Techniques for *In Situ* Measurements of the ν Flux

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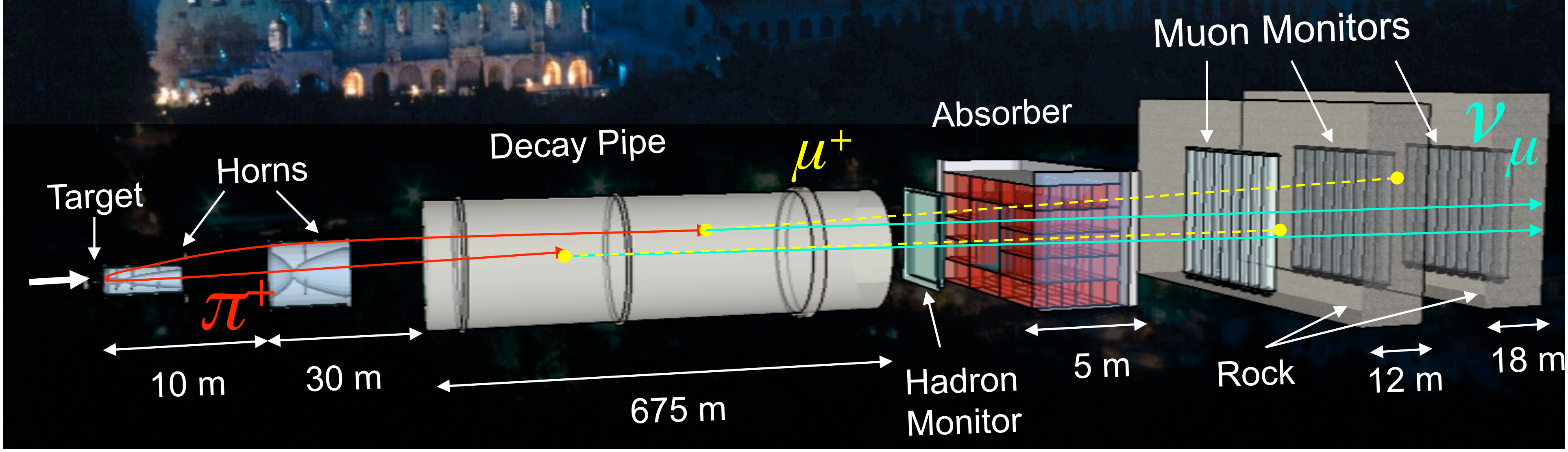
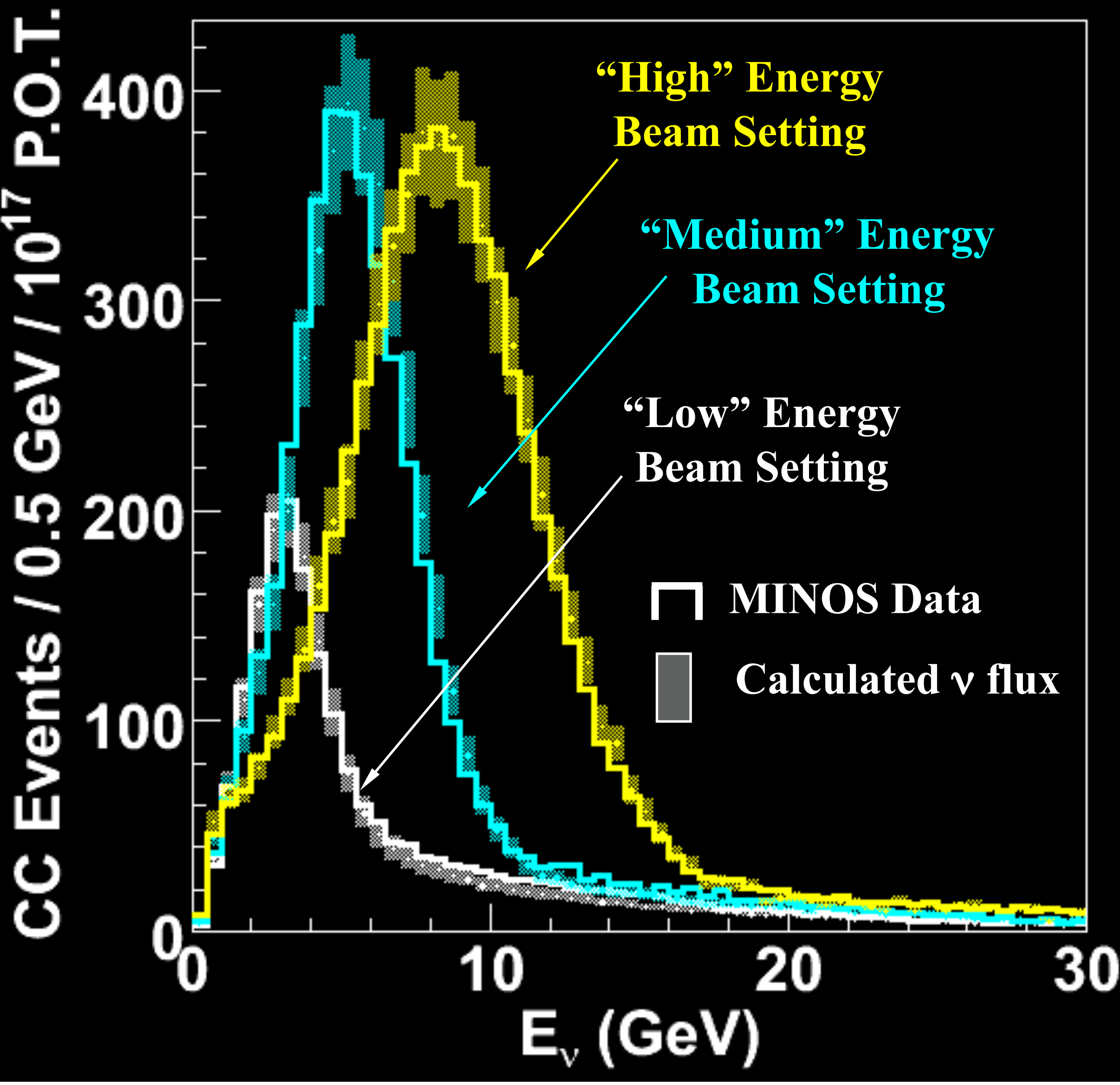
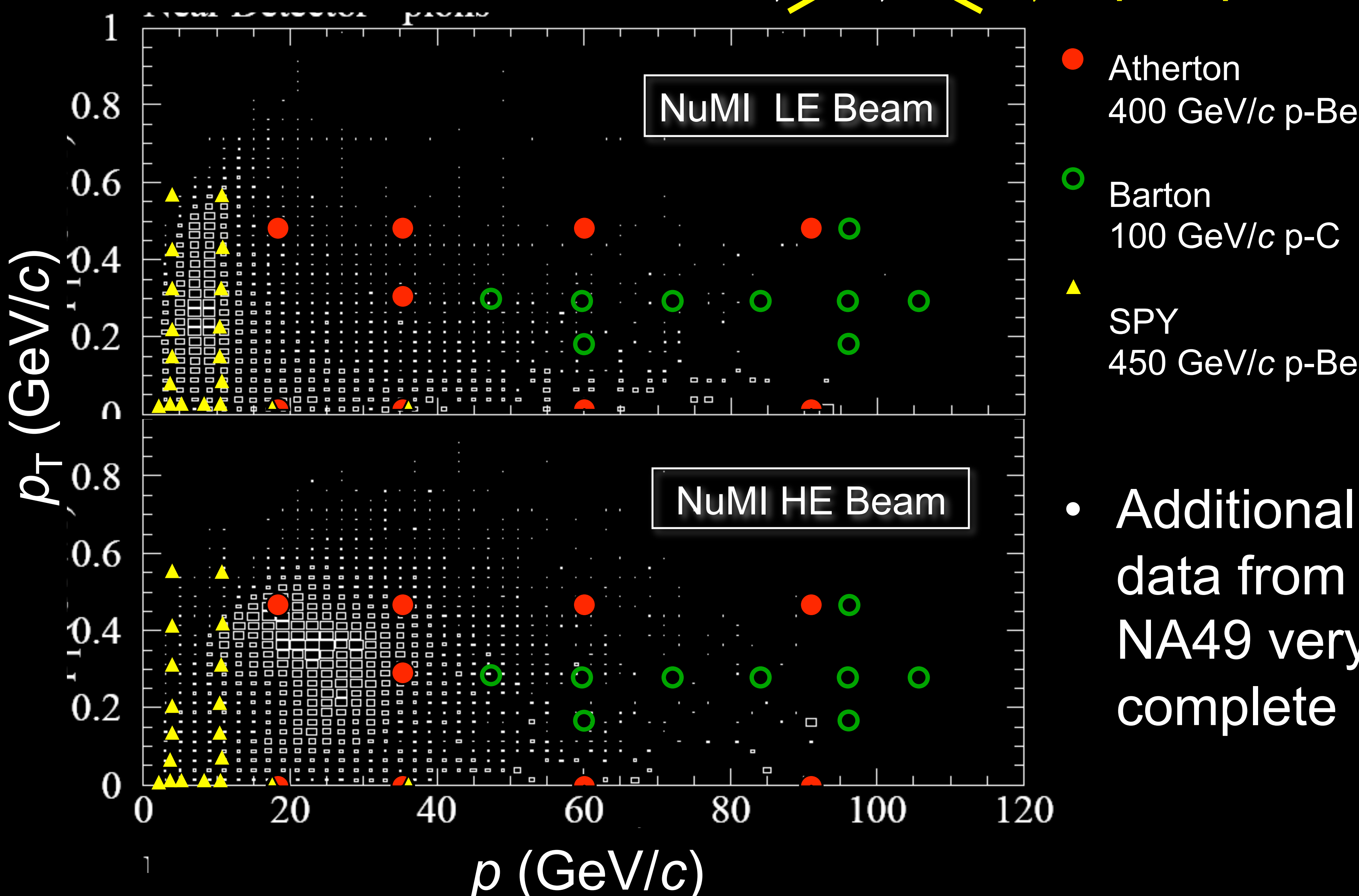


How Good is our Beam MC?



- Beam flux starting with Fluka2005 model of particle yield off target.
- NuMI has run several beam energy configurations (more on this later)
- Error bars are from the beam systematic errors (particle production off the target, horn and target alignment, focusing errors, *etc*).

You Really Want ~~$\phi_\nu(E_\nu)$~~ $\phi_\nu(x_F,p_T)$



- Additional data from NA49 very complete

Challenges Translating External Data

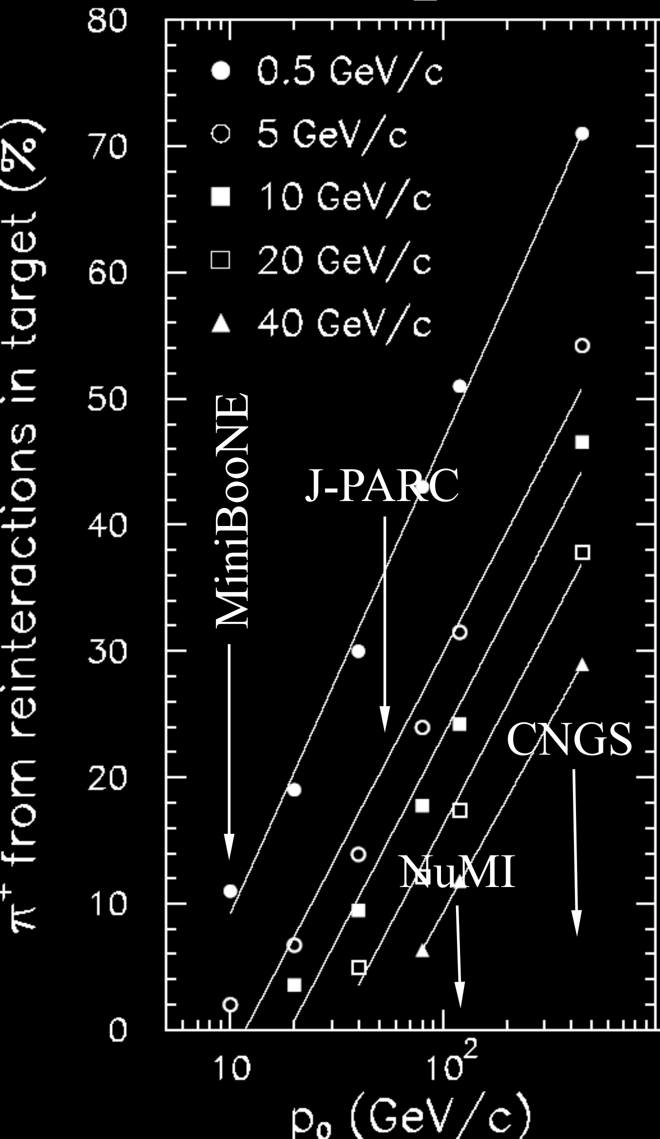
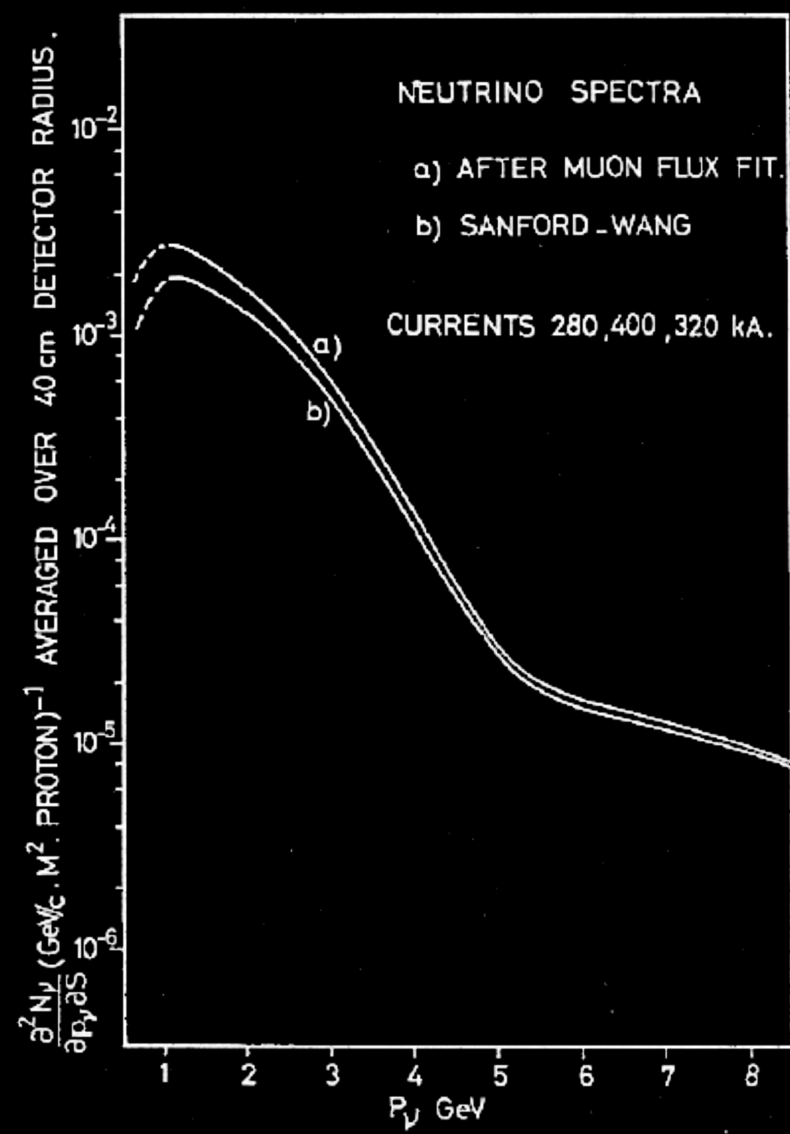


figure courtesy Z. Pavlovic

- Thick target effects
  (Z. Pavlovic, PhD thesis, UT Austin, 2008)
- In-situ variations
  (L. Loiacono, PhD thesis, UT Austin, 2010)
- Downstream Interactions
  (A. Himmel, PhD thesis, Caltech, 2010)

