NUMI BEAM LESSONS AND WORK IN PROGRESS MINOS/MINOS+

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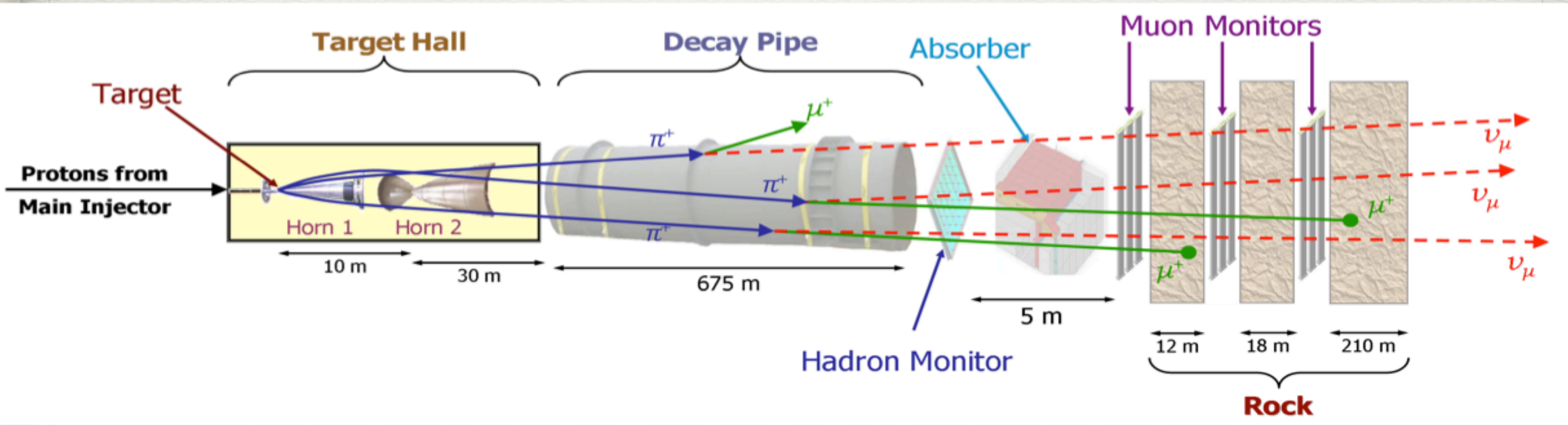
CERN CENF-ND Meeting

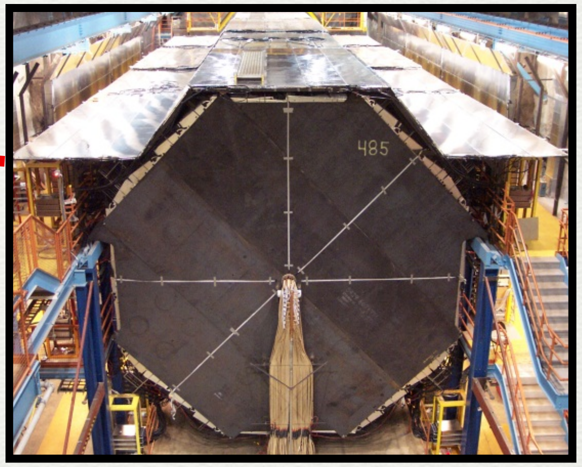
The NuMI Beam

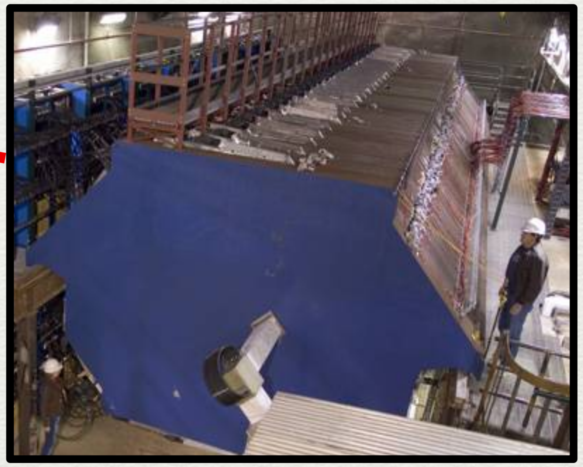


- 120 GeV protons from the Main Injector impact on a graphite target
- The resulting hadrons are focused by two magnetic horns
- They decay into neutrinos and other particles in the decay pipe
- The absorber and the subsequent rock absorb the latter, leaving only the neutrinos to travel towards the detectors

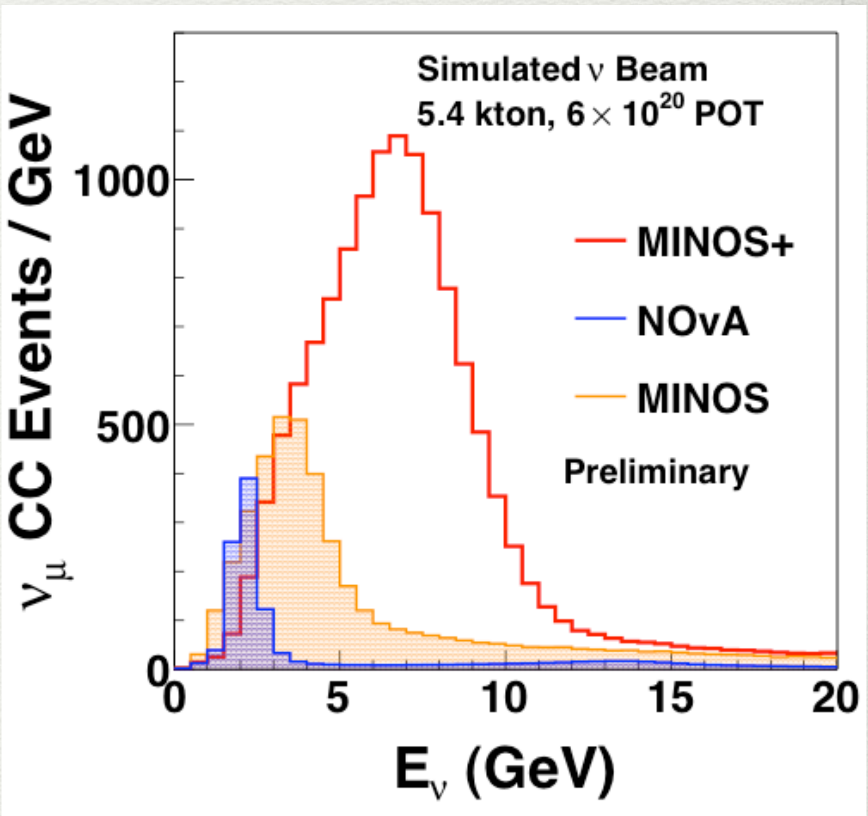
The MINOS/MINOS+ Experiment

Far Detector





Near Detector

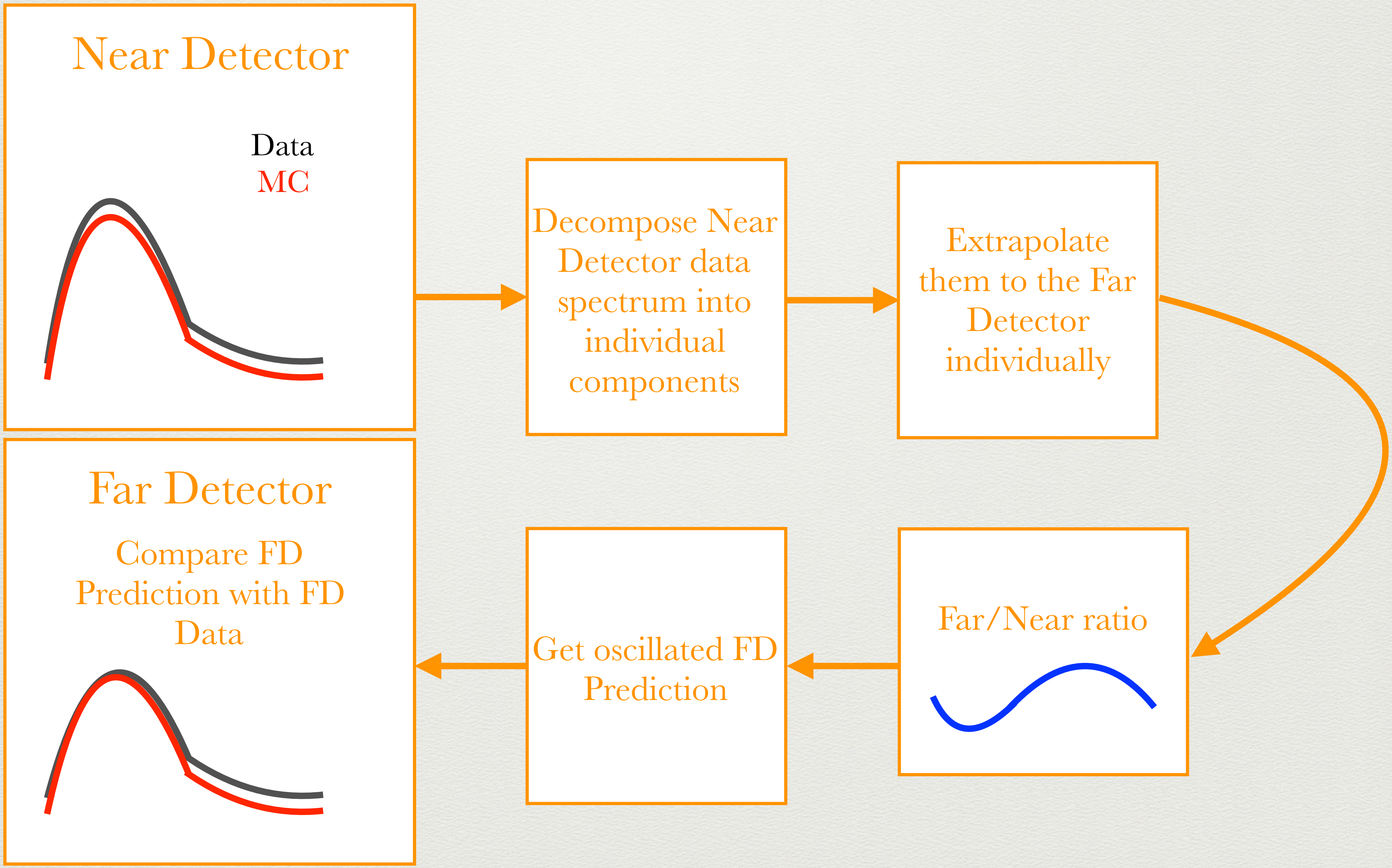


- MINOS is the oldest experiment in the NuMI Beam - it took beam data 2005-2016
- The ND still exists and serves as a beam monitoring device for NOvA and MINERvA
- MINOS is On-Axis, seeing a wide spectrum beam
- MINOS's Far /Near capabilities really helped with measuring the oscillation parameters, due to many systematic errors cancelling, including flux systematics

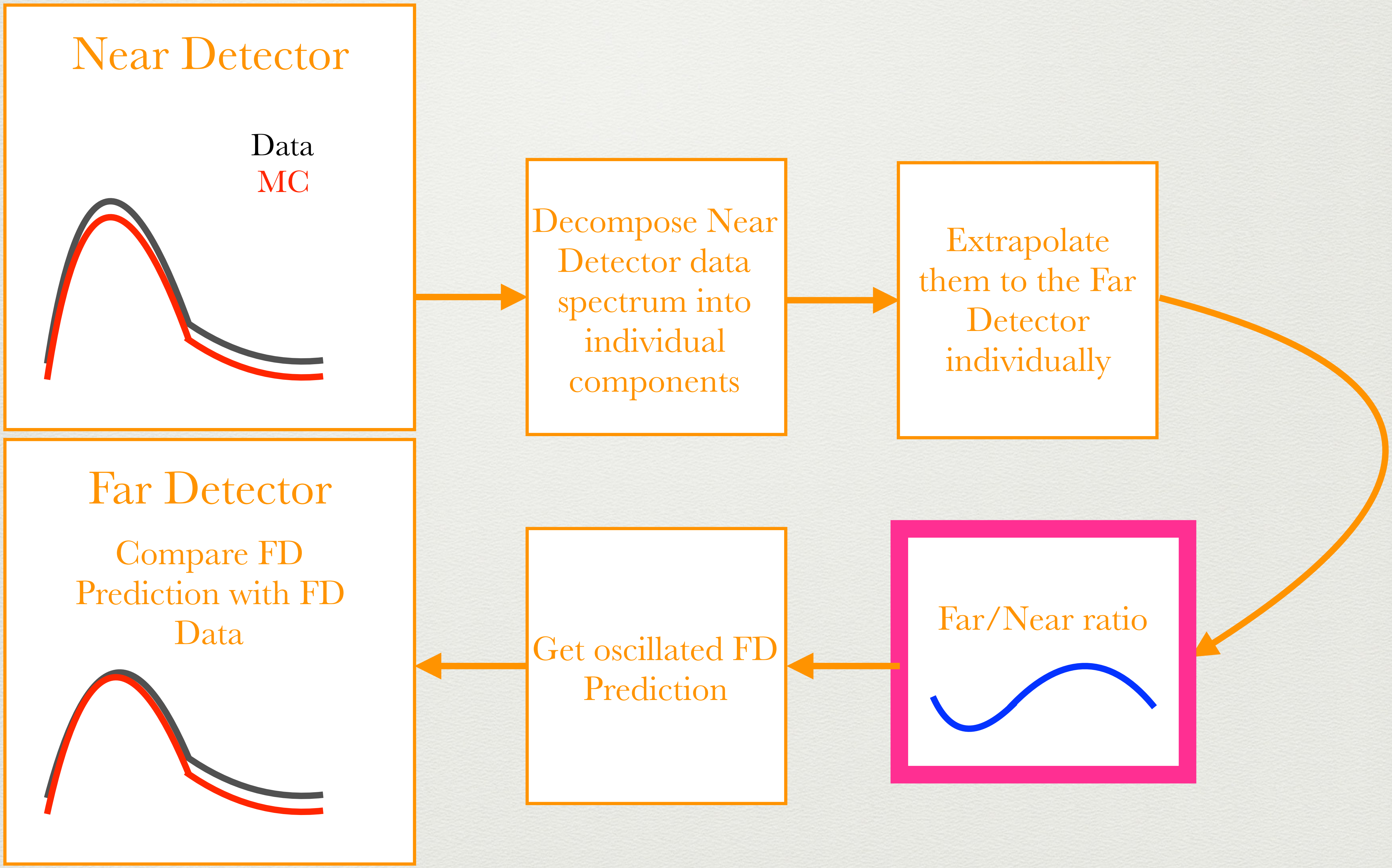
A few words

- I would like to discuss the value of knowing the neutrino beam flux as best we can
- A Near Detector is the best tool to help understand the beam flux
- It can serve to cancel systematic errors on the beam flux (and other errors like cross-sections etc)
- But the cancellation is not perfect as the ND is much closer to the beam source and sees neutrinos from a different pt-pz space than a FD
- A ND is essential because our flux modelling is imperfect
- The more instrumentation one can put in the beam the better

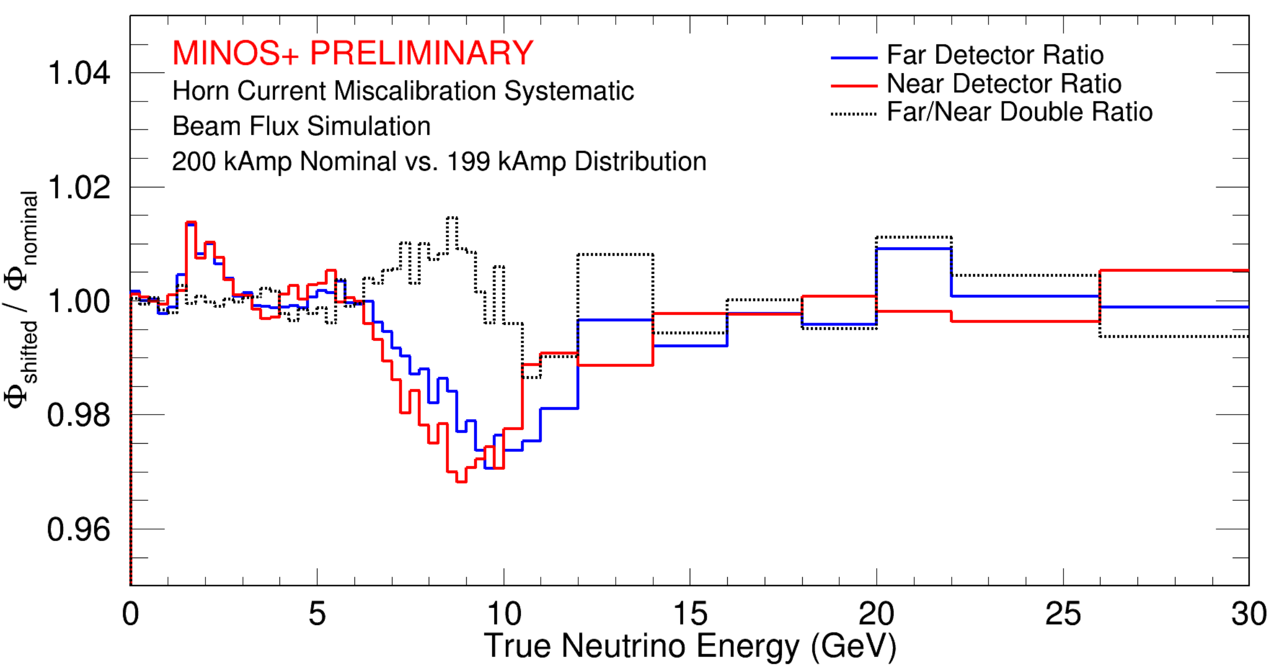
Oscillation analysis in simple terms

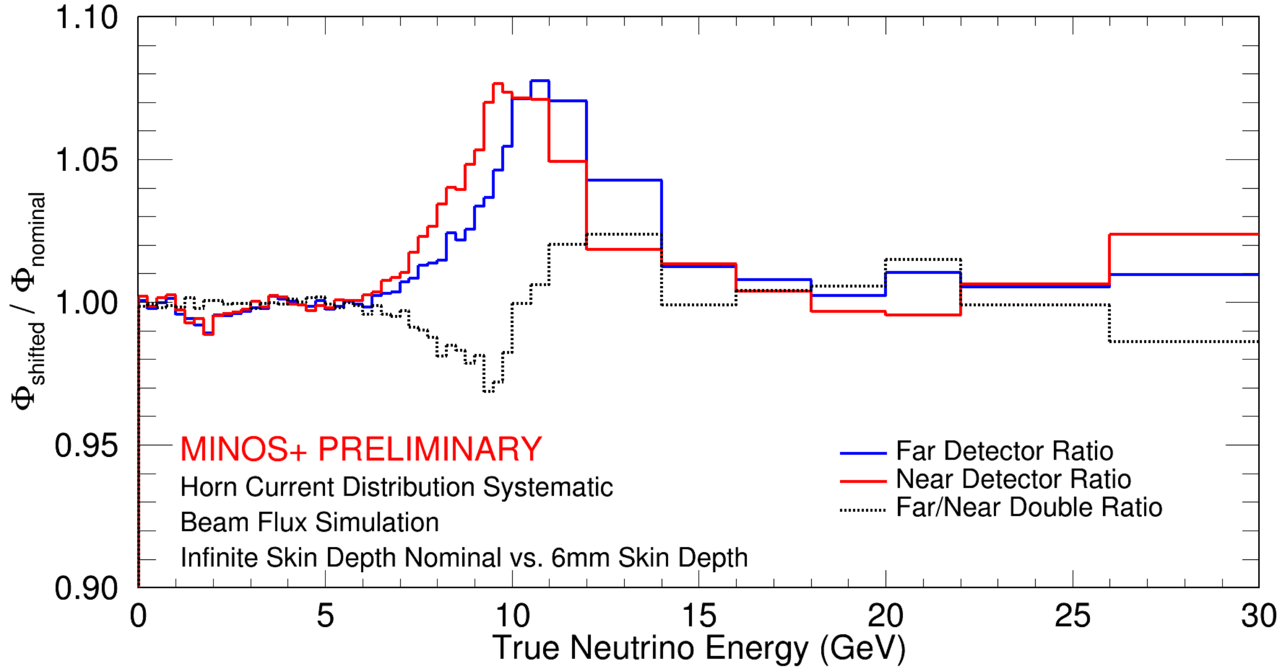


Oscillation analysis in simple terms



Beam Systematic Errors Cancellation



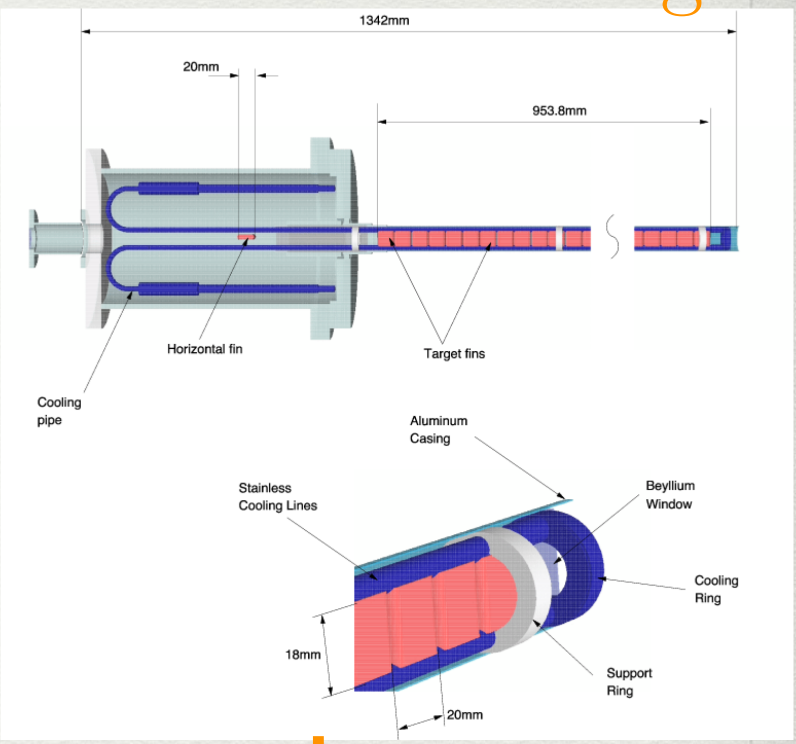


- To evaluate most beam flux systematic errors, special flux samples are generated where the given systematic is shifted by its associated uncertainty
- Systematic errors cancel to a large extent when taking a Far/Near ratio in a standard analysis
- e.g. 5% errors in one detector become 2% in F/N, 8% becomes 3%
- This is a huge advantage of a two detector experiment, however, we need to understand flux much better for future precision measurements

