NuMI Neutrino Flux Predictions

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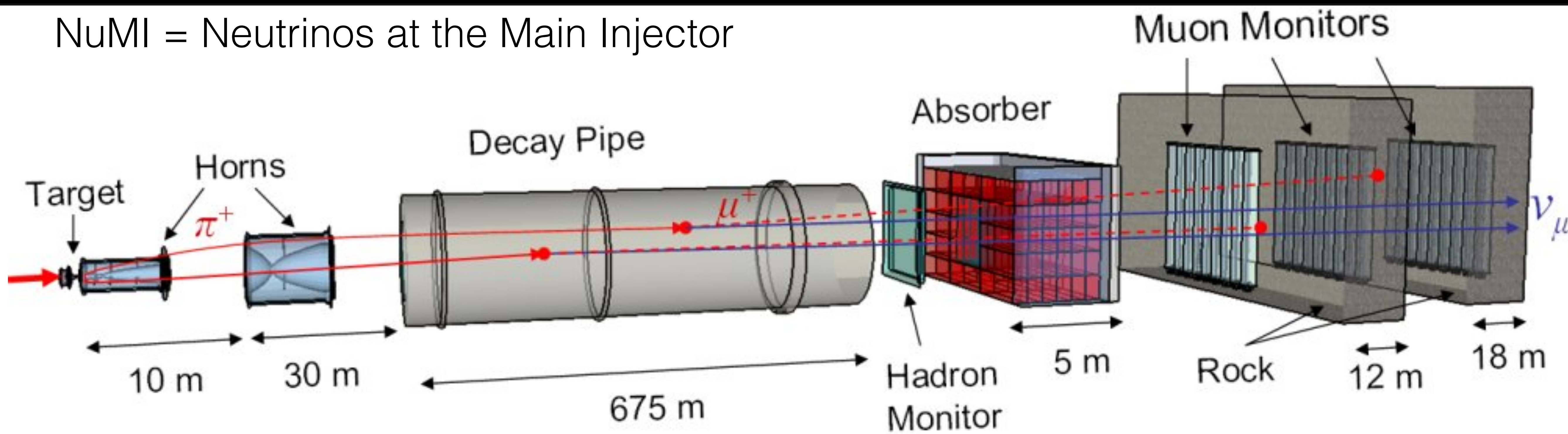
The NuMI Beam

NuMI = Neutrinos at the Main Injector



Target: two distinct styles (MINOS-era [le], NOvA-era [me])

- both are graphite, but internal structure is different
- MINOS-era target could be repositioned relative to horn 1

Two "horns" produce magnetic fields that focus secondaries

The NuMI Beam

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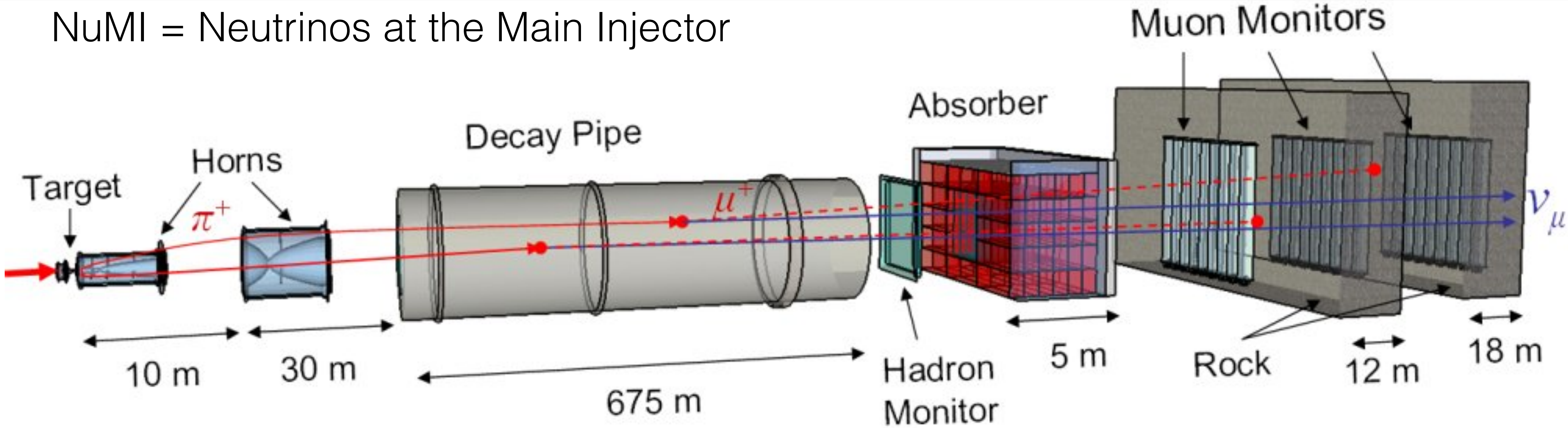
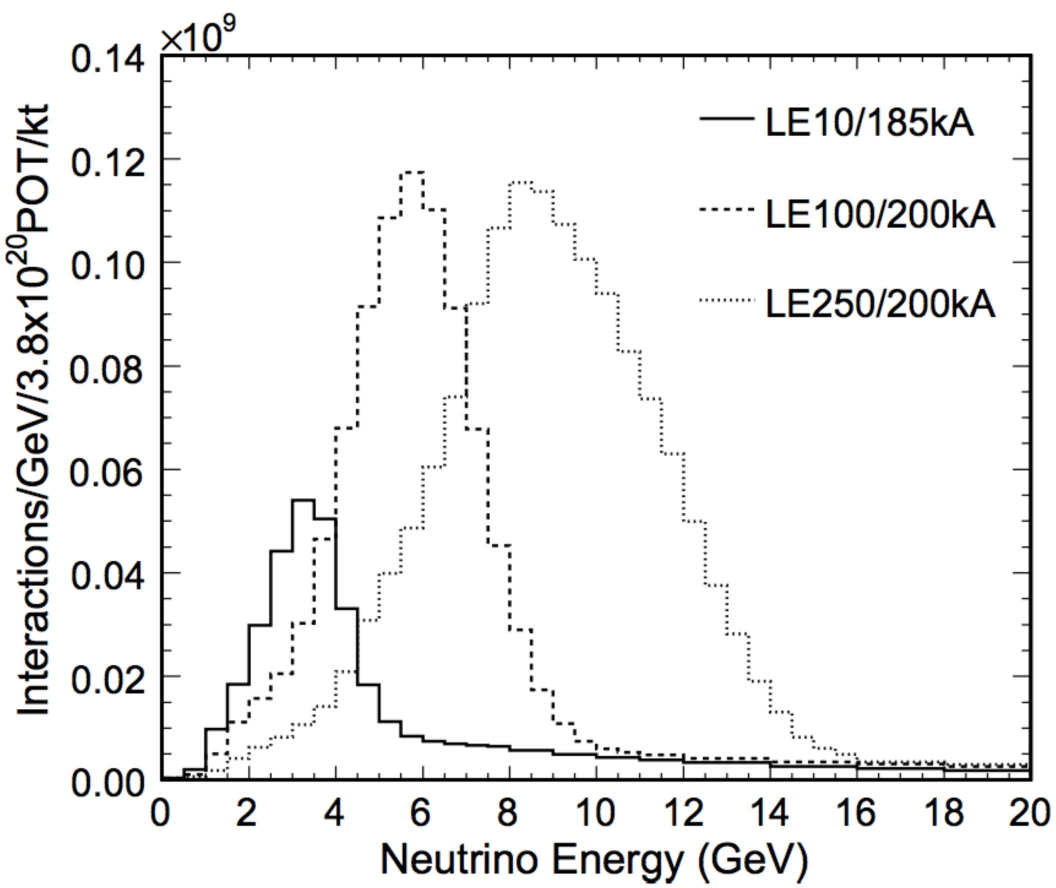




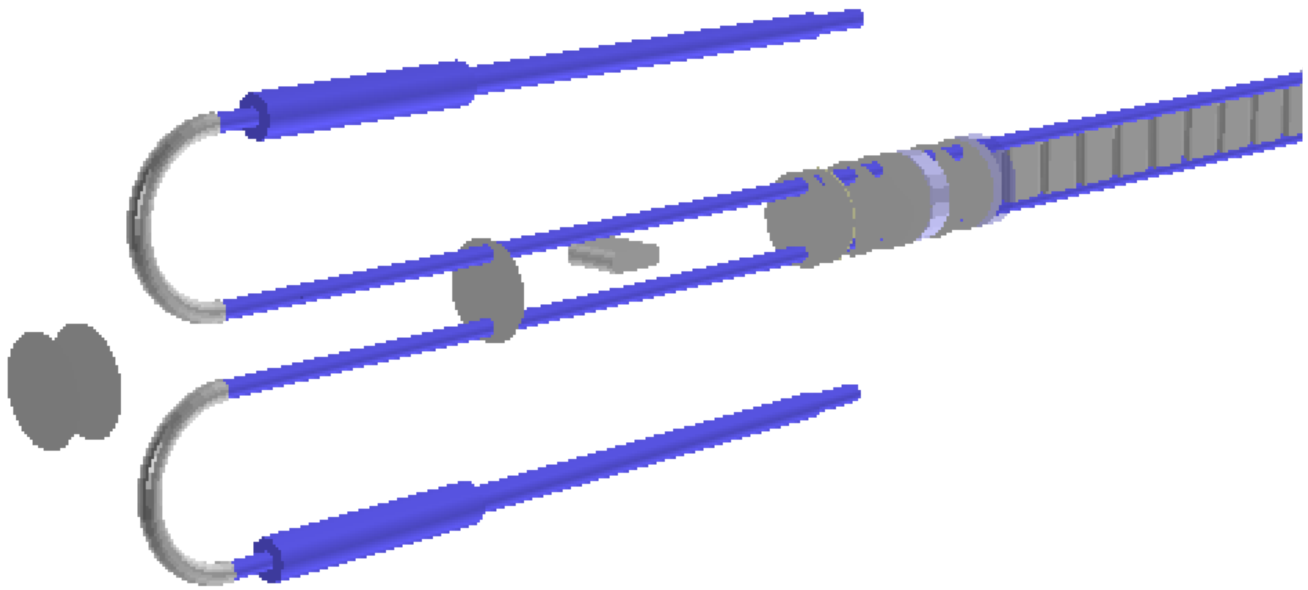
The NuMI Targets

MINOS (LE):

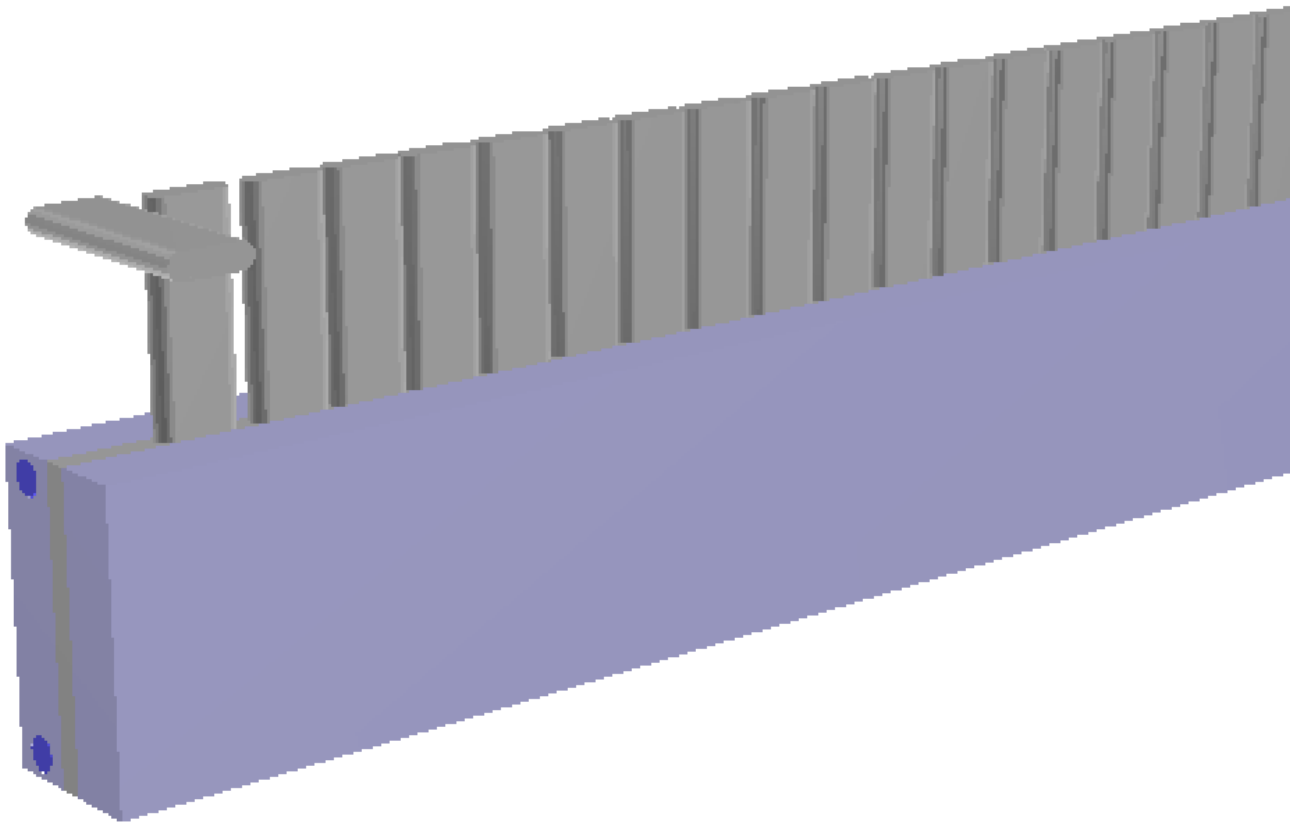
NOvA (ME):

The NuMI Targets

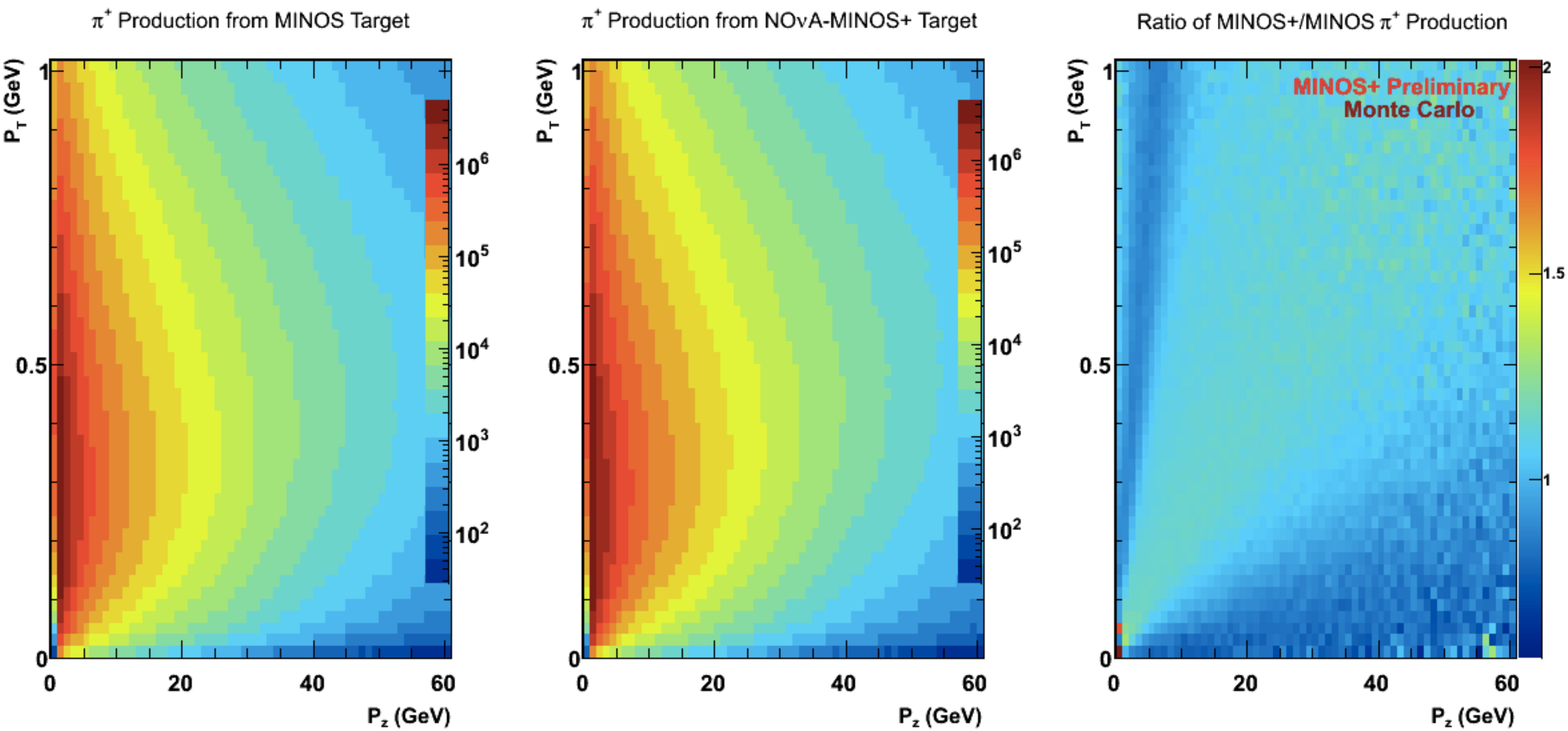
MINOS (LE):