Past Experience Urges Caution

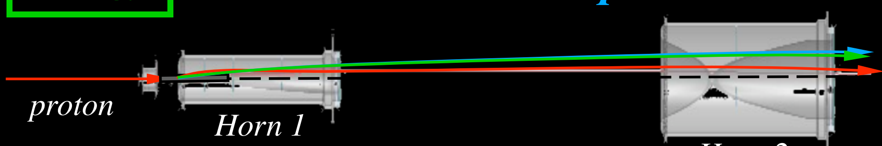
- CERN PS team did particle prod @ IHEP
  J.V. Allaby, et al., *Phys. Lett. 29B 48 (1969)*
- In-situ flux using μMons suggested 50% off?!
  D. Bloess, et al, CERN-69-28 (1969), Nucl. Inst. Meth. 91 (1971) 605.
- Particle production round two – ok to 15%
  J.V. Allaby, et al., *CERN-70-12.*
- More Recent Experience
  MiniBooNE, NOMAD, BNL



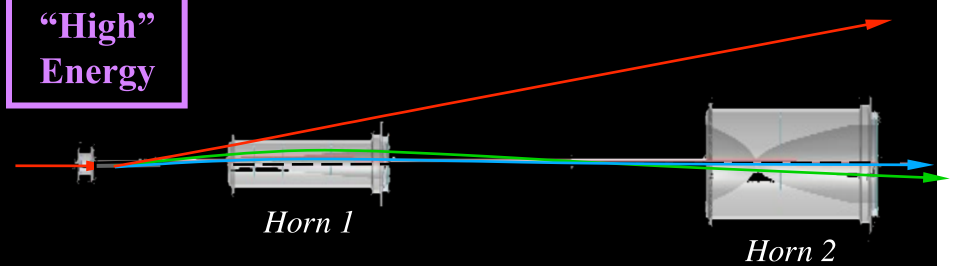
In situ ν Data to Determine Flux

π^+ with p_T=300 MeV/c and **p=5 GeV/c**, **p=10 GeV/c**, **p=20 GeV/c**

"Low" Energy

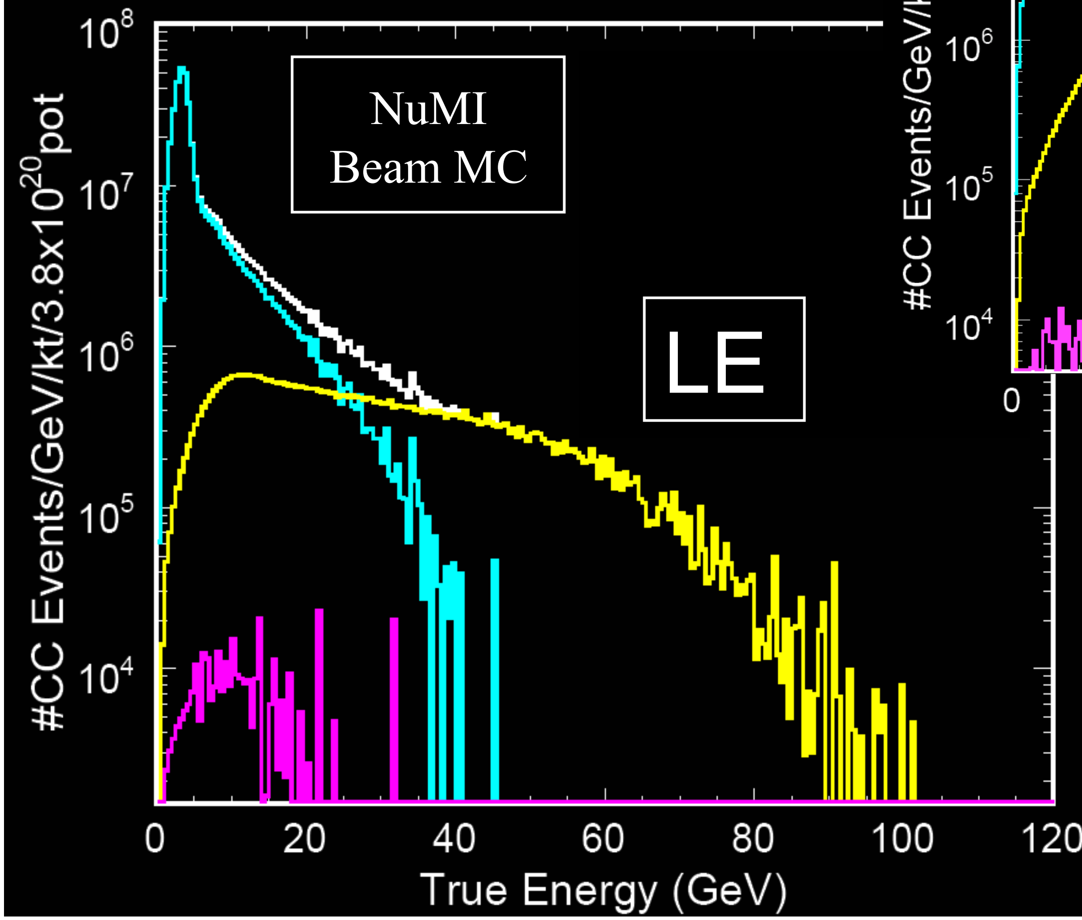


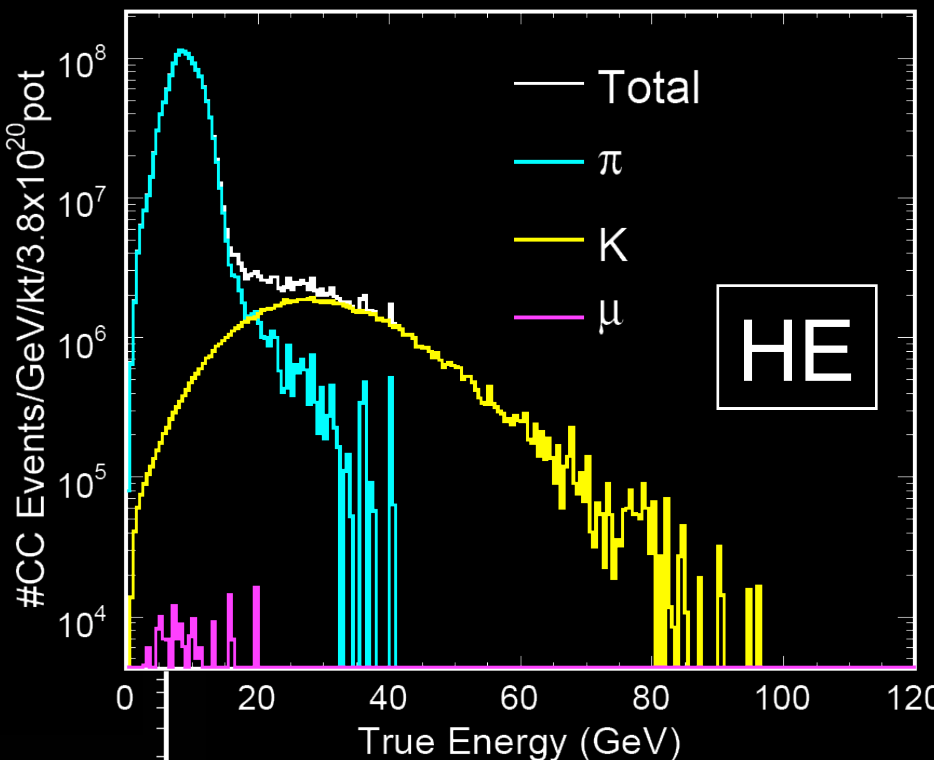
"High" Energy



NuMI Variable energy beam

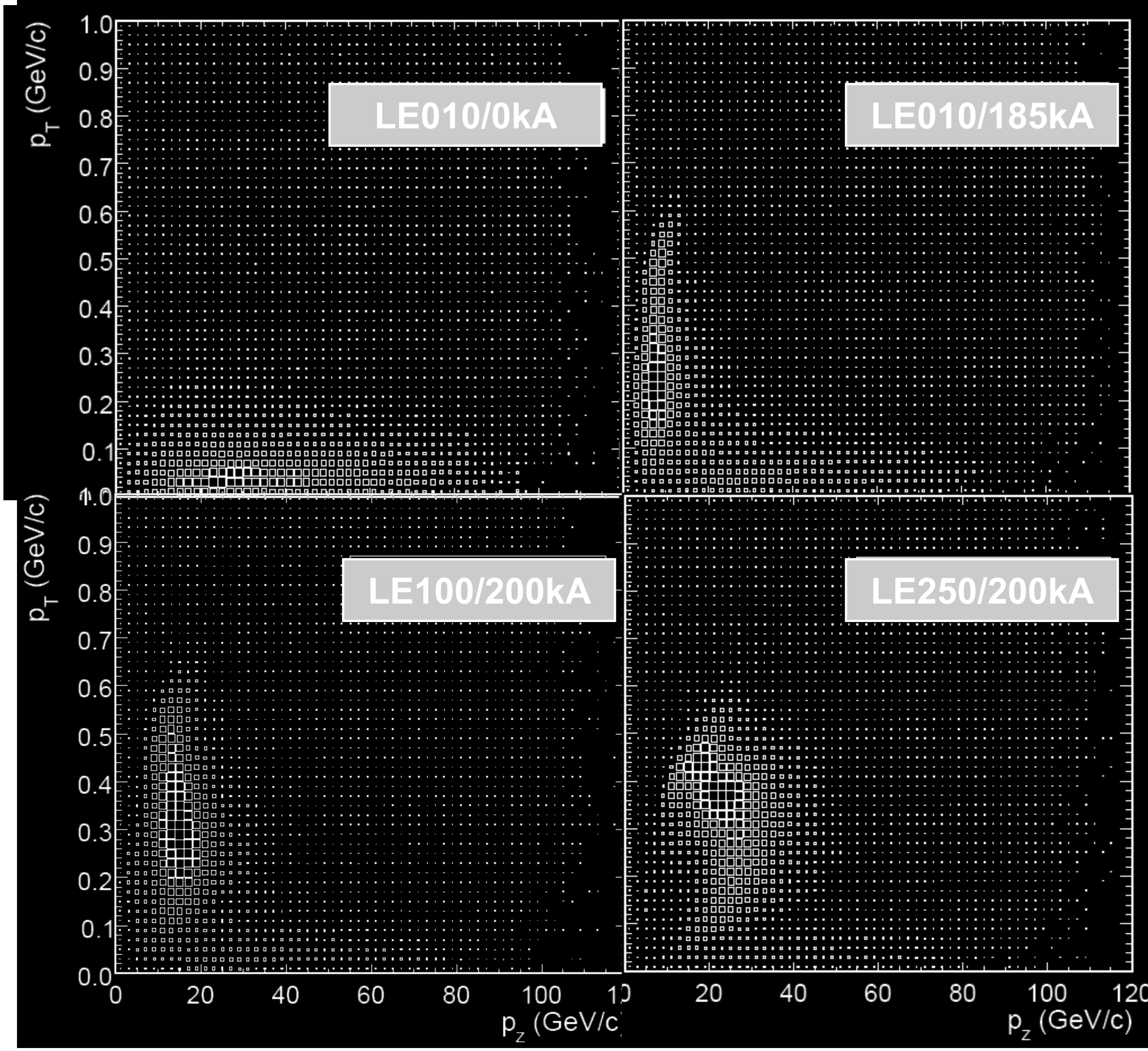
- Produce same E_ν using several beam focusing configurations





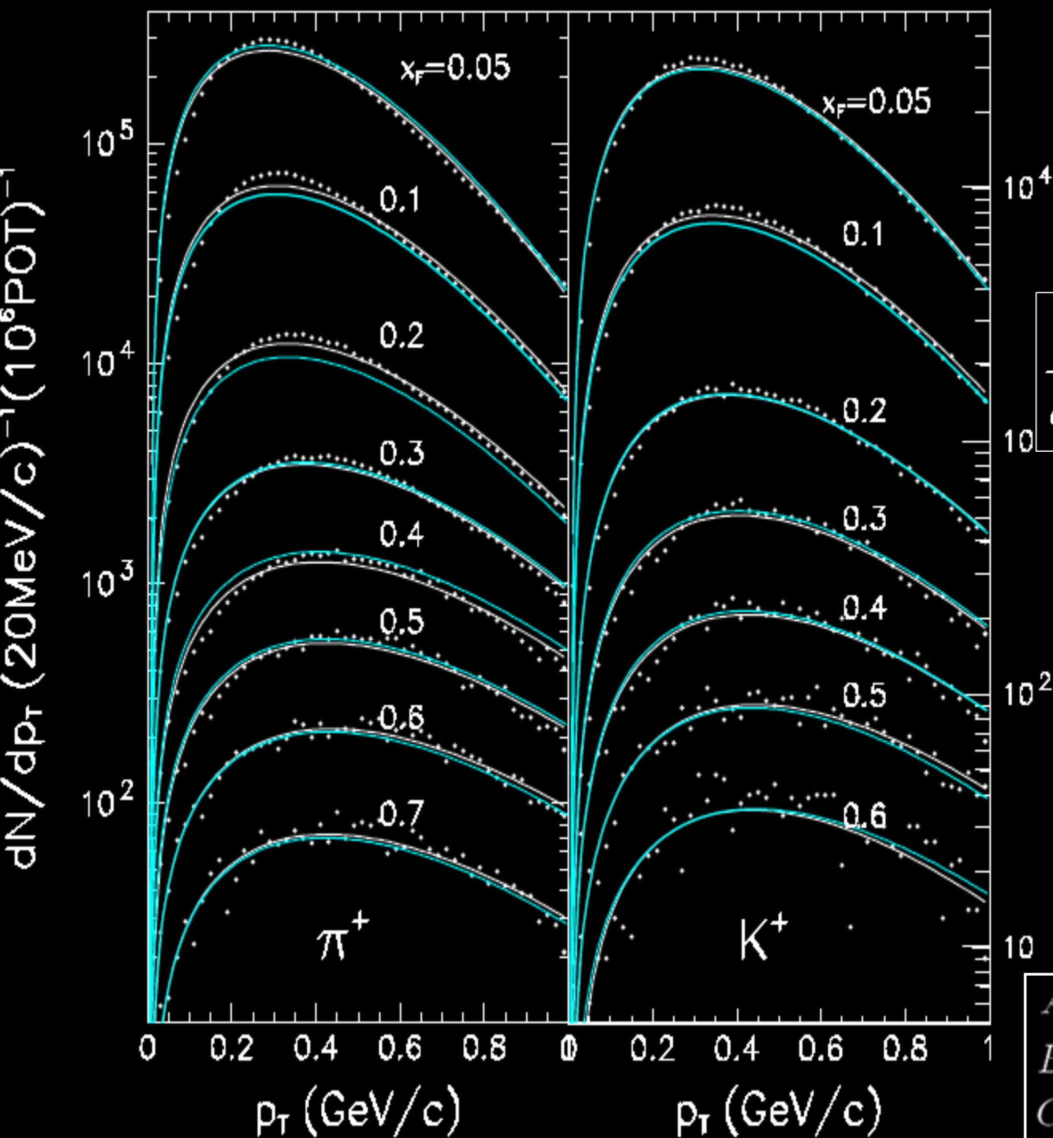
- Deconvolve systematics
  - Neutrino beam focusing
  - π/K production off target
  - Neutrino cross sections

NuMI Variable energy beam



- Can vary
  - Horn current (p_T kick supplied to π's)
  - Target Position (x_F of focused particles)
- Plots show (x_F ,p_T) of π^+ contributing to neutrino flux.
- Similar plots exist for kaons
- Acquired data from 8 beam configurations (here are 4)