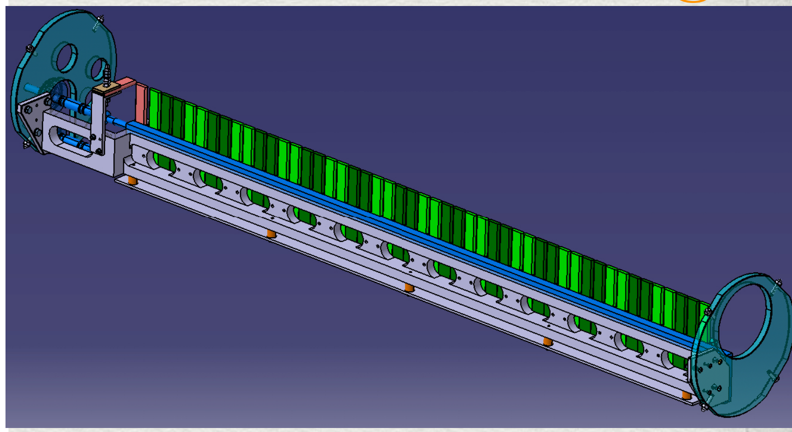
Beam Flux from a Target

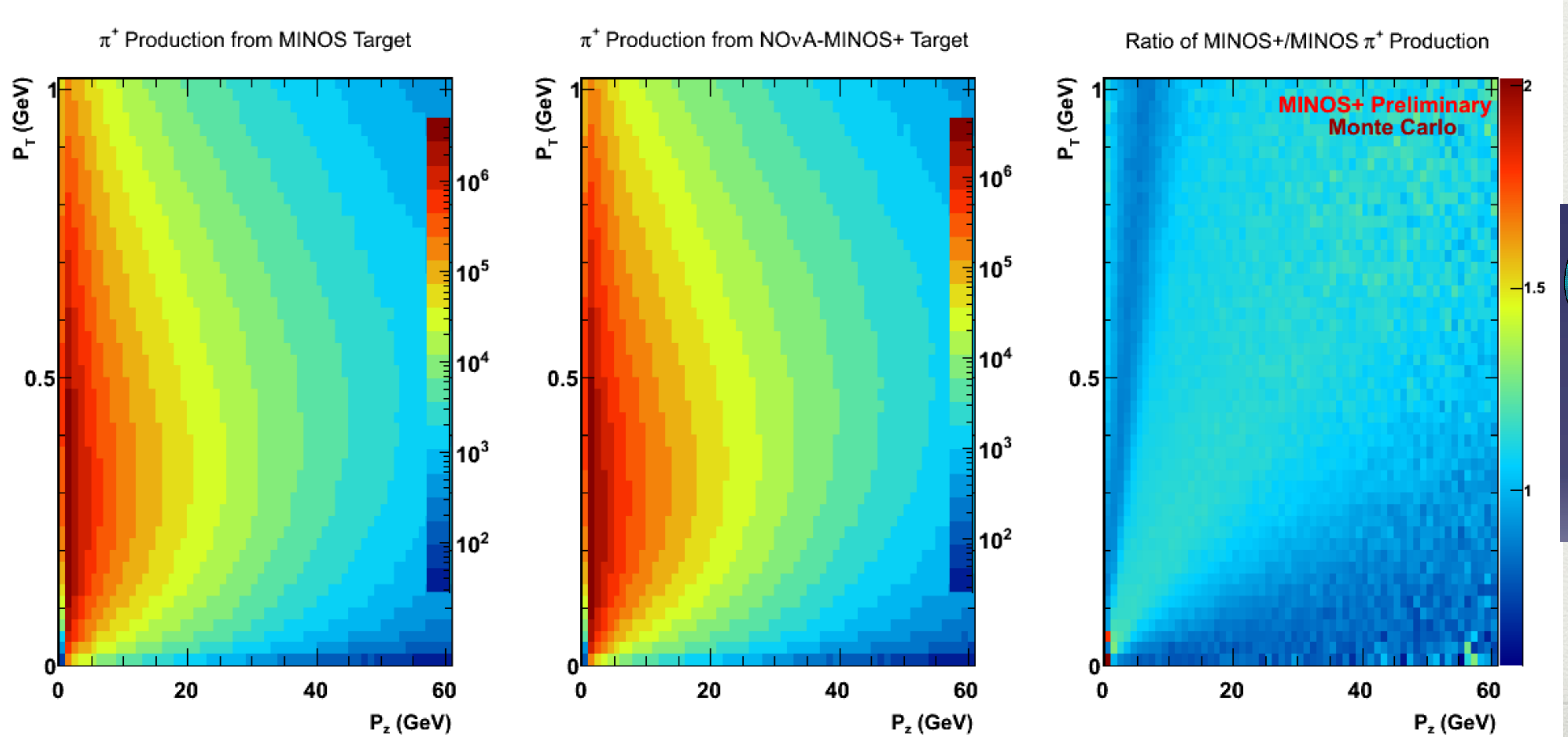
- Sometimes there can be a misconception that just because we have measured hadron production from thin target experiments, we understand it for any target (e.g. thick targets)
- This is not so - experiments spend a lot of time trying to understand their neutrino flux and it is a very difficult problem to solve
- Furthermore, hadron production in targets changes depending on the target geometry
- It is vital to know the flux from the actual target that is being used

LE Target

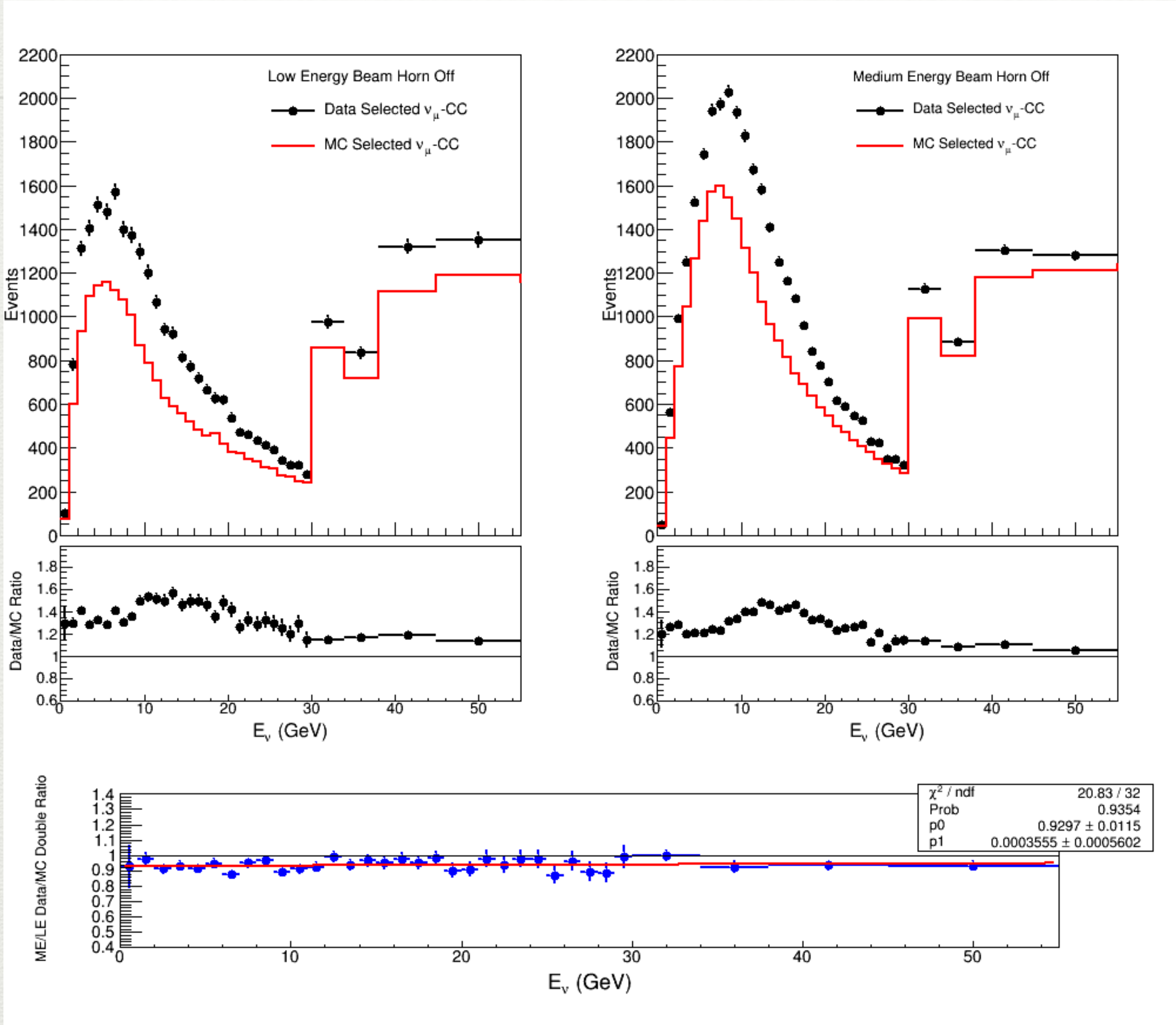


ME Target





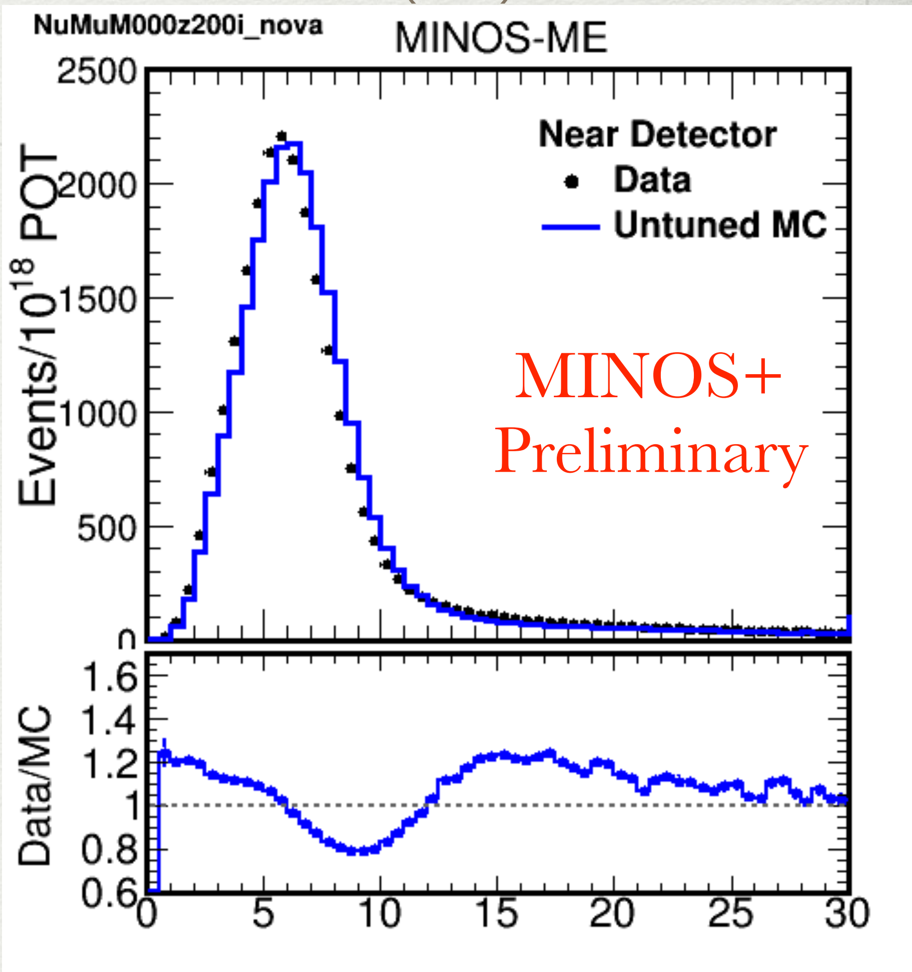
Horn Off Comparison

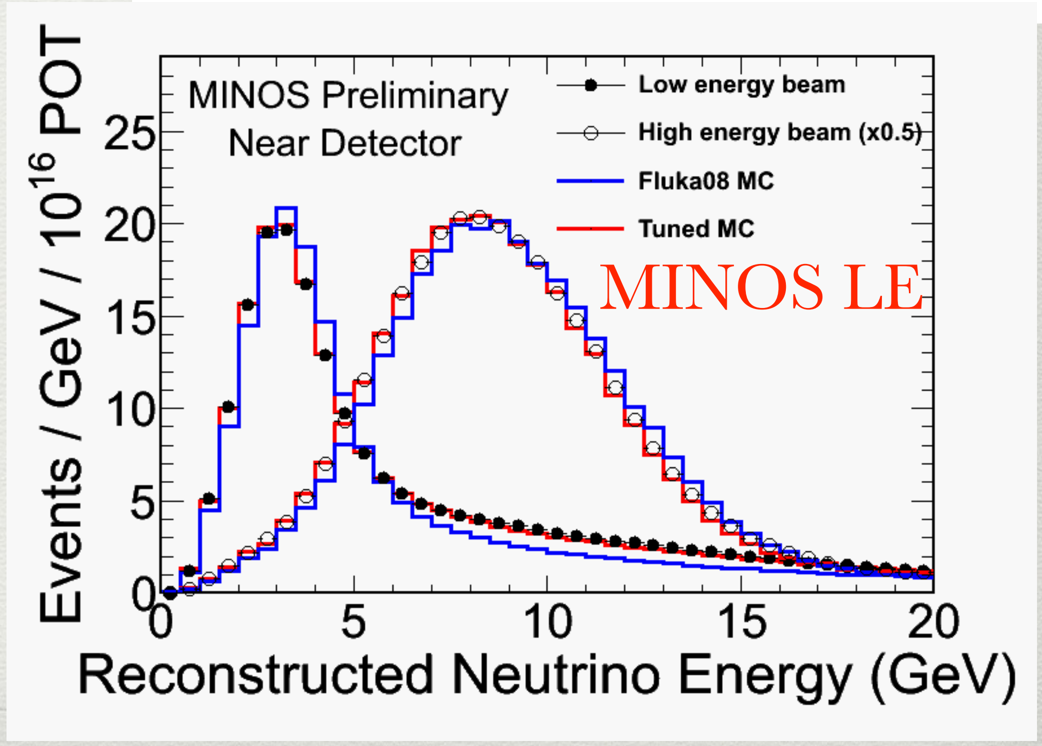


- The Horn Off sample (where the horns were not switched on) has no focusing, pure hadron production, we can use it to check whether the difference in hadron production between the LE and ME targets is well modelled
- The MC does not model the difference between the LE and ME target very well as can be seen from the data/MC ME/LE double ratio - would expect it to be 1.0 (even if the data/MC agreement itself is imperfect)

Data / MC agreement in MINOS(+)

- The Near Detector is the best beam flux monitoring device we have for the NuMI Beam
- But the data/MC agreement out of the box is not fantastic, especially at the falling edge of the beam peak
- Traditionally, for the standard 3-flavour oscillations analyses, it did not really matter since we use the ND data to predict the FD spectrum
- Also, we were able to correct the MC spectrum to achieve good data/MC agreement by using a beam fitting procedure





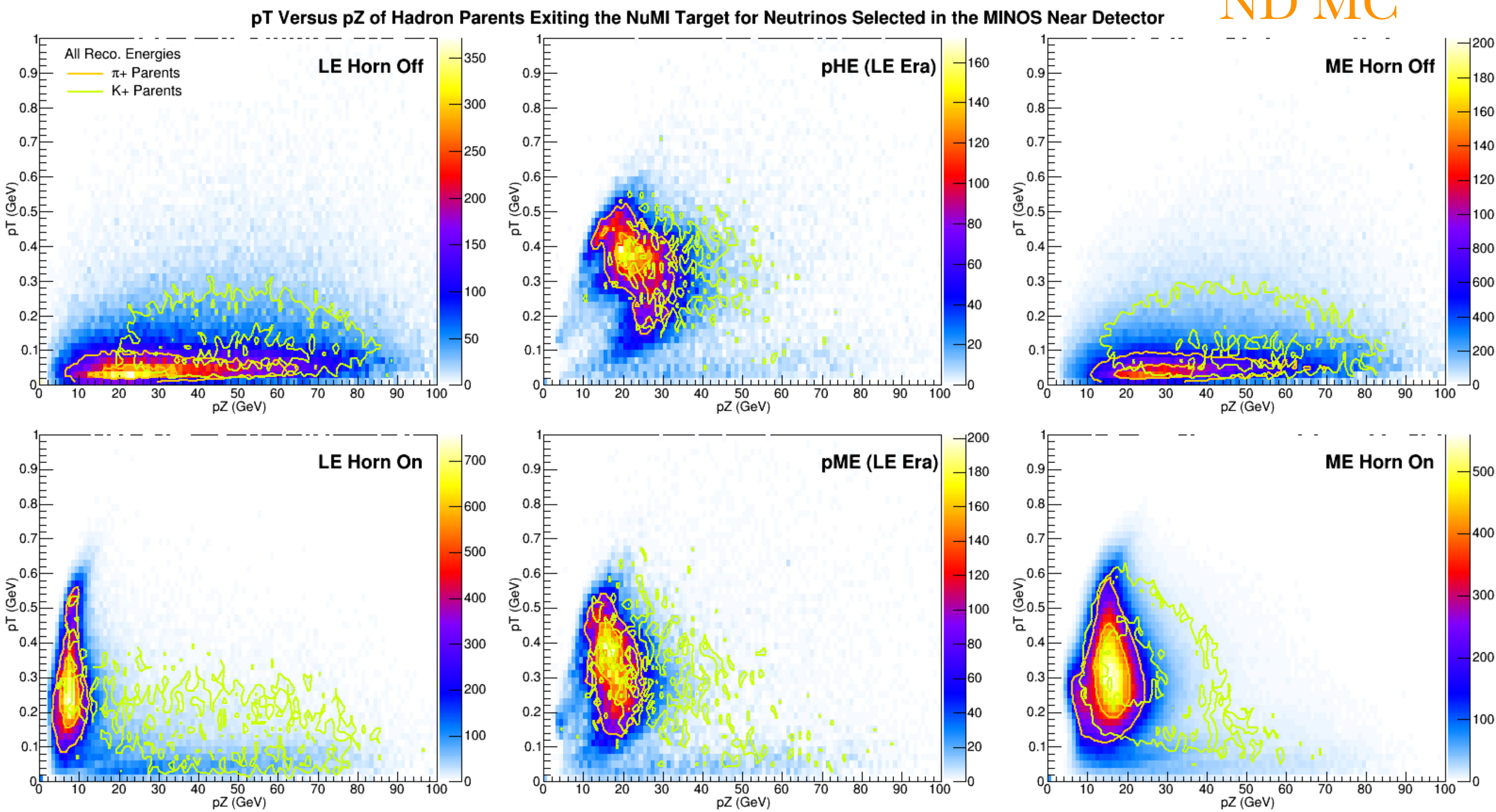
Beam Realities

- When we observe the beam in the Near Detector, there are several effects that are entangled:
  - Hadron production - those are the hadrons that are produced in the beam target, before being focused
  - Focusing Effects - when the horns are on, hadrons are focused (or out-focused) depending on their charge and the sign of the horn current
  - Neutrino cross-section in the ND
  - Possible detector effects, including detector acceptance, and detector occupancy effects
- All of those need to be disentangled!

What happens in the Beam Fits

- During beam fits, we normally include several beam configurations so as to disentangle those effects, and access different phase space in neutrino parent pT/pZ

ND MC



What happens in the Beam Fits

- A particularly important sample is the Horn Off sample, where the horns are not switched on which means that there are no focusing effects there
- Using several beam configurations also allows to cancel out detector effects in the fits
- We fit 3 parts (normally) at the same time:
    - Hadron production
    - Focusing effects
    - "detector" effects which include some background, energy mis-calibration and cross-section effects and are expected to be small

Beam Fitting - Hadron Production

- Traditionally, for the 3-flavour analysis, we have been using a fitting framework developed early on for MINOS (see Zarko Pavlovic Thesis)
- This uses a BMPT-type parametrisation in order to fit the hadron production part of the neutrino flux

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

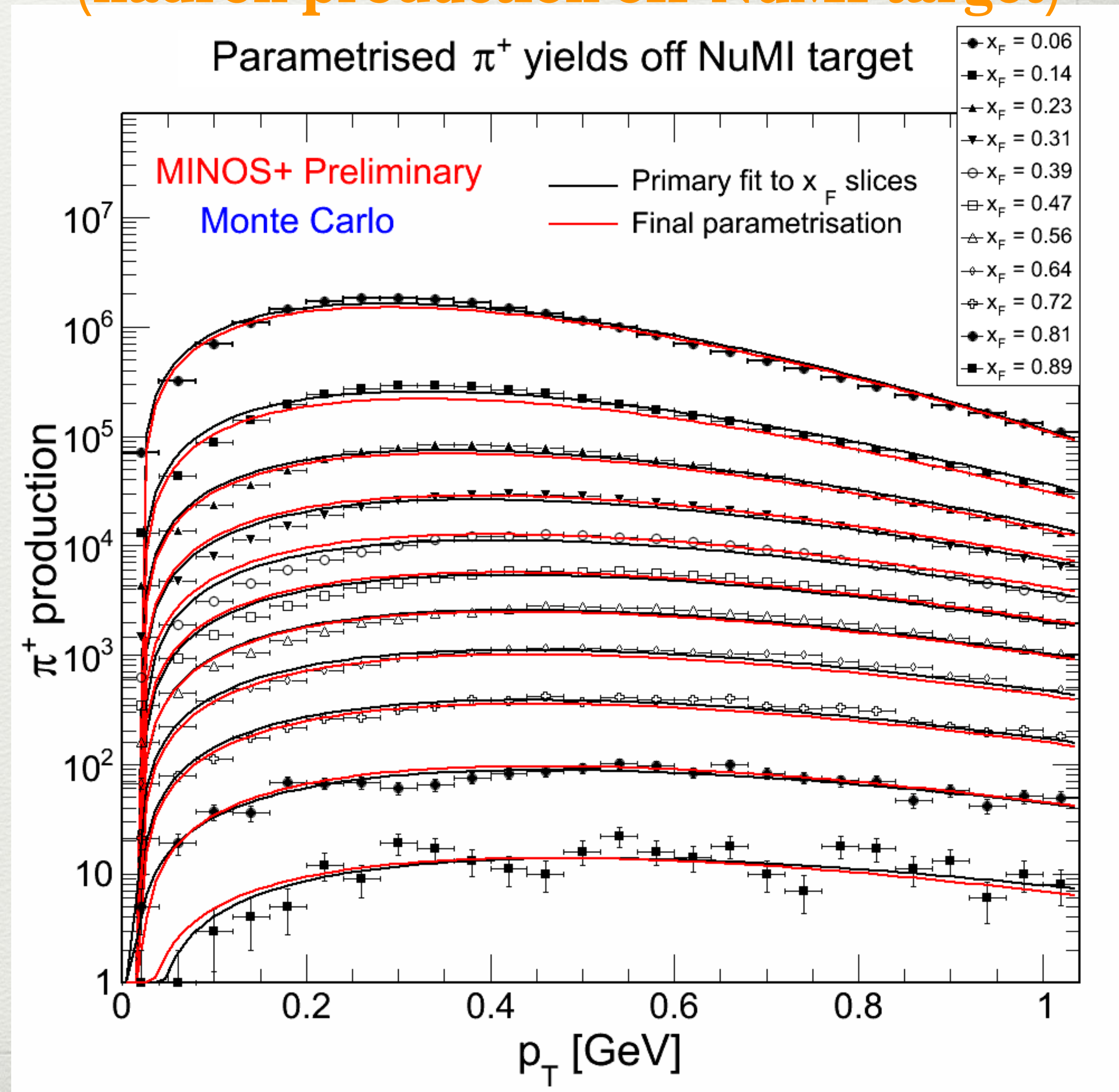
$$A(x_F) = a_1(1-x_F)^{a_2}(1+a_3x_F)x_F^{-a_4}$$