NOvA (ME):



Comparing LE and ME Hadron Production



NuMI-X

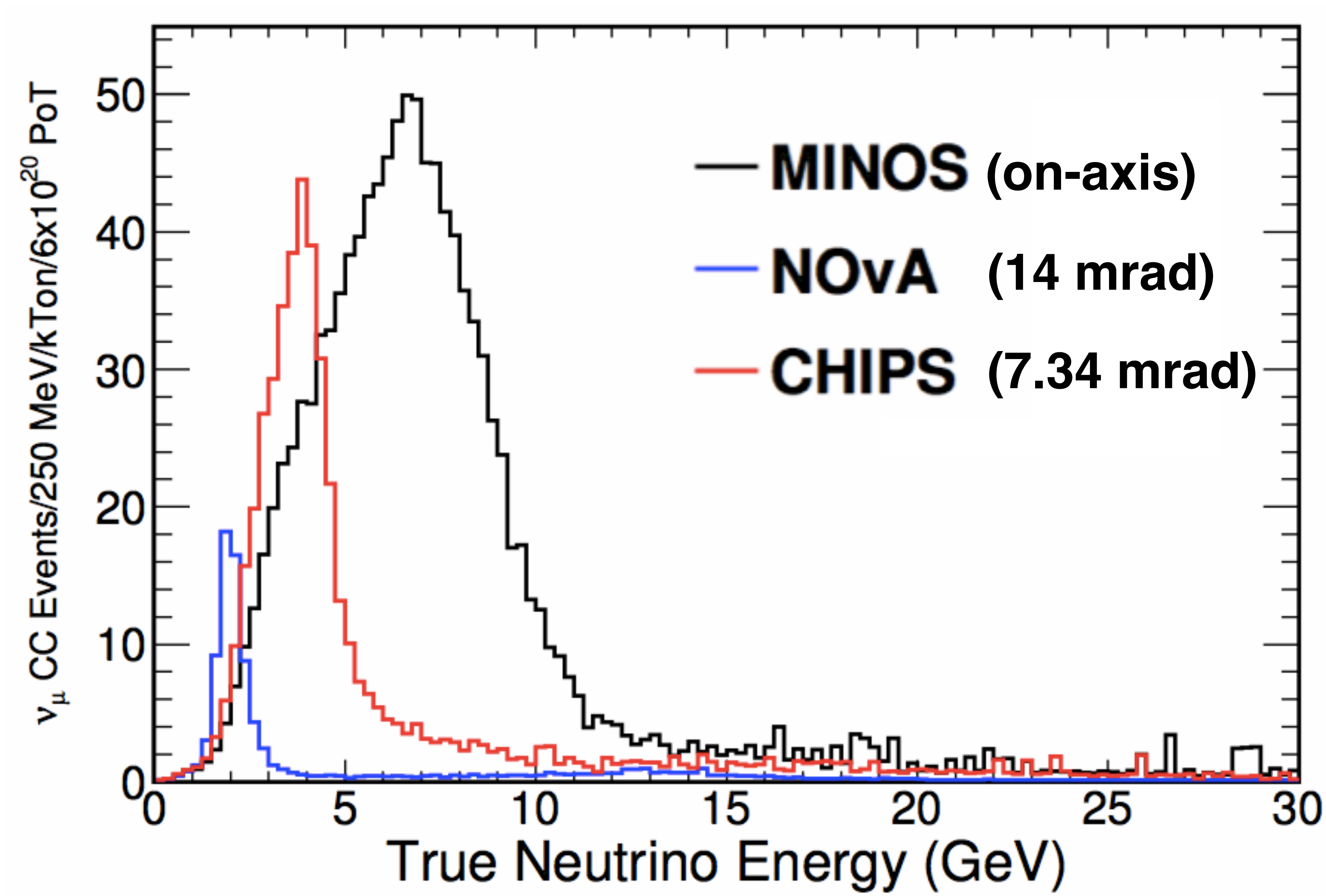
Who uses NuMI? One Beamline - Many Experiments:

- MINOS (+): steel & plastic scintillator sandwich (Near + Far), on axis
- MiniBooNE: liquid scintillator, off-axis 121mrad
- ArgoNeuT: small liquid Ar TPC, on axis
- Minerva: fine grained calorimeter w/ variety of nuclear targets, on axis
- NOvA: large segmented liquid scintillator (Near + Far), off-axis 14mrad
- other soon to exist experiments (e.g. off-axis microBooNE, far future LBNF)

The NuMI-X mission statement: Get all the NuMI experiments “on board” to work on Beam Simulation and Beam Analysis (including hadron production studies). To produce a reference flux that all NuMI experiments can use.

The NuMI Beam Seen at the NuMI Experiments

Relative positioning affects focusing, and thus the spectrum:



A Priori Predictions and Uncertainties

What do we know a priori?

Recent NuMIX Efforts

Unifying disparate code bases:

- steps taken, still work to be done
- g4numi and g4numi_flugg should use the same geometry
  - — but, sadly, they currently don't

Unifying the output format — Dk2Nu:

- more structured; standardized naming conventions; flexibility for storing pre-calculated detector location energies and weights
- carry on Minerva's addition of recording full ancestry
- non-NuMI specific; LBNE & Booster adoption in progress

The MC

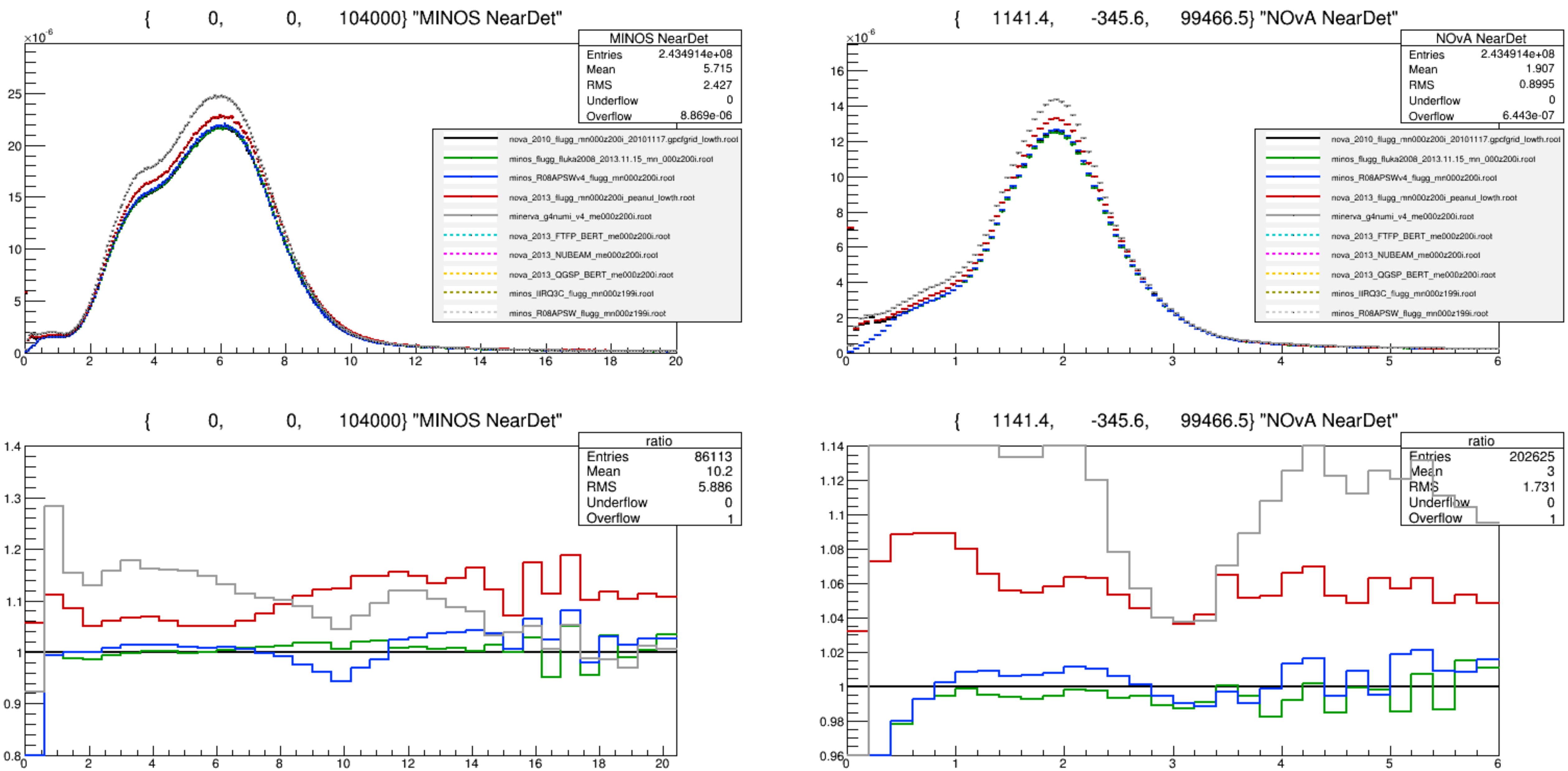
g4numi_flugg = fluka physics + G4 geometry + flugg “glue”:

- all (recent) MINOS and NOvA analyses to date have used flugg
  - historically it seemed to better represent what was seen in data when used “out of the box”

g4numi = pure Geant4:

- primarily used by Minerva
  - interesting new development work being done here
- more choices of physics models
- local experts/development of G4

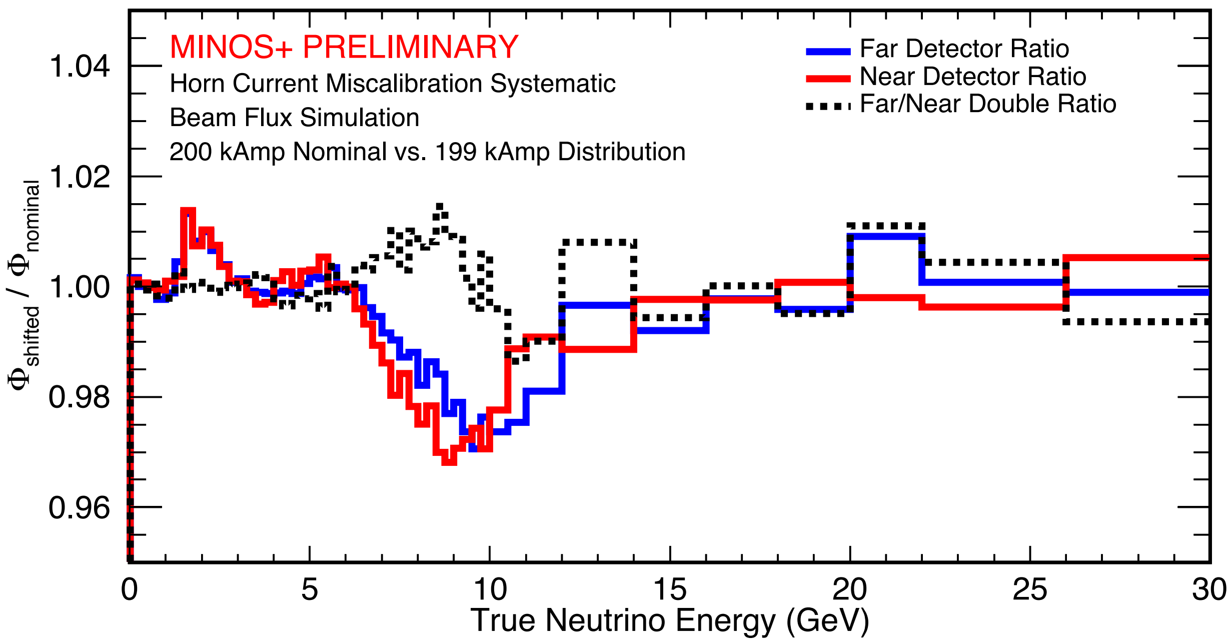
ME at MINOS & NOvA Near Detectors

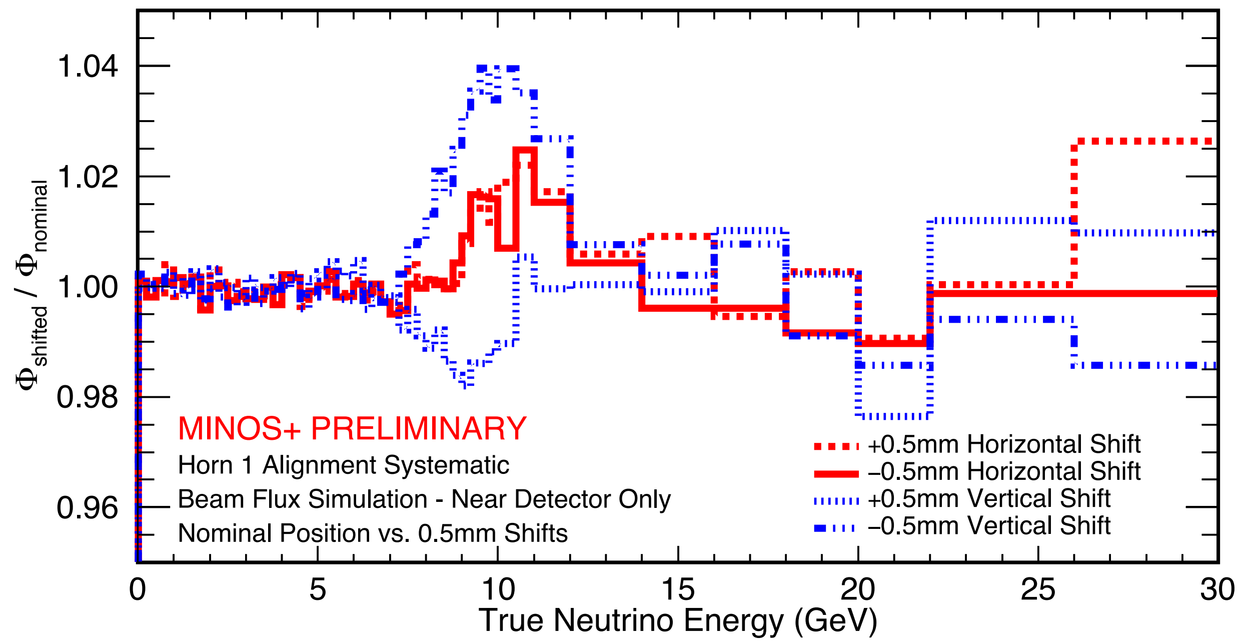


Focusing Uncertainties

Neutrino flux prediction is notoriously difficult, relying on the extrapolation of sparse fixed target data to the energies seen on the NuMI target.

Estimates of focusing and geometric uncertainties in the final flux prediction are estimated by producing alternative flux MC shifted to their 1sigma uncertainties.





Beam Constraints

What can we learn about the beam from our data and external constraints?