Parameterizing Hadron Production



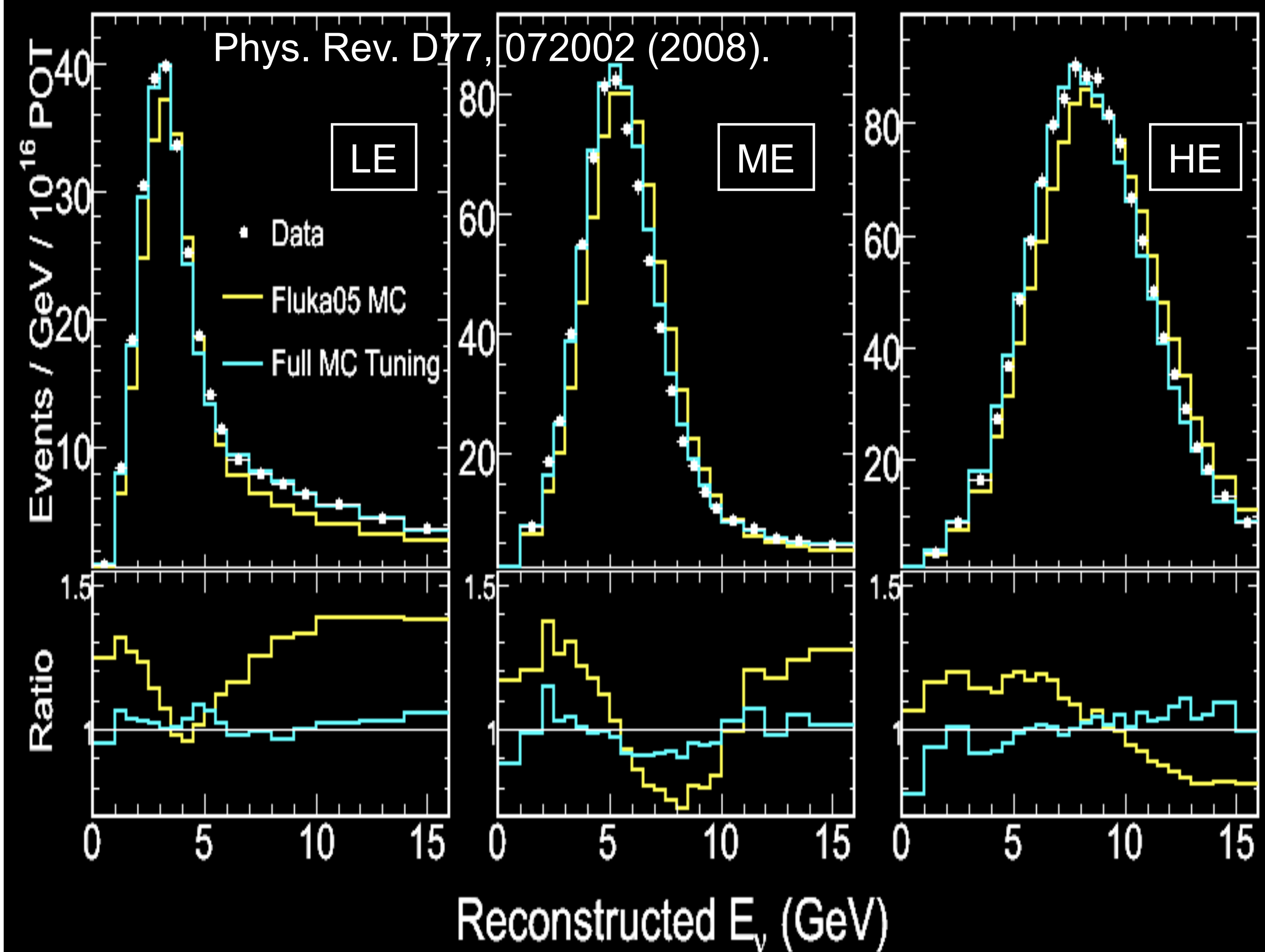
- Used empirical form *similar* to BMPT to parameterize Fluka2005:

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

- Fit was to a MC of our thick-target yield estimated by Fluka2005.
- Tune parameters of the fit to match ND data.

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

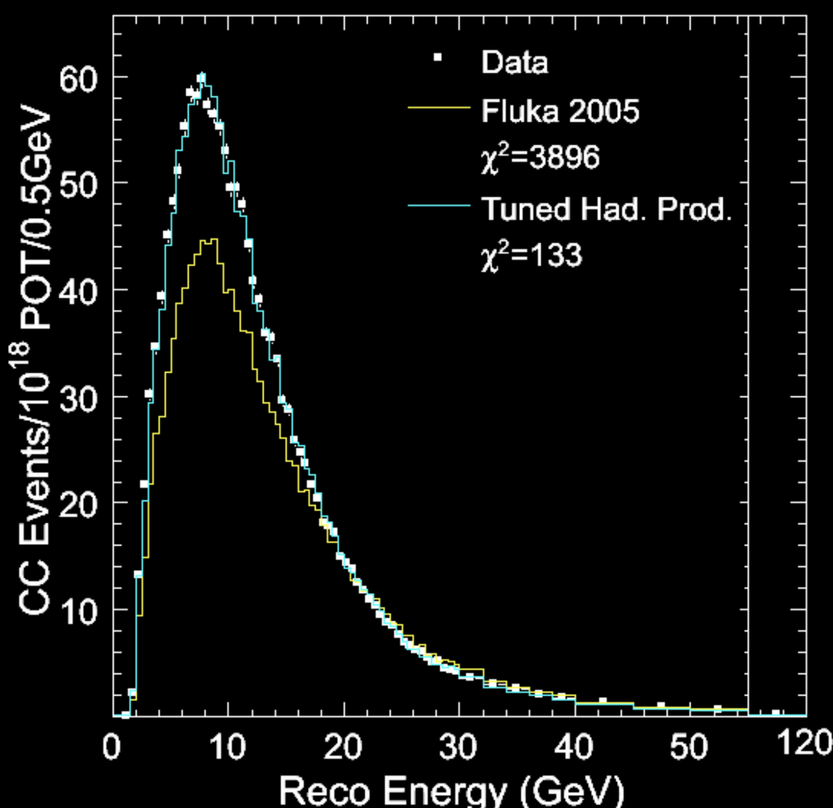
NuMI Flux Tuning

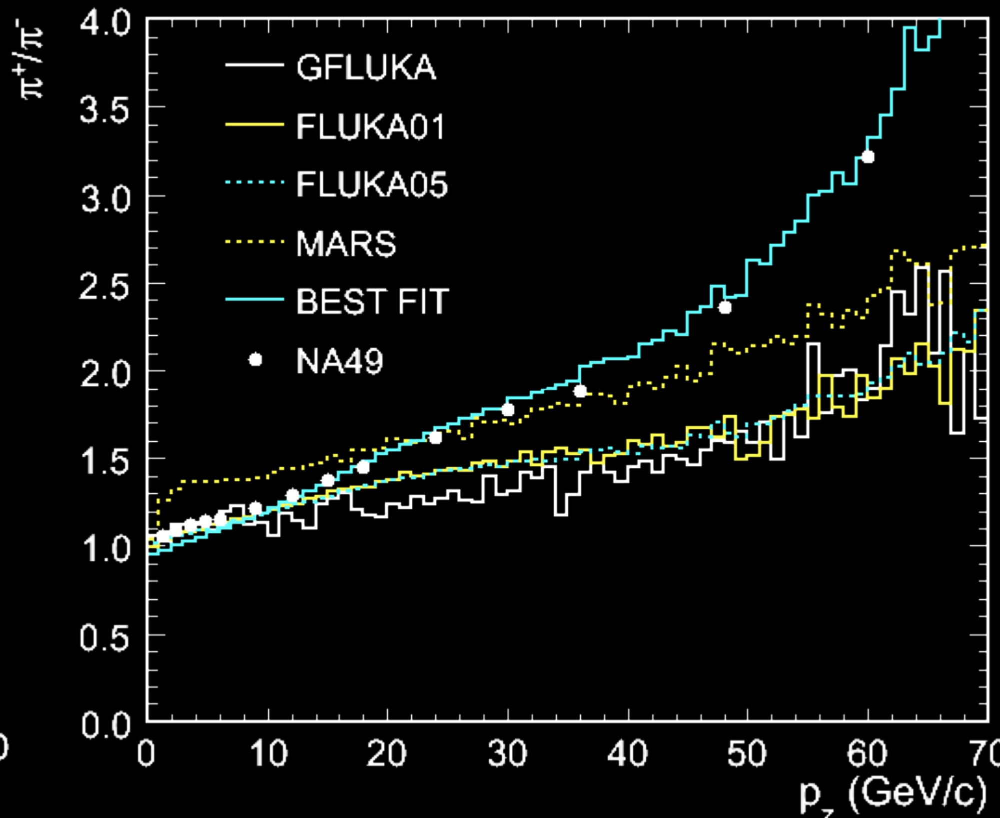


- Fit all 8 beam runs.
- Fit ν_μ and $\bar{\nu}_\mu$ spectra
- Done by MINOS with inclusive events to adjust F/N ratio

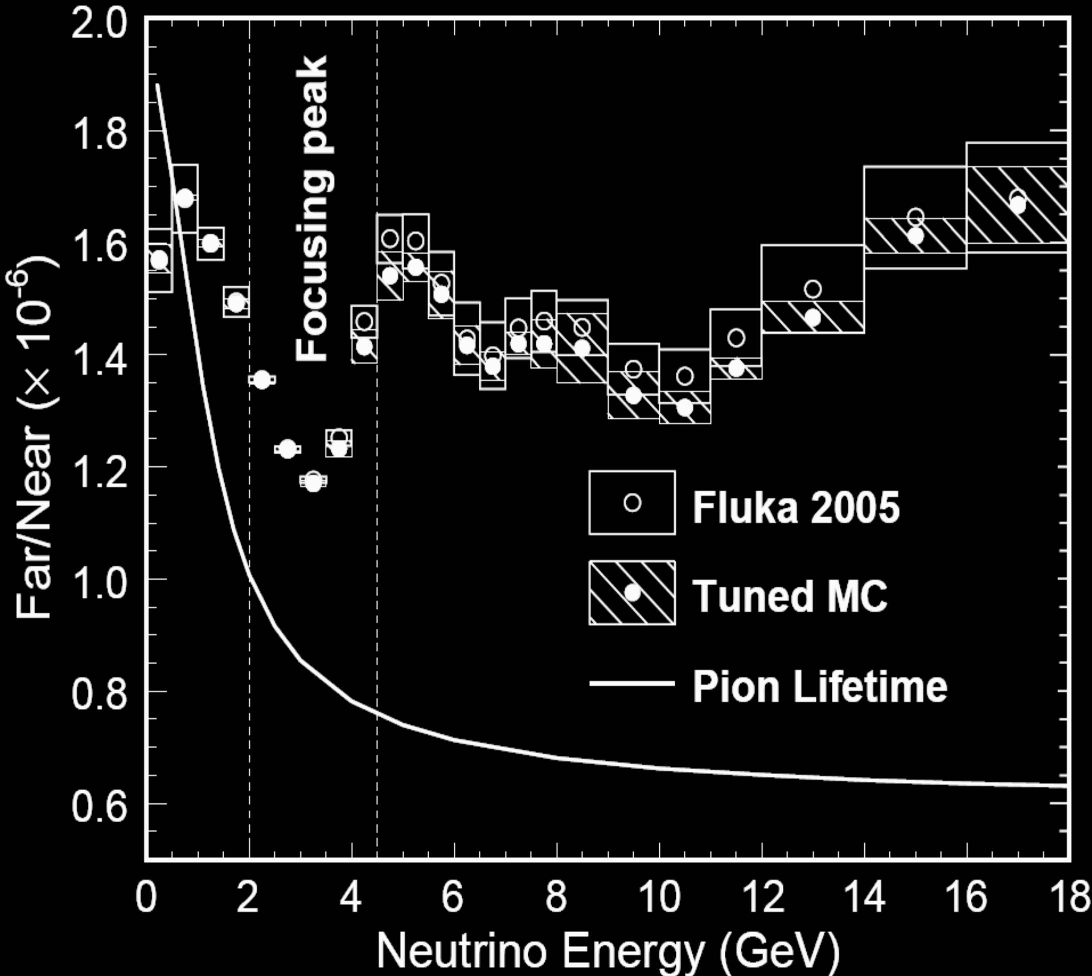
Simultaneous fit to Antineutrinos

- Antineutrinos come from π^- off the target
- Our simultaneous ν_μ and anti-ν_μ fit came surprisingly close to new p+C data available from CERN NA49 experiment!
- Soon can compare K/π fit to NA49 data



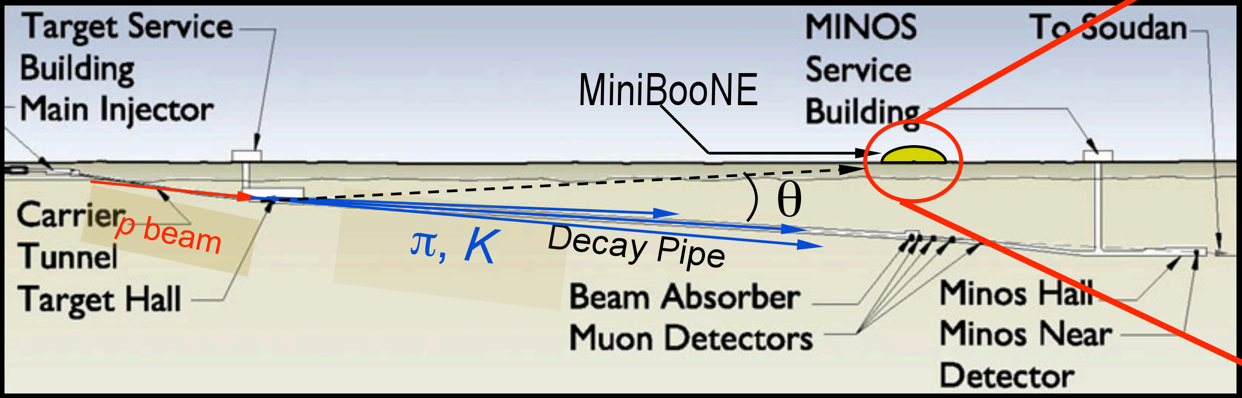


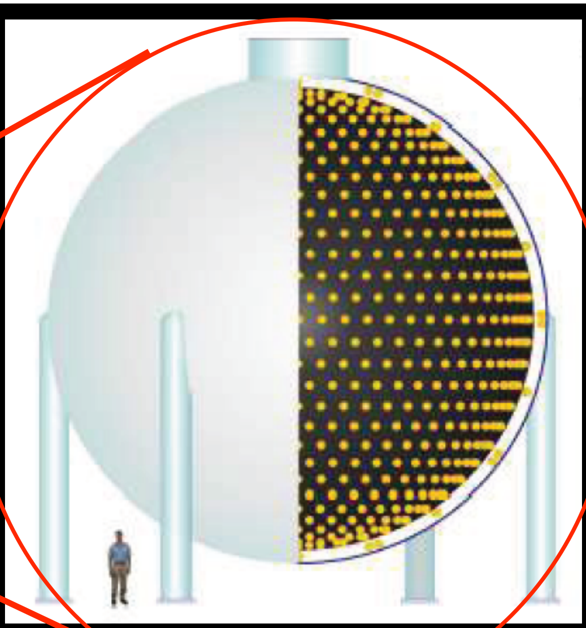
Using NuMI Flux Tuning



- In 2-detector oscillation experiment, refine near-to-far extrapolation
- For cross section experiment, can use to tune flux, but requires "known" mode or something flat with E_ν (MINERvA will use moderate Q^2 QELs)

Confirmation in Off-Axis Beam

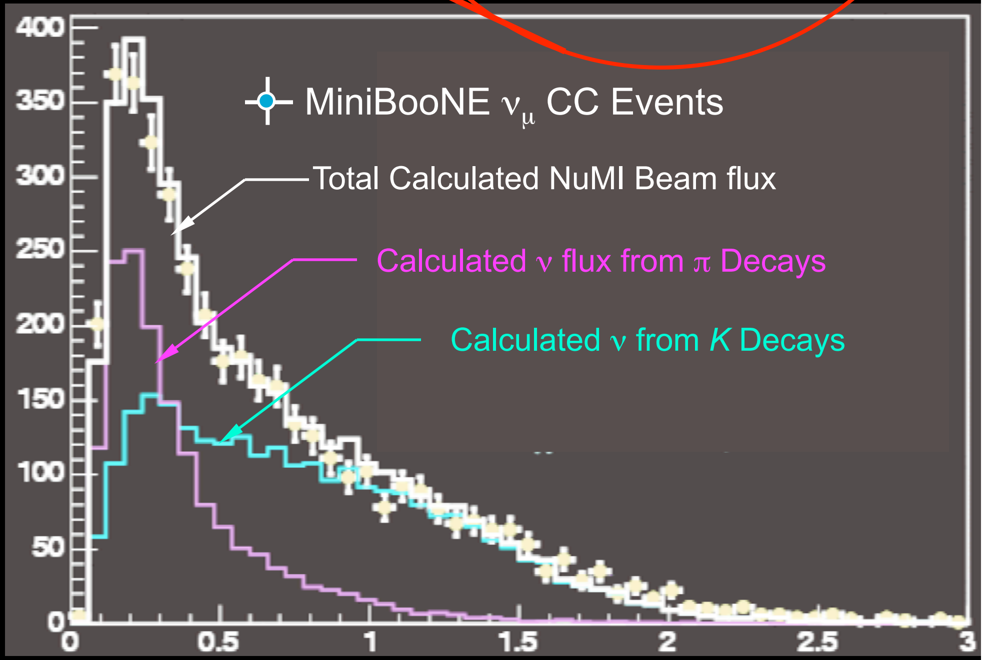




- NuMI ν's sprayed in all directions.
- *K*→μν and π→μν decays lead to lower E_ν at large decay angle

