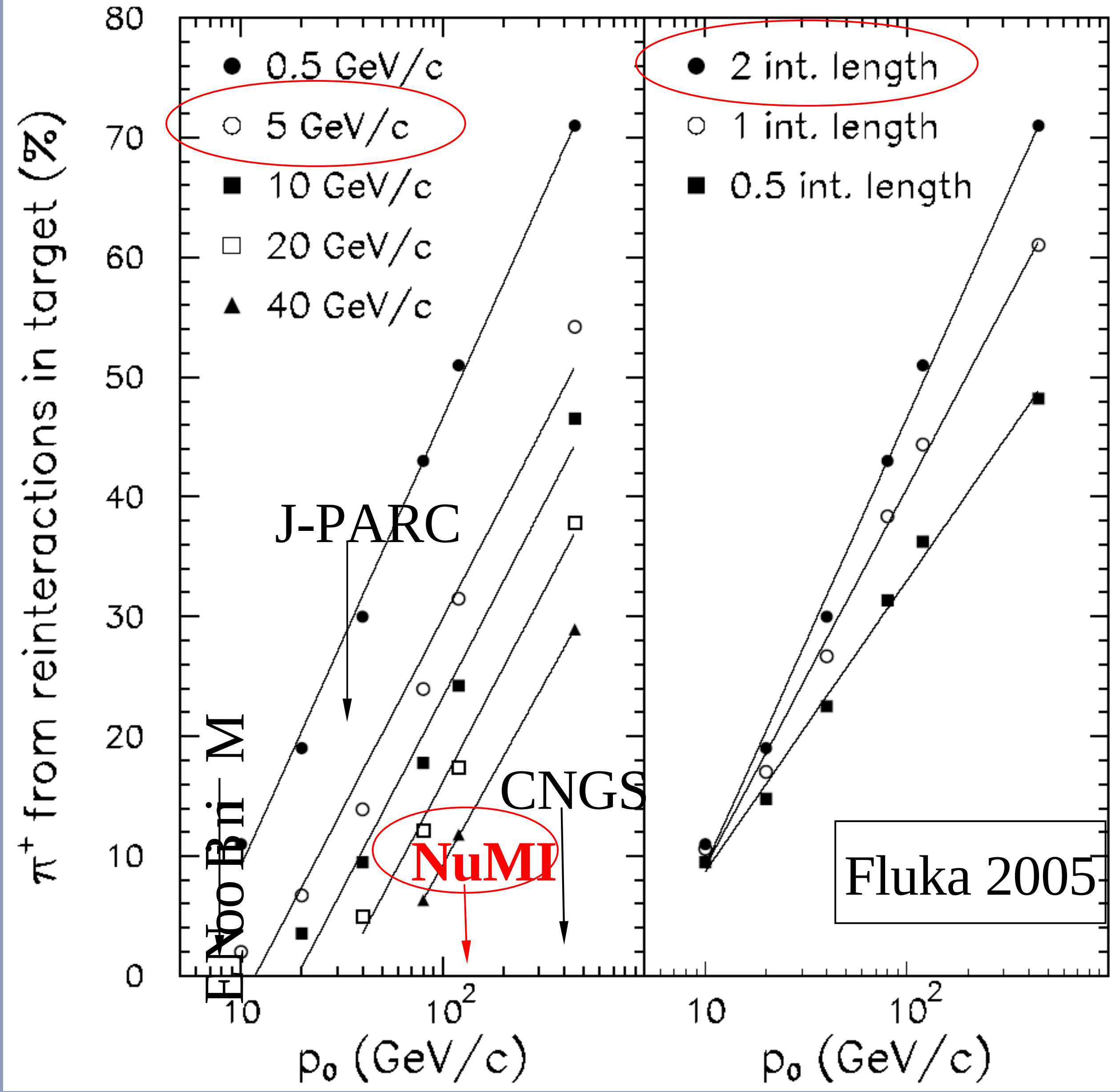
Hadron production



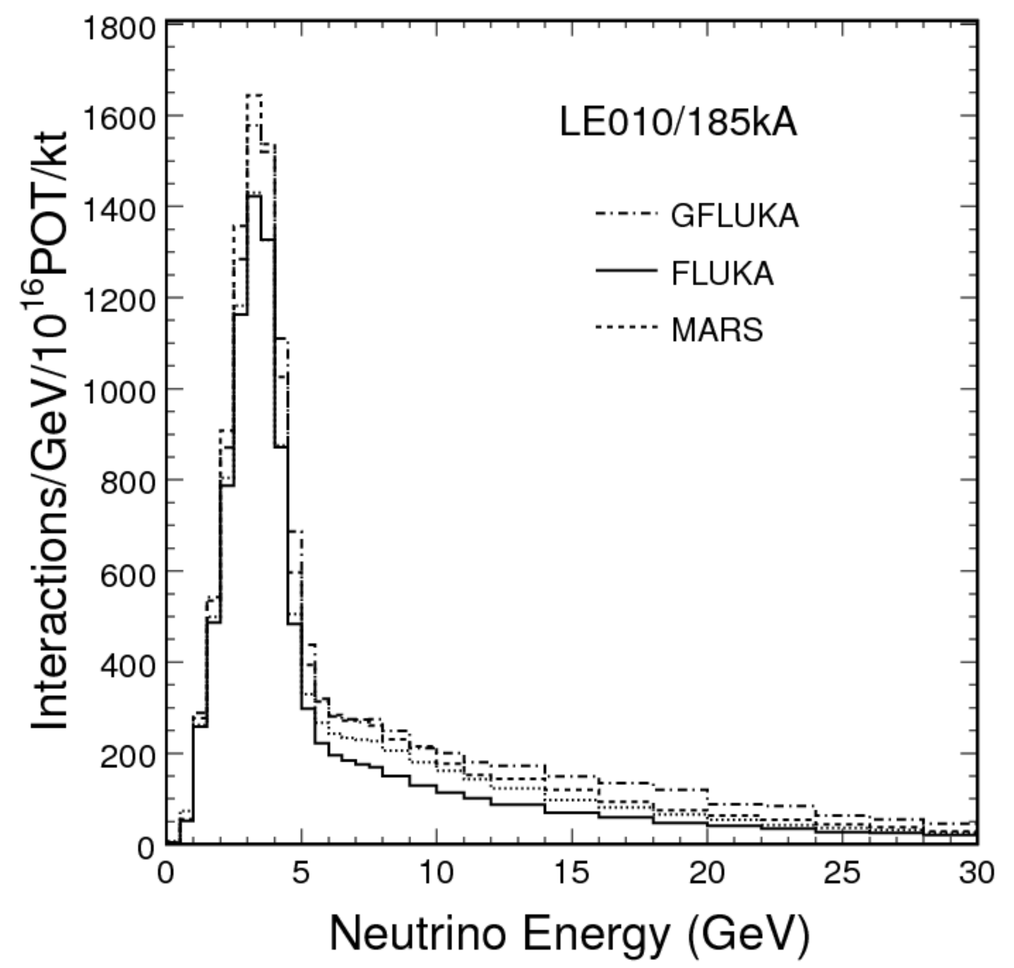
- Proton beam momentum
- Target material
- Thick target

Thick-Target Effects

- Hadron production data largely from ‘thin’ targets.
- Particles are created from reinteractions in NuMI target.
- Approx 30% of yield at NuMI p_0=120 GeV/*c*



Cascade models

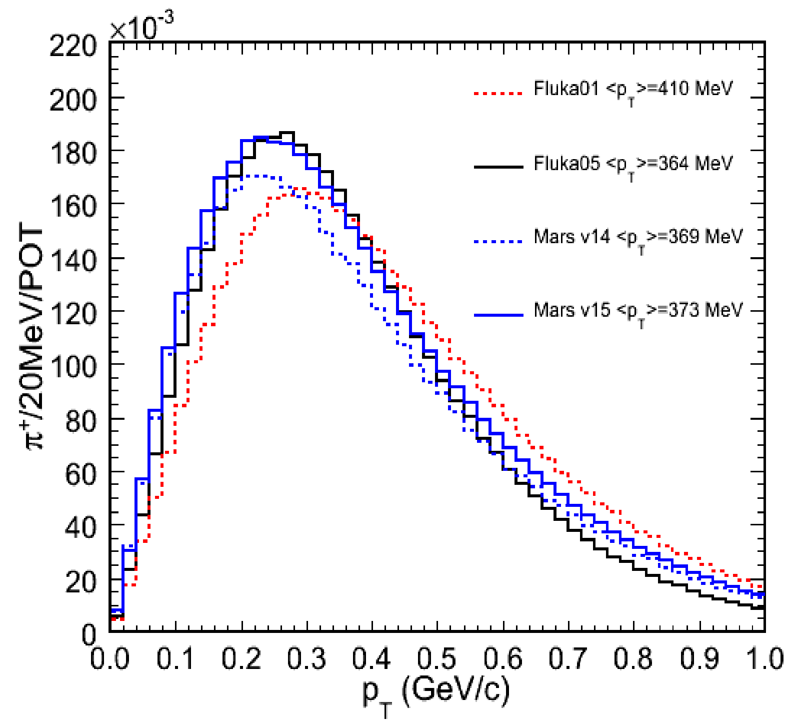


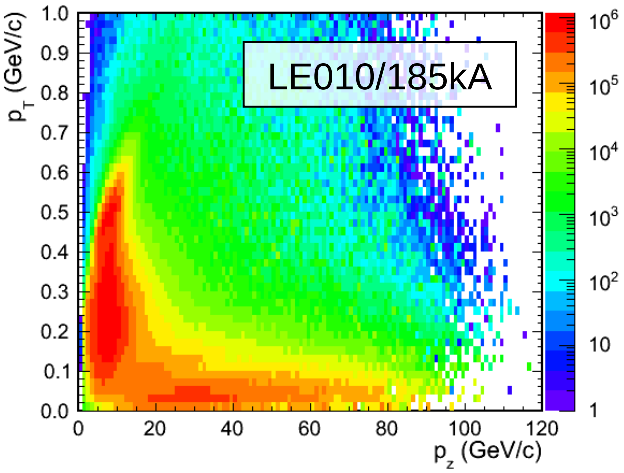
- Variation in calculated flux depending on the cascade model