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

$$C(x_F) = \frac{c_1}{x_F^{c_2}} + c_3 \quad \text{for } x_F < 0.22$$

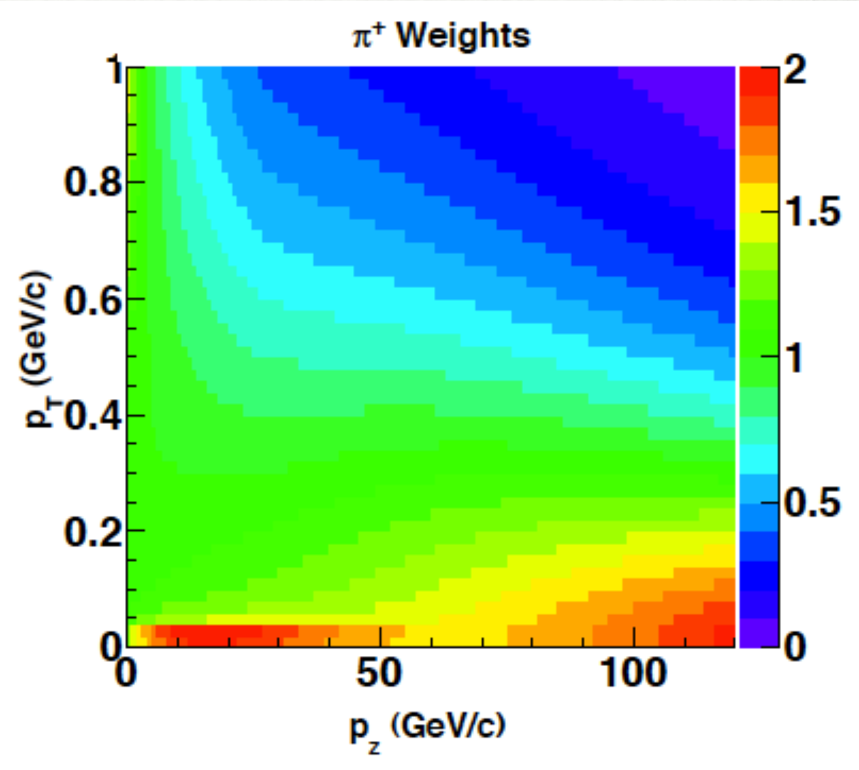
$$C(x_F) = \frac{c_1}{e^{(x_F+c_2)c_3}} + c_4x_F + c_5 \quad \text{for } x_F > 0.22$$

Fitting of parametrisation to flux MC (hadron production off NuMI target)



Beam Fitting - Hadron Production Step 2

- Once the hadron production has been fitted, the resulting parametrisation can be used to calculate weights as a function of neutrino parent pt-pz (the parent as it exits the target, before any focusing)
- Those weights are extracted by fitting ND MC to ND Data to improve Data/MC agreement
- The weights are calculated as a ratio, therefore the parametrisation serves as a handle to warp the hadron production



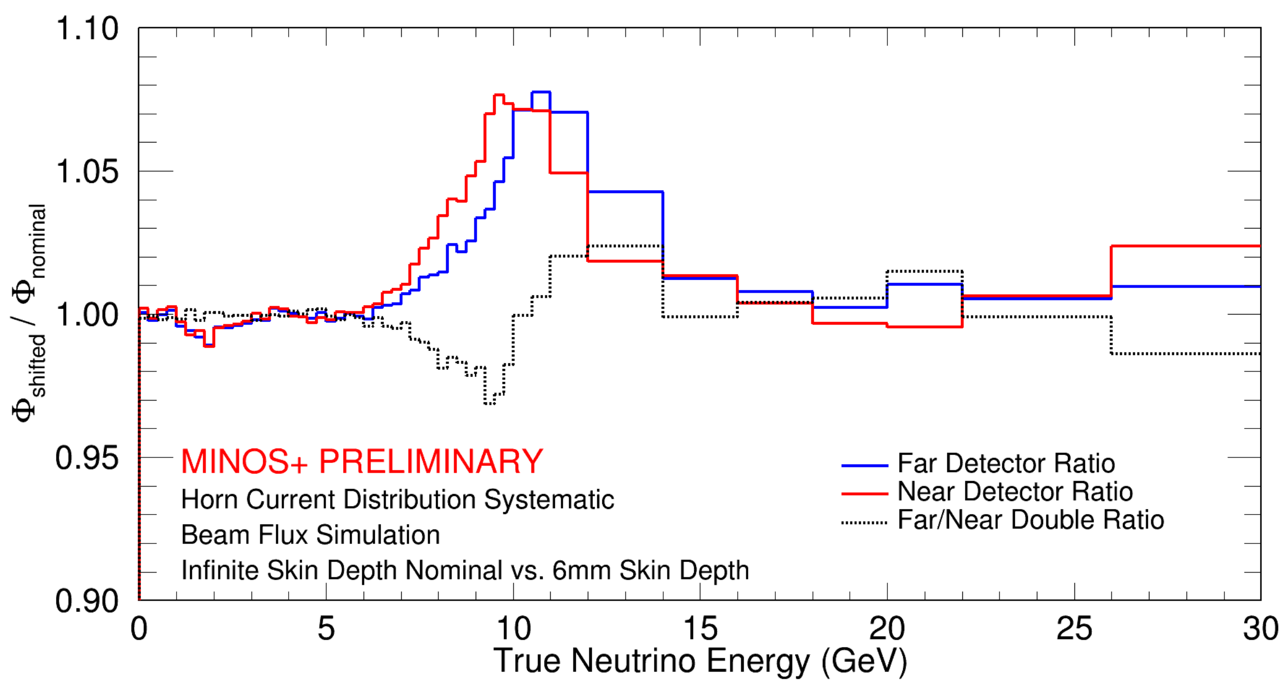
$$W(p_T, x_F) = \frac{[A' + B'p_T]exp(-C'p_T^{3/2})}{[A + Bp_T]exp(-Cp_T^{3/2})}$$

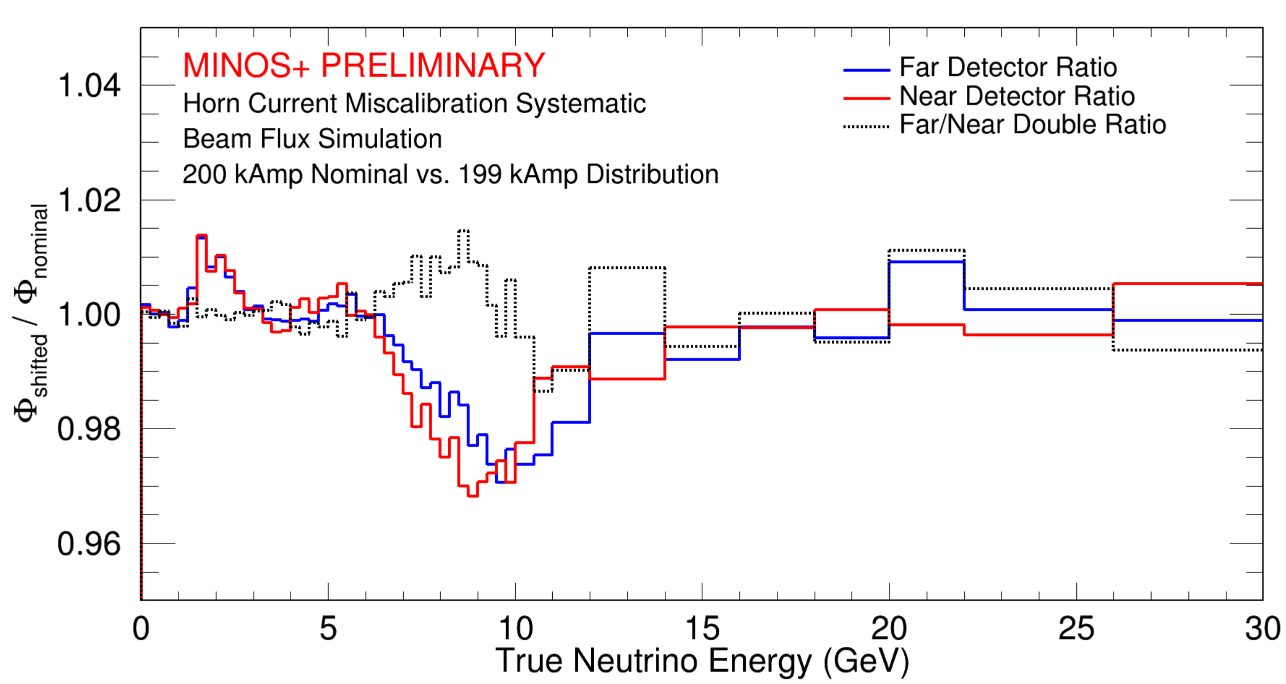
$$A'(x_F) = (\mathrm{par}[0] + \mathrm{par}[1]x_F)A(x_F)$$
$$B'(x_F) = (\mathrm{par}[2] + \mathrm{par}[3]x_F)B(x_F)$$
$$C'(x_F) = (\mathrm{par}[4] + \mathrm{par}[5]x_F)C(x_F)$$

$$W(K^-, p_T, x_F) = (\mathrm{par}[0] + \mathrm{par}[1]x_F)W(K^+, p_T, x_F)$$

Beam Focusing

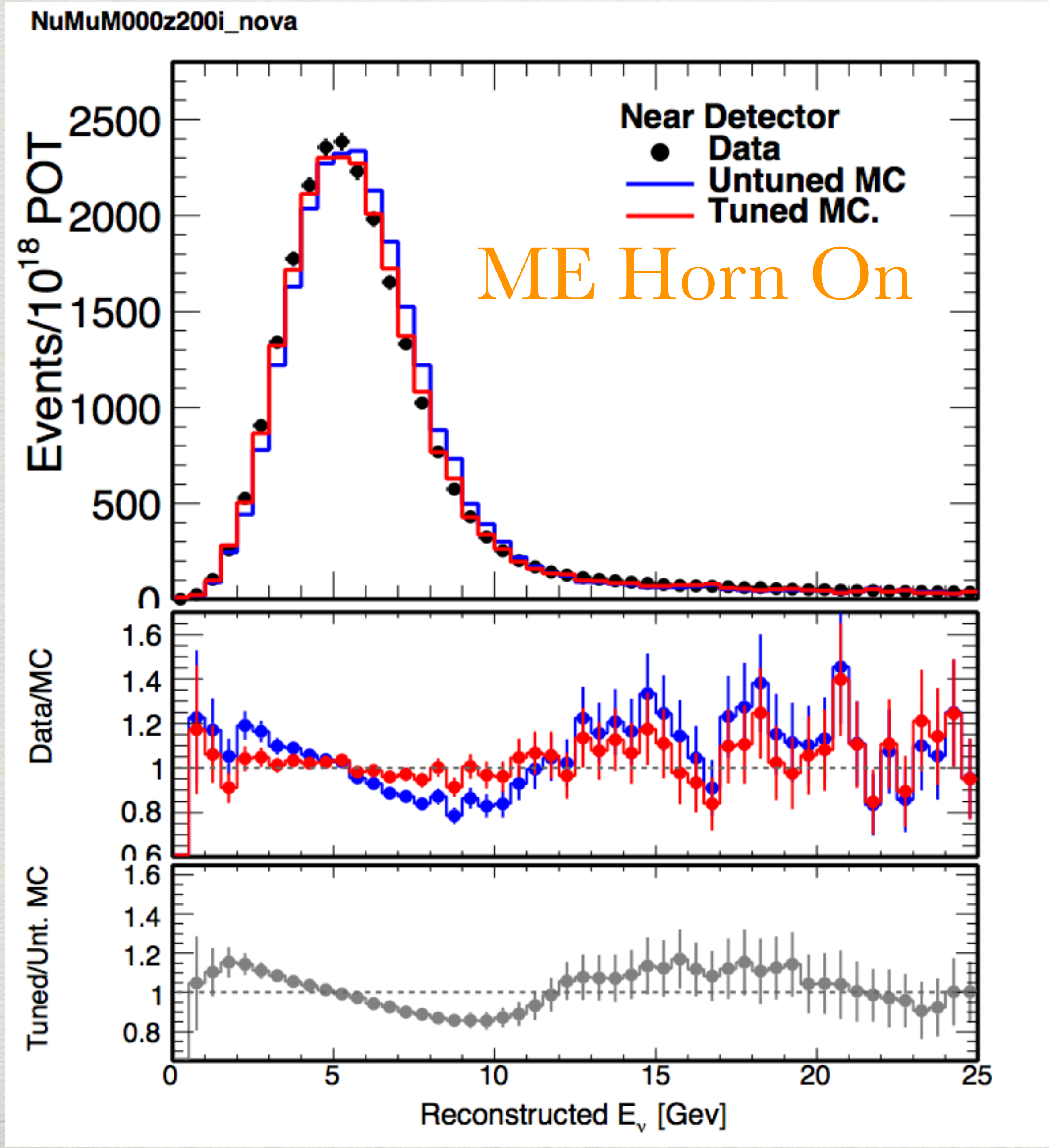
- Over the running of MINOS we have evolved the flux fits so as to fit two focusing parameters as effective parameters
- They go in opposite directions and provide a nice handle to fit the falling edge of the peak
- We already used them in MINOS LE, and are using them in MINOS ME too
- Fit them in terms of +/- sigma applied as weights in true neutrino energy to MC

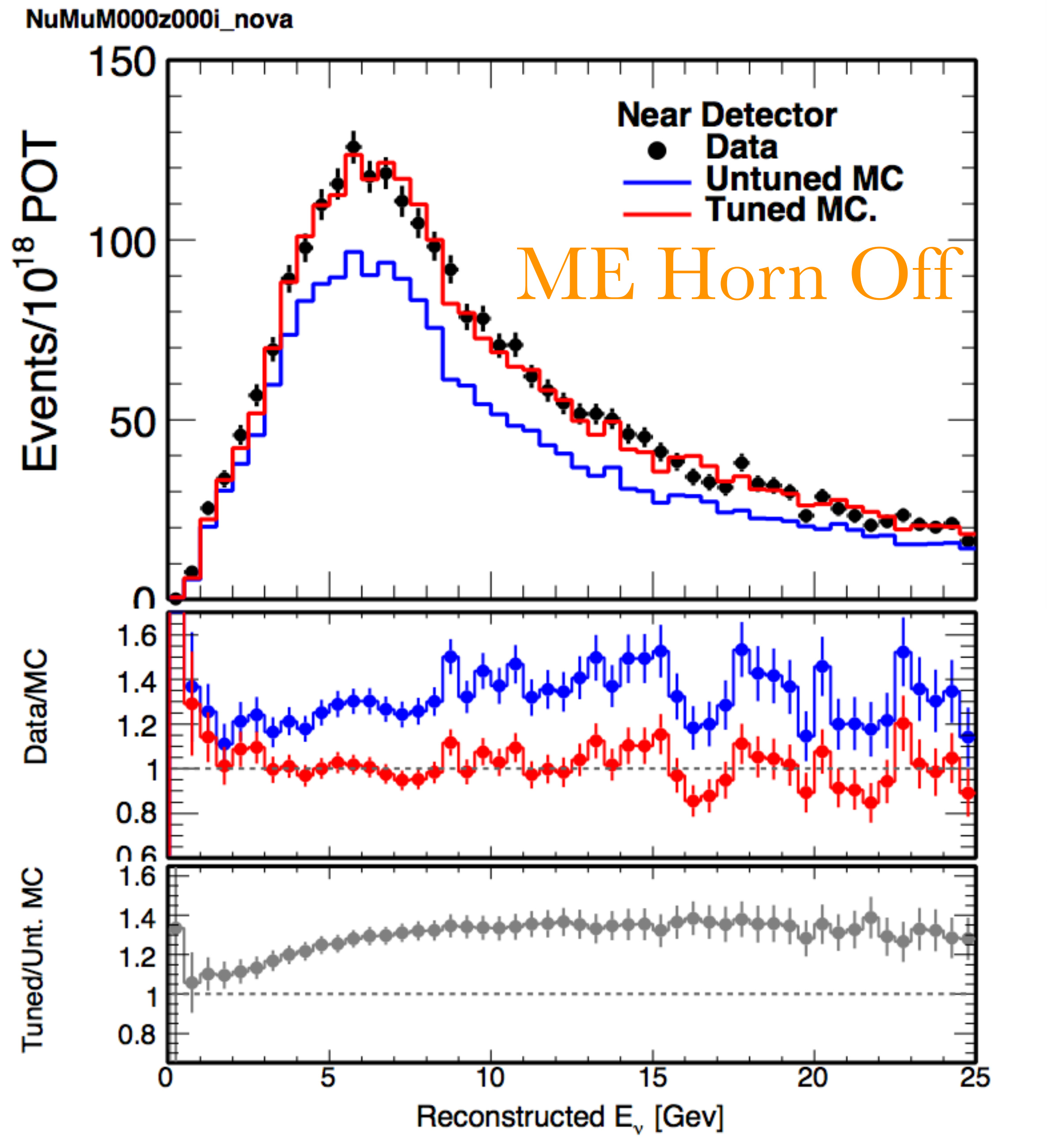




Some beam fit results

- These are the results of the current official MINOS+ beam fits
- Those ME fits used four samples: Horn On Neutrinos, Horn On Anti-Neutrinos, Horn Off Neutrinos, Horn Off Anti-Neutrinos

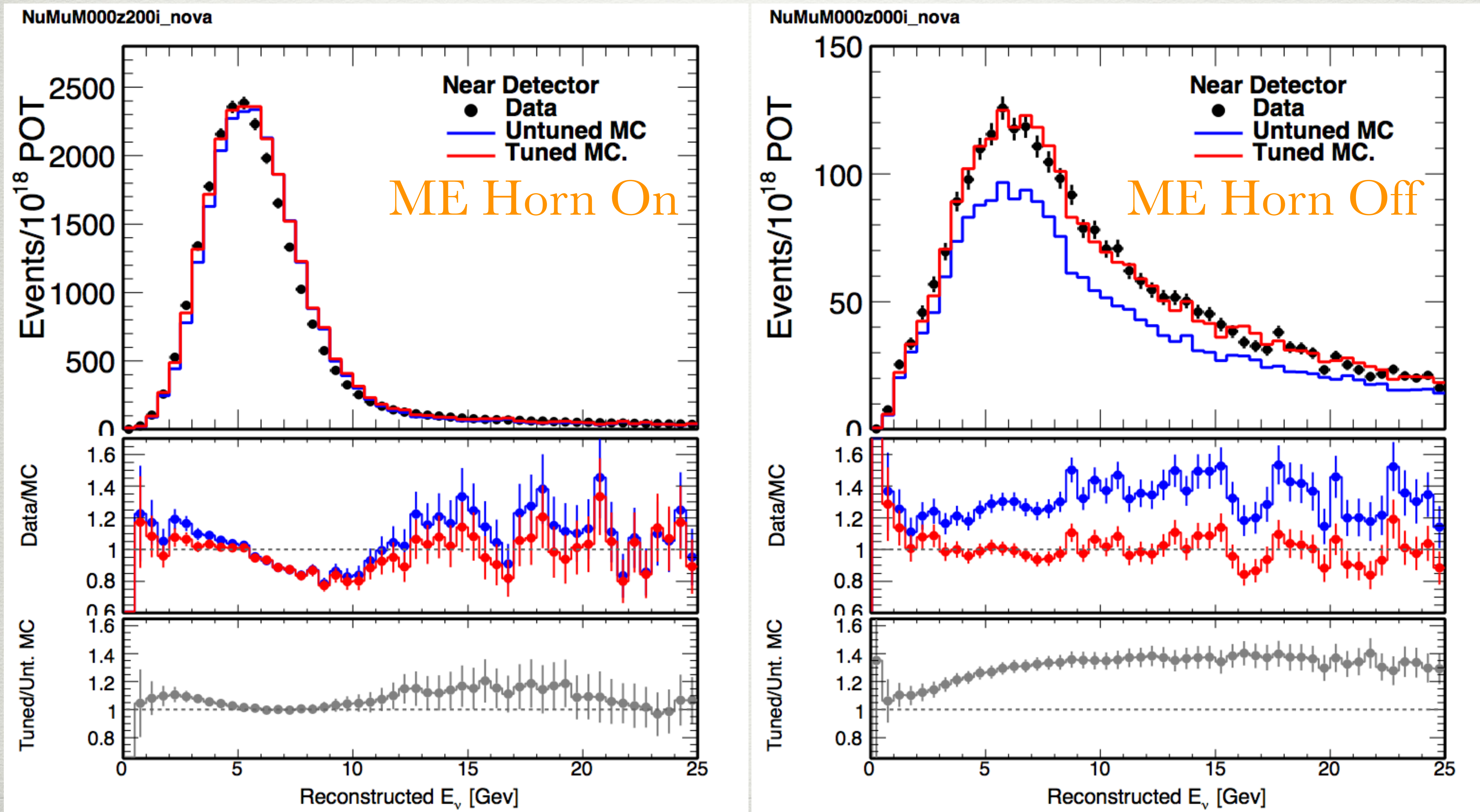




Effect of Hadron Production Only

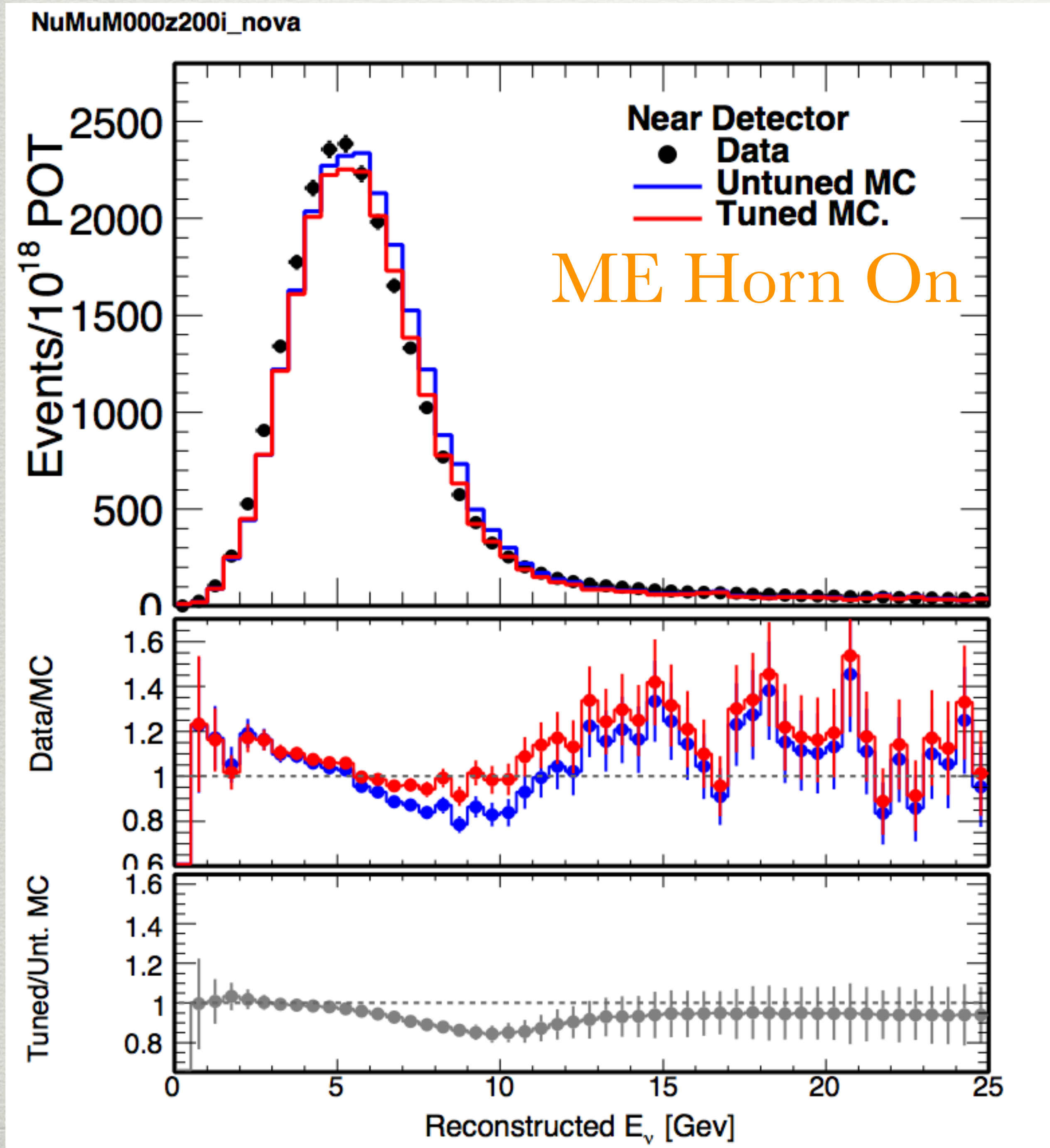
- It is possible to apply only part of the weights after having extracted the fit parameters, to see what contribution the different components make to the final data/MC agreement