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

~110mrad to MiniBooNE

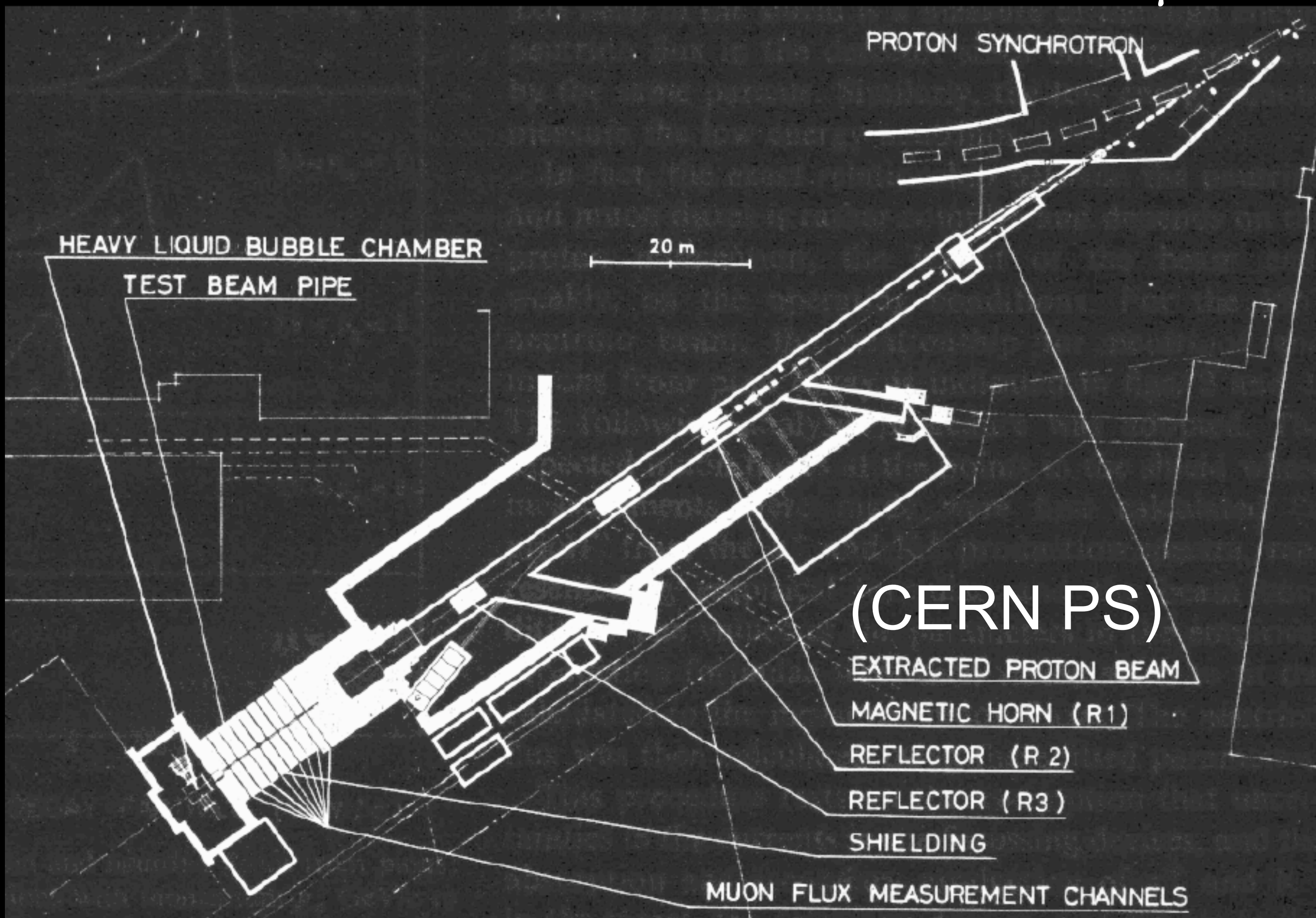


- P. Adamson *et al*, Phys.Rev.Lett.**102:**211801 (2009)

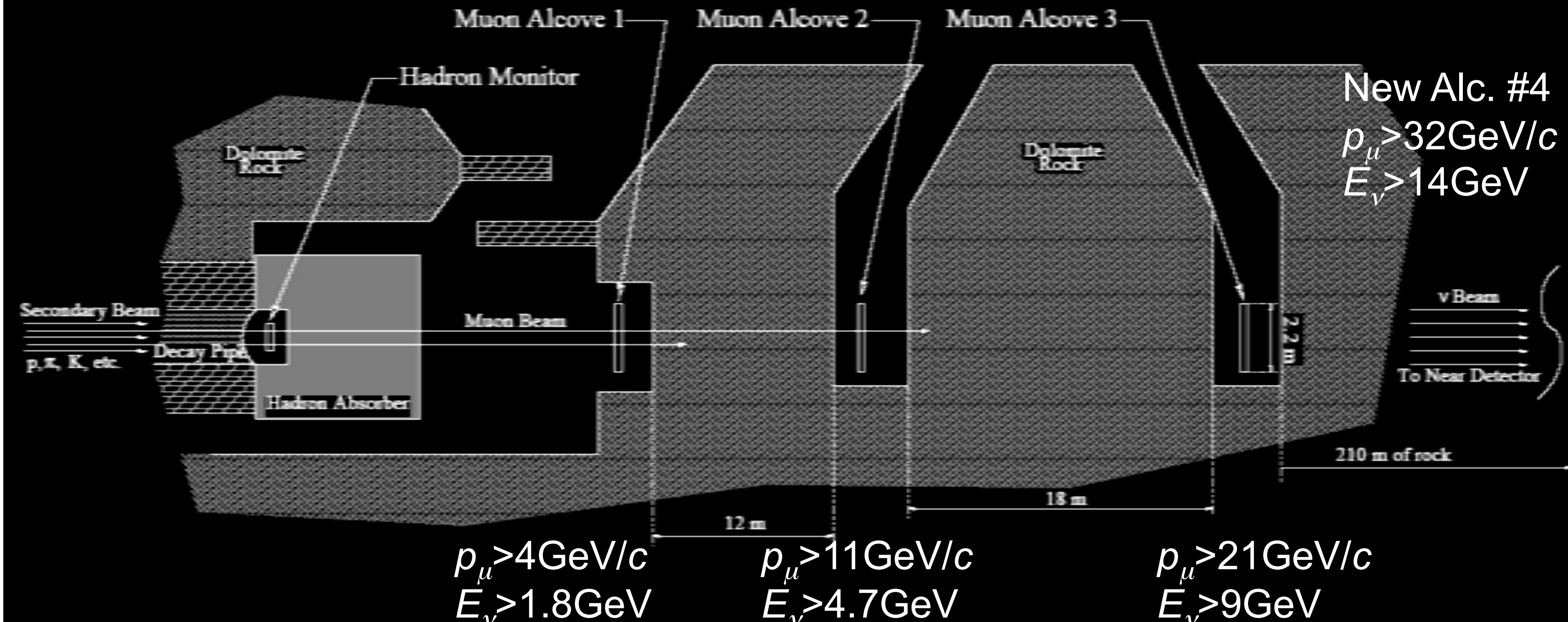
Using μ Beam to Measure ν_μ Flux

- Conventional wide band ν_μ beams from meson decays also produce muons – sensitive to same hadrons
- Decay kinematics favor capture of *more* of μ beam than ν_μ beam.
- Past examples from BNL, CERN PS, WANF, IHEP, FNAL E616, NuMI

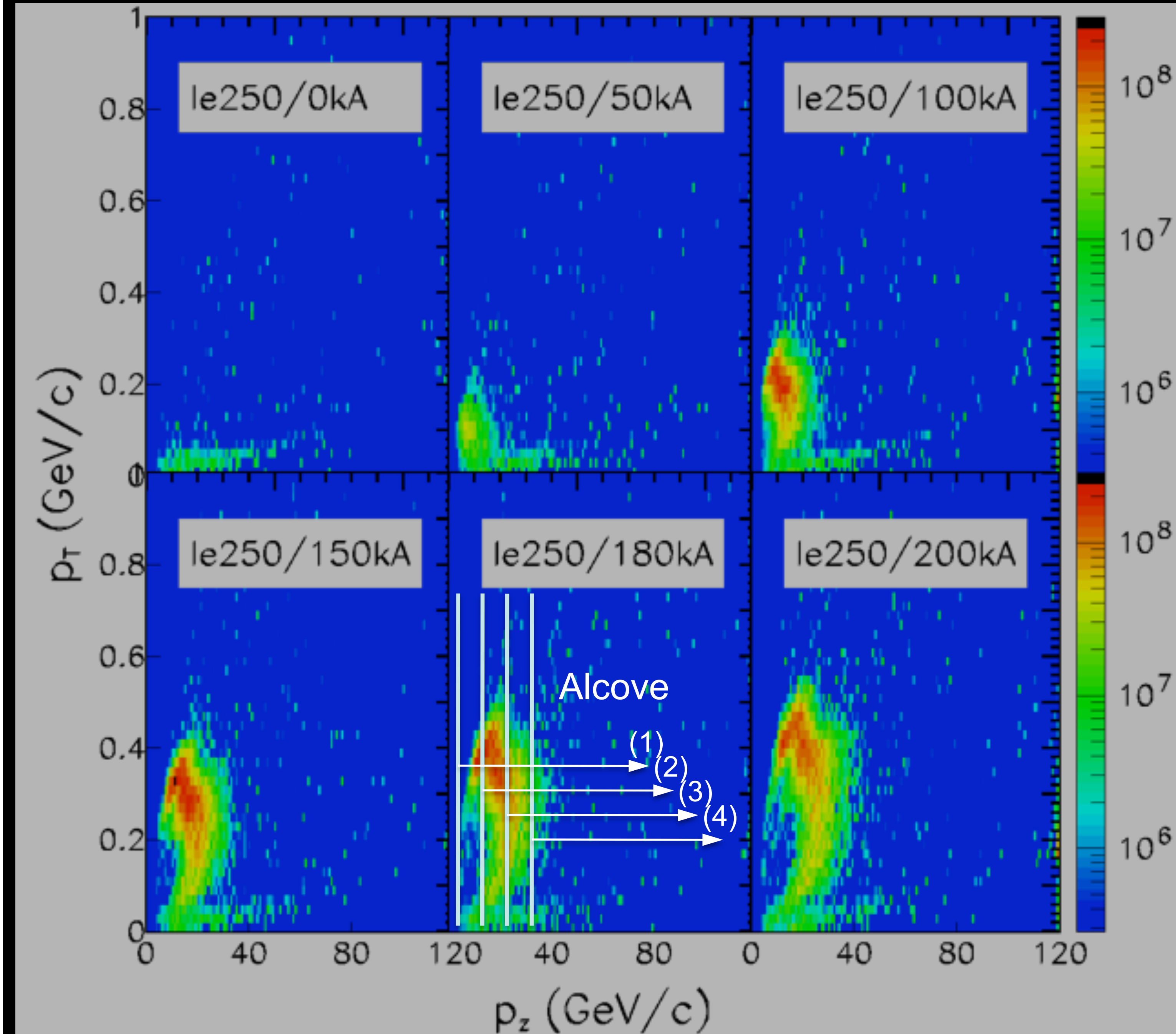
Using μ Beam to Measure ν_μ Flux



NuMI Muon Monitors



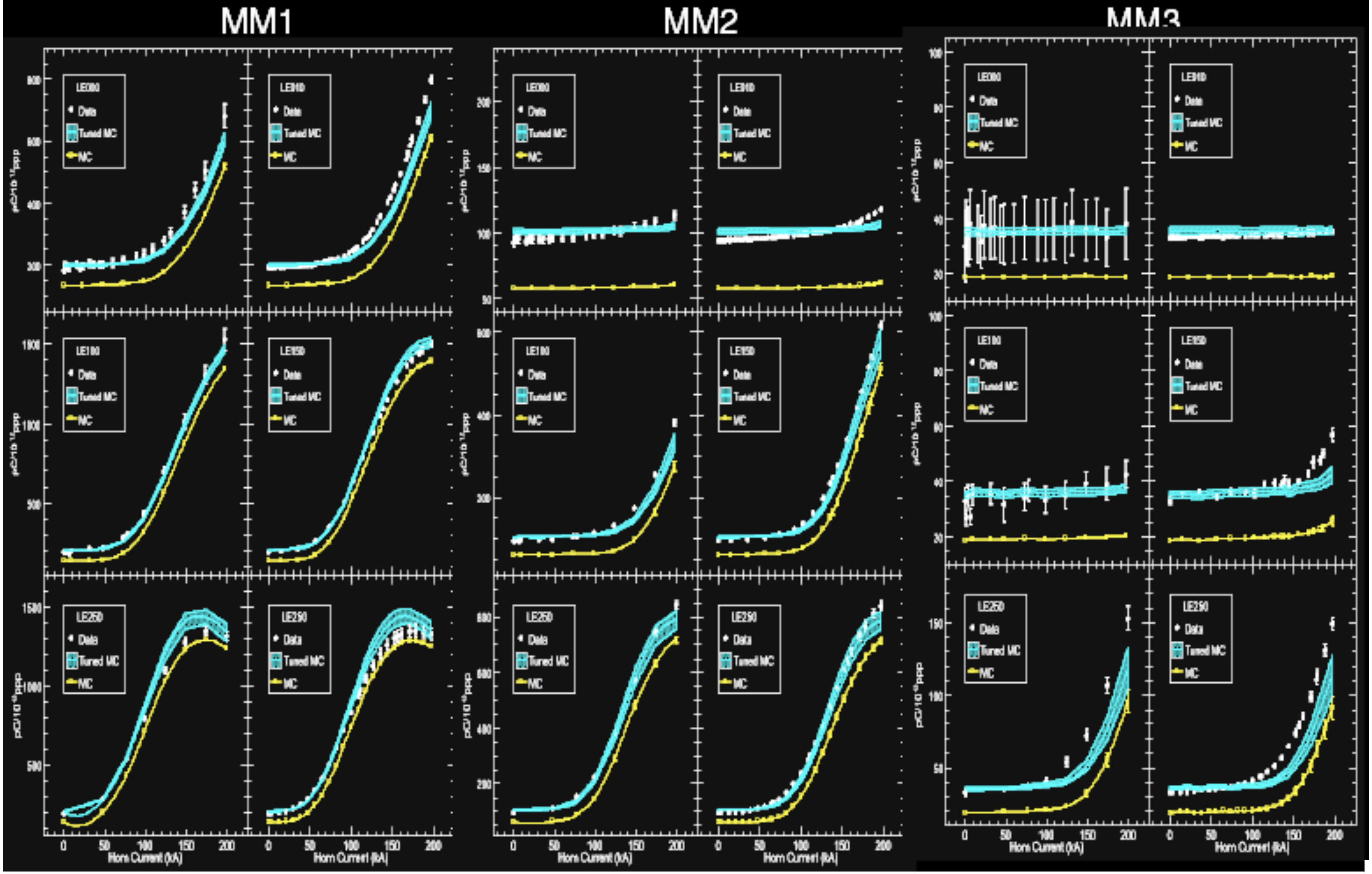
- Smaller angular acceptance (~1mrad)
- Higher momentum threshold (~4 GeV/*c*)
- Only 3 (soon to be 4!) alcoves