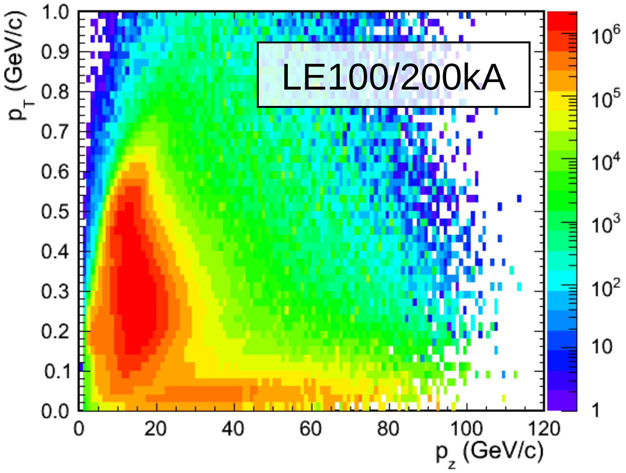
- Indicates ~8% uncertainty in peak and ~15% in high energy tail

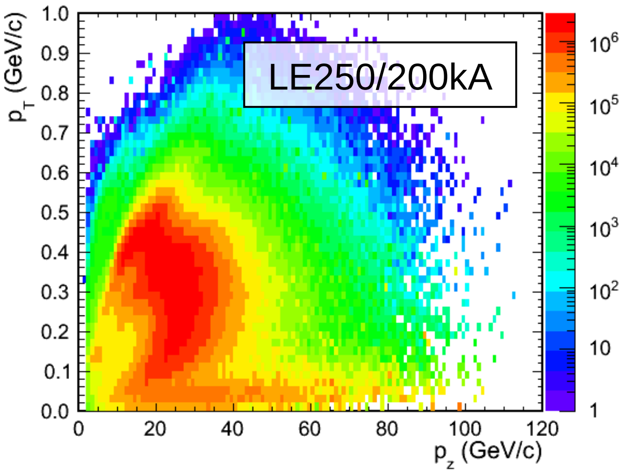
Underlying Hadron Production

- Different beams access regions of π's (x_F,p_T) off the target.
- Models disagree on these distributions
- Use variable beam configurations to map this out.