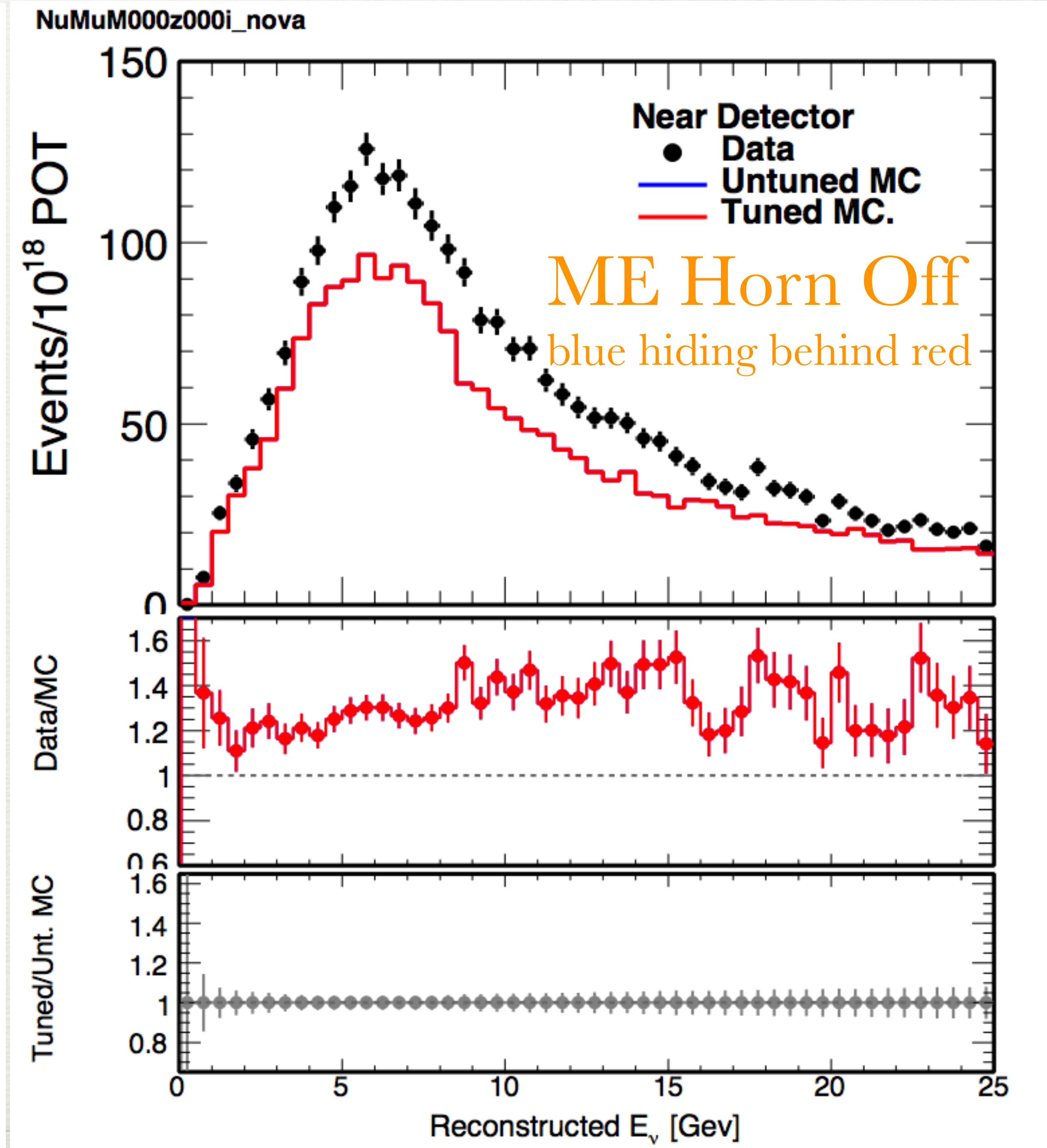
- Applying only the Hadron Production weights



Effect of Focusing Only

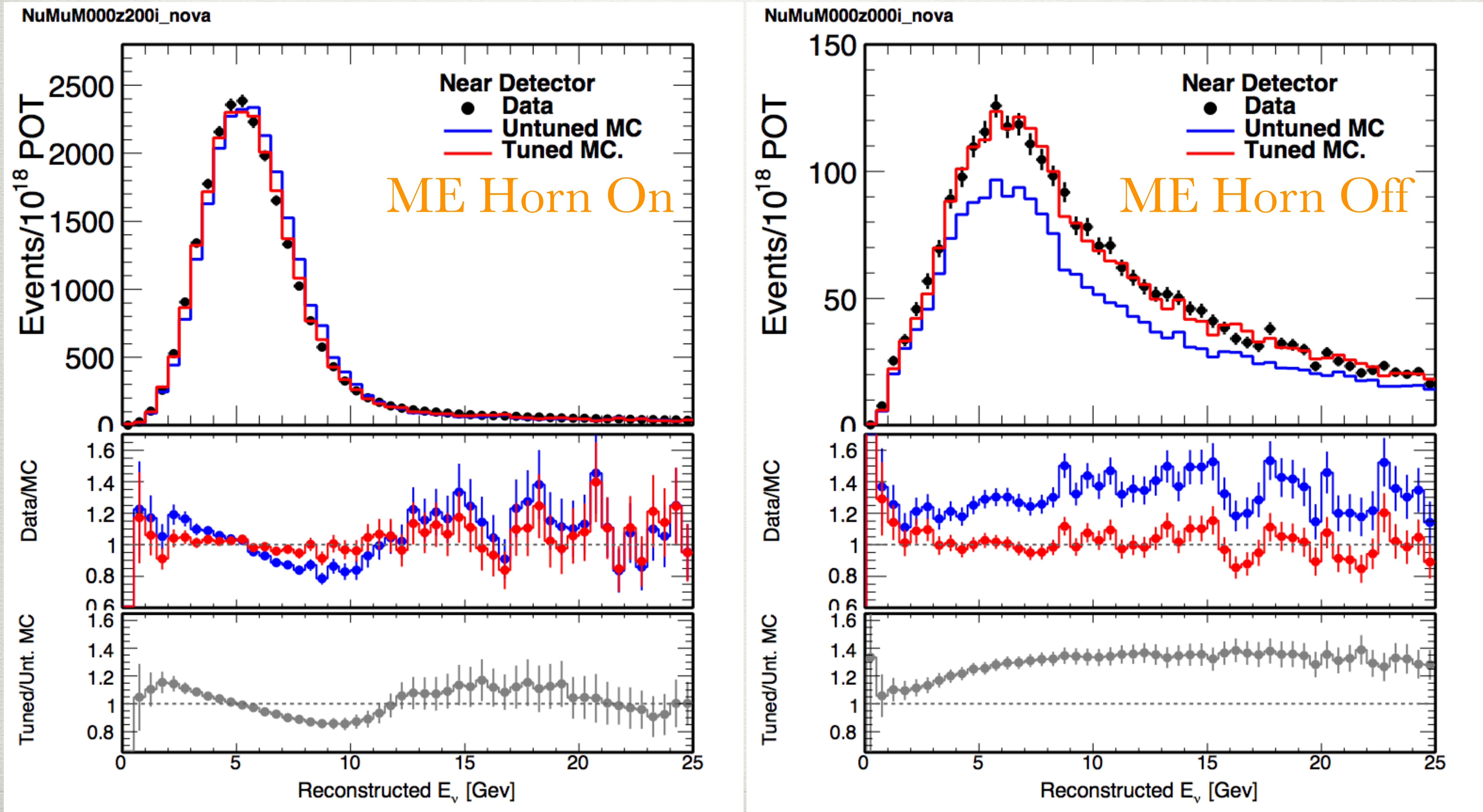
- It is possible to apply only part of the weights after having extracted the fit parameters, to see what contribution the different components make to the final data/MC agreement
- Applying only the focusing weights - no effect on Horn Off sample - good sanity check





Effect of both Hadron Production and Focusing

- Applying both the Hadron Production weights and the Focusing weights yields good data/MC agreement



Some Comments

- We can fit the data / MC disagreement out by fitting the hadron production in parent hadron pT-pZ space (as the parent hadron exits the target) and using focusing systematics
- To date, the focusing component required is large and not understood though we are slowly making progress towards this goal
- None of this really mattered for the MINOS LE or ME standard oscillations (3-flavour) numu-CC disappearance analysis
- This is because we could take the ND as the un-oscillated sample to get the FD oscillated prediction
- MINOS ran checks on the FD oscillations results with/without beam flux weights and the results were practically identical

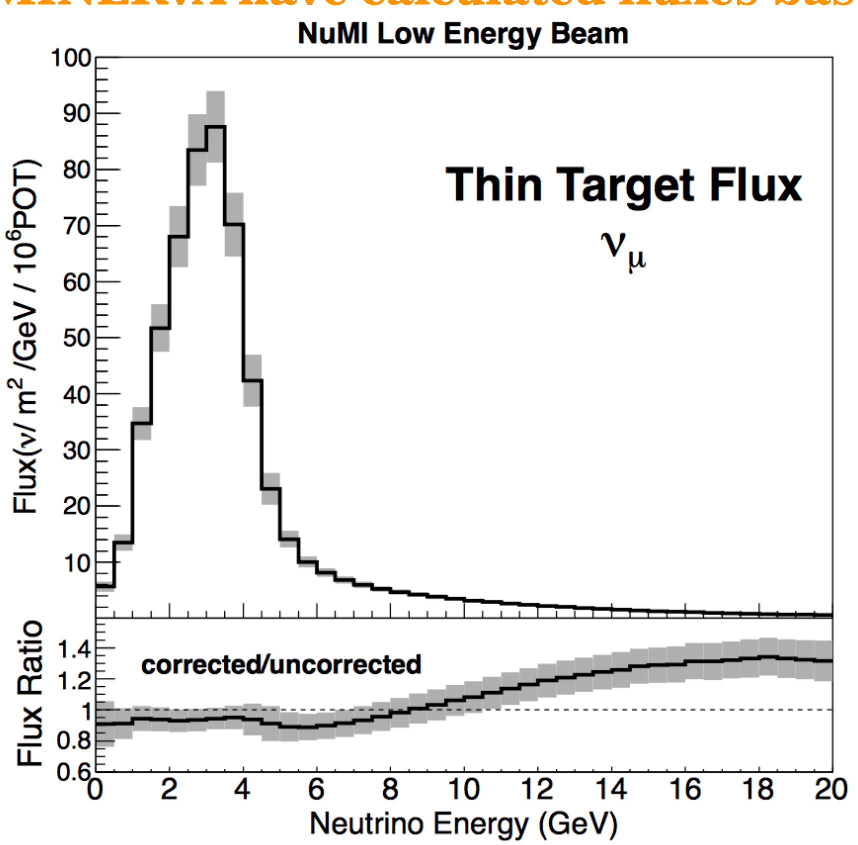
Impact on Analyses

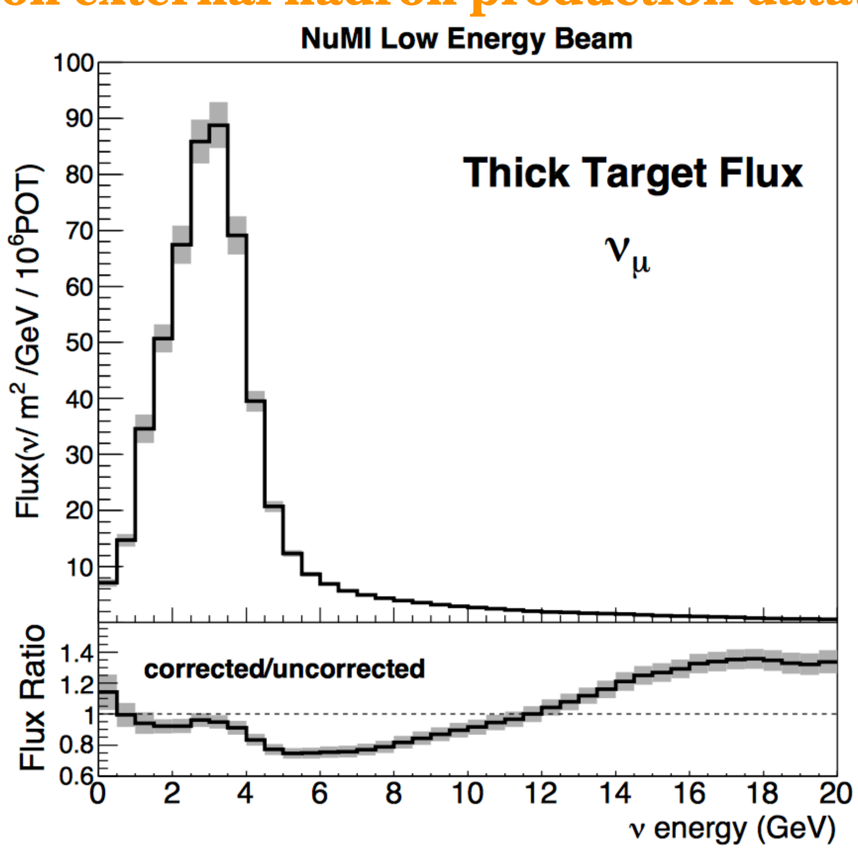
- However, there are other analyses apart from the standard disappearance
- The electron neutrino appearance analysis for example - with higher statistic we will need to understand any focusing or hadron production effects, including those affecting the intrinsic beam nue background and also the beam peak
- We can't afford to have a 1GeV peak shift between data and MC for the high precision DUNE measurements - we really need to understand the flux very well
- What about other methods of getting the flux?
- Currently on MINOS(+) we are using PPFX as an a priori flux for the sterile analysis since using the standard beam weights can't be used here since that would be using flux derived from the same data set that we are using to look for a sterile neutrino

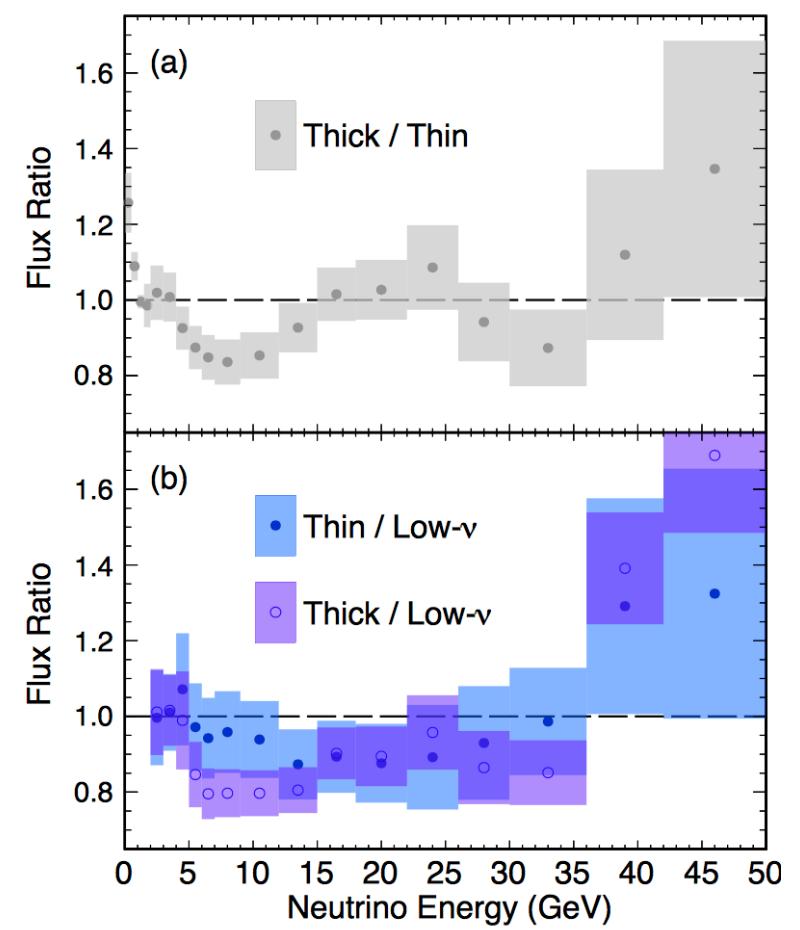
PPFX a priori flux

- MINERvA have calculated a flux spectrum based on external hadron production data (https://arxiv.org/pdf/1607.00704.pdf)
- They used the external data to calculate an a-priori flux from the NuMI target - now used by NOvA and the MINOS sterile analysis
- The calculated thin target flux mostly uses NA49 data, the thick target flux mostly MIPP, but they have used other external data to fill out gaps in phase space where one or the other data was missing
- They used their own data (with tracks ranging out in the MINOS ND) to evaluate the data/MC agreement after applying their correction to their MC from the calculated flux

MINERvA have calculated fluxes based on external hadron production data:

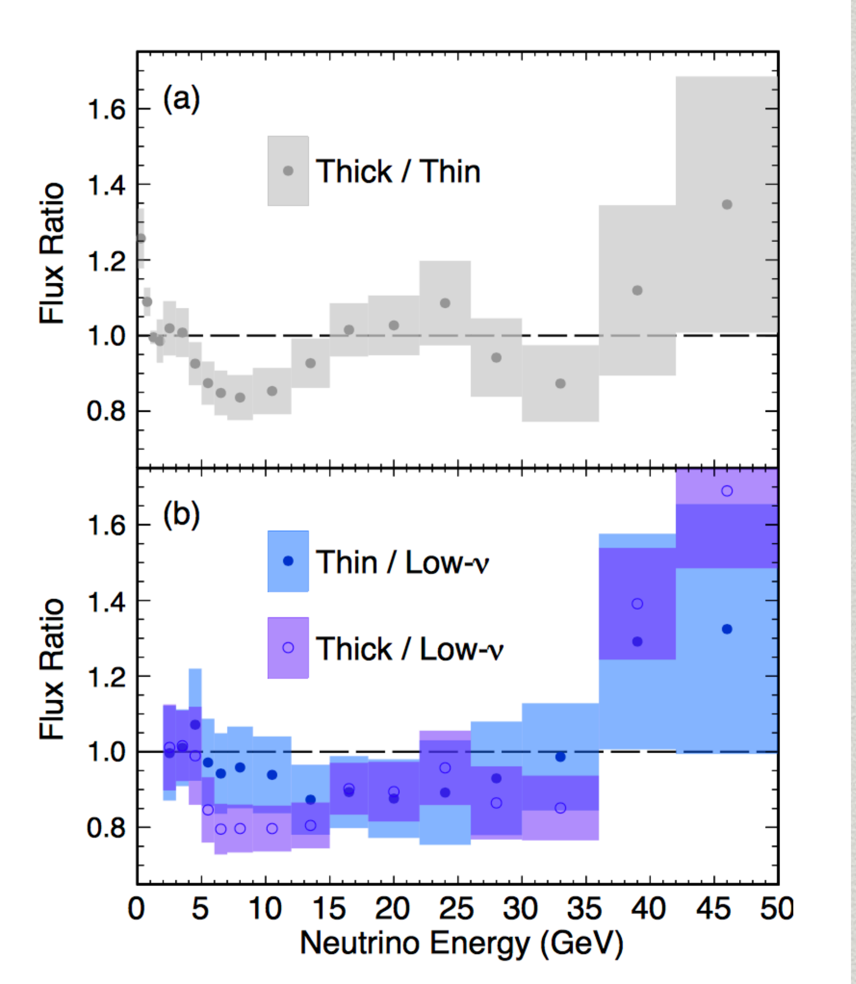






PPFX Horn Off Check

- I studied how the PPFX flux (thin target) would affect the horn off data/MC agreement for ME beam in MINOS+
- Horn Off doesn't have any focusing, so provides a direct window on the hadron production component of beam flux
- Perfect sample to check what PPFX does to the hadron production
- PPFX also uses a multi-verse technique to provide an error band on the calculated flux