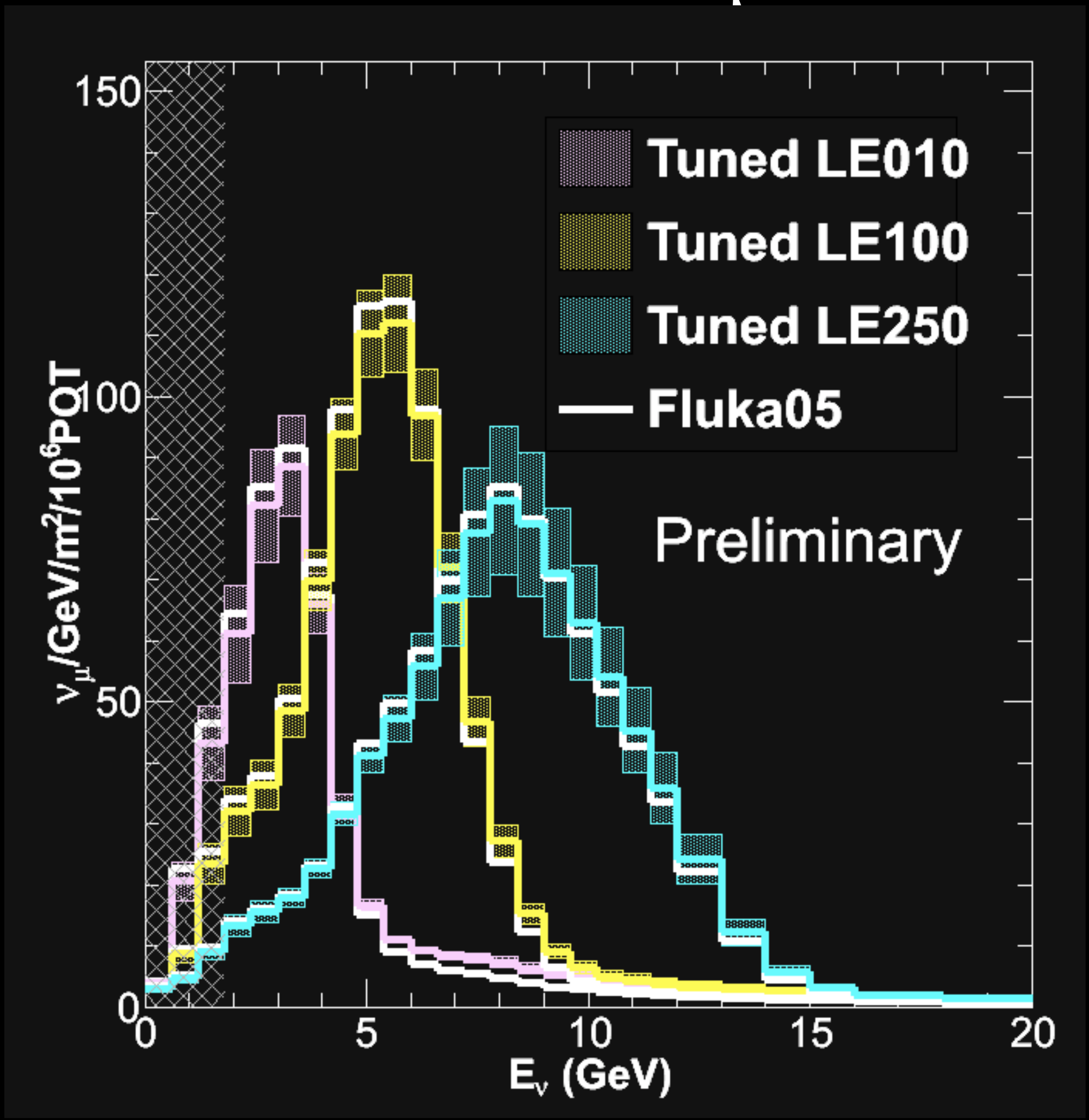
Scan I_{horn}, watch focused π^+ shift

Similar graphs for LE010, LE100, *etc*

Fit to MuMon Data



NuMI μMon Flux



- Similar to tuning by MINOS, but uses μMon event rates (no error from ν x-sec)
- L. Loiacono, poster session
- 20-30% errors now, aim for 10% in MINERvA

Summary

- Can we design ν beams in advance for *in situ* checks and for x-sec measurements?

- *Ab initio* measurements may not replicate *in situ* effects – especially in intense beams!
- *In situ* measurements can deconvolve cross section and flux effects
- We found that ν beam flexibility benefits this effort

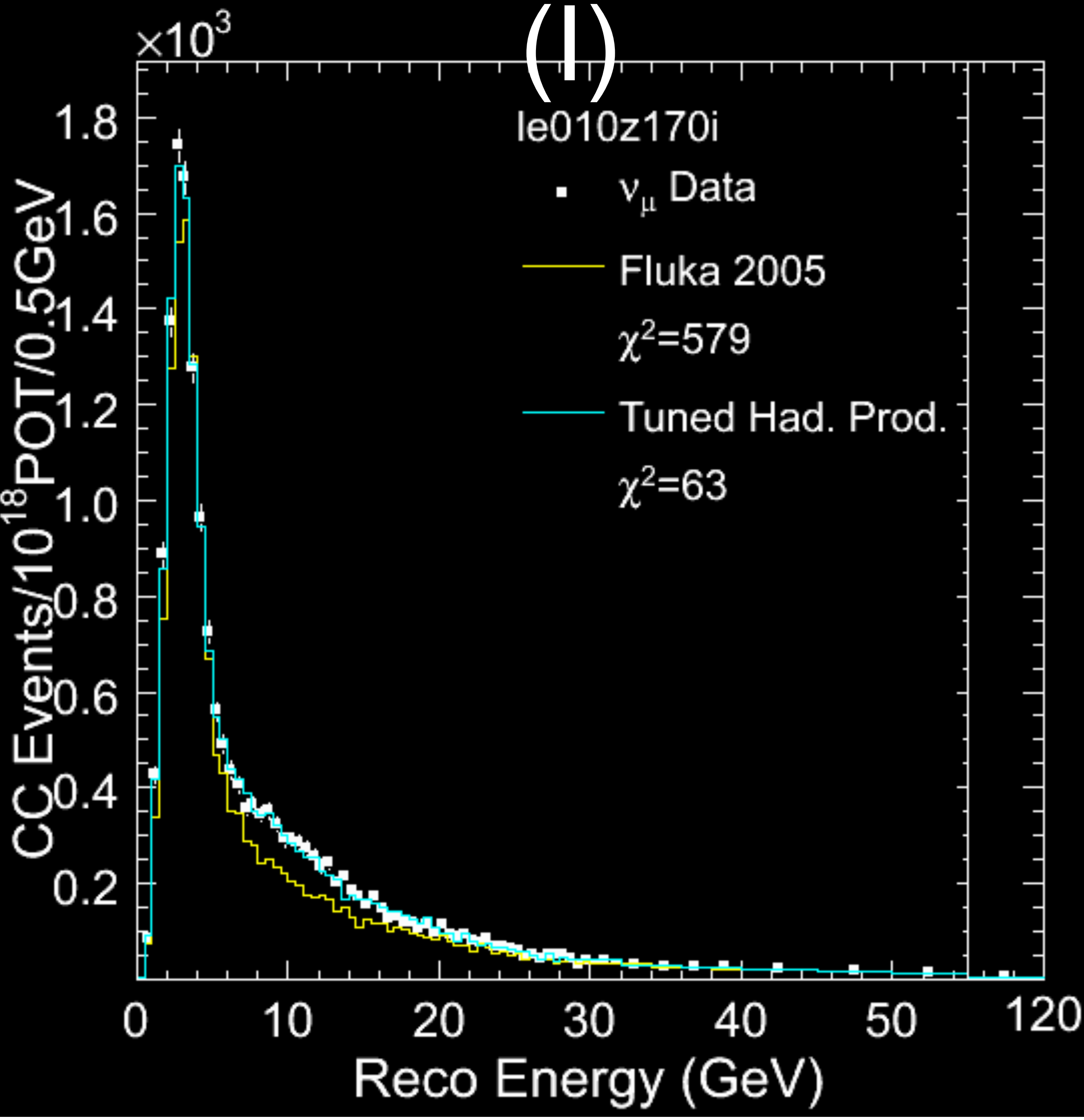
References

- Z. Pavlovic, PhD Thesis, University of Texas, 2008
- L. Loiacono, PhD Thesis, University of Texas, 2010
- S. Kopp, "*Accel. Neutrino Beams*," Phys. Rep. **439**, 101 (2007)
- M. Kostin *et al*, "Proposal for Continuously-Variable Neutrino Beam Energy," Fermilab-TM-2353-AD (2001).
- S. Kopp *et al*, "The Secondary Beam Monitoring System for the NuMI Facility at FNAL," Nucl. Instr. Meth. **A568**, 503 (2006)

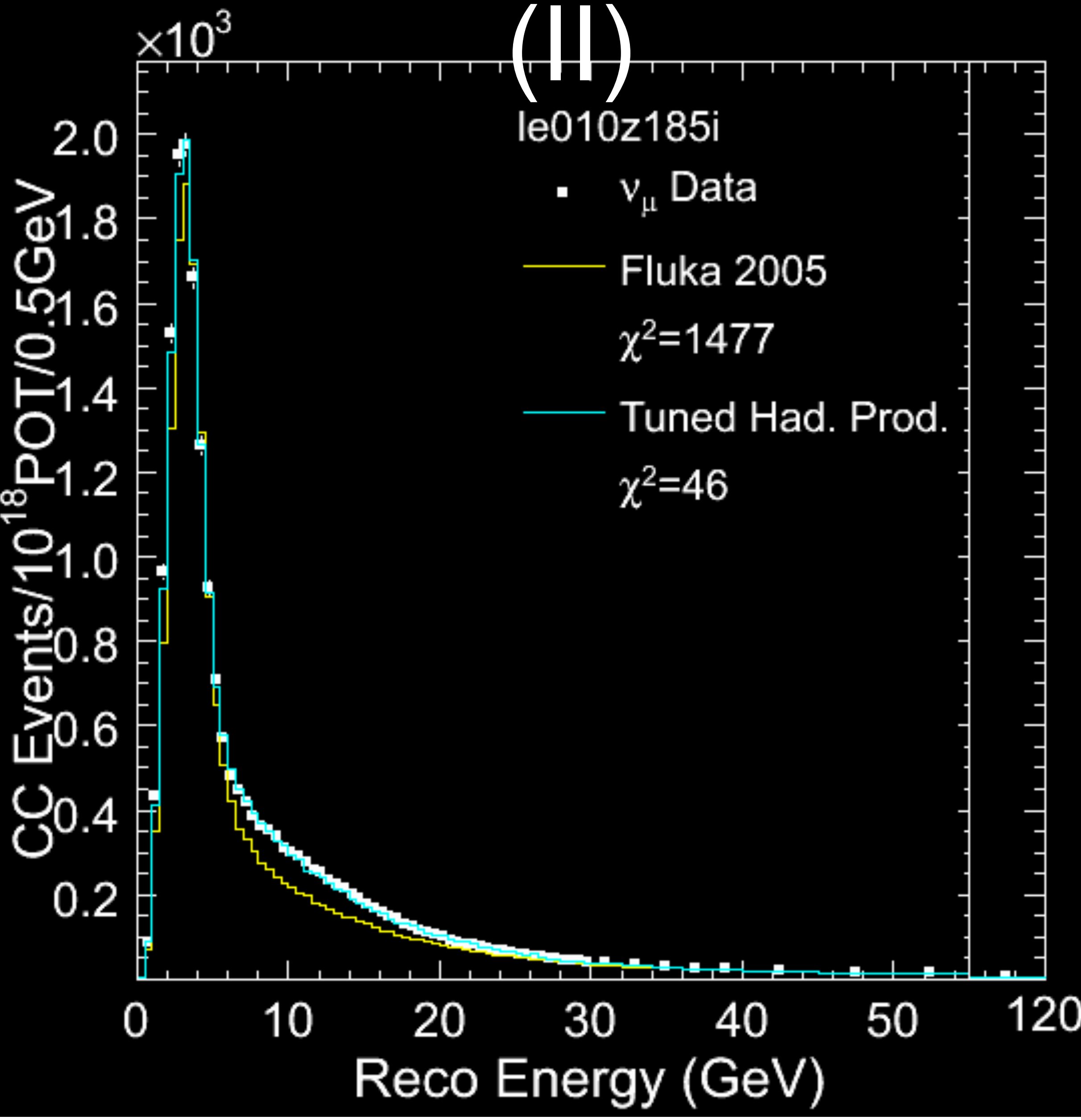
Acknowledgements

- R. Zwaska, P. Vahle, D. Harris, D. Indurthy, K. Lang, J. Thomas, S. Wojcicki, and members of MINOS and Minerva collaborations
- J. Hylen, A. Marchionni, S. Childress, M. Wendt, J. Morfin, M. Messier, A. Para for years of collaboration and vigorous discussions.

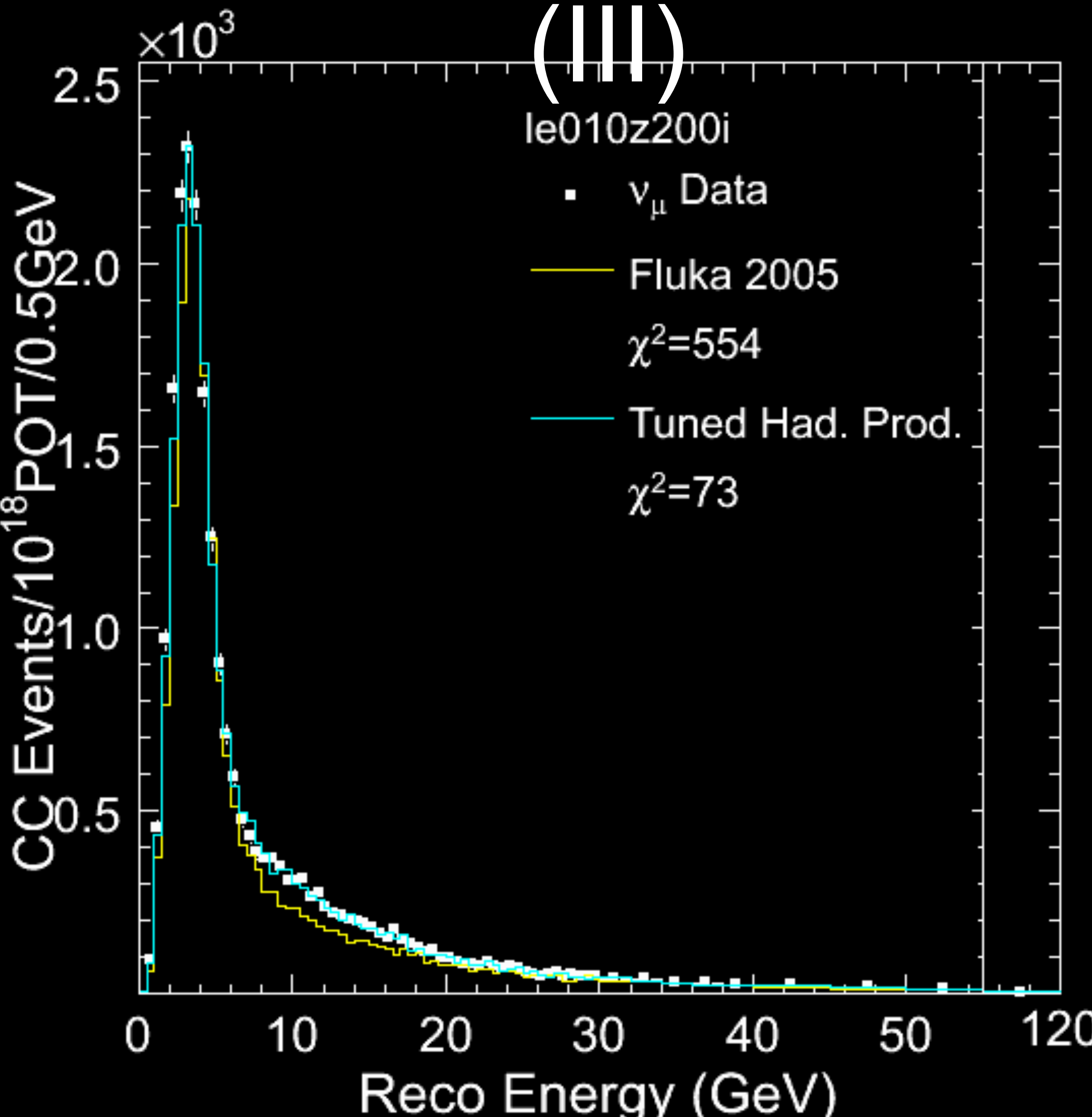
ND Spectra After Reweighting (I)