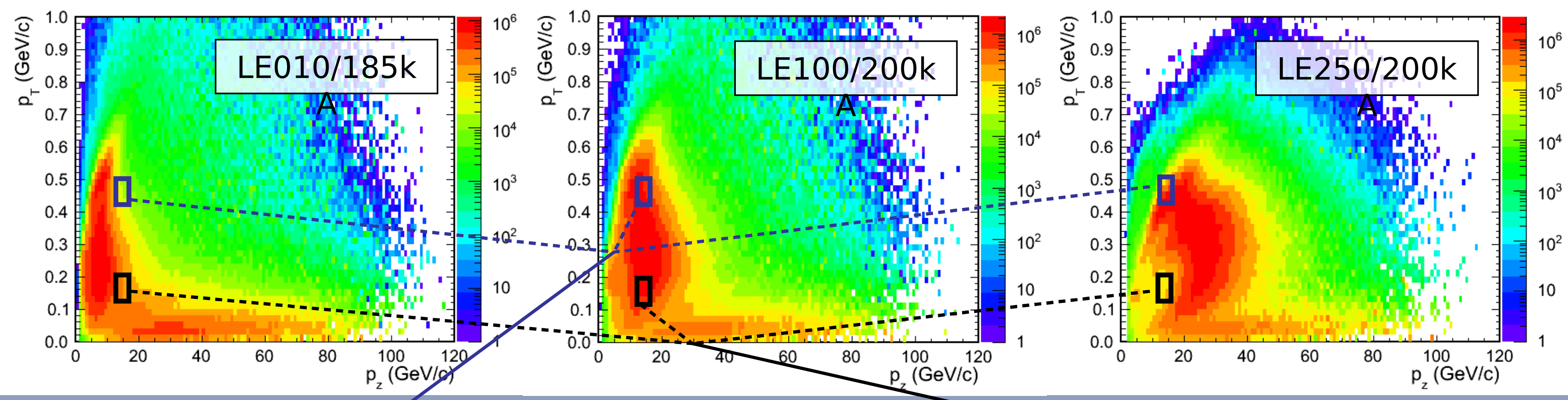


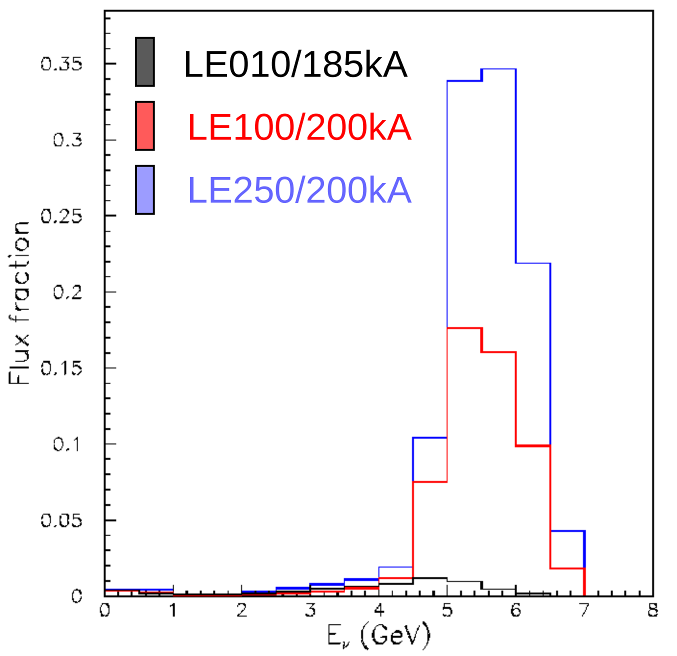




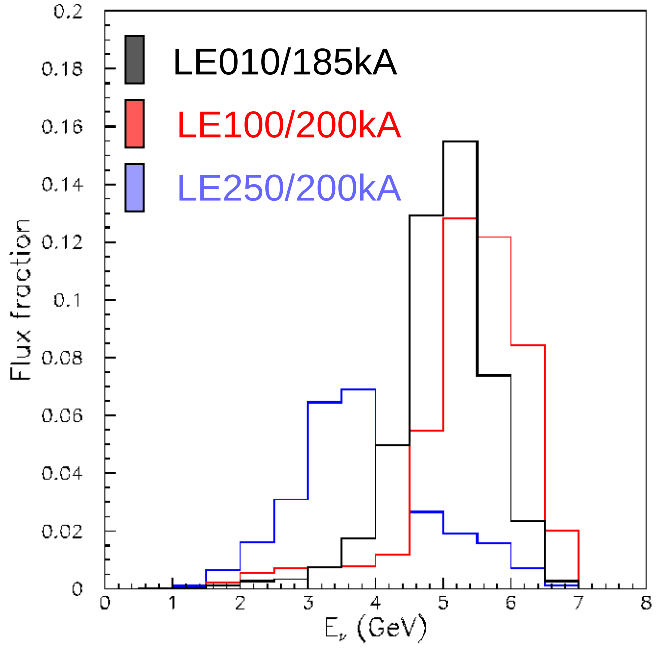


Hadron Production

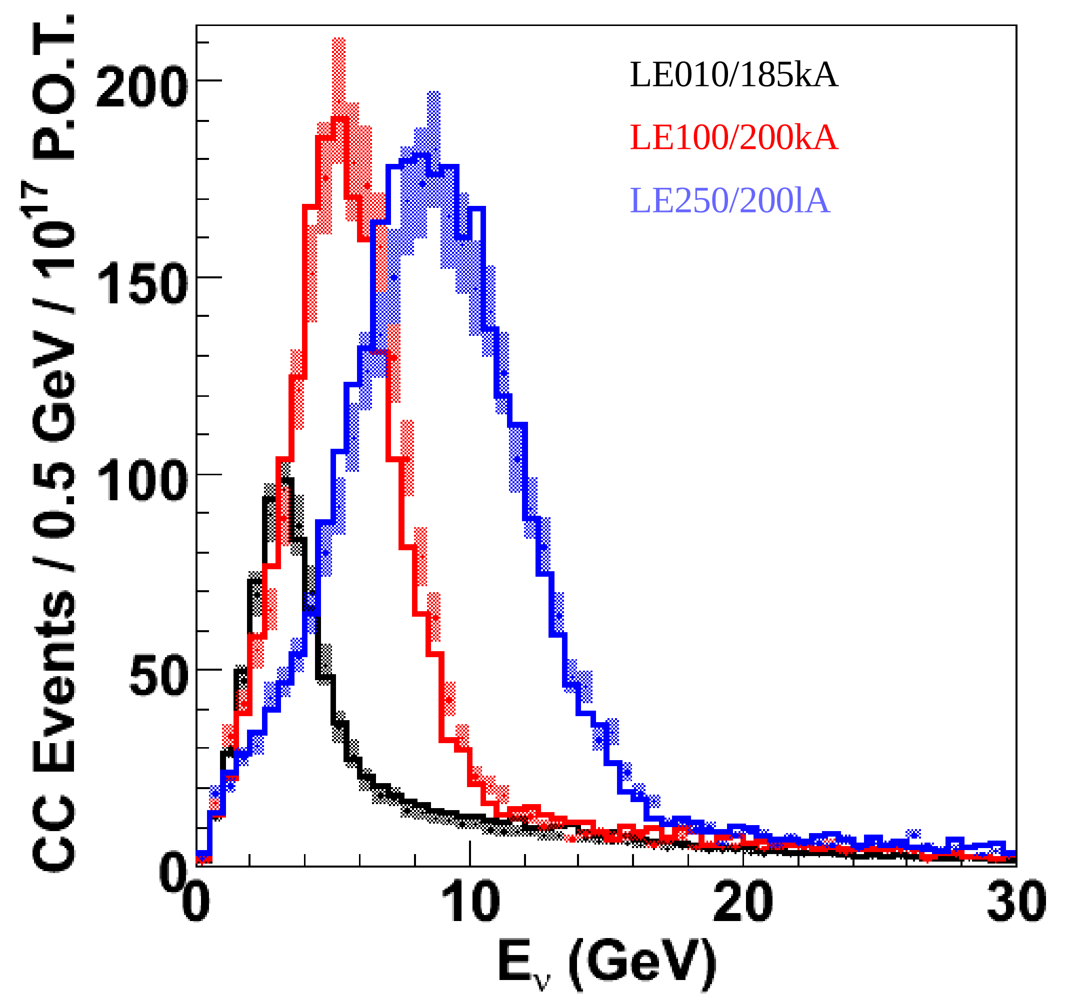




- Same pT-xF bin contributes differently to different beams

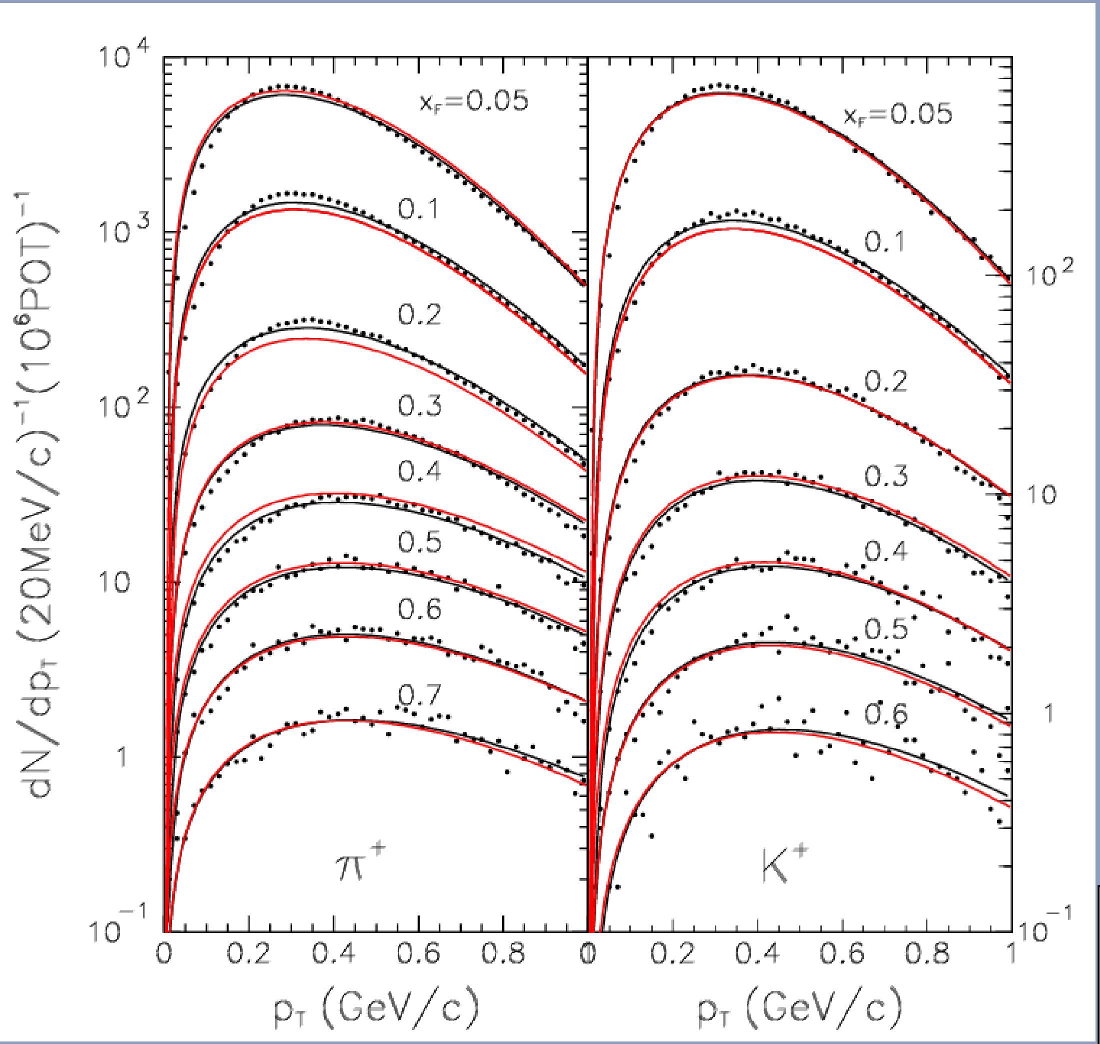


MC tuning



- Adjust the yields of $\pi^\pm$ and $K^\pm$
- Include focusing uncertainties
- Allow that some discrepancy is due to detector effects or neutrino cross sections

Hadron production parameterization



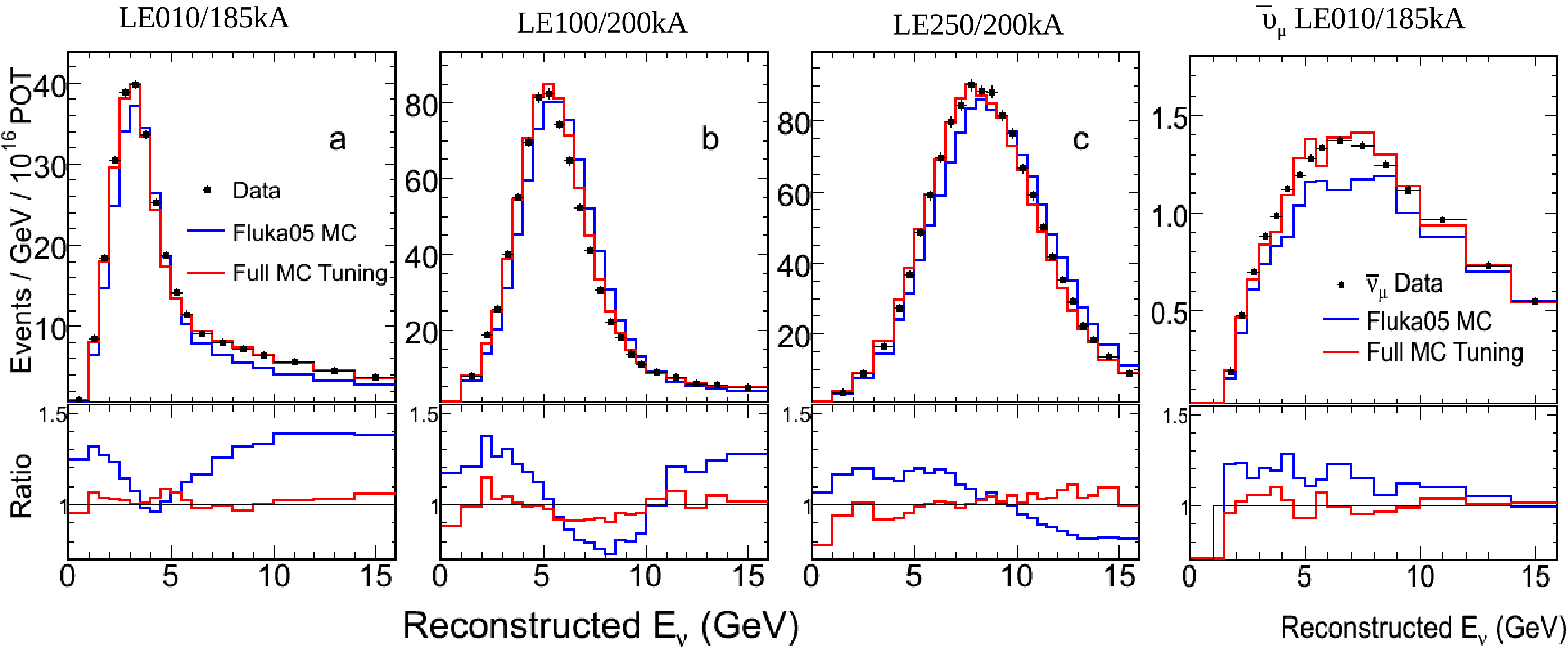
- Adjust yields as a function of pt-pz
- Parameterize fluka yields using 16 parameters

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

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

Tuning MC

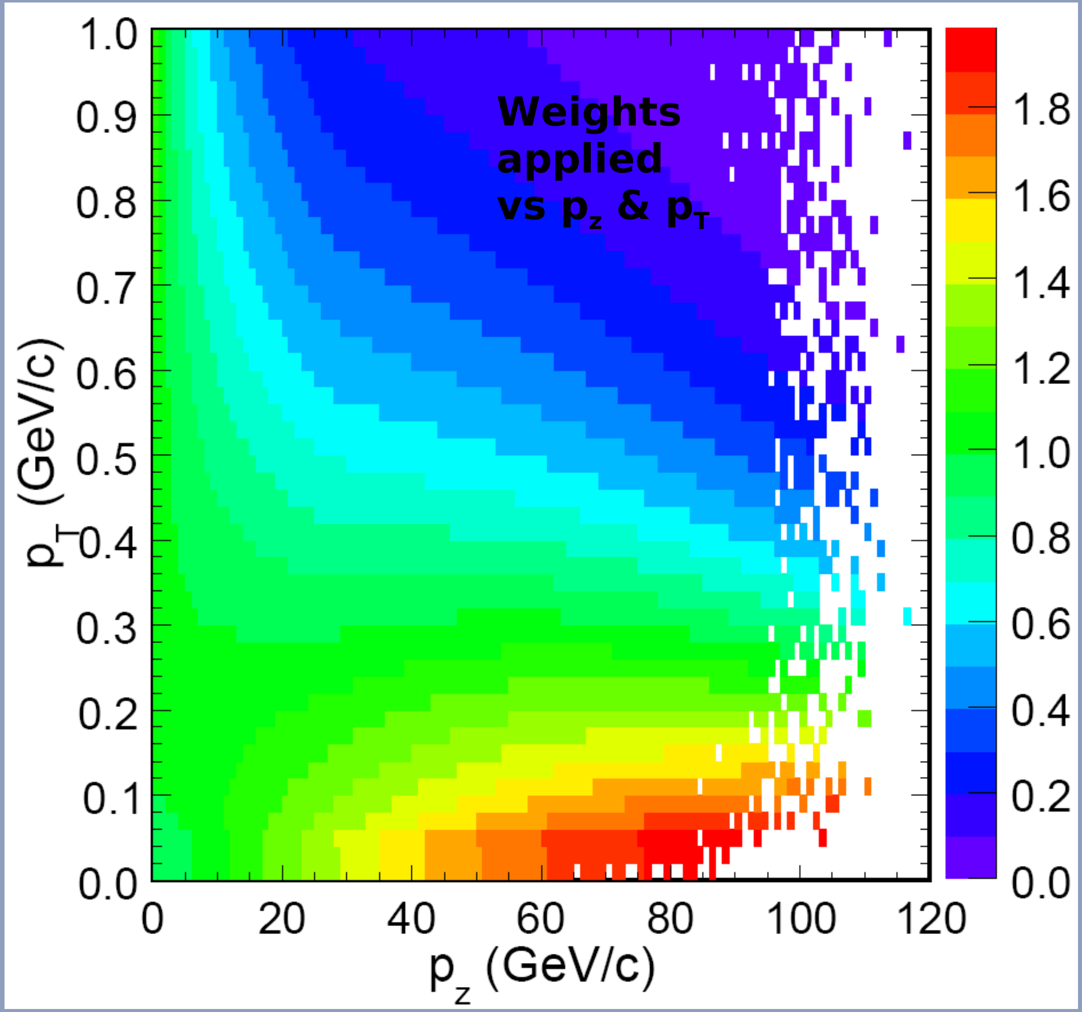
- Fit ND data from all beam configurations
- Simultaneously fit ν_μ and $\bar{\nu}_\mu$ spectra