NuMI Constraints

Multiple detector locations:

- Angle relative to beam direction
  - on-axis yields a broad spectrum beam
  - off-axis sees a more narrow spectrum
- Different positions are sensitive to π production in different regions of p_t & p_z

Multiple target designs:

- MINOS-era target could be repositioned relative to the horn

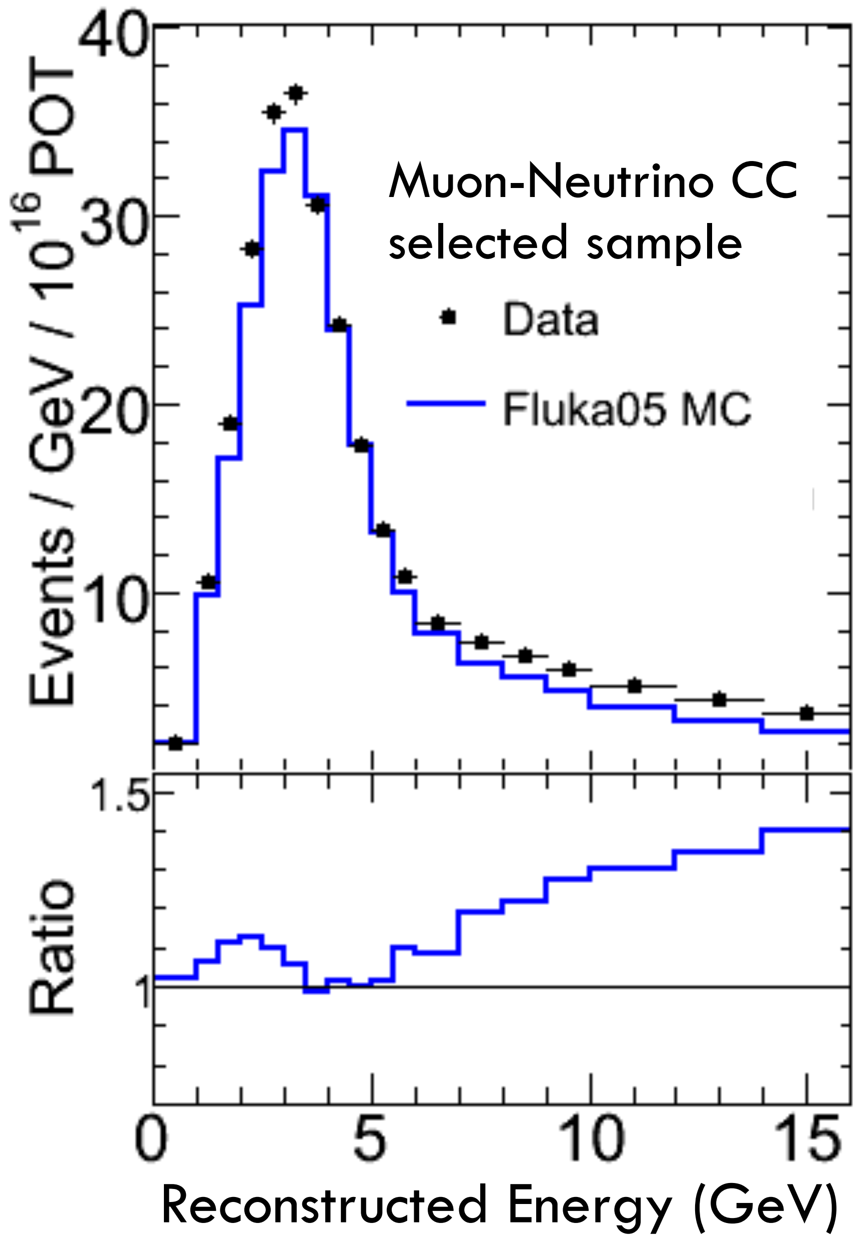
Horn current affects focussing:

- “horn off” is valuable running condition

Tuning to Measured Spectra

One approach is to use a physically motivated hadron production parameterization and focusing uncertainties to create a fit which uses all our available beam modes to constrain our flux prediction.

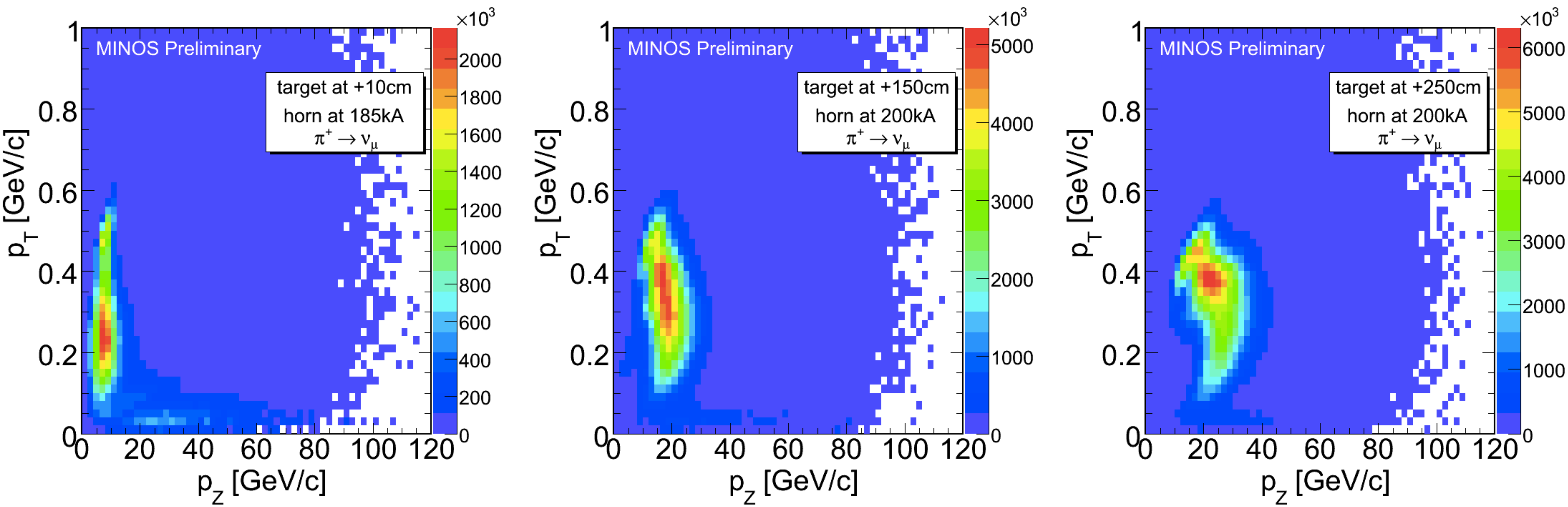
At MINOS the hadron production parameterization is a slightly altered version of the BMPT parameterization where we use linear warpings of some of it's key variables to tune hadron production in the fit.



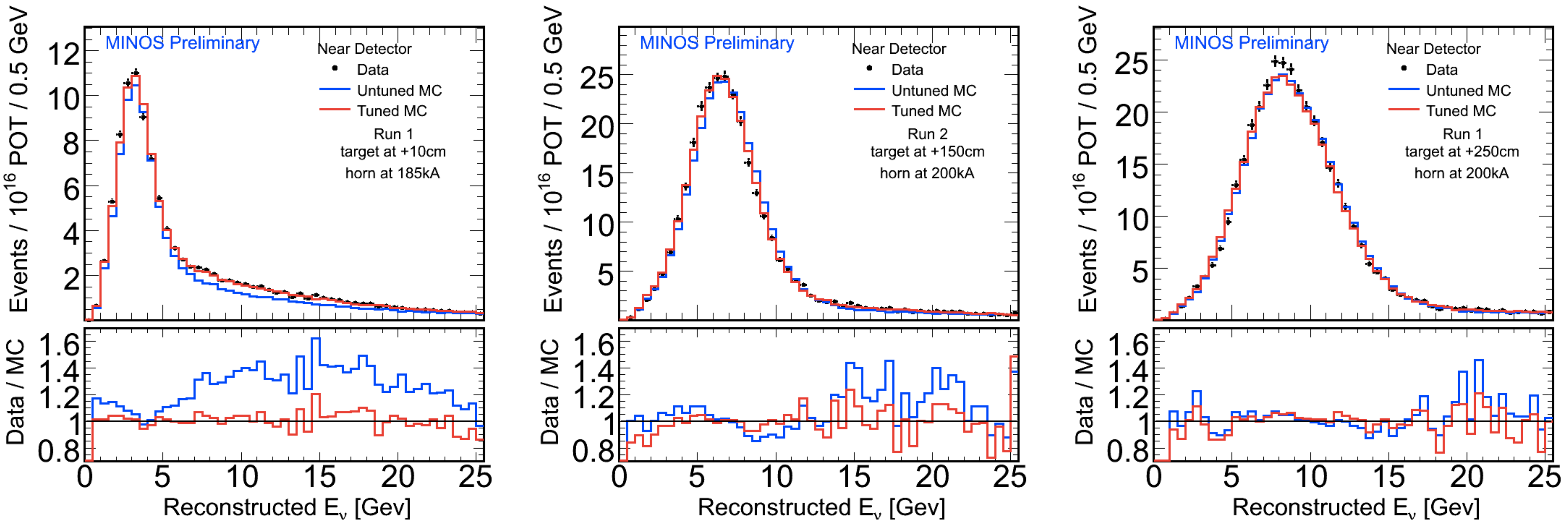
Different Beam Modes

Data/MC disagreement varies as a function of energy in different beam modes, suggesting that flux uncertainties rather than detector or cross-section uncertainties are dominating the Near Detector Discrepancy.

Each beam mode also gives us access to a different region of Pion and Kaon production phase space so that we can better constrain our parameterization of the raw yield of hadron production coming off of the target.



Fit Result: Final Tuned Flux



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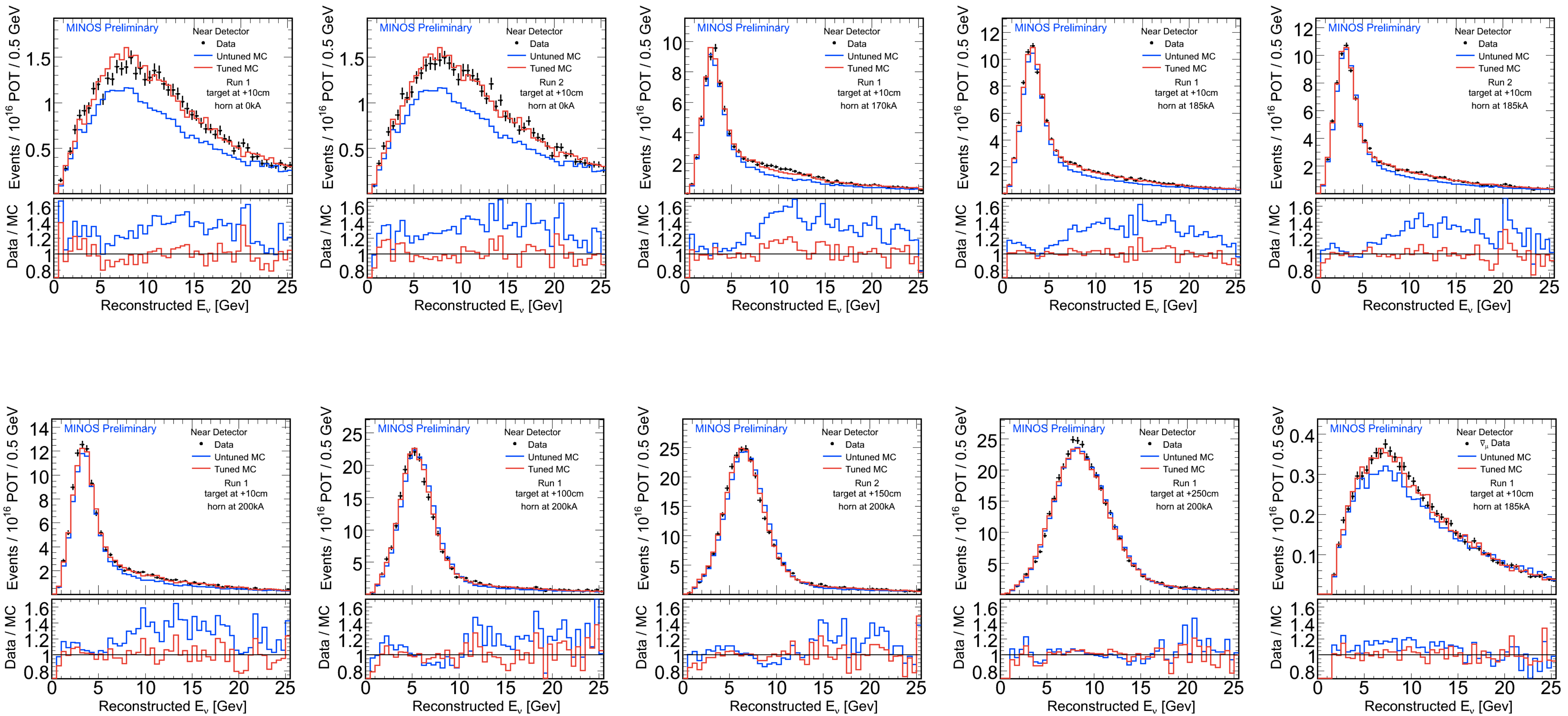
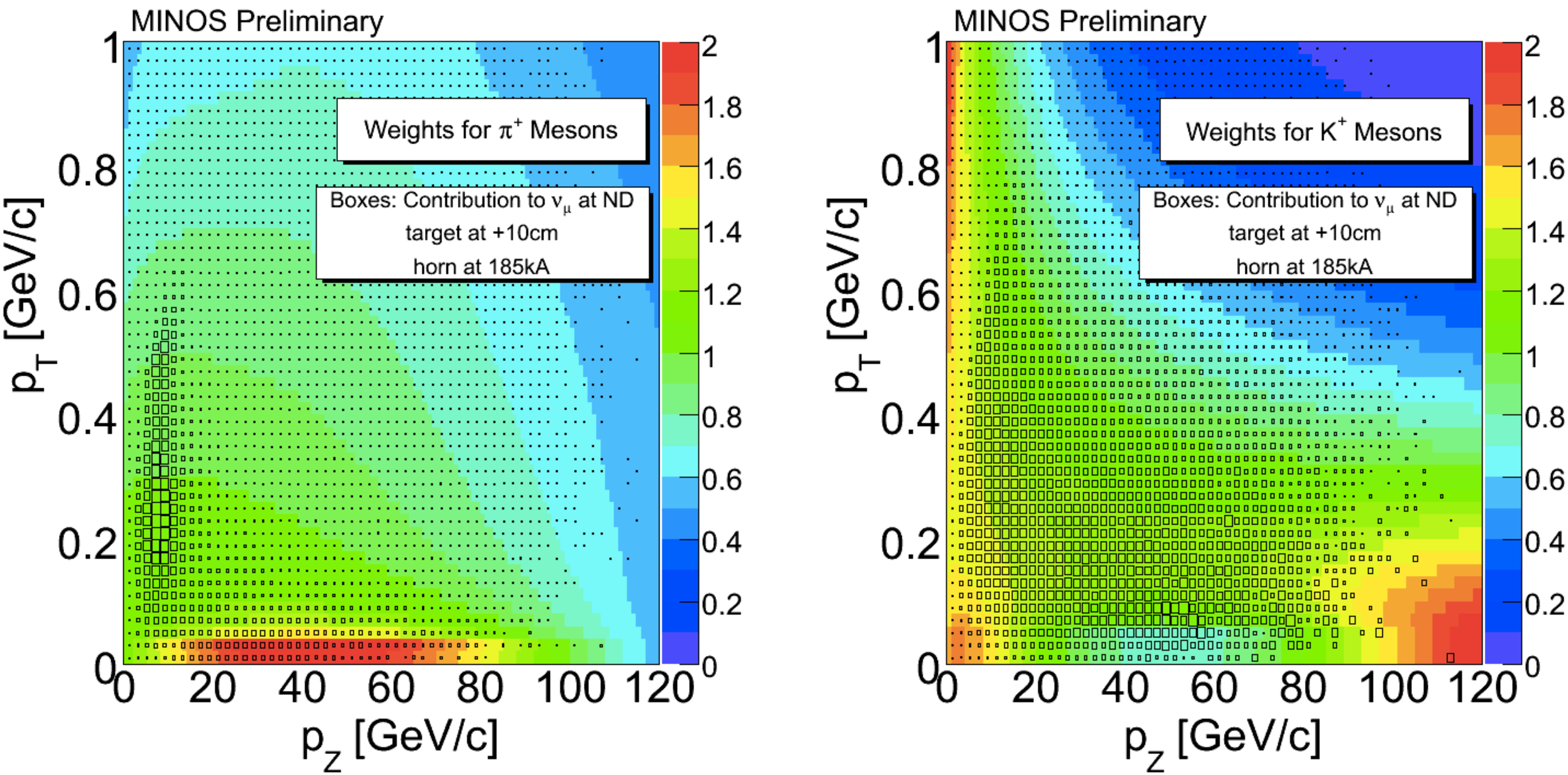
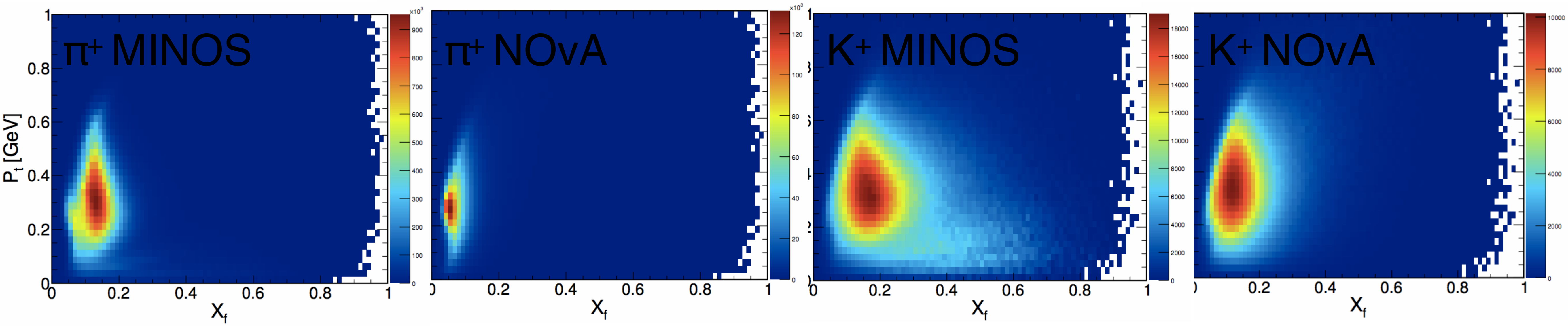


Fit Result: Hadron Production Weights



Tuning in the ME Era

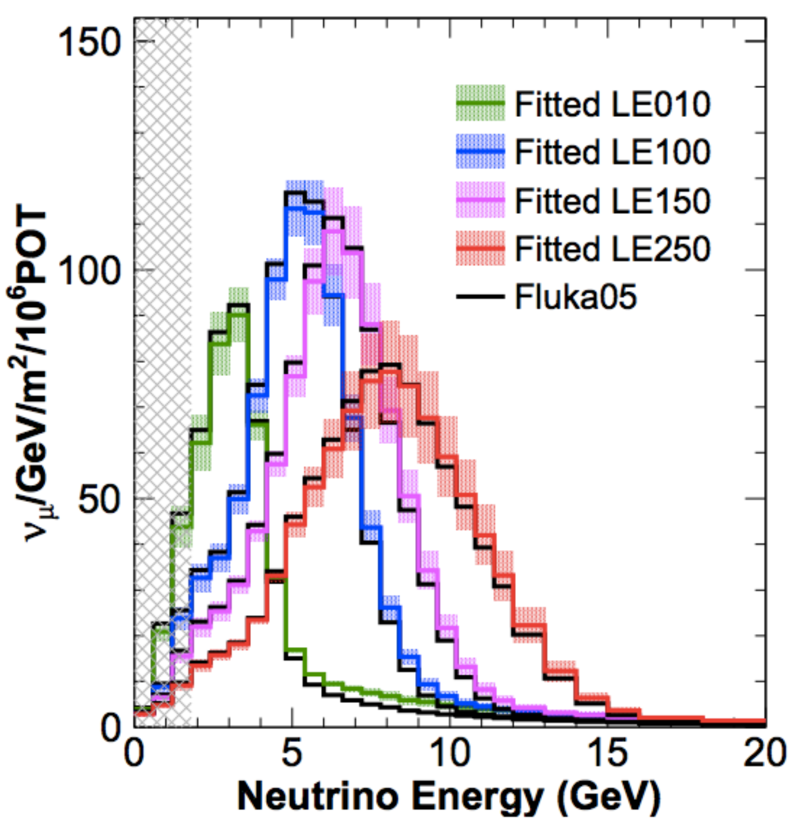
Historically we made use of the power of the old beam to run in different beam modes to access a wide range of Pion/Kaon kinematics and deconvolve cross section effects. Can we do something similar in the ME beam by looking at different spectra in the same beam?