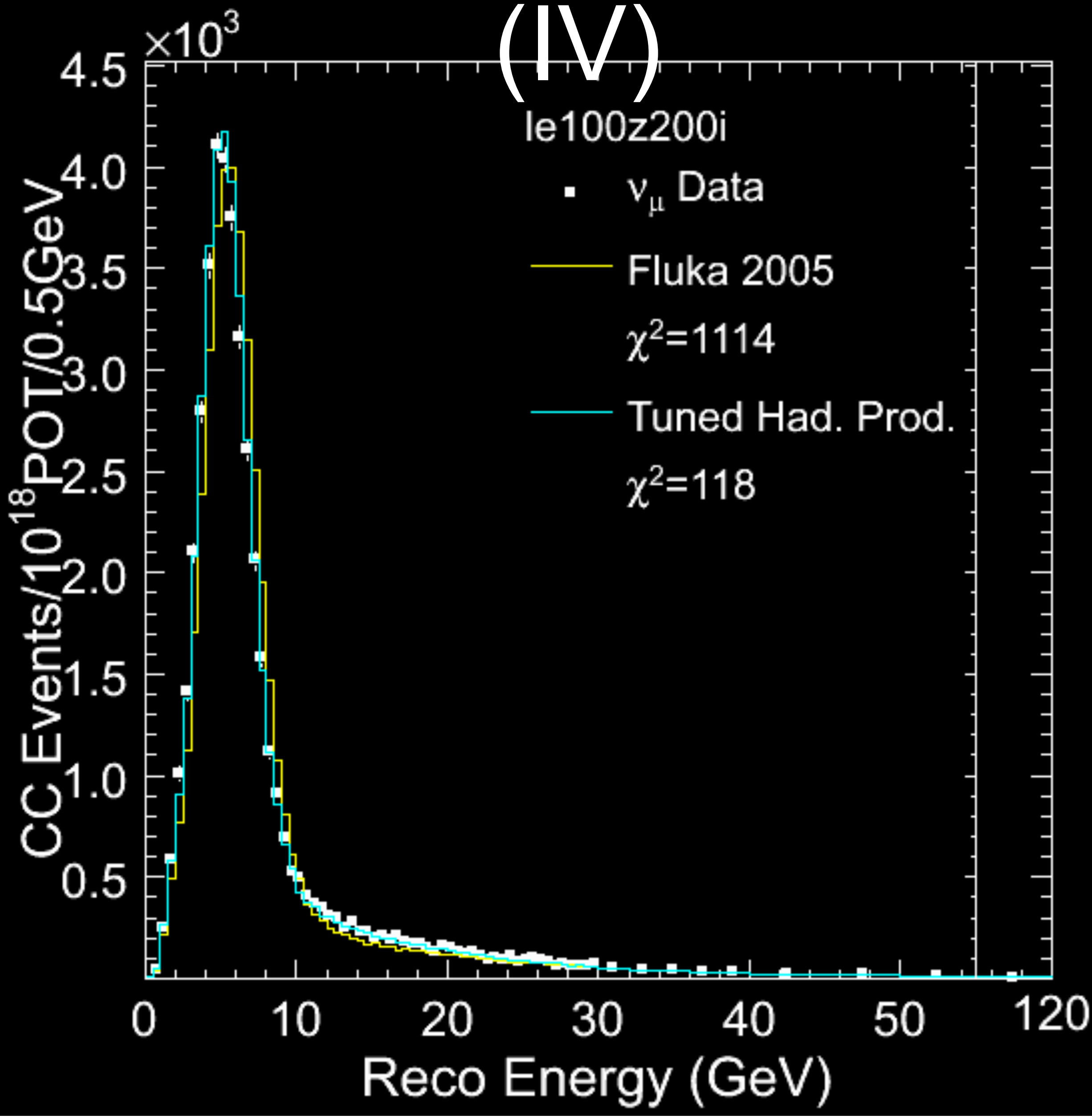
ND Spectra After Reweighting (II)



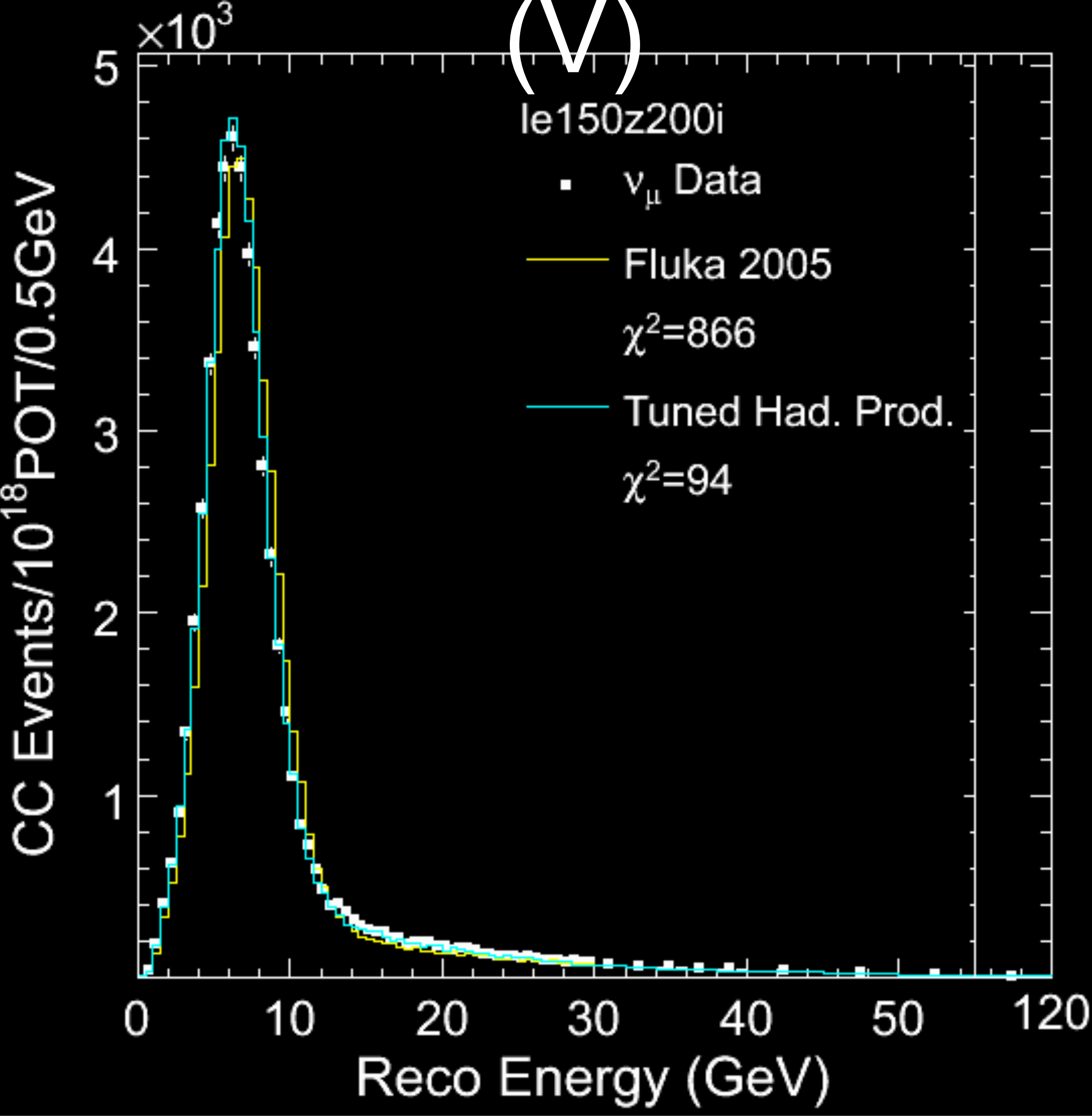
ND Spectra After Reweighting (III)



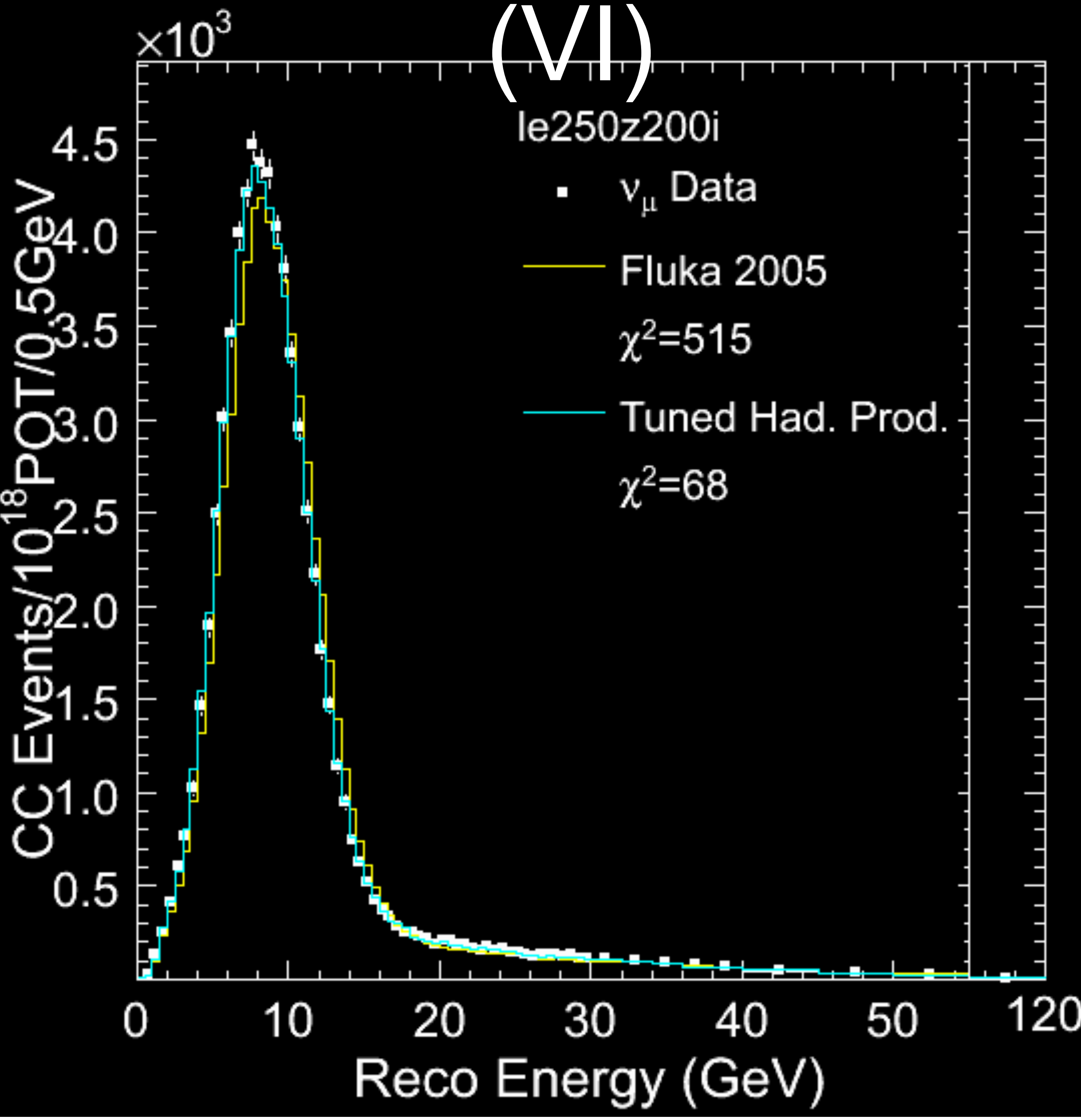
ND Spectra After Reweighting (IV)



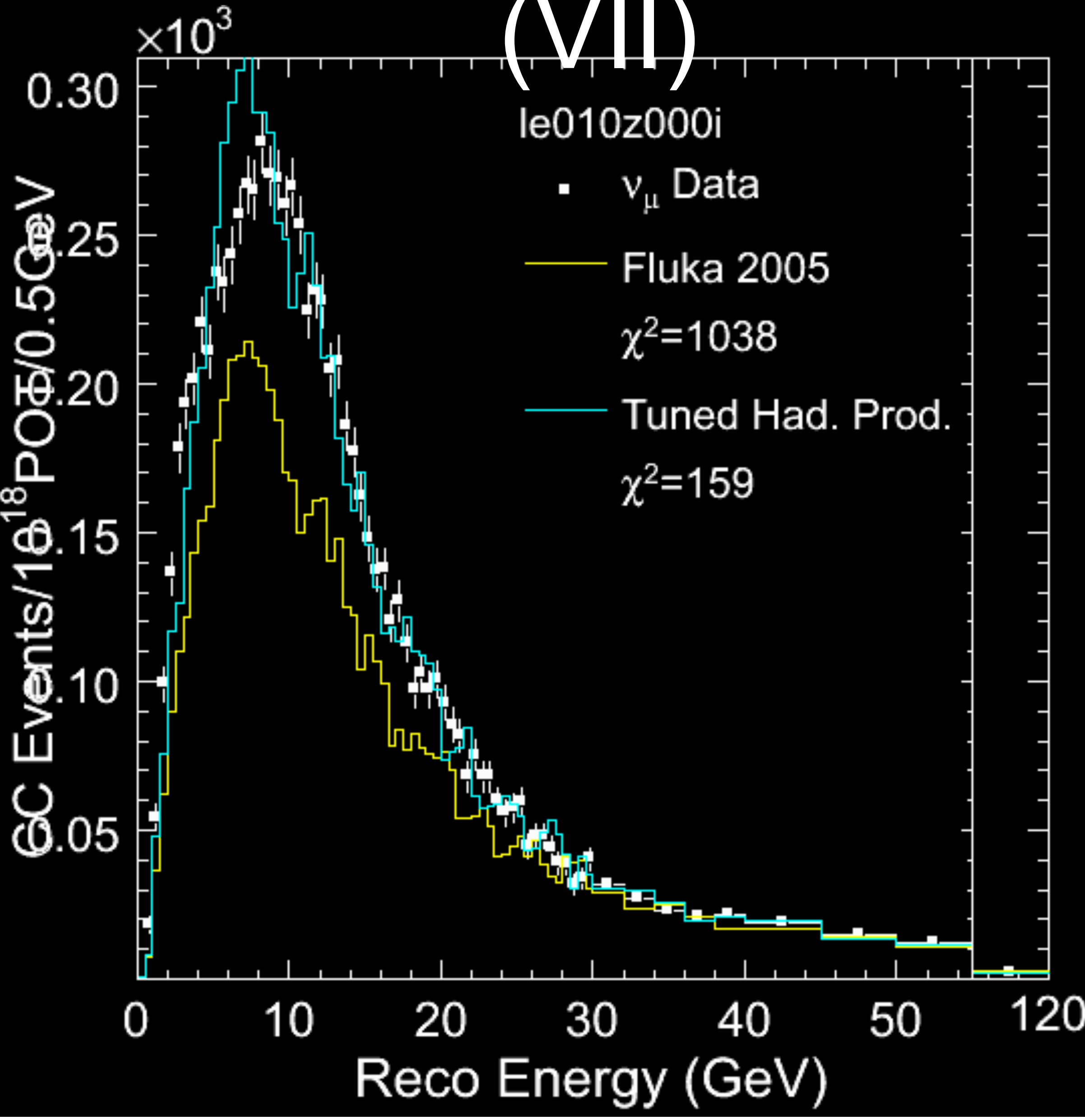
ND Spectra After Reweighting (V)