Pion weights

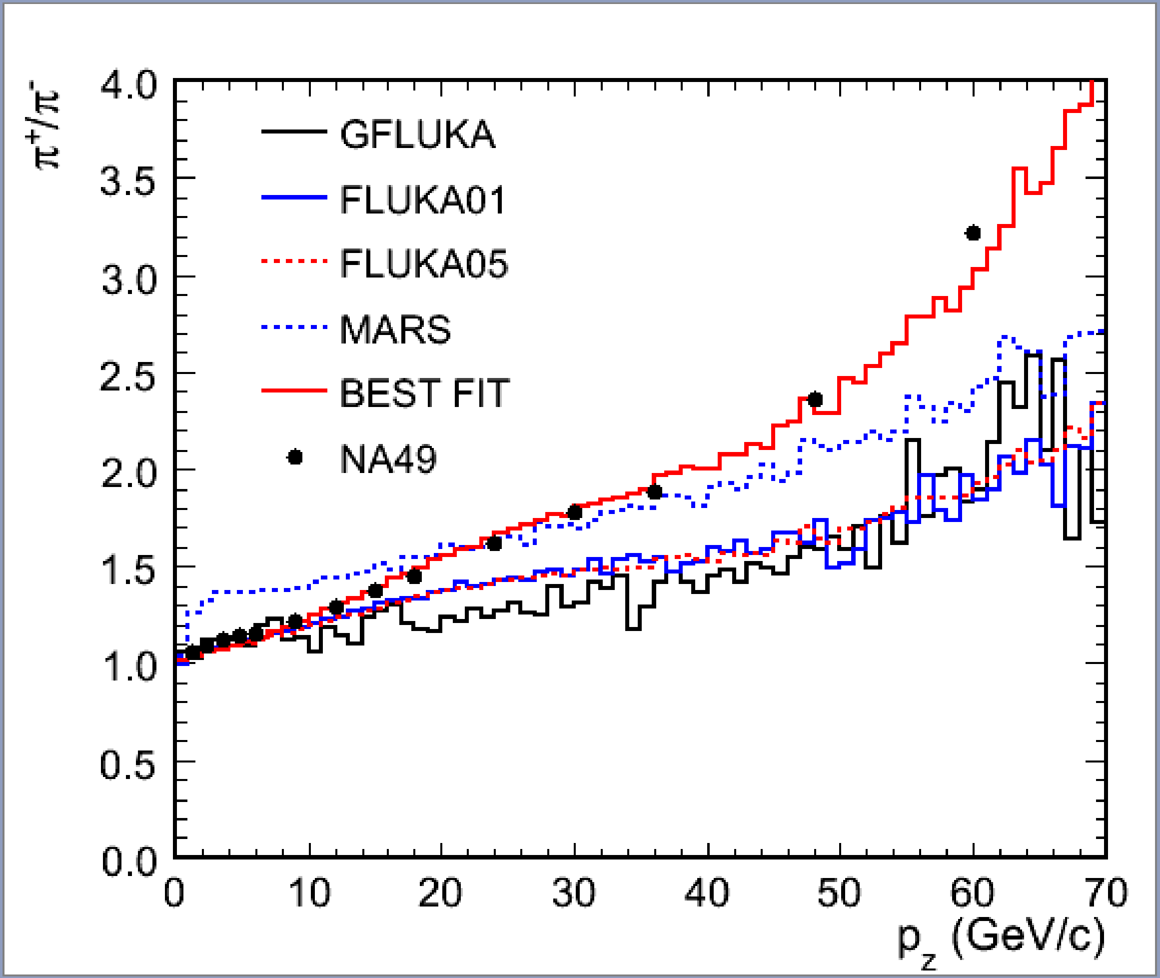
- Re-weight MC based on p_T-x_F

- Include in fit: Horn focusing, beam misalignments, neutrino energy scale, cross section, NC background



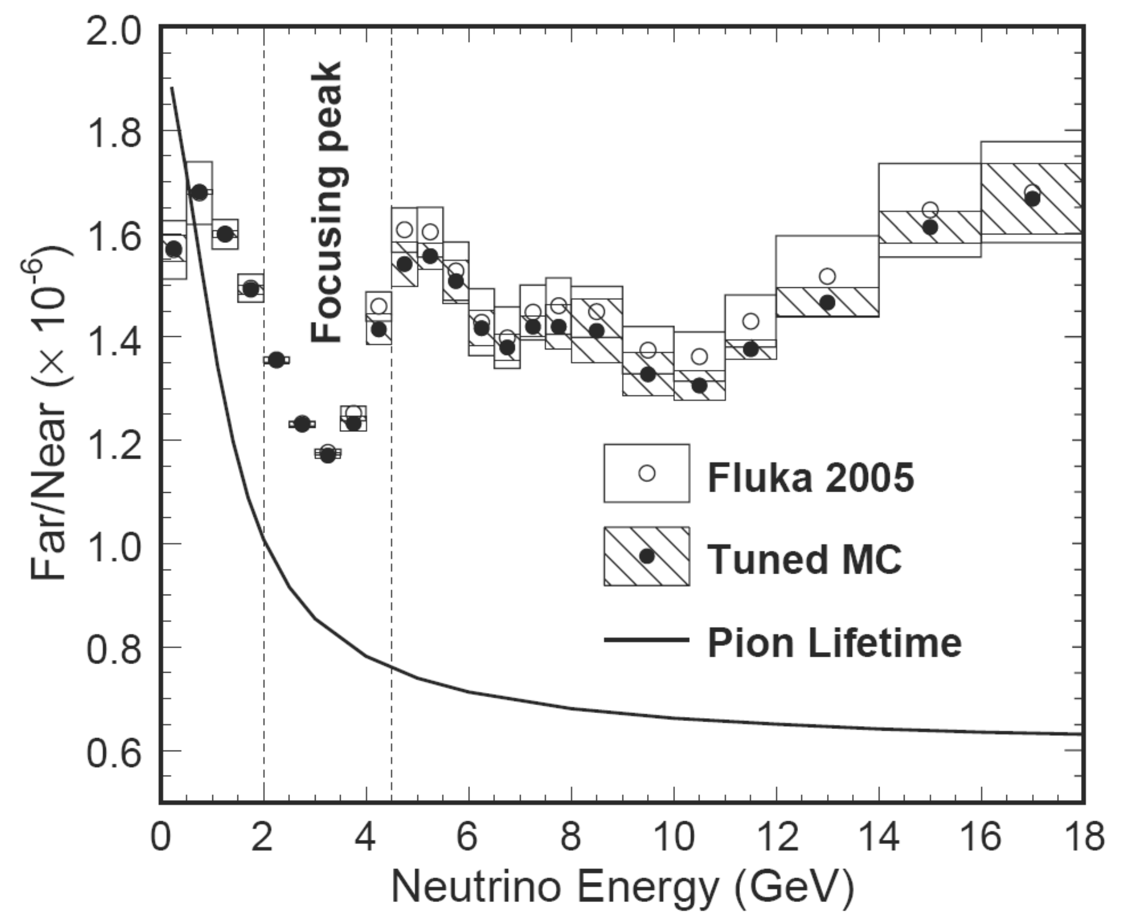
π^+/π^- ratio

- Best fit to ν_μ and $\bar{\nu}_\mu$ changes the π^+/π^- ratio
- Good agreement with NA49 data and MIPP