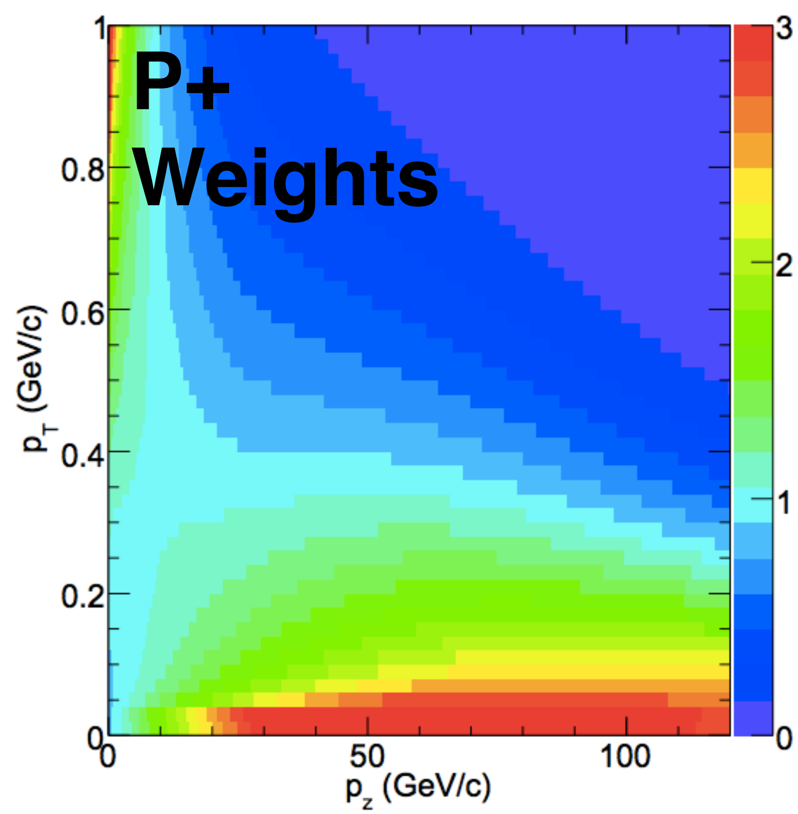


The Muon Monitors

Yet another approach is to attempt to measure the flux by measuring the rate and energy of muons produced in pion and kaon decays in the NuMI decay pipe.

Laura Loiacono performed that analysis* using the Muon Monitors just after the decay pipe. Whilst the fit has a large uncertainty the final result is largely consistent with that of the MINOS beam fitting. With work they could be a powerful constraint on the new beam.

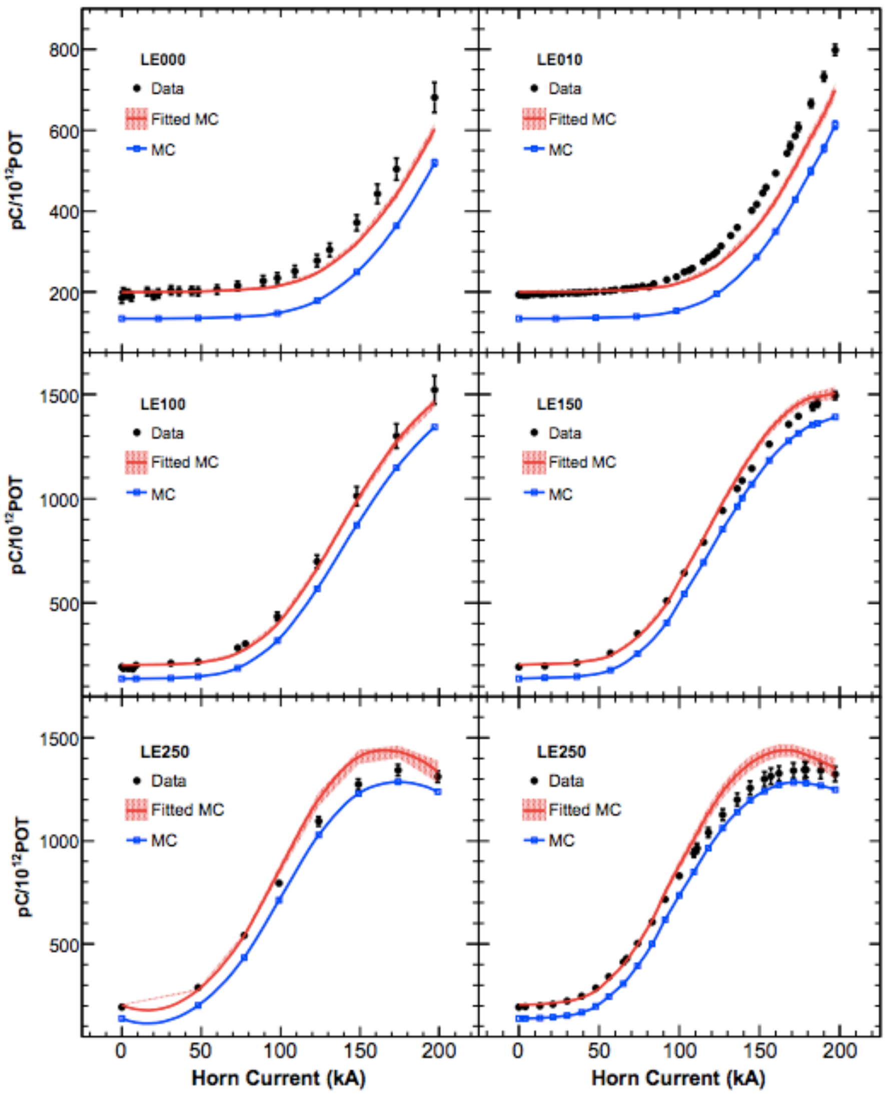




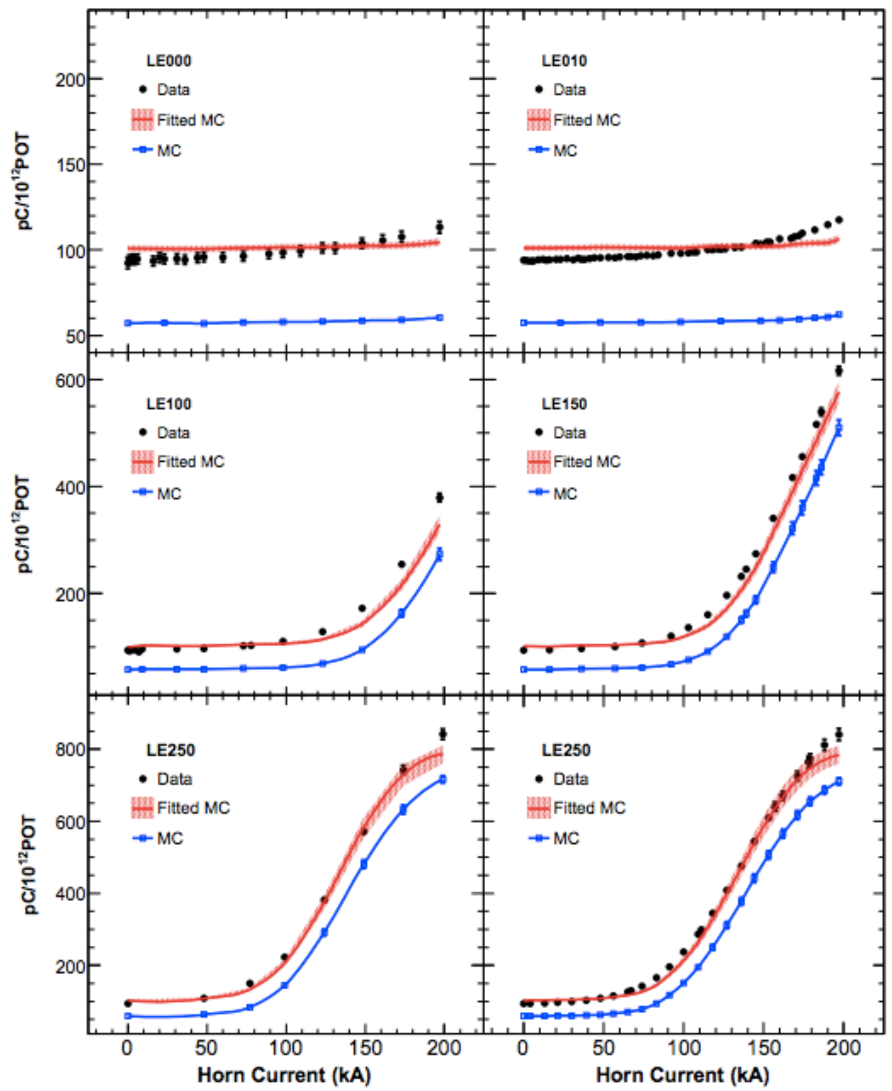
*Laura Jean Loiacono, University of Texas at Austin, May 2010 "Measurement of the muon neutrino inclusive charged current cross section on iron using the MINOS detector" Fermilab-Thesis-2011-06

The Muon Monitors

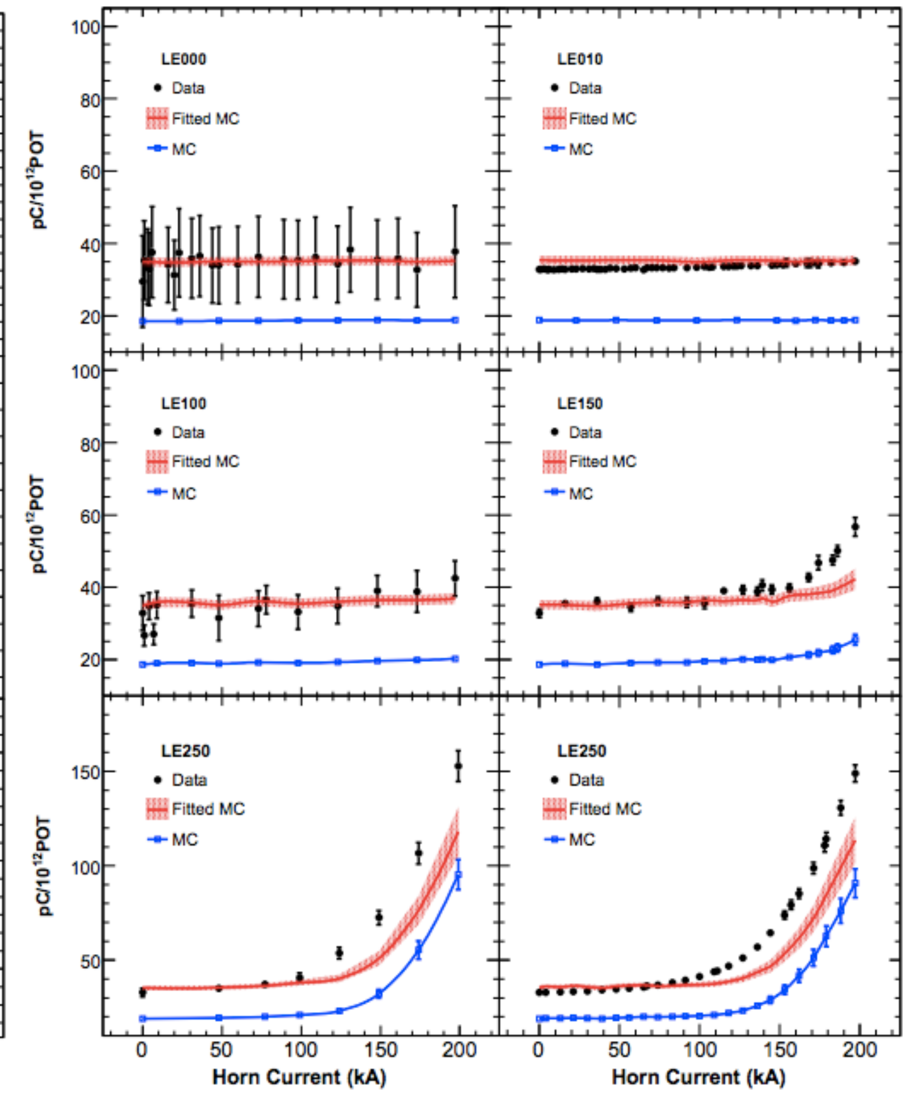
Monitor 1:



Monitor 2:



Monitor 3:

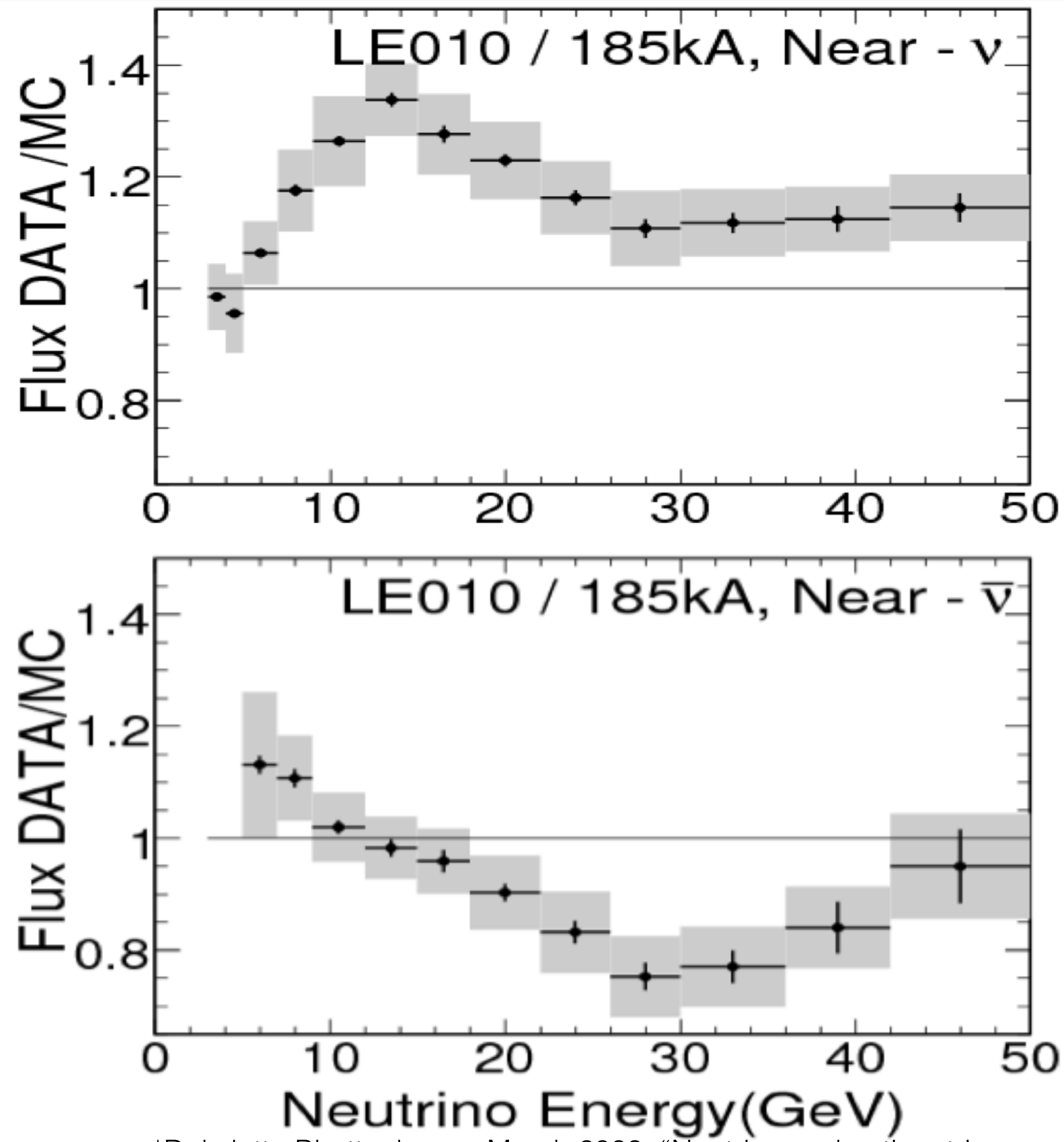


The Low ν Method

Another approach is to attempt to measure the flux by selecting events with a well understood cross section.