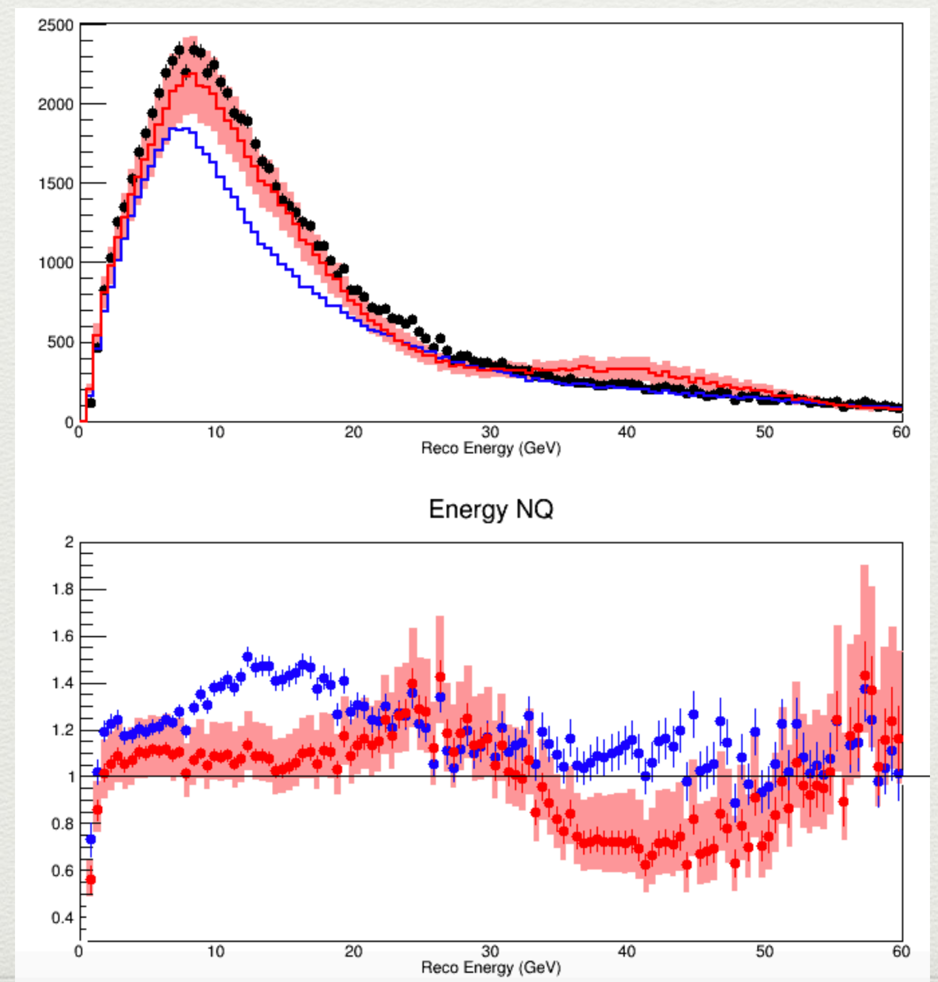
PPFX Horn Off Check

- At lower energies, the data / MC agreement is improved
- At higher energies this is not the case - disagreement driven by kaons
- Further discussions with Leo Aliaga Soplin have shed further light on this
- In this phase pt-pz phase space, the information comes mostly from adding in MIPP data
- Those low pT higher pZ neutrino parents are not well measured

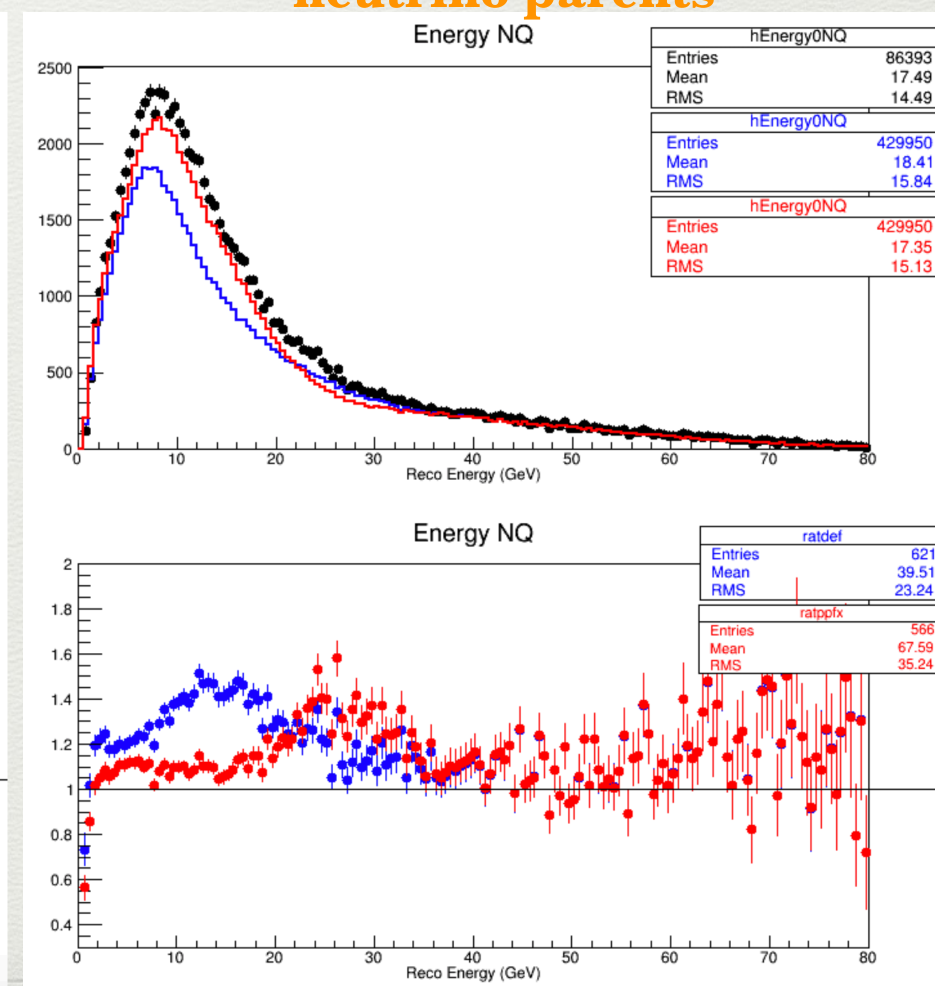
Horn Off Data
Default MC
PPFX weighted MC

Data / Default MC
Data / PPFX weighted MC

Applying PPFX weights to all neutrinos

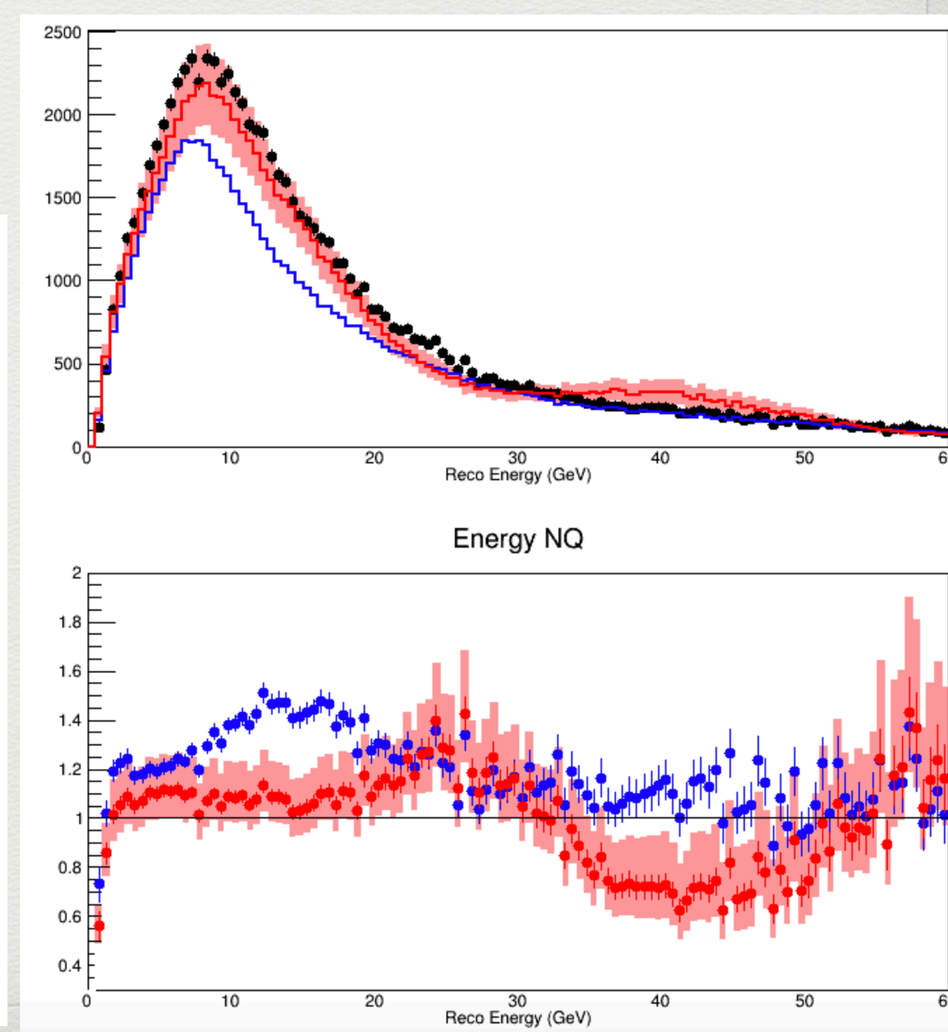


Applying PPFX weights only to pion neutrino parents

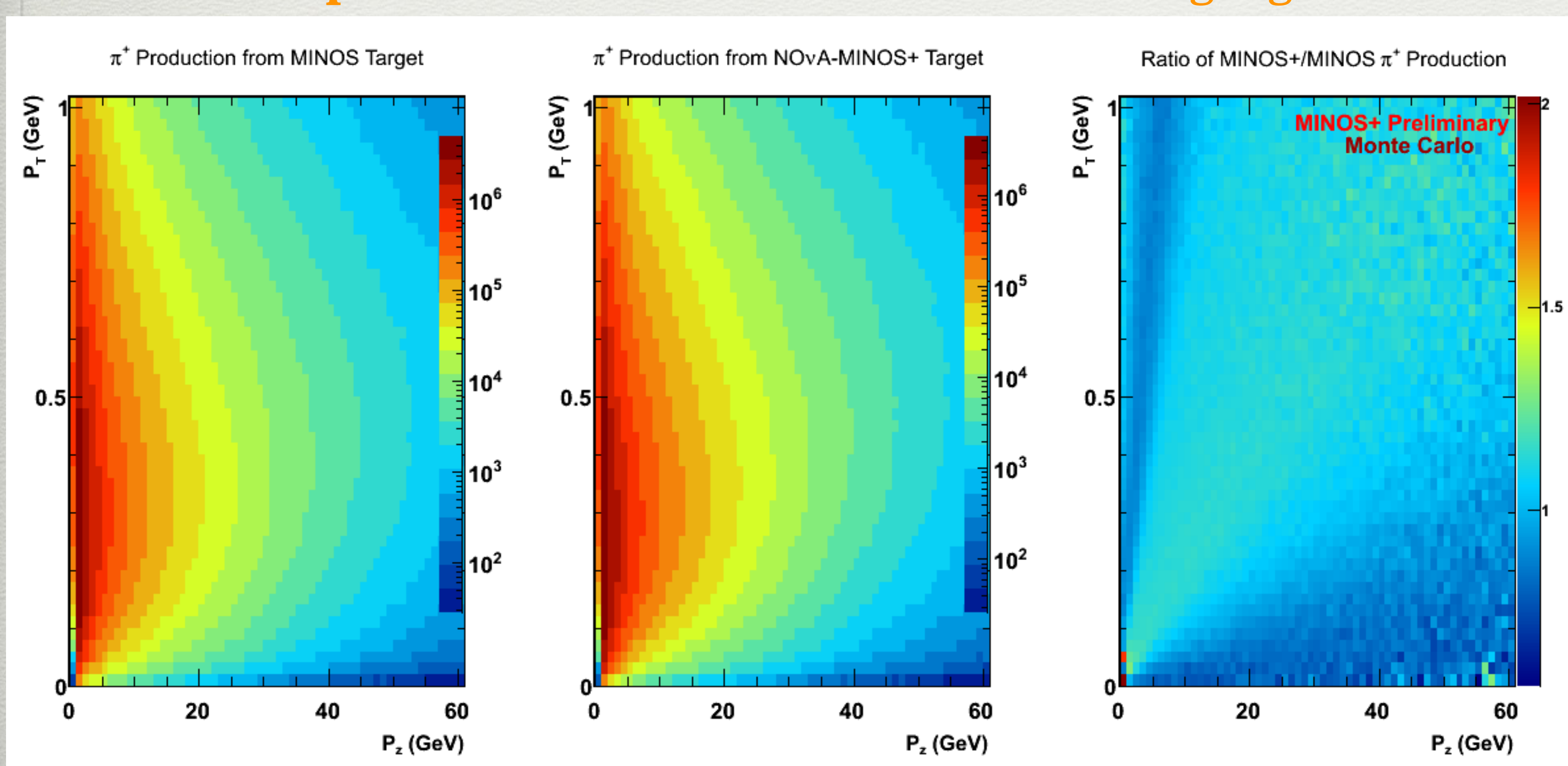


Comments

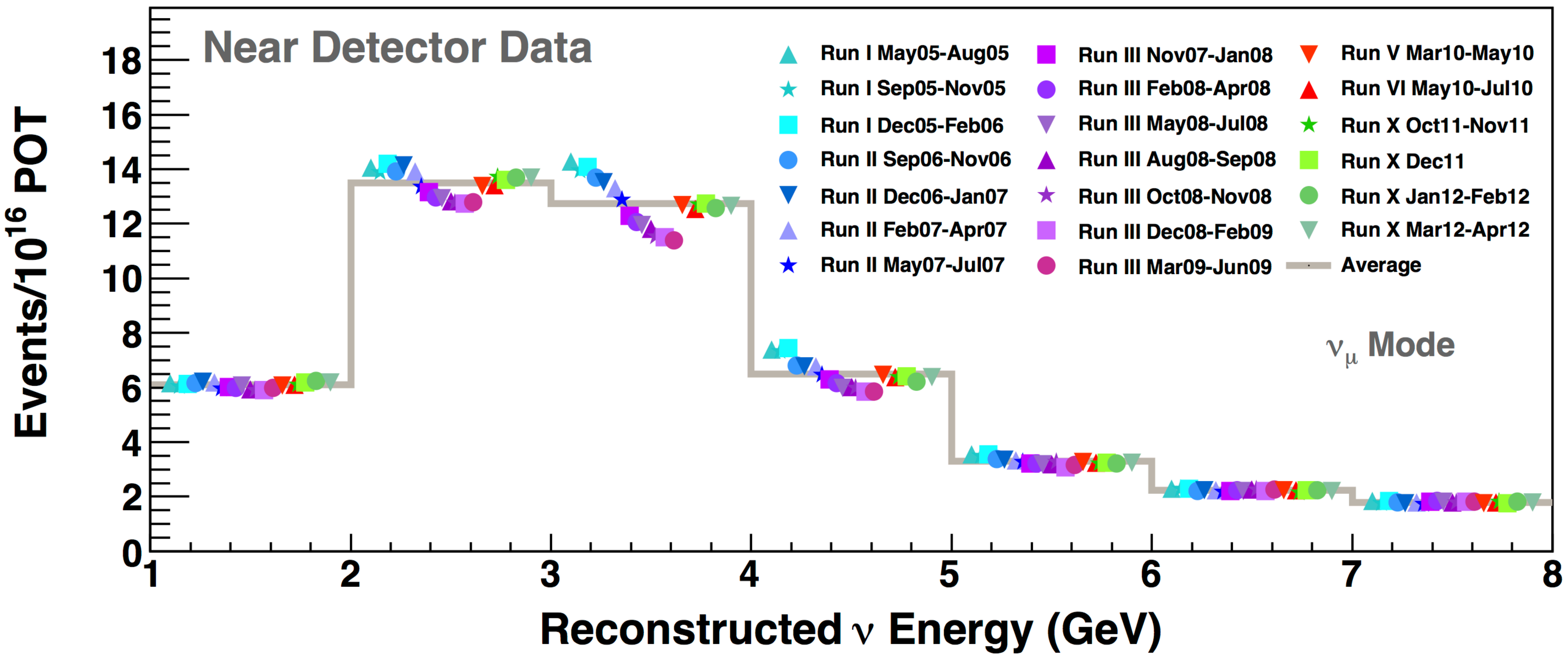
- While at lower energies, PPFX does a good job, especially for the LE beam, the horn off comparison shows that it is not perfect and the hadron production data we currently have is not really helping at higher energies - the low energy agreement may be creating a false sense of security that we understand the flux
- One needs to remember that every target design is different and yields different hadron production
- Any additional instrumentation in the beam line that we can use to observe the hadron production would be immensely helpful to disentangle various flux effects



The hadron production is different for different target geometries:



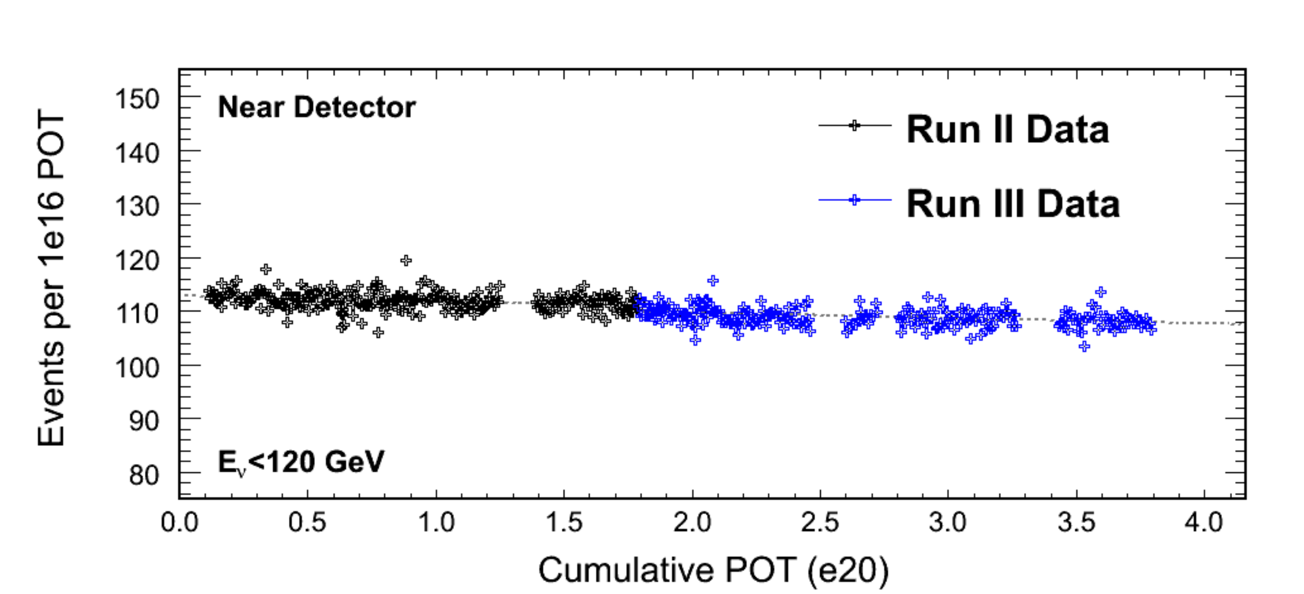
Data Quality Monitoring / Flux Monitoring

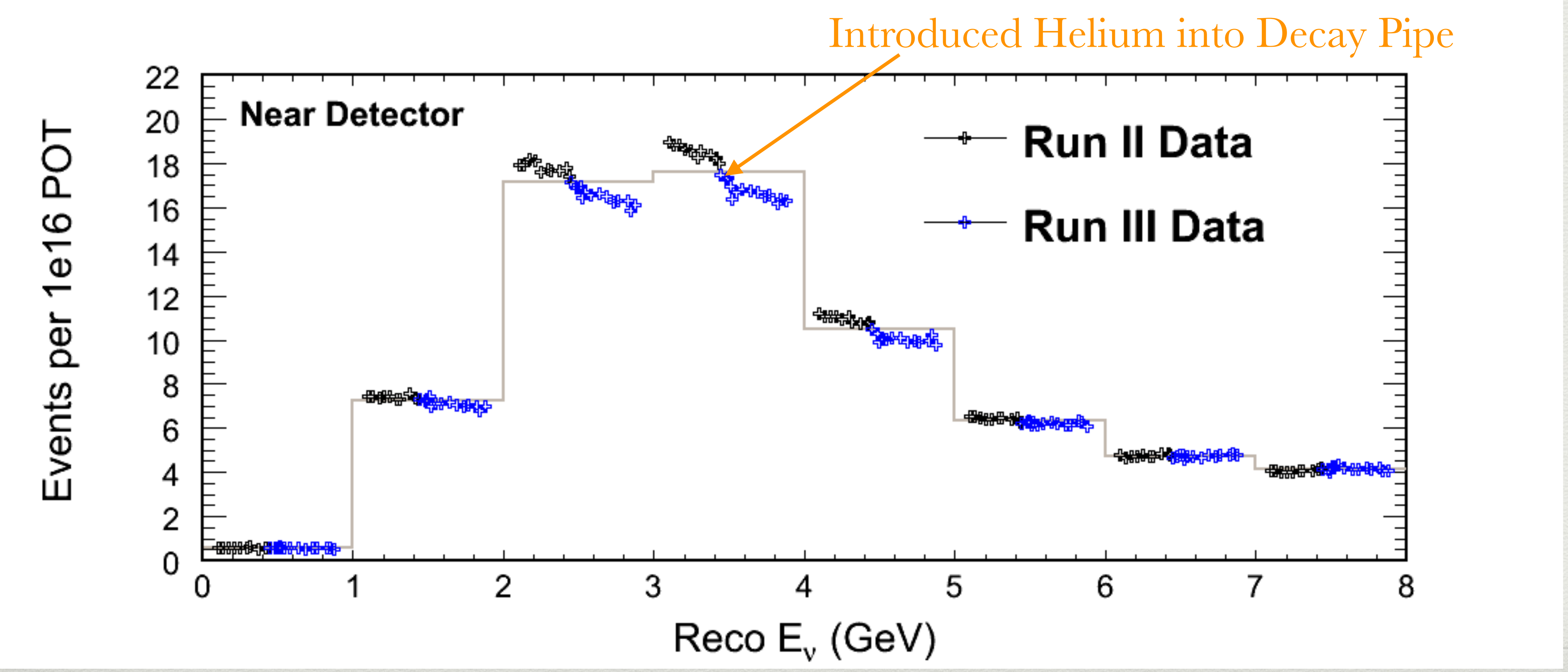


- A Near Detector spectrum serves as one of the first red flags that something is going wrong/not as it should be
- This is a plot of the data spectrum in the MINOS ND for the totality of LE running
- A significant drop off can be seen in the peak region for LE Runs II and III

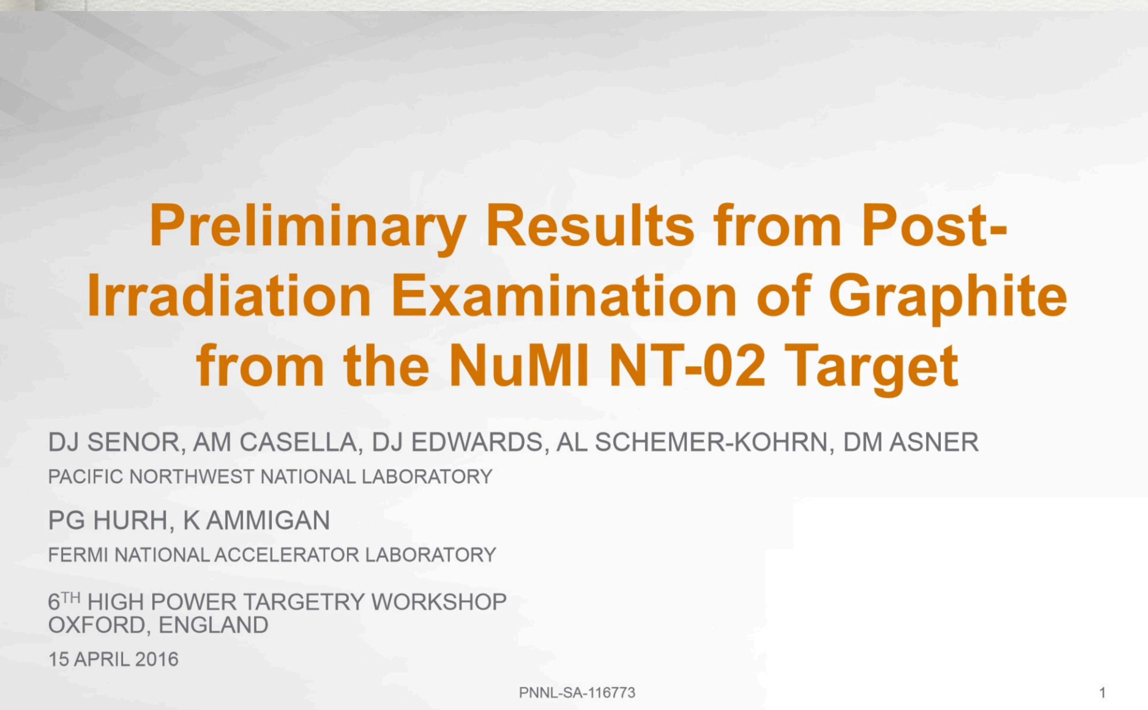
Target Decay?