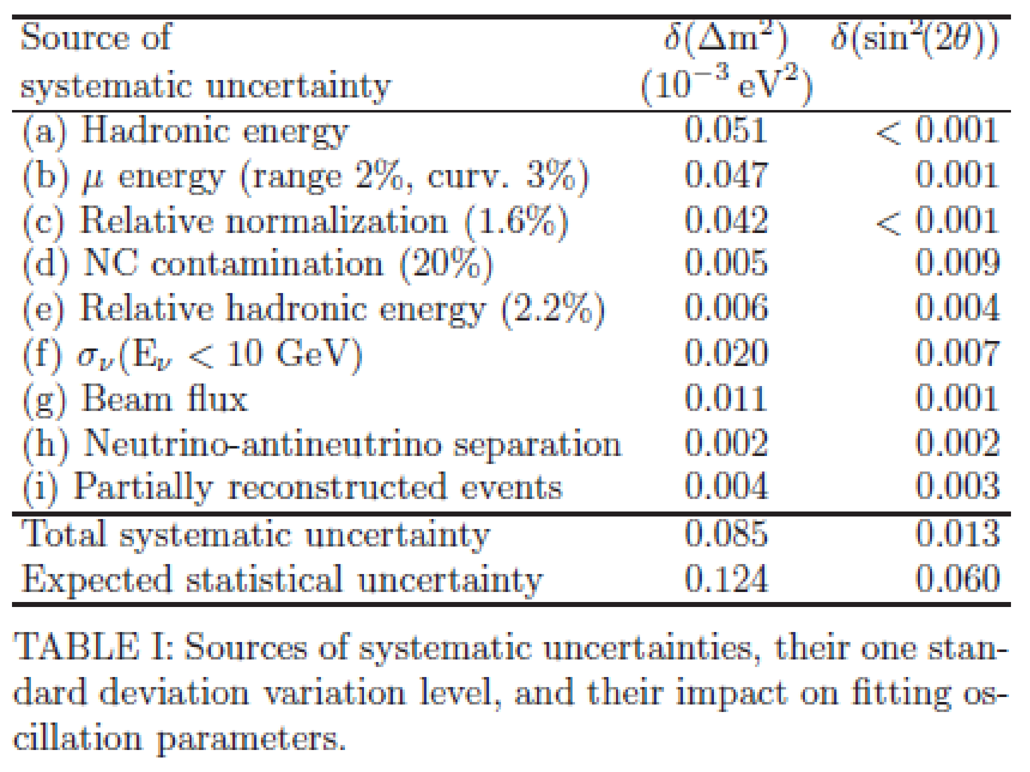
Far/Near Ratio

- Fits to ND data constrain the F/N ratio
- Errors are at <2% level



MINOS Systematic Errors

- Systematic errors from 2011 analysis (7.25e20 POT)
- Beam uncertainty small

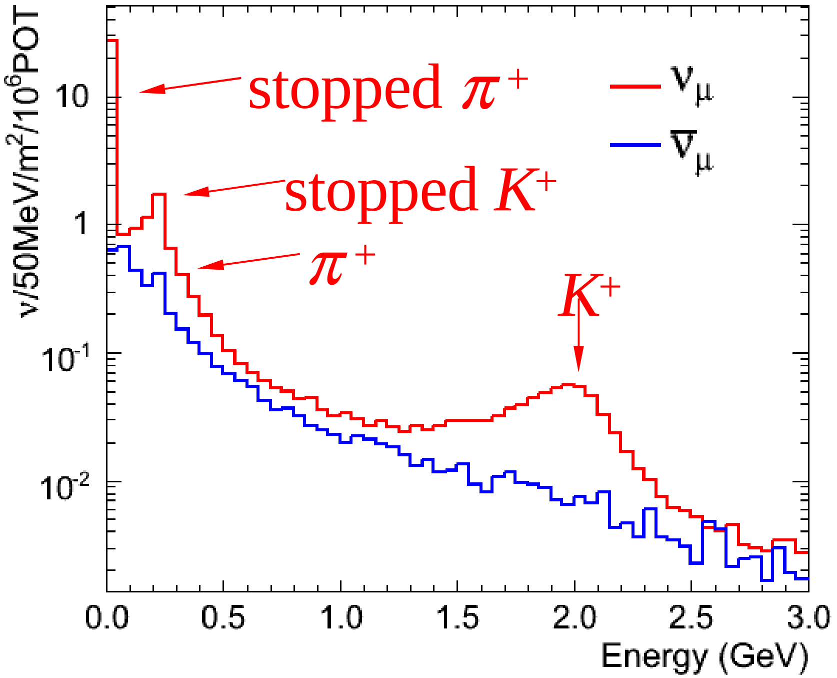


Source of systematic uncertainty	$\delta(\Delta m^2)$ $(10^{-3}\,\mathrm{eV}^2)$	$\delta(\sin^2(2\theta))$
(a) Hadronic energy	0.051	< 0.001
(b) μ energy (range 2%, curv. 3%)	0.047	0.001
(c) Relative normalization (1.6%)	0.042	< 0.001
(d) NC contamination (20%)	0.005	0.009
(e) Relative hadronic energy (2.2%)	0.006	0.004
(f) $\sigma_\nu(E_\nu < 10\ \mathrm{GeV})$	0.020	0.007
(g) Beam flux	0.011	0.001
(h) Neutrino-antineutrino separation	0.002	0.002
(i) Partially reconstructed events	0.004	0.003
Total systematic uncertainty	0.085	0.013
Expected statistical uncertainty	0.124	0.060

TABLE I: Sources of systematic uncertainties, their one standard deviation variation level, and their impact on fitting oscillation parameters.

Phys.Rev.Lett.106:181801,2011

Offaxis neutrino beam



$$E_\nu \simeq \frac{\left(1-\frac{m_\mu^2}{M_{\pi,K}^2}\right)E_{\pi,K}}{1+\gamma^2\theta^2}$$

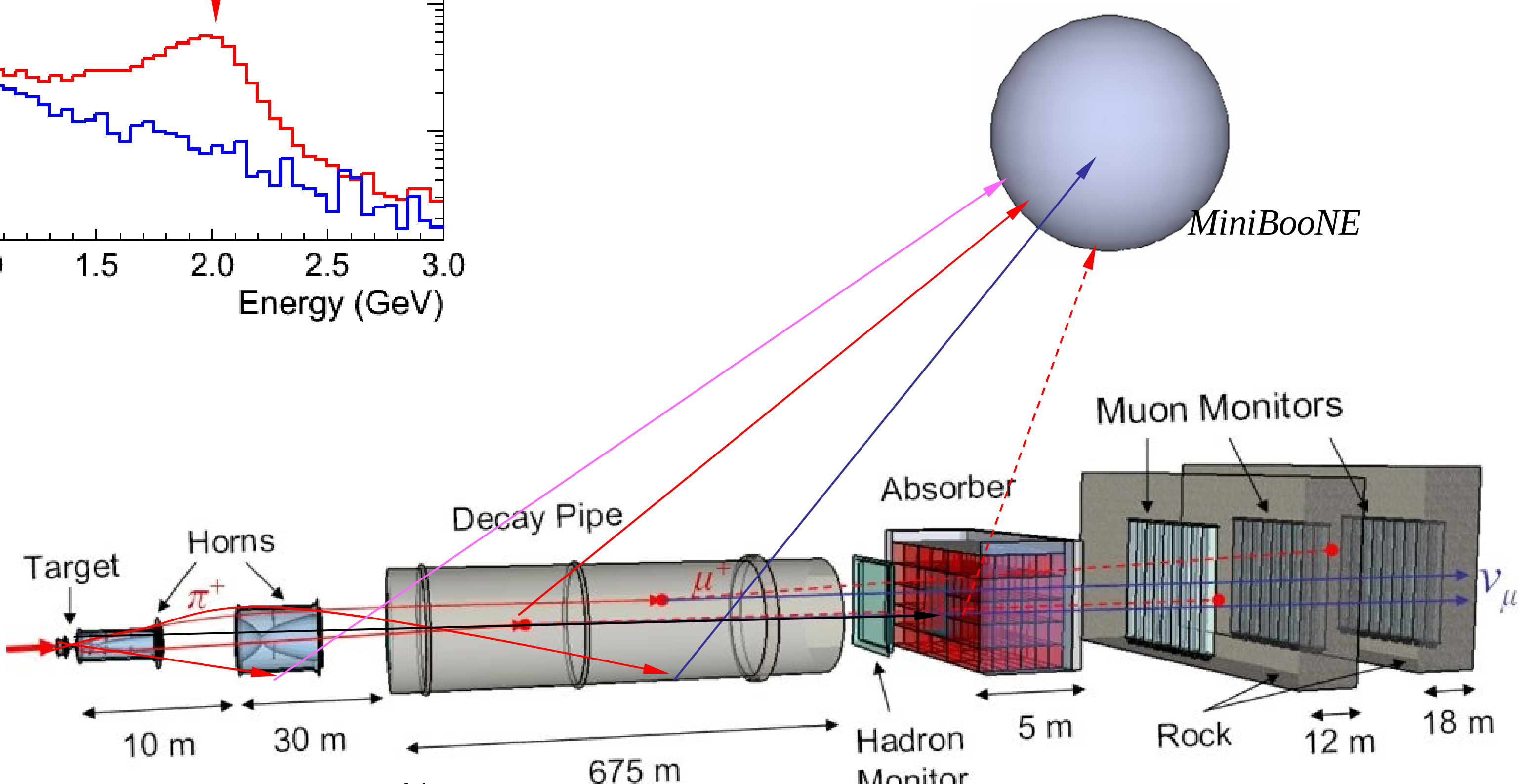
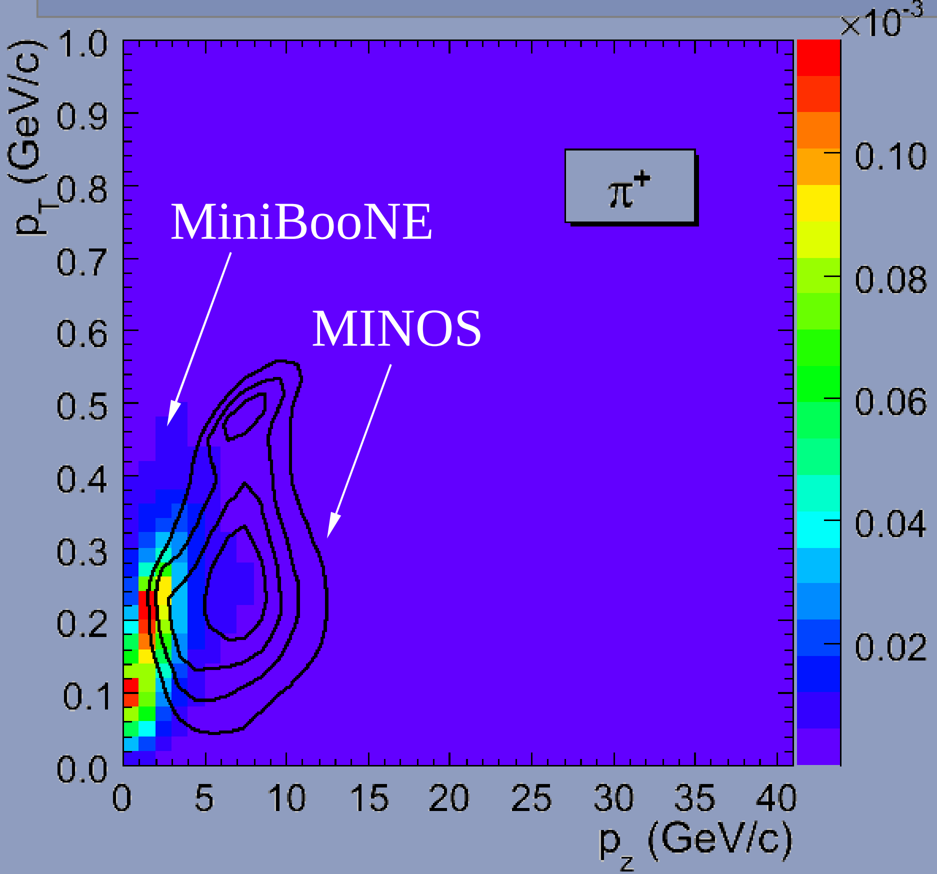
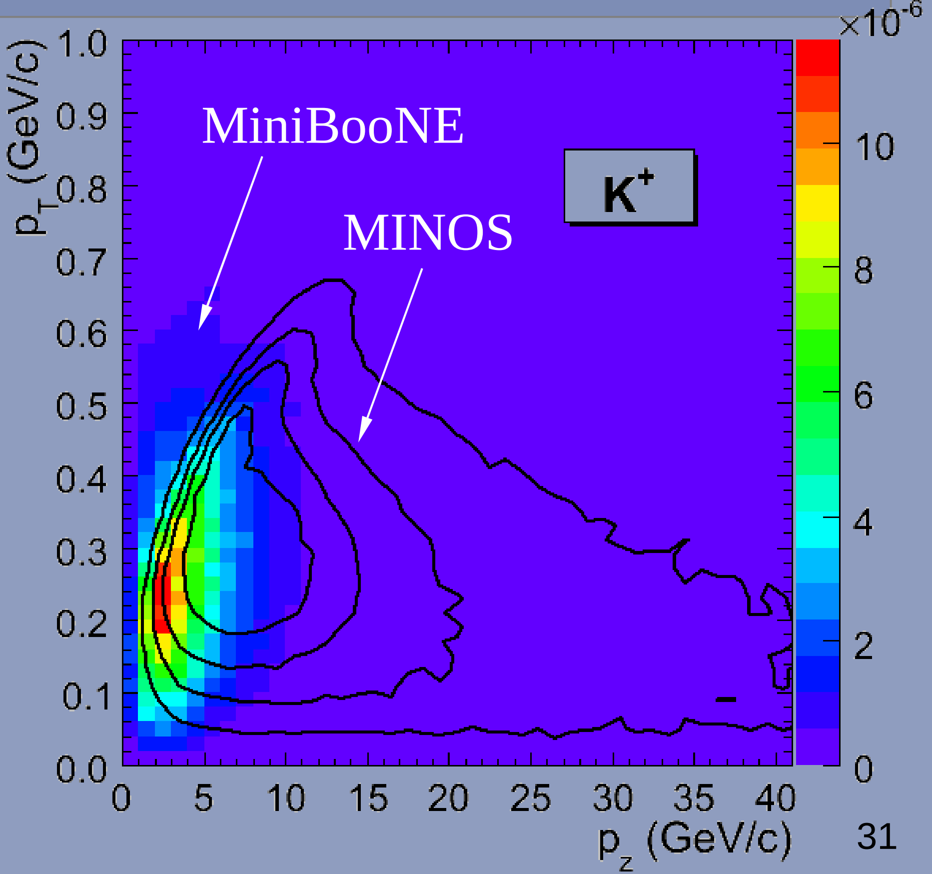