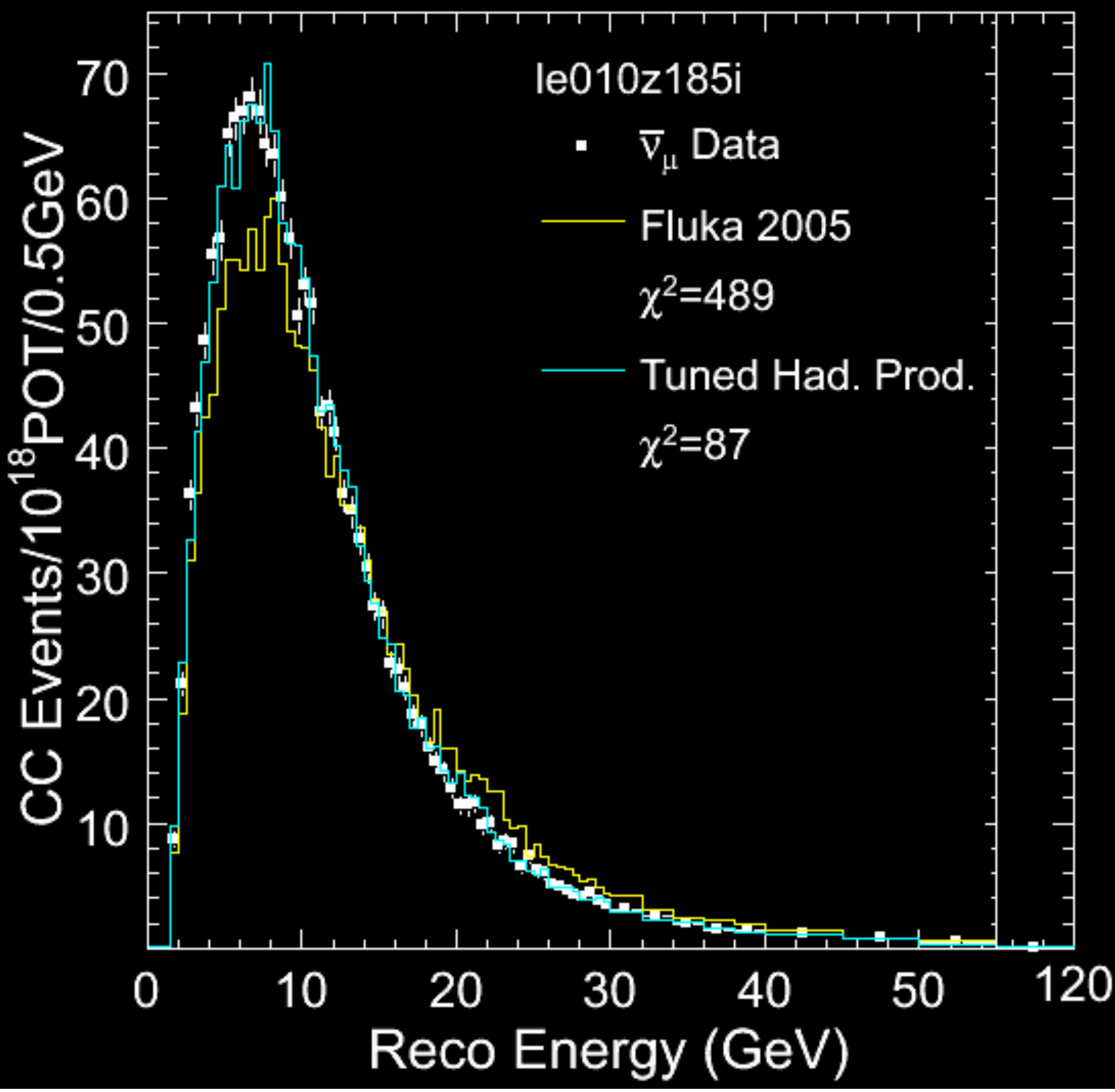
ND Spectra After Reweighting (VI)



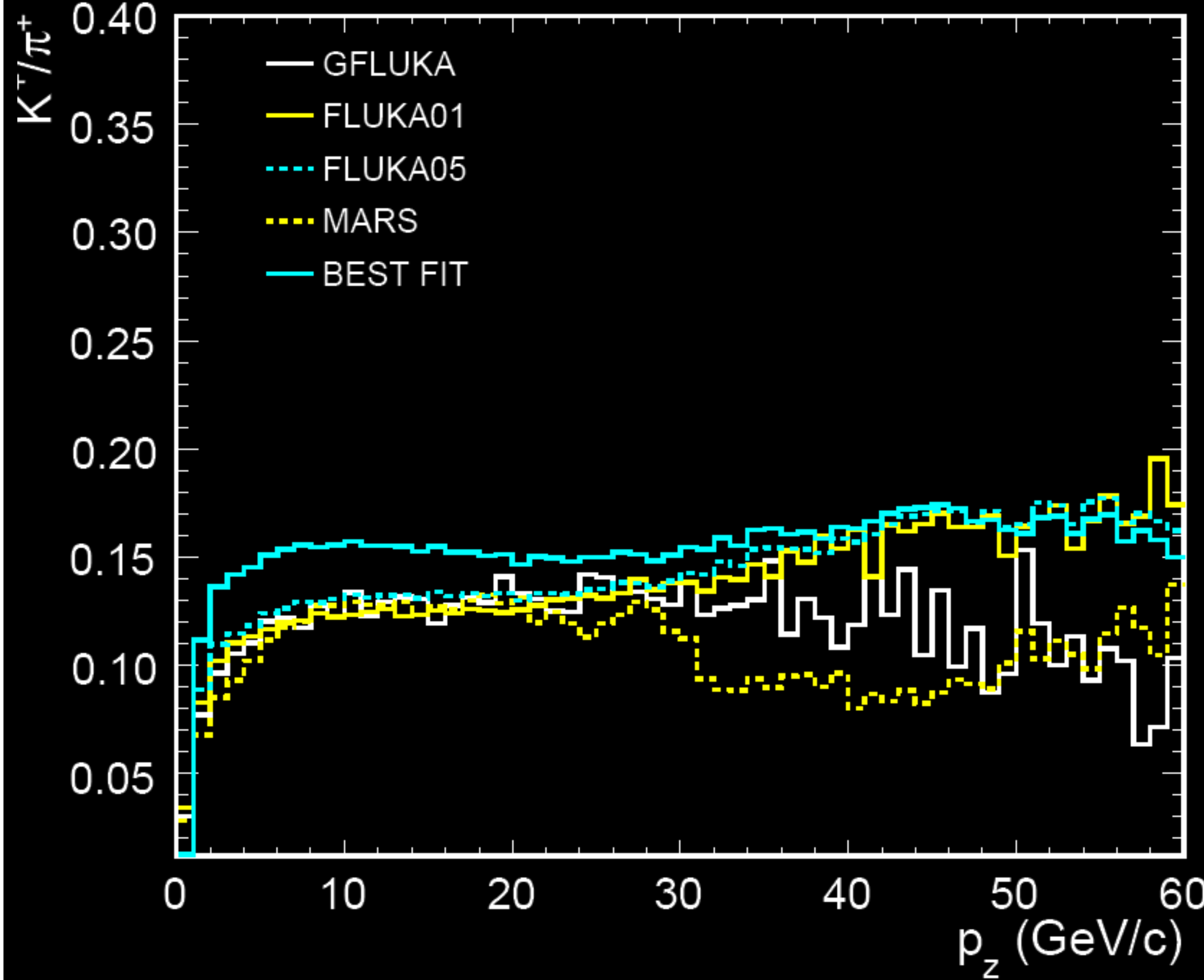
ND Spectra After Reweighting (VII)



ND Spectra After Reweighting (VIII)



Constraint of fit on *K*/π ratio



- Recent data from FNAL E907 to which we can compare
- See talk by J.Paley later this session.

A Cautionary Tale (2)

- ANL did particle production experiment on "actual" target:

  R.A. Lundy, et al., *Phys. Rev. Lett. 14 (1965) 504.*

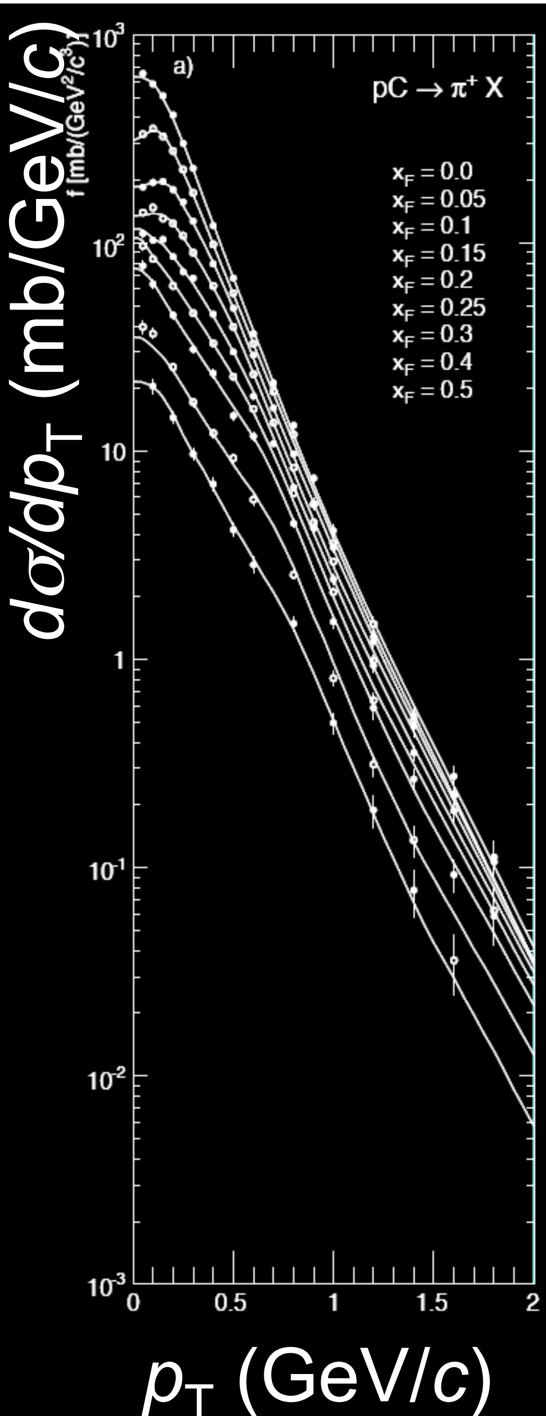
- Motivated by bad fit to Sanford-Wang, did second round with limited points

  J.G. Asbury, et al., *Phys. Rev. 178 (1969) 2086.*

  G.J. Marmer, et al.,Phys. Rev. 179 (1969) 1294.

- Finally had to do "round three"

  Y. Cho, et al., *Phys. Rev. D 4 (1971) 1967.*



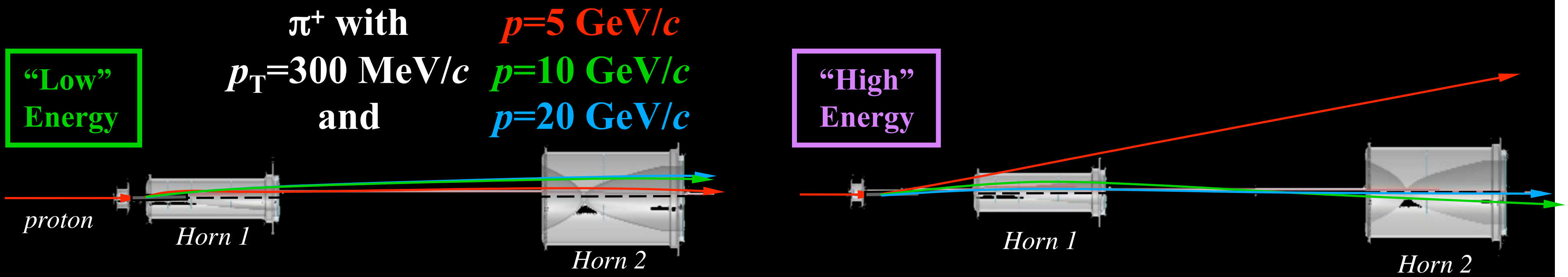
Modern Data Sets are $%#&! Good!

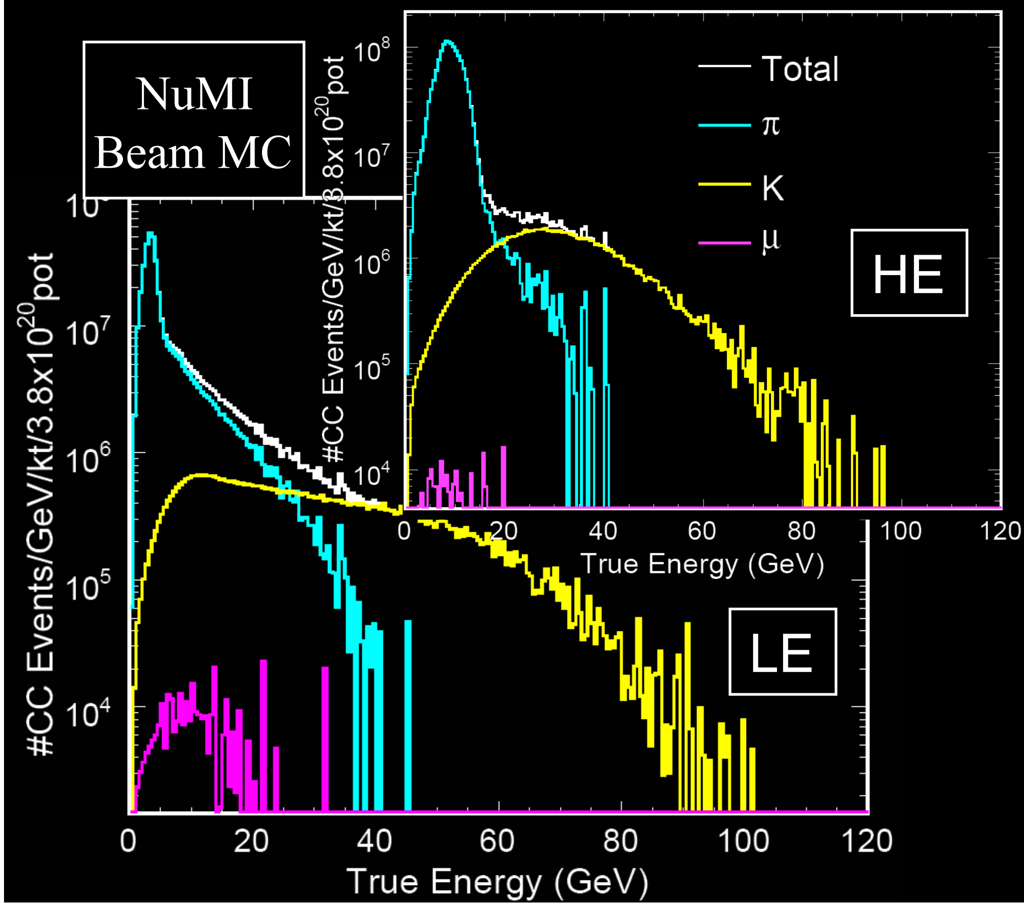
eg: C. Alt *et al*, Eur.Phys.J.C49:897-917,2007

- Modern data sets better than original 'beam surveys'
  - single particle detection
  - particle ID
  - large acceptance