One approach is to select for CC events with a low inelasticity*neutrino energy or "ν".

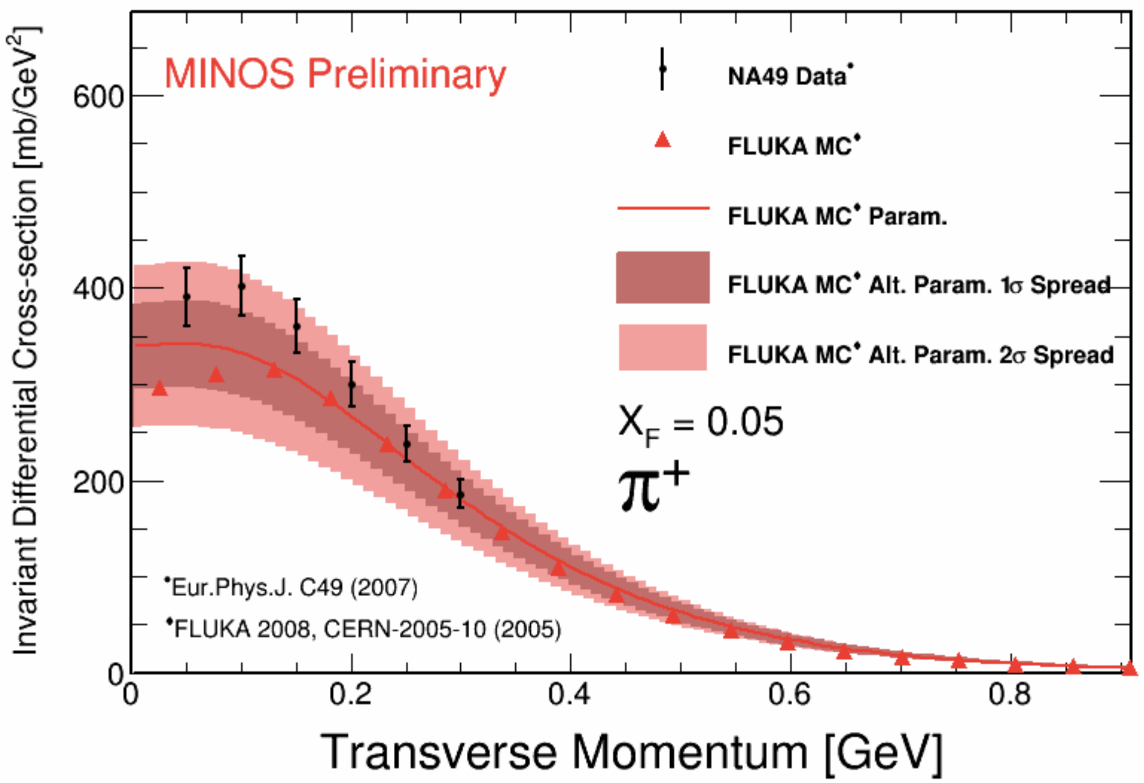
Used in a preliminary MINOS cross section analysis* this study showed that data/MC discrepancy at the MINOS ND was indeed largely driven by the difference between the measured and predicted flux.

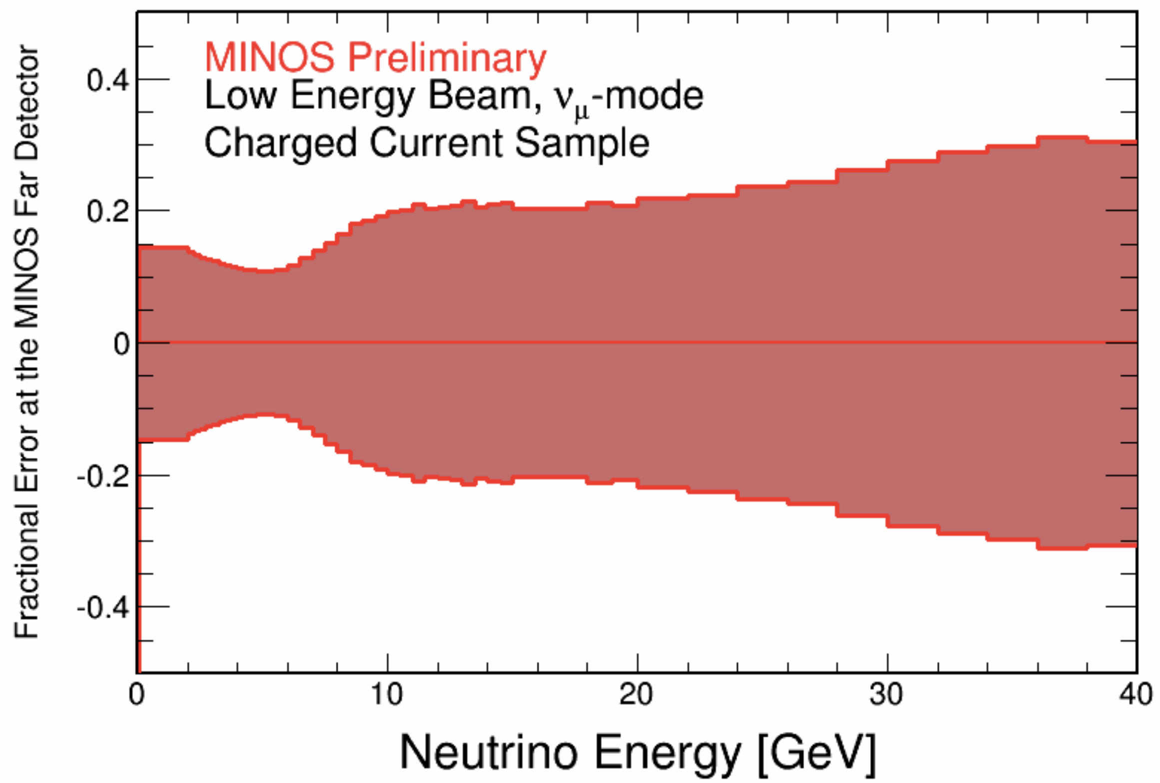


*Debdatta Bhattacharya, March 2009, "Neutrino and antineutrino inclusive charged-current cross section measurement with the MINOS near detector", Fermilab-Thesis-2009-11

Using External Data

Alternatively we can reweight our MC our yield of cross-sections to information from fixed target experiments. MINERvA will cover this topic in detail in the next talk, but broadly we can use thin target data (NA49 etc.) and reweight each interaction or use thick target data (MIPP, USNA61) and reweight the yield. New thick target data is needed to characterize the new ME beam.





Summary

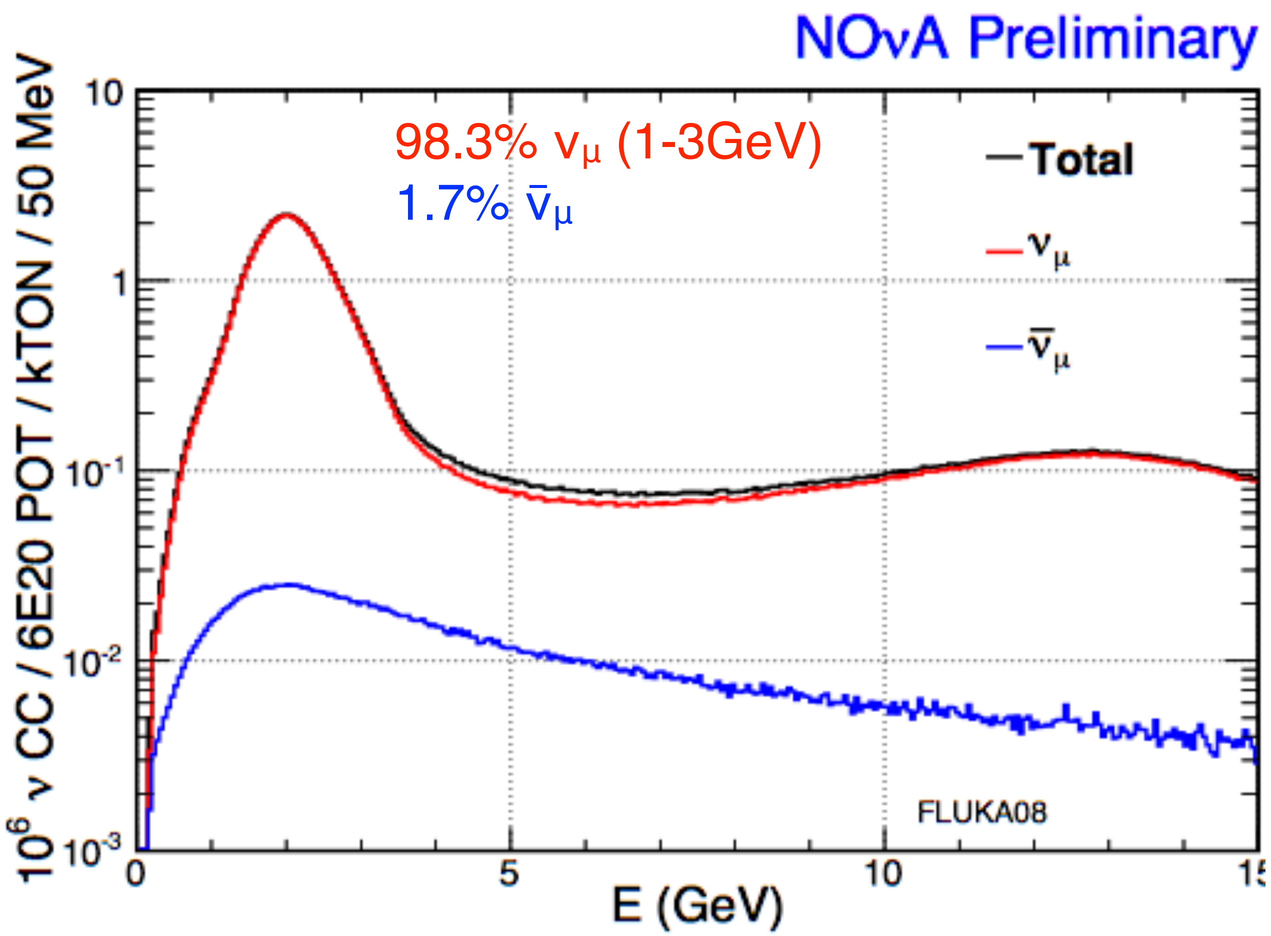
- Working together the NuMI experiments can more thoroughly & efficiently test and tune their MC geometries.

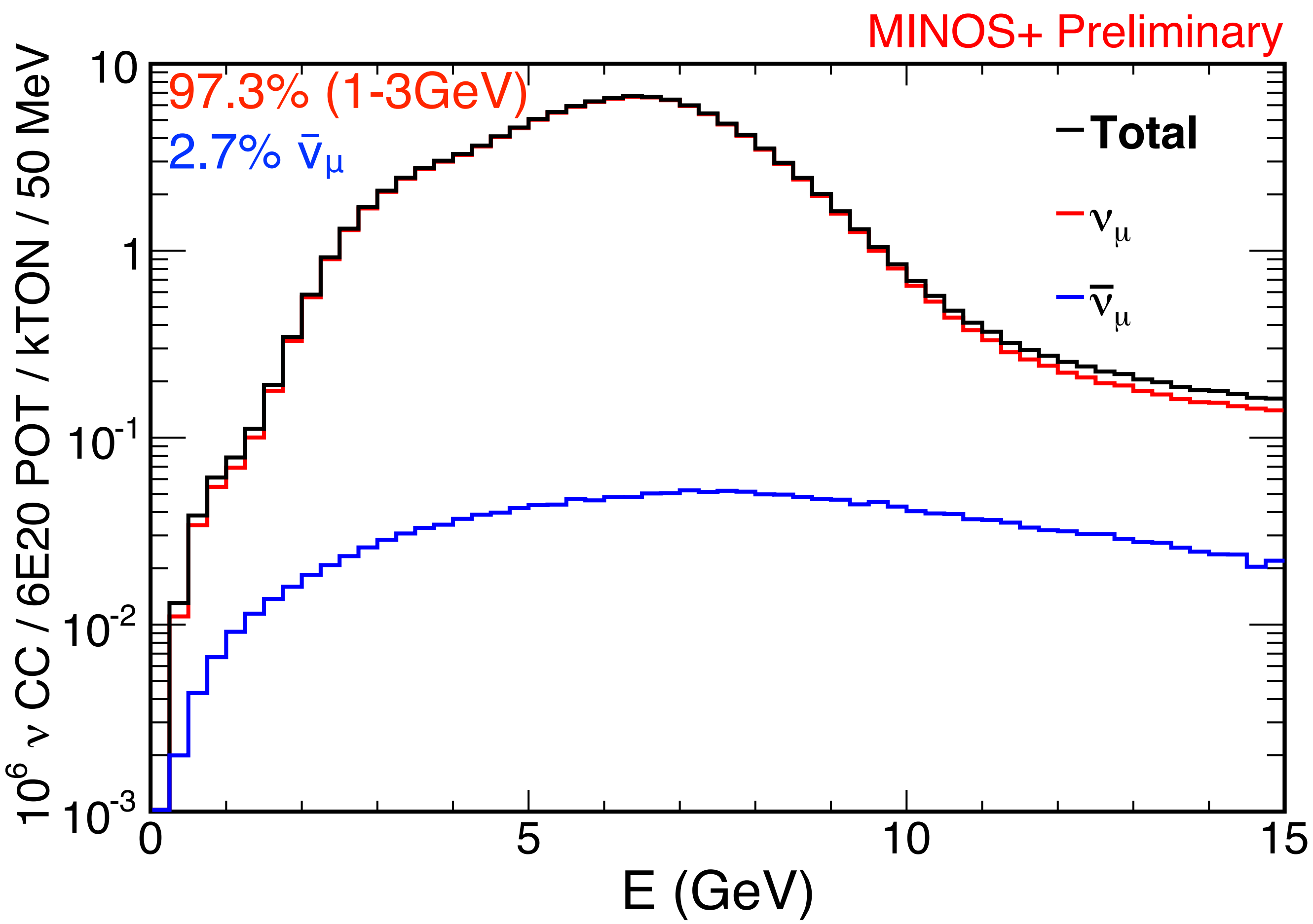
- Thin and Thick target experiments like NA49/MIPP give us strong constraints on our hadron yield but we need USNA61 to really understand the new beam.

- NuMI-X has inherited some powerful tools for constraining and understanding the new NuMI beam but will have to work harder than ever before now that we no longer have access to a plethora of alternative beam modes.