diagram not to scale!

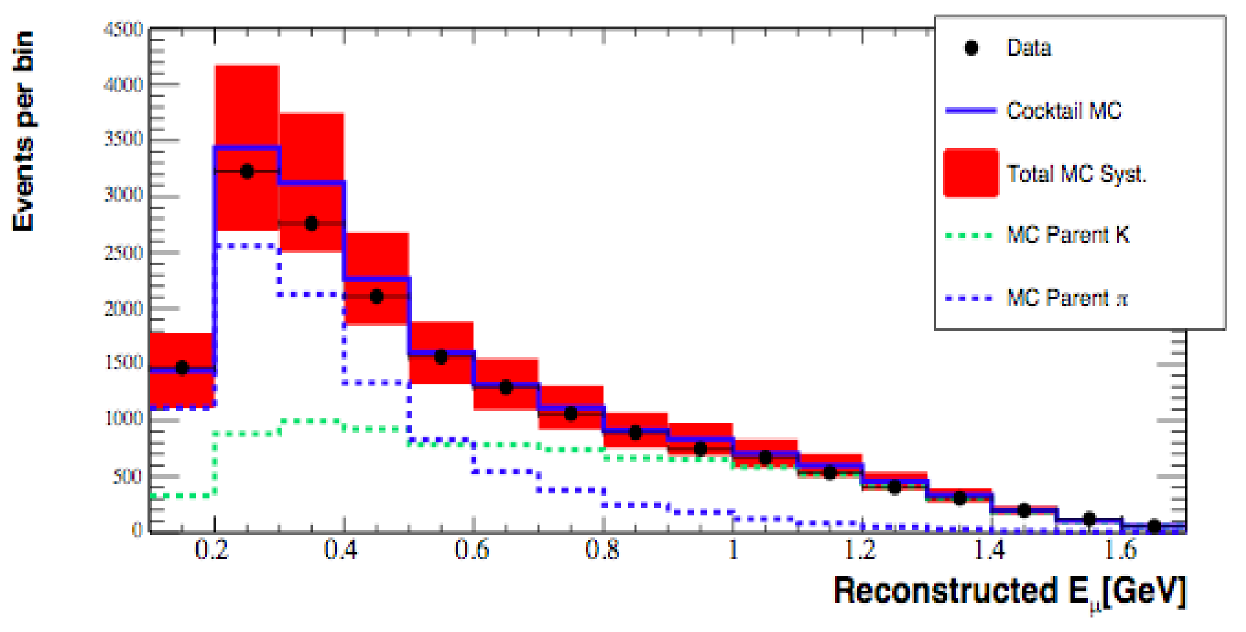
Two views of the same decays

- Decays of hadrons produce neutrinos that strike both MINOS and MiniBooNE
- Parent hadrons ‘sculpted’ by the two detectors’ acceptances.
- Plotted are p_T and $p_{||}$ of hadrons which contribute neutrinos to MINOS (contours) or MiniBooNE (color scale)