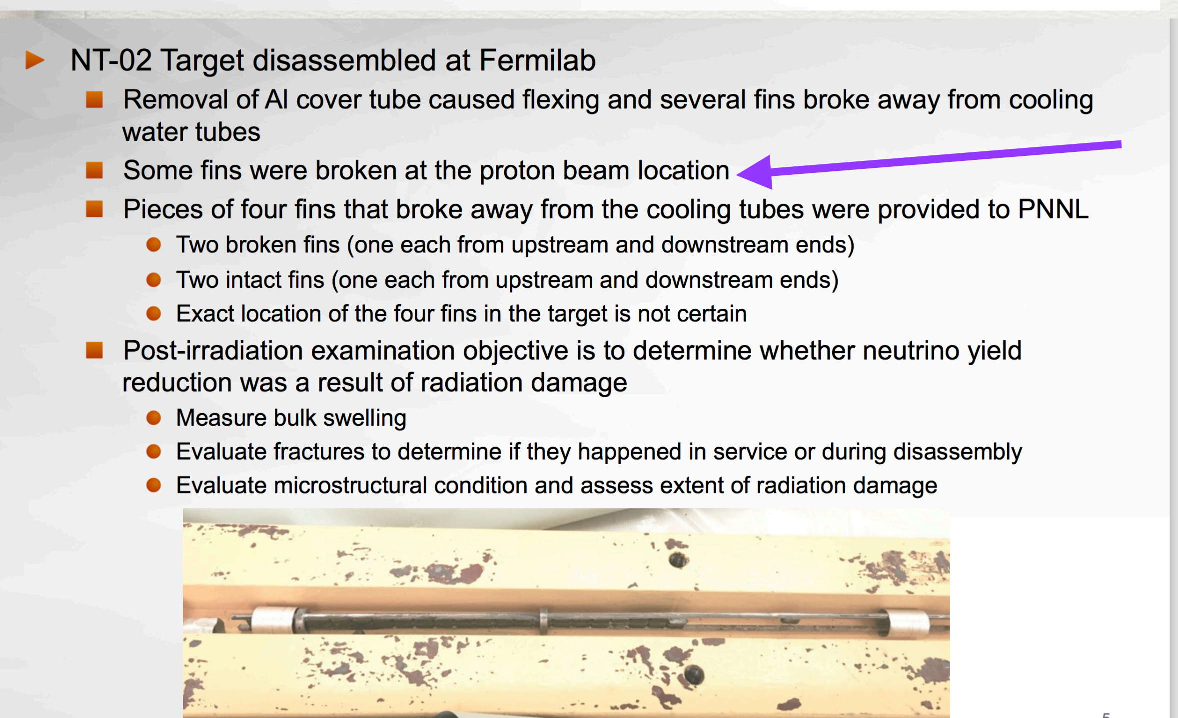
- We believe that we had target decay in target NT2: 2006->2009 (MINOS LE runs 2 and 3, Helium in 3)
- This was the best explanation of what we saw at the time when monitoring the time evolution of the beam spectrum





What actually happened?

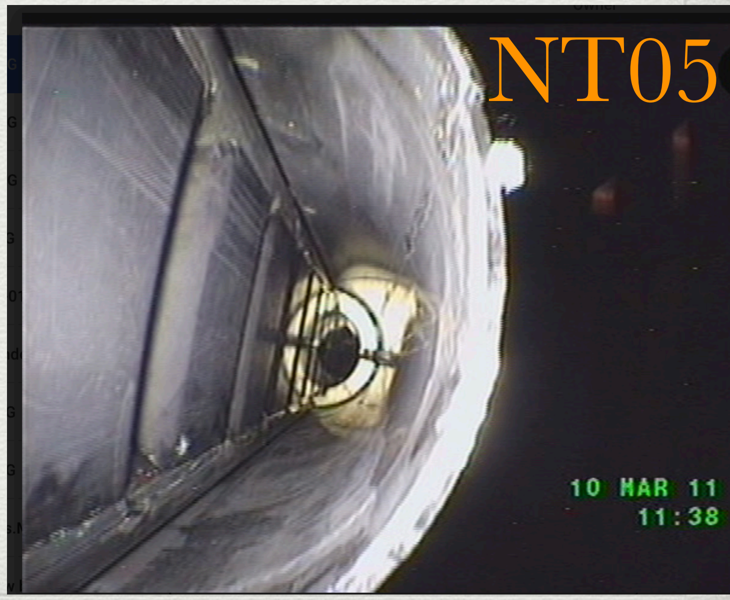




- Ways we modelled it at the time: fins 7+8 (shower max) missing
- Or 1mm hole in 4 target segments - less good fit
- I wanted to see what actually happened with the NT02 target
- Were 2 of the fins really missing?
- There was a movie available to watch from the target autopsy (thank you Jim Hylen)
- However, there were some problems when they opened the target can for the autopsy which could have potentially damaged the target, so conclusions are not certain, however…

NT02 Target

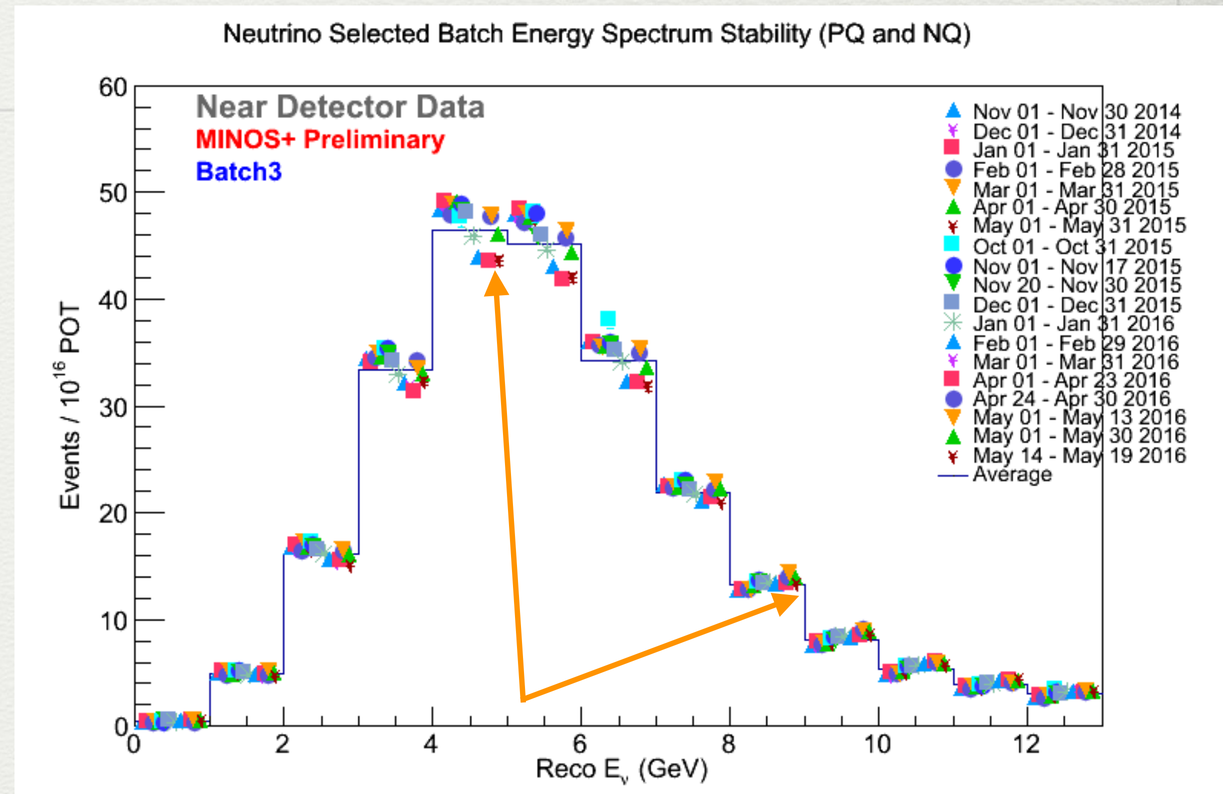
- It does appear that many of the Upstream fins were broken in the middle where the beam centre is
- It is clear that without a ND, we would not have known about the target degradation
- The high statistics data in the ND allowed us to see that there was a problem and we were able to include this effect in our FD predictions and add a systematic error for this effect for the affected runs, as well as use the corresponding ND data to predict the FD



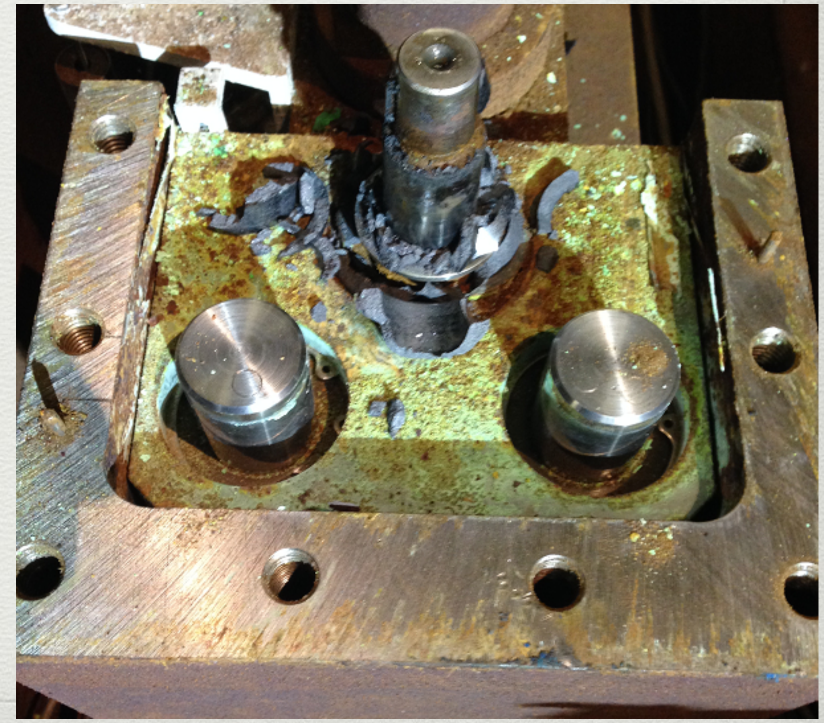
- There is currently no evidence of other targets having been damaged in this way

Horn Tilt, Beam Spot Size

- In the ME running, the number of effects that have happened has increased
- This is due to the increased power of the beam which requires slip-stacking, a larger beam spot size and other changes
- All those effects can be seen in the MINOS ND
- Again, there was something that happened to the NuMI beam in early 2016 which no-one had predicted - the horn tilted slightly due to a corroded part
- We saw it in the MINOS ND
- We are currently working on fitting for this effect in our beam fits to use this information in our analyses



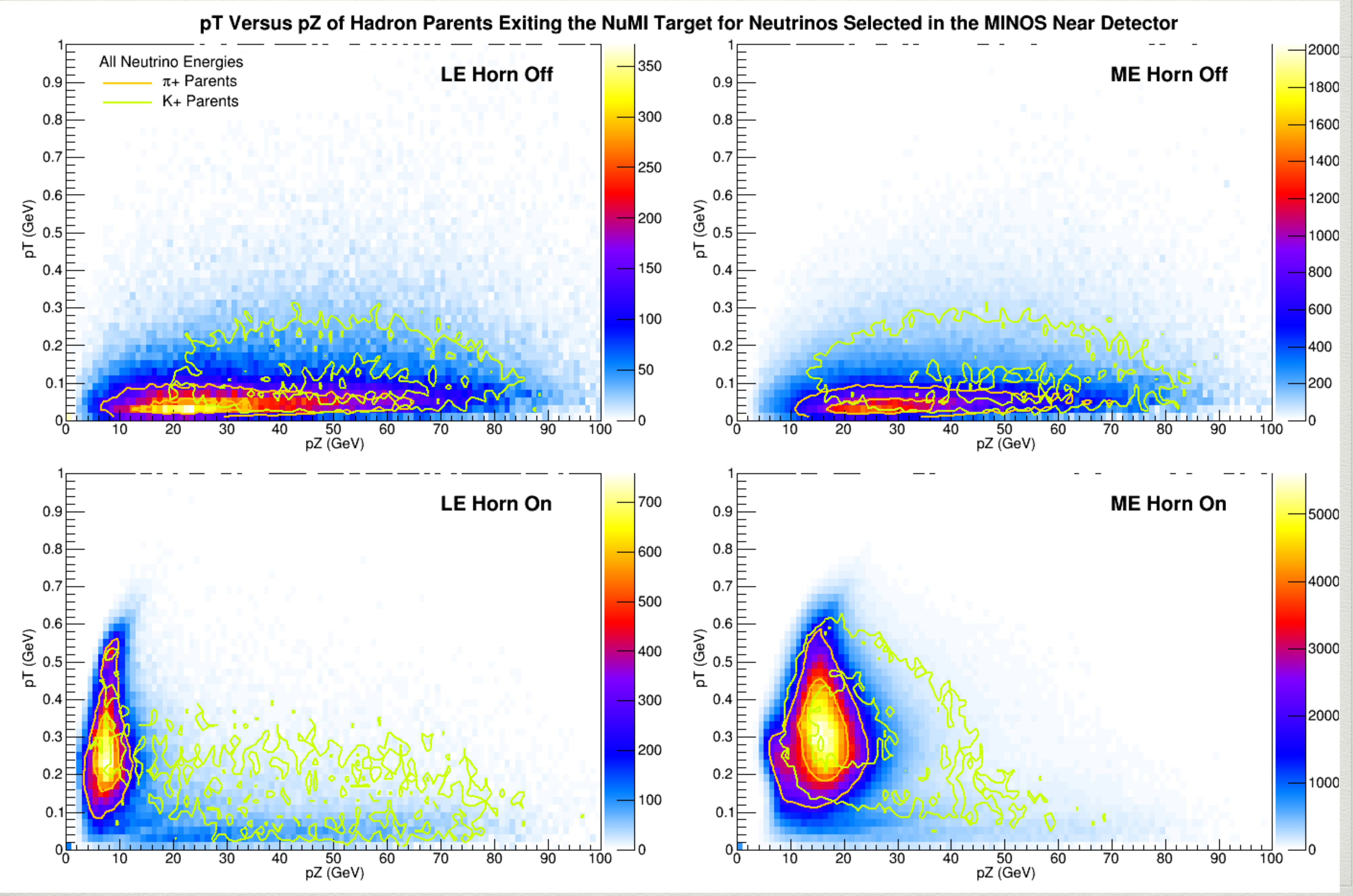
Jim Hylen, NuMI OPS, Nov 2016



Ongoing work

- Currently a lot of work is focusing on the last run of data we took with MINOS+, where the horn tilt happened
- We are also trying to understand the falling edge of the focusing peak data/MC differences - none of the effects considered / found so far explain the data/MC difference there
- We have been continuing work on better beam fits (especially for the horn tilt problem), also experimenting with using Horn Off samples only for the hadron production part of the fit, however, this needs to be considered very carefully because of the pT-pZ space that the neutrino parents come from (see next slide) - work in progress

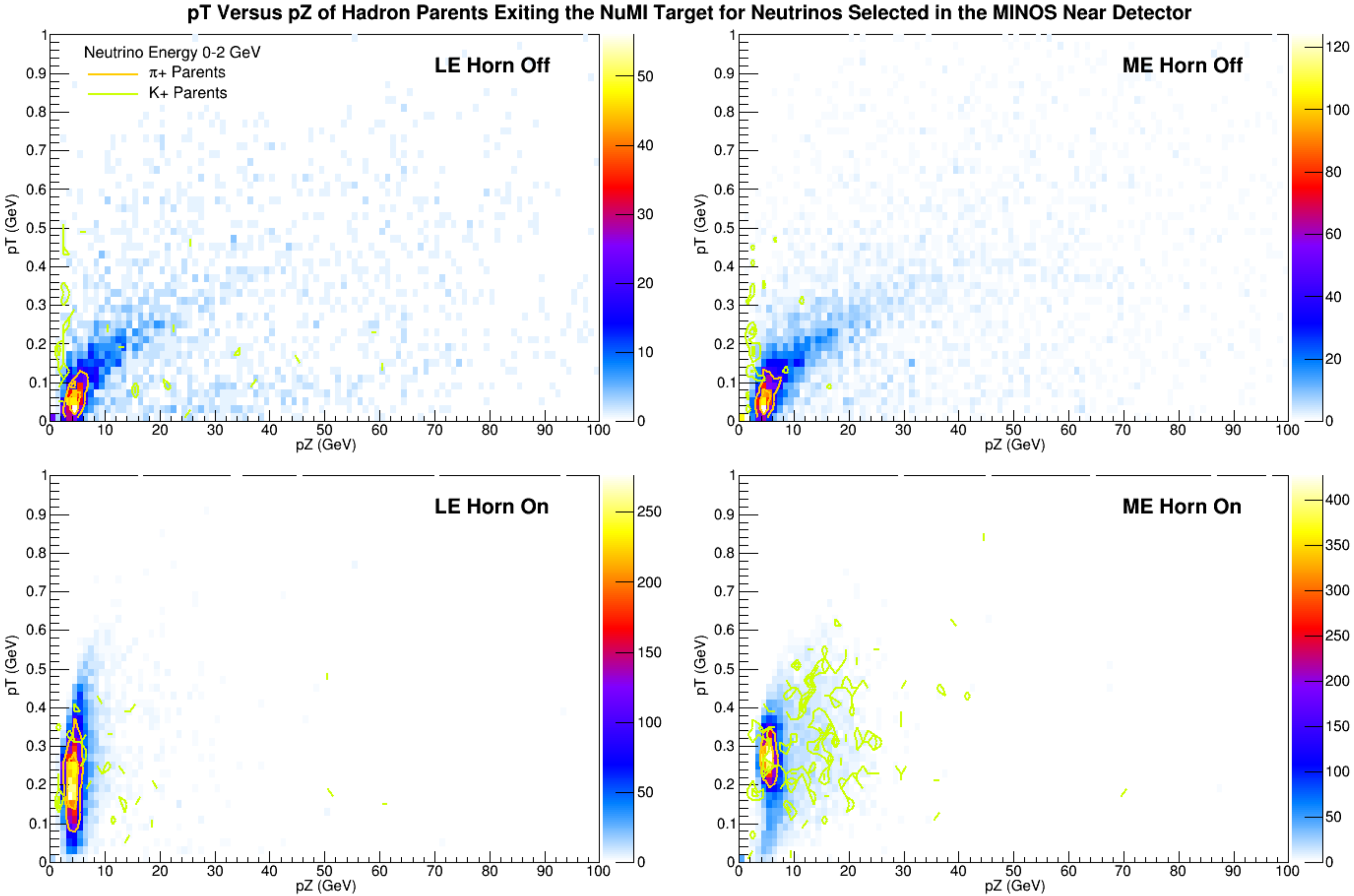
Parent hadron pT-pZ for different beams (Monte Carlo)



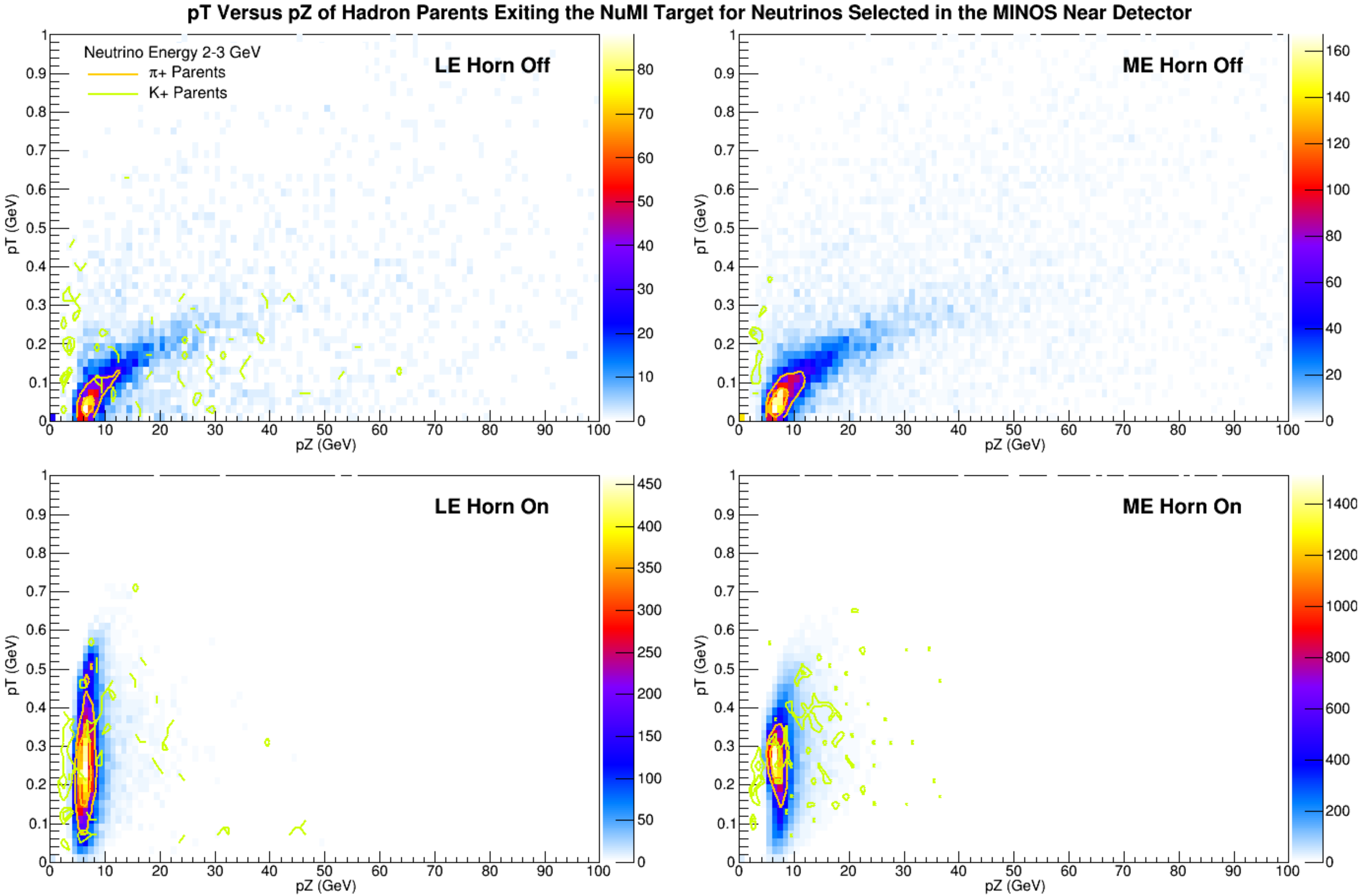
pT-pZ for different beams

- The following slides illustrate the magnitude of the task ahead, what we are essentially trying to understand here
- The plots will be the same as on the slide before, however, in slices of reconstructed energy seen by the MINOS ND