The NuMI Beam Seen at the NuMI Experiments

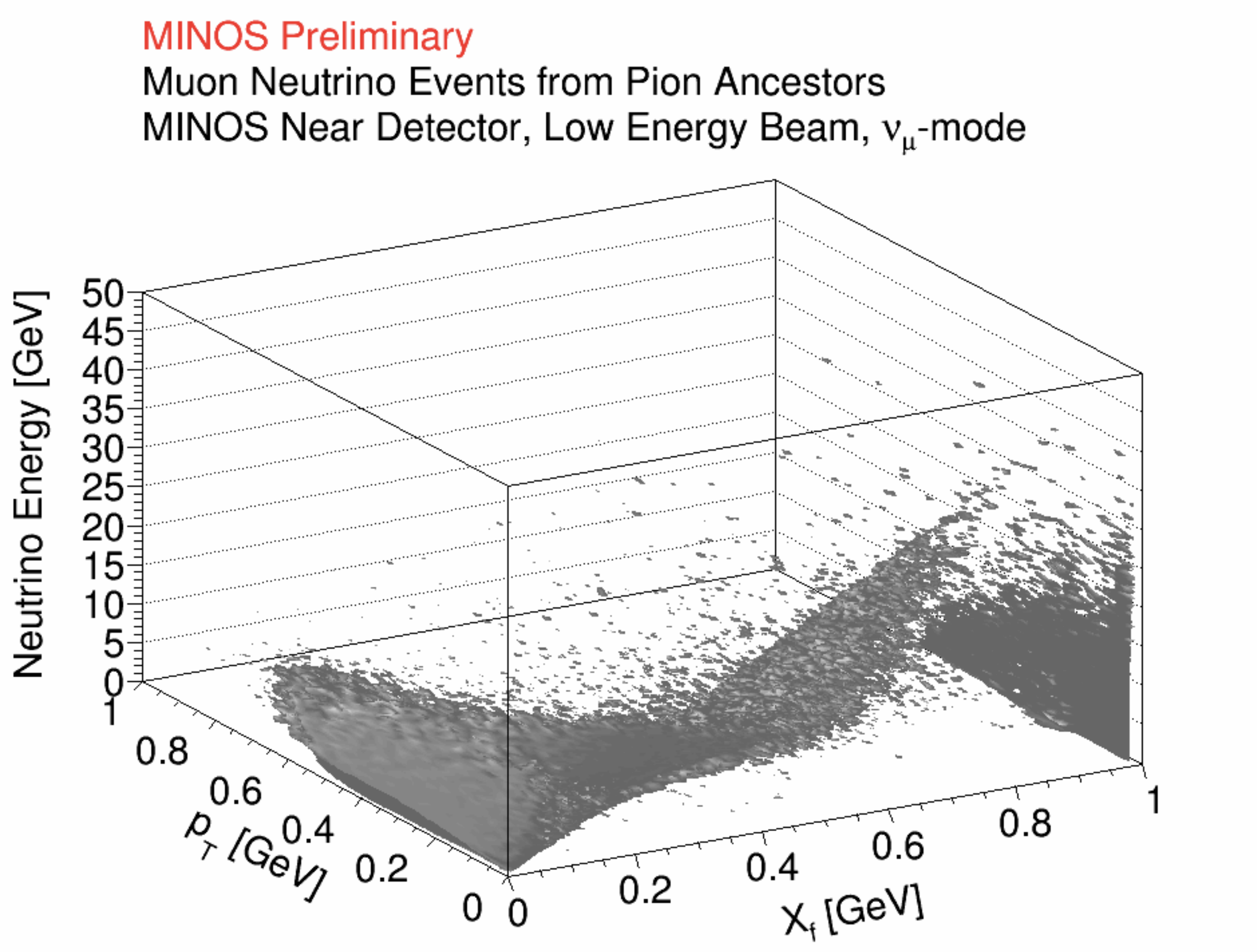
Relative positioning affects focusing, and thus the spectrum:

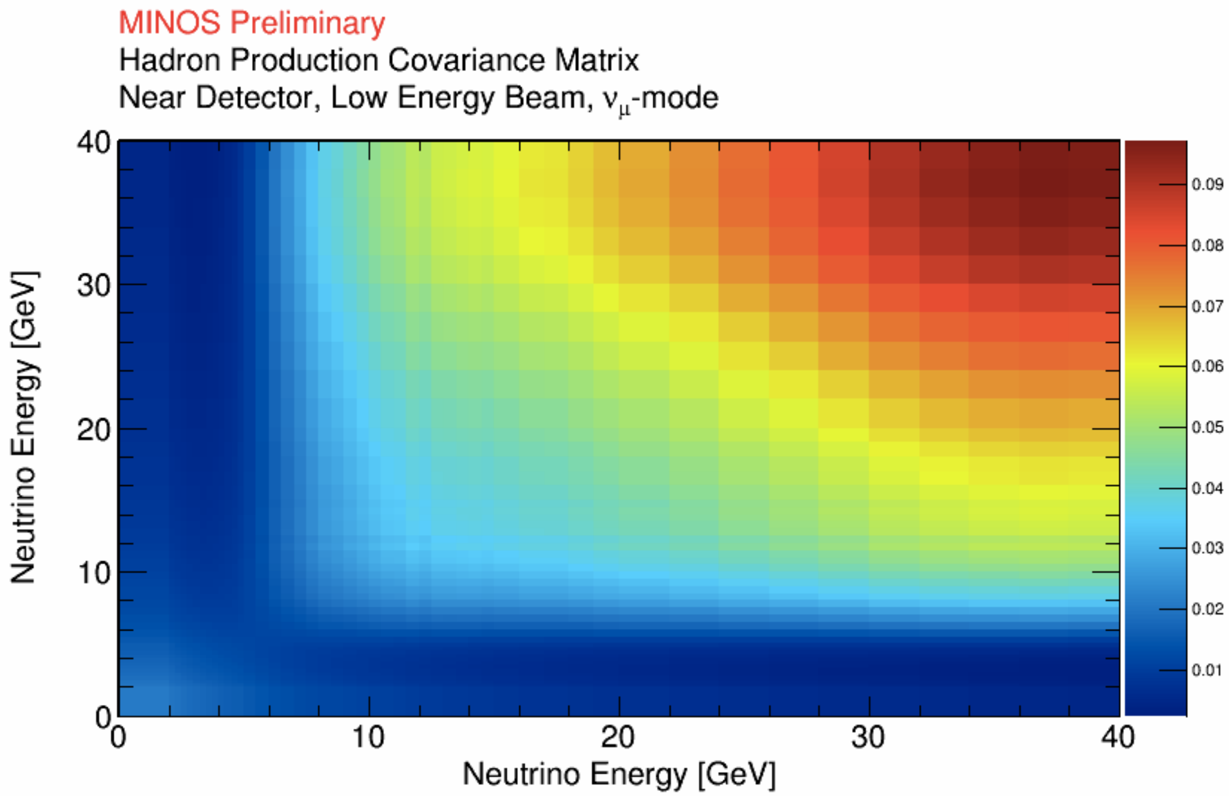




A Priori Flux Prediction and Uncertainties

Those alternative parameterizations can then be propagated to our final MC neutrino reconstructed energy and used to generate a covariance matrix describing both the uncertainty on individual bins and how we would expect that any shifts to be correlated with neighboring energy bins.





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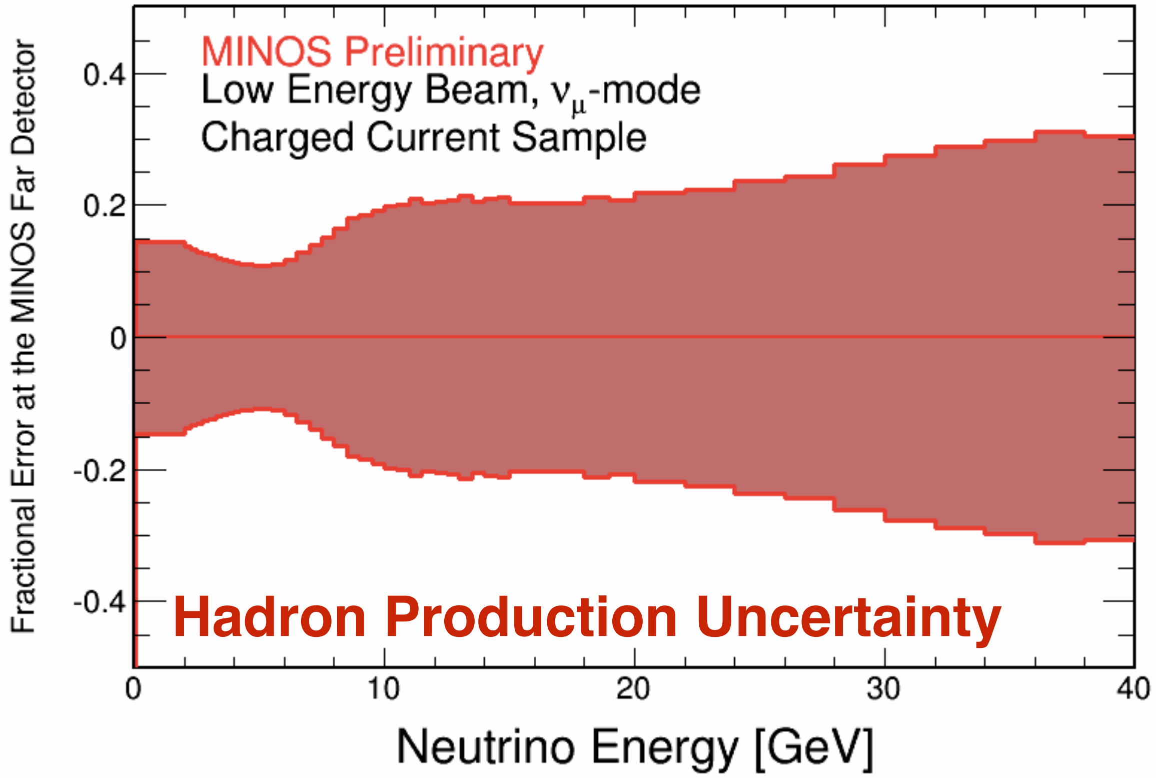
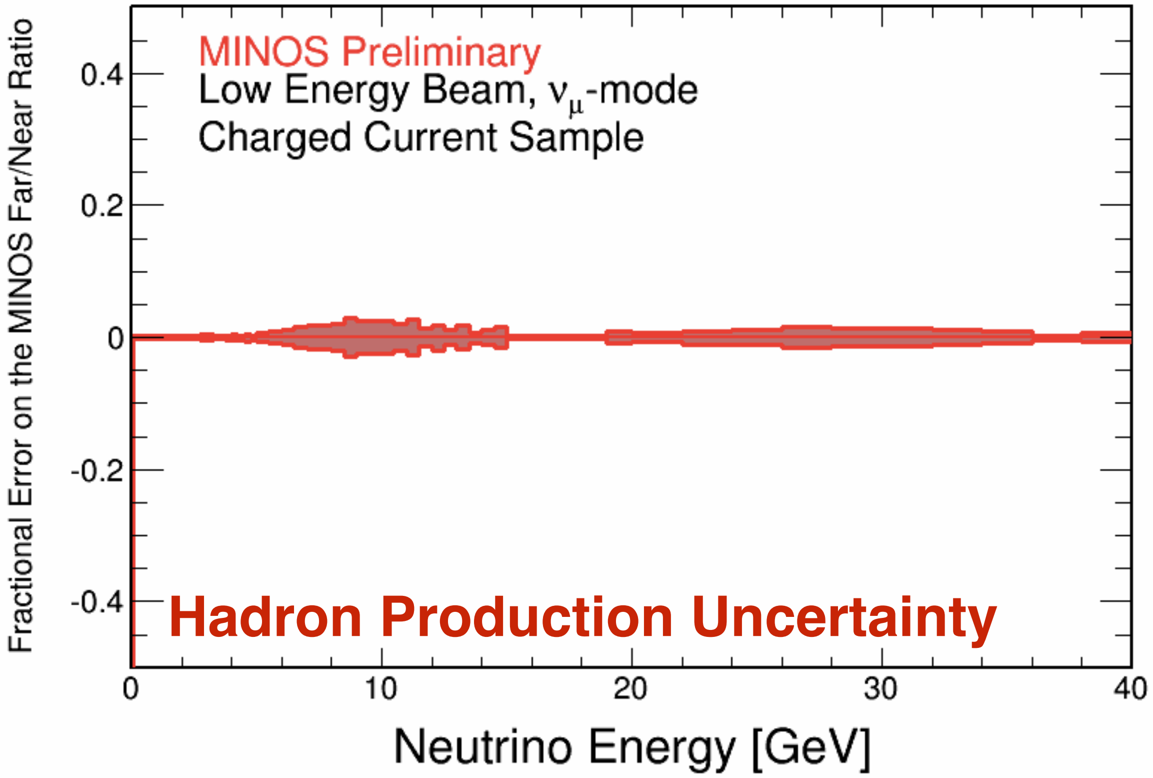
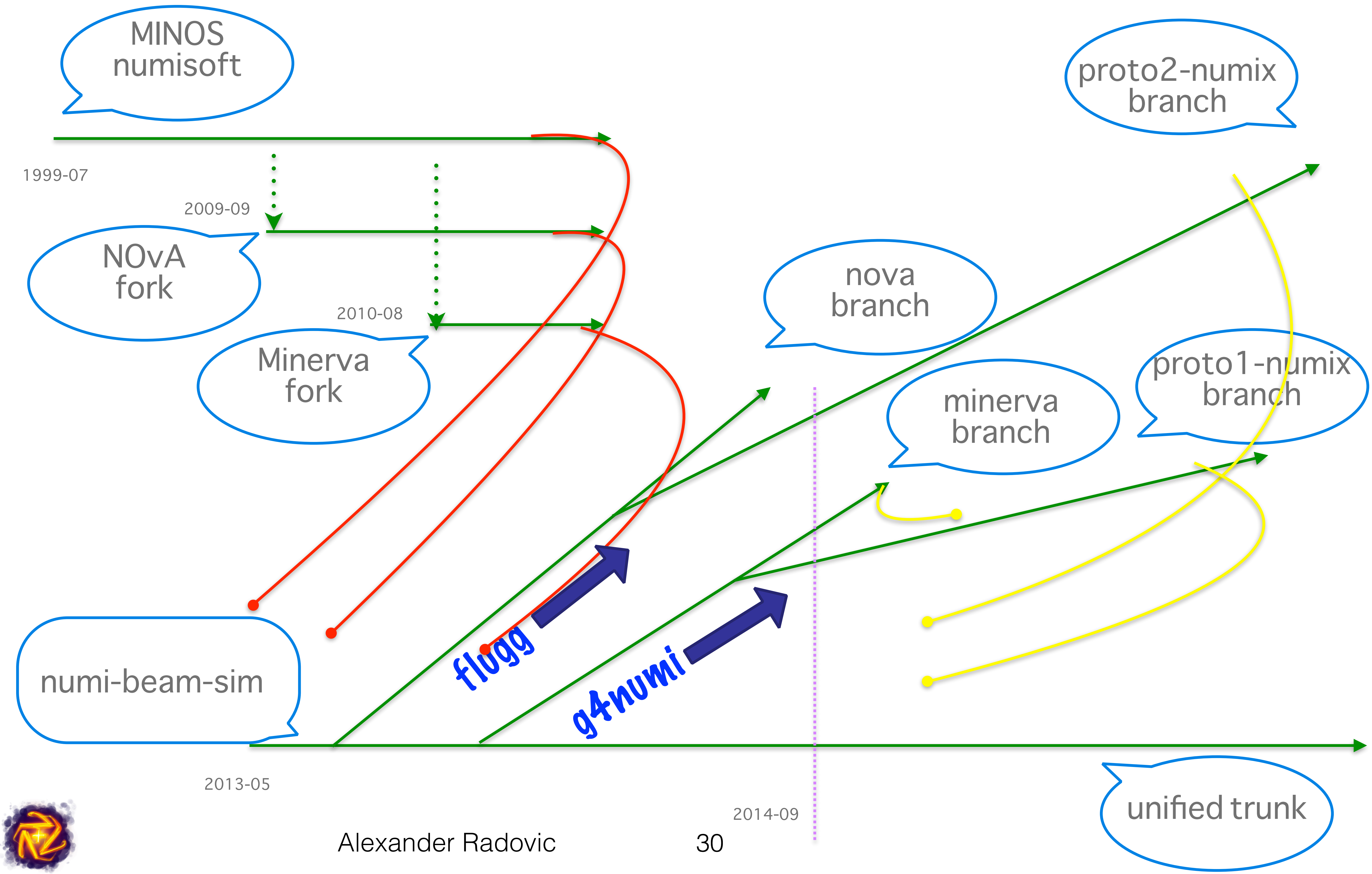