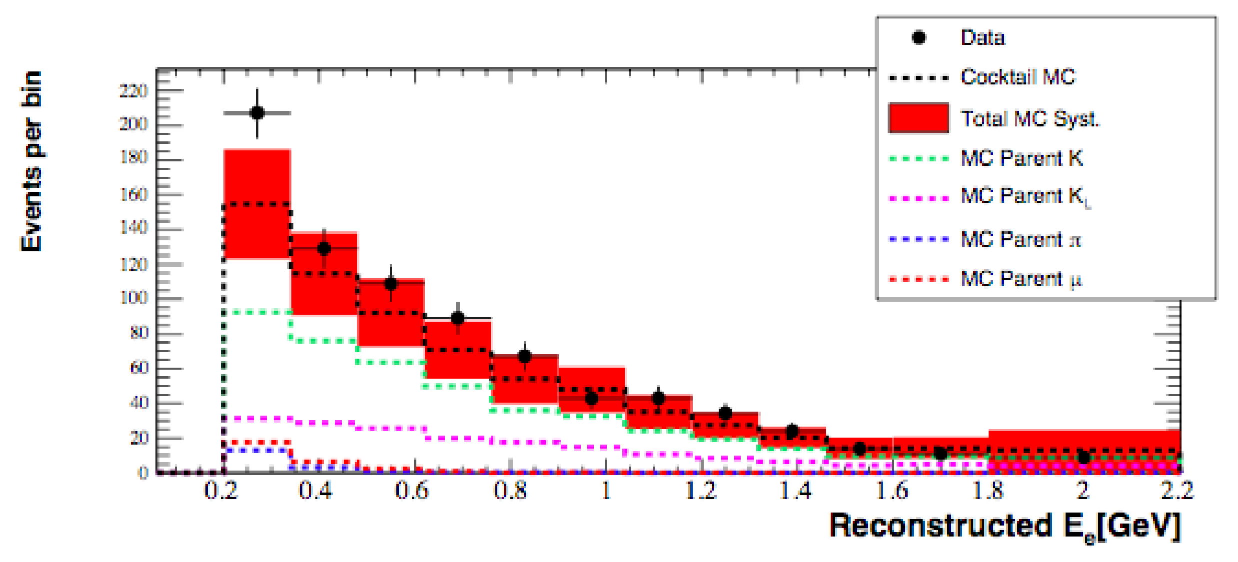




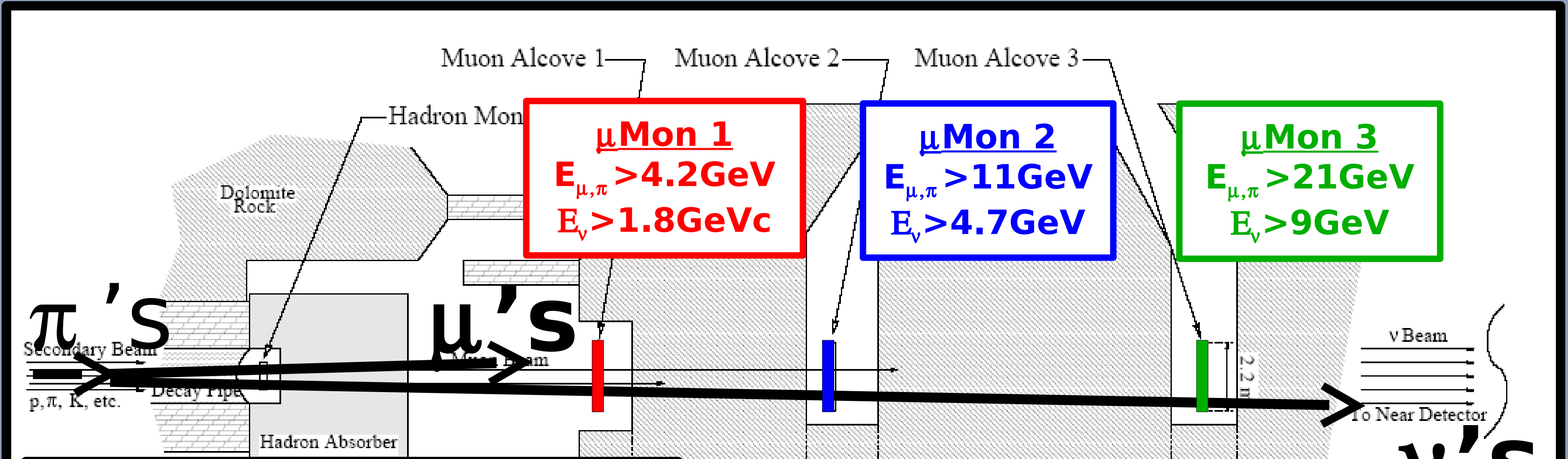
NumiBooNE

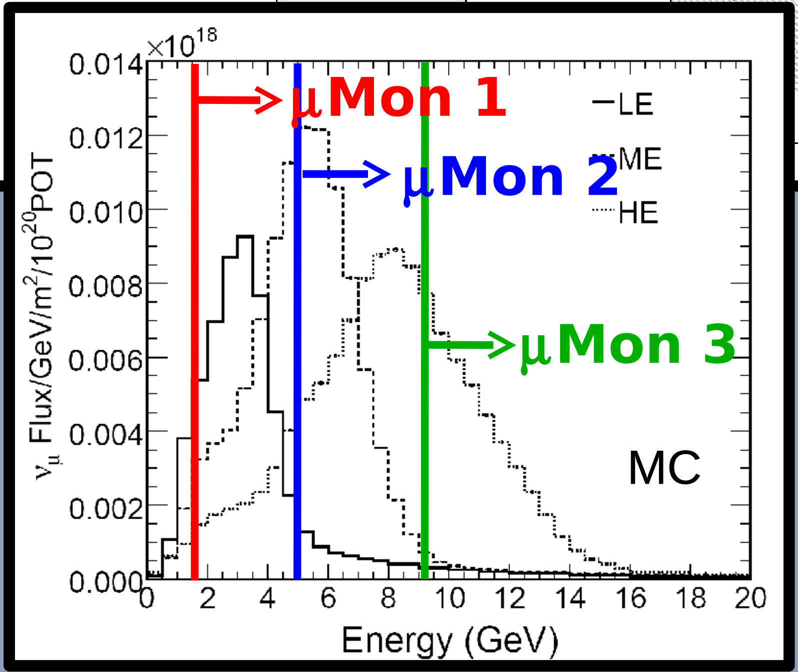


- Good agreement between data and MC



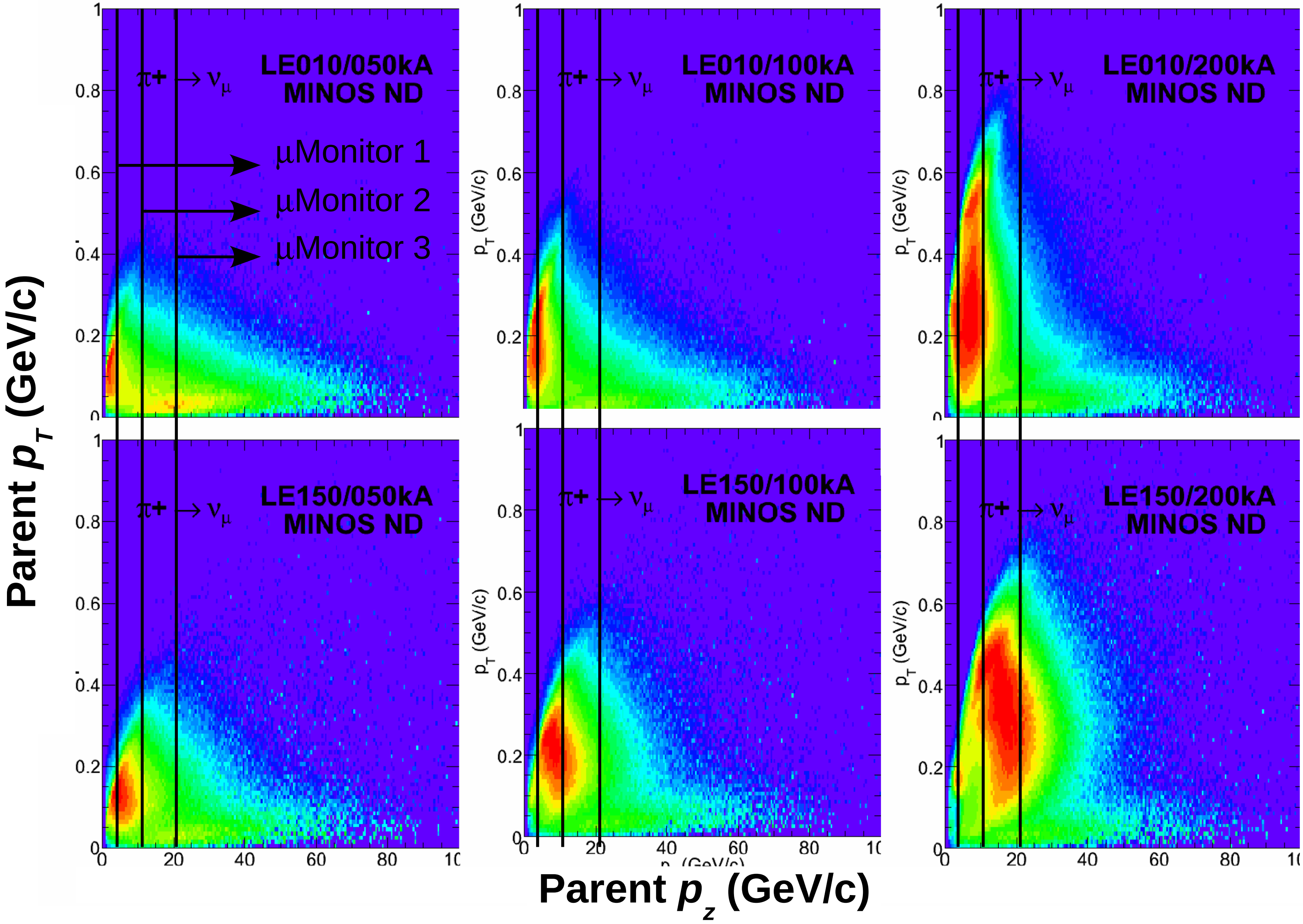
NuMI μ monitors





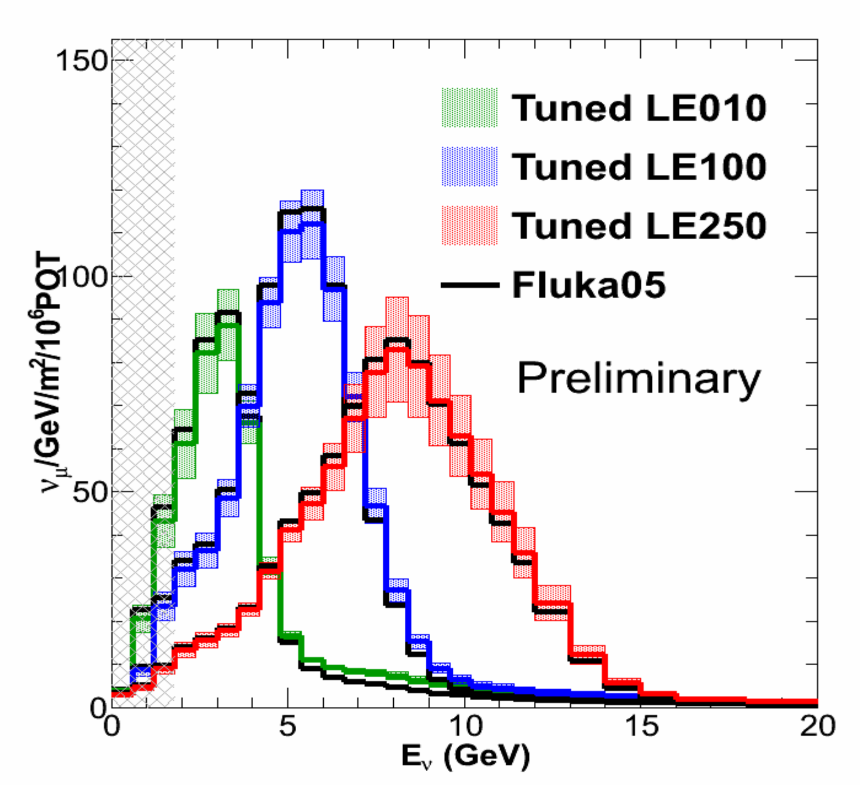
- 3 arrays of ionization chambers

Pion parents

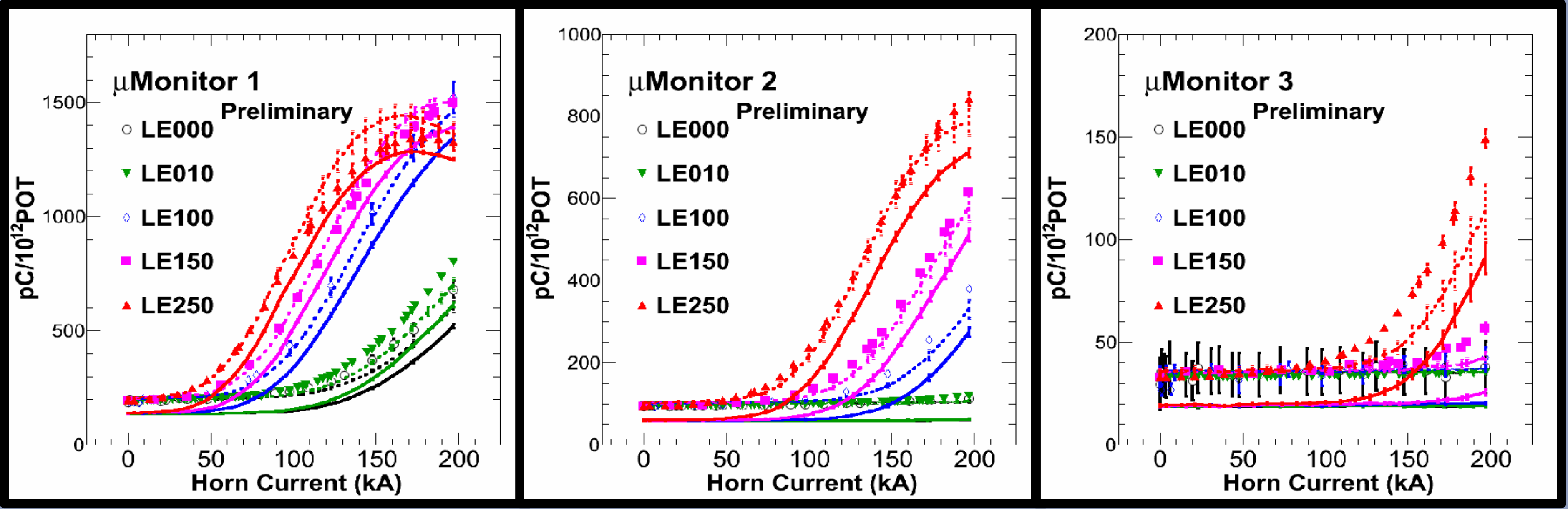


Fit to muon monitors

- Consistent with ND fits



L. Loiacono, thesis (2010)



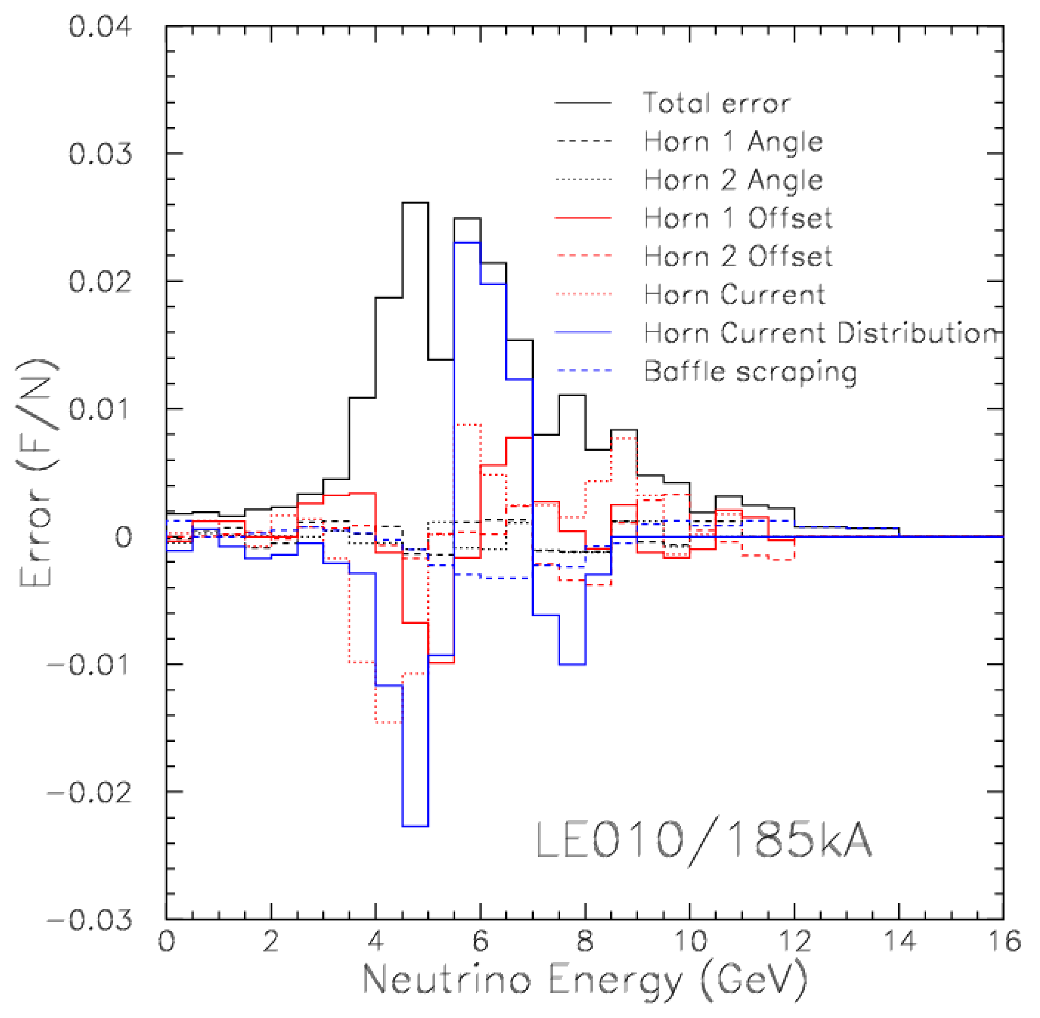
Conclusion

- MINOS tunes hadron production to simultaneously fit all ND data