- **So can't we just use this to map $\phi_\nu(x_F,p_T)$??**

NuMI Variable energy beam

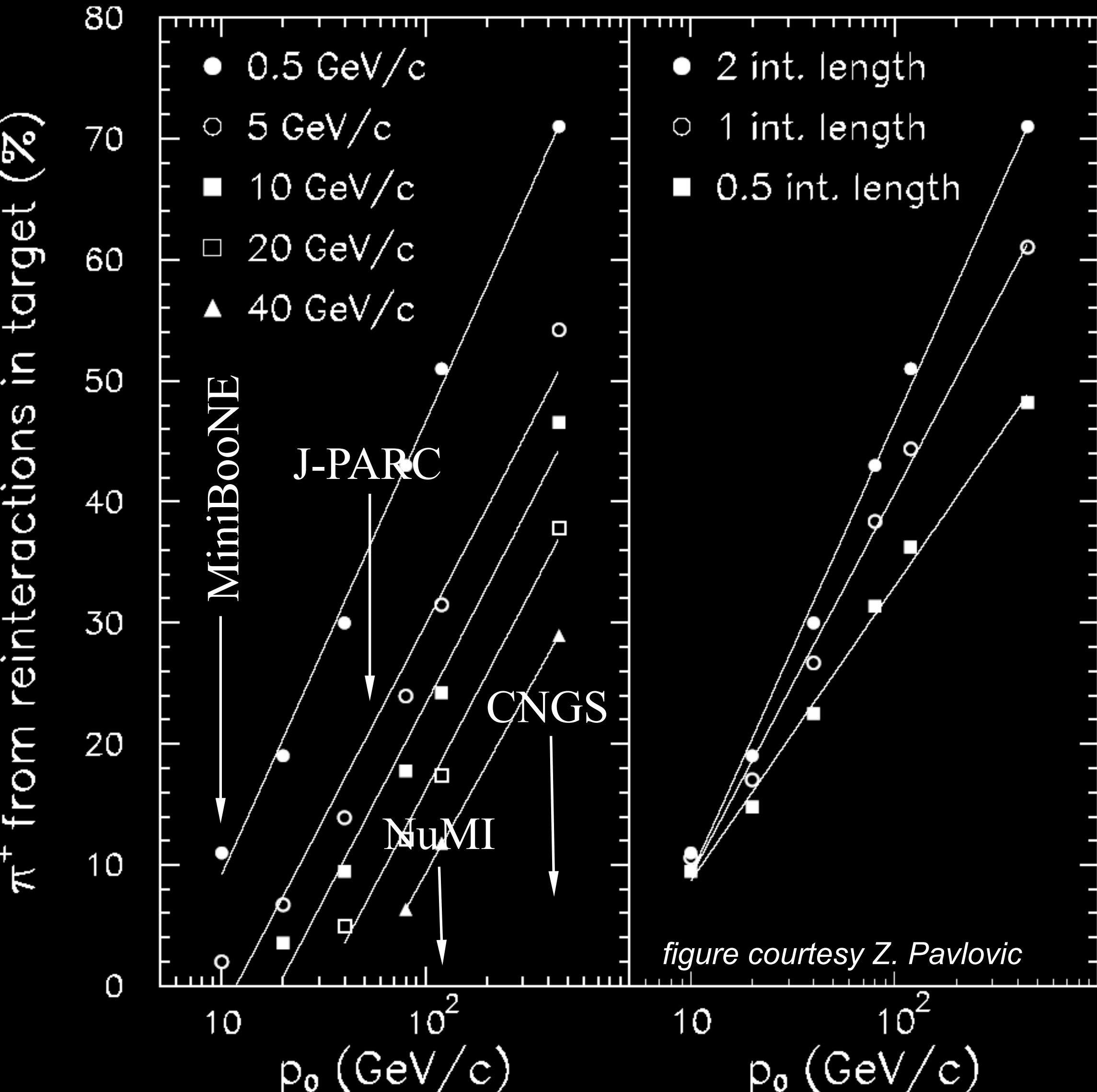




CRUCIAL POINT

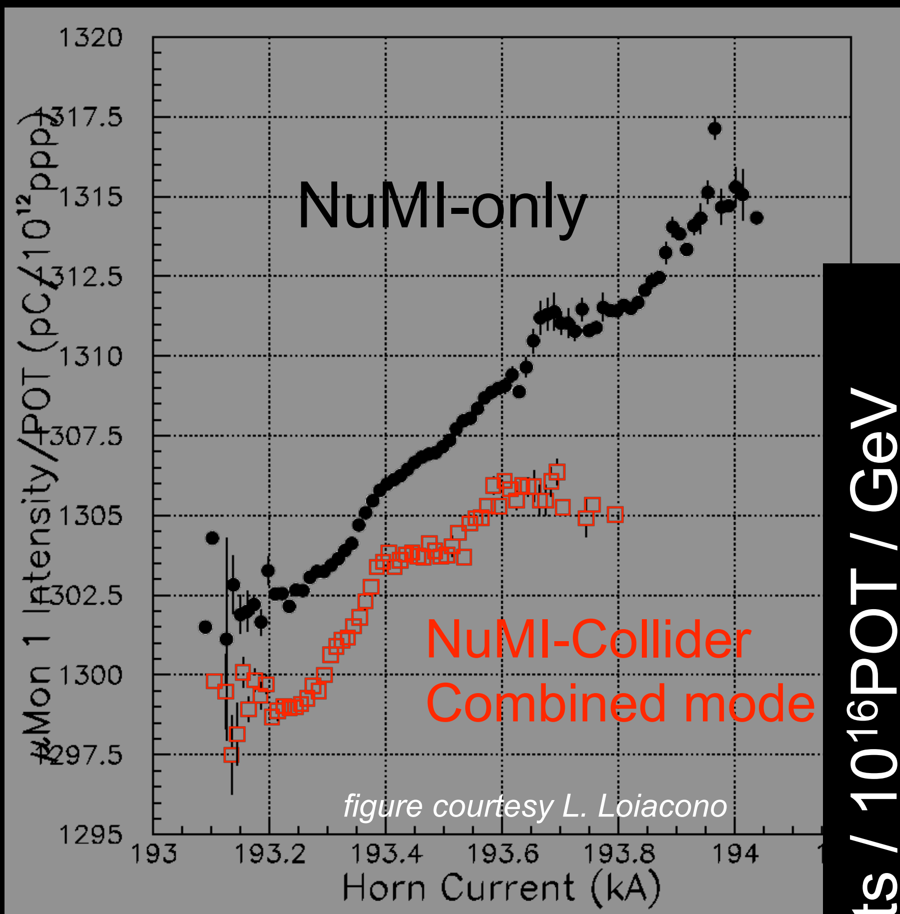
- *Produce same E_ν using several beam focusing configurations*
- Deconvolve systematics
  - Neutrino beam focusing
  - *π/K* production off target
  - Neutrino cross sections

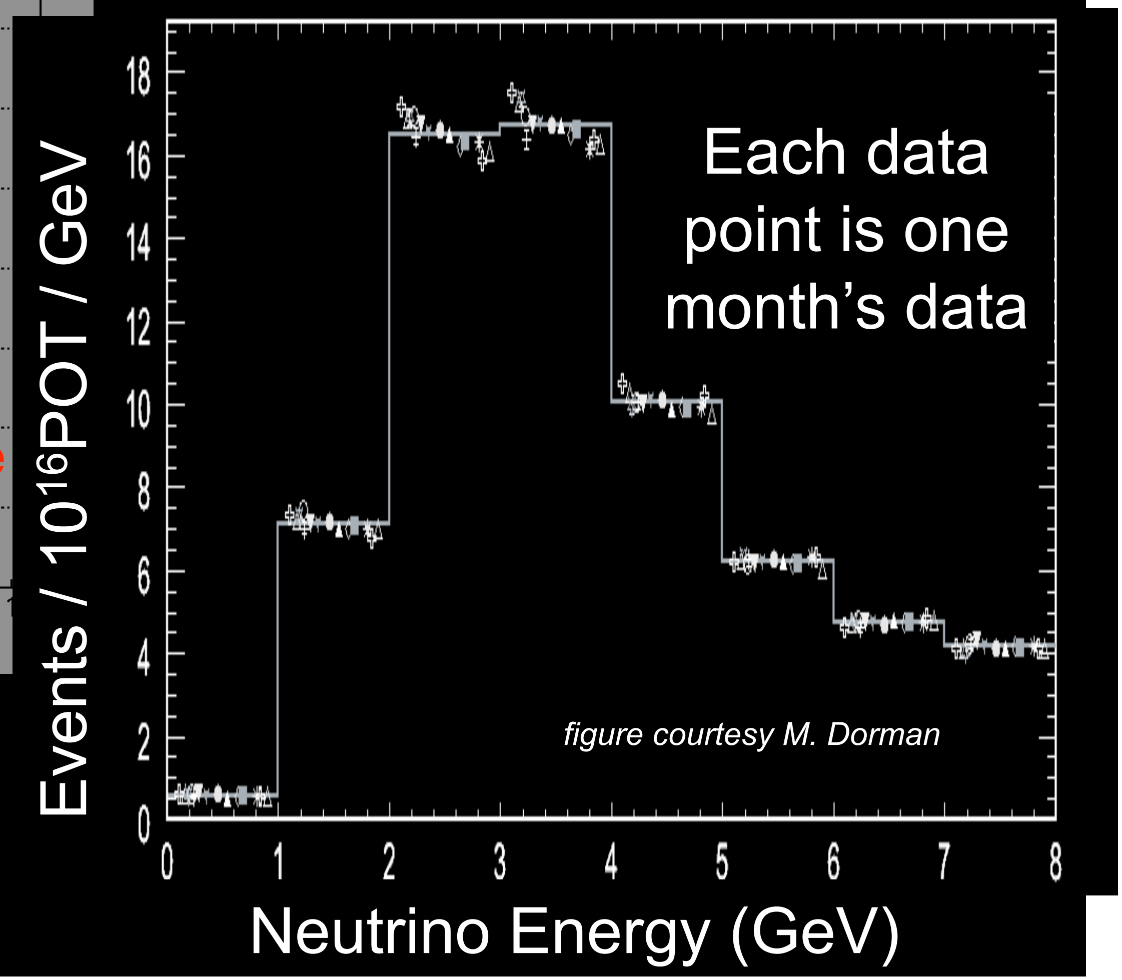
Caution #1: Thick Target Effects



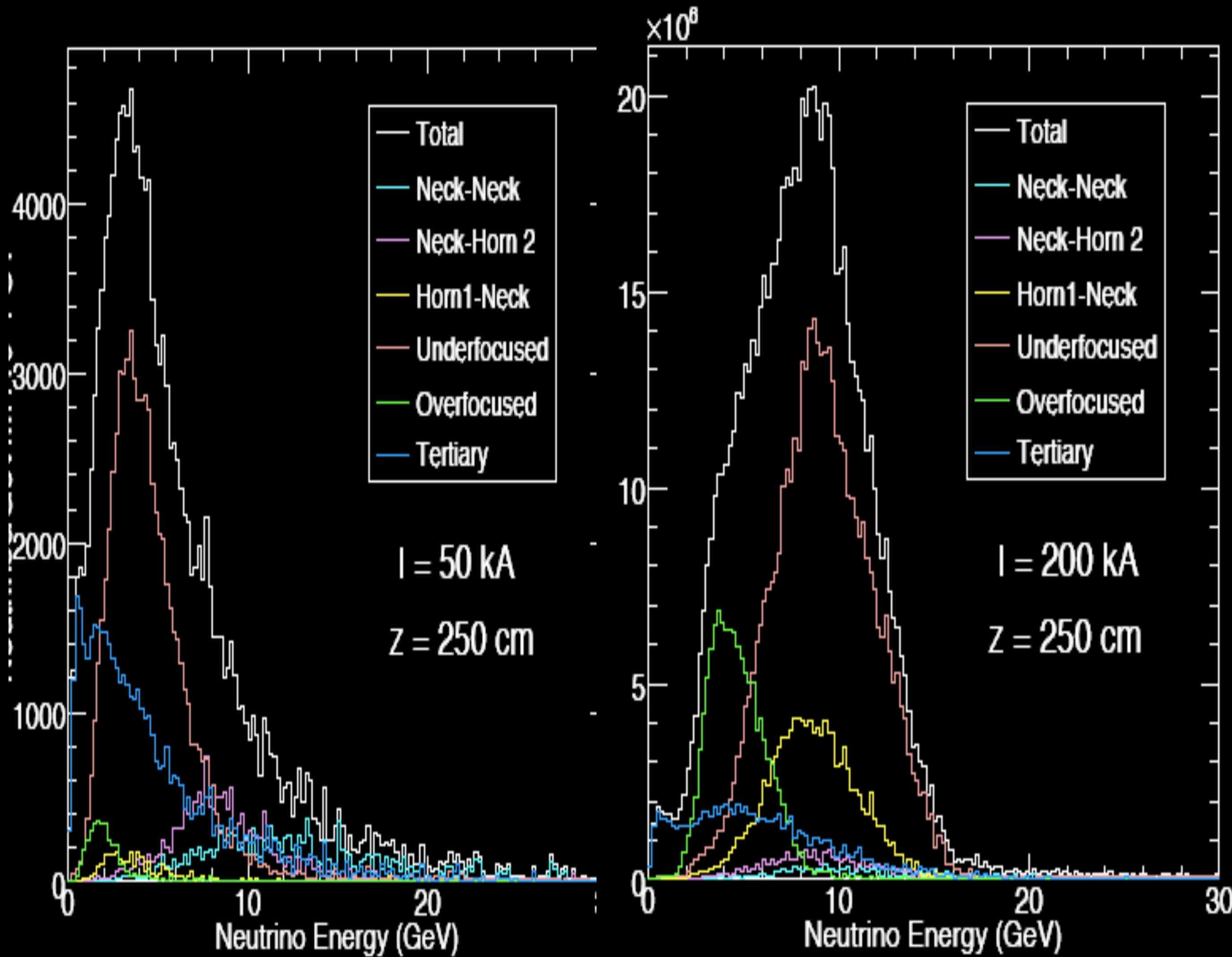
- Most production exp'ts on thin targets
- Nu target ~ $2\lambda_{int}$
- Reinteractions 20-30% effect
- Motivates MIPP, NA69, HARP data on thick targets

Caution #2: In-situ variations



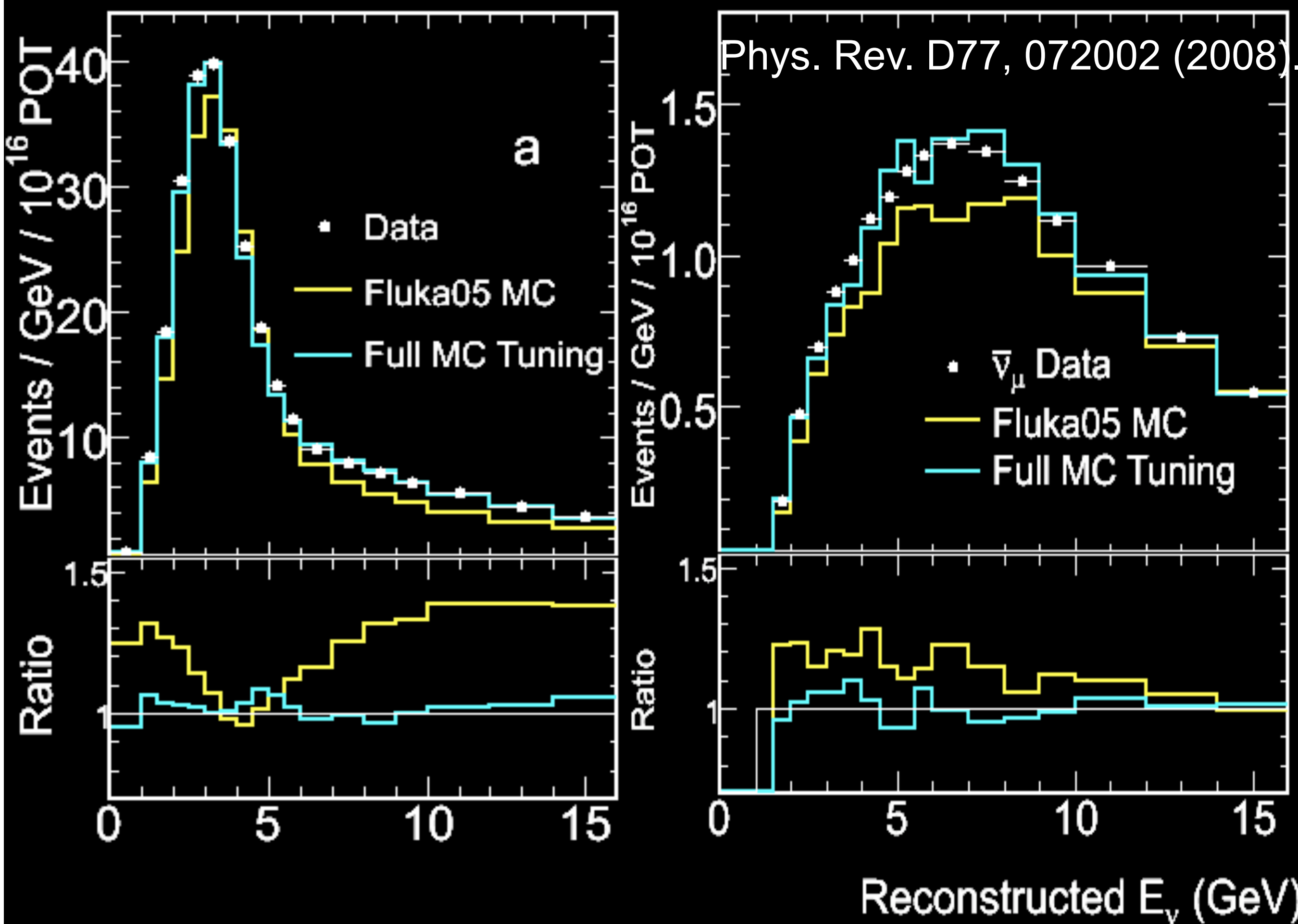


Caution #3: Downstream Interactions



- Require some technique to measure this contribution

NuMI Flux Tuning



- Fit all 8 beam runs.
- Fit ν_μ and $\bar{\nu}_\mu$ spectra
- Done by MINOS with inclusive events to adjust F/N ratio

- To be replicated by MINERvA using moderate Q^2 QELs as standard candle.