Ultimately these large FD uncertainties cancel in a Far/Near ratio

The Branching MC



The MINOS Parameterization

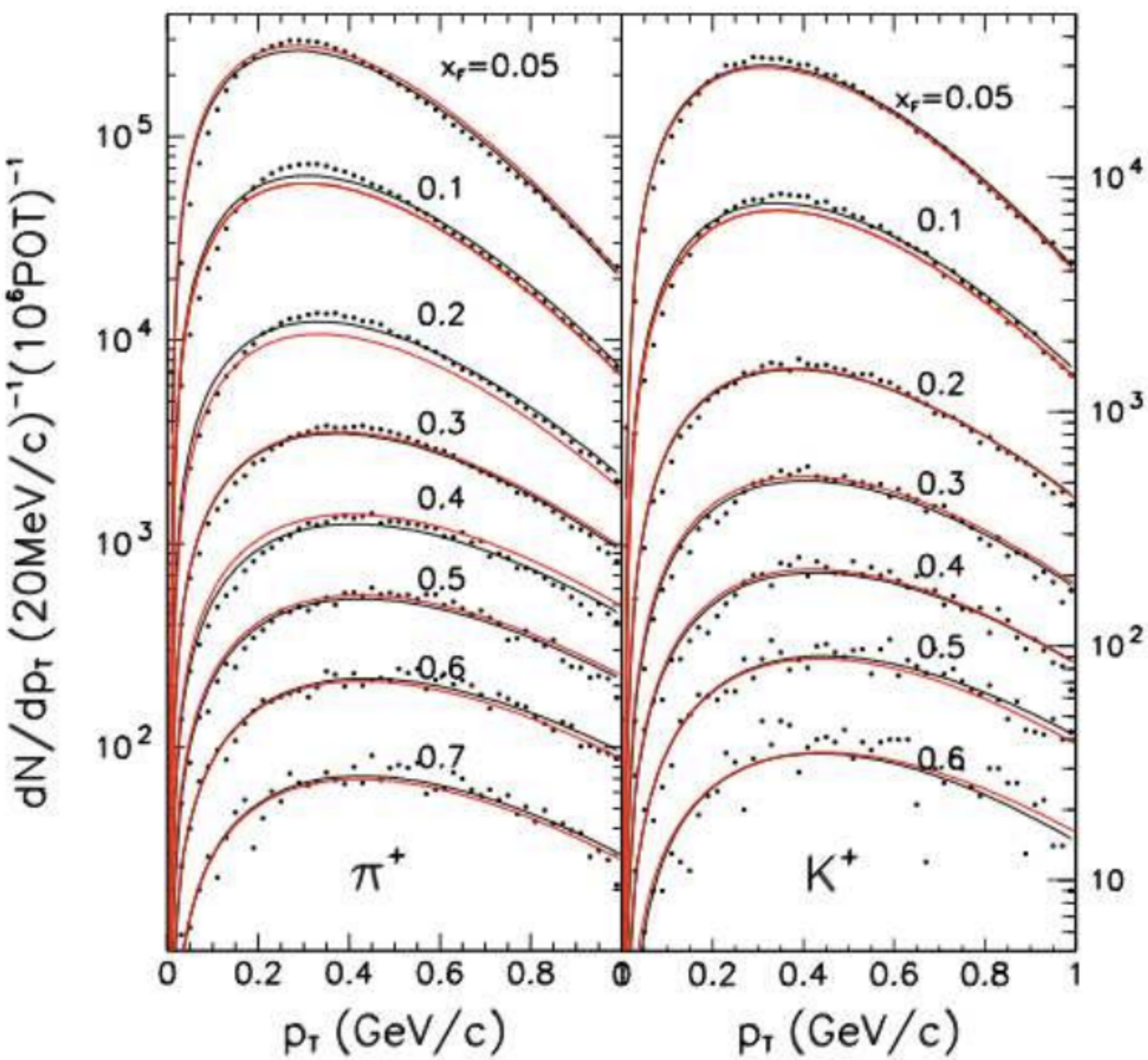
Original Fit to Hadron yield:

$$\frac{d^2N}{dx_F dp_T} = [A + Bp_T]\exp(-Cp_T^{3/2})$$

$$A(x_F) = a_1(1-x_F)^{a_2}(1+a_3x_F)x_F^{-a_4}$$

$$B(x_F) = b_1(1-x_F)^{b_2}(1+b_3x_F)x_F^{-b_4}$$

$$\begin{aligned} C(x_F) &= c_1/x_F^{c_2} + c_3 \qquad [\text{for } x_F < 0.22] \\ &= c_1\exp((x_F+c_2)c_3) + c_4x_F + c_5 \\ &\qquad [\text{for } x_F > 0.22] \end{aligned}$$



The MINOS Parameterization

What we fit for:

$$A'(x_F) = (par[0] + par[1]x_F)A(x_F)$$

$$B'(x_F) = (par[2] + par[3]x_F)B(x_F)$$

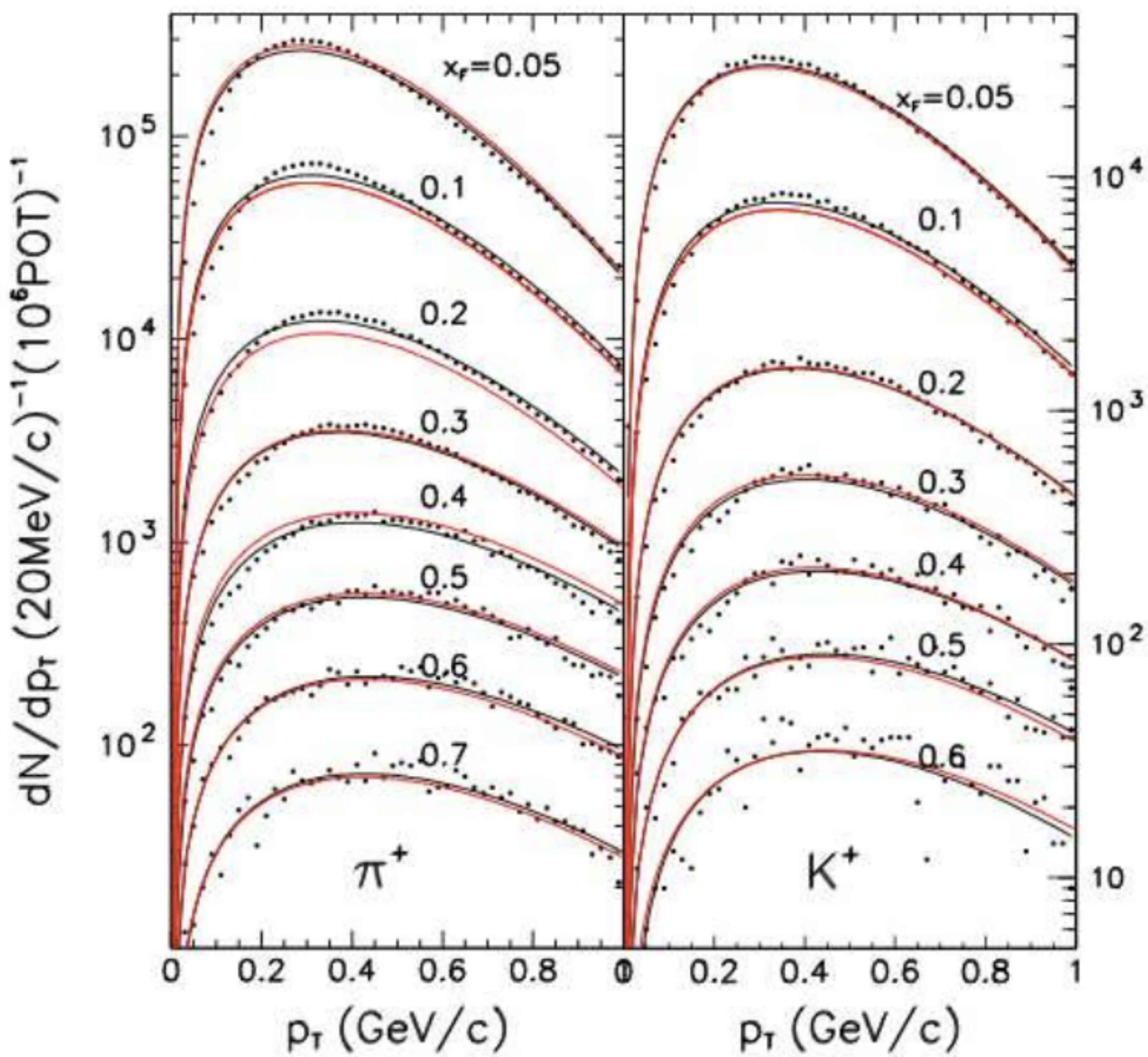
$$C'(x_F) = (par[4] + par[5]x_F)C(x_F)$$

$$W(\pi^+/K^+, p_T, p_Z) = \frac{[A' + B'p_T]\exp(-C'p_T^{3/2})}{[A + Bp_T]\exp(-Cp_T^{3/2})}$$

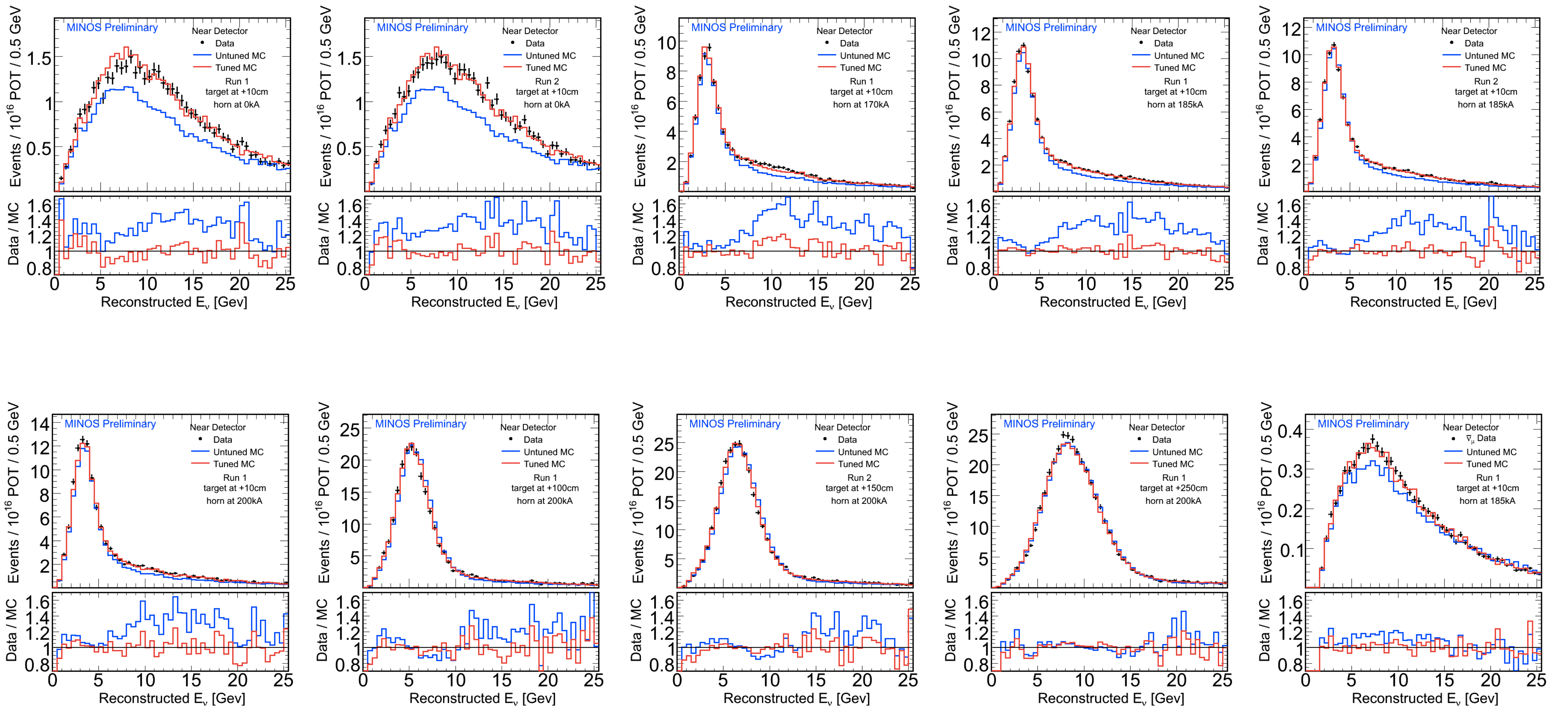
$$W(\pi^-, p_T, p_Z) = (par[12] + par[13]x_F)W(\pi^+, p_T, p_Z)$$