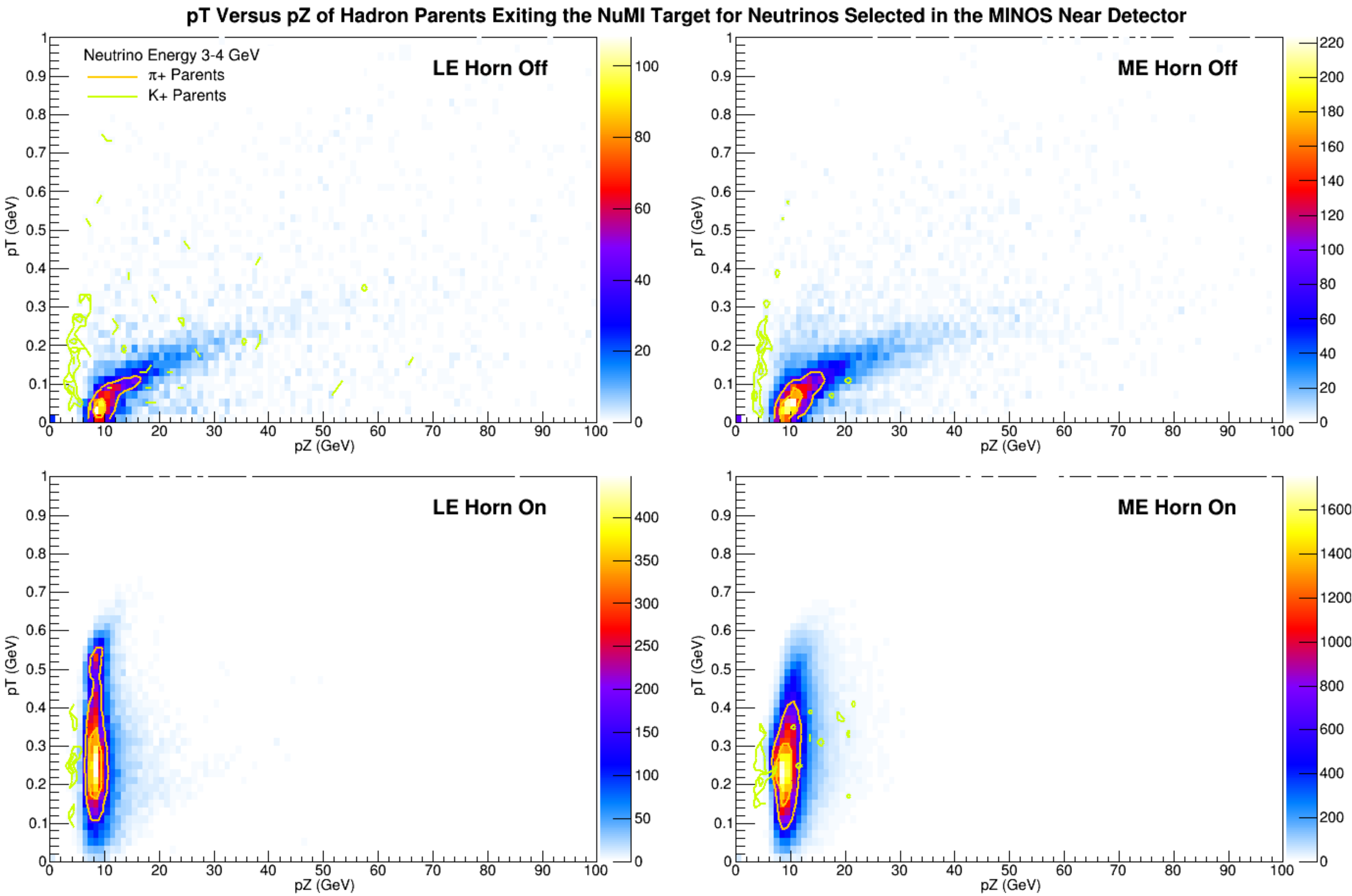
Reconstructed Energy in MINOS ND 0-2GeV



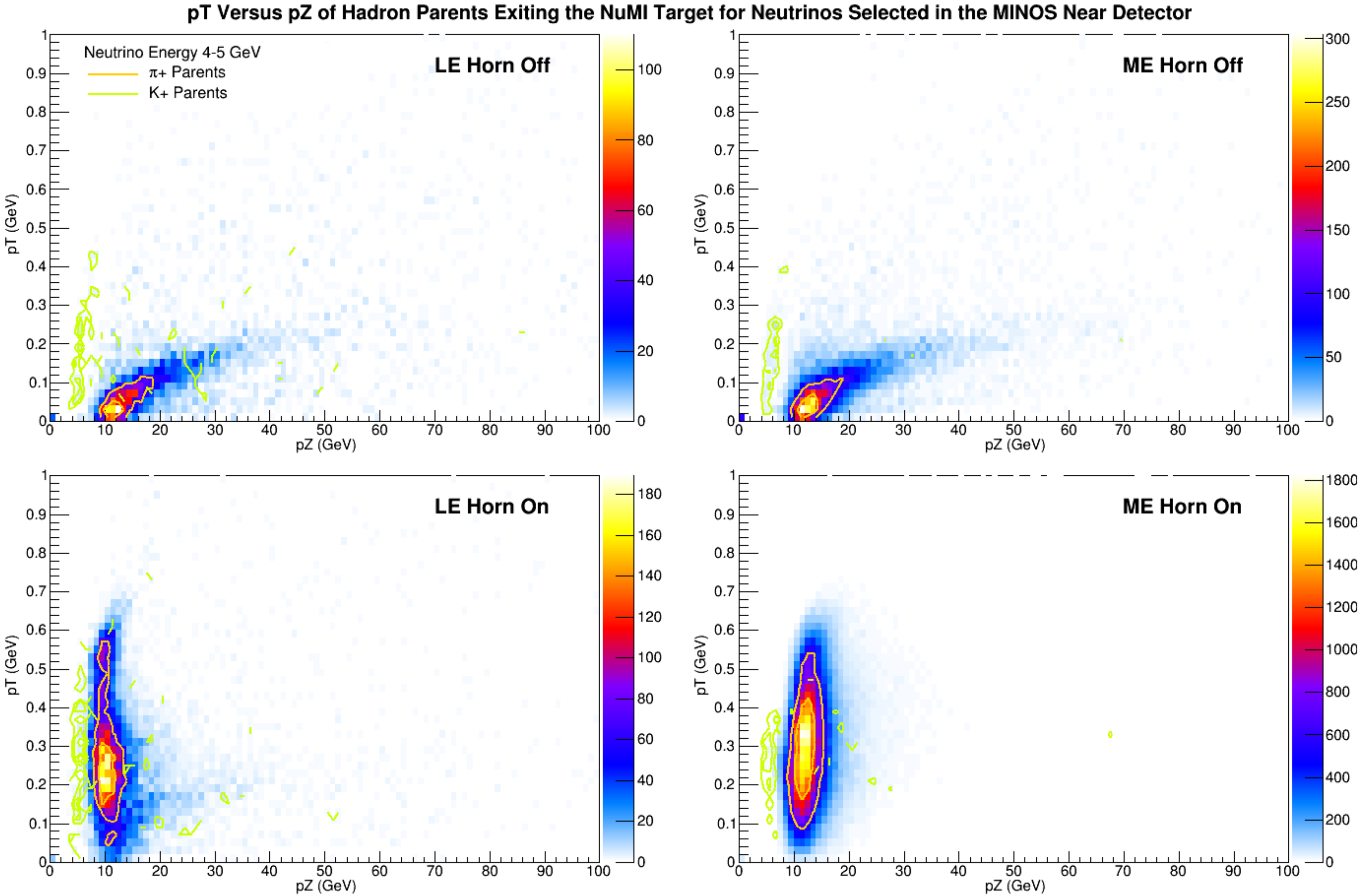
Reconstructed Energy in MINOS ND 2-3GeV



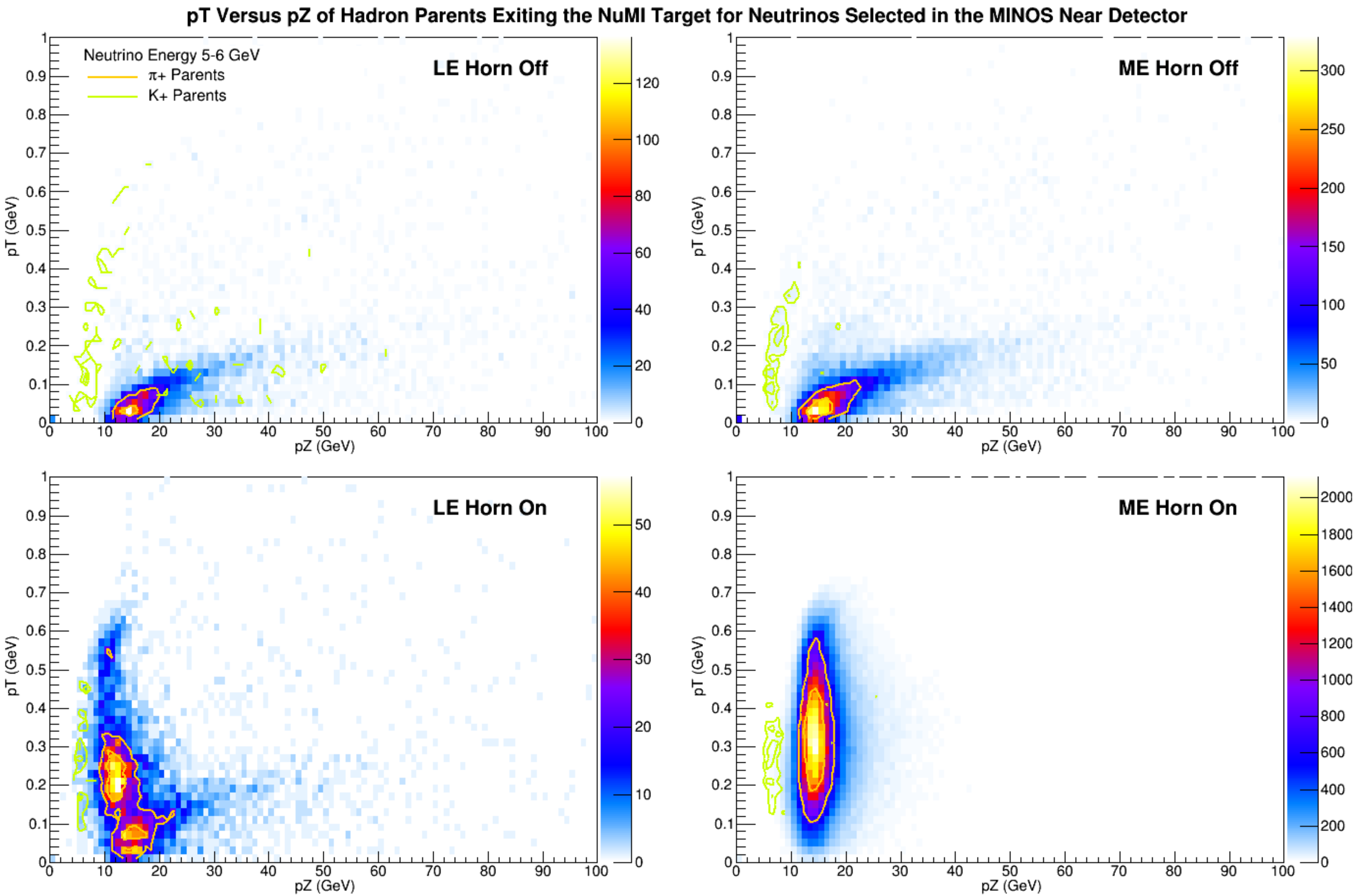
Reconstructed Energy in MINOS ND 3-4GeV



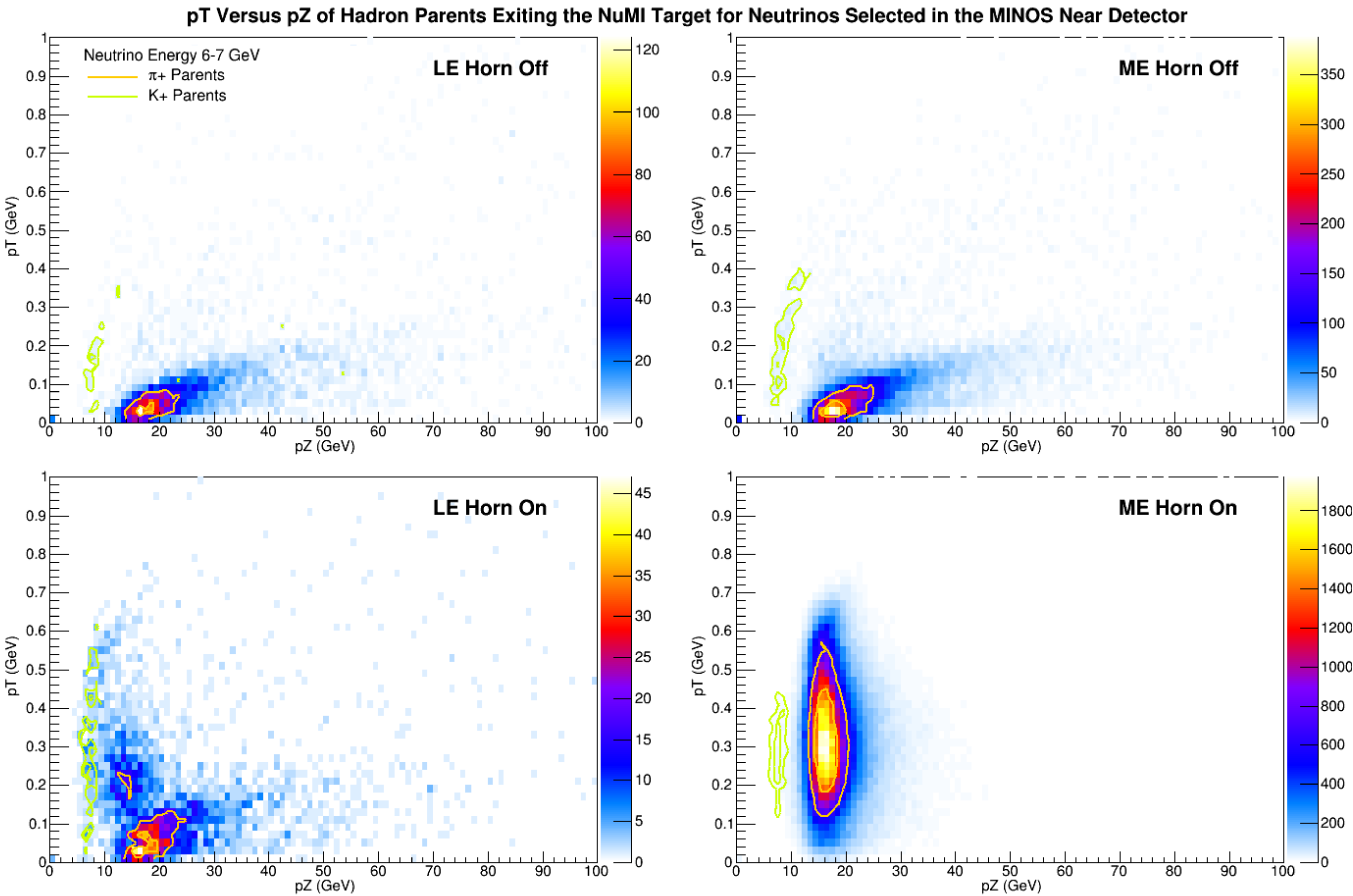
Reconstructed Energy in MINOS ND 4-5GeV



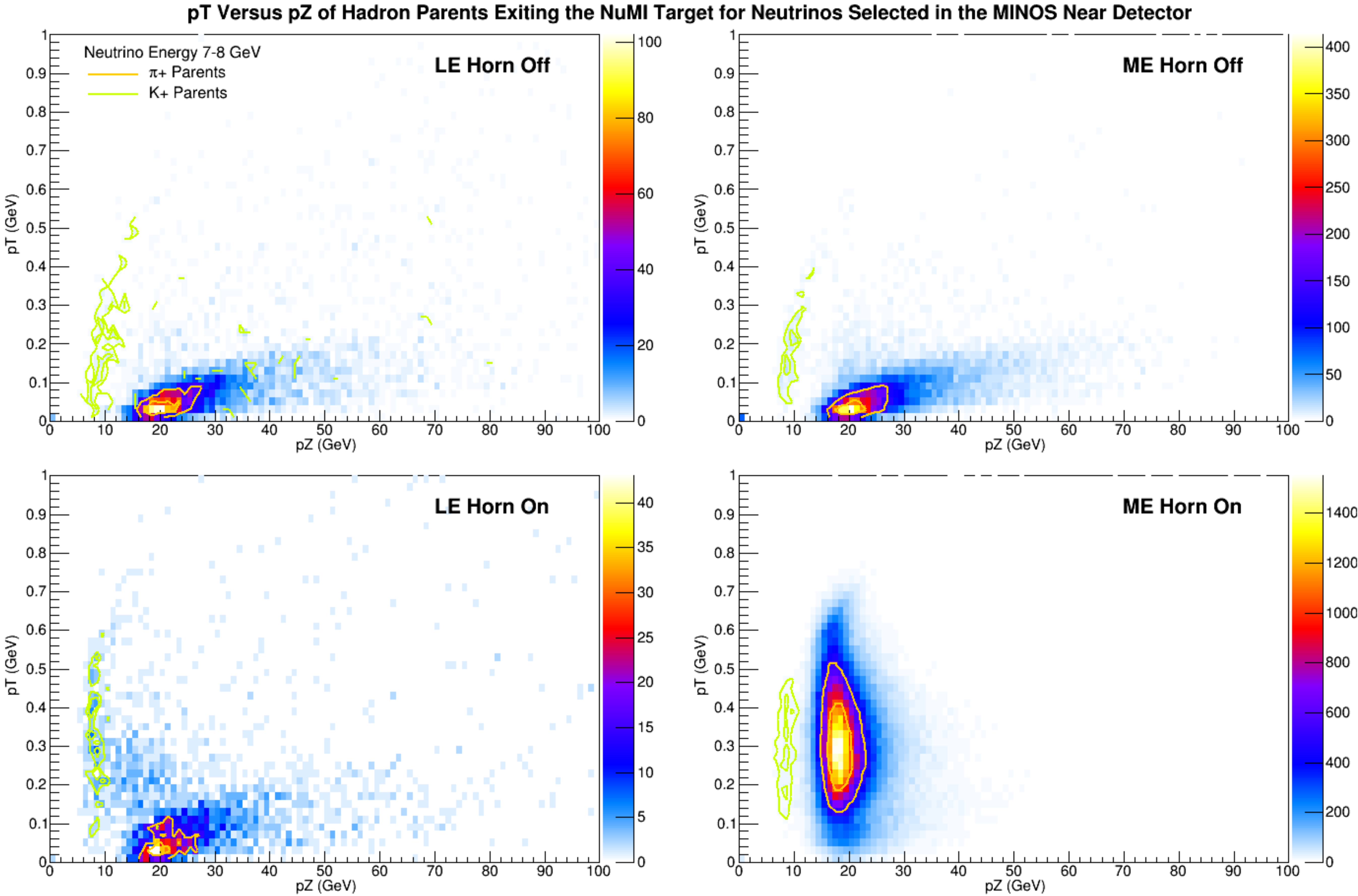
Reconstructed Energy in MINOS ND 5-6GeV



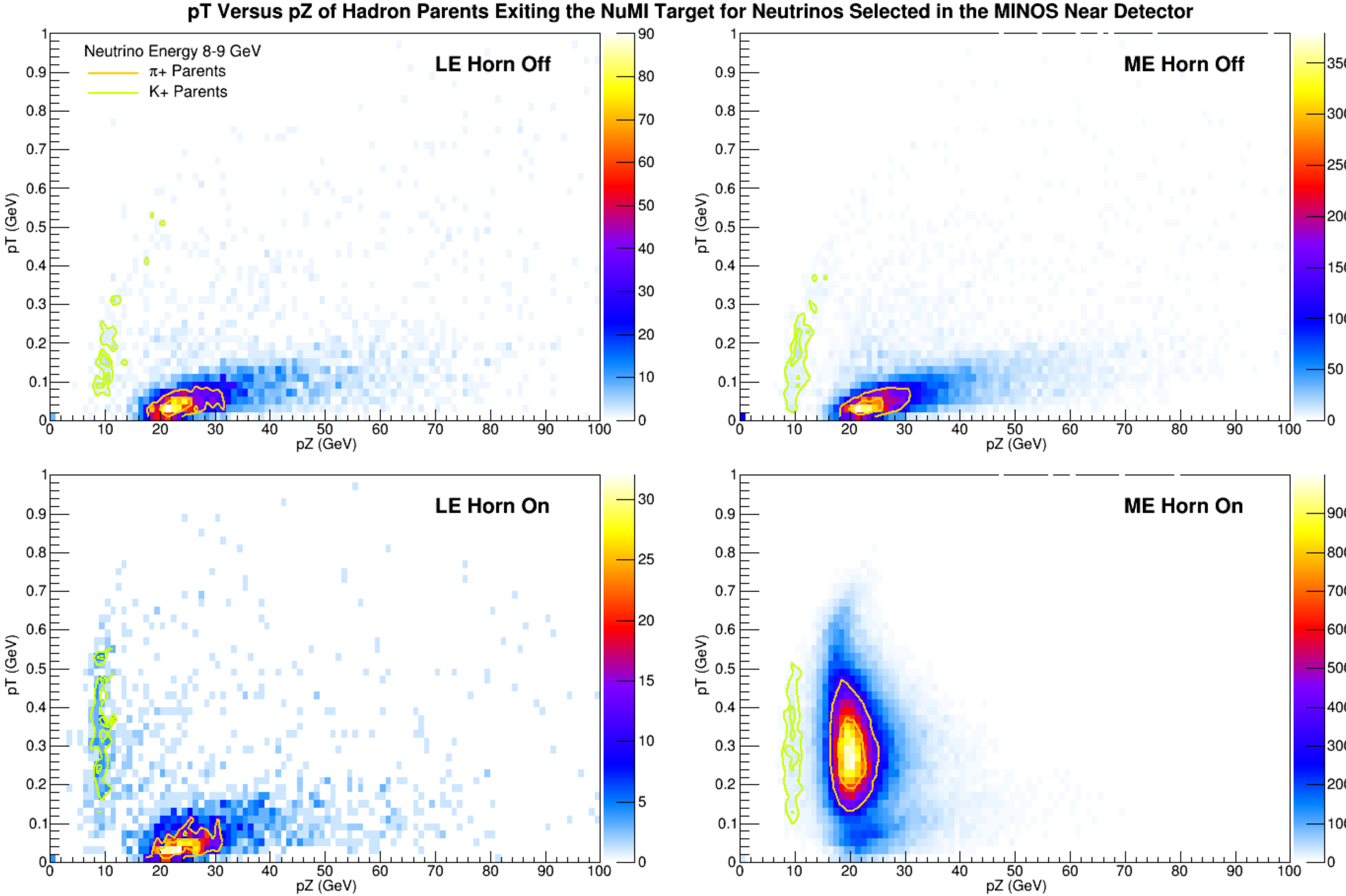
Reconstructed Energy in MINOS ND 6-7GeV



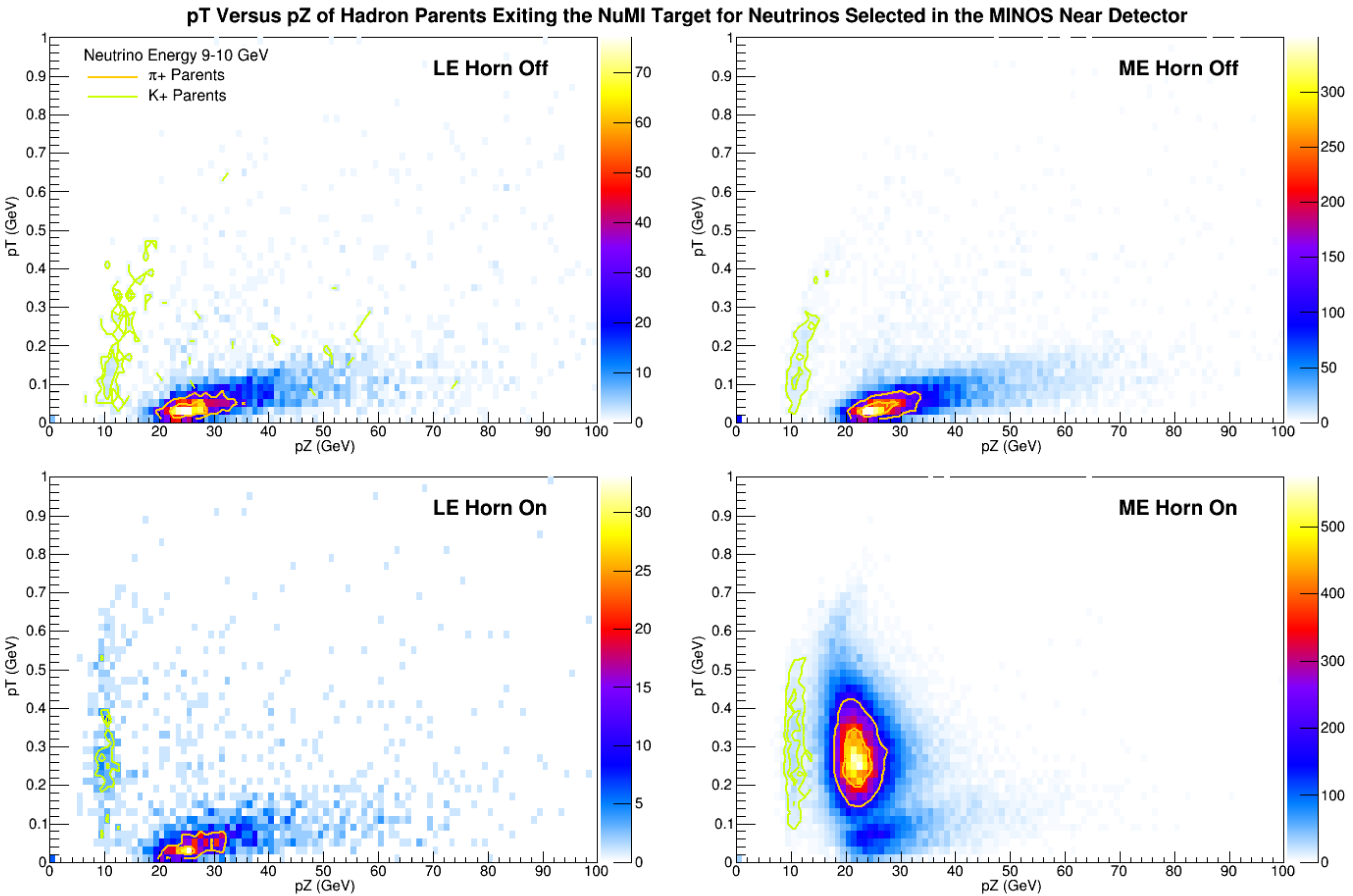
Reconstructed Energy in MINOS ND 7-8GeV



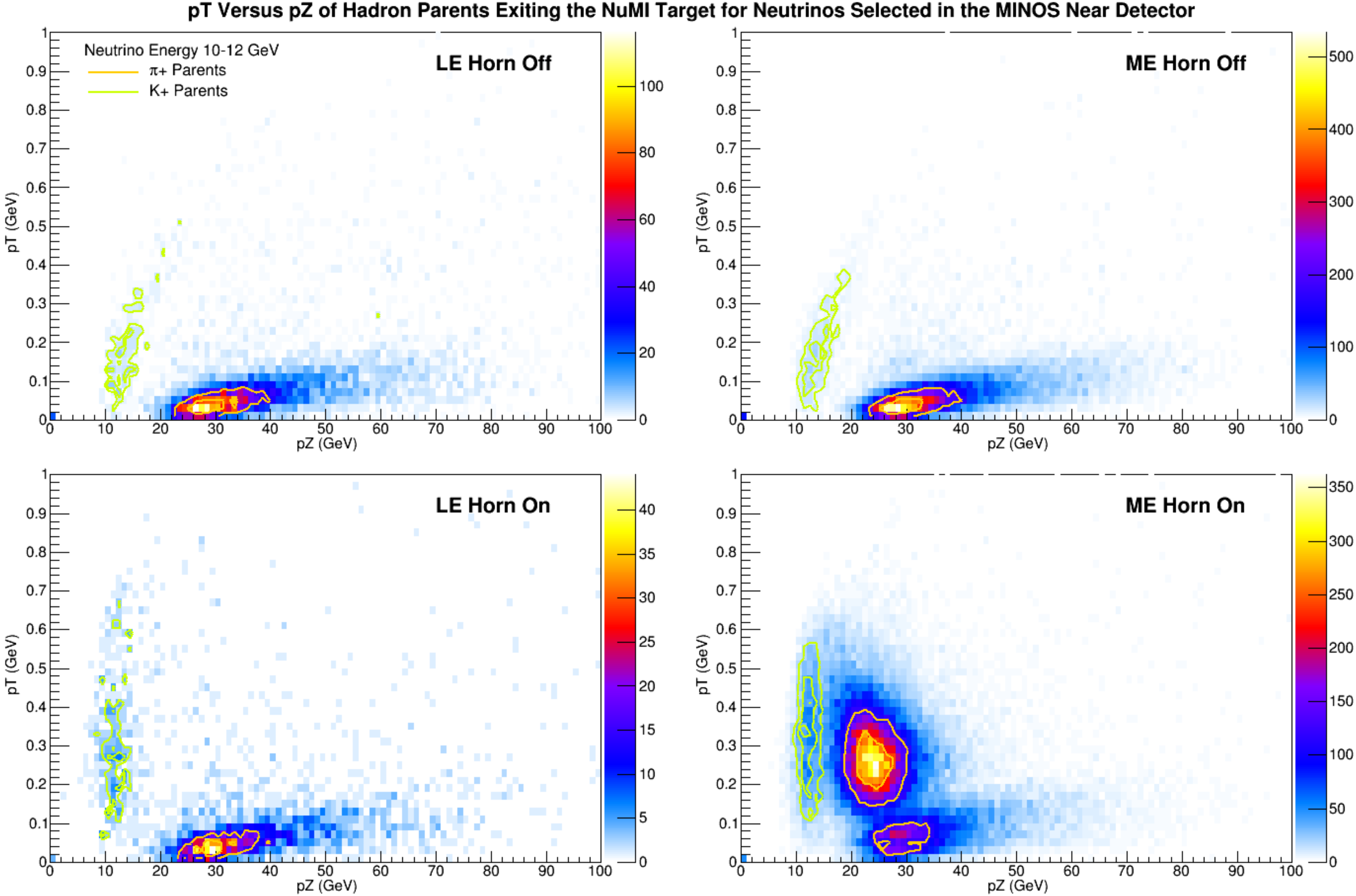
Reconstructed Energy in MINOS ND 8-9GeV



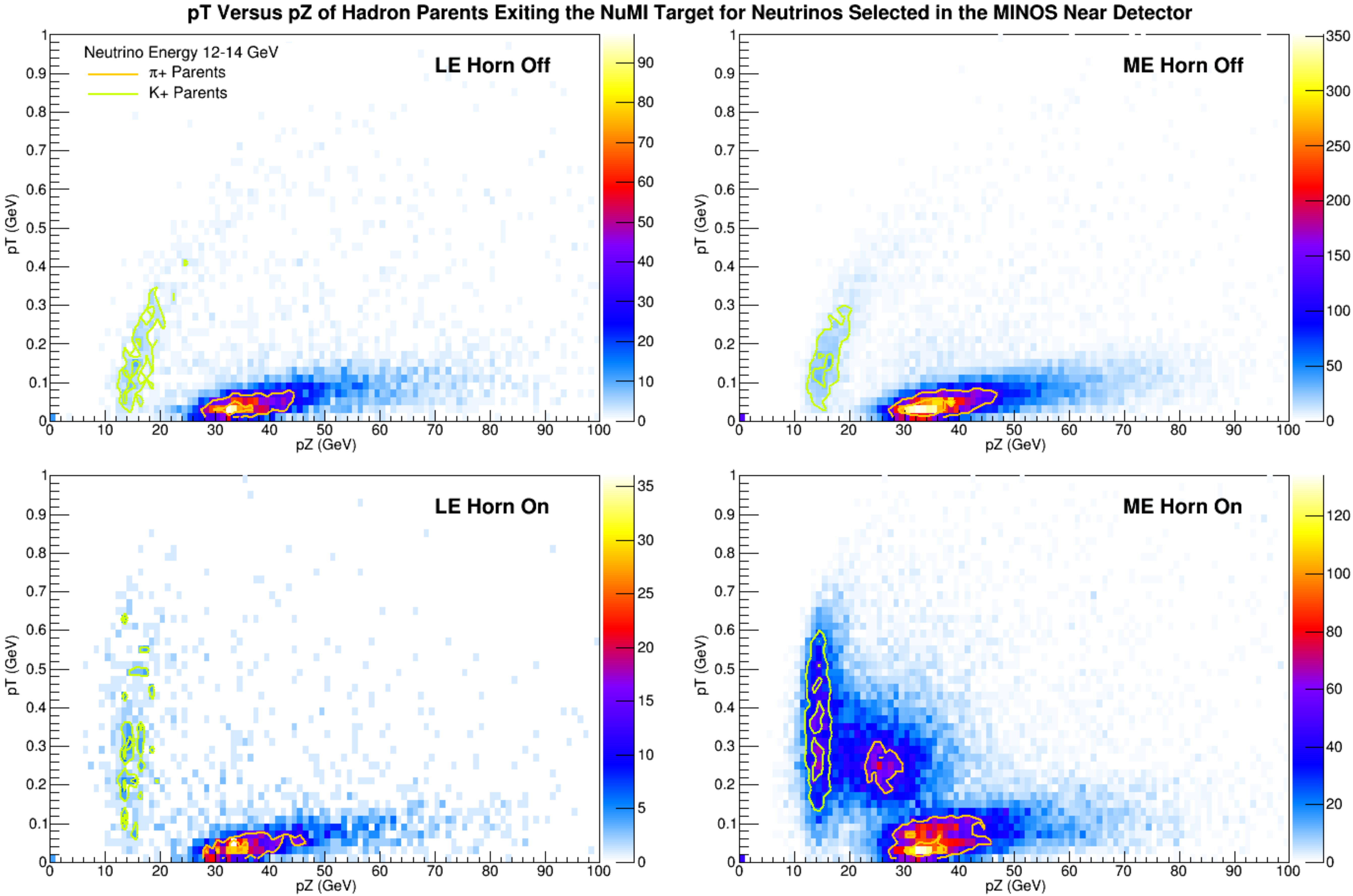
Reconstructed Energy in MINOS ND 9-10GeV



Reconstructed Energy in MINOS ND 10-12GeV

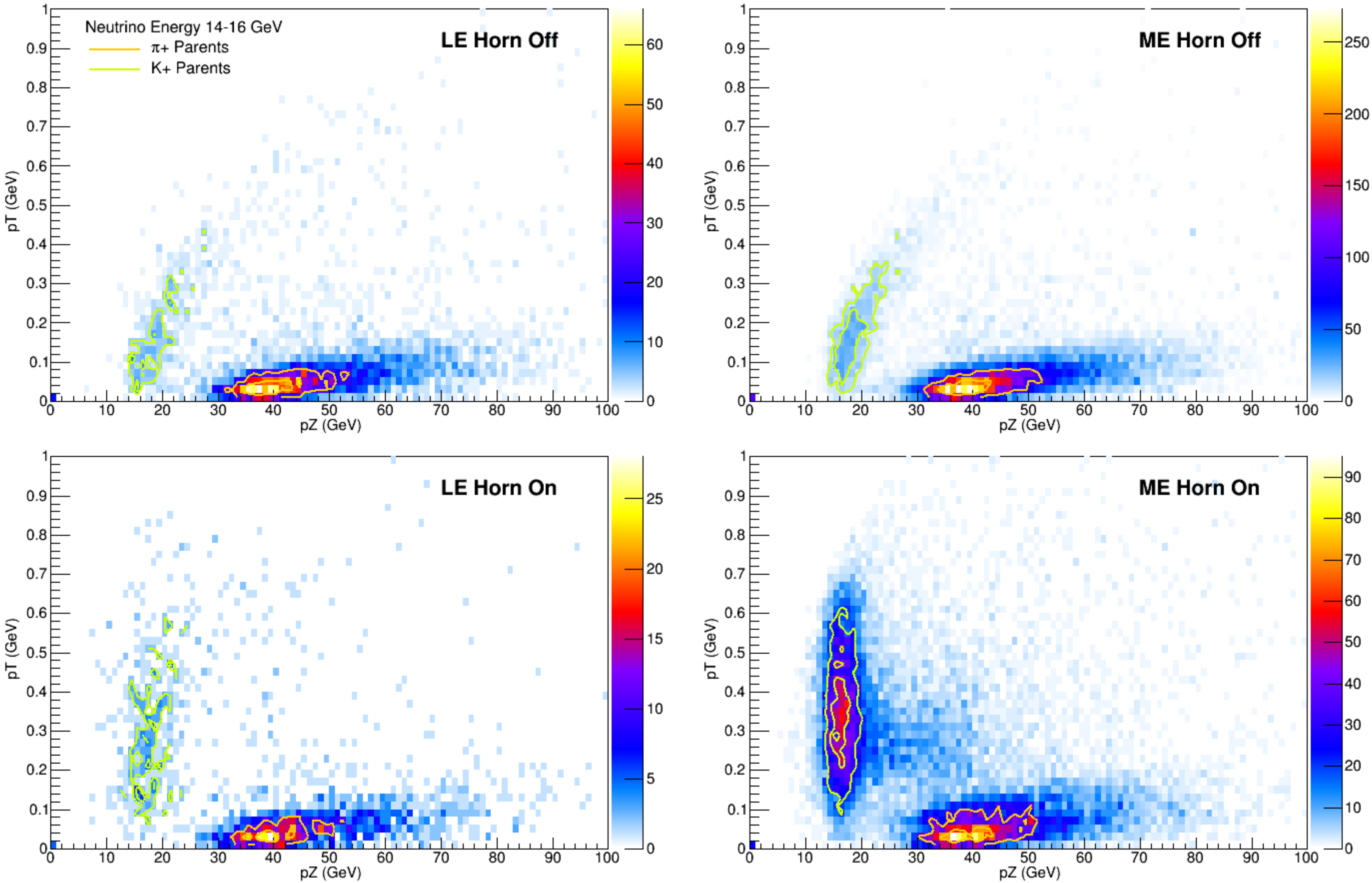


Reconstructed Energy in MINOS ND 12-14GeV

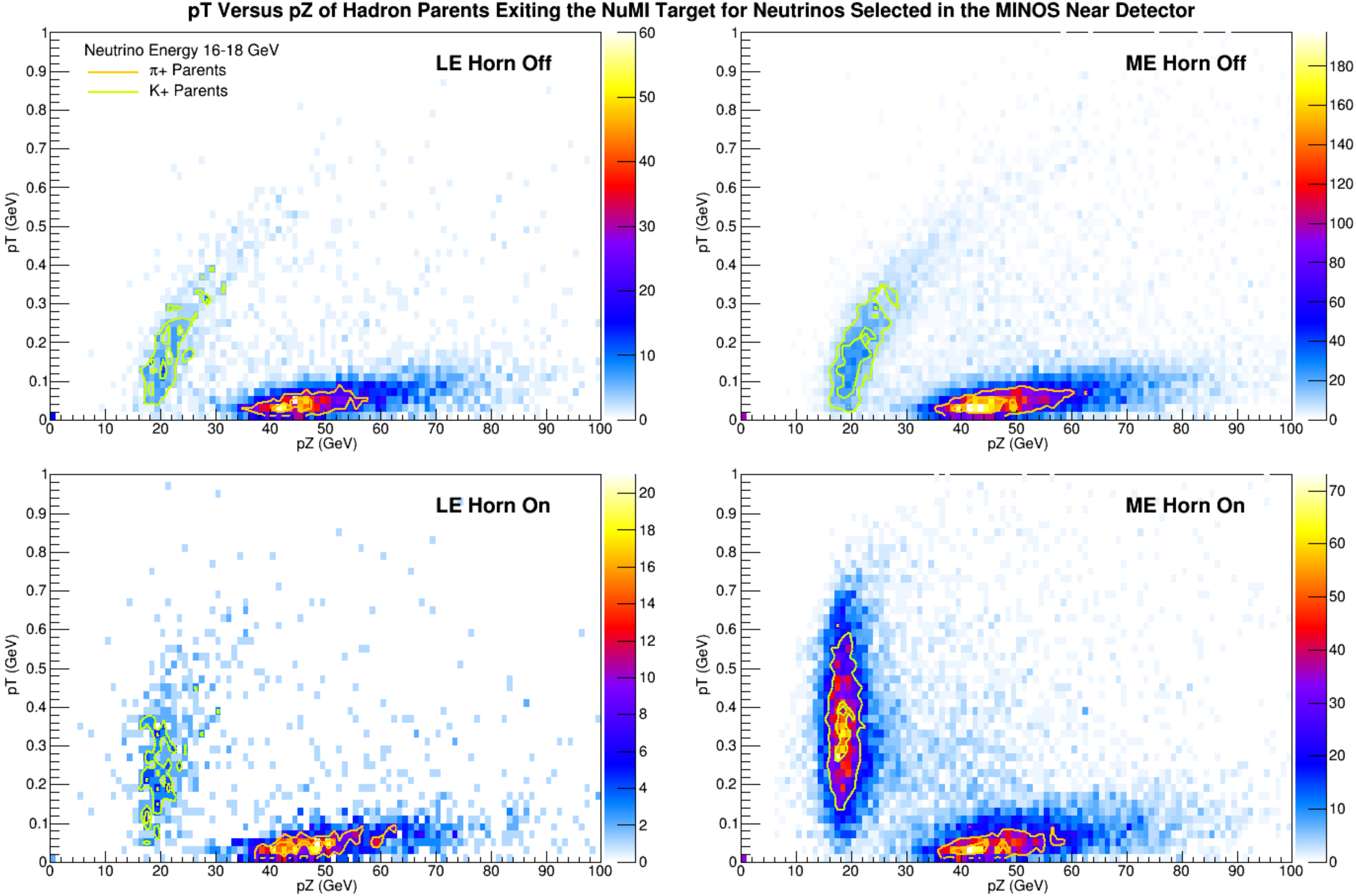


Reconstructed Energy in MINOS ND 14-16GeV

pT Versus pZ of Hadron Parents Exiting the NuMI Target for Neutrinos Selected in the MINOS Near Detector



Reconstructed Energy in MINOS ND 16-18GeV



Summary

Summary

- From our experience on MINOS(+), a ND is absolutely vital for several reasons:
  - Cancellation of systematic errors, provides un-oscillated sample for Far Detector prediction
  - Understanding the beam flux using a high statistics sample for a given target
  - It provides a high statistics sample to improve one's MC simulation and to understand various detector effects
  - Monitoring of the beam - always the first indication that something is going wrong!
  - In the case of imperfect data/MC agreement in the ND, can use the ND data spectrum to predict the FD (ideally functionally identical detector to reduce detector systematics) - this can use data taken at the same time as the FD data to remove any effects to do with fluctuations / changes in the beam
  - Opportunity to carry out a multitude of other analyses like cross-section and flux analyses for example

Summary

- My recommendation would be to use as much instrumentation in the beam as possible to understand the beam flux (muon monitors were of limited use, they suffered from man power issues among others and a ND usually provides better information) - Ideally at least one functionally identical (to the FD) ND

- Possibly directly measuring hadron production would be a large bonus and extremely useful to minimise flux errors

- THE IMPORTANCE OF AT LEAST ONE NEAR DETECTOR AND THE UNDERSTANDING OF THE BEAM FLUX CANNOT BE UNDER-ESTIMATED, ESPECIALLY FOR FUTURE HIGH PRECISION NEUTRINO MEASUREMENTS