- Technique independent of particle production experiments
- Beam systematics well constrained

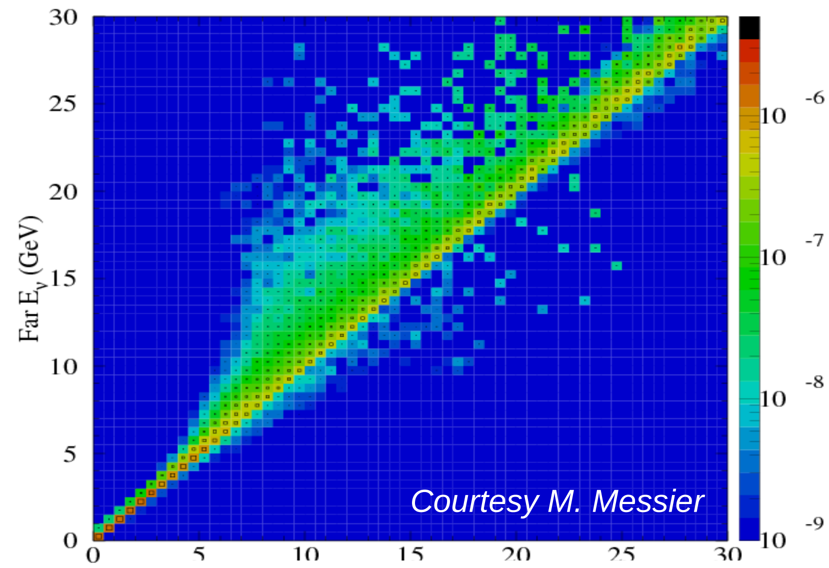
Backup

F/N focusing uncertainties

- F/N ratio affected at 2% level

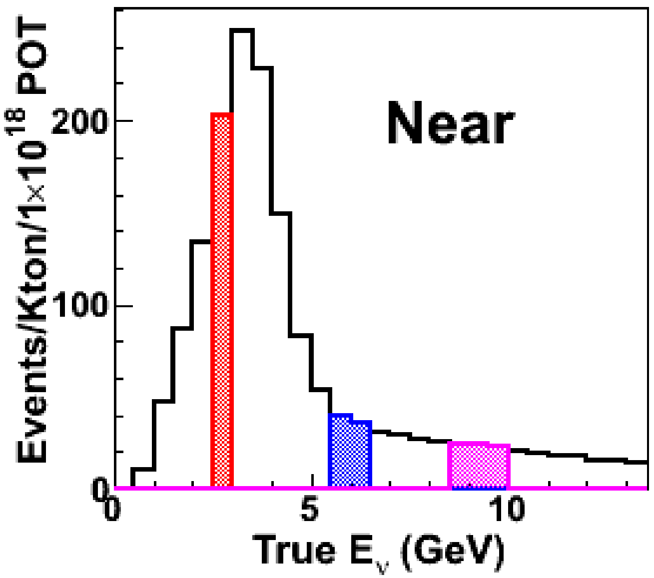


Predicting far spectrum



Courtesy M. Messier

X



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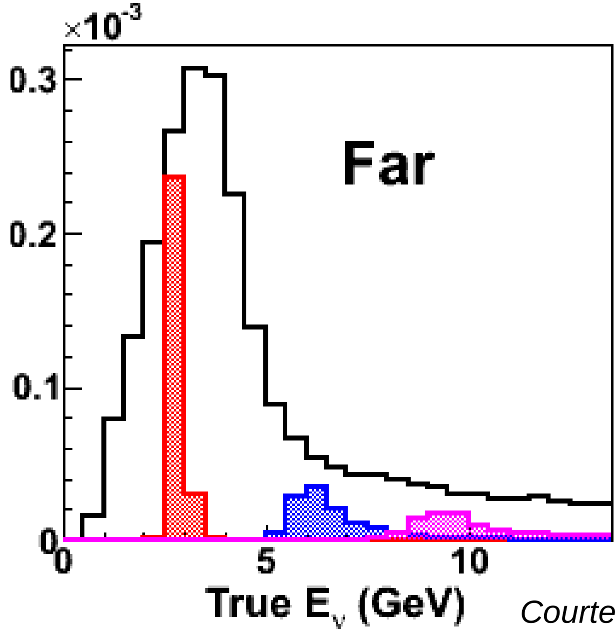

Courtesy T. Vahle

- Construct beam matrix using MC
- Use Near Detector data to predict the “unoscillated” spectrum at the Far detector