$$W(K^-, p_T, p_Z) = (par[14] + par[15]x_F)W(K^+, p_T, p_Z)$$

$$N(K_L^0) = \frac{N(K^+) = 3N(K^-)}{4} = N(K_S^0)$$



Fit Result: Final Tuned Flux



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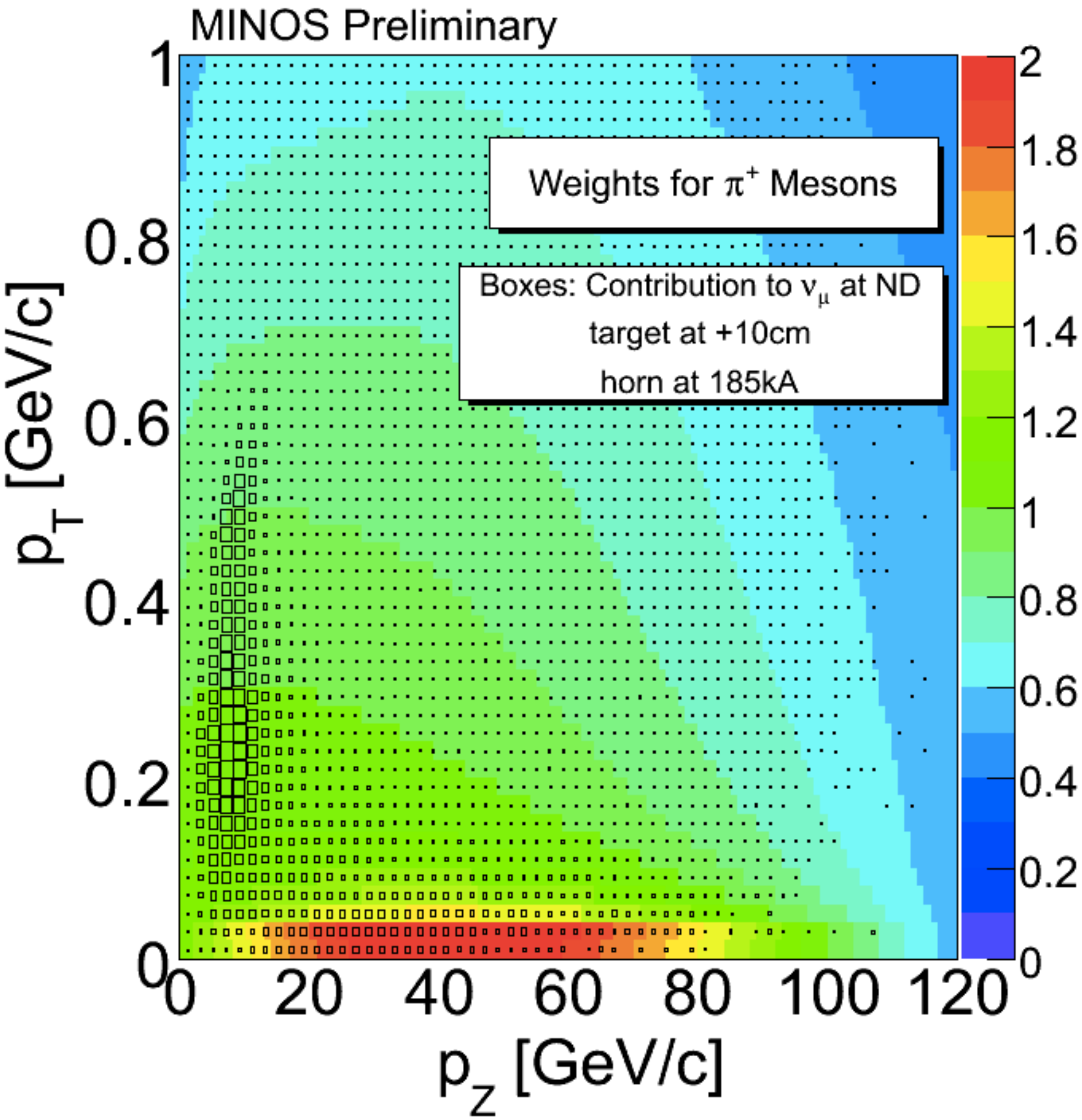
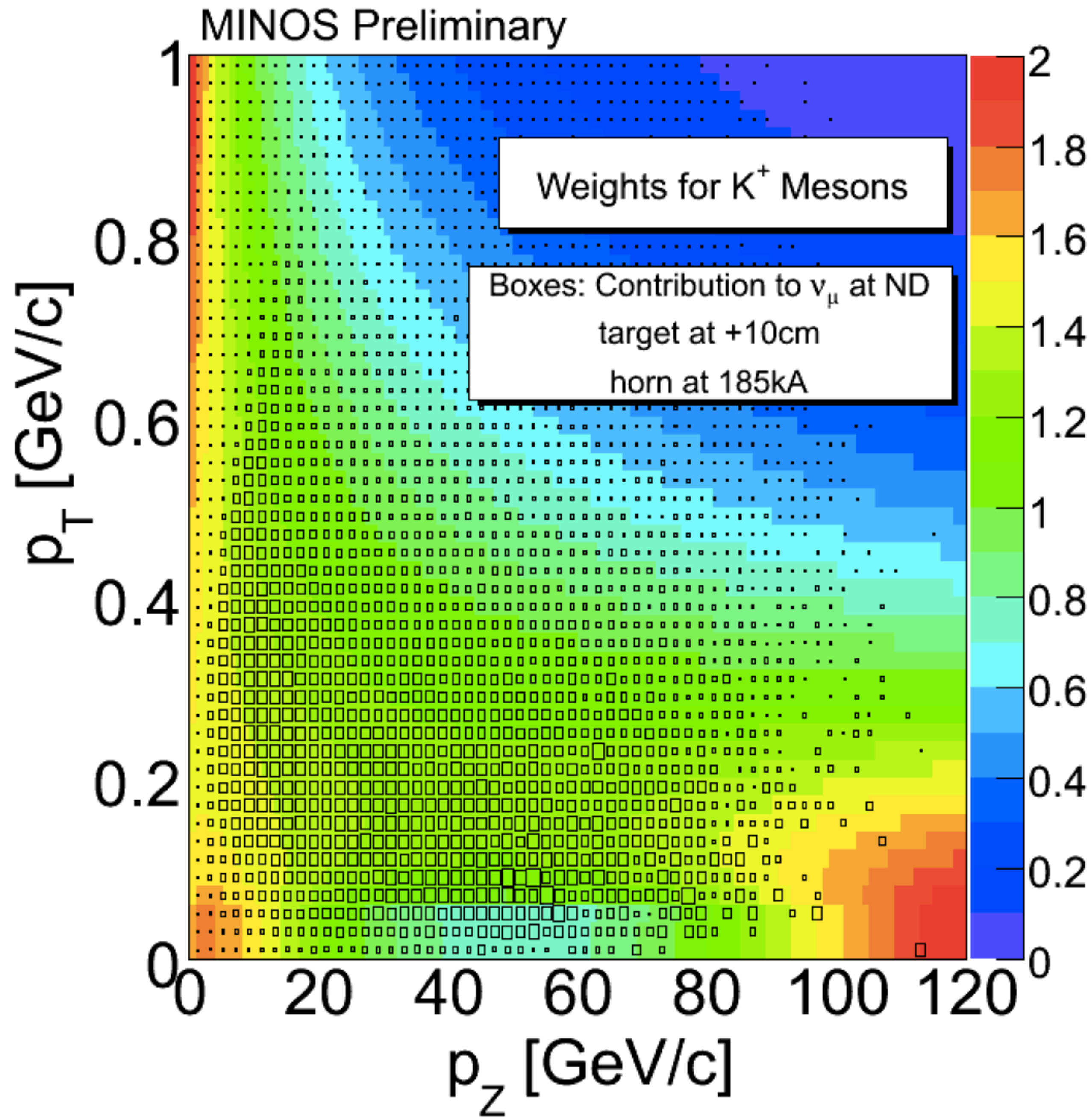
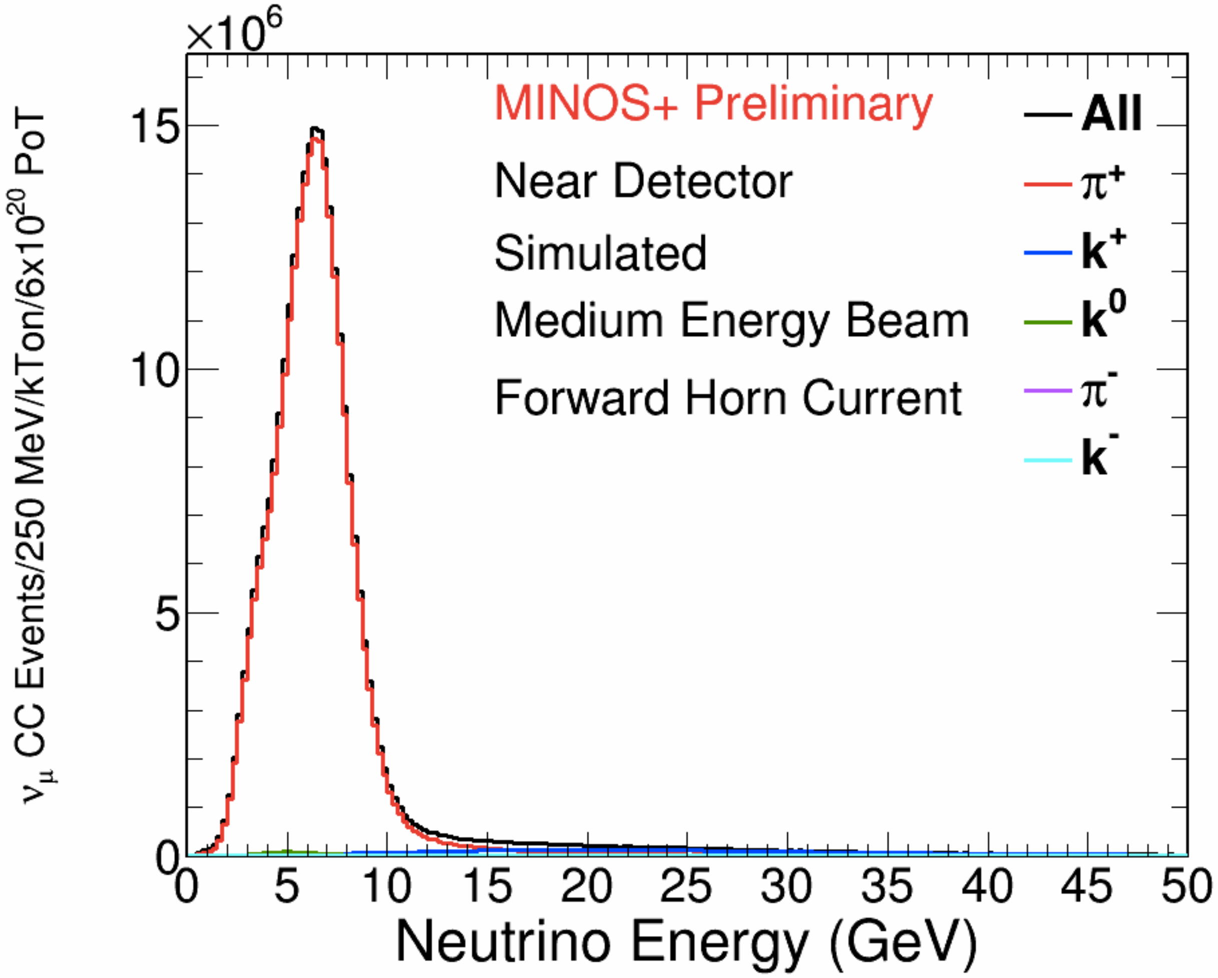
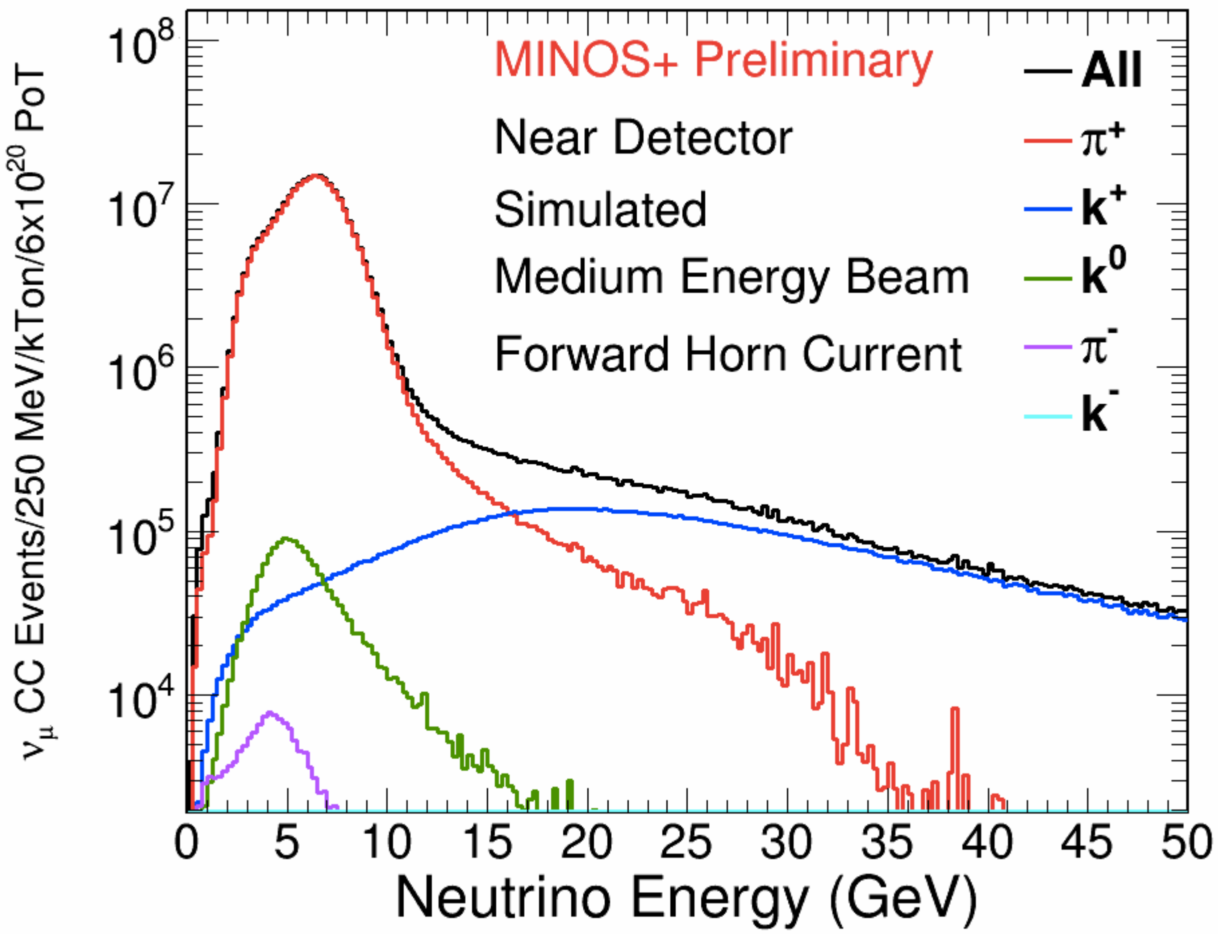


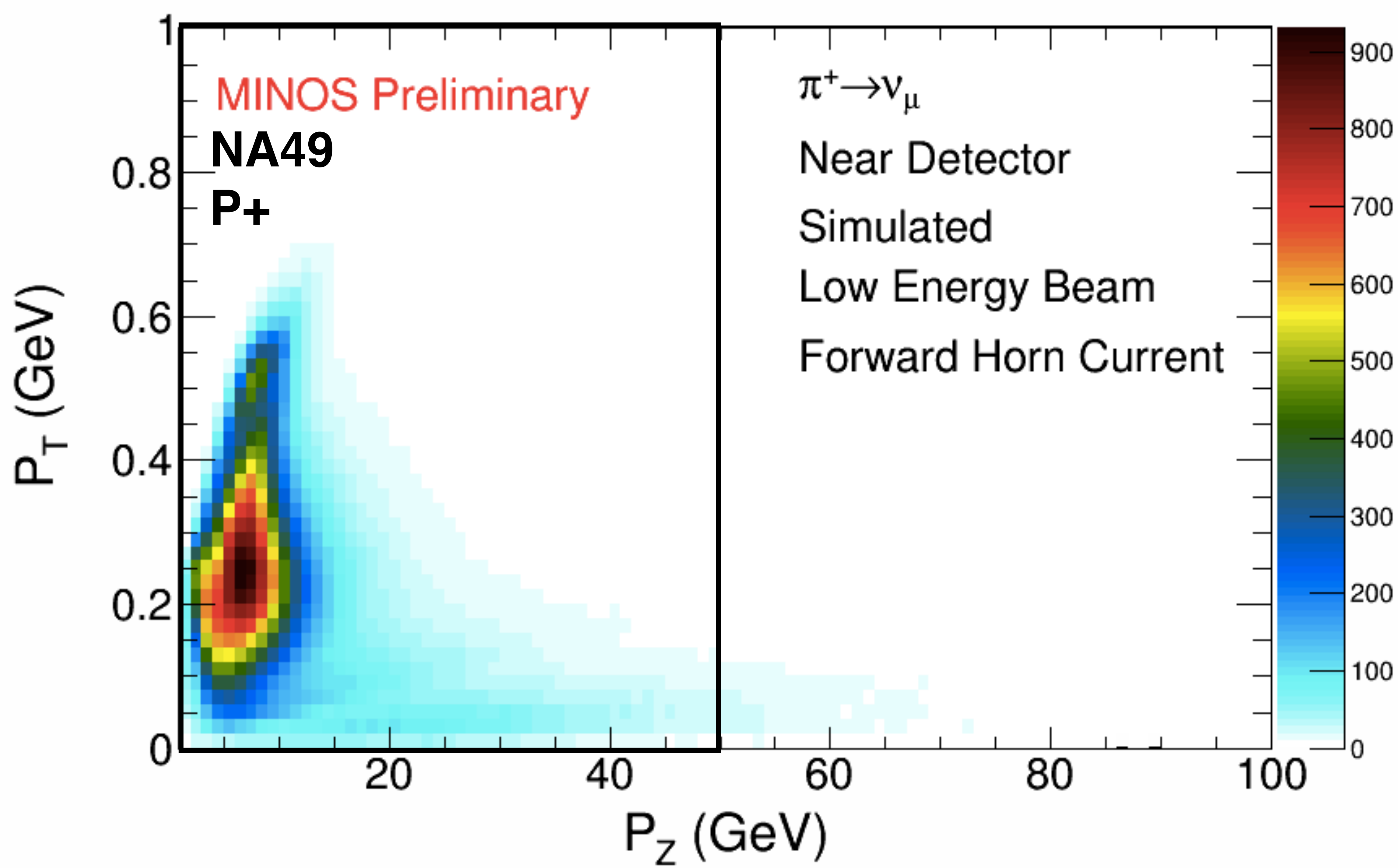


Components of the MINOS+ Beam





Region of Interest and NA49 Coverage



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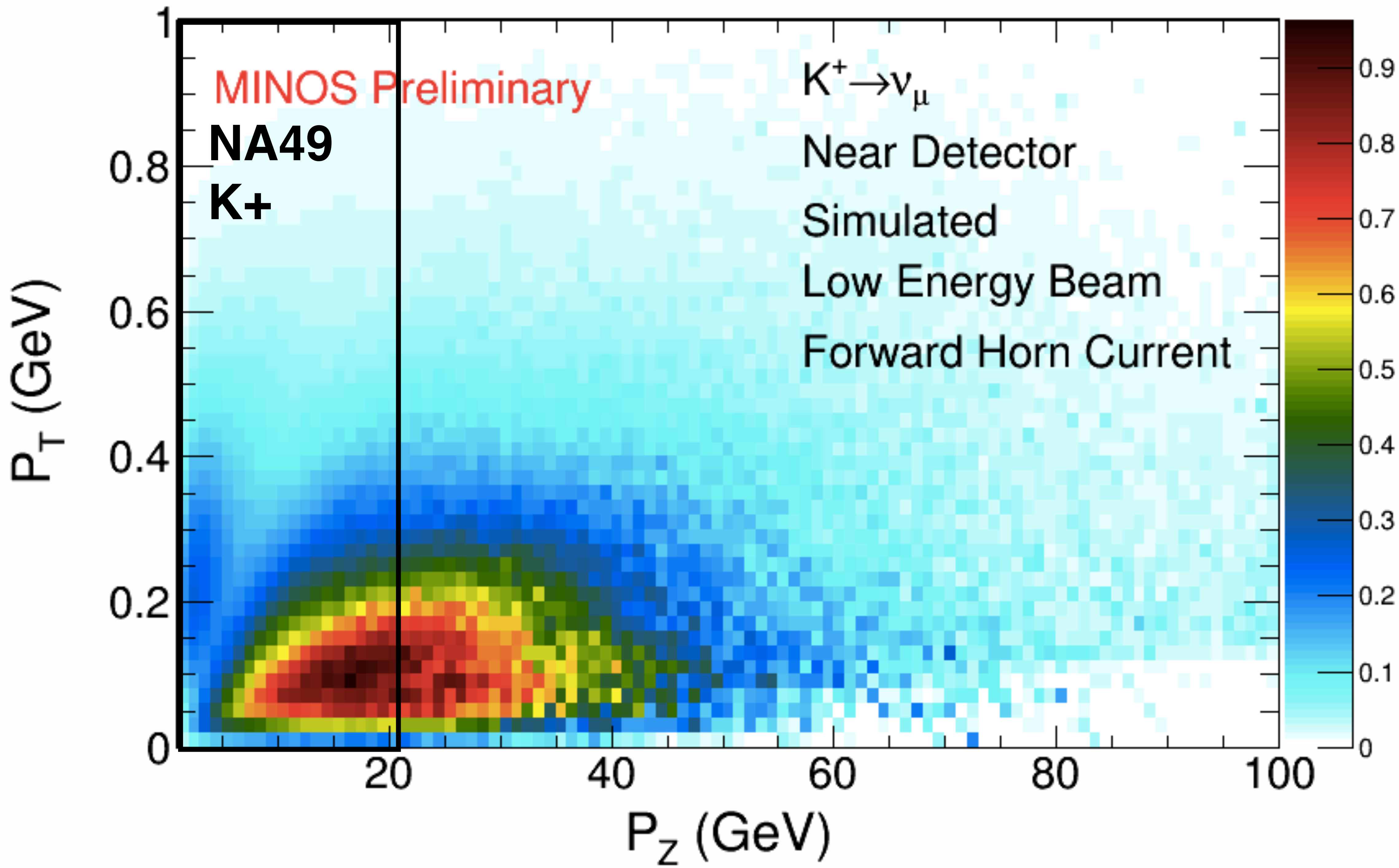

Example Alternative Parameterizations